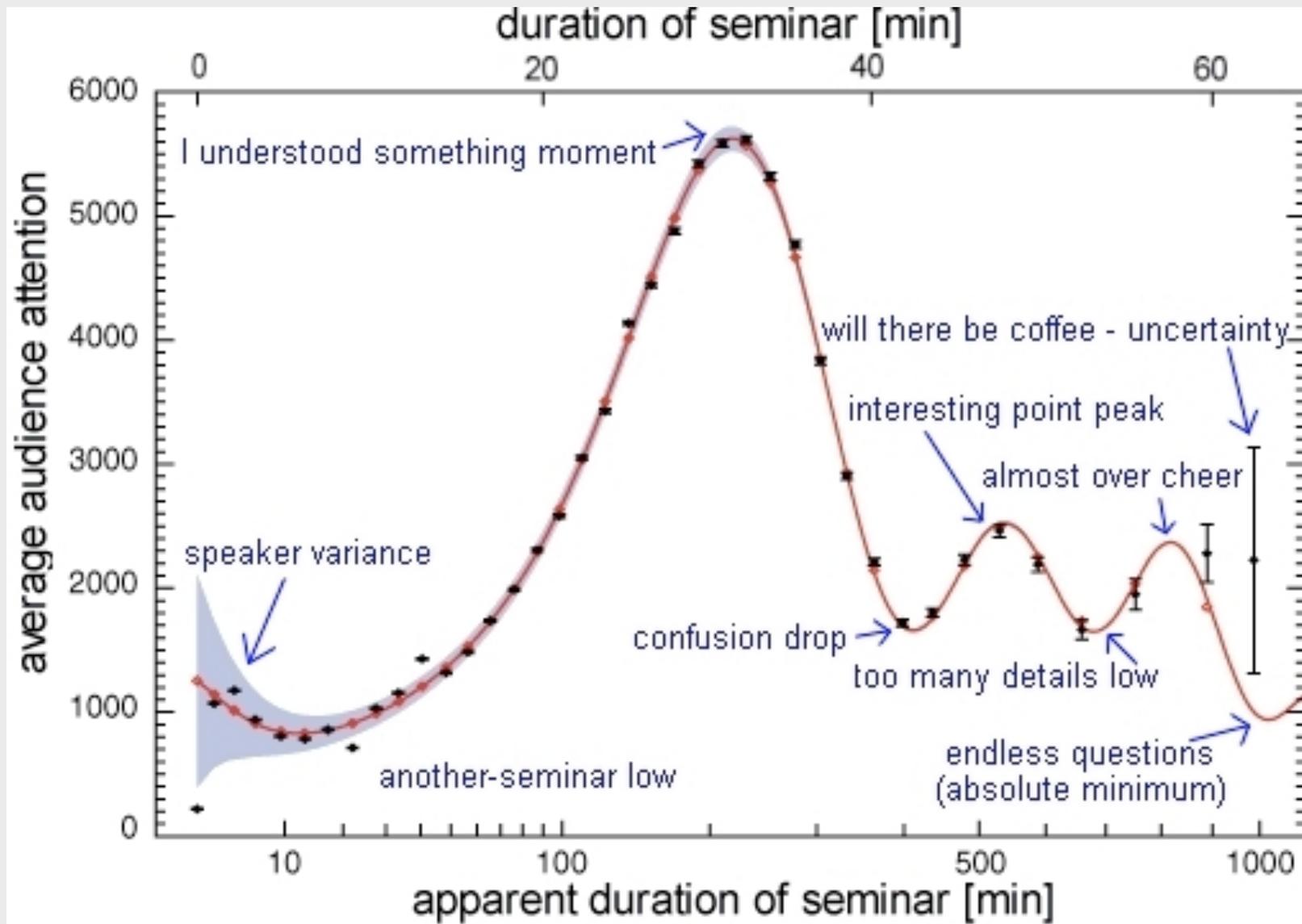
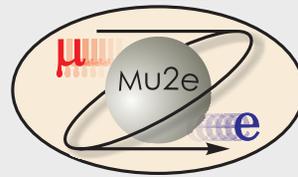
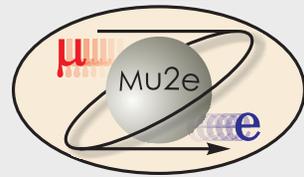




# Outline



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



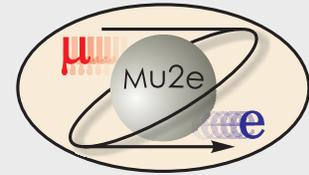
# A New Charged Lepton Flavor Violation Experiment: Muon-Electron Conversion at FNAL

---

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*

*Duke University*

*Fermilab*

*University of Houston*

*University of Illinois, Urbana-Champaign*

*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*

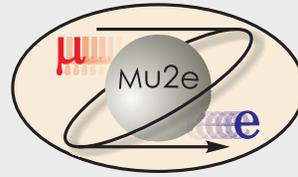
*College of William and Mary*

*University of Washington, Seattle*

**~120 collaborators**



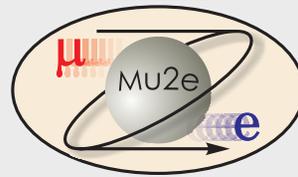
# Outline



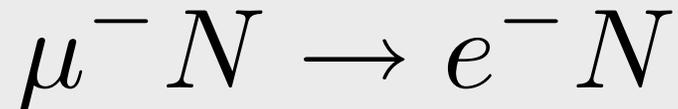
- The search for muon-electron conversion
- Experimental Technique
- Fermilab Accelerator
- Project X Upgrades and Mu2e
- Cost and Schedule
- Conclusions



# What is $\mu e$ Conversion?



muon converts to electron in the presence of a nucleus



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

- Charged Lepton Flavor Violation (CLFV)

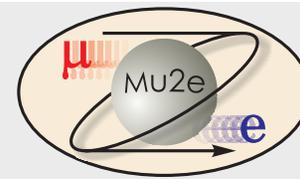
- will measure  $R_{\mu e} < 6 \times 10^{-17}$  @ 90%CL

- Related Processes:

$\mu$  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-1 Spring/Summer 2011



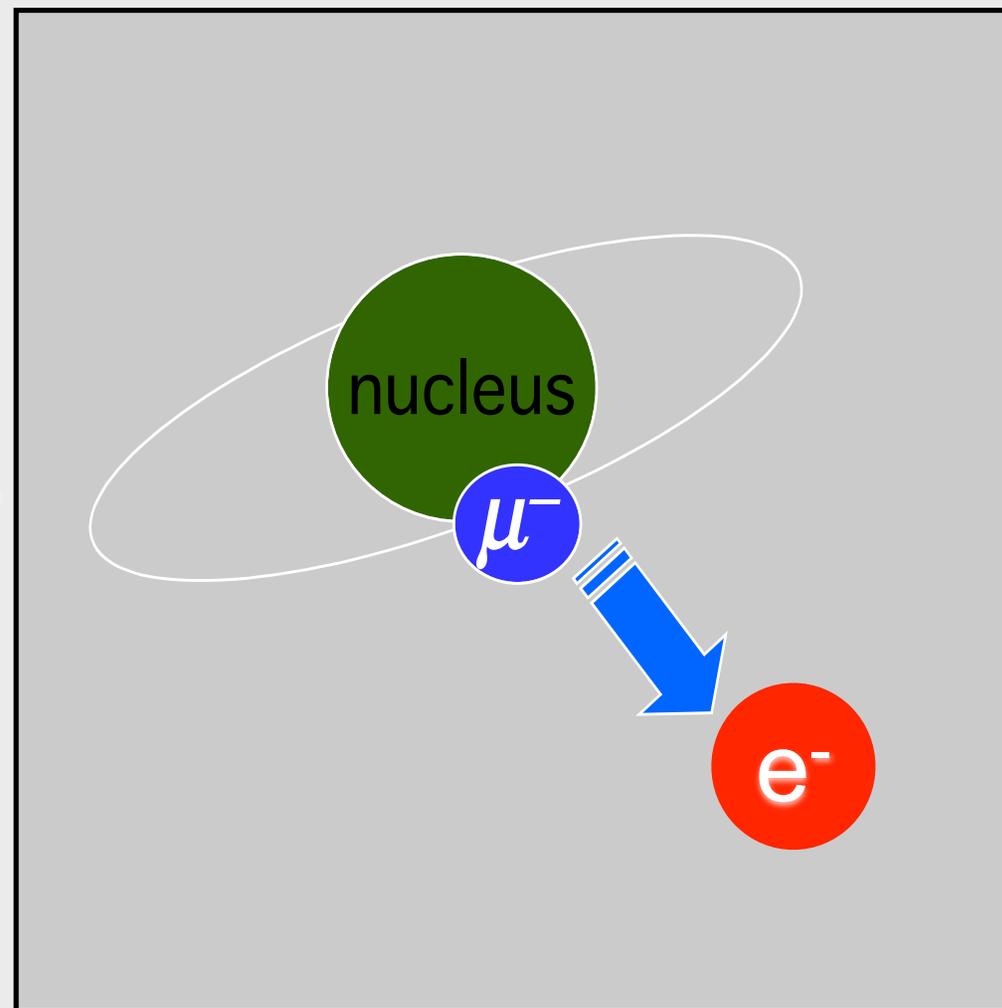
CD process



# Experimental Signal

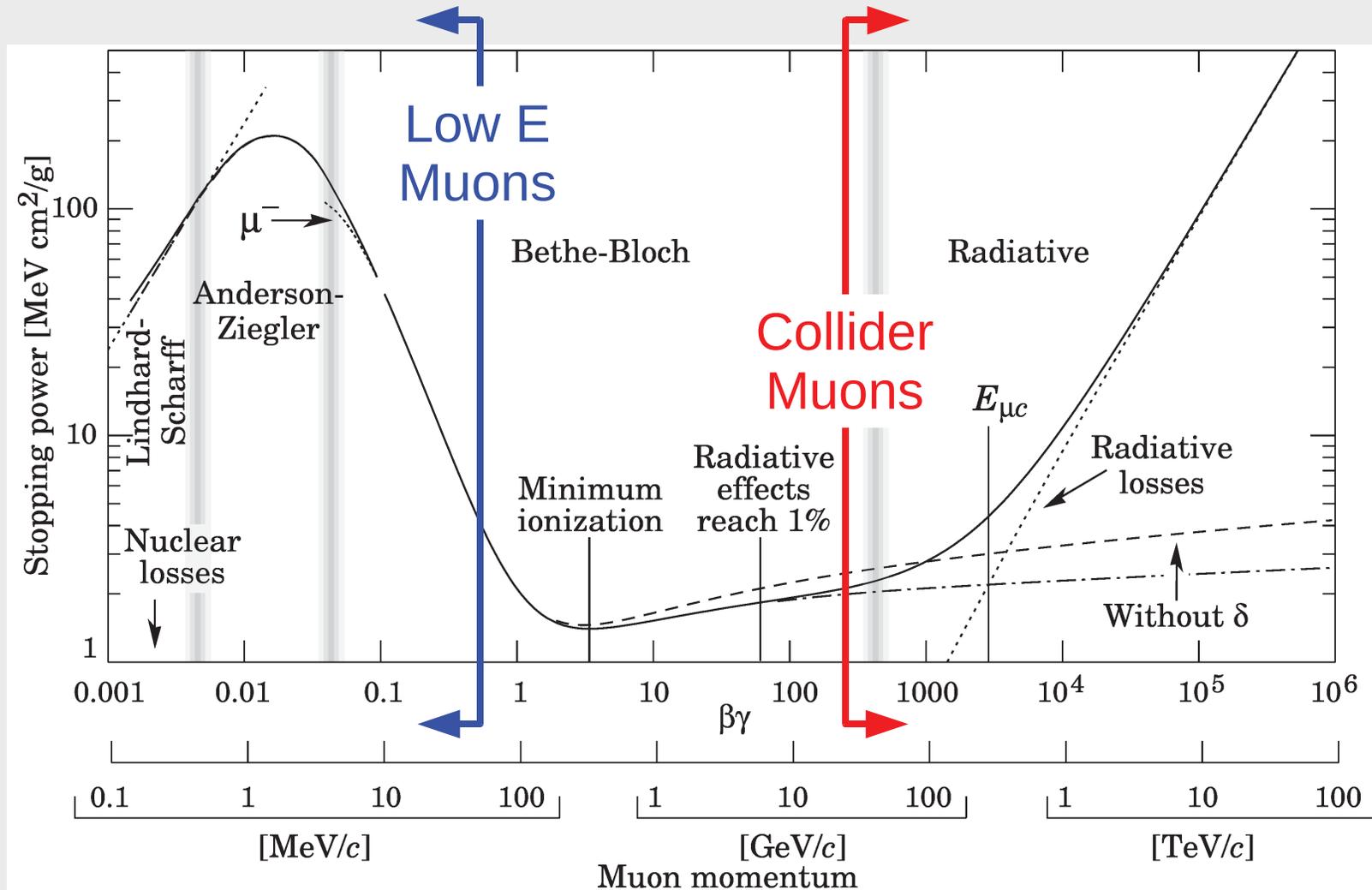
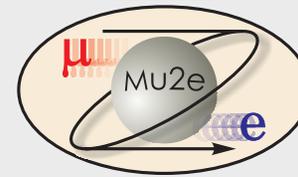


- A Single Monoenergetic Electron
- If  $N = \text{Al}$ ,  $E_e = 105. \text{ MeV}$ 
  - electron energy depends on  $Z$
- Nucleus coherently recoils off outgoing electron, no breakup





# Physics is Different at these energies!





# “Who ordered that?”

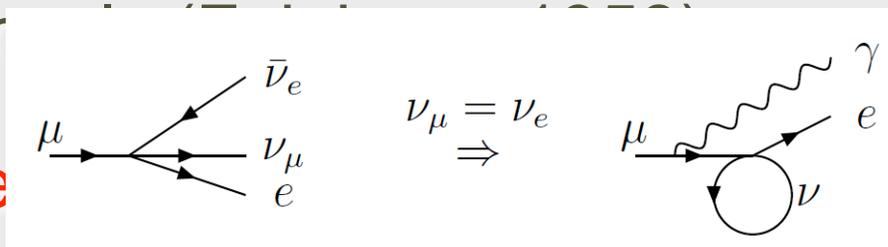


– I.I. Rabi, 1936

After the  $\mu$  was discovered, it was logical to think the  $\mu$  is just an excited electron:

- expect  $\text{BR}(\mu \rightarrow e\gamma) \approx 10^{-4}$
- Unless another  $\nu$ , in Intermediate Vector Boson Loop, can

→ same

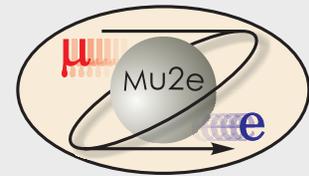


<sup>1</sup>Unless we are willing to give up the 2-component neutrino theory, we know that  $\mu \rightarrow e + \nu + \bar{\nu}$ .





# Where did that last estimate come from?



<http://www.hawaii.edu/suremath/jsand.html>

Moral: jobs at Hawaii are more fun than at Pittsburgh

## Estimate the number of grains of sand on all the beaches of the earth.

The number of grains of sand will be the volume of sand divided by the volume per grain.

$$N = \frac{\text{Volume\_of\_sand}}{\text{Volume\_of\_grain}}$$

The volume of sand is available from the product of the length of all beaches in the world, their average width and average depth.

$$\text{Volume\_of\_sand} = (\text{length\_of\_beaches}) (\text{width}) (\text{depth})$$

We will need to estimate the parameters on the right. To get going we use the idea that the length of beaches is some percentage of the length of shores.

$$\text{length\_of\_beaches} = \frac{\% \text{shores}}{100} \text{length\_of\_shores}$$

The length of shores is related to the size of the earth. We choose to include the size in terms of the circumference.

$$\text{length\_of\_shores} = (\text{multiple\_of\_circumference}) (\text{earth\_circumference})$$

$$N = \frac{\left( \frac{\% \text{shores}}{100} \left( (\text{multiple\_of\_circumference}) \text{earth\_circumference} \right) \right) (\text{width}) (\text{depth})}{\text{Volume\_of\_grain}}$$

We use rough but reasonable values for the parameters.

$$\% \text{shores} = 25$$

$$\text{multiple\_of\_circumference} = 5$$

$$\text{earth\_circumference} = 40000 \text{ km} \quad \text{km} = 1000 \text{ m} \quad \text{m} = 1000 \text{ mm}$$

$$\text{width} = 30 \text{ m}$$

$$\text{depth} = 5 \text{ m}$$

$$\text{Volume\_of\_grain} = 1 \text{ mm}^3$$

$$N = \frac{\left( \frac{25}{100} \left( (5) (40000 (1000 (1000 \text{ mm}))) \right) \right) (30 (1000 \text{ mm})) (5 (1000 \text{ mm}))}{1 \text{ mm}^3}$$

$$N = 7.5 \times 10^{18}$$

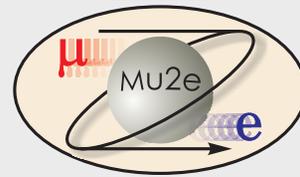
The numbers used can readily be varied to introduce more refined estimates of the parameters.



Pittsburgh Snowstorm – January 11, 2011 – January 12, 2011

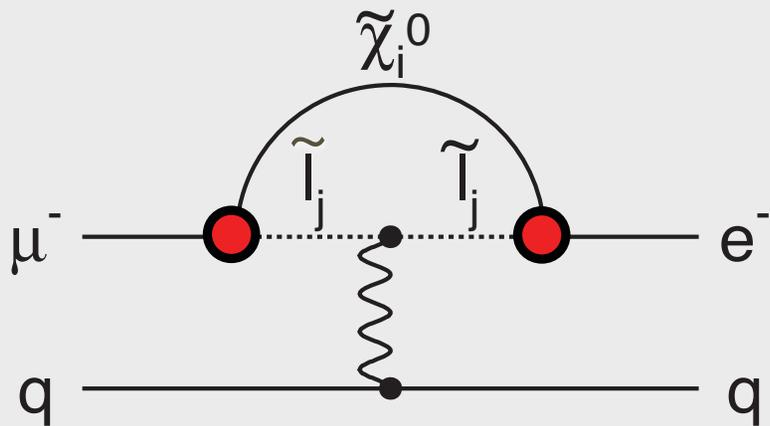


# LFV, SUSY and the LHC



## Supersymmetry

rate  $\sim 10^{-15}$



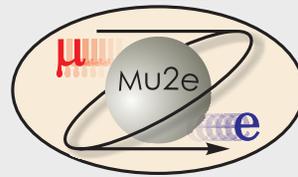
***Access SUSY  
through loops:***

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

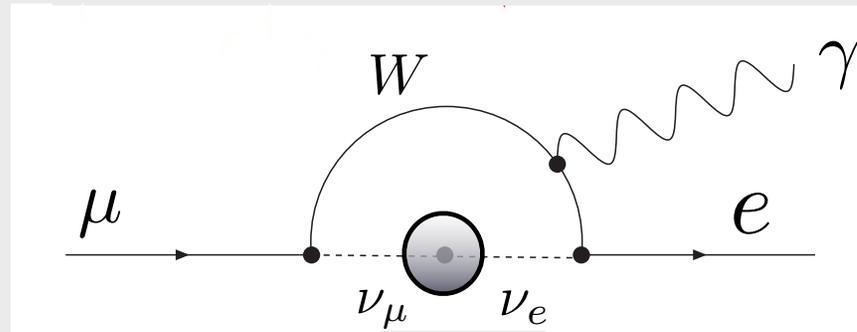
***~40 event signal /  
0.4 bkg in this  
experiment***



# Neutrino Oscillations and Muon-Electron Conversion



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



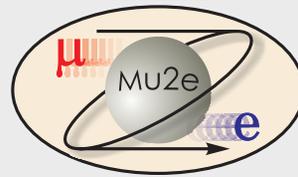
**NO STANDARD  
MODEL  
BACKGROUND!**

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



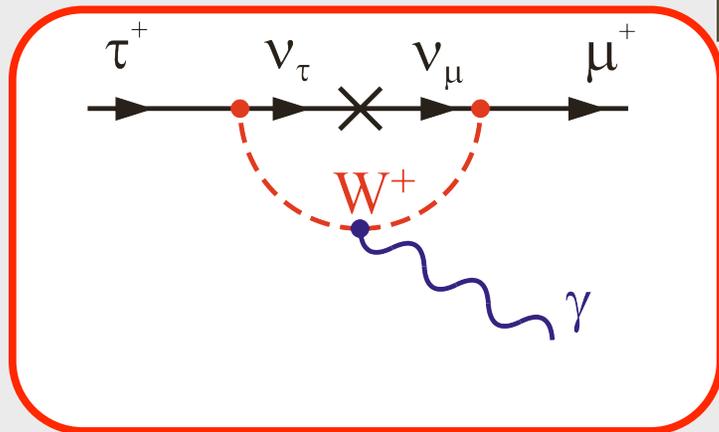


# CLFV and Tau Decays



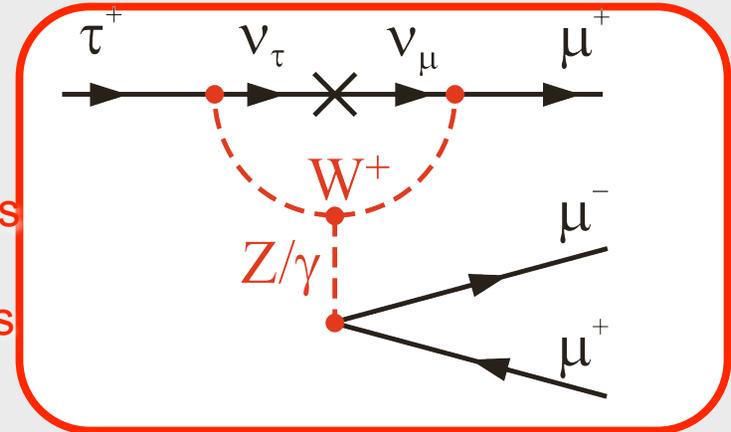
$\tau$  processes also suppressed in Standard Model

but less:



SM  $\sim 10^{-40}$

Smaller  
GIM  
Cancellations  
because of  
large  $\tau$  mass



SM  $\sim 10^{-14}$

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

Pham, hep-ph/9810484

## Good News:

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

## Bad News:

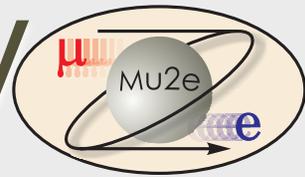
$\tau$ 's hard to produce:  
 $\sim 10^{10}$   $\tau$ /yr vs  $\sim 10^{11}$   $\mu$ /sec in fixed-target experiments (Mu2e/COMET)

also  $e \rightarrow \tau$  at electron-ion collider?

[M. Gonderinger](#), [M. Ramsey-Musolf](#), arXiv:1006.5063v1



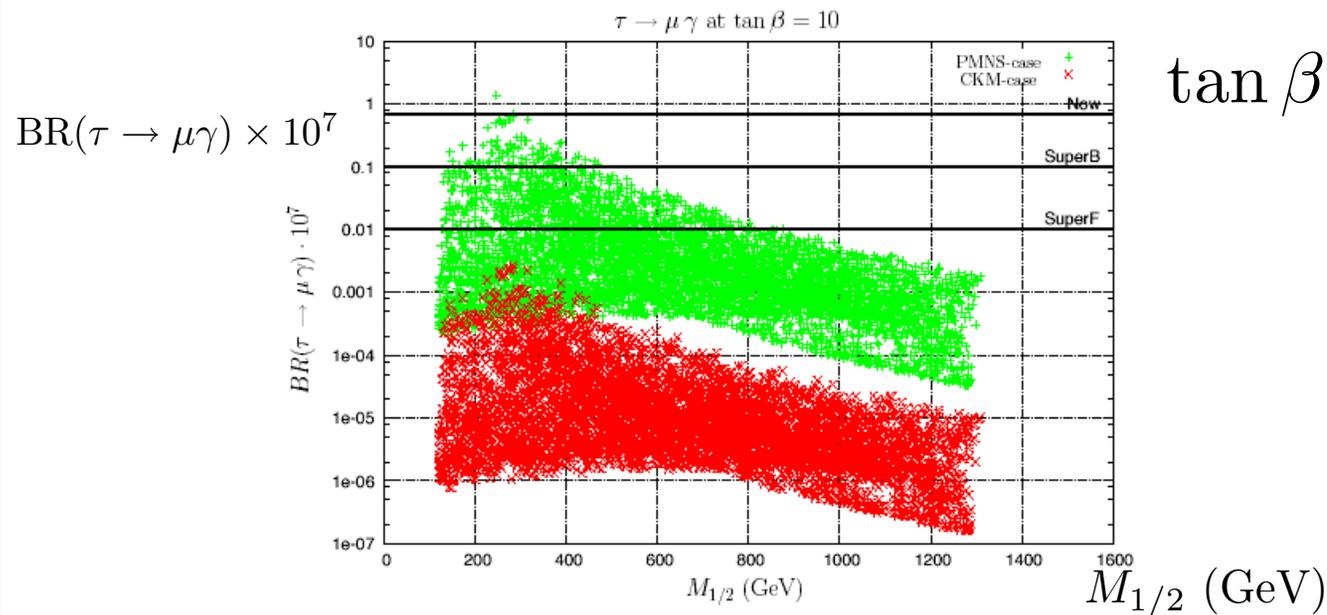
# Supersymmetry in Tau LFV



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

Neutrino-Matrix Like (PMNS)

Minimal Flavor Violation (CKM)



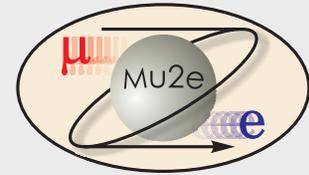
$\tan \beta = 10$

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



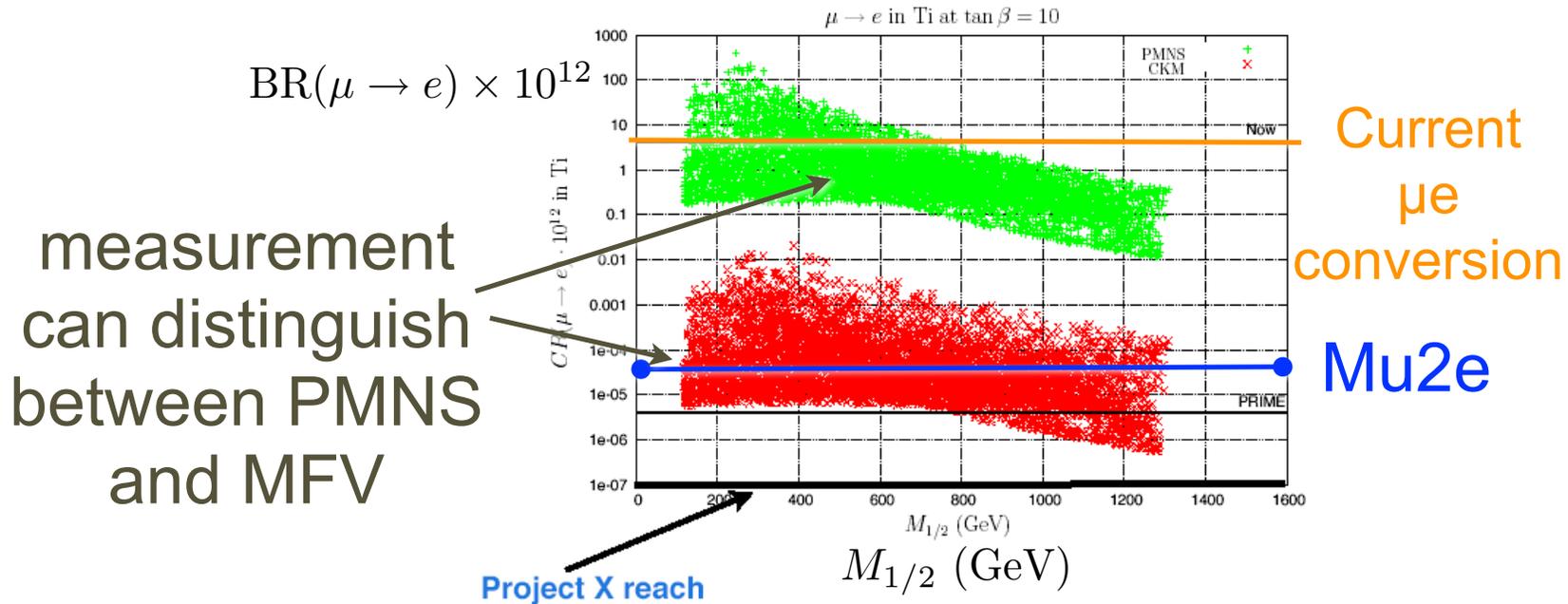
# And Muon-Electron Conversion



$$\tan \beta = 10$$

Neutrino-Matrix Like (PMNS)

Minimal Flavor Violation (CKM)

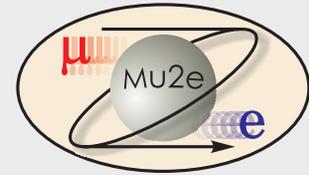


L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

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

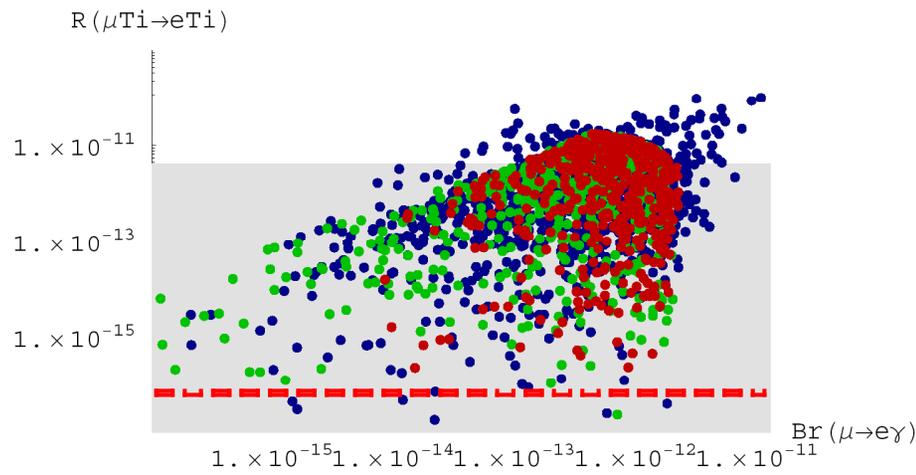


# Combining $\mu \rightarrow e \gamma$ with $\mu \rightarrow e$ Conversion

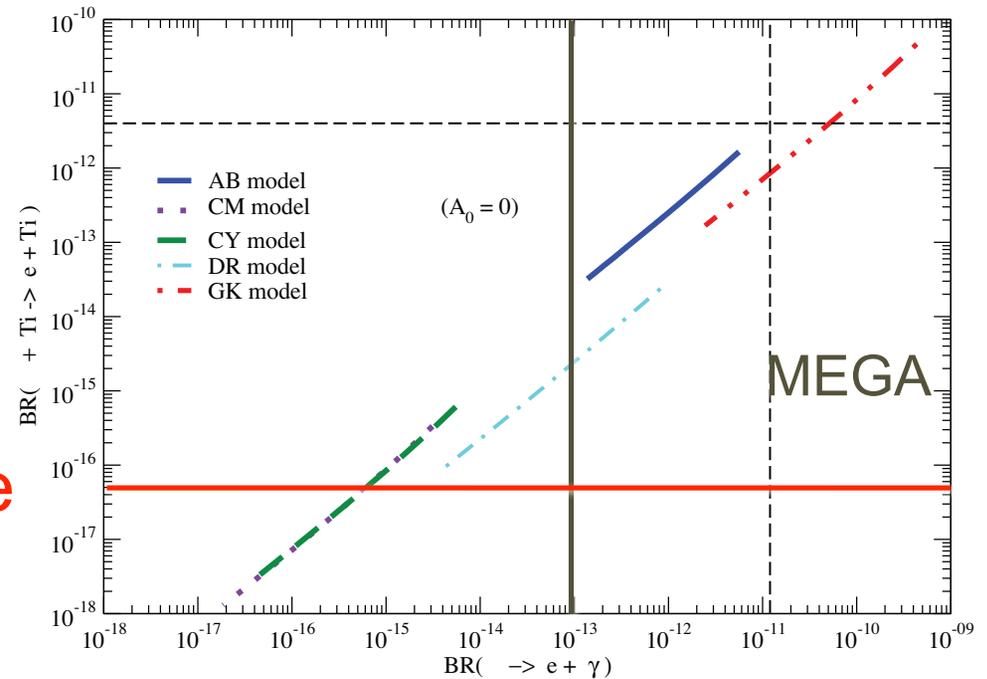


Randall-Sundrum

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.

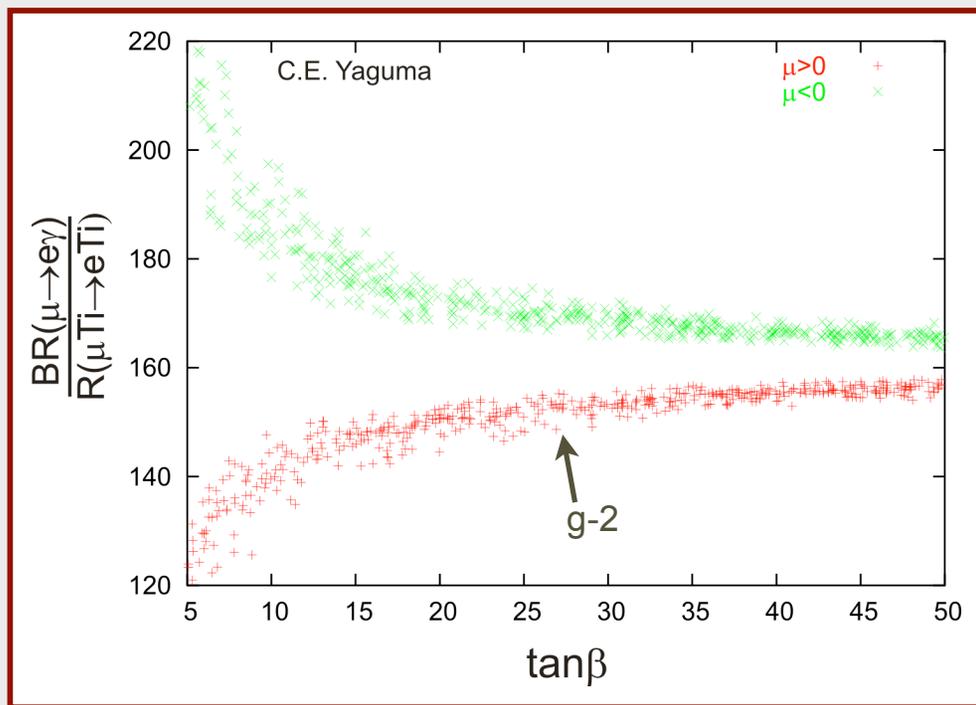
Mu2e



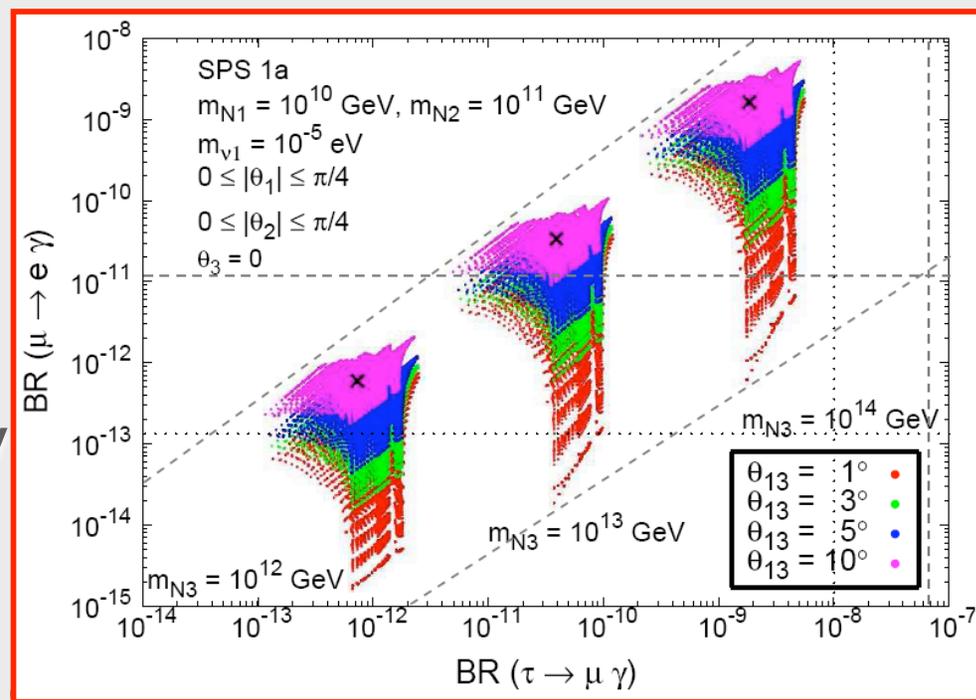
# Pinning Down SuperSymmetry

MSSM w mSUGRA

CMSSM - seesaw



Yaguna, hep-ph/0502014v2

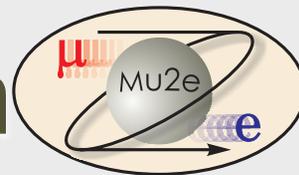


Antusch et al., hep-ph/0610439

to allow discrimination among different models

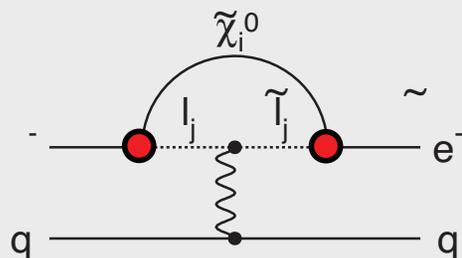


# Contributions to $\mu e$ Conversion



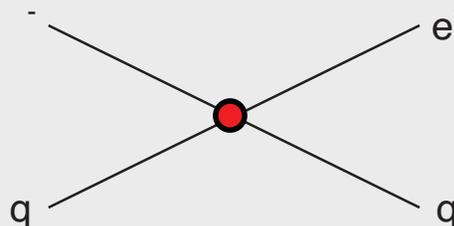
## Supersymmetry

rate  $\sim 10^{-15}$



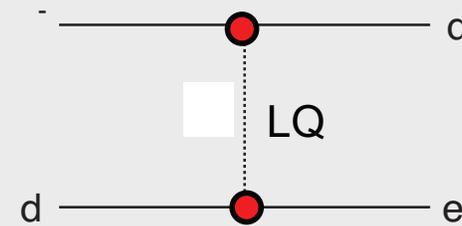
## Compositeness

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



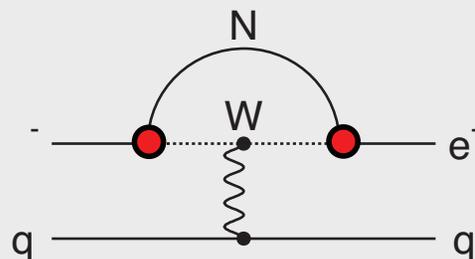
## Leptoquark

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



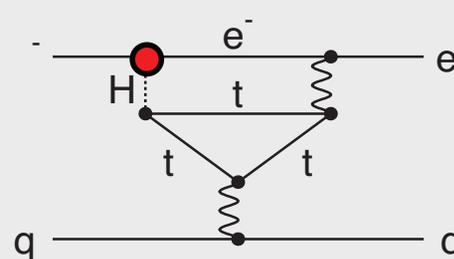
## Heavy Neutrinos

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



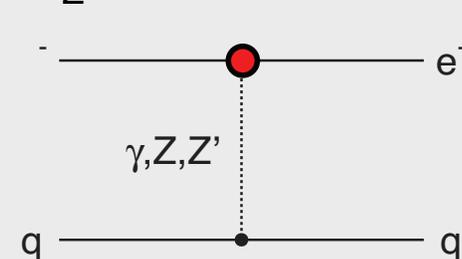
## Second Higgs Doublet

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



## Heavy $Z'$ Anomal. Z Coupling

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

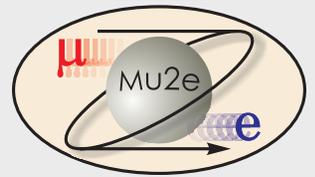


also see Flavour physics of leptons and dipole moments, [arXiv:0801.1826](https://arxiv.org/abs/0801.1826)

and Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:[10.1146/annurev.nucl.58.110707.171126](https://doi.org/10.1146/annurev.nucl.58.110707.171126)



# “Model-Independent” Form

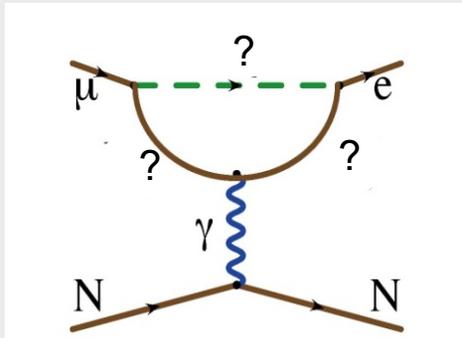


$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma_\mu u_L + \bar{d}_L \gamma_\mu d_L)$$

“Loops”

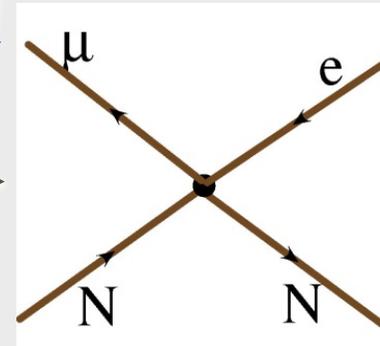
“Contact Terms”

$\kappa=0$



mass scale  $\Lambda$

$\kappa$



$\kappa=1$

Supersymmetry and Heavy Neutrinos

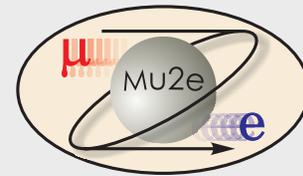
Contributes to  $\mu \rightarrow e\gamma$

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

Quantitative Comparison?



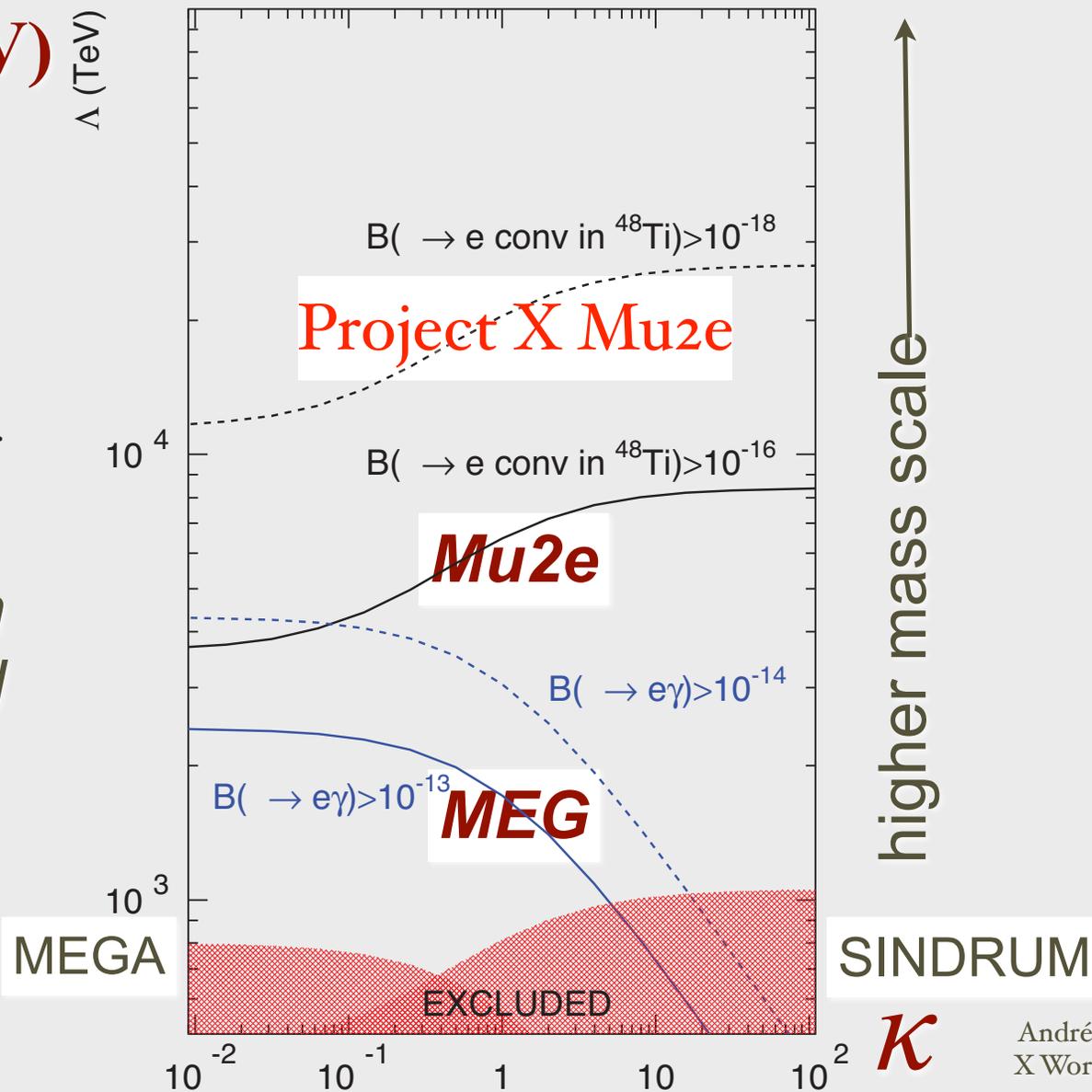
# $\mu e$ Conversion and $\mu \rightarrow e \gamma$



$\Lambda$  (TeV)

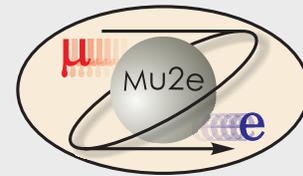
1) Mass Reach to  $\sim 10^4$  TeV

2) about x2 beyond MEG in loop-dominated physics





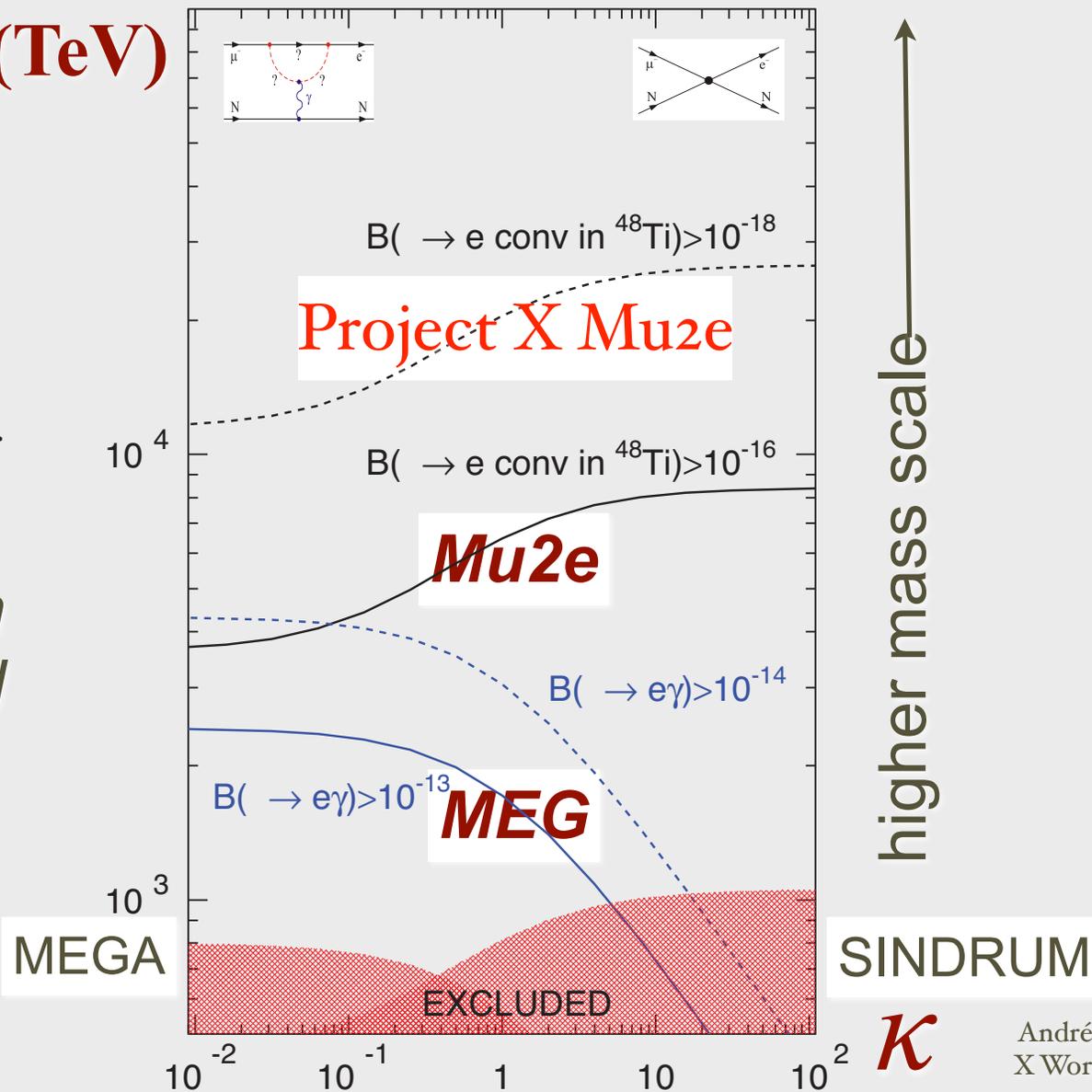
# $\mu e$ Conversion and $\mu \rightarrow e \gamma$



$\Lambda$  (TeV)

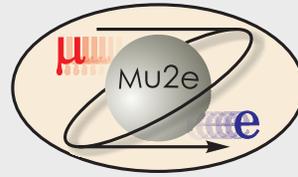
1) Mass Reach to  $\sim 10^4$  TeV

2) about  $\times 2$  beyond MEG in loop-dominated physics





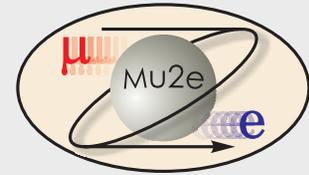
# Outline



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



# Overview Of Processes

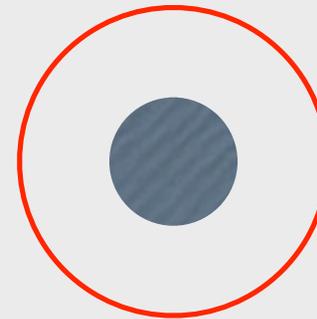


$\mu^-$  stops in thin Al foil

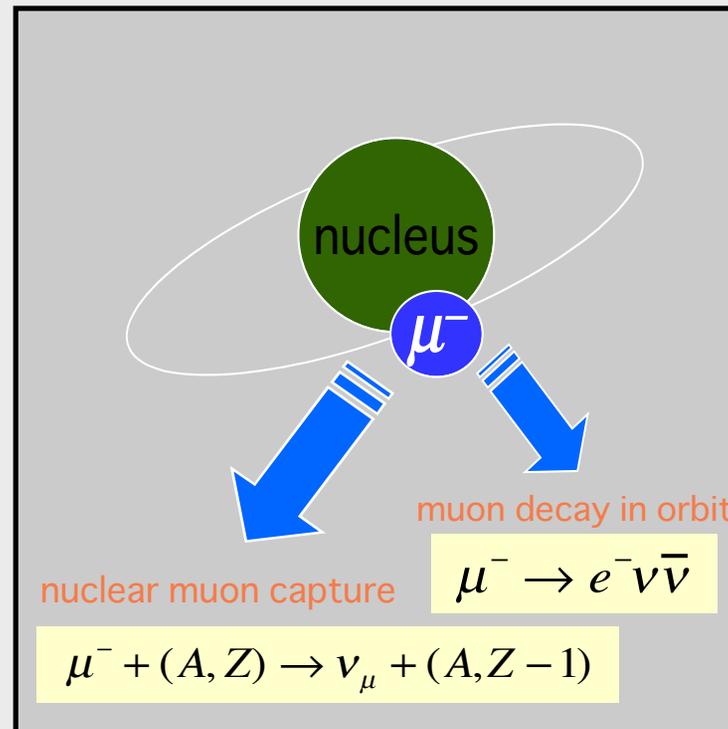


the Bohr radius is  $\sim 20$  fm,  
so the  $\mu^-$  sees the nucleus

$\mu^-$  in 1s state



Al Nucleus  
 $\sim 4$  fm



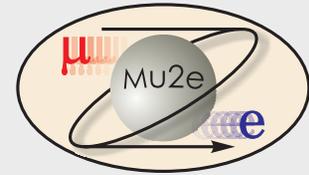
muon capture,  
muon “falls into”  
nucleus:  
**normalization**

60% capture  
40% decay

Decay in Orbit:  
**background**



# Three Possibilities: Normalization

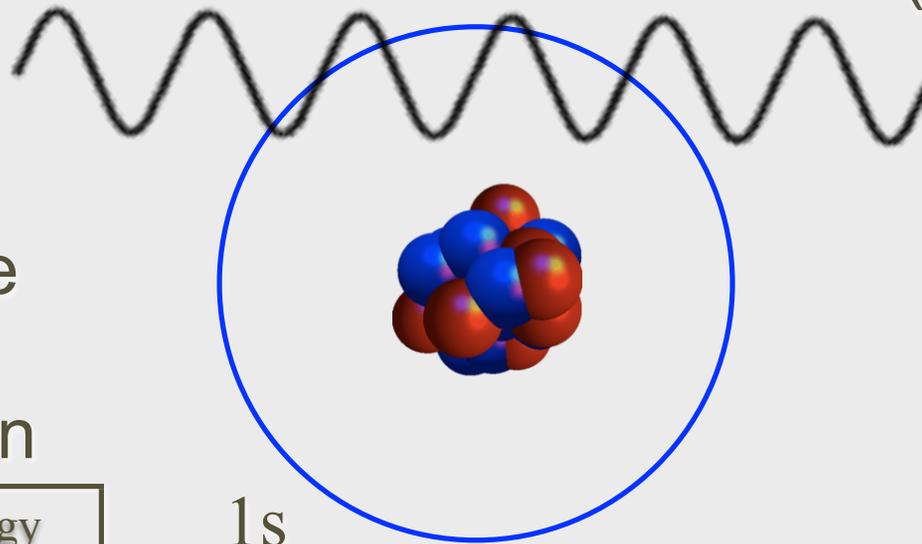


muon stops



$\mu$

X-Rays from  
cascade  
(occurs in psec)

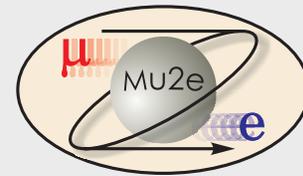


detect these  
for  
normalization

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



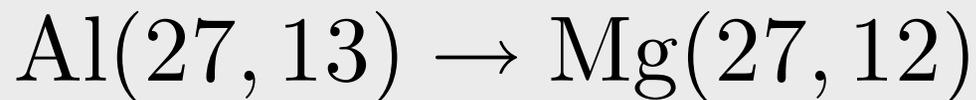
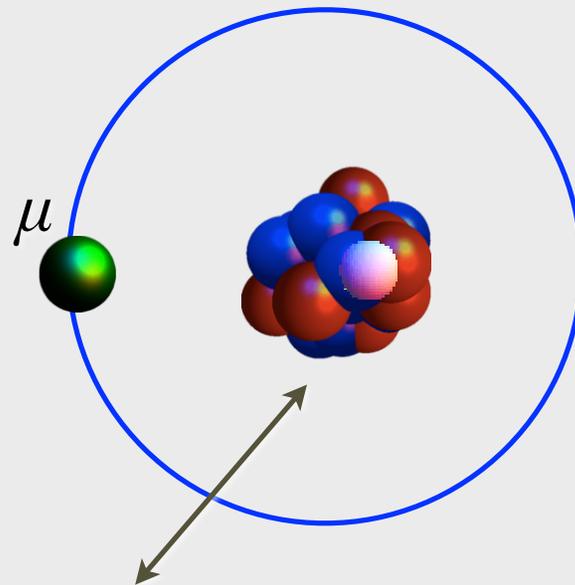
# Normalization to Nuclear Capture



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

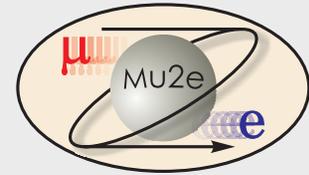
$\nu_\mu$



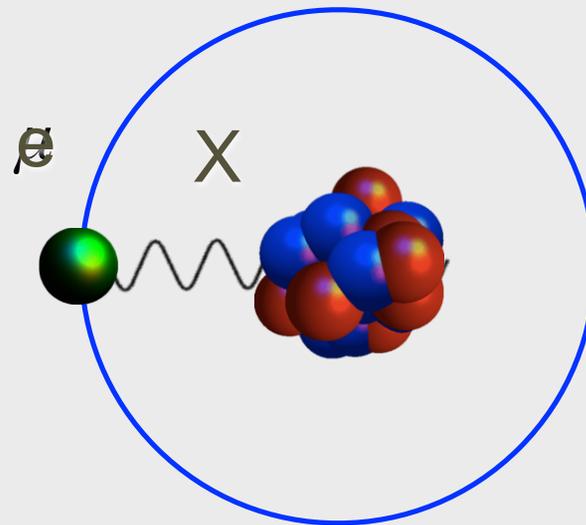
$$\text{then compute } R_{\mu e} = \frac{\mu N \rightarrow e N}{\mu \text{ Al}(27, 13) \rightarrow \nu_\mu \text{ Mg}(27, 12)}$$



# Three Possibilities: Signal



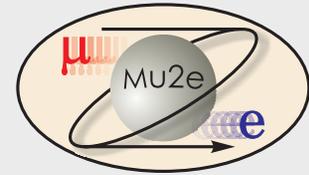
*off to detector!*



coherent recoil of nucleus

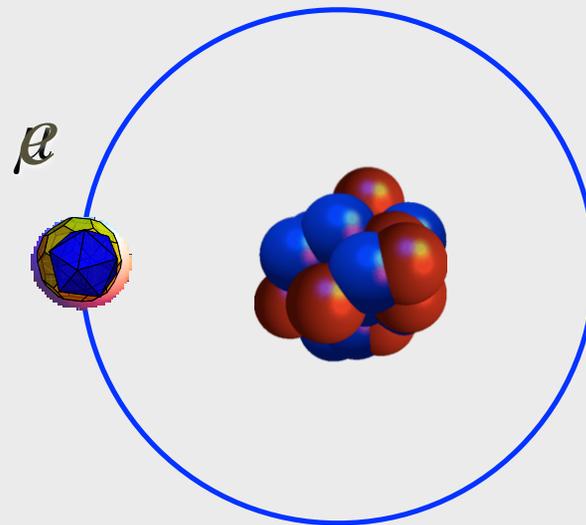


# Three Possibilities: Background

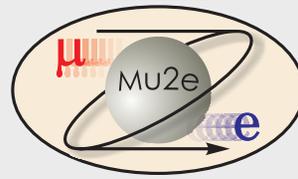


this electron can be background;  
let's see how

$\nu_{\mu}$



$\bar{\nu}_e$

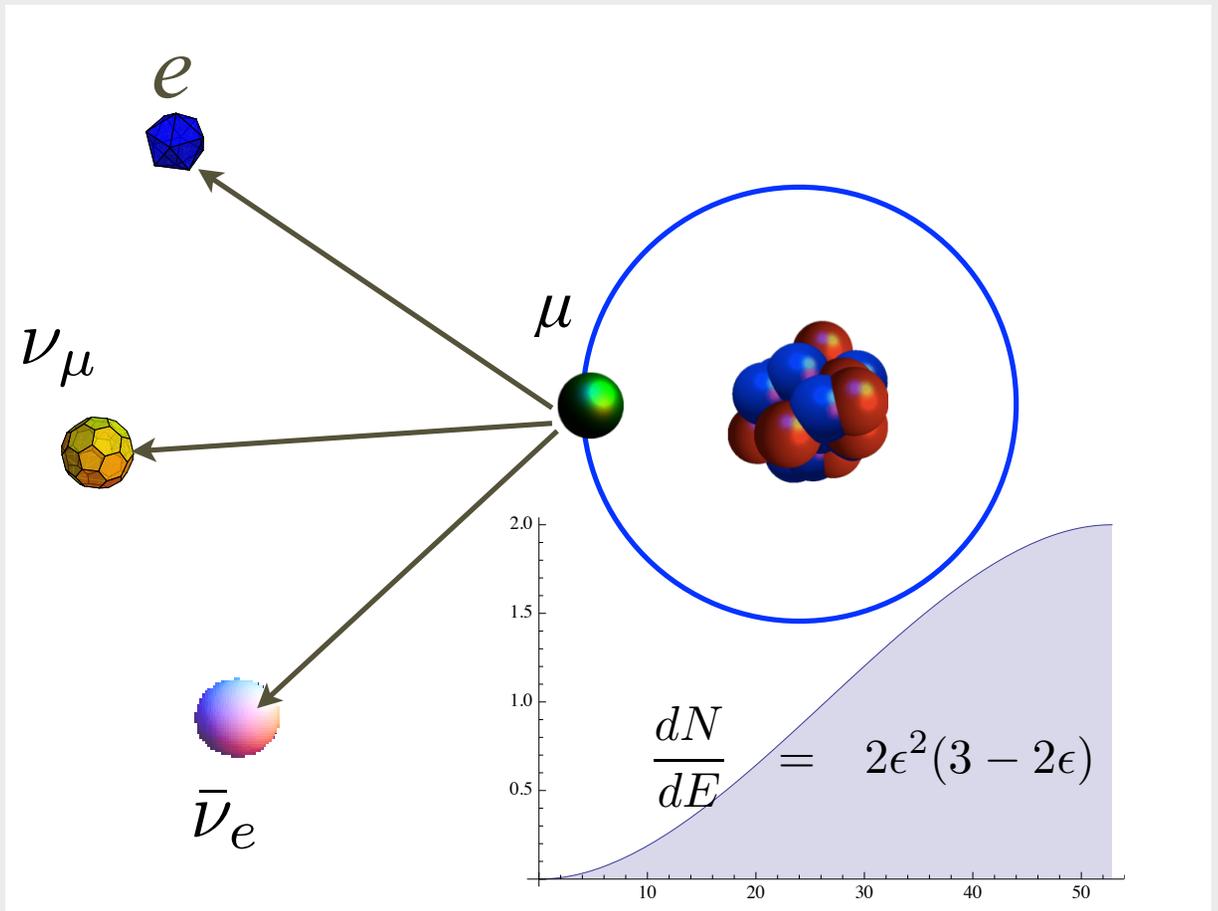


# Decay-In-Orbit: Not always Background

- Peak and Endpoint of Michel Spectrum is at

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

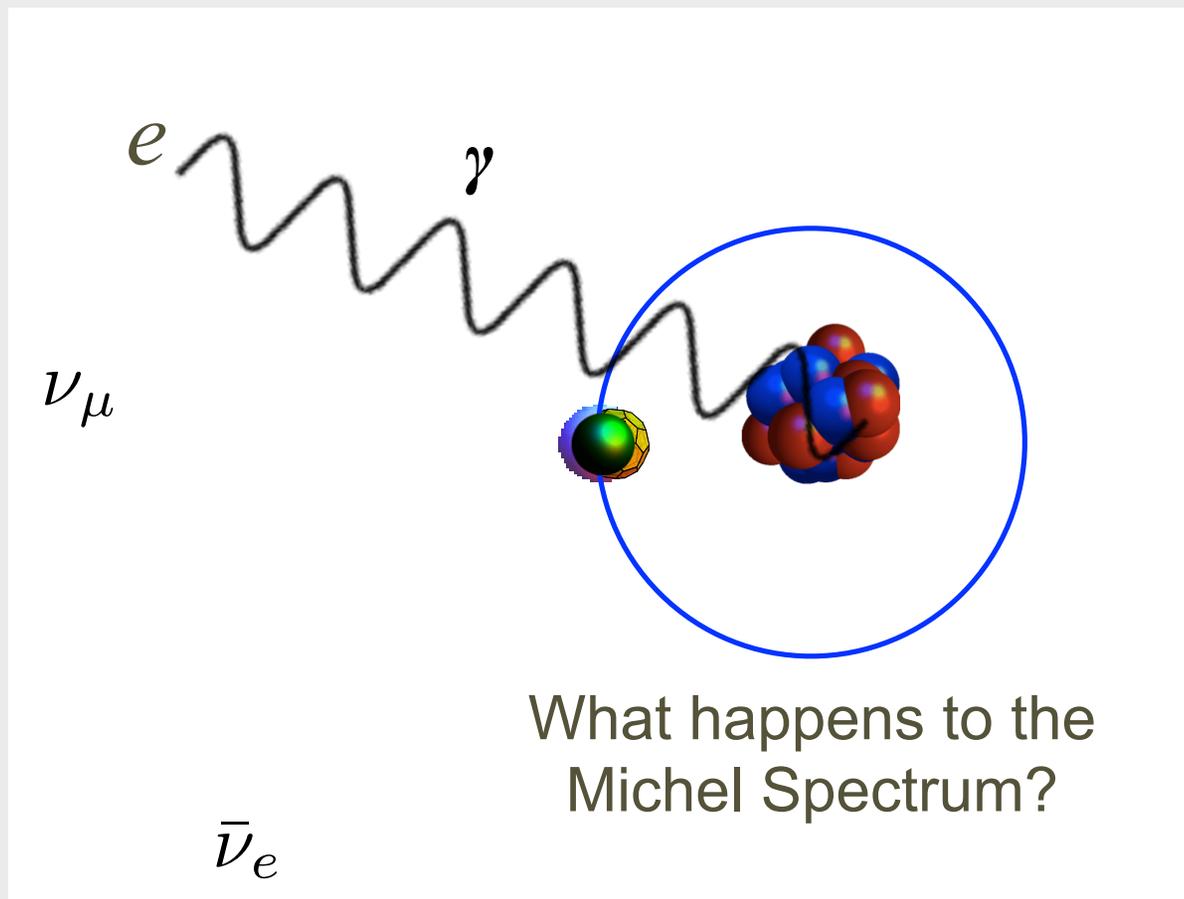
- Detector will be insensitive to electrons at this energy
- Recall *signal* at  $105 \text{ MeV} \gg 52.8 \text{ MeV}$





# 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 Shape



$\mu$  Decay in Orbit Spectrum  $^{27}\text{Al}$

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

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

Michel spectrum  
from free decay

coil

at the endpoint

$$(E_{\text{conversion}} - E)^5$$

$E_e$  (MeV)

$E_g$  MeV

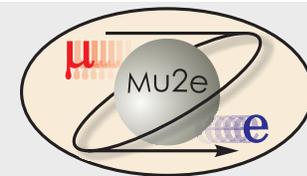


# DIO Background Calculation

- 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

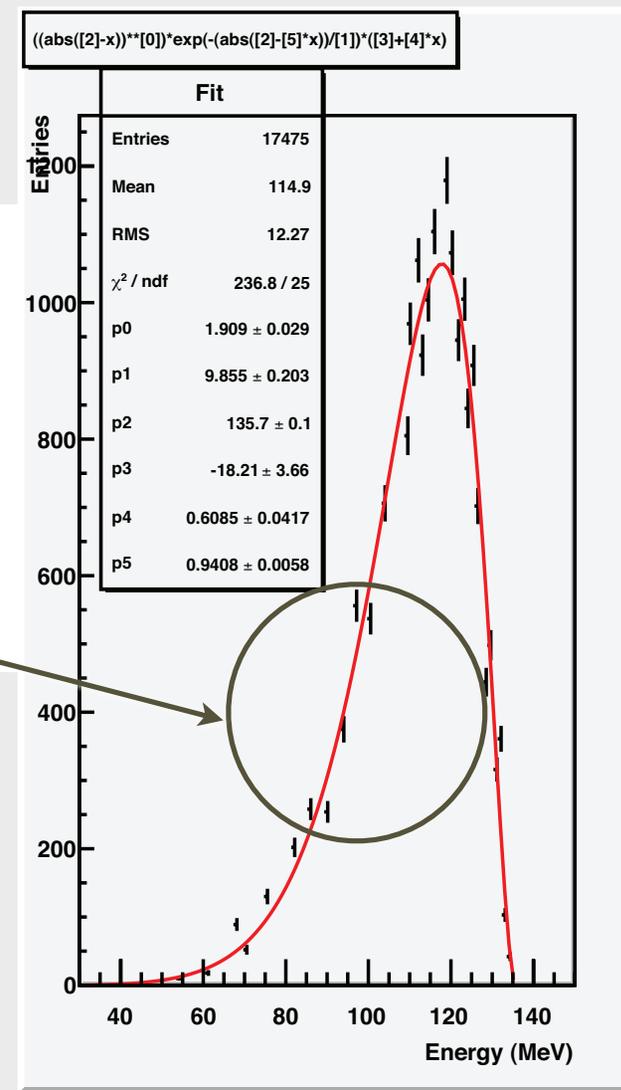


*Particles produced by proton pulse which interact almost immediately when they enter the detector:  $\pi$ , neutrons, pbars*

- **Radiative pion capture,  $\pi^- + A(N,Z) \rightarrow \gamma + X$ .**
  - $\gamma$  up to  $m_\pi$ , peak at 110 MeV;  $\gamma \rightarrow e^+e^-$ ; if one electron  $\sim 100$  MeV in the target, looks like signal: **limitation in best existing experiment, SINDRUM II?**

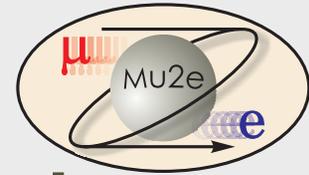
energy spectrum of  $\gamma$  measured on Mg  
J.A. Bistirlich, K.M. Crowe et al., Phys Rev C5, 1867 (1972)

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





# Review:



## Two Classes of Backgrounds

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

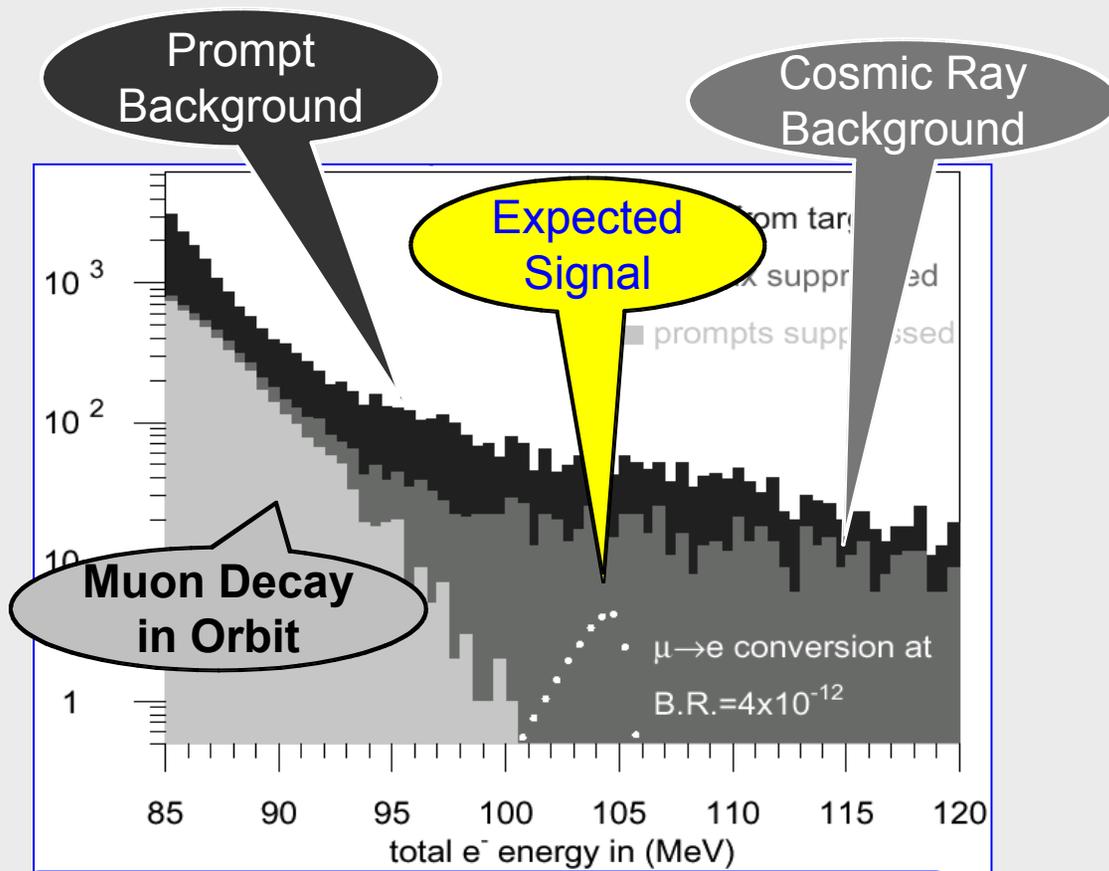


# Previous Best Experiment



## *SINDRUM-II*

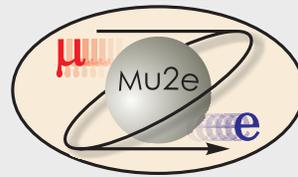
- $R_{\mu e} < 6.1 \times 10^{-13}$  in Au
- Want to probe to  $6 \times 10^{-17}$
- $\approx 10^4$  improvement



**Experimental signature is 105 MeV  $e^-$  originating in a thin Ti stopping target**



# SINDRUM-II Results



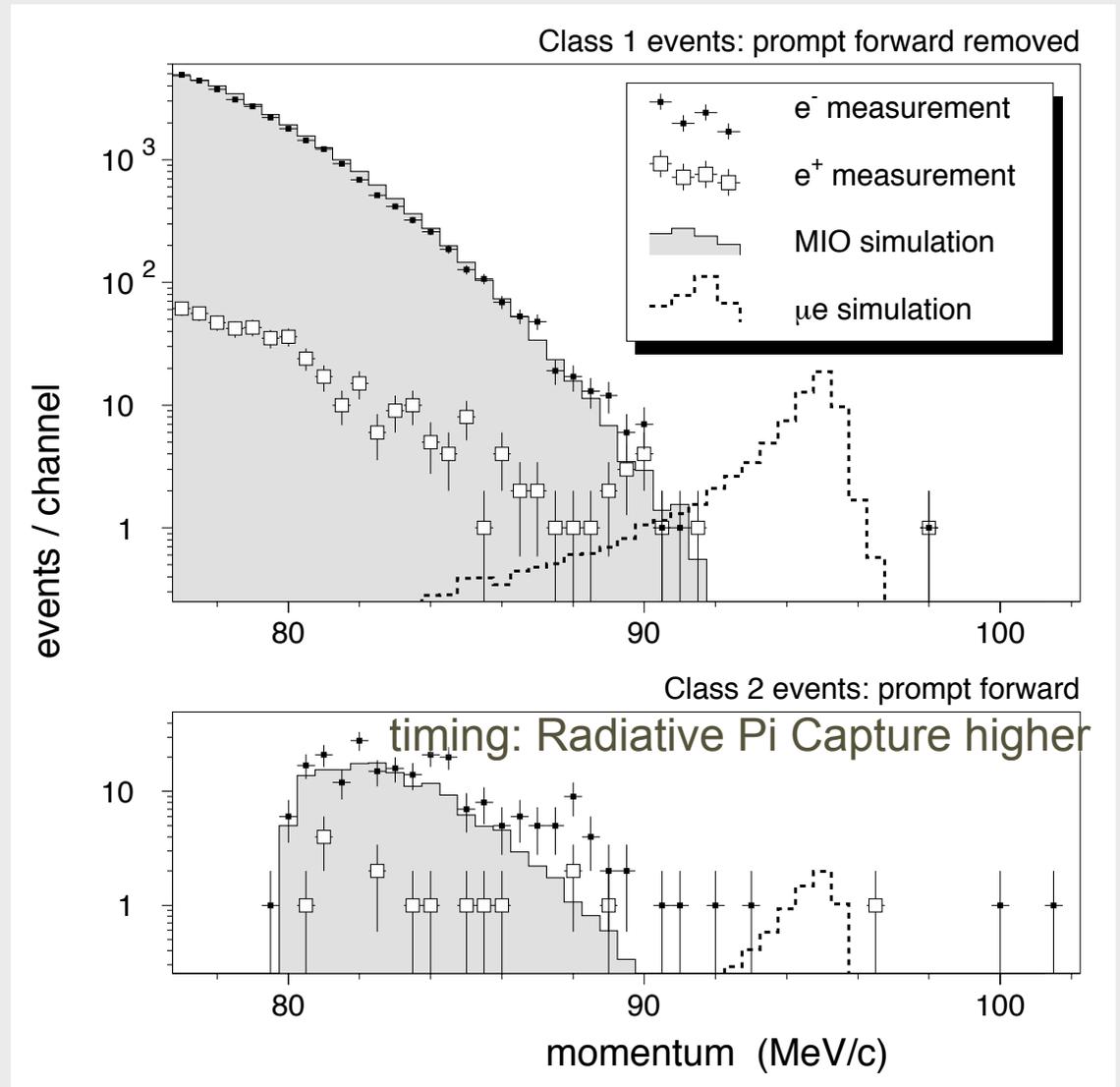
W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006)

- Final Results on Au:

$$B_{\mu e}^{\text{Au}} < 7 \times 10^{-13} \text{ @ 90\% CL}$$

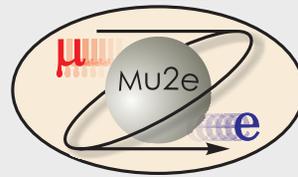
**51 MHz (20 nsec)  
repetition rate,  
width of pulse  
~0.3 nsec**

**little time separation  
between  
signal and prompt  
background**





# How Can We Do Better?

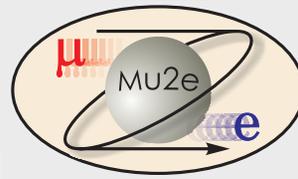


>10<sup>3</sup> increase in muon intensity from SINDRUM

## *Requiring*

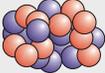
Pulsed Beam to Eliminate prompt backgrounds like radiative  $\pi$  capture and CR

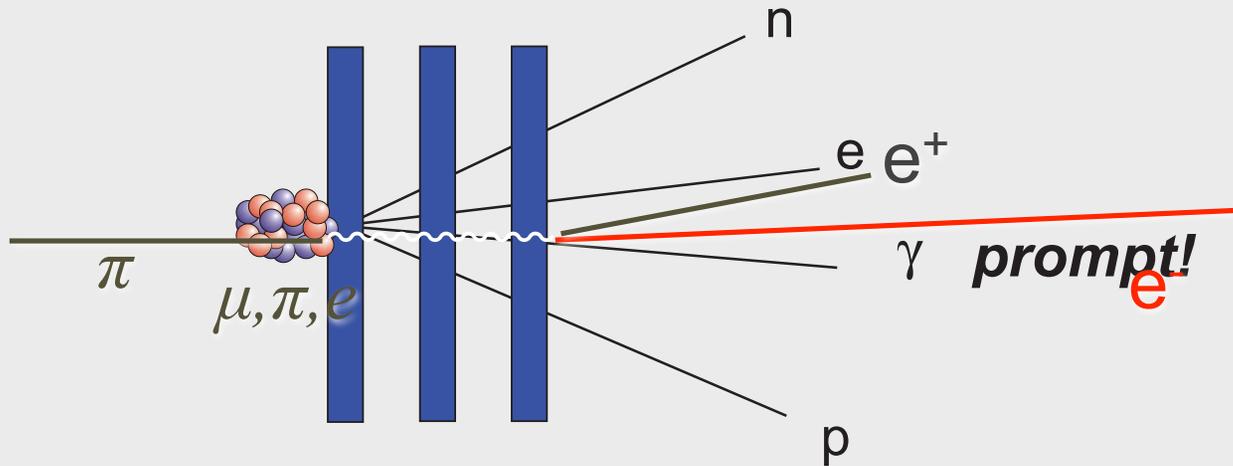
protons out of beam pulse/ protons in beam-pulse < 10<sup>-10</sup>  
*and we must measure it*



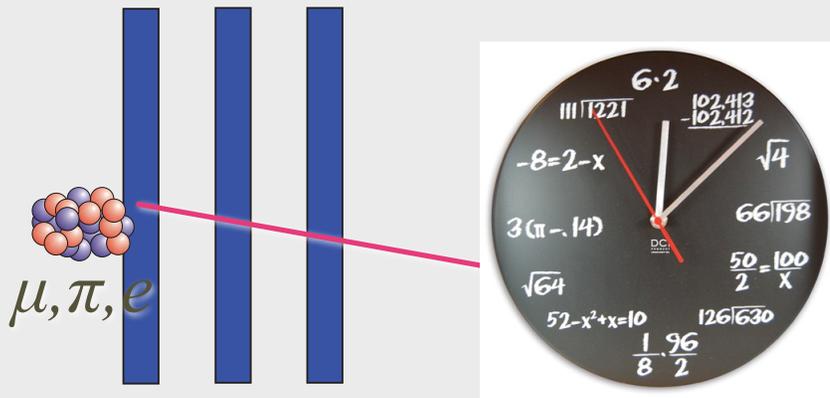
# Advantage of Pulsed Beam

target foils: muon converts here

 = muons, electrons, pions



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



delayed 105 MeV electron

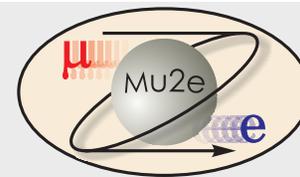
RPC:

$$\pi N \rightarrow \gamma N$$

$$\gamma \rightarrow e^+ e^- \text{ in foils}$$

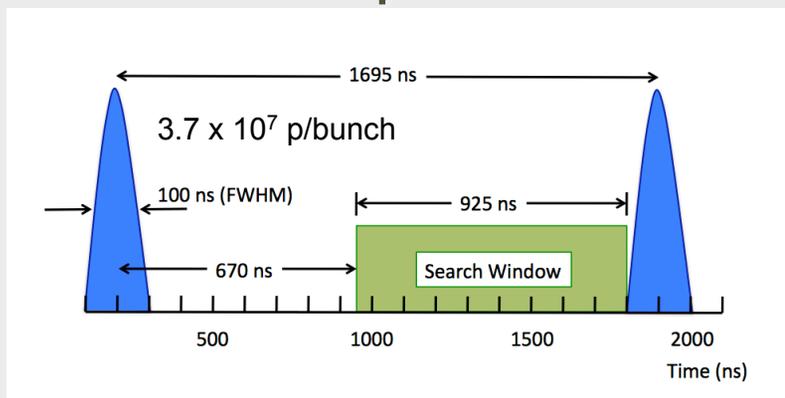


# Pulsed Beam Structure



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

= # protons out of pulse/# protons in pulse



- $10^{-10}$  based on simulation of prompt backgrounds and beamline

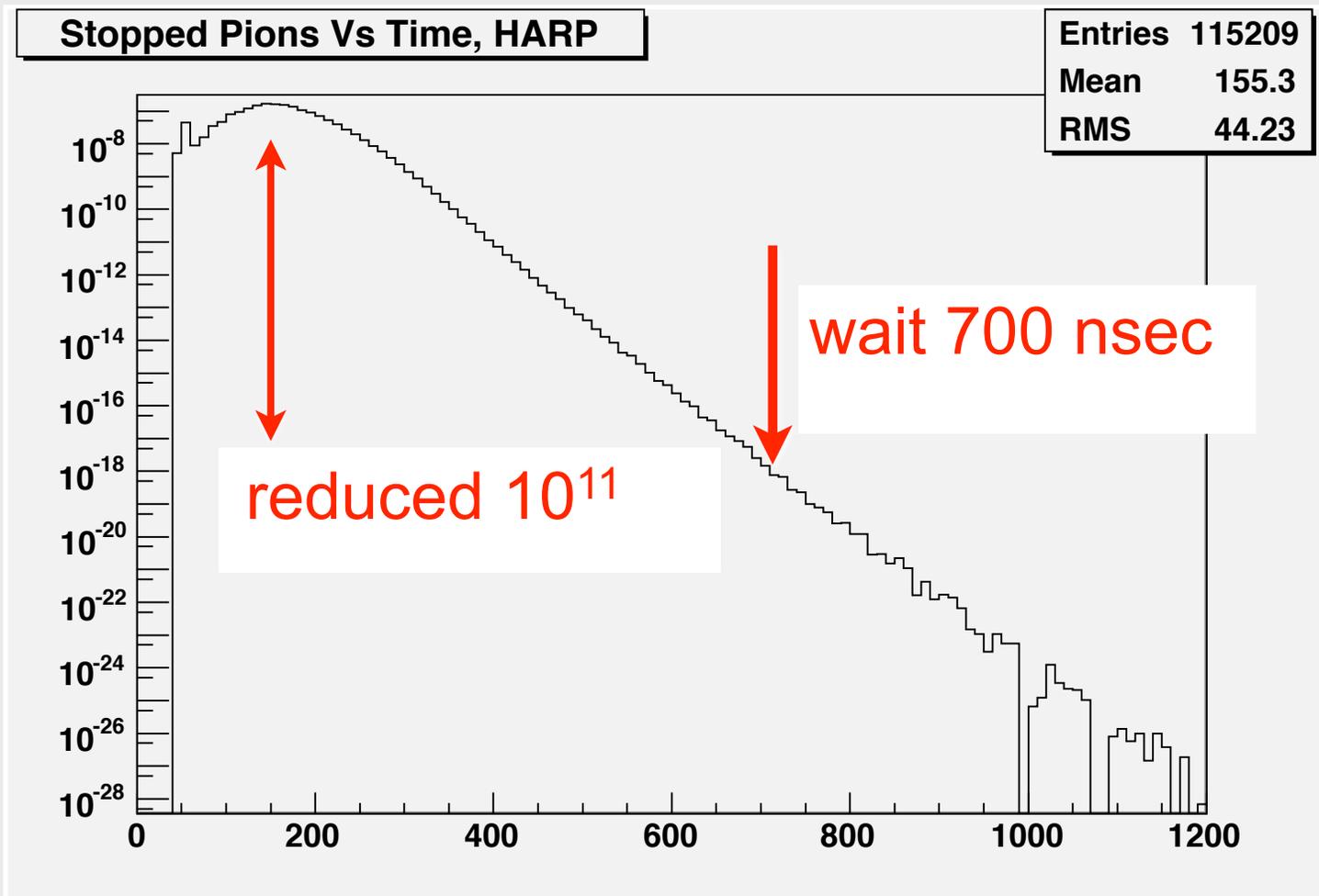
← Extinction  $\sim 10^{-10}$  →



# Pulsed Beam Structure and Radiative $\pi$ Capture



$$\pi N \rightarrow \gamma N, \gamma \rightarrow e^+ e^-$$

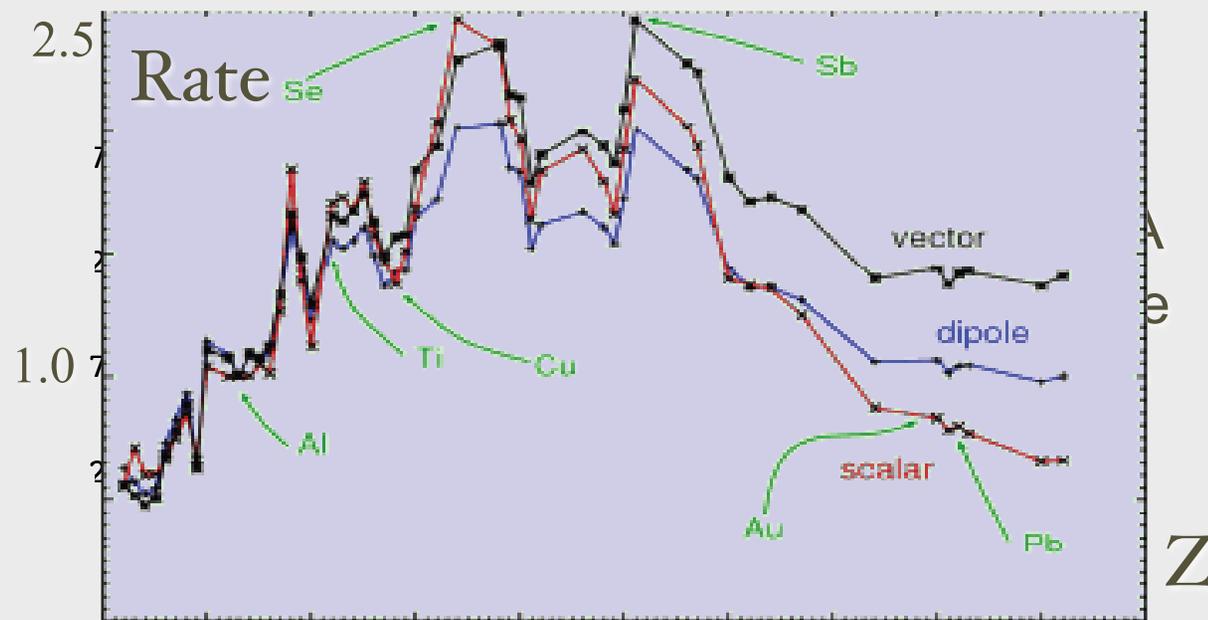




# Choice of Stopping Material: rate vs wait

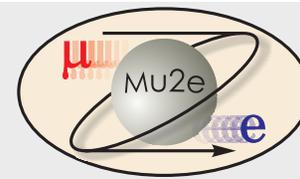
rate normalized to Al

- 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?



V. Cirigliano, B. Grinstein, G. Isidori, M. Wise **Nucl.Phys.B728:121-134,2005.**  
 Kitano, et al. **PRD 66:096002 (2002)**  
 e-Print: [hep-ph/0507001](http://arxiv.org/abs/hep-ph/0507001)

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



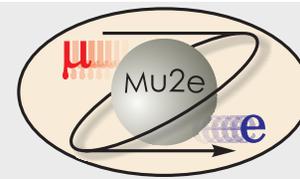
# Prompt Background and Choice of Z

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

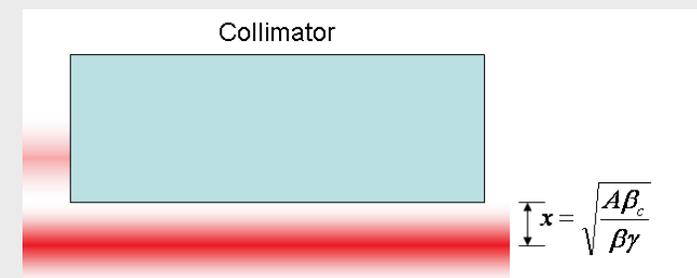
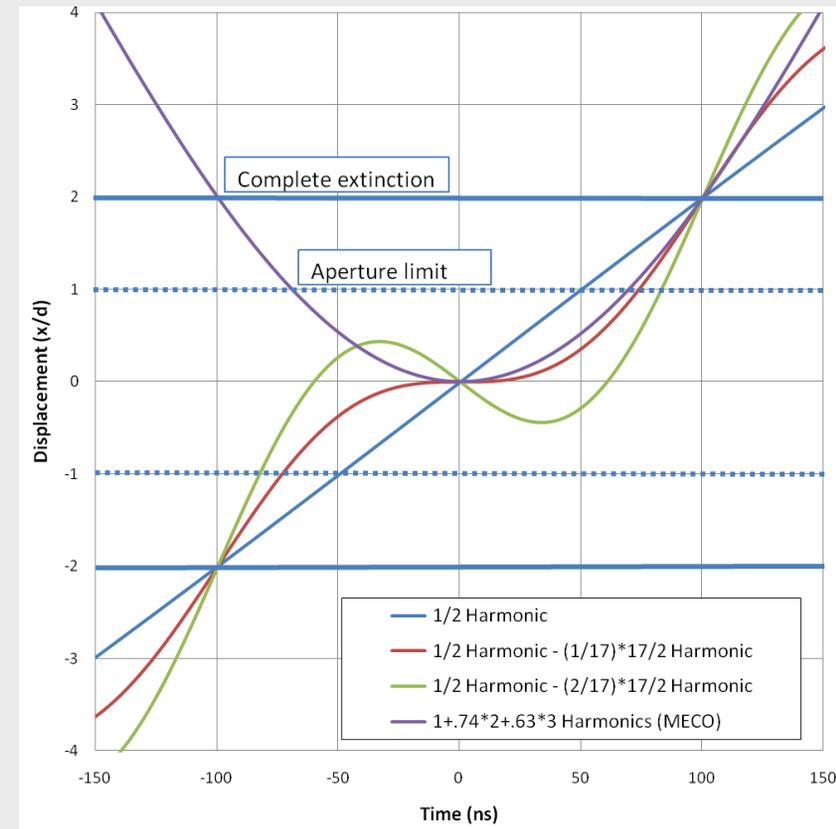


# Extinction Scheme



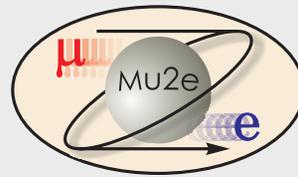
*achieving  $10^{-10}$  is hard; normally get  $10^{-2} - 10^{-3}$*

- Two methods, Internal and External:
- External:
  - high frequency (300 KHz) dipole with smaller admixture of 17th harmonic (5.1 MHz)
  - Sweep Unwanted Beam into collimator
  - Calcs show this sufficient

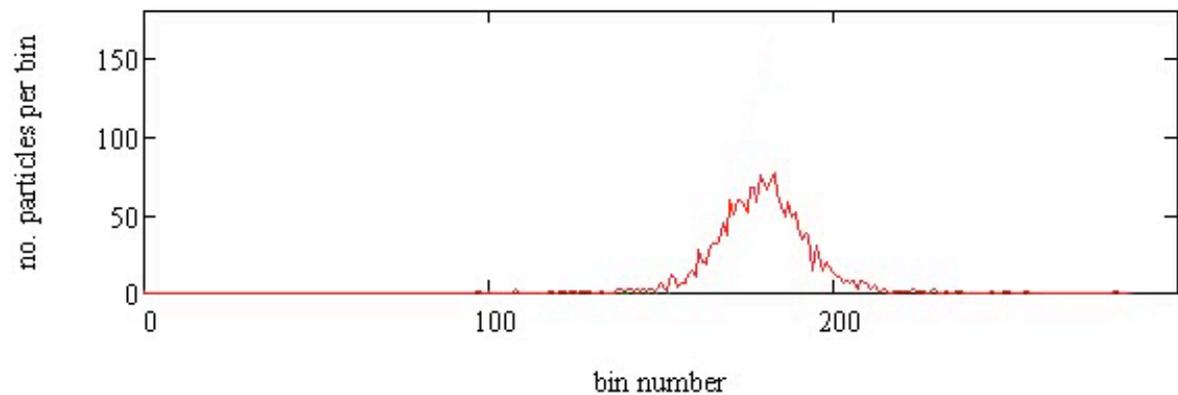
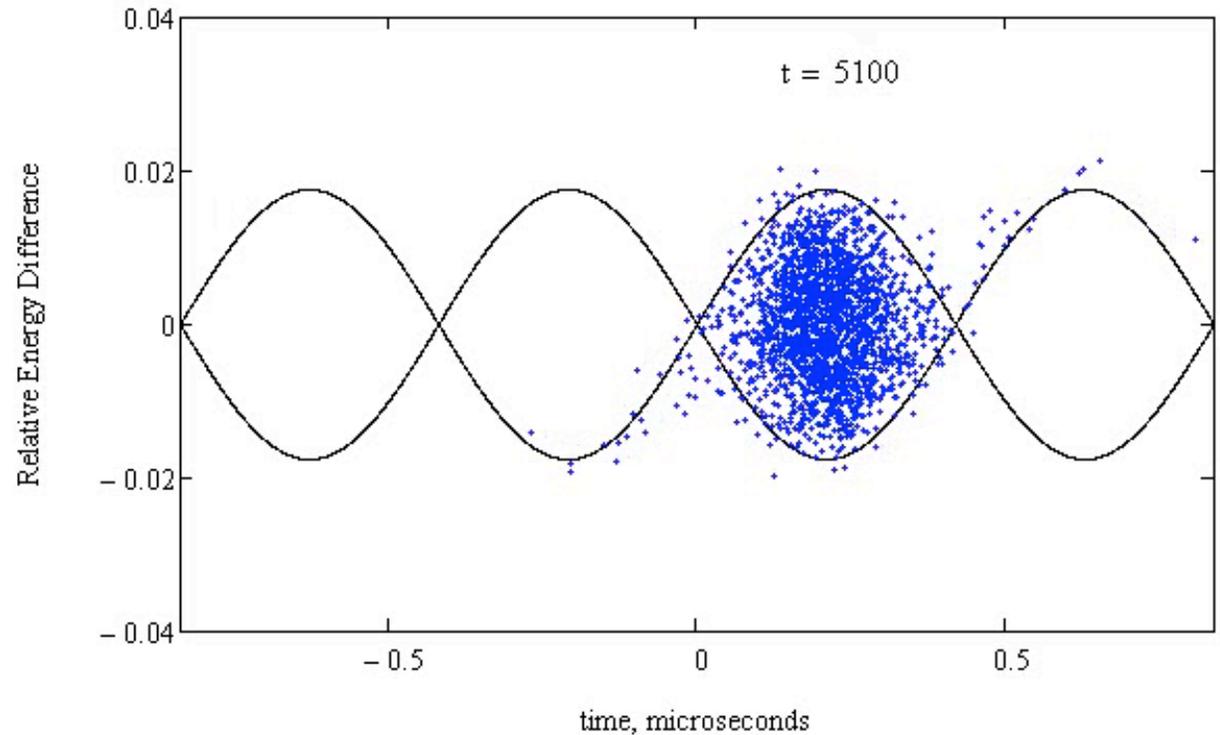




# Extinction (Internal)

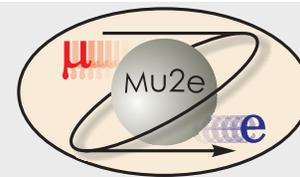


- RF jitter, scattering, etc can cause protons to wander out of their bucket

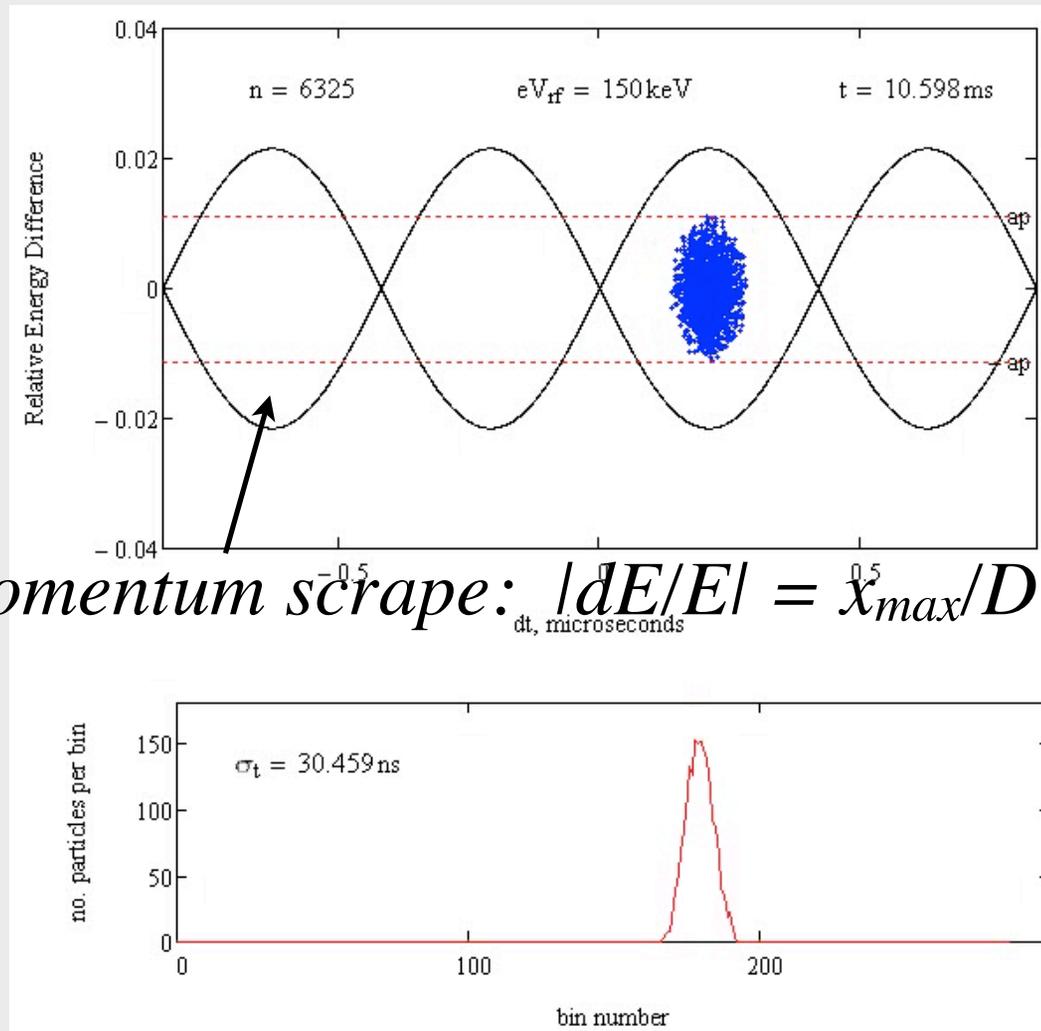




# Extinction (internal)



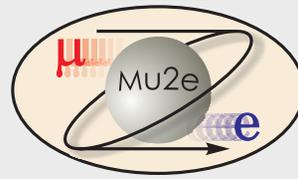
- *Internal*: “momentum scraping”: wait for beam to be wide, then use collimators
- Perform in Debuncher
- Have also modified beam transfer scheme from Accumulator to Debuncher to improve cleanliness



*momentum scrape:  $|dE/E| = x_{max}/D$*



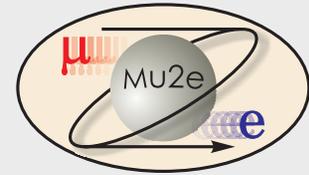
# Extinction Measurement



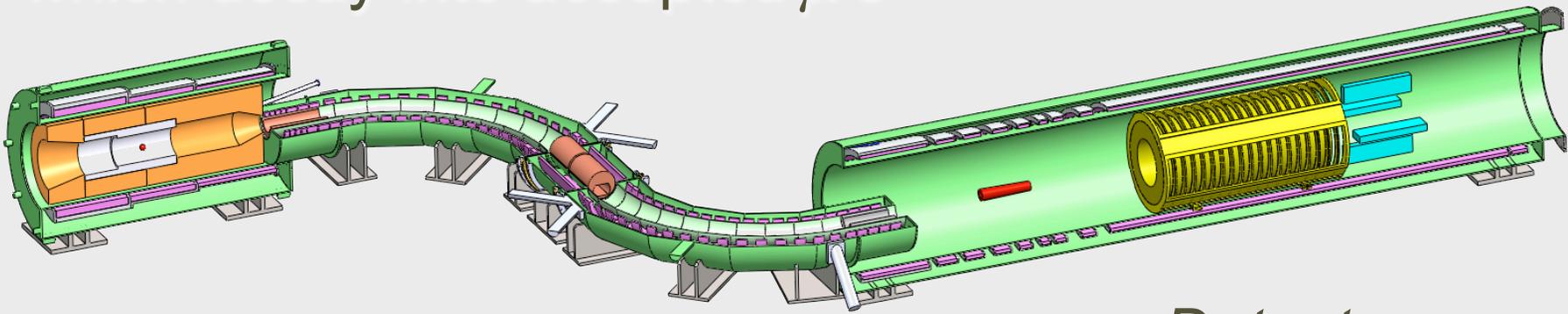
- Continuous Extinction monitoring techniques under study
  - Can we count protons directly?
    - dynamic range:  $3e7$  in-spill to 1 out-of-spill
  - Statistical:
    - count diffracted protons from target
    - see 1 event/hr or so for  $10^{-10}$ ,  $\sim 10$  in spill



# Mu2e Overview

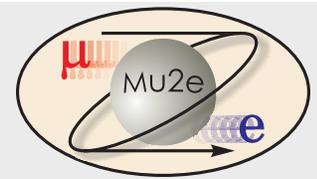


- *Production:* Magnetic bottle traps  $\pi$ 's, which decay into accepted  $\mu$ 's

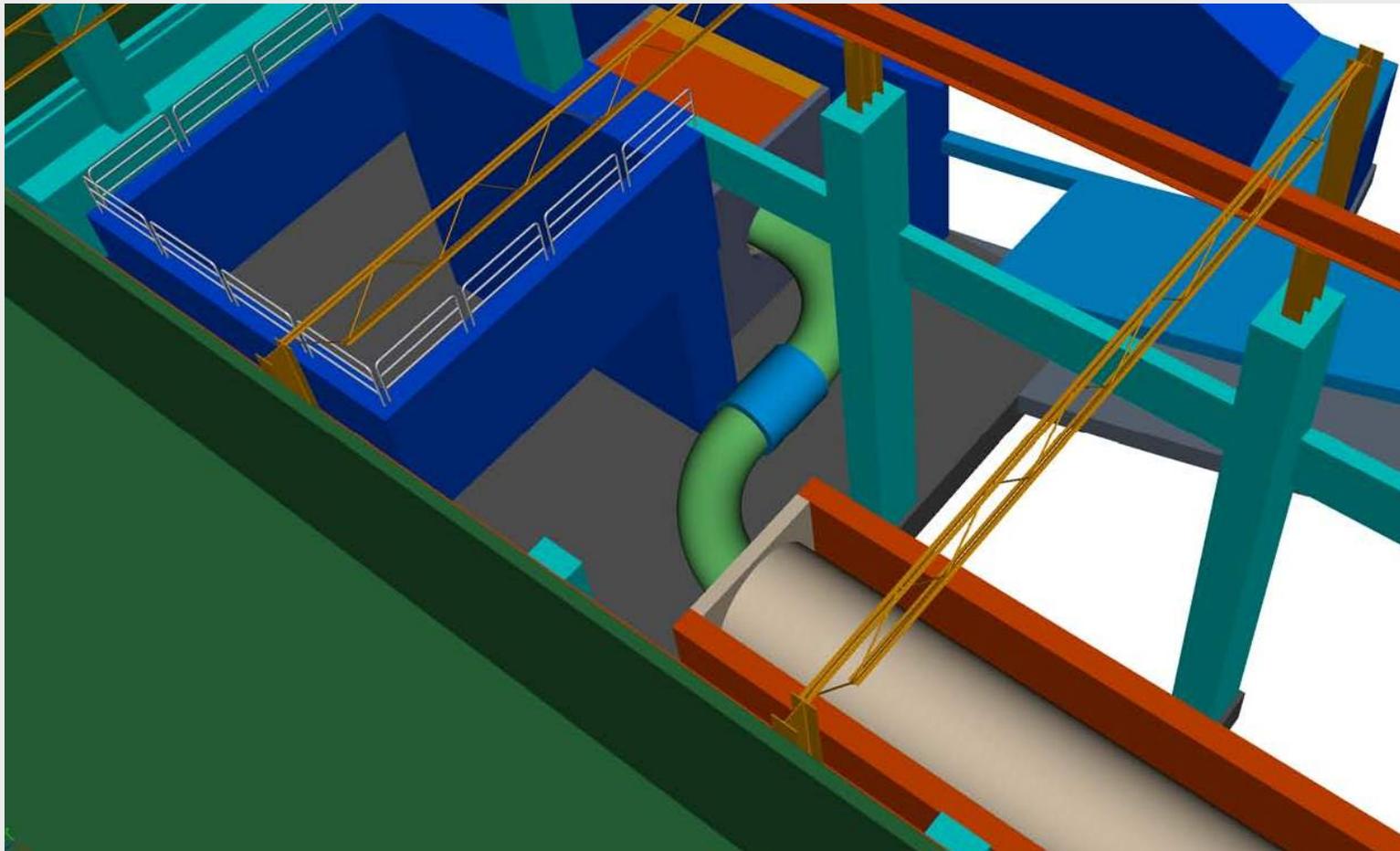


- *Transport:* S-curve eliminates backgrounds and sign-selects

- *Detector:* Stopping Target, Tracking and Calorimeter

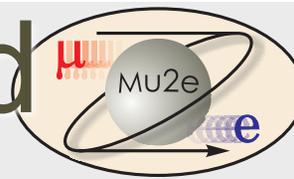


# Solenoid in the Hall

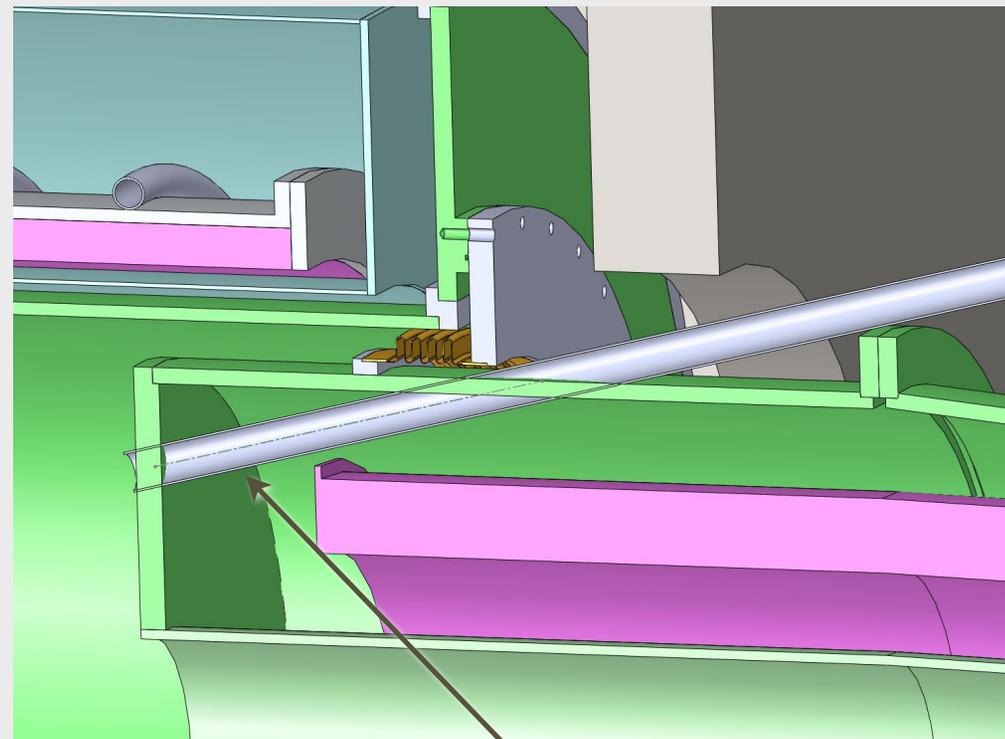
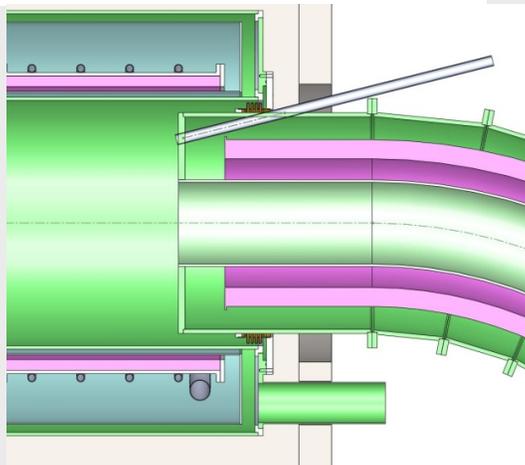
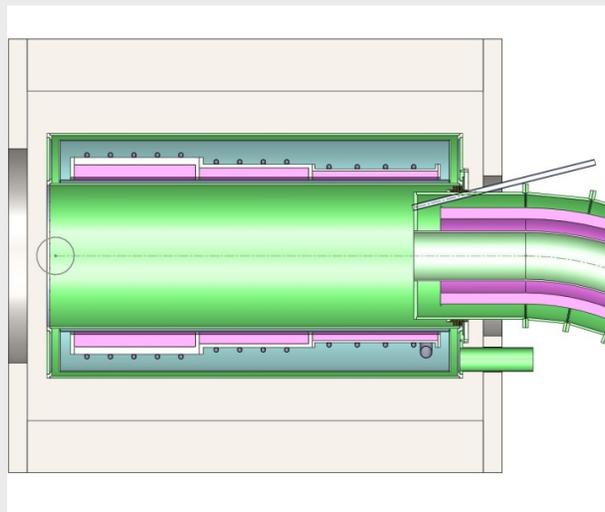




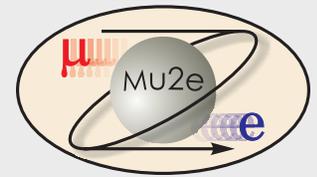
# Much Progress in Solenoid Design



- Starting to talk with vendors about construction of solenoids; much interest in bids



incident proton beam pipe



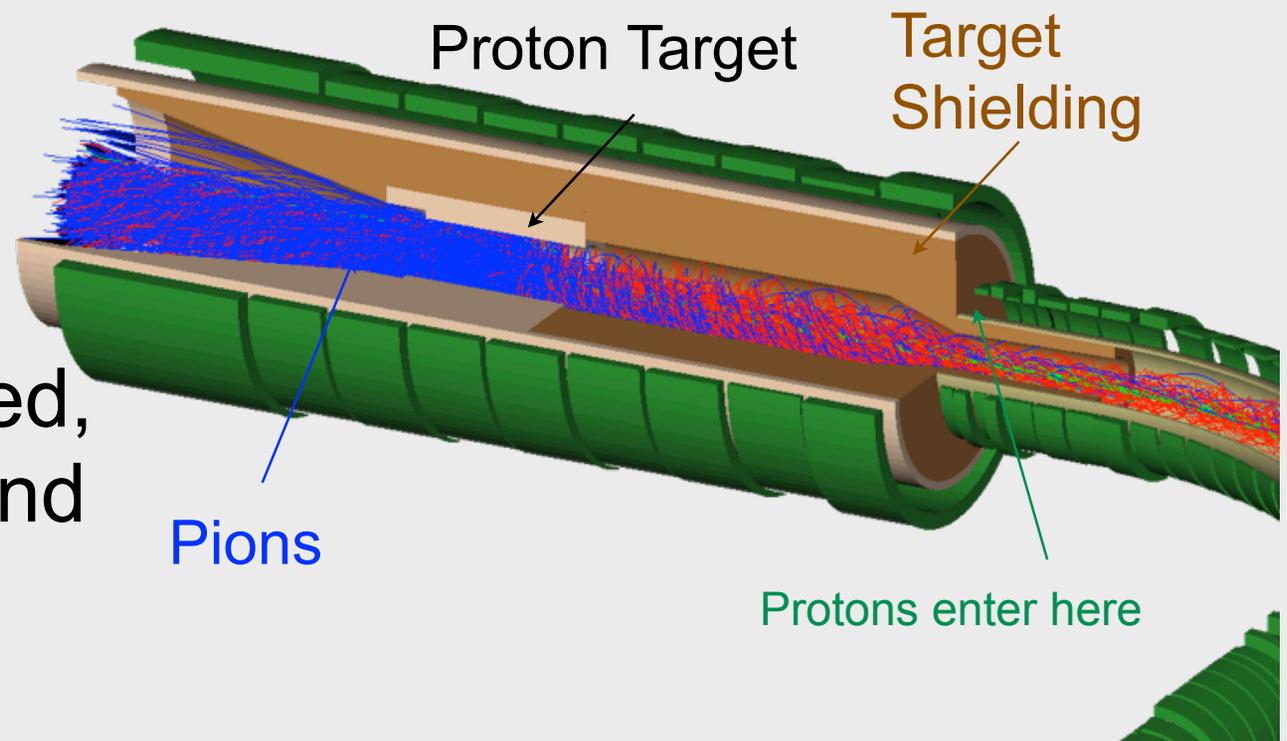
# Production Solenoid:

Protons enter opposite to outgoing muons

Protons leave through thin window

$\pi$ 's are captured, spiral around and decay

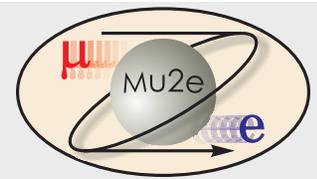
muons exit to right



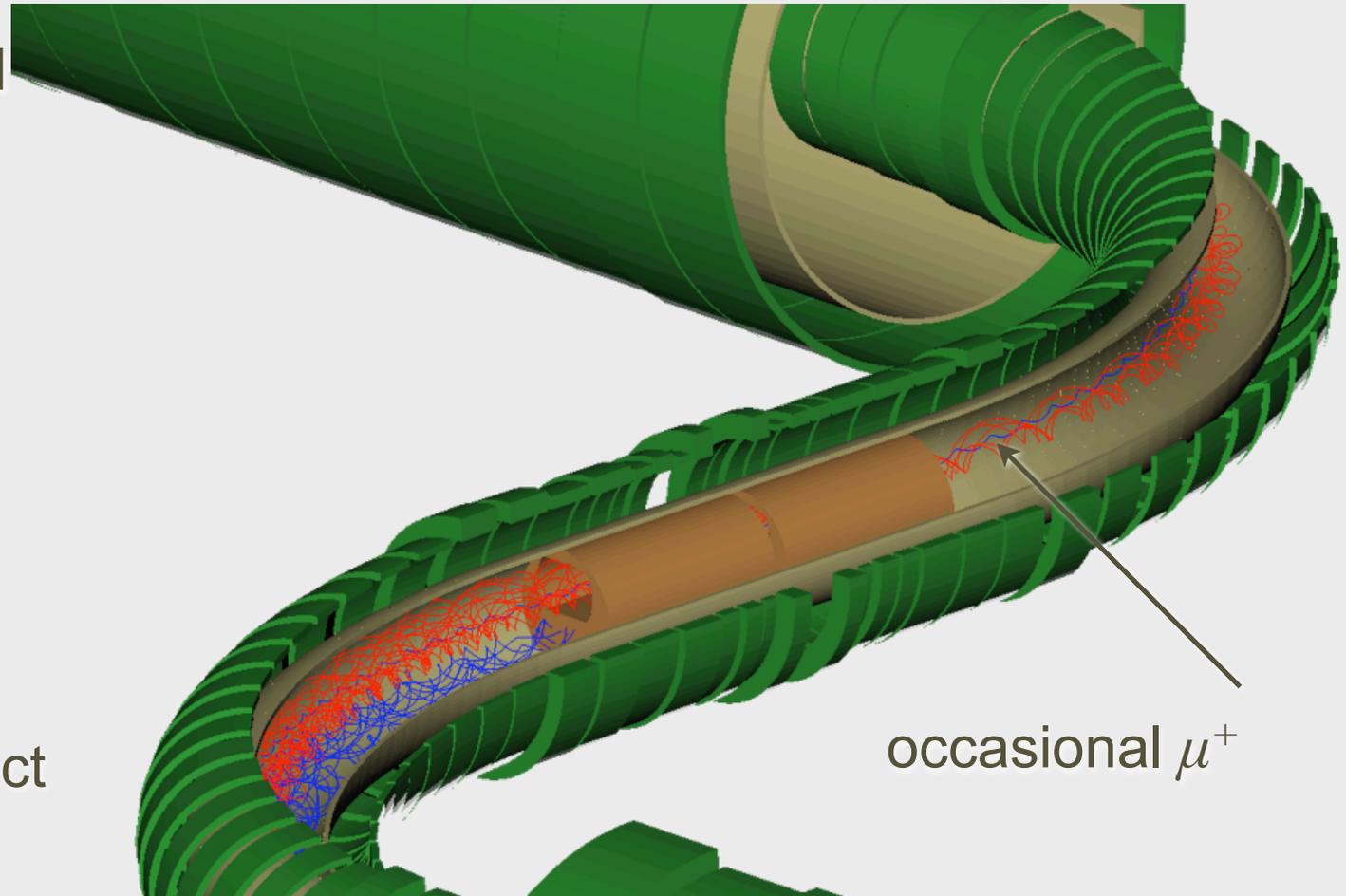
4 m × 0.30 m



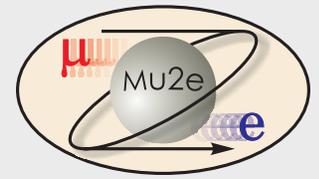
# Transport Solenoid



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



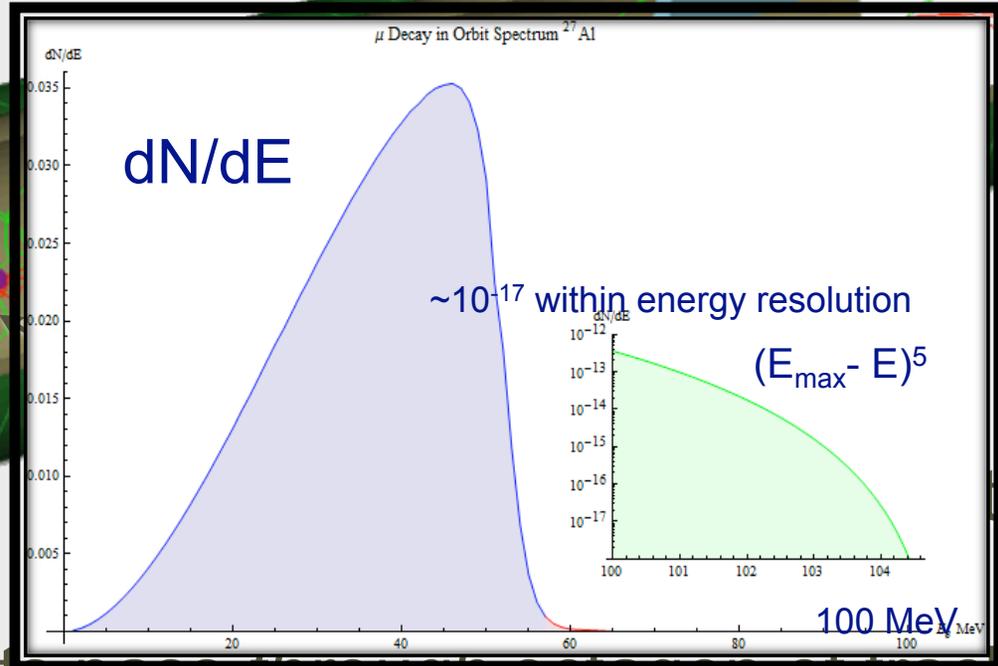
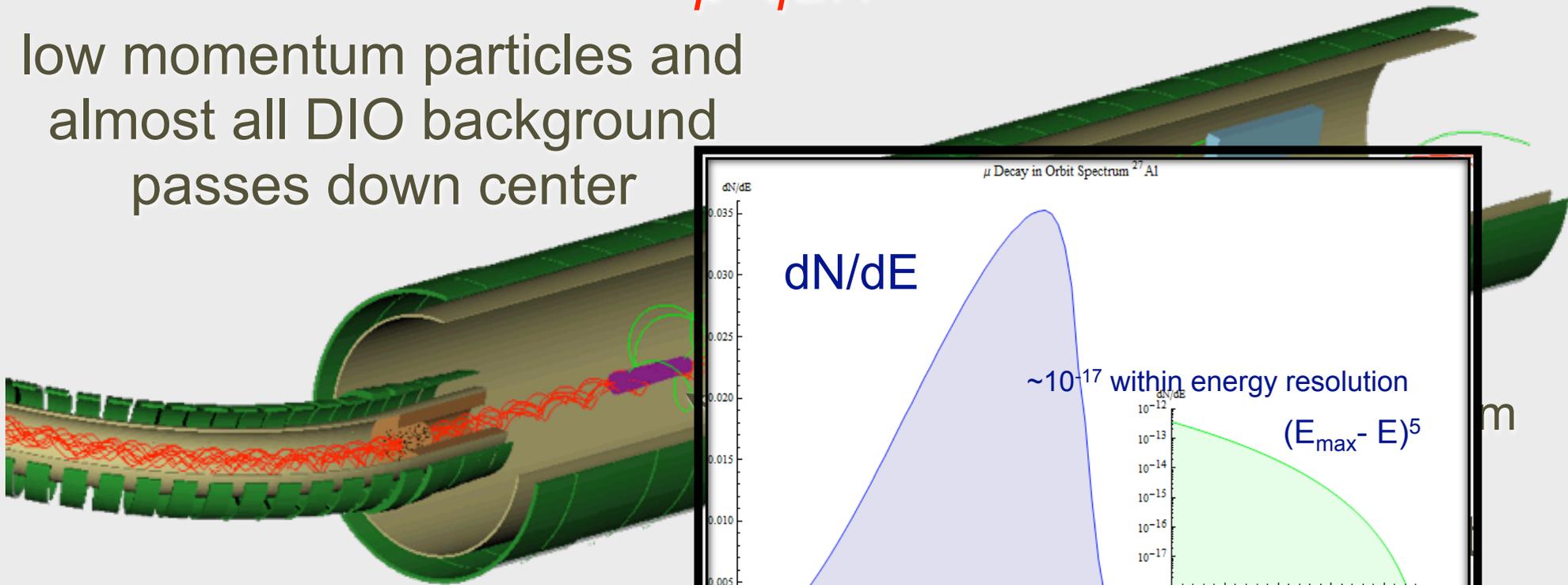
13.1 m along axis  $\times$   $\sim 0.25$  m



# Detector Solenoid

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

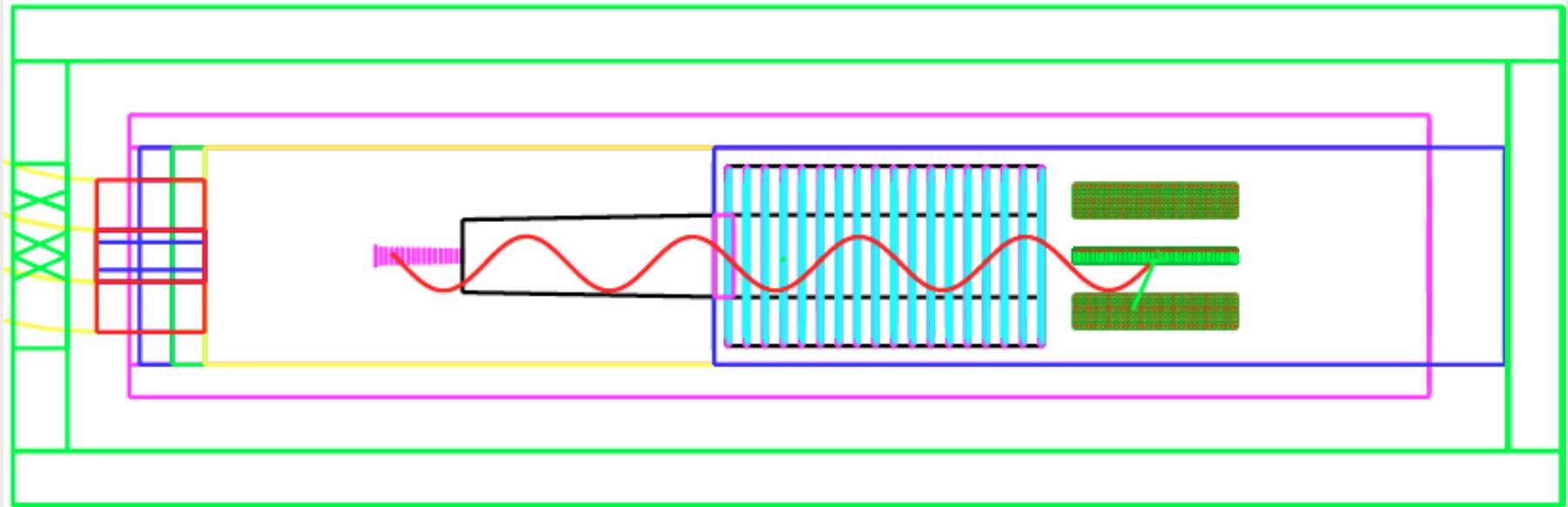
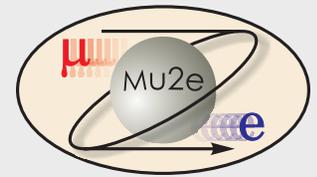
low momentum particles and  
almost all DIO background  
passes down center



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



# Detector



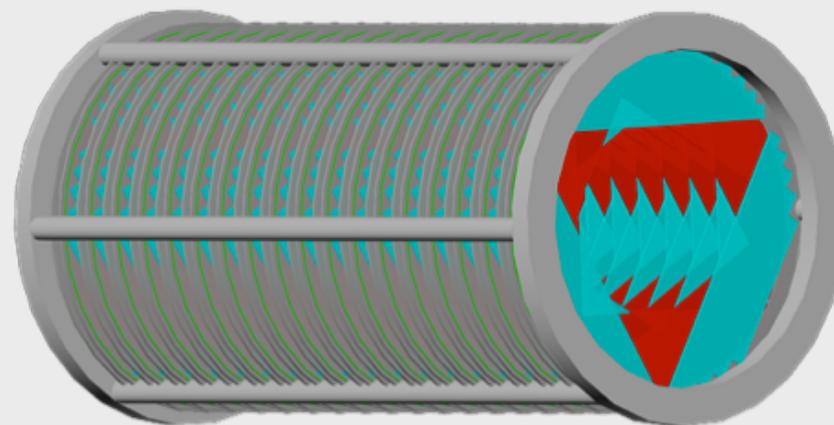
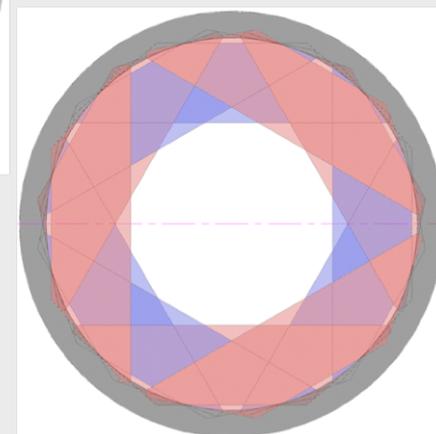
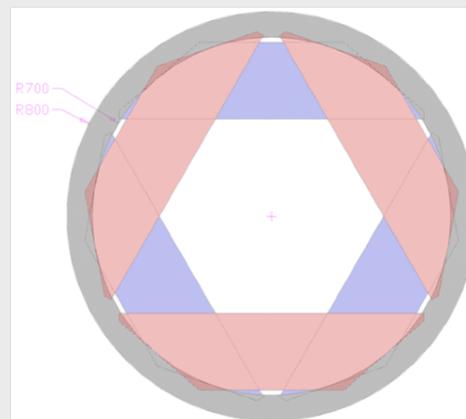
- Immersed in solenoidal field, so electrons follow near-helical path
- Conversion Electron born in Stopping Target
- Tracker followed by Calorimeter
- Tracker: (straw tubes with axes transverse to beam)
  - 216 sub-planes
    - sixty 5 mm diameter conducting straws
    - length from 70-130 cm
    - total of 13,000 channels
  - Calorimeter:
    - 1024 3.5 × 3.5 × 12 cm PbWO<sub>4</sub> or LYSO
    - 4--5% resolution



# T-Tracker Details

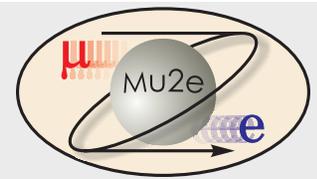


- This “windowframe” is repeated, rotated each time
- Just know which straw is hit
  - Makes PR complicated!
  - Have preliminary and encouraging results
- Are investigating time or charge division to provide 3rd coordinate



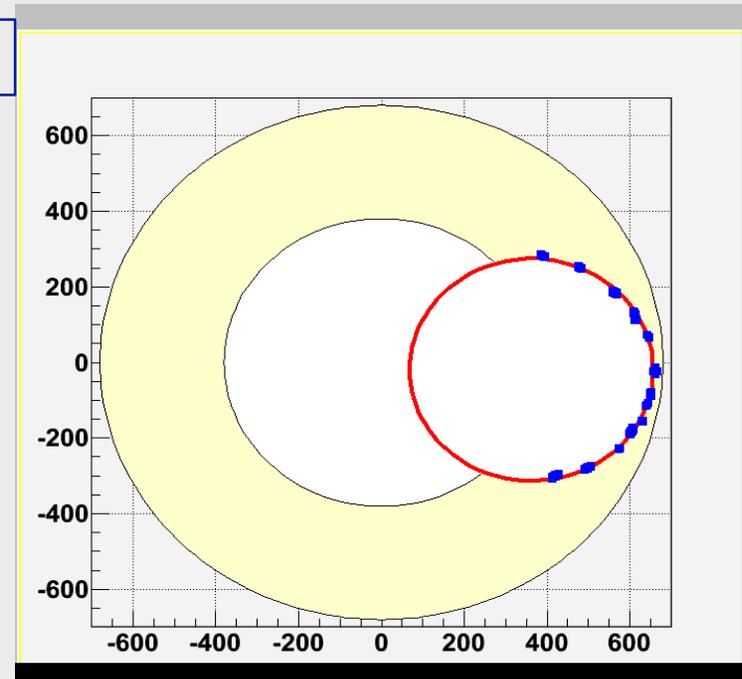


# Pattern Recognition and Tracking

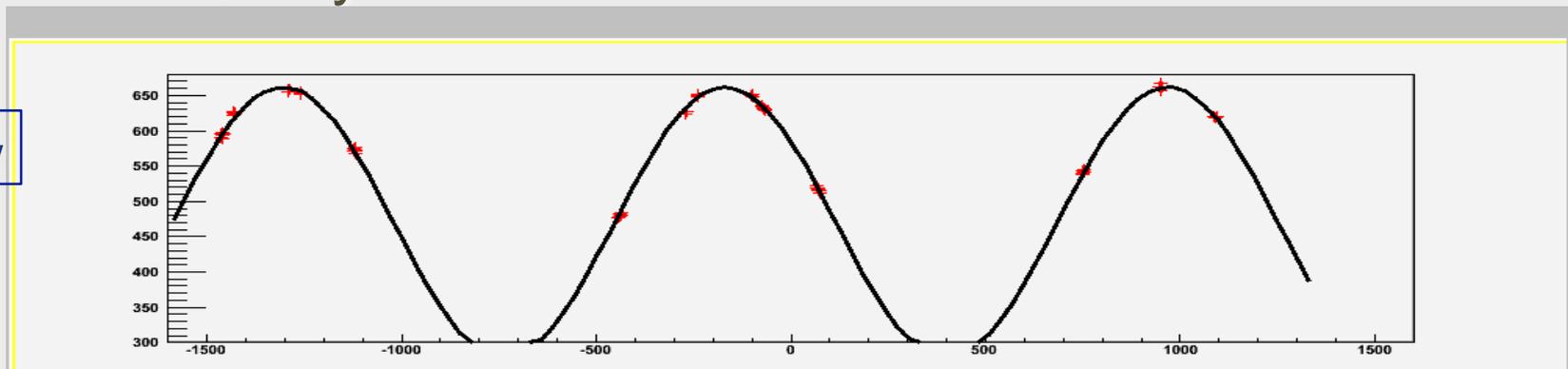


- Using Hough Transform for Pattern Recognition
- Have ported BaBar Kalman Filter for Track Fitting
  - robust against noise so far
  - extensive misreconstruction studies underway

X-Y View

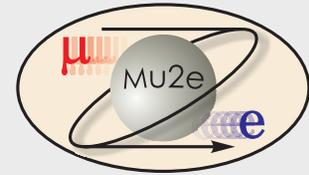


R-Z view





# Backgrounds...

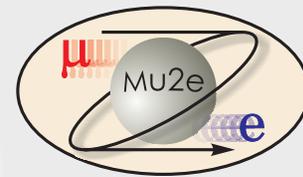


Type	Description
$e_t$	beam electrons
$n_t$	neutrons from muon capture in muon stopping target
$\gamma_t$	photons from muon capture in muon stopping target
$p_t$	protons from muon capture in muon stopping target
$e(DIO)_t < 55$	DIO from muon capture in muon stopping target, $< 55$ MeV
$e(DIO)_t > 55$	DIO from muon capture in muon stopping target, $> 55$ MeV
$n_{bd}$	neutrons from muon capture in beam stop
$\gamma_{bd}$	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

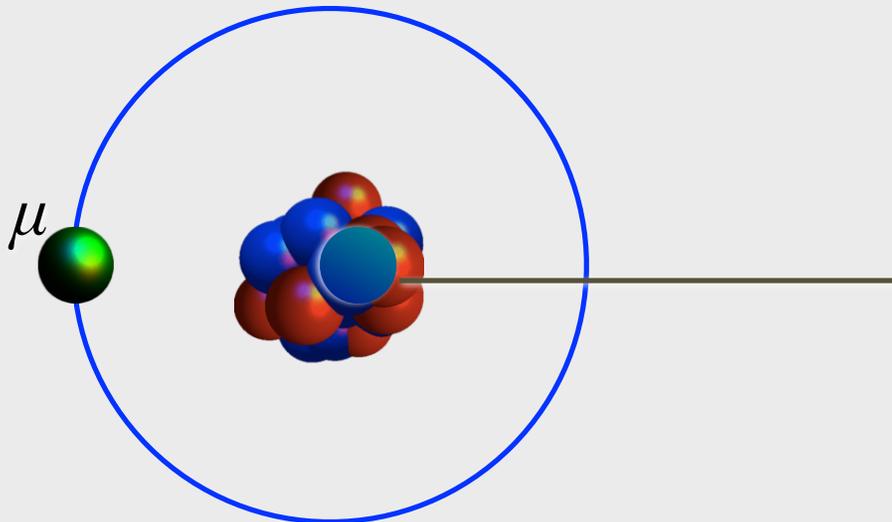
bd = albedo from beam stop (after calorimeter): splashback, extra hits  
confusing pattern recognition



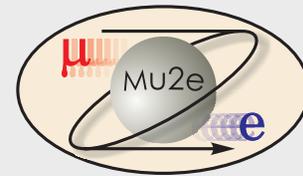
# Recall Our Normalization



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

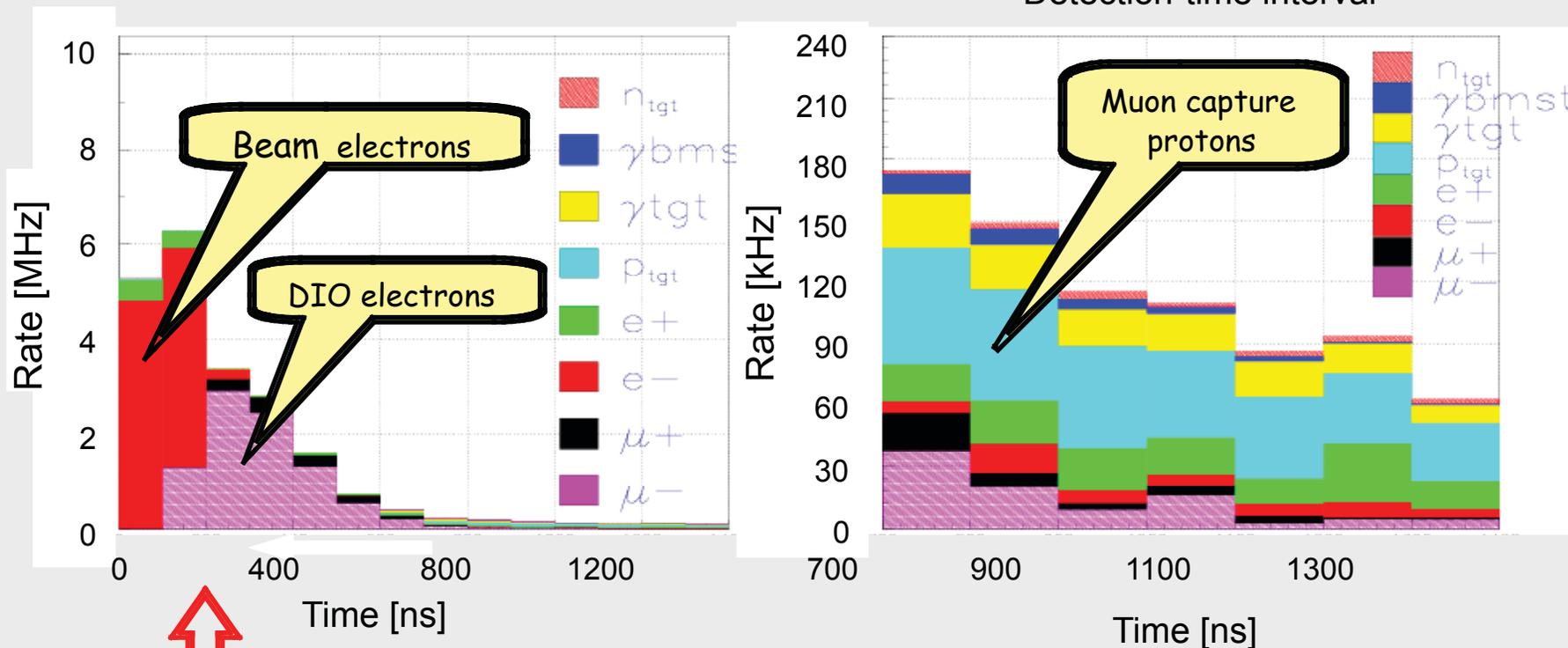


these can enter the detector and cause rate problems:  
slow protons are highly ionizing and can deaden wires



# Magnetic Spectrometer: Rates vs. Time

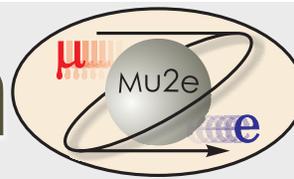
Detection-time interval



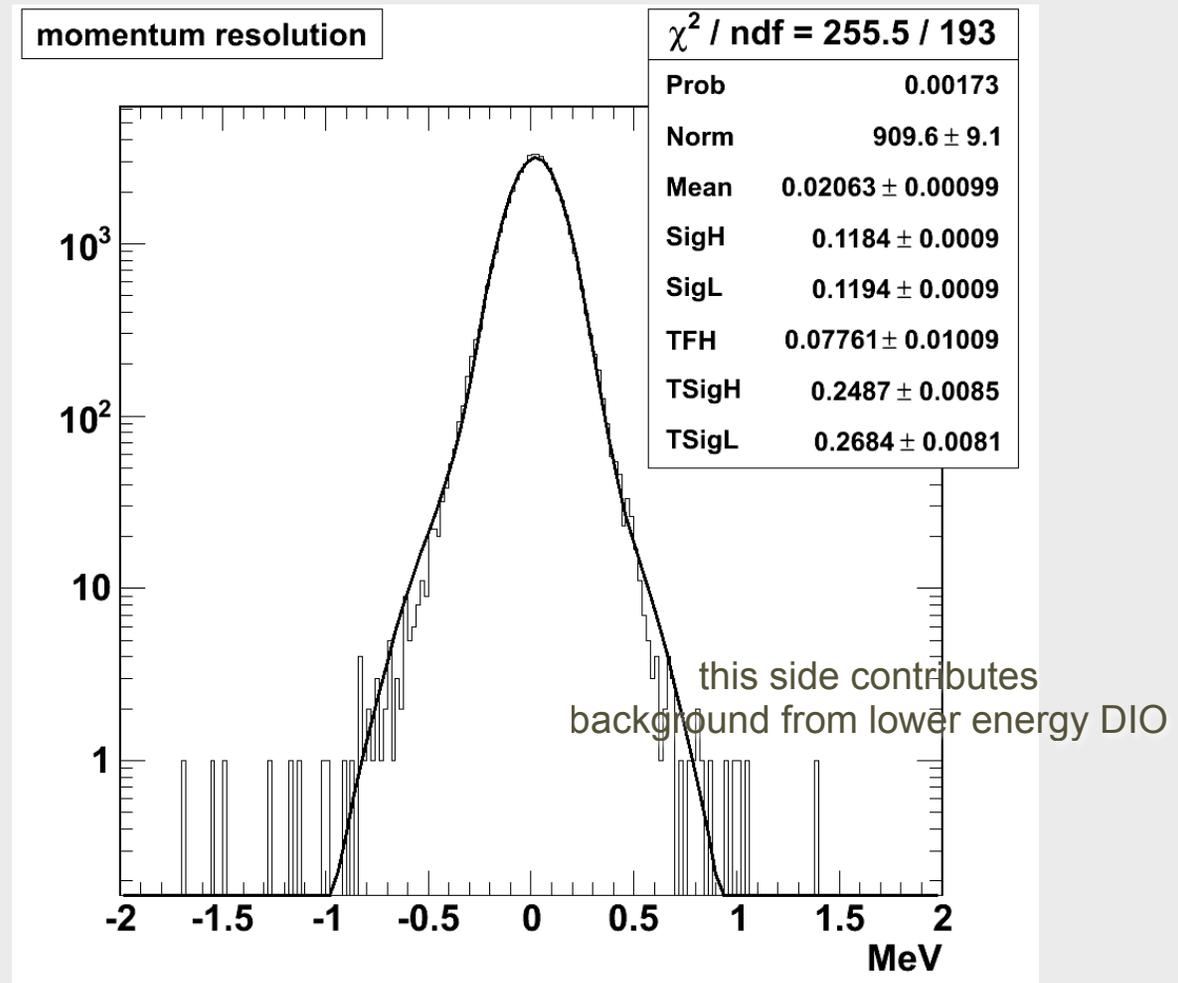
- Rates *start* at 6 MHz/wire but  $\approx$  180 kHz/wire in live time window
- Each muon capture produces  $2\gamma$ ,  $2n$ ,  $0.1p$



# Understanding Resolution

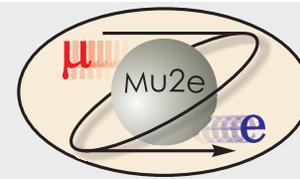


- Measure resolution/  
check acceptance:
  - special runs  
varying target foils,  
field, location of  
stopping target
  - Use  $\pi^+ \rightarrow e\nu$  decay:  
monochromatic  
line at  $\sim 70$  MeV
  - Gaussian part  
yield  $< .01$  DIO  
smeared upwards



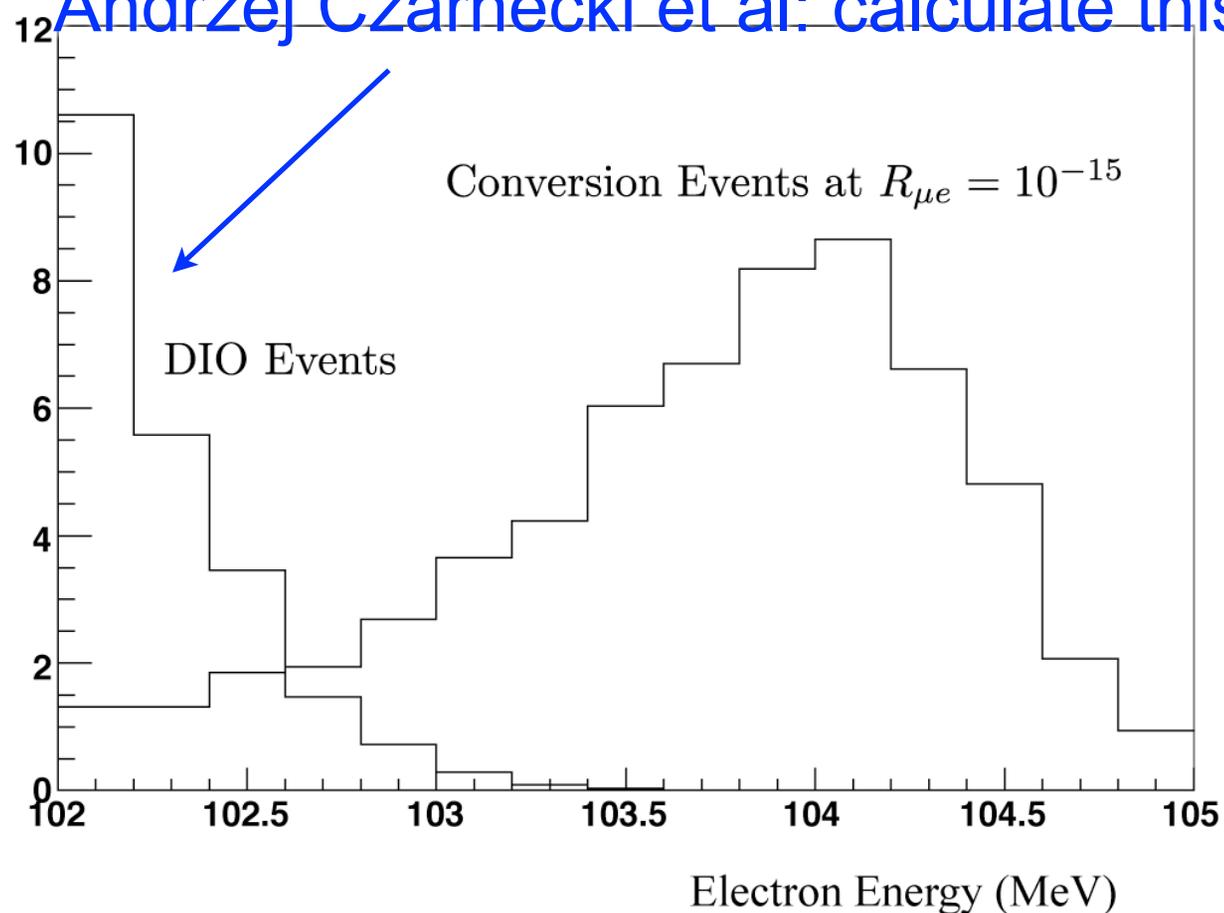
core: 92% 120 keV/c

tail: 8% 250 keV/c



# Signal and Background

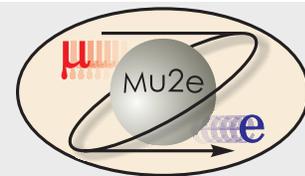
Andrzej Czarnecki et al: calculate this tail



energy loss in stopping target and other material shifts  
electron down to  $\sim 104$  MeV

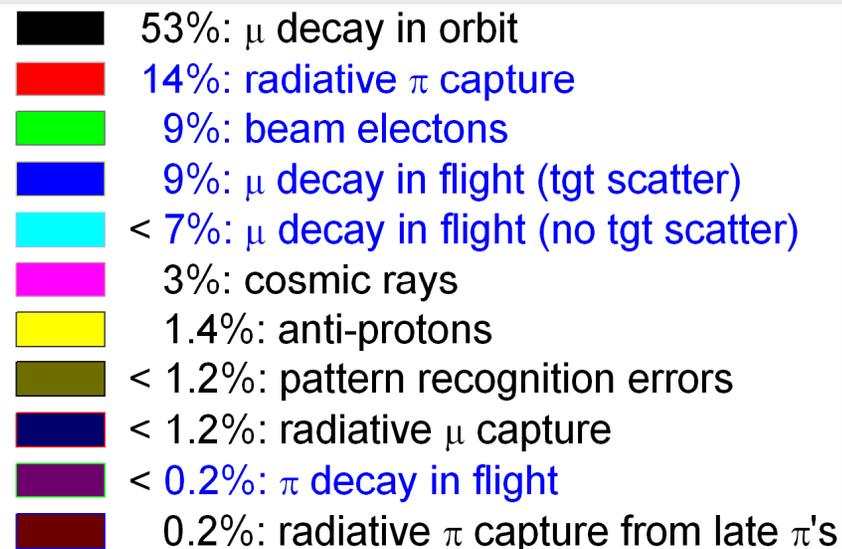
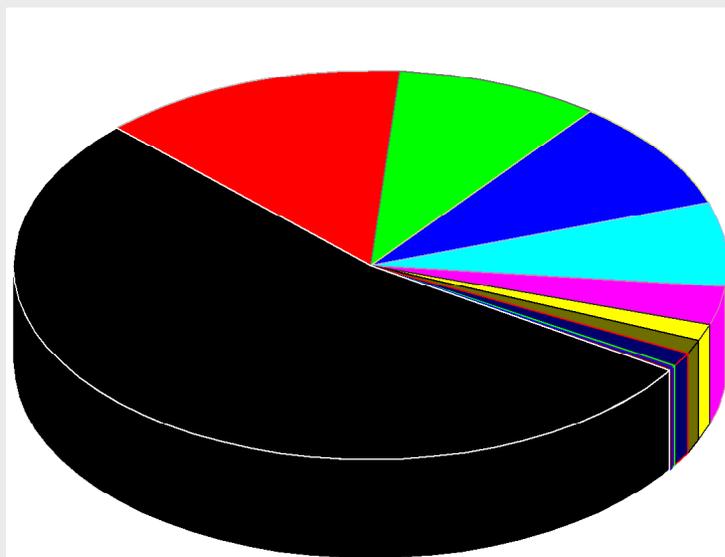


# Final Backgrounds



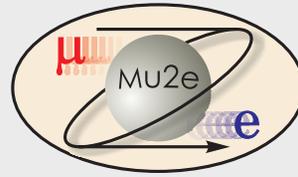
- For  $R_{\mu e} = 10^{-15}$   
~40 events / 0.4 bkg  
(LHC SUSY?)
- For  $R_{\mu e} = 10^{-16}$   
~4 events / 0.4 bkg

Source	Number
DIO	0.225
Radiative $\pi$ capture	0.072
$\mu$ decay-in-flight	0.072
Scattered e-	0.035
$\pi$ decay in flight	<0.0035





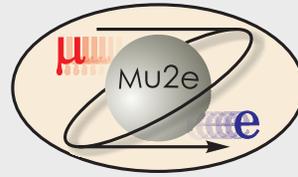
# Outline



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



# FNAL Beam Delivery



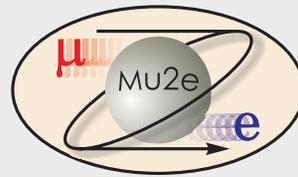
- FNAL has unique, major strength:

## Multiple Rings

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



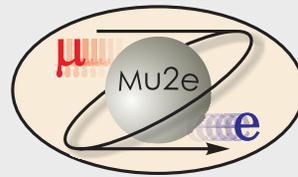
# Quick Fermilab Glossary



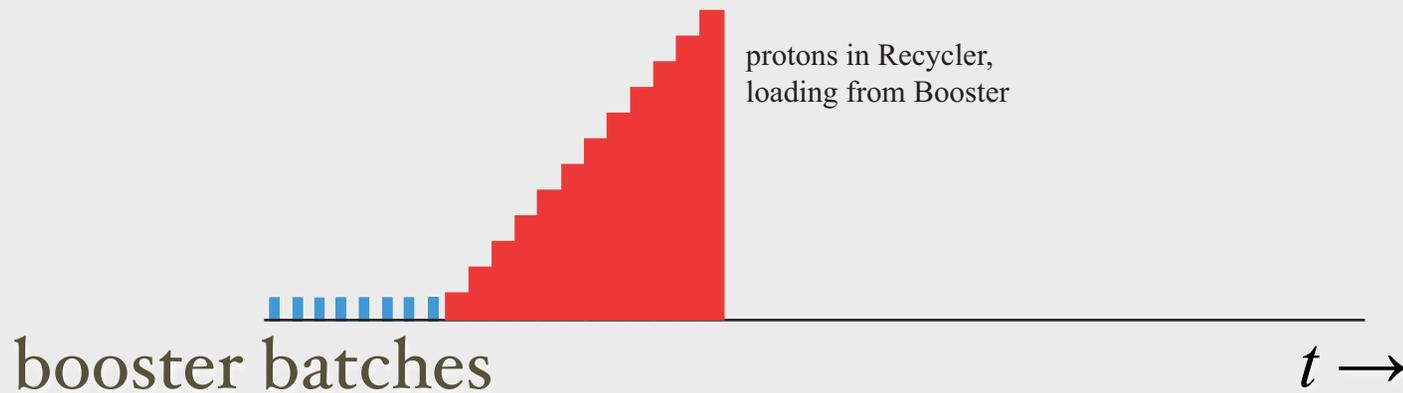
- Booster:
  - The Booster accelerates protons from the 400 MeV Linac to 8 GeV
- Accumulator:
  - momentum stacking successive pulses of antiprotons now, 8 GeV protons for Mu2e
- Debuncher:
  - smooths out bunch structure to stack more  $\bar{p}$  now; rebunch for Mu2e
- Recycler:
  - holds more  $\bar{p}$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



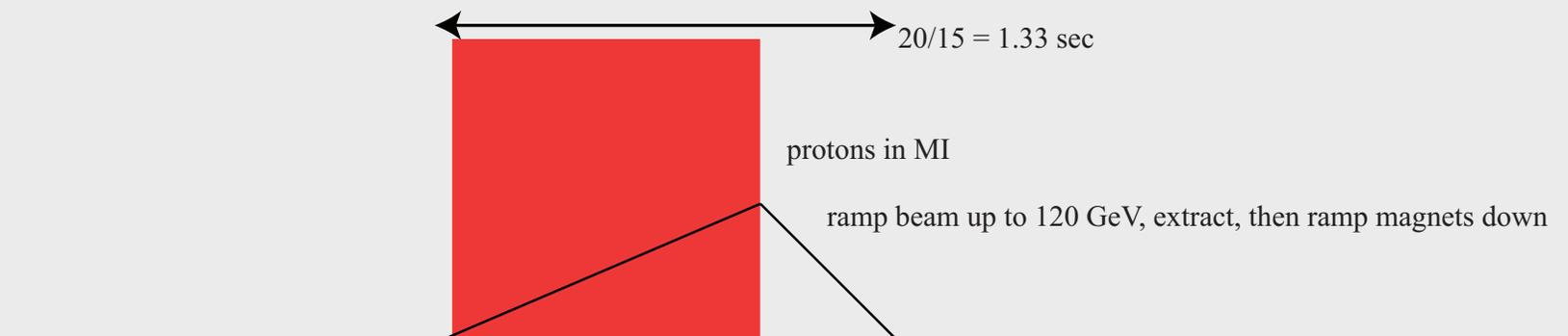
# NovA Era and Mu2e



- Load from Booster to Recycler; Booster 'ticks' at  $4 \times 10^{12}$ , 15 Hz

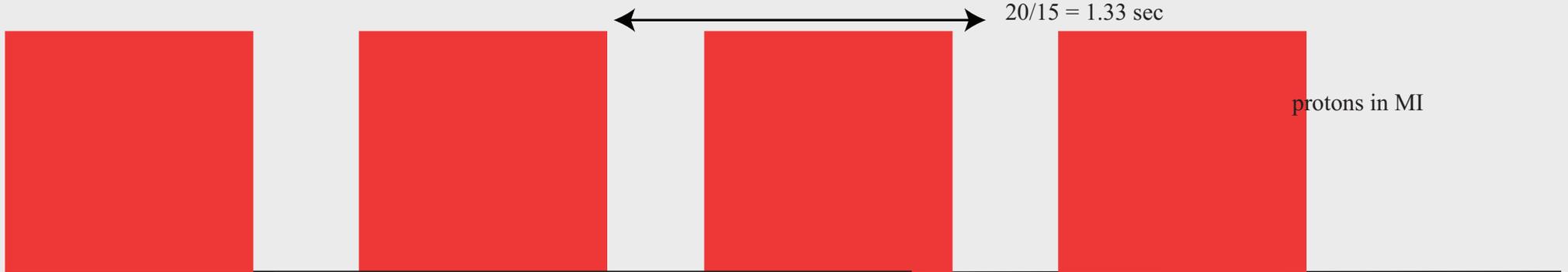
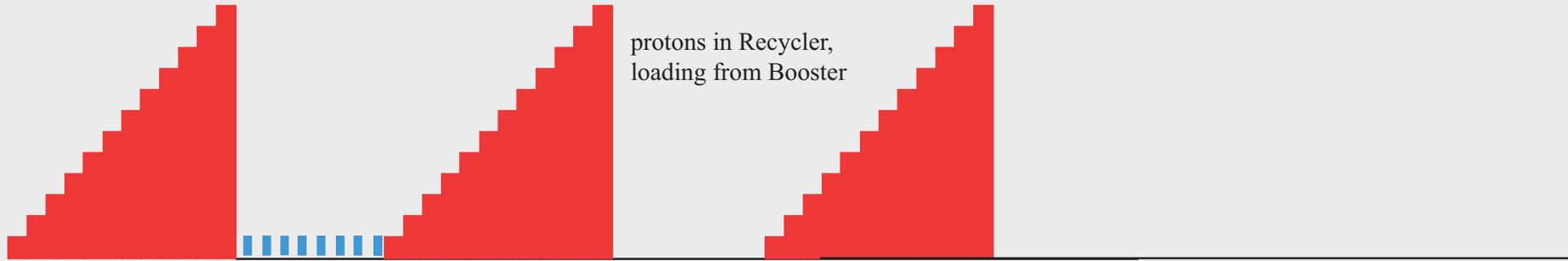
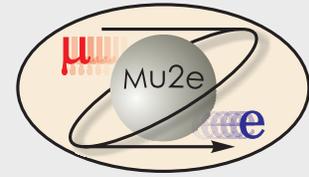


- Single-Turn Transfer to MI

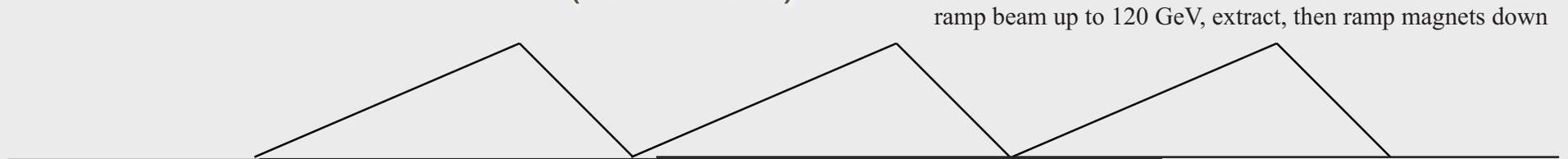




# All Together...

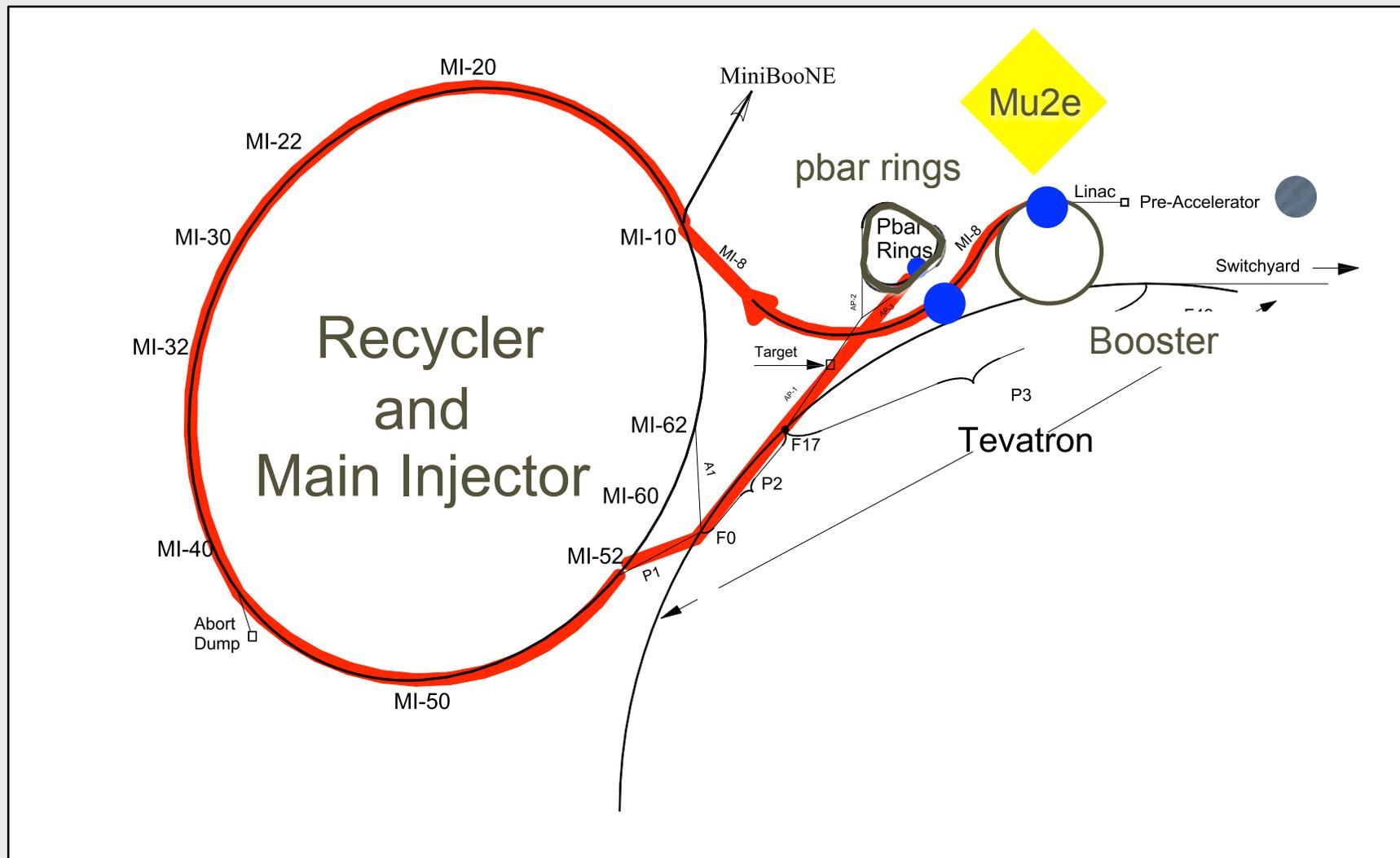


time to ramp allows us to fit eight extra Booster batches for Mu2e  
(can use 6)





# “Boomerang” Scheme





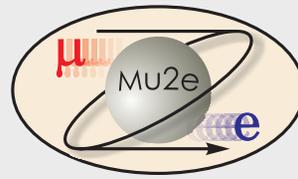
# And on the Civil Construction



Figure 2 –Site Photo Indicating Location of Proposed mu2e Conventional



# Outline



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# Upgrades at Project X

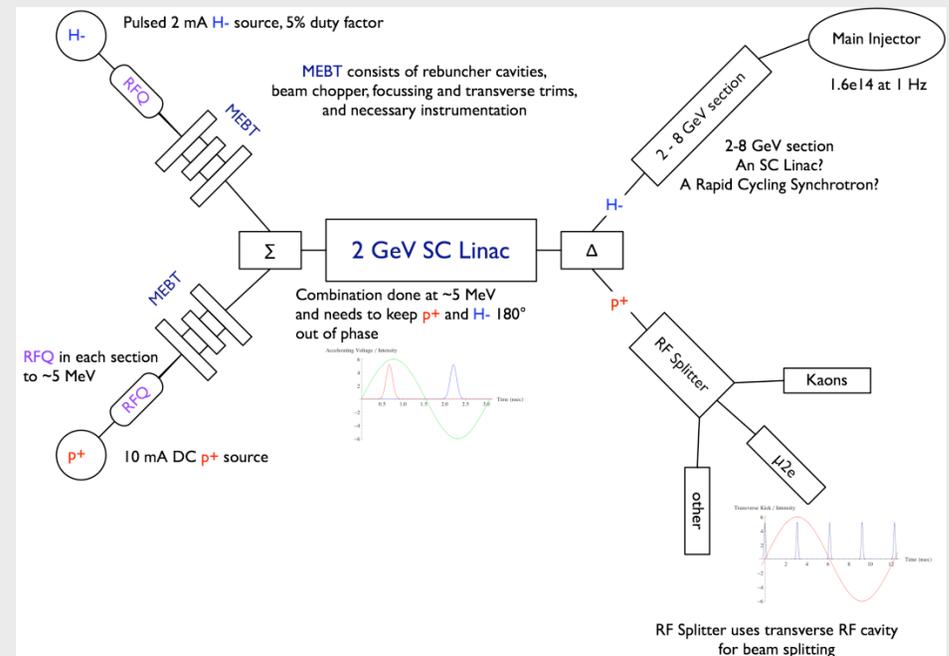
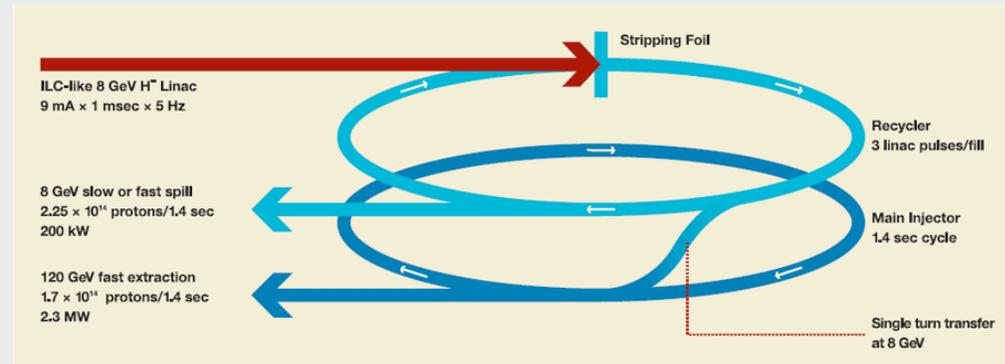


- Project X is a concept for an intense 8 GeV proton source that provides beam for the Fermilab Main Injector and an 8 GeV physics program.

- Can drive next generation experiments in intensity frontier physics: rare processes, neutrinos

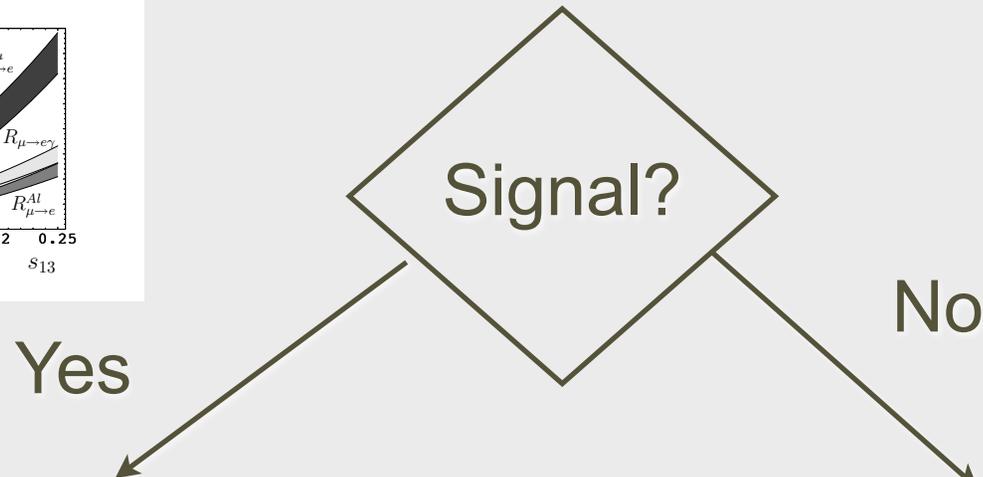
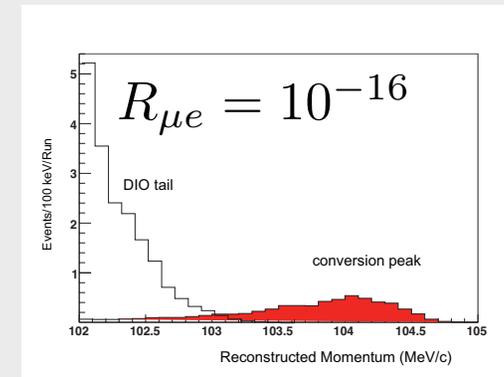
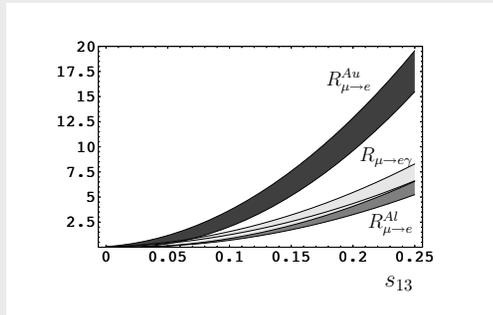
- Potential to upgrade Mu2e by  $x100$

- *study new physics*
- *set stronger limit*





# Upgrade Plans...



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

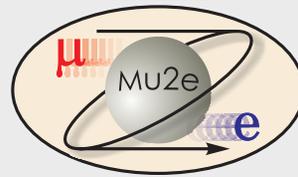
2. Prompt Rates will go up at higher Z, have to redesign detector and muon transport

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

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



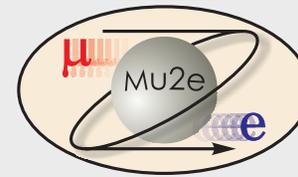
# Outline



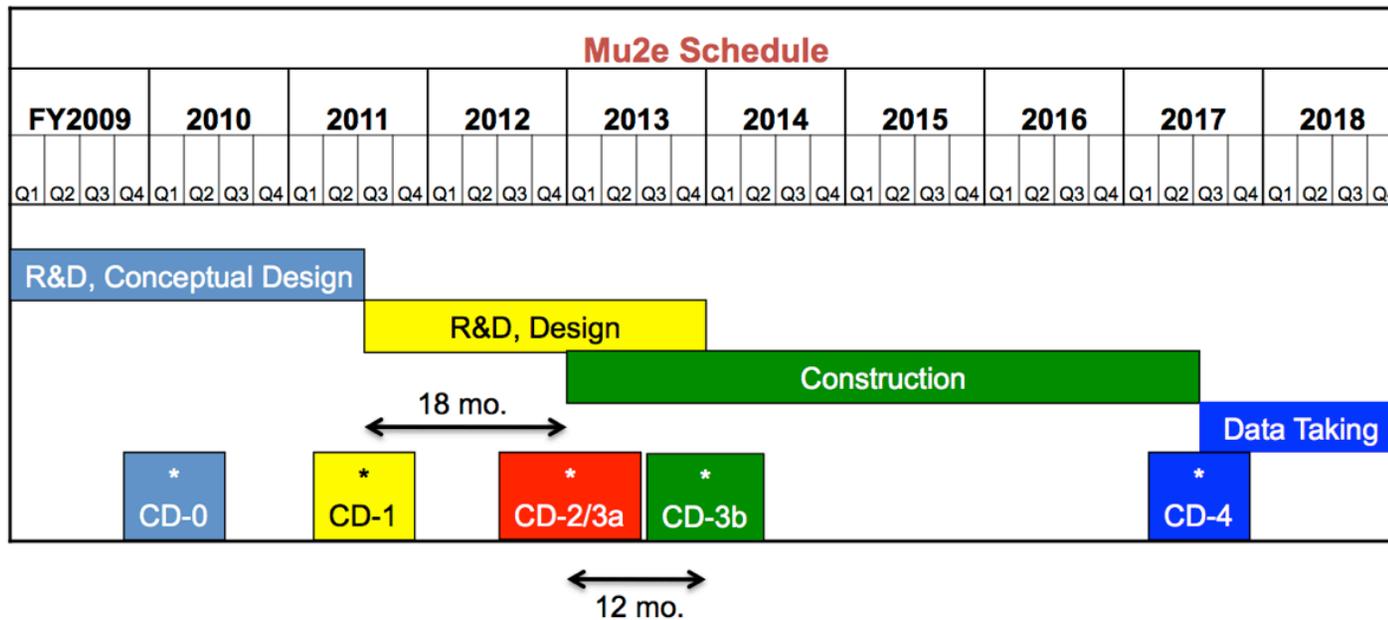
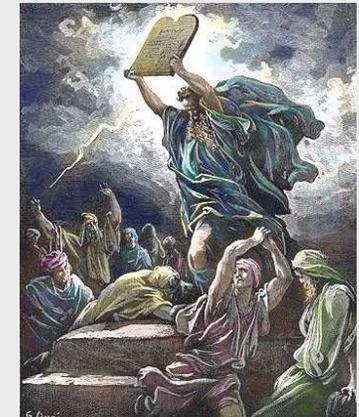
- The search for muon-electron conversion
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# Cost and Schedule

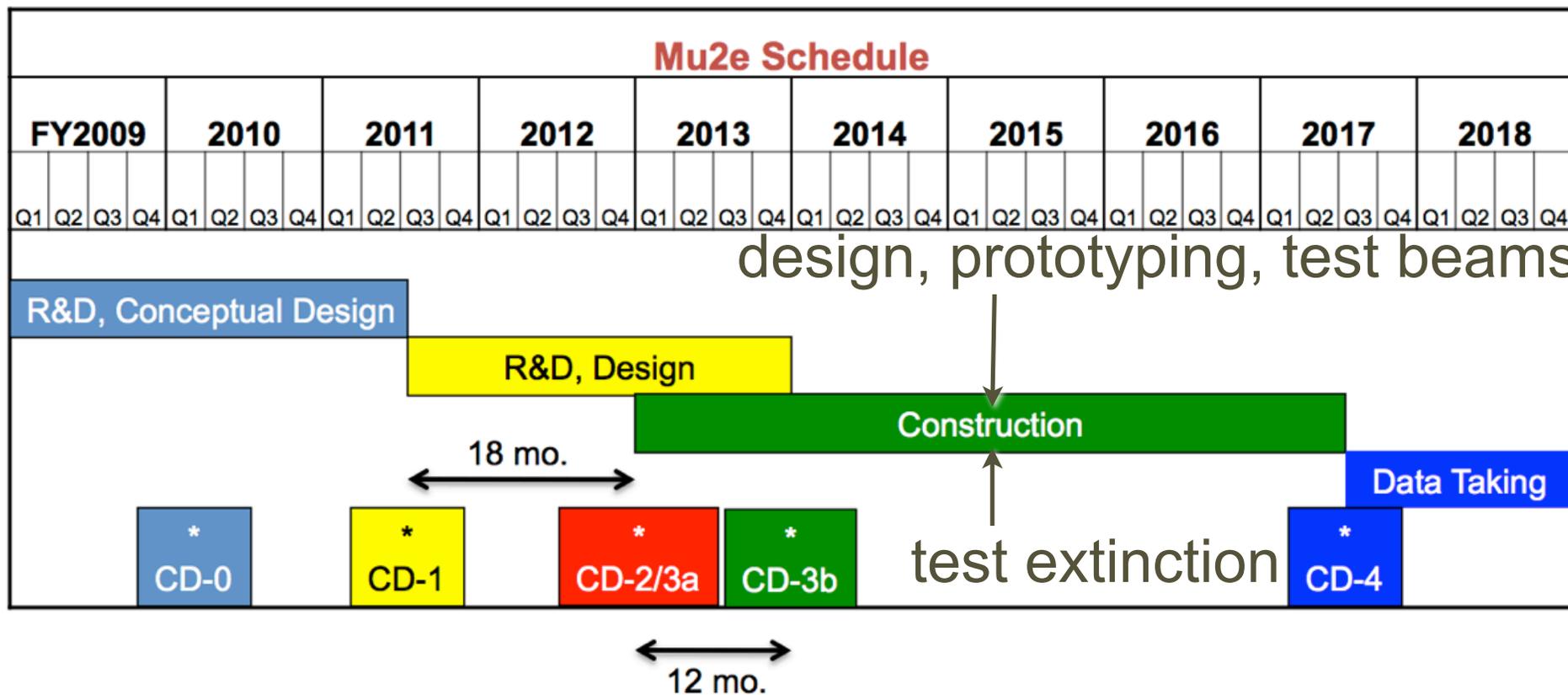


- *This is a technically limited schedule*
- Critical Path is Superconducting Solenoids
- \$200M “fully-loaded” Total Cost



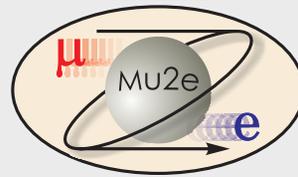


# What Does This Mean?





# 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



Who ordered that?