# Charged Lepton Flavor Violation Experiments at Pulsed Beams: (and *g*-2)

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Fermilab

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Uppsala, Sweden

# Why Should Anyone Here Care About CLFV?

- Technology is linked:
  - When you make muon neutrinos, you make muons. Neutrino factories/nuSTORM, for example, make muon beams we can use for muon CLFV.
- Physics is linked: (Ana's talk! much deeper than this)
  - oscillations are neutral lepton flavor violation
  - explanations for neutral lepton mixing make predictions for charged lepton mixing; I'll show you examples.
  - *g-2:* can think of it as probing diagonal elements of a matrix; CLFV studies the off-diagonal

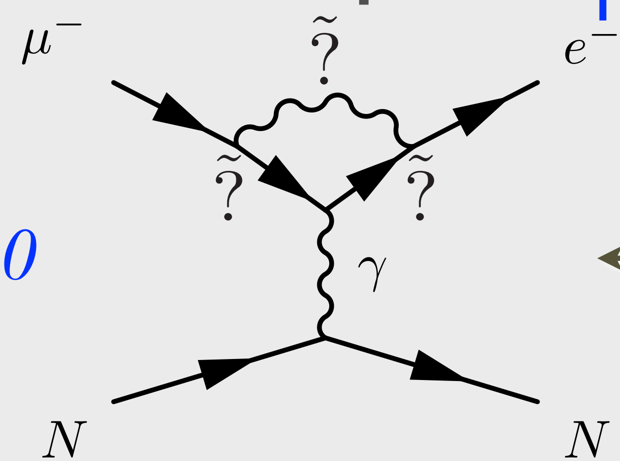
# Topics

- Why do CLFV experiments with muons?
- What are the experiments that will be done in pulsed muon beams, and what are their contributions?
  - focus on muon-to-electron conversion: $\mu^- N \to e^- N$
  - will not cover muon decay experiments at PSI: MEG ($\mu \to e \gamma$) or Mu3e ($\mu \to 3e$), except as needed: see next talk from Iwamoto-san
- A few words about collider CLFV and 3rd generation
- Will show data from first run of FNAL *g*-2!

# Effective Lagrangian

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

**"Loops"**




$\kappa = 0$

Supersymmetry and Heavy Neutrinos

Contributes to $\mu \to e\gamma$

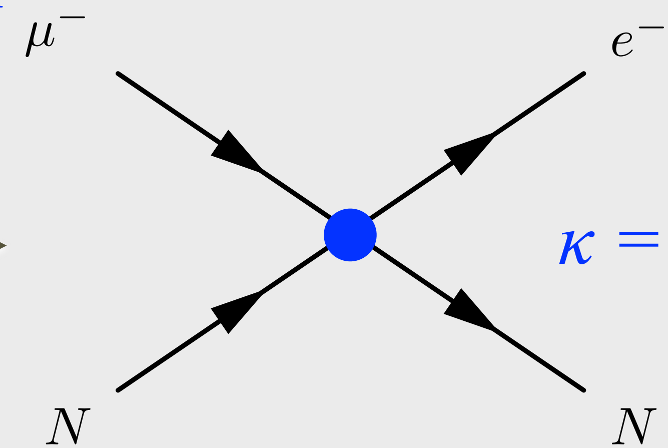
(just imagine the photon is real)

mass scale $\Lambda$

$\kappa$

$\longleftrightarrow$

**"Contact Terms"**




$\kappa = \infty$

New Particles at High Mass Scale (leptoquarks, heavy Z,...)

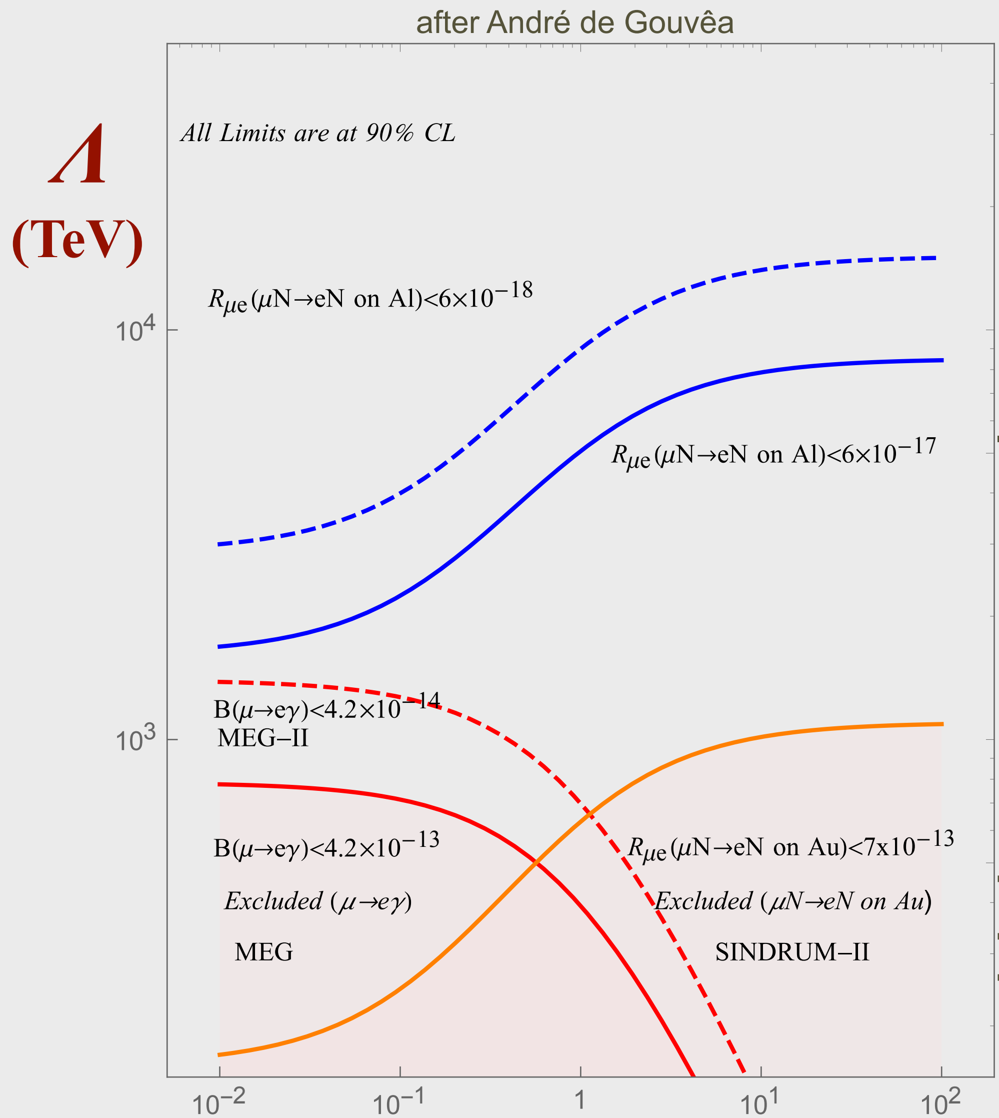
Does not produce $\mu \to e\gamma$

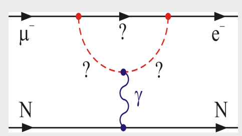
# $\mu e$ Conversion and $\mu \to e\gamma$

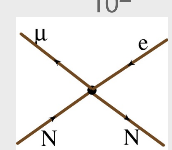
1) *Mass Reach to ~$10^4$ TeV for unit coupling*

2) *Mu2e/MEG upgrade complementary in loop-dominated physics.*

3) *These are discovery experiments*




higher mass scale

# CLFV and the LHC

LHC inverse problem

New physics at LHC?

yes

no

Look for new physics at very high mass scales

Does CLFV see a signal ?

yes

no

1) arXiv implodes

2) specific models have to reproduce results: MEG, Mu2e, Mu3e

Null results still have enormous discriminating power among models

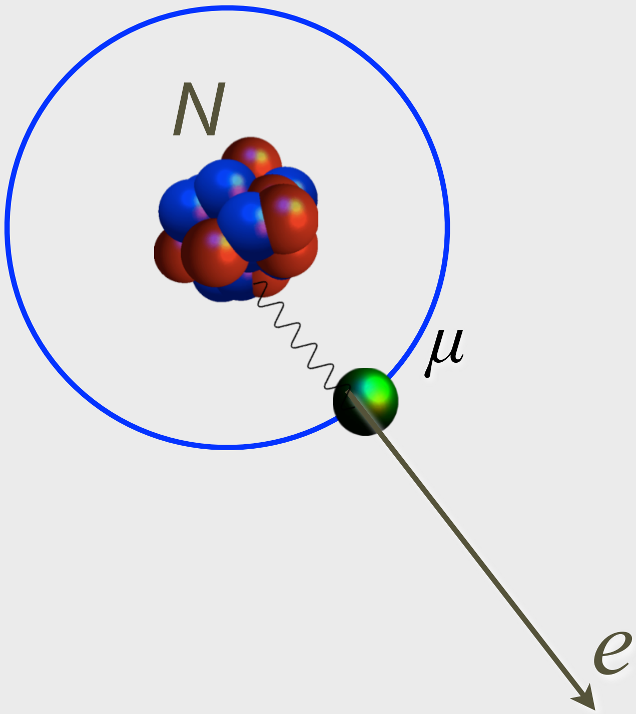
# What is Muon to Electron Conversion? $\mu^- N \rightarrow e^- N$

- Muon converts to an electron in the field of a nucleus
- Effectively zero Standard Model background — a signal is new physics
- Can measure a signal with SES of $\sim 10^{-17}$
  - typical predictions for EWSB predict $\sim 10^{-15}$
- Experiments to be discussed require pulsed beams

# Experimental Signal

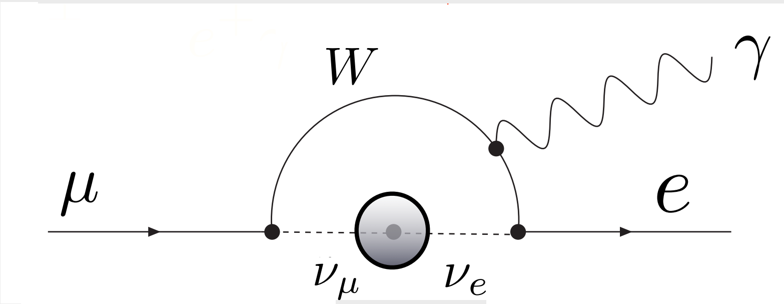
$$\mu^- N \to e^- N$$

- A Single Mono-energetic Electron
  - muon falls into 1s state in "target"
- Nucleus coherently recoils off outgoing electron, no breakup
- If $N$ = Al, $E_e$ ~ 105. MeV ~$m_\mu$
  - electron energy depends on $Z$
  - physics in $Z$-dependence of rate



# Neutrino Background

- Neutrino Oscillations are the only Standard Model background, except neutrino oscillations are not in the Standard Model




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

- nobody understood why $\mu \rightarrow e\,\gamma$ wasn't $10^{-4}$ until we hypothesized two neutrinos ($\nu_\mu \neq \nu_e$)!

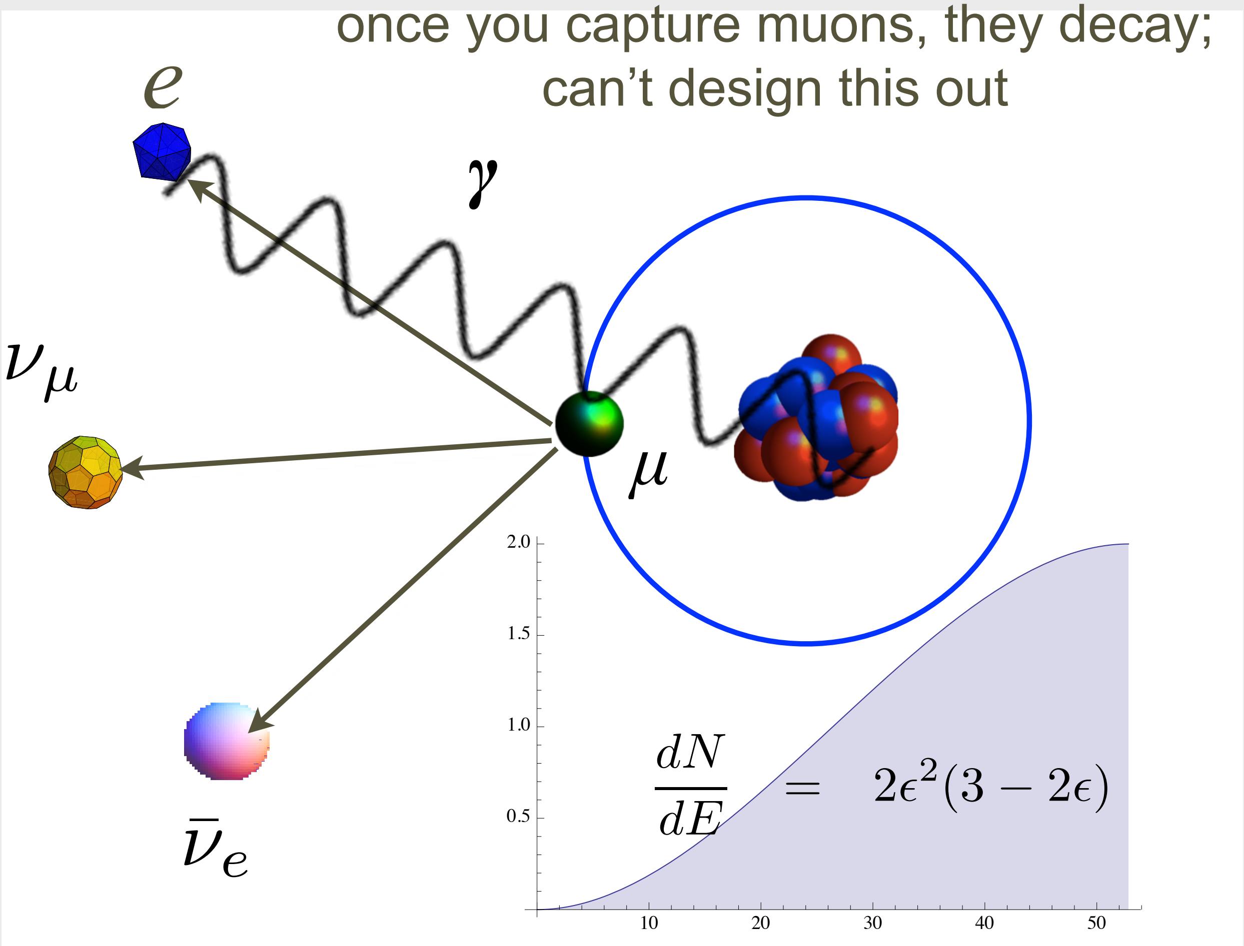
- told you neutrinos were important to us!

# Intrinsic Background: Decay-In-Orbit (DIO)

- Peak and Endpoint free muon decay of Michel Spectrum is at

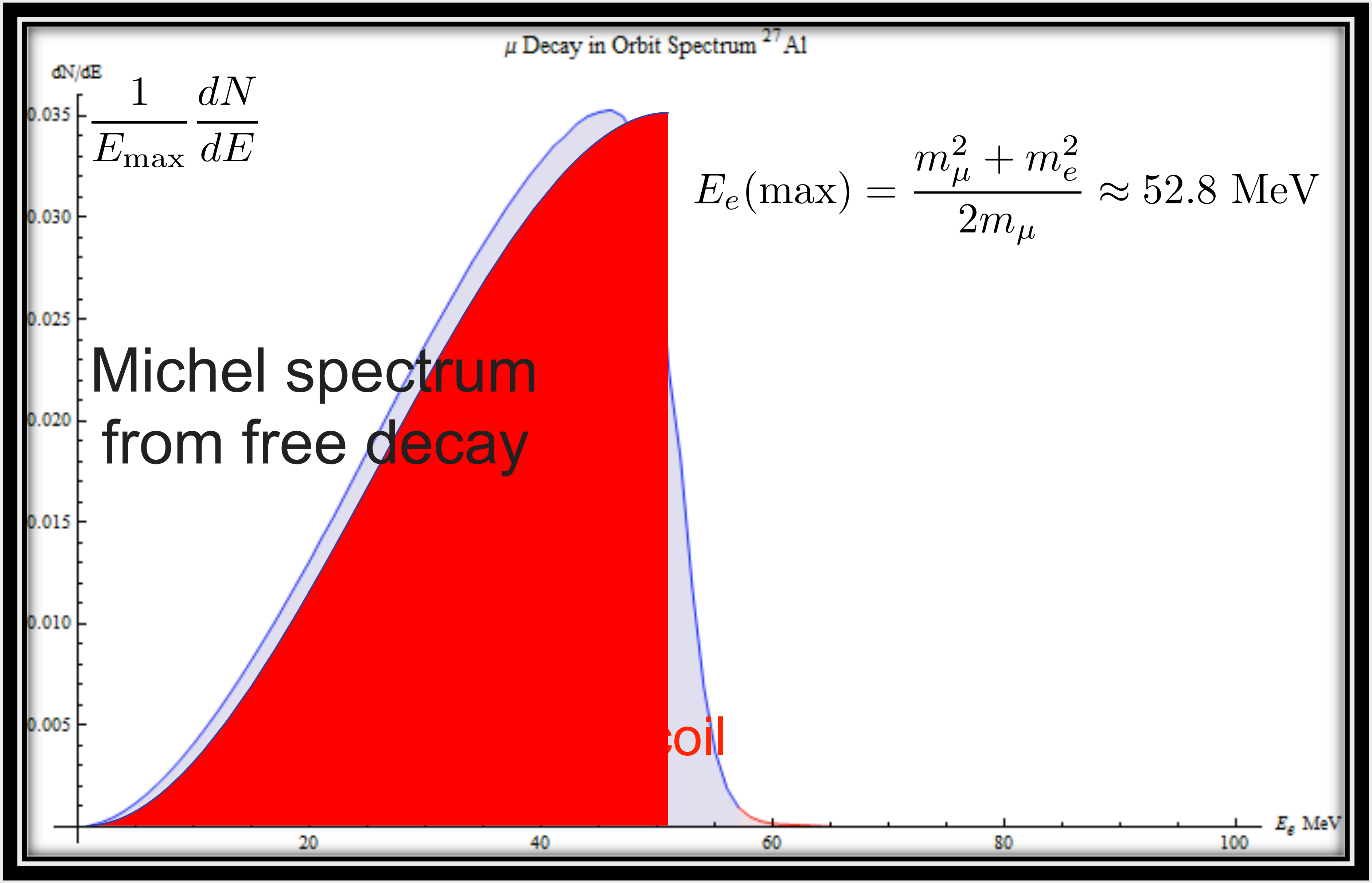
$$E_{\max} = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8 \text{ MeV}$$

- Far from our 105 MeV signal
- But in presence of nucleus, electron can exchange photon with nucleus
- Endpoint at signal energy (neglecting tiny neutrino mass) so excellent resolution is critical



# Decay-in-Orbit Shape

Szafron 10.5506/APhysPolB.46.2279: Radiative Corrections




Czarnecki: 10.1016/j.physletb.2015.12.008 many other papers

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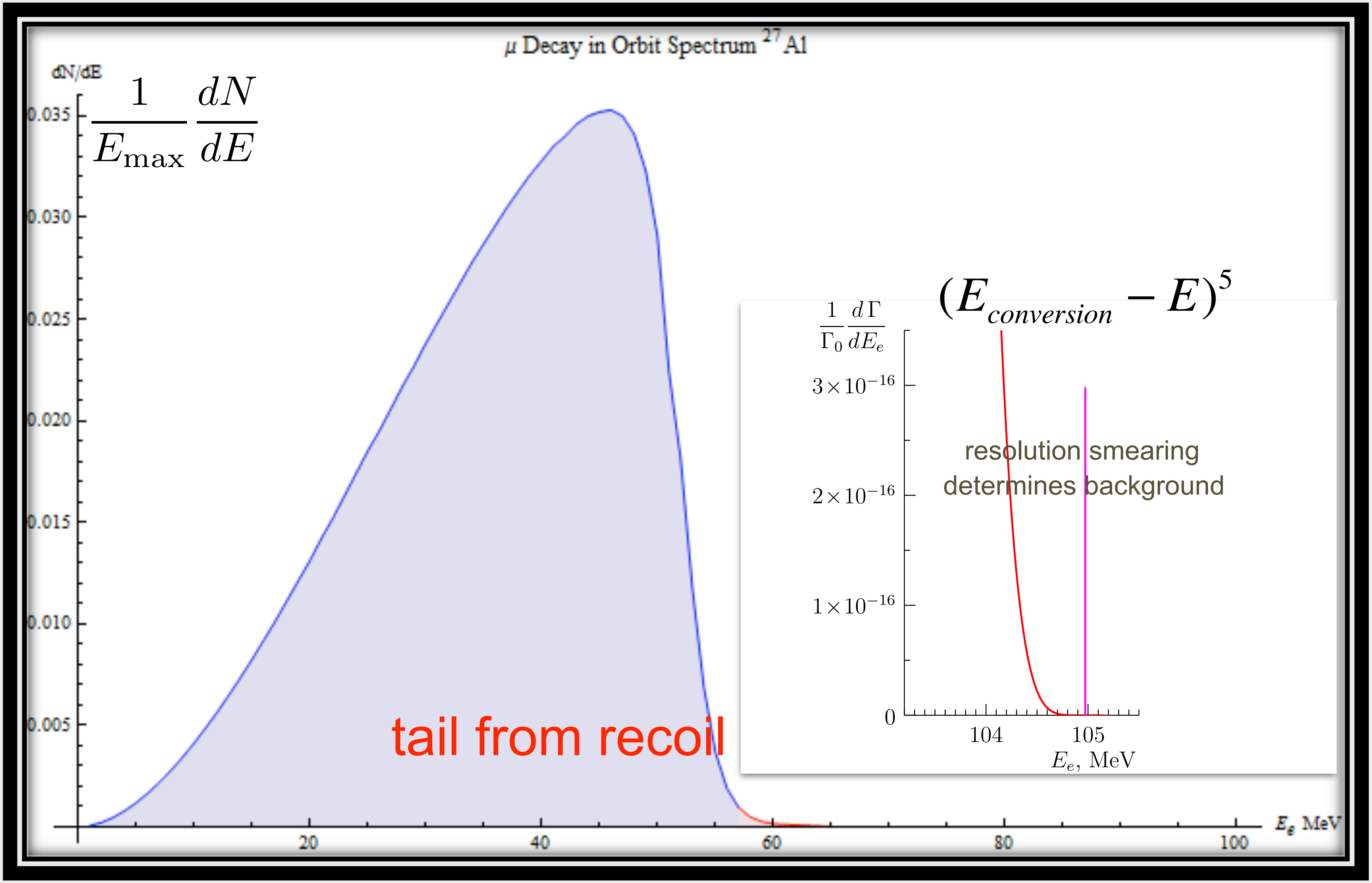


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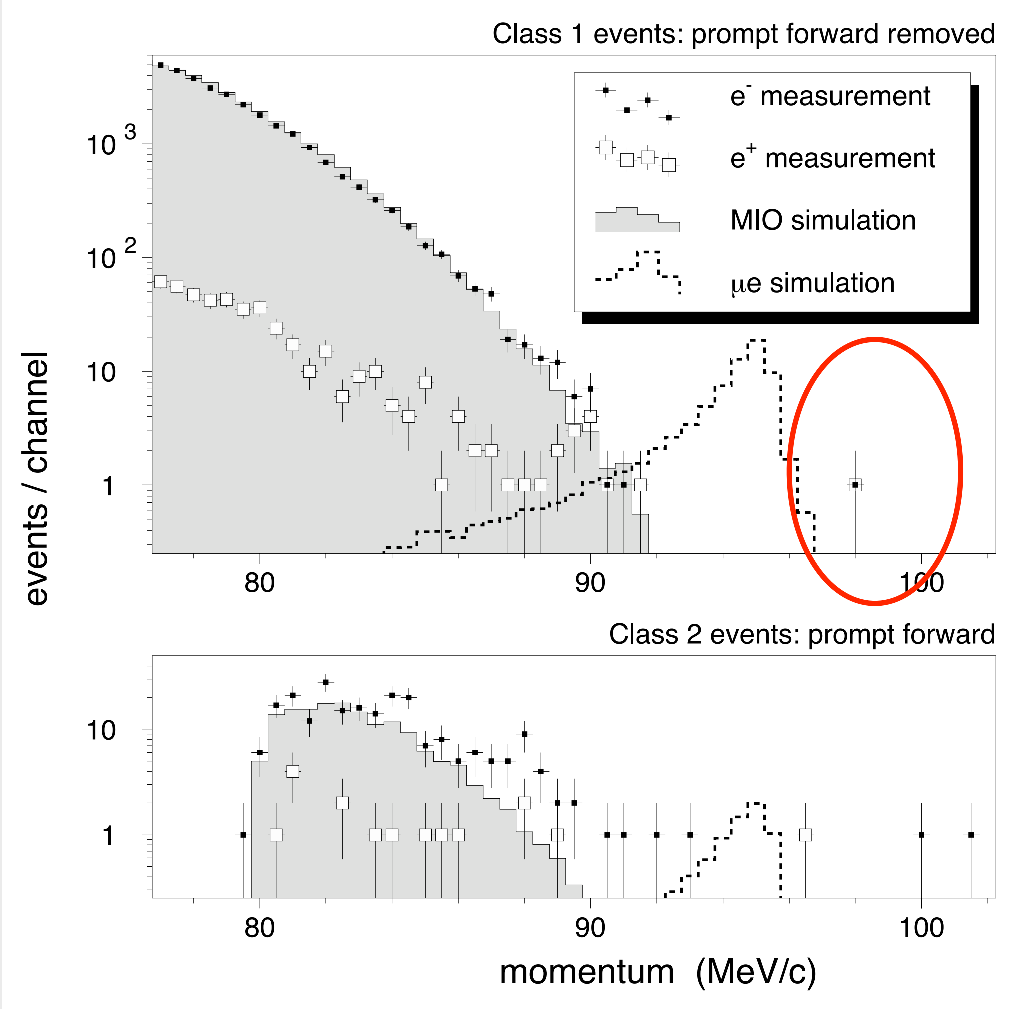
W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006)

# SINDRUM-II Results

- Effectively constant beam
  - 51 MHz (~20 nsec) repetition rate, ~0.3 nsec pulse
- Small time separation between signal and prompt pion backgrounds
  - bottom plot is first half of 20 nsec, top plot is 2nd half
  - time lowers background

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

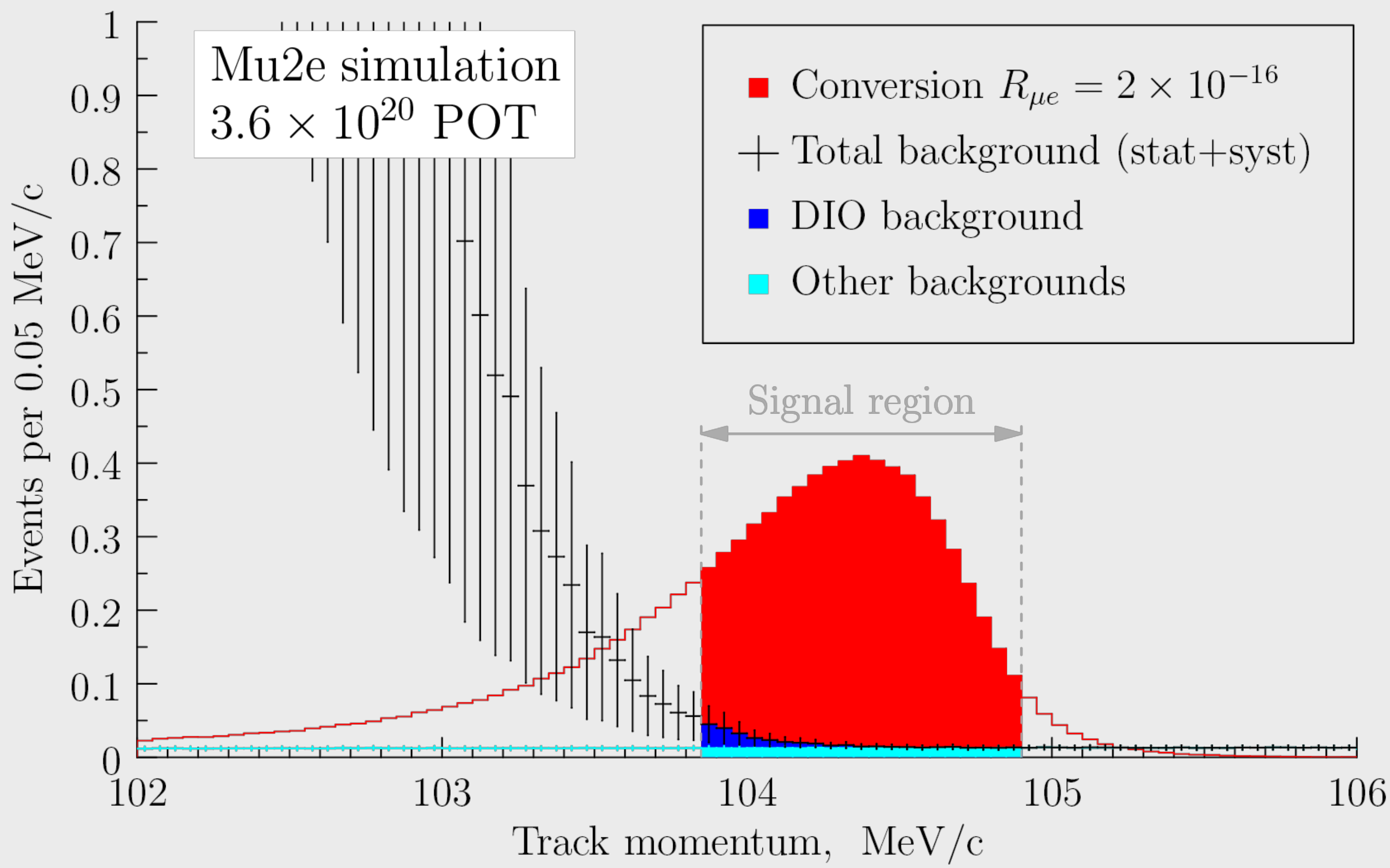


# Mu2e Design

90% CL ~ 8 x $10^{-17}$ 5$\sigma$~ 2 x $10^{-16}$

x10000 better than SINDRUM-II

Mu2e




***typical SUSY at $10^{-15}$:*** 40 events vs 0.4 bkg

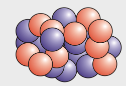
# How Do you get x10,000 Improvement?

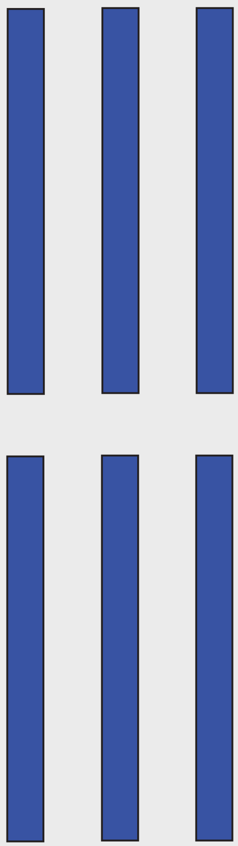
(K. Lynch, WG3)

- Pulsed Beam
  - will cover physics reasons
- World's most intense muon beam:
  - $10^{10}$ $\mu$/sec at detector under construction right now
  - don't have time to discuss accelerator technology
- Superconducting solenoid system

# Prompt Backgrounds and Pulsed Beam

Al target foils: muon converts here

 = muons, electrons, pions



Radiative Pion Capture:

$\pi N \rightarrow \gamma N$

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

pulsed beam lets us wait (1) until after beam flash, and (2) RPC background decays away

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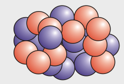
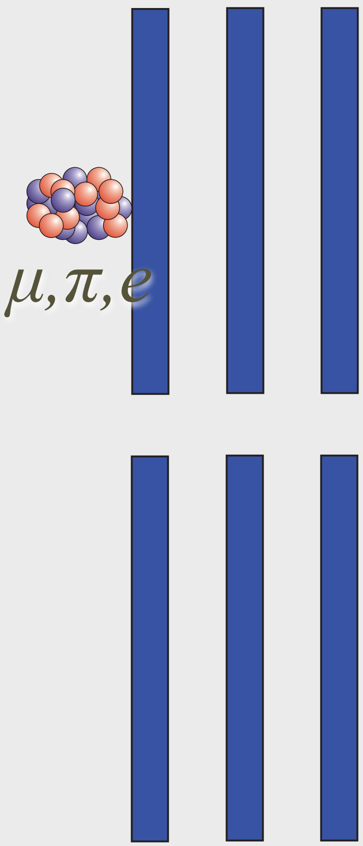
 = muons, electrons, pions

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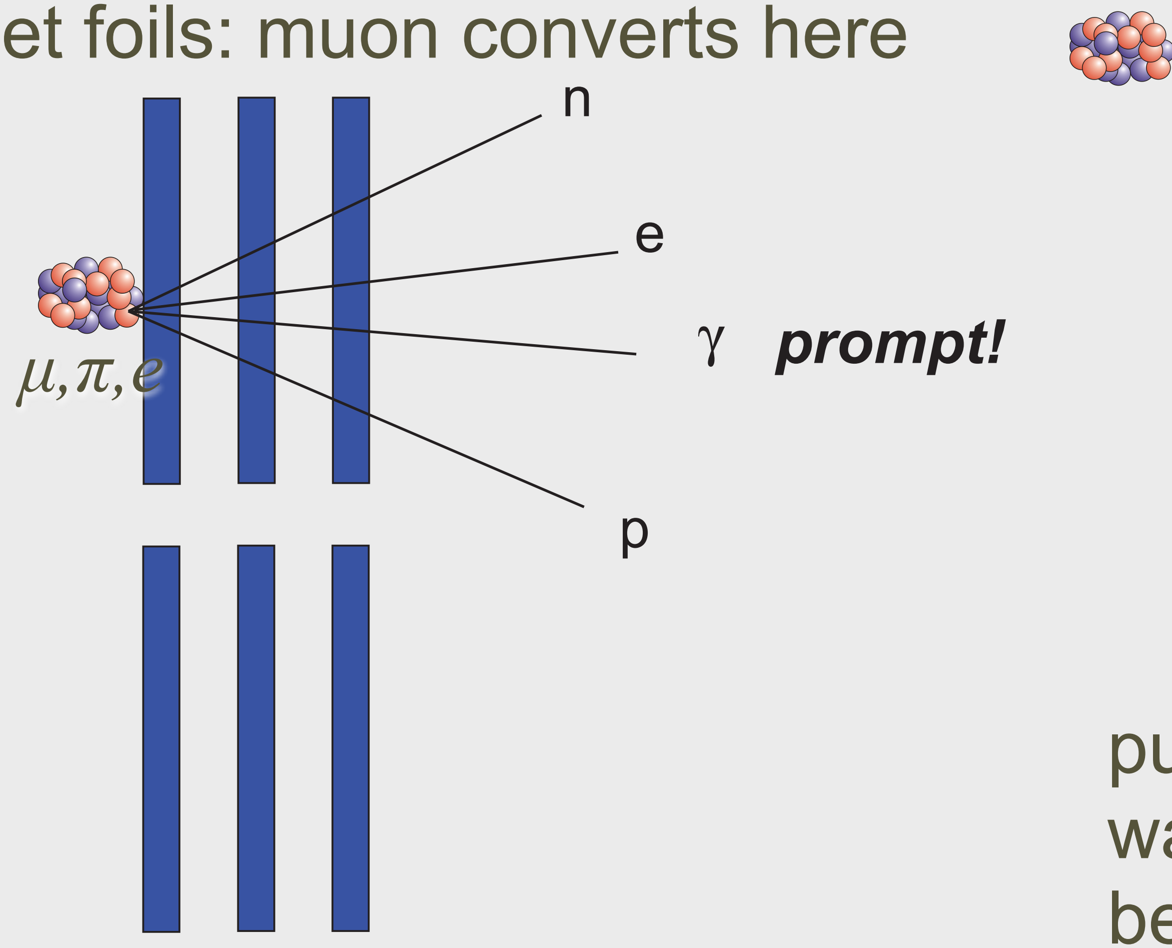


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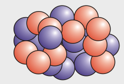
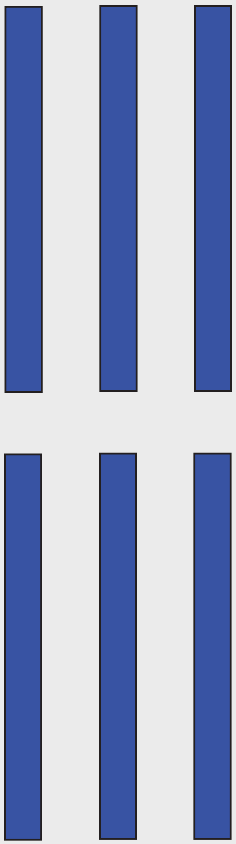
 = muons, electrons, pions



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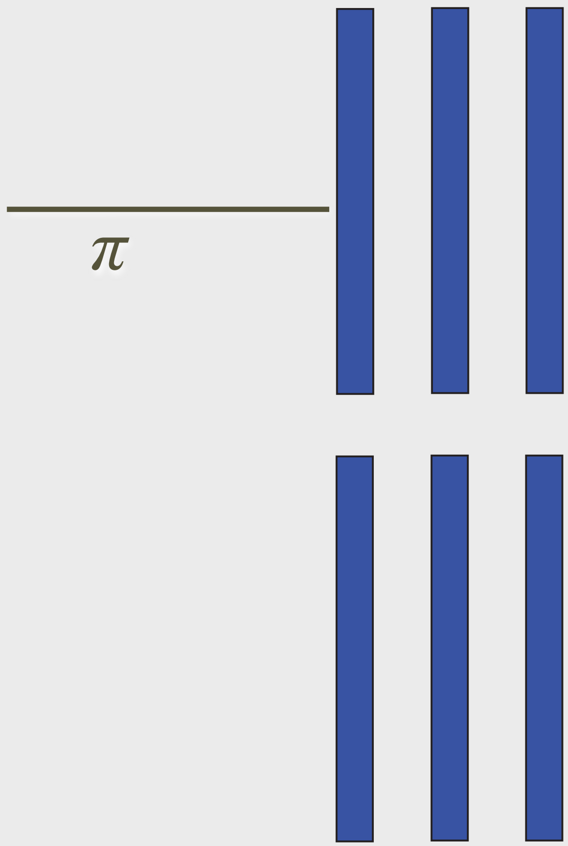


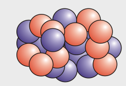 = muons, electrons, pions

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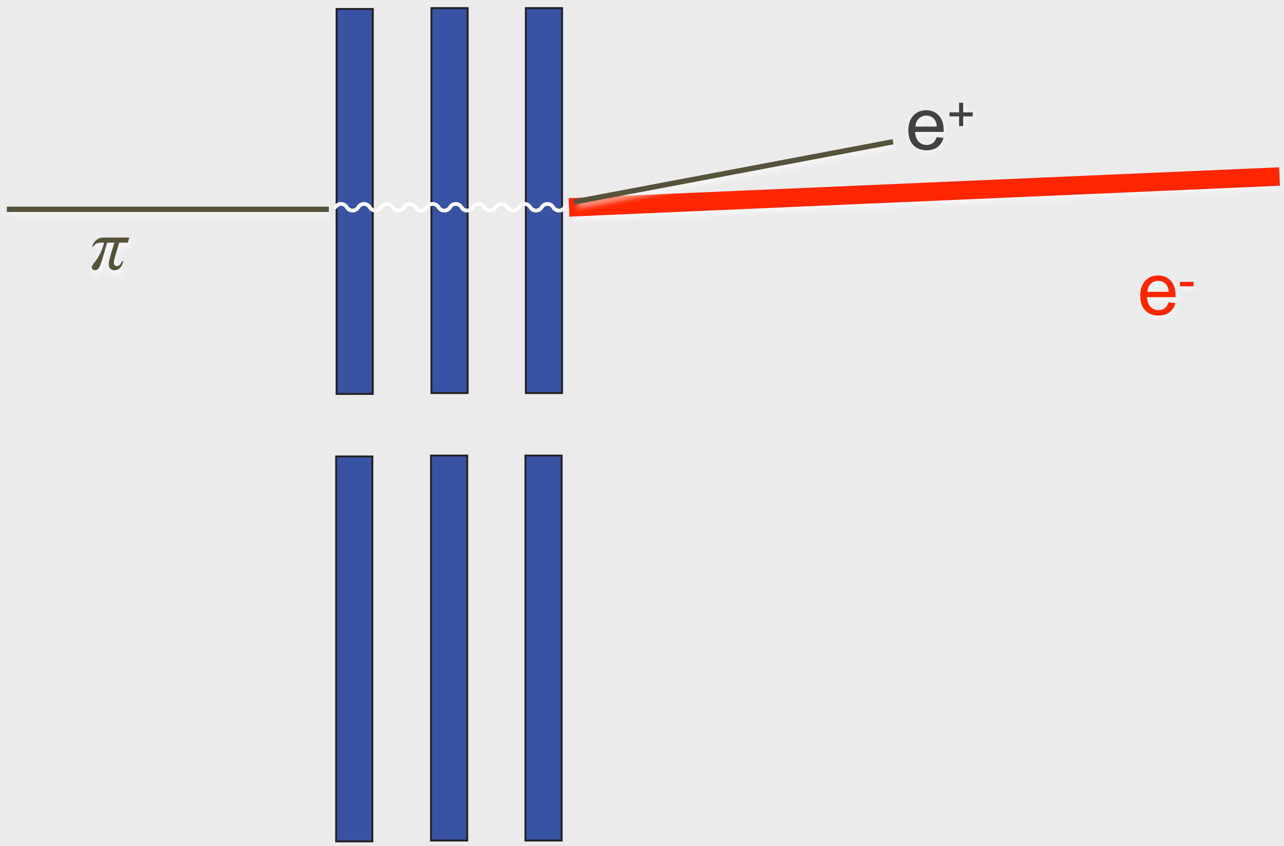


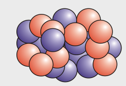


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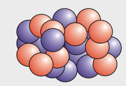

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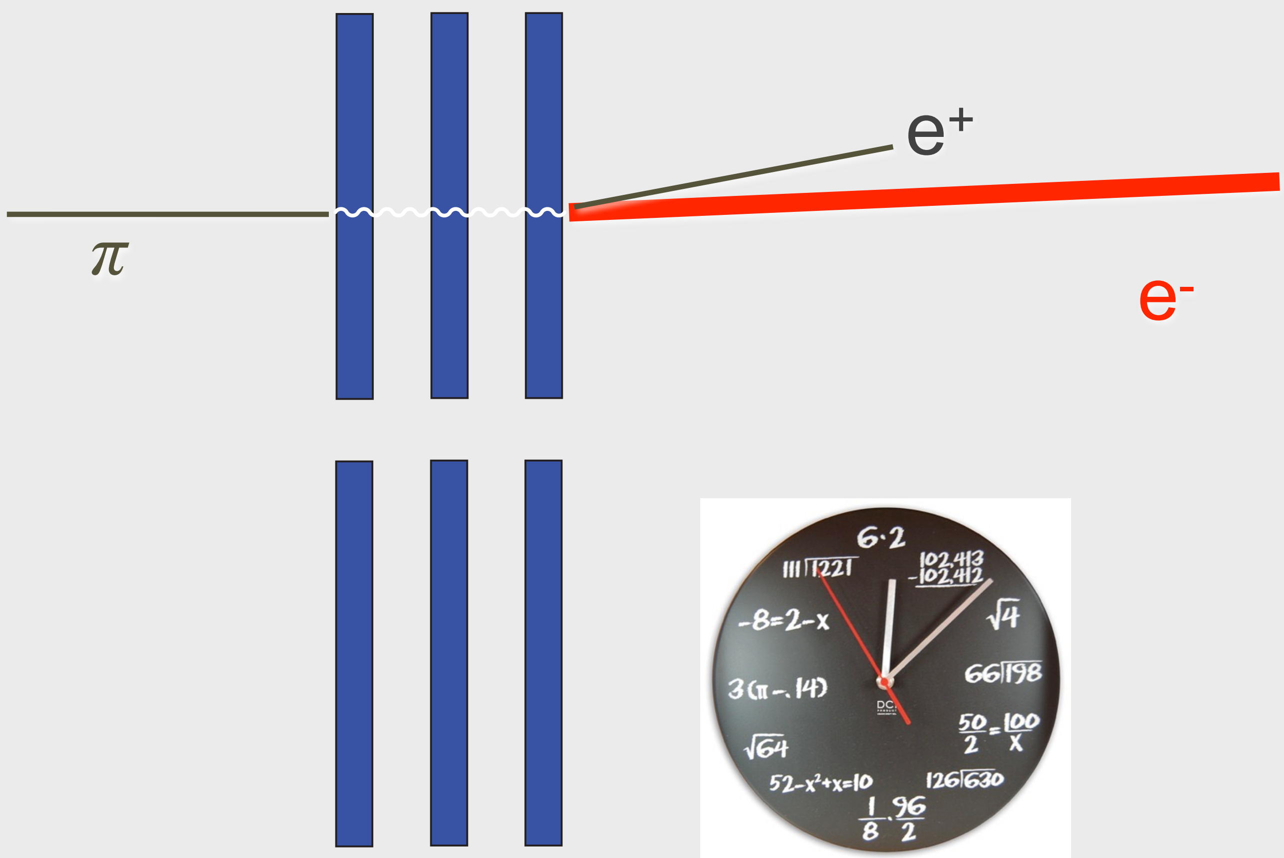


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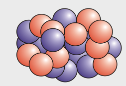
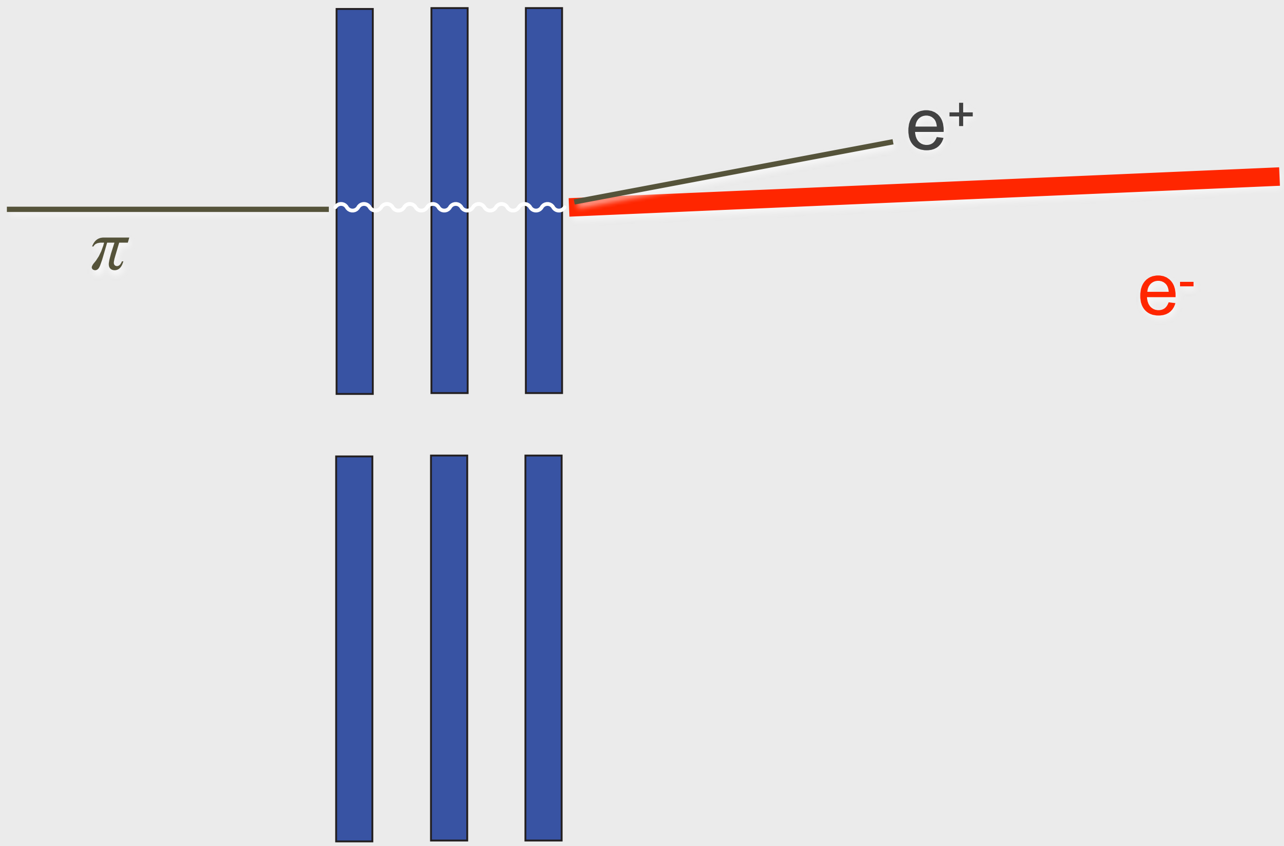
 = muons, electrons, pions

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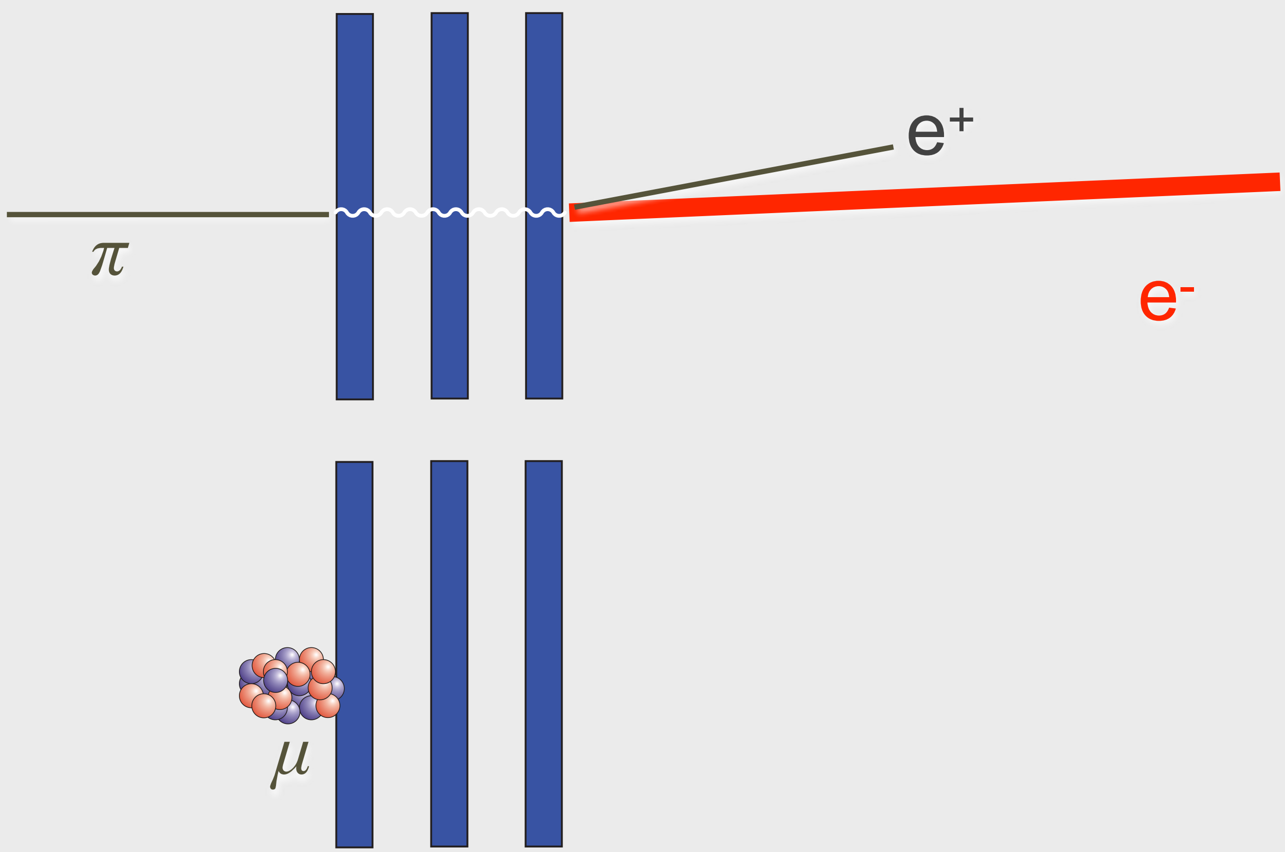


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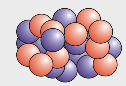
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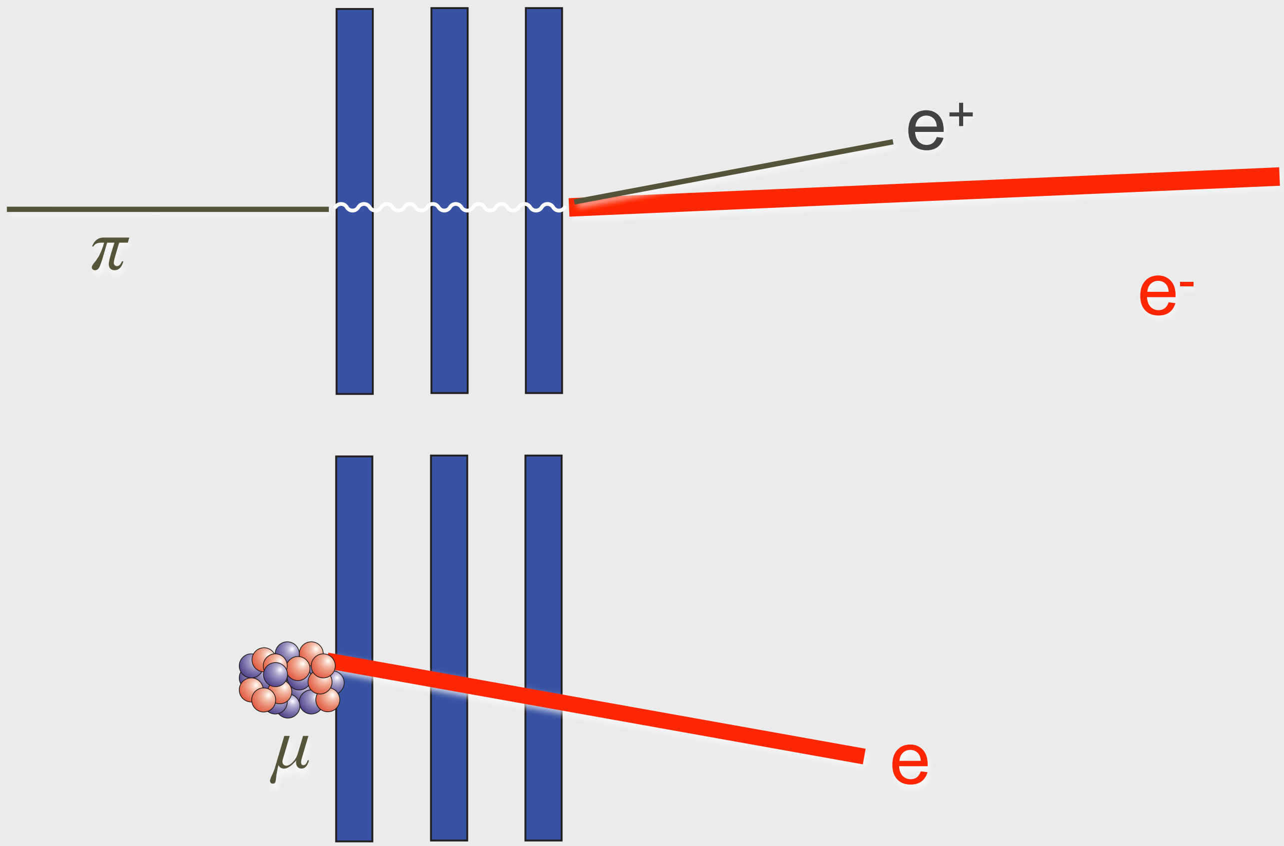


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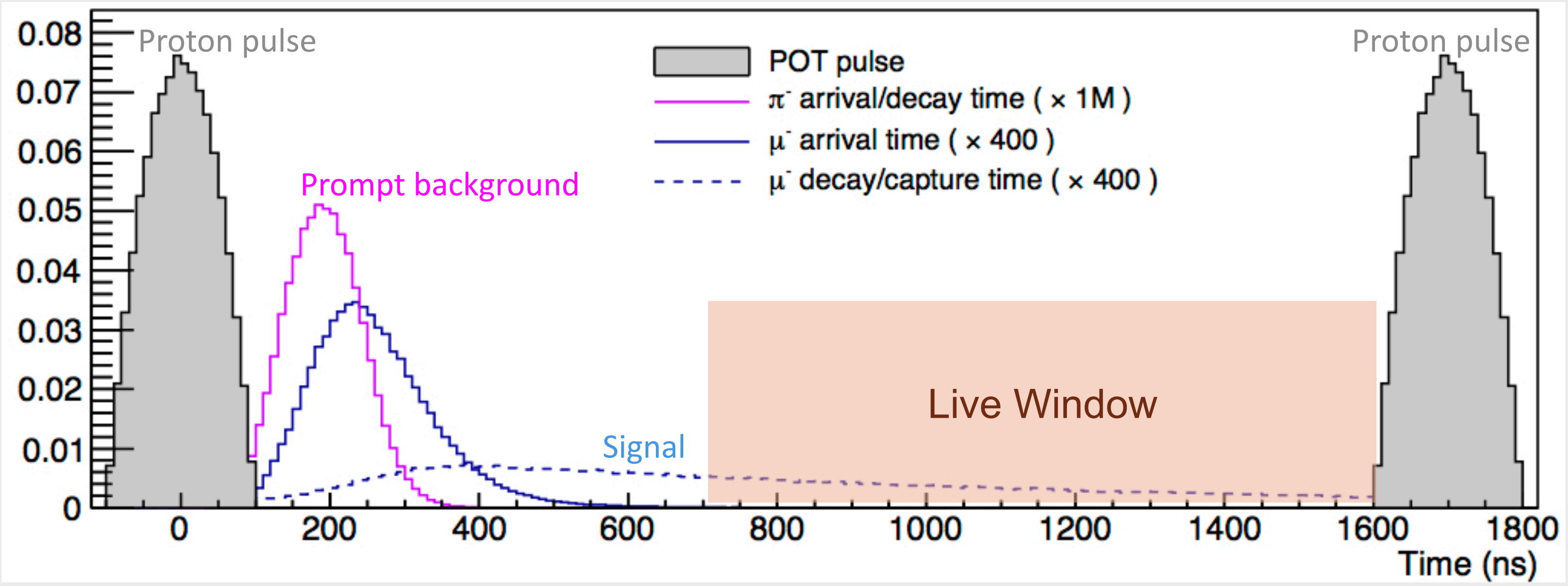
now $\mu$ is only source of 105 MeV electron

# Pulsed Beam Structure




$\pi$ backgrounds

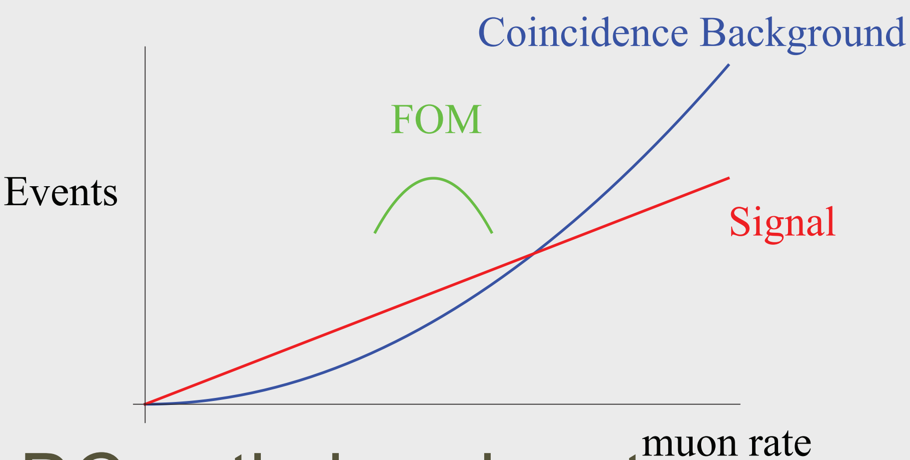
signal window

- Wait out pion backgrounds, then open signal window
- Can’t “restart the clock” with out-of-pulse protons
- Need $10^{-10}$ in-pulse/out-of-pulse ratio (**extinction**)
  - will monitor during experiment

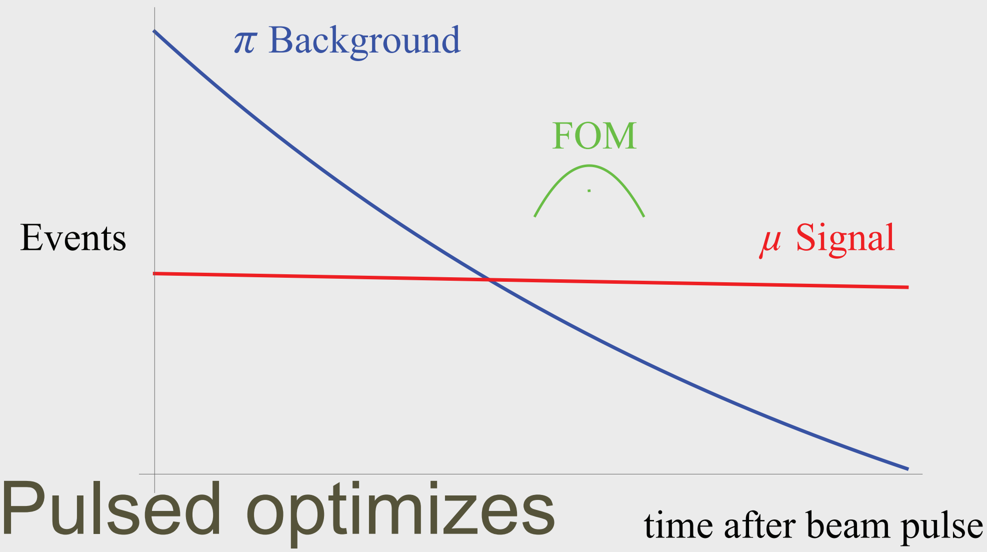
# Pulsed vs. "Steady" Beam

- Decay expts, $\mu \rightarrow e\gamma$ and $\mu \rightarrow eee$, want a steady beam: PSI
  - need to minimize backgrounds from coincidences of two decays
  - (Rate)$^2$ bkg vs Rate(signal)

- muon-electron conversion wants a pulsed beam: FNAL/J-PARC
  - Many pion-induced backgrounds after proton pulse
  - Take advantage of 26 nsec lifetime to "wait it out"



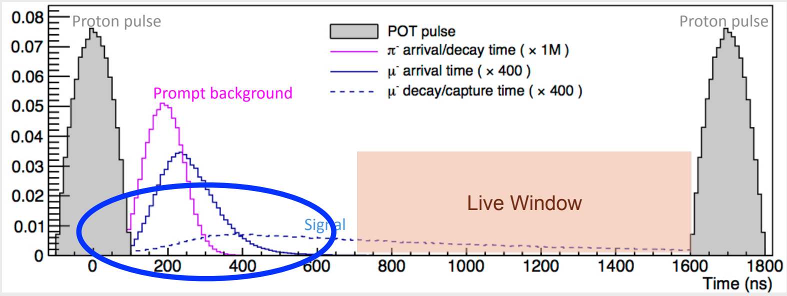

DC optimizes in rate




Pulsed optimizes in time

# Beam Flash

- After proton beam strikes target, “flash” of photons and electrons, and many electrons hit stopping target and detector
- Large neutron flux as well that would deaden detectors
- By waiting:

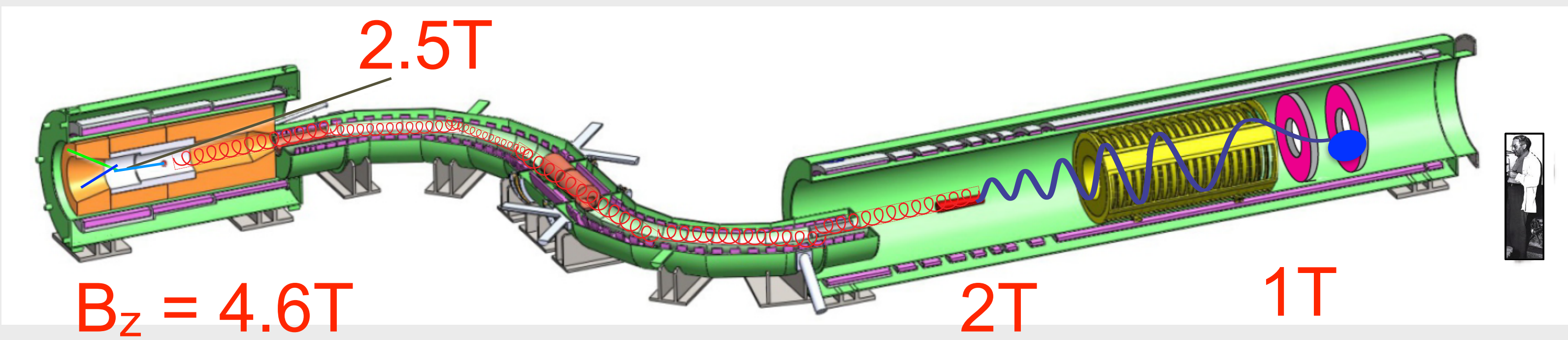



  - activity from beam flash is over
  - And pion backgrounds have decayed by $\sim 10^{11}$
- I will mention the flash throughout; has implications for Mu2e and especially for potential upgrades

Dukes, WG4

# Actual Experiments: Mu2e/COMET

4.6T ⟶ B-field gradient ⟶ 1T




Mu2e

- Target protons at 8 GeV inside superconducting solenoid at 8kW
- Capture muons and guide through S-shaped region to Al stopping target
- Stop muons, let them fall into a “1s” state
- Central hole for passage of remnant muon beam and background suppression

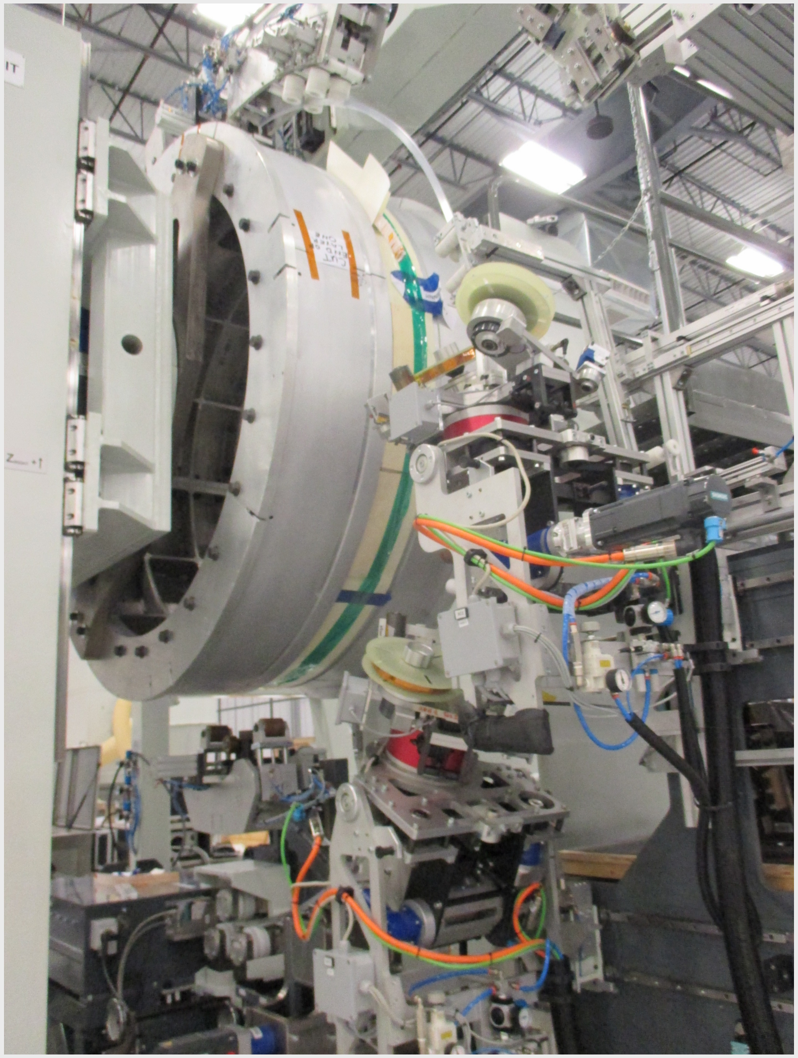
mu2e.fnal.gov

# Mu2e Solenoid

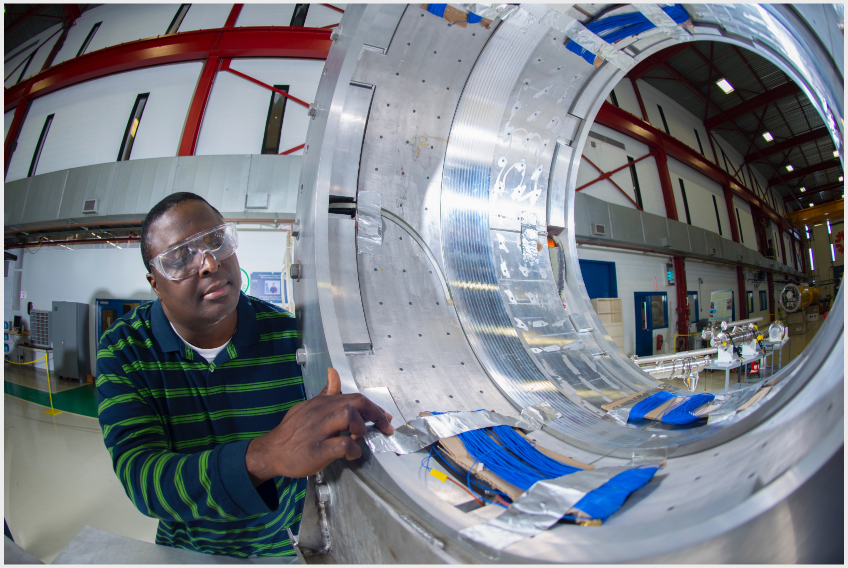
All 75 km of cable ordered

Coil modules at ASG

31/52 coils wound,
29 potted.
To be machined.

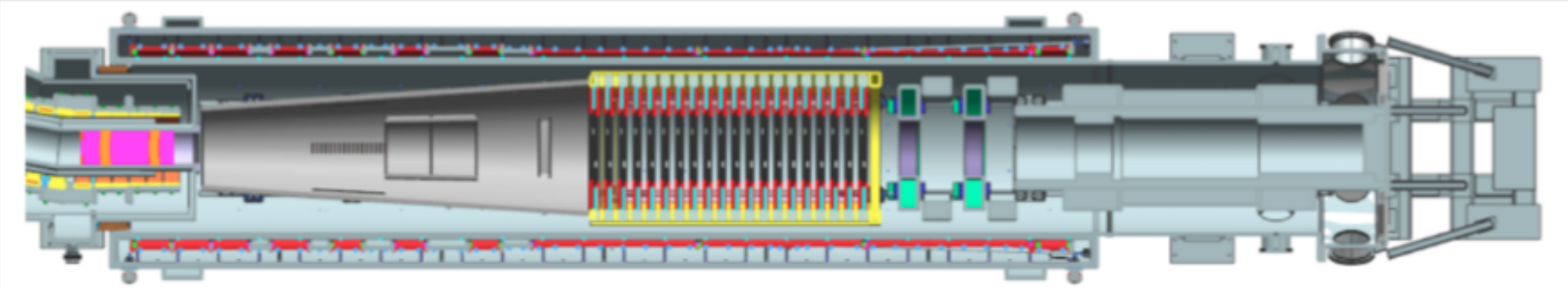


at General Atomics
splice between solenoids



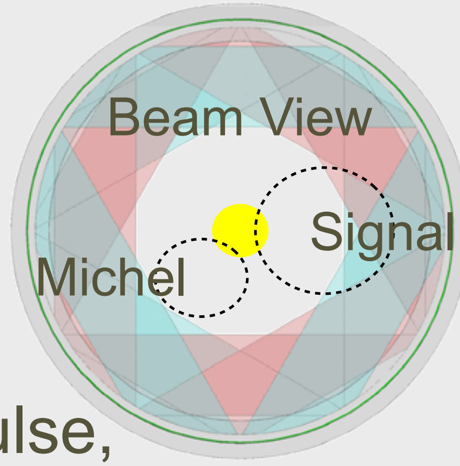
# Detector Layout

finding electron track and momentum determination: highest precision, needed to reject decay-in-orbit

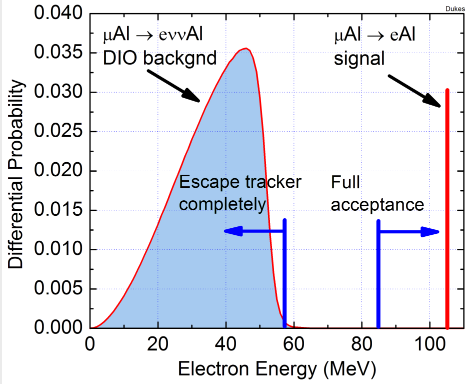



1) PID separation of $\pi/\mu/e$
2) Seed for Track Finder
3) Standalone Trigger

# Why Annular?

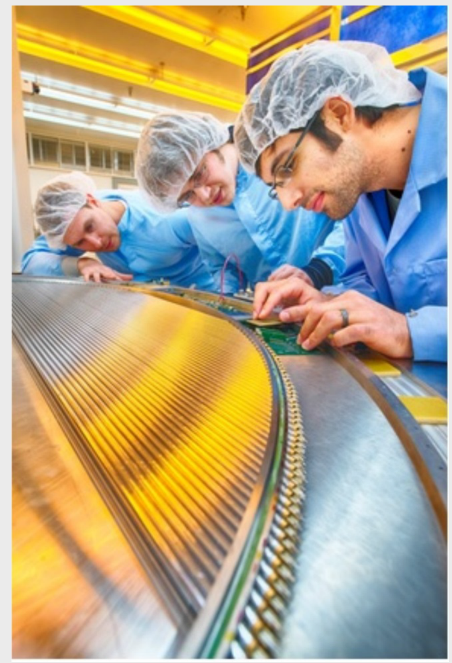



- Reduces beam activity and a background
  - don't want initial "flash" of activity from proton pulse, or remnant muon beam in detector (only ~1/2 of muon beam stops in target)
  - eliminates all but a tiny number of decay-in-orbit background (p ~ qBR in solenoid, Michel e- at small radius);
  - so we're not rejecting $10^{17}$; handful of events within resolution
- this will be different from COMET
  - advantages and disadvantages



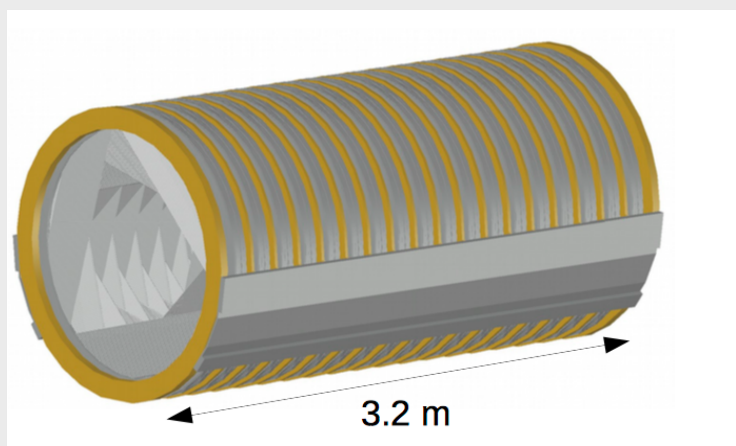
# Straw Tube Tracker

- 15 microns of Kapton (human hair = 10–80 microns)



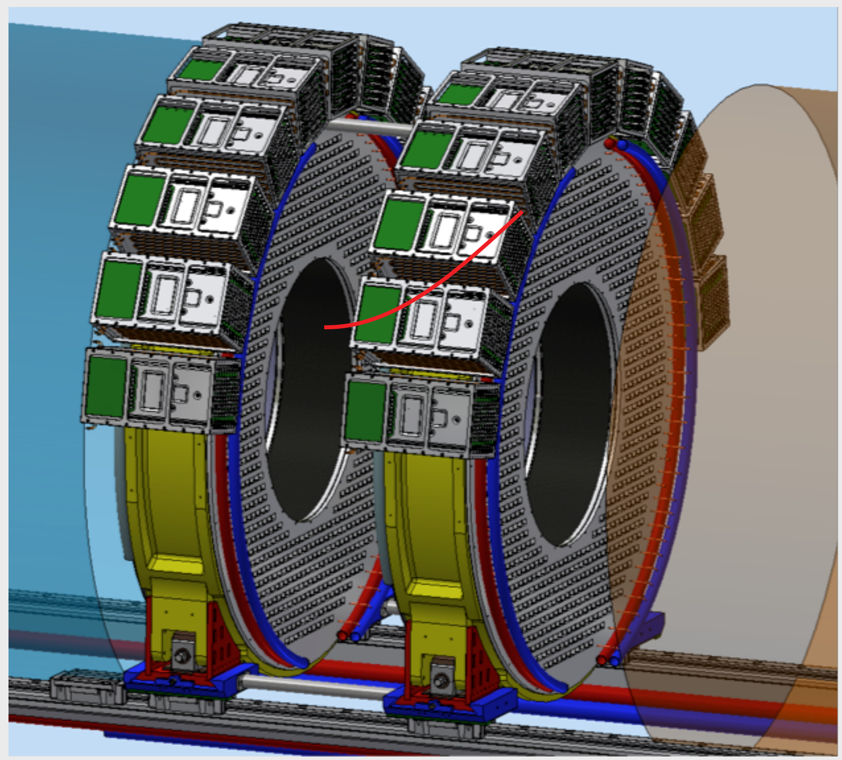
  - ~1 meter long straws, 5 mm diameter with a central gold-plated tungsten wire

- ~20,000 straws in a vacuum of $10^{-4}$ Torr



# Calorimeter

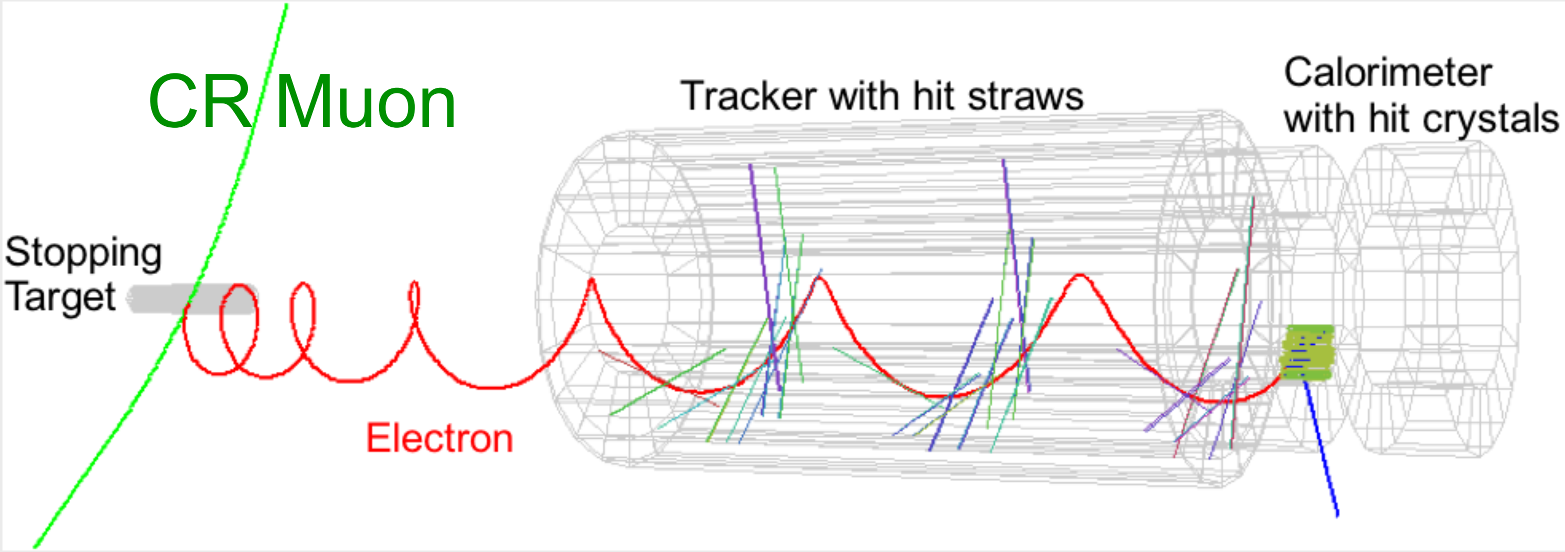
- Two CsI crystal disks
  - hole, as in tracker, for passage of muon beam
  - distance chosen such that if signal electron goes down hole, hits next disk



"module 0": 51 crystals

# Cosmic Ray Veto

- At $10^{-17}$ there's a lot of rare backgrounds; here's one that is surprising but not too rare: 1/day!



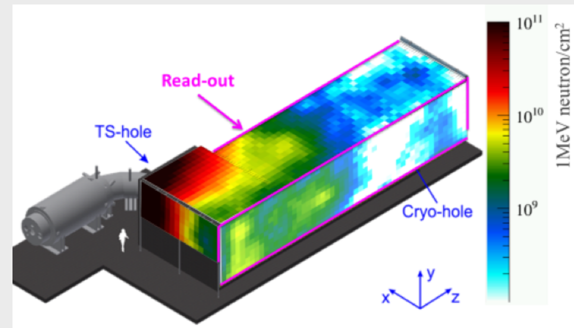

- the experiment needs a 99.99% efficient veto (3/4 layers)

- in an environment with $10^{10}$ neutrons/cm$^2$/sec from proton pulse

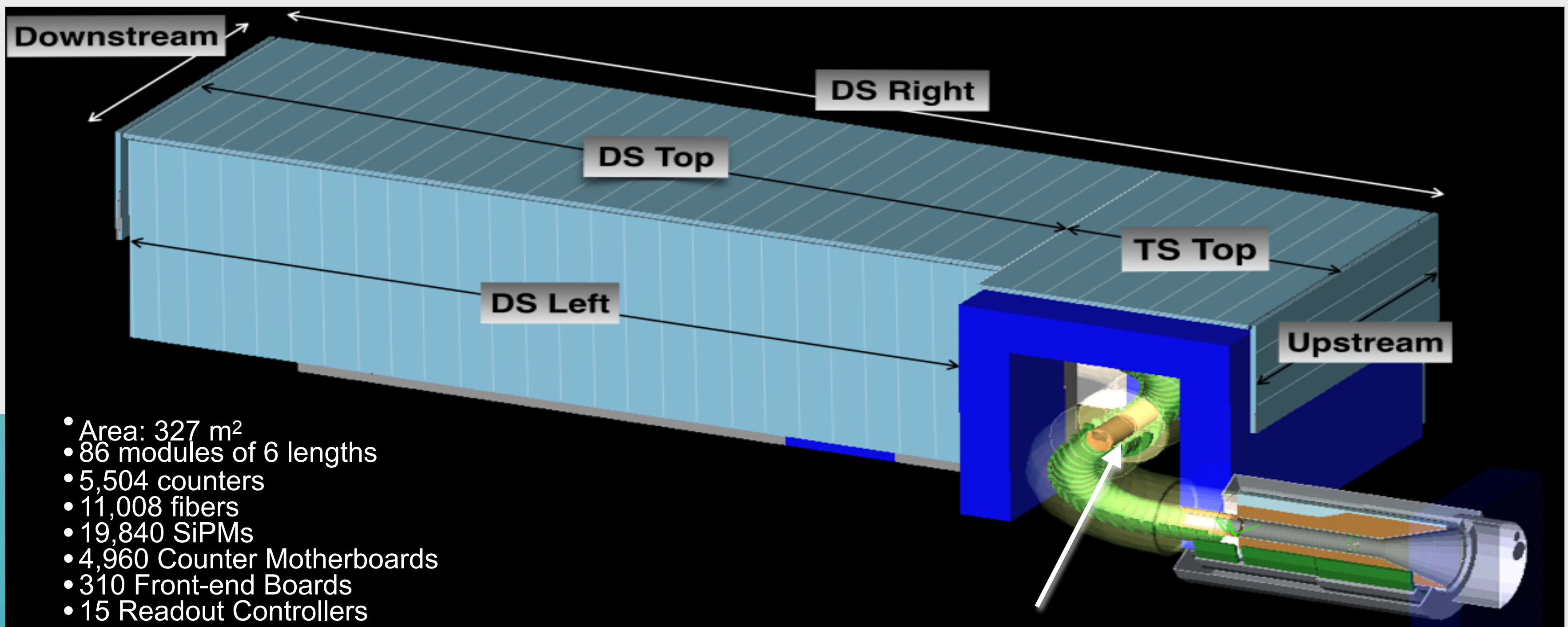
Yuri Oksuzian
UVA

# CR Veto Details

Neutron Rates




- Veto systems are never totally hermetic
- Simulated 250 experiment live-times in targeted regions

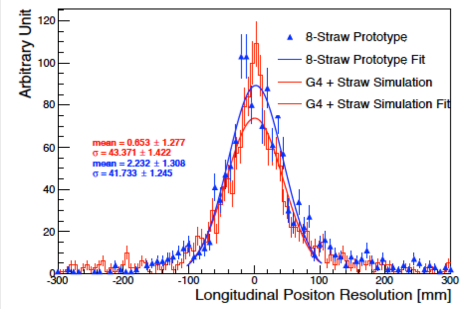



Ralf Erlich
UVA

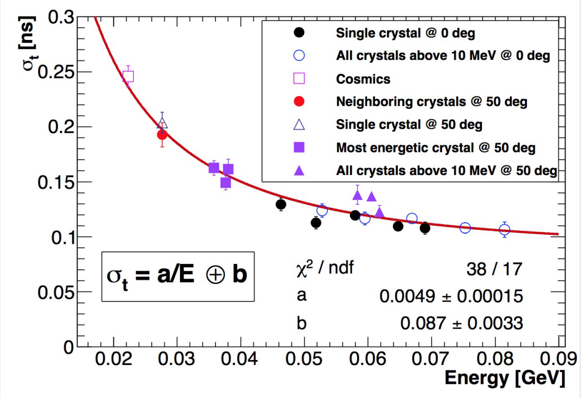
targeted simulations here, for example

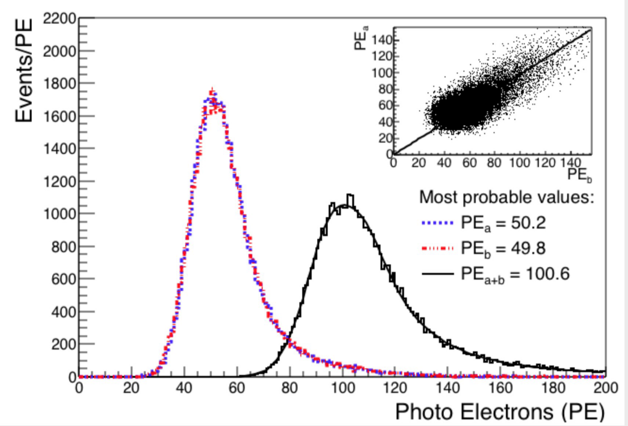
# Tracker/Calorimeter/ CRV Test Beam Results

- Energy and time response of 3X3 CsI crystal array
- PE yields of CRV scintillation counters read out by SiPMs
- Tracker Resolution measured and modeled at level of charge cluster formation
- *Measured resolutions and properties in the simulations*




Longitudinal Resolution
(Data vs MC)
$\sigma_{data} = 42 \pm 1$ mm
$\sigma_{MC} = 43 \pm 1$ mm




arXiv: 1709.06587, submitted to NIM

DOI: 10.1088/1748-0221/12/05/P05007

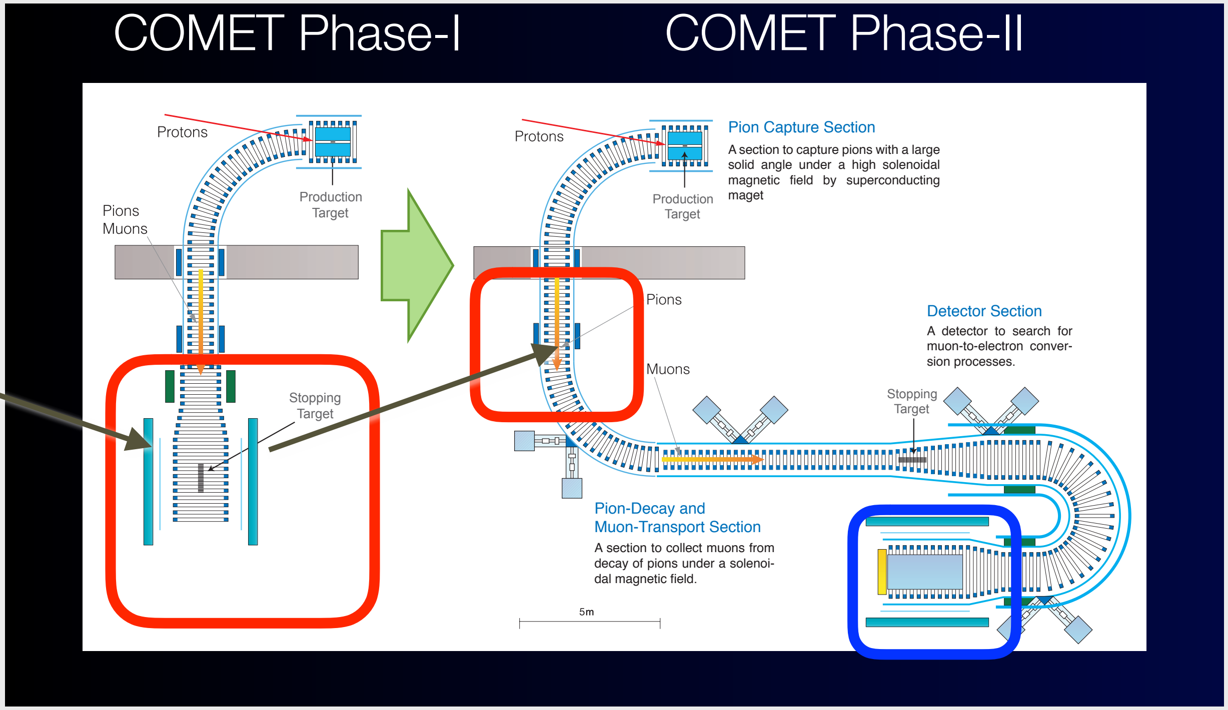
# Mu2e Status (Summary)

- We have a building!
- Superconducting solenoid production underway
- Beam under construction
- Advanced prototypes/ beginning production for detector elements
- Commissioning 2021
- One hour will equal existing limit;  one week ~ $10^{-15}$

>200 scientists from 34 institutions

# COMET at J-PARC

- Stage I: (2021)
  - x100 better than existing expt, SINDRUM-II




- Stage II
  - x10,000 better
  - same reach as Mu2e

M. Lee,WG4

- Important differences:
  - C- vs S- for transport

focus on this

- 2nd Bend in detector solenoid

# Mu2e and COMET

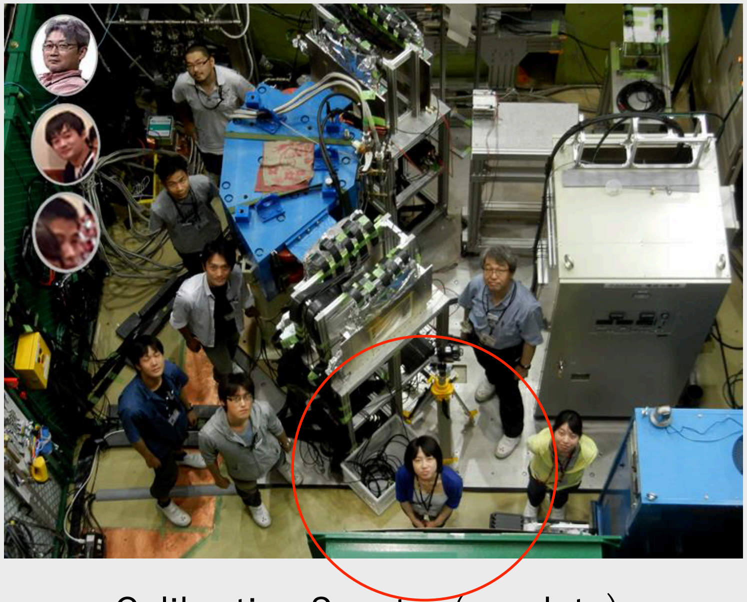
- COMET Staging has obvious advantages for learning as you go
- 2nd Bend in COMET Stage II momentum selects ~ 105 MeV $e^-$ only
    - needs no hole since $\mu^-$ beam and $e^-$ flash not transmitted
- Mu2e: charge symmetric, $e^+e^-$ the same
  - Backgrounds
    - many background sources of $e^-$ (RPC!) produce equal $e^+e^-$
    - Mu2e can measure them with $e^+$ *in situ*
    - *look "inside the box"*, no blinding needed since $e^+$
  - Mu2e can measure $\mu^- N \rightarrow e^+ N'$ , different/unique physics

Berryman, de Gouvea, Kelly, Knobloch PRD95(2017), 115010/ arXiv:1611.0032

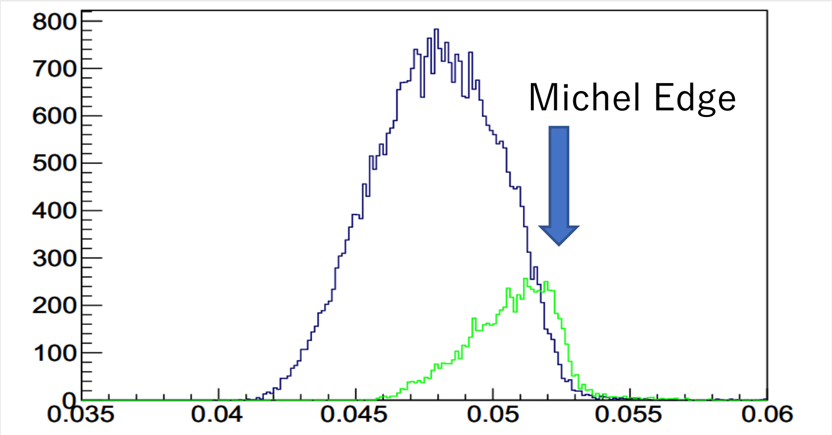
# DeeMe

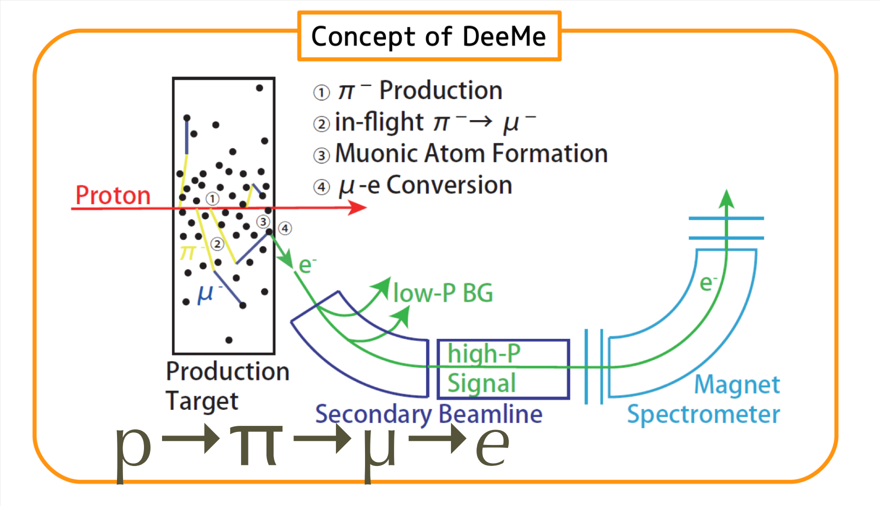
- DeeMe at J-PARC $\mu N \rightarrow eN$ with a 2 x $10^{-14}$ SES, x10 better than existing

- ***production target and conversion target are the same: not like Mu2e or COMET***



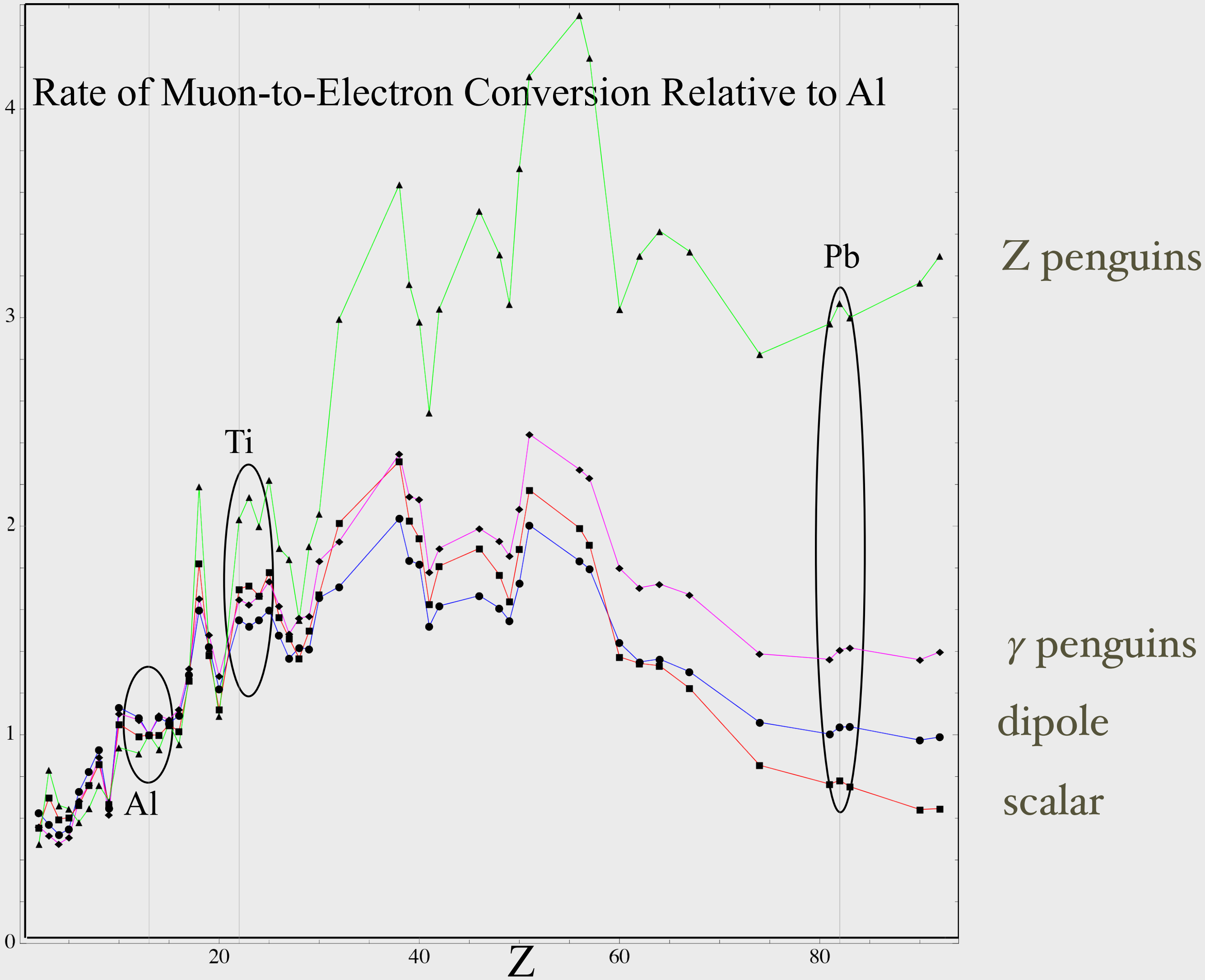
Calibration Spectra ($\mu^+$ data)




Teshima, WG4

# Upgrades and Z-Dependence




5% measurement on Al/Ti needed to see split

- Different Operators have different *Z*-dependence
- Combine depending on the particular model

Lepton flavor violating mu - e conversion rate for various nuclei

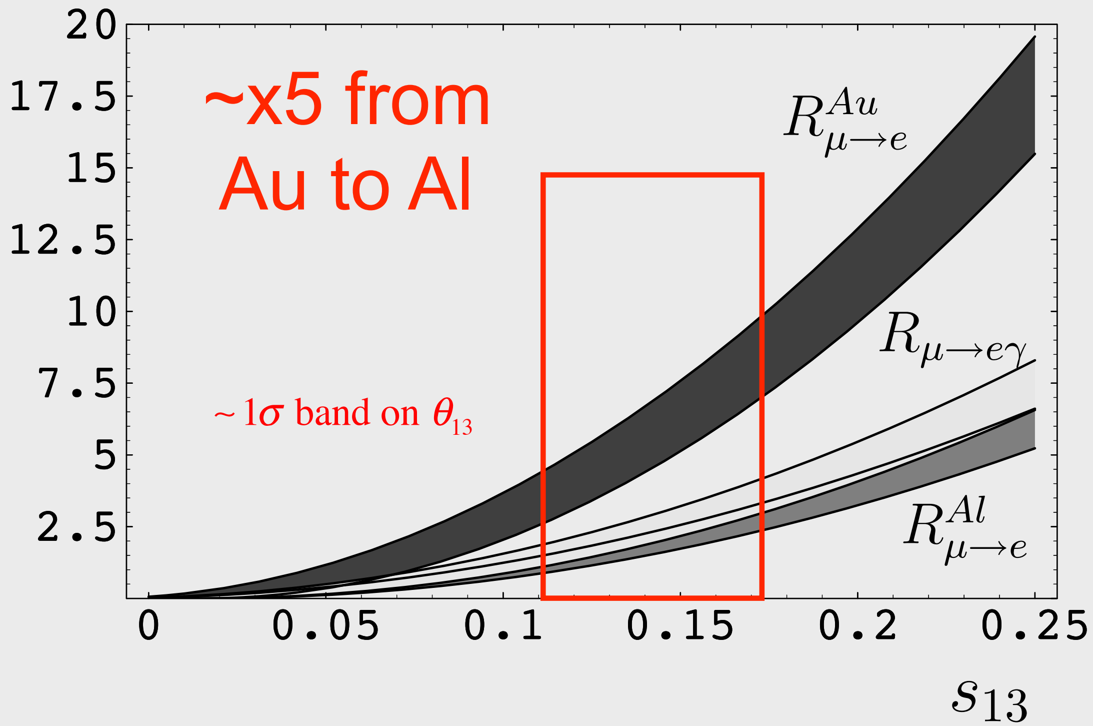
M. Koike et al., J.Phys. G29 (2003) 2051-2054

DOI: 10.1088/0954-3899/29/8/401

# Neutrinos Once Again!

- I left neutrinos to do Mu2e, but can't seem to get away…

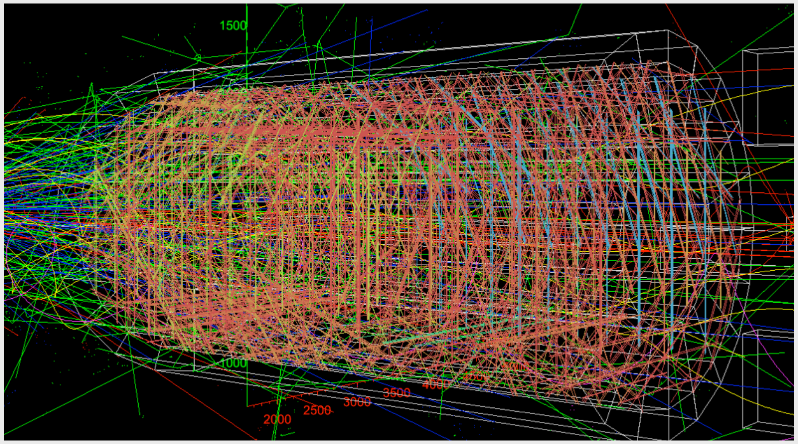
*PDG 2017*




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

# Choice of Z for Upgrade

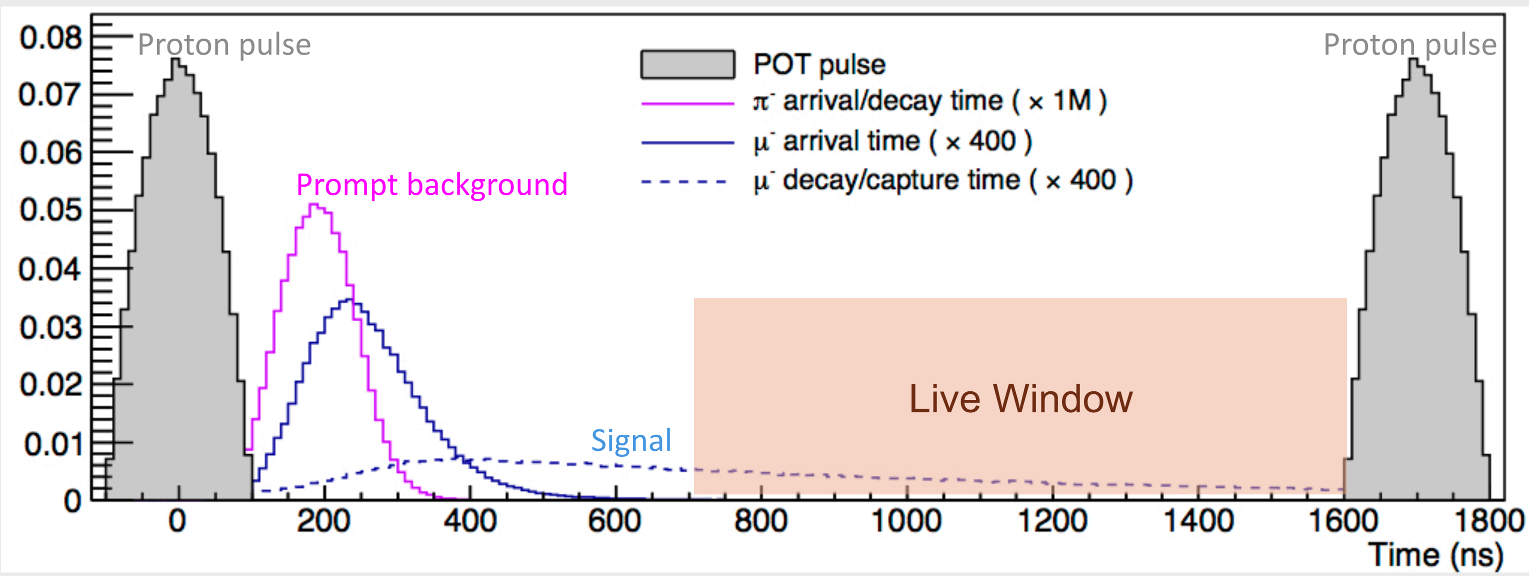
- What Sets Material Choice? Lifetime:



$$\tau_\mu(\mathrm{Al}) = 864\ \mathrm{ns}$$

$$\tau_\mu(\mathrm{Ti}) = 338\ \mathrm{ns}$$

$$\tau_\mu(\mathrm{Au}) = 74\ \mathrm{ns}$$



# Mu2e Upgrades

- Studies for x10 improvement with Ti look promising and will be continued; EOI being written (1307.1168)
- We need detector and solenoid improvements
- Longer term: Synergies with WG4
  - FFAG to make a muon beam? (PRISM)
  - FNAL PIP-II natural for both pulsed and non-pulsed CLFV, could do $\mu^- N \rightarrow e^- N$, $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, $\mu^- e^- \rightarrow e^- e^-$ at one facility

Pasternak, WG4

Sato,WG4

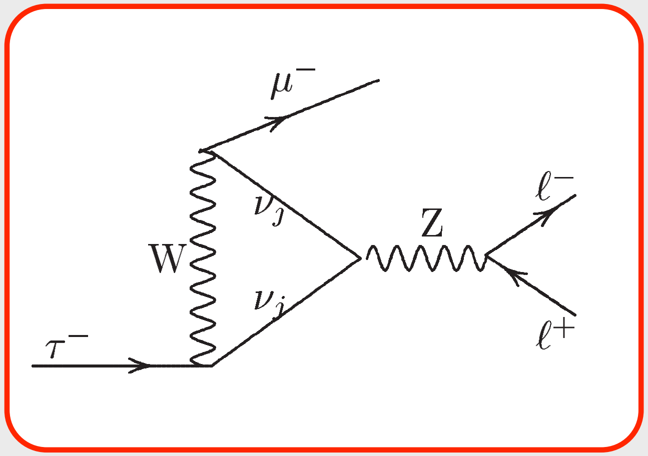
see Besjes, Clerbaux, Kang, Liventsev, Pais WG4; and kaons: A. Sergi, WG4, NA62

# Collider or Muon Beam?

- 1st/2nd generation processes ("solar")
  - ***Muon experiments orders of magnitude better than colliders in muon-electron processes because we can make beams***
- 2nd/3rd,1st/3rd ("atmospheric and $\theta_{13}$")
  - ***can't make $\tau$ beams, so colliders best there***
  - ***B*, K*, b→sll, b→ll and b→sγ puzzles: lepton universality***
  - *pp* or e+e- both have contributions depending on channel; e.g. CLFV Higgs decays or $\tau$ CLFV (ATLAS/CMS, LHCb, and BELLE-II or BES-III; don't overlook e+e- and B mesons)

# CLFV and Tau Processes

- Advantage:
  - Beyond SM rates can be orders of magnitude higher than in the corresponding muon channel
- Disadvantage
  - $\tau$'s hard to produce:
    - ~$10^{11}$ $\tau$/*yr* vs ~$10^{11}$ $\mu$/*sec* in muon experiments




SM ~ $10^{-14}$ ?

$\tau$'s help pin down models; e.g. Cheng-Sher Ansatz $\sqrt{m_i m_j}$

Holzbauer, WG4

# *g*-2

- Landé *g* relates magnetic moment to spin precession
- Do we understand how spin and momentum track as a muon circulates in a magnetic field? (Lande *g*)

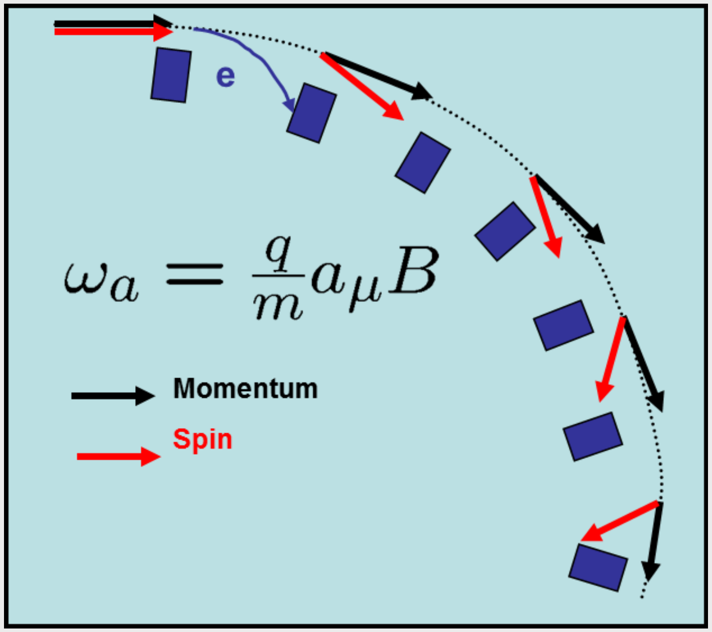
$$\omega_s = g\frac{eB}{2m};\ \omega_c = \frac{eB}{m} \qquad a_\mu = \frac{g-2}{2}$$

$$g \approx 2\left(1+\frac{\alpha}{2\pi}\right)$$

if g=2, $a_\mu = 0$
spin and momentum track

https://journals.aps.org/pr/pdf/10.1103/PhysRev.74.250

# Storage Ring *g*-2




this is precession in orbital plane

precession perpendicular orbital plane, sensitive to EDM.

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

Bargmann-Michel-Telegdi Eqn

# BNL Result

- ~3.6$\sigma$ deviation in $a_\mu$ (theory updated since PRD, exp't unchanged )

$$a_\mu(\mathrm{exp}) = 116{,}592{,}089\ (63) \times 10^{-11} (0.54\mathrm{ppm})$$

$$a_\mu(\mathrm{thy}) = 116{,}591{,}802\ (49) \times 10^{-11} (0.42\mathrm{ppm})$$

- Signal of SUSY? DM?
- No clear experimental problem, must repeat and check
- Attack dominant errors, both theory and experiment

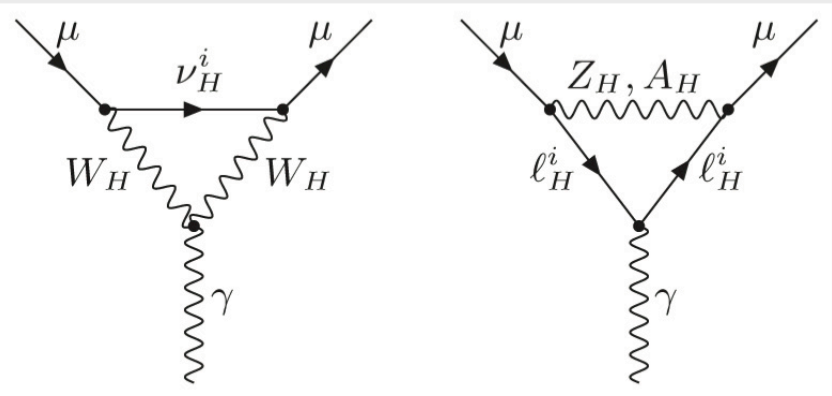
DOI: 10.1103/PhysRevD.73.072003

# Source of Deviation?

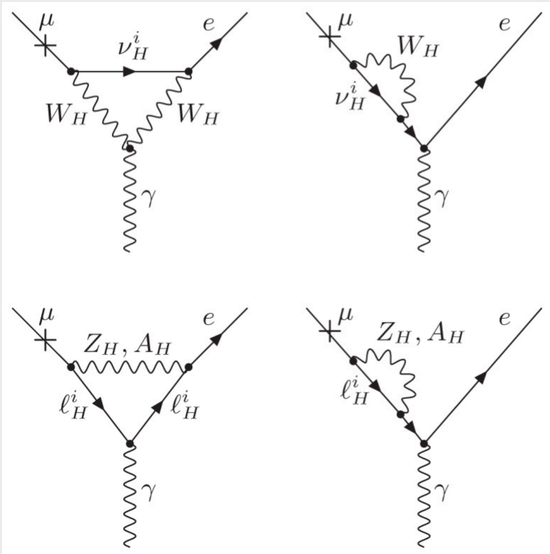
- *g*-2 terms can come from many sources, not just SUSY

$$a_\mu(\text{New Physics}) = O(1)\left(\frac{m_\mu}{\Lambda}\right)^2 \times \left(\frac{\delta m_\mu}{m_\mu}\right)$$

g-2




CLFV




$\mu \to e\gamma$

MEG and Mu2e

for example, Littlest Higgs can affect both g-2 and CLFV

# Magic γ

- Problem: E-field needed to keep muons in storage ring
  - but $\vec{\beta}\times\vec{E}$ looks like $\vec{B}$
  - *choose* γ to cancel $\vec{E}$ dependence :

"magic γ"

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\vec{\beta}\times\vec{E}\right] \quad \gamma = 29.3,\ p_\mu = 3.094\,\mathrm{GeV/c}$$

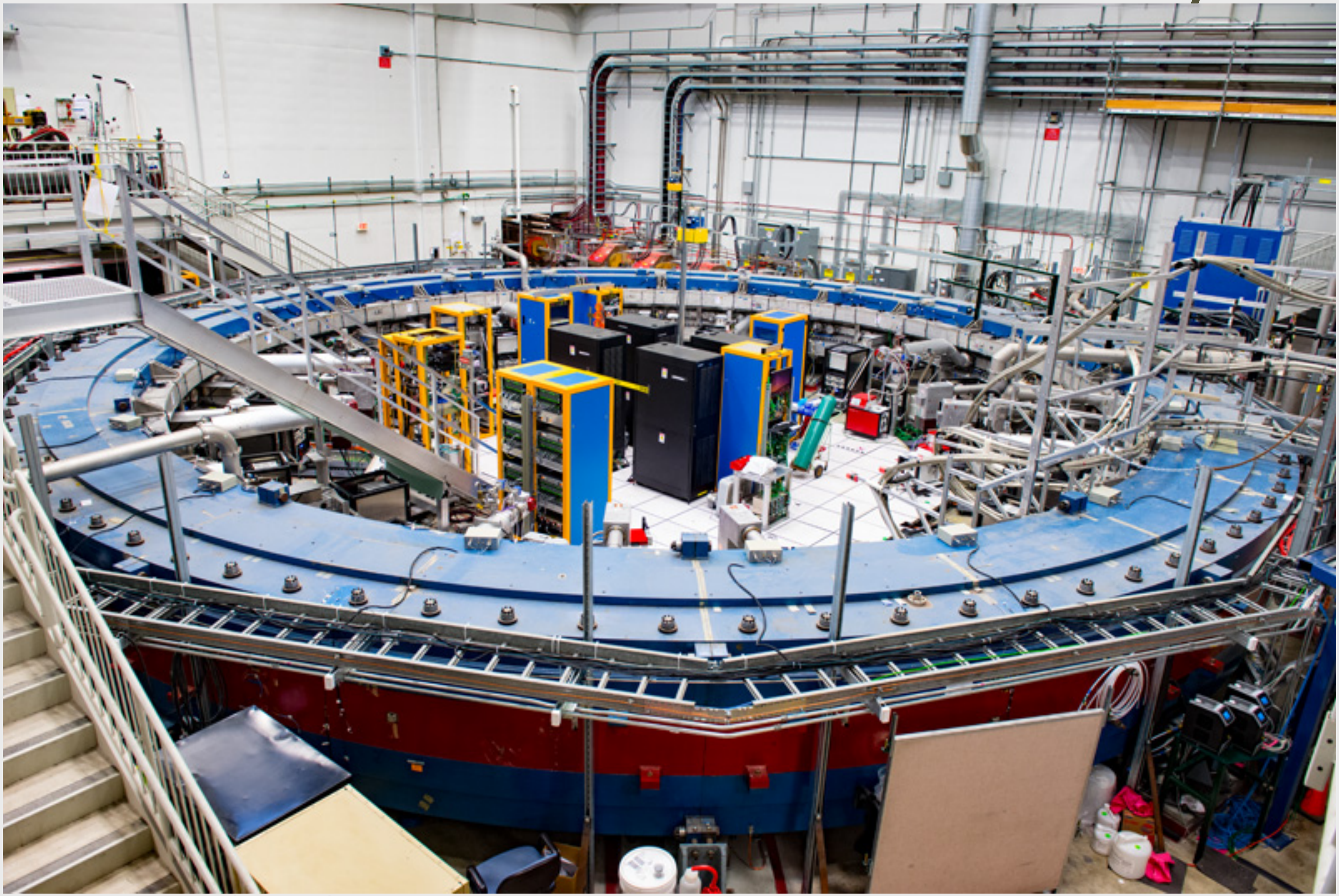
# *g*-2 Goals

- FNAL will improve and check BNL measurement
  - 3.6 σ→7-8 σ if central value unchanged
  - Experiment: x21 BNL statistics, x3 lower systematics
  - Theory: ~x2 improvement, will dominate uncertainty

$$\begin{array}{lcc} & \text{BNL} & \text{FNAL} \\ \Delta a_\mu(\text{exp}) = & 0.54\text{ppm} \Rightarrow & 0.14\text{ppm} \\ \Delta a_\mu(\text{thy}) = & 0.42\text{ppm} \Rightarrow & 0.25\text{ppm} \end{array}$$

- muon EDM will improve by x10-x30

# First Run: concluded 7 July

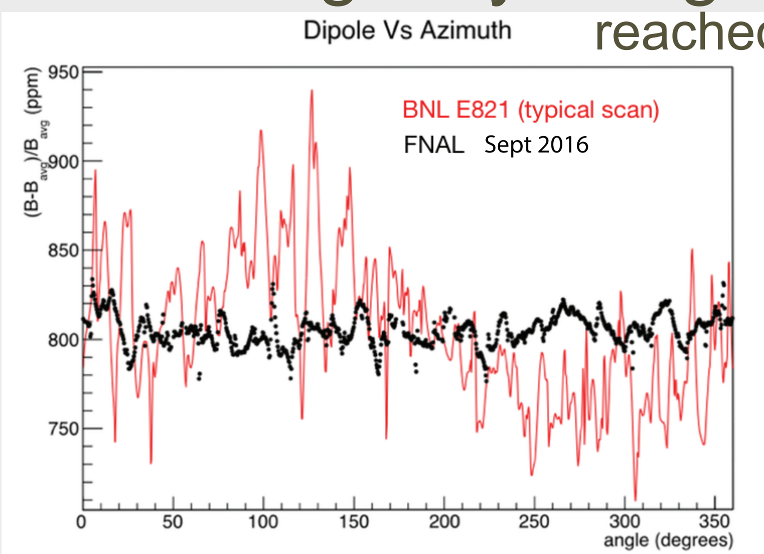


# First Run: concluded 7 July

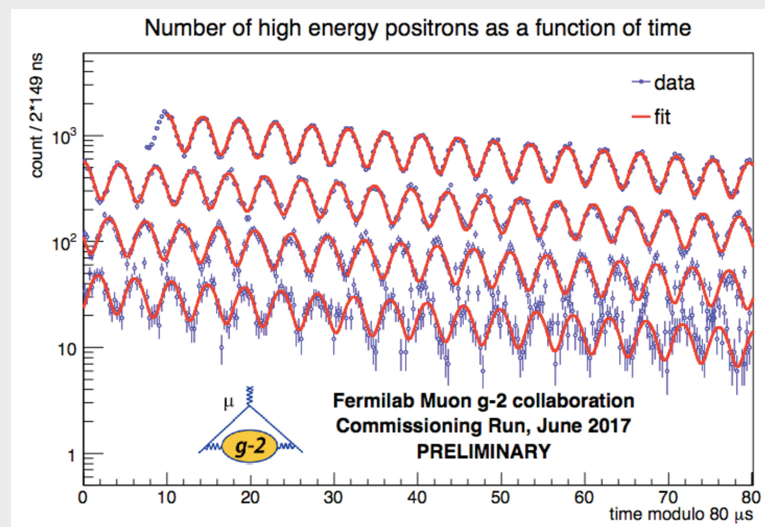
- Experiment: understanding field and location within field is central; need constant field and constant detector response.

- First "wiggle plots":

  - precession of spin vs. time on top of muon lifetime: extract g-2 by fitting this curve




reached goal!



# Muon *g*-2 / EDM at J-PARC

Ishida, WG4

- Storage ring requires electric field and magic $\gamma$

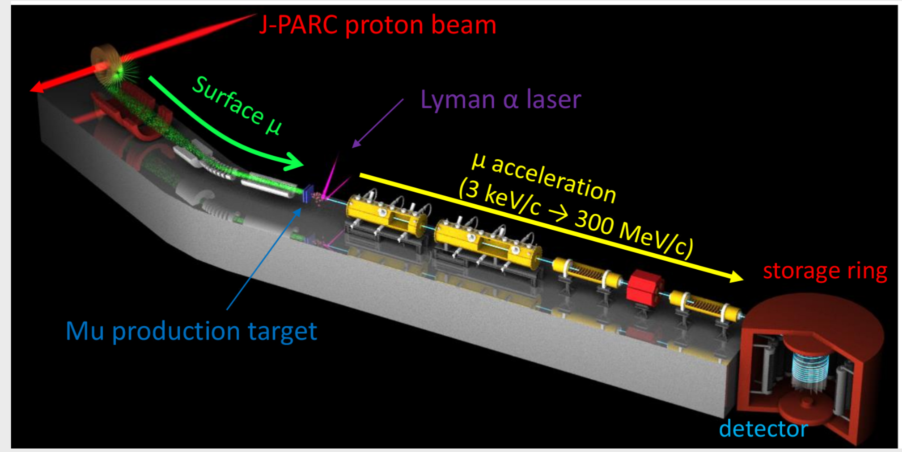
- Use ultra-cold muons (3 keV/c) with $\sigma_{pT} / p \approx 10^{-5}$

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

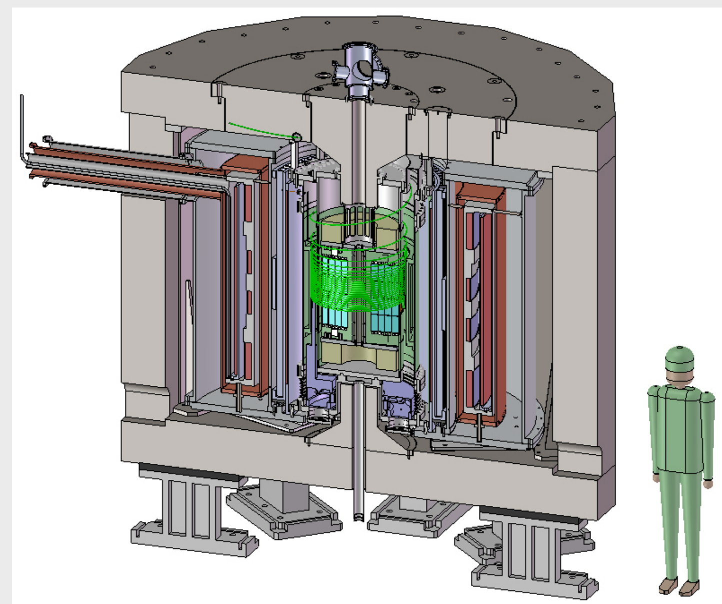
- becomes

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

# Experiment (E34) and Status



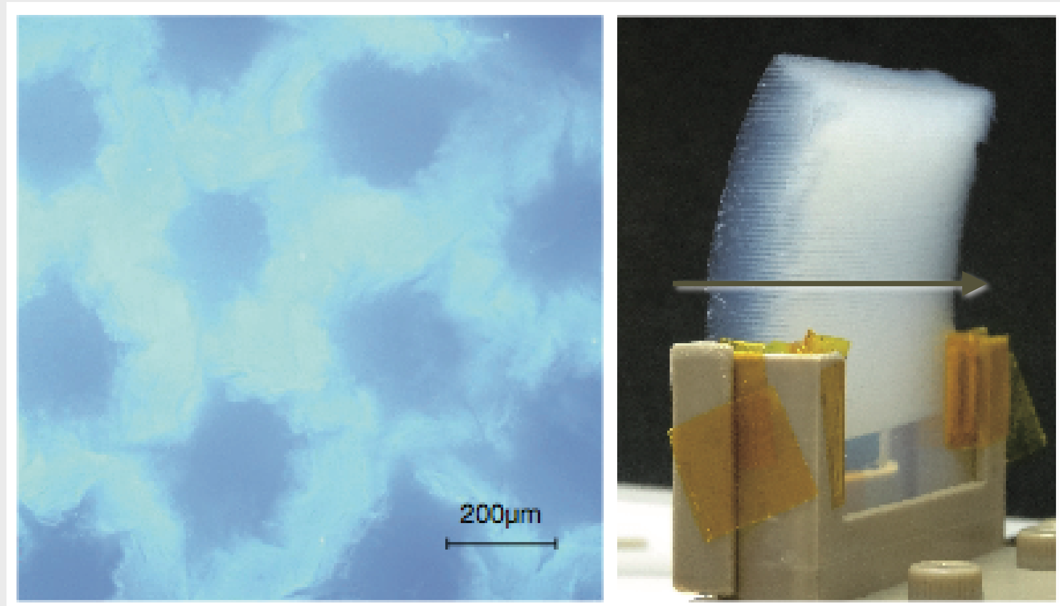

- Surface muon beam
- Stopped in aerogel target used to produce muonium ($\mu^+e^-$)
  - polarization largely preserved (~80%) for $\mu^+$ so you can see precession
- Electron stripped using laser
- Transport muon to detector

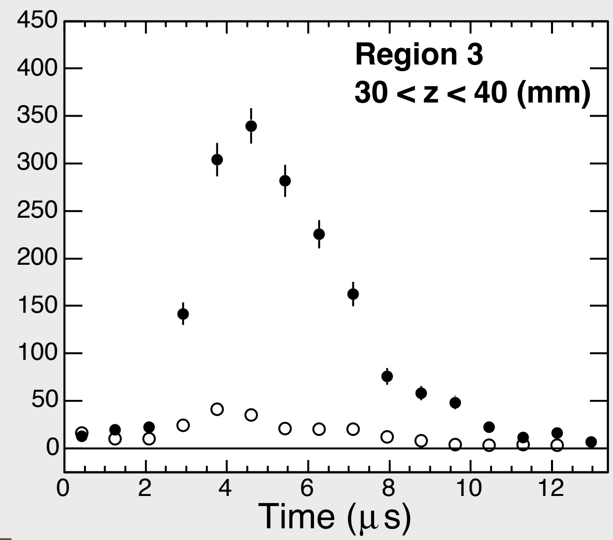


# E34 Status

10.7566/JPSCP.8.025008

- Muonium yield a challenging problem
  - significant advancement, but still x5 below ultimate goal
- Start ~2022 for $\sigma_{\mathrm{expt}}$=0.37 ppm
  - BNL was 0.54 ppm expt; FNAL plans 0.14 ppm
    - EDM:  x100 goal




e+ emission vs. time

# Problem with Review Talks

leave out people's work

cover everything

I've surely done both of these

# What I Hope You'll Remember

- Any signal is unambiguously new physics. We need multiple measurements to understand what we do or don't see
  - CLFV, neutrinos, g-2, EDMs, kaon decays, $0\nu 2\beta$, dark matter, collider CLFV are tightly linked and models have to fit *all* the data.
- The experiments are challenging theory and getting better fast, with upgrades on the way.
  - within next 5-10 years: muons improve by $10^4$, x10 in mass scale; Run-II data; $e^+e^-$ and LHCb will probe $\tau$ , B, and charm sectors. Kaon system continues to be incisive and unique.
- Neutrinos and charged leptons go together! We share both technology and physics