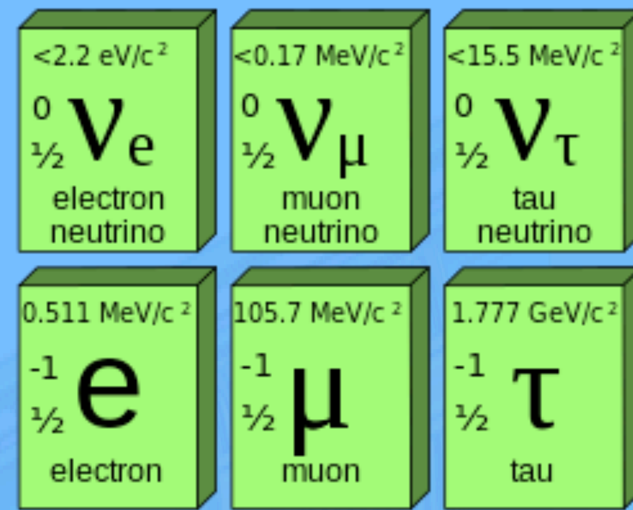
Mu2e: A μ→e Conversion Experiment at Fermilab

David Brown, LBNL
representing the mu2e collaboration

Lepton Mysteries

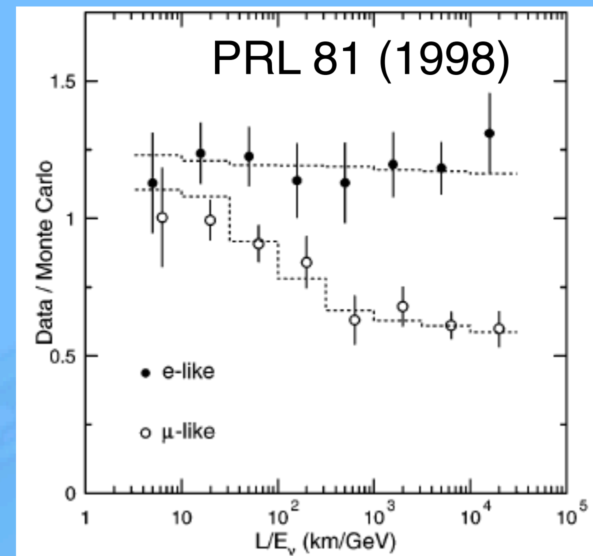
- The Standard Model posits lepton flavors as conserved currents
- Gauge invariance ⟹ conserved current (Noether's theorem)
- What (broken) symmetry(s) corresponds to lepton flavor conservation?
- Why are lepton couplings the same (universality)?
- What links quarks with leptons?
- Why are there >1 families of quarks + leptons? (who ordered that?)

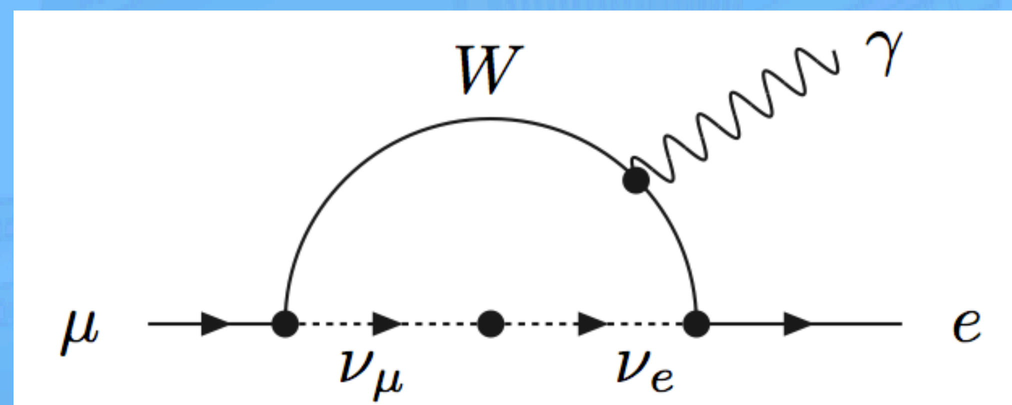


Lepton Flavor Violation

- Neutrinos mix: lepton flavor is not conserved
  - The Standard Model must be incomplete
- Neutrino-mediated CLFV is un-observably small
  - This is already ‘Beyond the Standard Model’ (BSM)
- Could there be other mechanisms for CLFV?
- Any observation of CLFV would be new information about BSM physics

Super-K atmospheric ν disappearance

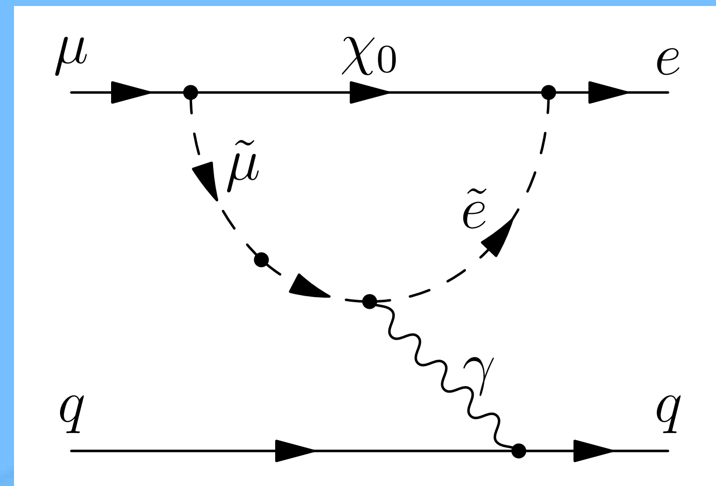


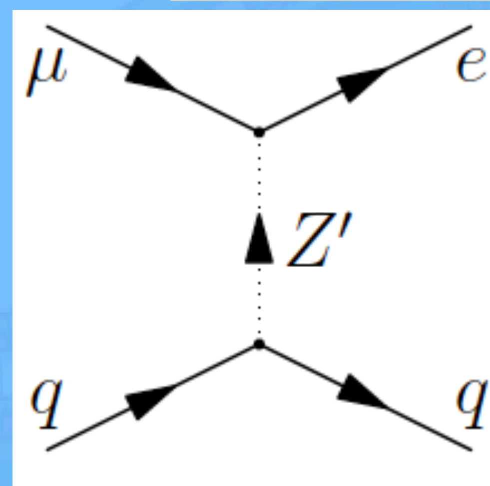


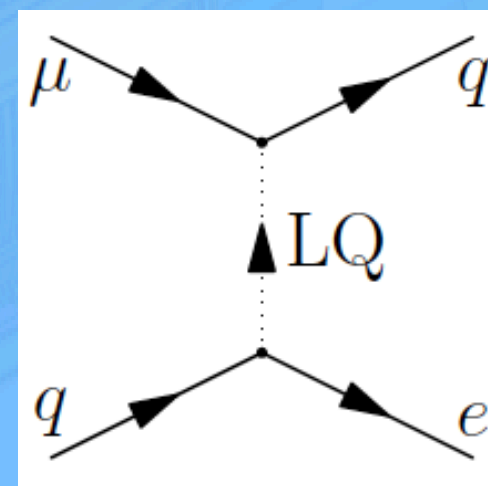
$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2}\right|^2 < 10^{-54}$$

μ→e Conversion

- ‘Dipole’ terms
  - i.e. SUSY
  - Also mediates μ→eγ
- ‘Contact’ terms
  - Direct coupling between quarks and leptons
  - Only accessible by μN→eN
- Effective Lagrangian
  - contact κ, mass scale Λ



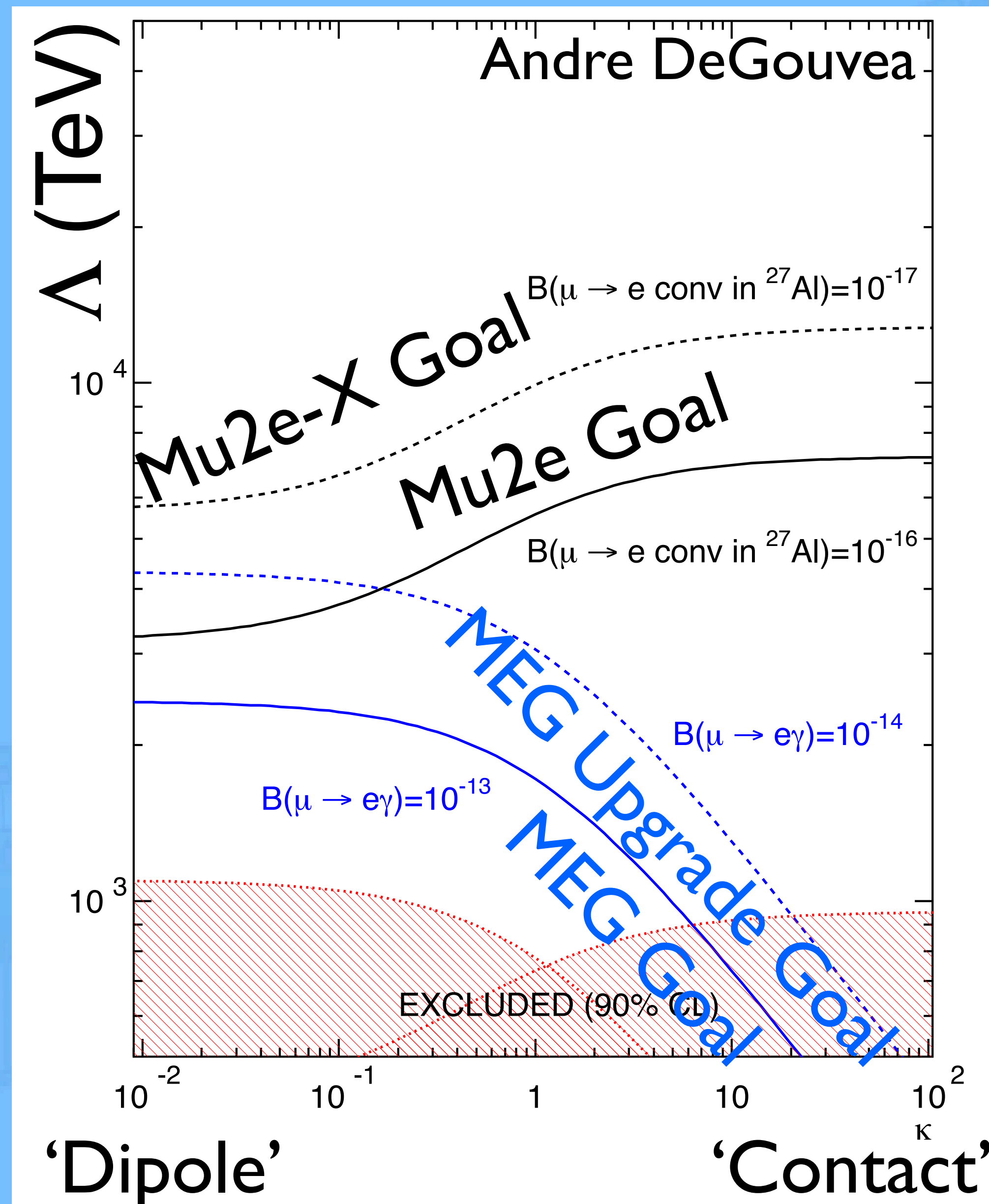




$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}R\sigma_{\mu\nu}e_L F_{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma^\mu q_L$$

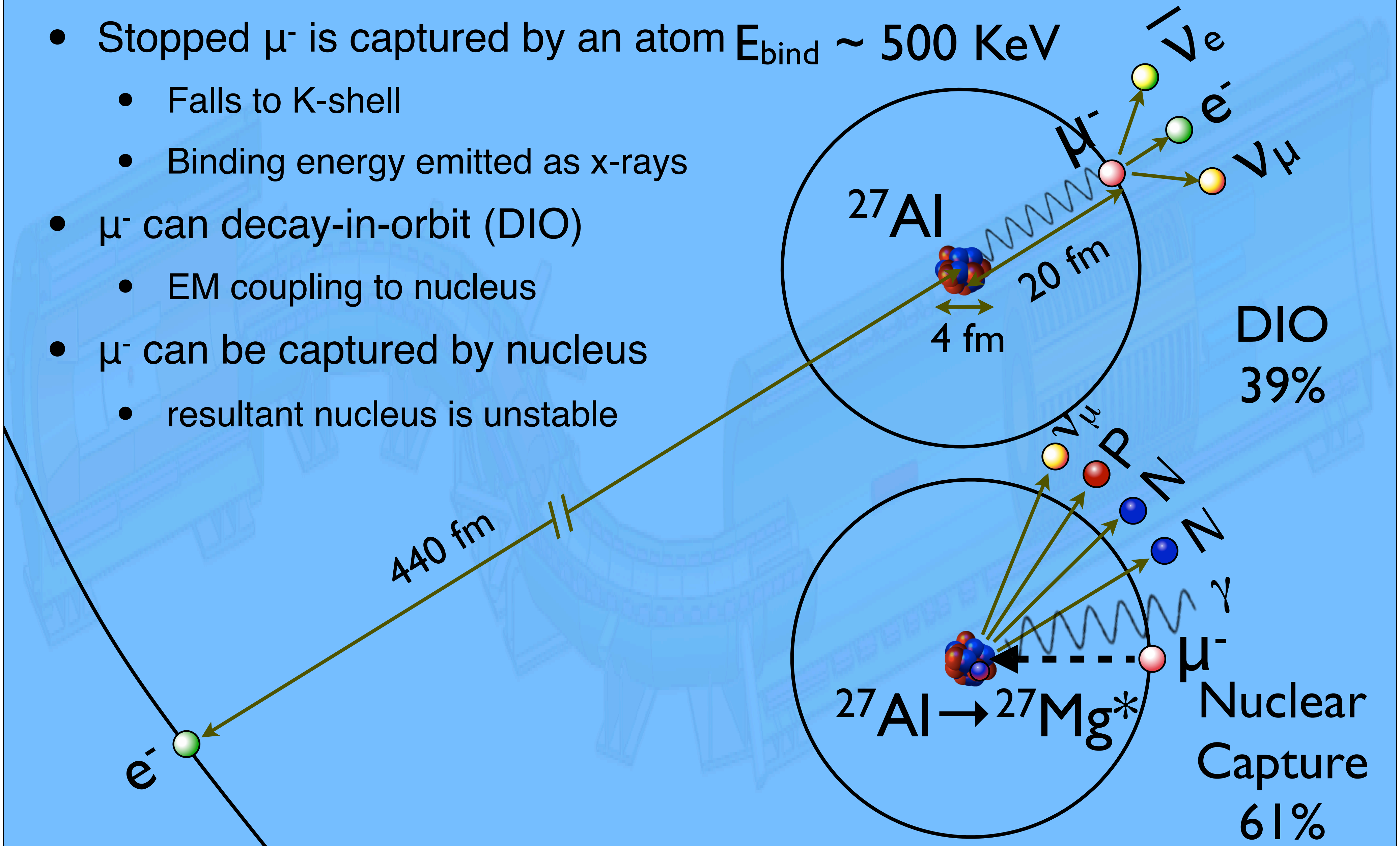
CLFV Sensitivity

- Effective mass scales up to 10^4 TeV are accessible
- Mu2e is sensitive over the full κ range



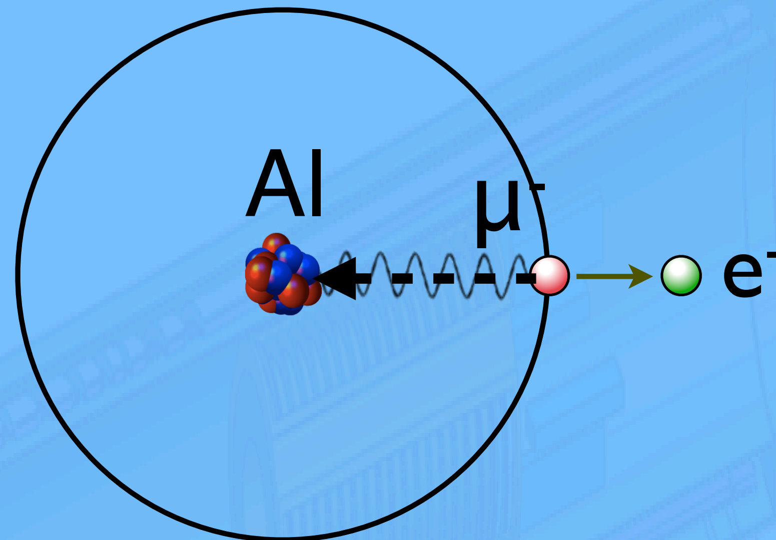
Atomic Capture of μ$^-$

- Stopped μ$^-$ is captured by an atom E_{bind} ~ 500 KeV
  - Falls to K-shell
  - Binding energy emitted as x-rays
- μ$^-$ can decay-in-orbit (DIO)
  - EM coupling to nucleus
- μ$^-$ can be captured by nucleus
  - resultant nucleus is unstable



μN→eN Conversion

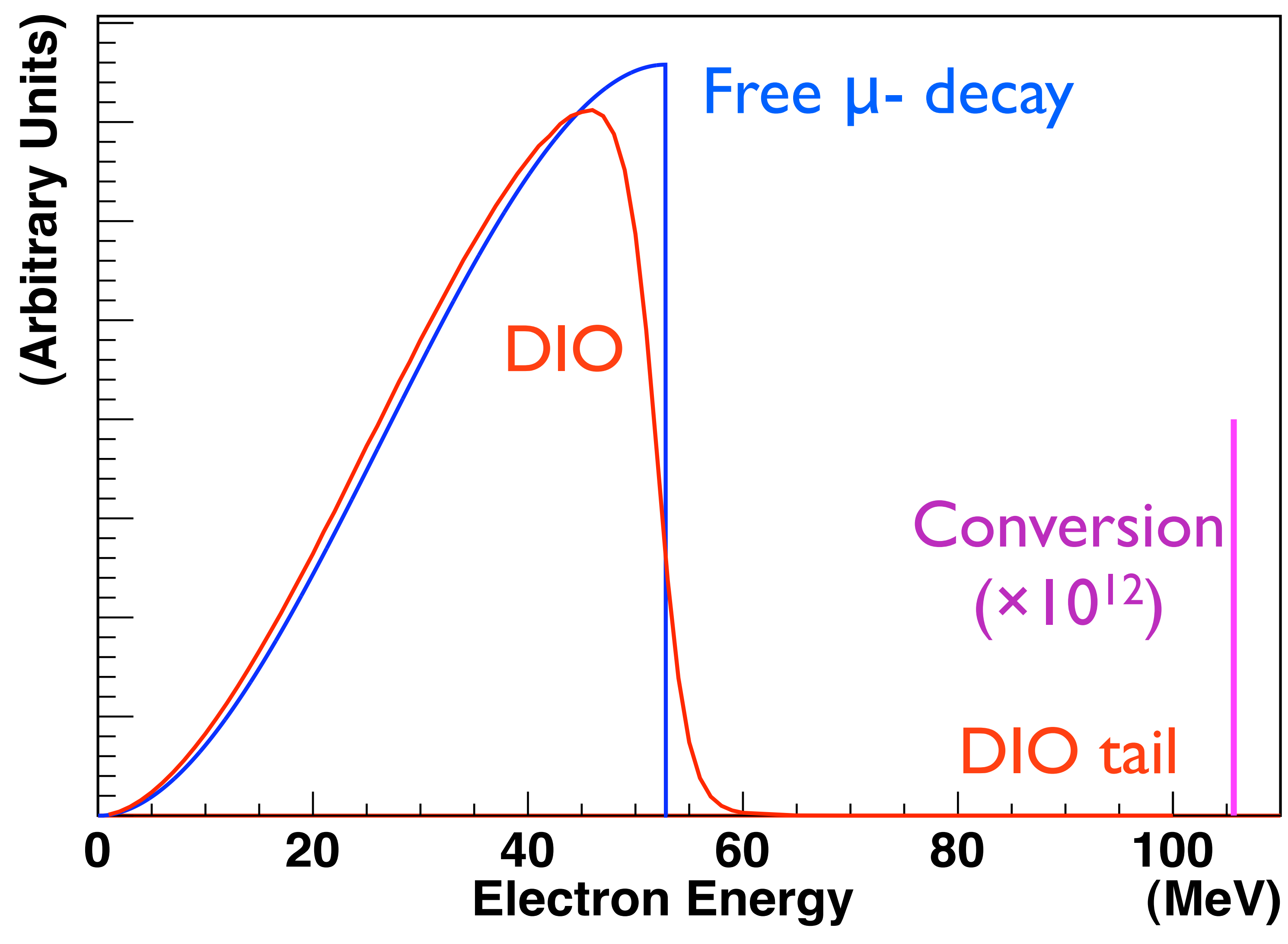
- μ^- converts coherently with N
  - no neutrino!
  - e^- recoil is against N
- Experimental Signature
  - isolated, mono-energetic e^-
  - $E_{conv} = m_\mu c^2 - E_{bind} - E_{recoil}$
  - E_{conv} = 104.973 MeV (for Al)



μN→eN
conversion $<10^{-12}$

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

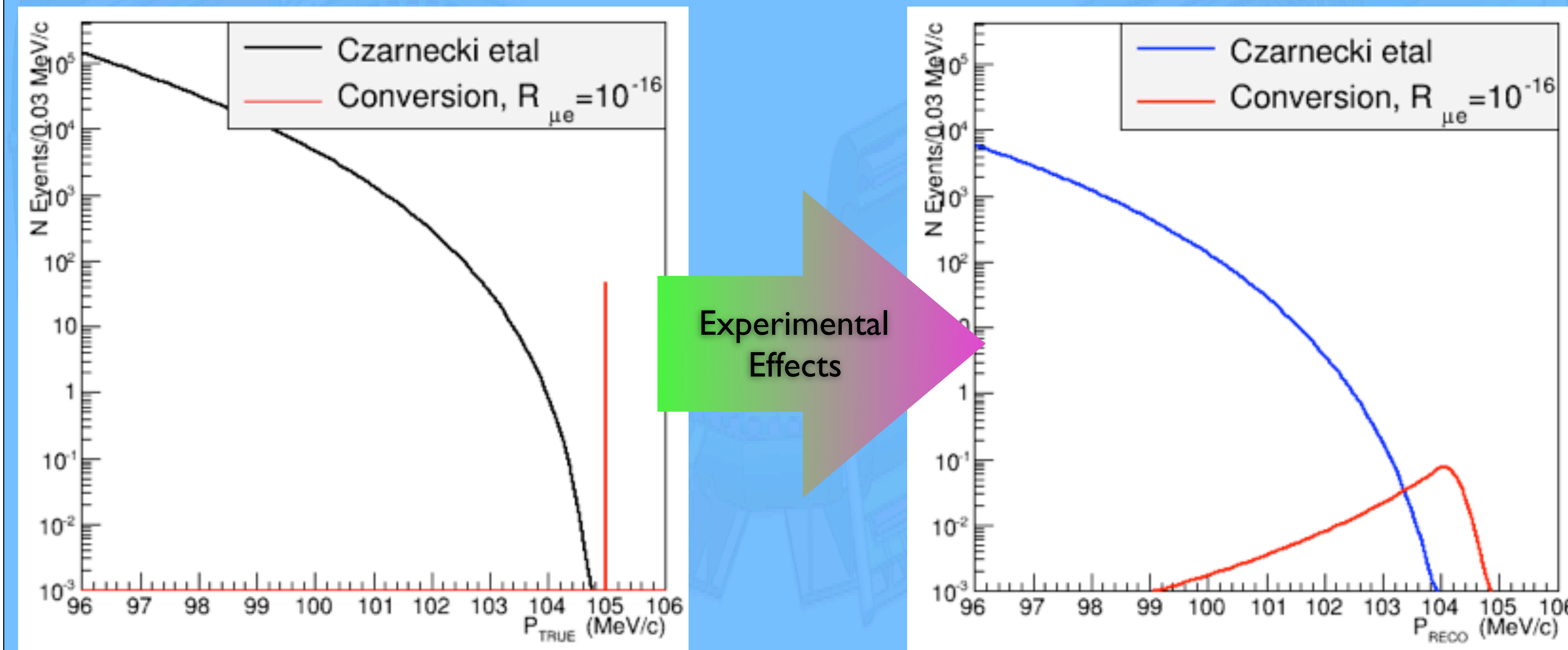
Electron Energy Spectra



DIO Endpoint

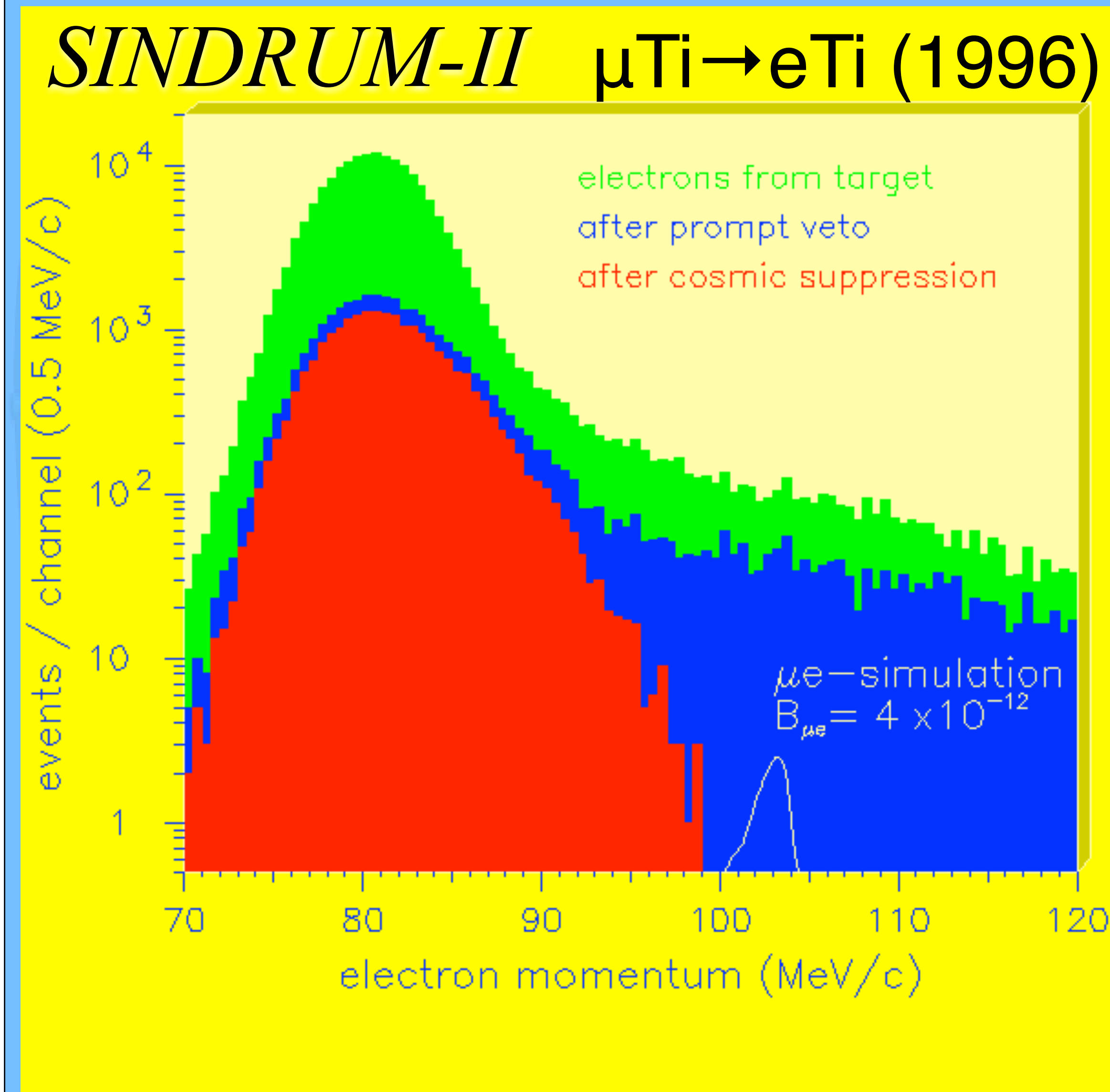
- Tail of DIO falls as $(E_{conv} - E_e)^5$
- Separation of ~few 100 KeV @ $R_{\mu e}=10^{-16}$

Czarnecki, Tormo, Marciano: arXiv:1106.4756



Phys.Rev. D84 (2011) 013006

Previous Measurements



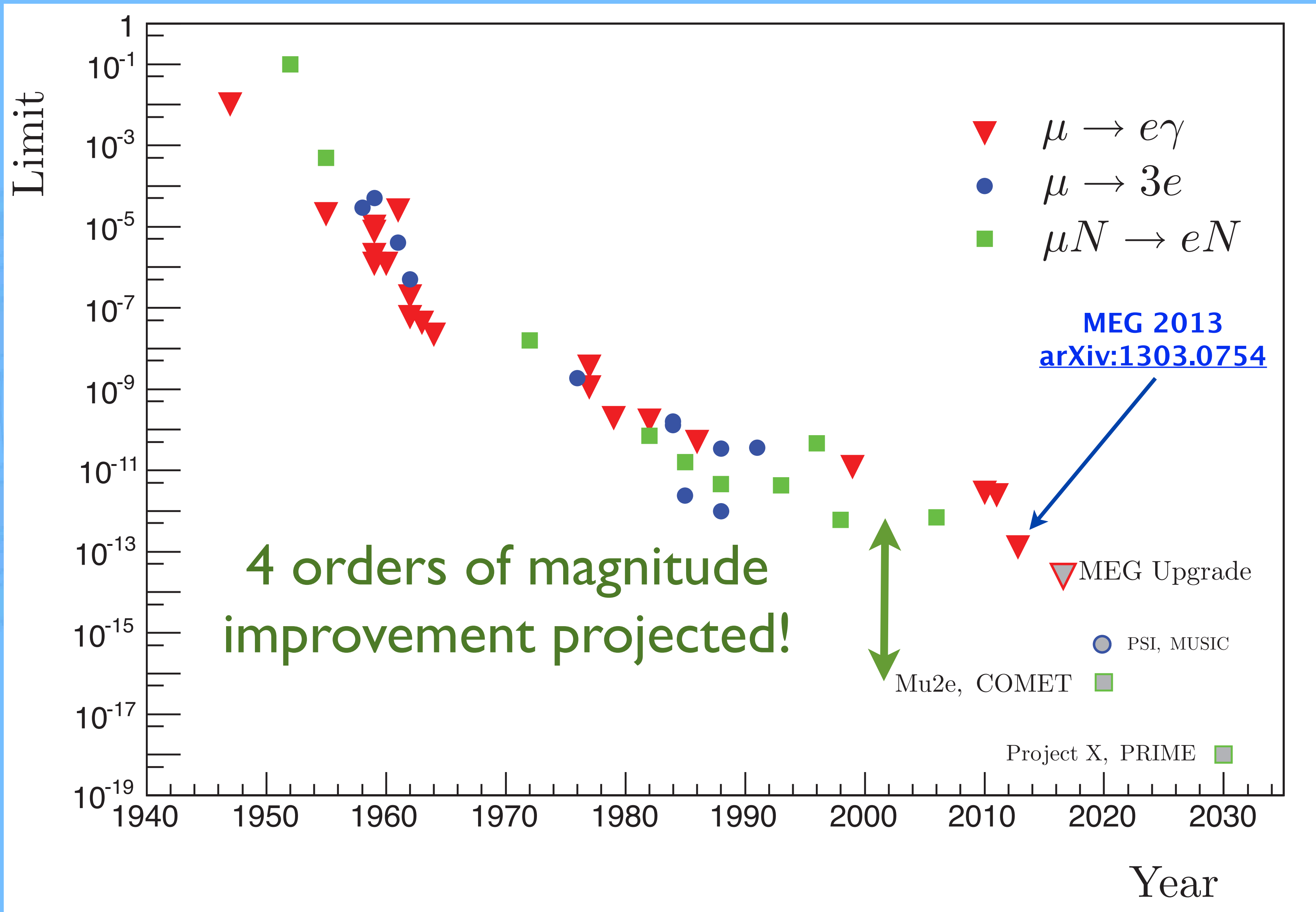
- Dominant background: beam π^-
  - Radiative Pion Capture (RPC)
  - suppressed with prompt veto
- Cosmic ray backgrounds also important

$R_{\mu e}(Ti) < 6.1X10^{-13}$
PANIC 96 (C96-05-22)

$R_{\mu e}(Ti) < 4.3X10^{-12}$
Phys.Lett. B317 (1993)

$R_{\mu e}(Au) < 7X10^{-13}$
Eur.Phys.J. C47 (2006)

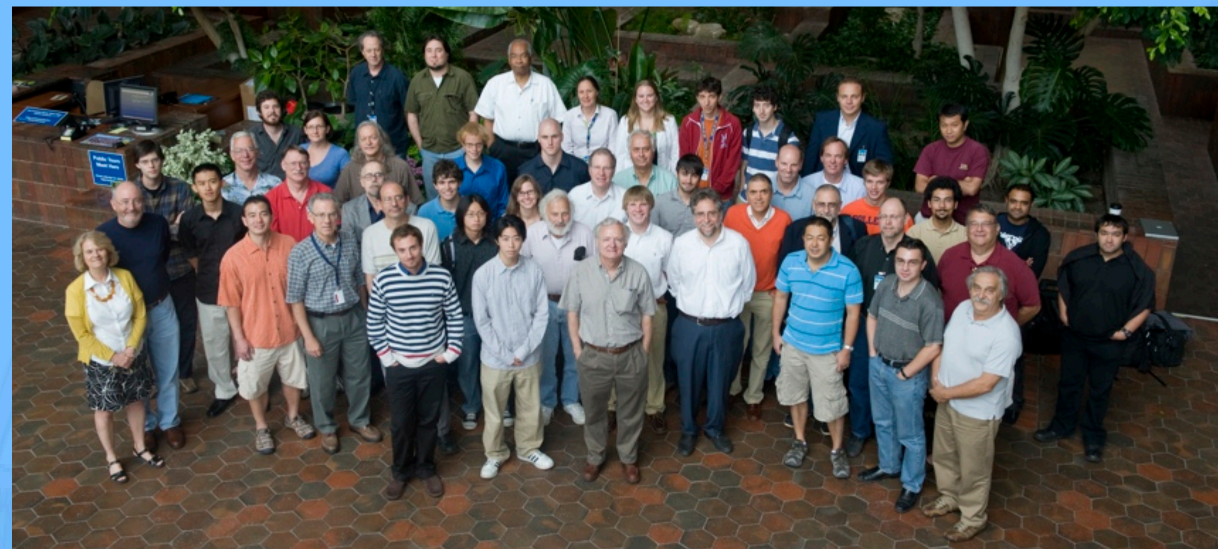
Status of CLFV Searches



The Mu2e Experiment

- Goal: Discover μN→eN conversion
- Target sensitivity: $R_{\mu e} = 6\times10^{-17}$ @ 90% C.L.
  - 4 orders of magnitude better than current limits
- Requires ~ 10^{18} stopped muons
  - ~ 4×10^{20} protons on target (3 year run @ 8 KW)
- Requires negligible (<1) background events
- Many challenges for the beamline and detector design

The Mu2e Collaboration



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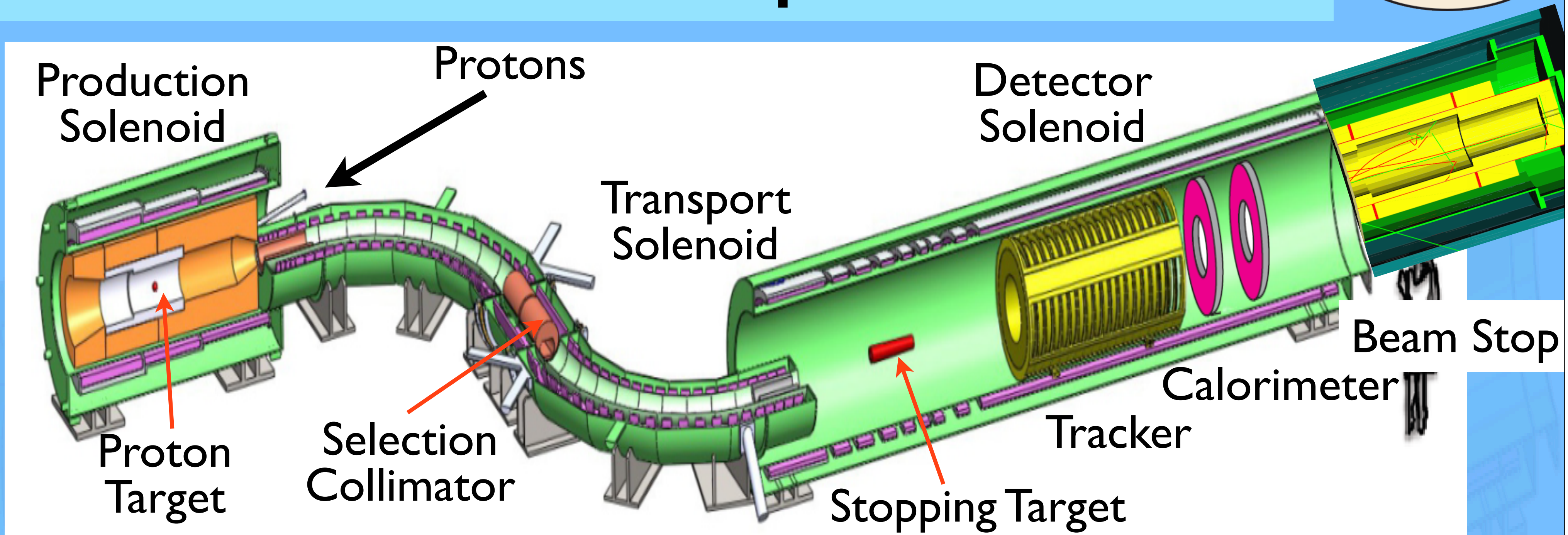
University of Illinois, Urbana-Champaign
University of Massachusetts, Amherst
Lawrence Berkeley National Laboratory
Northern Illinois University
Northwestern University
Pacific Northwest National Laboratory
Rice University
University of Virginia
University of Washington, Seattle

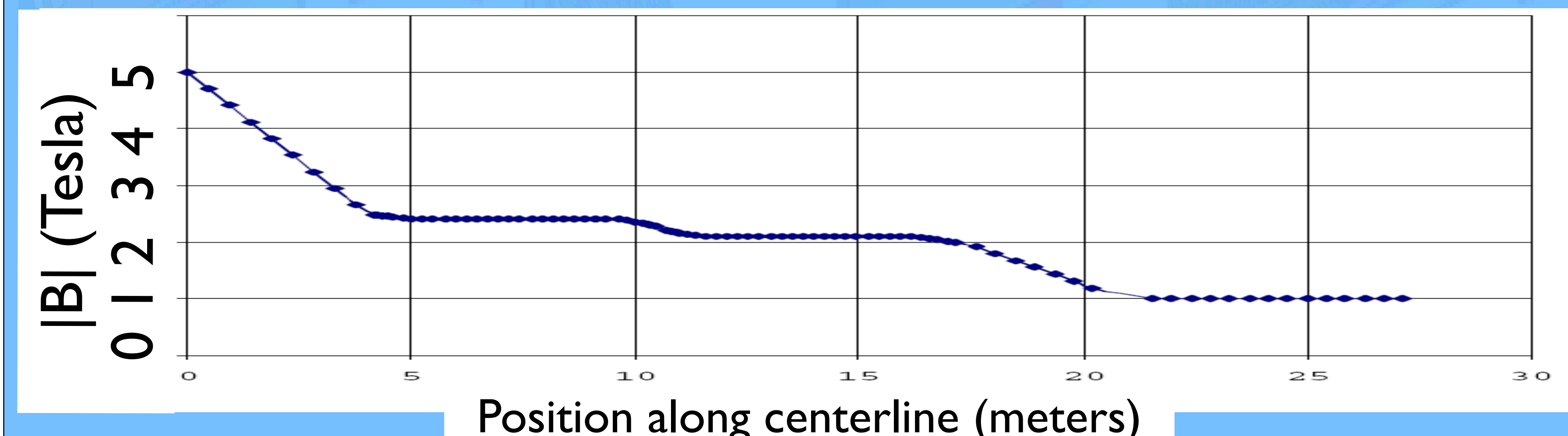
Istituto G. Marconi Roma
Laboratori Nazionale di Frascati
Università di Pisa, Pisa
INFN Lecce and Università del Salento
Gruppo Collegato di Udine

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

~130 collaborators

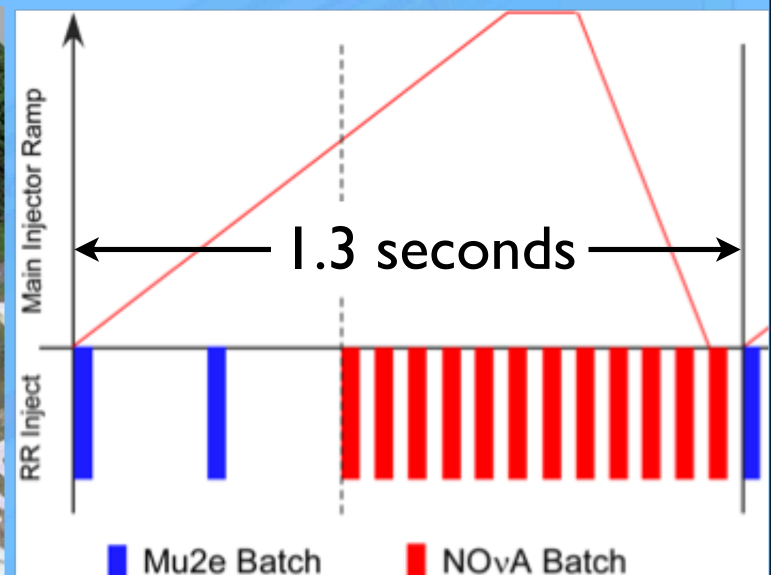
The Mu2e Experiment





Proton Source

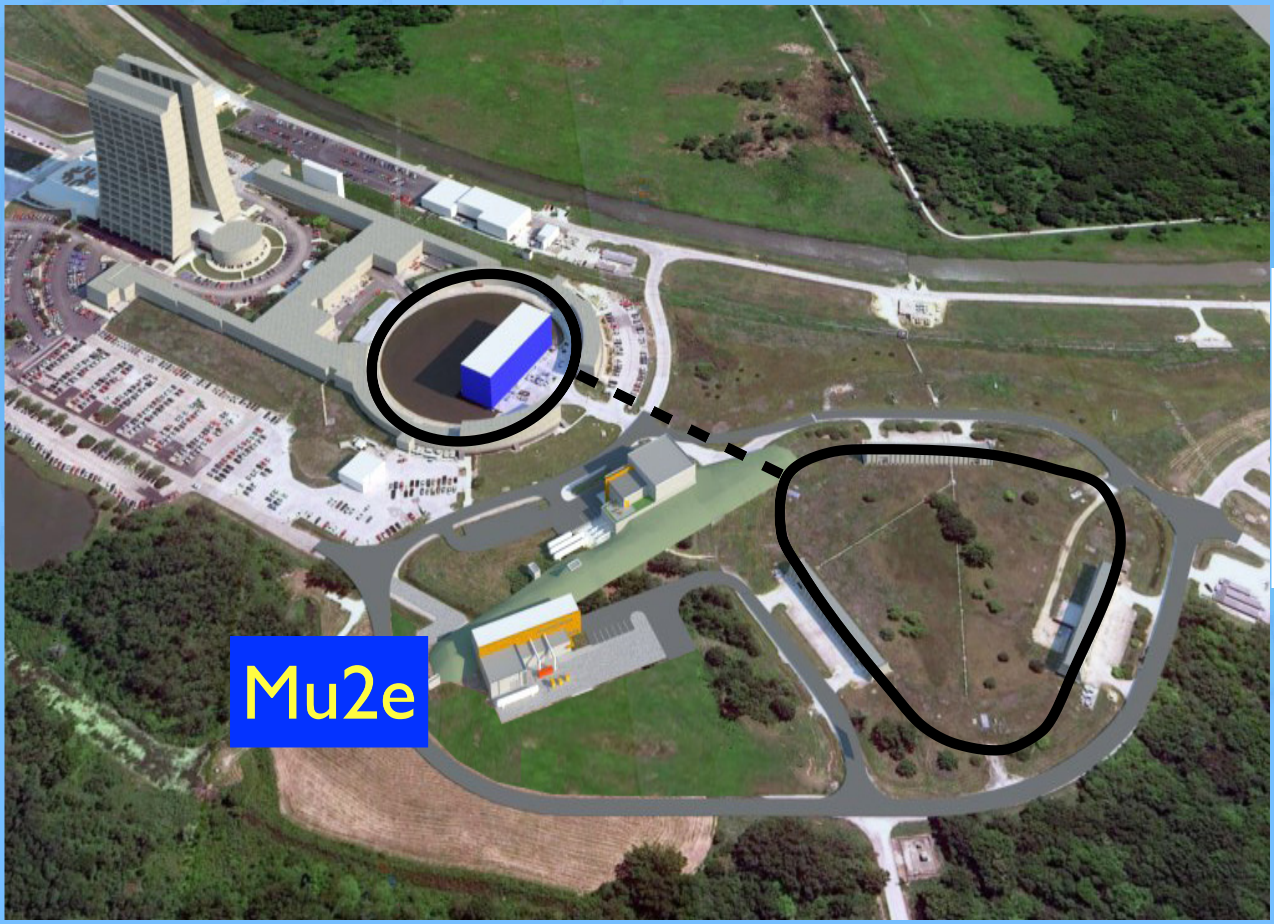
- 8 GeV protons from booster
  - Shared batches with NOVA ν production

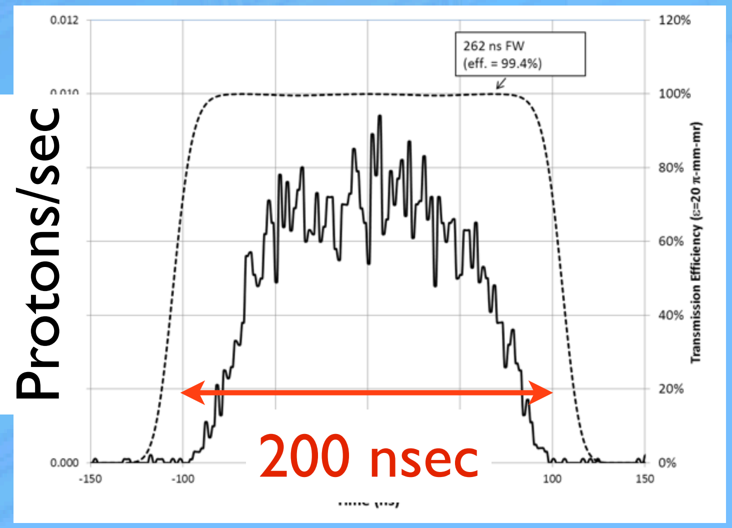


- 33% duty factor
- 1.2×10^{20} POT/year
  - 3-year run

Proton Bunch Formation

- Transfer P to former Anti-P Debuncher
  - Shape beam into narrow pulses, spaced 1.7 µsec

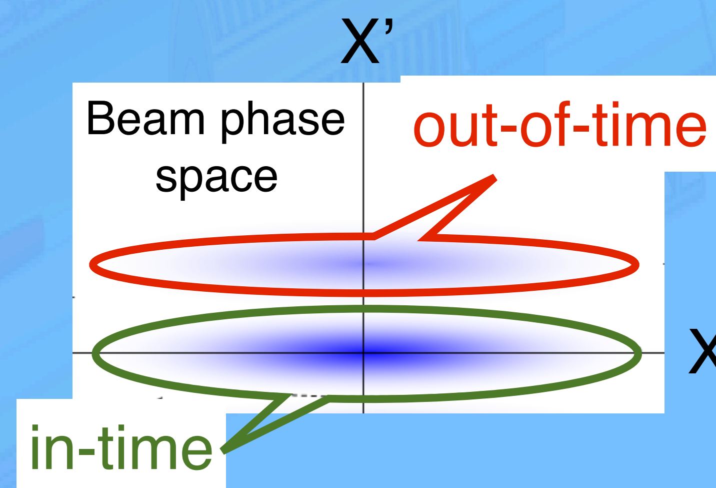




Out-of-time protons/ in-time protons < 10^{-4}

Proton Delivery

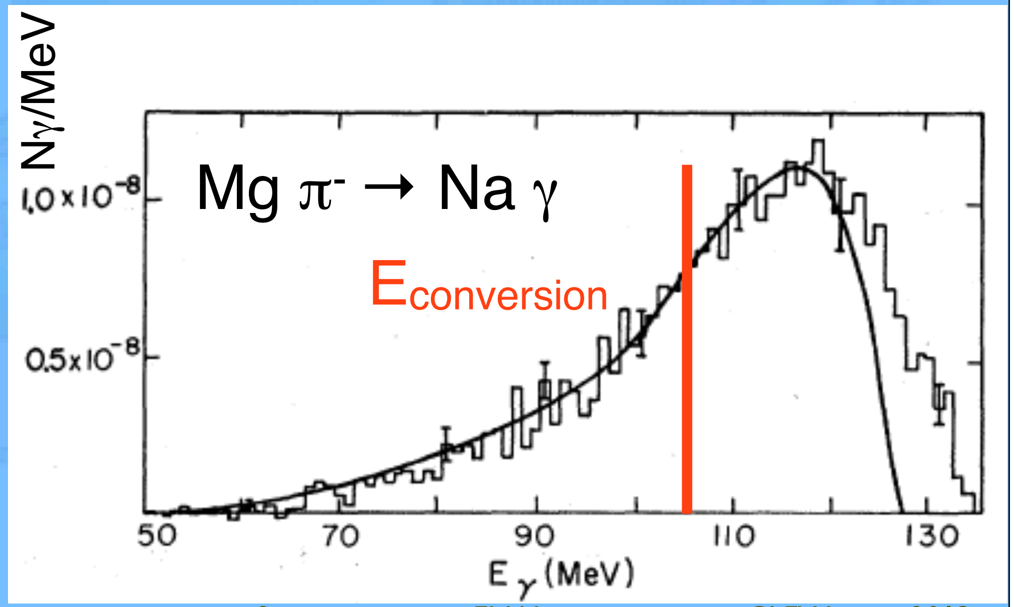
- System of resonant AC dipoles sweeps out-of-time protons into collimators
  - Out-of-time protons/in-time protons < 10^{-10} ('extinction')



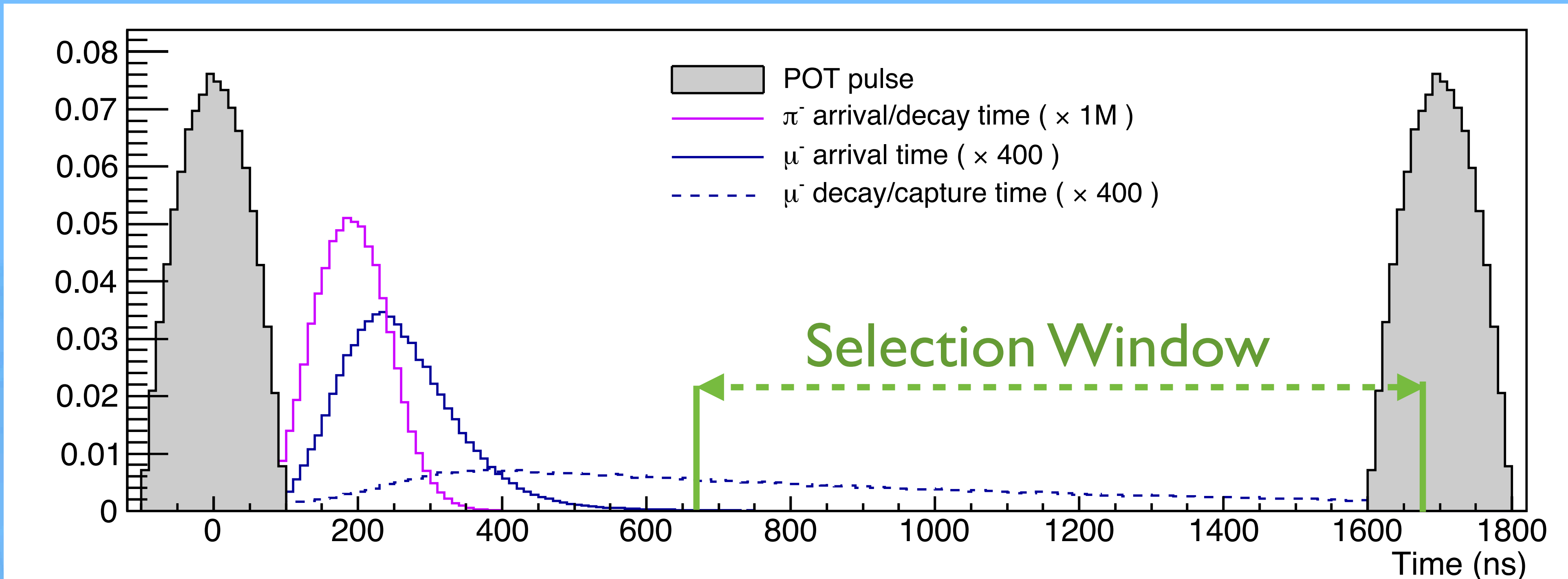
Beam delivery shared with g-2 experiment

Beam Backgrounds

- Mu2e beam is a mix of $\pi^\pm$, $\mu^\pm$, $e^\pm$, P and (a few) anti-P
  - Wide momentum spread ⇒ hard to separate species
- Positive particles are filtered by collimation
- beam e^- are rejected with timing, polar angle cuts
- Anti-P, π^- can produce fake conversion e^-
  - Capture → γ → asymmetric γ conversion
- Anti-P are reduced with degrader
  - costs ~10% of μ^- flux
- π^- are reduced by waiting
  - requires good extinction!



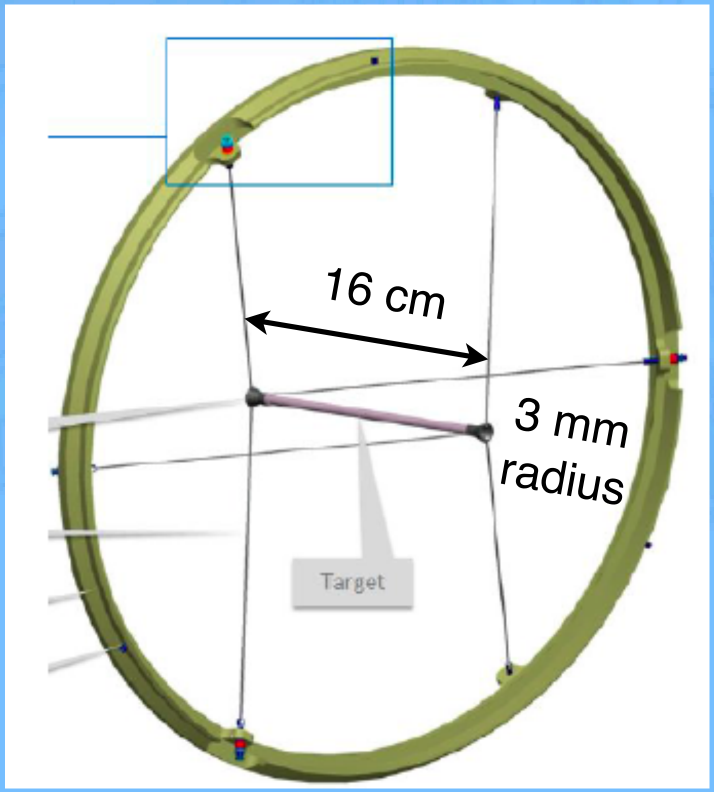
Timing (with Al target)

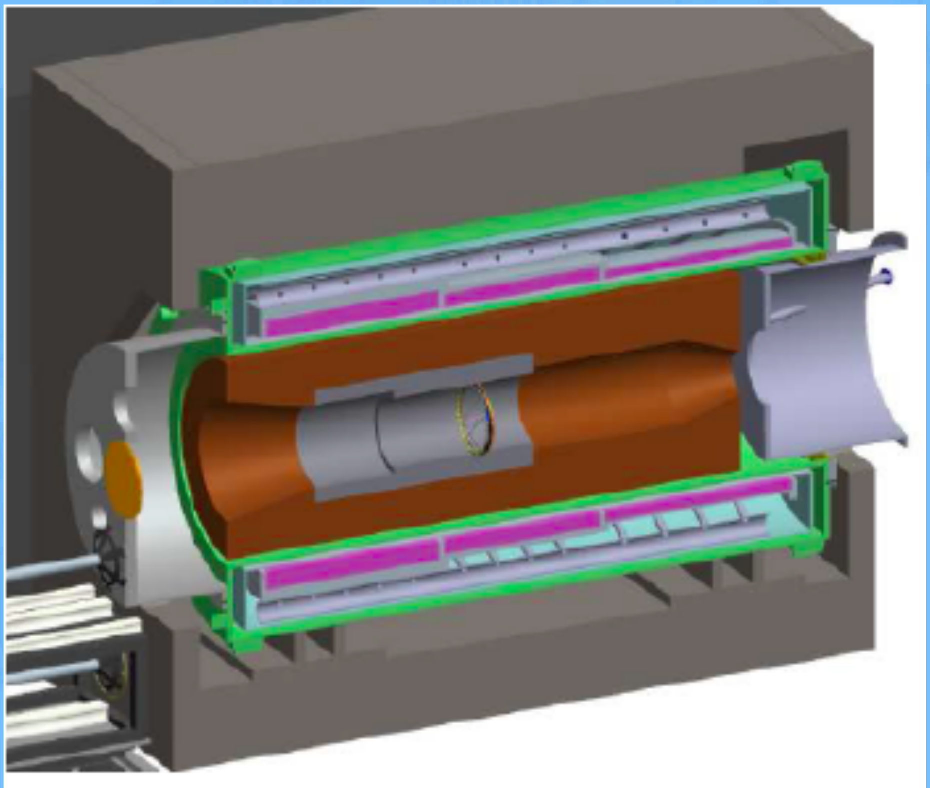


- Muons reach the stopping target in ~250 ns
  - Stopped muon lifetime on Al ~800 nsec
- Select tracks after beam, π^- decay
  - ~1 μsec window, ~50% acceptance

Target and Target Shield

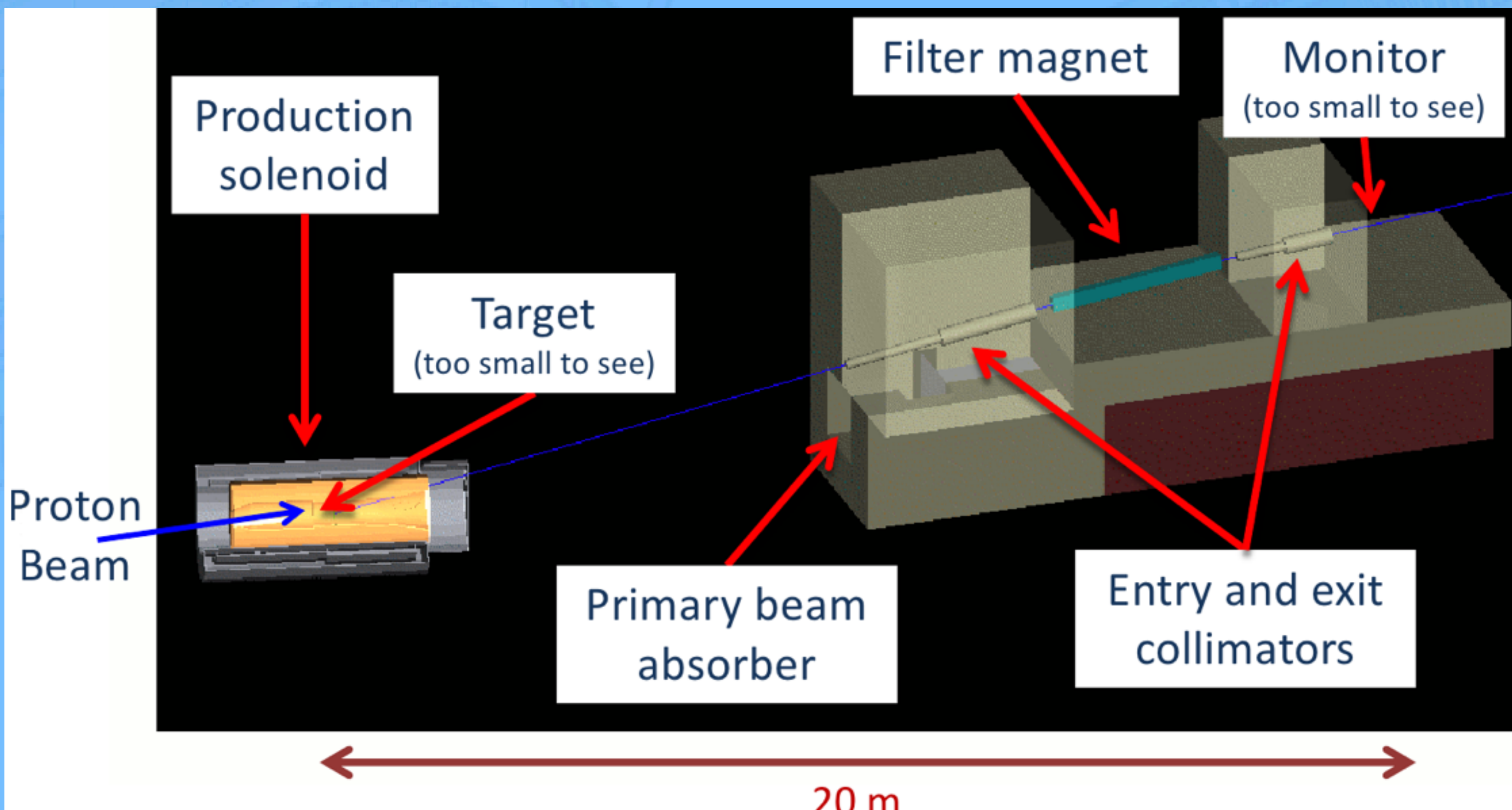
- Tungsten rod target
  - Radiative cooling (~1600° C!) under study
- ~25 tons of Brass to protect superconductor stabilizer
  - Limit Displacement Per Atom to < 10^{-5}/year





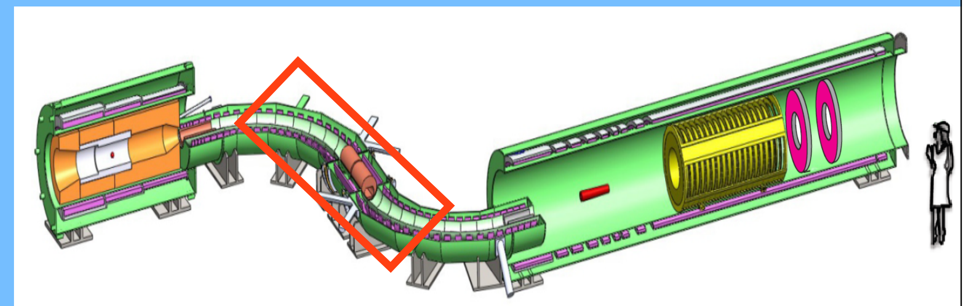
Extinction Detector

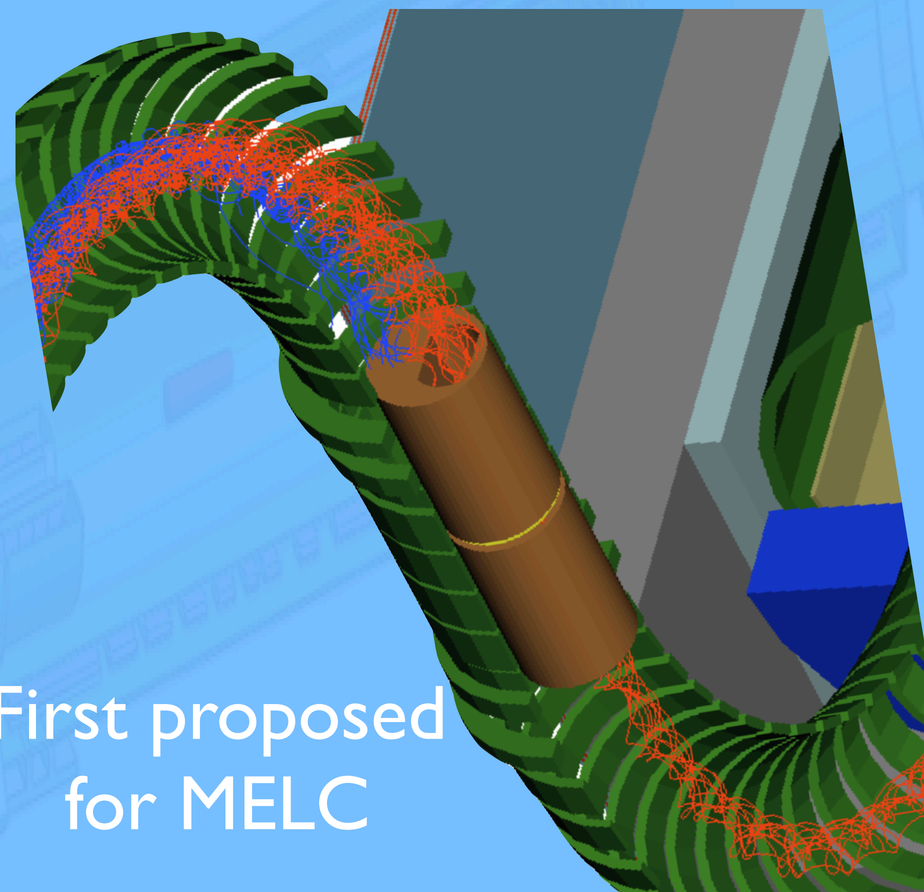
- Si pixel telescope spectrometer with narrow view of target
- Measure extinction to 10^{-10} in ~1 hour



Momentum + Charge Selection

- 'S' bend solenoid transports low-momentum charged particles
  - Neutrals have no line-of-sight to the detector
- Bend induces momentum and charge-dependent vertical translation
- 'D' shaped Collimator rejects positive charge and high-momentum particles
  - Can be rotated to select positive particles

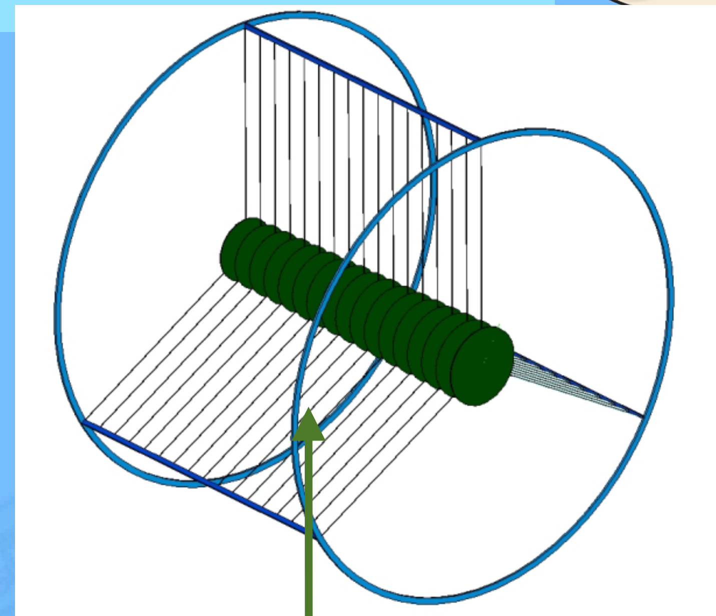


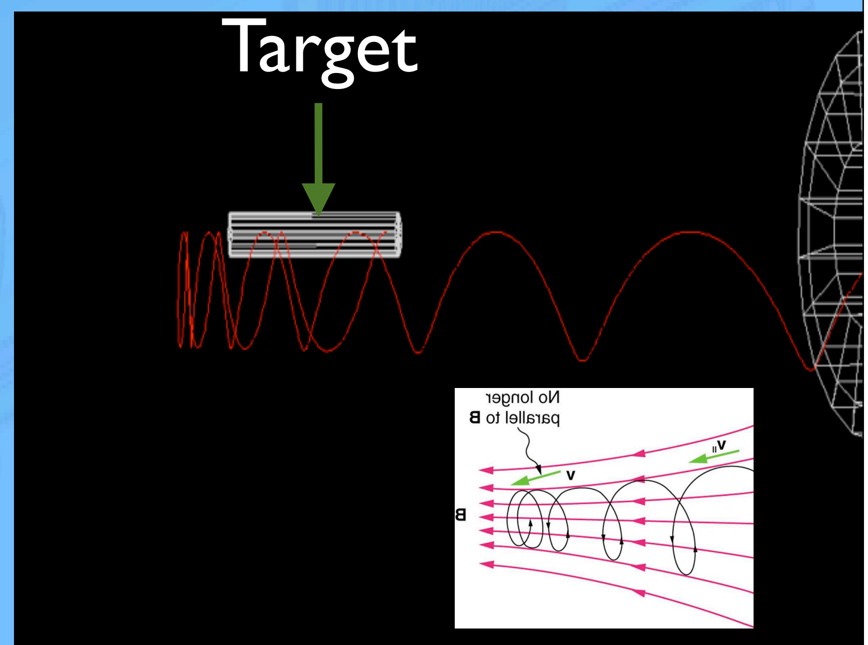


First proposed for MELC

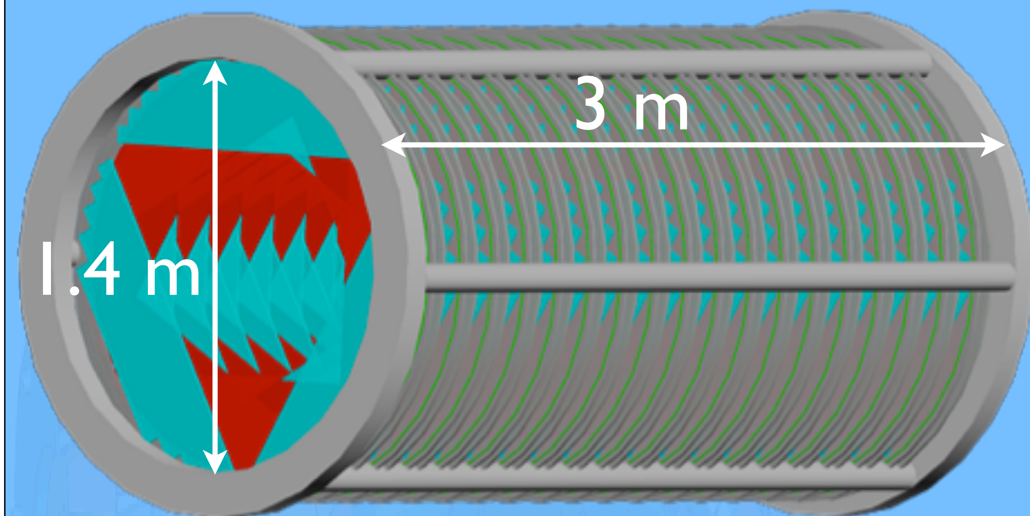
Stopping Target, Detector Solenoid

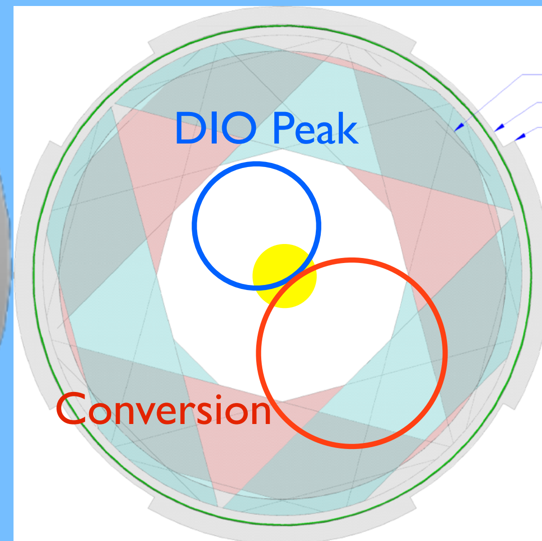
- Aluminum disks
  - 0.2 mm thick, ~10cm diameter
  - optimization in progress
- Graded magnetic field near target
  - $B_Z = 2.0\ T \rightarrow 1.0\ T$
  - ~50% increase in e^- acceptance
- Detector region ~1T field
  - 0.5 %/meter gradient sweeps out slow $e^{\pm}$, $\mu^{\pm}$





Straw Tracker

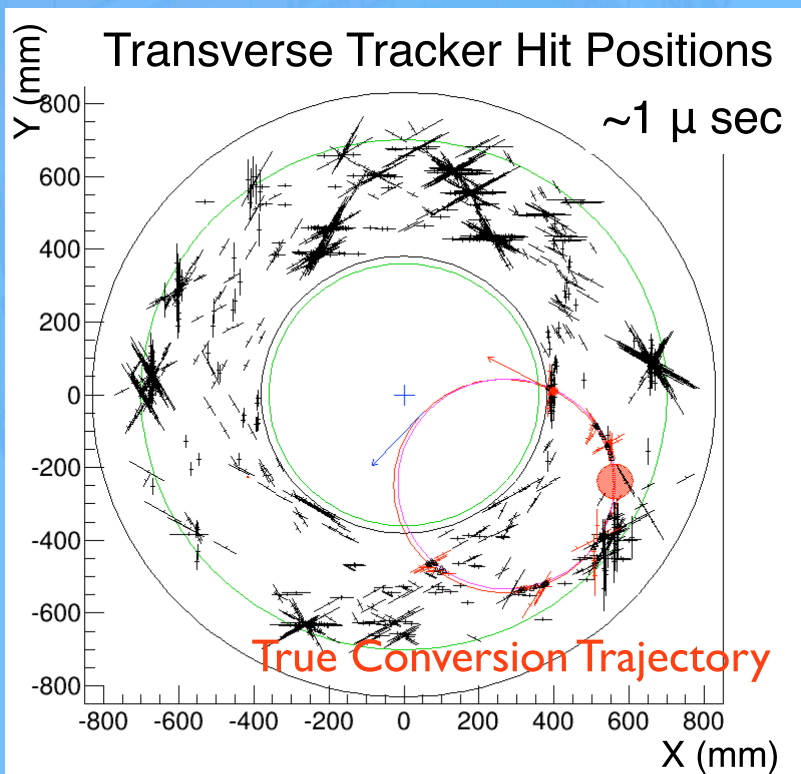


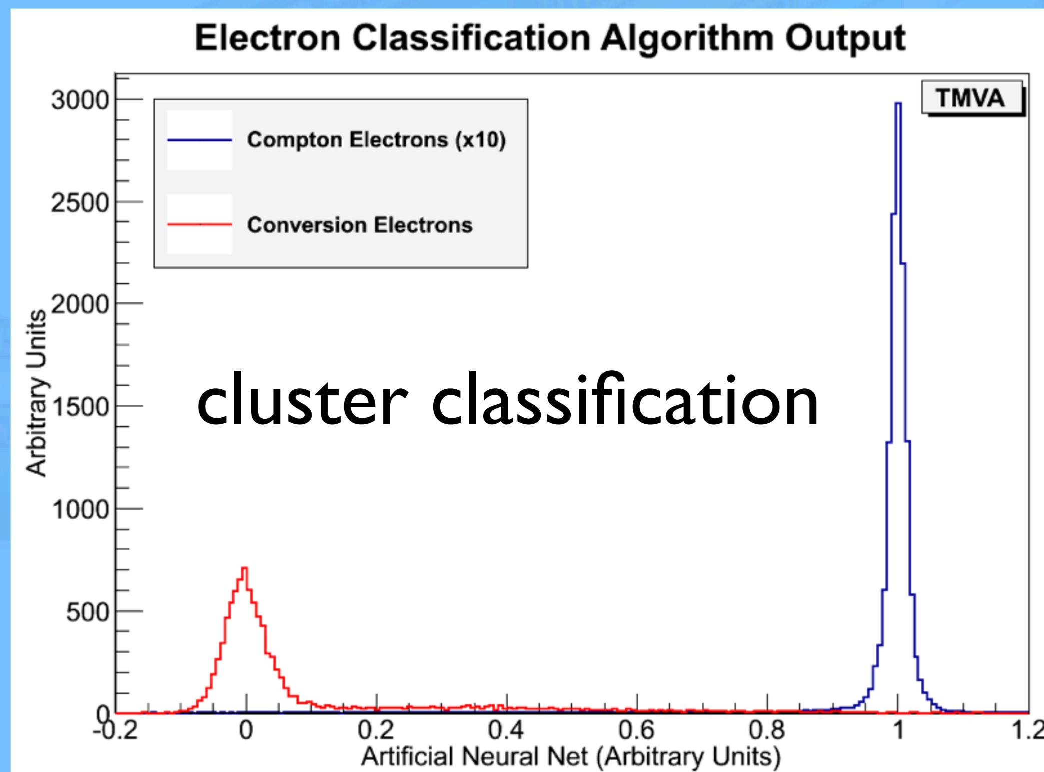


- 18 *stations* of straw chambers
  - 12 *panels* of parallel double-layer straws
- 21,600 straws
  - 5 mm diameter, 15 µm mylar walls
- Custom ASIC for Time Division readout
  - < 50 psec Δt resolution

Background Hit Removal

- Low-energy electrons from Compton scattering and γ-conversion generate ~500 MHz of background tracker hits
  - Neutrons produce photons, straw walls are radiators!
- We identify these hits by their tight clustering in space
- We use an Artificial Neural Net to refine the separation from conversion hits
- We also remove hits with large energy deposition (rejects most proton hits)





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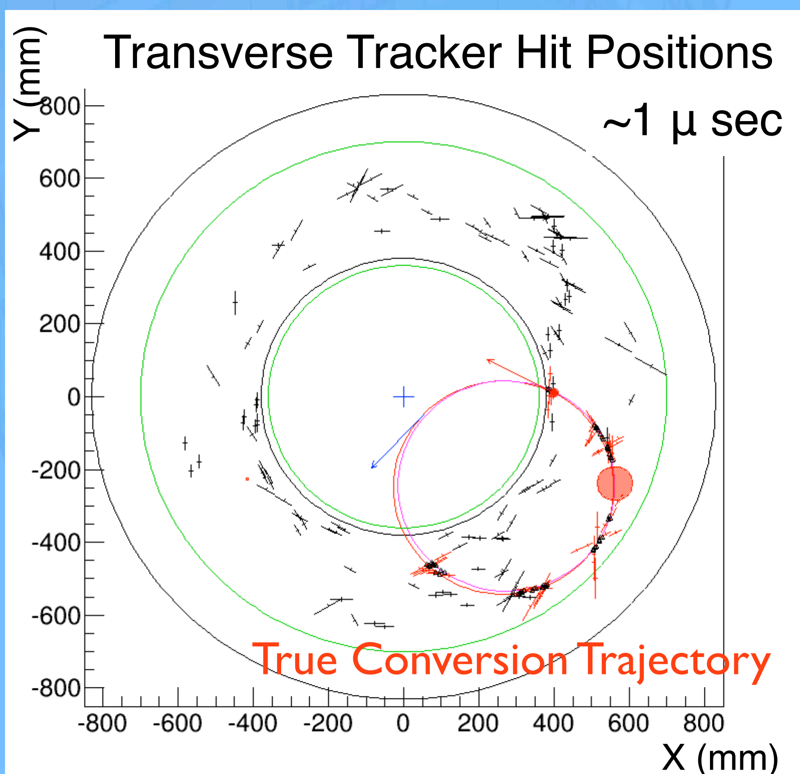
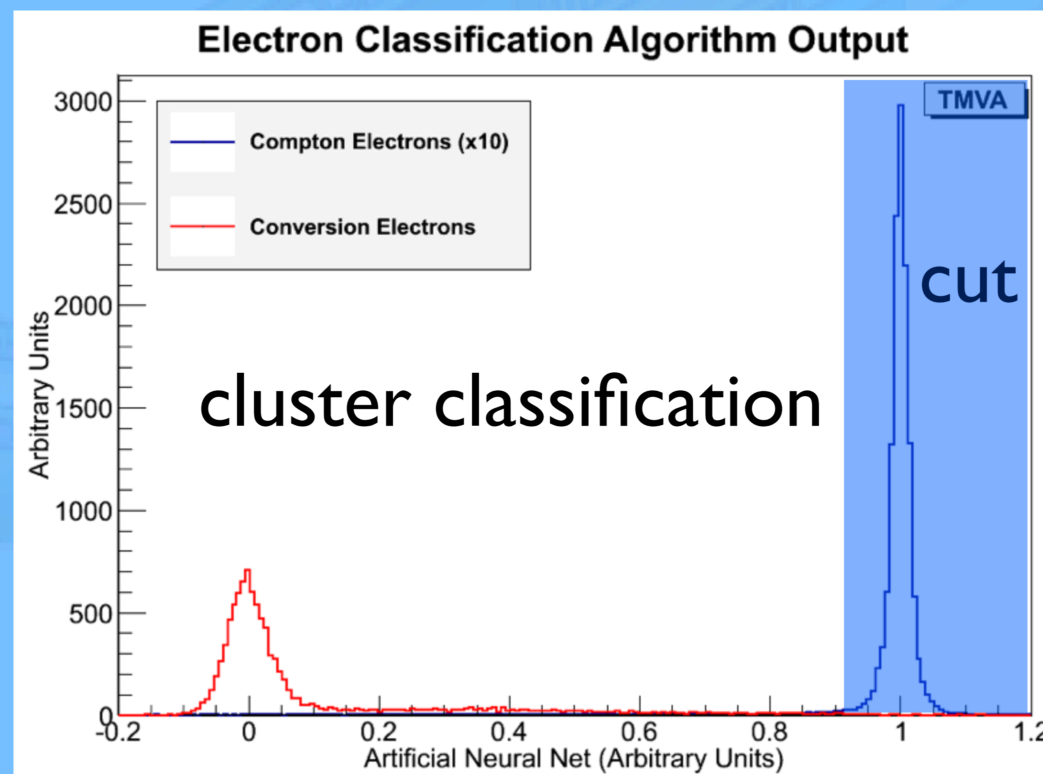
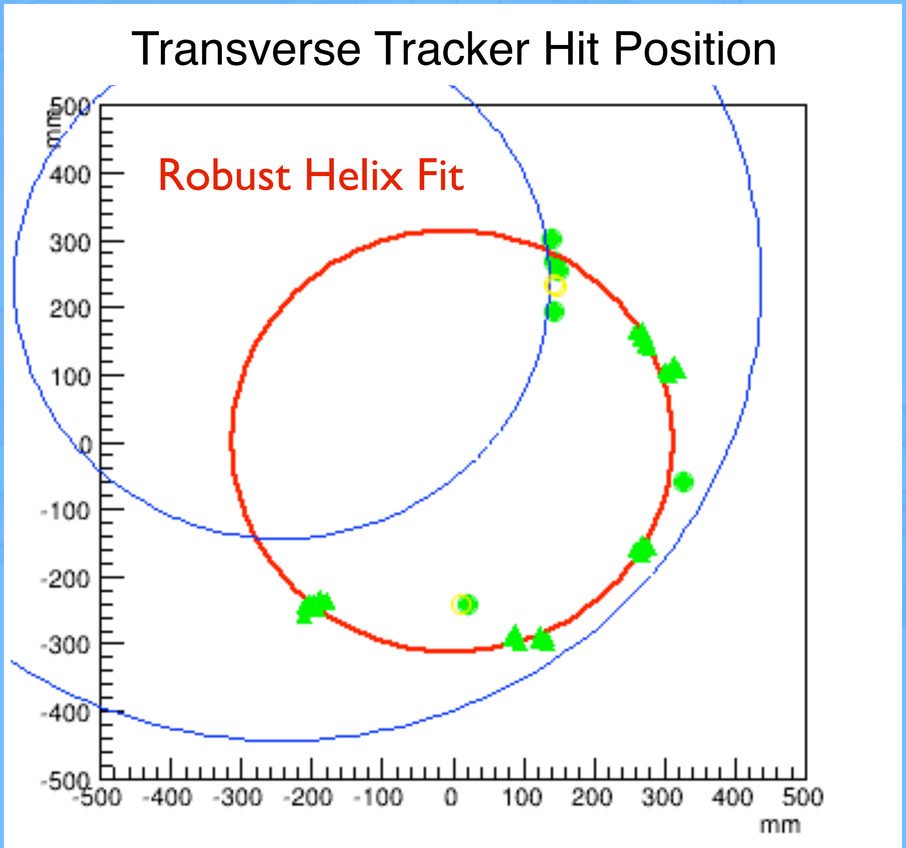
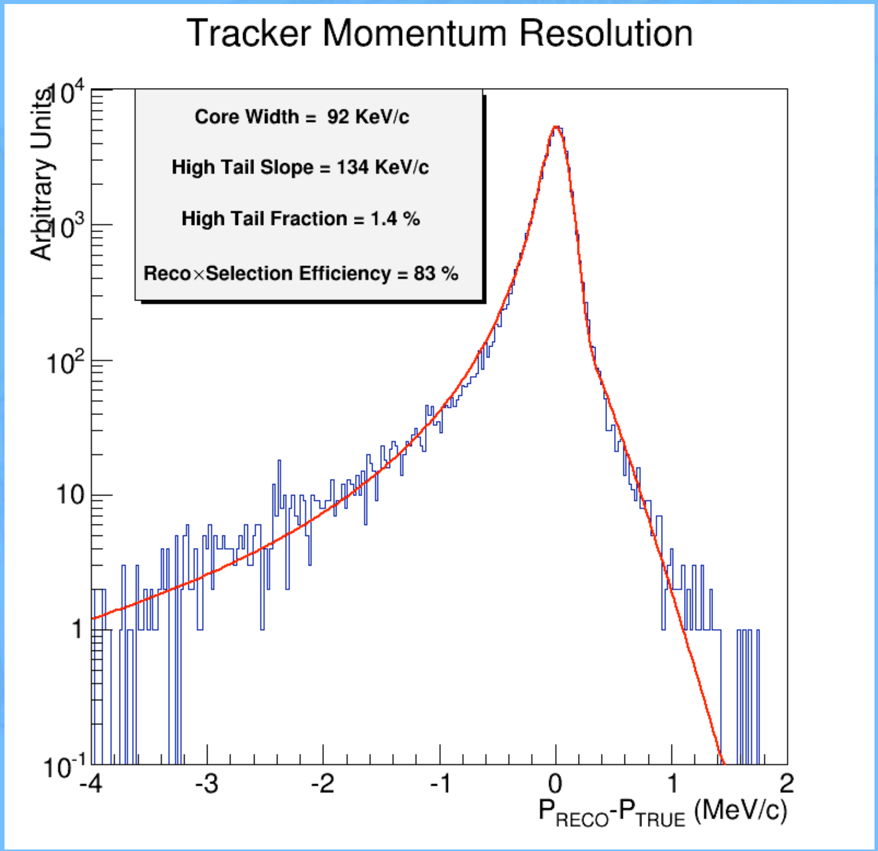




Track Reconstruction

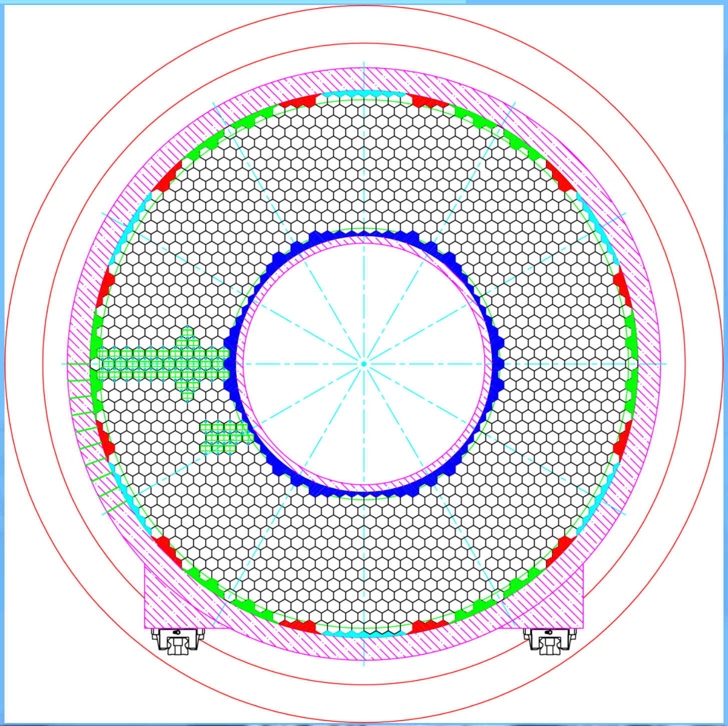
- Find tracks using time clustering + Robust Helix fit
  - J Math Imaging Vis, "Robust Fitting of Circle Arcs"
- Final fit using Kalman filter (code ported from BaBar)
  - Outlier filtering using Simulated Annealing

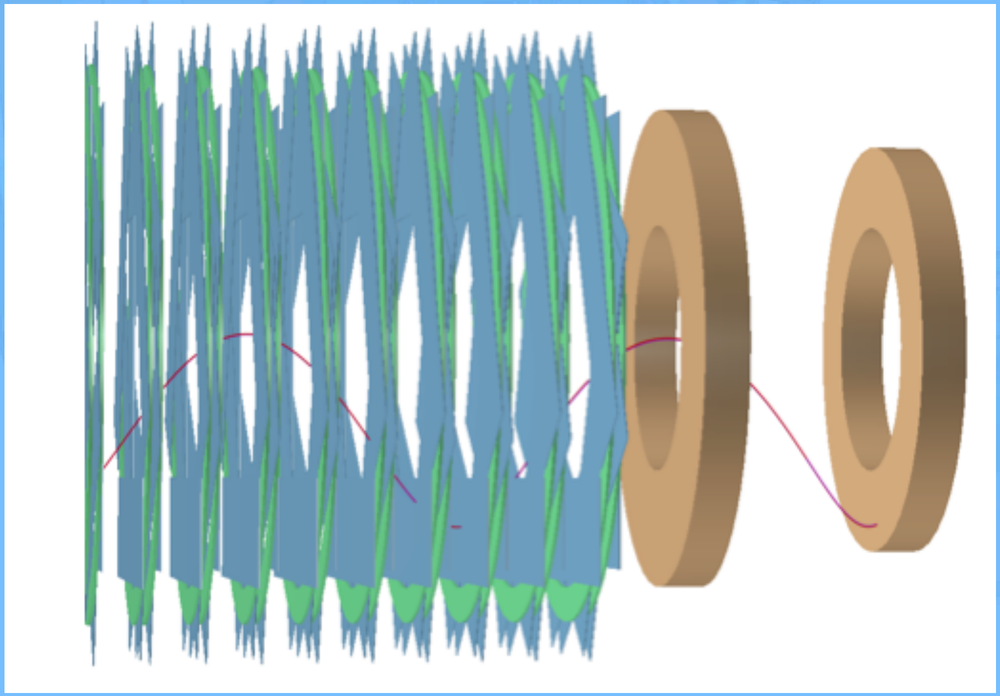




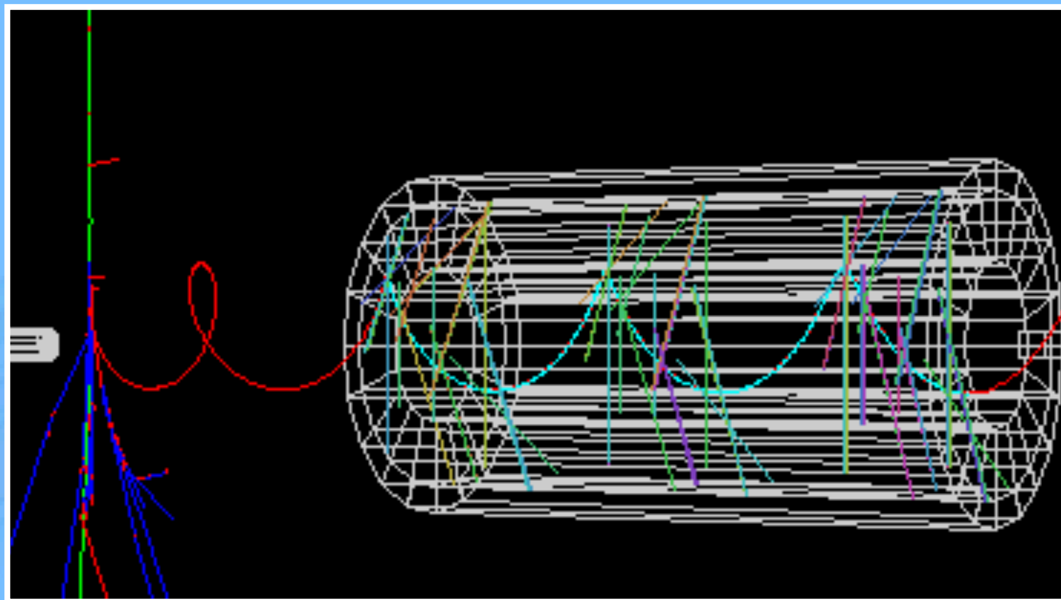
Calorimeter

- Hexagonal LYSO crystals
- Dual Disk geometry
- APD or SIPM readout
- Provides precise timing, PID, alternate track seed



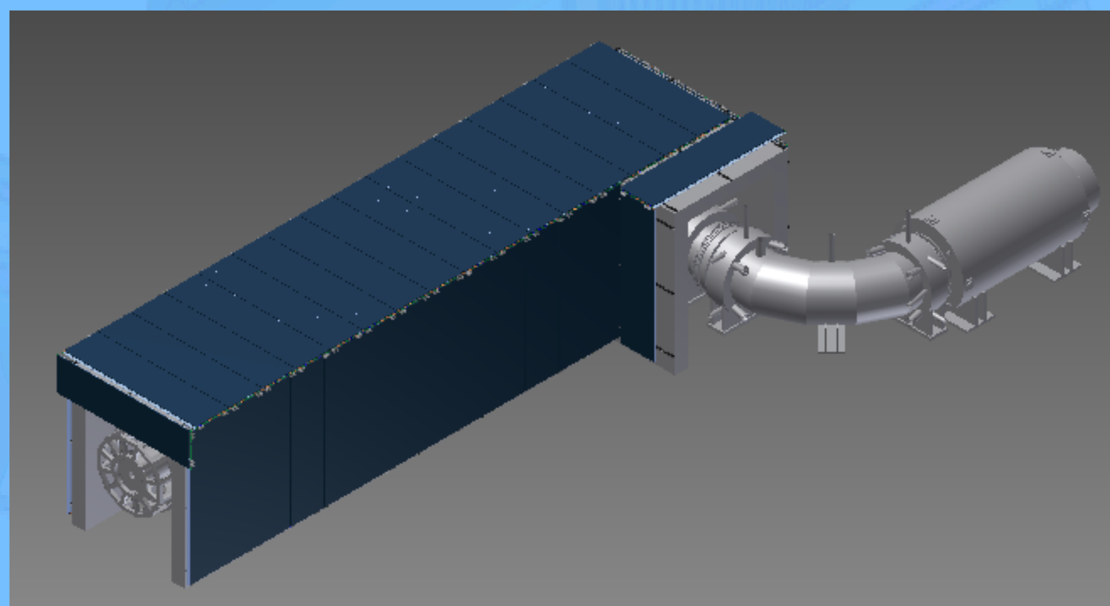


Cosmic Ray Backgrounds



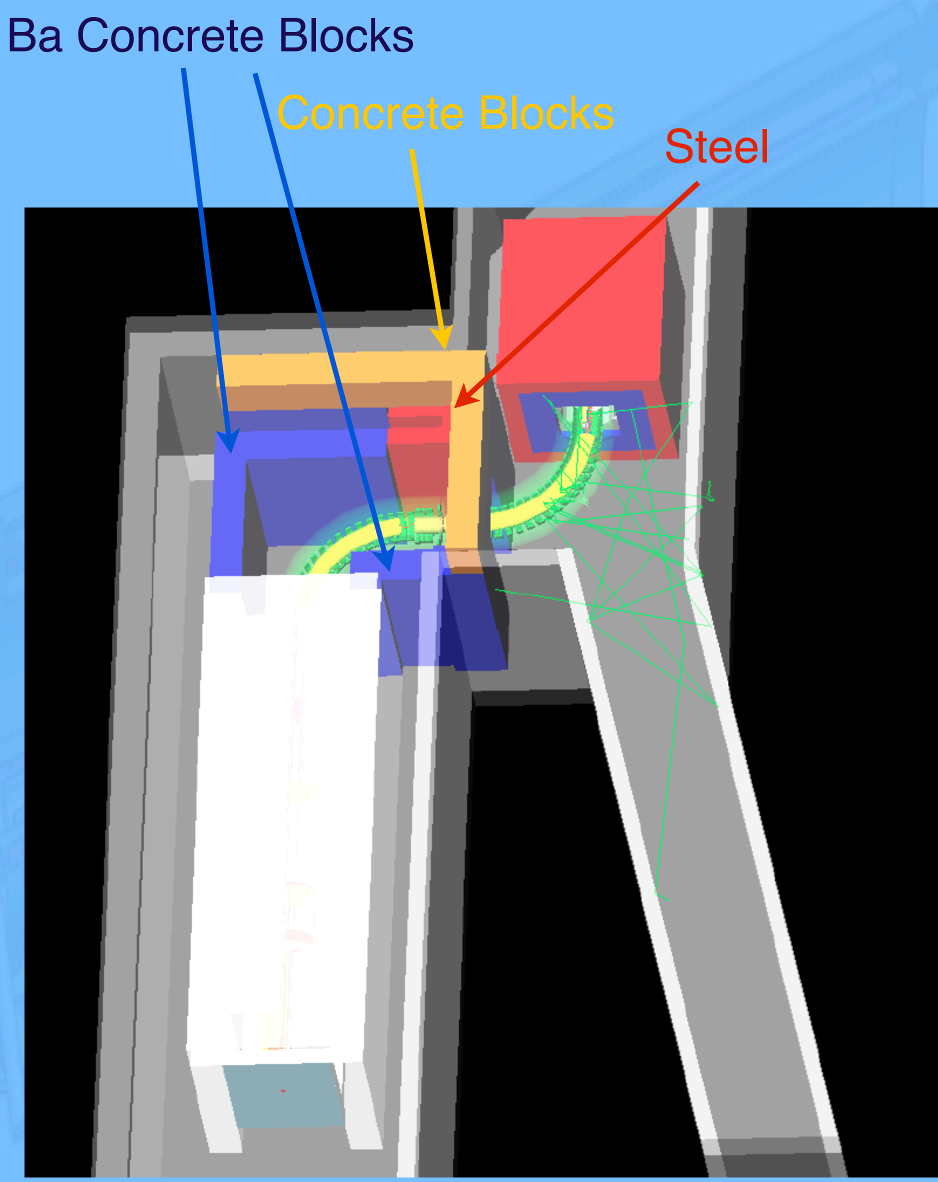
- Cosmic rays can produce e- that fake the signal
- Dedicated Cosmic Ray Veto (CRV) detector

- Overlapping scintillation counters
  - 99.99% efficiency
- Rejection also from tracker, calorimeter



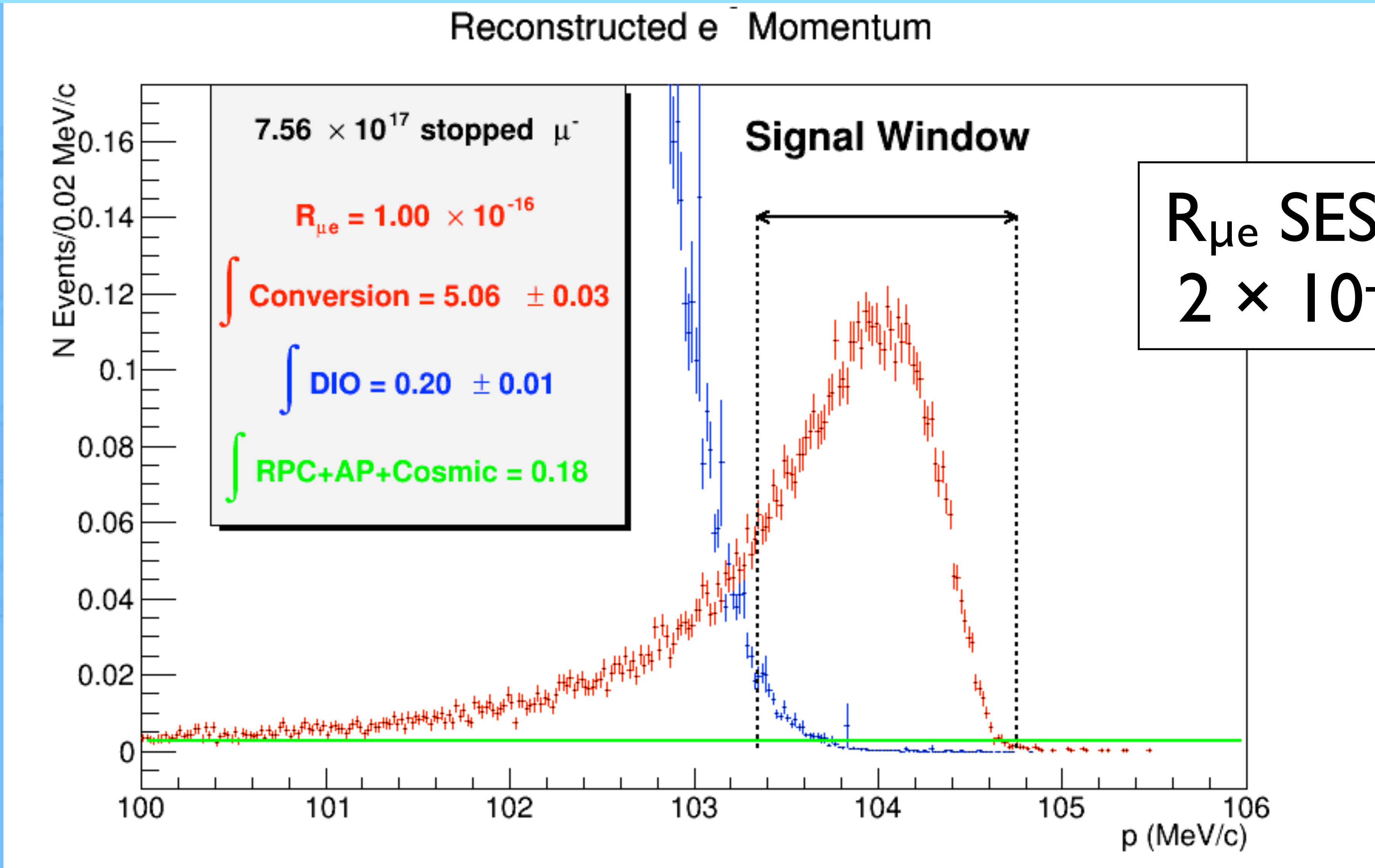
Neutron Backgrounds

- Neutrons are produced by several sources in Mu2e
  - Primary target, collimators, μ stopping target, beamstop, ...
- Neutrons affect the detectors
  - Radiation damage to SIPMs
  - Fake hits in the tracker and calorimeter
- Fake coincidences in CRV
  - Reduces conversion efficiency
- Neutron mitigation:
  - Shield CRV with concrete and steel
  - Use fiber readout to move SIPMs out of high-flux regions
  - Optimization still in progress



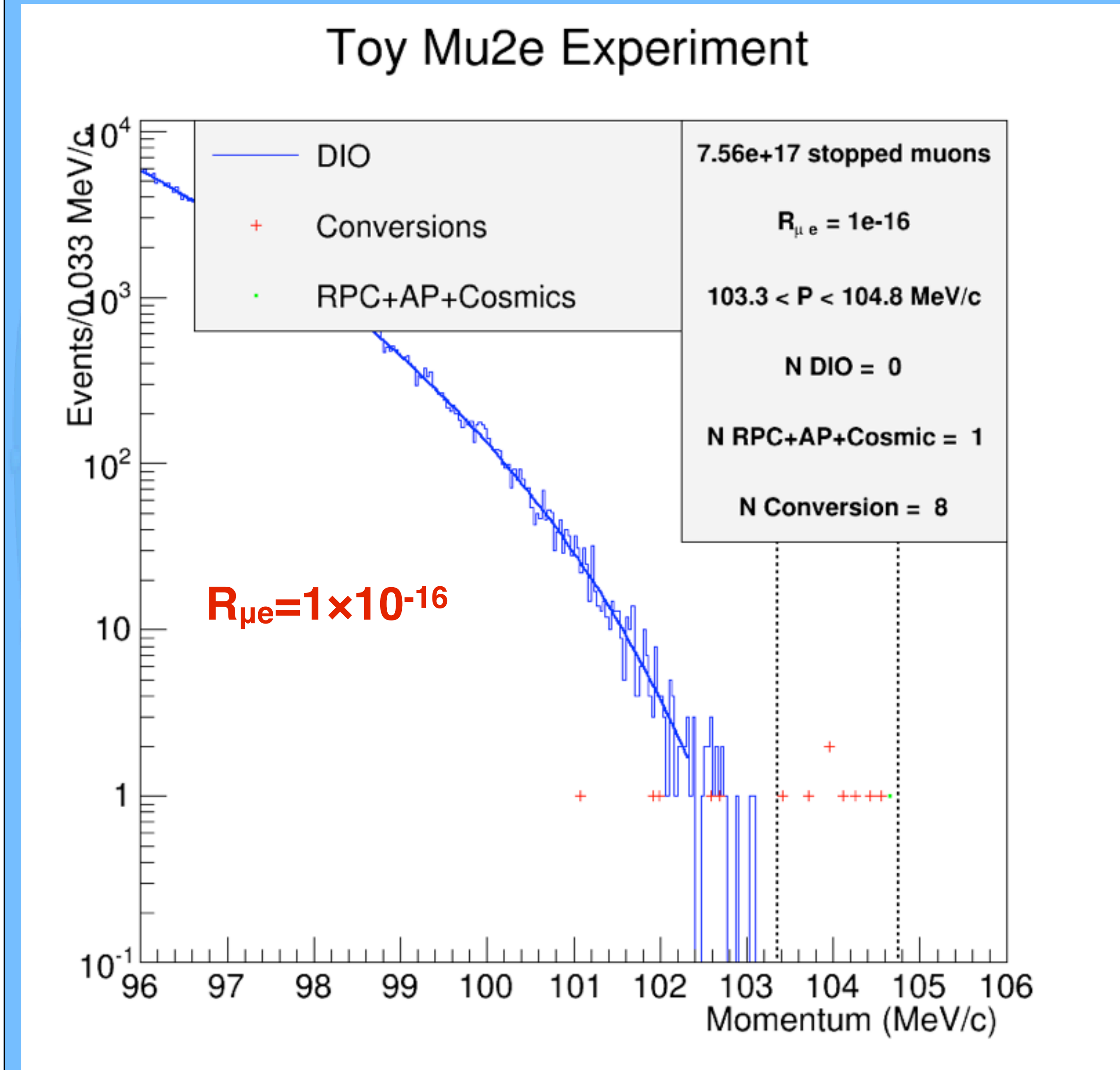
Mu2e Signal Sensitivity

Full G4 detector simulation, background overlay, reconstruction

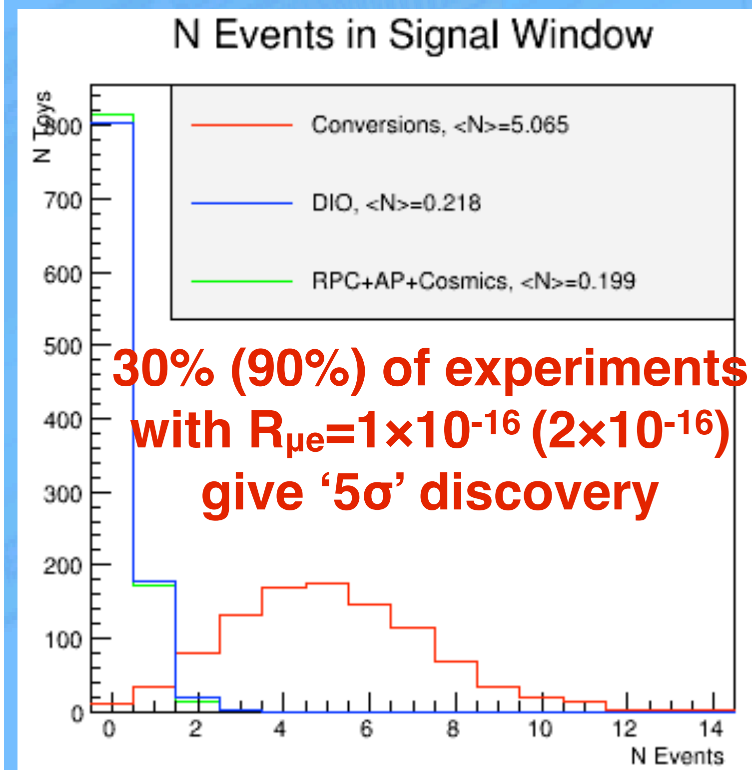


$R_{\mu e}$ SES = 2×10^{-17}

Toy Experiments



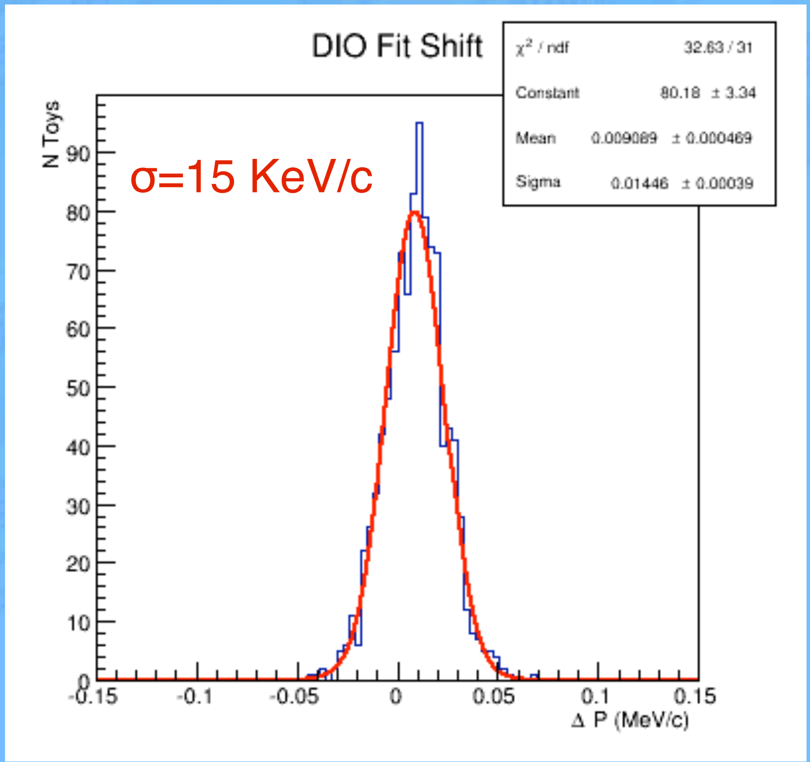
- Use G4 simulation results as PDFs
- Generate events as for a 3-year run



1000 toy experiments

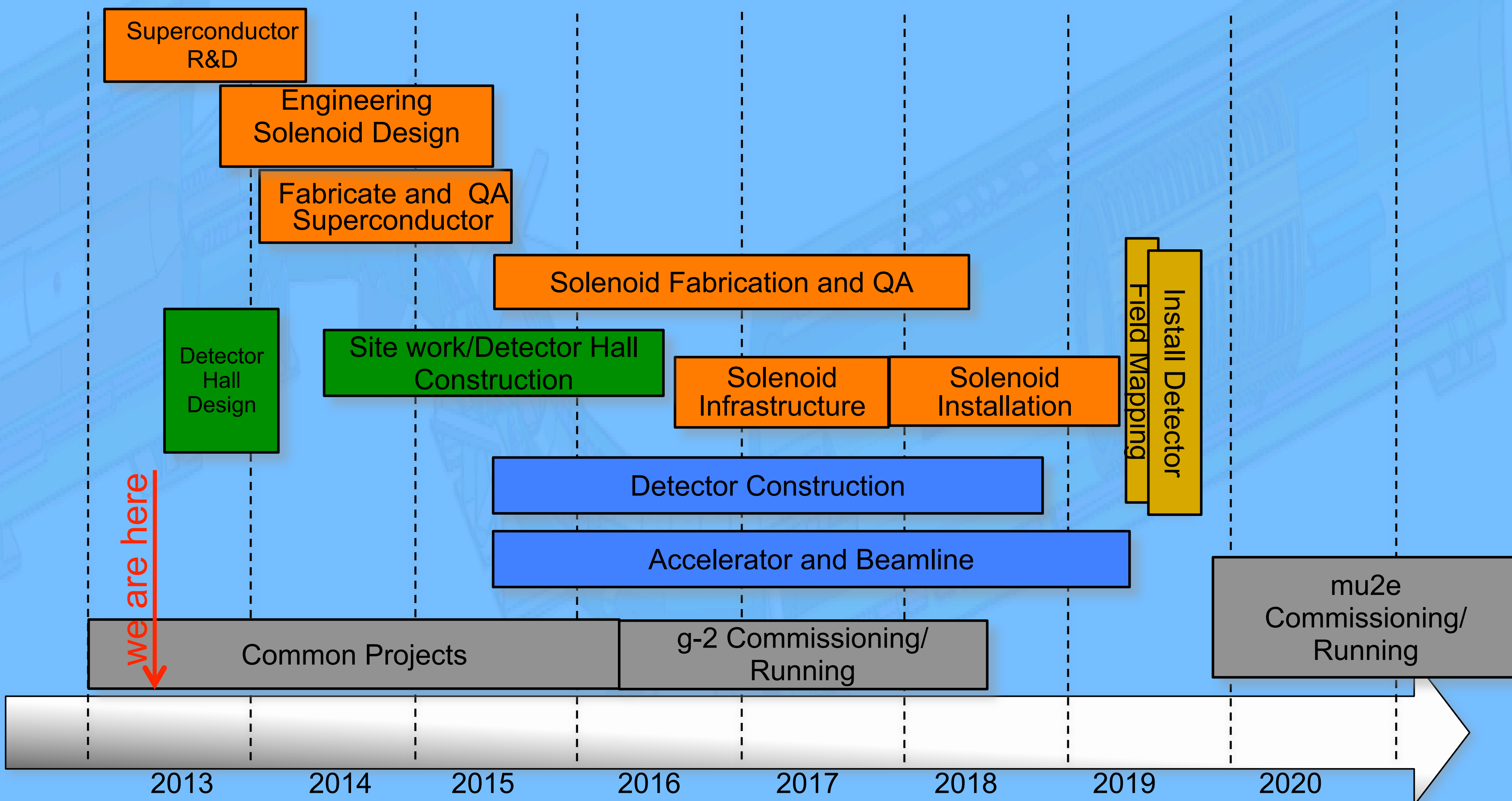
Tracker Momentum Calibration

- The absolute momentum scale is needed to separate DIO from conversion e^-
  - ± 50 KeV/c on |**p**| results in ± 0.08 DIO in signal window
- Precision Surveys
  - X-ray tracker wire positions
    - 50 μm precision
  - Map B-field (2 Gauss goal)
- Calibrate using $\pi^+ \rightarrow e^+ \nu$
  - Requires special detector and beam configuration
  - Still under study
- Fit DIO spectrum
  - Spectrum from theory
  - Resolution from cosmic e^-
- Toy MC study: 15 KeV/c statistical resolution possible



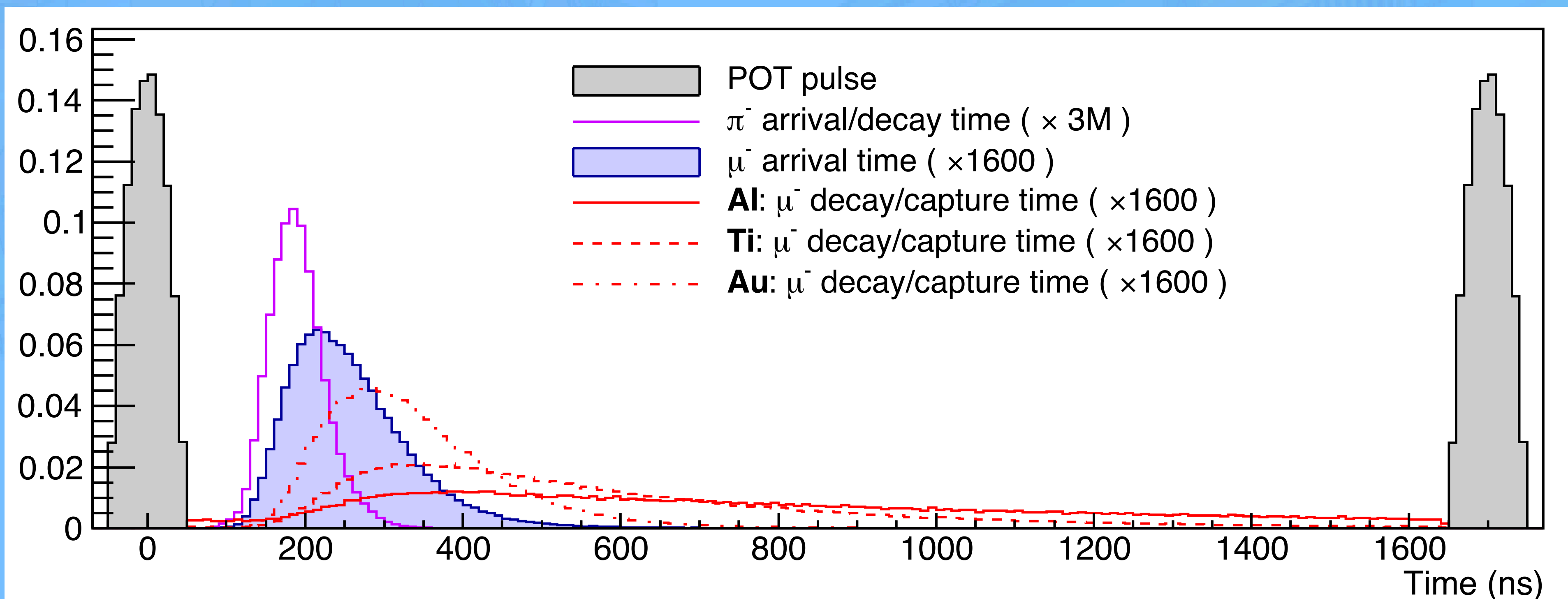
Mu2e Project Status

- Schedule is technically limited



Mu2e @ Project X

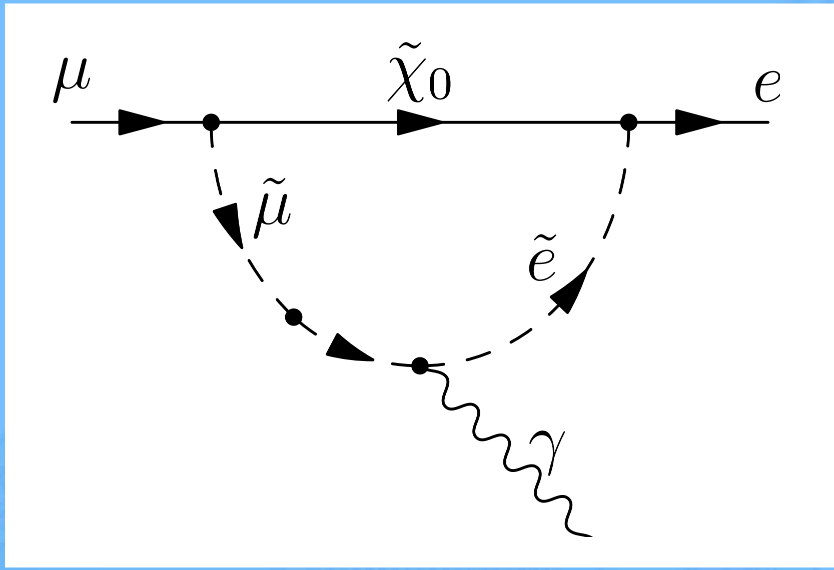
- Project-X will initially provide 10× the muons to Mu2e
  - Higher intensity, narrower time profile, lower energy beams
- Early studies show Mu2e will work with some mods
  - Main change: increased shielding of production target
  - Main challenge: keeping RPC and DIO backgrounds < 1 event



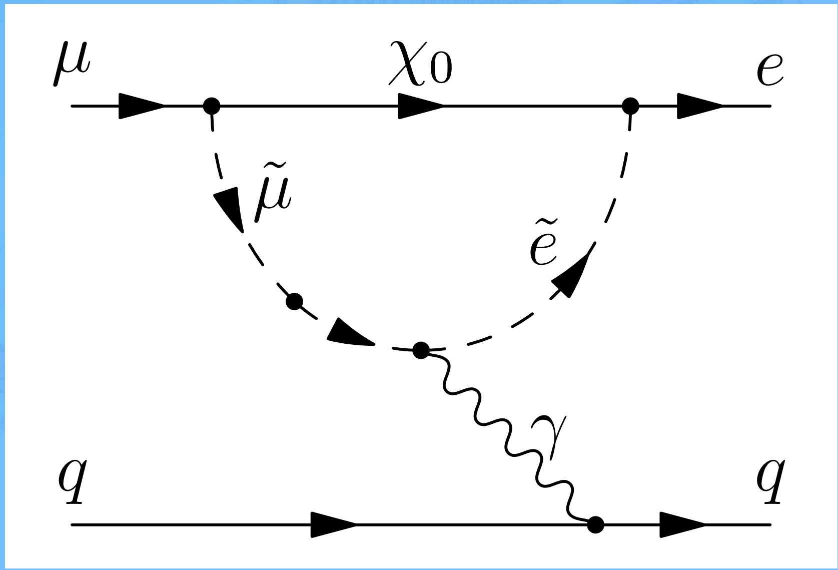
Backup

CLFV with Muons

- Mu to e gamma ($\mu \rightarrow e\gamma$)
  - Simplest model of lepton decay (μ^- = excited e^-)
  - Proceeds via a loop
  - Possible mechanism: SUSY



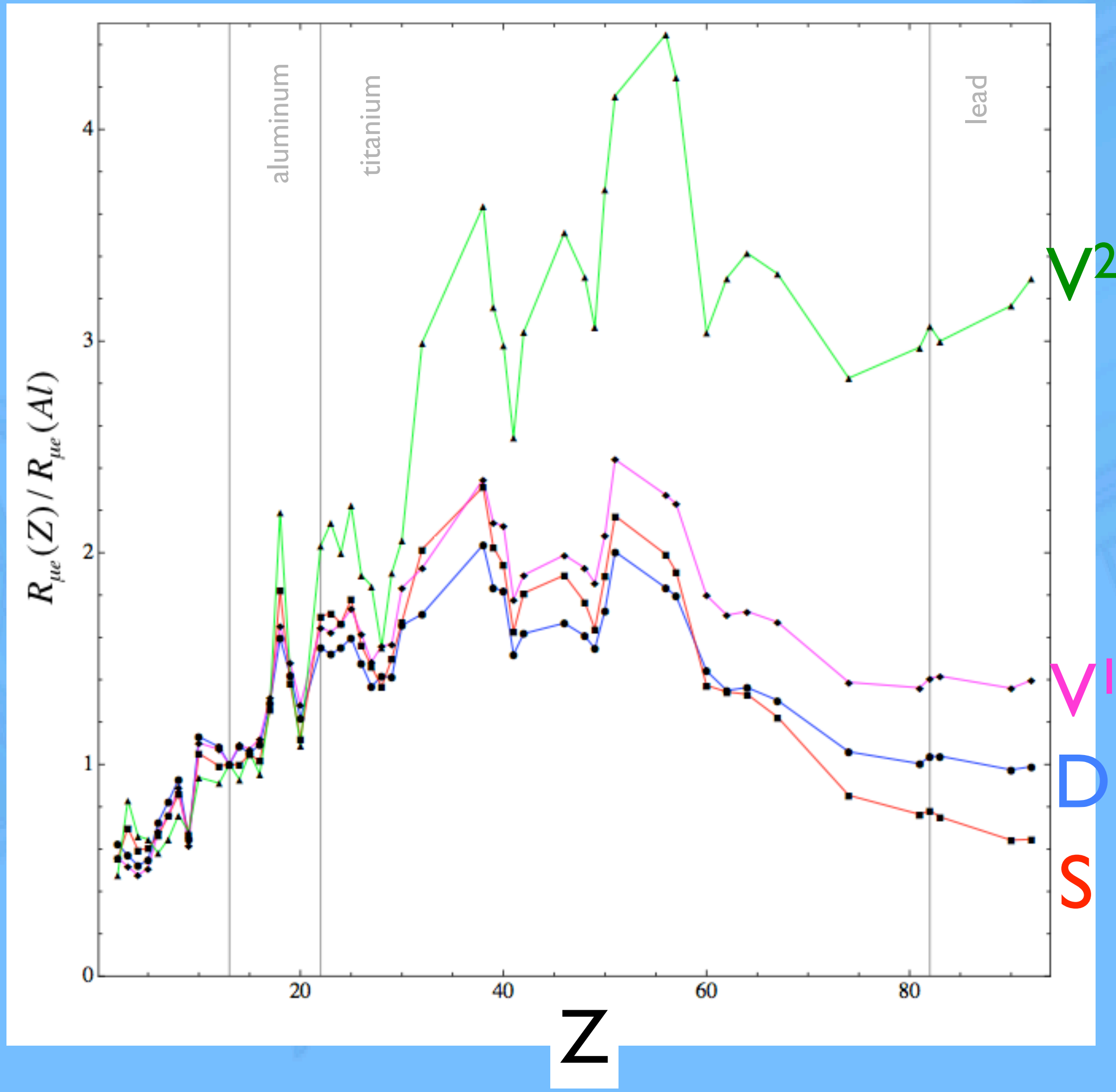
- Mu to e conversion ($\mu N \rightarrow eN$)
  - Can use the same loop as $\mu \rightarrow e\gamma$
  - Rate depends on A,Z



Stopping Target Material

- $R_{\mu e}$ sensitive to stopping target material in model-dependent way
- Larger Z→ smaller radius→ larger capture Γ→ smaller dipole fraction + shorter lifetime
- Heavier nuclei→ more neutrons→ larger d/u fraction

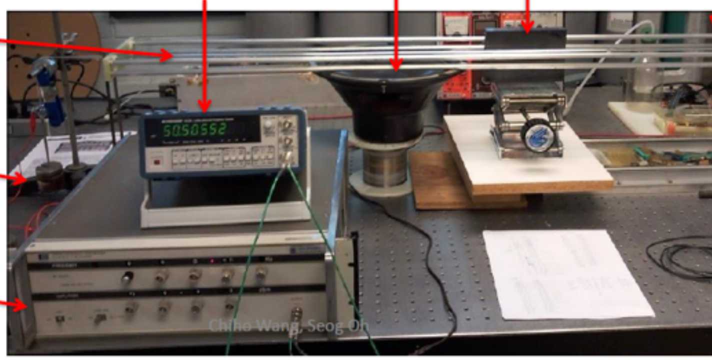
V. Cirigliano et al., phys. Rev. **D80** 013002 (2009)



Straw Creep

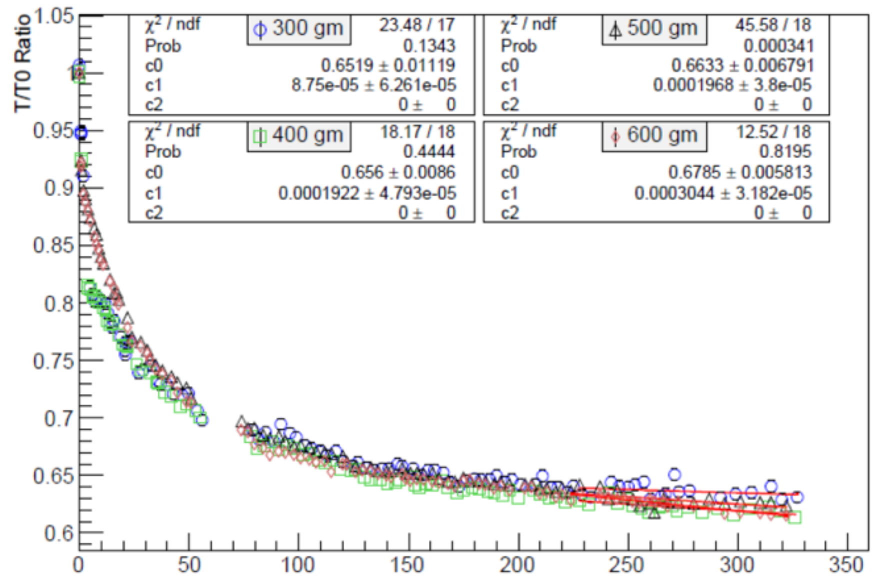
“Fixed Length” Creep Measurement

- Glue straws on a support frame (120cm) with tensions:
  - 300gm, 400gm, 500gm, 600gm.
- Measure straw tension by resonant frequency as a function of time.



- Straws will maintain adequate tension for at least 7 years

Fractional Tension change vs time
Exp Fit ($c0*e^{-c1*t}+0$)



(corrected for temperature & humidity variation)

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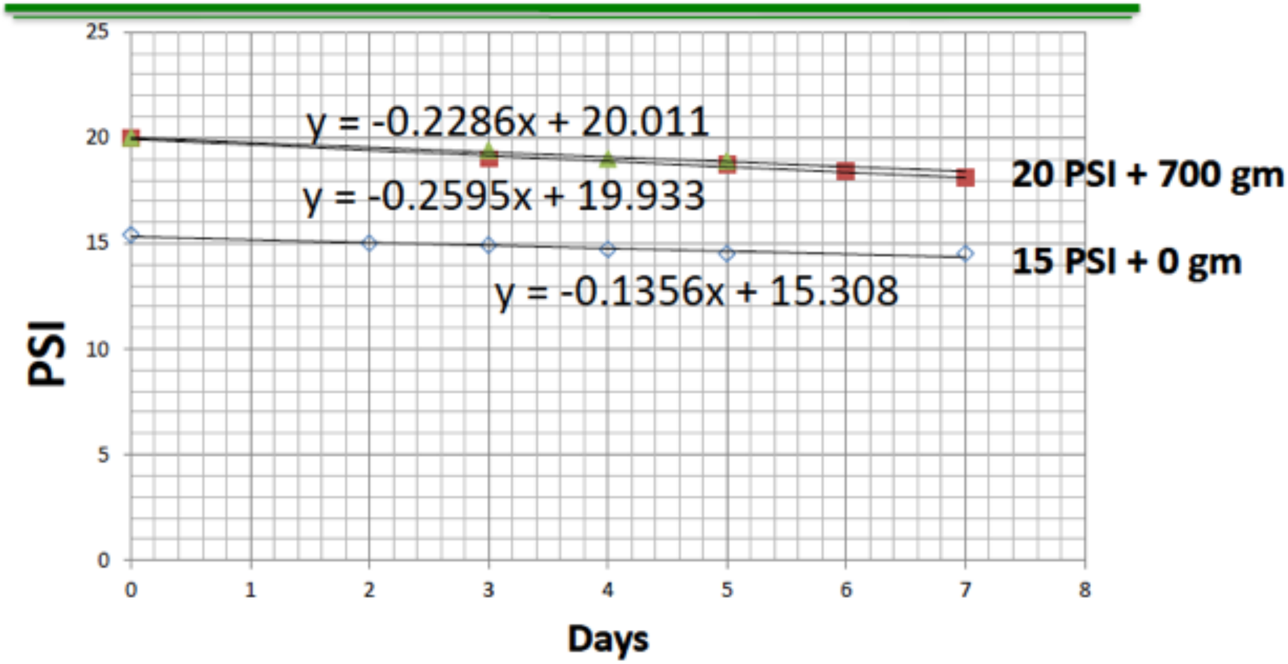
Straw Leak Test

Leak rate



- Pressure drop = 0.244 psi / day @ ~20psi (no env. corr.)
- Leak rate = 0.00847 mBar/Bar/min
- Previous test @ 15 psi + 0 gm weight ~0.00813/mBar/Bar/min
- 2 weeks under 20 psi + 700gm and no problem

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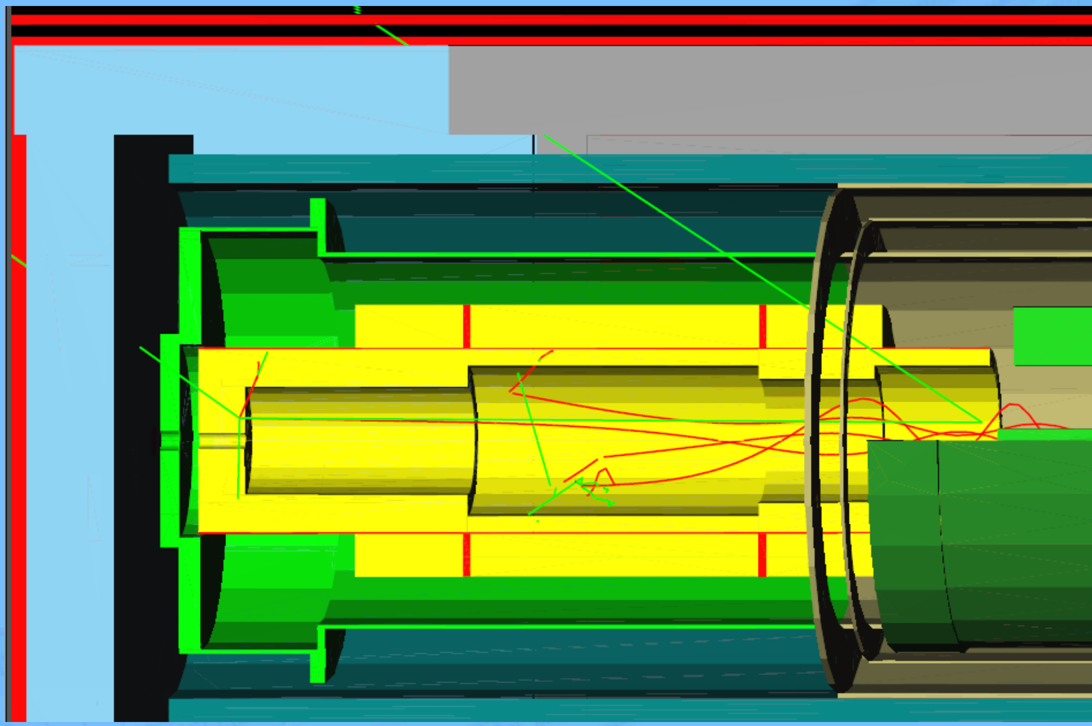
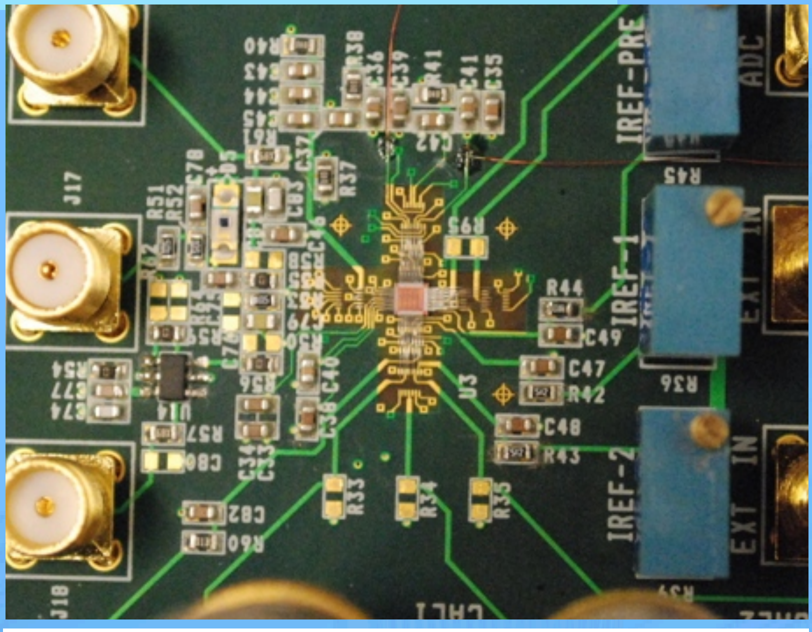
Muon Beamstop

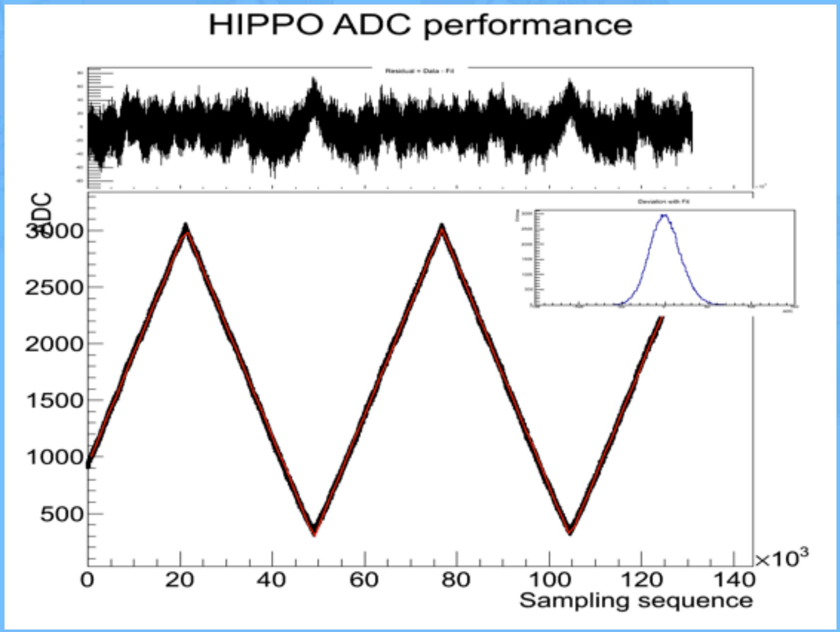
- Grey/Blue = concrete
- Red = CRV
- Green = cryostat
- Yellow = Polyethylene
- Teal = water tank
- Hole for beam monitor

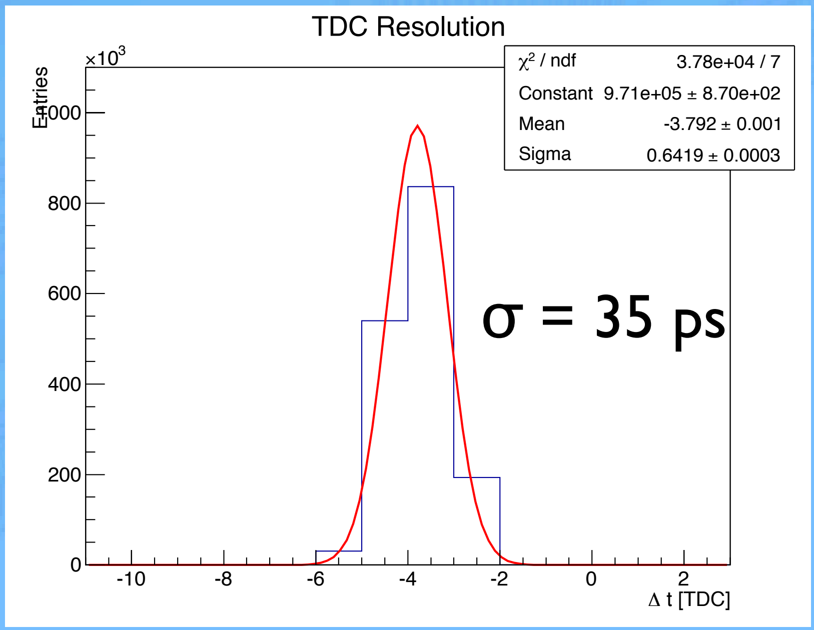


Tracker ASIC

- 65nm process
- Oscillator-ring dual 16-bit TDC
- 10 (12) bit ADC
- 4-channel prototype

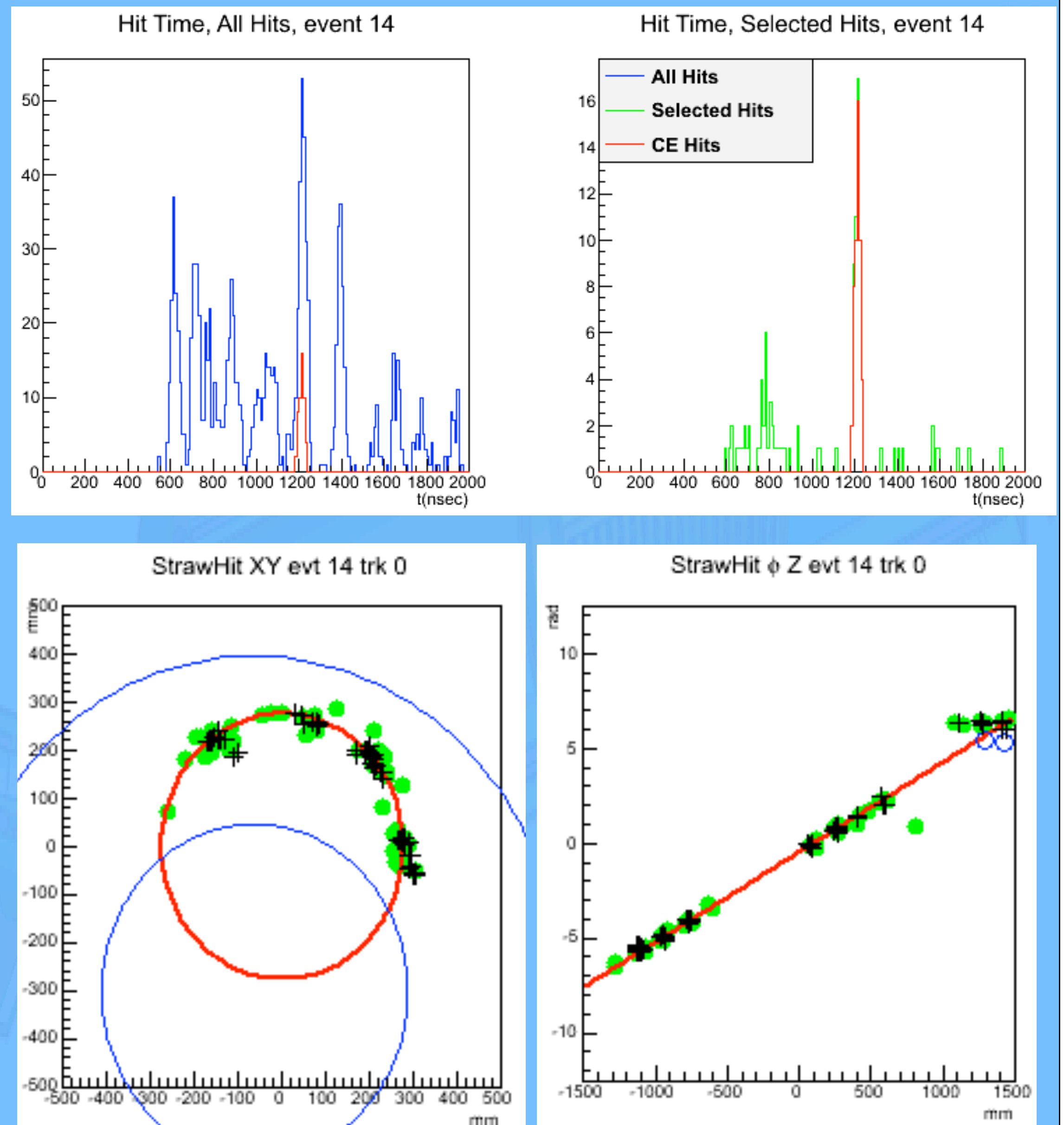




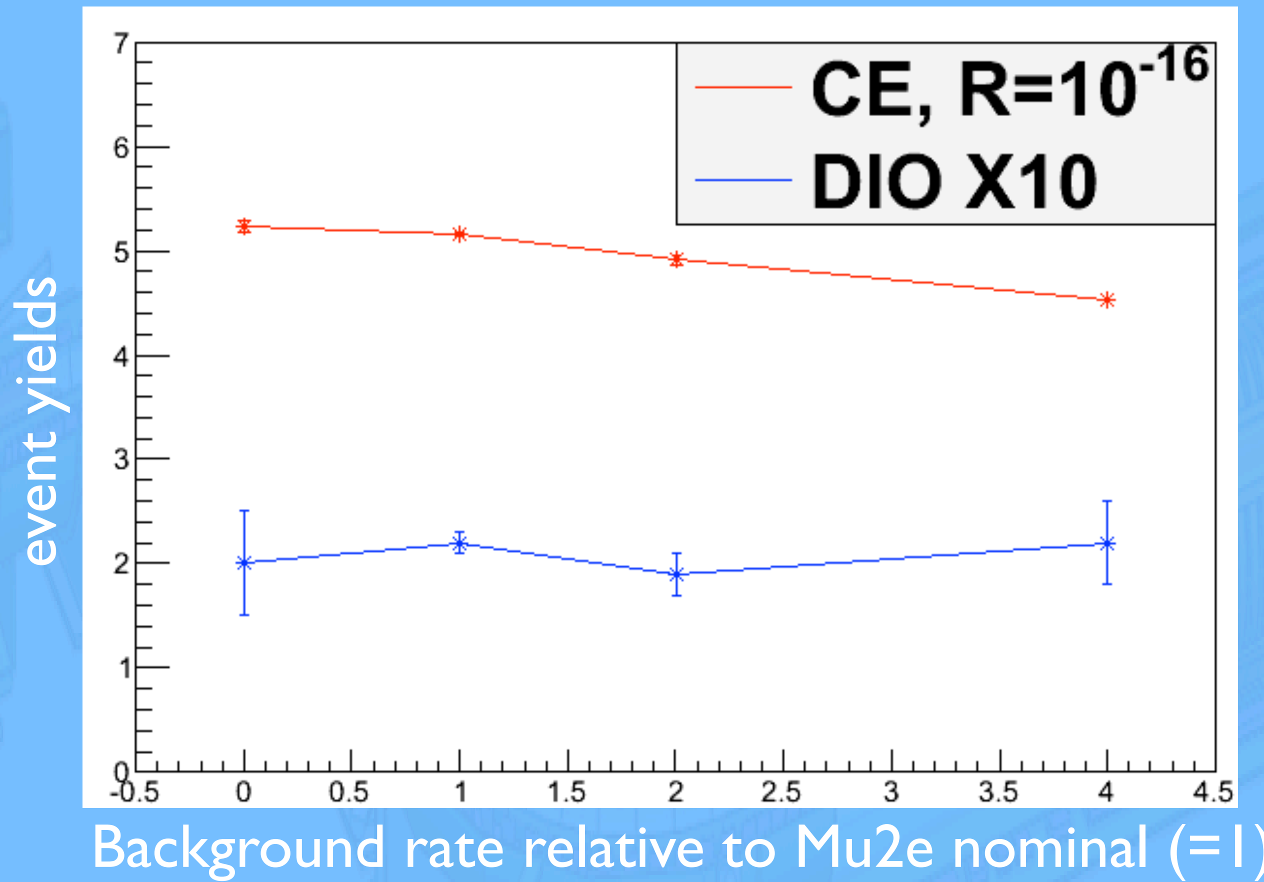


Track Finding and Fitting

- Remove hits from low-energy electrons
- Remove hits with large energy deposits (protons)
- Select hits which peak in time
- Fit in sequence:
  - Robust Helix
  - Least-squares
  - Kalman Filter

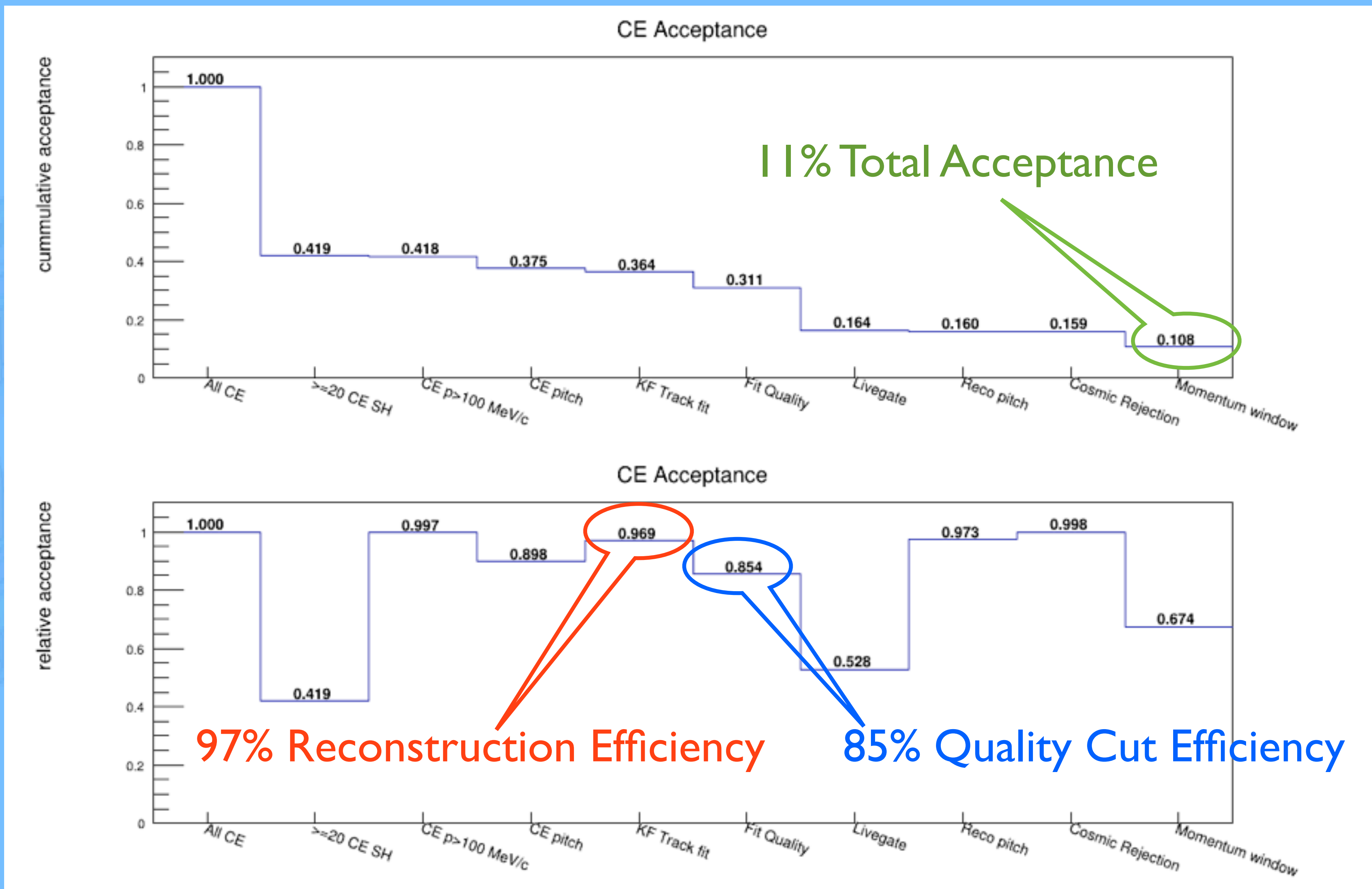


Background Sensitivity



- Momentum resolution unchanged, efficiency reduced by 5% (relative) with 4X nominal background

Reconstruction Efficiency



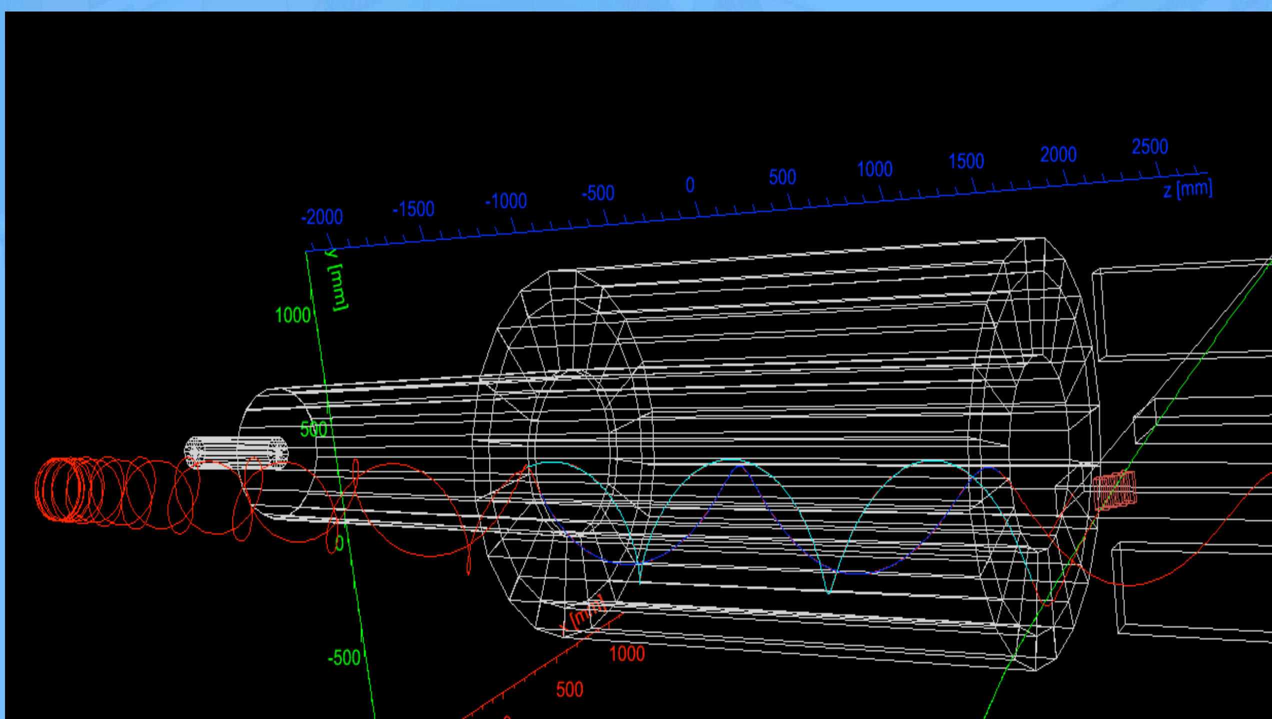
Backgrounds for 3 Year Run

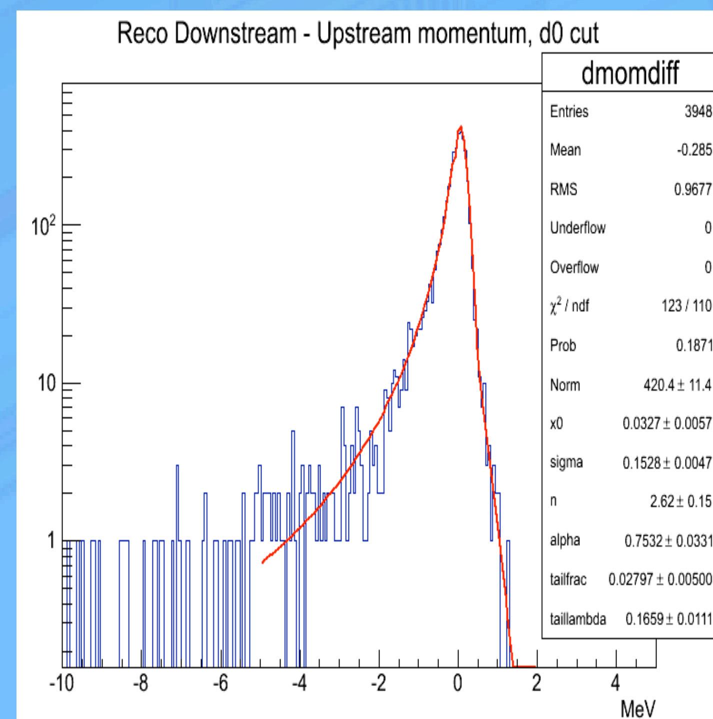
Source	Events	Comment
Anti-proton capture	0.1 ± 0.06	Assumes 10^{-10} extinction
Radiative π^- capture	0.04 ± 0.02	
Beam electrons	0.001 ± 0.001	
μ decay in orbit	0.2 ± 0.06	
Cosmic ray induced	0.025 ± 0.025	Assumes 10^{-4} inefficiency
μ decay in flight	0.01 ± 0.005	With e^- scatter in target
Total	0.4 ± 0.1	

$R_{\mu e}$ SES = 2×10^{-17}

Momentum Resolution from Cosmics

- Cosmic rays hitting the calorimeter can produce e^- that reflect in the upstream gradient field
  - Allows 2 independent measurements of the same particle
- The momentum difference gives the resolution function
  - Also measures the energy loss in passive material





The Project-X Research Program

- ***Neutrino experiments***

A high-power proton source with proton energies between 1 and 120 GeV would produce intense neutrino sources and beams illuminating near detectors on the Fermilab site and massive detectors at distant underground laboratories.

- ***Kaon, muon, nuclei & nucleon precision experiments***

These could include world leading experiments searching for lepton flavor violation in muons, atomic, muon, nuclear and nucleon electron dipole moments (edms), precision measurement of neutron properties (e.g. n,nbar oscillations) and world-leading precision measurements of ultra-rare kaon decays.

- ***Platform for evolution to a Neutrino Factory and Muon Collider***

Neutrino Factory and Muon-Collider concepts depend critically on developing high intensity proton source technologies.

- ***Material Science and Nuclear Energy Applications***

Accelerator, spallation, target and transmutation technology demonstrations which could investigate and develop accelerator technologies important to the design of future nuclear waste transmutation systems and future thorium fuel-cycle power systems. Possible applications of muon Spin Resonance techniques (muSR). as a sensitive probes of the magnetic structure of materials .

Detailed discussion on Project X website