Searching for Muon to electron conversion: The Mu2e experiment at Fermilab

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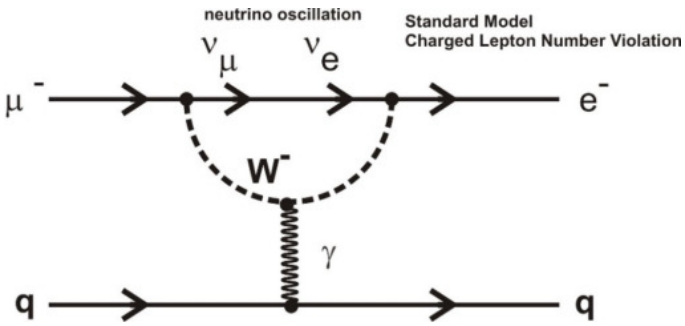
Mu2e: the basics

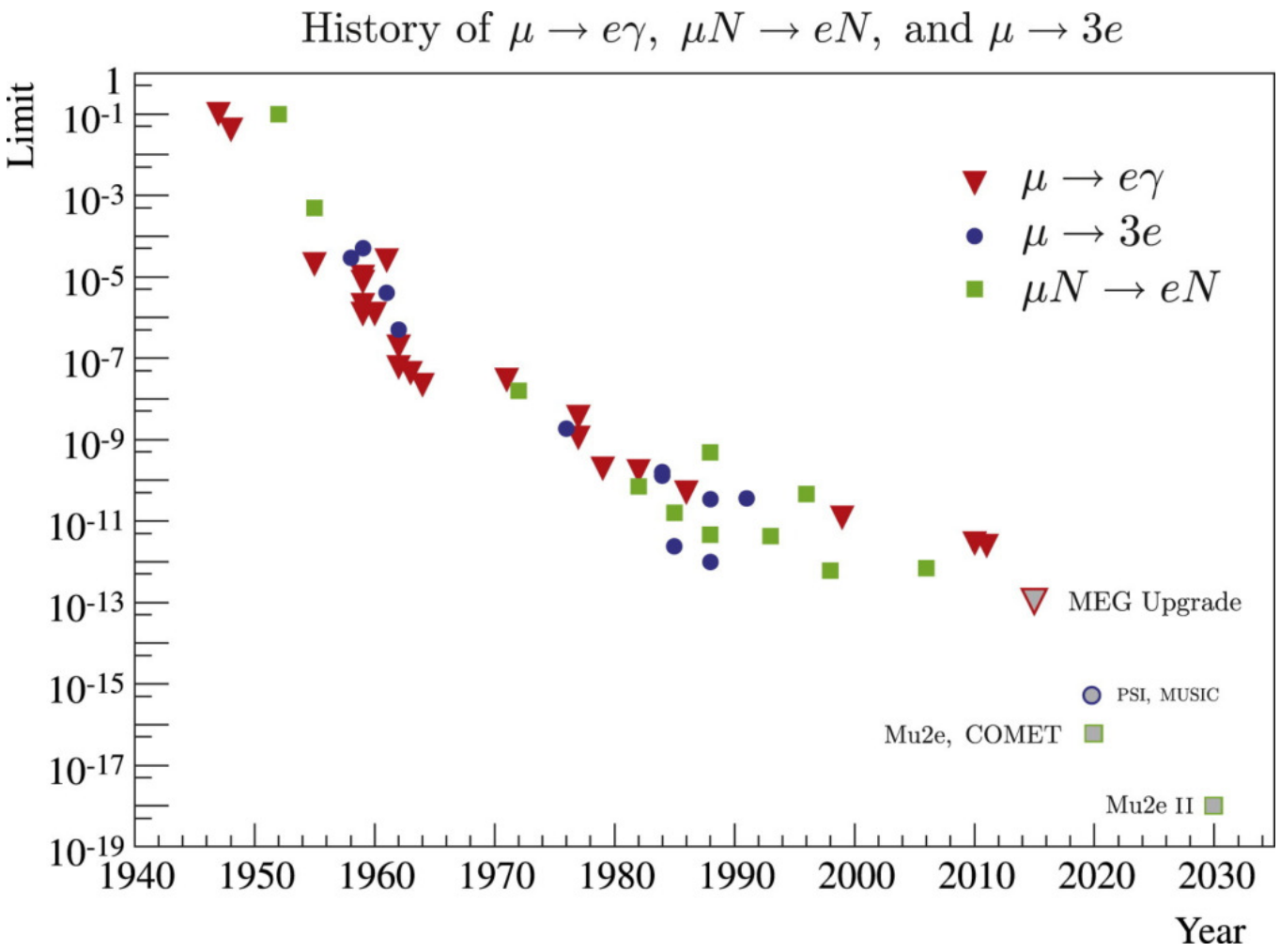
- Mu2e will search for neutrinoless conversion of a muon to an electron in a nuclear environment:

$$\mu^- N \to e^- N$$

- This would violate **charged lepton flavor**, something that has never been seen before
- Any detection of charged lepton flavor violation would be an unambiguous sign of new physics! (SM contribution is $< 10^{-50}$)



History

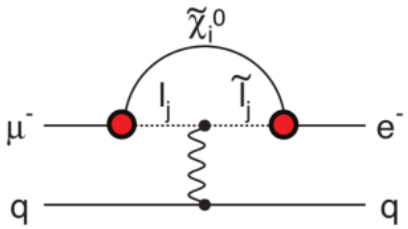


Mu2e goal is a 10^4 improvement!

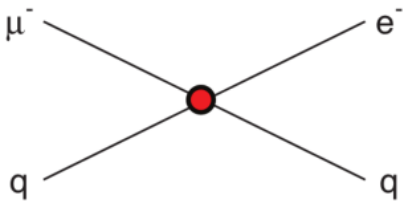
Charged Lepton Flavor Violation

- Many models of new physics predict contributions to CLFV:

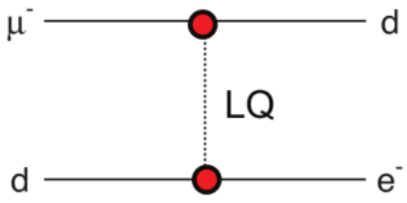
Supersymmetry



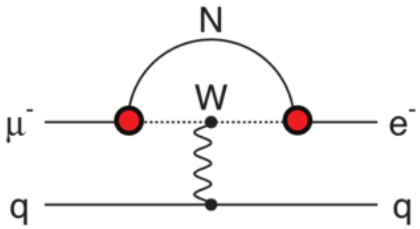
Compositeness



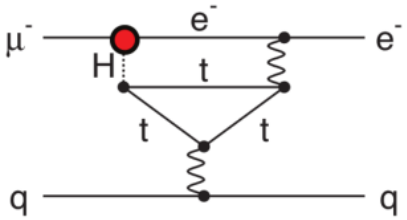
Leptoquark



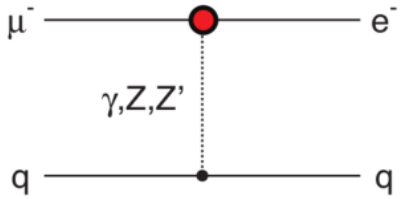
Heavy Neutrinos



Second Higgs Doublet



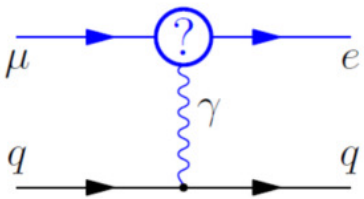
Heavy Z'
Anomal. Z Coupling

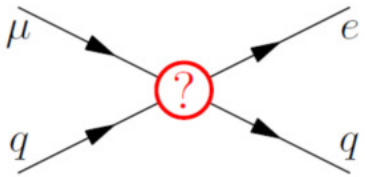


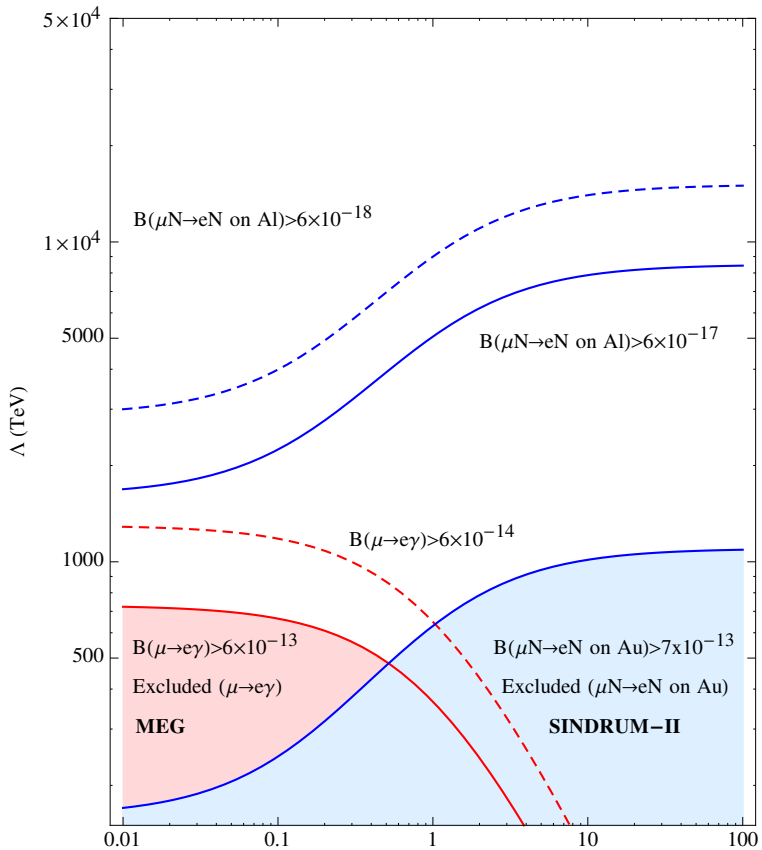
Kuno, Y. and Okada, Y. Rev. Mod. Phys. 73, 151 (2001).
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58 (2008).
M. Raidal et al, Eur.Phys.J.C57:13-182, (2008).
de Gouvea, A., and P. Vogel, arXiv:1303.4097 [hep-ph] (2013).

CLFV Effective Lagrangian

$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\overline{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\overline{\mu}_L\gamma_\mu e_L\left(\sum_{q=u,d}\overline{q_L}\gamma^\mu q_L\right)$$







Bernstein, de Gouvea

- loop: $\kappa \ll 1$, μN$\to$ eN and $\mu \to e\gamma$
- contact: $\kappa \gg 1$, μN$\to$ eN only
- Complementary to LHC: can probe mass scales up to 10^4 TeV

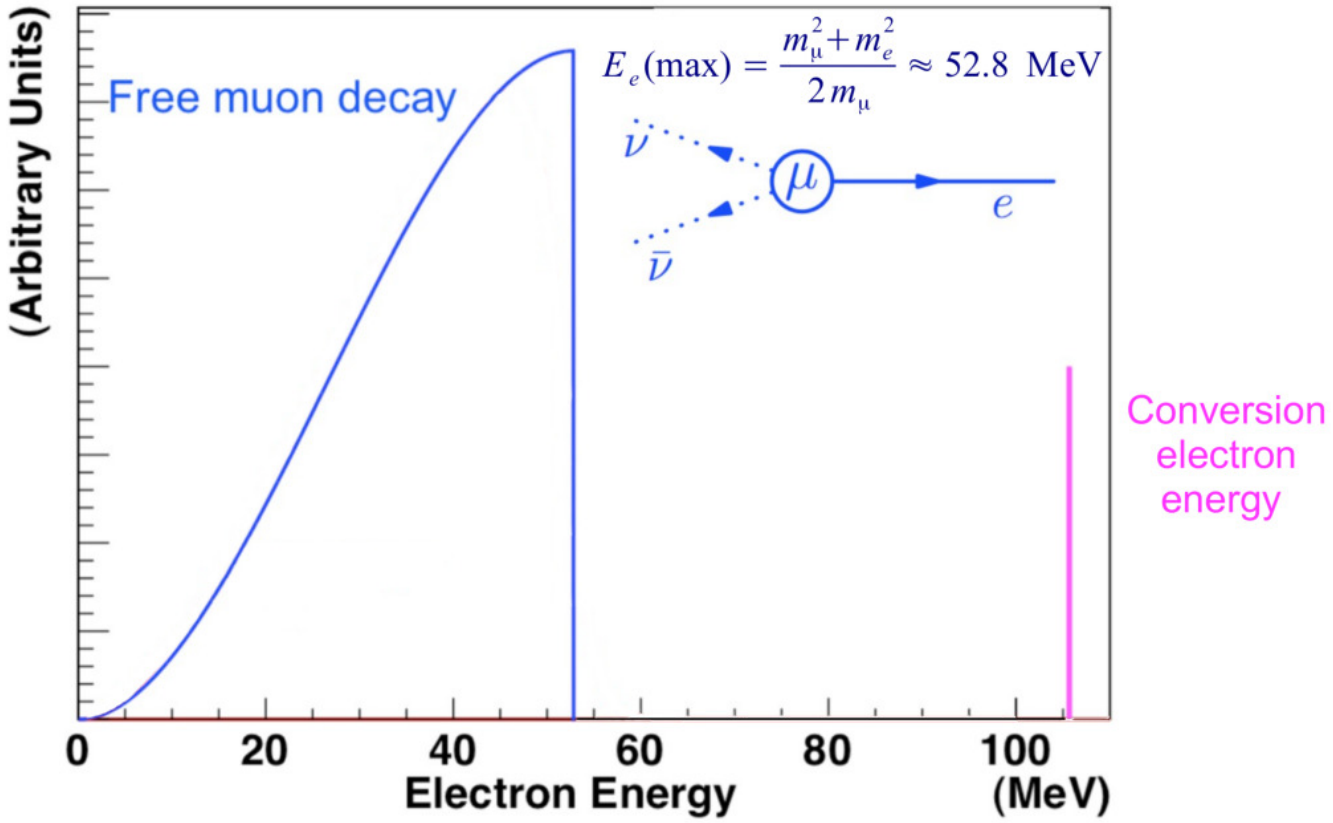
Measuring μ to e conversion

Measure the ratio of conversions to muon captures:

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

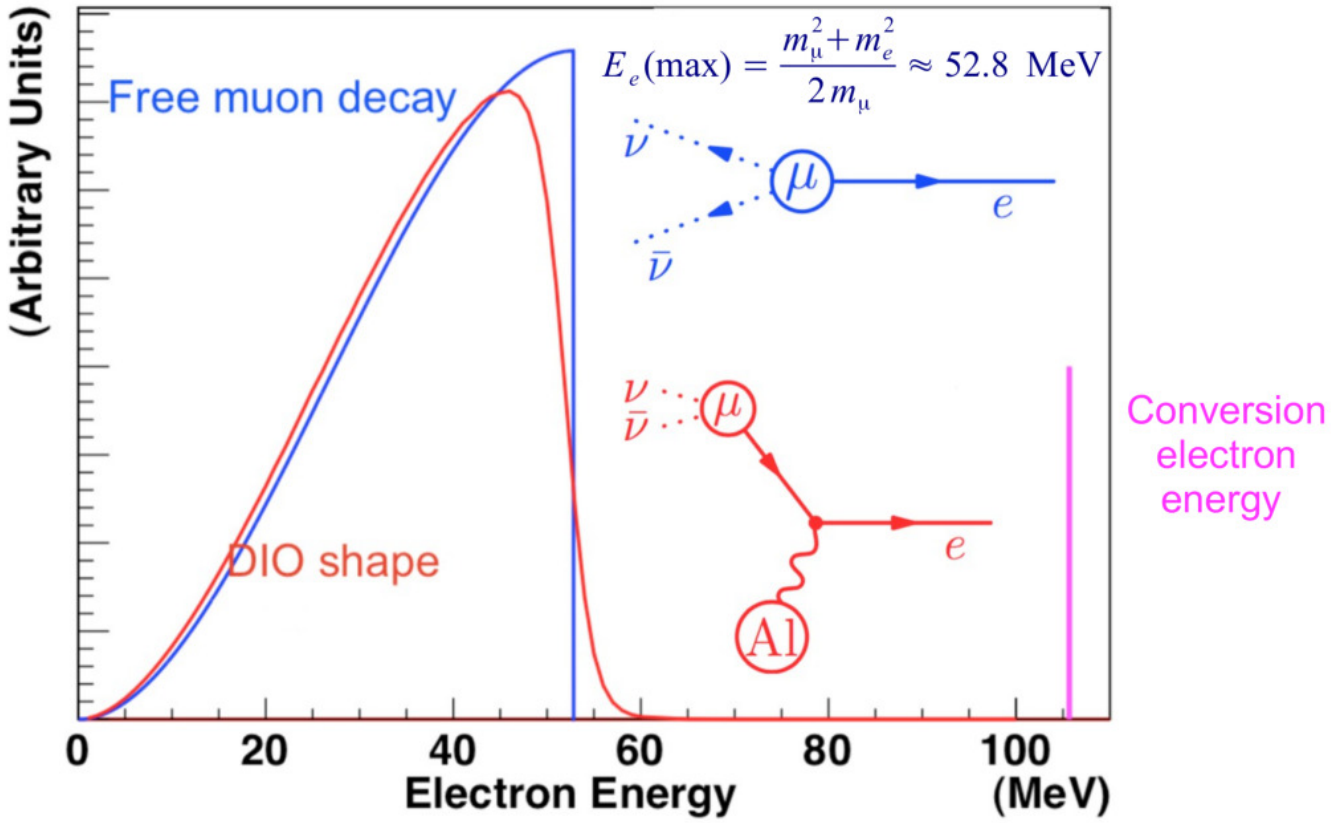
- Signal of CLFV conversion is single monoenergetic electron
- Backgrounds:
  - Beam related: $\pi^- N \to \gamma N'$, $\gamma \to e^+ e^-$
  - Cosmic rays: $\mu^- \to e^- \nu_\mu \overline{\nu_e}$
  - Muon Decay in orbit: $\mu^- N \to e^- N \nu_\mu \overline{\nu_e}$

Backgrounds: Decay in orbit ($\mu^- N \to e^- N \nu_\mu \overline{\nu_e}$)



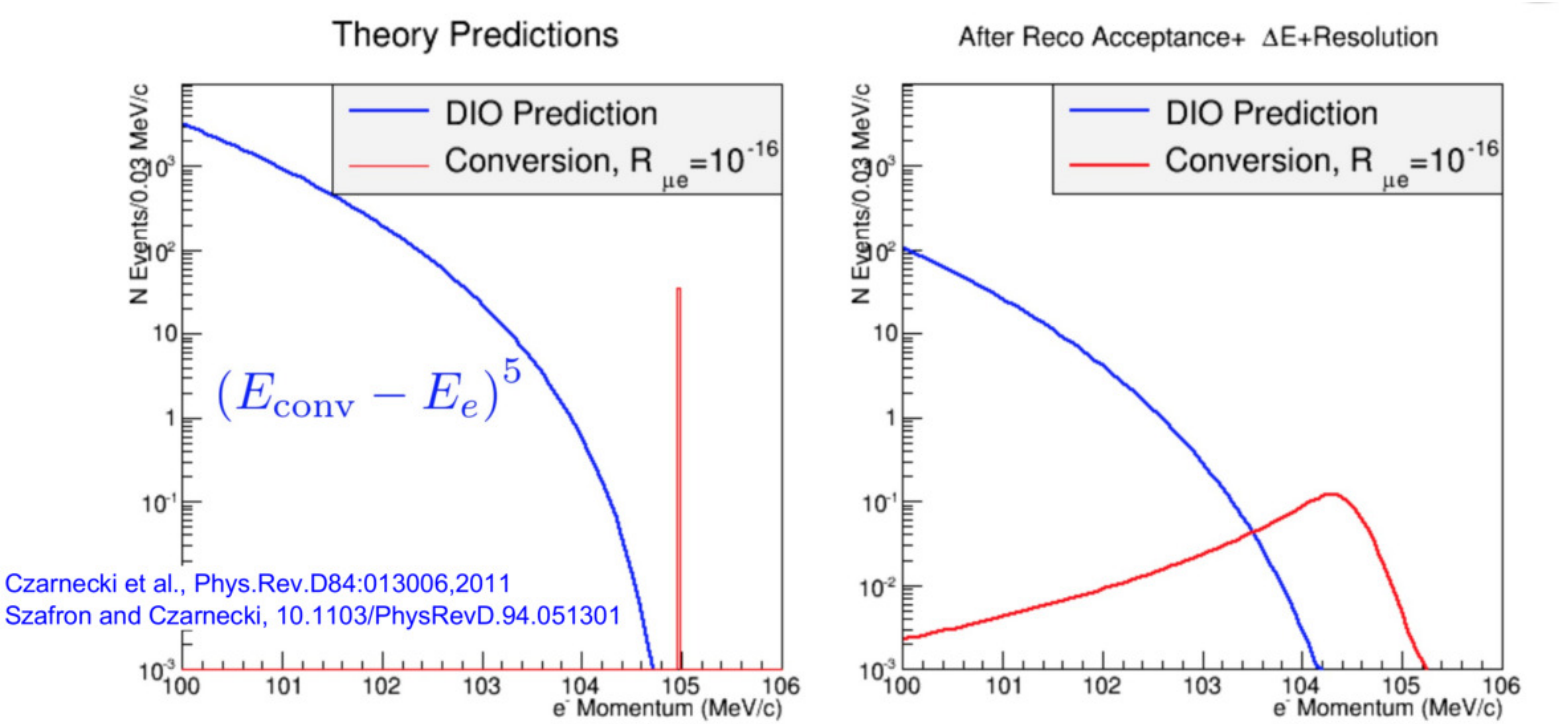
- Muon decay electron energy much lower than from conversion

Backgrounds: Decay in orbit ($\mu^- N \to e^- N \nu_\mu \overline{\nu_e}$)



- Muon decay electron energy much lower than from conversion
- Recoil off nucleus pushes tail all the way up to conversion peak

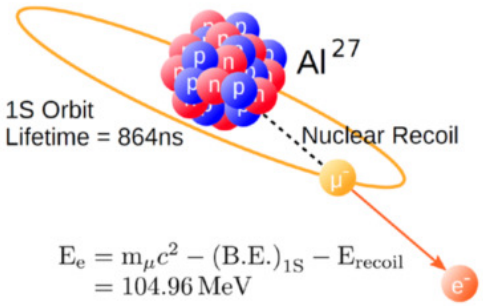
Backgrounds: Decay in orbit ($\mu^- N \to e^- N \nu_\mu \overline{\nu_e}$)



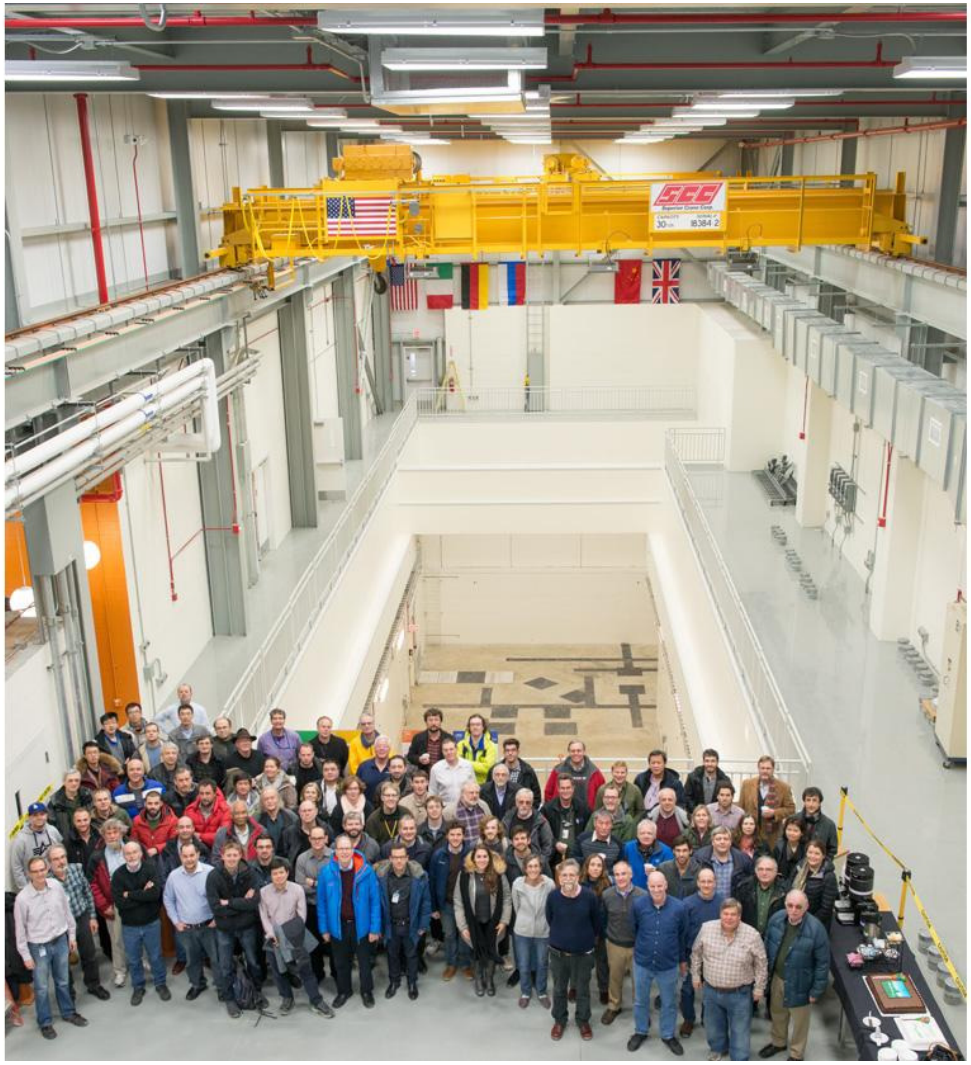
- Need to measure energy precisely to reject this background
- Maximize resolution while minimizing energy loss in detector materials

The Mu2e Experiment at Fermilab

- Stop a lot more muons! O(10^{18})
- Use timing to reject beam backgrounds
  - Pulsed proton beam 1.7 μs between pulses
  - Pions decay with 26 ns lifetime
  - Muons capture on Aluminum target with 864 ns lifetime

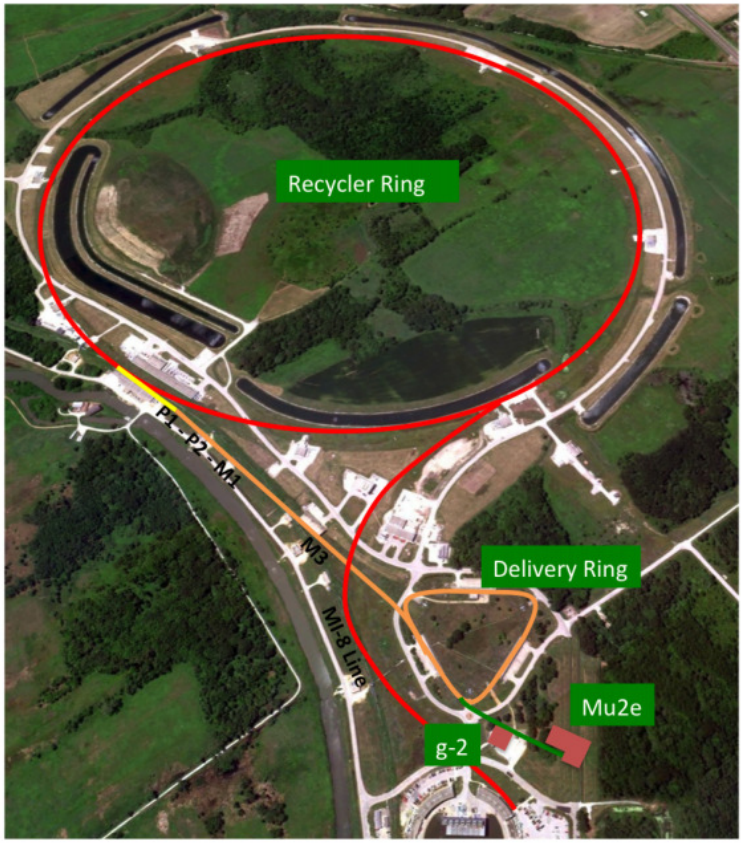


The Mu2e Collaboration



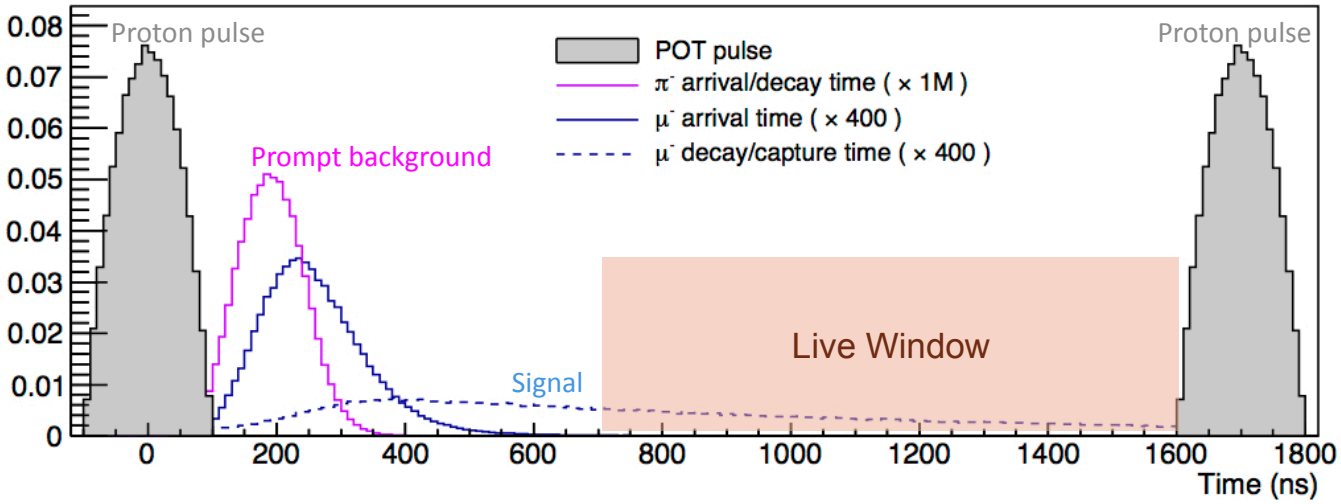
Over 200 scientists from 37 institutions in 6 countries

Mu2e Proton Beam



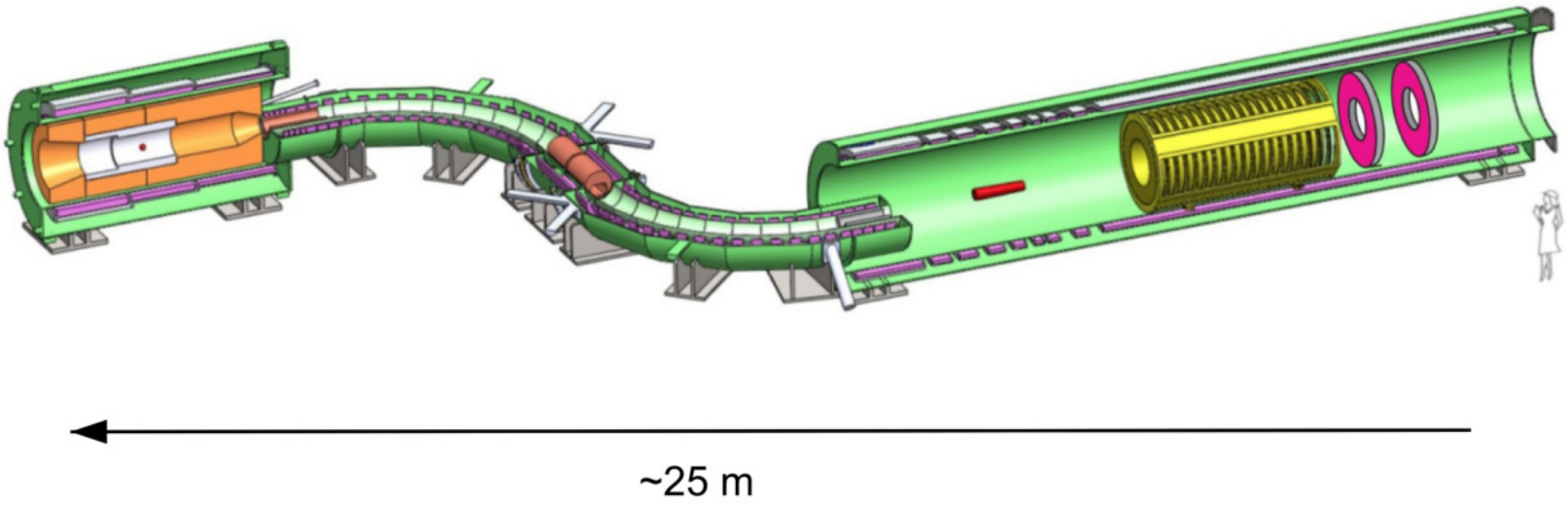
- 8 GeV 8 kW proton beam using protons from booster
- Resonantly extracted to get pulses of 4×10^7 protons separated by 1.7 μs
- Runs simultaneously with NOVA

Proton extinction between beam pulses allows us to reject RPC events (π^- Al $\rightarrow$ Mg$^* + \gamma$)



- 700 ns delay followed by 1 μs livegate
- Extinction factor (ratio of out-of-time protons to in-time protons) of 10^{-10} is needed

Mu2e experimental setup



- Consists of three superconducting solenoids:
  - Production Solenoid (PS)
  - Transport Solenoid (TS)
  - Detector Solenoid (DS)

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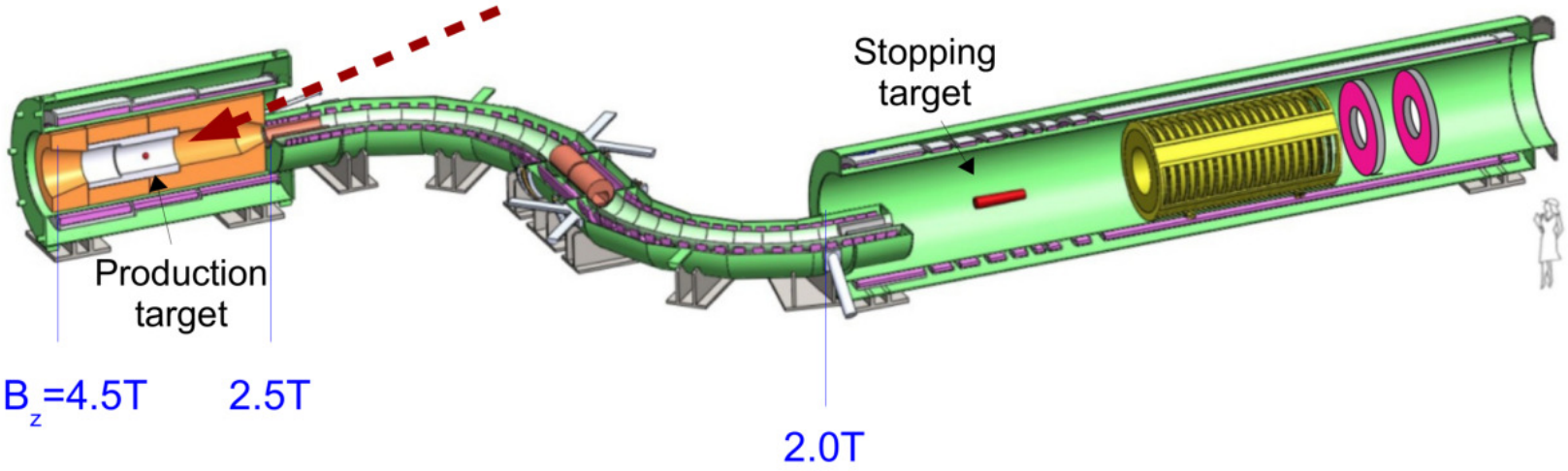

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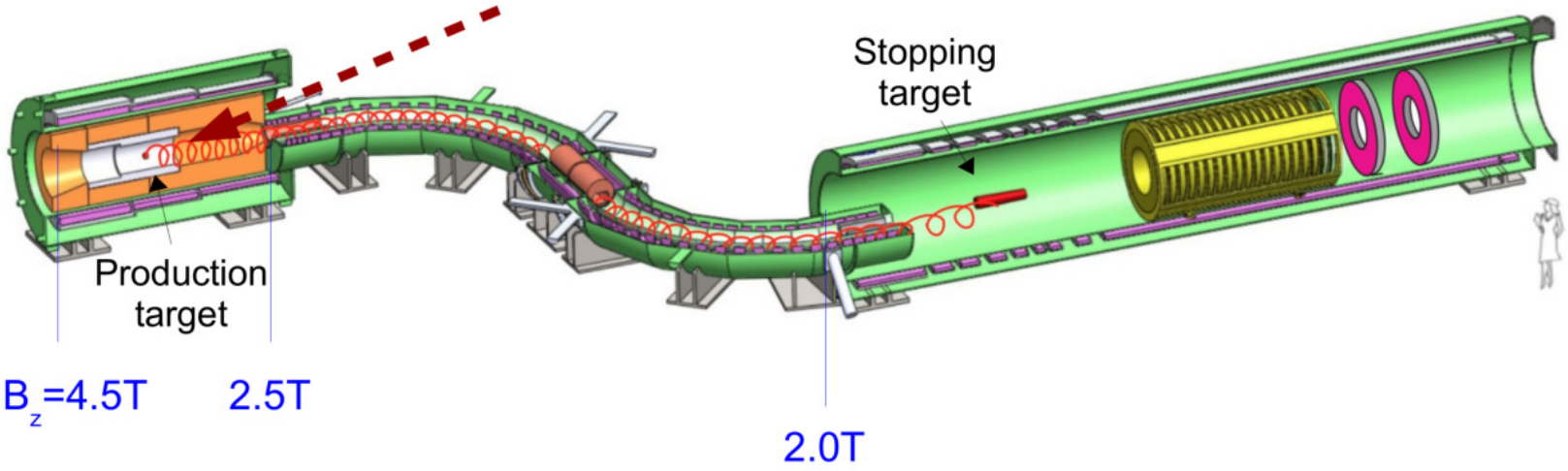

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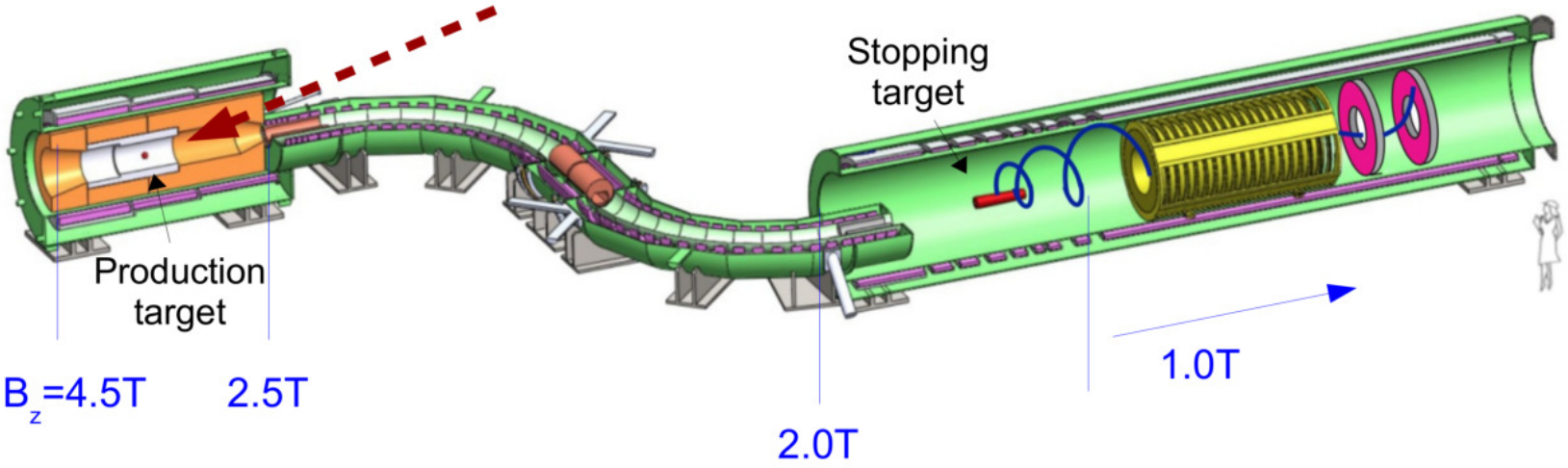

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  - Production Solenoid (PS)
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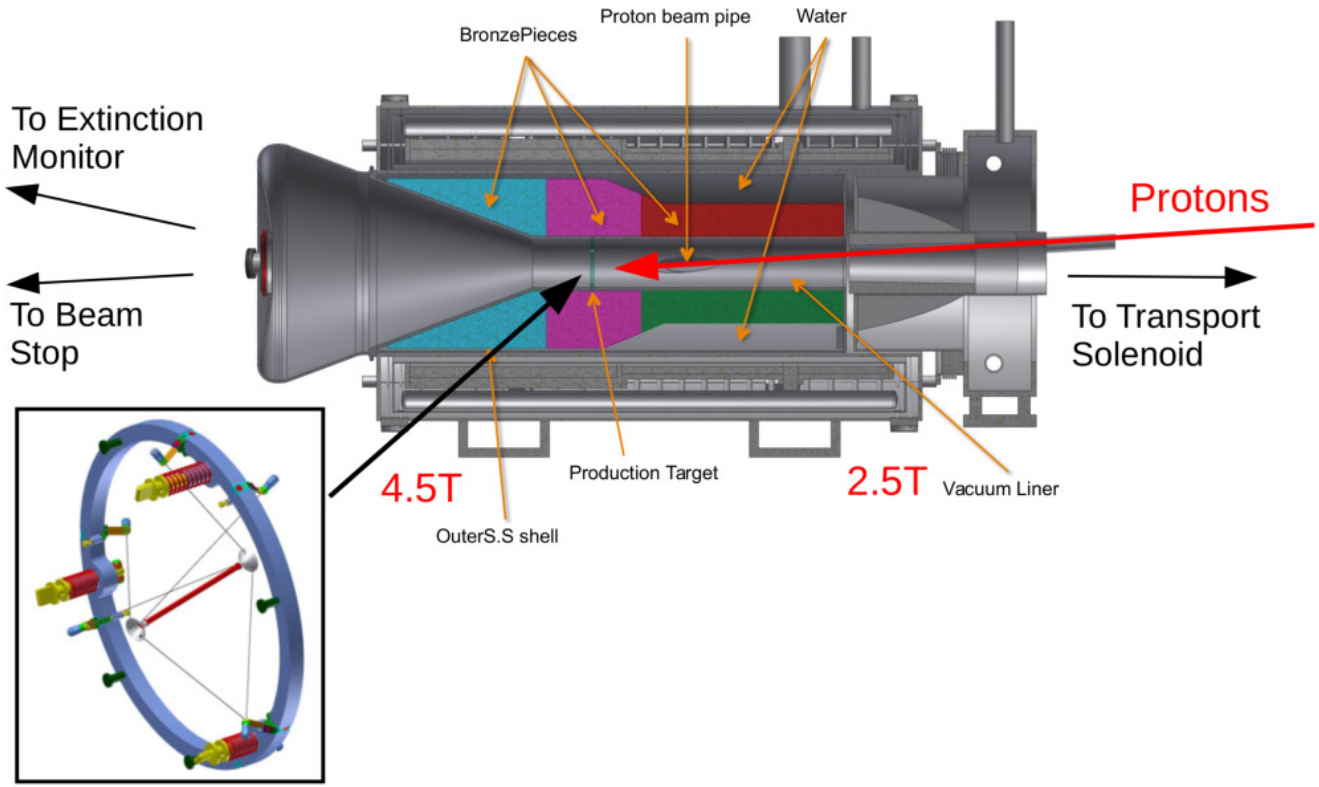
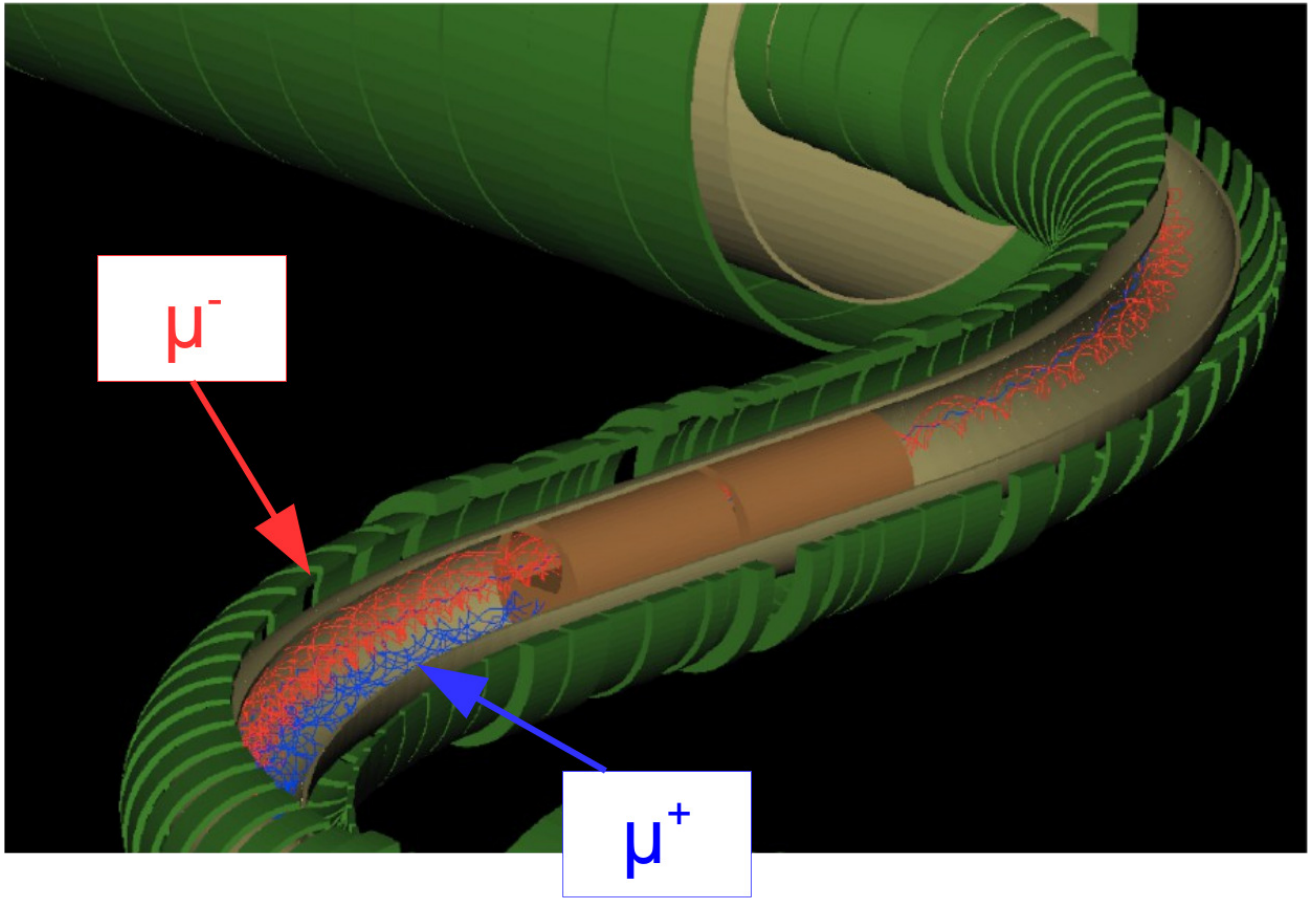
  - Detector Solenoid (DS)

Production Target and Solenoid produce slow muon beam in the reverse direction of the proton beam

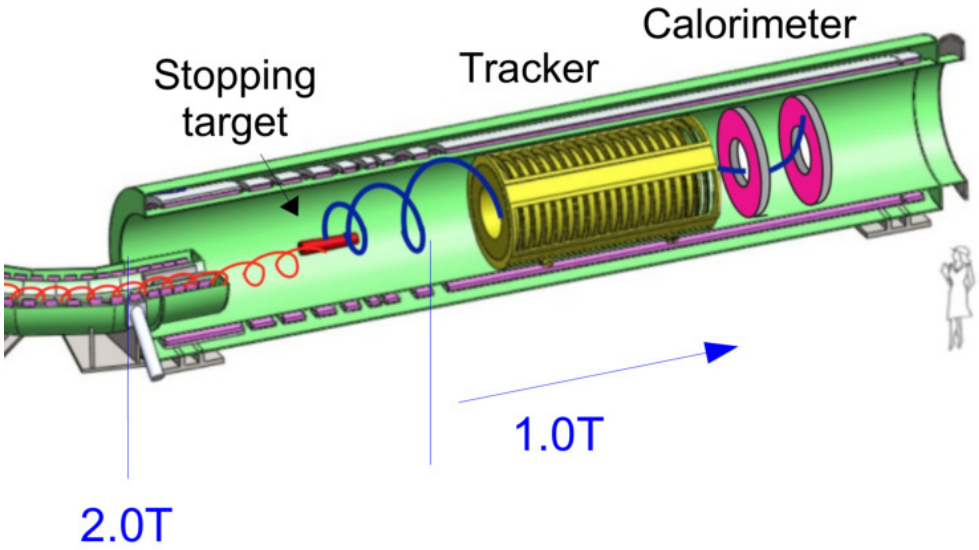


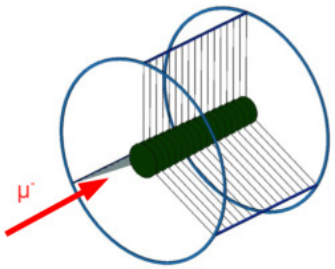
- Protons hit production target and produce pions, decay to muons
- Magnetic mirror traps and redirects back to TS

Transport Solenoid sign selects charged particles



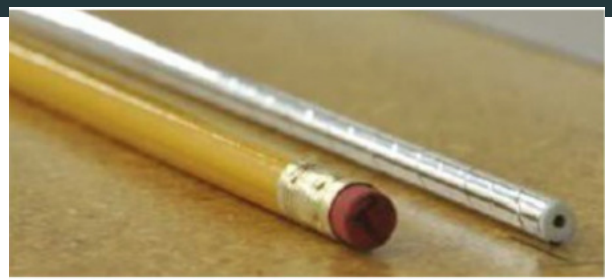
Detector solenoid directs electrons to detector elements

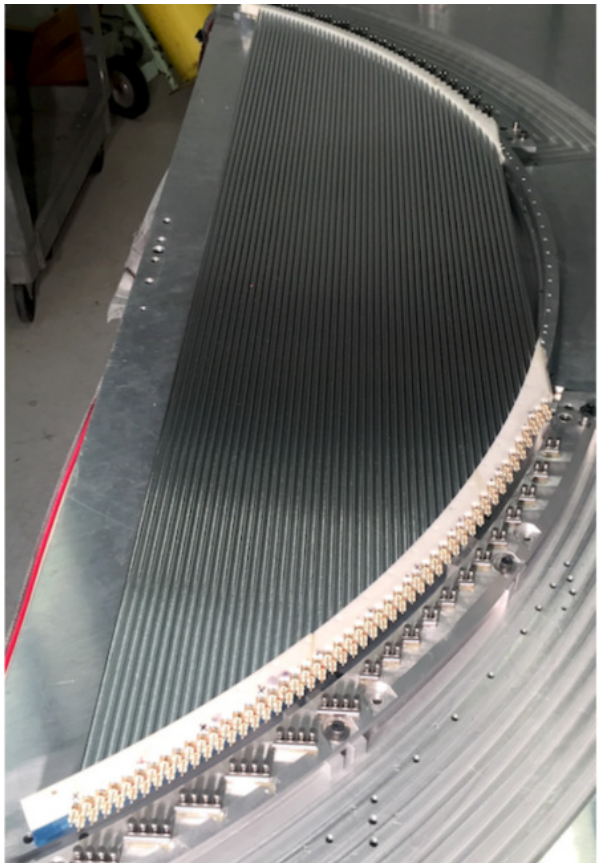




- Muons stop on thin aluminum foils, are captured or decay
  - Decay products emitted isotropically
  - Graded field directs electrons back through detector elements in helical path
  - Flat field in straw tracking volume
- High precision straw tracker for momentum measurement
- Electromagnetic calorimeter for PID

Straw Tracker provides the energy measurement to reject DIO background

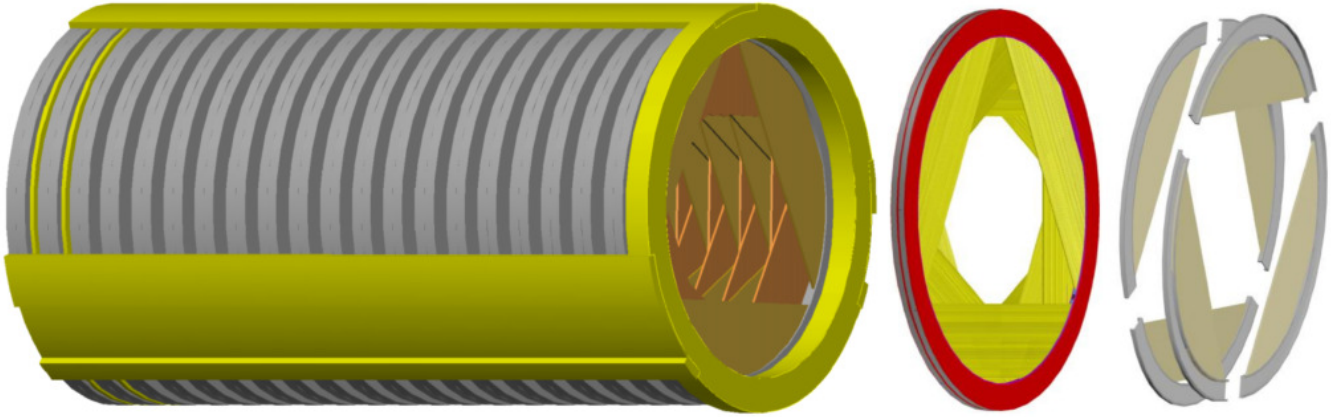


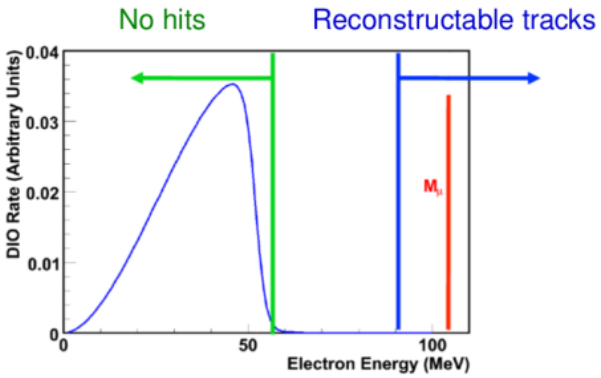


$\sim$21,000 low mass straw tubes in vacuum

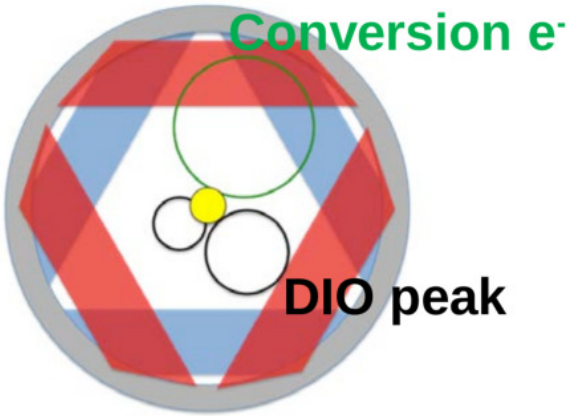
- 5 mm diameter, 15 μ thick walls
- 80/20 ArCO2 gas mixture
- instrumented on both ends - measure:
  - drift time to get radial position ($\sim$ 100μm resolution)
  - time difference between ends to get position along straw ($\sim$ 4cm resolution)
  - pulse size to identify highly ionizing proton hits

Straw Tracker provides the energy measurement to reject DIO background

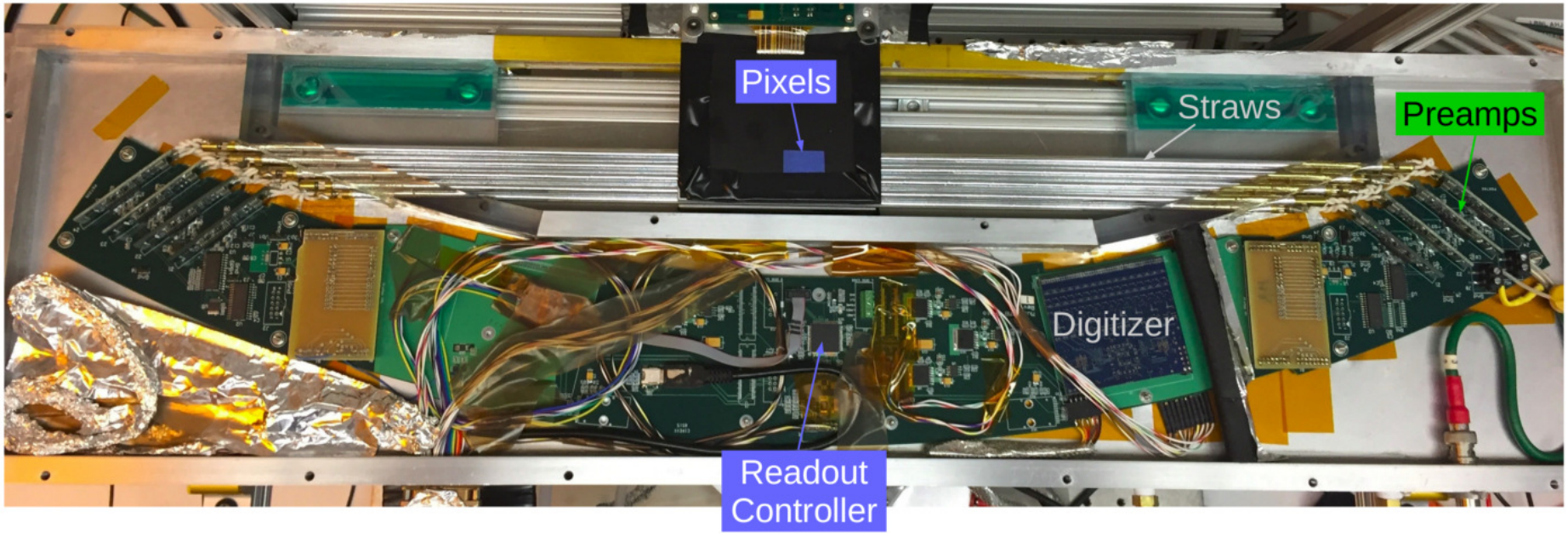




- 18 stations, each containing 12x 120° panels for stereo measurement
- Blind to DIO electron momentum peak and beam flash
- Expected resolution better than 200 keV/c



8 straw tracker prototype used to tune simulation and verify expected resolution

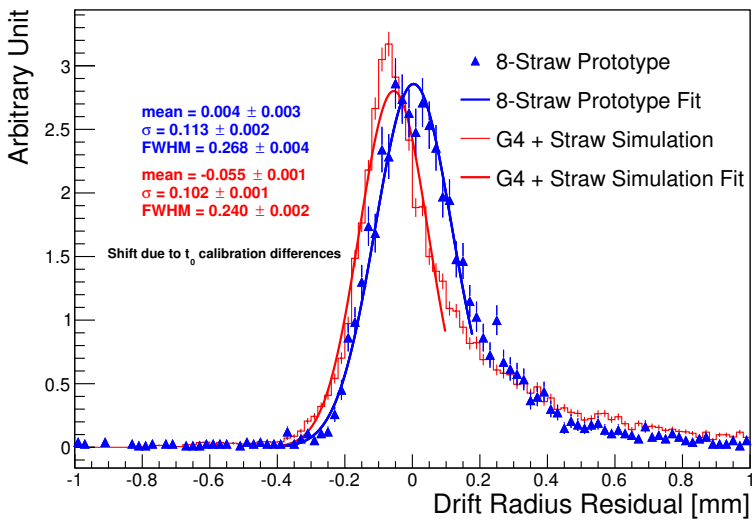


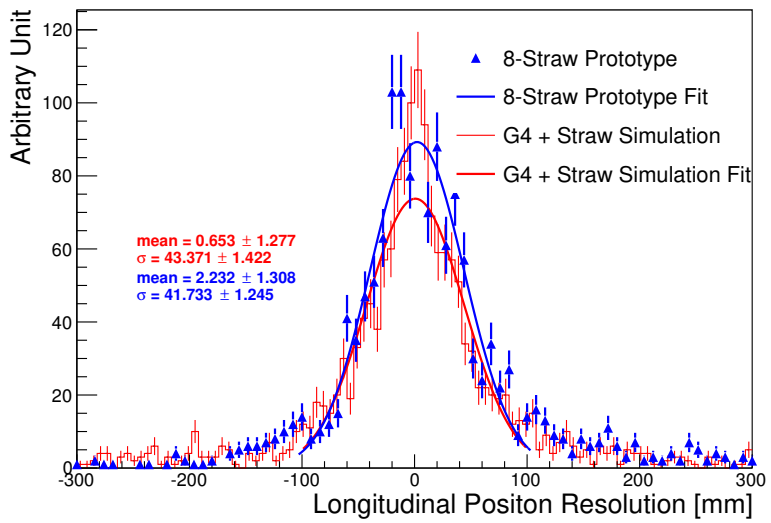
A

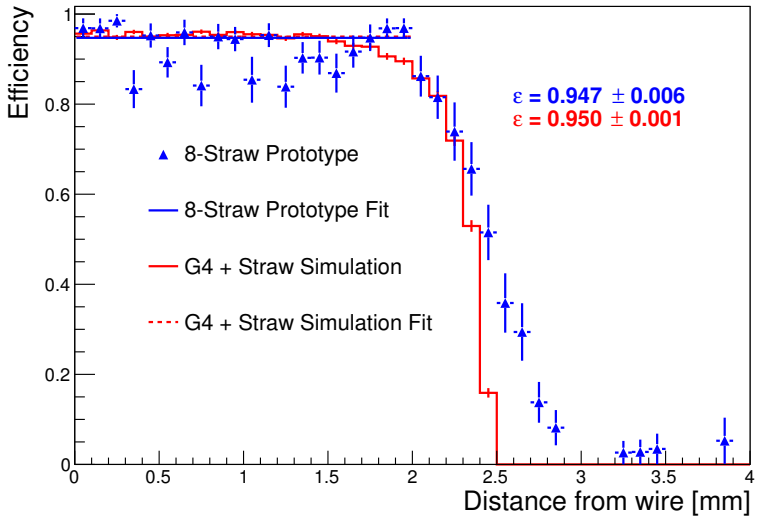
pixel detectors used to determine cosmic ray track position

- Prototype also used to develop/test electronics and DAQ/firmware

8 straw tracker prototype used to tune simulation and verify expected resolution

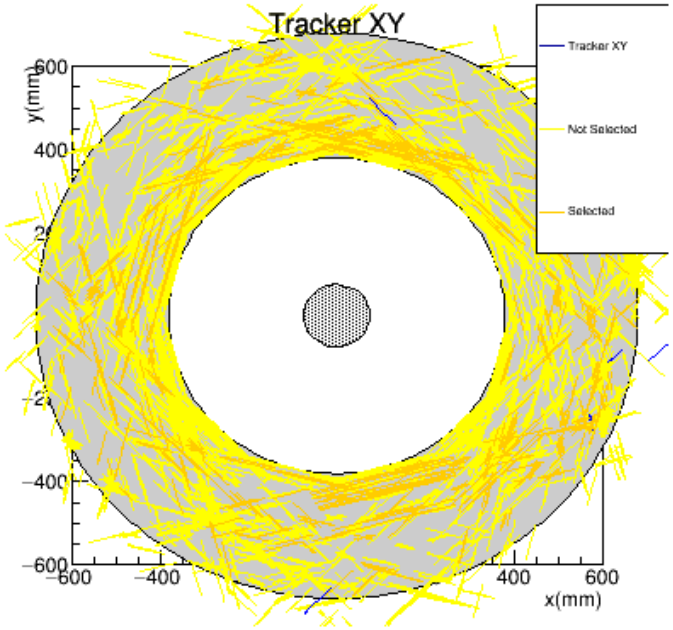






Parameter	Value	Reference
N electrons per ionization	$< N >= 2$	NIMA 301, 202(1991)
Energy per ionization electron	39 eV	NIST (27-100 eV) and G4
Avg. Straw Gain	70k	Prototype (PAM, ^{55}Fe)
Threshold Value	12 mV	Prototype (DVM, ^{55}Fe)
Threshold Noise	3 mV	Spice Sim. (V. Rusu)
Shaping Time	22 ns	Prototype (^{55}Fe)

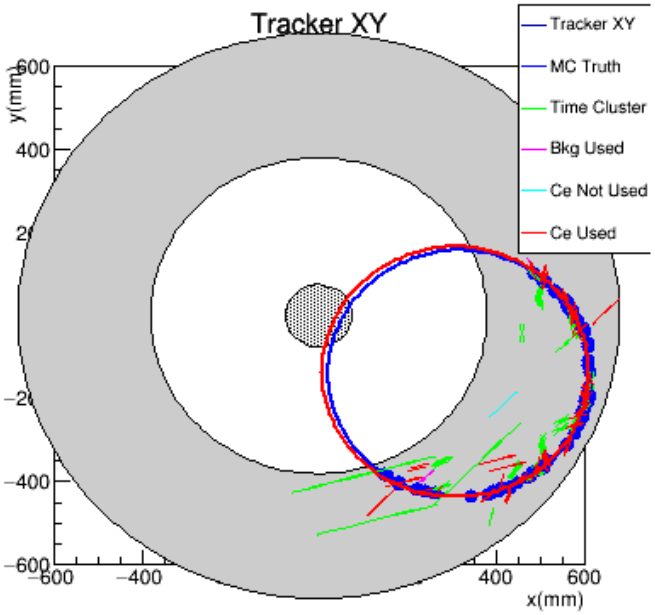
Mu2e Detector Simulation



1 μs selection window after beam flash

- Detailed Geant4 simulation of full detector
- Simulate from production target forward (including backgrounds)
- Response tuned to data and detector prototype measurements

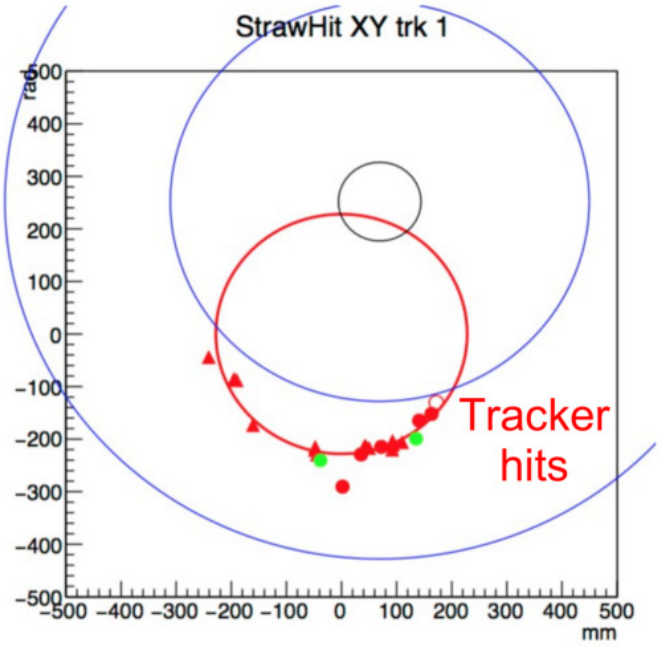
Mu2e Detector Simulation

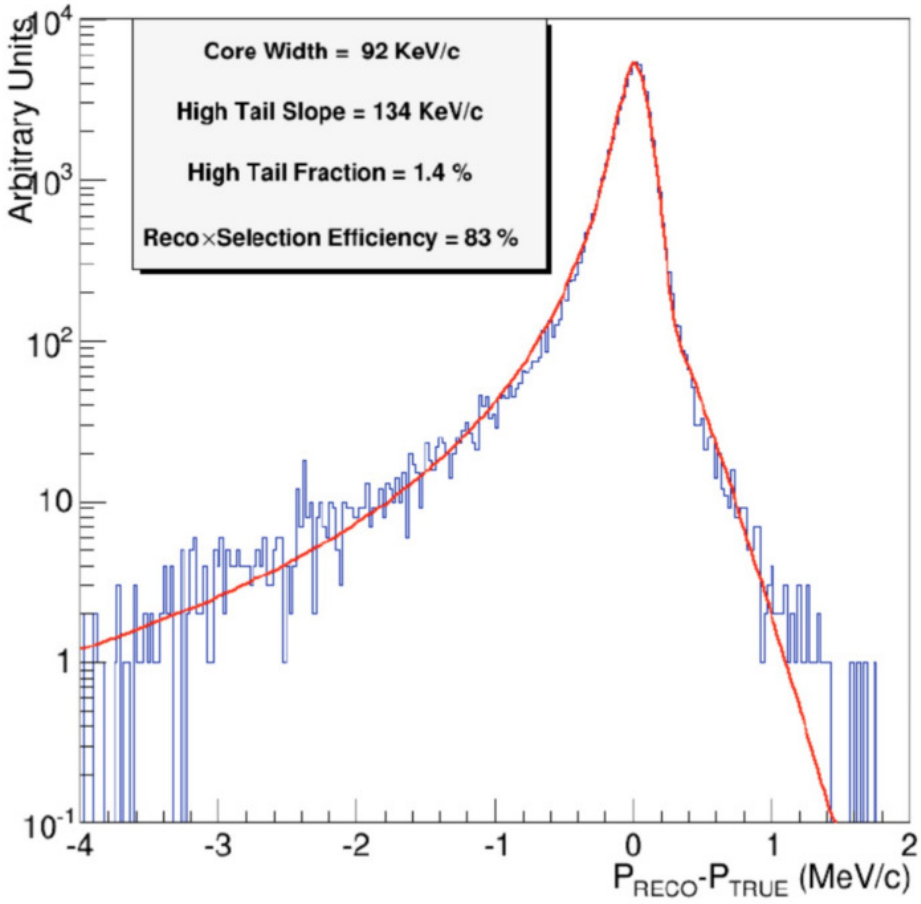


Hits selected by track finder within ±50 ns selection window around potential track

- Detailed Geant4 simulation of full detector
- Simulate from production target forward (including backgrounds)
- Response tuned to data and detector prototype measurements

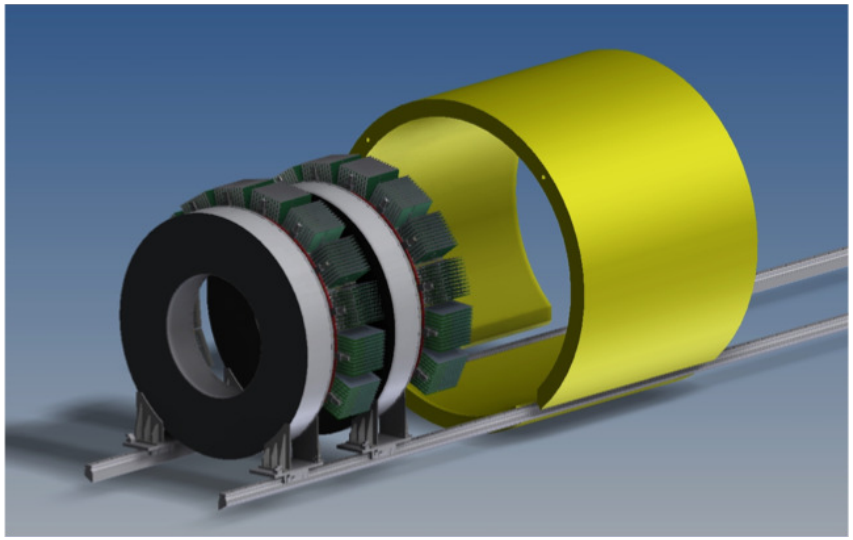
Track Reconstruction





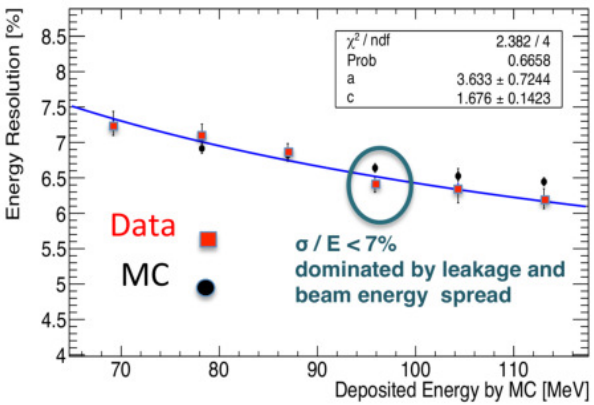
- Filter background hits (protons / Compton electrons)
- Least squares helix fit, followed by iterative Kalman Filter track fit

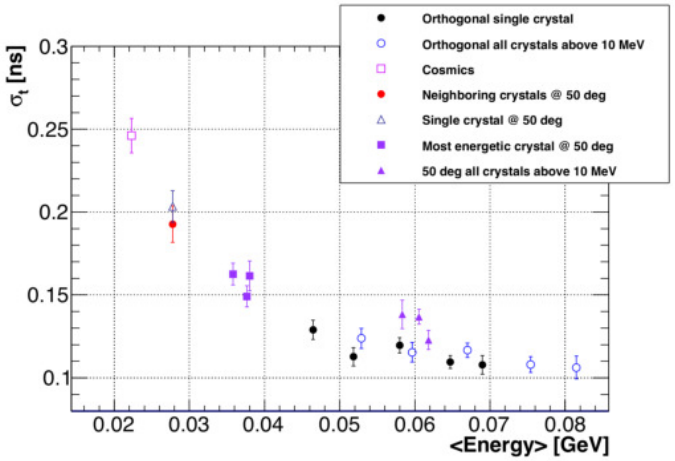
Calorimeter



- Two annular disks separated by half a "wavelength" (70cm) of electron's helical path
  - Maximize probability to hit at least one disk
- Each disk contains 860 CsI crystals read out by SiPMs
- 5% energy, 0.5 ns time, 1 cm position measurement independent of straw tracker
- Provides particle ID for track rejection

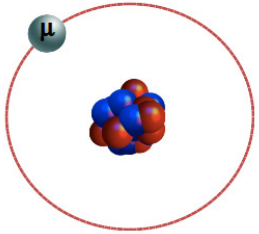
Calorimeter prototype agrees with simulation



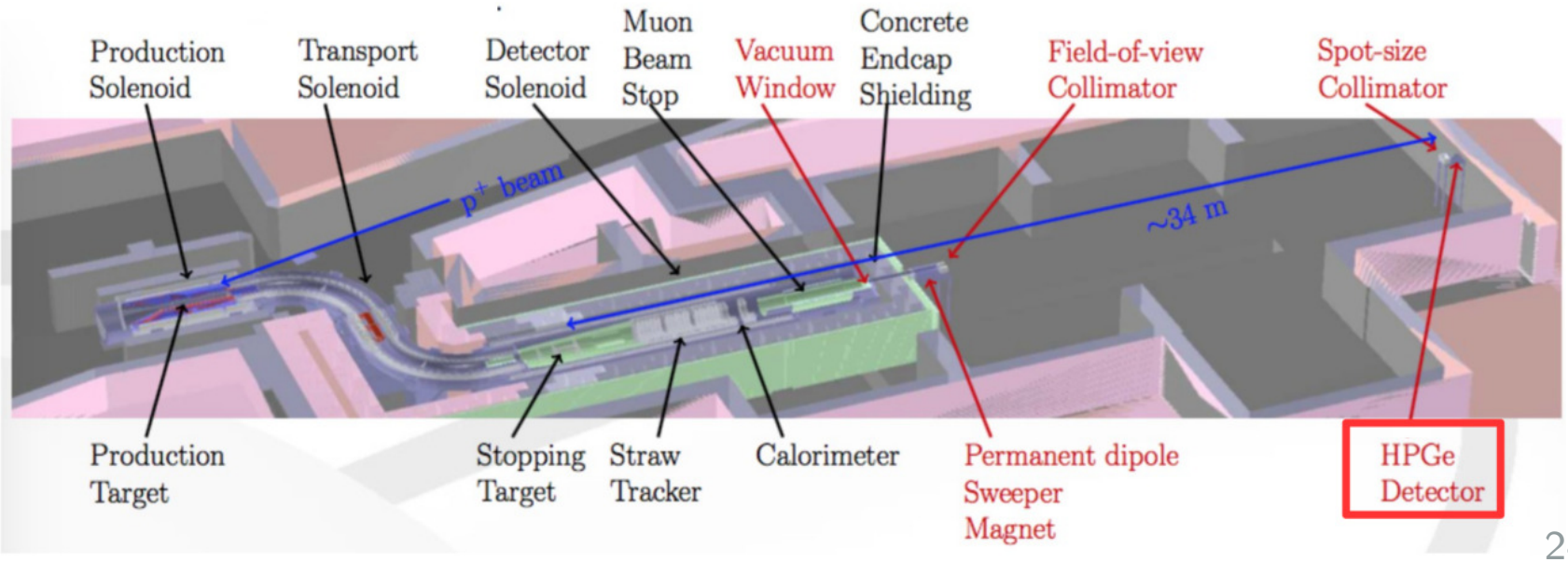


- 3x3 matrix of undoped CsI crystals 3x3x20 cm^3
- Tested under 80 to 120 MeV electron beam
- Energy response (7%) and time resolution (110 ps) meet specifications

Stopping Target Monitor measures capture rate



- Muons cascade to 1s state emitting x-rays
- HPGe detector monitor these x-rays to measure capture rate
- Normalization of measurement $R_{\mu e} = \frac{\mu^- + A(Z,N) \to e^- + A(Z,N)}{\mu^- + A(Z,N) \to \nu_\mu + A(Z-1,N)}$



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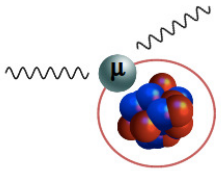

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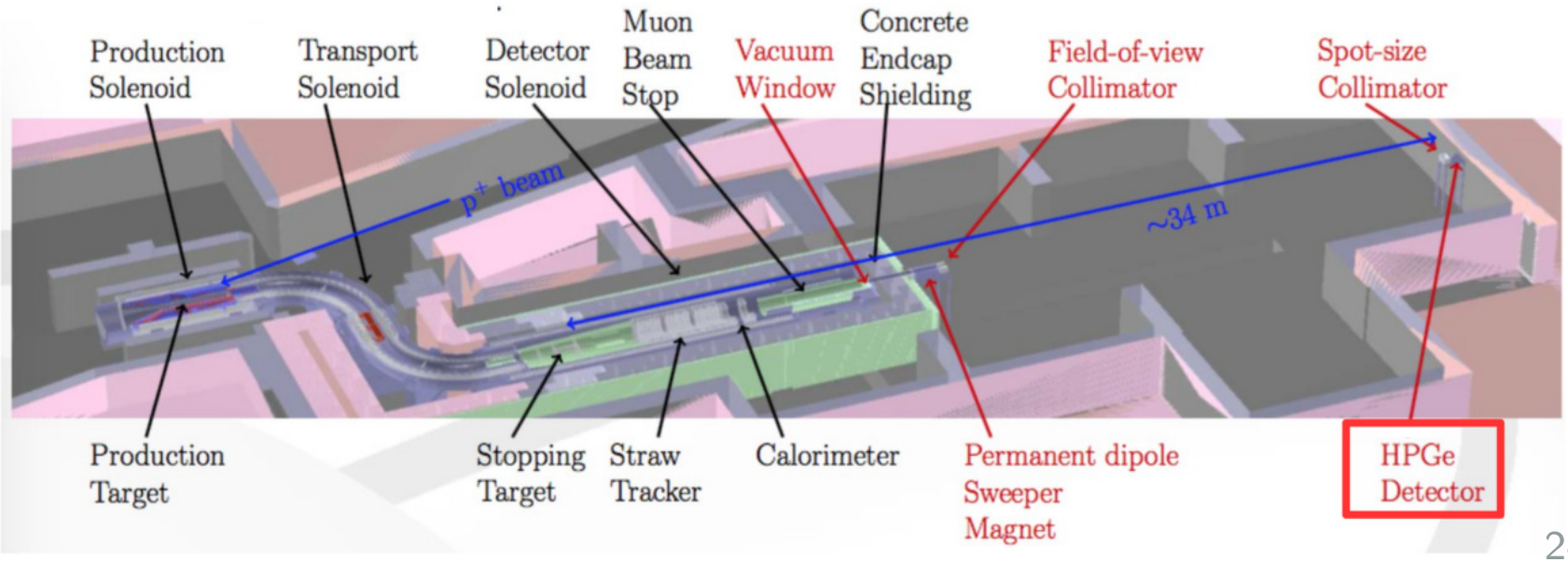
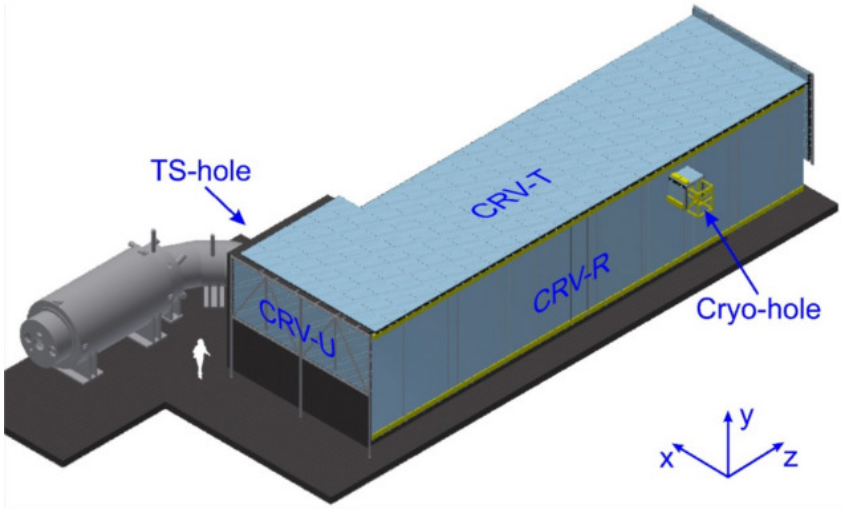
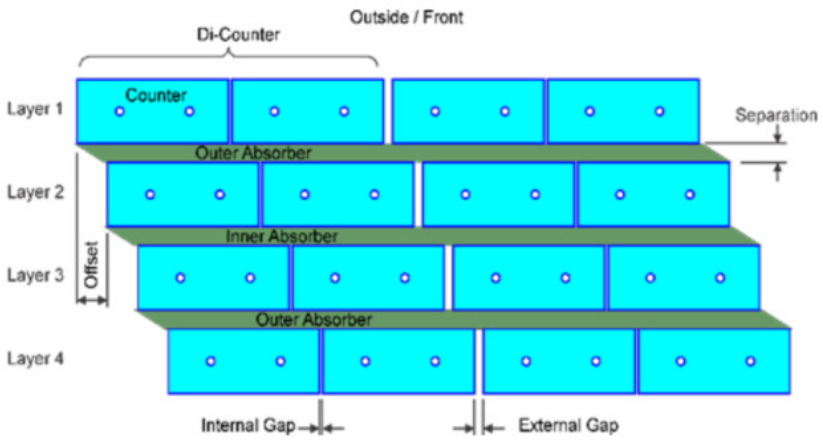


Cosmic ray veto

- Expect cosmic rays to produce 1 conversion-like event per day
- 4 overlapping layers of scintillator, read out on both ends with SiPMs
- Covers entire DS, half of TS, better than 10^{-4} inefficiency



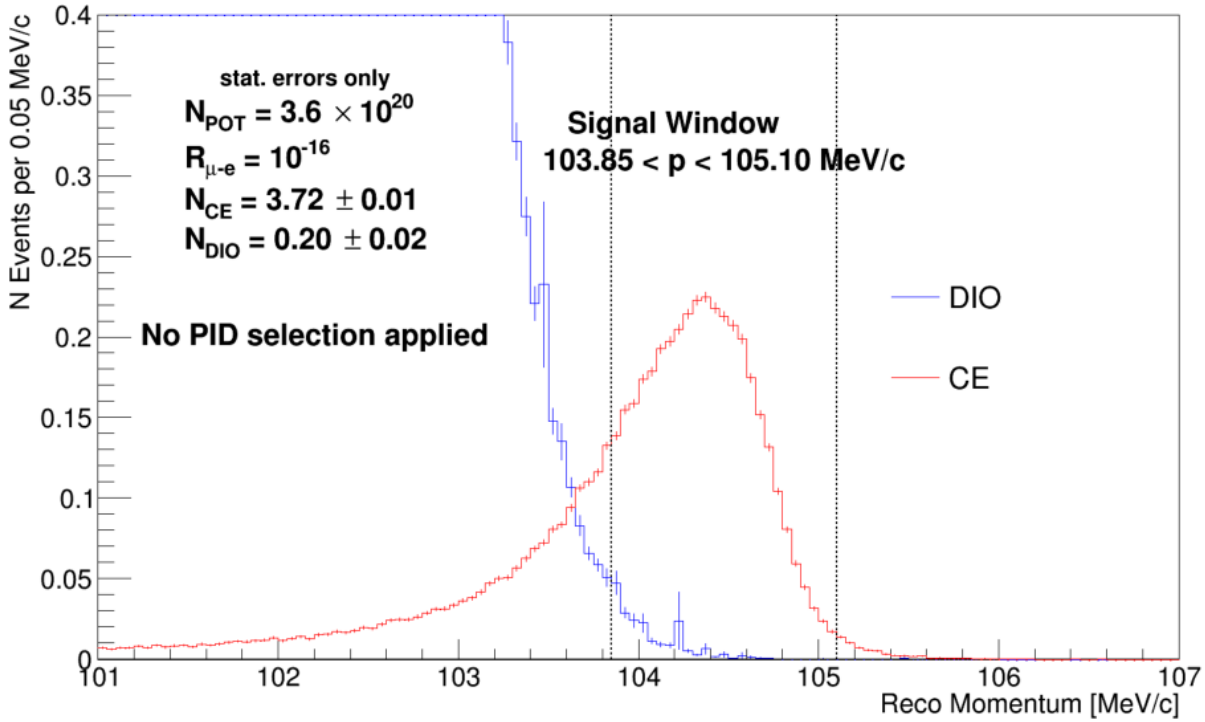


Expected backgrounds for 3 year run

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late Arriving	Pion capture (RPC)	0.023 ± 0.006
	Muon decay-in-flight (μ-DIF)	<0.003
	Pion decay-in-flight (π-DIF)	$0.001 \pm <0.001$
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic ray induced	0.082 ± 0.018
	Total	0.36 ± 0.10

- Fewer than ∼0.5 background events expected over entire run
- 3.6 x 10^{20} protons on target over 3 years → ∼ 10^{18} stopped muons

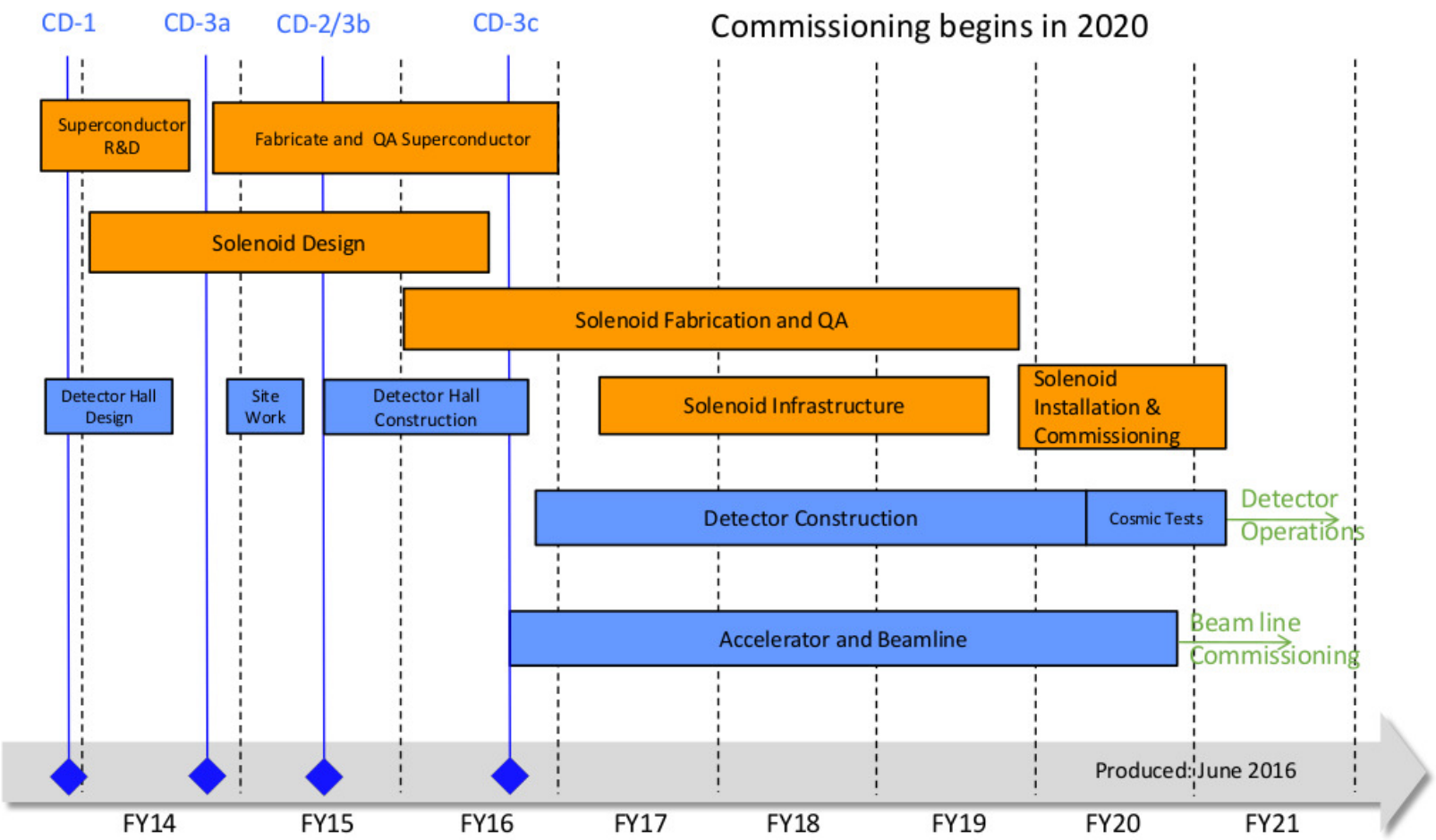
Sensitivity



- Single event sensitivity: $R_{\mu e} < 3x10^{-17}$
- Typical SUSY prediction of $10^{-15} \rightarrow \sim$50 signal events

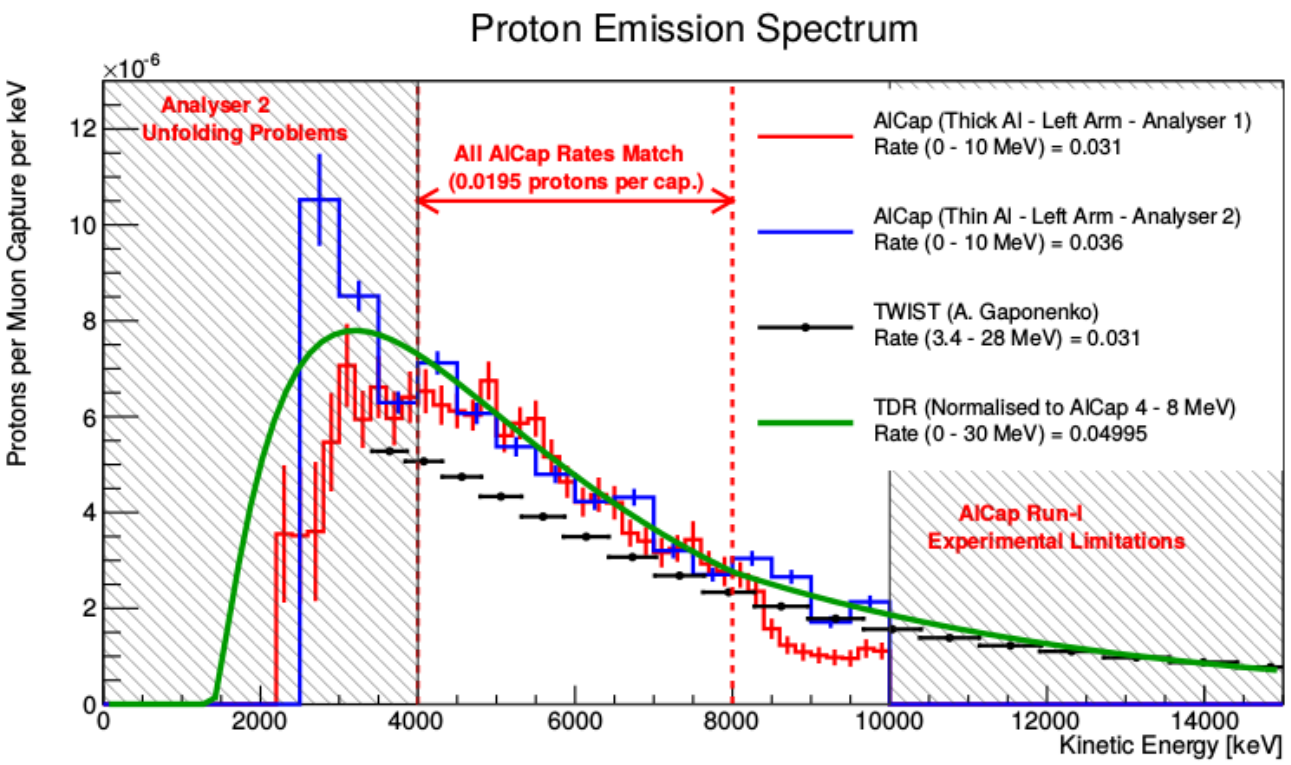
Civil construction

Mu2e is fully approved! Moving ahead on schedule



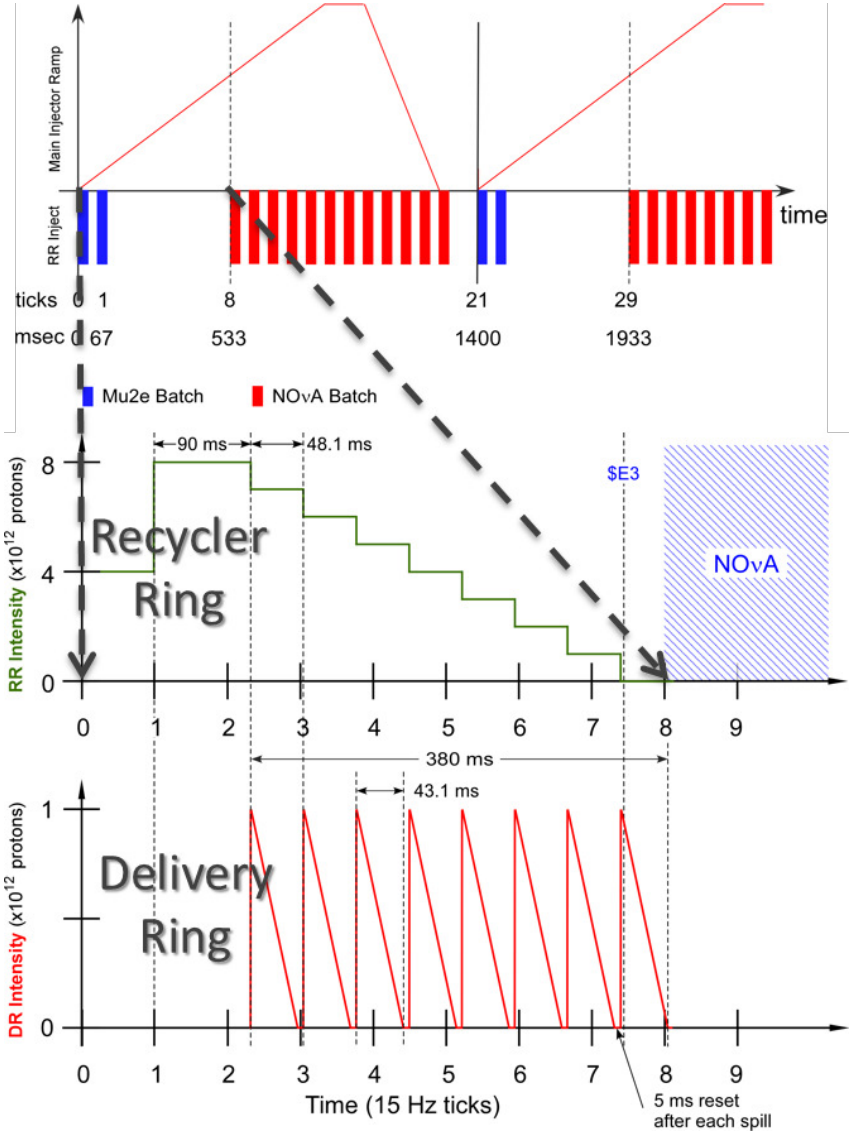
Backup

AlCap



- Joint project by Mu2e and COMET
- Measure particles emitted after muon capture on Al

Beam structure



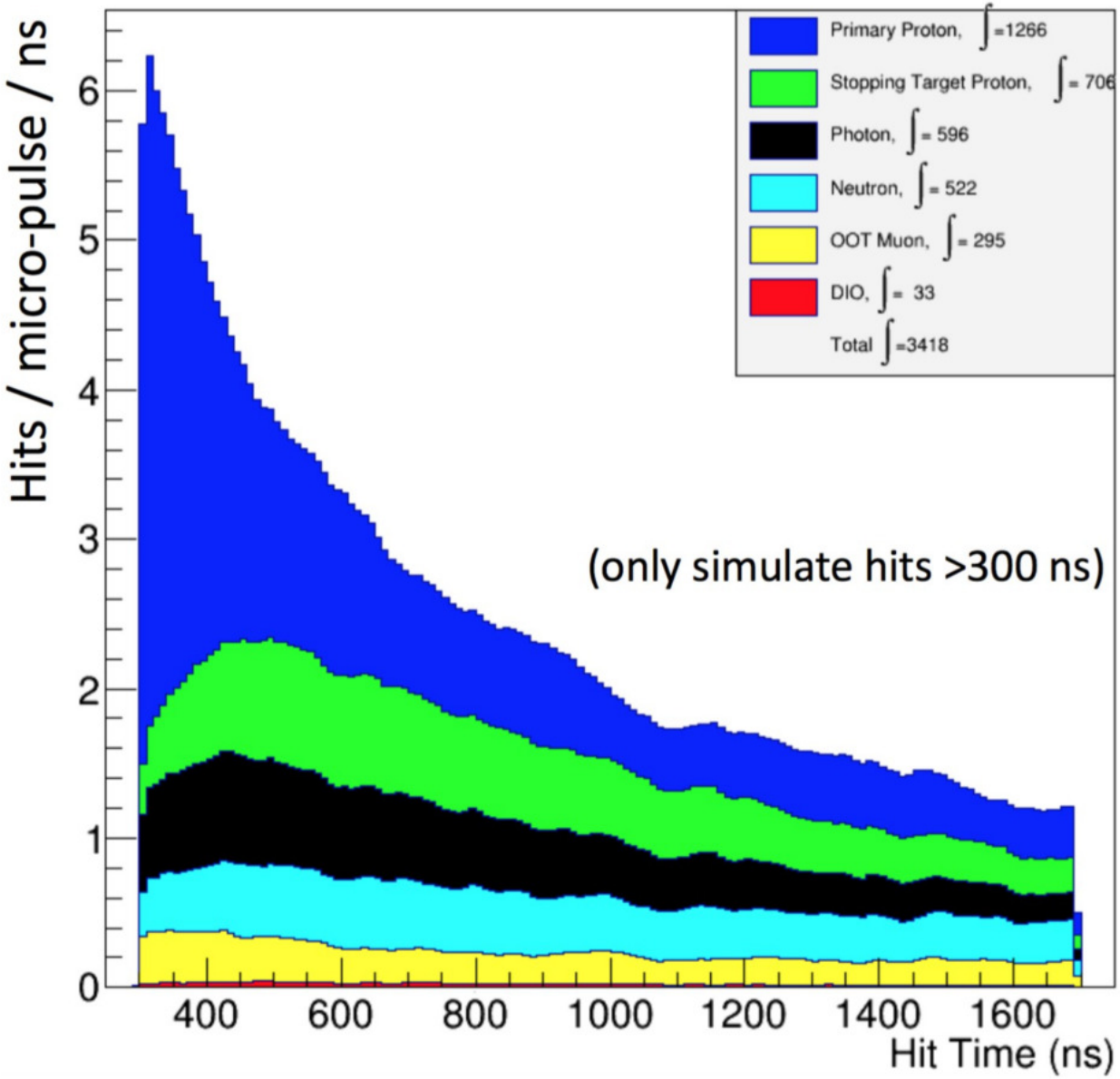
Beam requirements

	Parameter	Design Value	Requirement	Unit
	Total protons on target	4.7×10^{20}	$\geq 4.7\times10^{20}$	protons
Time Structure	Time between beam pulses	1695	> 864	nsec
Time Structure	Maximum variation in pulse separation	< 1	10	nsec
Time Structure	Spill duration	43.1	> 20	msec
Time Structure	Beamline Transmission Window	230	< 250	nsec
Time Structure	Transmission Window Jitter (rms)	< 5	<10	nsec
Time Structure	Out-of-time extinction factor	1.6×10^{-12}	$\leq 10^{-10}$	
Intensity	Average proton intensity per pulse	3.9×10^{7}	$< 5.0\times10^{7}$	protons/ pulse
Intensity	Maximum Pulse to Pulse intensity variation	50	50	%
Beam Size	Target rms spot size	1	0.5 – 1.5	mm
Beam Size	Target rms beam divergence	0.5	< 4.0	mrad

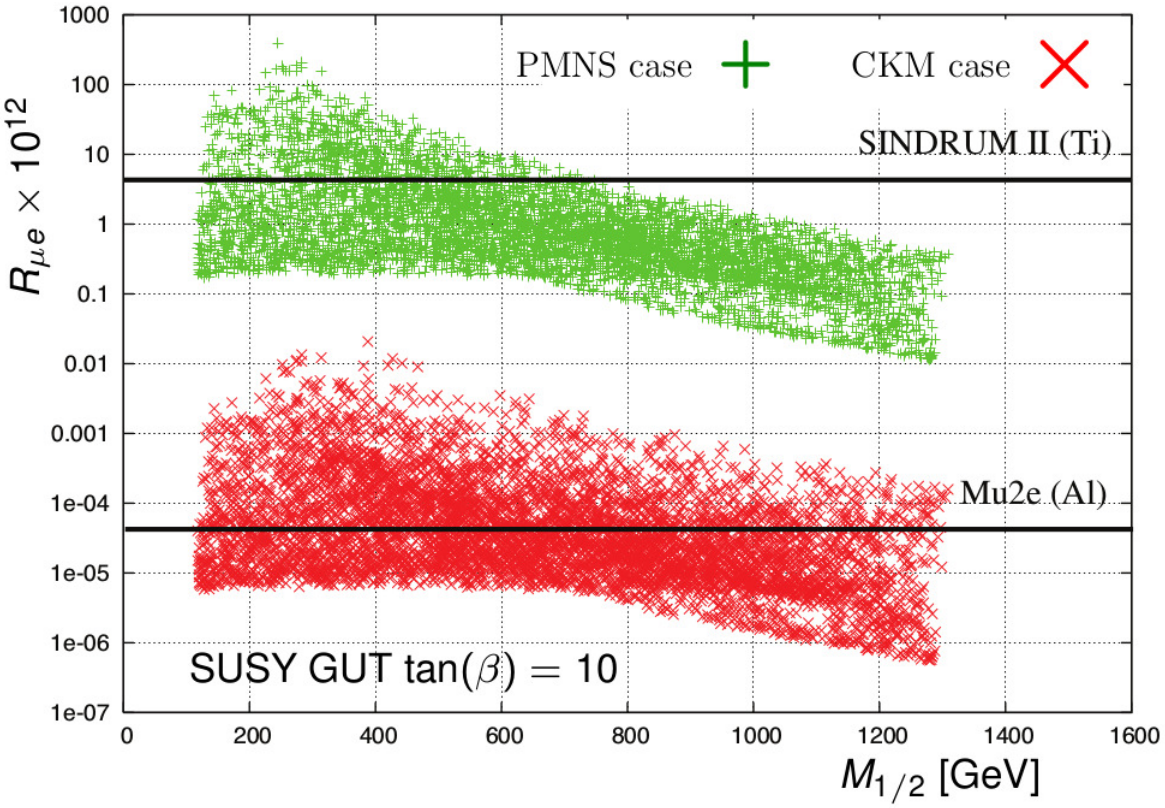
Systematics

Effect	Uncertainty in DIO background yield	Uncertainty in CE single-event-sensitivity ($\times 10^{-17}$)
MC Statistics	±0.02	±0.07
Theoretical Uncertainty	±0.04	-
Tracker Acceptance	±0.002	±0.03
Reconstruction Efficiency	±0.01	±0.15
Momentum Scale	+0.09, -0.06	±0.07
μ-bunch Intensity Variation	±0.007	±0.1
Beam Flash Uncertainty	±0.011	±0.17
μ-capture Proton Uncertainty	±0.01	±0.016
μ-capture Neutron Uncertainty	±0.006	±0.093
μ-capture Photon Uncertainty	±0.002	±0.028
Out-Of-Target μ Stops	±0.004	±0.055
Degraded Tracker	-0.013	+0.191
Total (in quadrature)	+0.10, -0.08	+0.35, -0.29

Tracker Occupancy

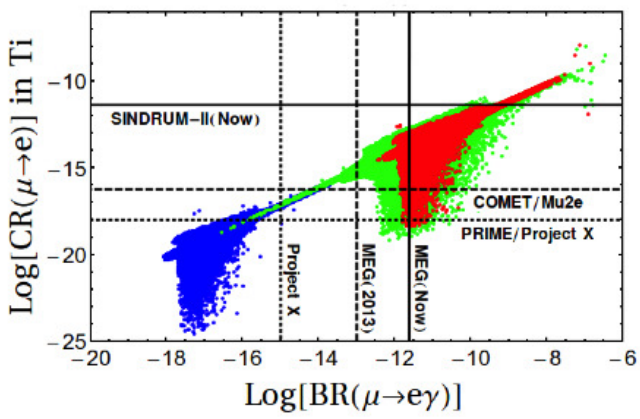


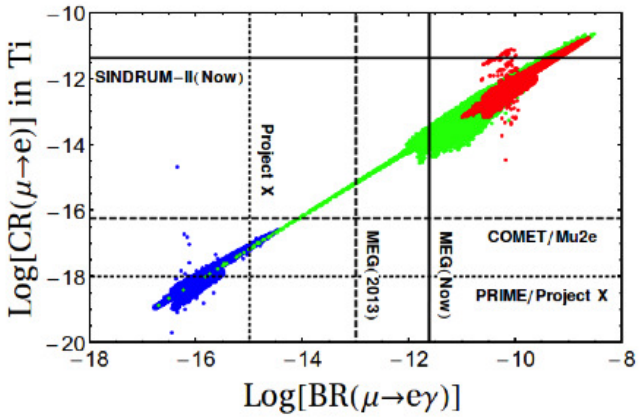
SUSY model constraints



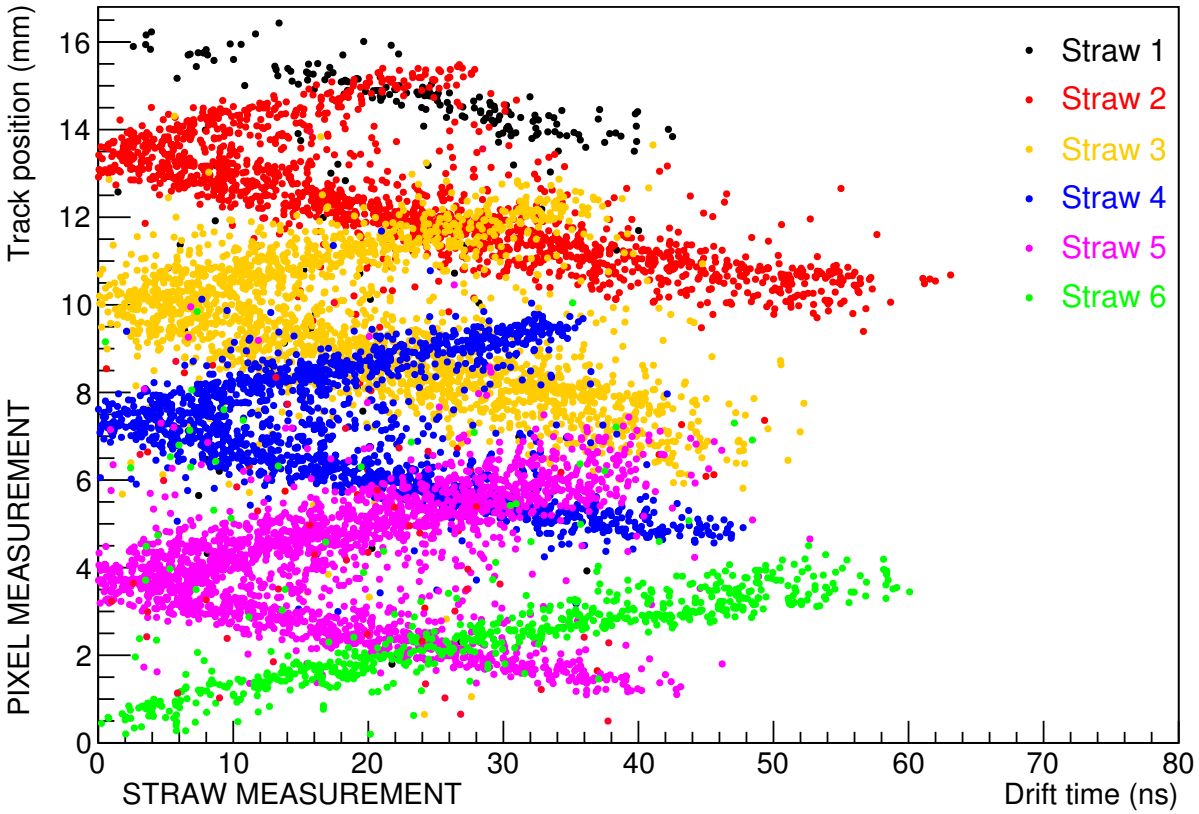
*Calibbi, Faccia, Masiero, Vempati, Phys.Rev.**D74** (2006) 116002*

SUSY model constraints

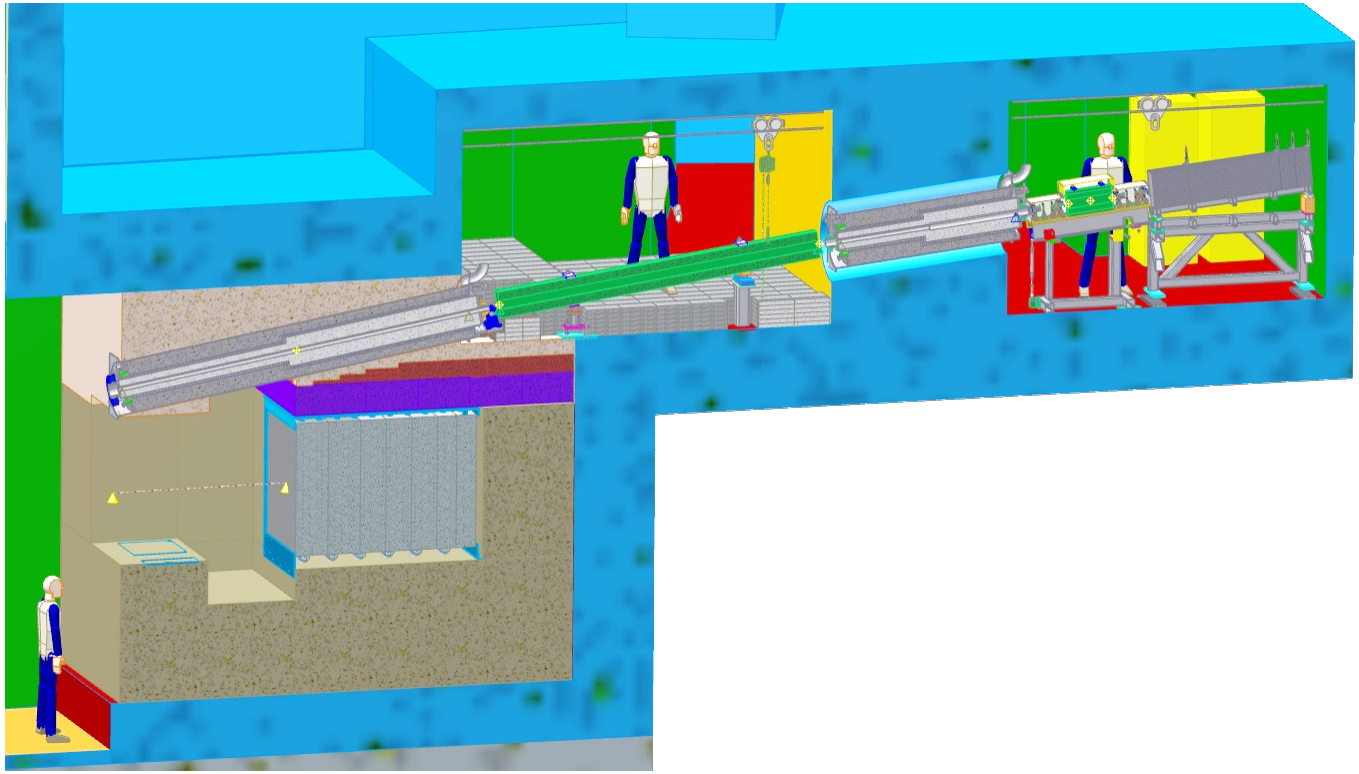




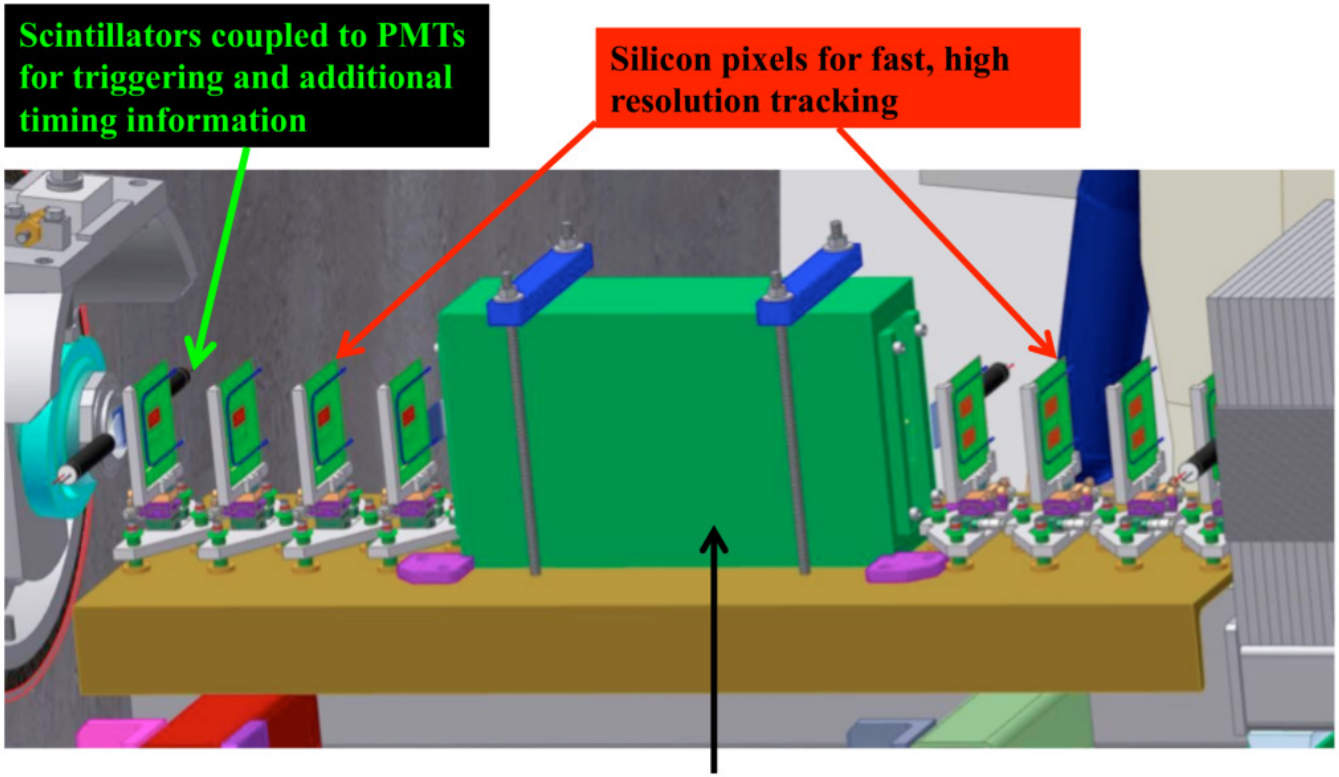
Tracker prototype



Extinction Monitor located downstream of production target



Extinction Monitor located downstream of production target



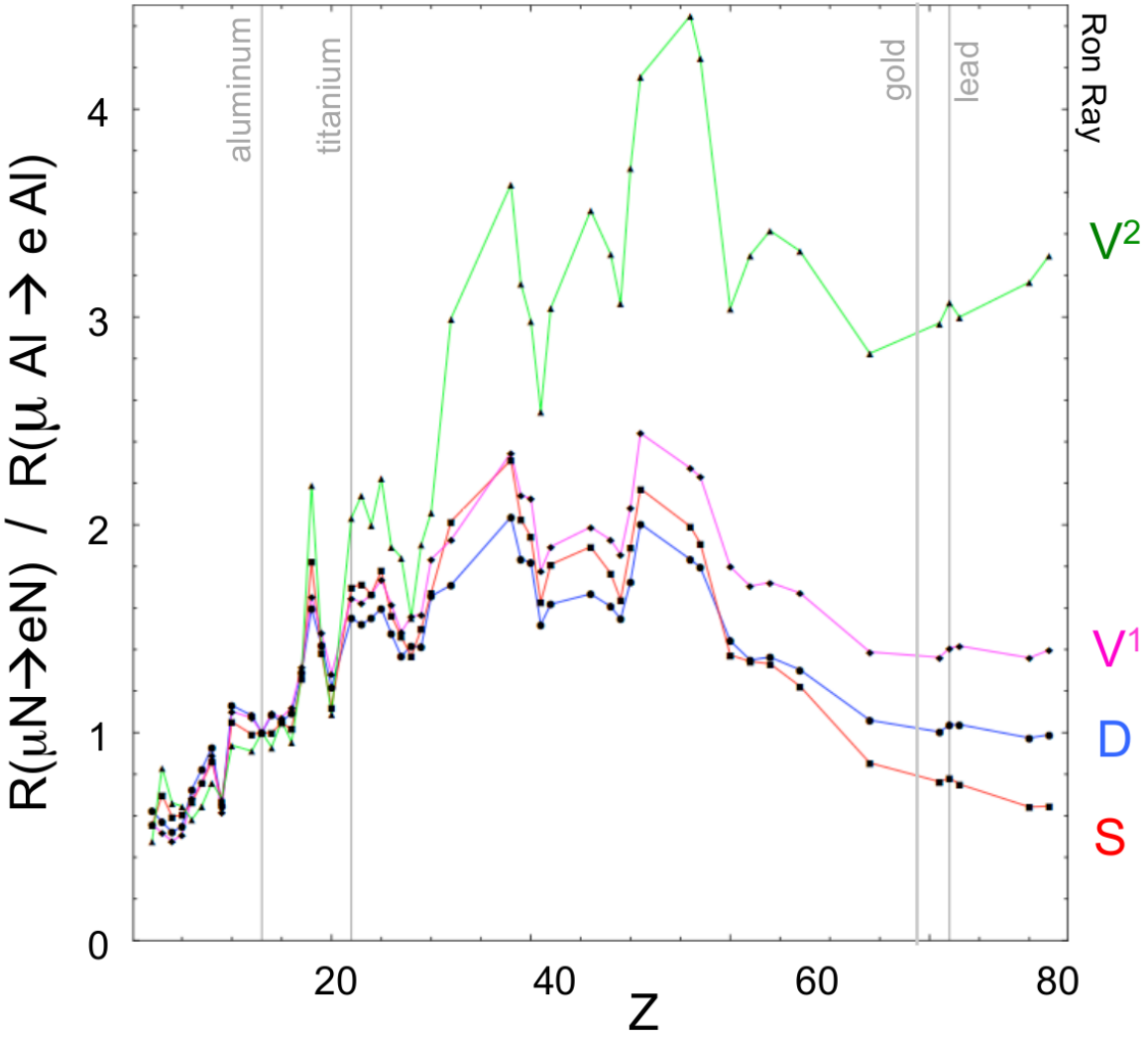
Spectrometer Magnet:
Repurposed dipole magnet bends out low energy elections generated by muons stopping in the upstream silicon

Types of CLFV measurements

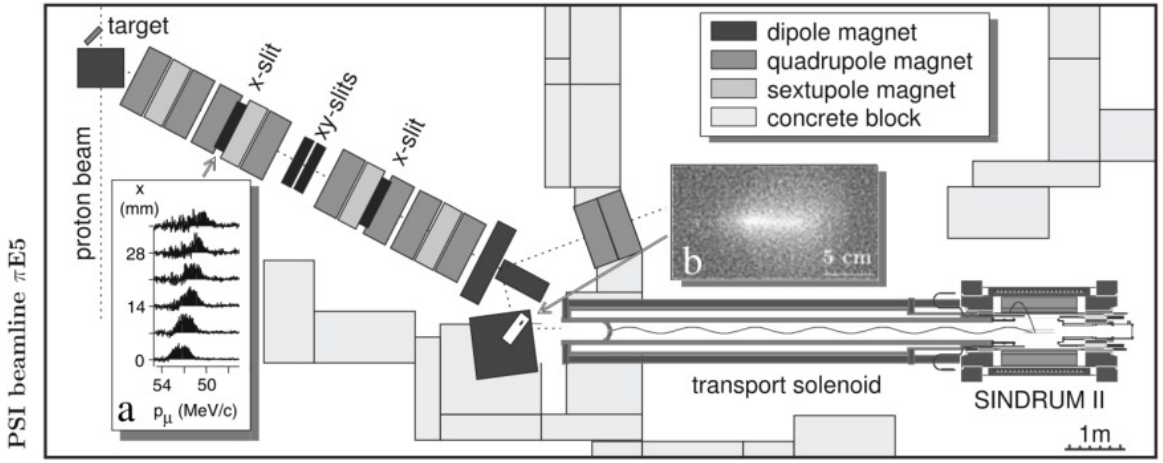
Process	Current Limit	Next Generation exp.
$\tau \to \mu\eta$	BR $<$ 6.5 E-8	10^{-9} - 10^{-10} (Belle II, LHCb)
$\tau \to \mu\gamma$	BR $<$ 6.8 E-8	
$\tau \to \mu\mu\mu$	BR $<$ 3.2 E-8	
$\tau \to$ eee	BR $<$ 3.6 E-8	
$K_L \to e\mu$	BR $<$ 4.7 E-12	
$K^+ \to \pi^+ e^- \mu^+$	BR $<$ 1.3 E-11	
$B^0 \to e\mu$	BR $<$ 7.8 E-8	
$B^+ \to K^+ e\mu$	BR $<$ 9.1 E-8	
$\mu^+ \to e^+\gamma$	BR $<$ 4.2 E-13	10^{-14} (MEG)
$\mu^+ \to e^+e^+e^-$	BR $<$ 1.0 E-12	10^{-16} (PSI)
$\mu^- N \to e^- N$	$R_{\mu e} <$ 7.0 E-13	10^{-17} (Mu2e, COMET)

Determining model with CLFV

V. Cirigliano, R. Kitano, Y. Okada, P. Tuzon, Phys. Rev. **D80** 013002 (2009)

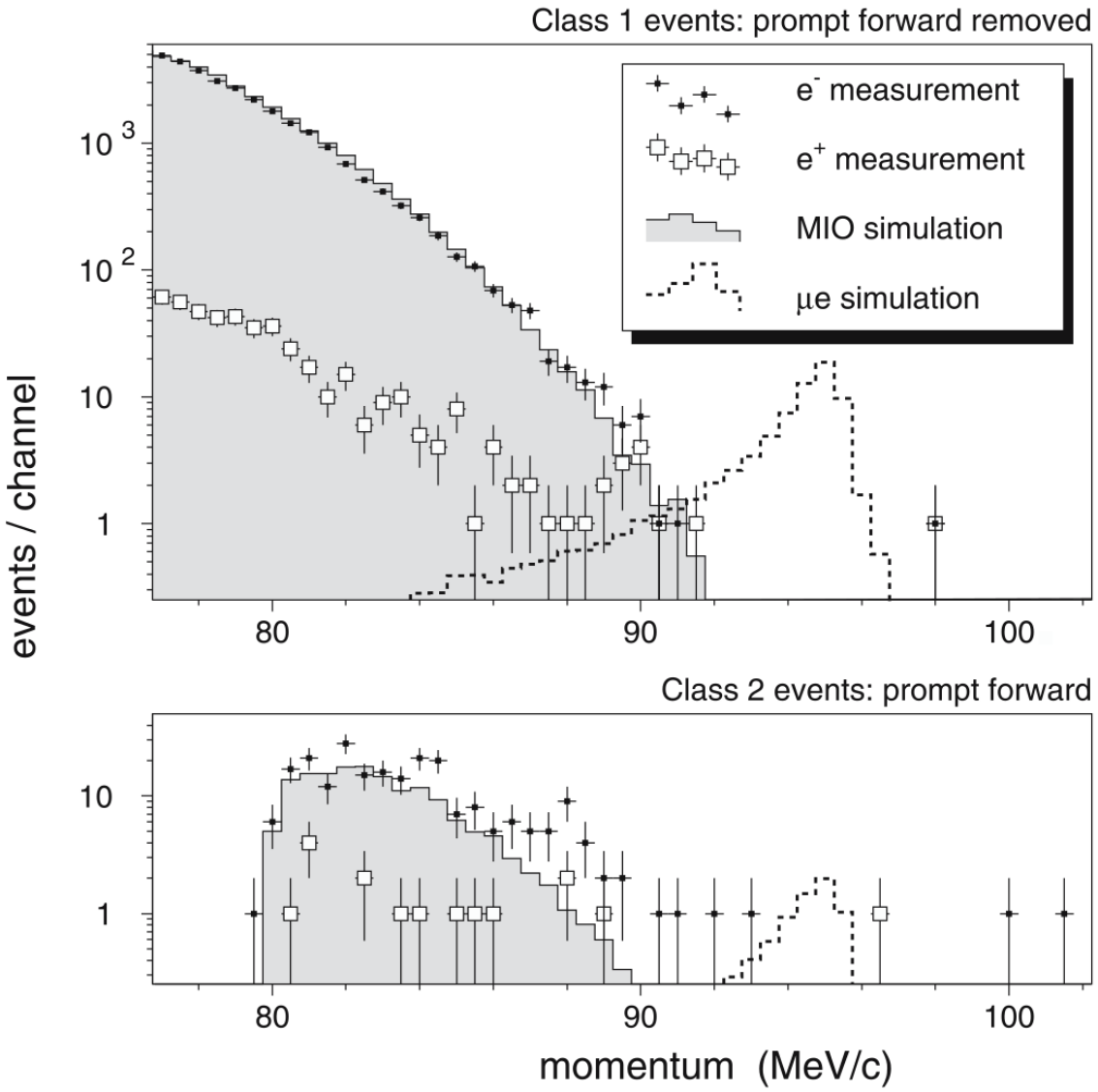


Previous experiments: SINDRUM II

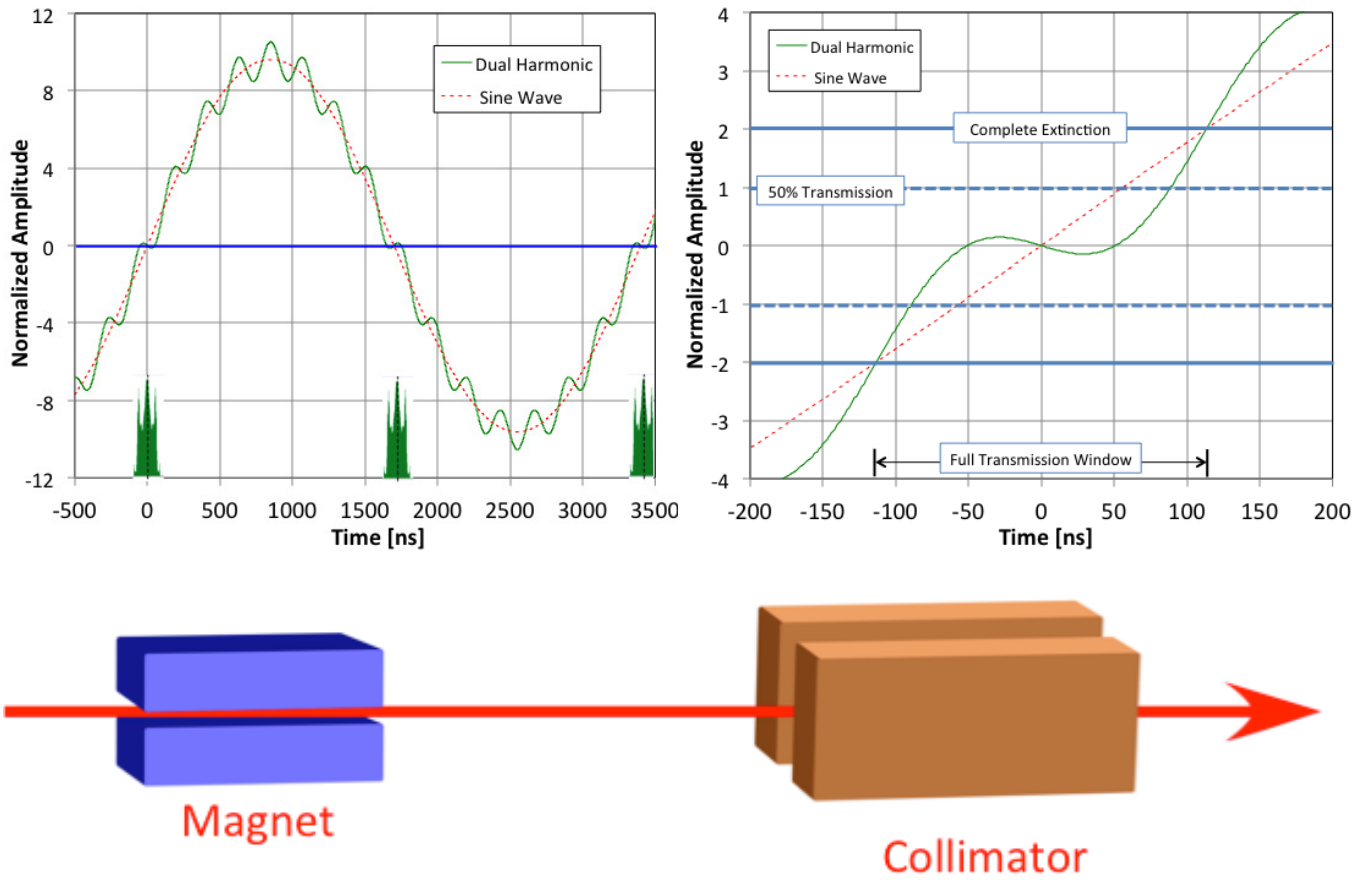


- Beam backgrounds reduced by degrader
  - Pions have half the range in CH_2 compared to muons
- Limit: 7×10^{-13} (90% confidence) on Au

Previous experiments: SINDRUM II

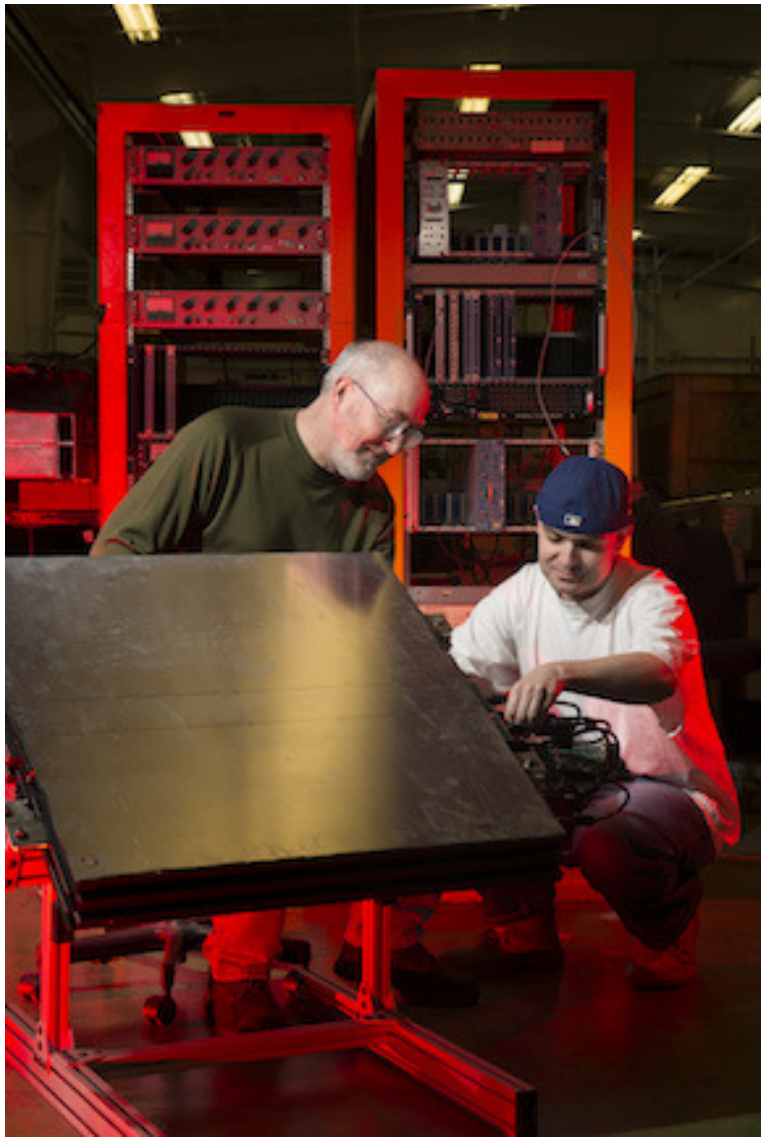


Achieving required beam extinction

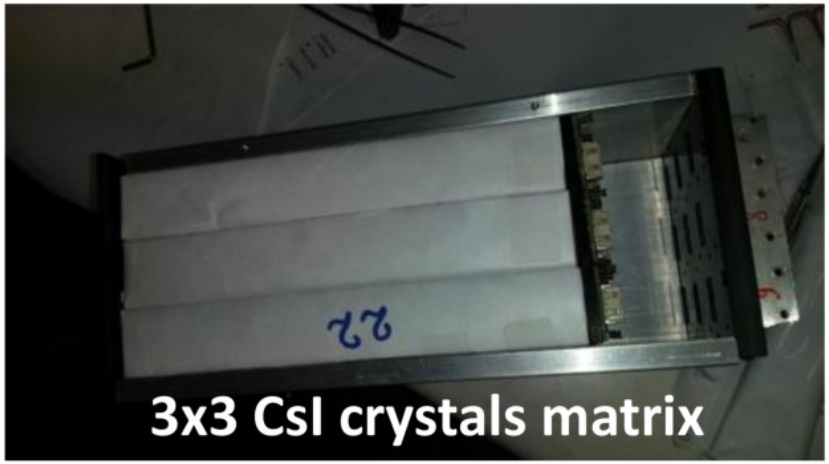


- Beam from delivery ring starts with 10^{-4} extinction
- 2 AC dipoles coupled with collimators expected to bring extinction to 10^{-12}

More prototypes



Cosmic ray veto



TS prototype module