Status of the Mu2e experiment at Fermilab

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SLAC FPD Seminar

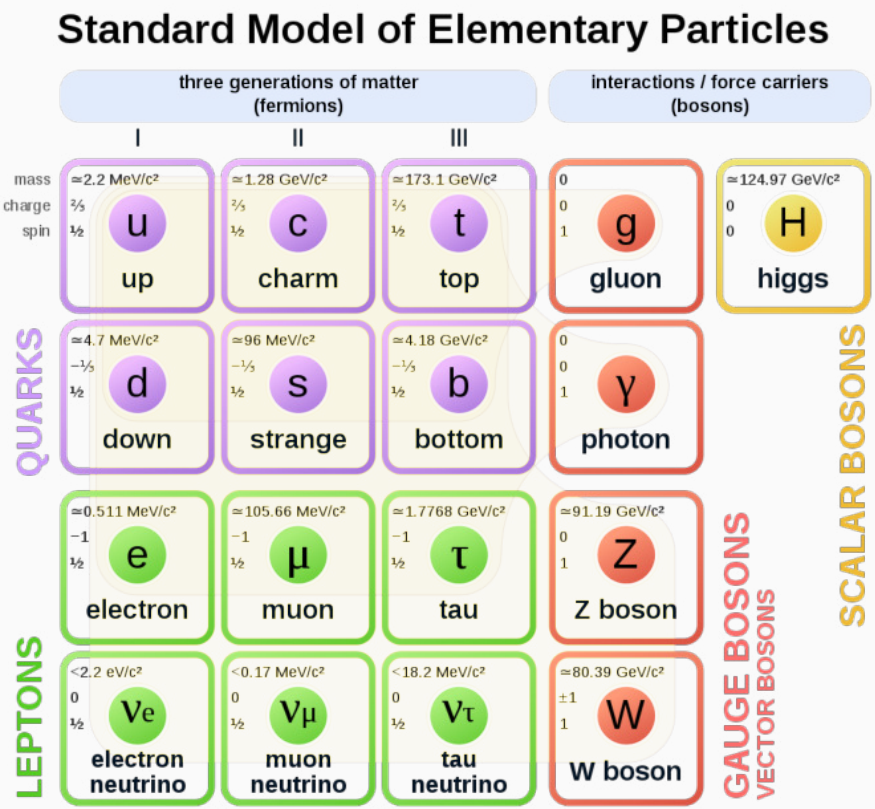
May 23rd, 2023

LBNL

Outline

- Charged Lepton Flavor Violation (CLFV) overview
- Mu2e overview
- Straw Tracker
  - Hardware design and testing
  - Track reconstruction
- Status of construction
- Future of muon physics

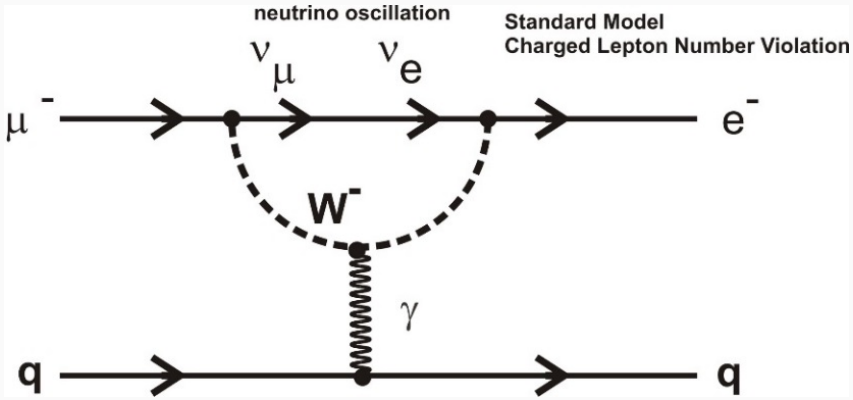
Standard Model: Very successful, but incomplete



- No dark matter candidate, no quantum theory of gravity
- No explanation of hierarchies, structure of flavor dynamics

- NLFV ✓, but CLFV has never been seen
- Neutrino oscillations imply CLFV

Charged Lepton Flavor Violation in the standard model



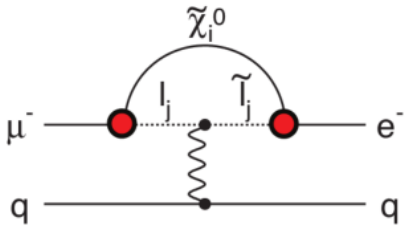
- Standard model CLFV contribution is undetectably small ($< 10^{-50}$)
- Any detection of charged lepton flavor violation would be an unambiguous sign of new physics!

CLFV is a powerful tool for new physics searches

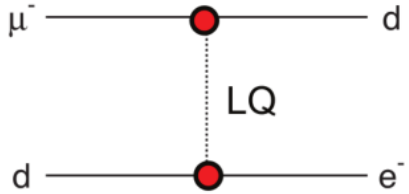
- Sensitive to a very broad range of models
- Probes very high mass scales
- Combining with other measurements reveals structure of new physics
- Hints of other lepton flavor physics? (g-2, lepton flavor universality violations)

Many possible sources of CLFV that can predict observables rates in next gen. experiments

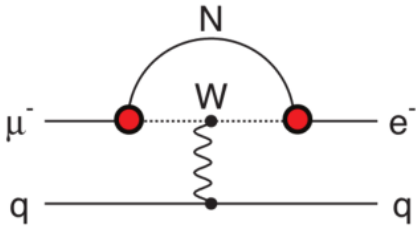
Supersymmetry



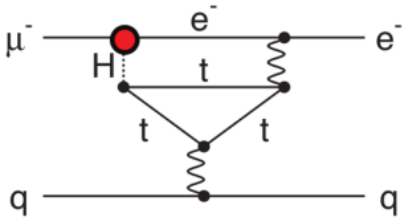
Leptoquark



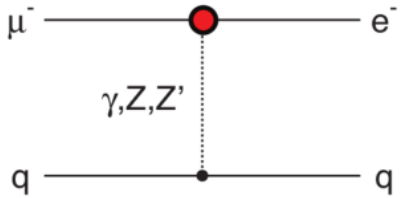
Heavy Neutrinos



Second Higgs Doublet

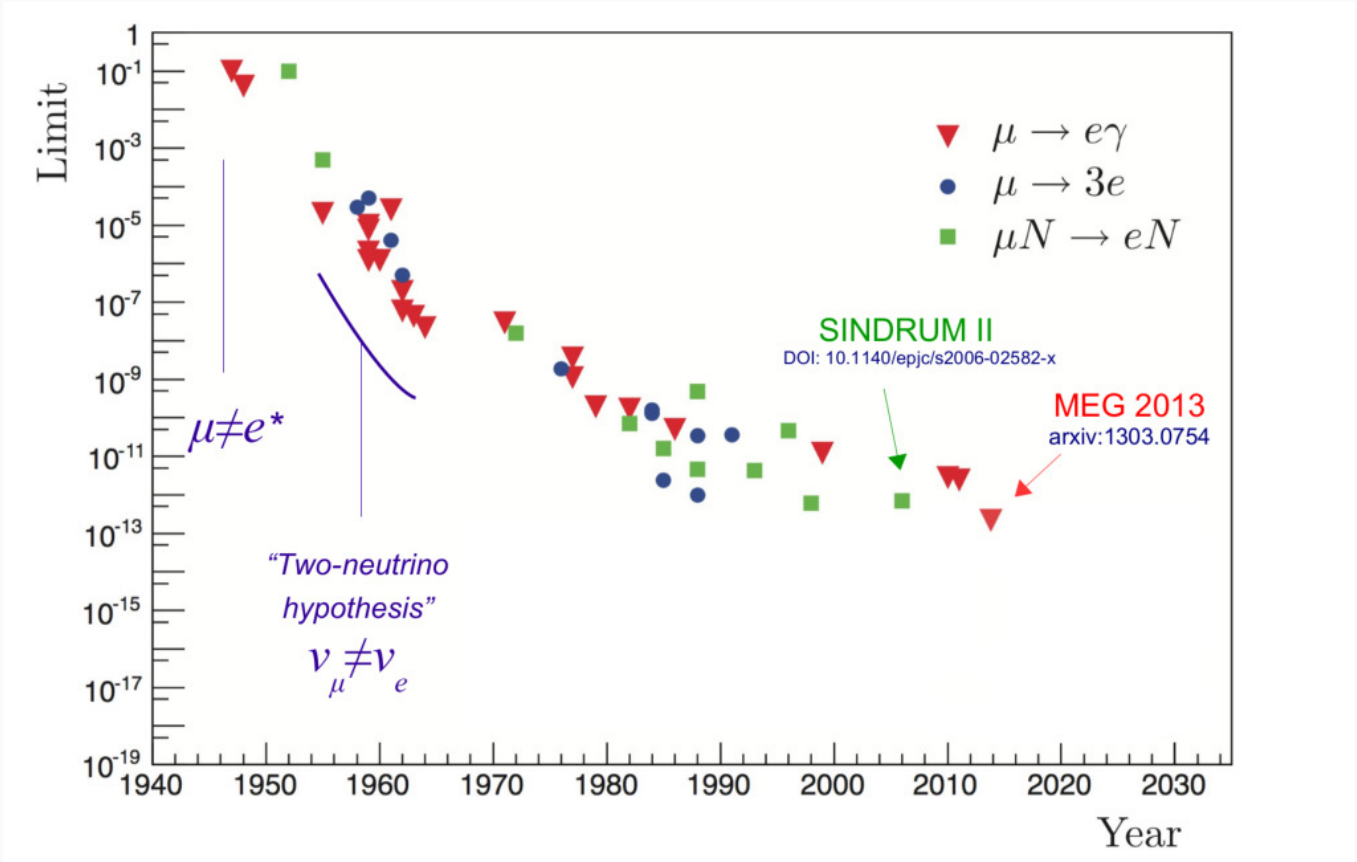


Heavy Z'
Anomal. Z Coupling

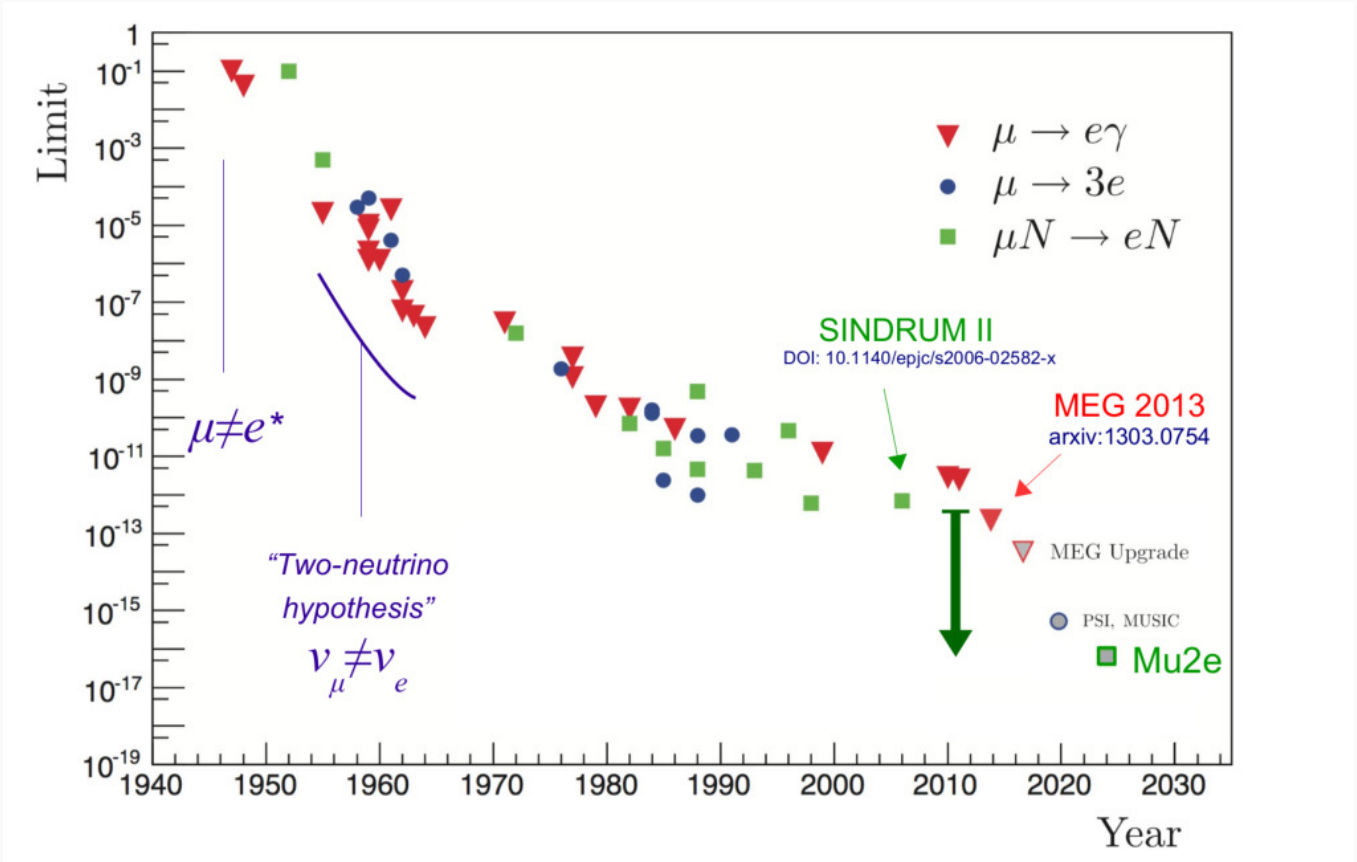


Kuno, Y. and Okada, Y. Rev. Mod. Phys. 73, 151 (2001)
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58 (2008)
M. Raidal et al, Eur.Phys.J.C57:13-182, (2008)
de Gouvea, A., and P. Vogel, Prog. Part. Nucl. Phys. 71, 75 (2013)

Search for CLFV has helped drive our understanding of lepton flavor



Search for CLFV has helped drive our understanding of lepton flavor

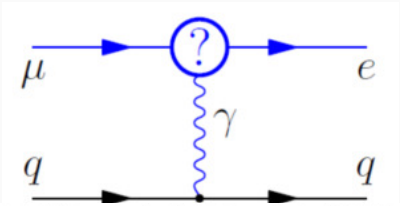


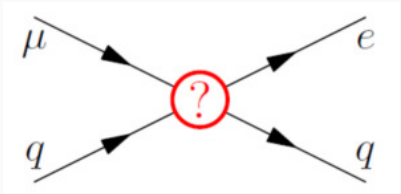
Comparing different methods: Muon searches reach the smallest branching ratio limits on CLFV processes

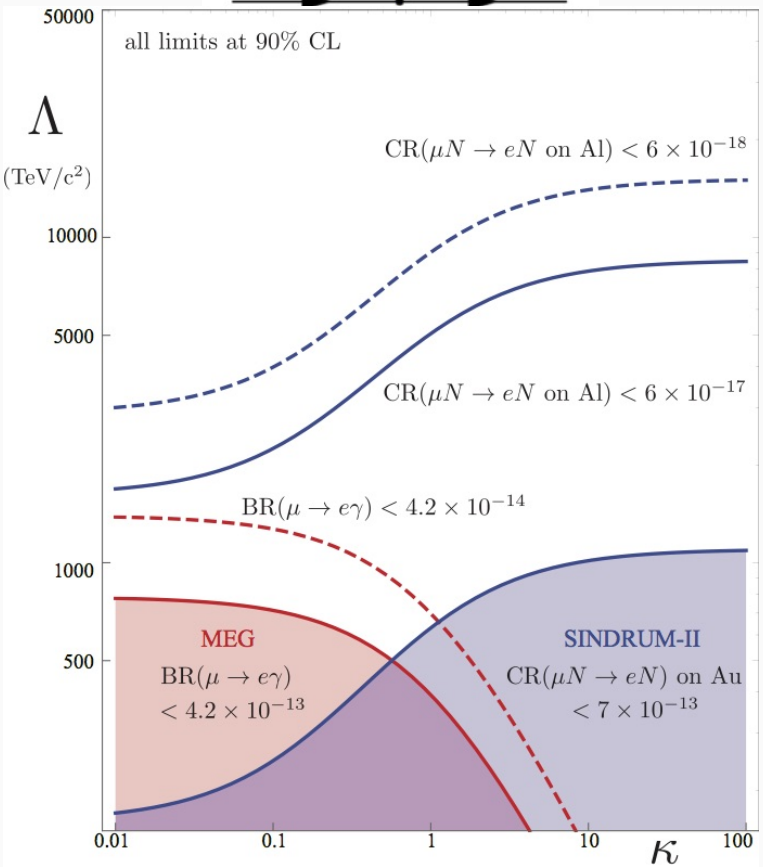
Process	Current Limit	Next Generation exp.
$\tau \to \mu\eta$	BR $< 6.5\times10^{-8}$	10^{-9} - 10^{-10} (Belle II, LHCb)
$\tau \to \mu\gamma$	BR $< 4.2\times10^{-8}$	
$\tau \to \mu\mu\mu$	BR $< 2.1\times10^{-8}$	
$\tau \to$ eee	BR $< 2.7\times10^{-8}$	
$K_L \to e\mu$	BR $< 4.7\times10^{-12}$	
$K^+ \to \pi^+ e^- \mu^+$	BR $< 1.3\times10^{-11}$	
$B^0 \to e\mu$	BR $< 1.0\times10^{-9}$	
$B^+ \to K^+ e\mu$	BR $< 6.4\times10^{-9}$	
$\mu^+ \to e^+\gamma$	BR $< 4.2 \times 10^{-13}$	10^{-14}(MEG)
$\mu^+ \to e^+e^+e^-$	BR $< 1.0 \times 10^{-12}$	10^{-16}(Mu3e)
$\mu^- N \to e^- N$	$R_{\mu e} < 7.0 \times 10^{-13}$	10^{-17}(Mu2e, COMET)

Mu2e sensitivity allows it to probe mass scales up to 10^4 TeV (assuming unit coupling)

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



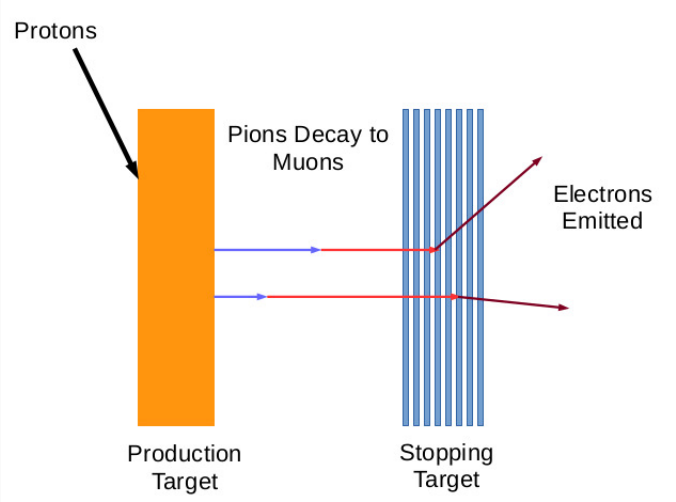


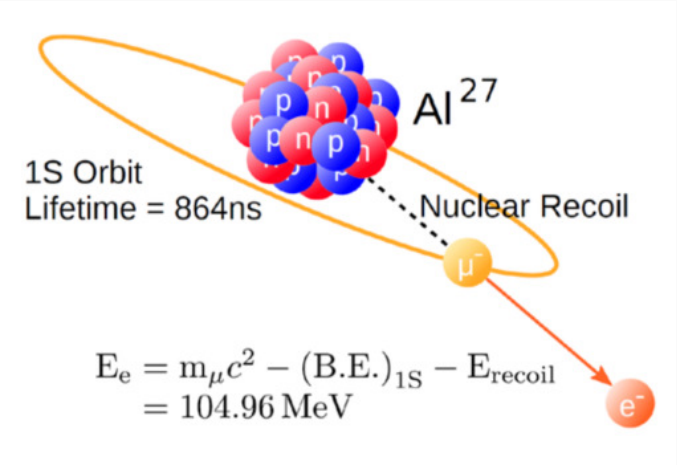


- loop: $\kappa \ll 1$, μN$\rightarrow e$N and $\mu \rightarrow e\gamma$
- contact: $\kappa \gg 1$, μN$\rightarrow e$N only
- Mu2e aims for 10^4 improvement over SINDRUM-II
- Mass scale reach makes these measurements complementary to LHC

Derived from A. de Gouvea, P. Vogl, Prog. Part. Nucl. Phys. 71 (2013) 75

Basics of a muon conversion experiment



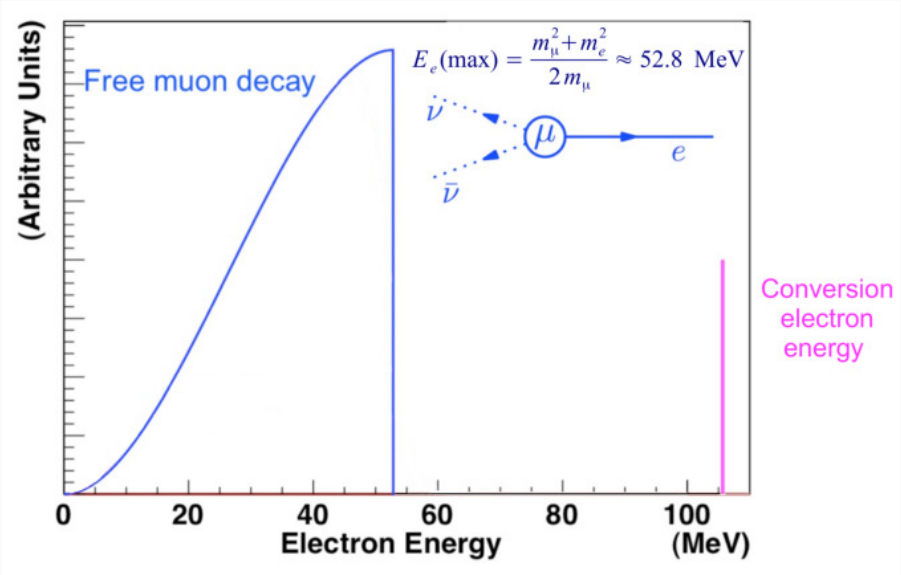


Measure the ratio of conversions to muon nuclear captures:

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

- Signal of CLFV conversion is single monoenergetic electron

Anything that can produce a ∼105 MeV electron can be a background to a μ to e conversion search



Robert Szafron and Andrzej Czarnecki, Phys. Rev. D 94, 051301 (2016)

Backgrounds

- Muon Decay in orbit (DIO): $\mu^- N \to e^- N \nu_\mu \overline{\nu_e}$
- Beam related: $\pi^- N \to \gamma N'$, $\gamma \to e^+ e^-$
- Cosmic rays: $\mu^- \to e^- \nu_\mu \overline{\nu_e}$

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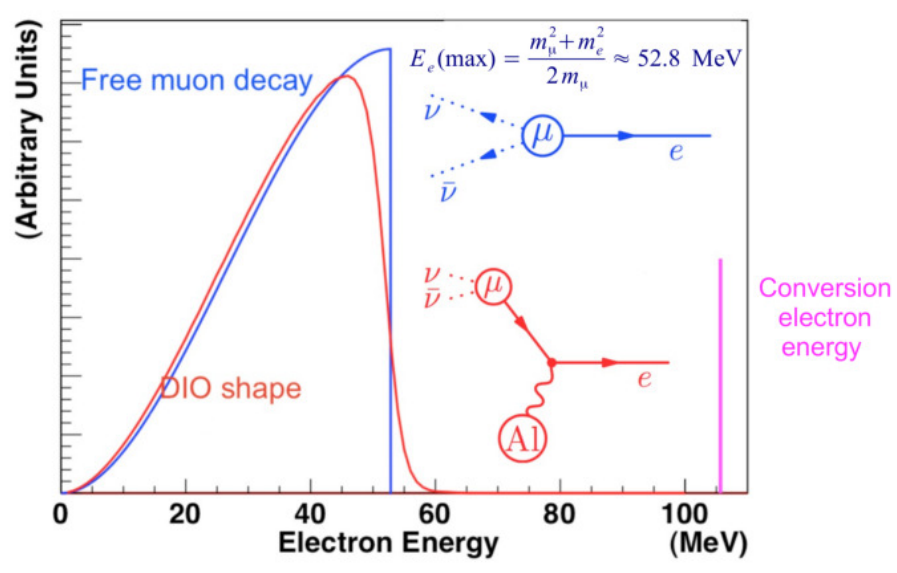

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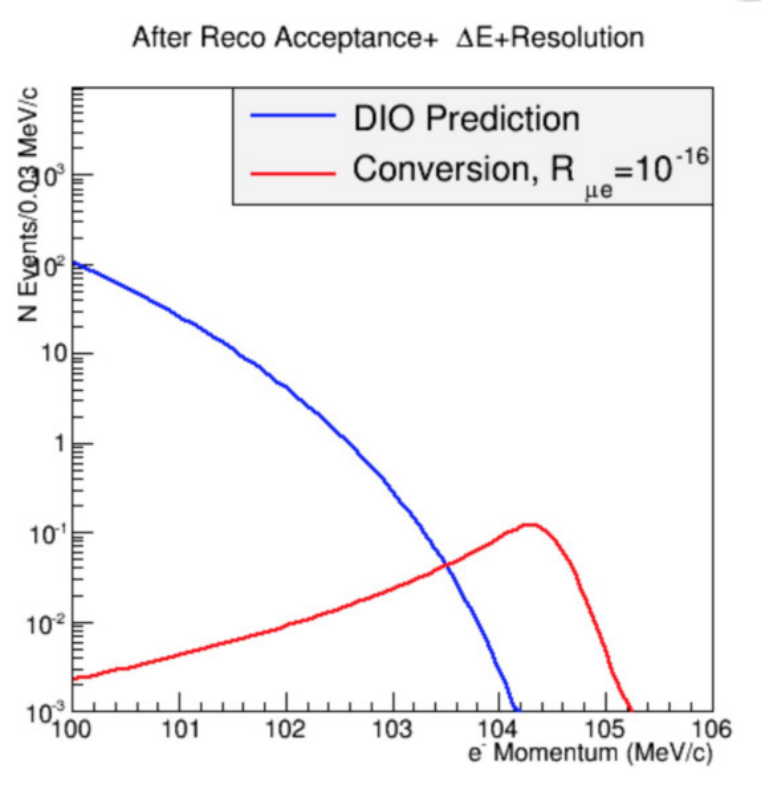
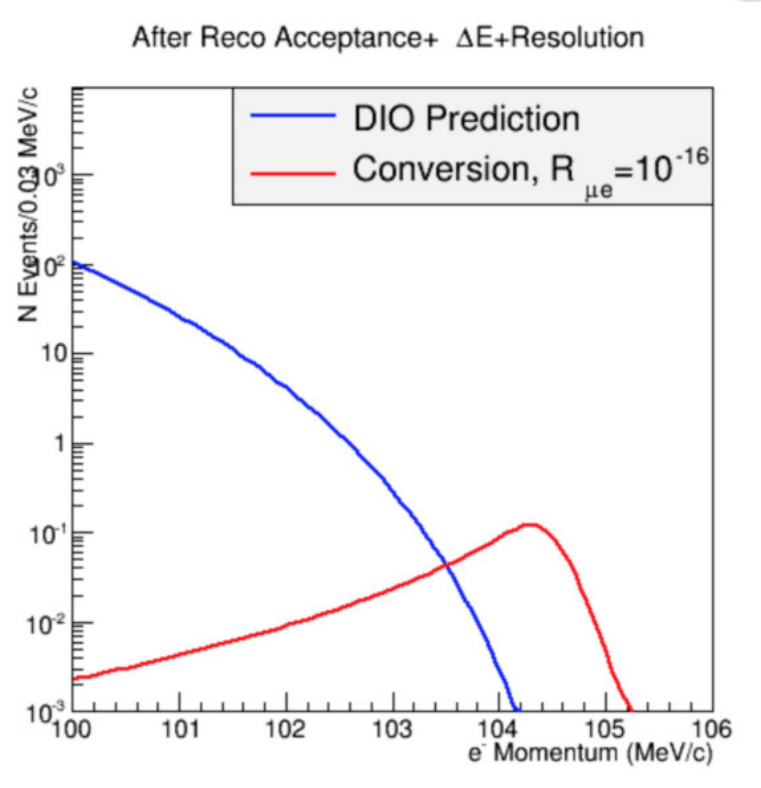


Backgrounds

- Muon Decay in orbit (DIO): $\mu^- N \to e^- N \nu_\mu \overline{\nu_e}$ (Momentum resolution)
- Beam related: $\pi^- N \to \gamma N'$, $\gamma \to e^+ e^-$
- Cosmic rays: $\mu^- \to e^- \nu_\mu \overline{\nu_e}$

Anything that can produce a ∼105 MeV electron can be a background to a μ to e conversion search



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- Beam related: $\pi^- N \to \gamma N'$, $\gamma \to e^+ e^-$ (Pulsed proton beam)
- Cosmic rays: $\mu^- \to e^- \nu_\mu \overline{\nu_e}$

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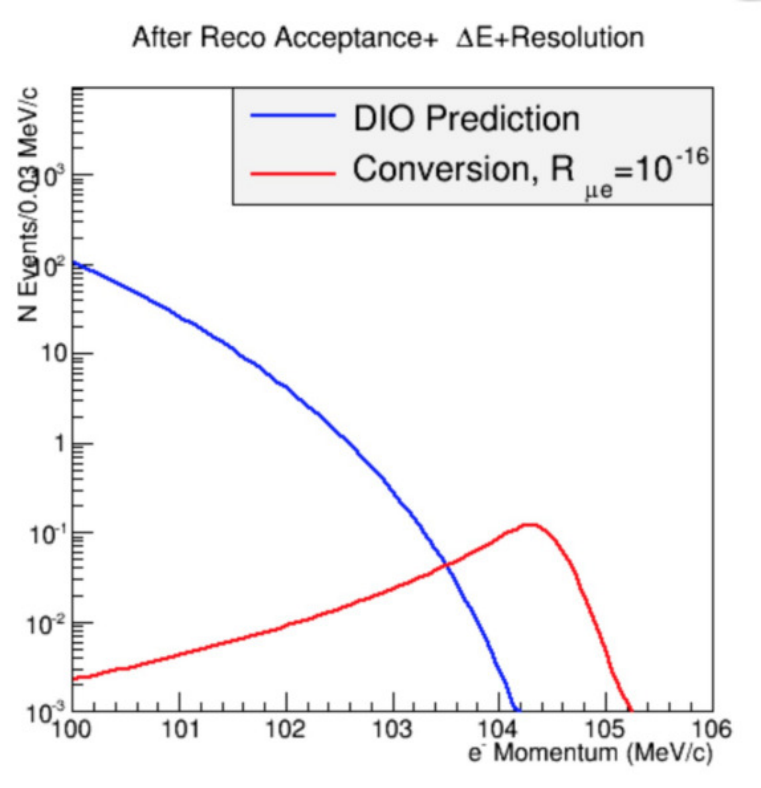

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- Beam related: $\pi^- N \to \gamma N'$, $\gamma \to e^+ e^-$ (Pulsed proton beam)
- Cosmic rays: $\mu^- \to e^- \nu_\mu \overline{\nu_e}$ (Active veto)

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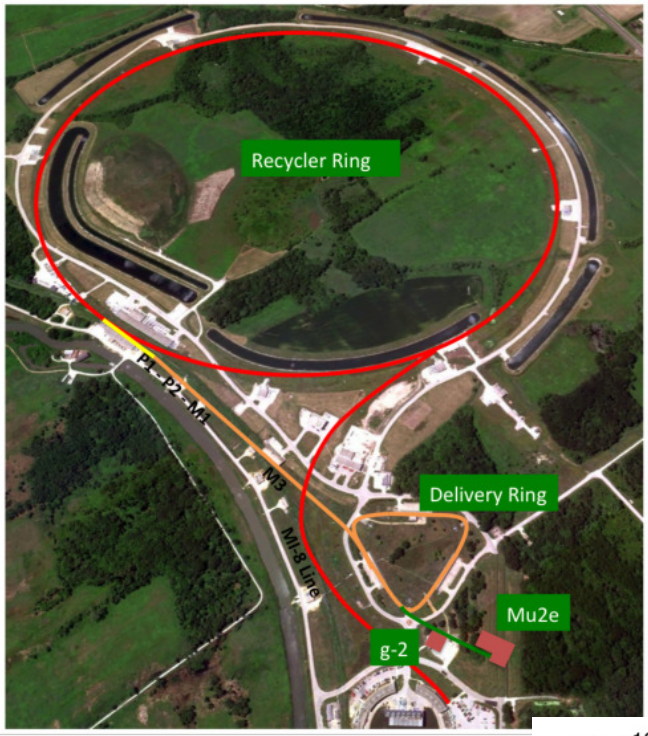
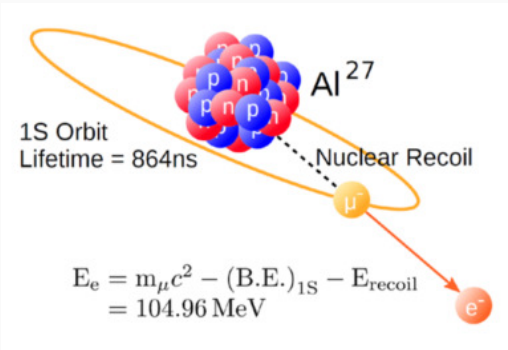
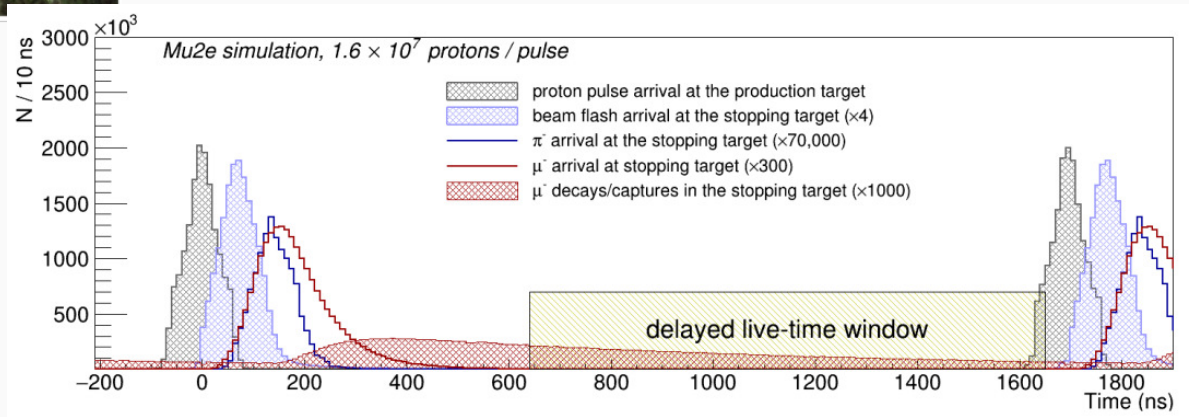
Pulsed proton beam allows us to reject radiative pion capture events ($\pi^- + \mathrm{Al} \rightarrow \mathrm{Mg}^\star + \gamma$)

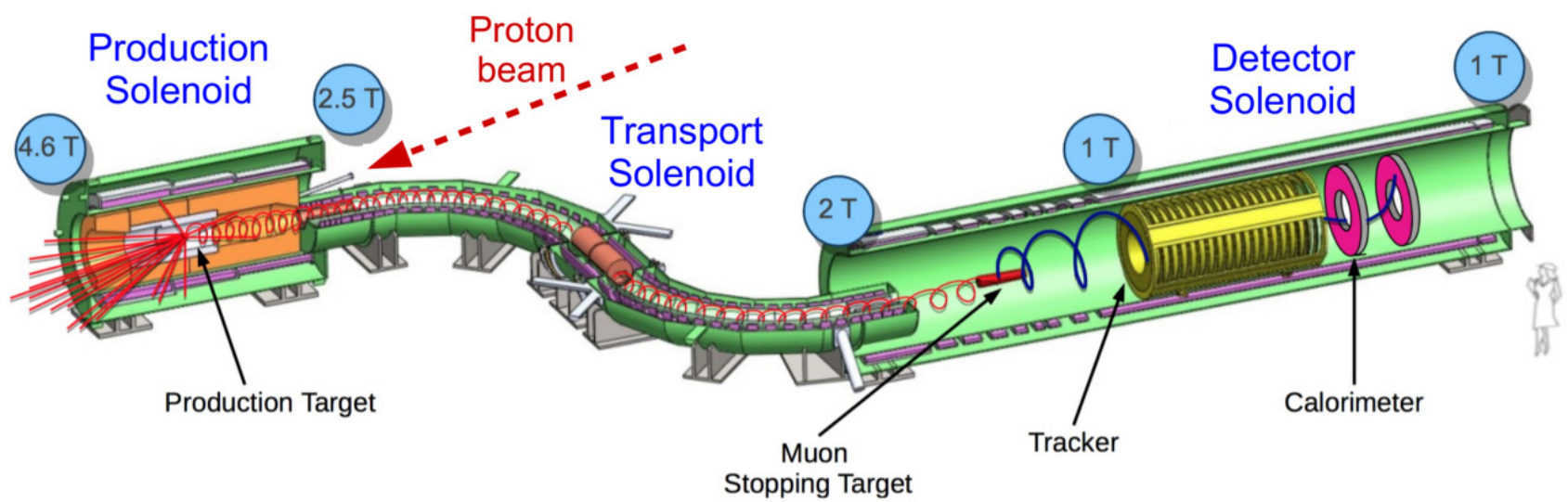


- 8 GeV 8 kW proton beam from Fermilab booster
- Resonantly extracted to get pulses of protons separated by 1.7 μs
- 700 ns delay followed by 1 μs livegate
- Must have very few protons outside of pulse (ratio to in-pulse $< 10^{-10}$)





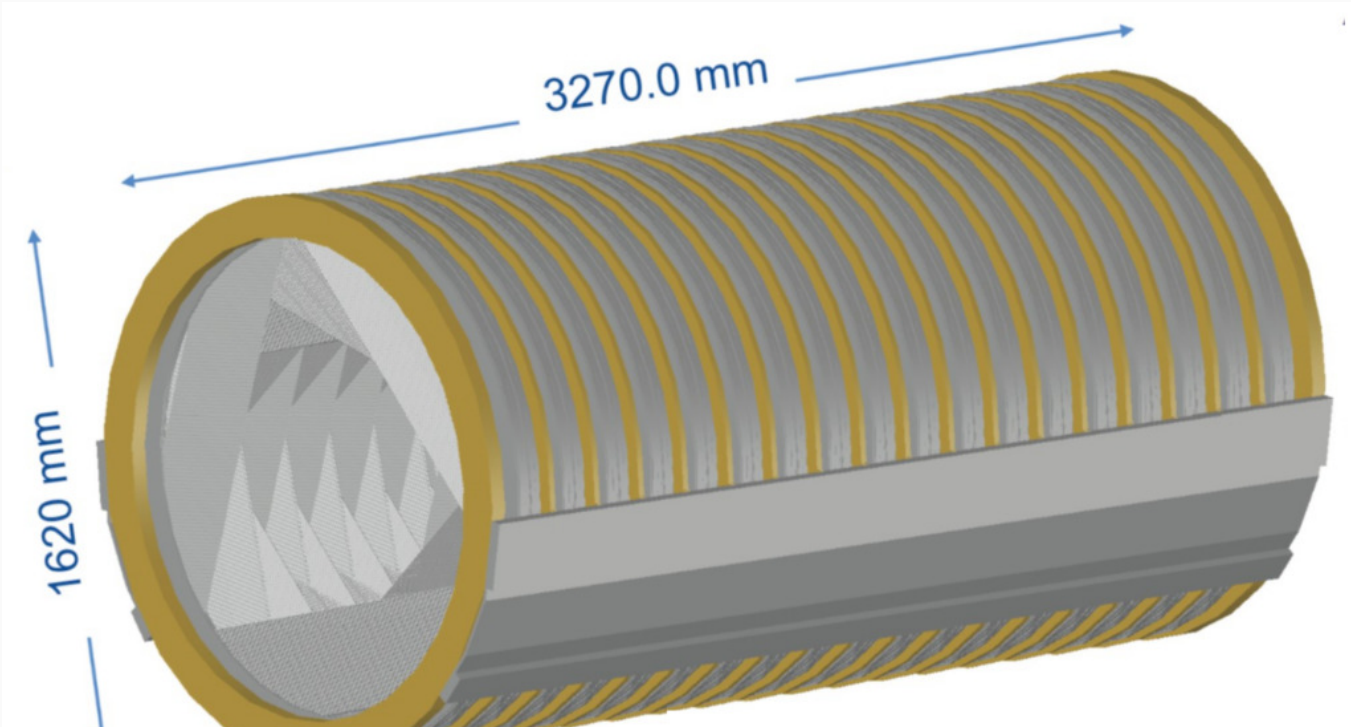
Mu2e experimental setup

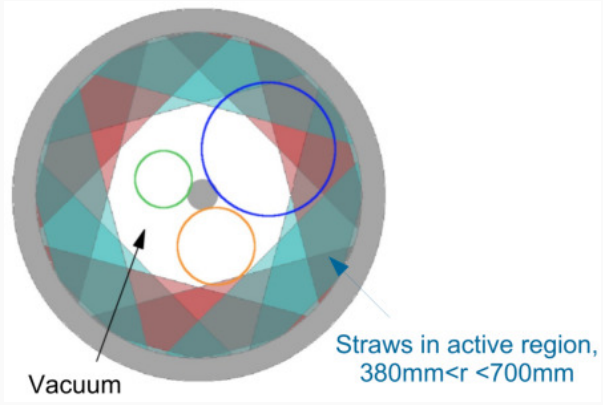


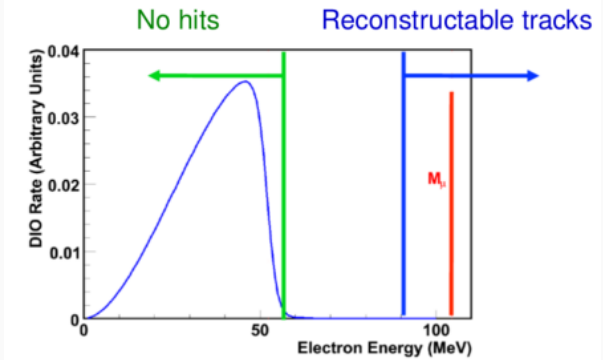
- Production solenoid
  - Proton beam hits tungsten production target
  - Magnetic mirror directs low momentum pions/muons to transport solenoid
- Transport solenoid
  - S-shape sign and momentum selects
- Detector solenoid
  - Muons stop on Al target, muonic decay or convert
  - Resulting electrons detected by straw tracker and electromagnetic calorimeter
  - Look for 105 MeV electrons

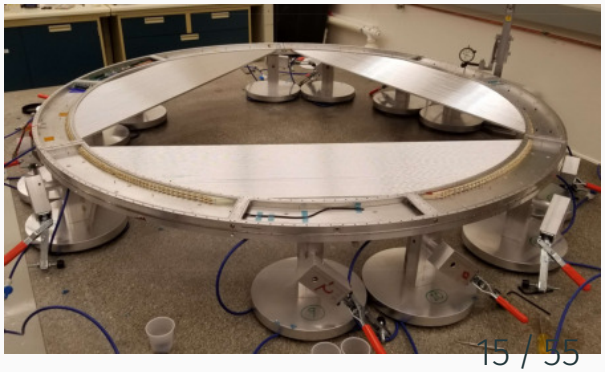
Detectors: Straw tracker for high precision momentum measurement

- 36 planes, each containing 6× 120° panels for stereo measurement
- Each panel contains 96 straws for a total of 21,000
- Blind to DIO electron momentum peak and beam flash
- Momentum resolution better than 200 keV



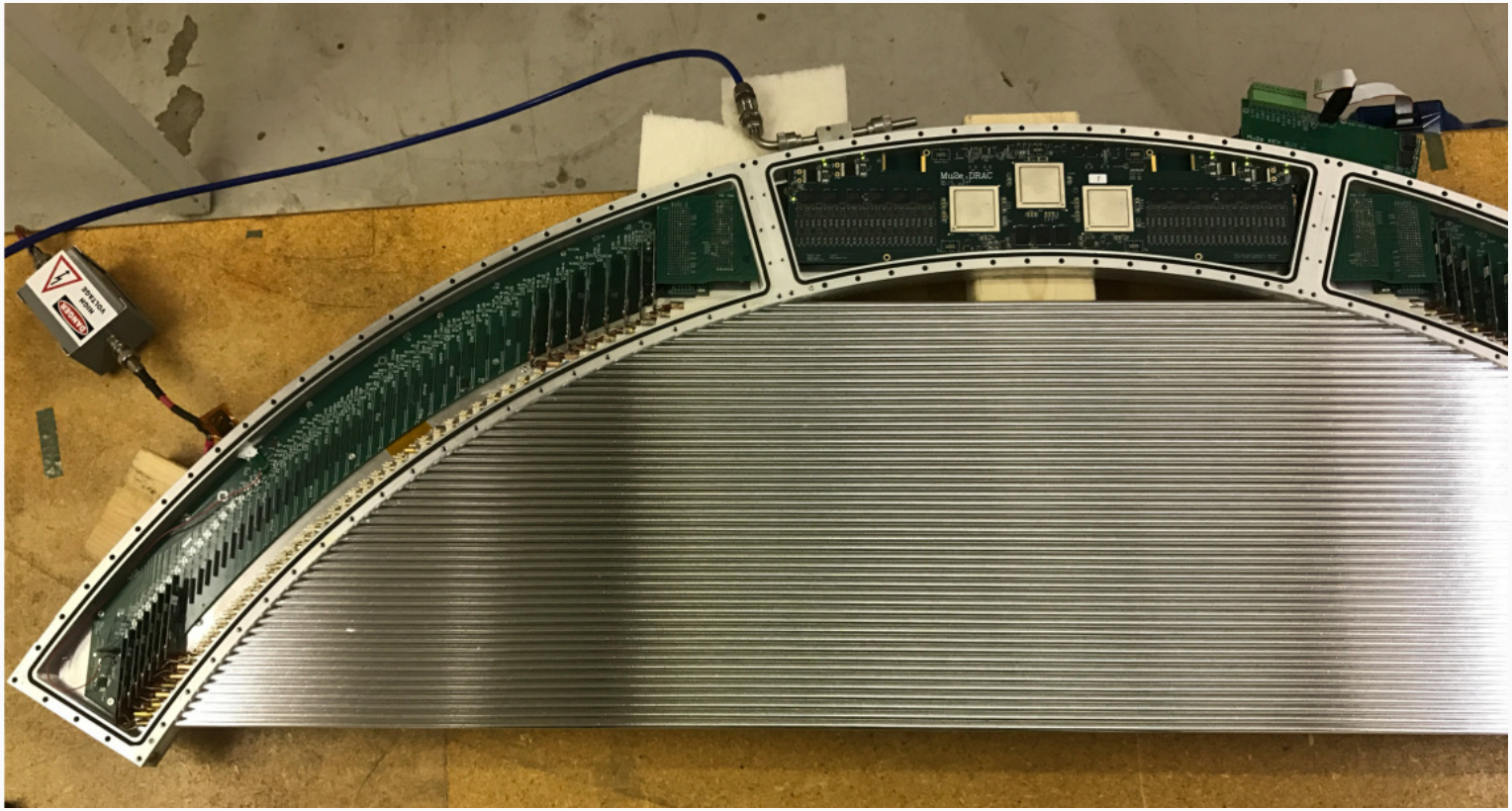




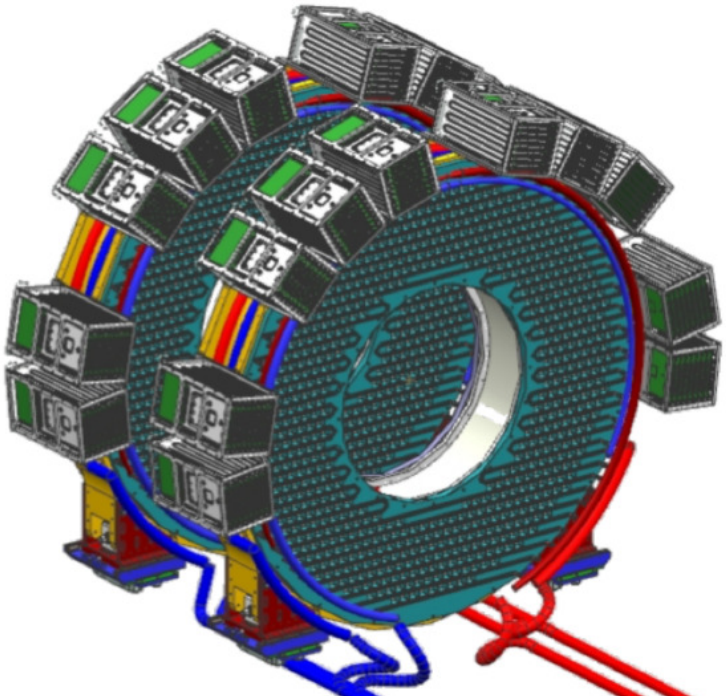


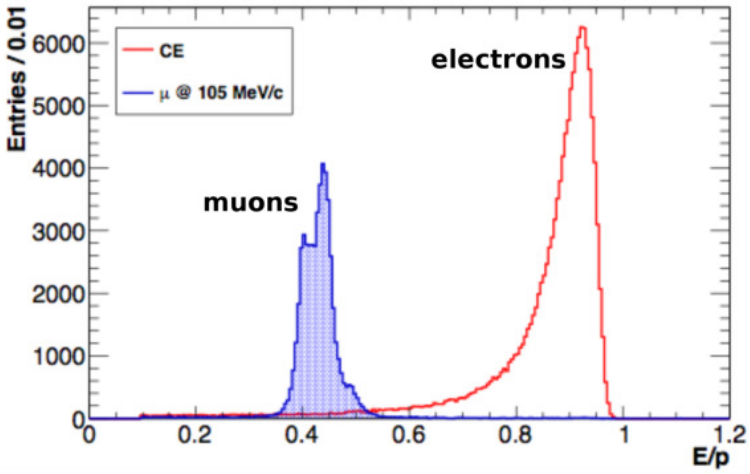
Detectors: Straw tracker for high precision momentum measurement

- Tracker sits in vacuum, straws held at tension
- 5 mm diameter, 15 μm thick mylar walls



Detectors: Calorimeter for particle ID

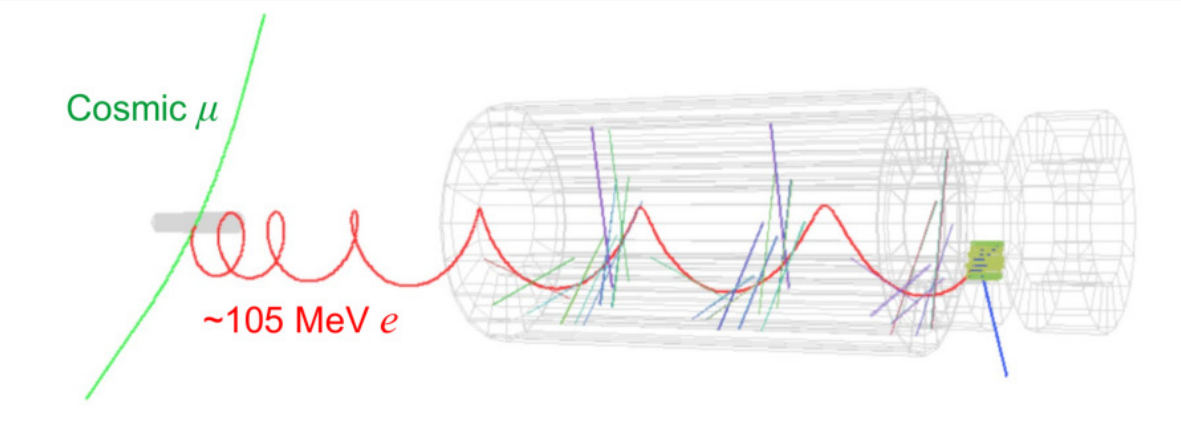




- Two annular disks separated by half a "wavelength" (70cm) of electron's helical path
  - Maximize probability to hit at least one disk
- Each disk contains 674 undoped CsI 34x34x200 mm^3 crystals read out by SiPMs
- 0.5 ns time, 10% energy, 1 cm position measurement independent of straw tracker
- $> 200\times$ rejection of muons
- Seed for tracking algorithm

Detectors: CRV to reject cosmic backgrounds

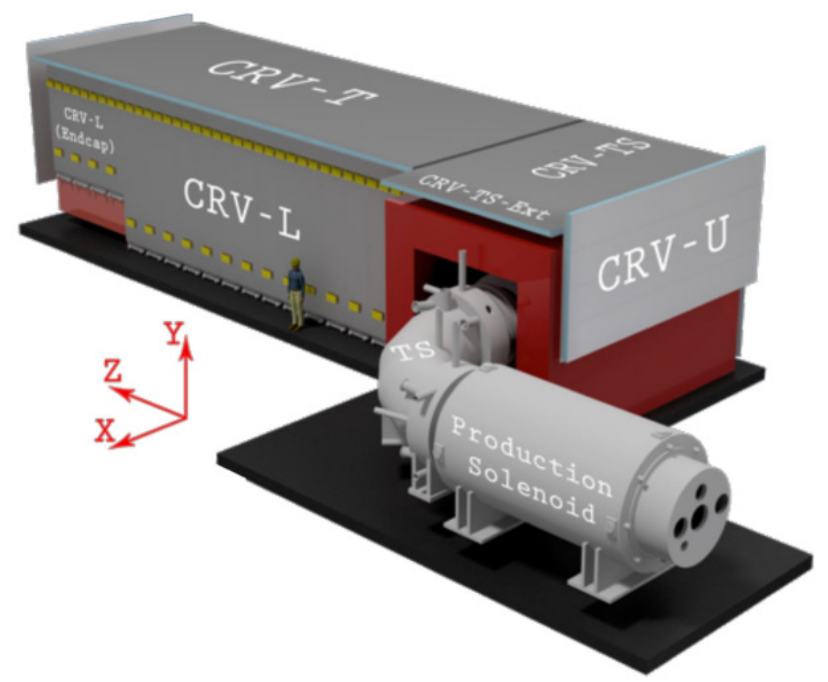
- Cosmic muon track can look like 105 MeV/c electron (mitigated by Calorimeter PID)
- Or - cosmic muon can decay inside the detector volume or knock out electron from stopping target $\rightarrow$ indistinguishable from signal

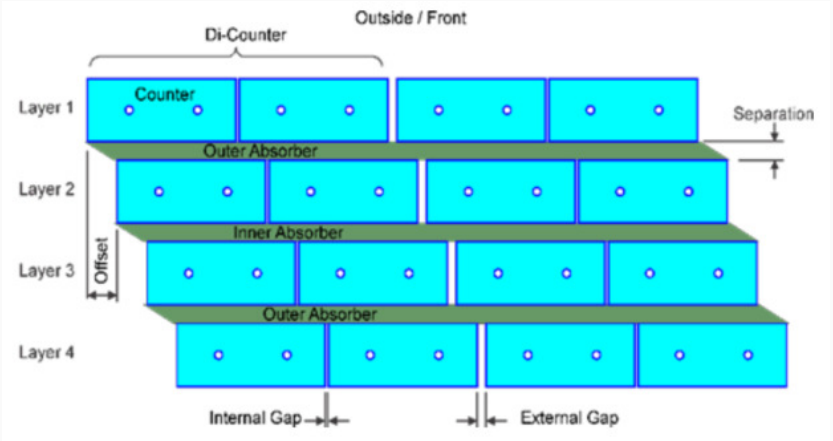


- Expect 1 such event per day
- Need highly efficient cosmic ray veto

Detectors: CRV to reject cosmic backgrounds

- 4 overlapping layers of scintillator, read out on both ends with SiPMs
  - Veto on 3-fold coincidence
- Covers entire DS, half of TS, better than 10^{-4} inefficiency





Run-I sensitivity analysis

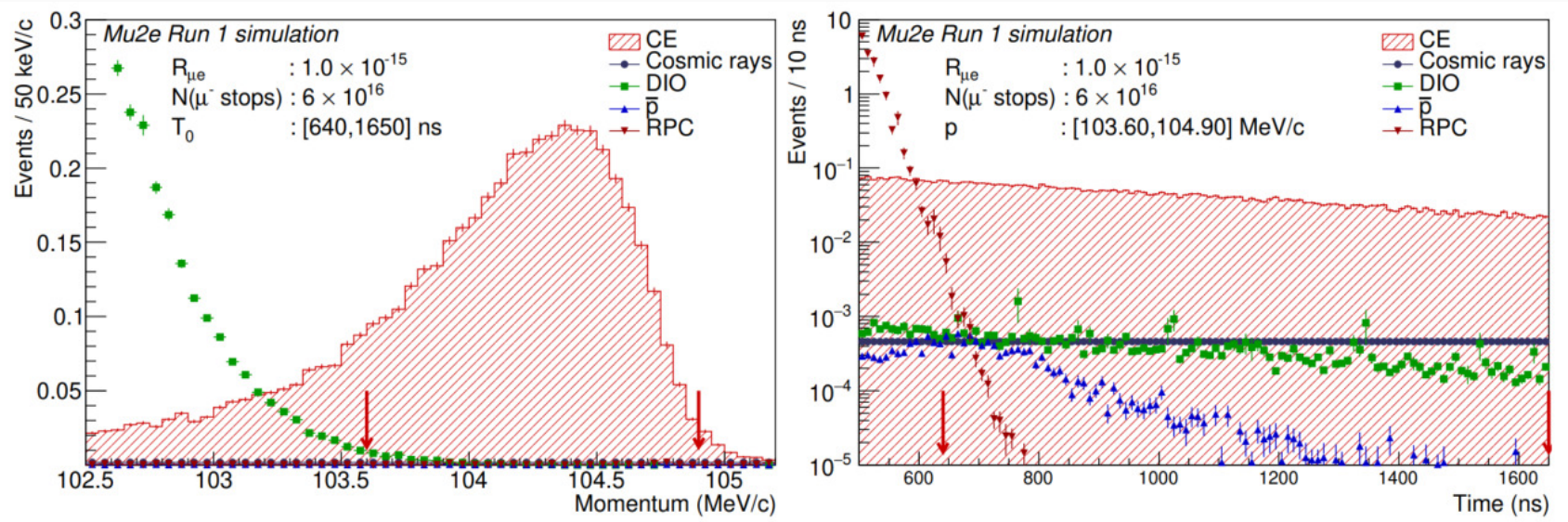
- Expect two running periods, separated by approximately 2 year long shutdown for the PIP-II beam upgrade
  - First run in 2026-2027
- Recently published sensitivity analysis for run I, assuming 3.8e19 POT (∼10% of expected total)

  Universe 2023, 9, 54
- Expected backgrounds in run I:

Channel	**Mu2e Run I**
SES	2.4×10^{-16}
Cosmic rays	$0.046 \pm 0.010\ (\text{stat}) \pm 0.009\ (\text{syst})$
DIO	$0.038 \pm 0.002\ (\text{stat})\ ^{+0.025}_{-0.015}\ (\text{syst})$
Antiprotons	$0.010 \pm 0.003\ (\text{stat})\ \pm 0.010\ (\text{syst})$
RPC in-time	$0.010 \pm 0.002\ (\text{stat})\ ^{+0.001}_{-0.003}\ (\text{syst})$
RPC out-of-time ($\zeta = 10^{-10}$)	$(1.2 \pm 0.1\ (\text{stat})\ ^{+0.1}_{-0.3}\ (\text{syst})) \times 10^{-3}$
RMC	$< 2.4 \times 10^{-3}$
Decays in flight	$< 2 \times 10^{-3}$
Beam electrons	$< 1 \times 10^{-3}$
Total	0.105 ± 0.032

Run-I sensitivity analysis

- Discovery reach (5σ): $R_{\mu e} \geq 1.2 \times 10^{-15}$
- Exclusion power (90% CL): $R_{\mu_e} \geq 6.2 \times 10^{-16}$
- Run II data taking starting in 2029 to reach additional order of magnitude improvement in sensitivity (10^4 over SINDRUM-II)



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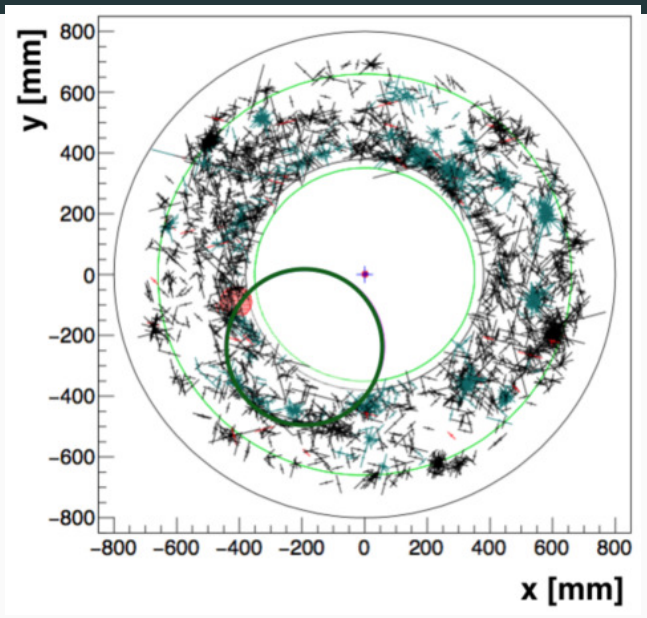
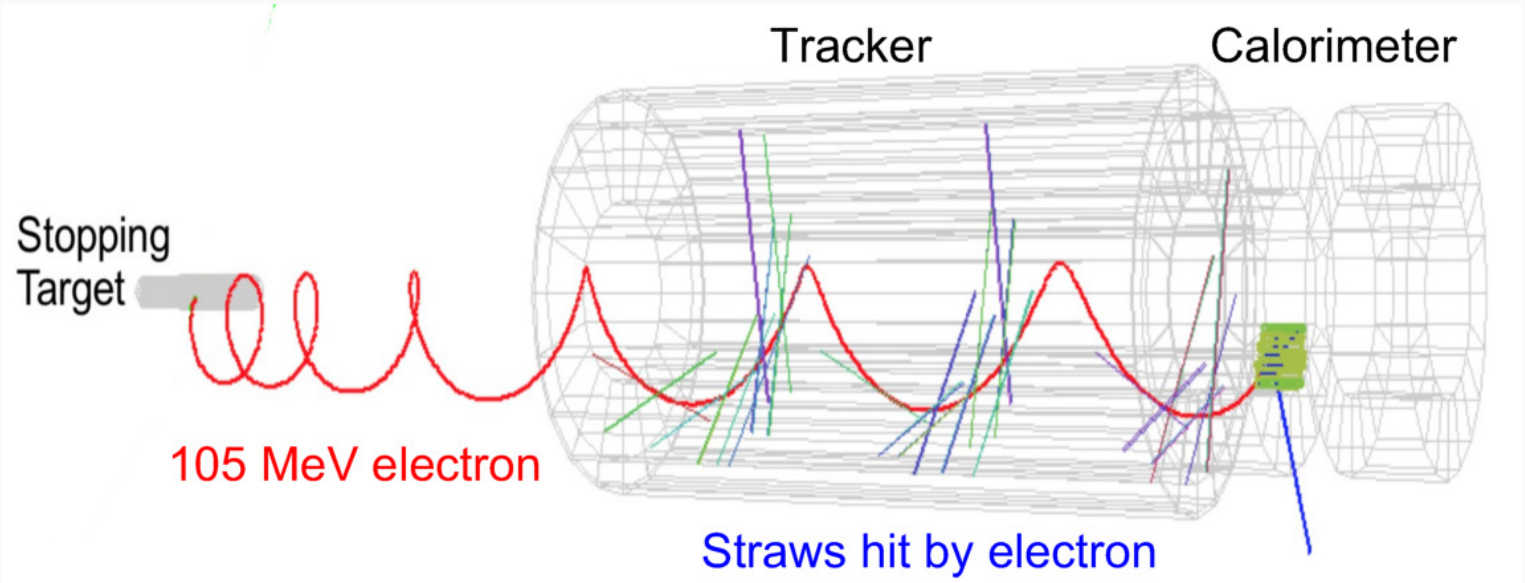
The Mu2e tracking environment

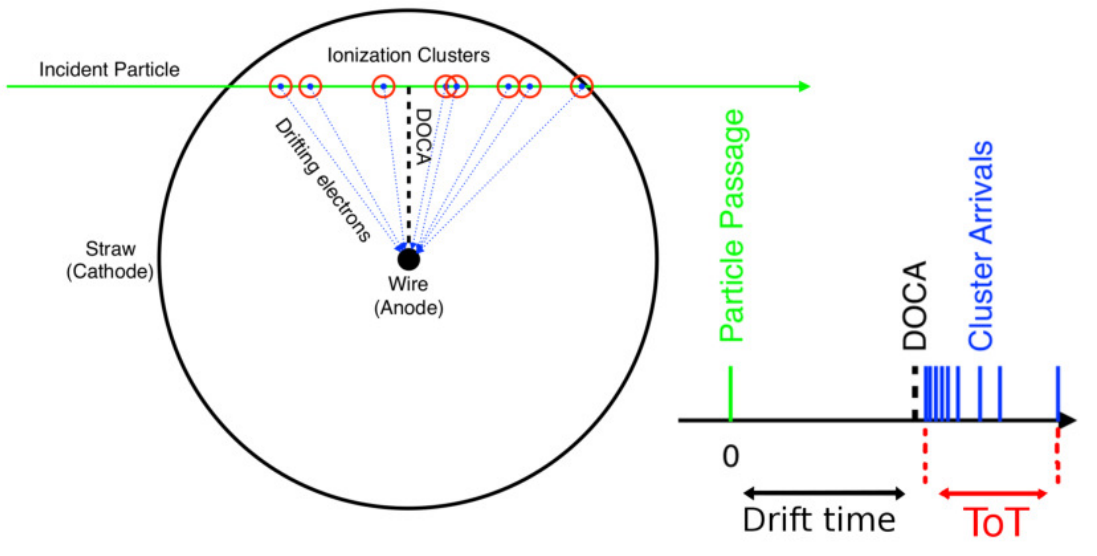
- 105 MeV signal makes 1.5-3 turns
  - ∼40 straws hit on average
- High pileup rate (∼100 KHz/straw)
  - >5 GHz of stopped muons
  - No hardware trigger
- No external or event t_0 constraint
  - muons are pulsed, but decay time is random

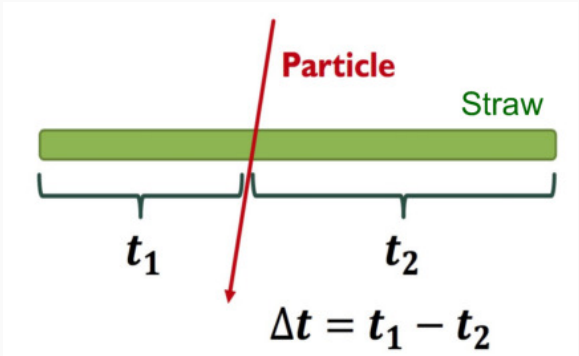


Simulated straw hits in one event with CE (green line)



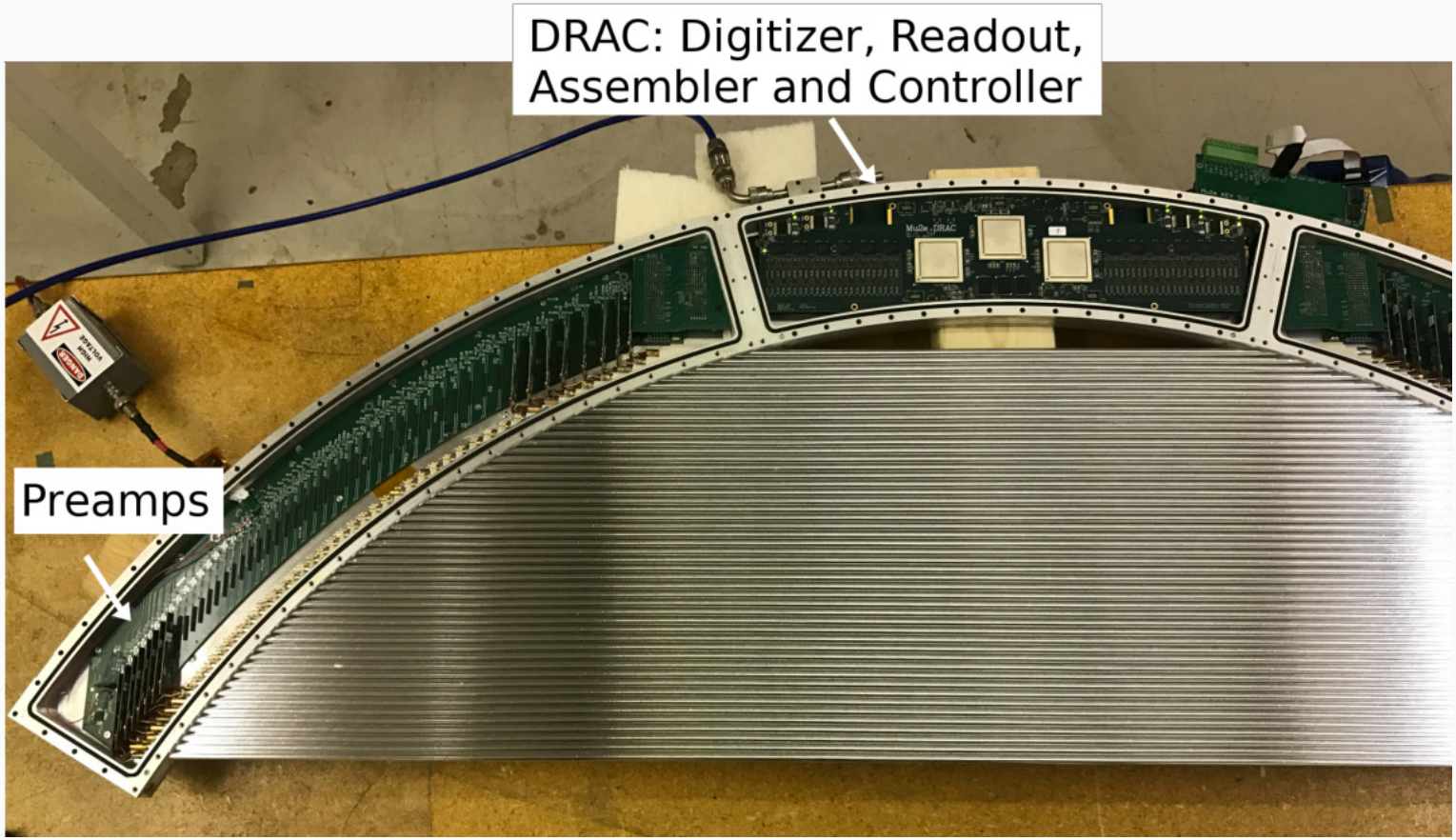
Measurements from each hit straw





- Drift time $\rightarrow$ radial resolution $\sim$250 μm (requires t_0)
- Time-over-threshold $\rightarrow$ Measure of path length / radius independent of t_0
- Time division $\rightarrow$ longitudinal resolution $\sim$4 cm
- Digitize waveform to reject highly ionizing backgrounds

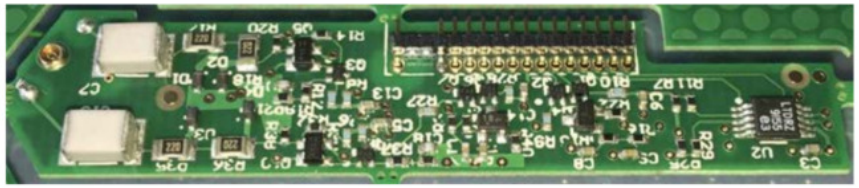
Front end electronics positioned directly next to straws inside vacuum



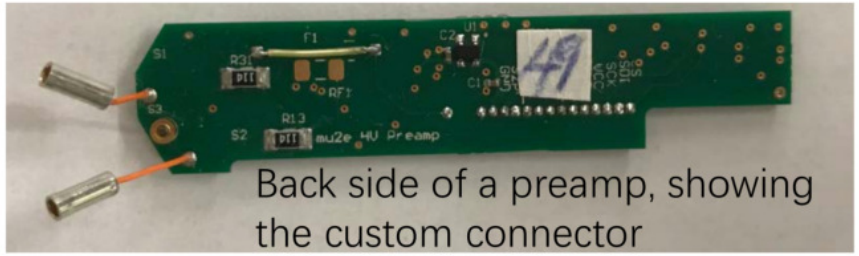
- Preamps on both ends of each straw
- Single digitization and readout board for each panel

Front end electronics: preamps

- Compact vertical installation
- Custom connectors to straws
- Custom HV fuse
- Charge injection for calibration



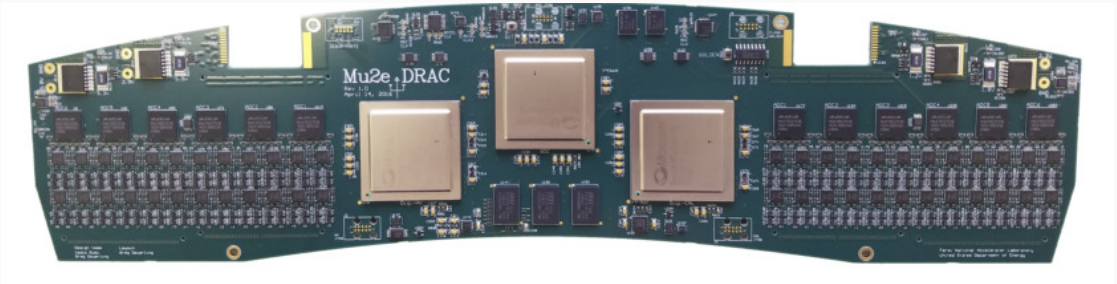
Front side of a preamp. Each preamp serves two straws

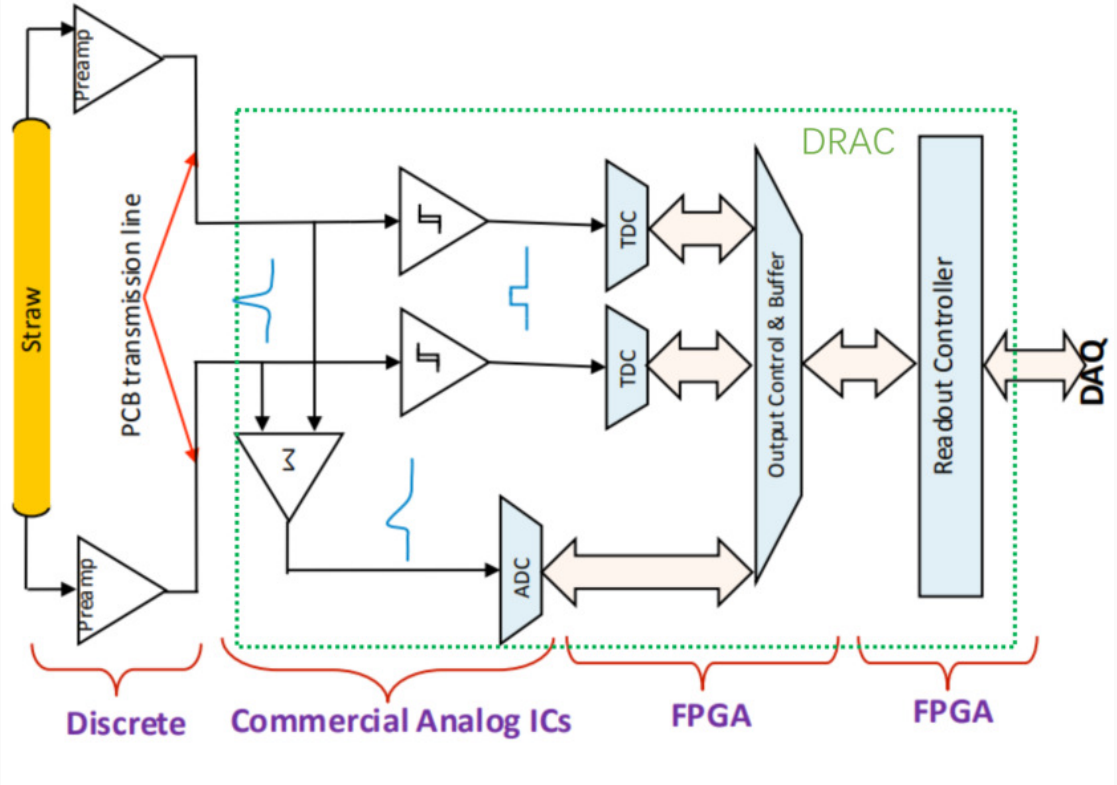


Back side of a preamp, showing the custom connector

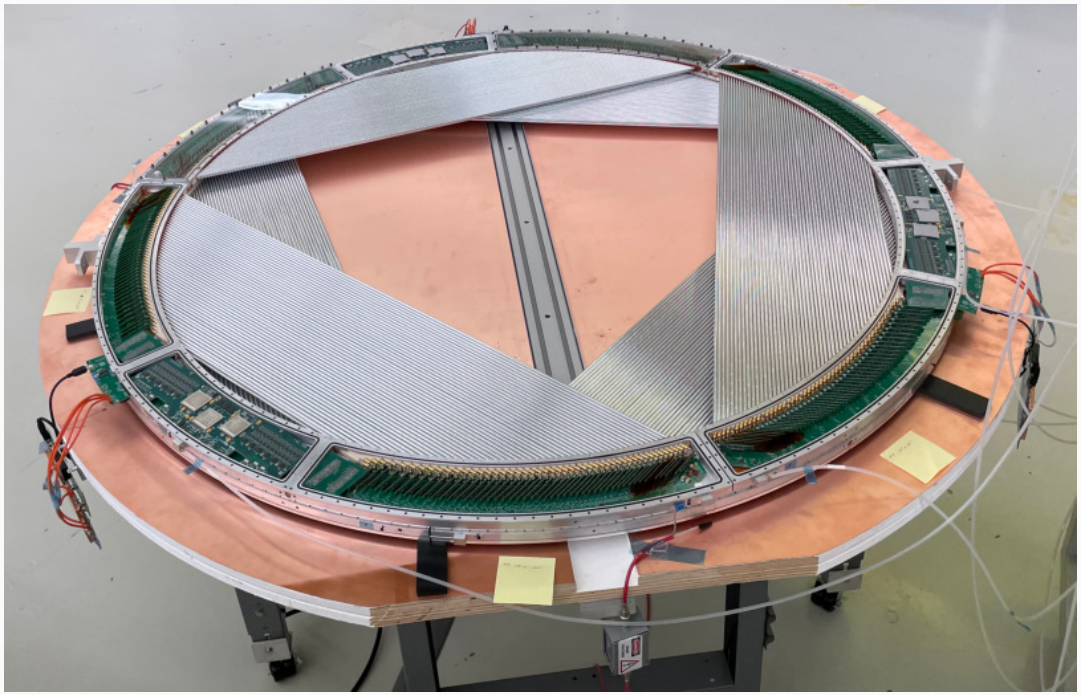
Front end electronics: DRAC

- 3x Microsemi PolarFire FPGAs
  - SEE and TID tolerance
  - 192× firmware TDCs (two per straw) with ∼50 ps resolution
  - Require coincidence between straw ends
- 50 MHz commercial ADCs to digitize waveform
- DDR3 memory for buffering
  - Takes advantage of ∼30% beam dutyfactor
- VTRx optical transceivers to DAQ
  - 200 MHz detector clock and time synchronization from DAQ over fiber
- Handle >250 KHz per channel



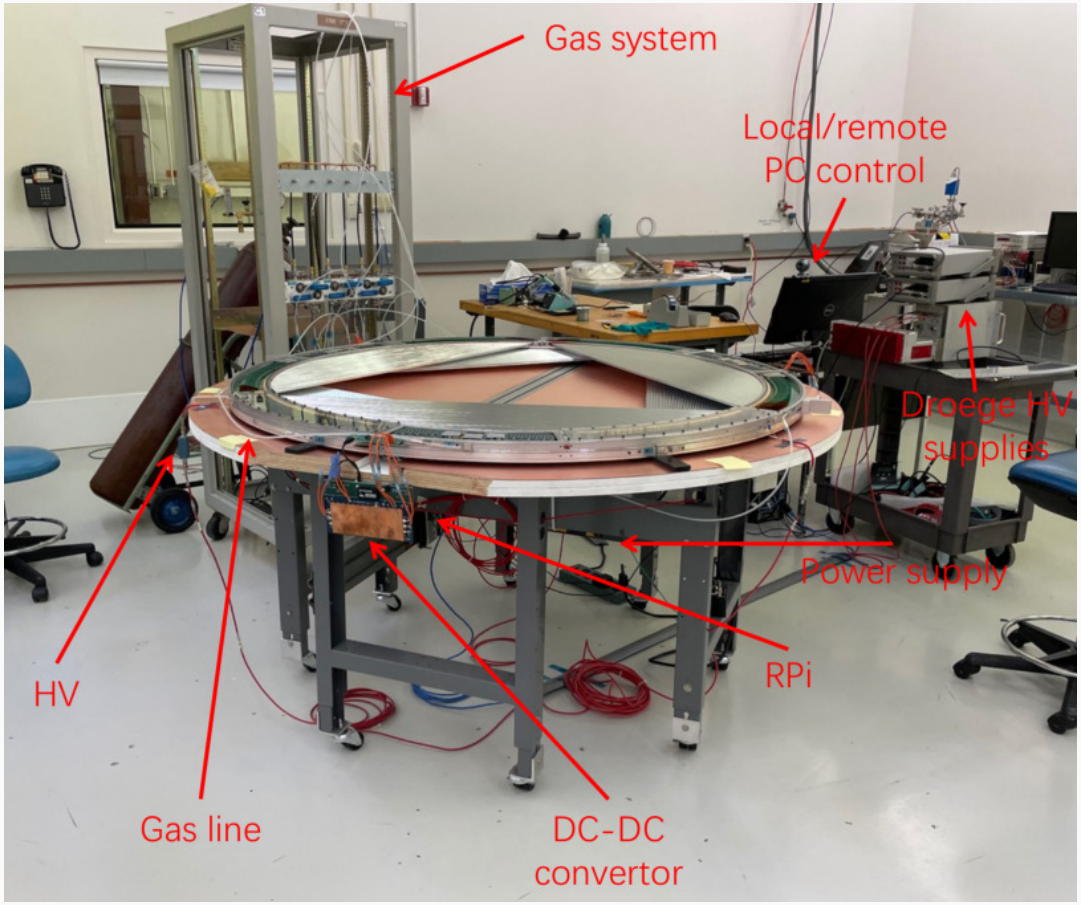


Tracker vertical slice test (VST) overview



- 'Vertical slice': Testing full chain from straws to readout to processed data on disk
- Six fully instrumented pre-production panels (576 straws) in plane configuration with associated HV/gas/cooling infrastructure
- Read out by streaming DAQ over optical fiber
- Source and cosmic ray data taken in several configurations

Tracker vertical slice test (VST) overview



- 'Vertical slice': Testing full chain from straws to readout to processed data on disk
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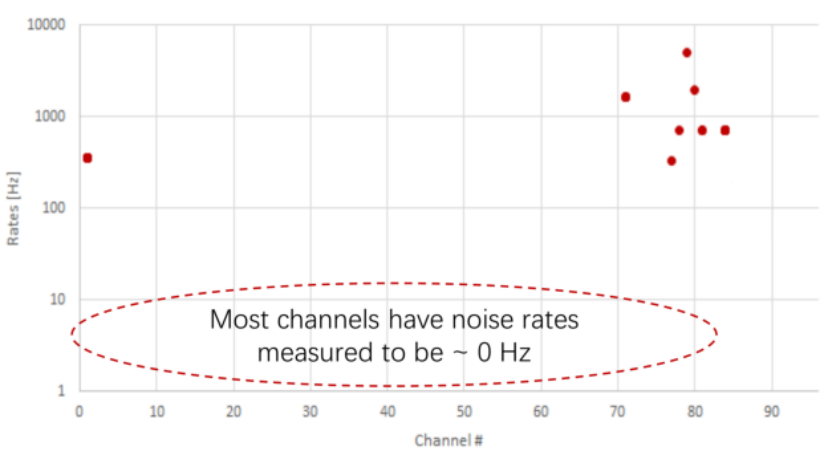
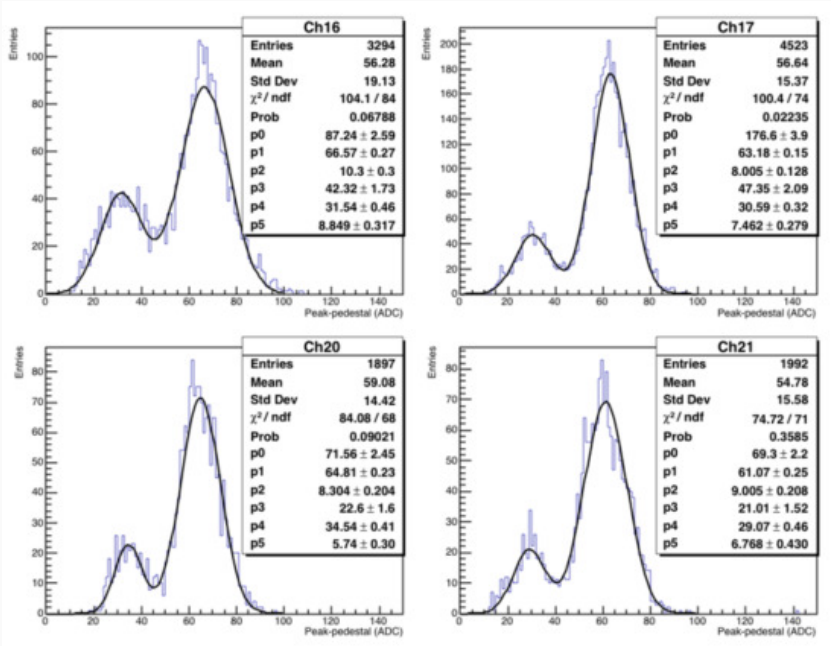
- Read out by streaming DAQ over optical fiber
- Source and cosmic ray data taken in several configurations

Demonstrated performance in realistic conditions, scaled up to large number of straws



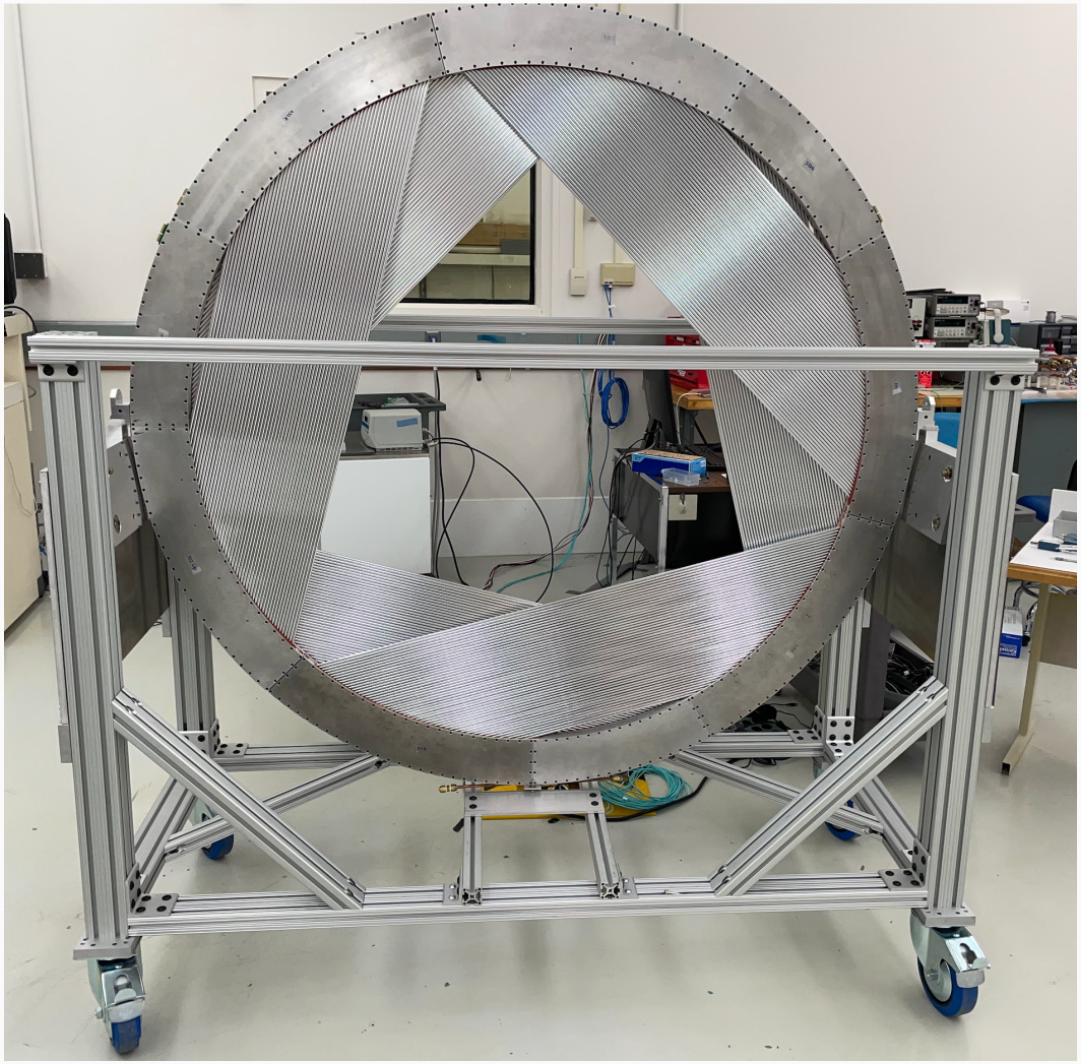
Coincidence noise rates on VST panel



Energy deposition measurements of ^{55}Fe source

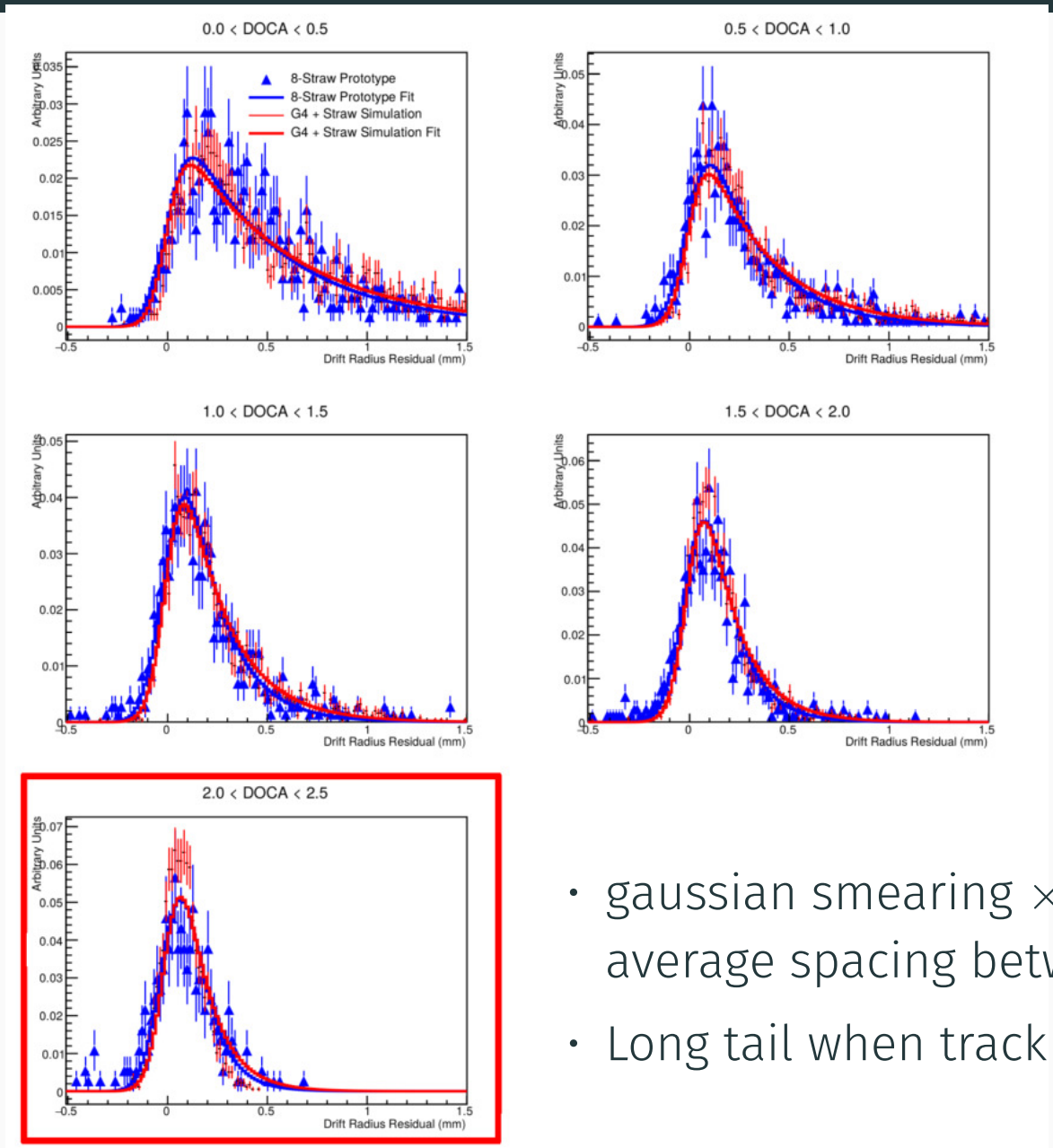
- Near zero noise rates at below required channel thresholds
- Synchronized time readout across six panels
- Measured gain / timing response across panels and straws

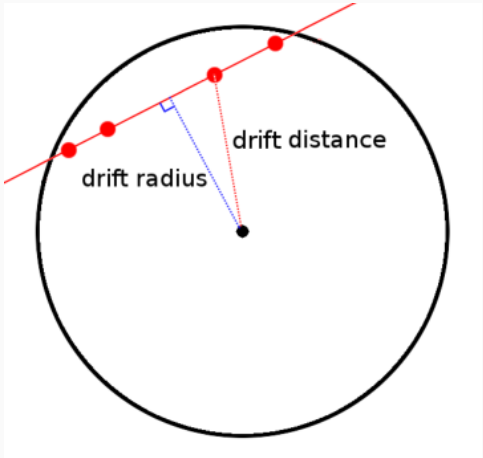
Cosmic ray data taken in vertical configuration allow track reconstruction and measuring straw hit resolution



- Alternative straight line track reconstruction
  - Minuit based likelihood fit
- Includes both drift time and time division measurements
- Uses detailed drift response model including cluster statistics effects

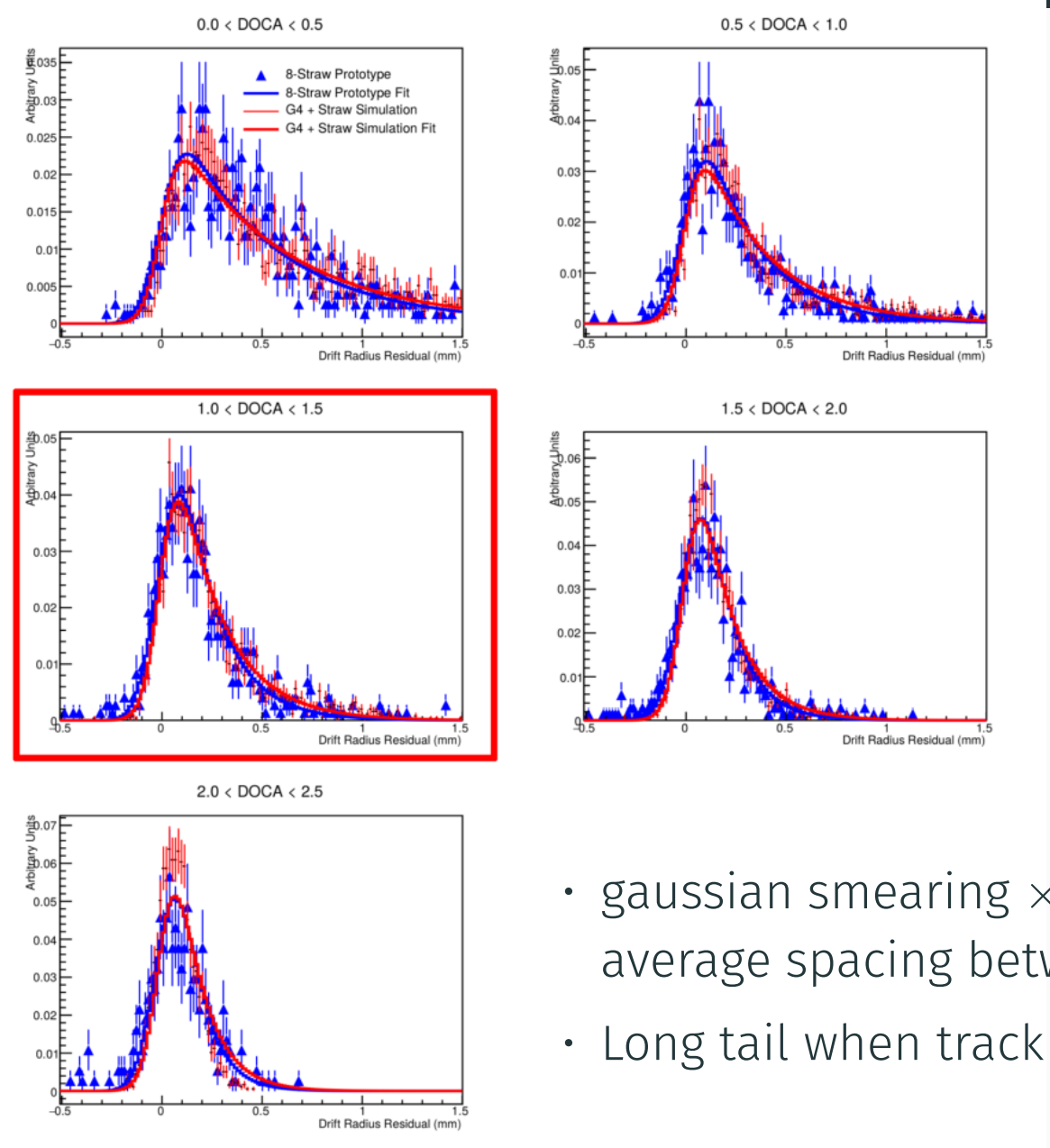
Drift response model

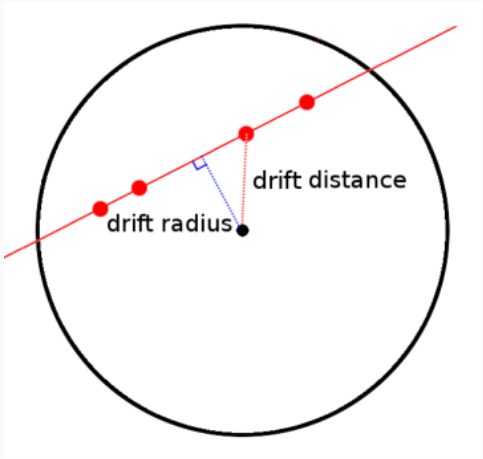




- gaussian smearing $\times$ exponential encoding average spacing between ionizations
- Long tail when track near wire

Drift response model





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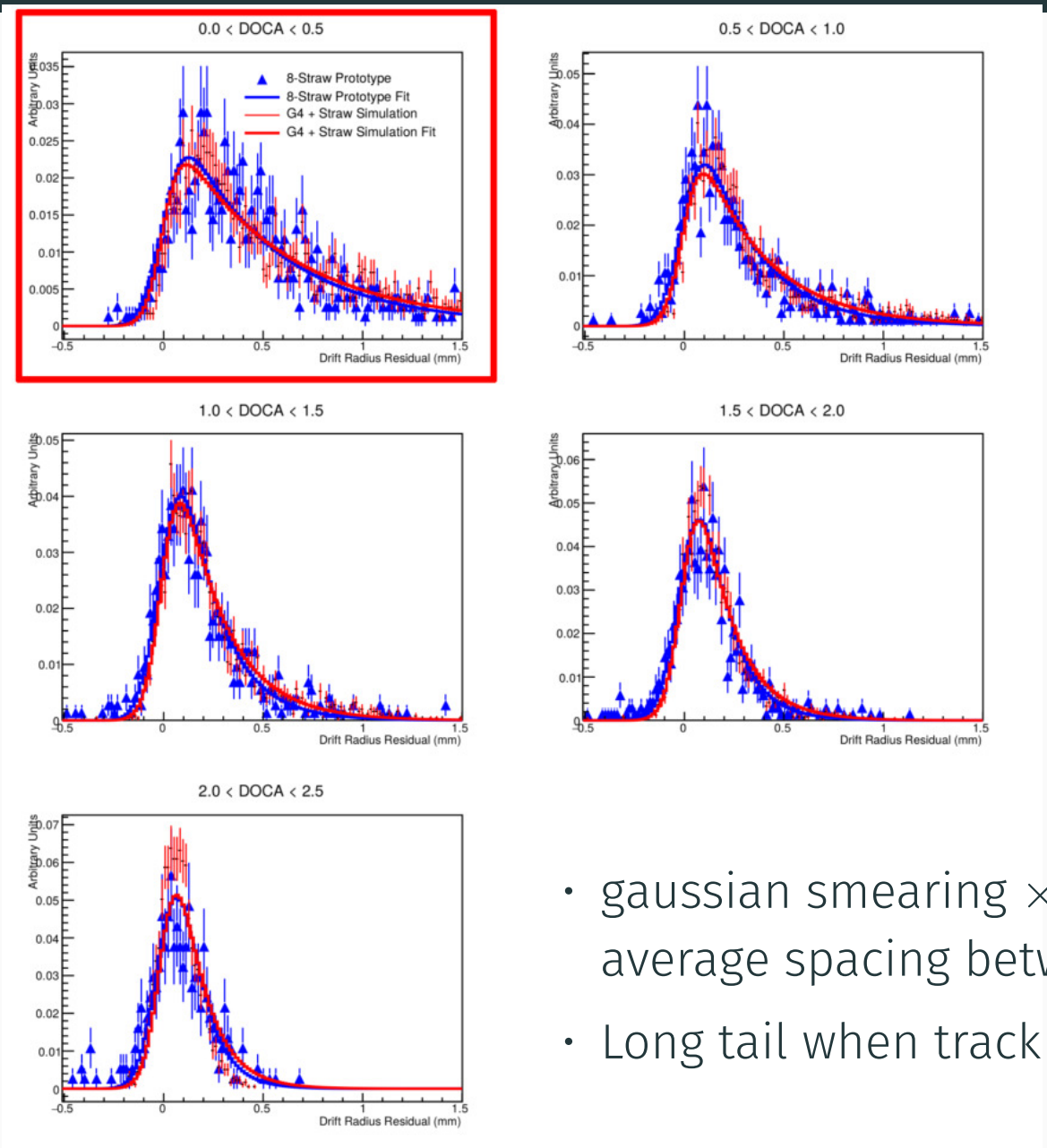
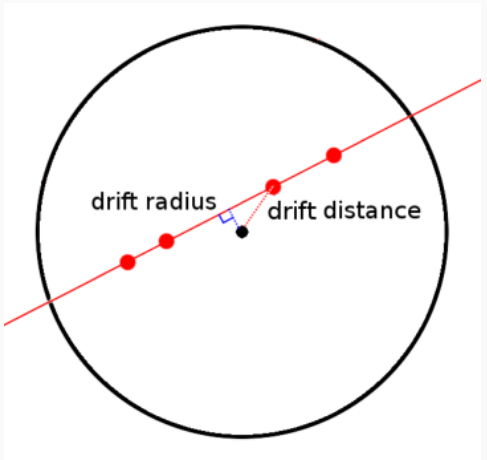
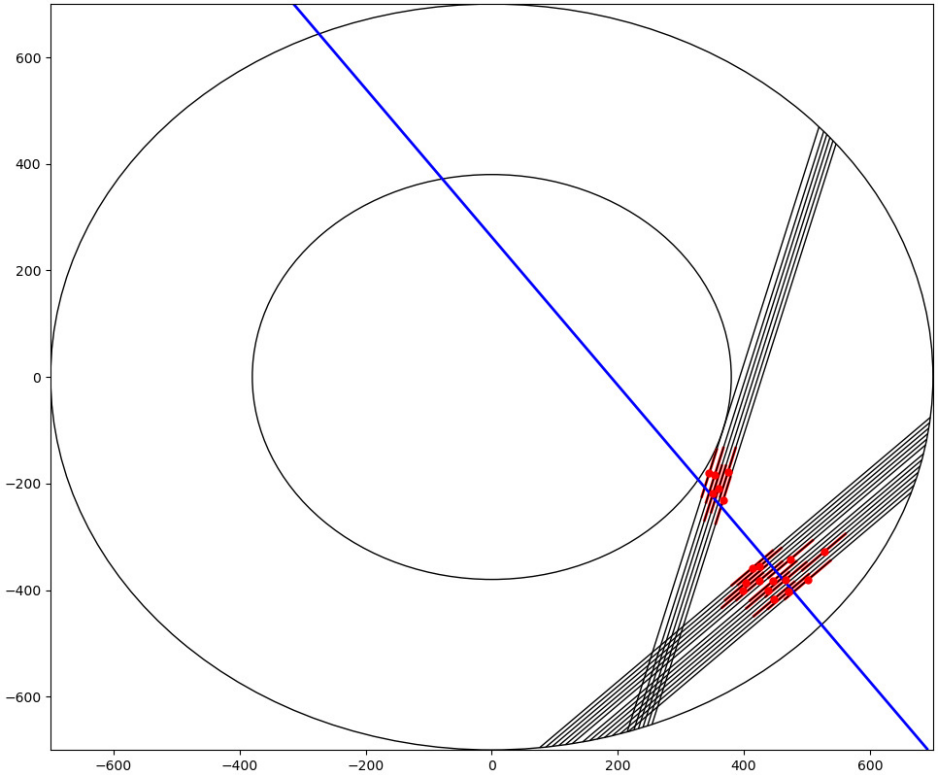
Drift response model

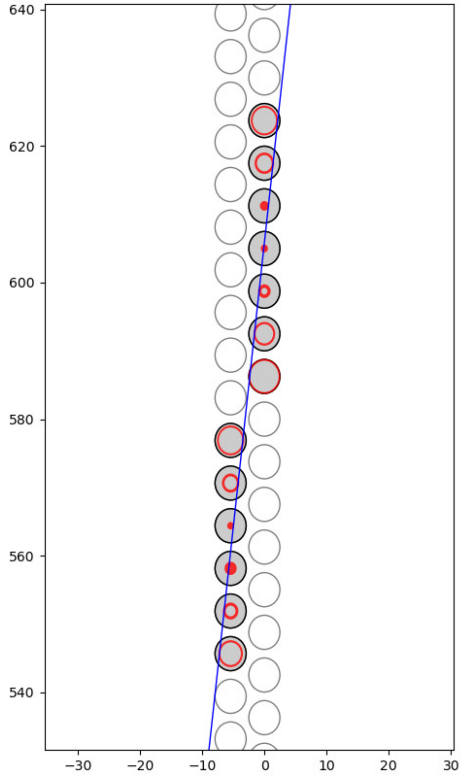


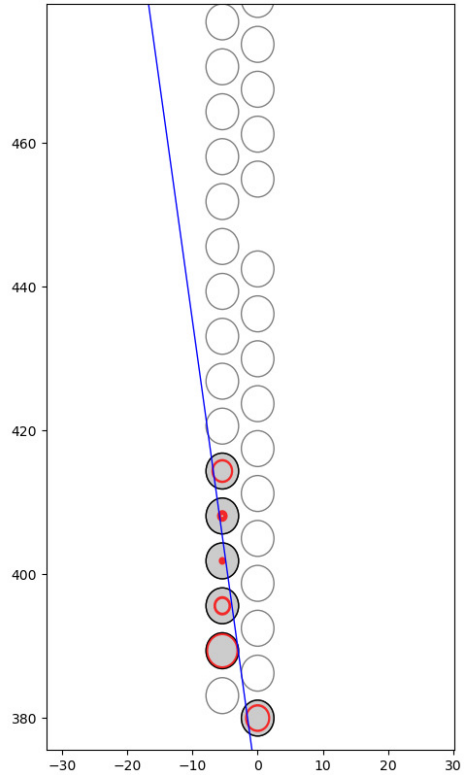


- gaussian smearing $\times$ exponential encoding average spacing between ionizations
- Long tail when track near wire

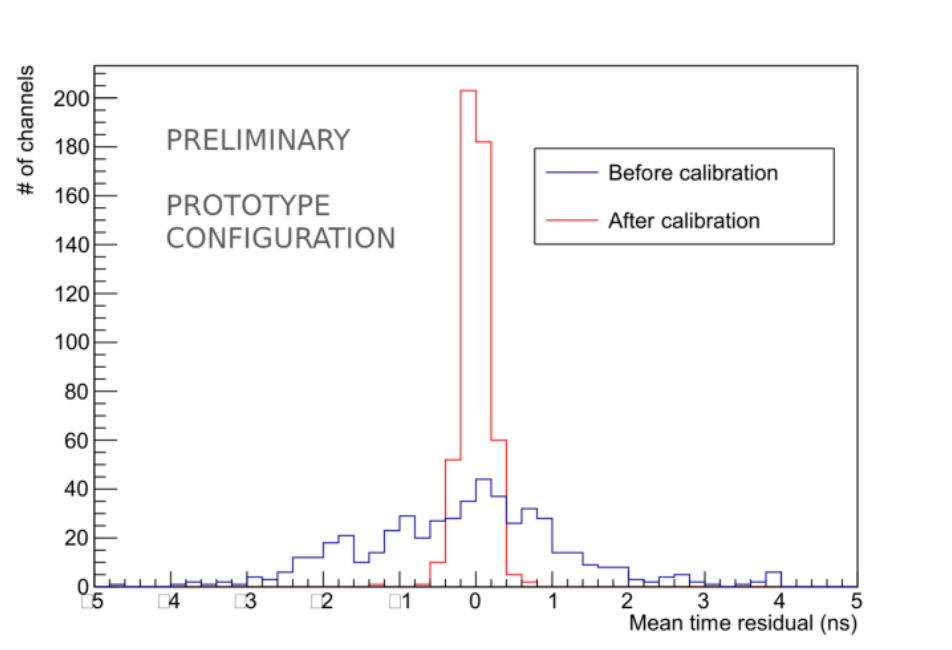
Example straight line track fit (VST data)



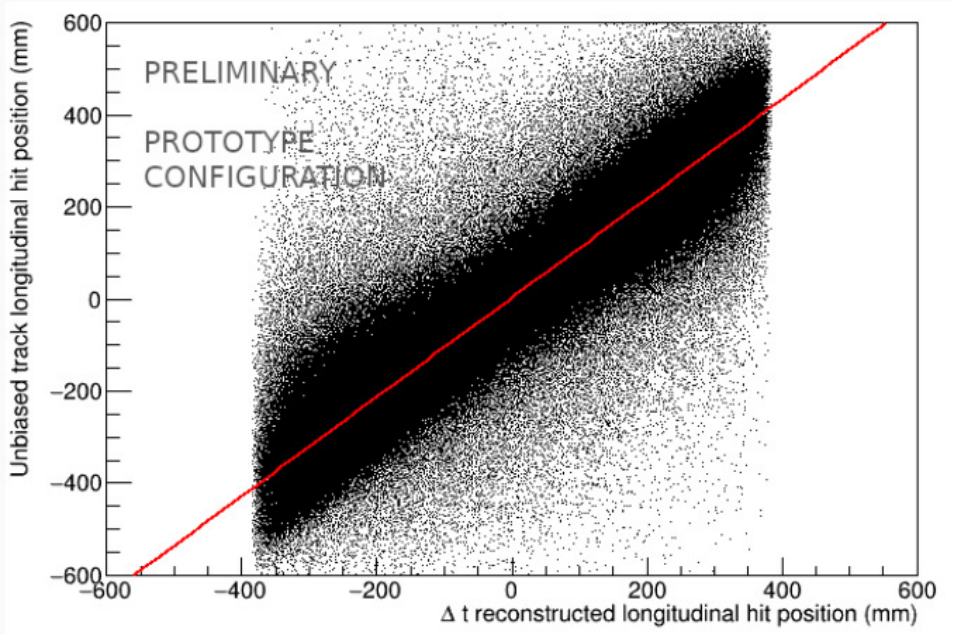




Calibrated time offsets, hit reconstruction using fit residuals

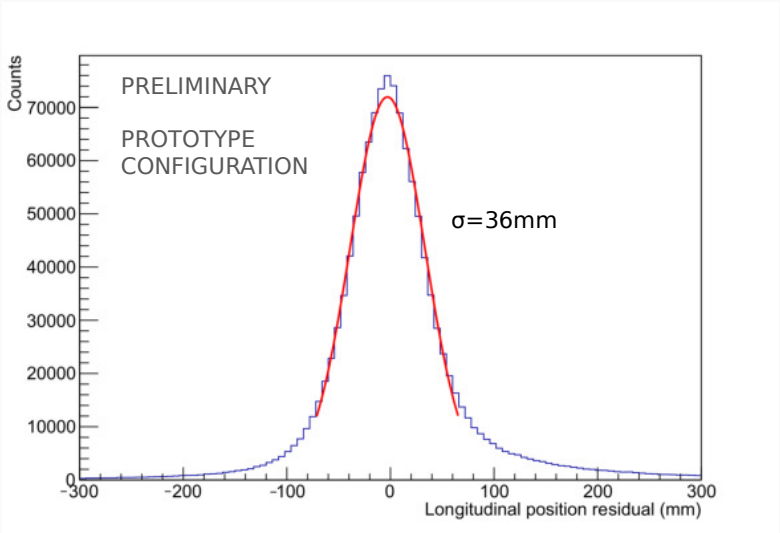


Mean time residuals for each straw before and after calibration (VST data)

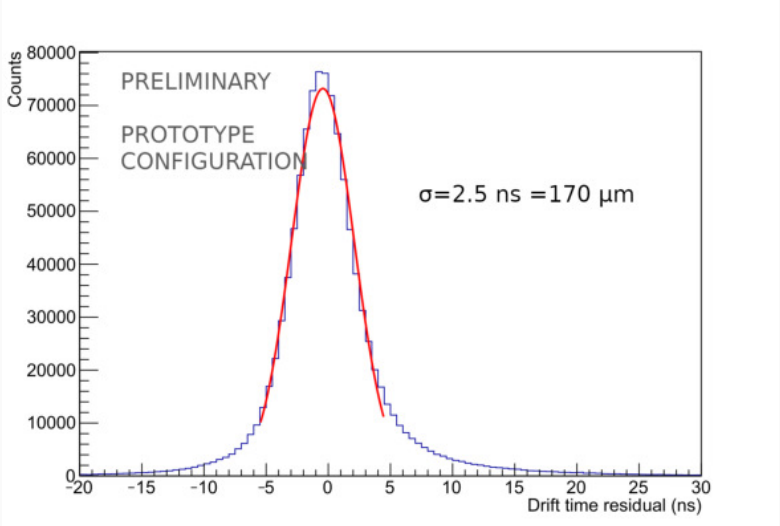


Example fit for longitudinal reconstruction correction (VST data)

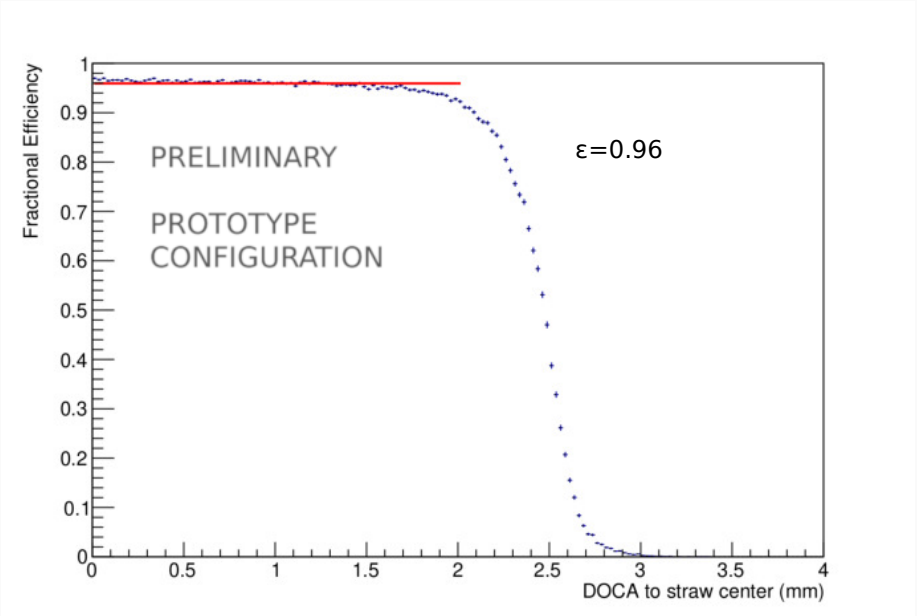
Hit level performance demonstrated across entire VST plane



Longitudinal resolution, middle 80% of straw length (VST data), requirement <40 mm



Drift resolution, excluding inner 0.5mm (VST data), requirement <250 mm

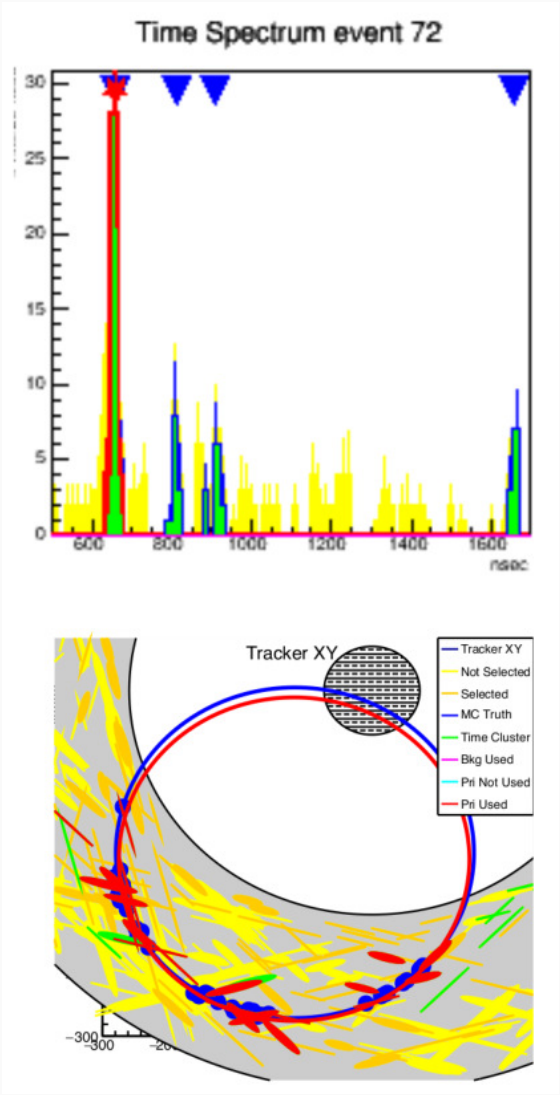


Efficiency vs distance to straw center (VST data), requirement >90%

Outline

- Charged Lepton Flavor Violation (CLFV) overview
- Mu2e overview
- Straw Tracker
  - Hardware design and testing
  - **Track reconstruction**
- Status of construction
- Future of muon physics

Reconstruct multi-loop helix to extract momentum

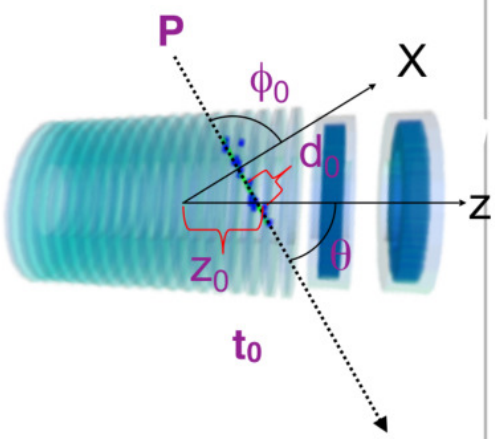
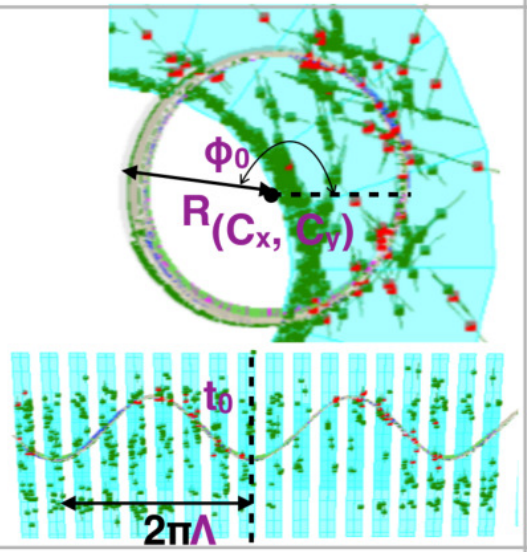
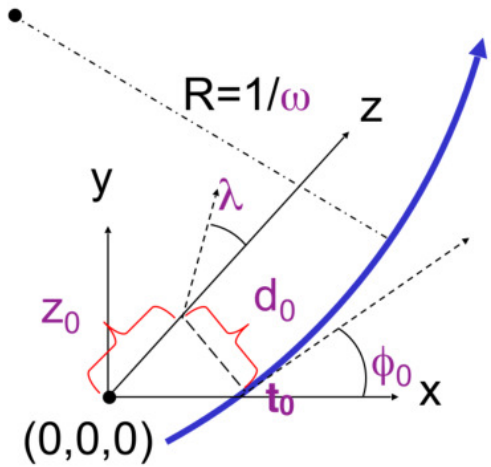


- Initial time clustering and pattern recognition
  - Hits clustered within ∼50 ns time window
    - TOT used for initial drift time correction
  - Initial helix estimate from separate XY (circle) and ϕZ (linear) fits
- Iterative Kalman Filter fit for helix
  - Includes material effects, magnetic field corrections
  - fast fit for software trigger - no drift information used (hits treated as 2-D constraint to wire position)
  - Final fit using drift time

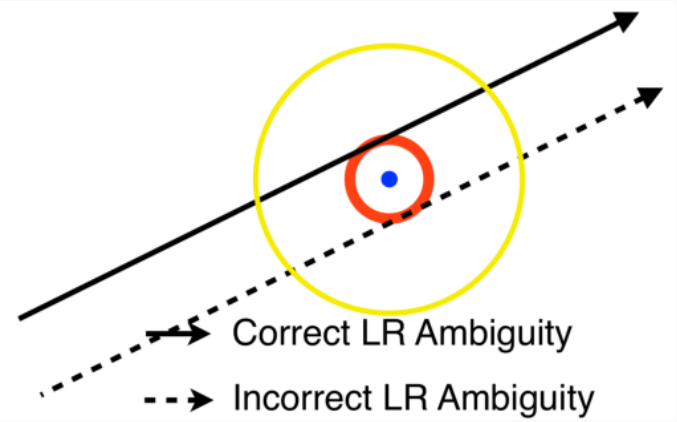
KinKal kinematic extended kalman filter fit

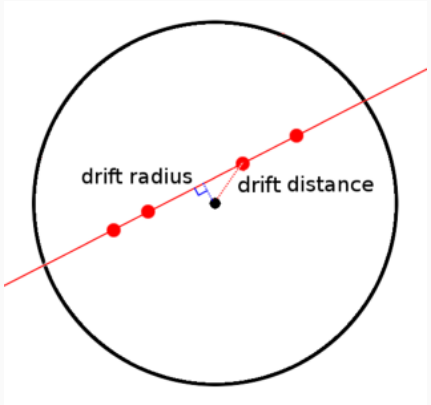
github.com/KFTrack/KinKal

- Experiment independent modern implementation, replaced previous Mu2e fitter (based on BaBar's) in 2022
- Kinematic - time as parametric variable
  - More consistent, better time and error estimates
- Templated fitter, works with multiple track types

Field-off cosmic μ±	Conversion e±	Field-on cosmic μ±
		
KinematicLine	**LoopHelix**	**CentralHelix**

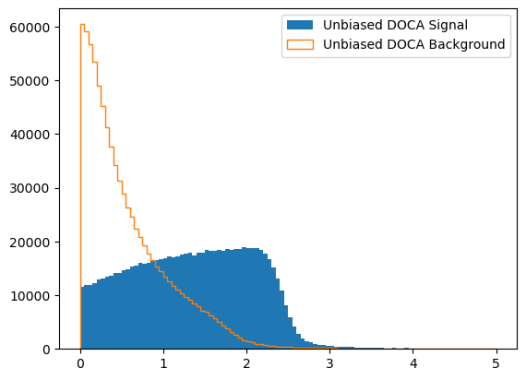
KinKal: fast fit to final fit including drift

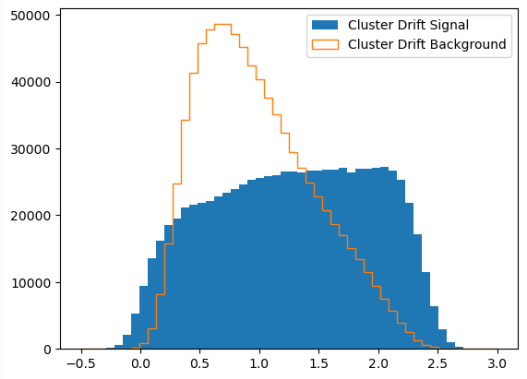


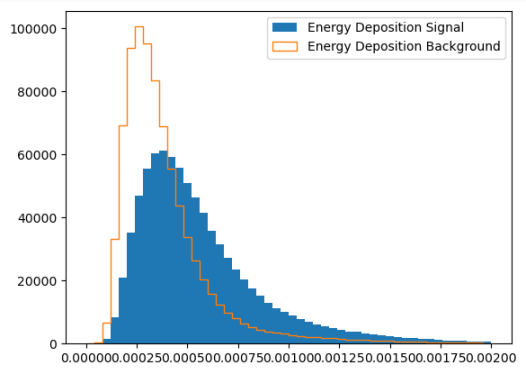


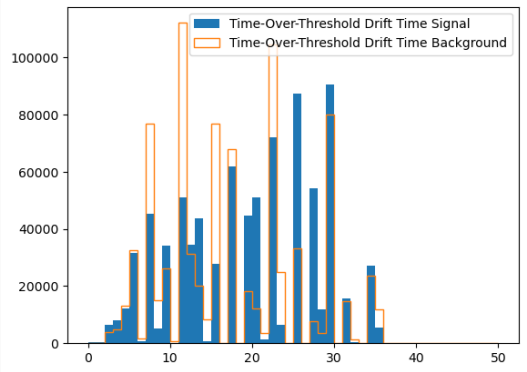
- Trigger fit only constrains to wire position (∼2 ms per event)
- Final fit adds drift information to get needed resolution but:
  - 'Left-right' ambiguity
  - 'Bad drift' where drift distance of cluster does not approximate DOCA
- Iterative fit with simulated annealing
- Between iterations assign state of each hit using MVAs
  - Filter background hits
  - Determine if L/R ambiguity can be conclusively set (otherwise continue to constrain only to wire)
  - Flag hits where drift time is not trustworthy

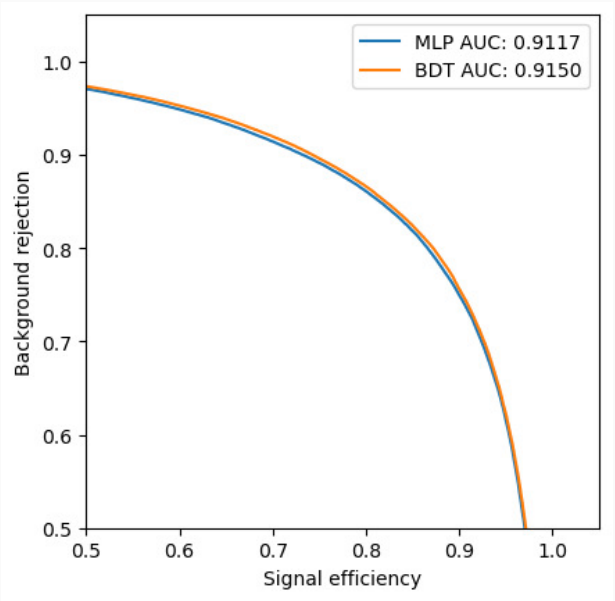
Iterating with MVAs







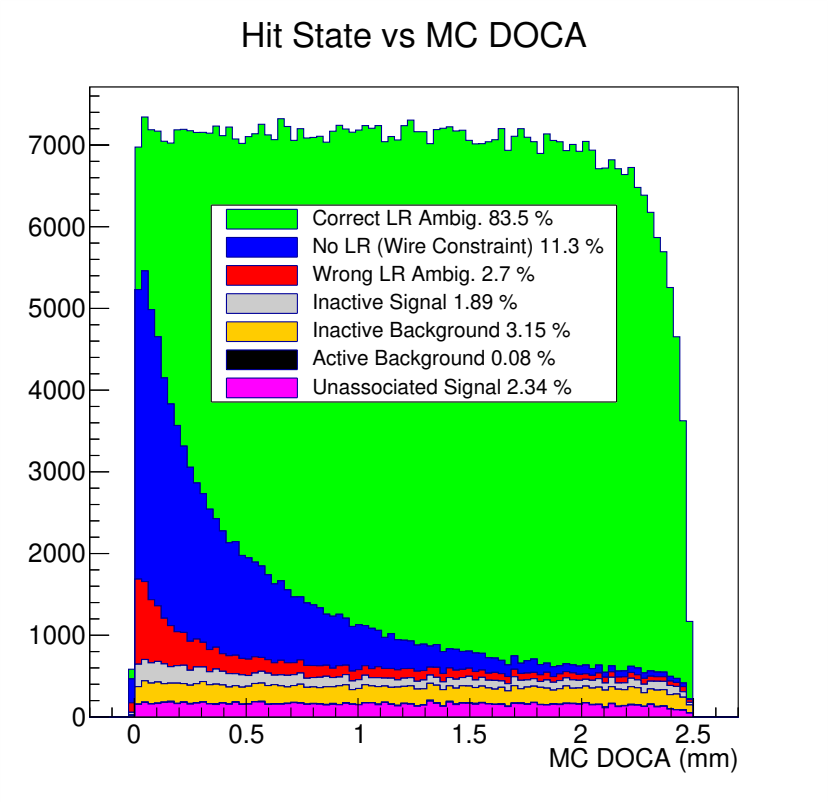


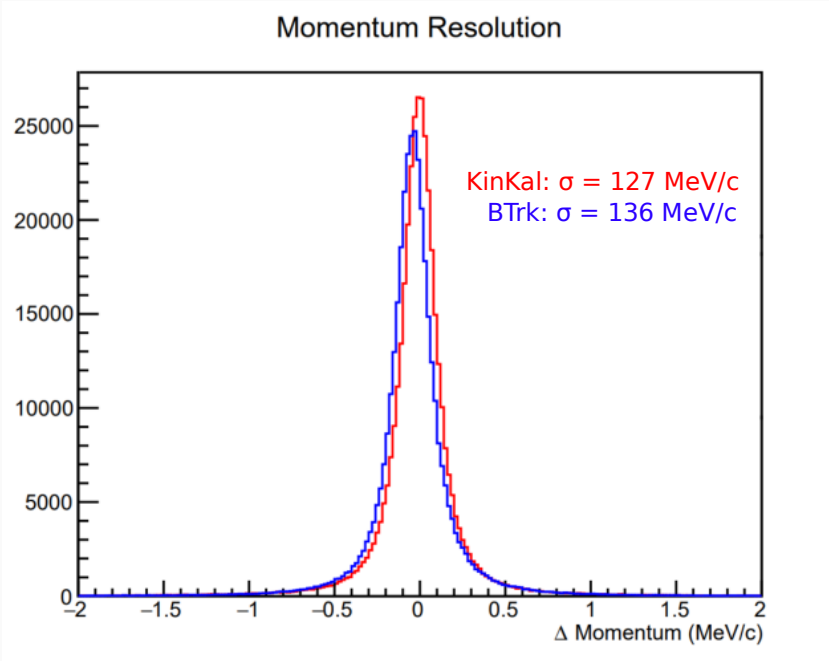


Simulated inputs to 'Good drift' MVA

- Inputs to MVAs include track predicted position and uncertainty, position residuals, TOT, dE/dX, etc.
  - Fit results as input parameters → iterative training
- Training with Tensorflow
- TMVA::SOFIE for fast inference in C++

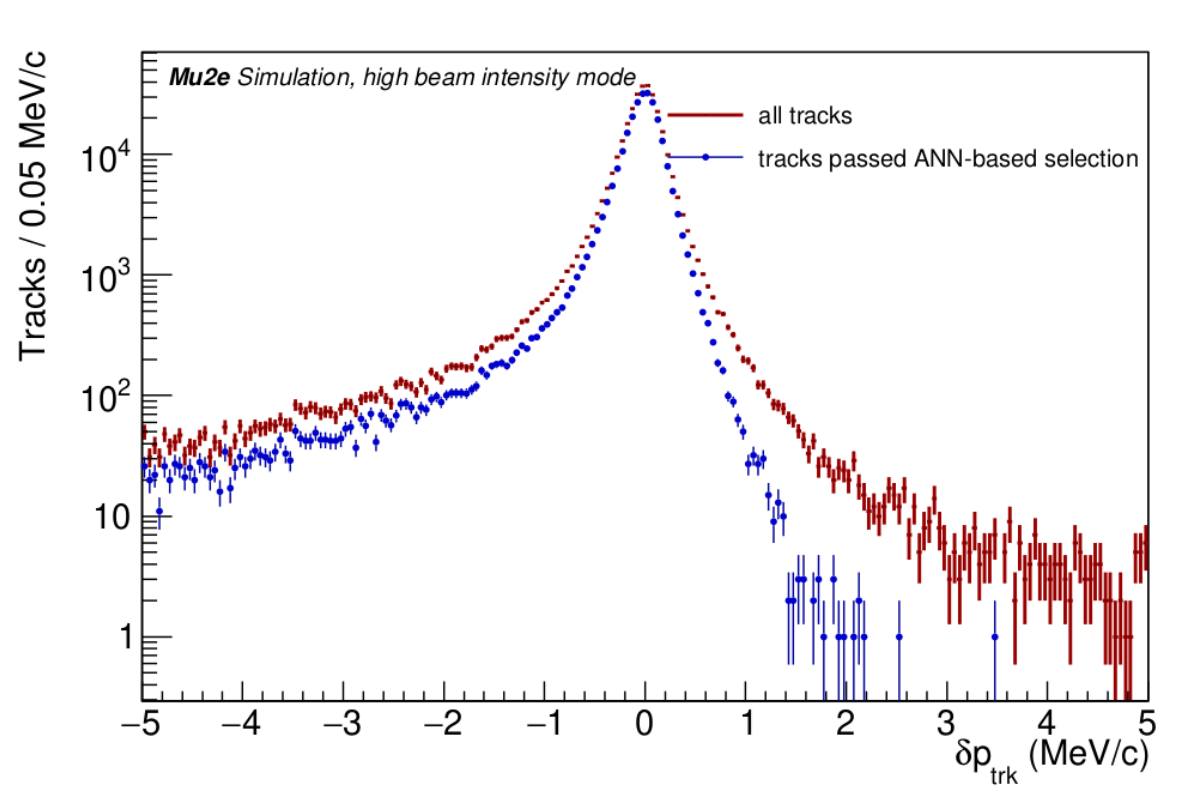
Performance





- By end of iterations >80% of hits using drift information with correctly resolved L/R ambiguity
- Core momentum resolution <130 MeV/c

ANN based track quality selection



Track quality cut for Run-I sensitivity analysis

- Another ANN is used select only high quality tracks to greatly reduce tails of momentum resolution

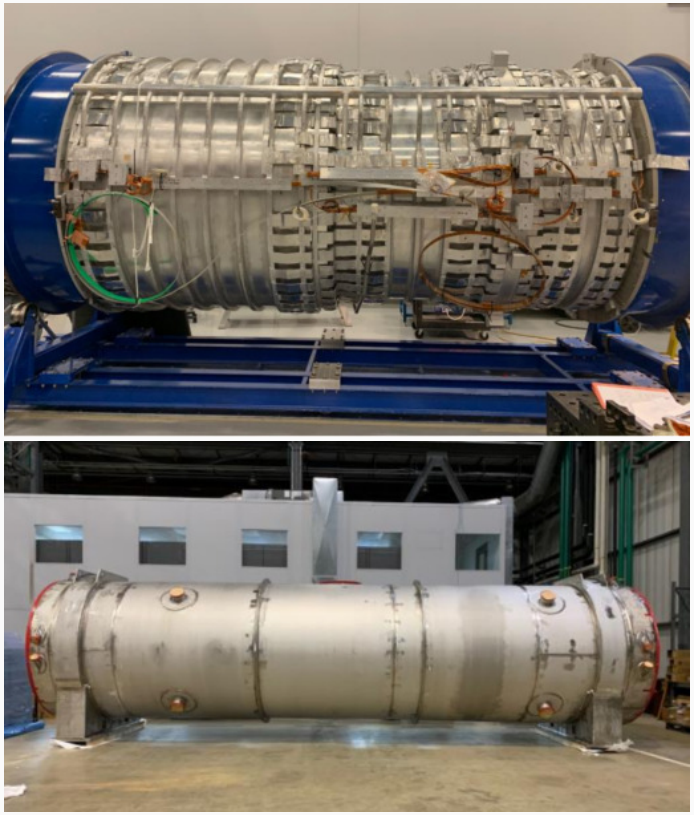
Outline

- Charged Lepton Flavor Violation (CLFV) overview
- Mu2e overview
- Straw Tracker
  - Hardware design and testing
  - Track reconstruction
- Status of construction
- Future of muon physics

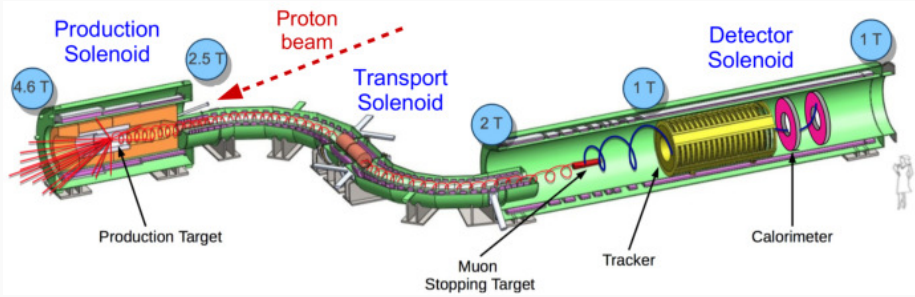
Mu2e status overview

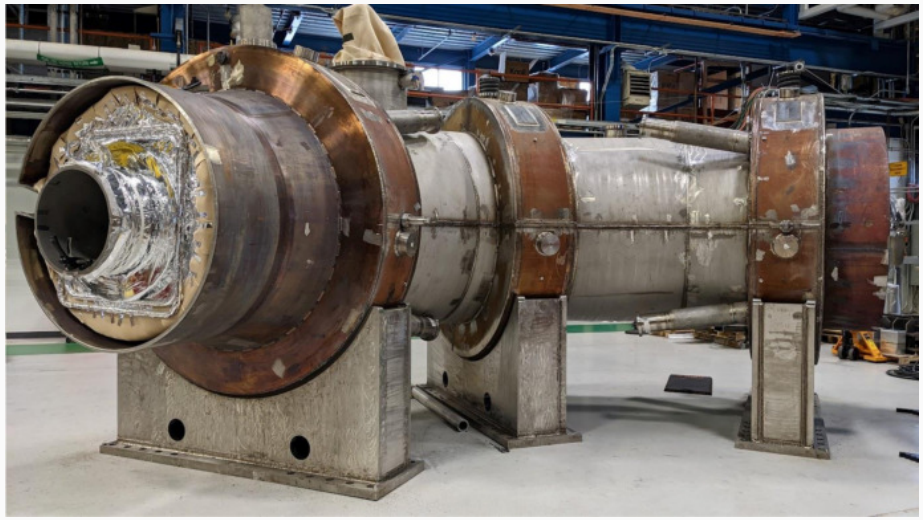
- Mu2e project was recently rebaselined
  - Additional funding to reach project completion in time for Run-I before shutdown
  - Strong support from new Fermilab management
- Significant fraction of construction is complete, installation and integration beginning soon

Construction status: Solenoids



PS cold mass (top) and DS vacuum vessel (bottom)

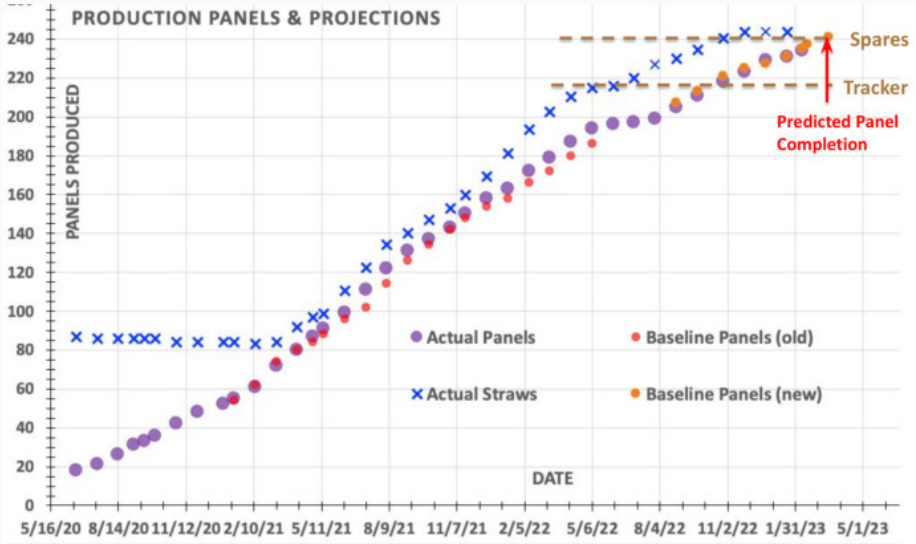


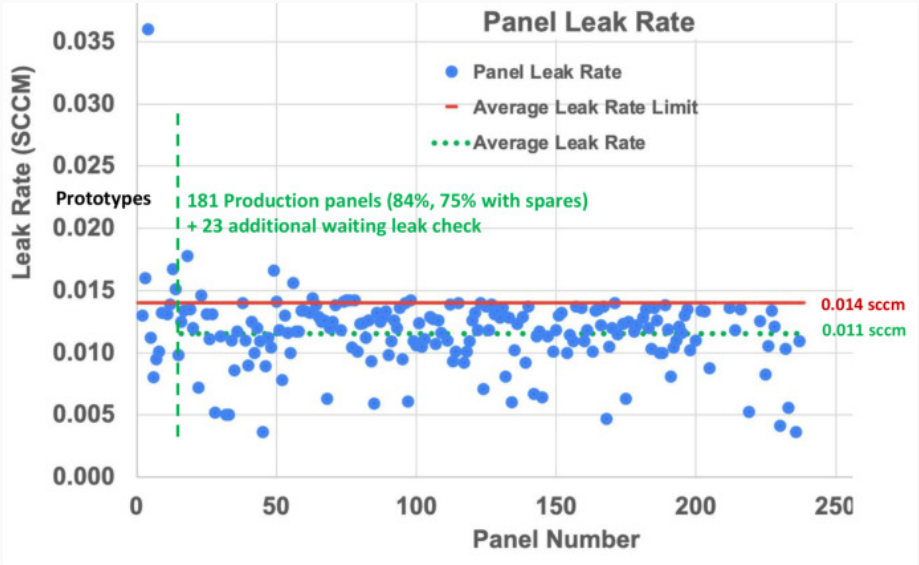


TS downstream assembled

- Transport solenoids nearly complete, installed in cryostats
- Production and detector solenoids well under way, expected this year

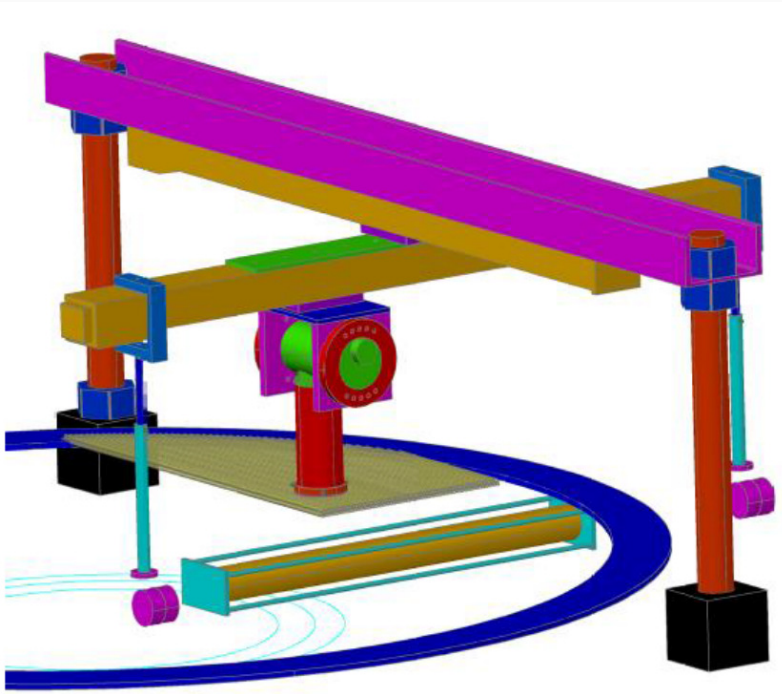
Construction status: Straw tracker

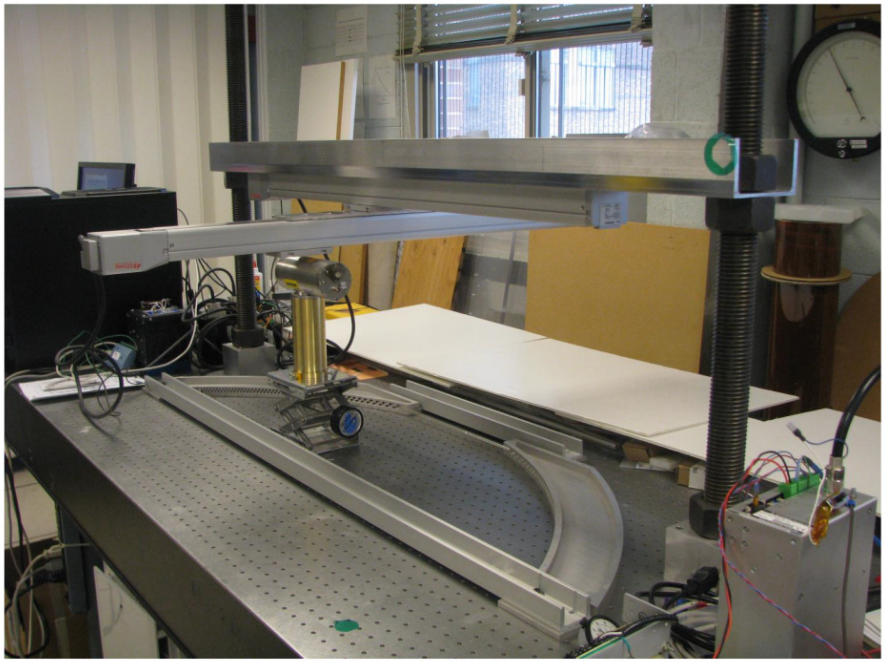


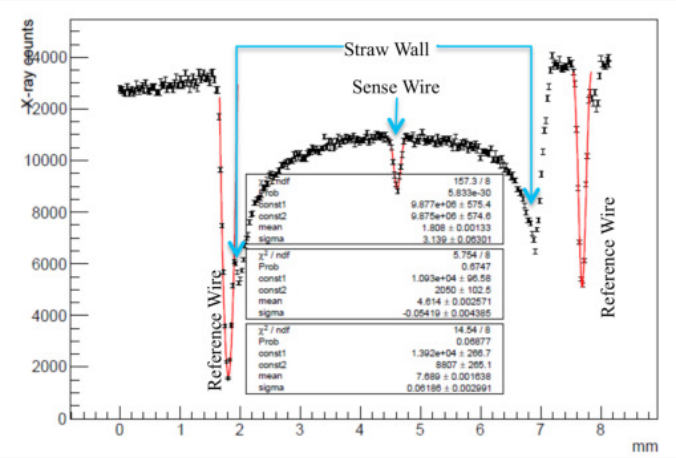


- 100% of straws/panels produced, achieved required leak rate

Construction status: Straw tracker



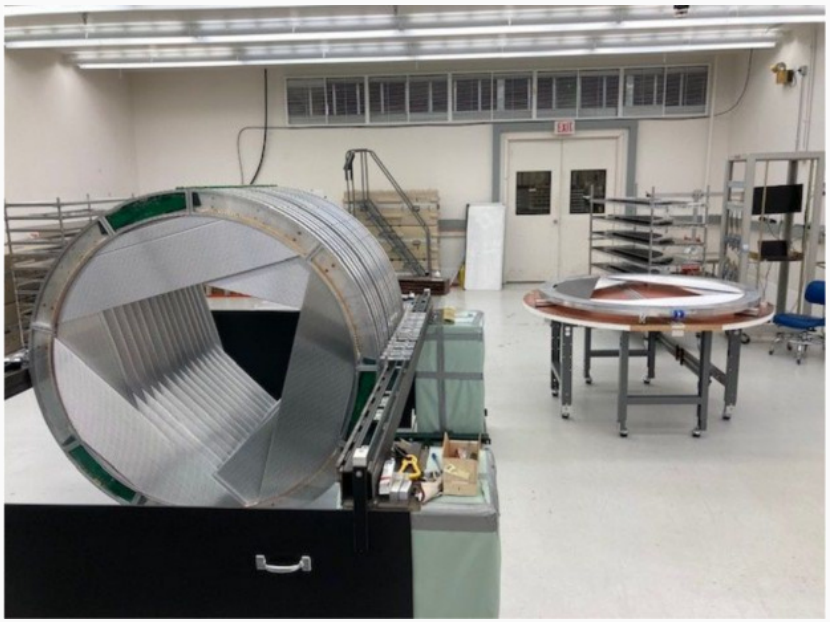




Example scan of Mu2e straw

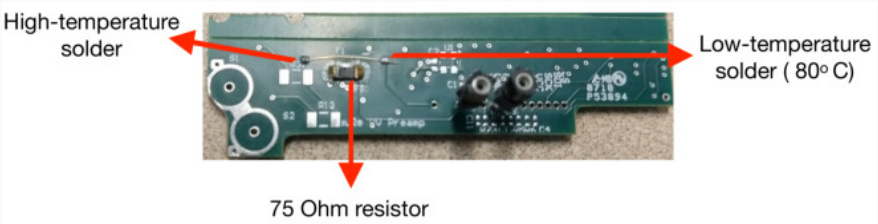
- Each panel x-ray scanned to measure straw and wire positions
- X-ray scan measures position of each straw and wire to 25 μm/75 μm in y and z respectively
- 3 points on each panel for optical survey after tracker assembly

Construction status: Straw tracker



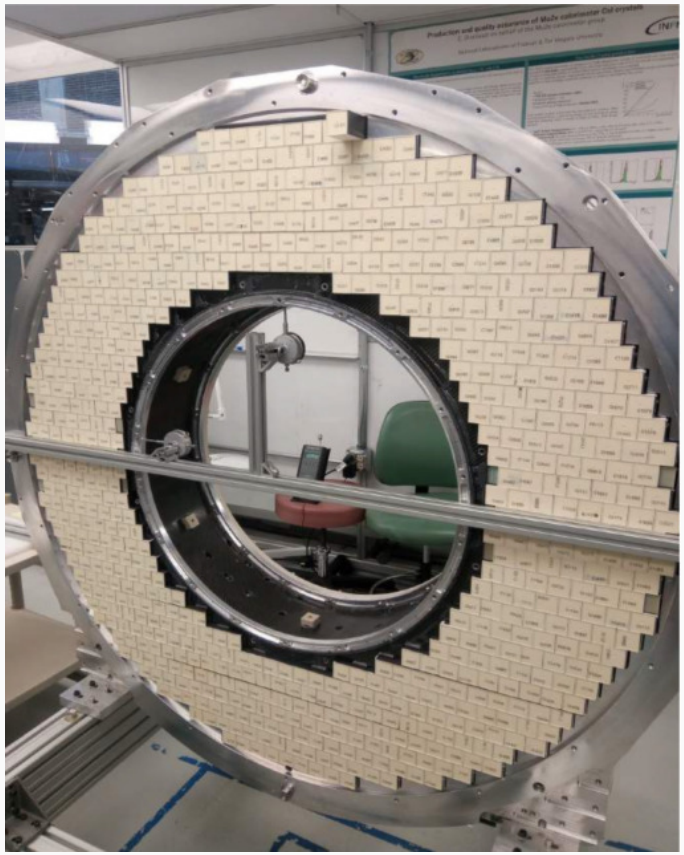
- >50% of planes, full frame complete

Construction status: Straw tracker



- Electronics processing and QA/QC at UC Berkeley
  - Parylene coating 50μm
  - Installation of preamp HV fuse
  - QA/QC tests (continuity, digital/analog functionality, HV sparking checks)

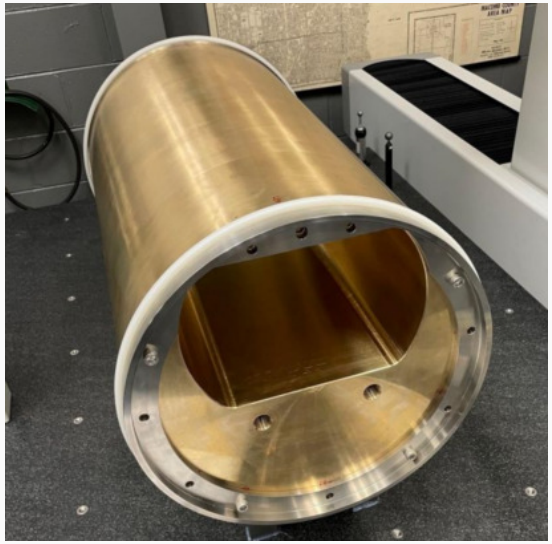
Construction status: Calorimeter and CRV



- All crystals and SiPMs for the calorimeter have been produced
  - Assembly of first disk well underway
- >80% of CRV modules completed
- Ongoing vertical slice and cosmic ray tests

Construction status: Other components

Tungsten production target



Muon beamline collimator

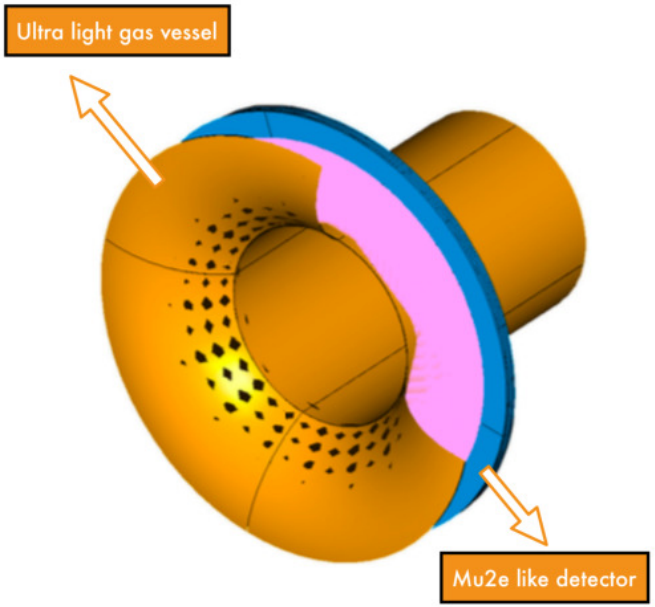
Aluminum stopping target

Outline

- Charged Lepton Flavor Violation (CLFV) overview
- Mu2e overview
- Straw Tracker
  - Hardware design and testing
  - Track reconstruction
- Status of construction
- Future of muon physics

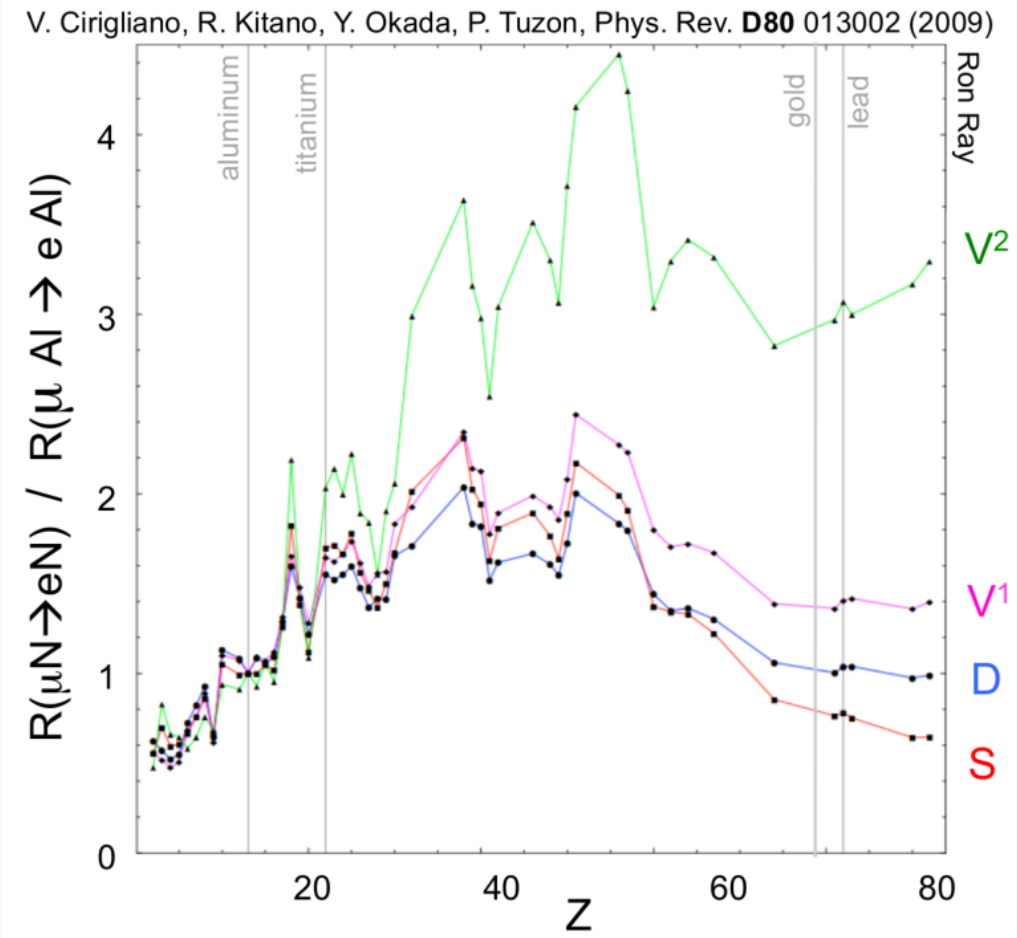
Muon physics with PIP-II beam: Mu2e-II

	Mu2e	Mu2e-II
Wall thickness (μm)	18.1	8.2
Al thickness (μm)	0.1	0.2
Au thickness (μm)	0.02	0.0
Linear Density (g/m)	0.35	0.15
Pressure limits (atm)	0–5	0–3
Elastic Limit (gf)	1600	500



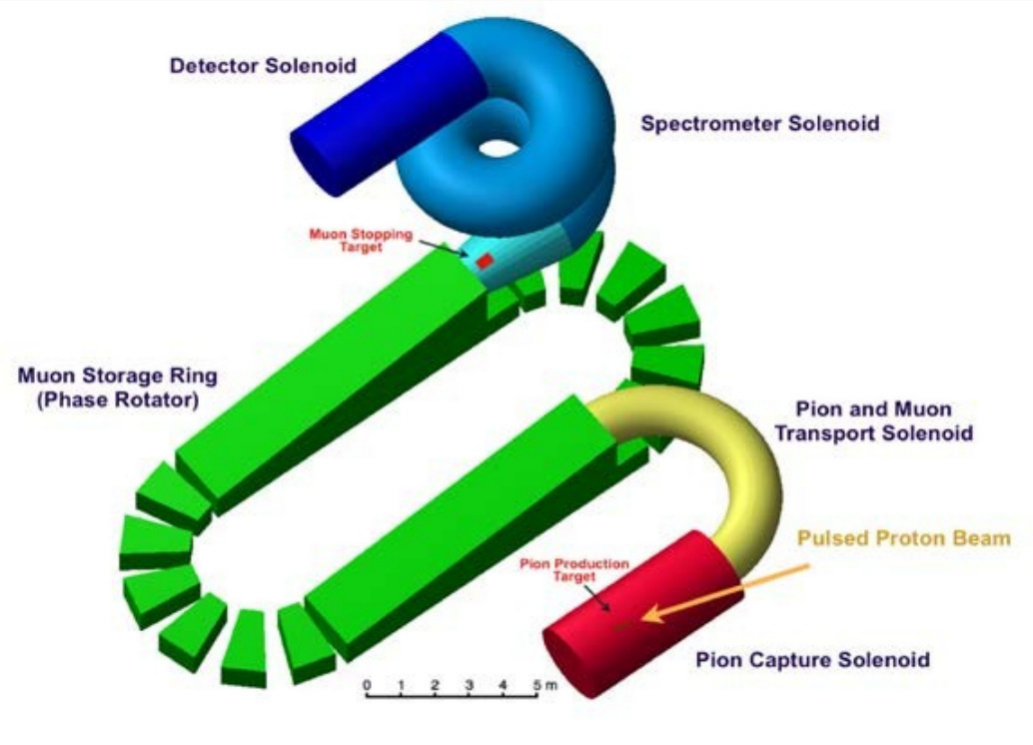
- Goal: increase sensitivity over full Mu2e Run-I + II by another order of magnitude
  - Start a few years after Mu2e, 5 year run
  - 100kW 800MeV from PIP-II beam
- Detector upgrades
  - Better resolution, less material, higher rates, higher dose
  - ASIC?
- arXiv:2203.07569

Muon physics with PIP-II beam: Different target materials



Muon physics with PIP-II beam: AMF - An advanced muon facility for Fermilab beyond Mu2e-II

- Up to 1MW of PIP-II unused by LBNF/DUNE
- CLFV, muonium, muon EDM, etc.
- New technologies:
  - Production solenoid and target @ 1MW
  - Fixed-field alternating (FFA) gradient ring
- Synergies with development of muon collider



Summary

- Mu2e represents a huge advancement in muon conversion searches
  - Sensitive to scales beyond direct searches
  - Discriminates between models if NP is seen anywhere else
- Vertical slice tests have confirmed design performance
- Construction is well under way
- Major commissioning and cosmic ray run in 2025
- First physics run in 2026-2027 will allow us to improve SINDRUM II limit by $\times 1000$