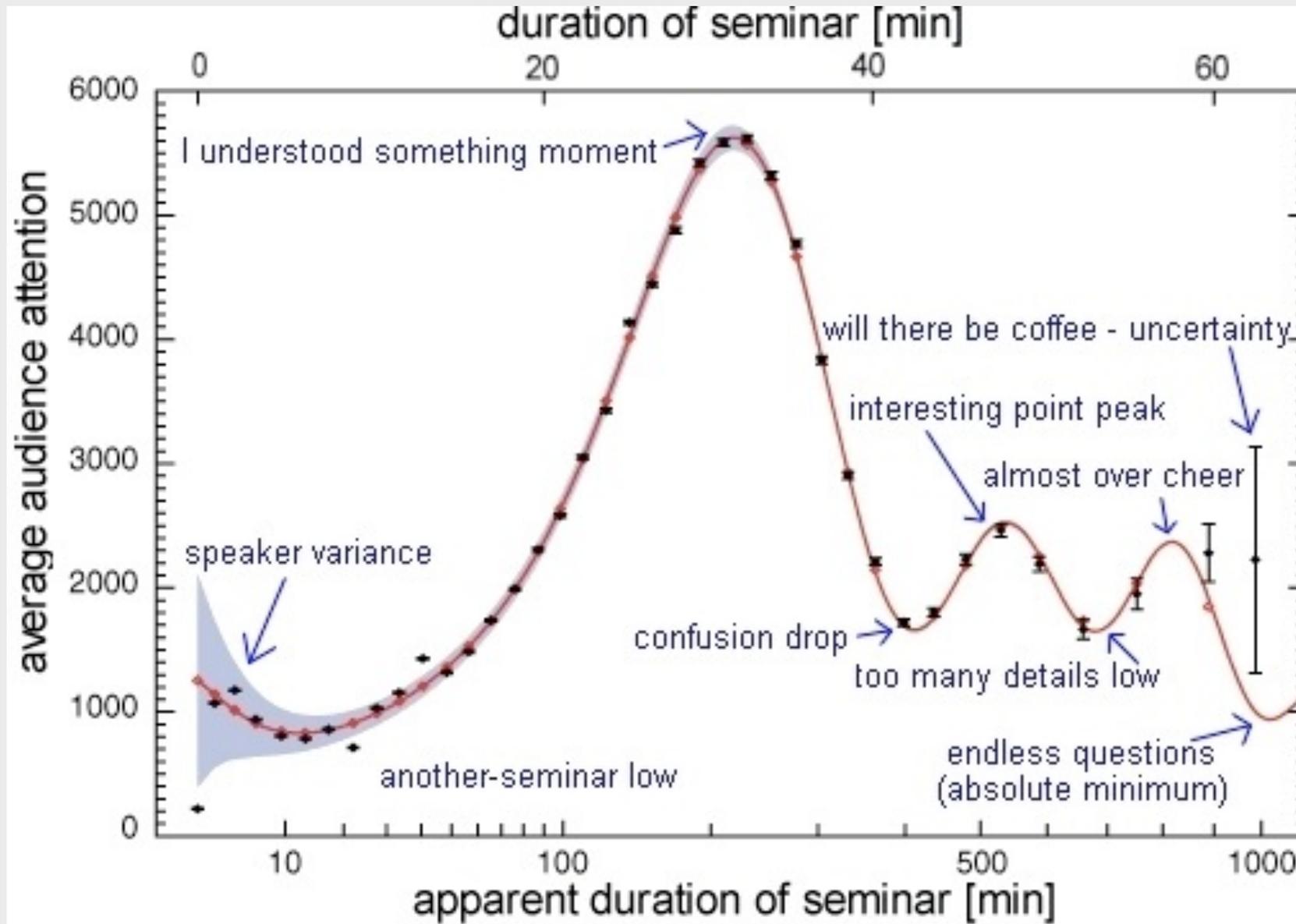
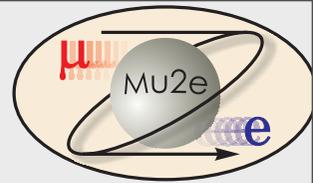
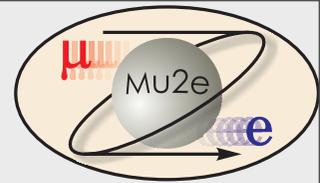
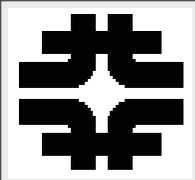


Outline



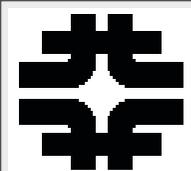
<http://th.physik.uni-frankfurt.de/~hossi/Bilder/BR/powerspectrum.jpg>



A New Charged Lepton Flavor Violation Experiment: Muon-Electron Conversion at FNAL



R. Bernstein
Fermilab
for the Mu2e Collaboration
5 April 2010



Collaboration



Boston University
Brookhaven National Laboratory
University of California, Berkeley
University of California, Irvine
City University of New York
Fermilab
University of Illinois, Urbana-Champaign
R. Bernstein, FNAL

Institute for Nuclear Research, Moscow, Russia
JINR, Dubna, Russia
Lawrence Berkeley National Laboratory
Los Alamos National Laboratory
Northwestern University
INFN Frascati
INFN Pisa, Università di Pisa, Pisa, Italy

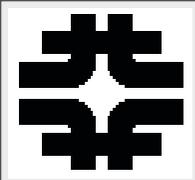
INFN Lecce, Università del Salento, Italy
Rice University
Syracuse University
University of Virginia
College of William and Mary

103 collaborators

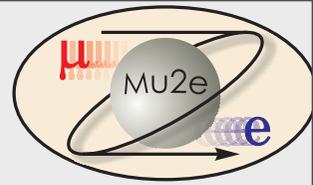
3

Mu2e

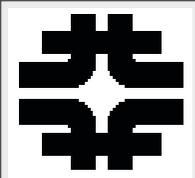
U. Chicago 5/17/10



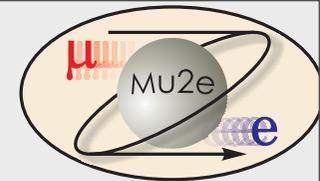
Outline



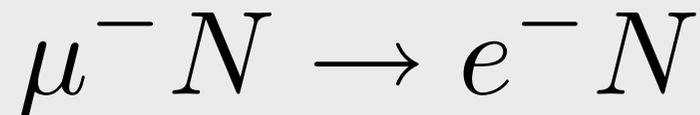
- The search for muon-electron conversion
- Experimental Technique
- Fermilab Accelerator
- Project X Upgrades and Mu2e
- Cost and Schedule
- Conclusions



What is μe Conversion?



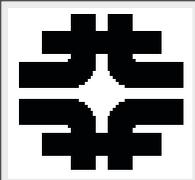
muon converts to electron in the presence of a nucleus



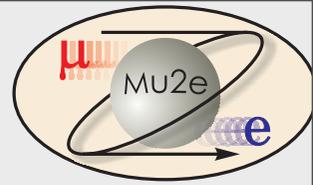
$$R_{\mu e} = \frac{\Gamma(\mu^- + (A, Z) \rightarrow e^- + (A, Z))}{\Gamma(\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1))}$$

- Charged Lepton Flavor Violation (CLFV)
 - will measure $R_{\mu e} < 6 \times 10^{-17}$ @ 90%CL
- Related Processes:

μ or $\tau \rightarrow e\gamma$, e^+e^-e , $K_L \rightarrow \mu e$, and more



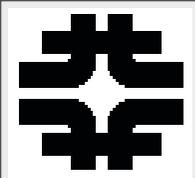
Bureaucratic Status



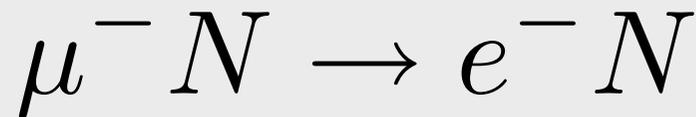
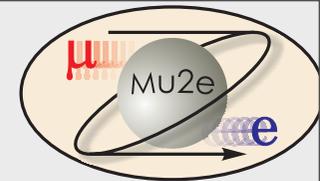
- Strong P5 endorsement:
 - **The panel recommends pursuing the muon-to-electron conversion experiment... under all budget scenarios considered by the panel”**
- Approved by Fermilab
- CD-0! (30 Nov 2009)



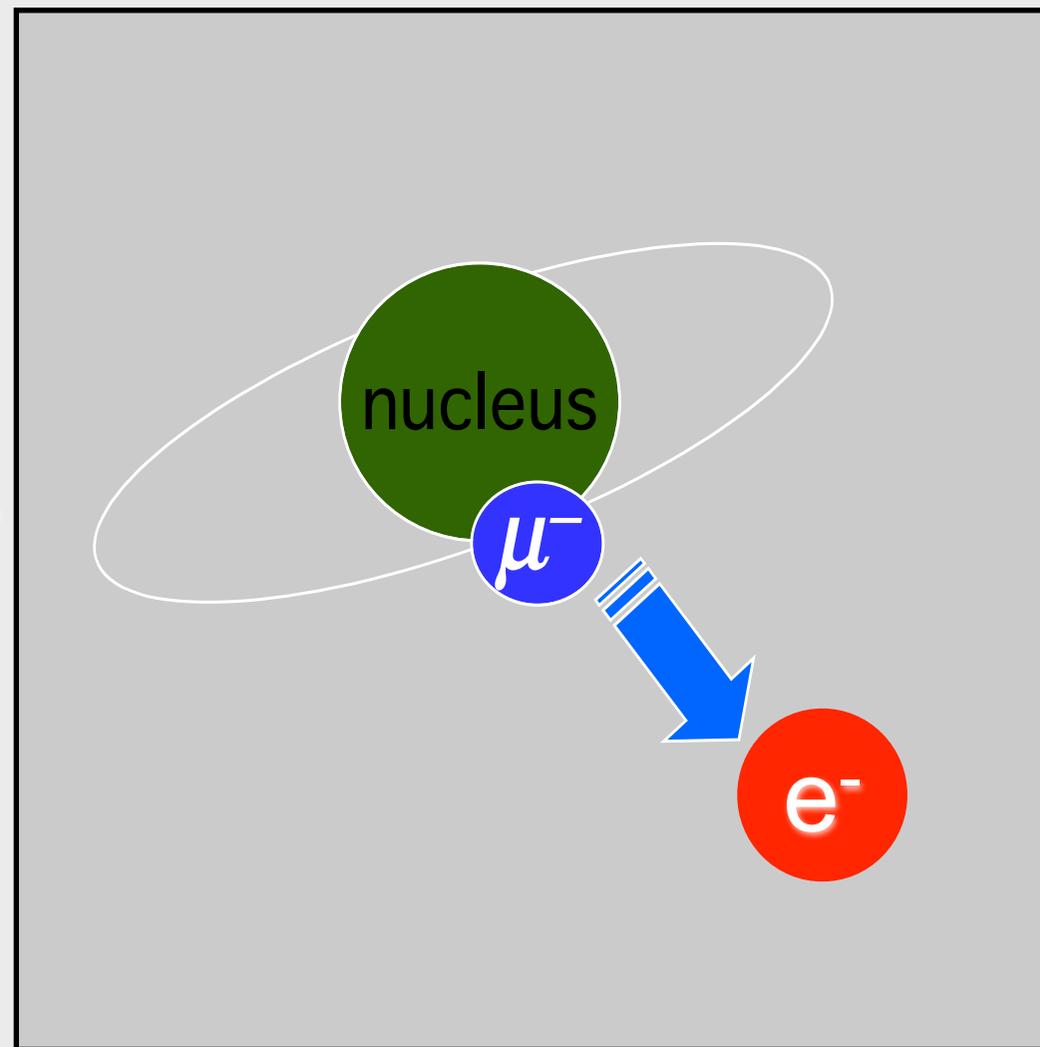
CD process

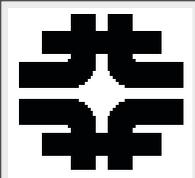


Experimental Signal

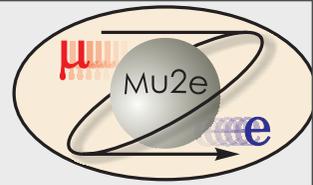


- A Single Monoenergetic Electron
- If $N = \text{Al}$, $E_e = 105. \text{ MeV}$
 - electron energy depends on Z
- Nucleus coherently recoils off outgoing electron, no breakup





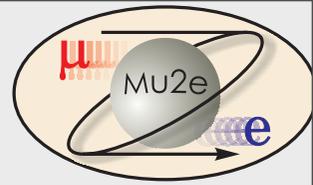
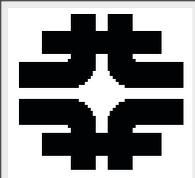
“Who ordered that?”



– I.I. Rabi, 1936

After the μ was discovered, it was logical to think the μ is just an excited electron:

- expect $\text{BR}(\mu \rightarrow e\gamma) \approx 10^{-4}$
- Unless another ν , in Intermediate Vector Boson Loop, cancels (Feinberg, 1958)
 - ➔ same as GIM mechanism!



“Who ordered that?”

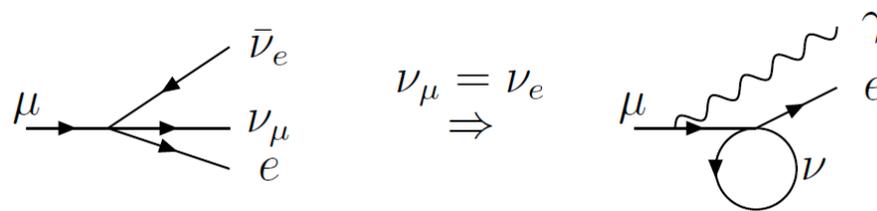


– I.I. Rabi, 1936

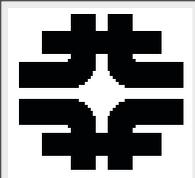
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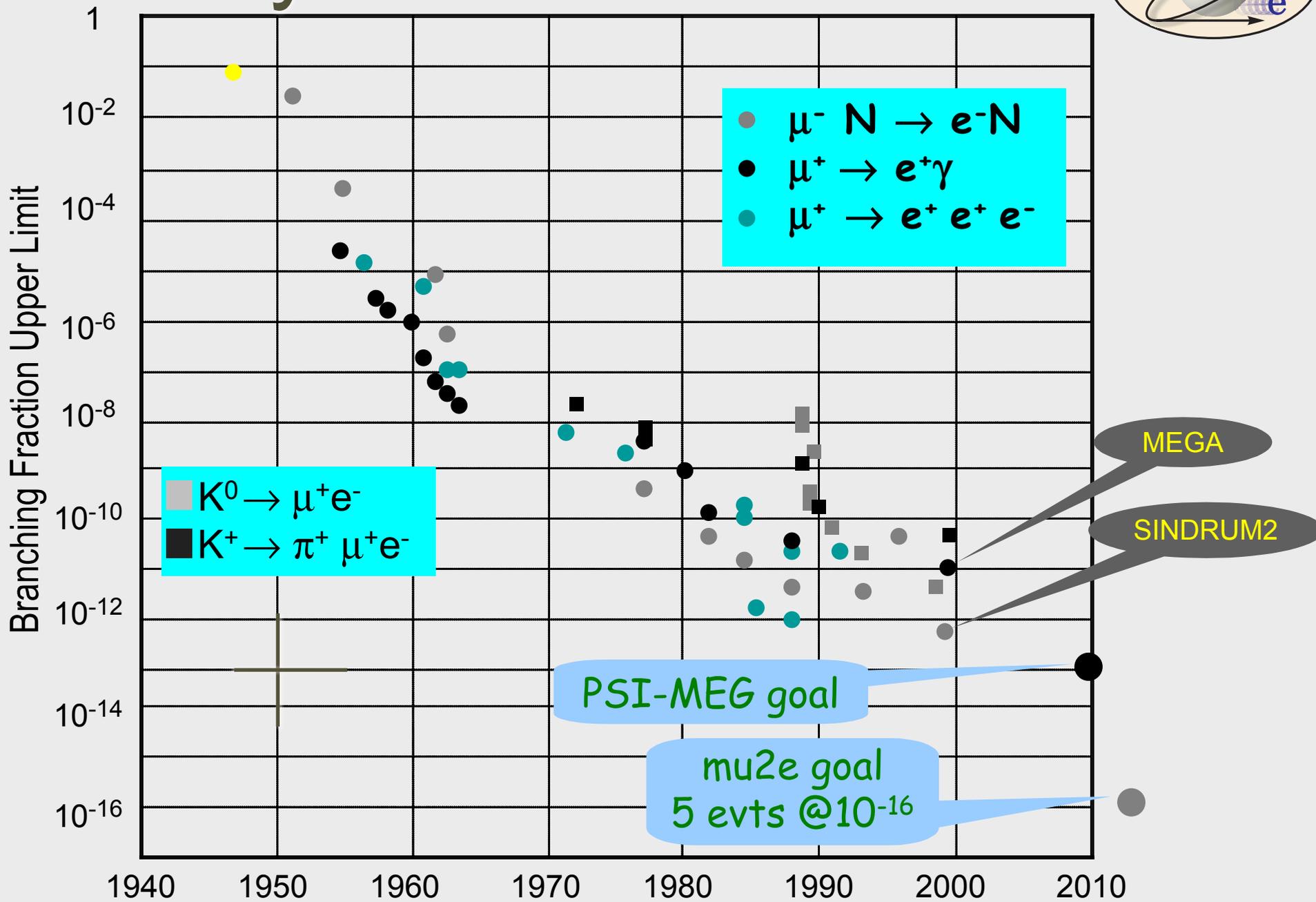
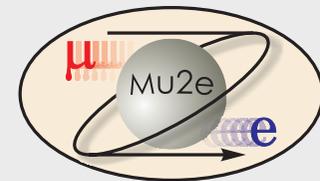
➔ same

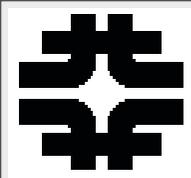


¹Unless we are willing to give up the 2-component neutrino theory, we know that $\mu \rightarrow e + \nu + \bar{\nu}$.

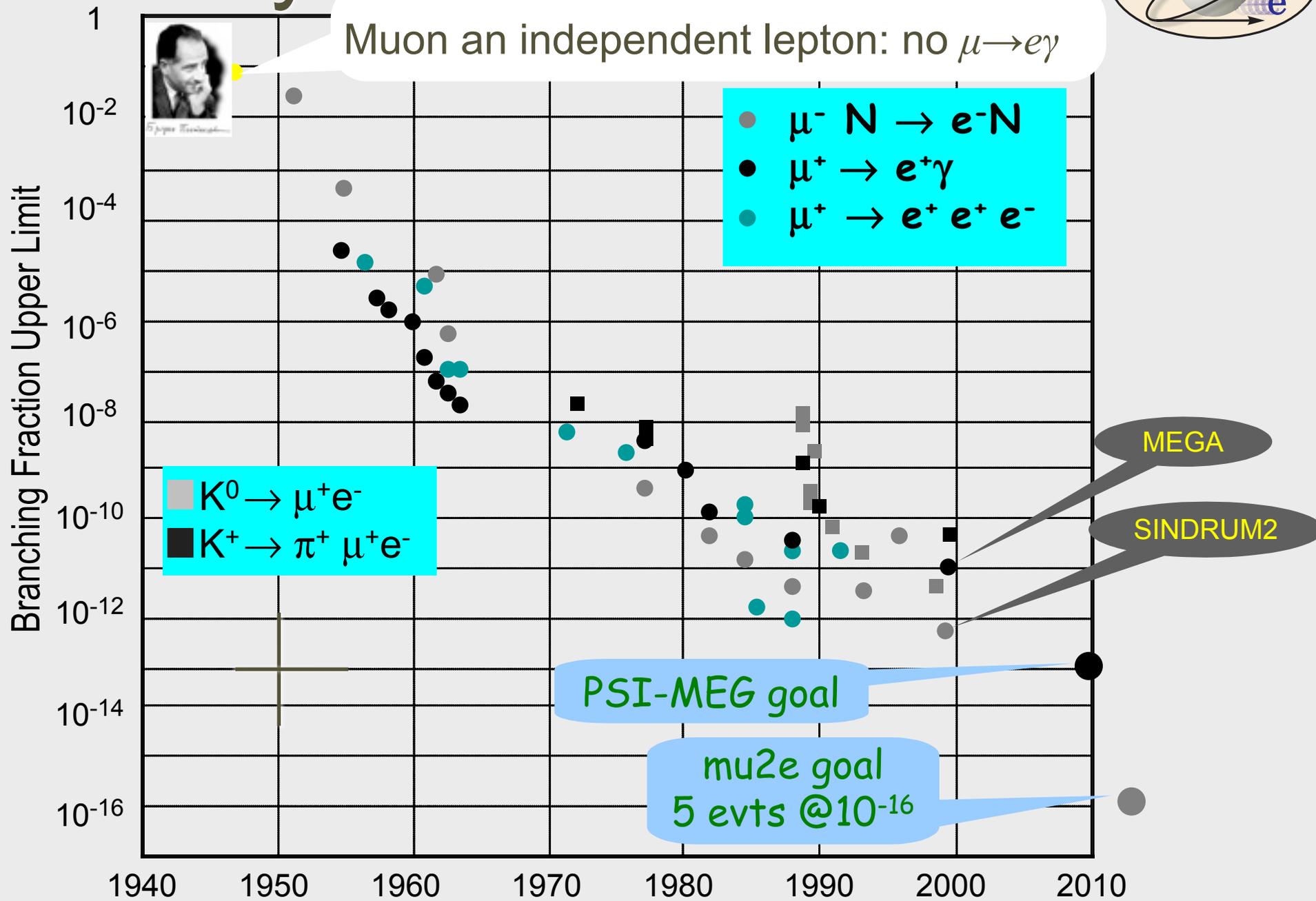
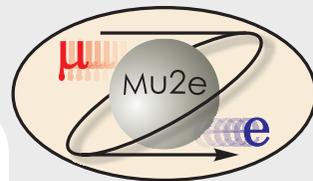


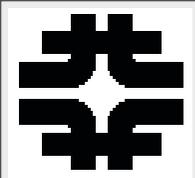
History of CLFV Searches



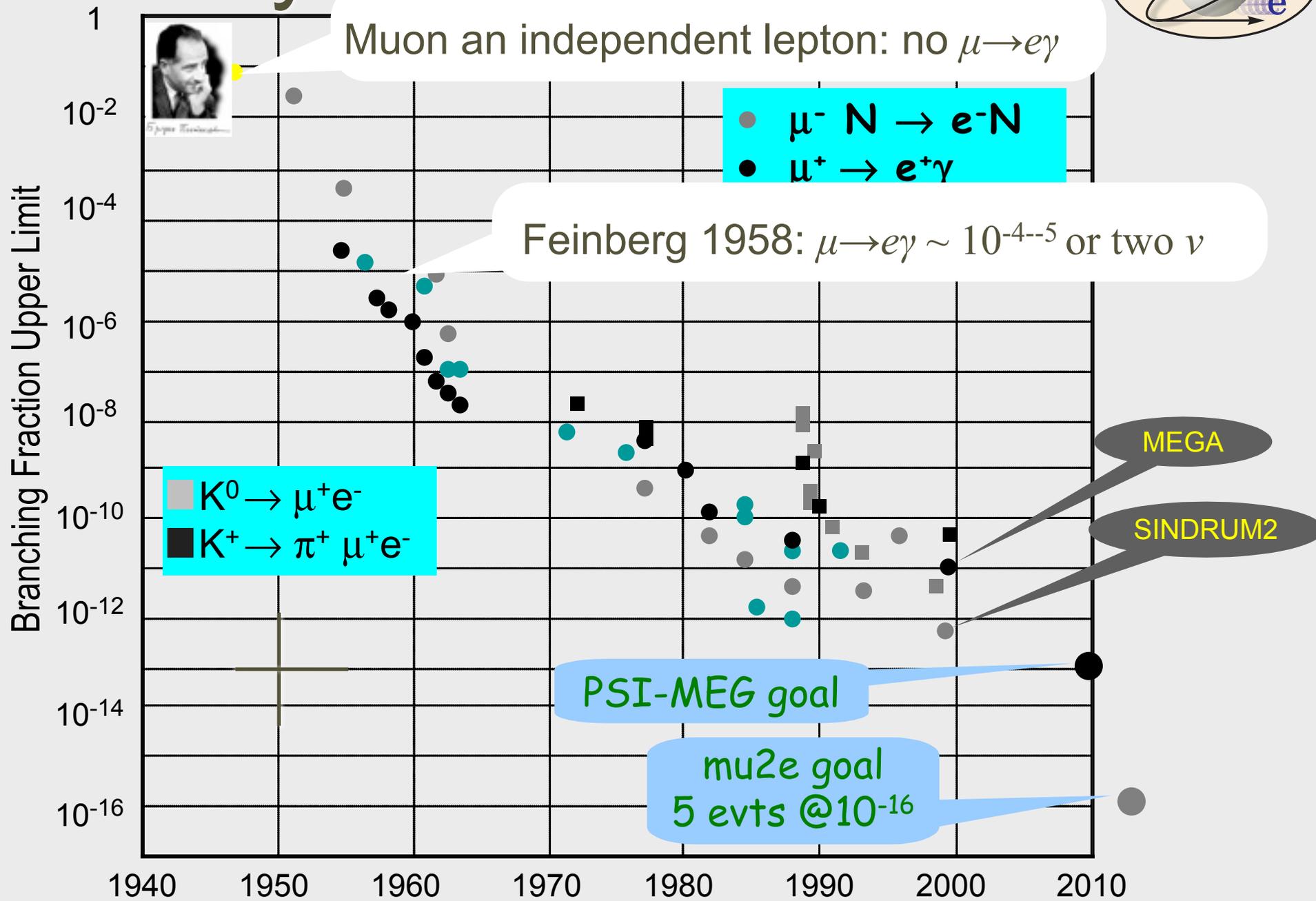
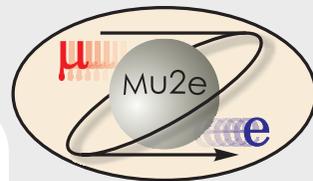


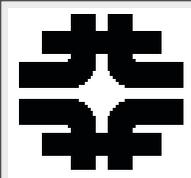
History of Cl FV Searches



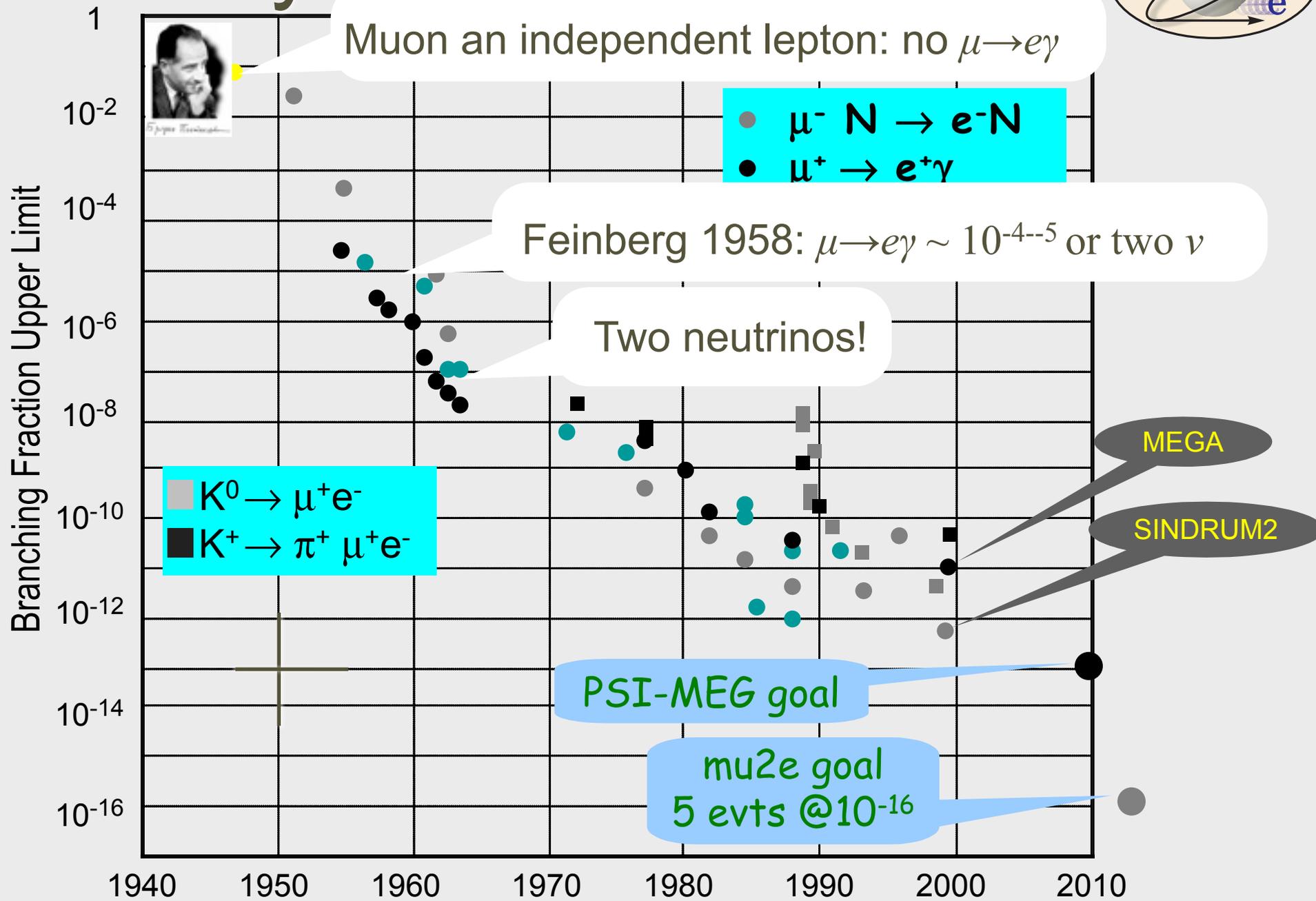
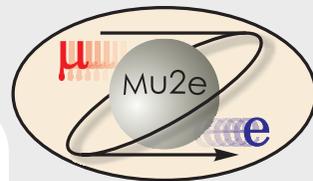


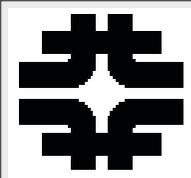
History of Cl FV Searches



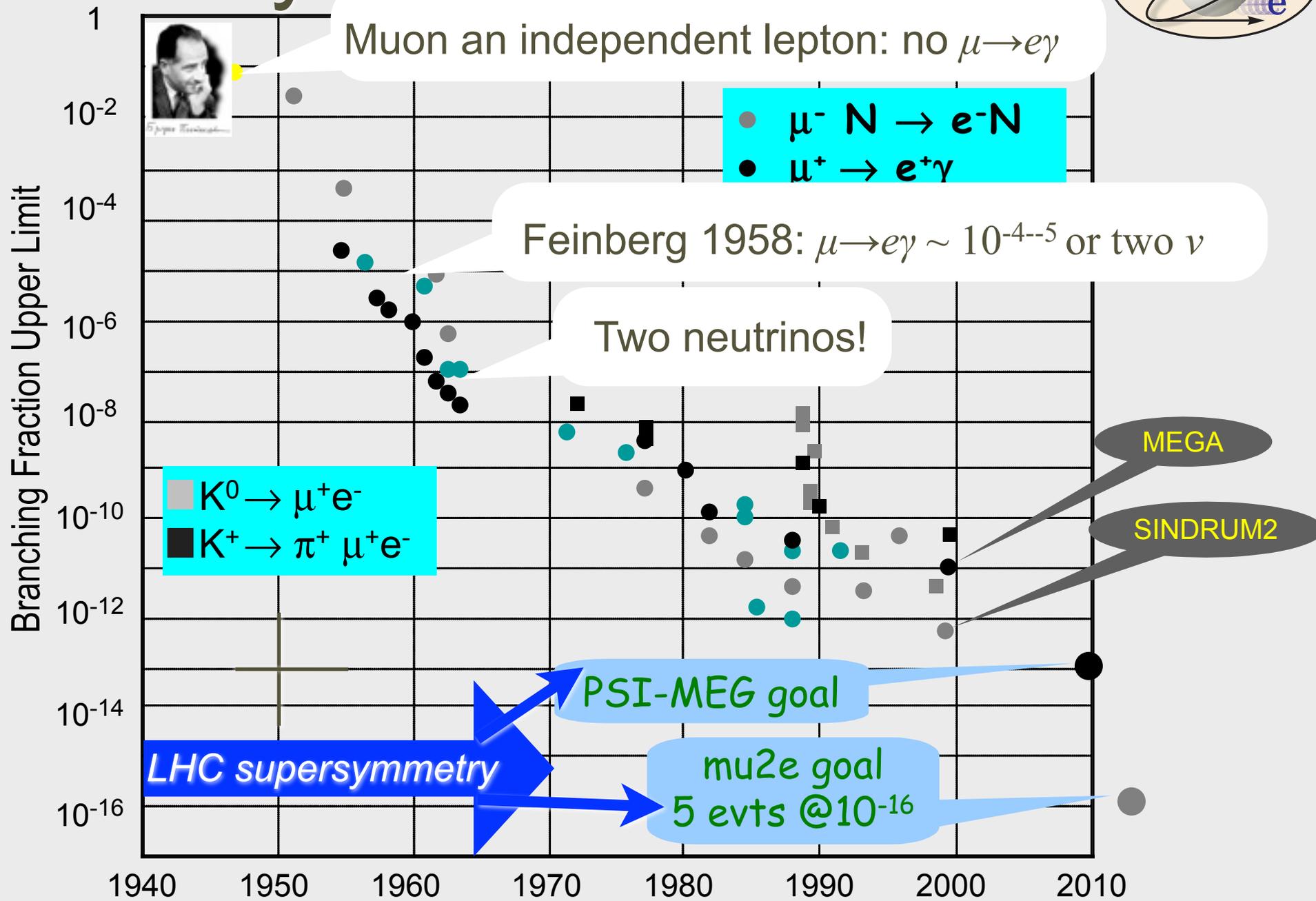
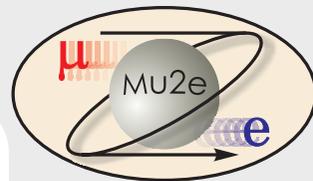


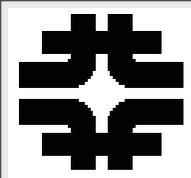
History of Cl FV Searches



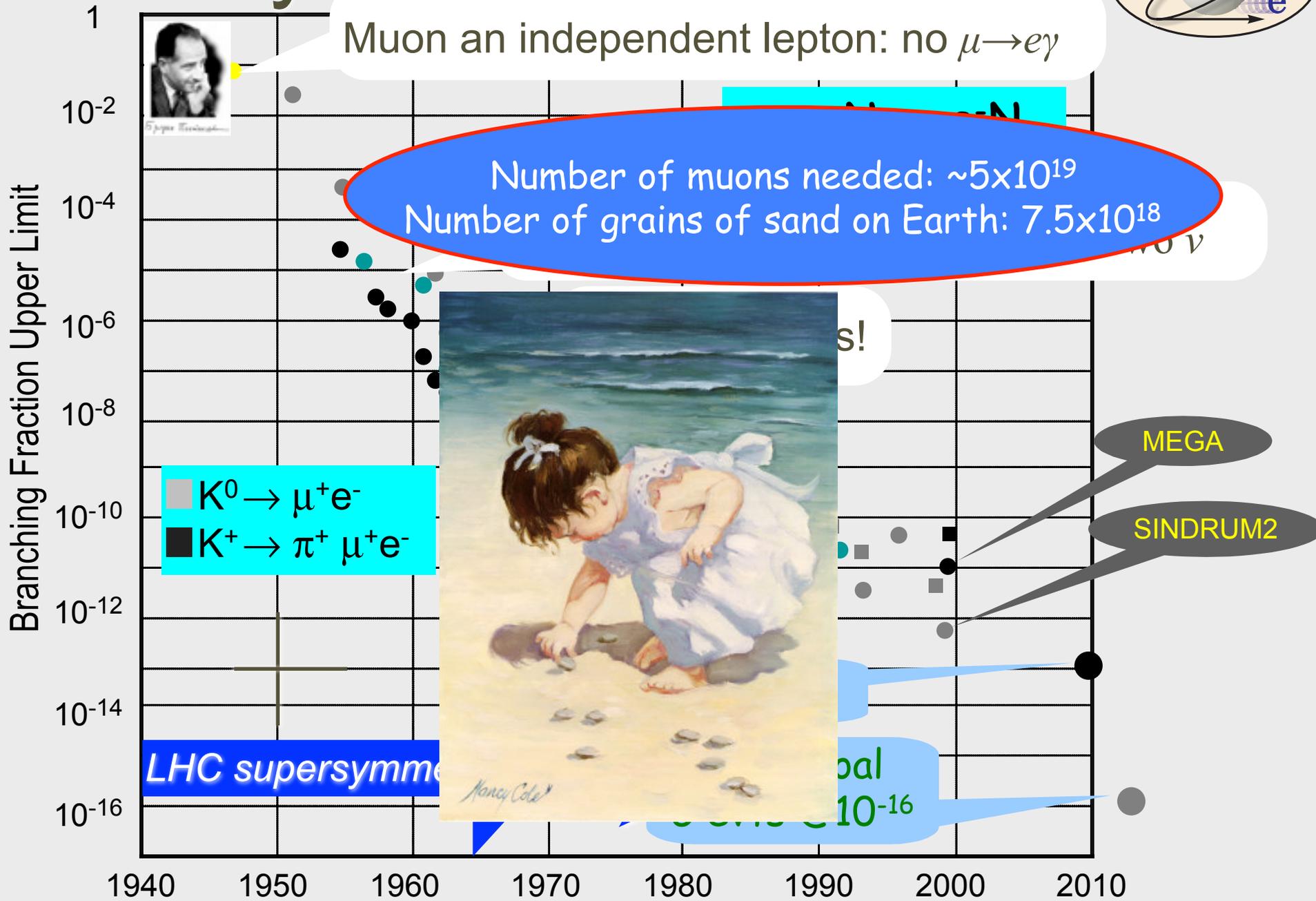
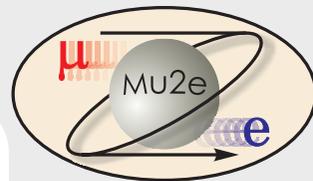


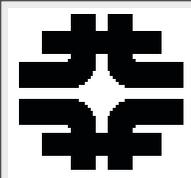
History of Cl FV Searches



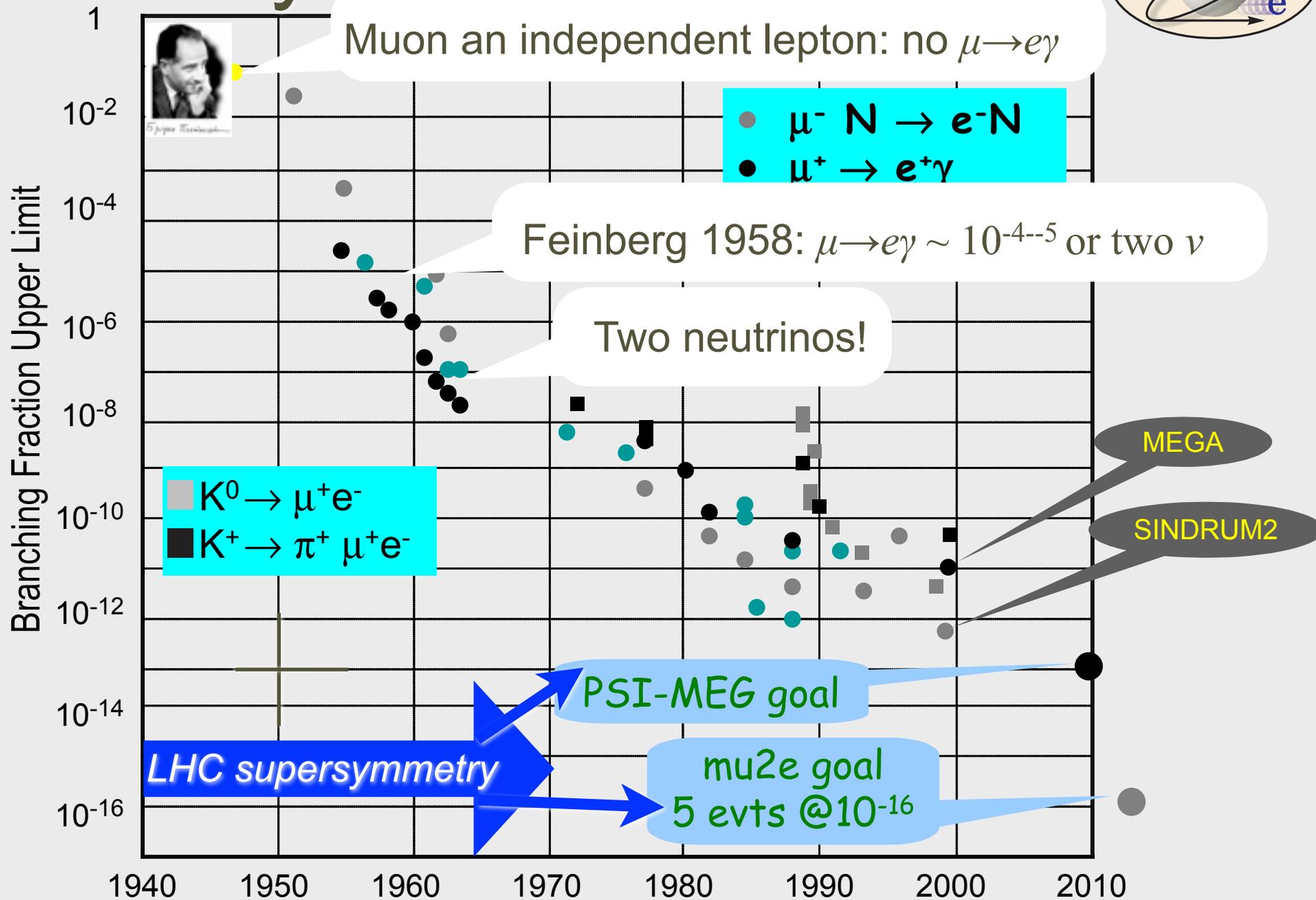
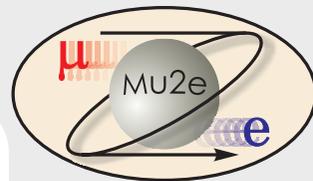


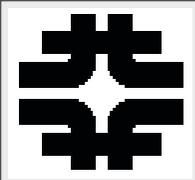
History of Cl FV Searches



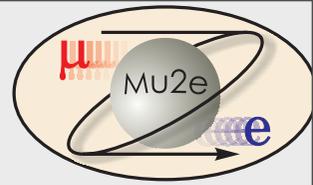


History of Cl FV Searches

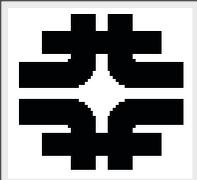




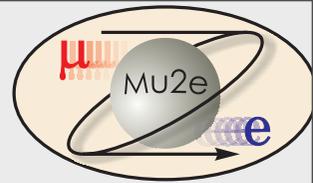
Current and Planned Lepton Flavor Violation Searches



- CLFV in SUSY
- LFV with τ 's/ $e^+ e^-$
- MEG and $\mu \rightarrow e \gamma$
- Mu2e:
 - Strengths of muon-electron conversion
 - Complementarity to other processes

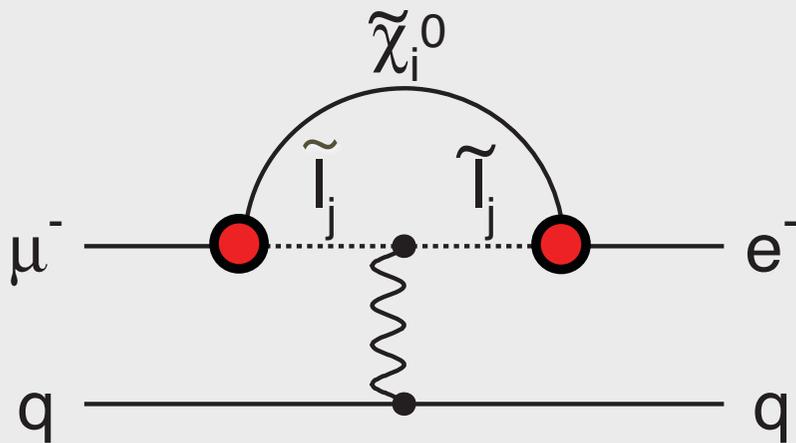


LFV, SUSY and the LHC



Supersymmetry

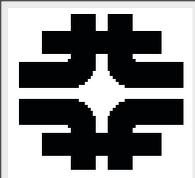
rate $\sim 10^{-15}$



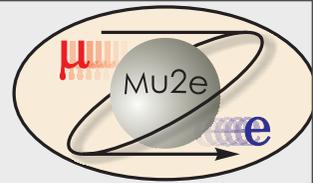
***Access SUSY
through loops:***

***signal of
Terascale at LHC
implies***

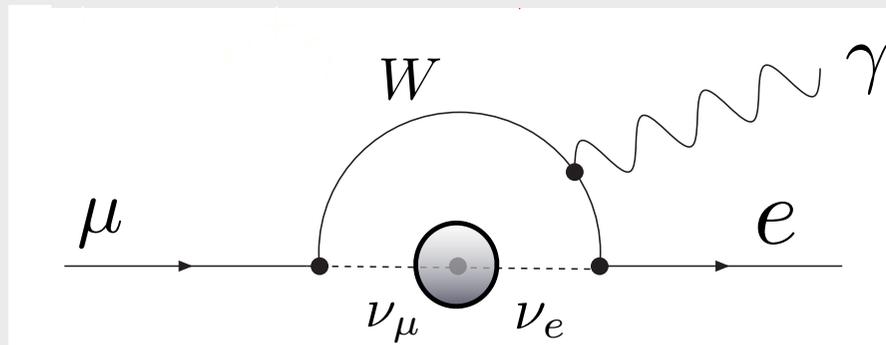
***~40 event signal /
0.4 bkg in this
experiment***



Neutrino Oscillations and Muon-Electron Conversion



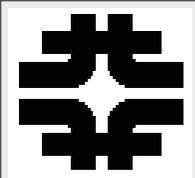
- ν 's have mass! *individual lepton numbers are not conserved*
- Therefore Lepton Flavor Violation occurs in Charged Leptons as well



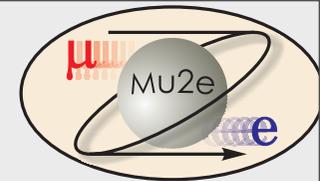
**NO STANDARD
MODEL
BACKGROUND!**

$$\text{BR}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54}$$



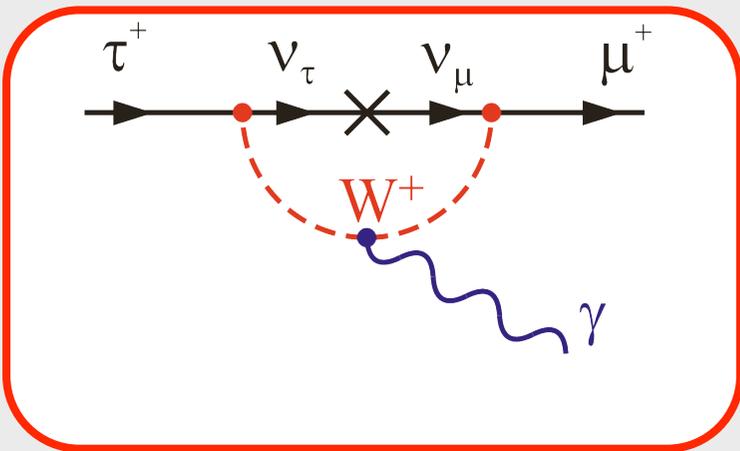


CLFV and Tau Decays



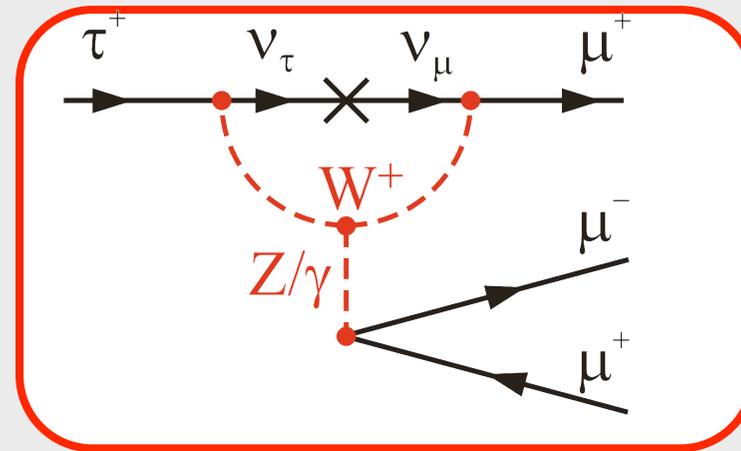
Highly suppressed in Standard Model

Lee, Shrock
Phys.Rev.D16:1444,1977



SM $\sim 10^{-40}$

Milder
GIM
Cancellations



SM $\sim 10^{-14}$

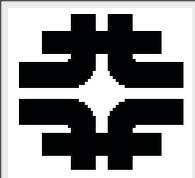
Pham, hep-ph/9810484

Good News:

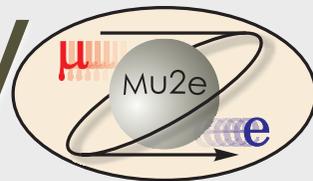
BSM rates are several orders of magnitude larger than in associated muon decays

Bad News:

τ 's hard to produce:
 $\sim 10^9 \tau/\text{yr}$ vs $\sim 10^{11} \mu/\text{s}$ in fixed-target experiments (Mu2e/COMET)



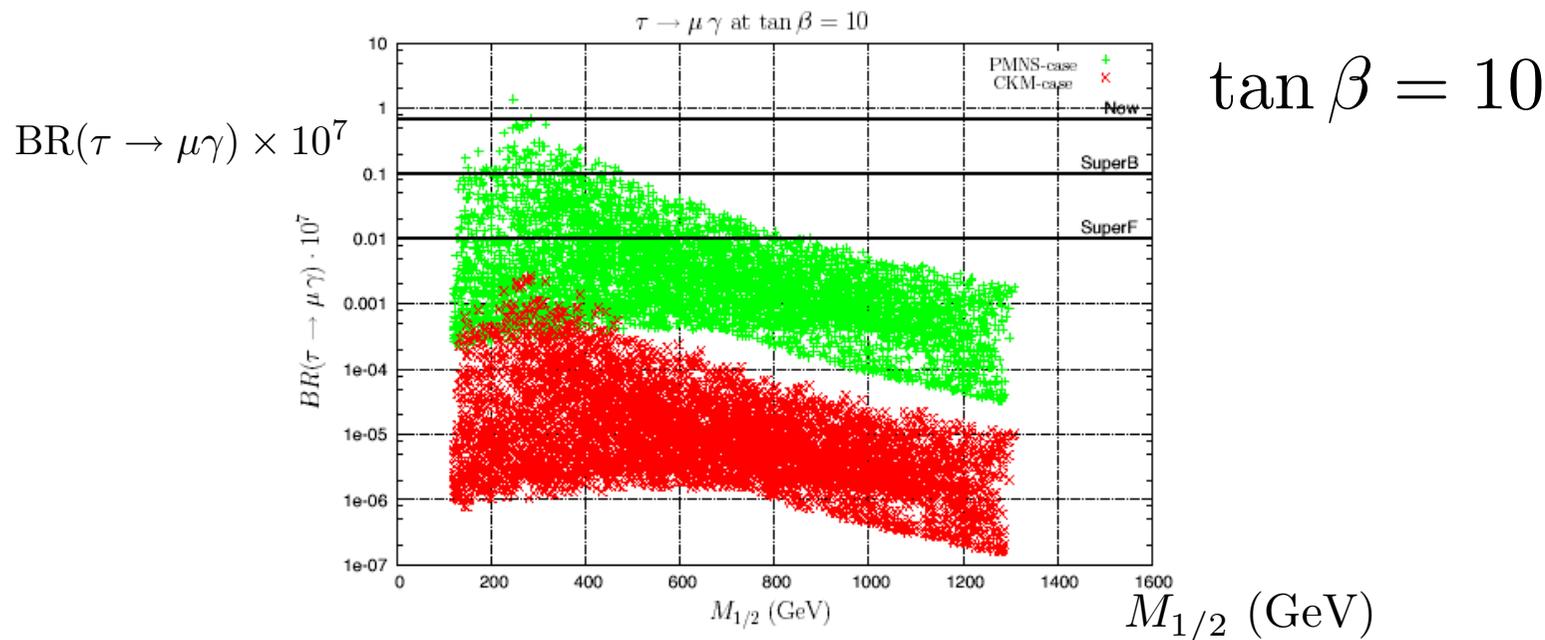
Supersymmetry in Tau LFV



L. Calibbi, A. Faccia, A. Masiero, S. Vempati hep-ph/0605139

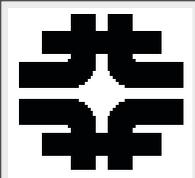
Neutrino-Matrix Like (PMNS)

Minimal Flavor Violation(CKM)

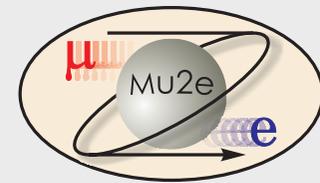


L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

neutrino mass via the see--saw mechanism, analysis is performed in an SO(10) framework



And Muon-Electron Conversion

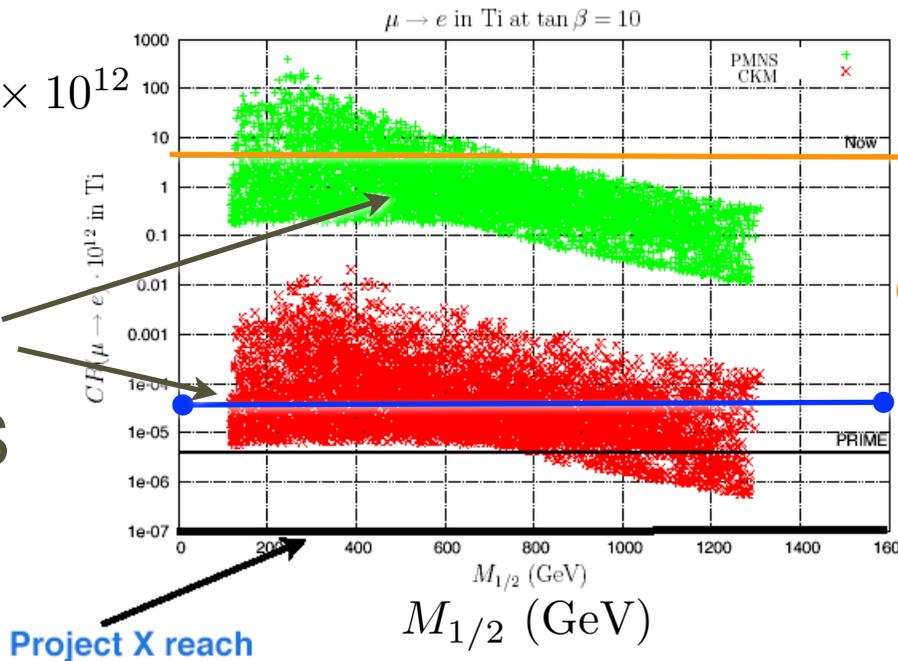


$$\tan \beta = 10$$

Neutrino-Matrix Like (PMNS) Minimal Flavor Violation(CKM)

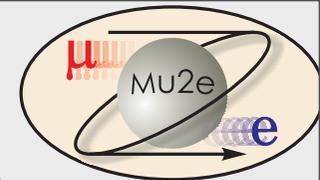
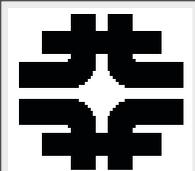
$$\text{BR}(\mu \rightarrow e) \times 10^{12}$$

measurement
can distinguish
between PMNS
and MFV



L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

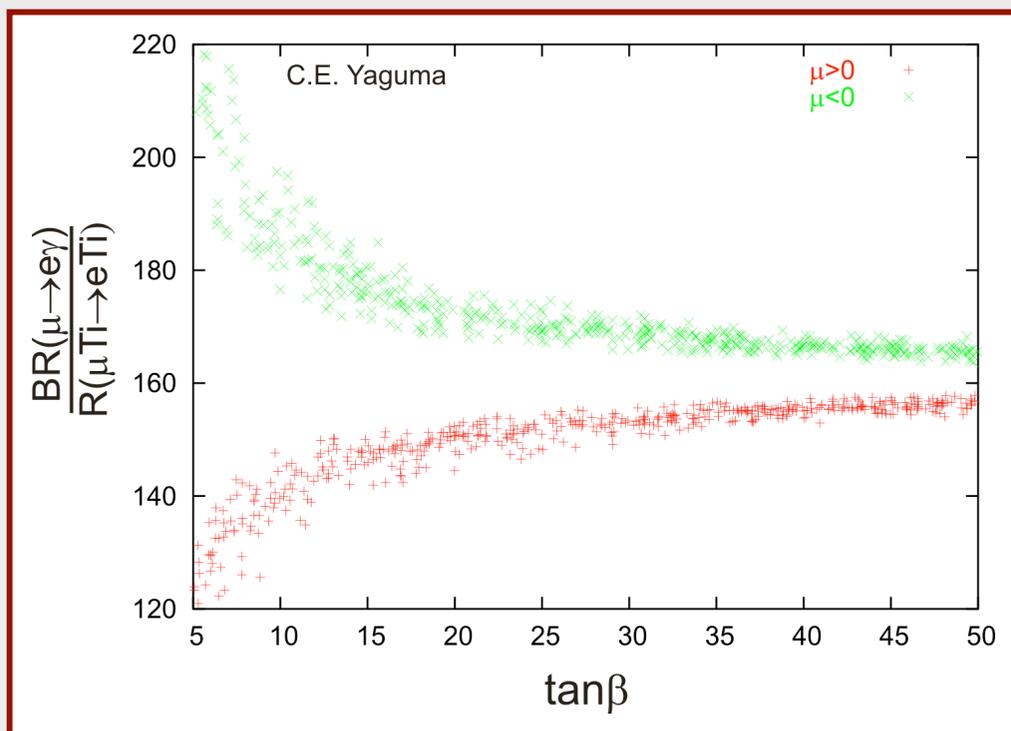
complementarity between Lepton Flavor Violation (LFV) and LHC experiments



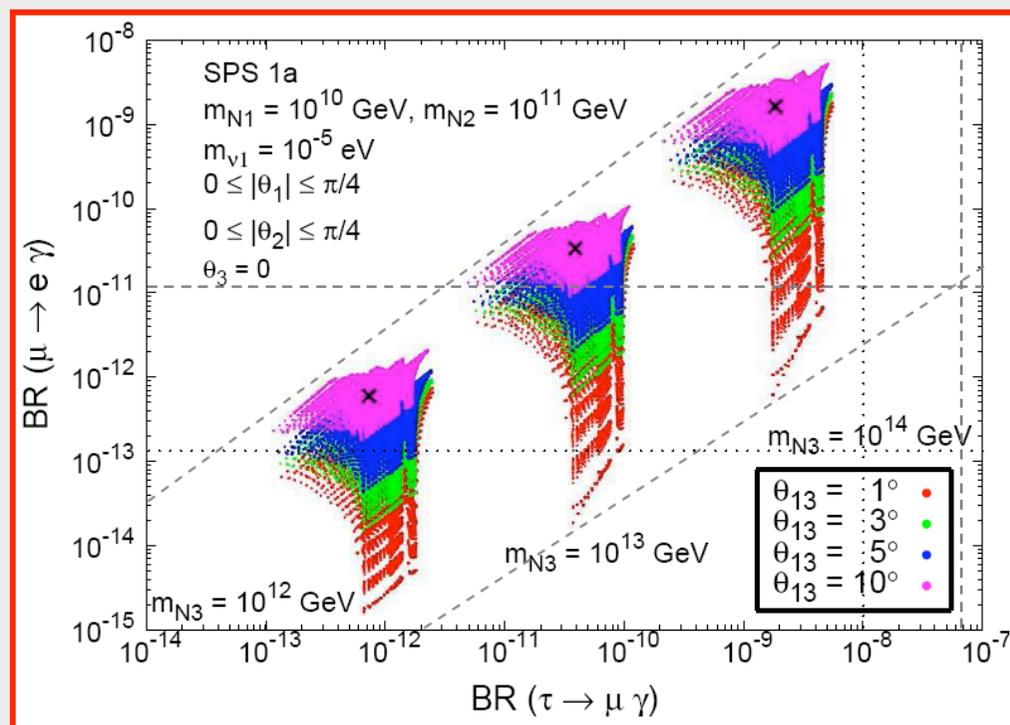
Pinning Down SuperSymmetry

MSSM w mSUGRA

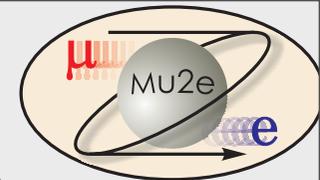
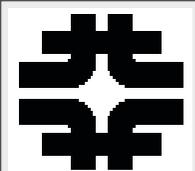
CMSSM - seesaw



Yaguna, hep-ph/0502014v2



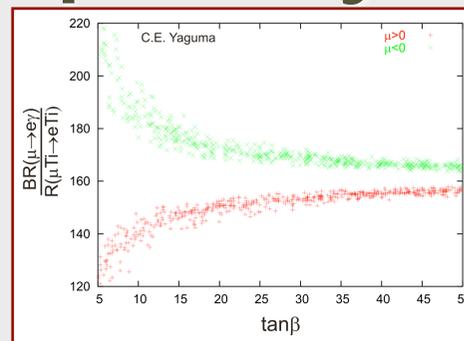
Antusch et al., hep-ph/0610439



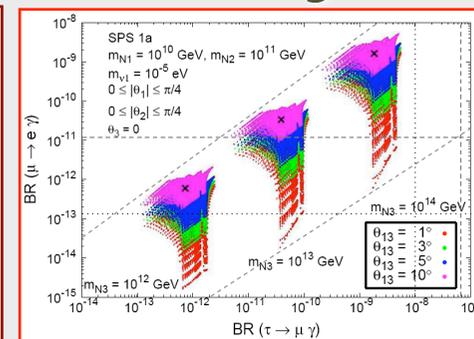
Pinning Down SuperSymmetry

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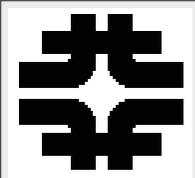


Yaguna, hep-ph/0502014v2

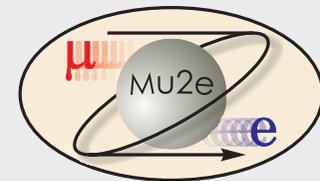


Antusch et al., hep-ph/0610439

- Need:
 - observation of CLFV in more than one channel, and/or
 - evidence from LHC, g-2, or elsewhere
- to allow discrimination among different models

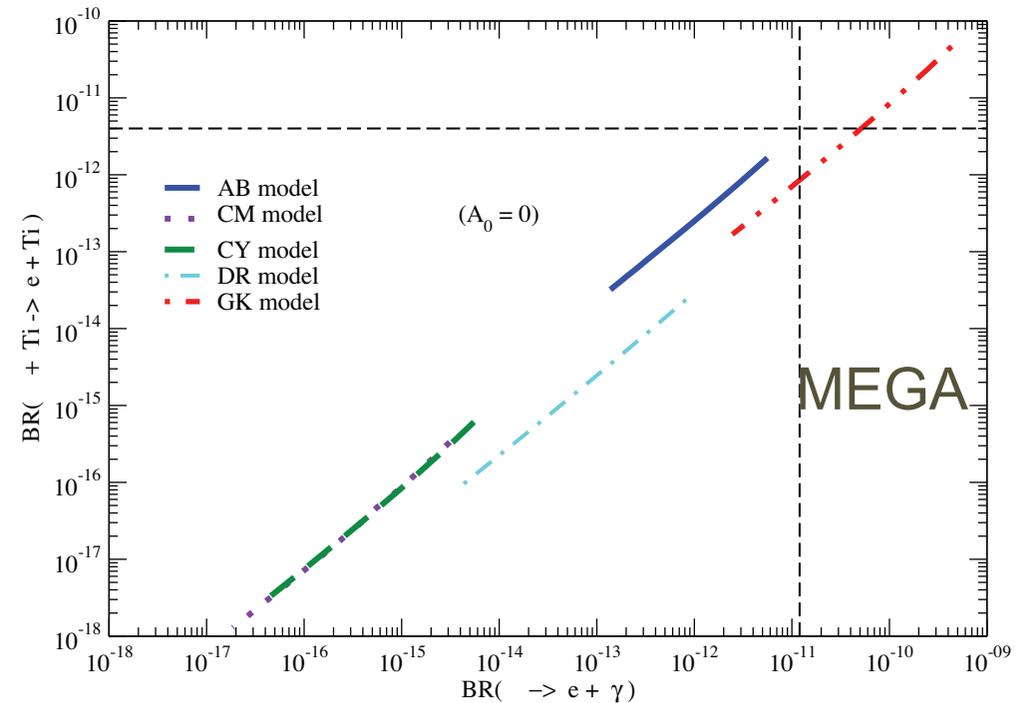
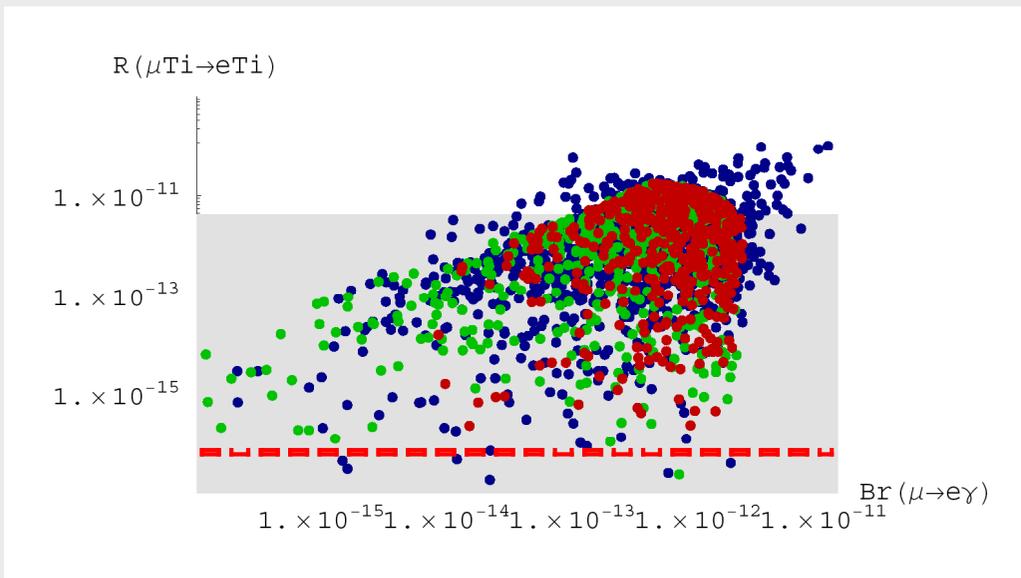


Combining $\mu \rightarrow e \gamma$ with $\mu \rightarrow e$ Conversion



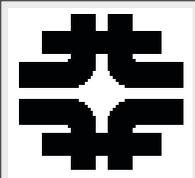
Randall-Sundrum

M. Blanke, A. J. Buras, B. Duling, A. Poschenrieder and C. Tarantino, JHEP 0705, 013 (2007).

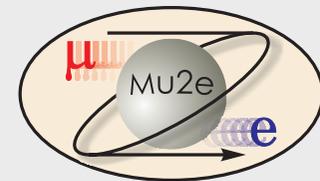


SO(10) models:

C. Albright and M. Chen, arXiv:0802.4228, PRD D77:113010, 2008.

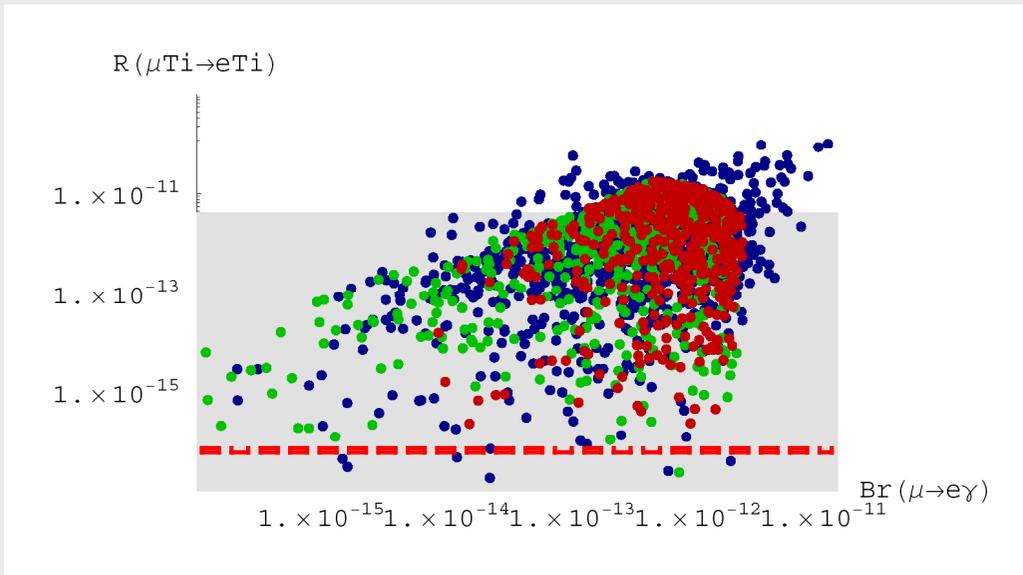


Combining $\mu \rightarrow e \gamma$ with $\mu \rightarrow e$ Conversion



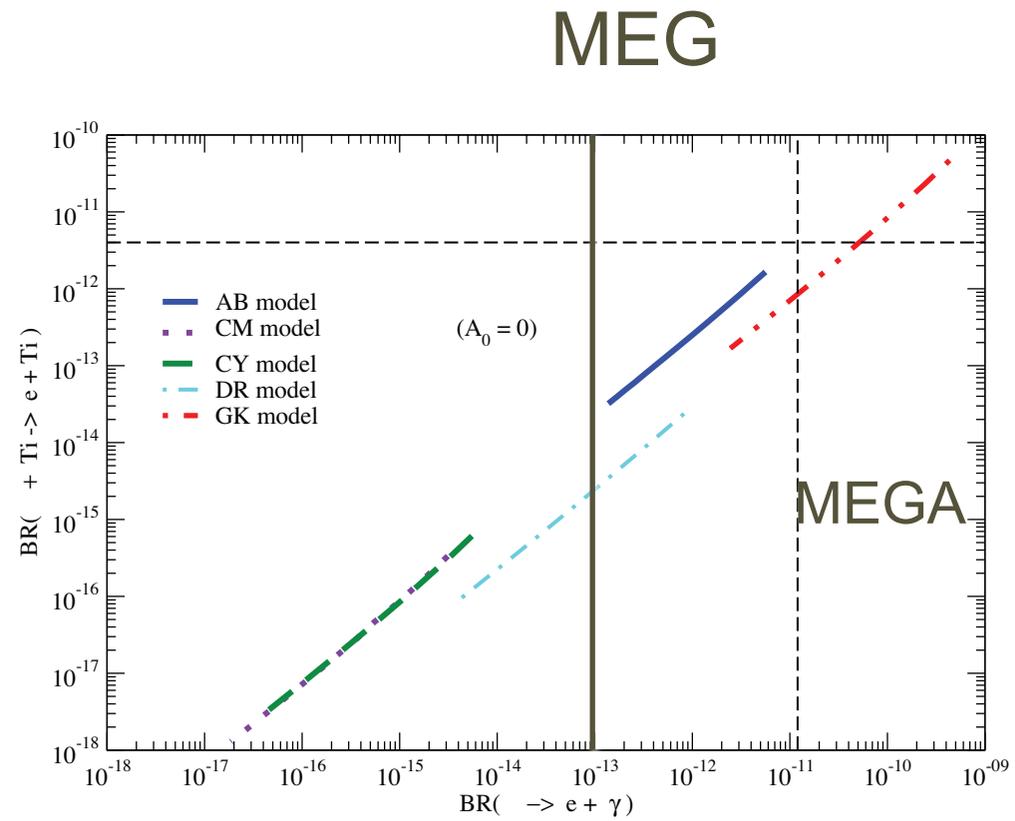
Randall-Sundrum

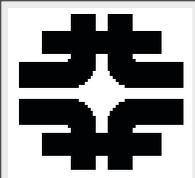
M. Blanke, A. J. Buras, B. Duling, A. Poschenrieder and C. Tarantino, JHEP 0705, 013 (2007).



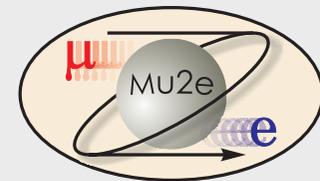
SO(10) models:

C. Albright and M. Chen, arXiv:0802.4228, PRD D77:113010, 2008.



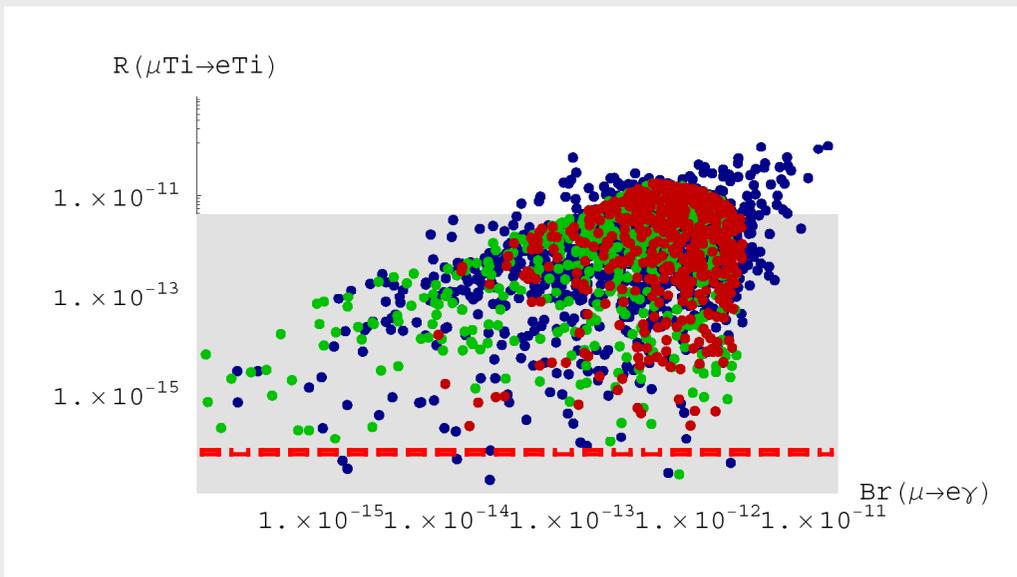


Combining $\mu \rightarrow e \gamma$ with $\mu \rightarrow e$ Conversion

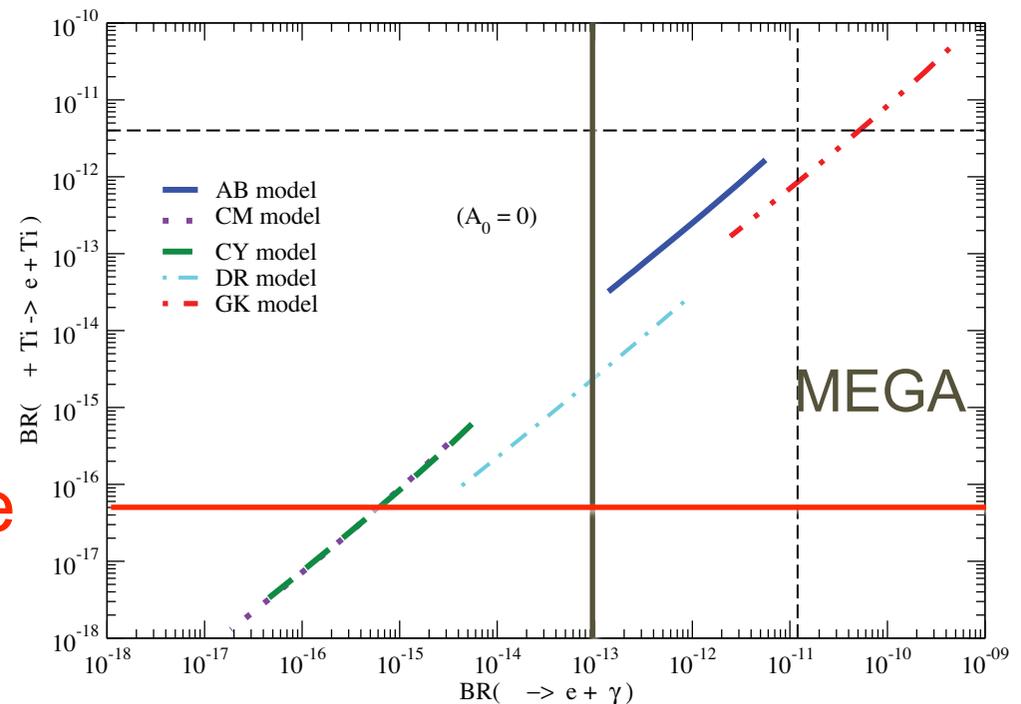


Randall-Sundrum

M. Blanke, A. J. Buras, B. Duling, A. Poschenrieder and C. Tarantino, JHEP 0705, 013 (2007).



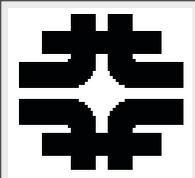
MEG



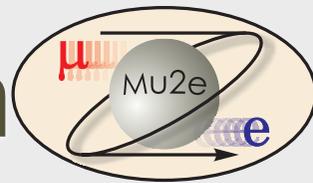
SO(10) models:

C. Albright and M. Chen, arXiv:0802.4228, PRD D77:113010, 2008.

Mu2e

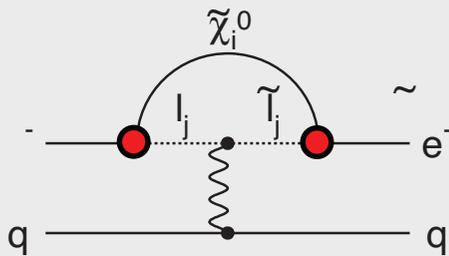


Contributions to μe Conversion



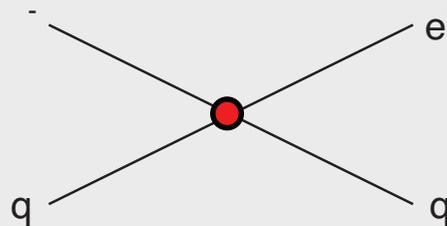
Supersymmetry

rate $\sim 10^{-15}$



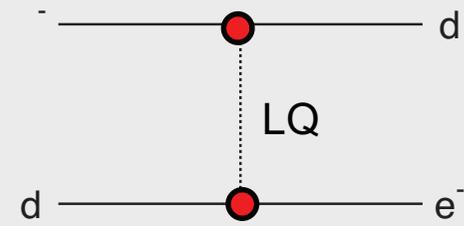
Compositeness

$\Lambda_c \sim 3000 \text{ TeV}$



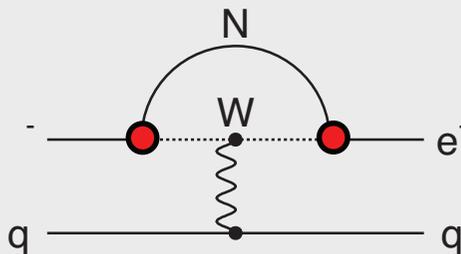
Leptoquark

$M_{LQ} = 3000 (\lambda_{\mu d} \lambda_{ed})^{1/2} \text{ TeV}/c^2$



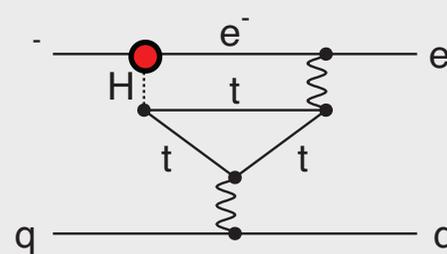
Heavy Neutrinos

$|U_{\mu N} U_{eN}|^2 \sim 8 \times 10^{-13}$



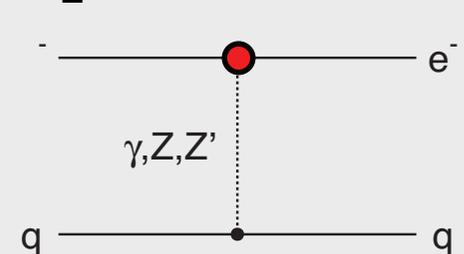
Second Higgs Doublet

$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$

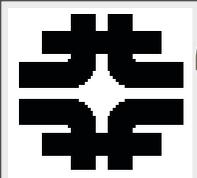


Heavy Z' Anomal. Z Coupling

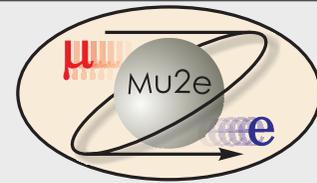
$M_{Z'} = 3000 \text{ TeV}/c^2$



also see Flavour physics of leptons and dipole moments, [arXiv:0801.1826](https://arxiv.org/abs/0801.1826)

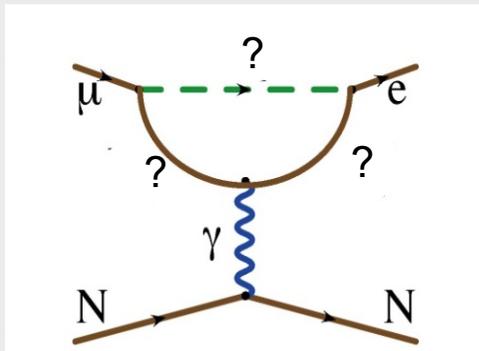


“Model-Independent” Form



$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma_\mu u_L + \bar{d}_L \gamma_\mu d_L)$$

“Loops”

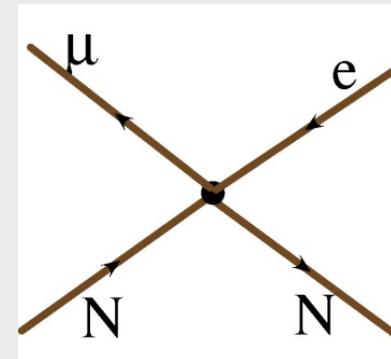


κ

Supersymmetry and Heavy Neutrinos

Contributes to $\mu \rightarrow e\gamma$

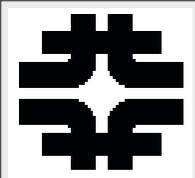
“Contact Terms”



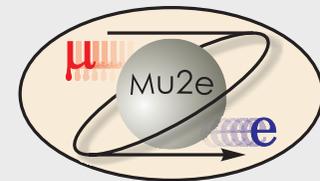
Λ

Does not produce $\mu \rightarrow e\gamma$

Quantitative Comparison?



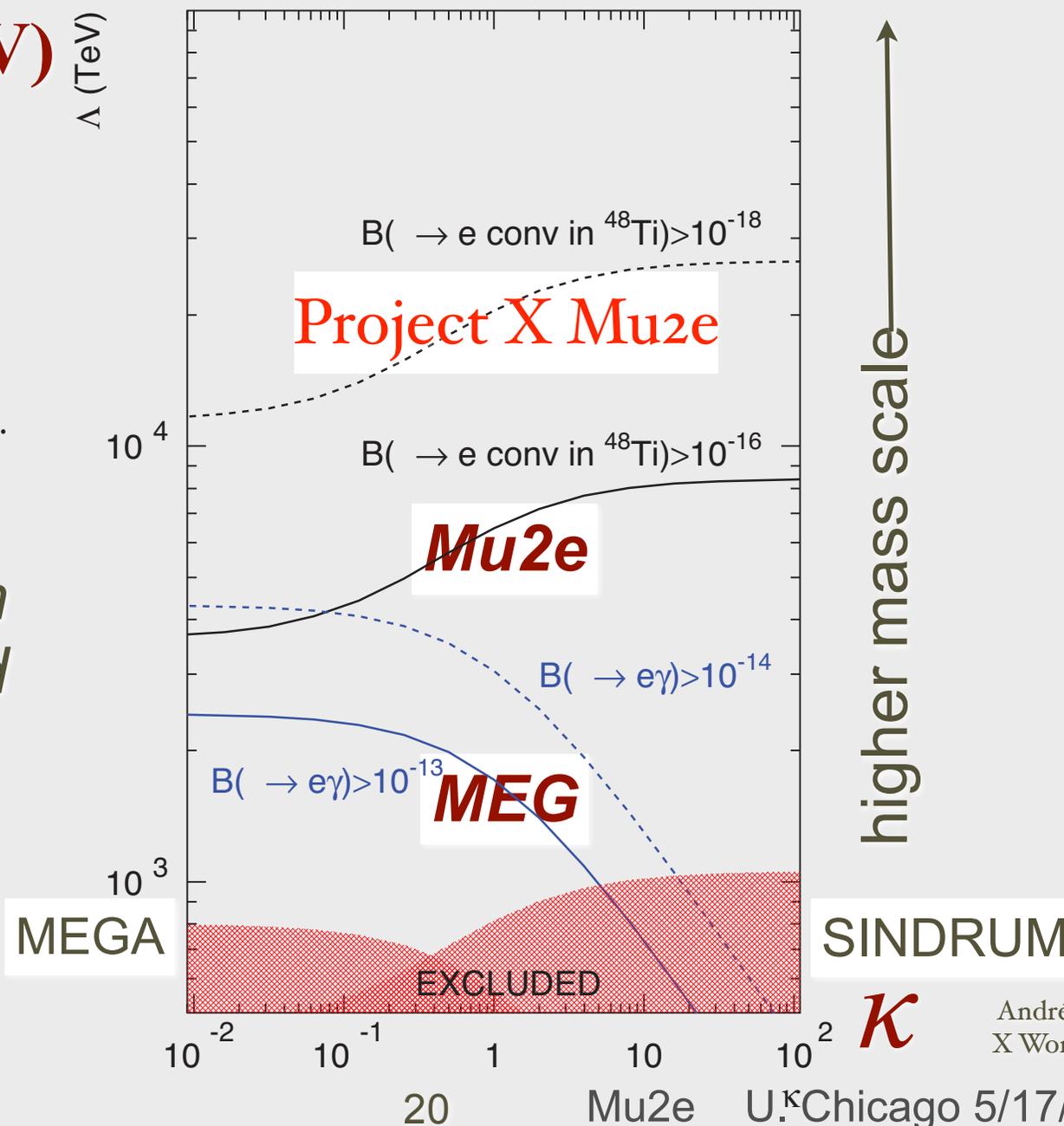
μe Conversion and $\mu \rightarrow e \gamma$



Λ (TeV)

1) *Mass Reach to $\sim 10^4$ TeV*

2) *about x2 beyond MEG in loop-dominated physics*



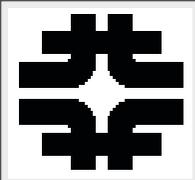
R. Bernstein, FNAL

20

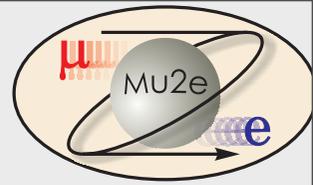
Mu2e

U. Chicago 5/17/10

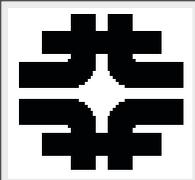
André de Gouvêa, Project X Workshop Golden Book



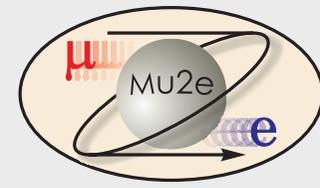
Outline



- The search for muon-electron conversion
- *Experimental Technique*
- Fermilab Accelerator
- Project X Upgrades and Mu2e
- Cost and Schedule
- Conclusions



Overview Of Processes

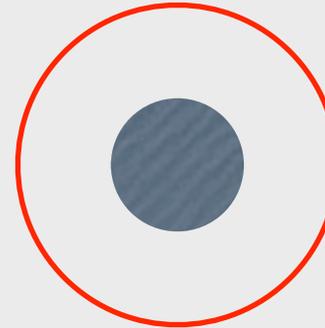


μ^- stops in thin Al foil

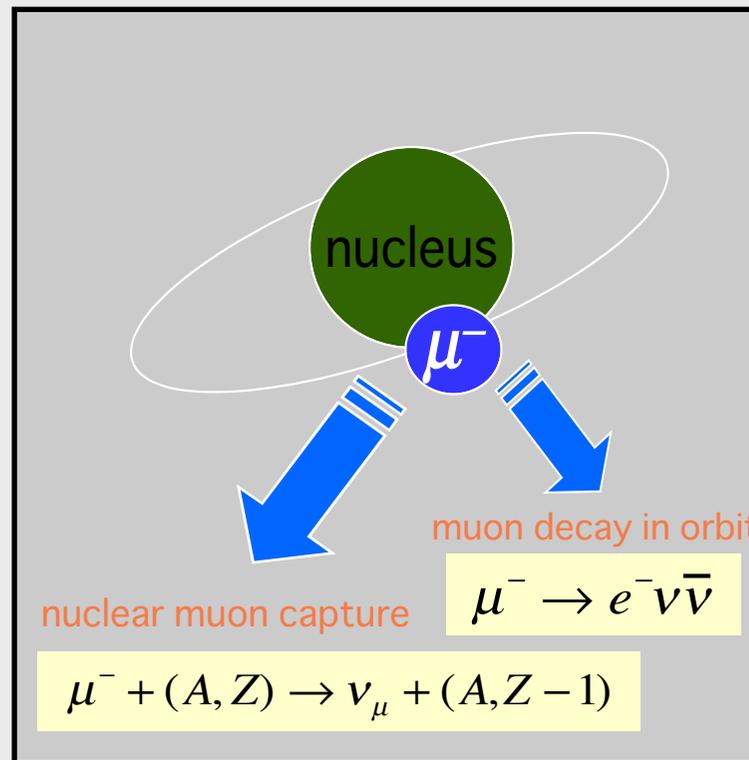


the Bohr radius is ~ 20 fm,
so the μ^- sees the nucleus

μ^- in 1s state



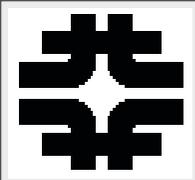
Al Nucleus
 ~ 4 fm



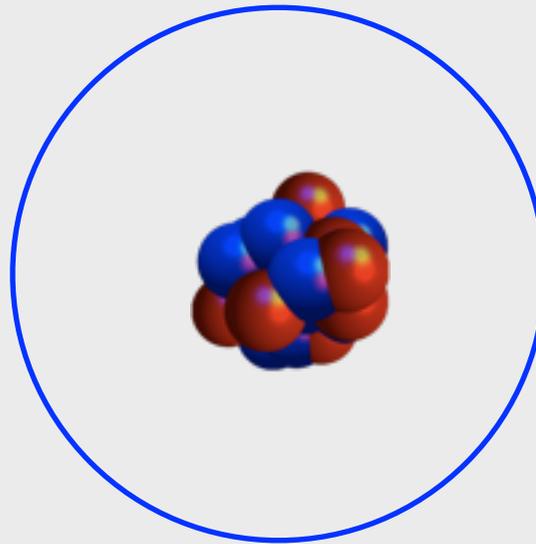
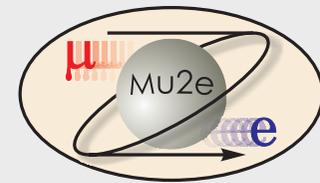
muon capture,
muon “falls into”
nucleus:
normalization

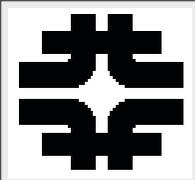
60% capture
40% decay

Decay in Orbit:
background

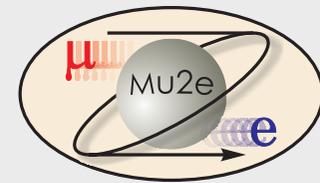


Three Possibilities: Normalization

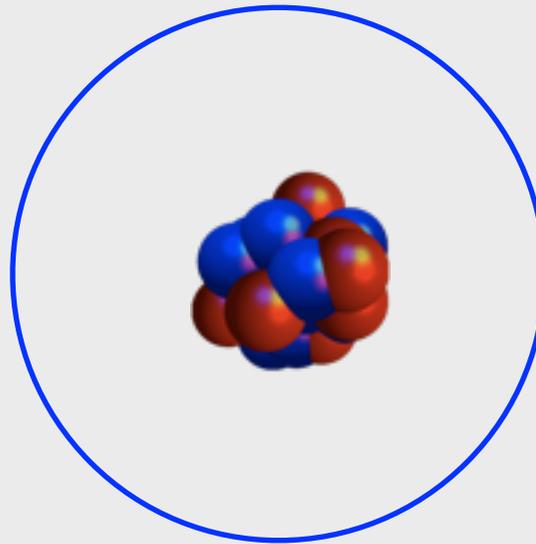


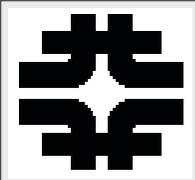


Three Possibilities: Normalization

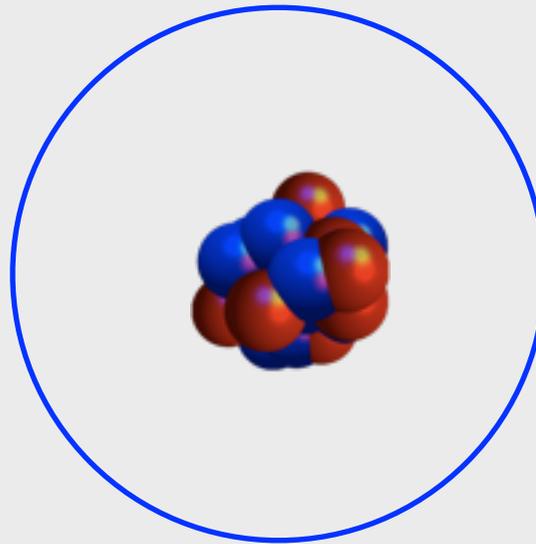
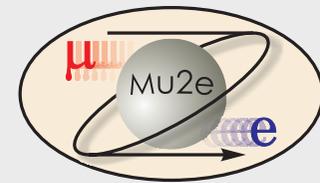


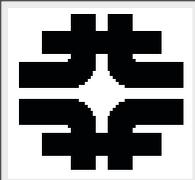
muon stops



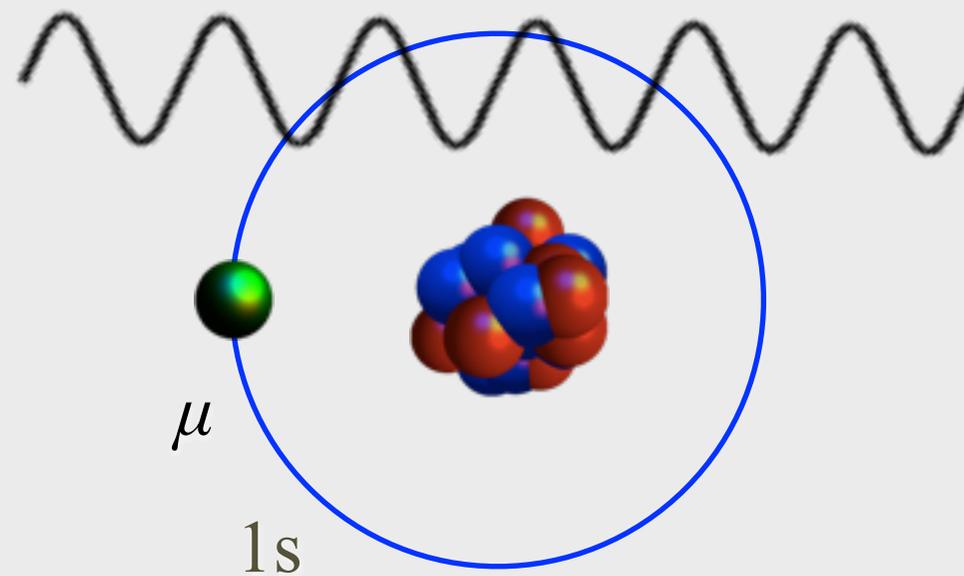
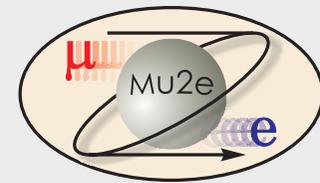


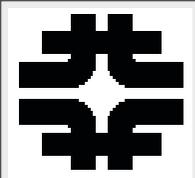
Three Possibilities: Normalization



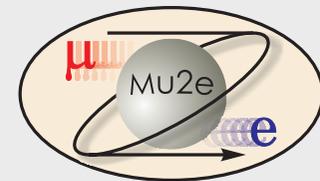


Three Possibilities: Normalization





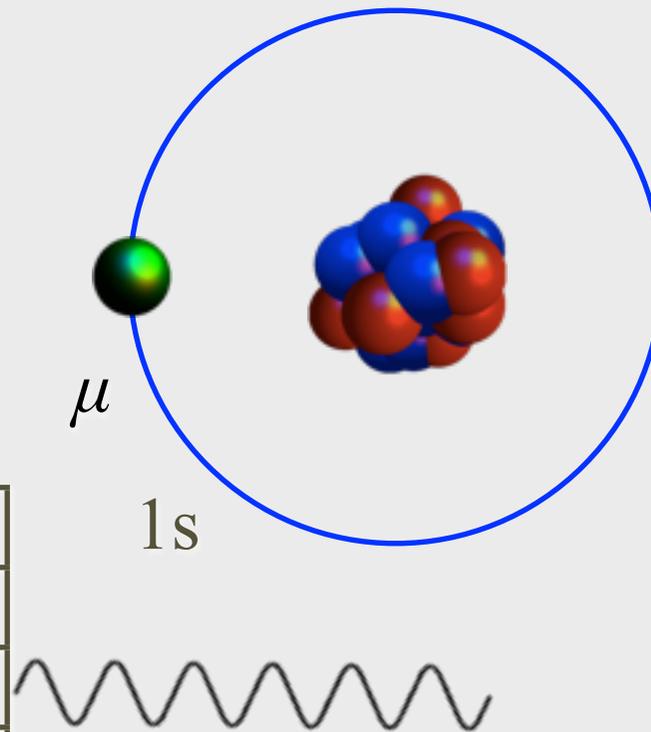
Three Possibilities: Normalization

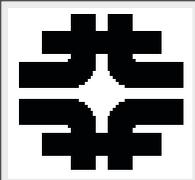


X-Rays from
cascade
(occurs in psec)

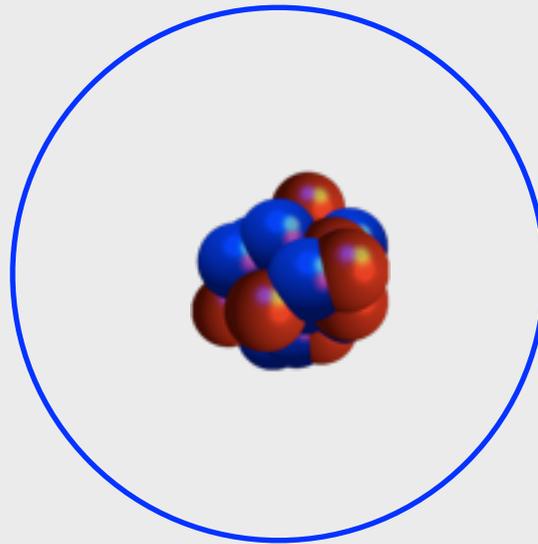
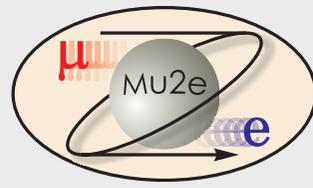
detect these
for
normalization

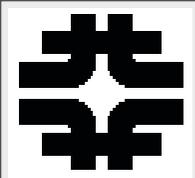
| Transition | Energy |
|------------|---------|
| 3d → 2p | 66 keV |
| 2p → 1s | 356 keV |
| 3d → 1s | 423 keV |
| 4p → 1s | 446 keV |



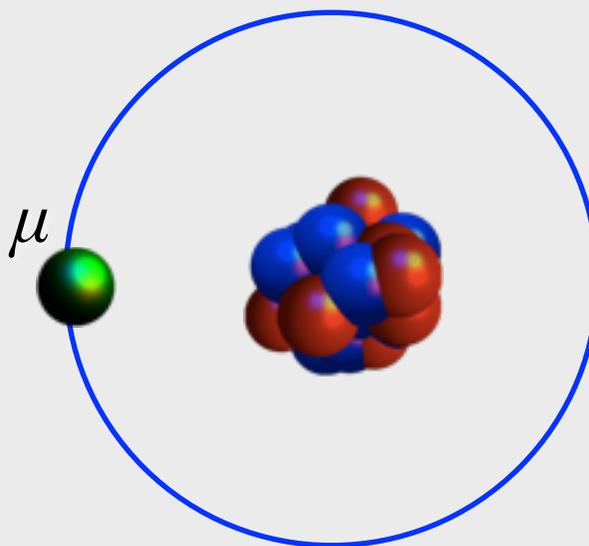


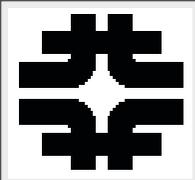
Normalization to Nuclear Capture



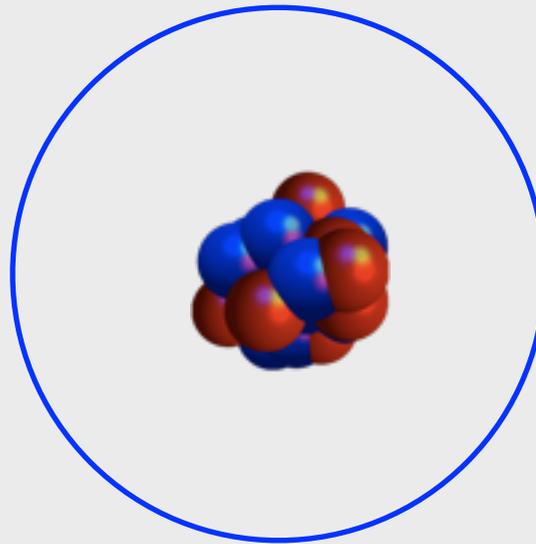
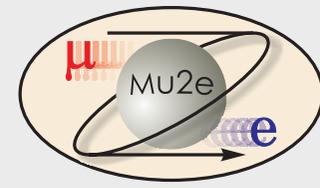


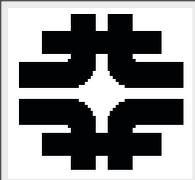
Normalization to Nuclear Capture



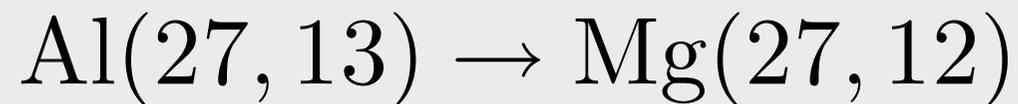
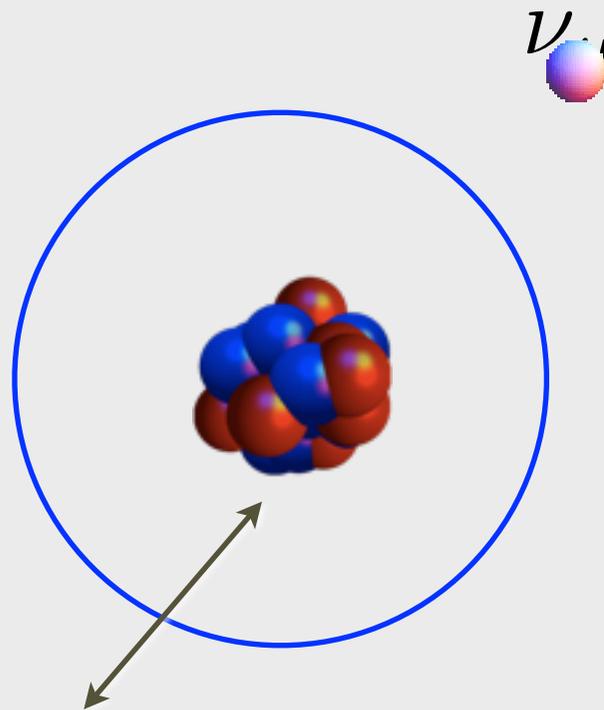
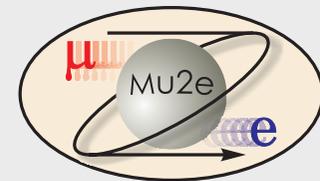


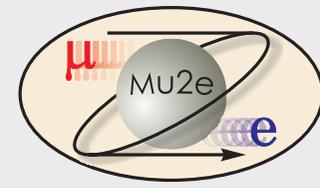
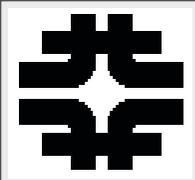
Normalization to Nuclear Capture





Normalization to Nuclear Capture

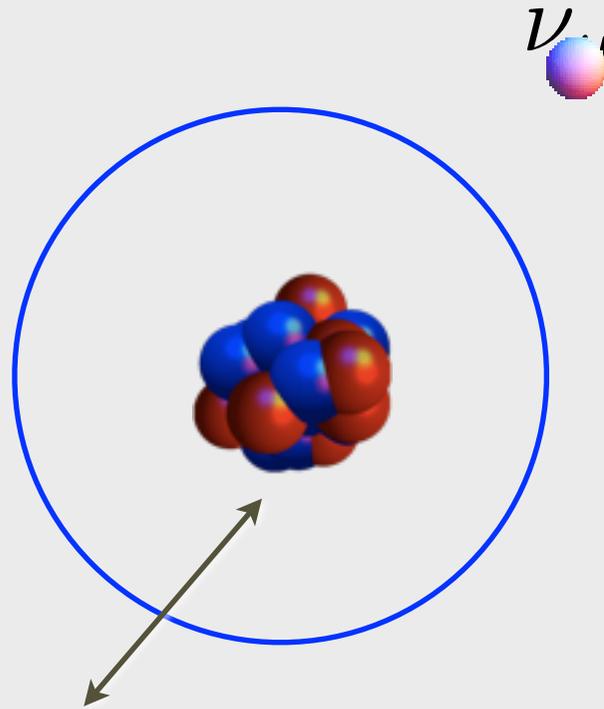




Normalization to Nuclear Capture

1) measure stop rate 2) calculate capture rate/stop

Kitano et al. ,Phys.Rev.D66:096002,2002, Erratum-ibid.D76:059902,2007. e-Print: hep-ph/0203110



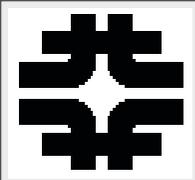
$$\text{then compute } R_{\mu e} = \frac{\mu N \rightarrow e N}{\mu \text{ Al}(27, 13) \rightarrow \nu_\mu \text{ Mg}(27, 12)}$$

R. Bernstein, FNAL

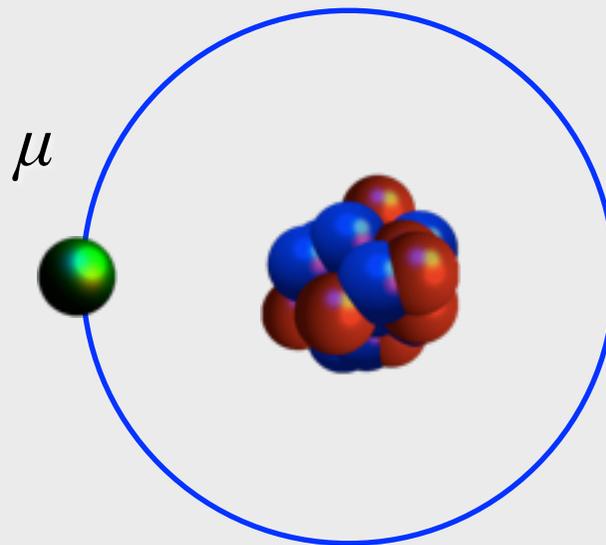
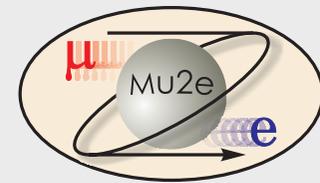
24

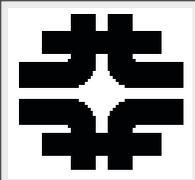
Mu2e

U. Chicago 5/17/10

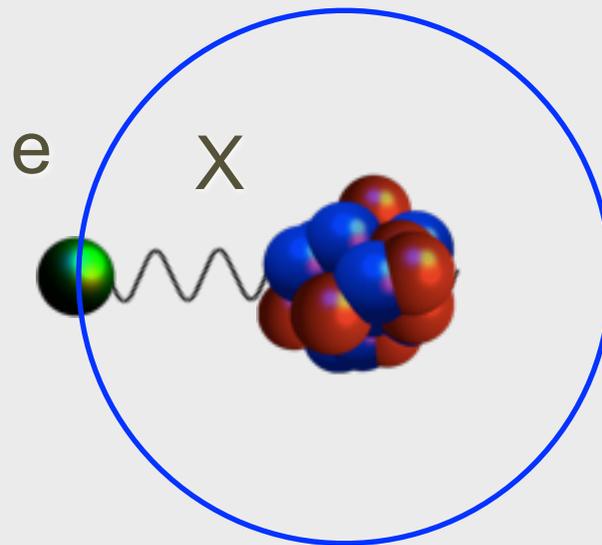
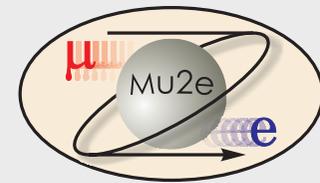


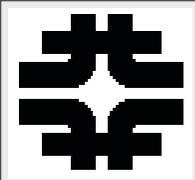
Three Possibilities: Signal



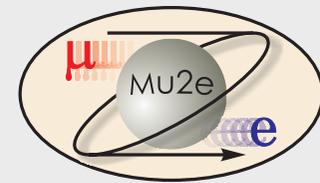


Three Possibilities: Signal

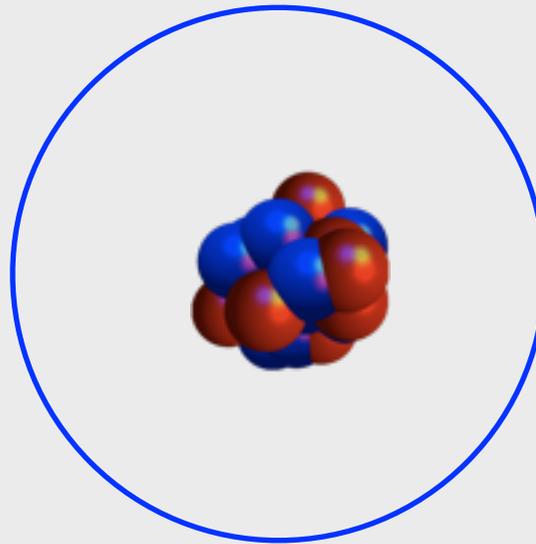


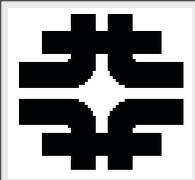


Three Possibilities: Signal

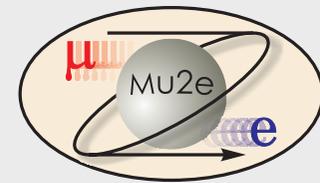


e

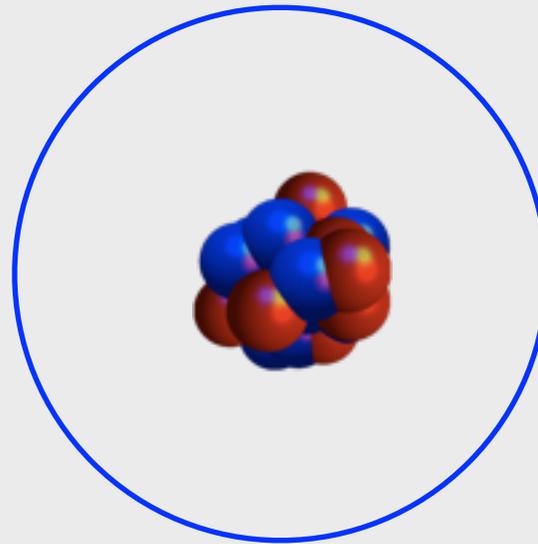




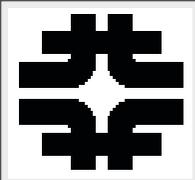
Three Possibilities: Signal



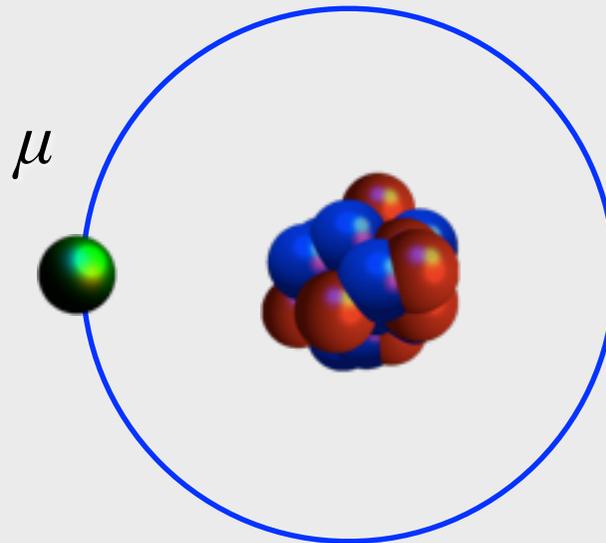
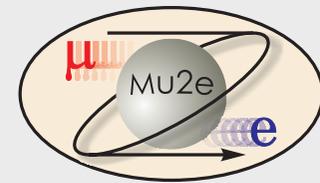
e *off to detector!*

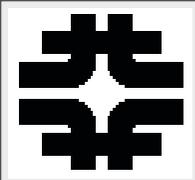


coherent recoil of nucleus

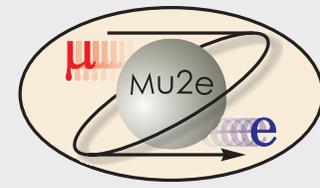


Three Possibilities: Background





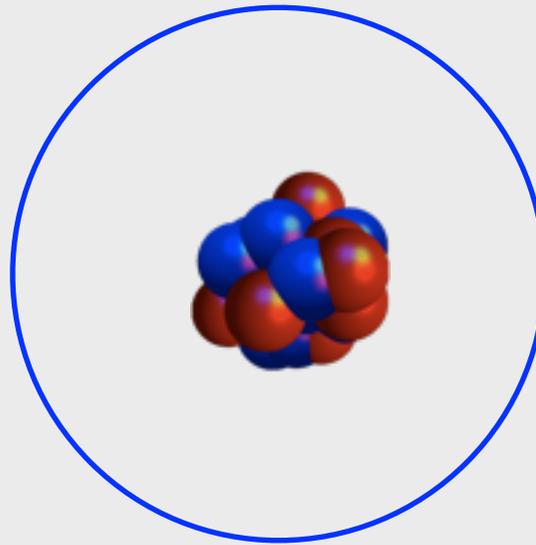
Three Possibilities: Background



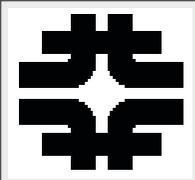
e



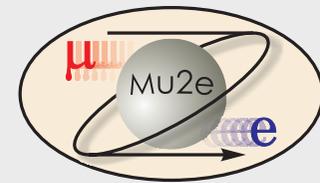
ν_{μ}



$\bar{\nu}_e$



Three Possibilities: Background

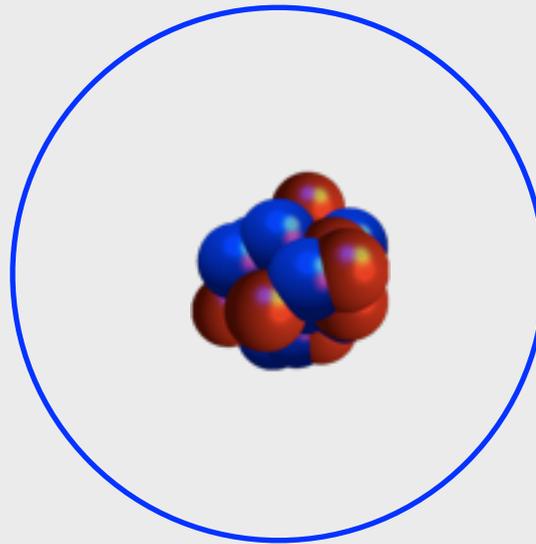


this electron can be background;
let's see how

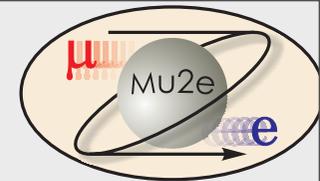
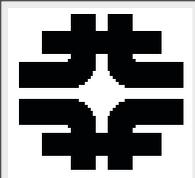


e

ν_{μ}



$\bar{\nu}_e$

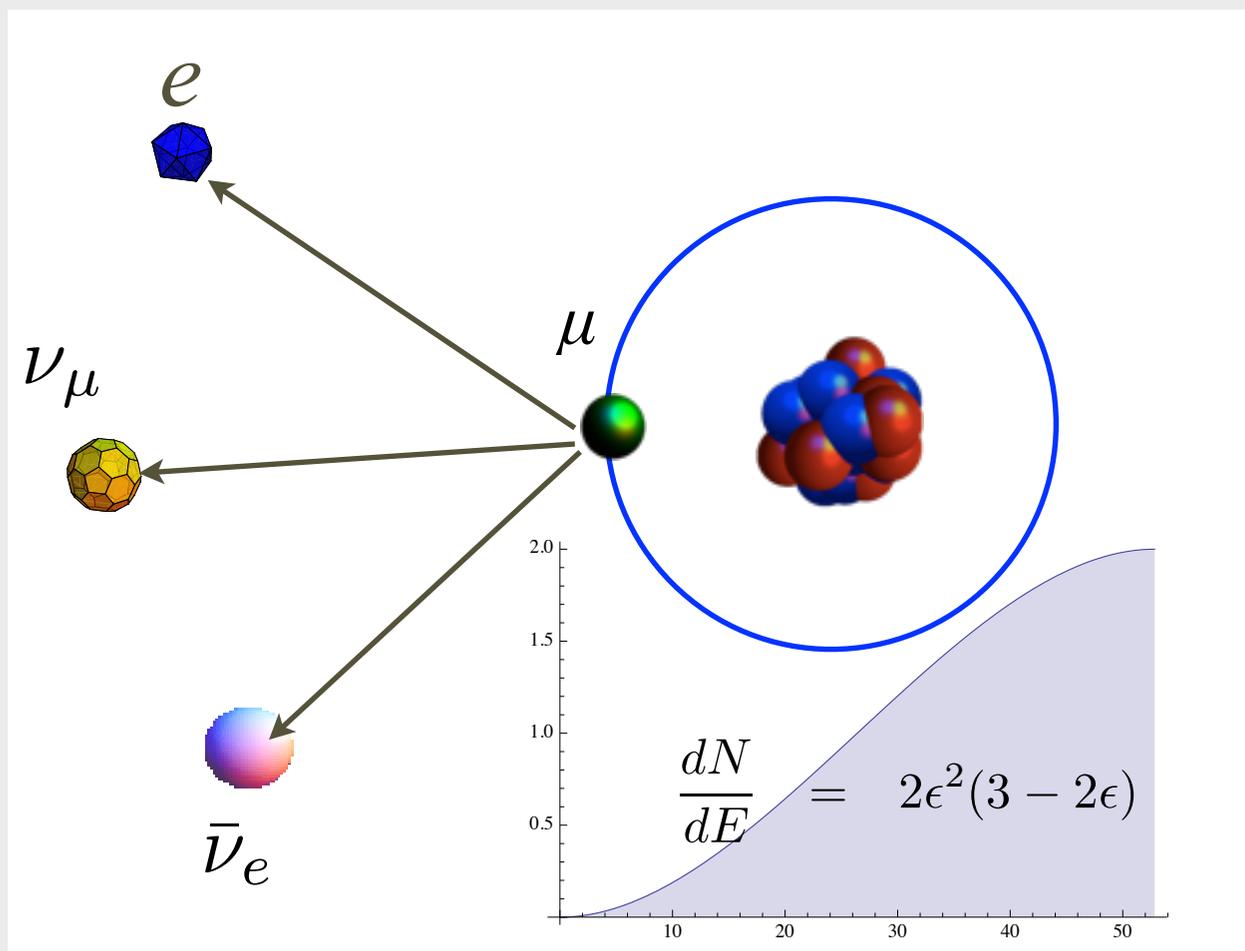


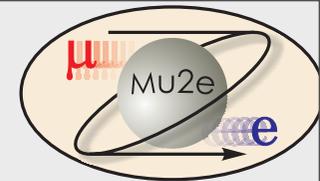
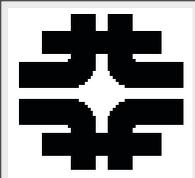
Decay-In-Orbit: Not always Background

- Peak and Endpoint of Michel Spectrum is at

$$E_{\max} = \frac{m_{\mu}^2 + m_e^2}{2m_{\mu}} \approx 52.8 \text{ MeV}$$

- Detector will be insensitive to electrons at this energy
- Recall *signal* at $105 \text{ MeV} \gg 52.8 \text{ MeV}$



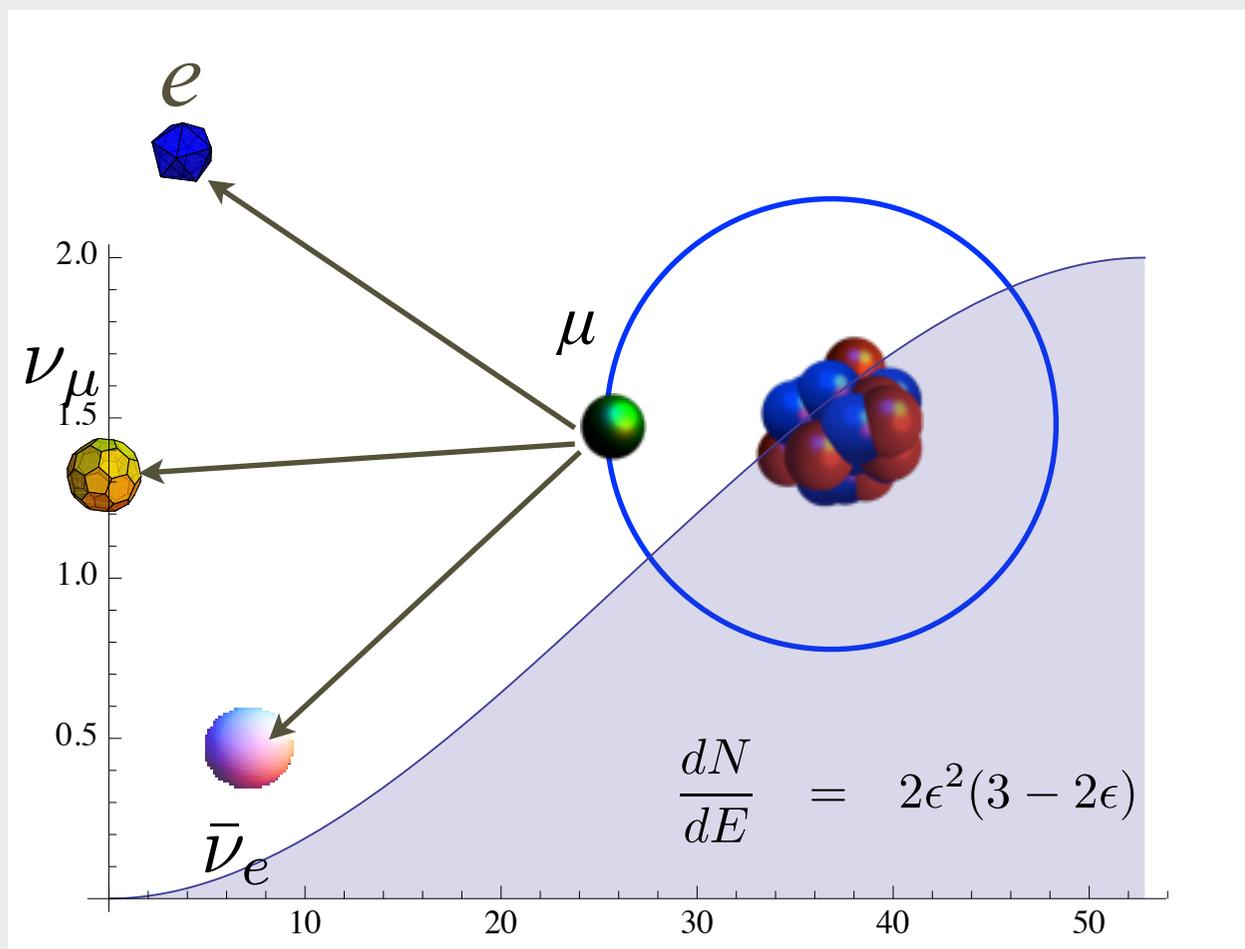


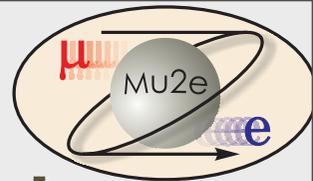
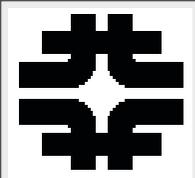
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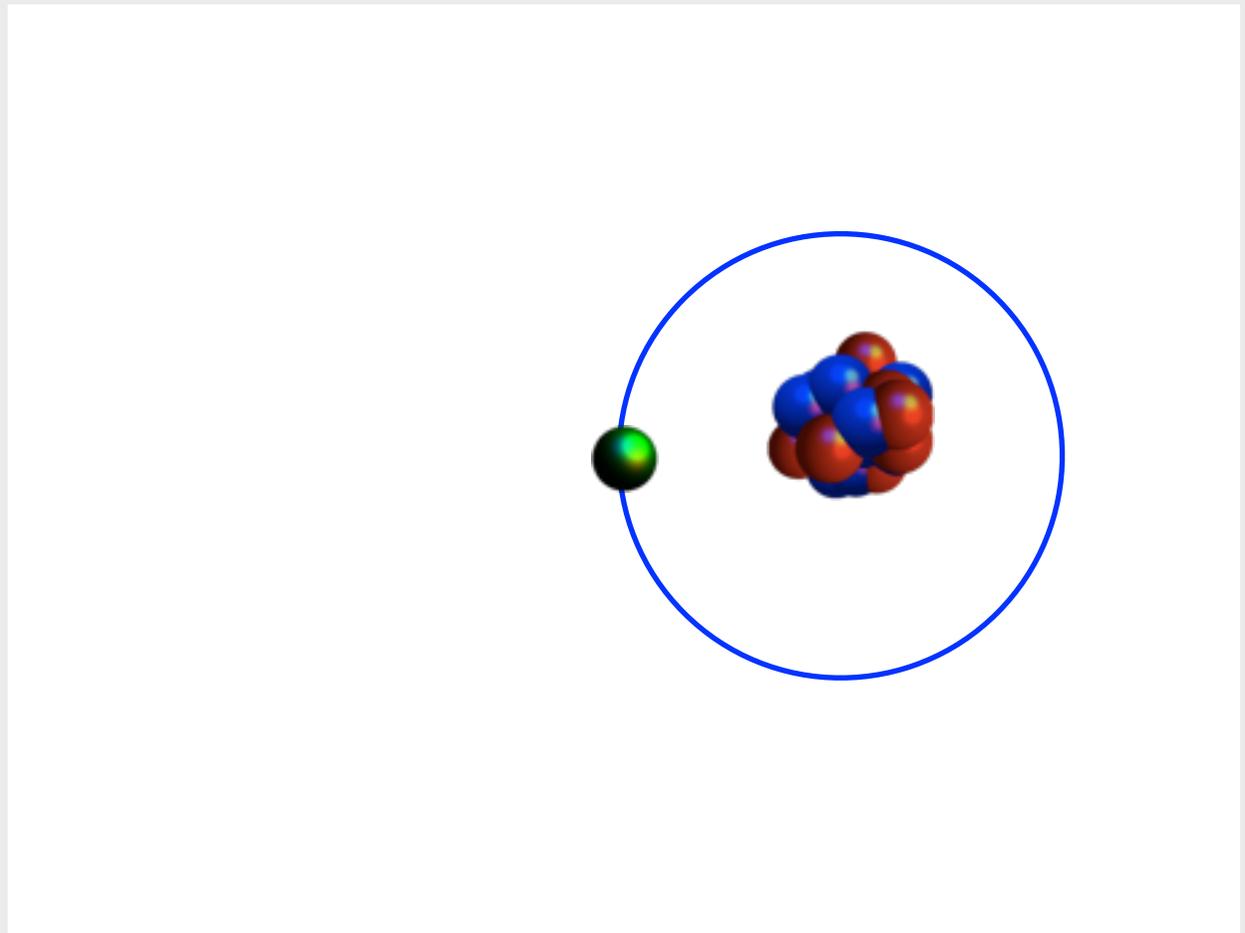
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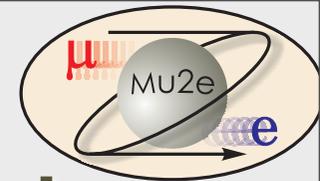
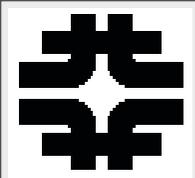




Decay-In-Orbit Background

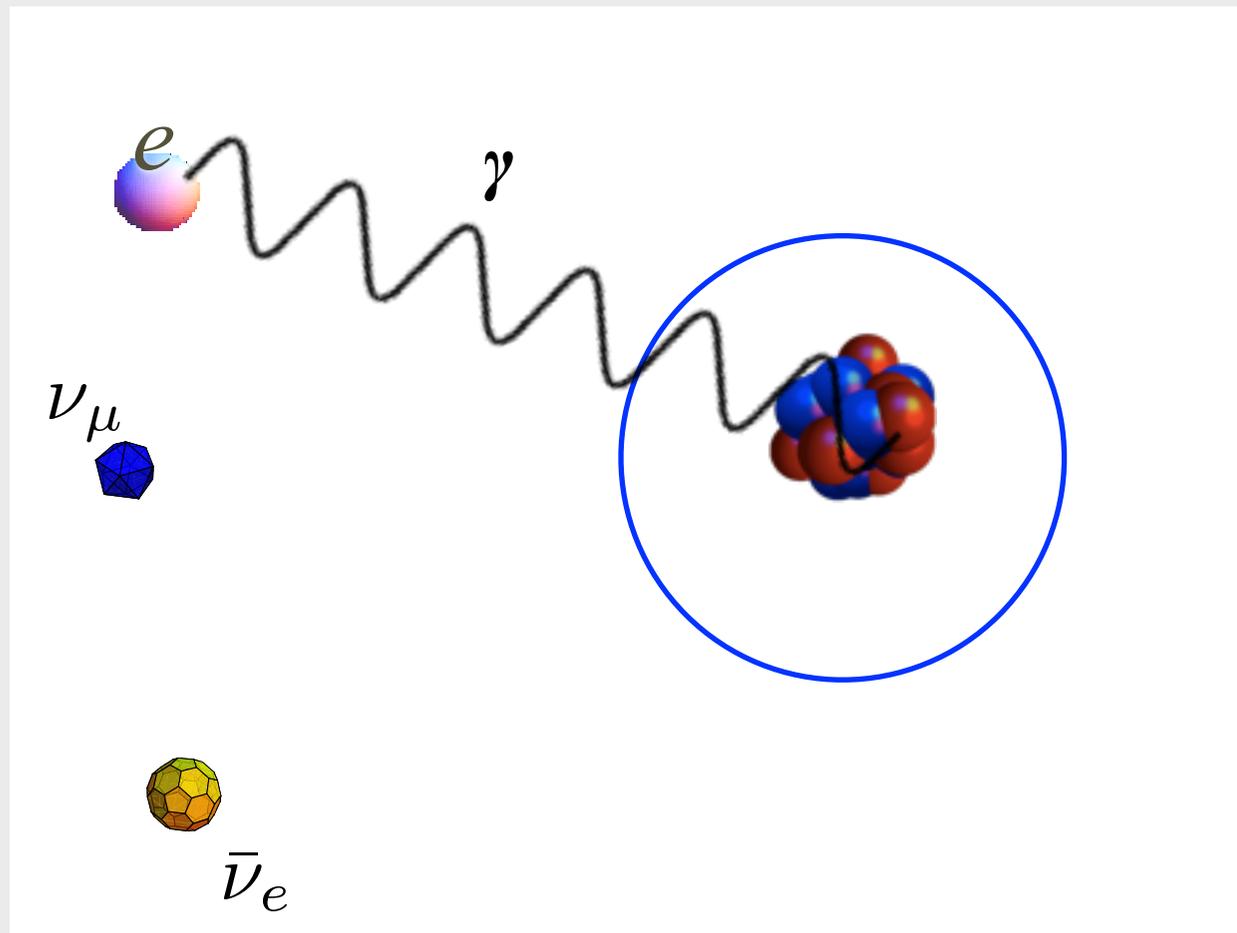
- Same process as before
- But this time, include electron recoil off nucleus
- If neutrinos are at rest, **the DIO electron can be exactly at conversion energy** (up to neutrino mass)

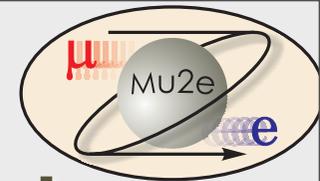
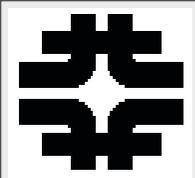




Decay-In-Orbit Background

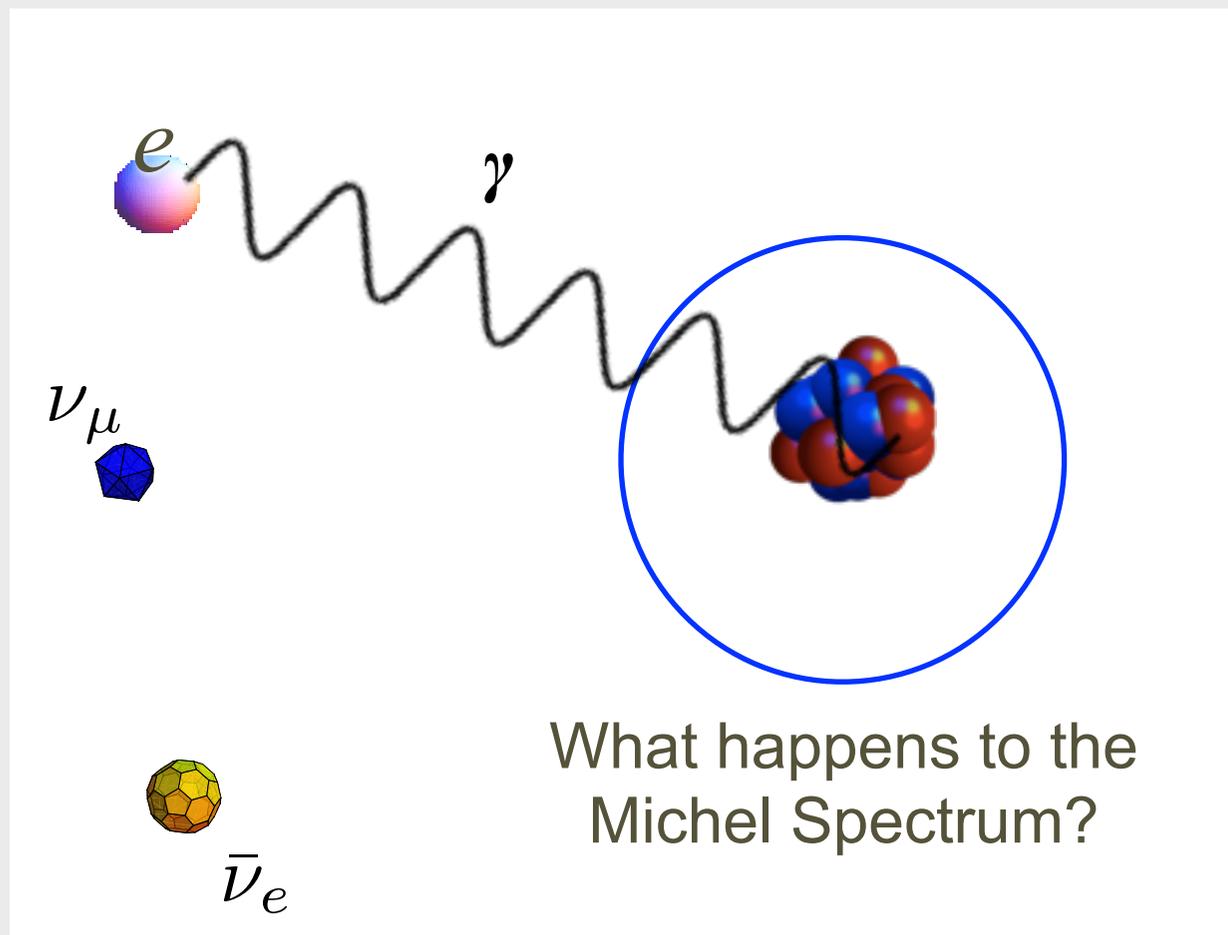
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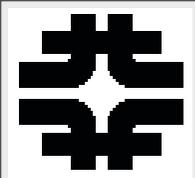




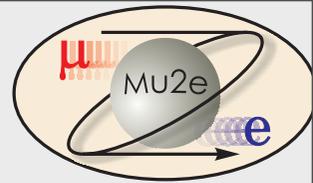
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Decay-in-Orbit Shape

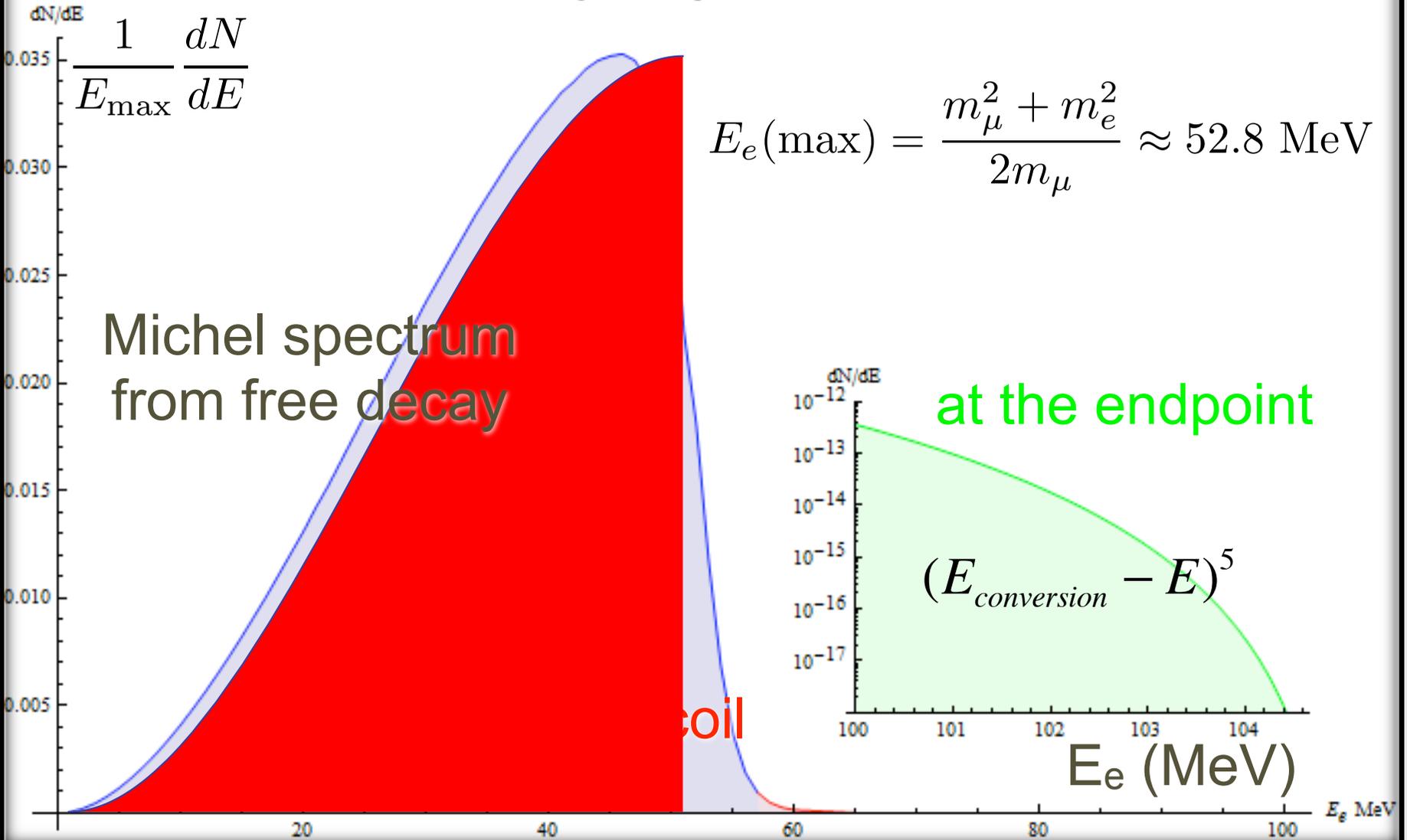


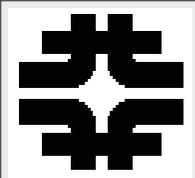
μ Decay in Orbit Spectrum ^{27}Al

$$\frac{dN/dE}{E_{\text{max}}} = \frac{1}{E_{\text{max}}} \frac{dN}{dE}$$

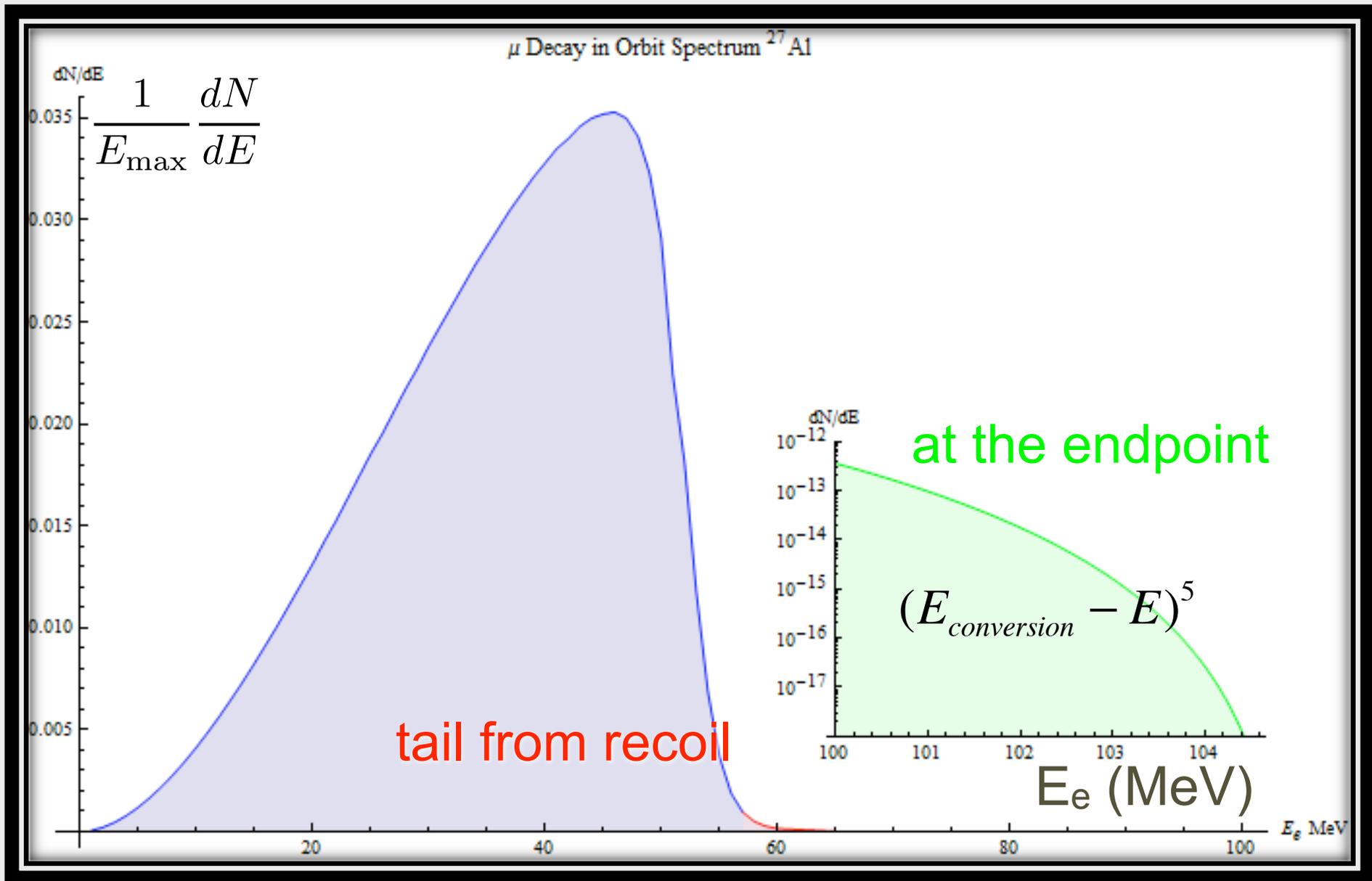
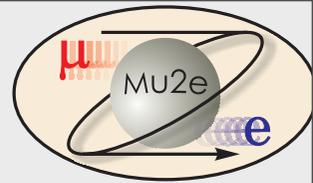
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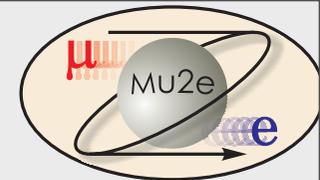
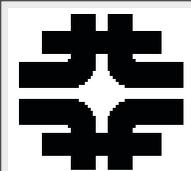
Michel spectrum
from free decay





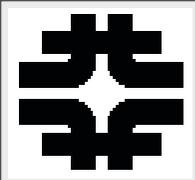
Decay-in-Orbit Shape



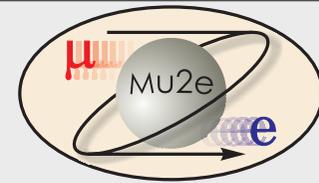


DIO Background Calculation

- Two Ingredients: Shape and Normalization
 - Very hard to calculate 10^{-17} portion of the spectrum; Marciano, Czarnecki are doing this
- Real DIO background is from these near-to-endpoint events combining with spurious or extra hits from other events to form catastrophically mis-reconstructed signal events
 - one advantage of FNAL over BNL is x 3 lower instantaneous rate, lowering this background



Prompt Backgrounds



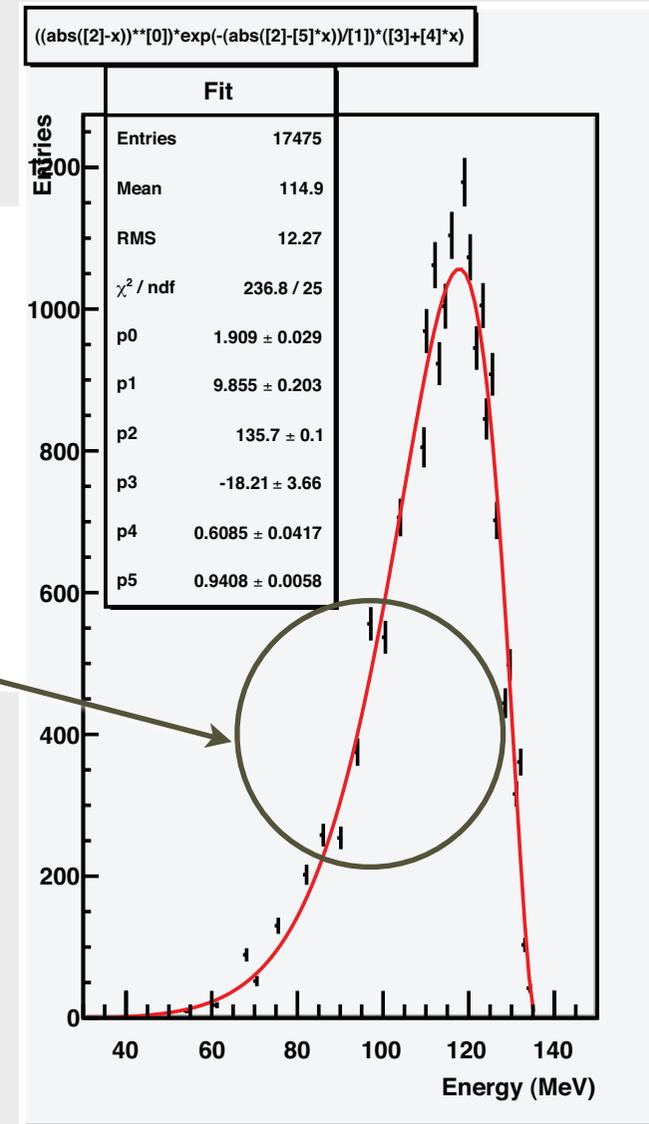
Particles produced by proton pulse which interact almost immediately when they enter the detector: π , neutrons, p bars

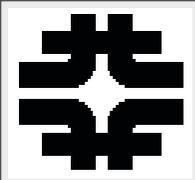
- **Radiative pion capture, $\pi^- + A(N,Z) \rightarrow \gamma + X$.**

- γ up to m_π , peak at 110 MeV; $\gamma \rightarrow e^+e^-$; if one electron ~ 100 MeV in the target, looks like signal: **limitation in best existing experiment, SINDRUM II?**

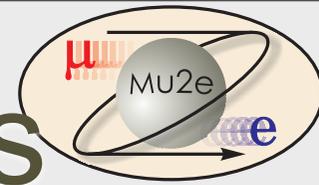
energy spectrum of γ measured on Mg
J.A. Bistirlich, K.M. Crowe et al., Phys Rev C5, 1867 (1972)

also internal conversion, $\pi^- N \rightarrow e^+e^- X$
need calculation given this data

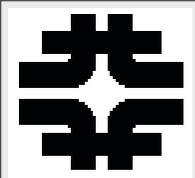




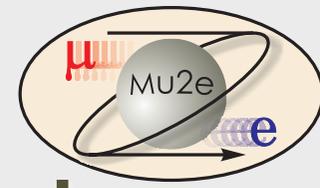
Other Prompt Backgrounds



- Beam electrons: incident on the stopping target and scatter into the detector region.
 - Need to suppress e^- with $E > 100$ MeV near 105 MeV signal
- In-flight muon decays yielding electrons:
 - if they decay with momentum > 76 MeV/c, can yield electron in signal region

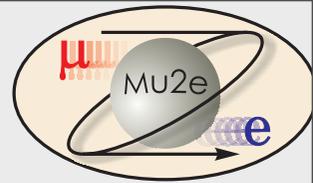
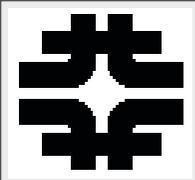


Review:



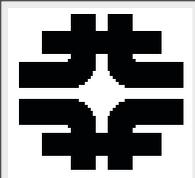
Two Classes of Backgrounds

| | Decay-In-Orbit | Prompt |
|----------|---|--|
| Source | Intrinsic Physics Background | Radiative π Capture: Mostly π 's produced in production target |
| Solution | Spectrometer Design: resolution and pattern recognition | Design of Muon Beam, formation, transport, and time structure |

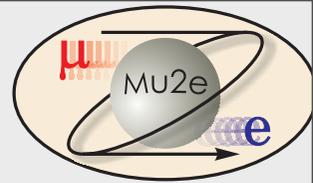


Outline

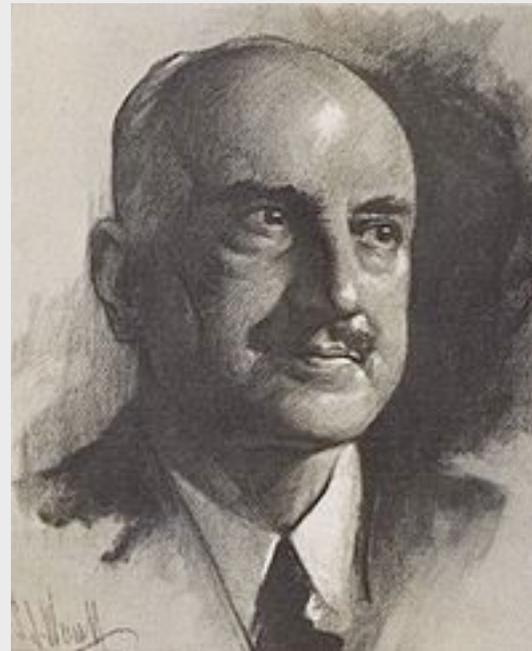
- The search for muon-electron conversion
- *Experimental Technique*
- Fermilab Accelerator
- Project X Upgrades and Mu2e
- Cost and Schedule
- Conclusions

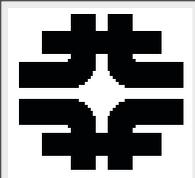


What Limited Previous Measurements?

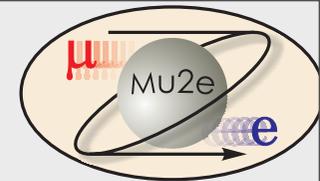


- “Those who cannot remember the past are condemned to repeat it” --G. Santayana



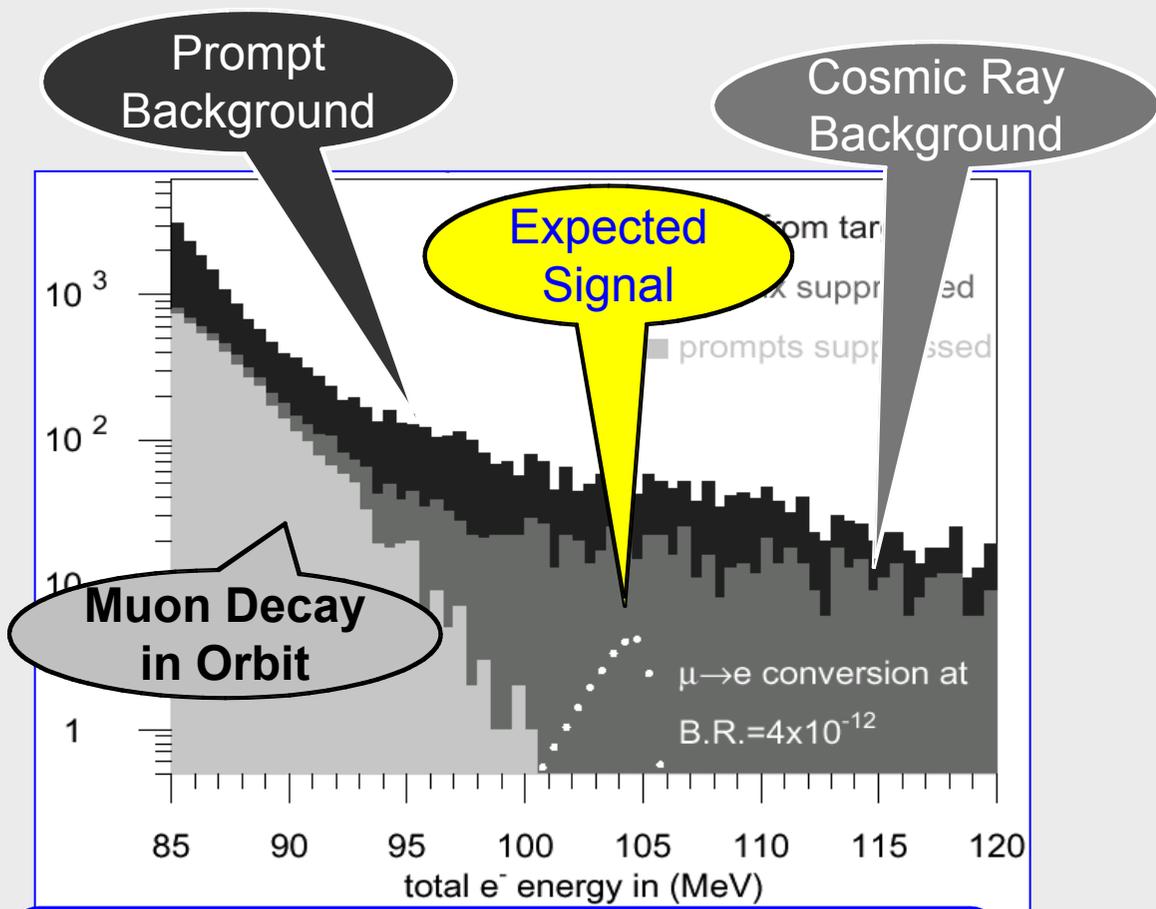


Previous Best Experiment

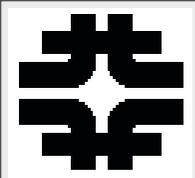


SINDRUM-II

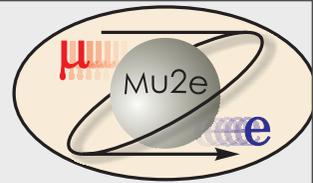
- $R_{\mu e} < 6.1 \times 10^{-13}$ in Au
- Want to probe to 6×10^{-17}
- $\approx 10^4$ improvement



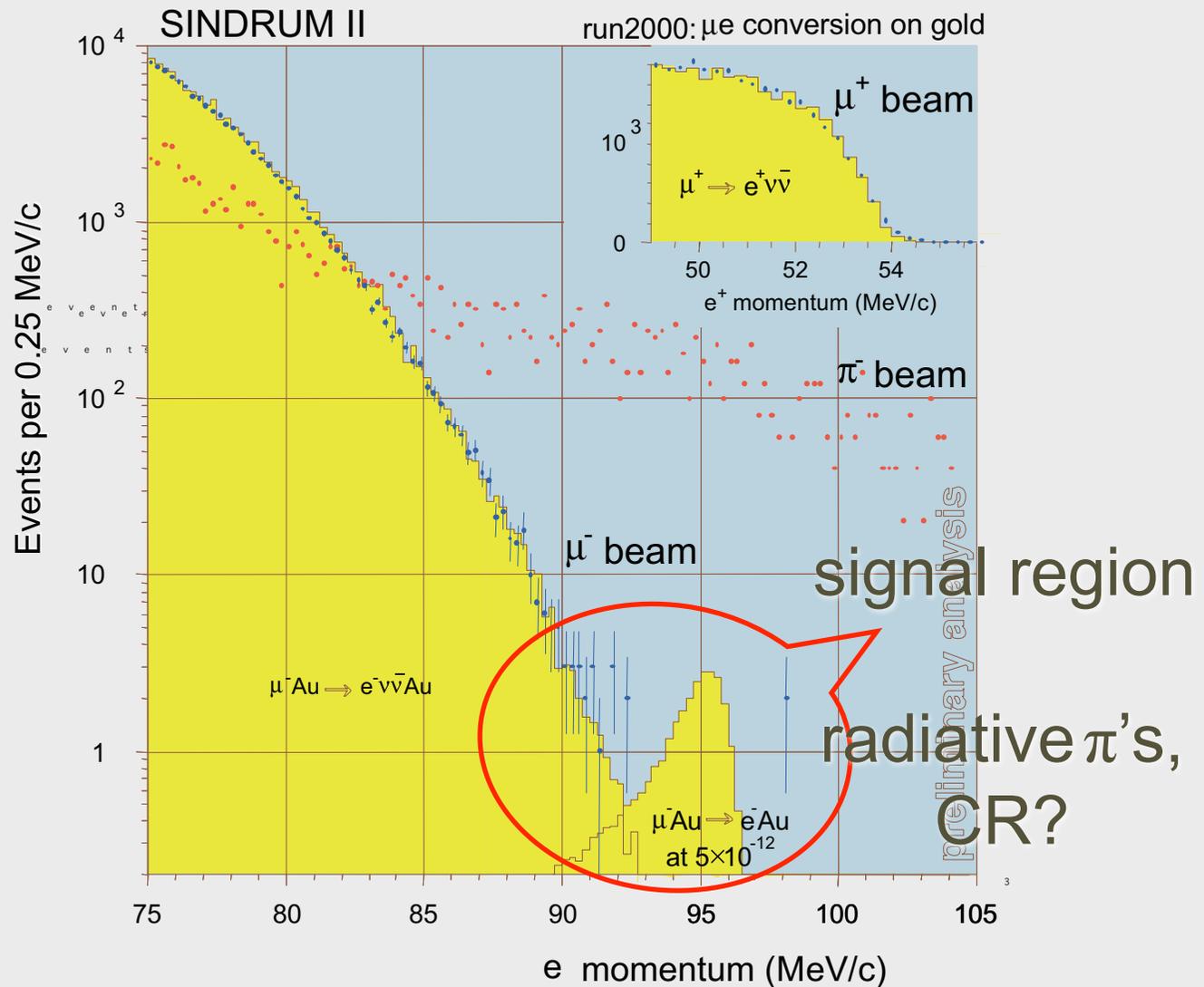
Experimental signature is 105 MeV e⁻ originating in a thin Ti stopping target



SINDRUM II Results



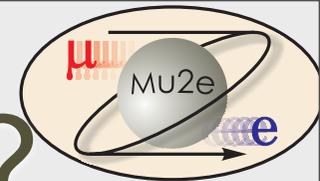
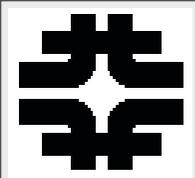
- Final SINDRUM-II on Au
- Note Two Background Events past Signal Region



W. Bertl et al, Eur. Phys. J. C **47**, 337-346 (2006)

July 14, 2001

HEP 2001 (W.Bertl - SINDRUM II collaboration)



What Limited SINDRUM-II?

PSI PAUL SCHERRER INSTITUT

Background : b) pion induced

DC Beam

Radiative Pion Capture (RPC) : $\pi^- Au \rightarrow \gamma + Pt^*$ followed by $\gamma \rightarrow e^+ e^-$

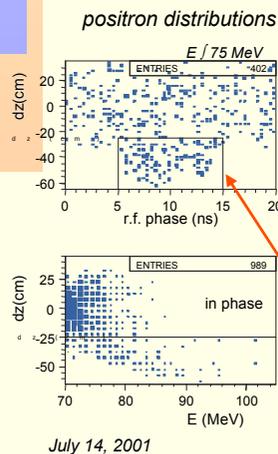
Kinematic endpoint of photon spectrum around 130 MeV ! Branching ratio of order 2%.

No way to distinguish an asymmetric $e^+ e^-$ -pair (with little e^+ energy and e^- energy at 95 MeV) from μe !

=> Needs strong pion suppression : only ~ 1 pion every 5 minutes is allowed to reach gold target!

no time separation between signal and prompt background

radiative π capture

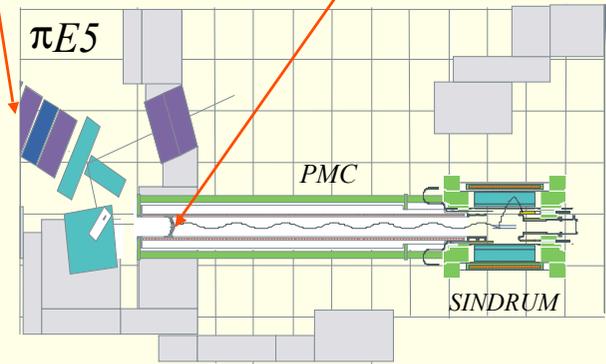


BUT: Degrader is now pion stop target $\rightarrow e^+ e^-$ pairs from RPC are collected by B_{PMC} and transported towards the gold target where they may scatter into spectrometer acceptance (typ. forward scattering)

=> use solid angle and cyclotron phase correlation to cut.

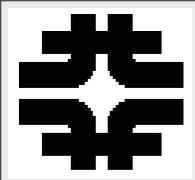
=> tune beamline to suppress high momentum tail

=> use degrader 8m in front of gold target to separate μ 's and π 's by their different stopping power. Penetrating slow pions decay in PMC.

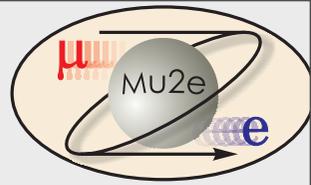


HEP 2001 (W.Bertl - SINDRUM II collaboration)

cosmic rays also an issue; need excellent veto, ~99.9%



How Can We Do Better?

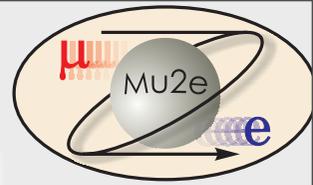
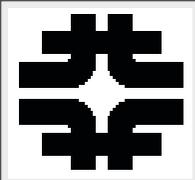


>10³ increase in muon intensity from SINDRUM

Requiring

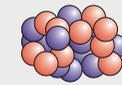
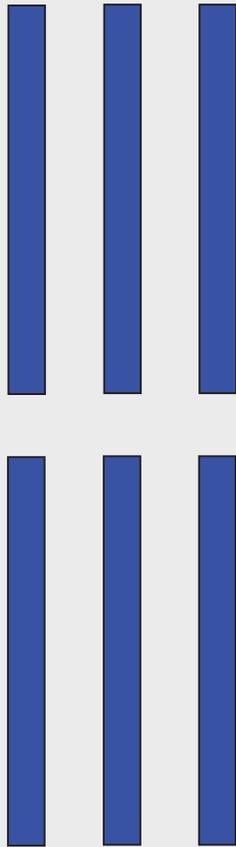
Pulsed Beam to Eliminate prompt backgrounds like radiative π capture and CR

protons out of beam pulse/ protons in beam-pulse < 10⁻⁹
and we must measure it



Advantage of Pulsed Beam

target foils: muon converts here



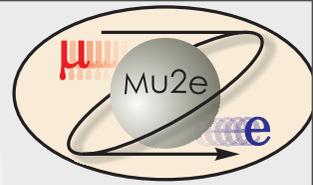
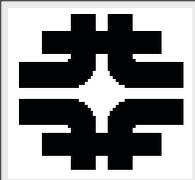
= muons, electrons, pions

Recall:

Muon-electron
conversion signal is a

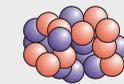
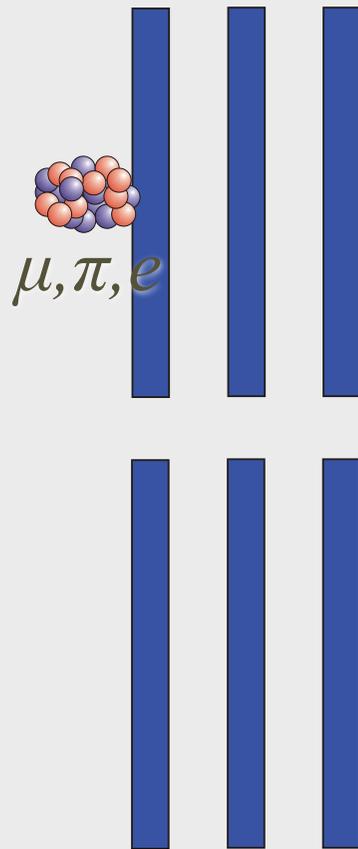
single, monoenergetic
electron

pulsed beam lets us
wait until after prompt
backgrounds
disappear and rate
lowered



Advantage of Pulsed Beam

target foils: muon converts here



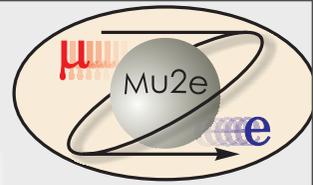
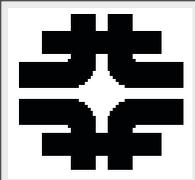
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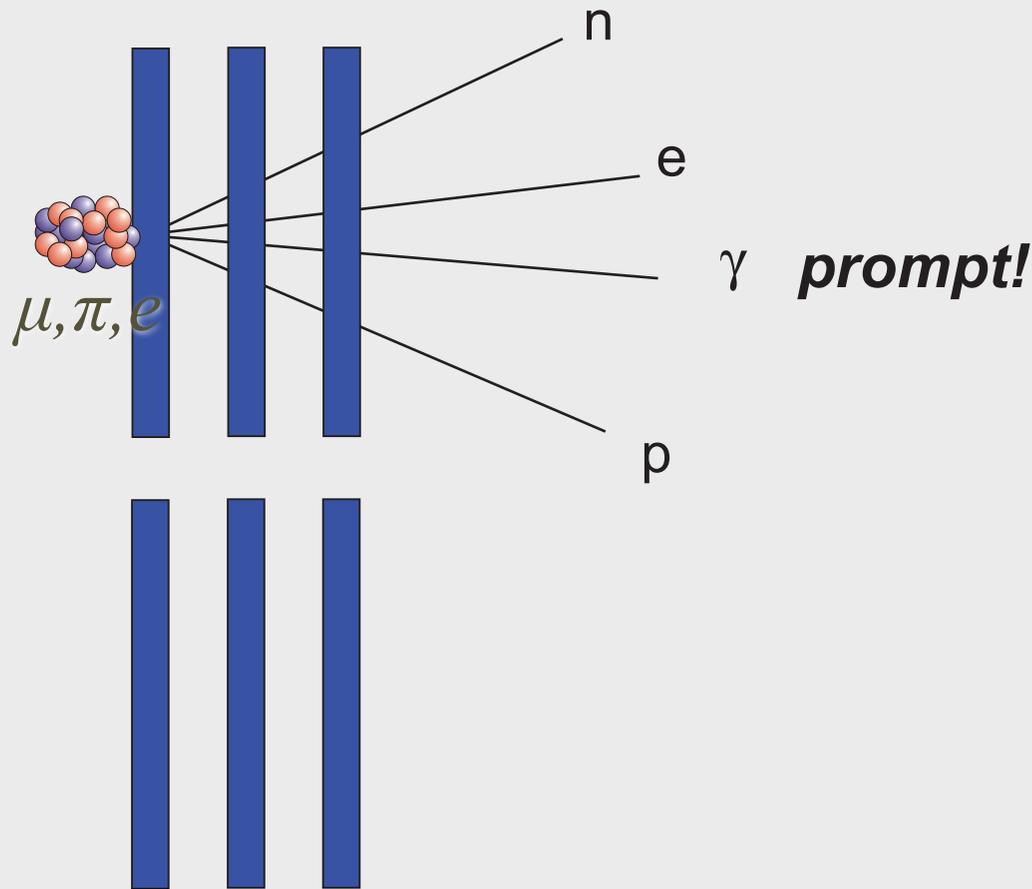
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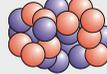
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Advantage of Pulsed Beam

target foils: muon converts here



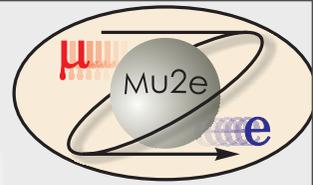
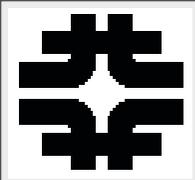
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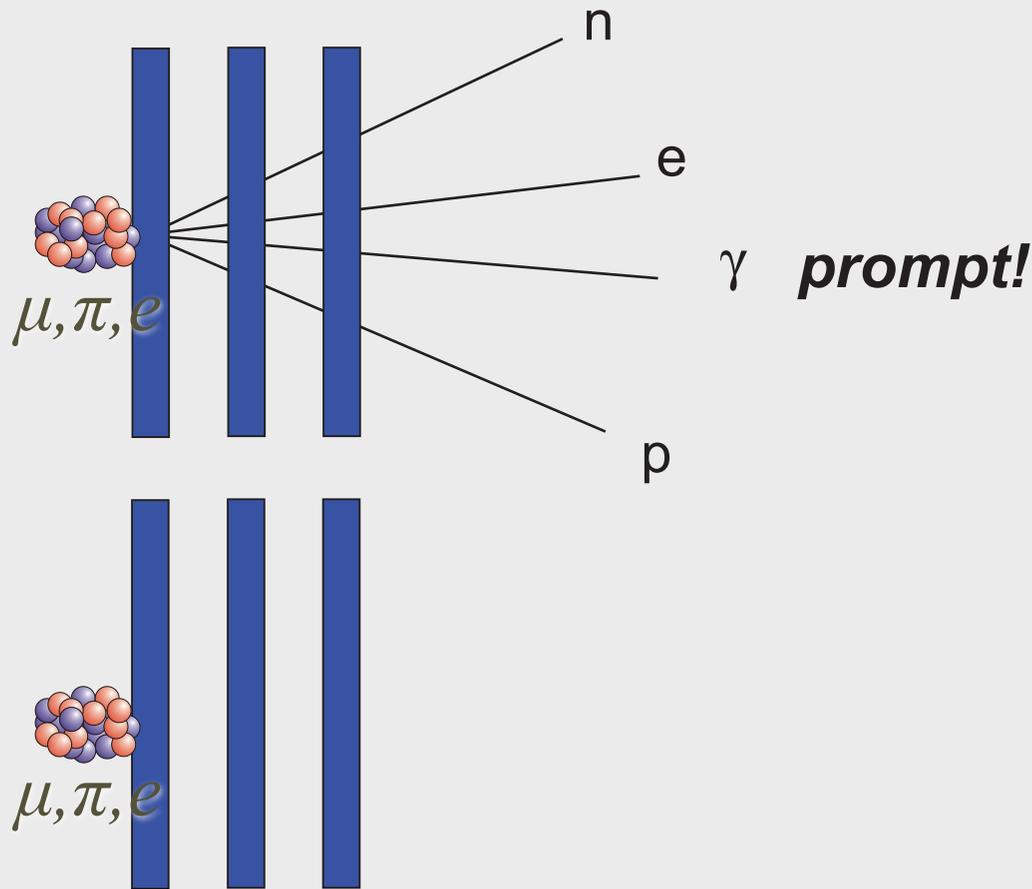
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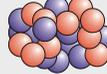
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Advantage of Pulsed Beam

target foils: muon converts here



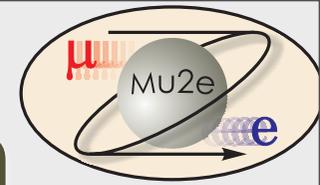
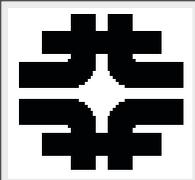
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Recall:

Muon-electron conversion signal is a

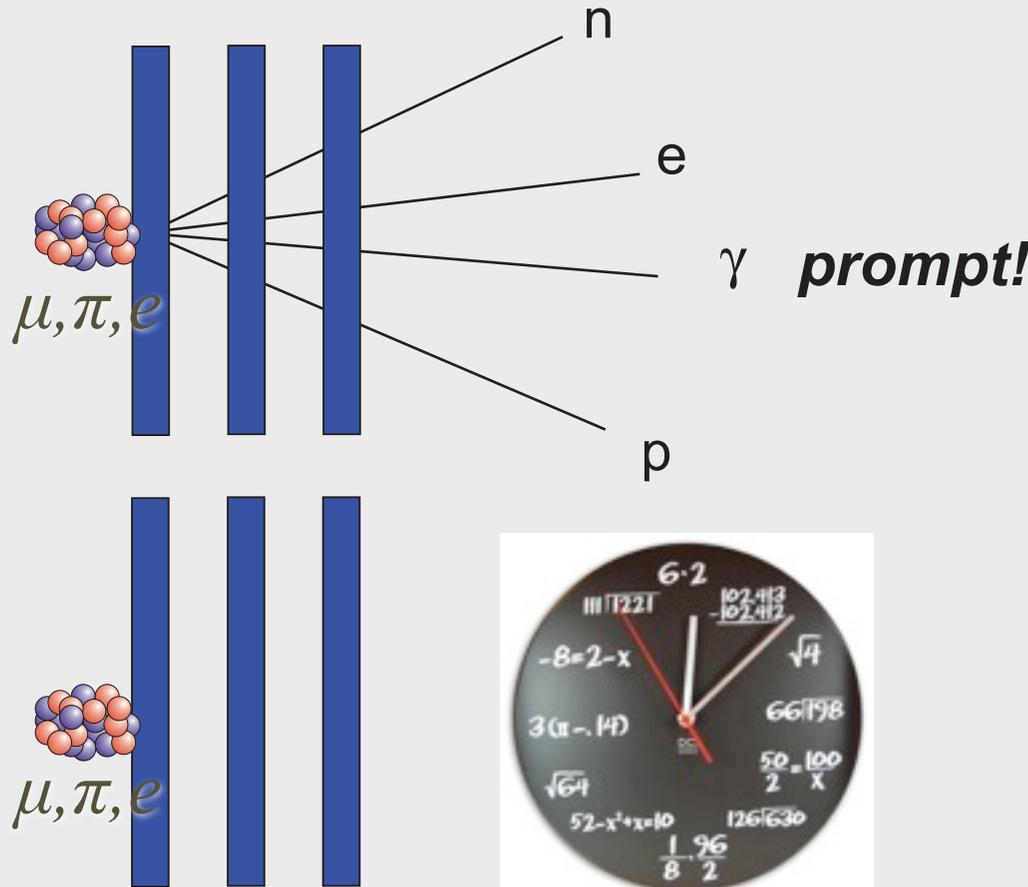
single, monoenergetic electron

pulsed beam lets us wait until after prompt backgrounds disappear and rate lowered



Advantage of Pulsed Beam

target foils: muon converts here



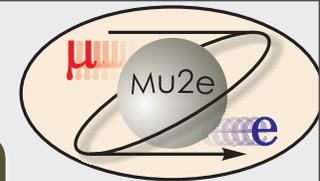
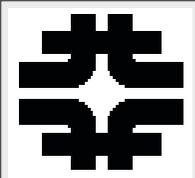
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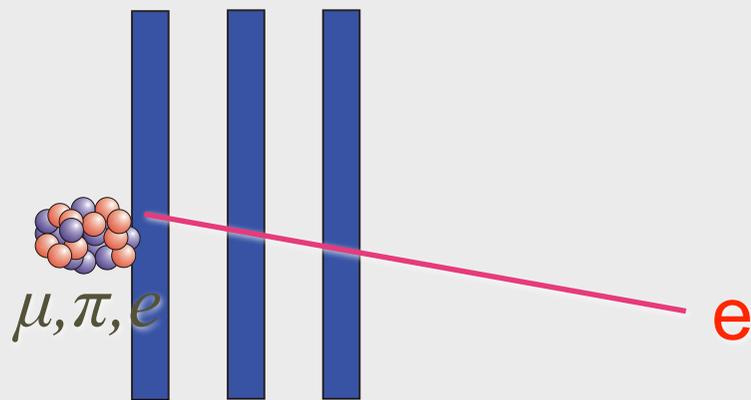
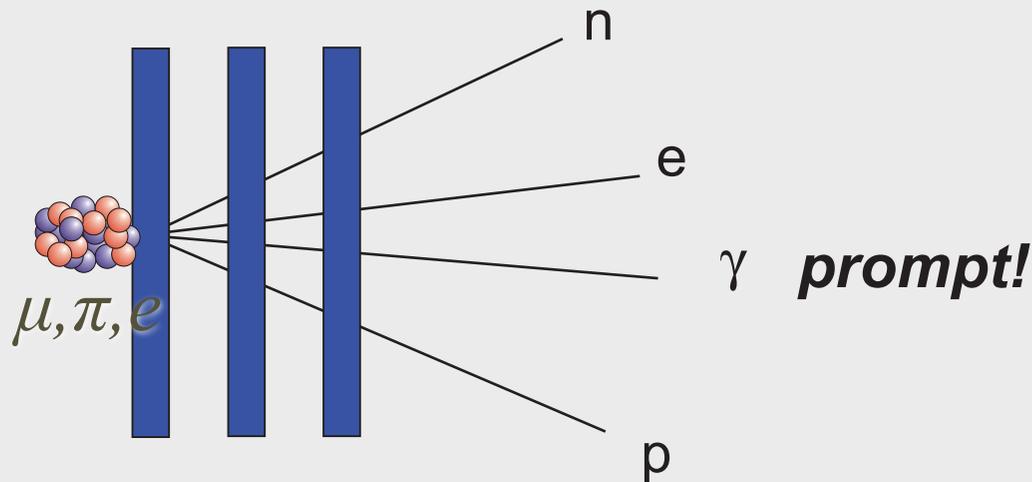
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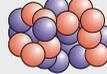


Advantage of Pulsed Beam

target foils: muon converts here



delayed 105 MeV electron

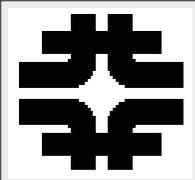
 = muons, electrons, pions

Recall:

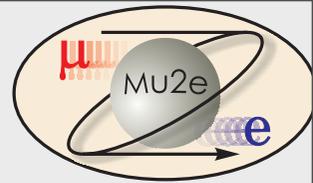
Muon-electron conversion signal is a

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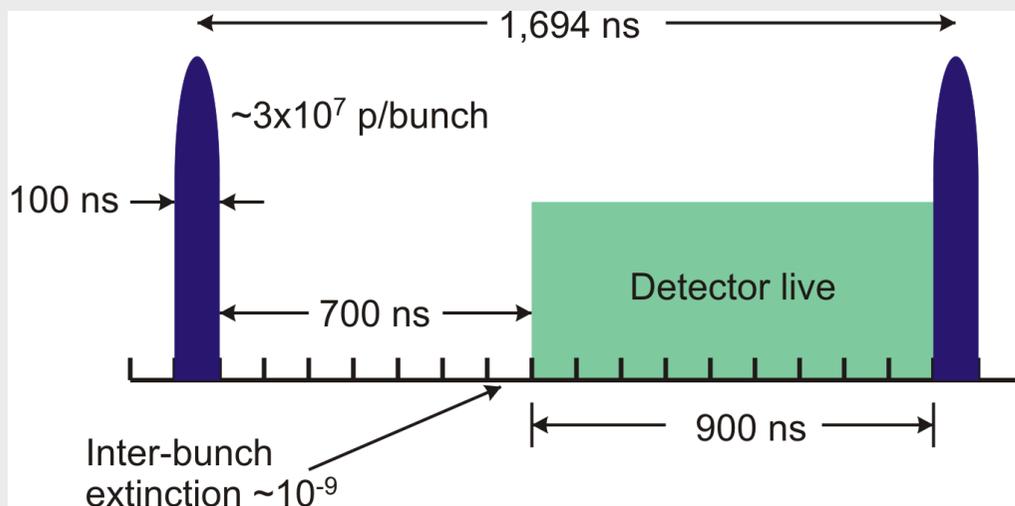


Pulsed Beam Structure

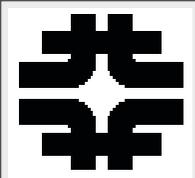


- Tied to prompt rate and machine: FNAL “perfect”
- Want **pulse duration** $\ll \tau_{\mu}^{Al}$, **pulse separation** $\approx \tau_{\mu}^{Al}$
 - FNAL Debuncher has circumference **1.7 μ sec** , $\sim x2 \tau_{\mu}^{Al}$
- Extinction between pulses $< 10^{-9}$ needed

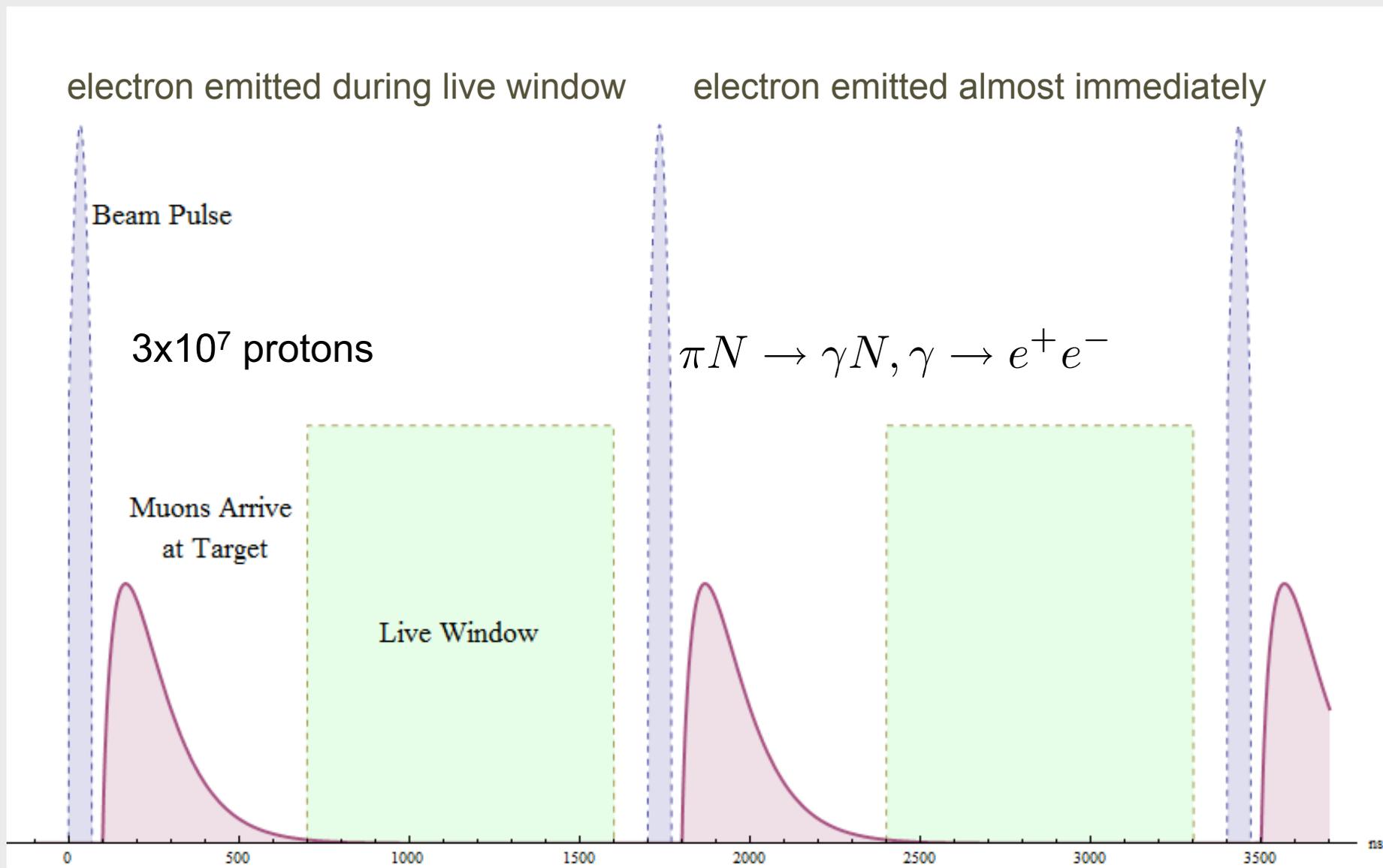
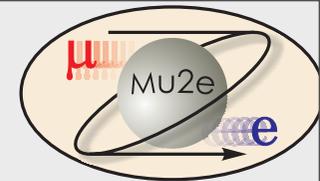
= # protons out of pulse/# protons in pulse



- 10^{-9} based on simulation of prompt backgrounds
- this # is an average, required extinction is time-dependent



Pulsed Beam Structure and Radiative π Capture

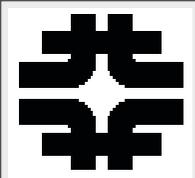


R. Bernstein, FNAL

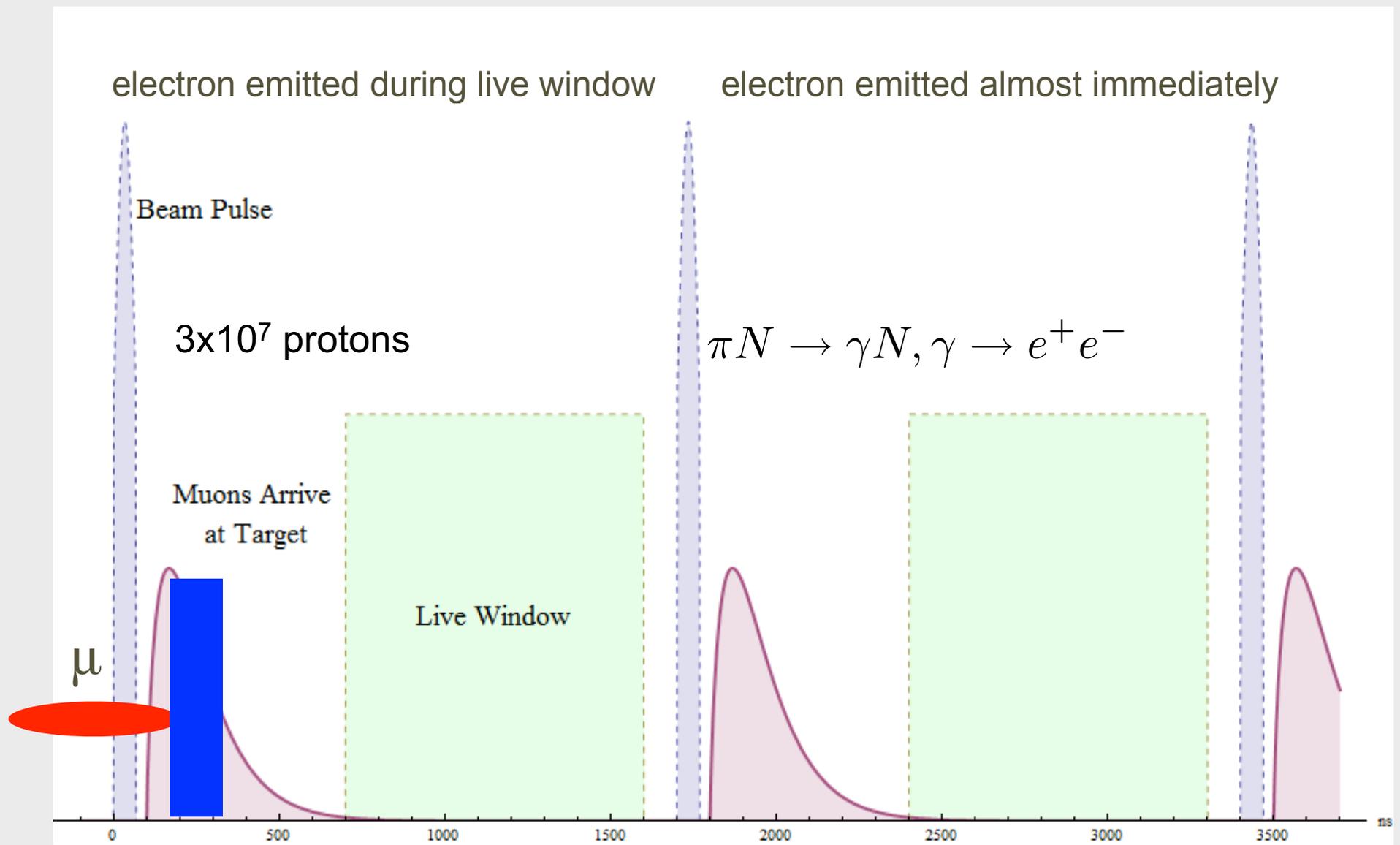
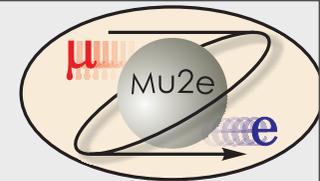
42

Mu2e

U. Chicago 5/17/10



Pulsed Beam Structure and Radiative π Capture

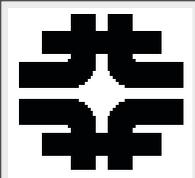


R. Bernstein, FNAL

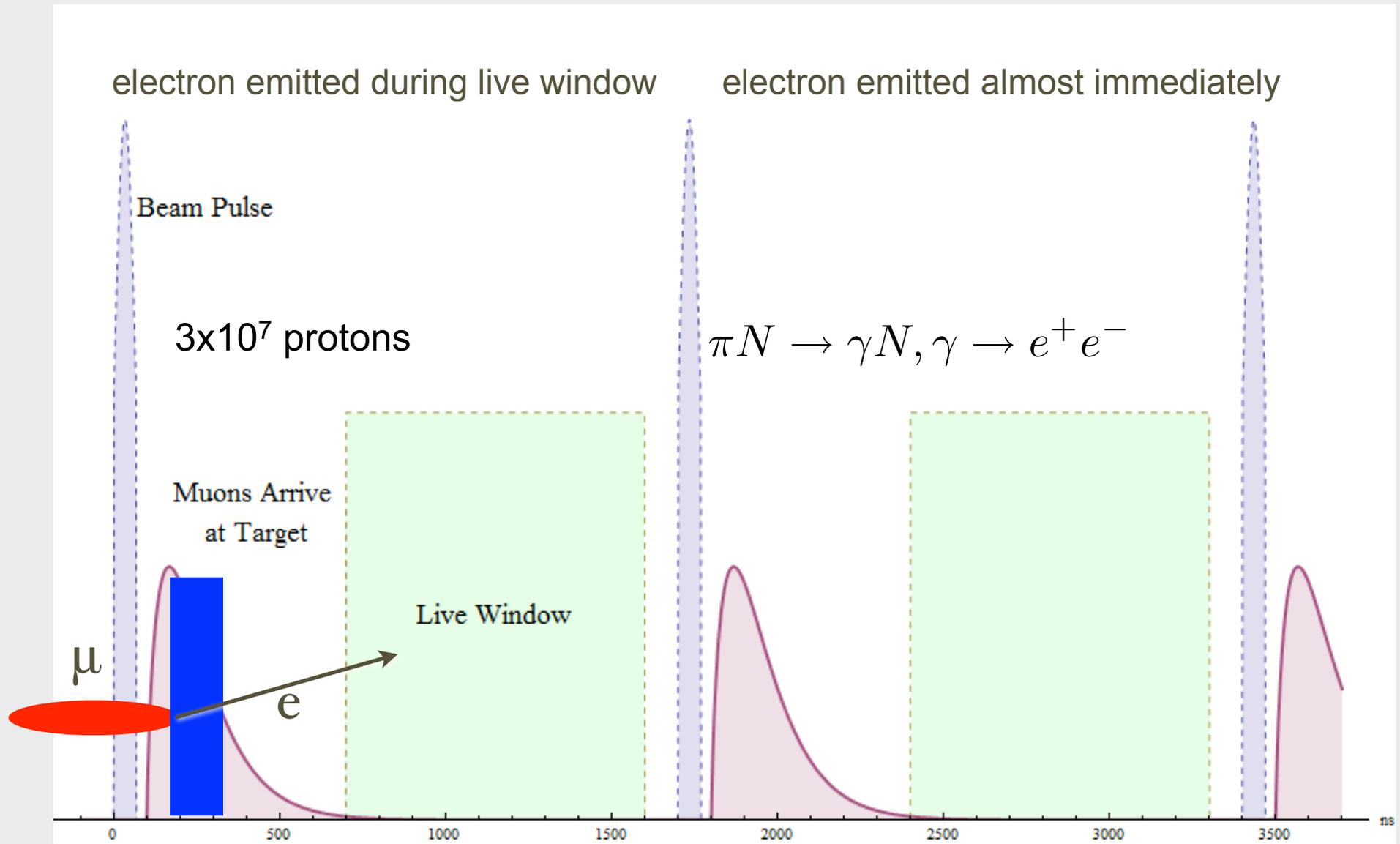
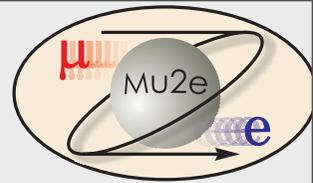
42

Mu2e

U. Chicago 5/17/10



Pulsed Beam Structure and Radiative π Capture

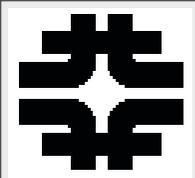


R. Bernstein, FNAL

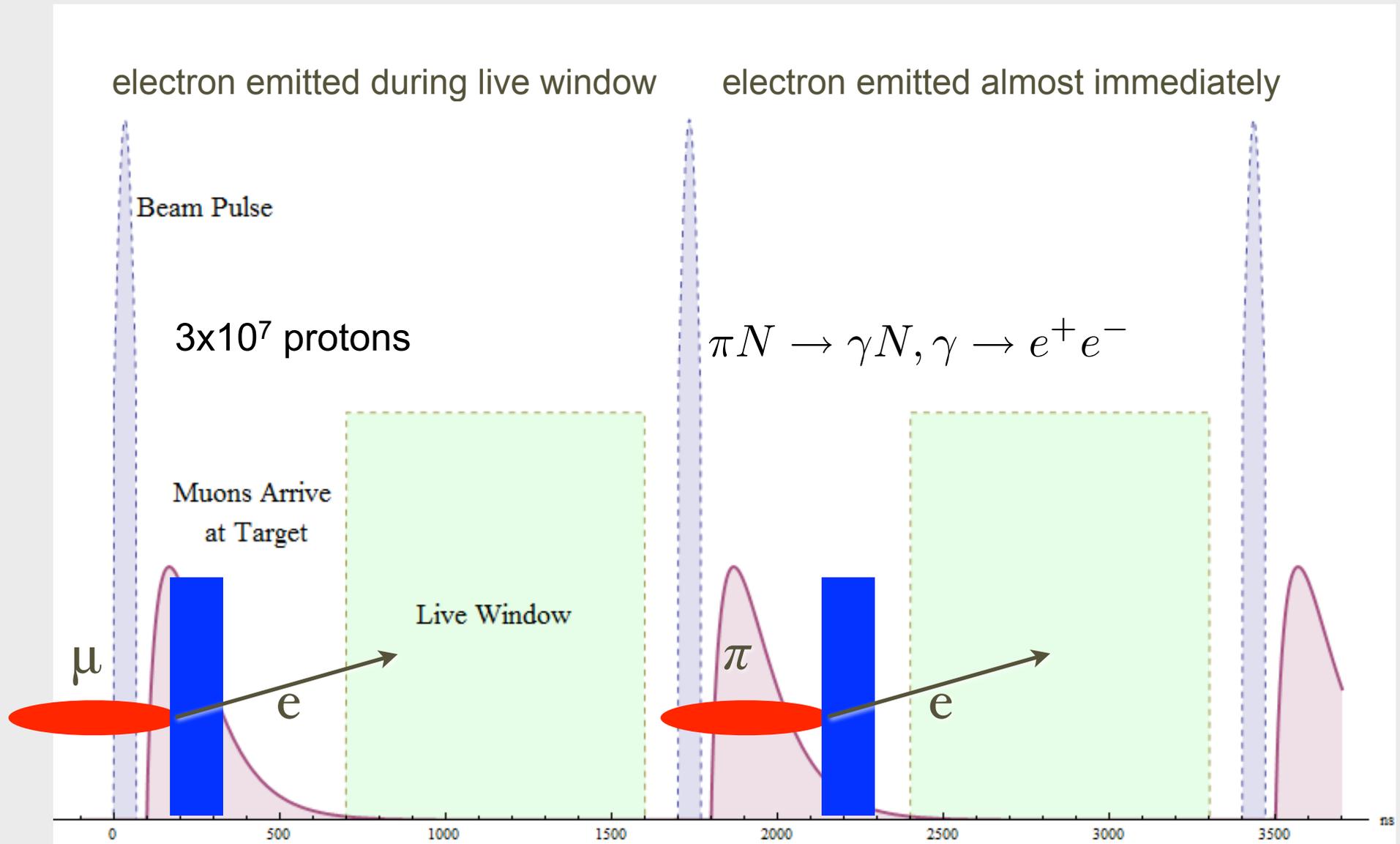
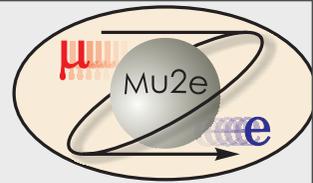
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Mu2e

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Pulsed Beam Structure and Radiative π Capture

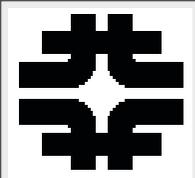


R. Bernstein, FNAL

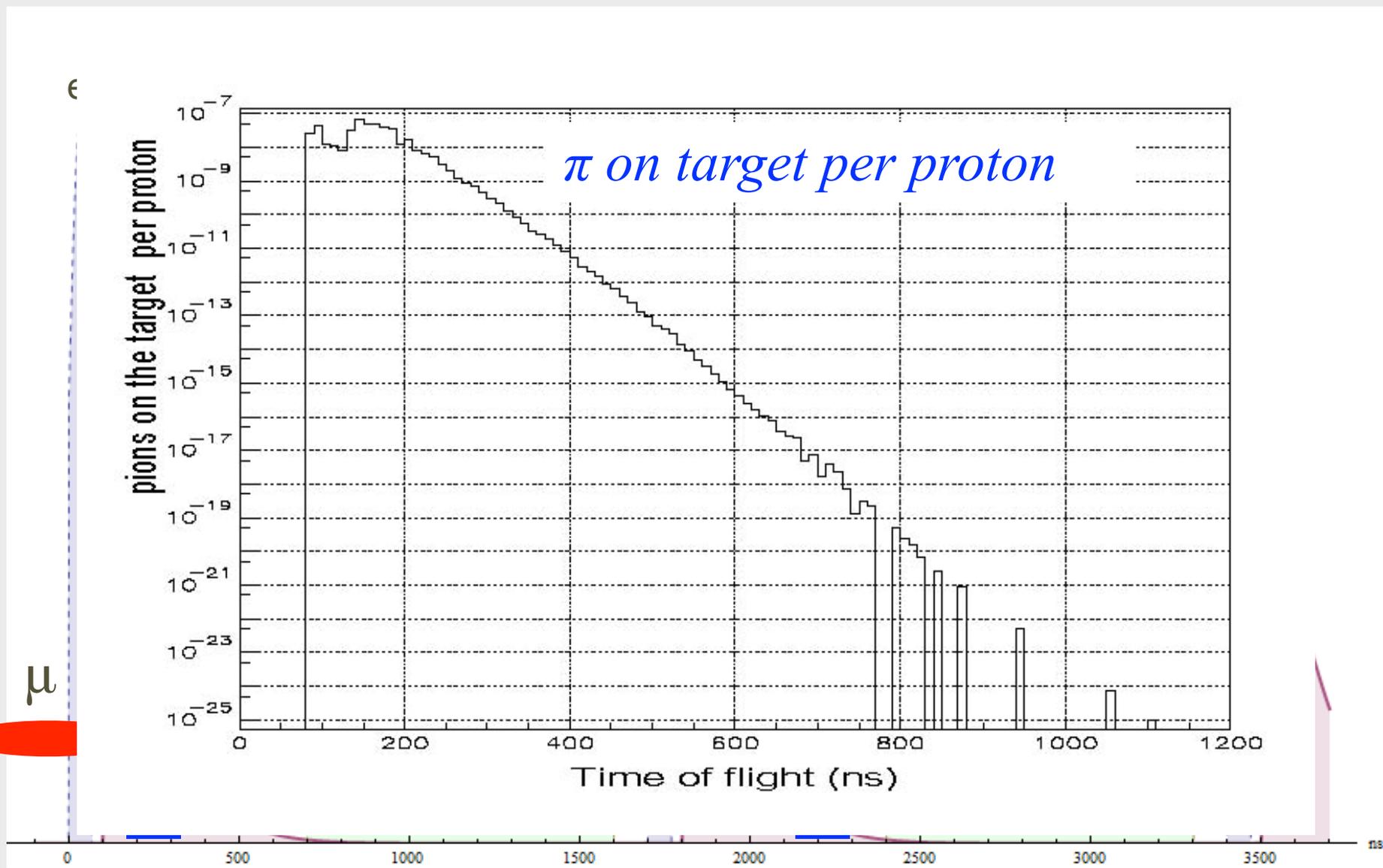
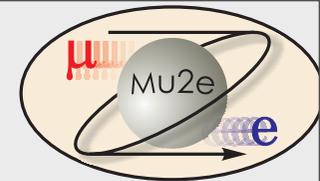
42

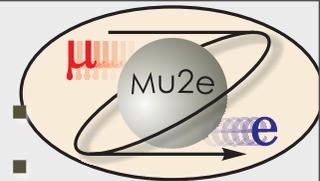
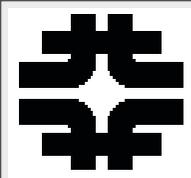
Mu2e

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Pulsed Beam Structure and Radiative π Capture



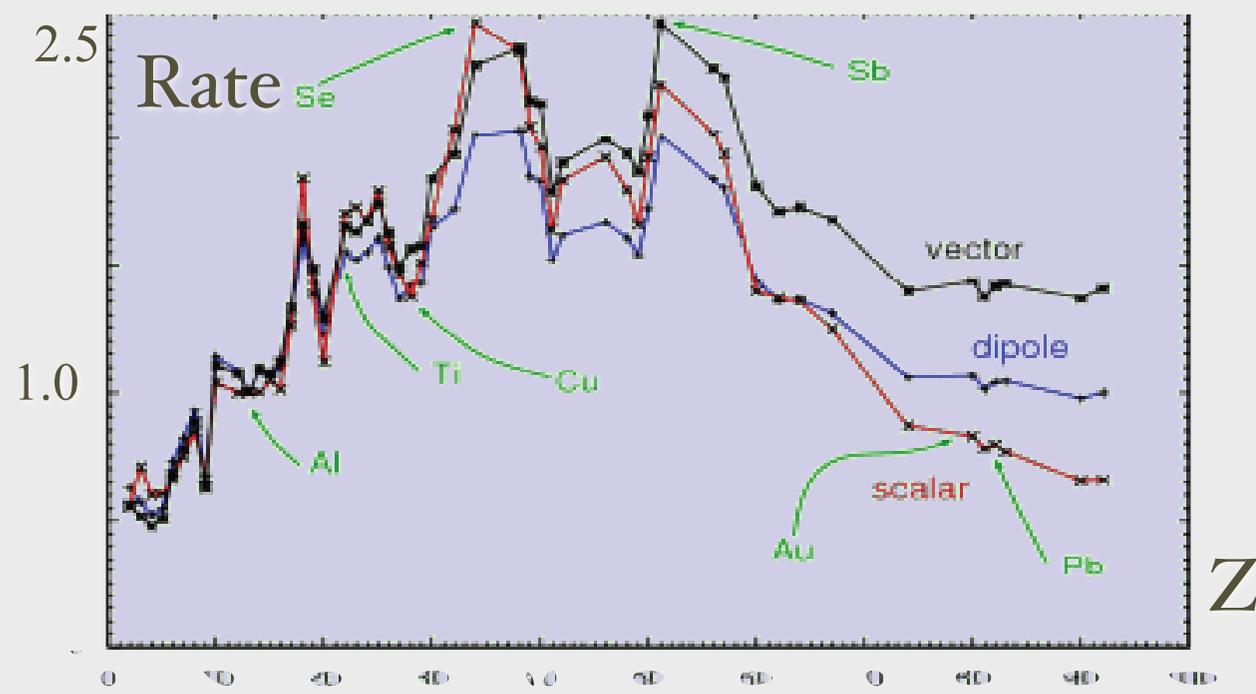


Choice of Stopping Material:

rate vs wait

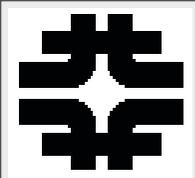
rate normalized to Al

- Stop muons in target (Z,A)
- Physics sensitive to Z: with signal, can switch target to probe source of new physics
- Why start with Al?

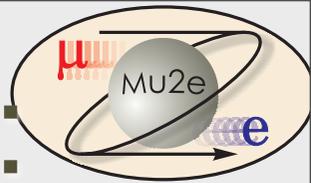


Kitano, et al., PRD 66, 096002 (2002)

shape governed by relative conversion/capture rate, form factors, ...

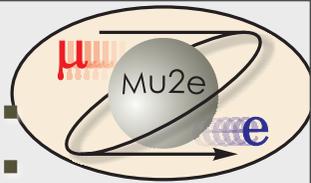
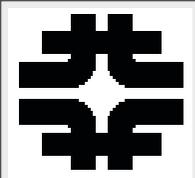


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- Stop muons in target
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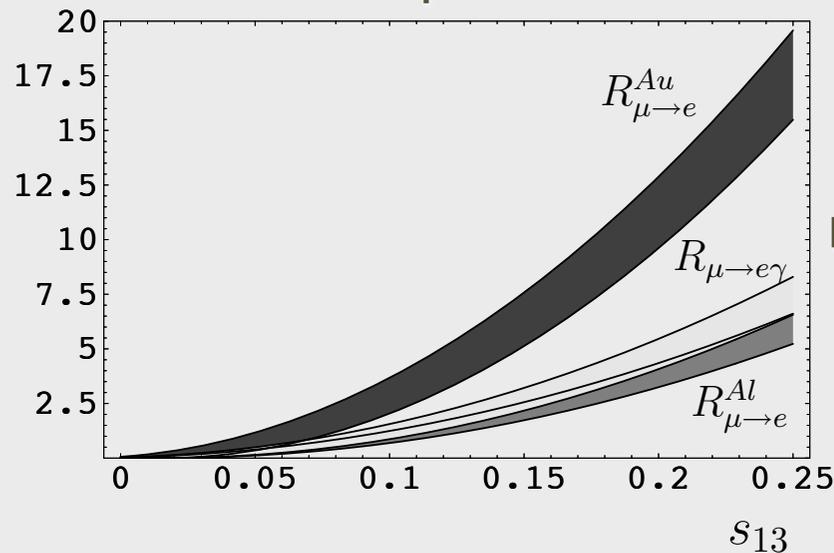
shape governed by relative conversion/capture rate, form factors, ...



Choice of Stopping Material: rate vs wait

- Stop muons in target (Z,A)
- Physics sensitive to Z: with signal, can switch target to probe source of new physics

can see up to x4 effect!



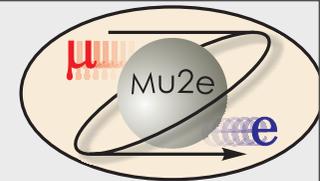
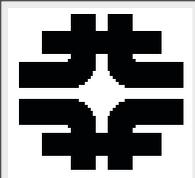
s_{13} is NOvA
mixing angle
< 0.2 or so

V. Cirigliano, B. Grinstein, G. Isidori, M. Wise **Nucl.Phys.B728:121-134,2005.**

e-Print: [hep-ph/0507001](https://arxiv.org/abs/hep-ph/0507001)

- Why start with Al?

shape governed by relative conversion/capture rate, form factors, ...



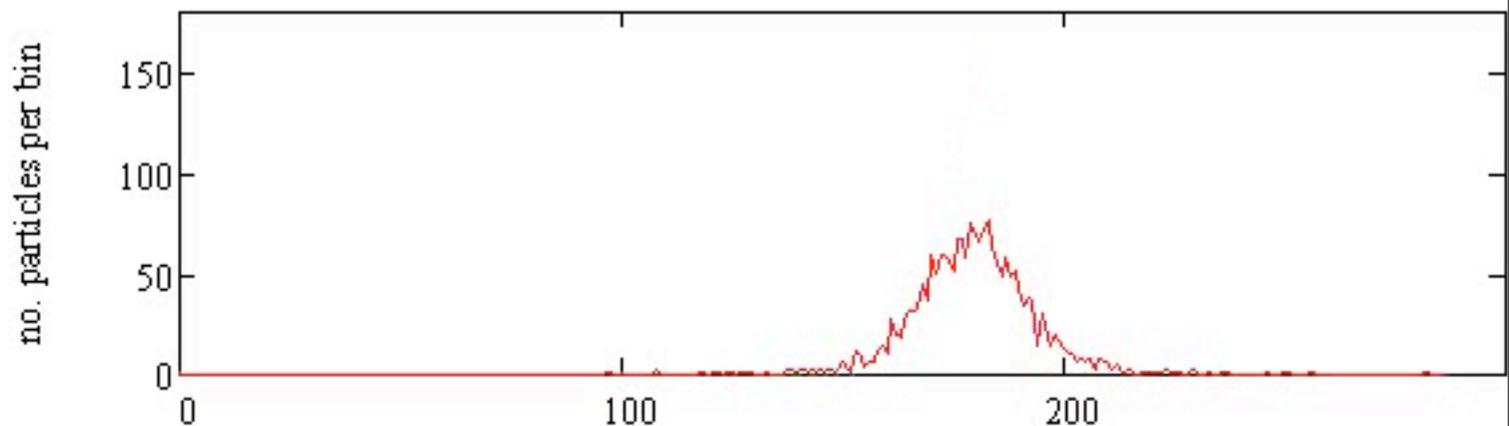
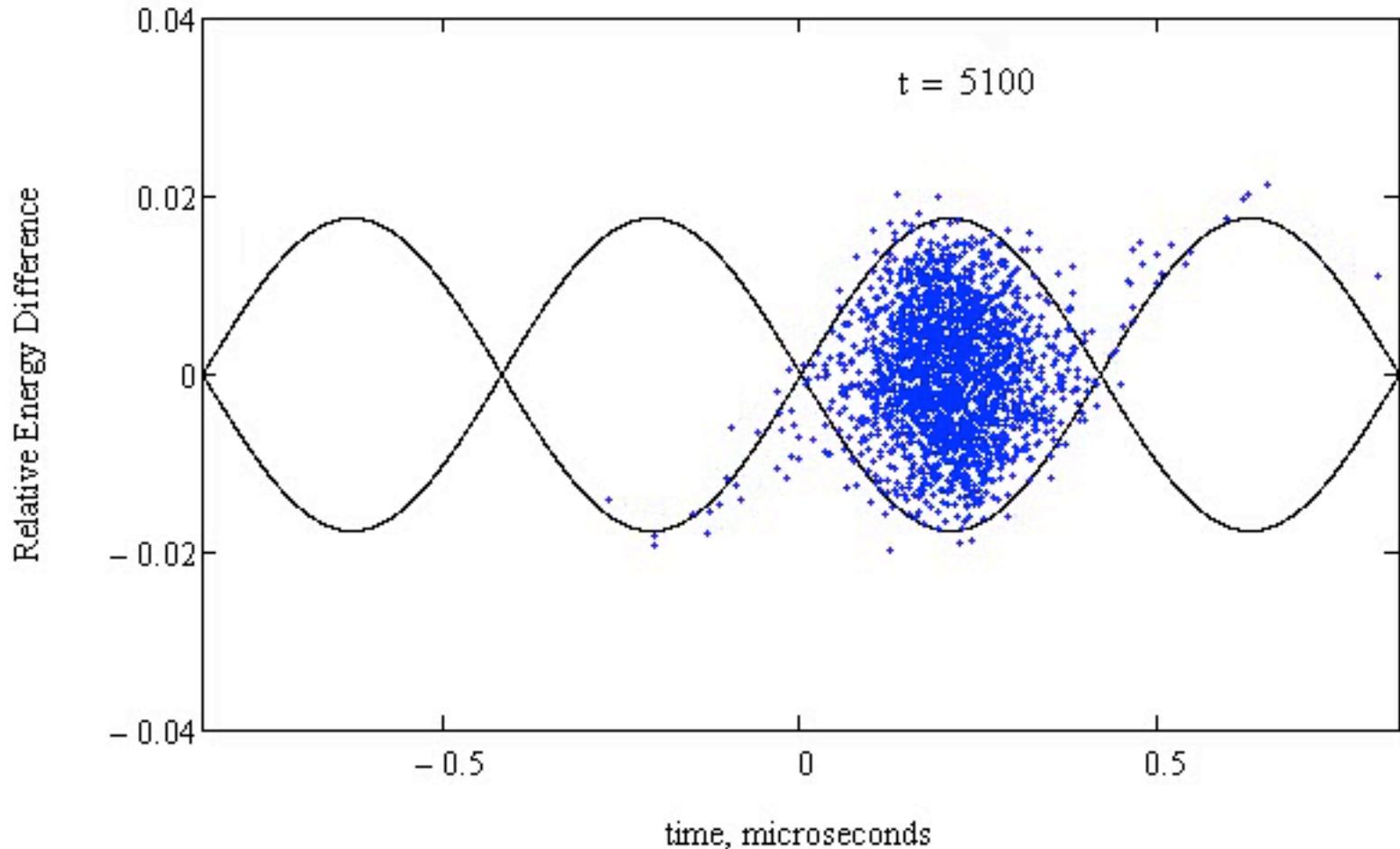
Prompt Background and Choice of Z

choose Z based on tradeoff between rate and lifetime:
longer lived reduces prompt backgrounds

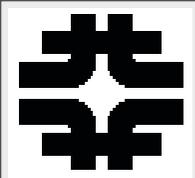
| Nucleus | $R_{\mu e}(Z) / R_{\mu e}(Al)$ | Bound Lifetime | Conversion Energy | Fraction >700 ns |
|-------------|--------------------------------|----------------|-------------------|------------------|
| Al(13,27) | 1.0 | 864 nsec | 104.96 MeV | 0.45 |
| Ti(22,~48) | 1.7 | 328 nsec | 104.18 MeV | 0.16 |
| Au(79,~197) | ~0.8-1.5 | 72.6 nsec | 95.56 MeV | negligible |

achieved

- Eliminate p...
beam in-be...
pulses:
- *Internal:*
scraping
beam to
then use

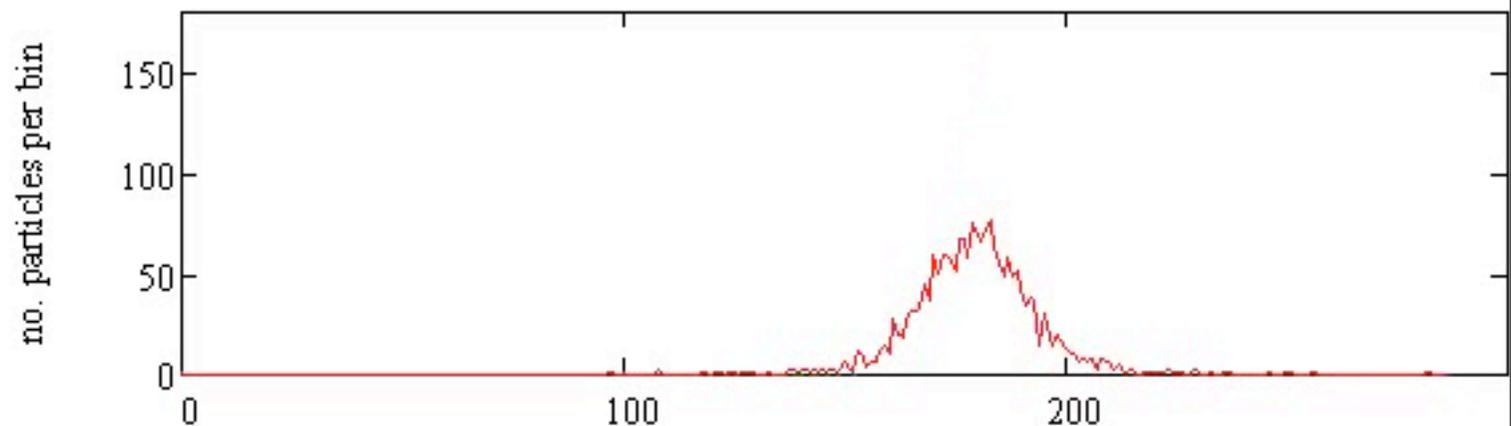
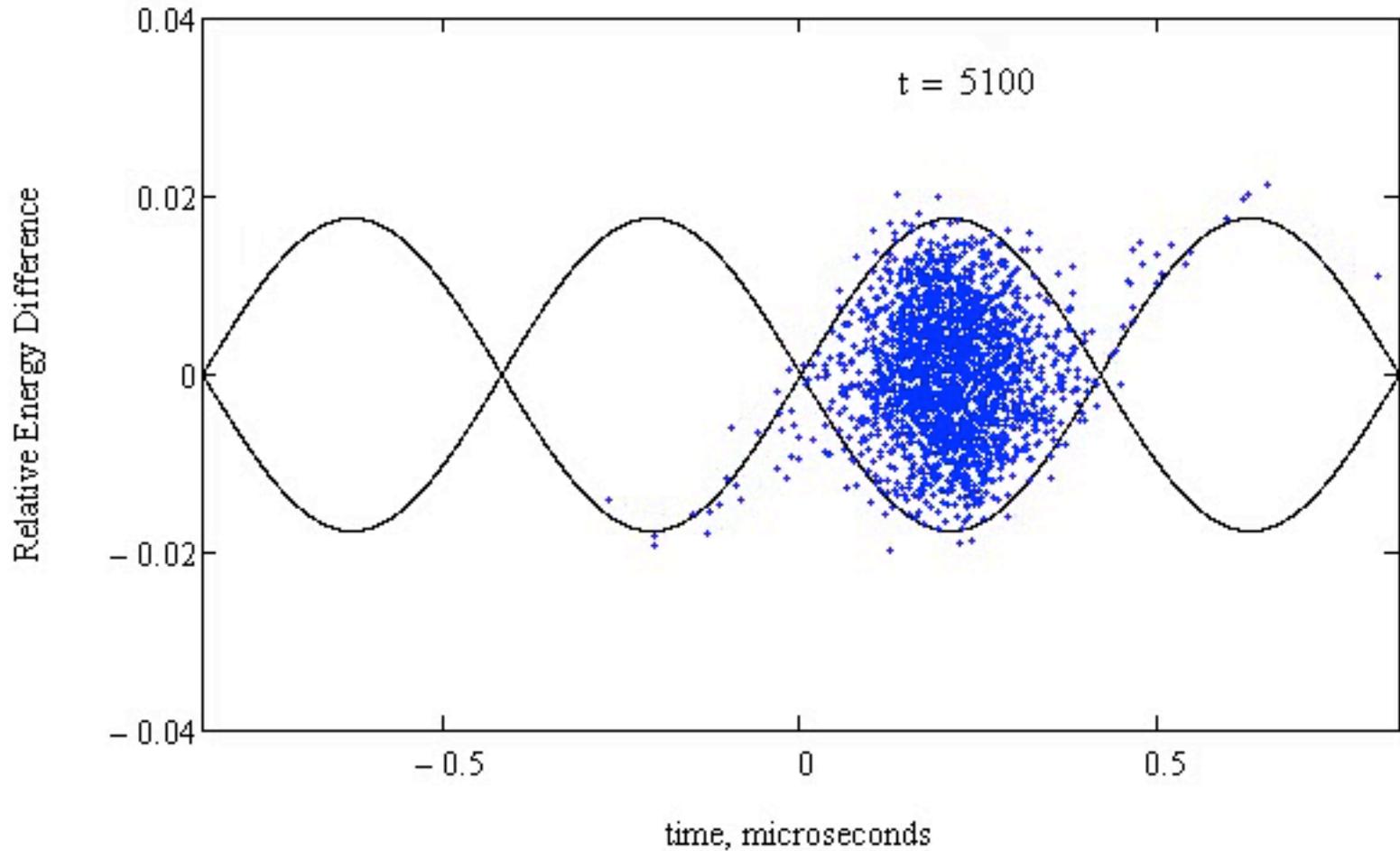


R. Bernstein, FNA

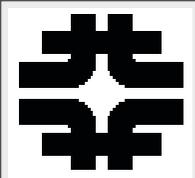


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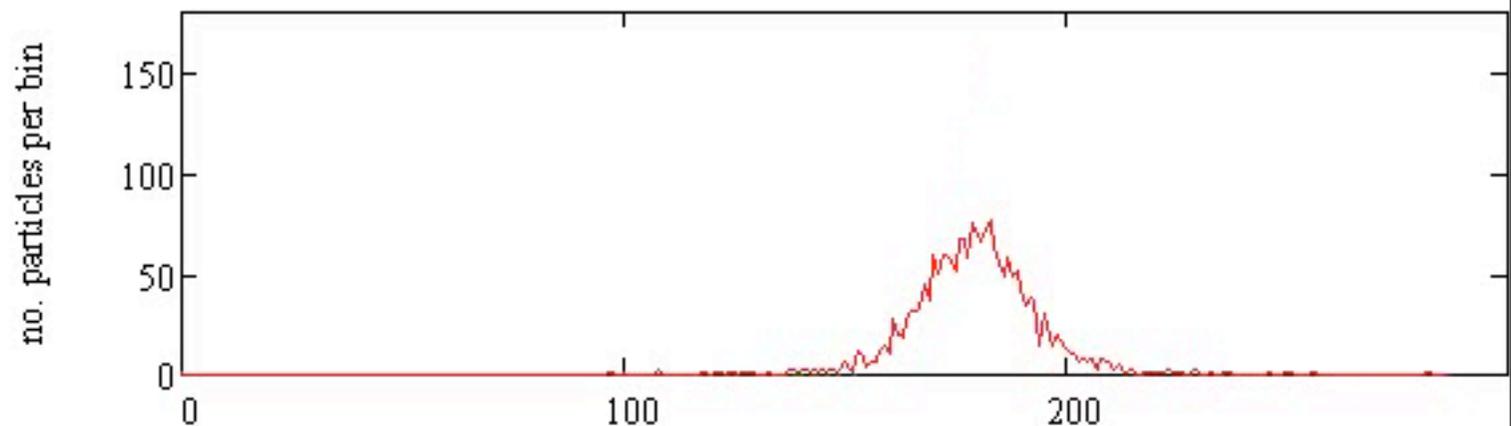
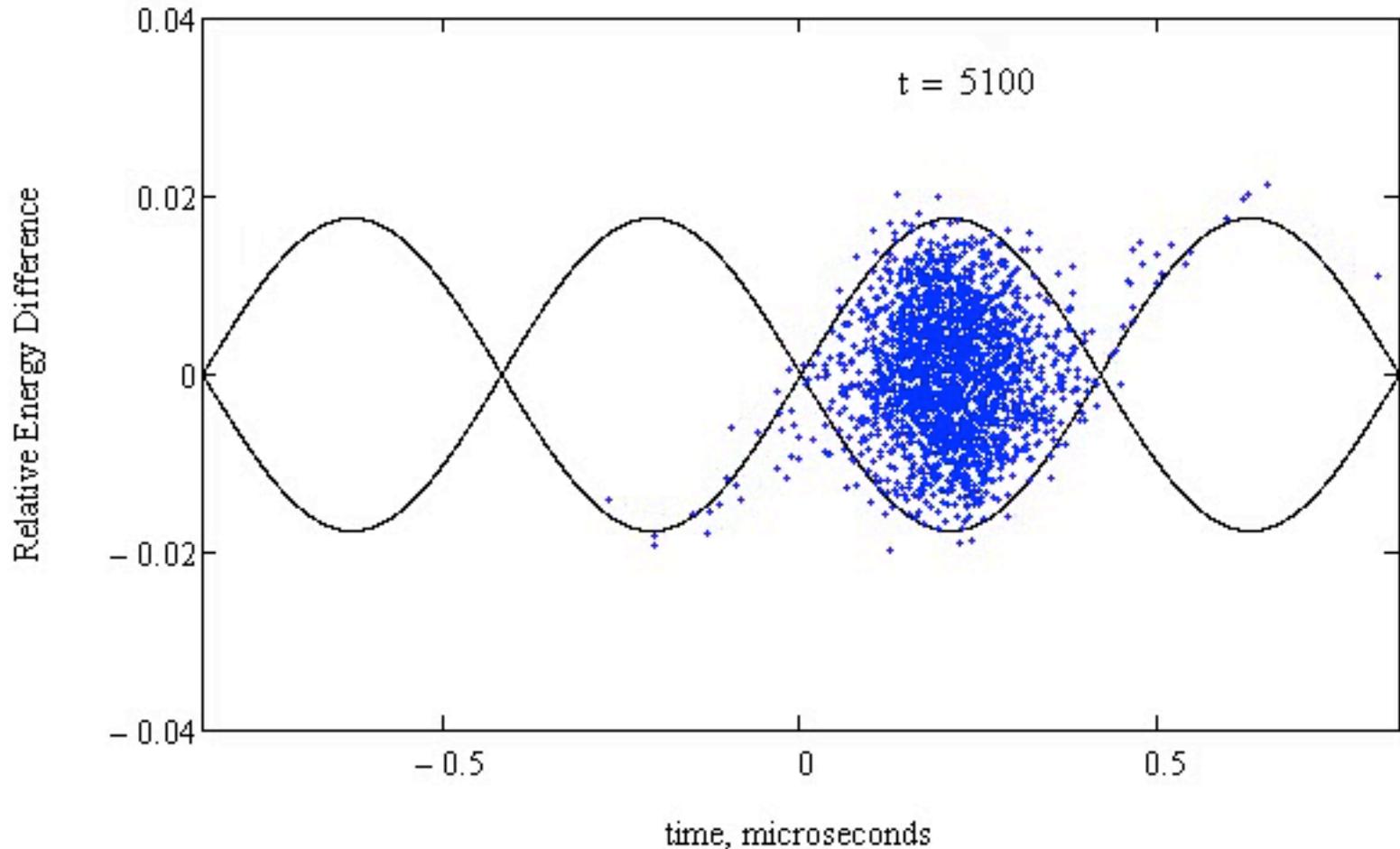


R. Bernstein, FNAL

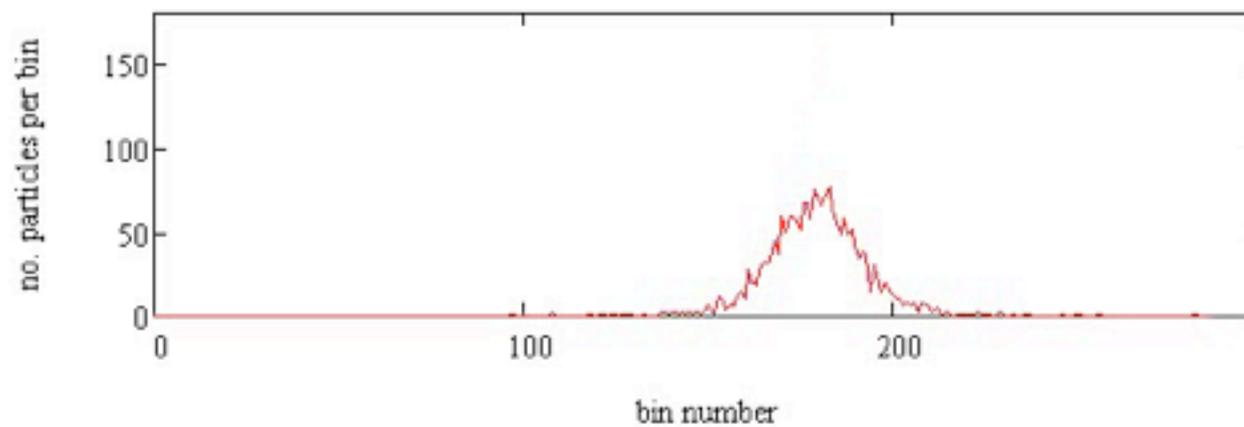
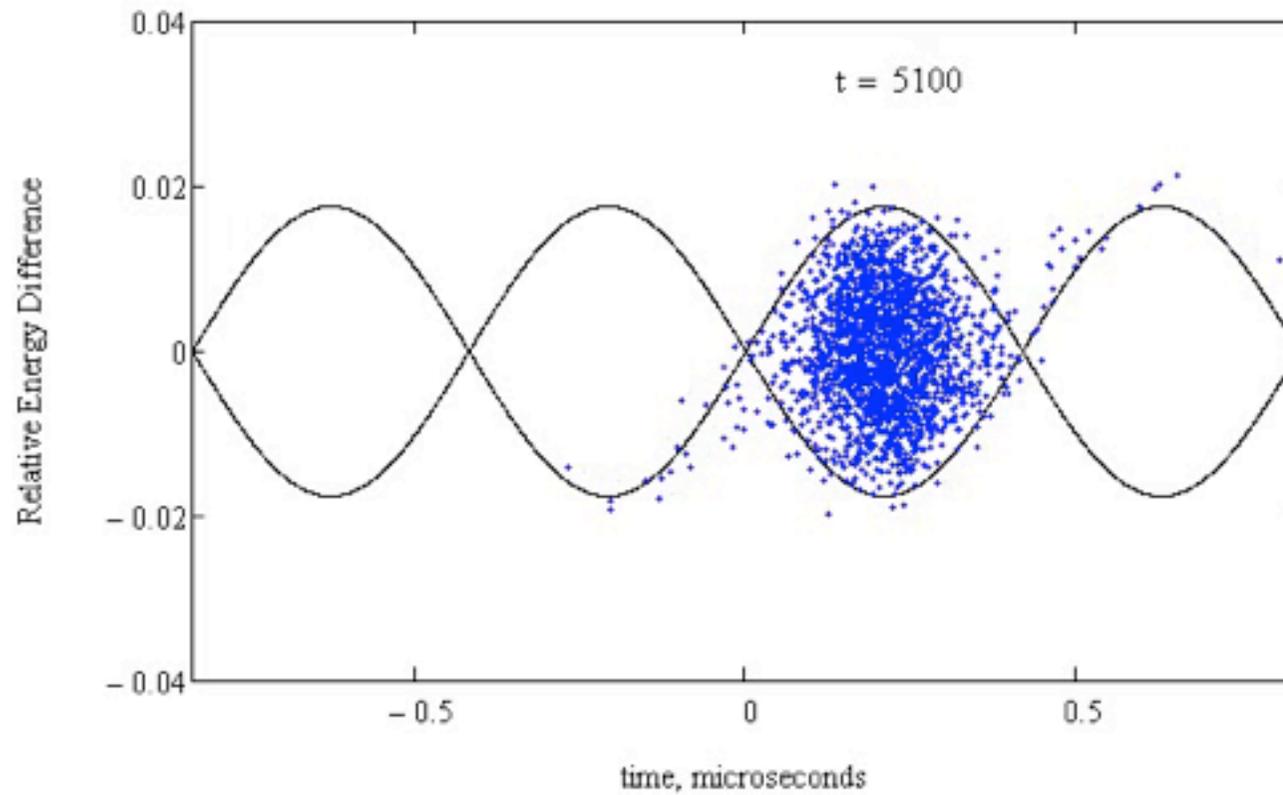
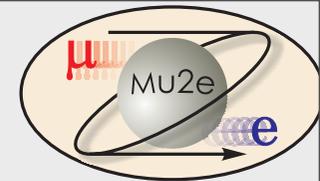
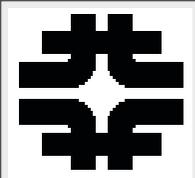


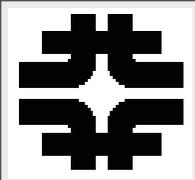
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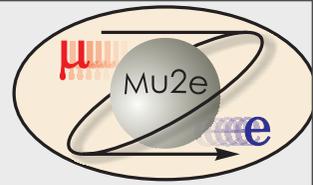


R. Bernstein, FNAL



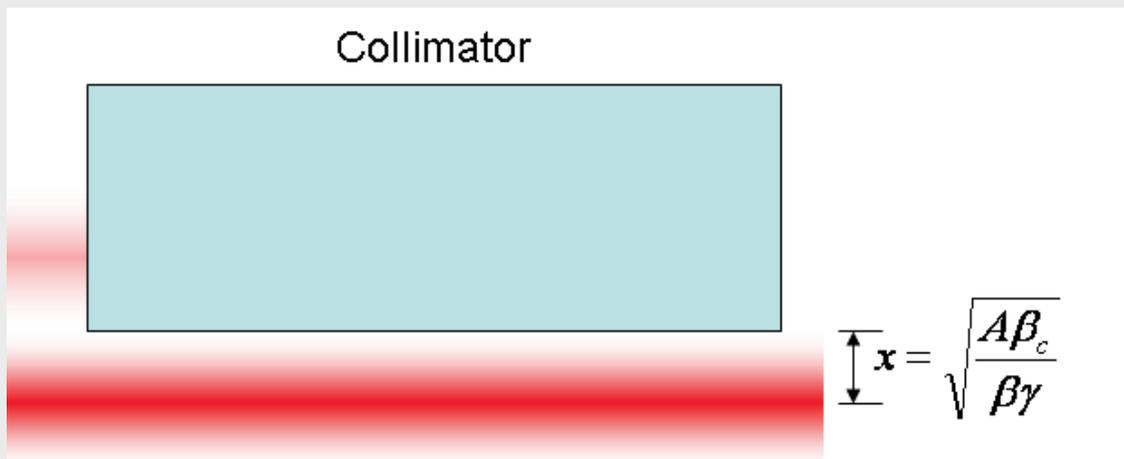


Extinction Scheme



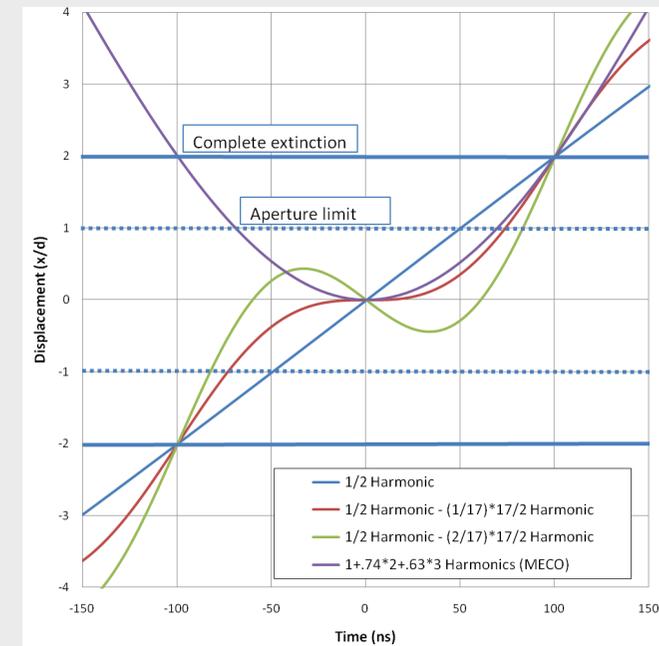
achieving 10^{-9} is hard; normally get $10^{-2} - 10^{-3}$

- Eliminate protons in beam in-between pulses:
 - “momentum scraping”: wait for beam to be wide, then use collimators
 - use high frequency dipole to sweep unwanted beam out of line

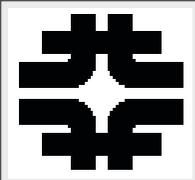


R. Bernstein, FNAL

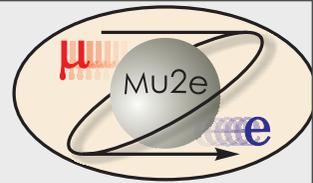
47



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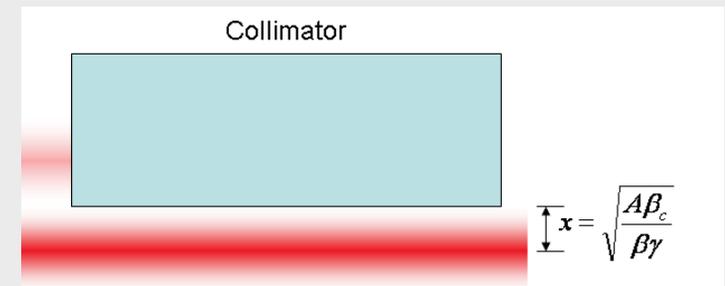
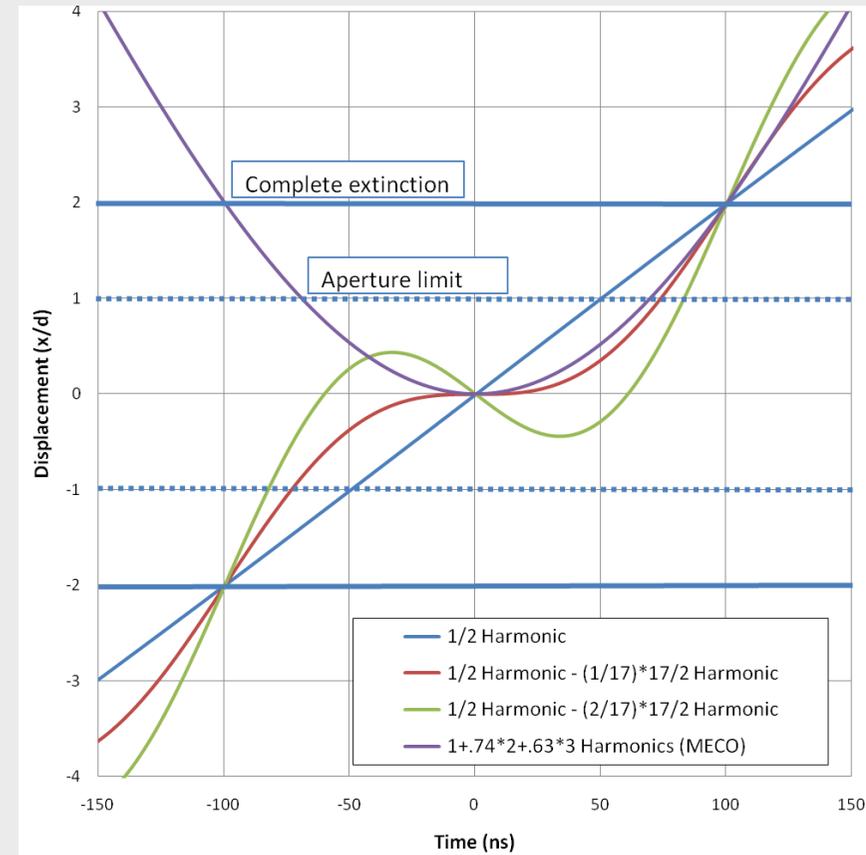


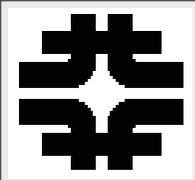
Extinction Scheme



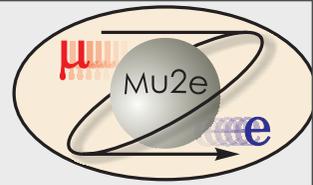
achieving 10^{-9} is hard; normally get $10^{-2} - 10^{-3}$

- External:
 - high frequency (300 KHz) dipole with smaller admixture of 17th harmonic (5.1 MHz)
 - Sweep Unwanted Beam (i.e. anything left after momentum scraping) into collimator

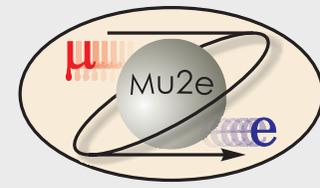
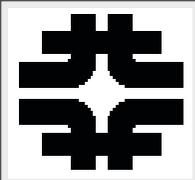




Extinction Measurement



- Continuous Extinction monitoring techniques under study
 - Cerenkov Counter set for 8 GeV protons
 - but light-detector must see burst of $3E7$ and then be sensitive to 1 proton 100 nsec or so later
- Work at Osaka for COMET
- independent FNAL effort underway



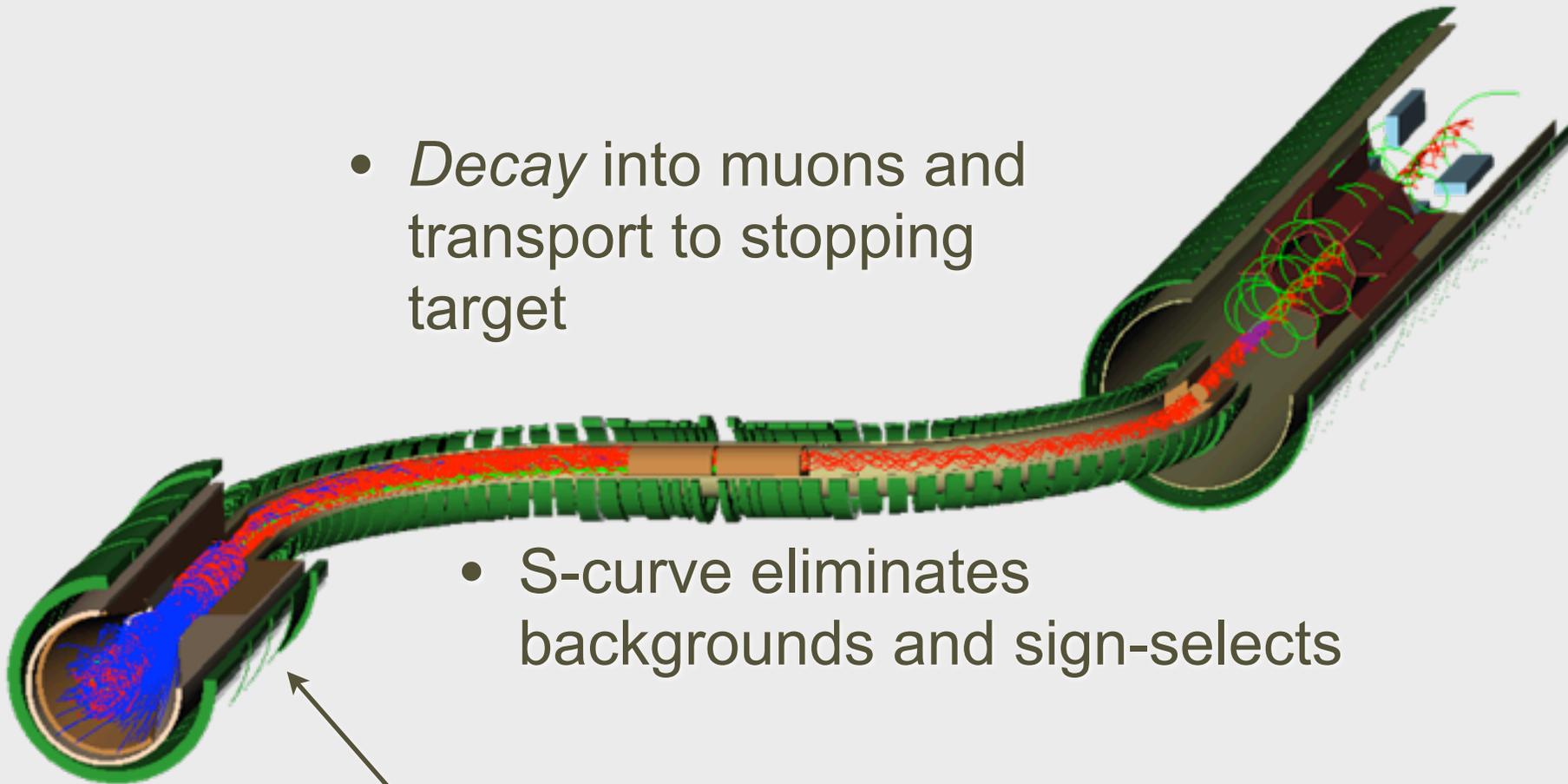
Detector and Solenoid

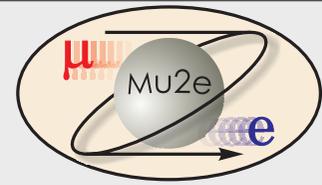
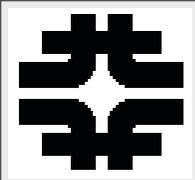
- *Tracking and Calorimeter*

- *Decay into muons and transport to stopping target*

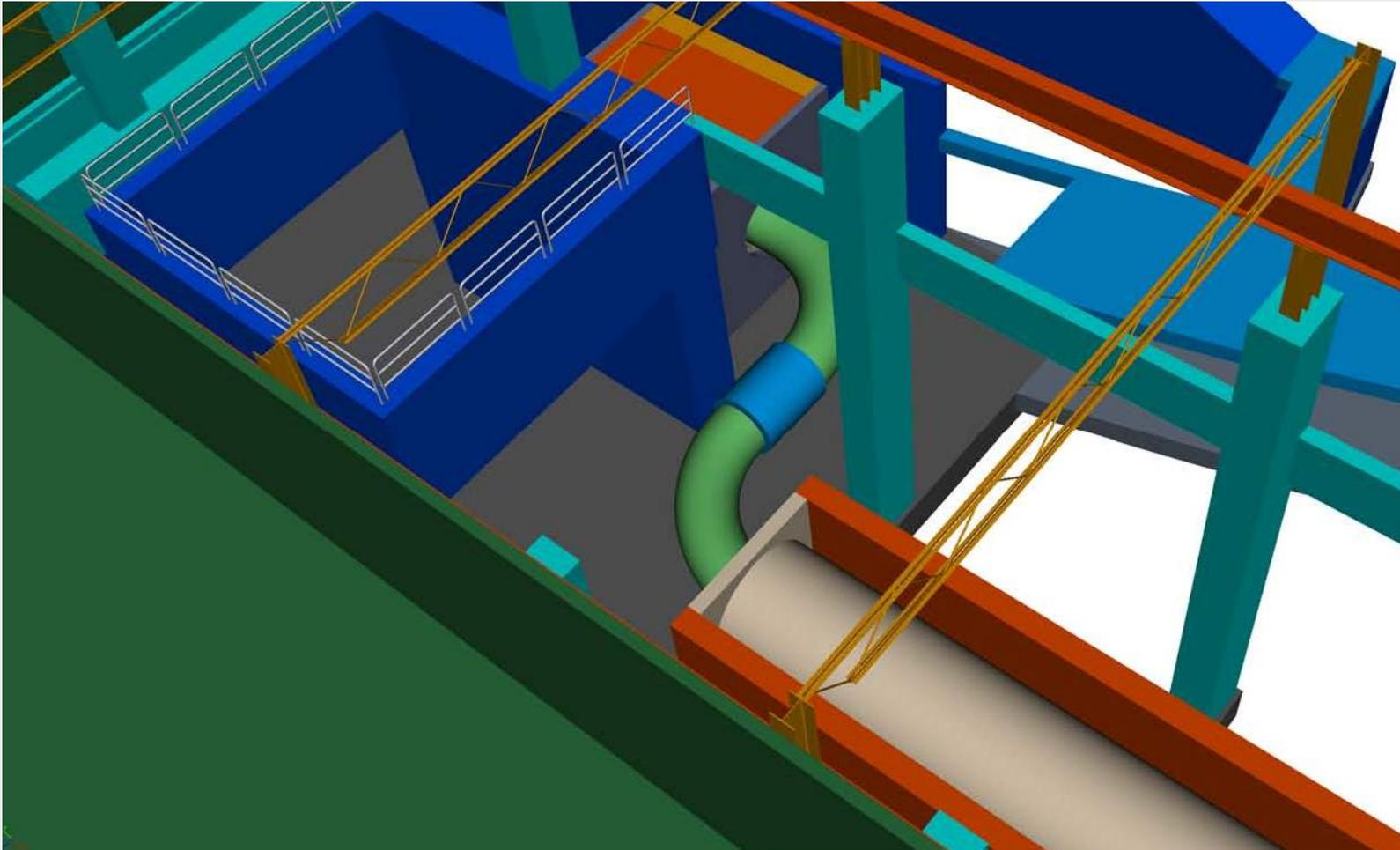
- S-curve eliminates backgrounds and sign-selects

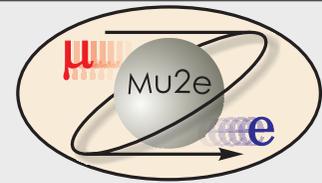
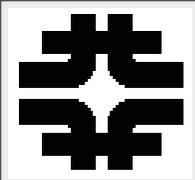
- *Production*: Magnetic bottle traps backward-going π that can decay into accepted μ 's





Solenoid in the Hall





Production Solenoid:

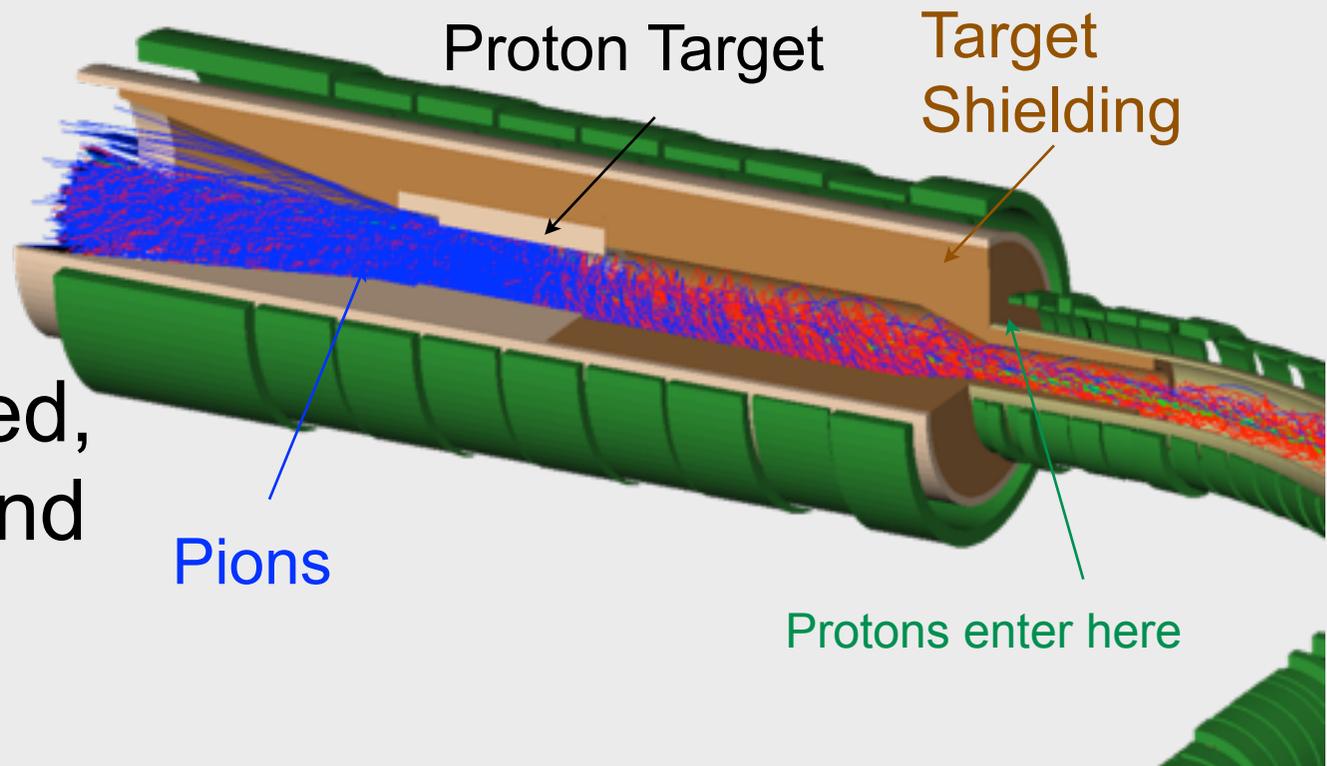
Protons enter opposite to outgoing muons

Protons leave through thin window



π 's are captured, spiral around and decay

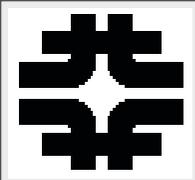
Pions



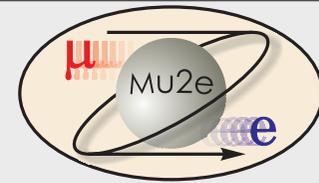
Protons enter here

muons exit to right

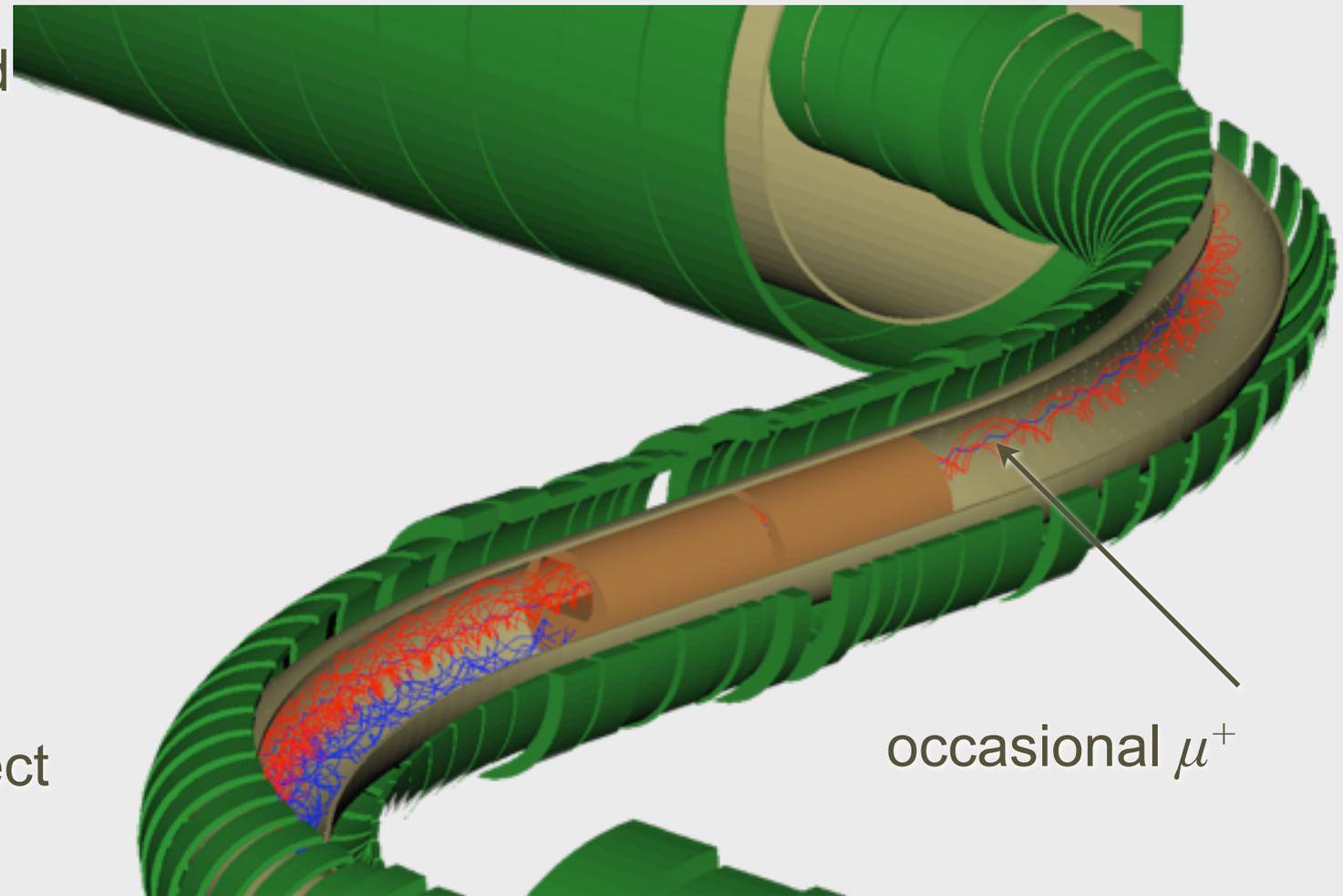
4 m × 0.30 m



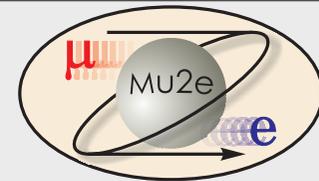
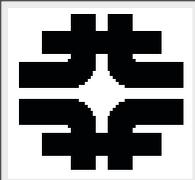
Transport Solenoid



- Curved solenoid eliminates line-of-sight transport of photons and neutrons
- Curvature drift and collimators sign and momentum select beam



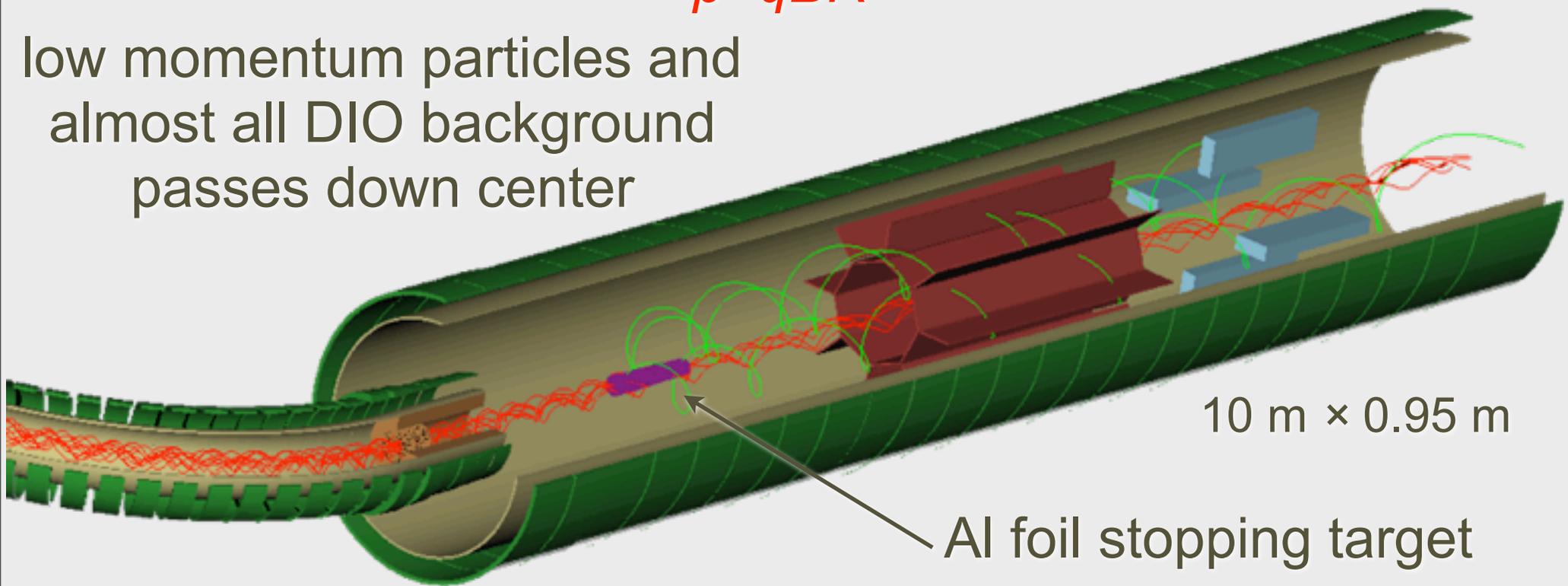
13.1 m along axis × ~0.25 m



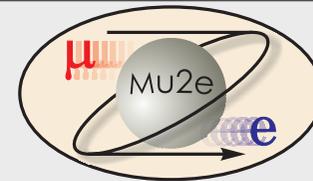
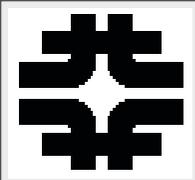
Detector Solenoid

*octagonal tracker surrounding central region:
radius of helix proportional to momentum,
 $p=qBR$*

low momentum particles and
almost all DIO background
passes down center



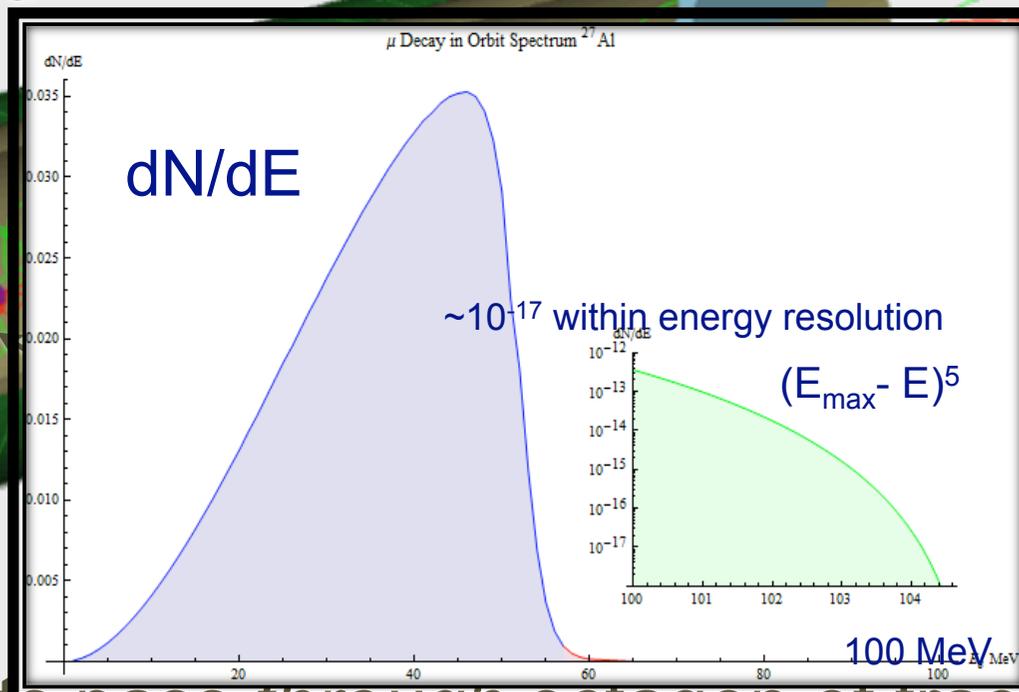
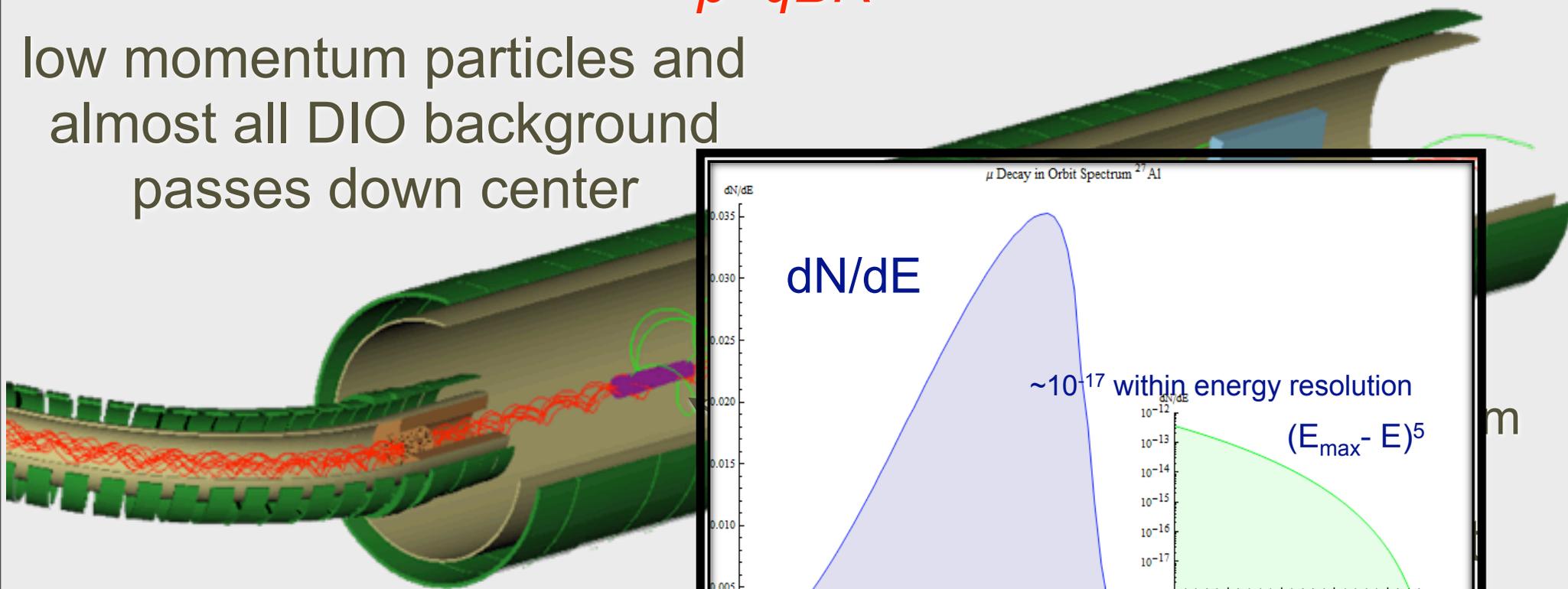
signal events pass *through* octagon of tracker
and produce hits



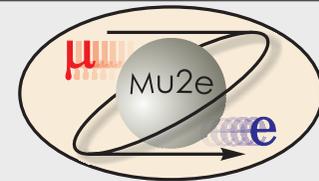
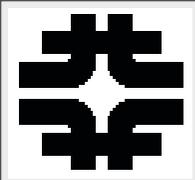
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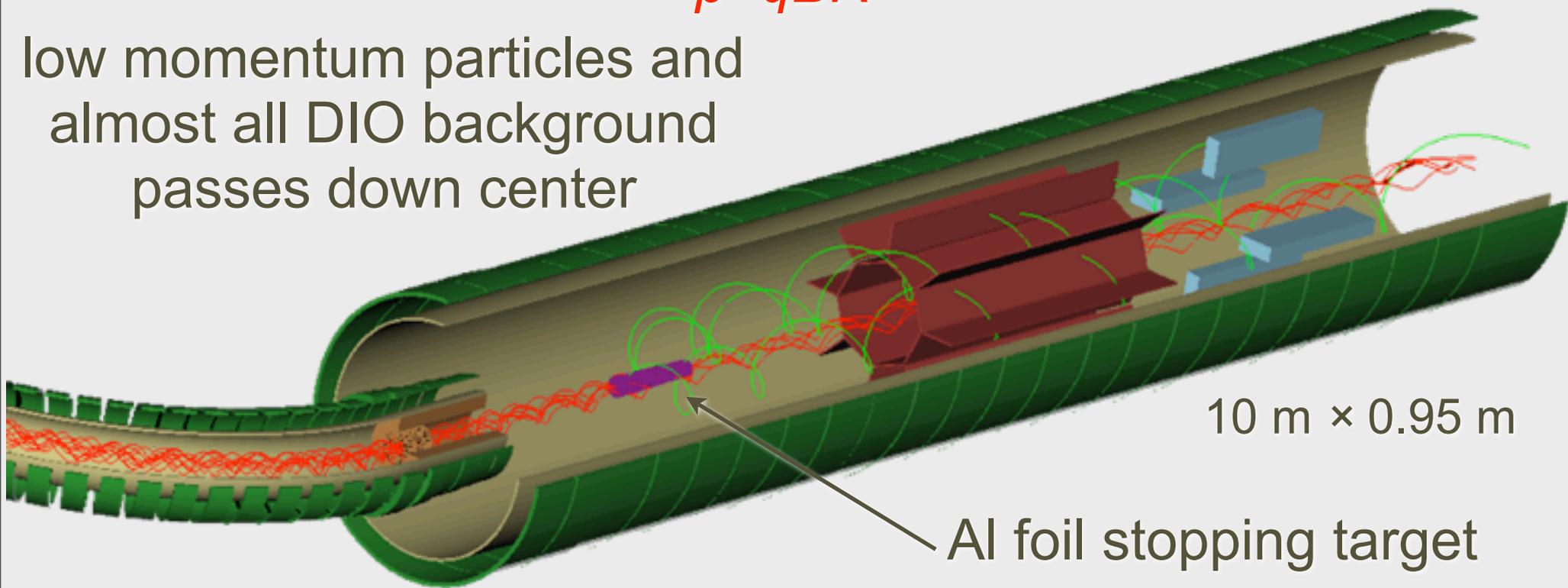
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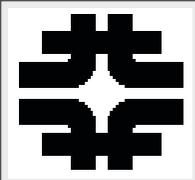
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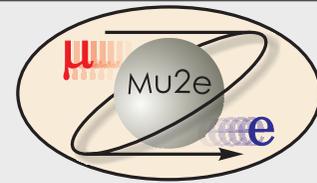
low momentum particles and
almost all DIO background
passes down center



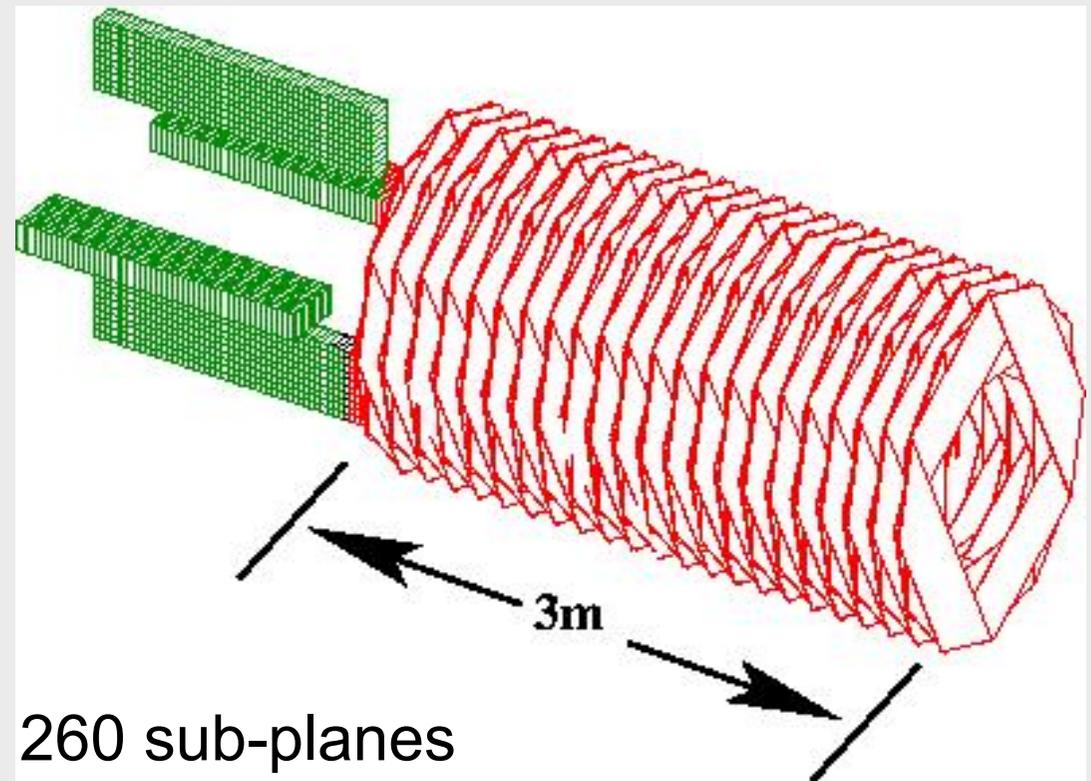
signal events pass *through* octagon of tracker
and produce hits



Detector



- T-Tracker (straw tubes with axes *transverse* to muon beam)
- Immersed in solenoidal field, so electrons follow near-helical path
- Electrons (DIOs!) with $p_T < 55 \text{ MeV}$ do not pass through detector, but down the center



- 260 sub-planes
 - sixty 5 mm diameter conducting straws
 - length from 70-130 cm
 - total of 13,000 channels

Calorimeter:

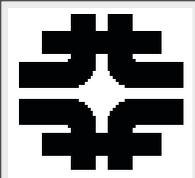
INFN/Dubna
investigating LYSO

$\sigma / E = 5\%$, 1024 $3.5 \times 3.5 \times 12 \text{ cm PbWO}_4$

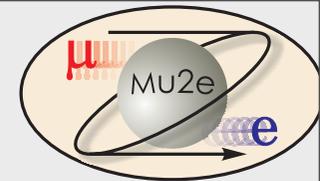
R. Bernstein, FNAL

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T-Tracker Details



- This “windowframe” is repeated, rotated each time

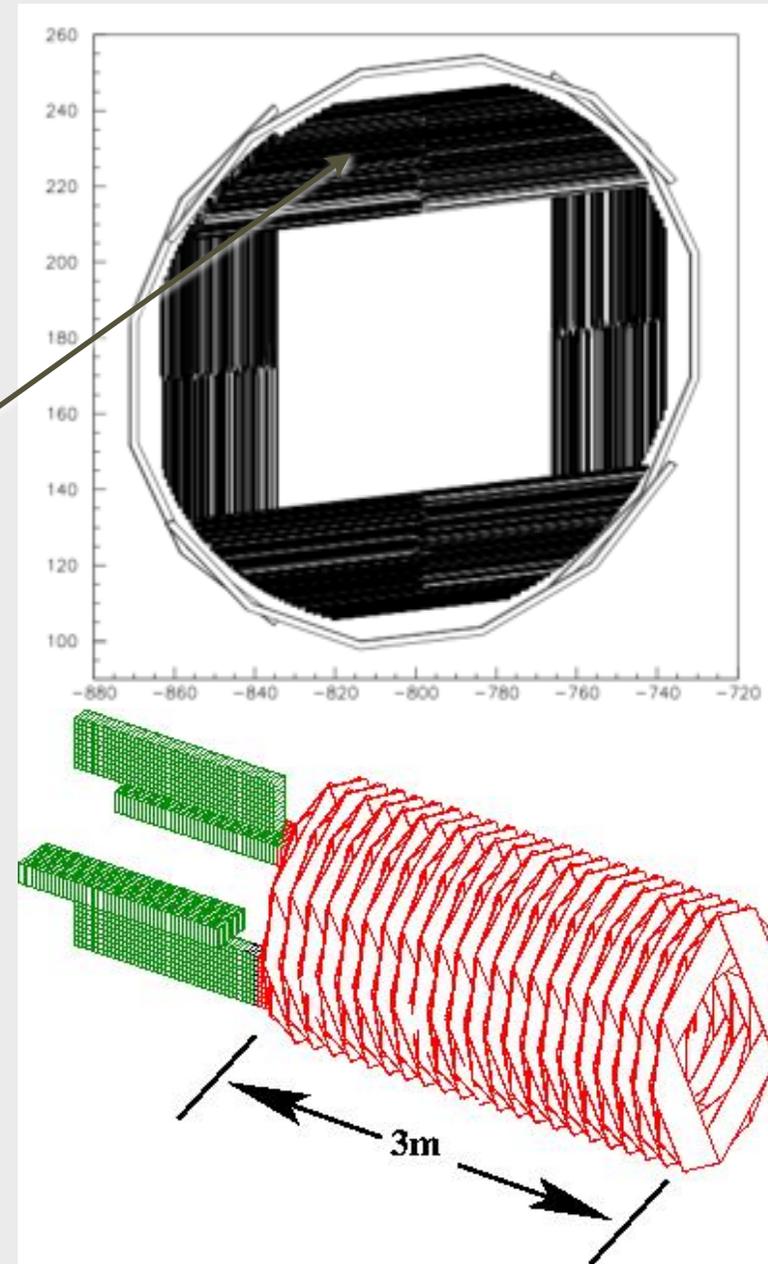
- Just know which straw is hit

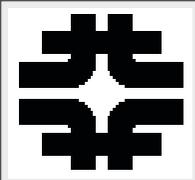


- Makes PR complicated!

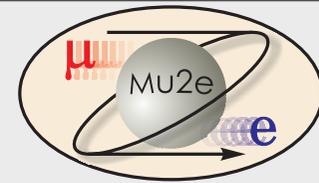
R. Djilkibaev, R. Konoplich, Apr 2009. *JINST* 4:P08004,2009.
[arXiv:0904.3792](https://arxiv.org/abs/0904.3792) [hep-ex]

- Are investigating time or charge division and waveform digitization to provide 3rd coordinate





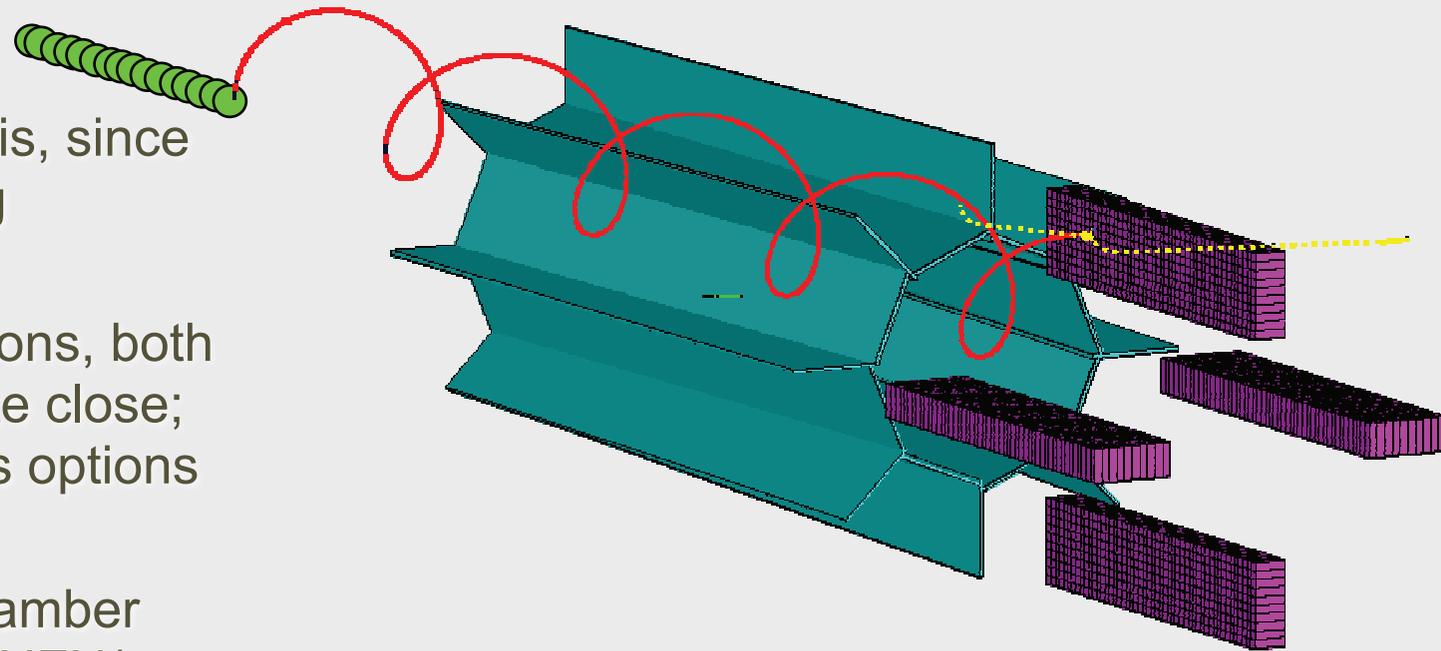
old L-Tracker

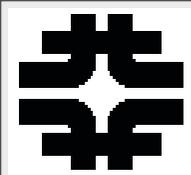


- Octagon and Vanes of Straw Tubes: get r and φ but not z , which then comes from pad readout
- Was MECO model
- Plots I will show use this, since we used it at beginning
- Indications are resolutions, both RMS and tails are quite close; we are keeping both as options
- Also cylindrical drift chamber under investigation at INFN/Lecce

$\sigma = 200 \mu$ transverse, 1.5 mm axially

2800 axial straw tubes, 2.6 m by 5 mm, 25 μ thick



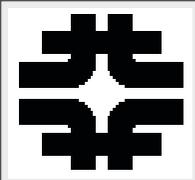


Backgrounds...

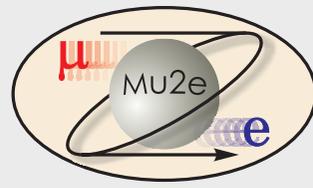


| Type | Description |
|--------------------|---|
| e_t | beam electrons |
| n_t | neutrons from muon capture in muon stopping target |
| γ_t | photons from muon capture in muon stopping target |
| p_t | protons from muon capture in muon stopping target |
| $e(DIO)_t < 55$ | DIO from muon capture in muon stopping target, < 55 MeV |
| $e(DIO)_t > 55$ | DIO from muon capture in muon stopping target, > 55 MeV |
| n_{bd} | neutrons from muon capture in beam stop |
| γ_{bd} | photons from muon capture in beam stop |
| $e(DIO)_{bd} < 55$ | DIO from muon capture in beam stop, < 55 MeV |
| $e(DIO)_{bd} > 55$ | DIO from muon capture in beam stop, > 55 MeV |
| $e(DIF)$ | DIO between stopping target and beam stop |

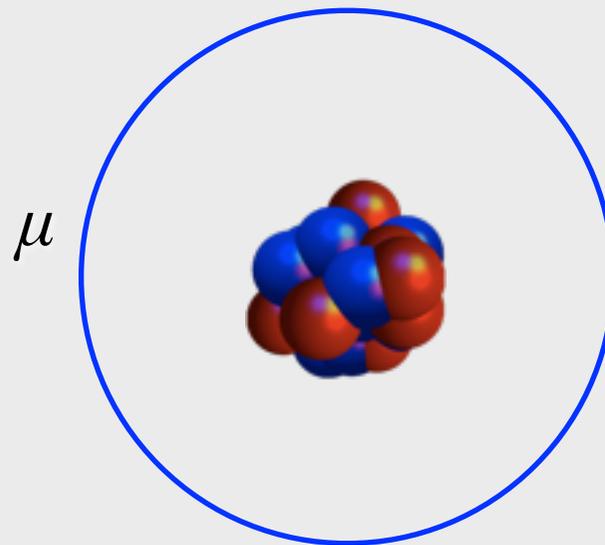
bd = albedo from beam stop (after calorimeter): splashback, extra hits
confusing pattern recognition



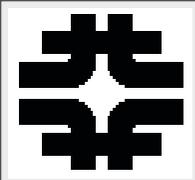
Recall Our Normalization



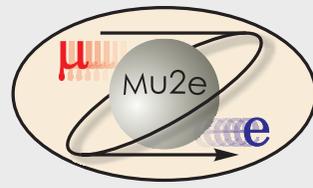
when a muon stops, about 10% of the time a proton is ejected



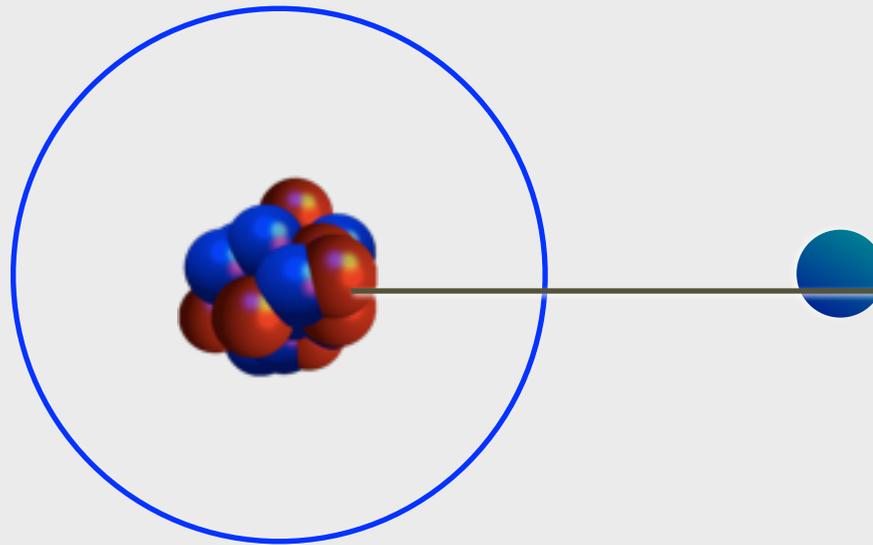
these can enter the detector and cause rate problems:
slow protons are highly ionizing and can deaden wires



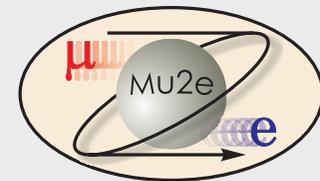
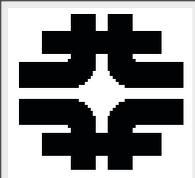
Recall Our Normalization



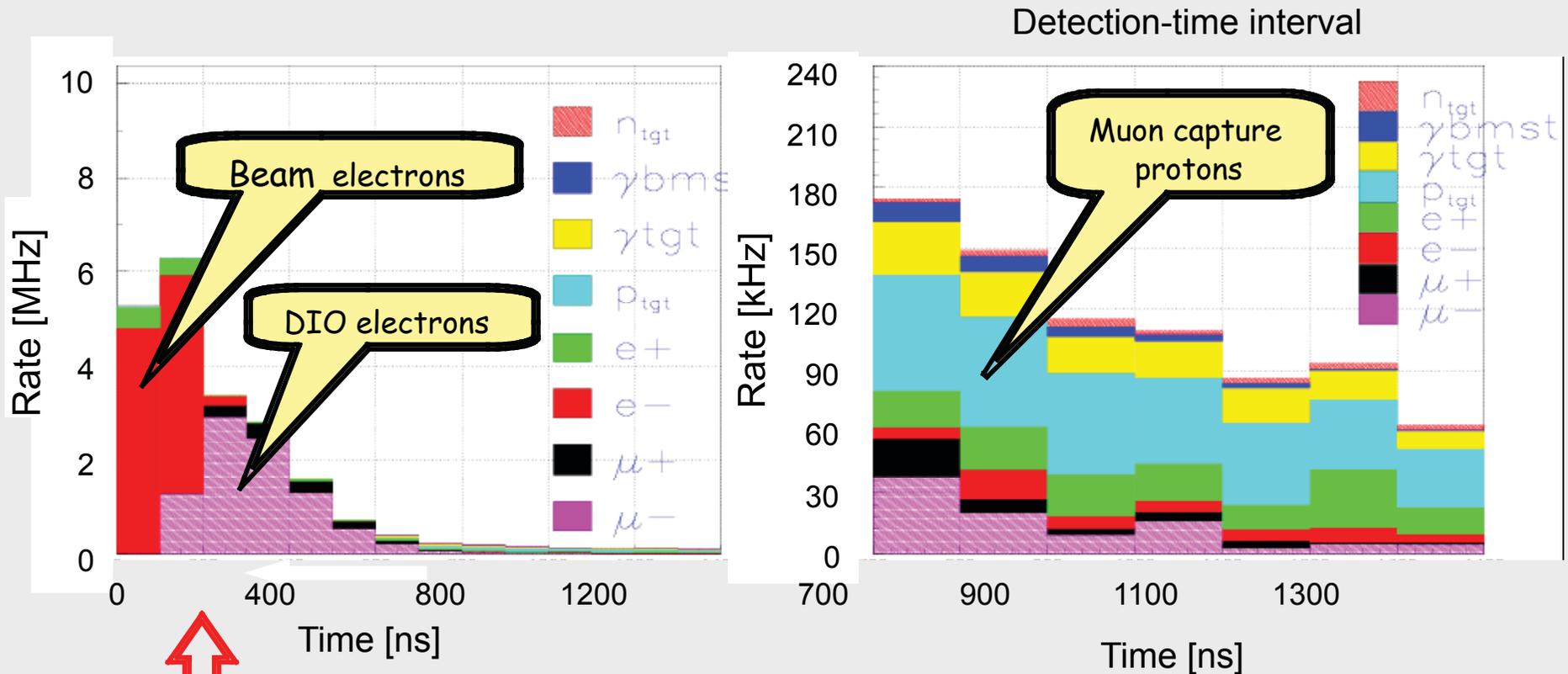
when a muon stops, about 10% of the time a proton is ejected



these can enter the detector and cause rate problems:
slow protons are highly ionizing and can deaden wires



Magnetic Spectrometer: Rates vs. Time



Initial flash from
electrons

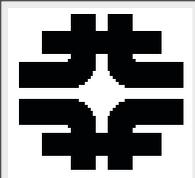
- Rates *start* at 6 MHz/wire but \approx 180 kHz/wire in live time window
- Each muon capture produces 2γ , $2n$, $0.1p$

R. Bernstein, FNAL

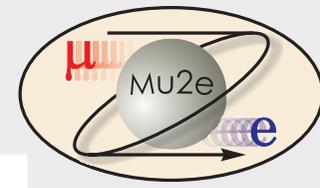
60

Mu2e

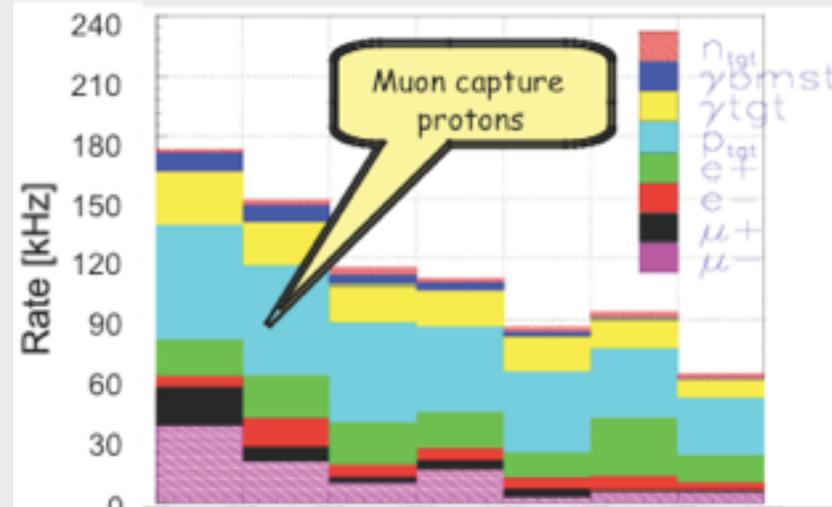
U. Chicago 5/17/10



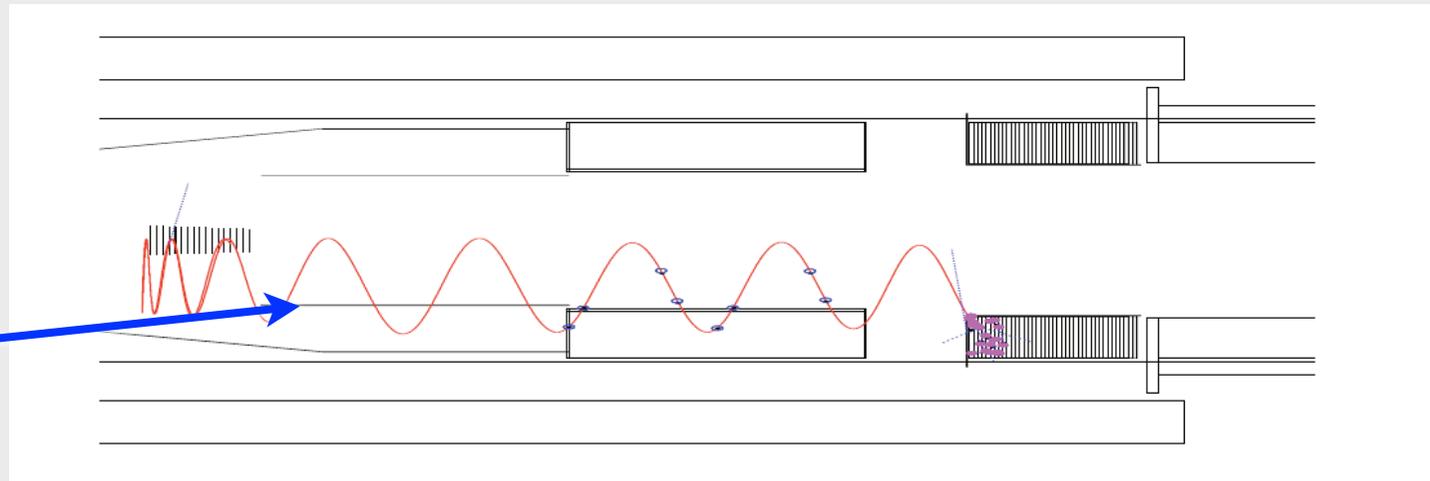
Note the proton rate



- this can be a significant problem (neutrons too): slowly moving protons are highly ionizing and can deaden straws

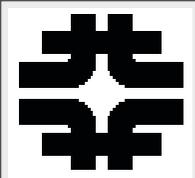


- detector has polyethylene absorbers, but that's energy loss degrading the resolution

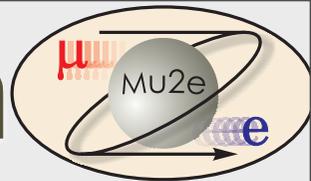


- rate and spectrum not well known, so amount of absorber required not clear

*so we measured the rate
at PSI*

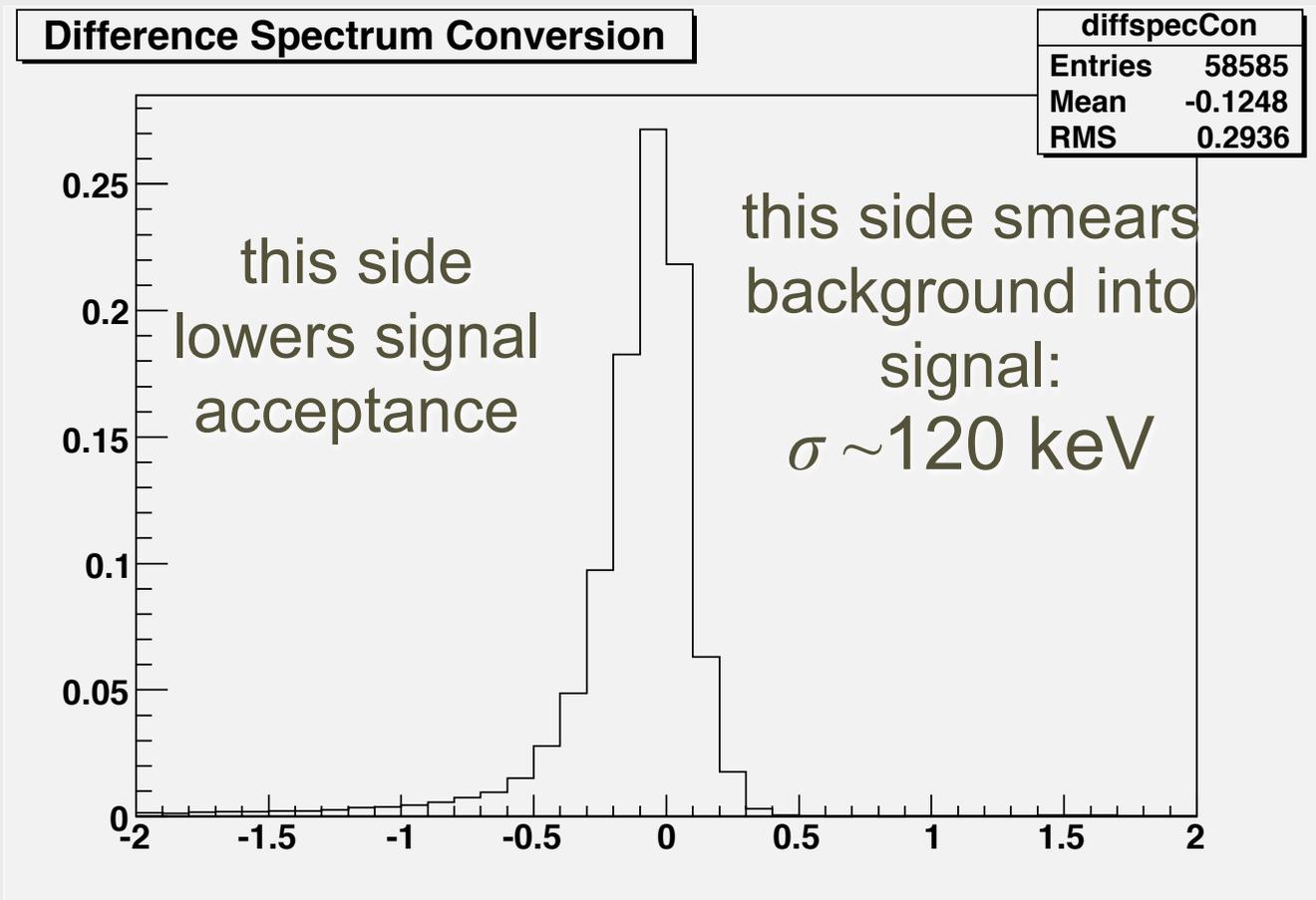


Understanding Resolution

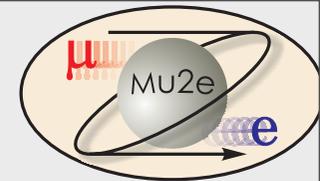
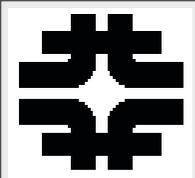


- Measure resolution/
check acceptance:

- special runs
varying target
foils, field,
location of
stopping target
- Use $\pi^+ \rightarrow e\nu$
decay:
monochromatic
line at ~ 70 MeV



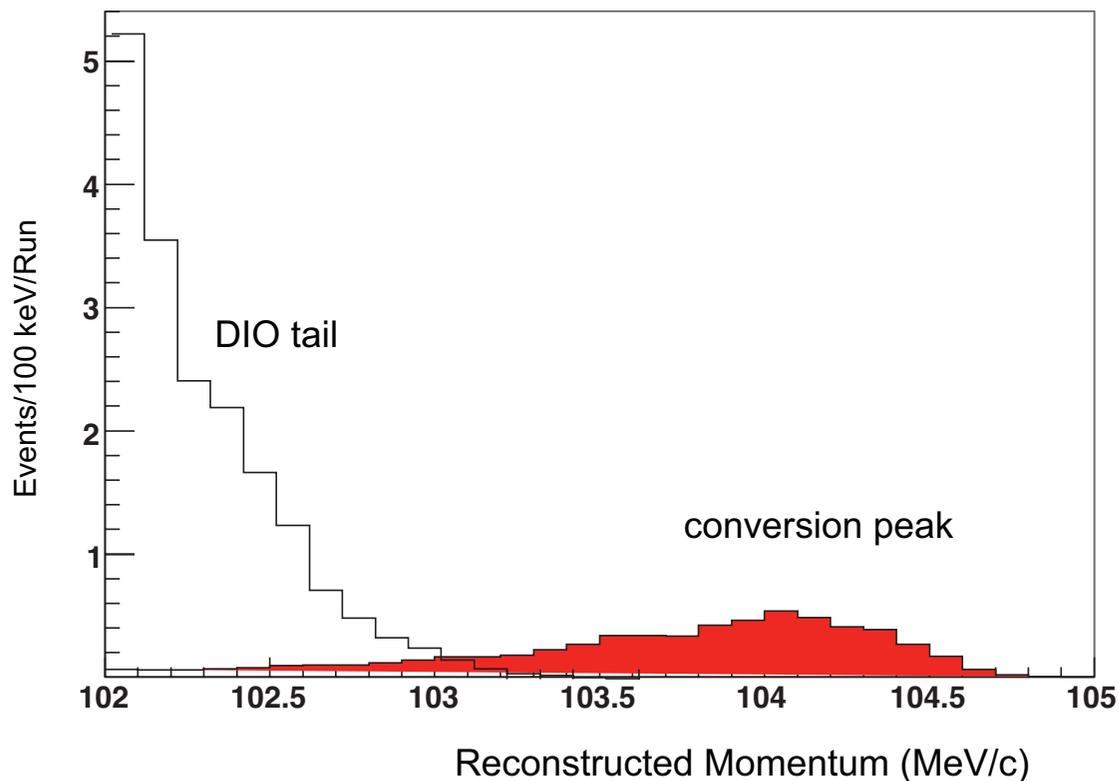
resolution of tracker



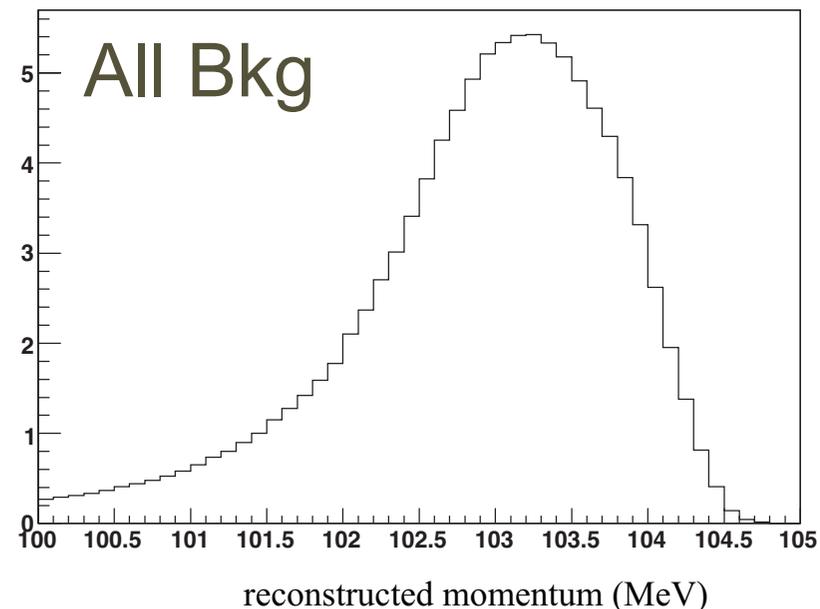
Signal and Background

- $R_{\mu e} = 10^{-16}$

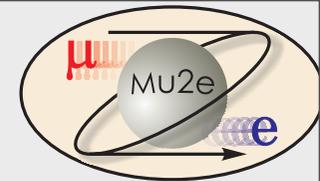
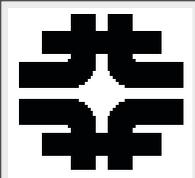
$$\frac{S}{\sqrt{B}} \sim 5.5$$



Signal/Sqrt(Bkg)



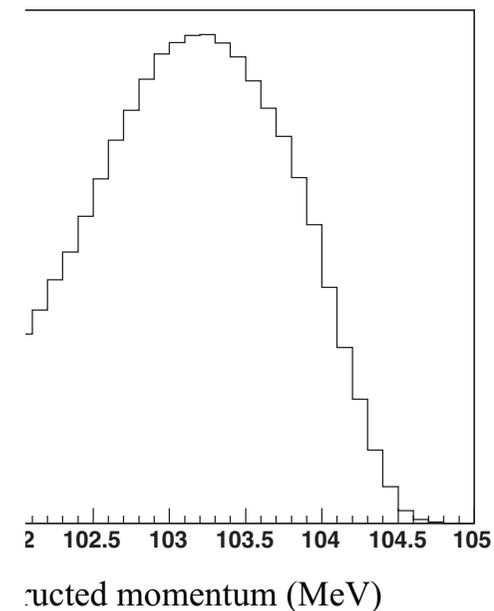
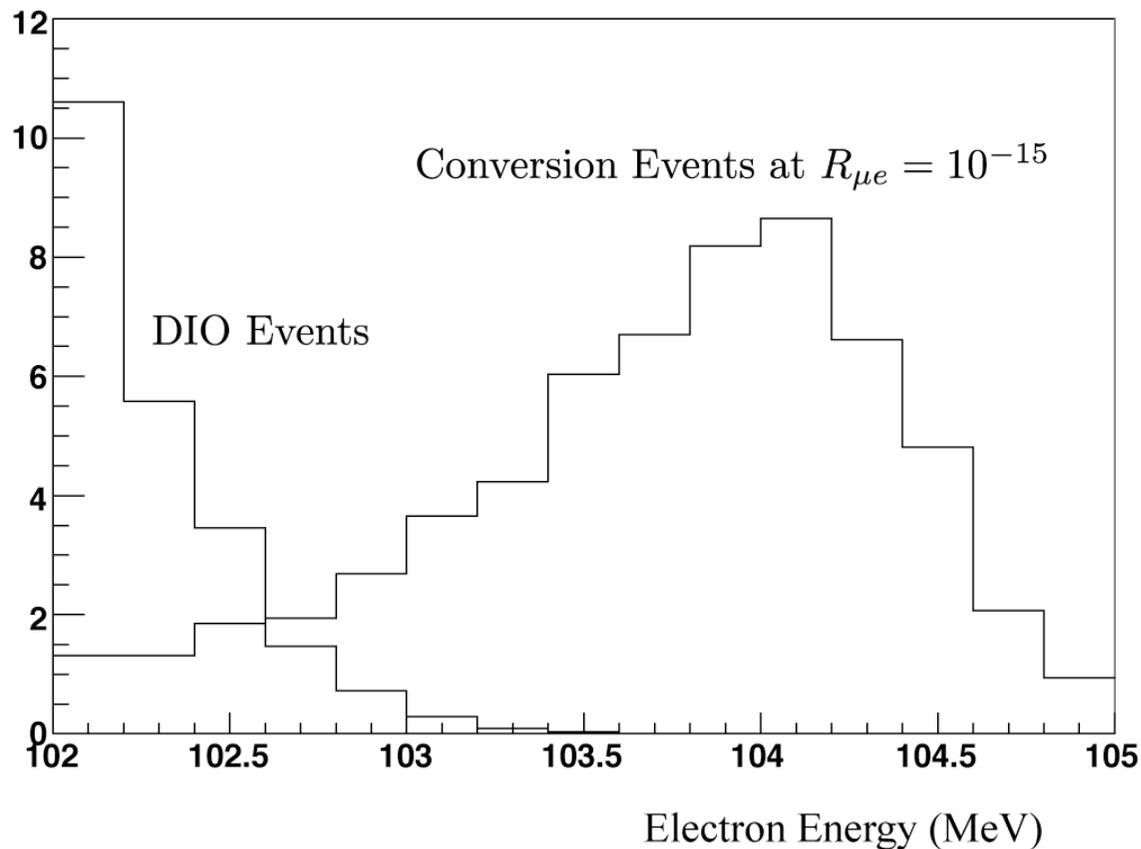
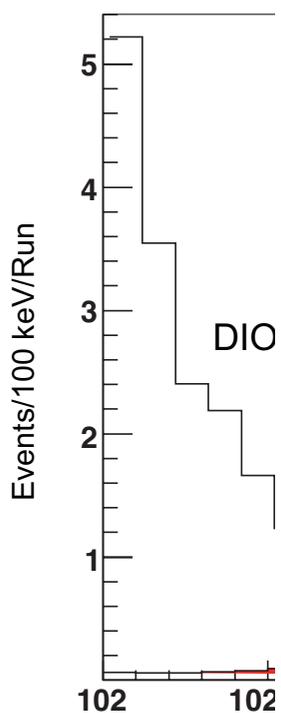
energy loss in stopping target and other material shifts
electron down to ~ 104 MeV



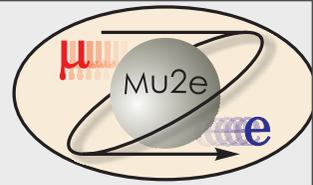
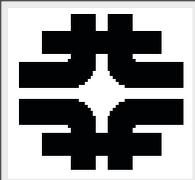
Signal and Background

- $R_{\mu e} = 10^{-16}$

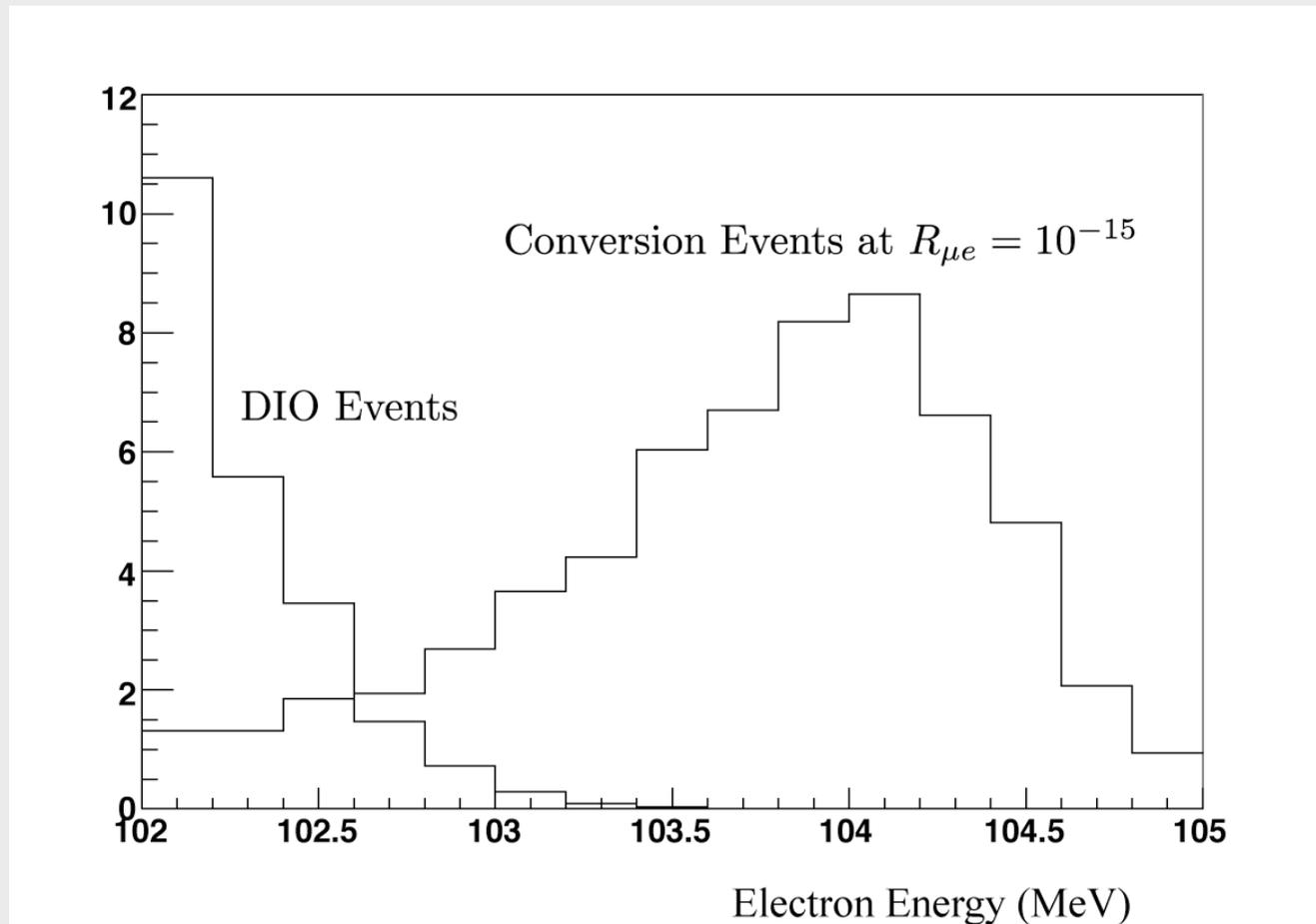
$$\frac{\mu}{e} \sim 5.5$$



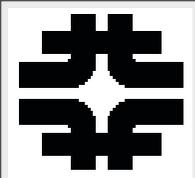
energy loss in stopping target and other material shifts
electron down to ~ 104 MeV



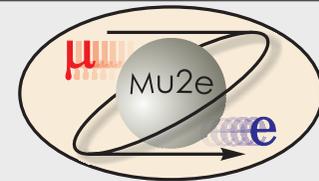
Signal and Background



energy loss in stopping target and other material shifts
electron down to ~ 104 MeV

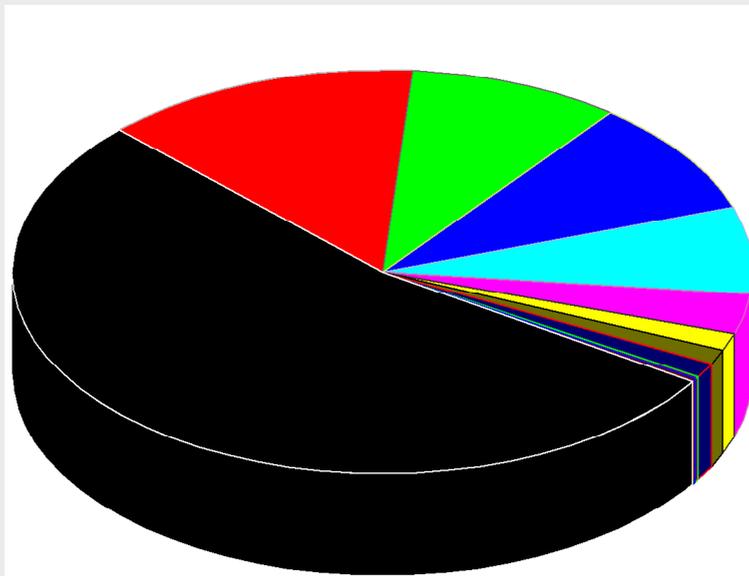


Final Backgrounds

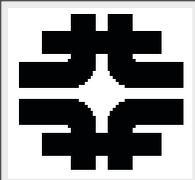


- For $R_{\mu e} = 10^{-15}$
~40 events / 0.4 bkg
(LHC SUSY?)
- For $R_{\mu e} = 10^{-16}$
~4 events / 0.4 bkg

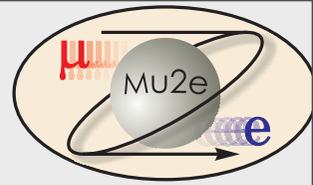
| Source | Number |
|-------------------------|---------|
| DIO | 0.225 |
| Radiative π capture | 0.072 |
| μ decay-in-flight | 0.072 |
| Scattered e- | 0.035 |
| π decay in flight | <0.0035 |



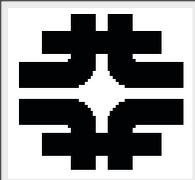
- 53%: μ decay in orbit
- 14%: radiative π capture
- 9%: beam electrons
- 9%: μ decay in flight (tgt scatter)
- < 7%: μ decay in flight (no tgt scatter)
- 3%: cosmic rays
- 1.4%: anti-protons
- < 1.2%: pattern recognition errors
- < 1.2%: radiative μ capture
- < 0.2%: π decay in flight
- 0.2%: radiative π capture from late π 's



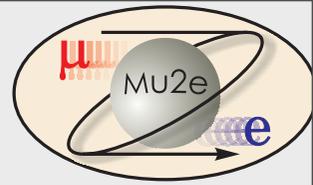
Outline



- The search for muon-electron conversion
- Experimental Technique
- *Fermilab Accelerator*
- Project X Upgrades and Mu2e
- Cost and Schedule
- Conclusions



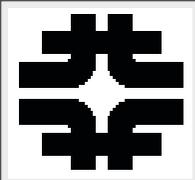
FNAL Beam Delivery



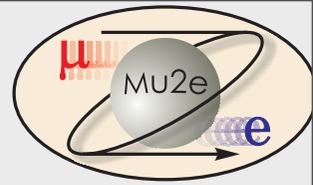
- FNAL has unique, major strength:

Multiple Rings

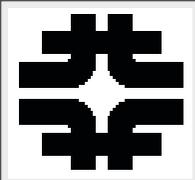
- *no interference* with NOvA neutrino oscillation experiment
- reuse existing rings with only minor modifications



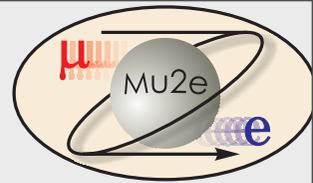
Quick Fermilab Glossary



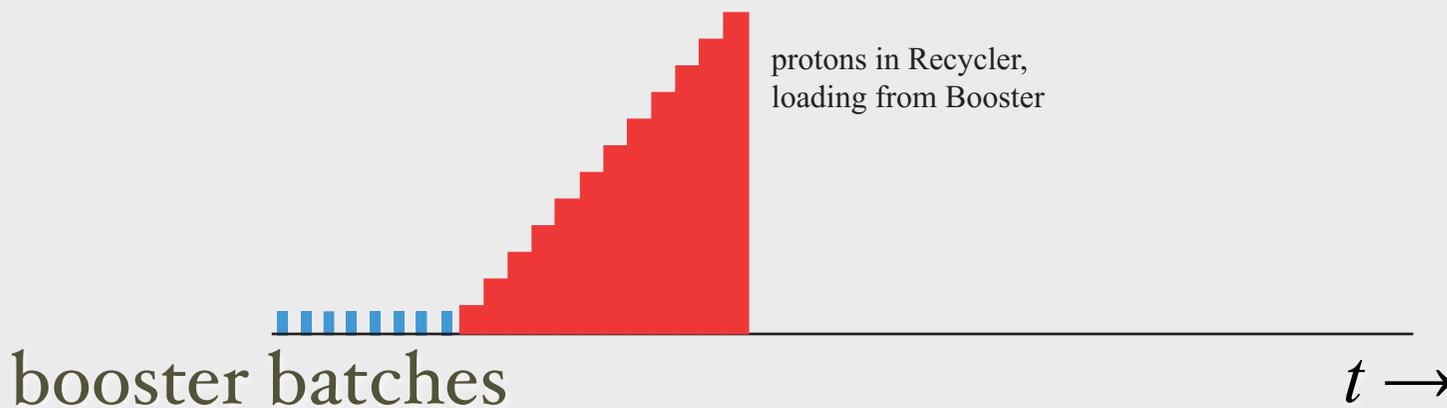
- Booster:
 - The Booster accelerates protons from the 400 MeV Linac to 8 GeV
- Accumulator:
 - momentum stacking successive pulses of antiprotons now, 8 GeV protons for Mu2e
- Debuncher:
 - smooths out bunch structure to stack more \bar{p} now; rebunch for Mu2e
- Recycler:
 - holds more \bar{p} than Accumulator can manage, “store” here; transport line for Mu2e



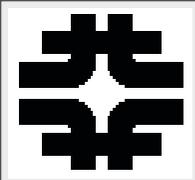
NovA Era and Mu2e



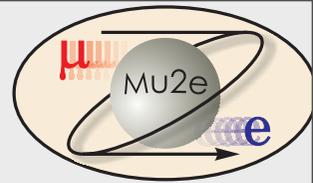
- Load from Booster to Recycler; Booster 'ticks' at $4E12, 15 \text{ Hz}$ 



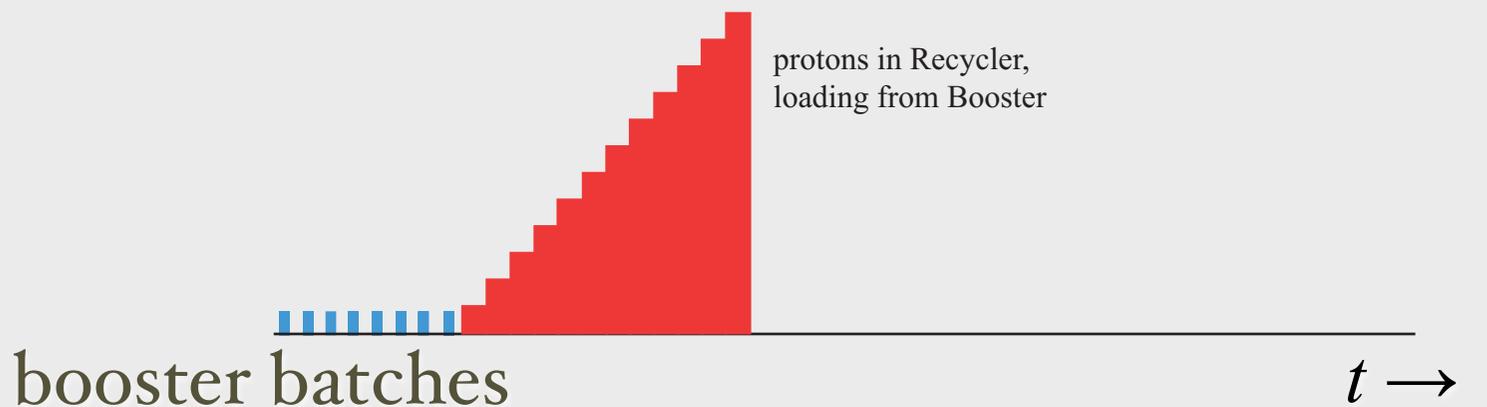
- Single-Turn Transfer to MI



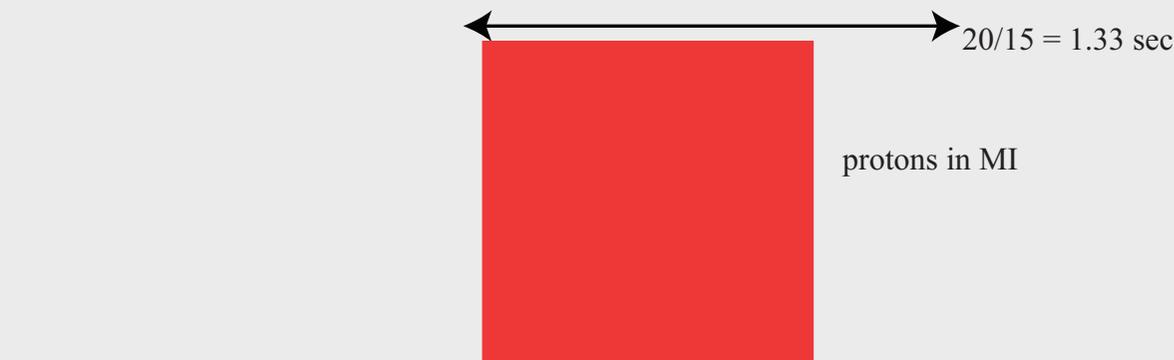
NovA Era and Mu2e

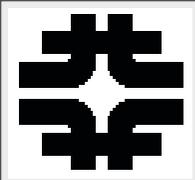


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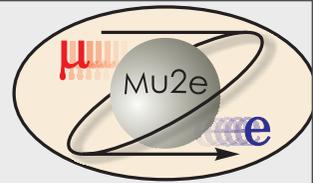


- Single-Turn Transfer to MI

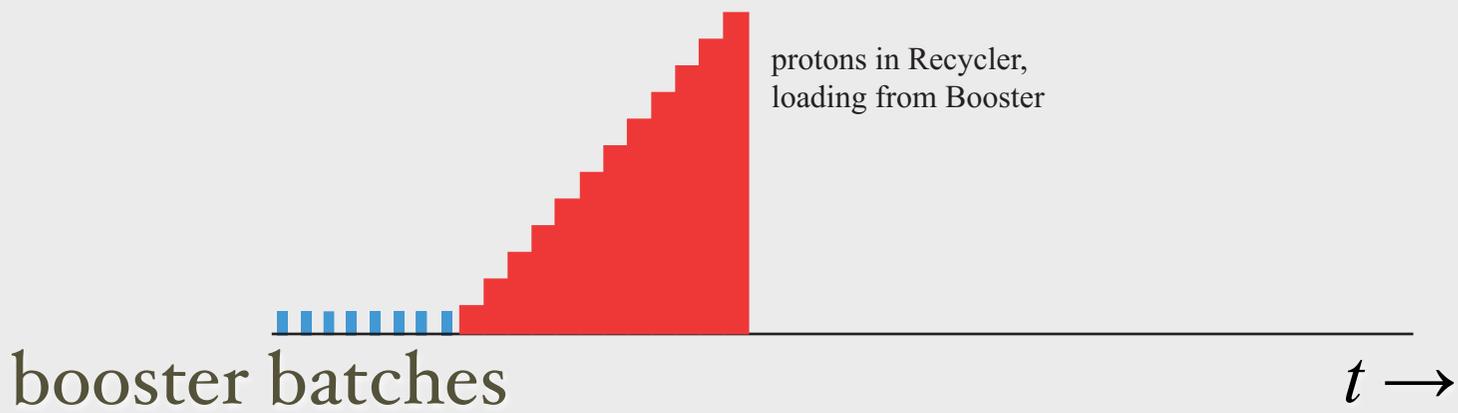




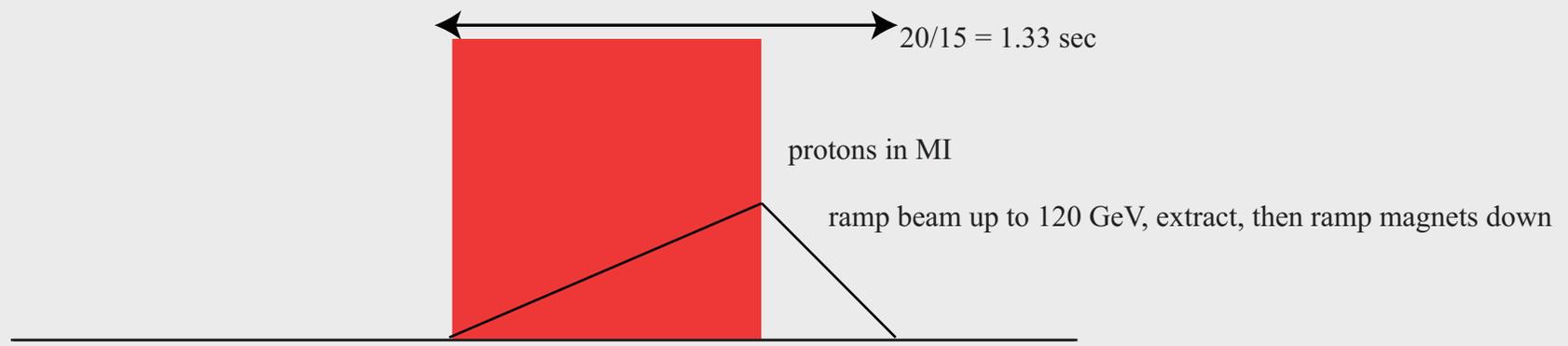
NovA Era and Mu2e

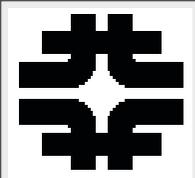


- Load from Booster to Recycler; Booster 'ticks' at $4E12$, 15 Hz 

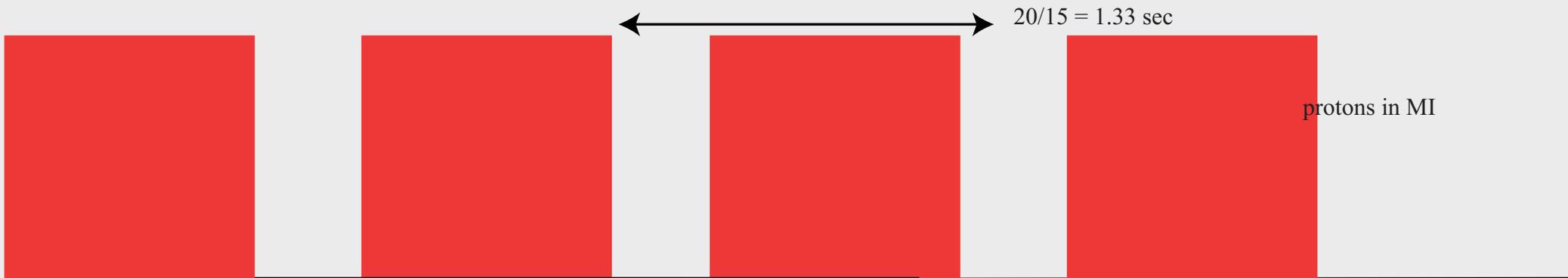
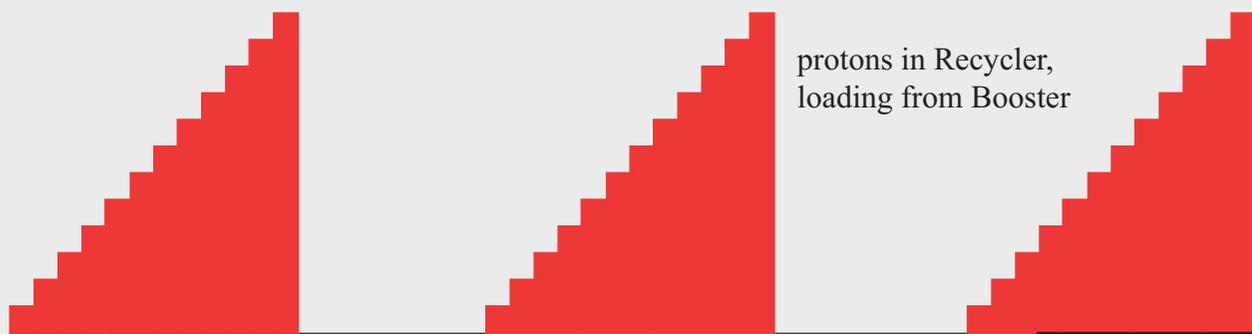
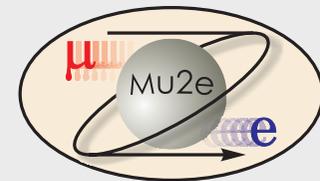


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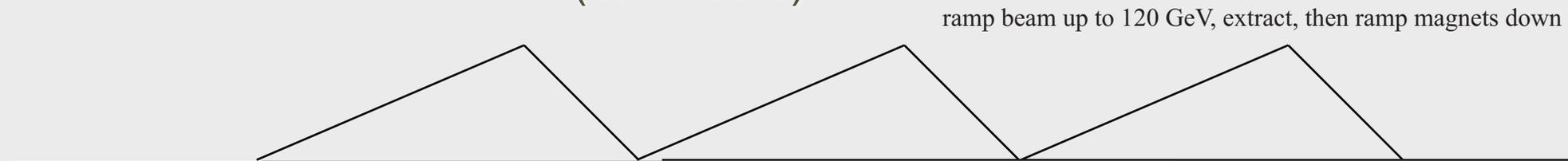


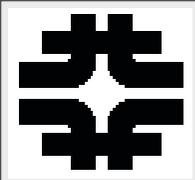


All Together...

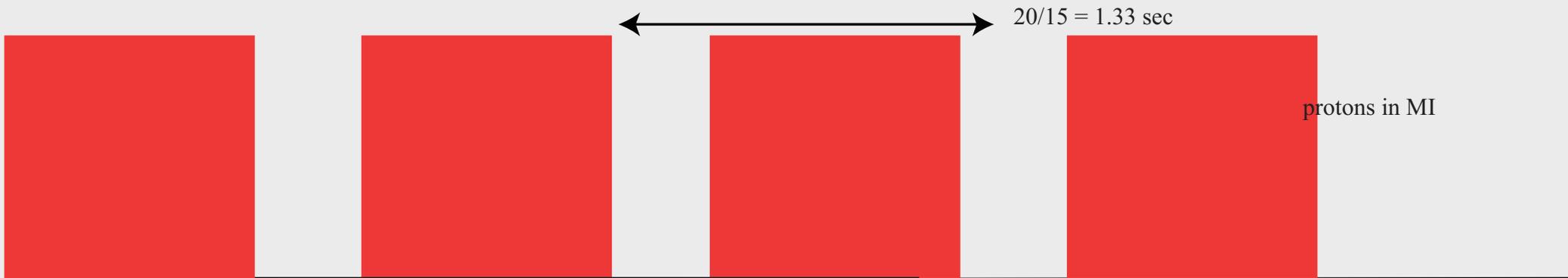
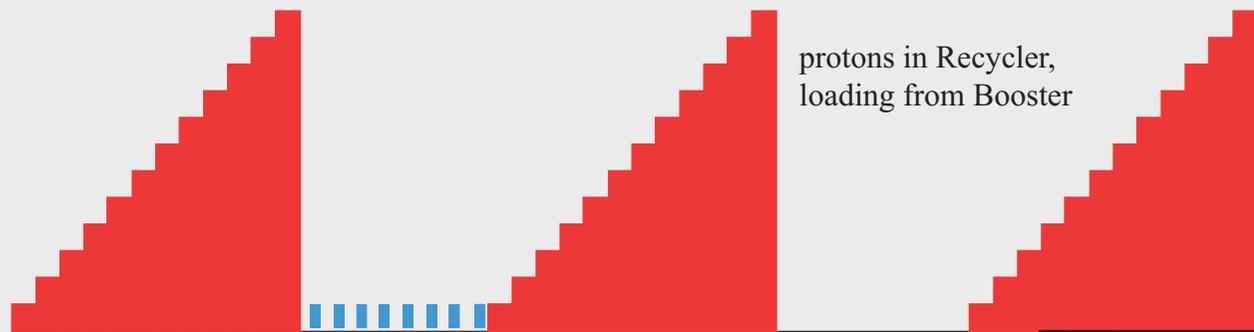
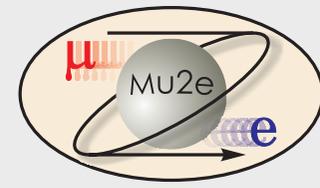


time to ramp allows us to fit eight extra Booster batches for Mu2e
(can use 6)



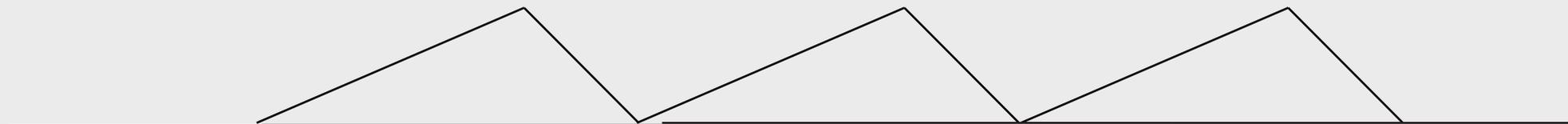


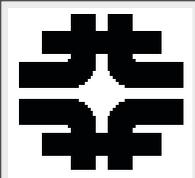
All Together...



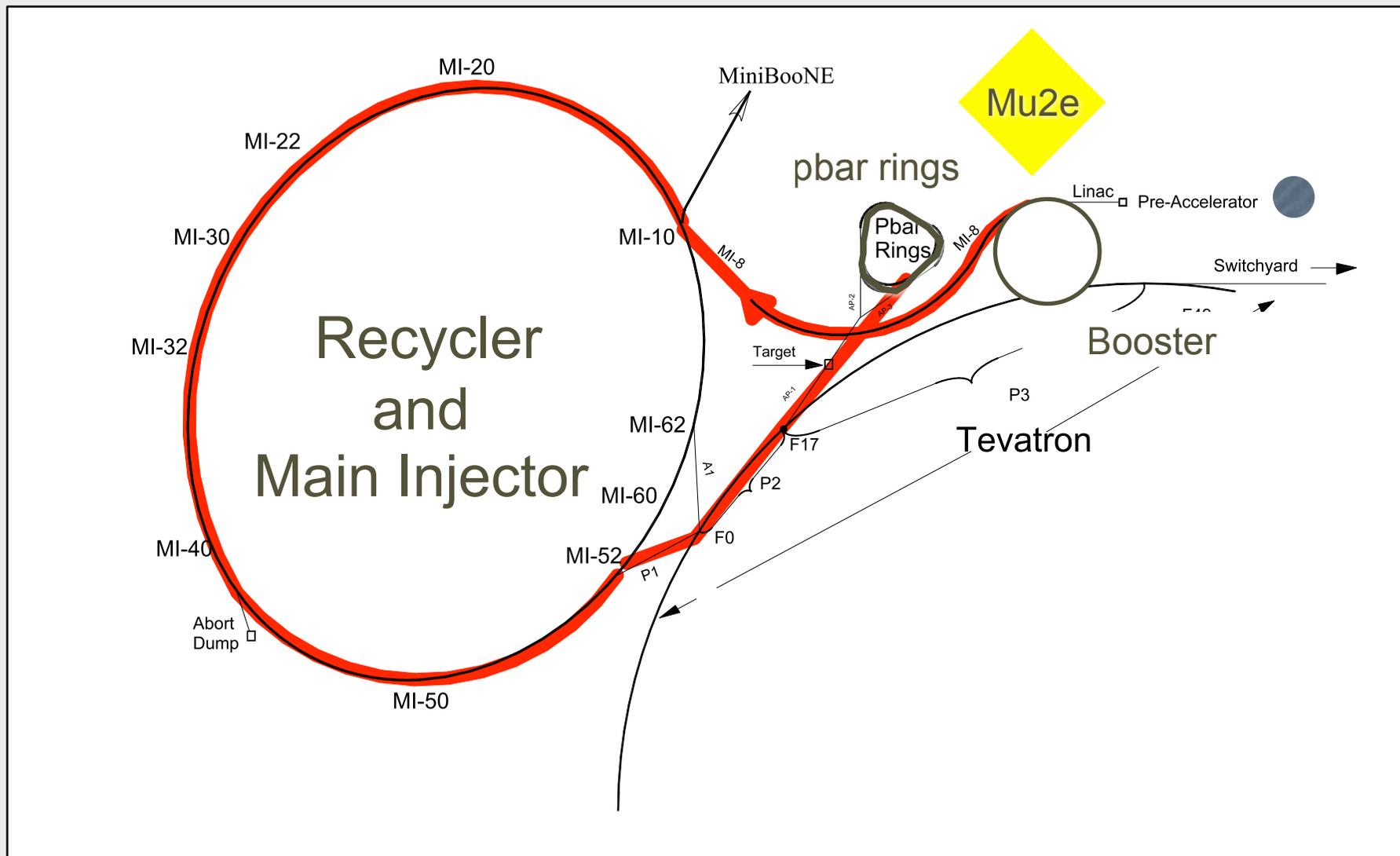
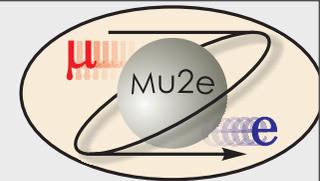
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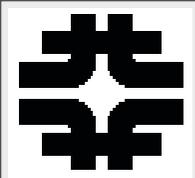
ramp beam up to 120 GeV, extract, then ramp magnets down



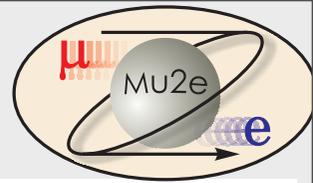


“Boomerang” Scheme

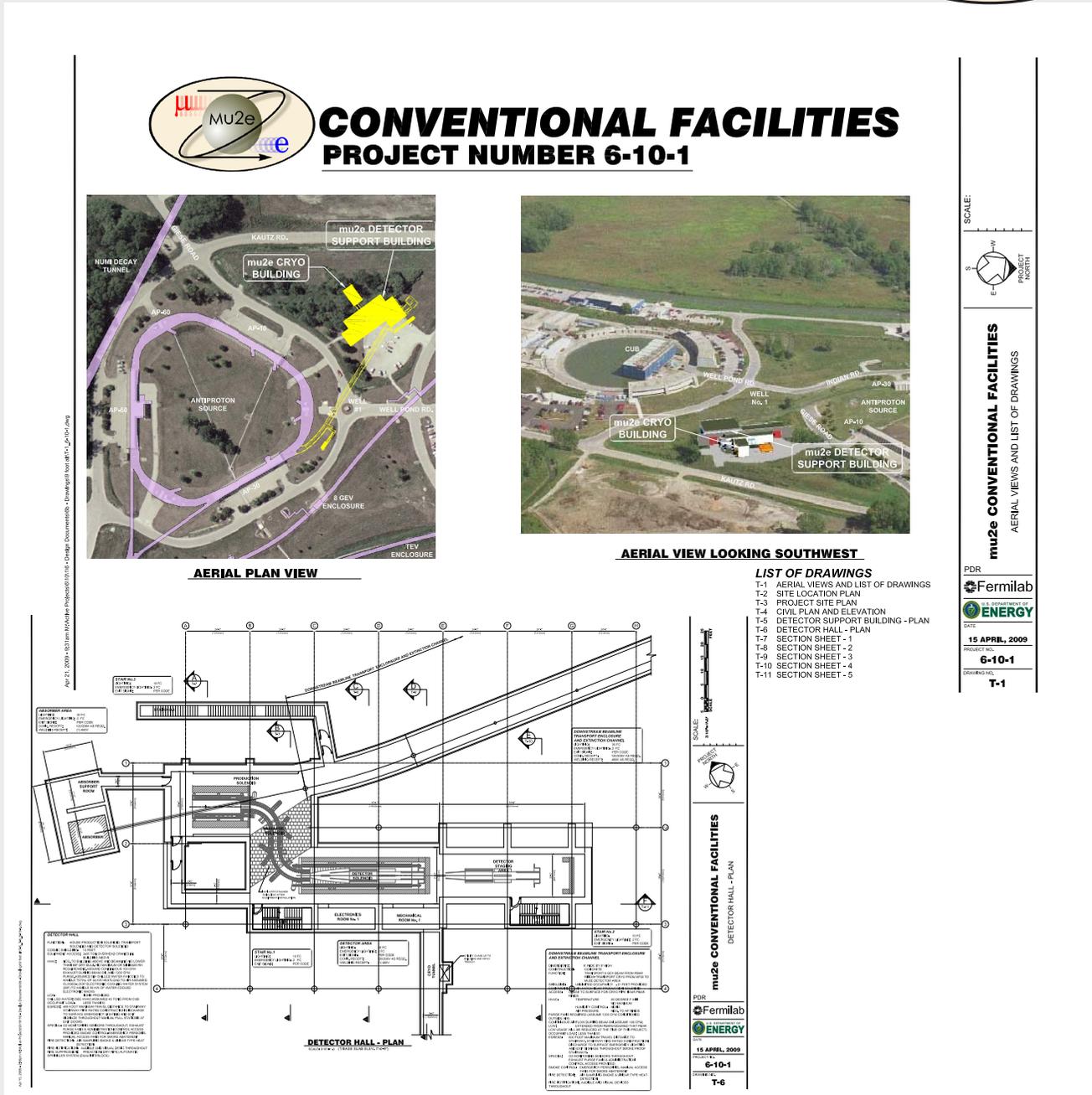


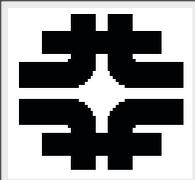


Site and Building Layout

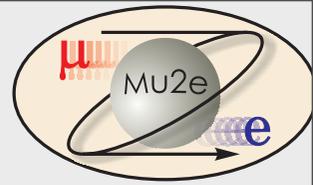


- Looking hard at variety of options
- Technical and cost considerations

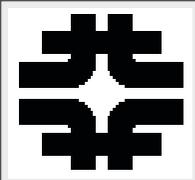




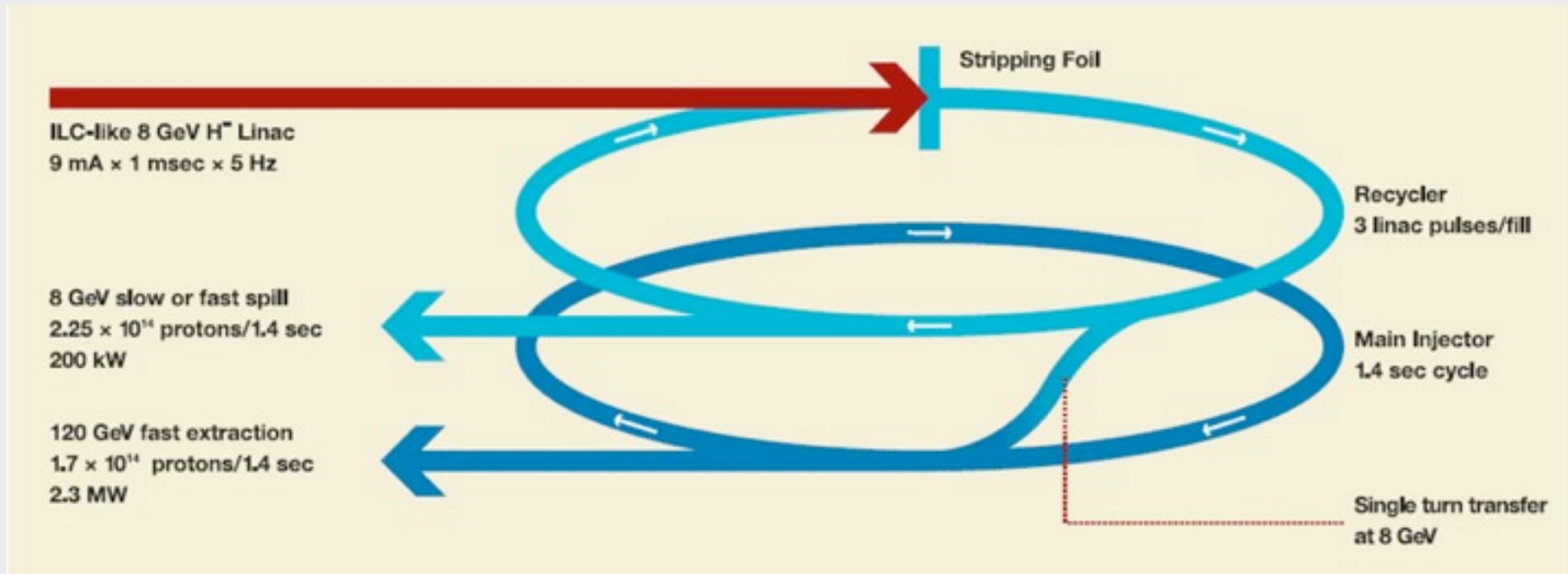
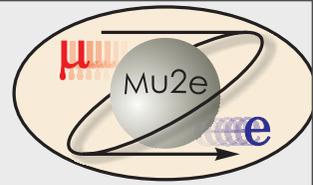
Outline



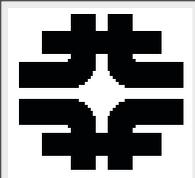
- The search for muon-electron conversion
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- Conclusions



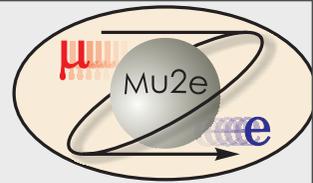
What is Project X?



- Project X is a concept for an intense 8 GeV proton source that provides beam for the Fermilab Main Injector and an 8 GeV physics program.
- The source consists of an 8 GeV superconducting linac that injects into the Fermilab Recycler

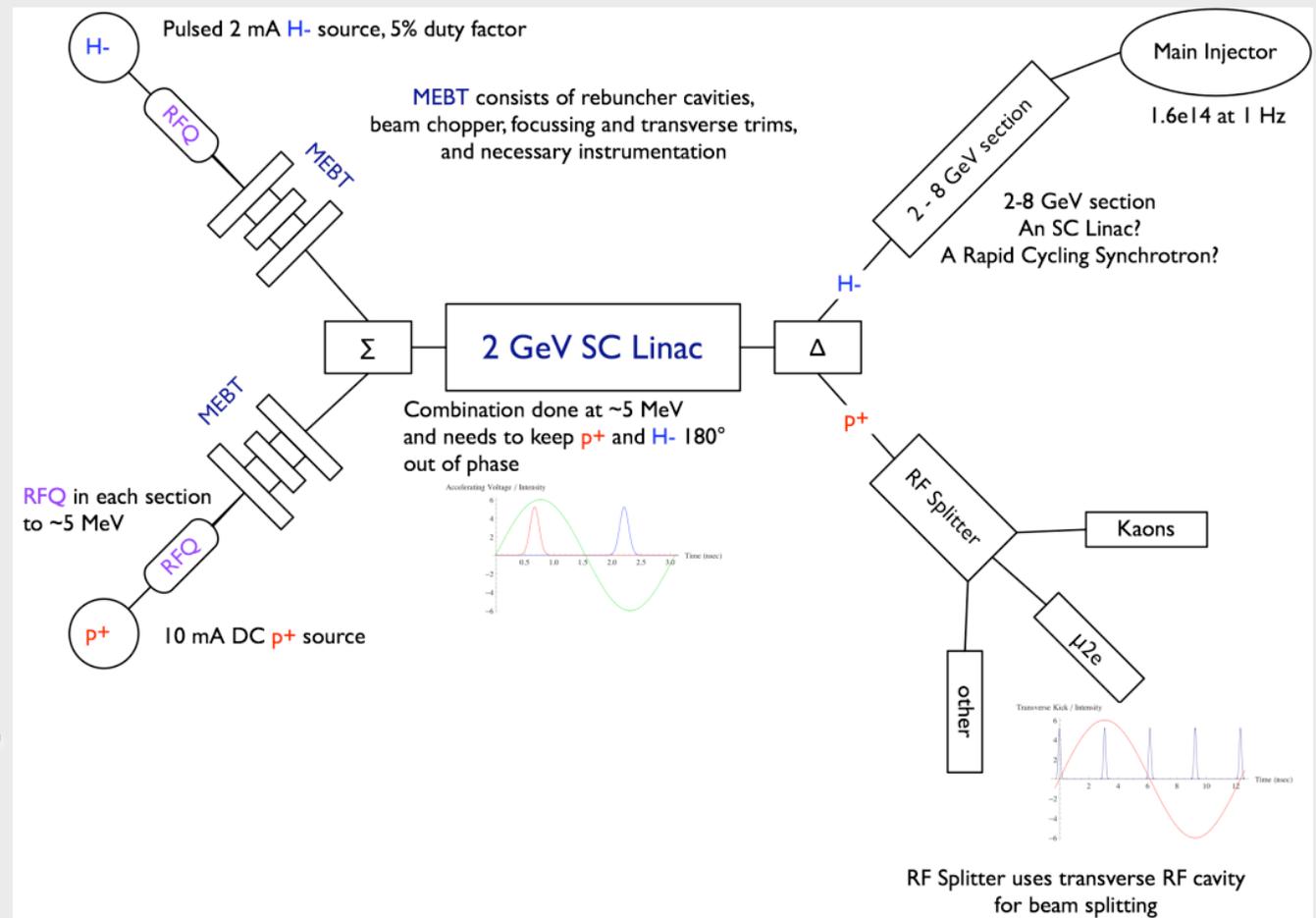


Project X ICD-2

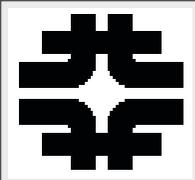


expect cost-comparison in Feb 2010
as part of CD process

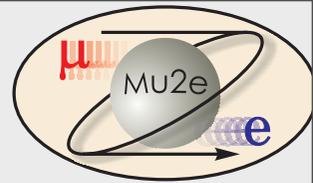
- Provides more flexibility for Mu2e, kaon, and neutrino programs
- Avoids inherent difficulties of slow extraction and replaces with RF splitter like JLab
- Beam power limit set by experiments, not accelerator
- Mu2e might look very different



Oct 1 physics process document on Project X website; Nov 9-10 workshop
http://www.fnal.gov/directorate/Longrange/Steering_Public/workshop-physics-4th.html
http://www.fnal.gov/directorate/Longrange/Steering_Public/workshop-muoncollider.html



Mu2e and Project X



*available 8 GeV Power
for intensity frontier*

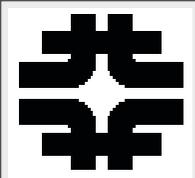
- First establish a signal or set a strong limit -- what do we do next?
- Project X gives us a chance to upgrade the experiment by up to x100

↓
20 kW
(current)

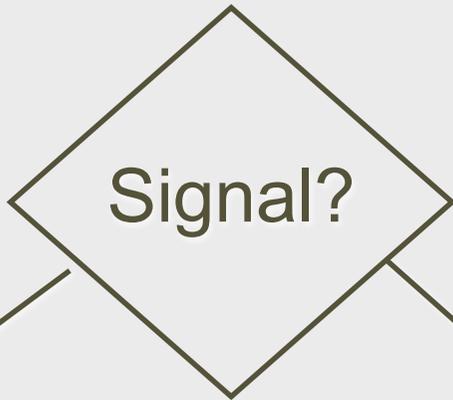
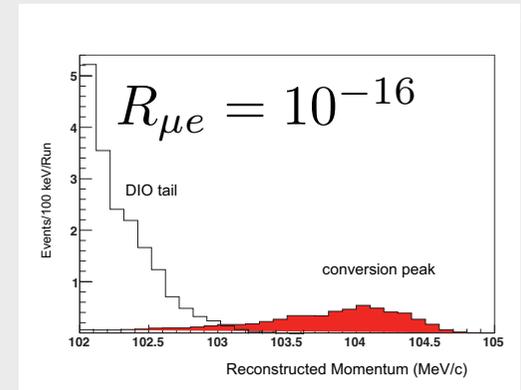
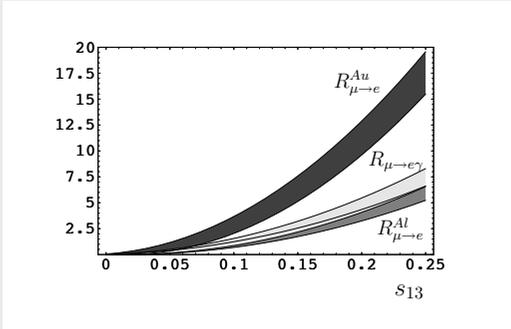
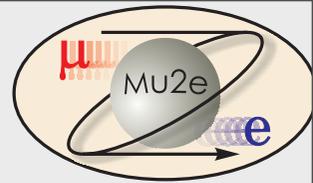
↓
200 kW
(Project X)

↓
2000 kW

(Project X Upgrades)



Upgrade Plans...



Yes

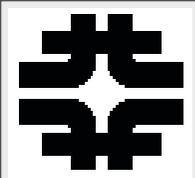
No

1. Change Z of Target to determine source of new physics

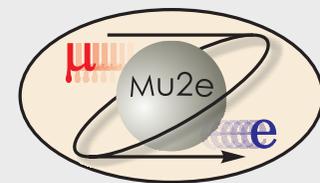
2. Prompt Rates will go up at higher Z, have to redesign detector and muon transport

1. Both Prompt and DIO backgrounds must drop to measure $R_{\mu e} \sim 10^{-18}$

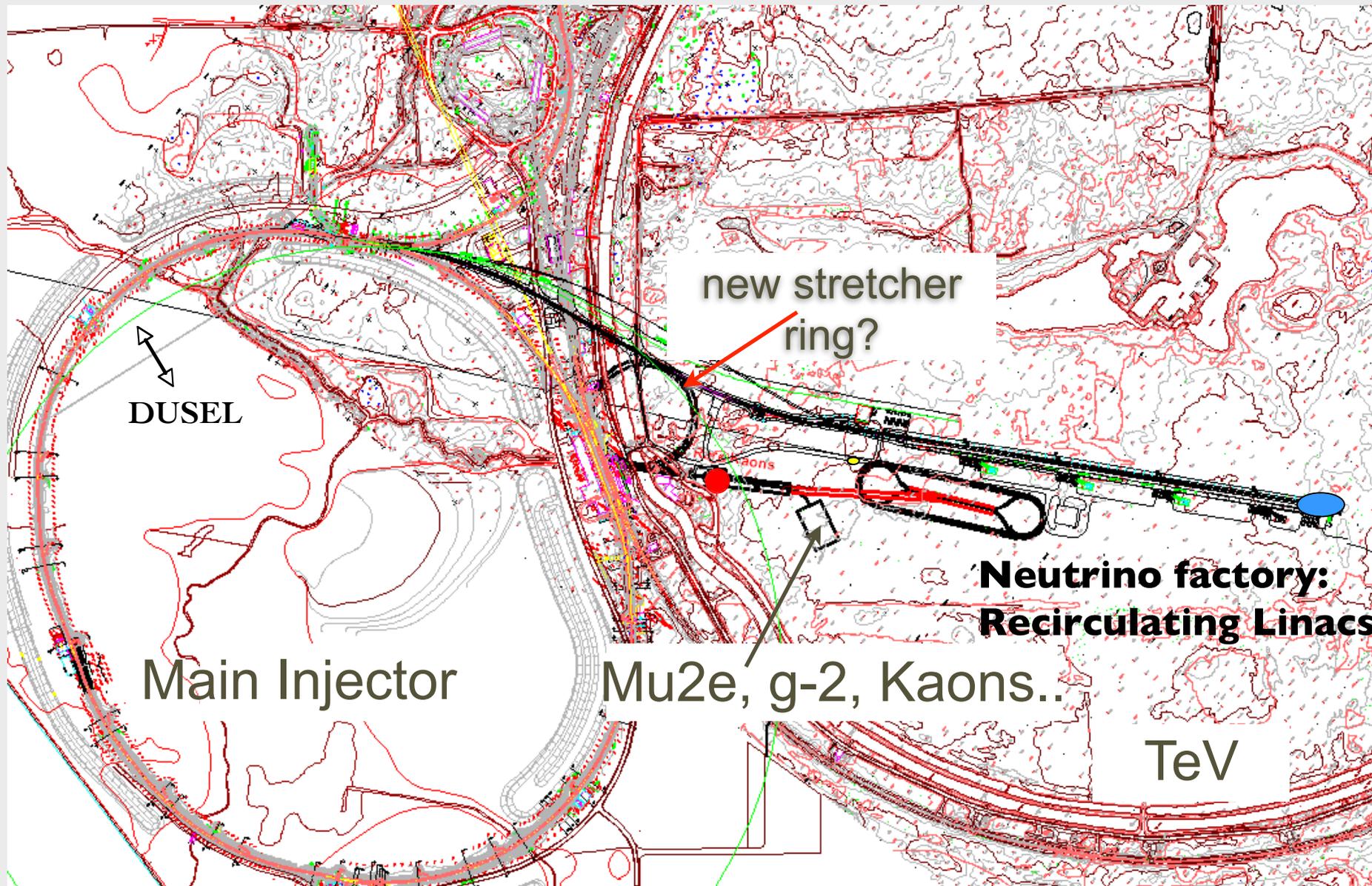
2. Detector, Muon Transport, Cosmic Ray Veto, Calorimeter

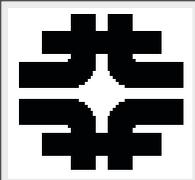


Project X Era?

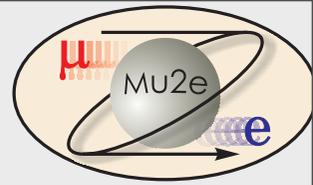


not approved or part of any official plan...

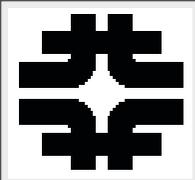




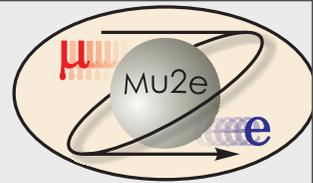
Outline



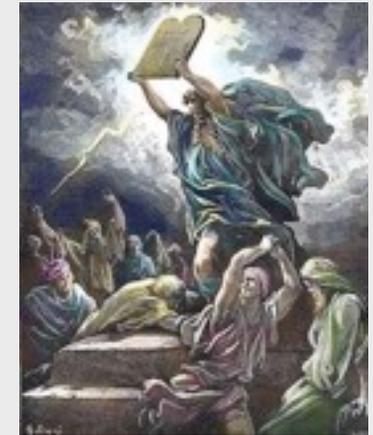
- The search for muon-electron conversion
- Experimental Technique
- Fermilab Accelerator
- Project X Upgrades and Mu2e
- **Cost and Schedule**
- Conclusions



Cost and Schedule

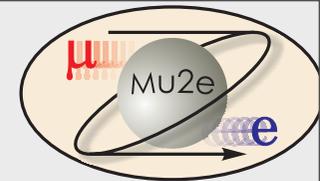
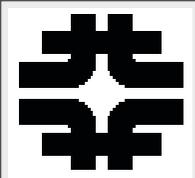


- *This is a technically limited schedule*
- Critical Path is Superconducting Solenoids
- \$200M “fully-loaded” Total Cost



| Solenoids | 2009 | | | | 2010 | | | | 2011 | | | | 2012 | | | | 2013 | | | | 2014 | | | | 2015 | | | | 2016 | | | |
|---|------|---|---|---|------|---|---|---|------|---|---|---|------|---|---|---|------|---|---|---|------|---|---|---|------|---|---|---|------|---|---|---|
| | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| Conceptual Design | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Final Design/place contracts | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| Construction/installation/commissioning | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |

data-taking 1st quarter Calendar 2016



What Does This Mean?

design, prototyping, test beams...



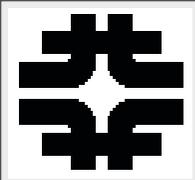
| Solenoids | 2009 | | | | 2010 | | | | 2011 | | | | 2012 | | | | | |
|---|------|---|---|---|------|---|---|---|------|---|---|---|------|---|---|---|--|--|
| | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | | |
| Conceptual Design | | | | | | | | | | | | | | | | | | |
| Final Design/place contracts | | | | | | | | | | | | | | | | | | |
| Construction/installation/commissioning | | | | | | | | | | | | | | | | | | |

busy measuring beam, detector properties, ...

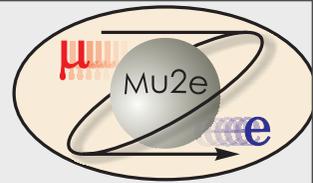
| | 2013 | | | | 2014 | | | | 2015 | | | | 2016 | | | |
|--|------|---|---|---|------|---|---|---|------|---|---|---|------|---|---|---|
| | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 | 1 | 2 | 3 | 4 |
| | | | | | | | | | | | | | | | | |
| | | | | | | | | | | | | | | | | |

background studies

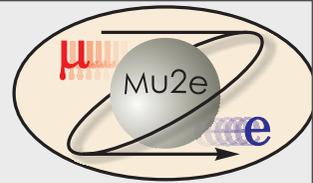
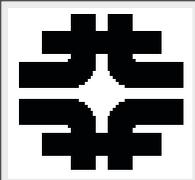
final data-taking



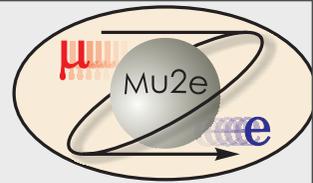
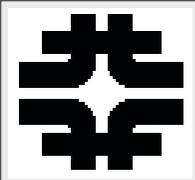
Conclusions



- Mu2e will either:
 - *Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude ($R_{\mu e} < 6 \times 10^{-17}$ @ 90% C.L.)*
 - *Discover unambiguous proof of Beyond Standard Model physics and*
 - *Provide important information either complementing LHC results or probing up to 10^4 TeV mass scales*
- With upgrades, we could extend the limit by up to two orders of magnitude or study the details of new physics



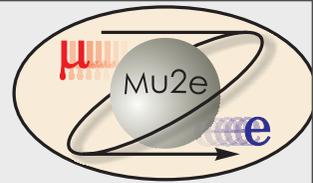
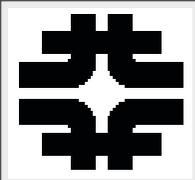
And Perhaps Answer Rabi's Question about the physics of flavor and generations



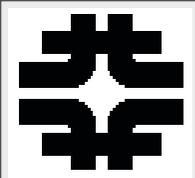
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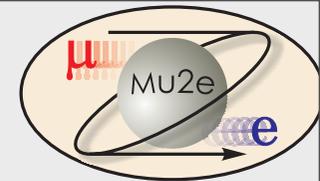
Who ordered that?



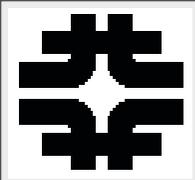
BACKUPS



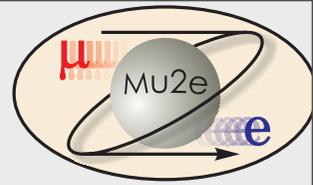
Changes in Cost from MECO



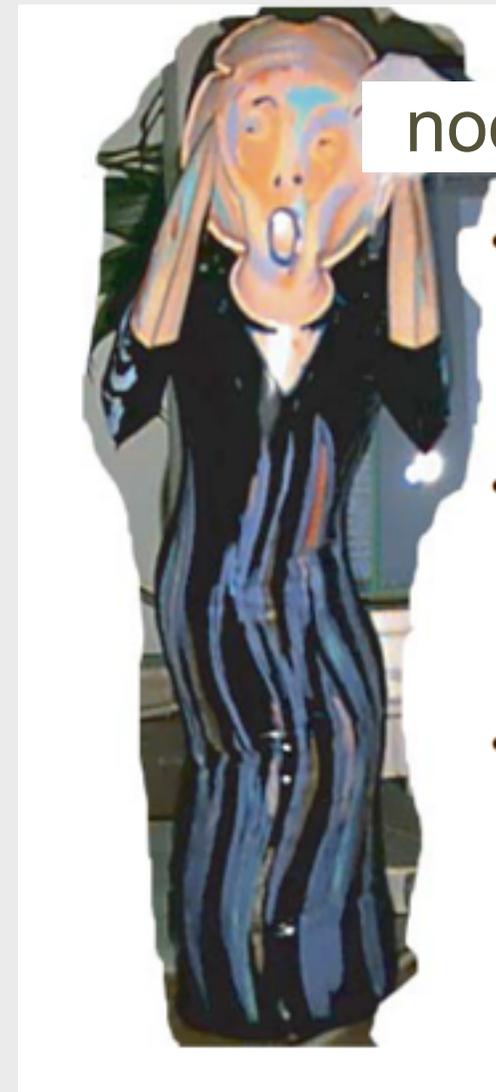
noooo!

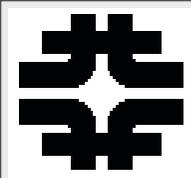


Changes in Cost from MECO

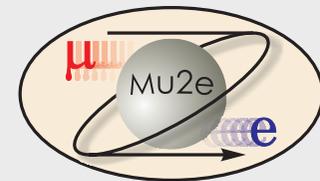


- Inflation at 3.5%/yr: **~\$15M**
- All Civil Construction from Accelerator through Experimental Hall : **~\$40M: not included in MECO**
- FNAL Accelerator Modifications: **~\$22M**
- Added **~\$15M** in contingency: MECO was 23.9%: experience and the DOE tell us that's too low for this level of development





COMET



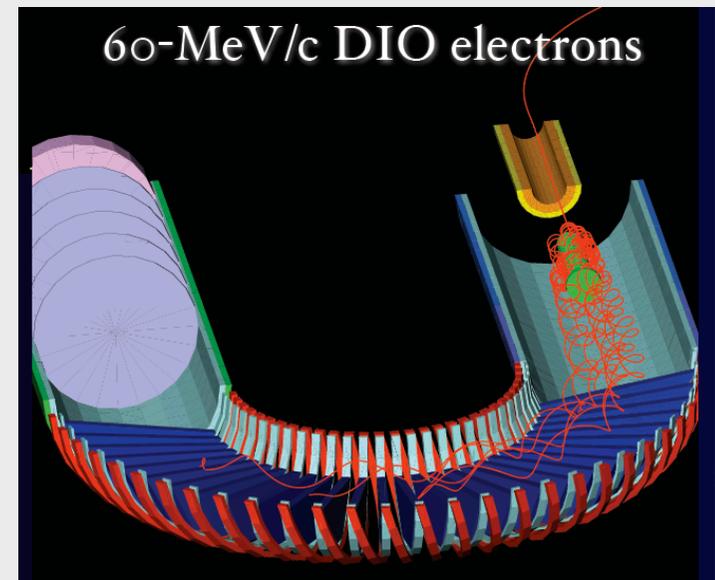
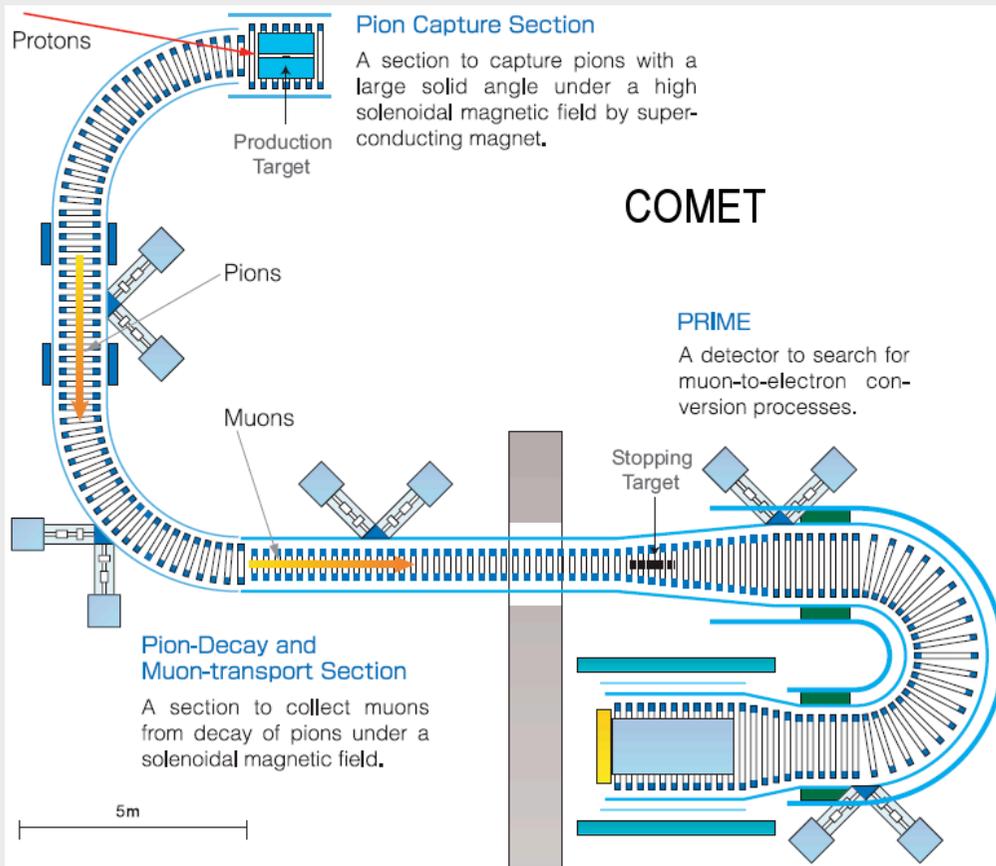
Similar to Mu2e:

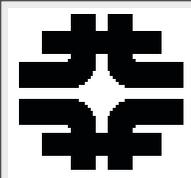
- $R(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$
- Same μ production scheme
- U, not S-shaped transport solenoid

Proposed to J-PARC

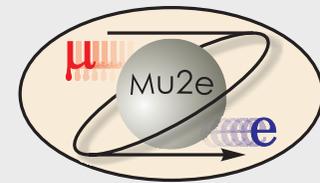
Detector different than Mu2e:

- In U-shaped solenoid
- No line of sight for neutrals
- Charged particles with $p < 80$ MeV/c not transported to spectrometer \Rightarrow rate lower





COMET



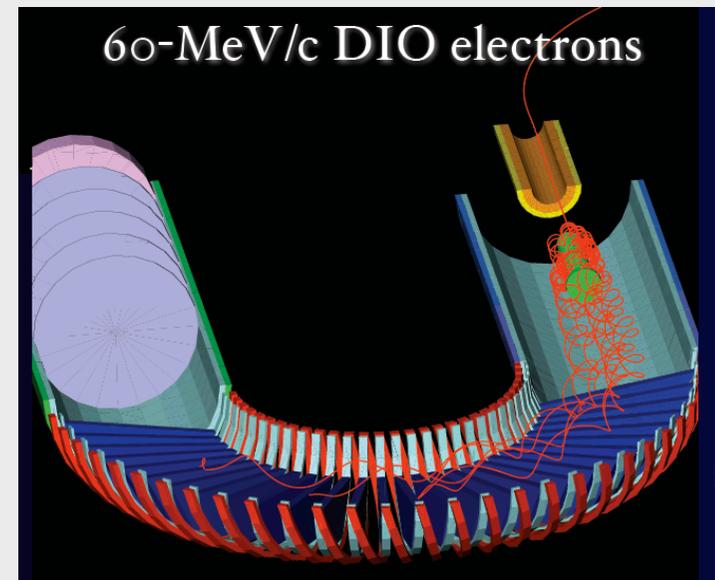
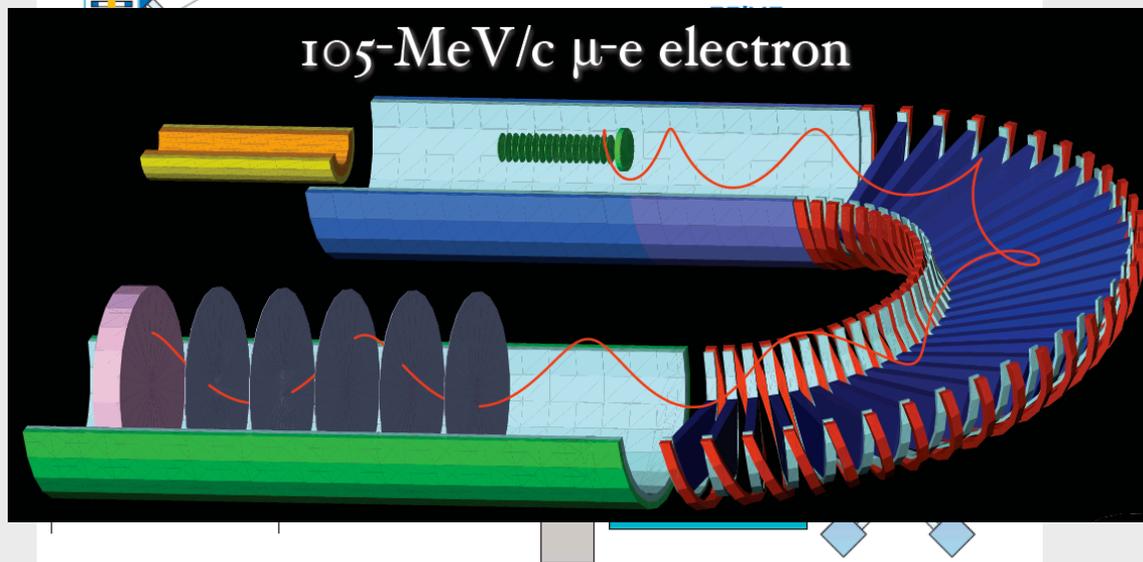
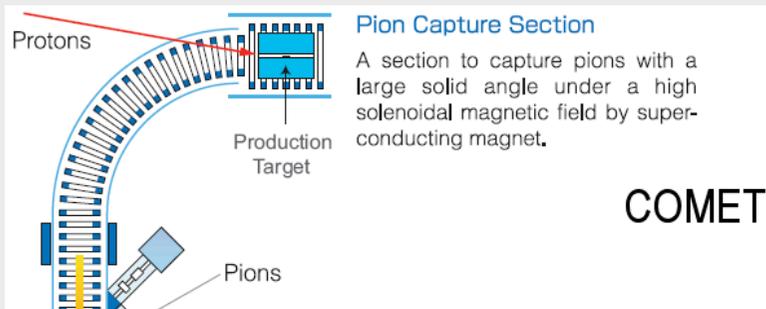
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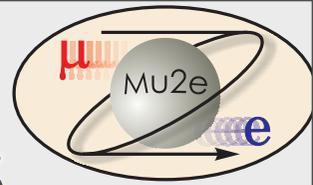
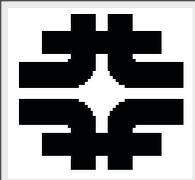
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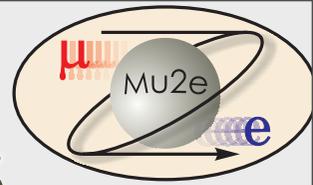
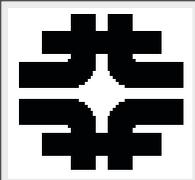


US Gov't DOE CD Process

Lasciate ogni speranza, voi ch'intrate



Inferno
fresco in Camposanto, Pisa



US Gov't DOE CD Process

Lasciate ogni speranza, voi ch'intrate



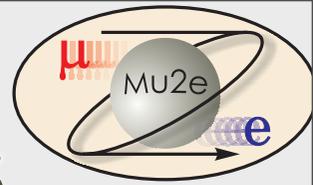
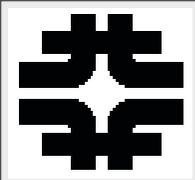
Inferno
fresco in Camposanto, Pisa

R. Bernstein, FNAL



CD
process

Mu2e U. Chicago 5/17/10



US Gov't DOE CD Process

Lasciate ogni speranza, voi ch'intrate

Experimenter's
Reward



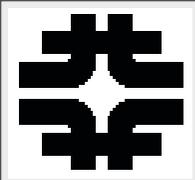
Inferno
fresco in Camposanto, Pisa

CD
process

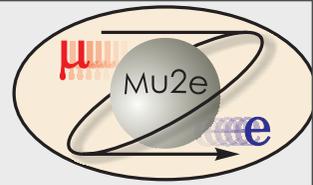
R. Bernstein, FNAL

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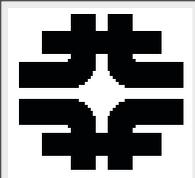
Mu2e U. Chicago 5/17/10



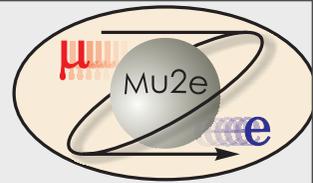
Guide to DOE CD Process



- CD-0: “mission need”
 - the DOE decides this is part of its goals and then DOE prepares document
 - ***DOE: Feb 2009 for Mu2e***
- CD-1: “conceptual design”
 - careful, systematic evaluation of alternatives
 - cost and schedule well along but not final
- CD-2: “baseline” / technical design
 - firm cost and schedule estimates for entire experiment
- CD-3: *spend money!*



g-2 At Fermilab



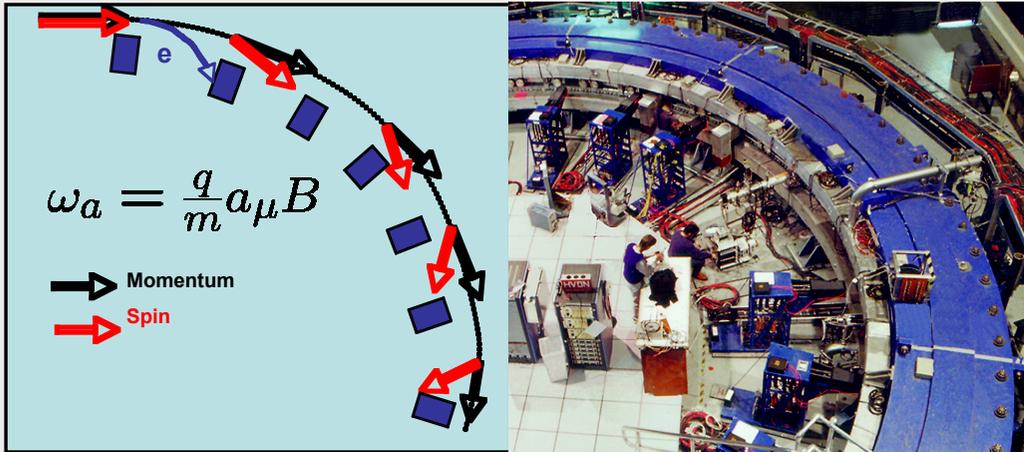
$$\Delta a_\mu = a_\mu^{(\text{Exp})} - a_\mu^{(\text{SM})} = 295 \pm 88 \times 10^{-10}$$

from $3.6\sigma \rightarrow >7\sigma$

current

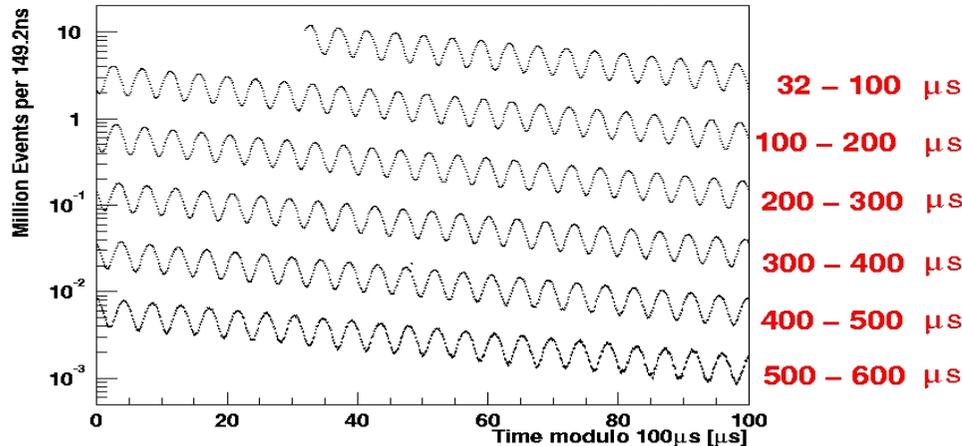
$$\sigma_{\text{stat}} = \pm 0.46 \text{ ppm}$$

$$\sigma_{\text{syst}} = \pm 0.28 \text{ ppm}$$

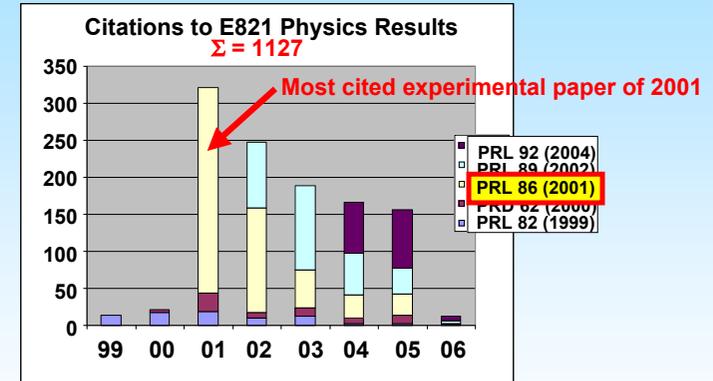


final g-2 result: Bennett et al, PRD 73, 072003 (2006)

electron time spectrum (2001)



This large number of citations demonstrate widespread interest in the community.



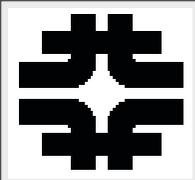
Precision measurements provide an alternate path to the frontier of particle physics. Whatever LHC finds, muon (g-2) will provide independent constraints on the parameter space for new physics.

$$\Delta a_\mu^{\text{MSSM}} \approx 130 \times 10^{-11} \tan \beta \text{ sign}(\mu) \left(\frac{100 \text{ GeV}}{M_{\text{SUSY}}} \right)^2$$

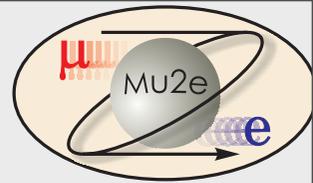
R. Bernstein, FNAL

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Mu2e U. Chicago 5/17/10



g-2 Method



We measure the difference frequency between the spin and momentum precession

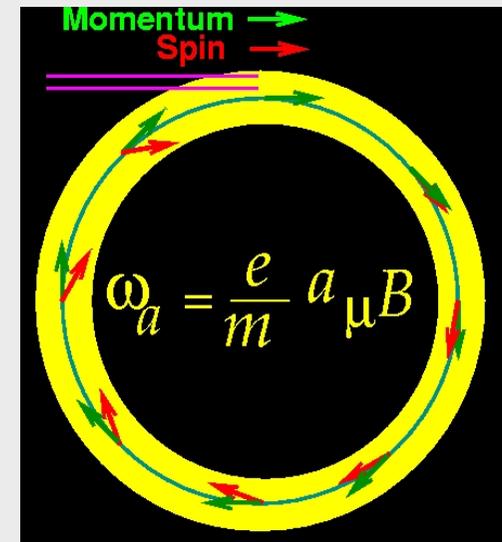
$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2} \right) \frac{eB}{mc} \quad B \Rightarrow \langle B \rangle_{\mu\text{-dist}}$$

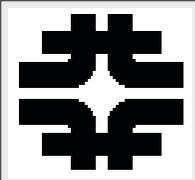
With an electric quadrupole field for vertical focusing

$$\vec{\omega}_a = -\frac{e}{m} \left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right]$$

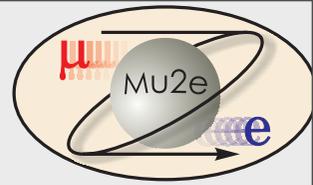
$$\gamma_{\text{magic}} = 29.3$$

$$p_{\text{magic}} = 3.09 \text{ GeV}/c$$

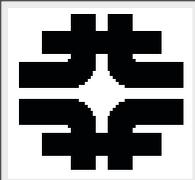




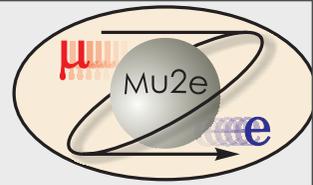
g-2 hadronic term



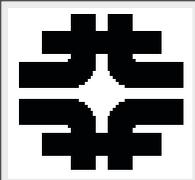
- Hadronic Cross-section measured here at KLOE
- BaBar *preliminary* result is different from others in tau and $e^+ e^-$; BaBar alone would reduce effect x2
- Complicated situation -- still, large effect and should be repeated



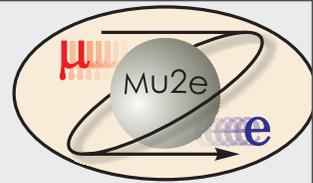
g-2 at Fermilab



- Not compatible with Mu2e for beam
- Can We Move Ring from BNL and run *before* Mu2e?
- FNAL would like to do this – but need to understand cost, beam requirements, etc. before making decision



Why so much trouble?



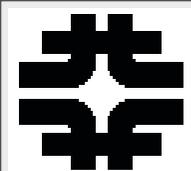
$$\frac{\text{final cost}}{\text{estimated cost}}$$

TABLE 6

SELECTED HISTORY OF PROJECT PERFORMANCE

| | <u>CE/IE*</u> |
|--|---------------|
| Early HEP Projects | 1.0 |
| Recent "Worst Case" ER Projects | 1.6 |
| Recent DOE-wide Projects | 2.5 |
| New Senate Office Building | 3.0 |
| Recent DOD Projects | 5.0 |
| Alaska Pipeline | 7.8 |
| Recent "Worst Case" Nuclear Power Plants | 10.4 |

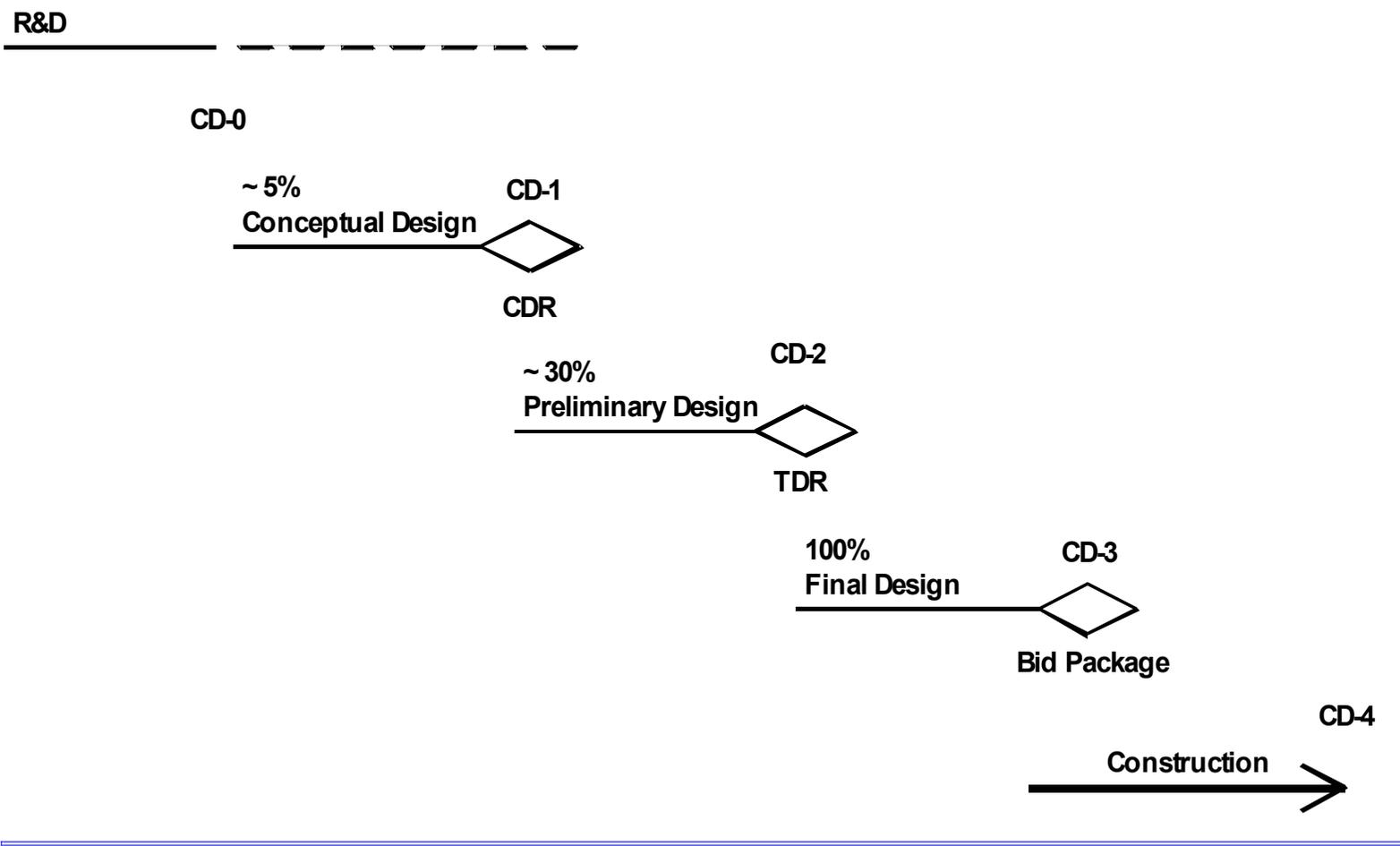
* CE/IE is the ratio of the current (or final) estimate to complete to the initial estimate. For government agencies the IE is taken to be initial formal request for funds from Congress.



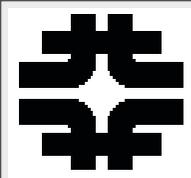
Overview



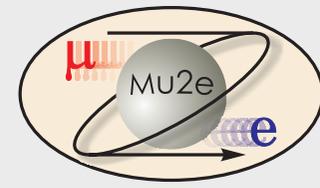
Project Design Phases



Fermilab's Office of Project
Management Oversight



CD Process

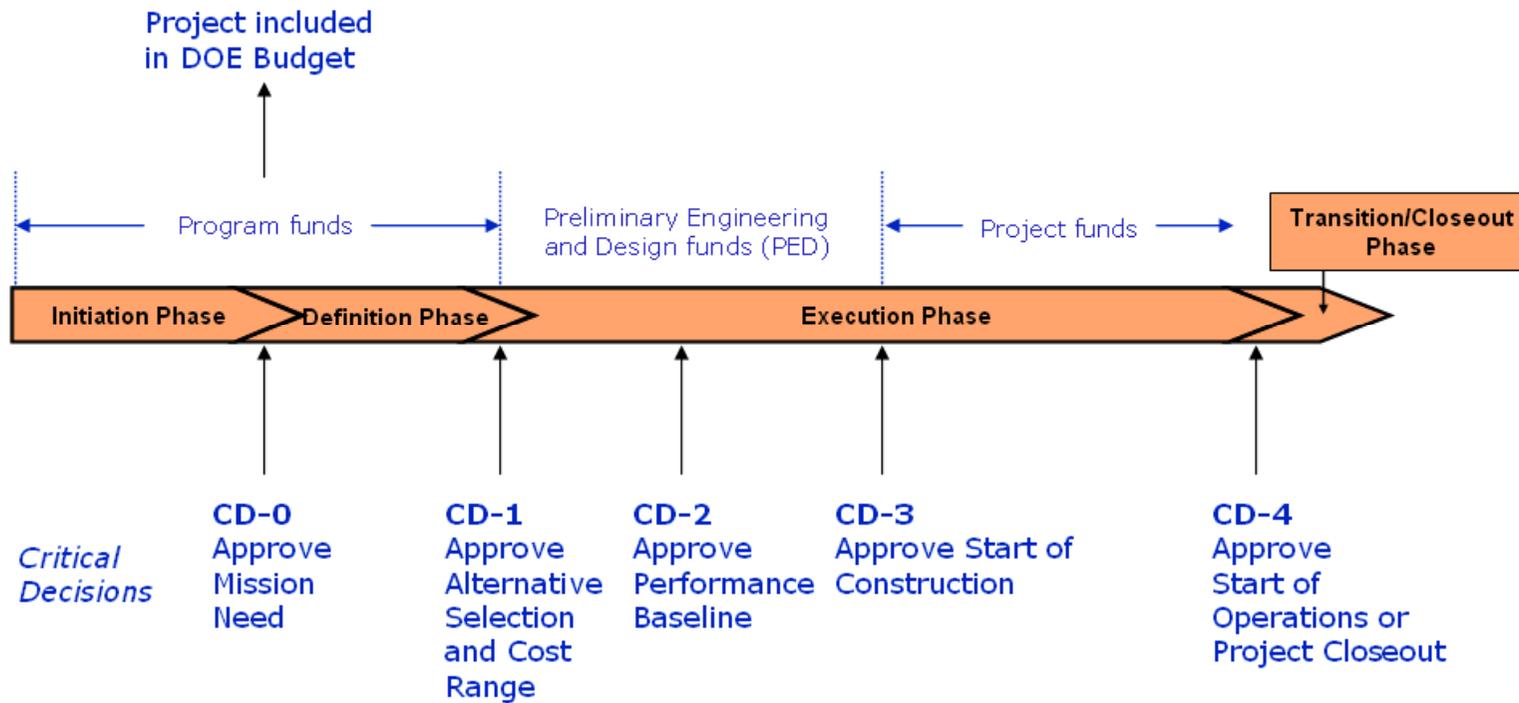


U.S. Department of Energy



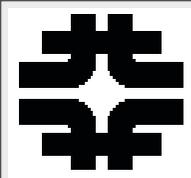
Office of Science

Project Management Process



new measurements: test beams,
prototypes

7



It Gets Worse

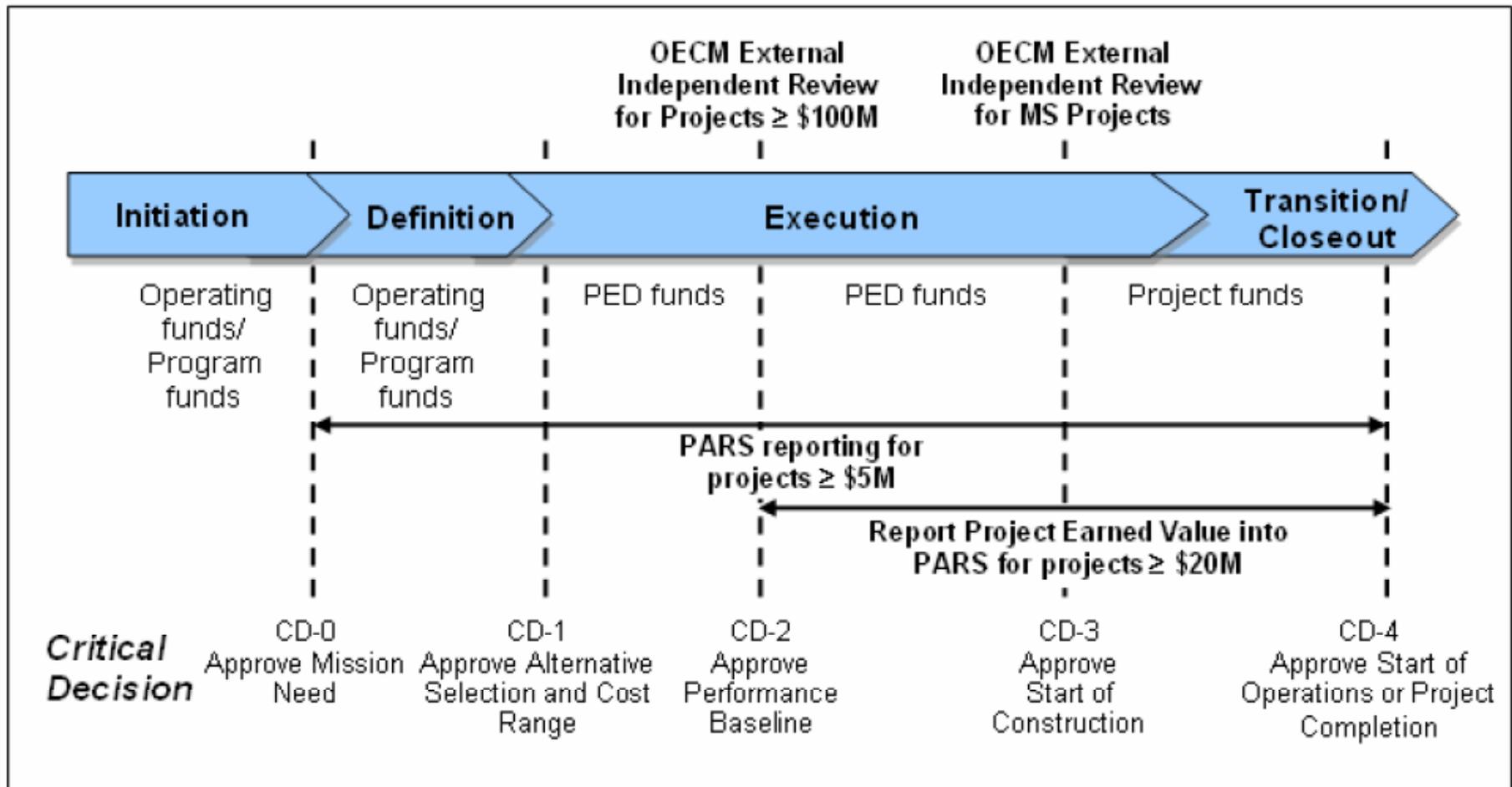
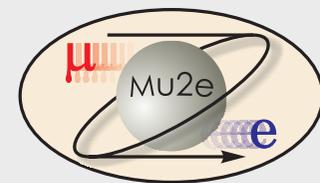
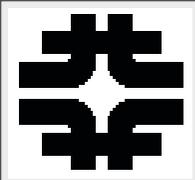
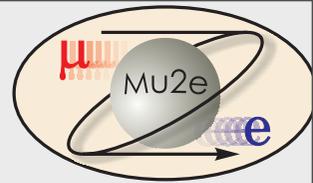


Figure 1. Typical DOE Acquisition Management System for Line Item Projects.

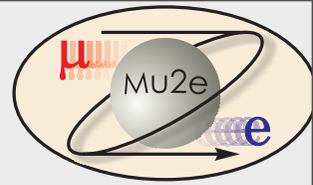
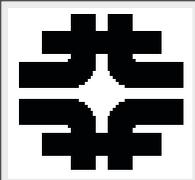


Details of Cost Estimate



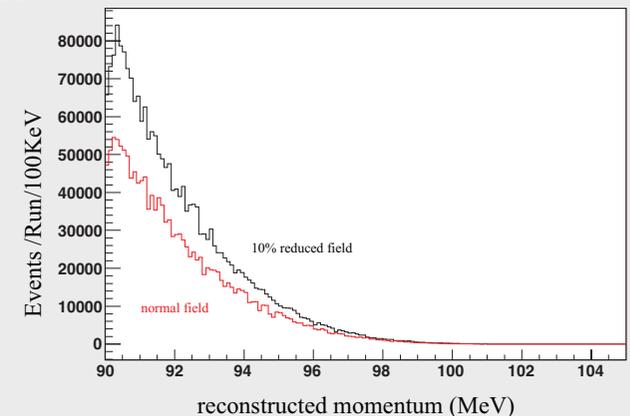
| | M&S (k\$) | Labor (k\$) | Base Cost FY05 k\$ | Base Cost FY09 k\$ | Contingency | Contingency (k\$) | Total FY09 k\$ |
|-------------------------------------|-----------------|-----------------|-----------------------|-----------------------|-------------|----------------------|------------------|
| Production Target and Shield | \$2,619 | \$237 | \$2,856 | \$3,277 | 50% | \$1,639 | \$4,916 |
| Muon Beamline | \$1,306 | \$1,377 | \$2,683 | \$3,079 | 50% | \$1,539 | \$4,618 |
| Straw Tracker | \$2,409 | \$1,080 | \$3,489 | \$4,004 | 50% | \$2,002 | \$6,006 |
| Calorimeter | \$3,688 | \$1,278 | \$4,966 | \$5,699 | 50% | \$2,849 | \$8,548 |
| Cosmic ray veto | \$1,060 | \$334 | \$1,394 | \$1,600 | 50% | \$800 | \$2,399 |
| Trigger and DAQ | \$955 | \$620 | \$1,575 | \$1,807 | 50% | \$904 | \$2,711 |
| Integration and Installation | \$136 | \$1,372 | \$1,508 | \$1,730 | 50% | \$865 | \$2,596 |
| Solenoids | \$37,973 | \$13,197 | \$51,170 | \$58,719 | 50% | \$29,359 | \$88,078 |
| Cryogenic Infrastructure | \$1,556 | \$1,988 | | \$3,544 | 50% | \$1,772 | \$5,316 |
| Beamline | \$4,747 | \$3,793 | | \$8,540 | 100% | \$8,540 | \$17,080 |
| Civil Construction | \$25,661 | \$5,456 | | \$31,117 | 31% | \$9,643 | \$40,760 |
| Project Office | \$556 | \$4,535 | | \$5,091 | 35% | \$1,782 | \$6,873 |
| Total | \$82,666 | \$35,267 | | \$128,207 | 48% | \$61,694 | \$189,901 |

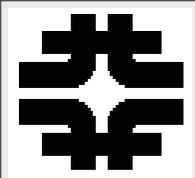
plus additional \$10M in R&D not in this table



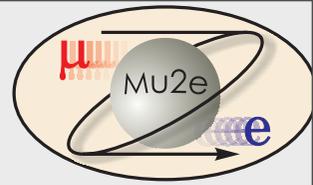
Measuring the Resolution

- Single/Multiple Foil Runs
 - (dE/dx and acceptance)
- Lower field and measure edge of $\pi^+ \rightarrow e\nu_e$
 - calibration and high-side tail
- Annular Foils
- “Etch-A-Sketch” target

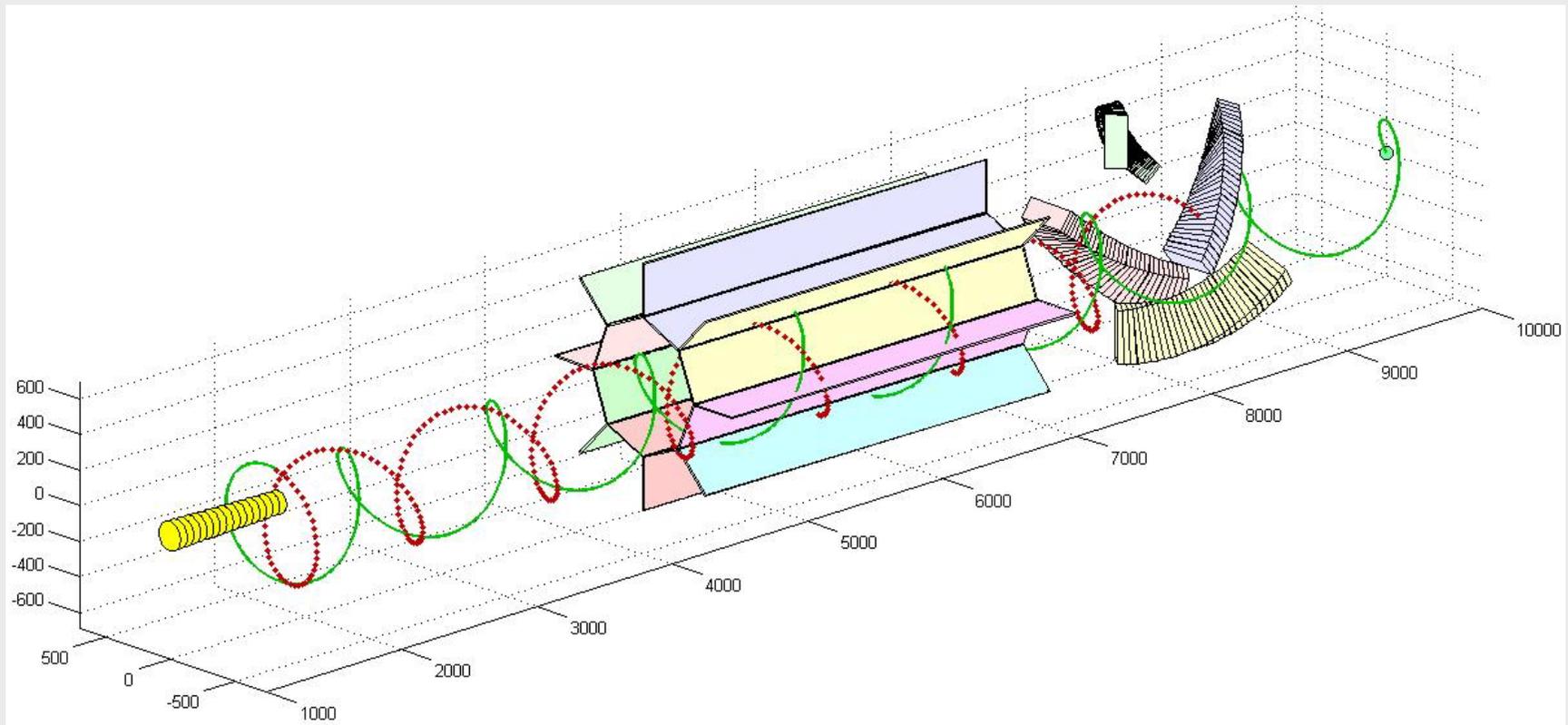


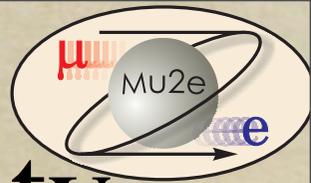
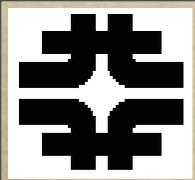


More Ambitious



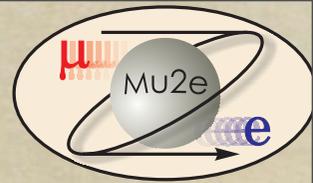
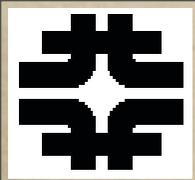
- In-situ electron source
 - (ILC cryomodule at 105 MeV)
- much to be worked out





Beam Flux and Radiation Safety

- *New particle rates for the “pbar” rings:*
 - *presently, Debuncher/Accumulator receive approximately 25×10^{10} particles per hour; for $\mu 2e$, expecting $\sim 2 \times 10^{13}$ per second: factor of 300,000*
 - *1% loss (scaling) \rightarrow ~ 290 W of beam loss power*
 - *Booster: ~ 500 W total, ~ 1 W/m (300 W, 0.6 W/m in uncontrolled regions)*
- *Will require new mitigation for “pbar” rings*
 - *passive system not enough; need \sim Booster system*
 - *const. energy rings help -- can monitor devices, inhibit beam*



When NOvA is “off”

○ *If have all Booster Cycles available for use in Mu2e:*

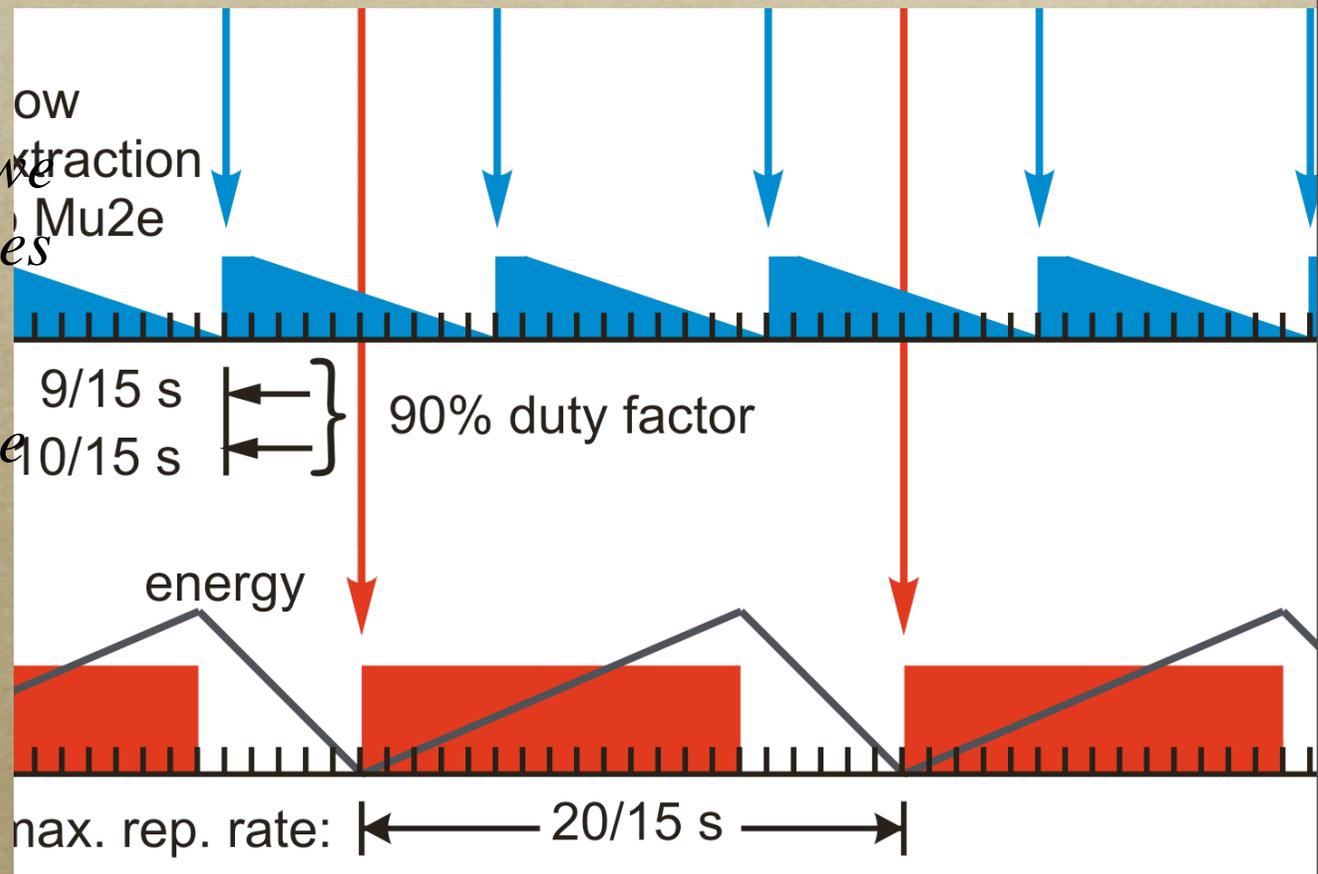
○ *Same fill scenario; IF we can “spill” over 4 cycles rather than 9, then,*

○ *4/5 = 80% duty cycle*

○ *36 Tp/sec (ave.)*

○ *45 Tp/sec (spill)*

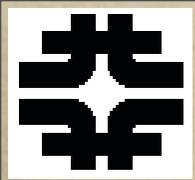
○ *7.7x10⁷ per “burst”*



R. Bernstein, FNAL

MJS / Fermilab

Mu2e U. Chicago 5/17/10



When NOvA is “off”

○ *If have all Booster Cycles available for use in Mu2e:*

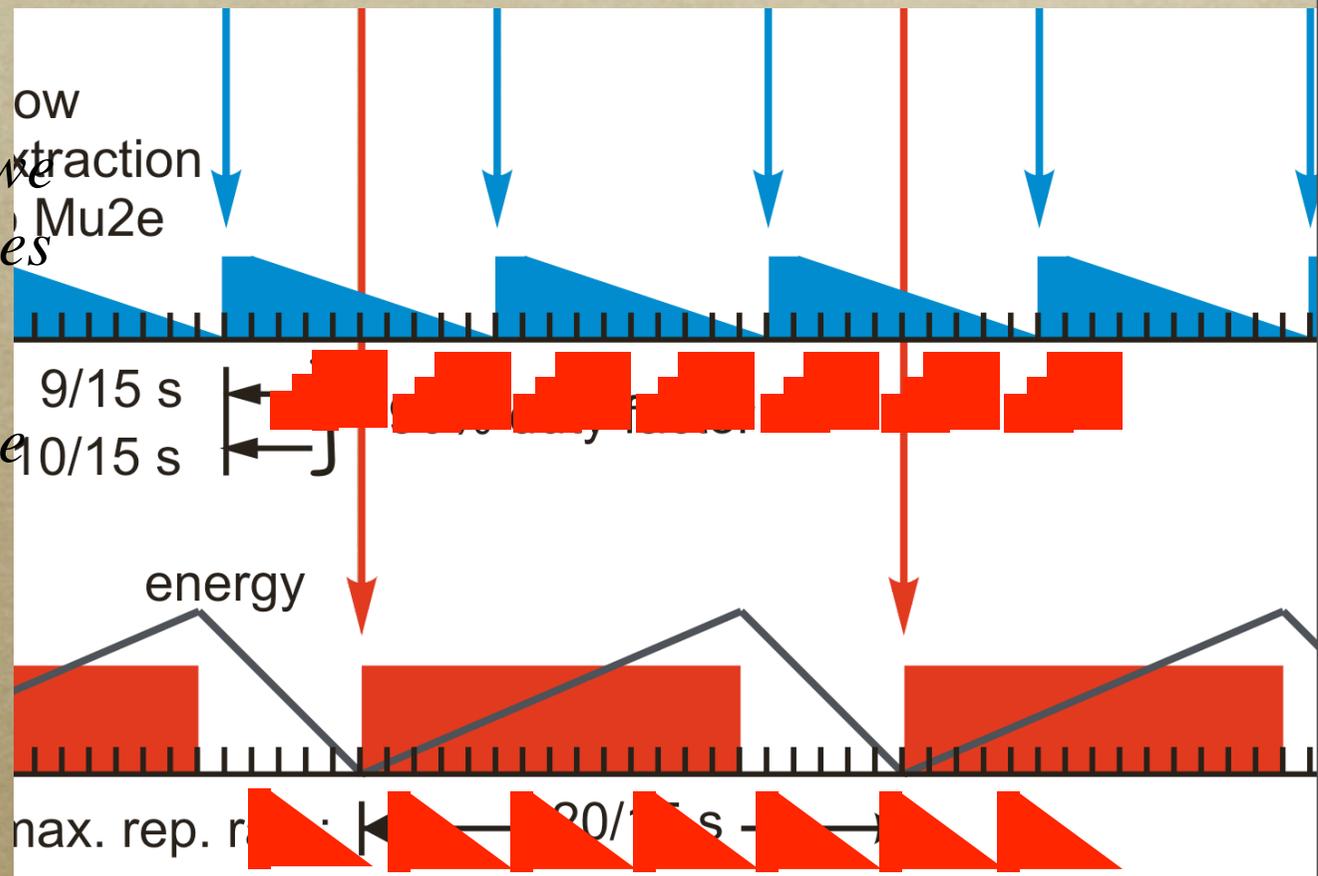
○ *Same fill scenario; IF we can “spill” over 4 cycles rather than 9, then,*

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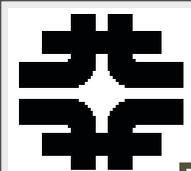
○ *7.7x10⁷ per “burst”*



Mu2e U. Chicago 5/17/10

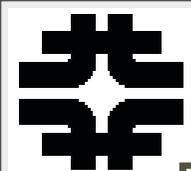
R. Bernstein, FNAL

MJS / Fermilab



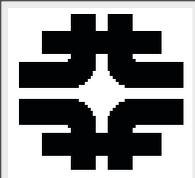
Better than MECO because of better beam structure

| | MECO | Mu2e Booster | Mu2e Project X, no expt. upgrade | Mu2e Project X, expt. upgrade |
|---|------------------------------------|---------------------------|----------------------------------|-------------------------------|
| protons/sec | 40x10 ¹² (design) | 18x10 ¹² | 70x10 ¹² | 160x10 ¹² |
| average beam power | 50 kW (design) | 23 kW | 90 kW | 200 kW |
| duty factor | 0.5 s on, 0.5 s off, 50% | 75-90% | 75-90% | 75-90% |
| instantaneous rate | 80x10¹² (design) | 20x10¹² | 77x10¹² | 220x10 ¹² |
| short term beam power | 100 kW (design) | 25 kW | 100 kW | 220 kW |
| Beam pulse period, μ sec | 1.35 | 1.65 | 1.65 | 1.65 |
| Data collection time interval μ sec | 0.7-1.35 | 0.7-1.65 | 0.7-1.65 | 0.7-1.65 |

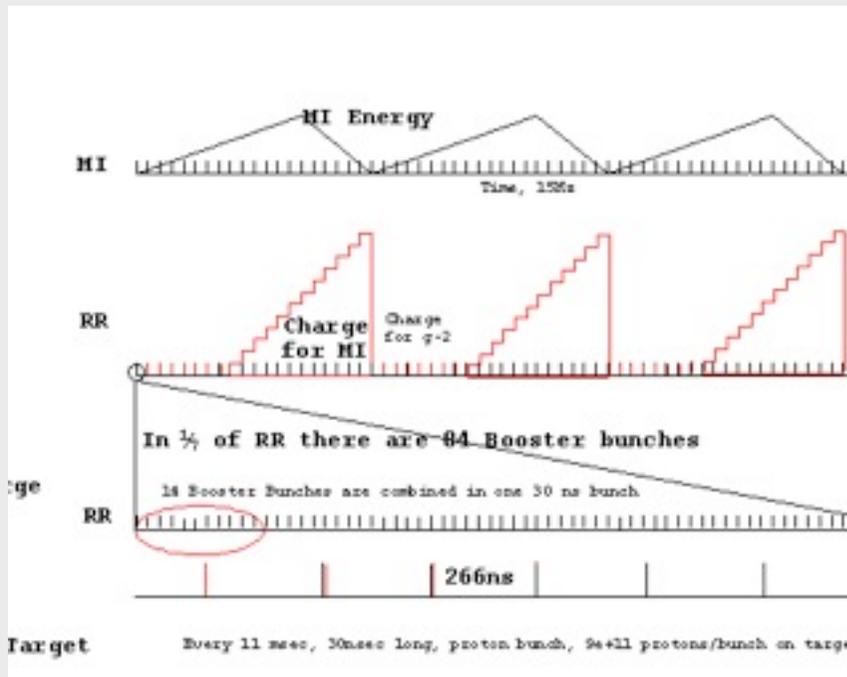
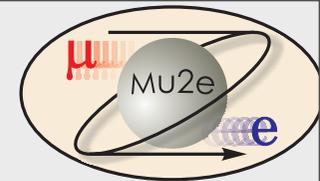


Better than MECO because of better beam structure
 if MECO could handle rates, Mu2e at FNAL can as well:
 pre-project X or with Project X

| | MECO | Mu2e Booster | Mu2e Project X, no expt. upgrade | Mu2e Project X, expt. upgrade |
|---|------------------------------------|---------------------------|----------------------------------|-------------------------------|
| protons/sec | 40x10 ¹² (design) | 18x10 ¹² | 70x10 ¹² | 160x10 ¹² |
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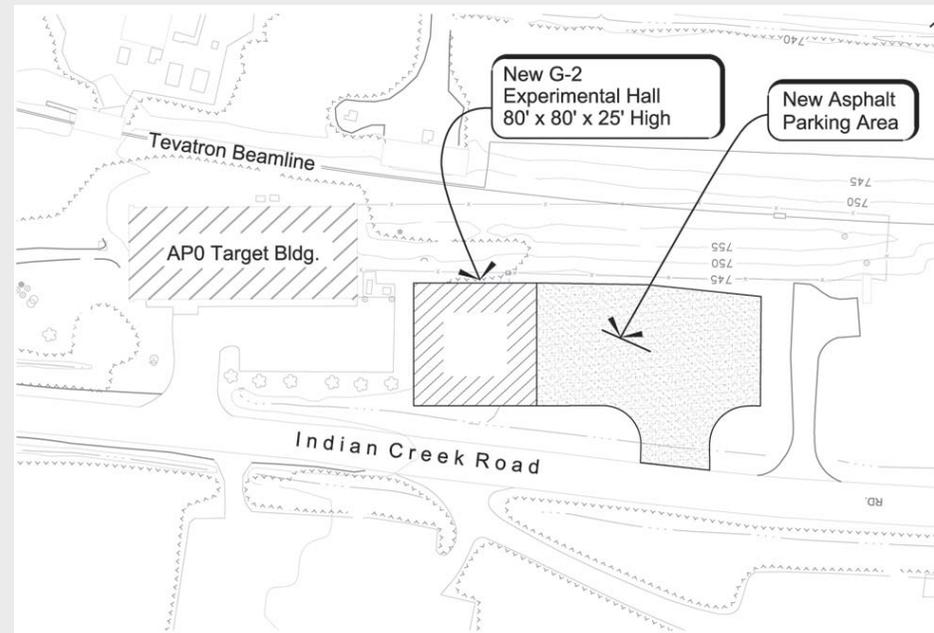
Possible Beam Scheme

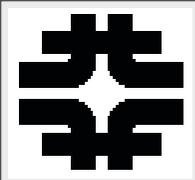


- use Accumulator/Debuncher to produce correct time structure
- house in new building near AP0
- runs *before* Mu2e

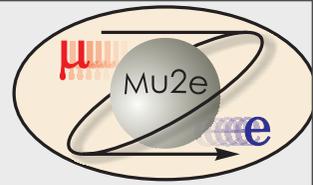
- move BNL ring to FNAL
- upgrade RF in Accumulator/Debuncher
- cost and schedule work begun

R. Bernstein, FNAL

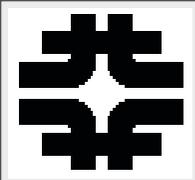




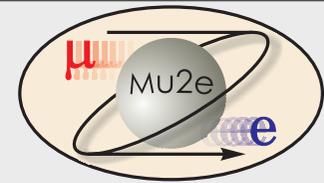
Z-Dependence



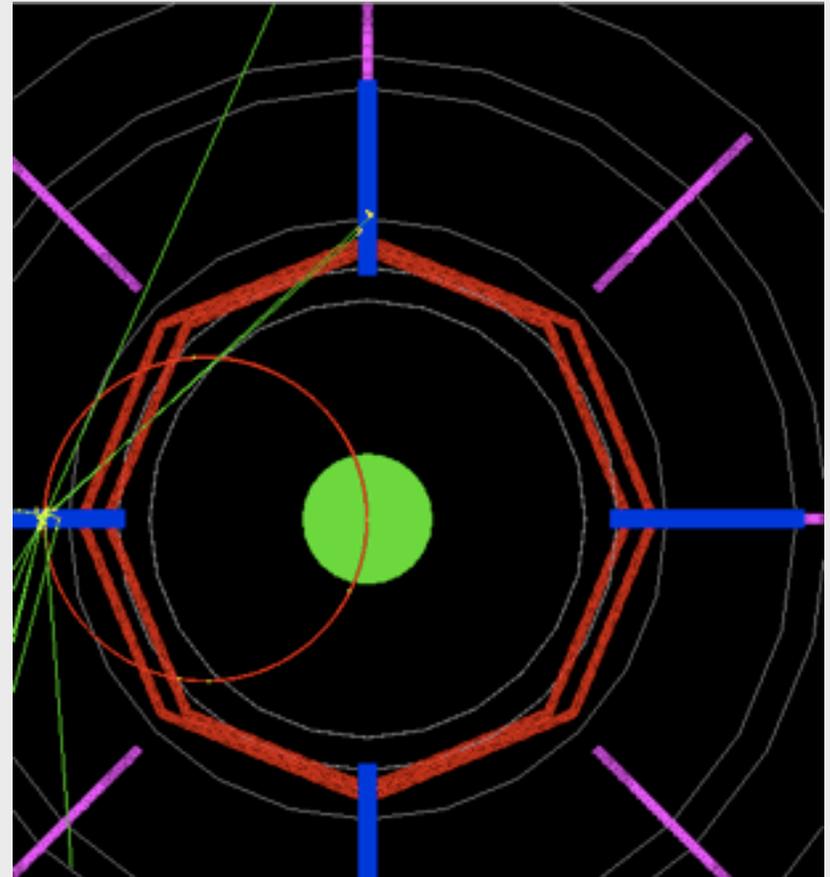
- For a small nucleus compared to the extent of the muon wf, the Schroedinger equation gives hydrogenic wavefunctions which scale like Z^{**3} at small radius. There are Z protons in the nucleus, so the probability of ordinary capture goes like Z^{**4} .
- For a conversion process, the cross section is coherent and therefore goes like Z^{**2} (or A^{**2}) rather than Z in the case of ordinary capture. So overall the process goes like Z^{**5} . Strictly speaking this overlap argument only works well for short-range forces like the weak force, since we assume that the probability of reaction is proportional to the overlap between the nuclear and the muon wavefunctions. For the EM force it will not work as well.
- Therefore $R_{\mu e}$ is proportional to $Z^5/Z^4 = Z$ for small Z .
- As Z increases, the finite size of the nucleus becomes important. The muon wavefunction is inside the nucleus and does not see the full Z , reducing the wavefunction overlap. Also, there are relativistic effects which reduce the Z dependence, and a few other effects.

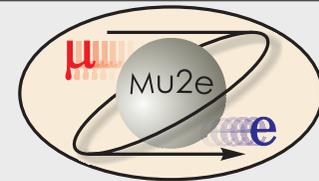
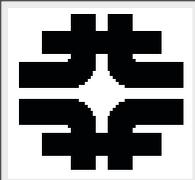


Software Needs



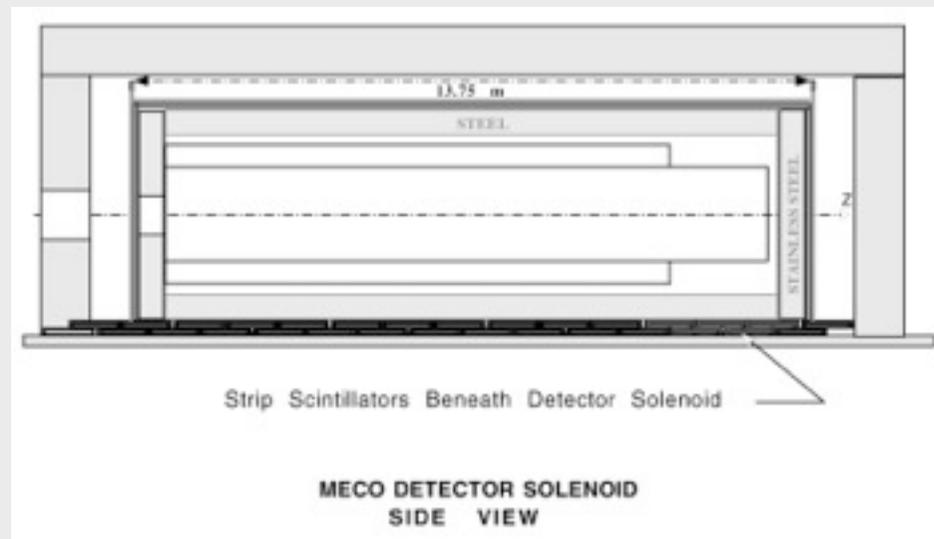
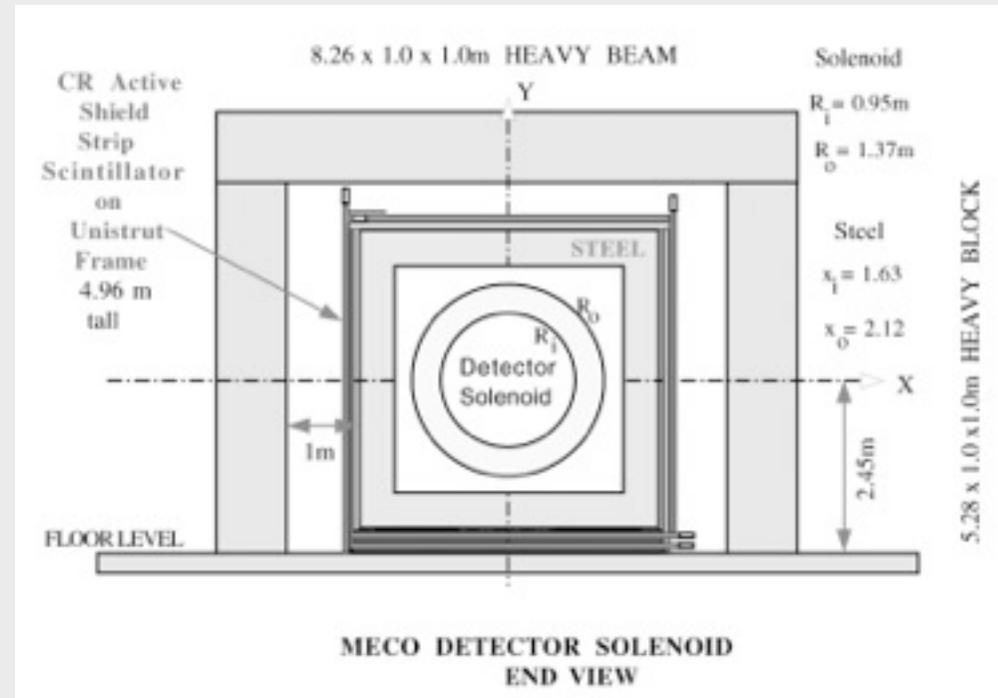
- primitive GEANT4 simulation begun
- old MC is GEANT3/FORTRAN/PAW
 - not unified, lots of different standalone codes that are not available or documented
- cannot do simple calculations to check MECO or improve design
- ***no hit-level MC ever written-- not acceptable for 10^{-17} experiment, and MECO reviews zeroed in on that***
- need software framework and infrastructure, best supplied and maintained by professionals in CD

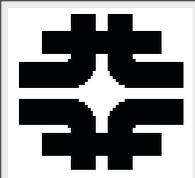




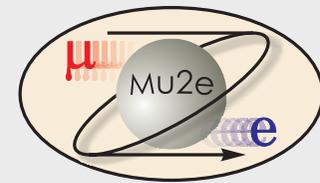
Cosmic Rays and Veto

- Cosmic ray (CR) induced electrons (or muons mistaken as electrons) may induce backgrounds.
- Both steel (also return yoke of iron) and concrete
- Three-Layer Veto of MINOS-type scintillator
- Mu2e is re-examining scintillator, and planning on placing solenoid below ground (MECO at ground-level)

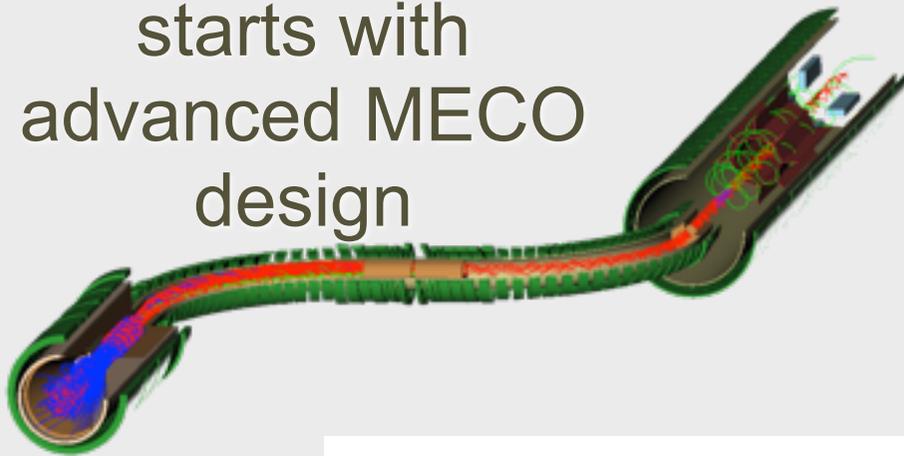




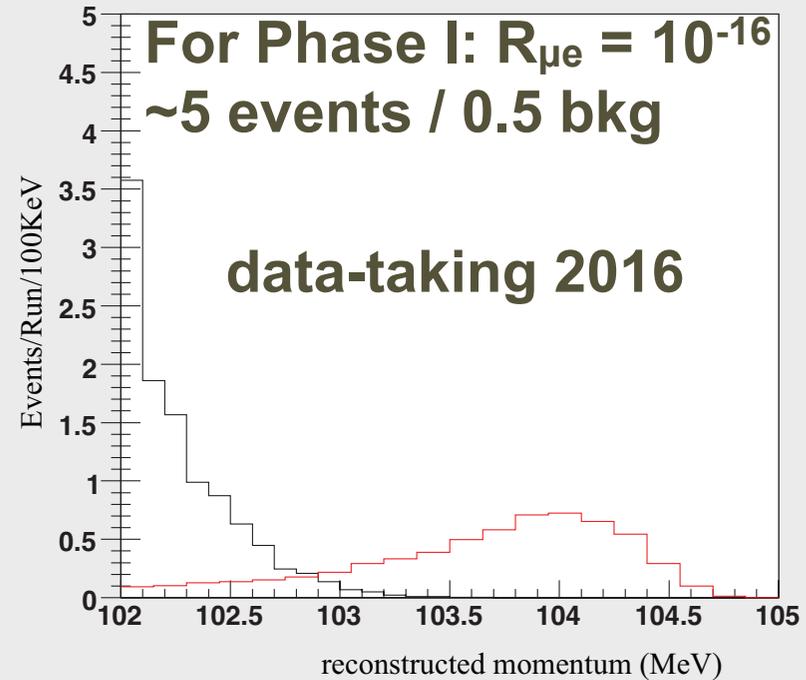
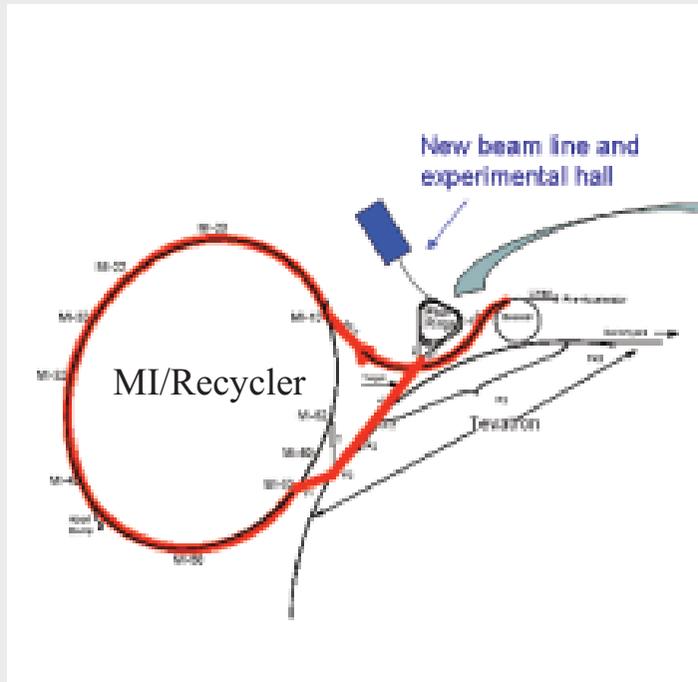
Mu2e: Muon-Electron Conversion at Fermilab



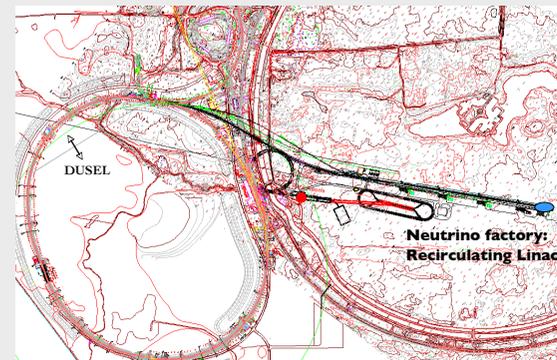
starts with advanced MECO design



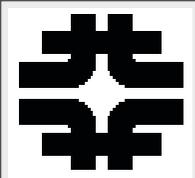
uses existing rings with minor changes: no effect on NOvA



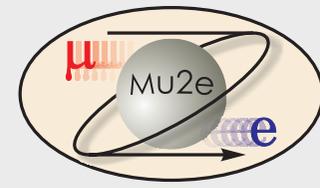
$R_{\mu e} \sim 10^{-18}$ at Project X



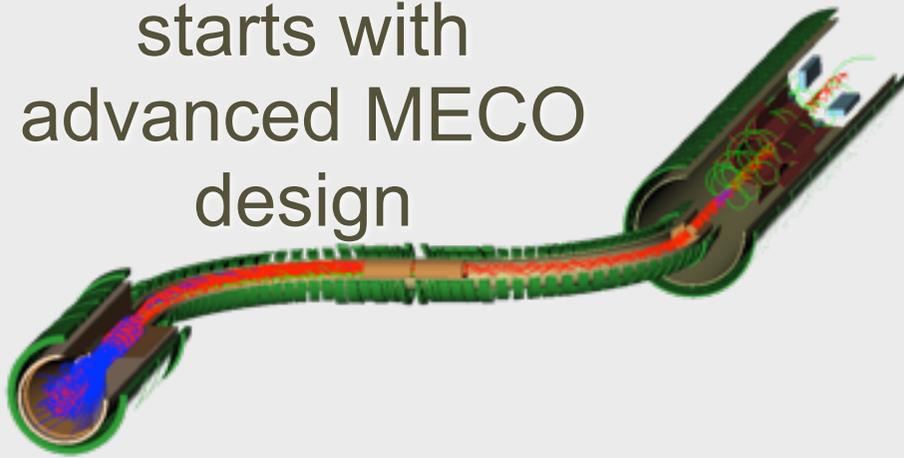
DUSEL,
kaons,
g-2,...



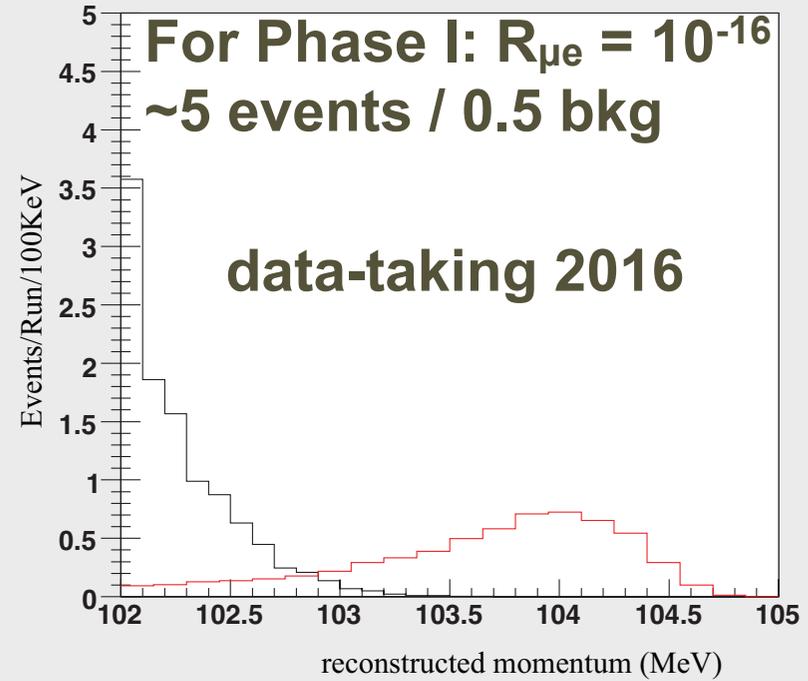
Mu2e: Muon-Electron Conversion at Fermilab



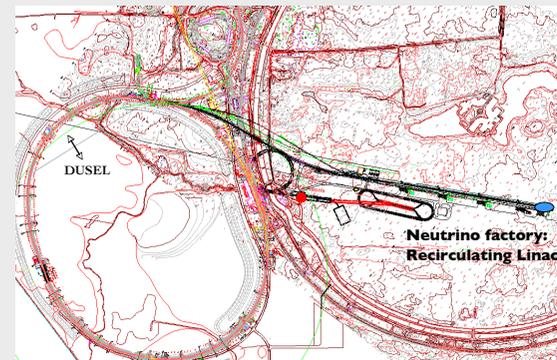
starts with advanced MECO design



uses existing rings with minor changes: no effect on NOvA



$R_{\mu e} \sim 10^{-18}$ at Project X

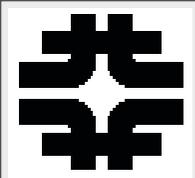


DUSEL, kaons, g-2, ...

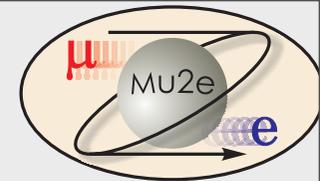
R. Bernstein, FNAL

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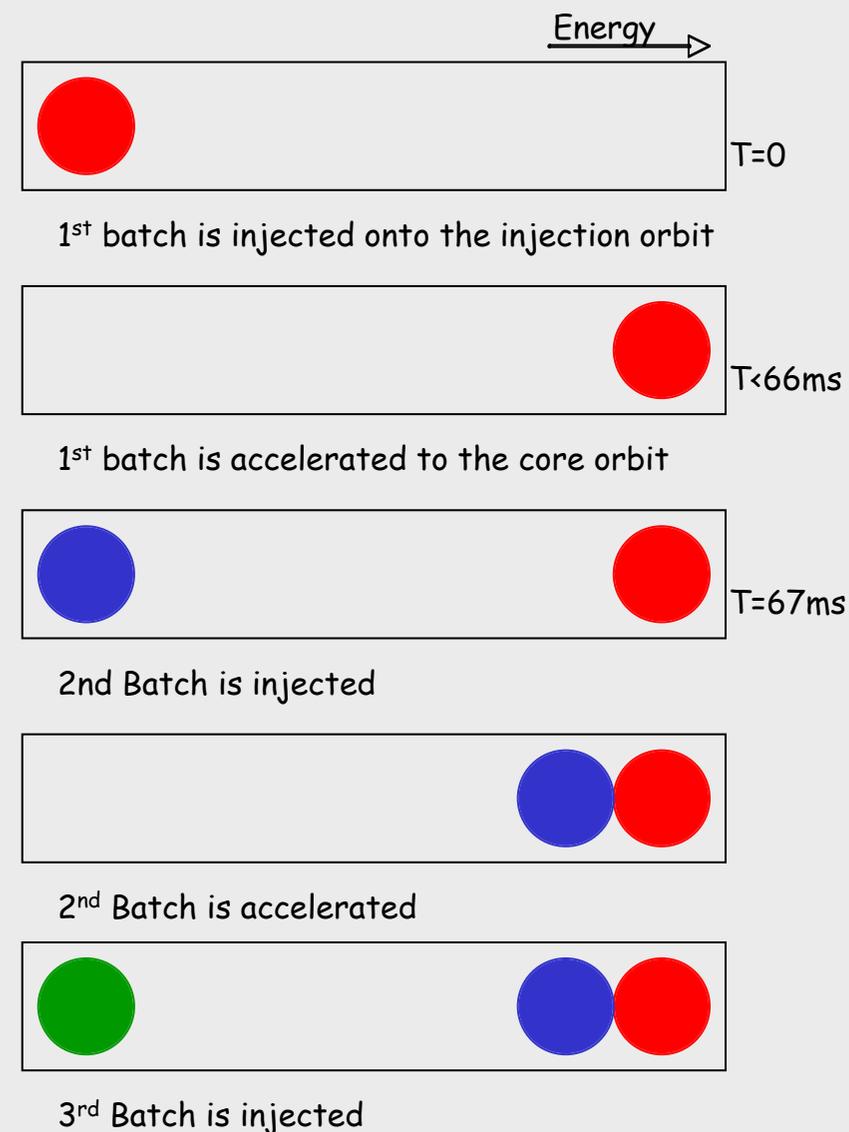
Mu2e U. Chicago 5/17/10

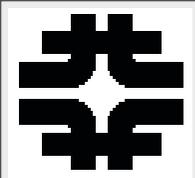


Quick Fermilab Glossary

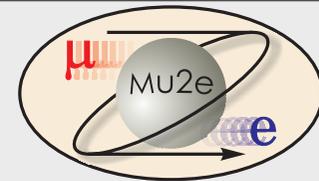


- Booster:
 - The Booster accelerates protons from the 400 MeV Linac to 8 GeV
- Accumulator:
 - momentum stacking successive pulses of antiprotons now, 8 GeV protons later
- Debuncher:
 - smooths out bunch structure to stack more \bar{p} now; rebunch for mu2e
- Recycler:
 - holds more \bar{p} than Accumulator can manage, "store" here



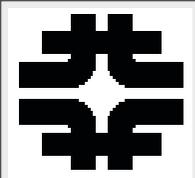


Rates In Tracker

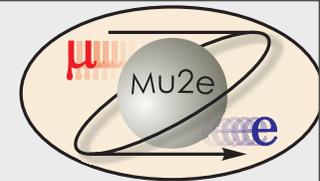


- Rates at Beginning of > 700 nsec Live Window, so these are highest
- ≈ 2 hits per straw during beam flash
- Rates are manageable: (1/4 of MECO instantaneous)

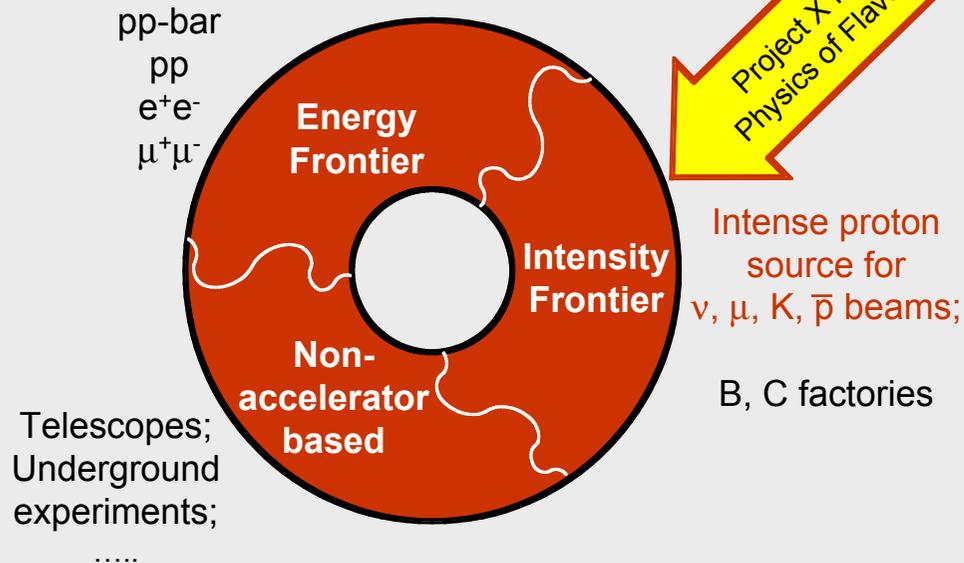
| Type | Rate(Hz) | \mathcal{P} hit | Mean N hits/bkg part | R_{wire} (kHz) |
|--------------------|-----------------------|-----------------------|----------------------|-------------------------|
| e_t | 0.62×10^{11} | 0.00032 | 1.54 | 16.3 |
| n_t | 0.62×10^{11} | 0.000142 | 2.887 | 12 |
| γ_t | 0.62×10^{11} | 0.000248 | 4.524 | 33.4 |
| p_t | 4.5×10^9 | 0.00362 | 6.263 | 50. |
| $e(DIO)_t < 55$ | 0.2×10^{11} | 9.8×10^{-5} | 1.44 | 1.4 |
| $e(DIO)_t > 55$ | 0.5×10^8 | 0.00127 | 22.7 | 0.5 |
| n_{bd} | 0.12×10^{11} | 7.1×10^{-5} | 5.0 | 1.5 |
| γ_{bd} | 0.12×10^{11} | 8.3×10^{-5} | 4.5 | 1.5 |
| $e(DIO)_{bd} < 55$ | 0.5×10^{11} | 8.9×10^{-5} | 1. | 1.65 |
| $e(DIO)_{bd} > 55$ | 1.4×10^8 | 1.82×10^{-4} | 1.5 | 0.0125 |
| $e(DIF)$ | 0.69×10^6 | 1 | 35.84 | 8.6 |
| total | | | | 116 |



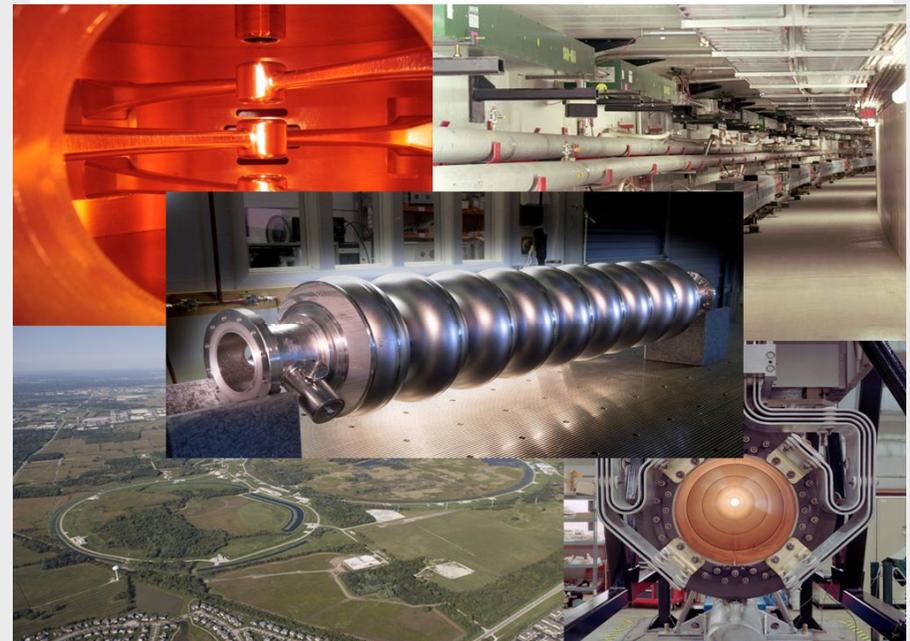
Why Project X?



Tools for Particle Physics

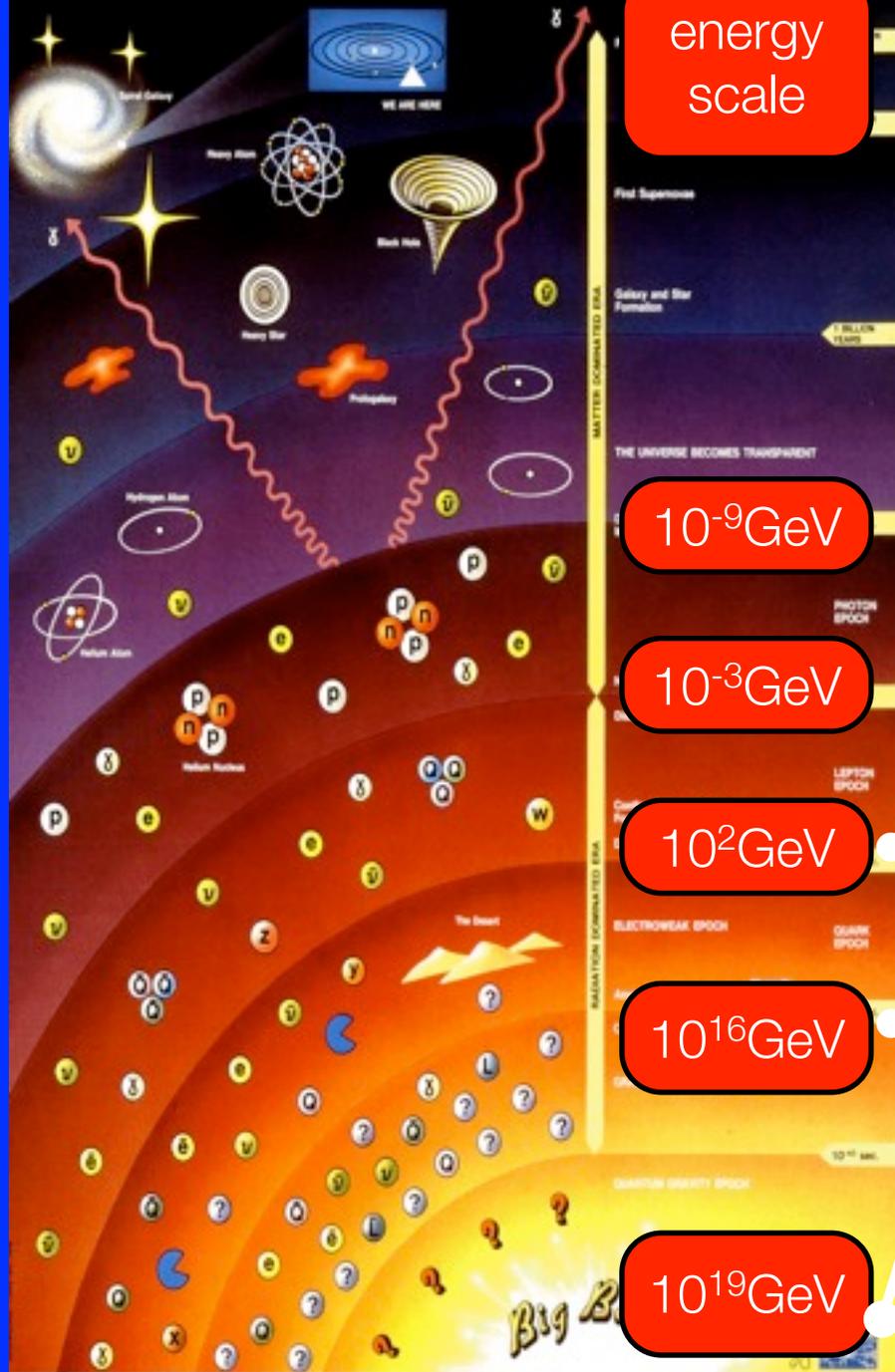


Project X



- FNAL Booster cannot provide sufficient intensity for the Intensity Frontier Program: neutrinos, muons, kaons,...

History of the Universe



Electroweak Epoch

Higgs particles

Supersymmetry

Unification Epoch

Grand unification of fundamental forces

Origin of Neutrino mass

Leptogenesis (baryogenesis)

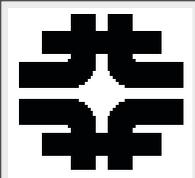
Quantum Gravity Epoch

Superstrings

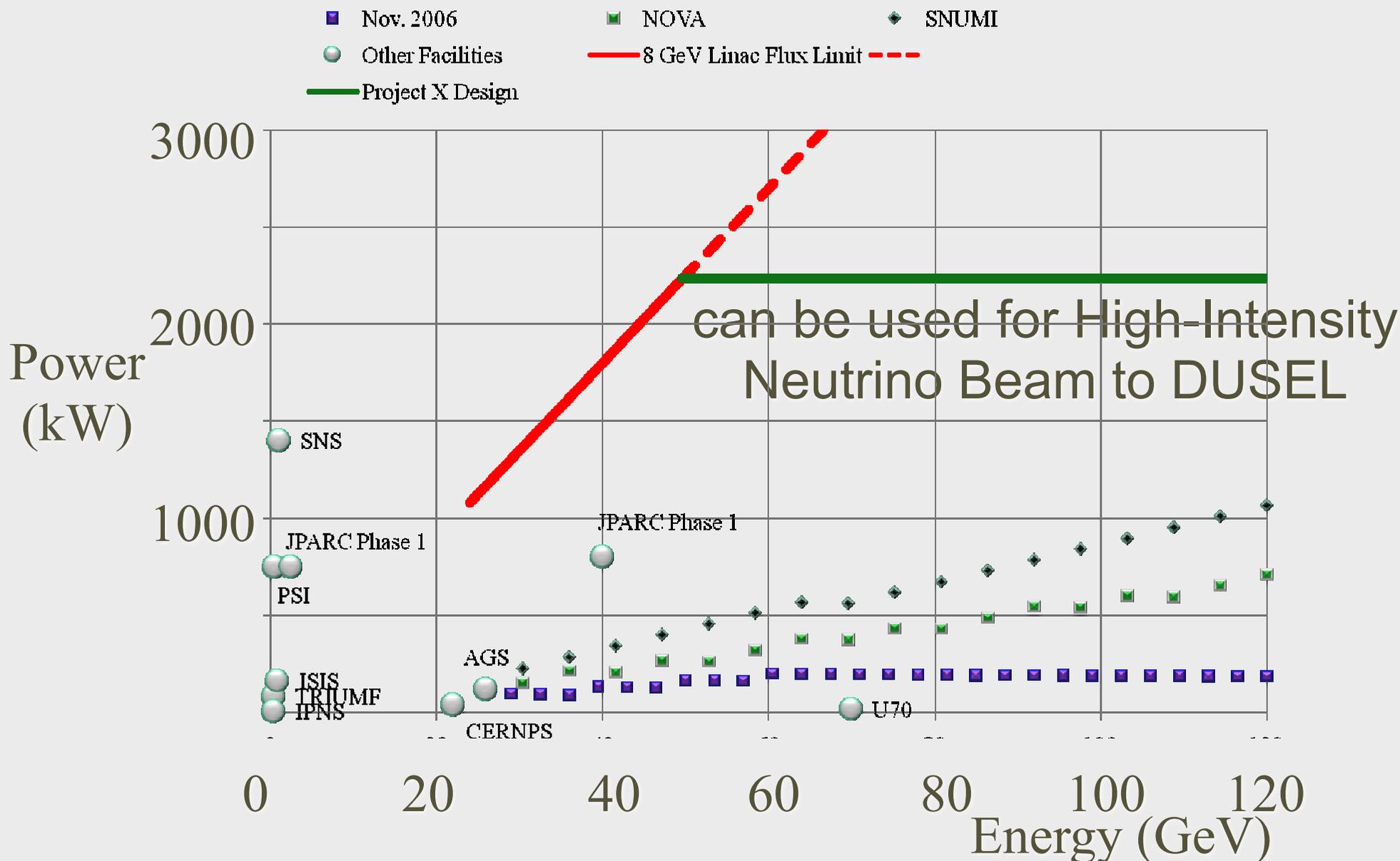
Nucleon decays

Neutrino physics

Lepton Flavor Violation



Project X Intensity Goals



R. Bernstein, FNAL

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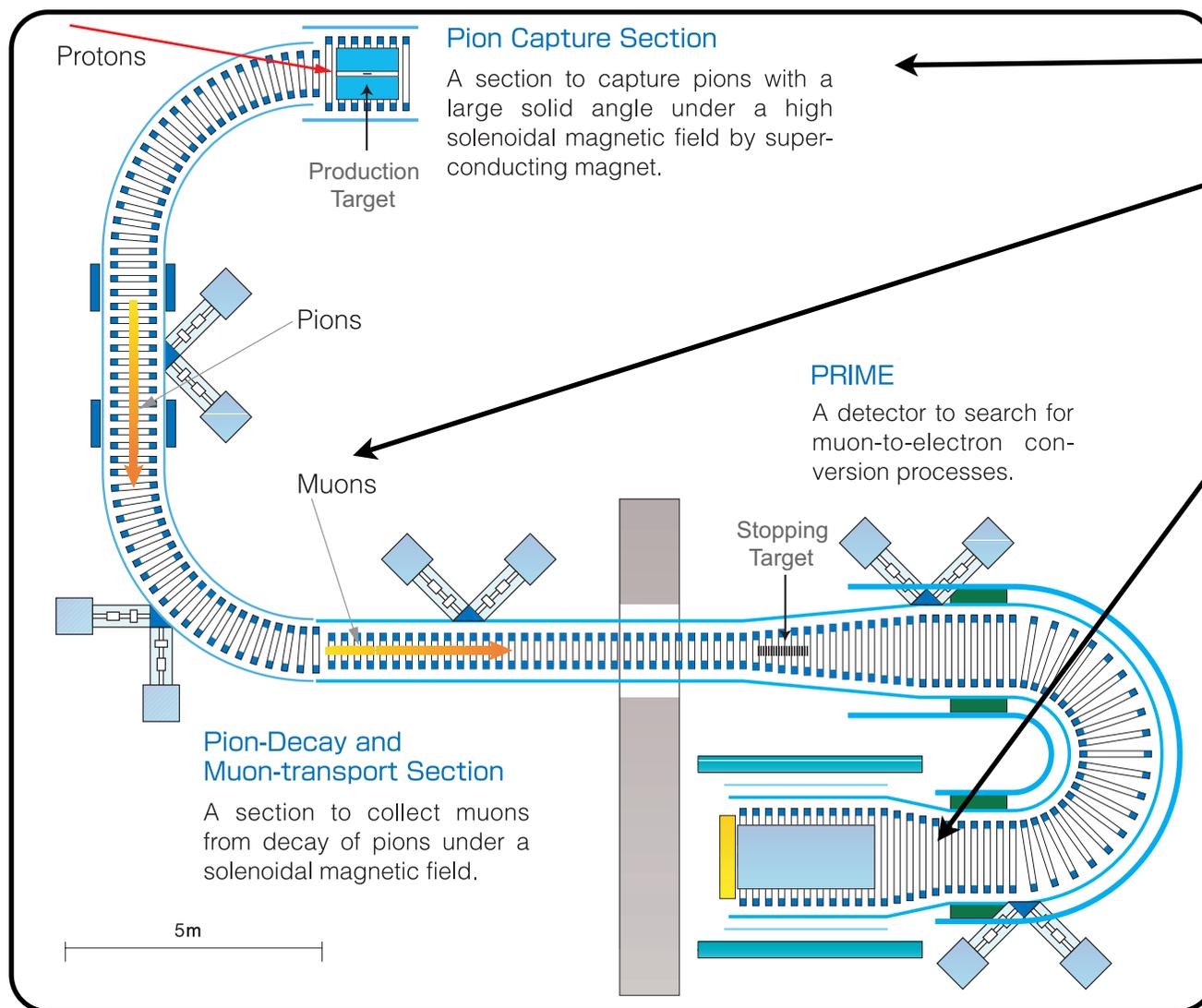
Mu2e

U. Chicago 5/17/10

COMET (COherent Muon to Electron Transition) in J-PARC (Japan)

from Y. Kuno

$$B(\mu^- + Al \rightarrow e^- + Al) < 10^{-16}$$



Proton Beam

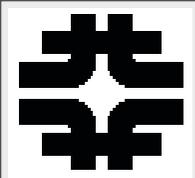
The Muon Source

- Proton Target
- Pion Capture
- Muon Transport

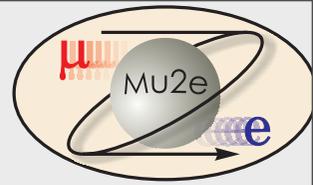
The Detector

- Muon Stopping Target

proposed to
J-PARC

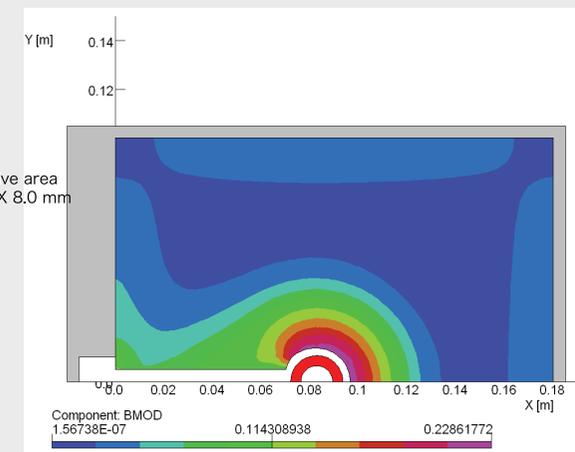
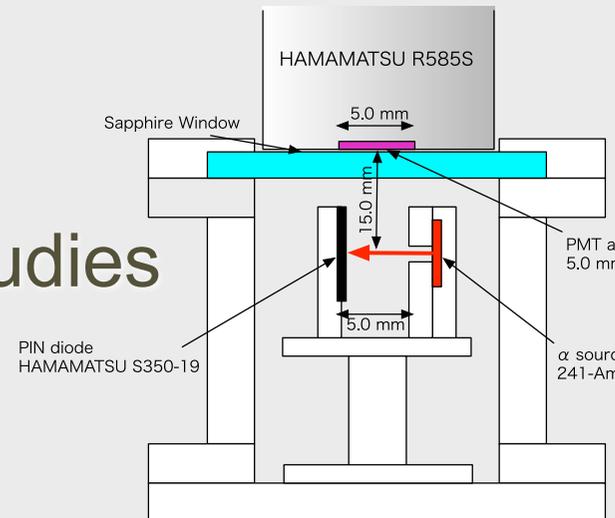
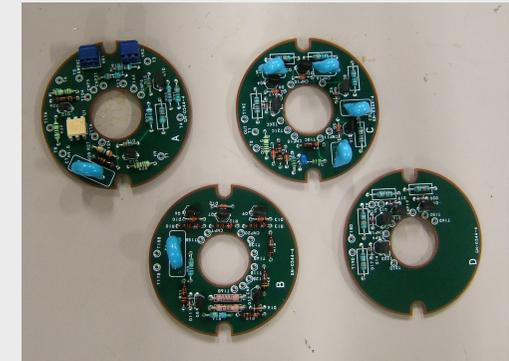
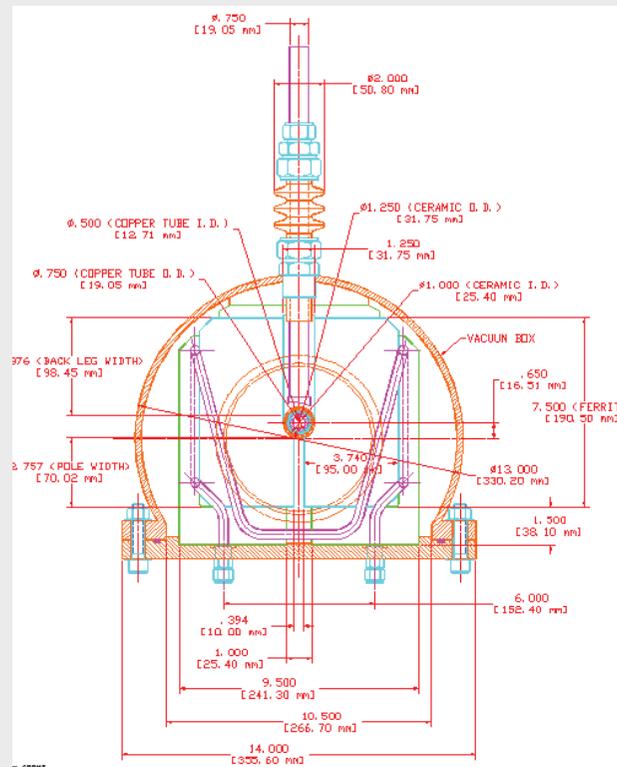


Collaboration with Japan



- COMET/Mu2e are collaborating on
 - AC Dipole (FNAL)
 - Extinction Monitor (Osaka)
- US-Japan Agreement
 - KEK/FNAL
- ~\$50K this year for studies
- **THANKS!**

• **Critical For Progress!**

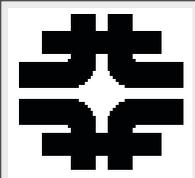


R. Bernstein, FNAL

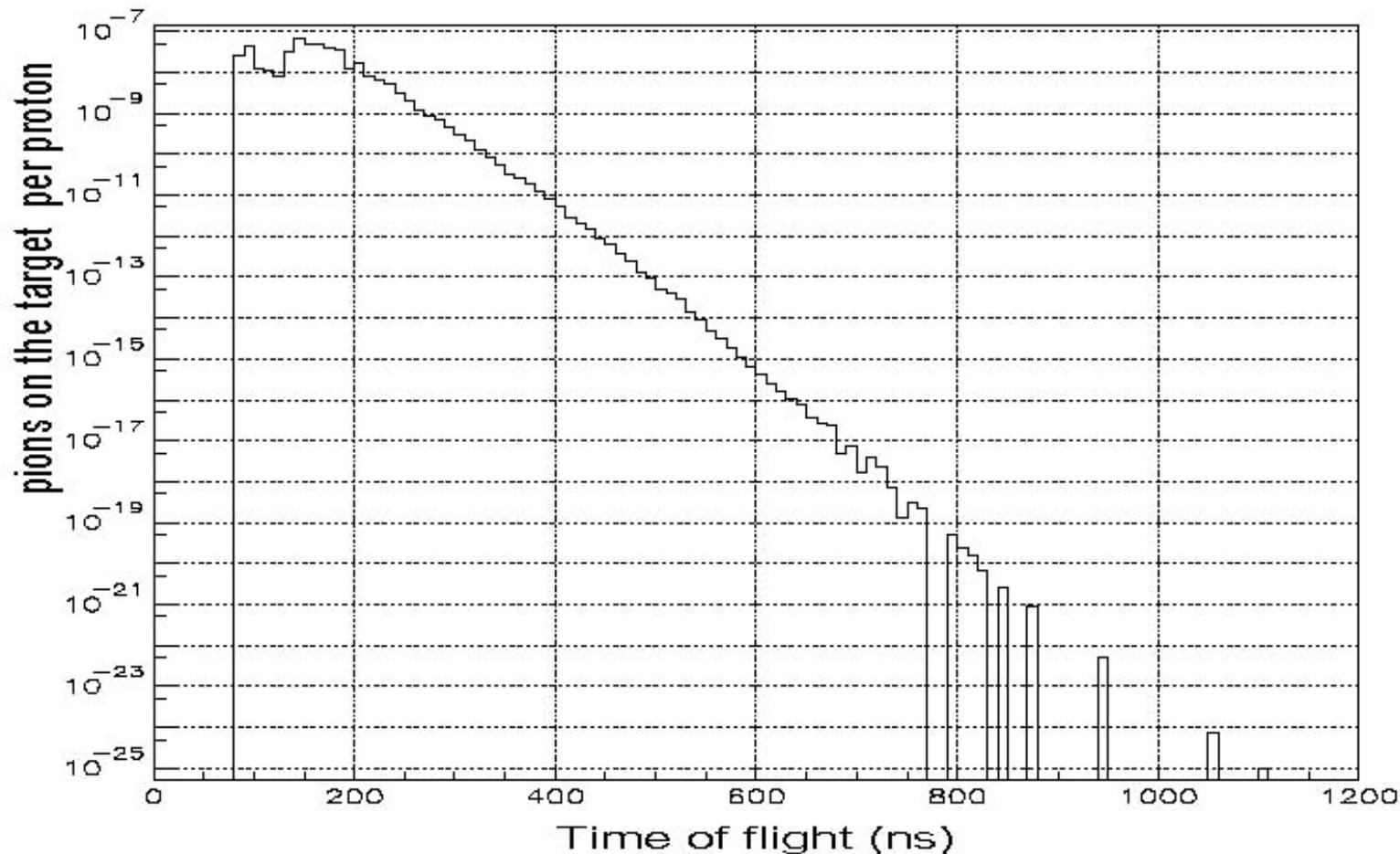
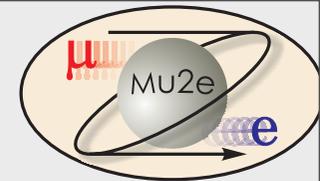
113

Mu2e

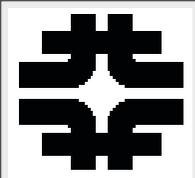
U. Chicago 5/17/10



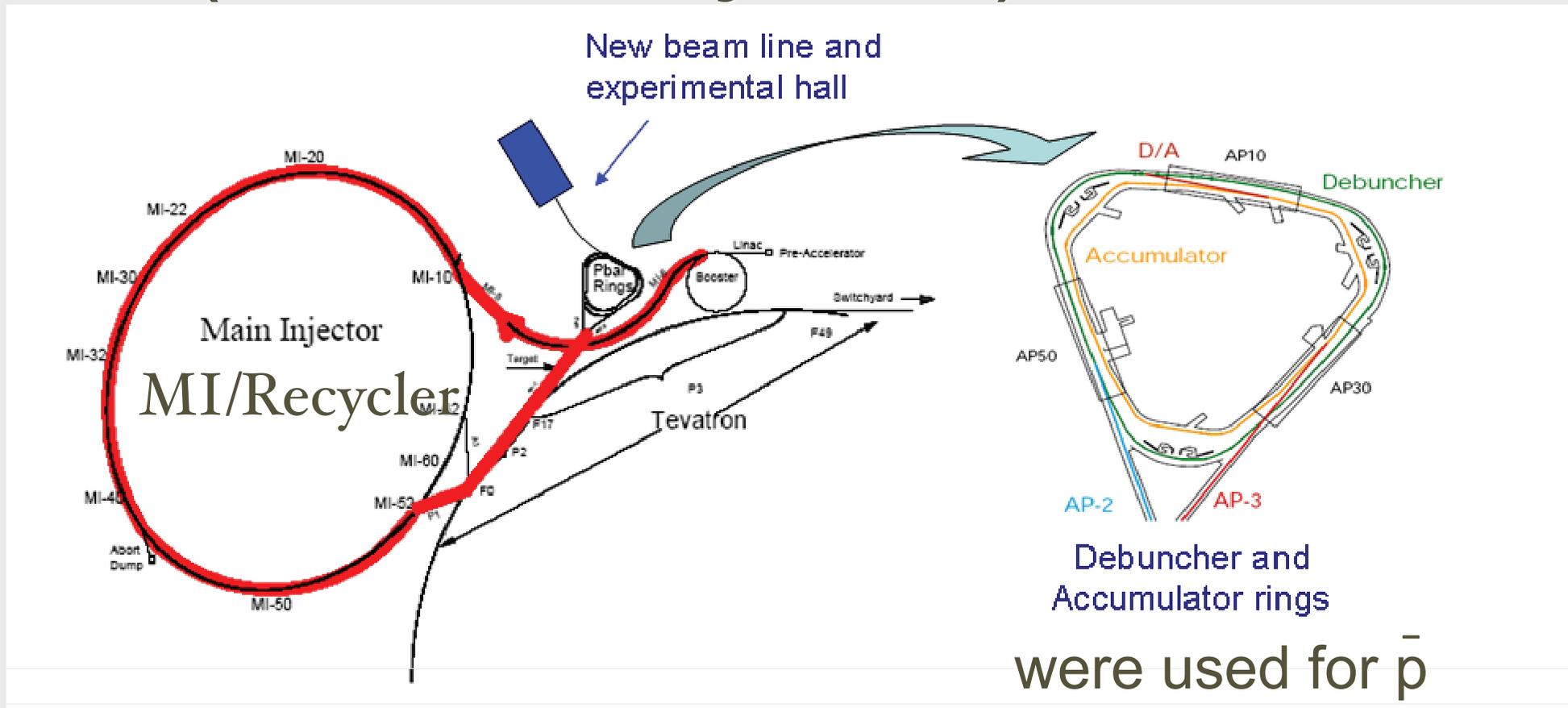
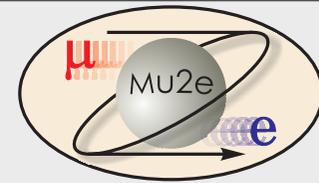
Radiative π and Pulsed Beam



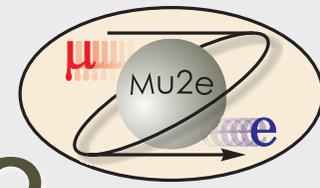
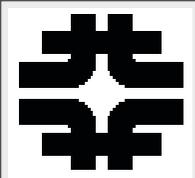
- waiting 700 nsec suppresses by 10^{11}



Booster-Era (before Project X) Beam



- After Tevatron shut-down, Accumulator, Debuncher, and Recycler no longer needed for antiprotons



Why Normalize to Capture?

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A, Z) \rightarrow e^- + (A, Z))}{\Gamma(\mu^- + (A, Z) \rightarrow \nu_\mu + (A, Z - 1))}$$

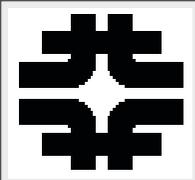
Al turns into Mg

- As muon cascades to 1s, X-rays give stop rate

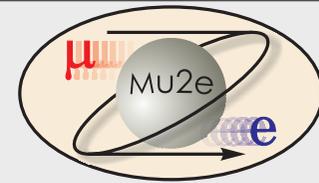
- and Mg \rightarrow Al yields a 2.6 MeV β followed by γ that can be used to measure capture rate

1. μ^- emits ν
2. Al turns into Mg

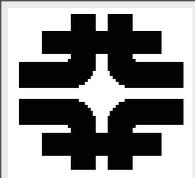
NORMALIZATION



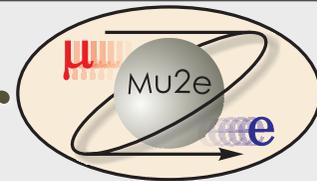
L-Tracker vs. T-Tracker



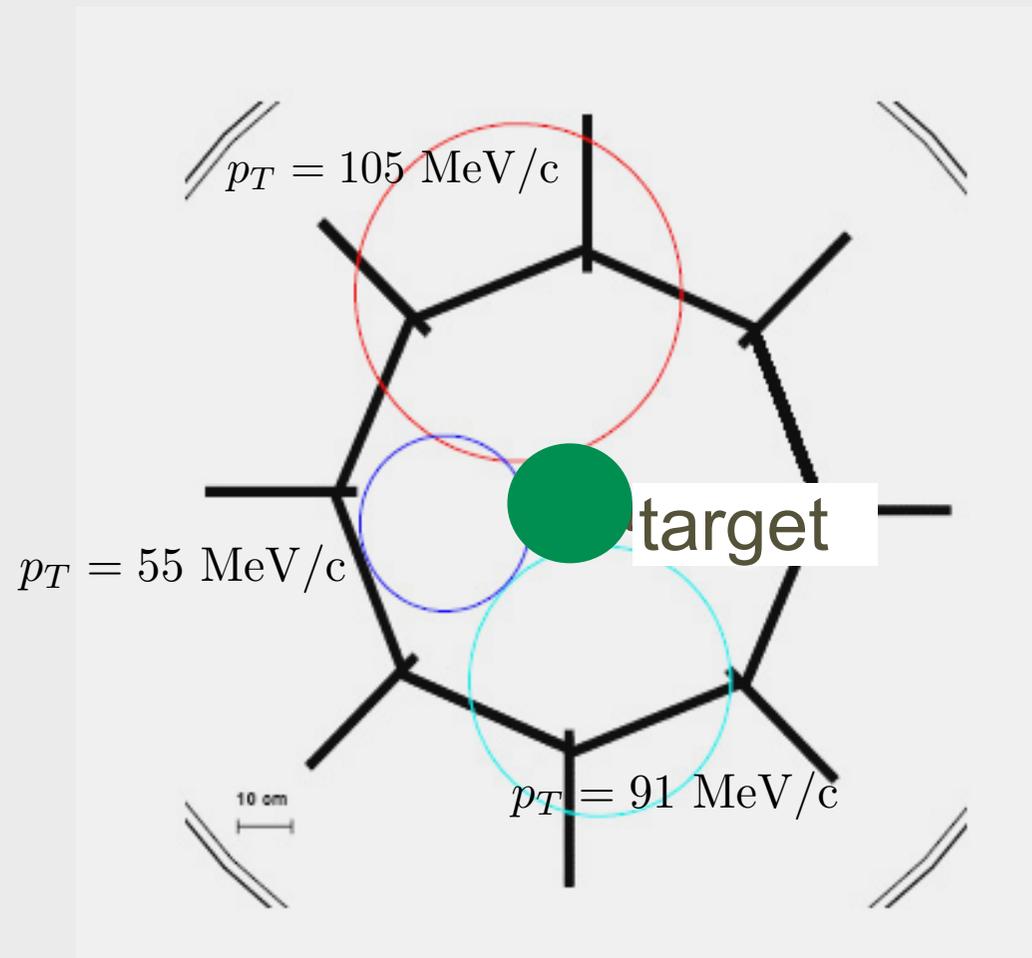
- L-Tracker: straws along beam
 - Conceptually simpler tracking
 - Basis of MECO
 - Where does support/infrastructure go? Material in electron path
 - Can anyone build straws 0.5 cm × 2.6m in vacuum?
- T-Tracker: straws perp to beam
 - More prone to pattern recognition errors?
 - **Active Investigation:**
 - **kalman filter, applied to both on same events**
 - **work just beginning**
 - **help welcome!**

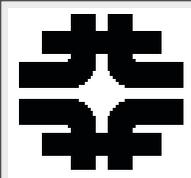


Beam's Eye View of Tracker

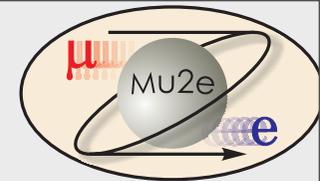


- Octagon and Vanes of Straw Tubes
- Immersed in solenoidal field
- Below $p_T = 55$ MeV, electron stays inside tracker and is not seen; about 60° at 103.5 MeV
- Looking for helix as particle propagates downstream





AC-Dipole R&D



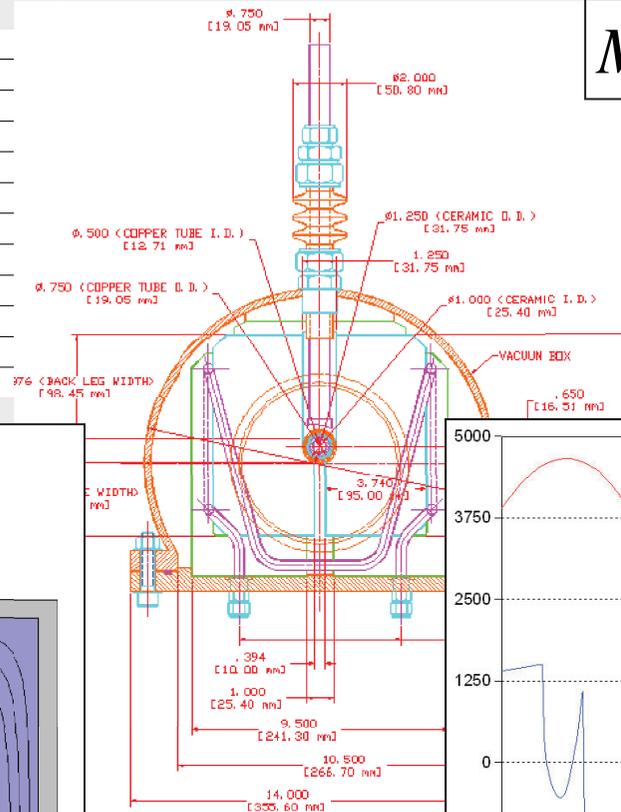
Conceptual Design of AC Dipole Magnet for μ to e^- Experiment

V.S. Kashikhin, D. Harding, V. V. Kashikhin, A. Makarov, D. Wolff Fermilab

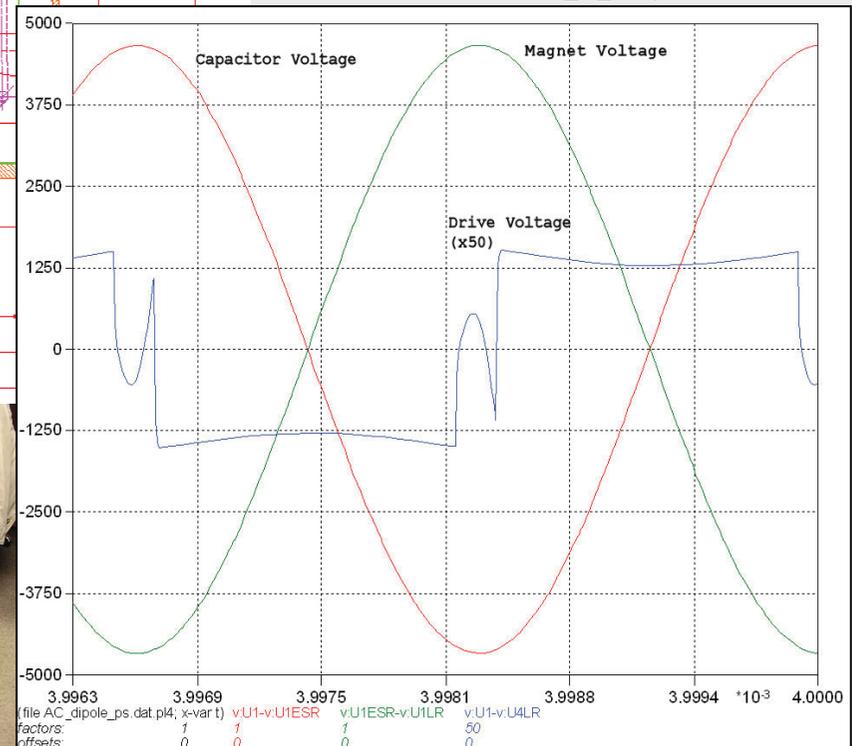
Table I. AC Dipole specification.

| Parameter | Unit | Value |
|-----------------------|------|------------|
| Integrated strength | T-m | 0.12 |
| Magnet gap | mm | 10 |
| Effective length | m | 2.0 |
| Good field area width | mm | 50 |
| Center field | T | 0.06 |
| Current form | | Sine wave |
| Current frequency | kHz | 300 |
| Operational regime | | Continuous |
| Radiation level | | low |

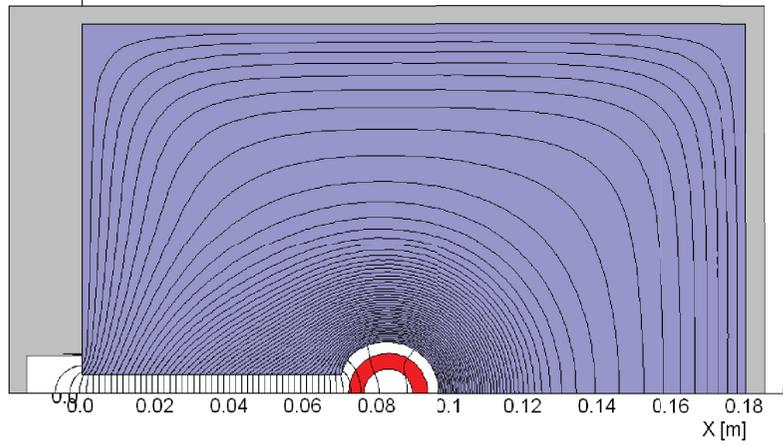
Magnet Design



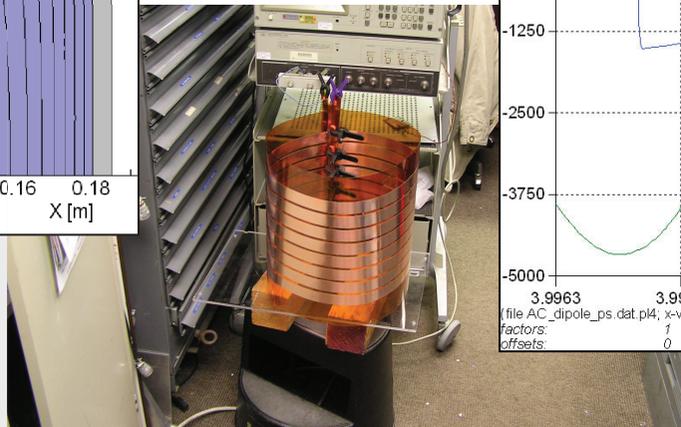
Power Supply Calc

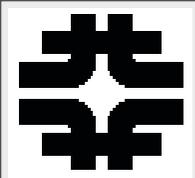


field calculation

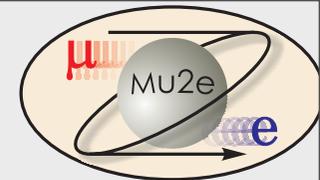


prototype transformer

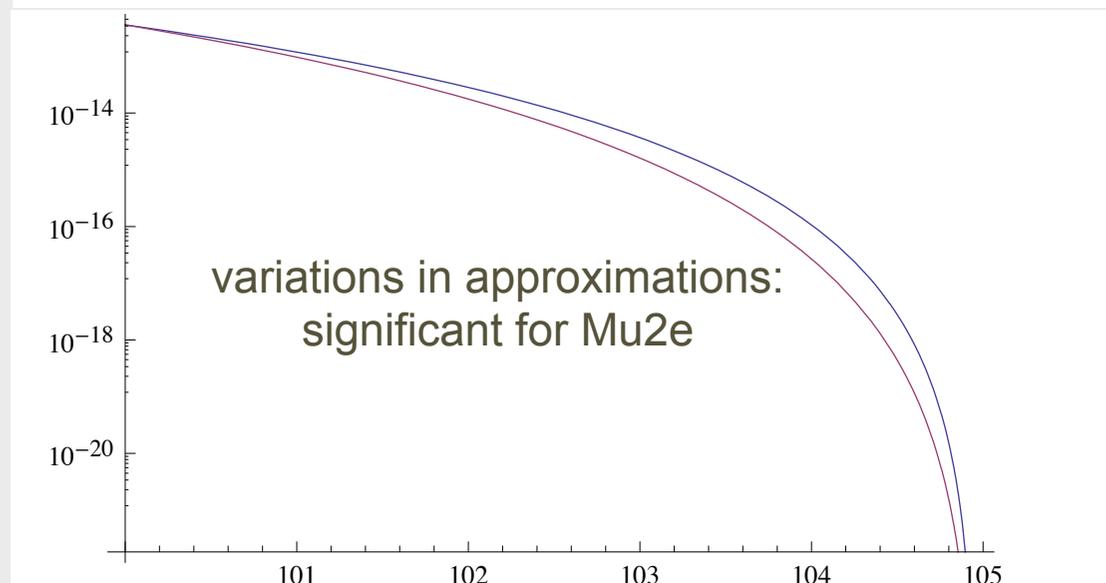
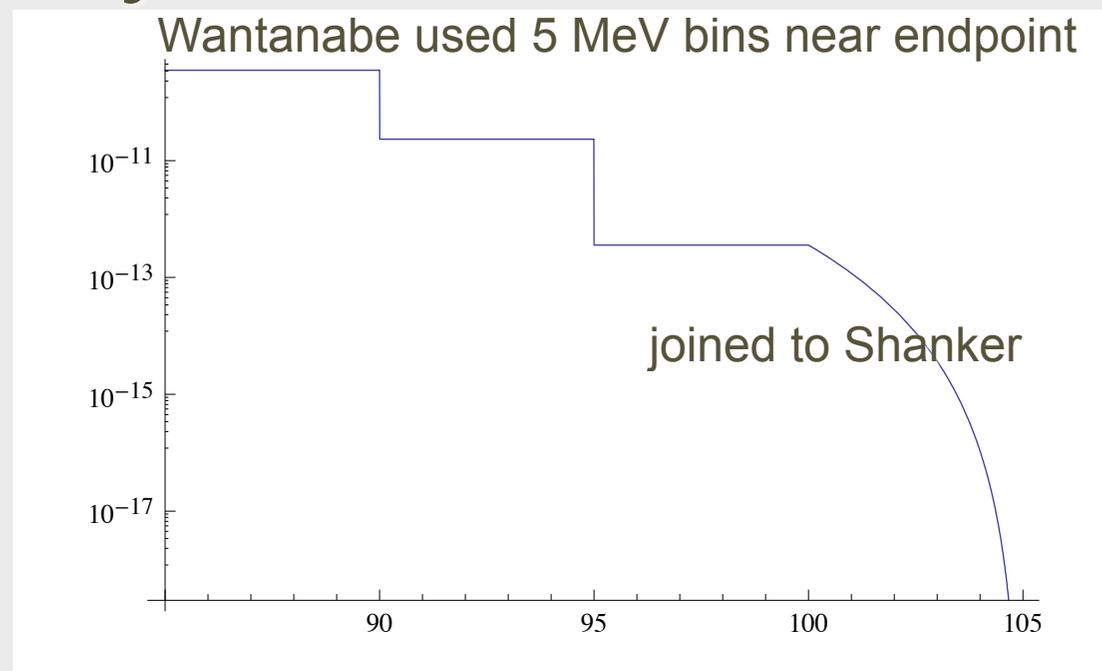




Shape and Normalization of Decay-in-Orbit



- Calculation is not in good enough shape for modern experiments
- Normalization joined by using different papers (Shanker and Wantanabe)
- Don't have exact calculations for Al – or other materials we may choose
- We care! imagine showing result with 25% uncertainty in DIO normalization...
- People in this room will help!

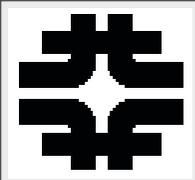


R. Bernstein, FNAL

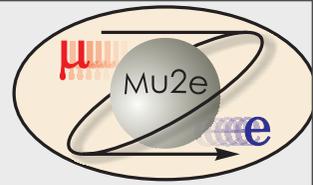
120

Mu2e

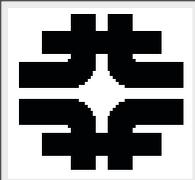
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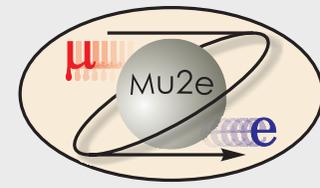
Next Steps:



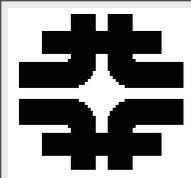
- This is the *beginning* of the process
- Lots of fun, interesting work to do
 - improvements and new work on detector, solenoid, beam
 - will examine every cost in detail
- Perfect time to join and participate!



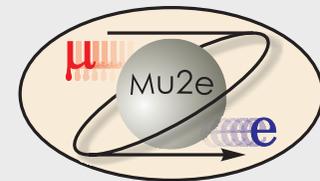
DOE CD Process



Hell:
fresco in
Camposanto



Collaboration



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B.L.Roberts

Idaho State University

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E.C.Dukes, M.Bychkov, E.Frlez,
R.Hirosky, A.Norman, K.Paschke,
D.Pocanic

College of William and Mary

J.Kane

19 institutions

71 collaborators

+ = co-spokespersons

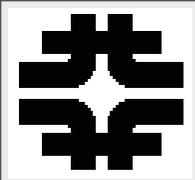
* = applied, not yet admitted

R. Bernstein, FNAL

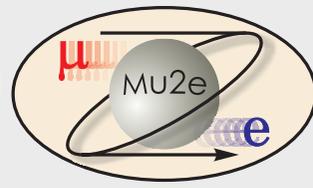
123

Mu2e

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Endorsed in US Roadmap

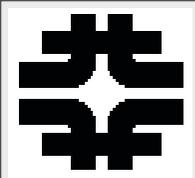


FNAL has proposed muon-electron conversion as a flagship program for the next decade

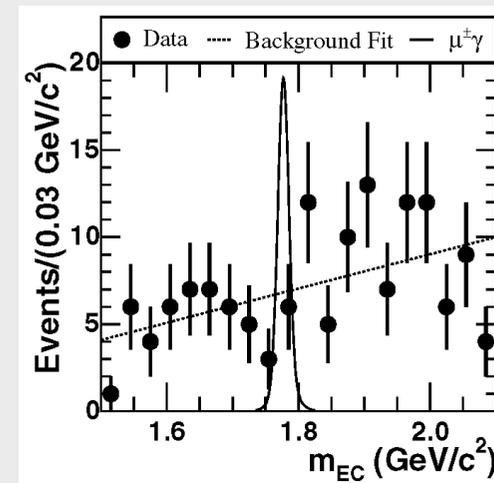
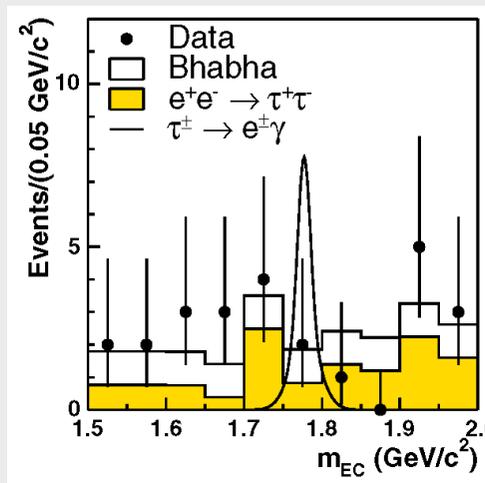
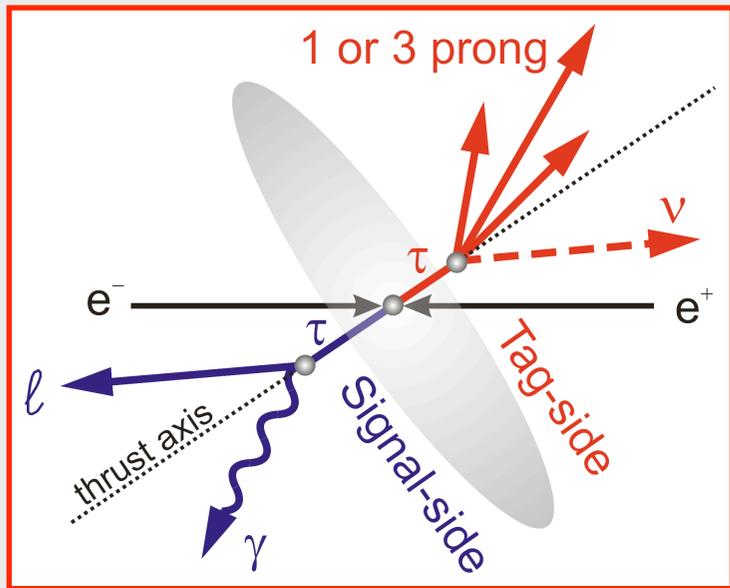
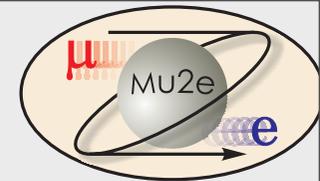
Strongly endorsed by P5:

“The experiment could go forward in the next decade with a modest evolution of the Fermilab accelerator complex. Such an experiment could be the first step in a world-leading muon-decay program eventually driven by a next-generation high-intensity proton source. **The panel recommends pursuing the muon-to-electron conversion experiment... under all budget scenarios considered by the panel**”

Mu2e is a central part of the future US program

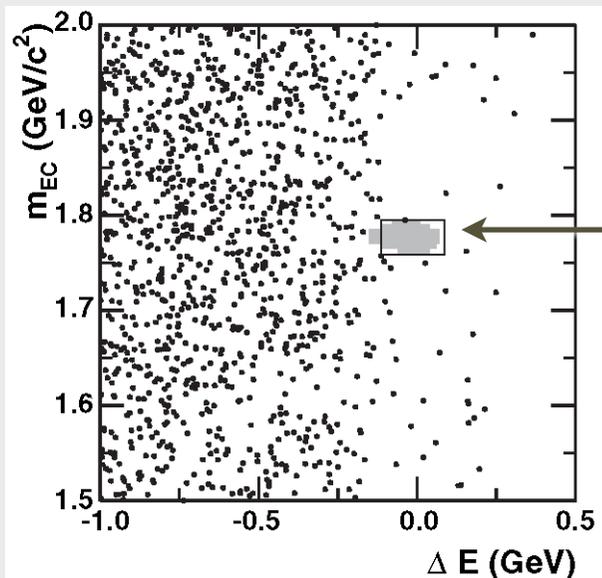


$\tau \rightarrow \mu\gamma, e\gamma$ at BABAR



$$B(\tau^- \rightarrow \mu^- \gamma) < 6.8 \times 10^{-8} \quad 4 \text{ Bkg}$$

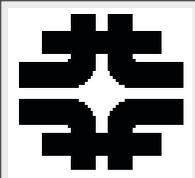
$$B(\tau^- \rightarrow e^- \gamma) < 11.0 \times 10^{-8} \quad 1 \text{ Bkg}$$



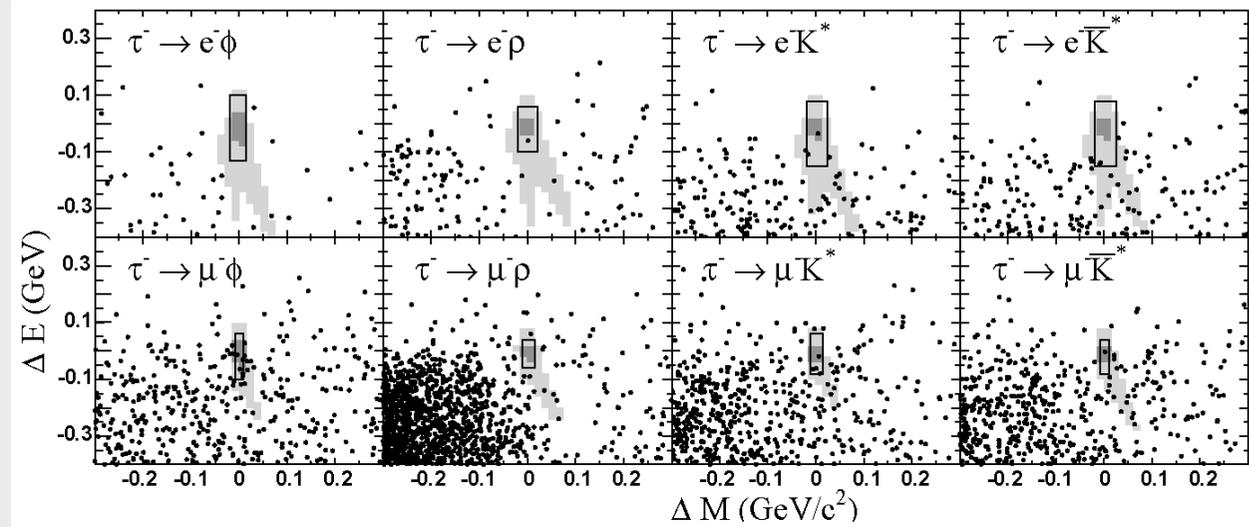
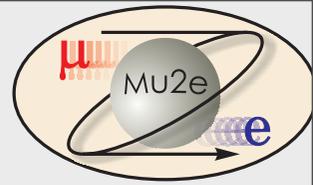
2σ signal region

$$B(\tau^- \rightarrow \mu^- \gamma) < 6.8 \times 10^{-8} \quad 4 \text{ Bkg}$$

$$B(\tau^- \rightarrow e^- \gamma) < 11.0 \times 10^{-8} \quad 1 \text{ Bkg}$$



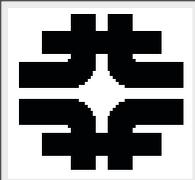
Semi-leptonic Modes



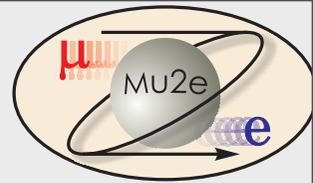
Non-zero Background

| Mode | ϵ [%] | N_{bgd} | N_{obs} | N_{UL}^{90} | $\mathcal{B}_{\text{exp}}^{90}$ | $\mathcal{B}_{\text{UL}}^{90}$ |
|----------------|-----------------|------------------|------------------|----------------------|---------------------------------|--------------------------------|
| $e\phi$ | 6.43 ± 0.16 | 0.68 ± 0.12 | 0 | 1.8 | 5.0 | 3.1 |
| $\mu\phi$ | 5.18 ± 0.27 | 2.76 ± 0.16 | 6 | 8.7 | 8.2 | 19 |
| $e\rho$ | 7.31 ± 0.18 | 1.32 ± 0.17 | 1 | 3.1 | 4.9 | 4.6 |
| $\mu\rho$ | 4.52 ± 0.41 | 2.04 ± 0.19 | 0 | 1.1 | 8.9 | 2.6 |
| eK^* | 8.00 ± 0.19 | 1.65 ± 0.23 | 2 | 4.3 | 4.8 | 5.9 |
| μK^* | 4.57 ± 0.36 | 1.79 ± 0.21 | 4 | 7.1 | 8.5 | 17 |
| $e\bar{K}^*$ | 7.76 ± 0.18 | 2.76 ± 0.28 | 2 | 3.2 | 5.4 | 4.6 |
| $\mu\bar{K}^*$ | 4.11 ± 0.32 | 1.72 ± 0.17 | 1 | 2.7 | 9.3 | 7.3 |

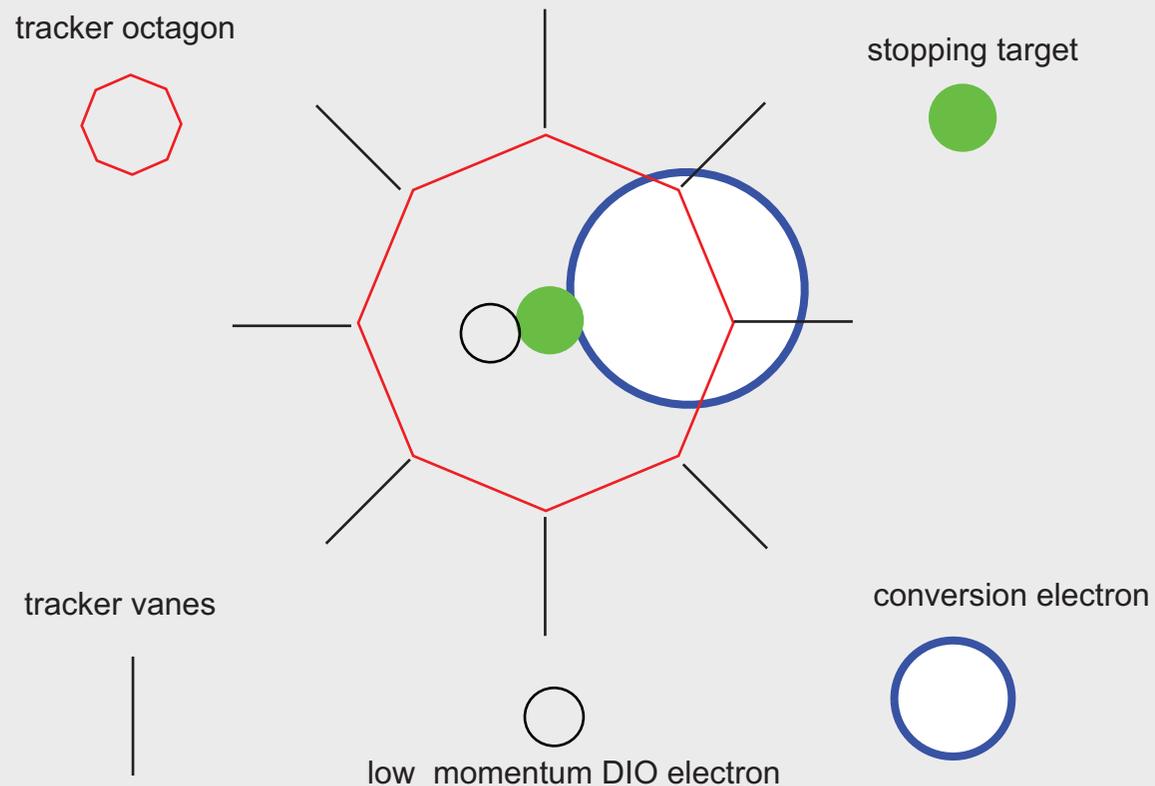
} $\times 10^{-8}$

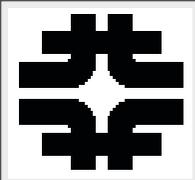


Tracking

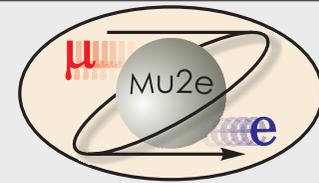


- Projection of helical track
- Conversion electron has high momentum (p_T) and has R large enough to pass outside octagon and is tracked
- DIO ($p_T < 55 \text{ MeV}/c$) does not!

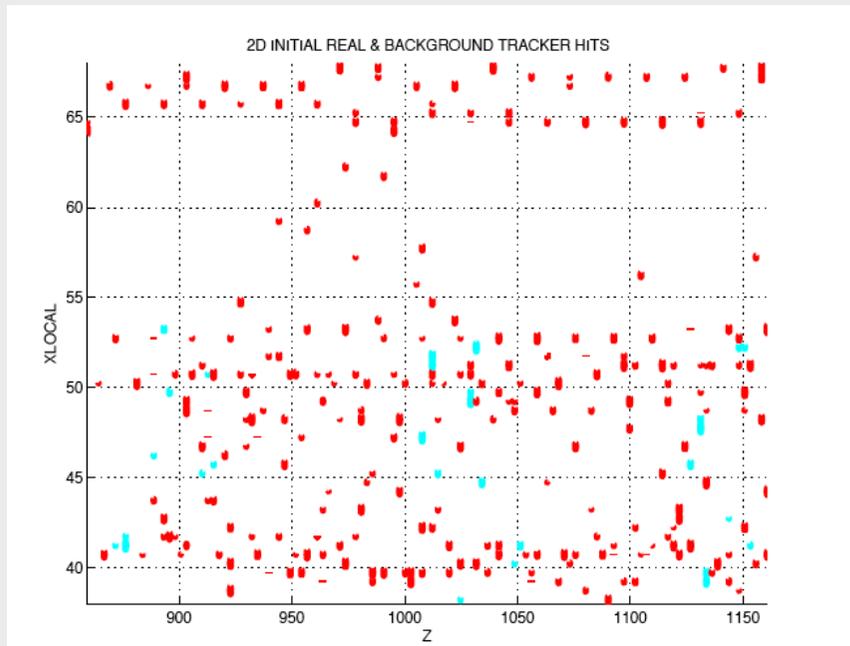
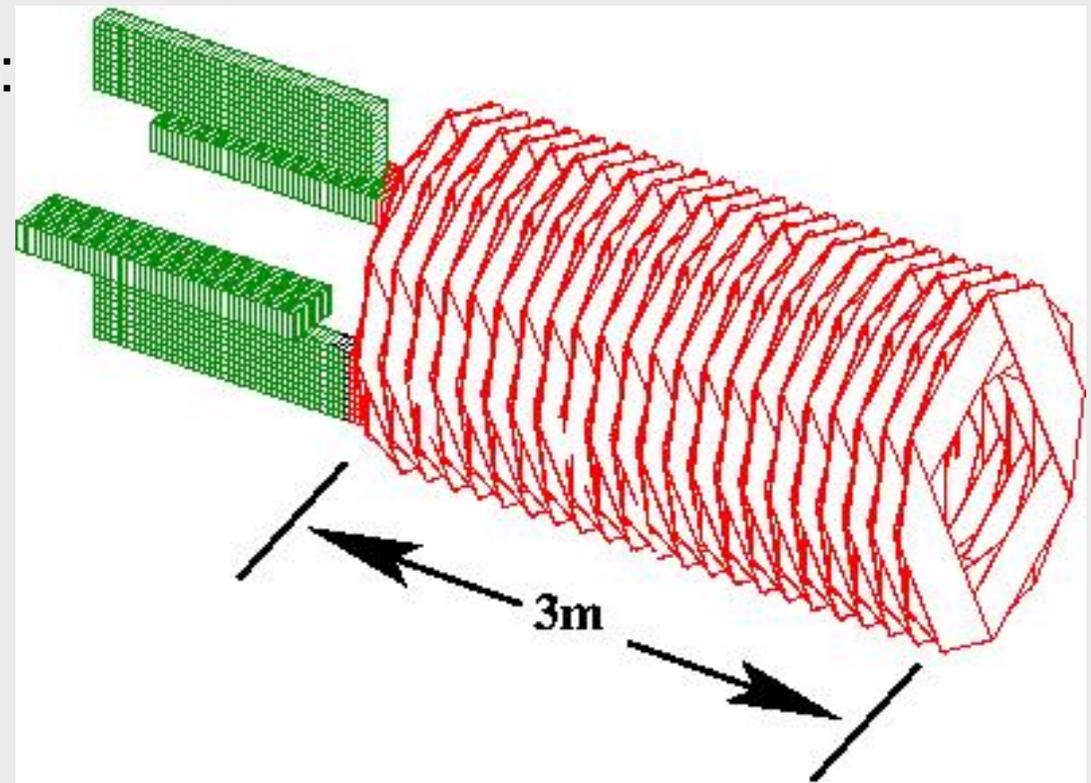




Alternative Tracker



- T-tracker (T for transverse):
- 260 sub-planes
 - sixty 5 mm diameter conducting straws
 - length from 70-130 cm
 - total of 13,000 channels



T-Tracker Pattern Recognition
Difficult but
Kalman Filter is promising