Charged Lepton Flavor Violation:

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

and

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

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Fermilab

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San Juan, Puerto Rico

Outline

- The search for muon-electron conversion: $\mu^- N \rightarrow e^- N$
  - Experimental Technique:
    - Mu2e, COMET, DeeMe
    - Mu2e-II
- Very preliminary comments on $\mu^- N \rightarrow e^+ N$

What is Muon to Electron Conversion?

- Muon converts to an electron in the field of a nucleus:

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

- Effectively zero Standard Model background
  - a signal is new physics
- Experiments to be discussed can measure a signal with SES of $\sim 3 \times 10^{-17}$, discovery at 2×10^{-16}
  - typical predictions for EWSB $\sim 10^{-15}$

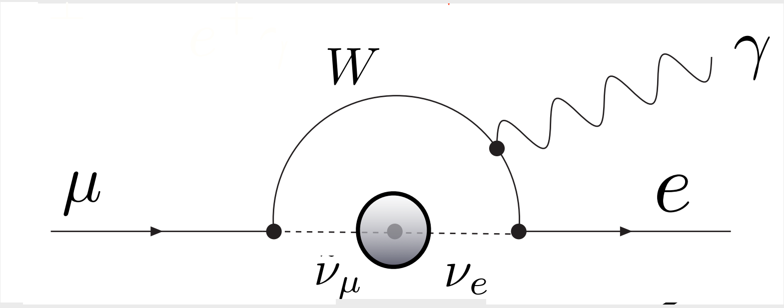
How Small is Our SES?

- Pretty Rare: let us know if this happens to you!
  You can immediately join the experiment

Probability of…	
rolling a 7 with two dice	1.67E-01
rolling a 12 with two dice	2.78E-02
getting 10 heads in a row flipping a coin	9.77E-04
drawing a royal flush (no wild cards)	1.54E-06
getting struck by lightning in one year in the US	2.00E-06
winning Pick-5	5.41E-08
winning MEGA-millions lottery (5 numbers+megaball)	3.86E-09
your house getting hit by a meteorite this year	2.28E-10
drawing two royal flushes in a row (fresh decks)	2.37E-12
your house getting hit by a meteorite today	6.24E-13
getting 53 heads in a row flipping a coin	1.11E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next six months	1.14E-16
your house getting hit by a meteorite AND you being struck by lightning both within the next three months	2.85E-17

Neutrinos and Mu2e

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



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

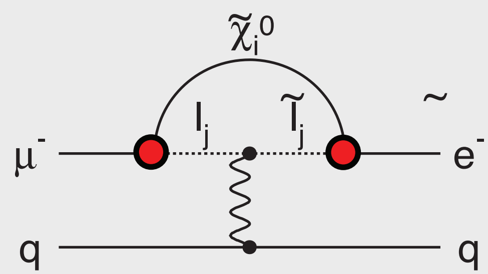
- nobody understood why $\mu \to e\,\gamma$ wasn't 10^{-4} until we hypothesized two neutrinos ($\nu_\mu \neq \nu_e$)

- linkage of CLFV to oscillations, see-saw, Majorana vs. Dirac are getting more interest

Contributions to μe Conversion

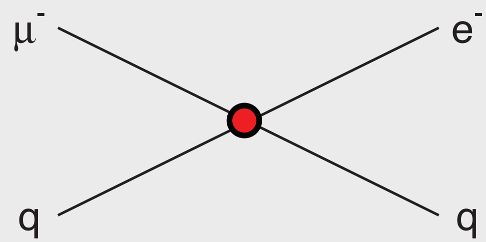
Supersymmetry

rate ~ 10^{-15}



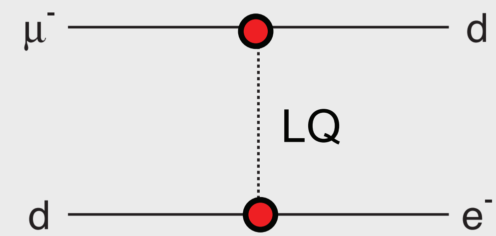
Compositeness

Λ_c ~ 3000 TeV



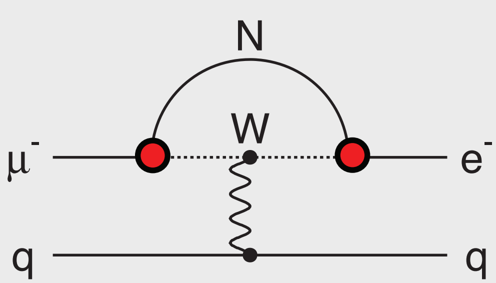
Leptoquark

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



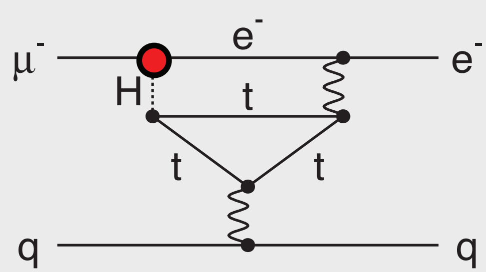
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



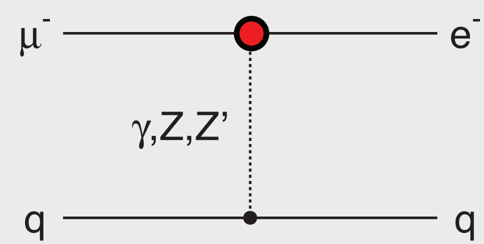
Second Higgs Doublet

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



Heavy Z' Anomal. Z Coupling

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



also see Flavour physics of leptons and dipole moments, arXiv:0801.1826 ;
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:10.1146/annurev.nucl.58.110707.171126 ;
de Gouvea and Vogel, arXiv:1303.4097v2

Effective Lagrangian

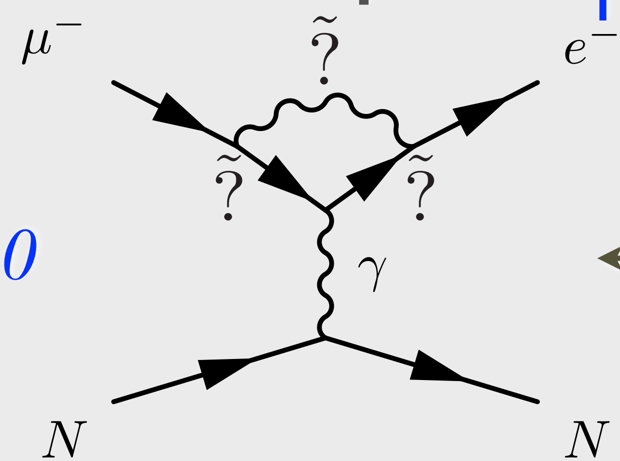
$$\mathcal{L}_{\rm CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma_\mu u_L + \bar{d}_L\gamma_\mu d_L)$$

"Loops"

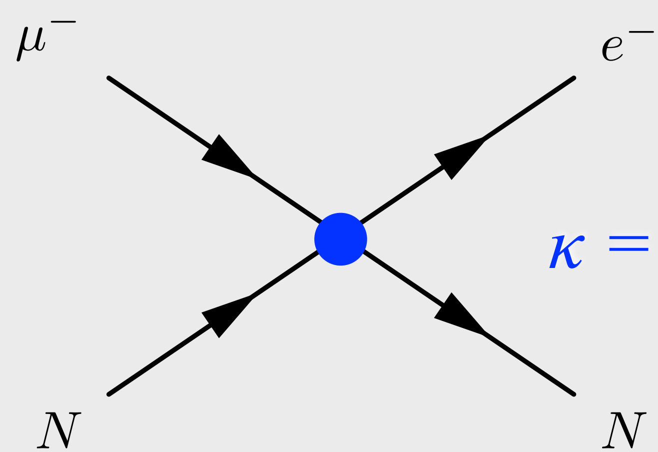
mass scale *Λ*

"Contact Terms"

$\kappa = 0$



κ



$\kappa = \infty$

Supersymmetry and Heavy Neutrinos

Contributes to μ→eγ

(just imagine the photon is real)

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

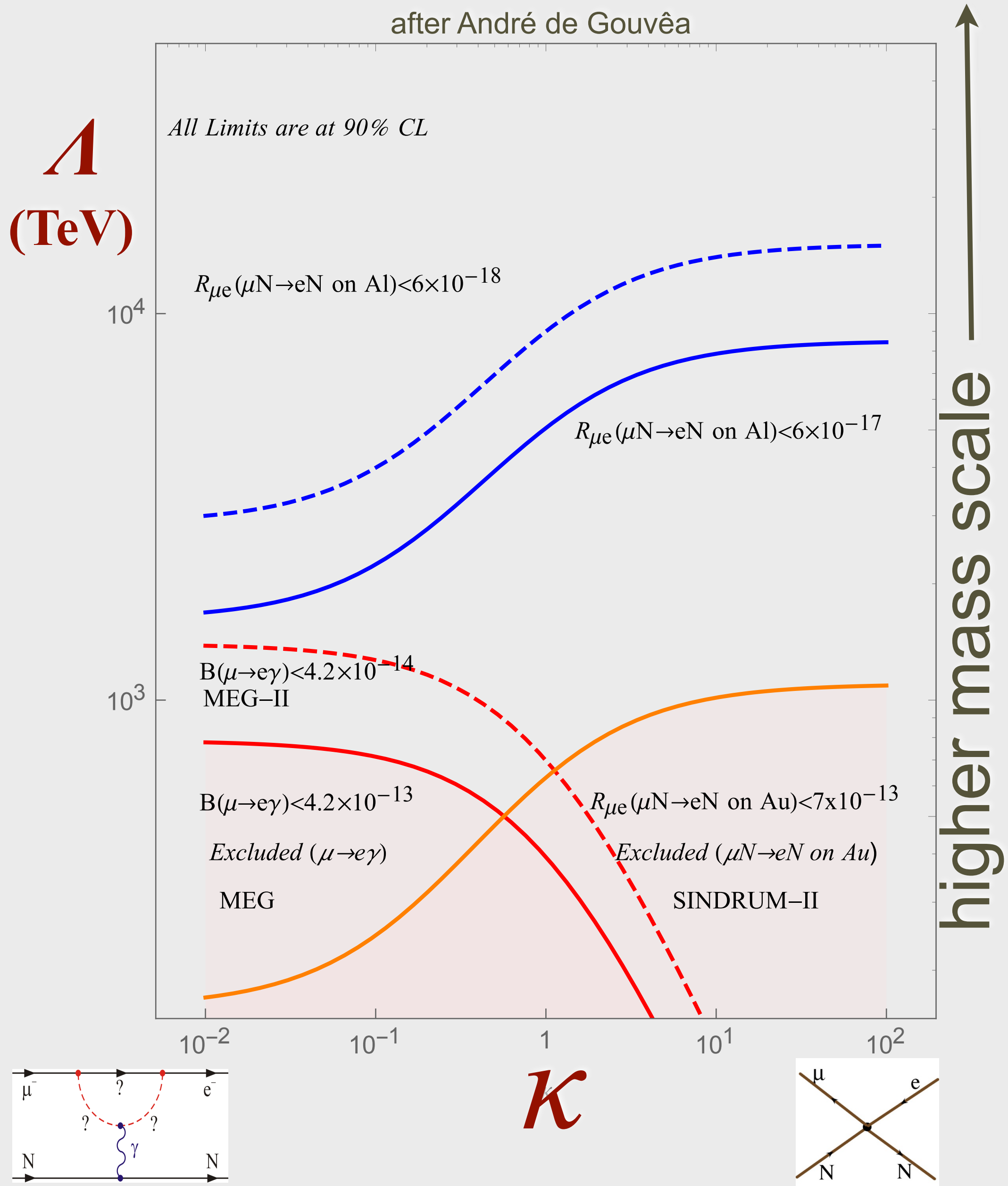
Does not produce μ→eγ

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

1) *Mass Reach to ~10^4 TeV for unit coupling, x10 in mass scale for dim-6*

2) *Mu2e and MEG-II are complementary in loop-dominated physics.*

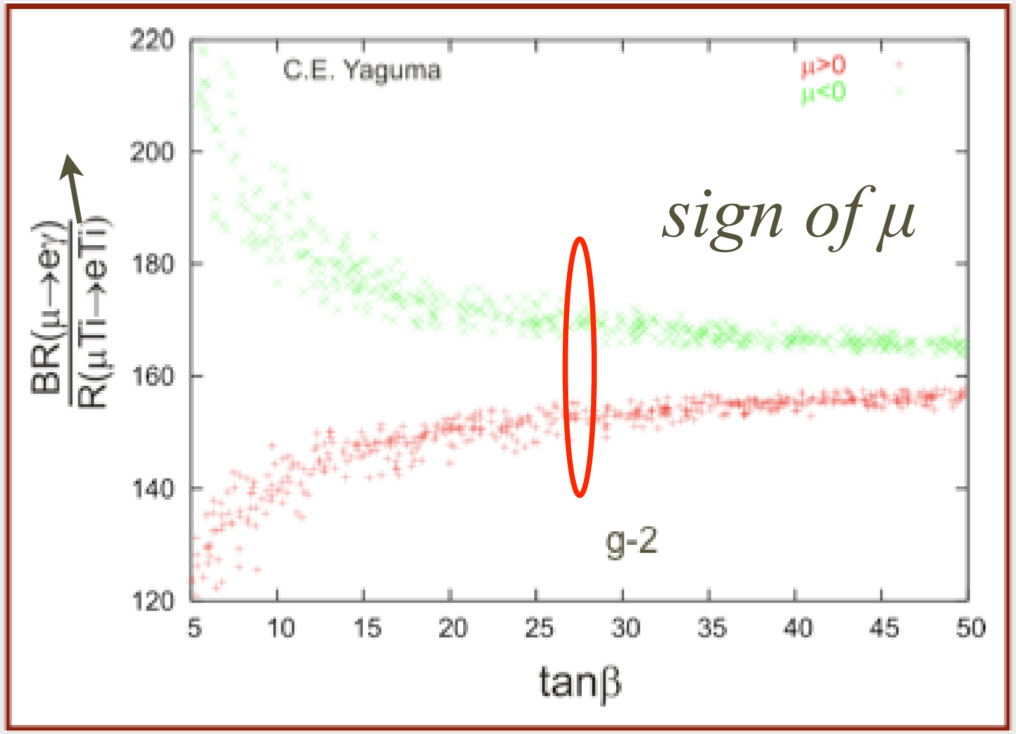
3) *These are discovery experiments*



Mu2e, g-2, and $\mu \to e\gamma$

Yaguna,
hep-ph/0502014v2

MSSM w mSUGRA



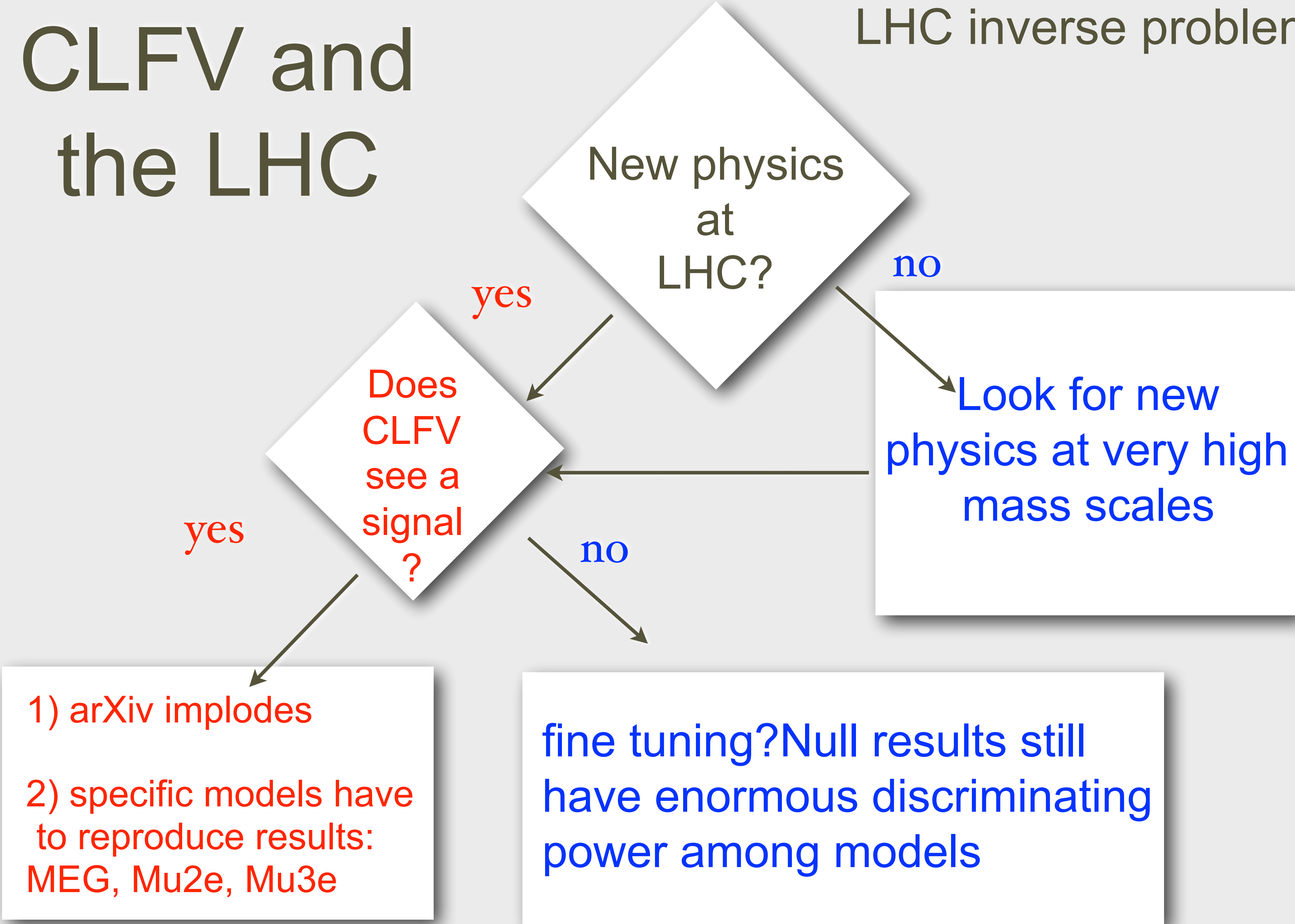
$M_{\mathrm{H}} = \sqrt{2}\ |\mu|$

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

to allow discrimination among different models

CLFV and the LHC

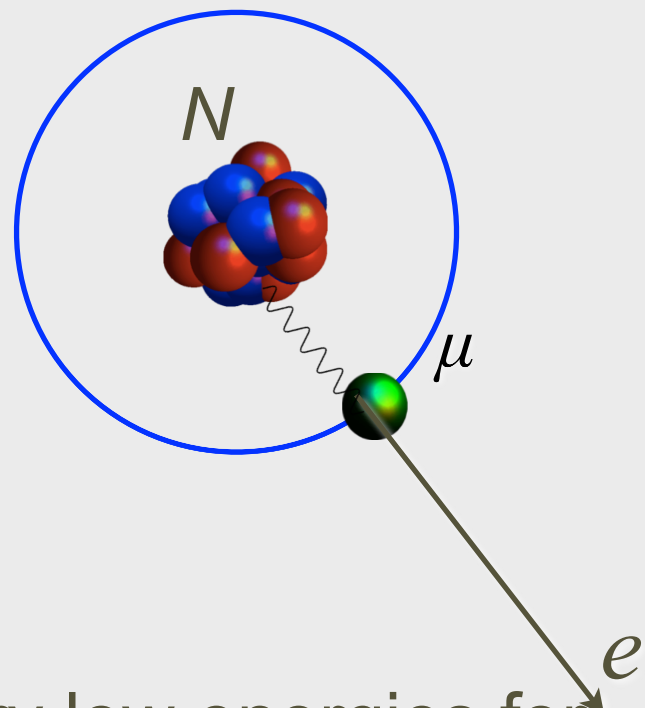
LHC inverse problem



Experimental Signal

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

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



very low energies for HEP!

Mu2e: x10,000 improvement

- World's most intense muon beam:
  - 10^{10} μ/sec at detector under construction
  - Superconducting solenoid system to form muon beam
    - Efficient muon collection; see ~10^{18} muons
- Have to reduce backgrounds to take advantage of statistics
  - Pulsed Beam reduces a background
  - And a high-resolution spectrometer to make muon-related backgrounds small

Backgrounds and Design

	source	*scales with*	*solution*
Intrinsic Backgrounds	decay-in-orbit	# of muons	detector resolution
Beam	radiative pion capture	closeness to beam pulse	pulsed beam
Running Time	cosmic ray	live time	veto system

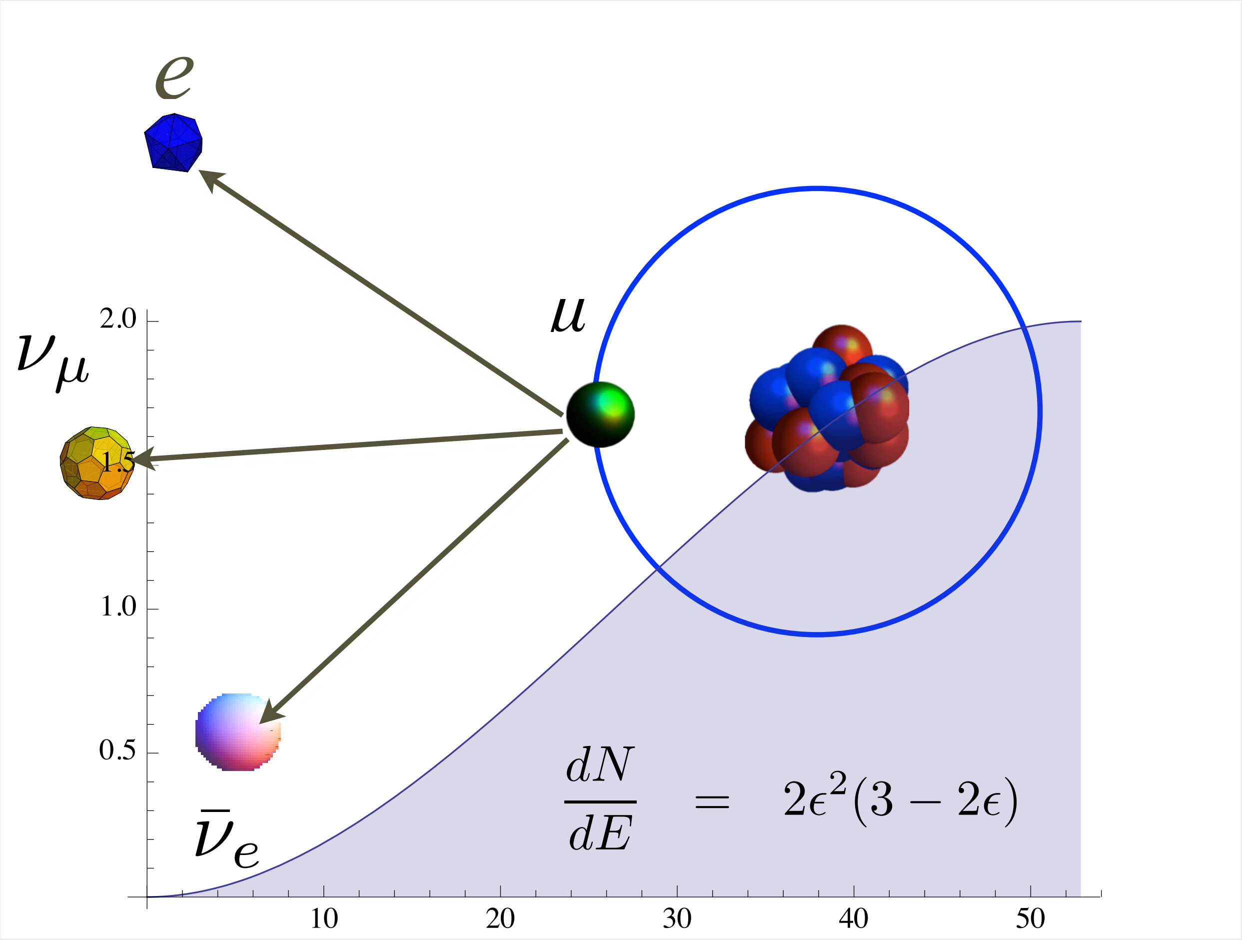
Decay-In-Orbit: usually not background

- Peak and Endpoint of free muon decay spectrum is at

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

- Detector will be insensitive to electrons at this energy

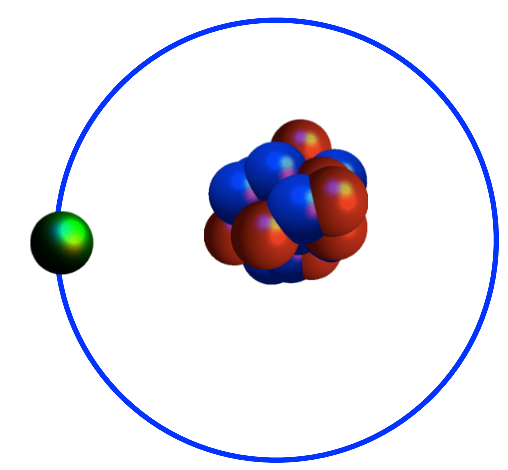
- Recall *signal* at 105 MeV>>52.8 MeV



Michel=free muon decay

Decay-In-Orbit Background

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



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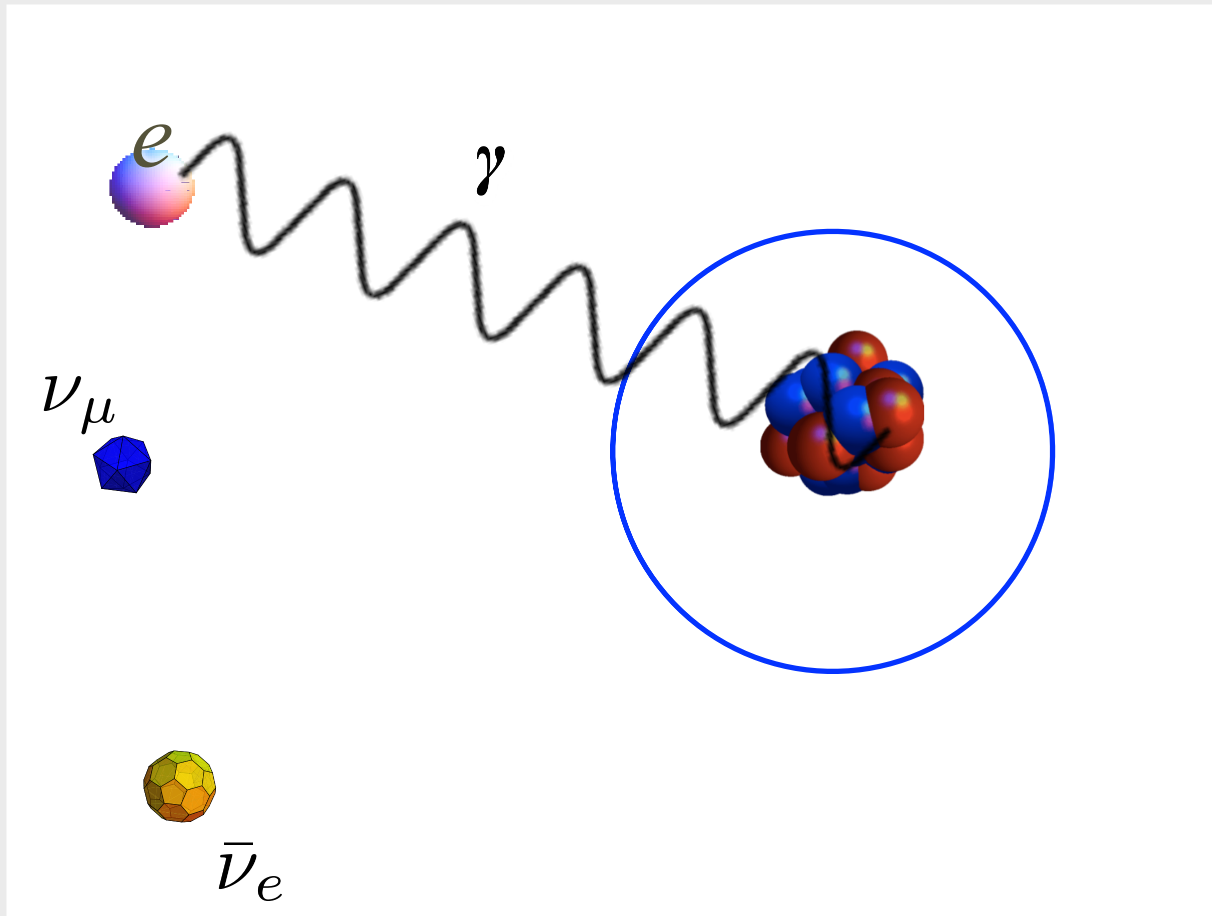

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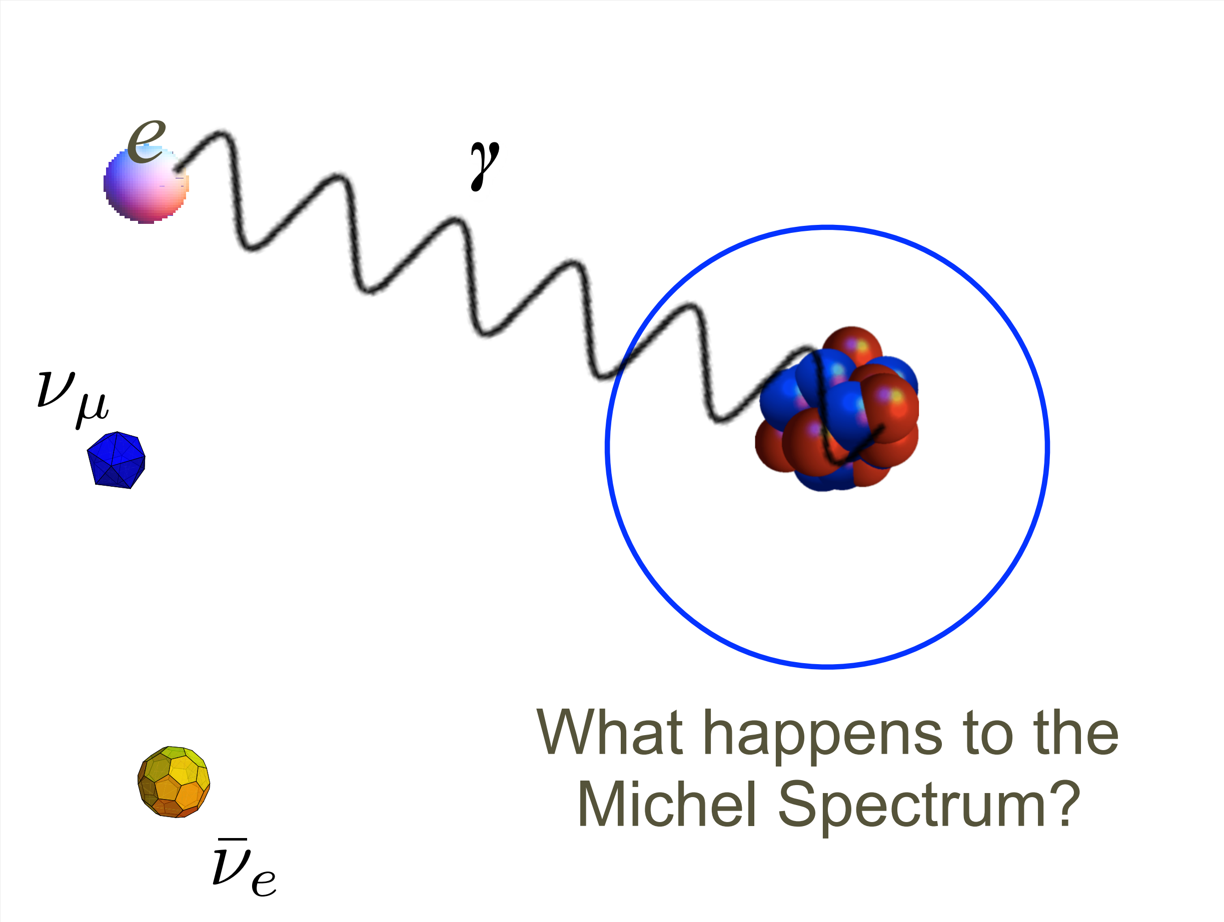
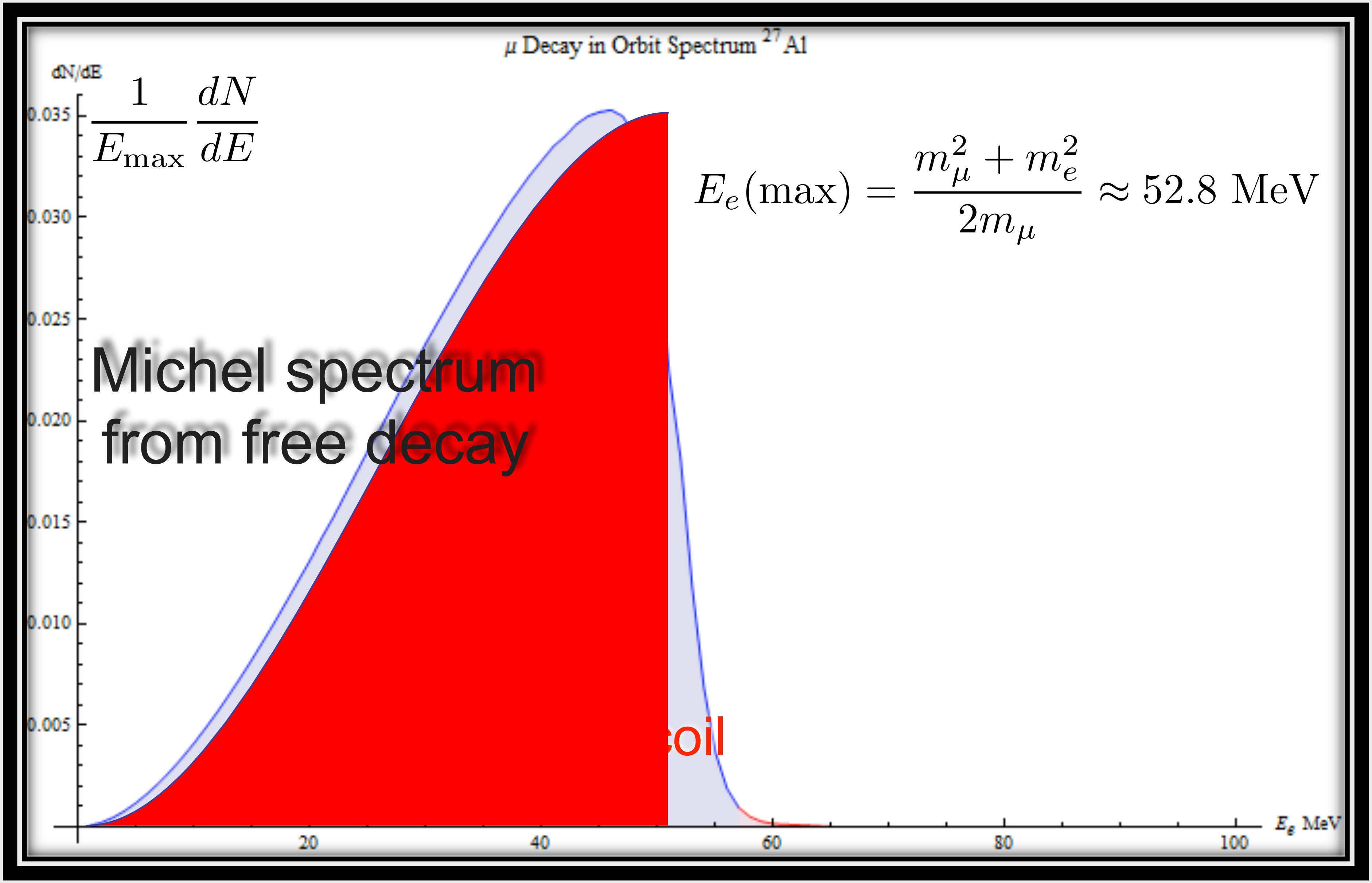


Decay-in-Orbit Shape

Szafron 10.5506/APhysPolB.46.2279: Radiative Corrections



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

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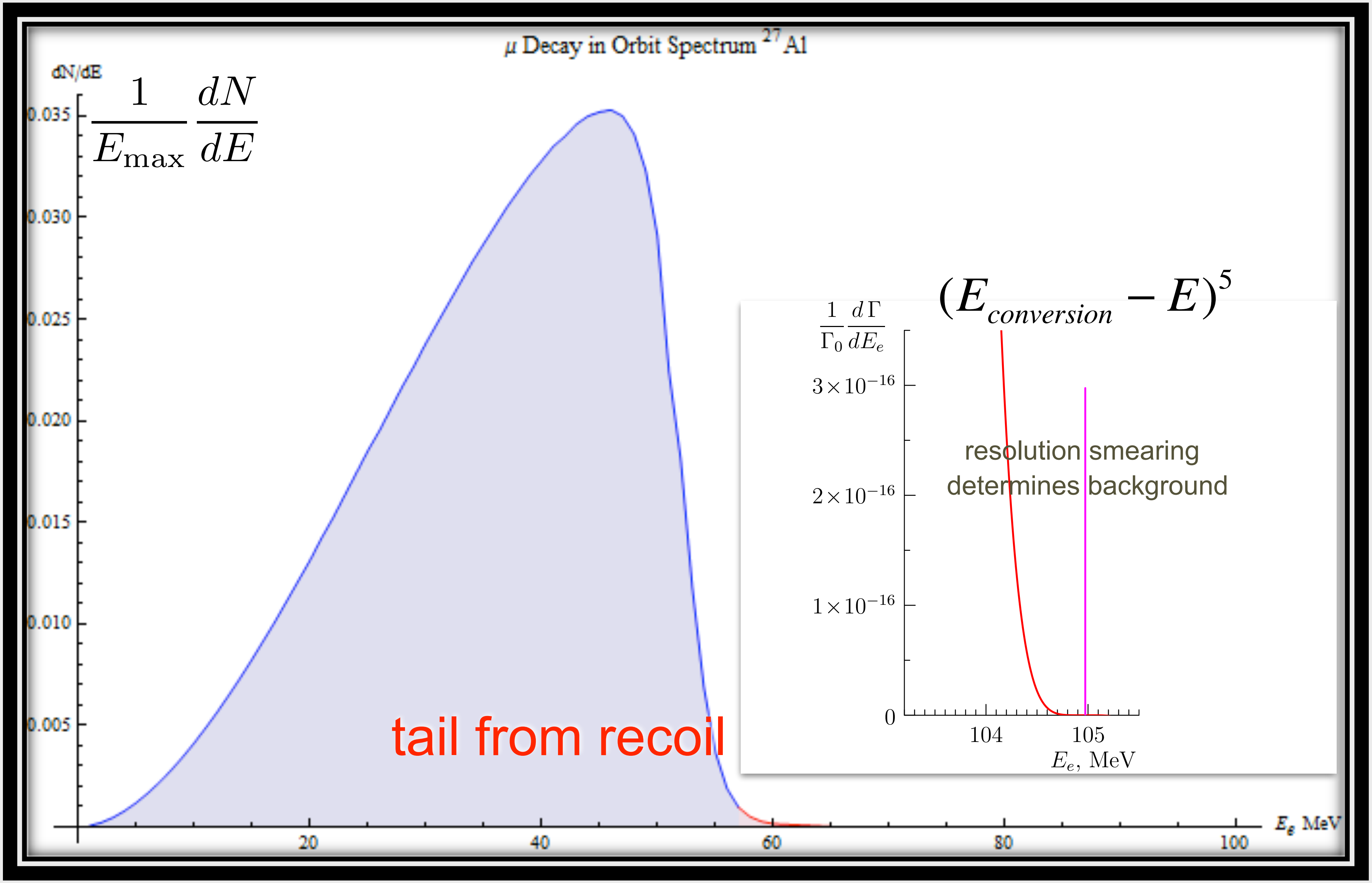

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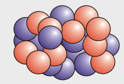
Intrinsic Backgrounds	decay-in-orbit	# of muons	detector resolution
Beam	radiative pion capture	closeness to beam pulse	pulsed beam
Running Time	cosmic ray	live time	veto system

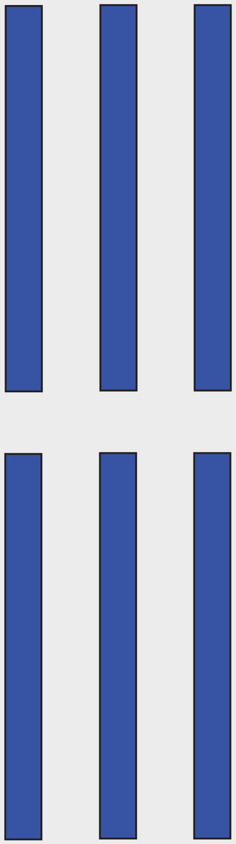
Radiative Pion Capture

- Need π's to make μ's
- Sometimes those π's live long enough to make it to the stopping target
- They can then undergo radiative pion capture (RPC):
    - $\pi N \to \gamma N'$ and the γ converts in the Al.
    - $\pi N \to \gamma N'$ and the γ internally converts
- Sometimes the e^- is at the signal energy

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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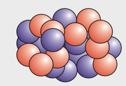
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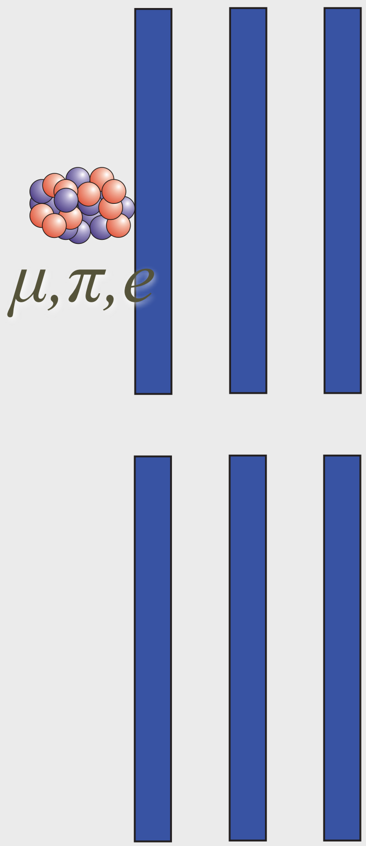

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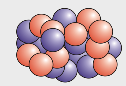
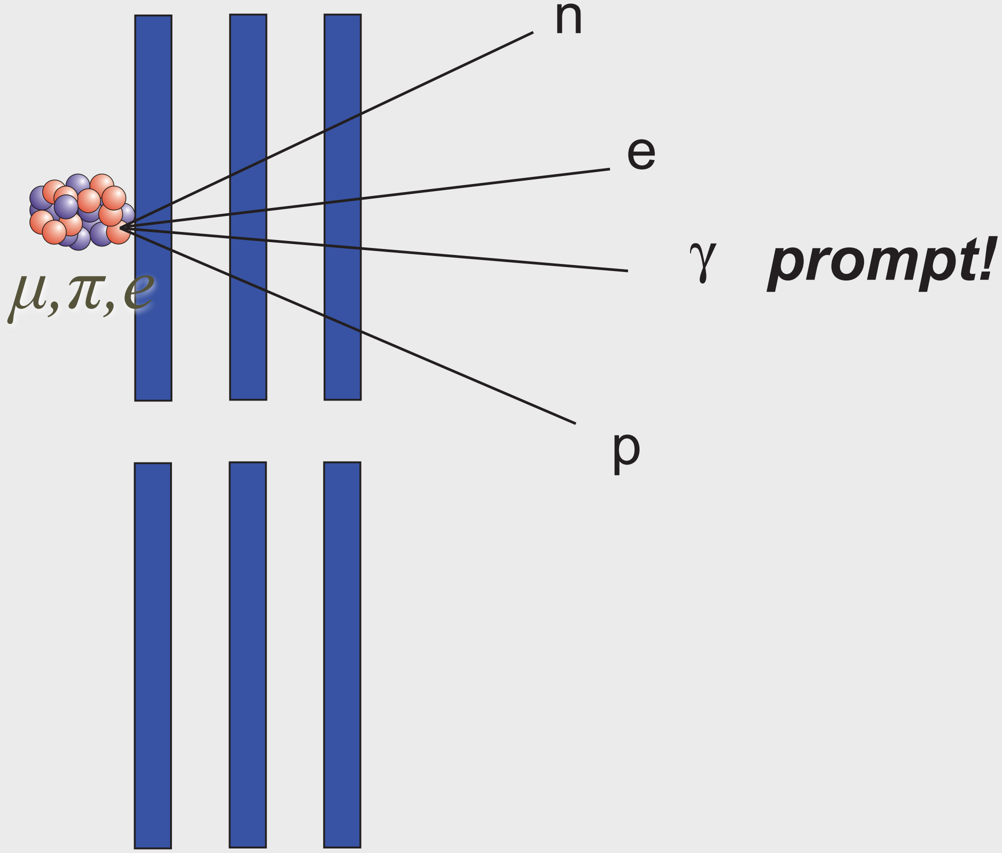
 = muons, electrons, pions



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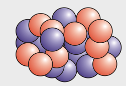
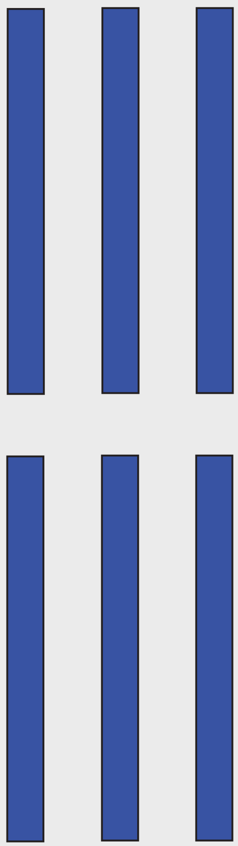
 = muons, electrons, pions



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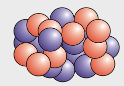
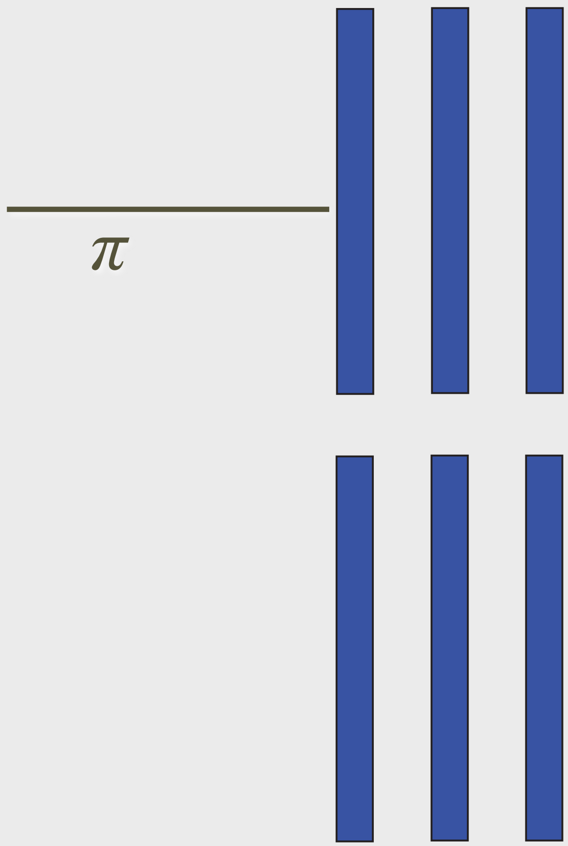
 = muons, electrons, pions



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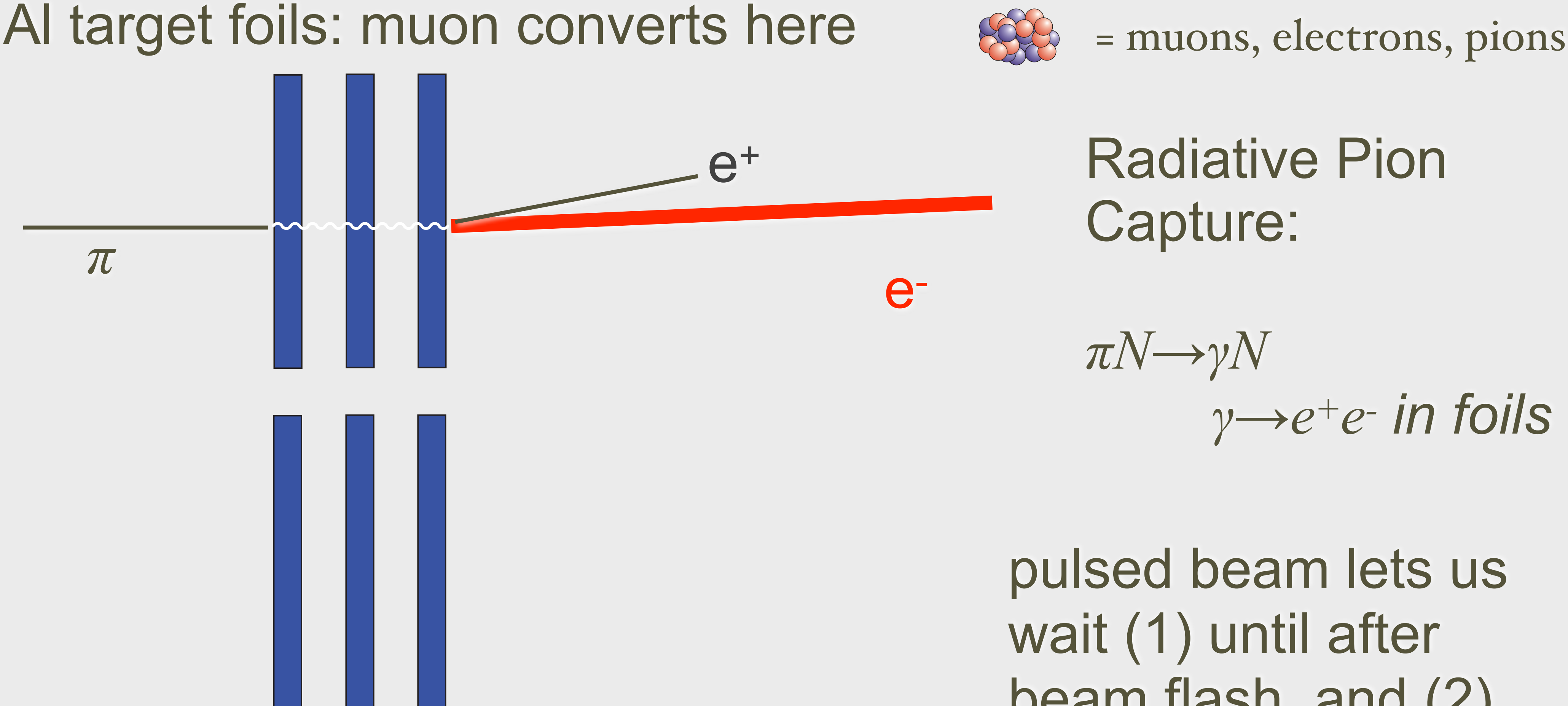

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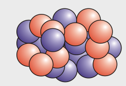

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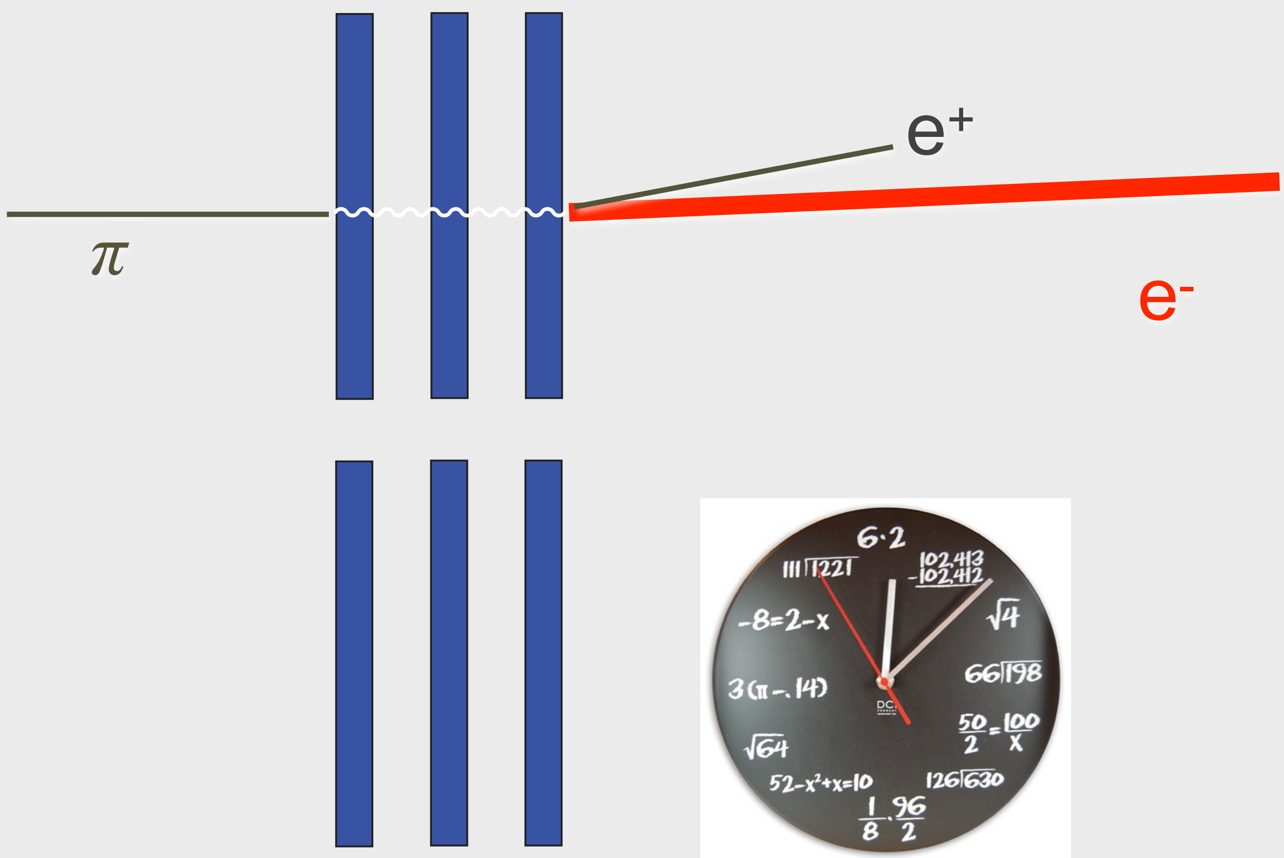

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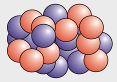
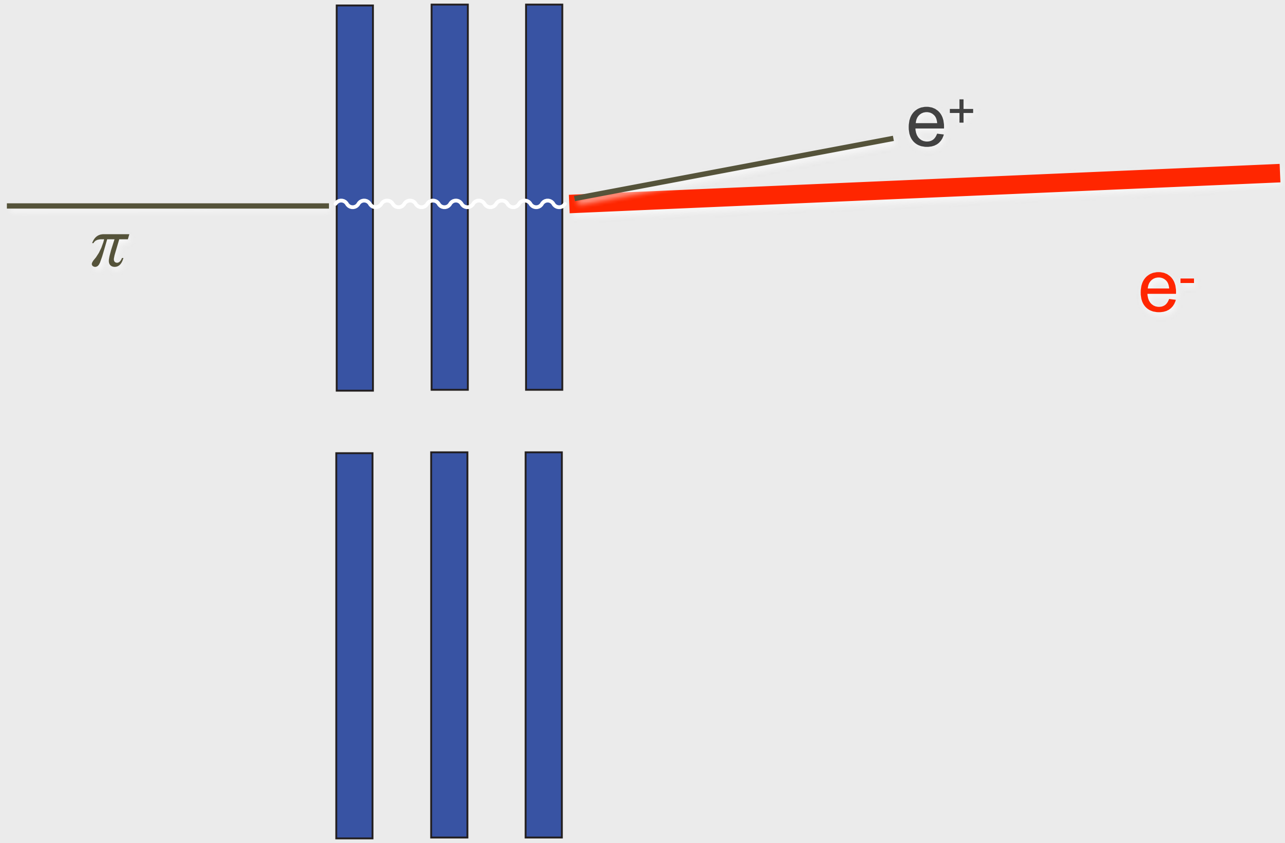
 = muons, electrons, pions



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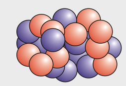
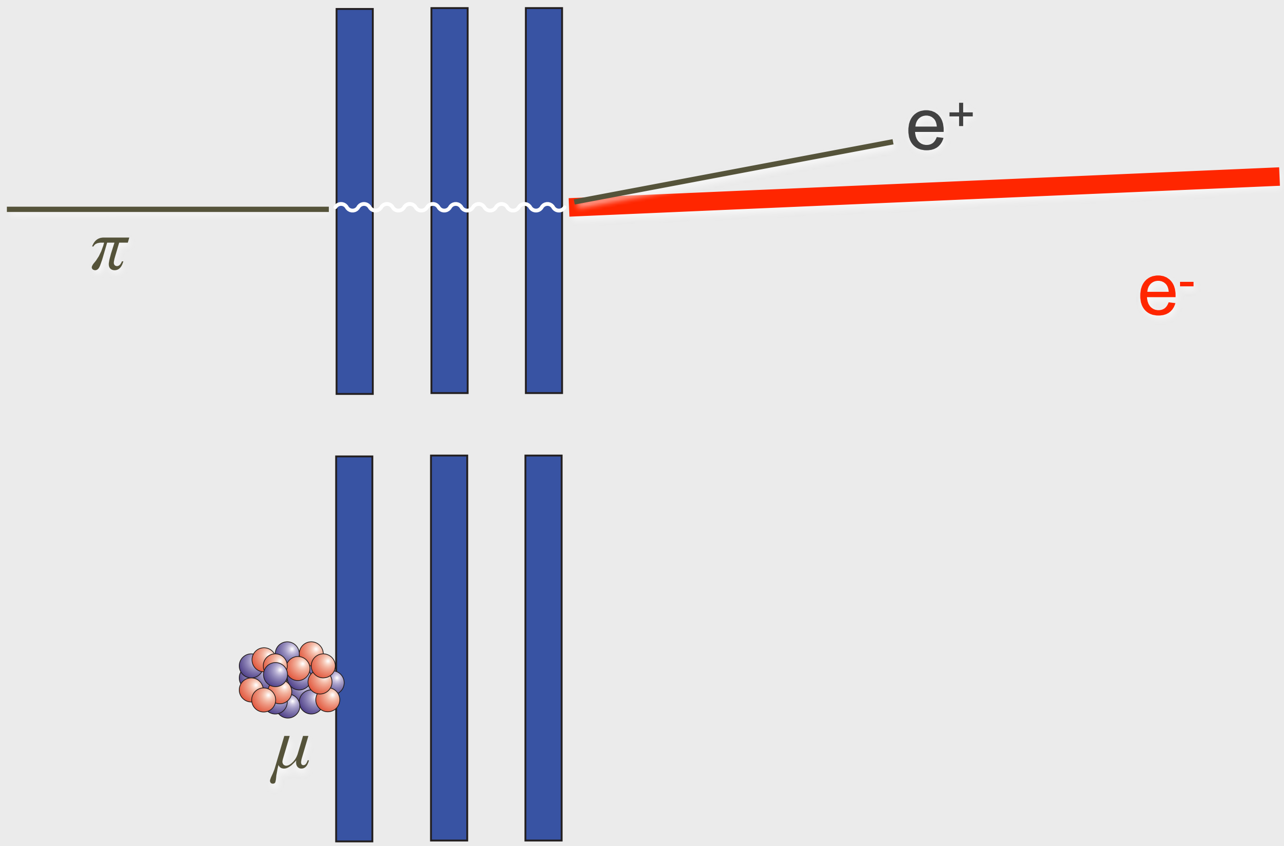
 = muons, electrons, pions



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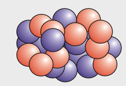
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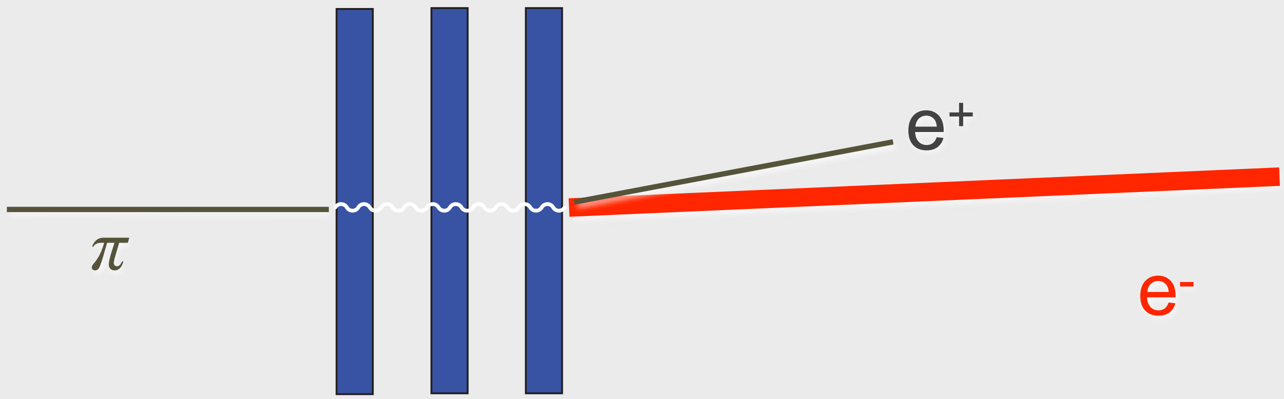

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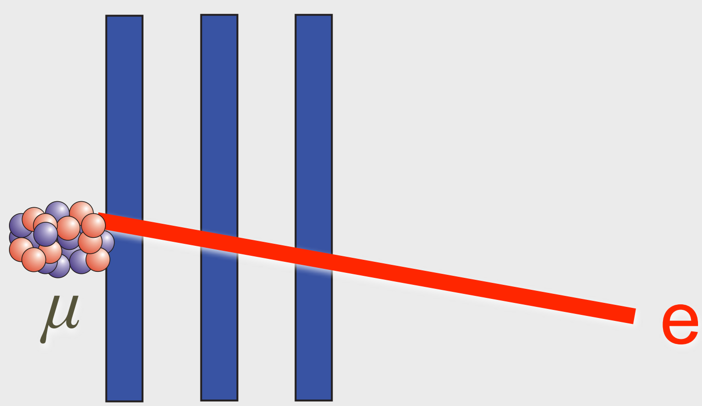


pulsed beam lets us wait (1) until after beam flash, and (2) RPC background decays away

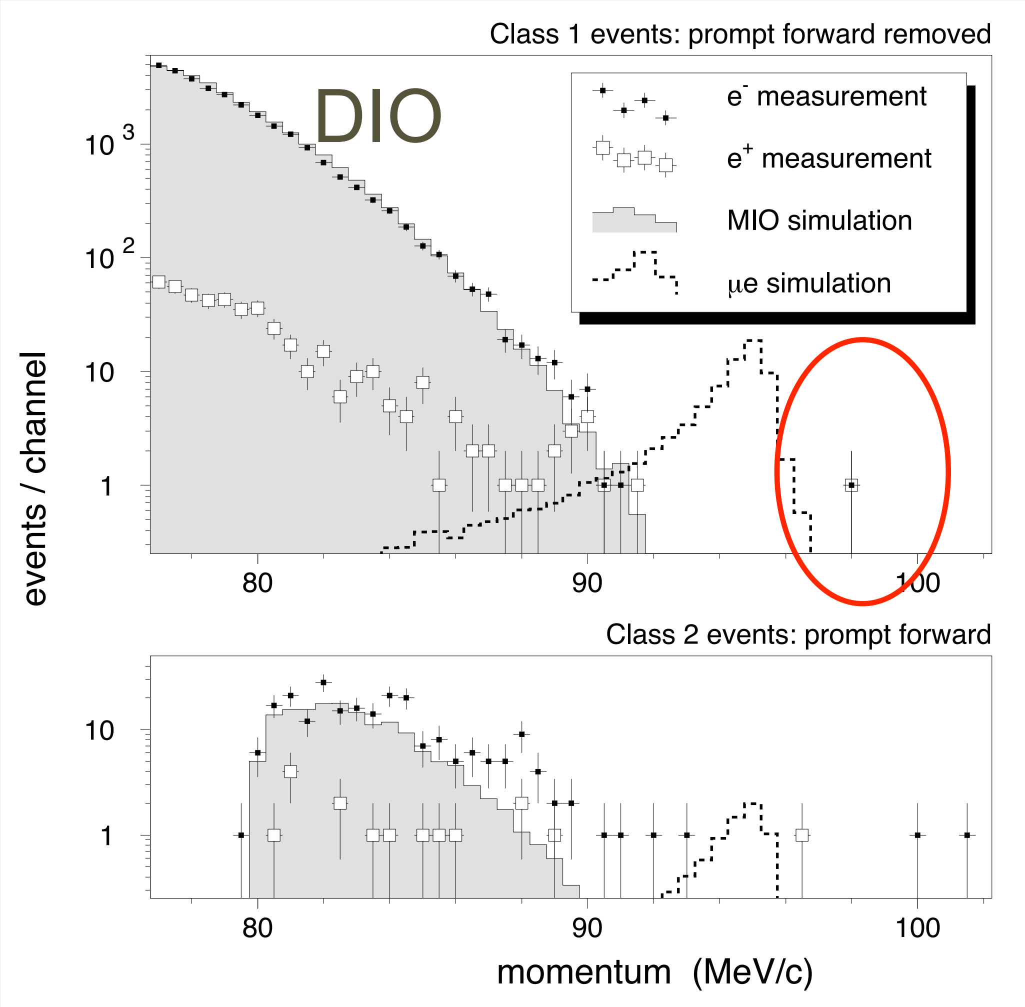
now μ is only source of 105 MeV electron

SINDRUM-II Results

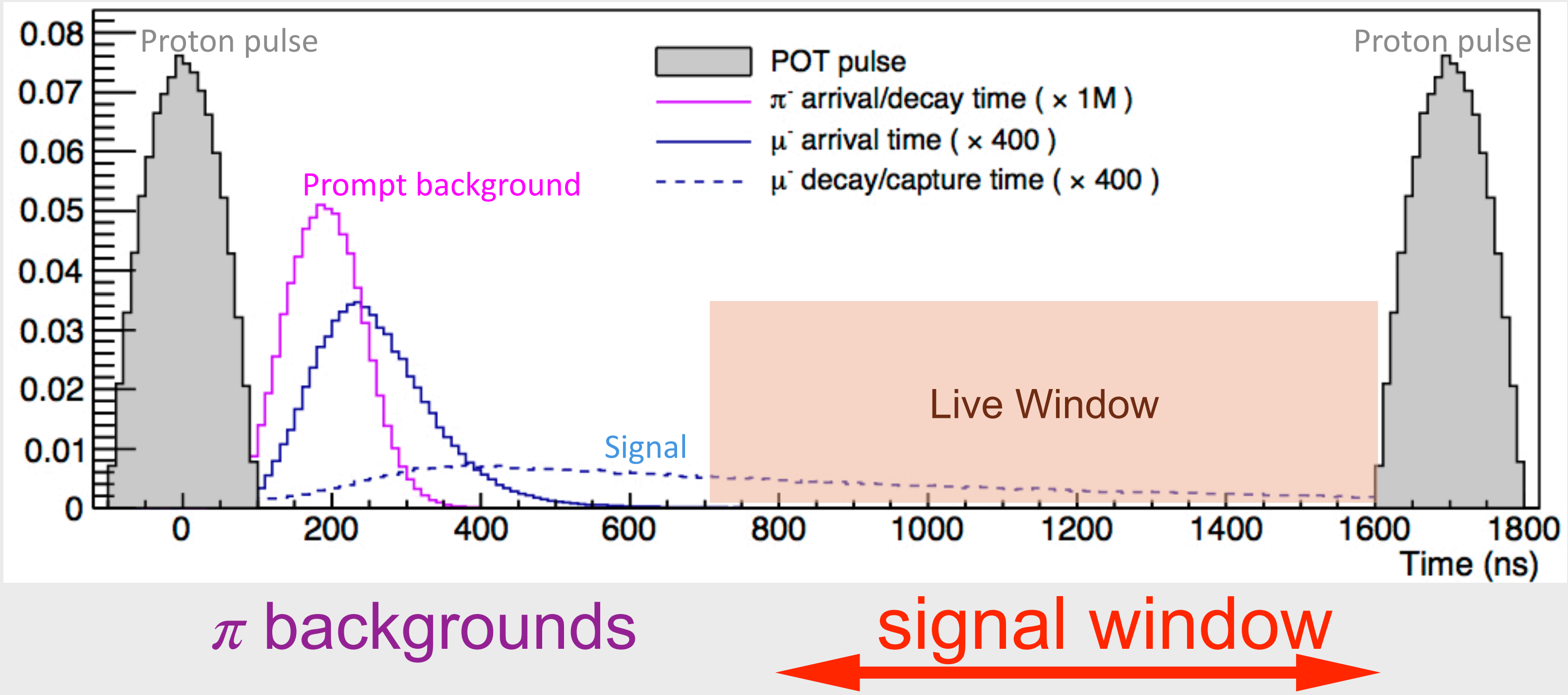
W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006)

- 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
    - delay lowers background

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



Pulsed Beam Structure



- 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 measure and monitor during experiment

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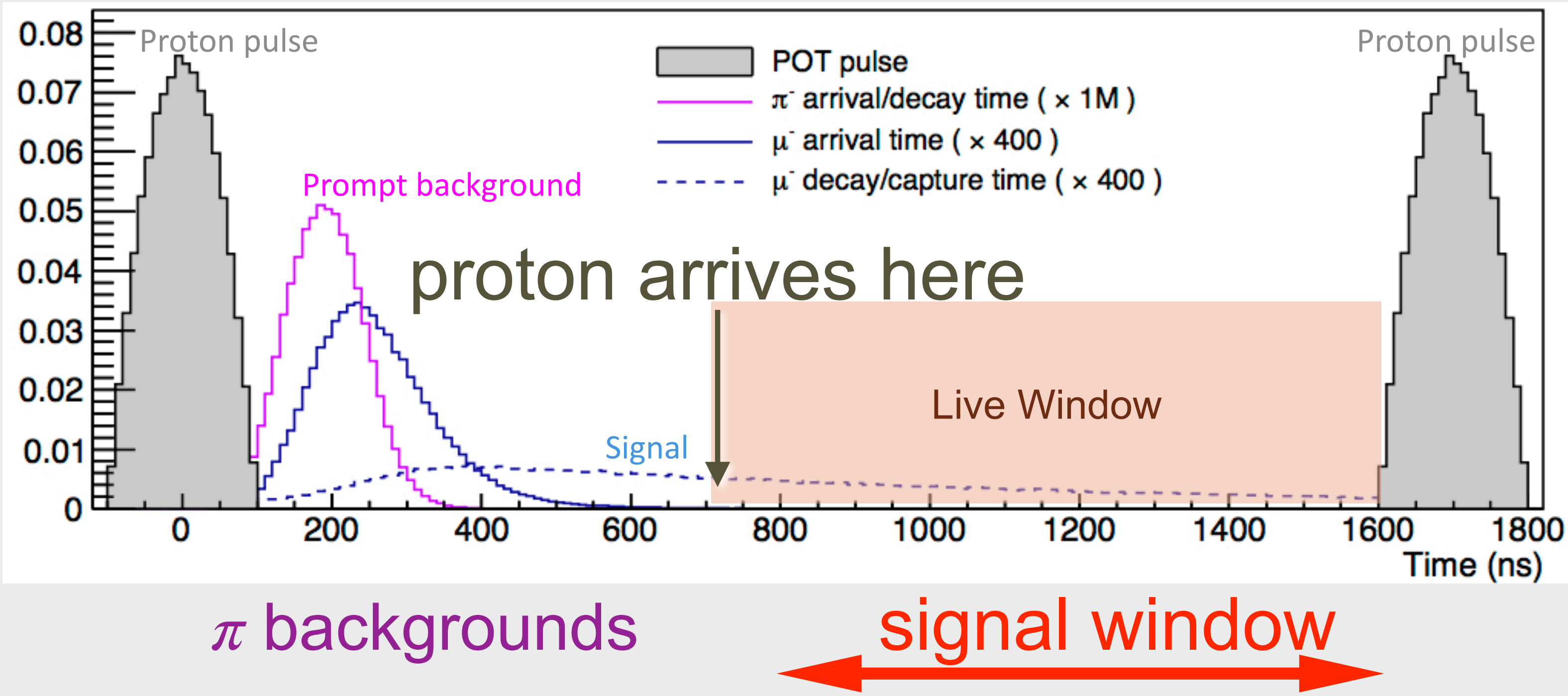

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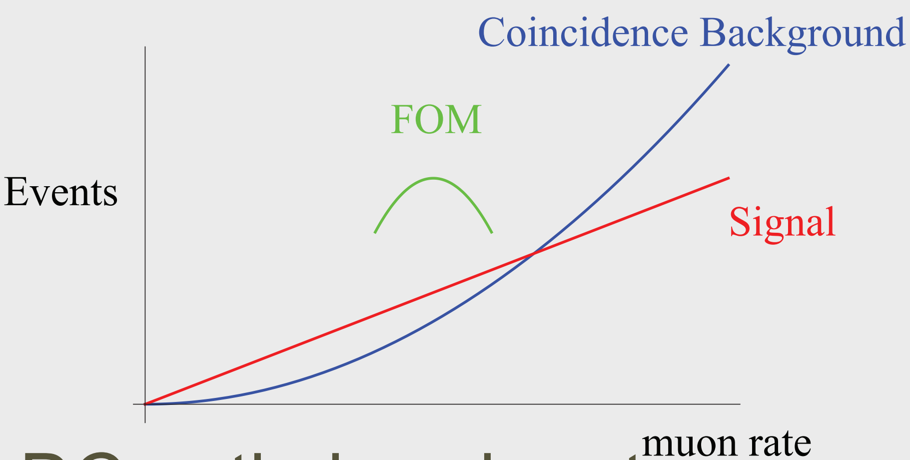
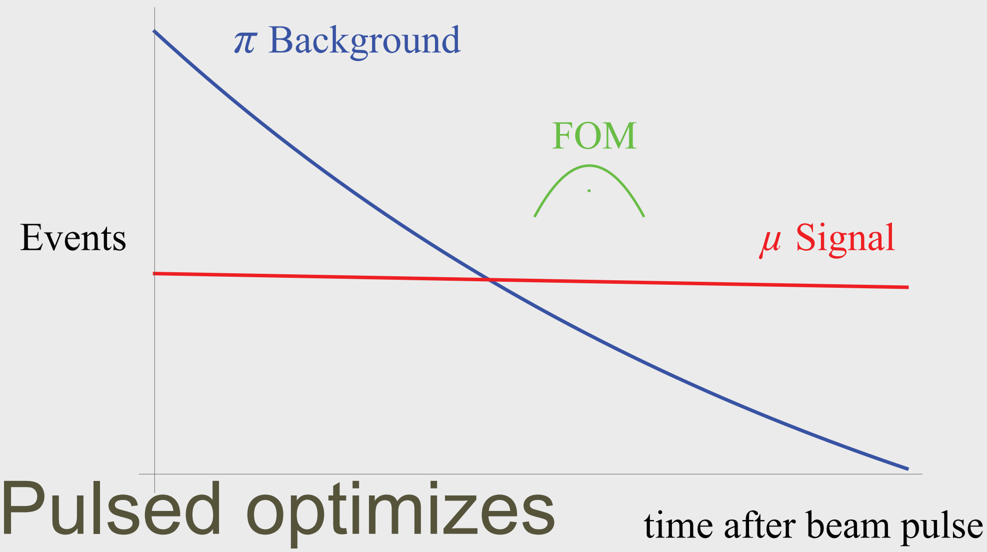
Pulsed vs. "Steady" Beam

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



DC optimizes in rate

- 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"

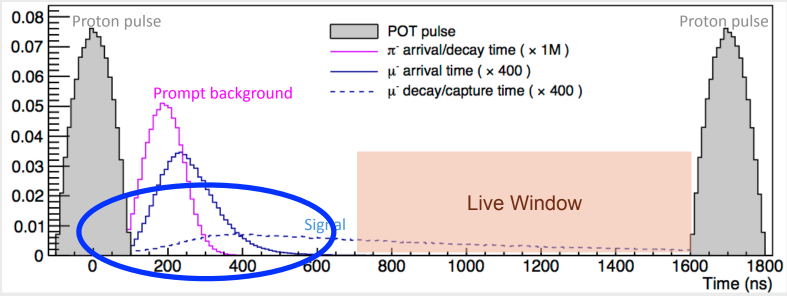


Pulsed optimizes in time

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



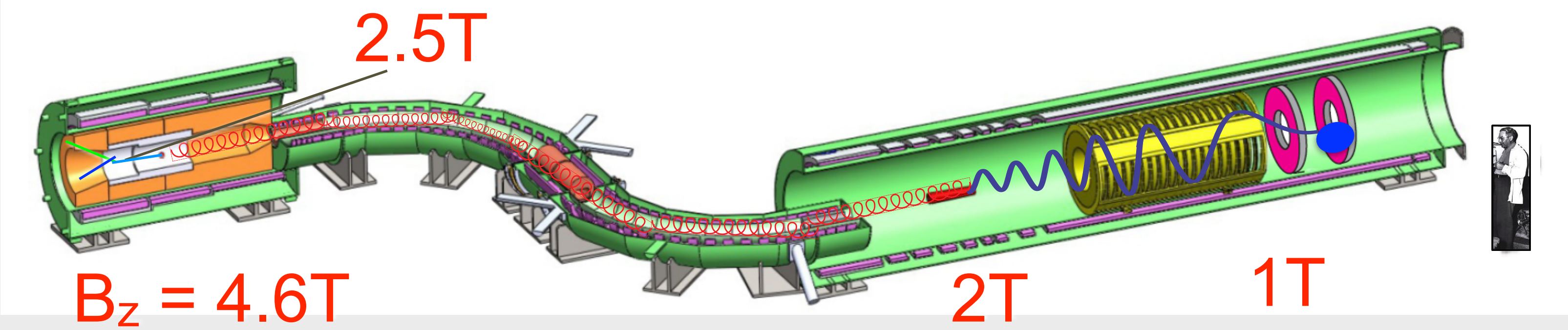
- By waiting:
  - activity from beam flash is over
  - And pion backgrounds have decayed by ~10^{11}

- This early flash has implications for Mu2e and especially for potential upgrades

Actual Experiments: Mu2e/COMET

mu2e.fnal.gov

4.6T → B-field gradient → 1T



Mu2e

Production Transport Detector

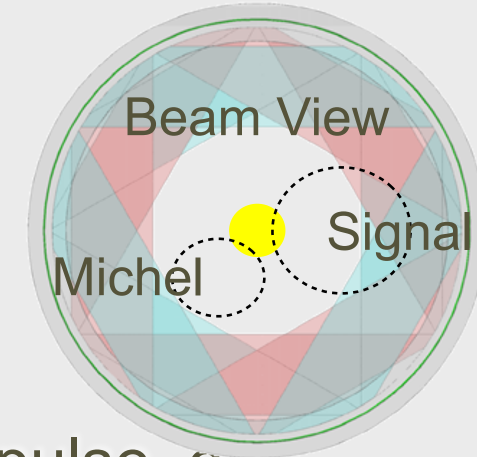
- Target protons at 8 GeV inside superconducting solenoid at 8kW: shielding a challenge
- Capture muons and guide through S-shaped region to Al stopping target

Detector Layout

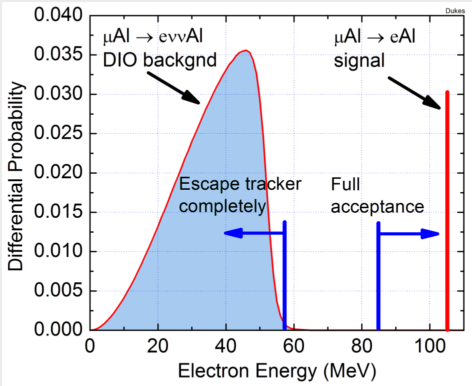
finding electron track and momentum determination: highest precision, needed to reject decay-in-orbit

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

Why Annular?

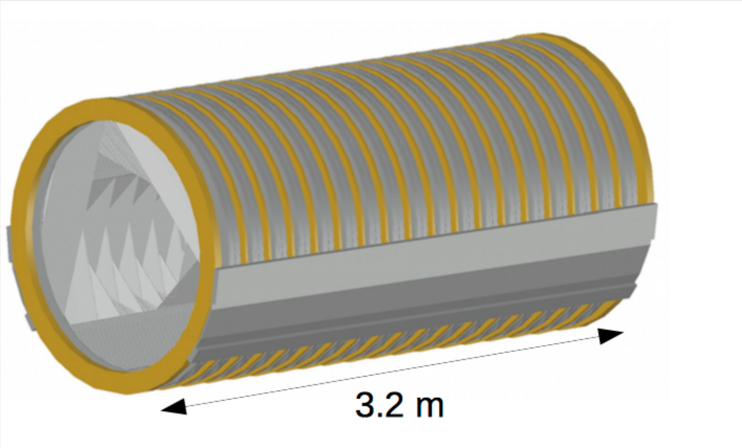


- Reduces beam activity and a background
  - don't want initial "flash" of activity from proton pulse, or remnant muon beam in detector (only ~1/2 of muon beam stops in target)
  - eliminates all but a tiny number of decay-in-orbit background
  - p sinθ ~ qBR in solenoid, Michel e- at small radius
  - so we're not rejecting 10^{18}; only ~10^5 even reconstructed
- COMET uses a different method; not annular
  - advantages and disadvantages

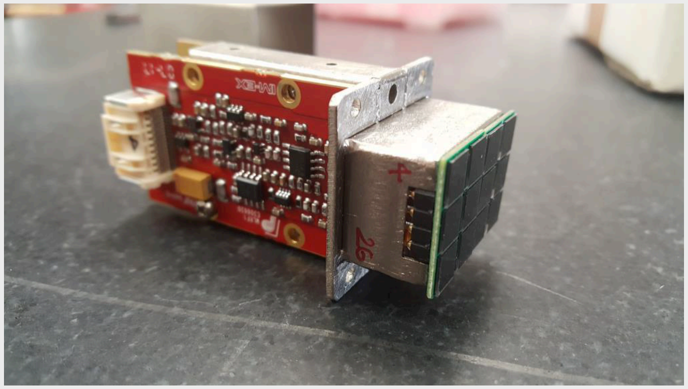


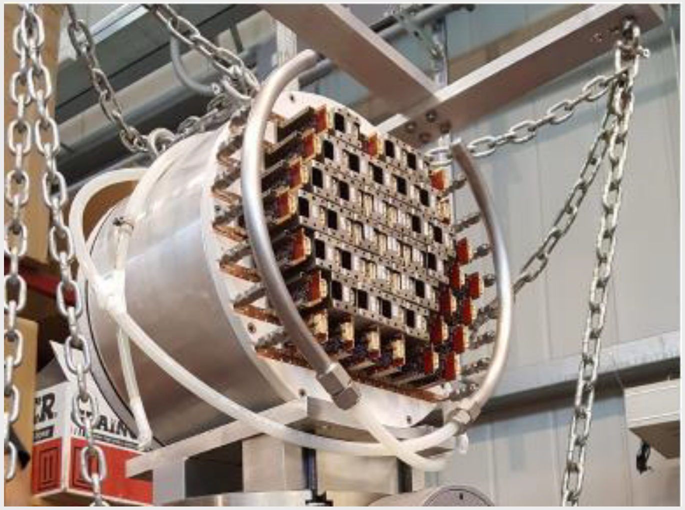
Straw Tube Tracker

- 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

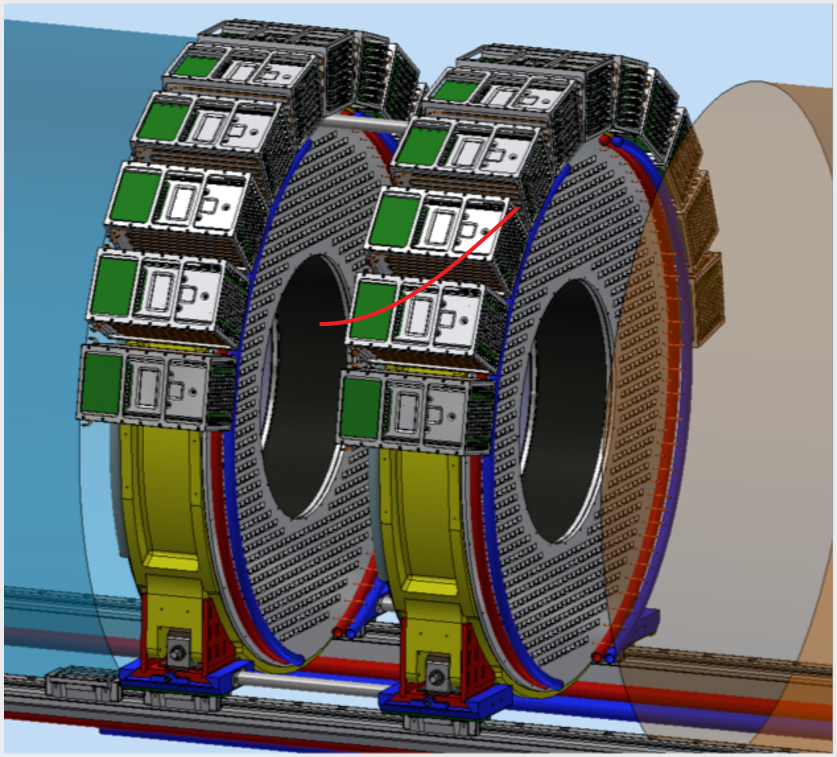


Calorimeter





- 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



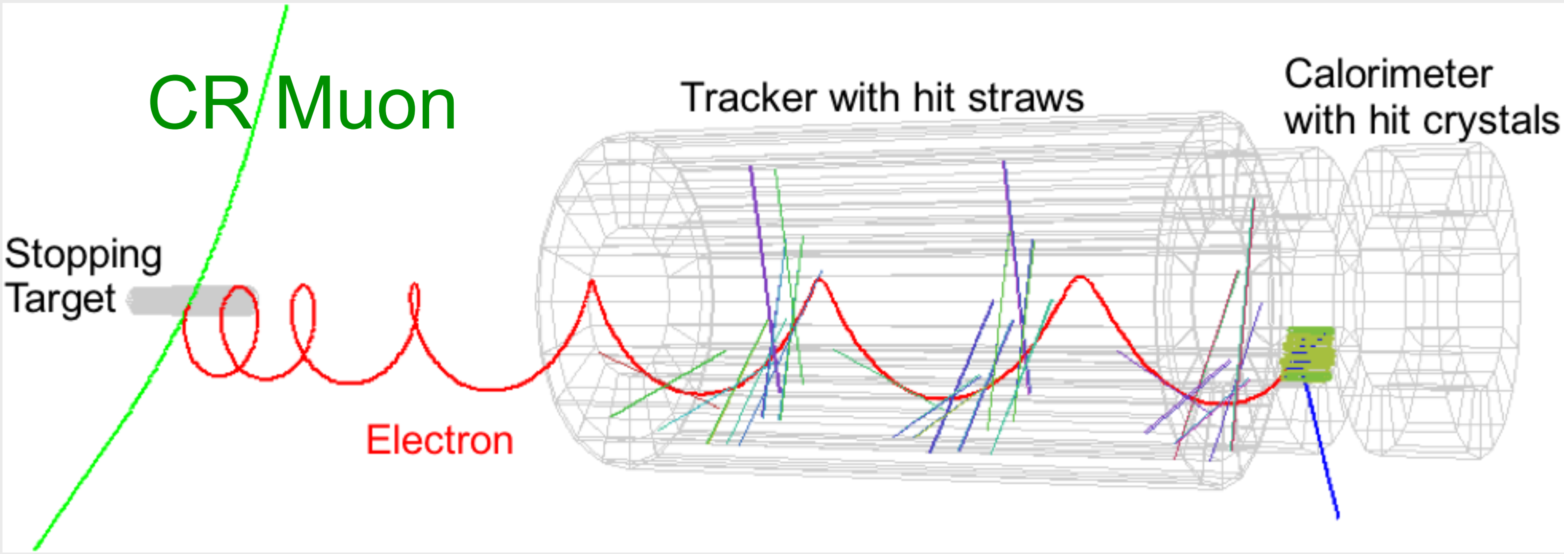
“module 0”: 51 crystals

Backgrounds and Design

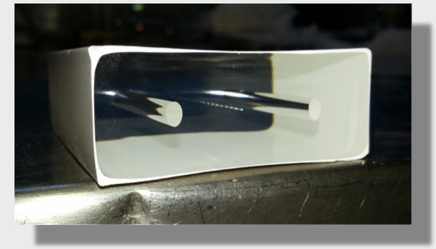
	source	*scales with*	*solution*
Intrinsic Backgrounds	decay-in-orbit	# of muons	detector resolution
Beam	radiative pion capture	closeness to beam pulse	pulsed beam
Running Time	cosmic ray	live time	veto system

Cosmic Ray Background

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



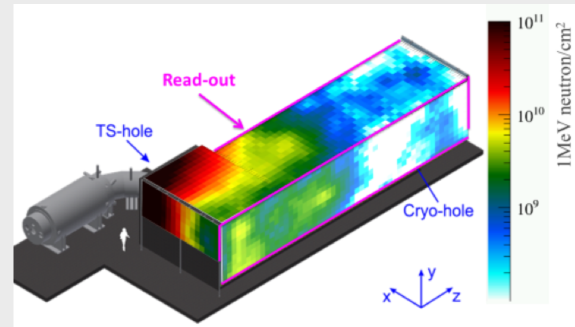
- the experiment needs a 99.99% efficient veto (3/4 layers)
- in an environment with 10^{10} neutrons/cm^2/sec from proton pulse

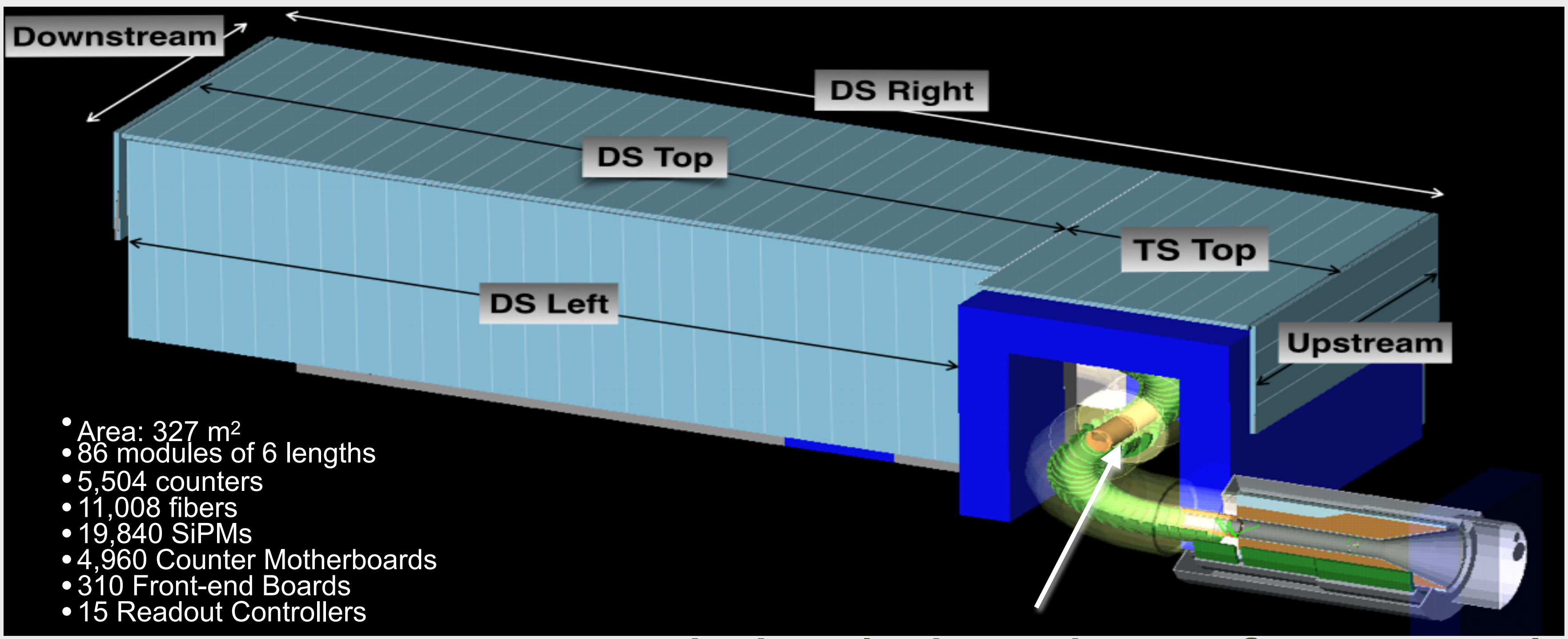


CR Veto Details

- Veto systems are never totally hermetic
  - even with 26 km of veto counters, area of a large house (~3000 ft^2) (extrusions completed)
- Simulated 250 experiment live-times in targeted regions

Neutron Rates

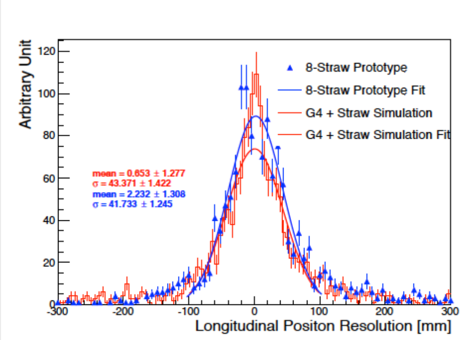




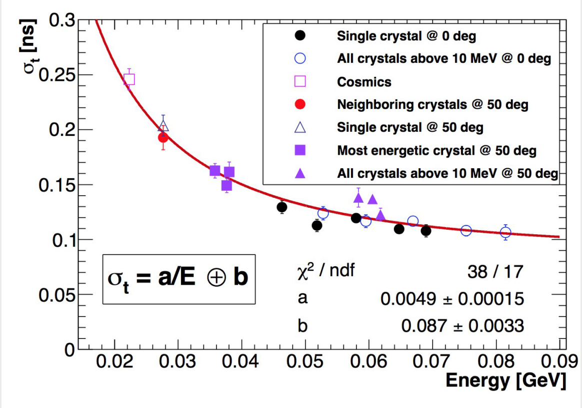
targeted simulations here, for example

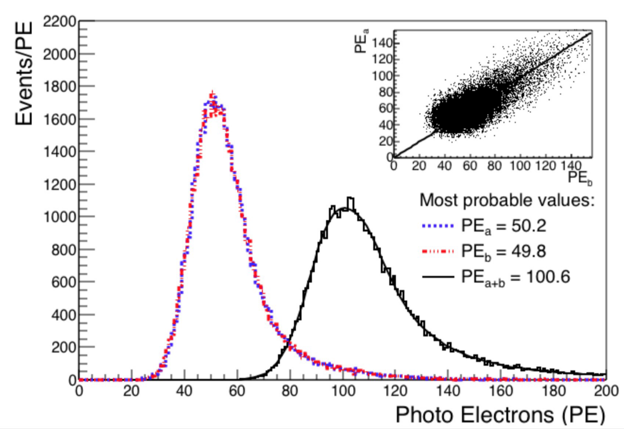
Tracker/Calorimeter/ CRV Test Beam Results

- 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

Beam Under Construction

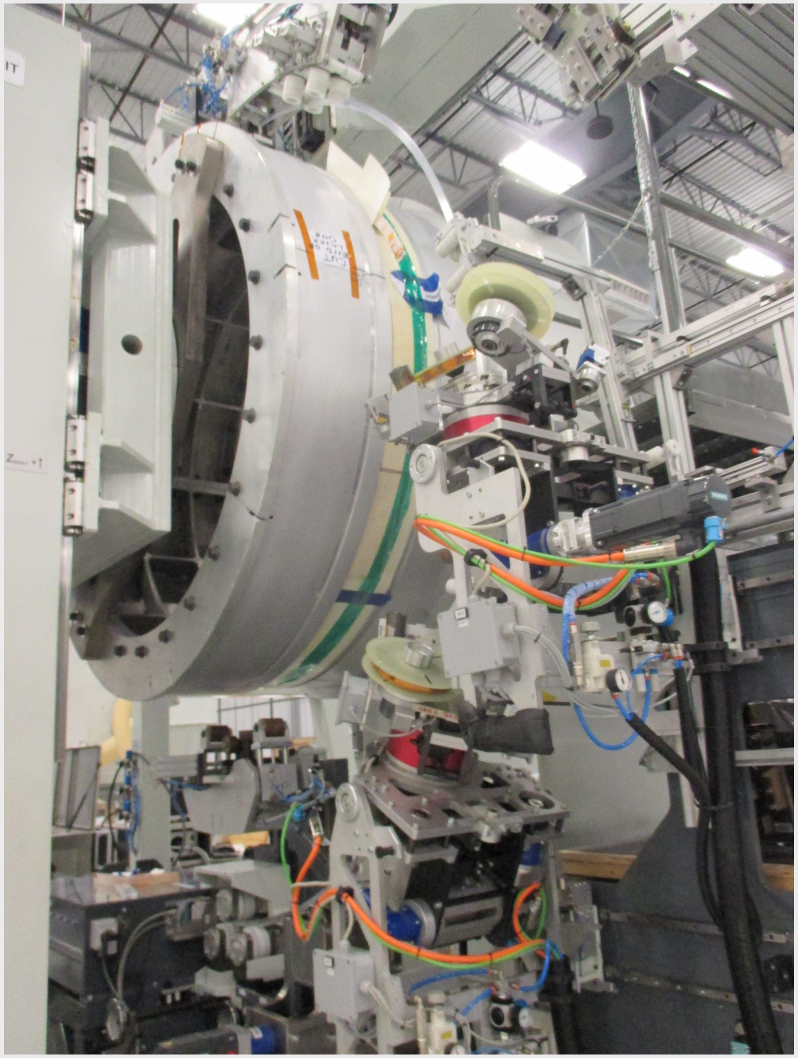
diagnostic absorber near g-2/Mu2e split:
is the beam as expected and does the
extinction work?

checking polarity now!
(before we turn on)

Mu2e Solenoid

Coil modules at ASG

~1 of 75 km of cable and spares (cable complete)

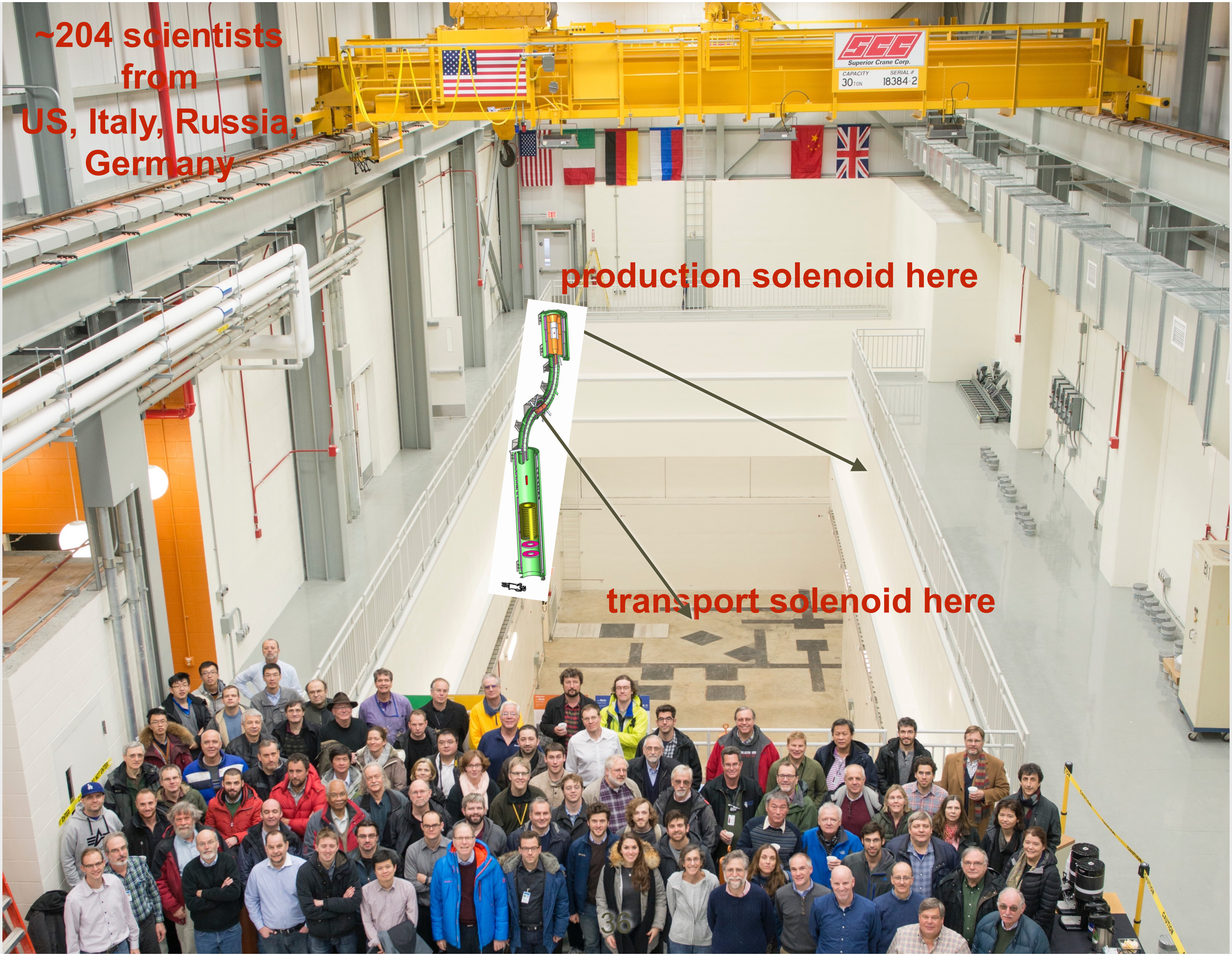


at General Atomics
splice between solenoids

Beginning Production

- Ramping up production and cold tests

CDF was here

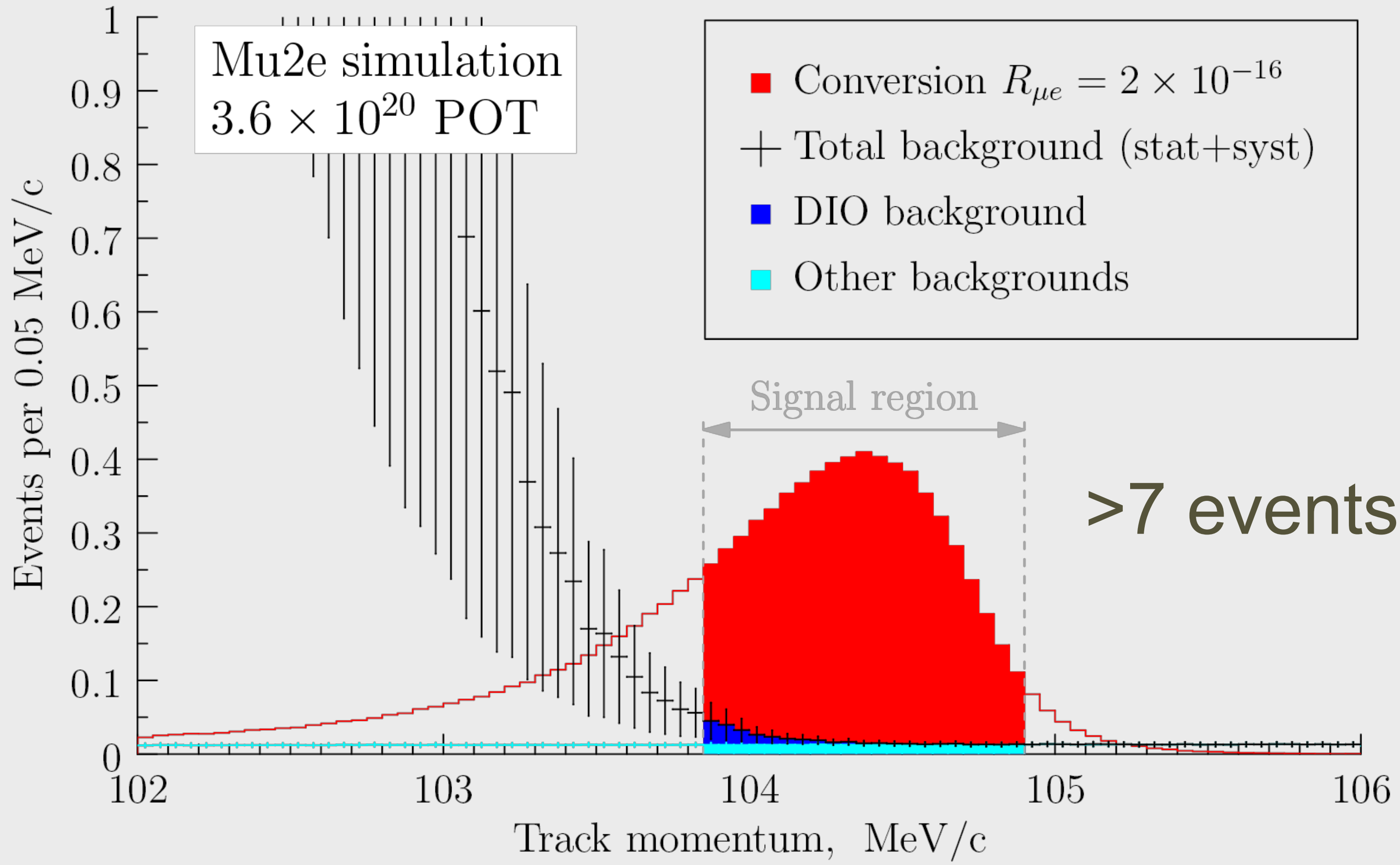

~204 scientists
from
US, Italy, Russia,
Germany
Superior Crane Corp.
CAPACITY 30 TON
SERIAL # 18384-2
production solenoid here
transport solenoid here

Mu2e Expected

90% CL ~ 8 x 10^{-17} 5σ~ 2 x 10^{-16}

x10000 better than SINDRUM-II

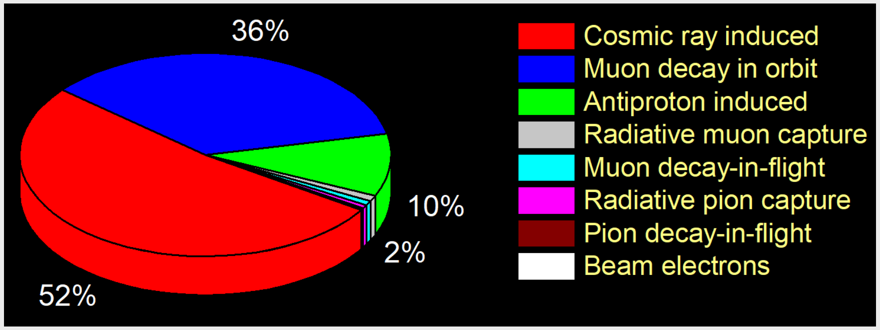
Mu2e



>7 events = 5σ

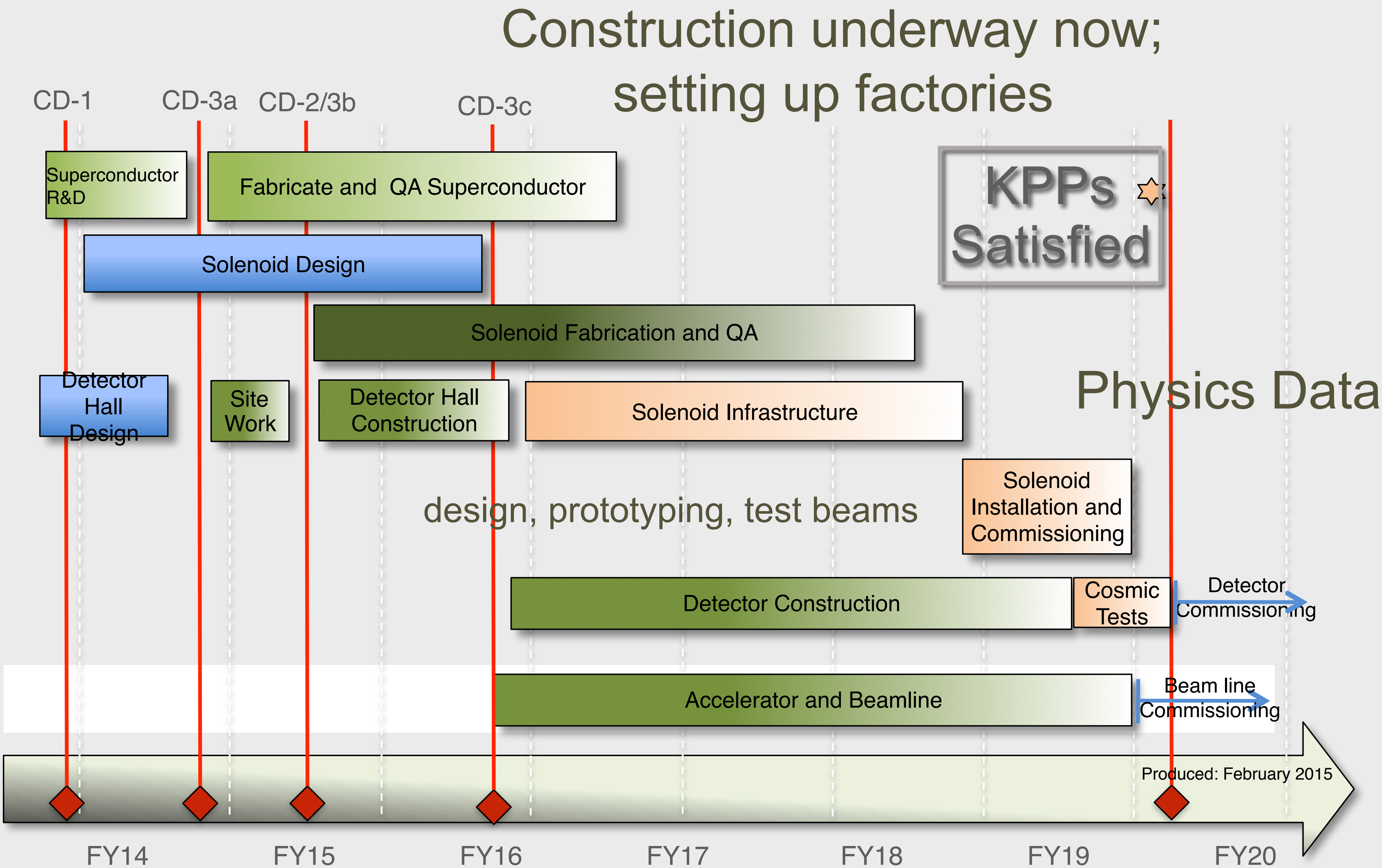
typical SUSY at 10^{-15}: 40 events vs 0.4 bkg

Background Estimates

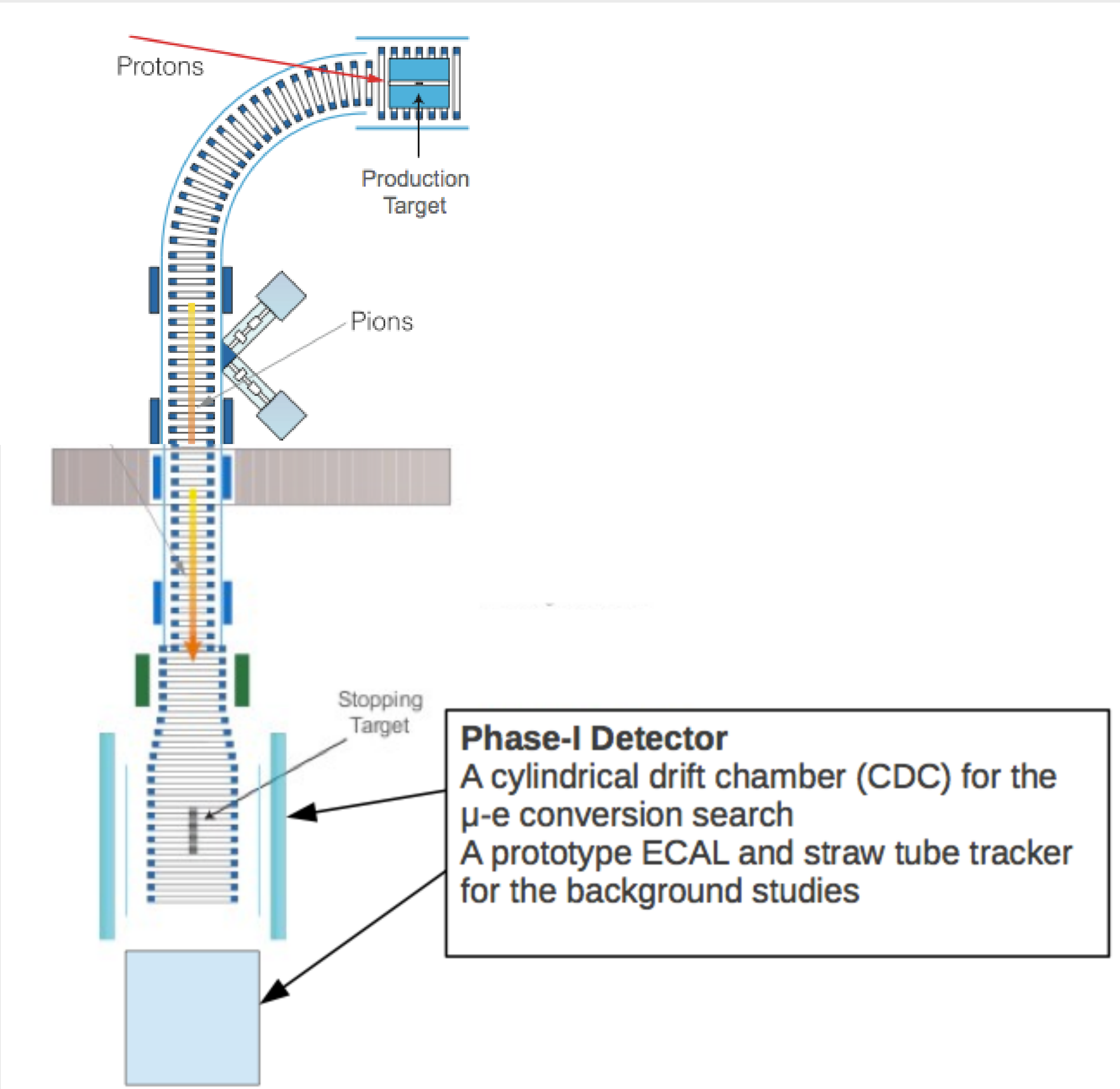


Process	Expected Number
Cosmic Ray Muons	0.25 ± 0.026
DIO	0.14 ± 0.09
RPC	0.025 ± 0.003
Antiprotons	0.047 ± 0.024
Muon DIF	< 0.003
Pion DIF	$0.001 \pm < 0.001$
Beam Electrons	$< 5 \times 10^{-4}$
Total	0.46 ± 0.03

Mu2e Schedule

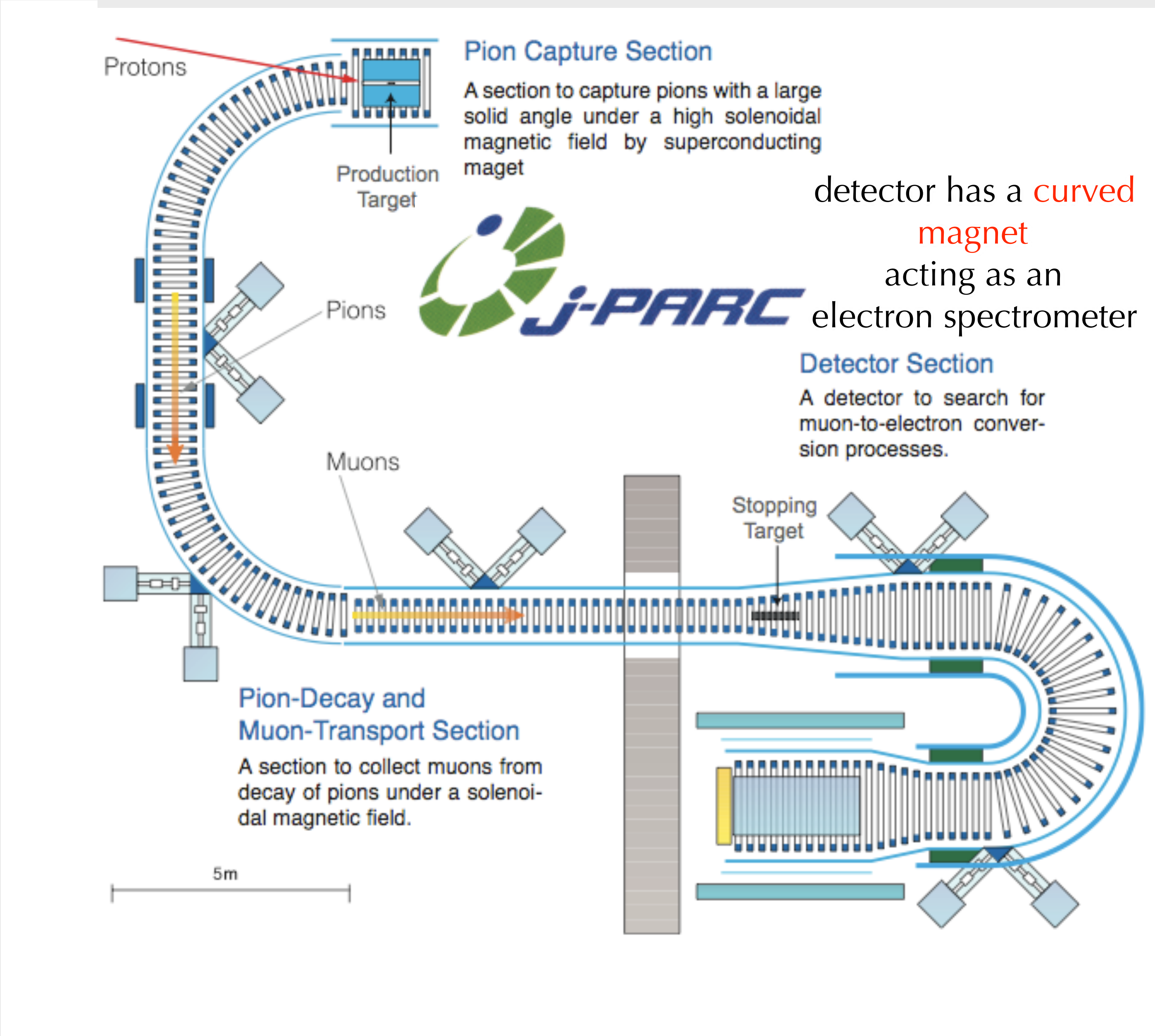


COMET



- Stage I: (2021)
  - x100 better than SINDRUM-II
- Stage II
  - x10,000 better
  - same reach as Mu2e
- Important differences:
  - C- vs S- for transport
  - 2nd bend in detector solenoid

COMET

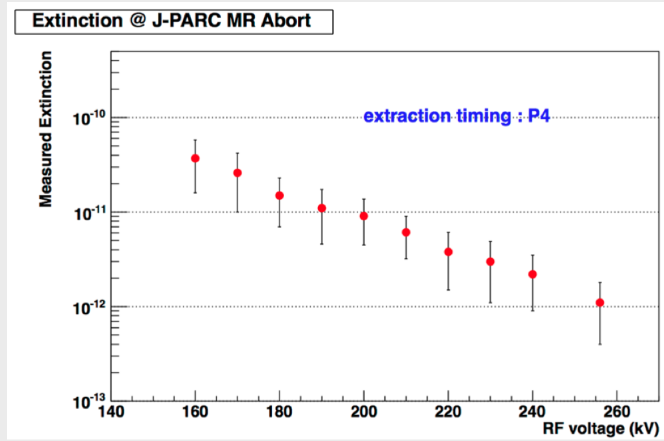


- Stage I: (2021)
  - x100 better than SINDRUM-II
- Stage II
  - x10,000 better
  - same reach as Mu2e
- Important differences:
  - C- vs S- for transport
  - 2nd bend in detector solenoid

COMET Progress

Chen Wu, Tau 2016
and
Y. Kuno, priv. comm

- Extinction measured ~ 10^{-11}

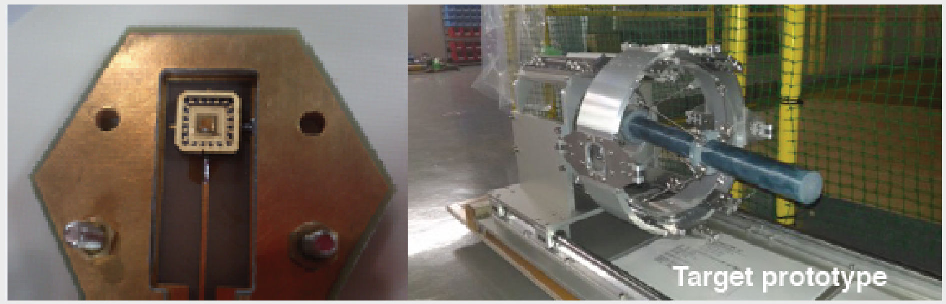


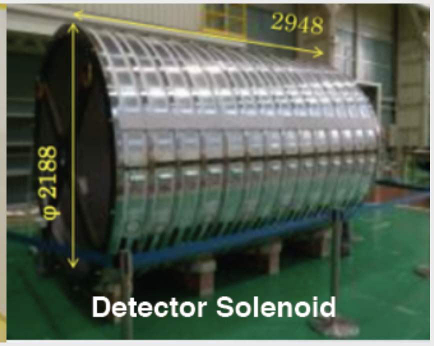
- Prototype Target

- Coil winding for capture solenoid

- Transport Solenoid in Hall

- 14 Coils of Detector Solenoid wound





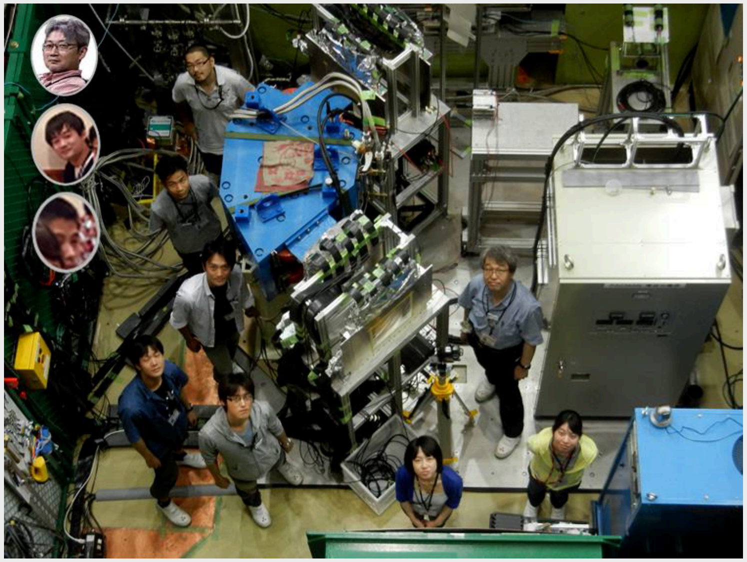
COMET Remaining

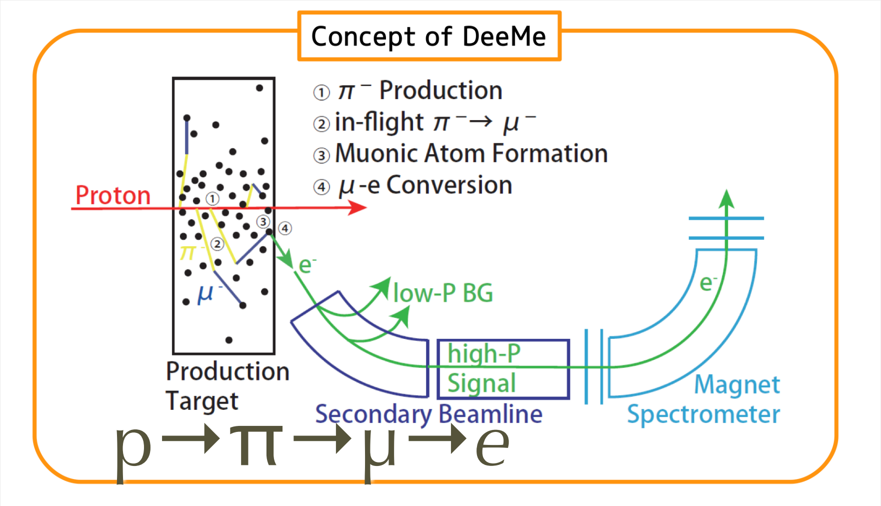
- Production Solenoid cable procured, but one has to then design a solenoid shielding system that will withstand heat and radiation
  - dumping up to 56 kW (Stage II) in a superconducting solenoid
  - design still underway
  - then needs construction
- Negotiation over running time with T2K
  - ~150 days live-time needed for Stage 1 (x100 improvement)
- Available schedules out-of-date, but Stage 1 ~ 2021

http://j-parc.jp/researcher/Hadron/en/pac_1707/PAC24thMinutes_final_draft.pdf

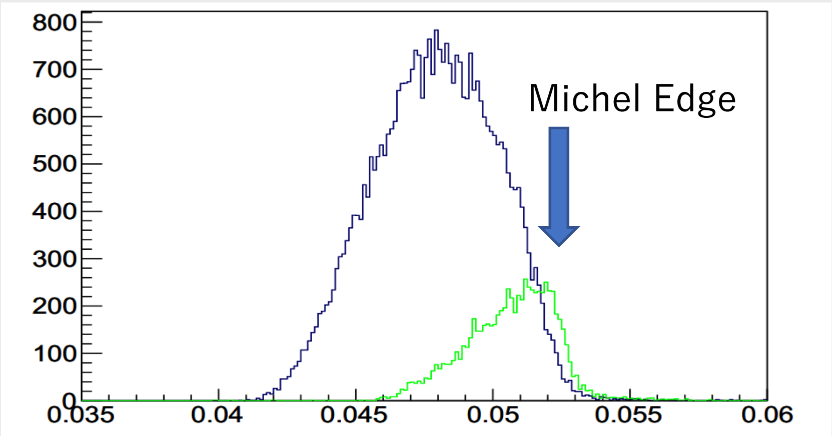
DeeMe

- DeeMe at J-PARC $\mu N \rightarrow eN$ with a 2 x 10^{-14} SES, x10 improvement
- ***production target and conversion target are the same: not like Mu2e or COMET***



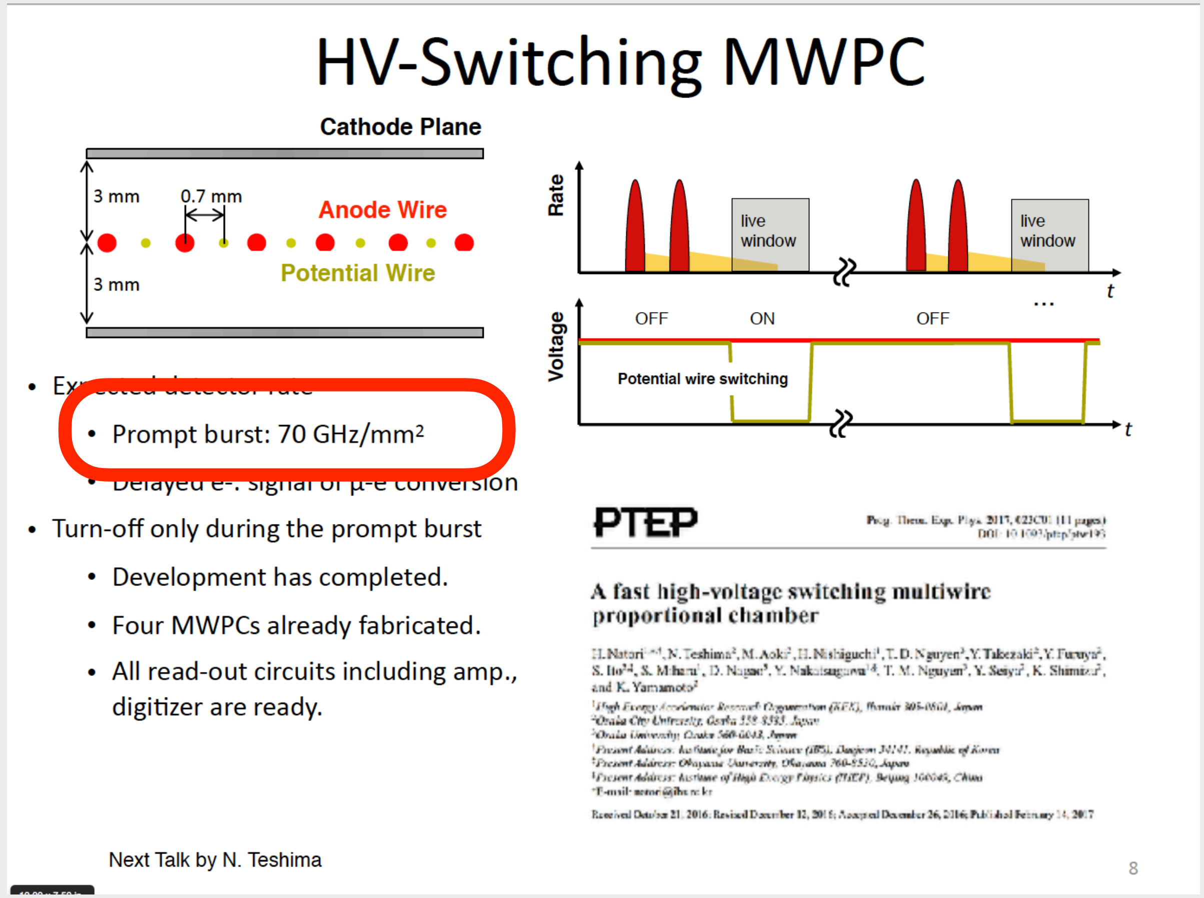


Calibration Spectra (μ^+ data)



DeeMe HV Switching

- Since the detector is so “close” to the production target, the detector has to be turned off near the beam flash
- HV switching on a MWPC



DeeMe Status

- Depends on J-PARC H-line construction (different from COMET, DeeMe in Materials Science section)

Summary

- There is a competitive merit of physics in searching for μ-e conversion at sensitivity of 10^{-14} in timely manner.
- **It is important to maximize the potential of major discovery at J-PARC**.
- DeeMe, yet another mu-e conversion search with totally different method from COMET and Mu2e, creates harmonious diversity for J-PARC.
- DeeMe has already acquired **Stage-2 Approval from muon-PAC of KEK/IMSS**.
- Construction of **detector system has completed** with Grant-in-Aid for Scientific Research of Japan (Basic Science S, 2012–2016).
- An **integration test of the whole detector system** including DAQ had **success**fully performed. A **DIO measurement** had done at the same time, and analysis is ongoing.
- The **Detector system is ready** for the physics data taking.
- We are hoping to start soon after the completion of the beamline construction. No beam-time conflicts with T2K, KOTO or whatever the physics programs with the main ring of J-PARC.
- Meanwhile, we are keeping collaboration activities with detector improvements and by-product research.

Mu2e and COMET: High-Level Differences

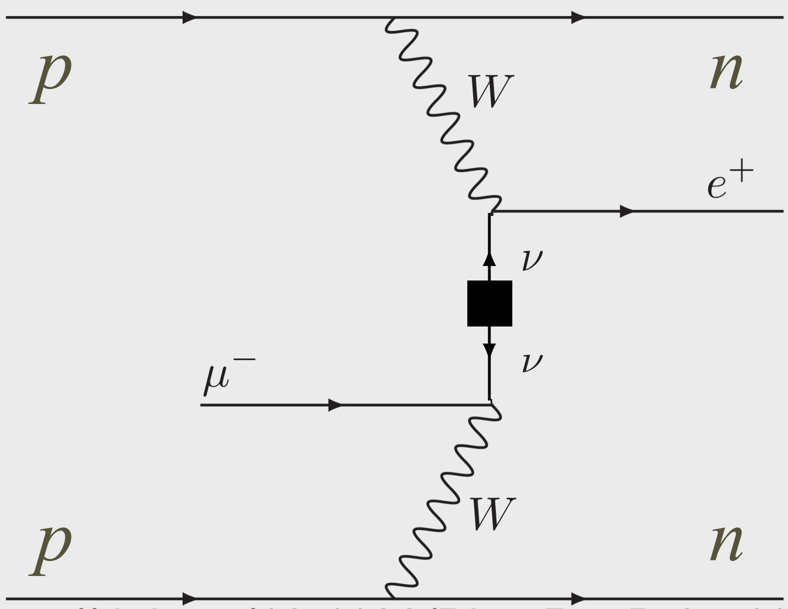
- COMET Staging has obvious advantages for learning as you go
- Charge Symmetry of Detector:
  - Mu2e: charge symmetric, e^+e^- the same
  - 2nd Bend in COMET Stage II momentum selects ~ 105 MeV e^- only
  - Mu2e needs hole, COMET does not

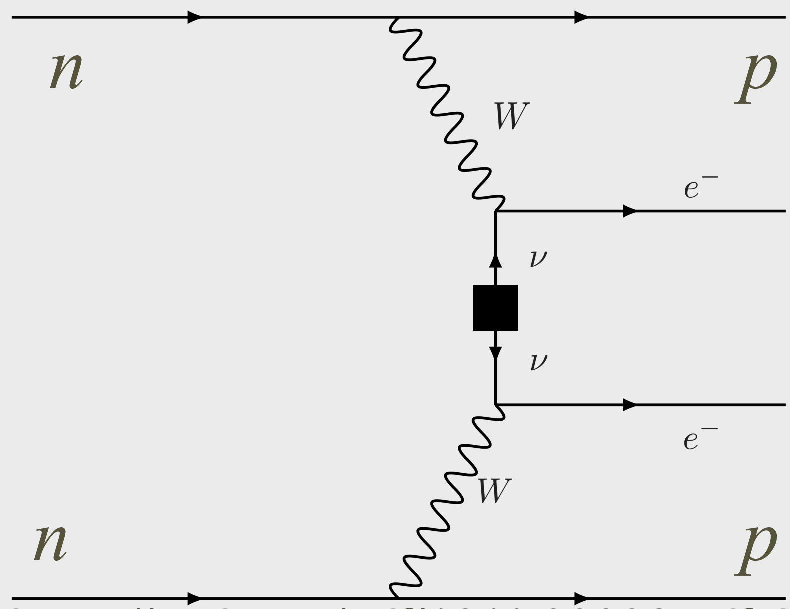
Effect of Charge-Symmetry Choice

- 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^+
- Physics (next topic)
  - Mu2e can simultaneously measure $\mu^- N \to e^+ N'$, different/unique physics
  - COMET would have to reverse field, not trivial: separate runs

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

- Closely related to *0ν2β*
    - or a leptoquark (not shown), …

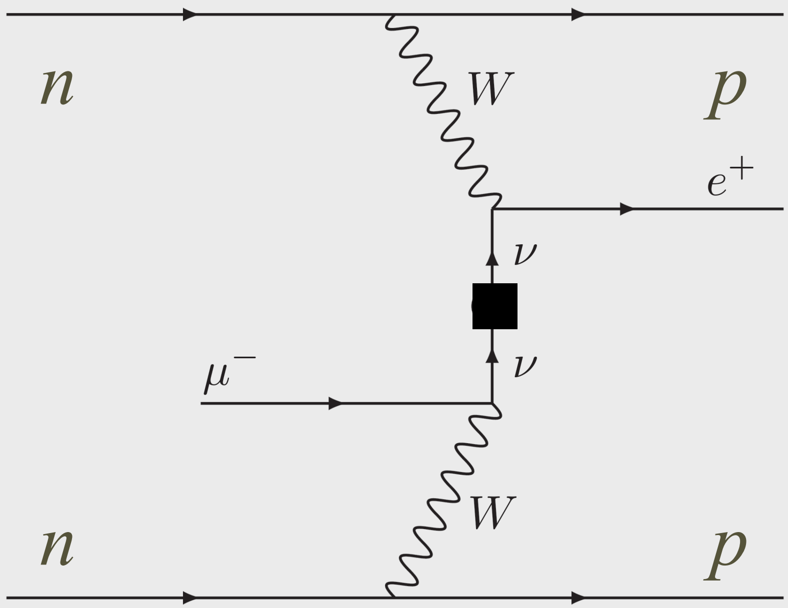




- https://doi.org/10.1103/PhysRevD.95.115010, https://arxiv.org/pdf/1611.00032.pdf, https://arxiv.org/pdf/1705.07464.pdf, Geib et al., Physics Letters B 764 (2017) 157–162 or https://arxiv.org/abs/1609.09088 discusses relation to *0ν2β*

$\mu^- N \rightarrow e^+ N^*$ Changes Nucleus

- The final state nucleus is different by $\Delta Z = 2$
  - different from muon-to-electron conversion, which is coherent and gets a Z^2 enhancement



One-Slide Summary

- Large Background from a physics process with the same μ- we use for $\mu^- N \rightarrow e^- N$, called radiative muon capture
  - Probably need to look for GS→GS Transitions between initial, final state nuclei. Numerically, transitions to ground state not well known
  - Probably Al is not the best, need higher *Z* material like Ti, but that is natural direction for Mu2e anyway
- These are not “show-stoppers”. Work underway.

$\mu^- N \to e^+ N^*$ GS $\to$ GS in Mu2e

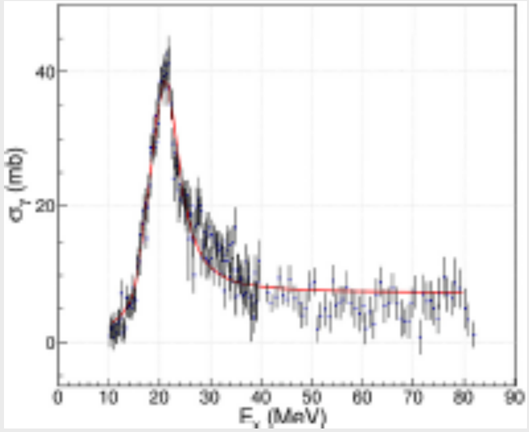
- mono-energetic positron at known energy If B is binding energy, R recoil (# for ^{27}Al to ^{27}Na)

$$
\begin{aligned}
E_{\mu^- e^+} &= m_\mu + M(A,Z) - [M(A,Z-2) + 2m_e - B_\mu - R(A)] \\
&= 92.31 \text{ MeV}
\end{aligned}
$$

- Mu2e acceptance at 92 MeV/c is relatively low; may need to turn down field, implying special run

Modeling $\mu^- N \rightarrow e^+ N^*$

Geib et al.
Physics Letters B 764 (2017) 157–162
and EXFOR database



- Usually imagine two possibilities:
  - transition to ground state
    - narrow
  - transition to giant dipole resonance (GDR)
    - very broad, 20 MeV → hard to do
  - and then since fraction to each not well known, quote separate limits

Calculating Signal: GS Transition Rate

- Ground State transitions are mono-energetic so can pick out positron.
- Last estimate:
  - P.C. Divari et al. / Nuclear Physics A 703 (2002) 409–431
  - Estimate 41% to GS; much larger than closure approximation estimates of GS rate

Background Processes

- Two that are relevant, and present different problems:
  - $\pi^- N \rightarrow \gamma N$ (Radiative Pion Capture = RPC)
  - $\mu^- N \rightarrow \gamma N$ (Radiative Muon Capture = RMC)
- The γ can convert either in the stopping target or undergo internal conversion (happen to be ~the same in Mu2e and COMET by coincidence).
  - RPC suppressed already, but RMC can't be: from μ^-
  - background e^+ for $\mu^- N \rightarrow e^+ N^*$

Calculating RMC Background: Closure Approximation

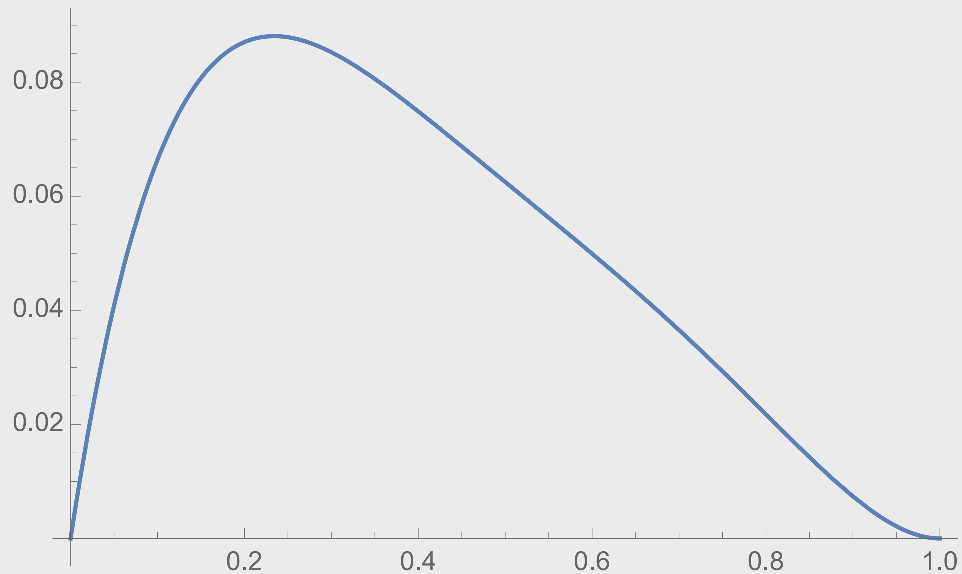
- Model transitions from an initial state to a single final state with a mean energy $\tilde{E}$ which is now a parameter

- So we also have a parameter k_{max} in the closure approximation

  - the biggest it could be is the kinematic limit from mass, recoil, and binding energy ~ 101.865 MeV/c^2 in Al

RMC Spectrum

- Theory: use the closure approximation to derive $N(x) \propto (1 - 2x + 2x^2) \times (1-x)^2$ where $x = k/k_{max}$



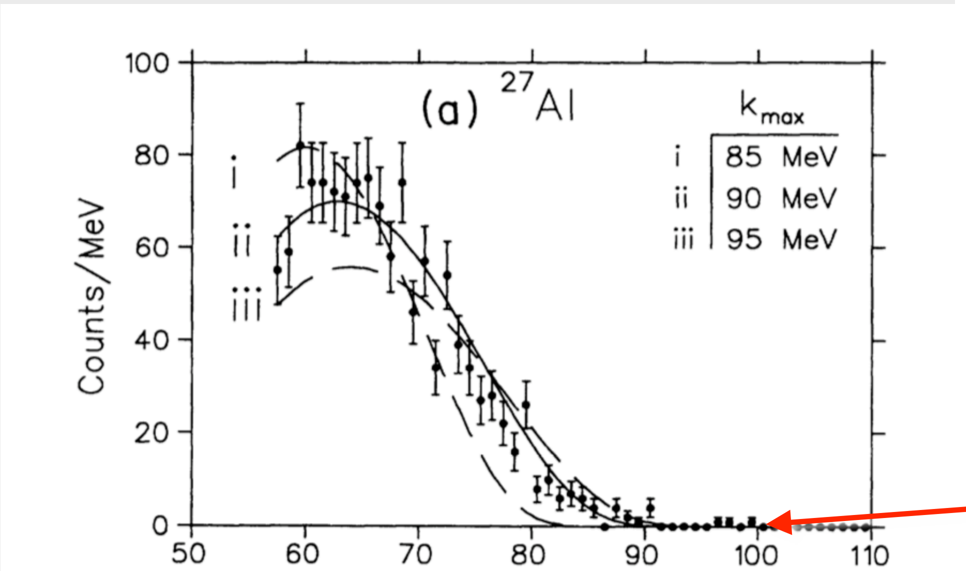
- Data?

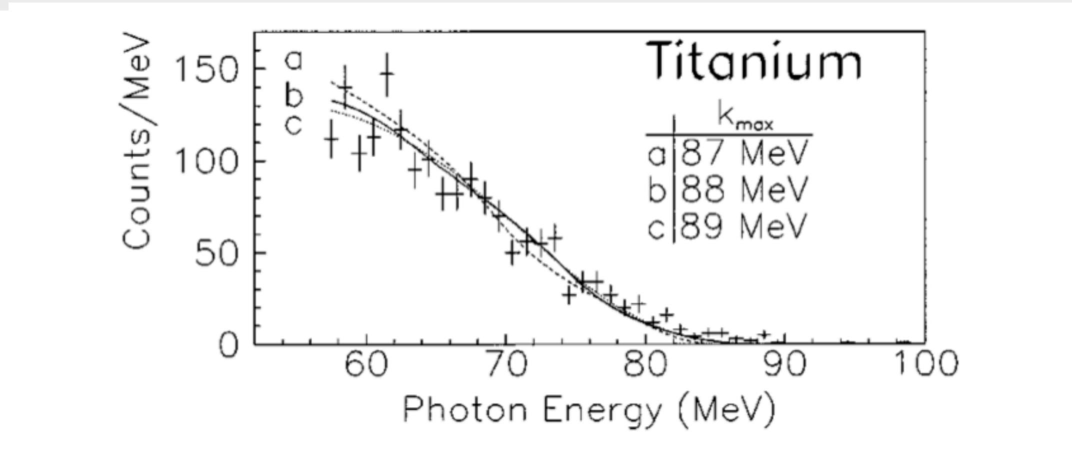
P. Christillin, Ref Th 2697, CERN

Armstrong et al., Phys Rev C46 No 3, 2853 (1992)

Bergsbuch et al., Phys Rev C59 No 5, 2853 (1999)

RMC Data





- How reliable is the closure approximation?
- Is there a tail?
- Can we minimize these uncertainties?
    - have signal region near endpoint of RMC spectrum

RMC vs Signal

- From Yeo et al. https://arxiv.org/pdf/1705.07464.pdf

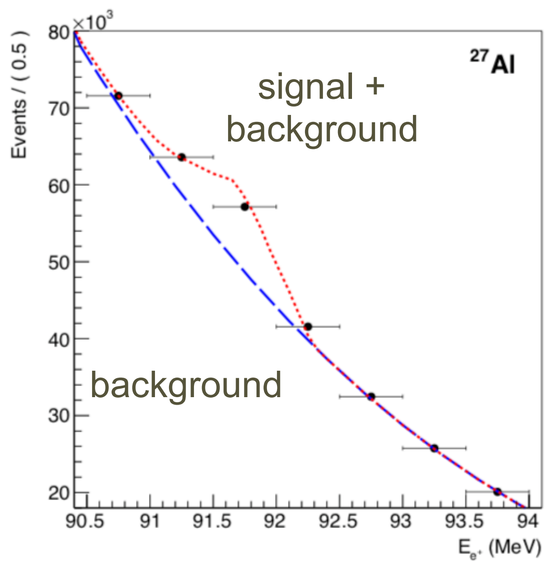
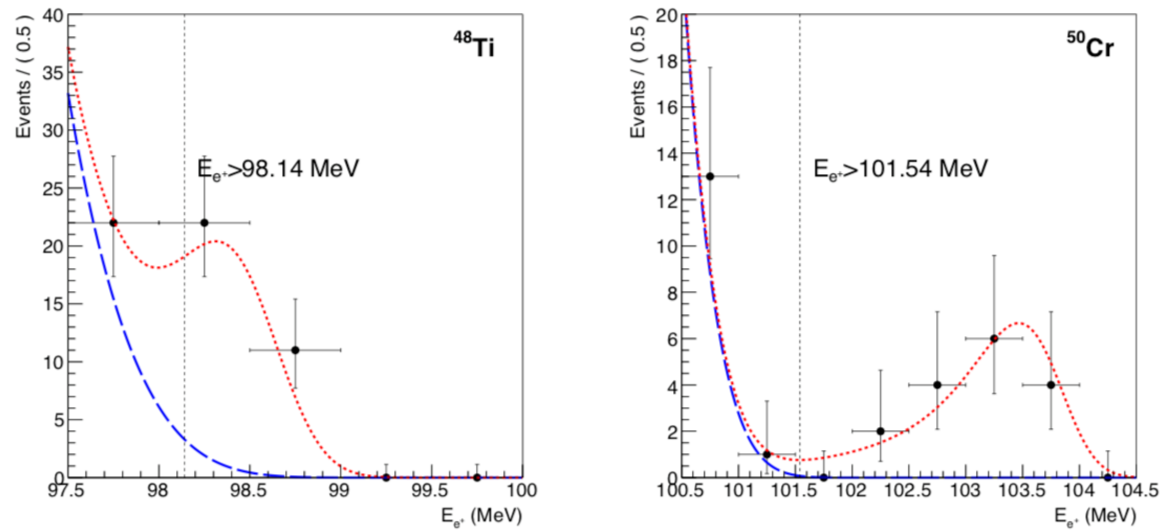


FIG. 1. Fitting result of the energy distribution of the $\mu^- - e^+$ signal (short dashed red line) stacked on the on-shell RMC photon background (long dashed blue line) from ^{27}Al muon-stopping target when $Br(\mu^- - e^+) = 1.7 \times 10^{-12}$ and $N_{\mu^-\text{stop}} = 10^{18}$. Black dots are pseudo data of positrons generated by the background and signal composite model.



kinematic k_{max} ;
just to indicate how much better you do at higher Z

Mu2e is working on making these plots in our simulations

Kaulard et al., Phys Lett B22(1998)

$\mu^- N \rightarrow e^+ N^*$ on Ti: Real Data

- SINDRUM actually used much older data on Ca to transfer to Ti
- Can't do better without measuring RMC and RPC
- Mu2e Simulations underway

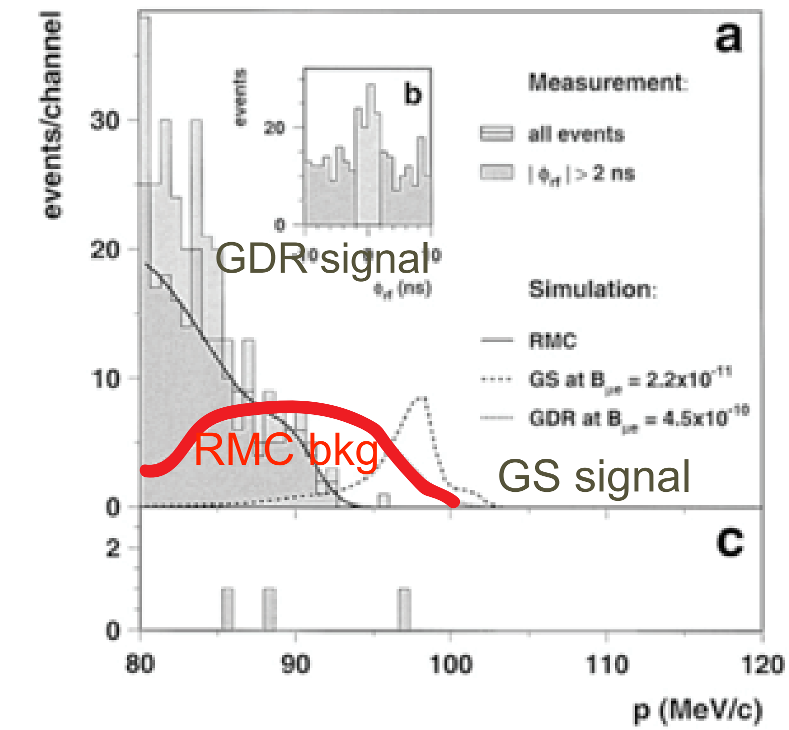


Fig. 2. Positron momentum distributions for measuring periods with (a,b) and without (c) muon beam. The measured distribution in part a is compared with the *GS* and *GDR* expectations for $\mu^- \rightarrow e^+$ conversion. The insert b shows the distribution of φ_{rf}, the decay time relative to the 50.63 MHz cyclotron frequency, exhibiting a peak caused by misidentified scattered beam electrons. The events from the grey region outside the peak have been interpreted as *RMC* events. Their momentum distribution is compared with the results from the *RMC* simulation discussed in the text.

Current Limits

- From SINDRUM-II, to ground state and GDR at 90% CL
  - other materials, just quoting Ti

$\mu^- + Ti \rightarrow e^+ Ca$	BR < 1.7×10^{-12}
$\mu^- + Ti \rightarrow e^+ Ca^*$	BR < 3.6×10^{-11}

Which Material?

- Don't want $k_{max,\ kinematic} > E_{e^+(GS)}$ to the extent possible

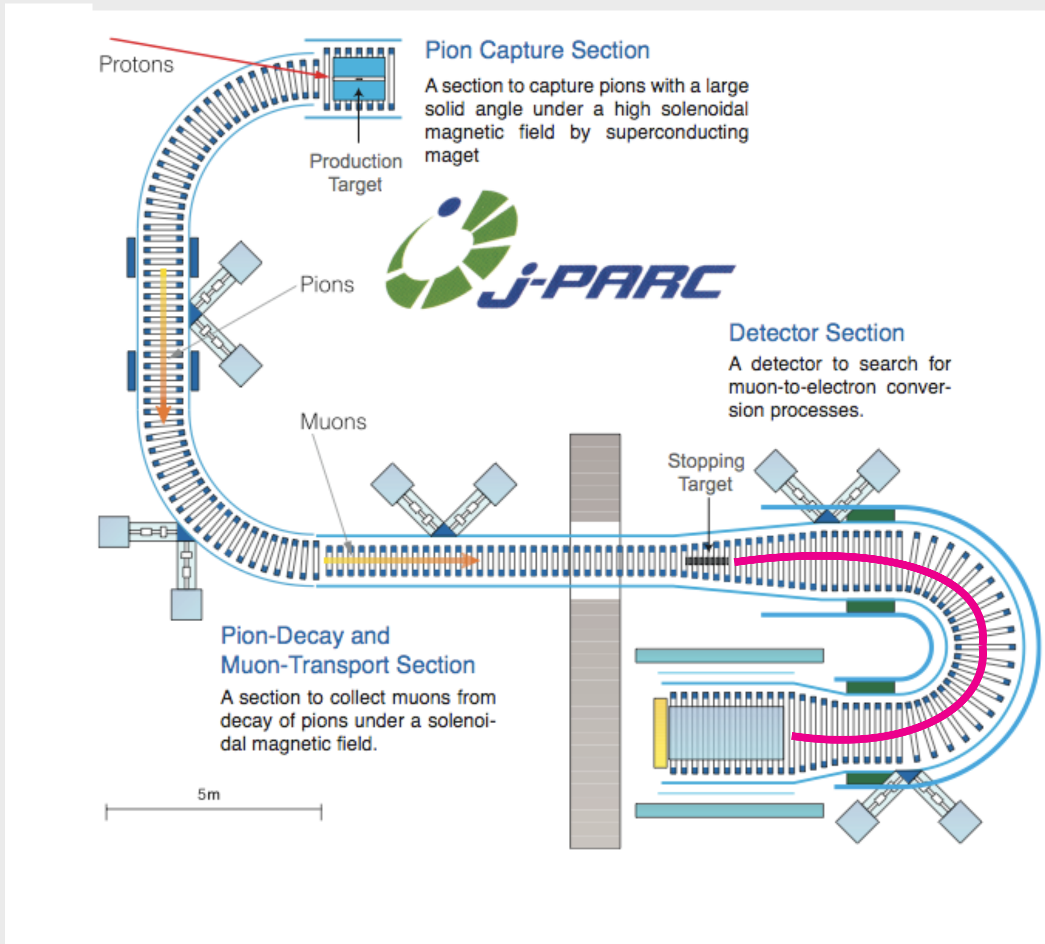
	rate > 57 MeV/ OMC	k_{max}	$k_{max,}$ kinematic	conversion energy
^{27}Al	$1.43 \pm 0.13 \times 10^{-5}$	90.0 ± 2.0	101.9	92.4
^{28}Si	$1.31 \pm 0.15 \times 10^{-5}$	89.4 ± 1.8	99.8	97.4
^{48}Ti	$1.31 \pm 0.15 \times 10^{-5}$	89.2 ± 2.0	99.7	98.9

- Al not best choice? Ti (or Si with active target) might be much better; Ti also good for $\mu^- N \rightarrow e^- N$ (later)

COMET and $\mu^- N \to e^+ N^*$

- 105 MeV conversion electron from $\mu^- N \to e^- N$
- e^+ follows opposite path
- have to reverse dipole portion of field in second section, so separate run is required

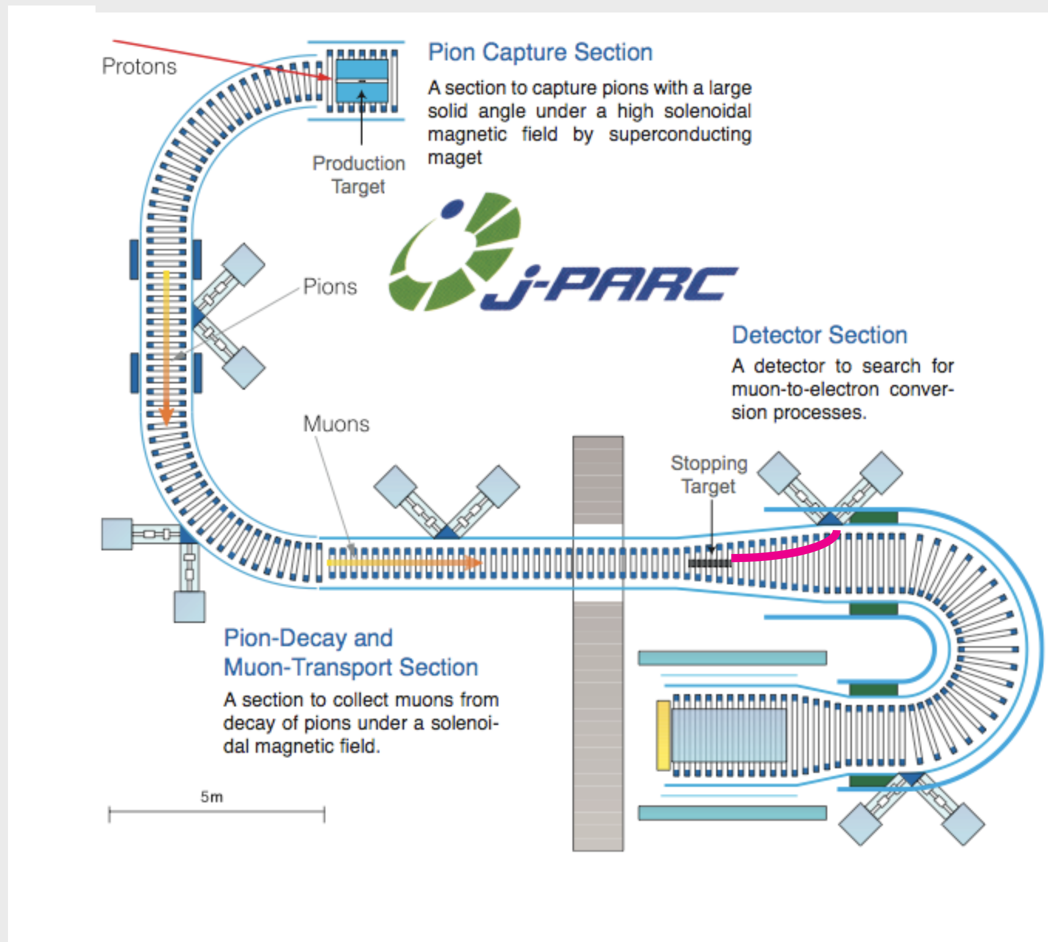
perhaps OK in Stage 1 where detector charge-symmetric



COMET and $\mu^- N \to e^+ N^*$

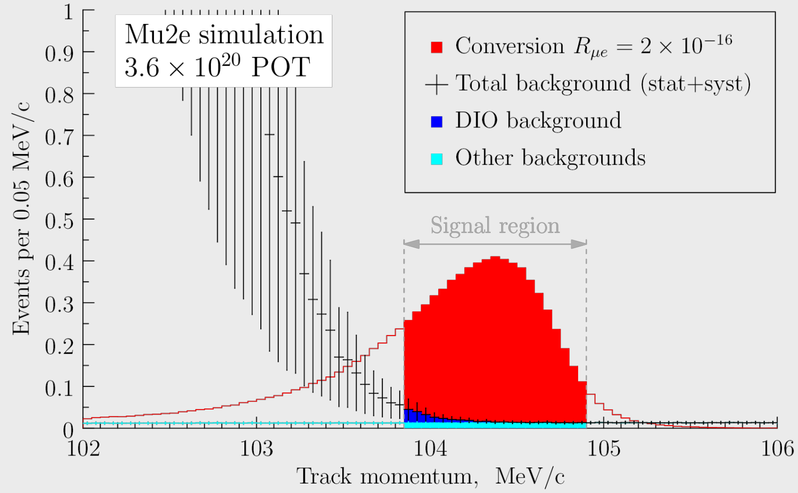
- 105 MeV conversion electron from $\mu^- N \to e^- N$
- e^+ follows opposite path
- have to reverse dipole portion of field in second section, so separate run is required

perhaps OK in Stage 1 where detector charge-symmetric



Mu2e Summary

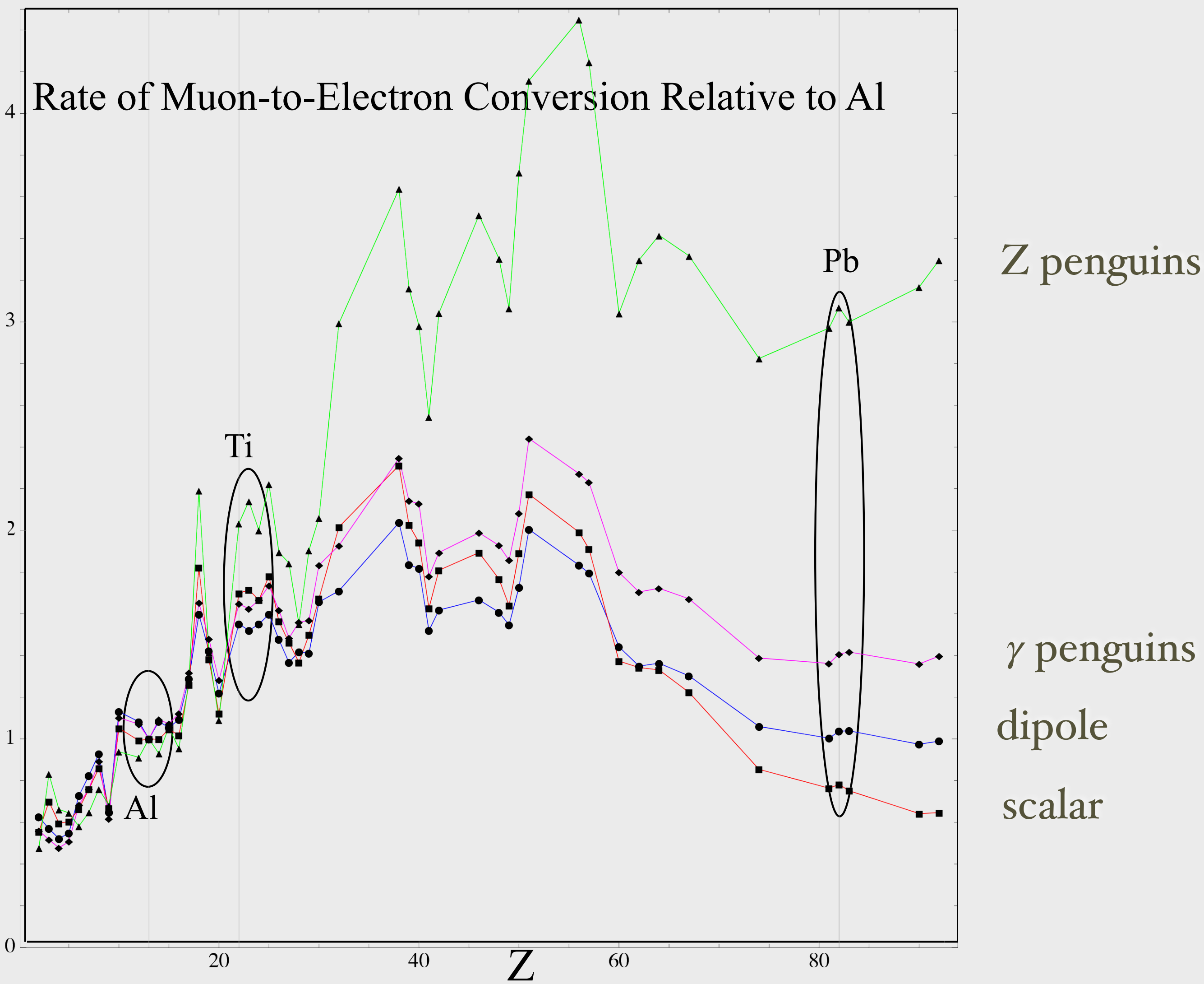
- $\mu^- Al \rightarrow e^- Al$
  - SES ~ 3×10^{-17}
  - 90% CL ~ 8×10^{-17}
  - 5σ discovery ~ 2×10^{-16}
  - Run for 3 years; physics data starting 2022
- Upgrades in intensity and changes in material already under examination



Mu2e Upgrades

- Next Step in cLFV Program:

Upgrades and Z-Dependence



5% measurement on Al/Ti needed to see split

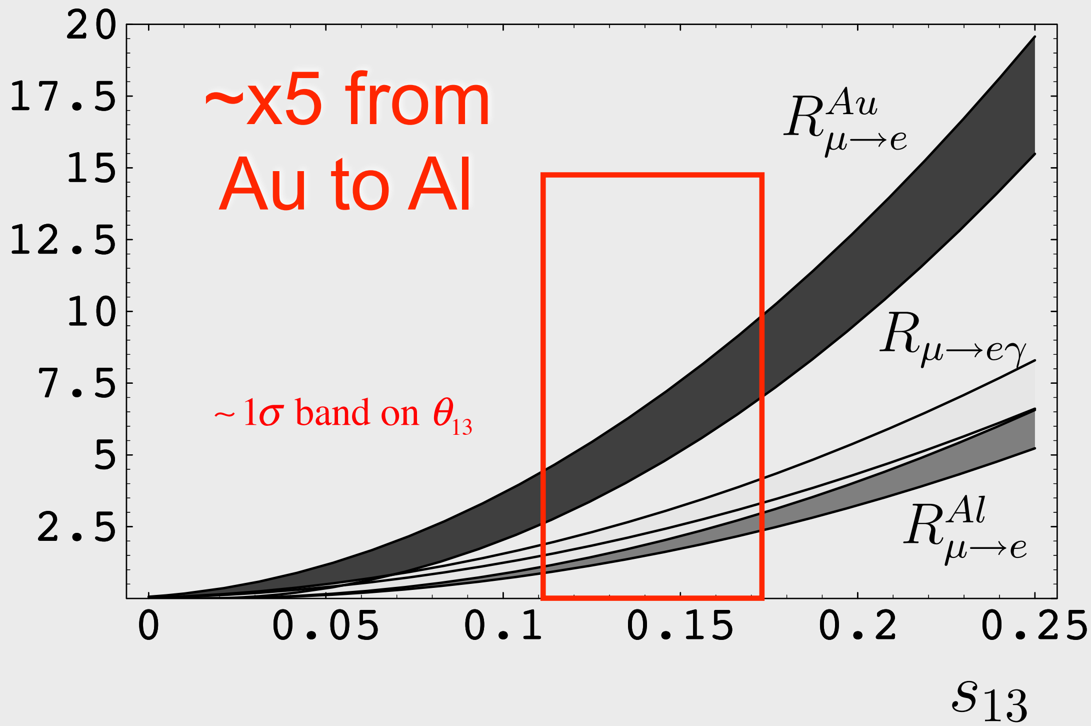
- Different Operators have different Z-dependence
- Combine depending on the particular model

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

Relationship to Neutrinos (aka neutral leptons)

- want as high a *Z* as possible

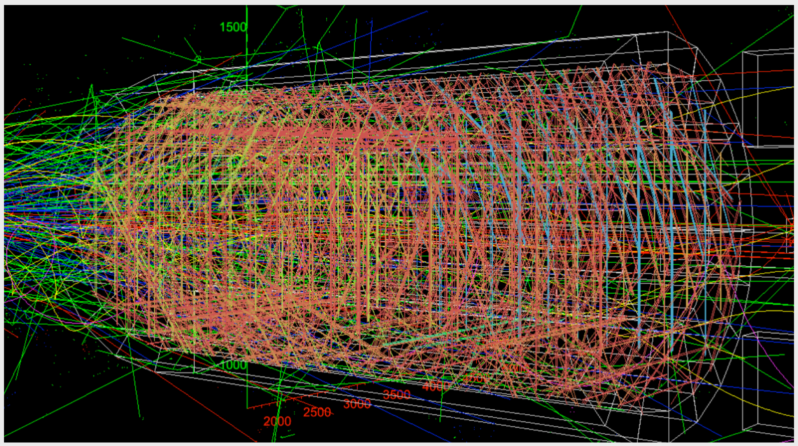
PDG 2017



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

Choice of Z for Upgrade

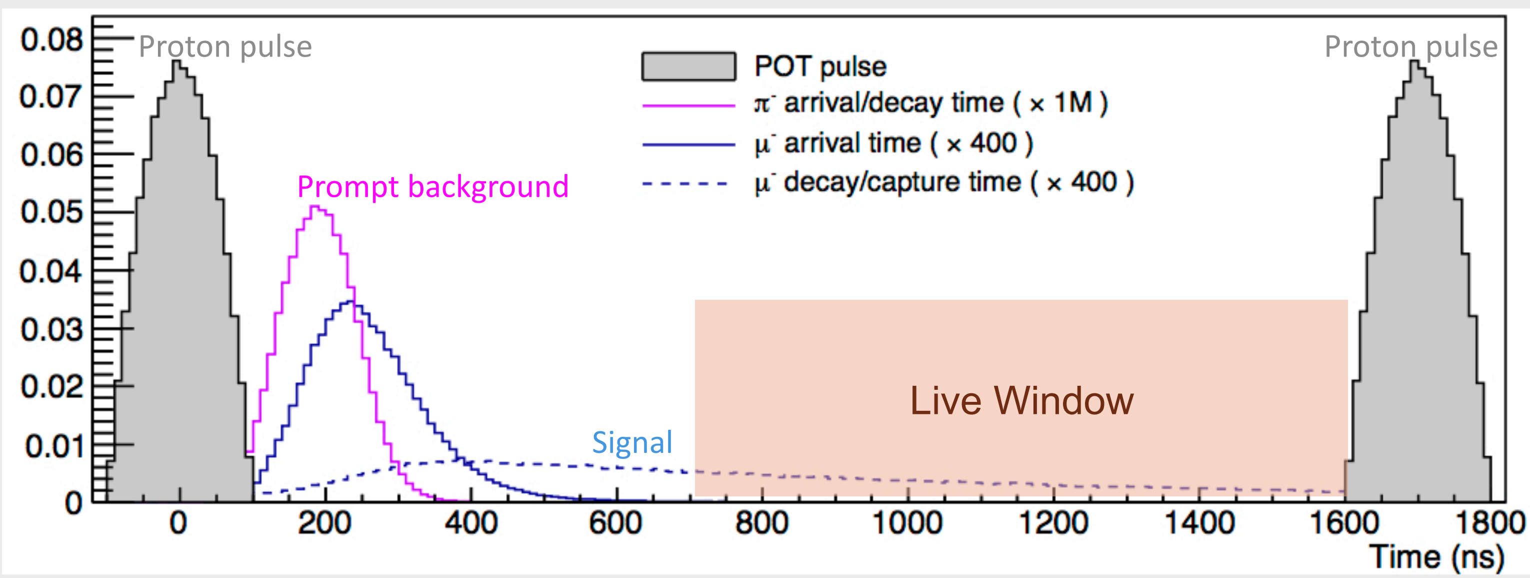
- What Sets Material Choice? Lifetime:



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

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

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



Mu2e Upgrades

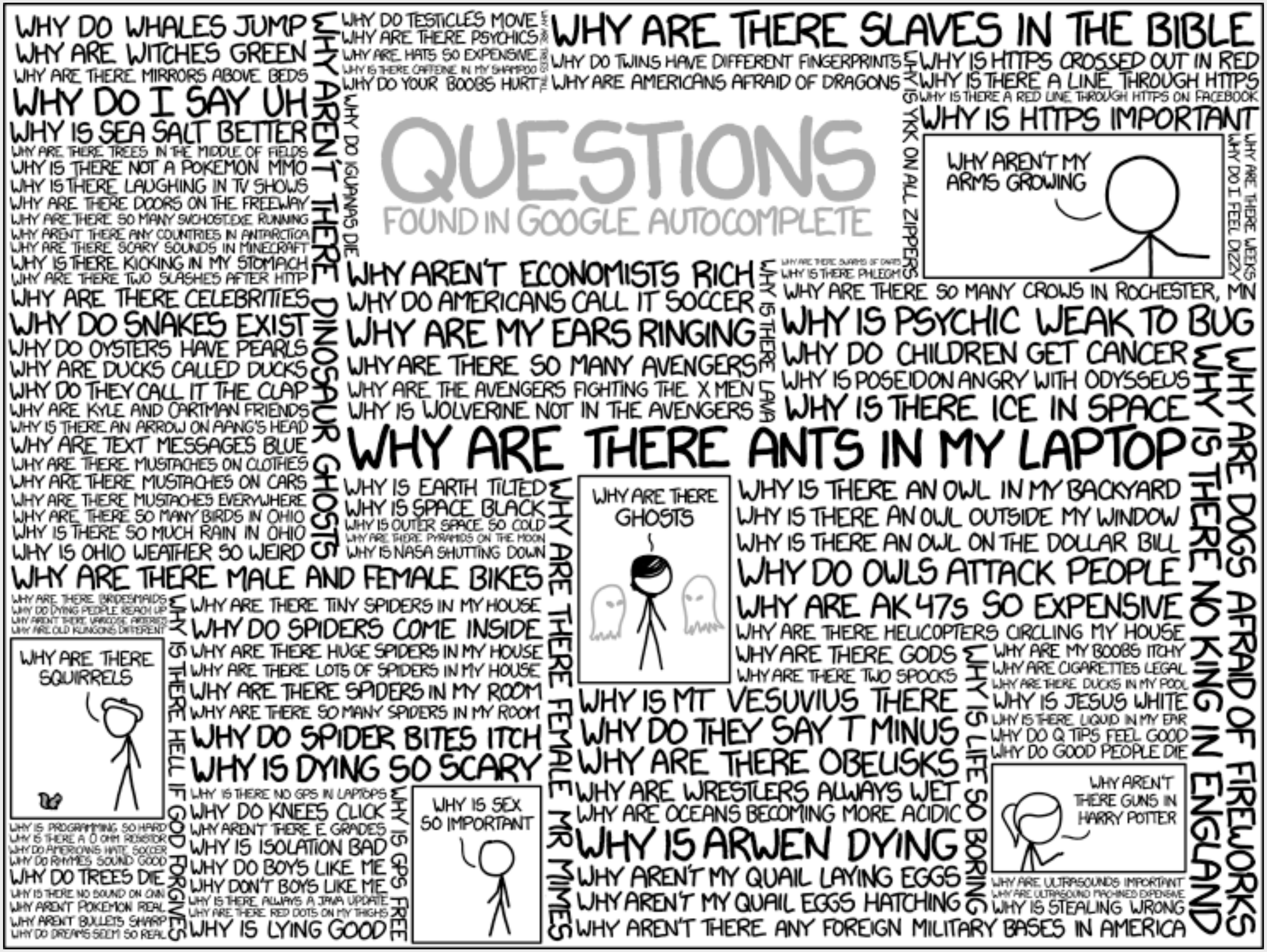
- Studies for x10 improvement with Ti look promising and will be continued; EOI written (1307.1168 and EOI at 1802.02599)
- We need detector and solenoid improvements
  - may need new production solenoid to handle lower energy beam and higher power.
- FNAL PIP-II natural for both pulsed and non-pulsed CLFV, could do $\mu^- N \rightarrow e^\pm N$, $\mu \rightarrow e\gamma$, $\mu \rightarrow 3e$, $\mu^- e^- \rightarrow e^- e^-$ at one facility

Advertisement

- 3rd International Conference on Charged Lepton Flavor Violation
  - we cover everything in CLFV: μ, τ, B, talks split between theory and experiment
  - three days, plenary only (w/posters)
  - 17-19 June 2019 at Kyushu U.
- For examples:
  - http://clfv2013.le.infn.it (referenced by Emilie P.)
  - https://indico.fnal.gov/event/11128/ (Julian H.)

Conclusions

- Mu2e will:
  - Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude, x10 in mass reach ($R_{\mu e}$ < 8×10^{-17} @ 90% C.L.)
  - Discover unambiguous proof of new physics or
  - Set powerful constraints on a wide variety of models
- Mu2e will therefore both complement LHC results and independently probe up to 10^4 TeV/c^2
- COMET and DeeMe in progress
- Upgrades already under consideration with a new muon CLFV program being mapped out


QUESTIONS
FOUND IN GOOGLE AUTOCOMPLETE
WHY DO WHALES JUMP
WHY ARE WITCHES GREEN
WHY ARE THERE MIRRORS ABOVE BEDS
WHY DO I SAY UH
WHY IS SEA SALT BETTER
WHY ARE THERE TREES IN THE MIDDLE OF FIELDS
WHY IS THERE NOT A POKEMON MMO
WHY IS THERE LAUGHING IN TV SHOWS
WHY ARE THERE DOORS ON THE FREEWAY
WHY AREN'T THERE ANY COUNTRIES IN ANTARCTICA
WHY ARE THERE SCARY SOUNDS IN MINECRAFT
WHY IS THERE KICKING IN MY STOMACH
WHY ARE THERE TWO SLASHES AFTER HTTP
WHY ARE THERE CELEBRITIES
WHY DO SNAKES EXIST
WHY DO OYSTERS HAVE PEARLS
WHY ARE DUCKS CALLED DUCKS
WHY DO THEY CALL IT THE CLAP
WHY ARE KYLE AND CARTMAN FRIENDS
WHY IS THERE AN ARROW ON AANG'S HEAD
WHY ARE TEXT MESSAGES BLUE
WHY ARE THERE MUSTACHES ON CLOTHES
WHY ARE THERE MUSTACHES ON CARS
WHY ARE THERE MUSTACHES EVERYWHERE
WHY ARE THERE SO MANY BIRDS IN OHIO
WHY IS THERE SO MUCH RAIN IN OHIO
WHY IS OHIO WEATHER SO WEIRD
WHY ARE THERE MALE AND FEMALE BIKES
WHY AREN'T THERE DINOSAUR GHOSTS
WHY DO IGUANAS DIE
WHY DO TESTICLES MOVE
WHY ARE THERE PSYCHICS
WHY ARE HATS SO EXPENSIVE
WHY DO YOUR BOOBS HURT
WHY ARE THERE SLAVES IN THE BIBLE
WHY DO TWINS HAVE DIFFERENT FINGERPRINTS
WHY ARE AMERICANS AFRAID OF DRAGONS
WHY IS YKK ON ALL ZIPPERS
WHY IS HTTPS CROSSED OUT IN RED
WHY IS THERE A LINE THROUGH HTTPS
WHY IS THERE A RED LINE THROUGH HTTPS ON FACEBOOK
WHY IS HTTPS IMPORTANT
WHY AREN'T MY ARMS GROWING
WHY ARE THERE WEEKS
WHY DO I FEEL DIZZY
WHY AREN'T ECONOMISTS RICH
WHY DO AMERICANS CALL IT SOCCER
WHY ARE MY EARS RINGING
WHY ARE THERE SO MANY AVENGERS
WHY ARE THE AVENGERS FIGHTING THE X MEN
WHY IS WOLVERINE NOT IN THE AVENGERS
WHY IS THERE LAVA
WHY ARE THERE SO MANY CROWS IN ROCHESTER, MN
WHY IS PSYCHIC WEAK TO BUG
WHY DO CHILDREN GET CANCER
WHY IS POSEIDON ANGRY WITH ODYSSEUS
WHY IS THERE ICE IN SPACE
WHY ARE THERE ANTS IN MY LAPTOP
WHY IS THERE NO KING IN ENGLAND
WHY ARE DOGS AFRAID OF FIREWORKS
WHY IS EARTH TILTED
WHY IS SPACE BLACK
WHY IS OUTER SPACE SO COLD
WHY IS NASA SHUTTING DOWN
WHY ARE THERE FEMALE MR MIMES
WHY ARE THERE GHOSTS
WHY IS THERE AN OWL IN MY BACKYARD
WHY IS THERE AN OWL OUTSIDE MY WINDOW
WHY IS THERE AN OWL ON THE DOLLAR BILL
WHY DO OWLS ATTACK PEOPLE
WHY ARE AK 47s SO EXPENSIVE
WHY ARE THERE HELICOPTERS CIRCLING MY HOUSE
WHY ARE THERE GODS
WHY ARE THERE TWO SPOCKS
WHY IS LIFE SO BORING
WHY ARE MY BOOBS ITCHY
WHY ARE CIGARETTES LEGAL
WHY ARE THERE DUCKS IN MY POOL
WHY IS JESUS WHITE
WHY IS THERE LIQUID IN MY EAR
WHY DO Q TIPS FEEL GOOD
WHY DO GOOD PEOPLE DIE
WHY AREN'T THERE GUNS IN HARRY POTTER
WHY ARE ULTRASOUNDS IMPORTANT
WHY IS STEALING WRONG
WHY IS MT VESUVIUS THERE
WHY DO THEY SAY T MINUS
WHY ARE THERE OBELISKS
WHY ARE WRESTLERS ALWAYS WET
WHY ARE OCEANS BECOMING MORE ACIDIC
WHY IS ARWEN DYING
WHY AREN'T MY QUAIL LAYING EGGS
WHY AREN'T MY QUAIL EGGS HATCHING
WHY AREN'T THERE ANY FOREIGN MILITARY BASES IN AMERICA
WHY ARE THERE TINY SPIDERS IN MY HOUSE
WHY DO SPIDERS COME INSIDE
WHY ARE THERE HUGE SPIDERS IN MY HOUSE
WHY ARE THERE LOTS OF SPIDERS IN MY HOUSE
WHY ARE THERE SPIDERS IN MY ROOM
WHY ARE THERE SO MANY SPIDERS IN MY ROOM
WHY DO SPIDER BITES ITCH
WHY IS DYING SO SCARY
WHY IS THERE HELL IF GOD FORGIVES
WHY ARE THERE SQUIRRELS
WHY IS SEX SO IMPORTANT
WHY IS GPS FREE
WHY DO KNEES CLICK
WHY AREN'T THERE E GRADES
WHY IS ISOLATION BAD
WHY DO BOYS LIKE ME
WHY DON'T BOYS LIKE ME
WHY IS LYING GOOD
WHY IS PROGRAMMING SO HARD
WHY DO AMERICANS HATE SOCCER
WHY DO RHYMES SOUND GOOD
WHY DO TREES DIE
WHY AREN'T POKEMON REAL
WHY AREN'T BULLETS SHARP
WHY DO DREAMS SEEM SO REAL