A New Charged Lepton Flavor Violation Experiment: Muon-Electron Conversion at Sensitivity < 10^{-16}

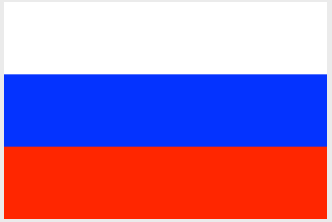
R. Bernstein
Fermilab

for the Mu2e Collaboration

Mu2e 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
University of Massachusetts, Amherst
Lawrence Berkeley National Laboratory
Northern Illinois University
Northwestern University
Pacific Northwest National Laboratory
Rice University
University of Virginia
University of Washington, Seattle

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



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

~130 collaborators

What is μe Conversion?

muon converts to electron in the field of a nucleus

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

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

- Standard Model Background of 10^{-54}
- Charged Lepton Flavor Violation (CLFV)
  - can measure a signal with SES of 2.3×10^{-17}
- Related Processes: μ or $\tau \rightarrow e\gamma$, $\tau \rightarrow 3l$, $K_L \rightarrow \mu e$, and more

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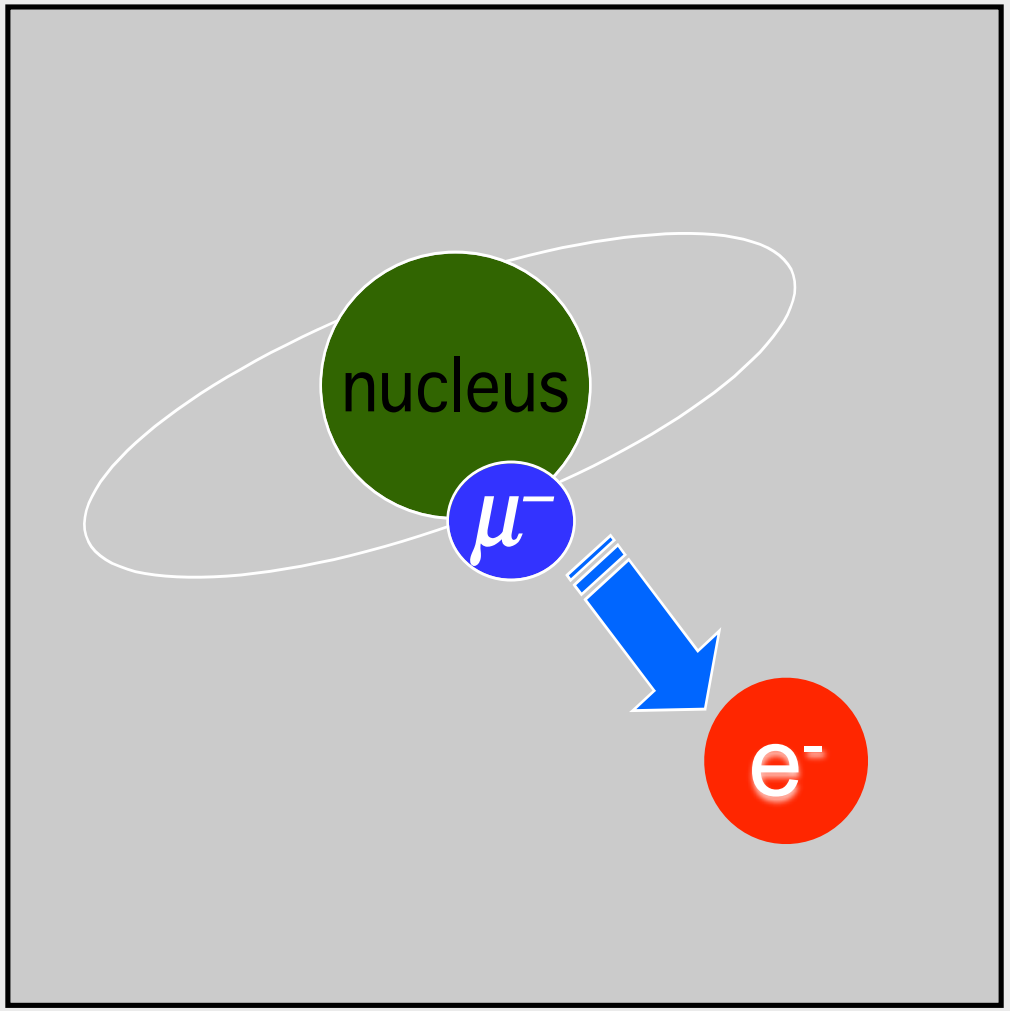
Experimental Signal

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

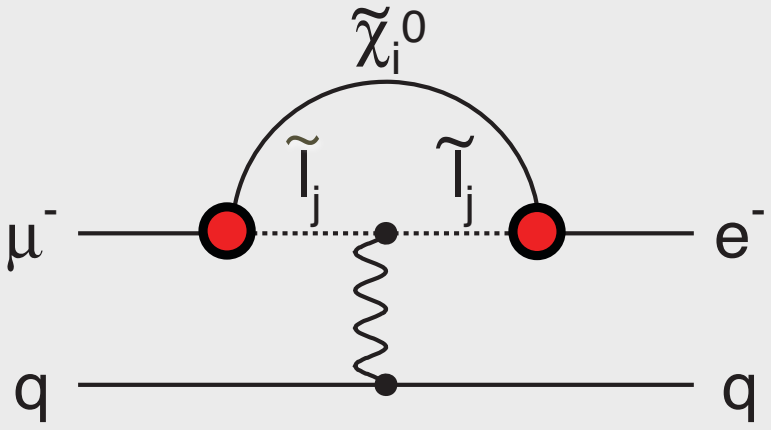
- A Single Monoenergetic Electron
- If *N* = Al, E_e = 105. MeV
  - electron energy depends on Z
- Nucleus coherently recoils off outgoing electron, no breakup



LFV, SUSY and the LHC

Supersymmetry

rate ~ 10^{-15}



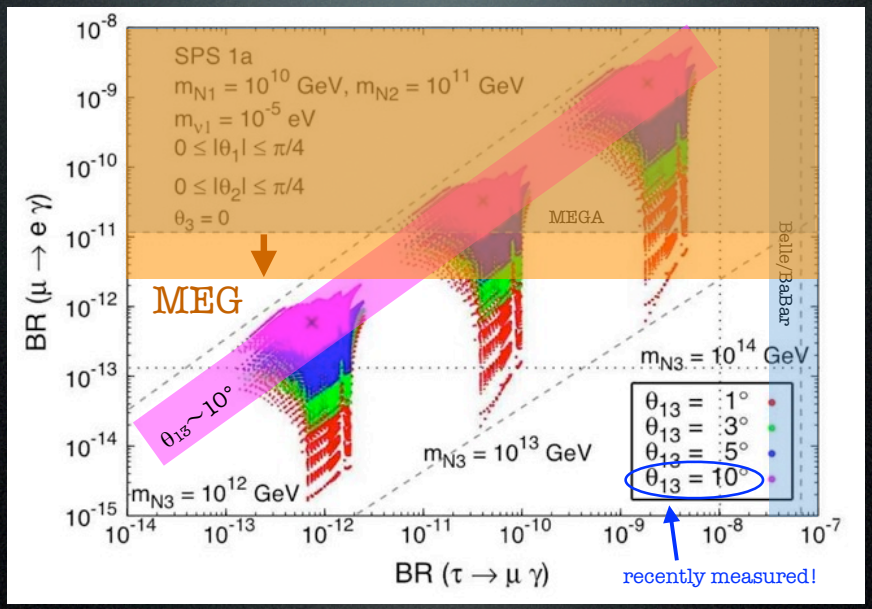
Access SUSY through loops:

signal of Terascale at LHC implies ~40 event signal / <0.5 bkg in this experiment

One Slide On Specific Models

Implication of Large θ_{13}

→ larger BR(μ→eγ)



S. Antusch et al. JHEP11 (2006) 090

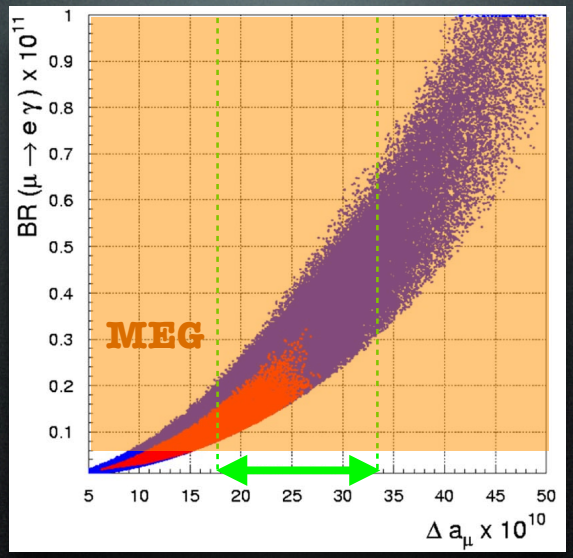
these are recent $\mu \to e\gamma$
but $\mu N \to eN$
typically x10 better

Combining MEG at PSI

with $\tau \to \mu\gamma$

with current g-2

muon (g-2) anomaly



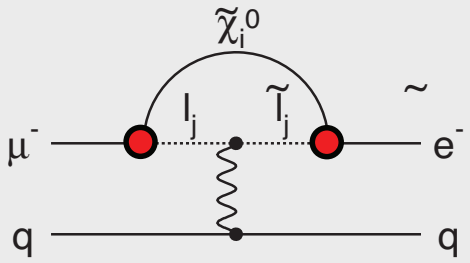
G.Isidori et al. PRD75, 115019

muon's anomalous magnetic moment

Contributions to μe Conversion

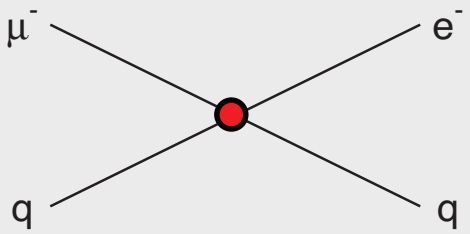
Supersymmetry

rate ~ 10^{-15}



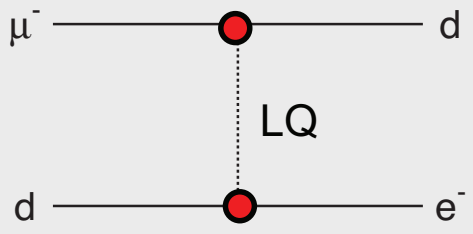
Compositeness

Λ_c ~ 3000 TeV



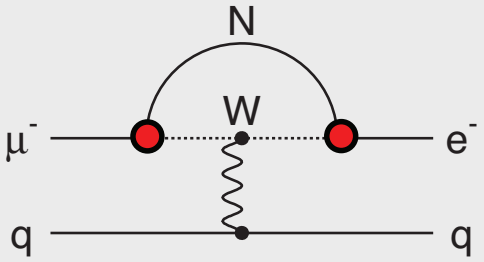
Leptoquark

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



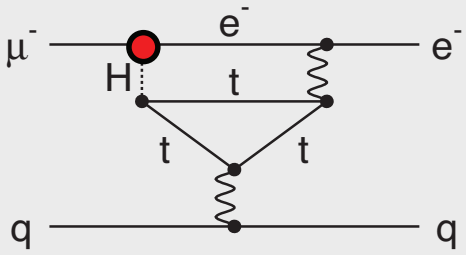
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



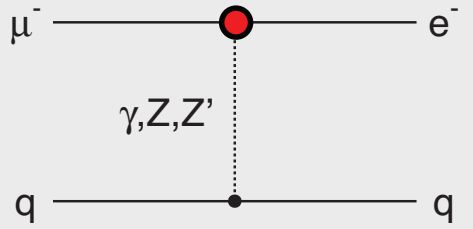
Second Higgs Doublet

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



Heavy Z' Anomal. Z Coupling

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

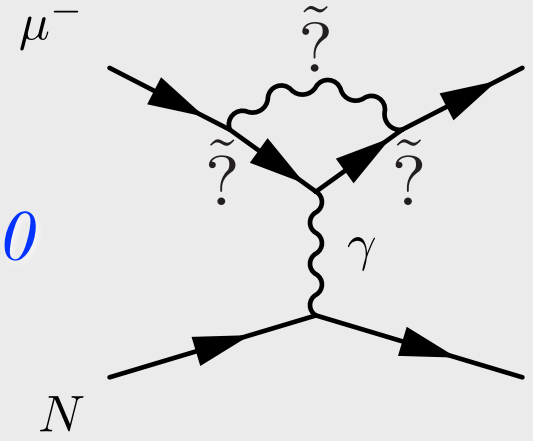


also see Flavour physics of leptons and dipole moments, arXiv:0801.1826 ;
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:10.1146/annurev.nucl.58.110707.171126 ;

"Model-Independent" Form

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

"Loops"



$\kappa = 0$

Supersymmetry and Heavy Neutrinos

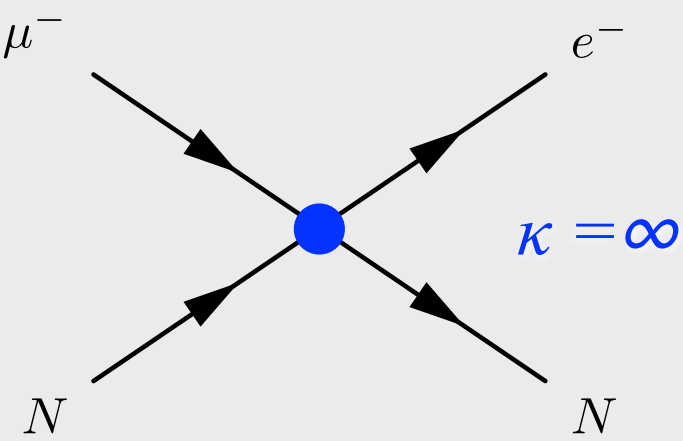
Contributes to $\mu \to e\gamma$

(just imagine the photon is real)

mass scale Λ

κ

"Contact Terms"



$\kappa = \infty$

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

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

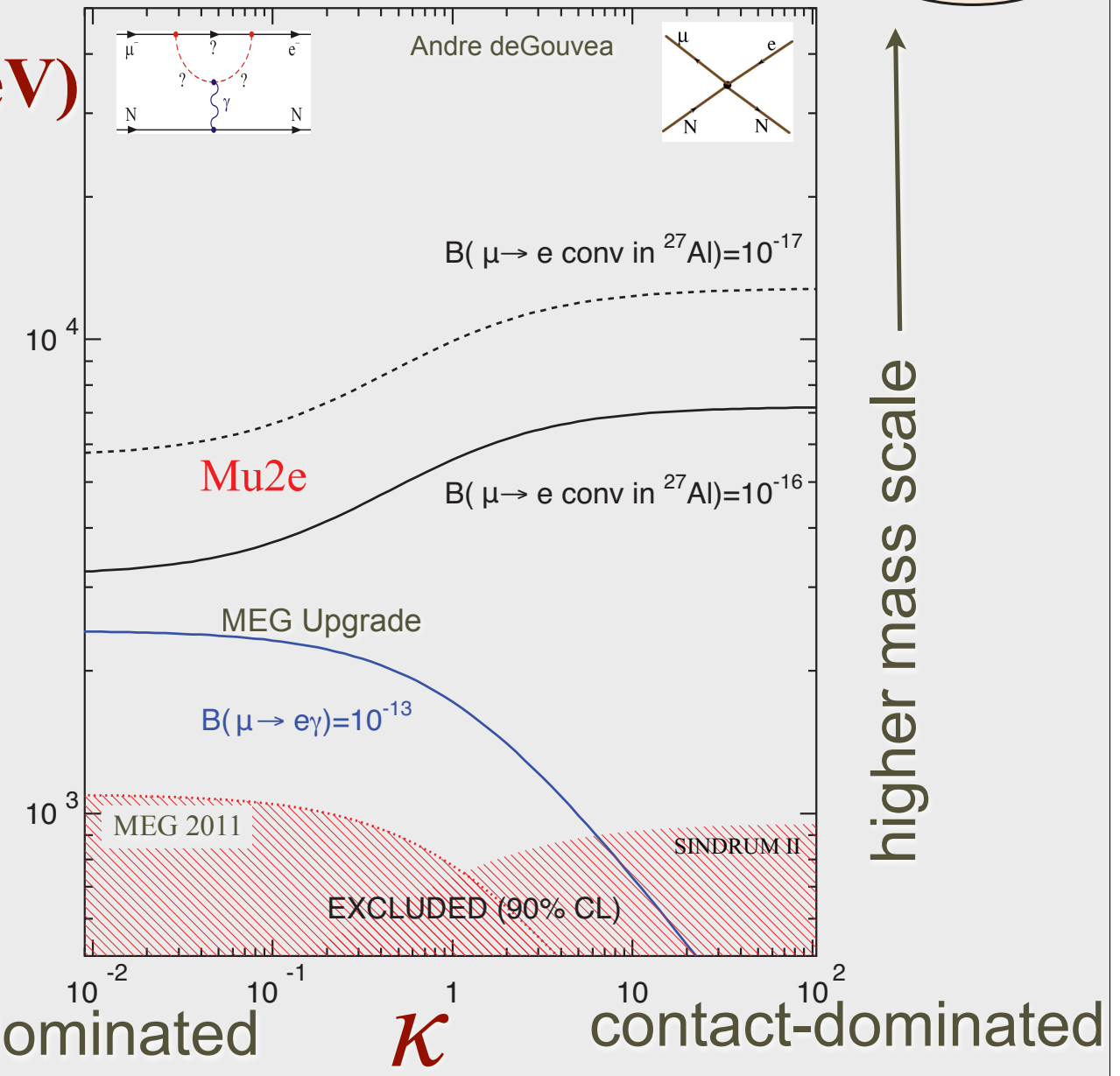
Quantitative Comparison?

μe Conversion and μ→eγ

1) *Mass Reach to ~10⁴ TeV/c²*

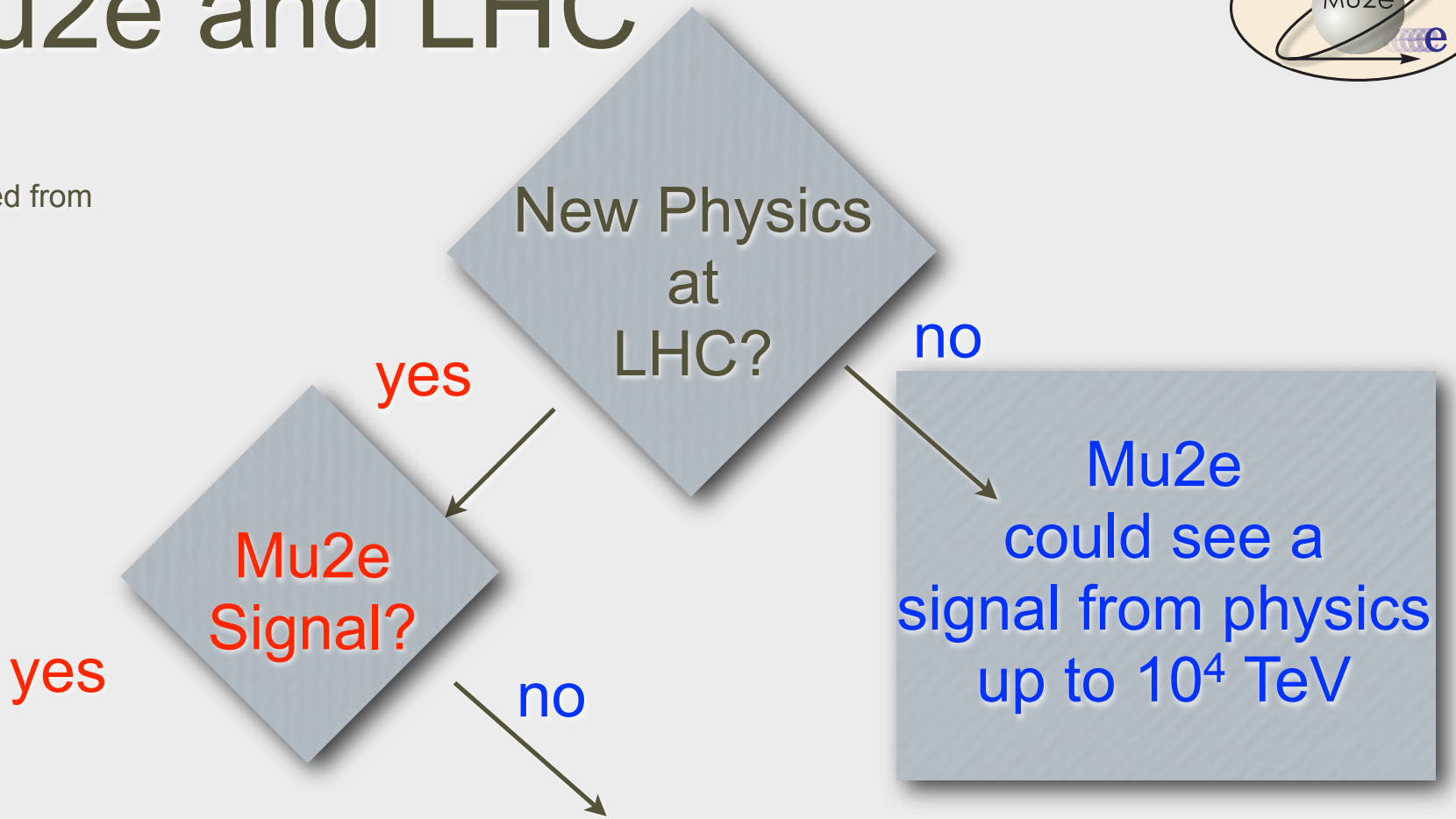
2) *roughly equal to MEG upgrade in loop-dominated physics*

3) *Mu2e is a discovery experiment*



Mu2e and LHC

gratefully adapted from
R. Ray



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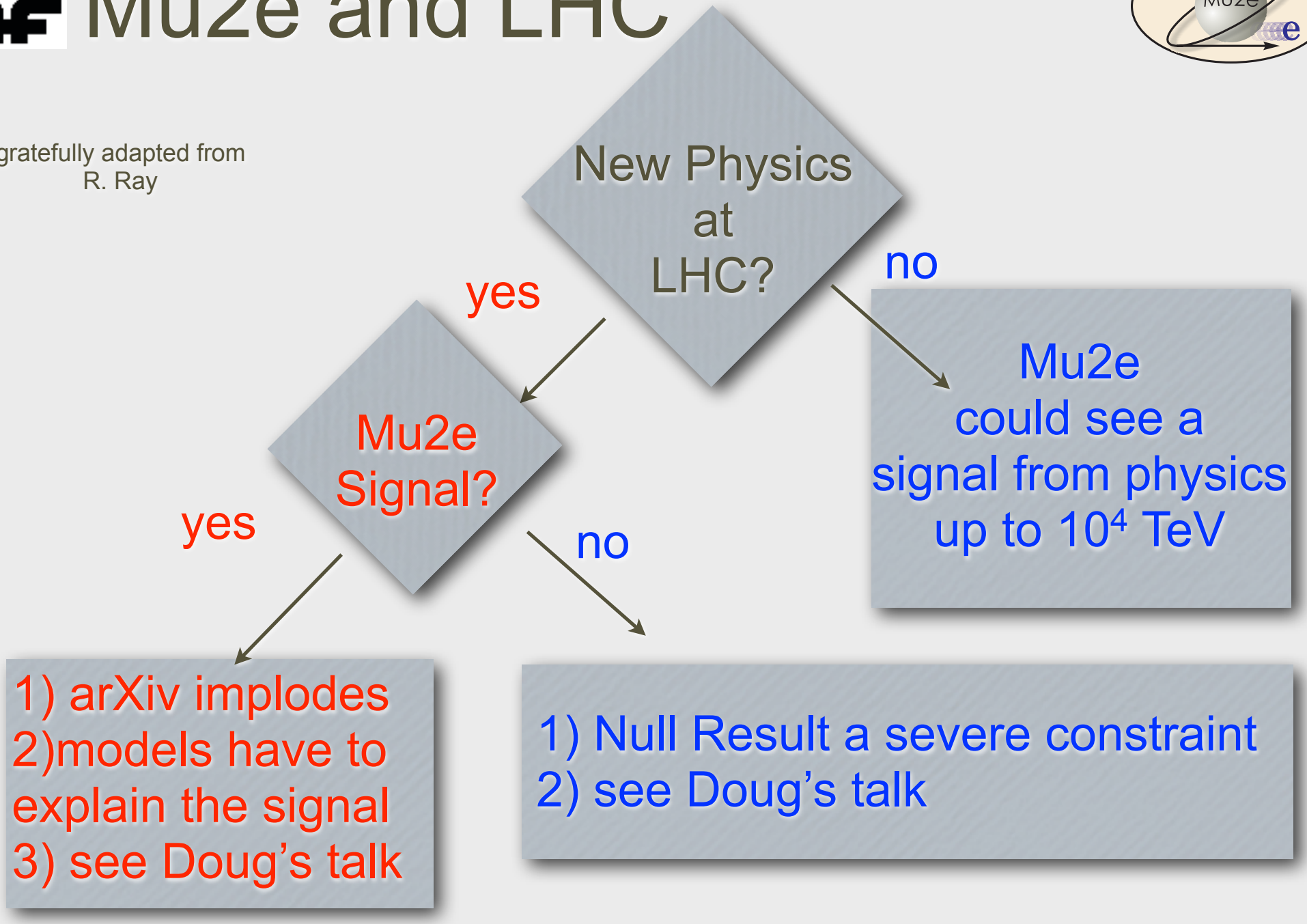
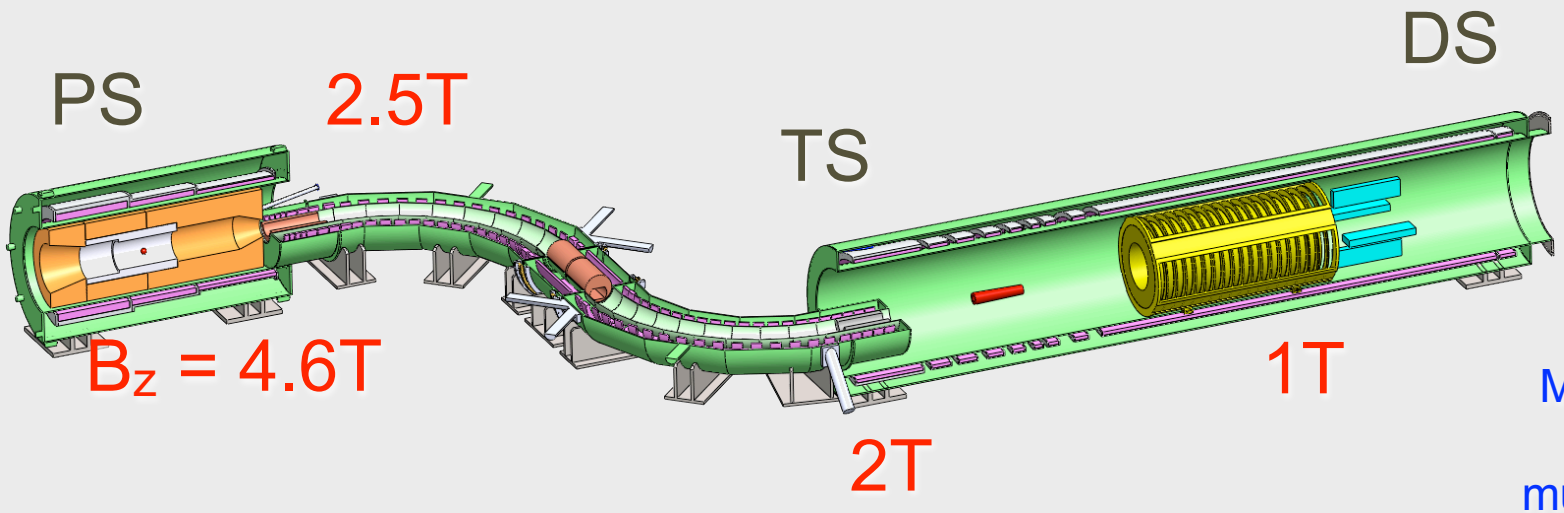
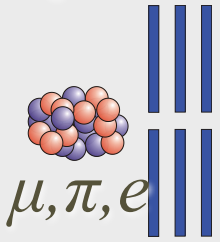


Mu2e Muon Beam: Three Solenoids and Gradient



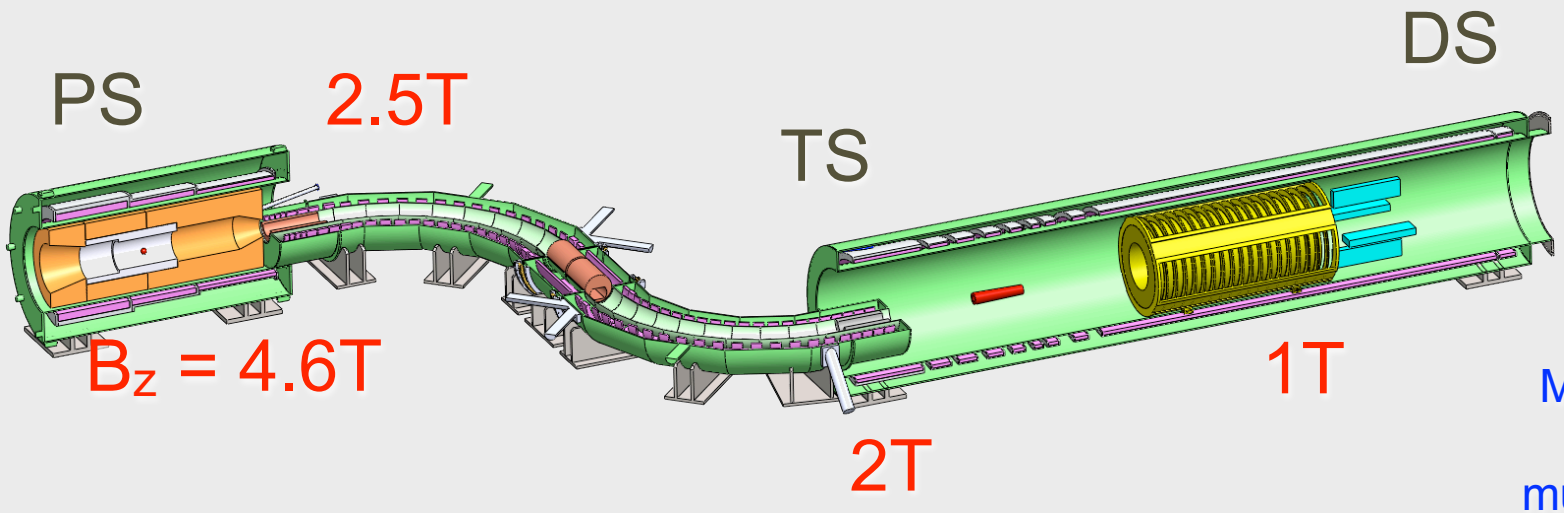
Muon Momentum ~ 50 MeV/c: muons range out in stopping foils



- Target protons at 8 GeV inside superconducting solenoid
- Capture muons and guide through S-shaped region to Al stopping target
- Gradient fields used to collect and transport muons

Mu2e Muon Beam: Three Solenoids and Gradient

4.6T ⟶ B-field gradient ⟶ 1T



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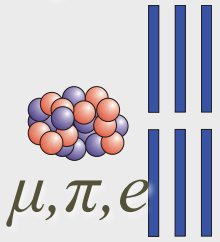

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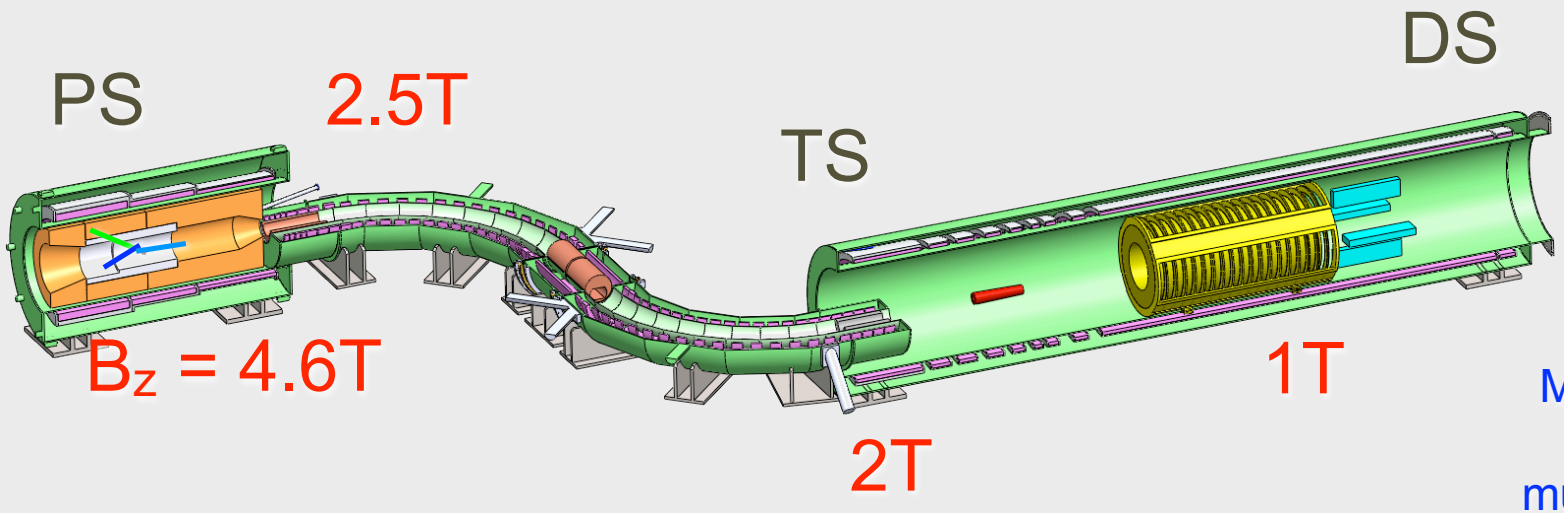

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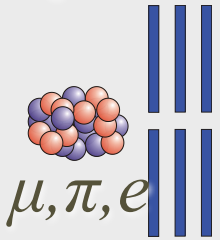

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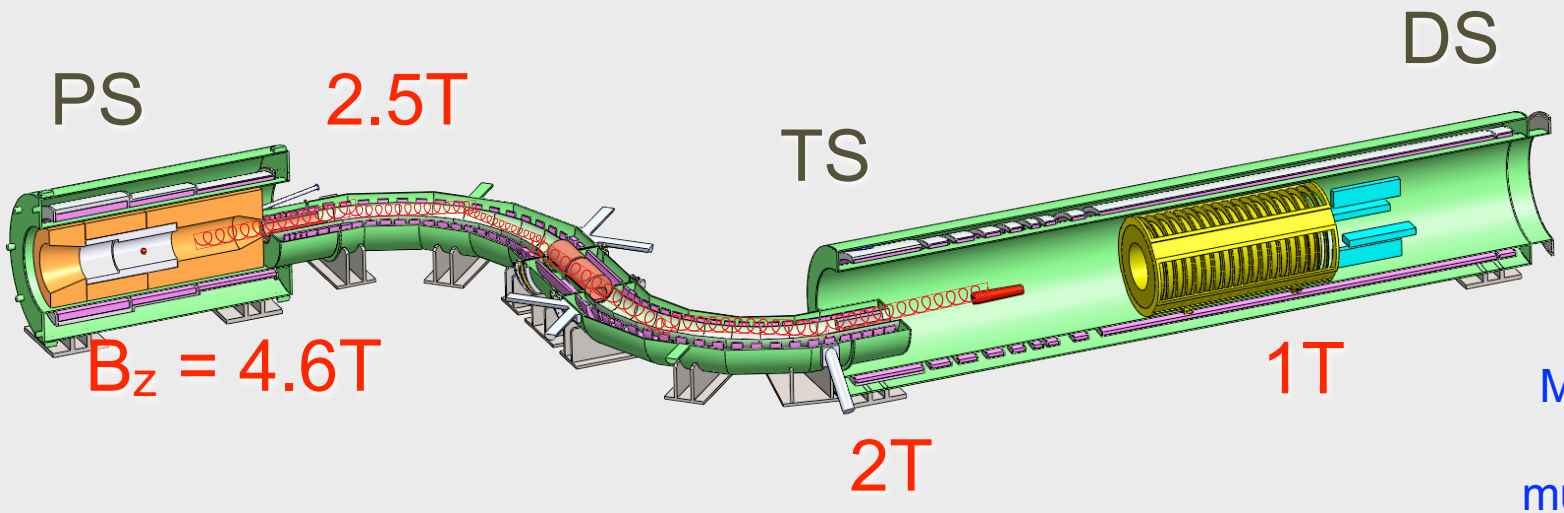

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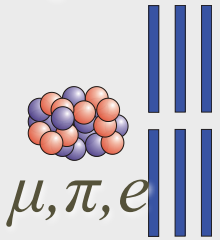

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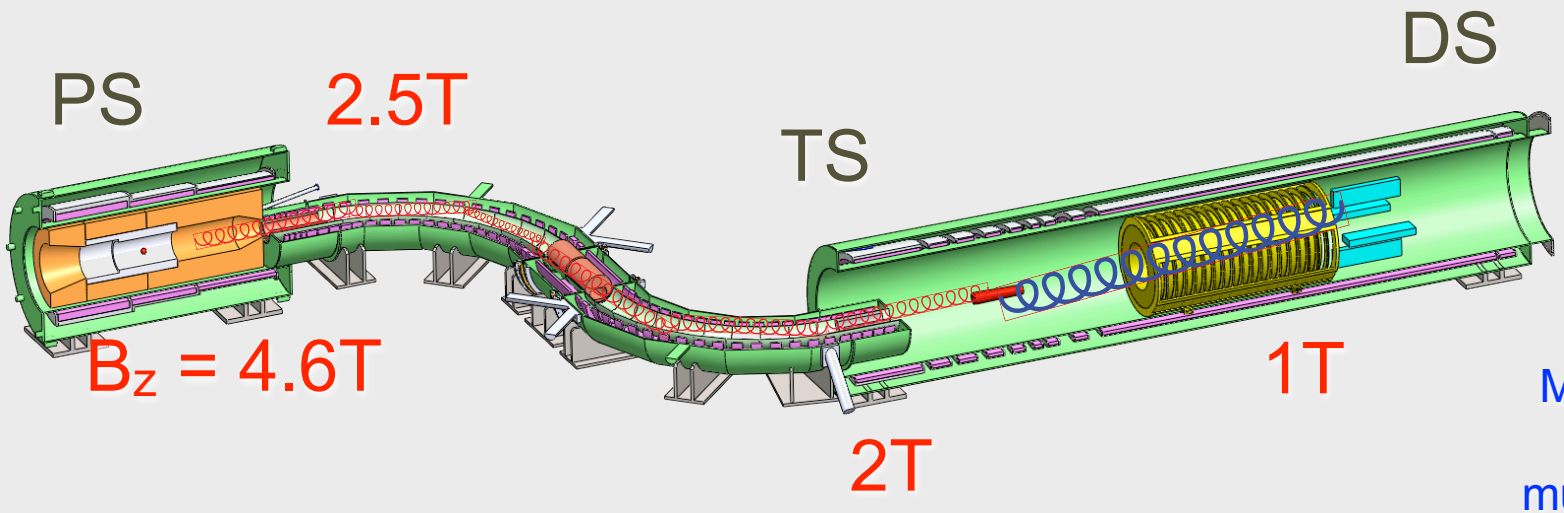

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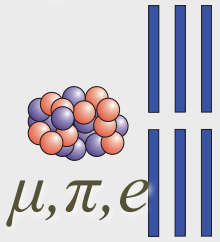

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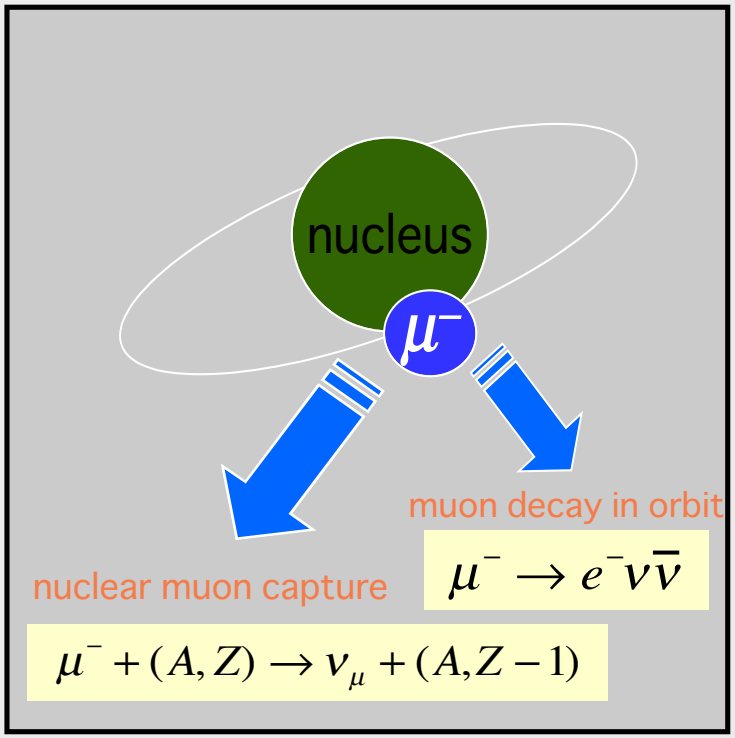
Overview Of Processes

μ^- stops in thin Al foil

the Bohr radius is ~ 20 fm, so the μ^- sees the nucleus

μ^- in 1s state

Al Nucleus
~4 fm



60% capture
40% decay

muon capture, muon "falls into" nucleus:
normalization

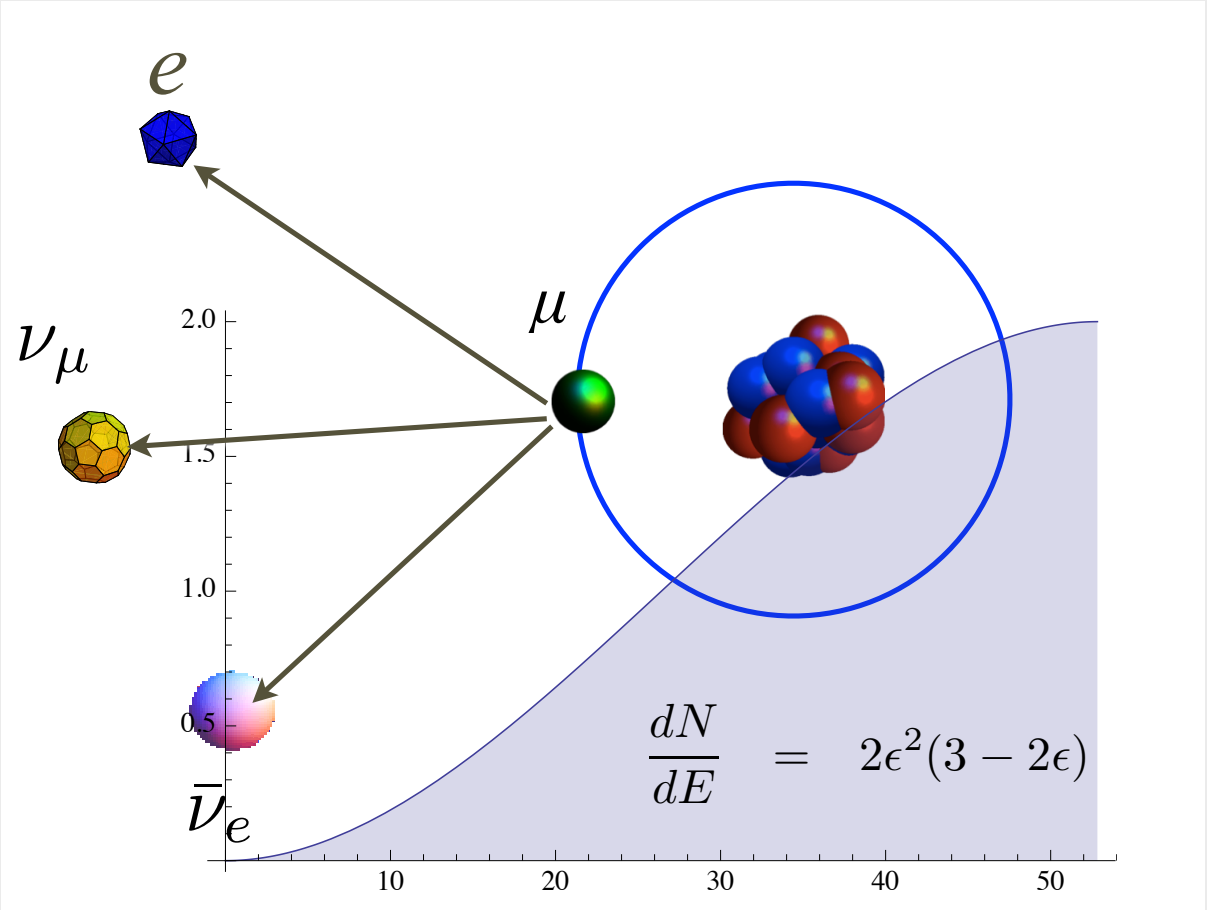
Decay in Orbit:
background

Decay-In-Orbit: Not always Background

- Peak and Endpoint of Michel Spectrum is at

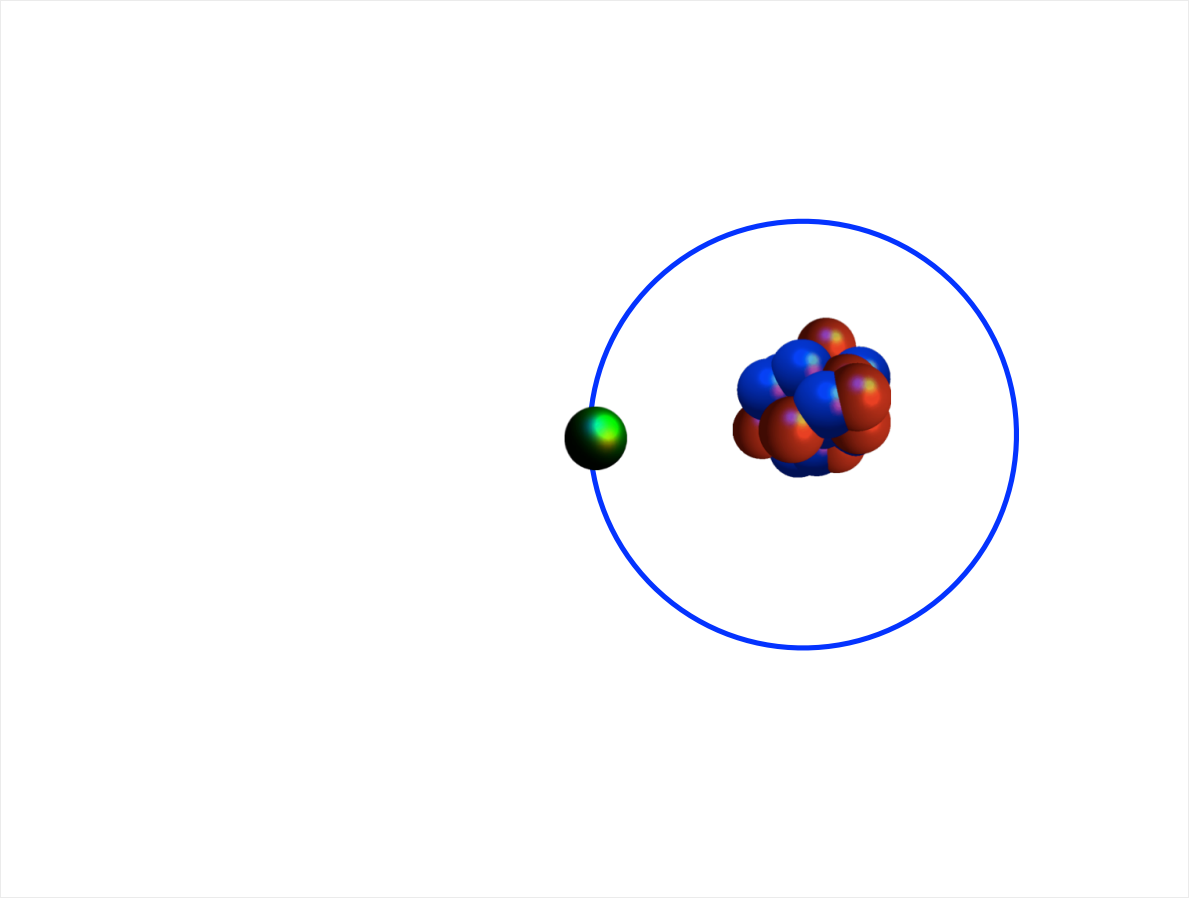
$$E_{\max} = \frac{m_\mu^2 + m_e^2}{2m_\mu} \approx 52.8 \text{ MeV}$$

- Detector will be insensitive to electrons at this energy
- Recall *signal* at 105 MeV>>52.8 MeV



Decay-In-Orbit Background

- Same process as before
- But this time, include electron recoil off nucleus
- The DIO electron can be exactly at conversion energy: both are two body states with electron and nucleus (up to neutrino mass)



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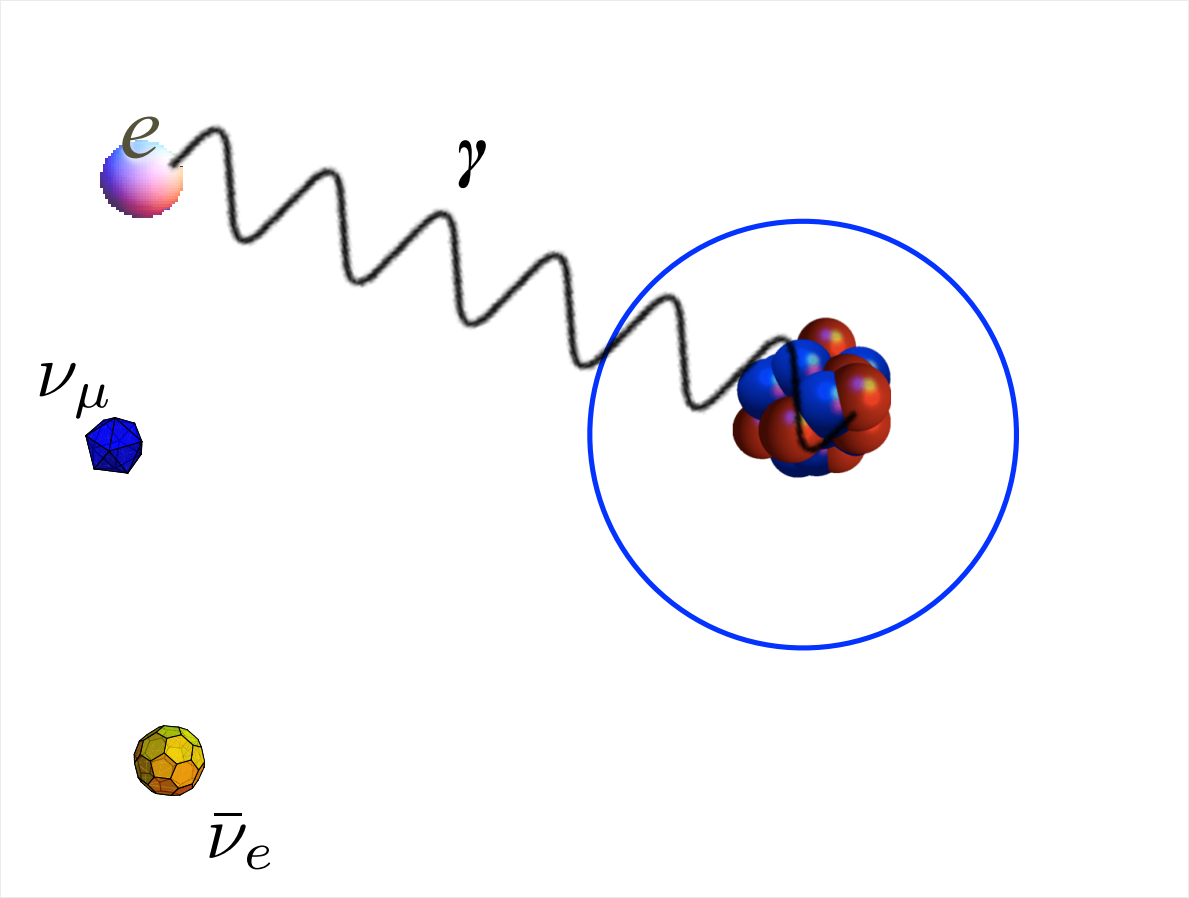
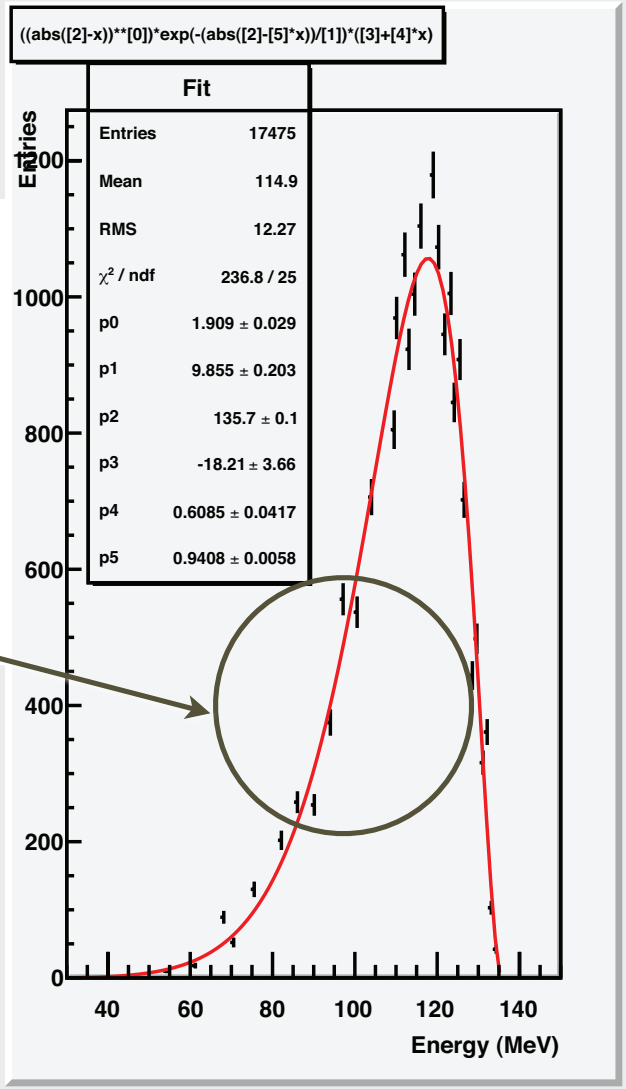


Prompt Backgrounds

Particles produced by proton pulse which interact almost immediately when they enter the detector: π, neutrons, pbars

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



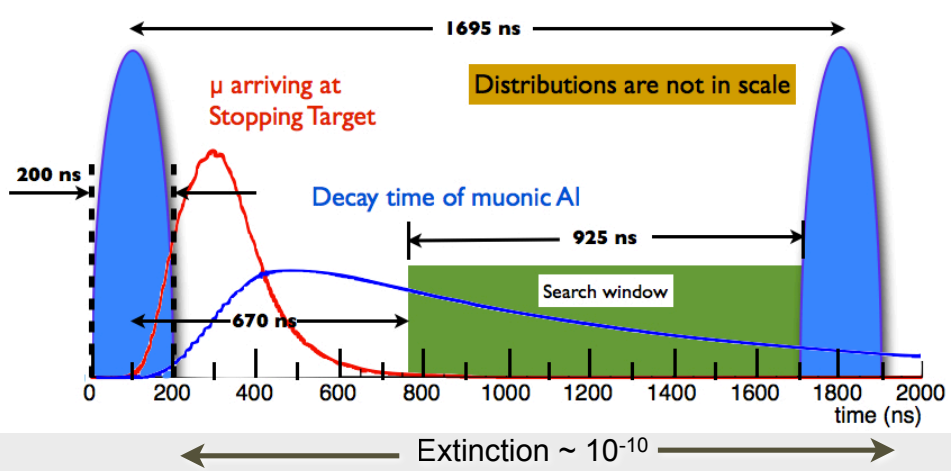
energy spectrum of γ measured on Mg
J.A. Bistirlich, K.M. Crowe et al., Phys Rev C5, 1867 (1972)

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

Pulsed Beam Structure

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

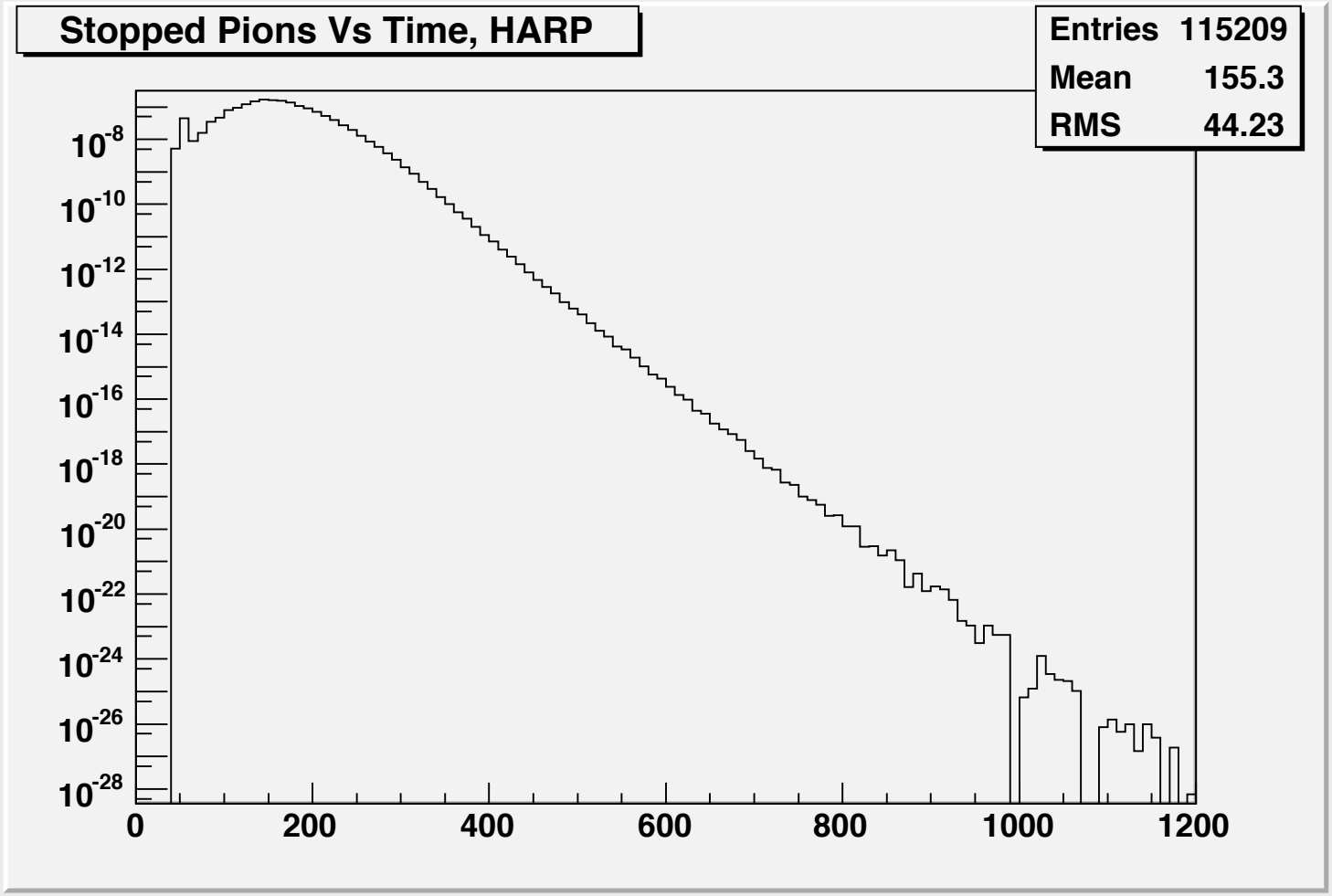
  = # protons out of pulse/# protons in pulse



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

Pulsed Beam Structure and Radiative π Capture

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



need a beam that lets us wait this long: FNAL

Pulsed Beam Structure and Radiative π Capture

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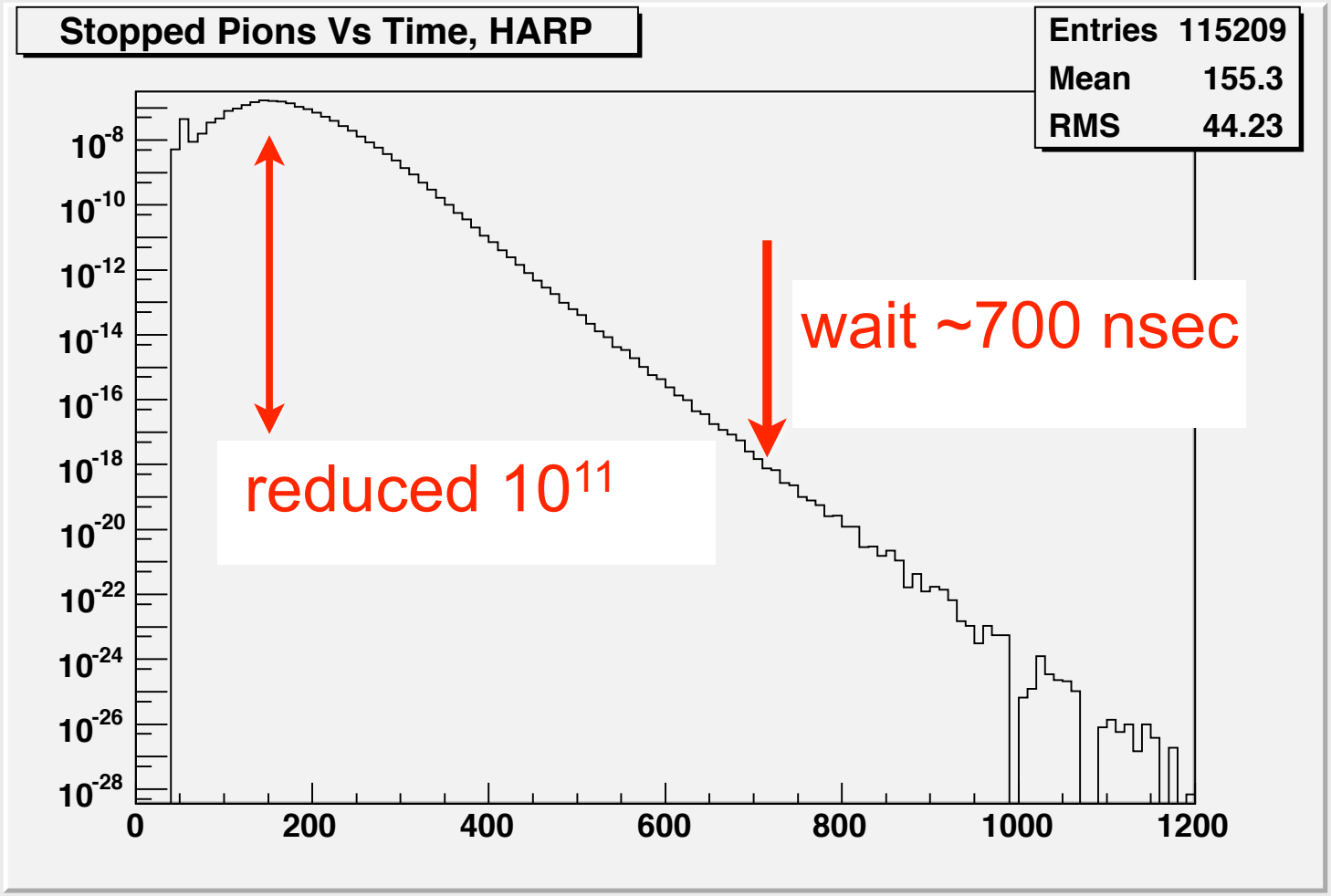
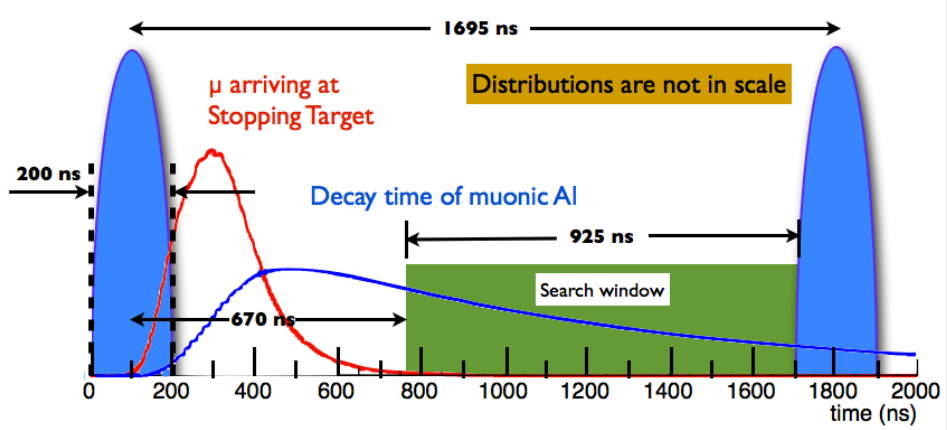


need a beam that lets us wait this long: FNAL

Prompt Background and Choice of Z

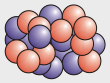
choose Z based on tradeoff between rate and lifetime: longer lived reduces prompt backgrounds

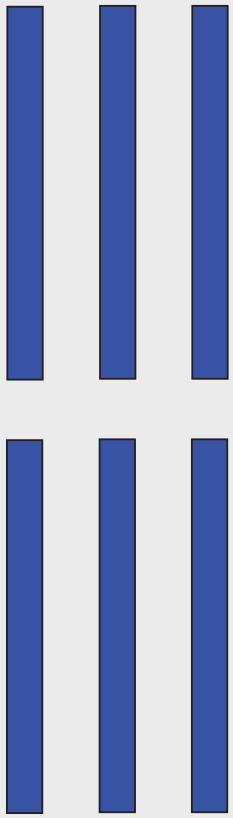


Nucleus	$R_{\mu e}(Z) / R_{\mu e}(Al)$	Bound Lifetime	Conversion Energy
Al(13,27)	1.0	864 nsec	104.96 MeV
Ti(22,~48)	1.7	328 nsec	104.18 MeV
Au(79,~197)	~0.8-1.5	72.6 nsec	95.56 MeV

Prompt backgrounds and Pulsed Beam

target foils: muon converts here

 = muons, electrons, pions



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

Prompt backgrounds and Pulsed Beam

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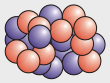
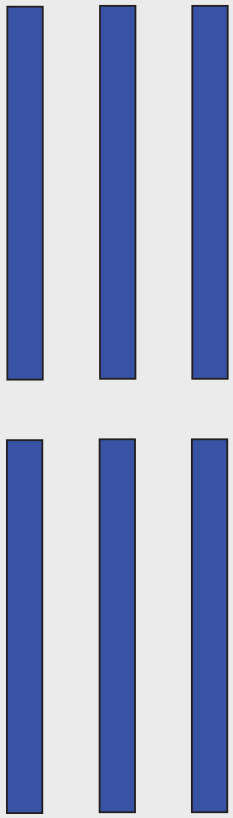
 = muons, electrons, pions



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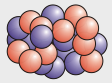
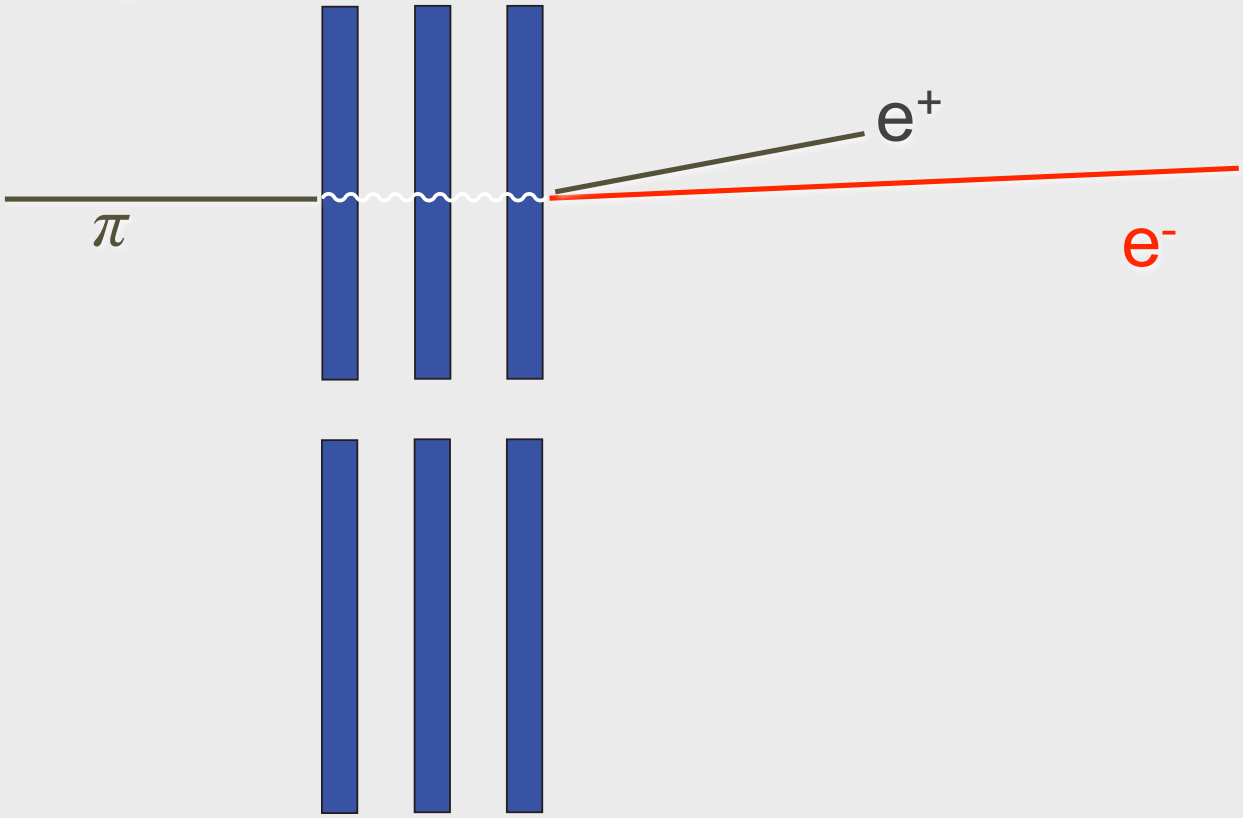


= muons, electrons, pions



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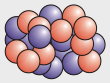
Radiative Pion Capture:

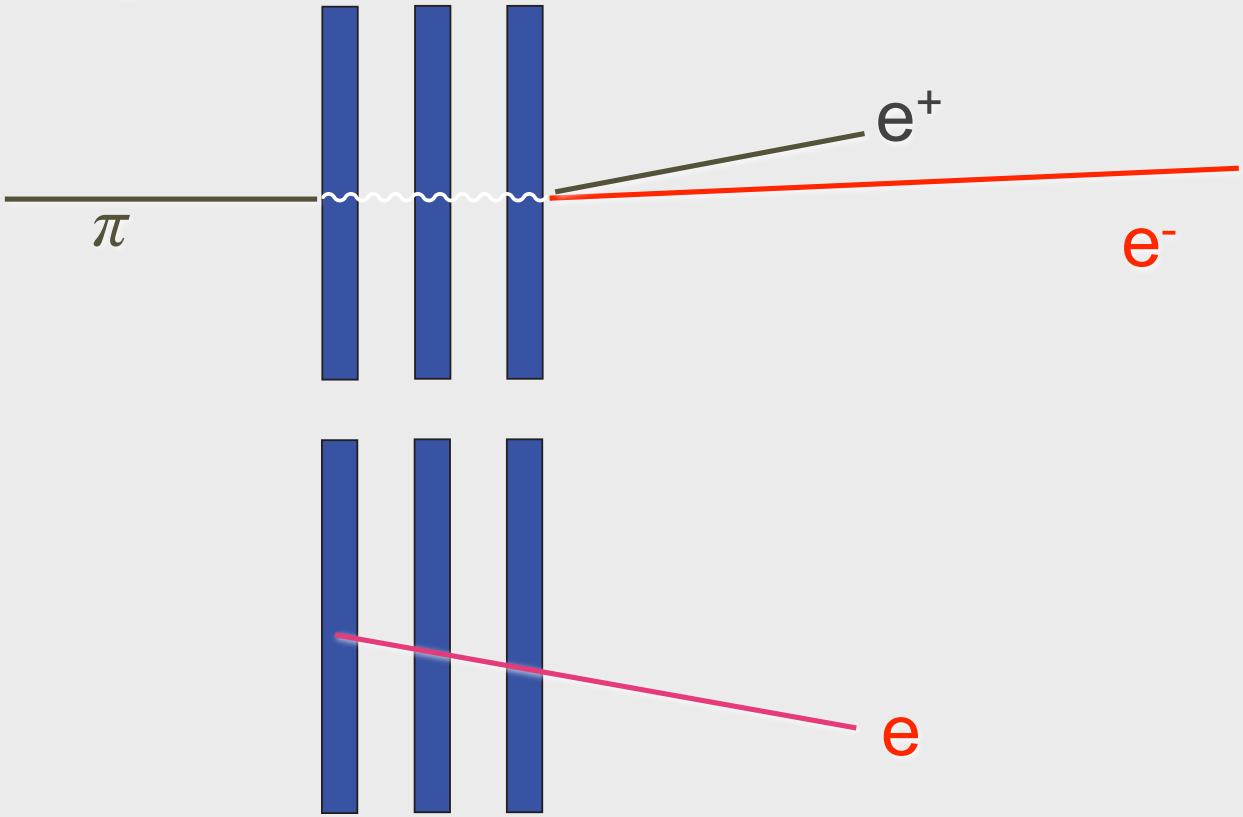
$\pi N \rightarrow \gamma N$

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

Prompt backgrounds and Pulsed Beam

target foils: muon converts here

 = muons, electrons, pions



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

delayed 105 MeV electron

Radiative Pion Capture:

$\pi N \rightarrow \gamma N$

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

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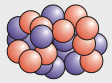

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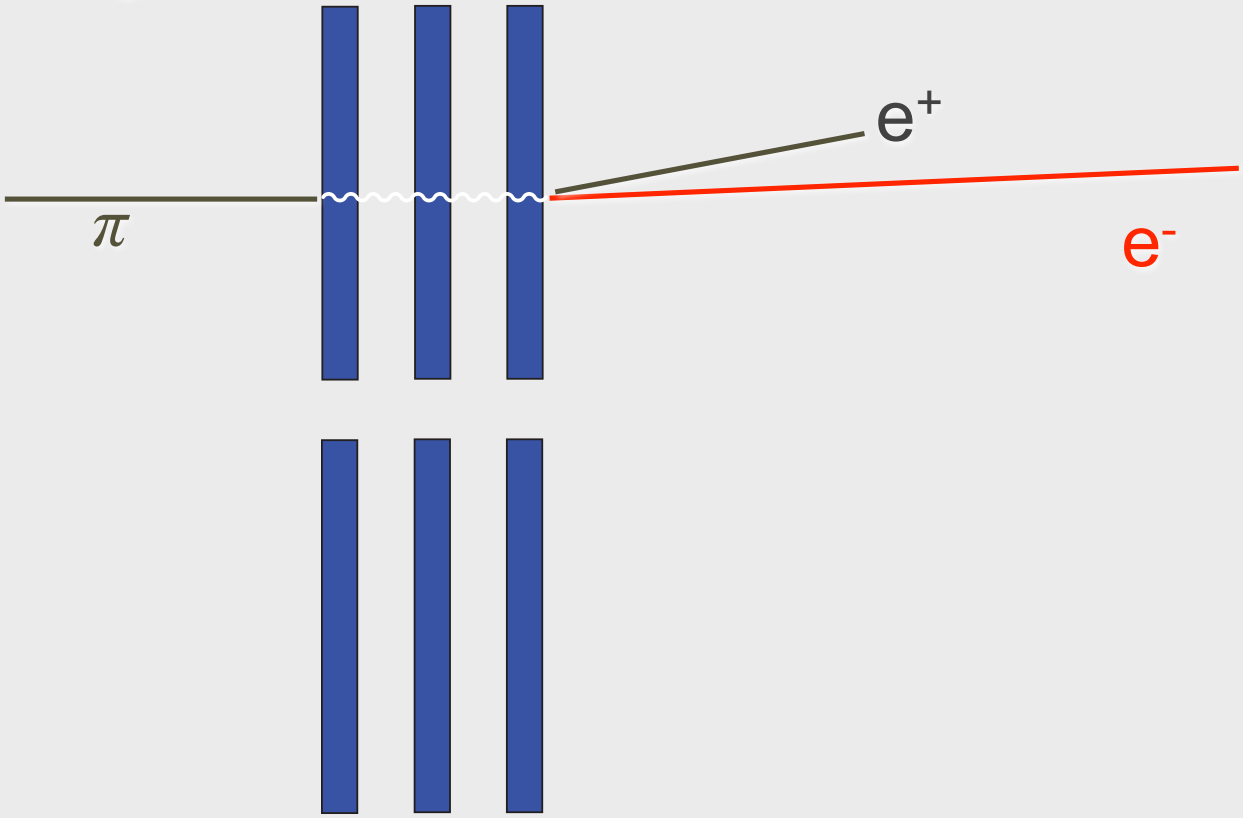

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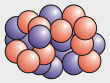
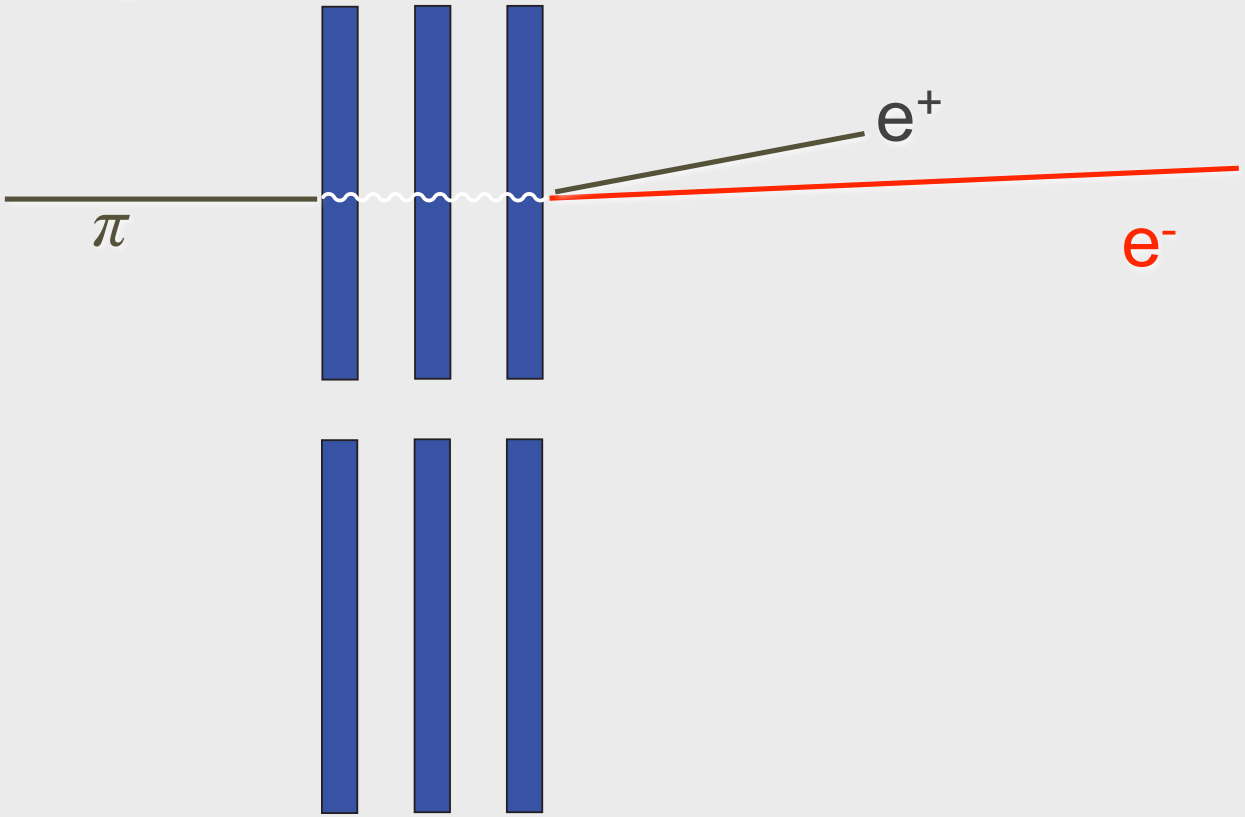
 = muons, electrons, pions



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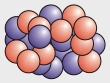

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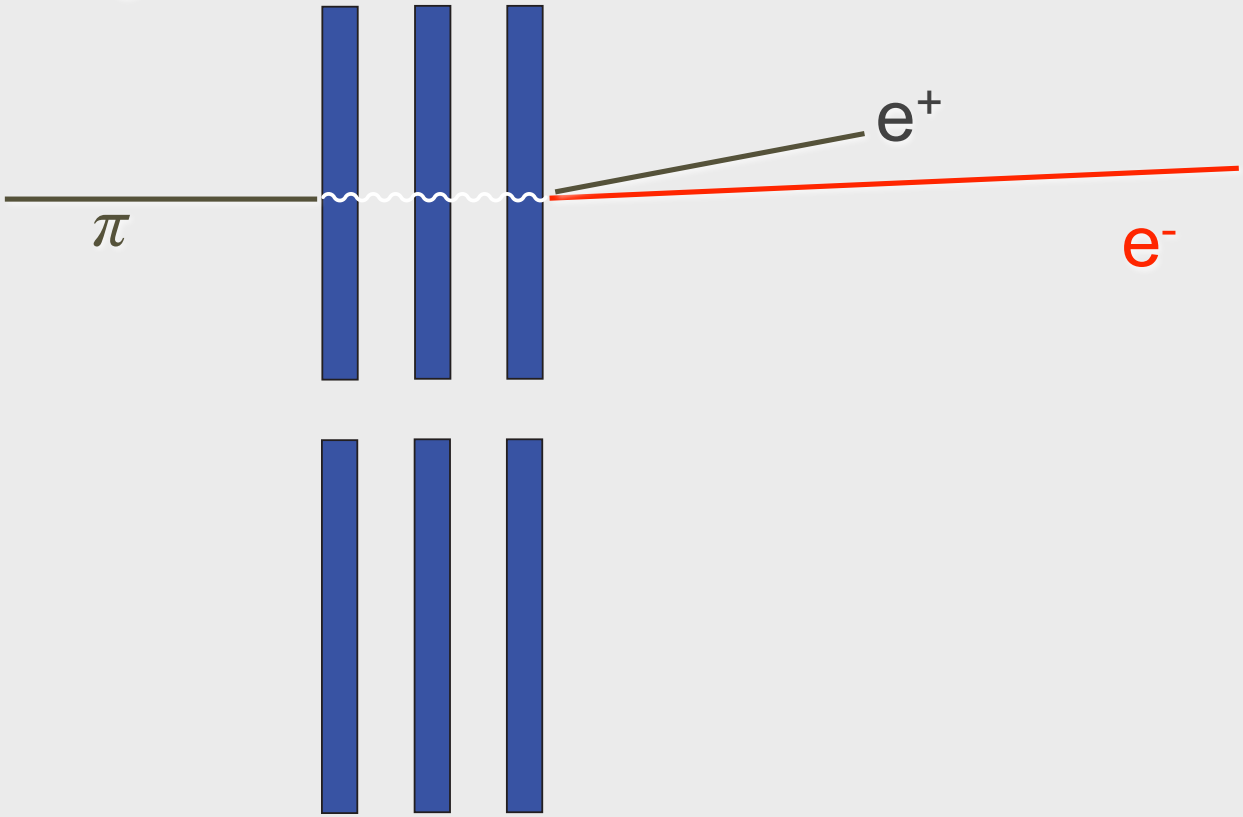

antiprotons take a long time to arrive at target; can show up any time, and pulsing doesn't help.

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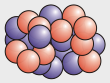
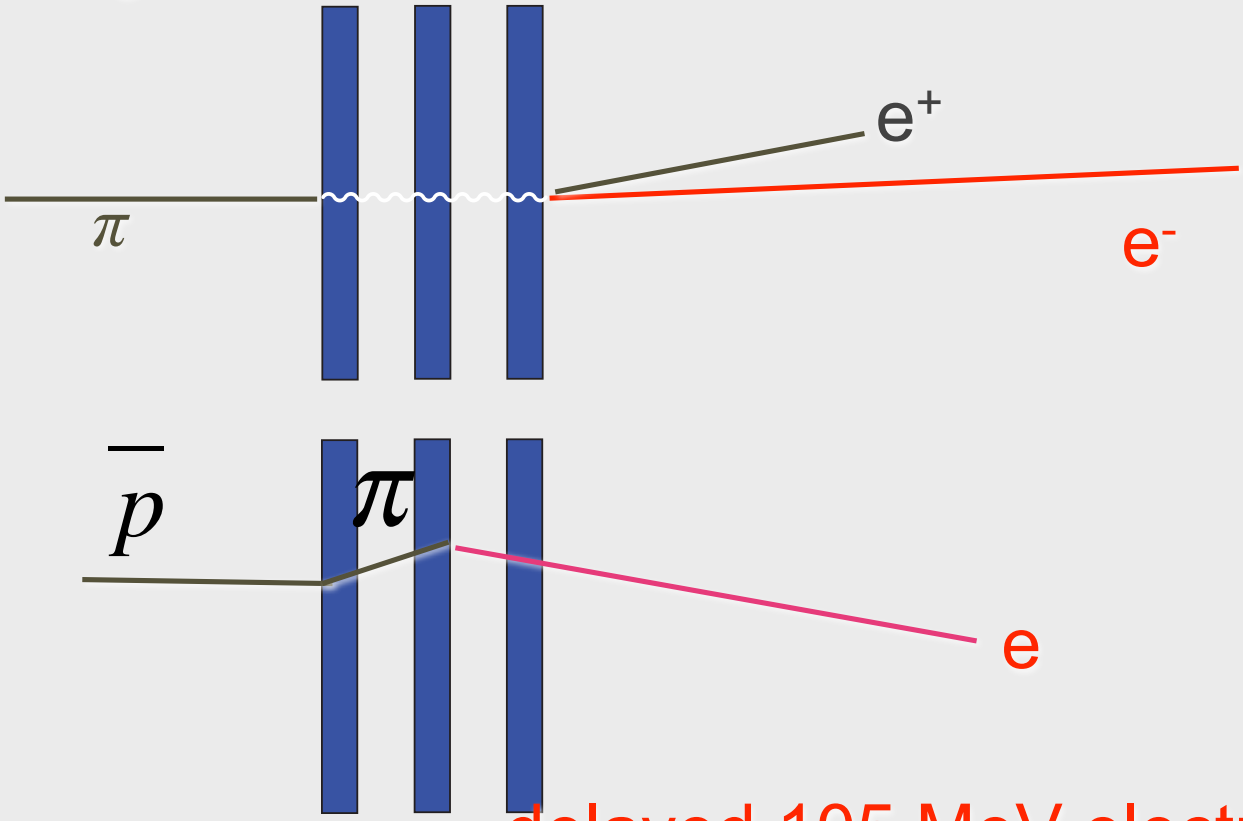
 = muons, electrons, pions



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delayed 105 MeV electron

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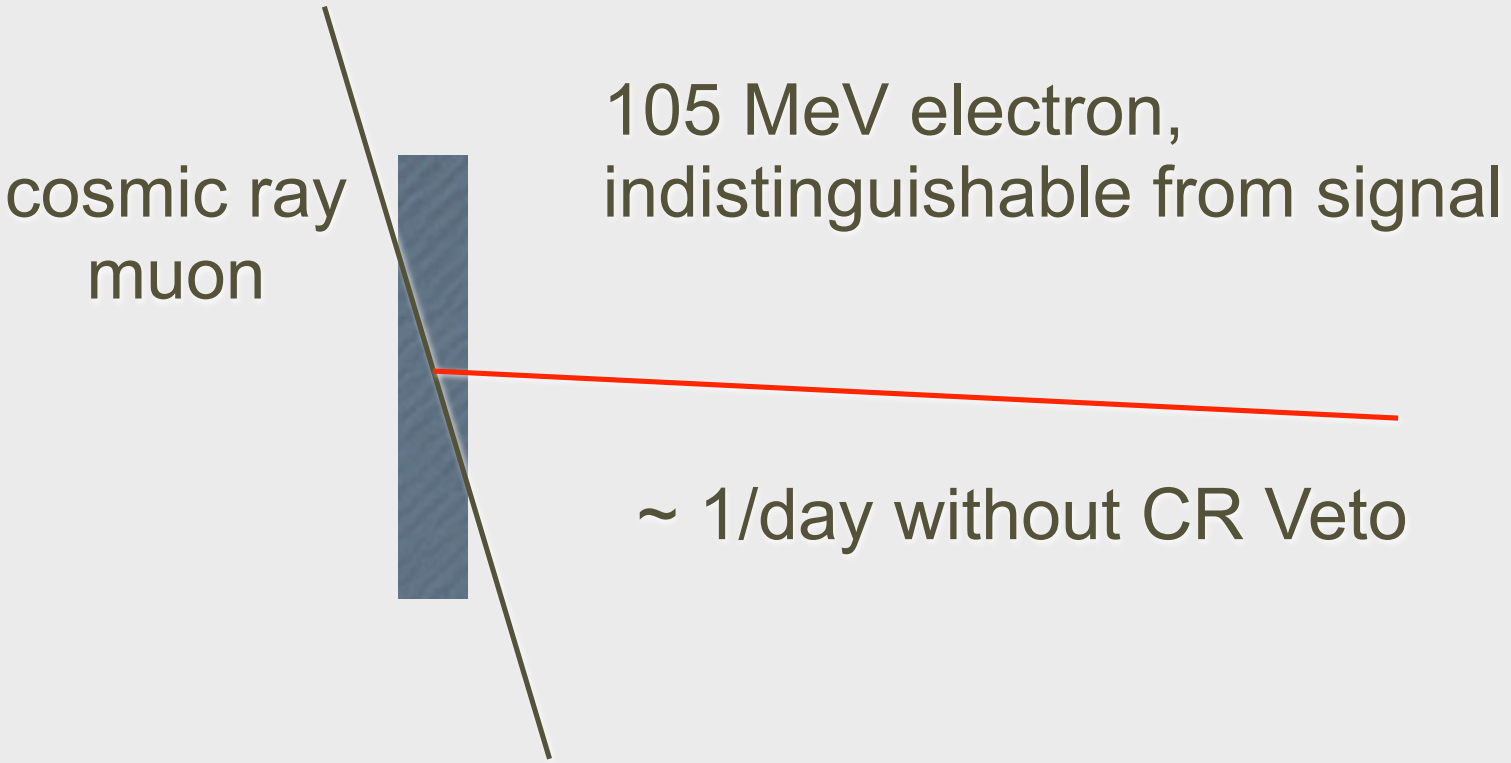
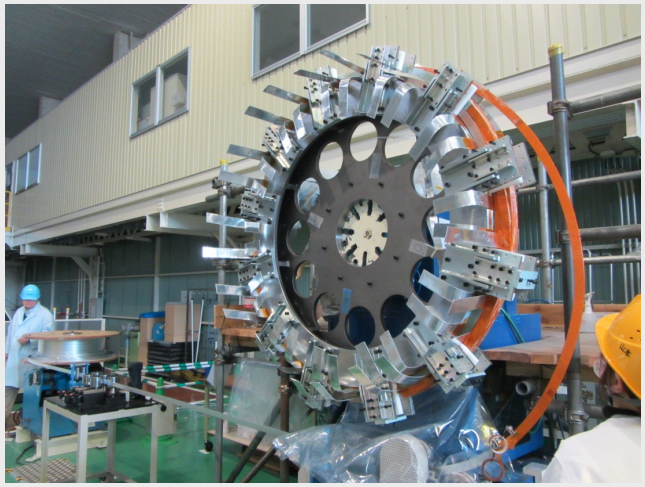
Cosmic Ray Backgrounds

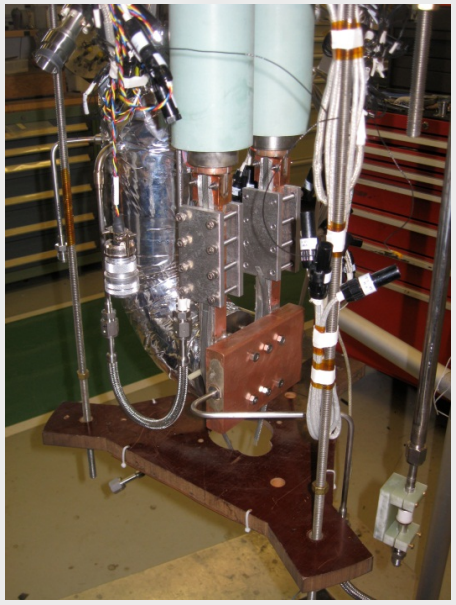
- Several Sources
- Most Problematic:

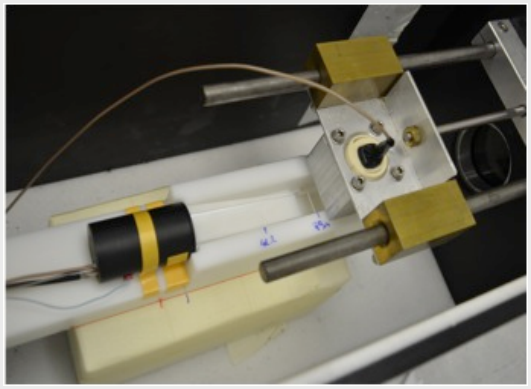


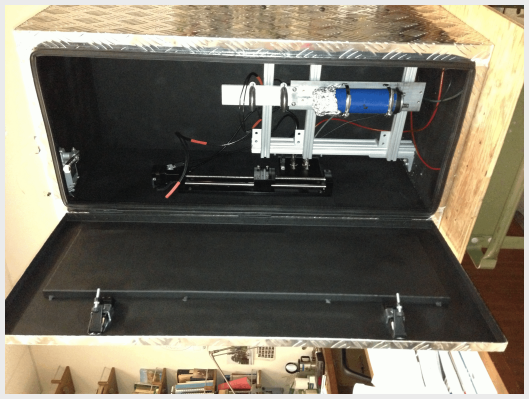
Not Just Paper

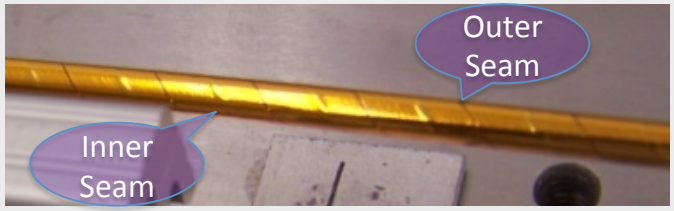
solenoids











25 micron tracker straws

LYSO crystals

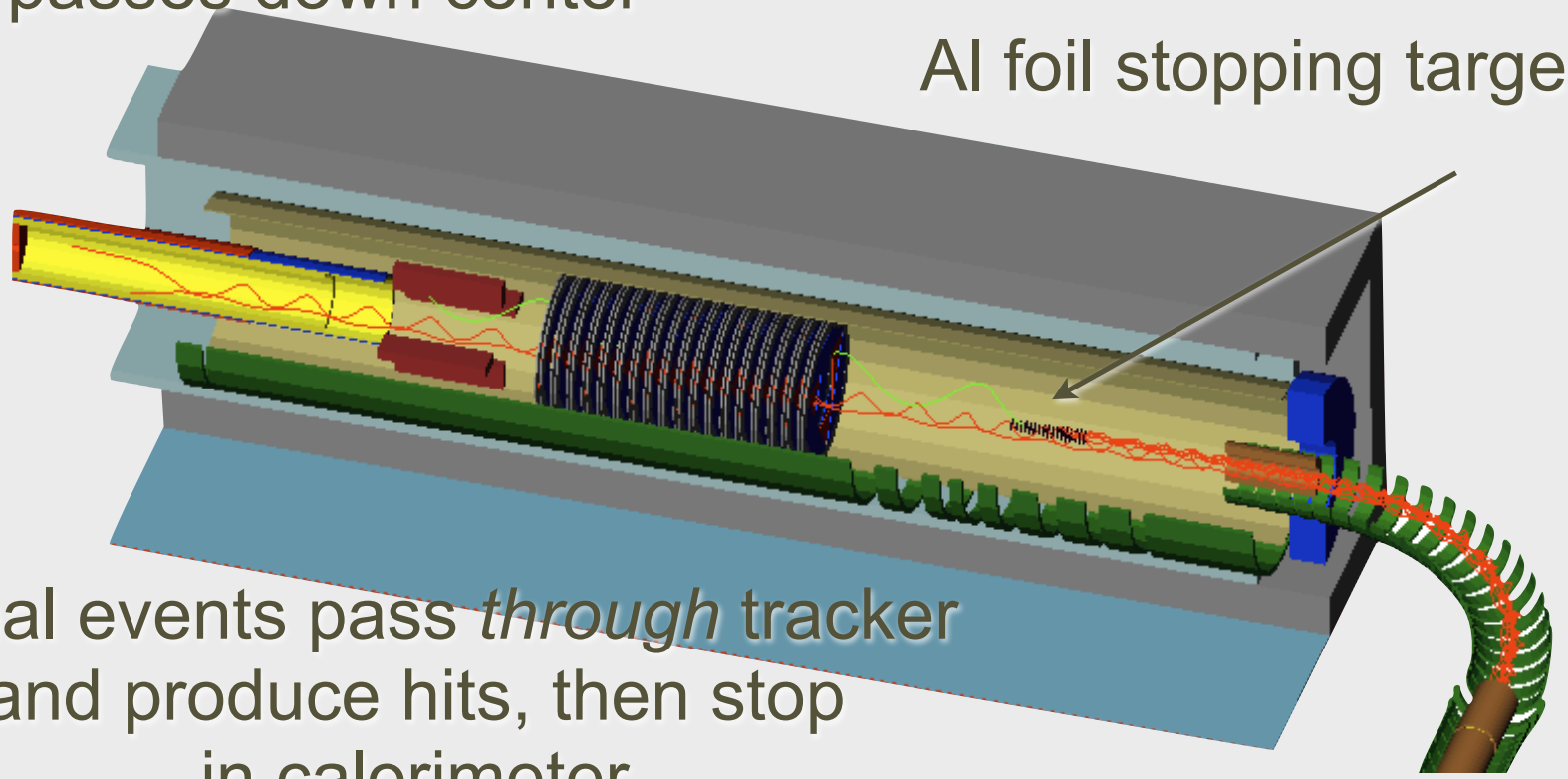
Detector Solenoid

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

low momentum particles and almost all DIO background passes down center

10 m × 0.95 m

Al foil stopping target

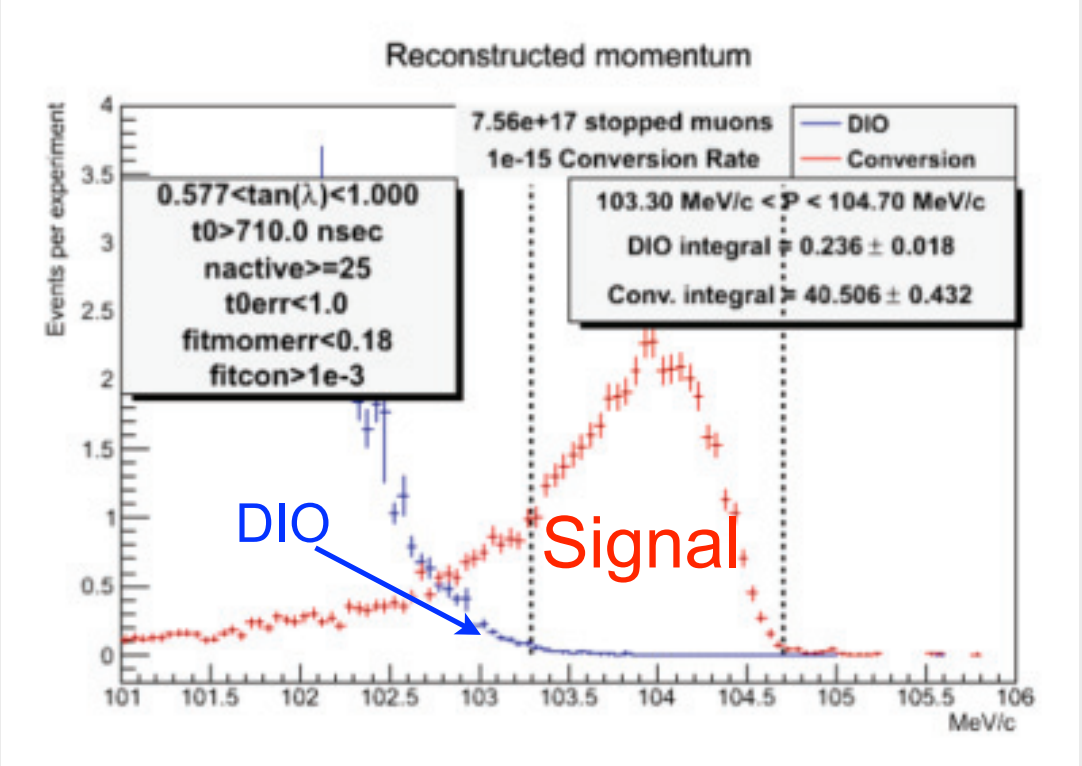


signal events pass *through* tracker and produce hits, then stop in calorimeter

Signal and Background

typical SUSY signal ~ 10^{-15}

- Hit-level MC with simulations of accidental activity
- BaBar Kalman Filter, cuts on *reconstructed* quantities
- Undergoing further refinements



this is a discovery experiment: 40 events vs <0.5 bkg

Backgrounds

- For $R_{\mu e} = 10^{-15}$
  ~40 events / 0.41 bkg
  (LHC SUSY?)
- For $R_{\mu e} = 10^{-16}$
  ~4 events / 0.41 bkg

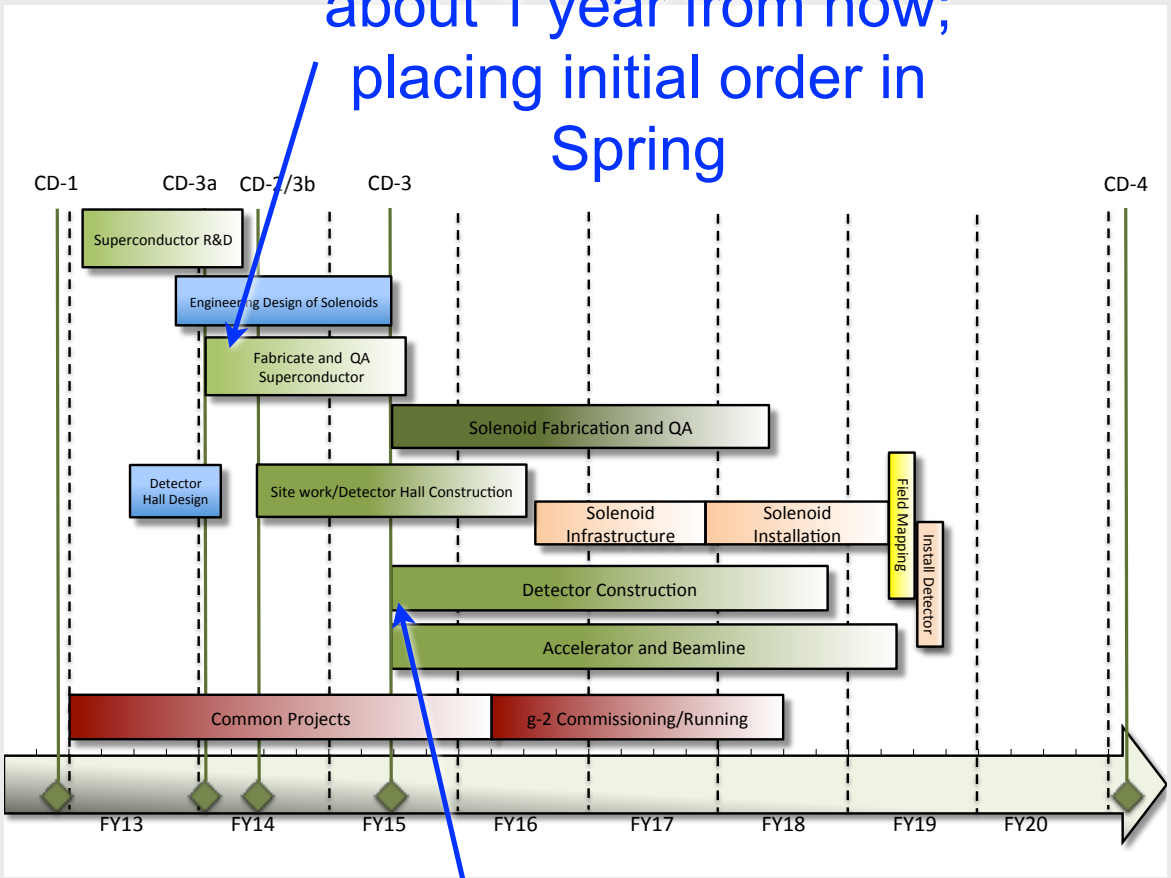
Background	Size	Uncertainty	Source of Uncertainty
Muon Decay-In-Orbit	0.22	± 0.06	Acceptance and Energy Loss Modeling
Antiproton RPC	0.10	± 0.05	Cross-Section and Acceptance
Cosmic Rays	0.05	± 0.05	Statistics of Sample
Radiative Pion Capture	0.03	± 0.007	Acceptance and Reconstruction
Muon Decay-in-Flight	0.01	± 0.003	Cross-Section, Acceptance and Modeling
Pion Decay-in-Flight	0.003	± 0.0015	same
Beam Electrons	0.0006	± 0.0003	same
Radiative Muon Capture	$< 2 \times 10^{-6}$	—	Calculation
Sum	0.41	± 0.08	**Added in Quadrature**

numbers are changing at 10% level as experiment matures

Mu2e Schedule

- Expect to start late 2019 with mapping solenoids, data in 2020
  - plenty of things for students to do before then on test beams, accelerator, cosmic ray system
- Driven by time to acquire solenoids
- *DOE is working with us to speed it up!*

buy superconducting cable about 1 year from now; placing initial order in Spring



start building detector ~ 2 years from now

Conclusions

- Mu2e will either:
  - *Reduce the limit for $R_{\mu e}$ by more than four orders of magnitude ($R_{\mu e}$ <6x10^{-17} @ 90% C.L.)*
  - *Discover unambiguous proof of Beyond Standard Model physics and*
- *In both cases, Mu2e will provide important information either complementing LHC results or probe up to 10^4 TeV/c^2*
- With Project X upgrades, we could extend the limit by up to two additional orders of magnitude, study the details of new physics, and build a new rare muon process program; Doug will talk about first x10 improvement