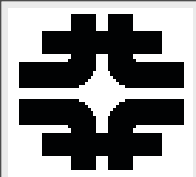


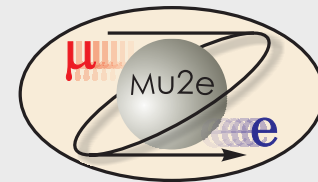
# A New Charged Lepton Flavor Violation Experiment: Muon-Electron Conversion at Fermilab

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*

*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*

**~130 collaborators**

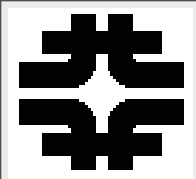
R. Bernstein, FNAL

2

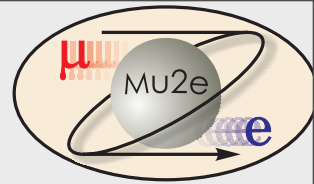
Mu2e

NuFact 2011

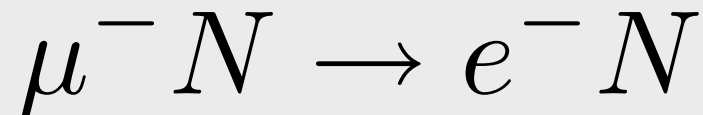




# What is $\mu e$ Conversion?



muon converts to electron in the presence of a nucleus

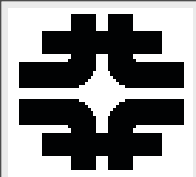


$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A, Z) \rightarrow e^- + N(A, Z))}{\Gamma(\mu^- + N(A, Z) \rightarrow \text{all muon captures})}$$

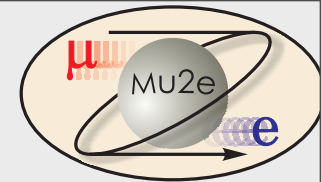
- Charged Lepton Flavor Violation (CLFV)
  - will measure  $R_{\mu e} < 6 \times 10^{-17}$  @ 90%CL
- Related Processes:

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



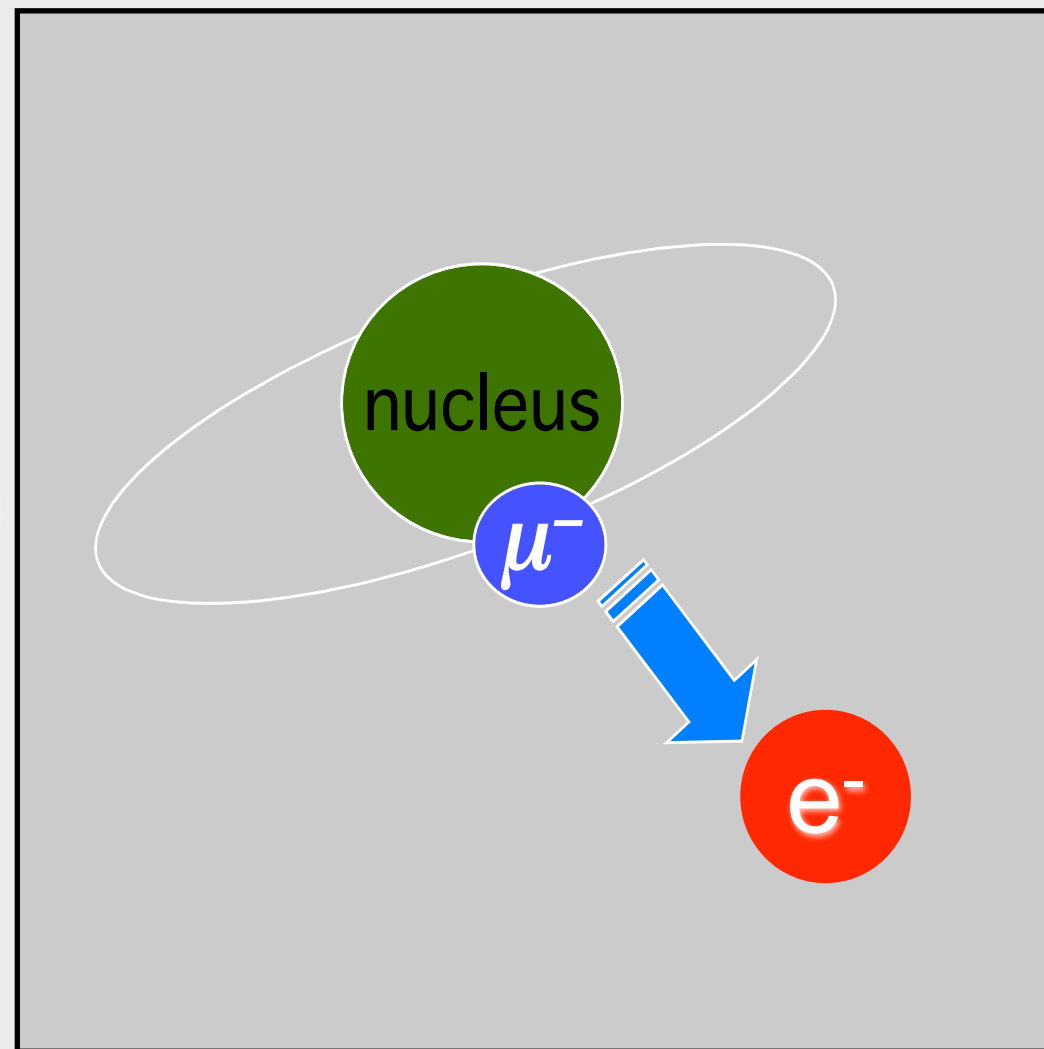


# Experimental Signal

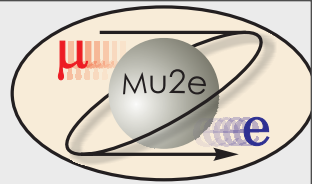
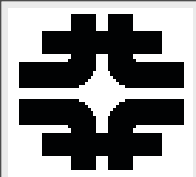


$$\mu^{-} N \rightarrow e^{-} N$$

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







# “Who ordered that?”



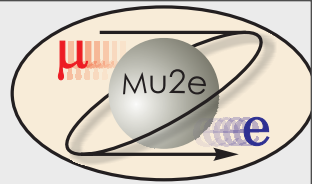
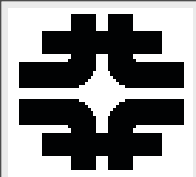
– I.I. Rabi, 1936

After the  $\mu$  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, cancels (Feinberg, 1958)

➡ same as GIM mechanism!





# “Who ordered that?”

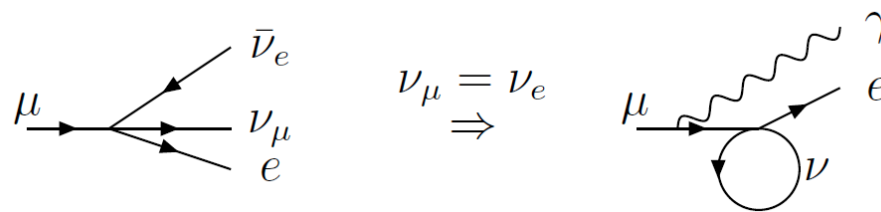


– I.I. Rabi, 1936

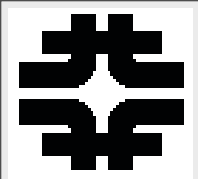
After the  $\mu$  was discovered, it was logical to think the  $\mu$  is just an excited electron:

- expect  $\text{BR}(\mu \rightarrow e\gamma) \approx 10^{-4}$
- Unless another  $\nu$ , in Intermediate Vector Boson Loop, can cancel (5) (1050)

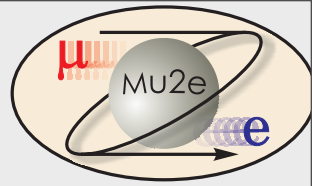
→ same



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

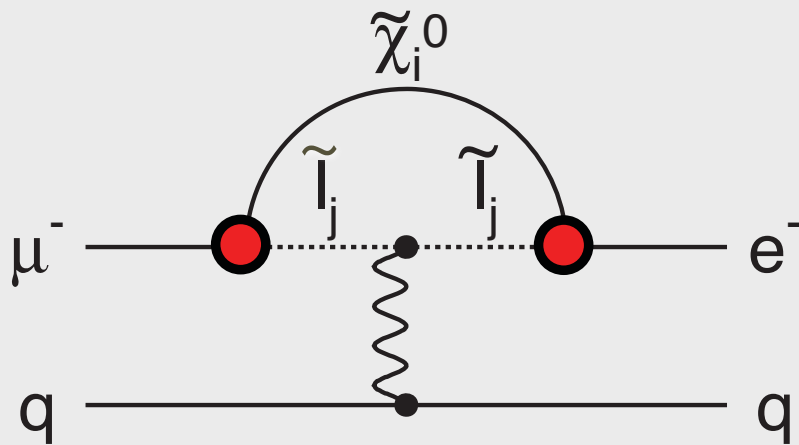


# LFV, SUSY and the LHC



## Supersymmetry

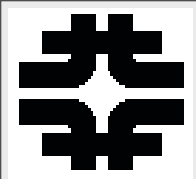
rate  $\sim 10^{-15}$



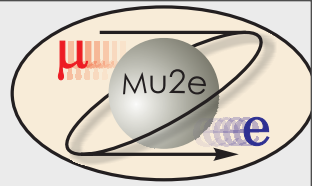
***Access SUSY  
through loops:***

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

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



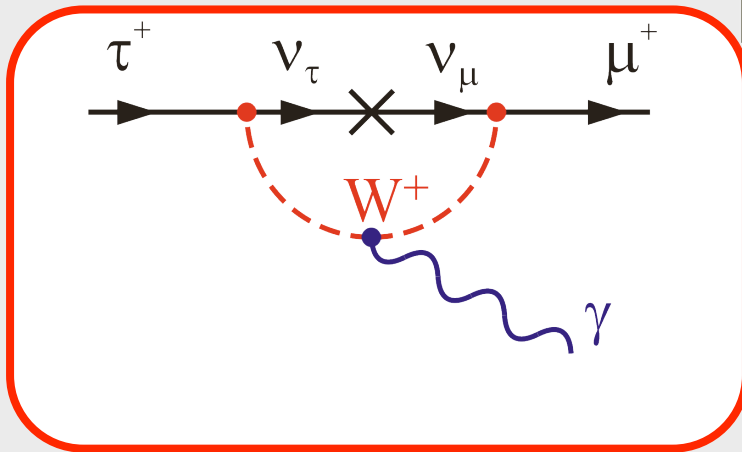
# CLFV and Tau Decays



$\tau$  processes also suppressed in Standard Model

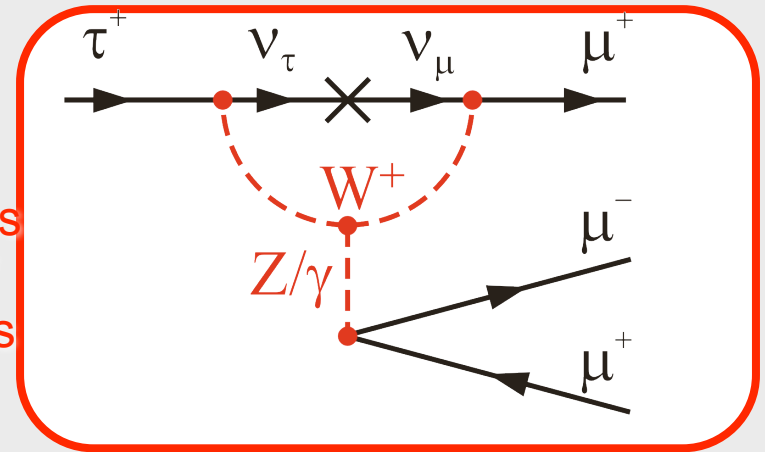
but less:

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



SM  $\sim 10^{-40}$

Smaller  
GIM  
Cancellations  
because of  
large  $\tau$  mass



SM  $\sim 10^{-14}$

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:  
 $\sim 10^{10}$   $\tau$ /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

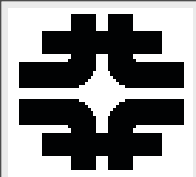
R. Bernstein, FNAL

7

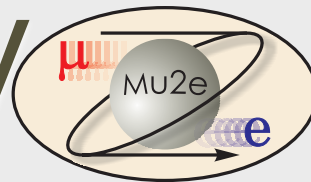
Mu2e

NuFact 2011





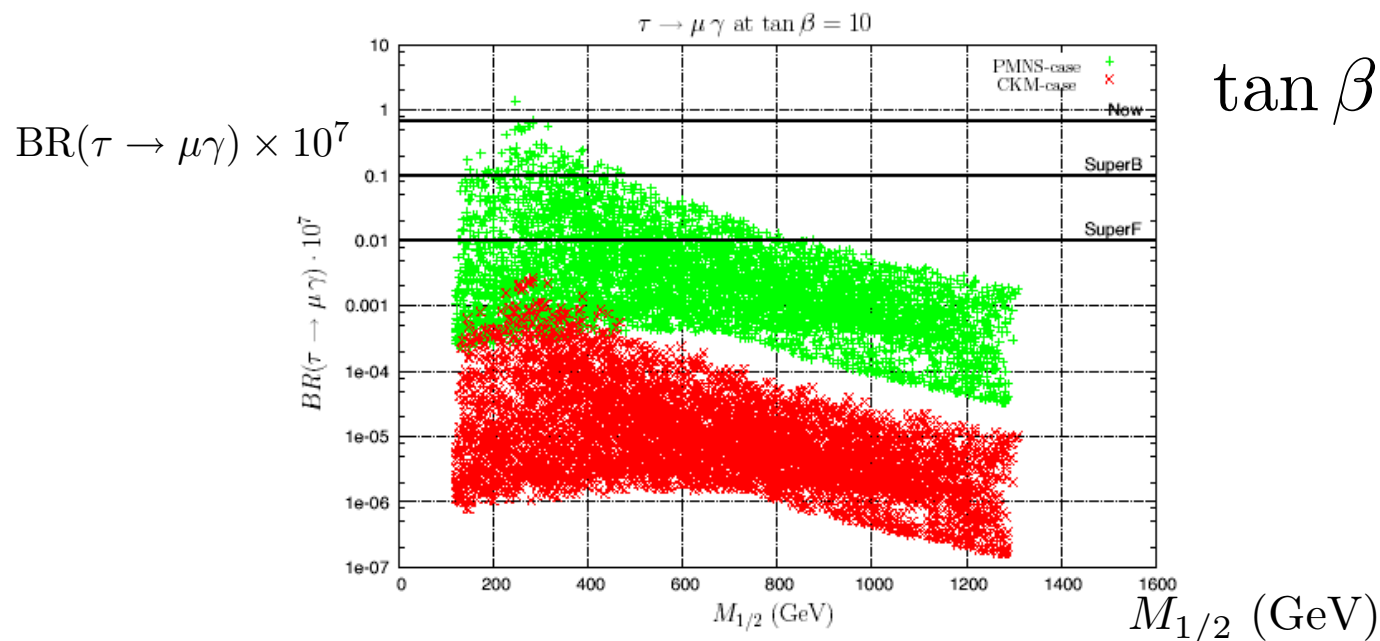
# Supersymmetry in Tau LFV



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

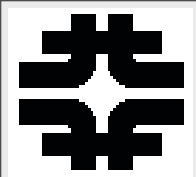
Neutrino-Matrix Like (PMNS)

Minimal Flavor Violation(CKM)

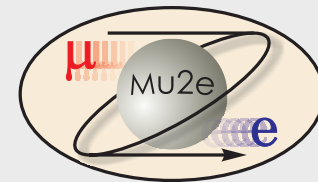


L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

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

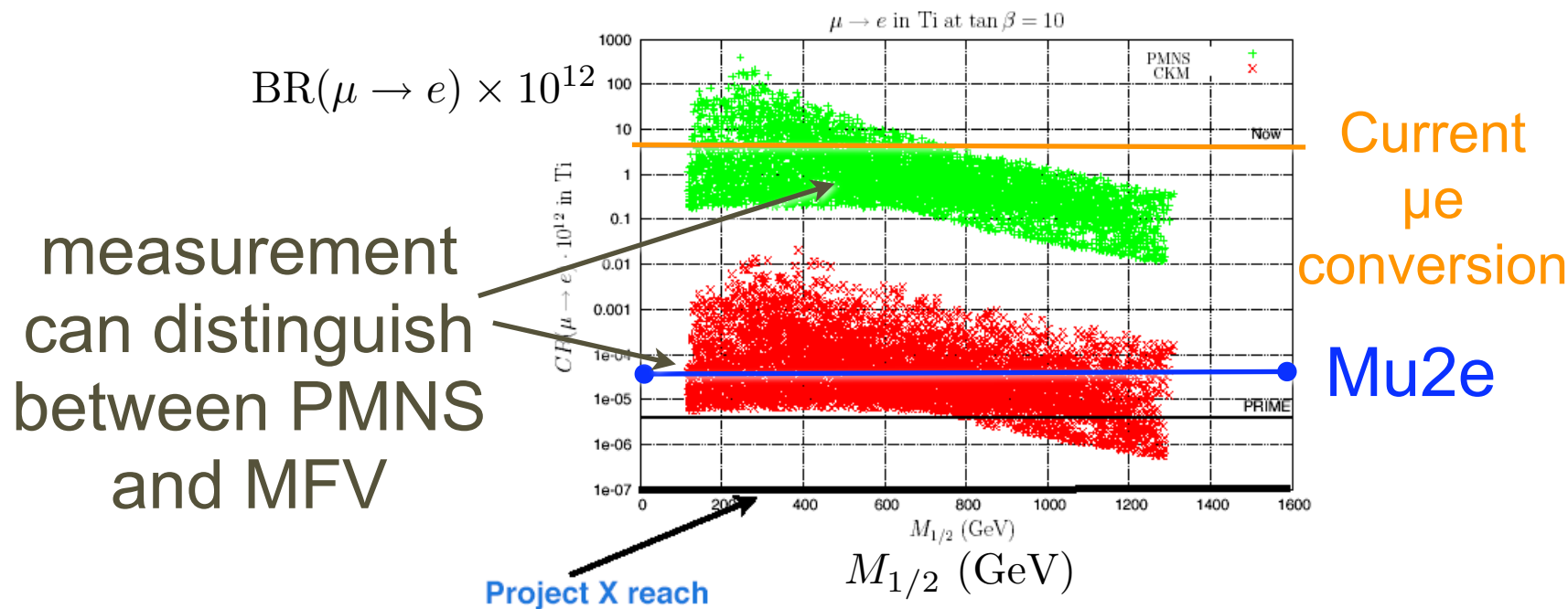


# And Muon-Electron Conversion



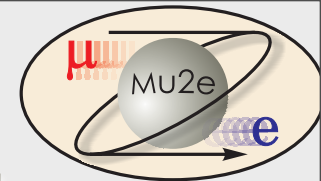
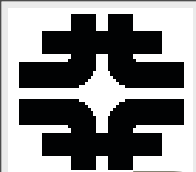
$$\tan \beta = 10$$

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



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

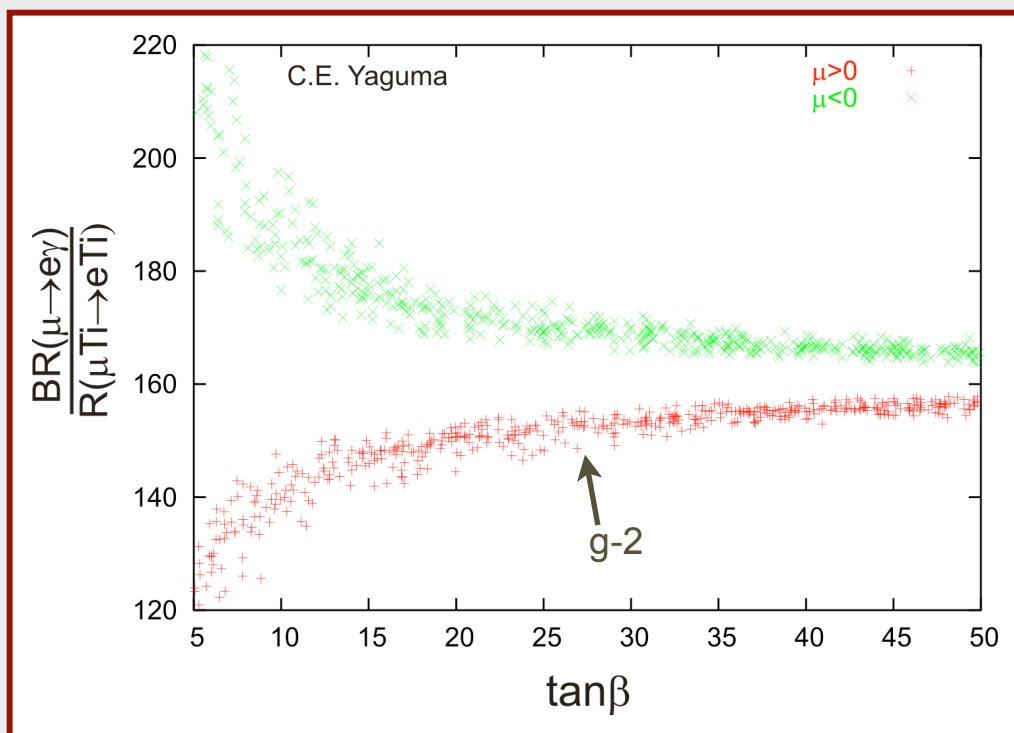
*complementarity between Lepton Flavor Violation (LFV) and LHC experiments*



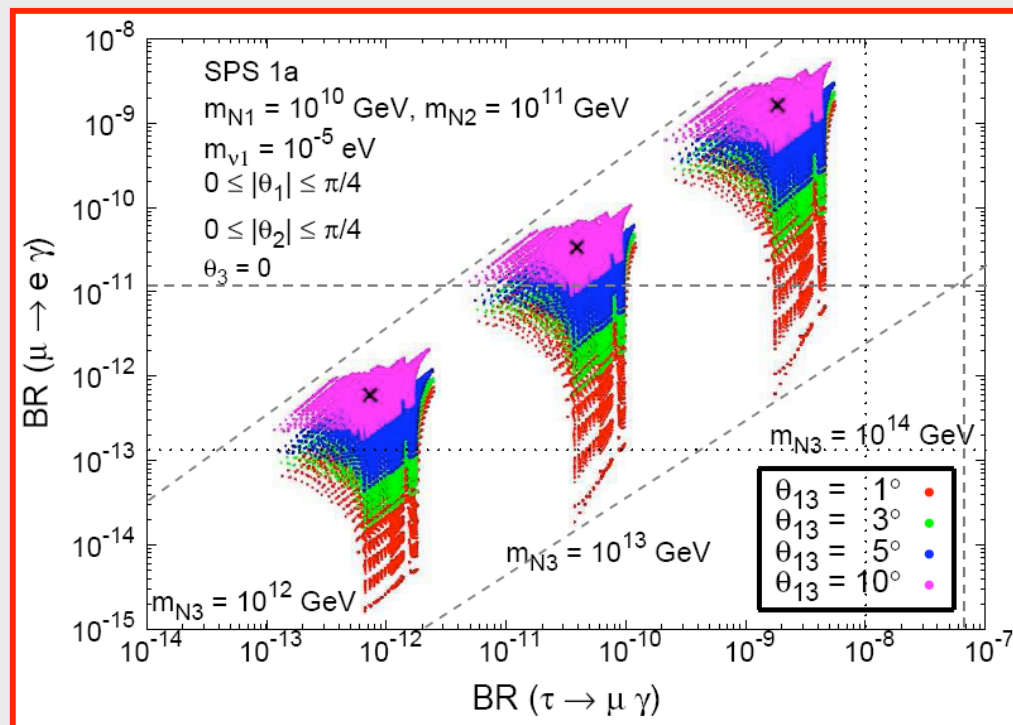
# Pinning Down SuperSymmetry

MSSM w mSUGRA

CMSSM - seesaw

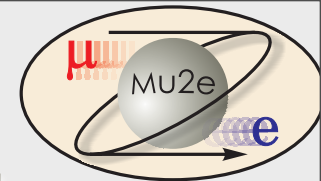
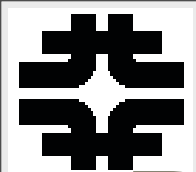


Yaguna, hep-ph/0502014v2



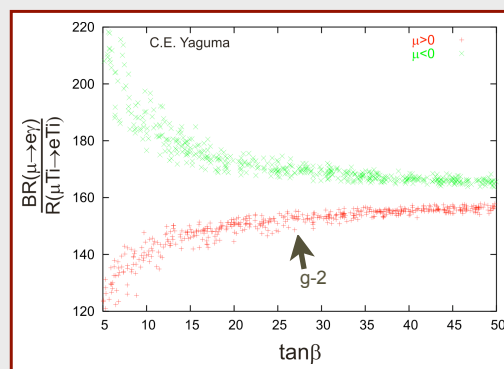
Antusch et al., hep-ph/0610439





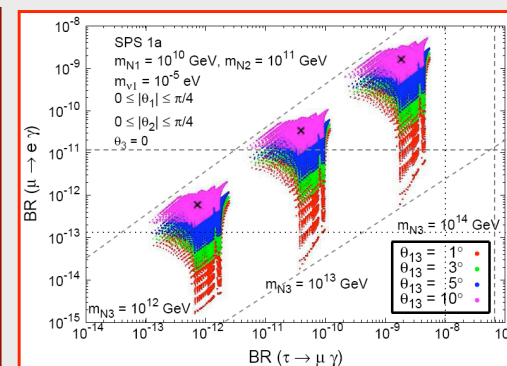
# Pinning Down SuperSymmetry

MSSM w mSUGRA



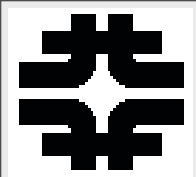
Yaguna, hep-ph/0502014v2

CMSSM - seesaw

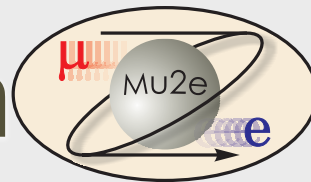


Antusch et al., hep-ph/0610439

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

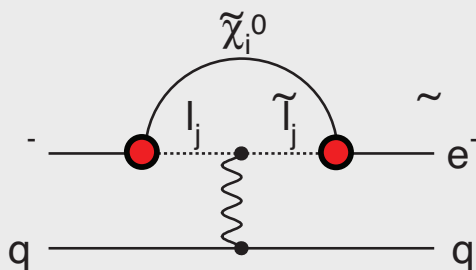


# Contributions to $\mu e$ Conversion



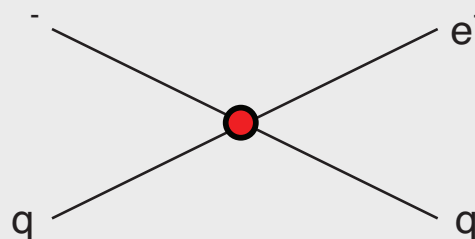
## Supersymmetry

rate  $\sim 10^{-15}$



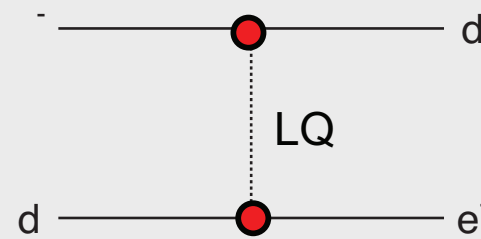
## Compositeness

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



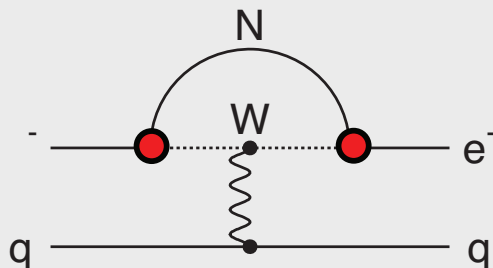
## Leptoquark

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



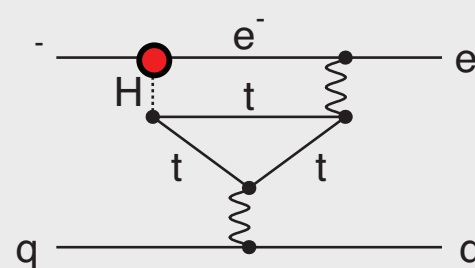
## Heavy Neutrinos

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



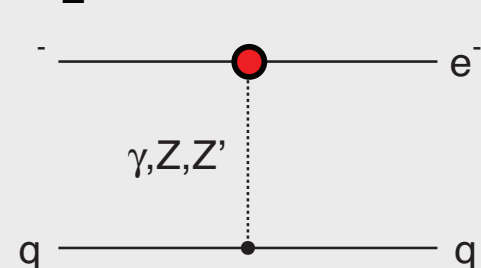
## Second Higgs Doublet

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



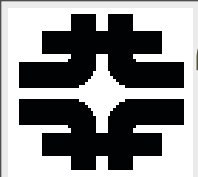
## Heavy $Z'$ Anomal. Z Coupling

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

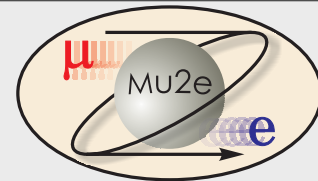


also see Flavour physics of leptons and dipole moments, [arXiv:0801.1826](https://arxiv.org/abs/0801.1826)

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

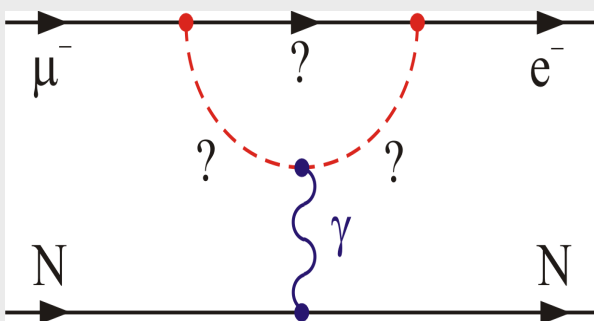


$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(\kappa + 1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1 + \kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma_\mu u_L + \bar{d}_L \gamma_\mu d_L)$$

“Loops”

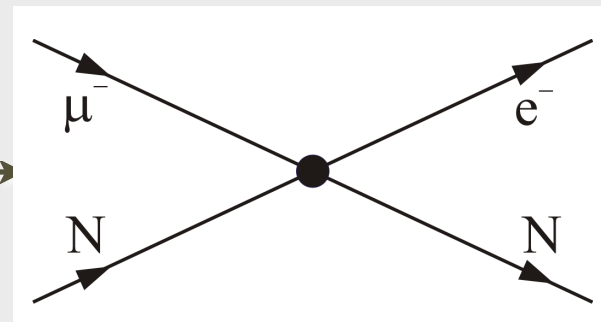
“Contact Terms”

$\kappa=0$



mass scale  $\Lambda$

$\kappa$



$\kappa=1$

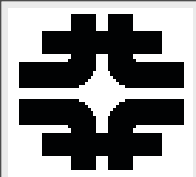
Supersymmetry and Heavy Neutrinos

Contributes to  $\mu \rightarrow e \gamma$  ( $\gamma$  real)

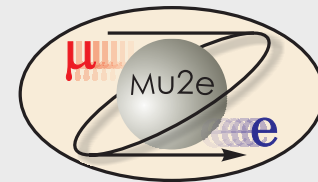
Does not produce  $\mu \rightarrow e \gamma$

Quantitative Comparison?





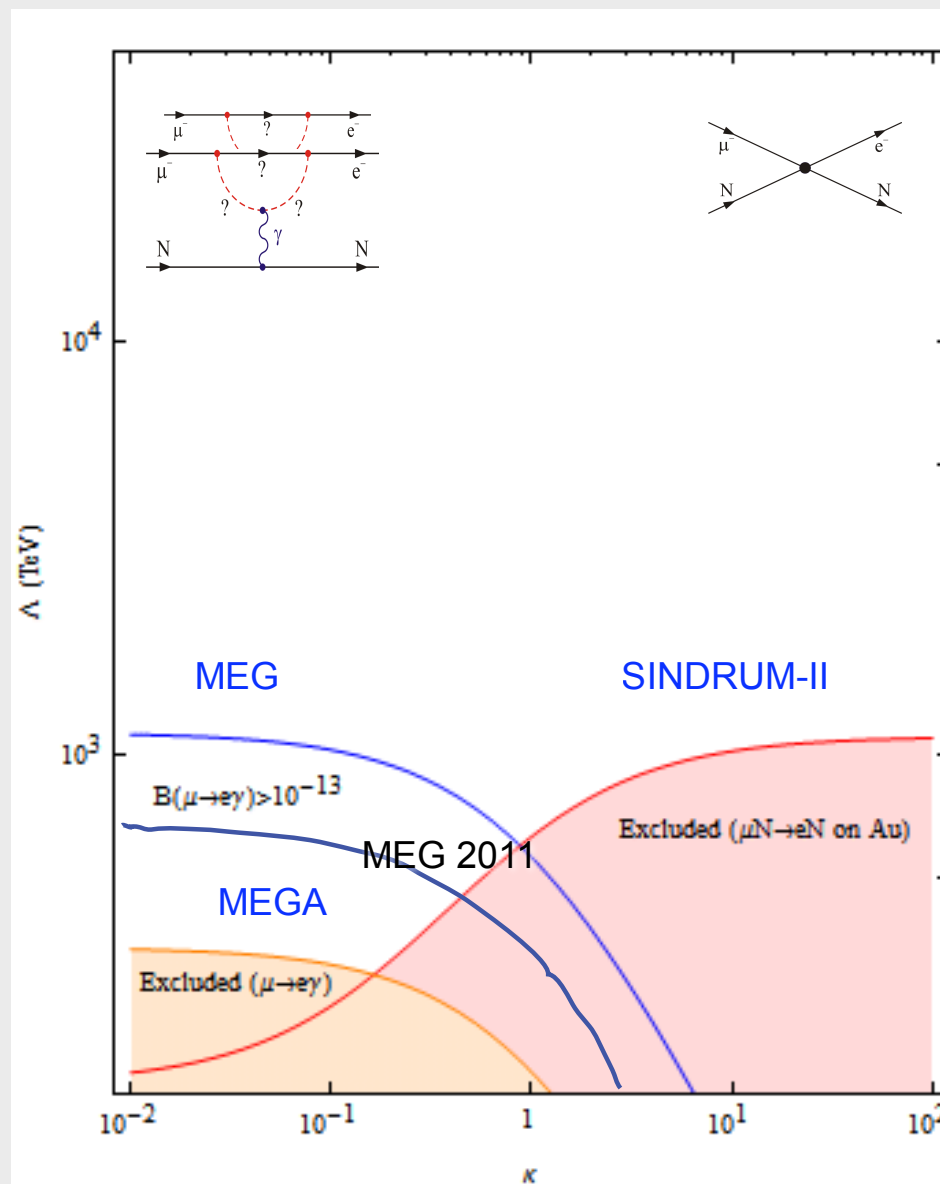
# $\mu e$ Conversion and $\mu \rightarrow e \gamma$



$\Lambda$  (TeV)

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

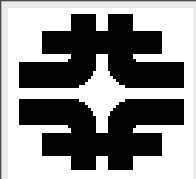
2) *about x2 beyond MEG in loop-dominated physics*



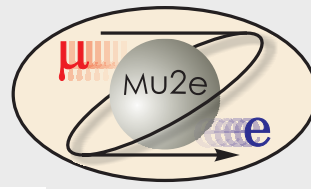
higher mass scale

$\mathcal{K}$

André de Gouvêa, Project X Workshop Golden Book



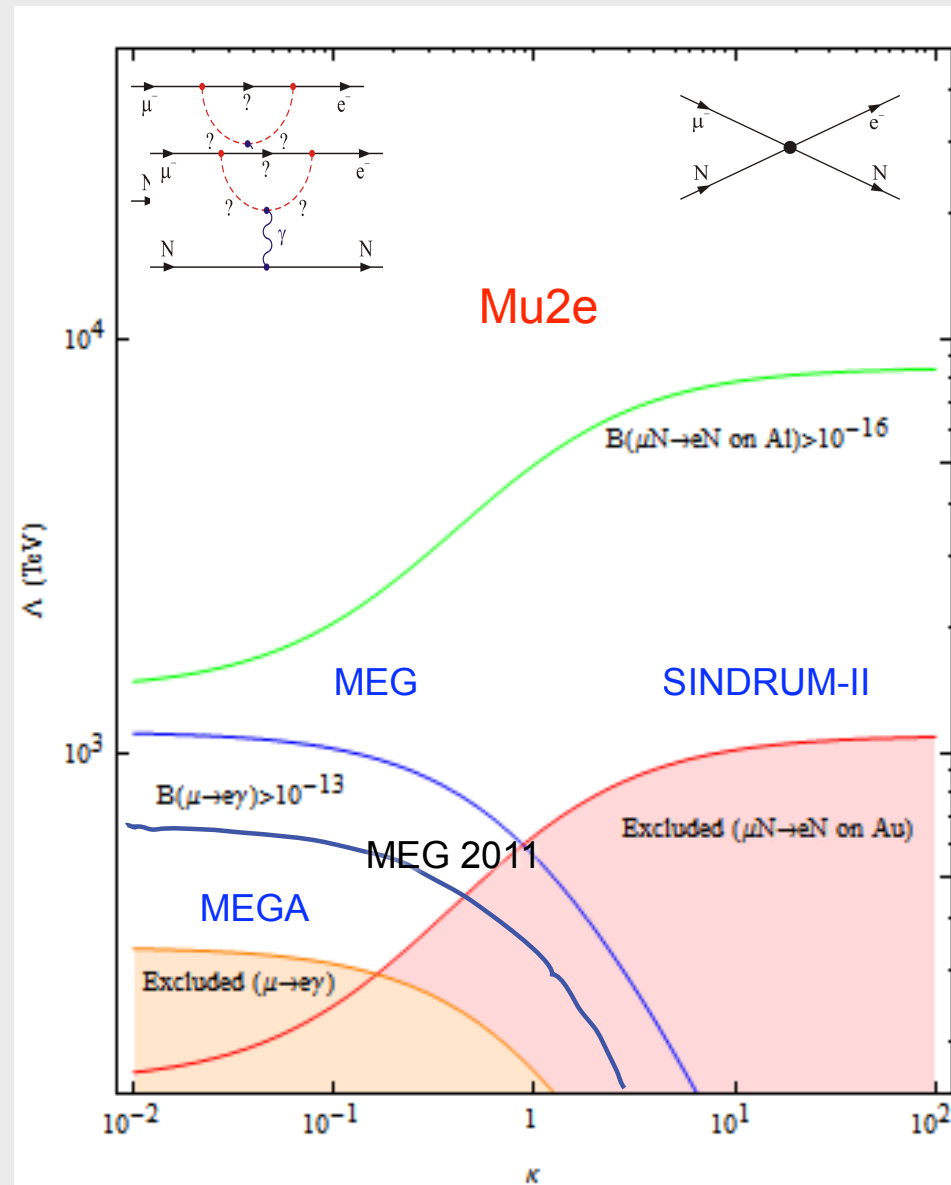
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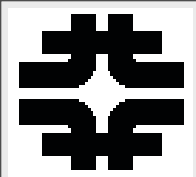
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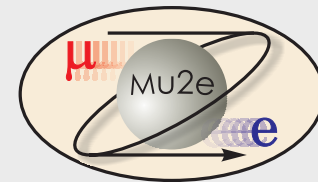
higher mass scale

$\mathcal{K}$

André de Gouvêa, Project X Workshop Golden Book



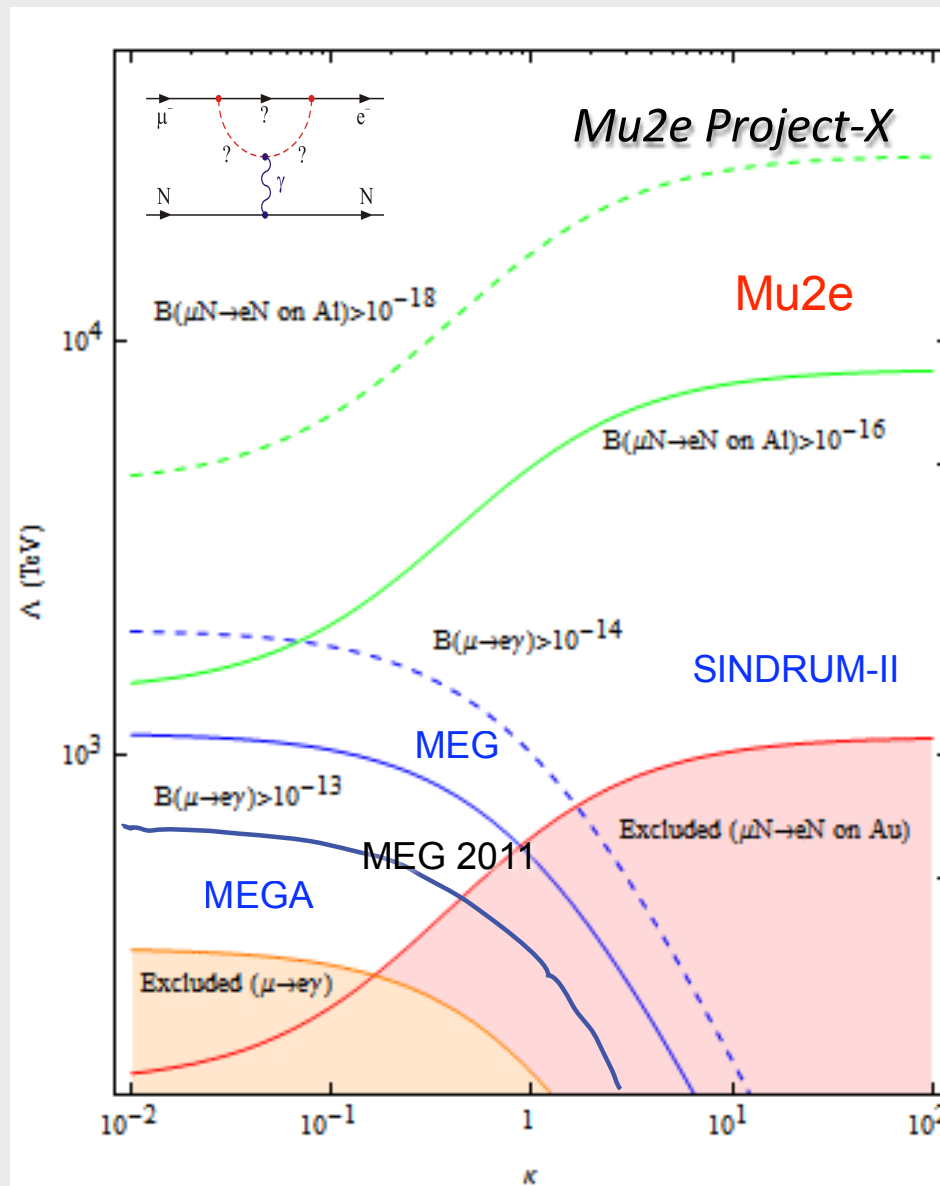
# $\mu e$ Conversion and $\mu \rightarrow e \gamma$



$\Lambda$  (TeV)

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to  $\sim 10^4$  TeV

2) about x2  
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loop-dominated  
physics

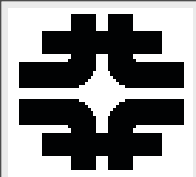


higher mass scale

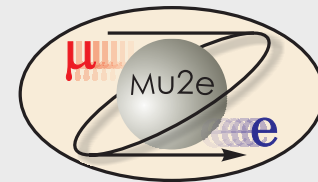
$\kappa$

André de Gouvêa, Project  
X Workshop Golden Book

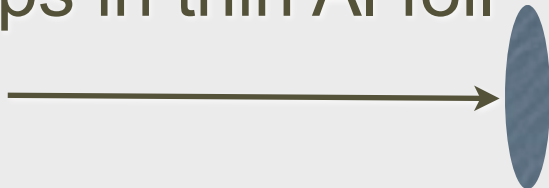




# Overview Of Processes

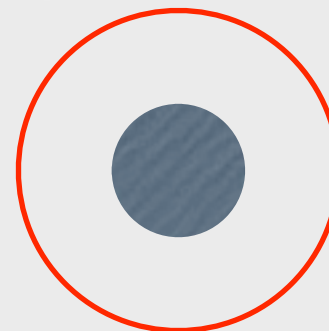


$\mu^-$  stops in thin Al foil



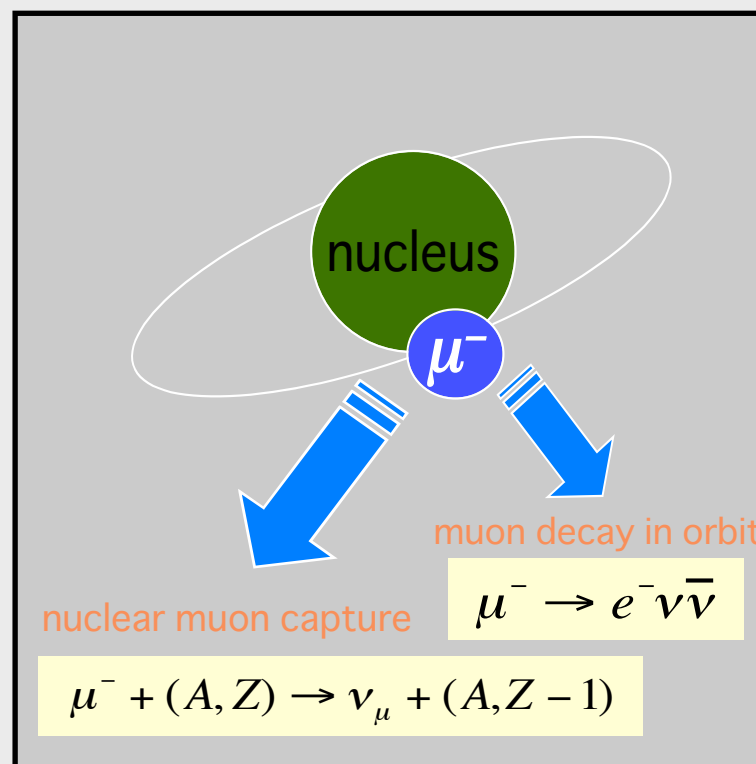
*the Bohr radius is  $\sim 20$  fm,  
so the  $\mu^-$  sees the nucleus*

$\mu^-$  in 1s state



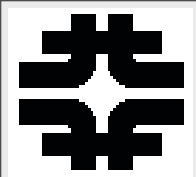
Al Nucleus  
 $\sim 4$  fm

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

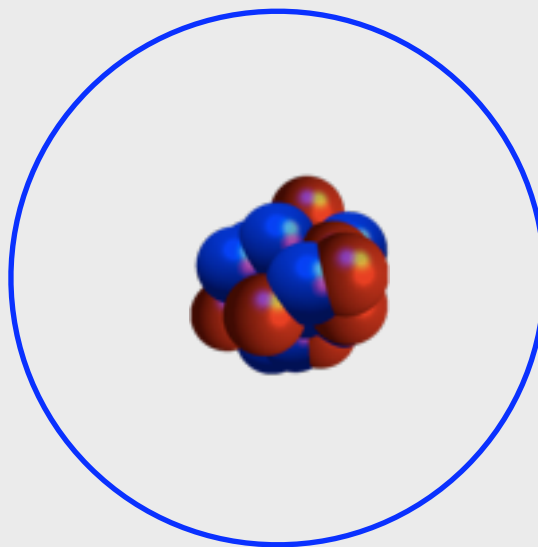
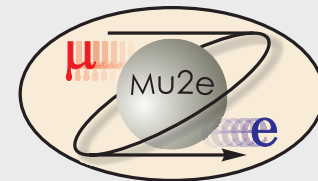


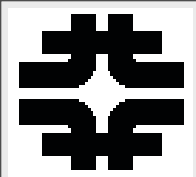
60% capture  
40% decay

Decay in Orbit:  
**background**

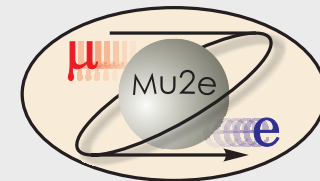


# Three Possibilities: Normalization

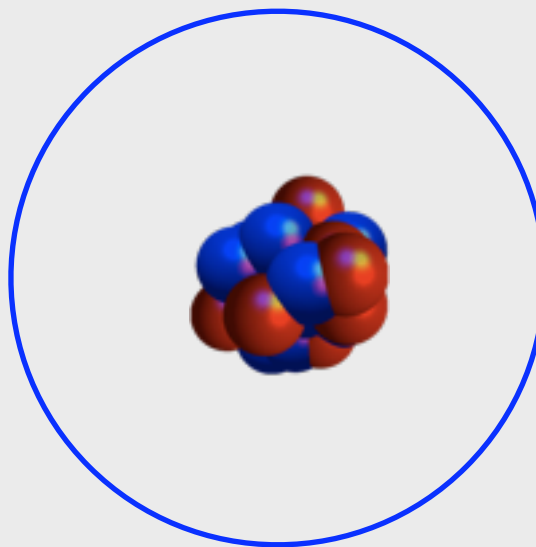


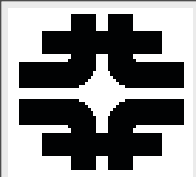


# Three Possibilities: Normalization

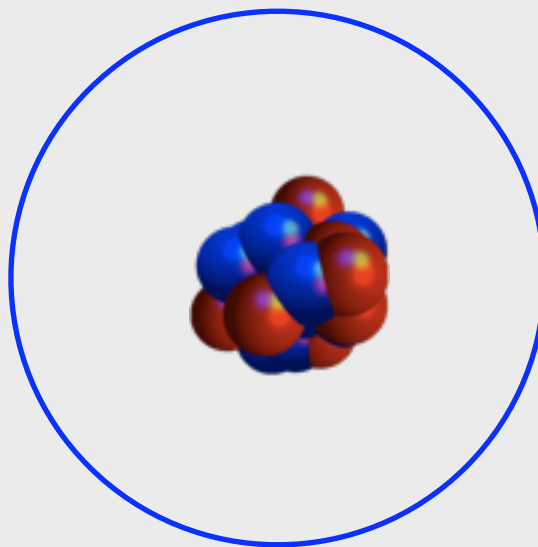
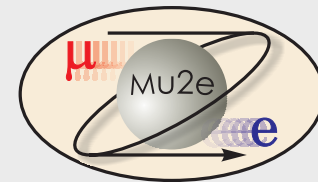


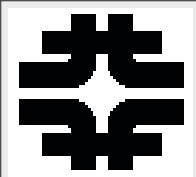
muon stops  
 $\mu$



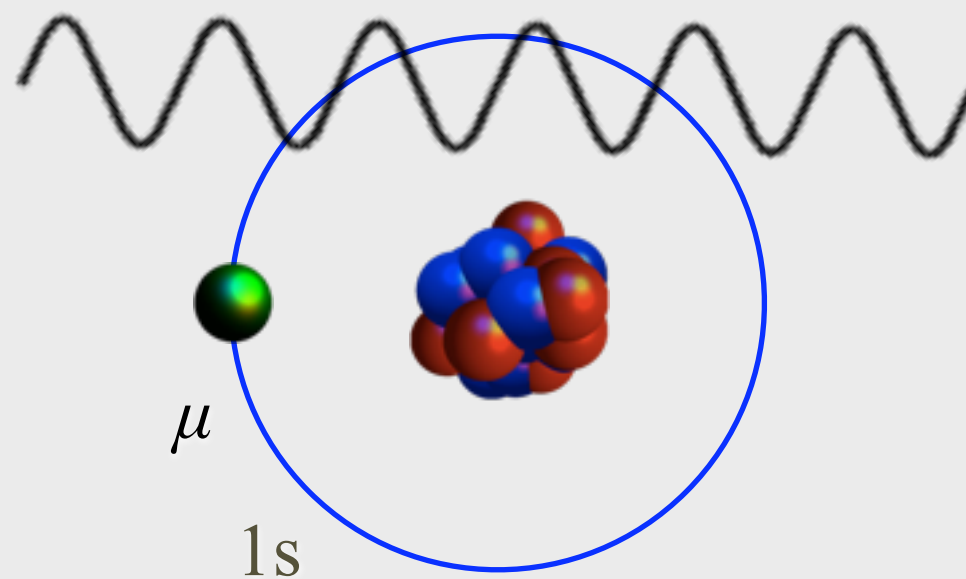
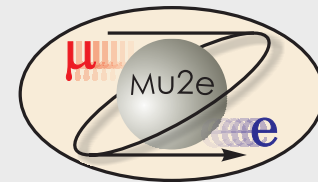


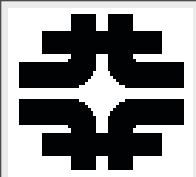
# Three Possibilities: Normalization



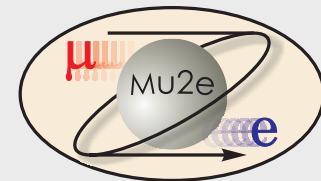


# Three Possibilities: Normalization





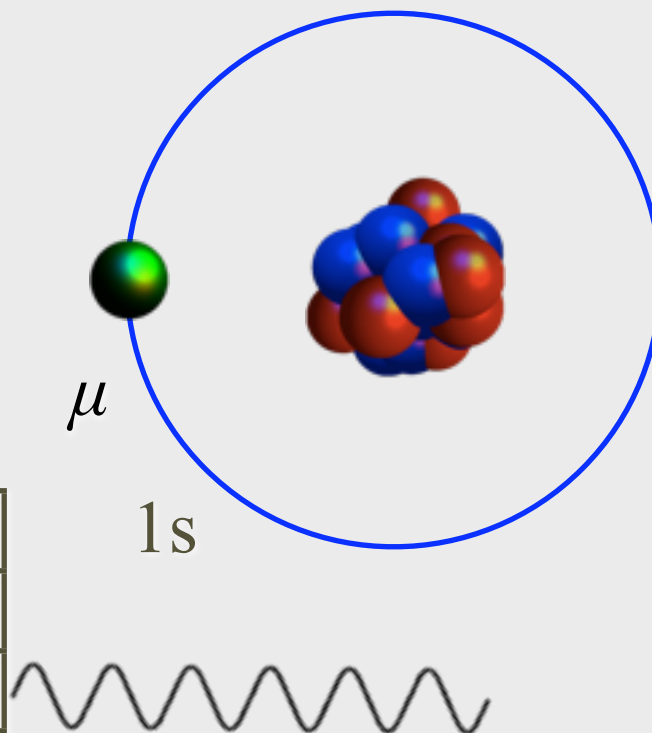
# Three Possibilities: Normalization



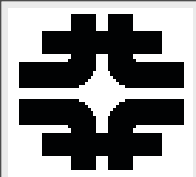
X-Rays from  
cascade  
(occurs in psec)

detect these  
for  
normalization

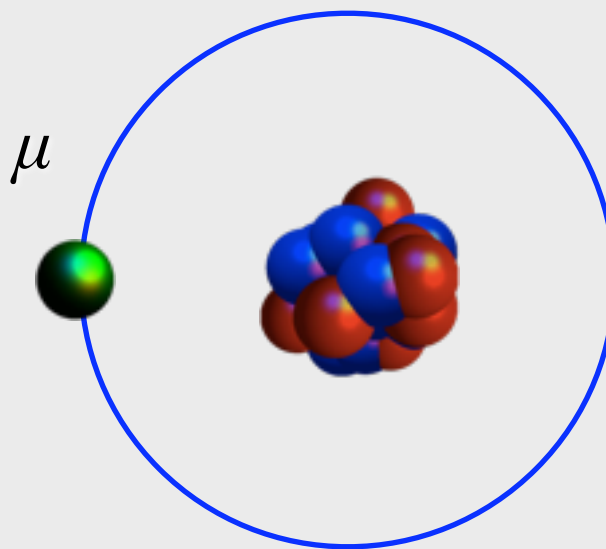
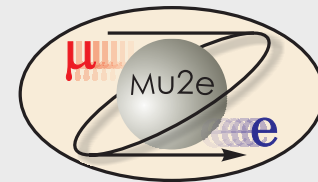
Transition	Energy
3d → 2p	66 keV
2p → 1s	356 keV
3d → 1s	423 keV
4p → 1s	446 keV

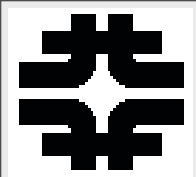




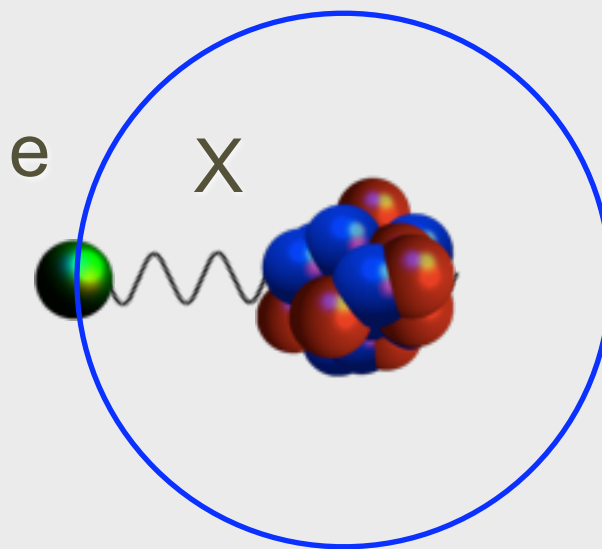
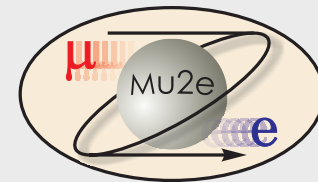


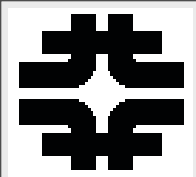
# Three Possibilities: Signal



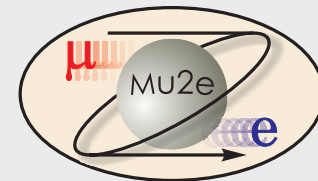


# Three Possibilities: Signal

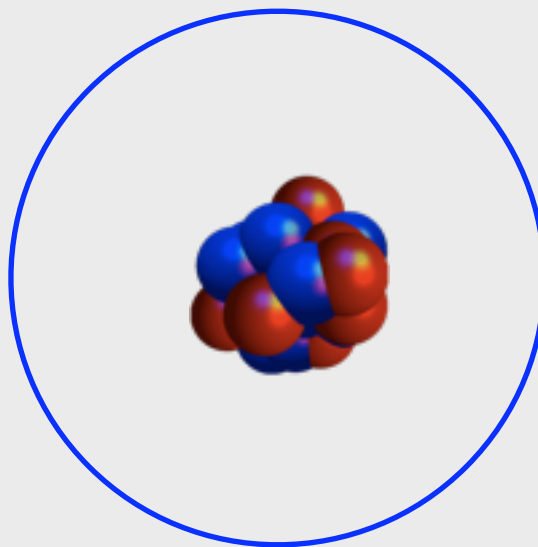


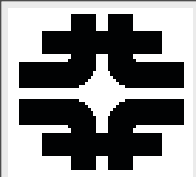


# Three Possibilities: Signal

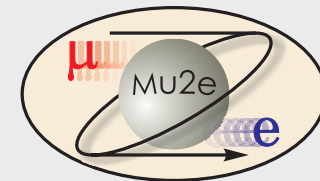


e

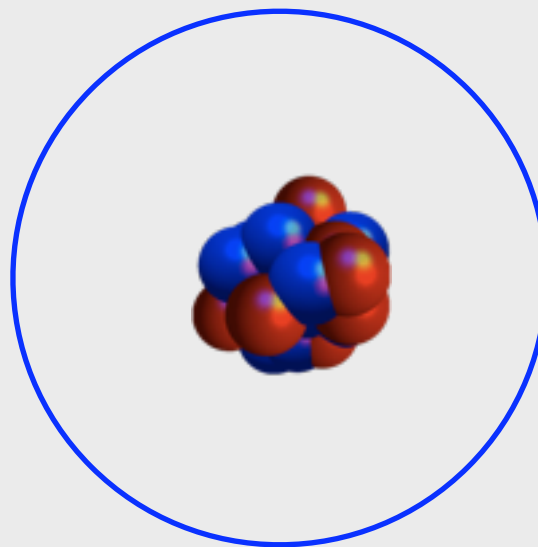




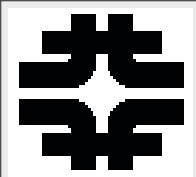
# Three Possibilities: Signal



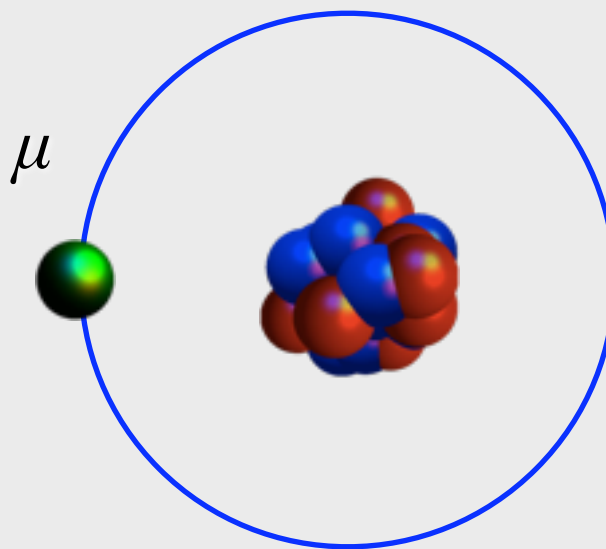
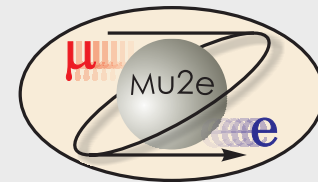
e *off to detector!*

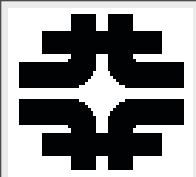


coherent recoil of nucleus

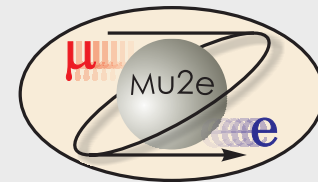


# Three Possibilities: Background





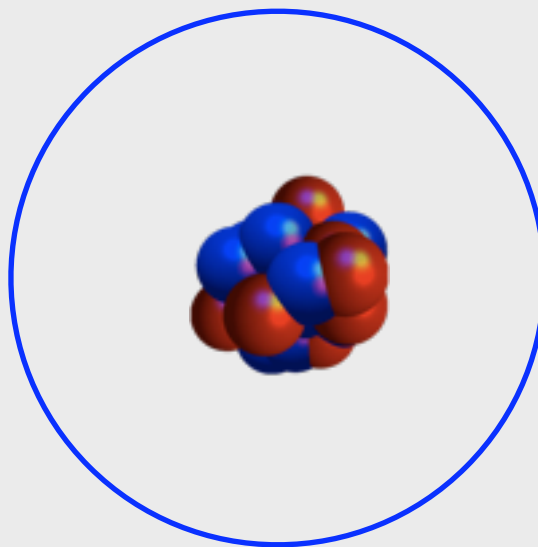
# Three Possibilities: Background



$e$

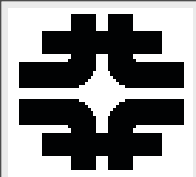


$\nu_{\mu}$

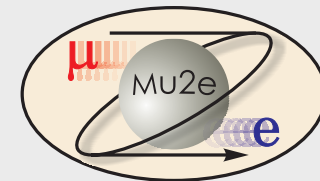


$\bar{\nu}_e$





# Three Possibilities: Background



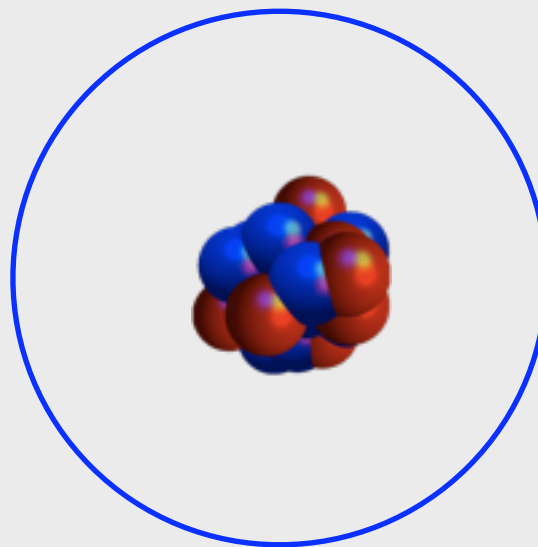
this electron can be background;  
let's see how



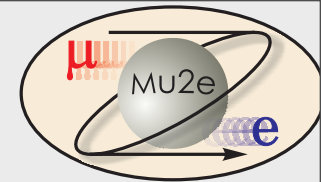
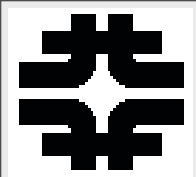
$e$



$\nu_{\mu}$



$\bar{\nu}_e$

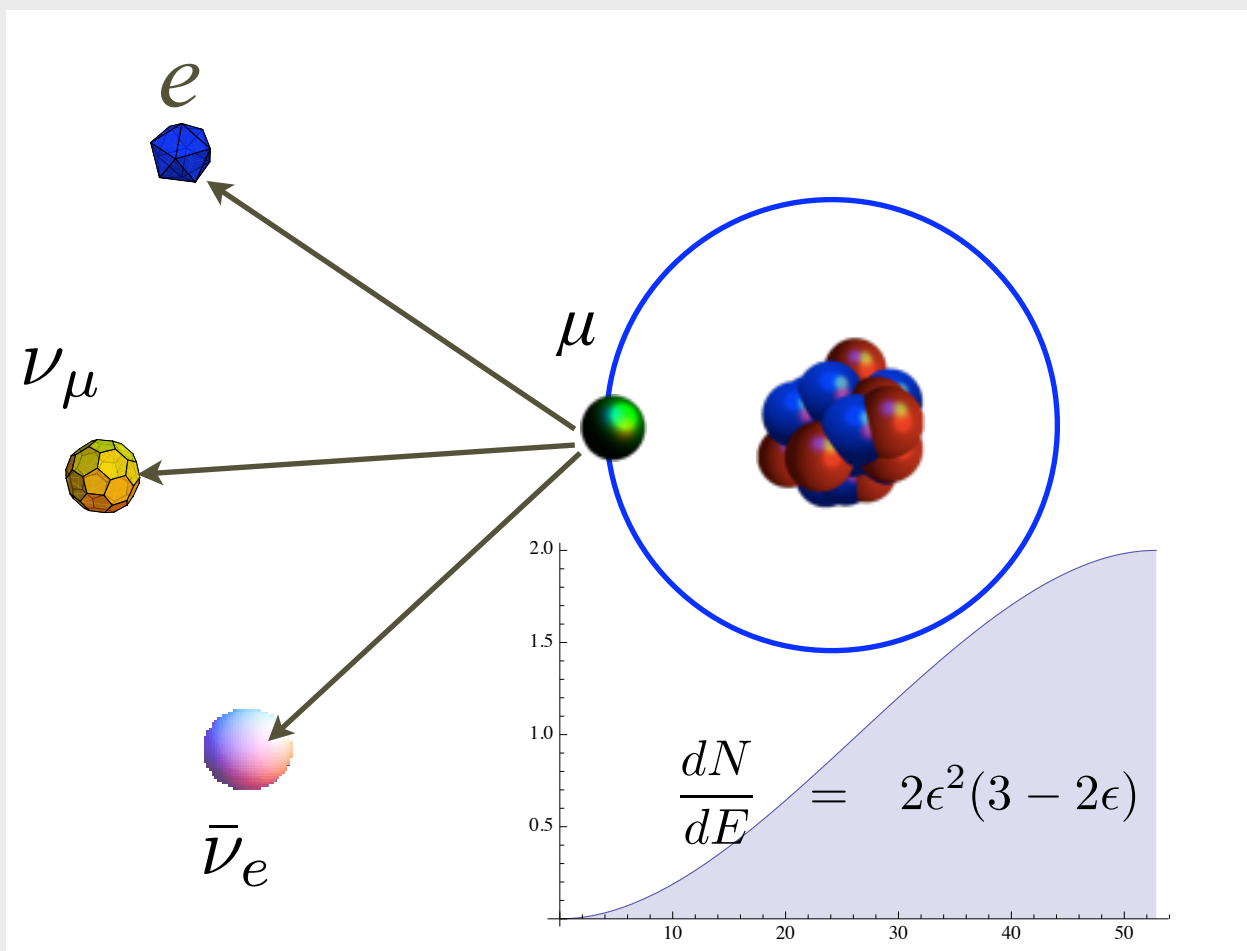


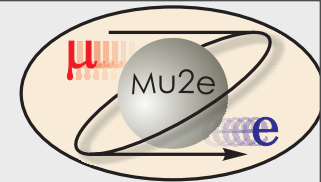
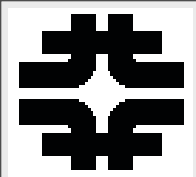
# Decay-In-Orbit: Not Normally Background

- Peak and Endpoint of Michel Spectrum is at

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

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



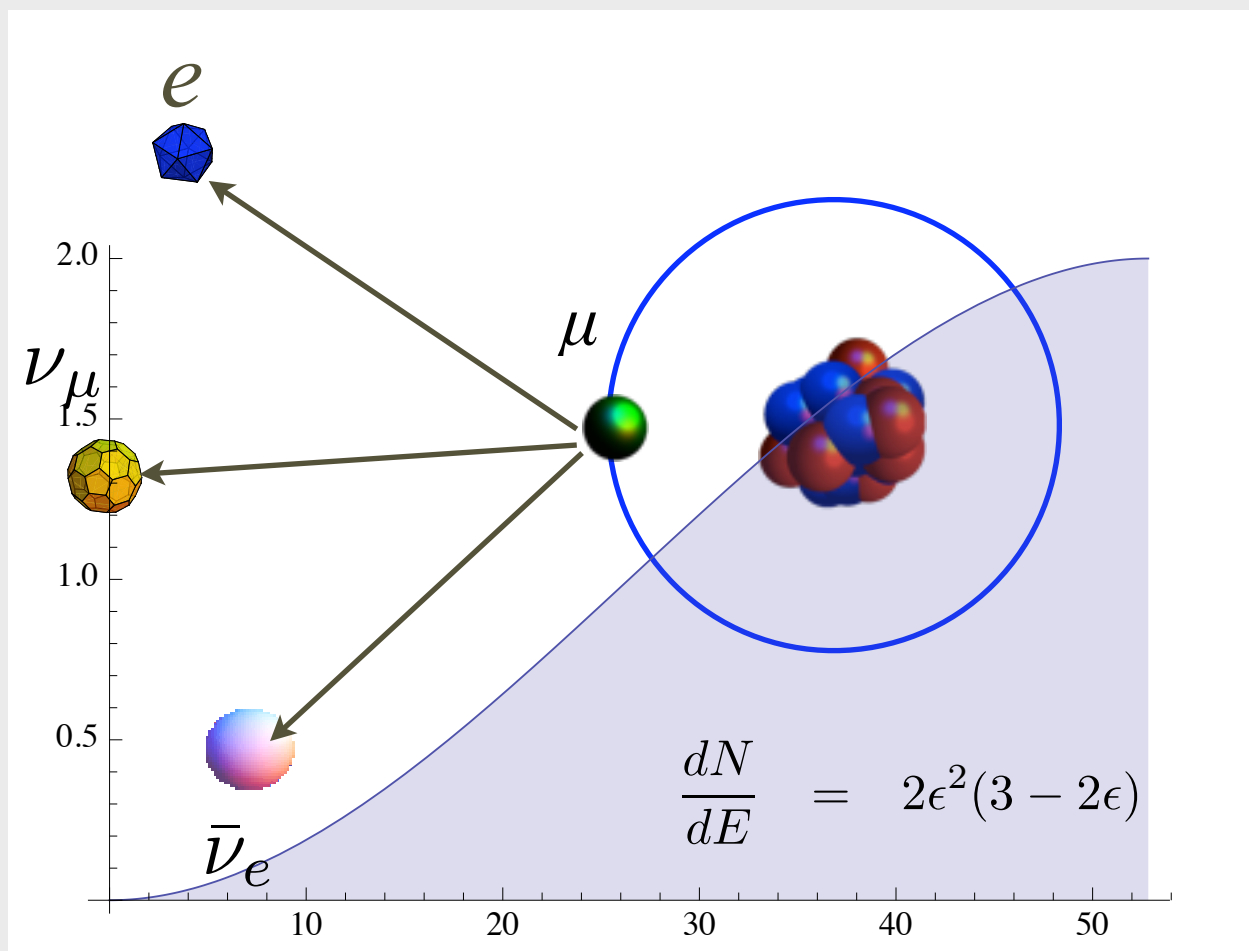


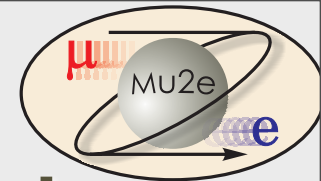
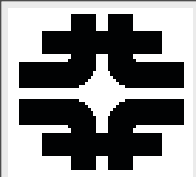
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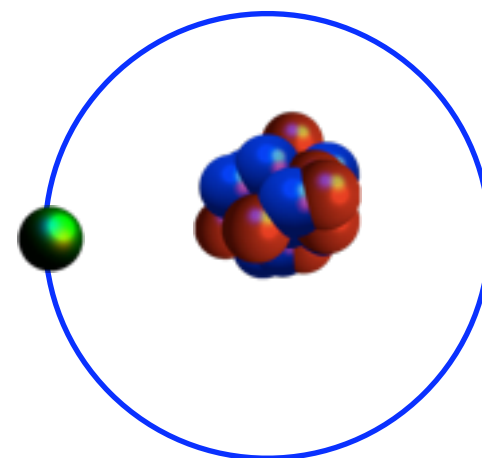
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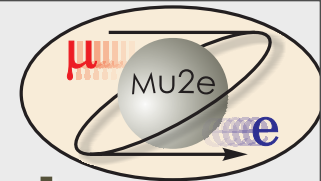
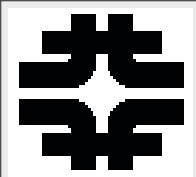




# Decay-In-Orbit Background

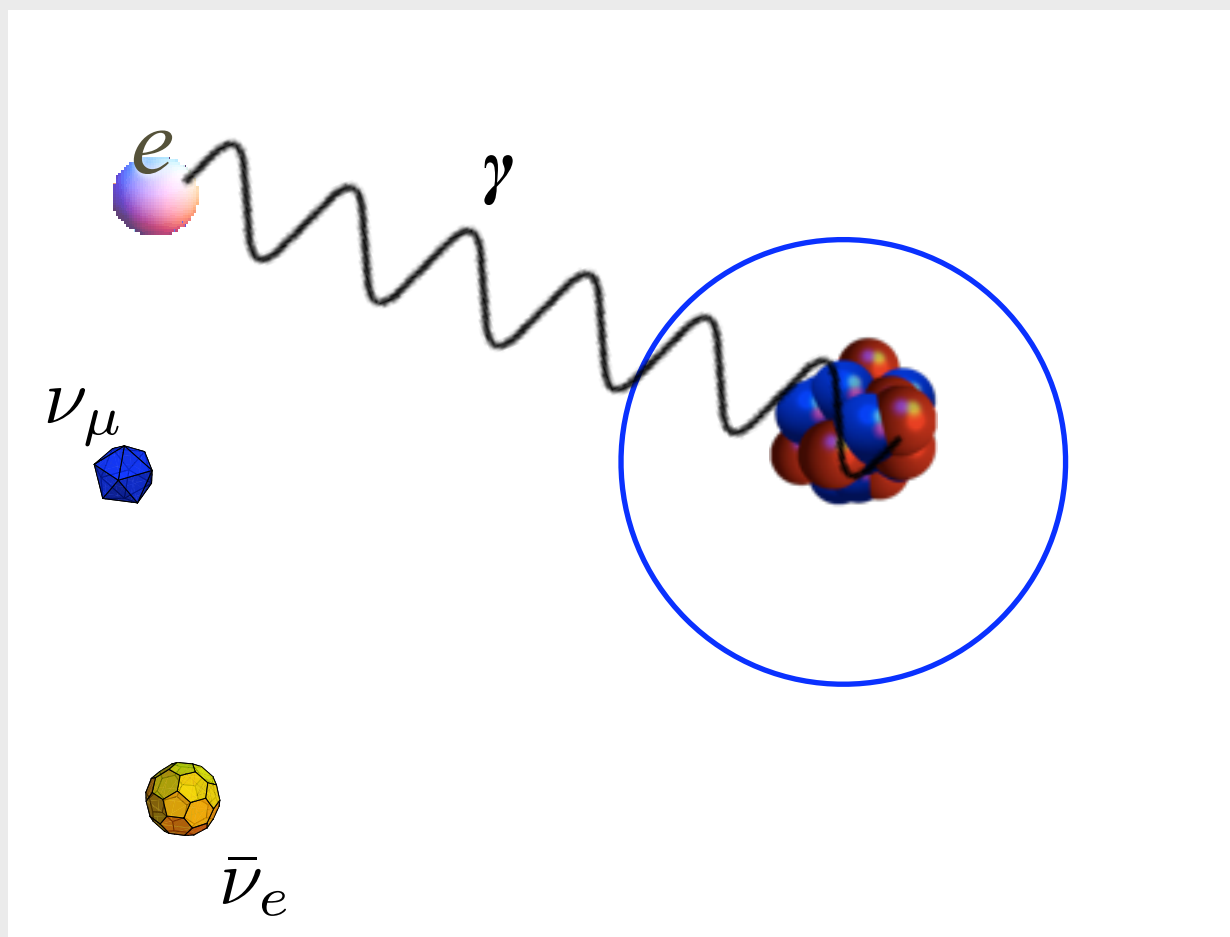
- Same process as before
- But this time, include electron recoil off nucleus
- If neutrinos are at rest, **the DIO electron can be exactly at conversion energy** (up to neutrino mass)

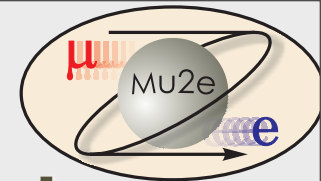
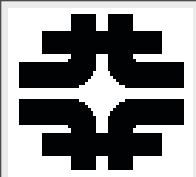




# Decay-In-Orbit Background

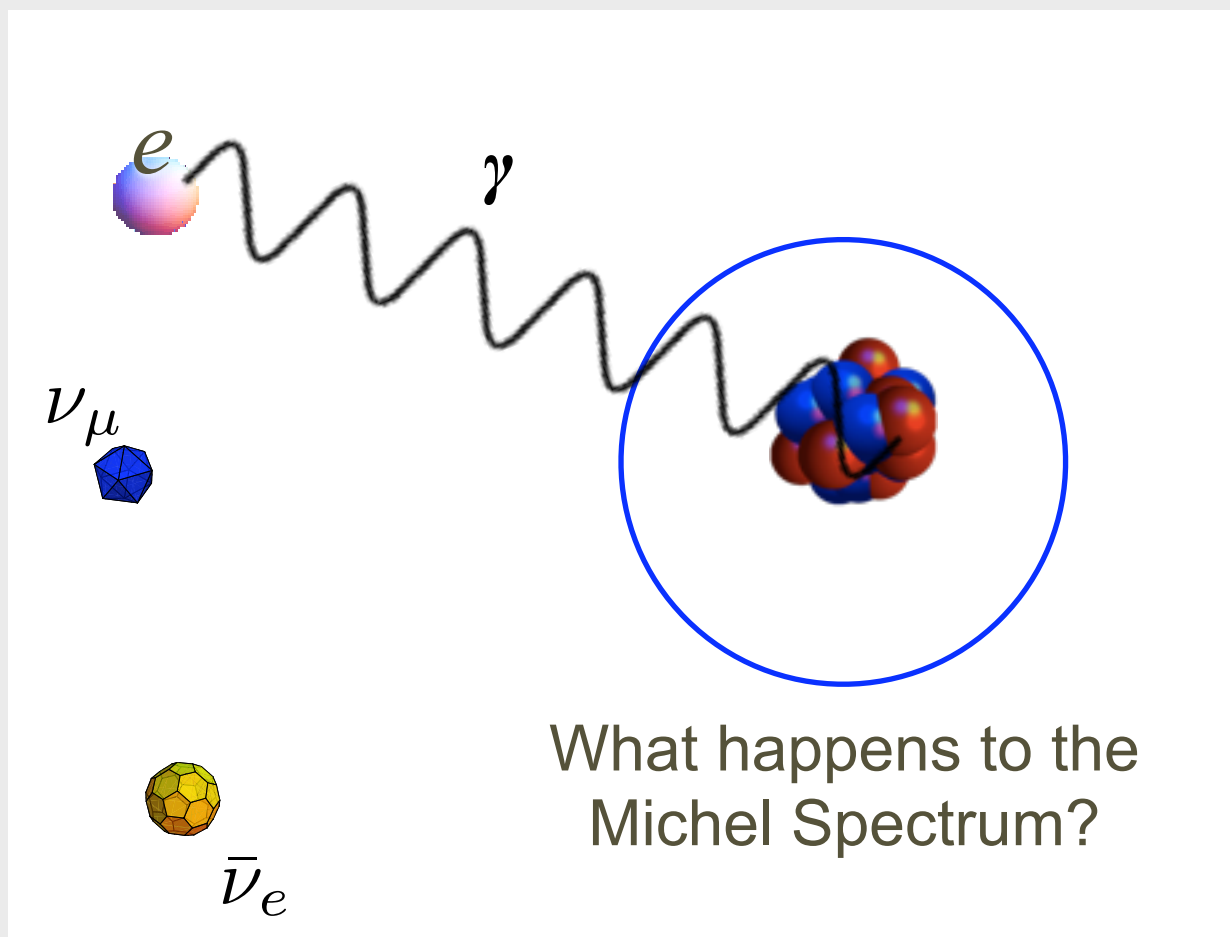
- Same process as before
- But this time, include electron recoil off nucleus
- If neutrinos are at rest, **the DIO electron can be exactly at conversion energy** (up to neutrino mass)



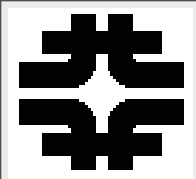


# Decay-In-Orbit Background

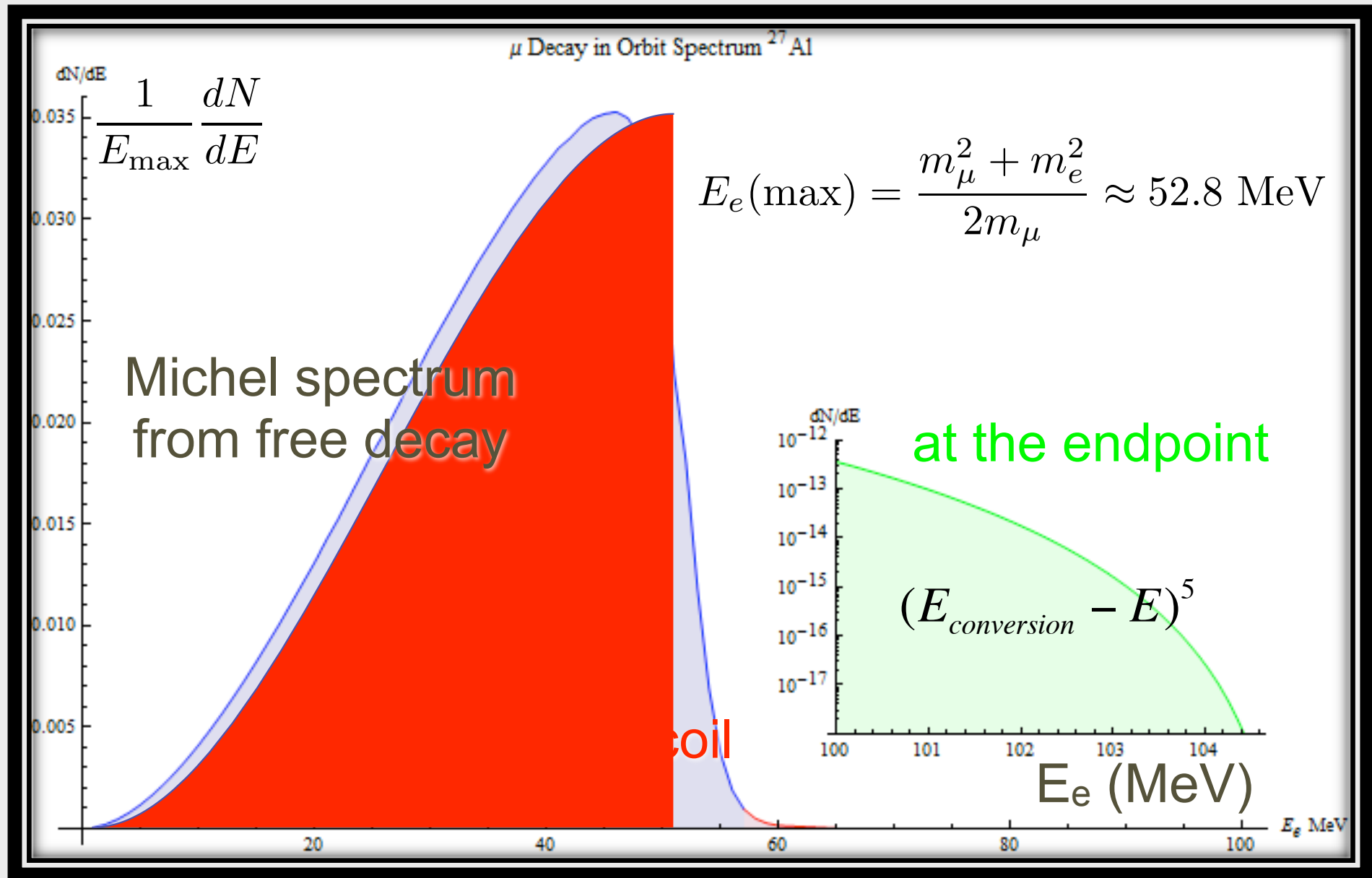
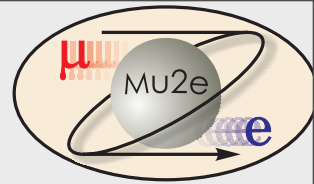
- Same process as before
- But this time, include electron recoil off nucleus
- If neutrinos are at rest, **the DIO electron can be exactly at conversion energy** (up to neutrino mass)

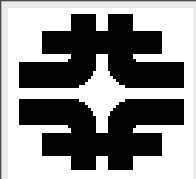




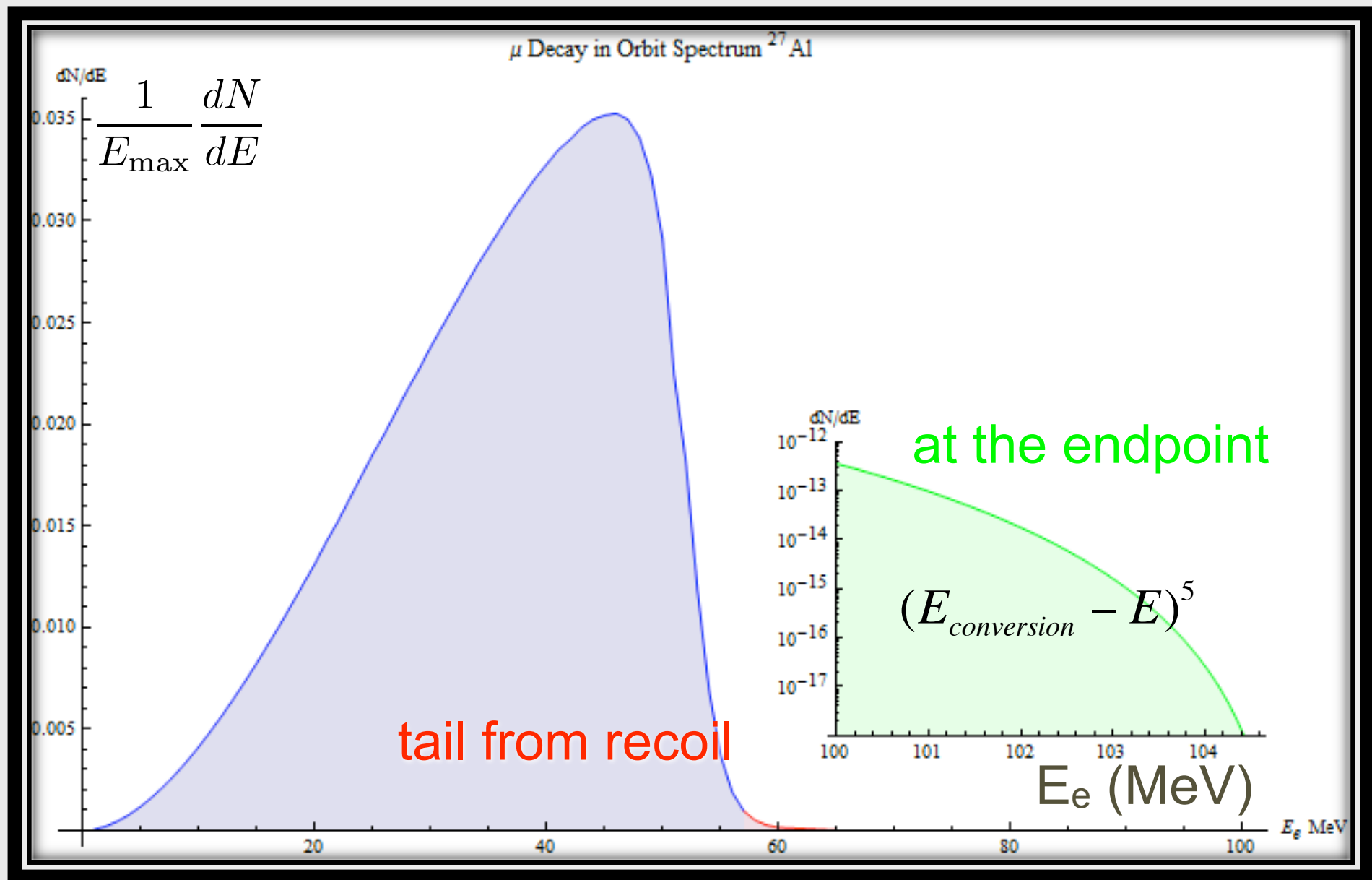
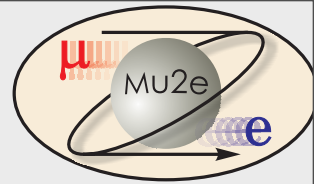


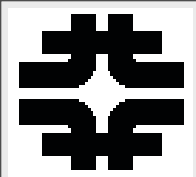
# Decay-in-Orbit Shape



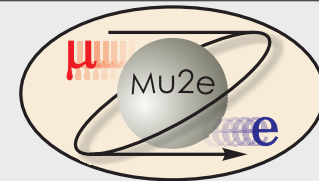


# Decay-in-Orbit Shape





# Prompt Backgrounds

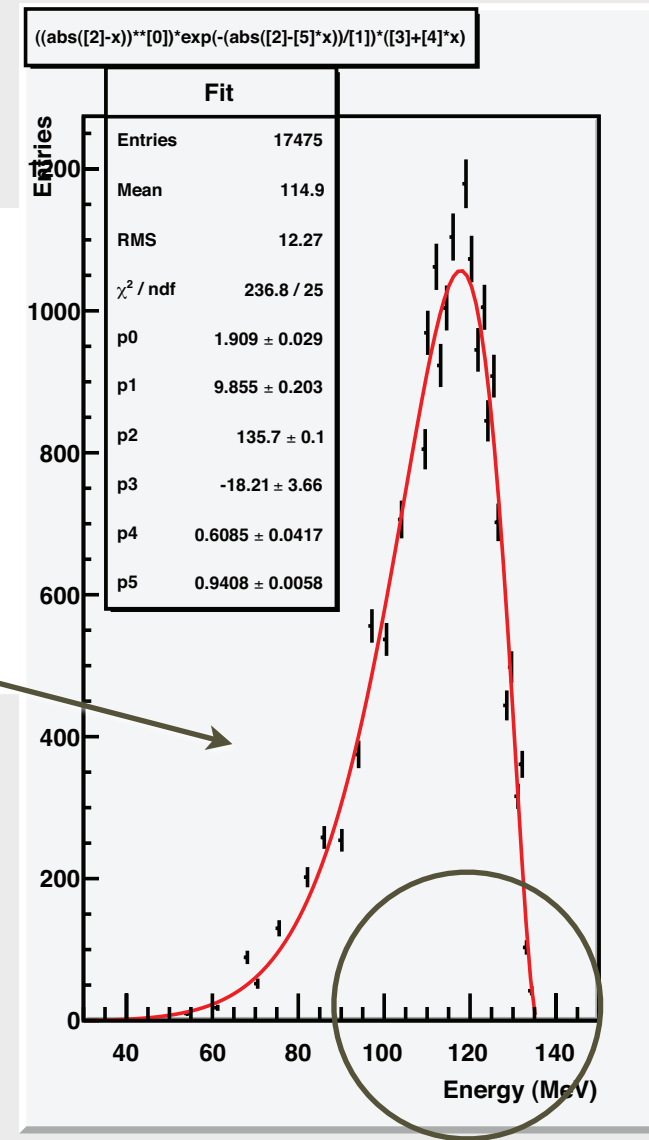


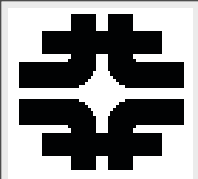
*Particles produced by proton pulse which interact almost immediately when they enter the detector:  $\pi$ , neutrons,  $p$ bars*

- **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

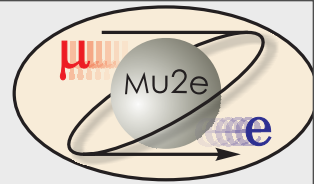
energy spectrum of  $\gamma$  measured on Mg  
J.A. Bistirlich, K.M. Crowe et al., Phys Rev C5, 1867 (1972)

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



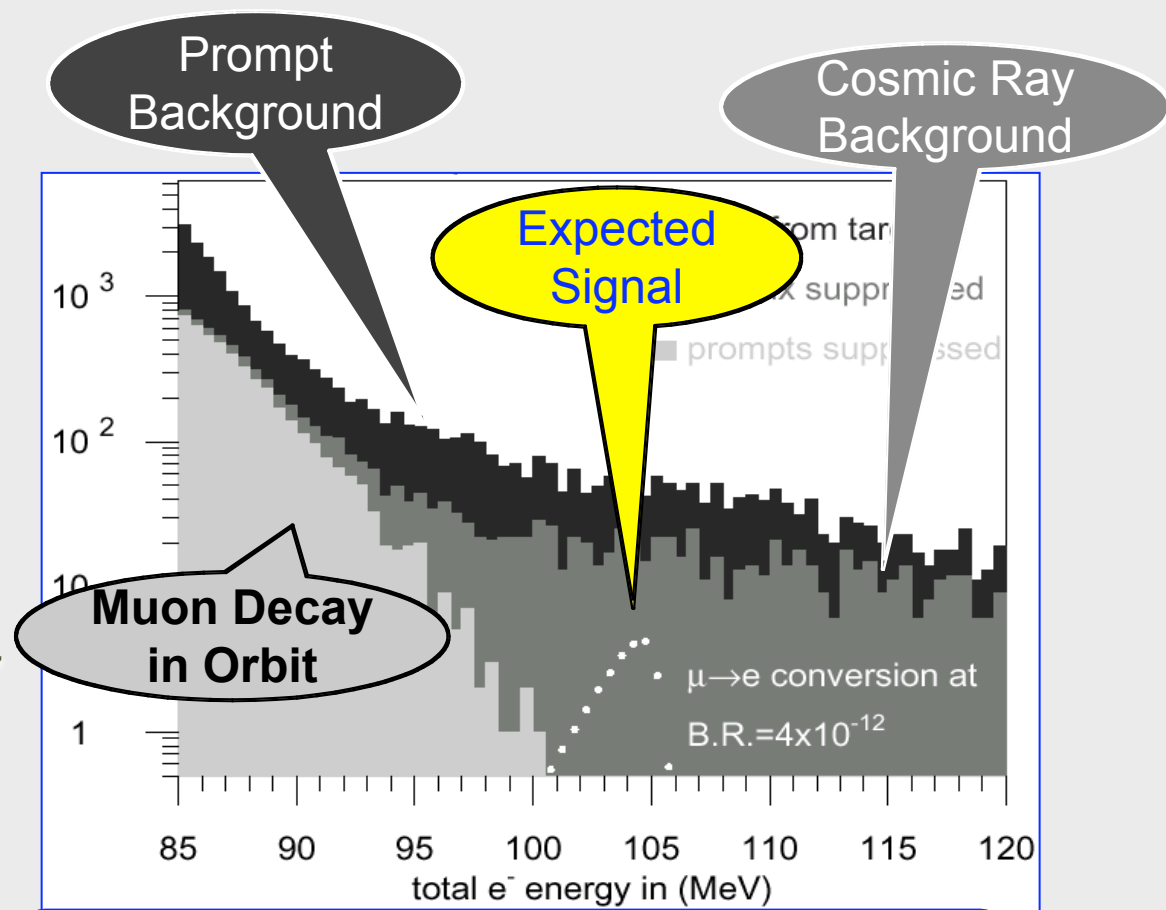


# Current Best Experiment

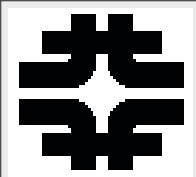


## *SINDRUM-II*

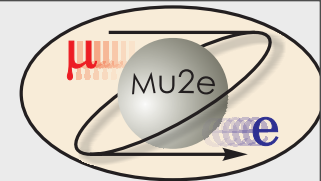
- $R_{\mu e} < 7 \times 10^{-13}$  in Au
- Want to probe to  $6 \times 10^{-17}$
- $\approx 10^4$  improvement



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



# SINDRUM-II Results



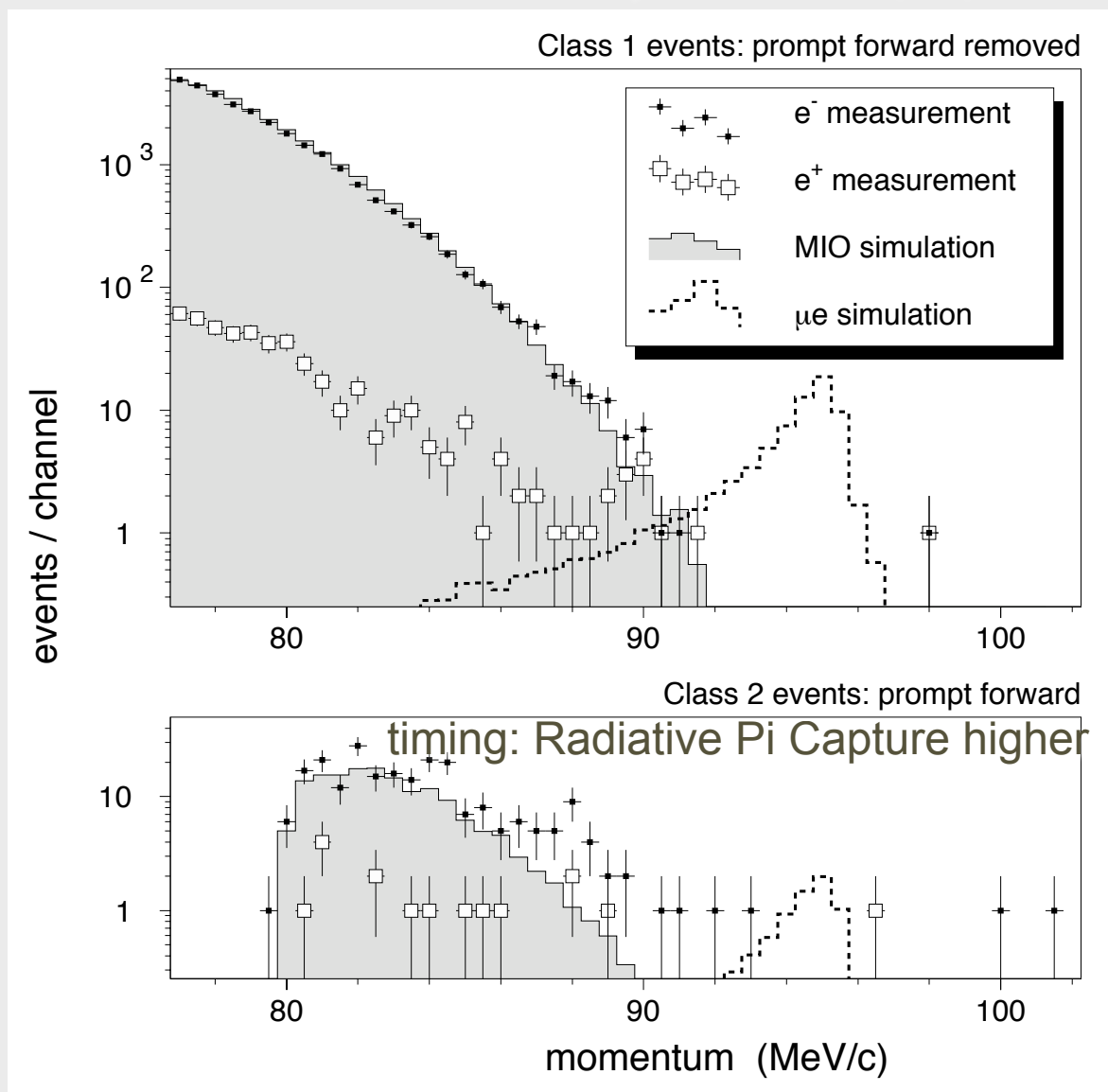
W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006)

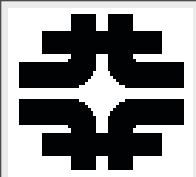
- Final Results on Au:

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

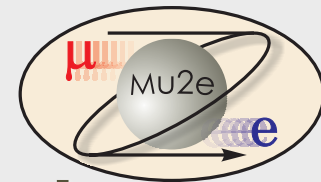
**51 MHz (20 nsec)  
repetition rate,  
width of pulse  
~0.3 nsec**

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





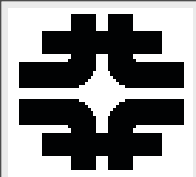
# Review:



## Two Classes of Backgrounds

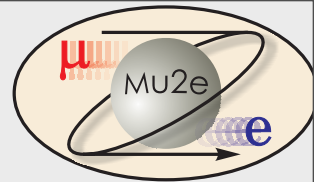
	Decay-In-Orbit	Prompt
Source	Intrinsic Physics Background	Radiative $\pi$ Capture: Mostly $\pi$ 's produced in production target
Solution	Spectrometer Design: resolution and pattern recognition	Design of Muon Beam, formation, transport, and time structure





# How Can We Do Better?

## Pulsed Beam Structure



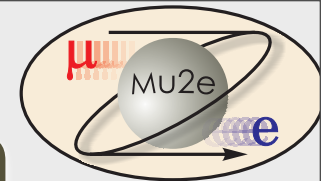
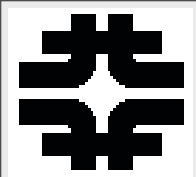
### *Main Improvements:*

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

and

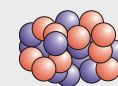
Pulsed Beam with waiting period to  
Eliminate radiative  $\pi$  capture

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

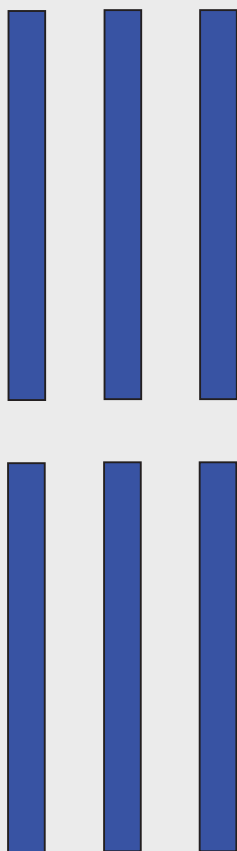


# Advantage of Pulsed Beam

target foils: muon converts here



= muons, electrons, pions

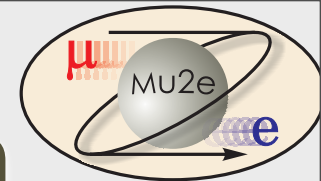
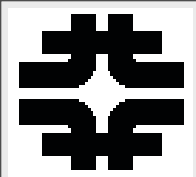


pulsed beam lets us  
wait until after prompt  
backgrounds  
disappear and rate  
lowered

RPC:

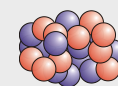
$$\pi N \rightarrow \gamma N$$

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

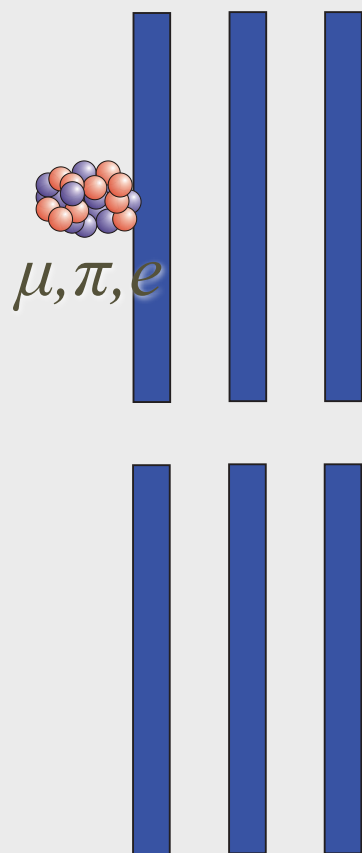


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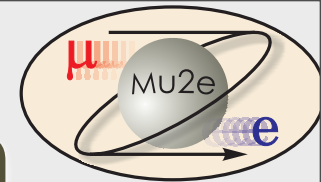
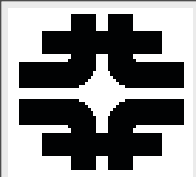


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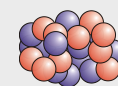
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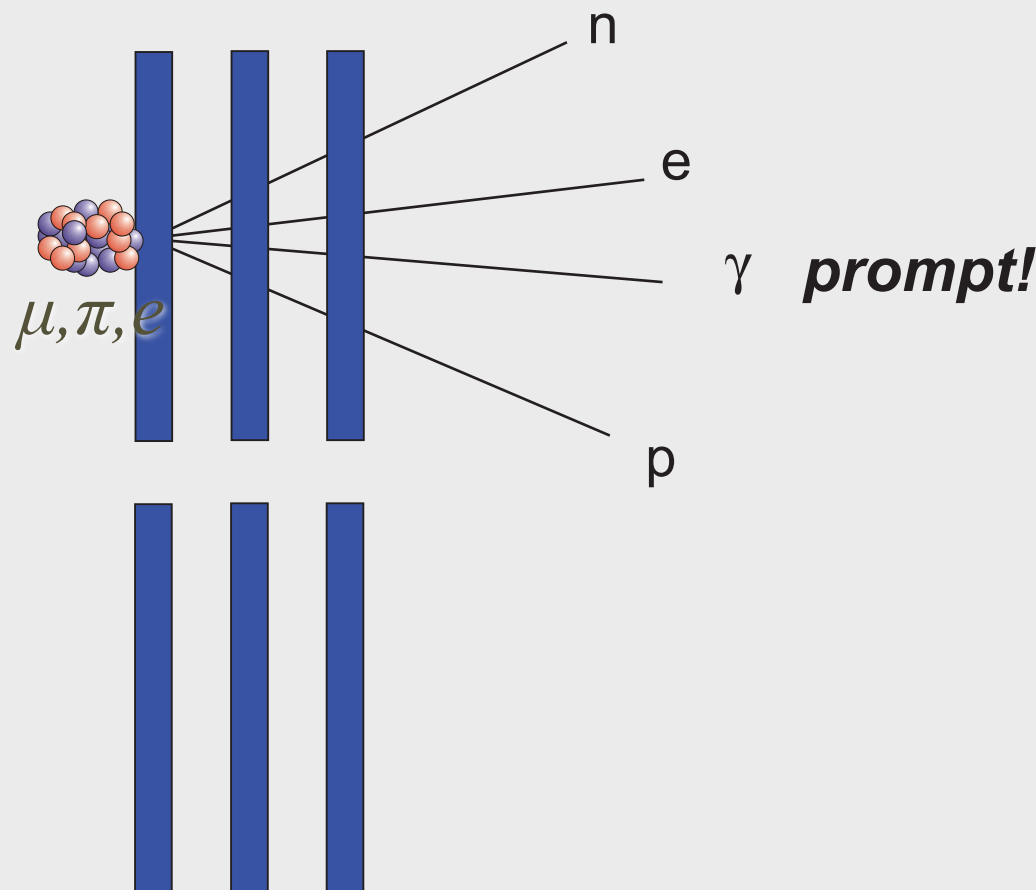


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= muons, electrons, pions

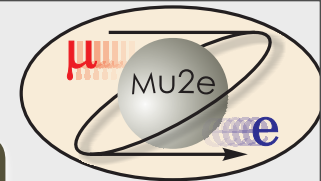
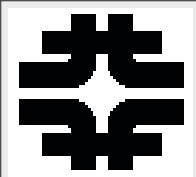


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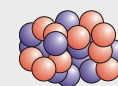
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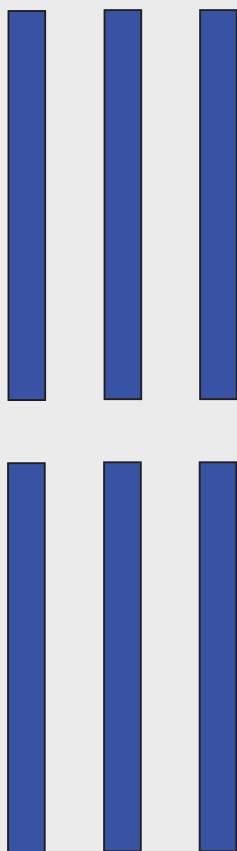


# Advantage of Pulsed Beam

target foils: muon converts here



= muons, electrons, pions

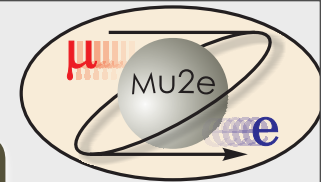
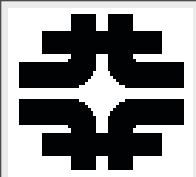


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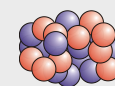
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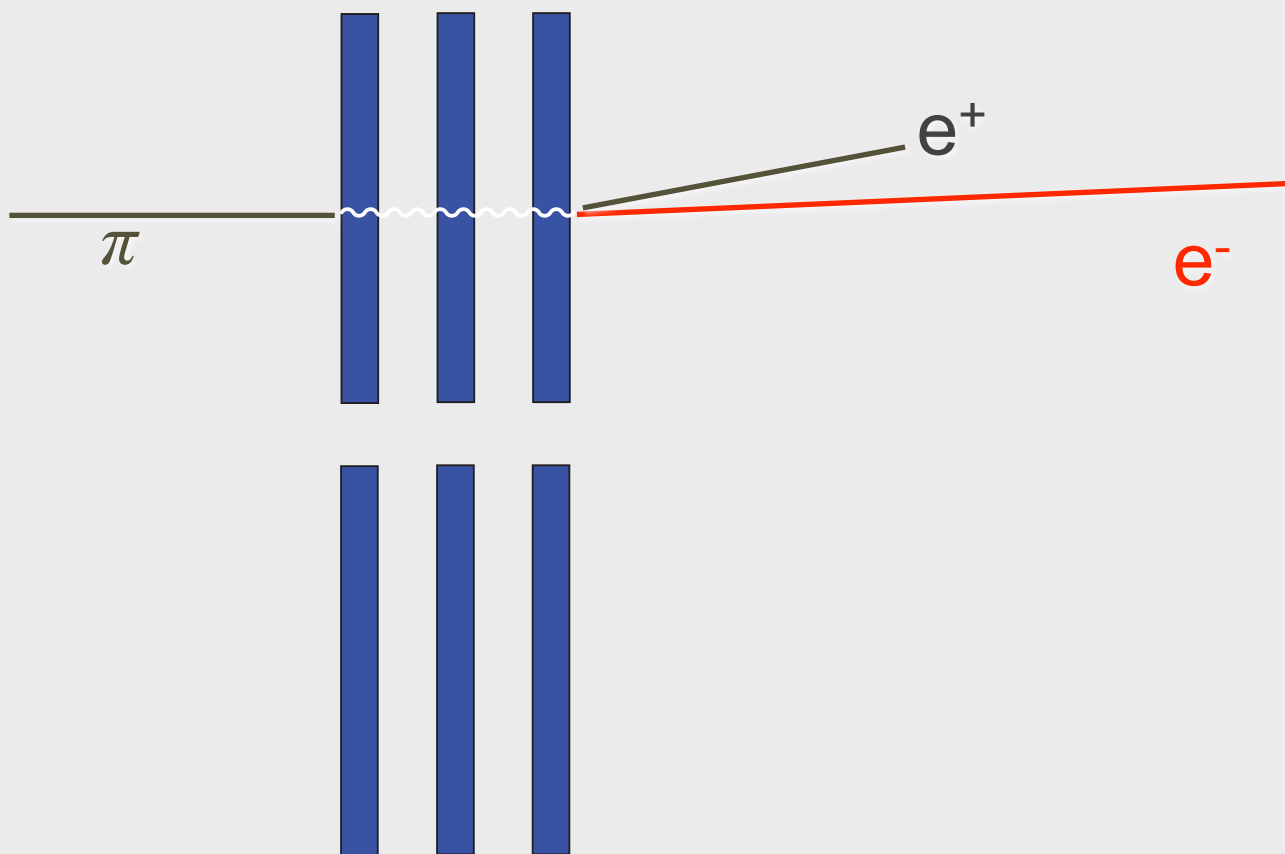


# Advantage of Pulsed Beam

target foils: muon converts here



= muons, electrons, pions

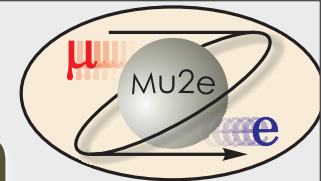
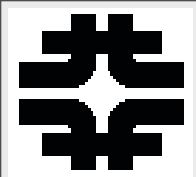


pulsed beam lets us  
wait until after prompt  
backgrounds  
disappear and rate  
lowered

RPC:

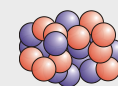
$$\pi N \rightarrow \gamma N$$

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

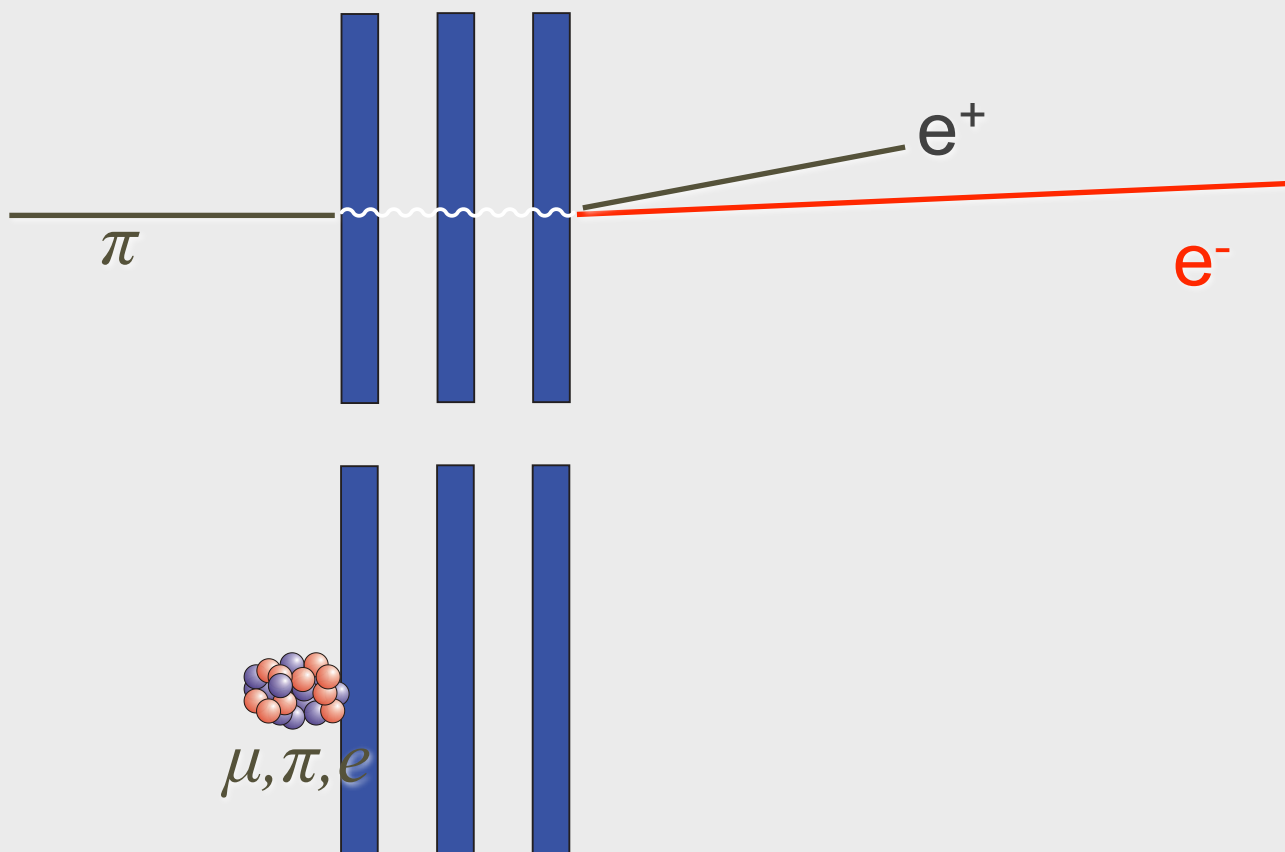


# Advantage of Pulsed Beam

target foils: muon converts here



= muons, electrons, pions

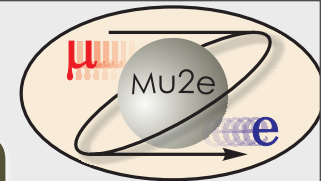
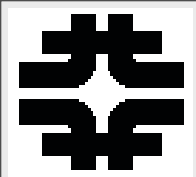


pulsed beam lets us  
wait until after prompt  
backgrounds  
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lowered

RPC:

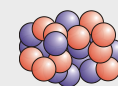
$$\pi N \rightarrow \gamma N$$

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

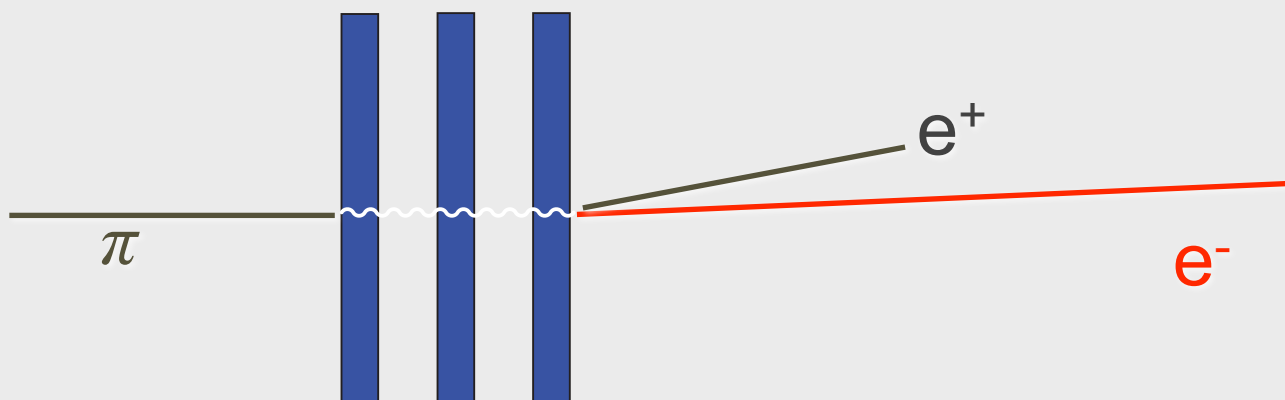


# Advantage of Pulsed Beam

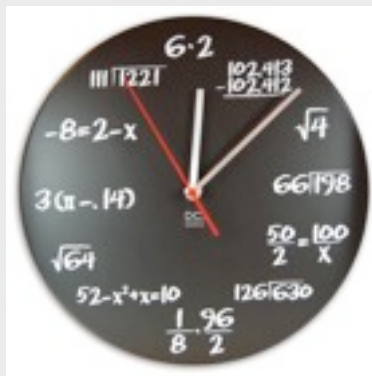
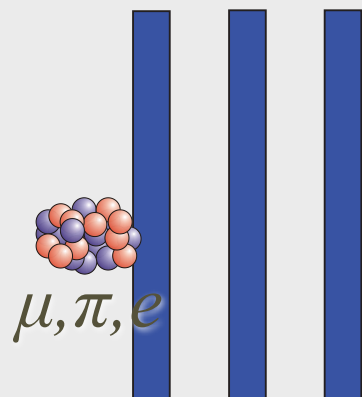
target foils: muon converts here



= muons, electrons, pions



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

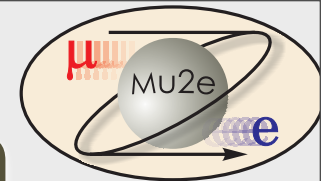
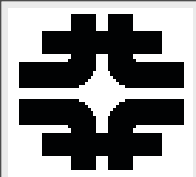


RPC:

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

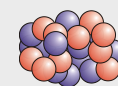
$$\gamma \rightarrow e^+ e^- \text{ in foils}$$



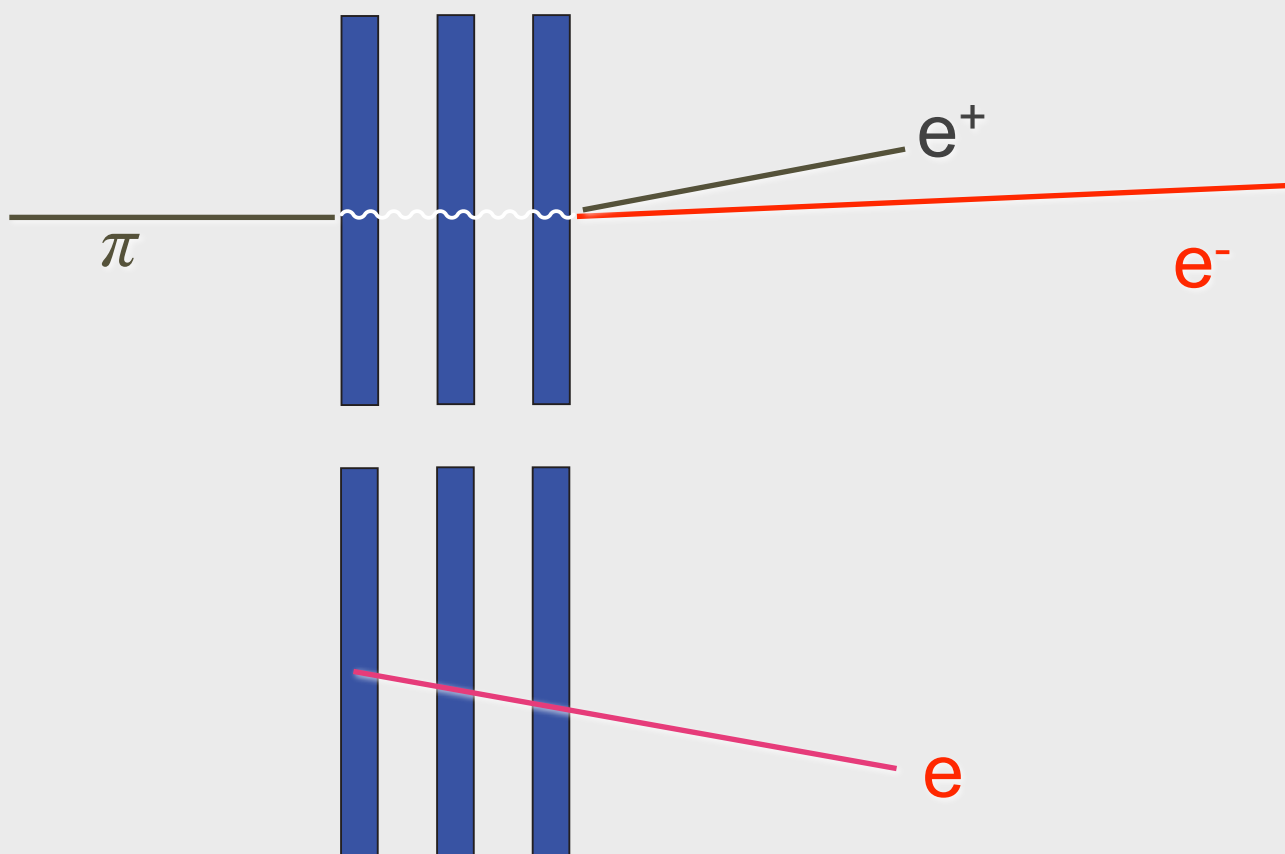


# Advantage of Pulsed Beam

target foils: muon converts here



= muons, electrons, pions

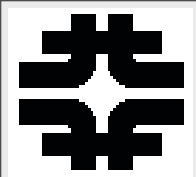


pulsed beam lets us  
wait until after prompt  
backgrounds  
disappear and rate  
lowered

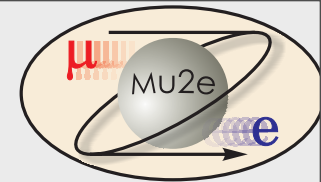
RPC:

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

delayed 105 MeV electron

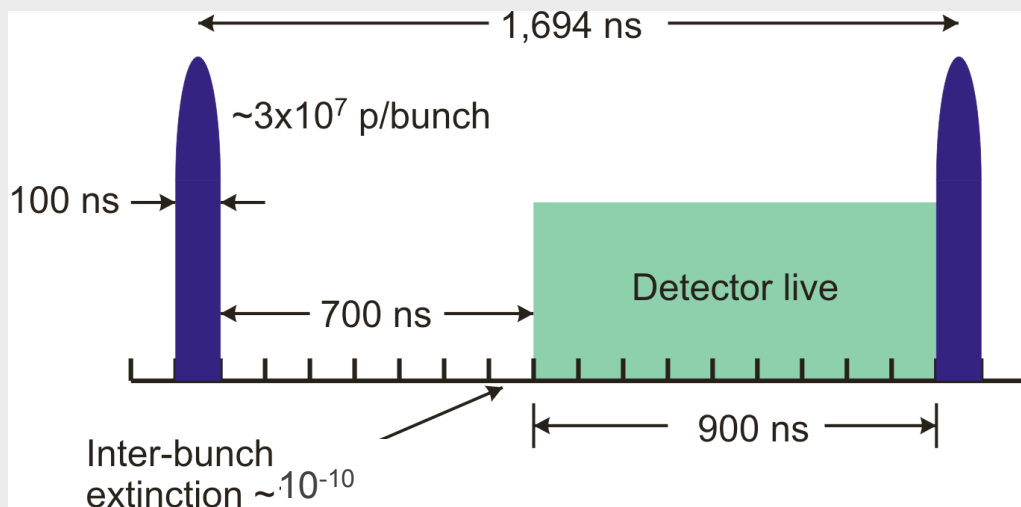


# Pulsed Beam Structure

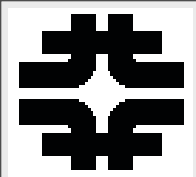


- Tied to prompt rate and machine: FNAL “perfect”
- Want **pulse duration  $\ll \tau_{\mu}^{Al}$**  , **pulse separation  $\approx \tau_{\mu}^{Al}$** 
  - FNAL Debuncher has circumference  **$1.7\mu\text{sec}$**  ,  $\sim x2 \tau_{\mu}^{Al}$
- Extinction between pulses  $< 10^{-10}$  needed

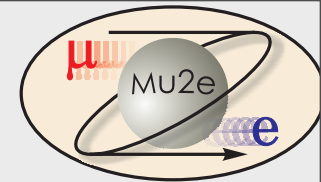
= # protons out of pulse/# protons in pulse



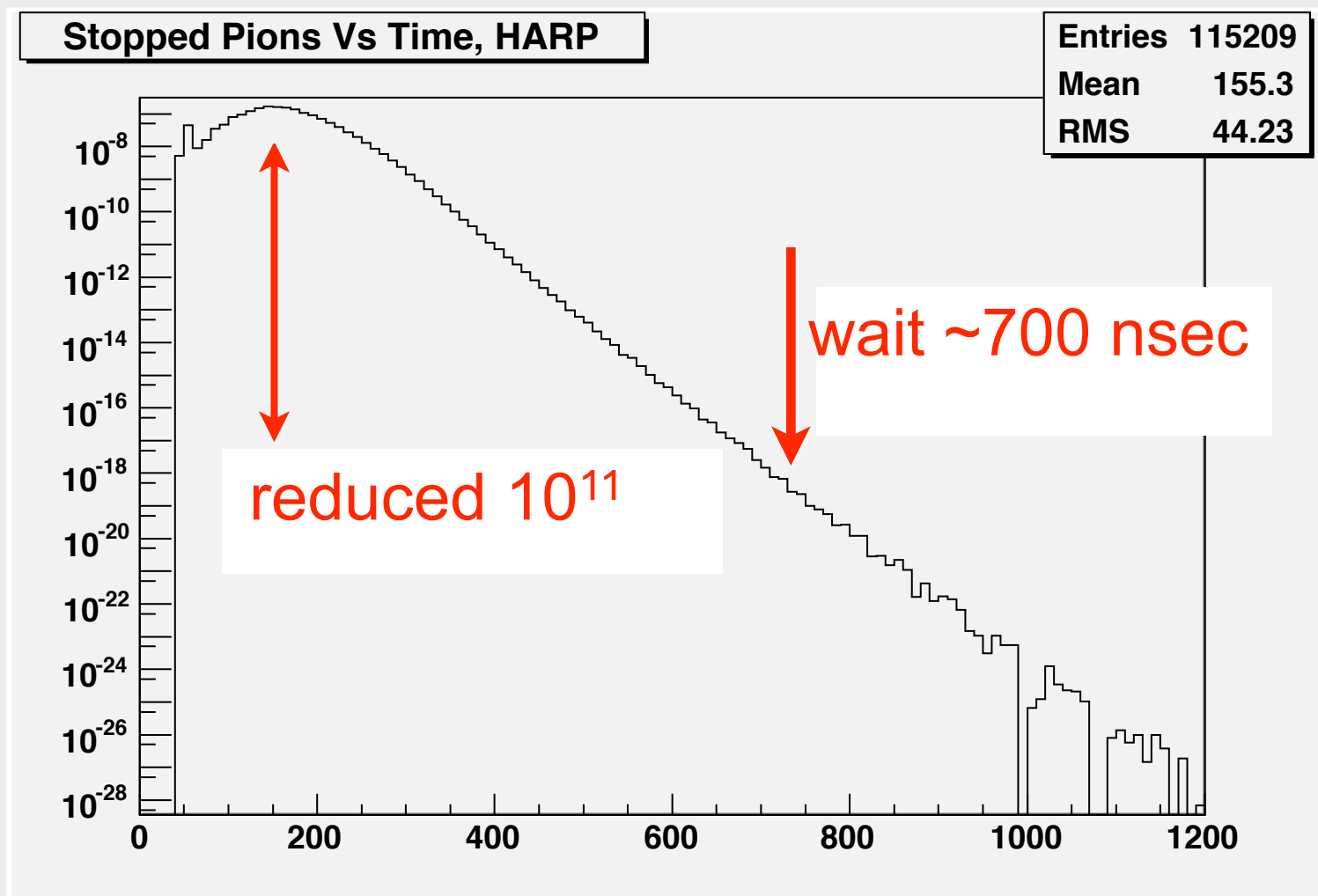
- $10^{-10}$  based on simulation of prompt backgrounds and beamline



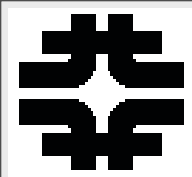
# Pulsed Beam Structure and Radiative $\pi$ Capture



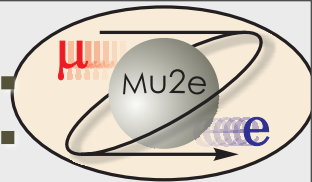
$$\pi N \rightarrow \gamma N, \gamma \rightarrow e^+ e^-$$



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



# 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

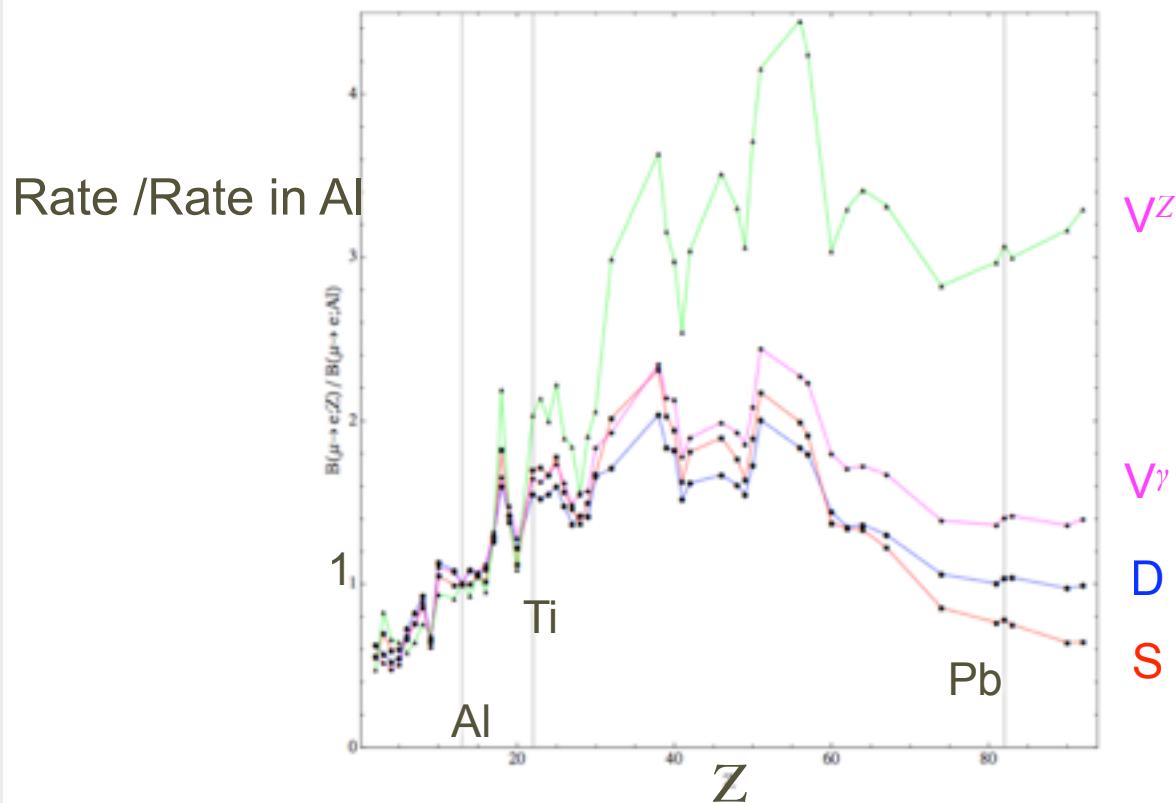
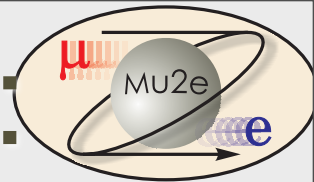
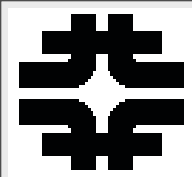


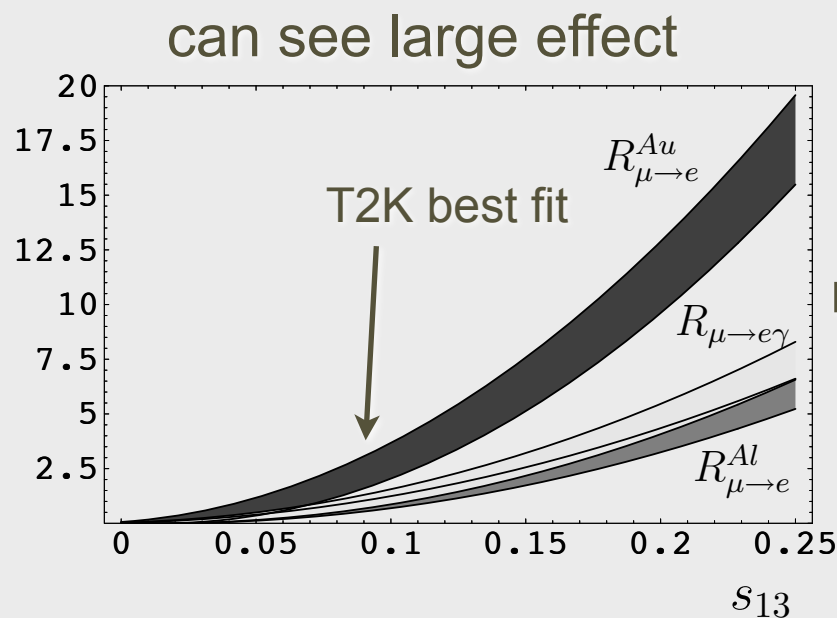
Figure 3: Target dependence of the  $\mu \rightarrow e$  conversion rate in different single-operator dominance models. We plot the conversion rates normalized to the rate in Aluminum ( $Z = 13$ ) versus the atomic number  $Z$  for the four theoretical models described in the text:  $D$  (blue),  $S$  (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

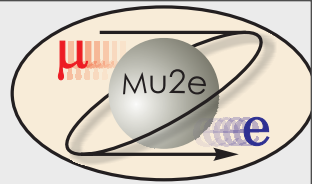
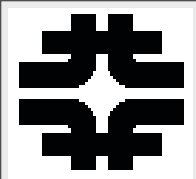
- Stop muons in target (Z,A)
- Physics sensitive to Z: with signal, can switch target to probe source of new physics
- Why start with Al?



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

V. Cirigliano, B. Grinstein, G. Isidori, M. Wise **Nucl.Phys.B728:121-134,2005.**  
e-Print: [hep-ph/0507001](https://arxiv.org/abs/hep-ph/0507001)

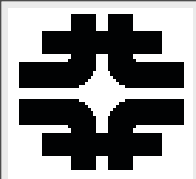
shape governed by relative conversion/capture rate, form factors, ...



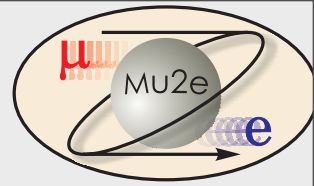
# Prompt Background and Choice of Z

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

Nucleus	$R_{\mu e}(Z) / R_{\mu e}(\text{Al})$	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

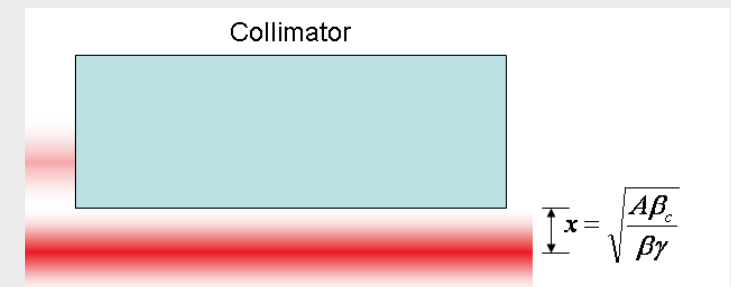
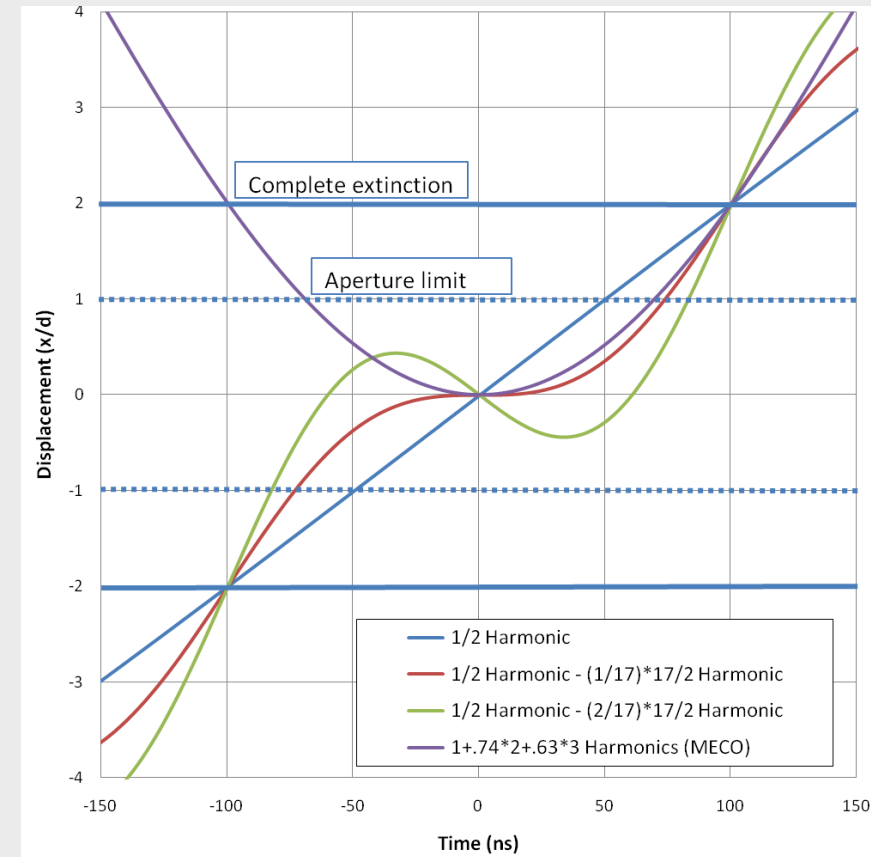


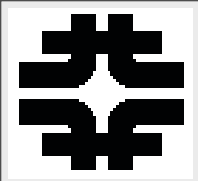
# Extinction Scheme



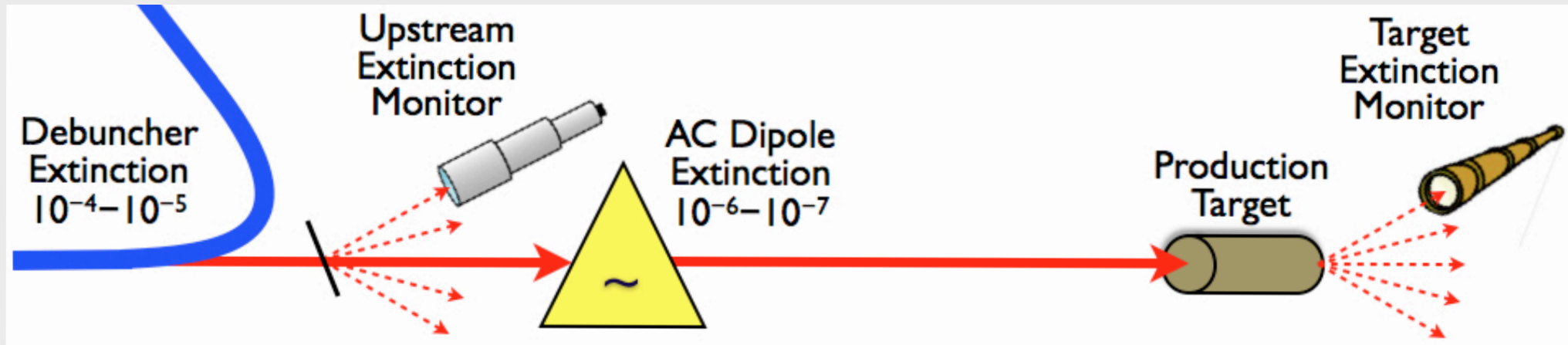
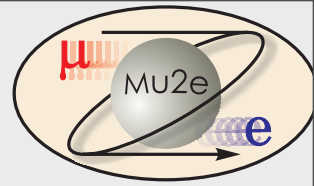
*achieving  $10^{-10}$  is hard; normally get  $10^{-2} - 10^{-3}$*

- 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  $\sim 10^{-12}$



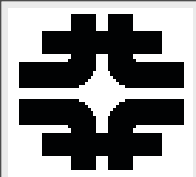


# Extinction Measurement

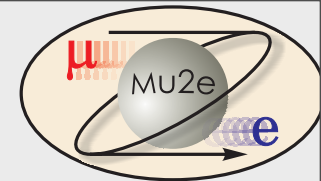


- Beam Formation(Debuncher, Momentum Scraping) and AC-Dipole provide extinction
- Measure with:
  - Thin foils in 8 GeV transport line (fast feedback on machine performance)
  - Off-axis telescope looking at production target (time scale of hour)
  - Also considering detecting individual out-of-time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





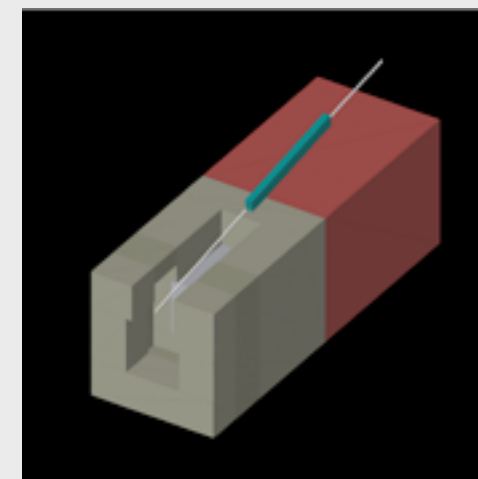
# Current Extinction Plan



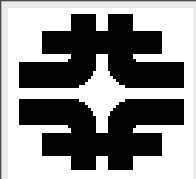
- Look at secondaries from target
  - Use a magnet to pick out signal
  - Count hits in-and-out of pulse, compare
- Current plan -- *not proton-by-proton*

G4Beamline Model

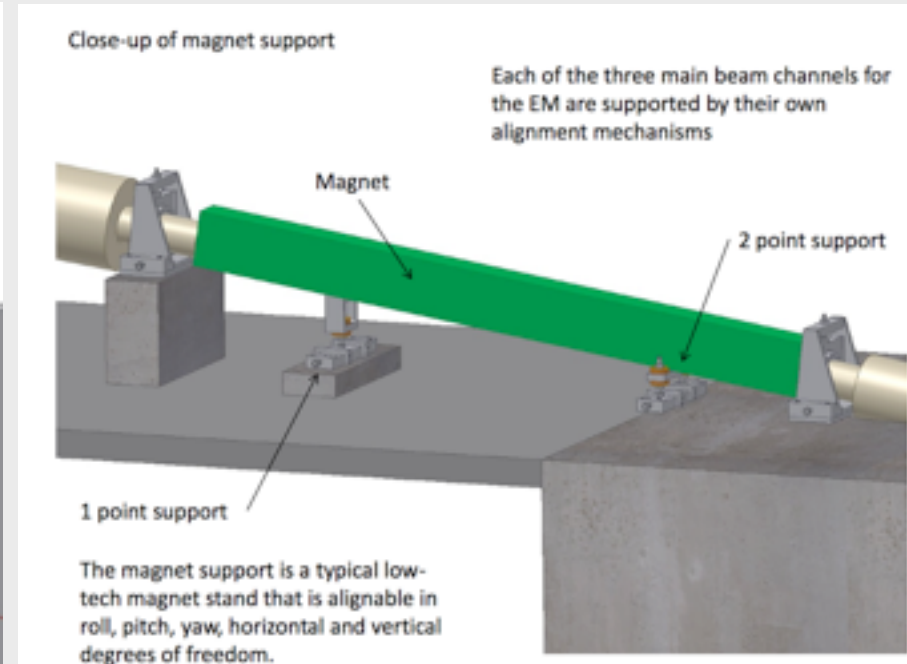
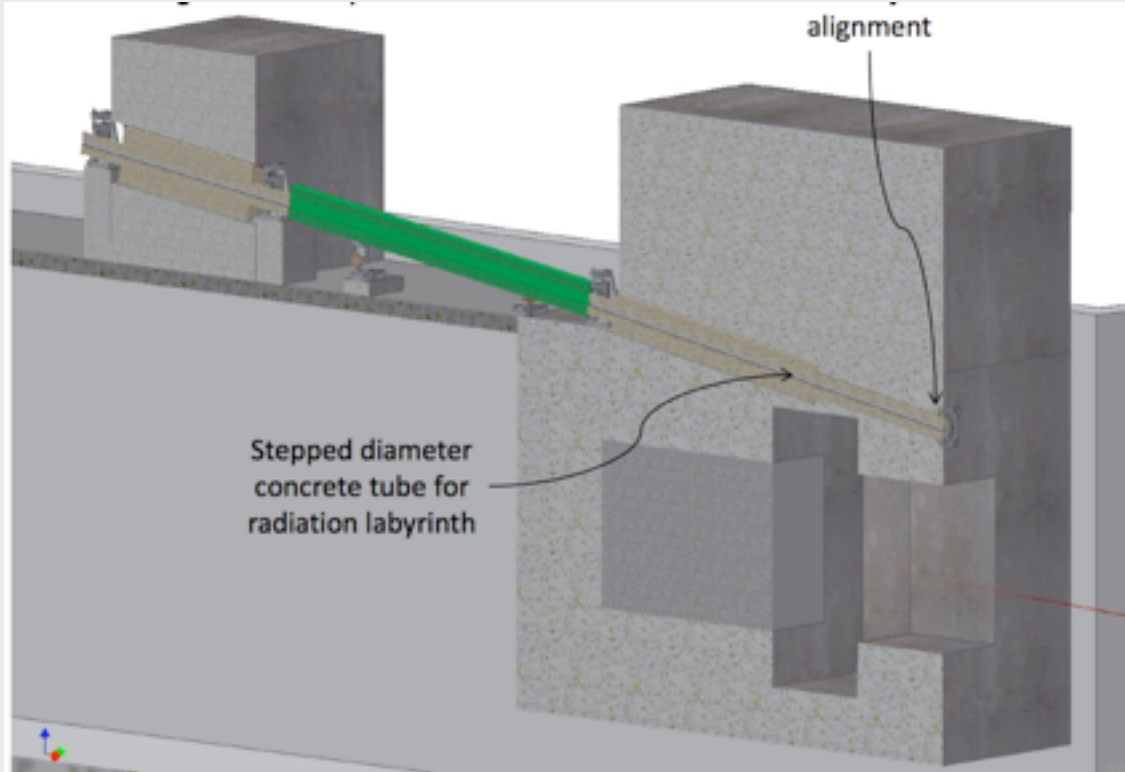
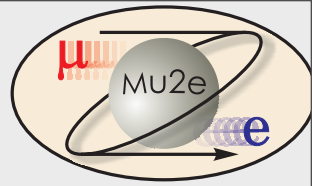
Nominal Momentum (GeV/c)	Transmitted tracks / bunch	Integration Time (min)		Proton Percentage	MeV Deposited / Proton-on-Target		
		No Bkgnd.	5 / hr		Entry Channel	Magnet	Exit Channel
2.0	40.5 ± 4.4	6.9	10.8	77.6	0.293	0.167	0.007
3.0	151.4 ± 8.5	1.8	2.1	82.7	0.258	0.168	0.037
4.0	240.0 ± 10.7	1.2	1.3	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



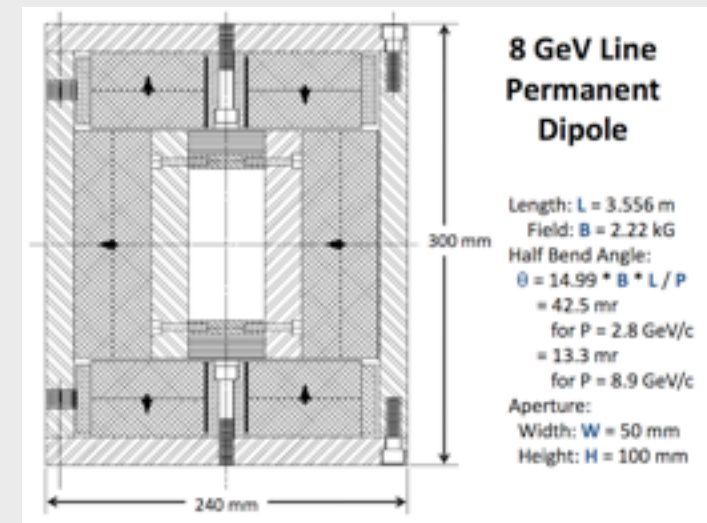
working on using diffractive protons:  
little-to-no background, easier to model

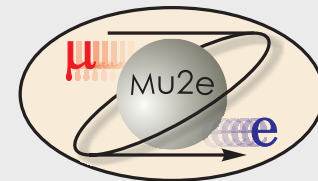
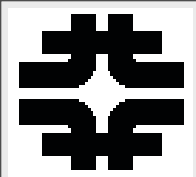


# Wide Variety of choices



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





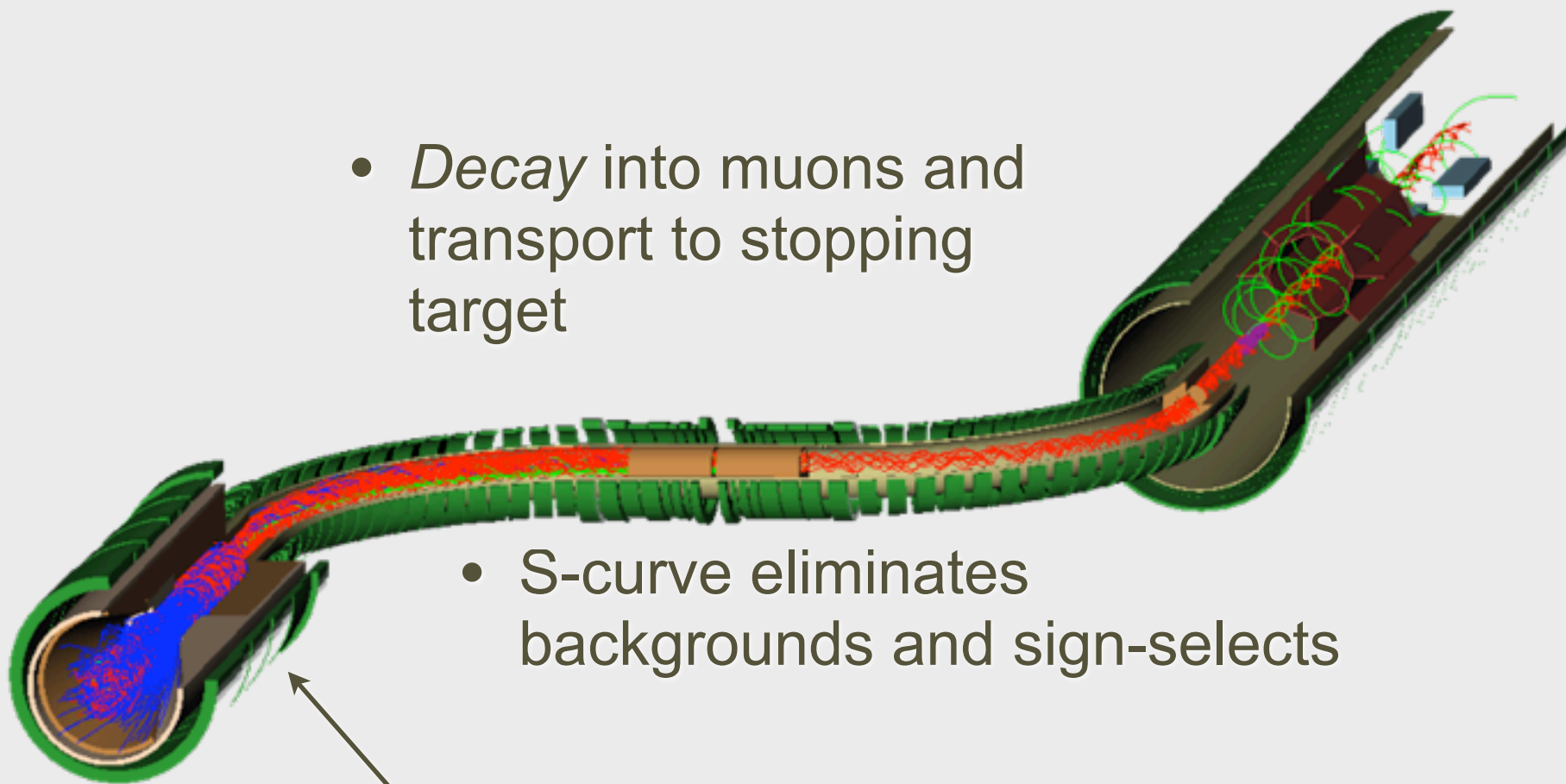
# Detector and Solenoid

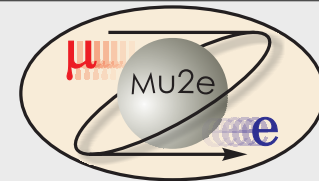
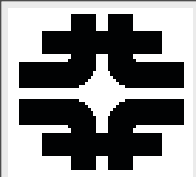
- *Tracking and Calorimeter*

- *Decay into muons and transport to stopping target*

- S-curve eliminates backgrounds and sign-selects

- *Production*: Magnetic bottle traps backward-going  $\pi$  that can decay into accepted  $\mu$ 's





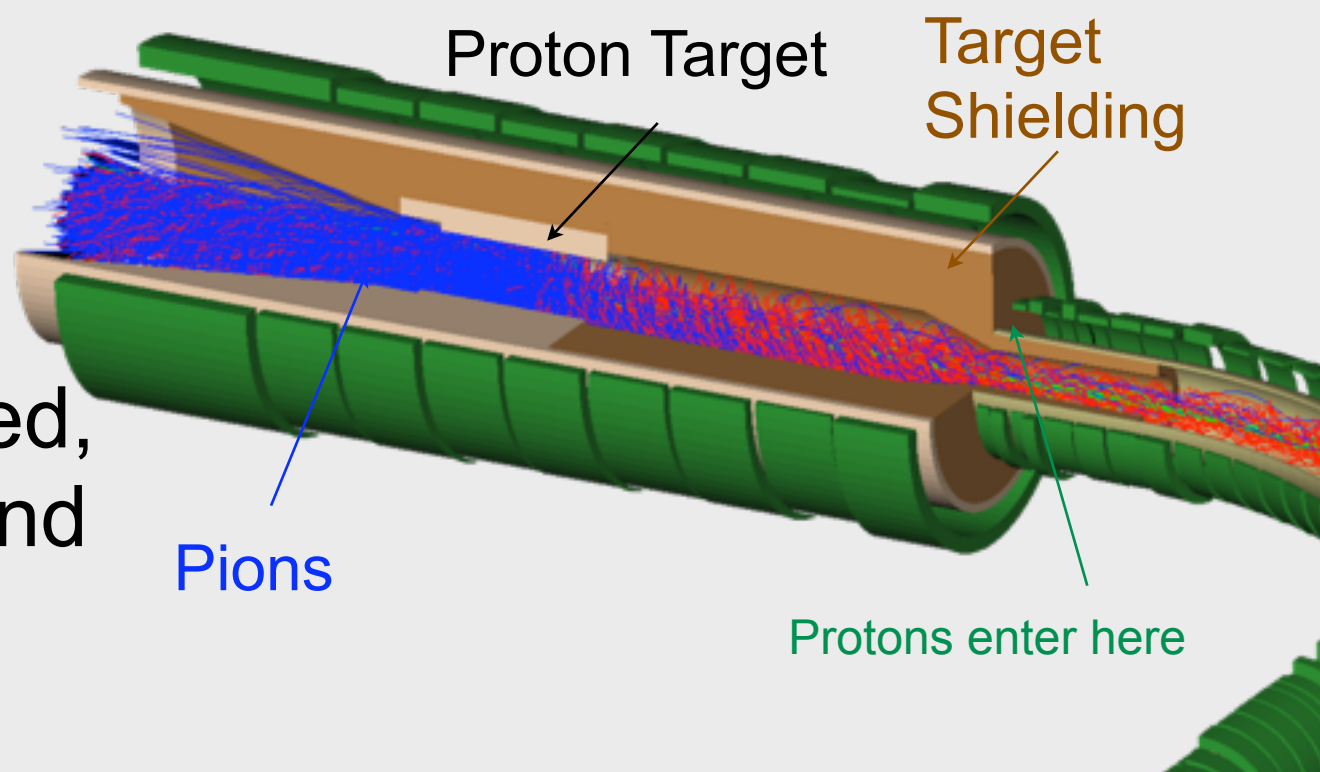
# Production Solenoid:

Protons enter opposite to outgoing muons

Protons leave  
through thin  
window

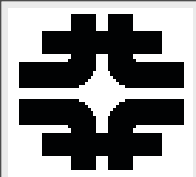
$\pi$ 's are captured,  
spiral around and  
decay

muons exit to right

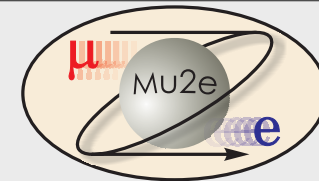


4 m  $\times$  0.30 m

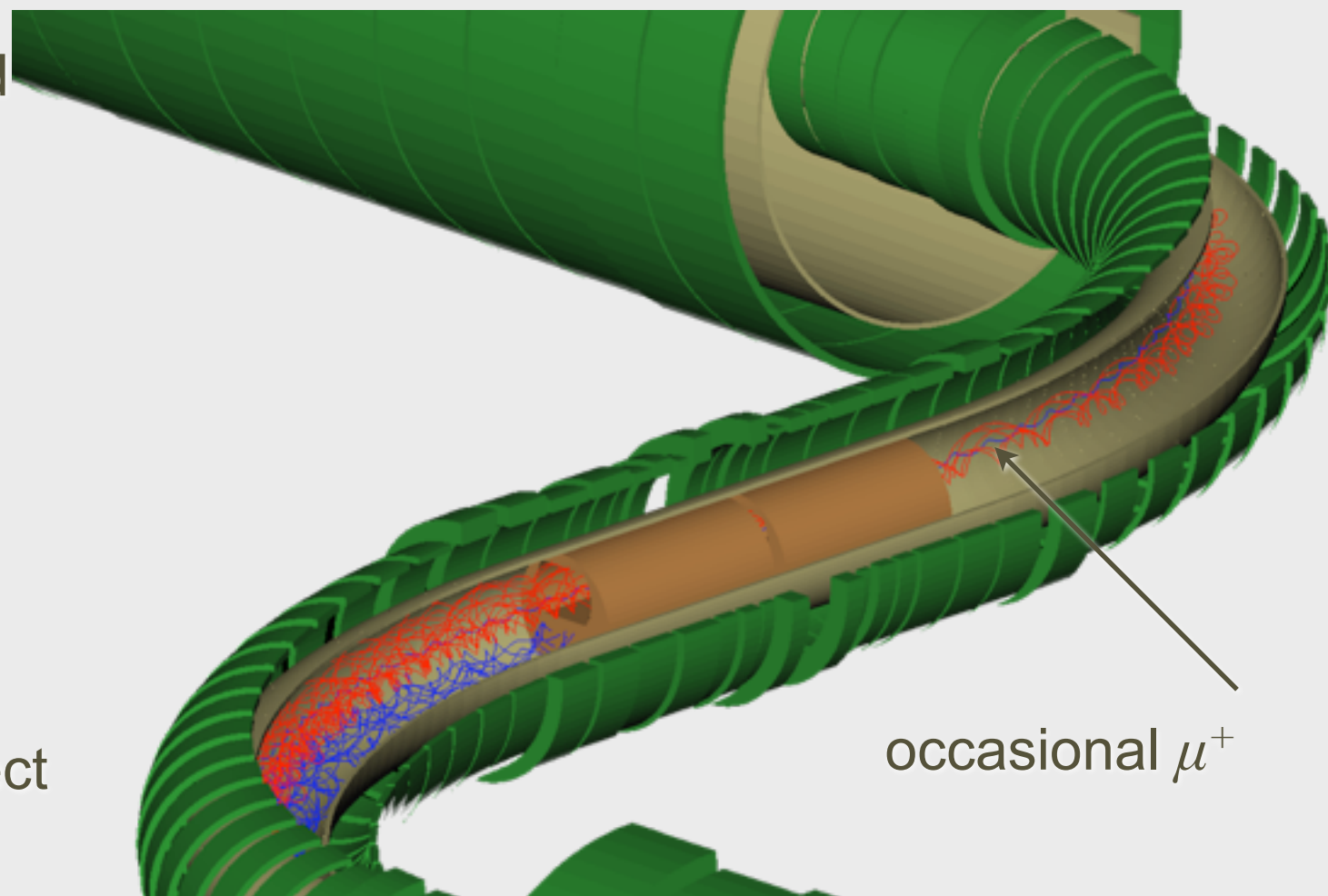




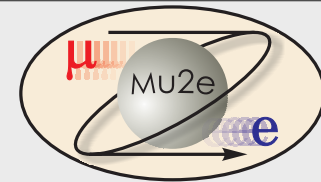
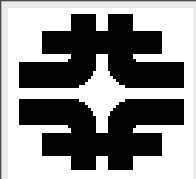
# Transport Solenoid



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



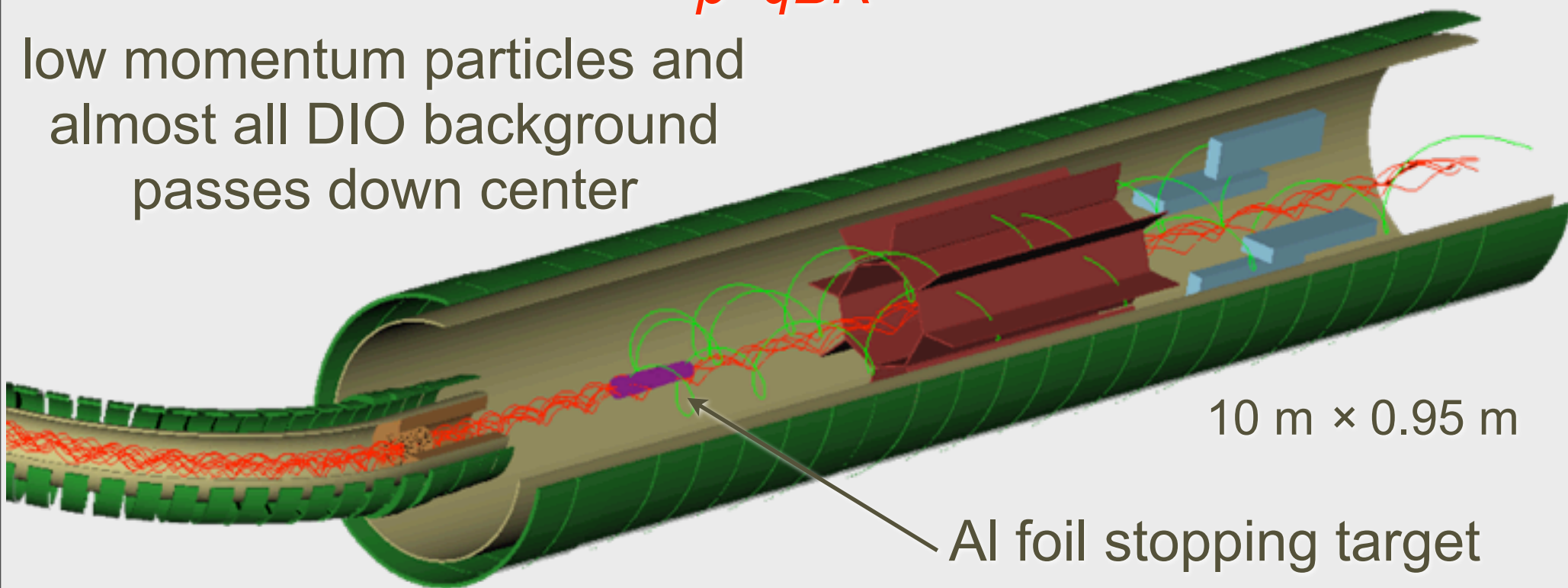
13.1 m along axis × ~0.25 m



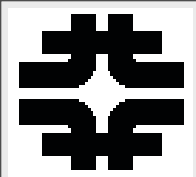
# Detector Solenoid

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

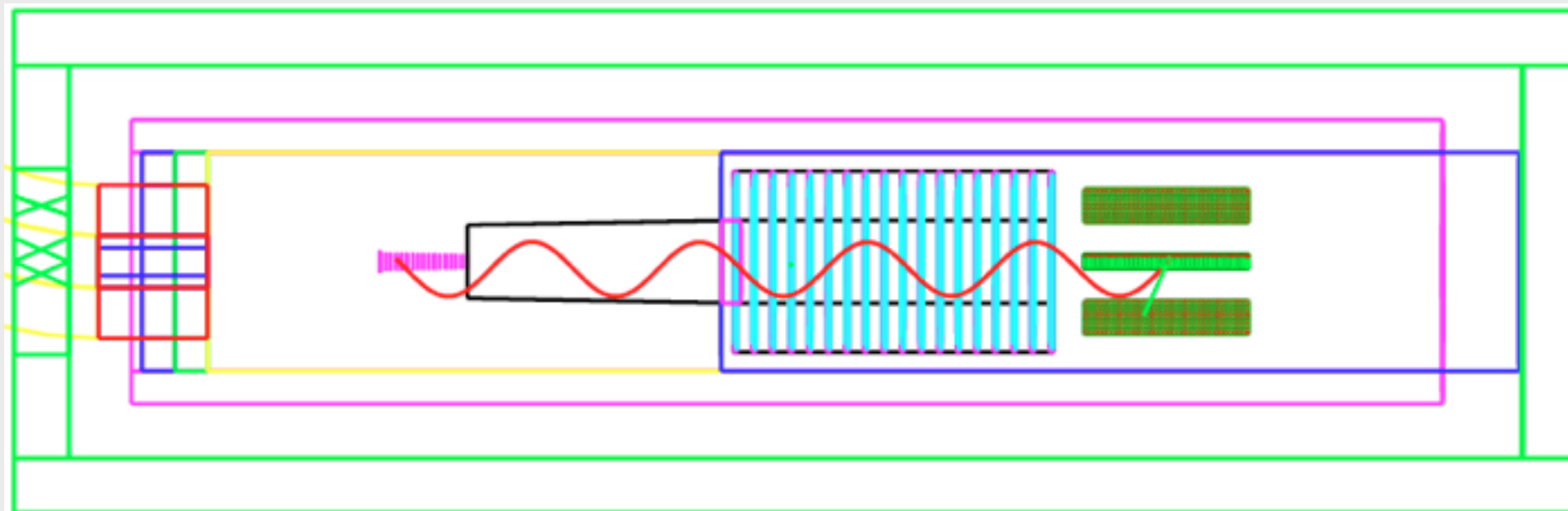
low momentum particles and  
almost all DIO background  
passes down center



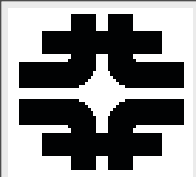
signal events pass *through* center of tracker  
and produce hits



# 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  $3.5 \times 3.5 \times 12$  cm  $\text{PbWO}_4$  or LYSO
  - 4--5% resolution

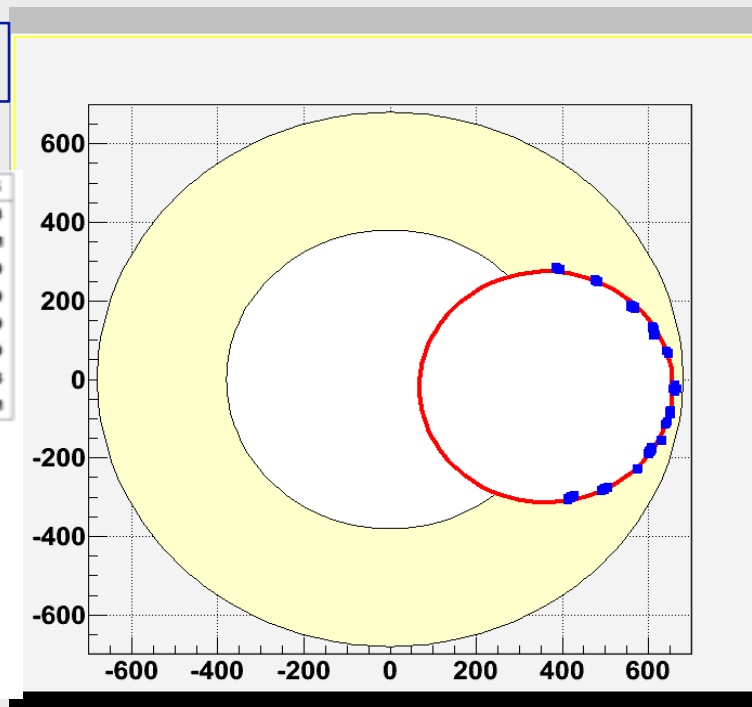
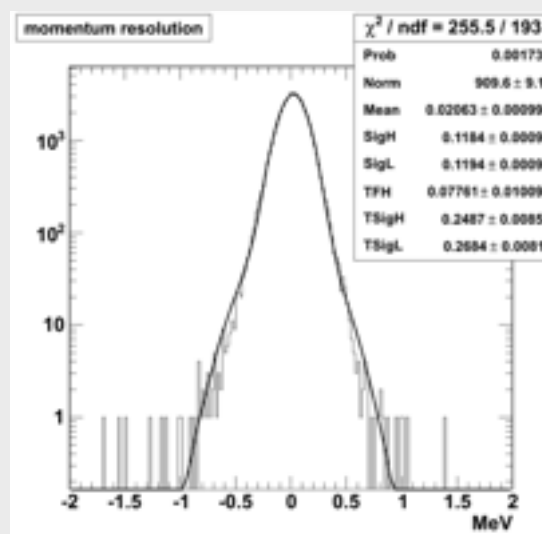


# Pattern Recognition and Tracking

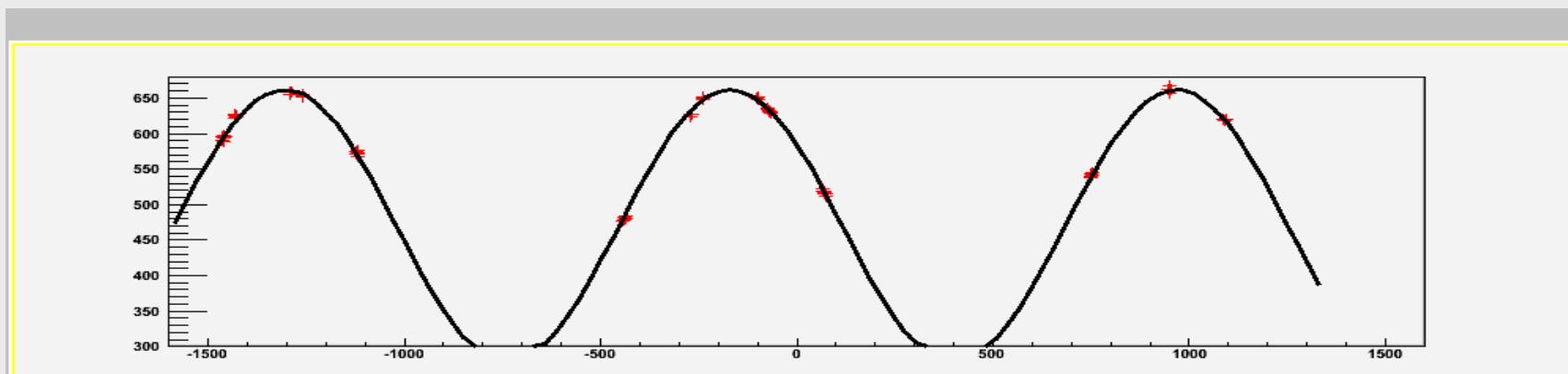


- Unified simulation from protons on target to end of detector in GEANT4
- Pattern Recognition Program joined to BaBar Kalman Filter
  - No sign of significant mis-reconstruction background with realistic rates from all known sources

X-Y View



R-Z view



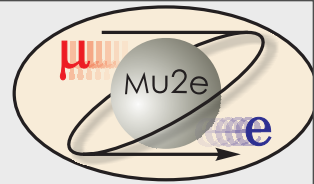
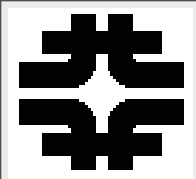
R. Bernstein, FNAL

40

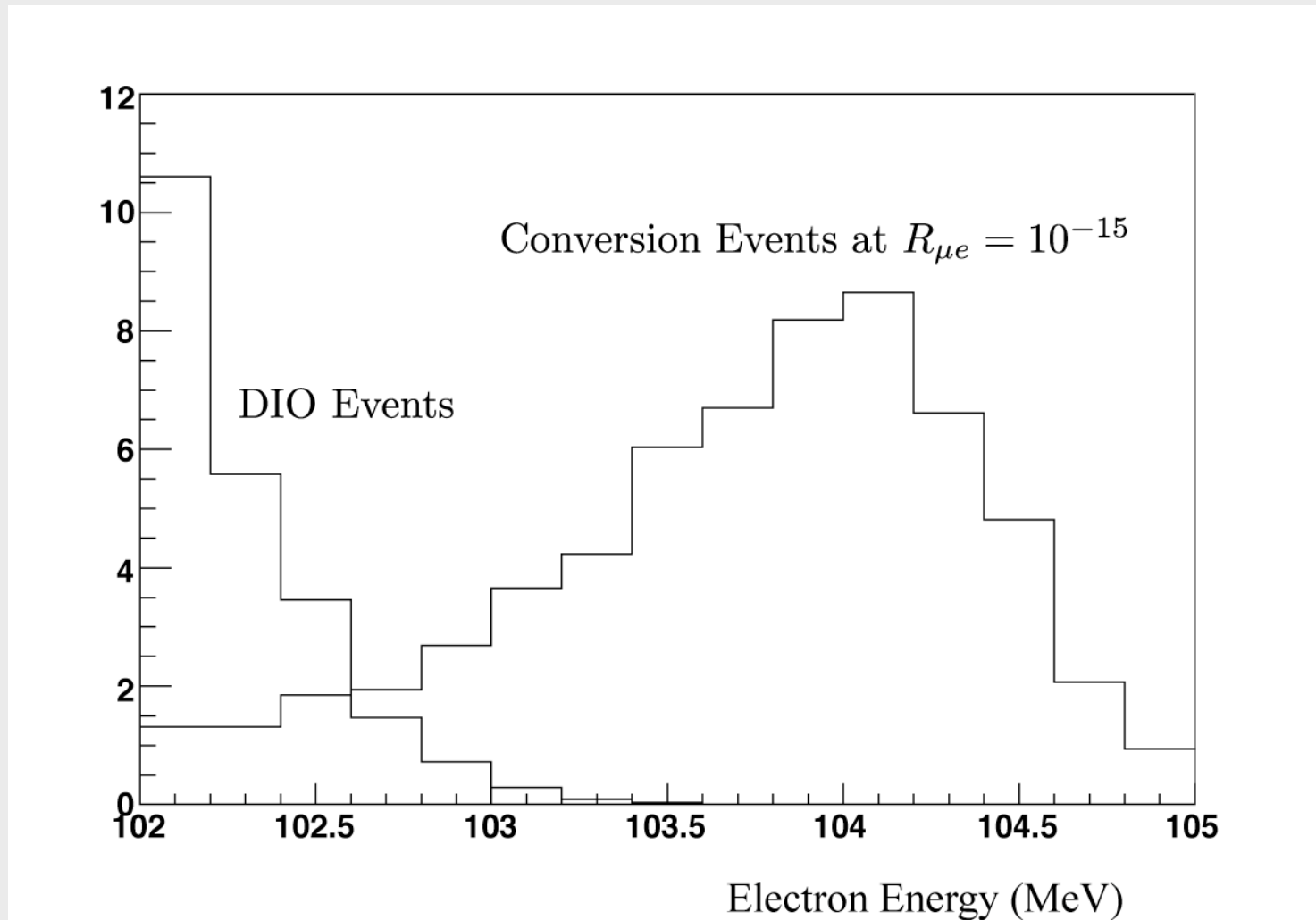
Mu2e

NuFact 2011

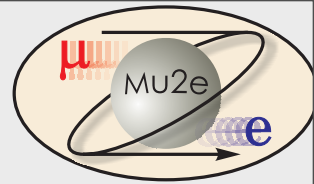
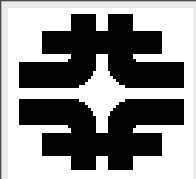




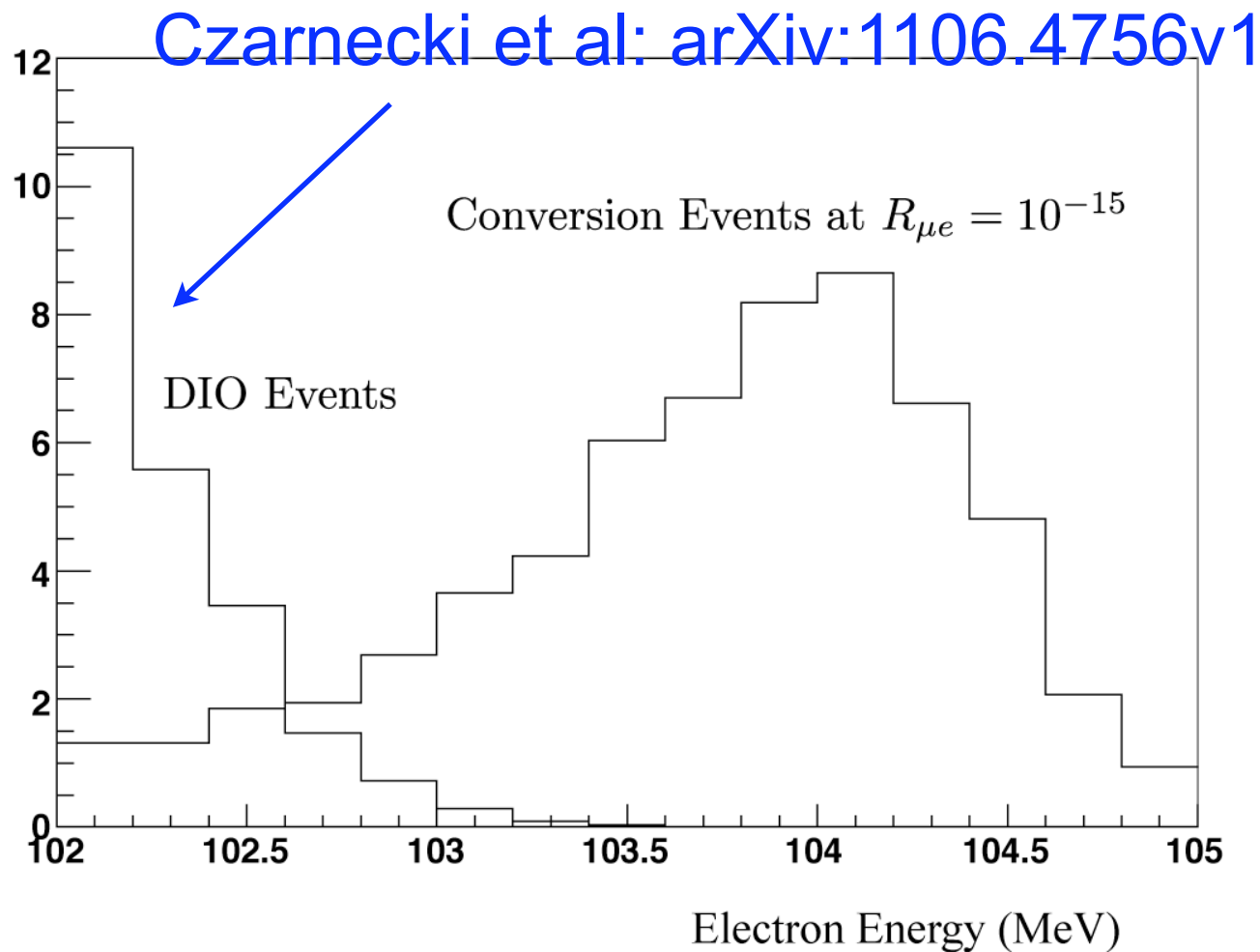
# Signal and Background



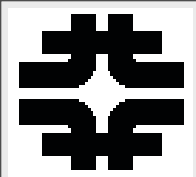
energy loss in stopping target and other material shifts  
electron down to  $\sim 104$  MeV



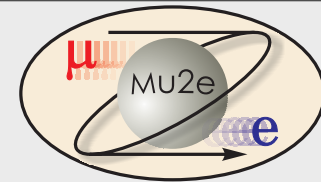
# Signal and Background



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



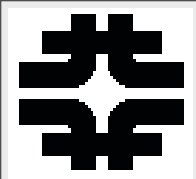
# Final Backgrounds



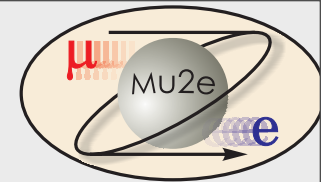
- For  $R_{\mu e} = 10^{-15}$   
~40 events / 0.18 bkg  
(LHC SUSY?)

- 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	$\pm 0.0055$
$\mu$ 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	$< 2 \times 10^{-6}$	—
<b>TOTAL</b>	<b>0.18</b>	$\pm \mathbf{0.07}$



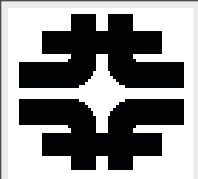
# FNAL Beam Delivery



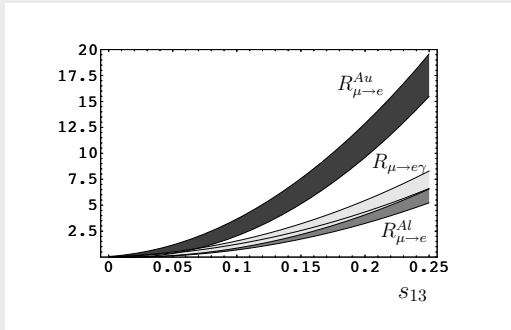
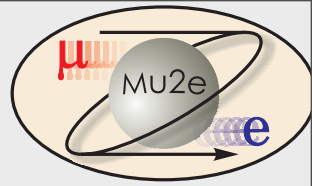
- FNAL has unique, major strength:

## Multiple Rings

- *no interference* with NOvA neutrino oscillation experiment:
  - Mu2e uses beam NOvA can't use
- reuse existing rings with only minor modifications
  - antiprotons for TeV use two rings and we will use those
  - we do not need access before Run III would end



# Upgrade Plans: Project X



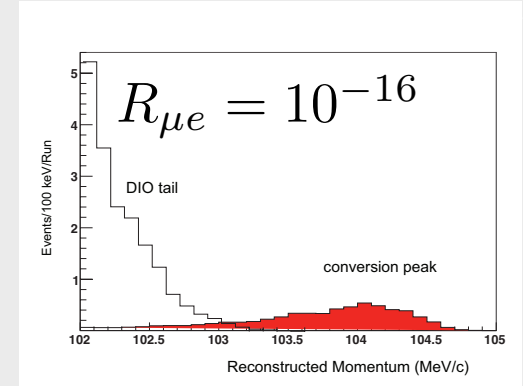
Yes

Signal?

No

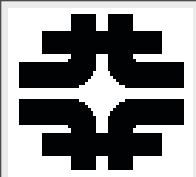
1. Change Z of Target to determine source of new physics

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

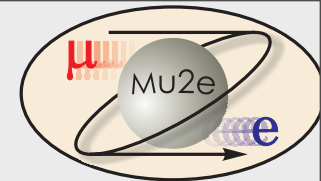


1. Both Prompt and DIO backgrounds must drop to measure  $R_{\mu e} \sim 10^{-18}$

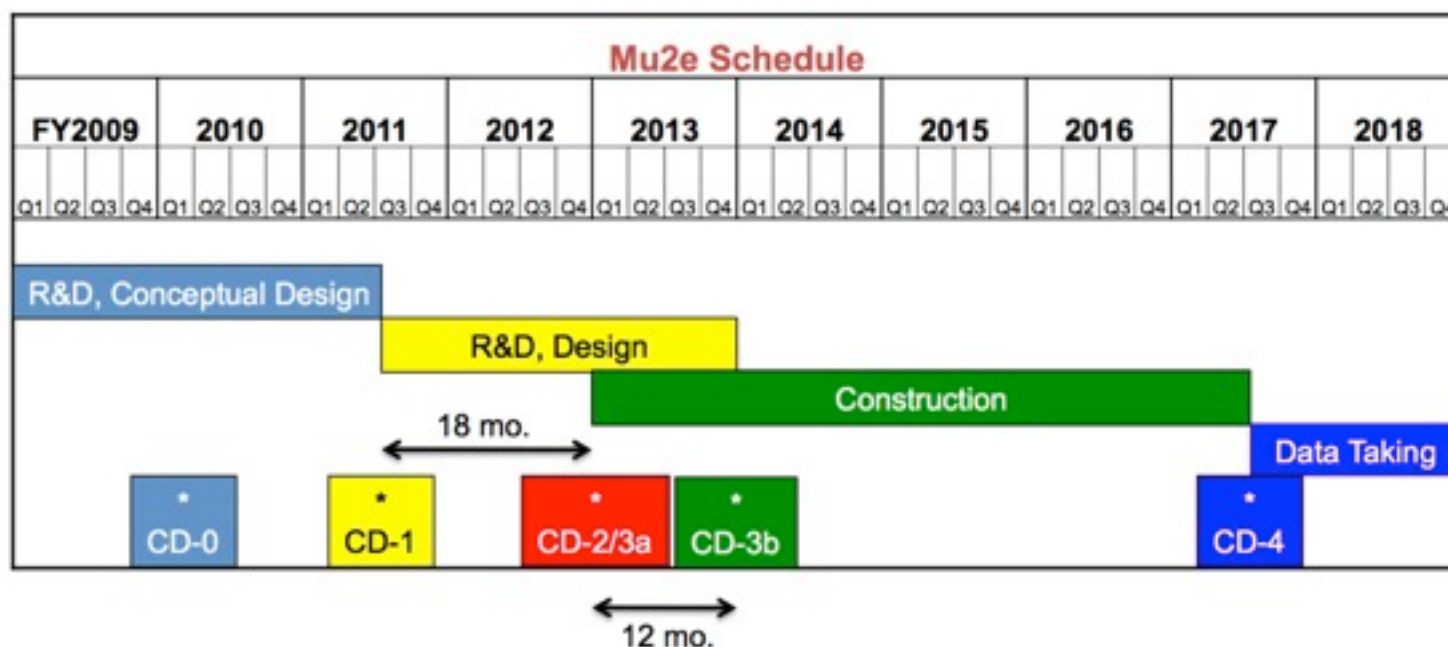
2. Detector, Muon Transport, Cosmic Ray Veto, Calorimeter

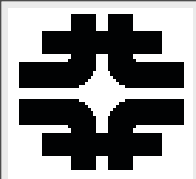


# Cost and Schedule

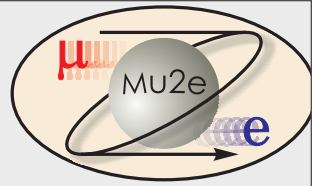


- *This is a technically limited schedule* data-taking 2018
- Critical Path is Superconducting Solenoids
- \$200M “fully-loaded” Total Cost



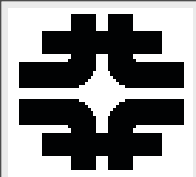


# Recent Progress

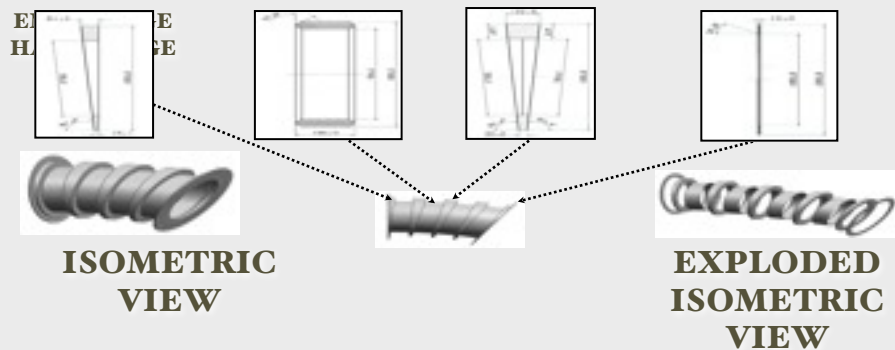
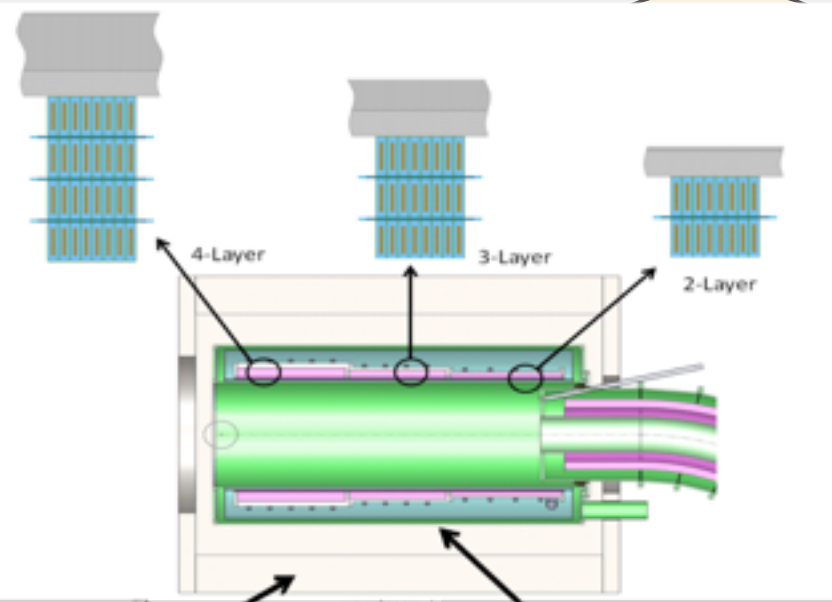
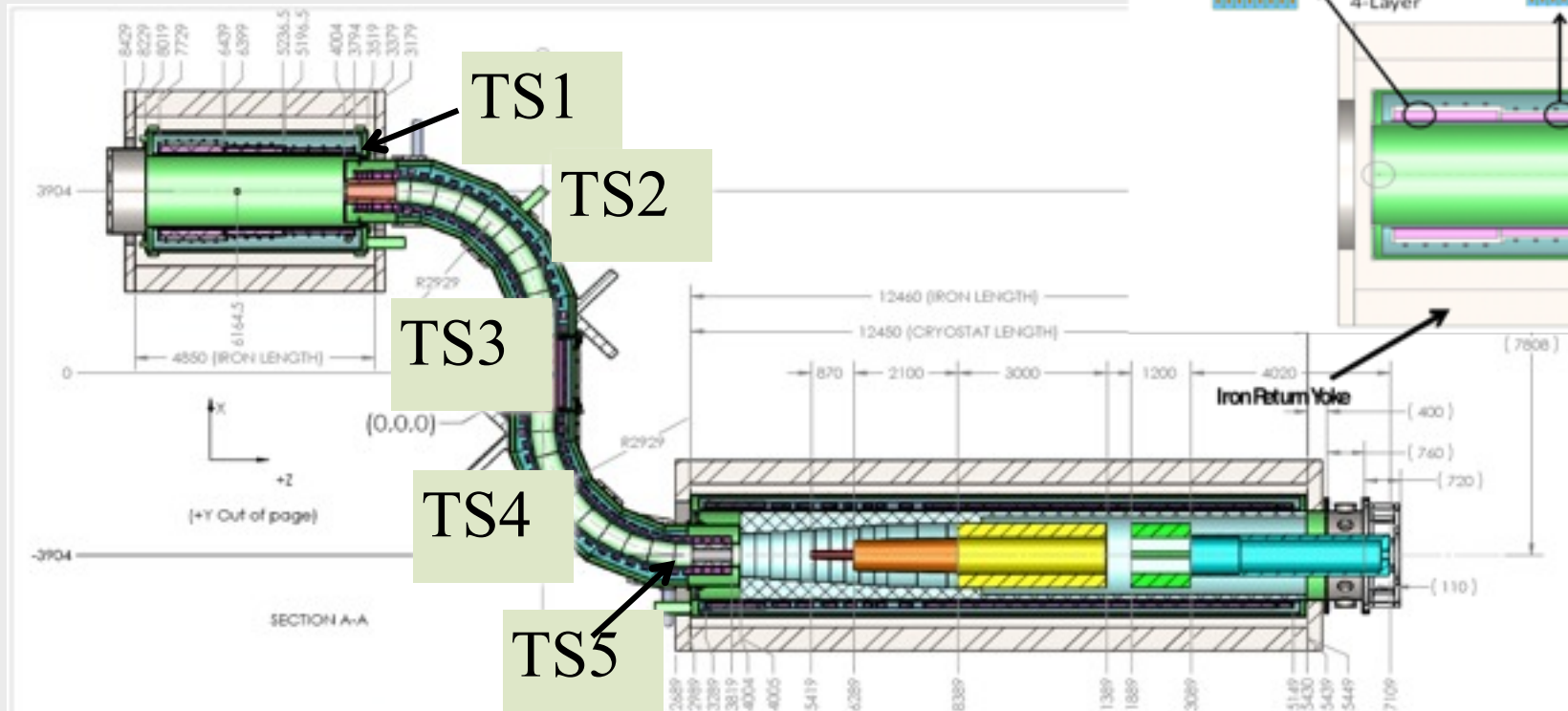


- Rapid progress both technically and in bureaucracy
  - Passed Internal Design Review May 5 2011, technically ready for DOE CD-1
  - Solenoid system has detailed field models and we are beginning to talk to vendors
  - Building prototypes of
    - Extinction Dipole (thanks to US-Japan fund)
    - Straw Tube Tracker (15 micron straws in vacuum; studying mechanical assembly, leak rate, readout)
    - Cosmic Ray Veto system

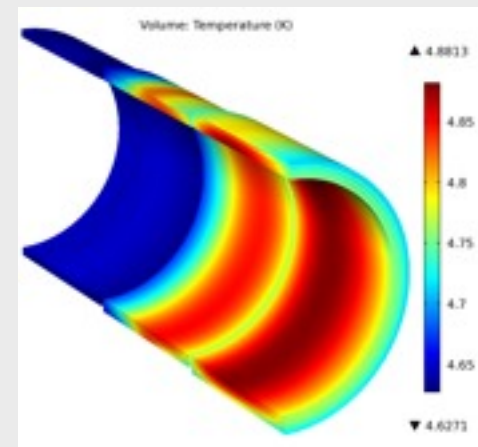




# Solenoids



**TS ASSEMBLY AND PARTS**



Production Solenoid:  
Radiation and Heat  
Load  
And thanks to KEK!  
 $T_0=4.6$  K,  
static+dynamic heat  
load

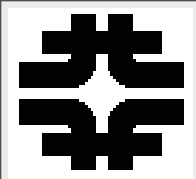
R. Bernstein, FNAL

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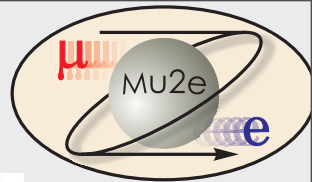
Mu2e

NuFact 2011

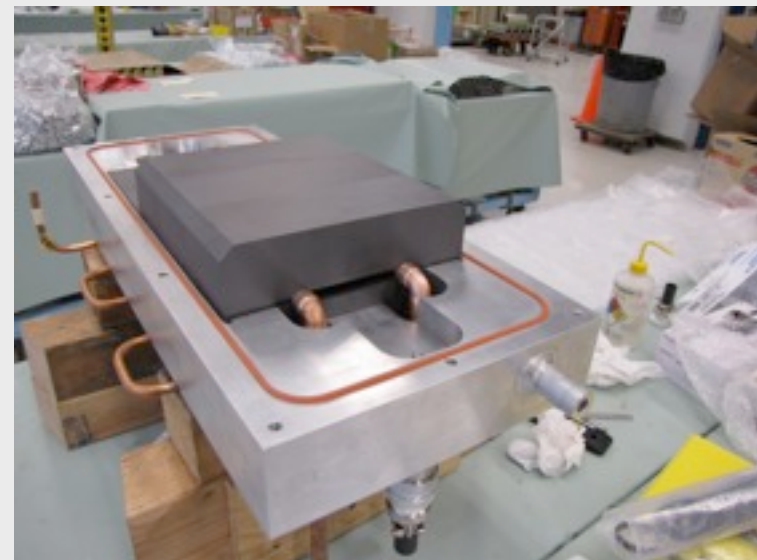
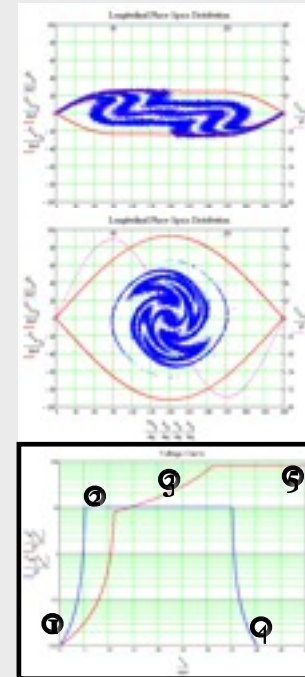
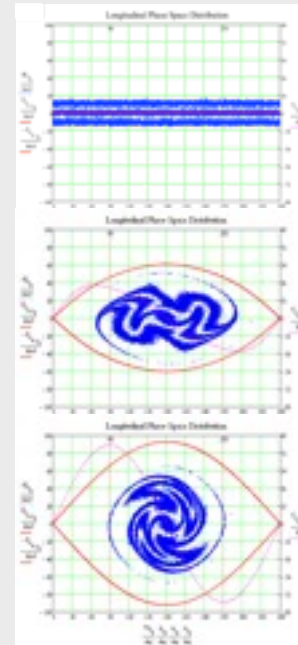


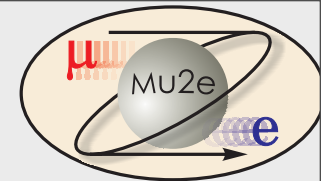
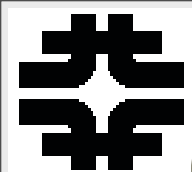


# Accelerator



- Advanced modeling of beam, including space charge effects
- Prototype of Extinction Model being studied as of 7/22/2011
  - Ferrites and power supplies for 300 kHz and 5.1 MHz components

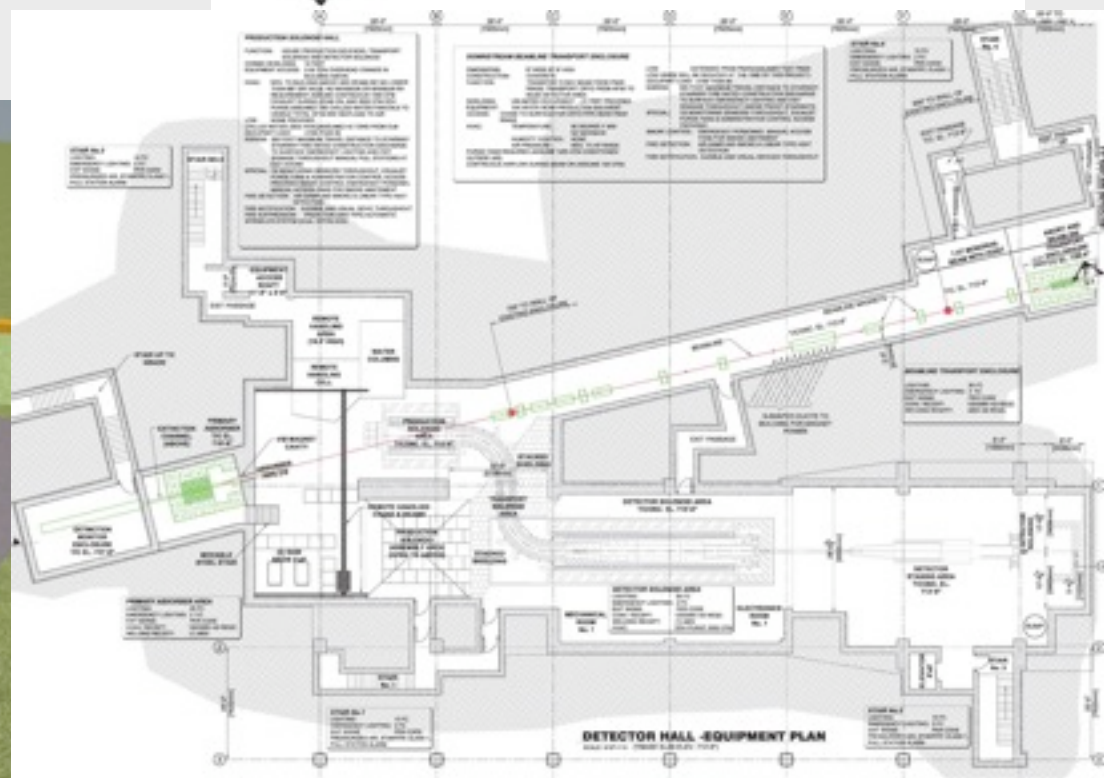
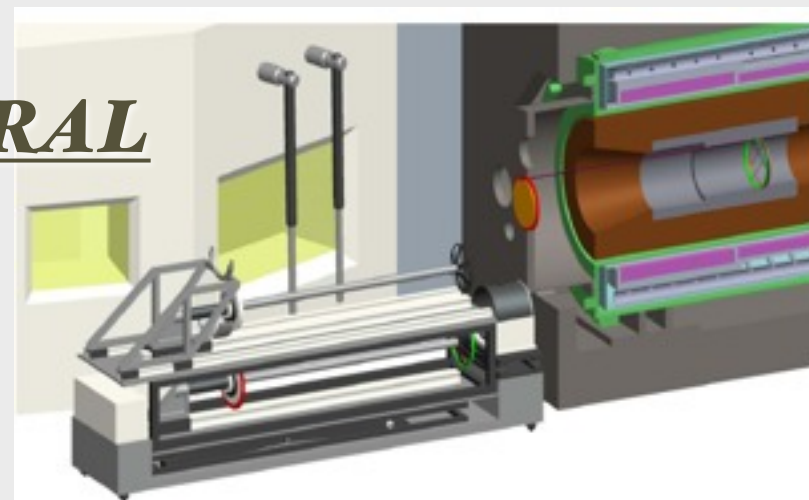




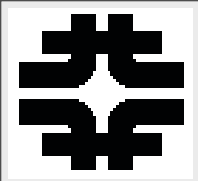
# Civil and Building

- Target Handling and Solenoid Assembly

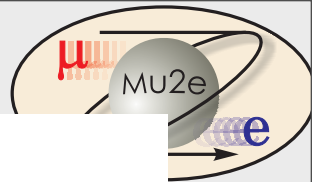
*RAL*



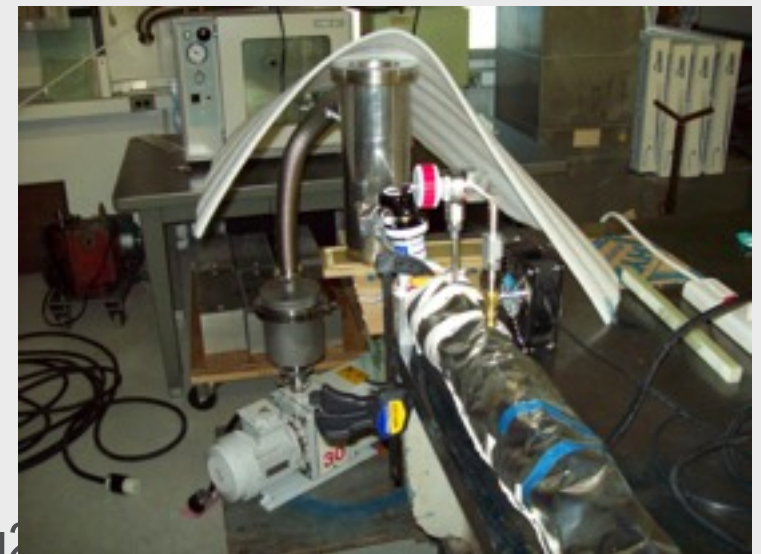
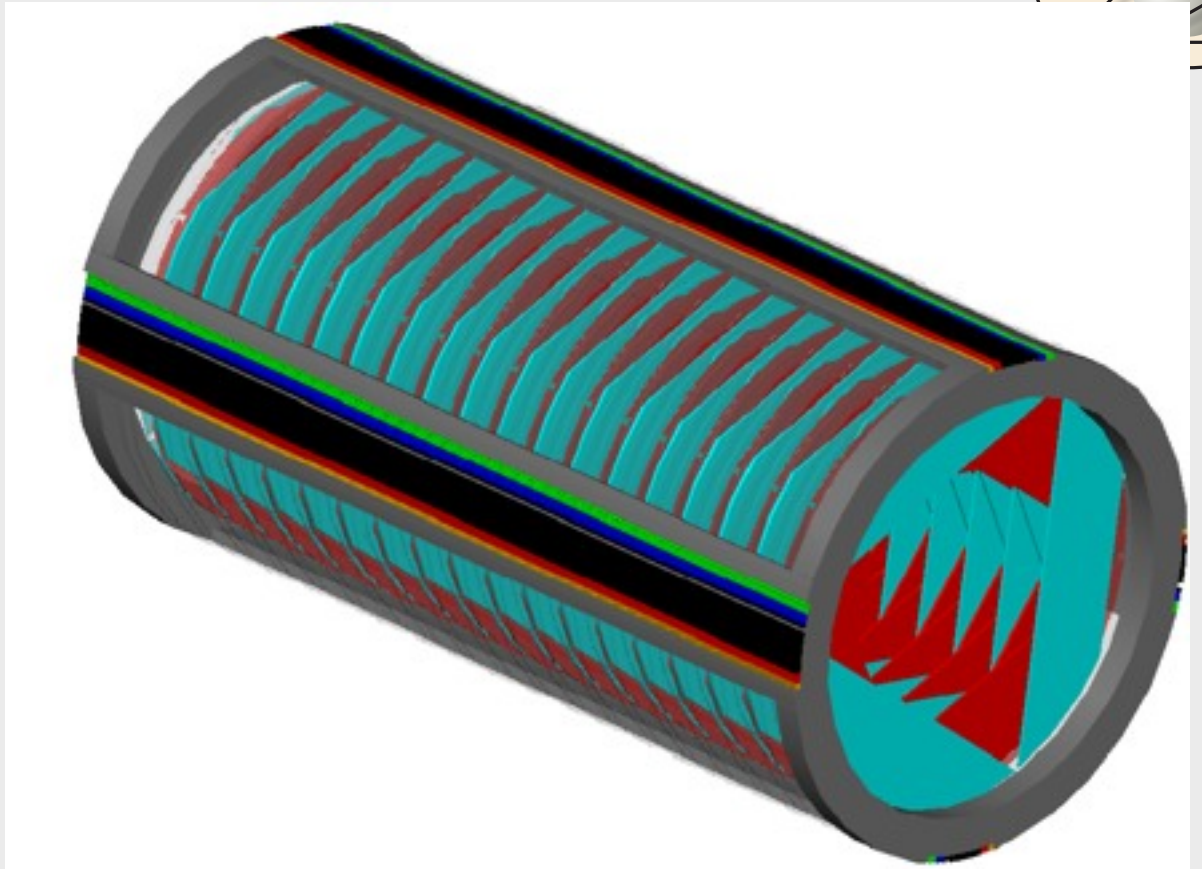


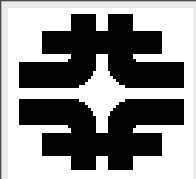


# Tracker

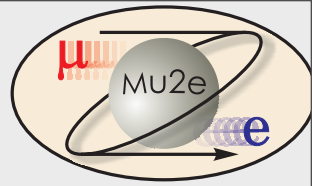


- “T”-tracker:
  - Leak test with vacuum
  - Aging studies
  - Tensioning

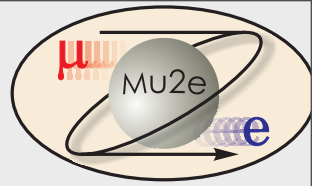
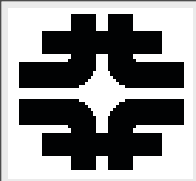




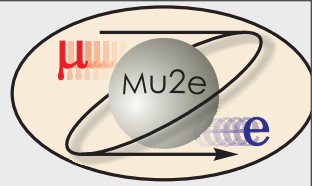
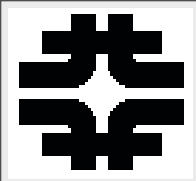
# Conclusions



- 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



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



Who ordered that?