The Mu2e Experiment

A Search for Charged Lepton Flavor Violation

MUSE Network General Meeting

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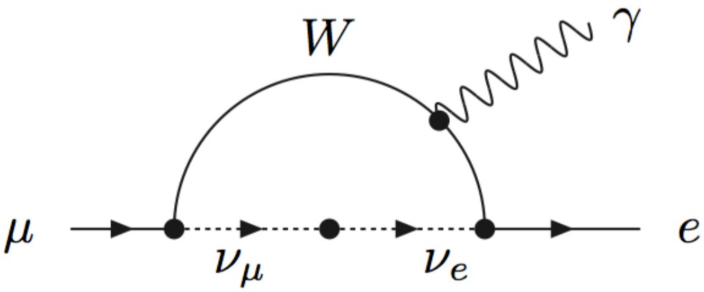
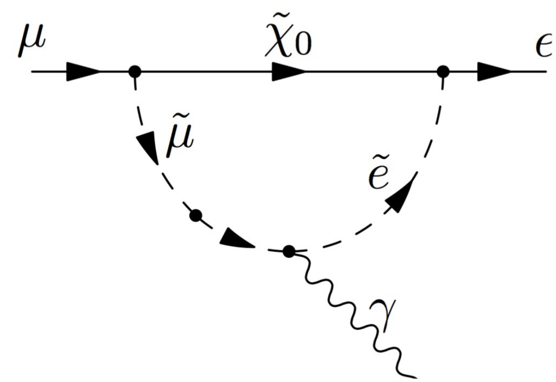
10/22/2018

Charged Lepton Flavor Violation

Neutrino oscillations: Direct evidence of lepton flavor violation
Mixing between charged leptons: Never observed
Violation of charged lepton flavor "forbidden" in SM



Loophole: neutrino oscillations
- Some CLFV *must occur*
- But rate is vanishingly small, $<10^{-50}$

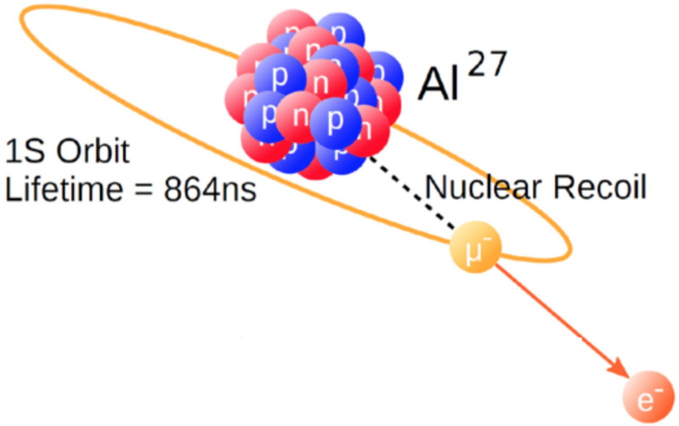


Any CLFV observation would be unambiguous sign of new physics
- Searches for CLFV are very powerful
- Well motivated, connections with:
  - Muon g-2
  - B meson decays, lepton flavor universality
  - Neutrino mass generation
  - … and more

$\mu \rightarrow e$ conversion: The Mu2e search

Coherent conversion $\mu \rightarrow e$ in the field of a nucleus

$$\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)$$



Clean experimental signature

- monochromatic e^- – for Al:

$$E_e(\mathrm{Al}) = M_\mu - E_b - E^{\mathrm{Al}}_{\mathrm{recoil}} \approx 104.97\ \mathrm{MeV}$$

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

Conversion process

Ordinary muon capture

Current limit: $R_{\mu e} < 7\times10^{-13}$ [SINDRUM II]

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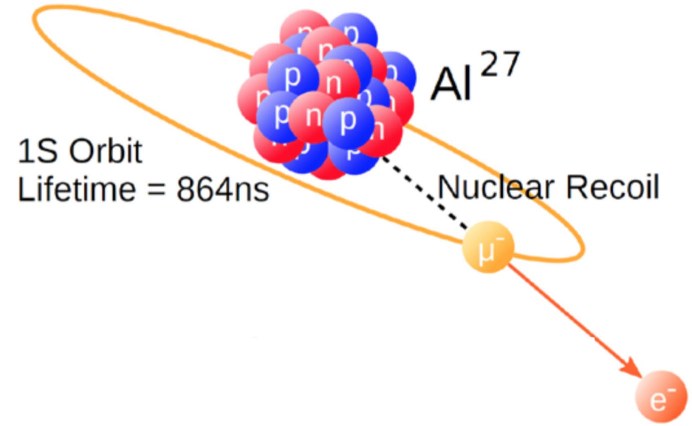

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Conversion process

Ordinary muon capture

Current limit: $R_{\mu e} < 7\times10^{-13}$ [SINDRUM II]

The Mu2e experiment will limit $R_{\mu e}$ to $\sim 8\times10^{-17}$ (90% CL)

- 4 orders of magnitude improvement – a rare opportunity!
- Exploring unconstrained phase space favored by many BSM models

$\mu \longrightarrow e$ conversion processes

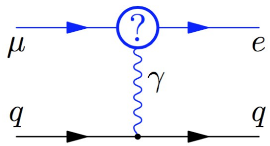
Effective Lagrangian:

$$\mathcal{L}_{\mathrm{CLFV}} = \underbrace{\frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu}}_{\text{Loop}} + \underbrace{\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)}_{\text{Contact}}$$

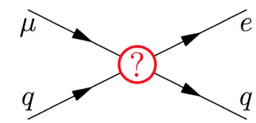
Λ: effective mass parameter

κ: relative strength of loop- and contact-dominated terms

Loop:

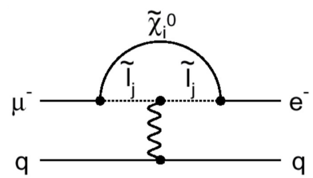


Contact:

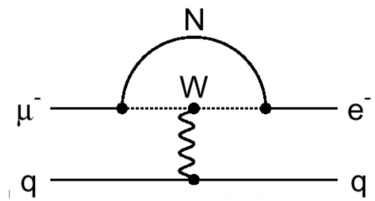


Loop terms:

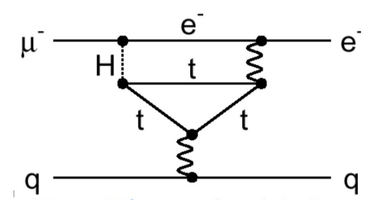
- Also mediate $\mu \longrightarrow e\gamma$



Supersymmetry



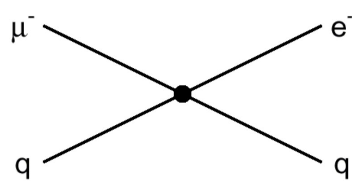
Heavy neutrino



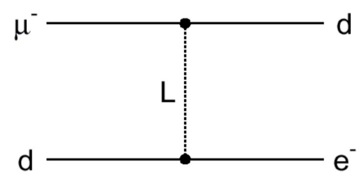
Two Higgs doublets

Contact terms:

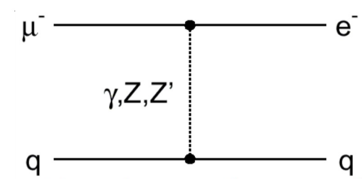
- ~~$\mu \longrightarrow e\gamma$~~



Compositeness



Leptoquarks



New heavy bosons

Model-independent Mu2e Physics reach: $\Lambda \sim$ 2,000 – 10,000 TeV (effective)

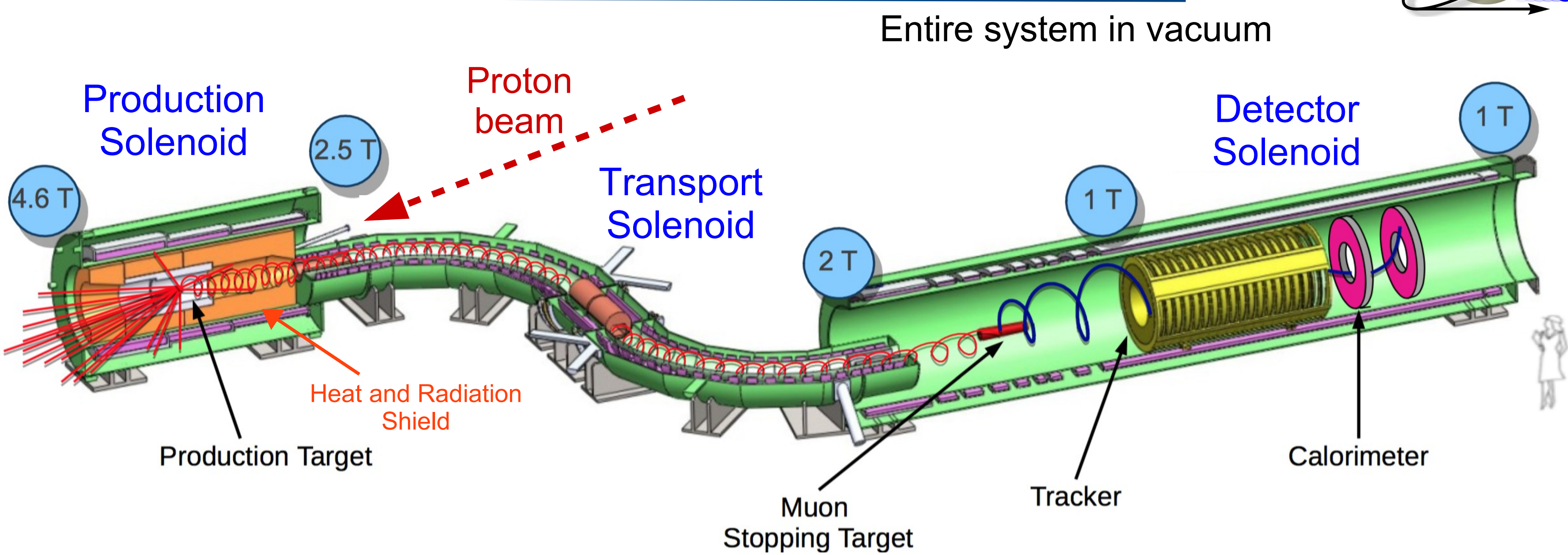
Unprecedented sensitivity, significant discovery potential

The Fermilab Mu2e experiment

The Fermilab Muon Campus

The Mu2e Collaboration
>200 scientists, 38 institutions

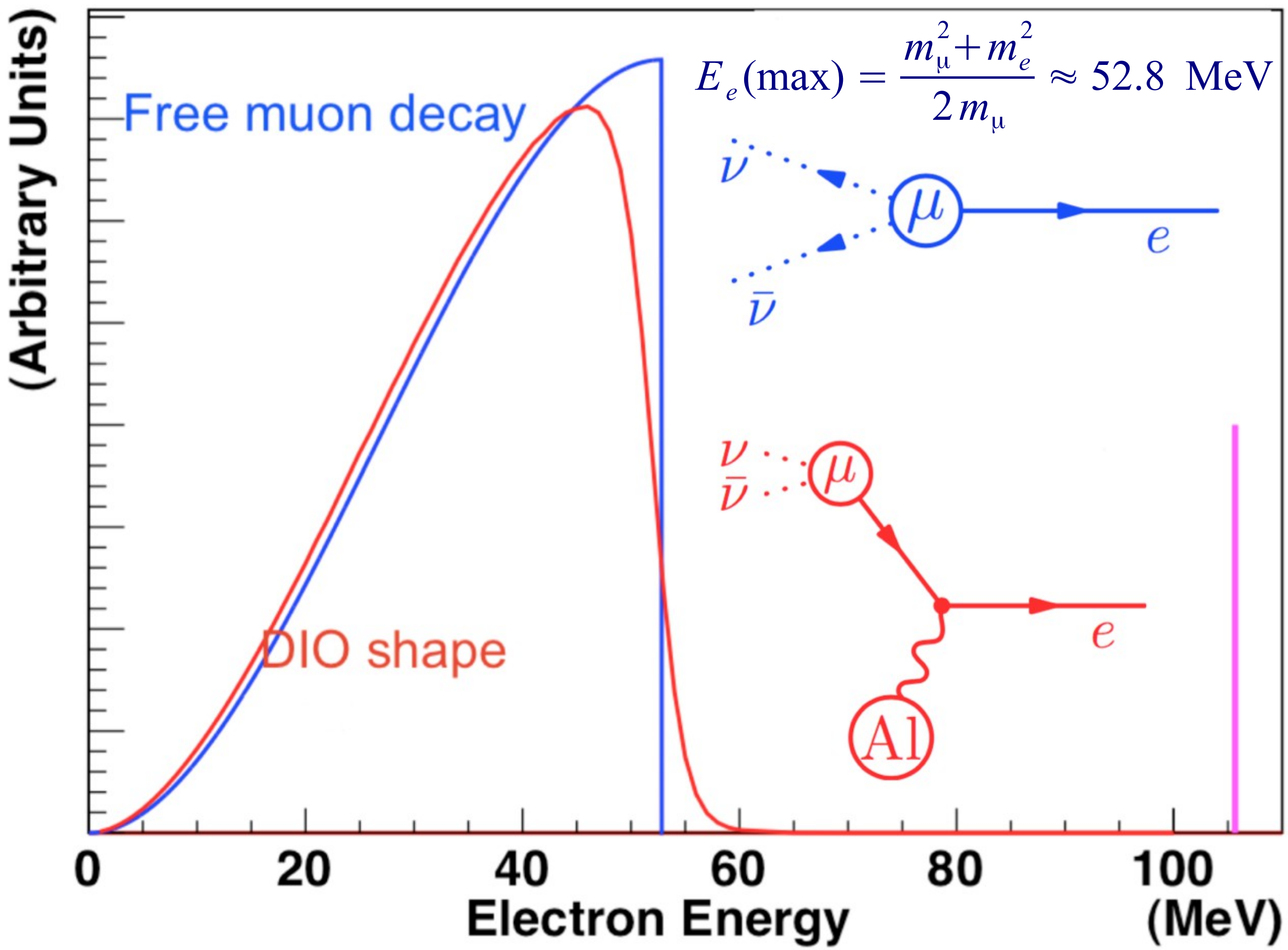
Mu2e experimental apparatus



- Production Solenoid
  - Pulsed proton beam hits target
  - Magnetic field gradient captures pions
- Transport Solenoid
  - Pions → muons
  - S-shape eliminates line-of-sight
  - Sign and momentum selection → only μ^- past collimator
- Detector Solenoid
  - Muons stopped in Al target
  - 10^{10} stopped μ/s
    - world's most intense muon beam
  - Detector system must identify 105 MeV conversion electron

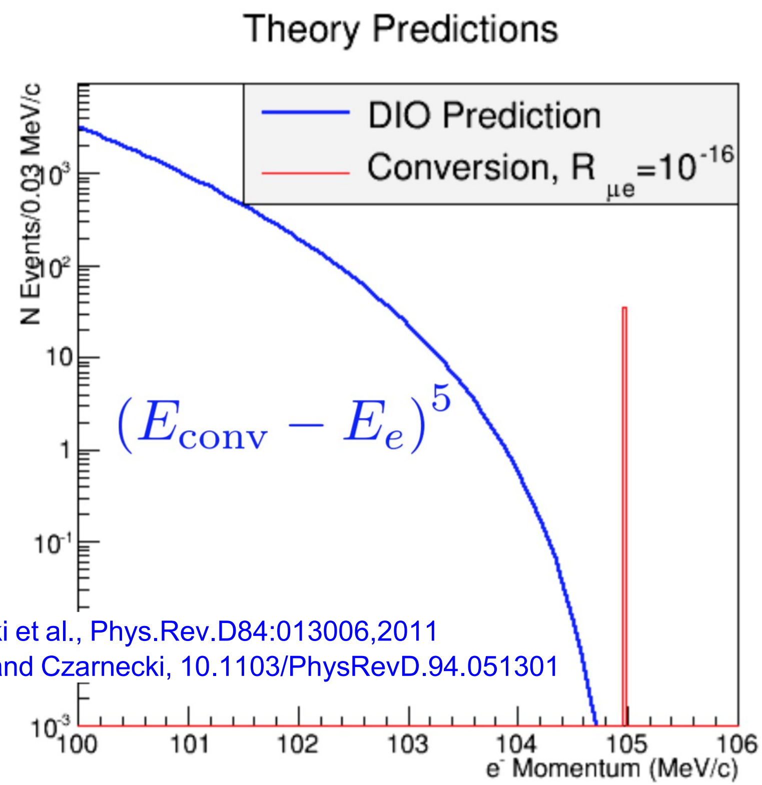
Background process: Decay in Orbit (DIO)

Michel spectrum of E_e after free muon decay, or modified in field of nucleus

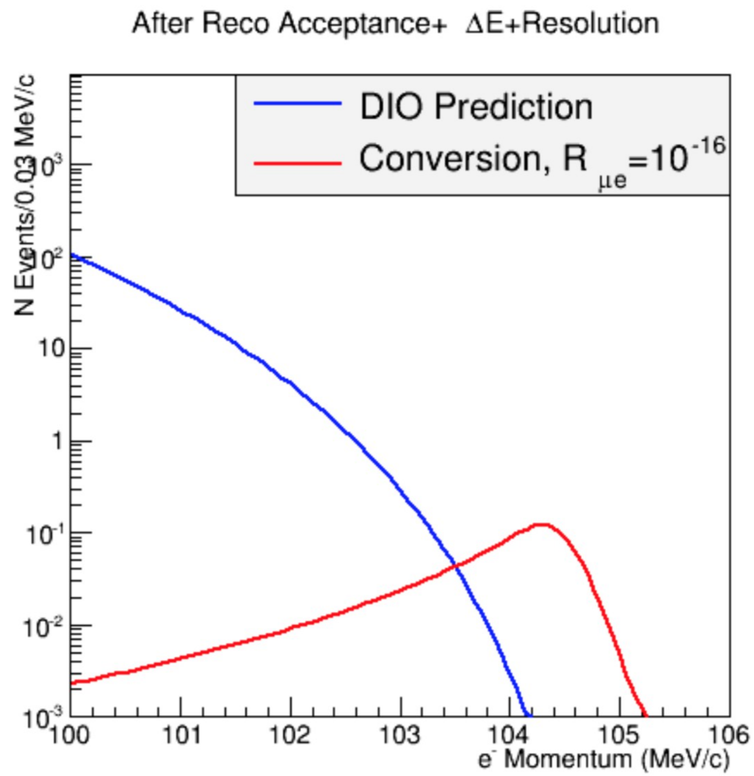


Conversion electron energy far from Michel peak

Background process: Decay in Orbit (DIO)



Czarnecki et al., Phys.Rev.D84:013006,2011
Szafron and Czarnecki, 10.1103/PhysRevD.94.051301

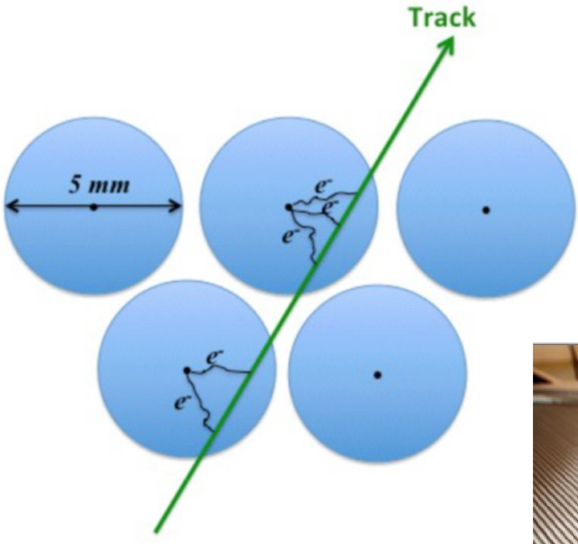


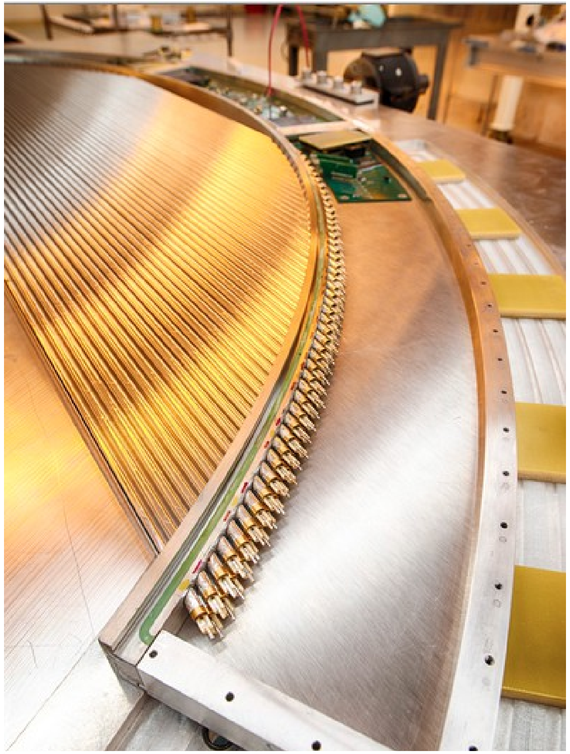
- Nuclear recoil pushes DIO spectrum near conversion electron energy
- Overlap after energy loss in material and detector resolution
- DIO electron only differs from signal through its momentum
  → Need low mass detector with high resolution

Straw tracker

Straw drift tubes

- 5mm diameter
- Wall: 12μm mylar + 3μm epoxy + 200Å Au + 500Å Al
- 25μm gold-plated tungsten wire at 1450V
- 80/20 Ar/CO_2 gas





120° panel of 2x48 straws, two staggered layers

Excellent fit to tracker requirements

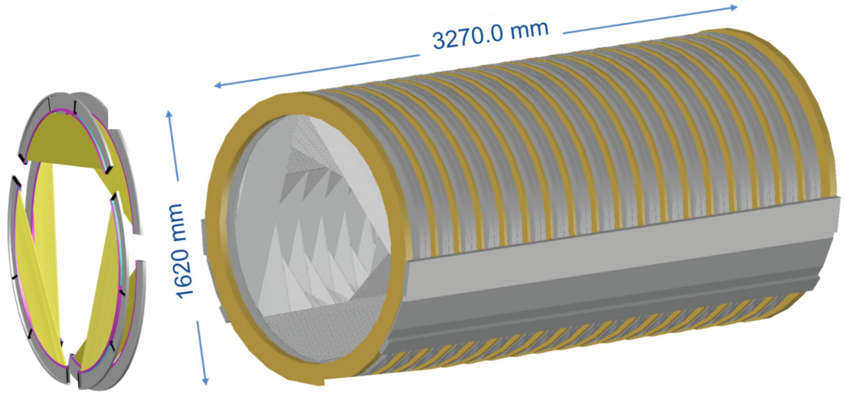
- Ultra low mass, minimize multiple scattering
- Highly segmented, handle high rates
- Reliable operation in vacuum, must not leak

Resolution <180 keV @ 105 MeV, or <0.18%

Tracker annular design

Panel unit is rotated and repeated

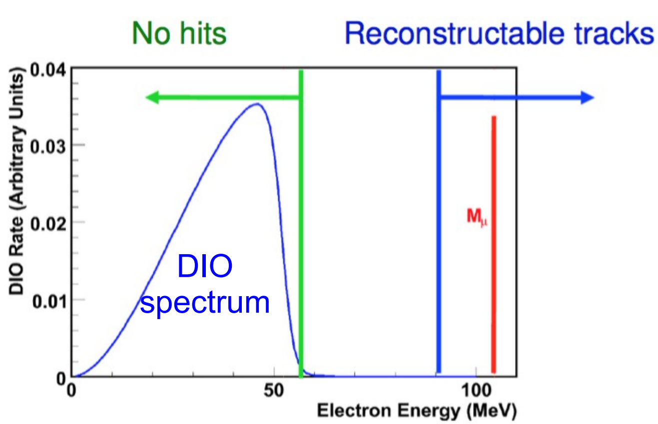
- 30º rotation for stereo reconstruction
- Total 216 panels, ~21,000 straws

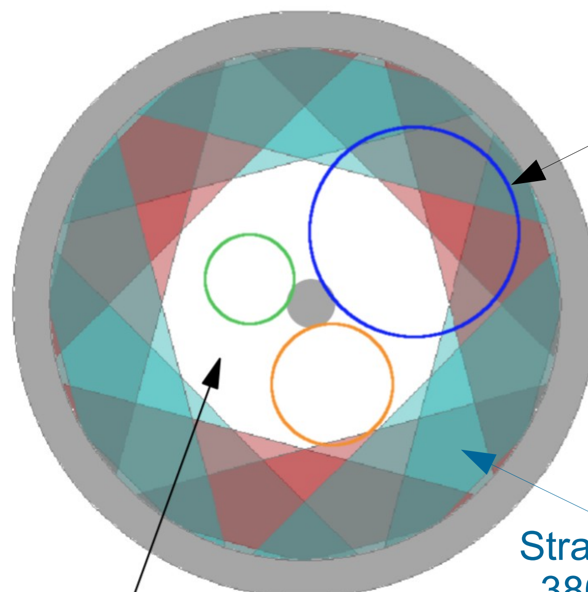


Annular design, with hole in center

Tracker is blind to nearly all DIO background

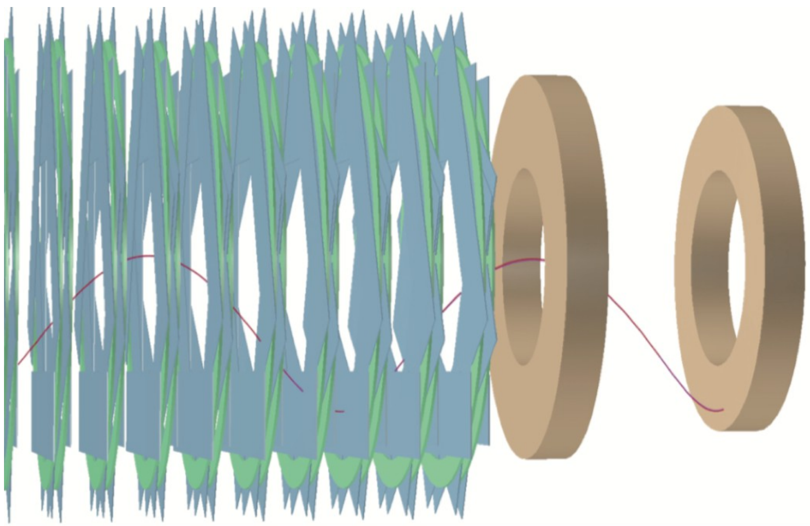
Only electrons >90MeV have reconstructable tracks

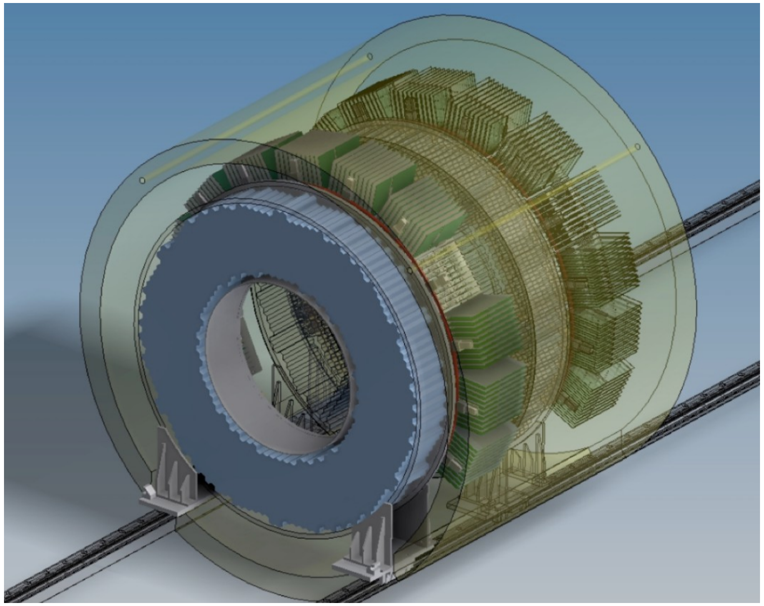




Calorimeter

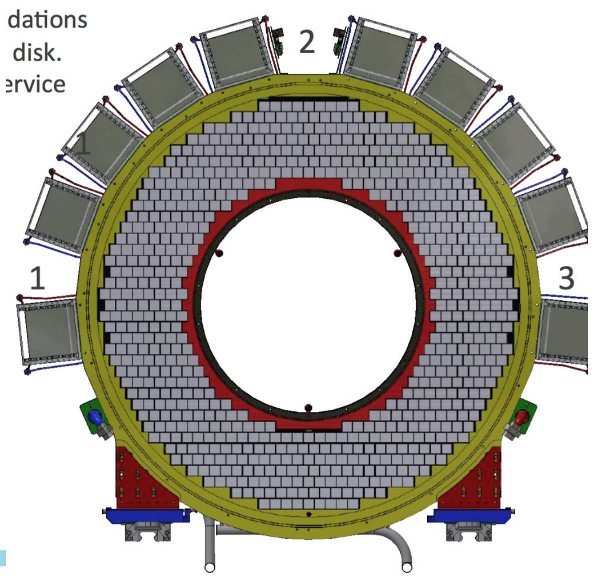
Two disks separated by half wavelength,
→ high acceptance for 105 MeV e^-



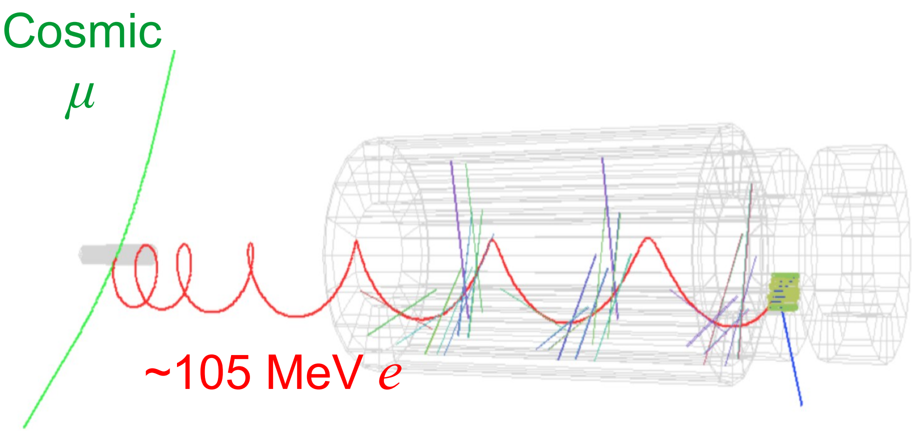


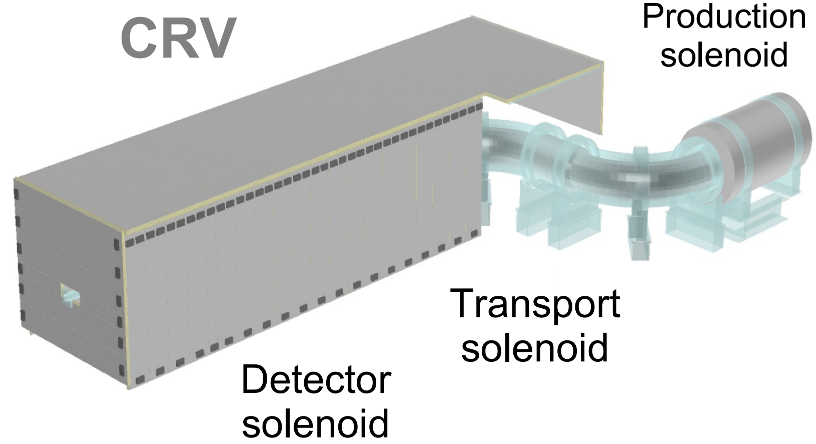
~1400 scintillating CsI crystals, 2 SiPMs/crystal

- Measurement of E, timing, and position
  - σ_E/E<10%, σ_t<0.5 ns, σ_x~1 cm
- Protection from pattern recognition errors in tracker
- Particle ID, additional rejection of cosmics background



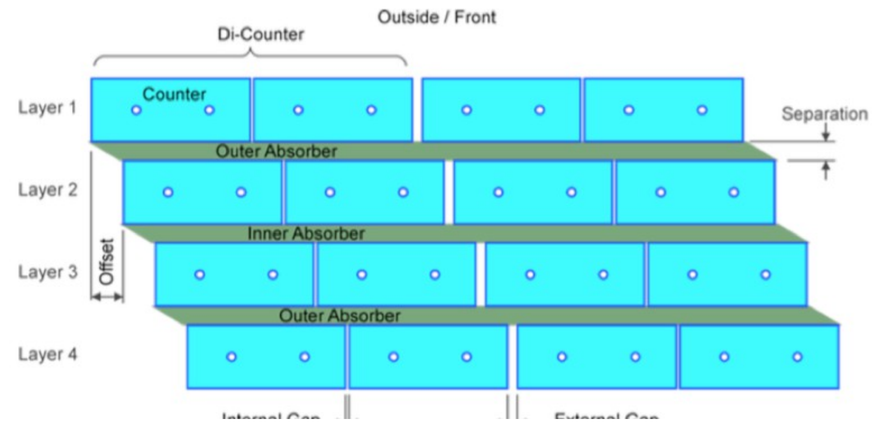
Cosmic Ray Veto (CRV) system



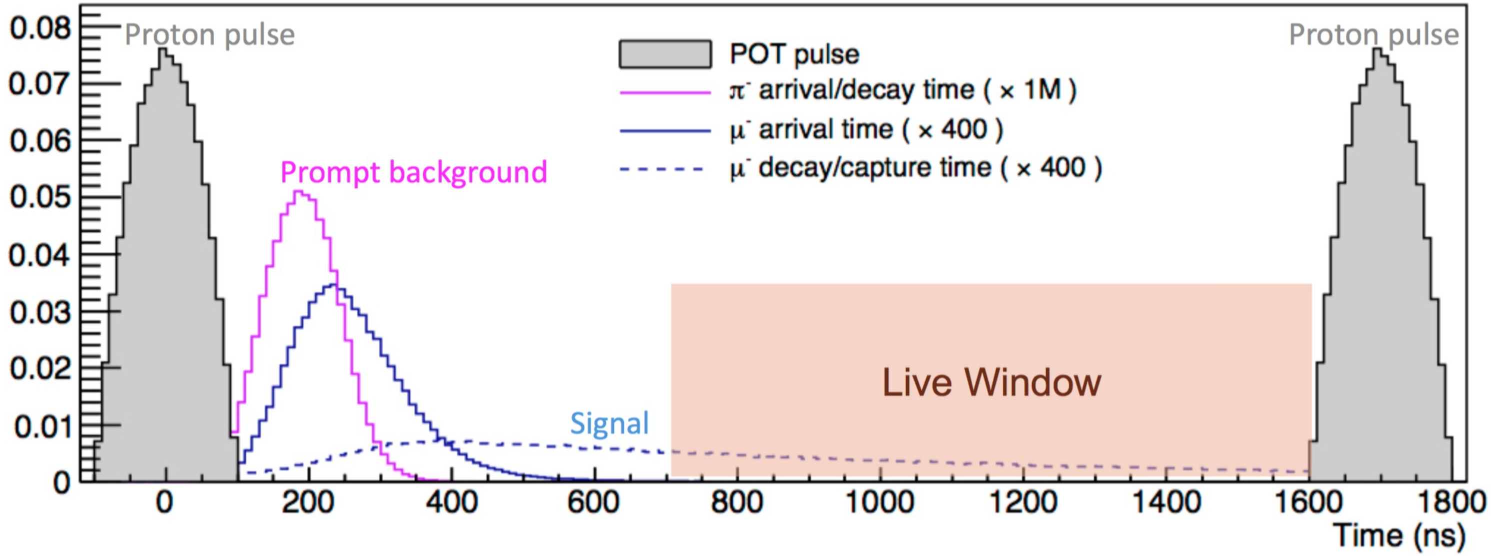


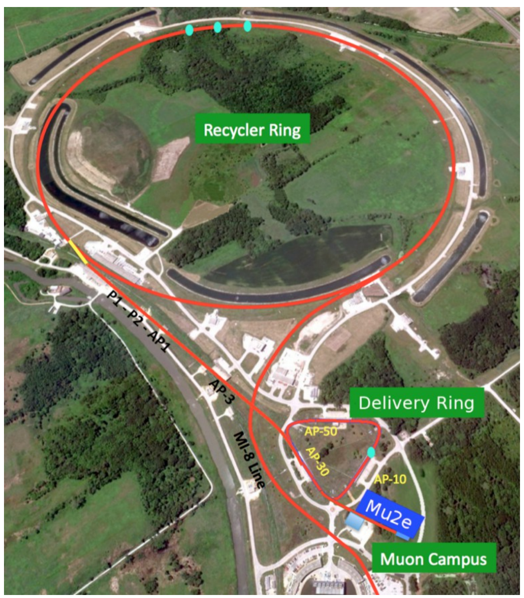
- Cosmic muon can decay or knock out electron from material
  → indistinguishable from conversion e⁻
  - Expectation of ~1 per day

- Cosmic Ray Veto covers TSd and DS
  - 4 stacked layers of scintillation counters
  - 99.99% efficiency requirement



Prompt backgrounds and delayed signal window





- Proton pulse period: 1695 ns (FNAL Delivery Ring)
- Pion lifetime: 26 ns
  - prompt backgrounds decay before signal window
- Delayed signal window: 700 → 1600 ns
  - Detector is live here
- Muonic Al lifetime: 864 ns

Must also eliminate late-arriving protons

Require beam extinction (fraction of beam between pulses) $<10^{-10}$

Backgrounds summary

For 3.6×10^{20} livetime protons on target (8 kW beam power for 3 years)

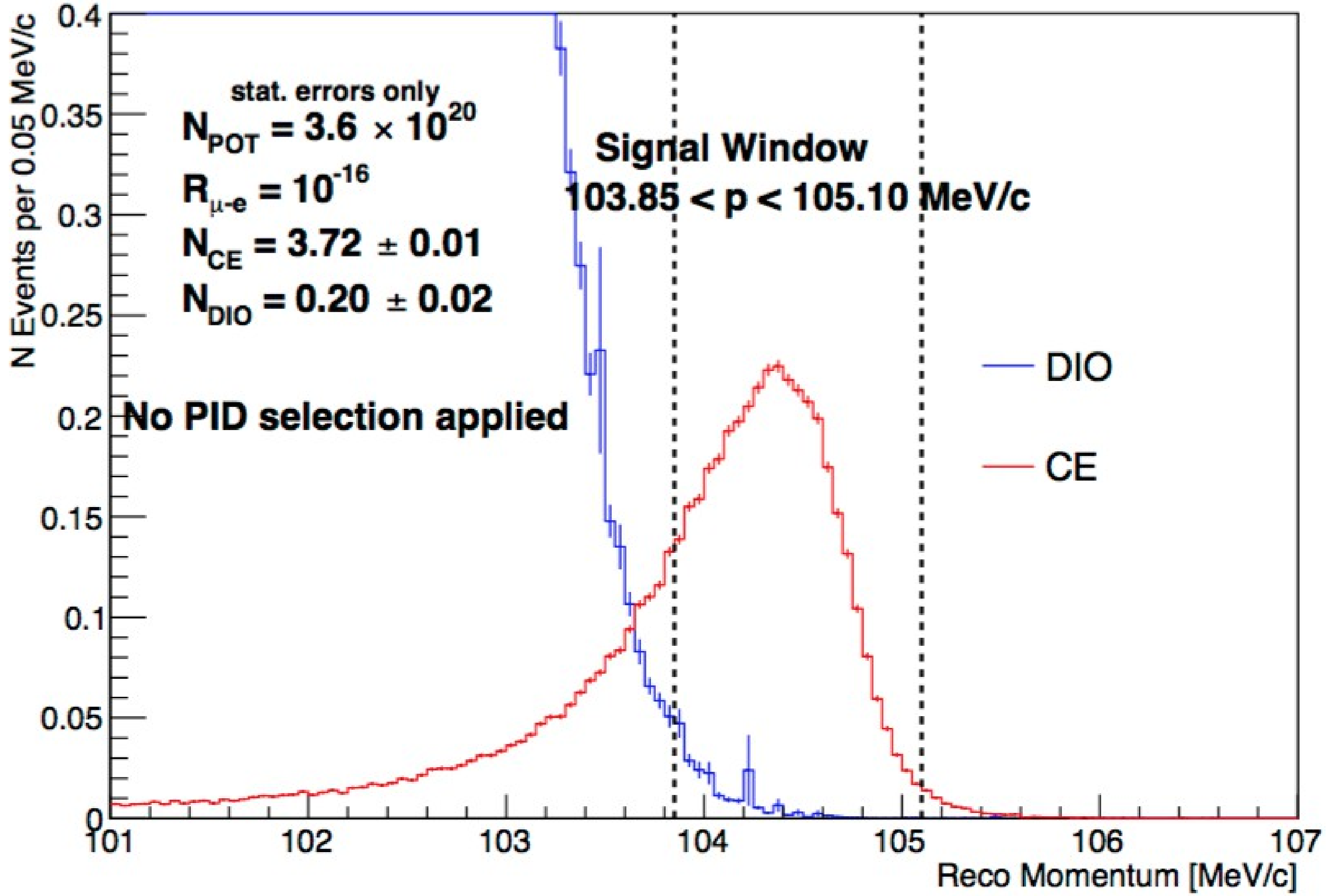
Process	Expected event yield
Cosmic ray muons	$0.21 \pm 0.02(\text{stat}) \pm 0.06(\text{syst})$
DIO	$0.14 \pm 0.03(\text{stat}) \pm 0.11(\text{syst})$
Antiprotons	$0.040 \pm 0.001(\text{stat}) \pm 0.020(\text{syst})$
Pion capture	$0.021 \pm 0.001(\text{stat}) \pm 0.002(\text{syst})$
Muon DIF	< 0.003
Pion DIF	$0.001 \pm < 0.001$
Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
RMC	$0.000^{+0.004}_{-0.000}$
Total	$0.41 \pm 0.13(\text{stat+syst})$

Any observation will be strong evidence of CLFV

Single event sensitivity $(3.01 \pm 0.03(\text{stat}) \pm 0.41(\text{syst})) \times 10^{-17}$

5σ discovery capability at $R_{\mu e} \sim 2\times10^{-16}$

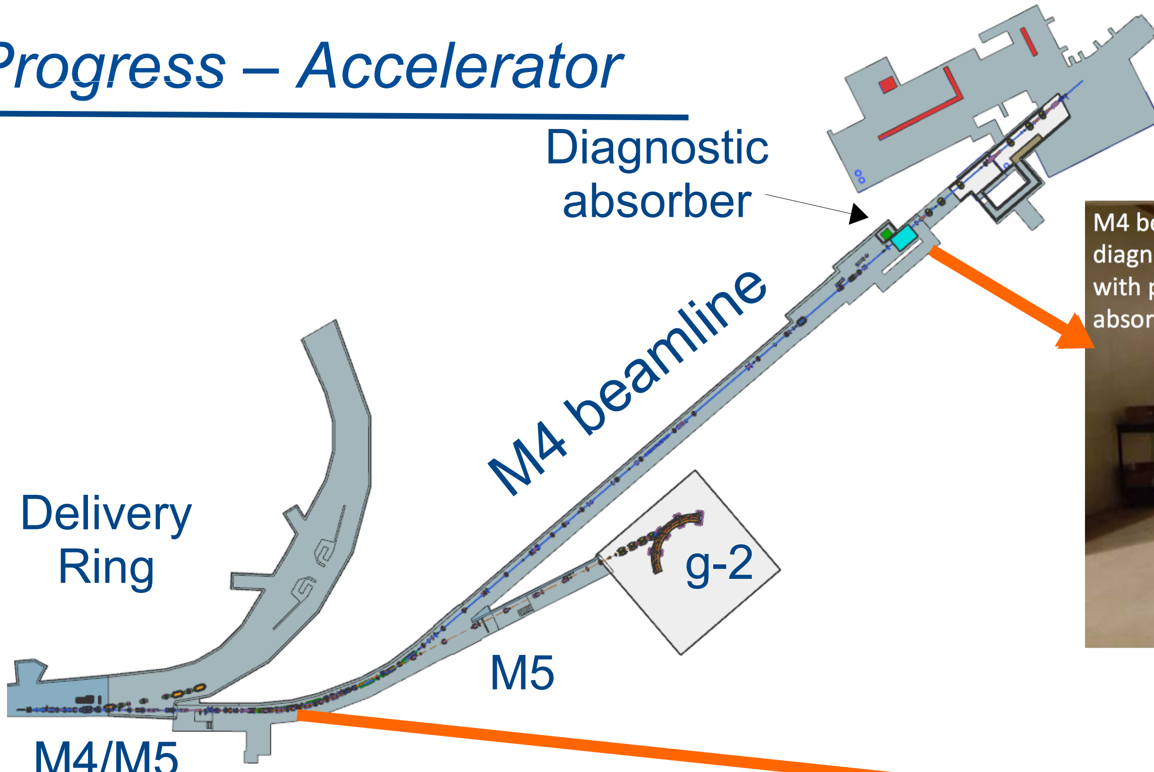
Signal and DIO background

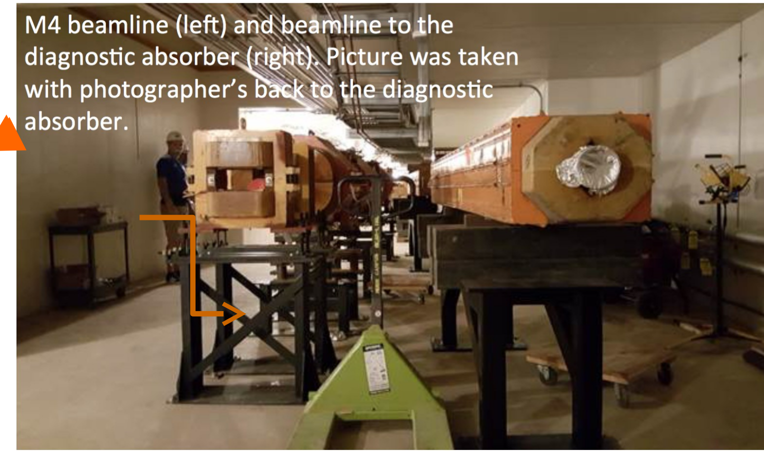


For R $_{\mu e}$ ≈10^{-16} we expect:

~4 conversion events, no background contamination

Progress – Accelerator





- M4 installation progress
    - Installation of magnets, instrumentation, cooling, almost complete to diagnostic absorber

- Muon Campus g-2 operations exercise many of the new facilities required for Mu2e

Progress – Production target and HRS

Commissioning production target delivered

Forged bronze for HRS procured

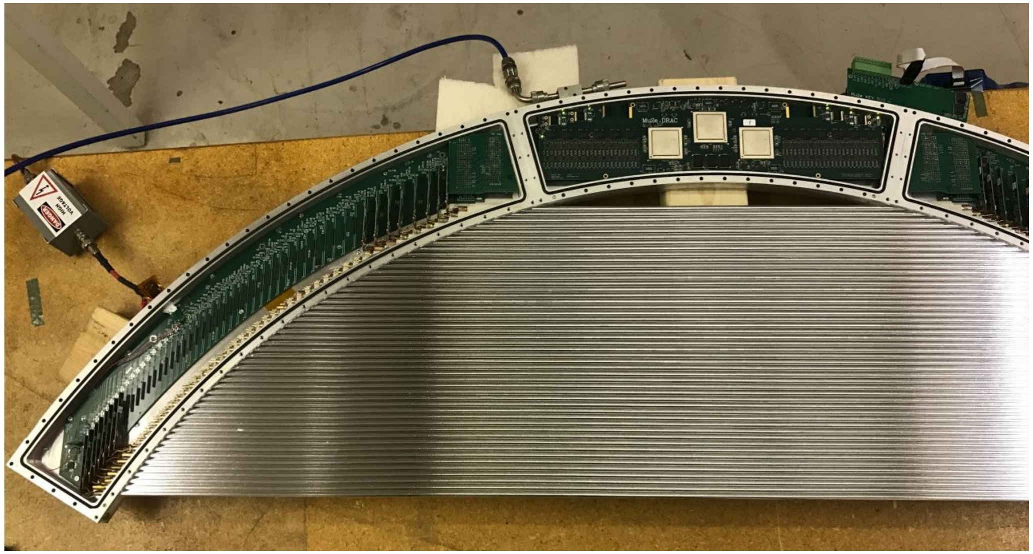
Progress – Solenoids

TS coil module fabrication at ASG (Italy).

First two production units delivered.

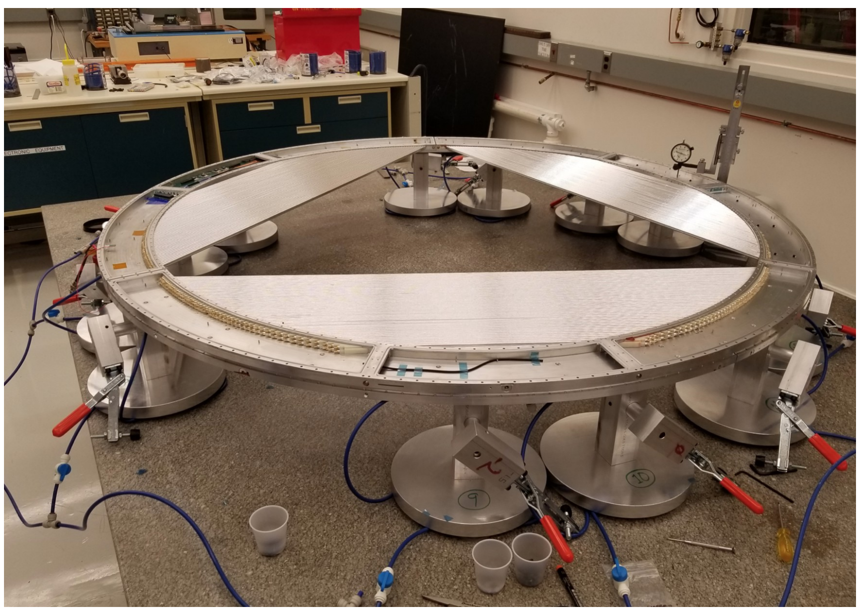
PS conductor winding at General Atomics.

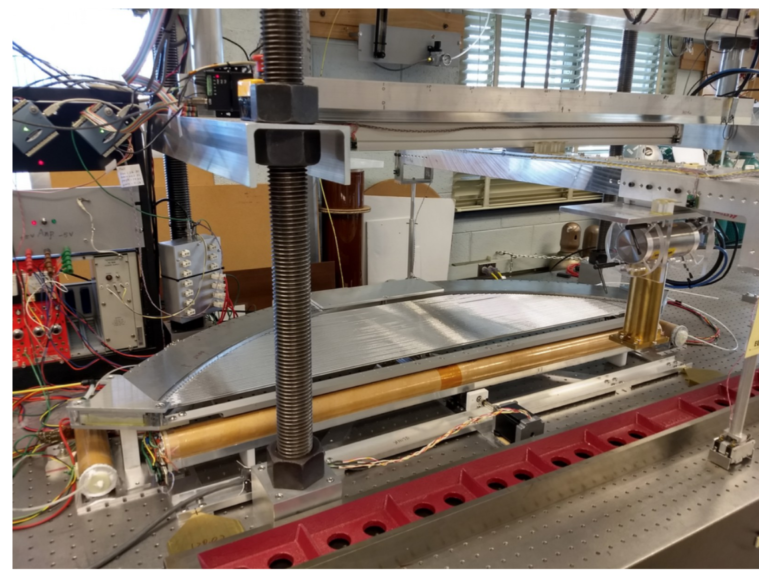
Progress – Tracker



FEE full scale prototypes validated.

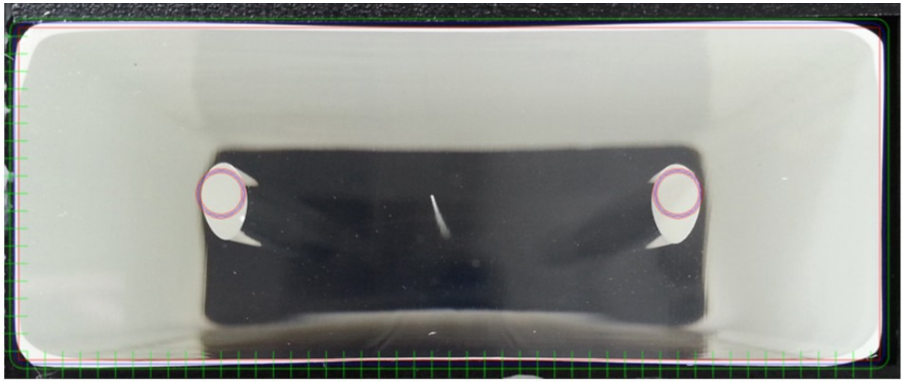
All straws manufactured, panel production ramping up.



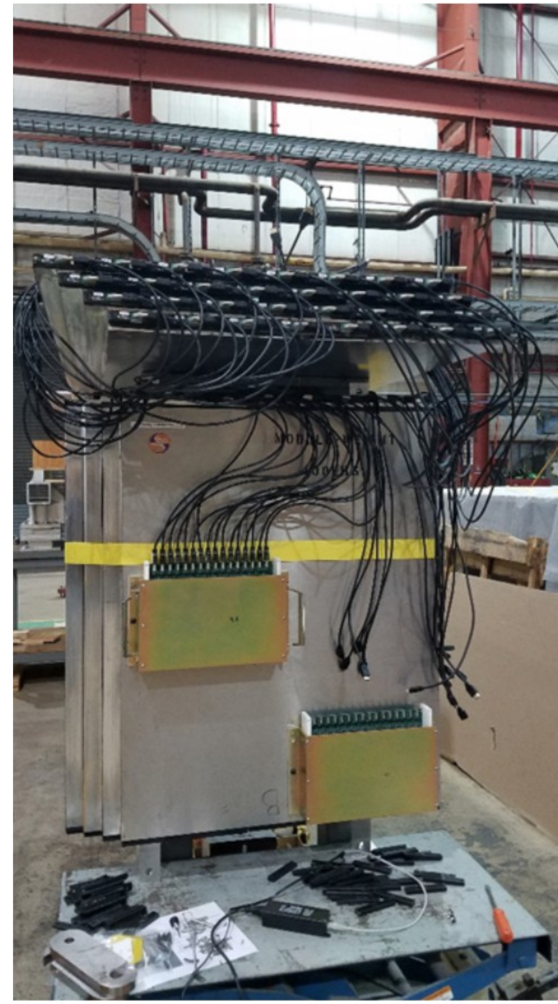


Progress – CRV

CRV scintillation counter



CRV module production



Summary/Outlook

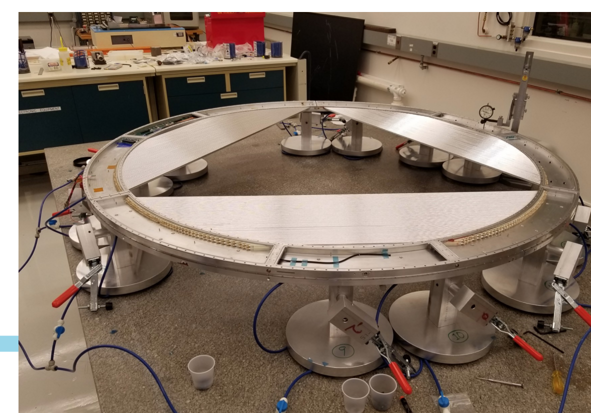
The Mu2e experiment

- A search for Charged Lepton Flavor Violation
  - 4 orders of magnitude sensitivity increase

- Proposed upgrade improves sensitivity by another order of magnitude
  - Mu2e-II expression of interest: https://arxiv.org/abs/1802.02599

- Recent PAC and DOE IPR commended the project on significant progress
  – Construction underway

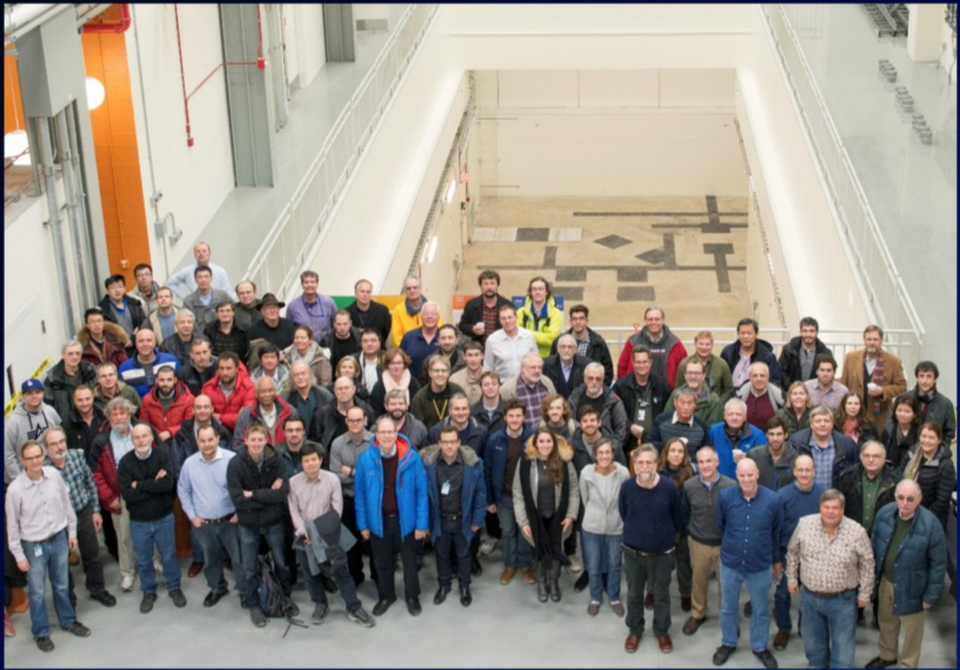
- Commissioning expected in 2021, followed by 3 years of data



The Mu2e Collaboration

Over 200 scientists from 38 institutions

The Mu2e Collaboration, Feb 2017



Argonne National Laboratory ● Boston University Brookhaven National Laboratory Lawrence Berkeley National Laboratory and University of California, Berkeley ● University of California, Davis ● University of California, Irvine ● California Institute of Technology ● City University of New York ● Joint Institute for Nuclear Research, Dubna ● Duke University ● Fermi National Accelerator Laboratory ● Laboratori Nazionali di Frascati ● INFN Genova ● Helmholtz-Zentrum Dresden-Rossendorf ● University of Houston ● Institute for High Energy Physics, Protvino ● Kansas State University ● INFN Lecce and Università del Salento ● Lewis University ● University of Liverpool ● University College London ● University of Louisville ● University of Manchester ● Laboratori Nazionali di Frascati and Università Marconi Roma ● University of Michigan University of Minnesota ● Institute for Nuclear Research, Moscow ● Muons Inc. ● Northern Illinois University ● Northwestern University ● Novosibirsk State University/Budker Institute of Nuclear Physics ● INFN Pisa ● Purdue University ● University of South Alabama ● Sun Yat Sen University ● University of Virginia ● University of Washington ● Yale University

Backup

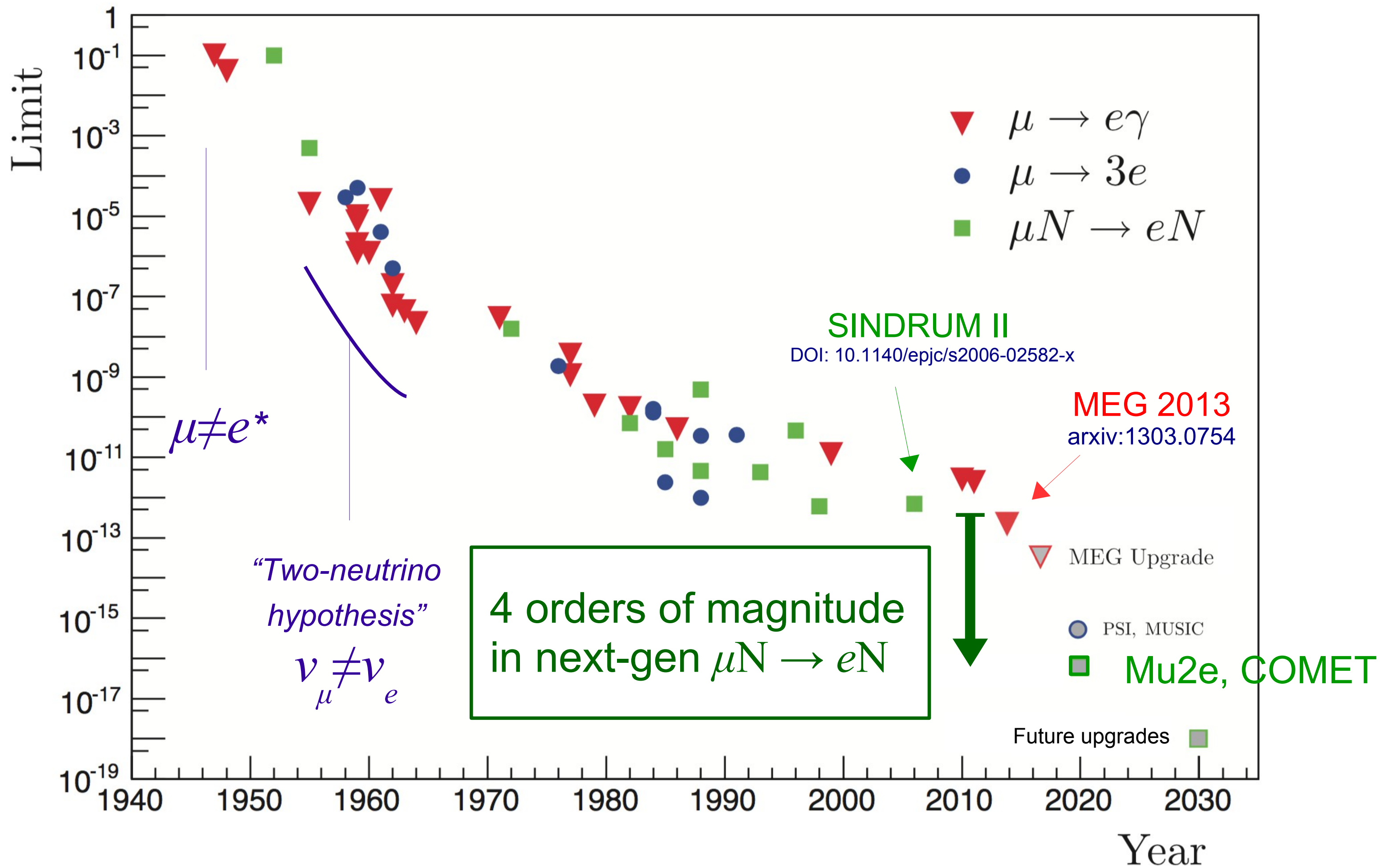
CLFV processes

Broad global interest in CLFV searches:

Process	Current limit	Planned Next Gen Experiment
$Z \to e\mu$	$\mathrm{BR} < 7.5 \cdot 10^{-7}$	
$\tau \to eee$	$\mathrm{BR} < 2.7 \cdot 10^{-8}$	10^{-9}, BELLE-II
$\tau \to \mu\mu\mu$	$\mathrm{BR} < 2.1 \cdot 10^{-8}$	
$\tau \to \mu ee$	$\mathrm{BR} < 1.5 \cdot 10^{-8}$	
$\tau \to \mu\eta$	$\mathrm{BR} < 6.5 \cdot 10^{-8}$	
$\tau \to e\gamma$	$\mathrm{BR} < 3.3 \cdot 10^{-8}$	
$\tau \to \mu\gamma$	$\mathrm{BR} < 4.4 \cdot 10^{-8}$	
$K_L \to e\mu$	$\mathrm{BR} < 4.7 \cdot 10^{-12}$	
$K^+ \to \pi^+ e\mu$	$\mathrm{BR} < 1.3 \cdot 10^{-11}$	
$B^0 \to e\mu$	$\mathrm{BR} < 7.8 \cdot 10^{-8}$	
$B^+ \to K^+ e\mu$	$\mathrm{BR} < 9.1 \cdot 10^{-8}$	
$\mu^+ \to e^+\gamma$	$\mathrm{BR} < 4.2 \cdot 10^{-13}$	10^{-14} (MEG)
$\mu^+ \to e^+e^-e^+$	$\mathrm{BR} < 1.0 \cdot 10^{-12}$	10^{-16} (Mu3e)
$\mu^- A \to e^- A$	$\mathrm{R}^{\mathrm{Au}}_{\mu e} < 7.0 \cdot 10^{-13}$	10^{-17} (Mu2e, COMET)

- Most stringent limits come from the muon sector
- The $\mu A \to eA$ process offers greatest potential sensitivity
  - Best control of backgrounds

History of CLFV searches



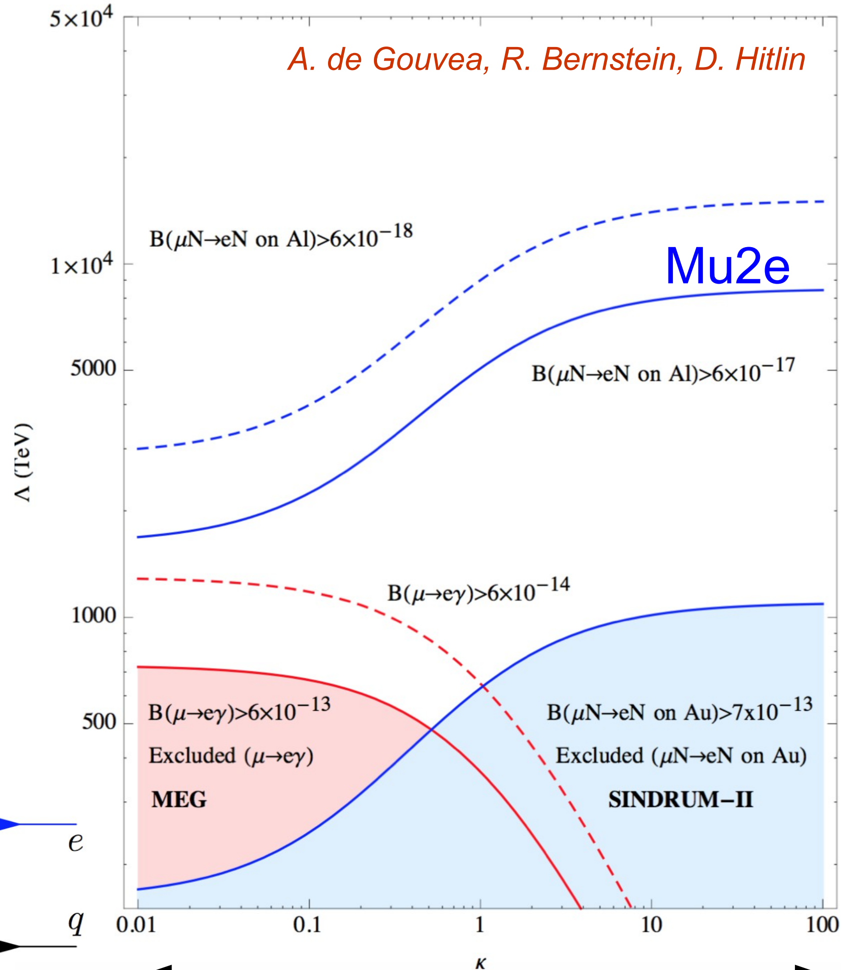
- Dramatic improvement in next generation experiments, especially $\mu\mathrm{N} \rightarrow e\mathrm{N}$
- Exploring unconstrained phase space favored by many New Physics models

Physics Reach

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

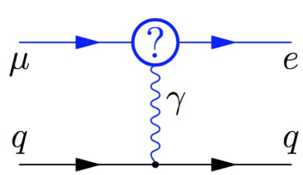
Λ: effective mass parameter

κ: relative strength of loop- and contact-dominated terms

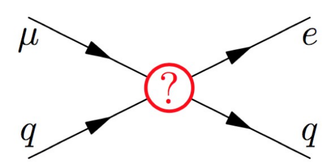


Mu2e improves sensitivity in all New Physics scenarios

Effective mass scale reach up to 10^4 TeV, well beyond the direct reach of current or future colliders



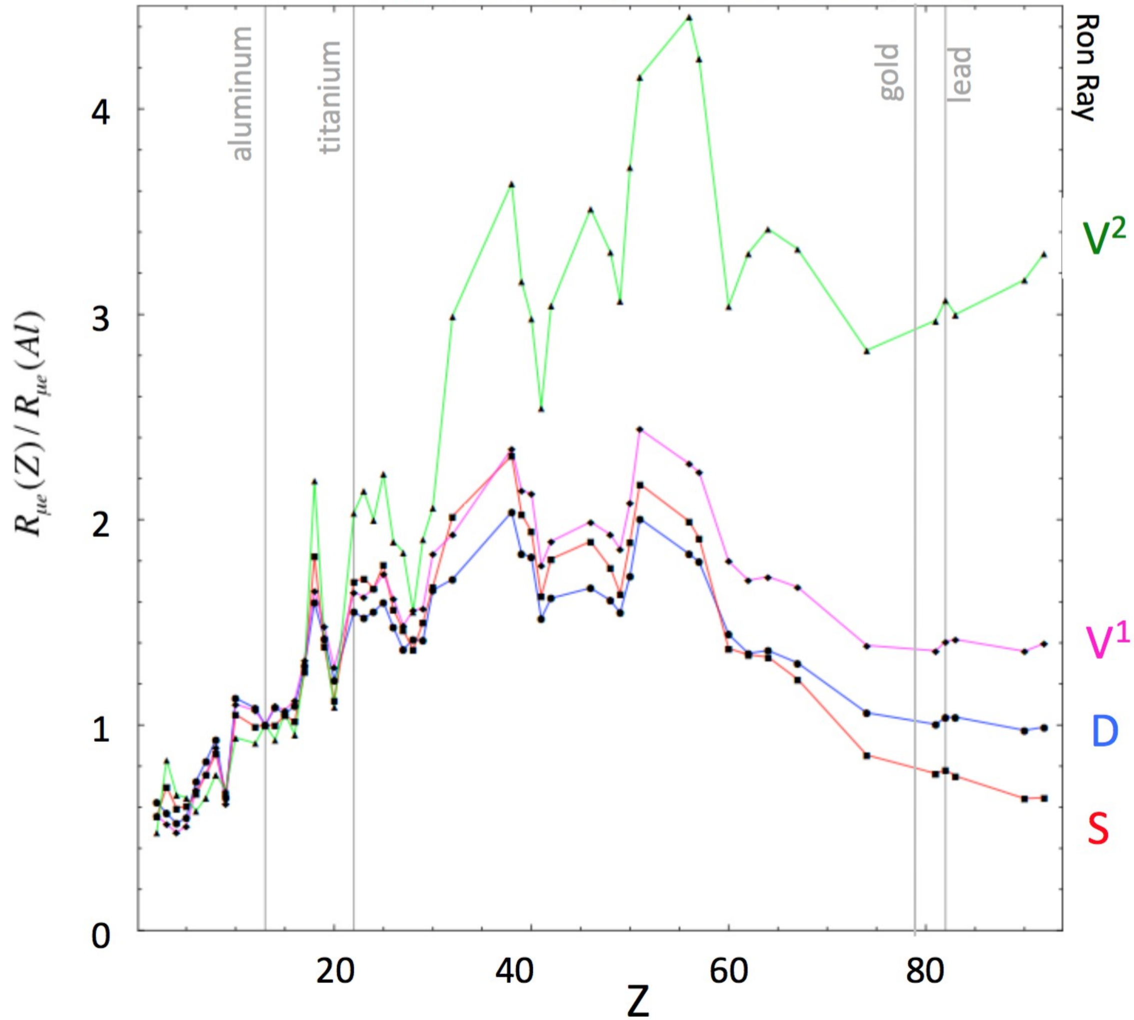
Loop-dominated



Contact-dominated

Model Discrimination

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

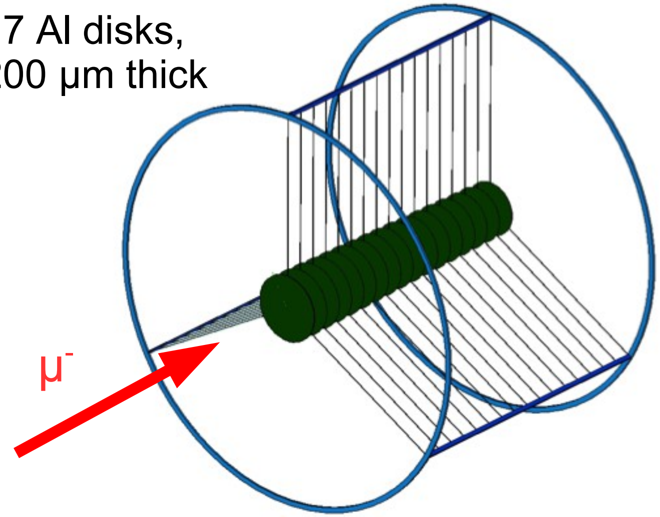


We obtain model discriminating power on underlying physics mechanism by comparing CLFV rates on different stopping targets

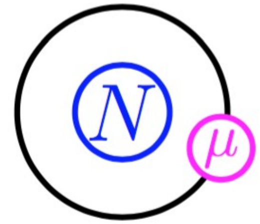
Mu2e-II expression of interest:
https://arxiv.org/abs/1802.02599

Stopping Target

17 Al disks,
200 μm thick

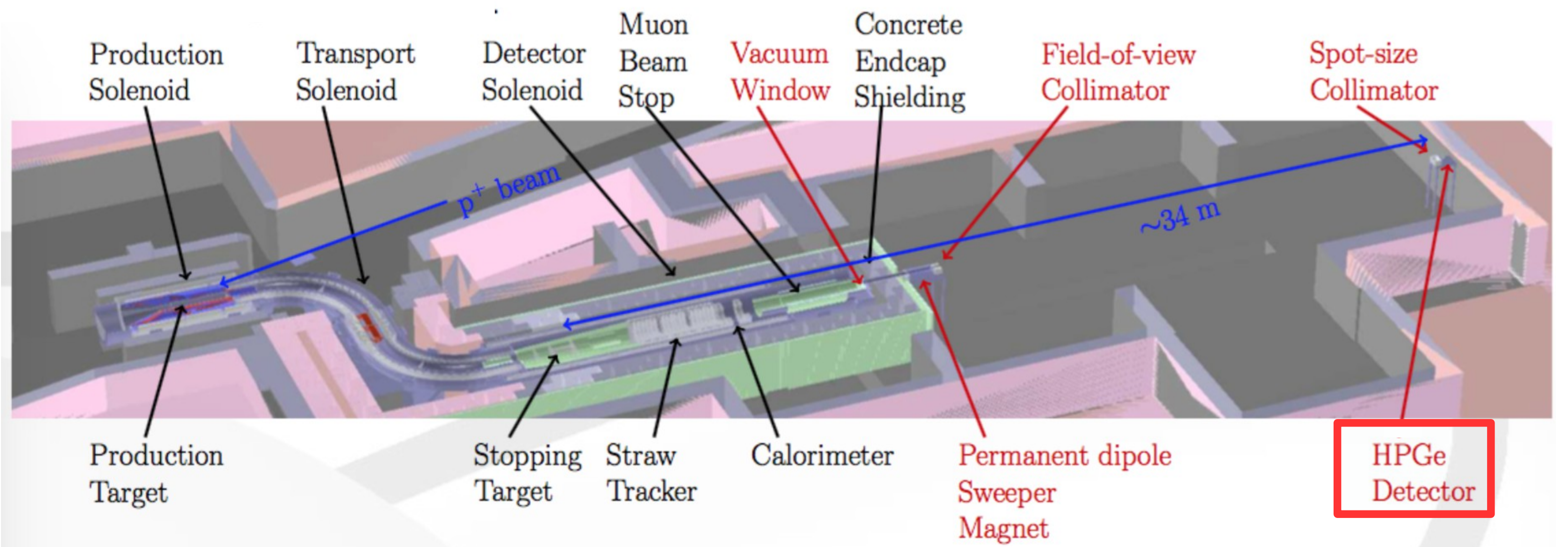


Muons stopped in thin Al target foils.
Quickly cascade to 1s ground state (~1 fs), emitting X-rays at characteristic energies



Fermi radius ~20 fm
Muonic Al lifetime: 864 ns

Muonic atom at rest



High-purity Ge detector monitors de-excitation X-rays from stopping target

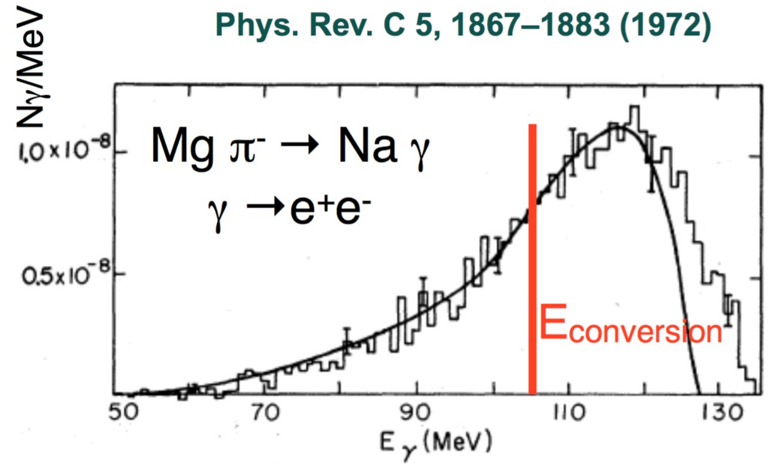
Mu2e Prompt Backgrounds

Prompt event: occurs shortly after particle reaches stopping target

Example: Radiative pion capture
Non-decayed pion reaches stopping target,
is radiatively captured, then photon converts.

$$\pi^- \mathrm{N} \rightarrow \gamma \mathrm{N}$$

$$\gamma \rightarrow e^- e^+$$



Photon momentum endpoint at m_π.
The electron can have momentum in signal window, and mimic conversion event.

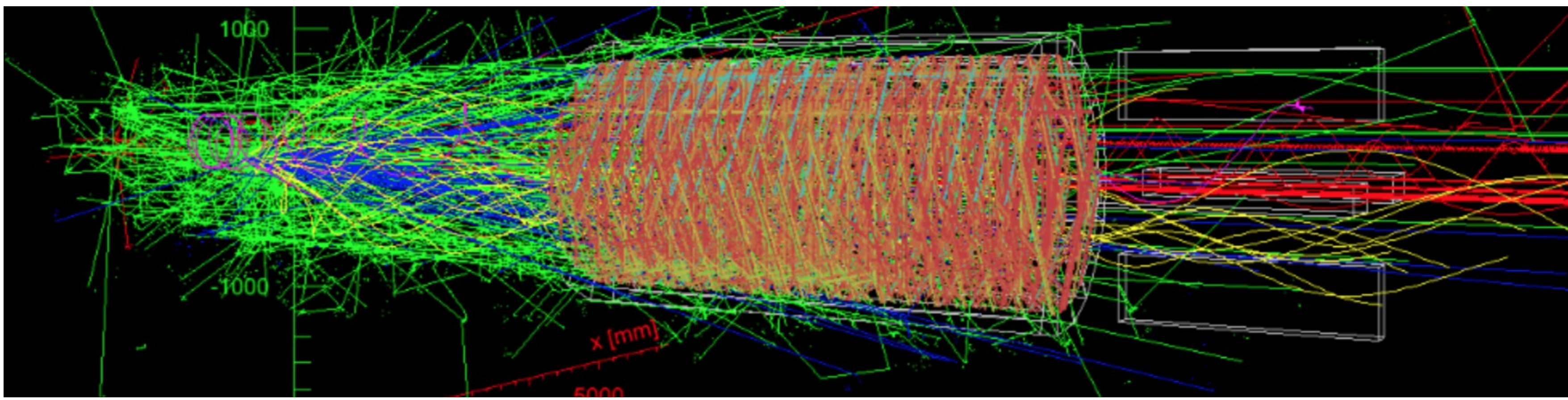
Pion lifetime: only ~26 ns, much shorter than muonic Al (864 ns)
Prompt backgrounds: decay quickly after proton pulse

Concept to suppress prompt backgrounds:
Simply wait until their rates are lowered
before initiating live window to look for signal.

Tracking

From individual straw hits in tracker we need to:

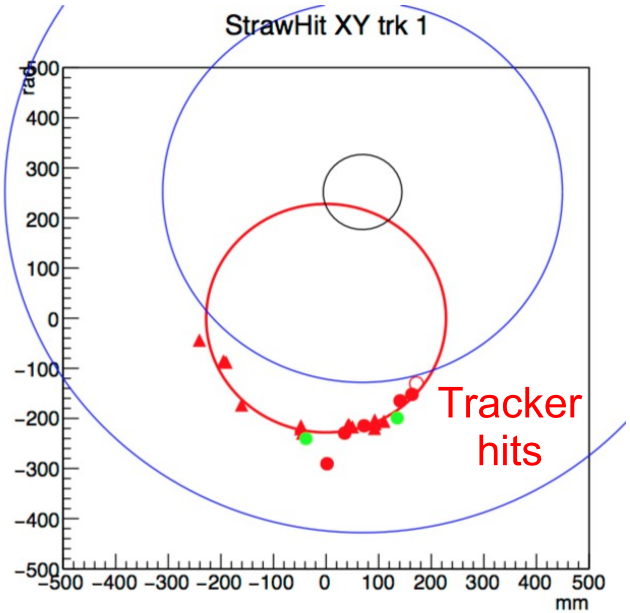
- Remove background hits
- Identify hits from single particle (pattern recognition)
- Reconstruct particle's trajectory (helix fitting)

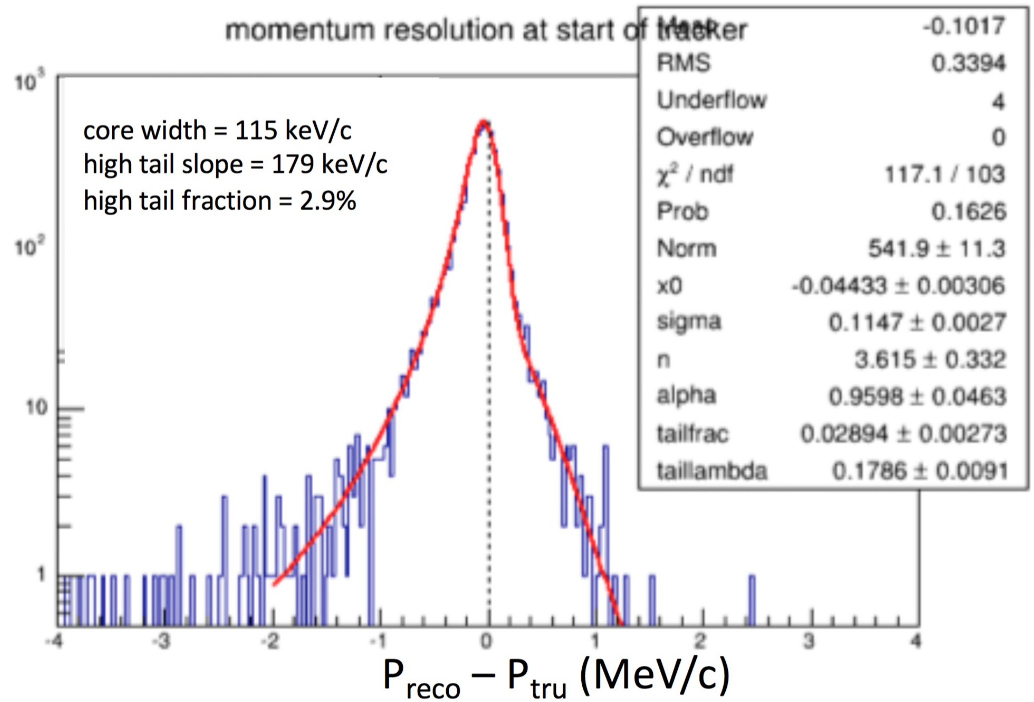


Signal electron + all hits over 500-1695 ns window

Detailed G4 model: straws, electronics, supports, B-fields

Tracker Momentum Resolution

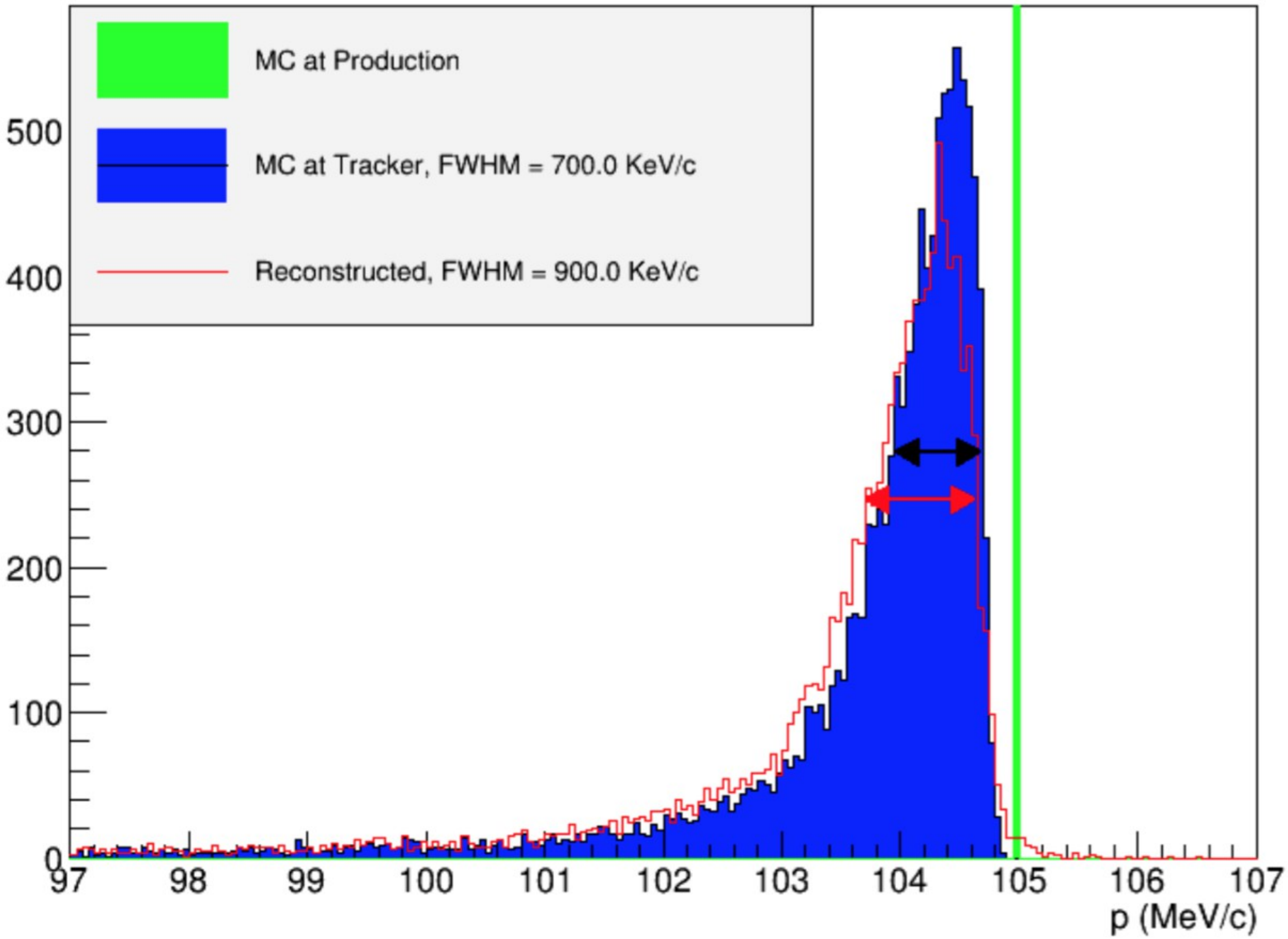




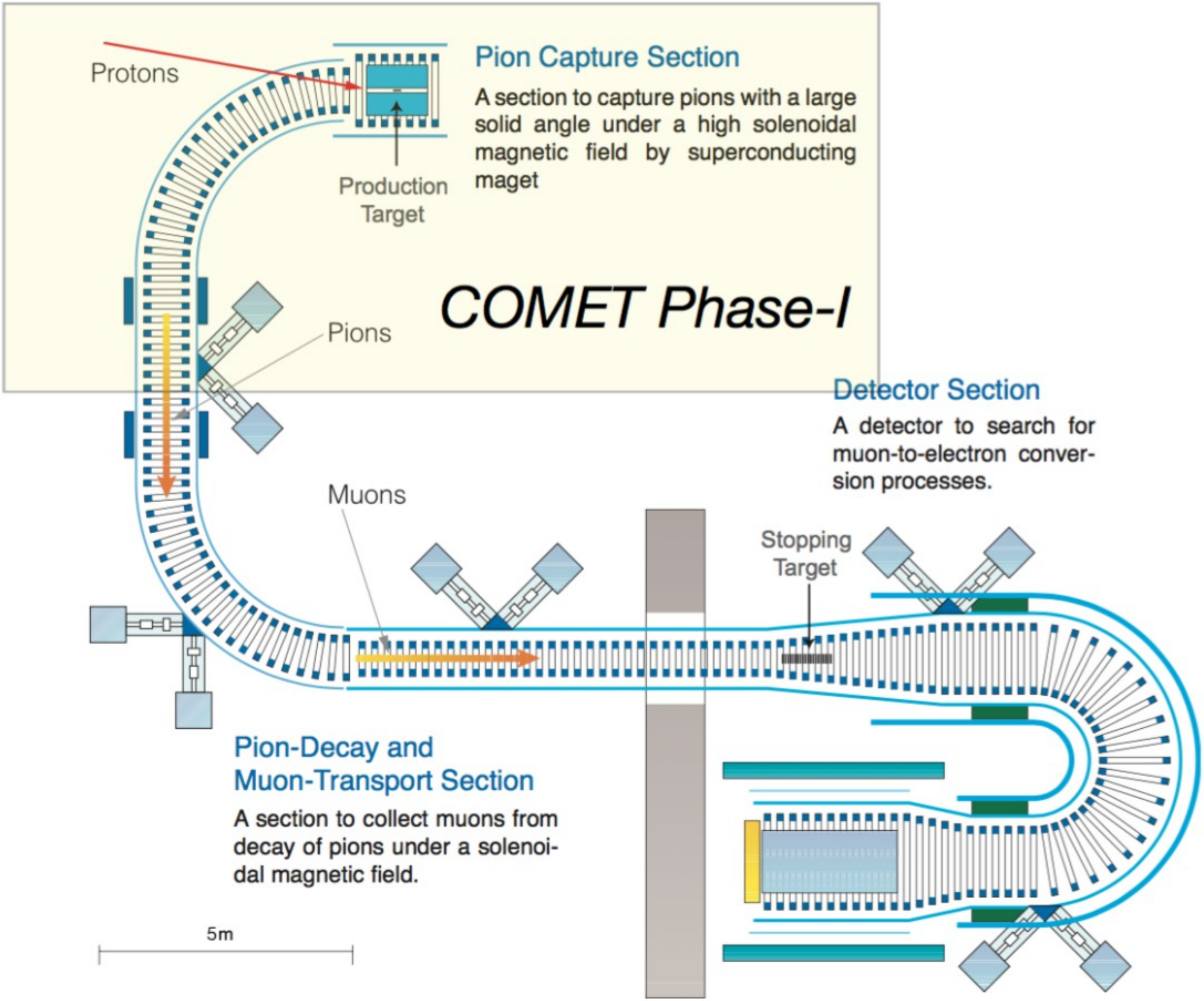
Helix fit, least squares fit, followed by iterative Kalman Filter track fit

Tracker momentum resolution requirement:
σ_p/p<0.2% for a 105 MeV electron, or σ_p<180 keV/c

Signal momentum spectrum



Smearing dominated by interactions at the target and at neutron/proton absorbers upstream of the tracker


Protons
Pion Capture Section
A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting maget
Production Target
COMET Phase-I
Pions
Detector Section
A detector to search for muon-to-electron conversion processes.
Muons
Stopping Target
Pion-Decay and Muon-Transport Section
A section to collect muons from decay of pions under a solenoidal magnetic field.
5m