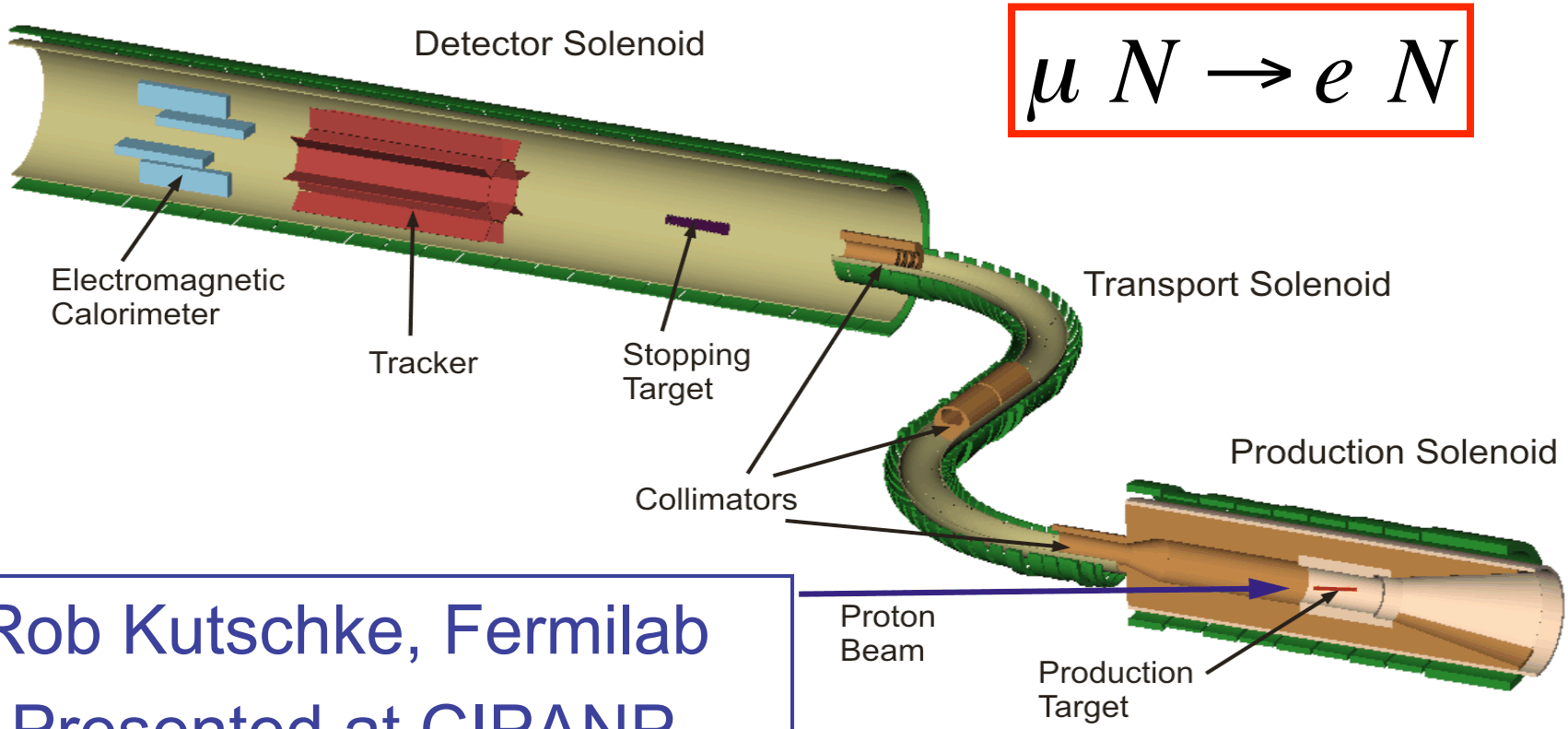
Mu2e-doc-546-v5

The Mu2e Experiment at Fermilab

$$\mu\ N \rightarrow e\ N$$



Rob Kutschke, Fermilab

Presented at CIPANP

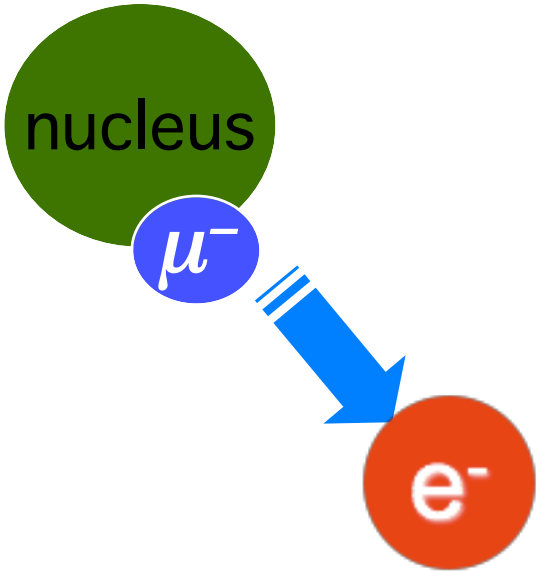
May 30, 2009

http://mu2e.fnal.gov

Coherent Neutrino-less μ to e Conversion

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

- Initial state: muonic atom
- Final state:
  - Single mono-energetic electron.
    - Energy depends on Z of target.
  - Recoiling nucleus (not observed).
    - Coherent: nucleus stays intact.
- Negligible rate in Standard Model.
- Observable in many New Physics scenarios.
- Related decays: Charged Lepton Flavor Violation (CLFV):



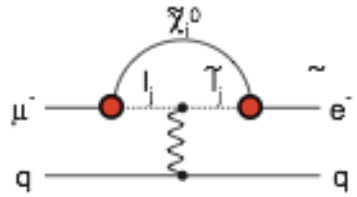
$$\mu \rightarrow e\gamma \quad \mu \rightarrow e^+e^-e^+ \quad K_L^0 \rightarrow \mu e \quad B^0 \rightarrow \mu e$$

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

Sensitivity to New Physics

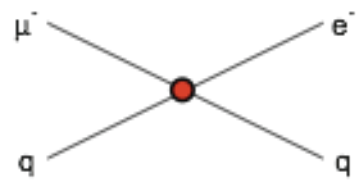
Supersymmetry

rate ~ 10^{-15}



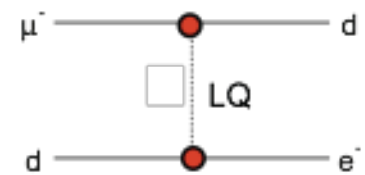
Compositeness

Λ_c ~ 3000 TeV



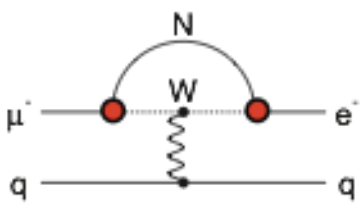
Leptoquark

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



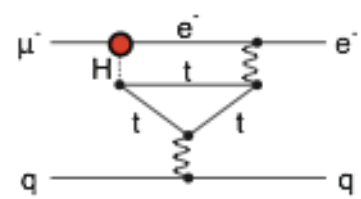
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



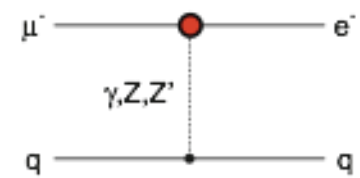
Second Higgs Doublet

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



Heavy Z' Anomal. Z Coupling

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



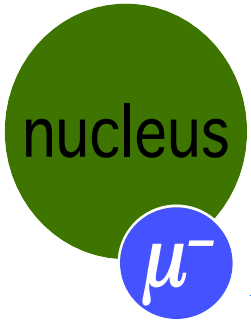
Sensitive to mass scales up to O(10,000 TeV)!

Do not contribute to μ→eγ

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

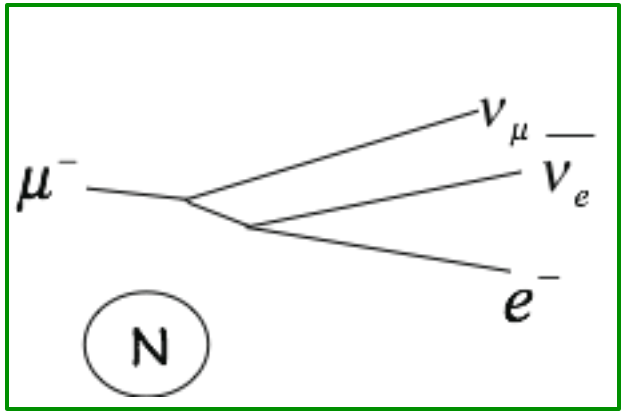
Mu2e in One Page

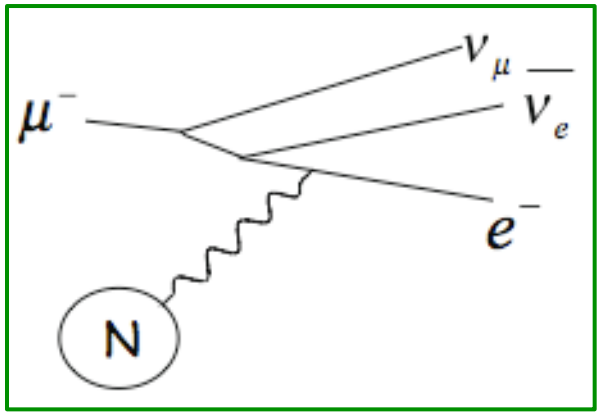
- Make muonic Al.
- Watch it decay:
  - Decay-in-orbit (DIO): 40%
    - Continuous E_e spectrum.
  - Muon capture on nucleus: 60%
    - Nuclear breakup: p, n, γ
  - Neutrino-less μ to e conversion
    - Mono-energetic $E_e \approx 105$ MeV
    - At endpoint of continuous spectrum.
- Measure E_e spectrum.



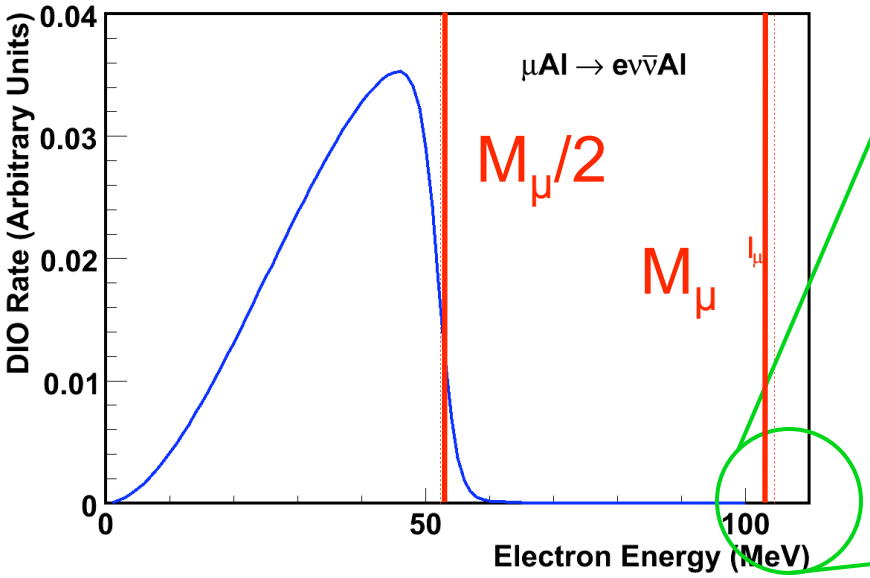
Bohr radius ≈ 20 fm
Al nuclear radius ≈ 4 fm
Lifetime: 864 ns

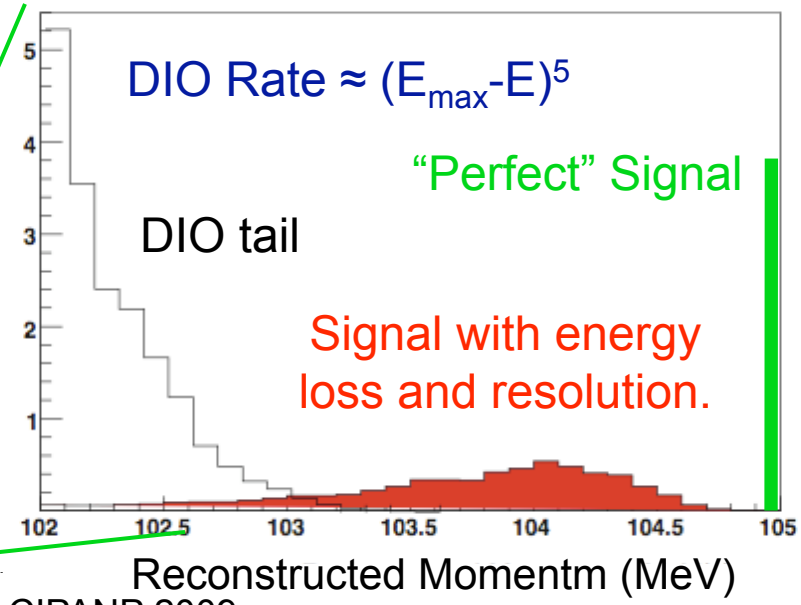
Decay-in-Orbit: Dominant Background





1.5×10^{-15} DIO e^- are with 2 MeV of endpoint.



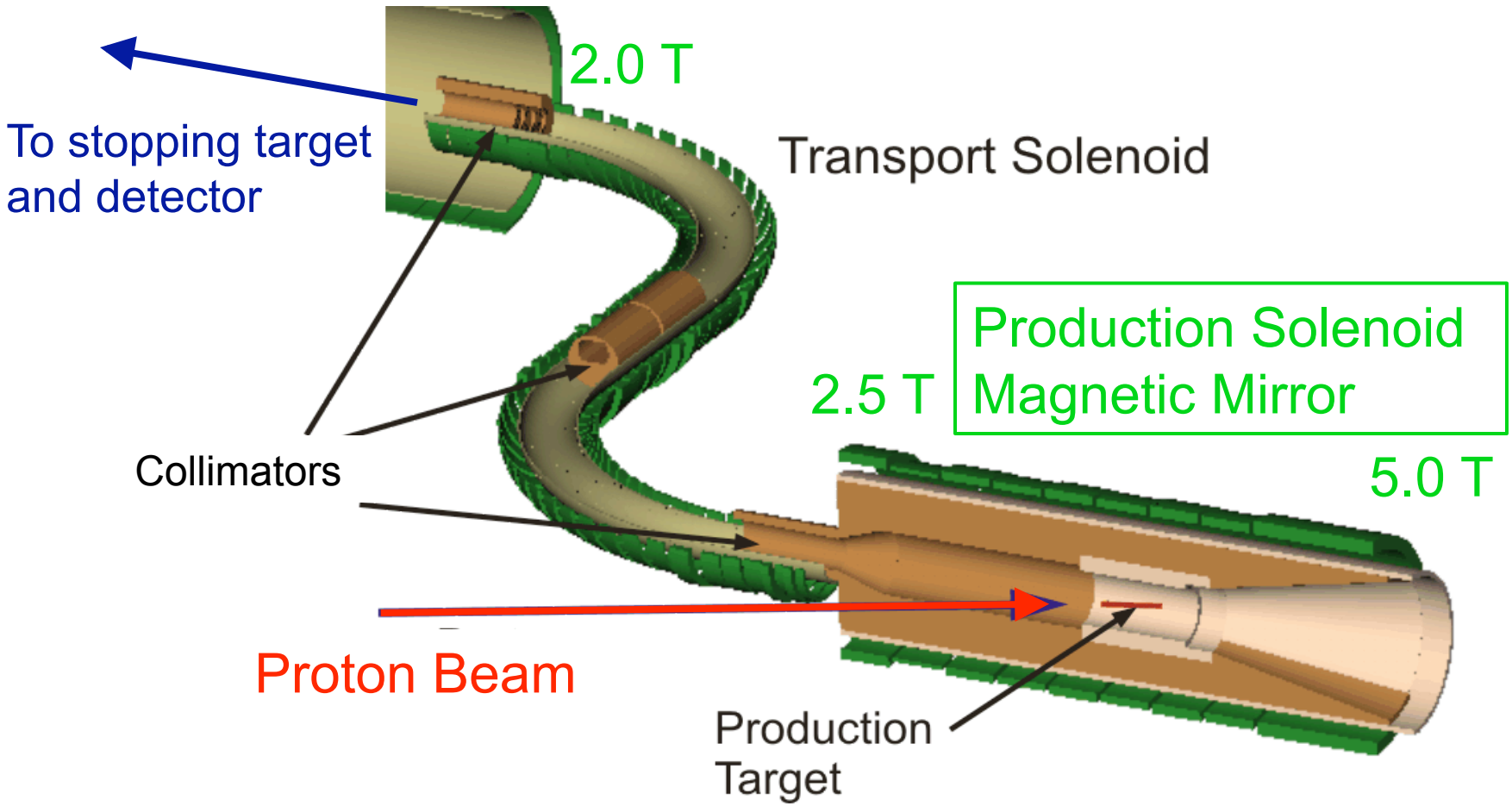


What do We Measure?

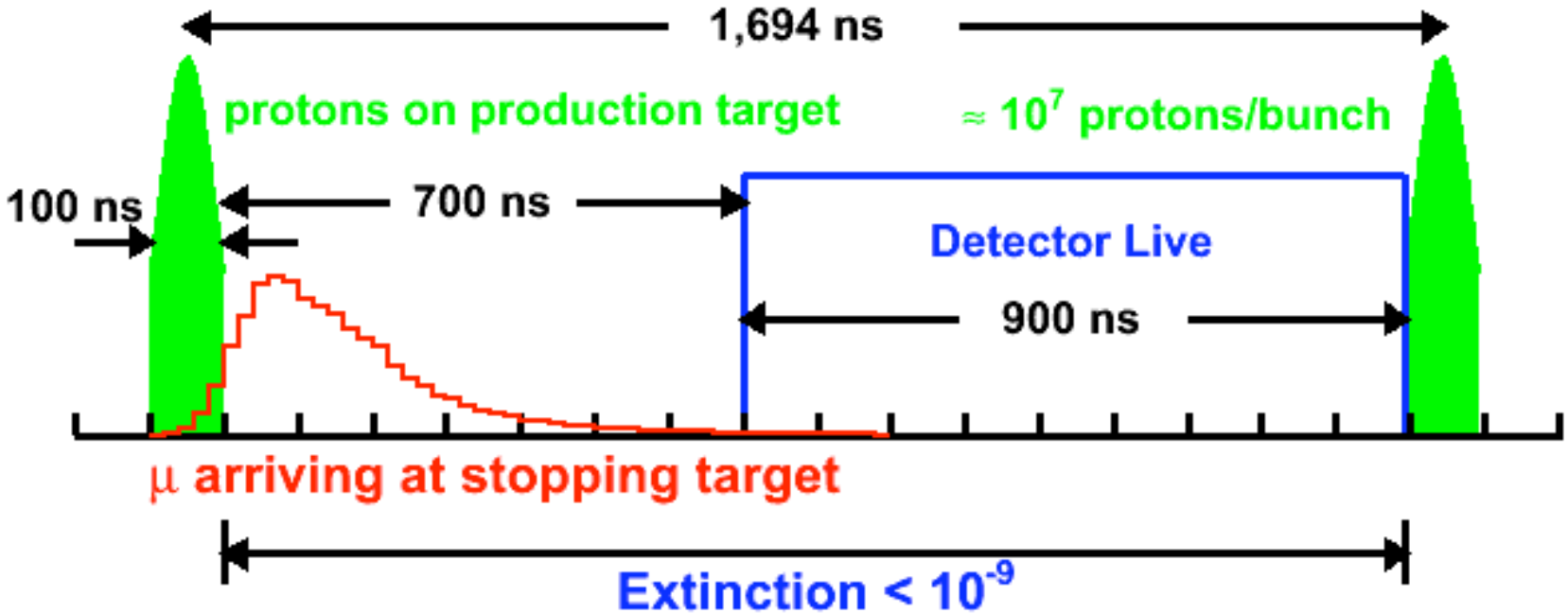
$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \rightarrow e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \rightarrow \nu_\mu + (A,Z-1))}$$

- Numerator:
  - Do we see an excess at the E_e end point?
- 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).

Back Scattered Muon Beam



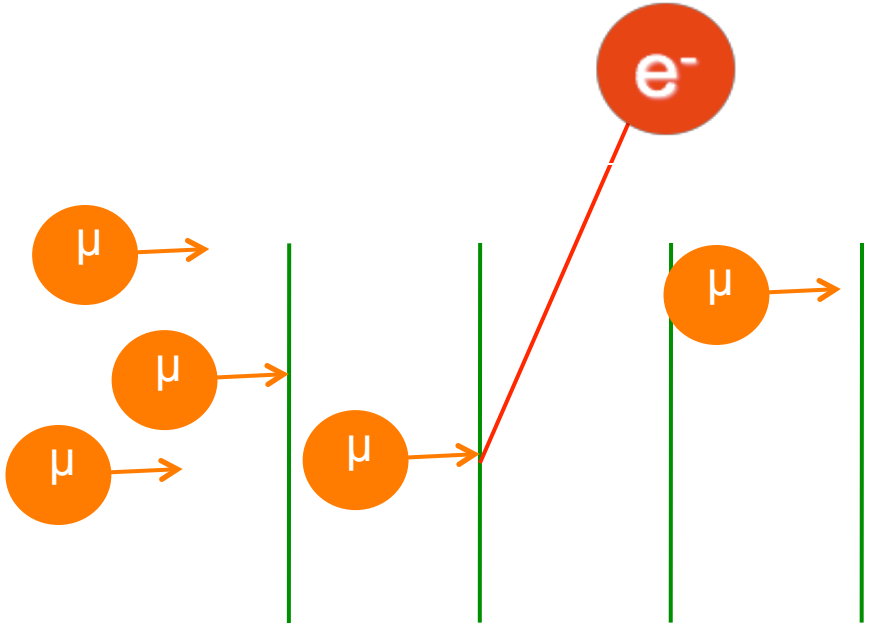
One Cycle of the Muon Beamline



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

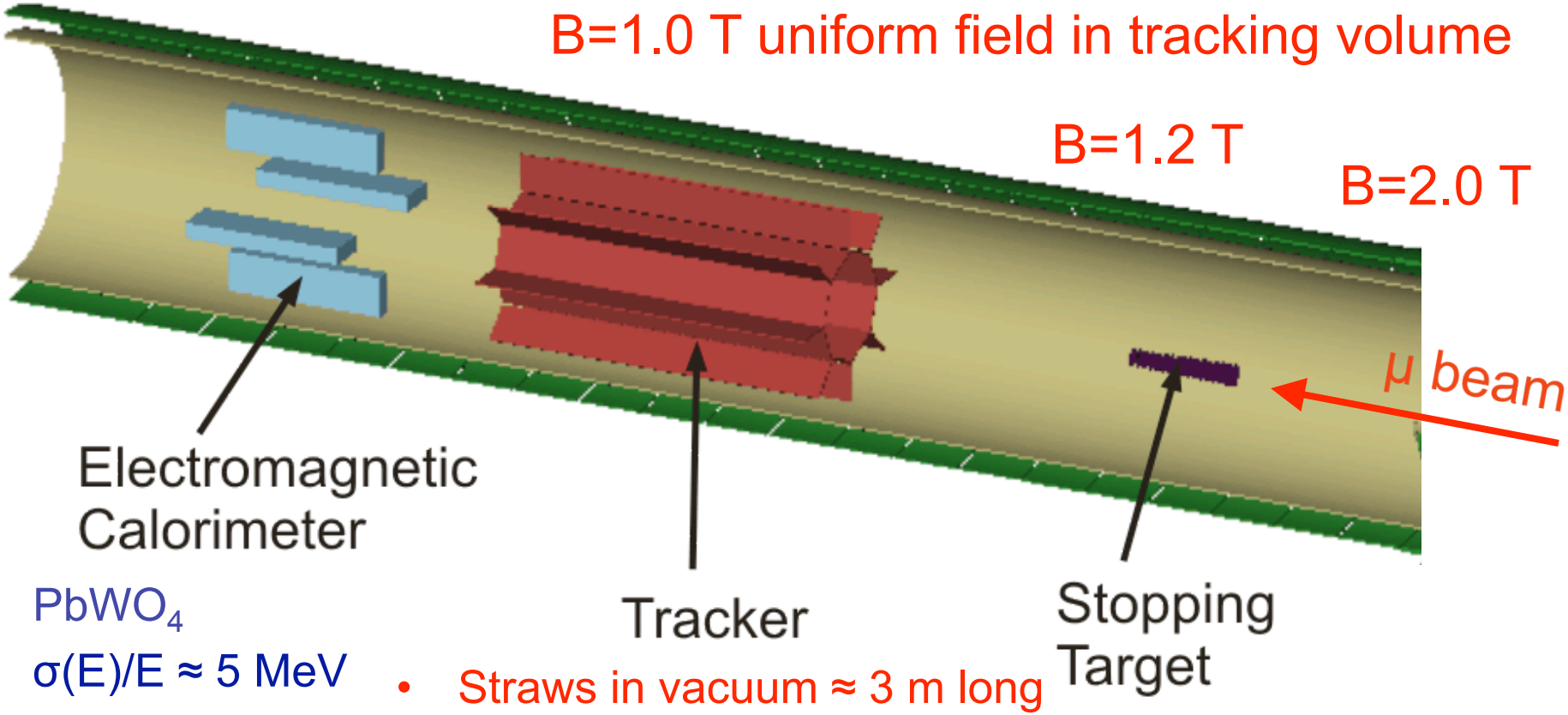
Stopping Target

- Pulse of low energy μ on thin Al foils; ≈60% capture.
- 1 stopped muon per 400 protons on production target.
- Wait for prompt backgrounds to go away.
- 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

Detector Solenoid and Detector

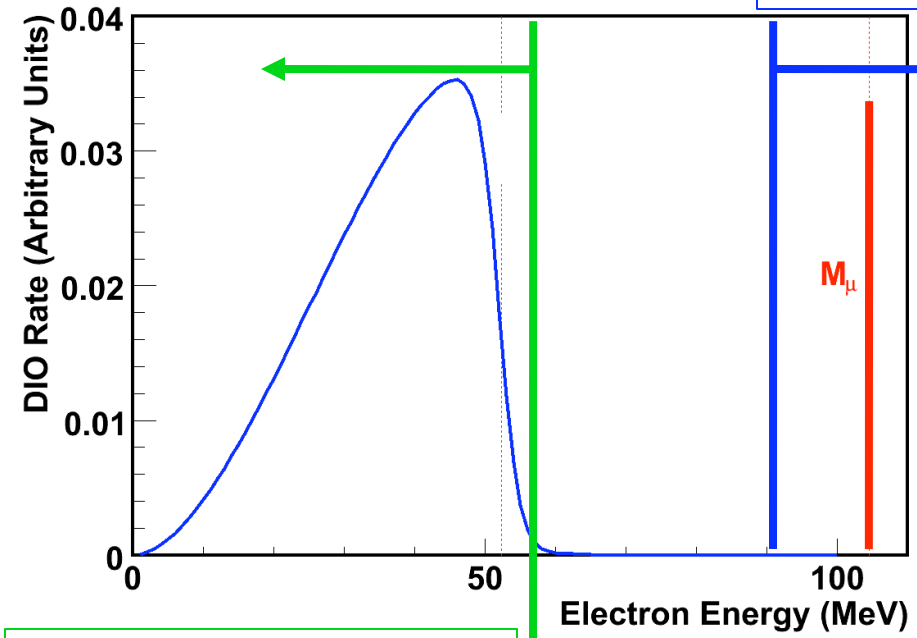


- $PbWO_4$
- $\sigma(E)/E \approx 5$ MeV
- Trigger + confirmation of track.

- Straws in vacuum ≈ 3 m long
- Cathode pads for z position
- Geom + reco efficiency: ≈ 20%
- $\sigma(p) \approx 150$ keV at p=105 MeV

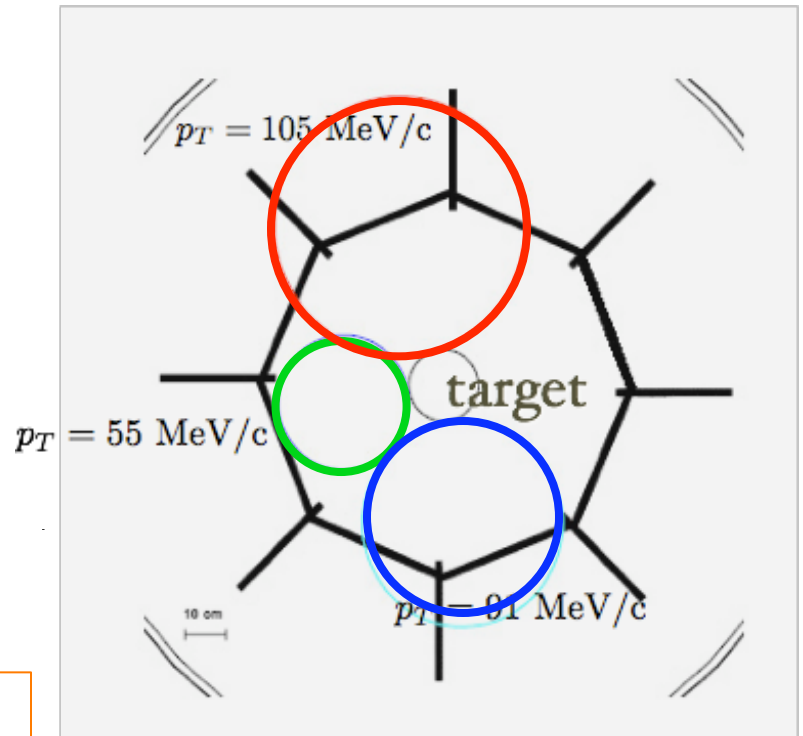
How do you measure 2×10^{-17} ?

Reconstructable tracks



No hits in detector

Some hits in detector.
Tracks not reconstructable.



Beam's-eye view of Tracker

Backgrounds for 2×10^7 s Running

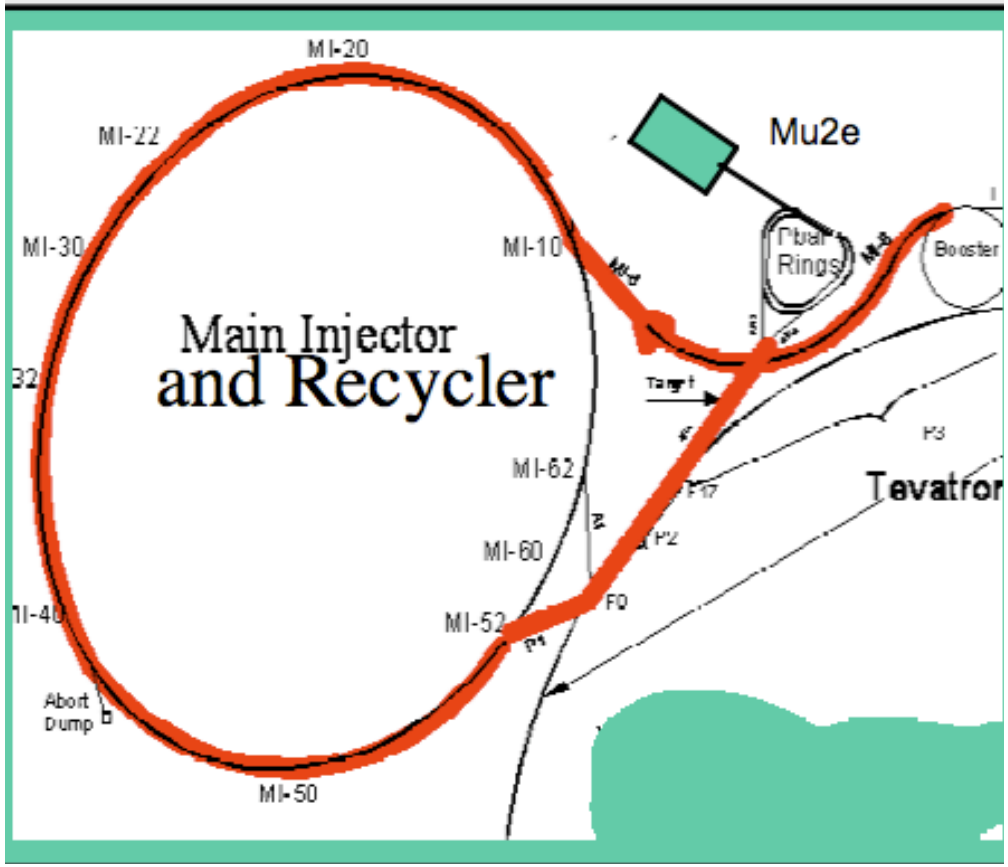
Source	Events	Comment
μ decay in orbit	0.225	
Radiative π^- capture*	0.063	From protons during detection time
Beam electrons*	0.036	
μ decay in flight*	0.036	With scatter in target
Cosmic ray induced	0.016	Assumes 10^{-4} veto inefficiency
Other	0.039	6 other processes
Total	0.42	

*: 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.

Proton Delivery and Economics

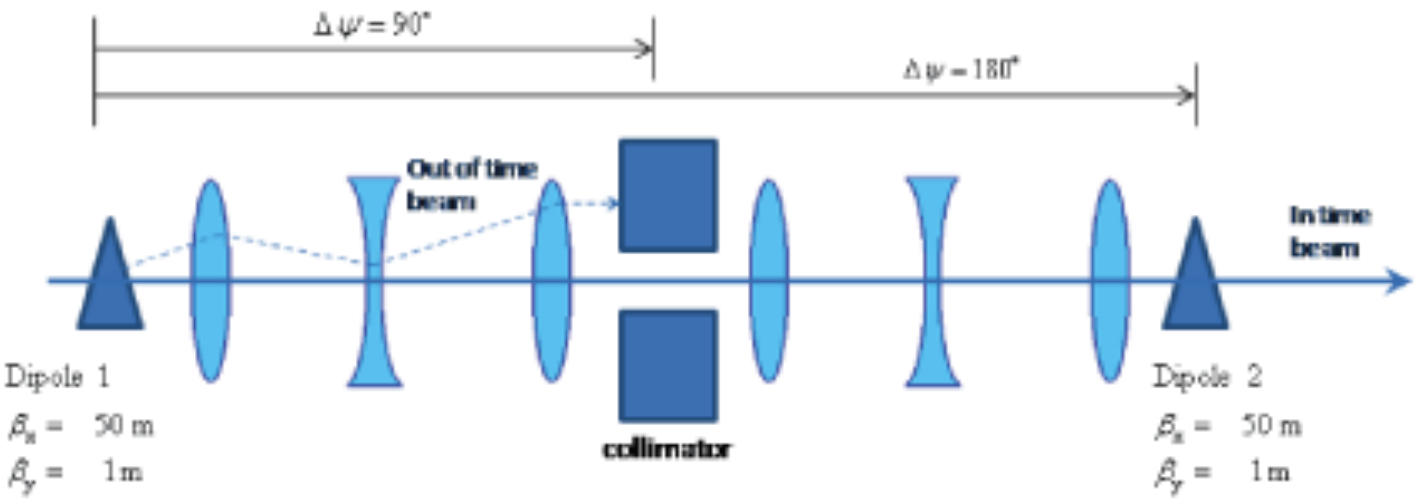
- Reuse existing Fermilab facilities with modest modifications.
- p-bar complex: 2 rings.
  - Use one ring as a “stash”.
  - Slow spill from the other.
  - 90% duty cycle slow spill.
  - Other schemes under study.
- Sharing p’s with NOVA:
  - NOVA 12/20 booster cycles.
  - Mu2e will use 6/20 cycles.



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

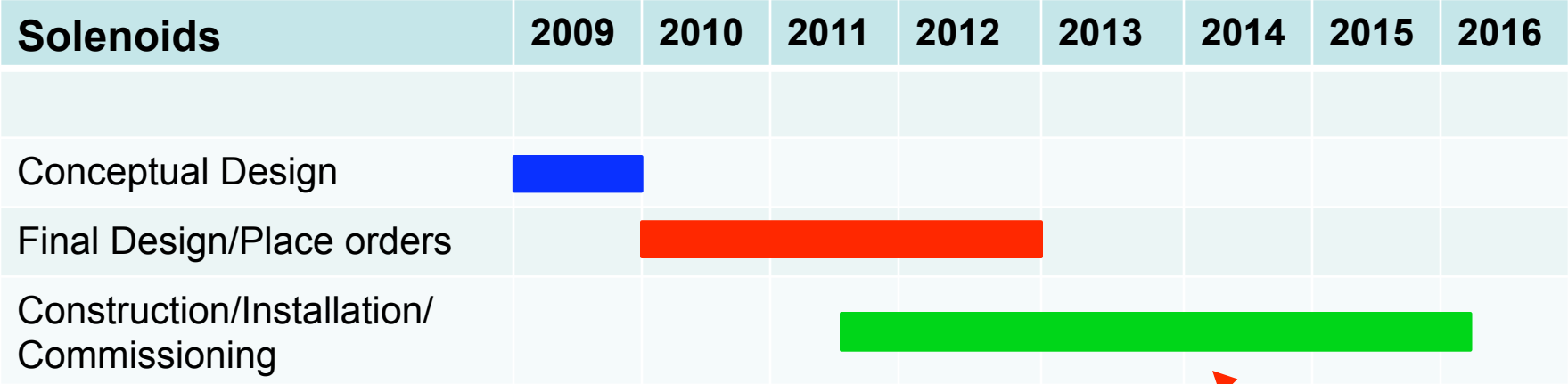
Required Extinction 10^{-9}

- 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.



Estimated Cost and Schedule

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



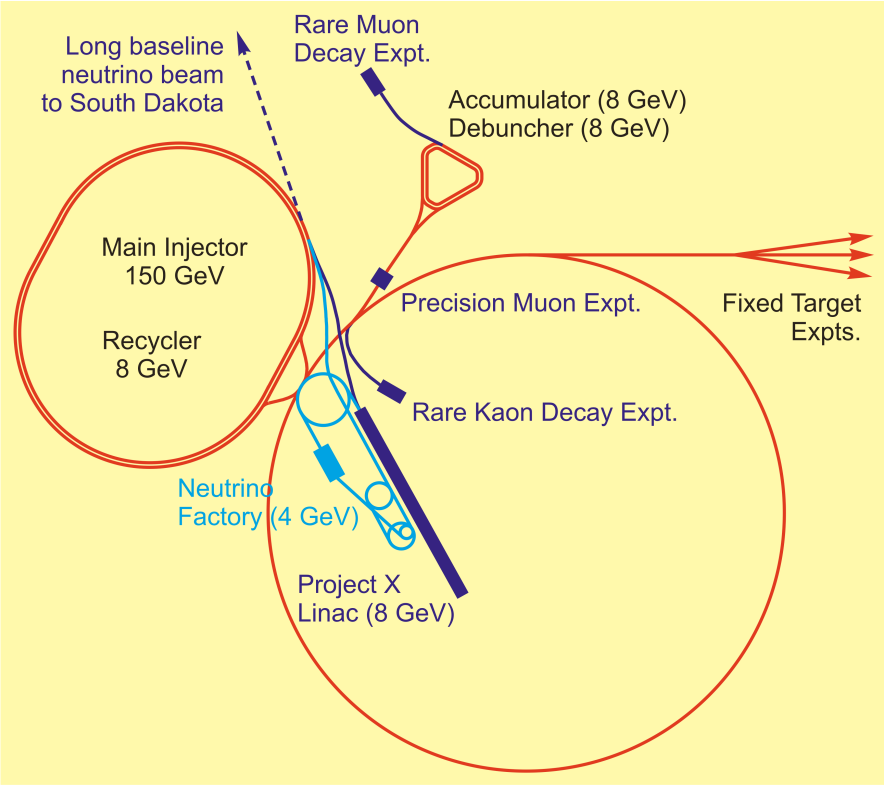
- R&D going on now or soon.
  - PSI: products of μ capture on Al.
  - FNAL: Extinction tests; straw tests.

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).
- 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.



Summary and Conclusions

- Sensitivity for 2 years of running:
  - $R\mu e < 6 \approx 10^{-17}$ @ 90% CL.
  - 10,000 × better than previous best limit.
  - Mass scales to O(10,000 TeV) are within reach.
- Many SUSY@LHC scenarios predict $R\mu e \approx 10^{-15}$,
  - Expect 40 events with < 0.5 events BG.
- Strongly endorsed by P5. Stage I approval from Fermilab.
- Critical path is the solenoid system:
  - Technically limited schedule: startup possible in 2016.
- Project X era:
  - If a signal, we can study N(A,Z) dependence.
  - If no signal, improve sensitivity up to 100 ×, $R\mu e < 10^{-18}$.

For Further Information

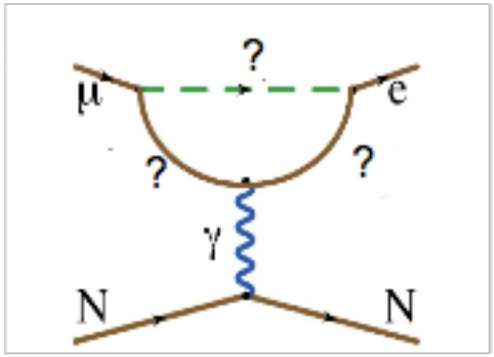
- Mu2e home page: http://mu2e.fnal.gov
- Mu2e Document Database:
  - http://mu2e-docdb.fnal.gov/cgi-bin/DocumentDatabase
  - Mu2e Proposal: Mu2e-doc-388
  - Mu2e Conference presentations

Backup Slides

Model Independent Parameterization

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

Loops

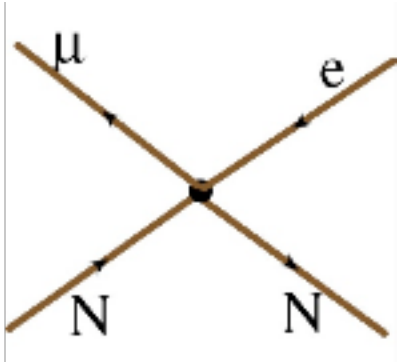


Contributes to μ→eγ

SUSY and massive neutrinos

Dominates if κ<<1

Contact terms



Does not produce μ→eγ

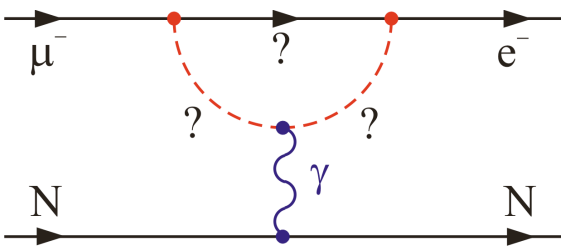
Exchange of a heavy particle

Dominates if κ>>1

Sensitivity to High Mass Scales

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

Loops



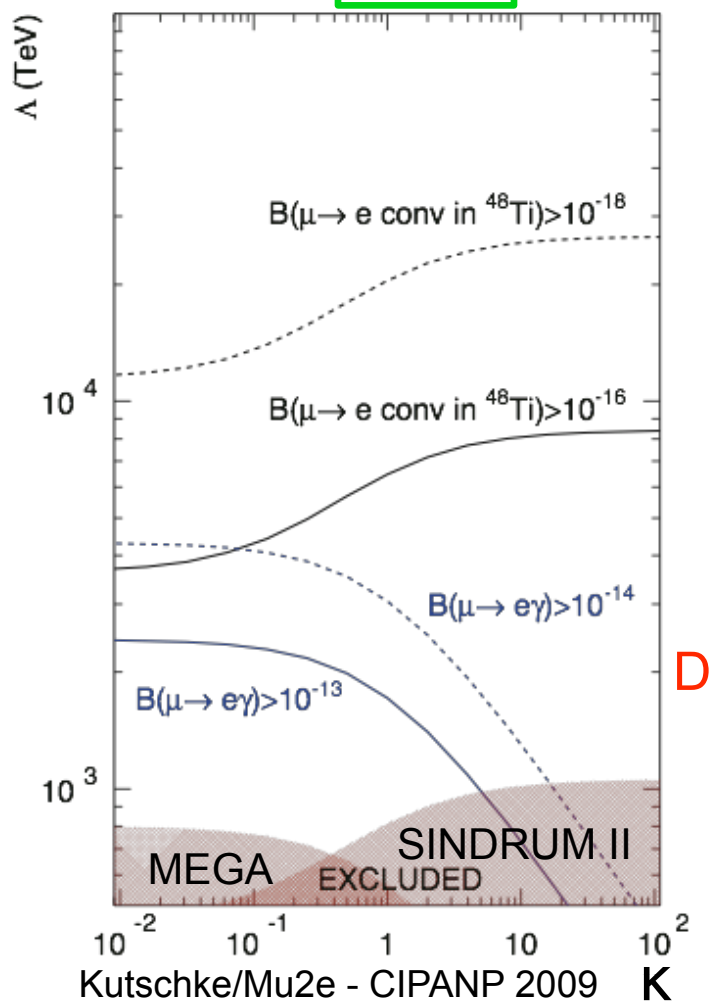
SUSY; massive neutrinos

Dominates if κ<<1

Contributes to μ→eγ

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

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



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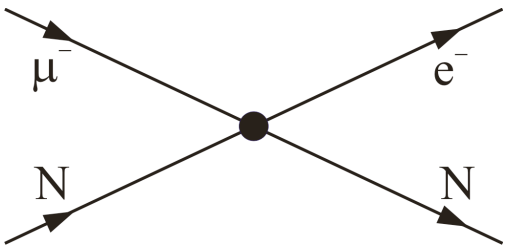


Exchange of a new massive particle

Dominates if κ>>1

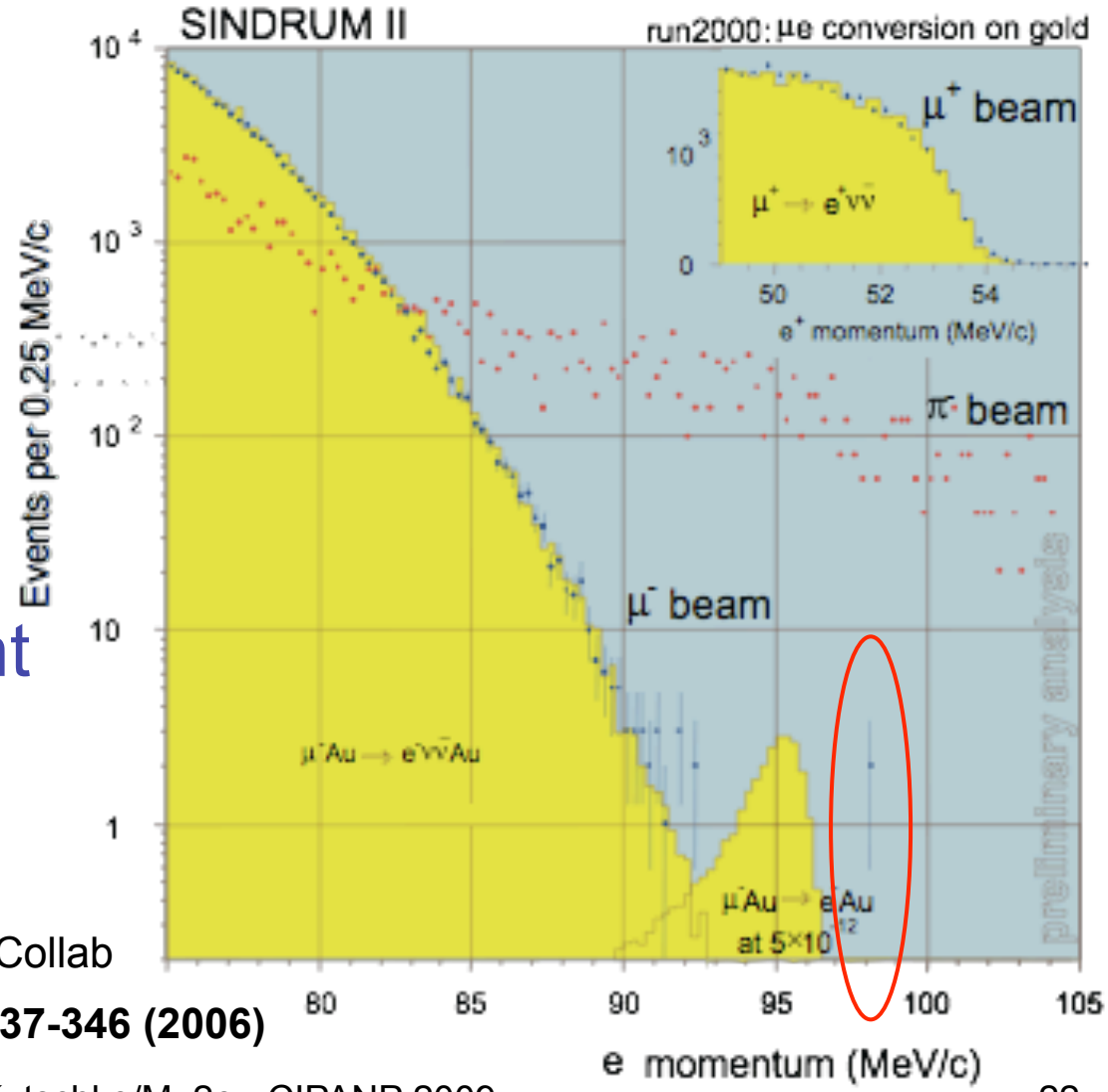
Does not produce μ→eγ

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

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

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.



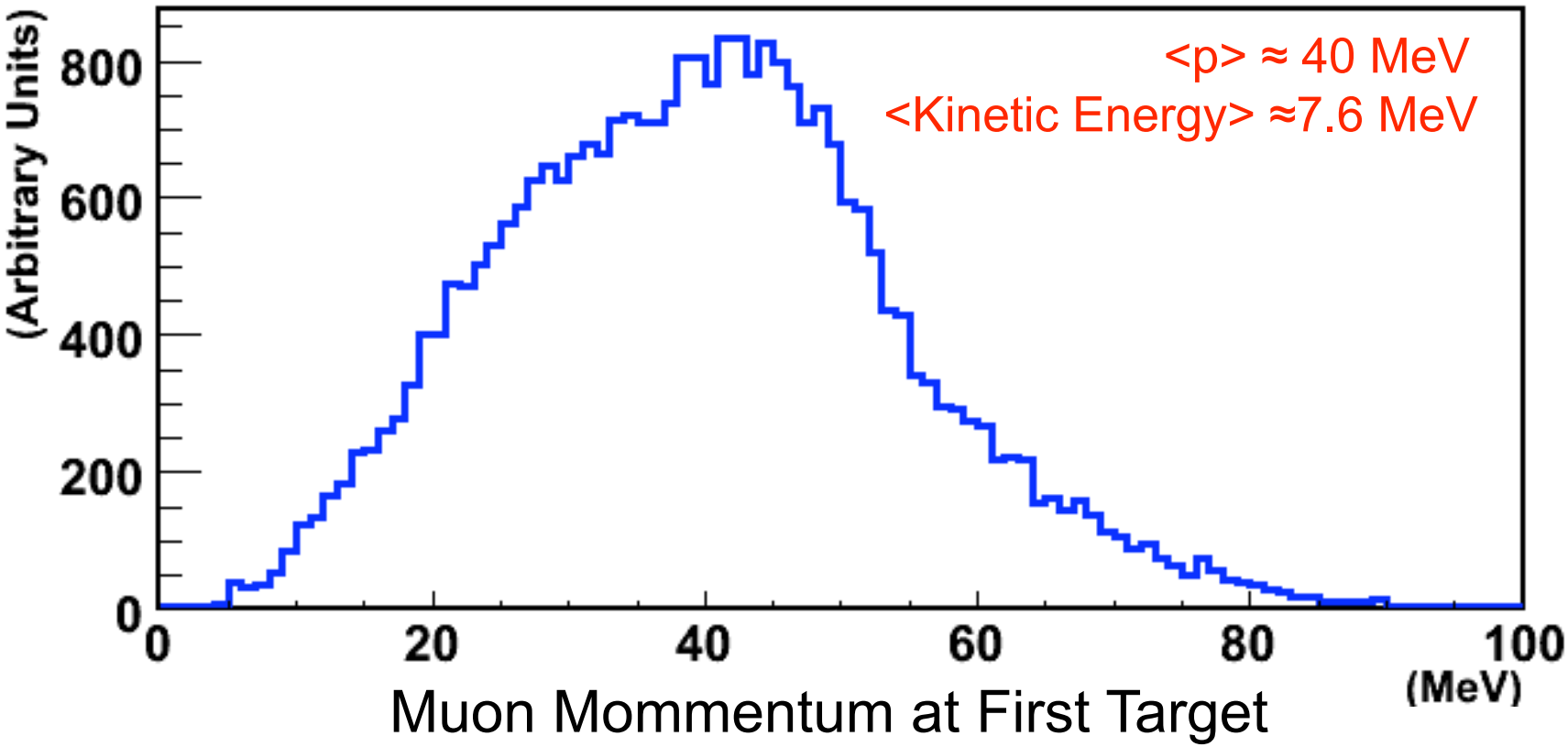
HEP 2001 W. Bertl – SINDRUM II Collab

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

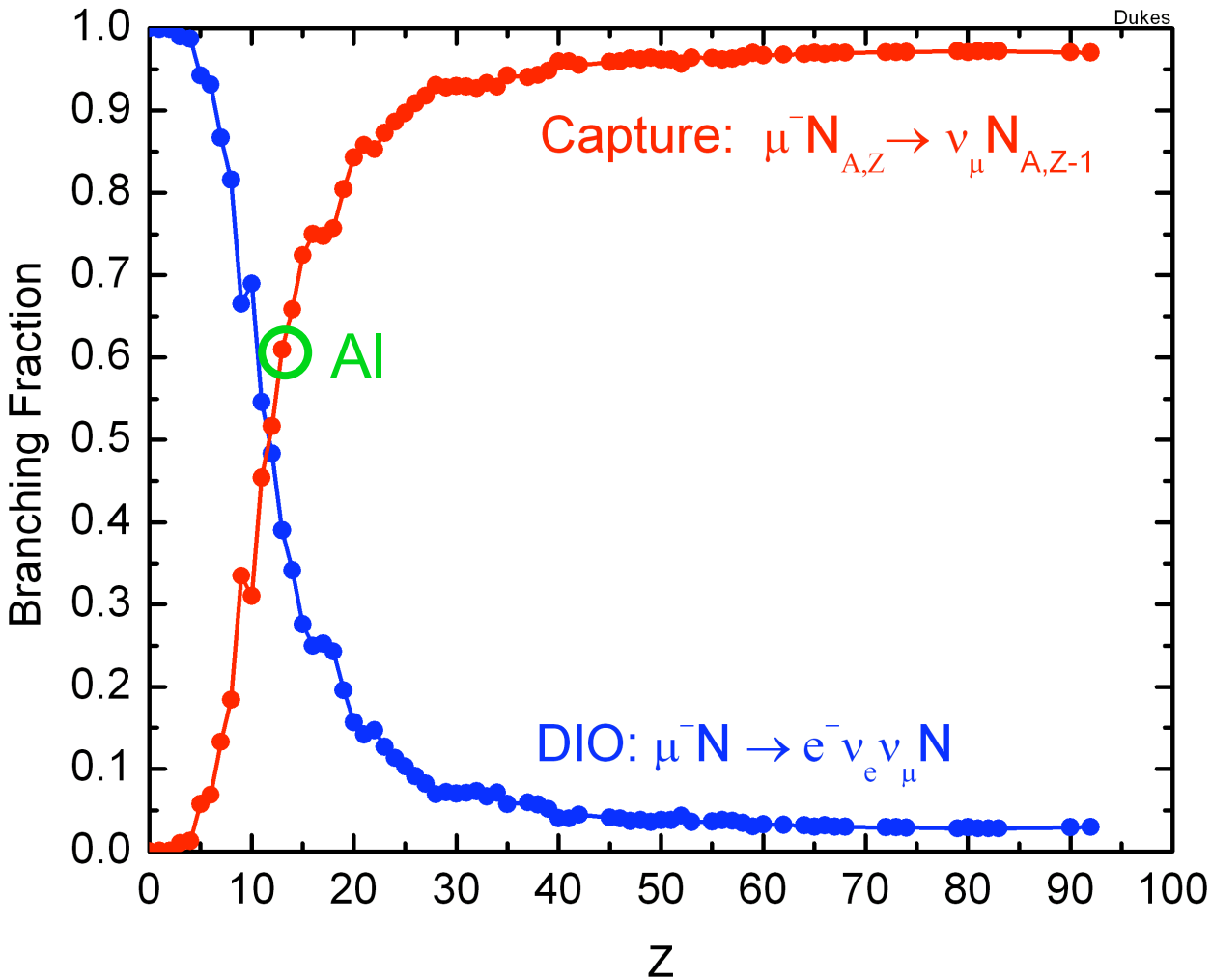
Why Mu2e Better than SINDRUM II?

- 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.

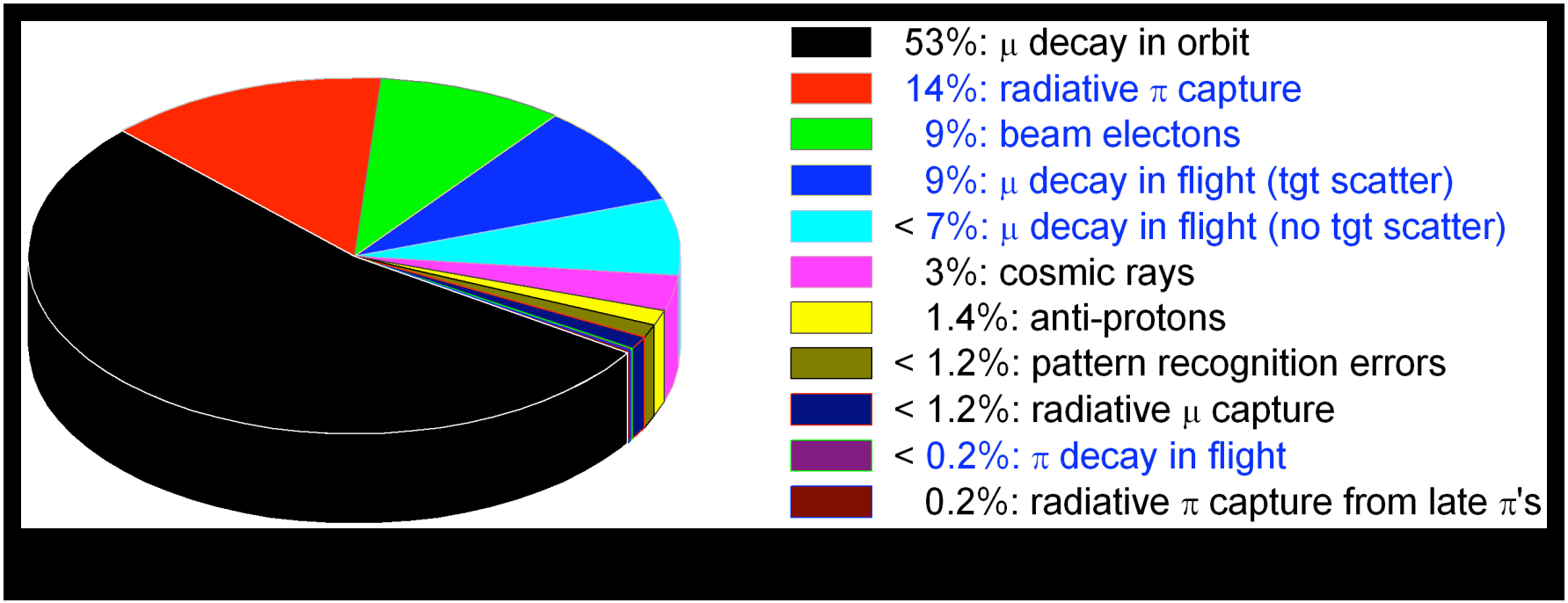
Muon Momentum



Capture and DIO vs Z

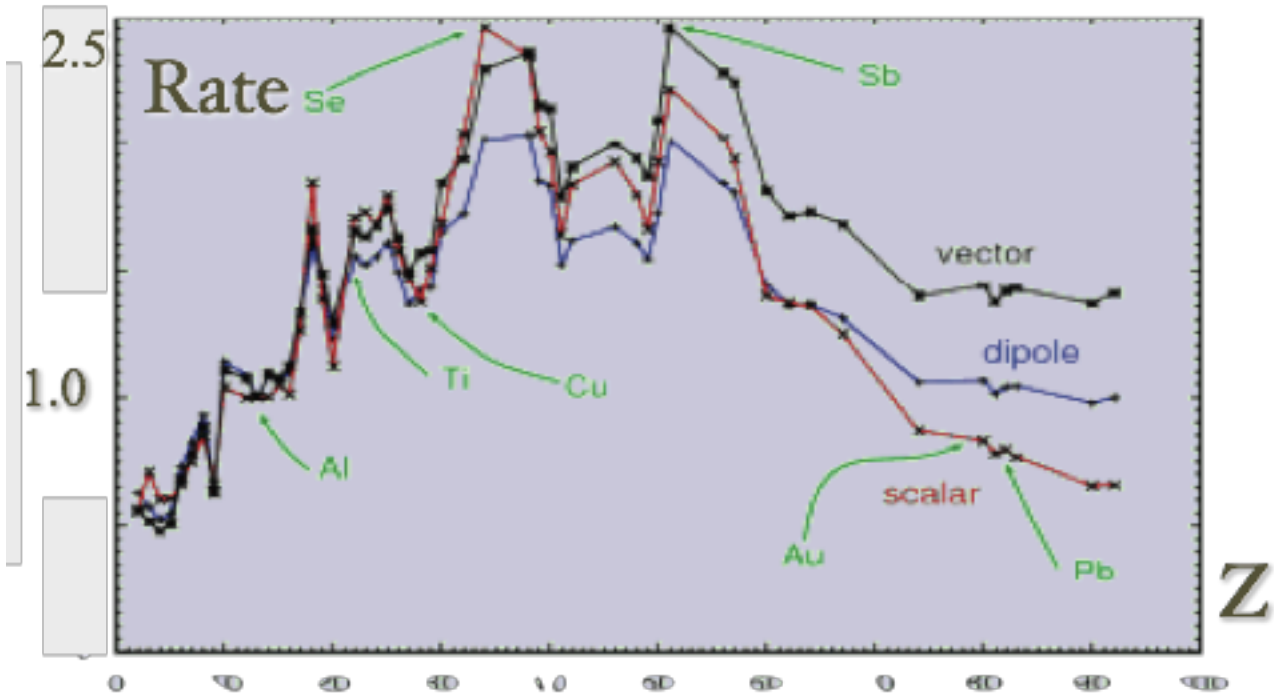


Distribution of Backgrounds



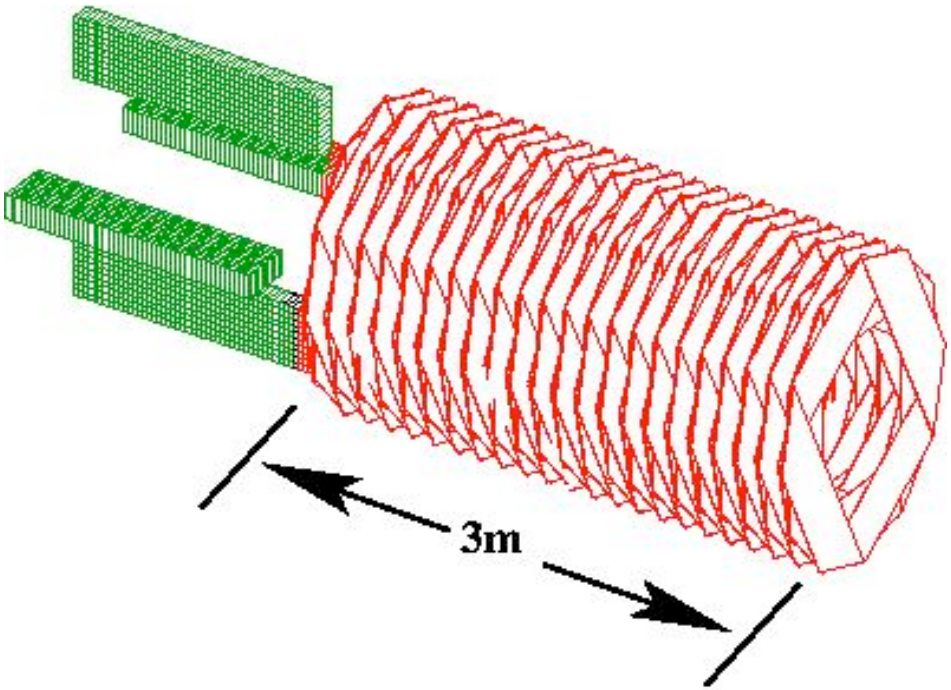
- About 50% of BG comes from protons out of time with bunches.
- In 2×10^7 s of running, estimate:
  - 0.42 background events
  - 40 signal events for $R\mu e = 10^{-15}$.

Conversion Rate, Normalized to Al



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

Alternative: T-Tracker

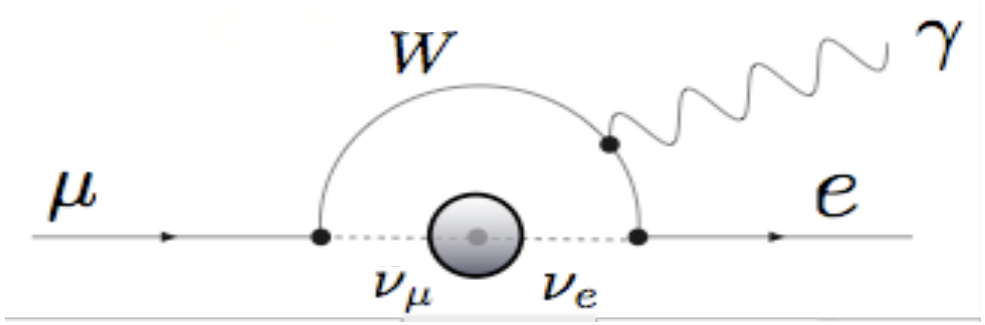


- 260 sub-planes; 60 straws per.
- No cathode pads.
- 5 mm diameter conducting straws
- Length from 70-130 cm
- Total of 13,000 channels

- L-Tracker
  - Not yet sure how to build it?
- T-Tracker
  - Robust pattern recognition may be harder?
- Need a fair head to head comparison.

CLFV Rates in the Standard Model

- With massive neutrinos, non-zero rate in SM.
- Too small to observe.



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

Backgrounds for 2×10^7 s Running

Source	Events	Comment
μ decay in orbit	0.225	
Pattern Recognition Errors	<0.002	
Radiative μ capture	<0.002	
Beam electrons*	0.036	
μ decay in flight*	<0.027	without scatter in target
μ decay in flight*	0.036	with scatter in target
π- decay in flight*	<0.001	
Radiative π^- capture*	0.063	from protons during live gate
Radiateive π^- capture	0.001	from late arriving π^-
Anti-proton induced	0.006	
Cosmic ray induced	0.016	
Total	0.415	

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