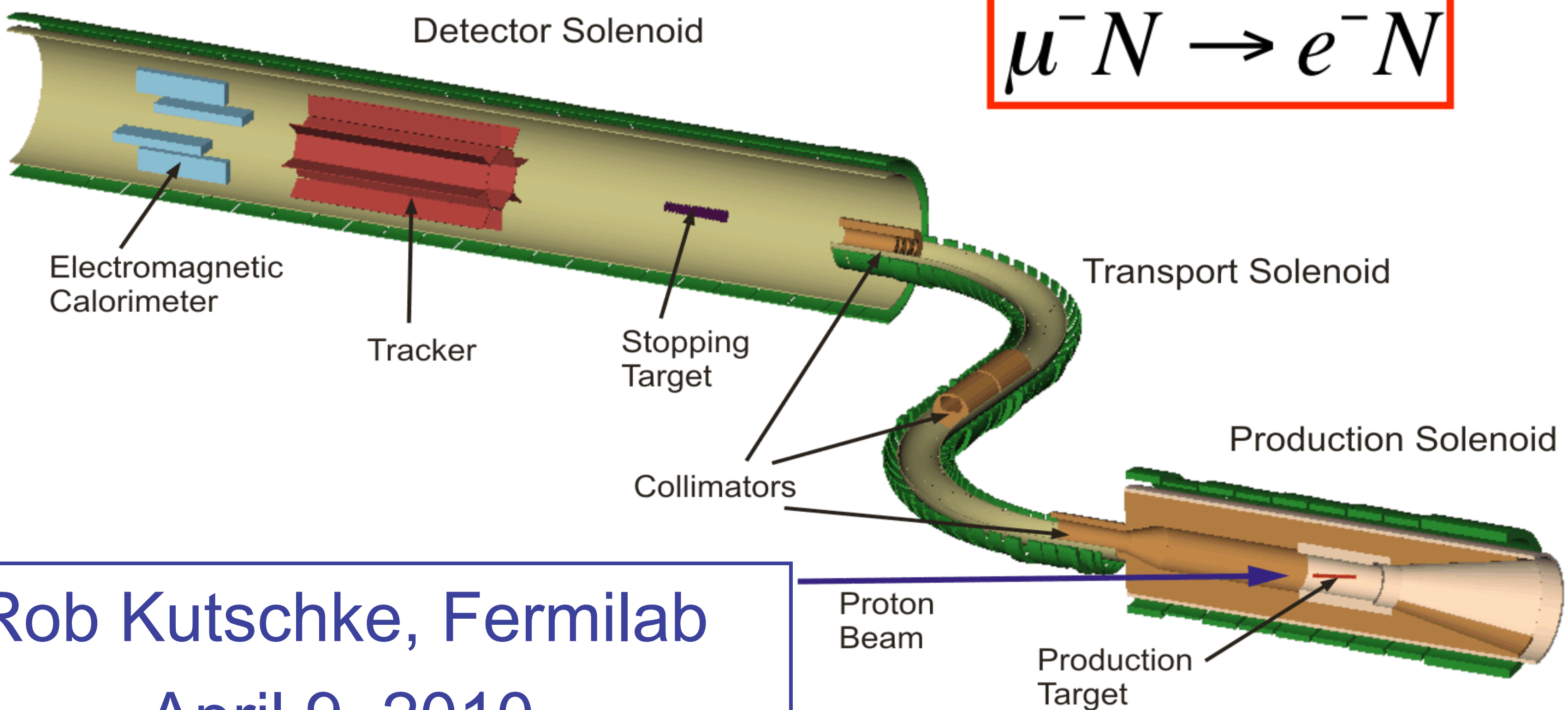
Mu2e-doc-846-v1

The Mu2e Experiment at Fermilab

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



Rob Kutschke, Fermilab

April 9, 2010

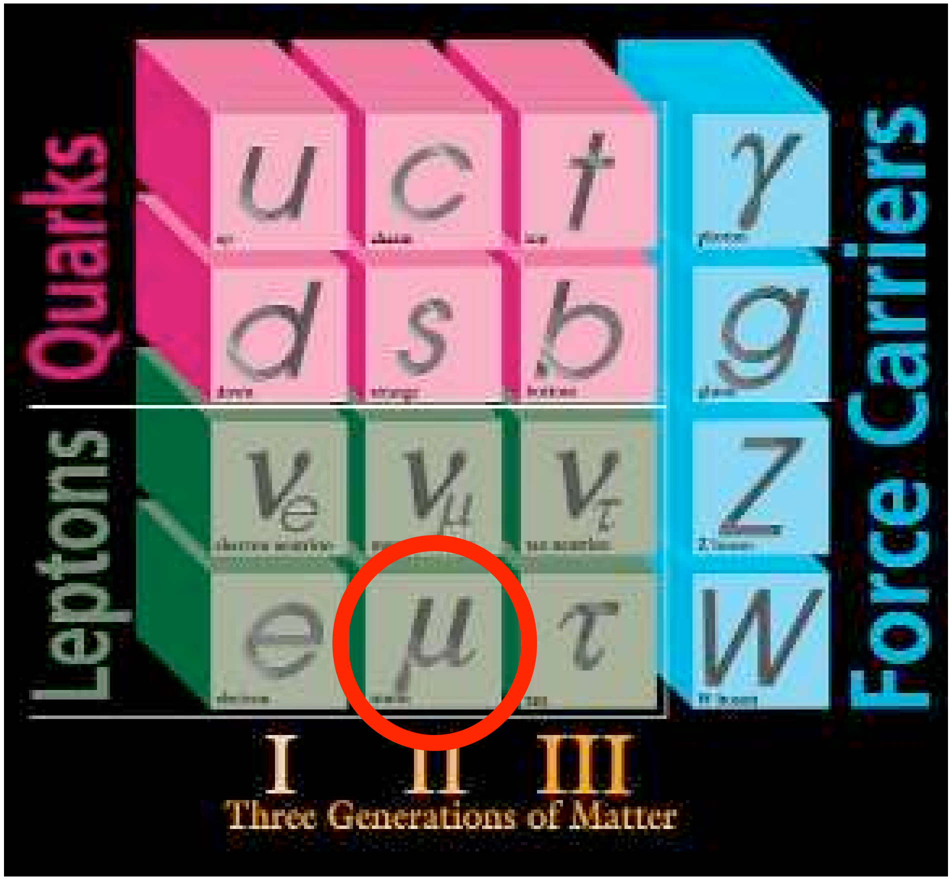
(NIU Physics Dept. Colloquium)

http://mu2e.fnal.gov

Outline

- Preliminaries:
  - Canonical Particle Physics in one page.
  - Who are we?
  - Where are we doing our experiment?
- What are we doing?
- Why are we doing it?
- How are we doing?
- When will we do it?
- Summary and Conclusions.

The Known Elementary Particles



- Standard Model
- Not self consistent !
  – Higgs boson?
  – Supersymmetry?
  – Strings …

The Muon

- Discovered 1936
- Like a "heavy electron"
- We are looking for a very, rare decay mode.

The Mu2e Collaboration

~100 Collaborators

Both HEP and Nuclear Physics groups.

Boston University
Brookhaven National Laboratory
University of California, Berkeley
University of California, Irvine
City University of New York
Fermilab
Idaho State University
University of Illinois, Urbana-Champaign

Institute for Nuclear Research, Moscow, Russia
JINR, Dubna, Russia
Los Alamos National Laboratory
Northwestern University
INFN Frascati
INFN Pisa,
Università di Pisa, Pisa, Italy
INFN Lecce, Università del Salento, Italy

Rice University
Syracuse University
University of Virginia
College of William and Mary

More opportunities for University groups.

Fermilab

- ≈ 20 miles east of here.
- Flagship: the Tevatron
  - proton anti-proton collider
  - E_{CM} =1.96 TeV
- Broad fixed target program.
- Strong and growing ν program.
- Dark Matter and Dark Energy.
- R&D for Future Colliders
- muon(g-2)?
- Mu2e

Mu2e: reuse resources freed by end of Tevatron program

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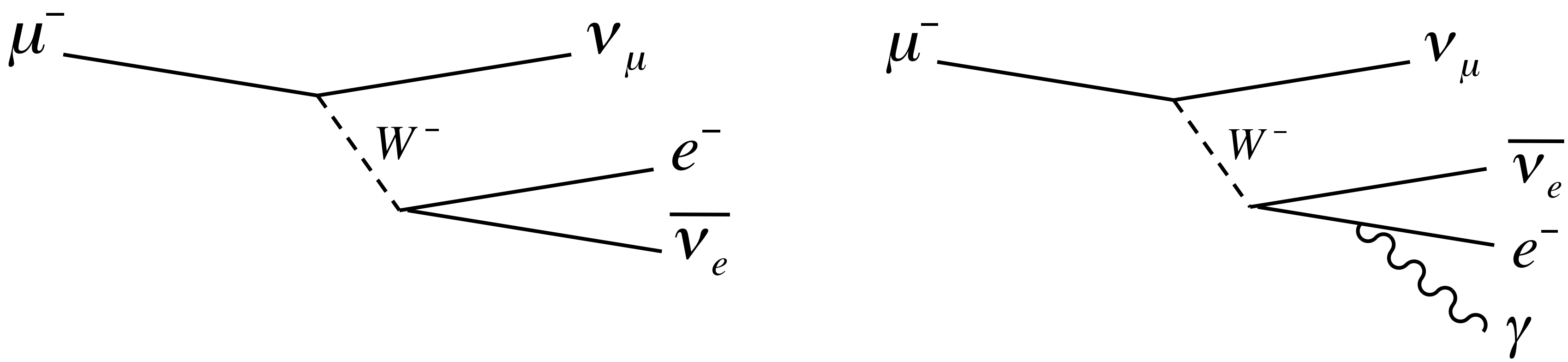
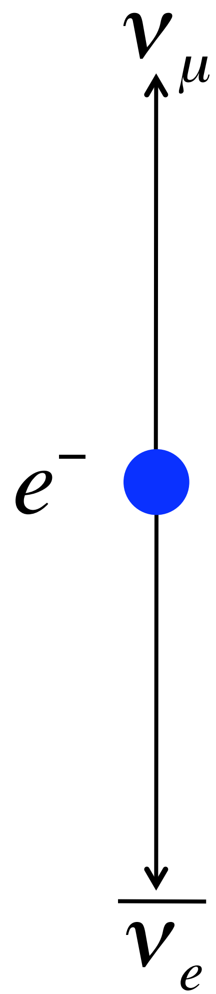
Decay of a Free Muon

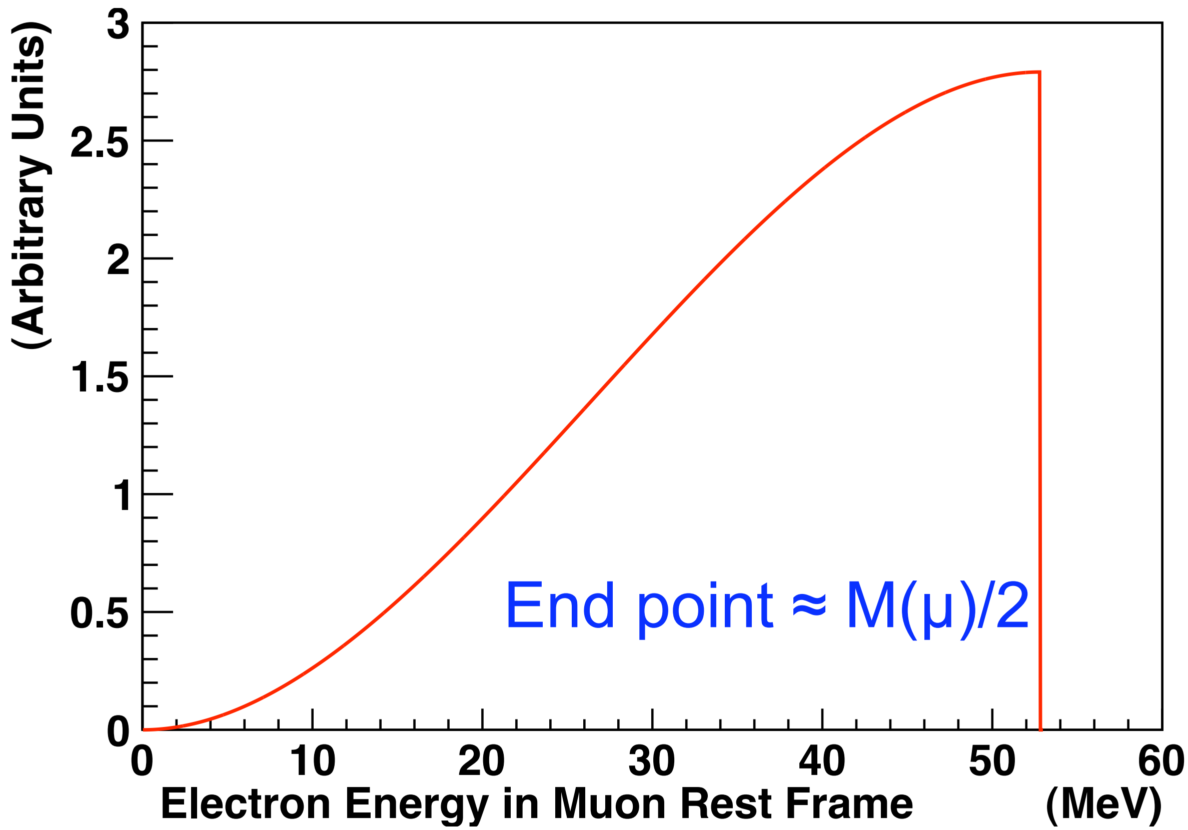


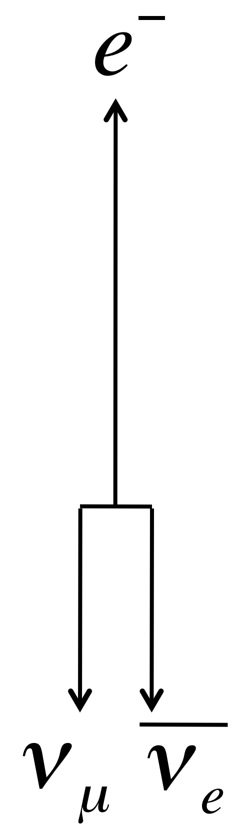
- Weak force: same as nuclear beta decay.
- 3 body final state
- Only electron observed.

Rest Mass: ≈ 105.6 MeV
Proper Lifetime: ≈ 2.2 μs

Decay of a Free Muon

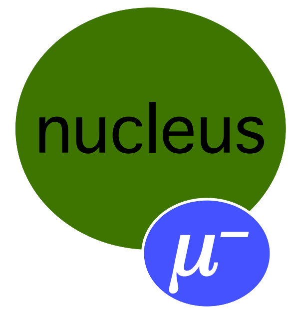






Muonic Aluminium

- Muonic Al
  - Cascade of X-rays
  - Lifetime 864 ns.
  - Free muon lifetime 2197 ns
- 2 Main Decay Modes
  - Decay-in-orbit (DIO): 40%
  - Capture on Nucleus: 60%

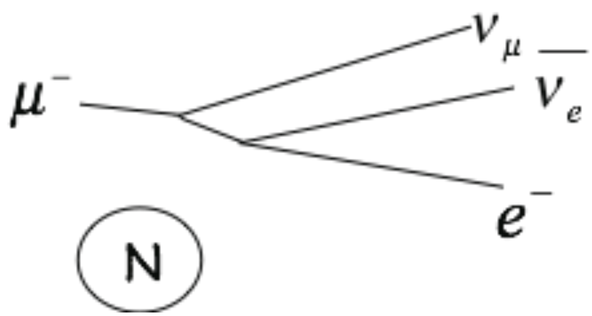


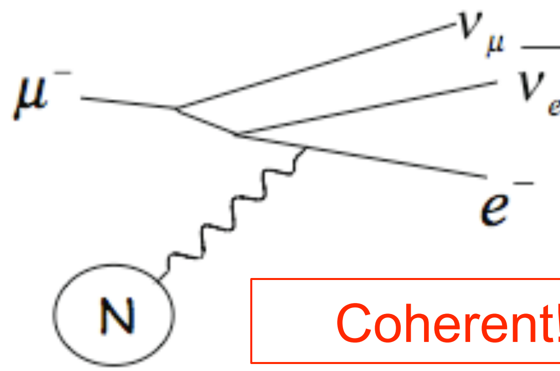
Bohr radius ≈ 20 fm

Al nuclear radius ≈ 4 fm

Decays of Muonic Al

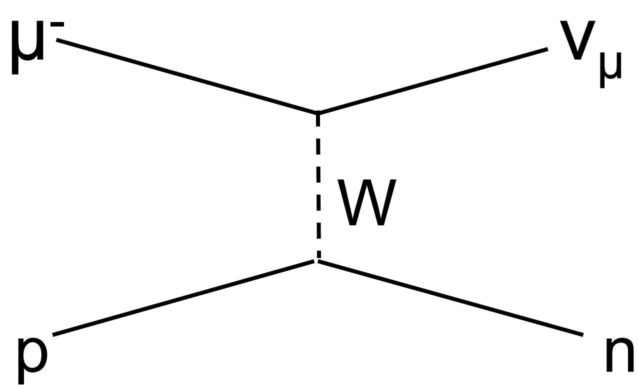
- Muon decay in orbit (DIO)





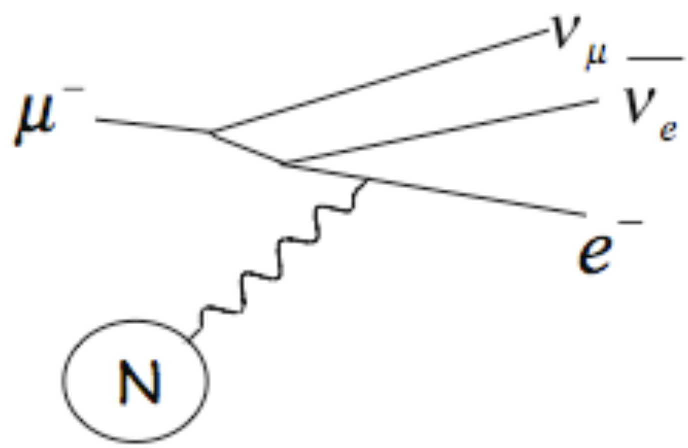
Coherent!

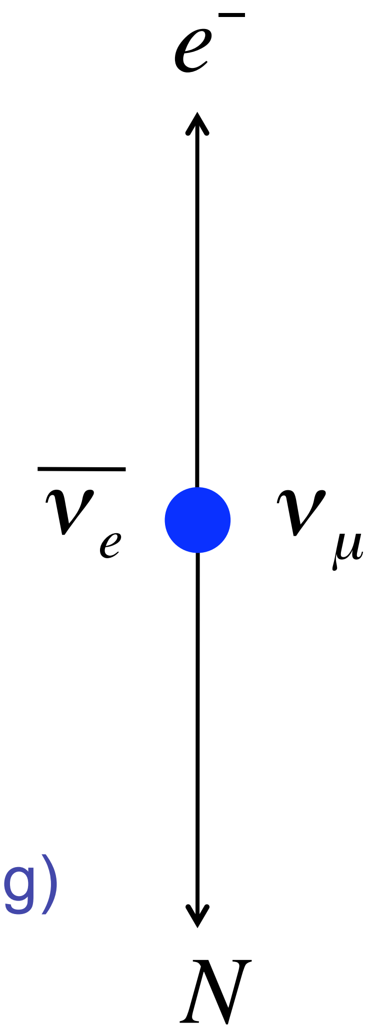
- Muon capture on the nucleus



Nuclear breakup:
2n, 2γ, 0.1 proton per interaction

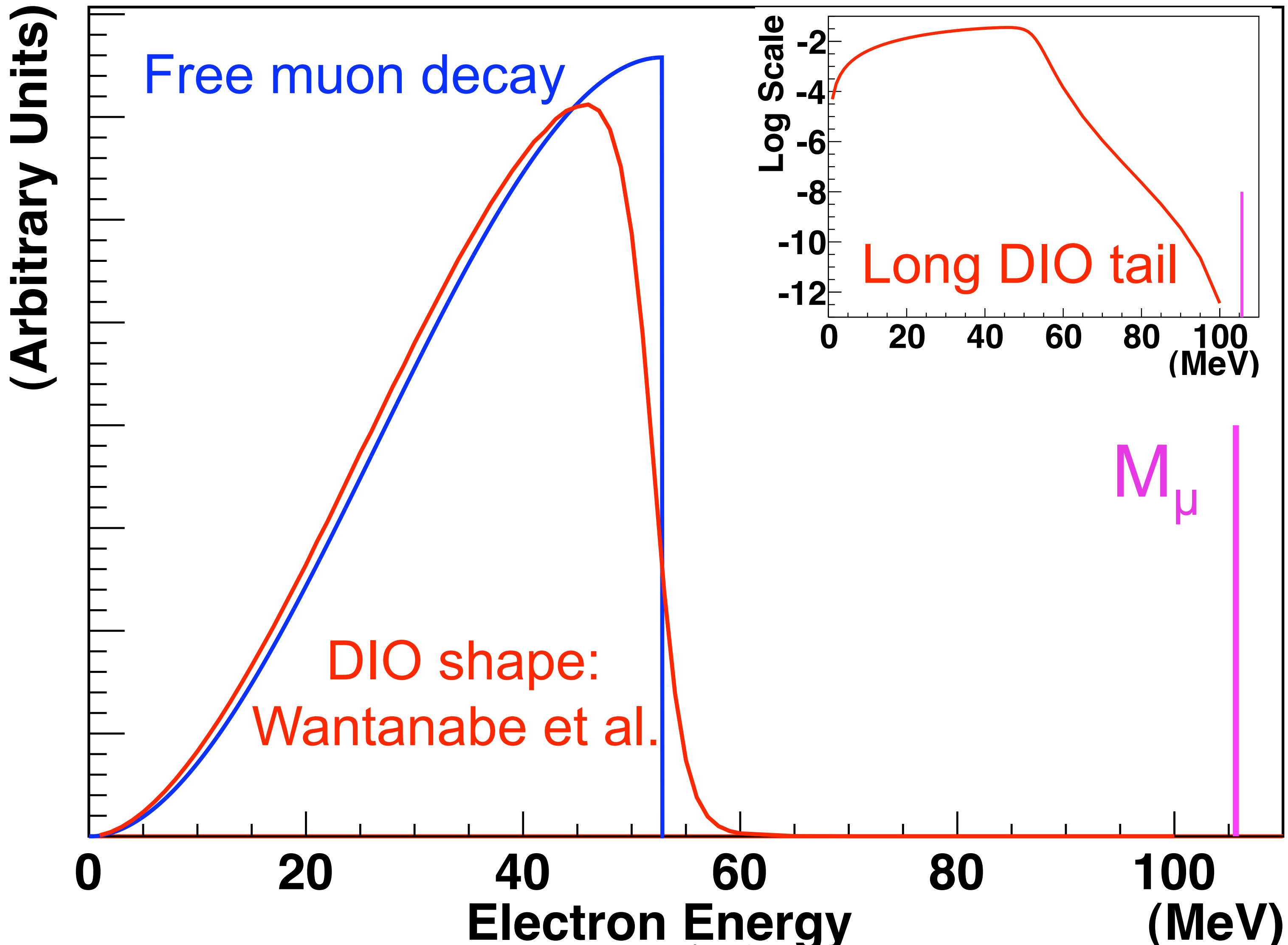
DIO Kinematics





- 4 body final state
- Only electron observed!
- Maximum E_e: both neutrinos at rest.
  - $E_e = M_\mu - M_e$ - (N recoil) – (K shell binding)
    = 104.97 MeV for Al

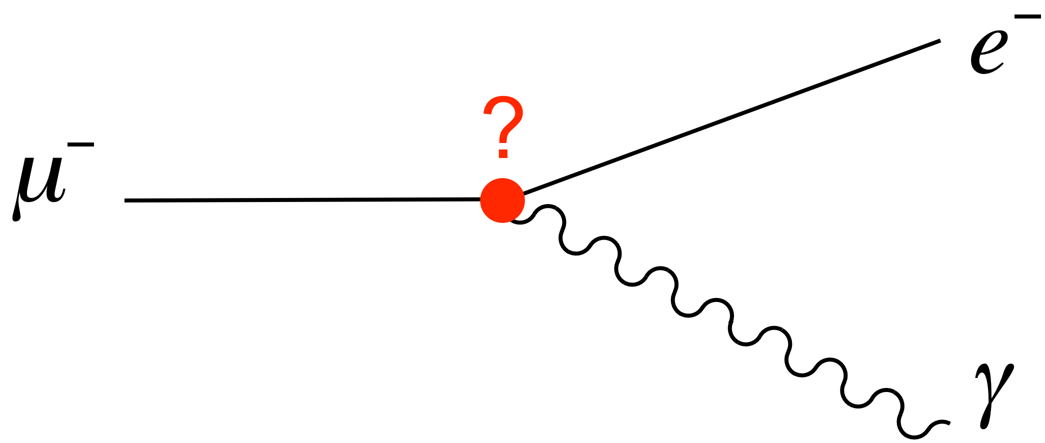
Energy Spectrum from DIO



Rare Decays of Free Muons

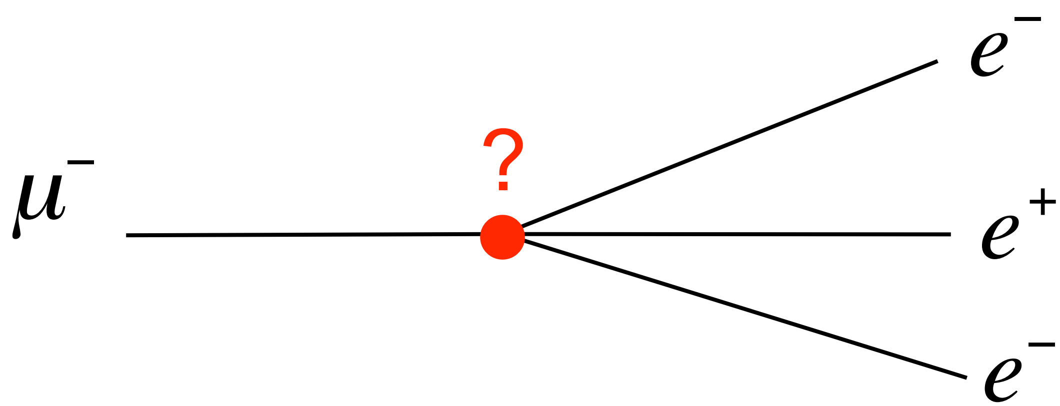
μeγ

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

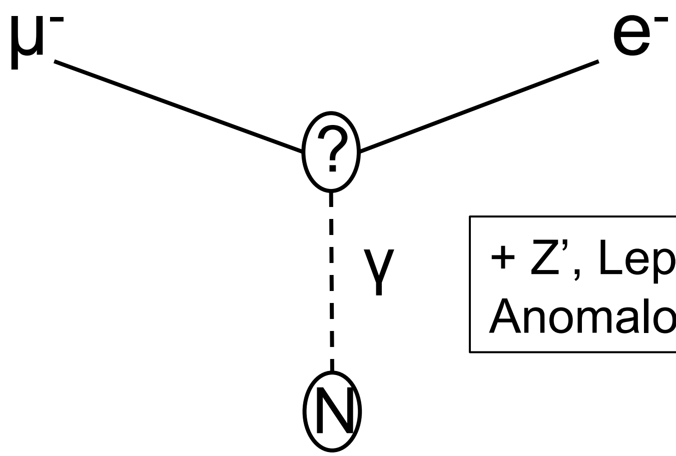


μ3e

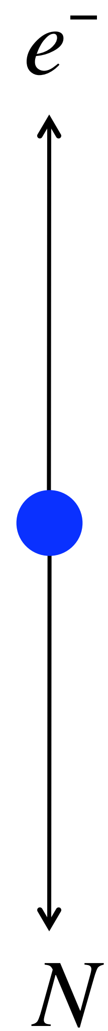
$$\mu^- \rightarrow e^- e^+ e^-$$



Muon to Electron Conversion



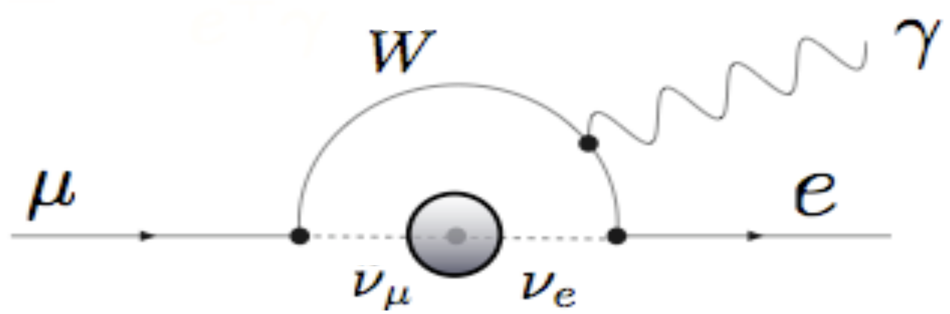
+ Z', Leptoquarks,
Anomalous Z couplings …



- Coherent: γ sees a nucleus
- Final state:
  - No do detect recoil nucleus
  - Mono-energetic electron.
  - Energy depends on nucleus
  - For Al, E ≈ 104.97 MeV

Rates in the Standard Model

μeγ

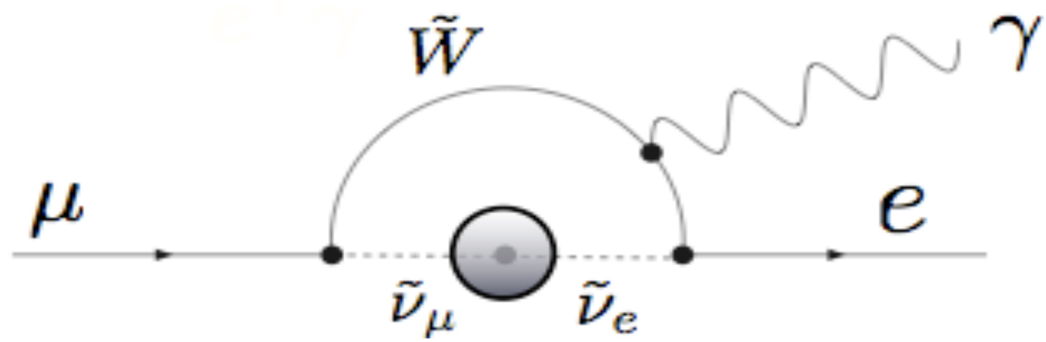


$$\mathrm{BR}(\mu \to e\gamma) \quad = \quad \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

- With massive neutrinos, non-zero rate in SM.
- Much, much too small to observe.

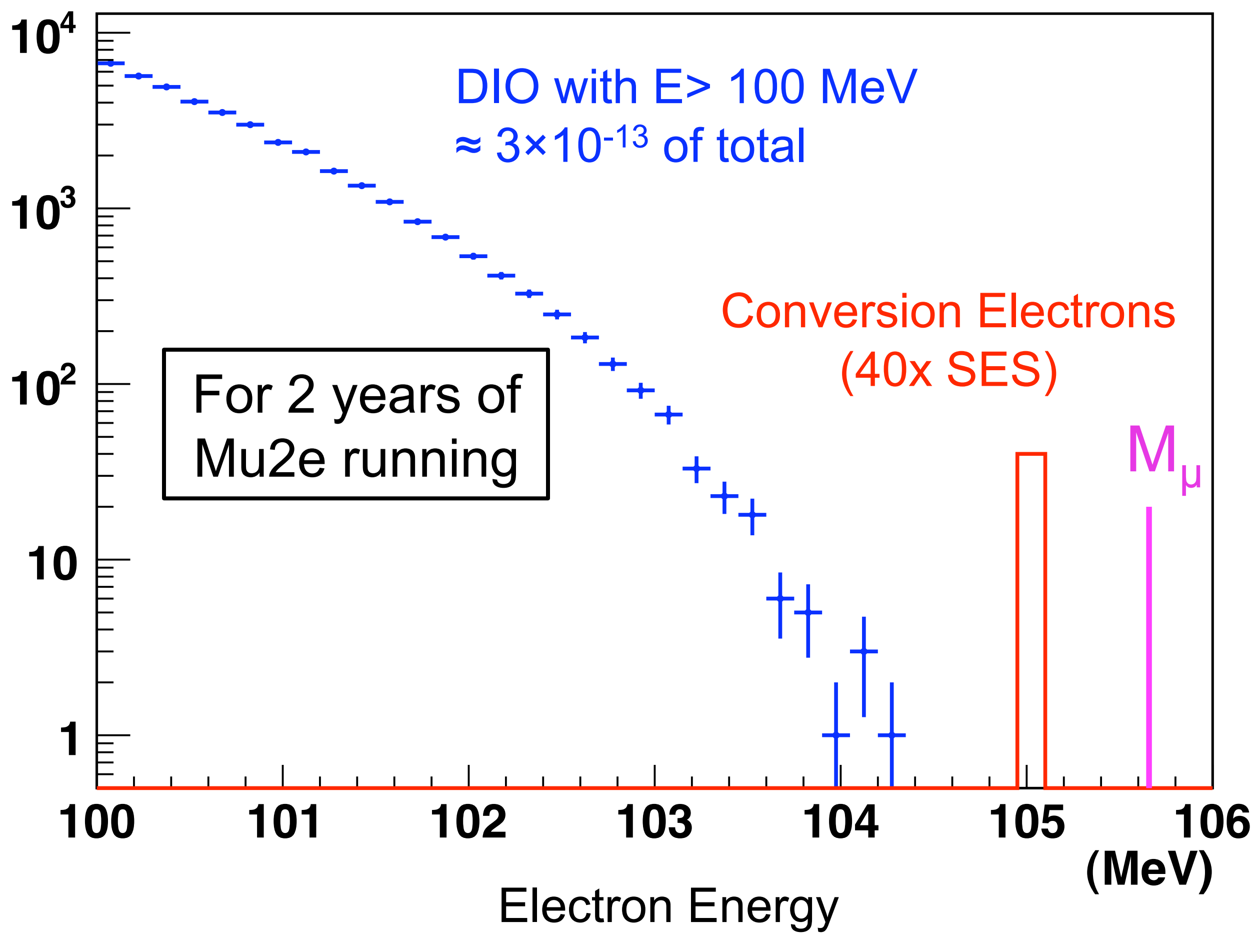
Beyond the Standard Model

μeγ



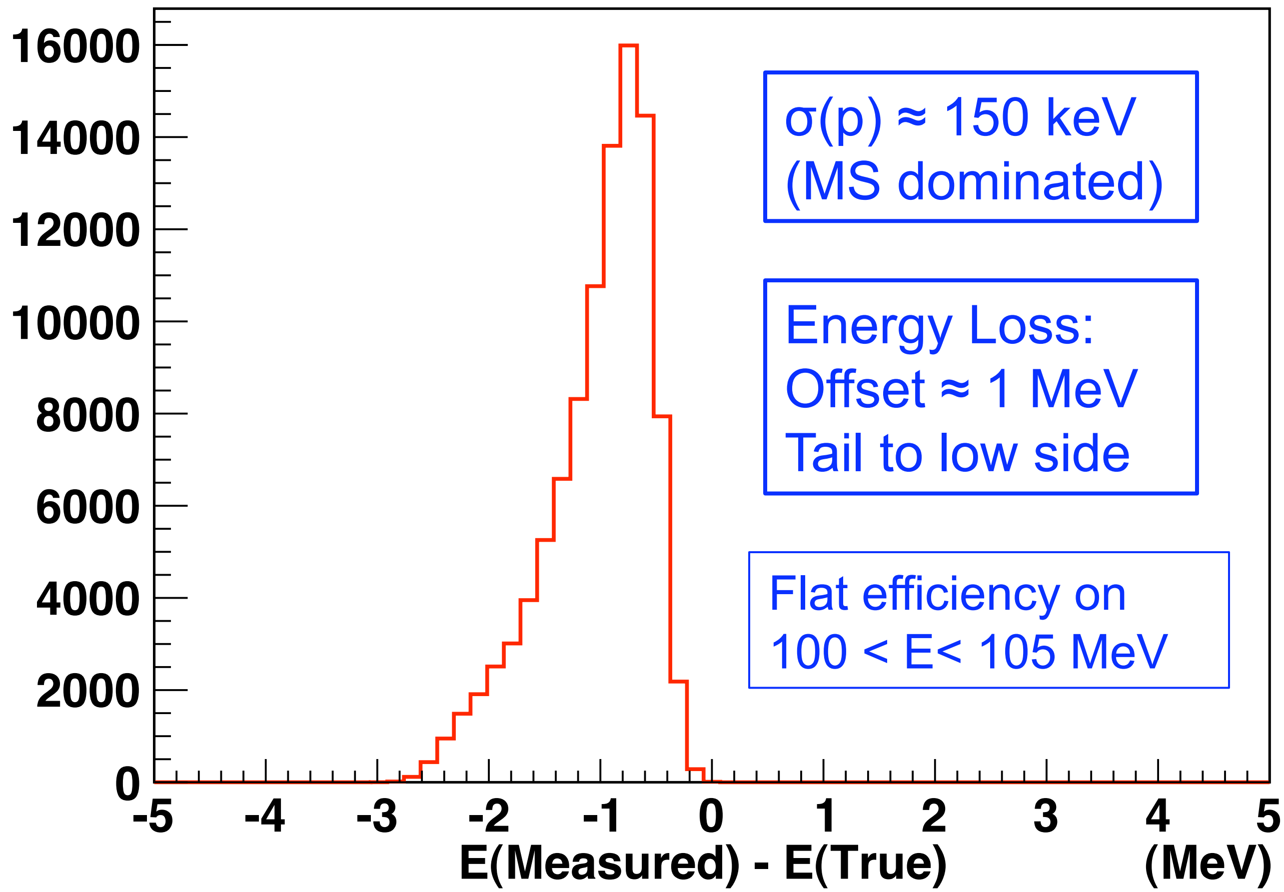
- Example shown using Super Symmetry (SUSY).
- Rates depend on SUSY parameters.
- Most Beyond SM scenarios predict rates >> SM.
- If SUSY is observable at LHC, Mu2e should see O(40) events with background <0.5 !

Conversion in A Perfect Detector

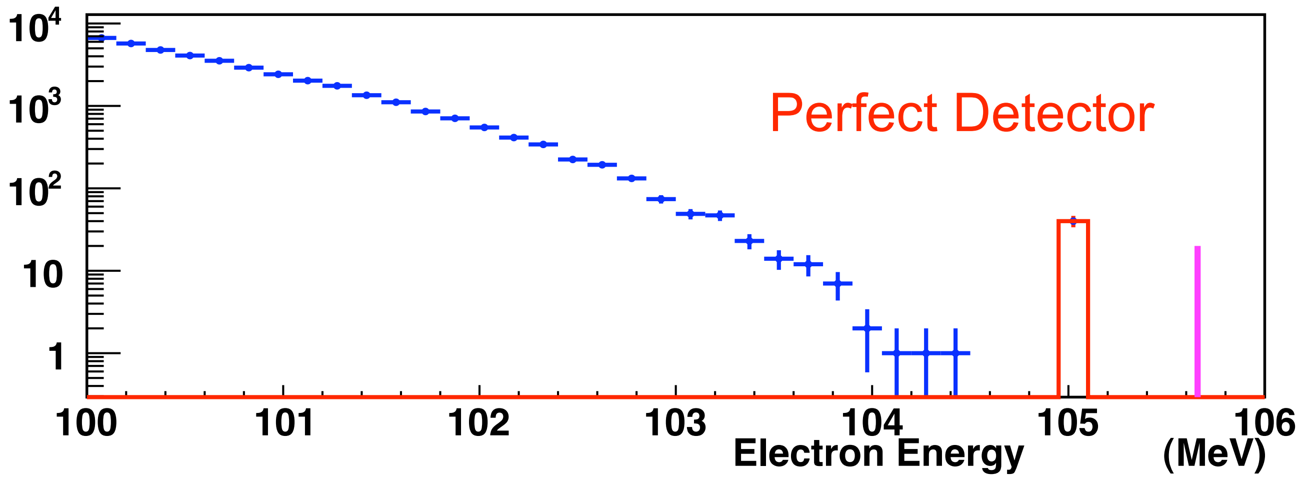


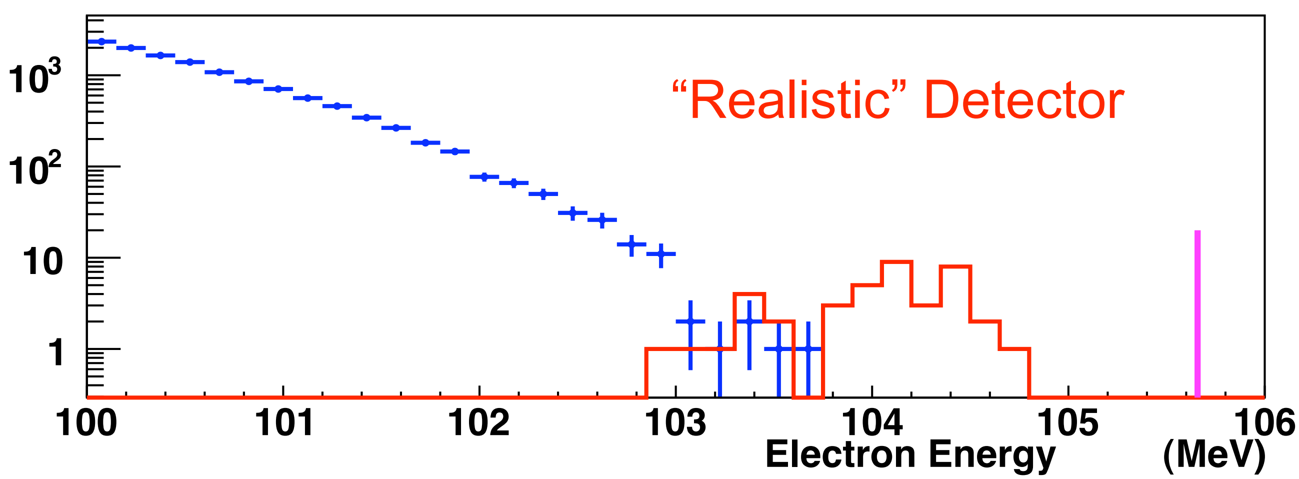
SES = Single Event Sensitivity.

Simple Model of Detector Response

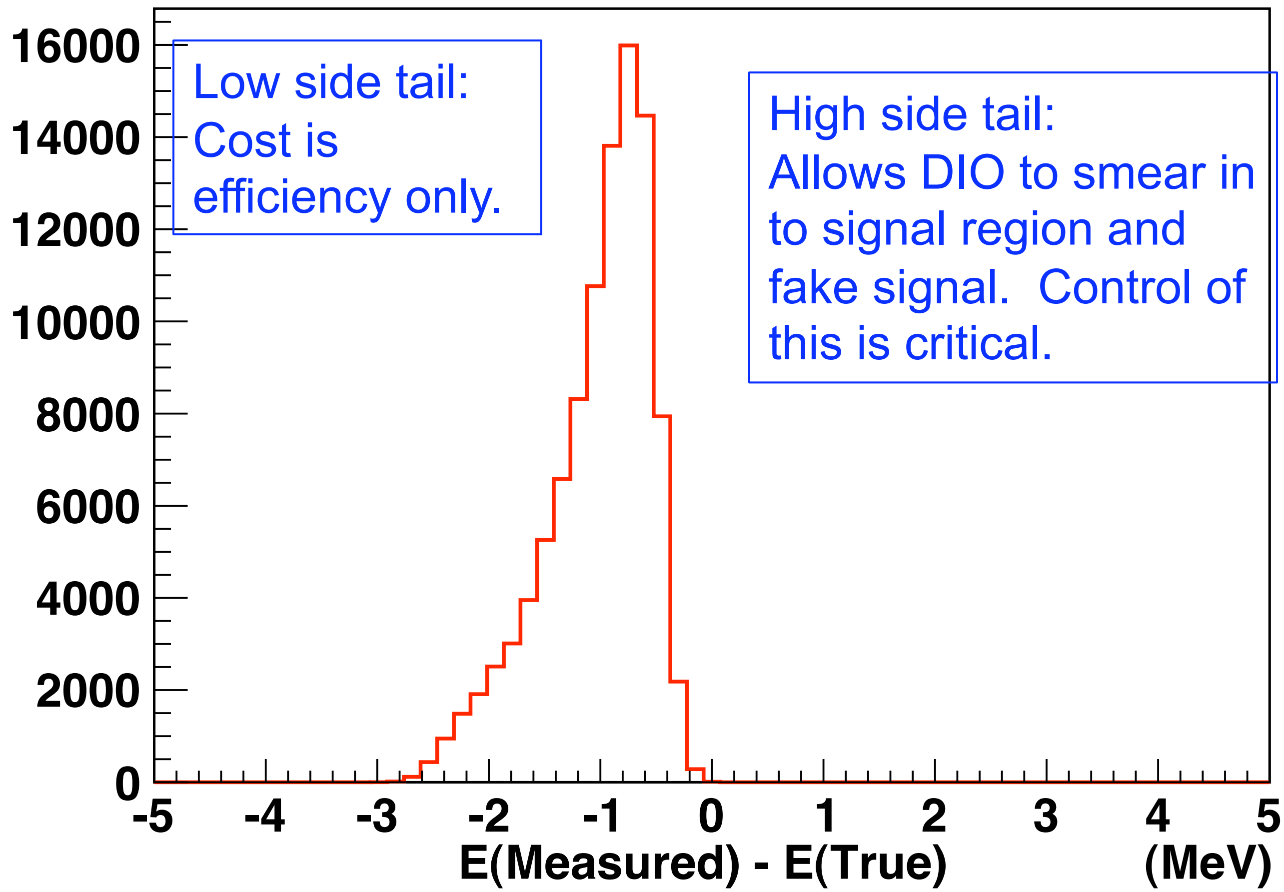


Detector Effects





Simple Model of Detector Response



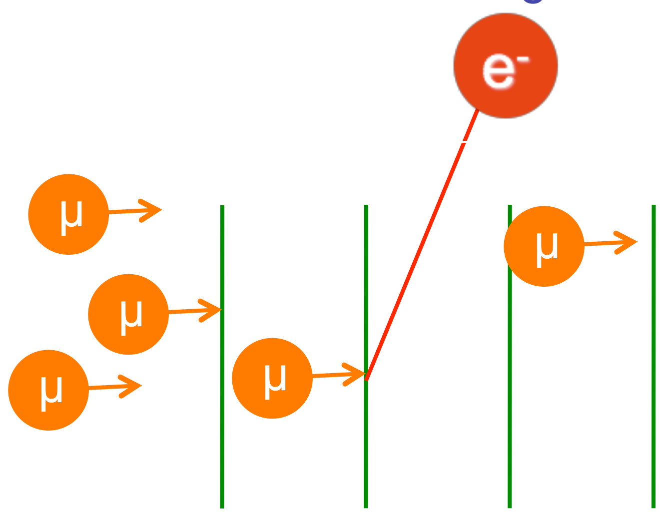
What do We Measure?

$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1))}$$

- Numerator:
  - Do we see an excess at the E_e end point?
  - Any signal is physics beyond SM.
- Denominator: Normal muon capture on Al.
- Sensitivity for a 2 year run (2×10^7 seconds).
  - $\approx 2.3 \times10^{-17}$ single event sensitivity.
  - $< 6 \times10^{-17}$ limit at 90% C.L.
  - 10,000 × better than previous limit (SINDRUM II).

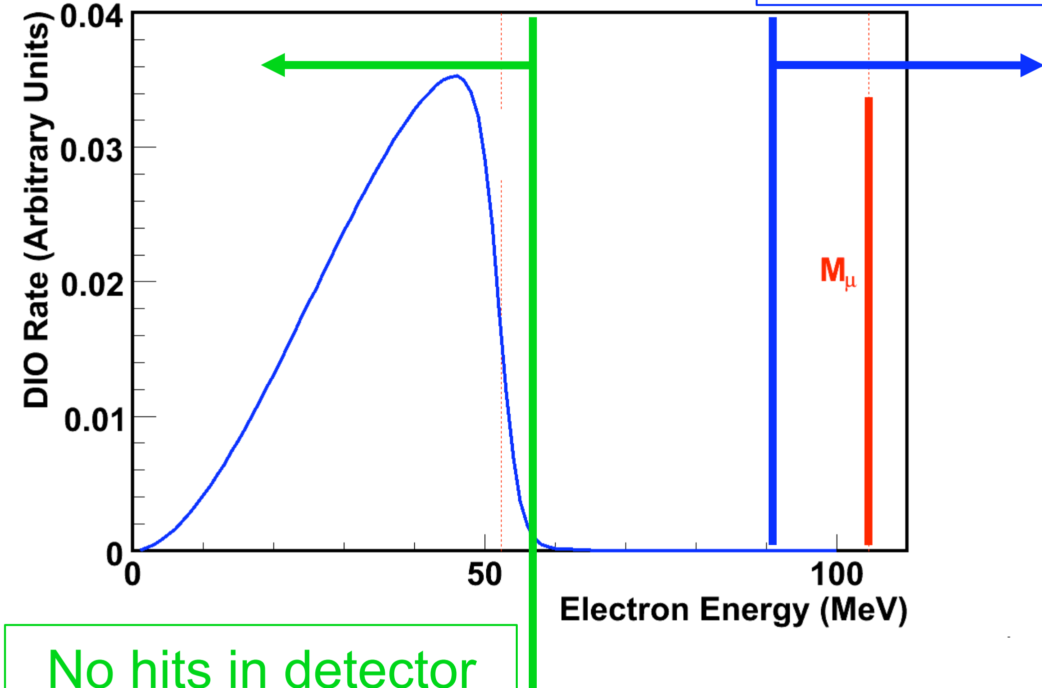
A Cartoon of the Experiment

- Muon pulse on thin Al target foils; capture.
- Wait for prompt backgrounds to go away, 700 ns.
- Measure E_e for electrons for 900 ns.
- Repeat every 1.7 μs.
- Look for peak at endpoint of E_e spectrum.



How do you measure 2.3×10^{-17} ?

Reconstructable tracks

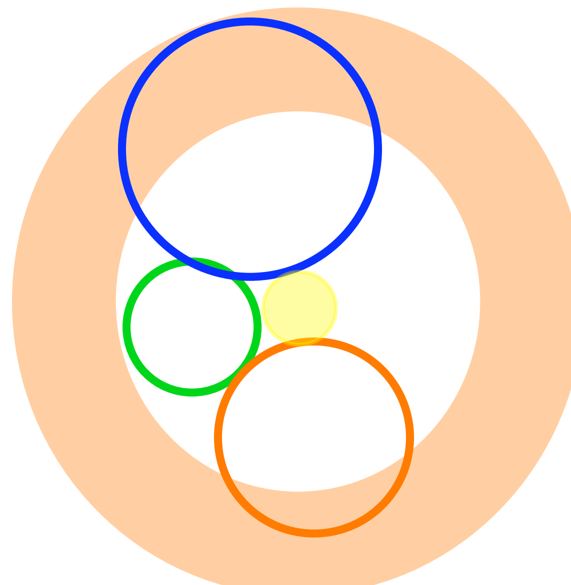


No hits in detector

Some hits in detector.
Tracks not reconstructable.

Instrumented Region

Target Foils



Beam’s-eye view of a generic magnetic spectrometer; solenoidal magnetic field into the page.

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Why do Mu2e?

- Access physics beyond the Standard Model (SM).
  – Precision measurements and searches for ultra-rare processes complement direct searches at the highest available energies.
- Negligible standard model backgrounds.
  – Wide discovery window.
  – Any non-zero observation is evidence for physics beyond SM.
- Violates conservation of lepton family number.
  – Already observed in neutrino sector.
  – Addresses the puzzle of generations.
  – Strength (or absence) of particular CLFV signals can help remove ambiguities from new physics signals seen elsewhere.
- Overlap with the physics explored by measuring muon g-2.

CLFV

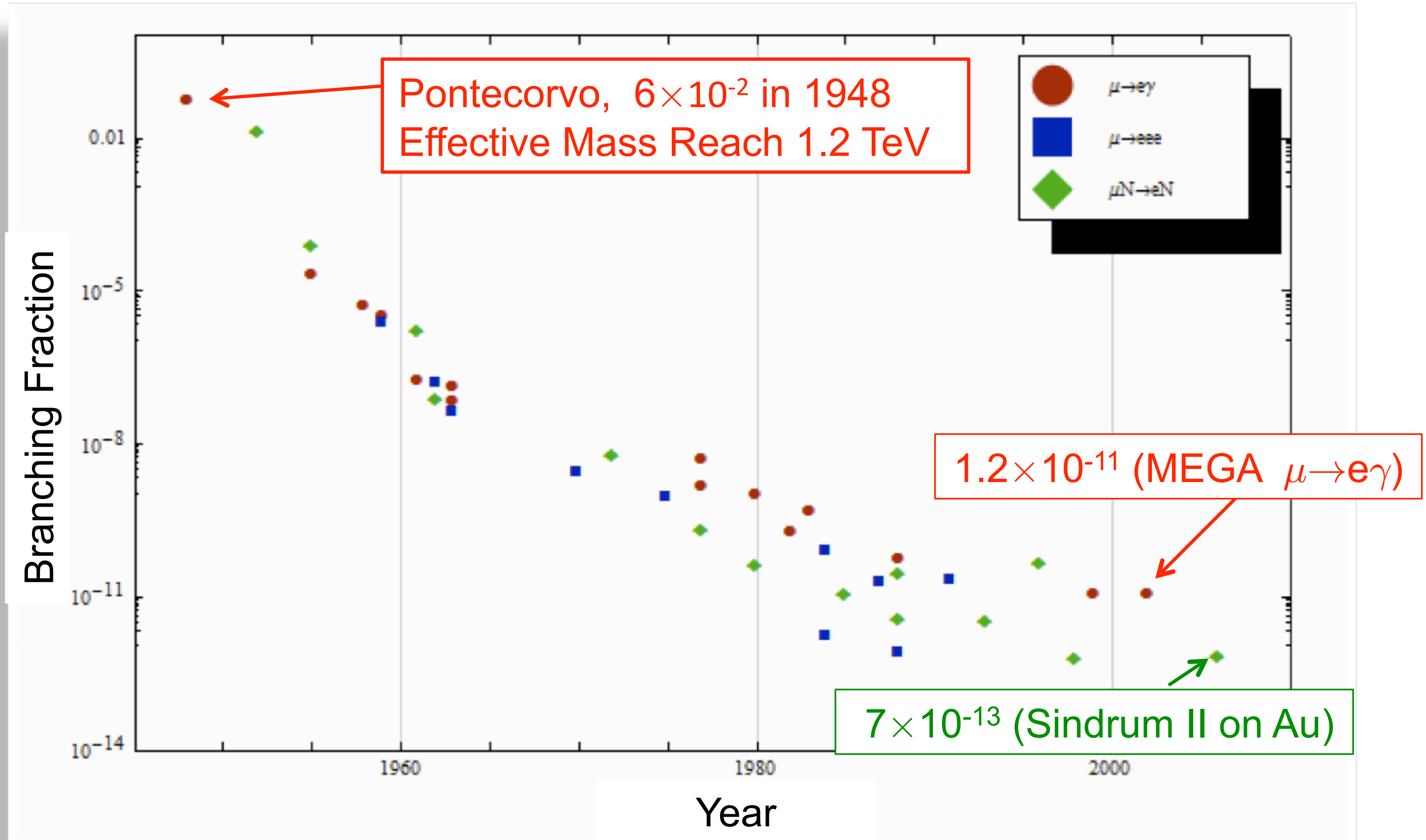
- Charged Lepton Flavor Violation
- Extremely rich phenomenology
- Widely explored at a variety of detectors

$$\mu \to e\gamma \quad \mu \to e^+e^-e^+ \quad K_L^0 \to \mu e \quad B^0 \to \mu e$$

$$\tau \to \mu\gamma \quad \tau \to \mu^+\mu^-\mu^+ \quad D^+ \to \mu^+\mu^+\mu^-$$

- So far only upper limits.
- Most beyond SM scenarios have rates >> SM.

History of μ LFV Measurements

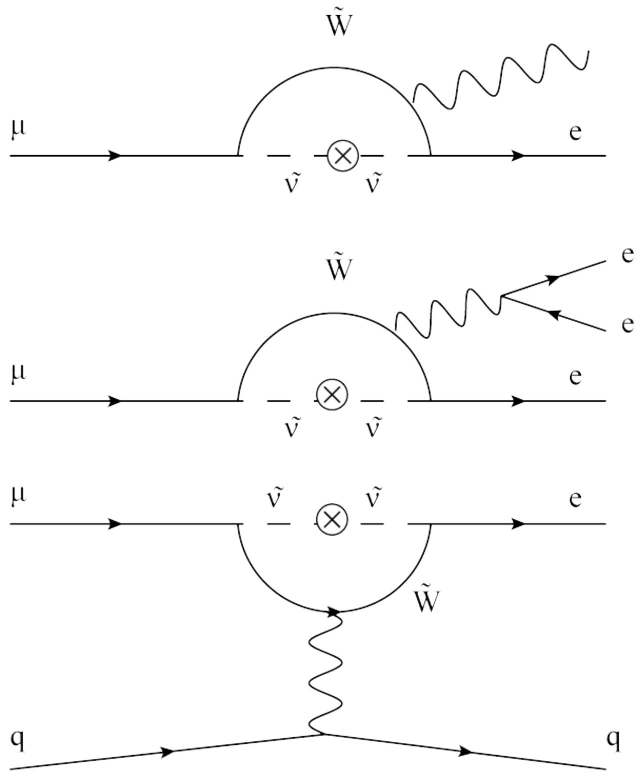


CLFV in Muon Decays

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

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

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



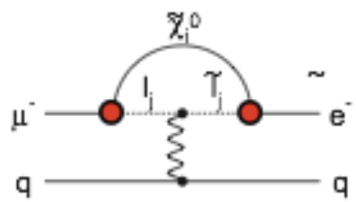
- Loops shown with SUSY; also works with heavy ν.
- If loops dominate over contact terms, then rates follow ≈ 400: 2: 1
- Contact terms do not produce μ➔eγ; so conversion can dominate over μ➔eγ .

$$\Gamma\left(\mu^- \rightarrow e^- e^+ e^-\right) < 1.0 \times 10^{-12} \quad \Gamma\left(\mu^- \rightarrow e^- \gamma\right) < 1.2 \times 10^{-11}$$

Contributions to μe Conversion

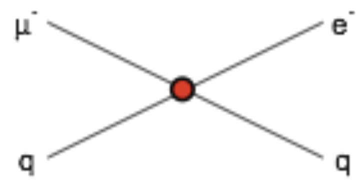
Supersymmetry

rate ~ 10^{-15}



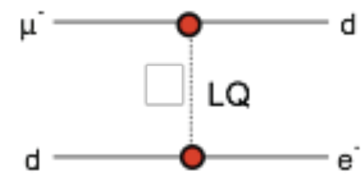
Compositeness

$\Lambda_c \sim 3000$ TeV



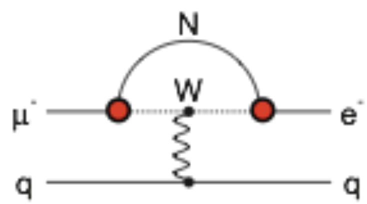
Leptoquark

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



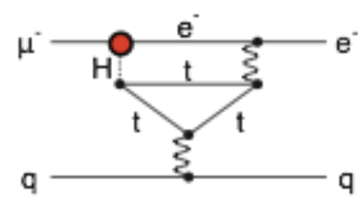
Heavy Neutrinos

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



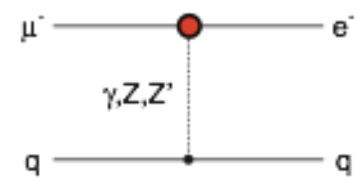
Second Higgs Doublet

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



Heavy Z' Anomal. Z Coupling

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



Sensitive to mass scales up to O(10,000 TeV)!

Do not contribute to μ→eγ

See Flavour physics of leptons and dipole moments, arXiv:0801.1826

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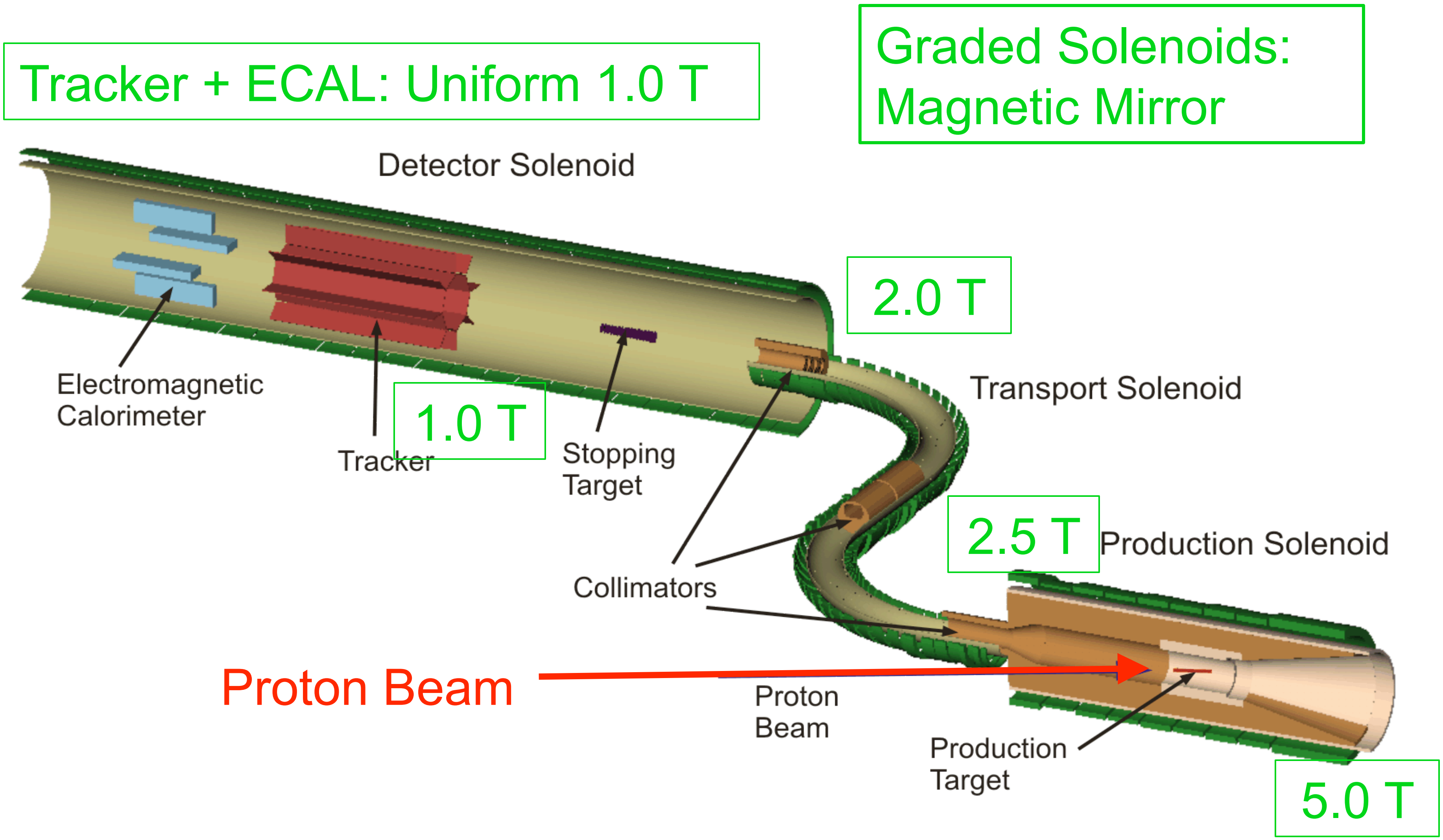
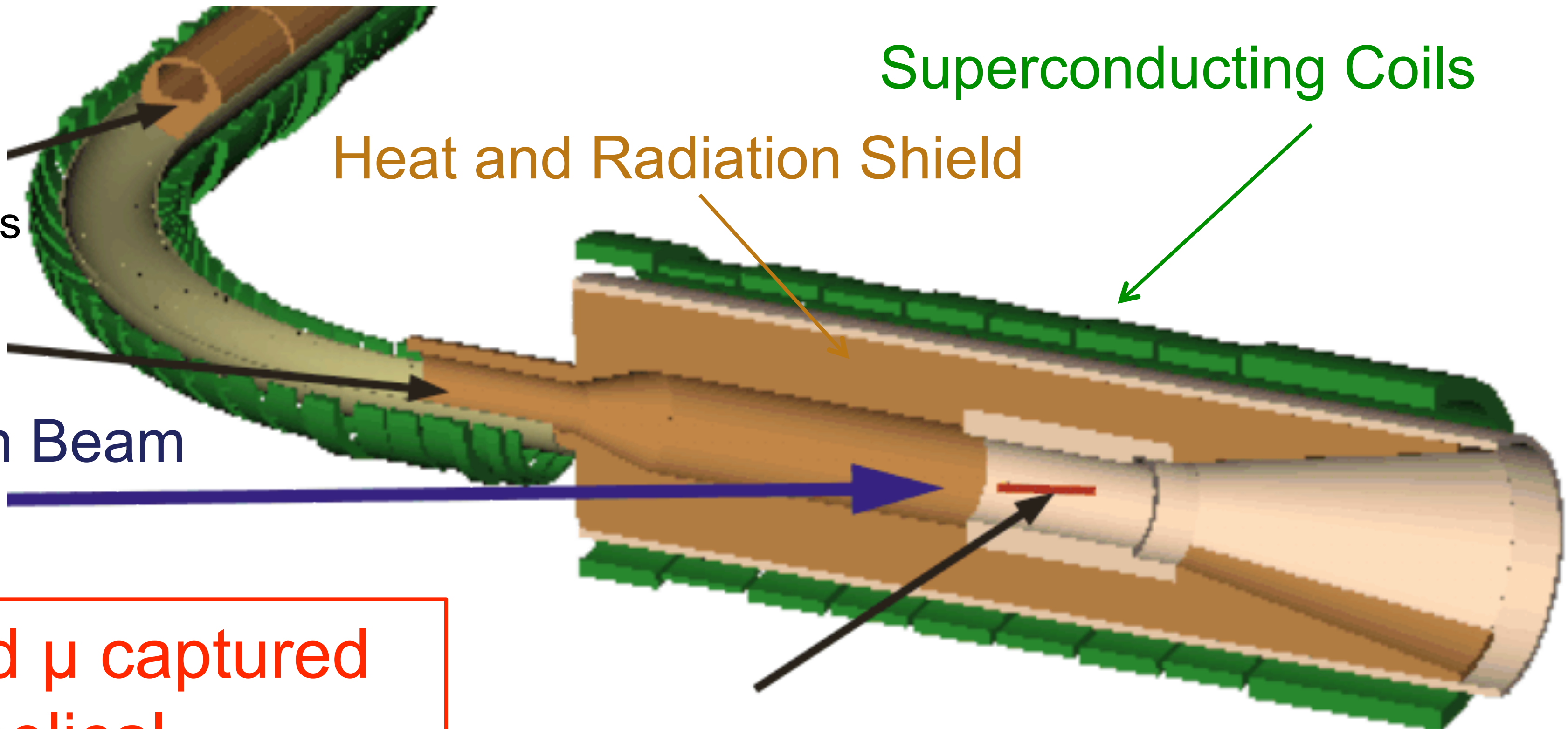
Credits

- Mu2e is an evolution of previous work
- MELC
  - 1992 proposed at Moscow Meson Factory
  - Basic idea of the muon beamline.
- MECO
  - 1997 Proposed
  - 1998-2005 Technical Design
  - 2005 Cancelled due to broader financial reasons.

A Backscattered Muon Beam



Production Solenoid

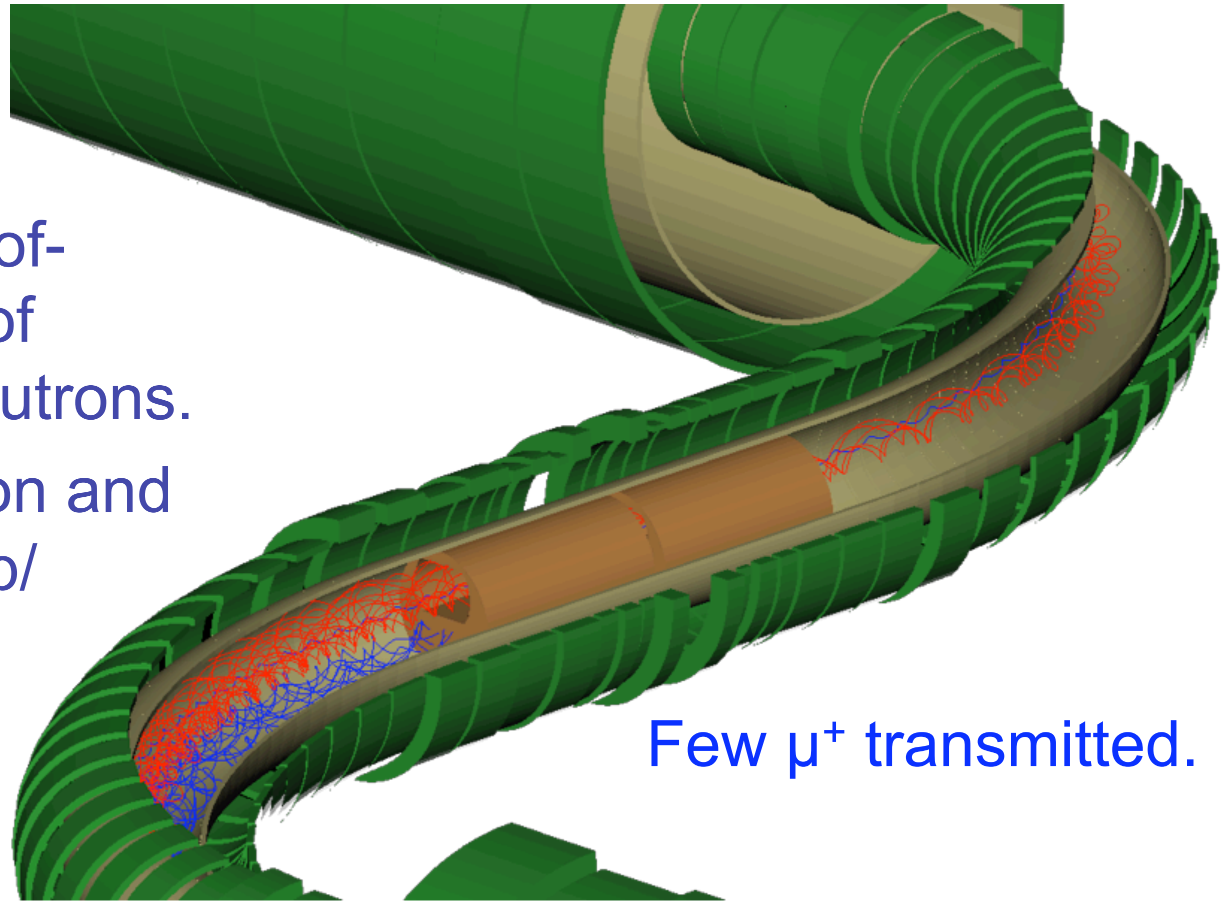


π and μ captured into helical trajectories

$$p\ Au \rightarrow \pi^- X \rightarrow \mu^- X$$

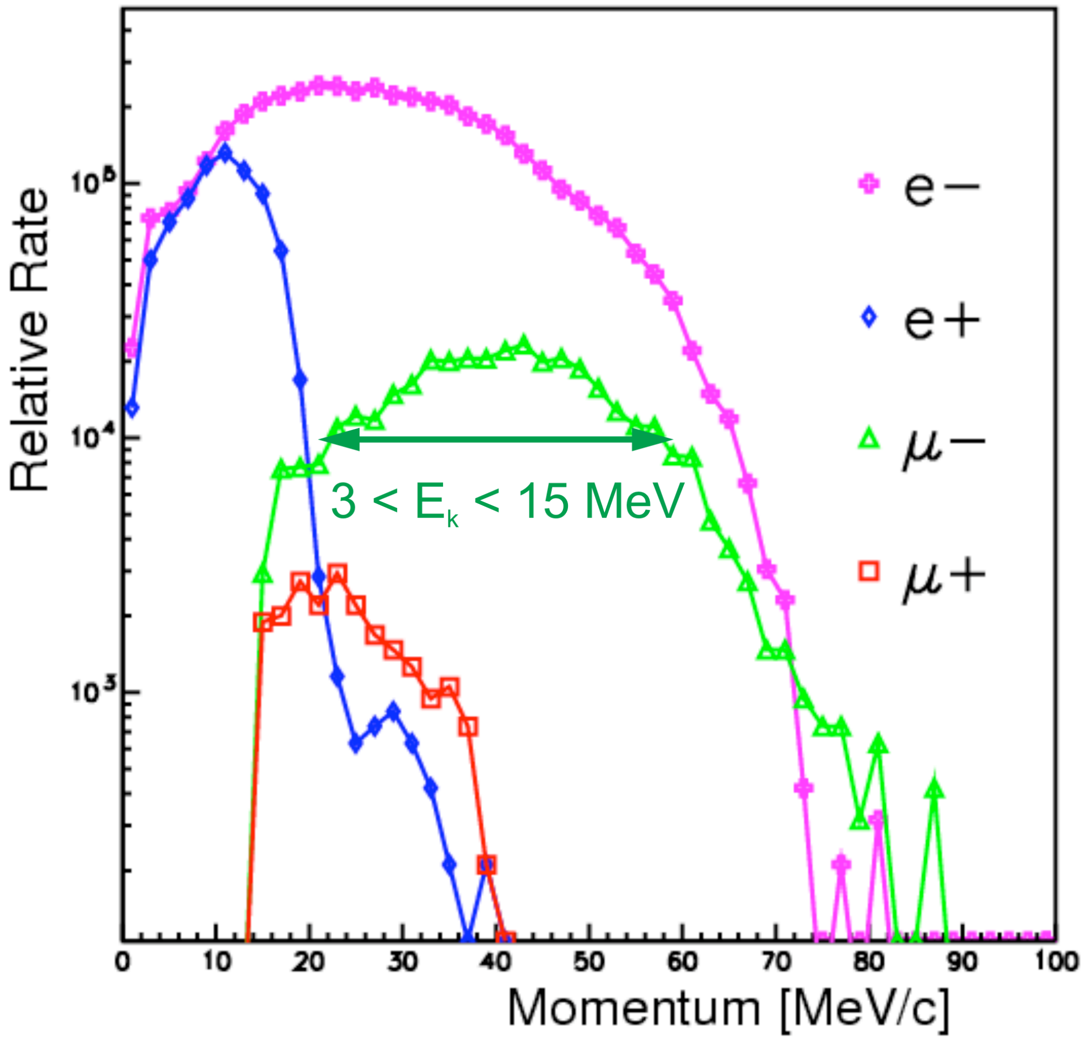
Transport Solenoid

- Curved solenoid:
  - Eliminates line-of-sight transport of photons and neutrons.
  - Negative/position and particles shift up/down.
- Collimators sign and momentum select the beam.



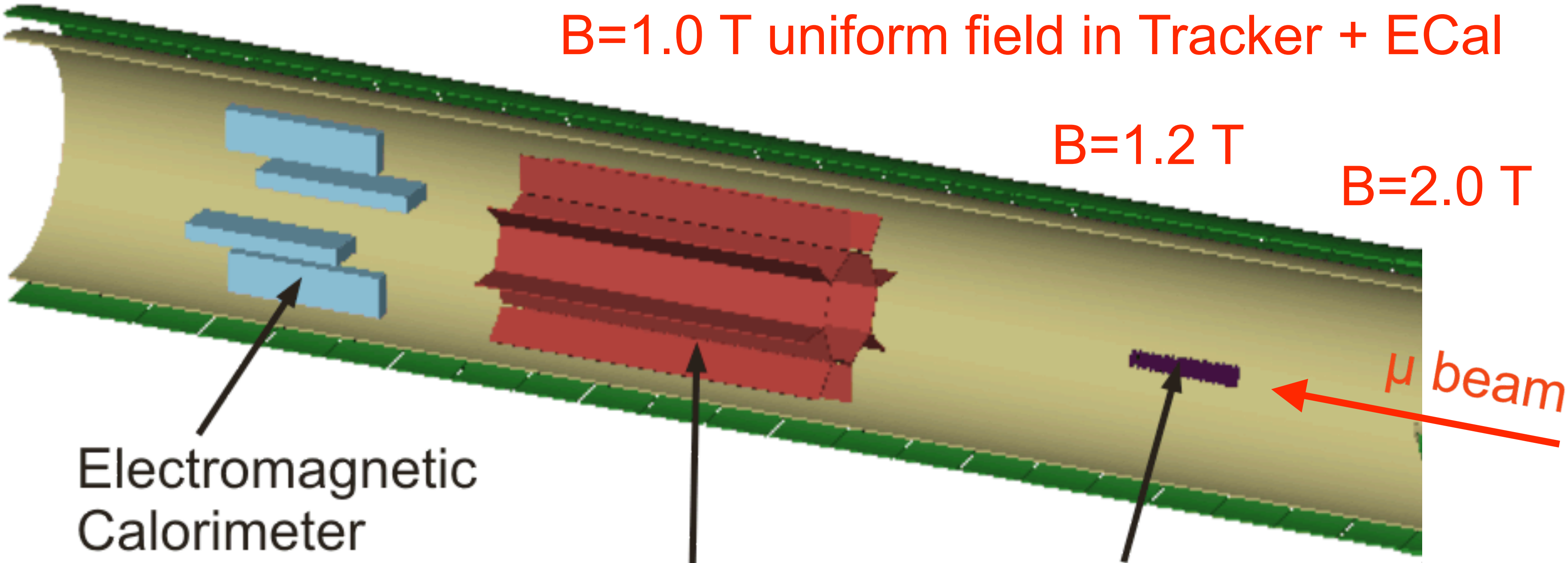
13.1 m along axis × *~0.25 m*

Particle Content of Muon Beam



- Electrons must not have energies in the signal region!
- Plus pions, which are an important source of background.

Detector Solenoid and Detector



Trigger + confirmation of a real track.

Tracker

Precision momentum measurement:

Require:

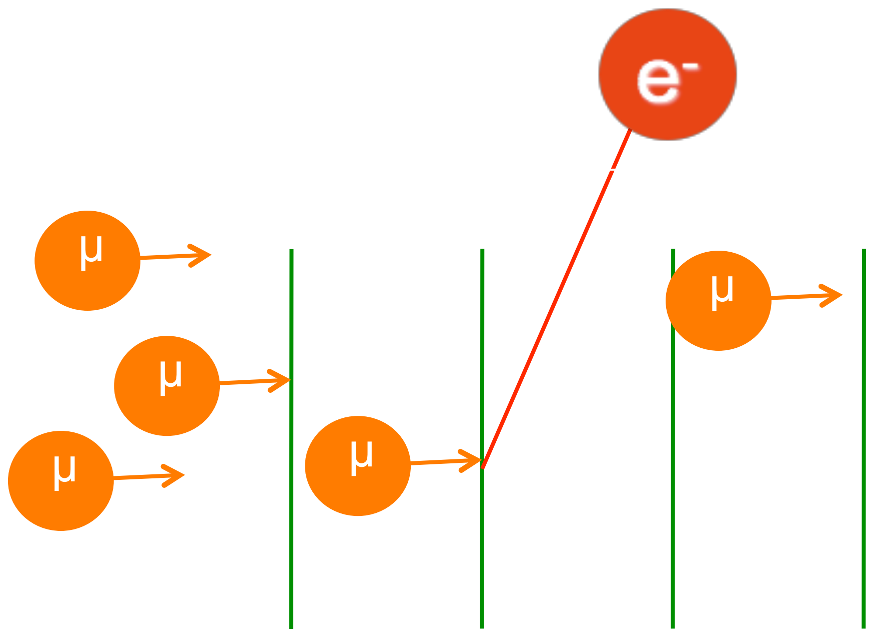
$\sigma(p) \approx 150$ keV at p=105 MeV

Stopping Target

In graded field

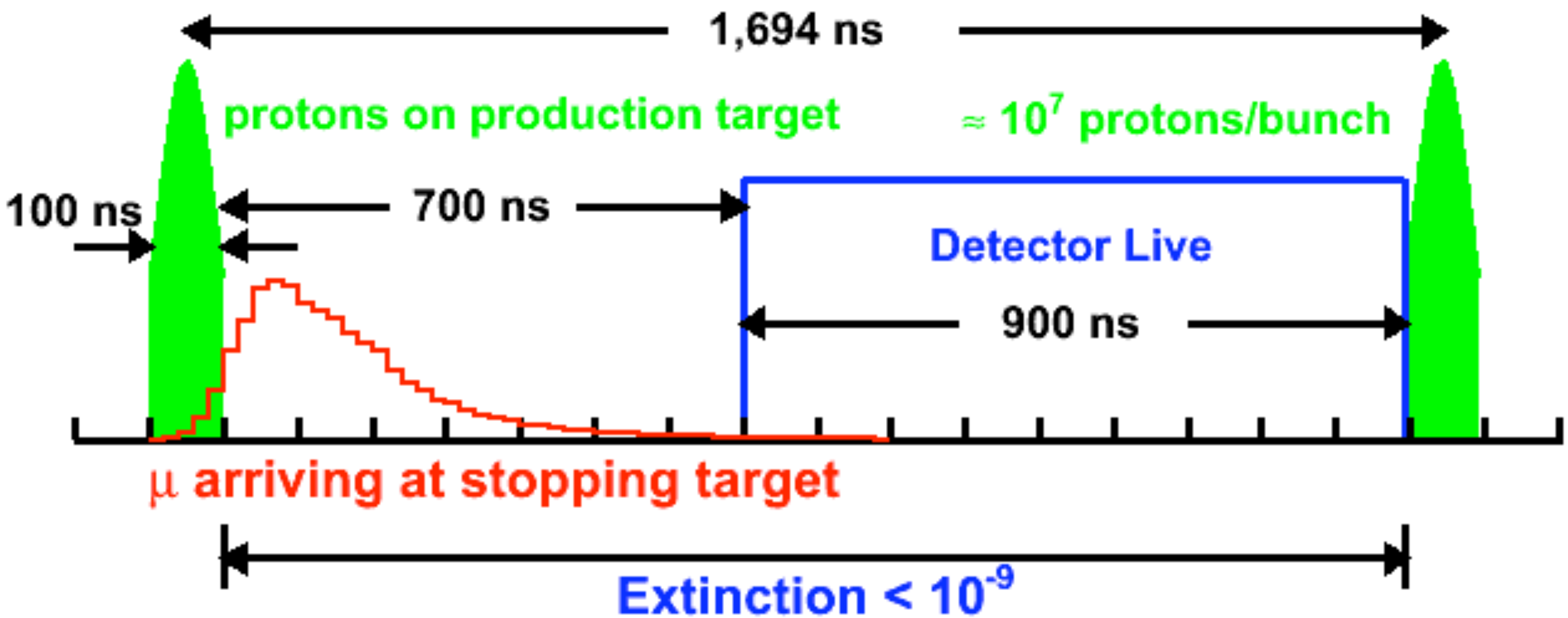
At the Stopping Target

- Pulse of low energy μ^- on thin Al foils.
- 1 stopped μ^- per 400 protons on production target.
  - X-ray cascade emitted during capture: normalization!
- Electrons pop out of foils (lifetime of 864 ns)



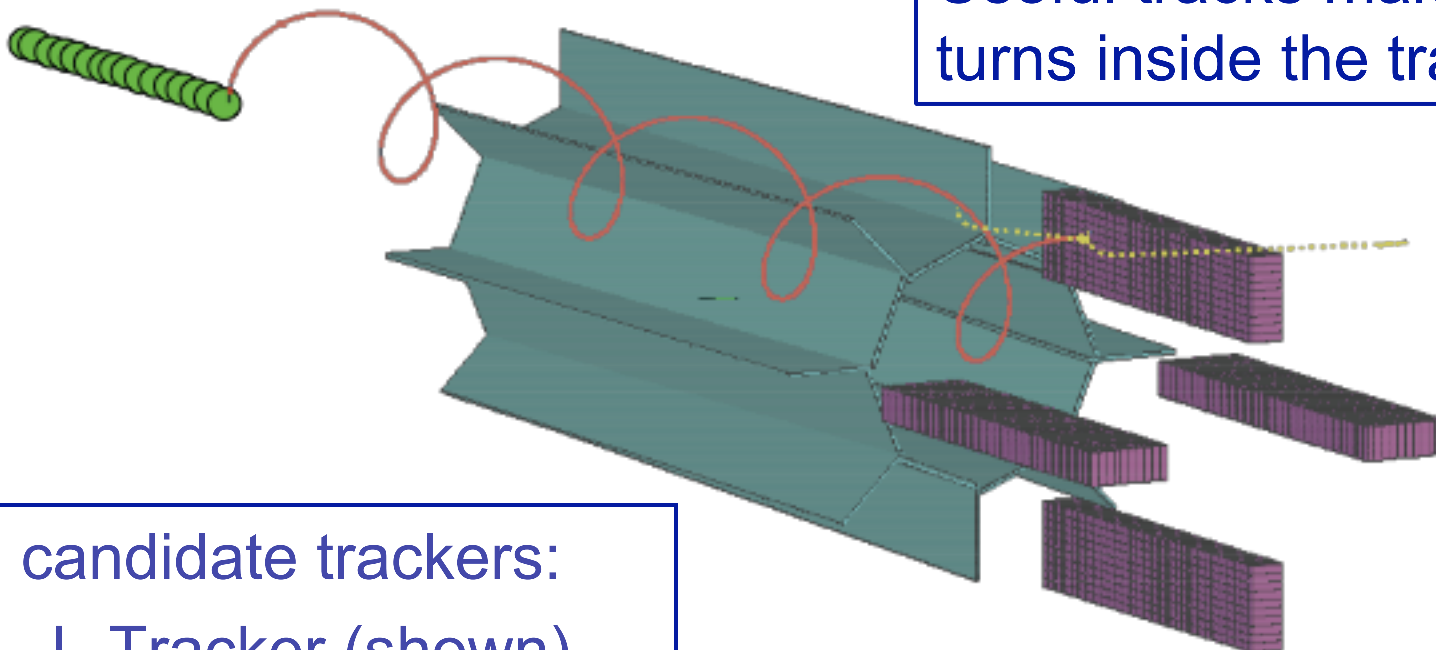
- 17 target foils
- 200 microns thick
- 5 cm spacing
- Radius:
  - ≈10. cm at upstream
  - ≈6.5 cm at downstream

One Cycle of the Muon Beamline



- μ^- accompanied by e^-, e^+, π^-, …, which make backgrounds
- "Extinction" required to reduce backgrounds.
  - 1 out of time proton per 10^9 in time protons.
- Lifetime of muonic Al: 864 ns.

Detector

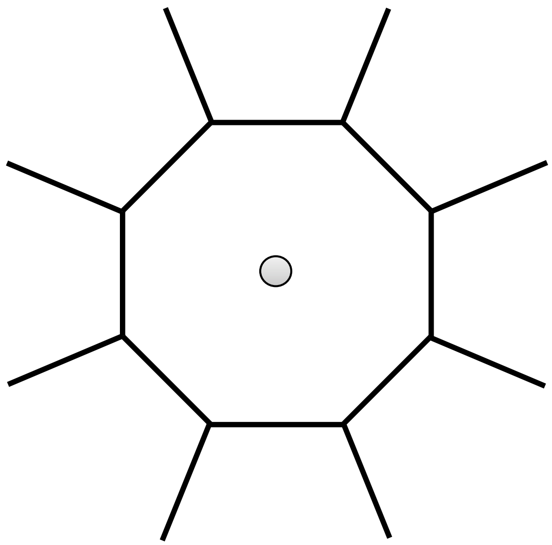


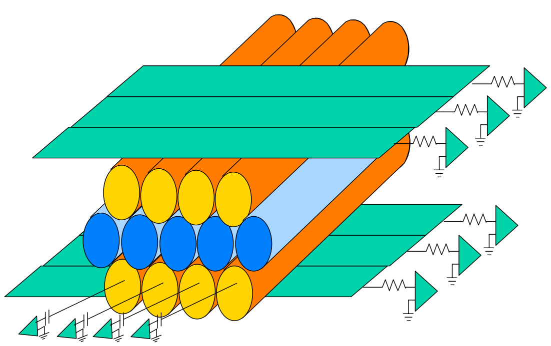
Useful tracks make 2 or 3 turns inside the tracker.

- 3 candidate trackers:
  - L-Tracker (shown)
  - T-Tracker
  - I-Tracker

L-Tracker (L=Longitudinal)

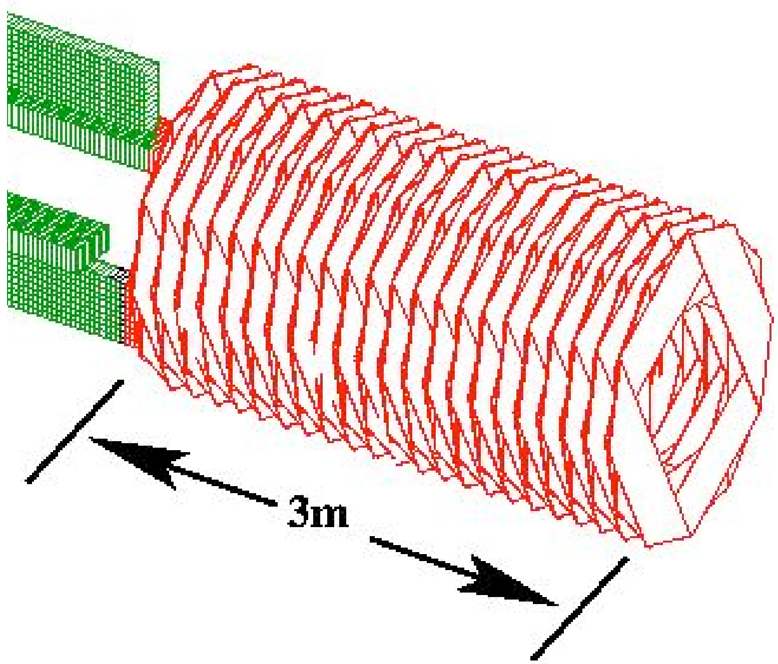
XY Cross-section of LTracker





- Octagon + vanes.
- ≈ 2800 axial straws in vacuum
  - ≈ 2.6 m long; 5 mm diameter
  - 25 μm wall thickness
- 3 layers; hex close packed.
  - Resistive walls on outer layers.
  - Cathode pads for z position.
- p_T < 55 MeV curls inside octagon.
- Issues:
  - Mechanical design; especially the cathode sheets.
  - High rates on resistive straws not yet demonstrated.
  - Enough measurements/track?

T-Tracker (T=Transverse)

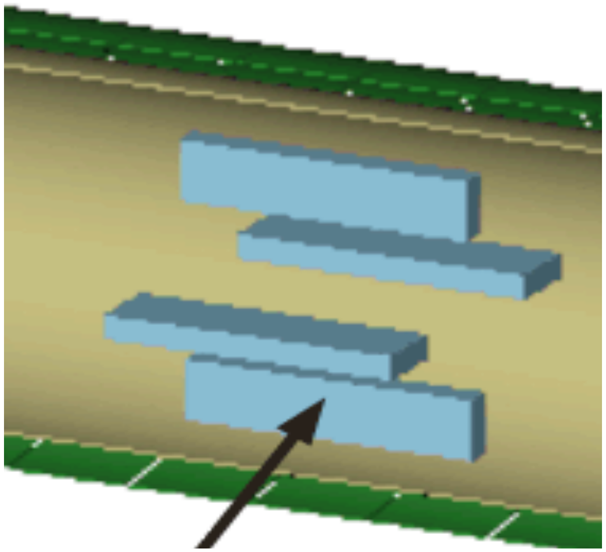


- ≈ 13,000 straws in vacuum.
- 70-130 cm long; 5 mm diameter.
- 260 sub-planes; ≈ 60 straws each.
- Conducting straws
  - Rates demonstrated in KTeV.
- Possible charge division?
- Straw ends are outside of the fiducial volume: support and readout easier.
- Issues:
  - Robust pattern recognition not yet demonstrated.
  - High priority to do so.

I-Tracker (I=Italian)

- Proposed by group from INFN Lecce.
- KLOE style cluster counting drift chamber.
  - Axial and stereo layers.
  - Central region empty (as with L and T).
- Advantage:
  - Robust pattern rec.; many measurements per track.
- Issues:
  - Material budget in upstream endplate.
  - Rates.

Crystal Calorimeter

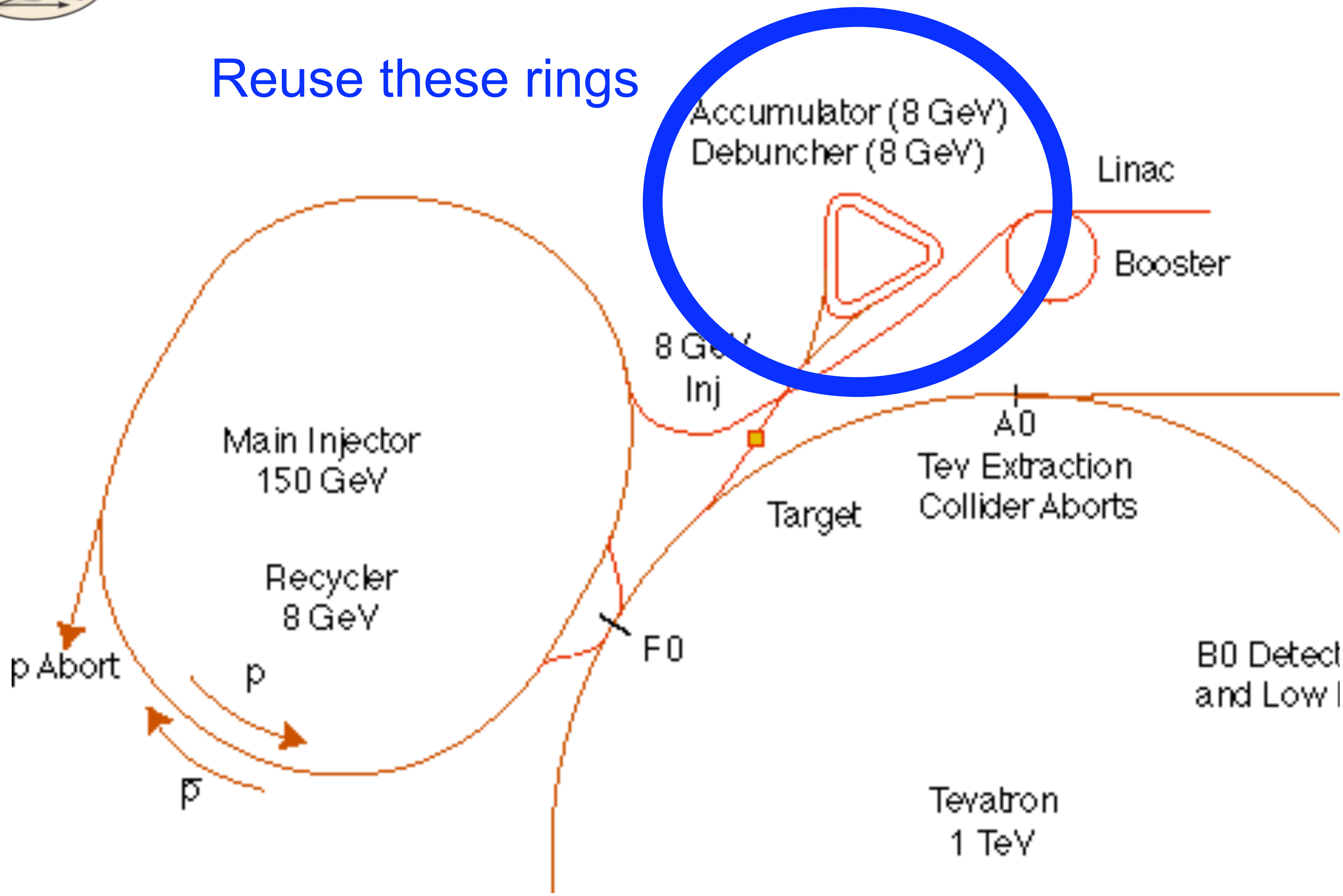


- 1024 $PbWO_4$ crystals.
  - 3.5×3.5×12 cm
- $\sigma(E)/E \approx 5$ MeV
- Main job is to trigger on interesting tracks.
- Spatial match of extrapolated track will help reject badly mis-reconstructed tracks.
- Most tracks from DIO curl inside.
- Pisa and LNF groups evaluating LXe, LSO, LYSO which might provide good enough $\sigma(E/p)$ to be interesting.

Other Systems

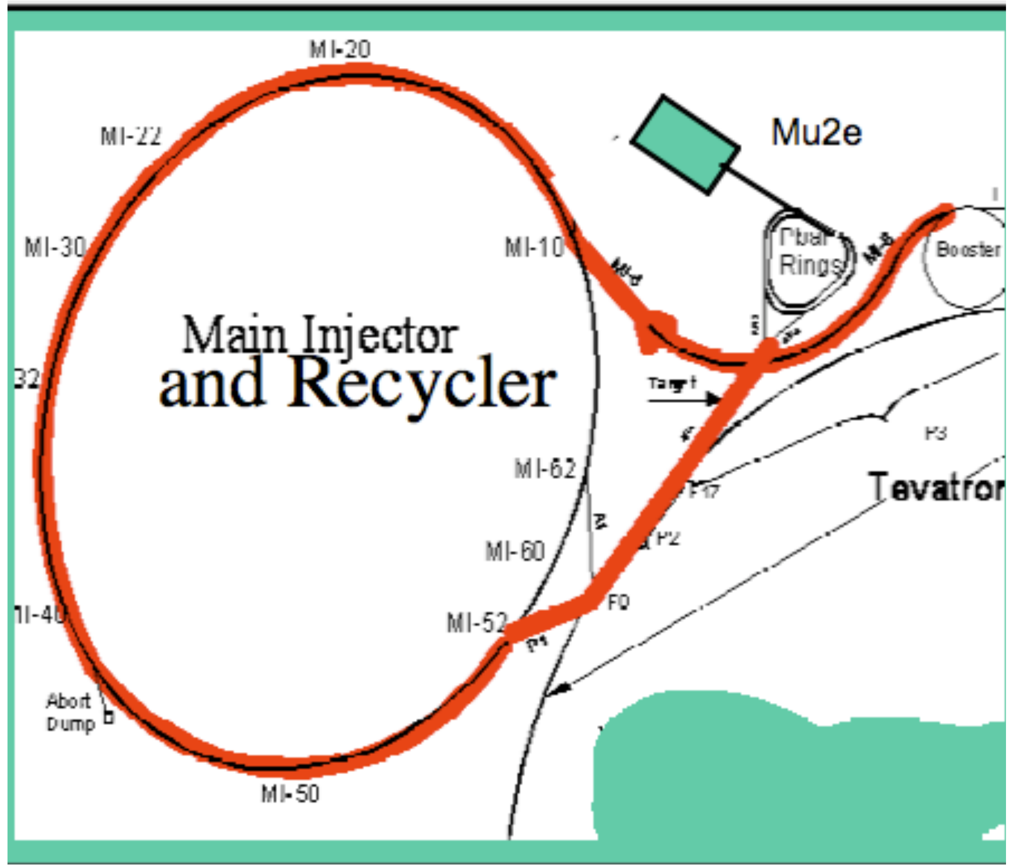
- Active Cosmic Ray Veto
  - 3 Layers of 1 cm thick scintillator;
    - MINOS Style WLS fiber readout.
  - Requirement: 99.99% efficiency to veto cosmic rays.
  - Do we need 4 layers?
- Muon Capture Monitor
  - One way to get at the denominator in Rμe.
  - Measure X-ray lines from muon capture on Al.
  - Ge detector located downstream of main beam dump.
  - Views target foils via tiny bore holes.

Proton Delivery



Proton Delivery and Economics

- Reuse existing Fermilab facilities with modest modifications.
- p-bar complex: 2 rings.
  - Use one ring as a “stash”.
  - Slow spill from the other.
  - 90% duty cycle slow spill.
  - Other schemes under study.
- Sharing p’s with NOVA:
  - NOVA 12/20 booster cycles.
  - Mu2e will use 6/20 cycles.



Making a stable, slow spill with a very intense proton beam is a big challenge.

Major Backgrounds

- From stopped μ^-
  - Decay in orbit (DIO) close to end point.
    - Irreducible component.
    - Mismeasured DIOs can smear into the signal region.
- Beam related (aka “prompt”):
  - Radiative π^- capture.
  - μ^- decay in flight + scatter in target.
  - Radiative μ^- capture.
  - e^- scattering out of beam.
- Cosmic rays

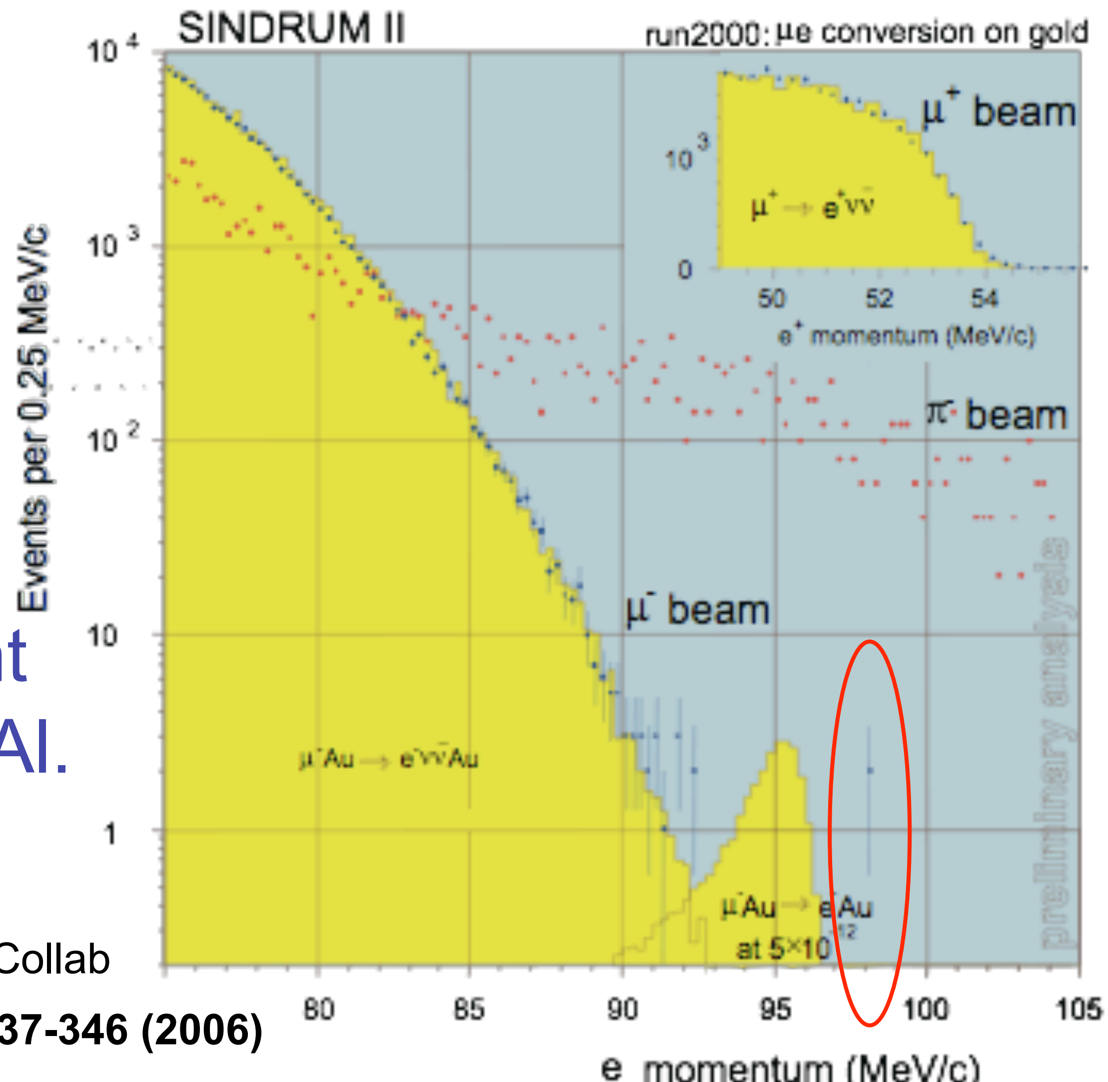
Radiative π^- Capture

$$\pi^- N(A,Z) \to \gamma X$$

- End-point of Eγ spectrum is m(π).
- Asymmetric conversions (internal or in material) can produce electrons at all energies up to m(π).
  - Includes the signal region.
- Believed to be the limiting background in SINDRUM II
- Mitigate by using pulsed beam with excellent extinction.

Previous Best Experiment

- SINDRUM II
- $R_{\mu e} < 6.1\times10^{-13}$ @90% CL
- 2 events in signal region
- Au target: different E_e endpoint than Al.



HEP 2001 W. Bertl – SINDRUM II Collab

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

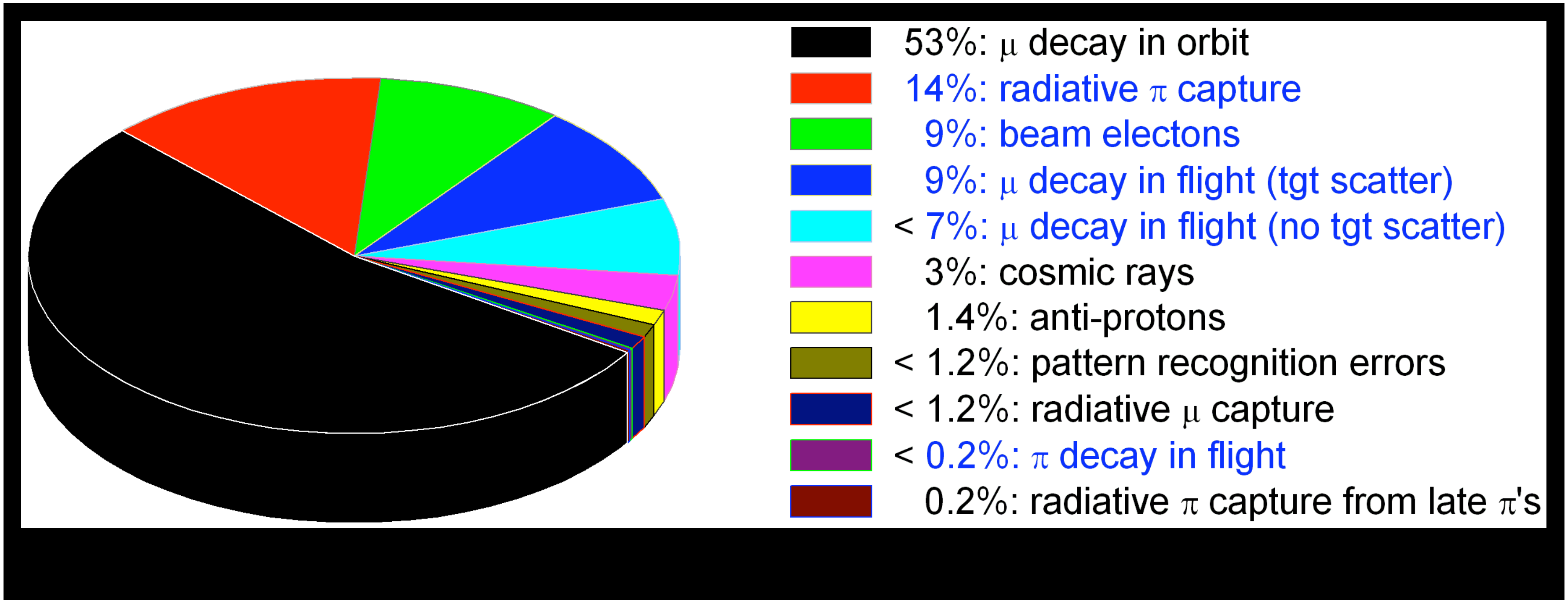
Backgrounds for 2×10^7 s Running

Source	Events	Comment
μ decay in orbit	0.225	
Radiative π^- capture*	0.063	From protons during detection time
Beam electrons*	0.036	
μ decay in flight*	0.036	With scatter in target
Cosmic ray induced	0.016	Assumes 10^{-4} veto inefficiency
Other	0.039	6 other processes
Total	0.42	

*: scales with extinction; values in table assume extinction of 10^{-9}.

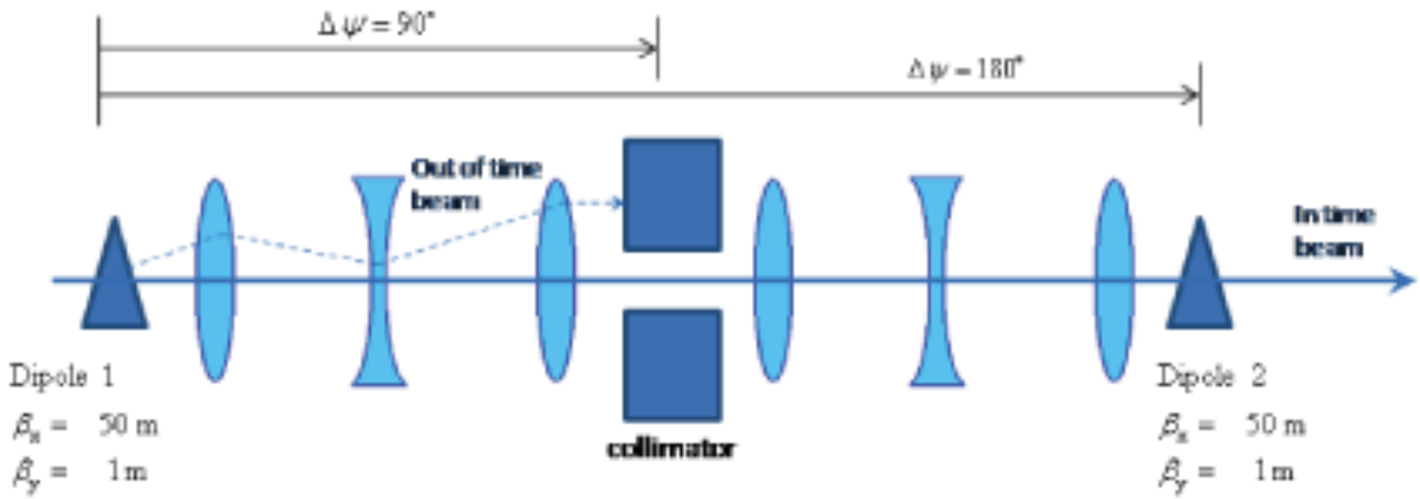
- Reduce DIO BG with excellent energy resolution, obtained by careful design of the tracker.
- Reduce next tier BGs with extinction.
- Reduce cosmic ray BG with shielding and veto.

All Estimated Backgrounds

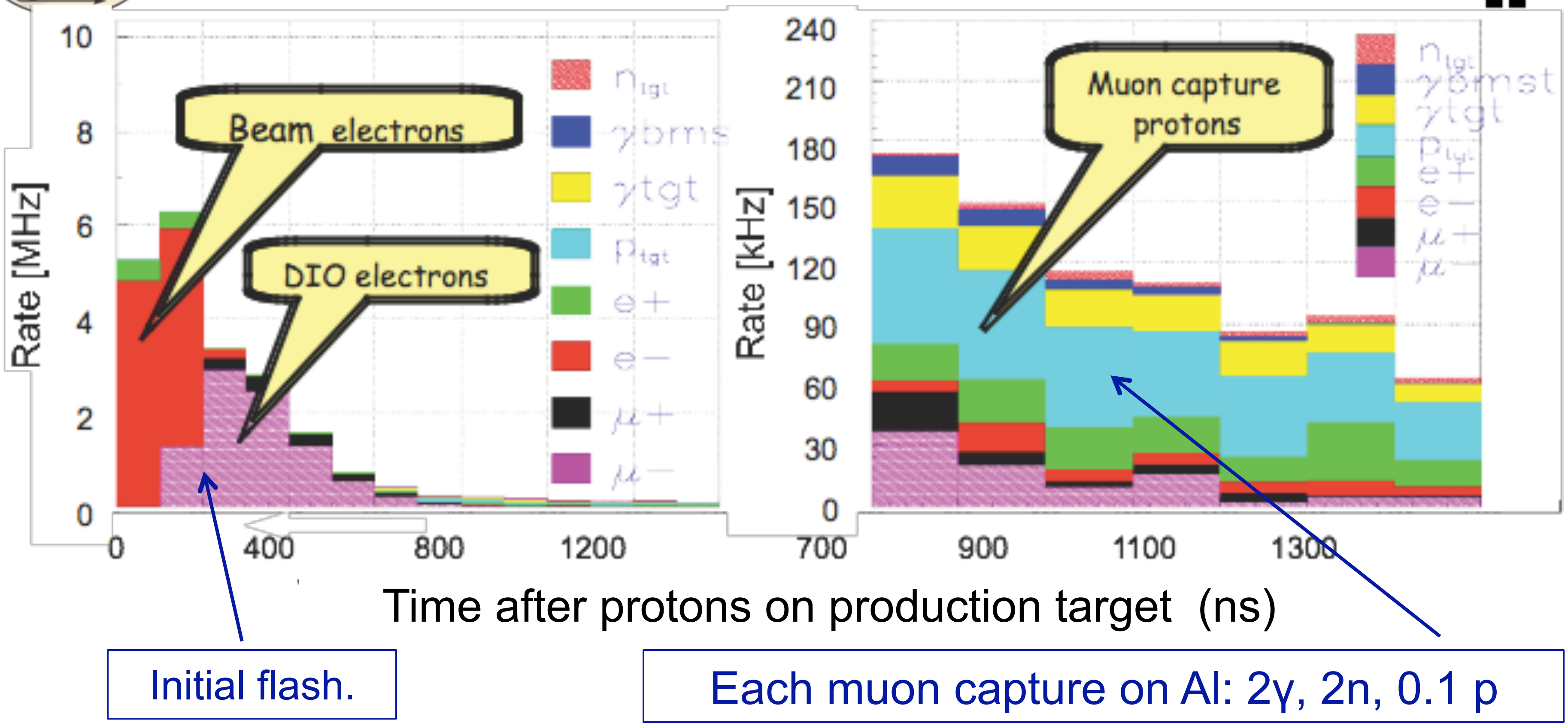


Required Extinction 10^{-9}

- Internal: 10^{-7} already demonstrated at AGS.
  - Without using all of the tricks.
  - Normal FNAL: 10^{-2} to 10^{-3}; but better has not yet been needed.
- External: in transfer-line between ring and production target.
  - Fast cycling dipole kickers and collimators.
- Monitoring techniques under study.



High Rates in the Tracker



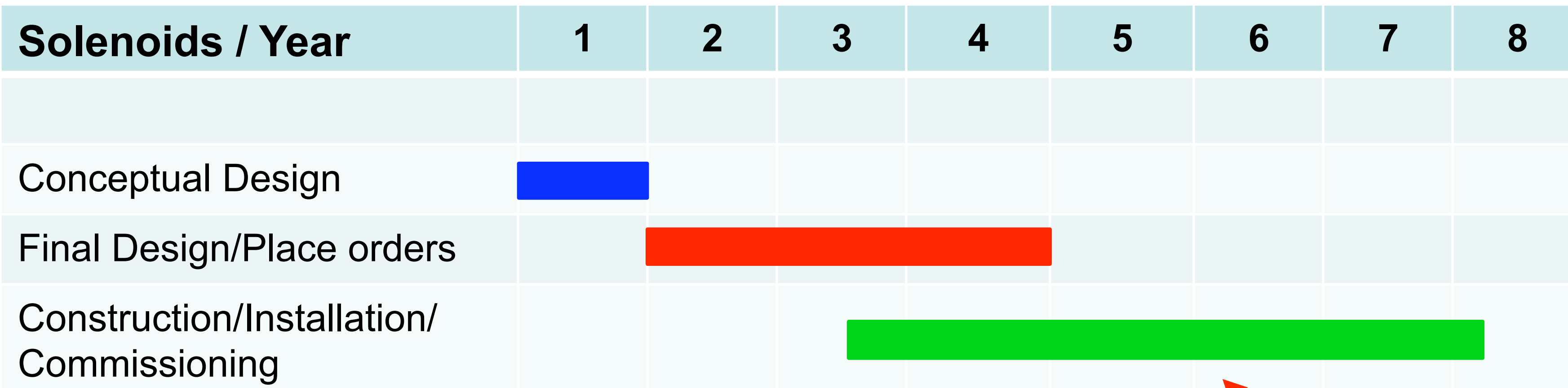
- Option: shield p from μ capture; but shield degrades resolution.
- Must prove that tracker design will perform robustly at these rates.
- Rates in live window imply an occupancy of O(1%).

Outline

- Preliminaries:
  - Canonical Particle Physics in one page.
  - Who are we?
  - Where are we doing our experiment?
- What are we doing?
- Why are we doing it?
- How are we doing?
- When are we doing it?
- Summary and Conclusions.

Estimated Cost and Schedule

- Estimated Total Project Cost O(M$200.).
  - Fully loaded, escalated. Overall contingency ≈50%.
- Critical path: solenoids.
  – Technically limited schedule:



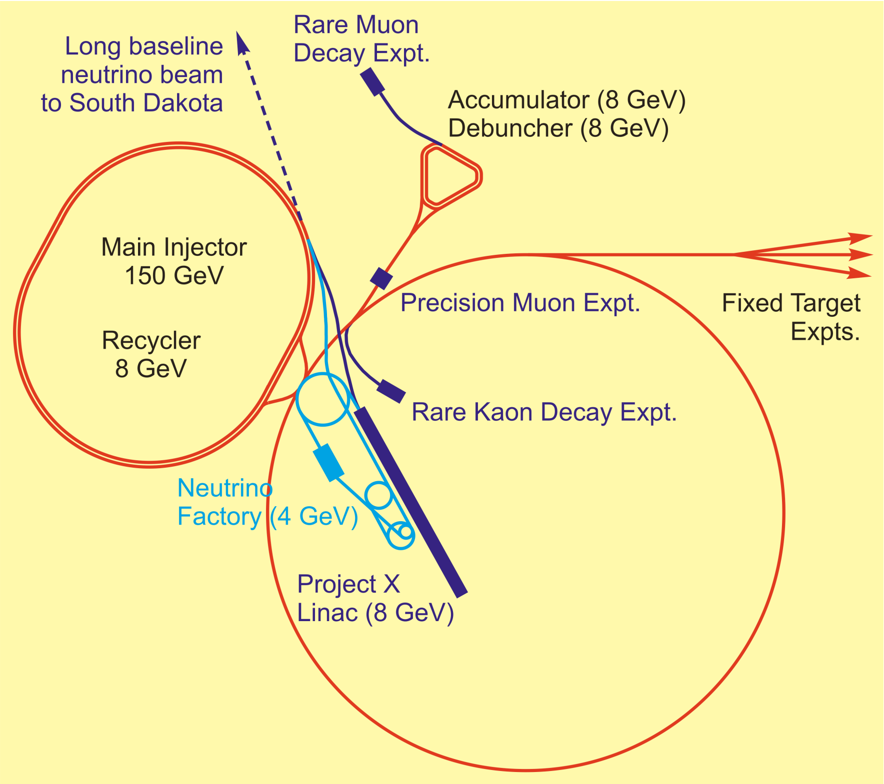
- R&D going on now or soon.
  - PSI: products of μ capture on Al.
  - FNAL: Extinction tests; straw tests.

Now

Opportunities for university groups.

Mu2e In the Project X Era

- Project X: high intensity proton source to replace existing Booster.
  - Booster: 20 kW beam power at 8 GeV.
  - Project X: 200 kW at 8 GeV (with upgrade path to 2000 kW).
  - With corresponding upgrades at 120 GeV.
- If we have a signal:
  - Study Z dependence by changing stopping target.
  - Helps disentangle the underlying physics.
- If we have no signal:
  - Up to to 100 × Mu2e physics reach, $R_{\mu e} < 10^{-18}$.
  - First factor of ≈10 can use the same detector.



Project-X Related Links

- 4^{th} Workshop on physics with a high intensity proton source, Nov 9-10, 2009.

http://www.fnal.gov/directorate/Longrange/Steering_Public/workshop-physics-4th.html

- Muon Collider Physics workshop, Nov 10-12, 2009.

http://www.fnal.gov/directorate/Longrange/Steering_Public/workshop-muoncollider.html

- Fermilab Steering Group Report, June 2008.

http://www.fnal.gov/directorate/Longrange/Steering_Public/

Summary and Conclusions

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

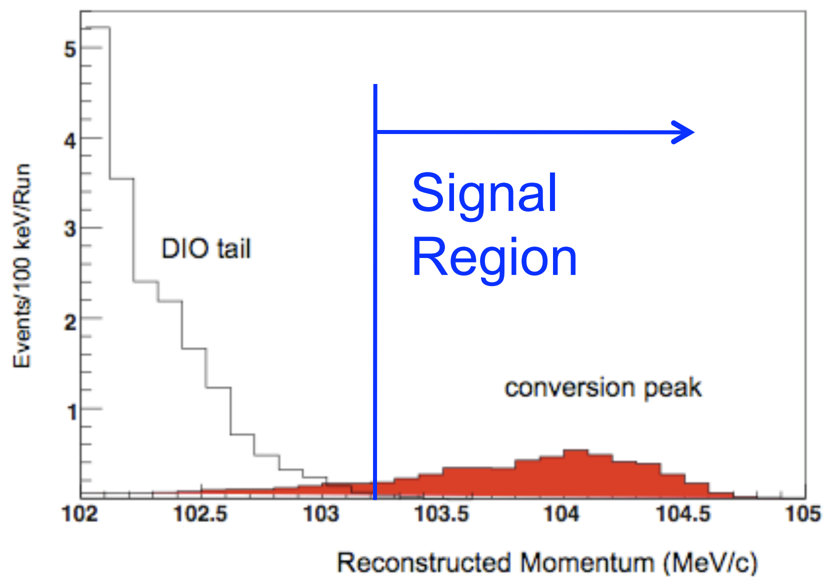
- Sensitivity for 2 years of running:
  - Discover new physics or $R_{\mu e} < 6 \approx 10^{-17}$ @ 90% CL.
  - Mass scales to O(10,000 TeV) are within reach.
  - 10,000 × better than previous best limit.
- Many SUSY@LHC scenarios predict $R_{\mu e} \approx 10^{-15}$,
  - Expect 40 events with < 0.5 events BG.
- Critical path is the solenoid system:
  - Planning: Construction: 2013-17; Operations 2018…
- Project X era:
  - If a signal, we can study N(A,Z) dependence.
  - If no signal, improve sensitivity up to 100 ×, $R_{\mu e} < O(10^{-18})$.
- Opportunities for new university groups.

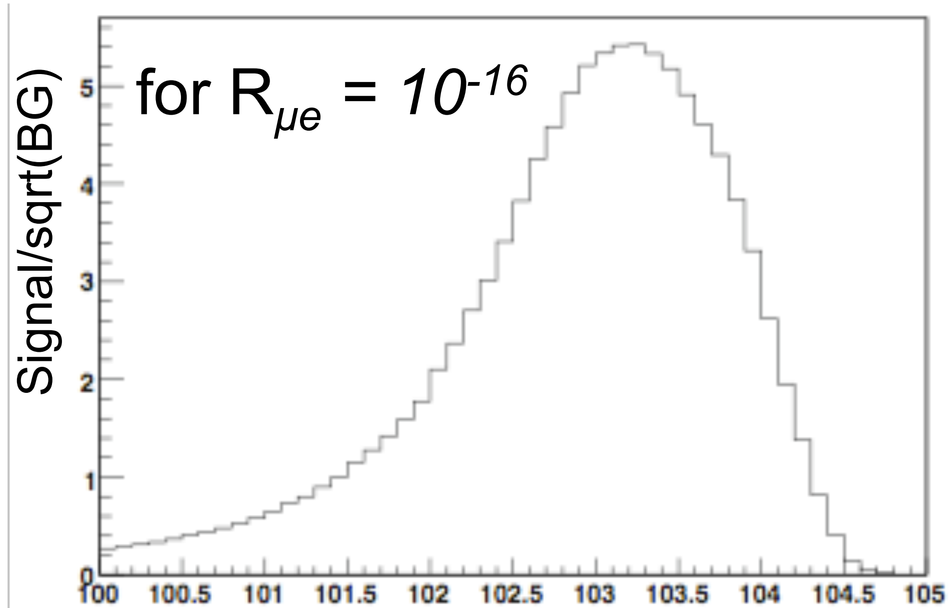
For Further Information

- Mu2e home page: http://mu2e.fnal.gov
- Mu2e Document Database:
  - http://mu2e-docdb.fnal.gov/cgi-bin/DocumentDatabase
  - Mu2e Proposal: Mu2e-doc-388
  - Mu2e Conference presentations

Backup Slides

Defining the Signal Region





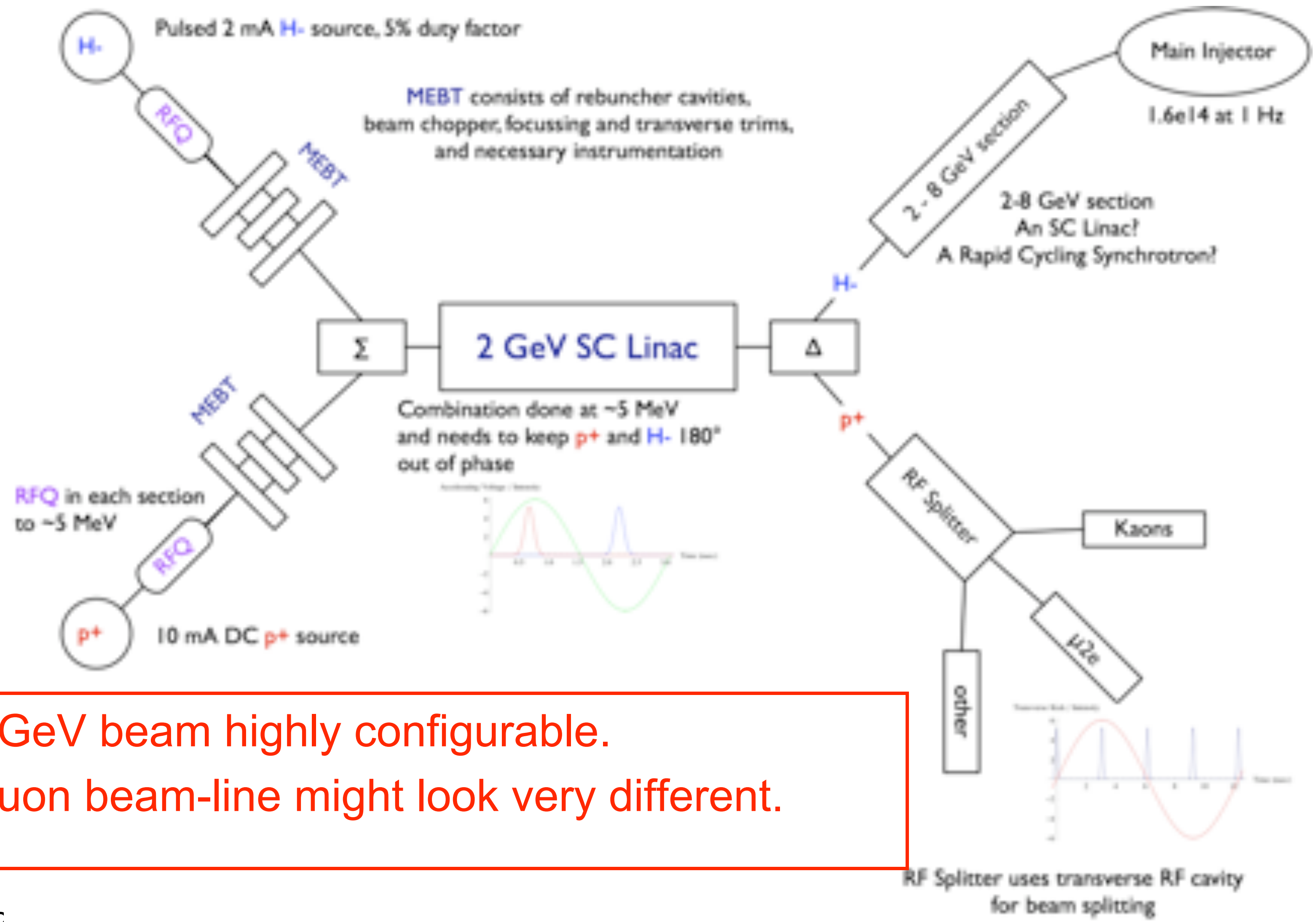
Low Edge of Signal Region

- There is an irreducible background component.
- In addition, mis-measured DIO events can be reconstructed in the signal region. Critical to understand high side tails in the momentum resolution function.

Fermilab 10 Year Plan

Programs / Projects	FY08	FY09	FY10	FY11	FY12	FY13	FY14	FY15	FY16	FY17	FY18	FY19
Energy Frontier												
Tevatron: CDF	Operation				Data Analysis							
Tevatron: DZero	Operation				Data Analysis							
LHC: CMS			Operation									
LHC: ATLAS					Operation							
LHC Phase I Upgrade	R&D			Construction								
LHC Phase II Upgrade	R&D				Construction							
Lepton Collider	R&D					Decision	ILC	or CLIC/Muon Collider				
Intensity Frontier												
ν: SciBooNE		Data Analysis										
ν: MiniBooNE				Data Analysis								
ν: MicroBooNE	R&D	CD-0	CD-1/2	Construction					Data Analysis			
ν: MINOS					Data Analysis							
ν: MINERvA	CD-3b				Shutdown		Data Analysis					
ν: NOvA	CD-2	CD-3a	CD-3b									Data Analy
ν: Long Baseline at DUSEL			CD-0	CD-1	CD-2		CD-3a					
μ: Mu2e			CD-0	CD-1	CD-2	CD-3a						
Project X				CD-0	CD-1	CD-2		CD-3a				
Cosmic Frontier												
Dark Matter: CDMS	4 kg			15 kg					~1 ton scale detector			
Dark Matter: COUPP	2 kg		60 kg						(tech choice: CDMS, COUPP, LAr TPC, ...)			
Dark Energy: SDSS		Data Analysis										
Dark Energy: DES	CD-3a									Data Analysis		
Dark Energy: JDEM	R&D											
Cosmic Rays: Pierre Auger	South					North to be determined						
Other Facilities												
Testbeam for Detector R&D	Operation				Shutdown							
Accelerator Research at A0	Operation											
SCRF Test / Accel. Research	Construction						Operation					
Lattice QCD	Operation											

Project X ICD-2

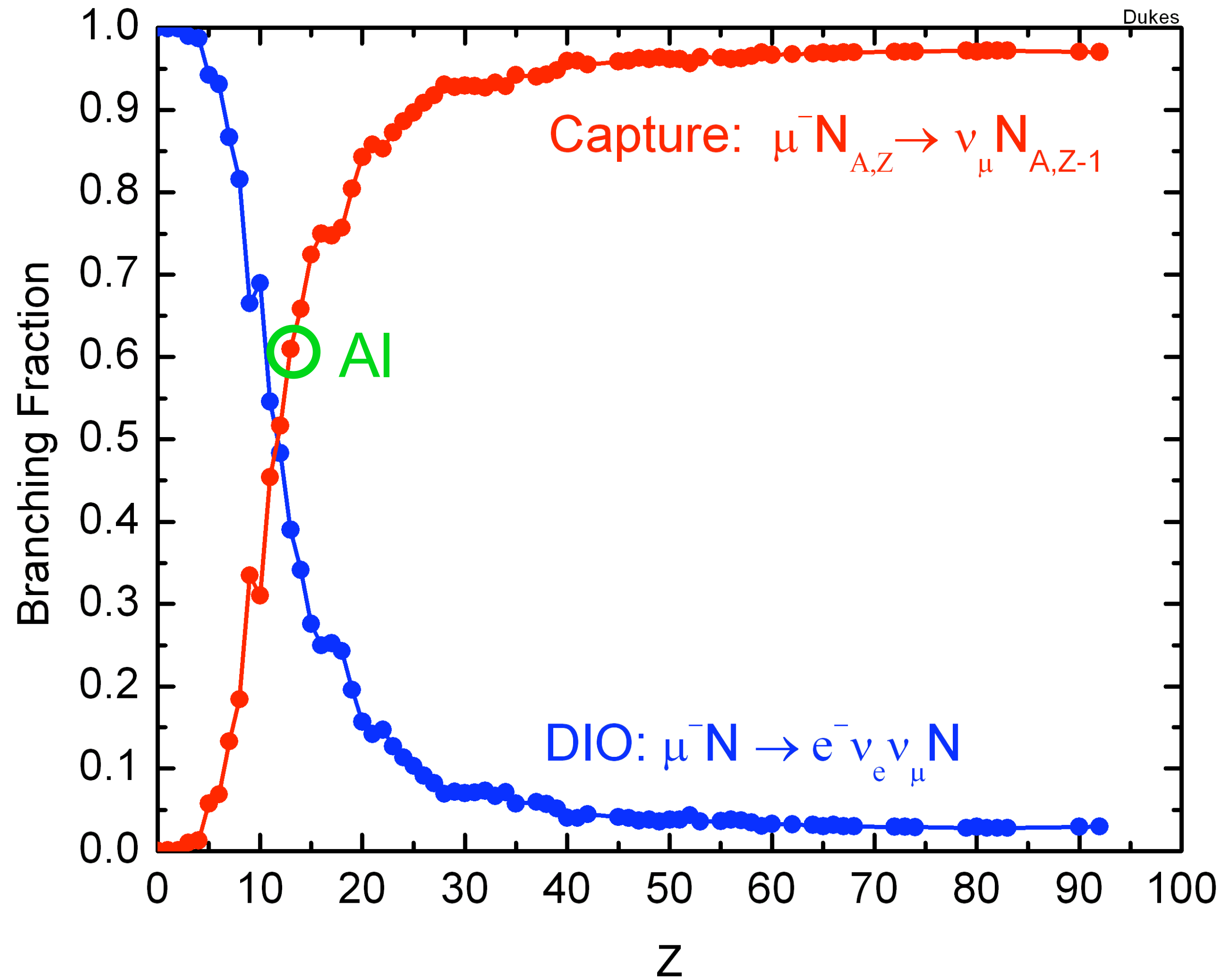


- 2 GeV beam highly configurable.
- Muon beam-line might look very different.

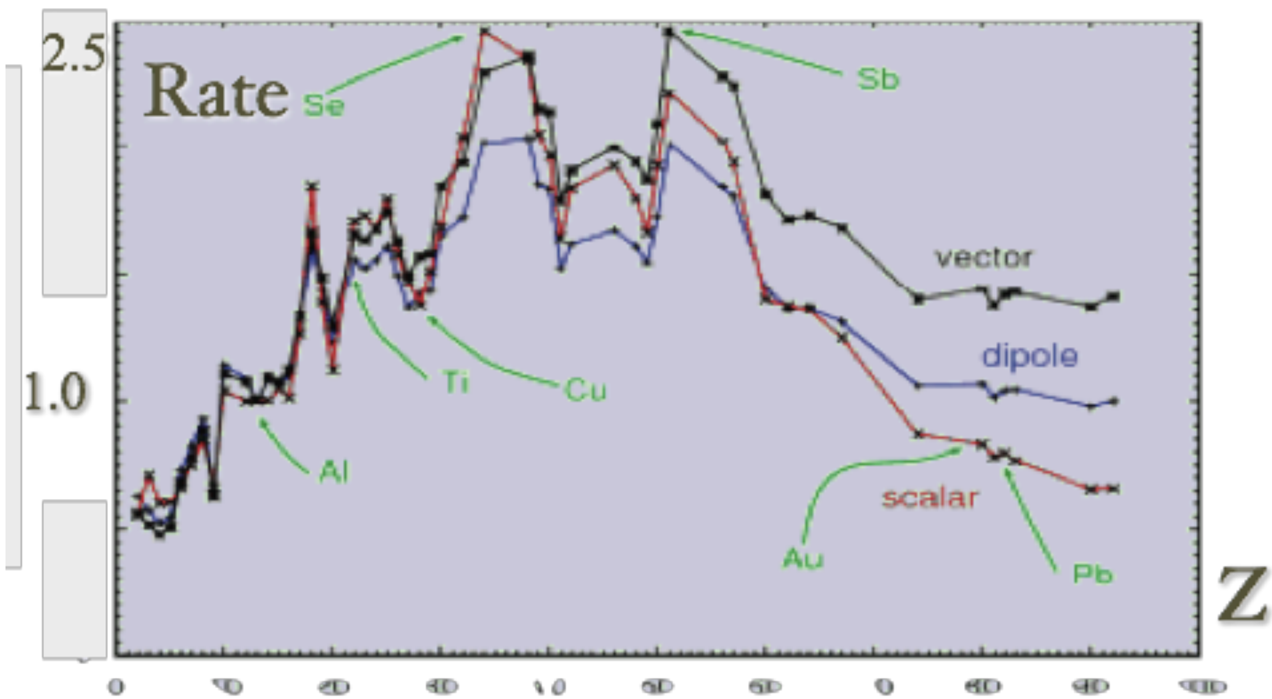
Why is Mu2e Better than SINDRUM II?

- FNAL can deliver ≈1000 × proton intensity.
- Higher μ collection efficiency.
- SINDRUM II was BG limited.
  - Radiative π capture.
  - Bunched beam and excellent extinction reduce this.
- So Mu2e can effectively use the higher proton rate.

Capture and DIO vs Z



Conversion Rate, Normalized to Al



Kitano, et al., PRD 66, 096002 (2002)

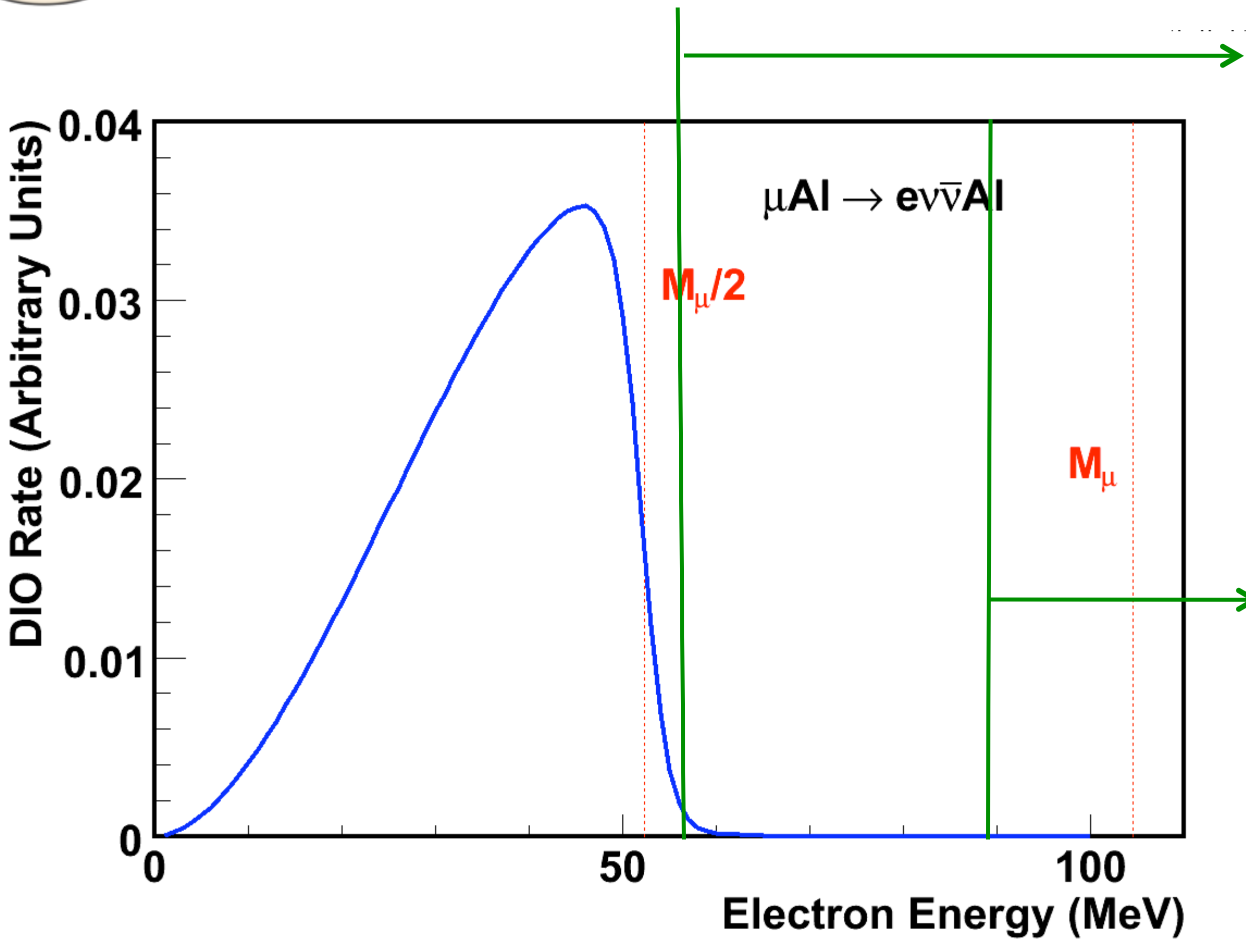
Recipe the Mu2e Experiment

- Make muonic atoms.
- Wait for them to decay.
- Measure E_e.
- Eliminate backgrounds that can fake a signal.
- Is there a bump at the end of the spectrum?

Recipe for our Experiment

- Make a beam of low energy muons
- Stop muons in a thin foil target
  - Make muonic atoms
- Wait for muonic atoms to decay.
- Measure E_e spectrum.
- Make sure we understand the DIO spectrum.
- Estimate background in signal region.
- Count events in signal region.
  - Is there a bump at the end of the spectrum?

How do you measure 1 in 10^{17} ?

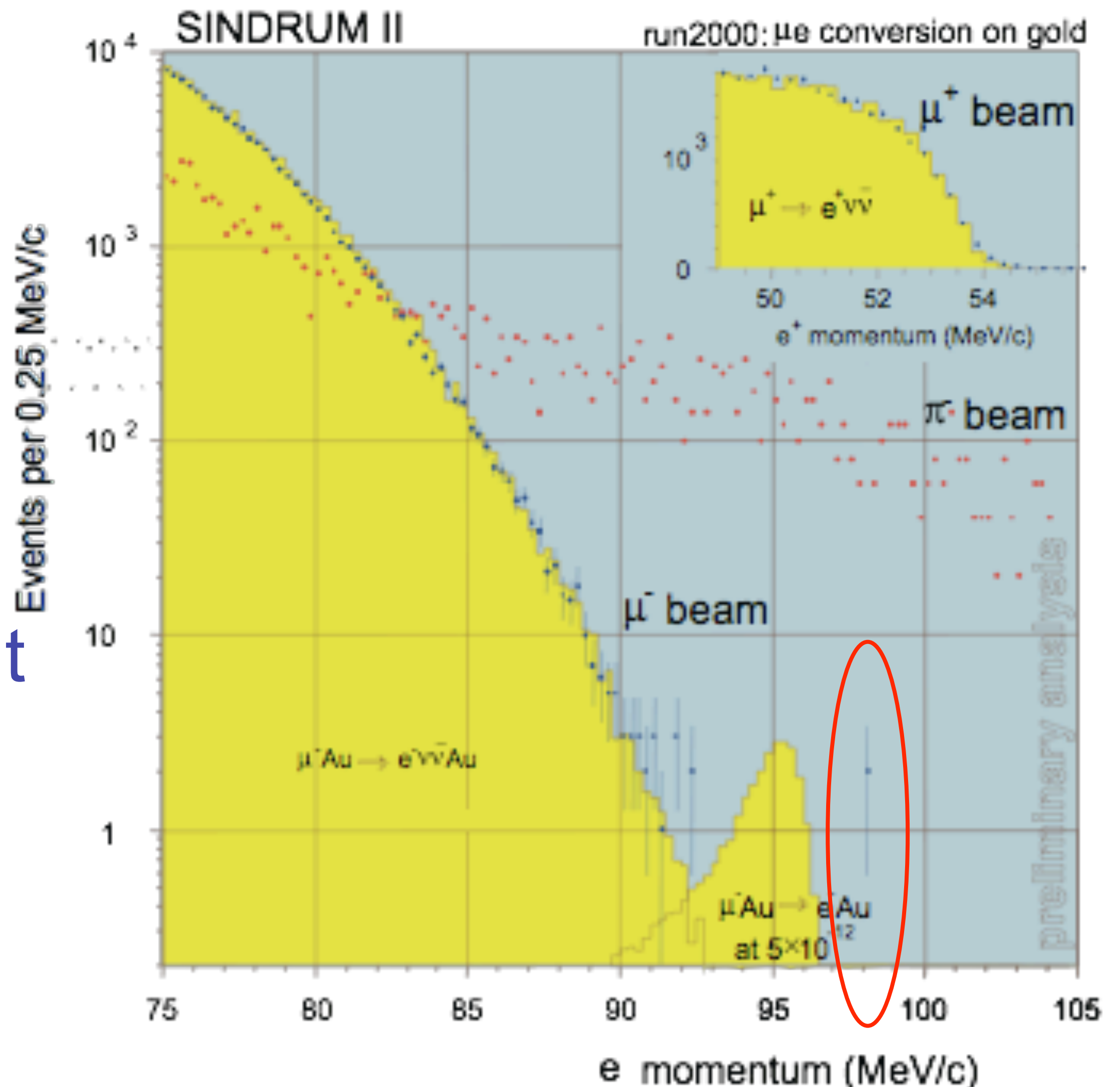


Only electrons with p_T > 55 MeV reach the inner boundary of the detector.

Only electrons with p_T > 90 MeV leave enough hits to reconstruct.

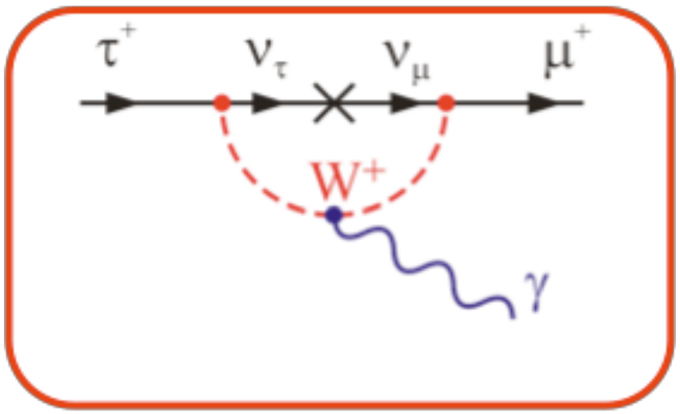
Previous Best Experiment

- SINDRUM II
- $R_{\mu e} < 6.1\times10^{-13}$ @90% CL
- 2 events in signal region
- Au target: different endpoint than Al.

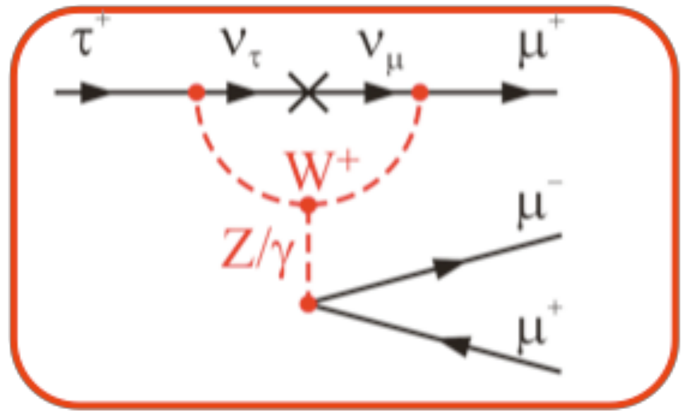


CLFV in Tau Decays

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



SM ~ 10^{-40}



SM ~ 10^{-14}

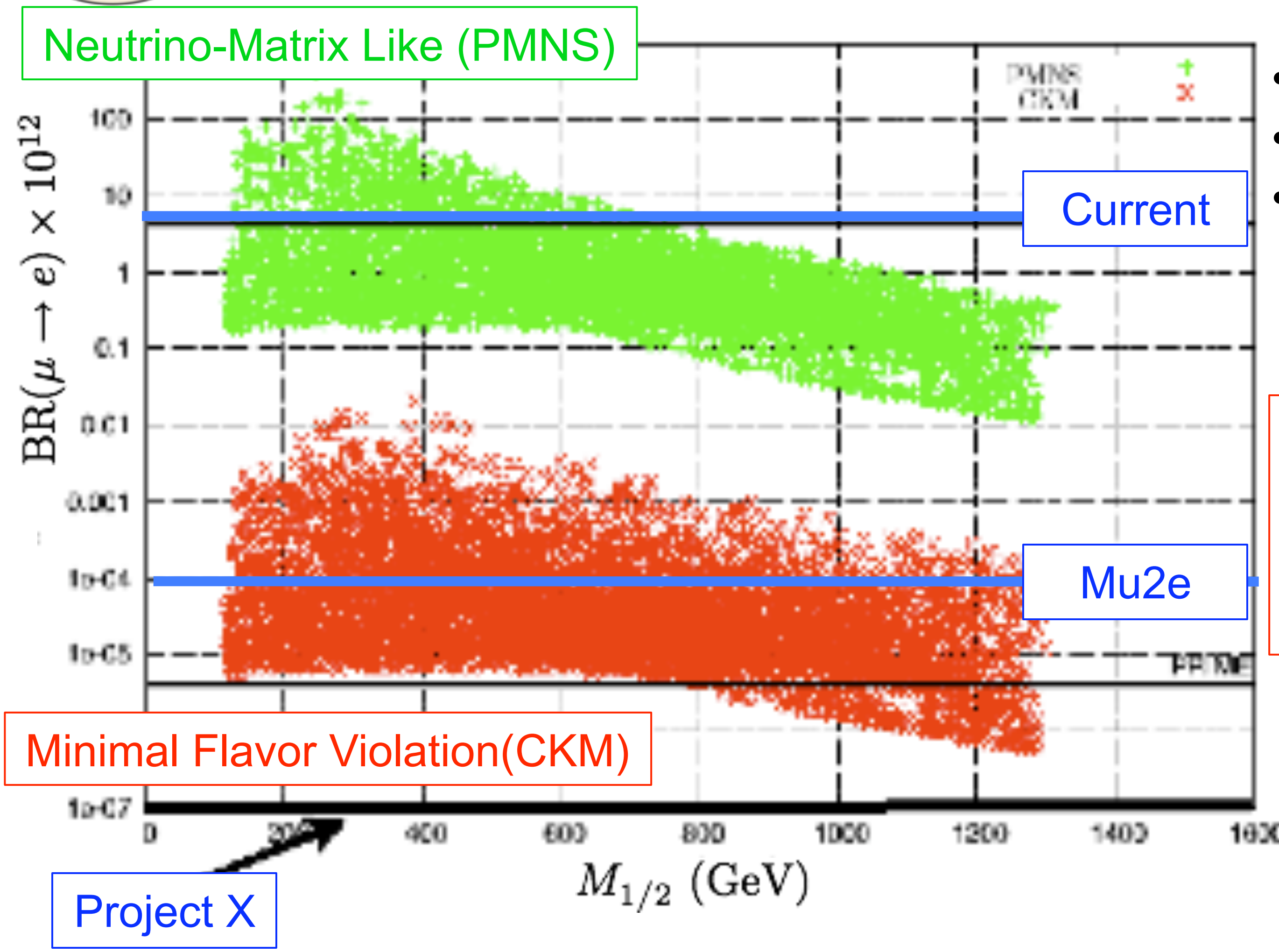
Pham, hep-ph/9810484

Beyond SM Rates higher than for muon decay; milder GIM suppression.

But only O(10^9 tau/year) at B factories, compared to 10^{11} muon/s at Mu2e/COMET.

- BaBar/Belle/CLEO working on CLFV in tau decay.
- Also in B and D decay.

Example of SUSY in Muon LFV



- tanβ=10
- SO(10)
- ν masses: see-saw.

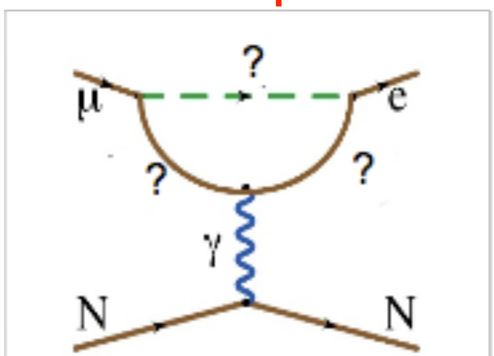
A CLFV signal can help resolve ambiguities in LHC data.

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

Parameterizing CLFV

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

Loops

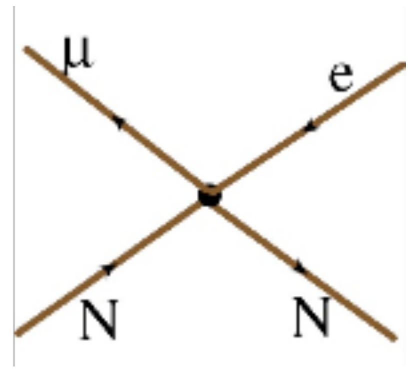


Contributes to μ→eγ

SUSY and massive neutrinos

Dominates if κ<<1

Contact terms



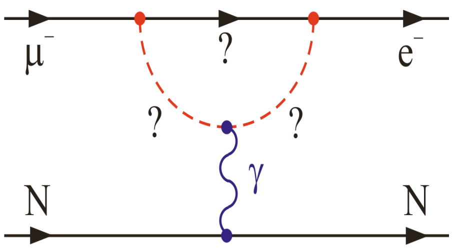
Does not produce μ→eγ

Exchange of a heavy particle

Dominates if κ>>1

Sensitivity to High Mass Scales

Loops



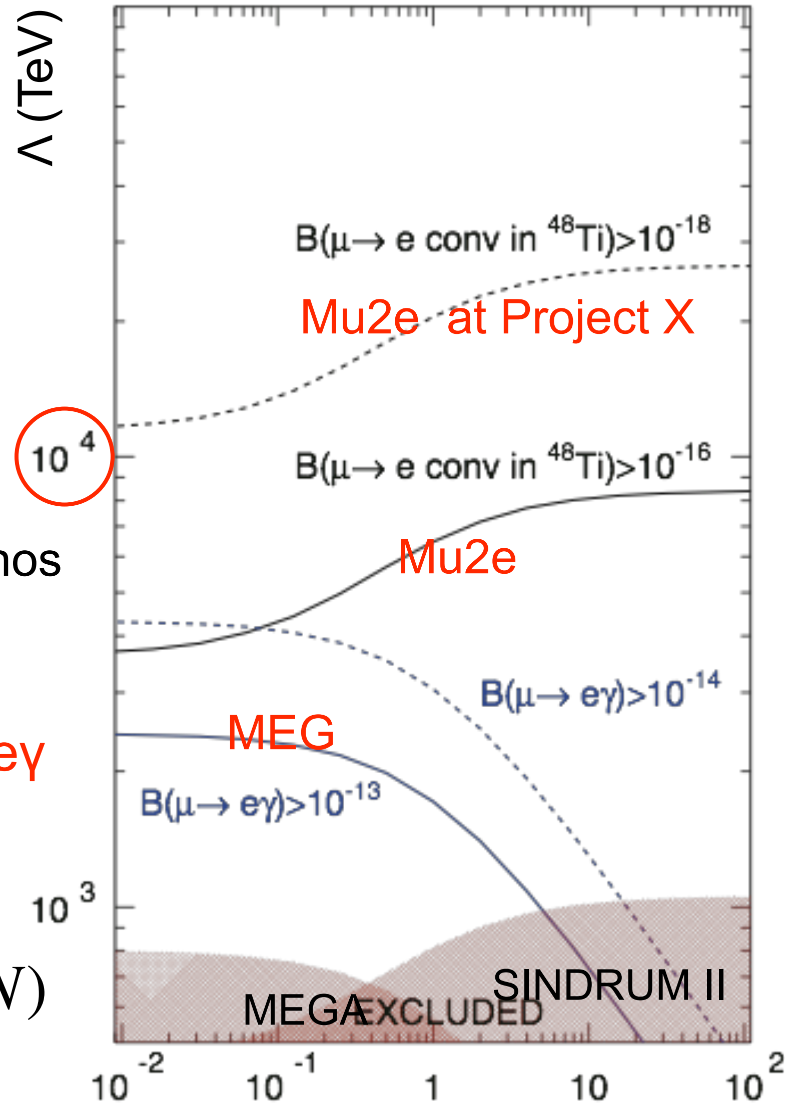
SUSY; massive neutrinos

Dominates if κ<<1

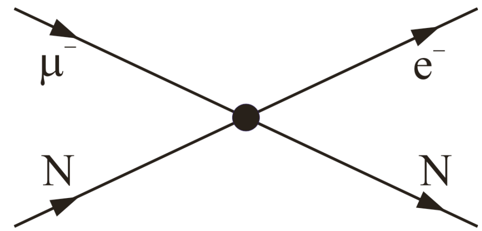
Contributes to μ→eγ

$$\Gamma(\mu \rightarrow e\gamma)$$

$$\approx 300\ \ \Gamma(\mu N \rightarrow eN)$$



Contact terms



Exchange of a new massive particle

Dominates if κ>>1

Does not produce μ→eγ

$$\Gamma(\mu N \rightarrow eN)$$

$$>> \Gamma(\mu \rightarrow e\gamma)$$

Magnetic Spectrometer

$$p_T = cqB\rho \times 10^{-9} \qquad p = p_T\sqrt{1+\cot^2\theta} \qquad E = \sqrt{p^2 + m_e^{\ 2}}$$

- Measured by fit: ρ: radius of curvature cotθ: a measure of the pitch

- pT: Transverse momentum
- B magnetic field
- p total momentum
- E Energy
- q magnitude of electric charge

- E in GeV
- p in GeV/c
- c in m/s
- ρ in m
- B inTesla
- q in units of proton charge