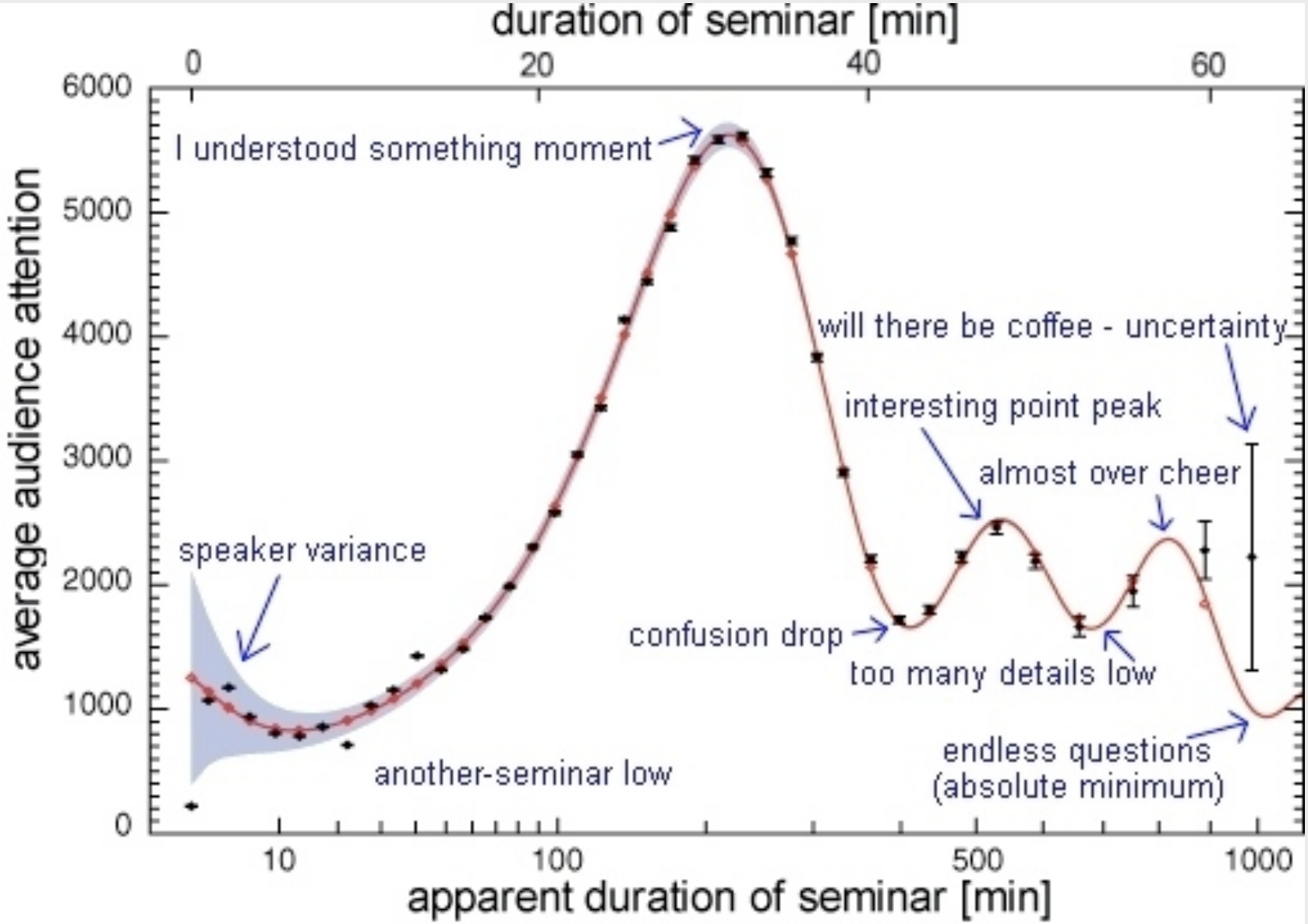
A New Charged Lepton Flavor Violation Experiment: Muon-Electron Conversion at FNAL

R. Bernstein
Fermilab
for the Mu2e Collaboration
October 2009

Outline



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

Collaboration

Boston University
Brookhaven National Laboratory
University of California, Berkeley
University of California, Irvine
City University of New York
Fermilab
Idaho State University
University of Illinois, Urbana-Champaign
Institute for Nuclear Research, Moscow, Russia
JINR, Dubna, Russia
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

96 collaborators

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

$$\mu^- N \rightarrow e^- N$$

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

- Charged Lepton Flavor Violation (CLFV)
- Related Processes:

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

Endorsed in US Roadmap

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

Strongly endorsed by P5:

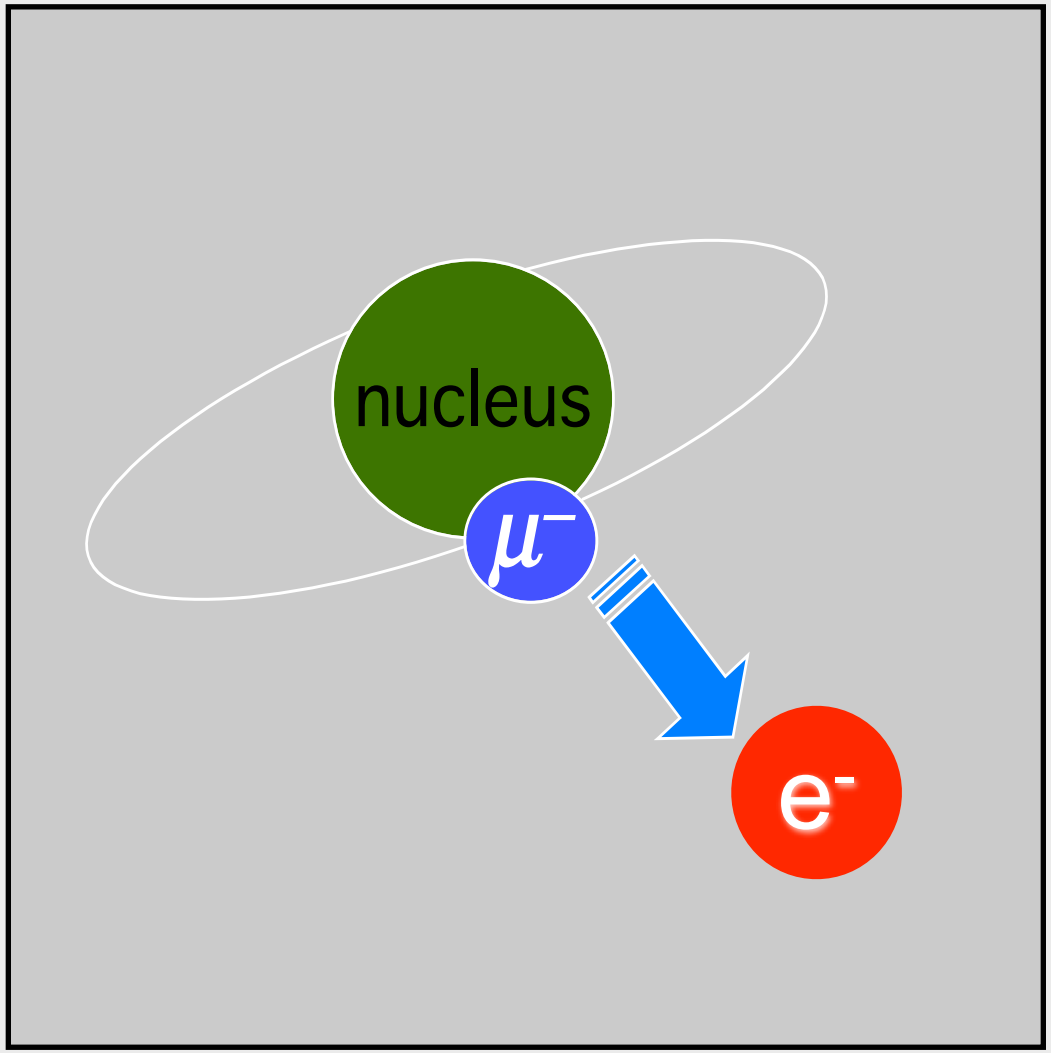
"The experiment could go forward in the next decade with a modest evolution of the Fermilab accelerator complex. Such an experiment could be the first step in a world-leading muon-decay program eventually driven by a next-generation high-intensity proton source. **The panel recommends pursuing the muon-to-electron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

Mu2e is a central part of the future US program

Experimental Signal

$$\mu^- N \rightarrow e^- N$$

- A Single Monoenergetic Electron
- If *N* = Al, E_e = 105. 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 BR($\mu \rightarrow e\gamma$) ≈ 10^{-4}
- Unless another ν, in Intermediate Vector Boson Loop, cancels (Feinberg, 1958)

➡ same as GIM mechanism!

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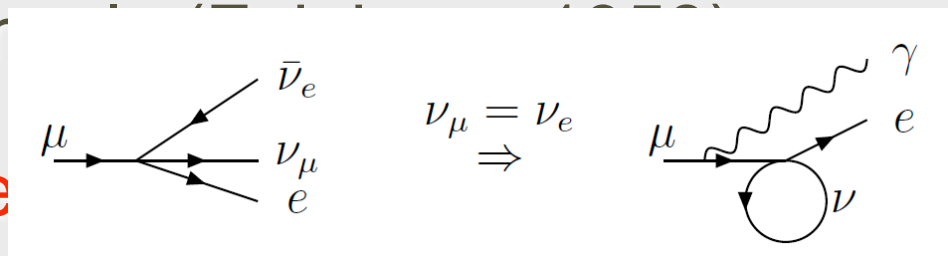
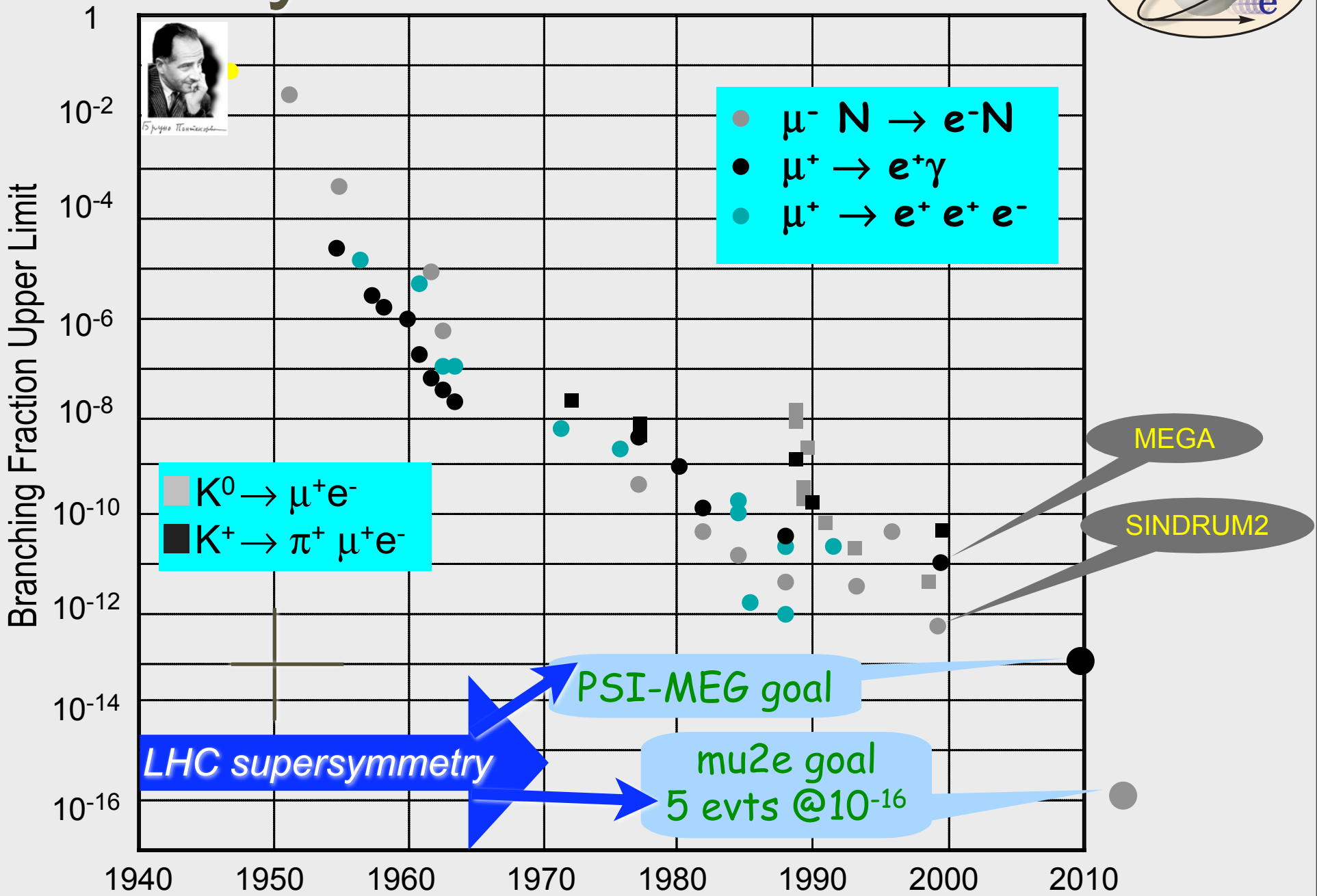


[1]Unless we are willing to give up the 2-component neutrino theory, we know that $\mu \rightarrow e + \nu + \bar{\nu}$.

History of CLFV Searches



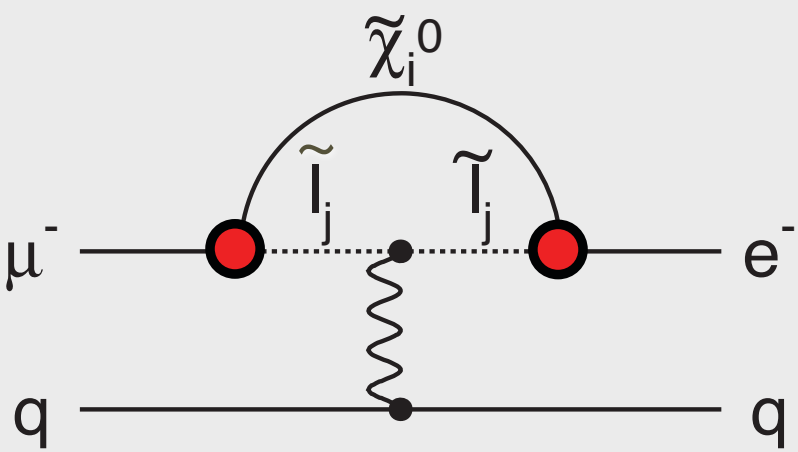
Current and Planned Lepton Flavor Violation Searches

- 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 ~ 10^{-15}

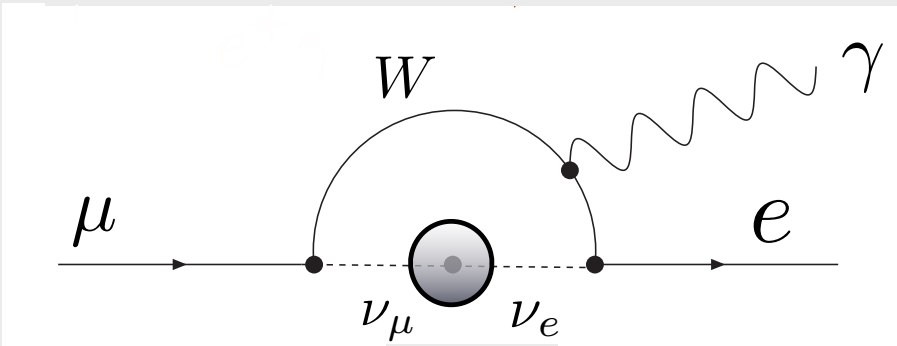


Access SUSY through loops:

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



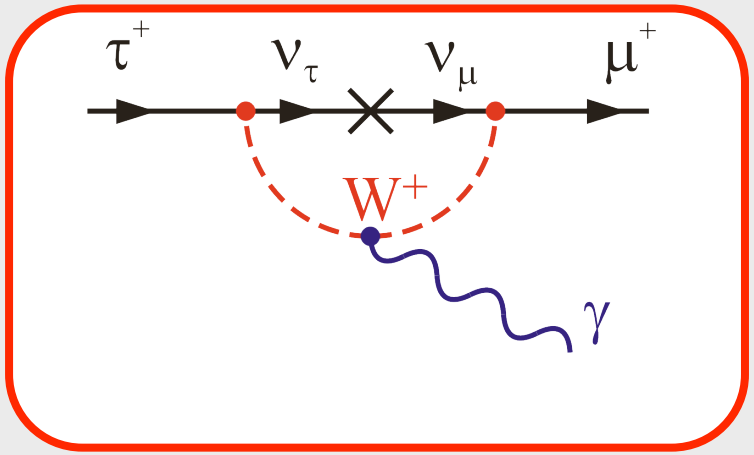
NO STANDARD MODEL BACKGROUND!

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

CLFV and Tau Decays

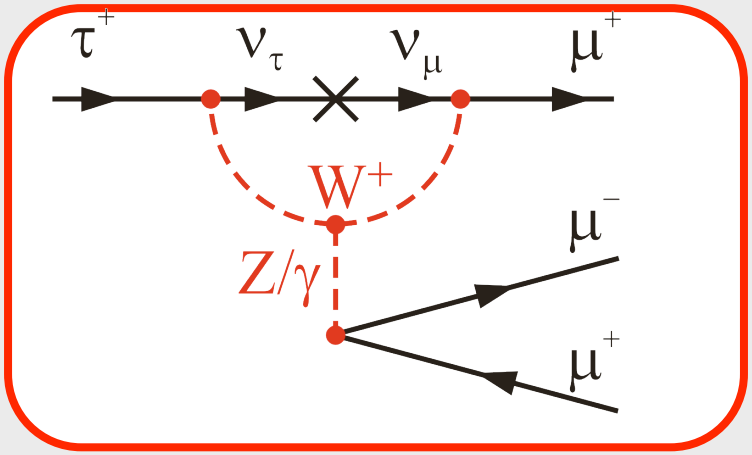
Highly suppressed in Standard Model

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



SM ~ 10^{-40}

Milder
GIM
Cancellations



SM ~ 10^{-14}

Pham, hep-ph/9810484

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

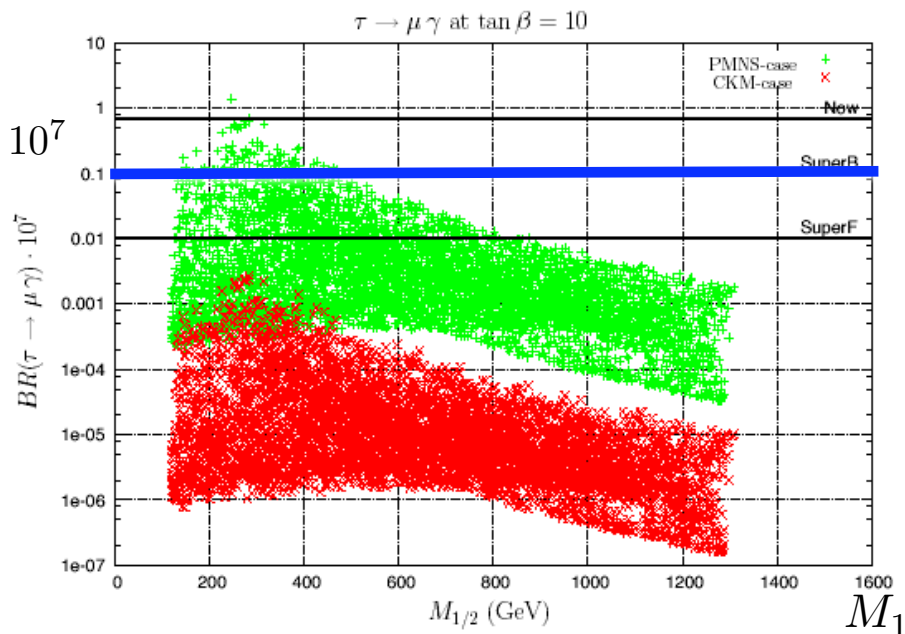
Bad News:
τ's hard to produce:
~10^9 τ/yr vs ~10^{11} μ/s in fixed-target experiments (Mu2e/COMET)

Supersymmetry in Tau LFV

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

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

$\mathrm{BR}(\tau \to \mu\gamma) \times 10^7$



$\tan\beta = 10$

SuperB

$M_{1/2}$ (GeV)

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

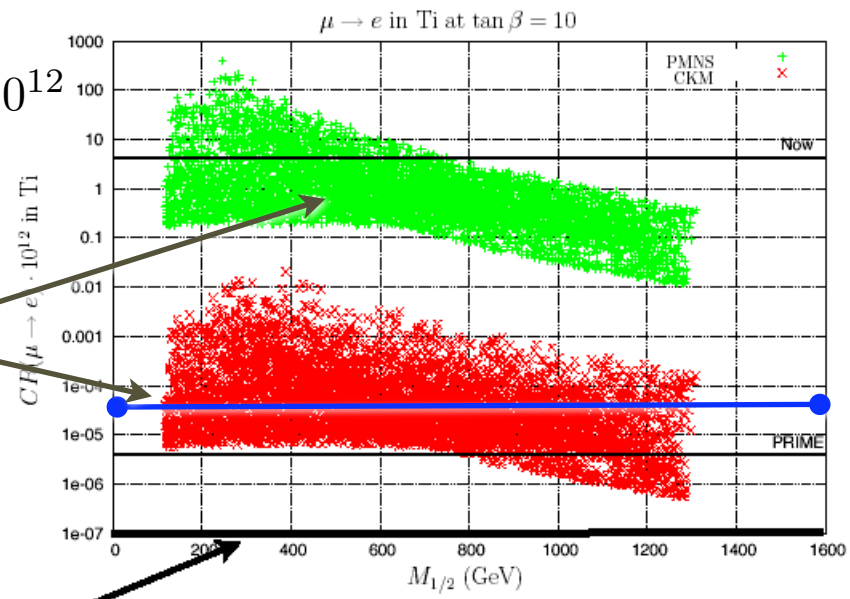
neutrino mass via the see--saw mechanism, analysis is performed in an SO(10) framework

And Muon-Electron Conversion

$\tan\beta = 10$

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

$\mathrm{BR}(\mu \to e) \times 10^{12}$



Current

Mu2e

measurement can distinguish between PMNS and MFV

Project X reach

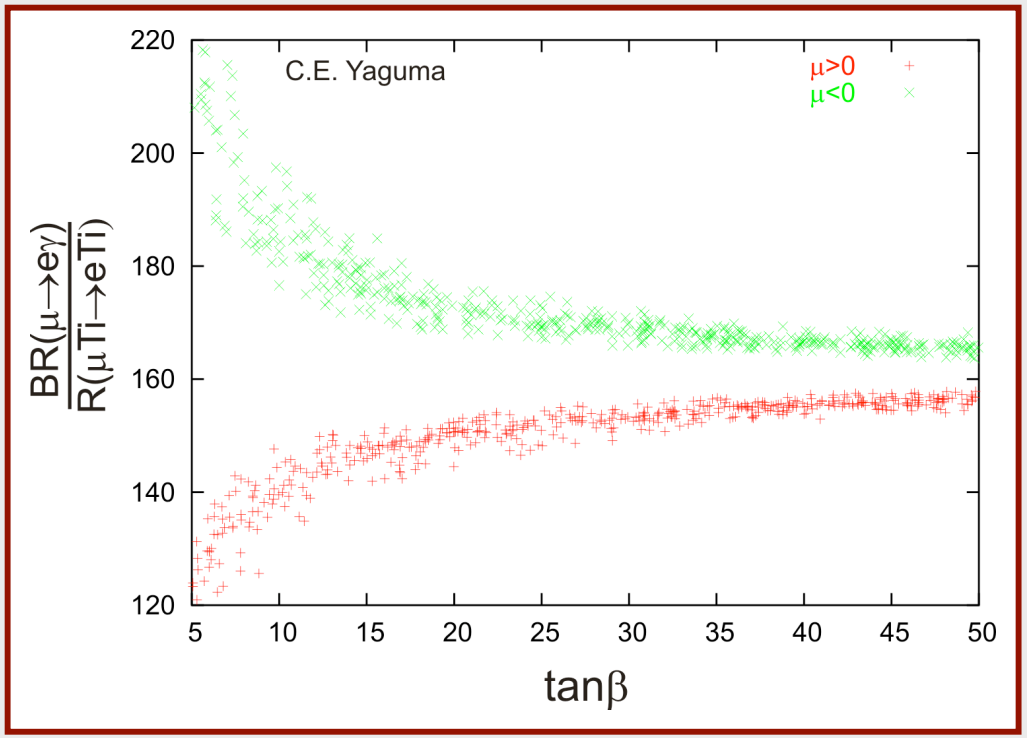
$M_{1/2}$ (GeV)

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

complementarity between Lepton Flavor Violation (LFV) and LHC experiments!

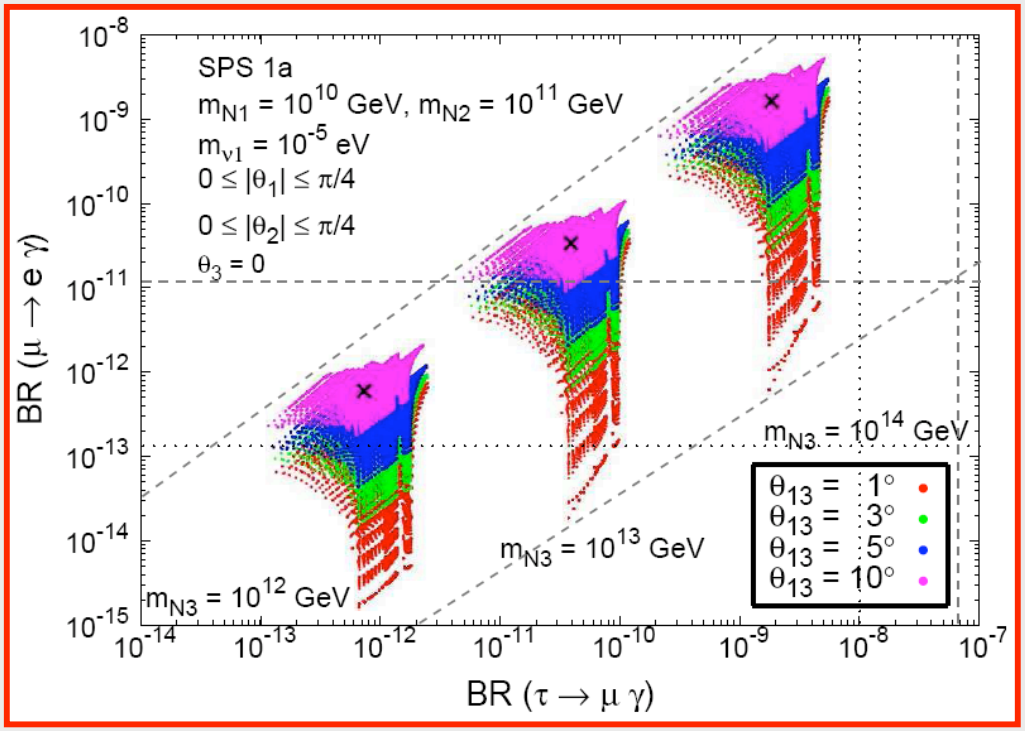
Pinning Down SuperSymmetry

MSSM w mSUGRA



Yaguna, hep-ph/0502014v2

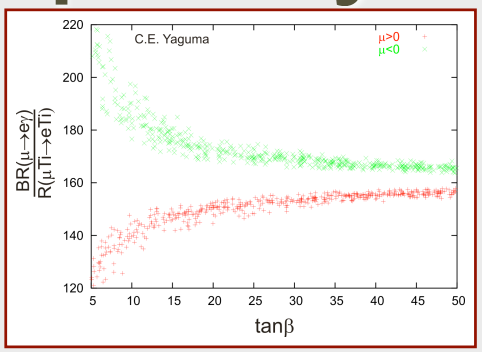
CMSSM - seesaw



Antusch et al.,hep-ph/0610439

Pinning Down SuperSymmetry

MSSM w mSUGRA



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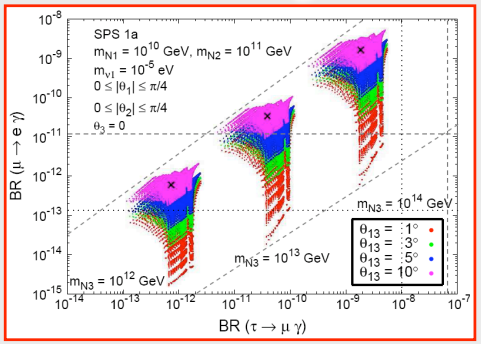


Antusch et al.,hep-ph/0610439

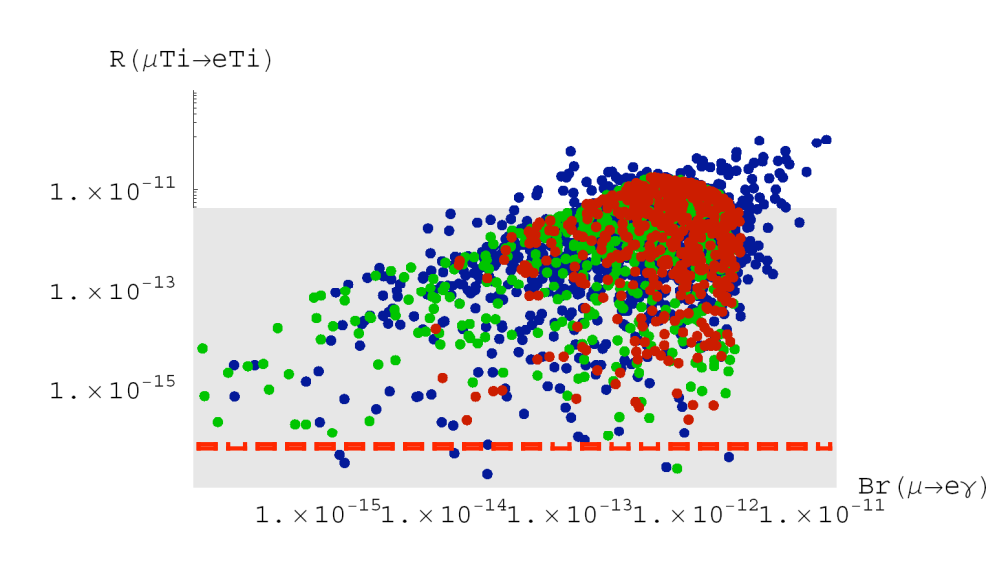
- Need:
  - observation of CLFV in more than one channel, and/or
  - evidence from LHC, g-2, or elsewhere

to allow discrimination among different models

Combining μ→eγ with μ→e Conversion

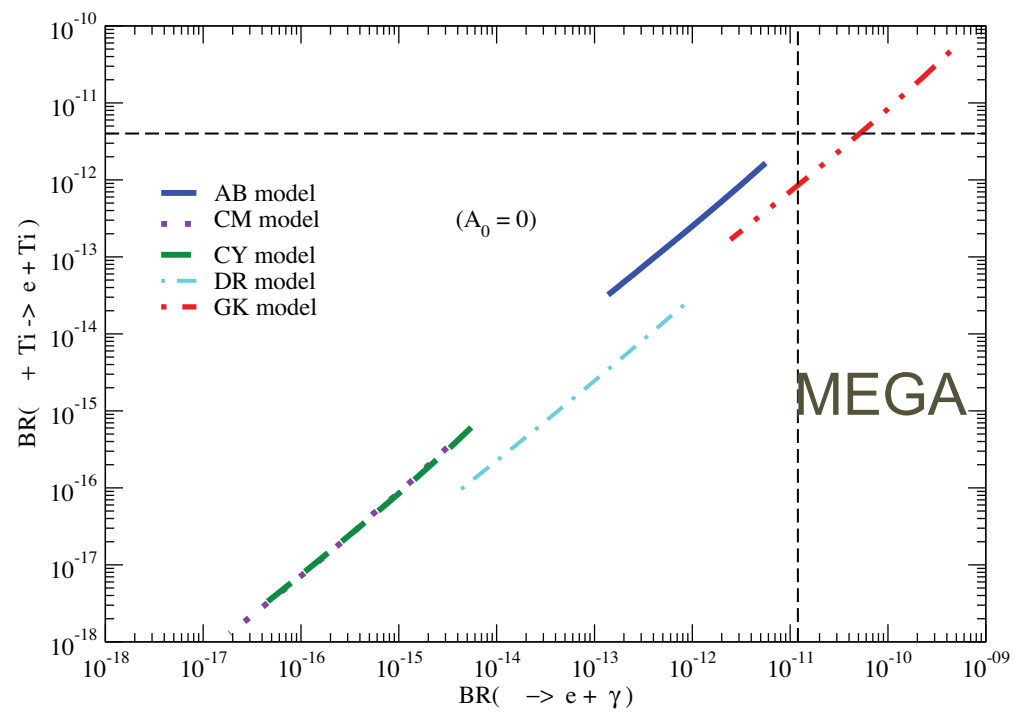
Randall-Sundrum

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.



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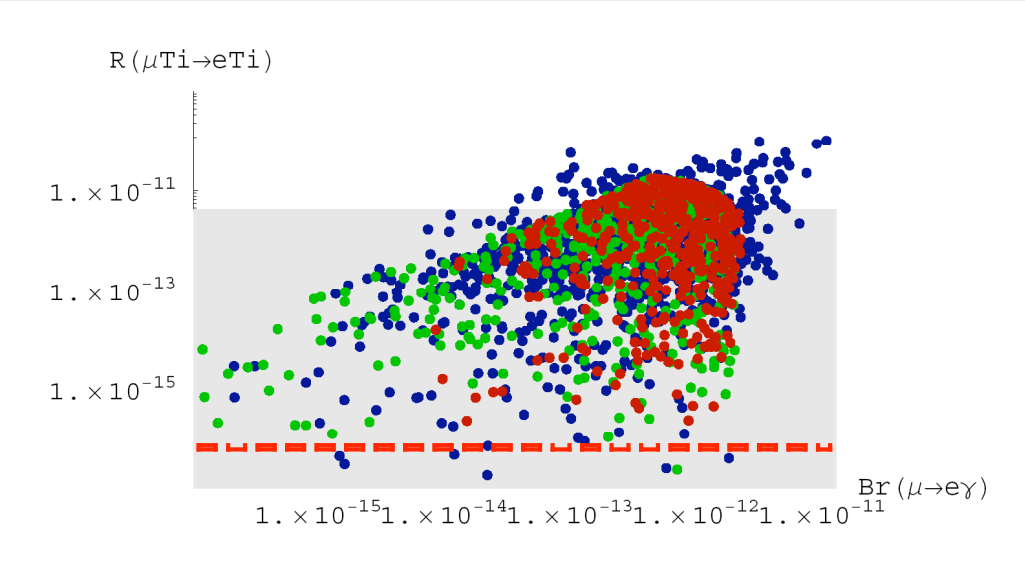
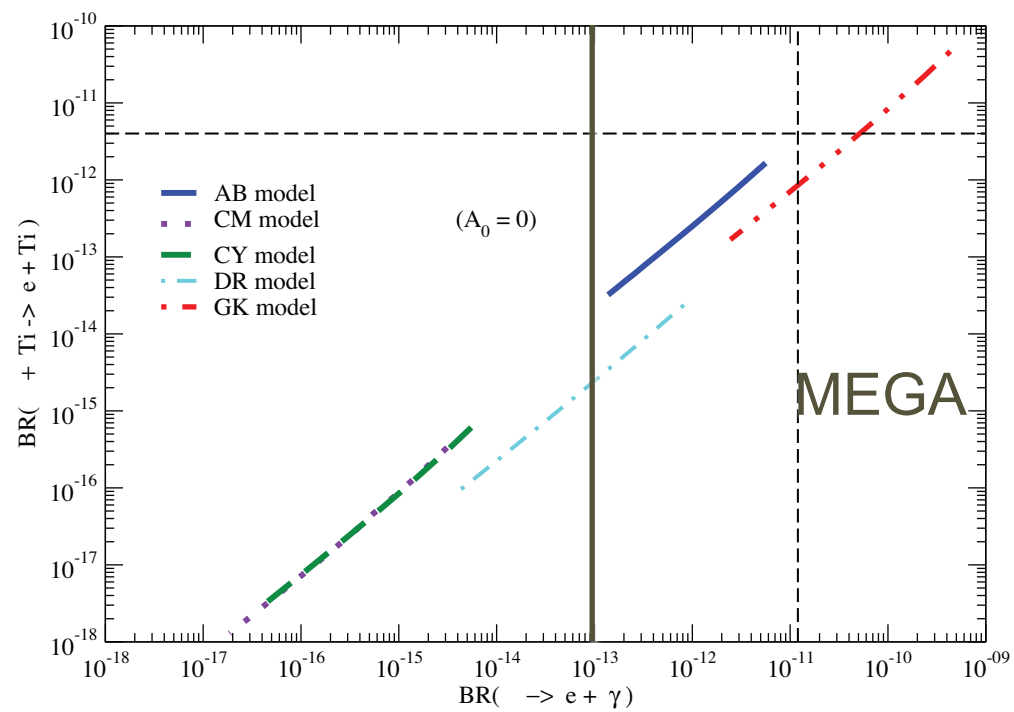


MEG



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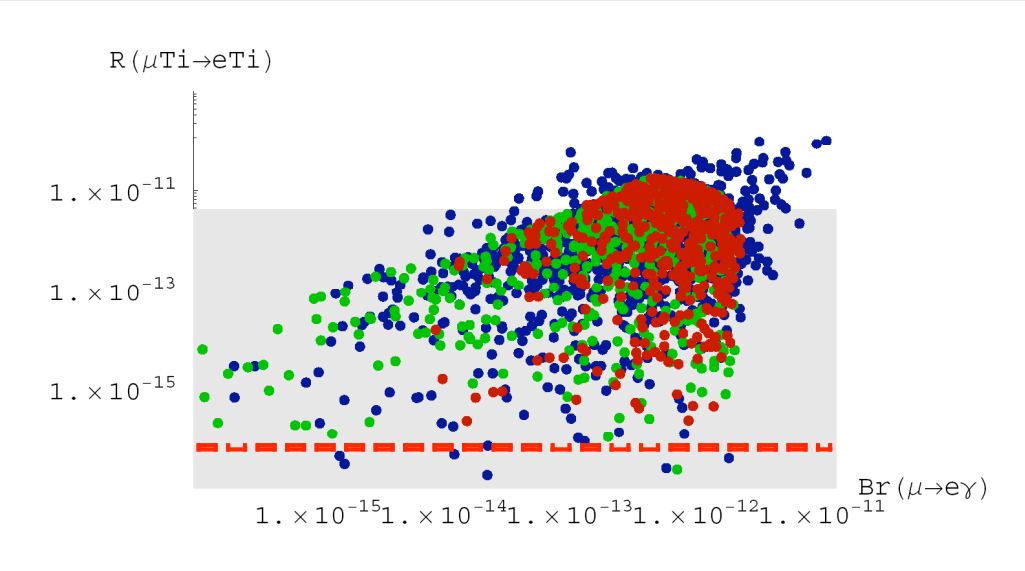

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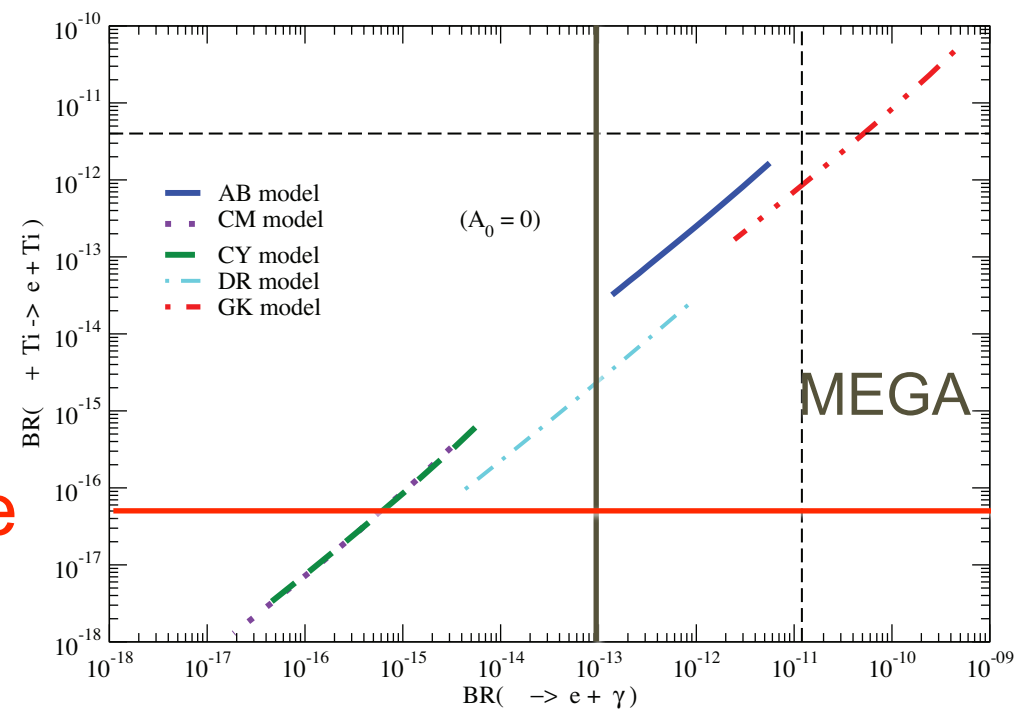

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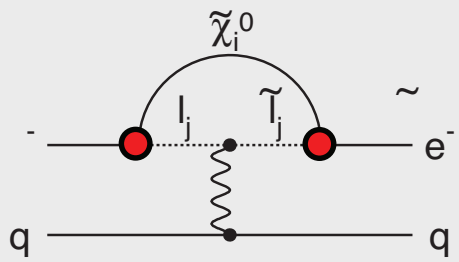
Mu2e

Contributions to μe Conversion

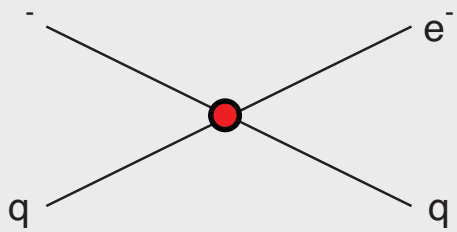
Supersymmetry

rate ~ 10^{-15}



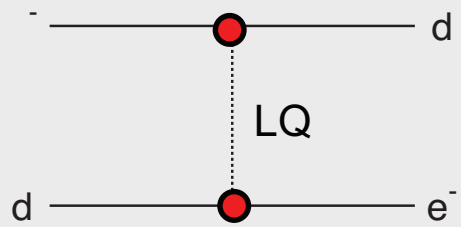
Compositeness

Λ_c ~ 3000 TeV



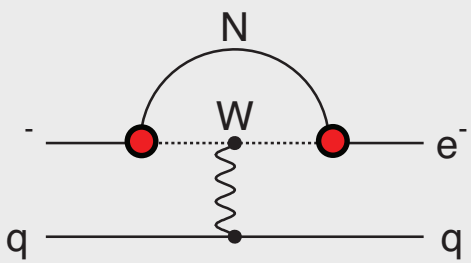
Leptoquark

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



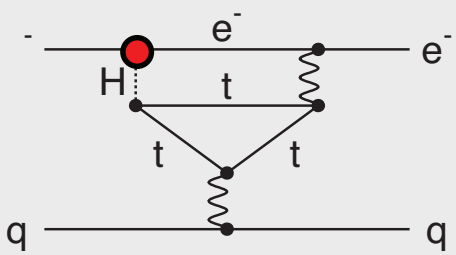
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



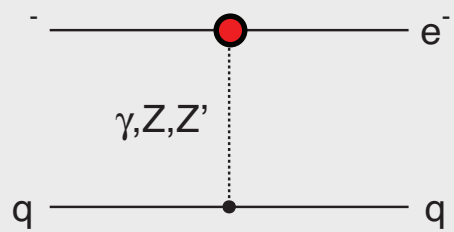
Second Higgs Doublet

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



Heavy Z' Anomal. Z Coupling

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

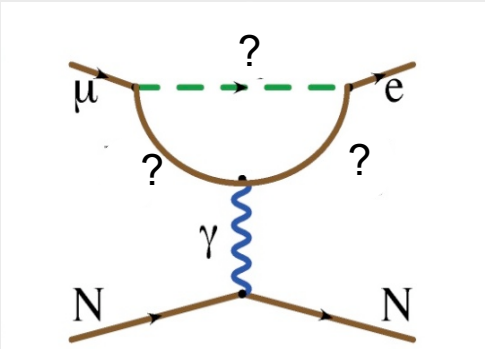


also see Flavour physics of leptons and dipole moments, arXiv:0801.1826

“Model-Independent” Picture

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

“Loops”

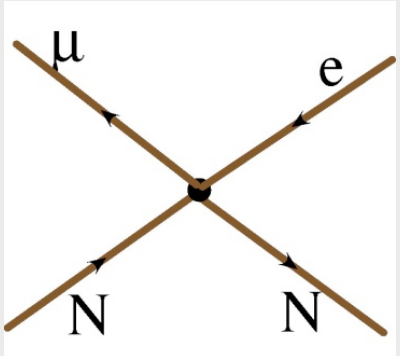


κ

Supersymmetry and Heavy Neutrinos

Contributes to $\mu \to e\gamma$

“Contact Terms”



Λ

Exchange of a new, massive particle

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

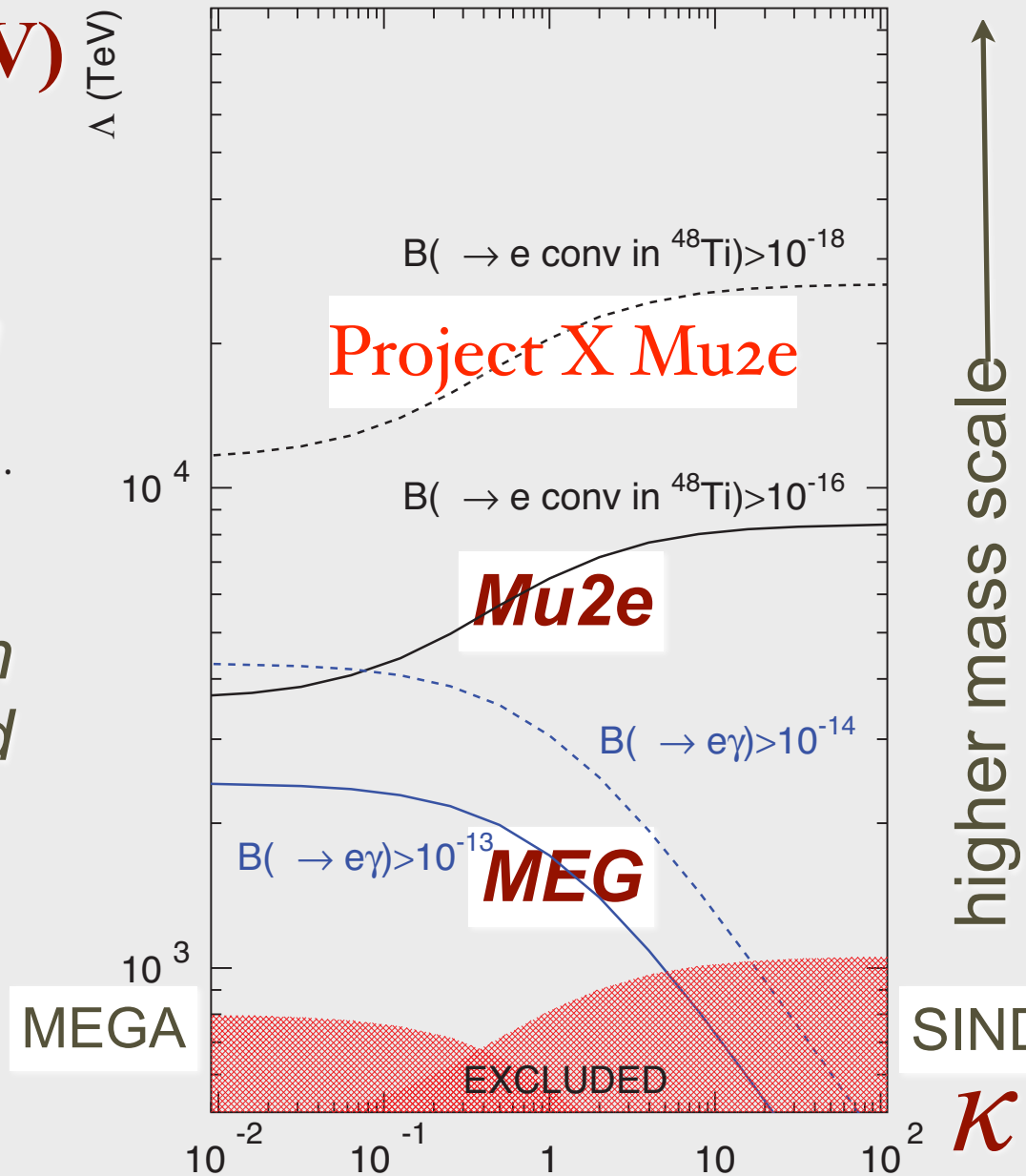
Quantitative Comparison?

μe Conversion and μ→eγ

Λ (TeV)

1) *Mass Reach to ~10^4 TeV*

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



MEGA

SINDRUM

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

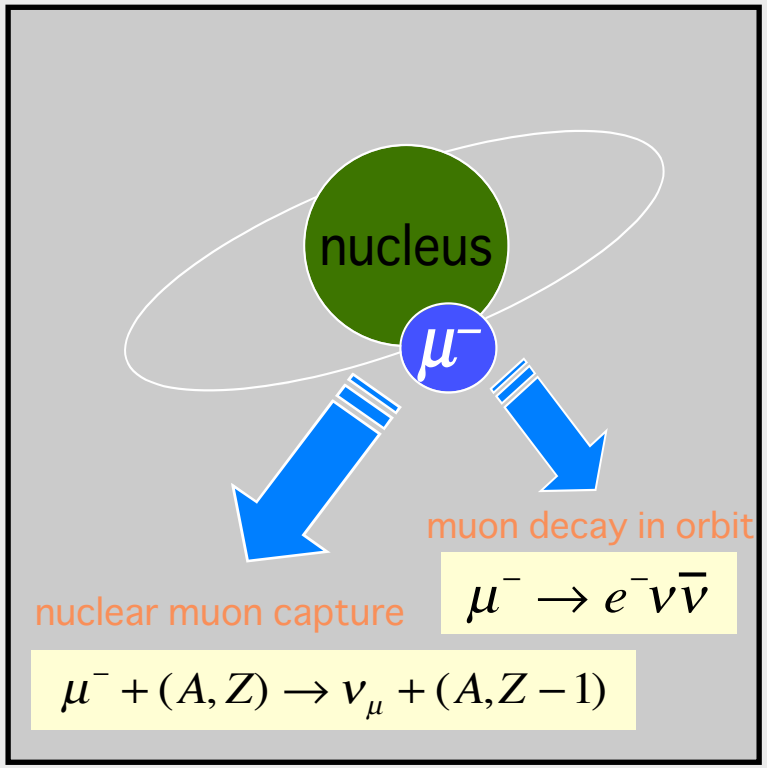
μ^- stops in thin Al foil

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

μ^- in 1s state

Al Nucleus
~4 fm

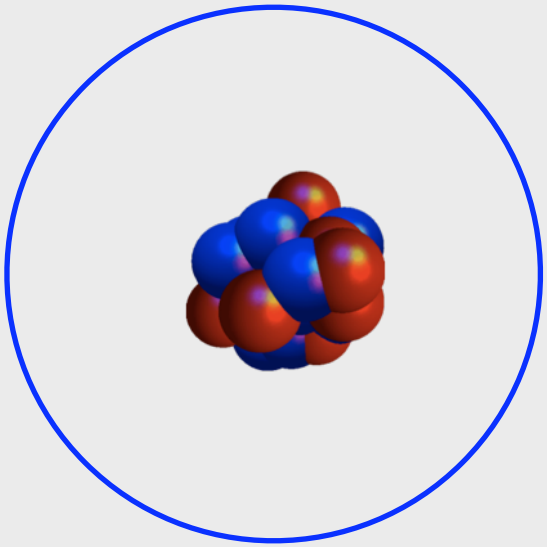
muon capture, muon "falls into" nucleus:
normalization



60% capture
40% decay

Decay in Orbit:
background

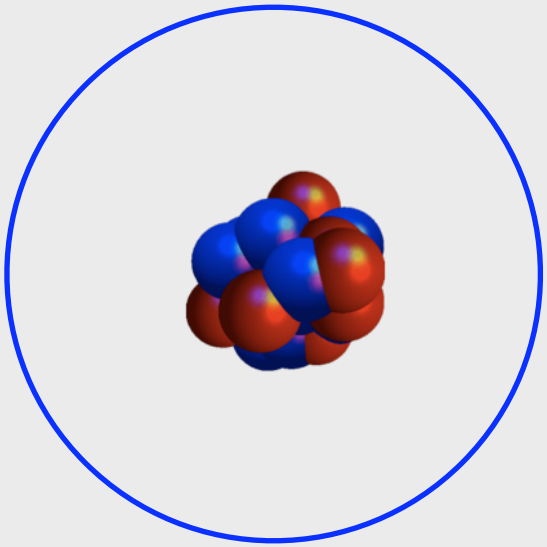
Three Possibilities: Normalization



Three Possibilities: Normalization

muon stops

μ



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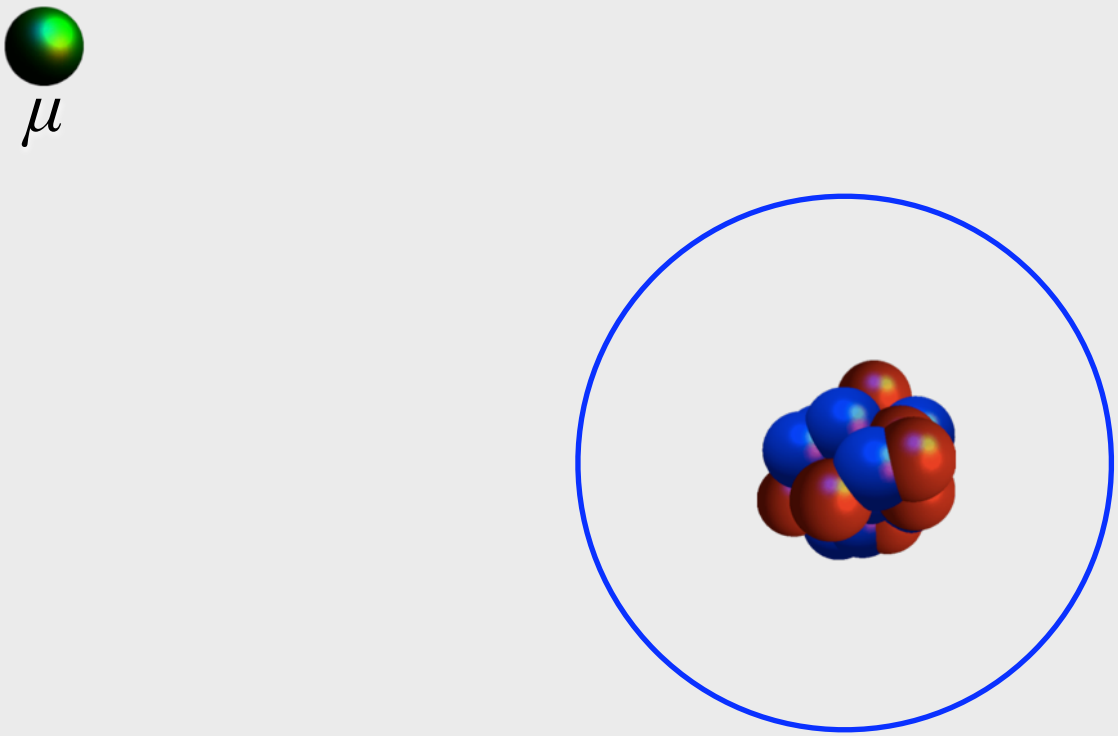

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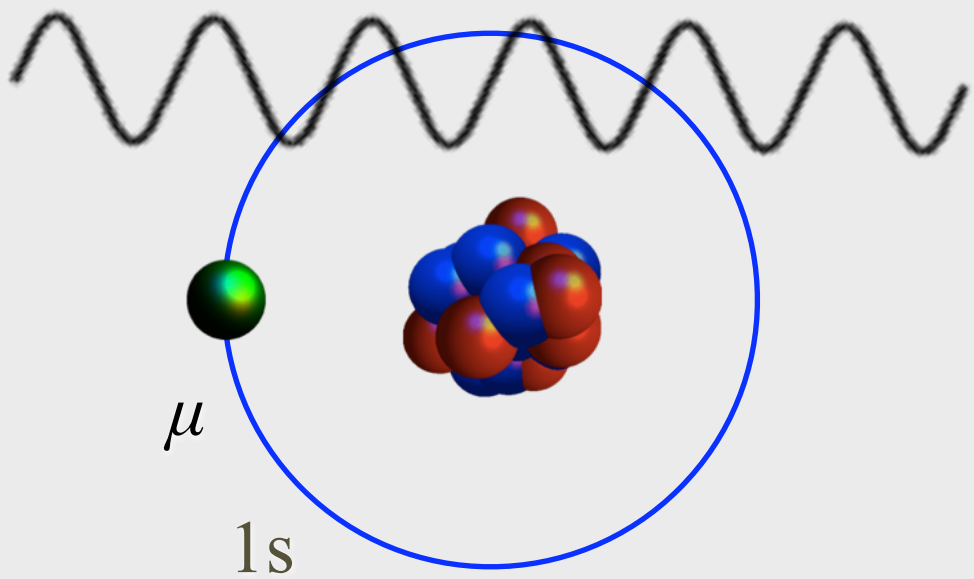
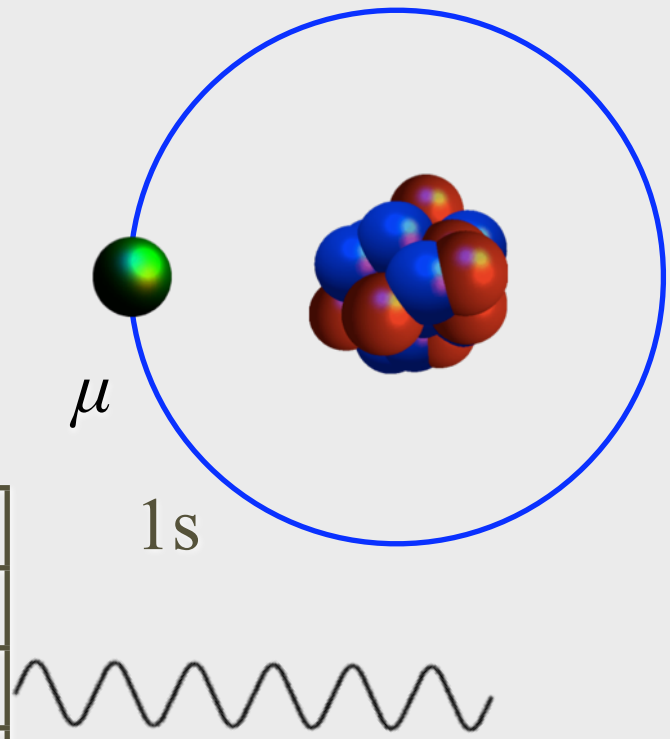


Three Possibilities: Normalization

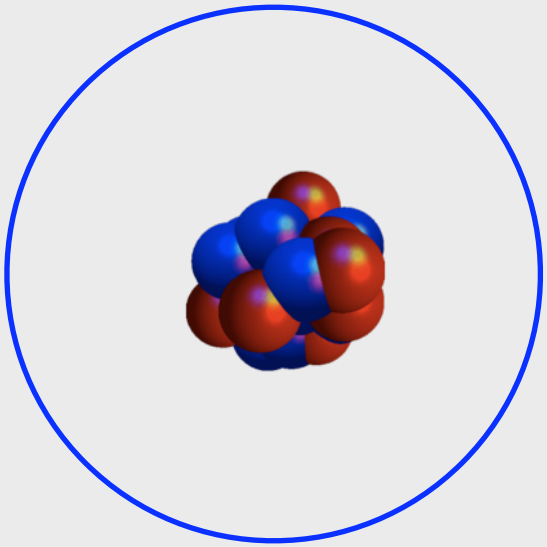
X-Rays from cascade (occurs in psec)



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



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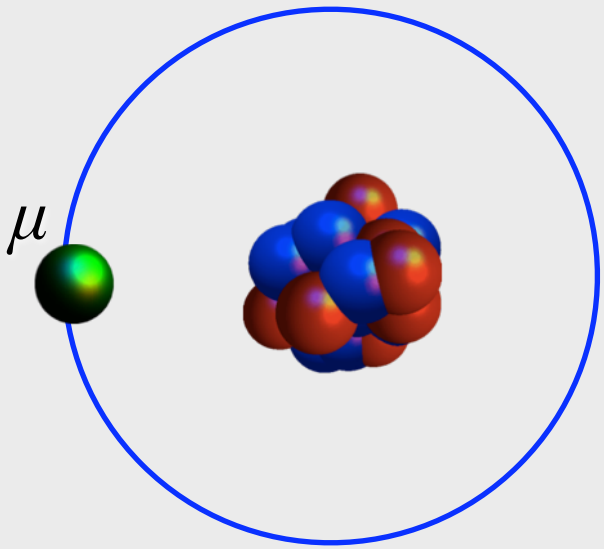

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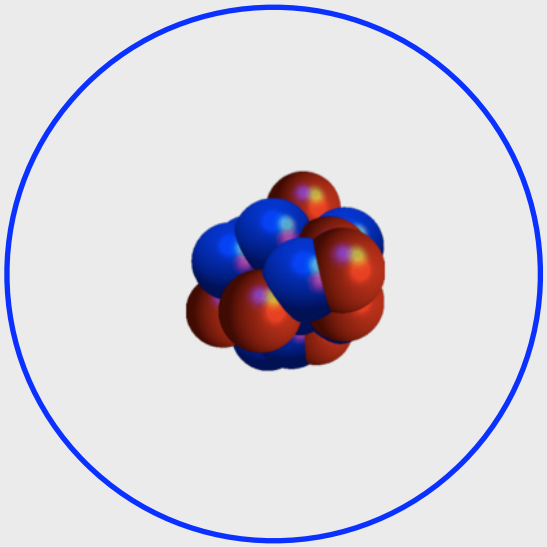

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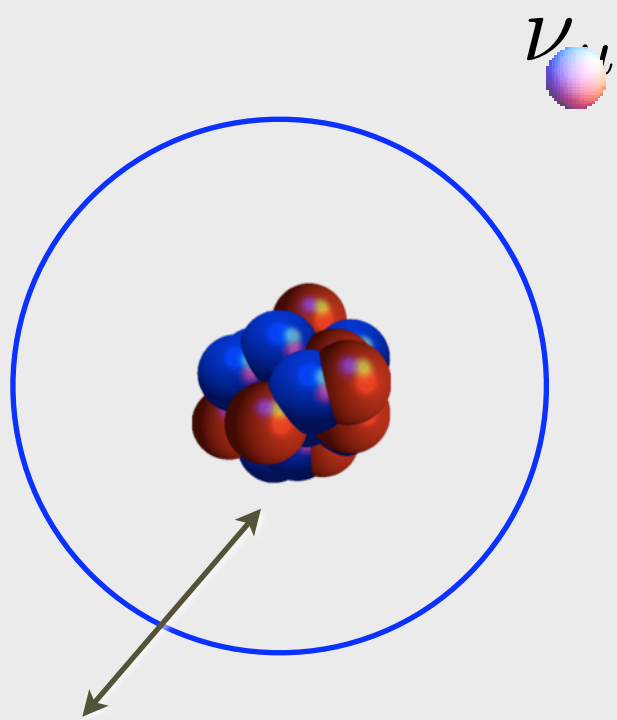
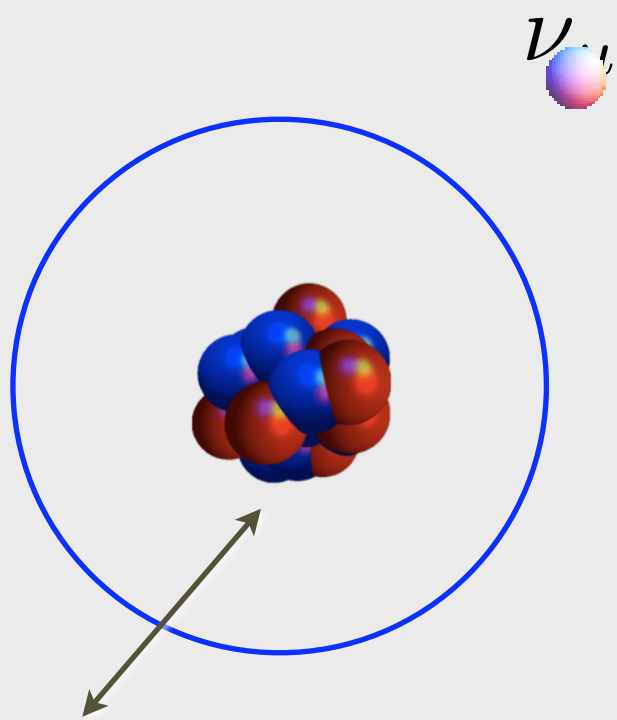


$$\mathrm{Al}(27,13) \rightarrow \mathrm{Mg}(27,12)$$

Normalization to Nuclear Capture

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

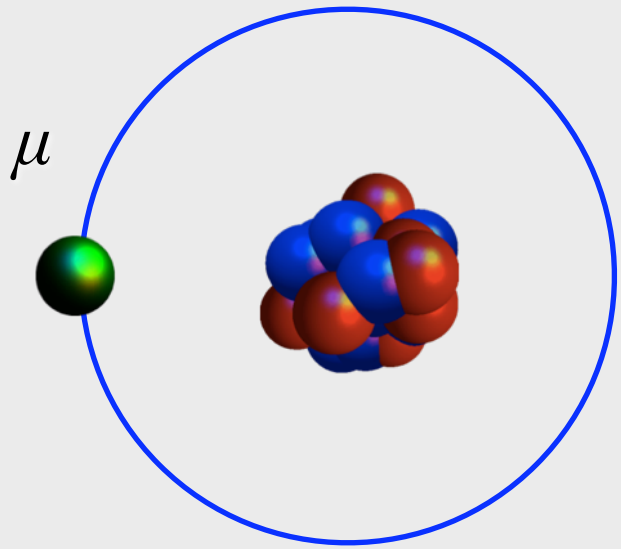
Kitano et al. ,Phys.Rev.D66:096002,2002, Erratum-ibid.D76:059902,2007. e-Print: hep-ph/0203110



$$\mathrm{Al}(27,13) \rightarrow \mathrm{Mg}(27,12)$$

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

Three Possibilities: Signal



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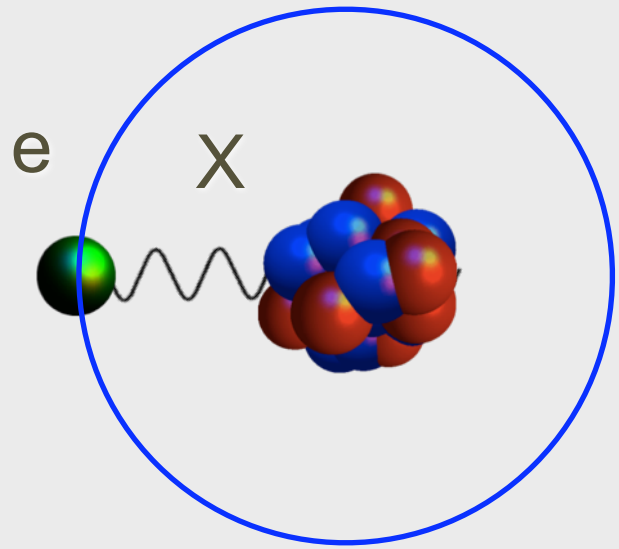
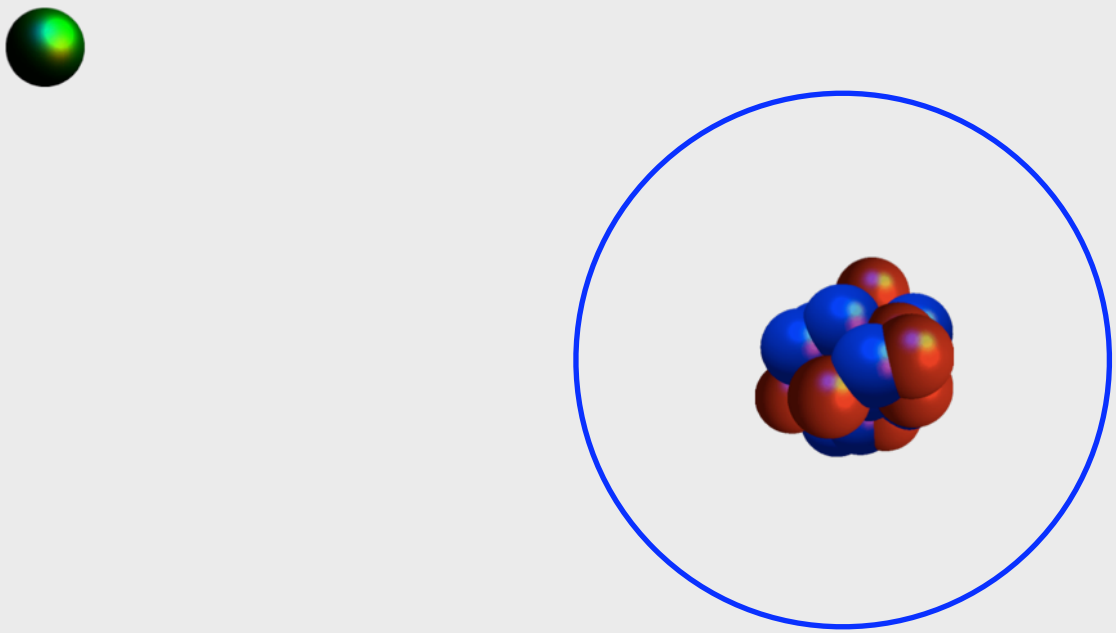


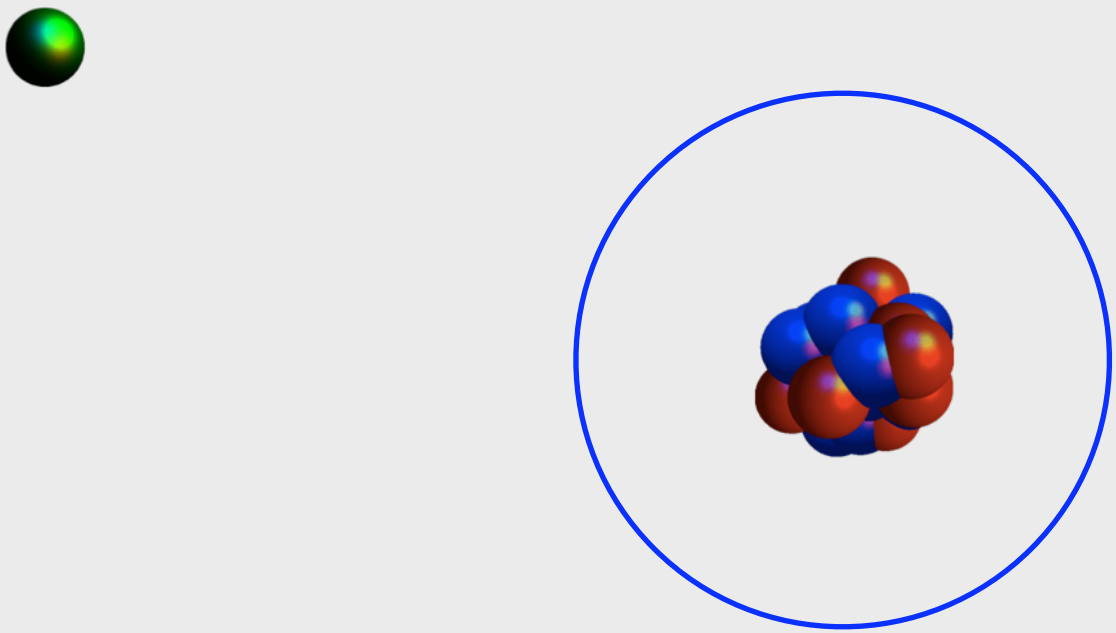
Three Possibilities: Signal

e



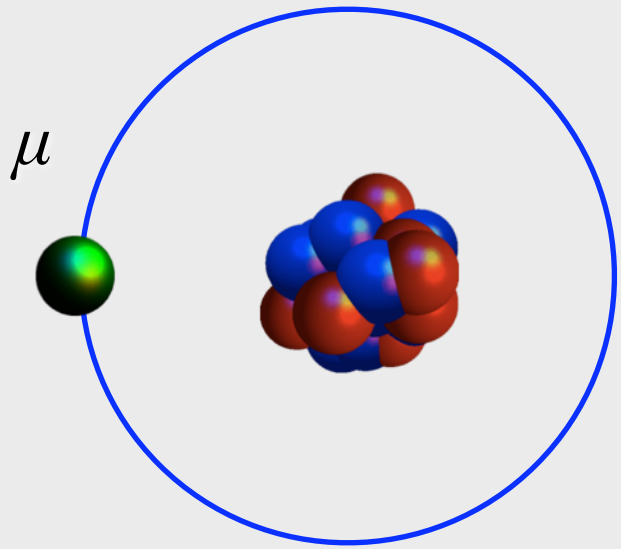
Three Possibilities: Signal

e *off to detector!*



coherent recoil of nucleus

Three Possibilities: Background



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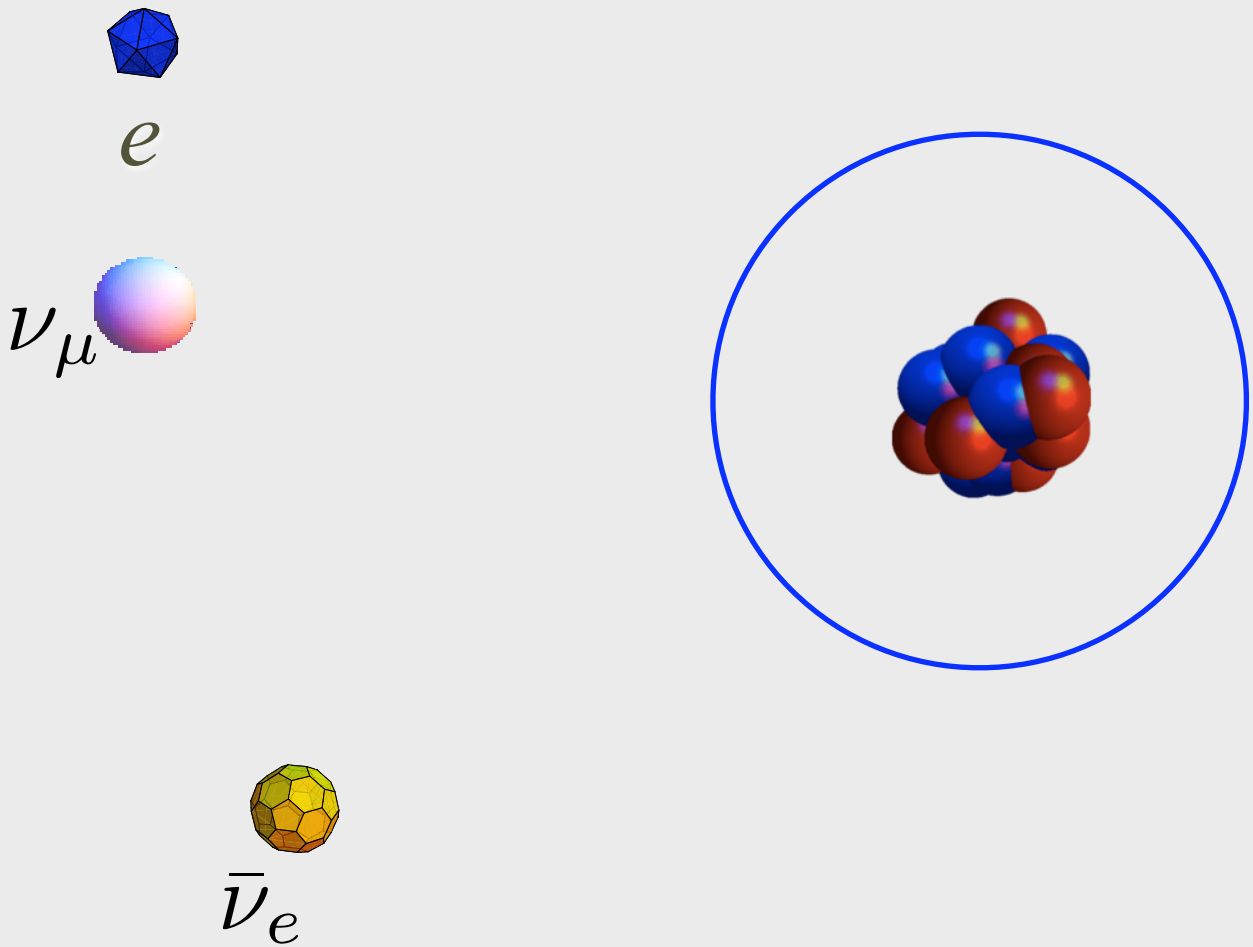
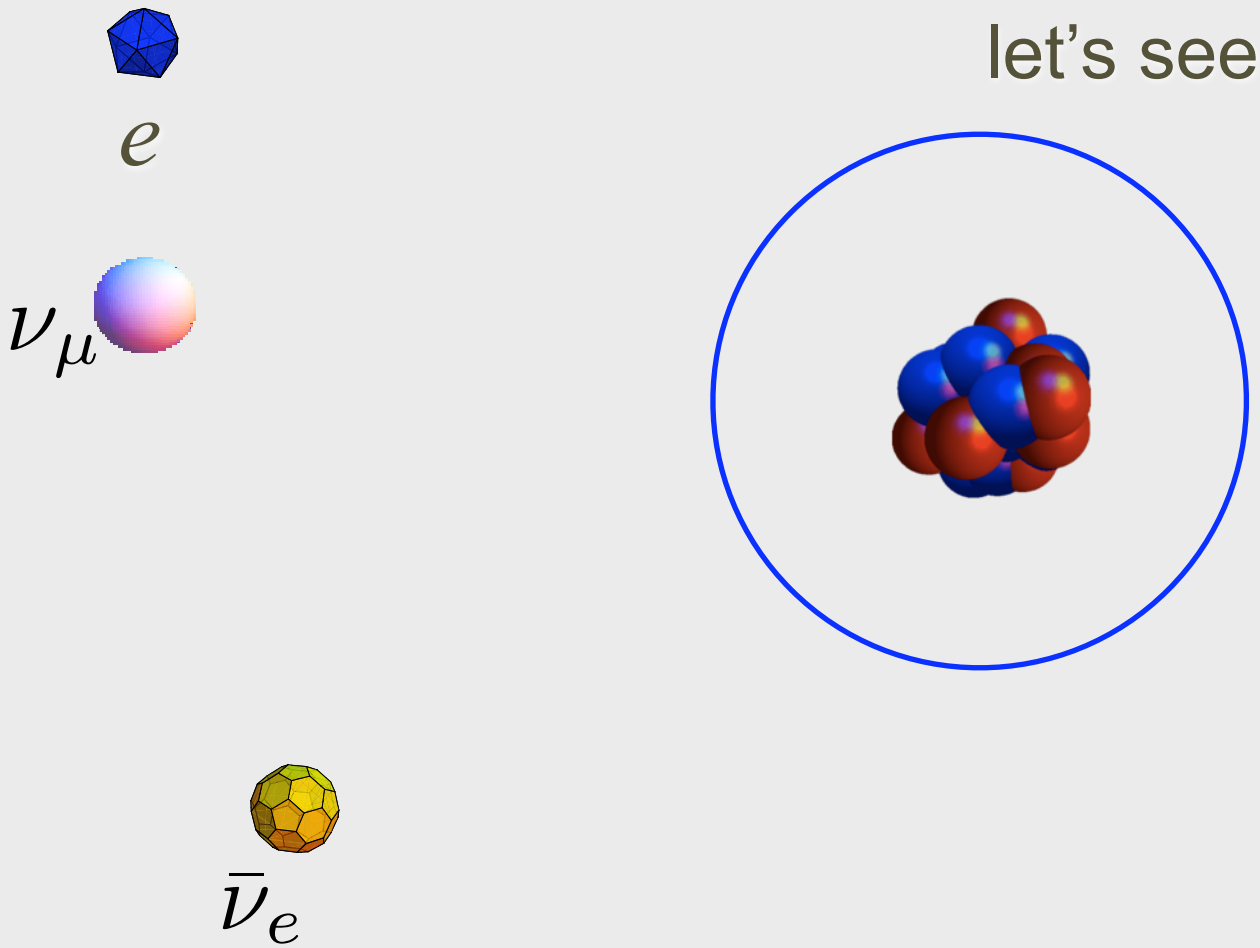


Three Possibilities: Background

this electron can be background;
let's see how



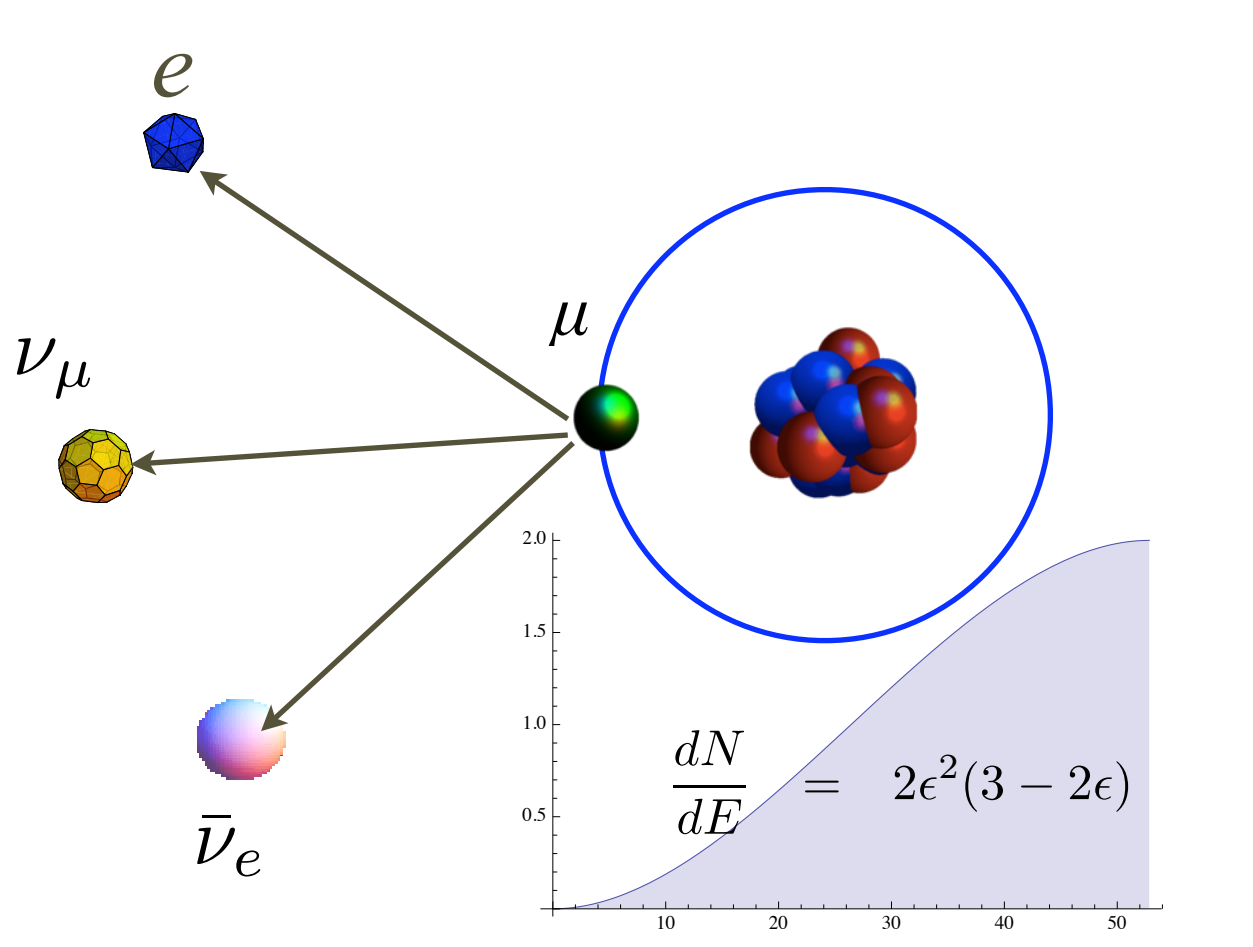
Decay-In-Orbit: Not always Background

- 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 MeV>>52.8 MeV



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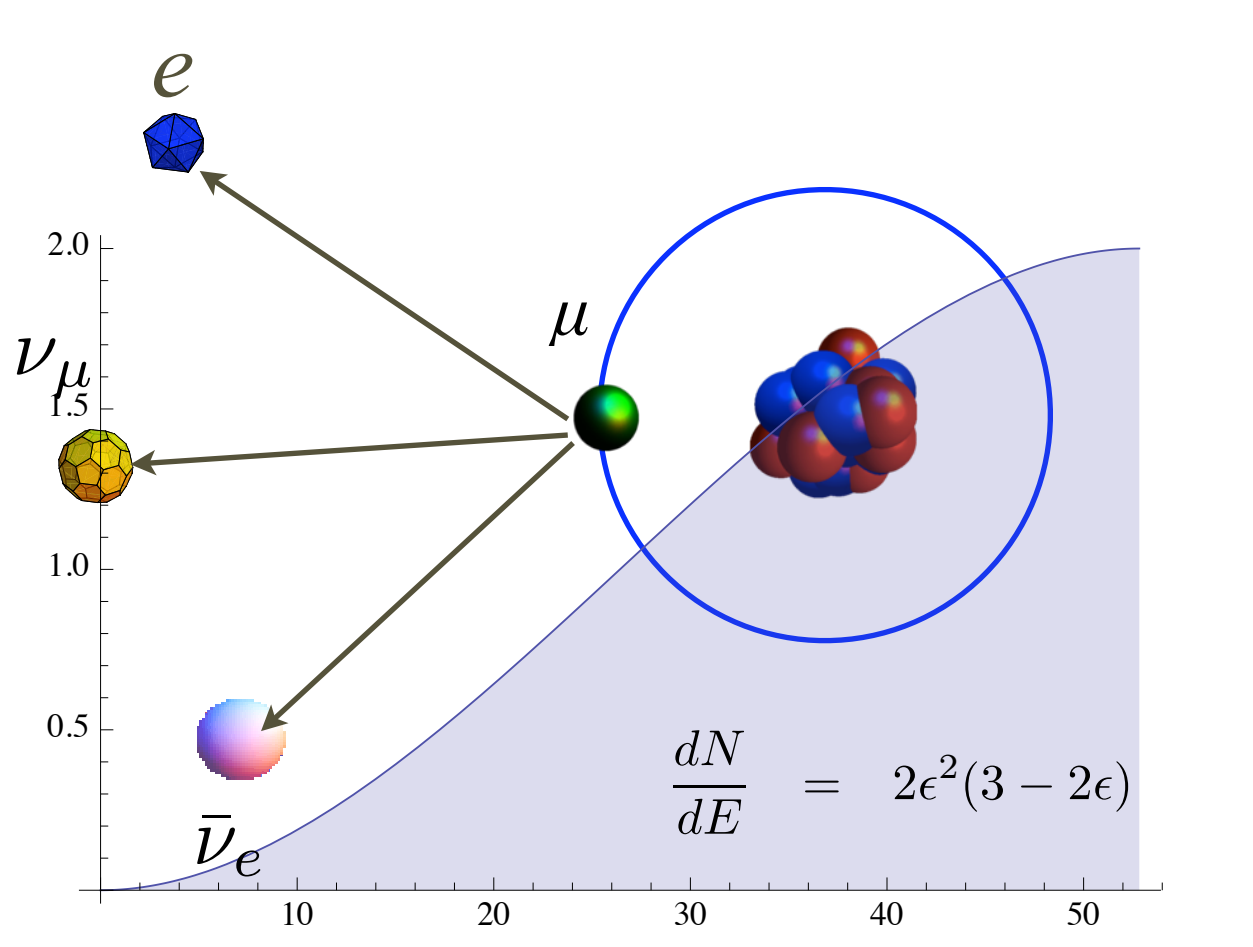
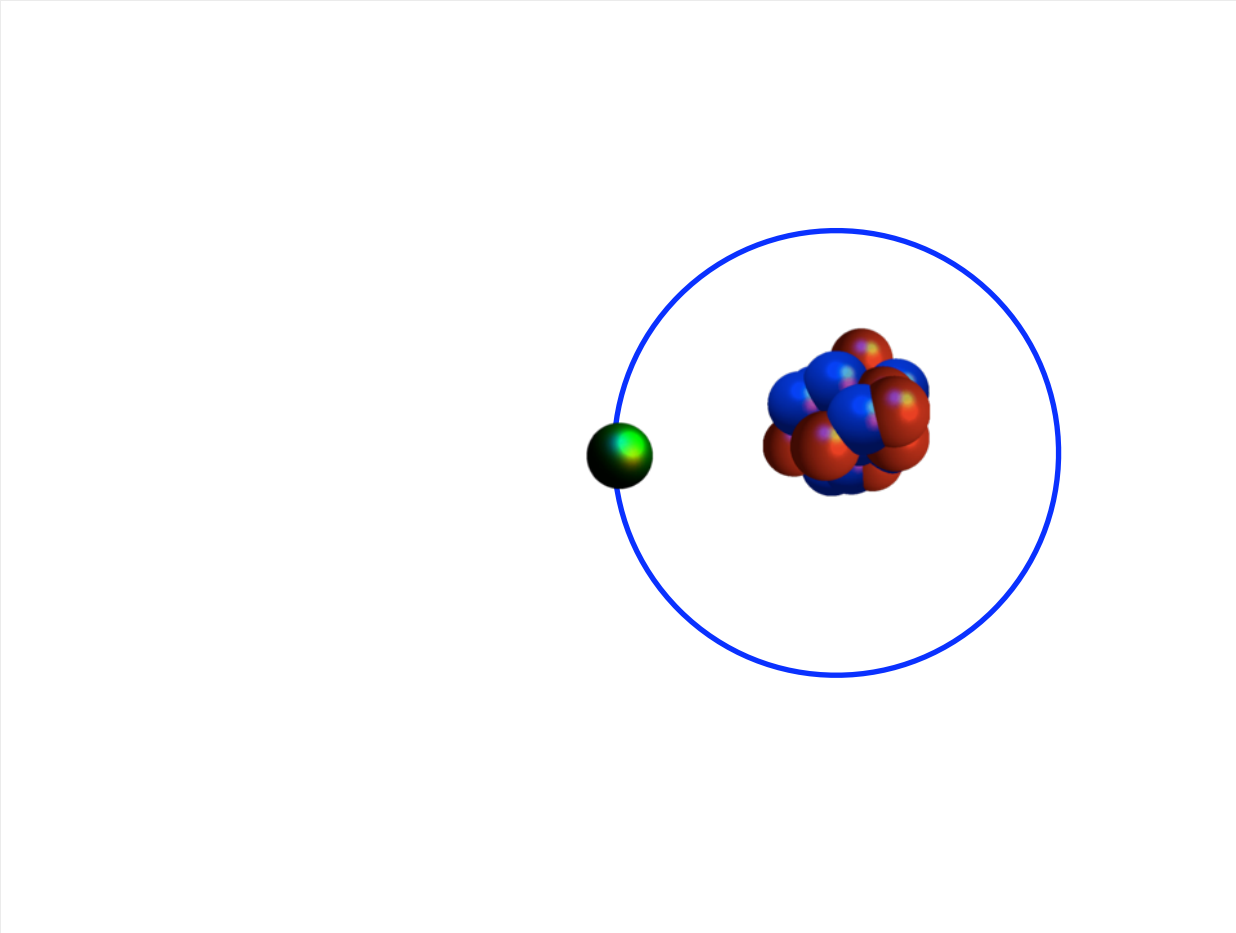


Decay-In-Orbit Background

- 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)



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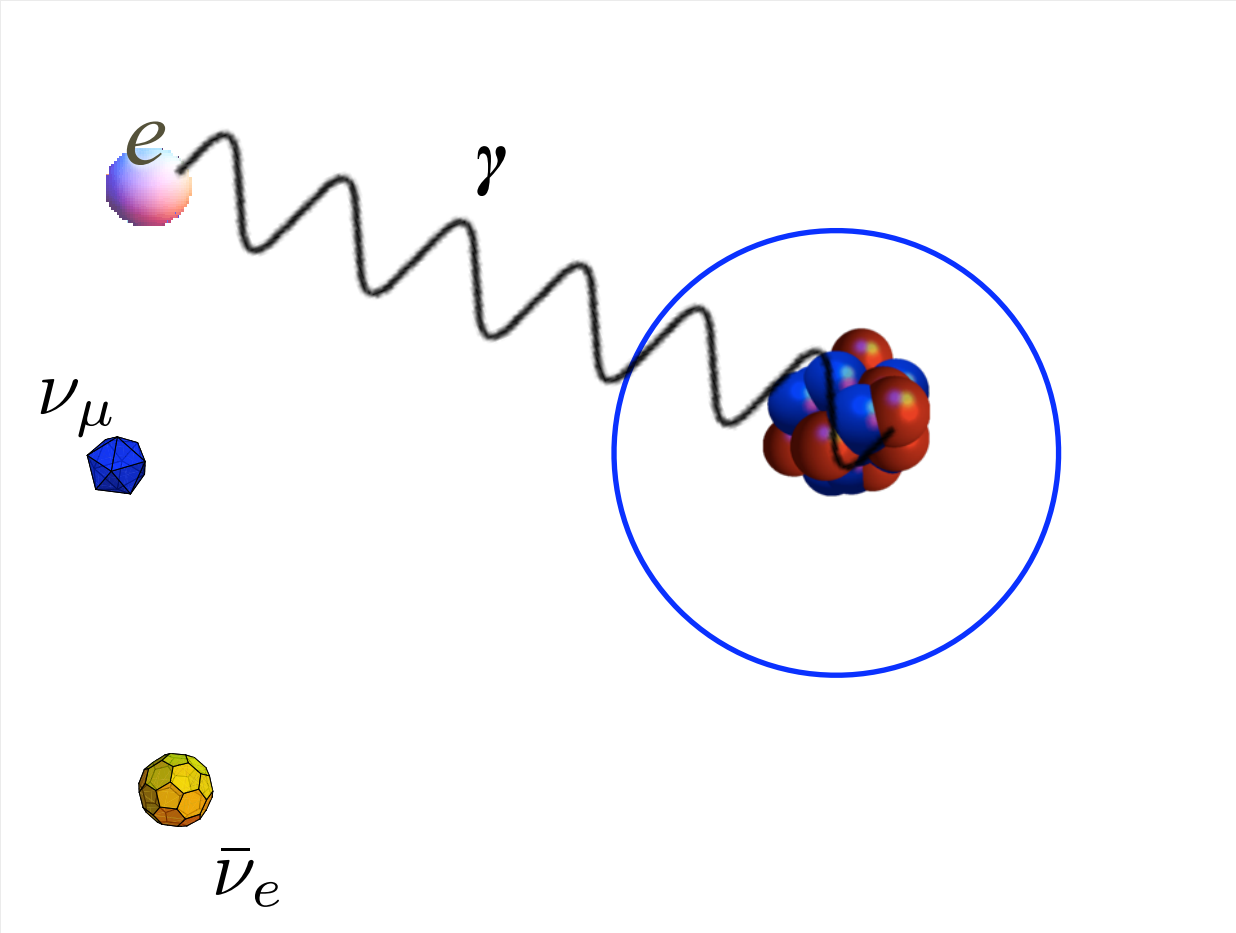

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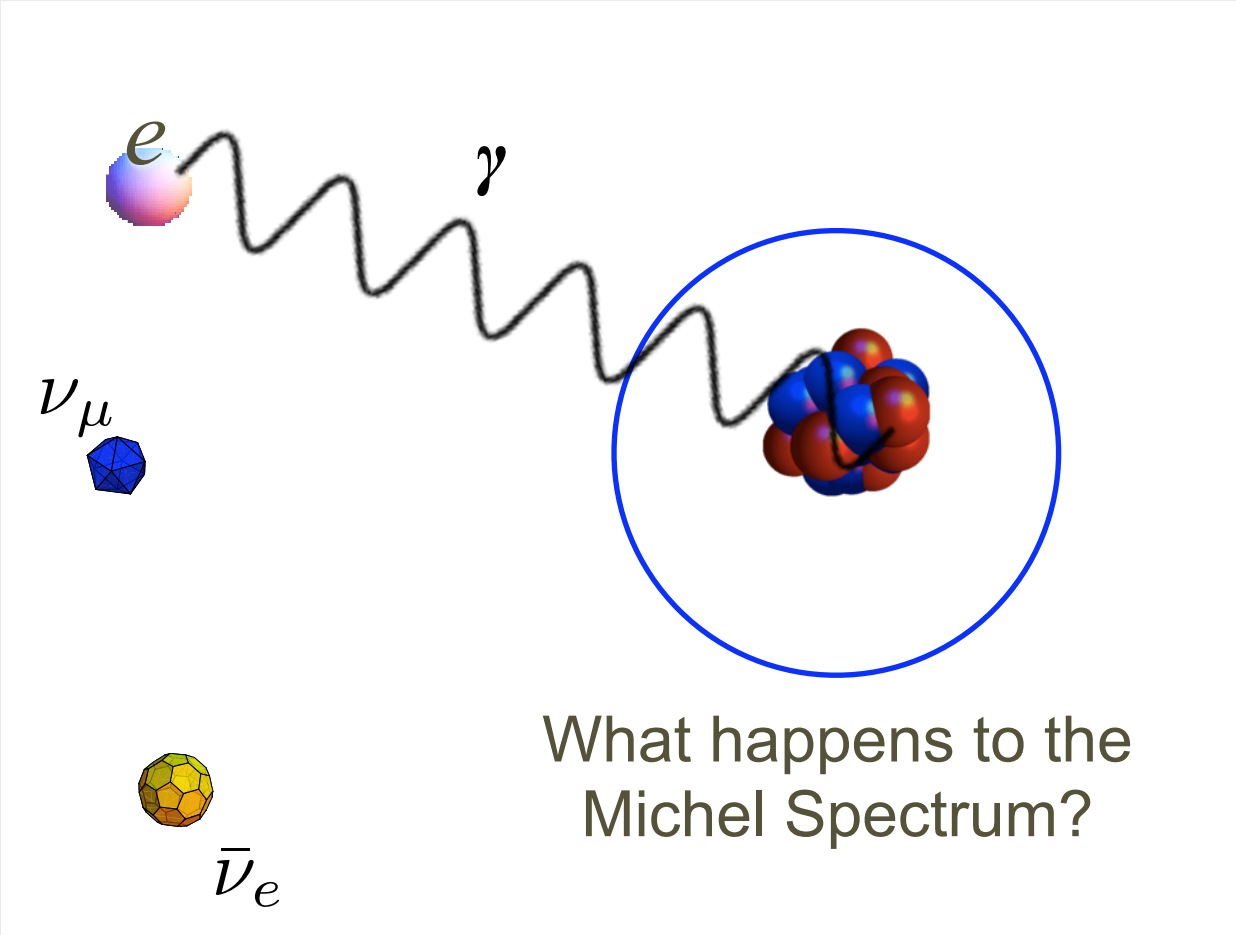
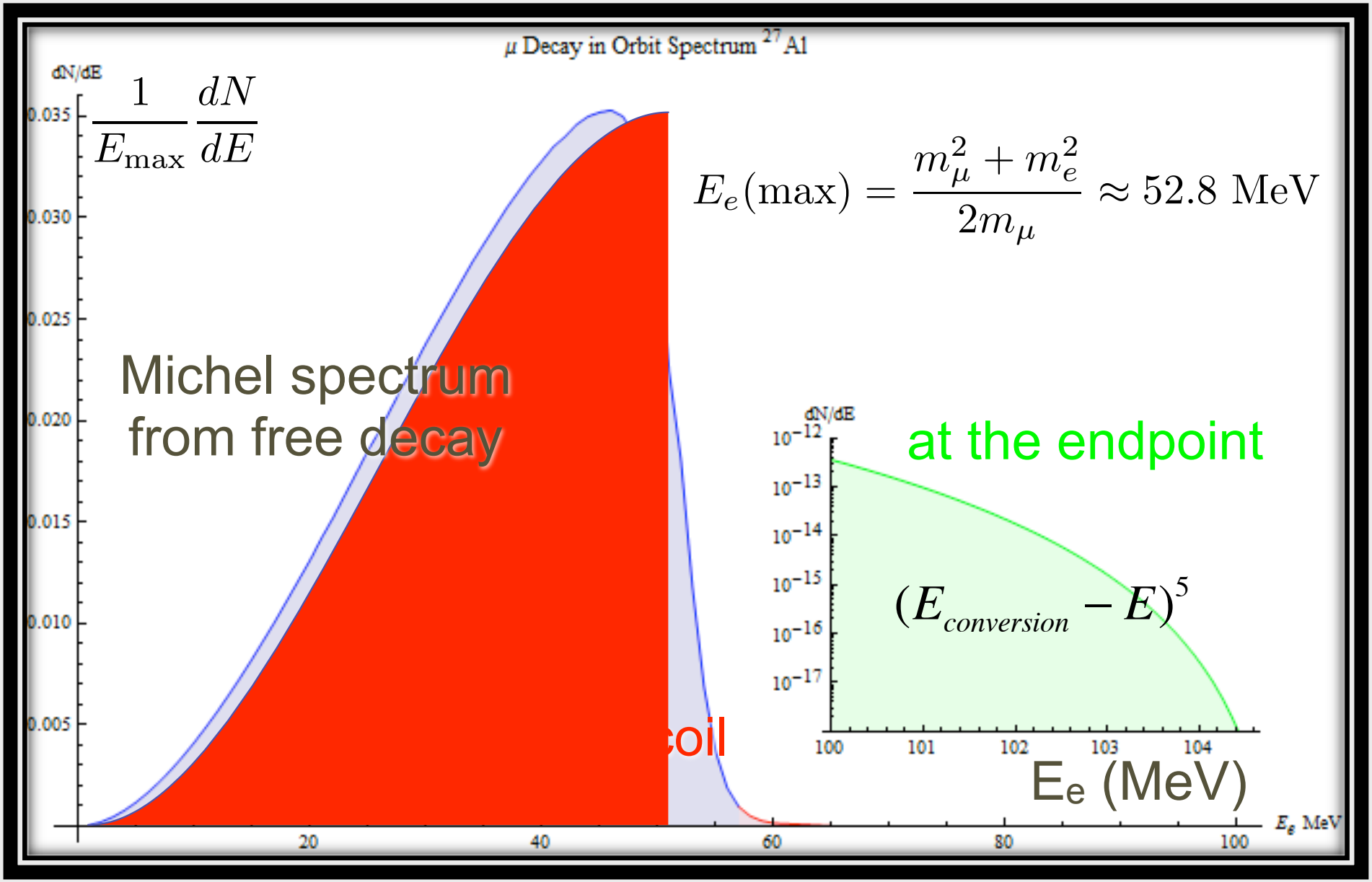
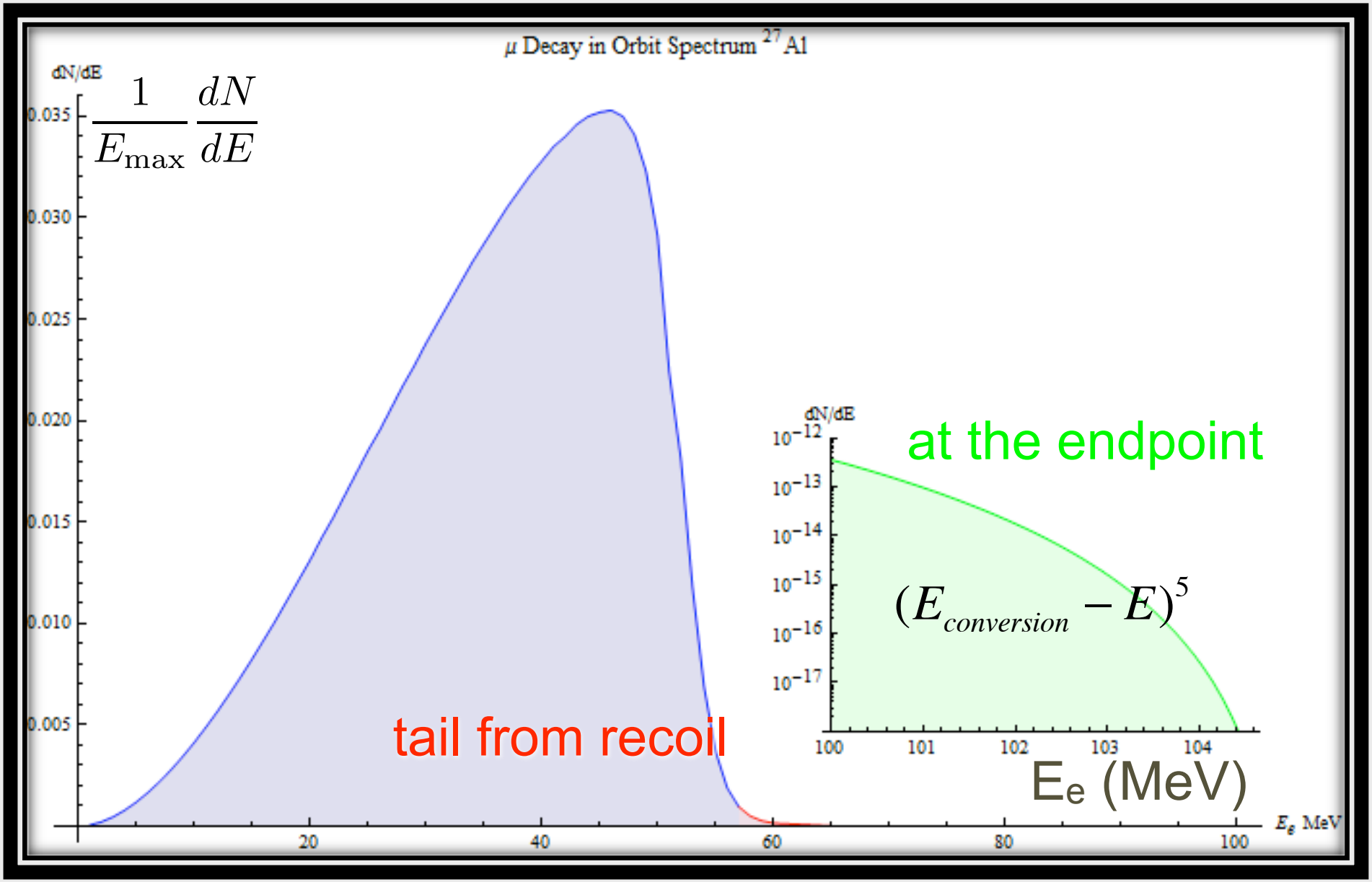


Decay-in-Orbit Shape



Decay-in-Orbit Shape



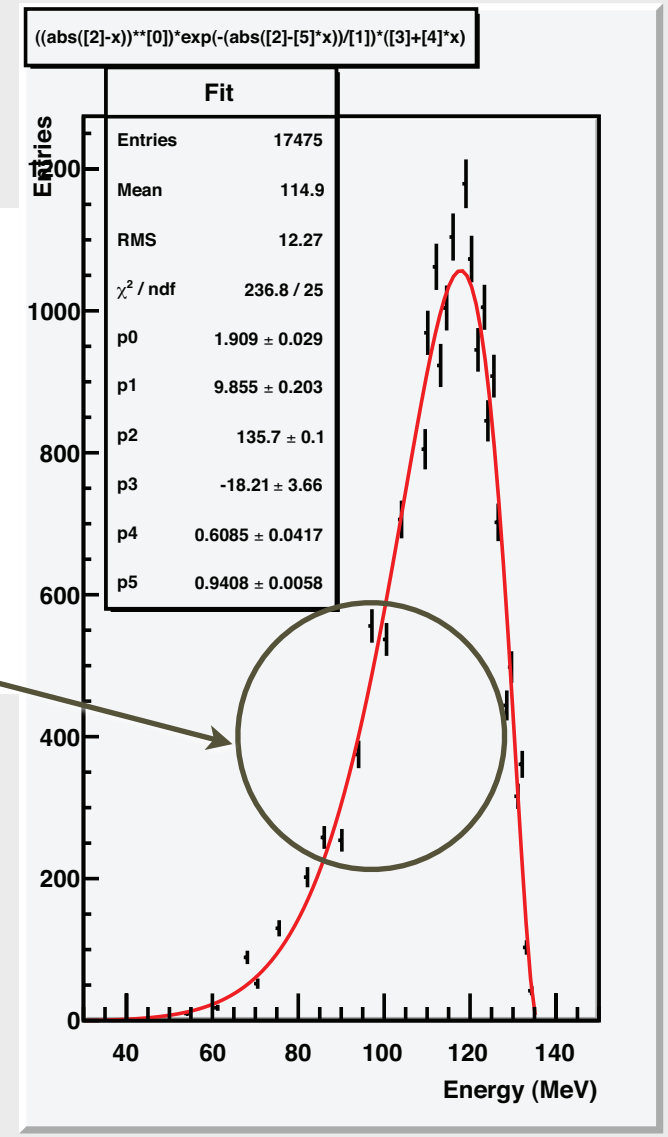
DIO Background Calculation

- 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, pbars

- **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)

fitted by I. Sarra, INFN Frascati/U. Roma

also internal conversion, $\pi^- N \rightarrow e^+ e^- X$

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

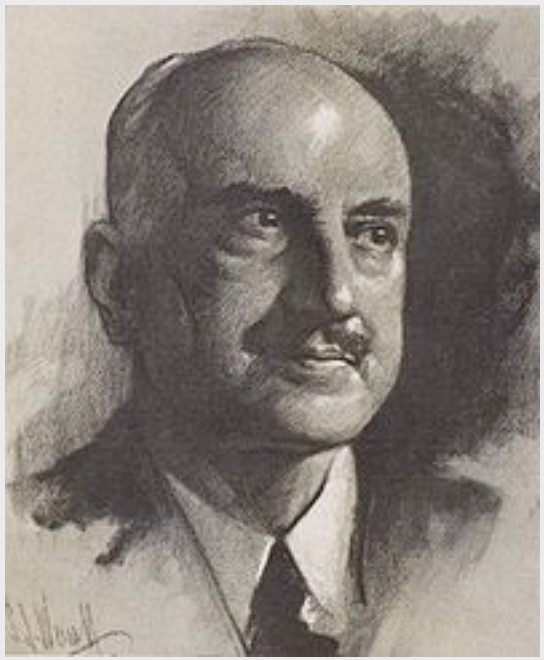
	Decay-In-Orbit	Prompt
Source	Intrinsic Physics Background	Radiative π Capture: Mostly π's produced in production target
Solution	Spectrometer Design: resolution and pattern recognition	Design of Muon Beam, formation, transport, and time structure

Outline

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

What Limited Previous Measurements?

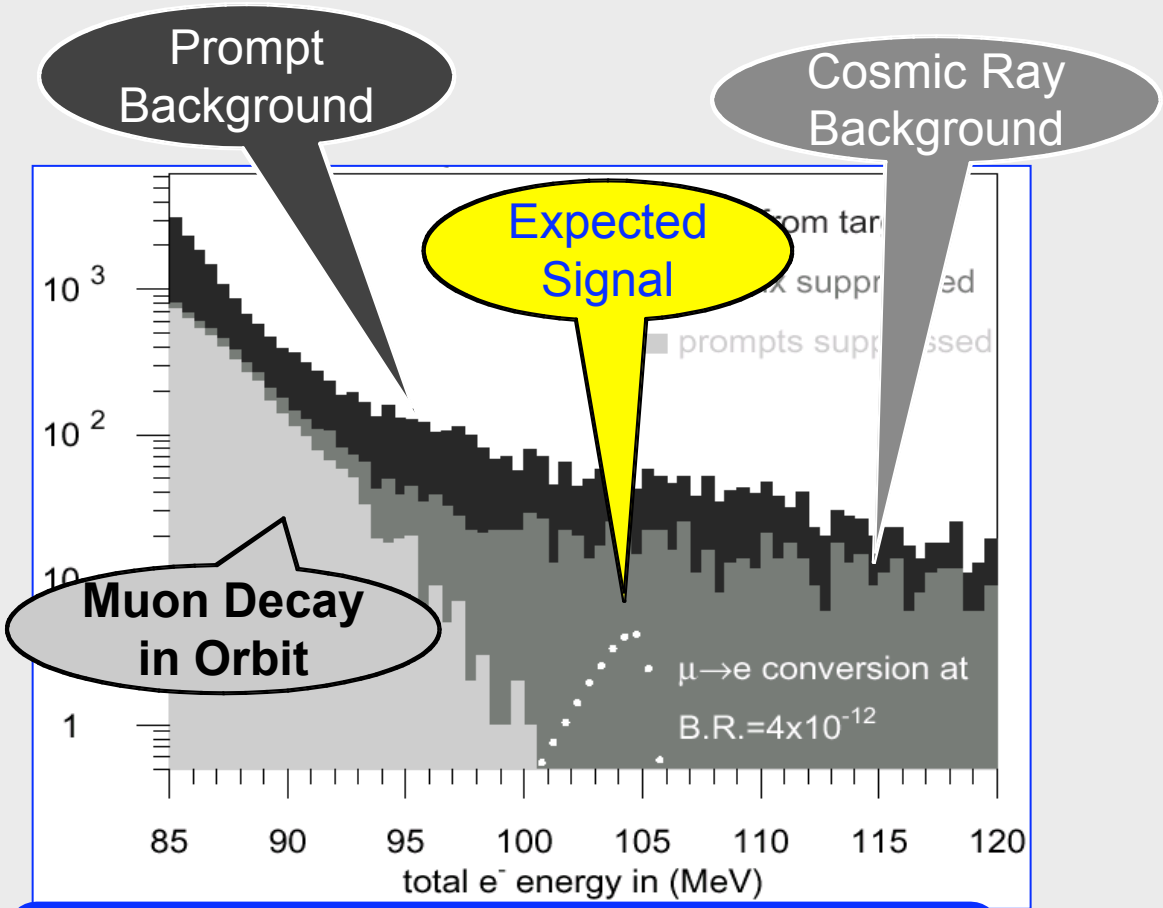
- “Those who cannot remember the past are condemned to repeat it” --G. Santayana



Previous Best Experiment

SINDRUM-II

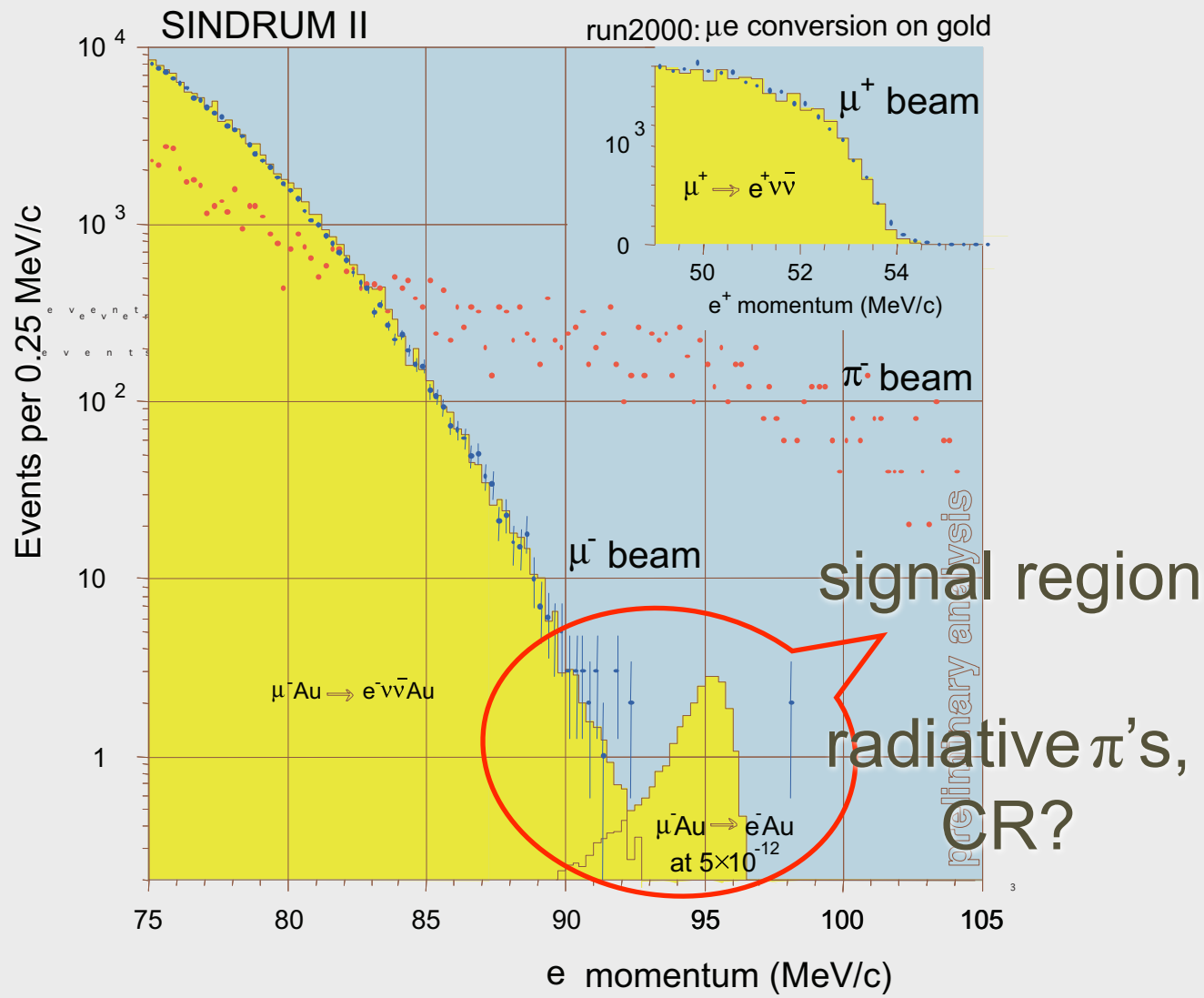
- $R_{\mu e} < 6.1 \times 10^{-13}$ in Au
- Want to probe to 6×10^{-17}
- $\approx 10^4$ improvement



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?

DC Beam

no time separation between signal and prompt background

radiative π capture

PAUL SCHERRER INSTITUT

Background : b) pion induced

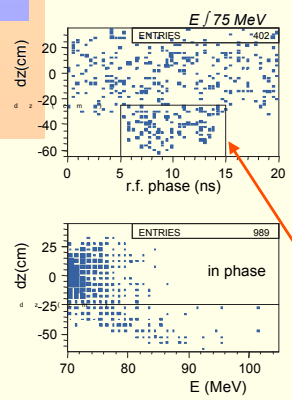
Radiative Pion Capture (RPC) : $\pi^- Au \rightarrow \gamma + Pt^*$ followed by $\gamma \rightarrow e^+ e^-$

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!

positron distributions



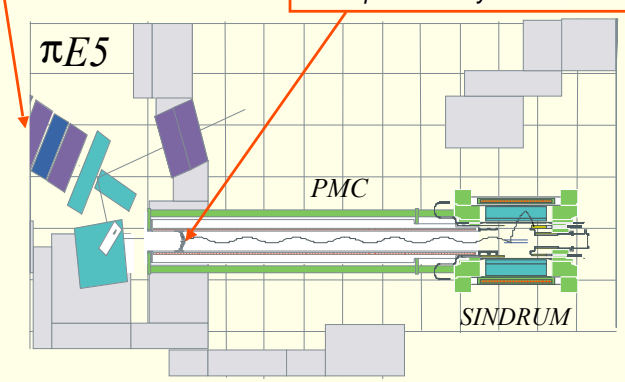
July 14, 2001

***BUT:** Degrader is now pion stop target → 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 near-limiting for DC beam

How Can We Do Better?

$>10^3$ increase in muon intensity from SINDRUM

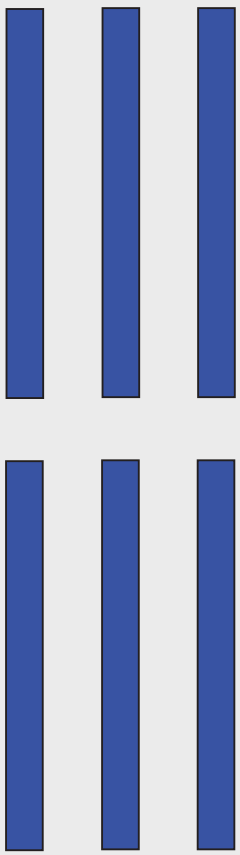
Requiring

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

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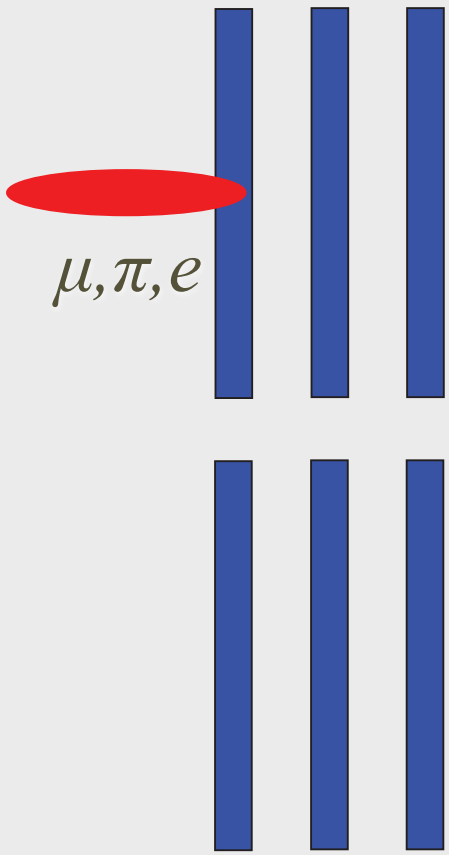

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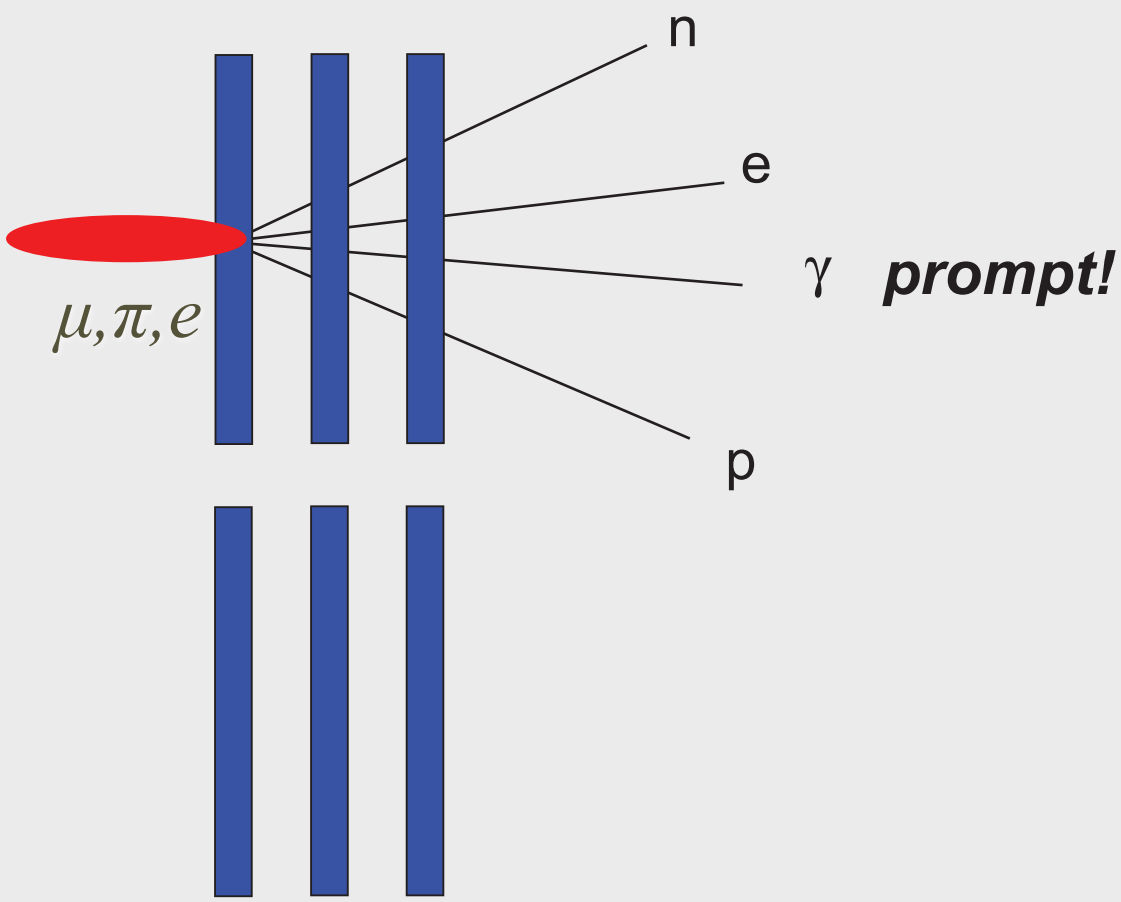

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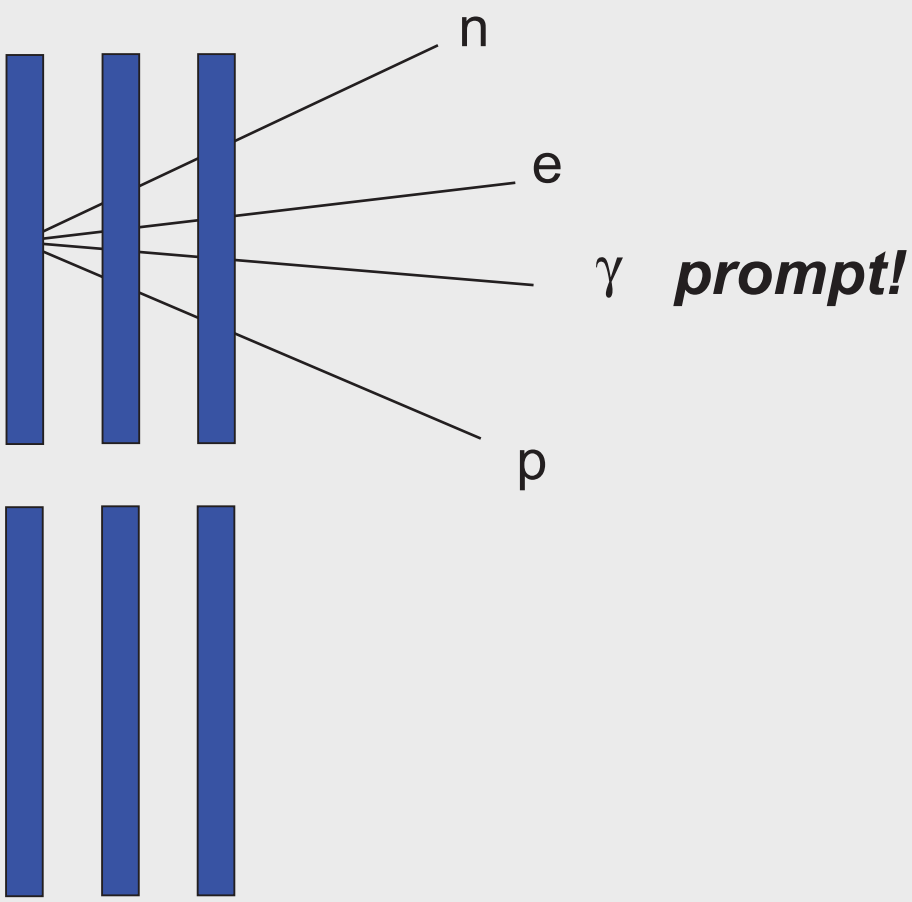

prompt!

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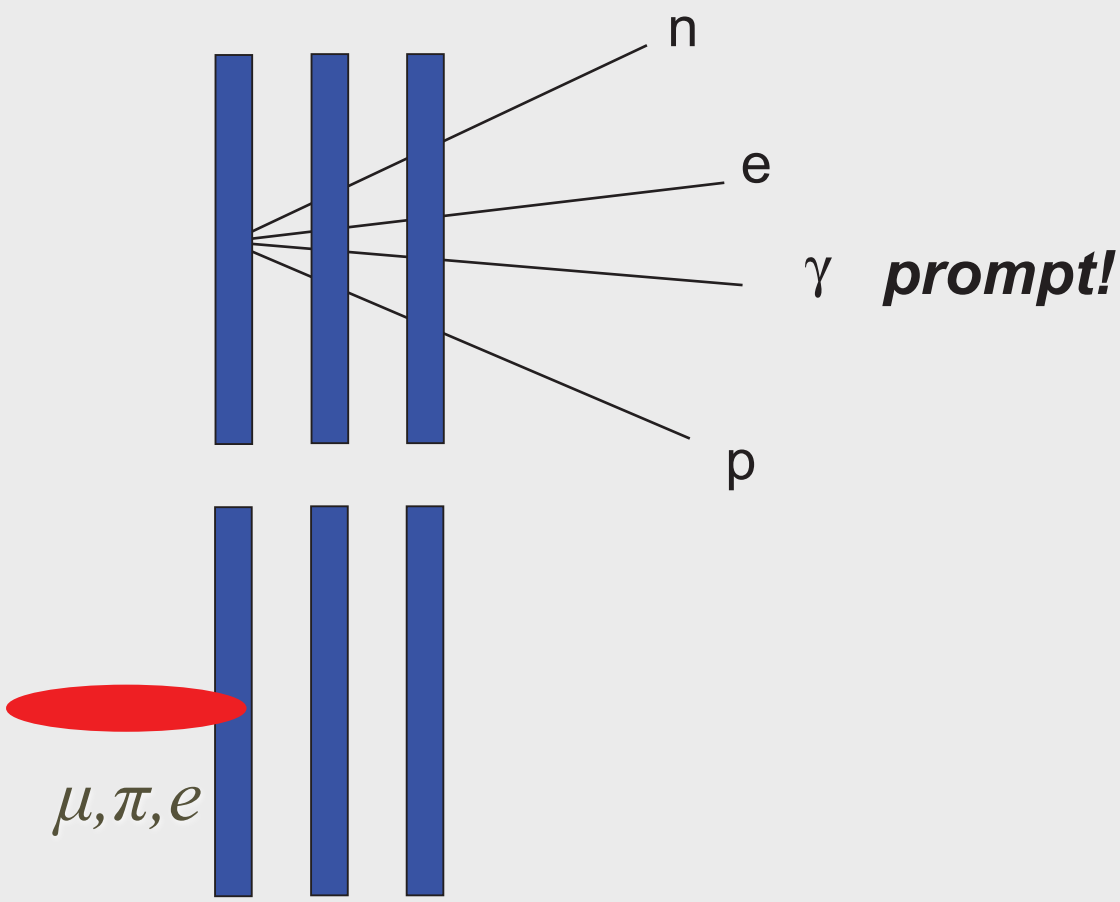

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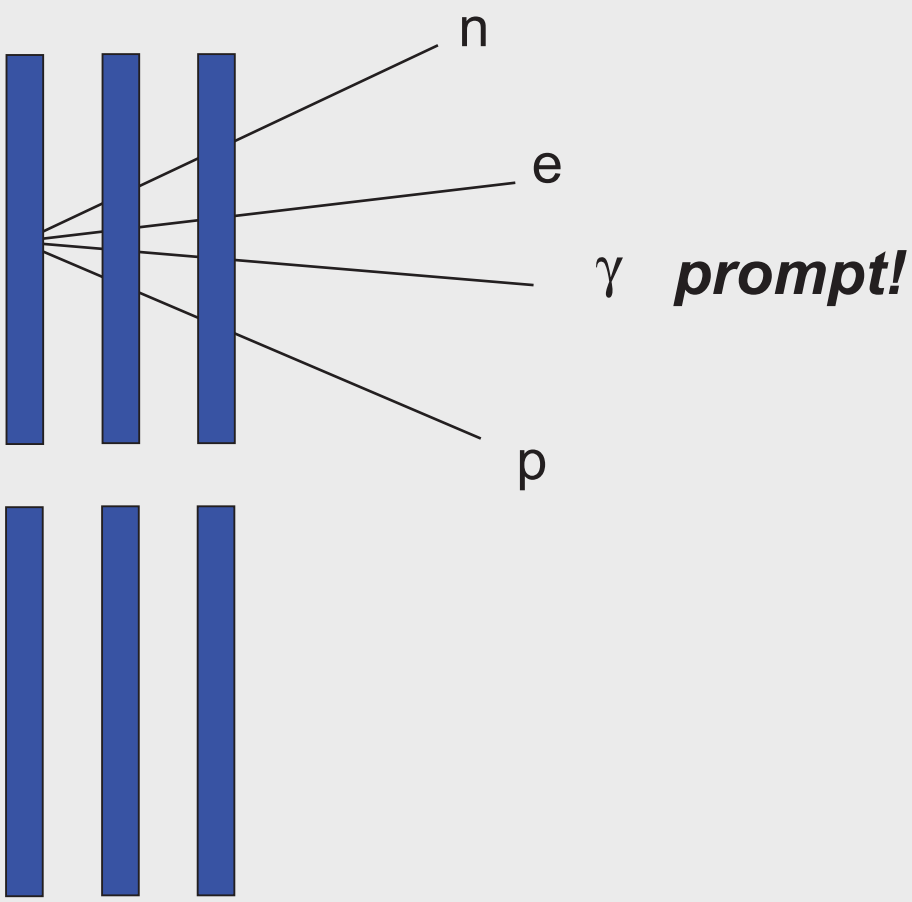

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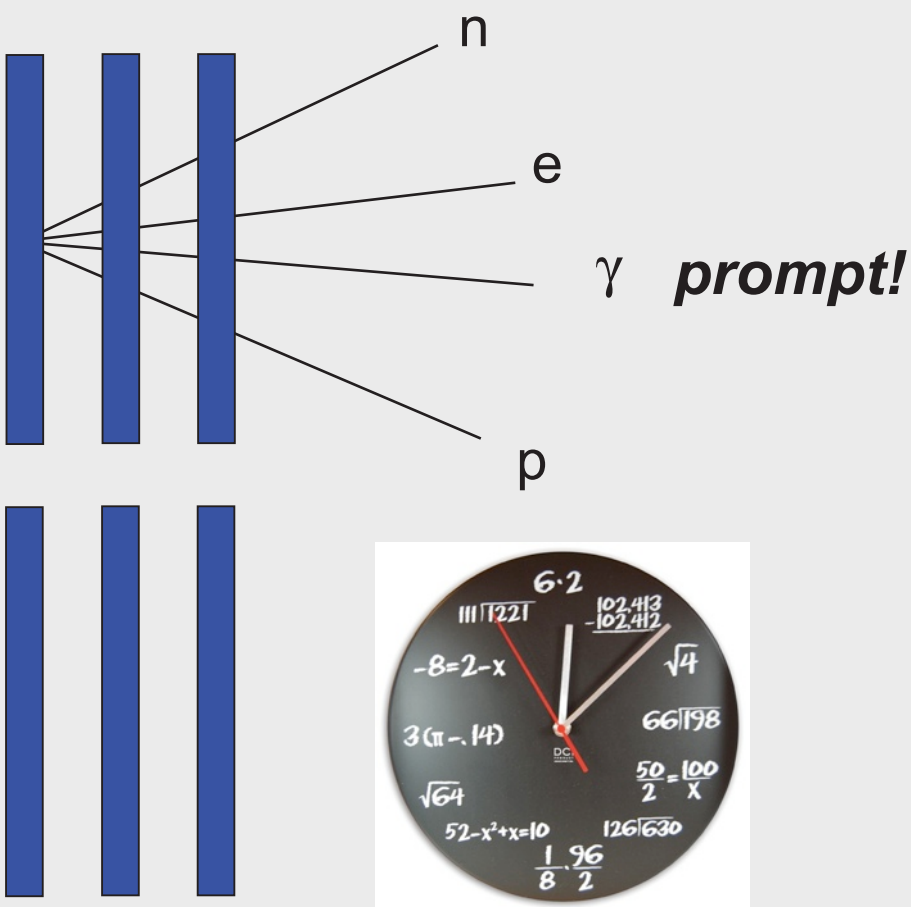

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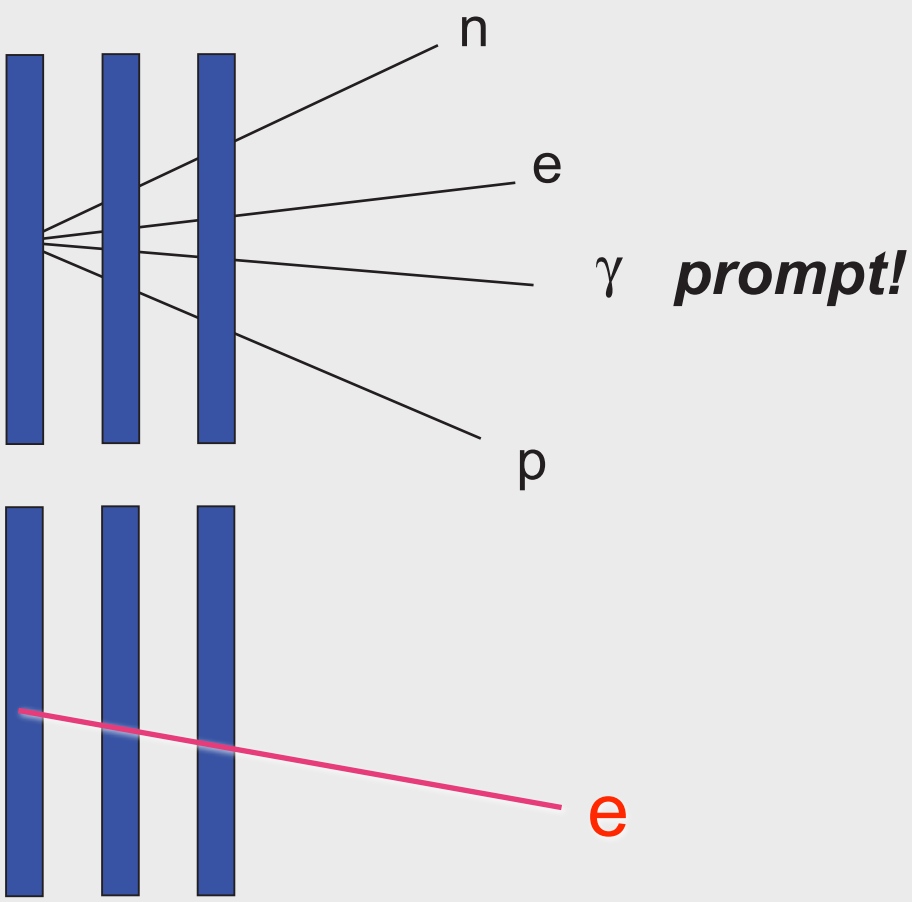

delayed 105 MeV electron

Recall:
Muon-electron conversion signal is a

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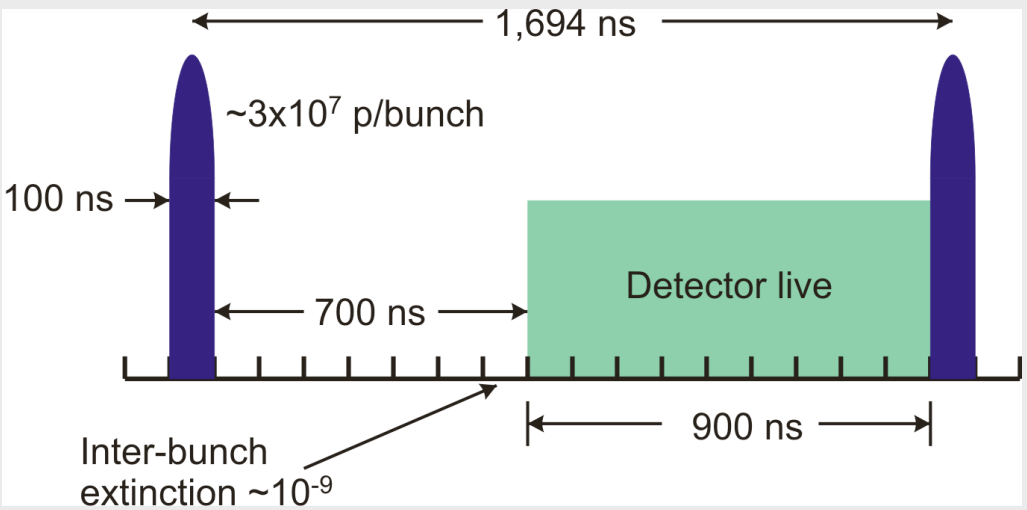
pulsed beam lets us wait until after prompt backgrounds disappear and rate lowered

Pulsed Beam Structure

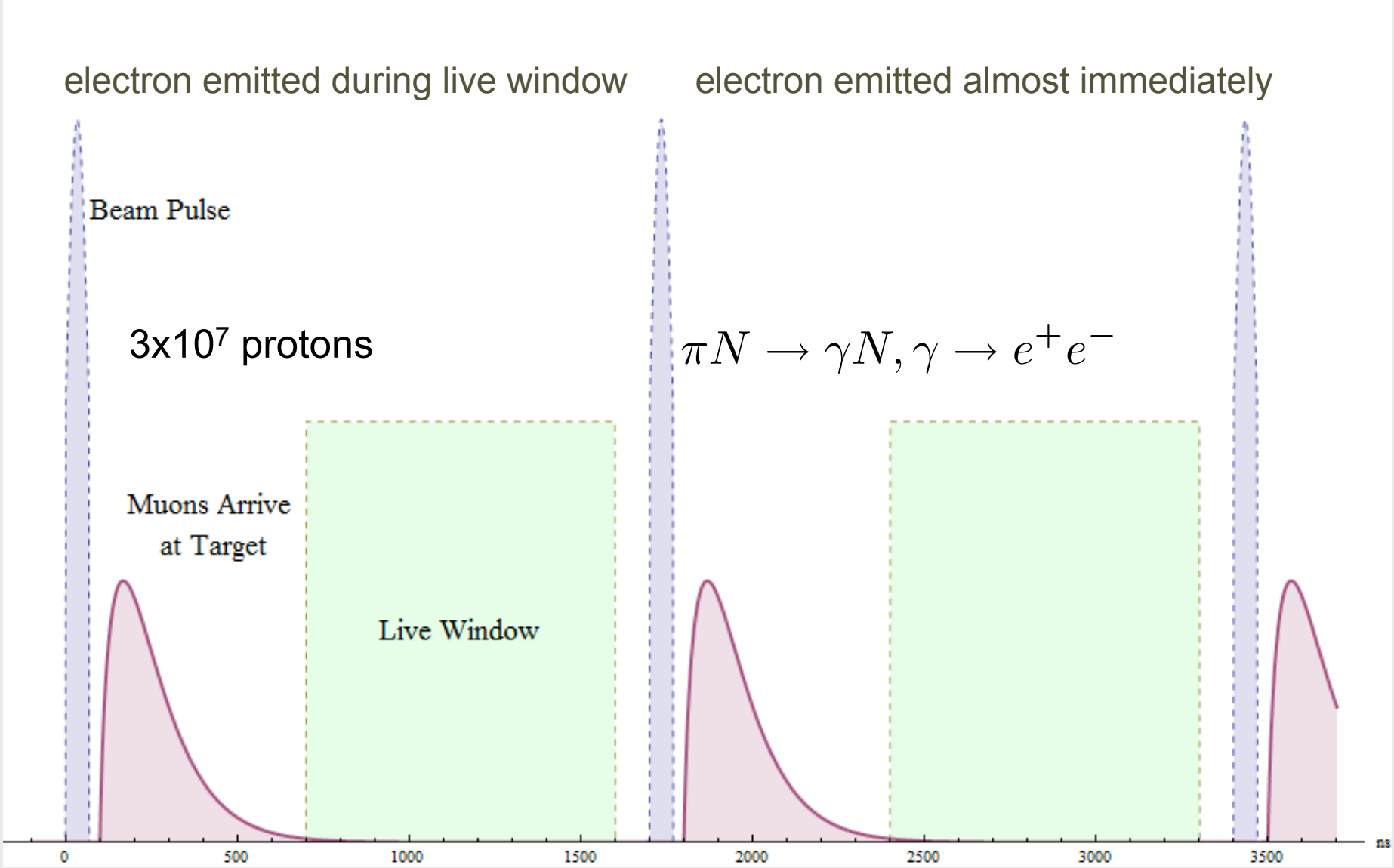
- Tied to prompt rate and machine: FNAL "perfect"
- Want pulse duration << τ_μ^{Al} , pulse separation ≈ τ_μ^{Al}
  - FNAL Debuncher has circumference 1.7μsec !
- Extinction between pulses < 10^{-9} needed

  = # protons out of pulse/# protons in pulse



- 10^{-9} based on simulation of prompt backgrounds

Pulsed Beam Structure and Radiative π Capture



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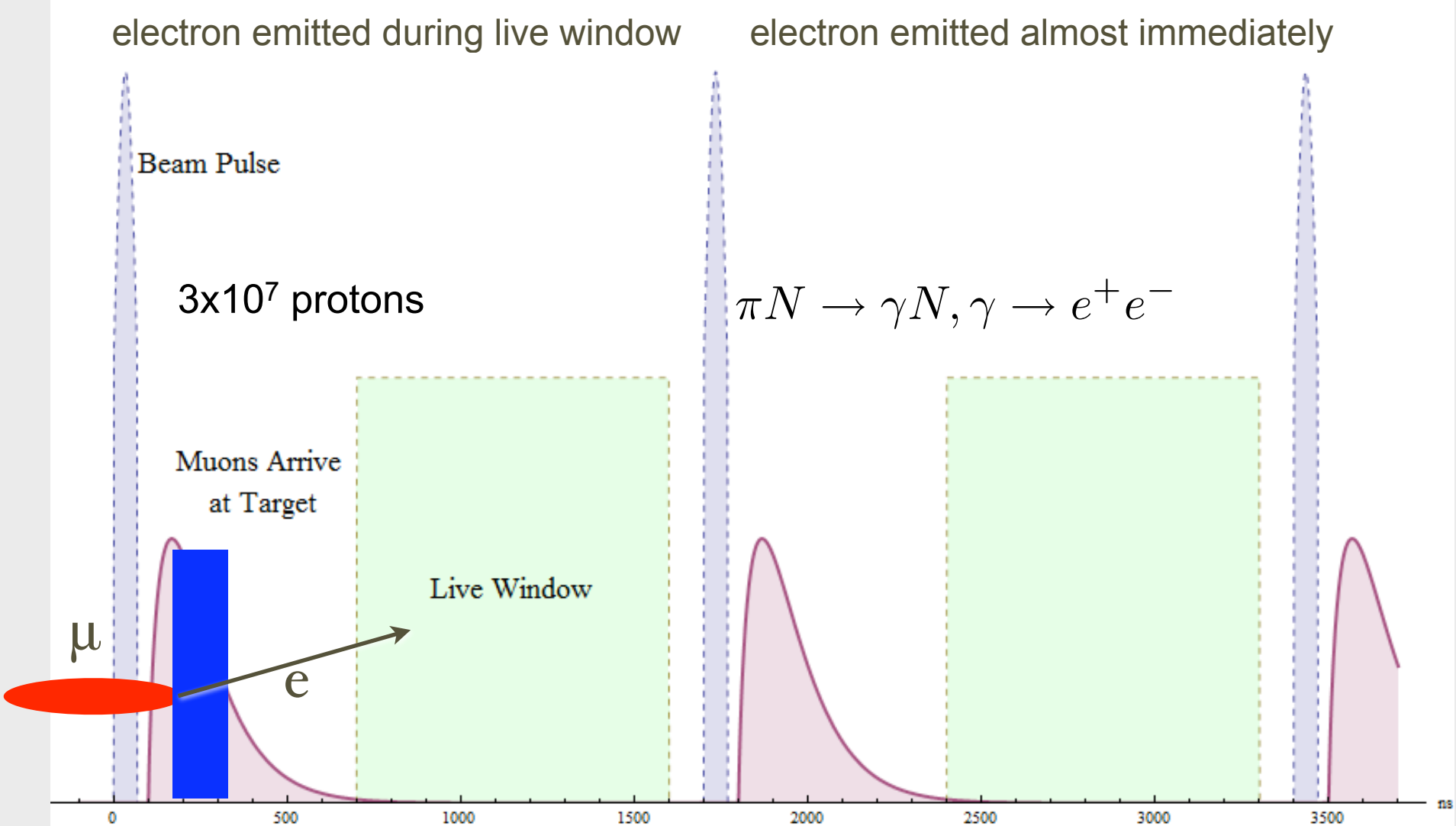

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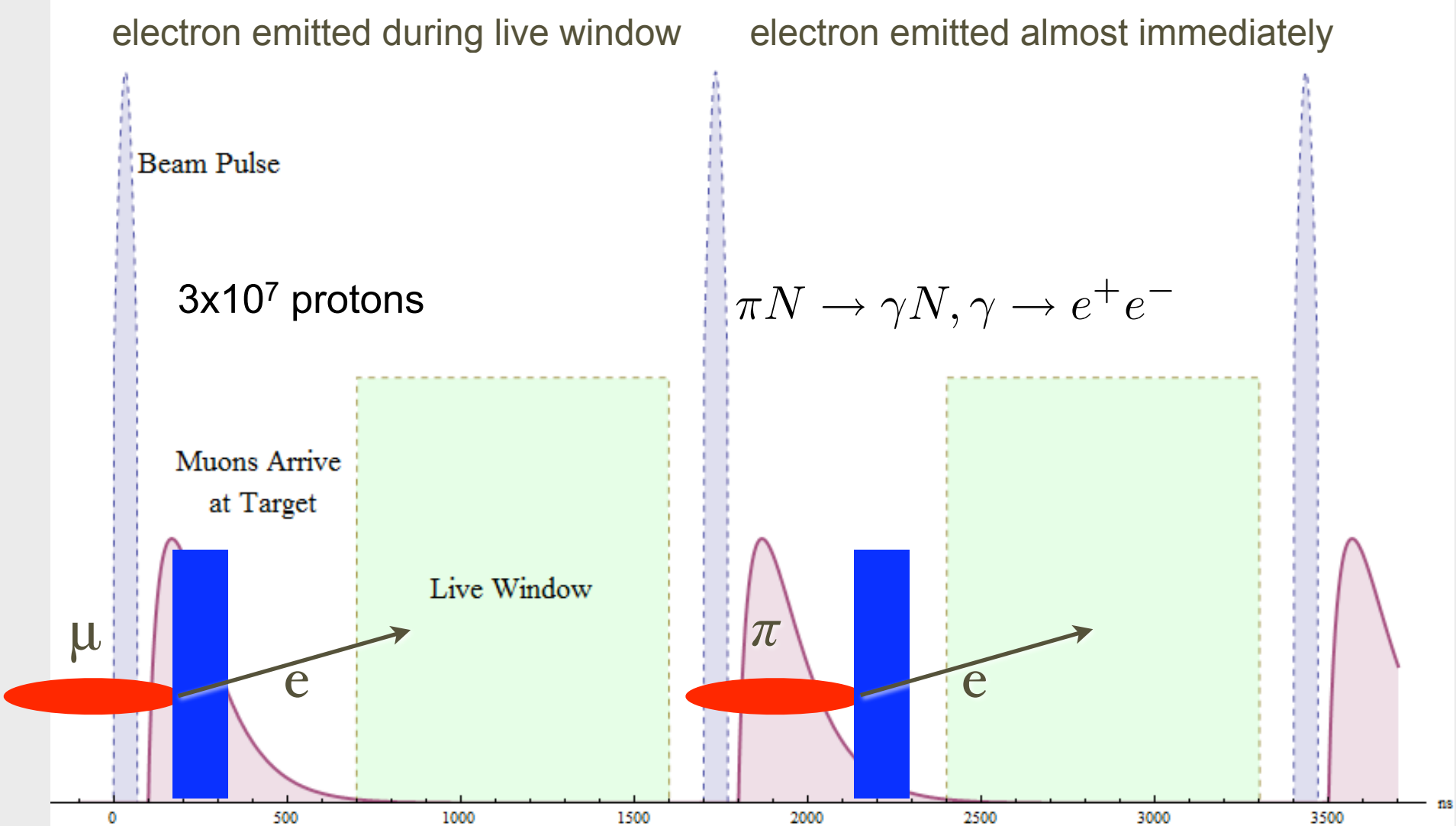

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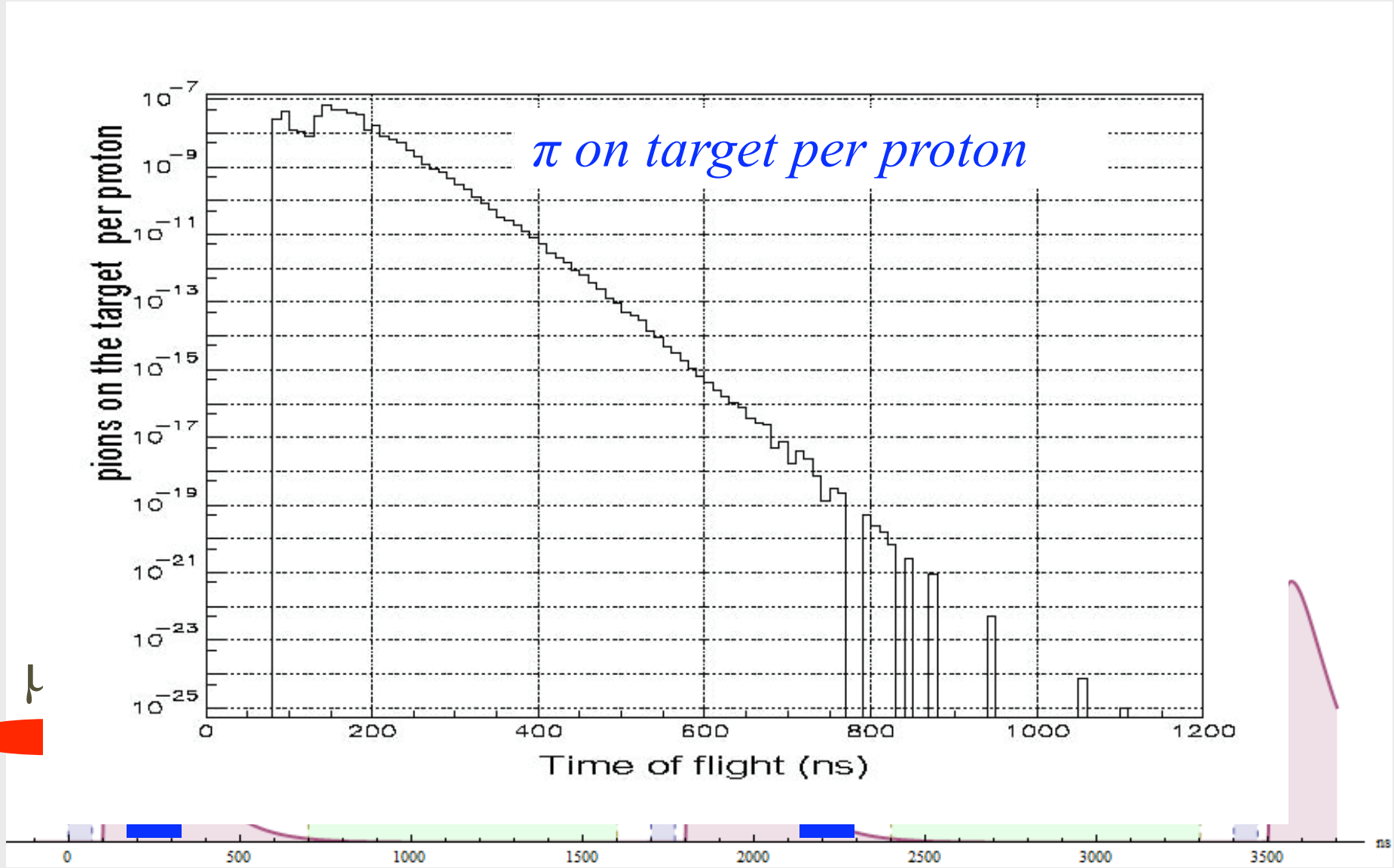

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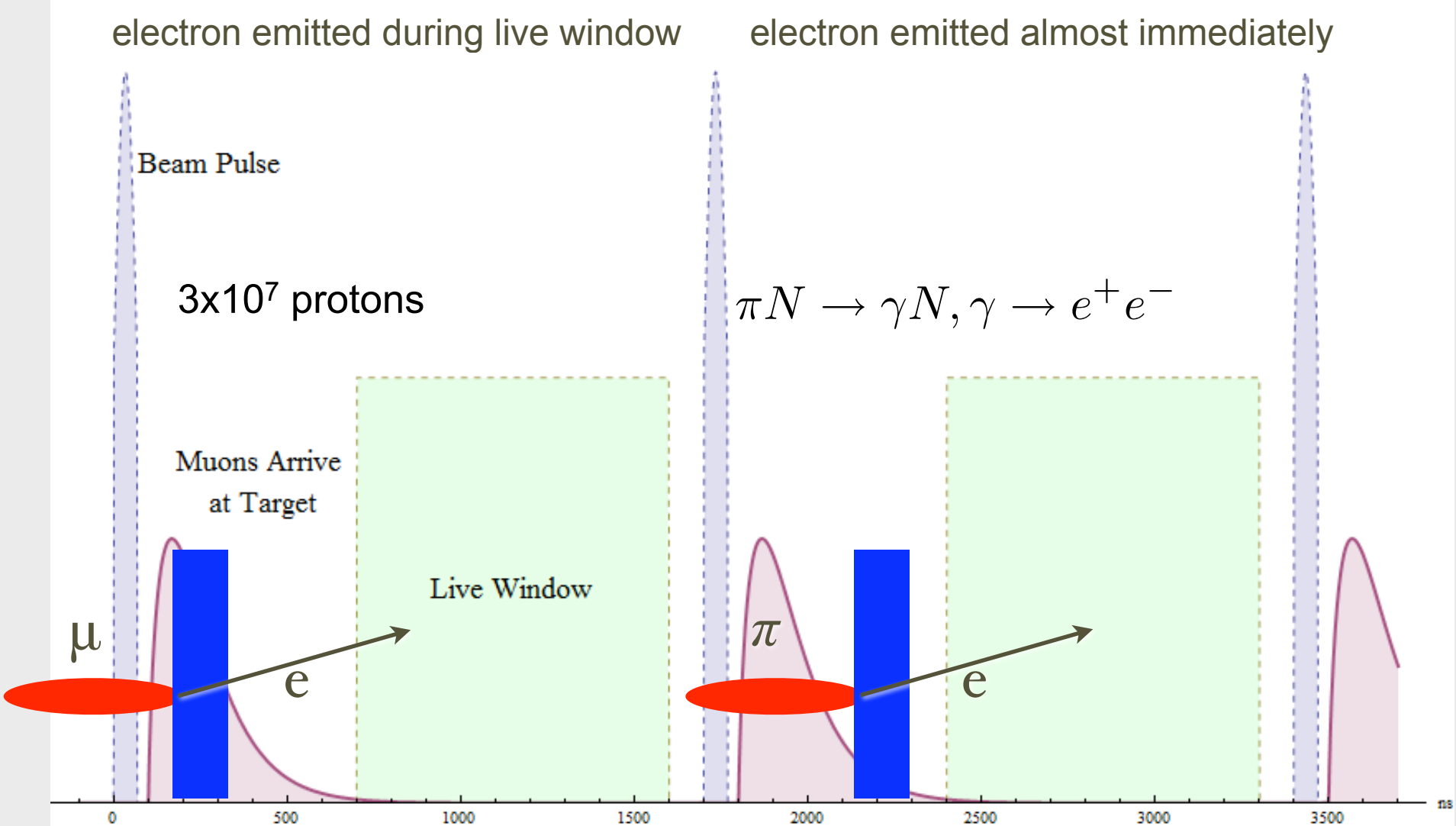
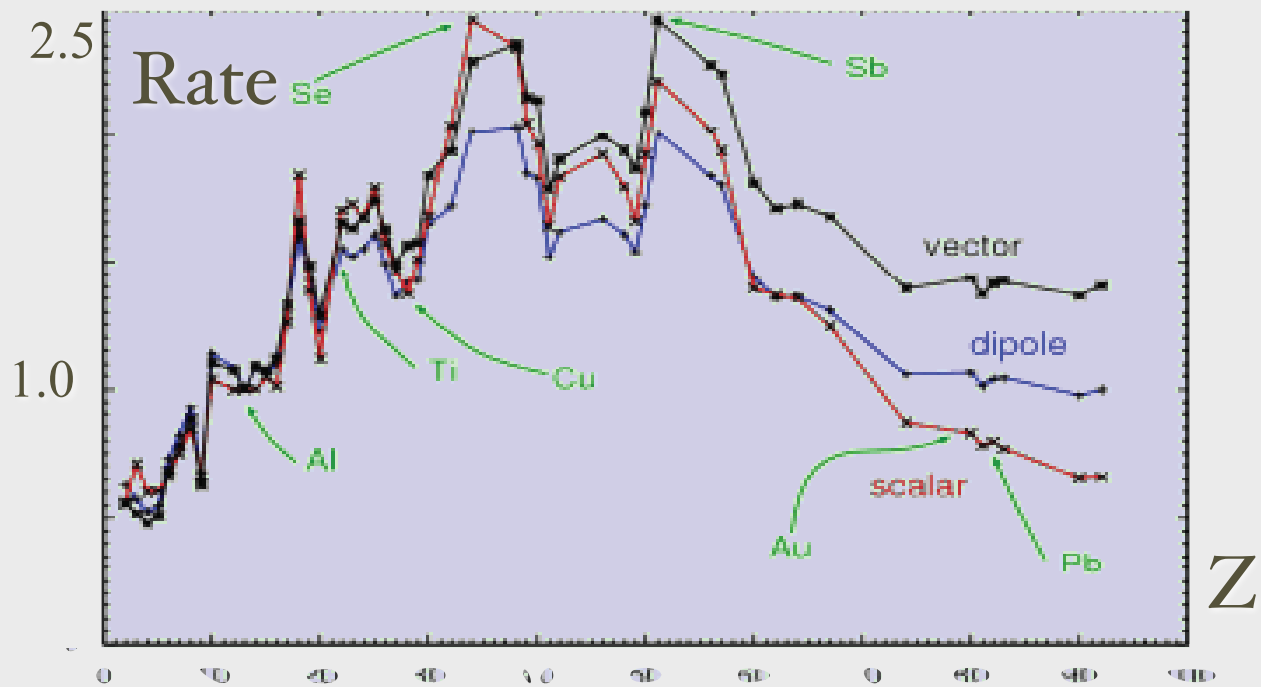


Choice of Stopping Material: rate vs wait

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

rate normalized to Al



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

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

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Choice of Stopping Material: rate vs wait

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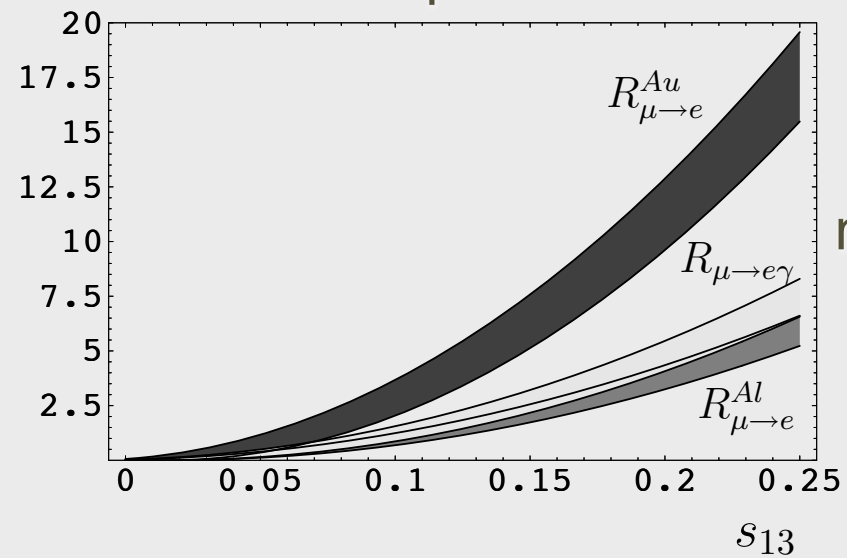
- Physics sensitive to Z: with signal, can switch target to probe source of new physics
- Why start with Al?

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**

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

Prompt Background and Choice of Z

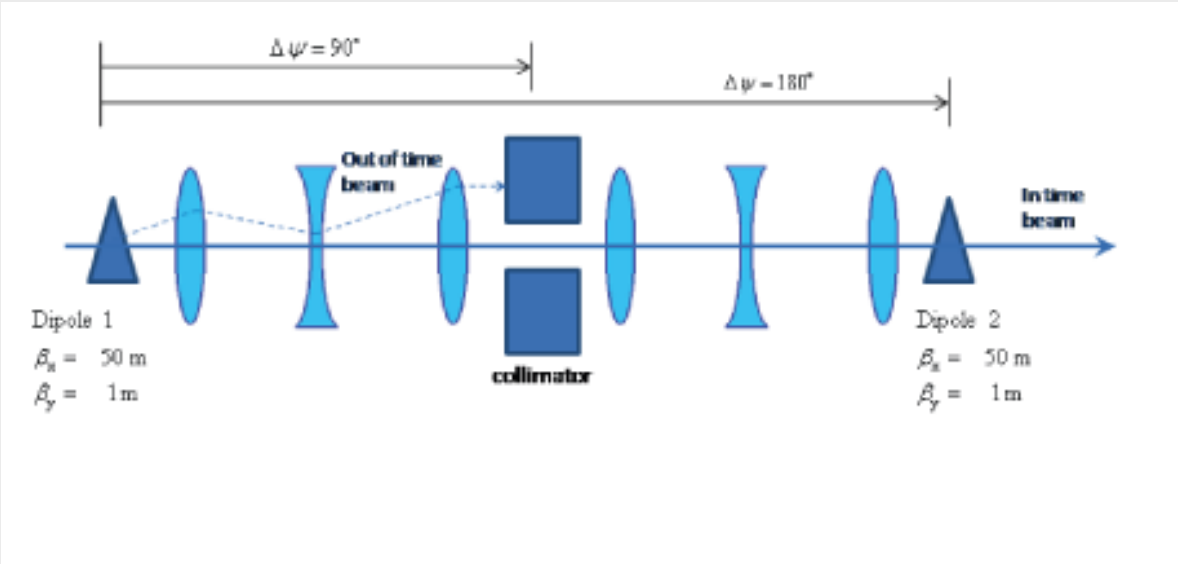
choose Z based on tradeoff between rate and lifetime: longer lived reduces prompt backgrounds

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

Extinction Scheme

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

- Eliminate protons in beam in-between pulses:

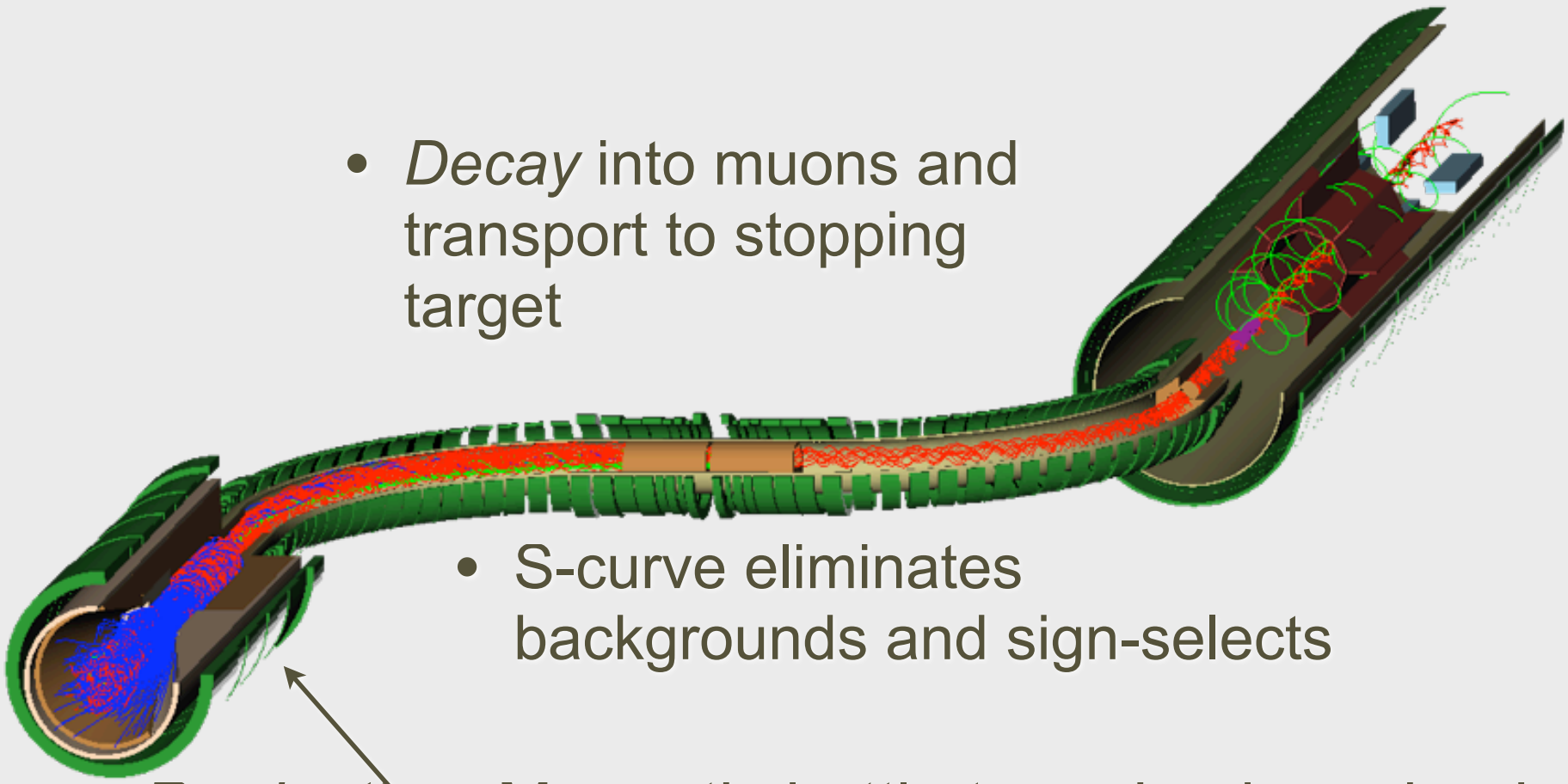


CDR under development

- 10^{-7} Achieved at BNL without above or other external methods
- Continuous Extinction monitoring techniques under study
  - telescope as in MECO
  - (also work at Osaka for COMET)

Detector and Solenoid

- *Tracking and Calorimeter*

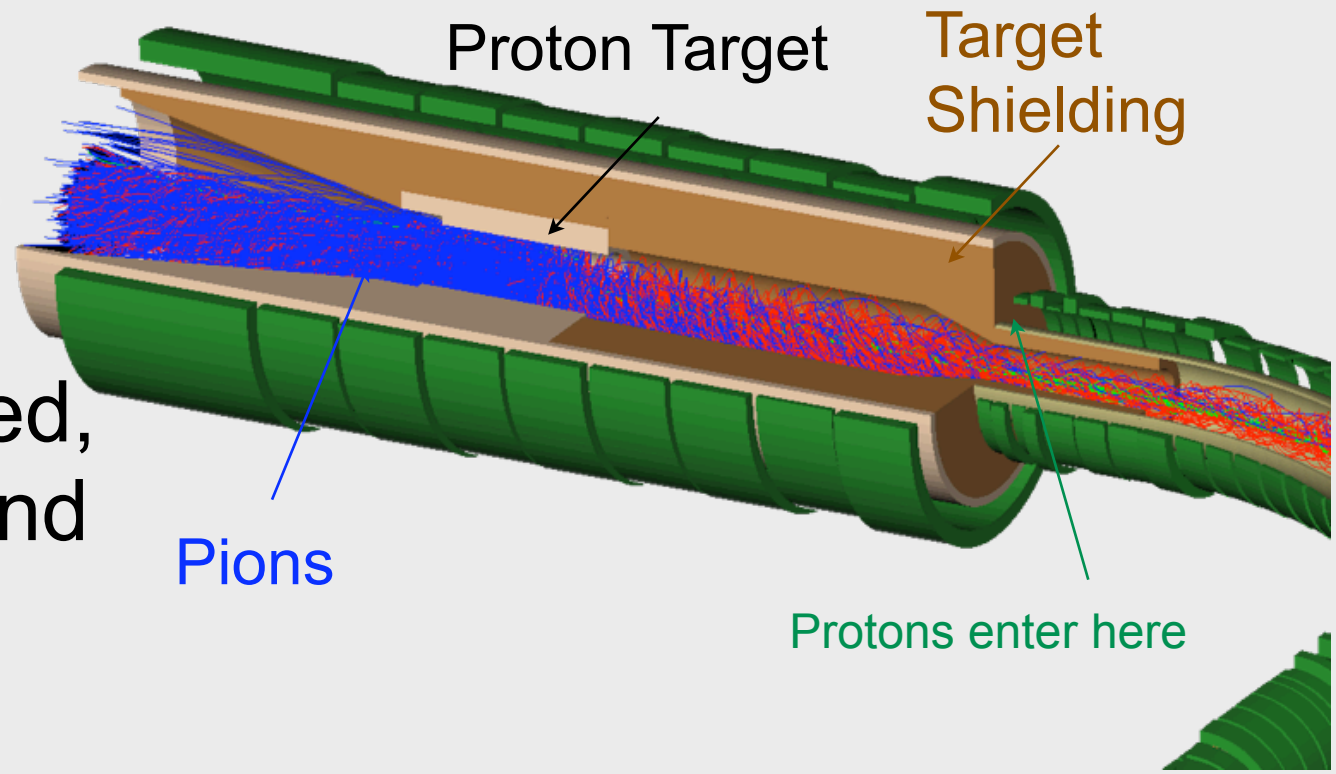


- *Decay* into muons and transport to stopping target
- S-curve eliminates backgrounds and sign-selects
- *Production*: Magnetic bottle traps backward-going π that can decay into accepted μ's

Production Solenoid:

Protons enter opposite to outgoing muons

Protons leave through thin window



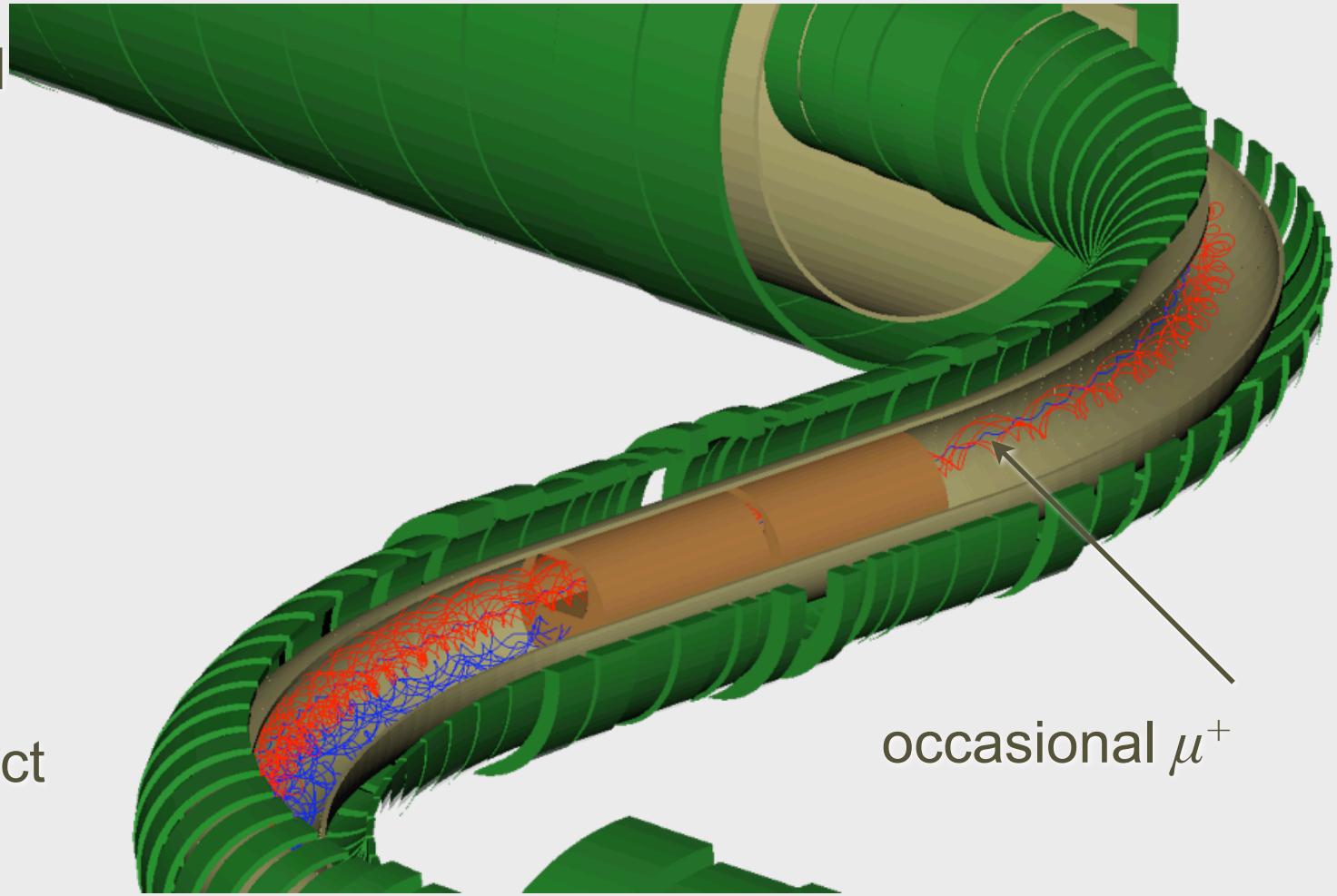
π's are captured, spiral around and decay

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

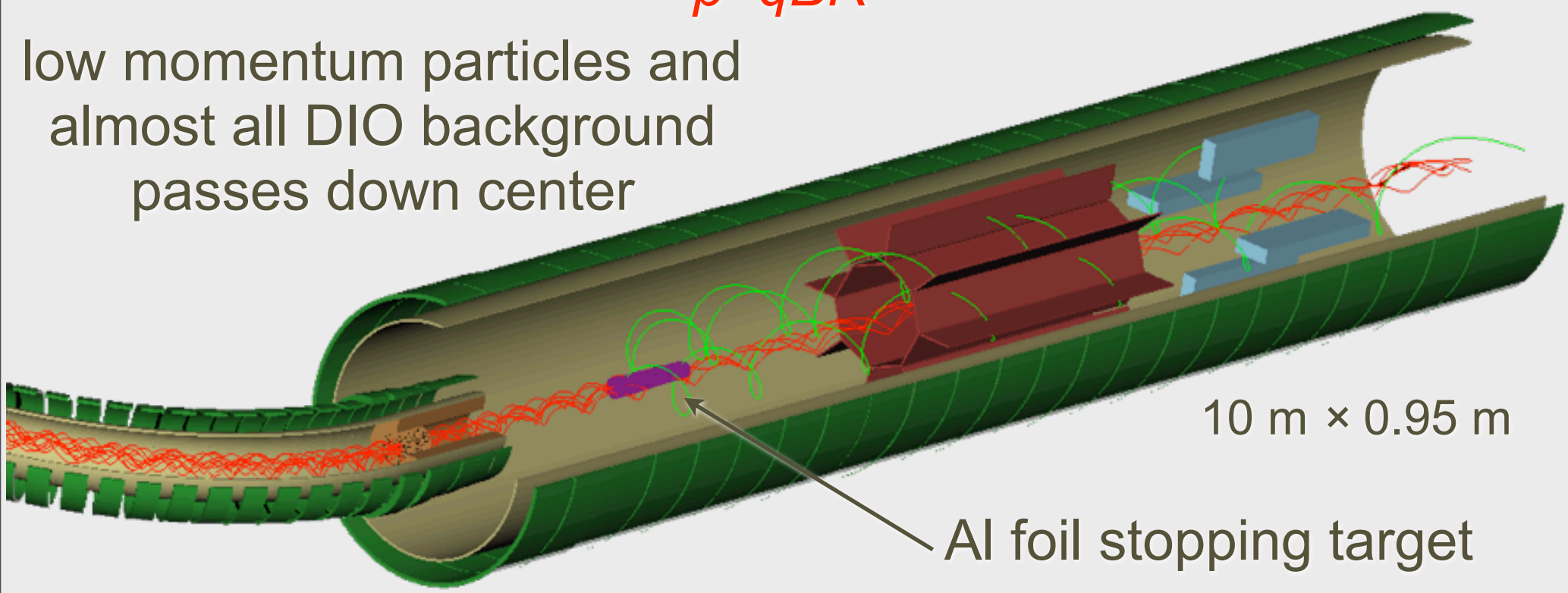


13.1 m along axis × ~0.25 m

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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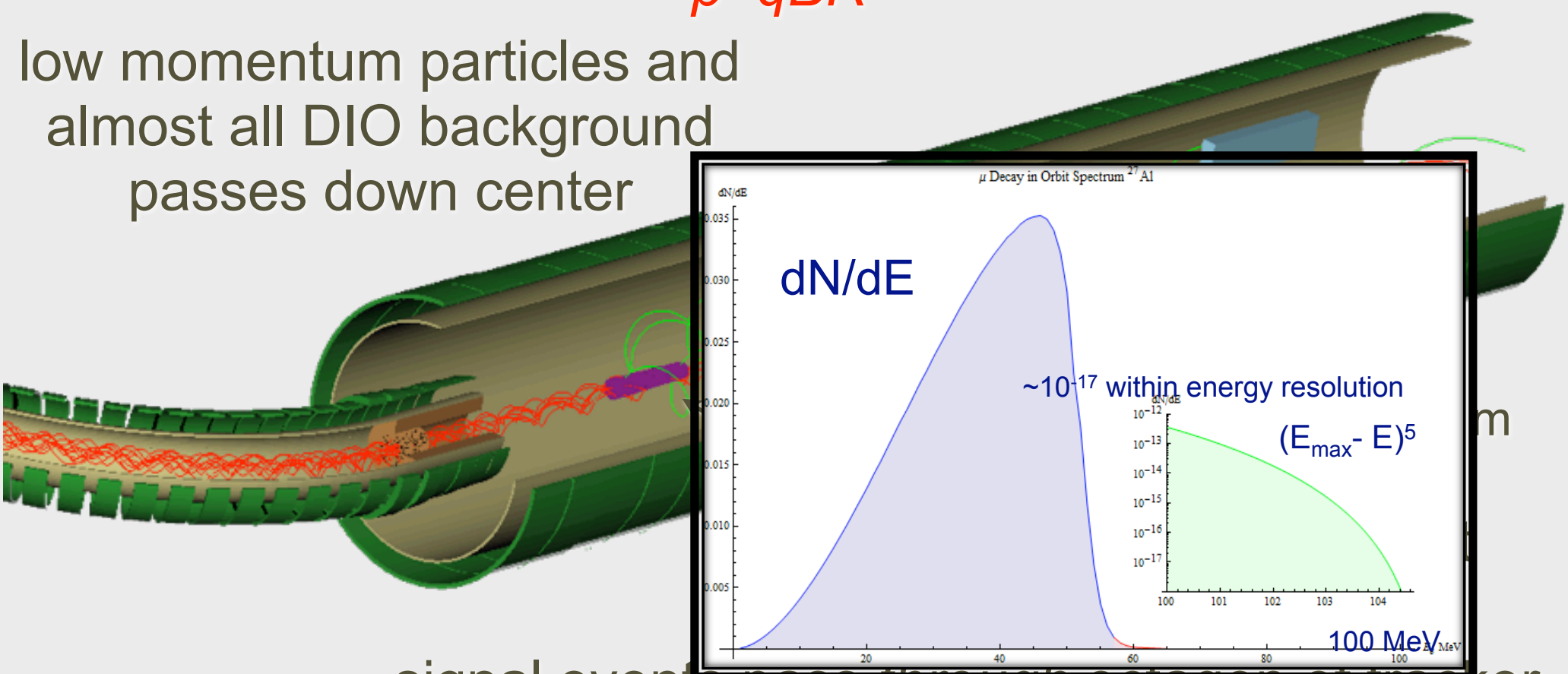

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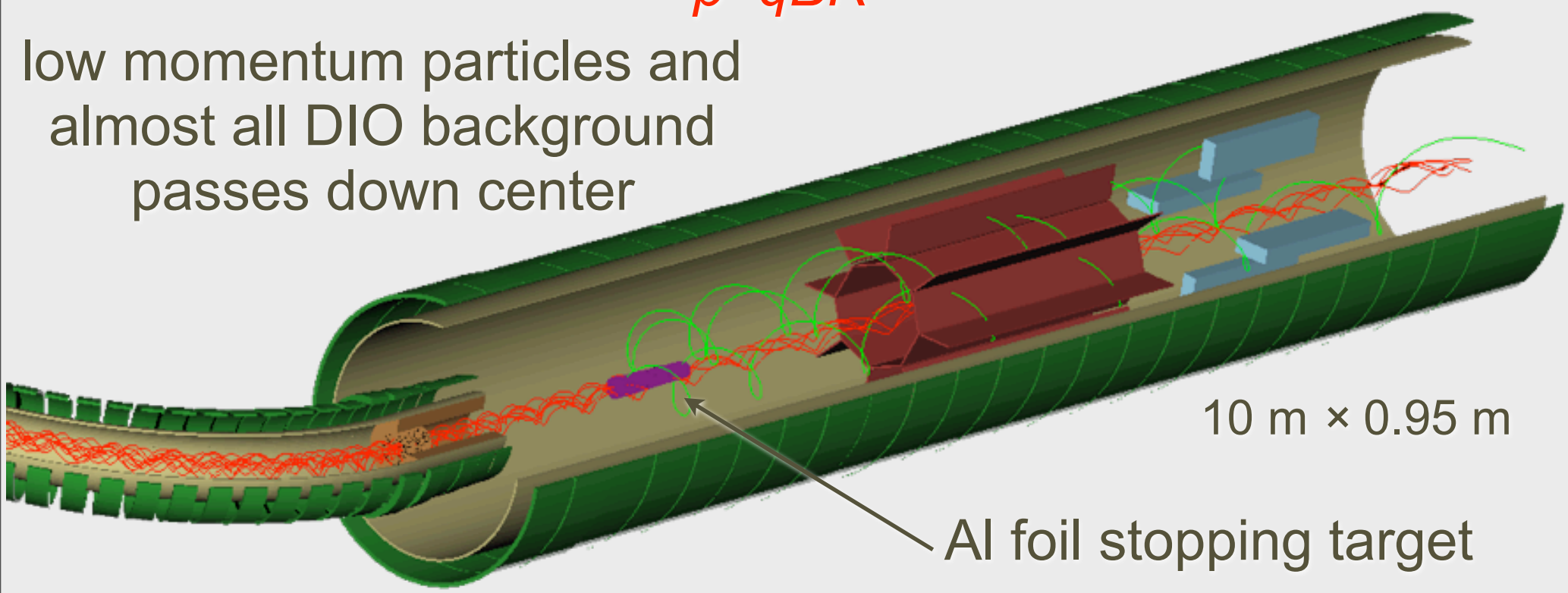


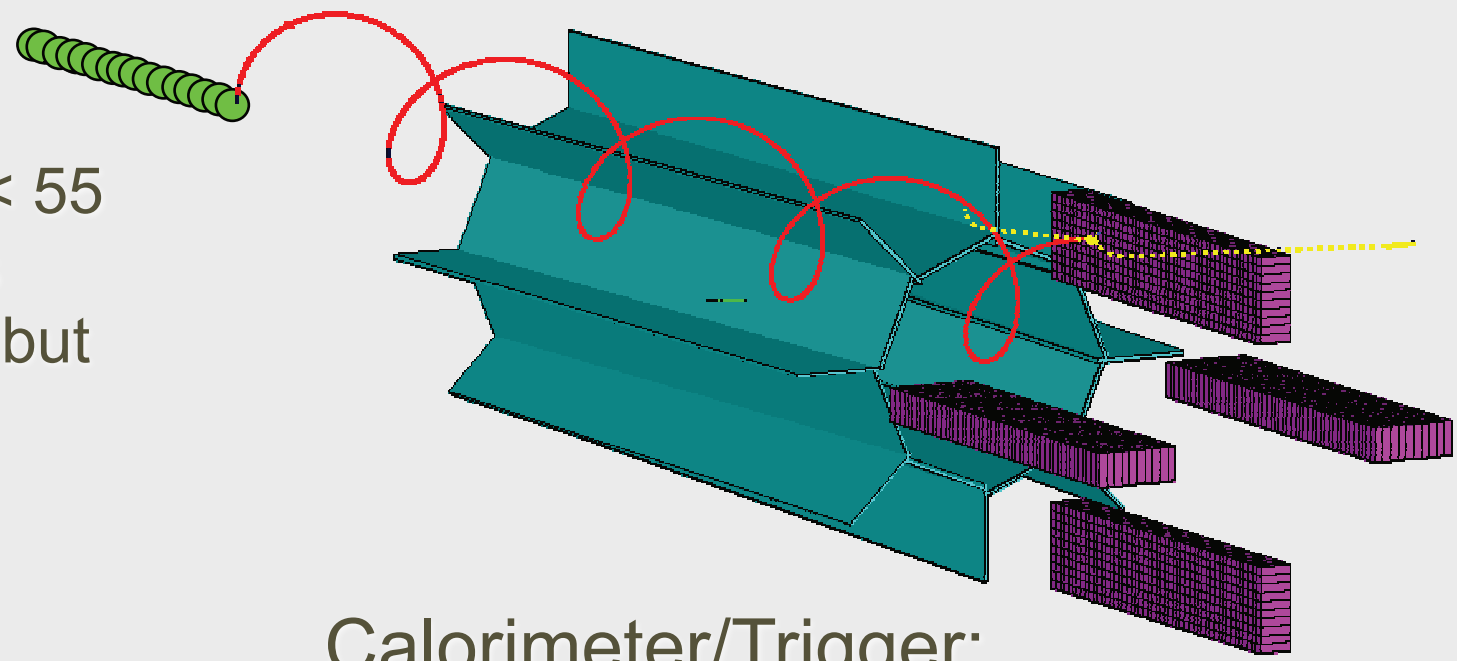
signal events pass *through* octagon of tracker and produce hits

Detector

- Octagon and Vanes of Straw Tubes
- Immersed in solenoidal field, so particle follows near-helical path
- Particles with $p_T < 55$ MeV do not pass through detector, but down the center
- Followed by Calorimeter

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

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

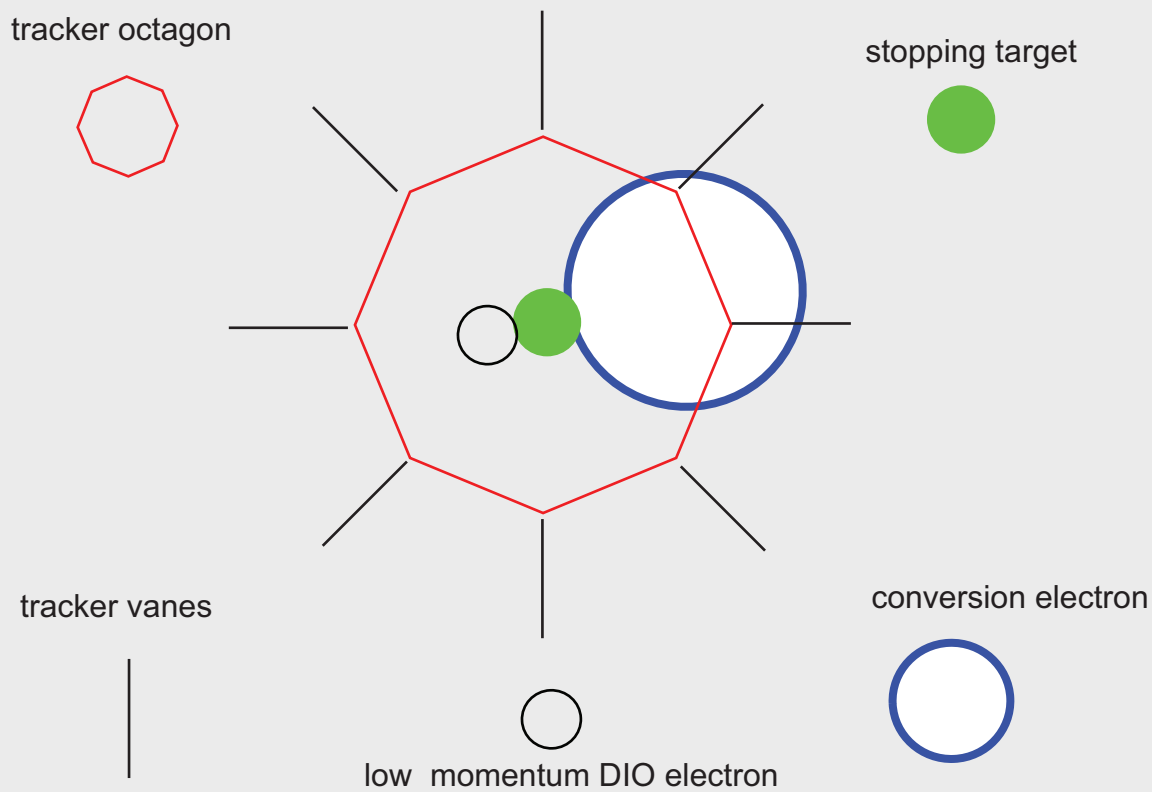


Calorimeter/Trigger:

$\sigma/E = 5\%$, 1024 $3.5 \times 3.5 \times 12$ cm $PbWO_4$

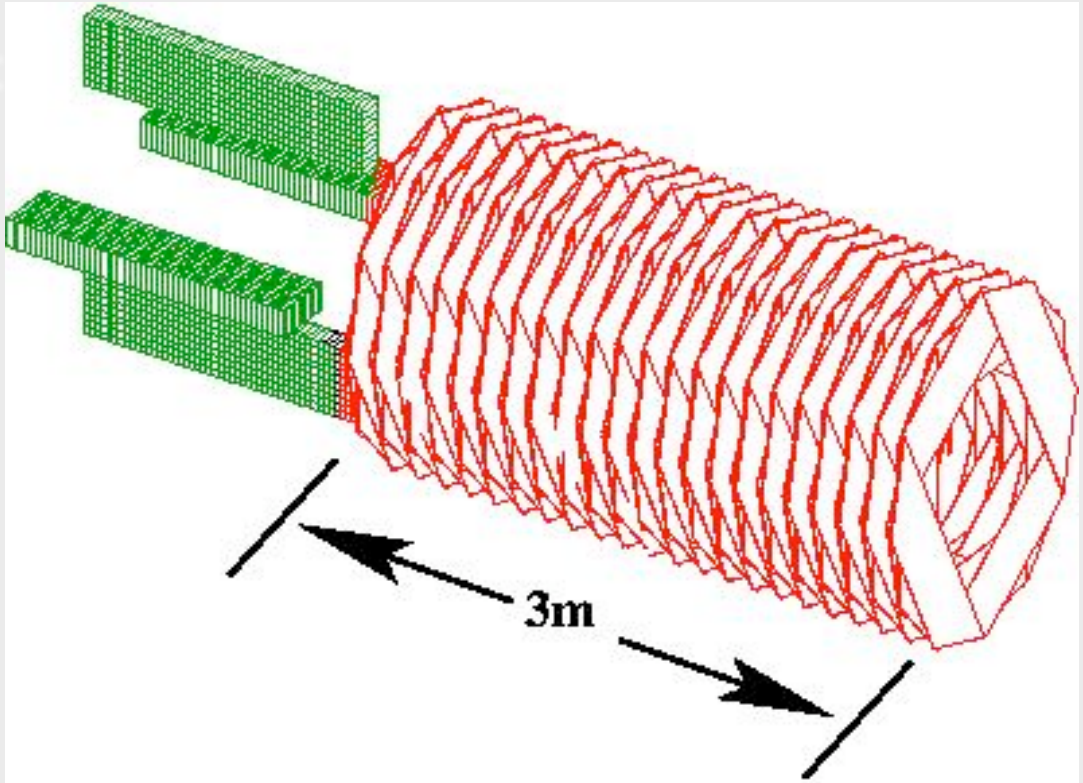
Tracking

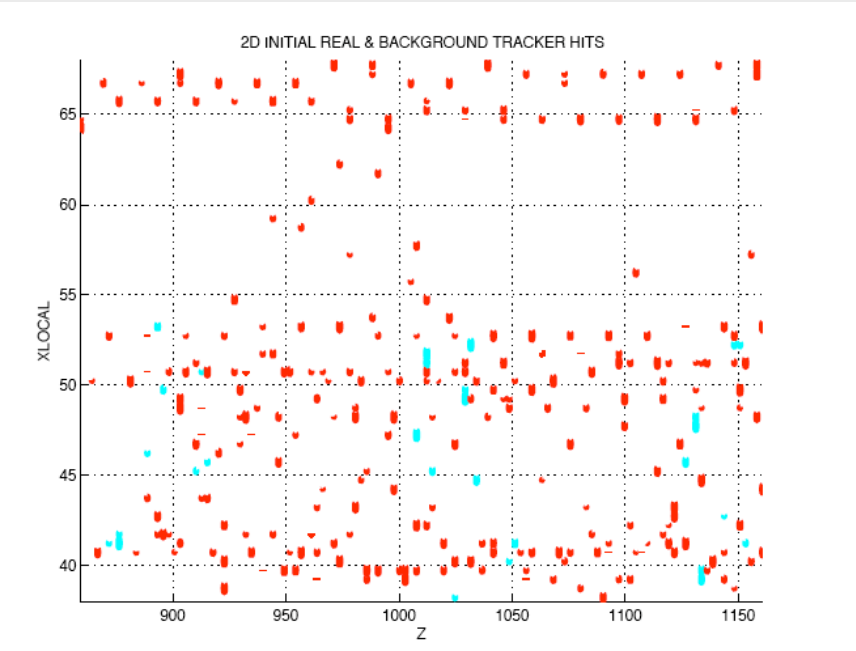
- Projection of helical track
- Conversion electron has high momentum (p_T) and has R large enough to pass outside octagon and is tracked
- DIO (p_T < 55 MeV/c) does not!



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

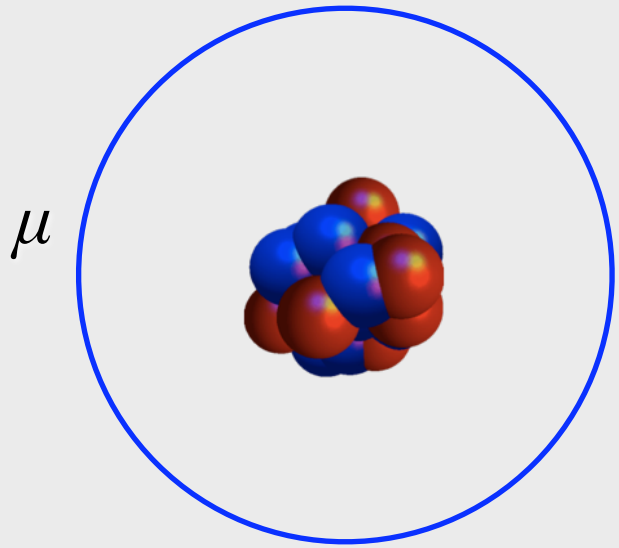
Backgrounds...

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

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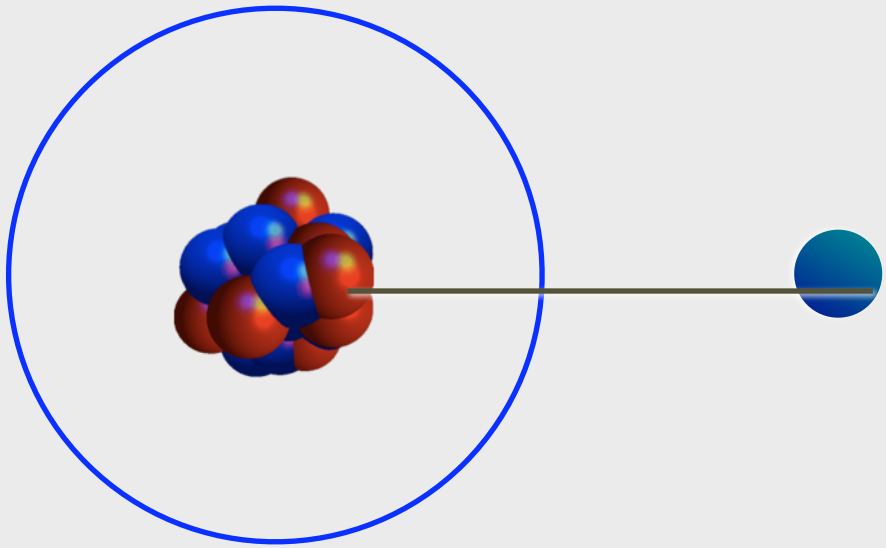

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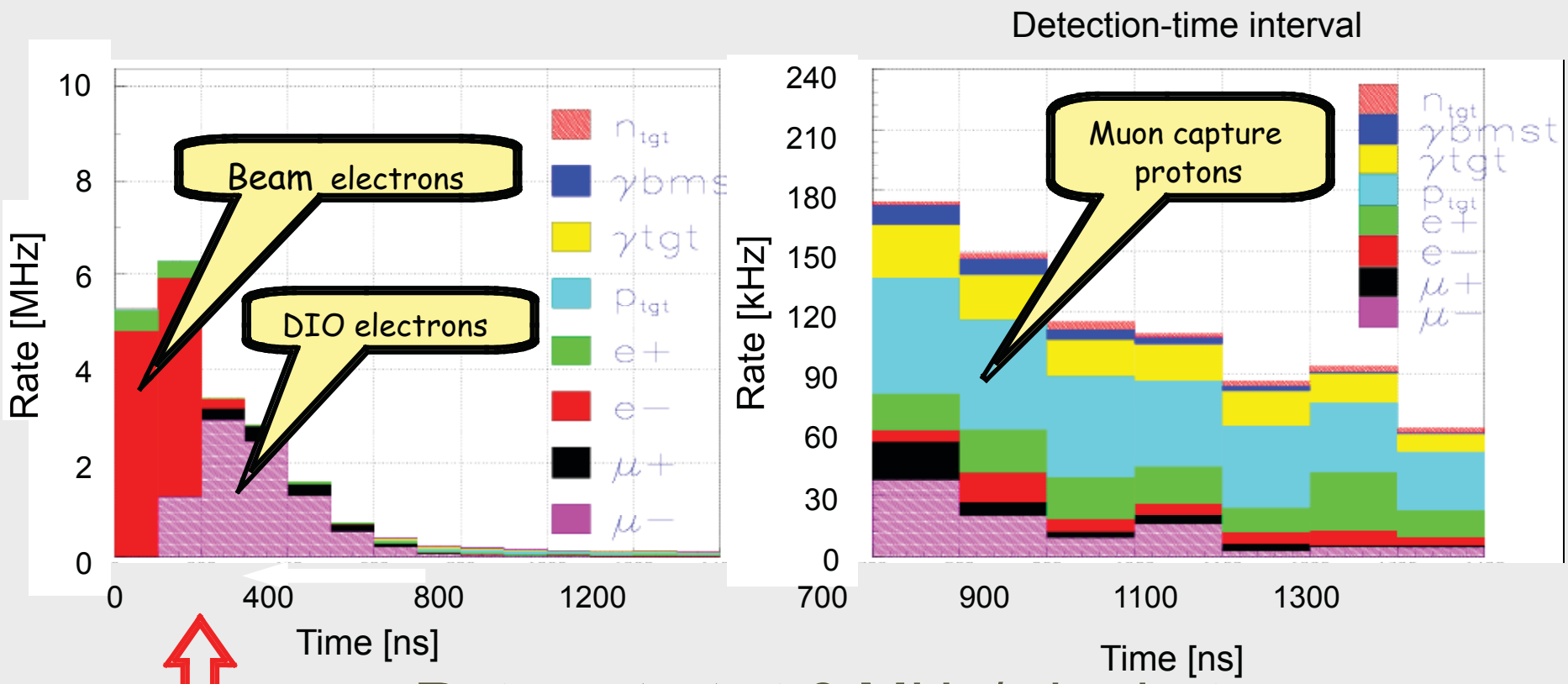
Magnetic Spectrometer: Rates vs. Time

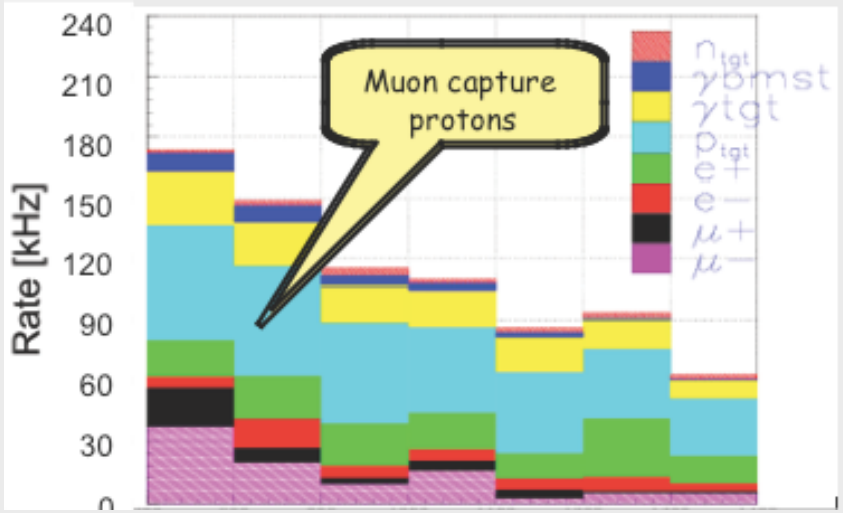


Initial flash from electrons

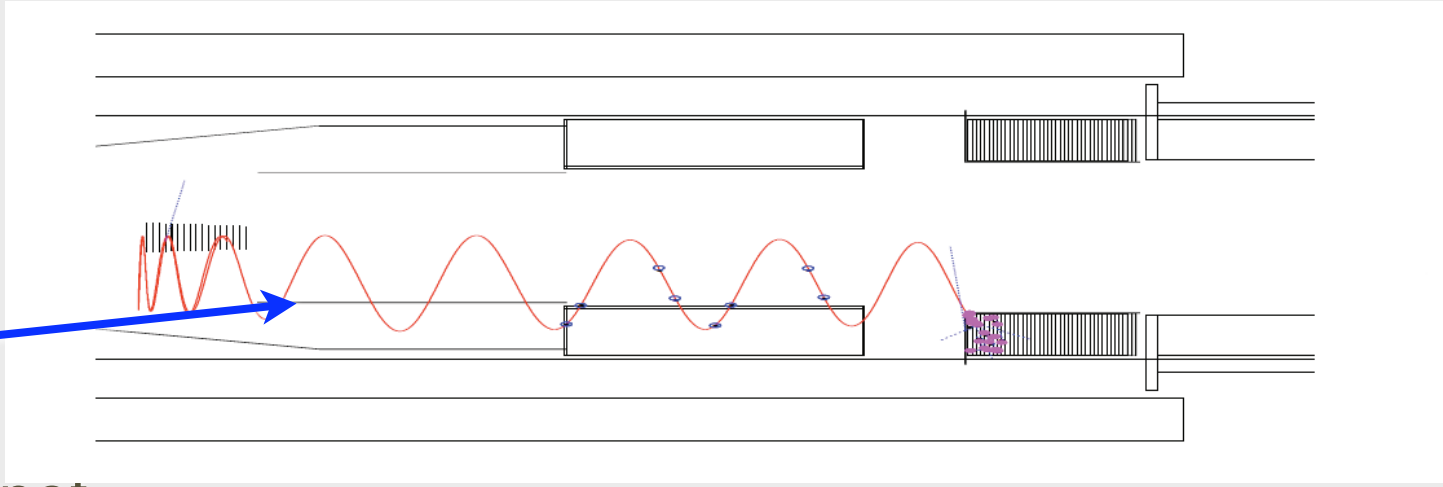
- Rates *start* at 6 MHz/wire but $\lesssim$ 180 kHz/wire in live time window
- Each muon capture produces 2γ, 2n, 0.1p

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

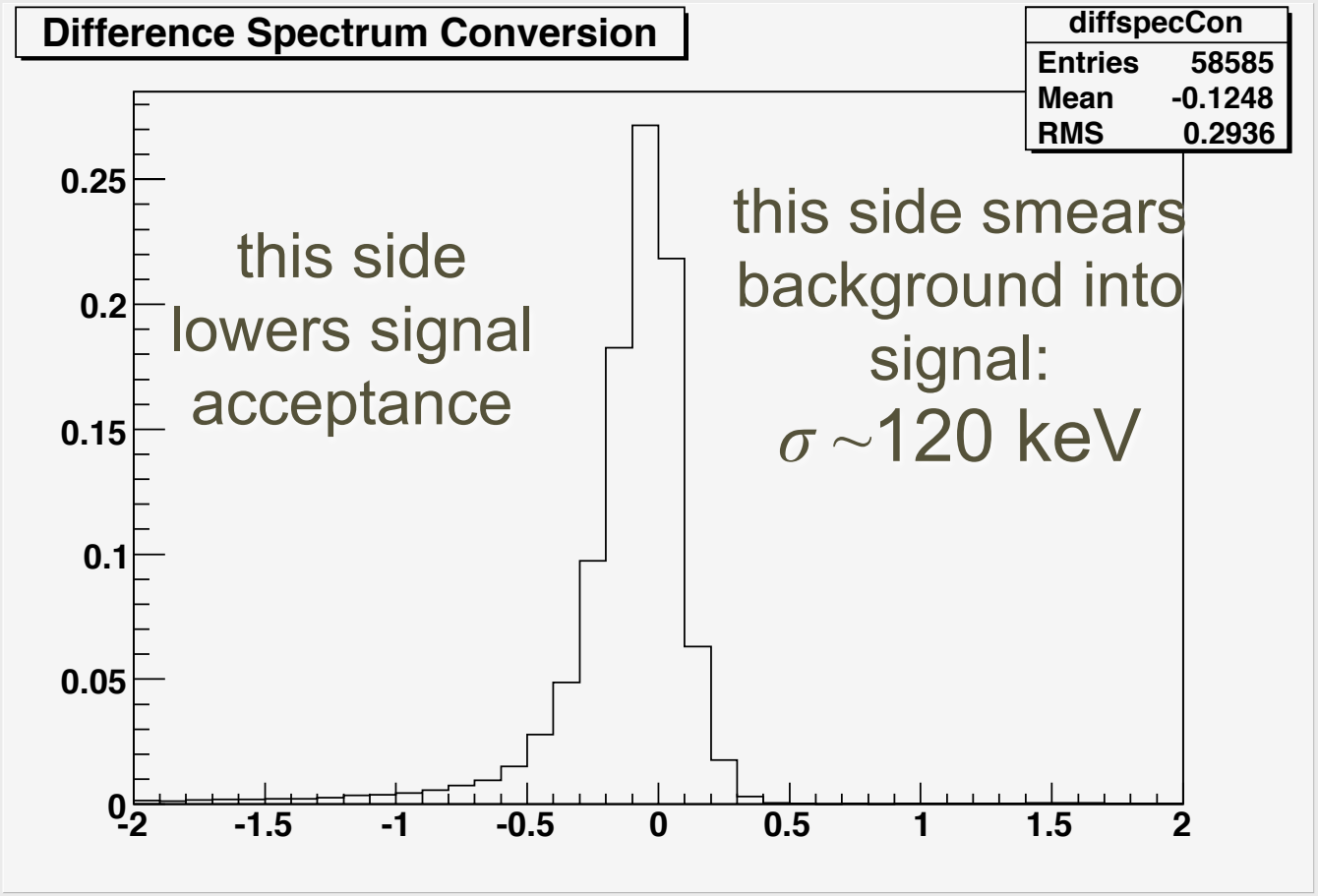


- rate and spectrum not well known, so amount of absorber required not clear

so we measured the rate this summer at PSI

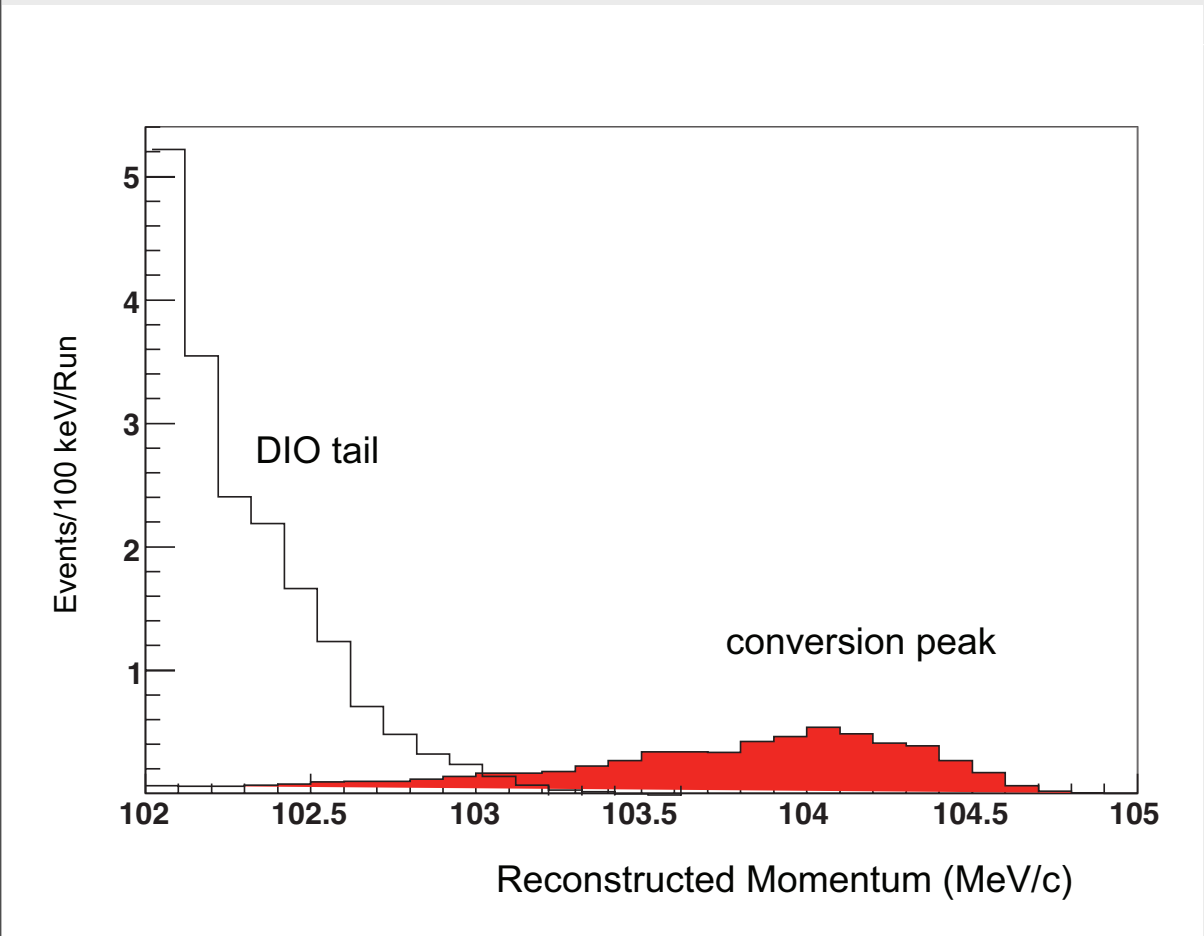
Understanding Resolution

- 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



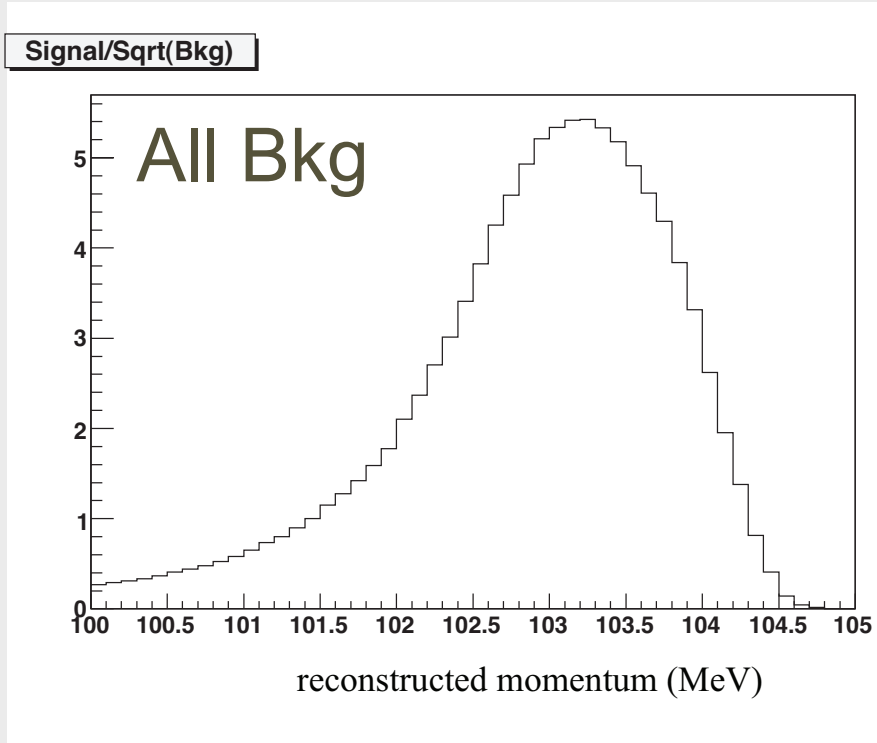
resolution of tracker

Signal and Background



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

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

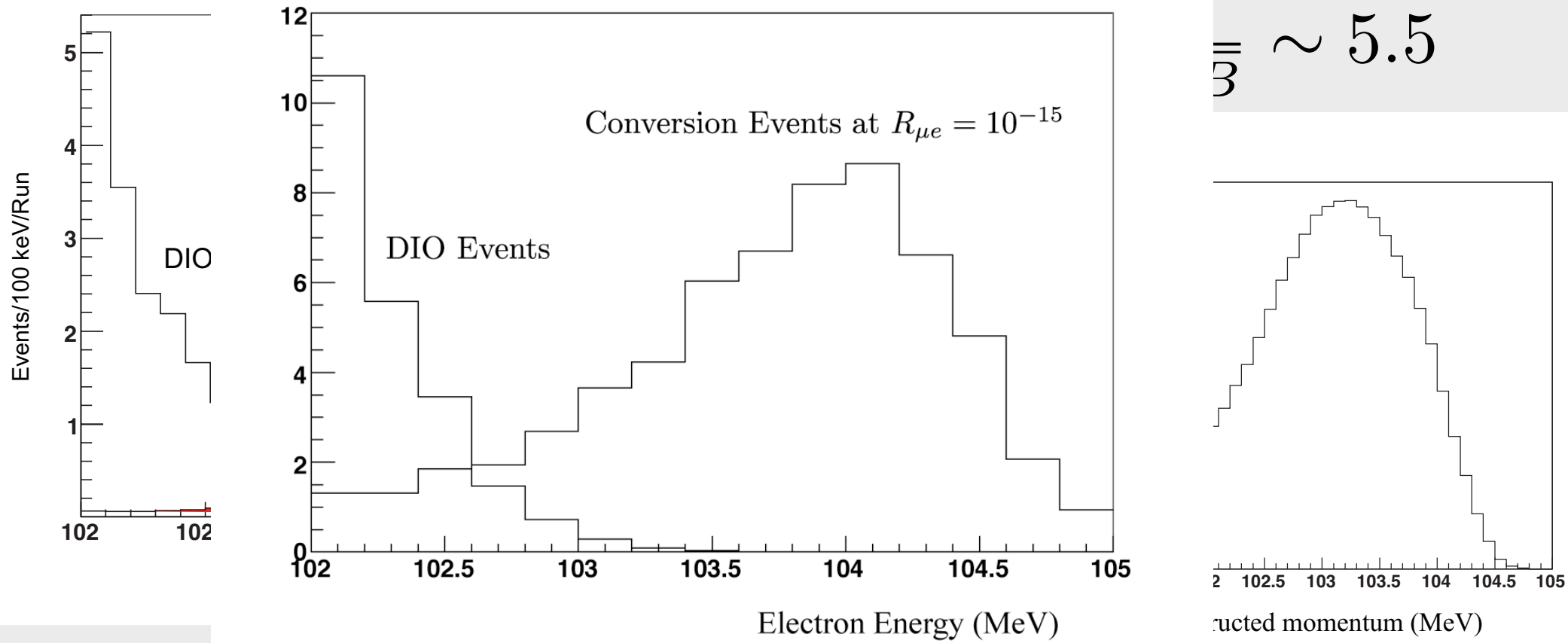


energy loss in stopping target and other material shifts electron down to ~104 MeV

Signal and Background

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

~ 5.5



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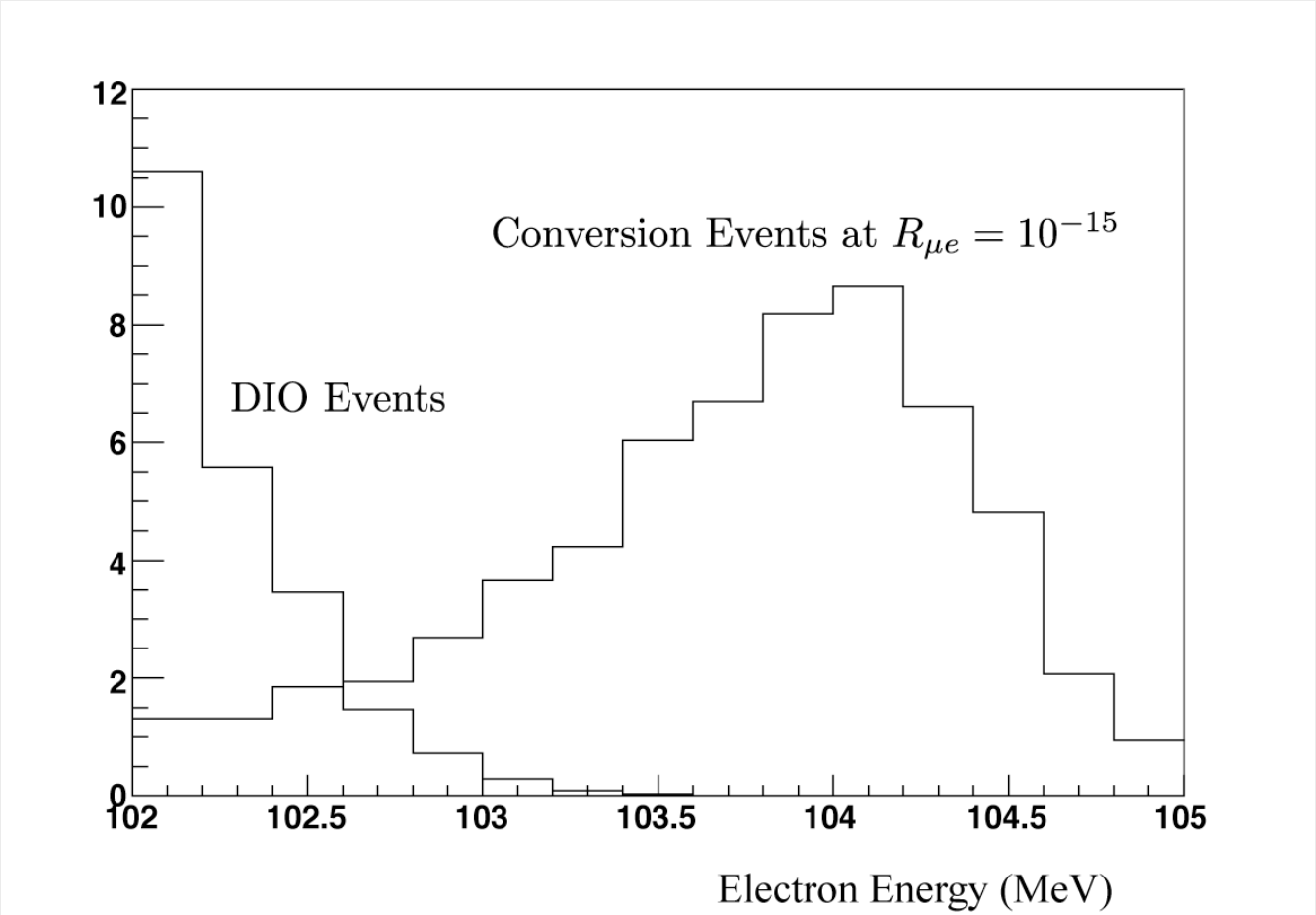


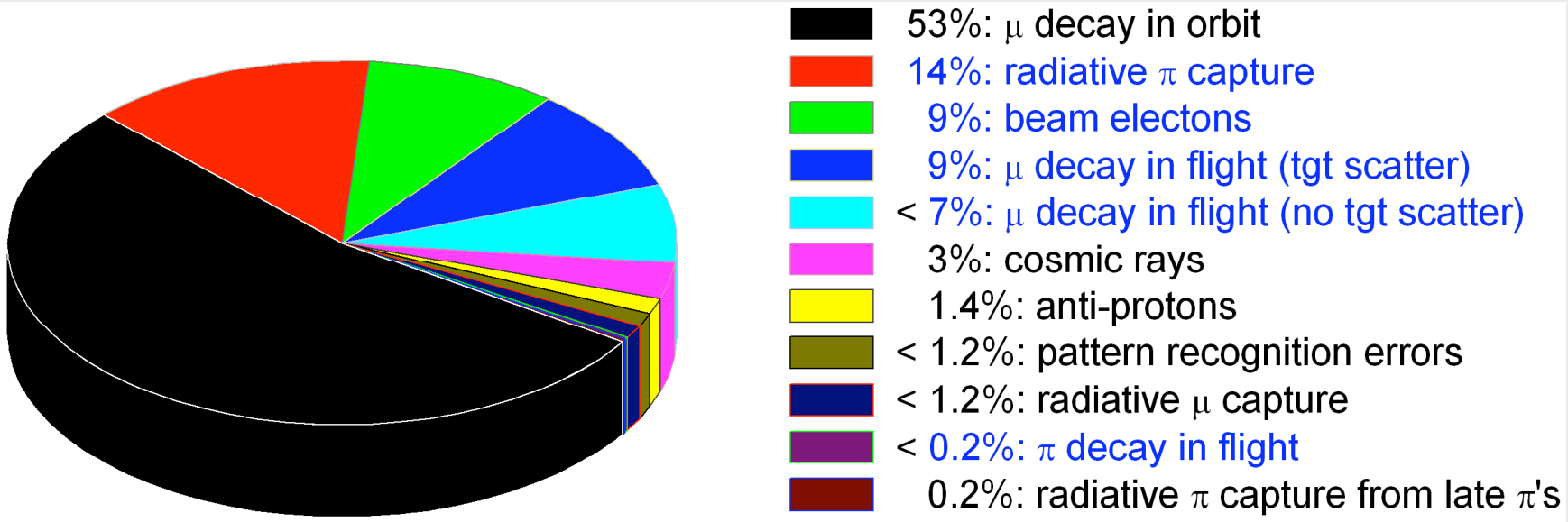
energy loss in stopping target and other material shifts electron down to ~104 MeV

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



Outline

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FNAL Beam Delivery

- FNAL has unique, major strength:

  Multiple Rings

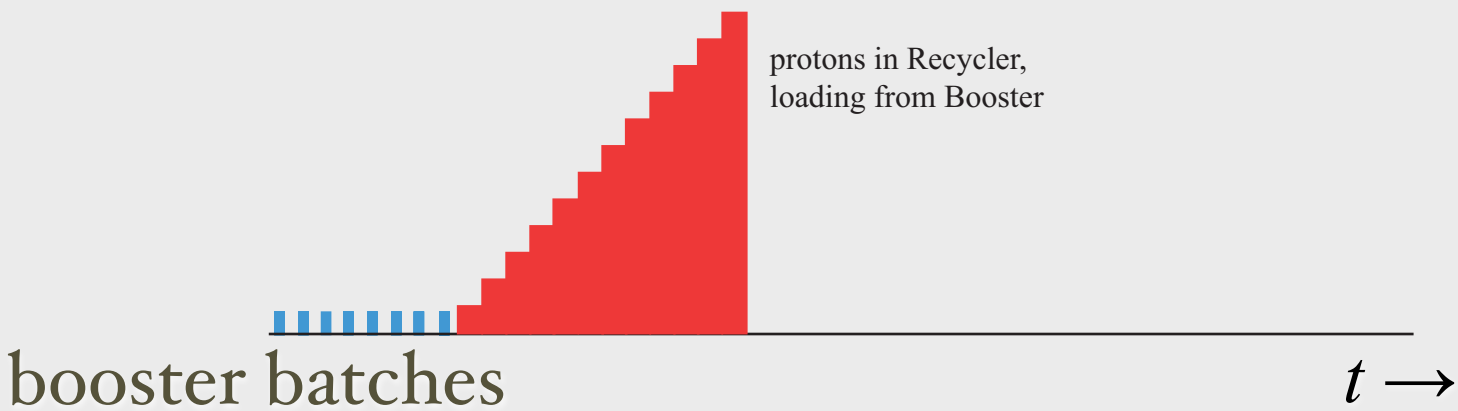
  - *no interference* with NOvA neutrino oscillation experiment
  - reuse existing rings with only minor modifications

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 Hz



- Single-Turn Transfer to MI

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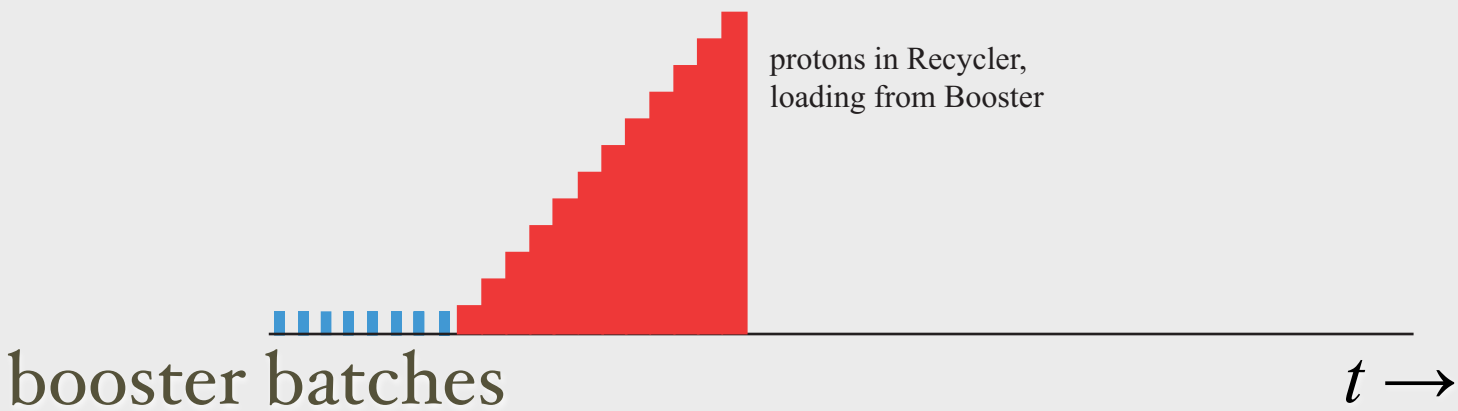

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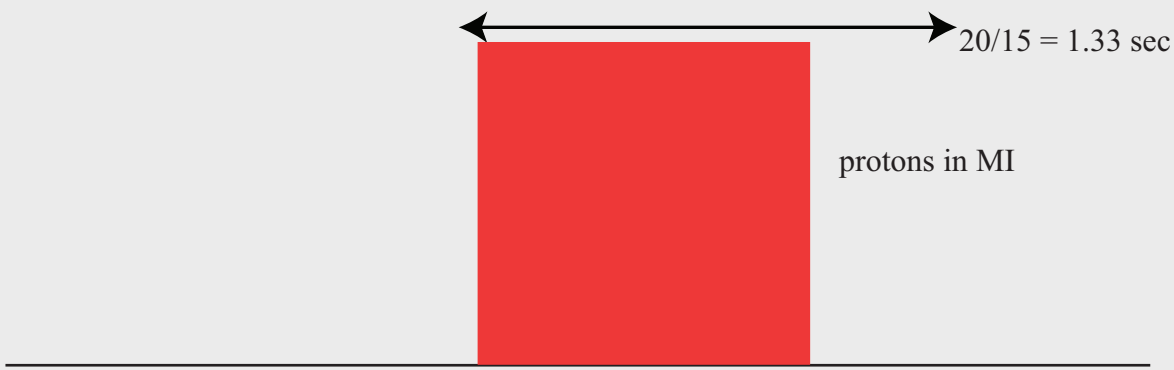

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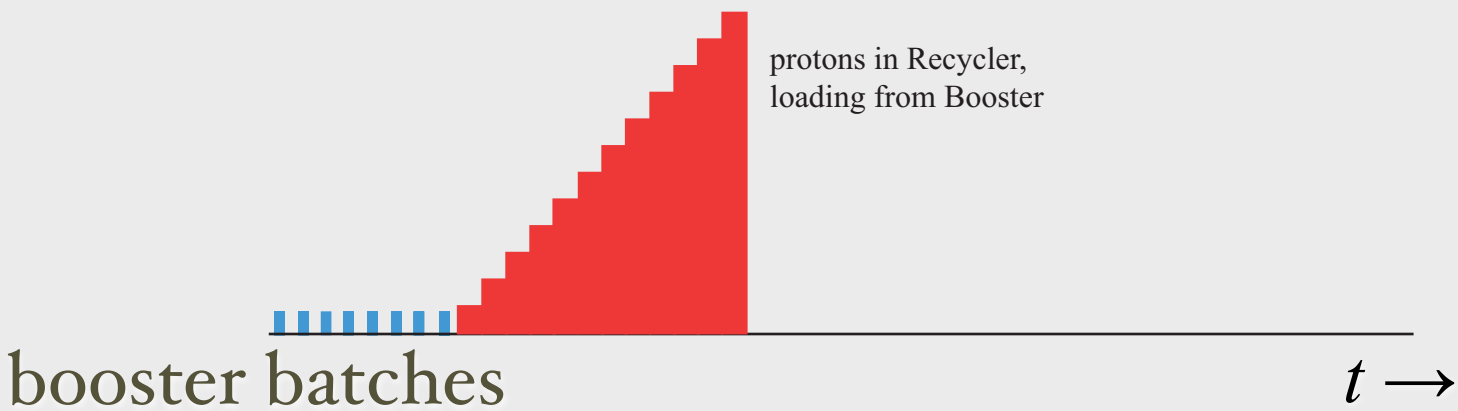

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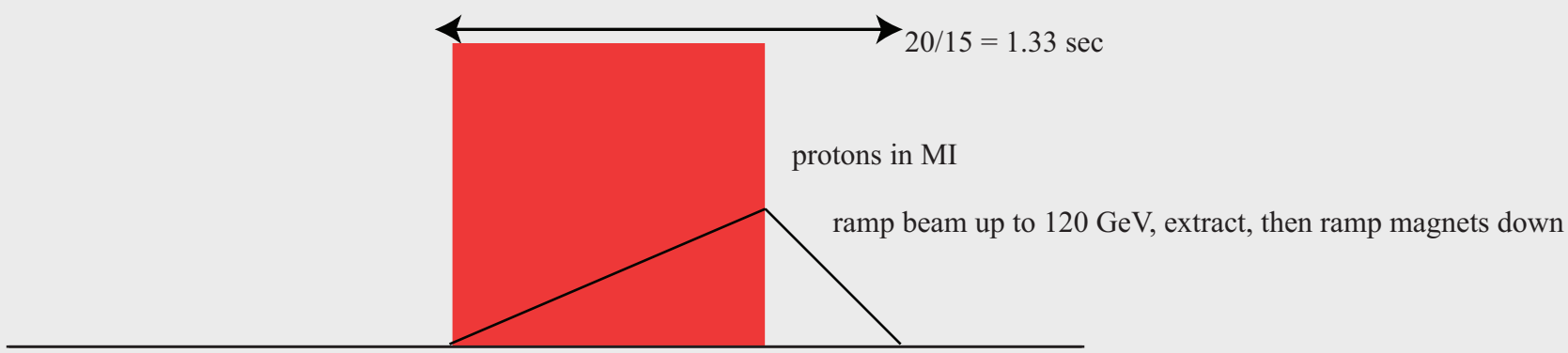
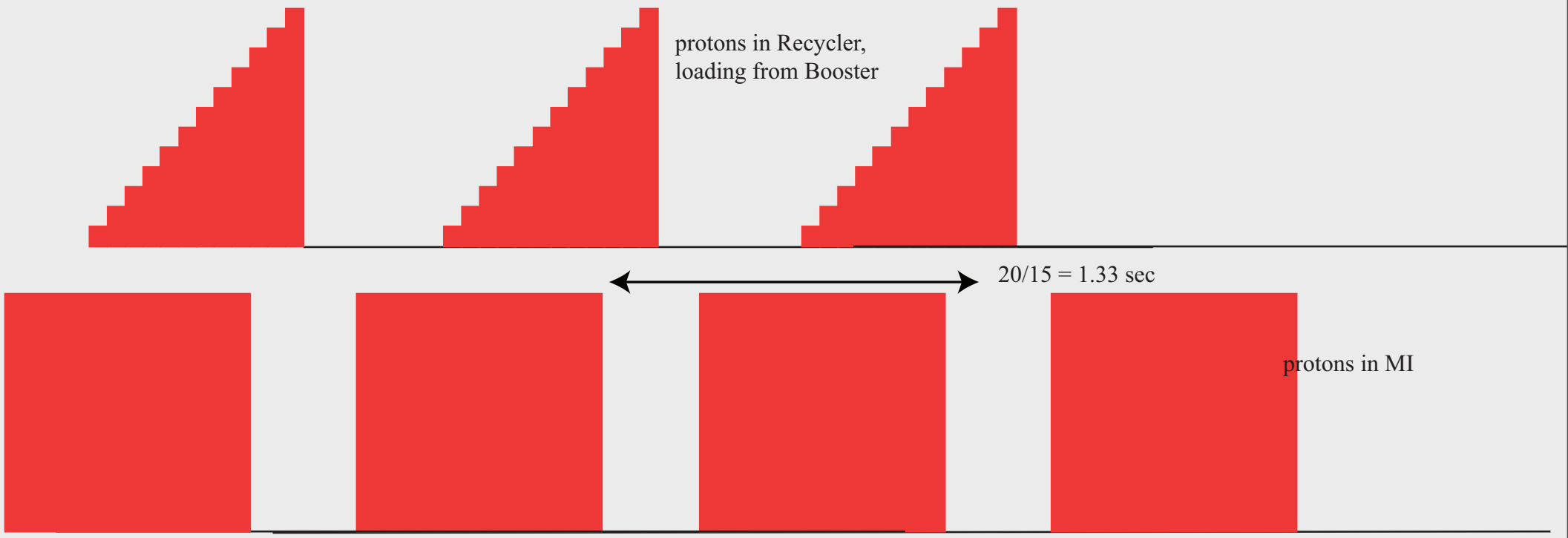


All Together...



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

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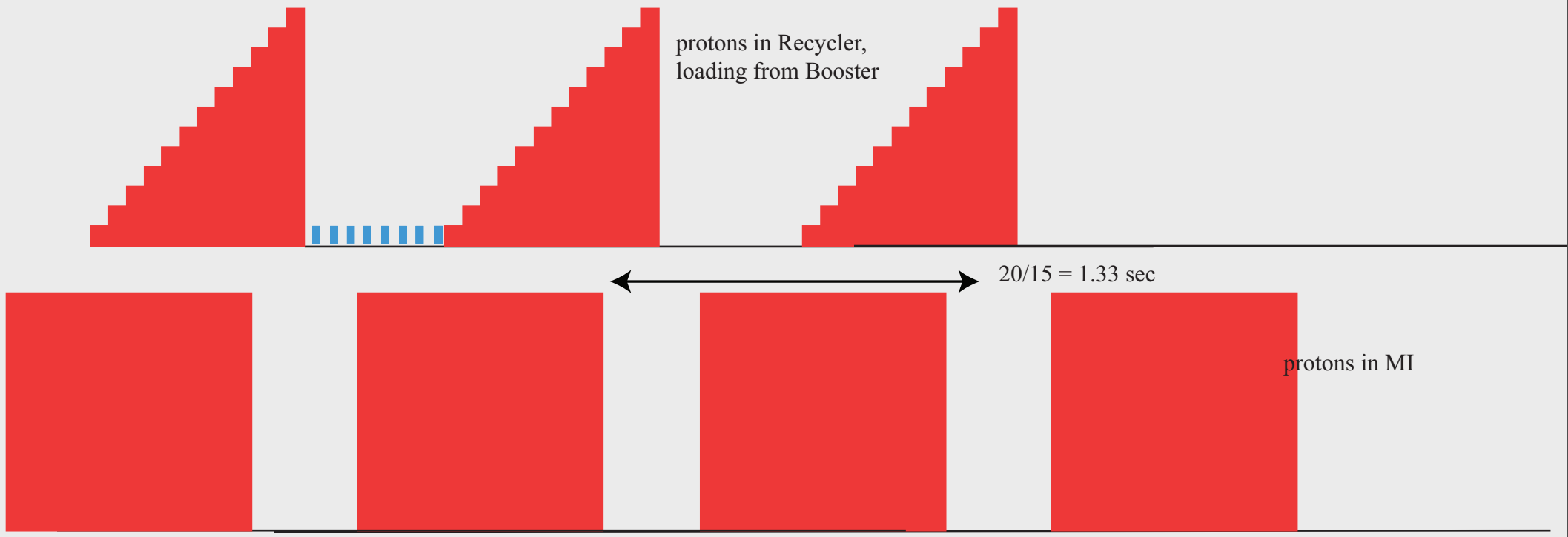

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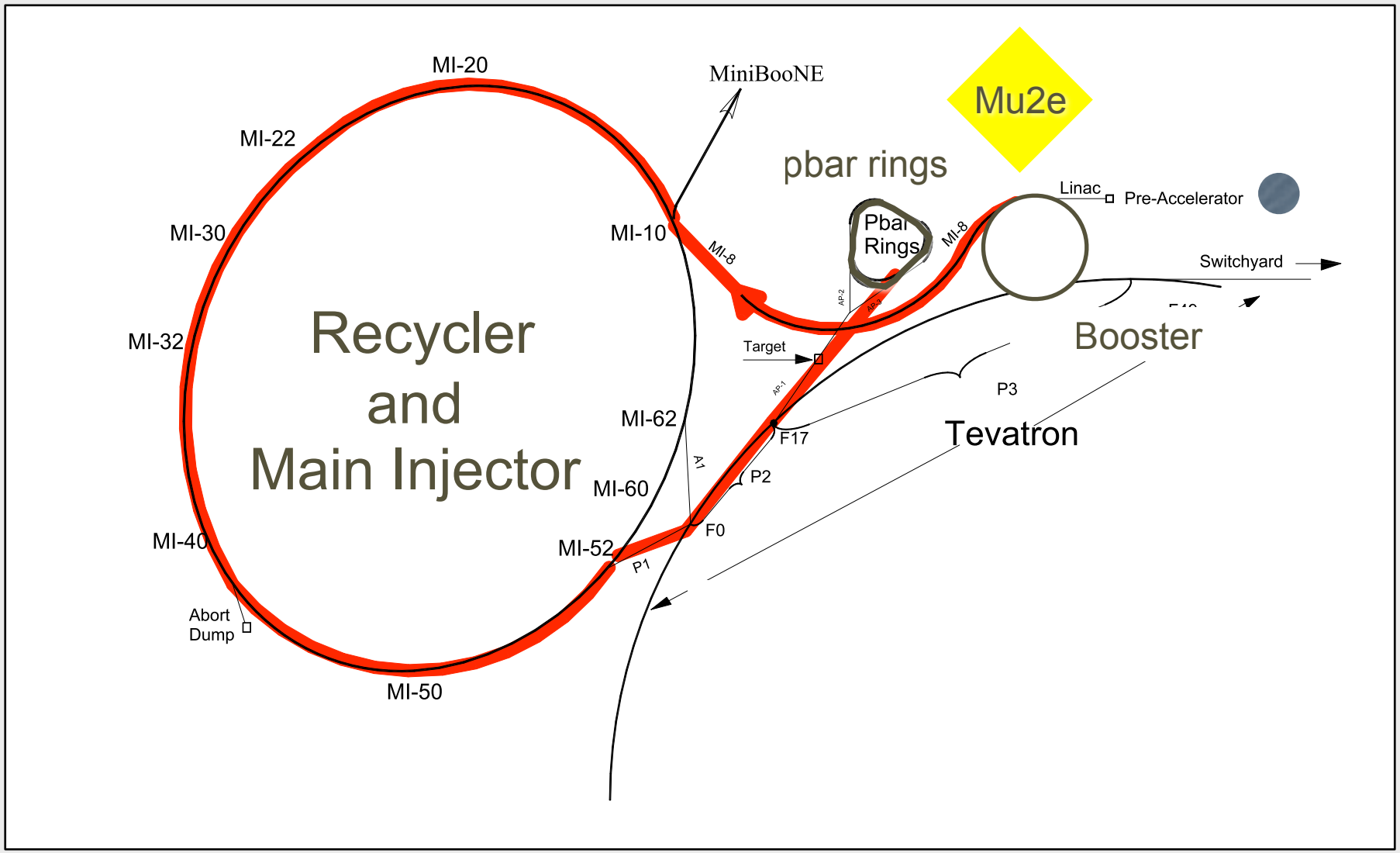
“Boomerang” Scheme



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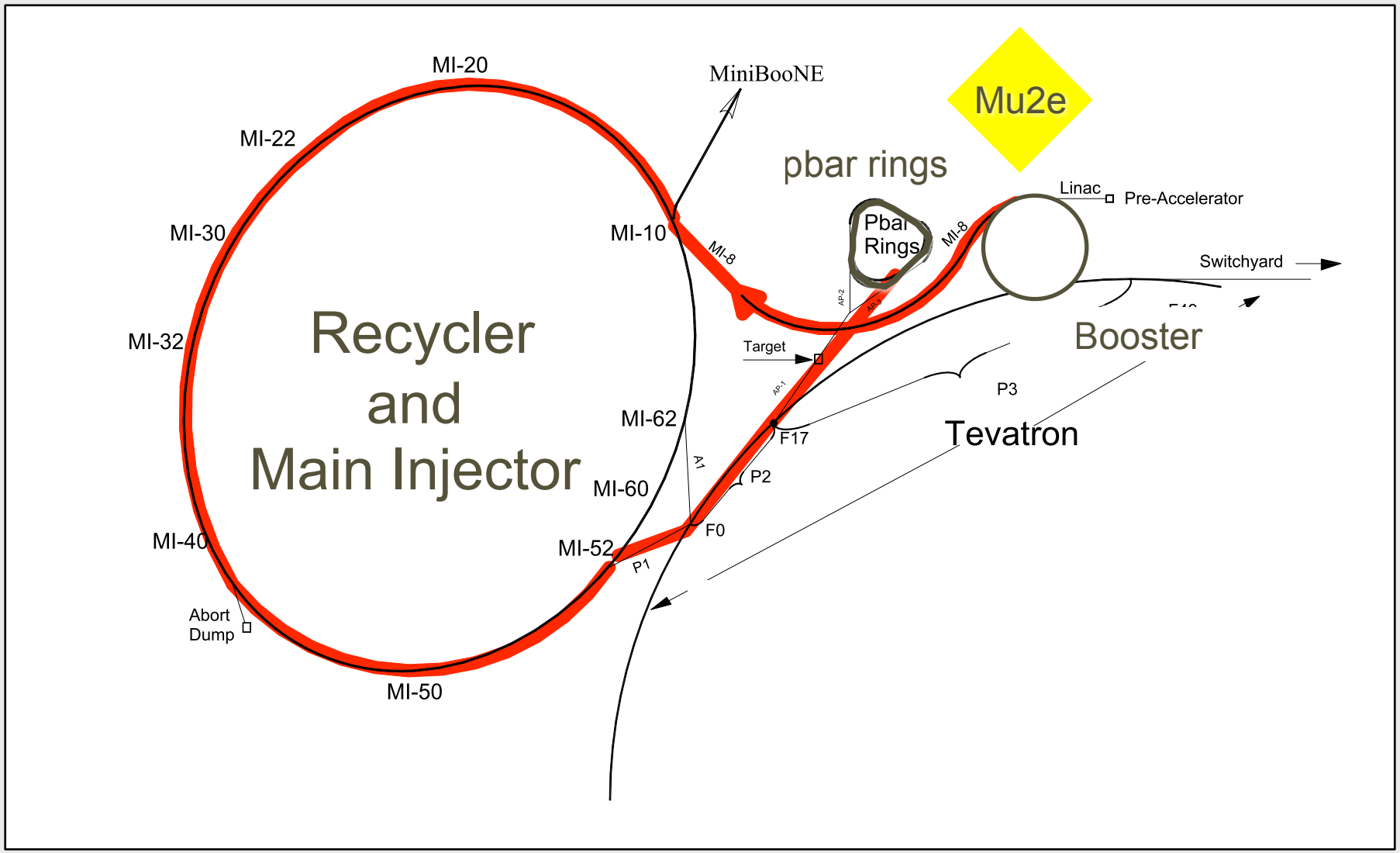

First-Pass Site

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

Outline

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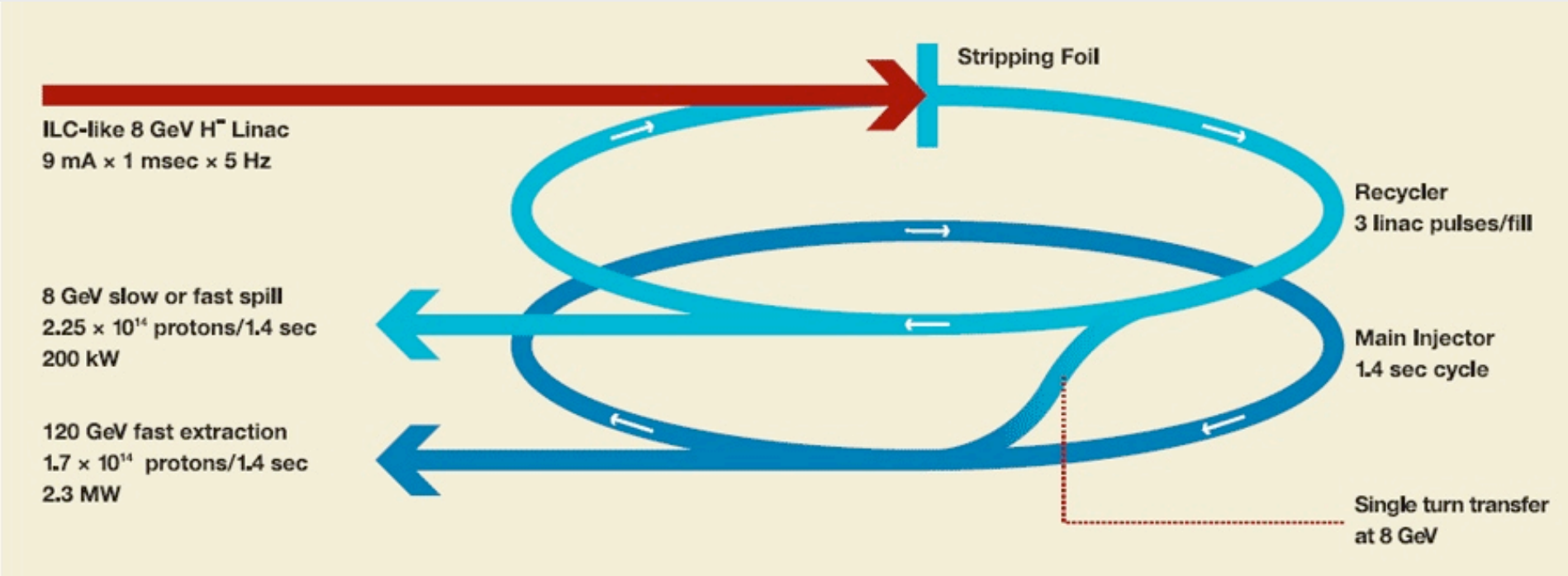
What is Project X?

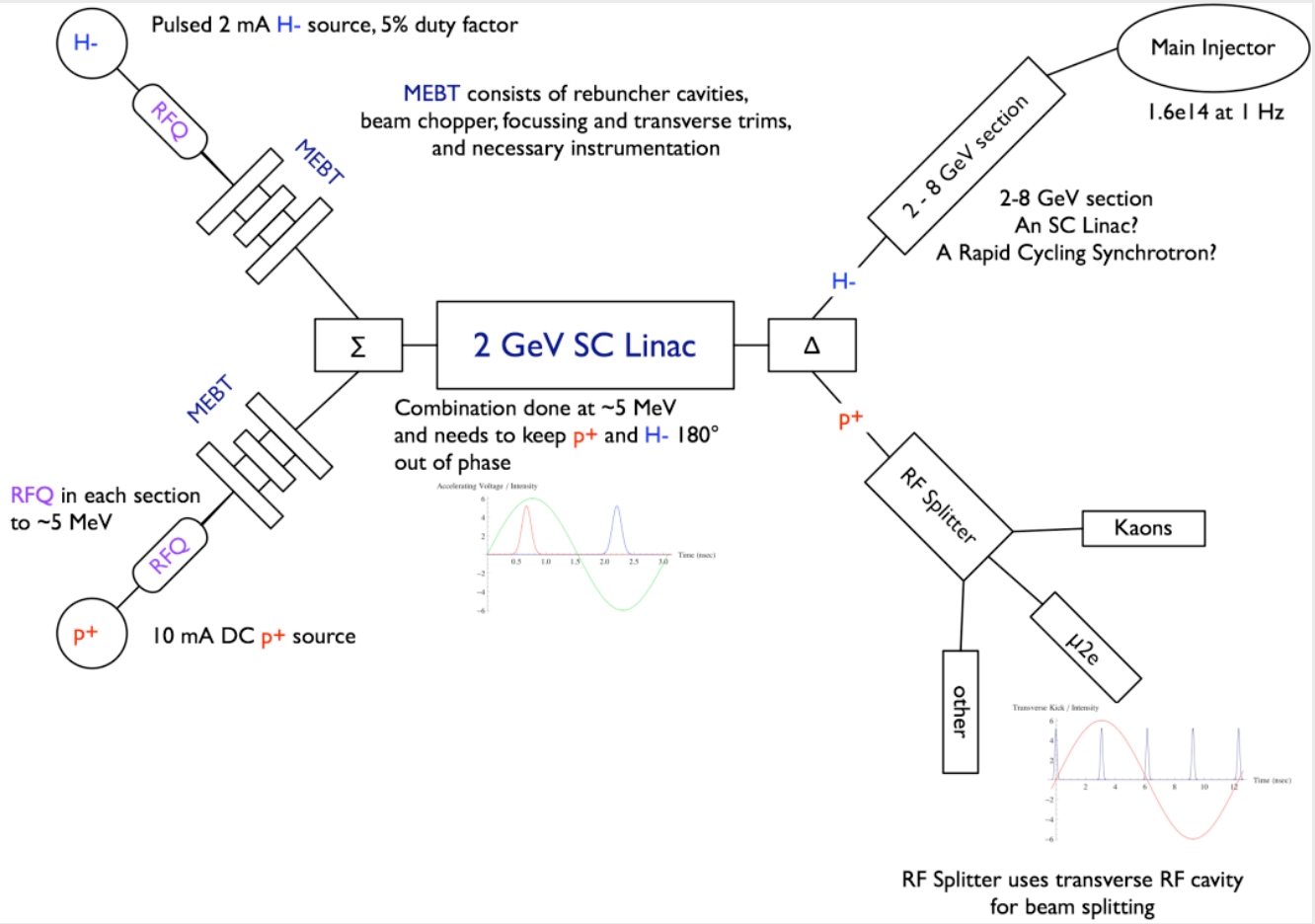


- Project X is a concept for an intense 8 GeV proton source that provides beam for the Fermilab Main Injector and an 8 GeV physics program.
- The source consists of an 8 GeV superconducting linac that injects into the Fermilab Recycler

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

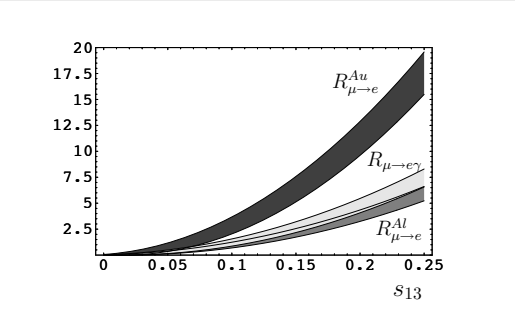
- First establish a signal or set a strong limit -- what do we do next?
- Project X gives us a chance to upgrade the experiment by up to x100

20 kW
(*current*)

200 kW
(**Project X**)

2000 kW
(***Project X Upgrades***)

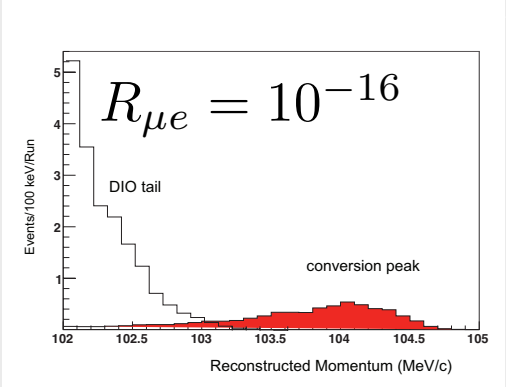
Upgrade Plans...



Signal?

Yes

No



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

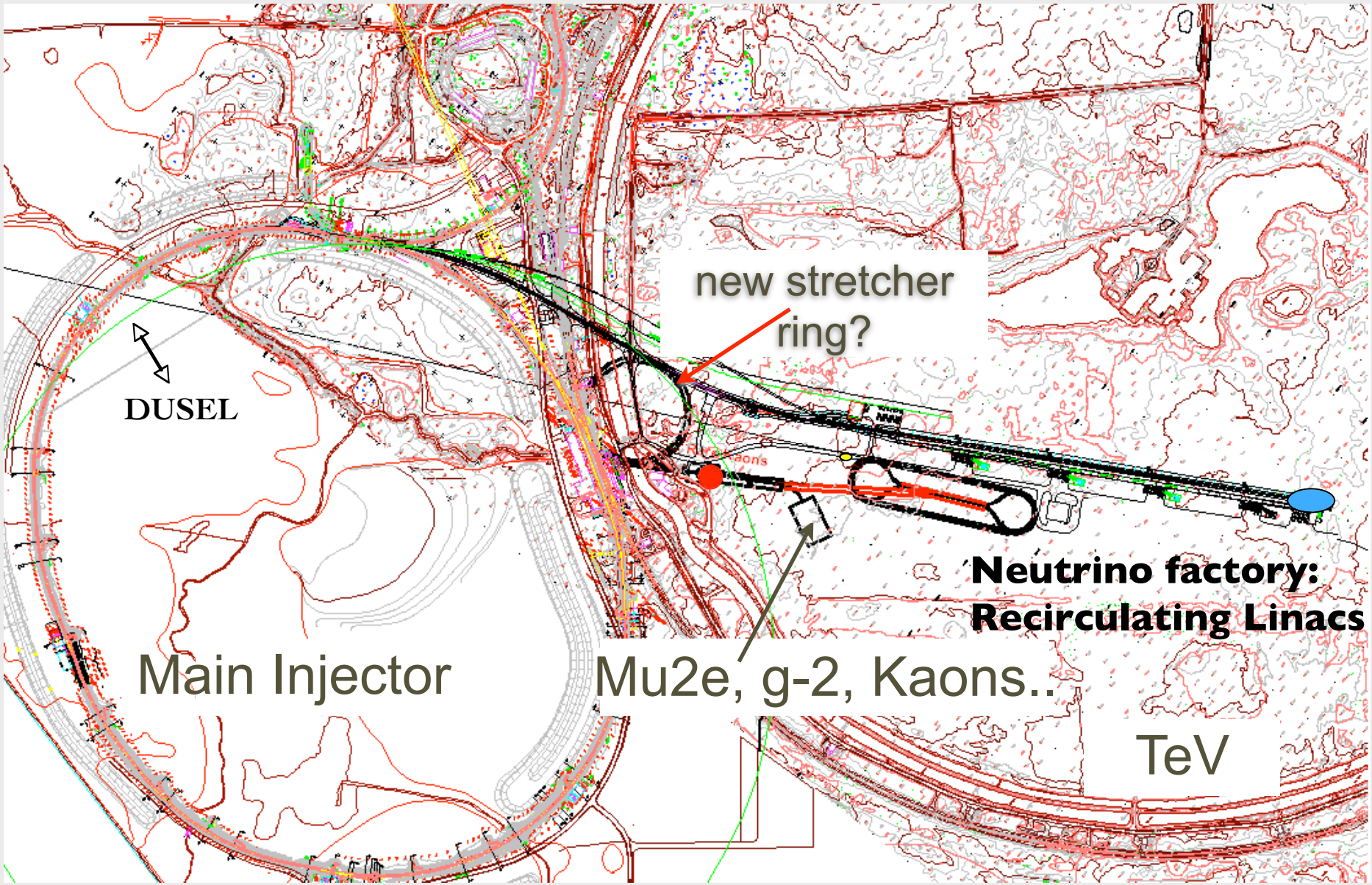
2. Prompt Rates will go up at higher Z, have to redesign detector and muon transport

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...



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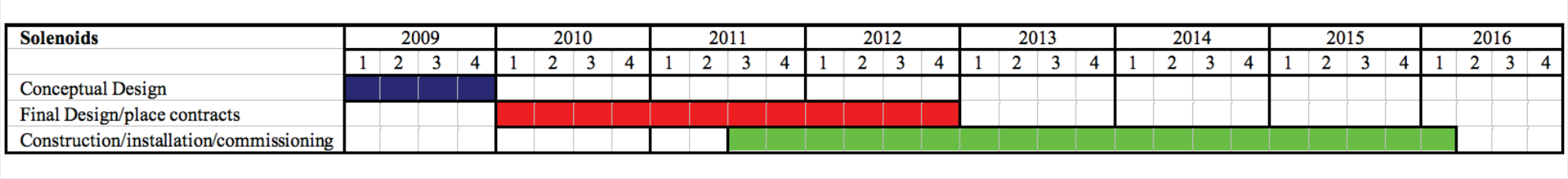
Cost and Schedule

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



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 ($R_{\mu e}$ <6x10^{-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

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

Who ordered that?

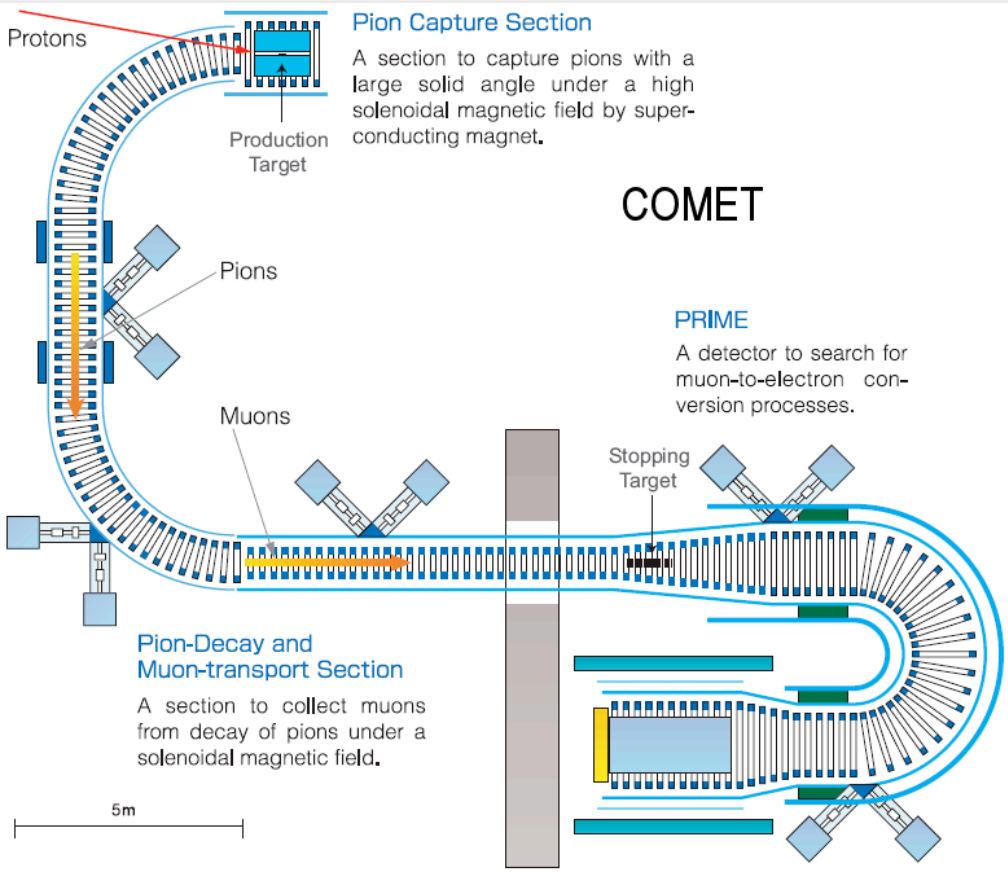
BACKUPS

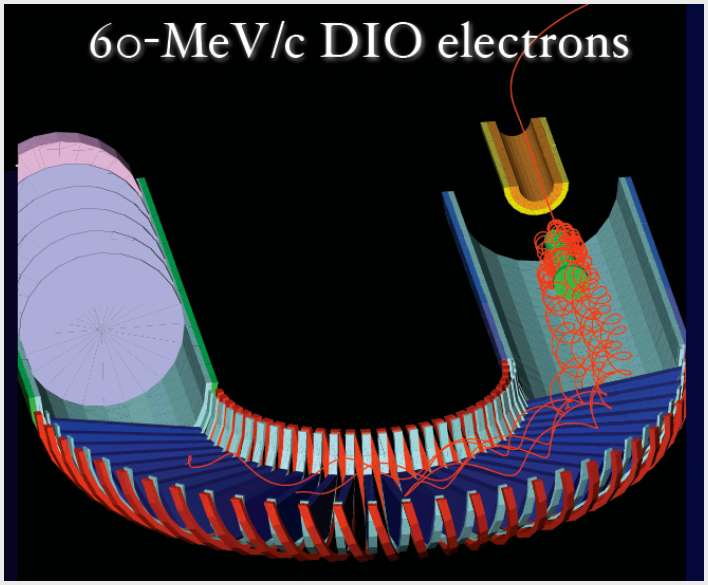
COMET

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 ⇨ rate lower





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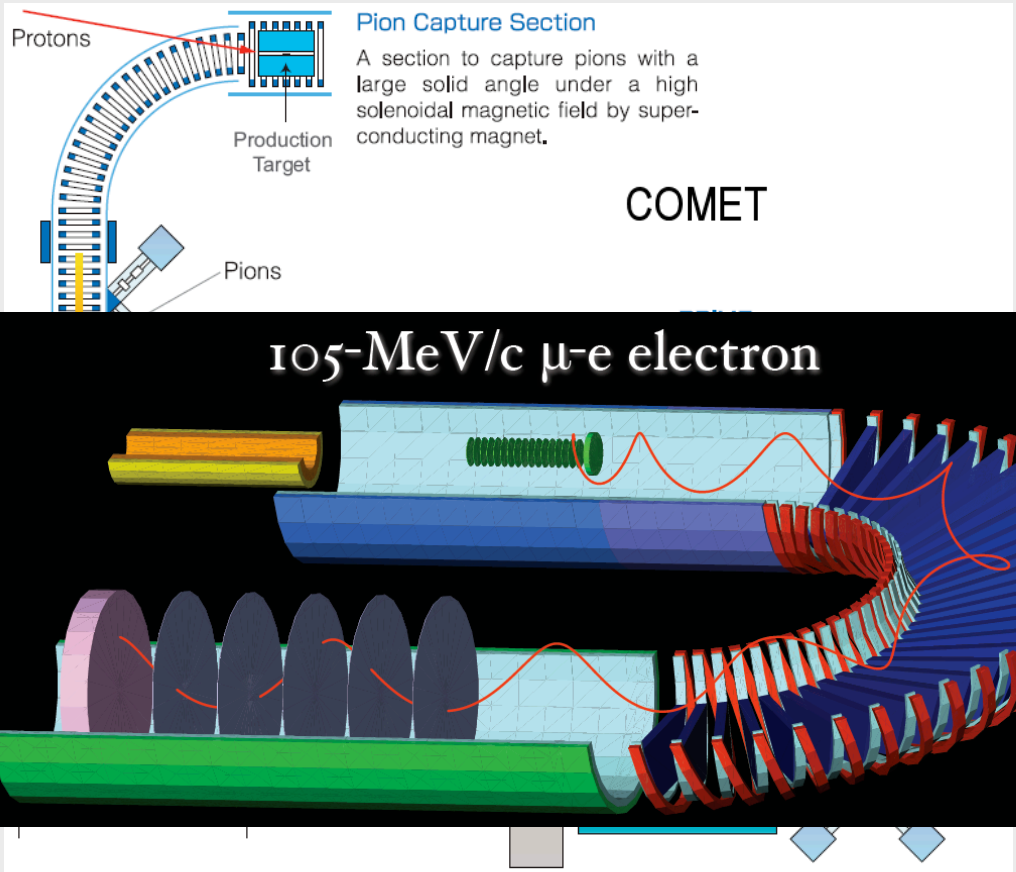
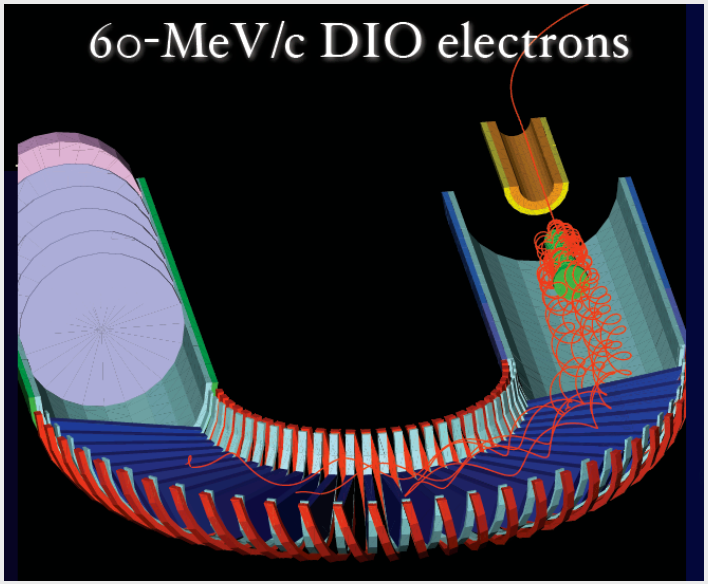




US Gov't DOE CD Process

Lasciate ogne speranza, voi ch'intrate

Inferno
fresco in Camposanto, Pisa

US Gov't DOE CD Process

Lasciate ogne speranza, voi ch'intrate

Inferno
fresco in Camposanto, Pisa

CD
process

US Gov't DOE CD Process

Lasciate ogne speranza, voi ch'intrate

Experimenter's Reward

Inferno
fresco in Camposanto, Pisa

CD
process

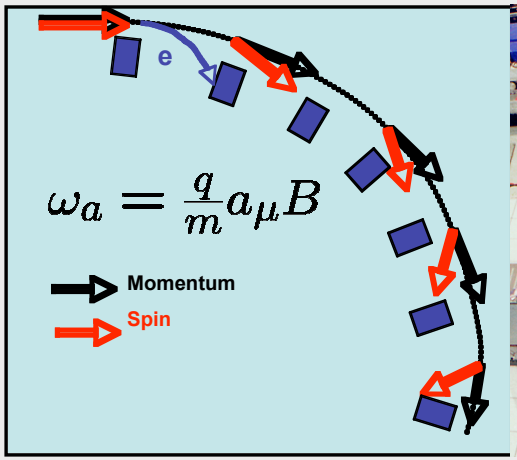
Guide to DOE CD Process

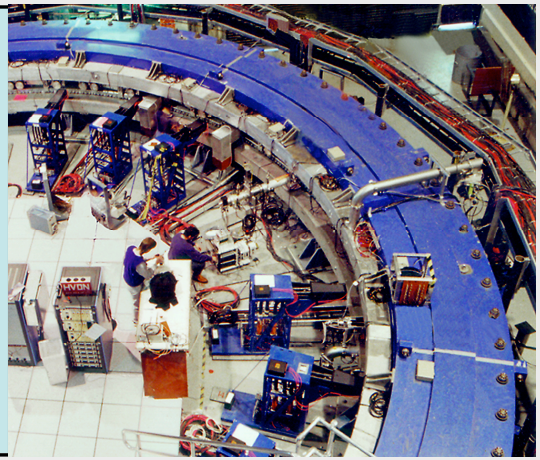
- CD–0: “mission need”
  - the DOE decides this is part of its goals and then DOE prepares document
  - ***DOE: Feb 2009 for Mu2e***
- CD–1: “conceptual design”
  - careful, systematic evaluation of alternatives
  - cost and schedule well along but not final
- CD–2: “baseline” / technical design
  -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

g-2 At Fermilab

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

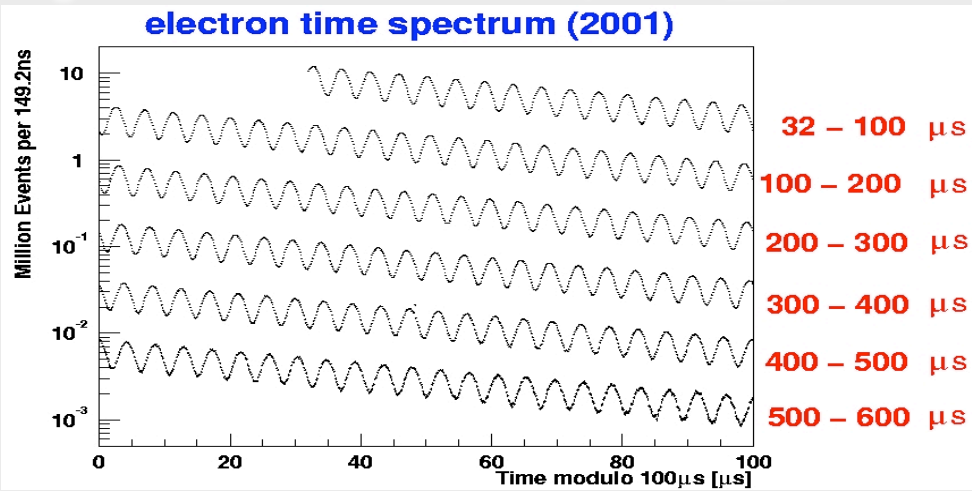
from 3.6σ → >7σ



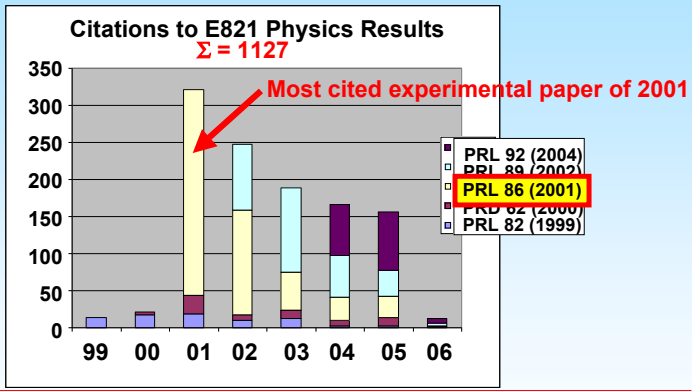


$$\text{current} \quad \begin{aligned} \sigma_{\mathrm{stat}} &= \pm 0.46 \text{ ppm} \\ \sigma_{\mathrm{syst}} &= \pm 0.28 \text{ ppm} \end{aligned}$$

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



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.

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

g-2 Method

We measure the difference frequency between the spin and momentum precession

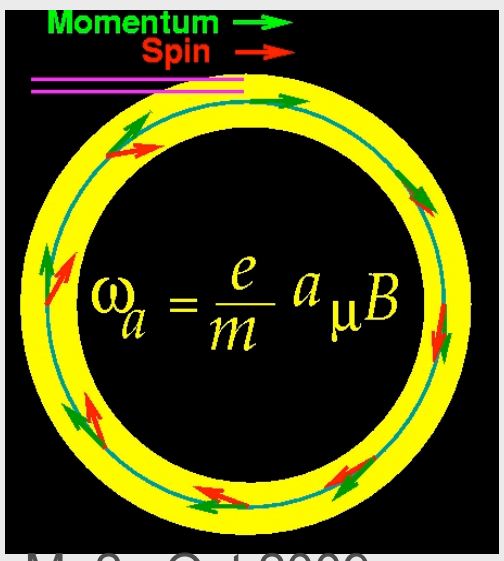
$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{mc} \qquad B \Rightarrow \langle B \rangle_{\mu-\text{dist}}$$

With an electric quadrupole field for vertical focusing

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \cancelto{0}{\left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c}}\right]$$

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

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



g-2 hadronic term

- Hadronic Cross-section measured here at KL0E
- 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

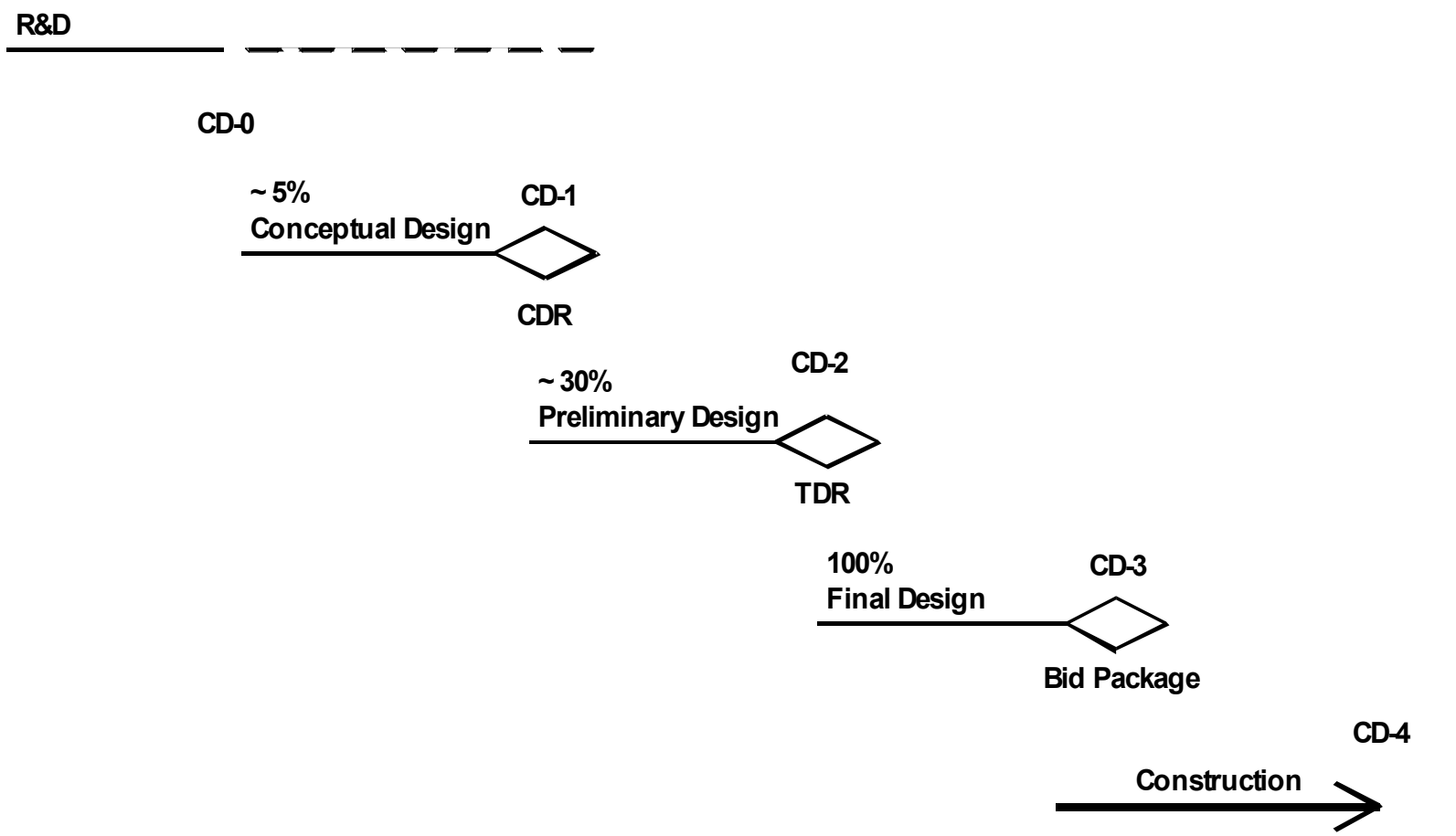
SELECTED HISTORY OF PROJECT PERFORMANCE

	CE/IE*
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



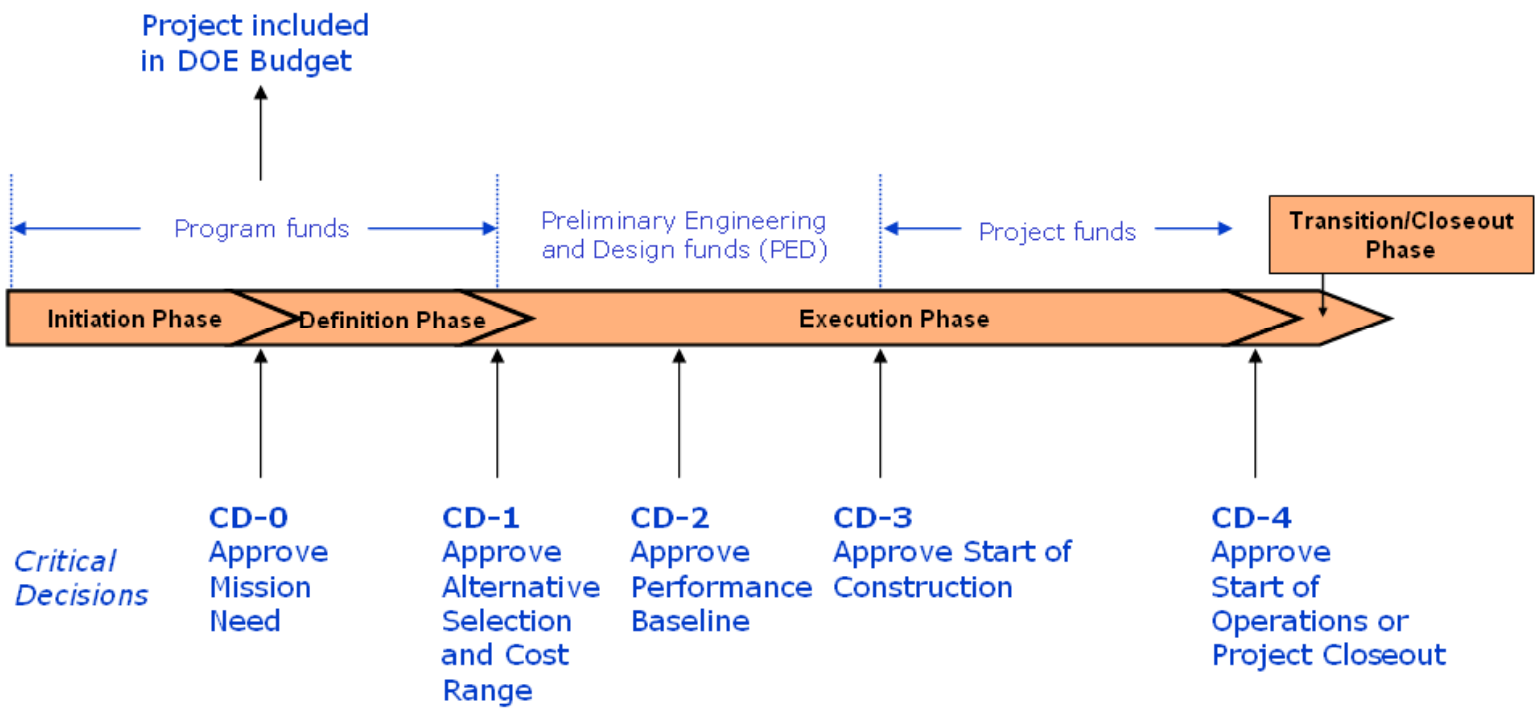
Fermilab's Office of Project Management Oversight

CD Process

U.S. Department of Energy

Project Management Process

Office of Science



new measurements: test beams, prototypes

7

It Gets Worse

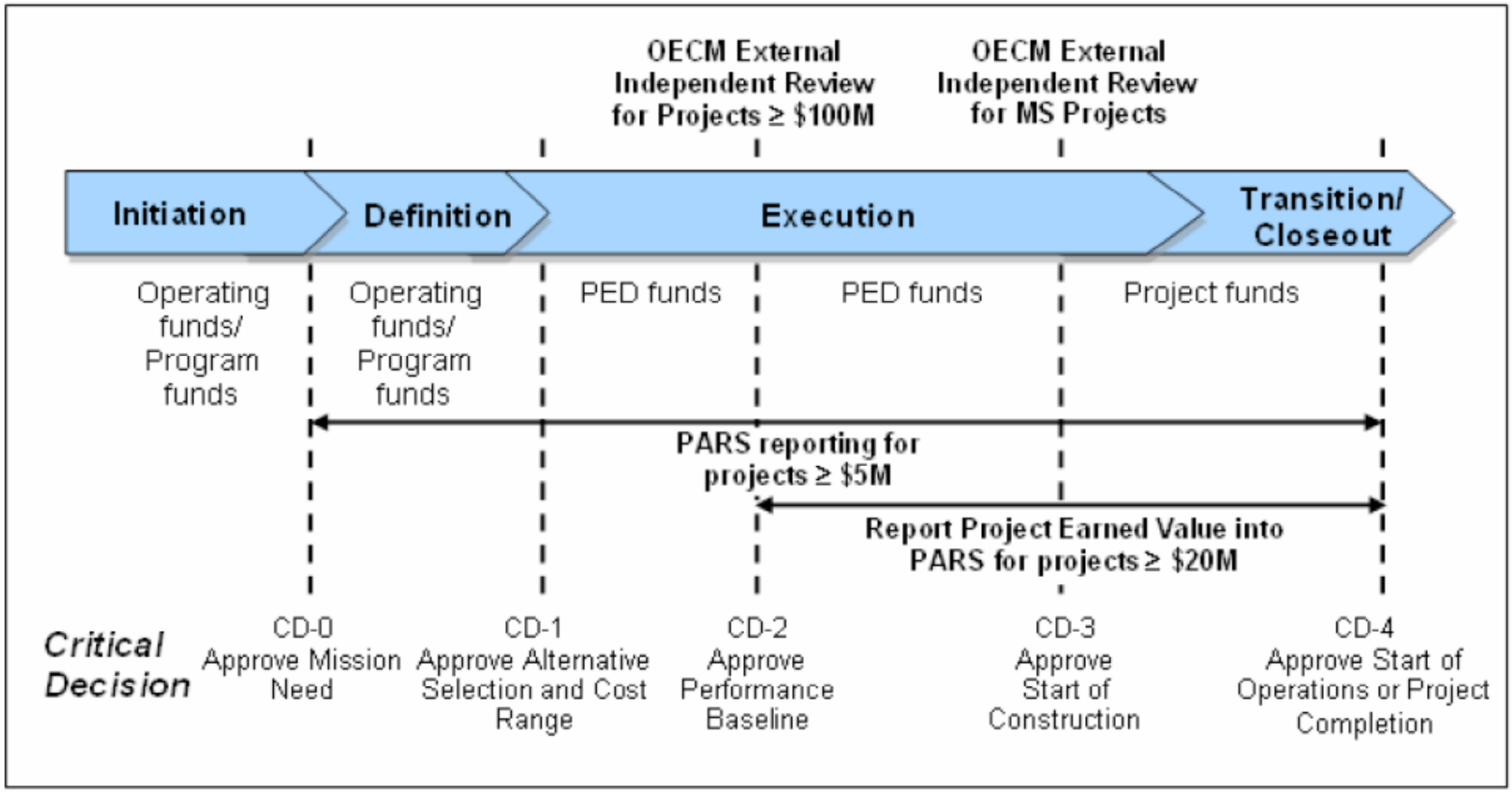


Figure 1. Typical DOE Acquisition Management System for Line Item Projects.

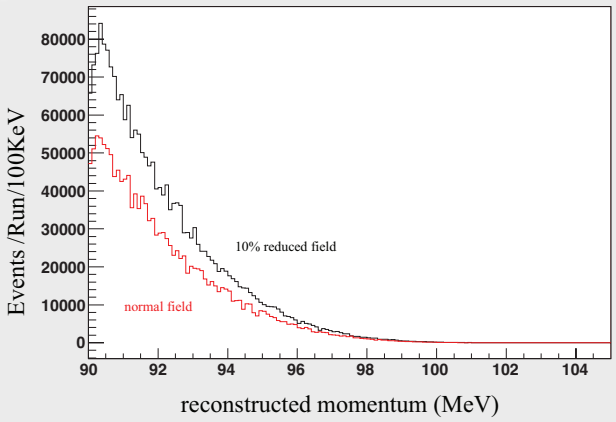
Details of Cost Estimate

	M&S (k$)	Labor (k$)	Base Cost FY05 k$	Base C ost 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

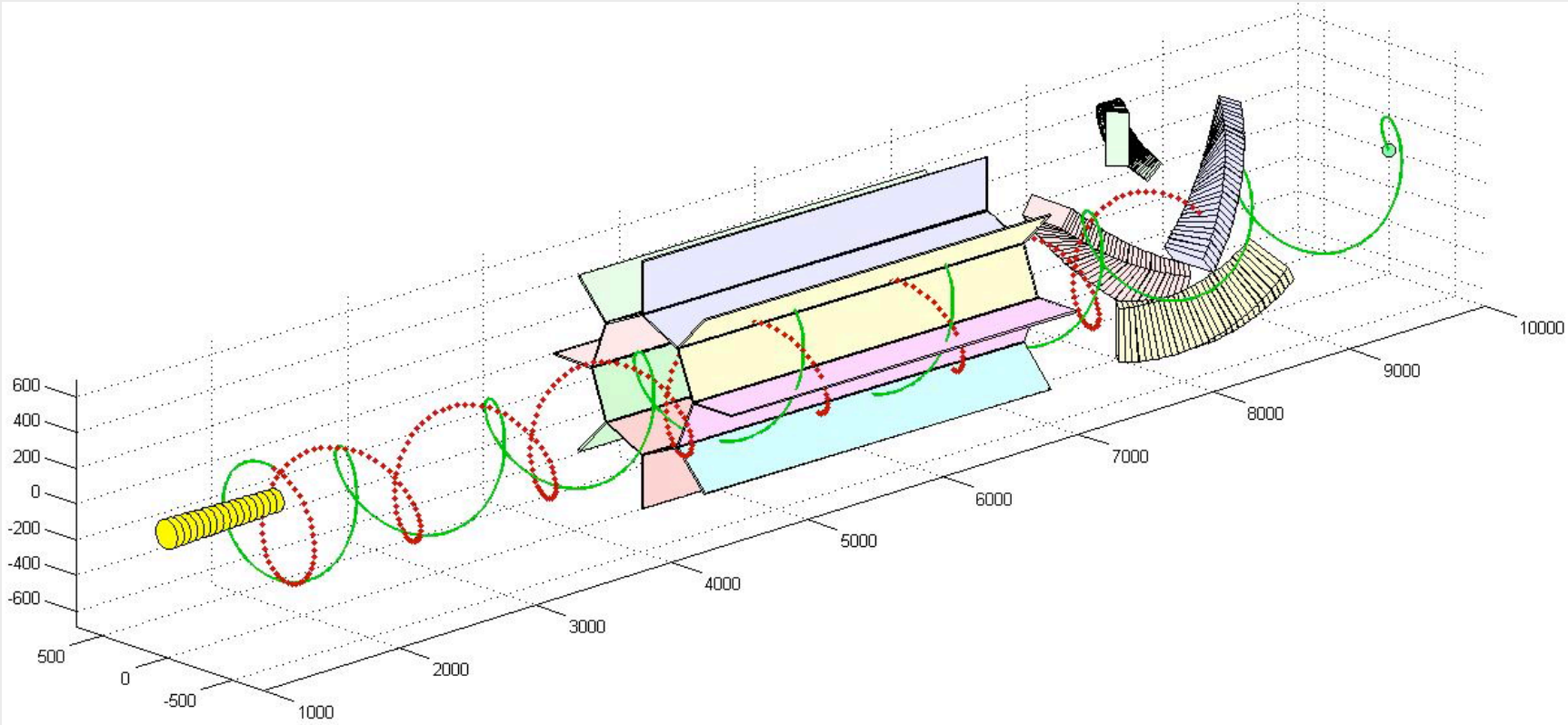
Measuring the Resolution

- 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

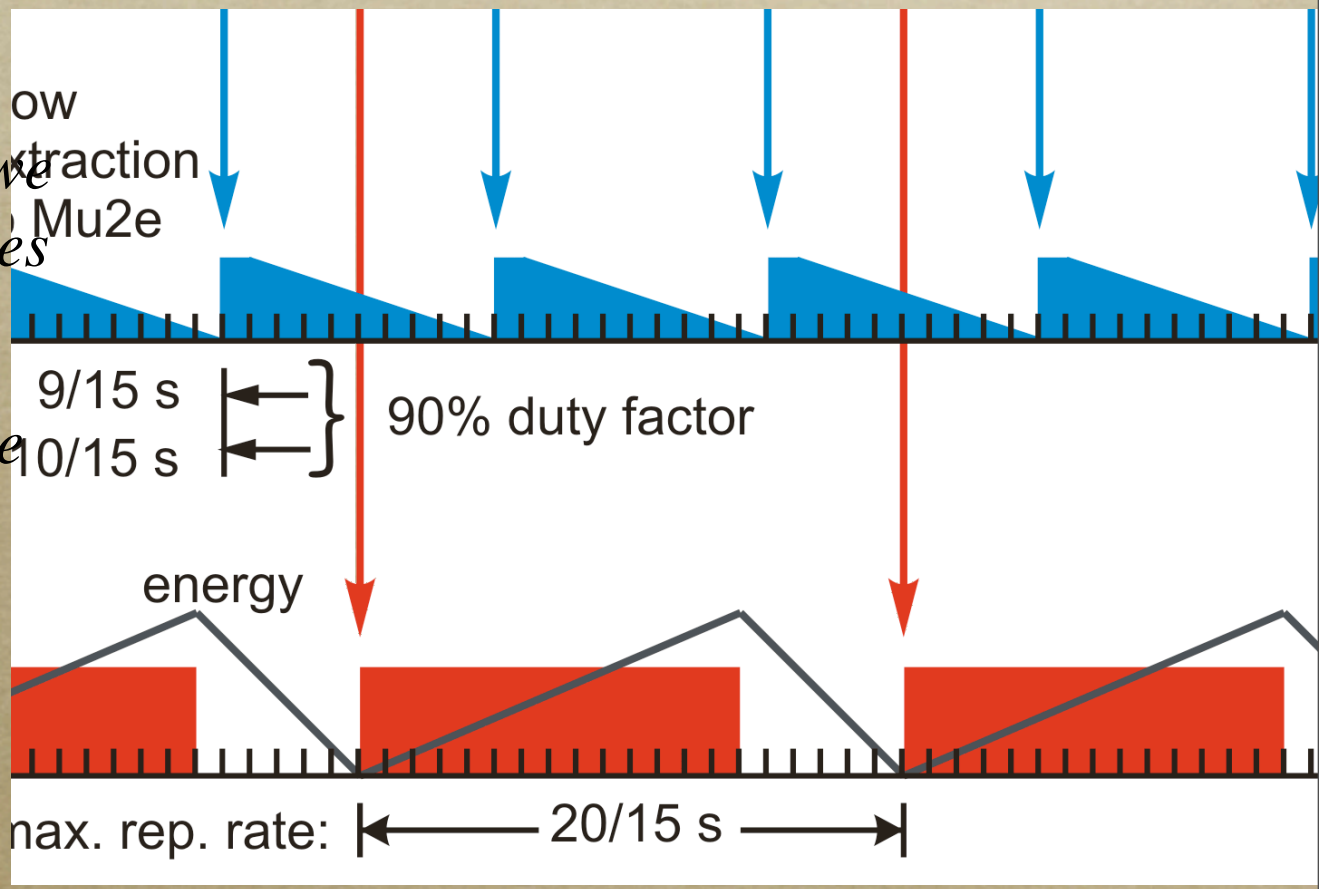


Beam Flux and Radiation Safety

- *New particle rates for the "pbar" rings:*
  - *presently, Debuncher/Accumulator receive approximately 25×10^{10} particles per hour; for μ2e, expecting ~2×10^{13} per second: factor of 300,000*
  - *1% loss (scaling) ➔ ~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 ~ Booster system*
  - *const. energy rings help -- can monitor devices, inhibit beam*

When NO*ν*A 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)*
    - *7.7×10^7 per "burst"*



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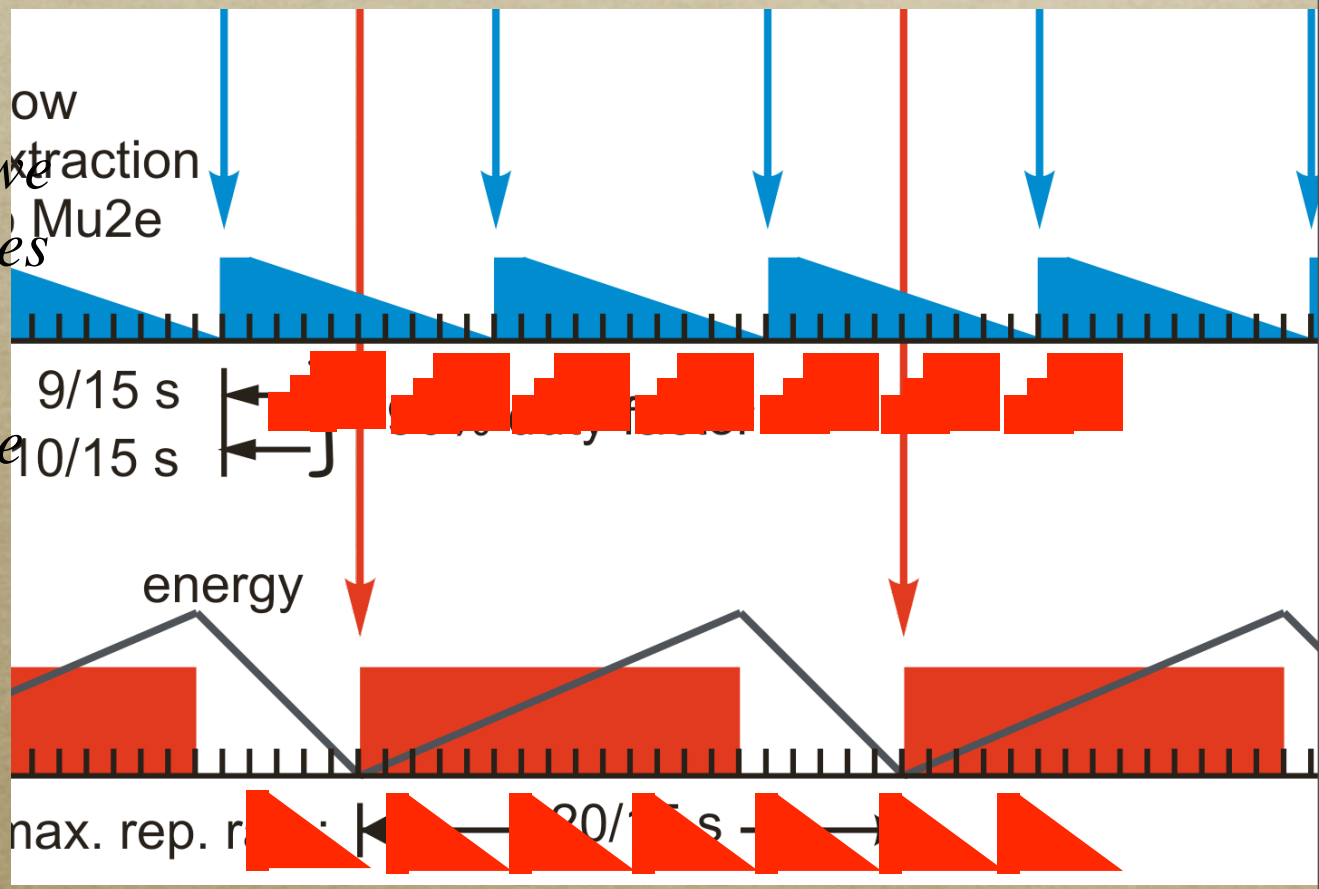

Better than MECO because of better beam structure

	MECO	Mu2e Booster	Mu2e Project X, no expt. upgrade	Mu2e Project X, expt. upgrade
protons/sec	40×10^{12} (design)	18×10^{12}	70×10^{12}	160×10^{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	**80×10^{12} (design)**	**20×10^{12}**	**77×10^{12}**	220×10^{12}
short term beam power	100 kW (design)	**25 kW**	100 kW	220 kW
Beam pulse period, μsec	1.35	1.65	1.65	1.65
Data collection time interval μsec	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	40×10^{12} (design)	18×10^{12}	70×10^{12}	160×10^{12}
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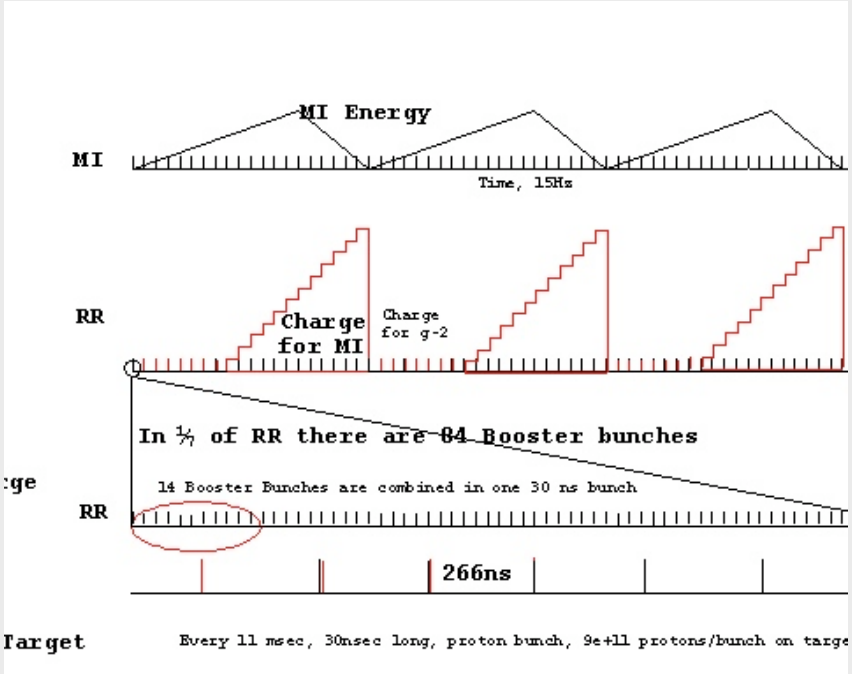
Data collection time interval μsec	0.7-1.35	0.7-1.65	0.7-1.65	0.7-1.65

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

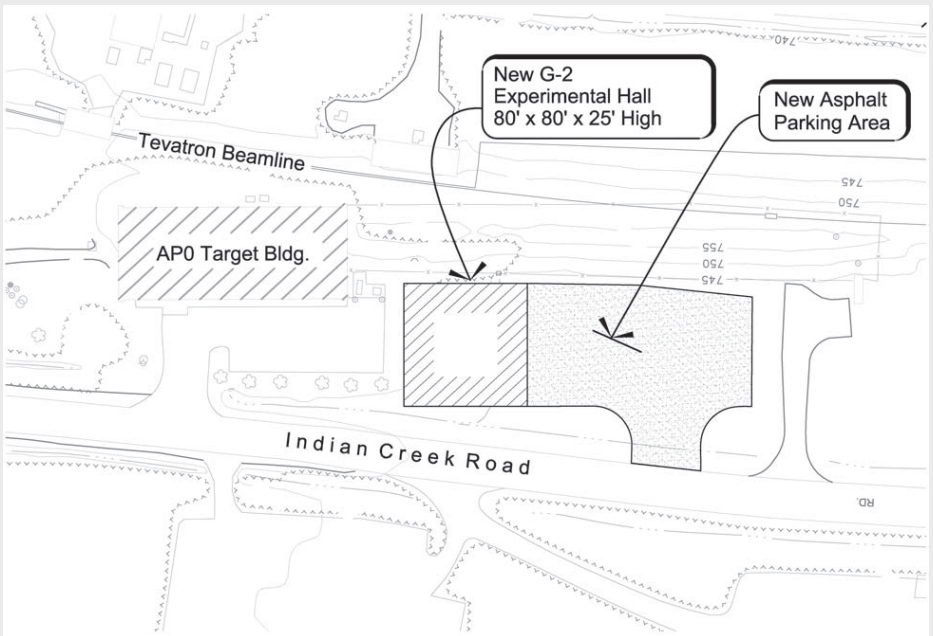


Figure 1.1 Location Plan of the New G-2 experimental Hall

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.

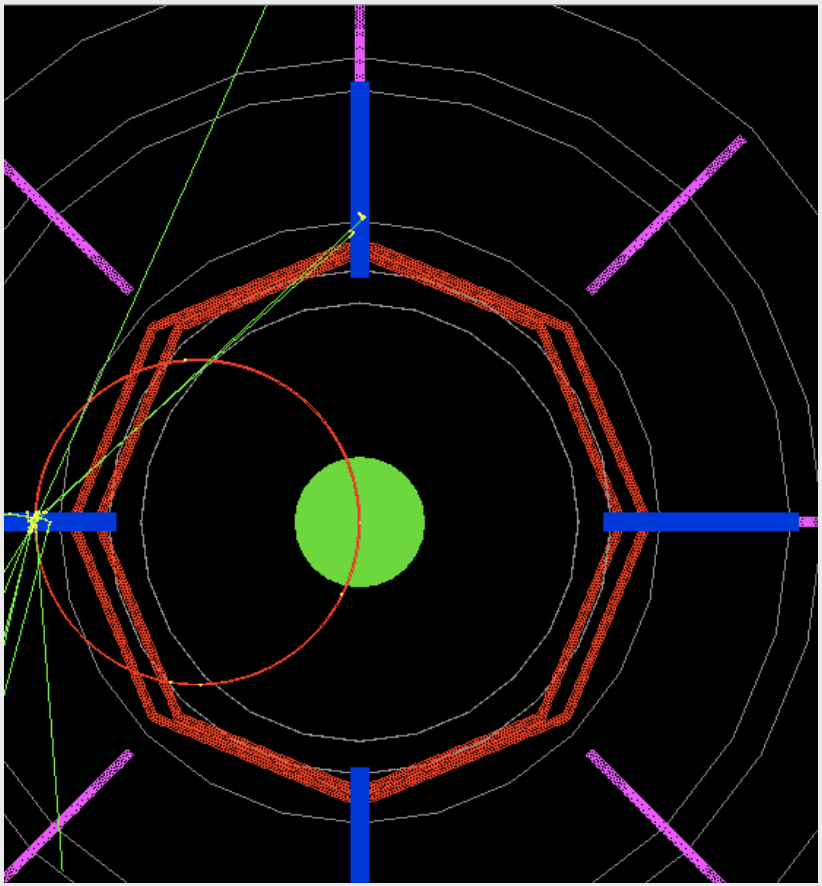
- For a conversion process, the cross section is coherent and therefore goes like Z**2 (or A**2) rather than Z in the case of ordinary capture. So overall the process goes like Z**5. Strictly speaking this overlap argument only works well for short-range forces like the weak force, since we assume that 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 $Z^4/Z^3 = Z$ 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.

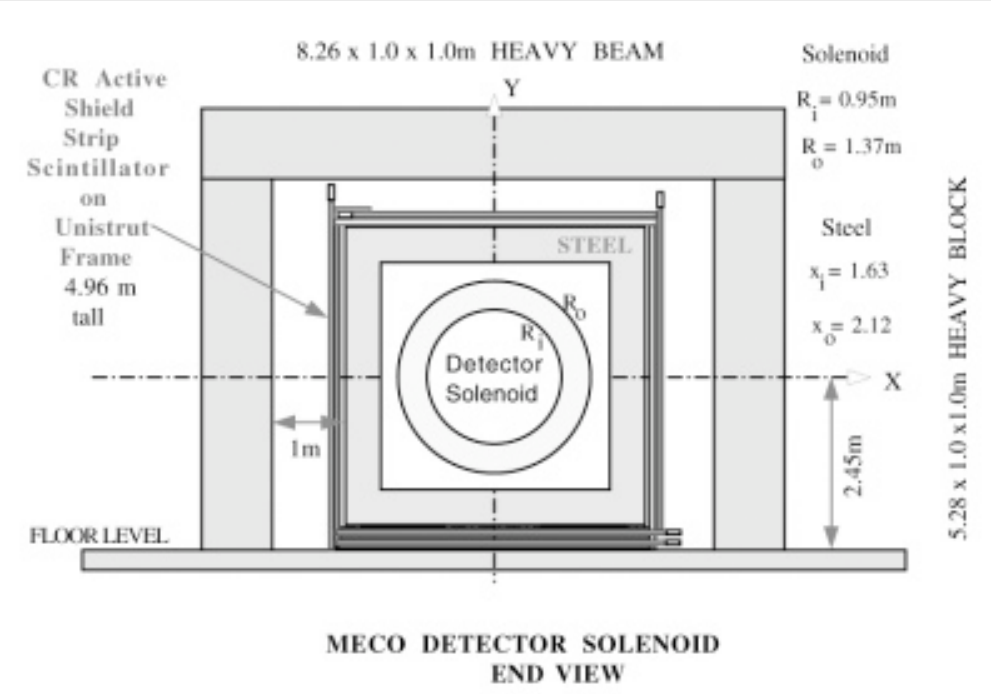
Software Needs

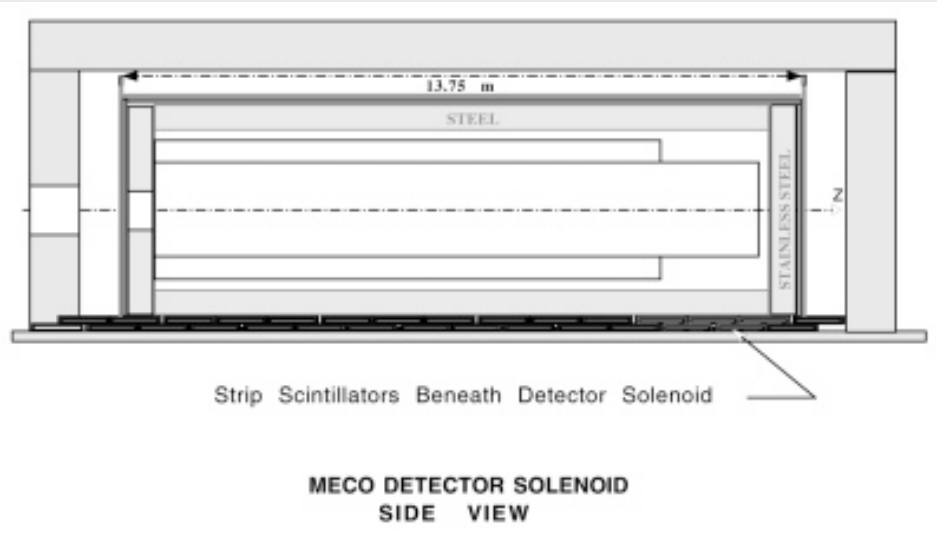
- primitive GEANT4 simulation begun
- old MC is GEANT3/FORTRAN/PAW
  - not unified, lots of different standalone codes that are not available or documented
- cannot do simple calculations to check MECO or improve design
- ***no hit-level MC ever written-- not acceptable for 10^{-17} experiment, and MECO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



Cosmic Rays and Veto

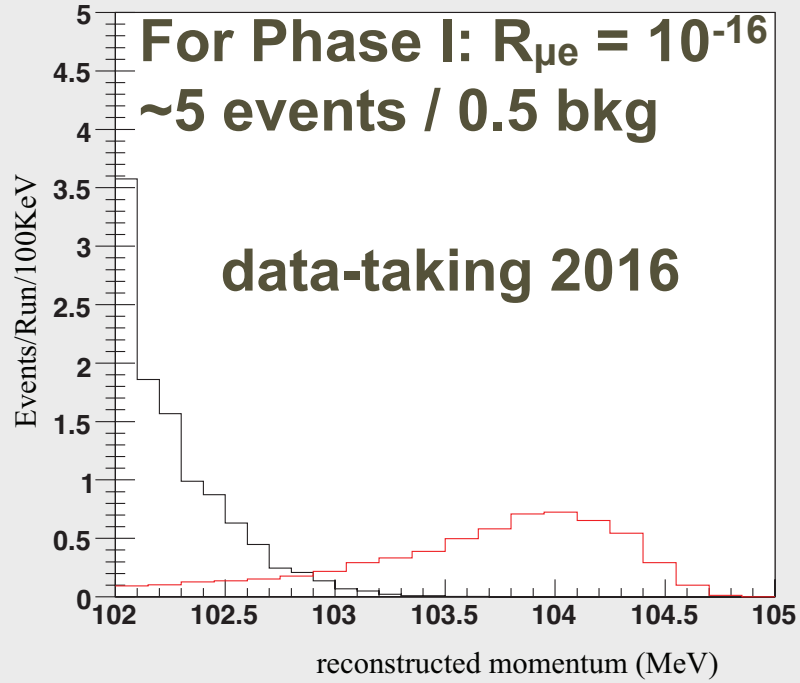
- Cosmic ray (CR) induced electrons (or muons mistaken as electrons) may induce backgrounds.
- Both steel (also return yoke of iron) and concrete
- Three-Layer Veto of MINOS-type scintillator
- Mu2e is re-examining scintillator, and planning on placing solenoid below ground(MECO at ground-level)



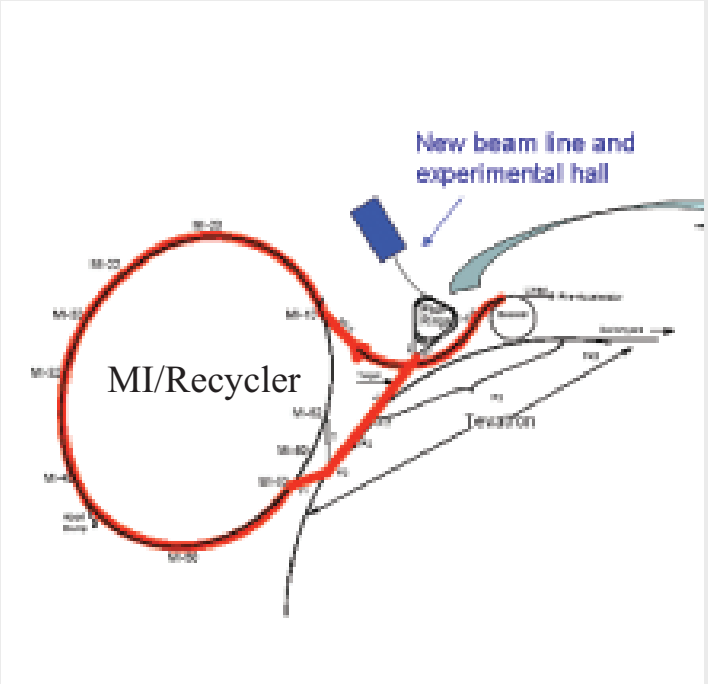


Mu2e: Muon-Electron Conversion at Fermilab

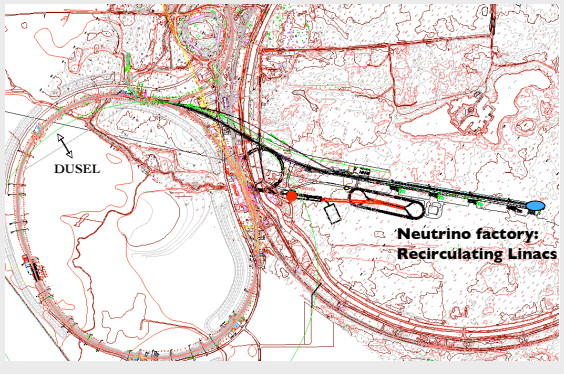
starts with advanced MECO design



uses existing rings with minor changes: no effect on NOvA



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



DUSEL, kaons, g-2,...

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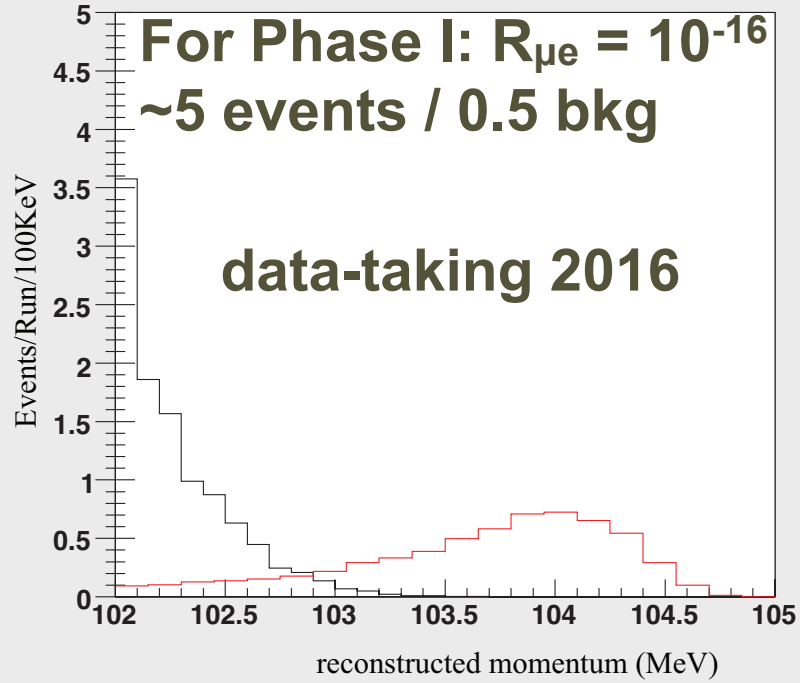

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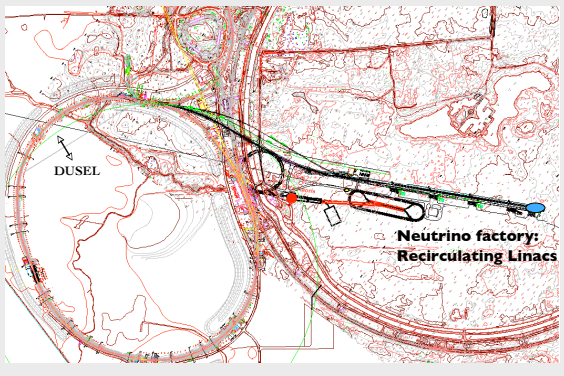
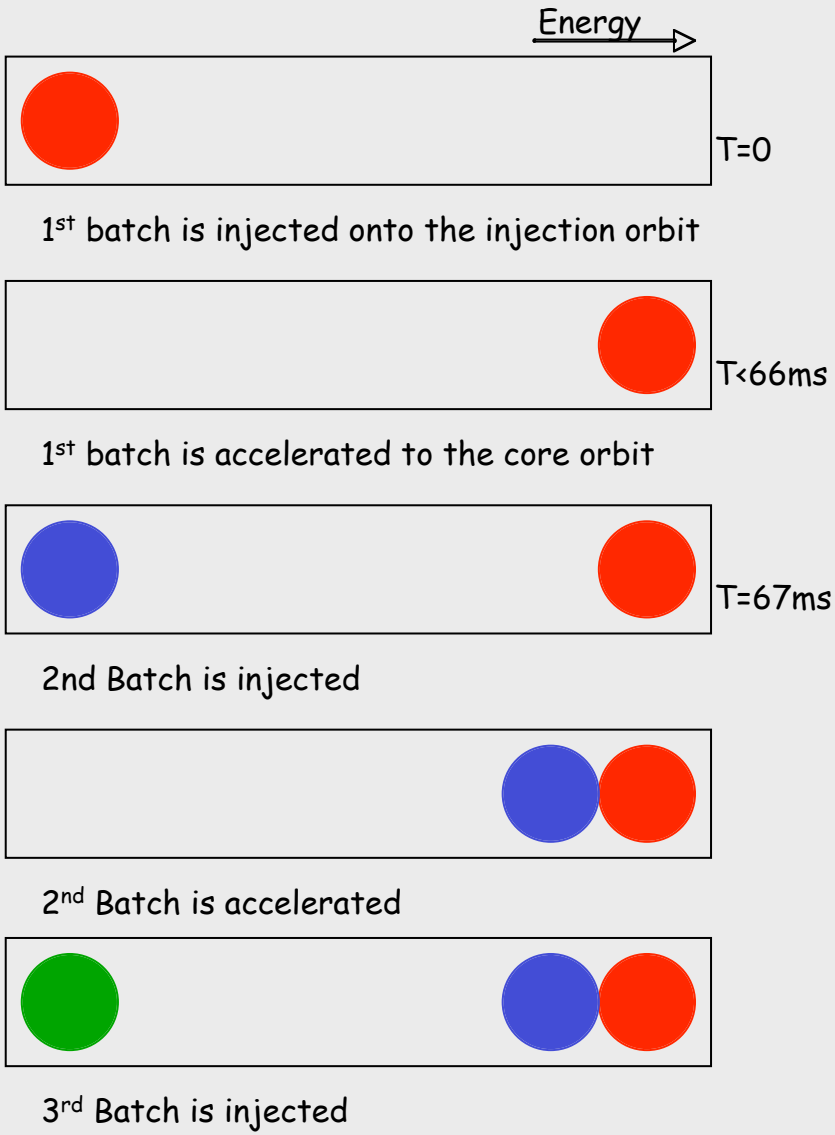


DUSEL, kaons, g-2,...

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 $\overline{p}$ now; rebunch for mu2e
- Recycler:
  - holds more $\overline{p}$ than Accumulator can manage, “store” here



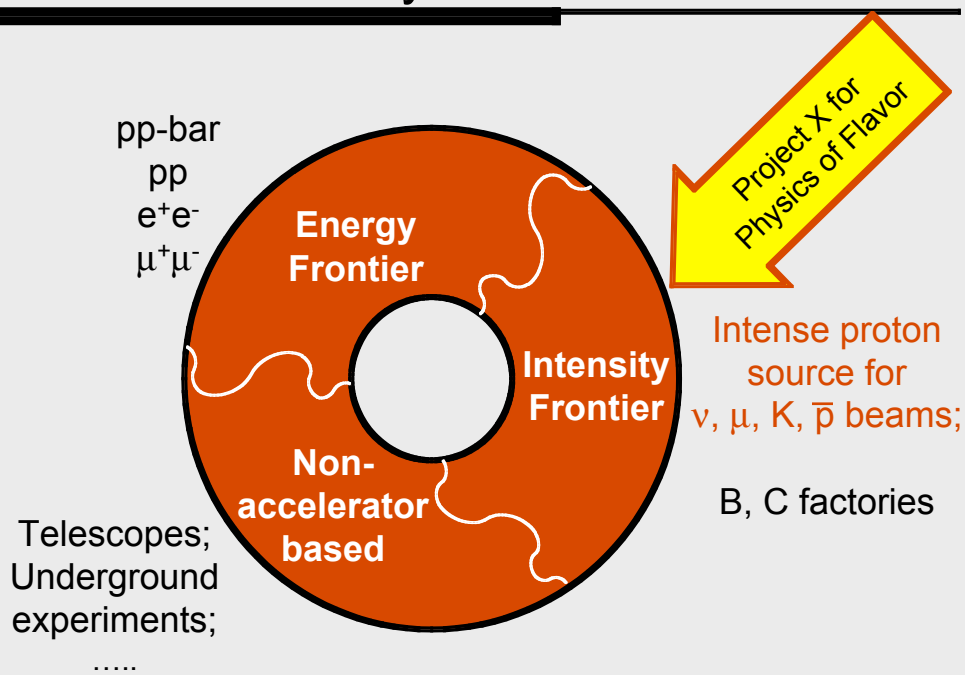
Rates In Tracker

- 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)

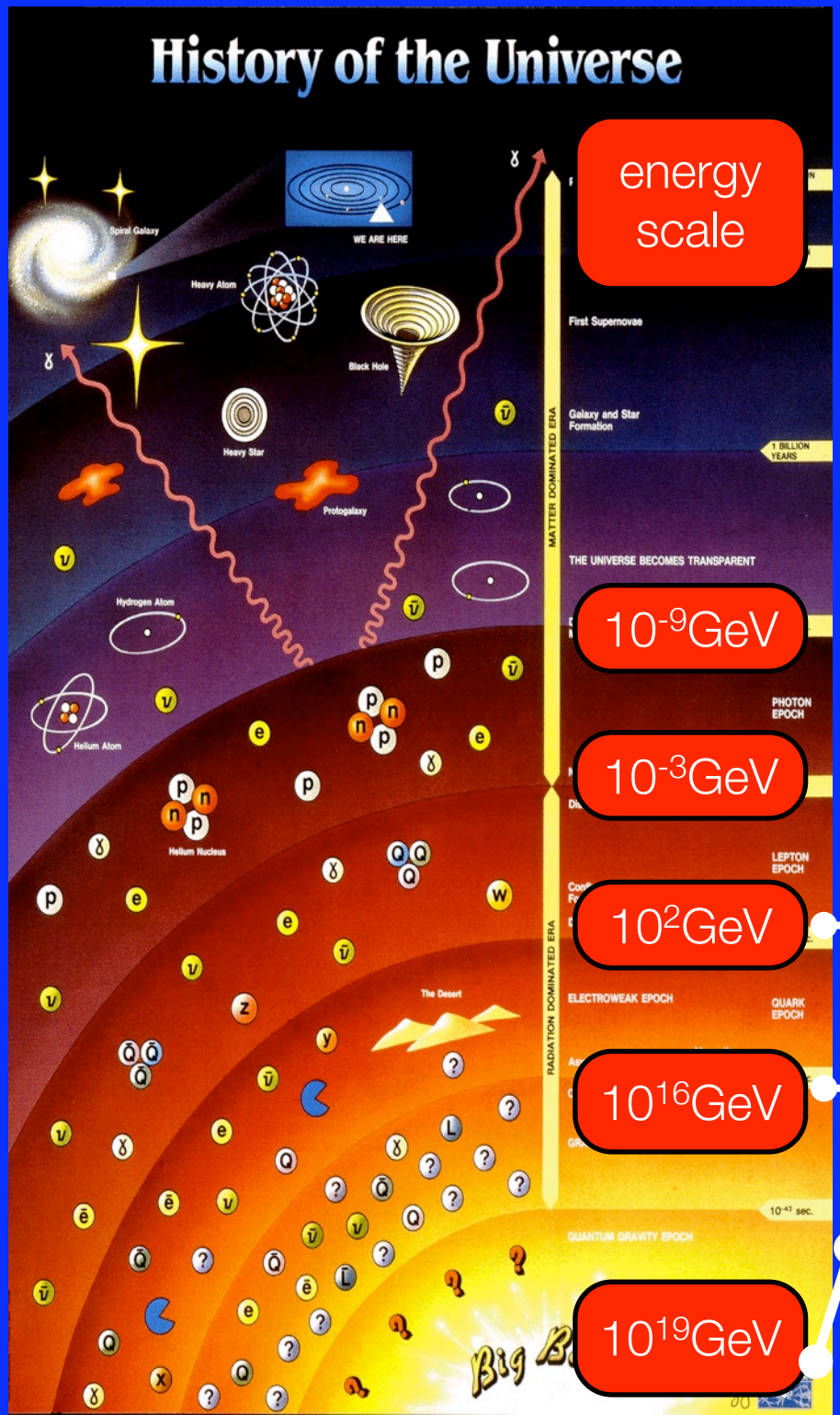
Type	Rate(Hz)	$\mathcal{P}$ hit	Mean N hits/bkg part	R_{wire} (kHz)
e_t	0.62×10^{11}	0.00032	1.54	16.3
n_t	0.62×10^{11}	0.000142	2.887	12
γ_t	0.62×10^{11}	0.000248	4.524	33.4
p_t	4.5×10^{9}	0.00362	6.263	50.
$e(DIO)_t < 55$	0.2×10^{11}	9.8×10^{5}	1.44	1.4
$e(DIO)_t > 55$	0.5×10^{8}	0.00127	22.7	0.5
n_{bd}	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



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



energy scale

10^{-9}GeV

10^{-3}GeV

10^{2}GeV

10^{16}GeV

10^{19}GeV

Electroweak Epoch

- Higgs particles
- Supersymmetry

Unification Epoch

- Grand unification of fundamental forces
- Origin of Neutrino mass
- Leptogenesis (baryogenesis)

Quantum Gravity Epoch

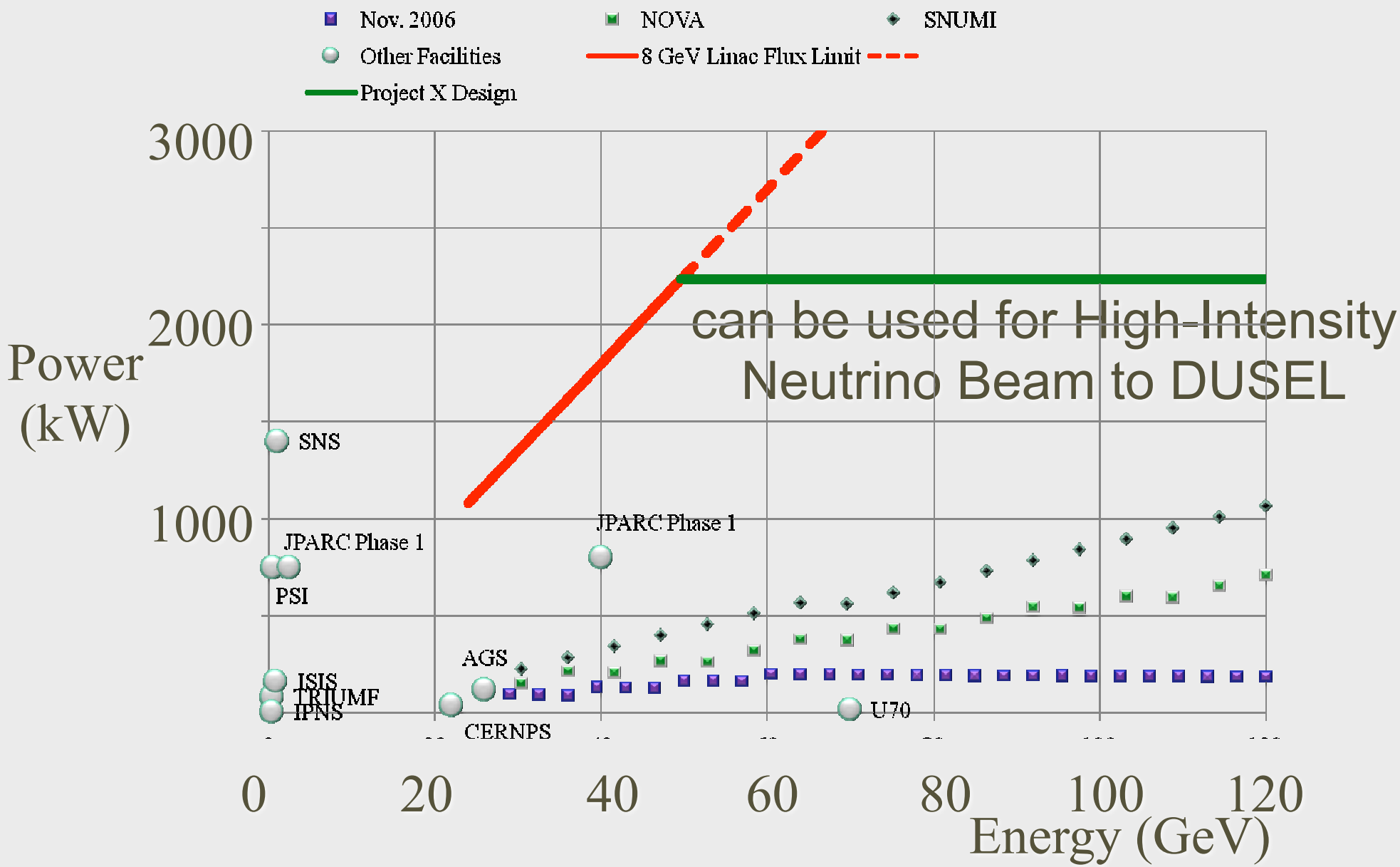
- Superstrings

Nucleon decays

Neutrino physics

Lepton Flavor Violation

Project X Intensity Goals

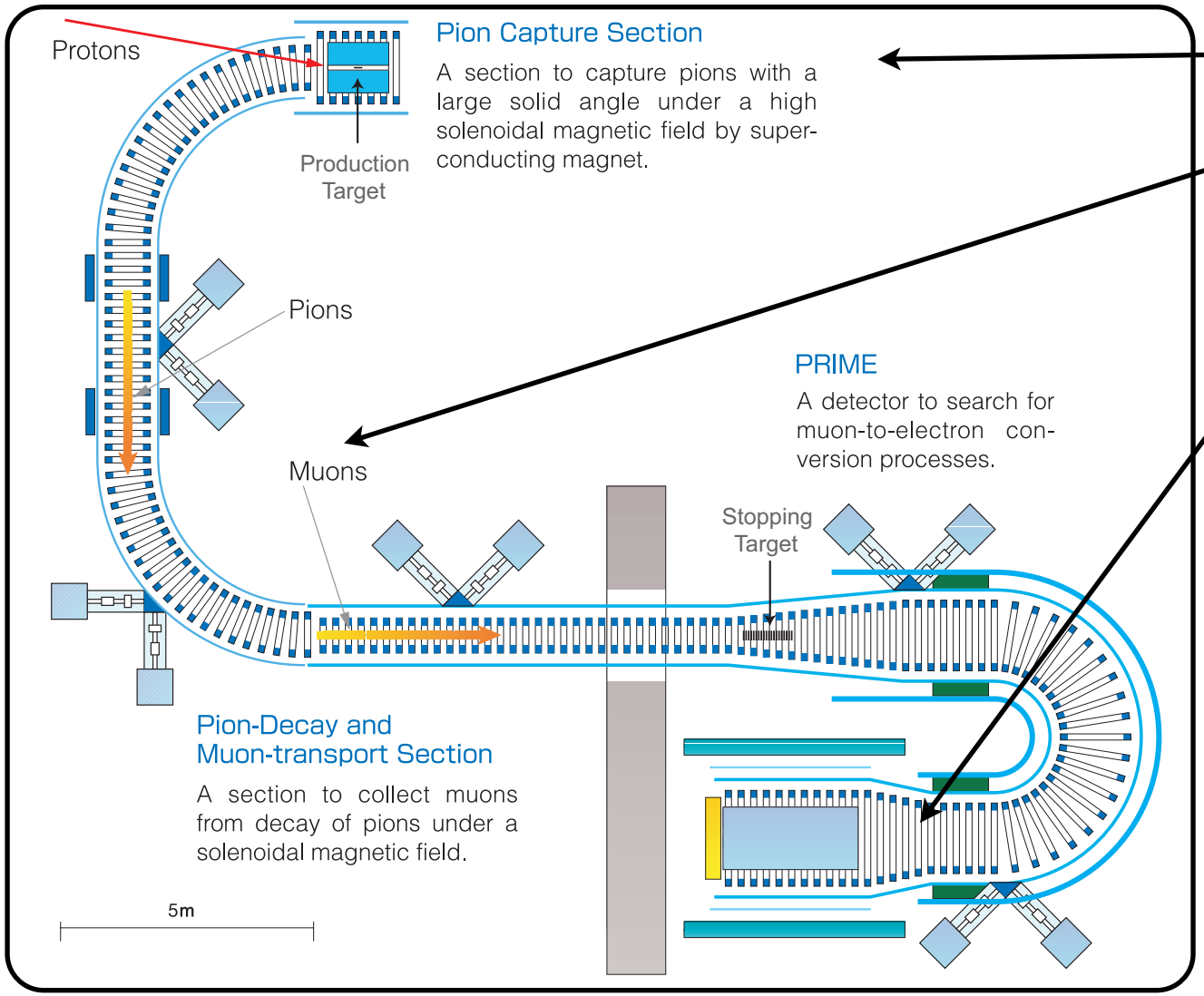


can be used for High-Intensity Neutrino Beam to DUSEL

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

from Y. Kuno

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



Proton Beam

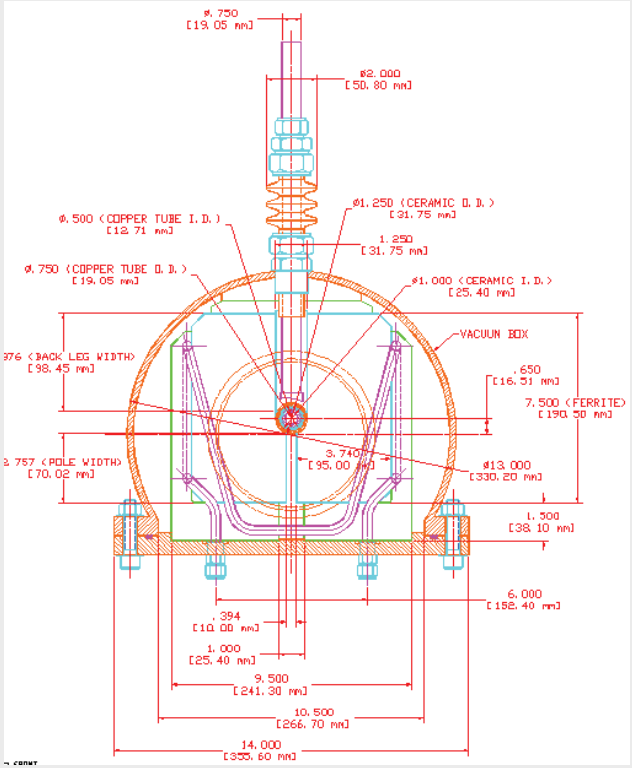
The Muon Source
- Proton Target
- Pion Capture
- Muon Transport

The Detector
- Muon Stopping Target

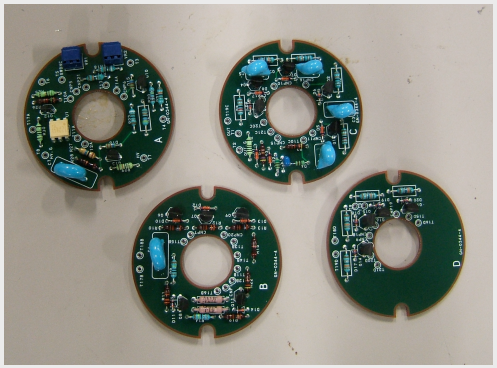
proposed to J-PARC

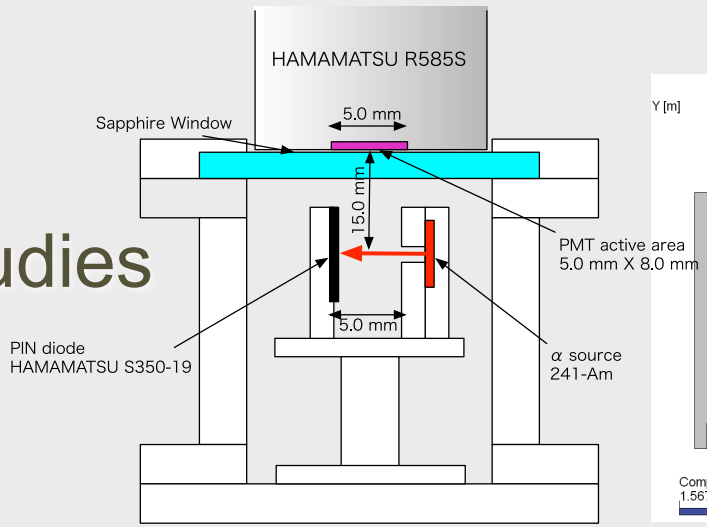
Collaboration with Japan

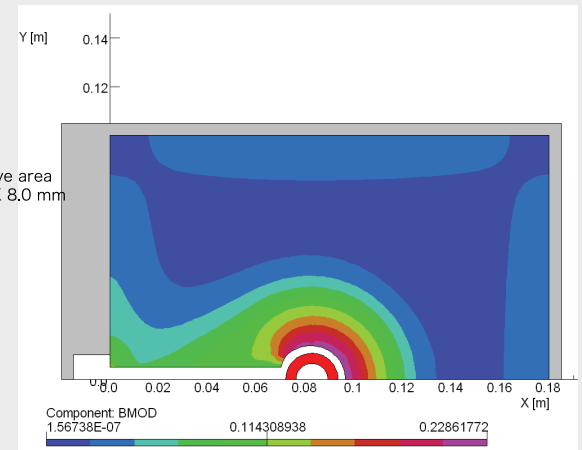
- COMET/Mu2e are collaborating on
  - AC Dipole (FNAL)
  - Extinction Monitor(Osaka)
- US-Japan Agreement
  - KEK/FNAL
- ~$50K this year for studies
- **THANKS!**



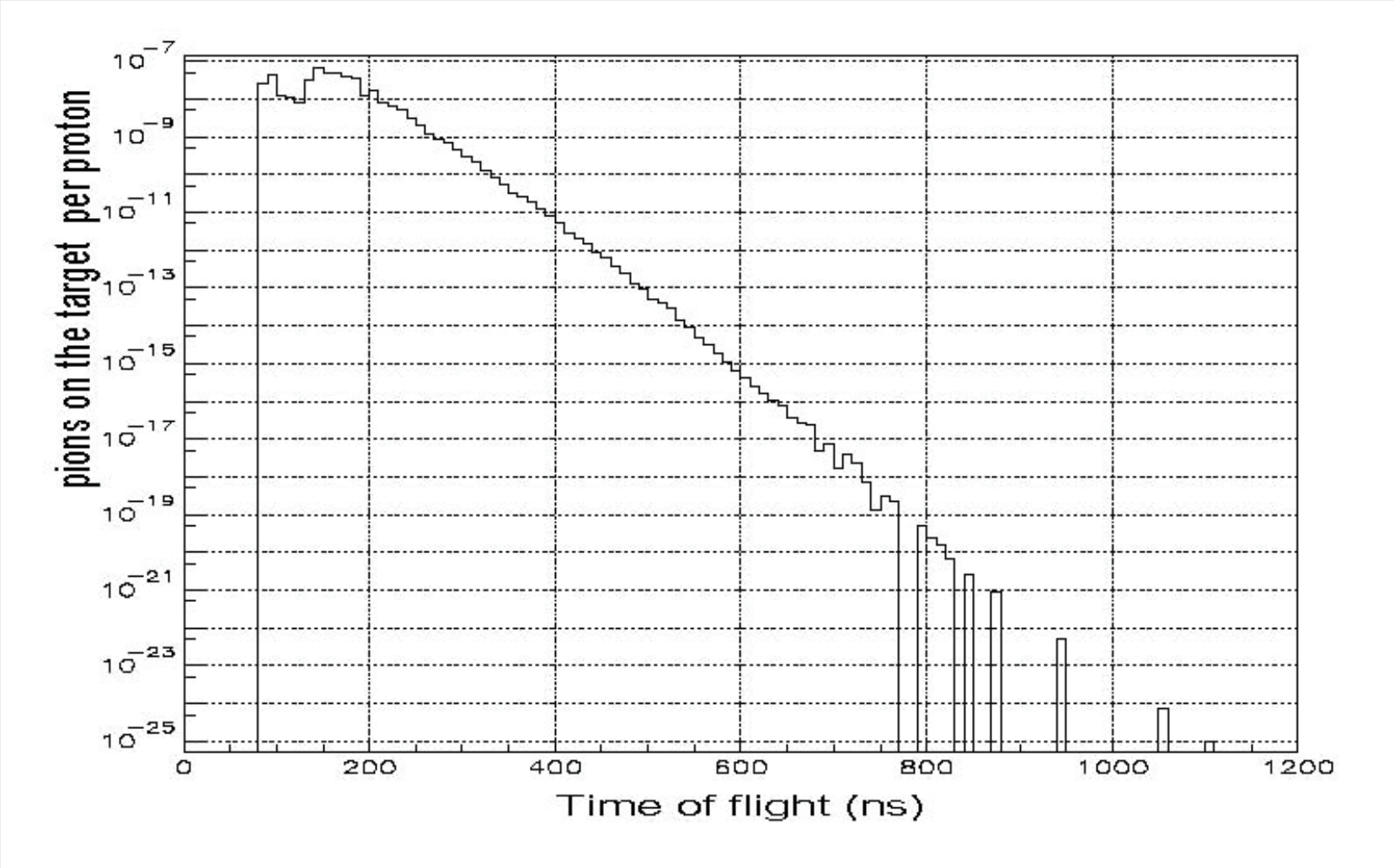
- **Critical For Progress!**





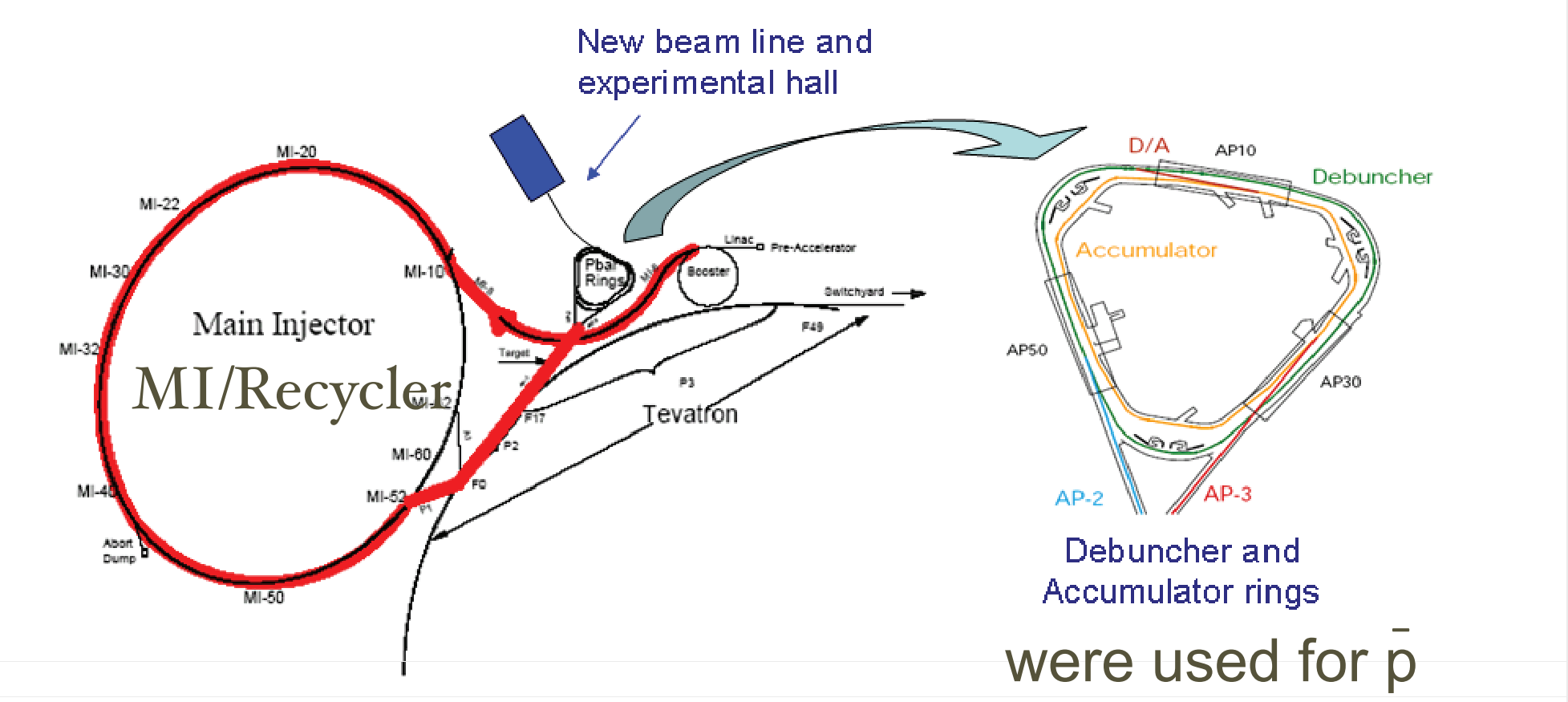


Radiative π and Pulsed Beam



- waiting 700 nsec suppresses by 10^{11}

Booster-Era (before Project X) Beam



were used for $\bar{p}$

- 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 →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

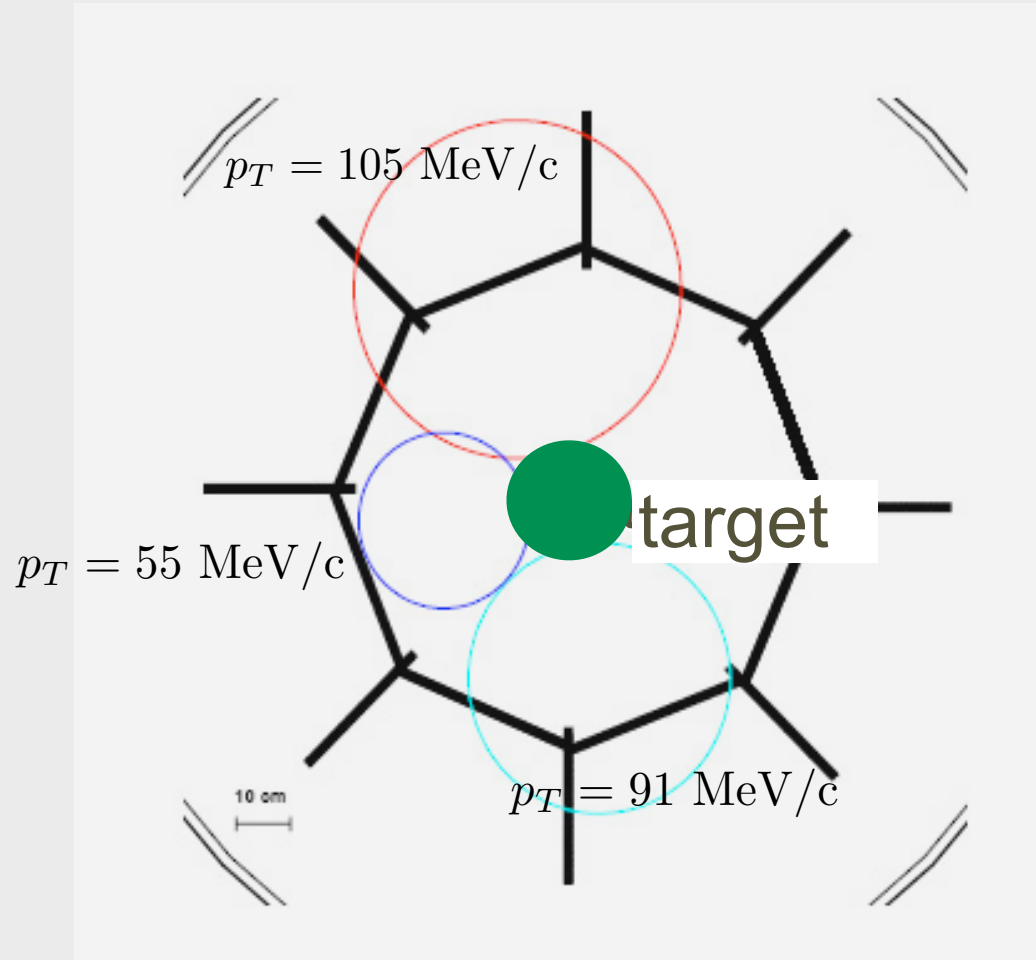
- L-Tracker: straws along beam
  - Conceptually simpler tracking
  - Basis of MECO
  - Where does support/ infrastructure go? Material in electron path
  - Can anyone build straws 0.5 cm × 2.6m in vacuum?

- 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

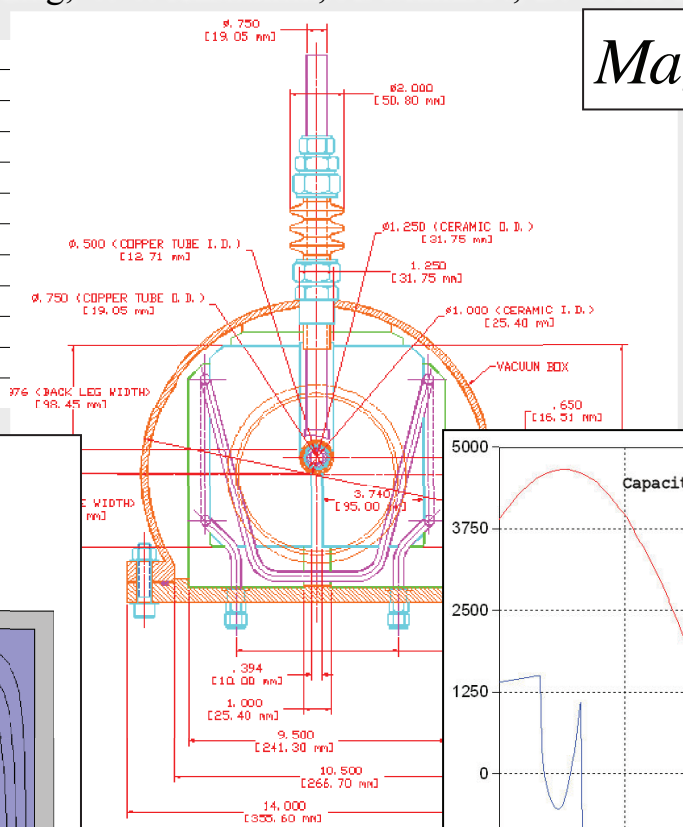
Conceptual Design of AC Dipole Magnet for μ to e- Experiment

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

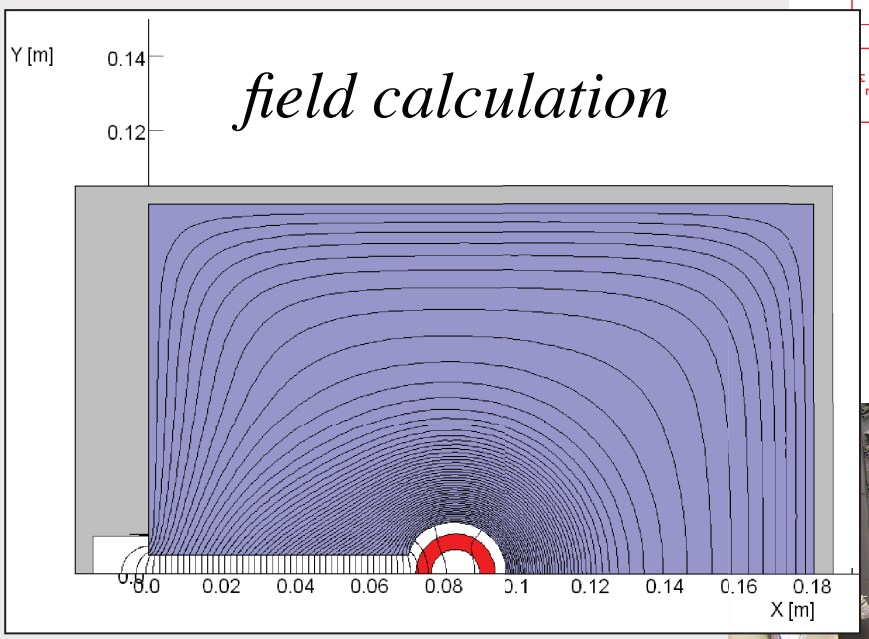
Table I. AC Dipole specification.

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

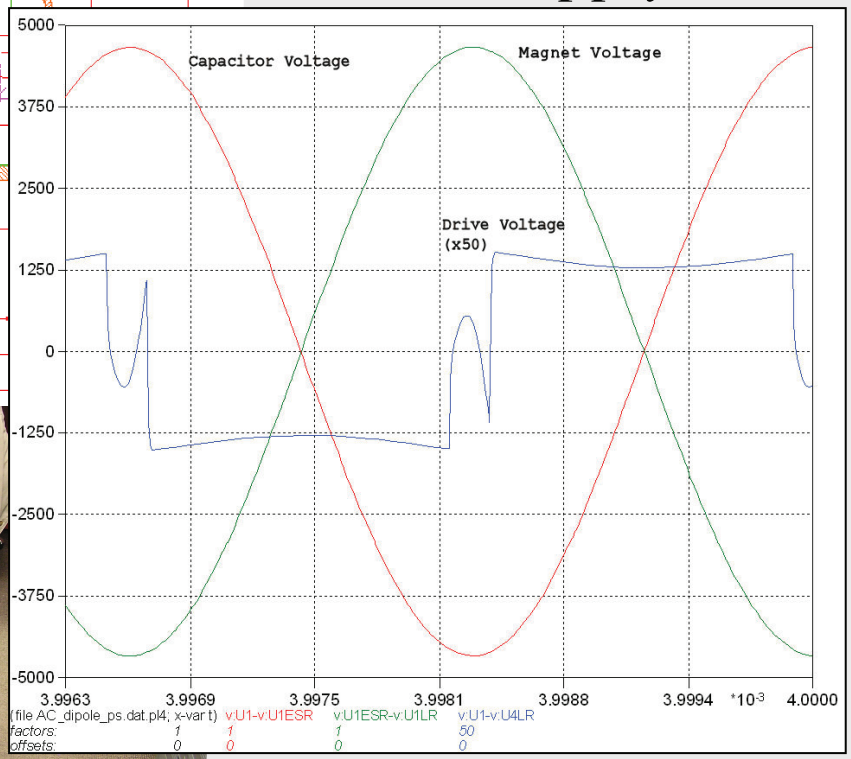
Magnet Design



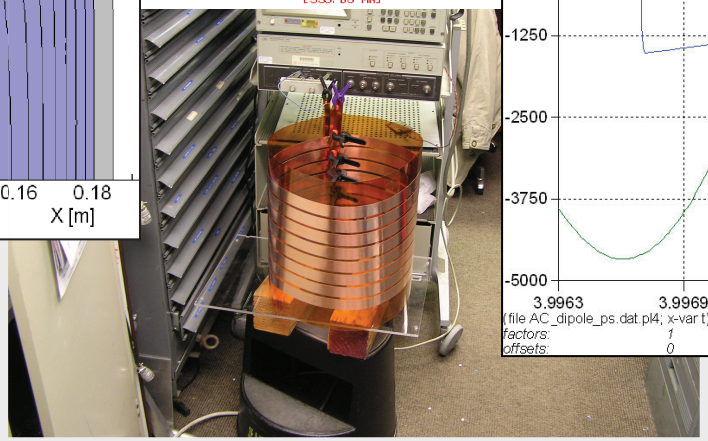
field calculation



Power Supply Calc

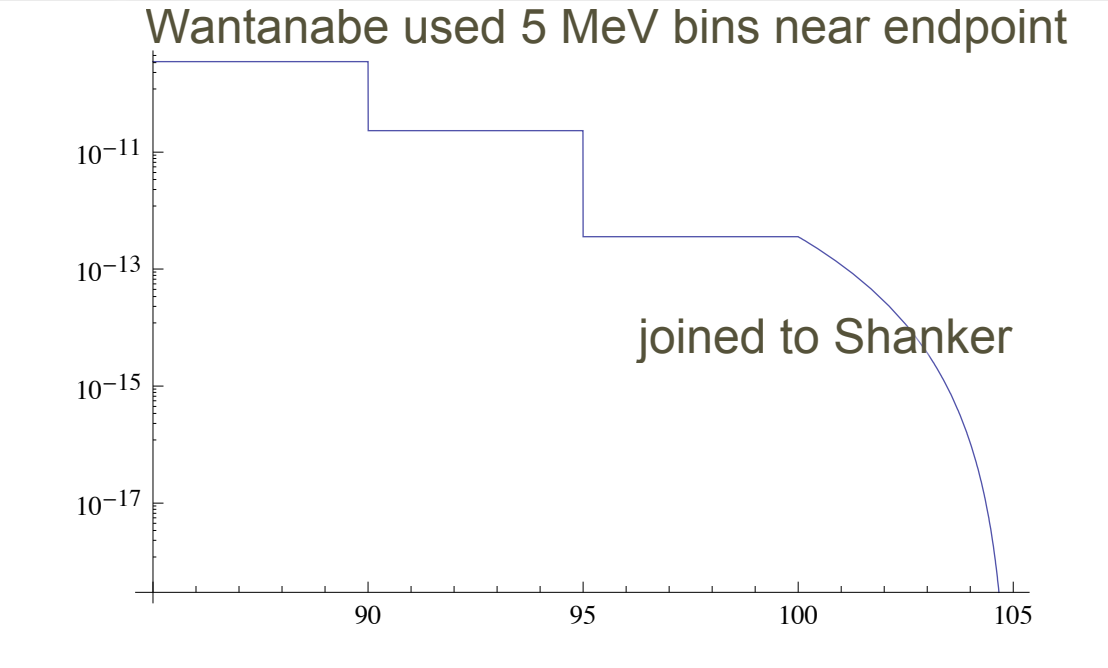


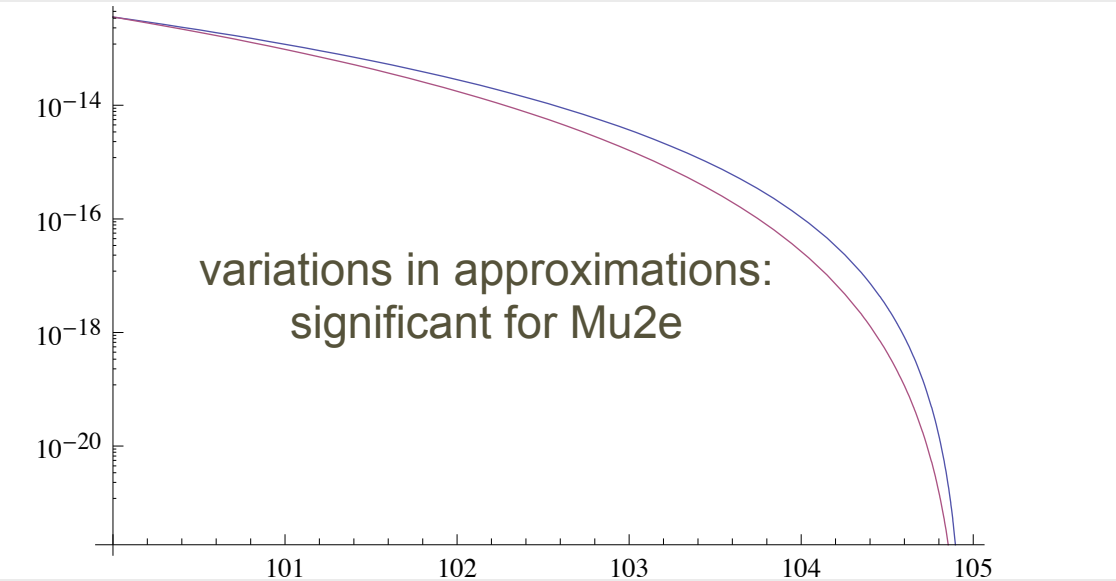
prototype transformer



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!





Changes in Cost from MECO

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

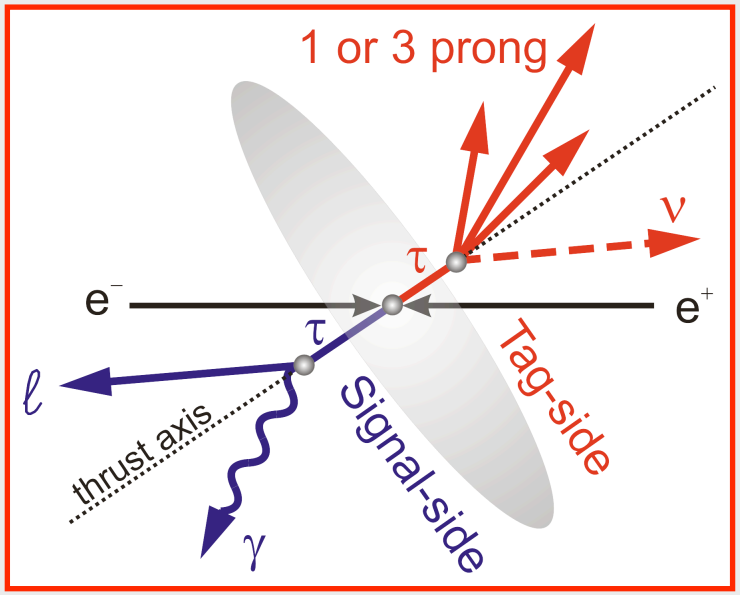
Next Steps:

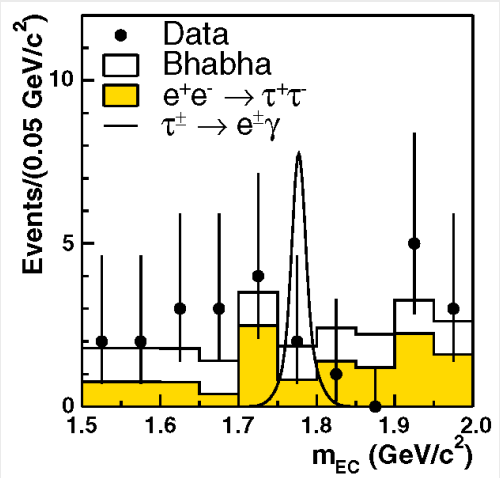
- This is the *beginning* of the process
- Lots of fun, interesting work to do
  - improvements and new work on detector, solenoid, beam
  - will examine every cost in detail
- Perfect time to join and participate!

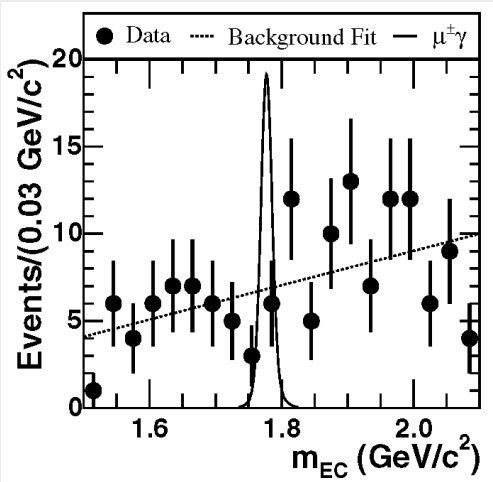
DOE CD Process

Hell:
fresco in
Camposanto

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

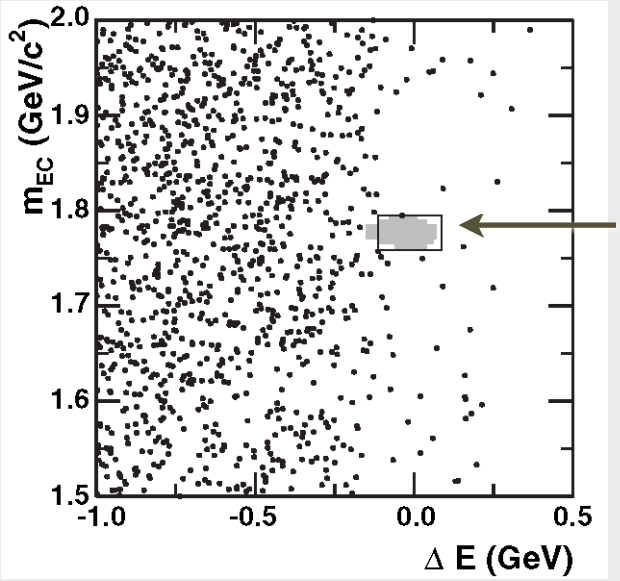






$B(\tau^- \to \mu^-\gamma) < 6.8 \times 10^{-8}$ 4 Bkg

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

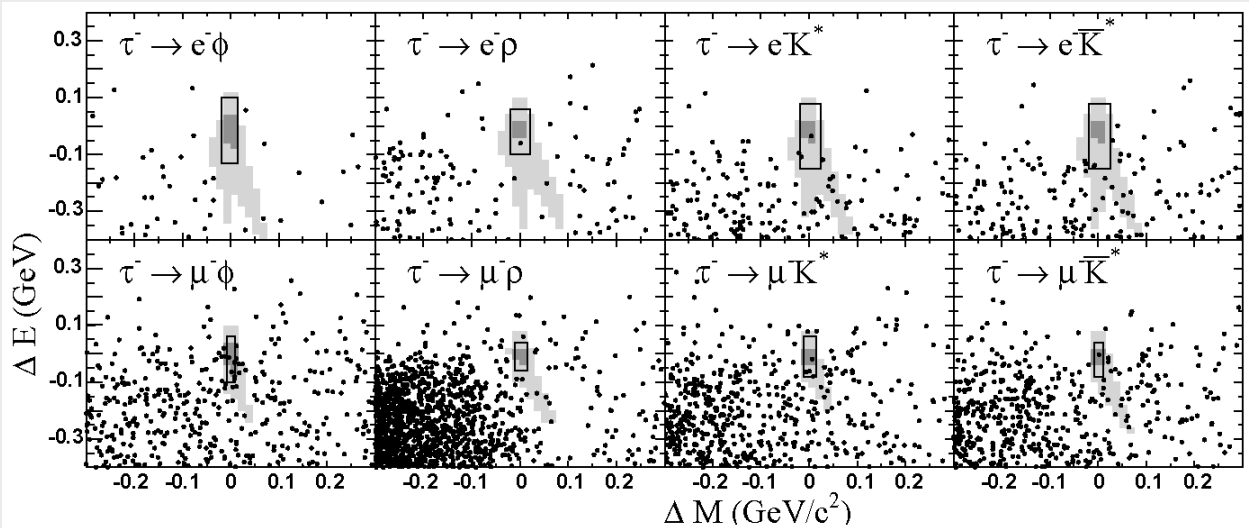


2σ signal region

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

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

Semi-leptonic Modes



Mode	ε[%]	$N_{\rm bgd}$	$N_{\rm obs}$	$N_{\rm UL}^{90}$	$\mathcal{B}_{\rm exp}^{90}$	$\mathcal{B}_{\rm UL}^{90}$
$e\phi$	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
$e\overline{K}^*$	7.76 ± 0.18	2.76 ± 0.28	2	3.2	5.4	4.6
$\mu\overline{K}^*$	4.11 ± 0.32	1.72 ± 0.17	1	2.7	9.3	7.3

} x 10^{-8}

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