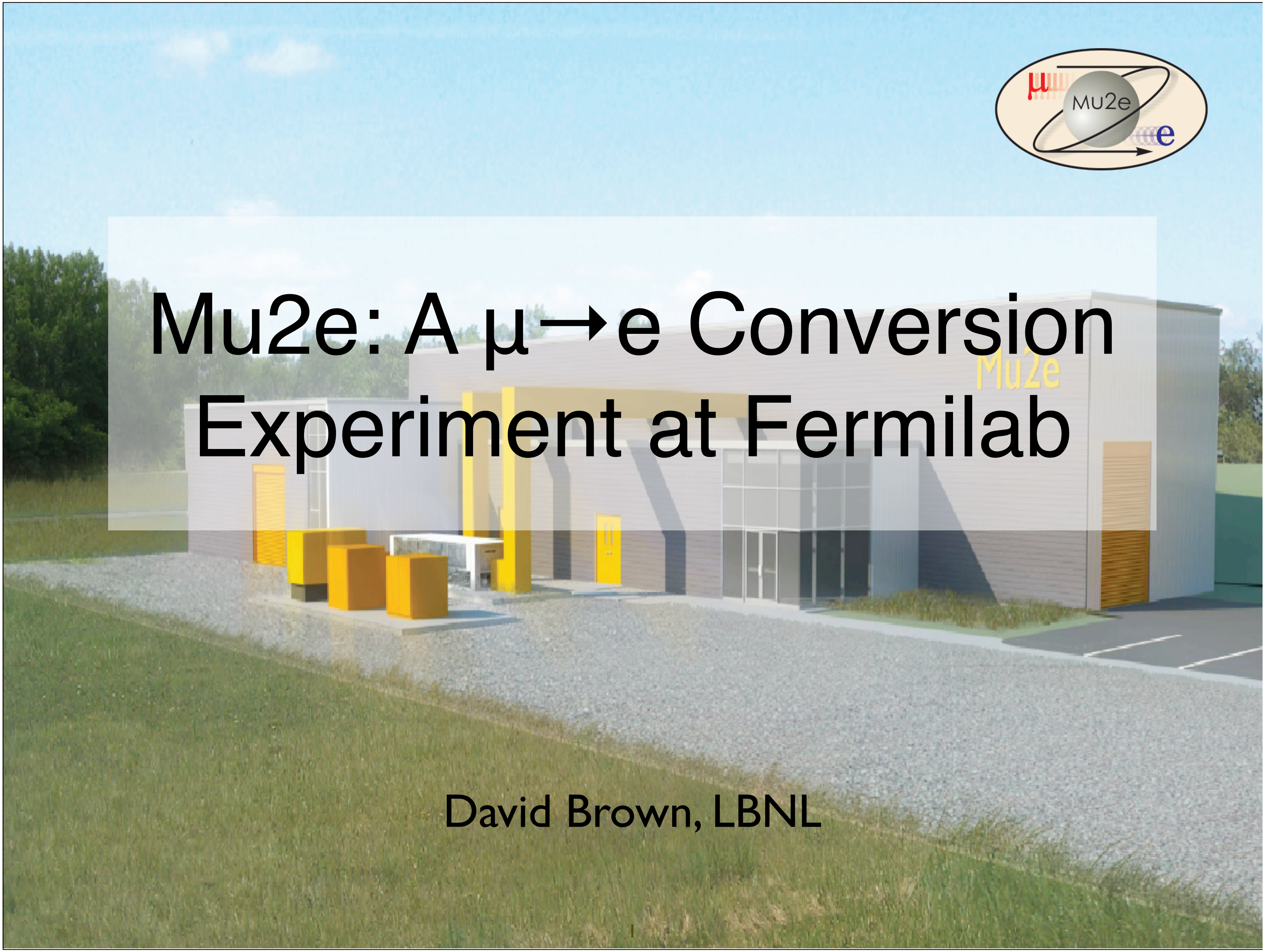
Mu2e: A μ→e Conversion Experiment at Fermilab



David Brown, LBNL

Outline

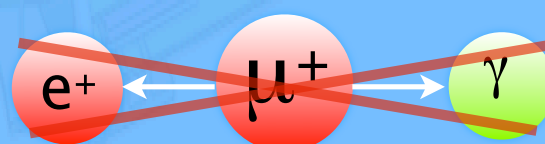
- Lepton Flavor
- μ→e Conversion
- The Mu2e Experiment
- Mu2e Performance Estimates
- Mu2e Schedule and Status
- Conclusions

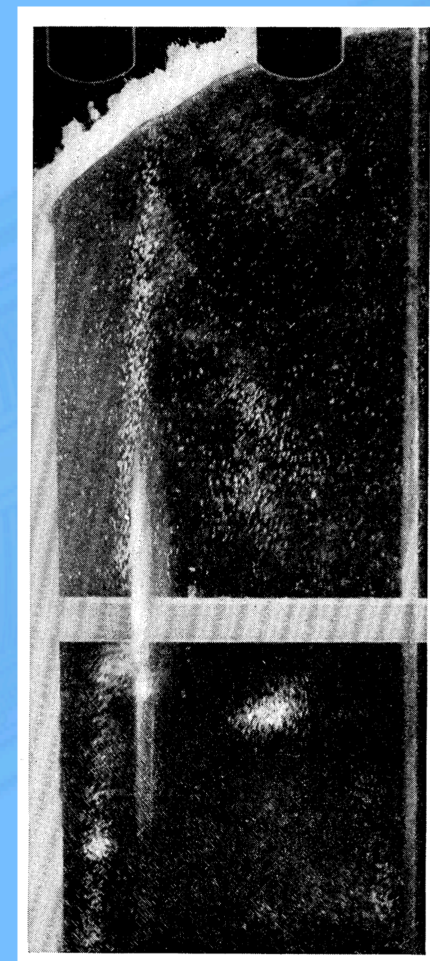
Lepton Flavor

“Who Ordered That?”*

*I.I. Rabi

- Meson (middle) mass particle in cosmic ray cloud chamber pictures
  - Anderson, Neddermeyer (1936), Street, Stevenson (1937)
  - Yukawa’s strong force condensate (1935)?
- Not absorbed by nucleus ➜ not Yukawa’s
  - Conversi etal (1947)
- π-meson distinct from “μ-meson”
  - (Perkins), Ochiallini, Powell (1947)
- No observation of $\mu \to e\gamma$
- A new kind of particle!

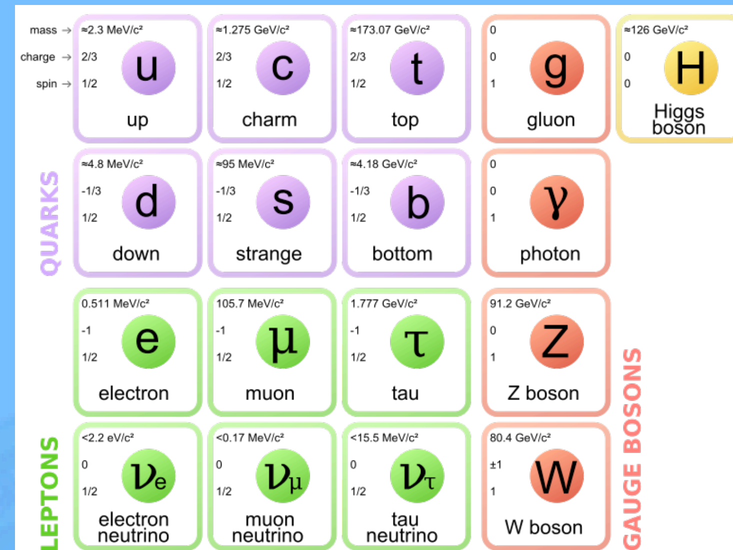


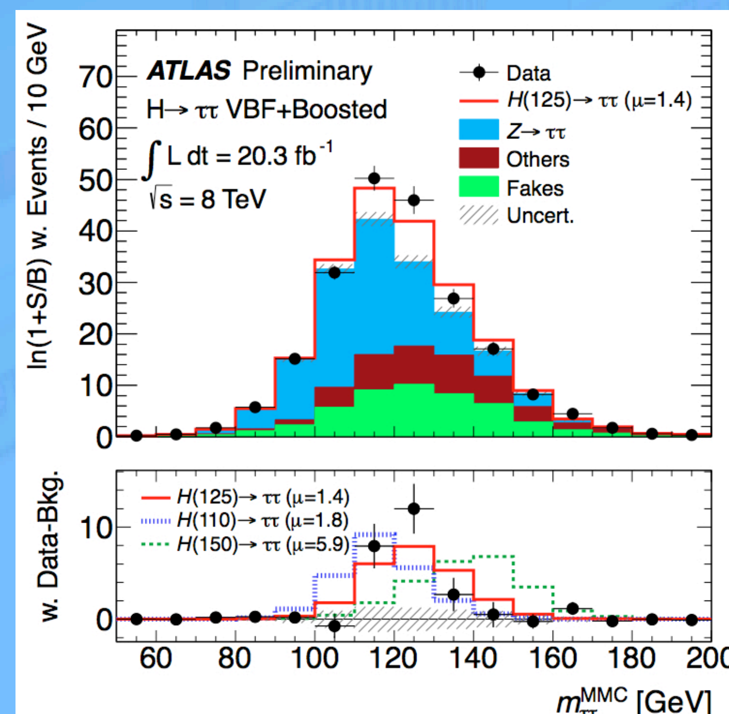


Street, Stevenson
PRL 52 (1937)

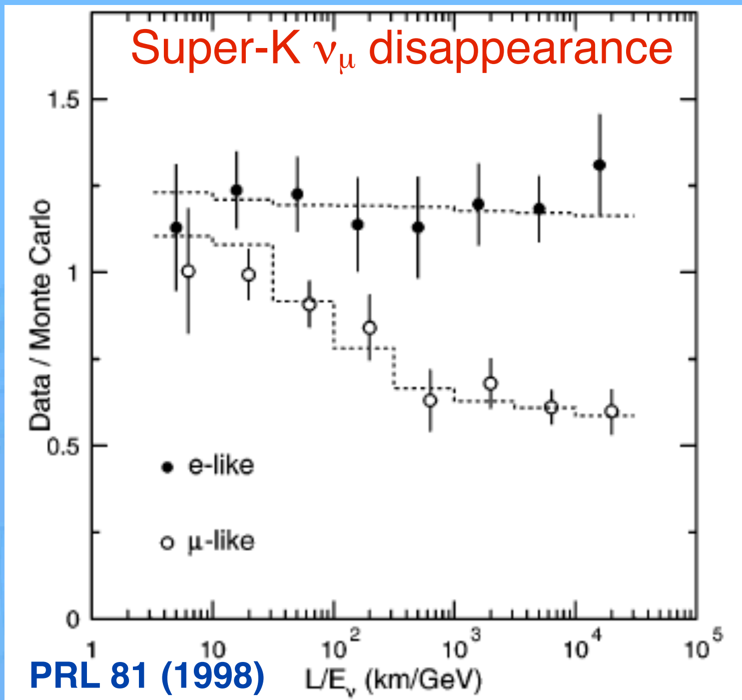
Standard Model Leptons

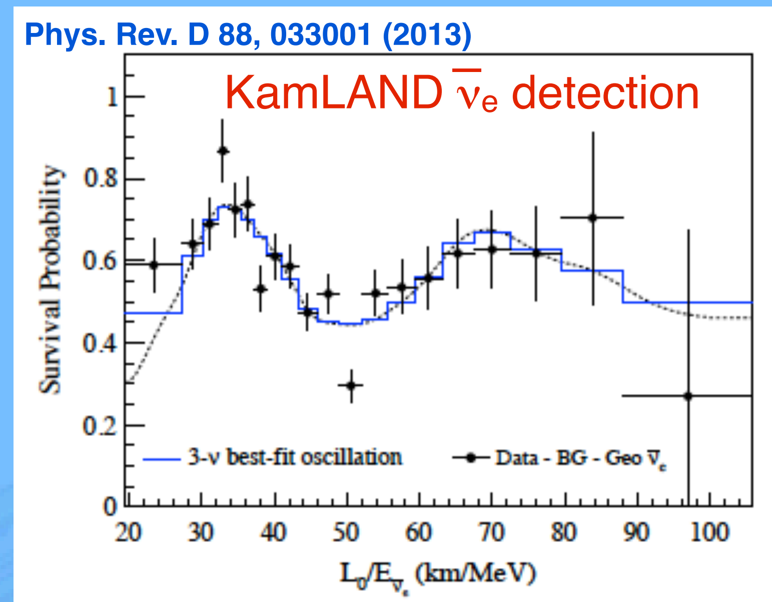
- Three generations of fermions
  - $\mu_L, \nu_{\mu L}$ form an EW doublet
  - μ_R is an EW singlet
  - Lepton flavor is conserved
- Higgs mechanism provides charged fermion masses, ν are massless
- Descriptive model! no answer to:
  - Why are there 3 generations?
  - What defines fermion masses?
  - What relates leptons to quarks?
  - What is the origin of the lepton asymmetry of the universe?
- Plus, it's "wrong"!

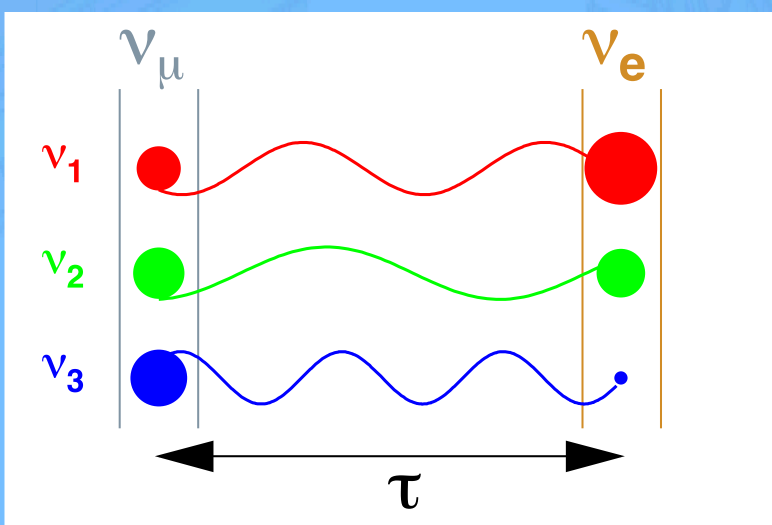




Neutrino Mixing/Oscillation



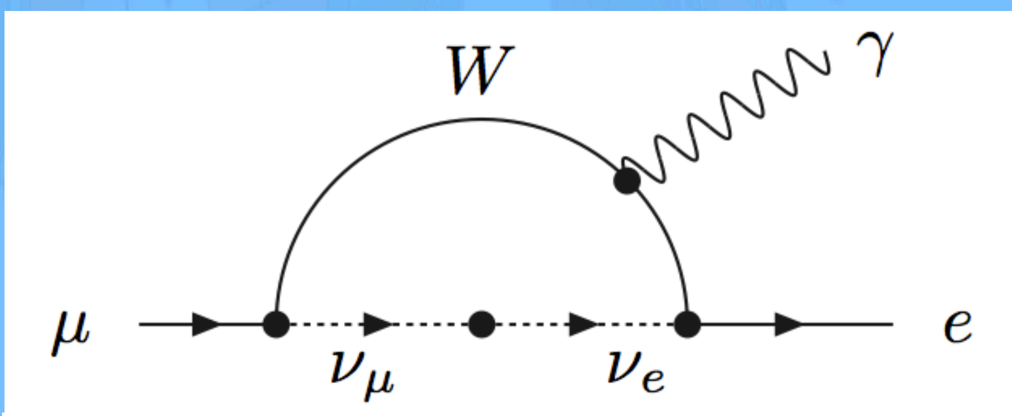




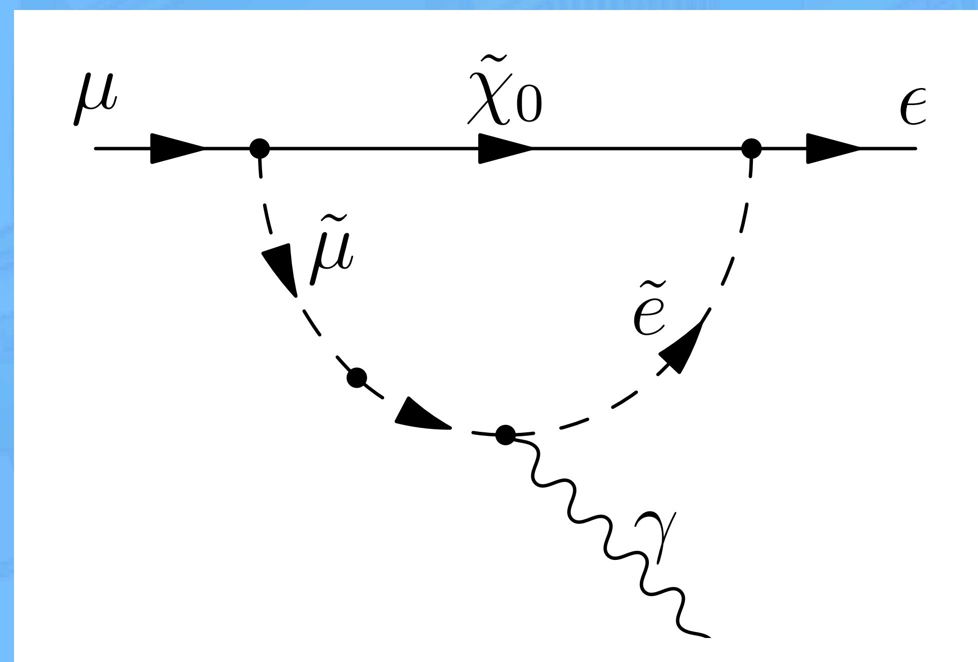
- Neutrinos have mass!
  - By what mechanism?
  - ν_R must exist (could be $\bar{\nu}_L$)
- Lepton flavor is not conserved
- The Standard Model is incomplete

Charged Leptons as New Physics Probes

- What prevents μ→eγ? Nothing!
  - Any mechanism that connects flavors is allowed
- ν-oscillation induced Charged Lepton Flavor Violation (CLFV) has an un-observably small rate
  - Any observation of CLFV would be an observation of New Physics
- Many SM extensions predict CLFV



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



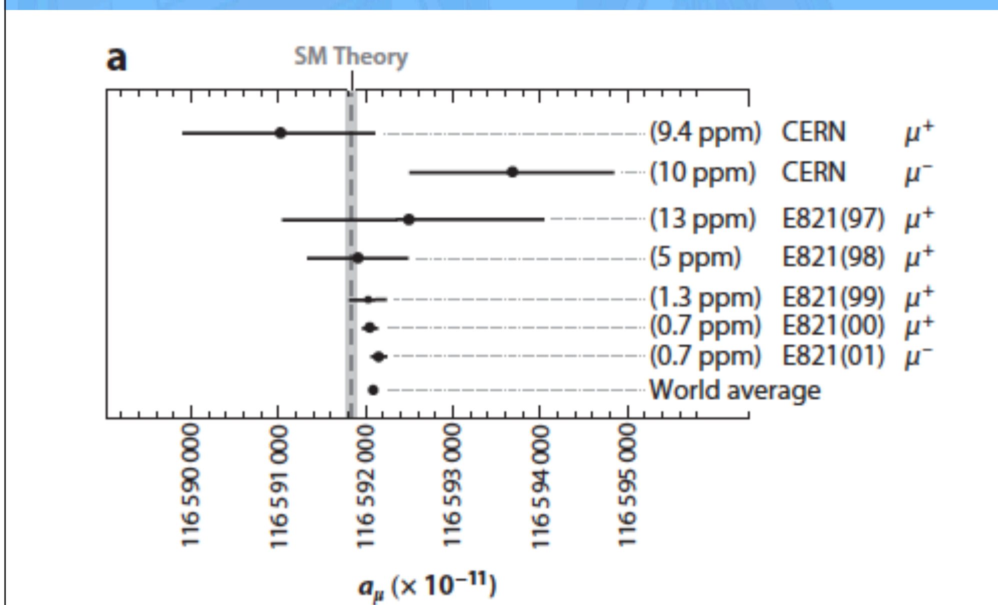
Muon Anomalies

Muon Magnetic Moment

~3.5σ discrepancy with theoretical calculations

$$\Delta a_\mu^{(today)} = a_\mu^{E821} - a_\mu^{SM} = (287 \pm 80) \times 10^{-11}$$

J. Miller etal., Annu. Rev. Nucl. Part. Sci. 2012. 62

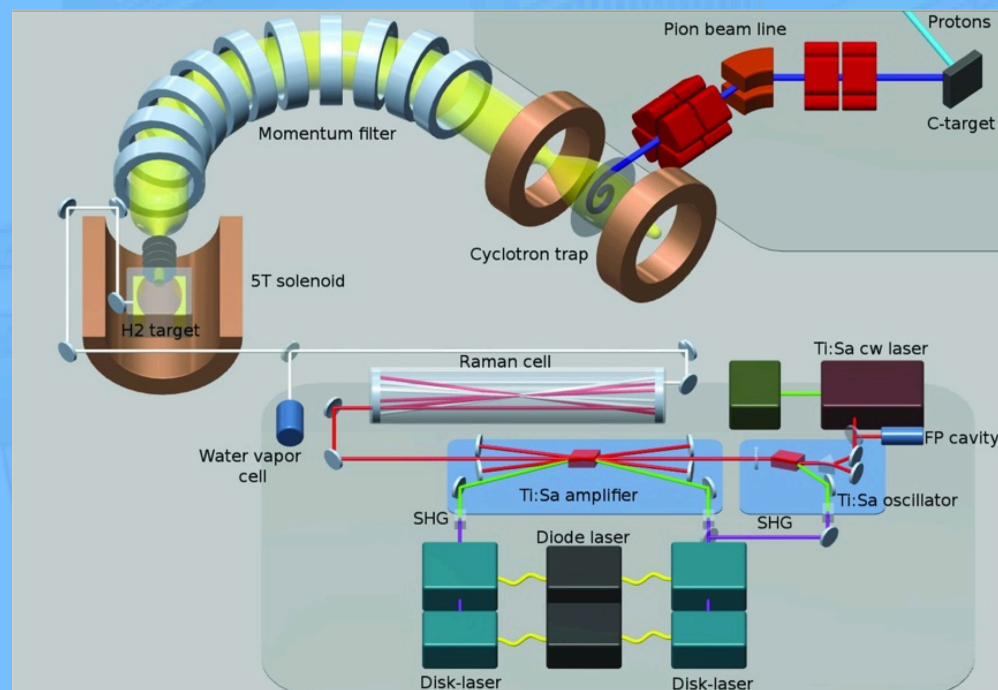


Hydrogen Charge Radius

~7σ discrepancy between muonic and electronic hydrogen

r_p = 0.84087(39) fm (muonic hydrogen lamb shift)
r_p = 0.8775(51) fm (electron scattering, spectroscopy)

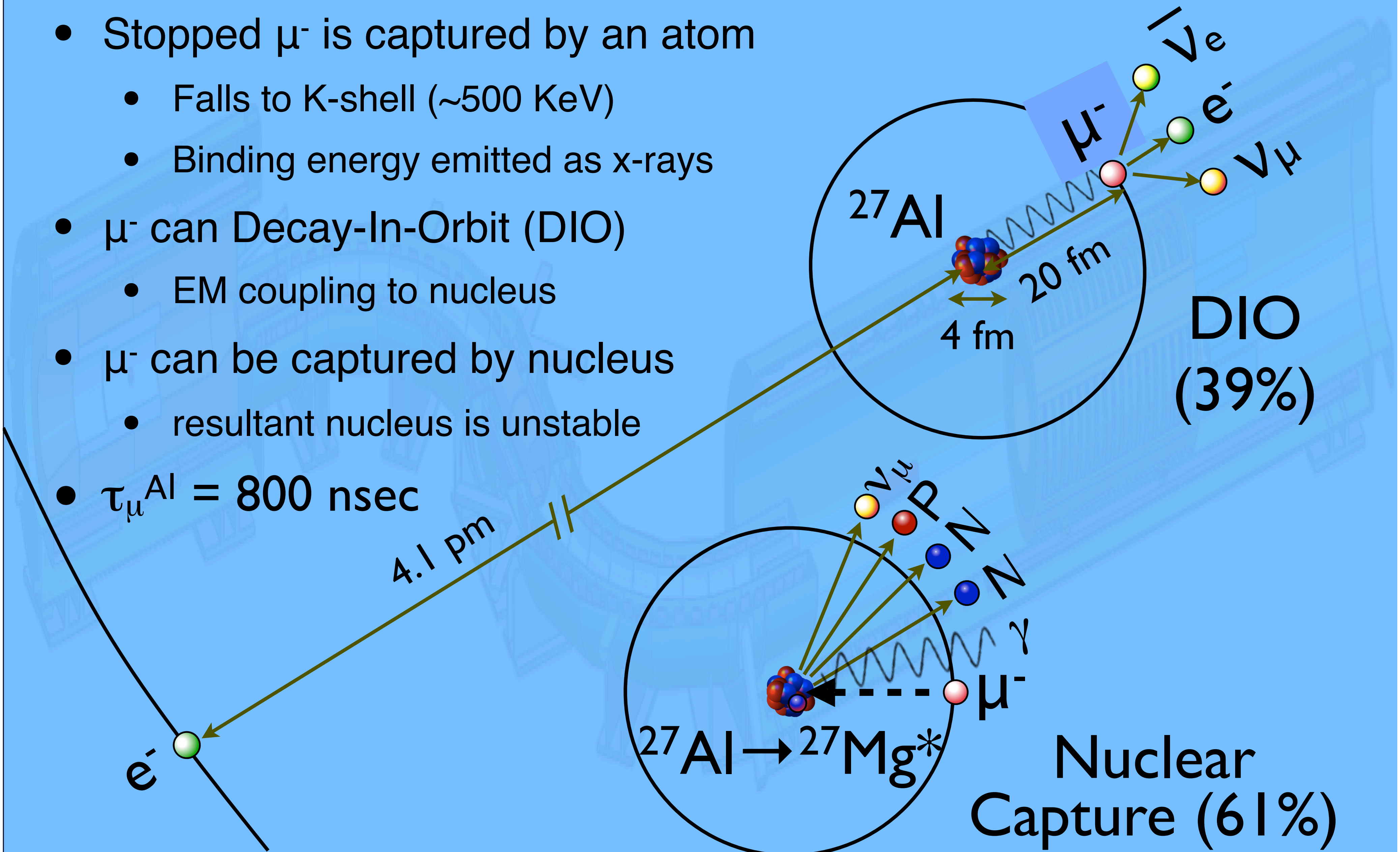
Antognini etal, Science 25 January 2013, Vol. 339 no. 6118



μ→e Conversion

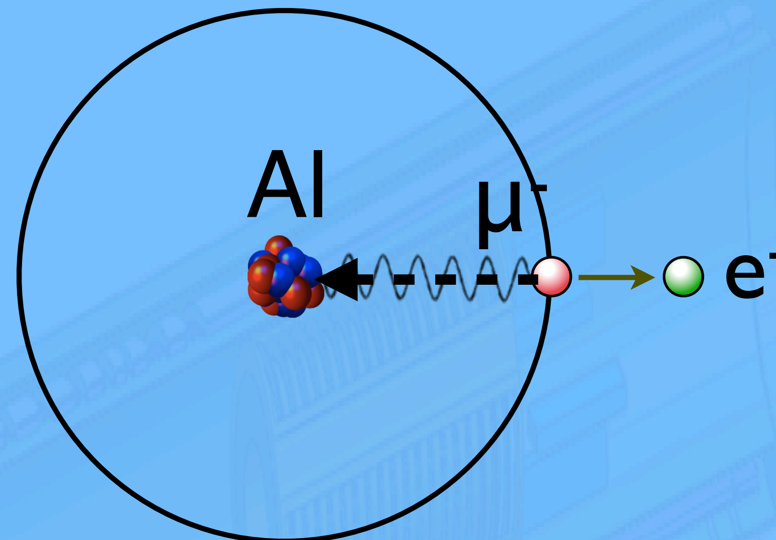
Atomic Capture of μ^-

- Stopped μ^- is captured by an atom
  - Falls to K-shell (~500 KeV)
  - 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
- τ_μ^{Al} = 800 nsec



$\mu N \to eN$ Conversion

- μ^- converts coherently with N
  - no neutrino!
  - e^- recoil is against N
  - N unchanged

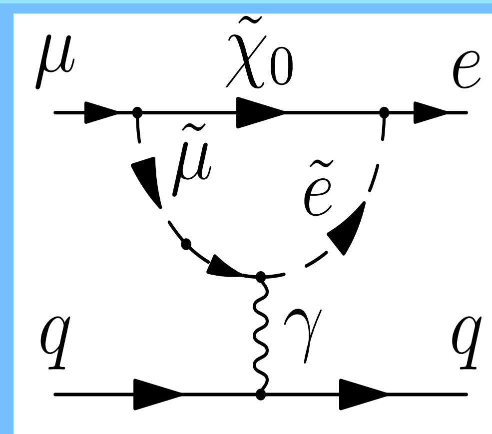


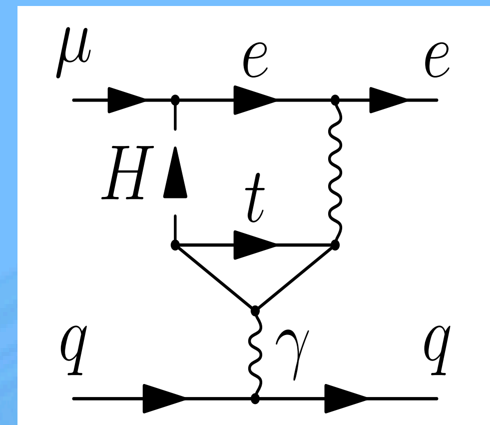
- Experimental Signature
  - isolated, mono-energetic e^-
  - $E_{conv} = m_\mu c^2 - E_{bind} - E_{recoil} = 104.973$ MeV (for Al)
- Rate defined as the ratio $R_{\mu e}$ = conversion/capture

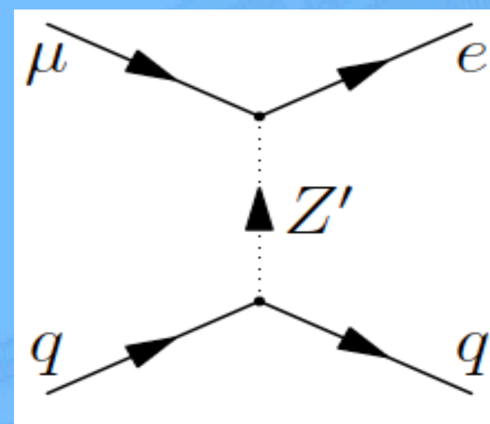
$$R_{\mu e} = \frac{\Gamma(\mu^- + (A,Z) \to e^- + (A,Z))}{\Gamma(\mu^- + (A,Z) \to \nu_\mu + (A,Z-1))}$$

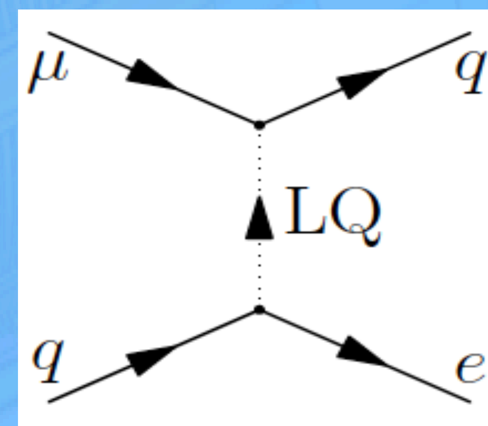
μ→e Conversion Processes

- ‘Loop’ terms
  - i.e. SUSY, Higgs doublets, ...
  - Also mediates μ→eγ
- ‘Contact’ terms
  - Couples leptons to quarks
  - Only accessible by μN→eN
- Effective Lagrangian
  - κ = contact/loop
  - Λ = mass scale





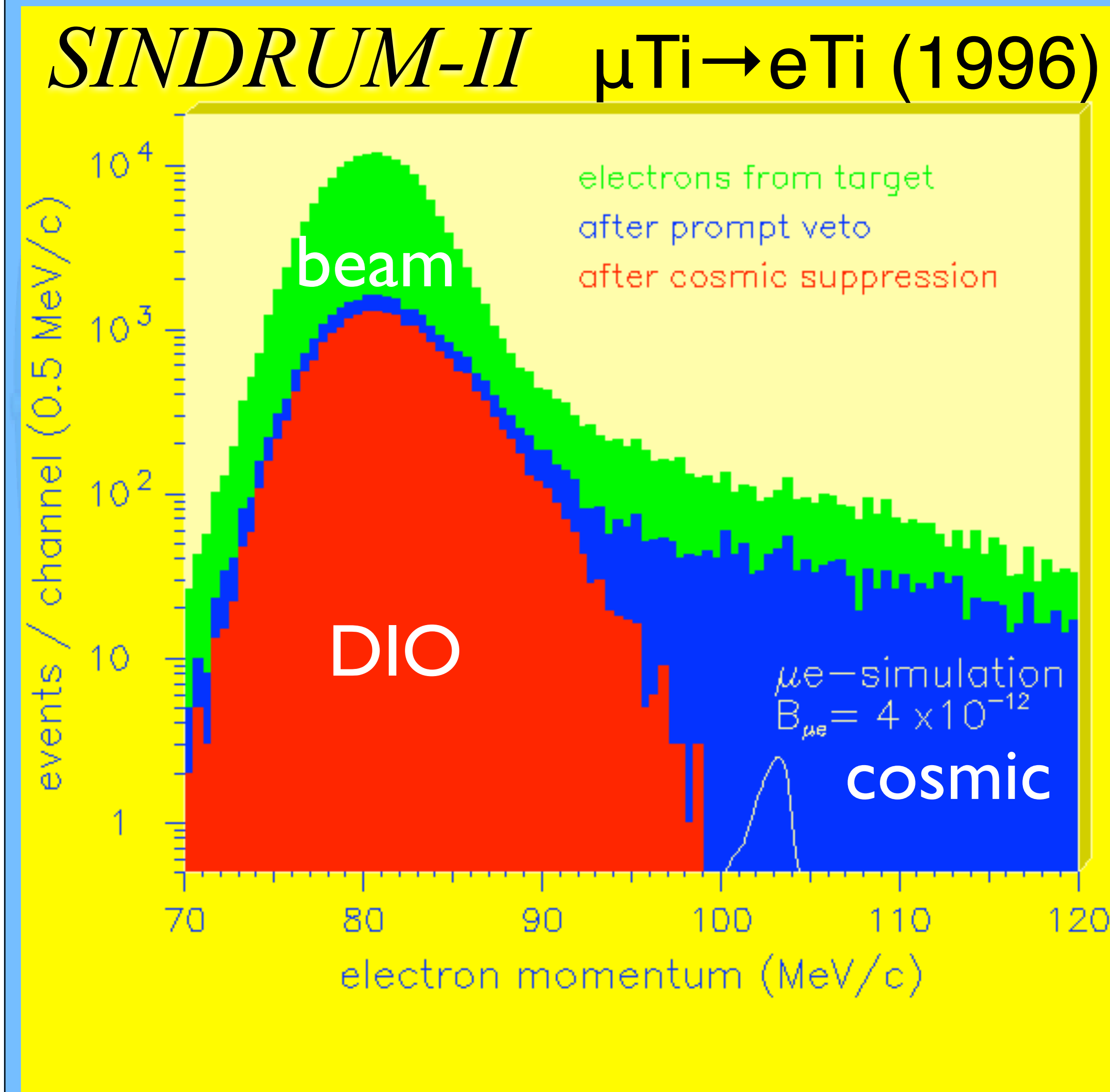




Loop | Contact

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

Previous Measurements



- PSI muon beam
- Signal: e⁻ momentum ~ 103 MeV
- Backgrounds:
  - beam π^- and e^-
  - cosmic muons
  - DIO

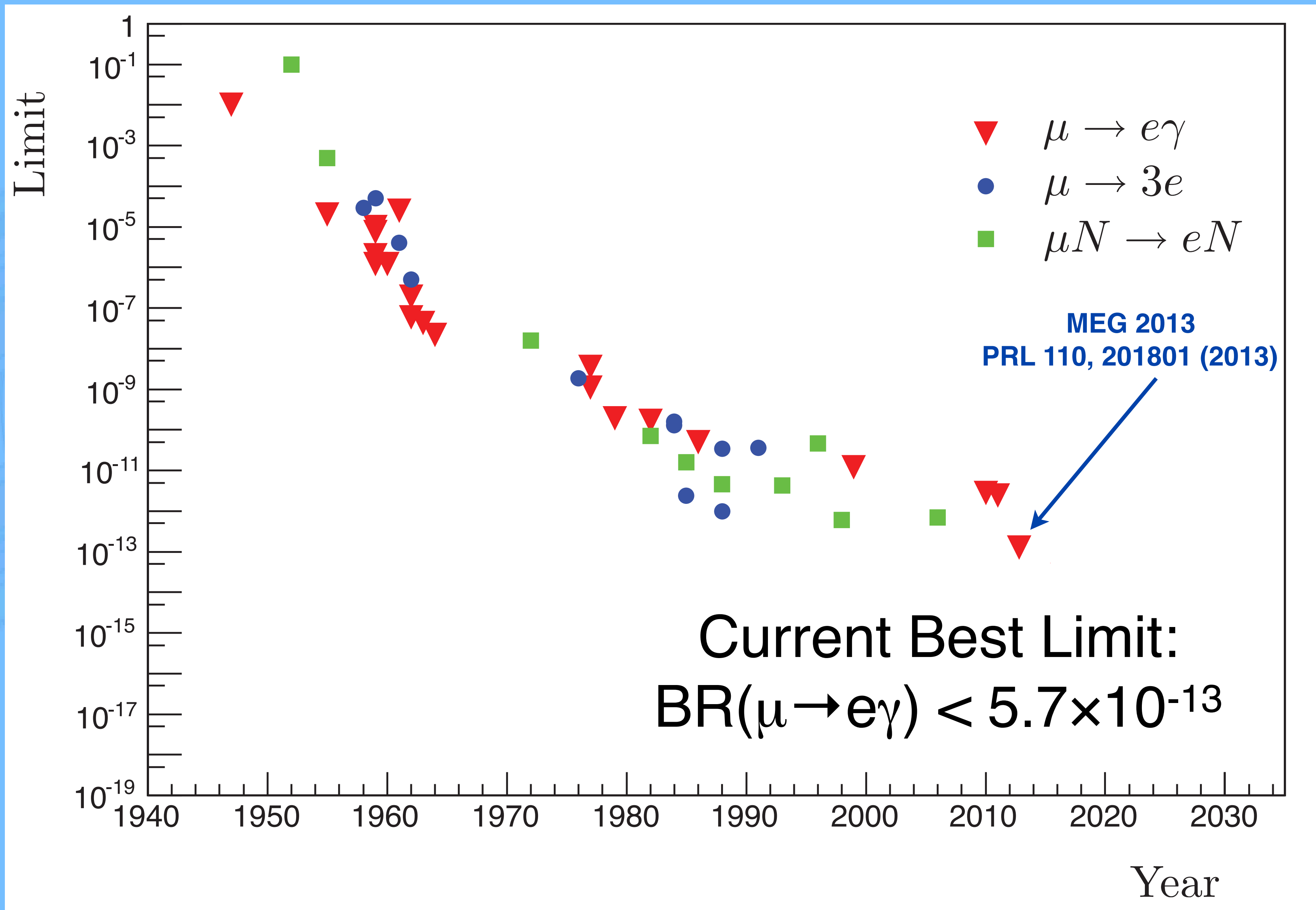
$R_{\mu e}^{Ti} < 6.1X10^{-13}$

PANIC 96 (C96-05-22)

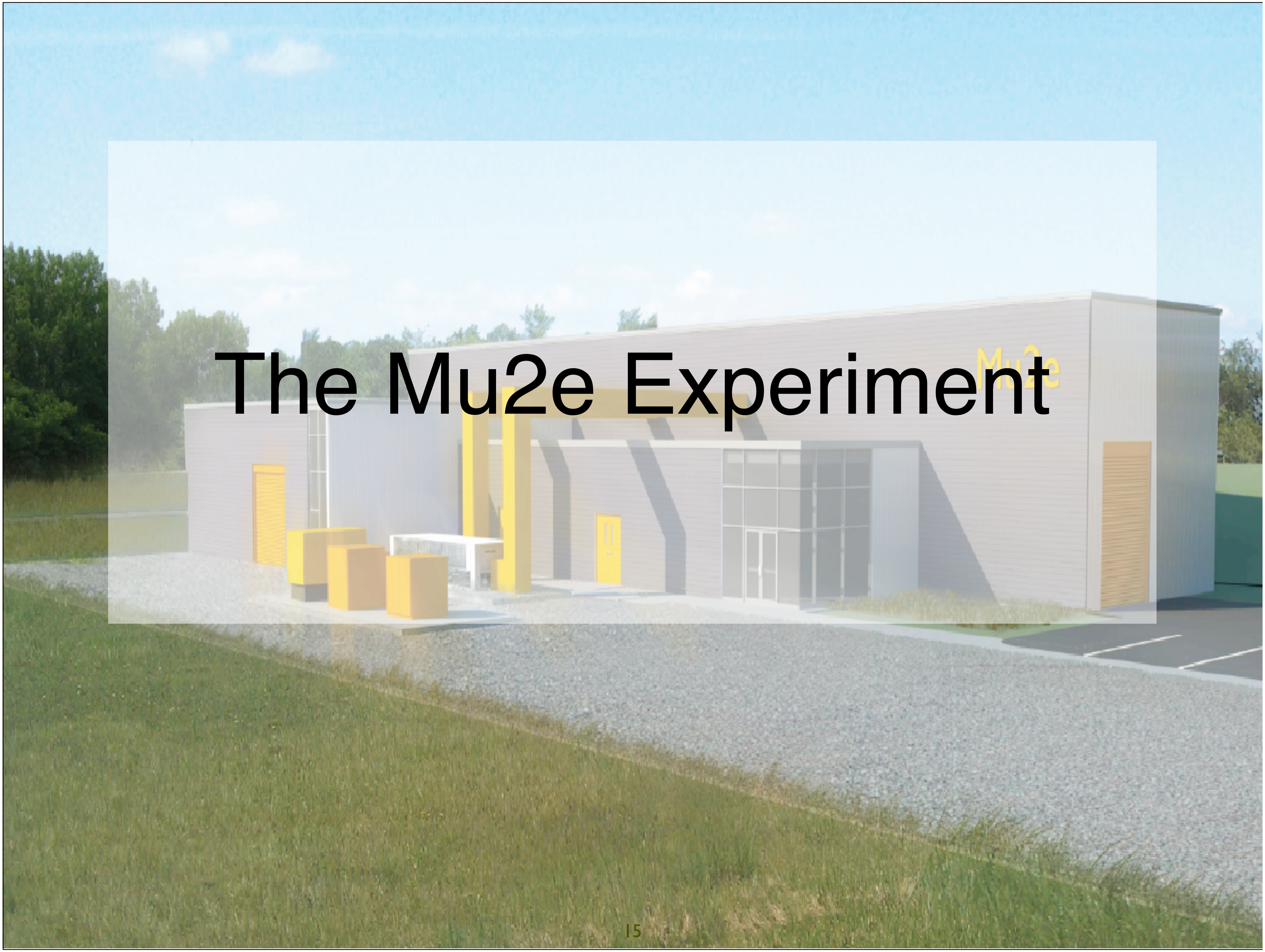
$R_{\mu e}^{Au} < 7X10^{-13}$

Eur.Phys.J. C47 (2006)

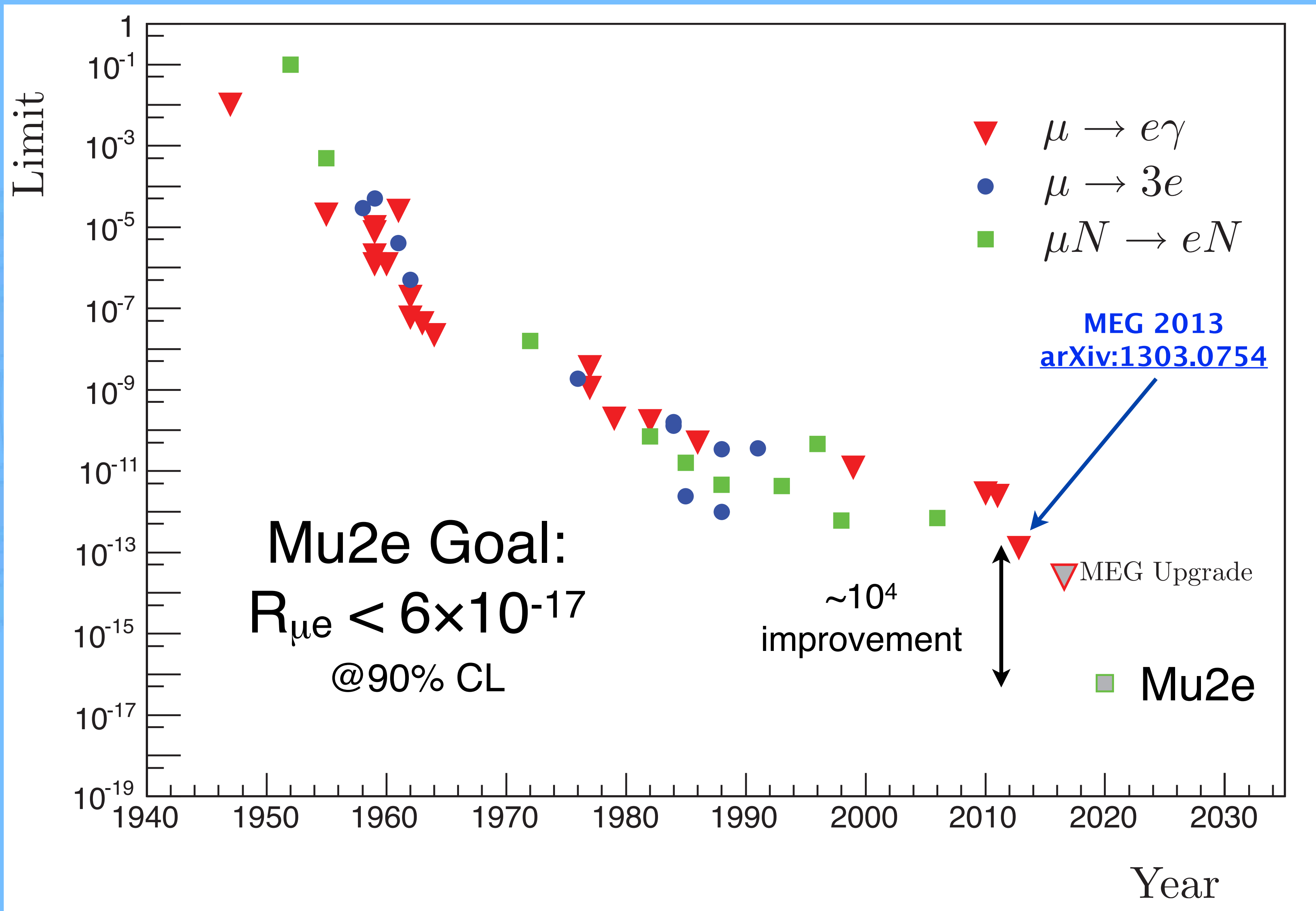
Muon CLFV Searches



The Mu2e Experiment

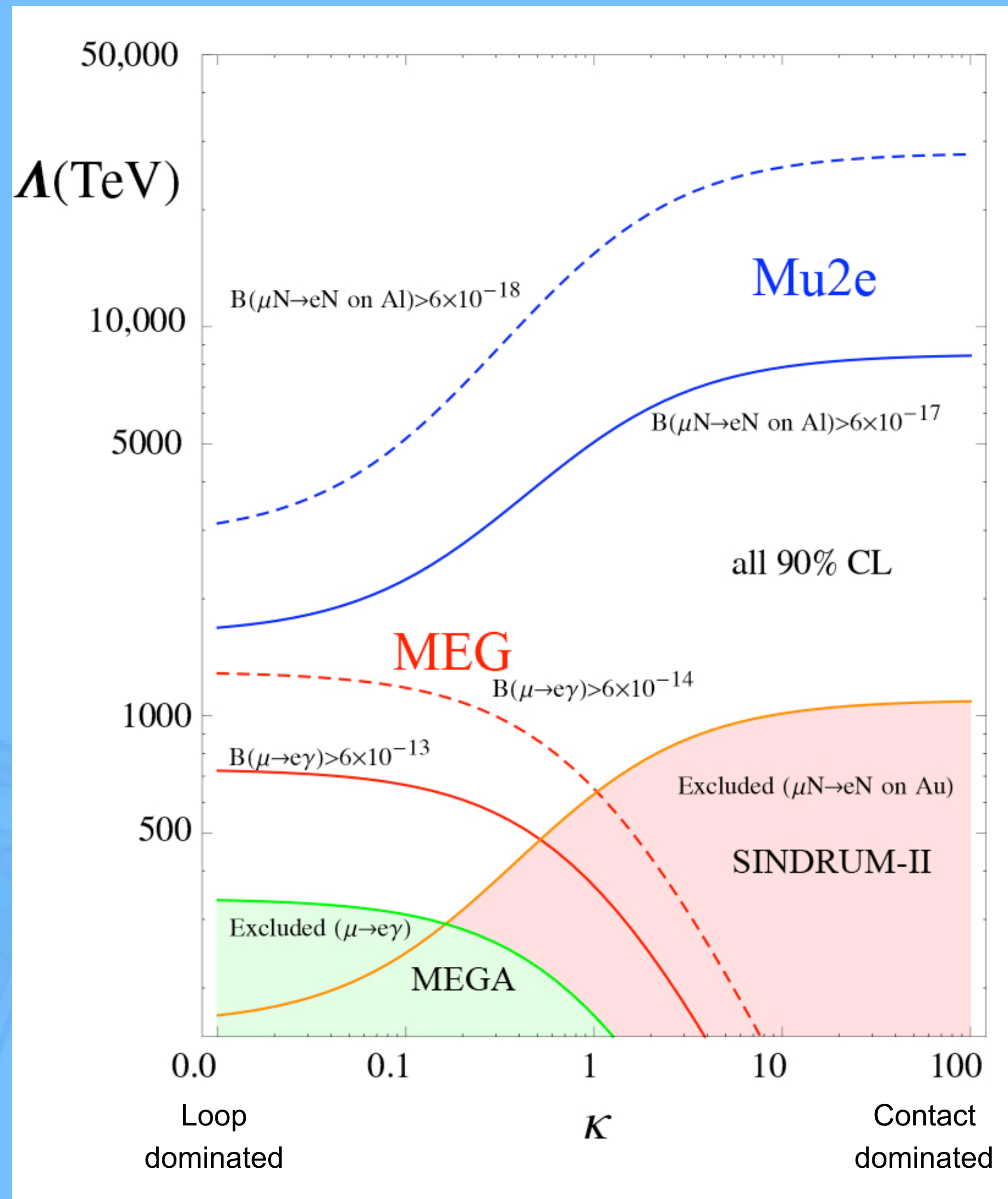


Mu2e Measurement Goal



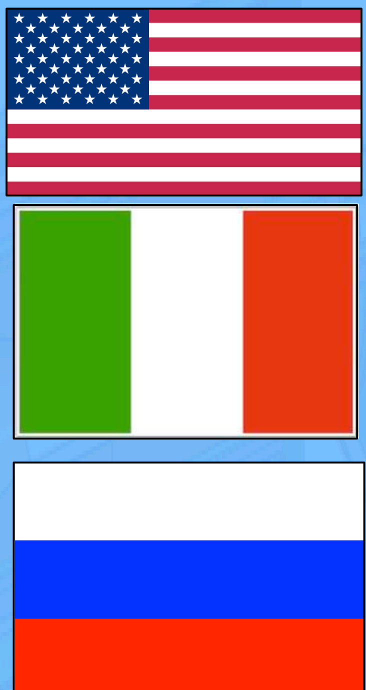
Mu2e Sensitivity Goal

- Mu2e will be sensitive over the full κ range
  - Exceed current (and future) limits for both Loop and Contact term interactions
- Mu2e will be sensitive to effective mass scales up to 10^4 TeV
  - ~1 order of magnitude improvement over current limits



Courtesy A. de Gouvea and B. Bernstein

The Mu2e Collaboration

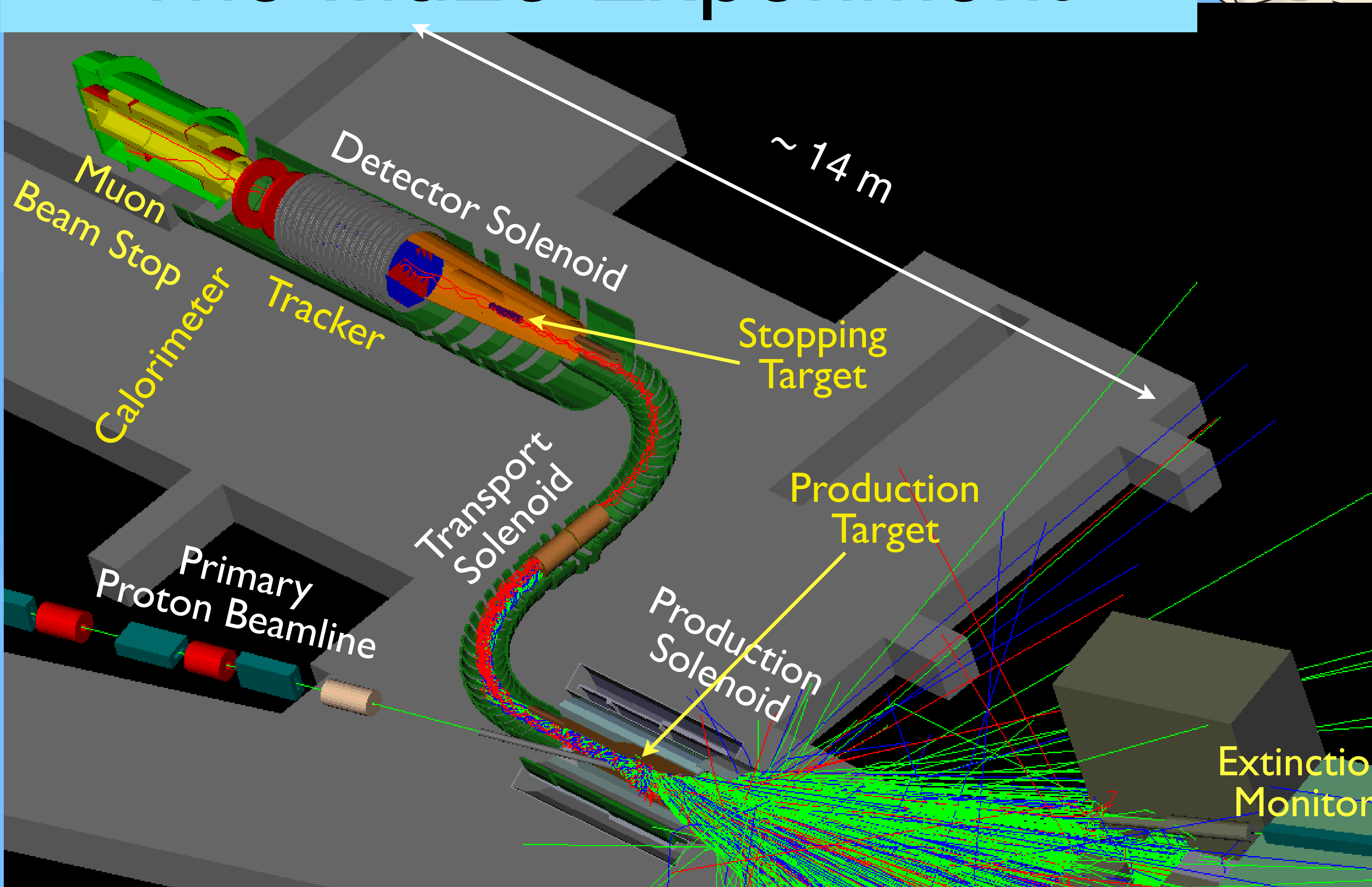


- ~130 Collaborators, 26 Institutions, 3 Countries

Mu2e Experimental Concept

- Produce μ^- via protons hitting a fixed target
  - P+Nucleus→ $\pi^- \rightarrow \mu^- \bar{\nu}_\mu$
- Collect and stop low-momentum μ^-
  - ~10^{18} stopped μ^- over a 3-year run
- Measure e^- momentum from μ^- decay at rest
  - conversion signature: mono-energetic line
- Principle experimental challenge: Background suppression (< 1 event for 3-year run)
  - Beam backgrounds ⇒ pulsed beam with good 'extinction'
  - DIO background ⇒ 1‰ momentum resolution and accuracy
  - Cosmic ray backgrounds ⇒ active shielding

The Mu2e Experiment

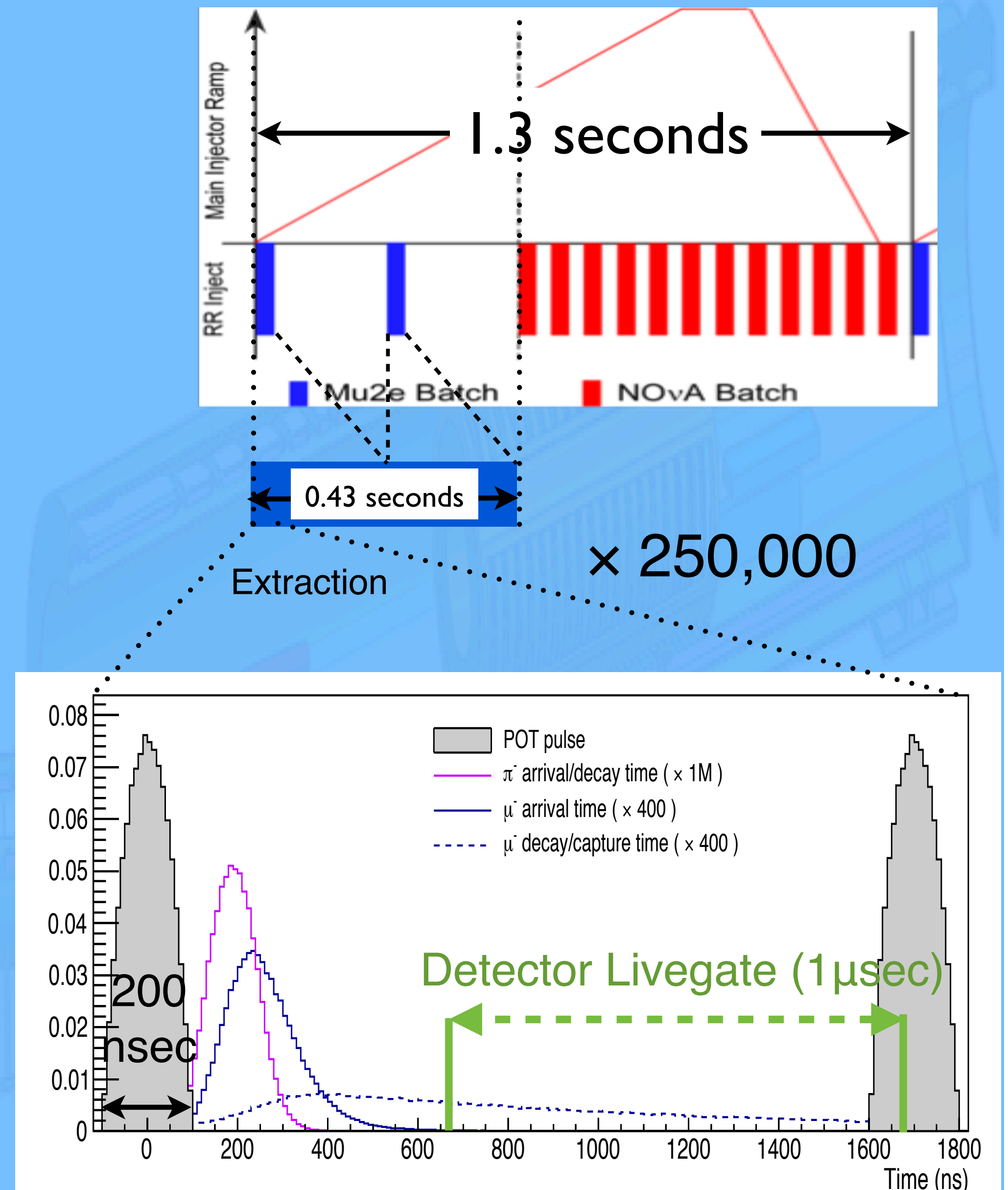


Mu2e Beam Delivery

- Protons accelerated in booster (8 GeV, 53MHz)
- Transported through Recycler
- Re-bunched and stored in the ‘Delivery Ring’
  - Was Anti-Proton Debuncher
  - Current limited by ‘sky shine’
- Resonant Extraction
- Sent to Muon campus through new M4 line
- Delivery shared with g-2

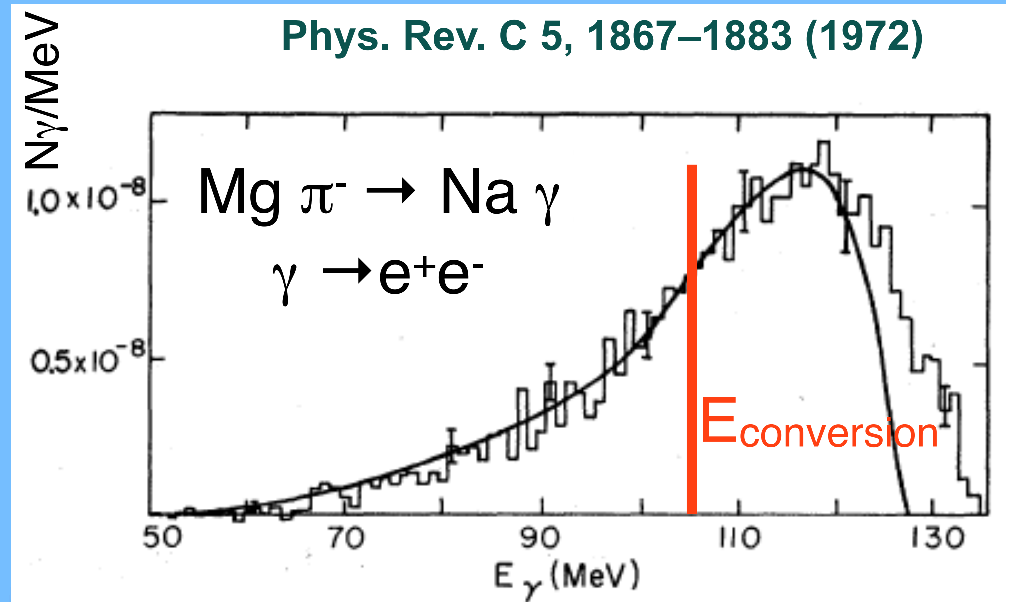
Beam Timing

- 2/20 booster batches
  - Shared running with NOVA
- Resonant extraction to M4 beamline
  - Narrow beam pulses
  - 1.7 µsec cycle
- Detector live for ~1 µsec
- 700 nsec delay avoids beam backgrounds
  - Beam ‘flash’ in first 300 nsec
    - Huge detector backgrounds
  - beam π^-
    - µ→e conversion background



Mu2e Beam Backgrounds

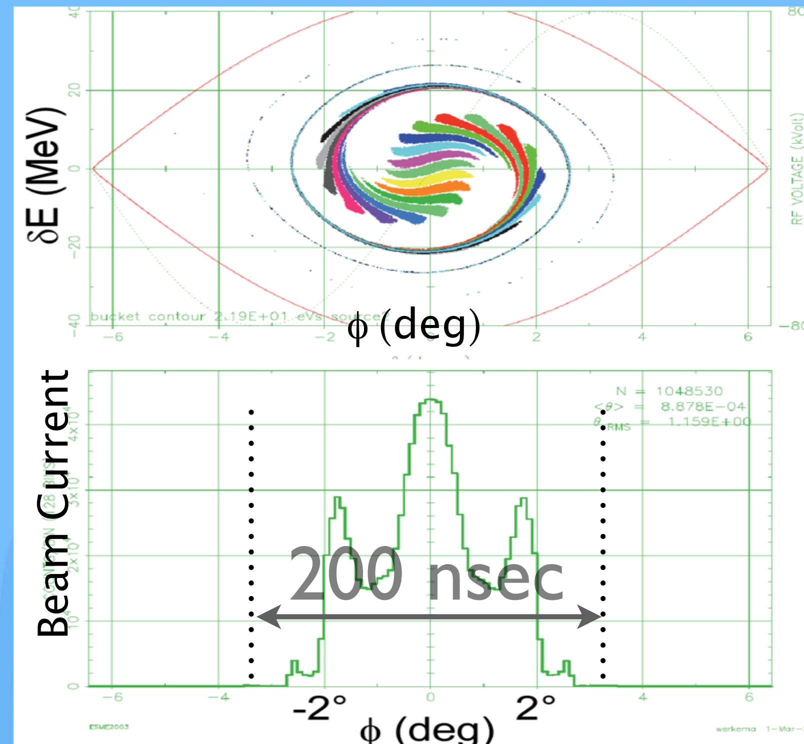
- 8 GeV Protons produce $\pi^{\pm}$, $\mu^{\pm}$, $e^{\pm}$, P and anti-P
  - Wide momentum spread ⇒ hard to separate species
- Anti-P, π^- can capture on target, produce conversion background
  - Capture → γ → asymmetric γ conversion → e^- in signal window
  - rate ~10^{-6}
- Anti-P are reduced with a degrader (3.5 mm Be)
  - costs ~10% of μ^- flux

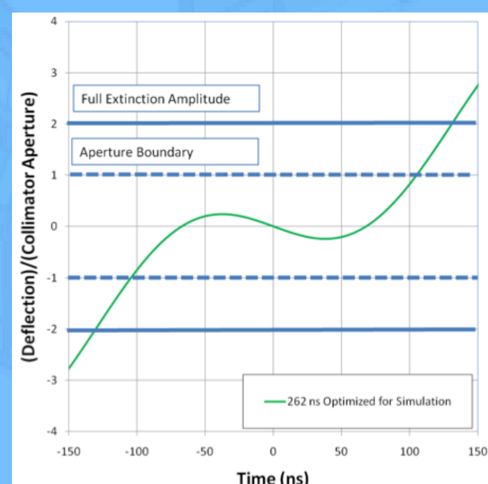


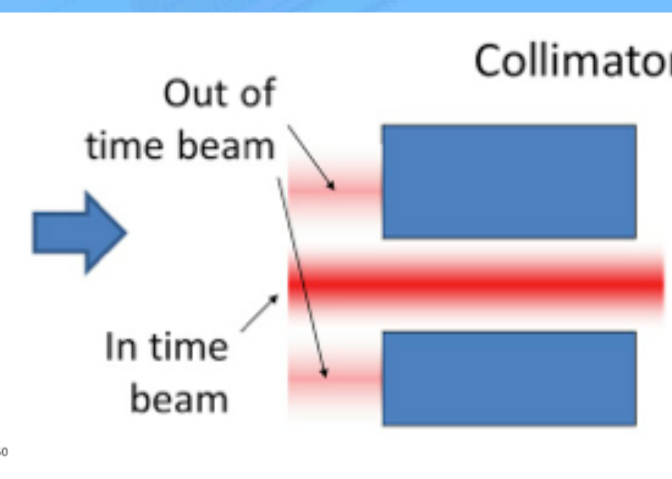
- π^- can waited out
  - $\tau_\pi/\tau_\mu \sim 30$
  - 700 nsec delay provides ~10^{-11} π^-/μ^- suppression
- Out-of-time protons must be similarly suppressed (‘extinction’)

Proton Pulse Formation

- Re-bunching forms narrow pulses
  - ~200 nsec wide
  - out-of-time proton fraction < 10^{-4}
- AC dipole deflects out-of-time protons
  - 300 KHz + 3.8 MHz
  - resonant with beam
  - Additional factor of 10^{-7} rejection
- Net ‘extinction’ of out-of-time protons < 10^{-10}

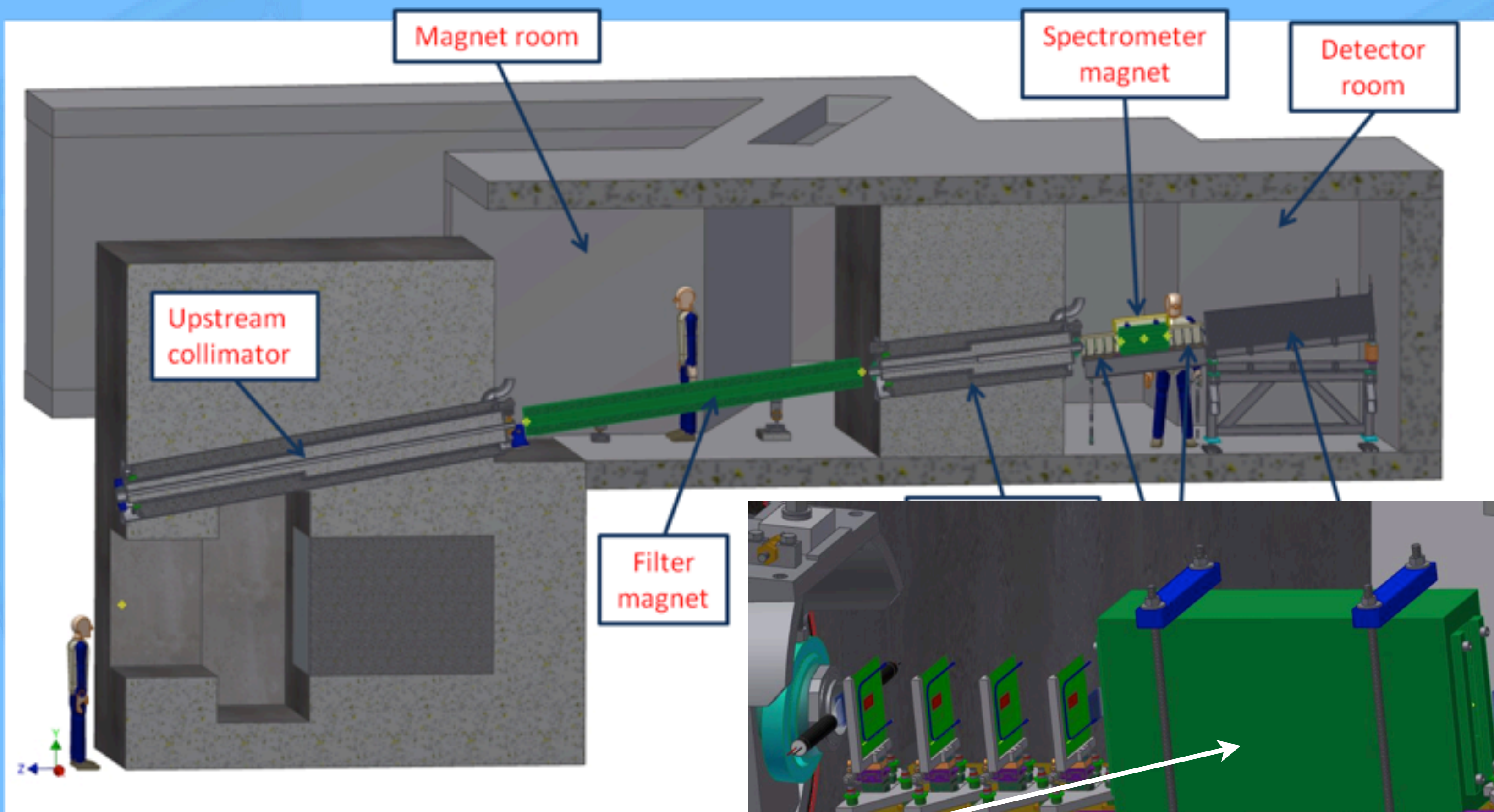




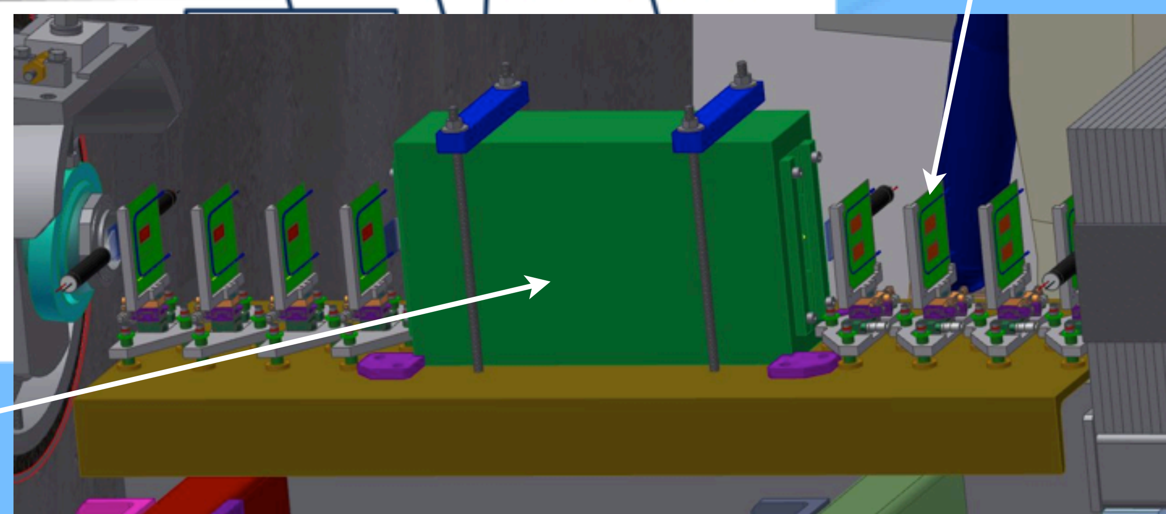


Extinction Monitor

- 'Pinhole' Si pixel telescope spectrometer
  - Measure extinction to 10^{-10} in ~1 hour



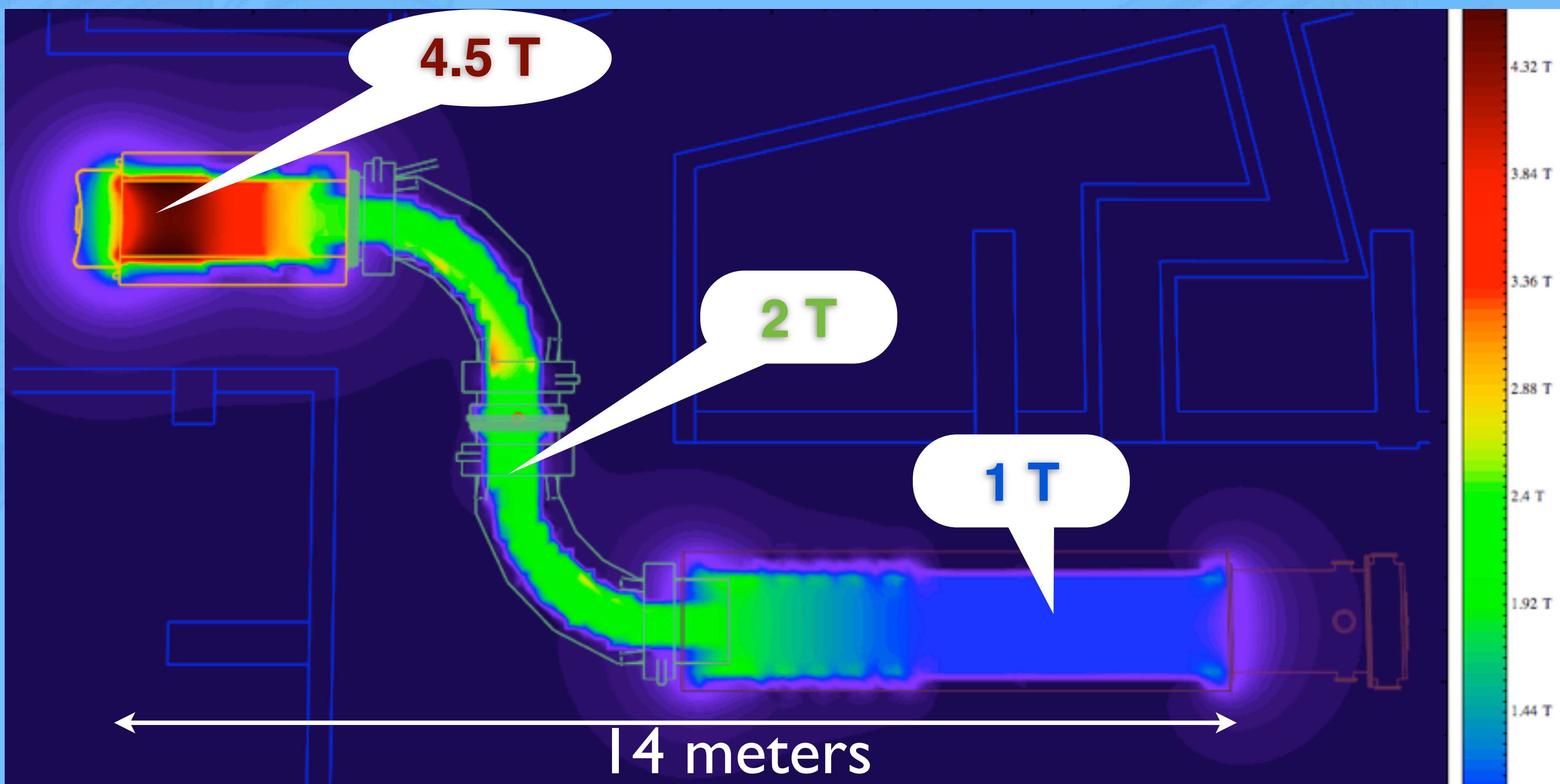
ATLAS IBL pixels + readout



Spectrometer magnet

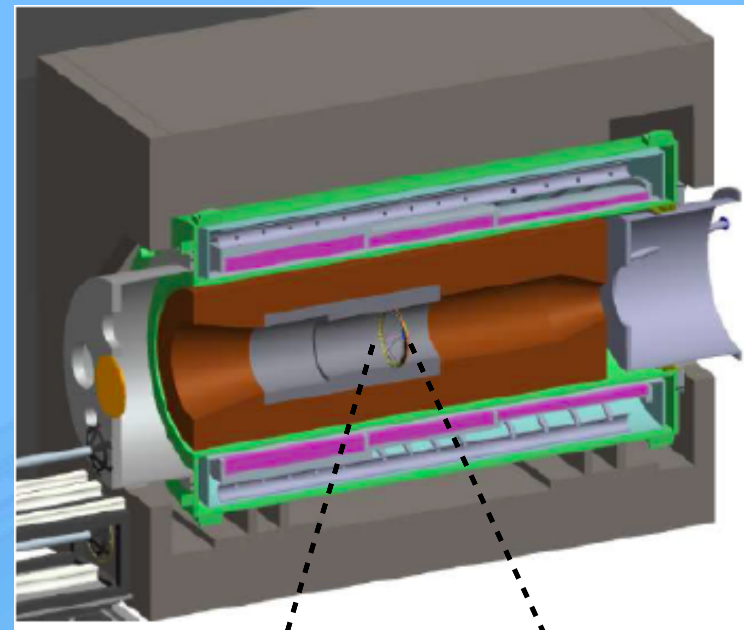
Solenoidal Transport

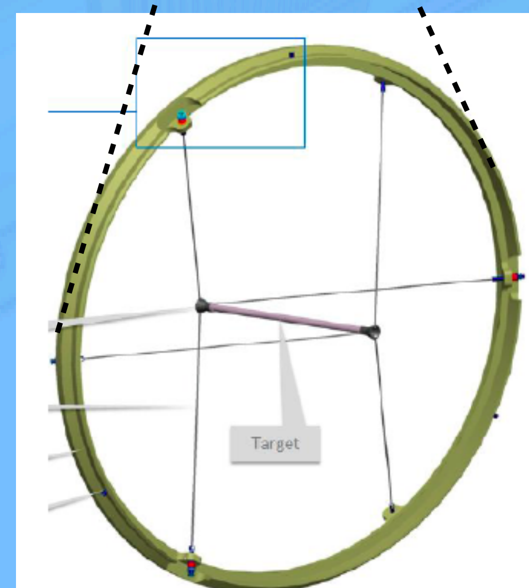
- Graded fields increase collection efficiency, sweep particles towards detector

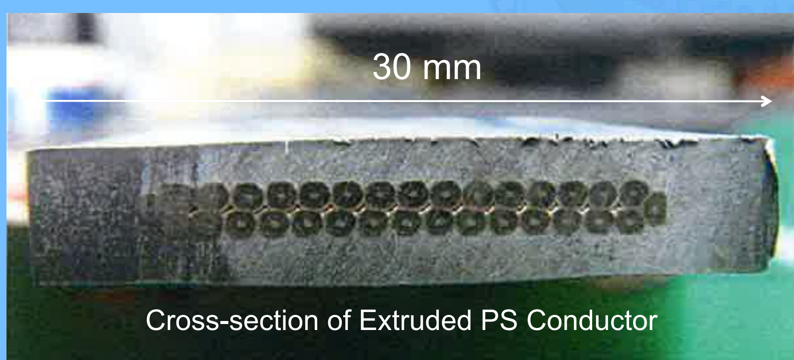


Production Solenoid

- High field, high radiation
  - Bronze shields superconductor
- Tungsten rod target
  - Radiation cooled: 1650° C!
  - 0.005 μ^- produced per POT
- Radiation limit: Al stabilizer atom displacement < 10^{-5}/year
  - Must anneal once/year!
- Cable samples meet requirements

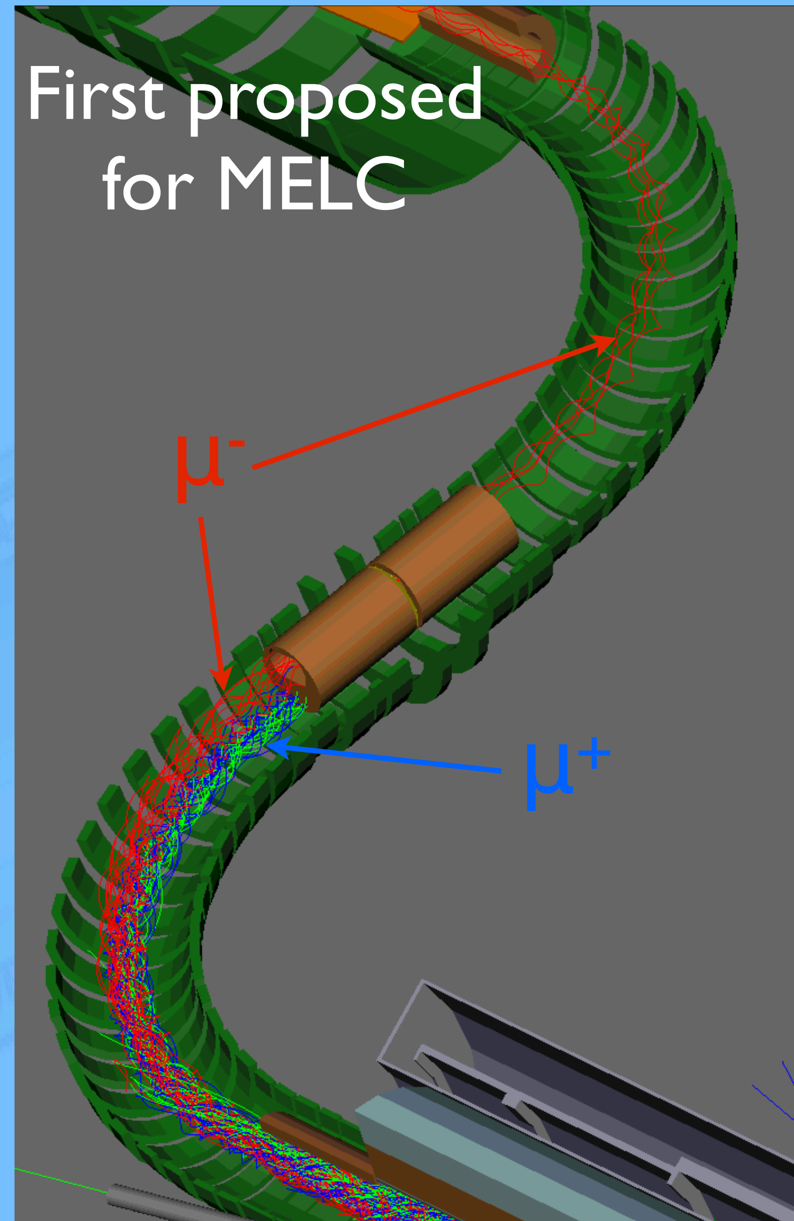




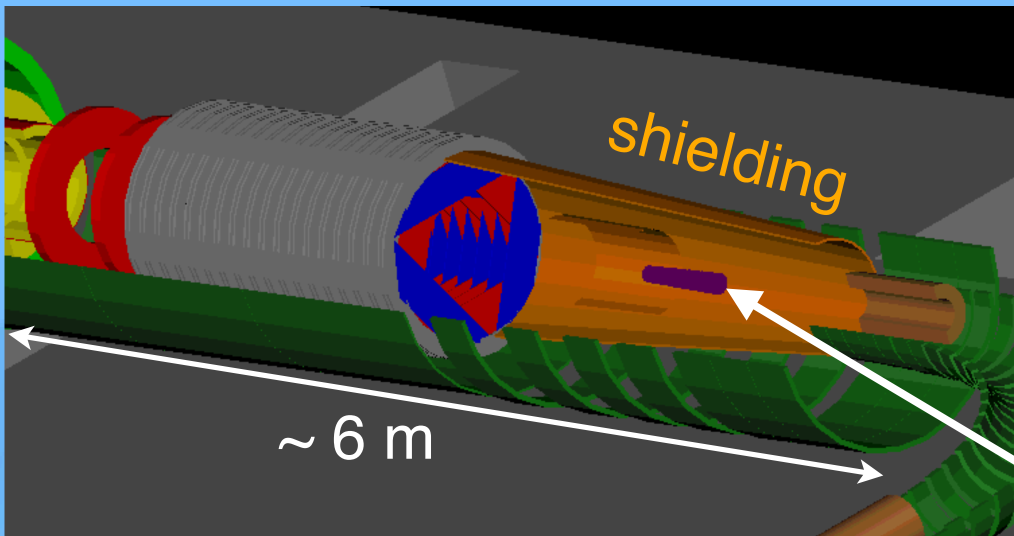


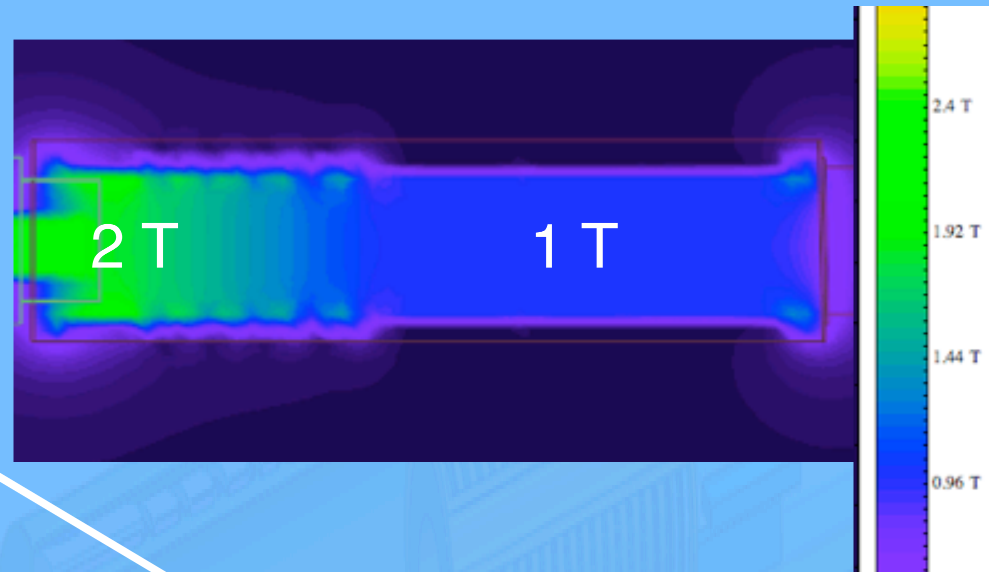
Transport Solenoid

- ‘S’ bend solenoid transports charged particles
  - no line-of-sight to detector
- Bend induces momentum, charge-dependent vertical shift
  - Reversed by 2nd bend
- Asymmetric collimator rejects positive and high-momentum particles
  - Can be rotated to select positive particles

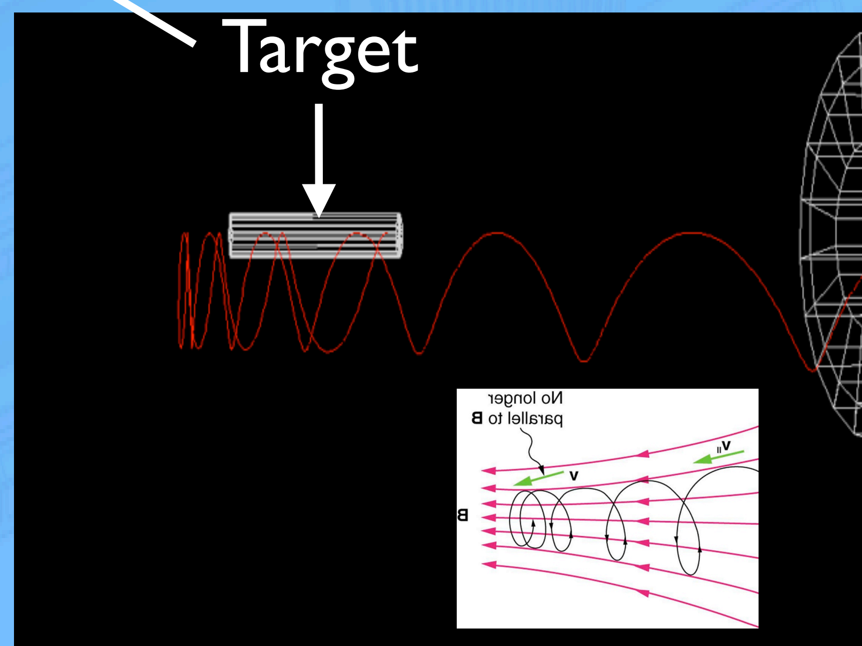


Detector Solenoid



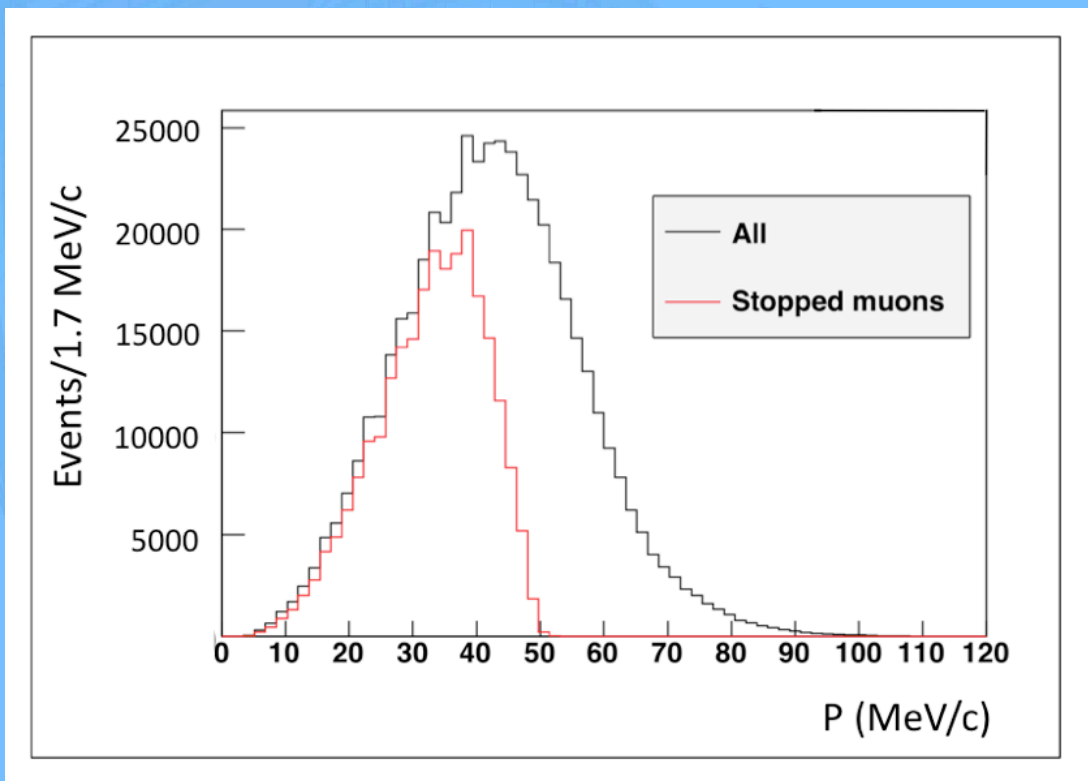


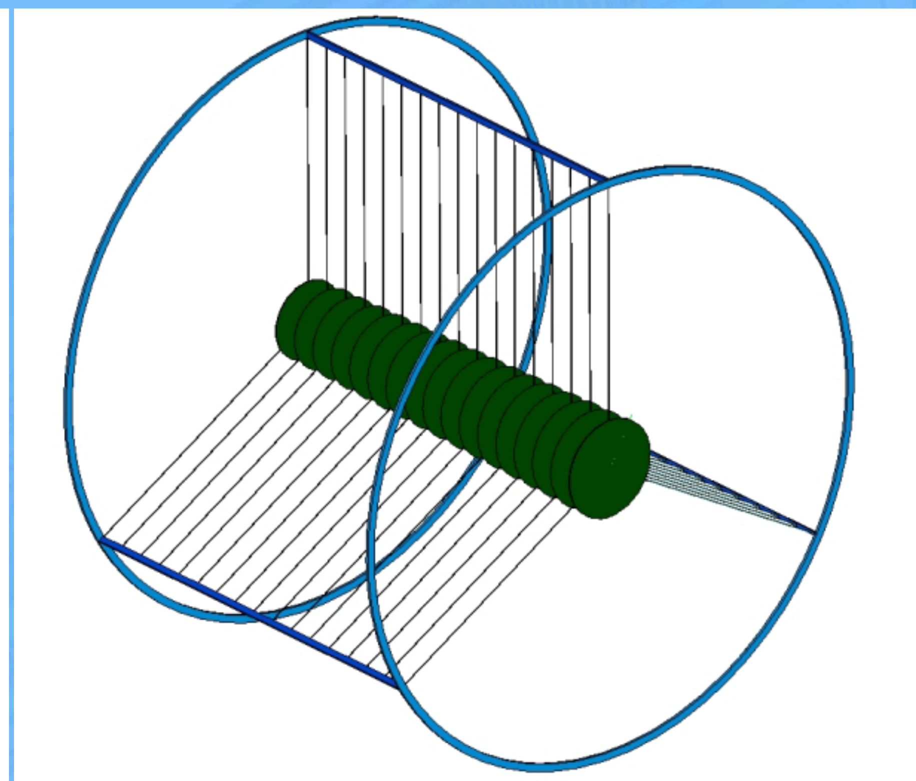
- 2.0T→1.0T near target
  - ~50% increase in e$^-$ acceptance
- 0.5 %/meter gradient in detector region
  - sweeps out slow e±, μ±



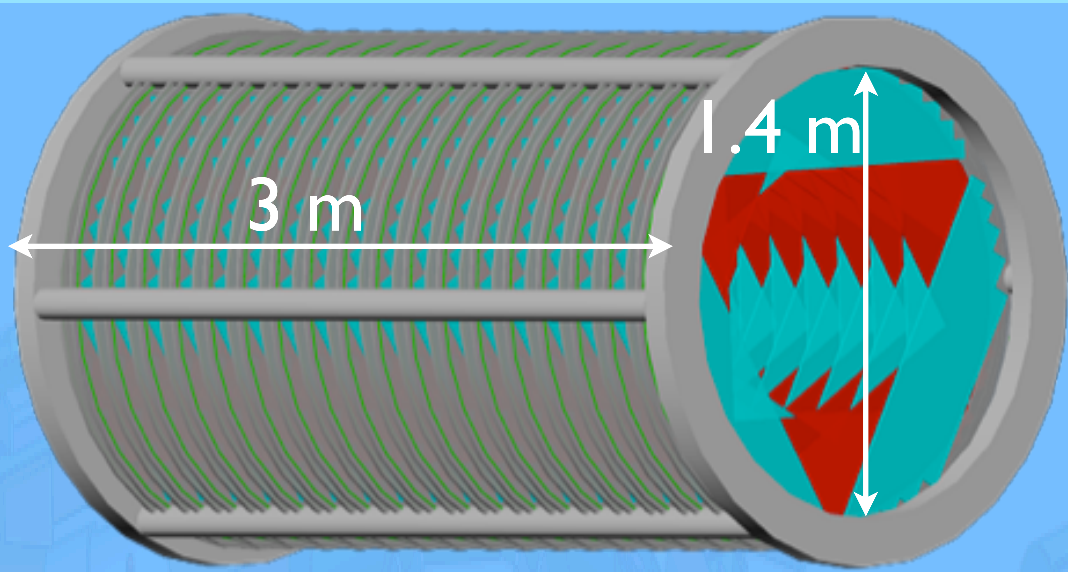
Stopping Target

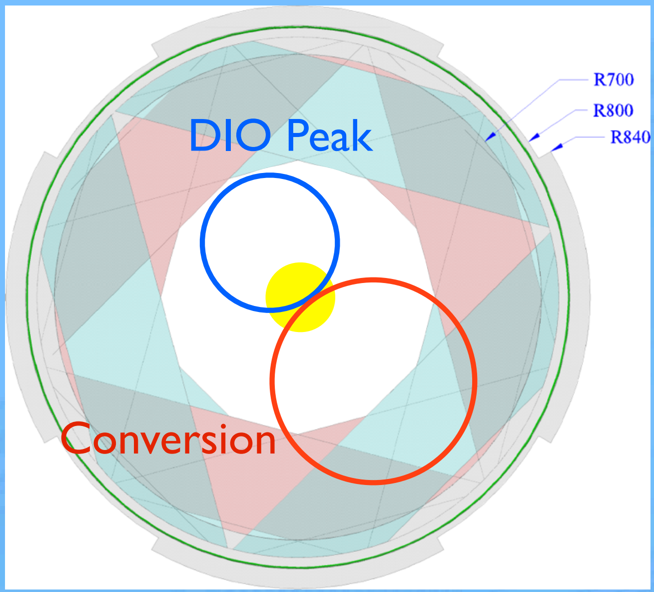
- (17) 200 µm thick, ~10cm diameter Aluminum disks
  - Compromise between stopping power and e^- straggling
- ~10^5 stopped μ^- each 1.7 µsec bunch



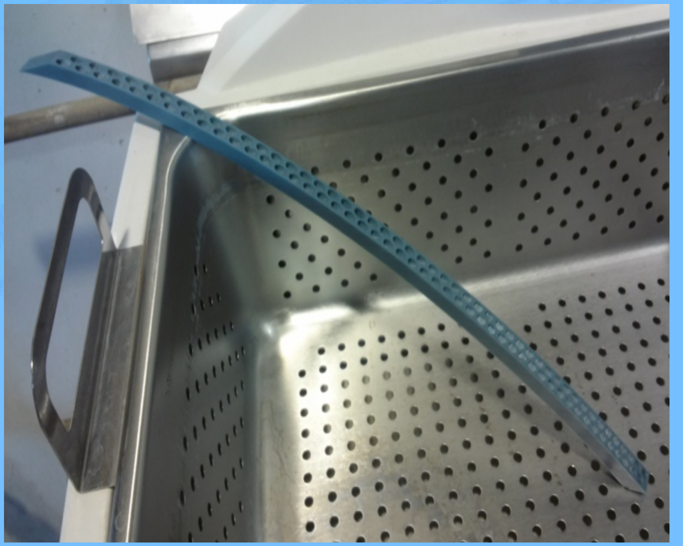


Low-Mass Straw Tracker



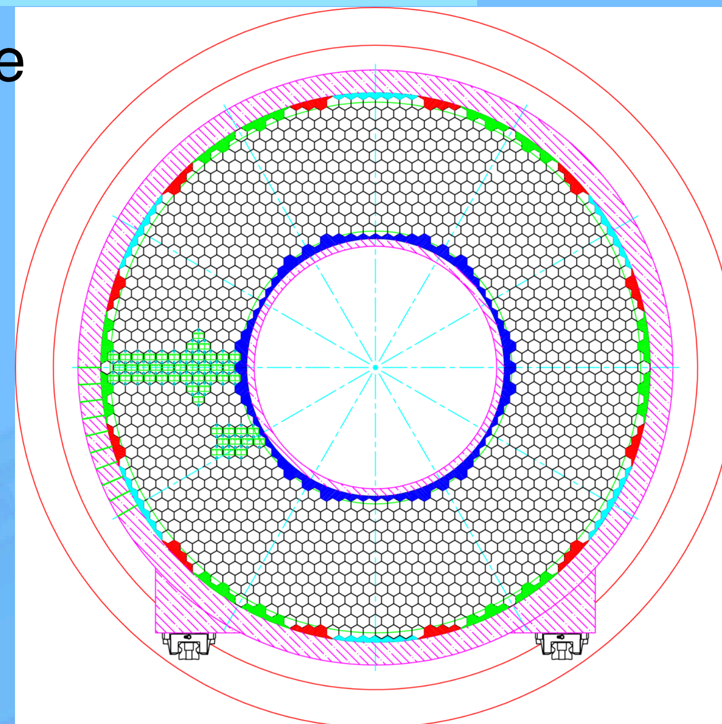


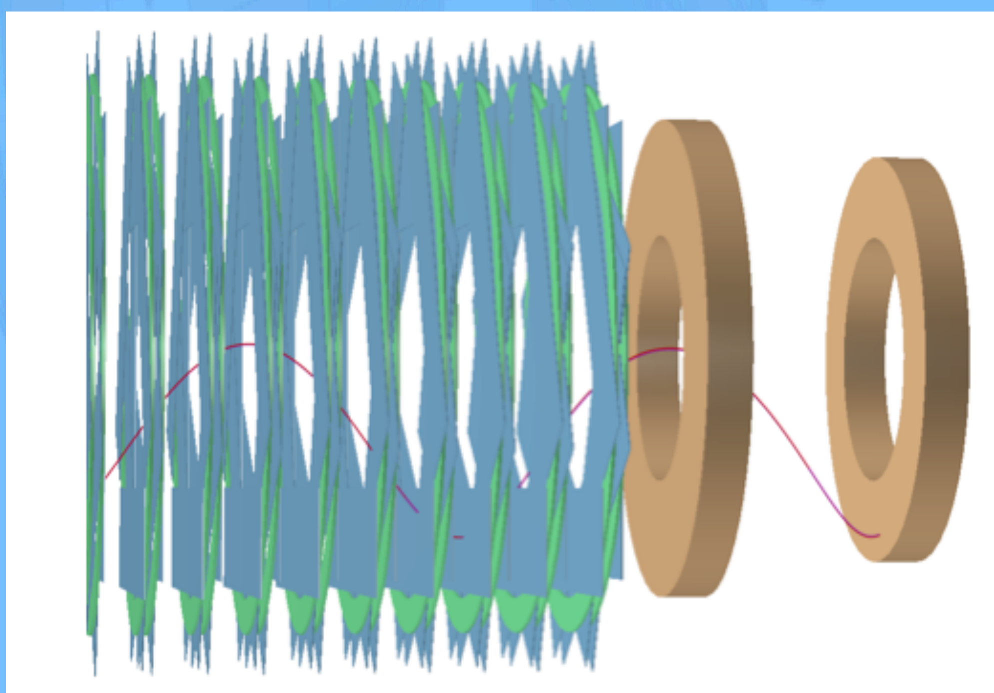
- 22 *stations* of straw chambers
  - 1 station = 12 semi-circular straw panels
  - 3-D printed manifolds
  - 15 µm mylar/Al/Au wall straws
  - Average mass transited by e^- ~1% x_0
- Time division readout (3-D points)
  - custom ASIC, few cm resolution (~100 ps)



Calorimeter

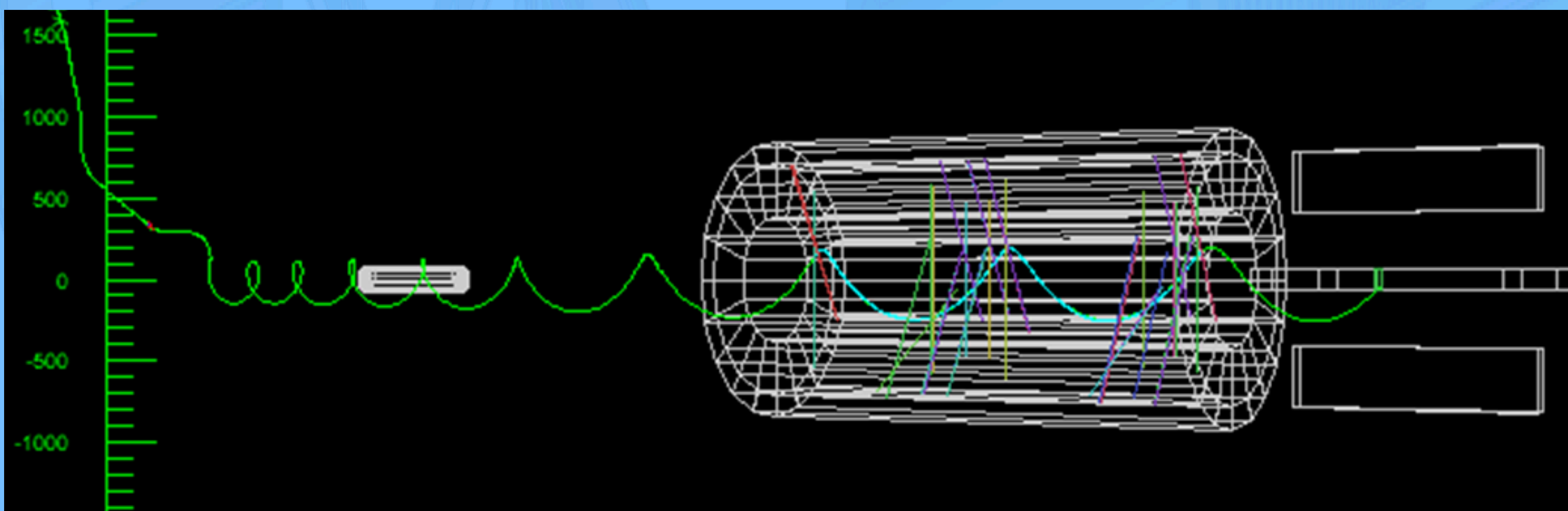
- Dual Disk geometry gives ~90% acceptance
- Hexagonal crystals
- APD or SiPM readout
- LYSO or BaF_3 crystals
- Provides precise timing, μ-e separation, alternate track finding seed



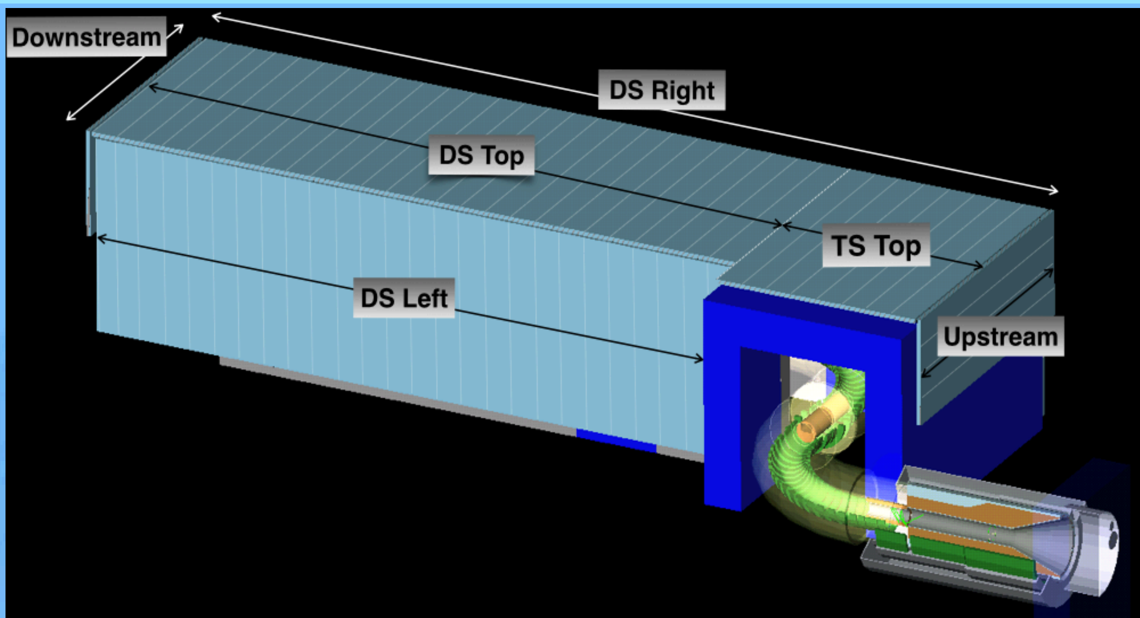


Cosmic Ray Backgrounds

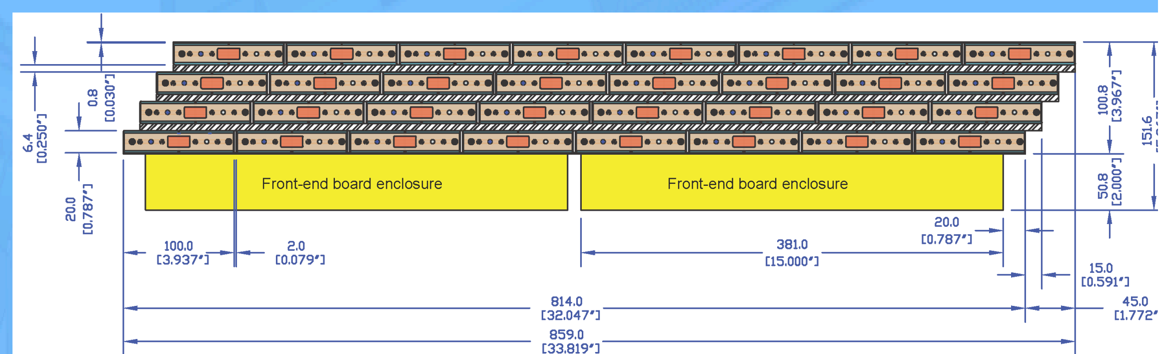
- < 10 mwe overburden (concrete)
  - large flux of cosmic ray muons!
- Detector is live ~30% of wall-clock time
- Cosmic μ^- can produce fake e^- tracks
- Tracker (dE/dx) + calorimeter provide modest cosmic rejection
  - Estimated background of ~10^3 in momentum signal window
- An active cosmic veto system is needed!



Cosmic Ray Veto System



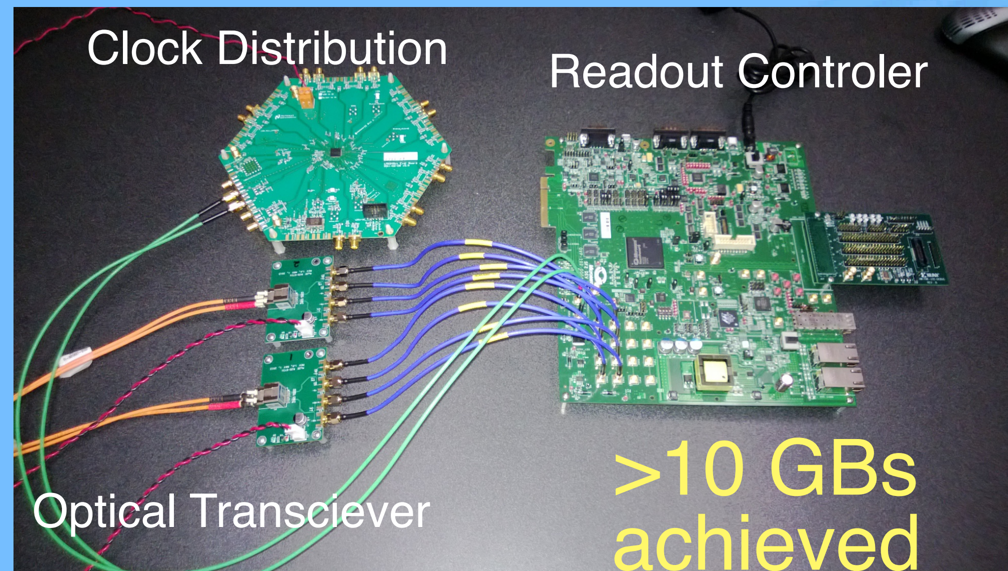
- Active veto coverage over detector and stopping target
- 4 layers of overlapping scintillation counters
  - SiPM readout (via fiber)
  - 99.99% net efficiency (3 of 4)
- Background of 0.05 events in signal window (3 year run)



DAQ

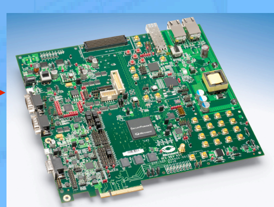
- 'Triggerless' architecture
  - Raw data streamed to online farm (36 servers)
- Fast track finding filter
  - 1/500 reduction to disk
  - 5ms/event, 400 Hz, 1Pb/year

Benchmark Tests



Detector

Readout Controler



⋮

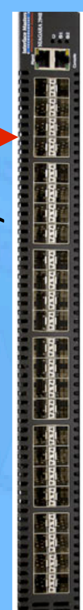
× 543

Server

⋮

× 36

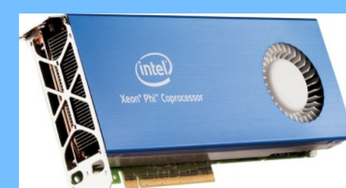
Event Building network (10G Ethernet switch)



Xeon-ES (32 cores/CPU)

190K events/sec (meets spec)

Xeon-Phi (120 cores/CPU)



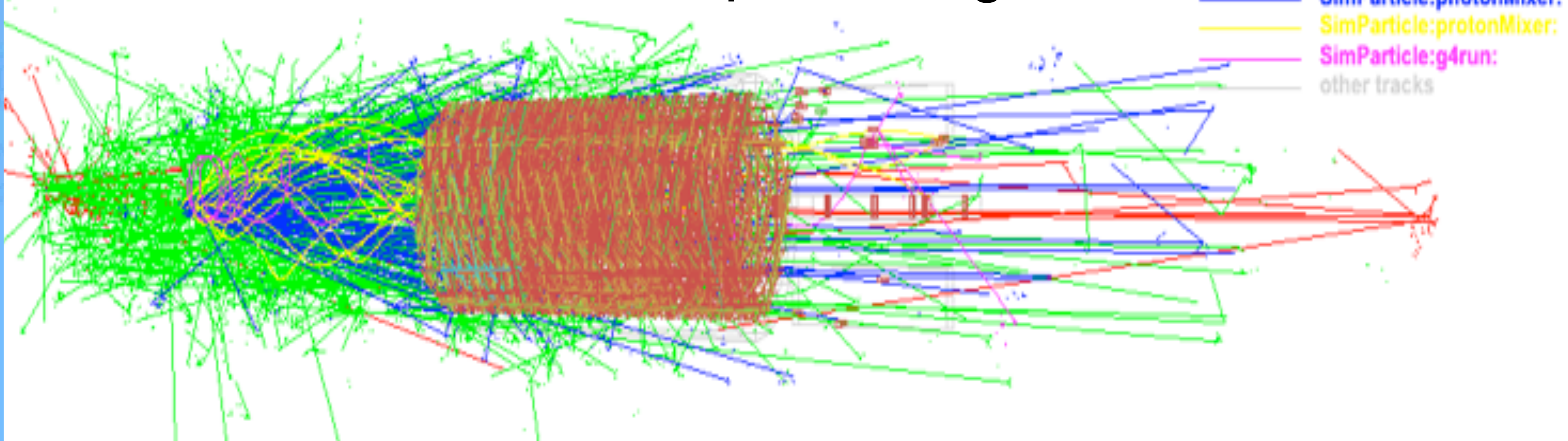
140K events/sec

Mu2e Performance Estimates

Tracker Backgrounds

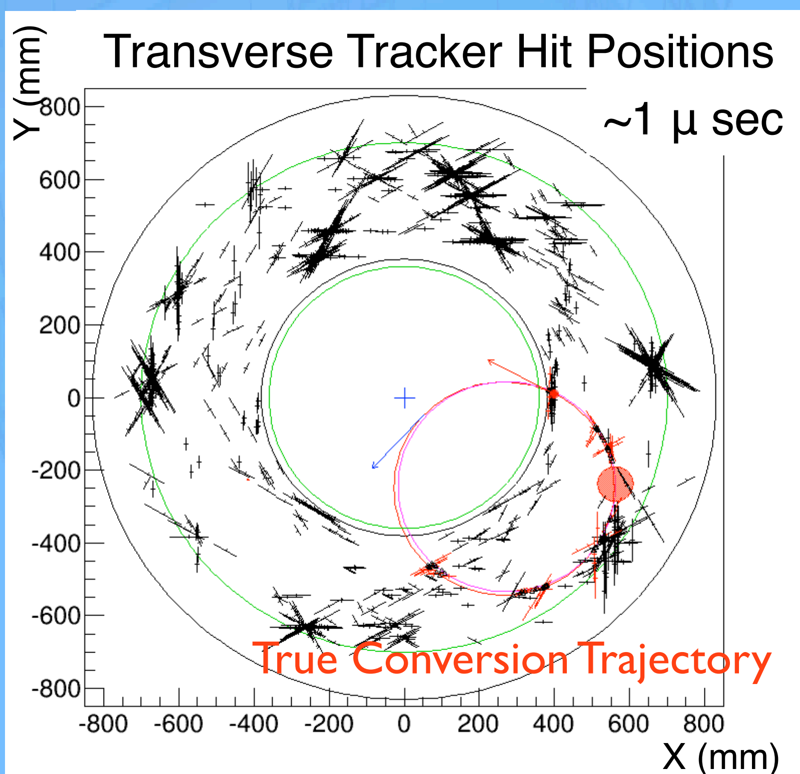
- Muon capture produces a high rate of particle backgrounds
  - protons, photons, and neutrons
  - neutron capture produces ~few MeV γ
- ~1 GHz of background tracker hits during livegate
  - γ→e (Compton scattering and γ-conversion)
  - straw walls are radiators!

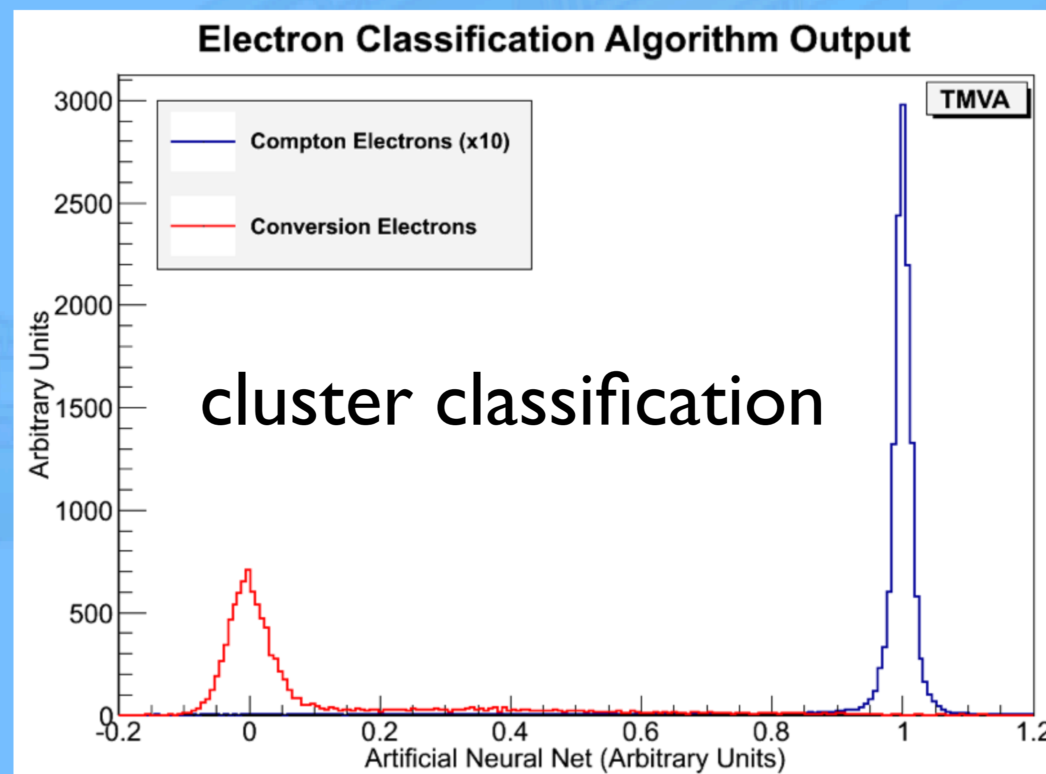
G4 Simulation, inside 1μsec livegate



Background Hit Removal

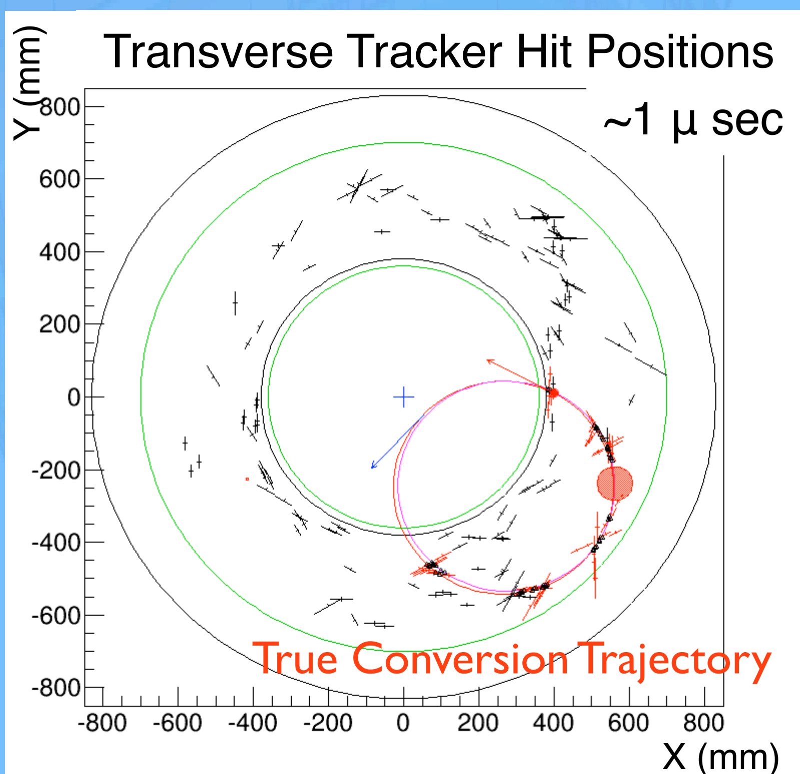
- An Artificial Neural Net separates low-energy electron hits from conversion hits
  - Clustering in space and time allows discrimination
  - 90% background hit rejection, 99% conversion hit efficiency

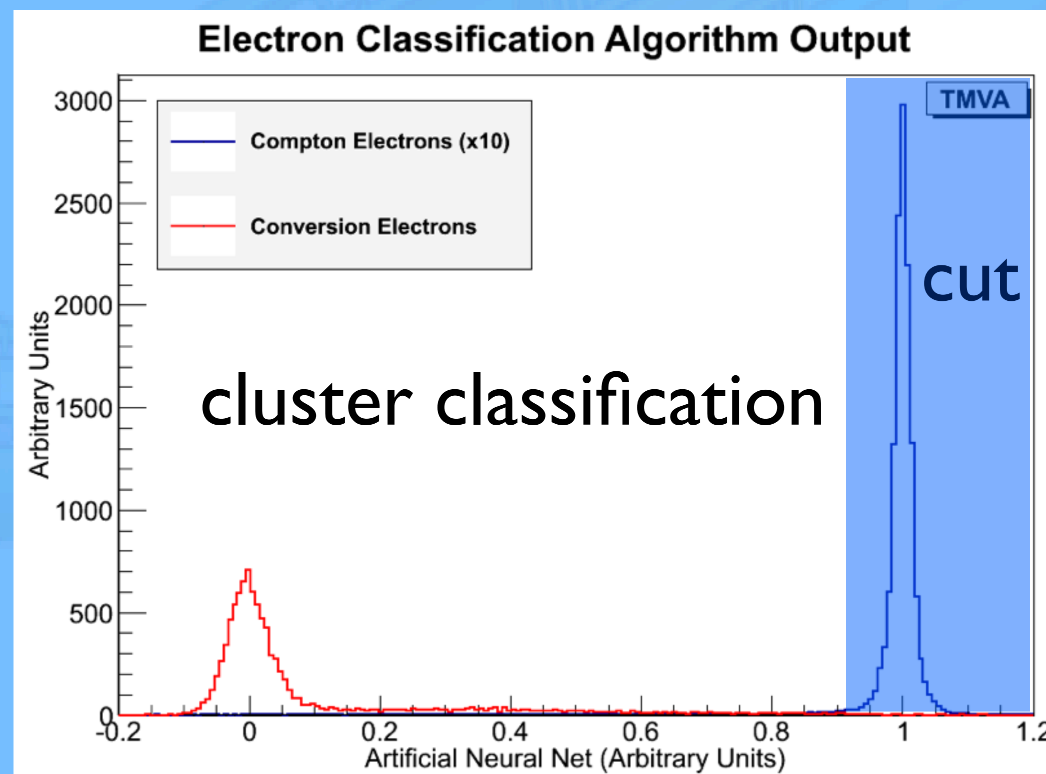




Background Hit Removal

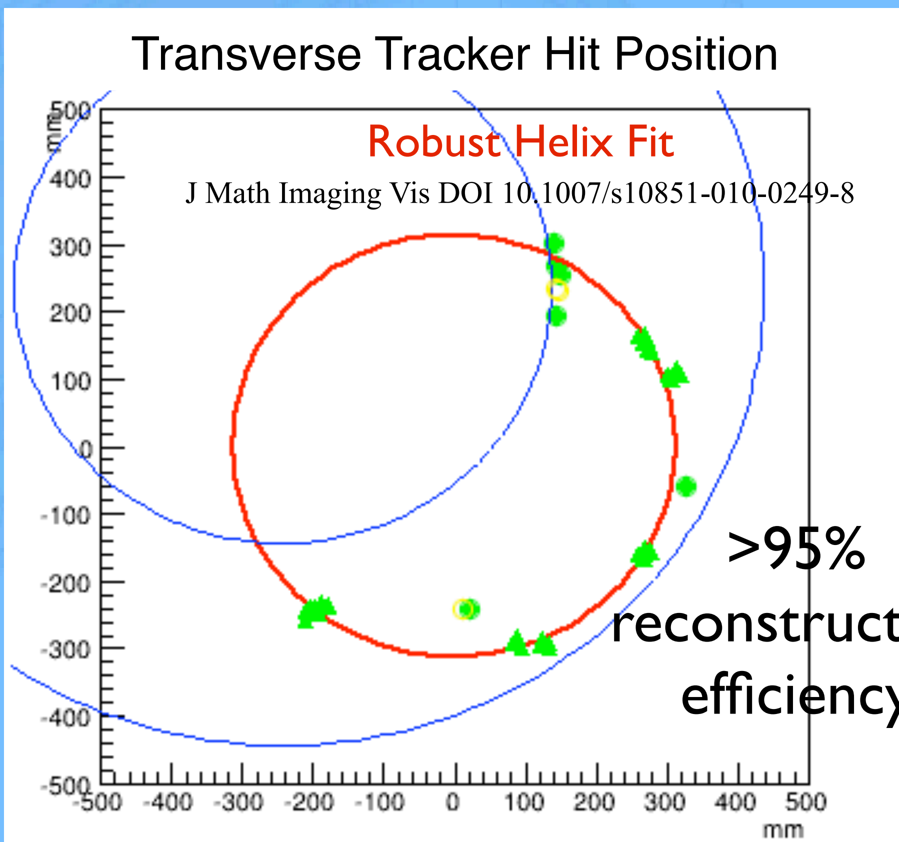
- An Artificial Neural Net separates low-energy electron hits from conversion hits
  - Clustering in space (3-D) and time allows discrimination
  - 90% background hit rejection, 99% conversion hit efficiency

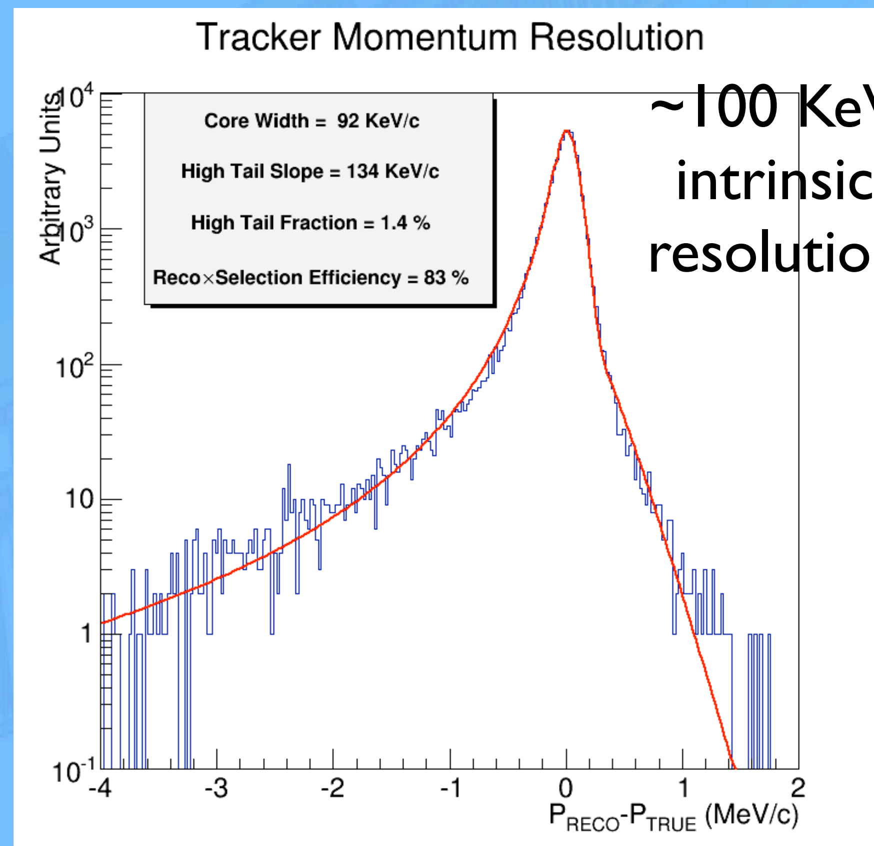




Track Reconstruction

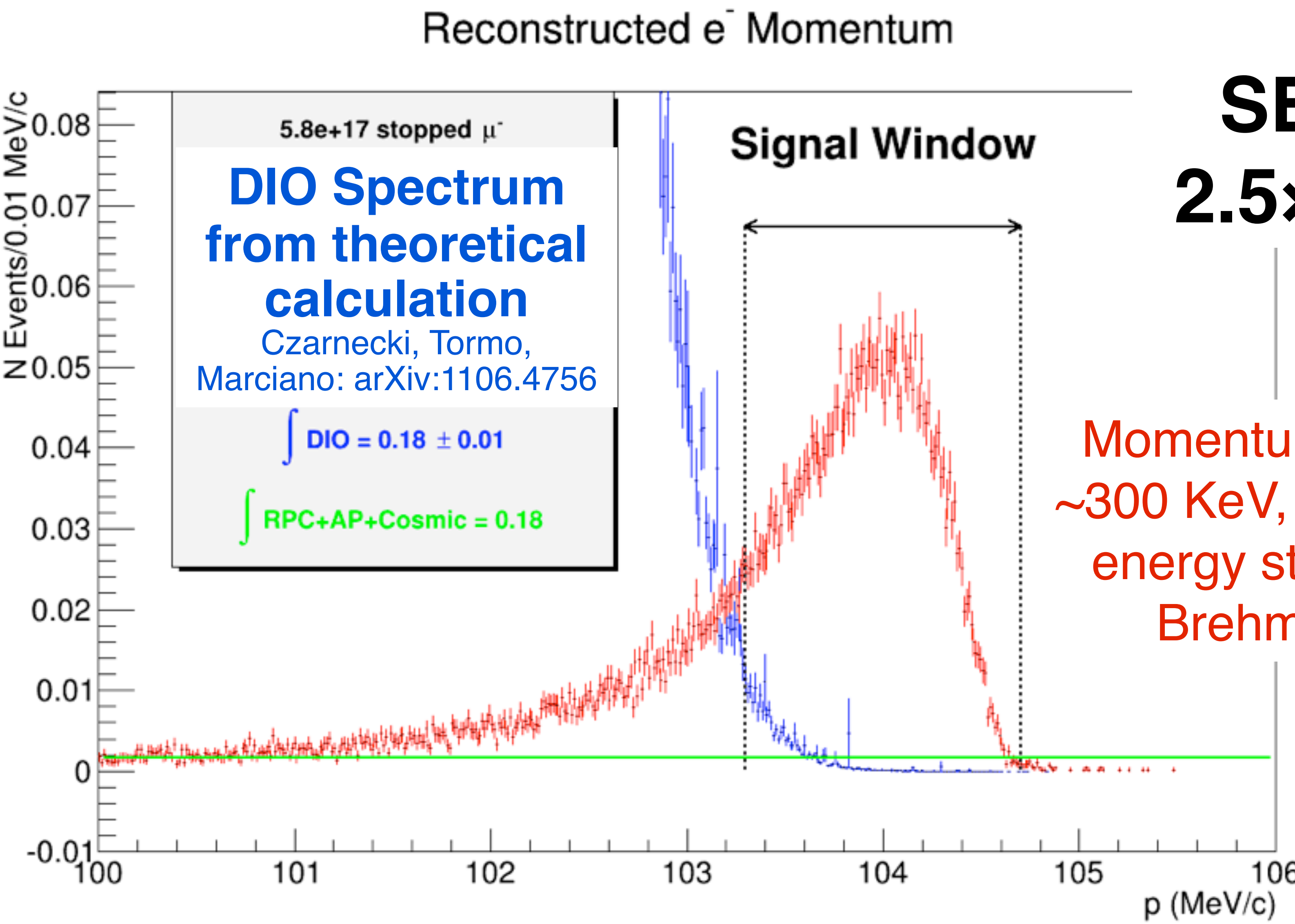
- Single-track events, no a-priori t_0, no primary vertex position
  - ⇒ Pattern recognition requires 3-D space points
- Kalman filter track fit (code ported from BaBar)
  - Outlier filtering using Simulated Annealing





Mu2e Signal Sensitivity

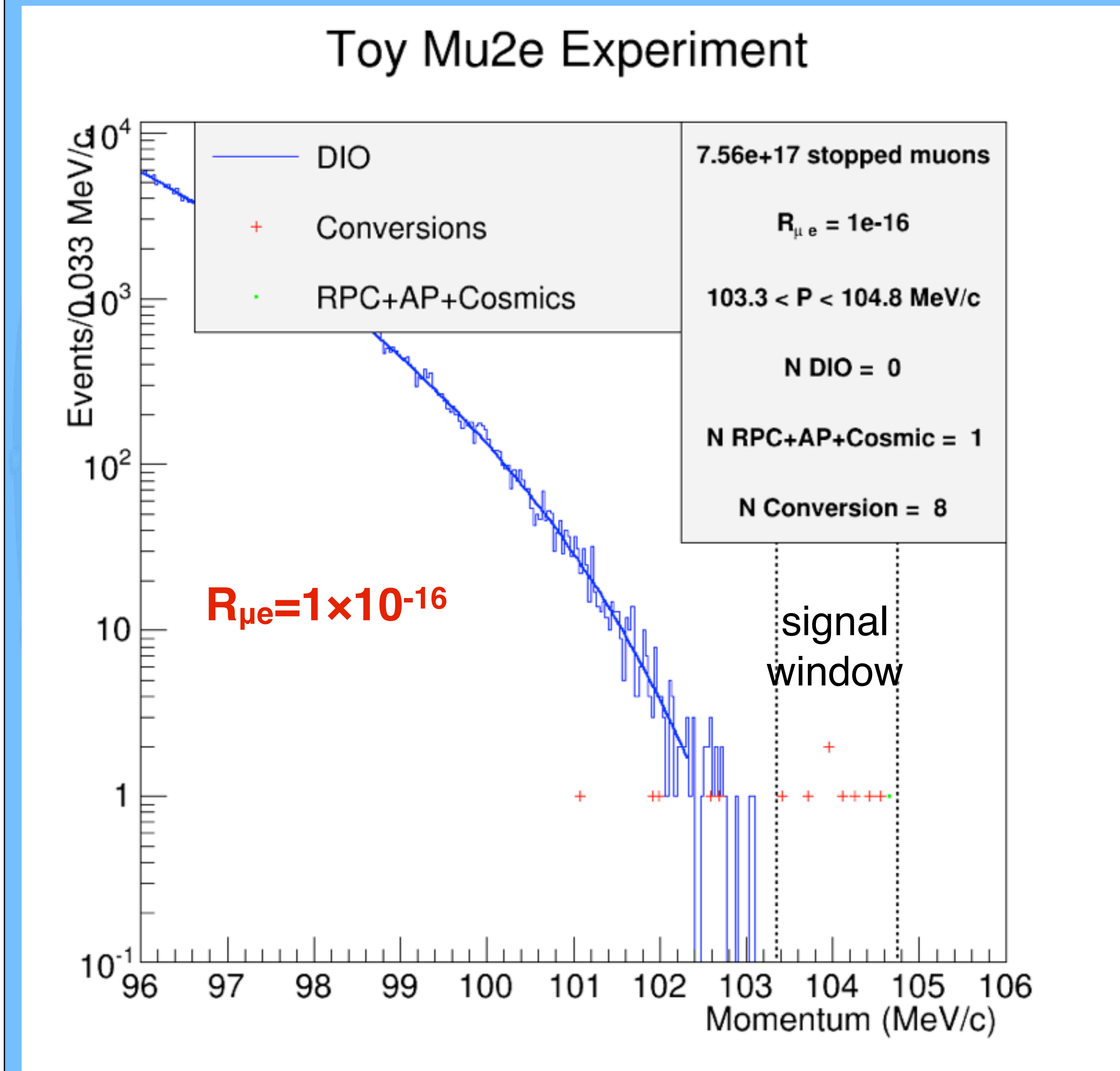
Full G4 detector simulation, background overlay, reconstruction



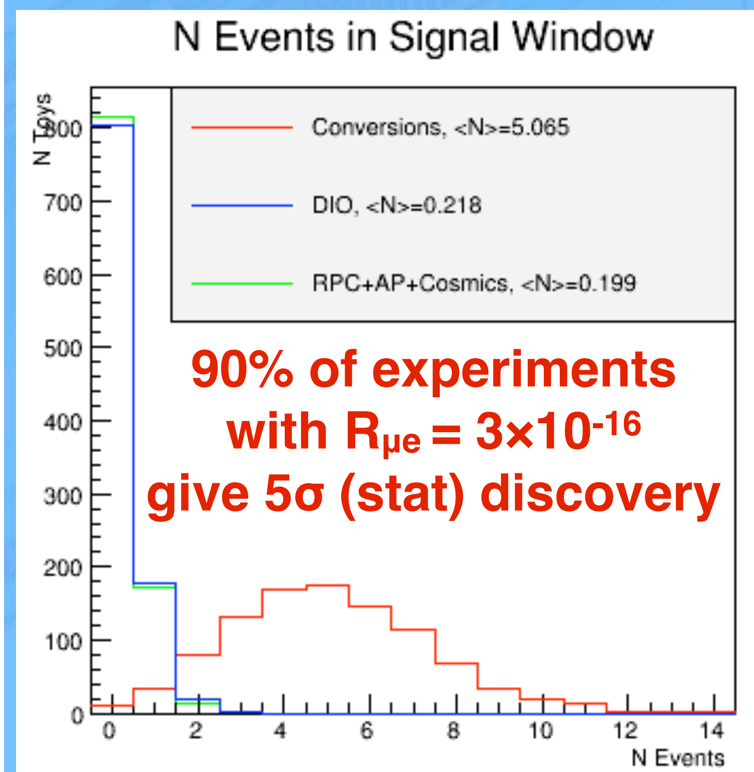
SES = 2.5×10^{-17}

Momentum Resolution ~300 KeV, Dominated by energy straggling and Brehmstrahlung

Toy Experiments



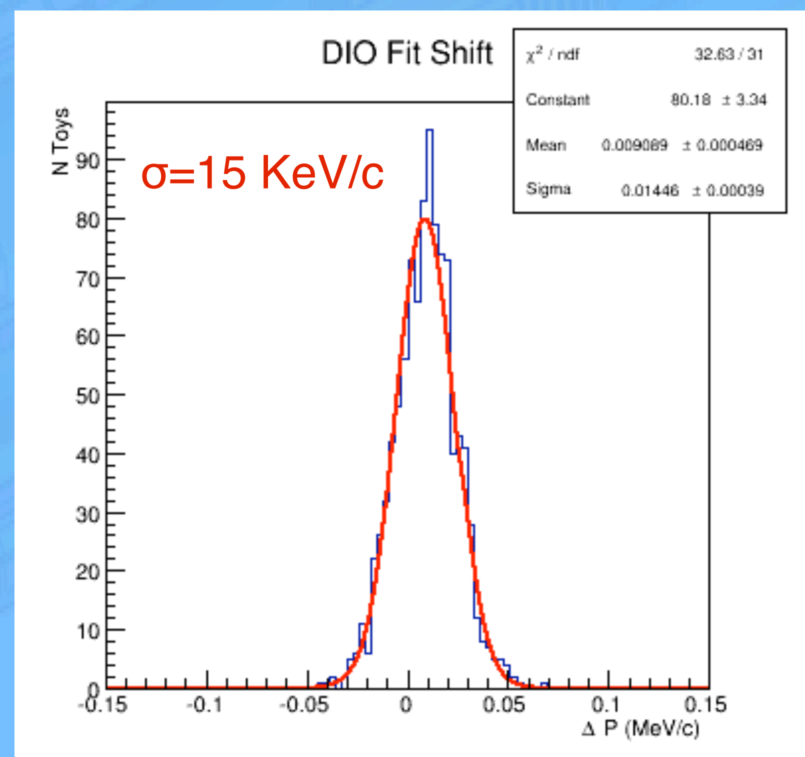
- G4 simulation used to define PDFs
- Simulate 3-year run



1000 toy experiments

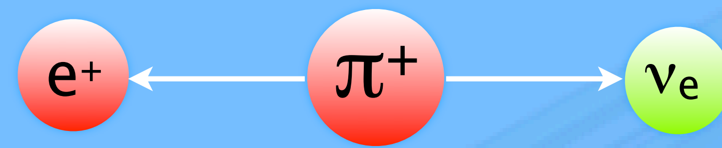
Tracker Momentum Calibration

- Absolute momentum scale separates DIO from conversion e⁻
  - ± 50 KeV/c on |p| results in ± 0.08 DIO in signal window
- 3 Redundant calibration methods:
- 1: Measure spectrometer
  - Wire position X-Ray Scan
    - <50 µm accuracy demonstrated
  - Map B-field
    - 2 Gauss accuracy in 3 directions
  - Net 20 KeV/c accuracy*
- 2: DIO spectrum edge fit
  - PDF from theoretical model
    - ~2% extrapolation accuracy
  - Resolution from cosmic muons
  - 15 KeV/c statistical error

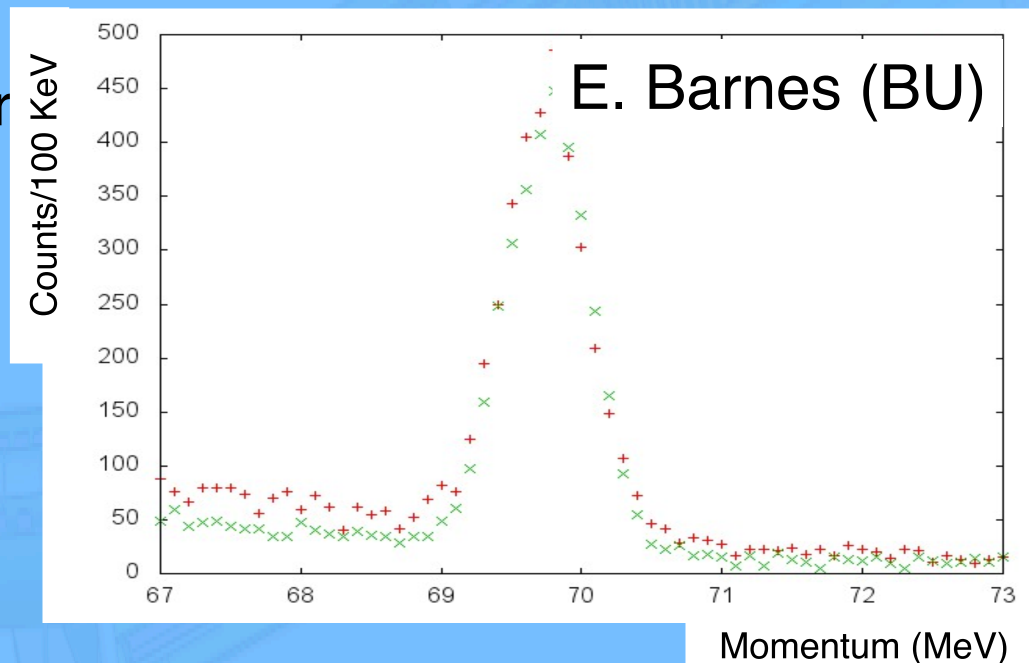


Method 3: $\pi^+ \rightarrow e^+ \nu_e$

- Stopped π^+ produce a mono-energetic electron
  - line source calibration
- Requires a special detector configuration
  - Reversed selection collimator
  - Reduced (70%) magnetic field
  - Reduced beam intensity
  - Earlier (< 300 nsec) event selection
- Preliminary studies show <100 KeV accuracy possible
  - ~1 day running time



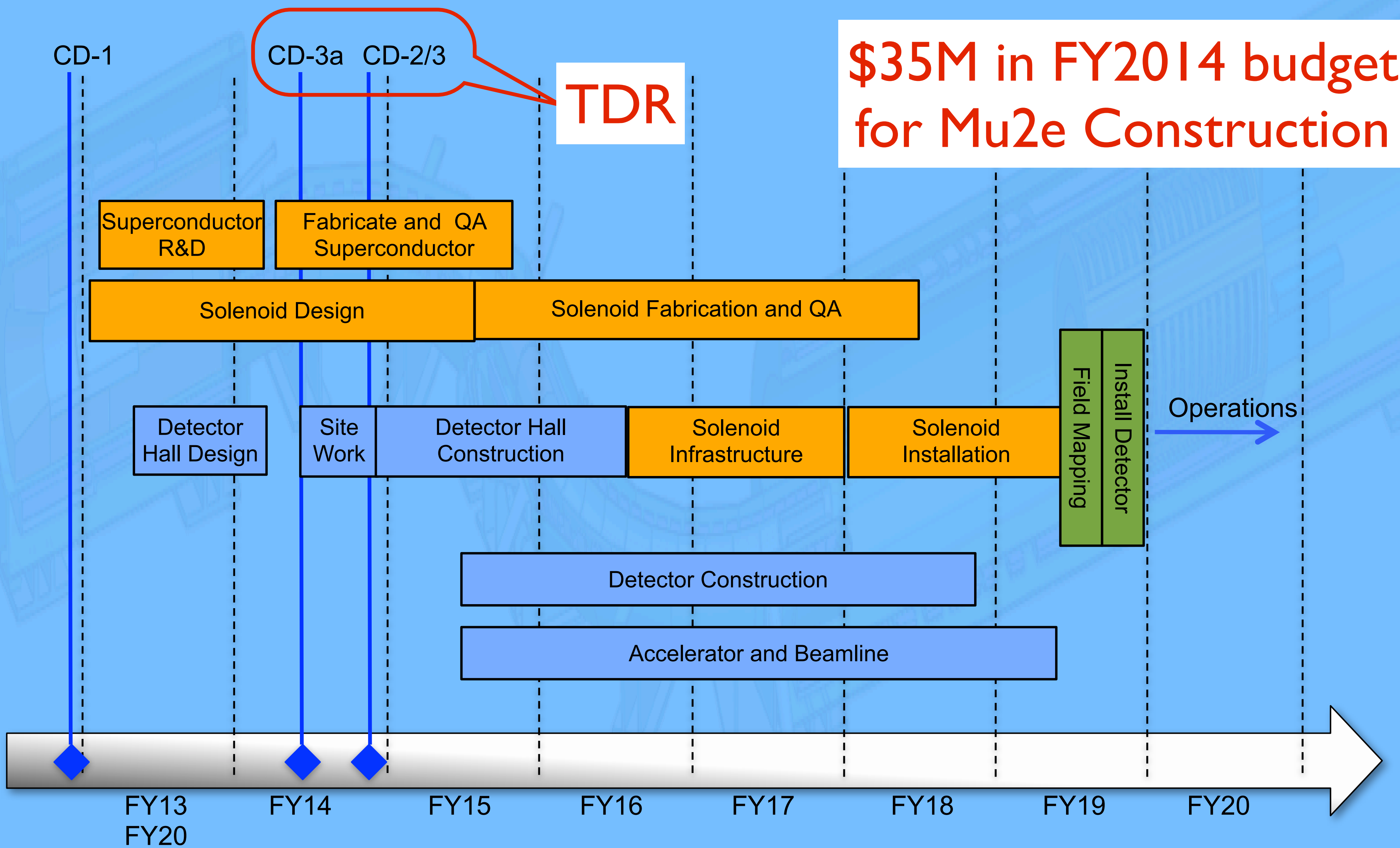
Reconstructed π^+ Momentum



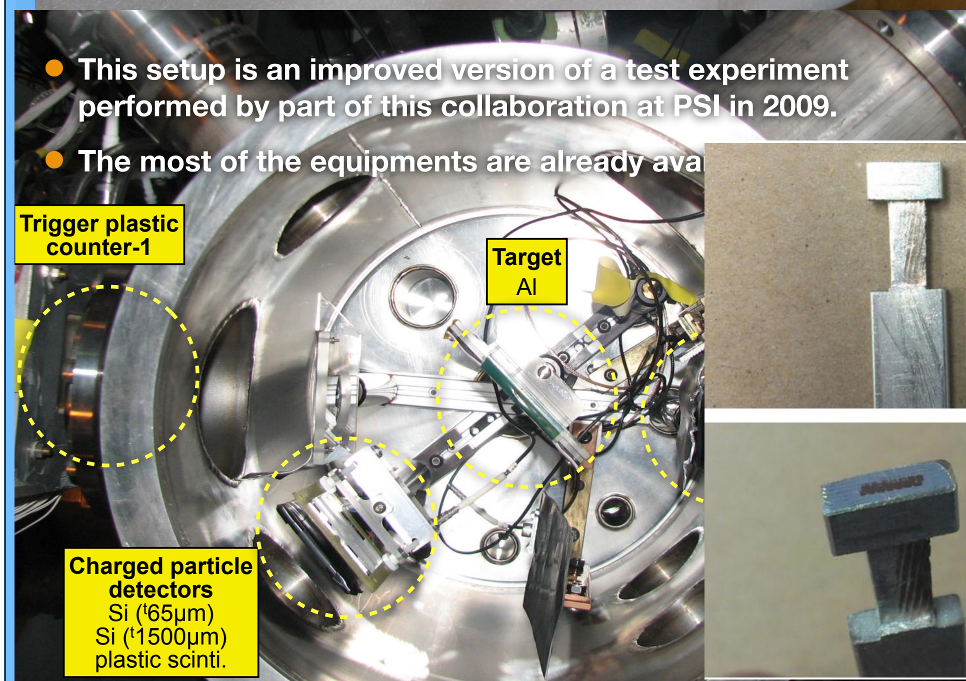
Mu2e Status and Prospects

Mu2e Project Status

- Critical path: Solenoid design, construction, commissioning

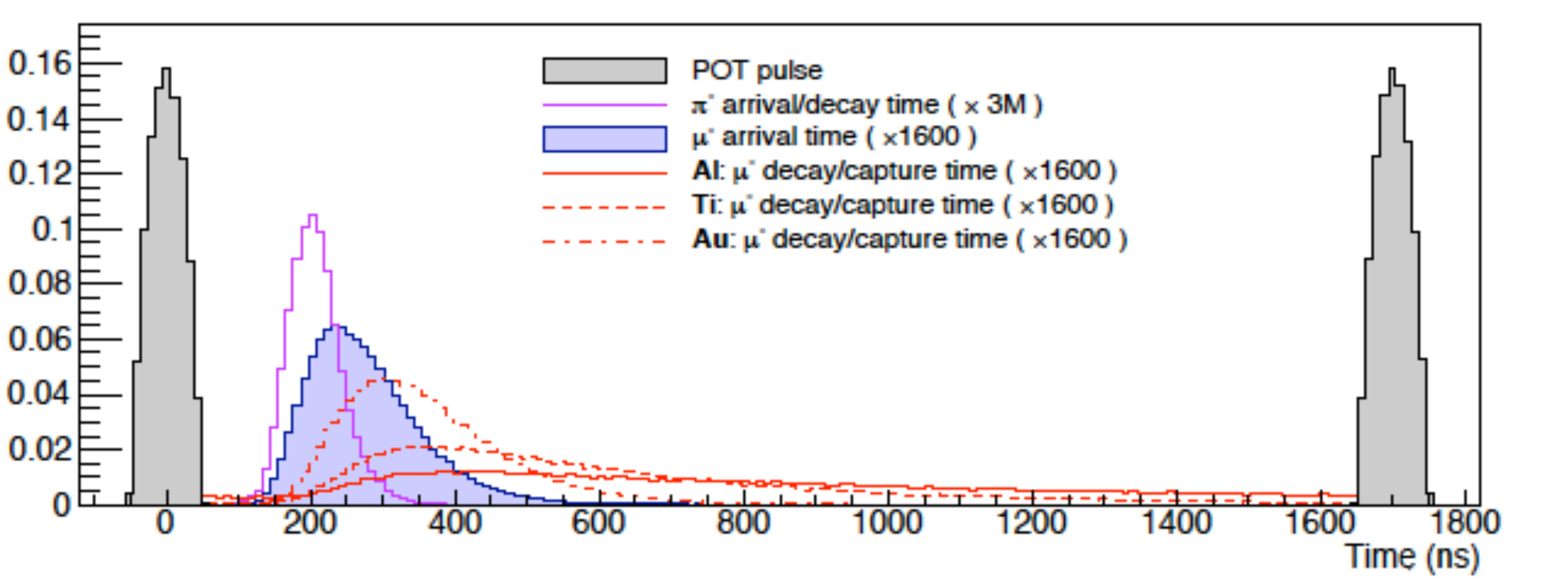


Lots of Activity Going On!



Mu2e Snowmass Studies

- Assumes a 'project-X' type linear proton source
  - 1-3 GeV proton primary
  - ~150 KW power (3 × Mu2e instantaneous rate)
  - 100 ns (Gaussian) time spread
- SES ~ 3×10^{-18} (×10 improvement) possible with modest experiment upgrades
- Follow-on studies to Mu2e: alternate target materials possible



arXiv:1307.1168

Conclusions

- Flavor is a poorly understood aspect of the Standard Model
  - Fundamental questions remain unanswered after nearly 80 years of study
  - Recent discoveries and hints show it is still relevant
- Muon → electron conversion (CLFV) is a powerful probe of New Physics
  - Sensitive to wide range of BSM models
  - A complimentary probe of high mass scale processes
- The Mu2e experiment will provide a 10^4 increase in sensitivity to muonic CLFV
  - On track for physics in 2020

Backup

Other CLFV Processes

- The most sensitive CLFV probes use muons

Process	Current Limit	Next Generation exp
$\tau \to \mu\eta$	BR < 6.5 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \to \mu\gamma$	BR < 6.8 E-8	
$\tau \to \mu\mu\mu$	BR < 3.2 E-8	
$\tau \to eee$	BR < 3.6 E-8	
$K_L \to e\mu$	BR < 4.7 E-12	NA62
$K^+ \to \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \to e\mu$	BR < 7.8 E-8	Belle II, LHCb
$B^+ \to K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \to e^+\gamma$	BR < 5.7 E-13	10^{-14} (MEG)
$\mu^+ \to e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \to eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

Mu2e Physics Reach

- Mu2e has discovery sensitivity across the board

★★★ = Discovery Sensitivity

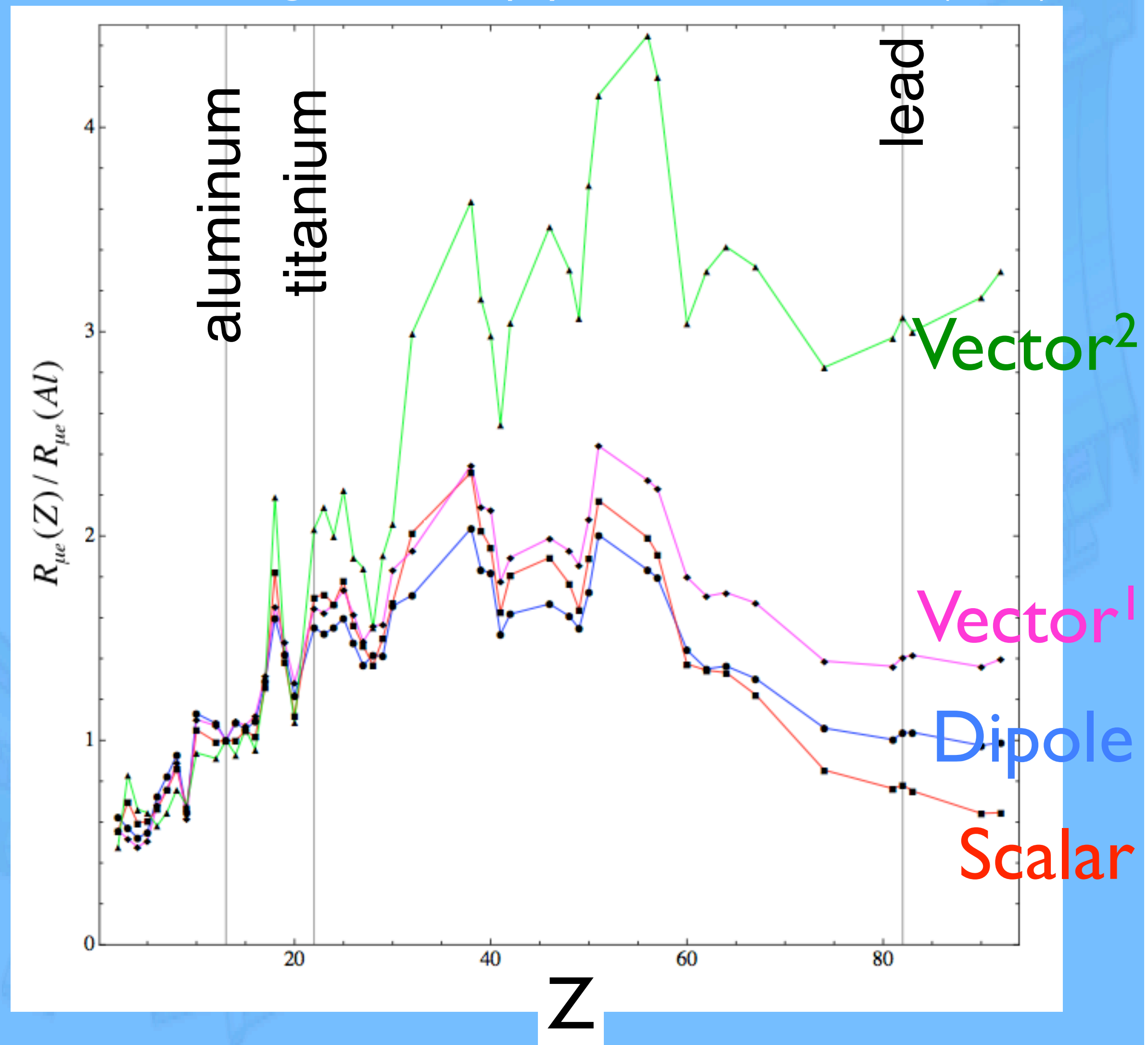
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Atomic Dependence

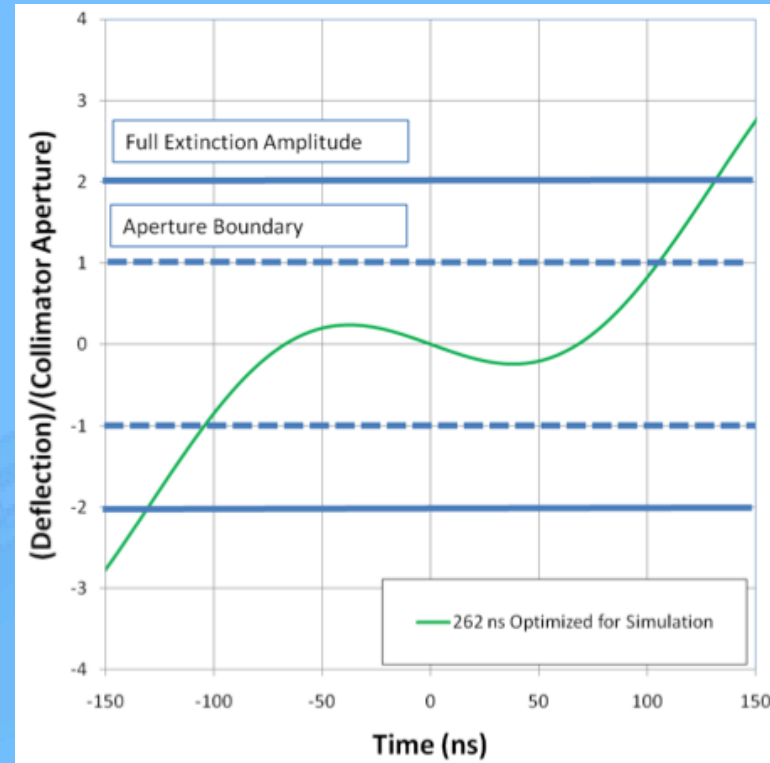
- Larger atomic Z→ smaller bohr radius→ larger capture Γ → greater contact term sensitivity
  - = shorter μ lifetime
- Heavier nuclei→ more neutrons→ larger d/u fraction
- Net result: $R_{\mu e}^{Z}$ is model sensitive

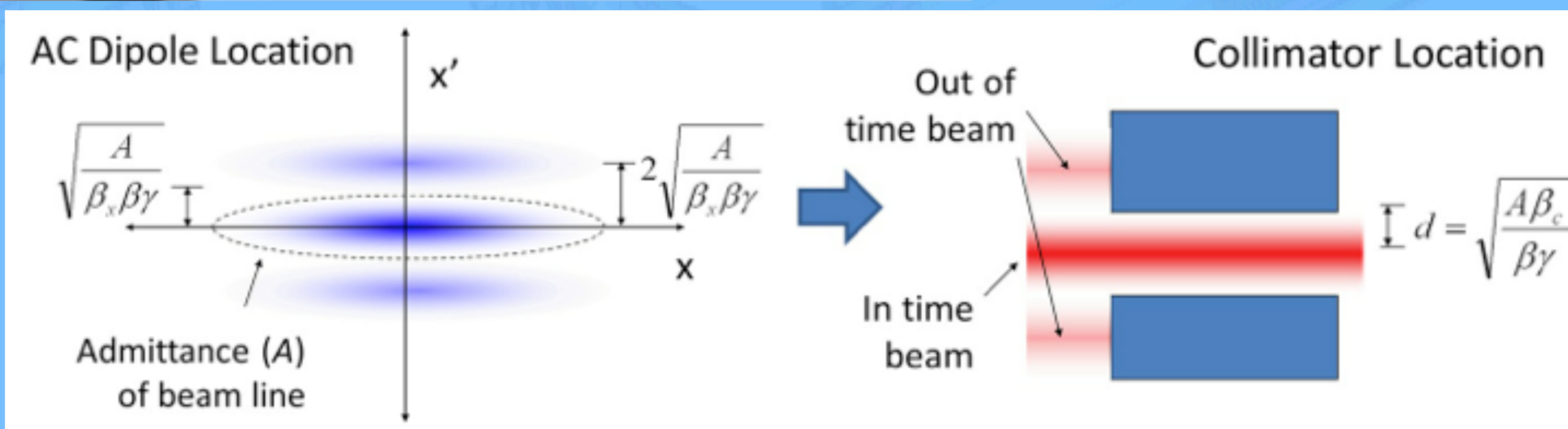
V. Cirigliano et al., phys. Rev. **D80** 013002 (2009)



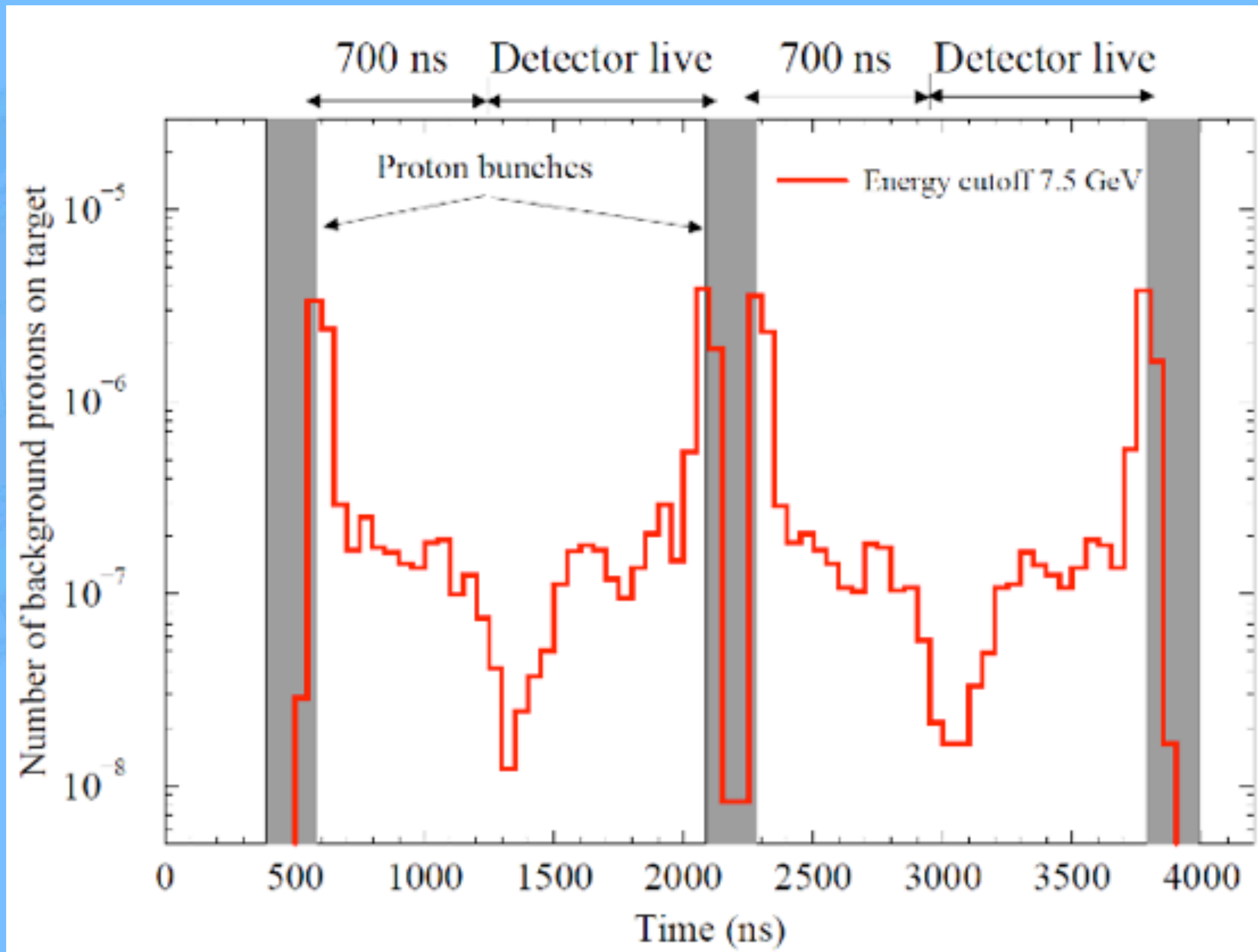
Active Extinction

- AC dipole driven with 300 KHz + 3.8 MHz
  - Out-of-time protons < 10^{-10}



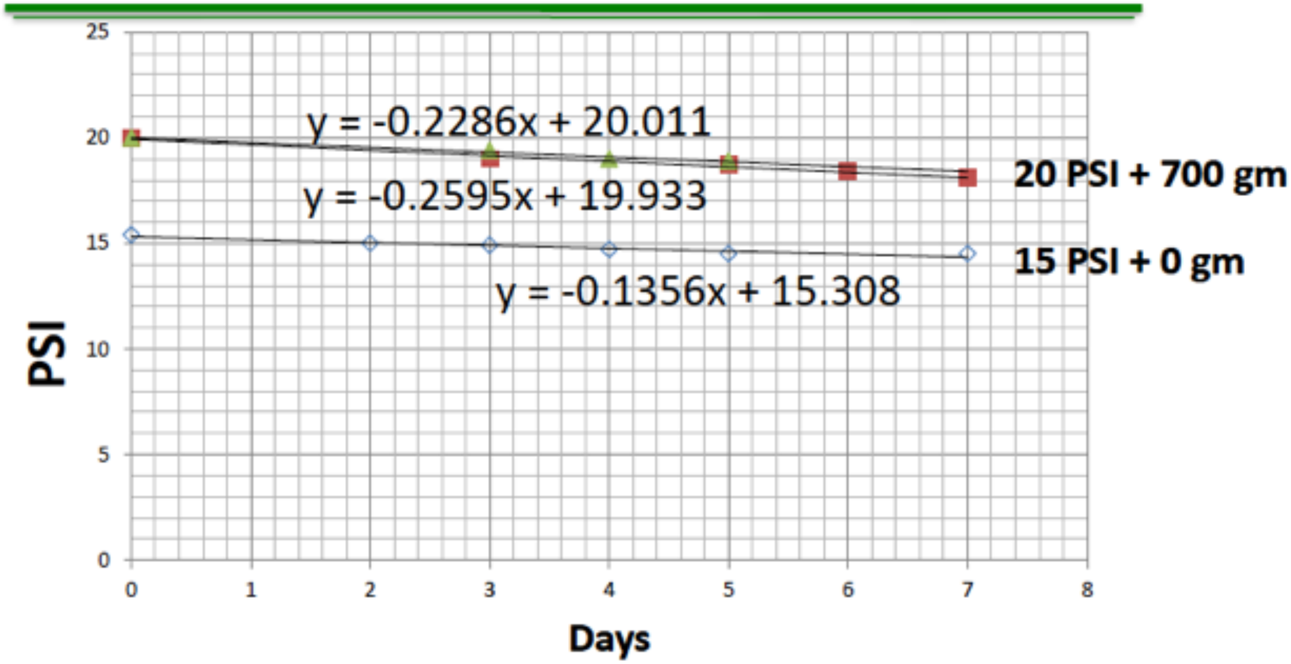


Out-Of-Time Protons



Straw Leak Test

Leak rate

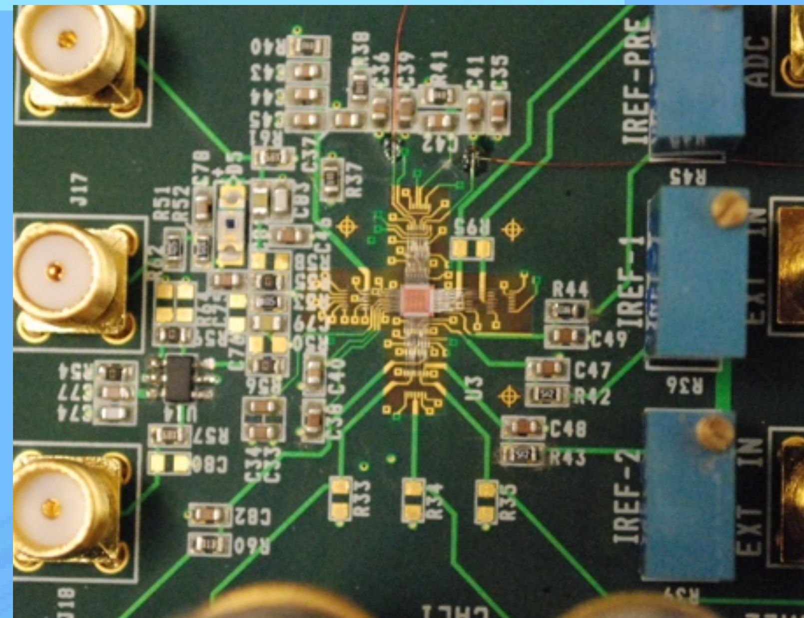


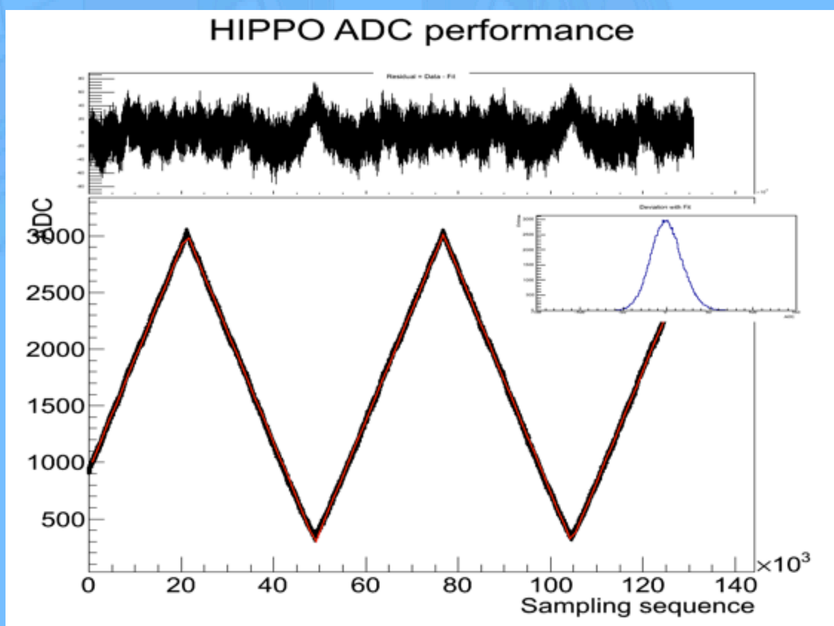
- Pressure drop = 0.244 psi / day @ ~20psi (no env. corr.)
- Leak rate = 0.00847 mBar/Bar/min
- Previous test @ 15 psi + 0 gm weight ~0.00813/mBar/Bar/min
- 2 weeks under 20 psi + 700gm and no problem

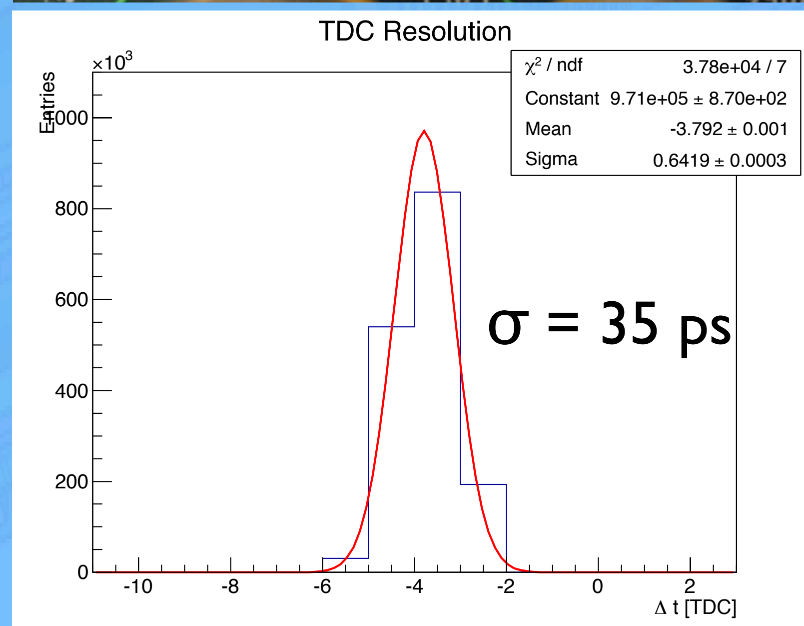
9/15/11 Chiho Wang & Seog Oh 3

Tracker Electronics

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

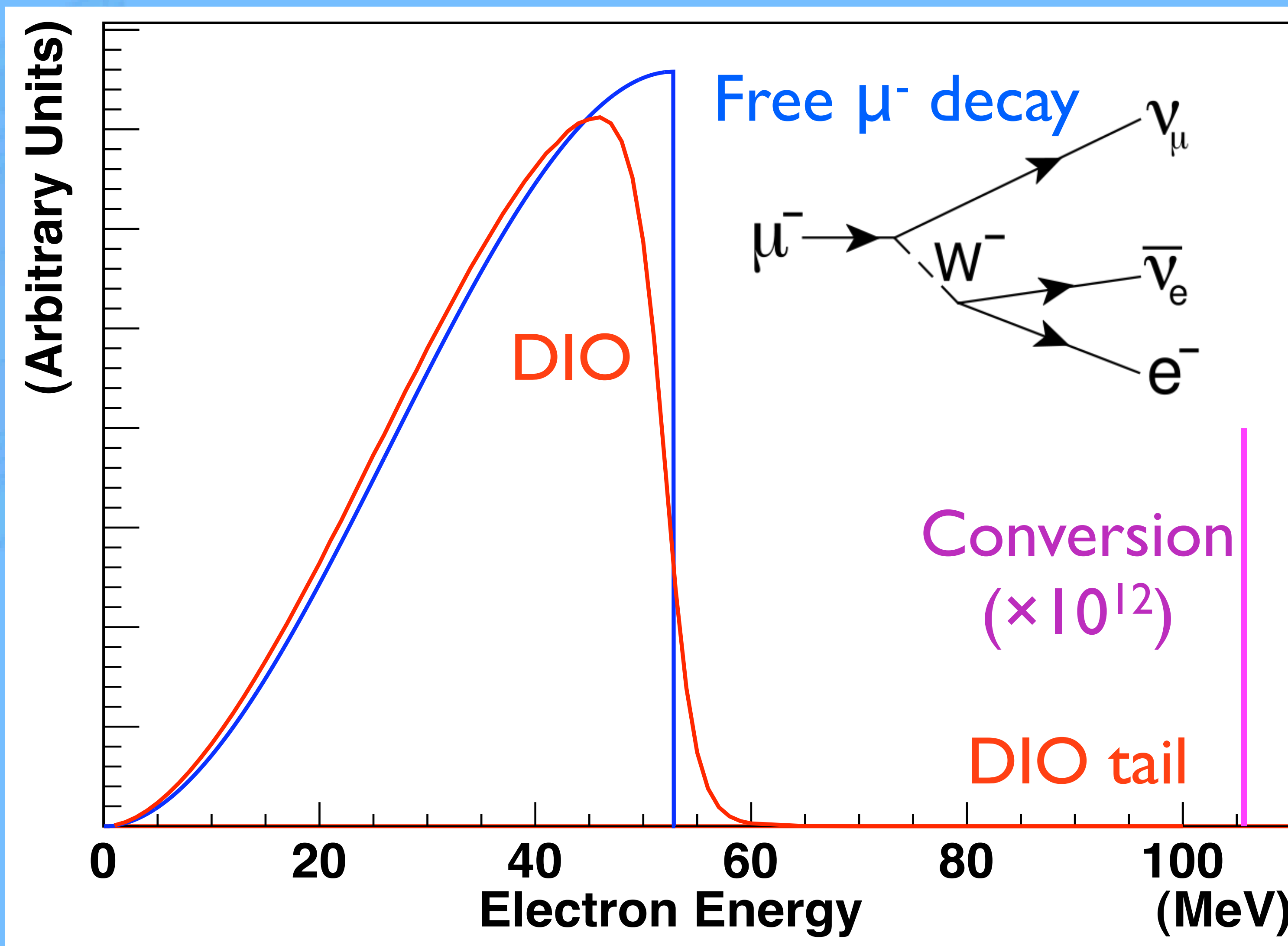






DIO Background

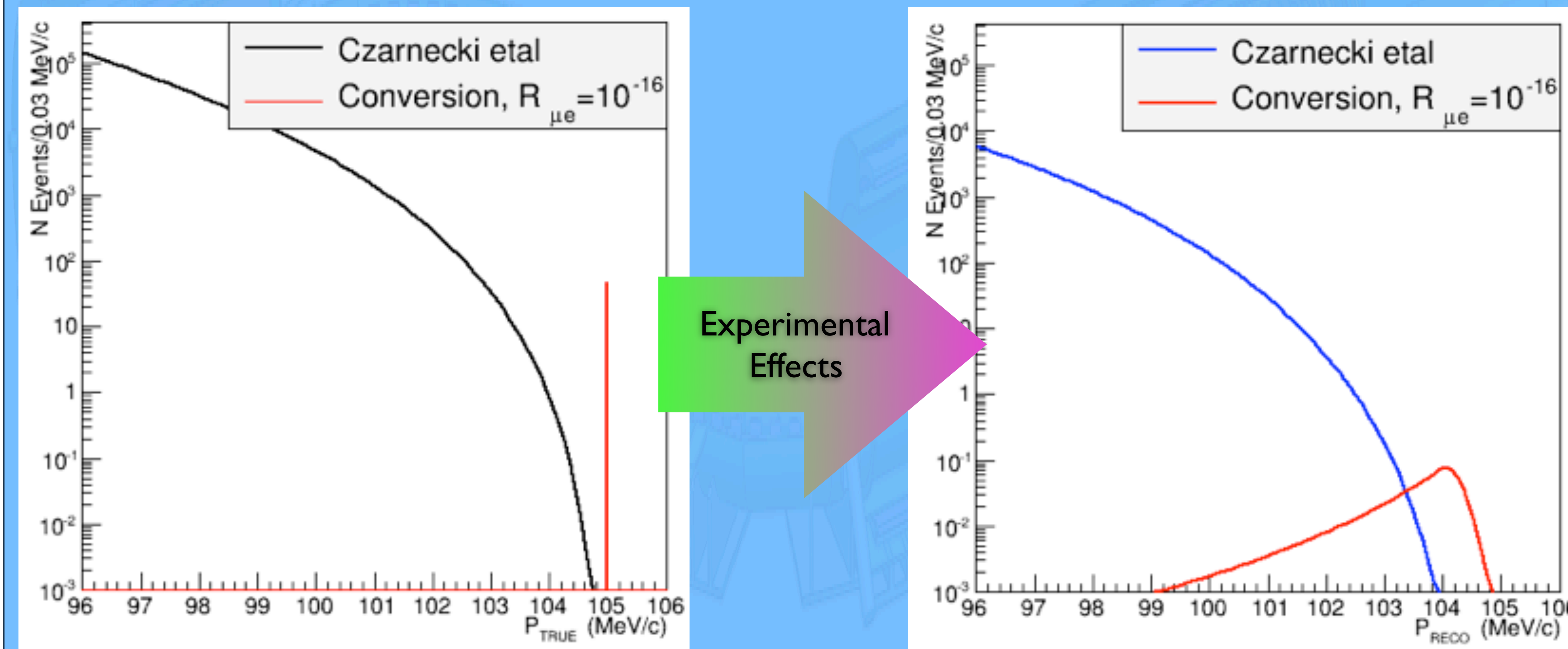
DIO are an irreducible background to conversion



DIO Endpoint

- Tail of DIO falls as $(E_{conv} - E_e)^5$
- Separation of ~1 MeV @ $R_{\mu e}=10^{-16}$

Czarnecki, Tormo, Marciano: arXiv:1106.4756

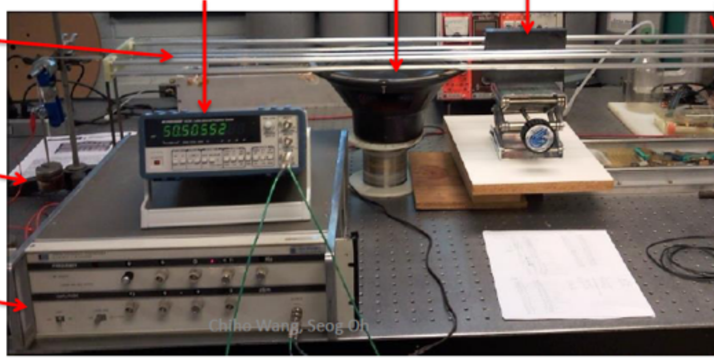


Phys.Rev. D84 (2011) 013006

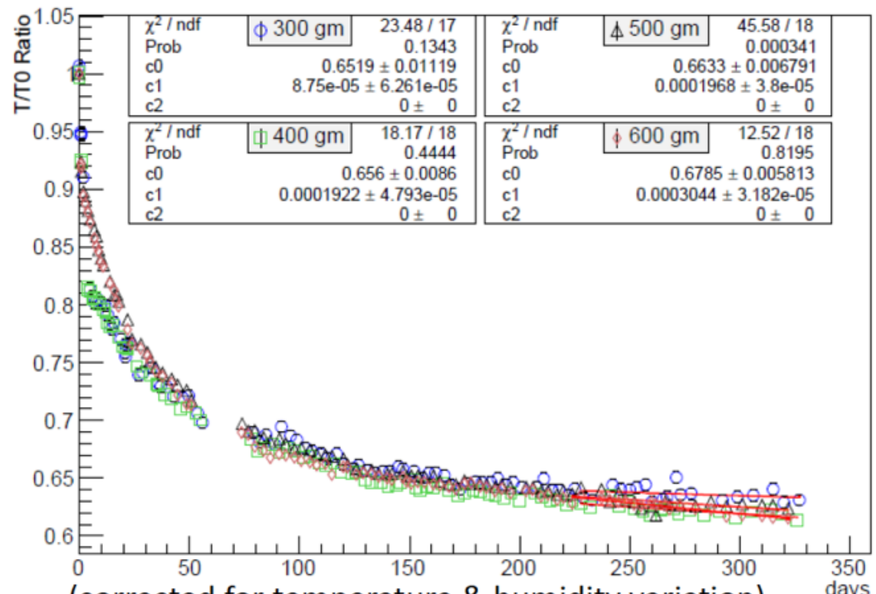
Straw Creep

"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.



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



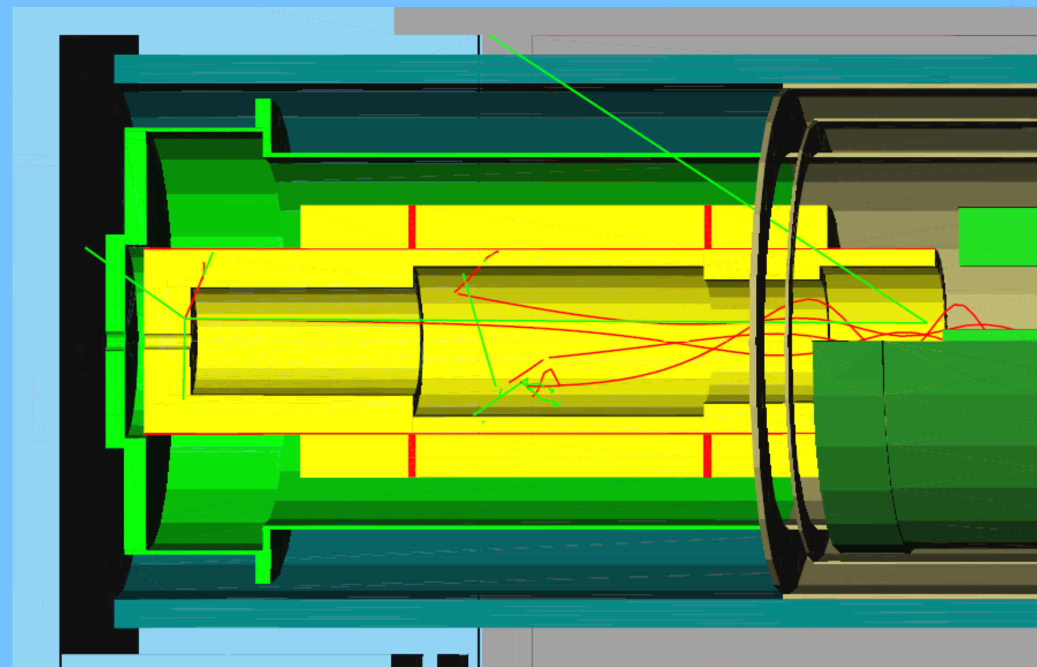
(corrected for temperature & humidity variation)

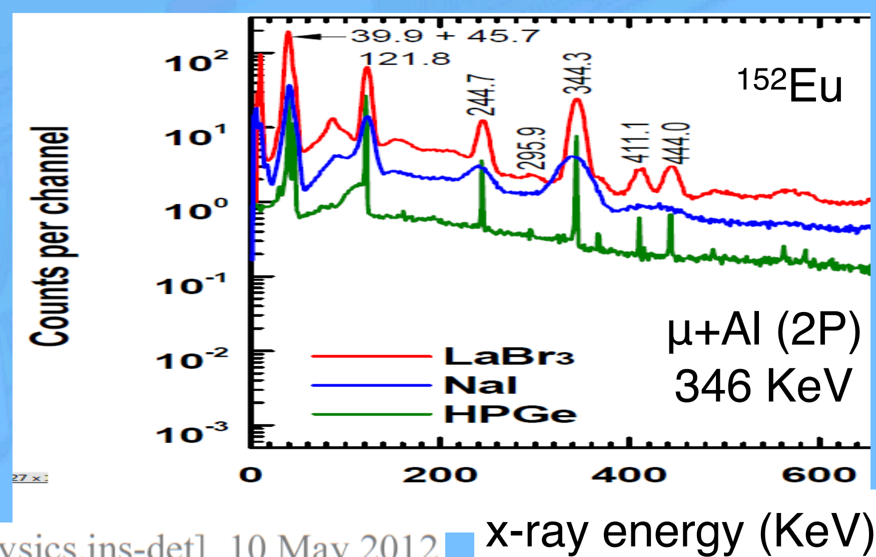
3/28/13 Chiho Wang, Seog Oh 14

- Straws will maintain adequate tension for at least 7 years

Muon Beamstop

- Absorbs muons with minimal backsplash
  - Poly + lead liners
- Pinhole camera detects μ^- atomic capture x-rays
  - Measures stopping rate
  - Requires high background tolerance and good energy resolution
  - Possible detectors:
    - HPGe
    - Lanthanum Bromide

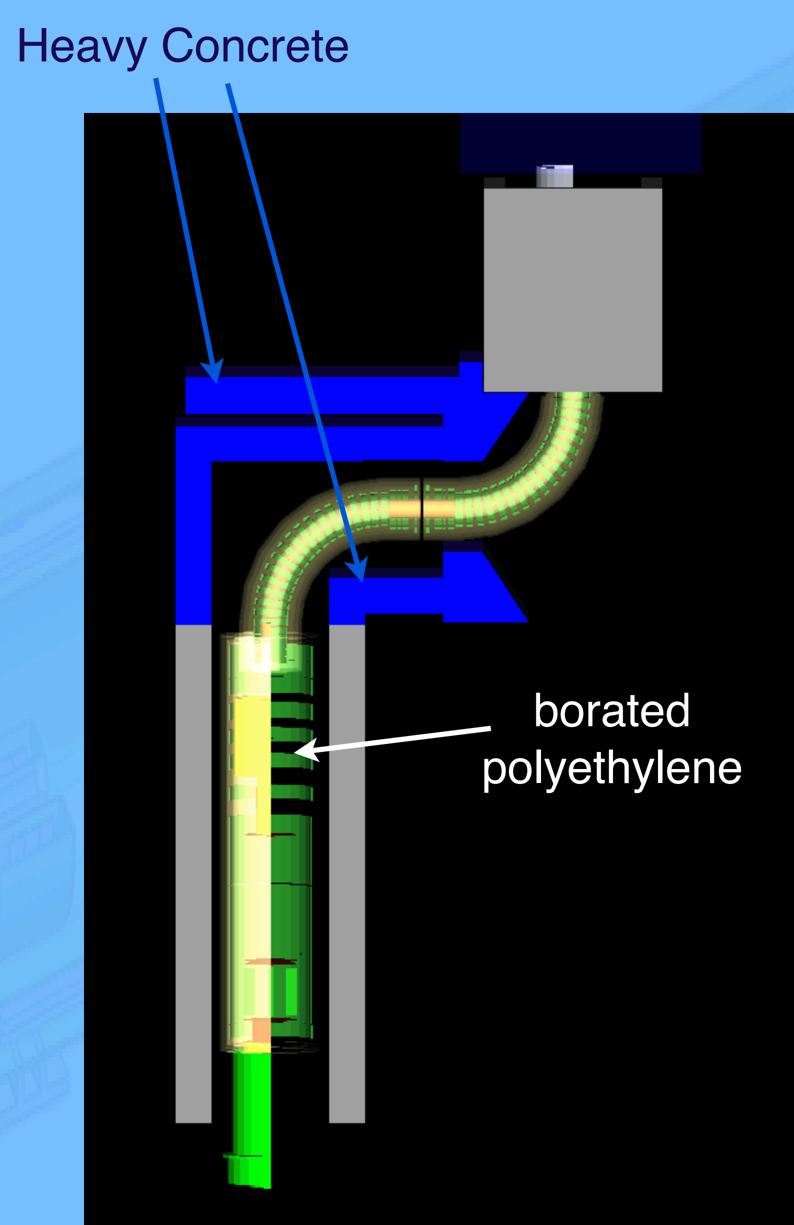




arXiv:1202.6495v2 [physics.ins-det] 10 May 2012

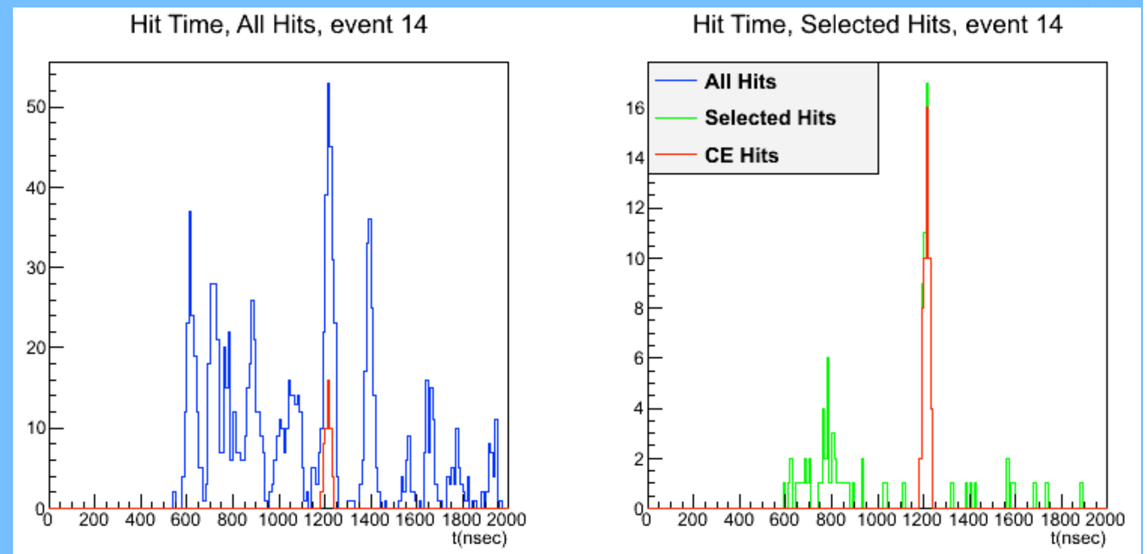
Neutron Background Mitigation

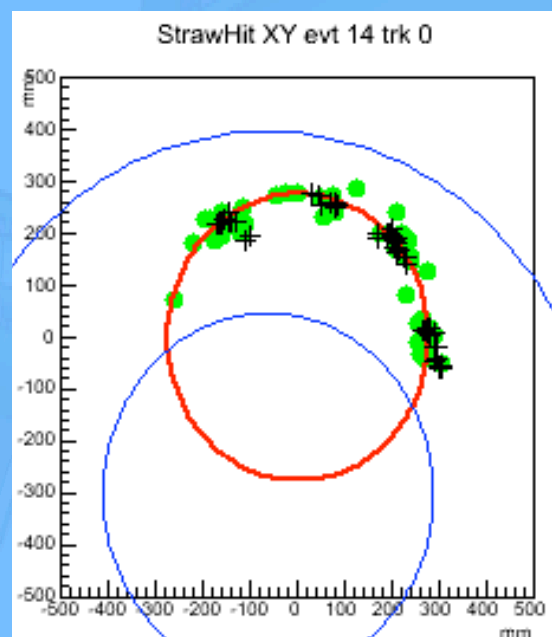
- Neutrons come from several sources in Mu2e
  - Primary target, collimators, μ stopping target, beamstop, ...
- Neutrons affect the detectors
  - Radiation damage to SIPMs
  - Tracker and calorimeter hits
- Fake coincidences in CRV
  - Reduces conversion efficiency
- Neutron mitigation:
  - Borated poly in the DS cryostat
  - Borated concrete + steel outside

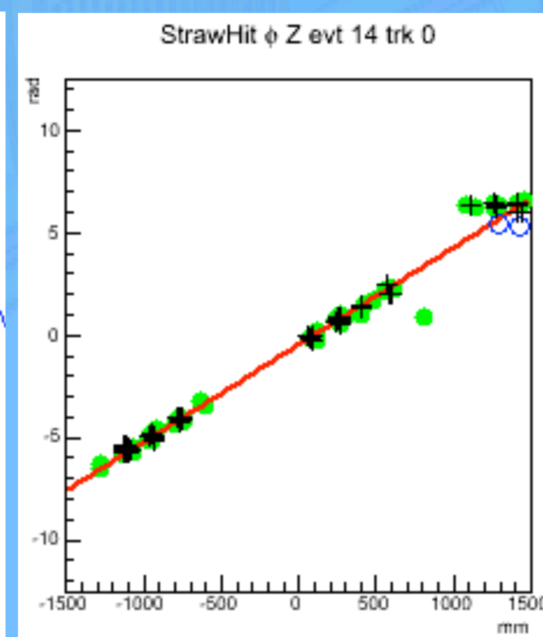


Track Finding and Fitting

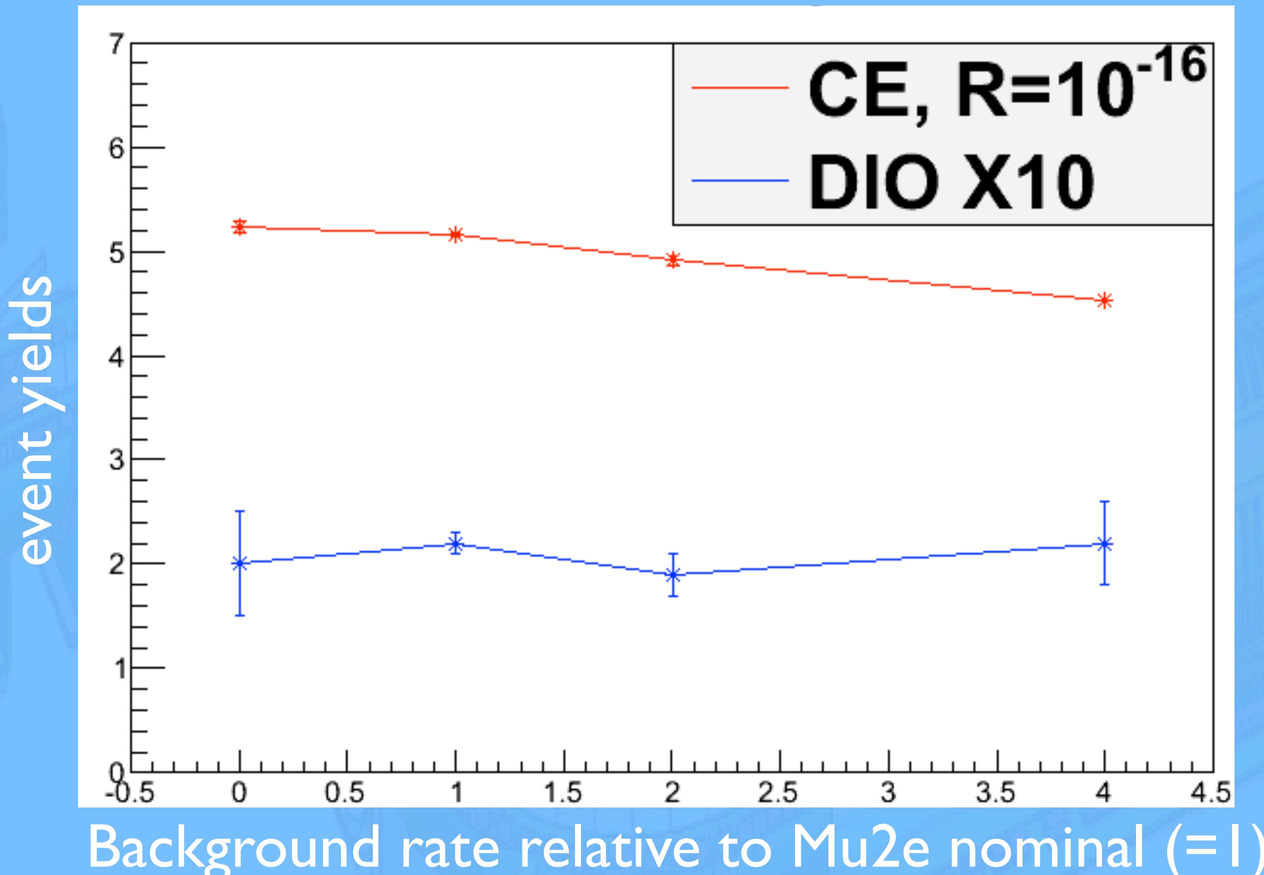
- Remove hits from low-energy electrons
- Remove hits with large energy deposits (protons)
- Select hits which peak in time
- Fit in sequence:
  - Robust Helix
  - Least-squares
  - Kalman Filter







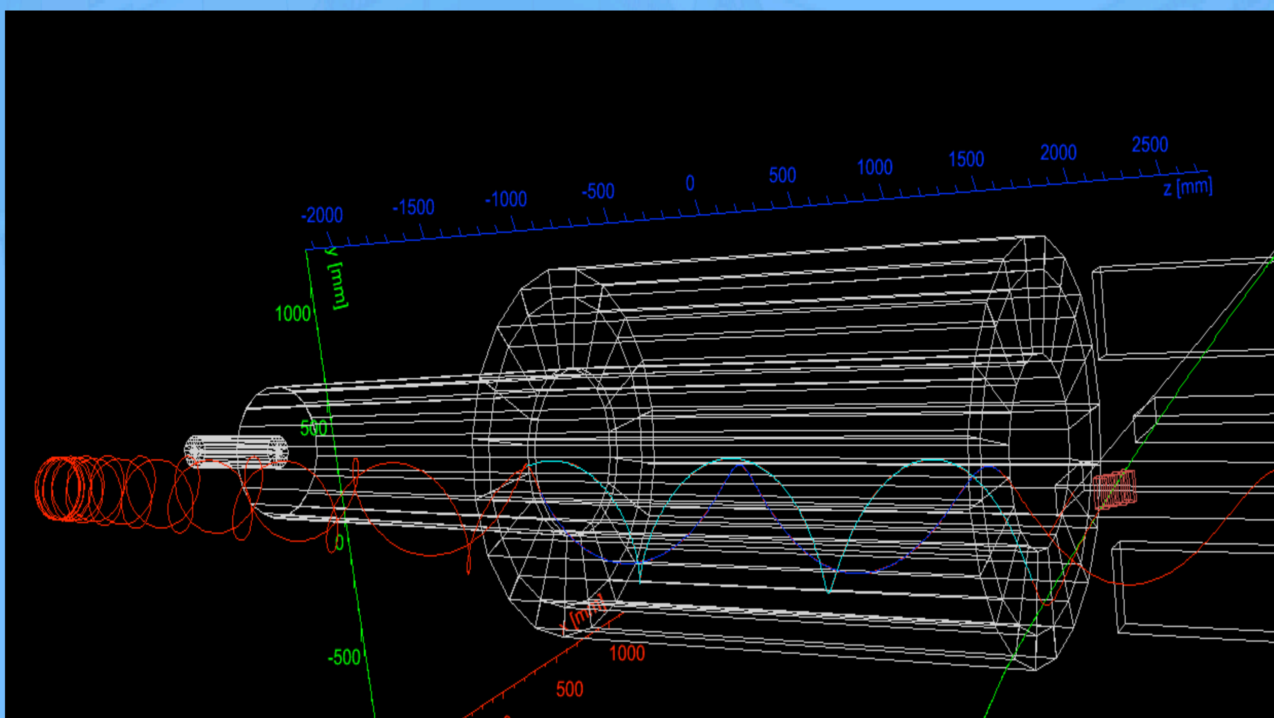
Background Sensitivity

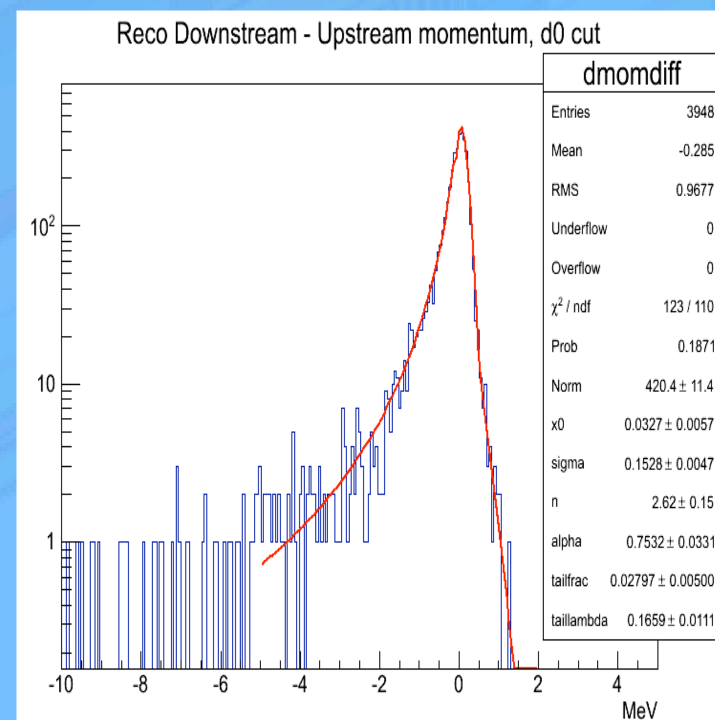


- Momentum resolution unchanged, efficiency reduced by 5% (relative) with 4X nominal background

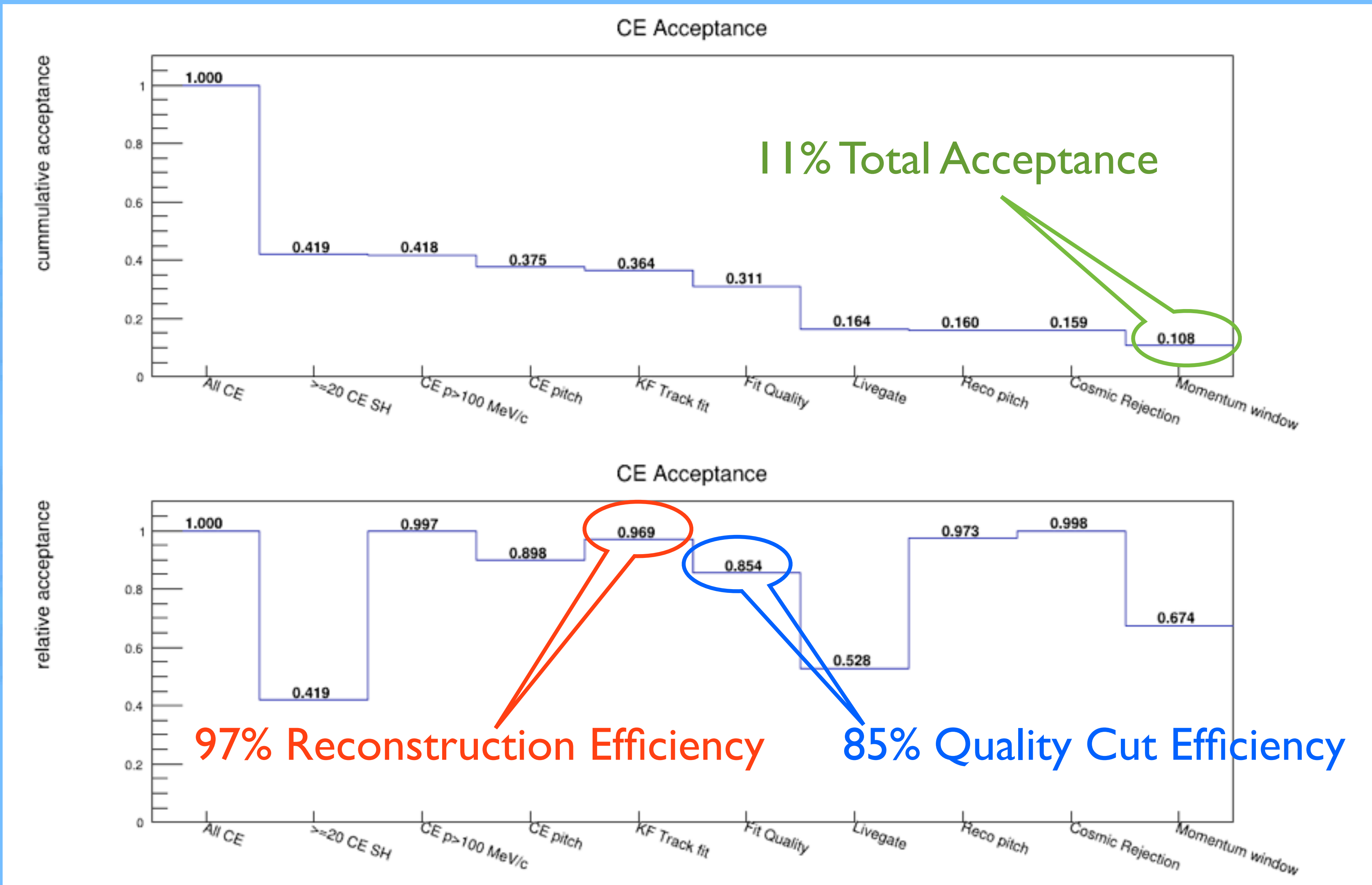
Momentum Resolution from Cosmics

- 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





Reconstruction Efficiency



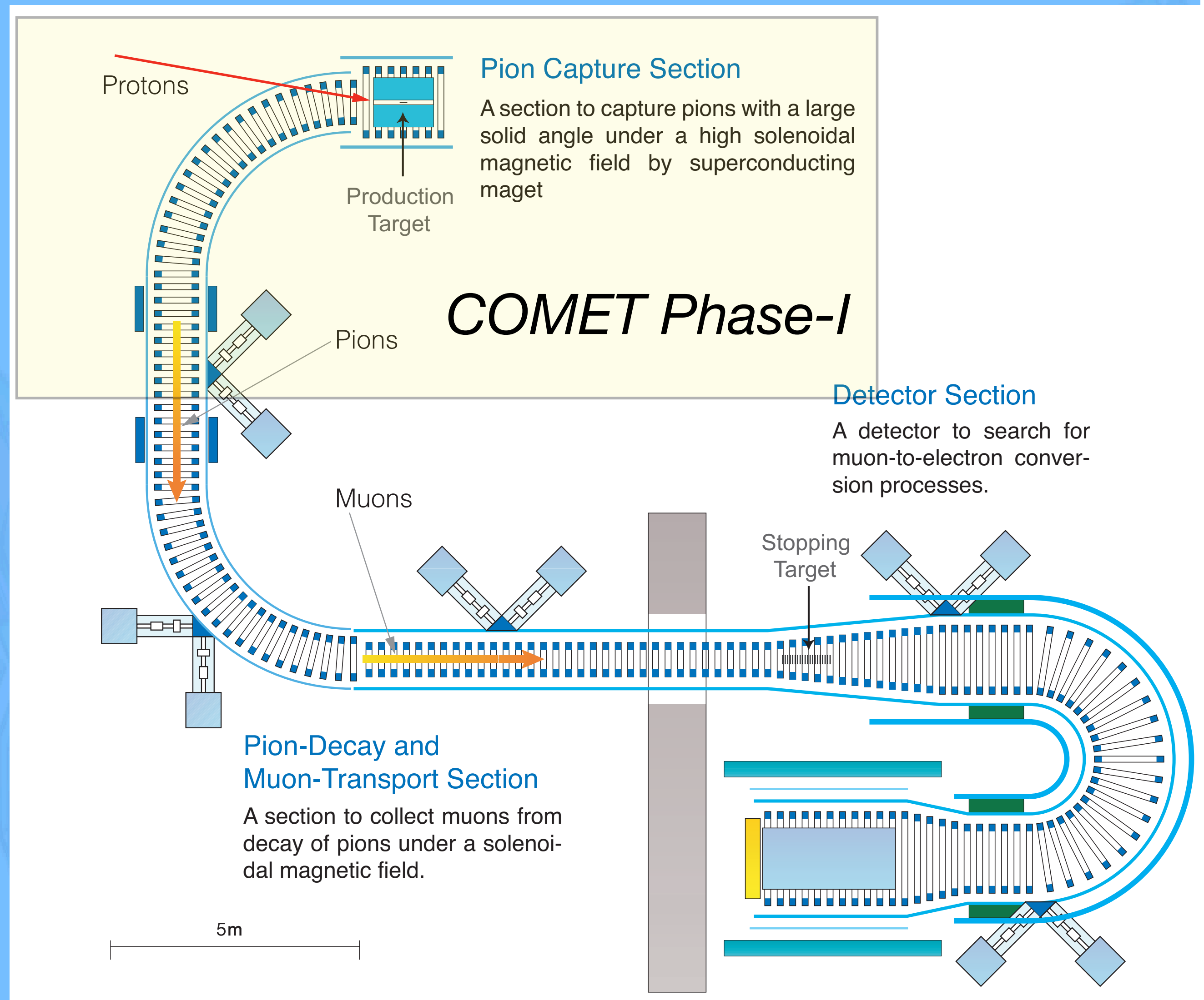
Backgrounds for 3 Year Run

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	0.05 ± 0.02	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 = 2.5×10^{-17}

COMET

- J-PARC experiment, similar to Mu2e
- Phase-1 approved and under construction
- Phase-1 sensitivity: $R_{\mu e} < 3.1\times10^{-15}$



μ Experiments @ FNAL

- g-2 (E821 revisited)
- Mu2e
- MAP
  - MUCOOL
  - MICE
  - MERIT
- Neutrino Factory
- Muon Collider