


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

R. Bernstein
Fermilab
for the Mu2e Collaboration

# Collaboration



*Boston University*
*Brookhaven National Laboratory*
*University of California, Berkeley*
*University of California, Irvine*
*California Institute of Technology*
*City University of New York*
*Duke University*
*Fermilab*
*University of Houston*
*University of Illinois, Urbana-Champaign*
*Lawrence Berkeley National Laboratory*
*Los Alamos National Laboratory*
*Northwestern University*
*Rice University*
*Syracuse University*
*University of Virginia*
*College of William and Mary*
*University of Washington, Seattle*

*Istituto G. Marconi Roma*
*Laboratori Nazionale di Frascati*
*Università di Pisa, Pisa*
*Università del Salento*
*Gruppo Collegato di Udine*

*Institute for Nuclear Research, Moscow, Russia*
*JINR, Dubna, Russia*

~130 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

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

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{all muon captures})}$$

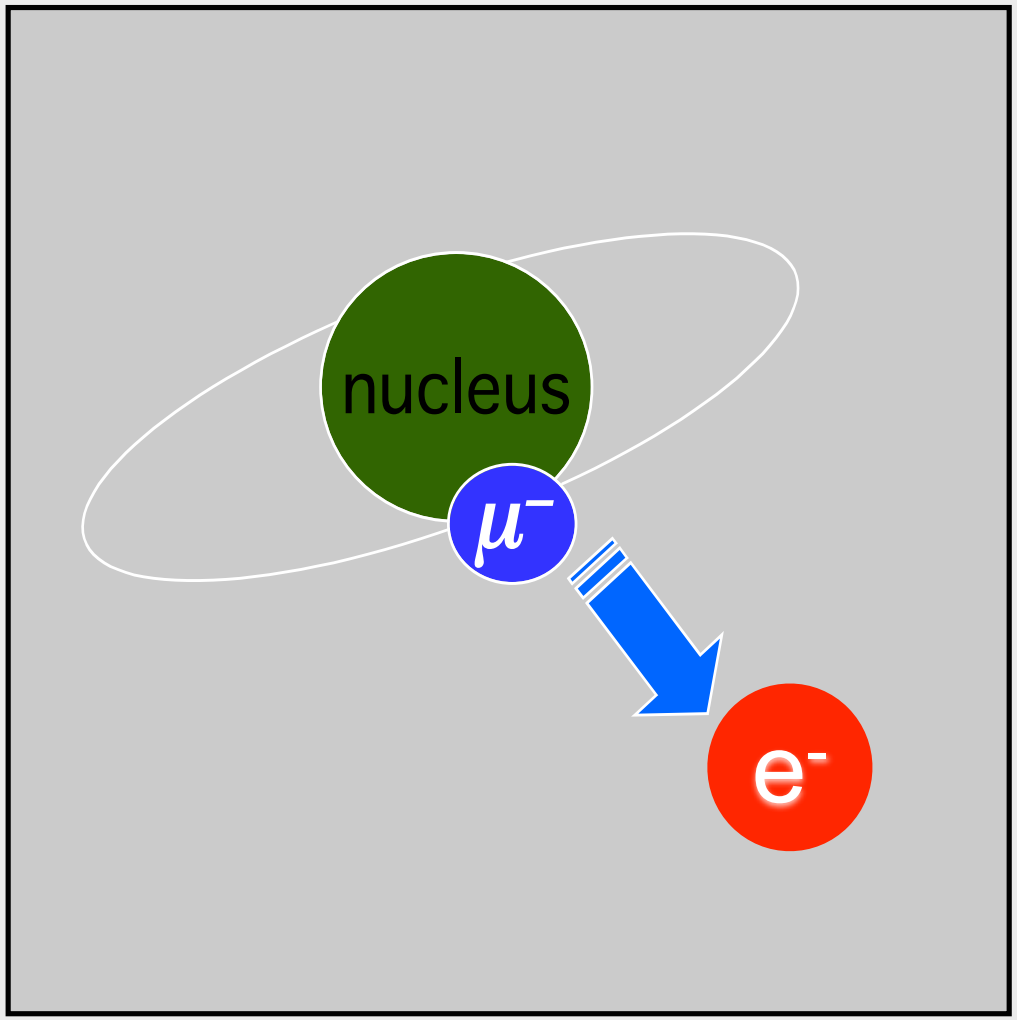
- Charged Lepton Flavor Violation (CLFV)
  - will measure $R_{\mu e} < 6 \times 10^{-17}$ @ 90%CL
- Related Processes:

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

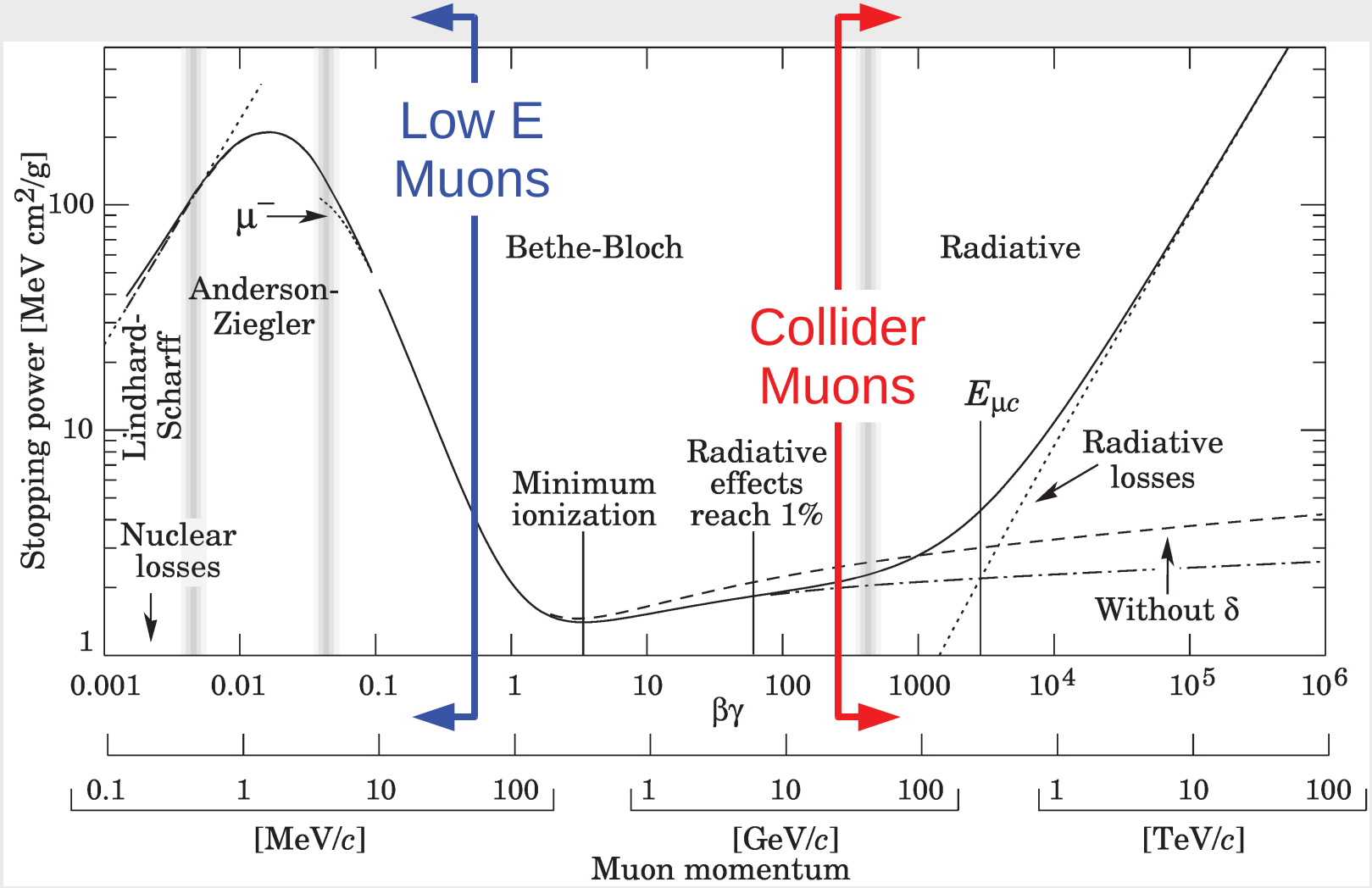
# Experimental Signal

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

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



# Physics is Different at these energies!



# "Who ordered that?"



– I.I. Rabi, 1937

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

- expect BR($\mu \rightarrow e\gamma$) ≈ $10^{-4}$
- Unless another $\nu$, in Intermediate Vector Boson Loop, cancels (Feinberg, 1958)

➡ same as GIM mechanism!

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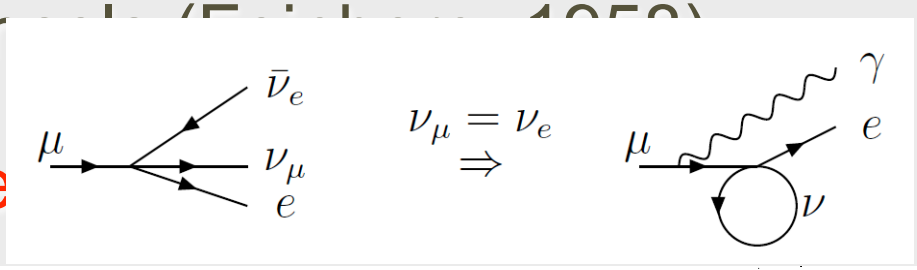
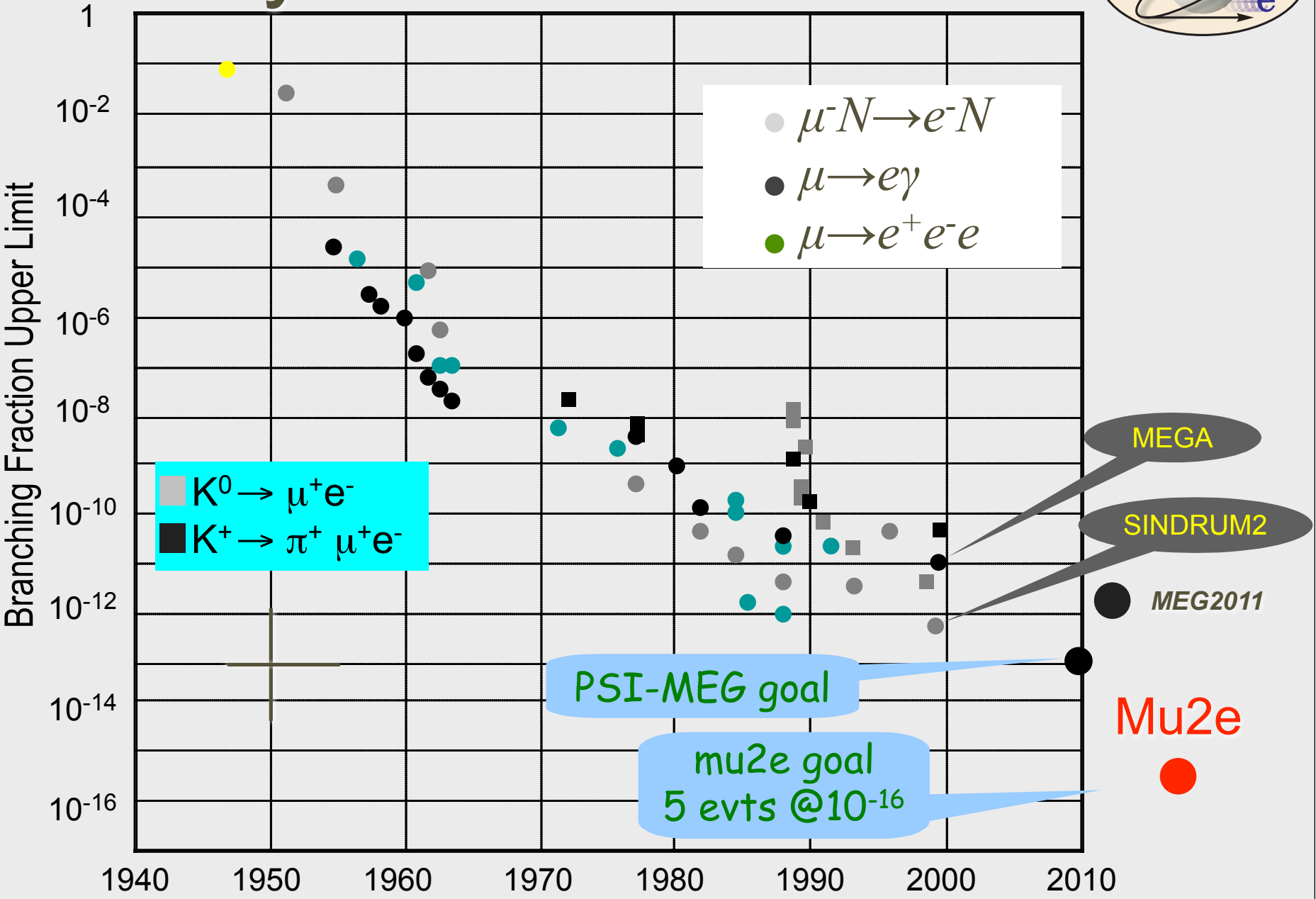



[1]Unless we are willing to give up the 2-component neutrino theory, we know that $\mu \to e + \nu + \bar{\nu}$.

# History of CLFV Searches



# History of CLFV Searches



Muon an independent lepton: no $\mu \rightarrow e\gamma$

Branching Fraction Upper Limit

1
$10^{-2}$
$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$10^{-14}$
$10^{-16}$

1940 1950 1960 1970 1980 1990 2000 2010

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

$K^0 \rightarrow \mu^+ e^-$
$K^+ \rightarrow \pi^+ \mu^+ e^-$

MEGA
SINDRUM2
MEG2011
PSI-MEG goal
Mu2e
mu2e goal
5 evts @$10^{-16}$

# History of CLFV Searches



Muon an independent lepton: no $\mu \rightarrow e\gamma$

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

Feinberg 1958: $\mu \rightarrow e\gamma \sim 10^{-4\text{--}5}$ or two $\nu$

Branching Fraction Upper Limit

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$K^0 \rightarrow \mu^+ e^-$
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Two neutrinos!

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MEGA

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Mu2e

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Branching Fraction Upper Limit

1, $10^{-2}$, $10^{-4}$, $10^{-6}$, $10^{-8}$, $10^{-10}$, $10^{-12}$, $10^{-14}$, $10^{-16}$

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MEGA

SINDRUM2

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PSI-MEG goal

Mu2e

LHC supersymmetry

mu2e goal
5 evts @$10^{-16}$

# History of CLFV Searches



Muon an independent lepton: no $\mu \rightarrow e\gamma$

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

$10^{-4-5}$ or two $\nu$

Number of muons needed: ~$5 \times 10^{19}$
Number of grains of sand on Earth: ~$10^{19}$



o neutrinos!

MEGA

SINDRUM2

MEG2011

-MEG goal

Mu2e

mu2e goal
5 evts @$10^{-16}$

$K^0$

$K^+$

LHC s

Branching Fraction Upper Limit

1
$10^{-2}$
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$10^{-14}$
$10^{-16}$

1940 1950 1960 1970 1980 1990 2000 2010

# Where did that last estimate come from?

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

Moral: jobs at Hawaii are more fun than at Fermilab

**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 the volume per grain.

$$N = \frac{Volume_of_sand}{Volume_of_grain}$$

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

$$Volume_of_sand = (length_of_beaches)\,(width)\,(depth)$$

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.

$$length_of_beaches = \frac{\%shores}{100}\,length_of_shores$$

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

$$length_of_shores = (multiple_of_circumference)\,(earth_circumference)$$

$$N = \frac{\left(\frac{\%shores}{100}\left((multiple_of_circumference)\,earth_circumference\right)\right)(width)\,(depth)}{Volume_of_grain}$$

We use rough but reasonable values for the parameters.

$\%shores = 25$

$multiple_of_circumference = 5$

$earth_circumference = 40000\ km$ $\quad km = 1000\ m$ $\quad m = 1000\ mm$

$width = 30\ m$

$depth = 5\ m$

$Volume_of_grain = 1\ mm^3$

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

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

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

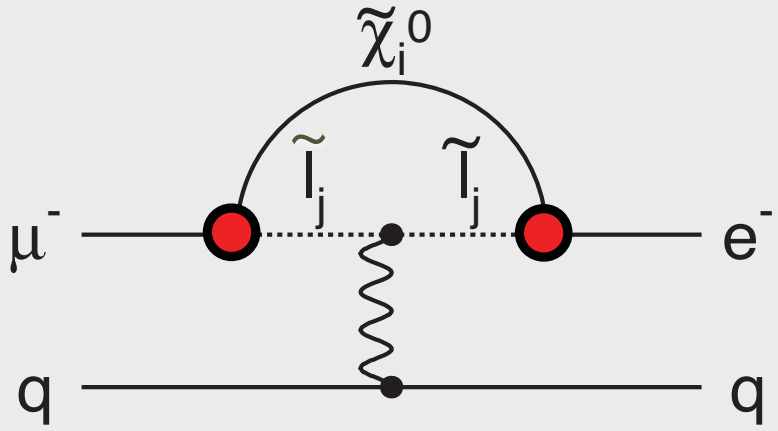




# LFV, SUSY and the LHC

## Supersymmetry

rate ~ $10^{-15}$

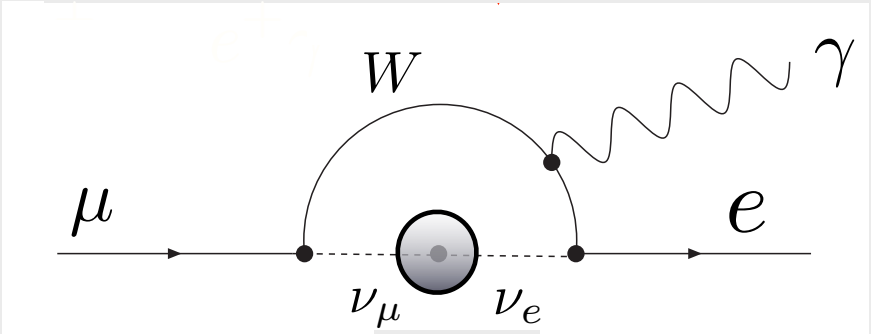



***Access SUSY through loops:***

***signal of Terascale at LHC implies ~40 event signal / <0.2 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!

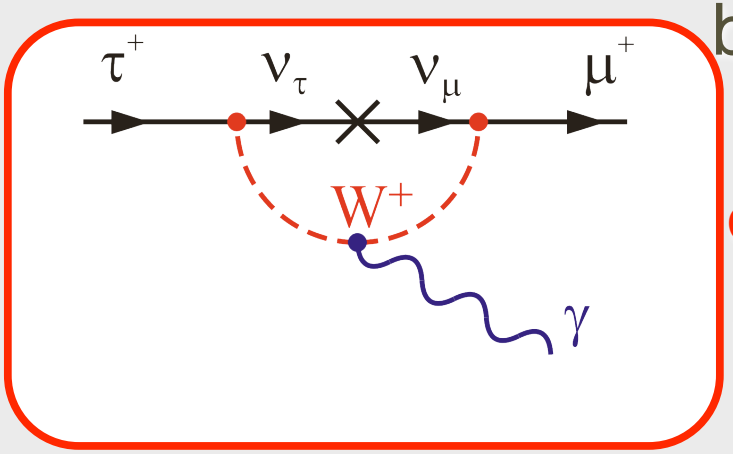
$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$



# CLFV and Tau Decays

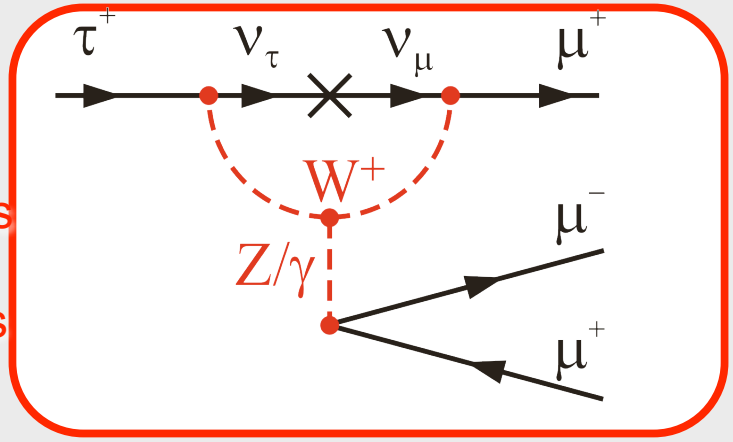
$\tau$ processes also suppressed in Standard Model but less:

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




SM ~ $10^{-40}$

Smaler GIM Cancellations because of large $\tau$ mass




SM ~ $10^{-14}$

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:
~$10^{10}$ $\tau/yr$ vs ~$10^{11}$ $\mu/sec$ in fixed-target experiments (Mu2e/COMET)

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

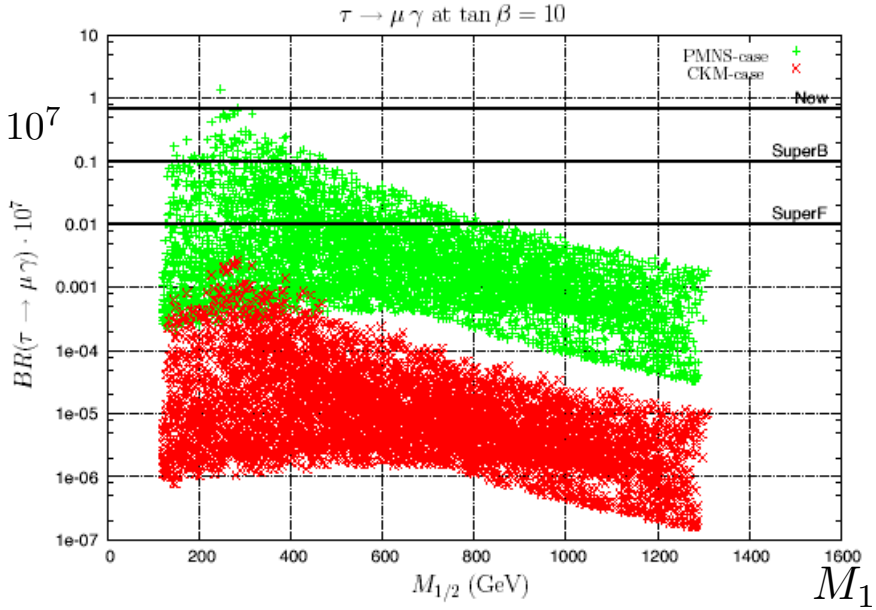
M. Gonderinger, M. Ramsey-Musolf, arXiv:1006.5063v1

# Supersymmetry in Tau LFV

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

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

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




$\tan\beta = 10$

$M_{1/2}$ (GeV)

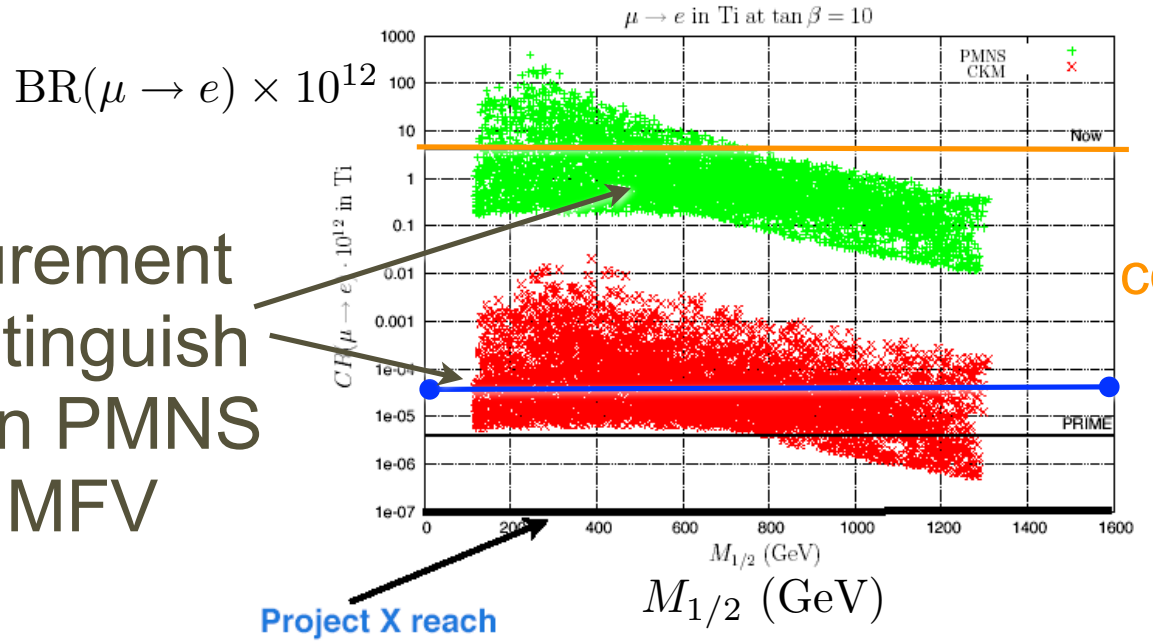
L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

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)




Current μe conversion

Mu2e

measurement can distinguish between PMNS and MFV

Project X reach

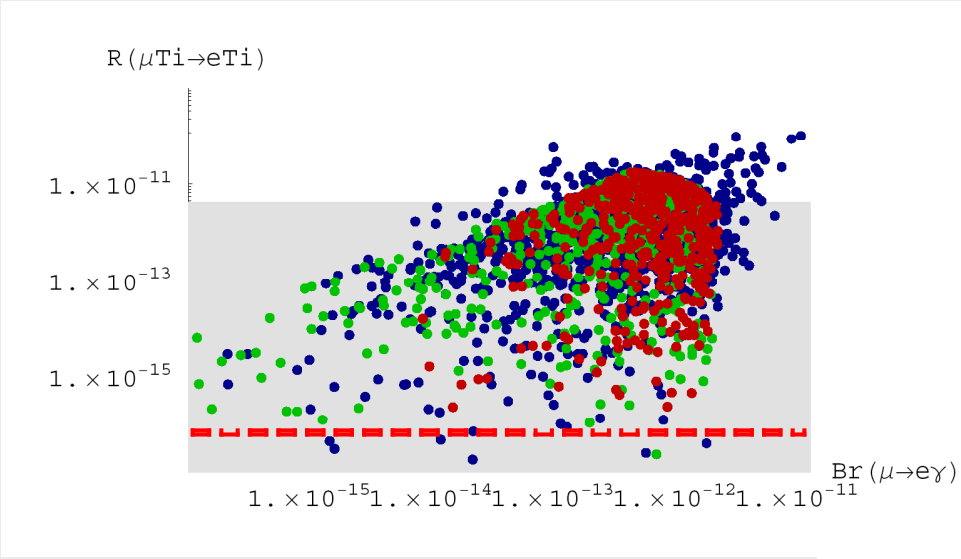
L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

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

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

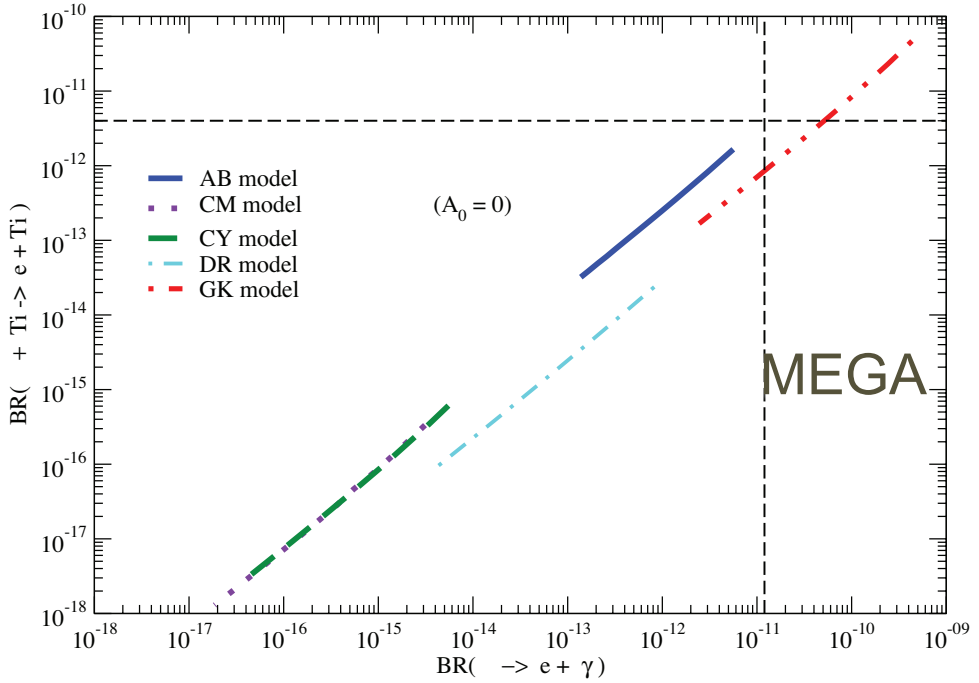
## Randall-Sundrum

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




## SO(10) models:

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



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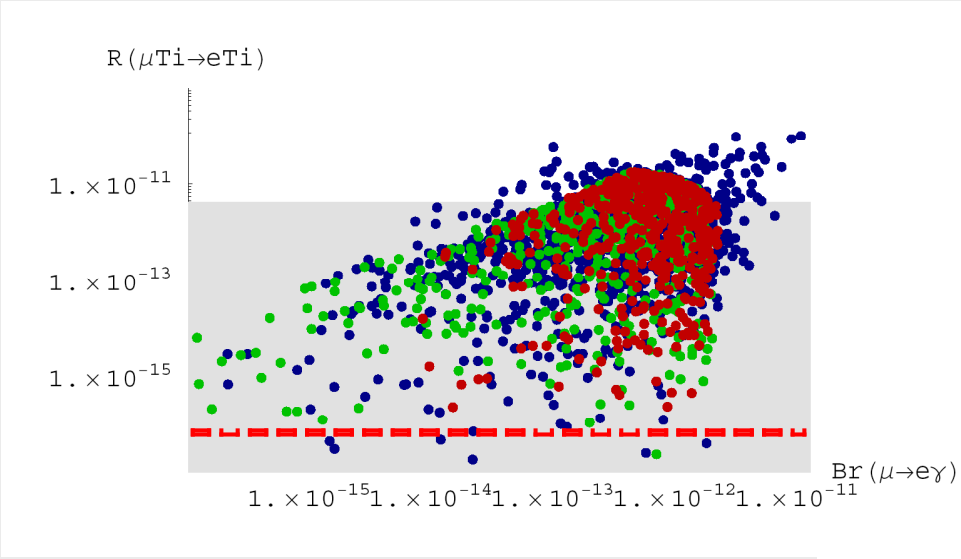


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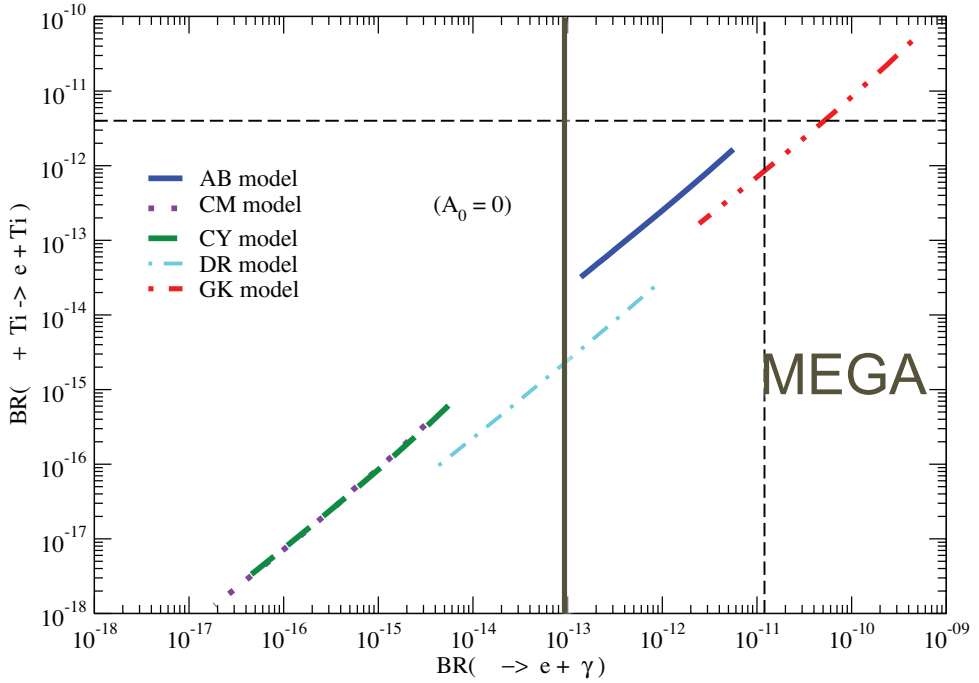
## MEG



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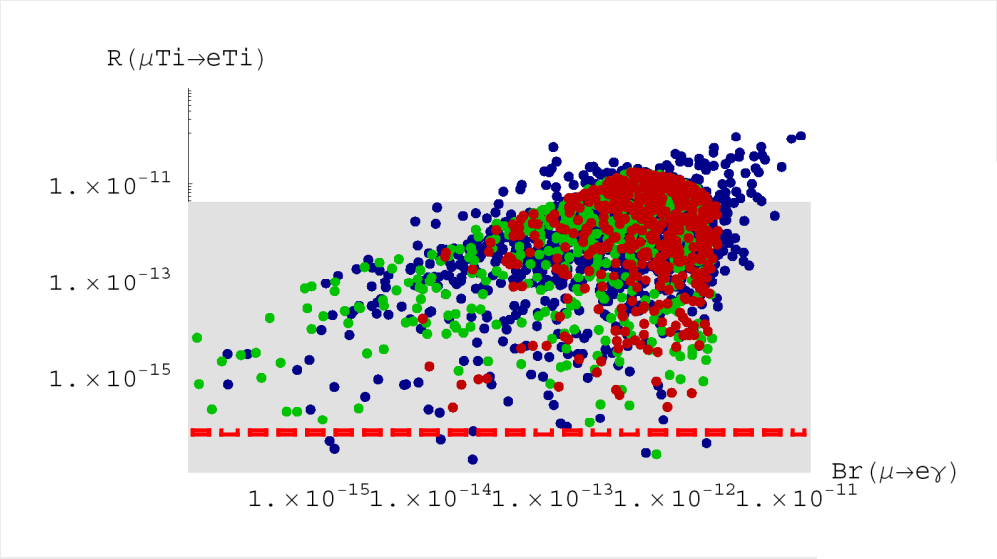


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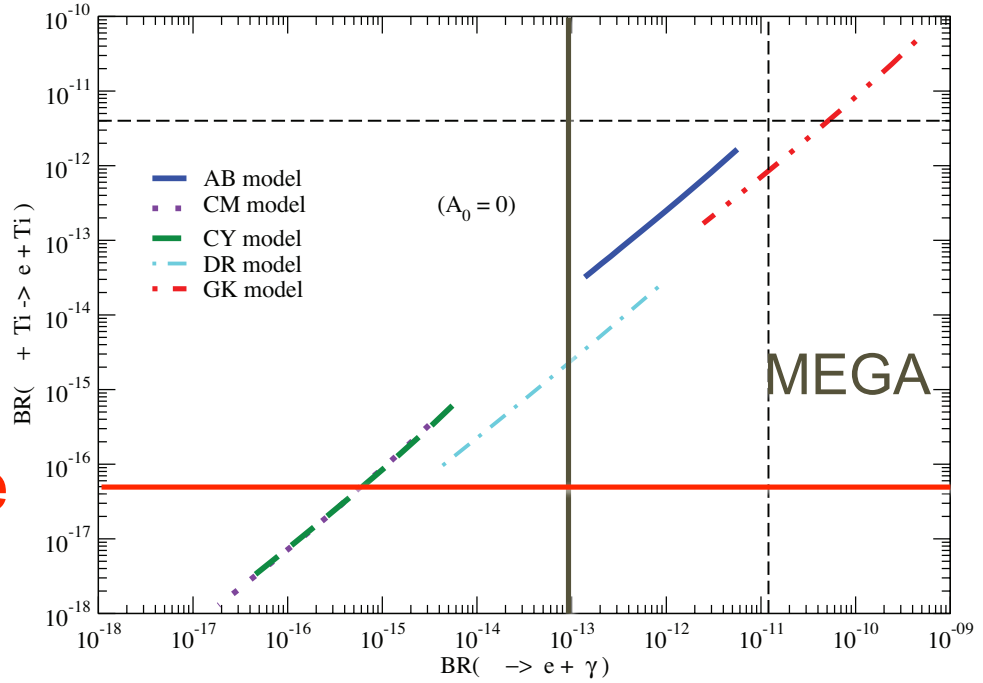
C. Albright and M. Chen, arXiv:0802.4228, PRD D77:113010, 2008.

Mu2e

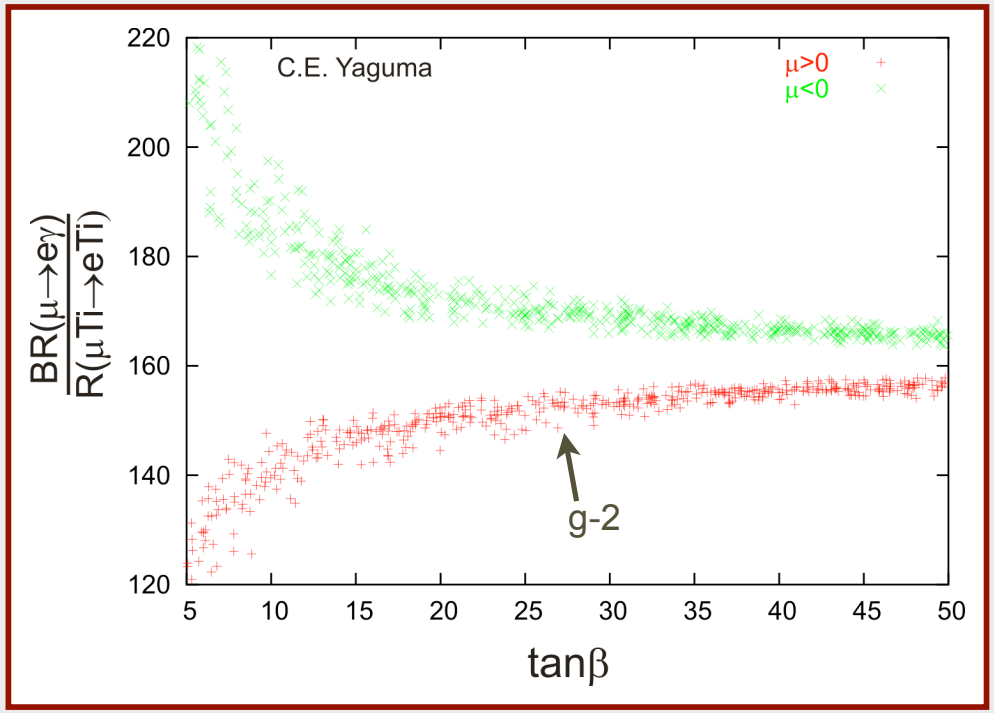
MEG

MEGA



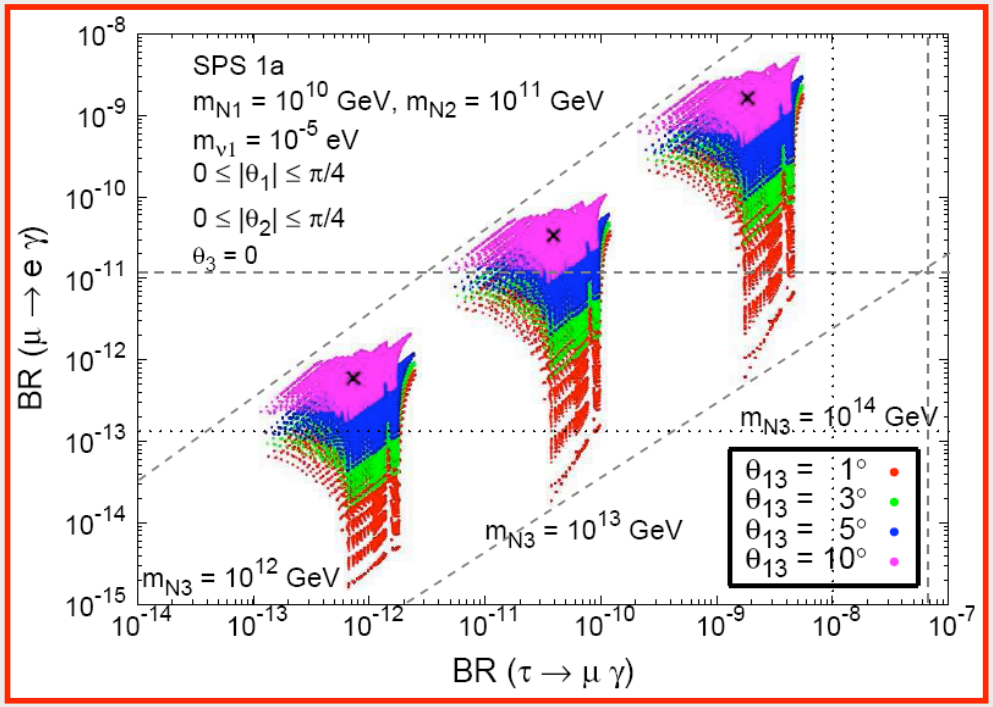
# Pinning Down SuperSymmetry

MSSM w mSUGRA




Yaguna, hep-ph/0502014v2

CMSSM - seesaw




Antusch et al.,hep-ph/0610439

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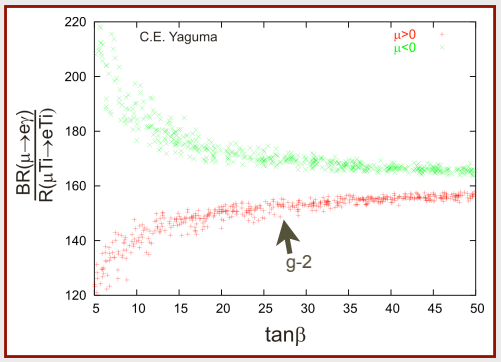


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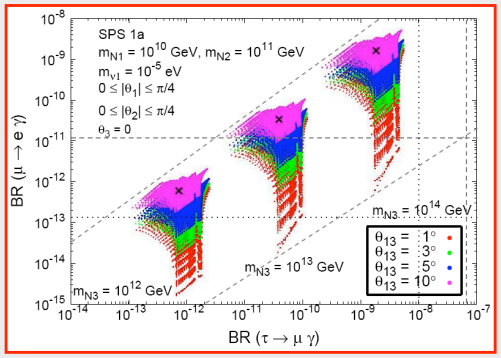



Antusch et al.,hep-ph/0610439

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

to allow discrimination among different models

# In SUSY

- Large effects in many models
  - only μ→eγ and μe conversion

★ ★ ★

| | AC | RVV2 | AKM | δLL | FBMSSM | LHT | RS |
|---|---|---|---|---|---|---|---|
| $D^0 - \bar{D}^0$ | ★★★ | ★ | ★ | ★ | ★ | ★★★ | ? |
| $\epsilon_K$ | ★ | ★★★ | ★★★ | ★ | ★ | ★★ | ★★★ |
| $S_{\psi\phi}$ | ★★★ | ★★★ | ★★★ | ★ | ★ | ★★★ | ★★★ |
| $S_{\phi K_S}$ | ★★★ | ★★ | ★ | ★★★ | ★★★ | ★ | ? |
| $A_{\rm CP}(B \to X_s\gamma)$ | ★ | ★ | ★ | ★★★ | ★★★ | ★ | ? |
| $A_{7,8}(B \to K^*\mu^+\mu^-)$ | ★ | ★ | ★ | ★★★ | ★★★ | ★★ | ? |
| $A_9(B \to K^*\mu^+\mu^-)$ | ★ | ★ | ★ | ★ | ★ | ★ | ? |
| $B \to K^{(*)}\nu\bar{\nu}$ | ★ | ★ | ★ | ★ | ★ | ★ | ★ |
| $B_s \to \mu^+\mu^-$ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★ | ★ |
| $K^+ \to \pi^+\nu\bar{\nu}$ | ★ | ★ | ★ | ★ | ★ | ★★★ | ★★★ |
| $K_L \to \pi^0\nu\bar{\nu}$ | ★ | ★ | ★ | ★ | ★ | ★★★ | ★★★ |
| $\mu \to e\gamma$ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| $\tau \to \mu\gamma$ | ★★★ | ★★★ | ★ | ★★★ | ★★★ | ★★★ | ★★★ |
| $\mu + N \to e + N$ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| $d_n$ | ★★★ | ★★★ | ★★★ | ★★ | ★★★ | ★ | ★★★ |
| $d_e$ | ★★★ | ★★★ | ★★ | ★ | ★★★ | ★ | ★★★ |
| $(g-2)_\mu$ | ★★★ | ★★★ | ★★ | ★★★ | ★★★ | ★ | ? |

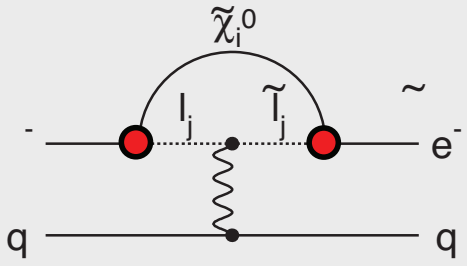
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

W. Altmanshofer et al., arXiv:0909.1333v2 [hep-ph] 26 Jan 2010

# Contributions to μe Conversion

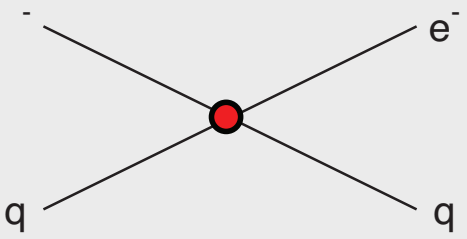
## Supersymmetry

rate ~ $10^{-15}$



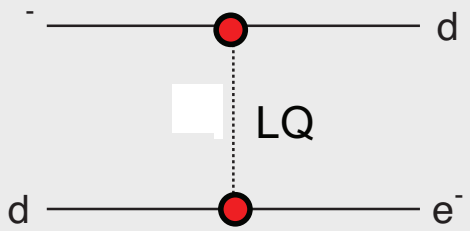

## Compositeness

$\Lambda_c$ ~ 3000 TeV



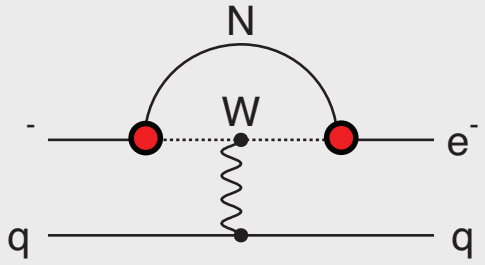

## Leptoquark

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



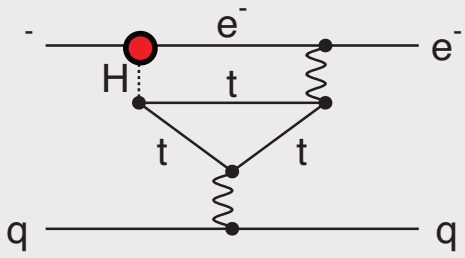

## Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ $8\times10^{-13}$



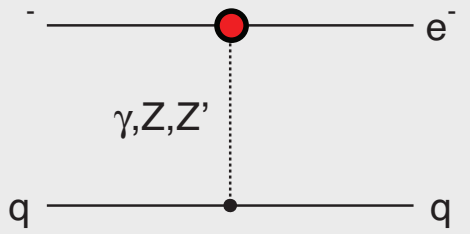

## Second Higgs Doublet

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




## Heavy Z' Anomal. Z Coupling

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




also see Flavour physics of leptons and dipole moments, arXiv:0801.1826 ;
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:10.1146/annurev.nucl.58.110707.171126 ;

# "Model-Independent" Form

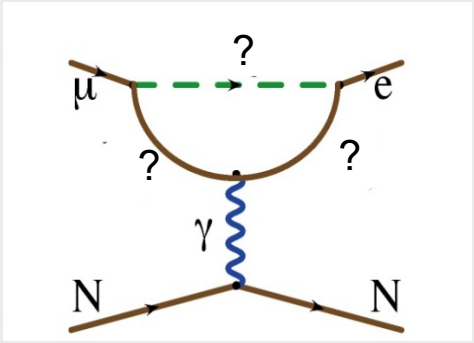
$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

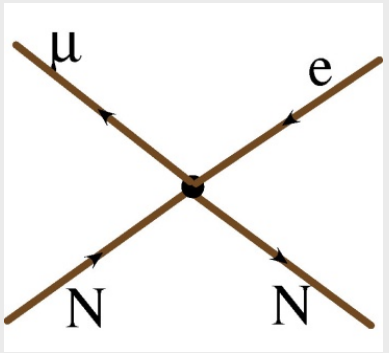
**"Loops"** **"Contact Terms"**

mass scale $\Lambda$

$\kappa$

$\kappa=0$ $\kappa=1$




Supersymmetry and Heavy Neutrinos

Contributes to $\mu \to e\gamma$

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

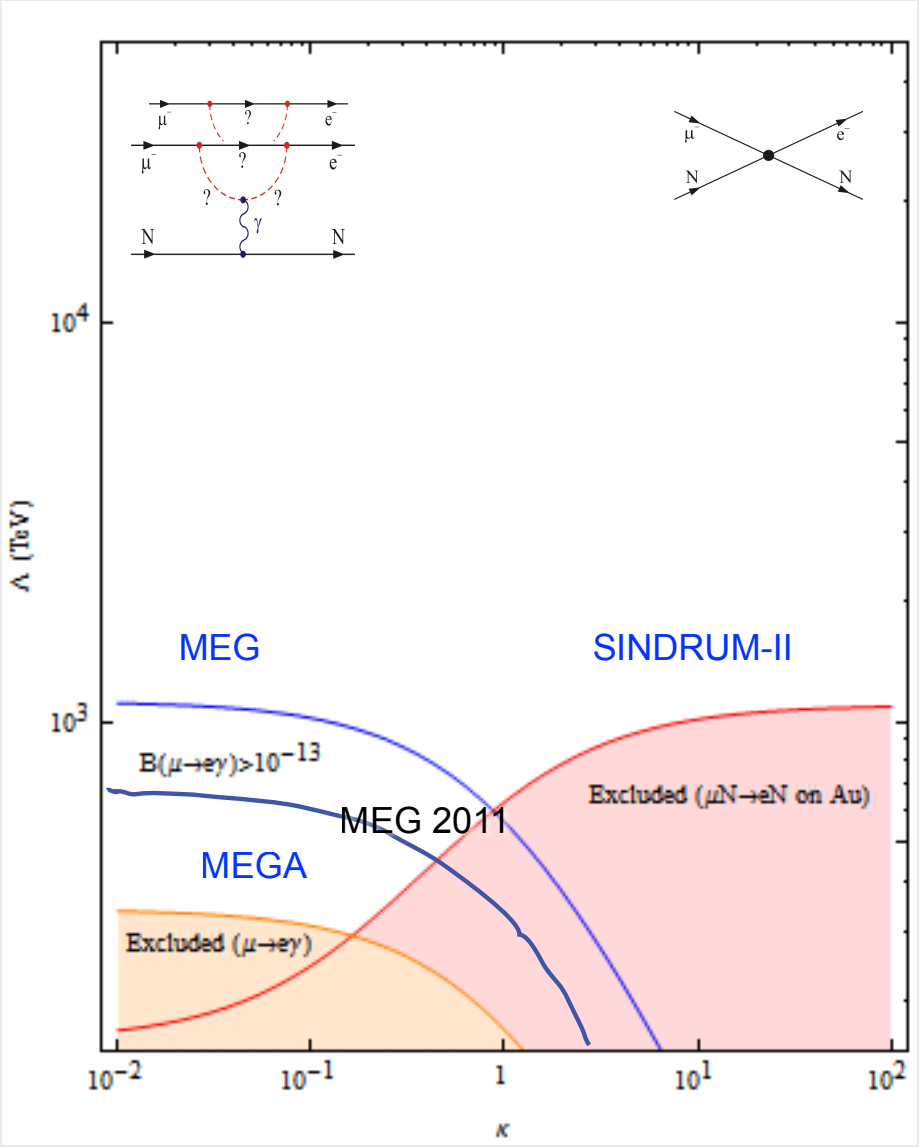
Quantitative Comparison?

# μe Conversion and μ→eγ

$\Lambda$ (TeV)

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

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




higher mass scale

$\kappa$

André de Gouvêa, Project X Workshop Golden Book

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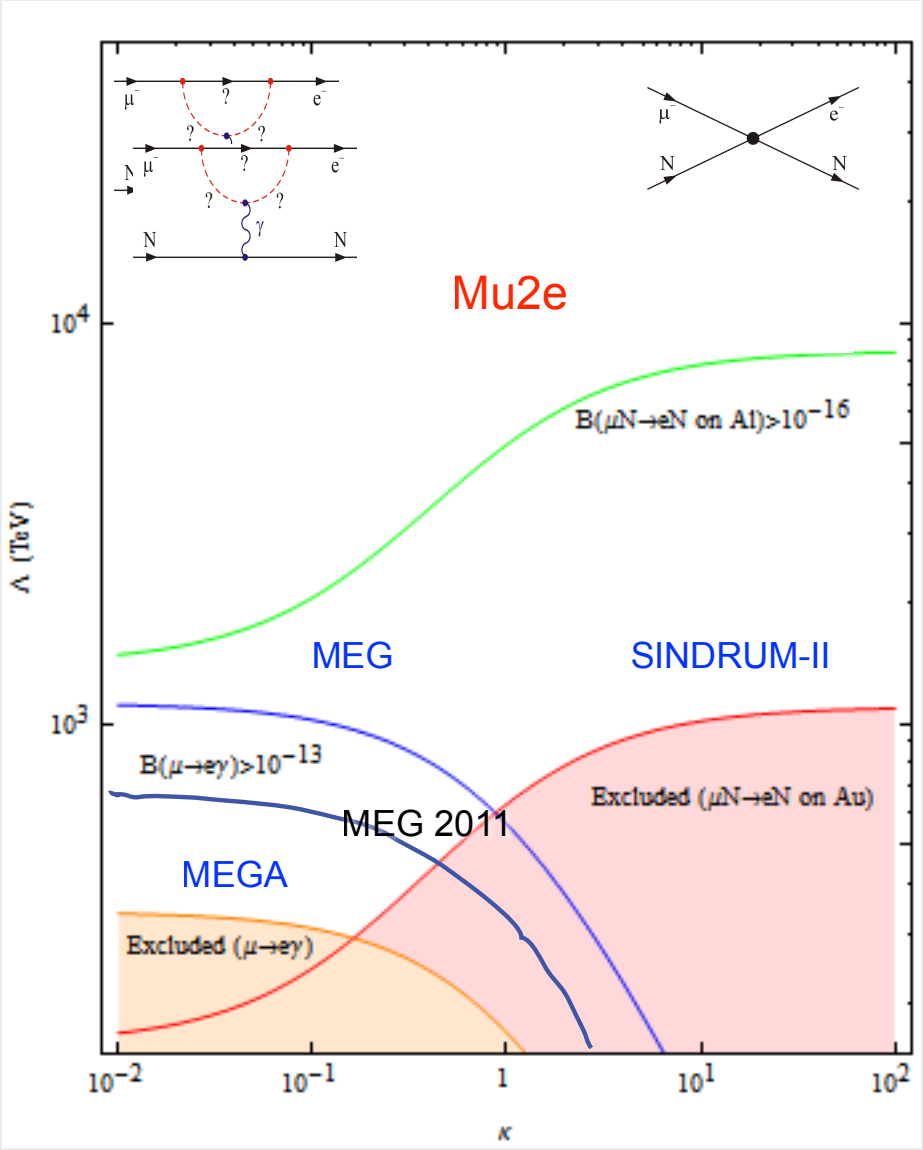


higher mass scale

$\kappa$

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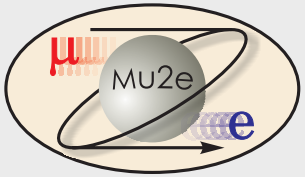
# μe Conversion and μ→eγ

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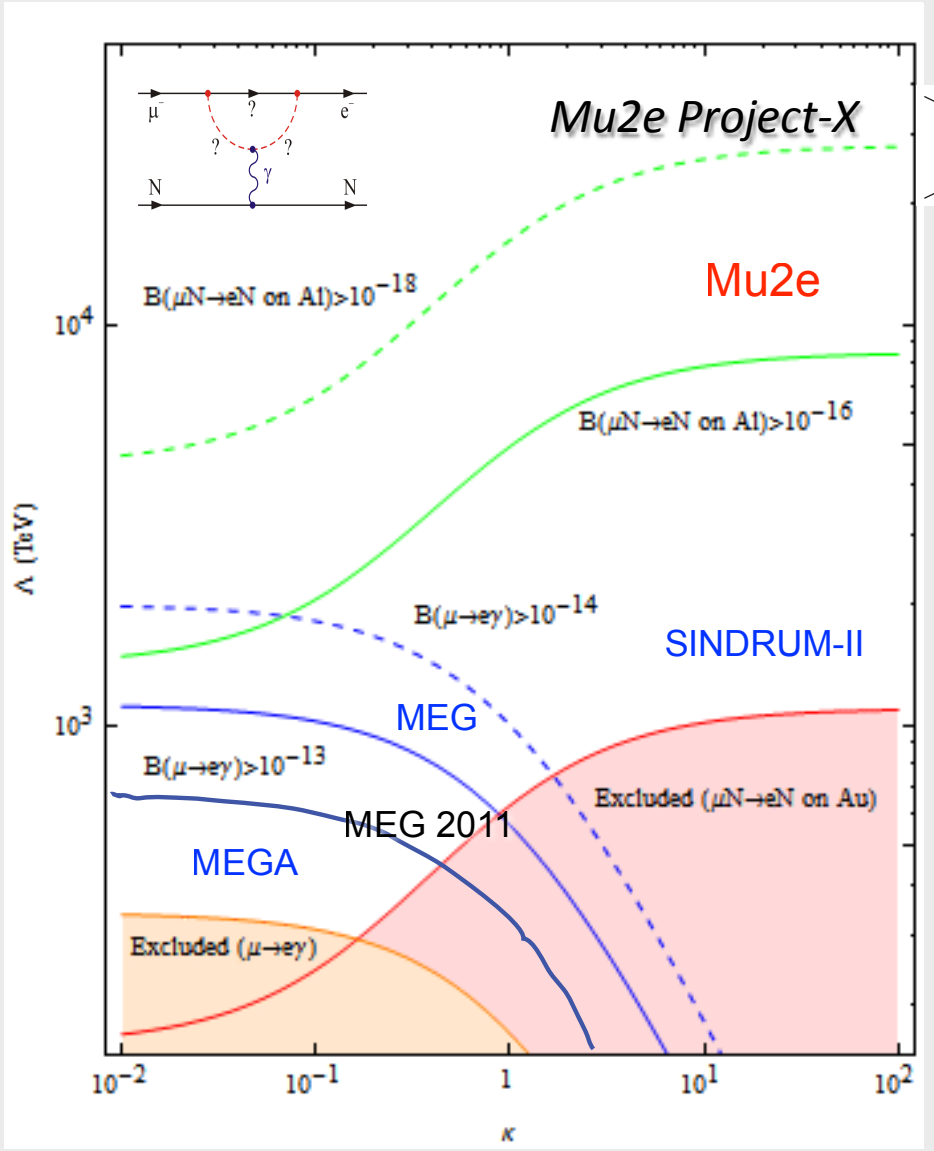
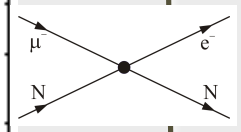



higher mass scale

$\kappa$

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

$\mu^-$ stops in thin Al foil

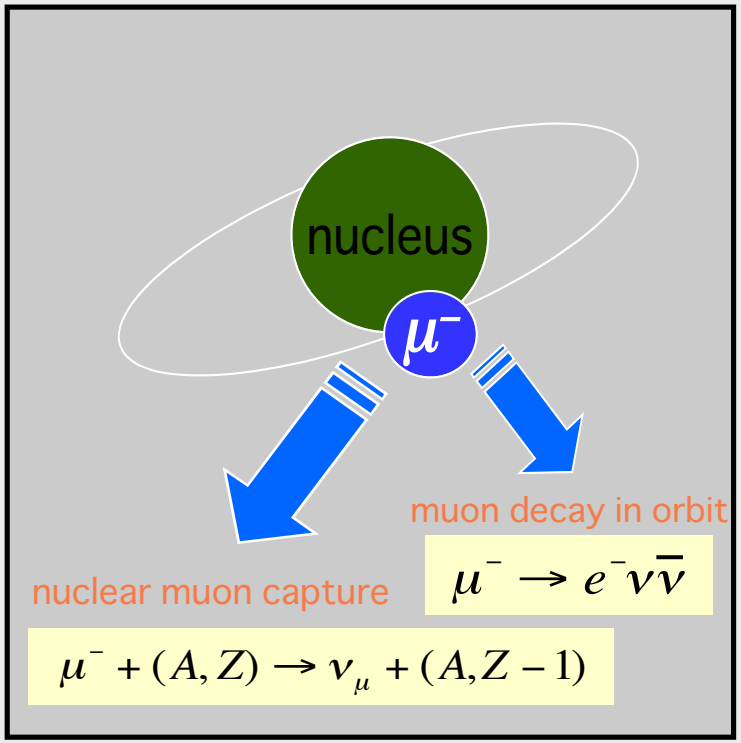


*the Bohr radius is ~ 20 fm, so the $\mu^-$ sees the nucleus*

$\mu^-$ in 1s state



Al Nucleus
~4 fm

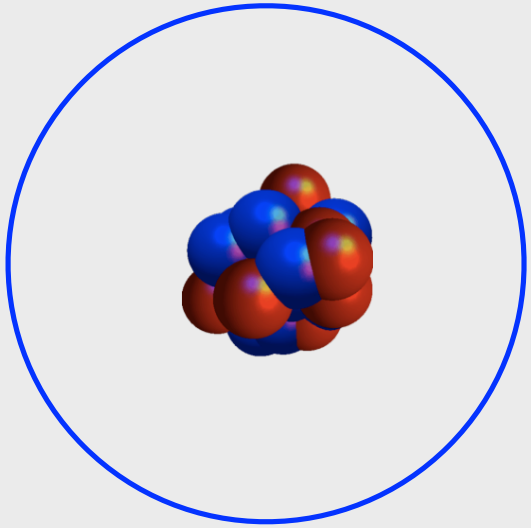



60% capture
40% decay

muon capture, muon "falls into" nucleus:
***normalization***

Decay in Orbit:
***background***

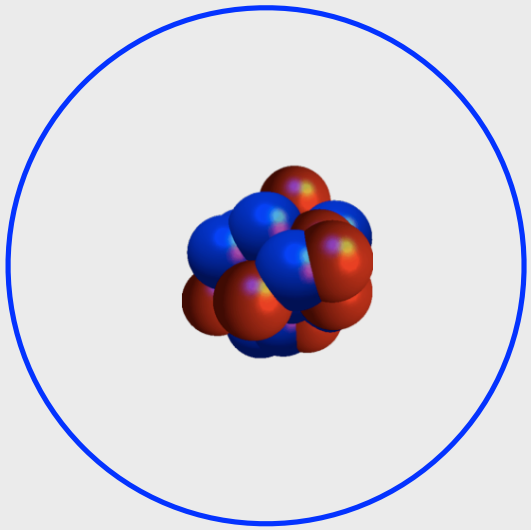
# Three Possibilities: Normalization



# Three Possibilities: Normalization

muon stops



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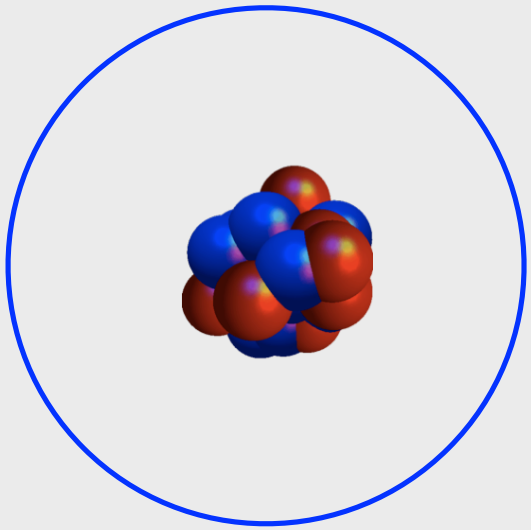

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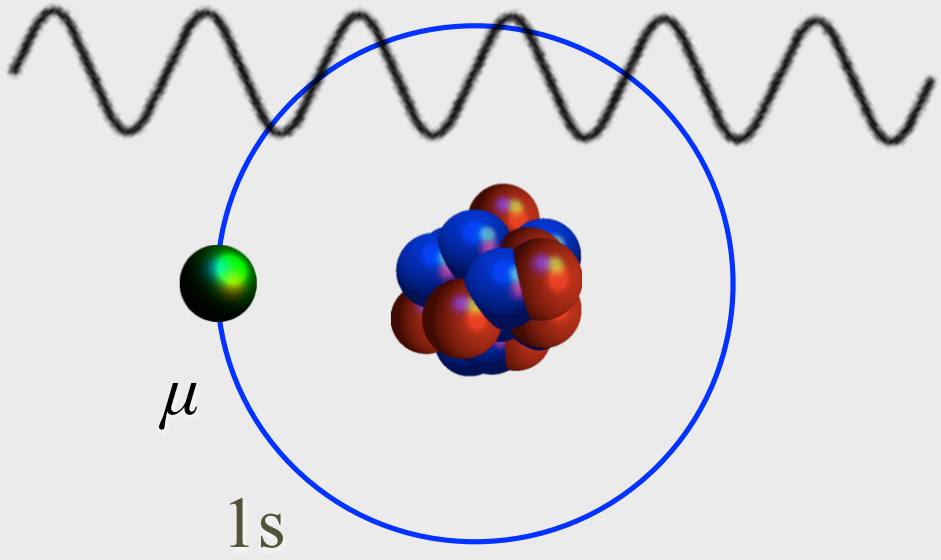
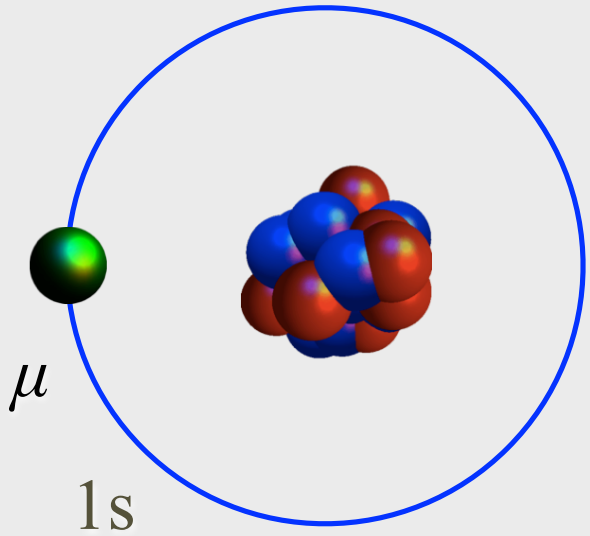


# Three Possibilities: Normalization

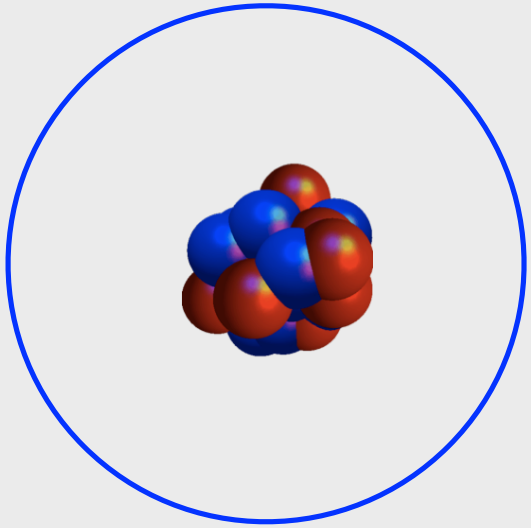
X-Rays from cascade (occurs in <psec)




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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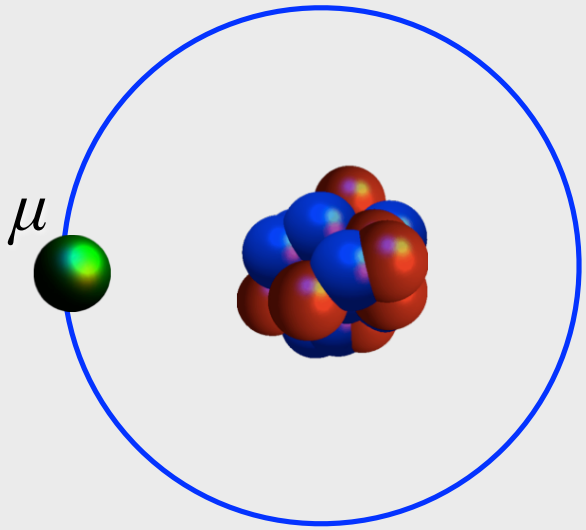

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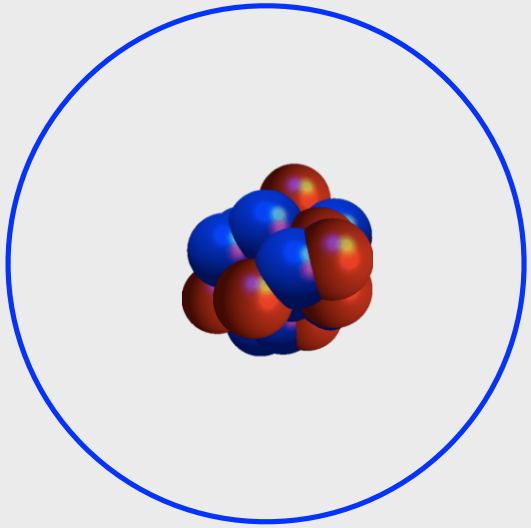

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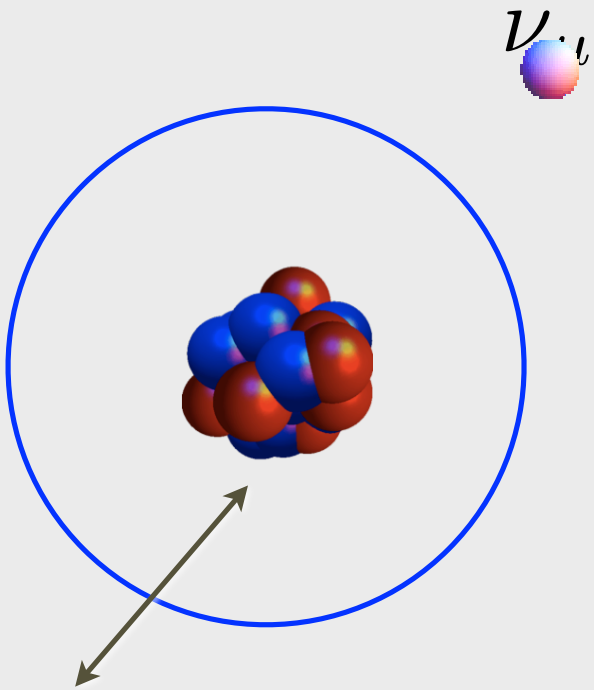
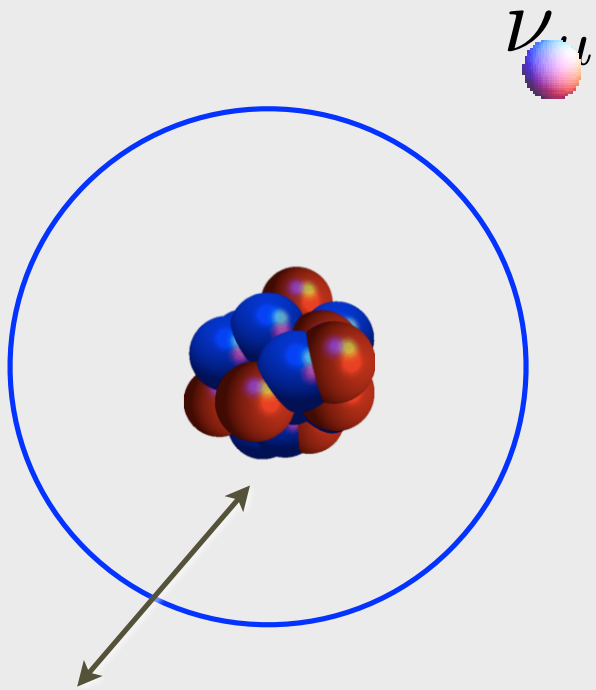



$$\mathrm{Al}(27,13) \rightarrow \mathrm{Mg}(27,12)$$

# Normalization to Nuclear Capture

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

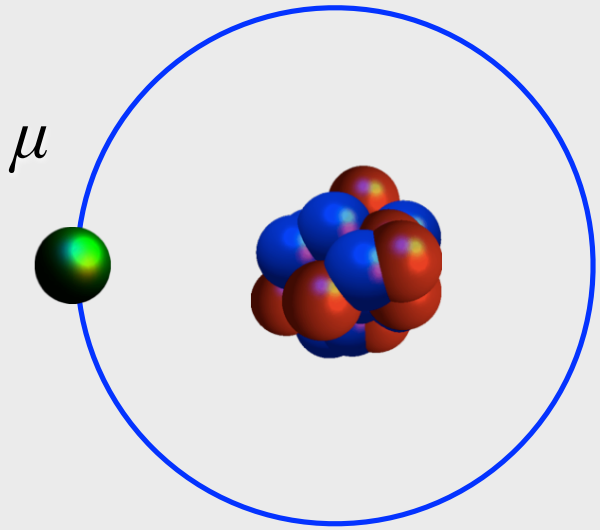
Kitano et al. ,Phys.Rev.D66:096002,2002, Erratum-ibid.D76:059902,2007. e-Print: hep-ph/0203110



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

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

# Three Possibilities: Signal



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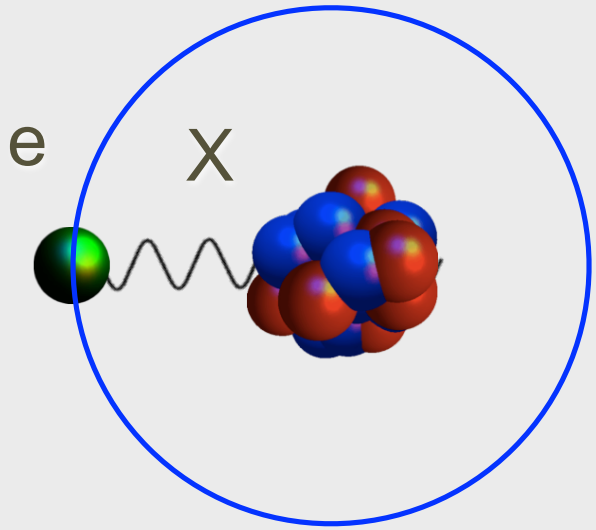
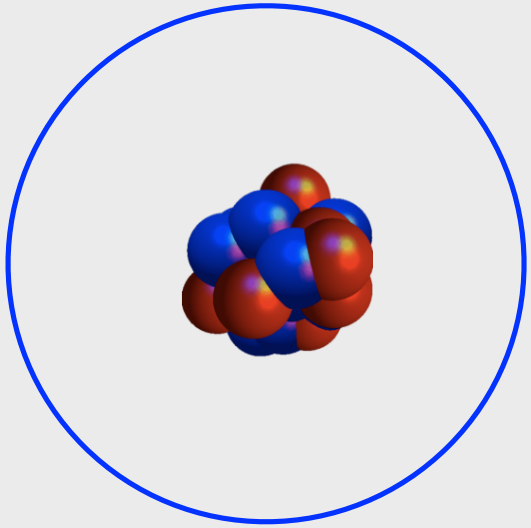


# Three Possibilities: Signal

e

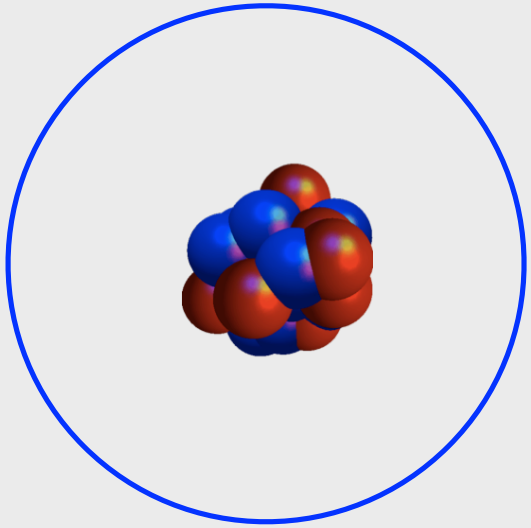




# Three Possibilities: Signal

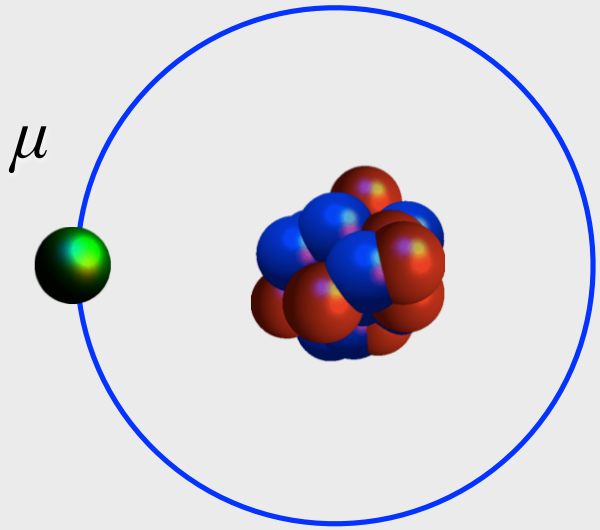
e *off to detector!*





coherent recoil of nucleus

# Three Possibilities: Background



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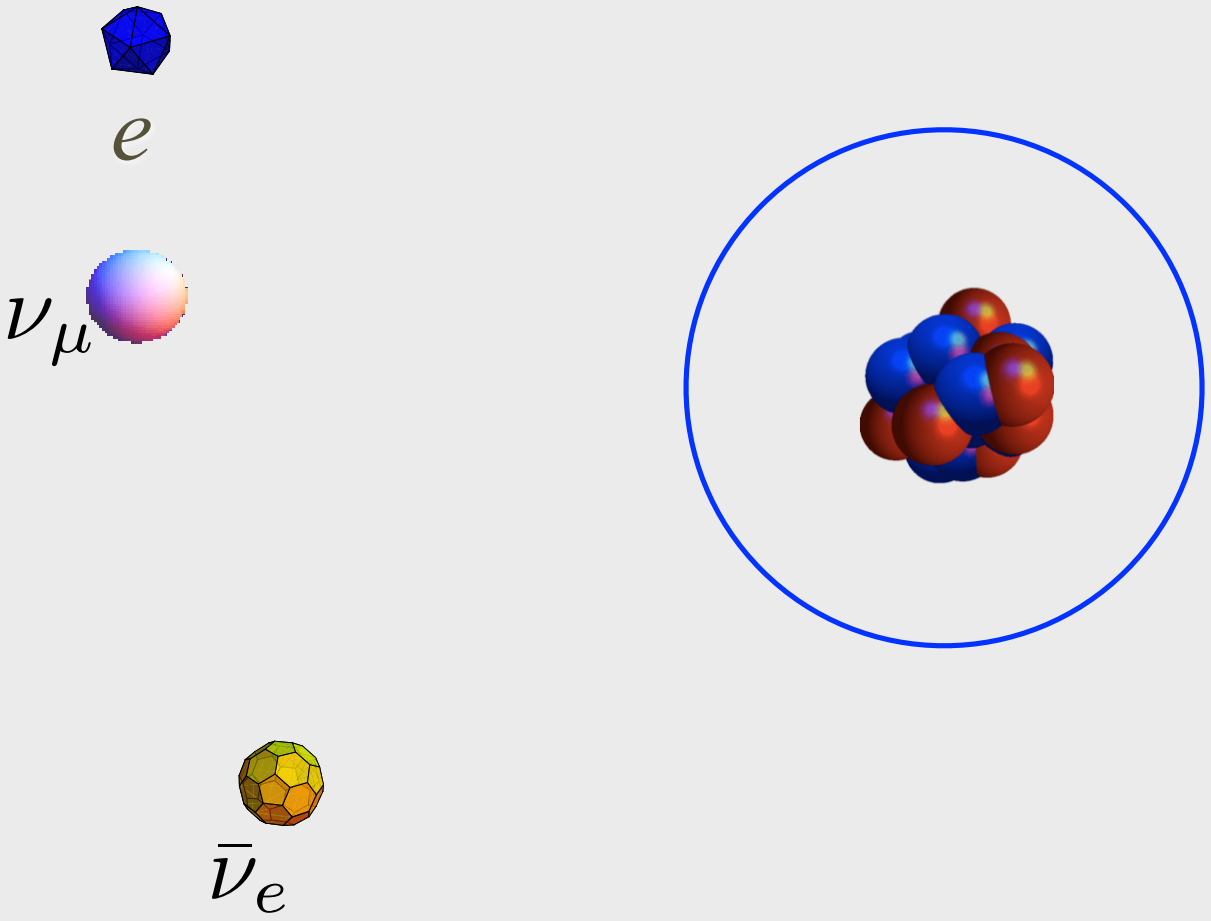


# Three Possibilities: Background

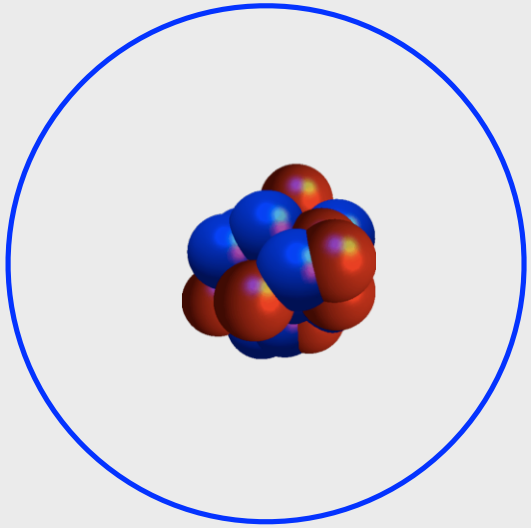
this electron can be background;
let's see how



$e$



$\nu_\mu$





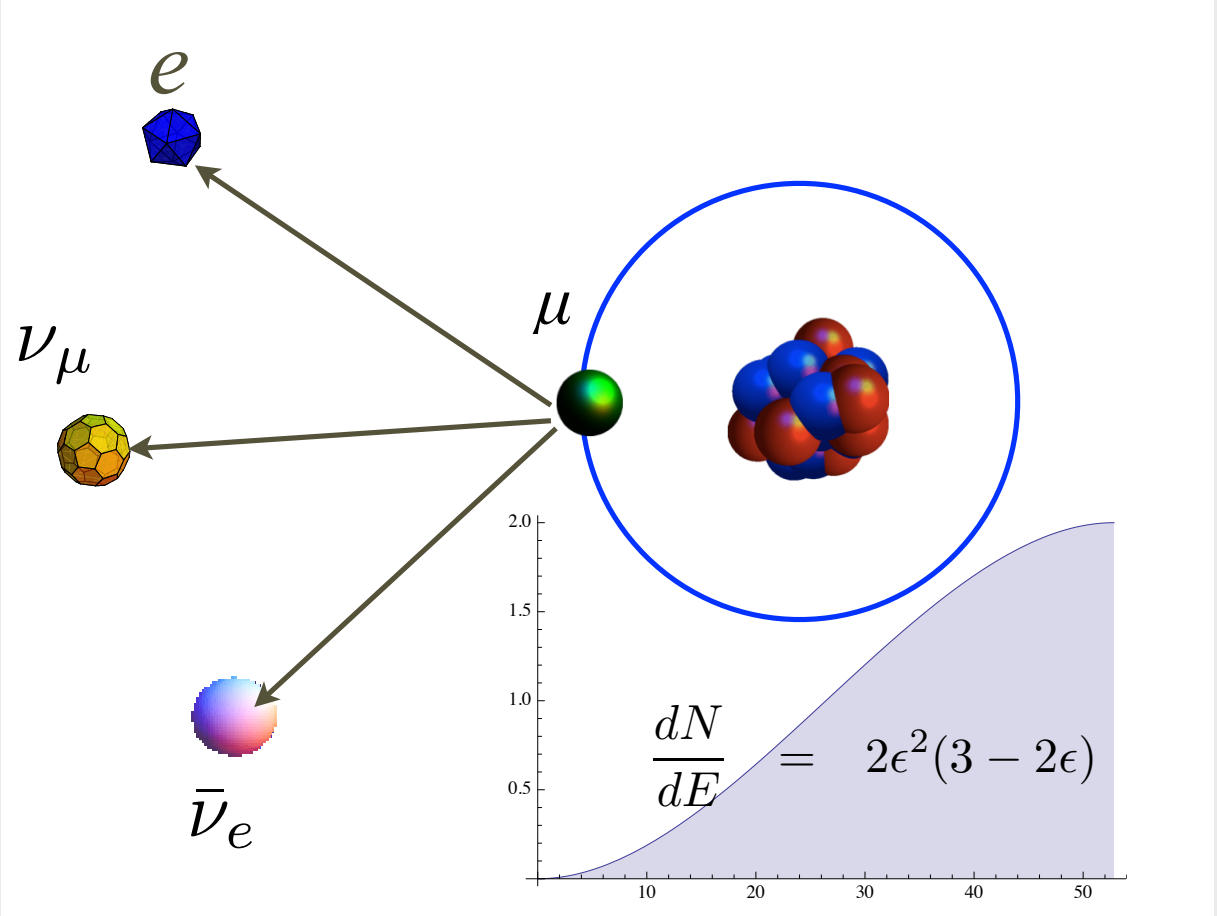
$\bar{\nu}_e$

# 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 MeV>>52.8 MeV



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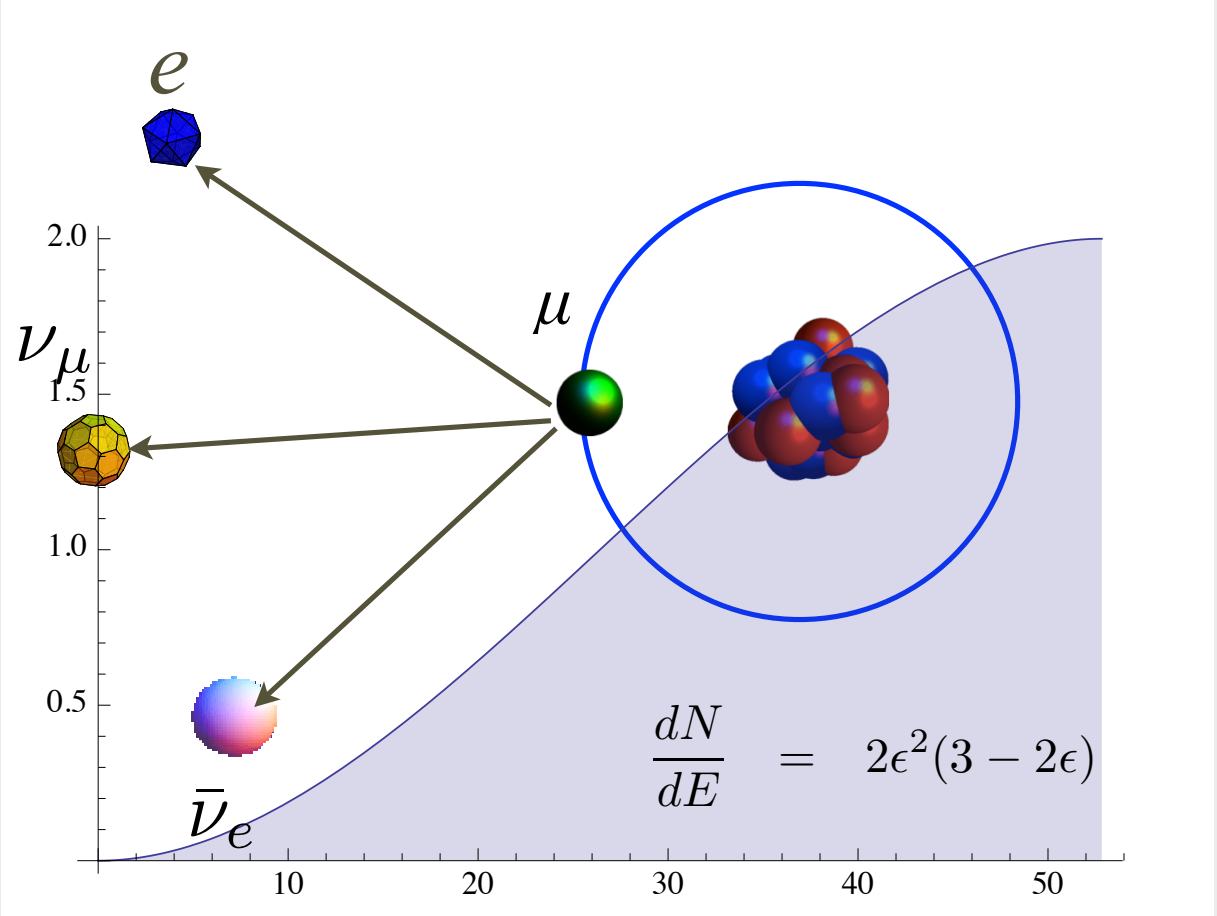
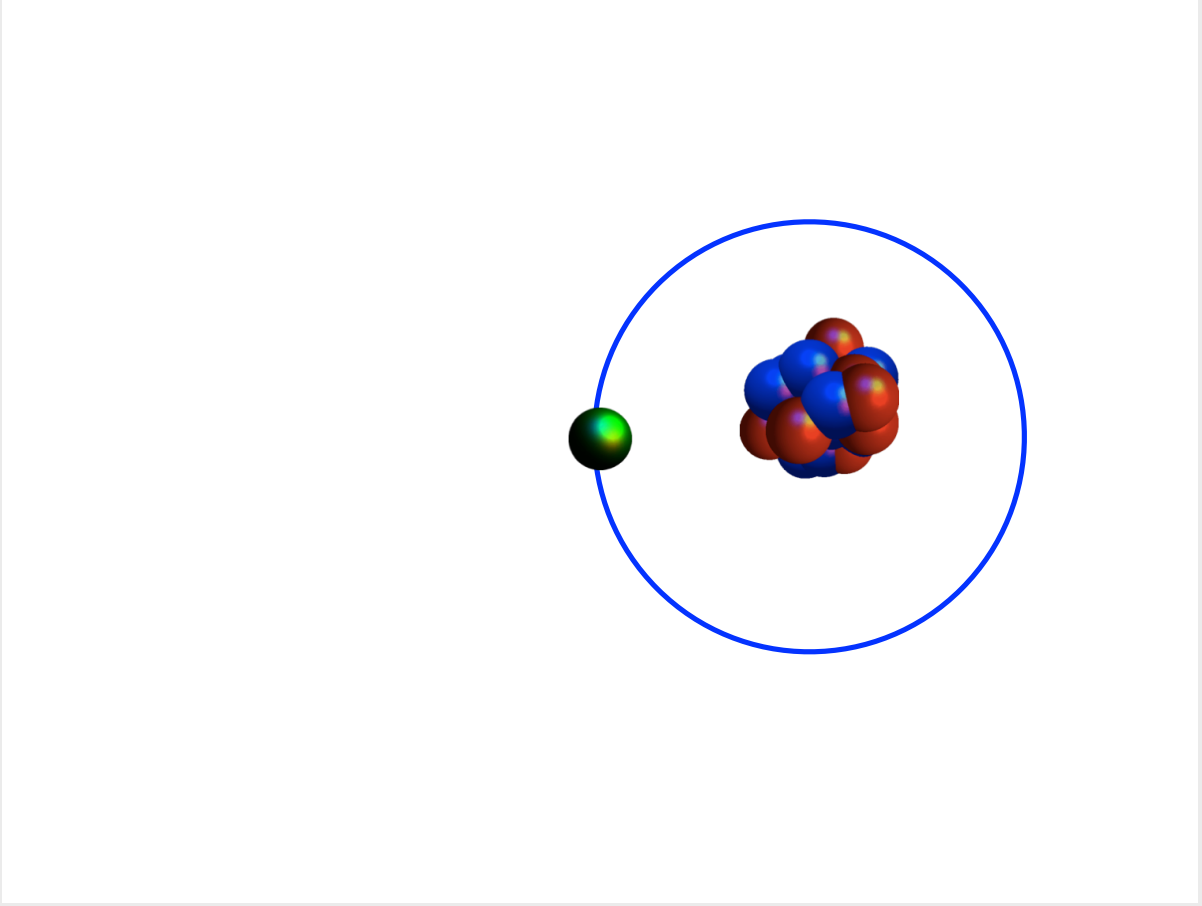


# Decay-In-Orbit Background

- 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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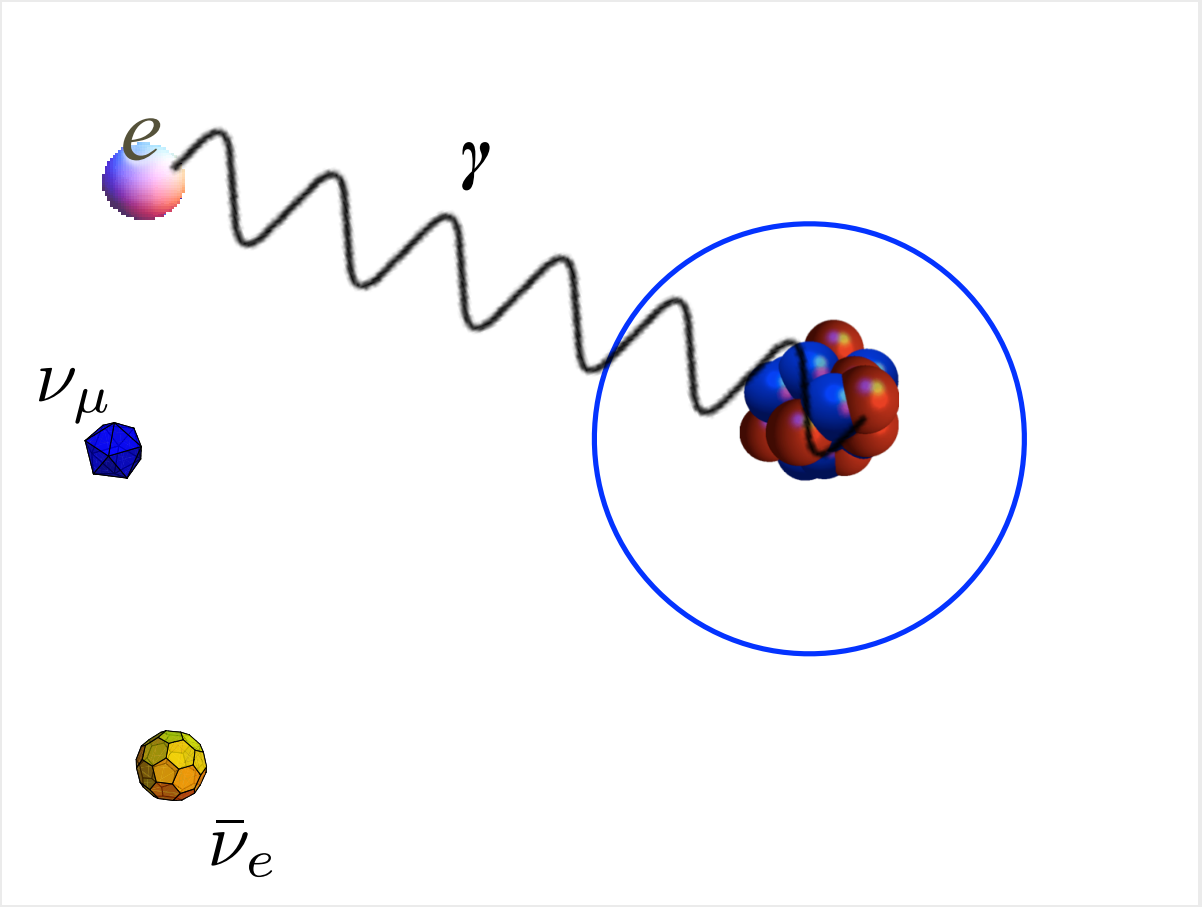

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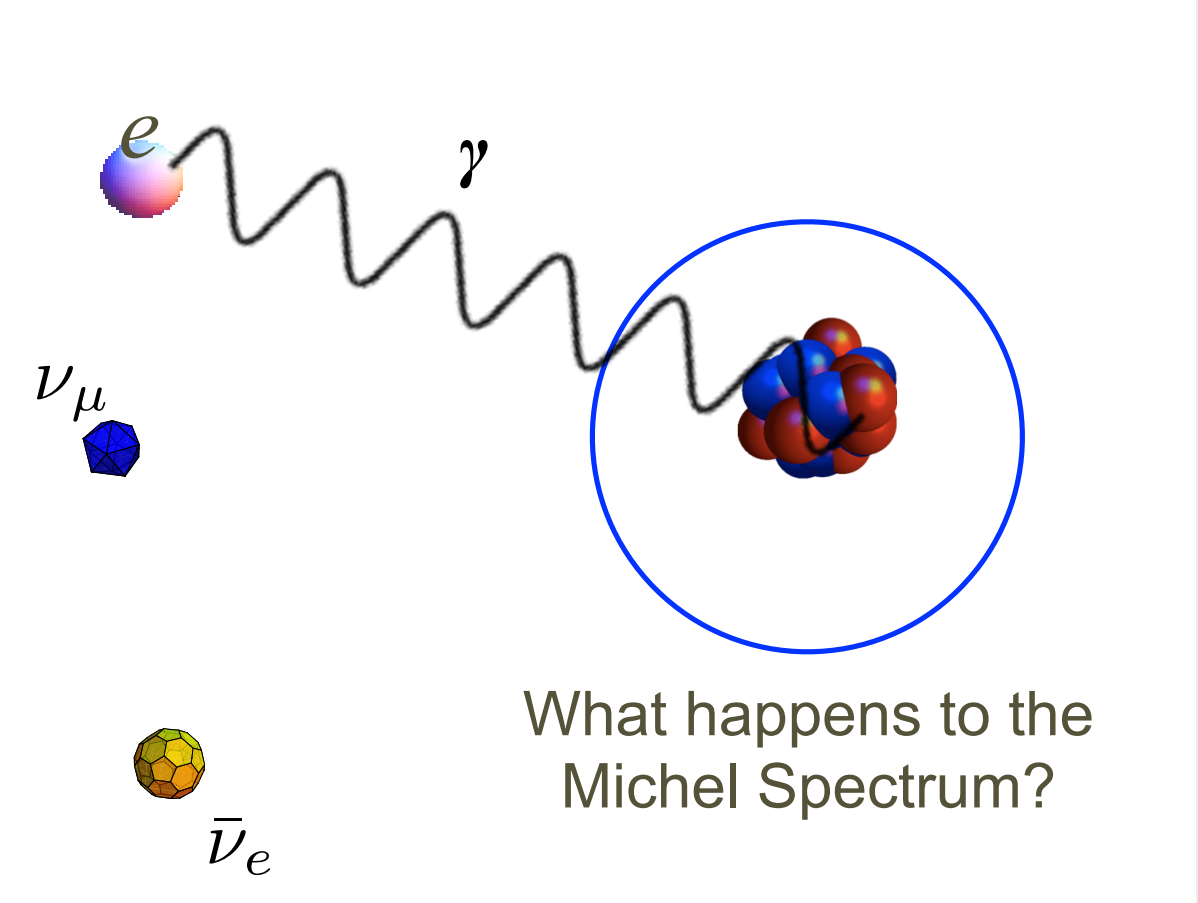
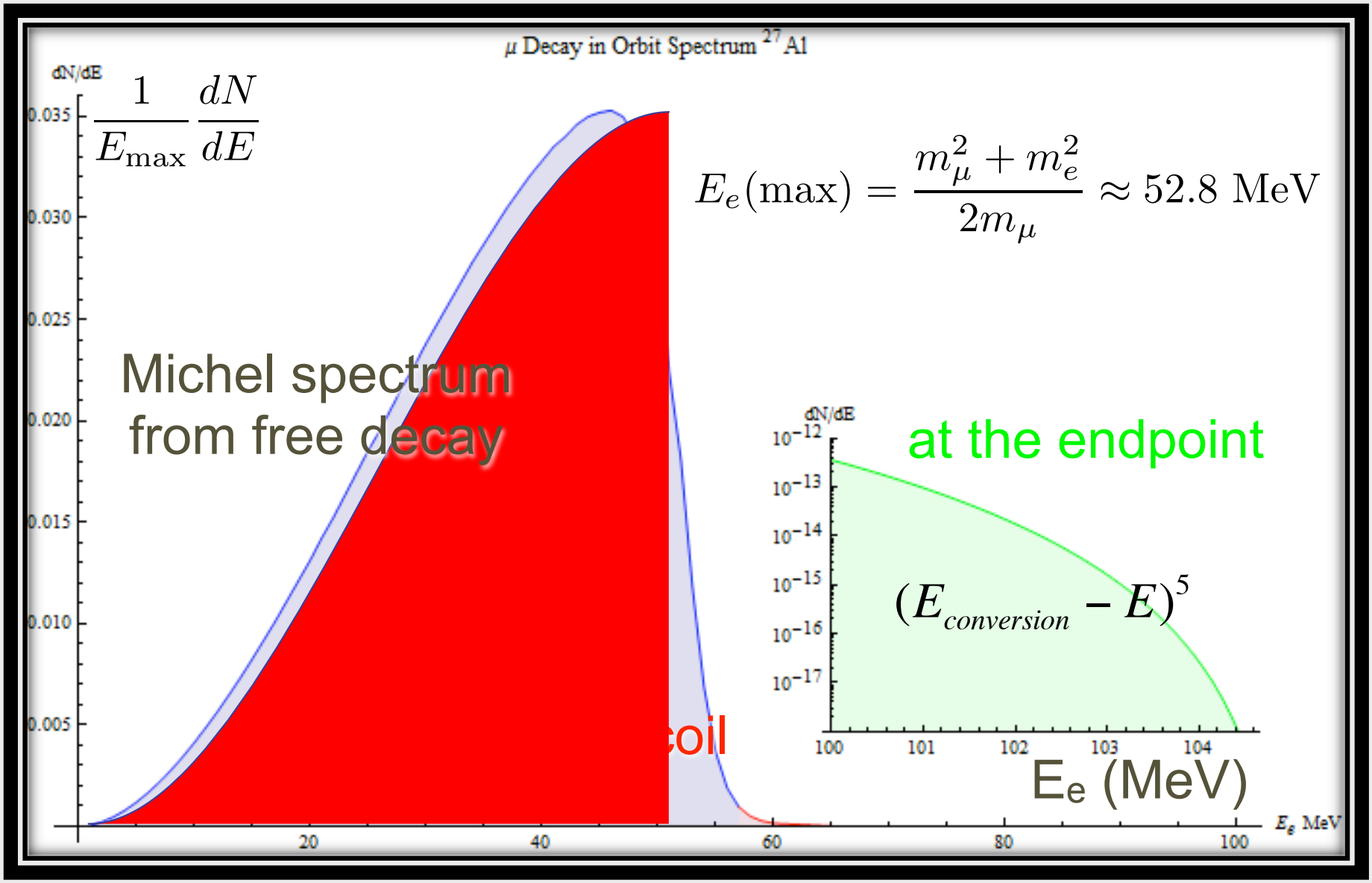


# Decay-in-Orbit Shape

Czarnecki et al., arXiv:1106.4756v2 [hep-ph] Phys. Rev. D 84, 013006 (2011)



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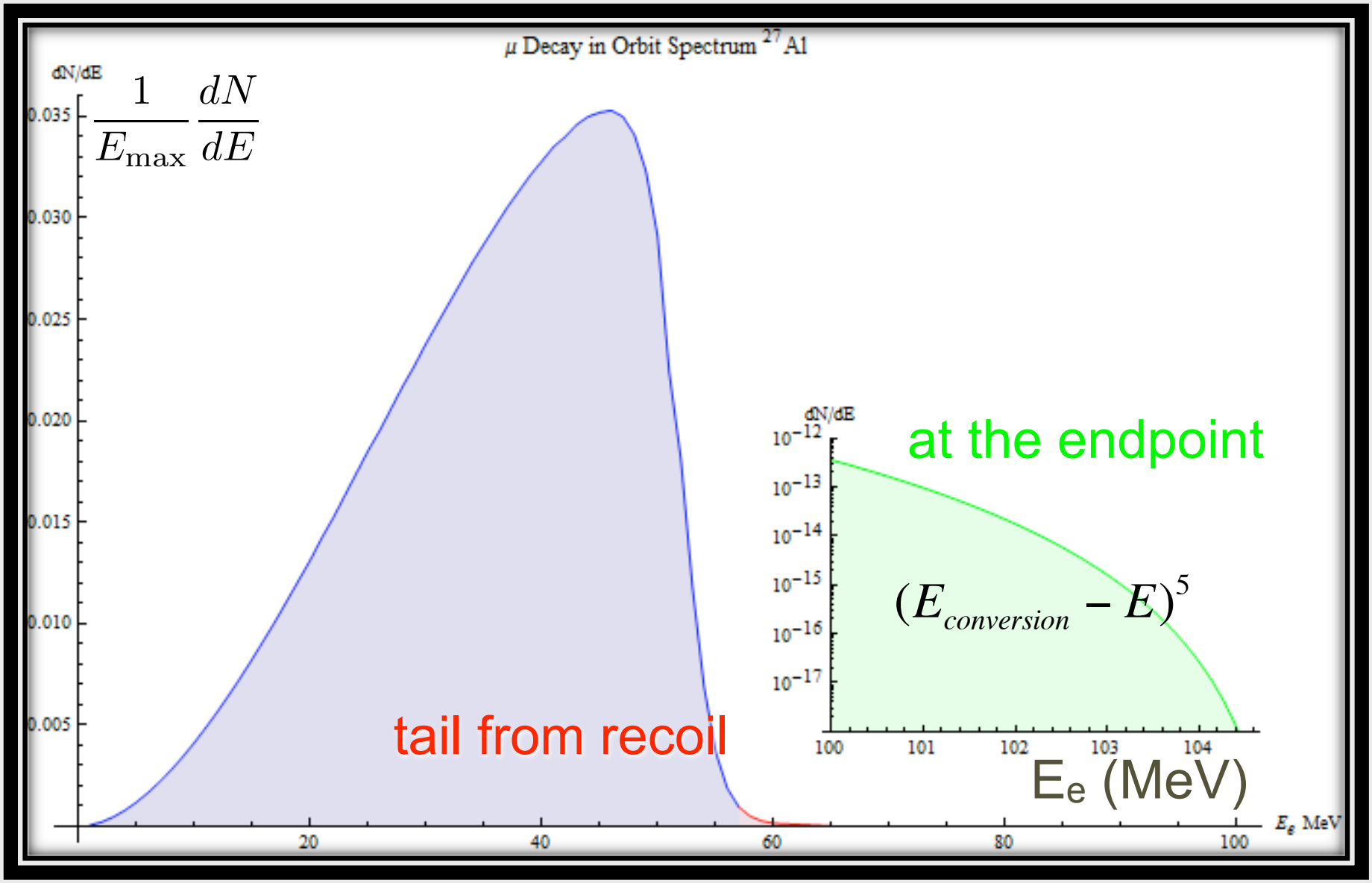
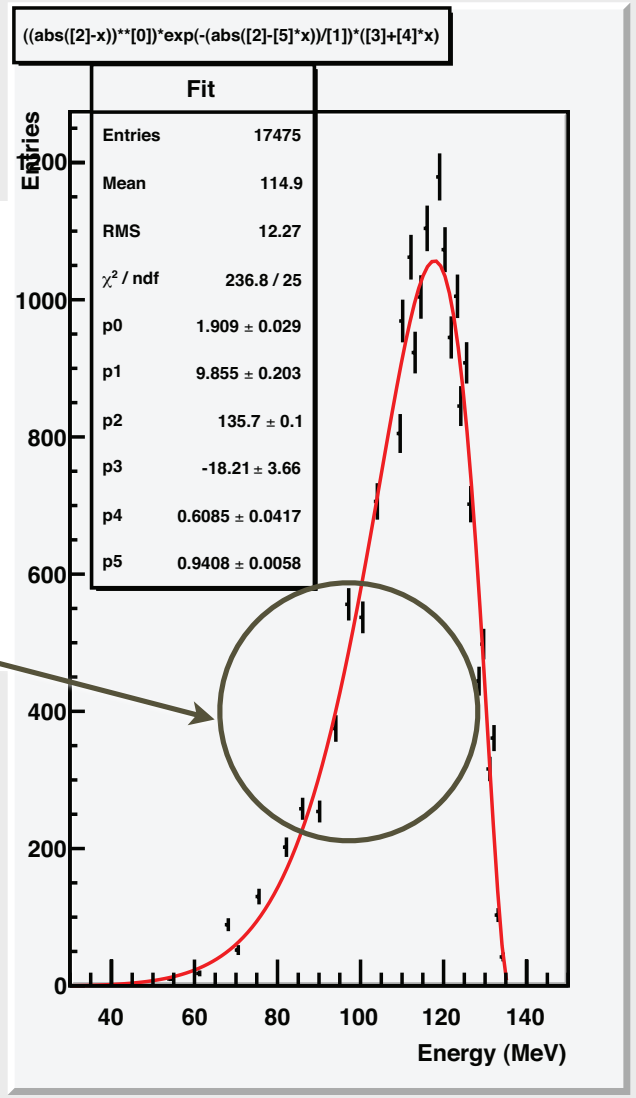


# Prompt Backgrounds

***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 ~ 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, $\pi^- N \rightarrow e^+ e^- X$

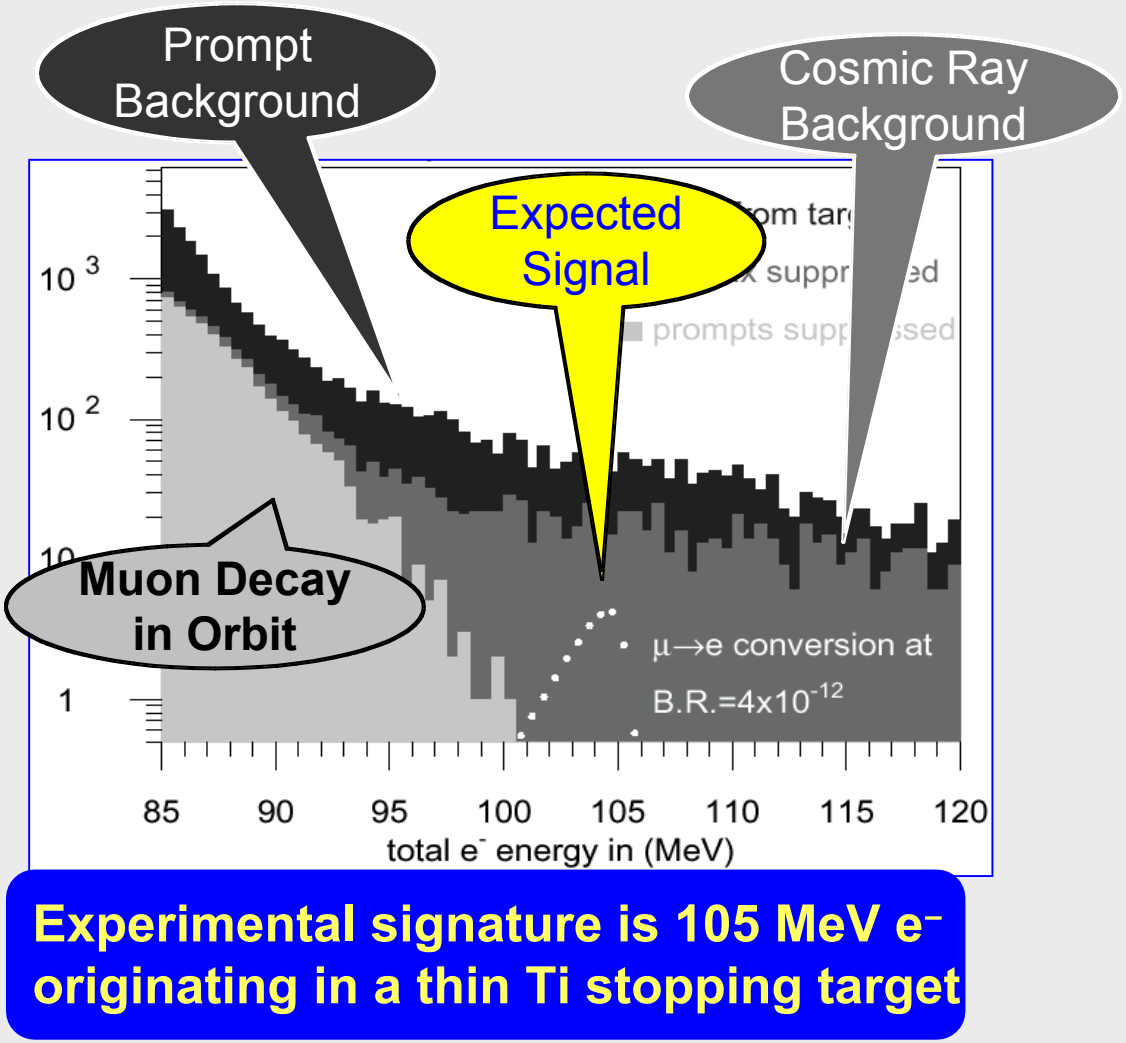
# Review:
# Two Classes of Backgrounds

| | 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

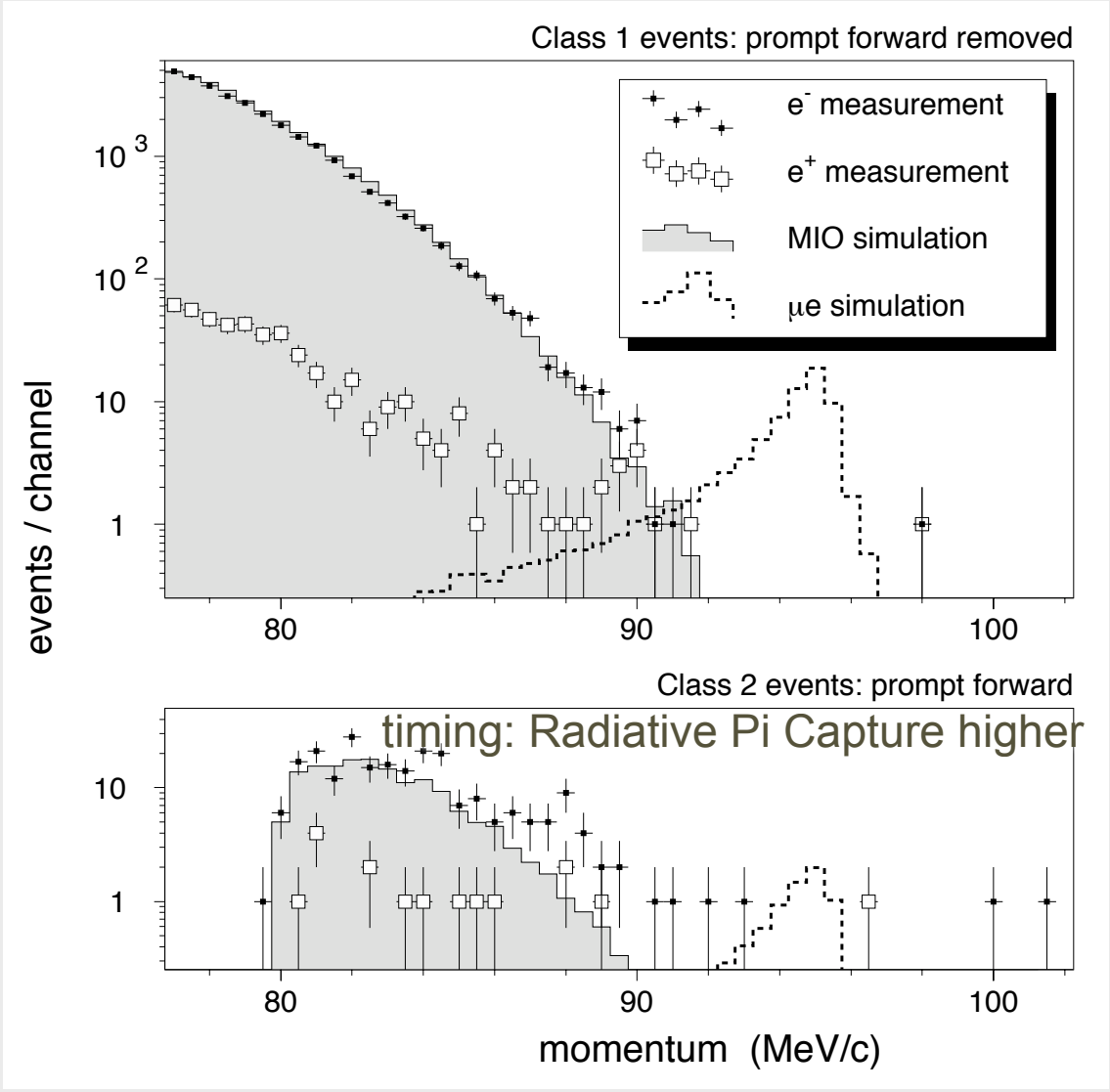
- Final Results on Au:

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

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

little time separation between signal and prompt background

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



# How Can We Do Better?

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

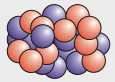
***Requiring***

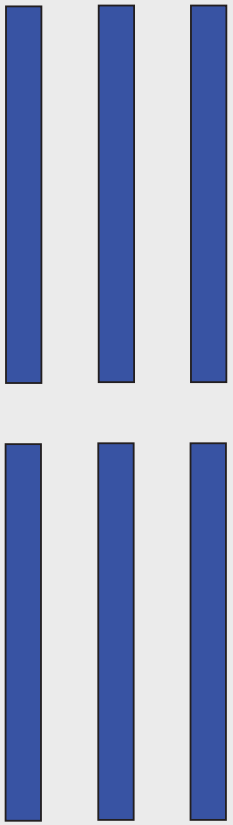
Pulsed Beam to Eliminate prompt backgrounds like radiative $\pi$ capture and CR

protons out of beam pulse/ protons in beam-pulse < $10^{-10}$
*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

RPC:

$\pi N \rightarrow \gamma N$

$\gamma \rightarrow e^+ e^-$ *in foils*

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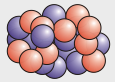
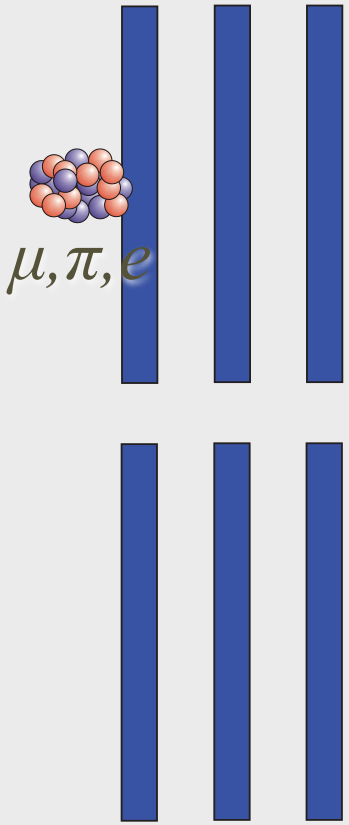
 = muons, electrons, pions

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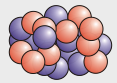
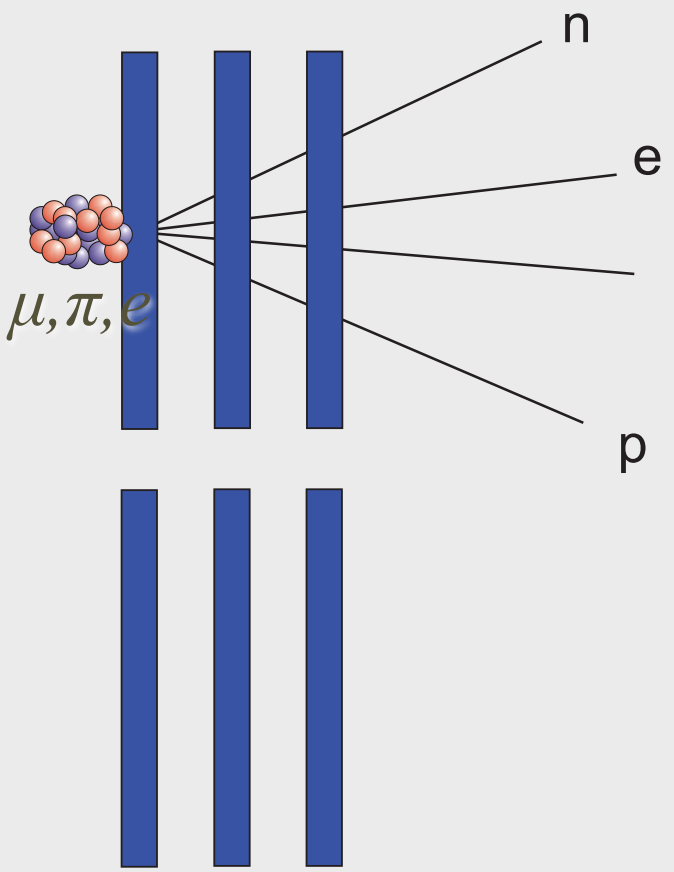
 = muons, electrons, pions




***prompt!***

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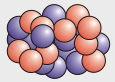
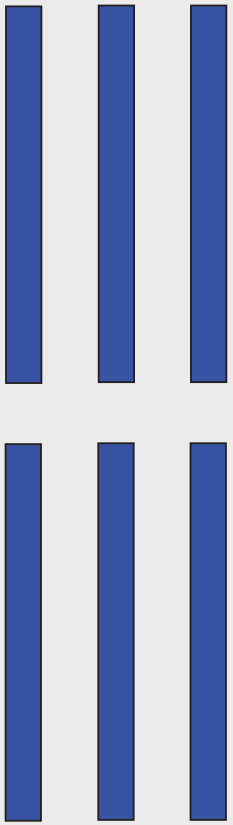
 = muons, electrons, pions



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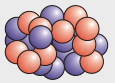
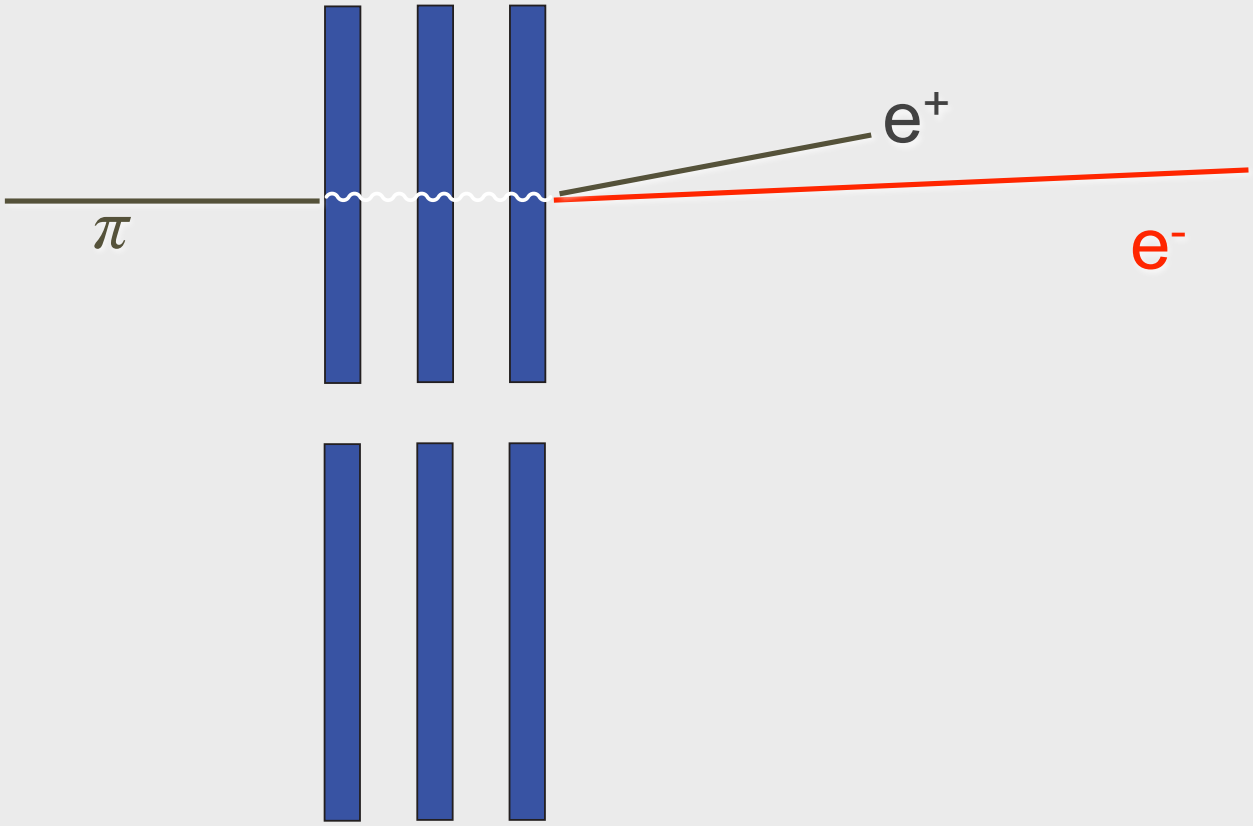
# Advantage of Pulsed Beam

target foils: muon converts here

 = muons, electrons, pions




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

RPC:

$\pi N \rightarrow \gamma N$

$\gamma \rightarrow e^+ e^-$ *in foils*

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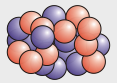
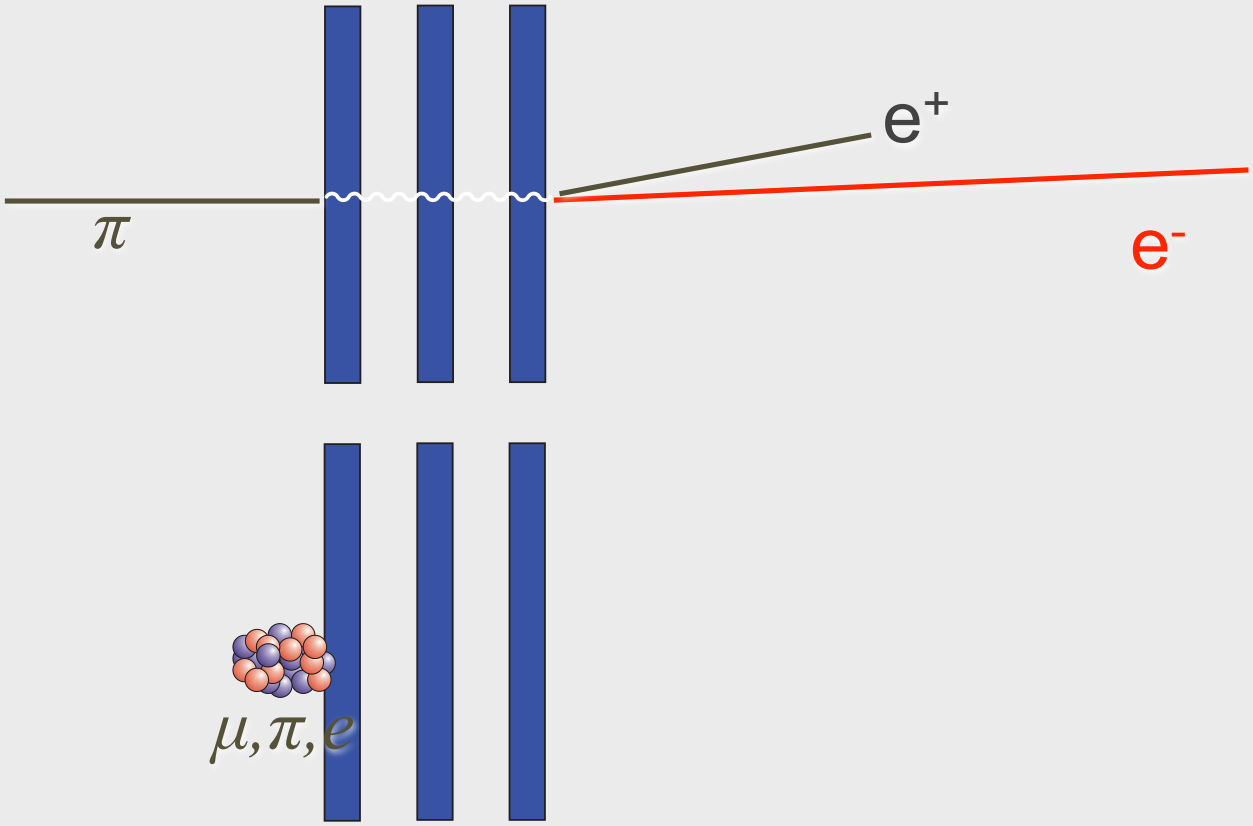
 = muons, electrons, pions

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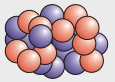
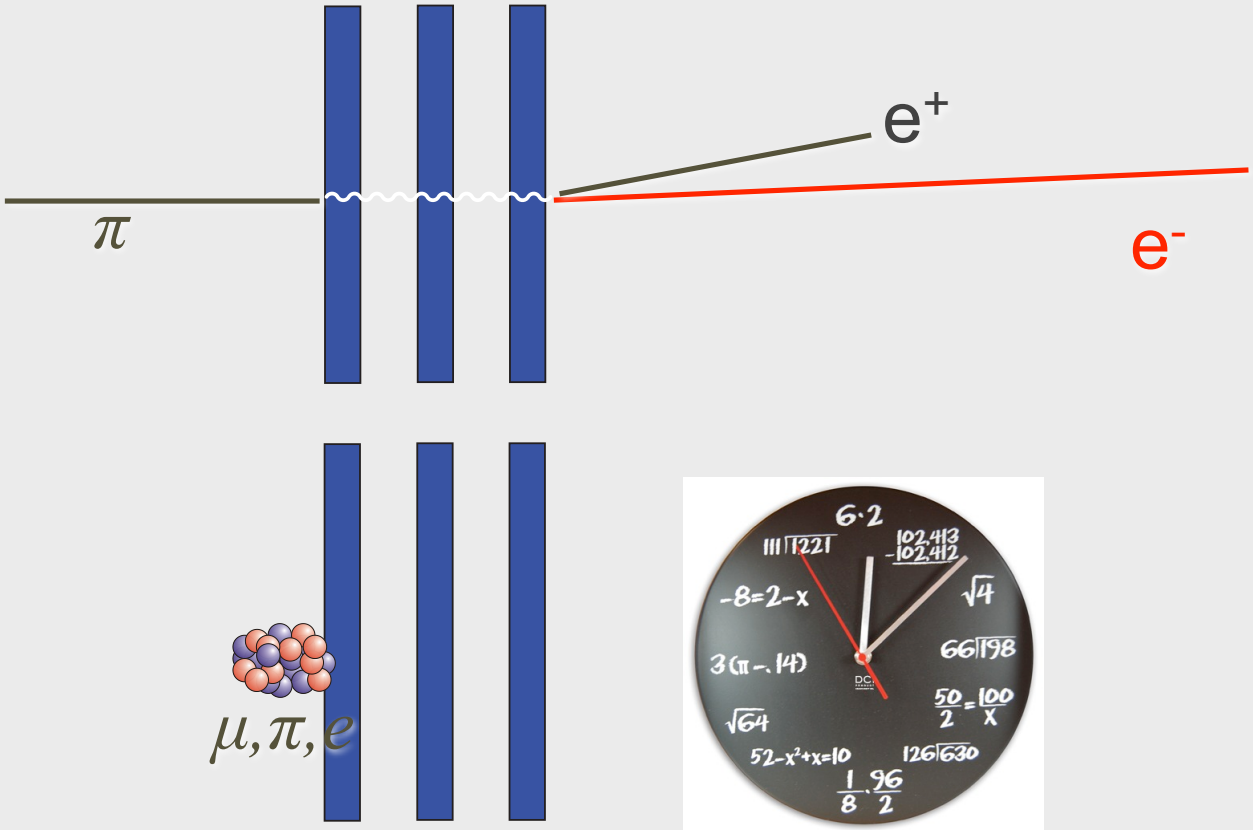
 = muons, electrons, pions







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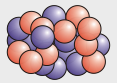
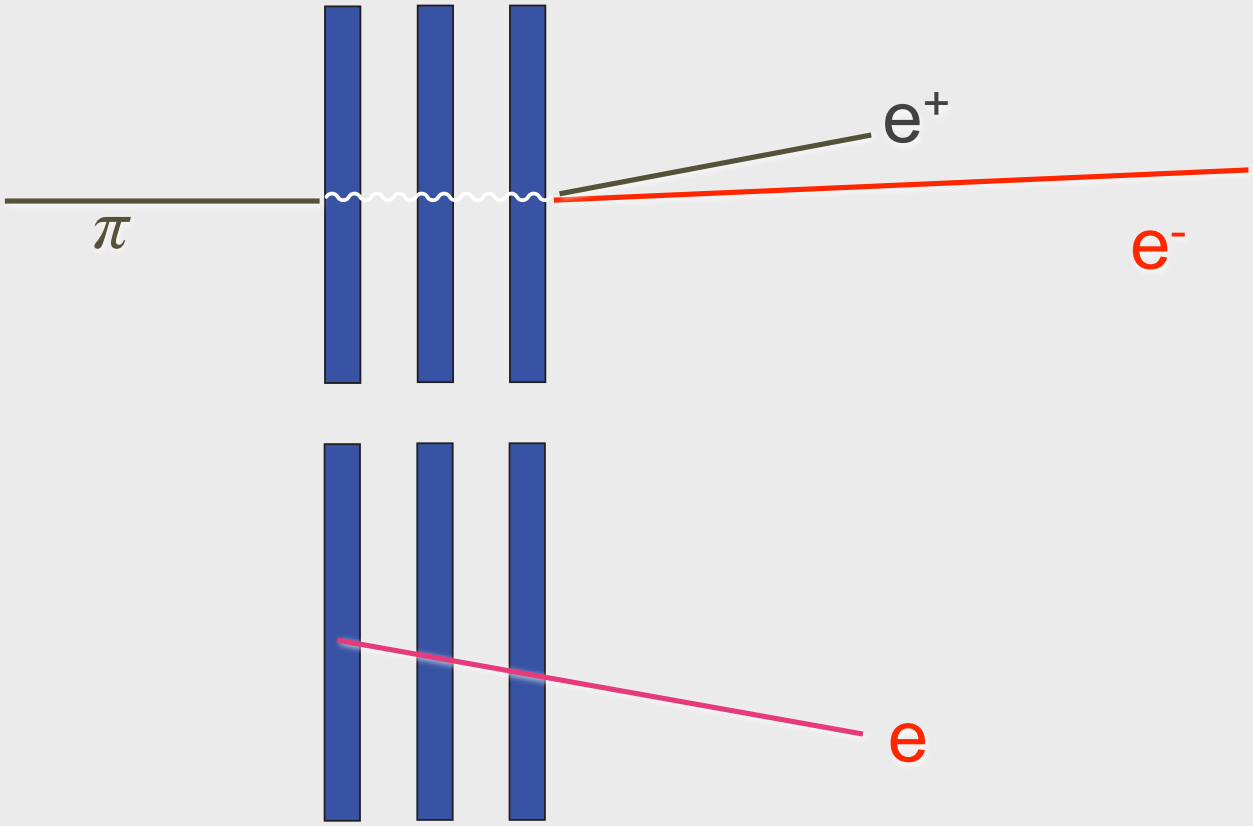
 = muons, electrons, pions

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RPC:

$\pi N \rightarrow \gamma N$

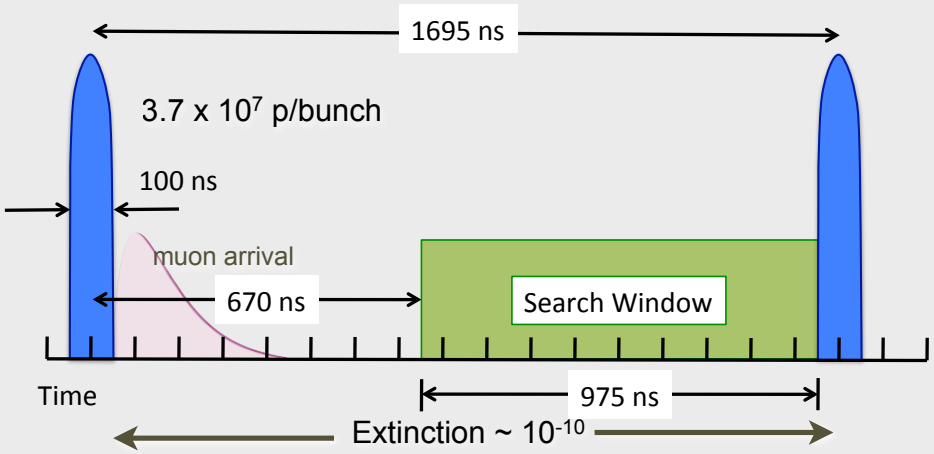
$\gamma \rightarrow e^+e^-$ *in foils*

delayed 105 MeV electron

# Pulsed Beam Structure

- Tied to prompt rate and machine: FNAL "perfect"
- Want pulse duration << $\tau_\mu^{Al}$ , pulse separation ≈ $\tau_\mu^{Al}$
  - FNAL Debuncher has circumference 1.7μsec , ~x2 $\tau_\mu^{Al}$
- Extinction between pulses < $10^{-10}$ needed

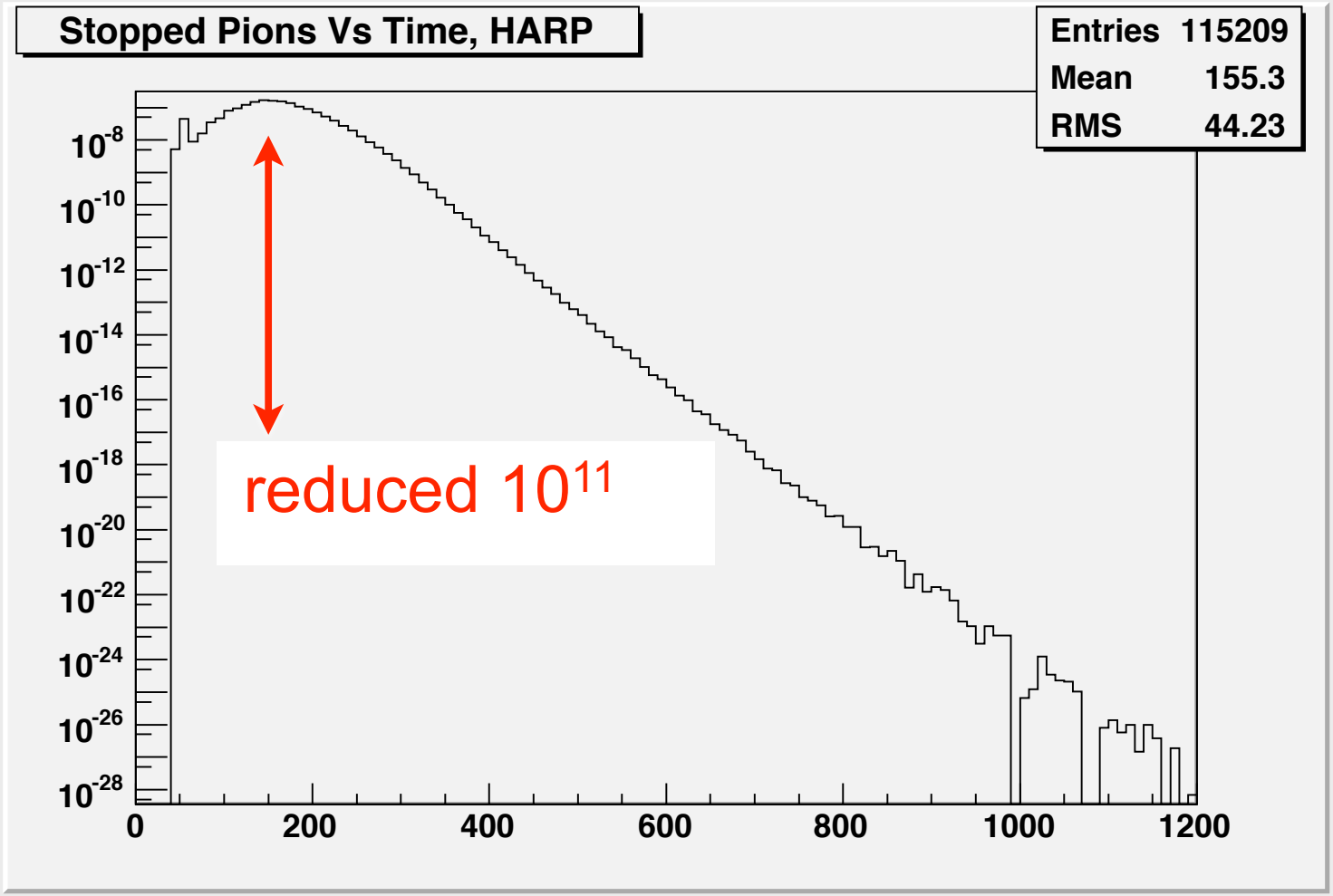
  = # protons out of pulse/# protons in pulse




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

# Pulsed Beam Structure and Radiative $\pi$ Capture

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




*need a beam that lets us wait this long: FNAL*

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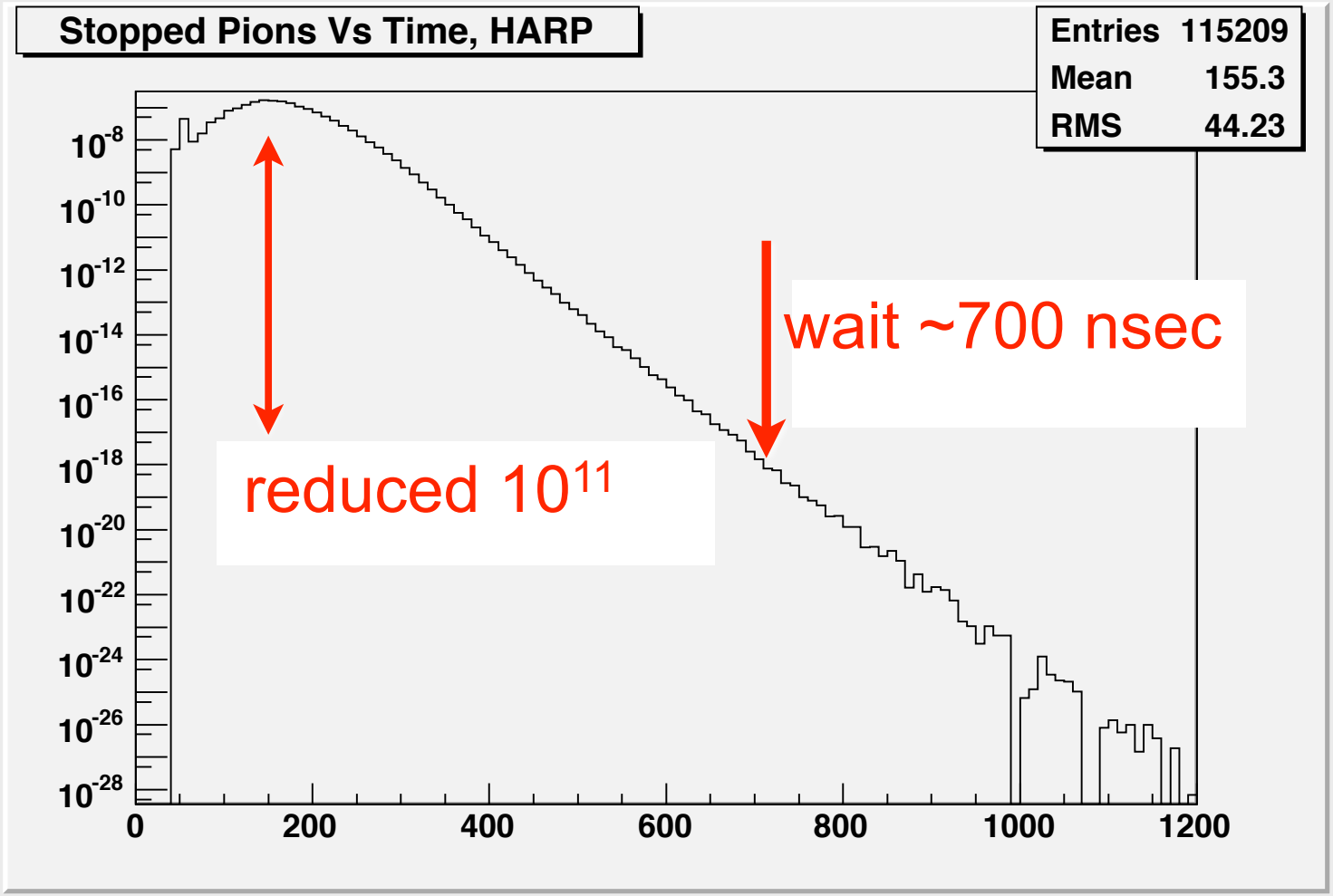



*need a beam that lets us wait this long: FNAL*

# 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?

V. Cirigliano et al., arXiv:0904.0957 [hep-ph]; Phys.Rev. D80 (2009) 013002

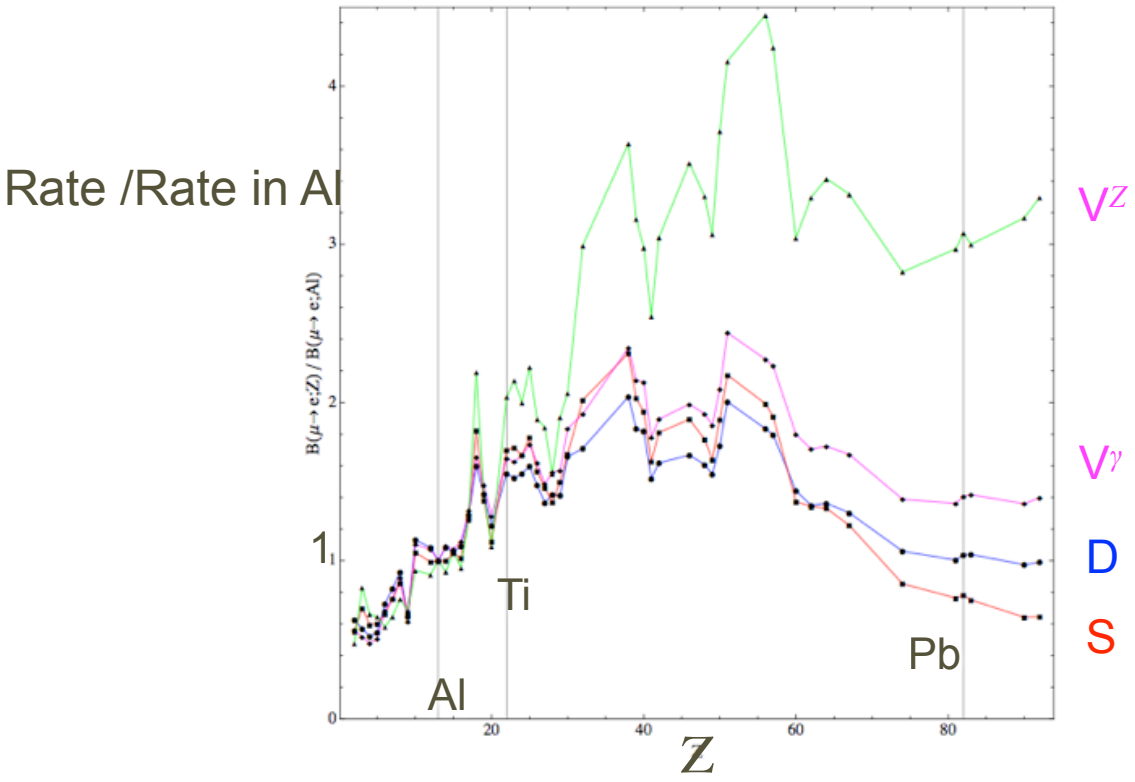


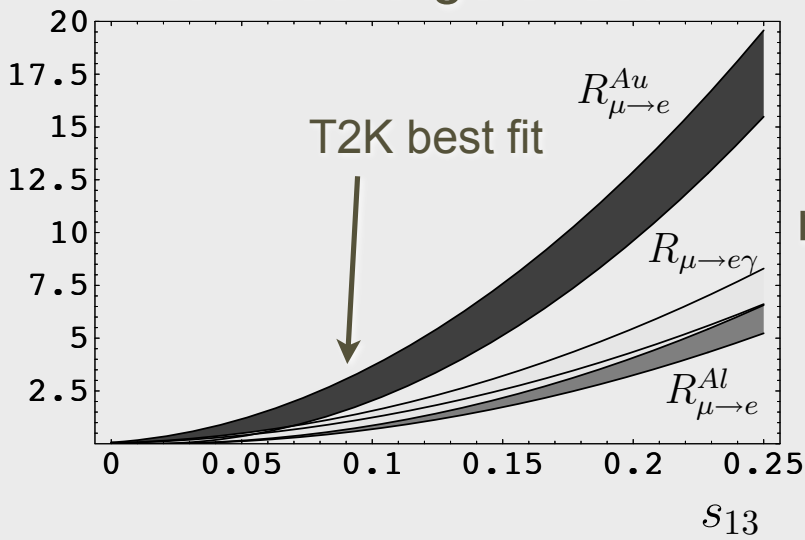

Figure 3: Target dependence of the $\mu \to e$ conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ($Z = 13$) versus the atomic number $Z$ for the four theoretical models described in the text: $D$ (blue), $S$ (red), $V^{(\gamma)}$ (magenta), $V^{(Z)}$ (green). The vertical lines correspond to $Z = 13$ (Al), $Z = 22$ (Ti), and $Z = 83$ (Pb).

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

# Choice of Stopping Material: rate vs wait

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

can see large effect



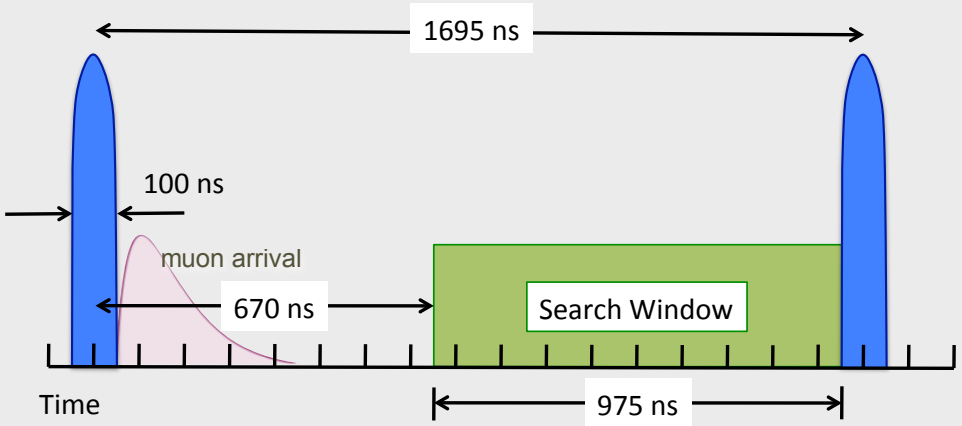

$s_{13}$ is NOvA mixing angle < 0.2 or so

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

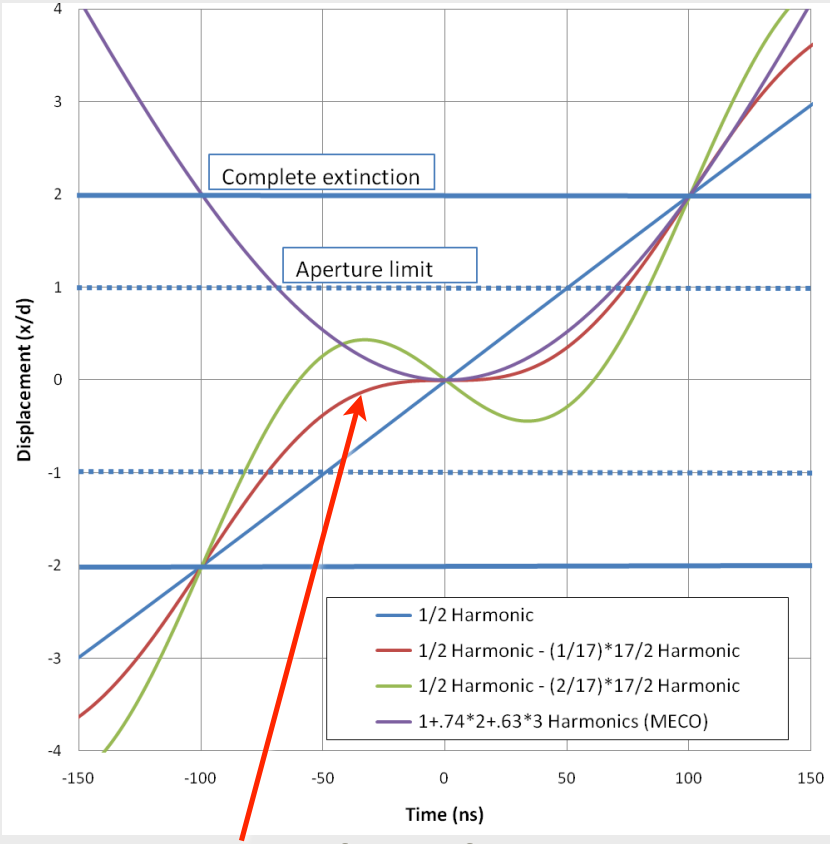



| Nucleus | $R_{\mu e}(Z) / R_{\mu e}(Al)$ | Bound Lifetime | Conversion Energy |
|---|---|---|---|
| Al(13,27) | 1.0 | 864 nsec | 104.96 MeV |
| Ti(22,~48) | 1.7 | 328 nsec | 104.18 MeV |
| Au(79,~197) | ~0.8-1.5 | 72.6 nsec | 95.56 MeV |

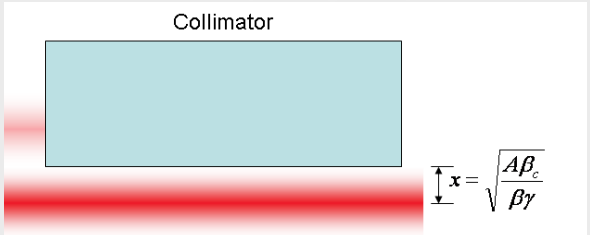
# Extinction Scheme

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

- Internal (momentum scraping) and bunch formation in Accumulator
- External: oscillating (AC) dipole
  - high frequency (300 KHz) dipole with smaller admixture of 17th harmonic (5.1 MHz)
  - Sweep Unwanted Beam into collimators
- Calculations (MARS) show this combination gets ~$10^{-12}$

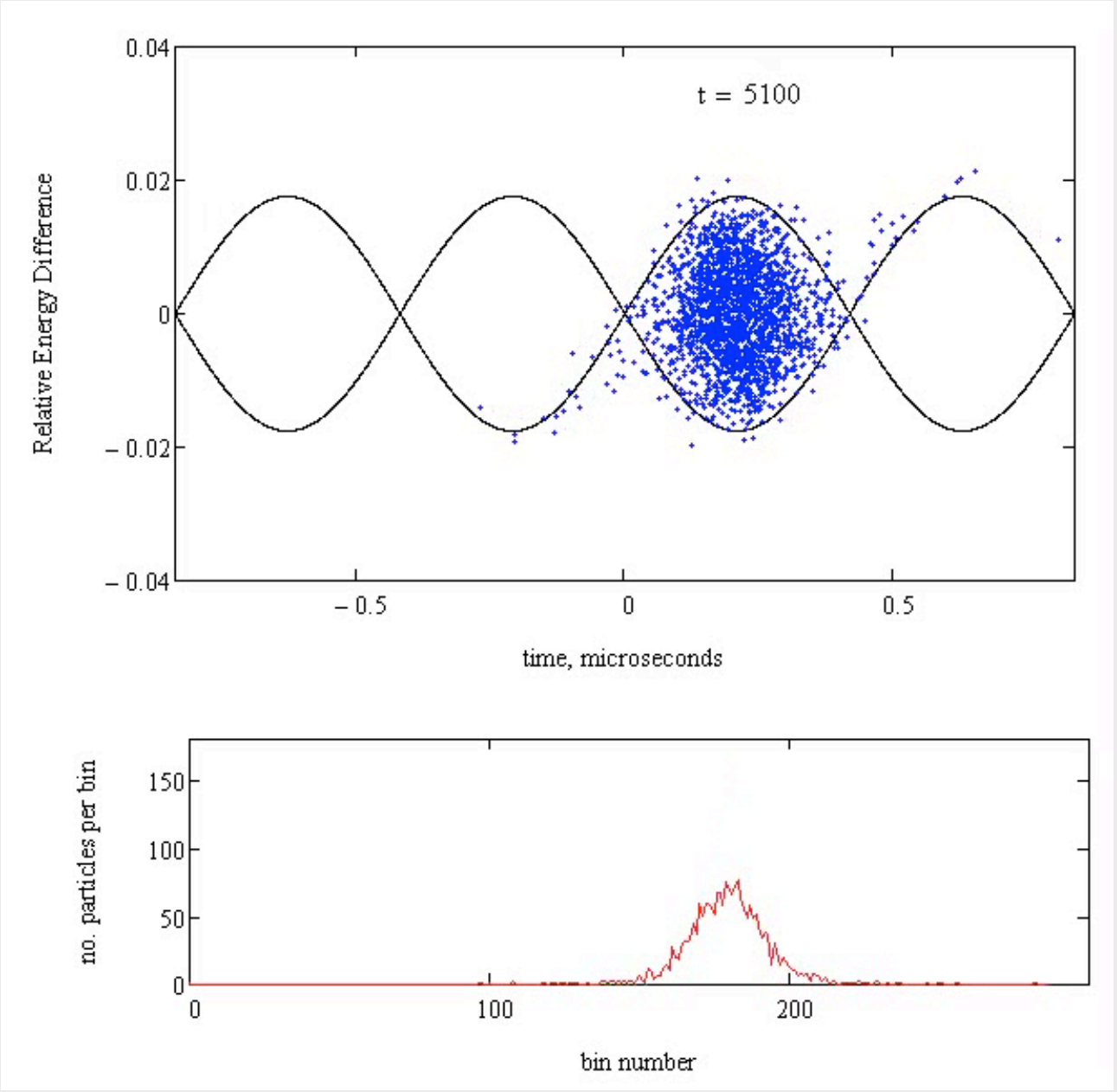



choose a field as flat as possible during the pulse that kicks beam out as quickly as possible

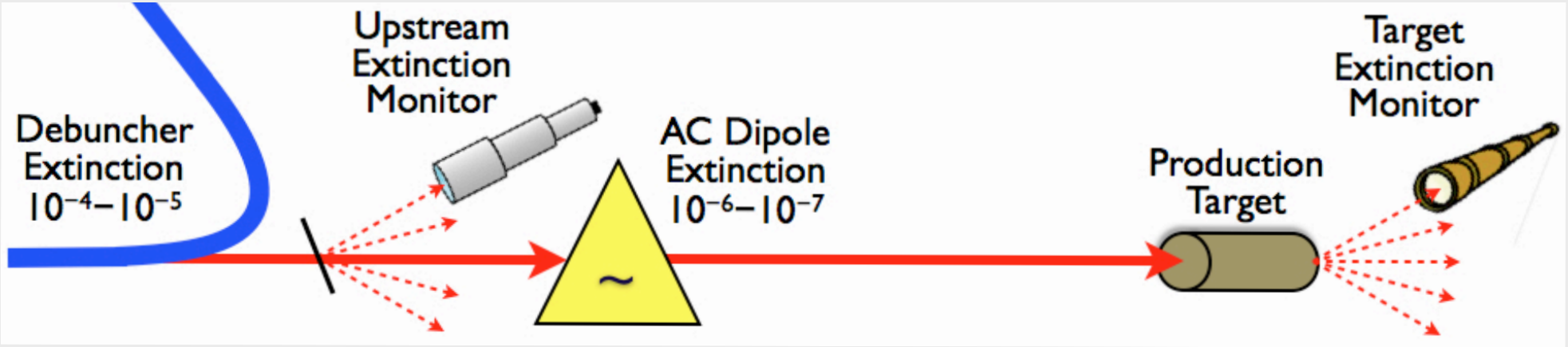


# Extinction (Internal)

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



# Extinction Measurement




- Beam Formation(Debuncher, Momentum Scraping) and AC-Dipole provide extinction
- Measure with:
  - Thin foils in 8 GeV transport line (fast feedback on machine performance)
  - Off-axis telescope looking at production target (time scale of hour)
  - Also considering detecting individual out-of-time protons but very difficult

# 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

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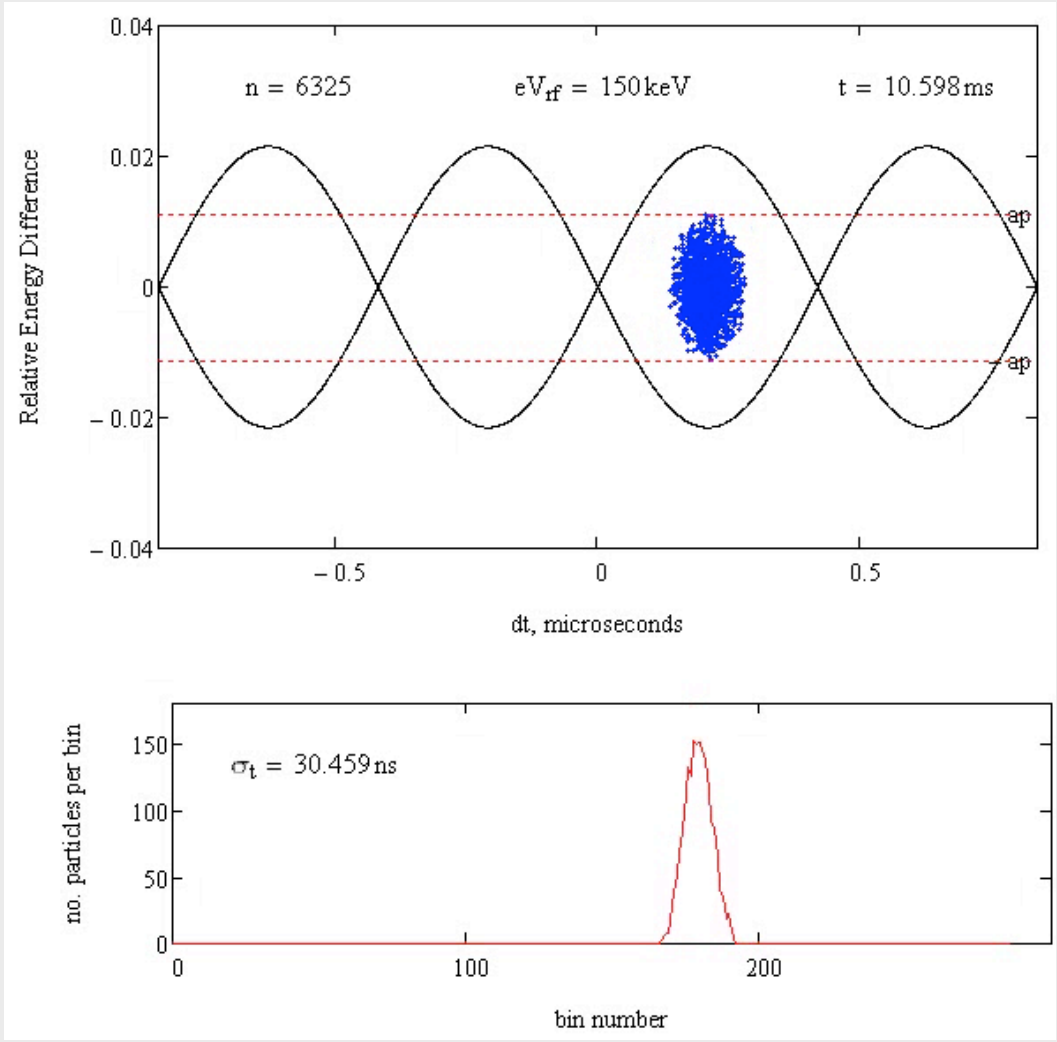

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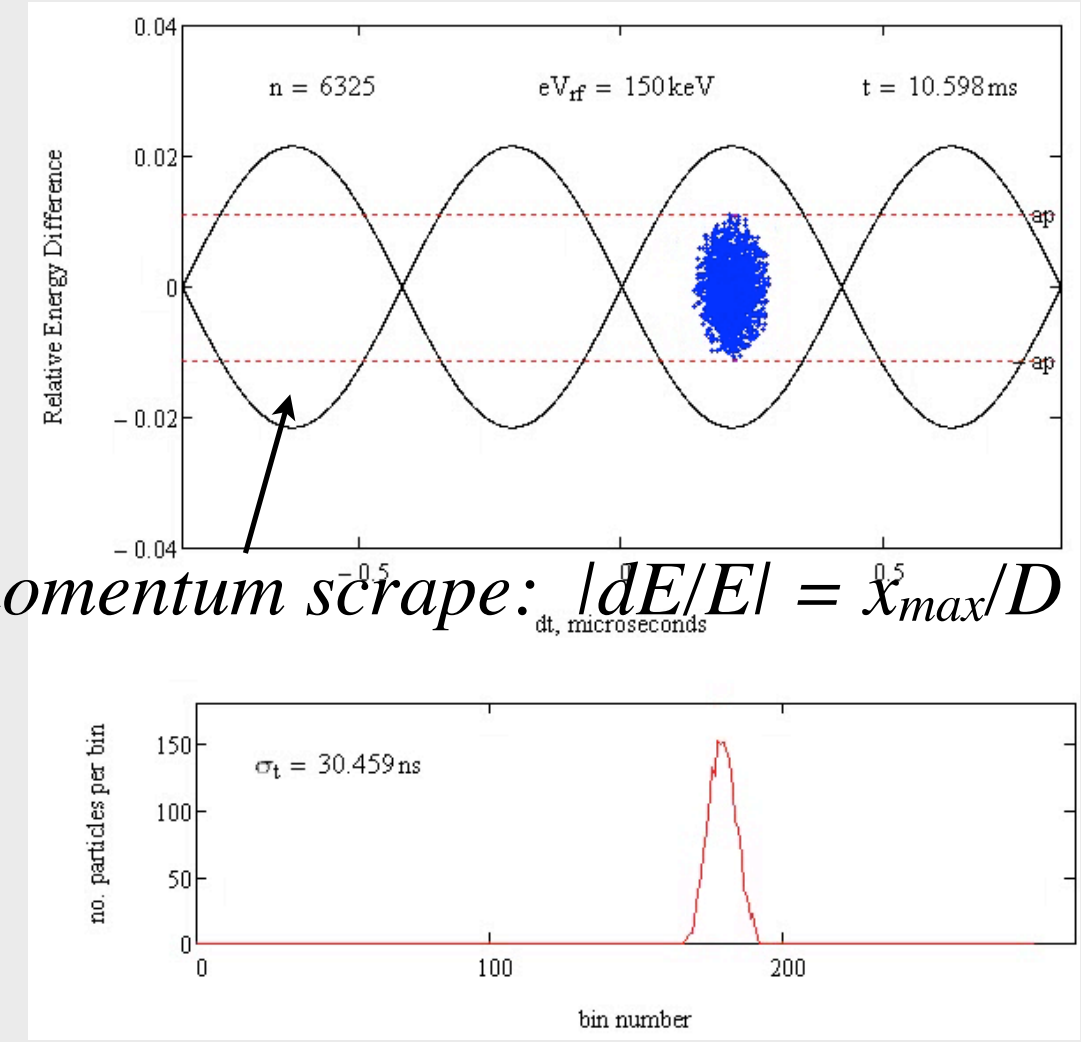
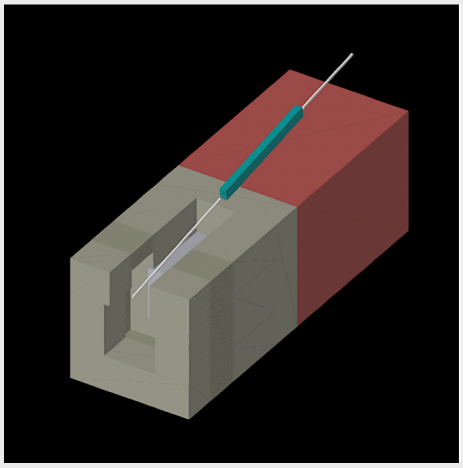


# Current Extinction Plan

- Look at secondaries from target
  - Use a magnet to pick out signal
  - Count hits in-and-out of pulse, compare
  - Current plan -- *not proton-by-proton*

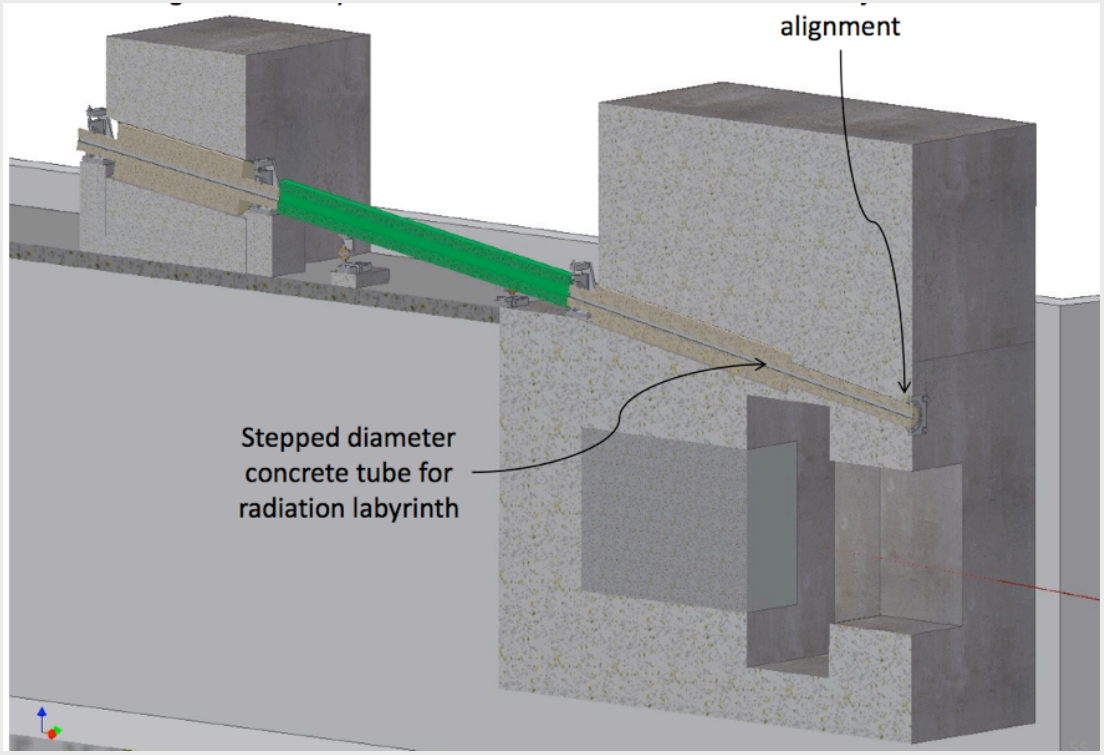
| Nominal Momentum (GeV/c) | Transmitted tracks / bunch | Integration Time (min) | | Proton Percentage | MeV Deposited / Proton-on-Target | | |
|---|---|---|---|---|---|---|---|
| | | No Bkgnd. | 5 / hr | | Entry Channel | Magnet | Exit Channel |
| 2.0 | 40.5 ± 4.4 | 6.9 | 10.8 | 77.6 | 0.293 | 0.167 | 0.007 |
| 3.0 | 151.4 ± 8.5 | 1.8 | 2.1 | 82.7 | 0.258 | 0.168 | 0.037 |
| 4.0 | 240.0 ± 10.7 | 1.2 | 1.3 | 89.9 | 0.246 | 0.164 | 0.037 |
| 5.0 | 191.0 ± 9.5 | 1.5 | 1.6 | 93.0 | 0.201 | 0.128 | 0.037 |
| 6.0 | 119.1 ± 5.8 | 2.3 | 2.8 | 96.4 | 0.172 | 0.112 | 0.026 |
| 7.0 | 69.4 ± 4.5 | 4.0 | 5.3 | 97.1 | 0.149 | 0.100 | 0.021 |
| 8.0 | 39.8 ± 2.9 | 7.0 | 11.0 | 99.0 | 0.133 | 0.095 | 0.015 |
| 9.0 | 26.1 ± 2.3 | 10.6 | 20.1 | 100.0 | 0.116 | 0.089 | 0.011 |

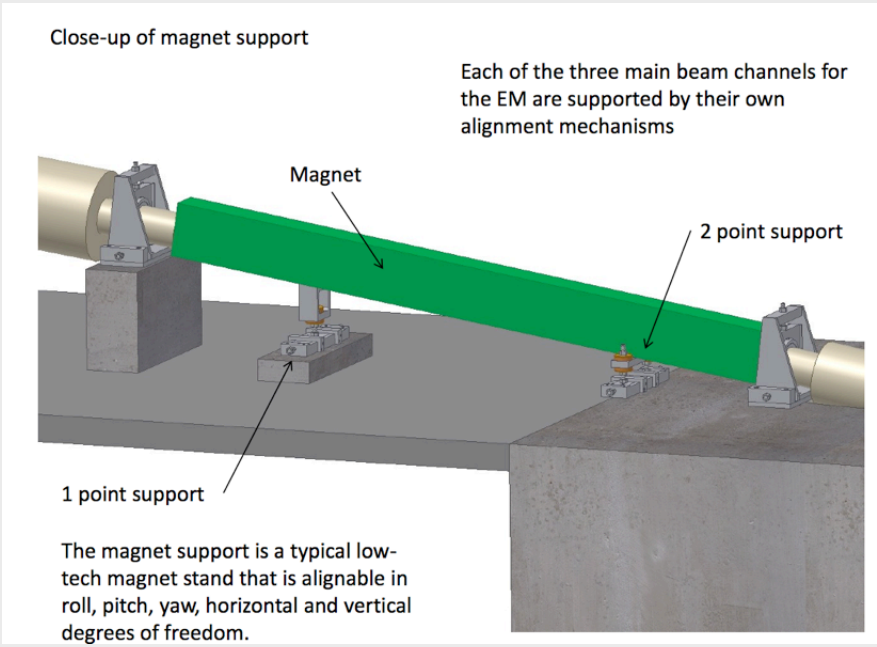
G4Beamline Model



working on using diffractive protons:
little-to-no background, easier to model

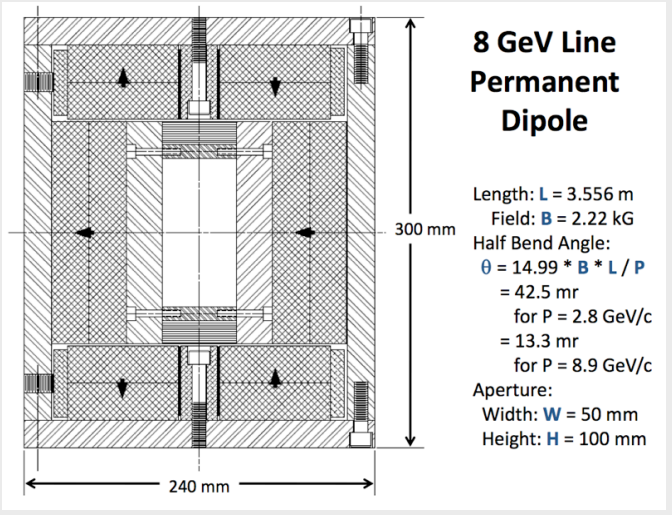
# Wide Variety of choices




- Working on detector modeling
  - ATLAS pixels?
  - TOF?
  - Calorimeter?

*interesting problem for post-docs!!*



# Mu2e Overview

V. Lobashev, MELC 1992:

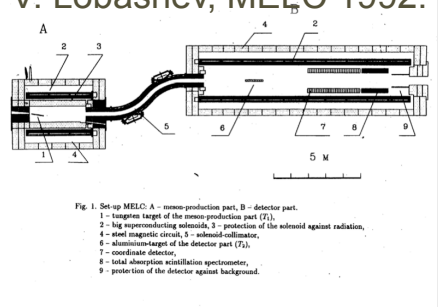
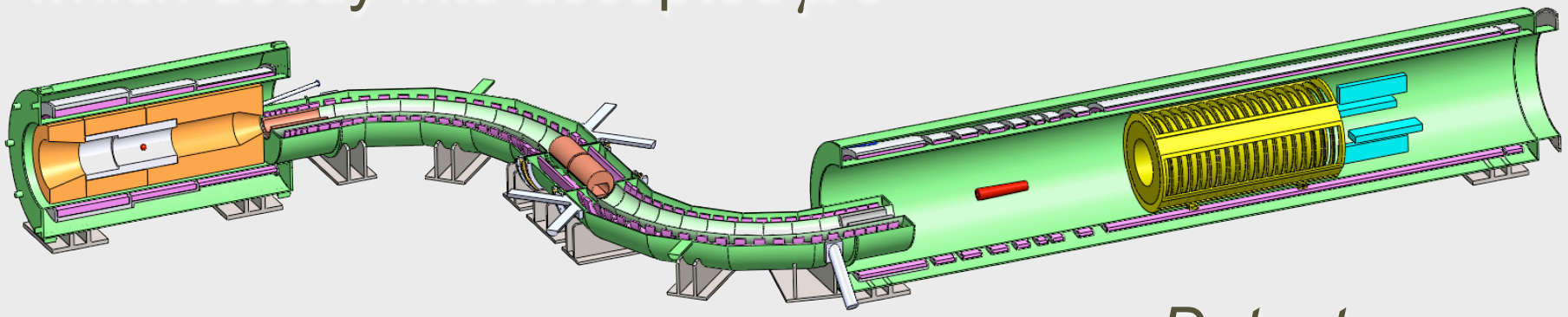


Fig. 1. Set-up MELC: A – meson-production part, B – detector part.
1 – tungsten target of the meson-production part ($T_1$),
2 – big superconducting solenoids, 3 – protection of the solenoid against radiation,
4 – steel magnetic circuit, 5 – solenoid-collimator,
6 – aluminium-target of the detector part ($T_2$),
7 – coordinate detector,
8 – total absorption scintillation spectrometer,
9 – protection of the detector against background.

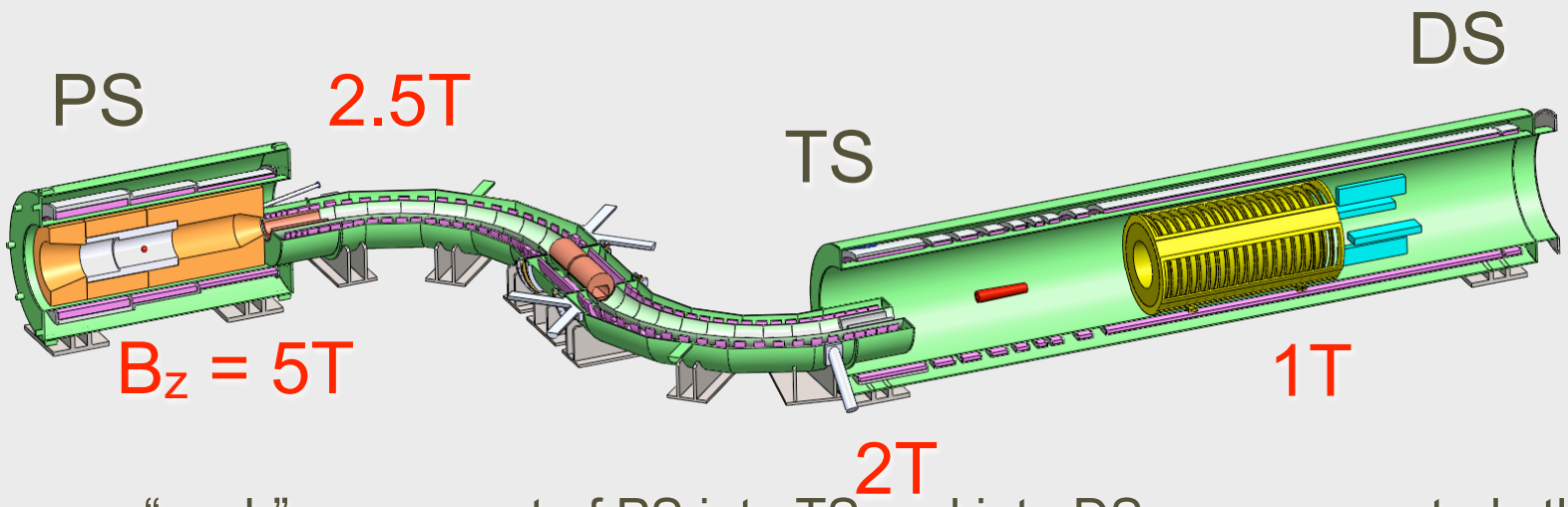
- *Production*: Magnetic bottle traps $\pi$'s, which decay into accepted $\mu$'s



- *Transport:* S-curve eliminates backgrounds and sign-selects
- *Detector:* Stopping Target, Tracking and Calorimeter

# Gradient Fields in Mu2e

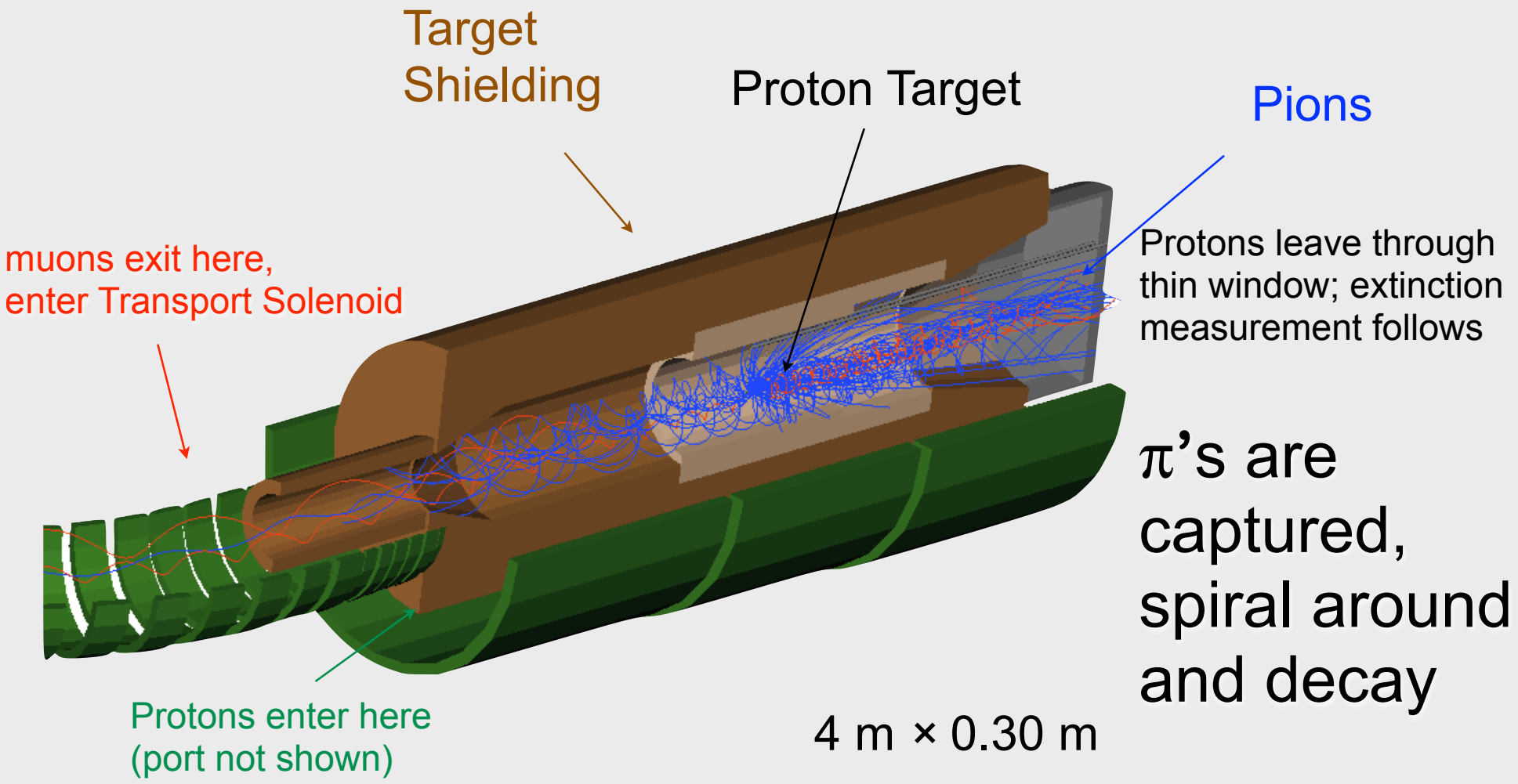
- Play a vital role throughout the design
- A lot of our intellectual effort!!




- "push" muons out of PS into TS and into DS so we can study them
- keep particles from spiraling around, arriving late
- conversions are isotropic in stopping target; the gradient over stopping target "reflects" backward going muons and nearly doubles the acceptance

# Production Solenoid:

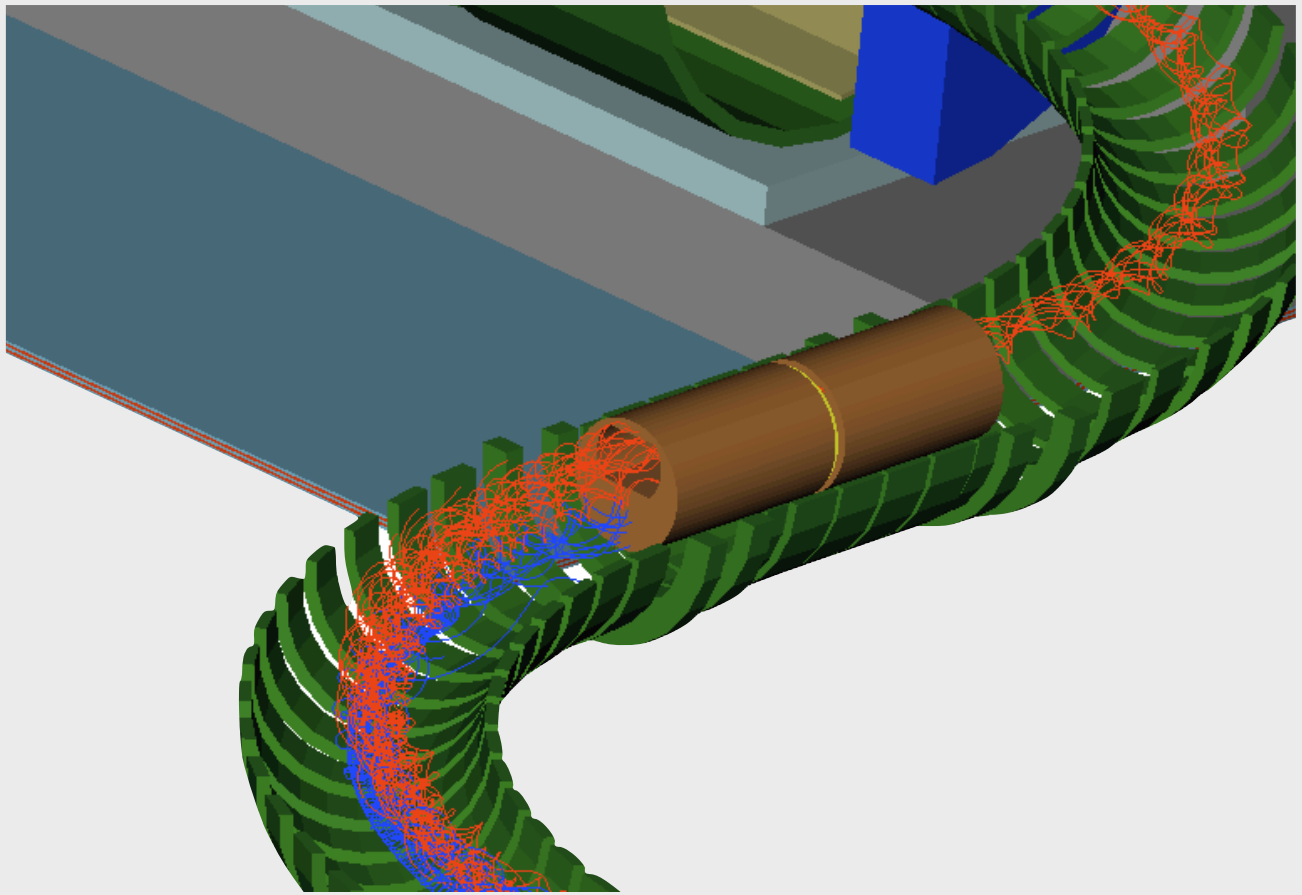
## Protons enter opposite to outgoing muons




π's are captured, spiral around and decay

# 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

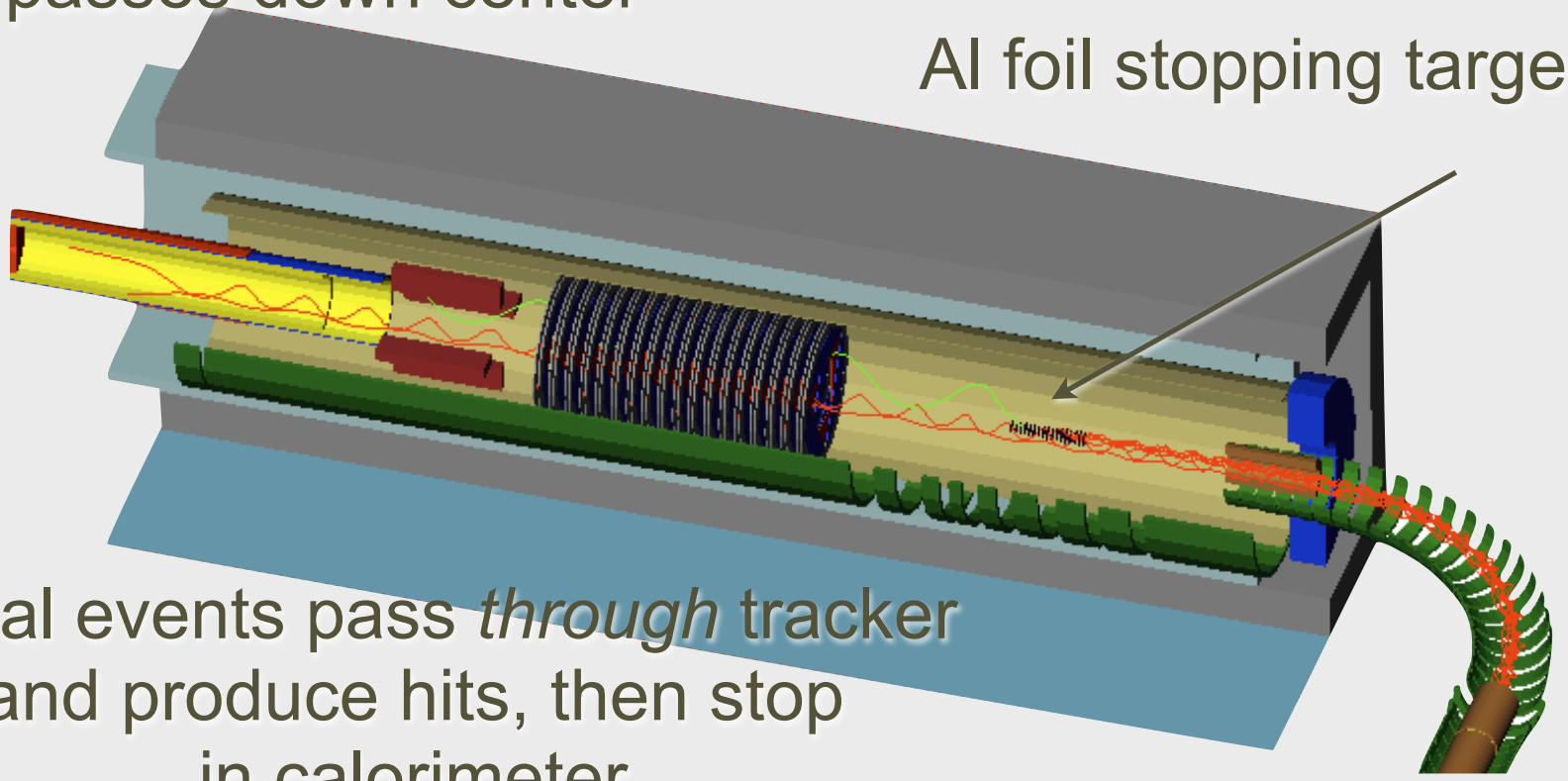
# Detector Solenoid

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

low momentum particles and almost all DIO background passes down center

10 m × 0.95 m

Al foil stopping target




signal events pass *through* tracker and produce hits, then stop in calorimeter

# Detector Solenoid

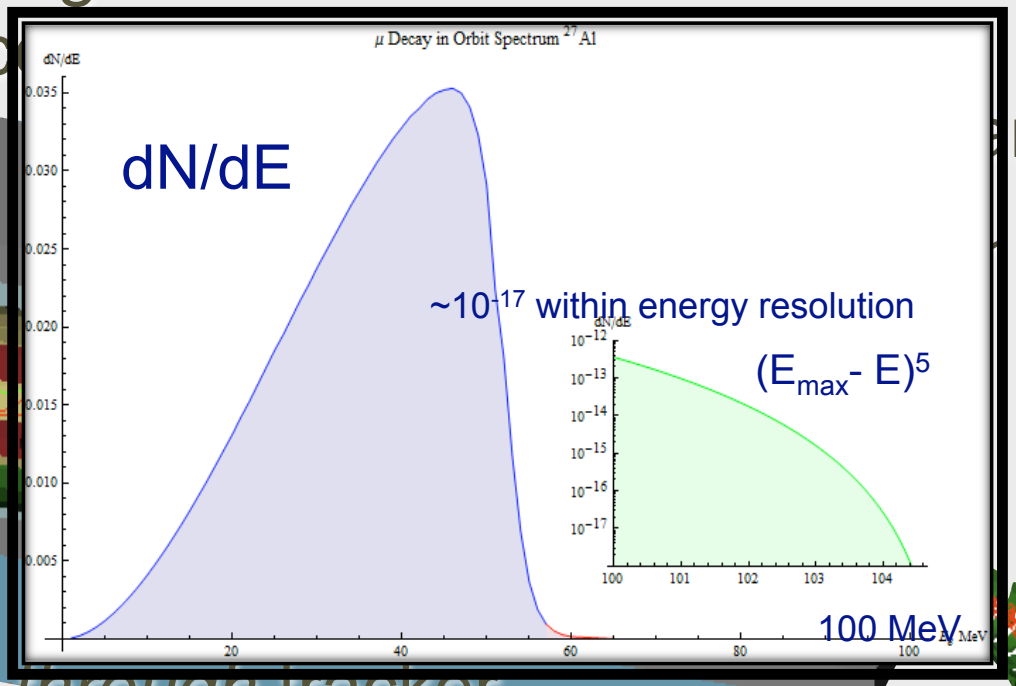
*octagonal tracker surrounding central region: radius of helix proportional to momentum, p=qBR*

low momentum particles and almost all DIO background passes down c

10 m × 0.95 m

rget

muon beam stop

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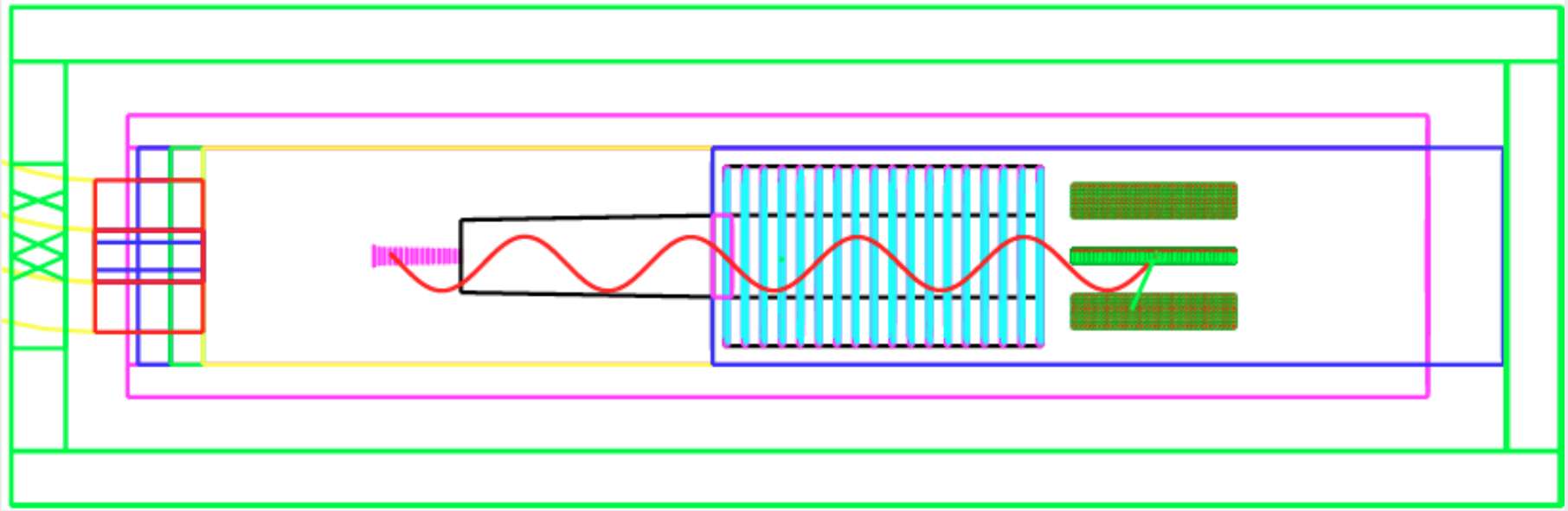
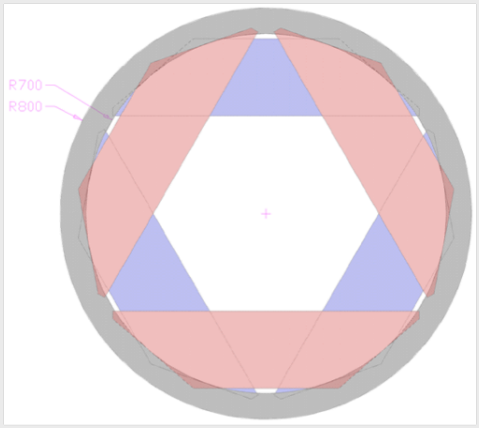
# Detector

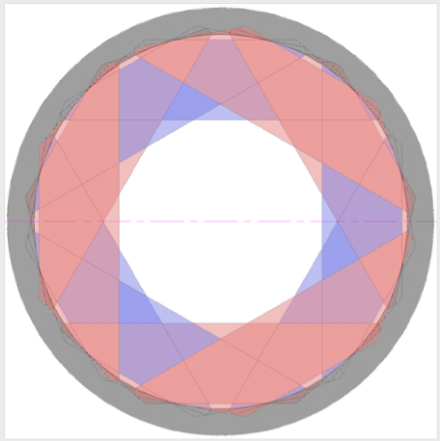


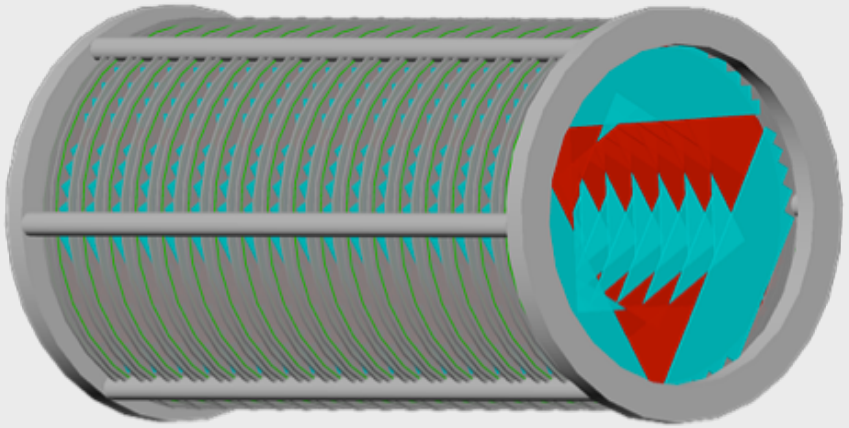
- Immersed in solenoidal field, so electrons follow near-helical path
- Conversion Electron born in Stopping Target
- Tracker followed by Calorimeter
- Tracker: (straw tubes with axes transverse to beam)
  - 21,600 straws
    - 18 stations of 5 mm diameter conducting straws
    - length from 33-118 cm
- Calorimeter:
  - 1024 3.5 × 3.5 × 12 cm $PbWO_4$ or LYSO
  - 4--5% resolution

# T-Tracker Details

- This “windowframe” is repeated, rotated each time
- Just know which straw is hit
  - Makes PR complicated!
- Using time division~ 8 cm $\sigma$ to give ($r,\phi$) and seed KF
  - very successful!



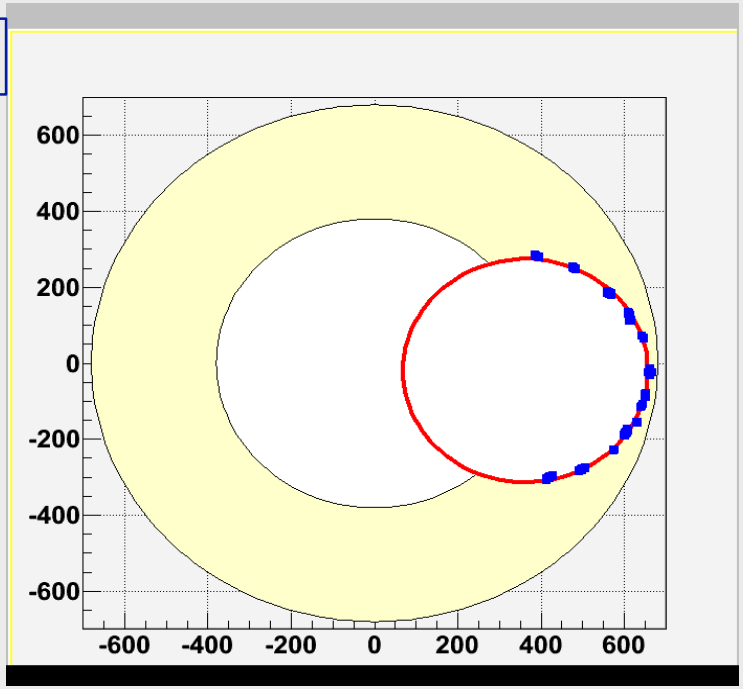





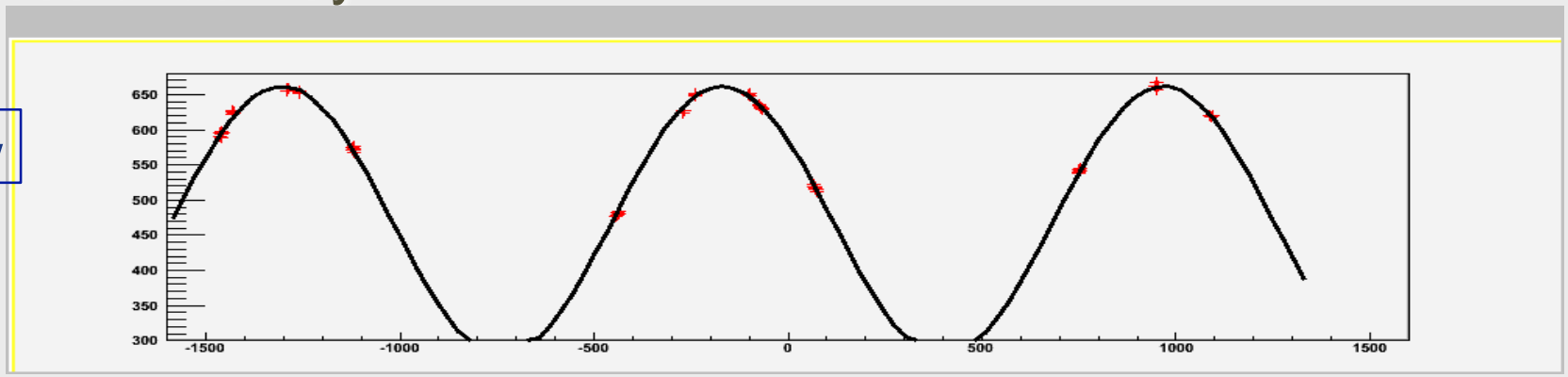
# Pattern Recognition and Tracking

- 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

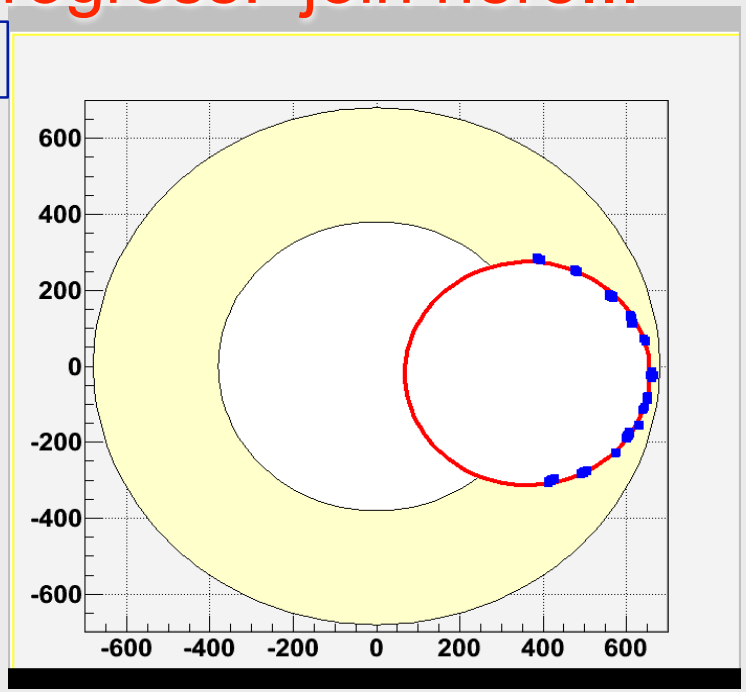


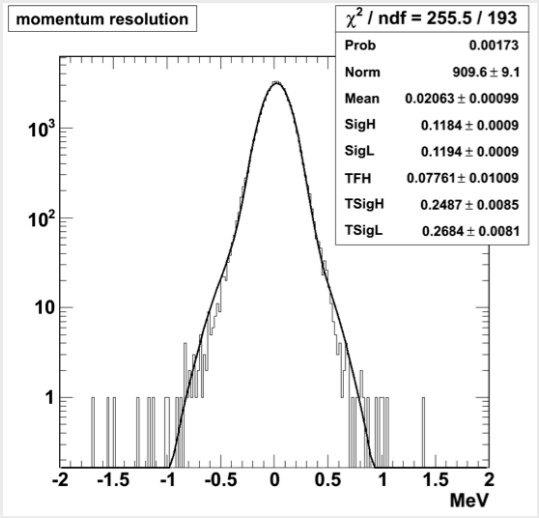
# Pattern Recognition and Tracking

- Unified simulation from protons on target to end of detector in GEANT4
- Pattern Recognition Program joined to BaBar Kalman Filter
  - No sign of significant mis-reconstruction background with realistic rates from all known sources

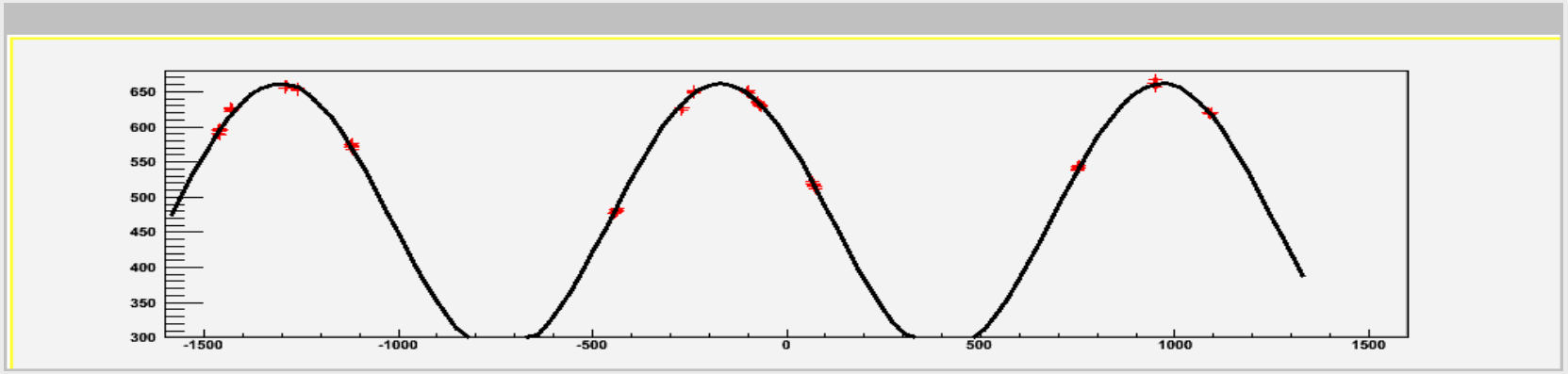
work in progress! join here...

X-Y View



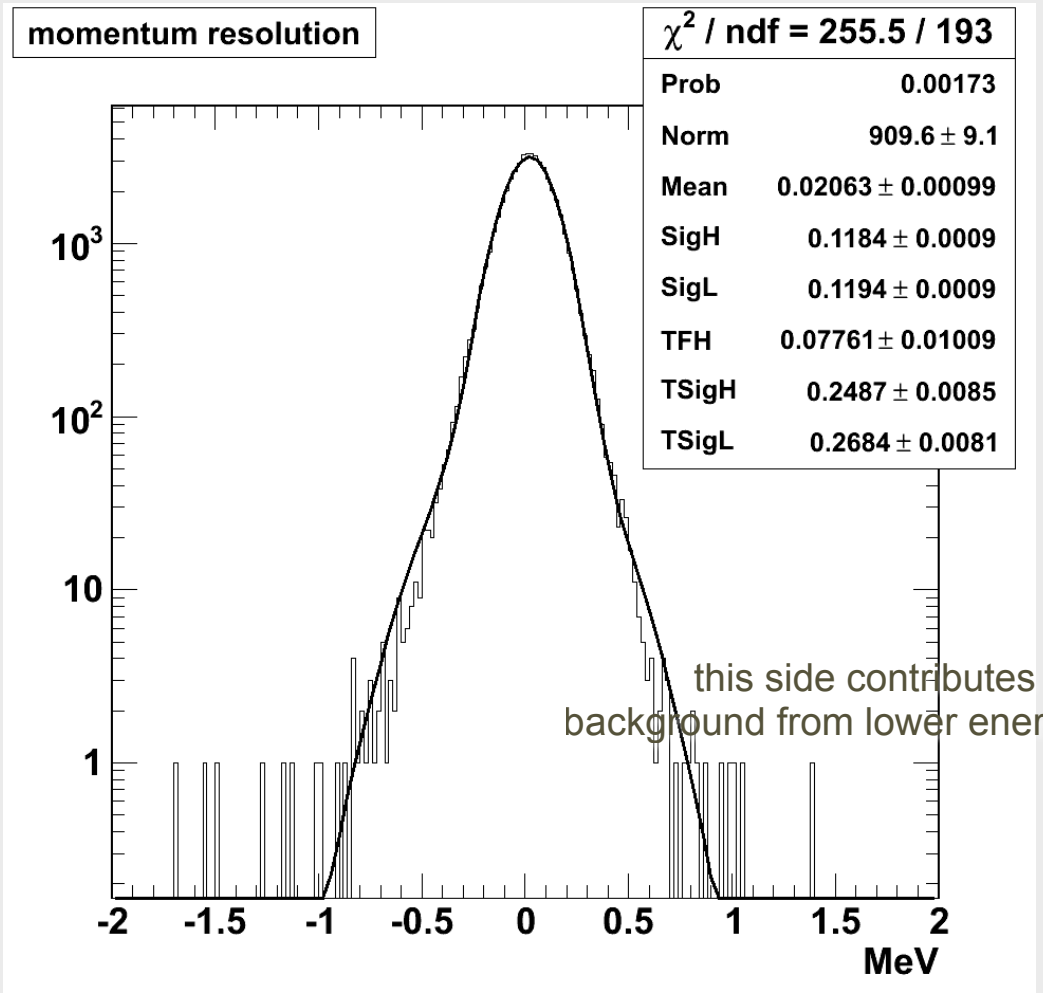




R-Z view



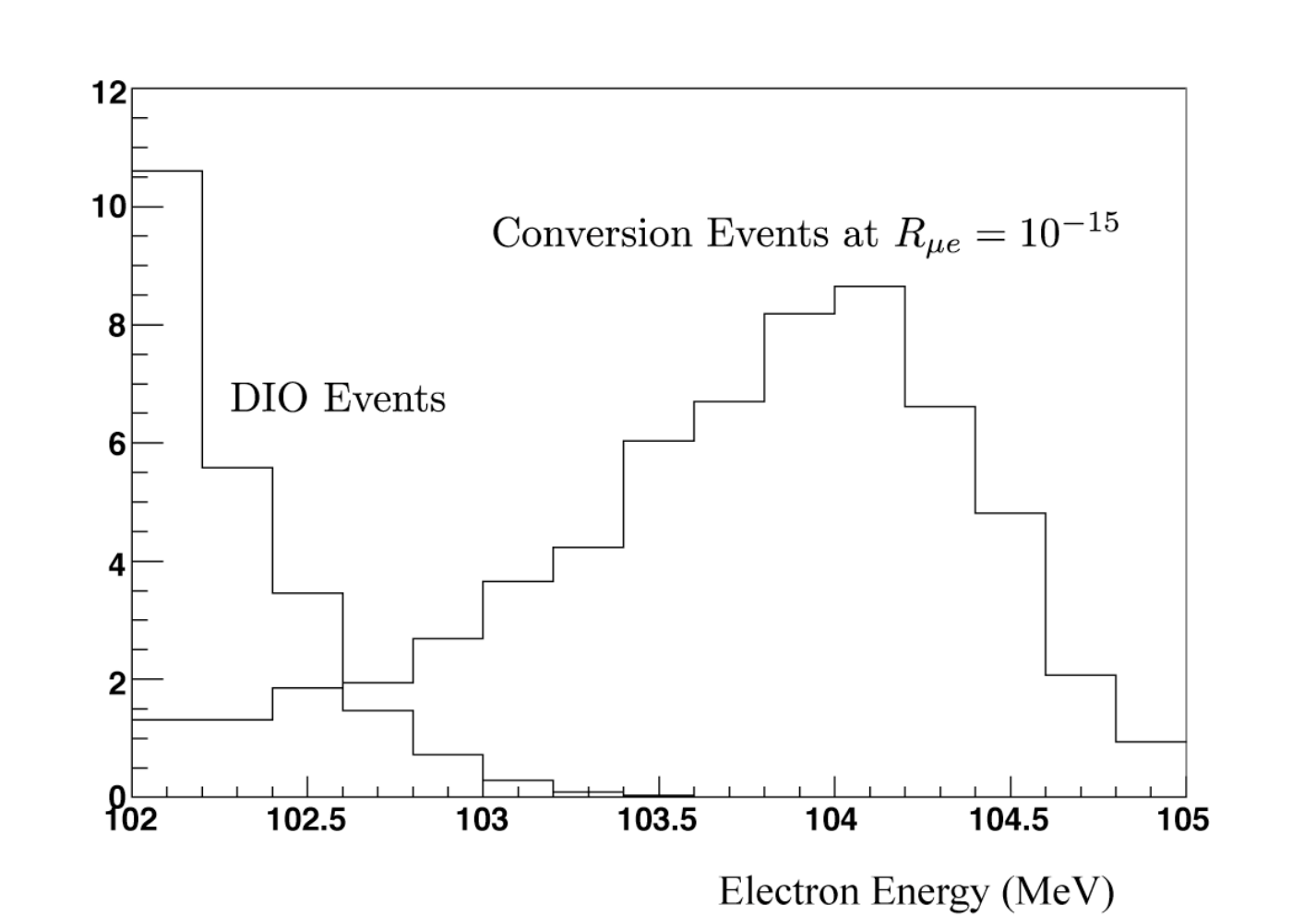
# Understanding Resolution

- 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
  - Gaussian part yield ~ .035 DIO smeared upwards



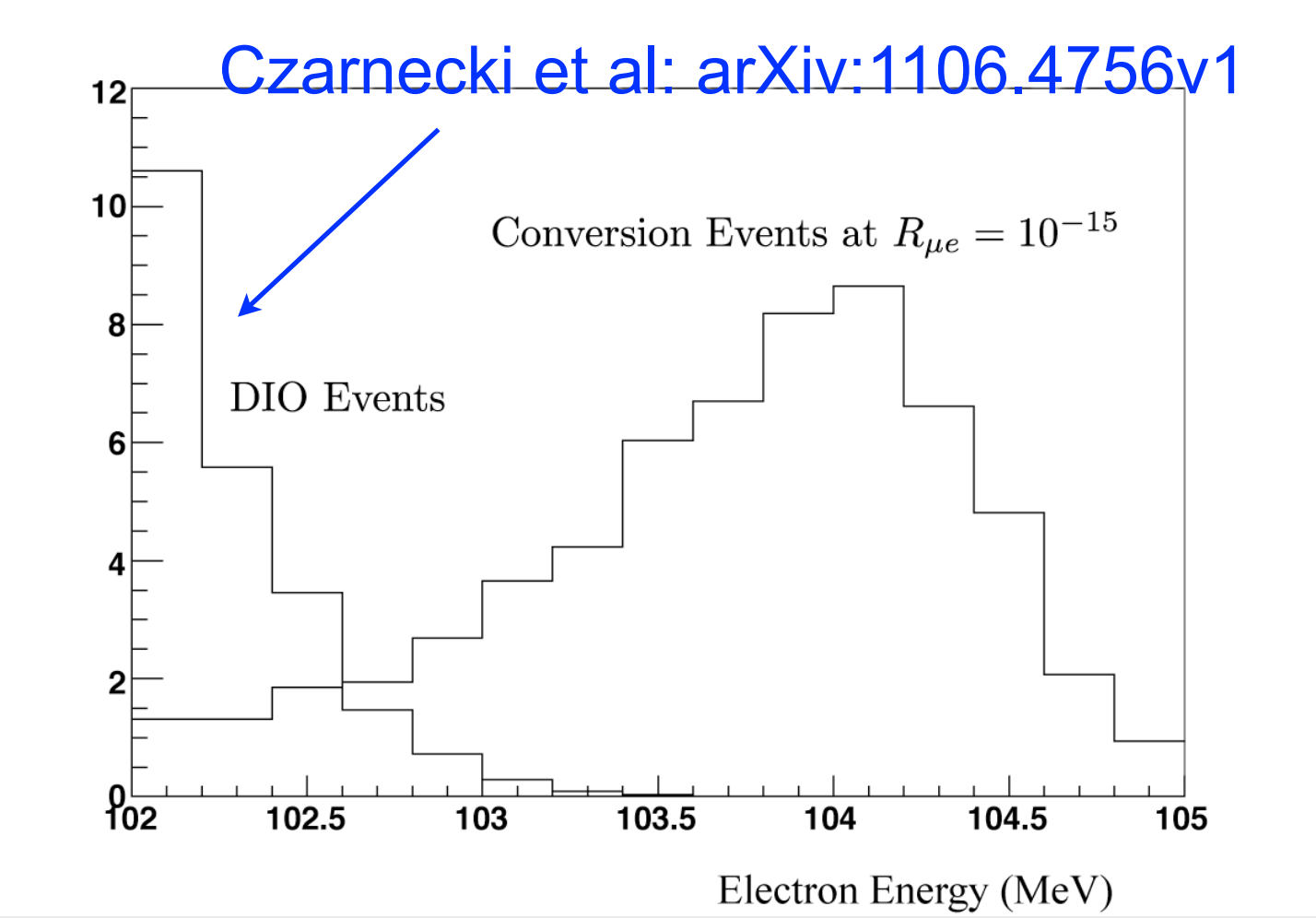

core: 92% 120 keV/c
tail: 8% 250 keV/c

# Signal and Background




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

# Signal and Background




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

# Final Backgrounds

- For $R_{\mu e} = 10^{-15}$
  ~40 events / 0.18 bkg
  (LHC SUSY?)
- For $R_{\mu e} = 10^{-16}$
  ~4 events / 0.18 bkg

| Source | Size | Error (not symmetric) |
|---|---|---|
| RPC ($\bar{p}$-induced) | 0.06 | $\pm$0.060 |
| RPC ($\pi$-induced) | 0.04 | $\pm$0.020 |
| CR | 0.025 | $\pm$0.025 |
| DIO | 0.035 | $\pm$0.018 |
| $\mu$ induced in-flight | 0.01 | $\pm$0.0005 |
| $\pi$ induced in-flight | 0.003 | $\pm$0.0015 |
| Scattered $e^-$ | 0.0006 | $\pm$0.0003 |
| Radiative $\mu$ Capture | $< 2 \times 10^{-6}$ | — |
| **TOTAL** | **0.18** | $\pm$ **0.08** |

# Outline

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

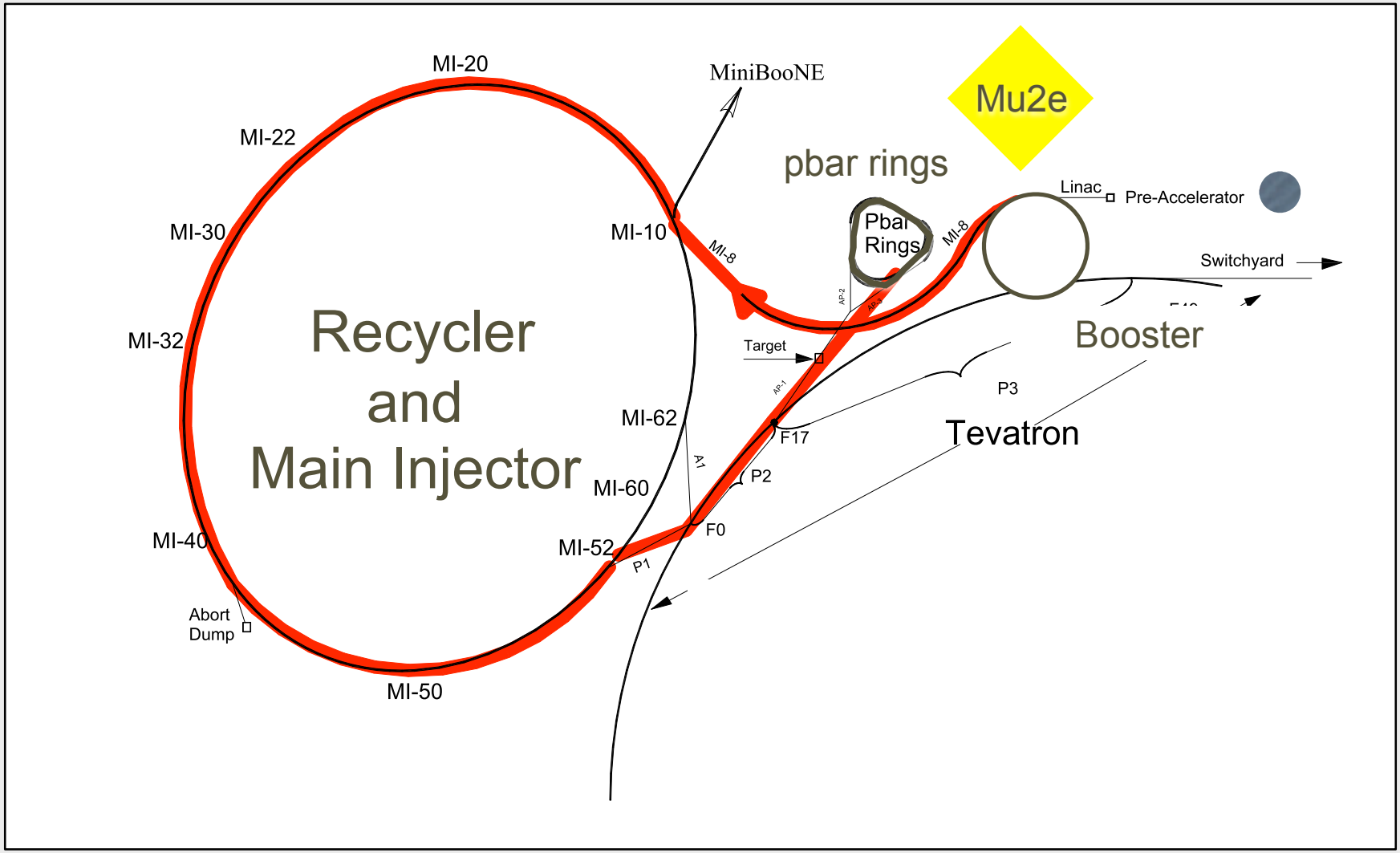
# FNAL Beam Delivery

- FNAL has unique, major strength:

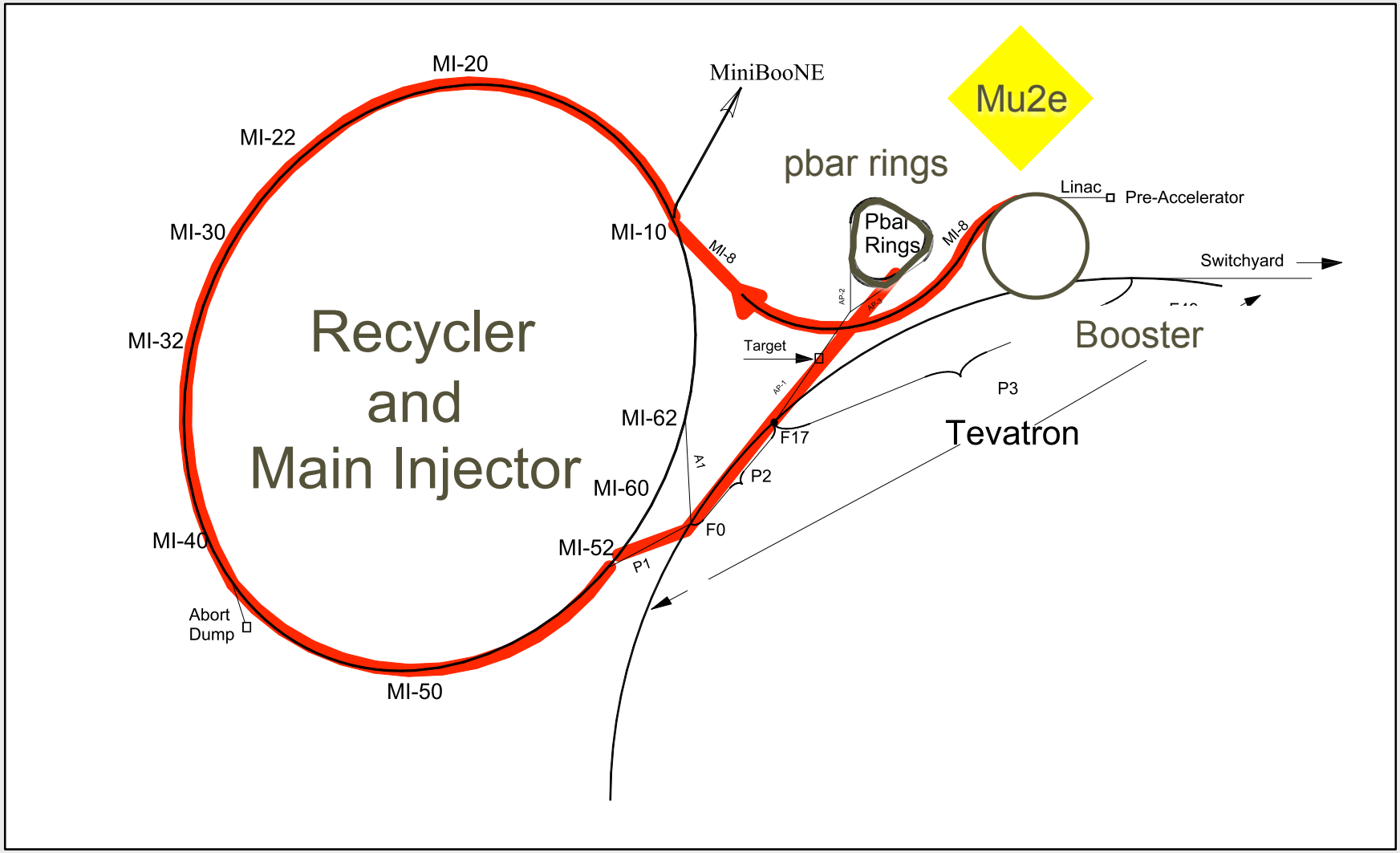
  Multiple Rings

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

# “Boomerang” Scheme



# “Boomerang” Scheme



# And on the Civil Construction




*Figure 2 –Site Photo Indicating Location of Proposed mu2e Conventional*

# And on the Civil Construction



# Outline

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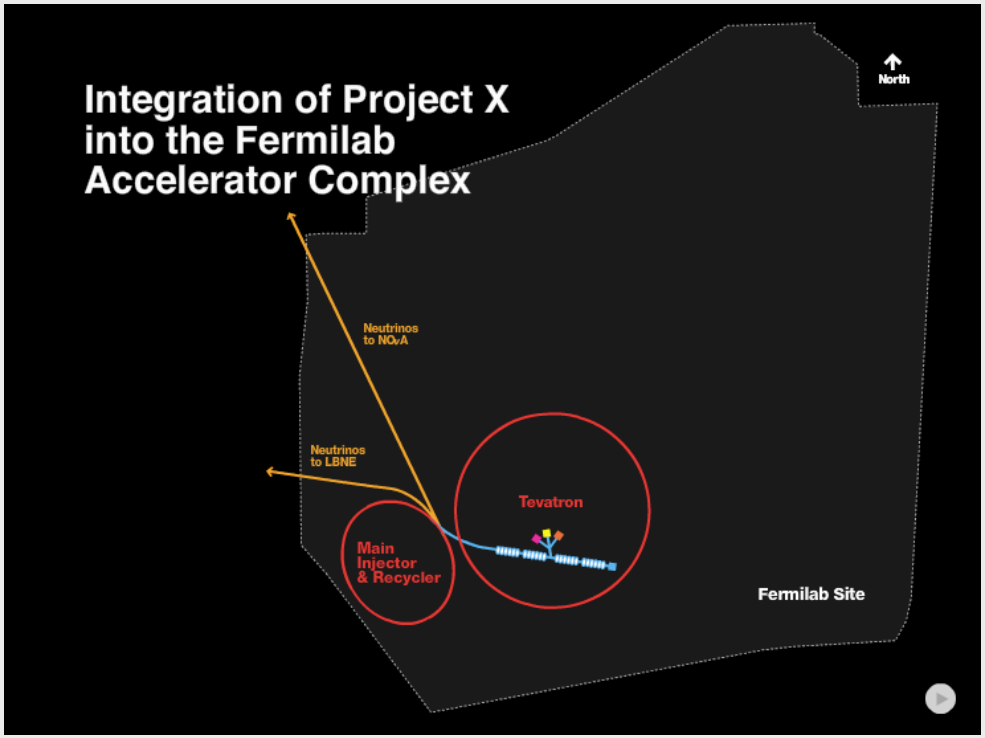
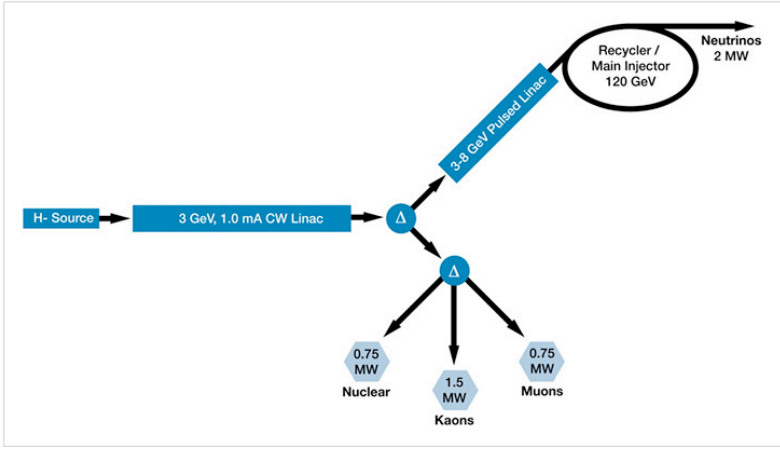
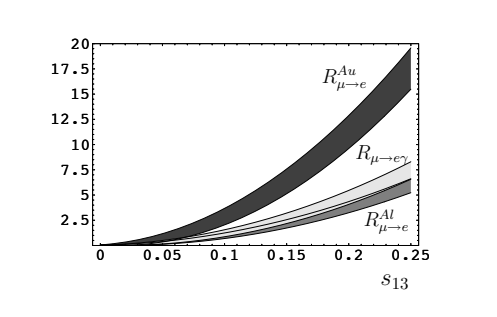
# Upgrades at Project X

- 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*



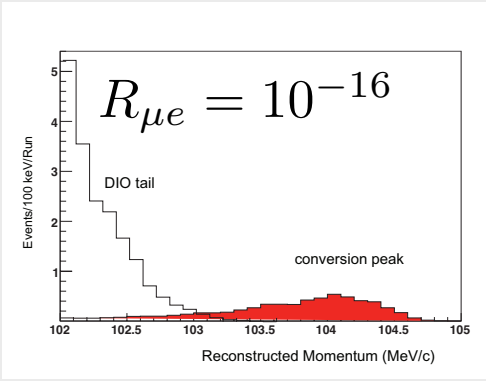
# Upgrade Plans...




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

# Outline

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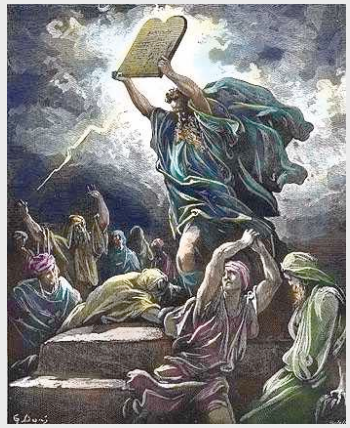
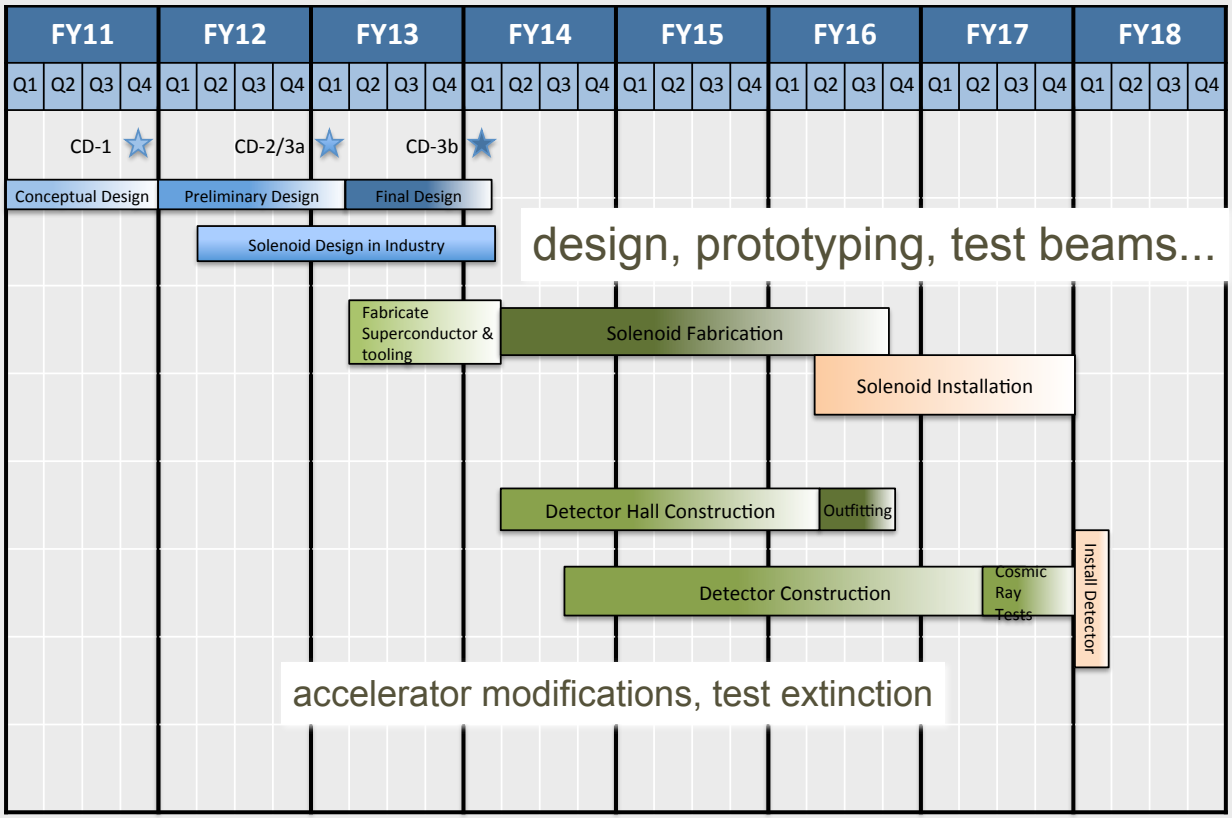
# Cost and Schedule

- ***This is a technically limited schedule***
- Critical Path is Superconducting Solenoids
- $200M "fully-loaded" Total Cost at CD-0

data-taking 2018

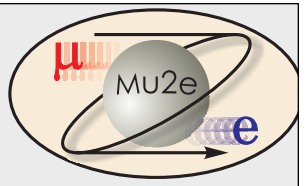




# Conclusions

- 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?