The Mu2e experiment

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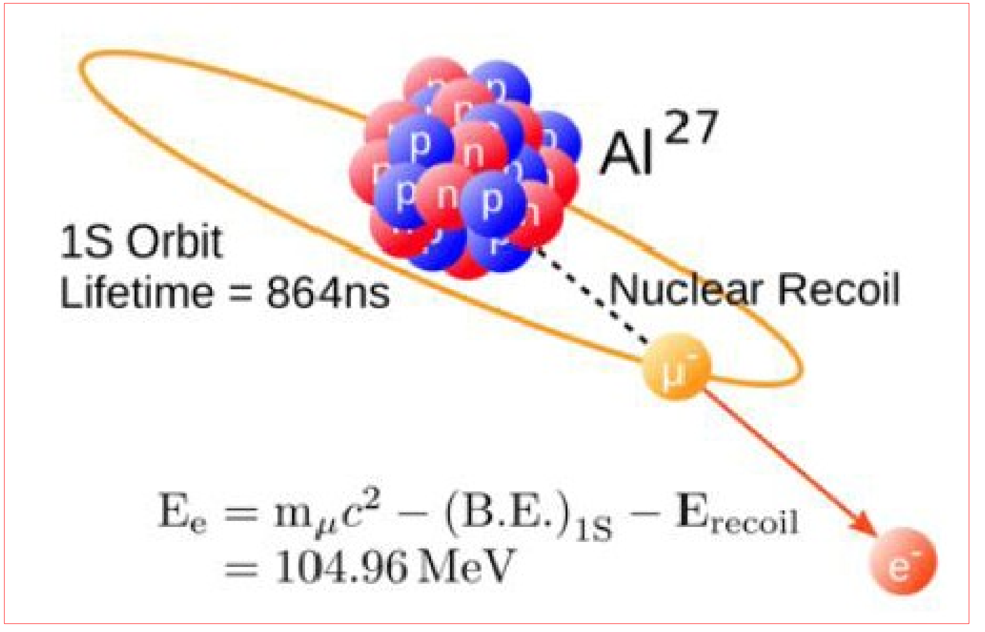
on behalf of the Mu2e Collaboration

EPS-HEP2023 conference

Hamburg August 20-25,2023

Searching for CLFV

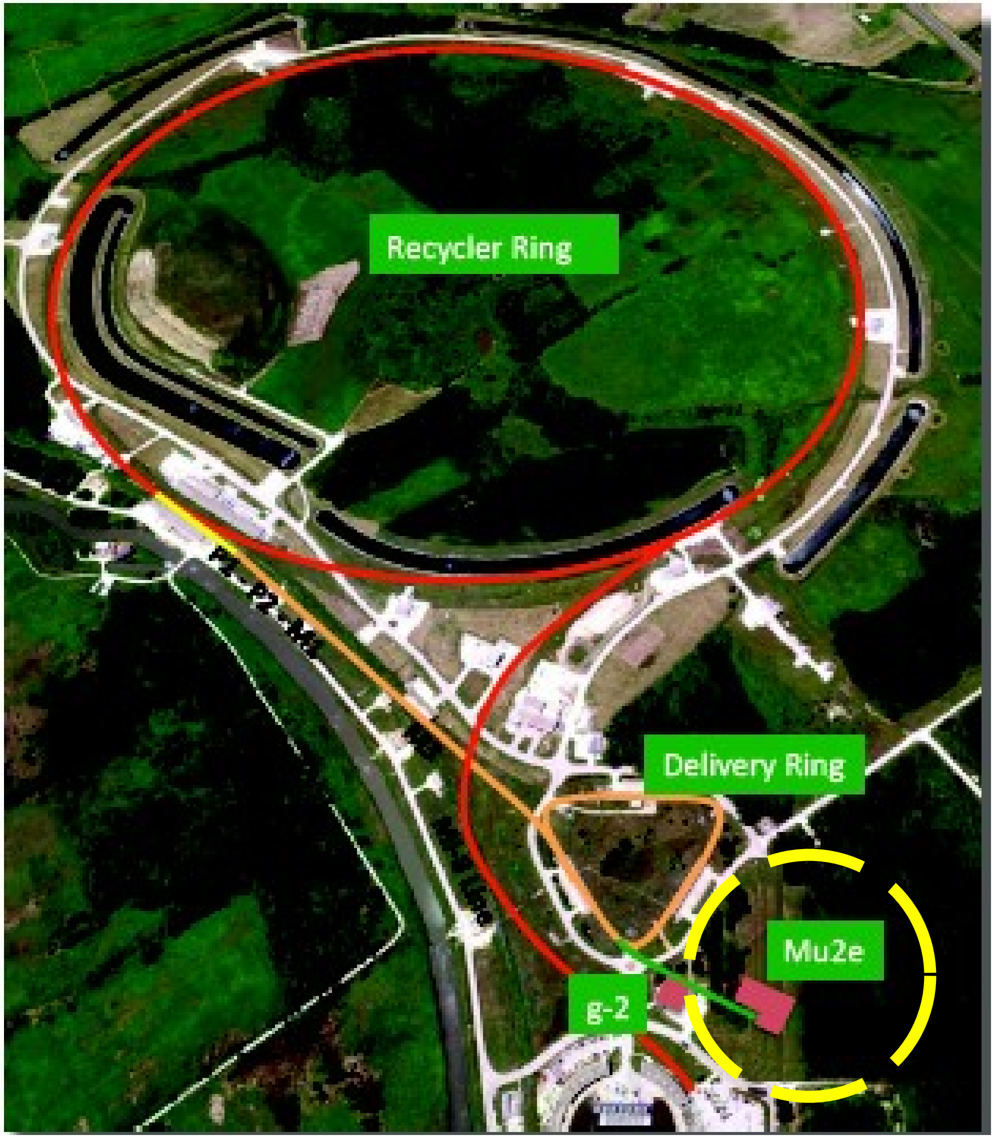


Mu2e searches for **Charged Lepton Flavor Violation (CLFV)** via the coherent conversion:

$$\mu^- + Al \rightarrow e^- + Al$$

Same channel as COMET, complementary to MEGII ($\mu^+ \rightarrow e^+\gamma$) and Mu3e ($\mu^+ \rightarrow e^+e^-e^+$)

The Mu2e experiment



Mu2e at
Fermilab Muon Campus

Mu2e **goal** is to improve by **a factor 10^4** the world's best sensitivity on:

$$R_{\mu e} = \frac{\Gamma(\mu^- + N \rightarrow e^- + N)}{\Gamma(\mu^- + N \rightarrow \text{all captures})}$$

SINDRUM II @PSI (2006, Au)*:

$$\mathbf{R_{\mu e} < 7 \cdot 10^{-13}\ (90\%\ CL)}$$

*W. Bertl et al., Eur.Phys.J. C47,337 (2006)

The Mu2e experiment

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SINDRUM II @PSI (2006, Au)*:

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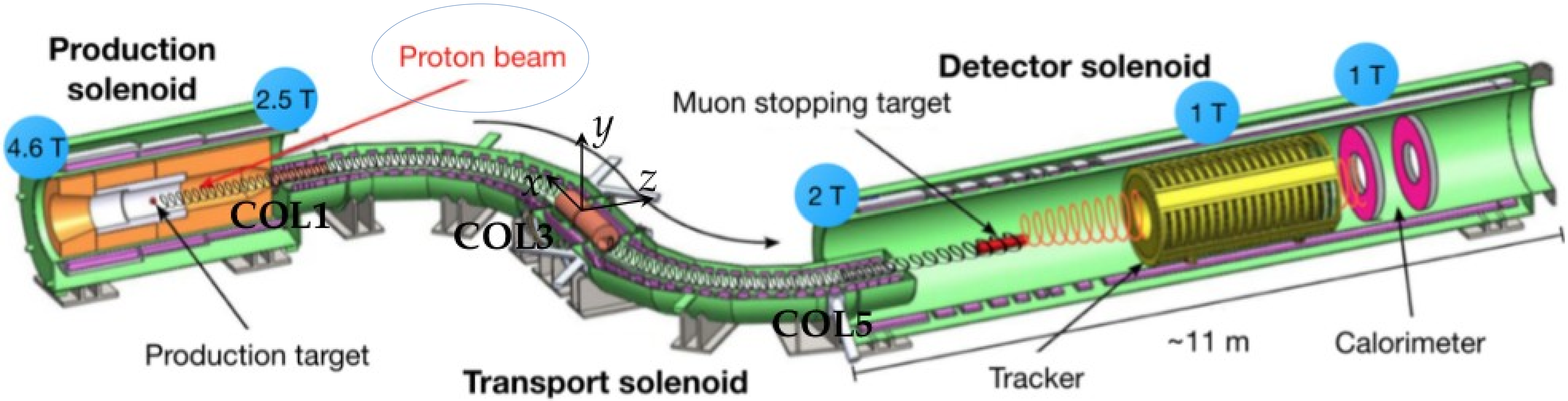
Still very far from the prediction of $m_\nu \neq 0$ SM extensions (**10^{-49}-10^{-52}**) but many theories BSM predict ratios up to 10^{-15} so Mu2e could really observe something!

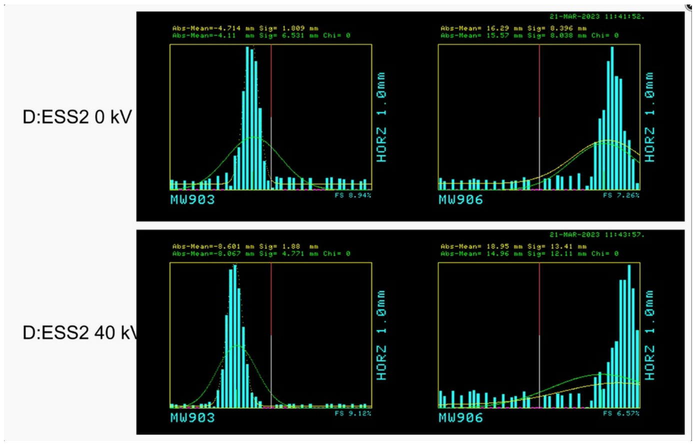
*W. Bertl et al., Eur.Phys.J. C47,337 (2006)

The Mu2e experimental apparatus: the beam

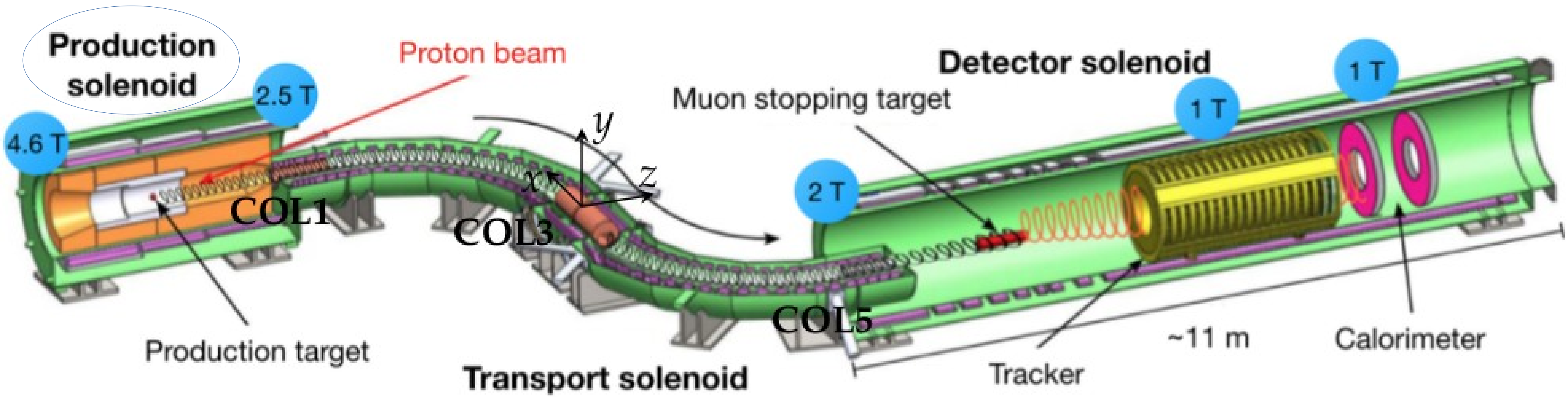


Pulsed proton beam:

- 8 GeV pulsed proton beam coming from the right
- First protons directed to the Mu2e beam line observed (July 2023)

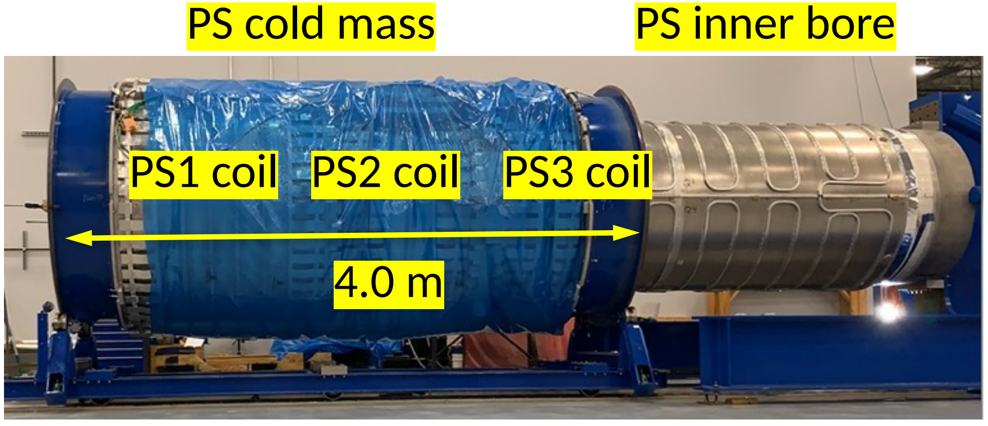


The Mu2e experimental apparatus: the 3 solenoids

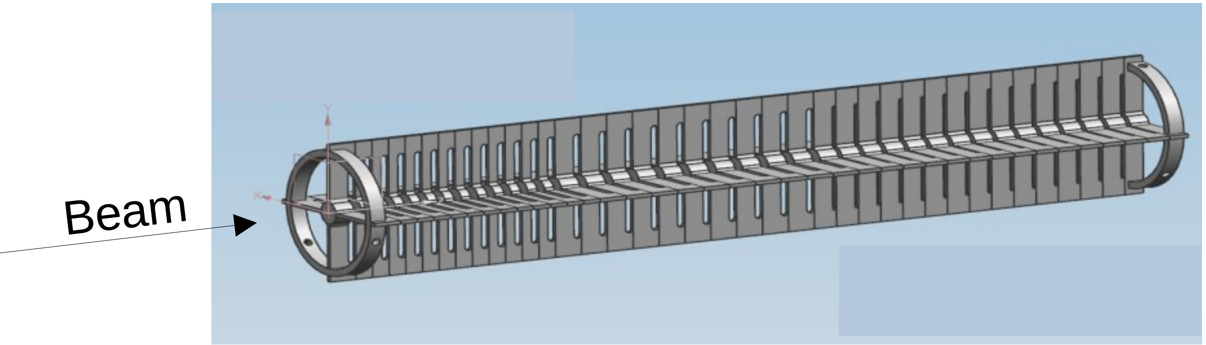


1) Production Solenoid:

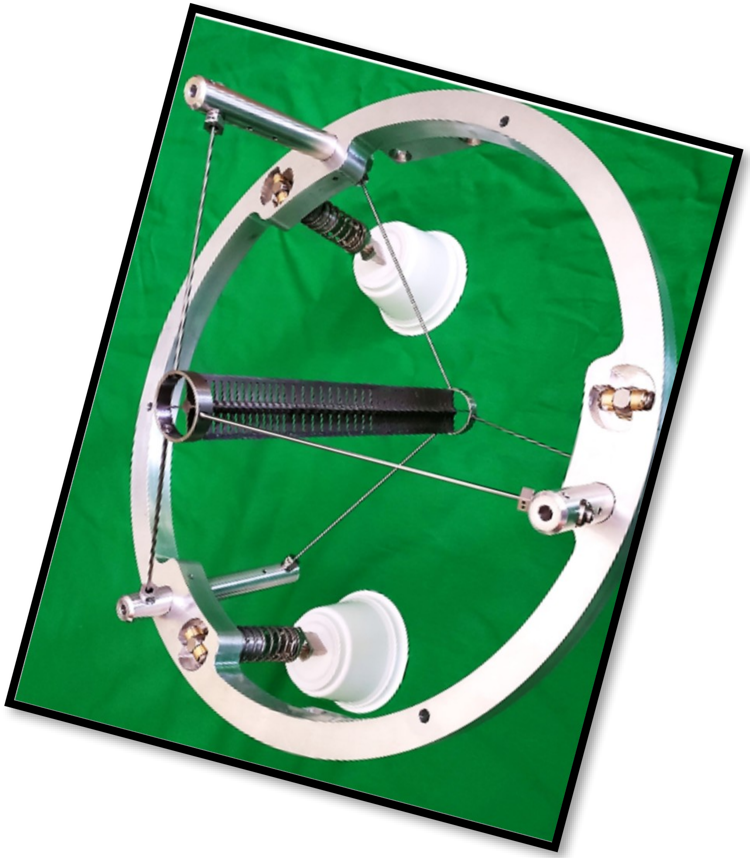
- 8 GeV pulsed proton beam entering from the right hits the tungsten target
- a graded magnetic field drives low momentum particles downstream
- Coils assembled with the inner bore
- Preliminary field map obtained



The Tungsten Production target



Target Geometry



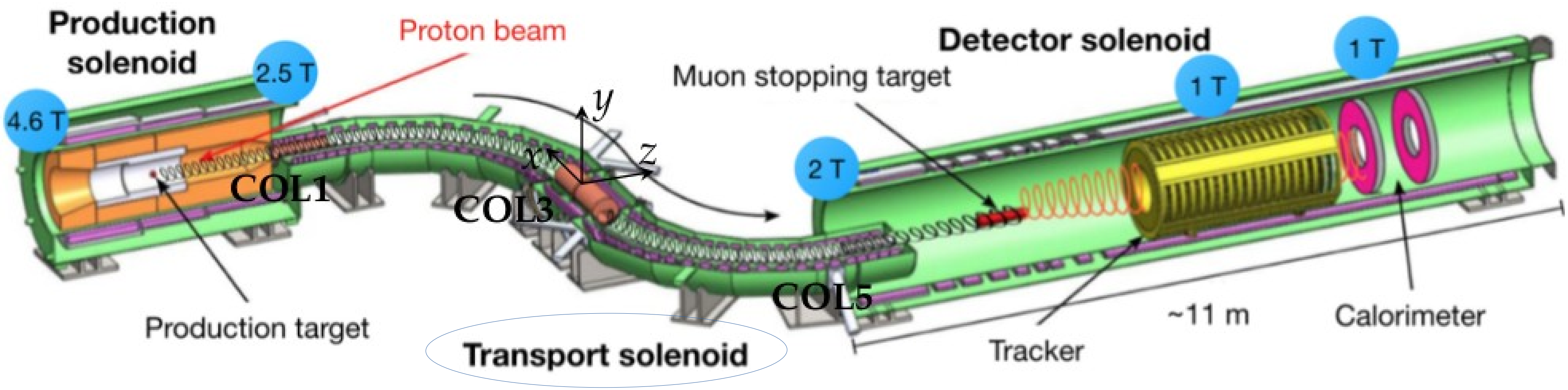
The production target with its support structure

Must resist to 5.7·10^{12} protons/s

Gaps and fins to help heat dissipation

Maximum T~1100 ^{o}C

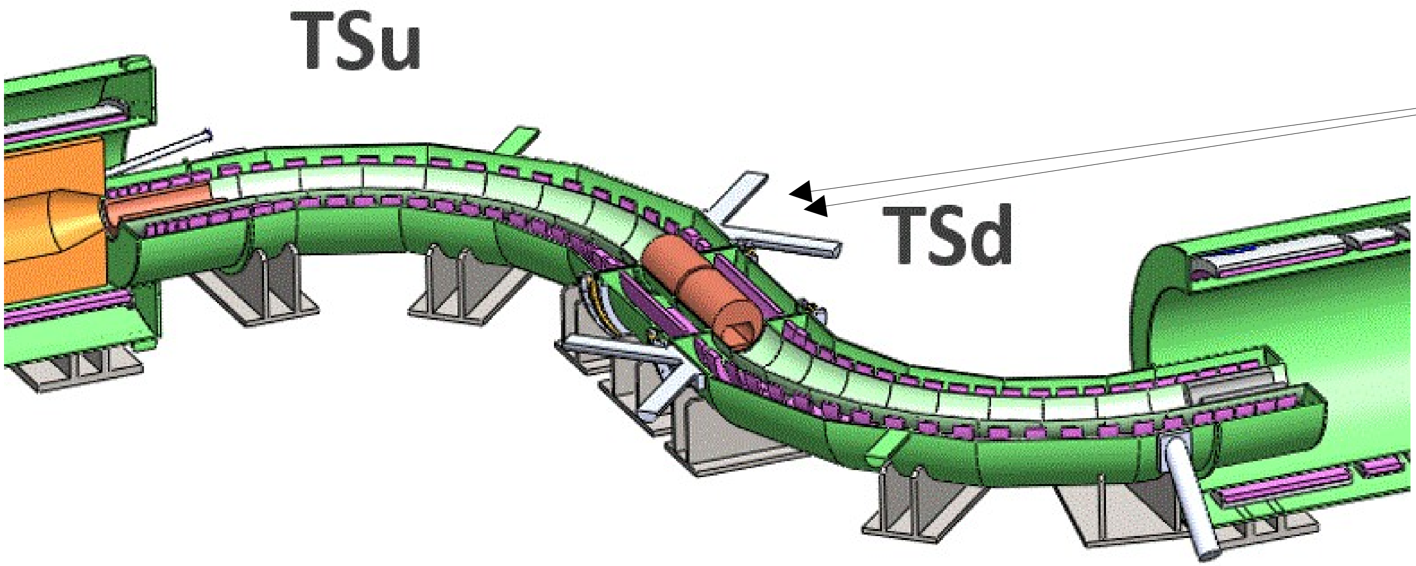
The Mu2e experimental apparatus: the 3 solenoids

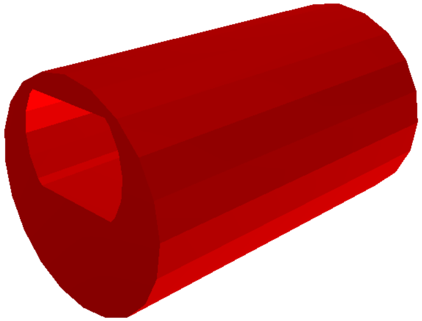


2) Transport solenoid:

- selects -/+ particles of wanted momentum with swivel collimators
- thin absober windows to reduce antiproton background
- small magnetic field gradient to avoid trapped particles

The transport solenoid



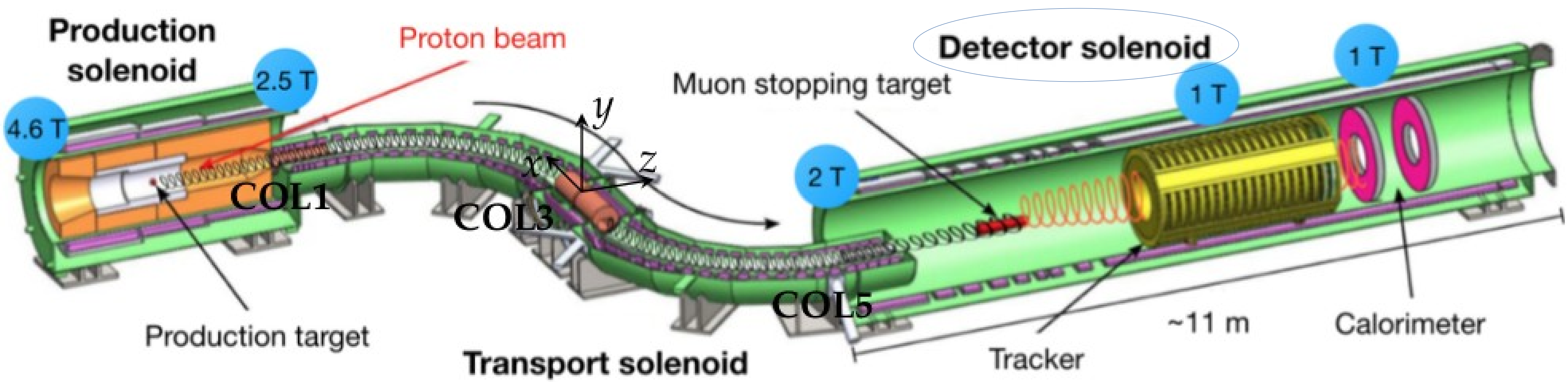


Swivel collimator

TSu assembled

TSd ready to be closed

The Mu2e experimental apparatus: the 3 solenoids

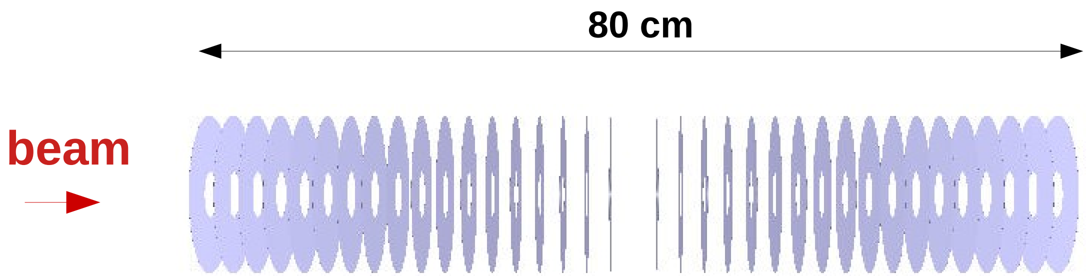


3) Detector Solenoid (11 coils):

- Contains the Al muon stopping target surrounded by proton/neutron absorbers
- field gradient increases acceptance and suppresses beam electrons
- 1 T uniform field in detectors region
- all 11 coils built, being assembled

A DS coil

The Aluminum muon stopping target



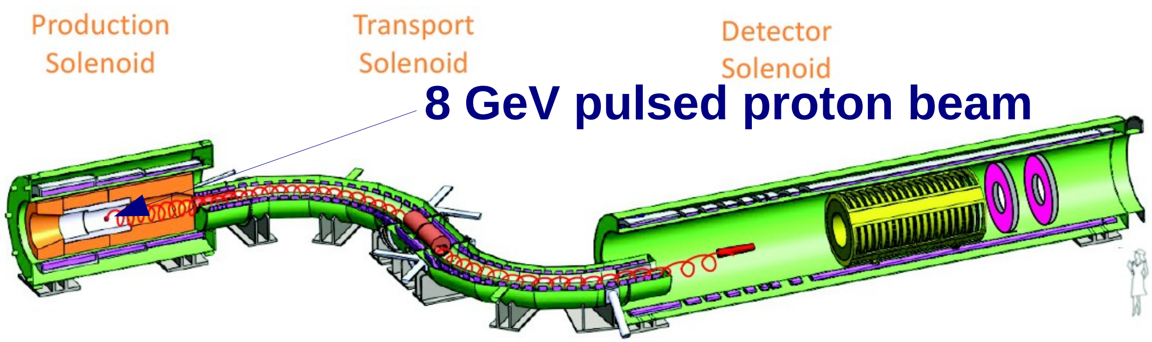
The stopping target:

37 foils of Al
105 μm thick
75 mm radius
22 mm central hole radius

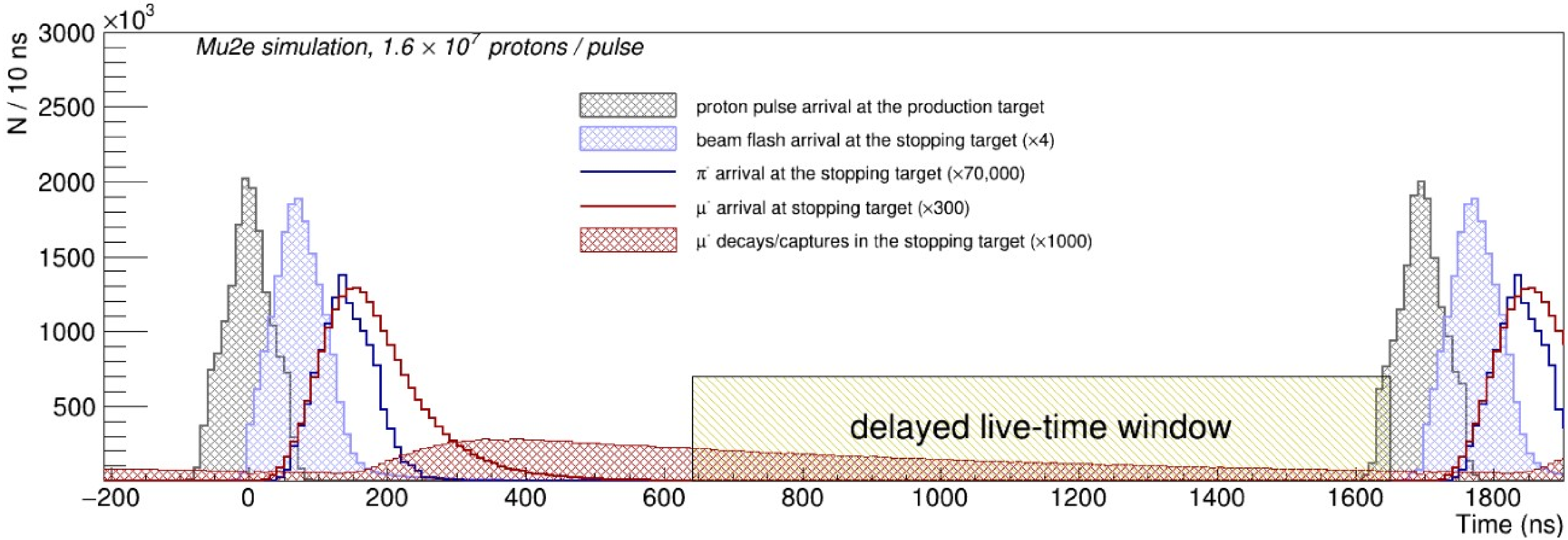
The segmented geometry helps to reduce electron energy losses (improving momentum resolution)

The central hole helps to reduce radiation in the detector

The pulsed proton beam structure



Full Beam intensity:
3.9 ·10⁷ p/pulse
(±50%)



Pulsed Proton Beam Structure:

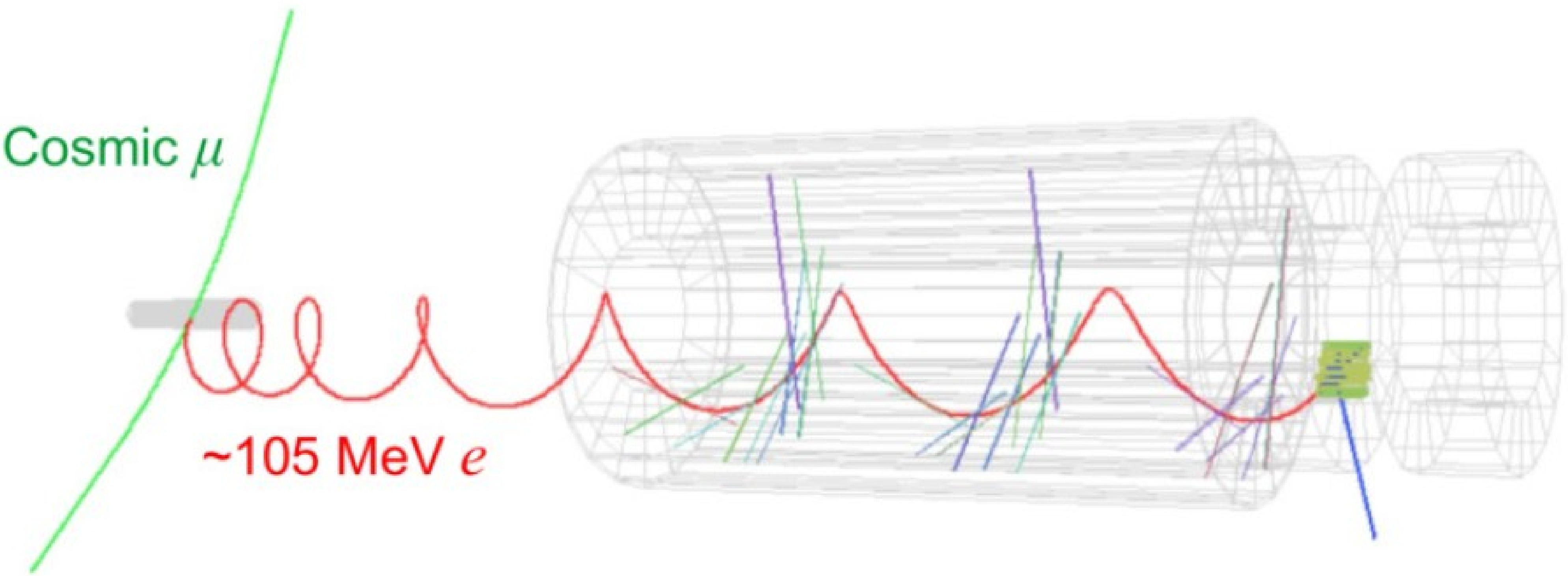
Beam period: 1.695 μs ~ $2\tau_{\mu}^{Al}$ (τ_{μ}^{Al} = 864 ns)

Delayed analysis window to suppress prompt backgrounds

Out of bunch proton fraction (“extinction factor”) < 10^{-10}

(measured by an extinction monitor downstream of the beam)

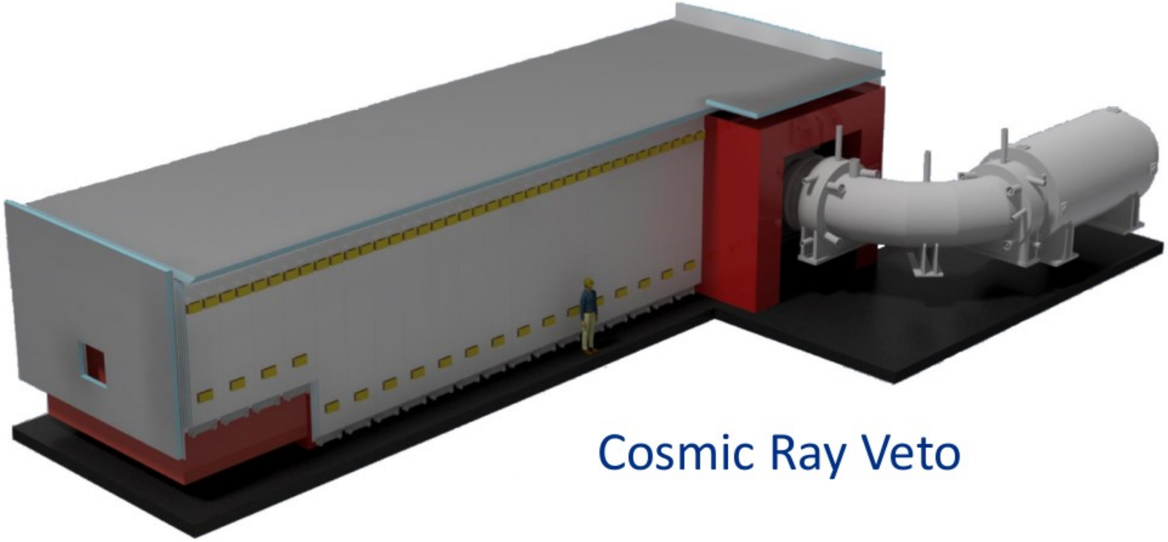
The Cosmic Background

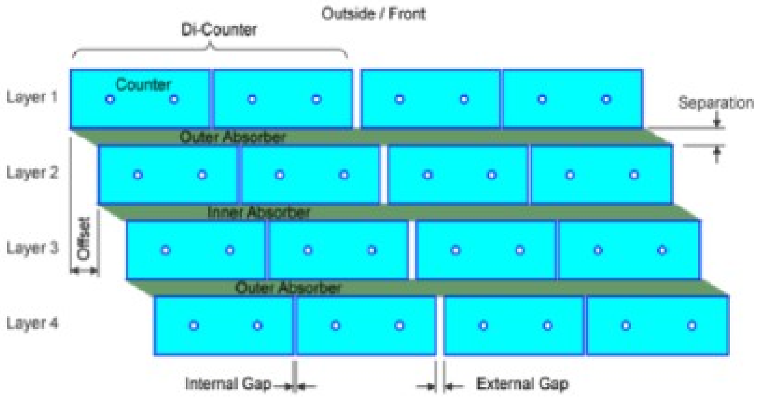


About 1 cosmic event/day can mimic a 105 MeV electron

The Cosmic Ray Veto

4 layers of scintillator counters covering Detector Solenoid and Lower Transport Solenoid





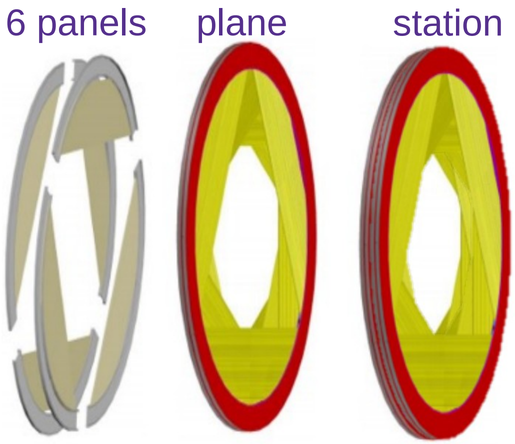
3 of 4 layers provides a veto efficiency >99.99%

All 83 modules built
Aging test ongoing

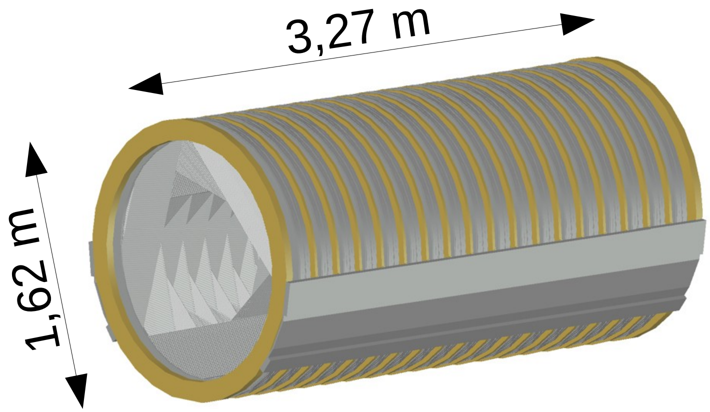
The straw tube tracker

straw tube

5 mm diameter
15μm mylar wall
80:20 $ArCO_2$ gas mixture
25 μm W wire @1450V
ADC & TDC at both ends



216 panels (made of straws)
36 planes (6 panels each)
18 stations (2 planes each)



Tracker structure

18 stations of 12 panels
(~21000 straw tubes)

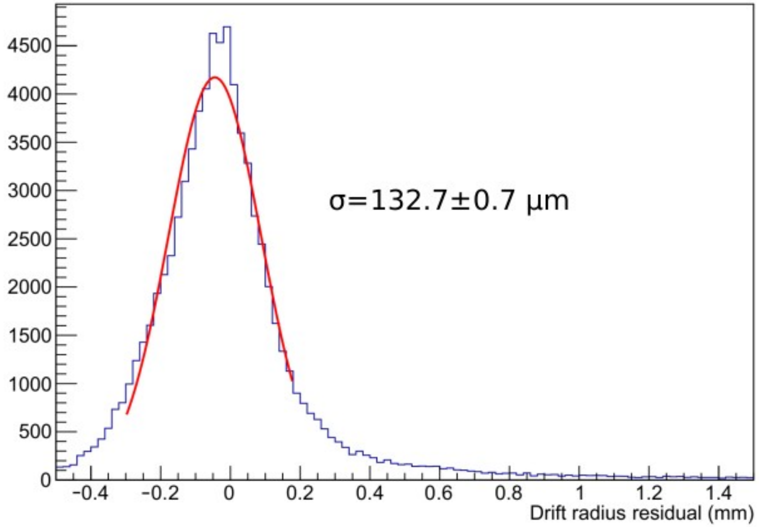
All panels completed
23/36 planes assembled

Leakage test ongoing

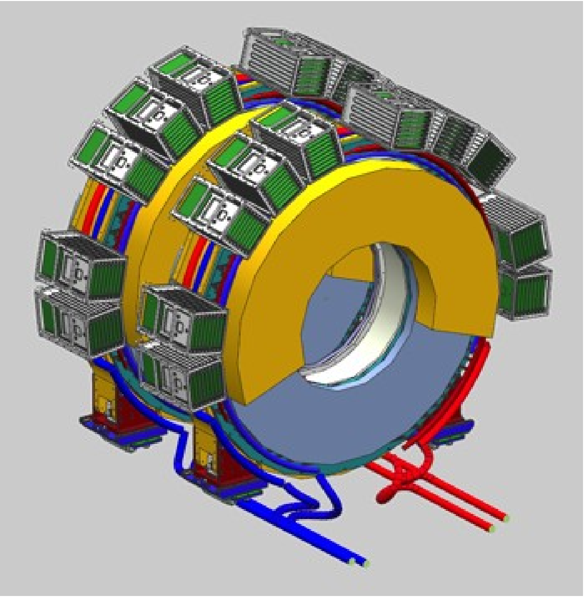
Performances confirm expectations

Expected completion and installation: end of 2024

Transverse coordinate resolution



The electromagnetic calorimeter

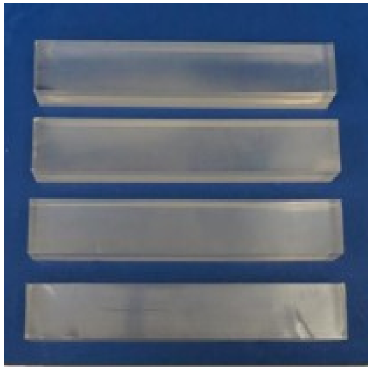


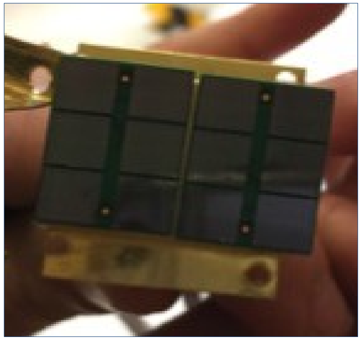
2 disks spaced by 70 cm

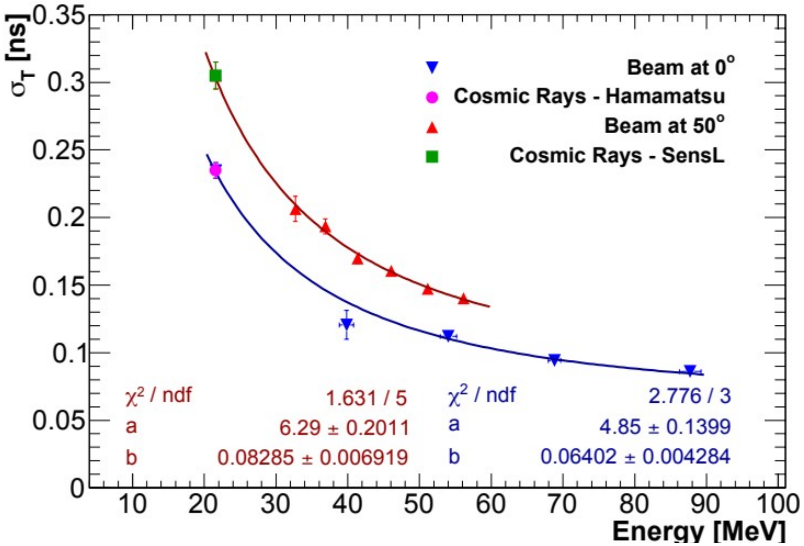
674 pure CsI crystals/disk
2 arrays of 6 SiPMs/crystal

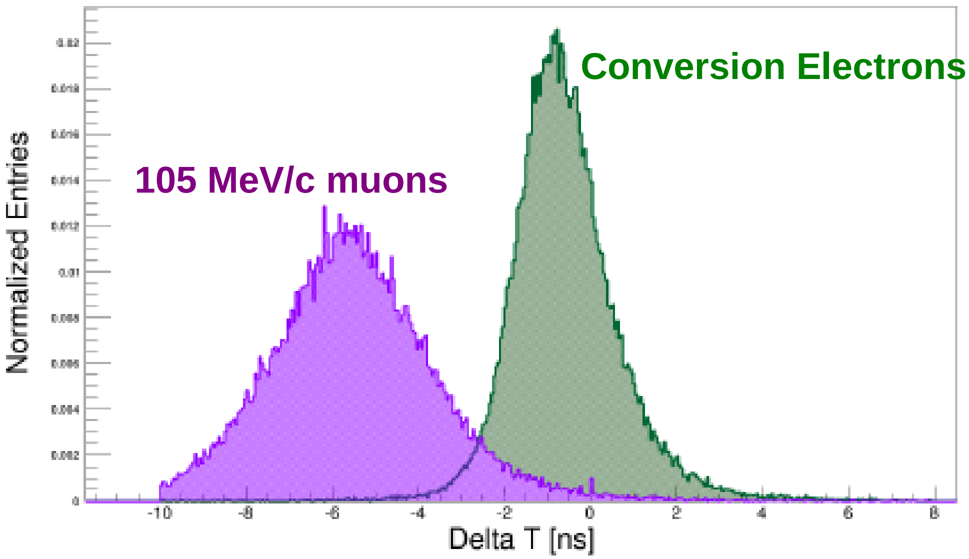
Main goal: e/μ separation

(See Wednesday talk)







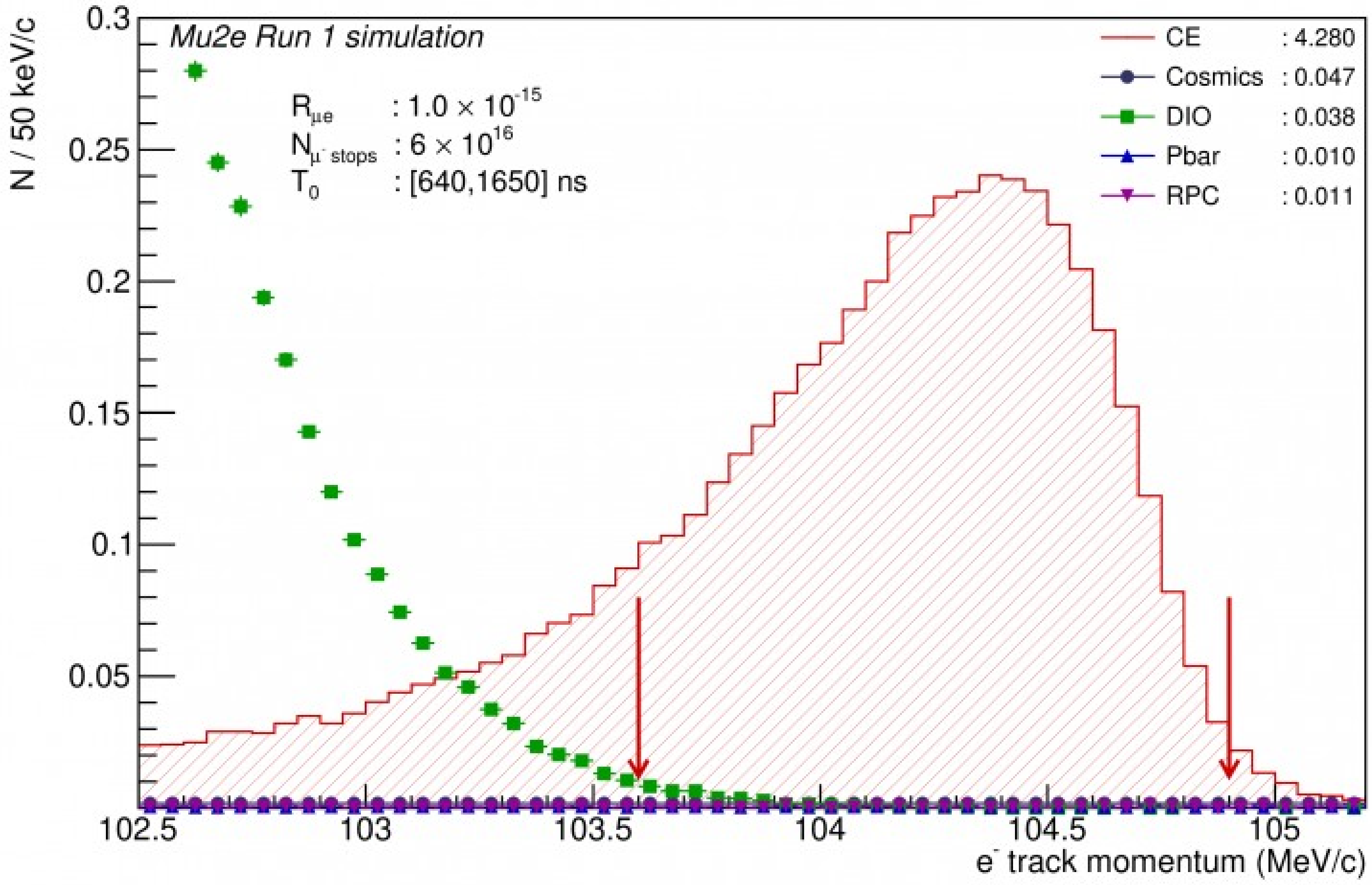


Mu2e expected backgrounds for Run 1 (assuming $6 \cdot 10^{16}$ stopped muons, mostly at half proton beam intensity*)

Channel	Mu2e Run I
SES	2.4×10^{-16}
Cosmic rays	0.046 ± 0.010 (stat) ± 0.009 (syst)
DIO	0.038 ± 0.002 (stat) $^{+0.025}_{-0.015}$ (syst)
Antiprotons	0.010 ± 0.003 (stat) ± 0.010 (syst)
RPC in-time	0.010 ± 0.002 (stat) $^{+0.001}_{-0.003}$ (syst)
RPC out-of-time ($\zeta = 10^{-10}$)	$(1.2 \pm 0.1$ (stat) $^{+0.1}_{-0.3}$ (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

** More details in "Mu2e Run I Sensitivity Projections for the Neutrinoless mu- --> e- Conversion Search in Aluminum", Universe 9 (2023) 1, 54 (38 pages) http://arxiv.org/abs/2210.11380*

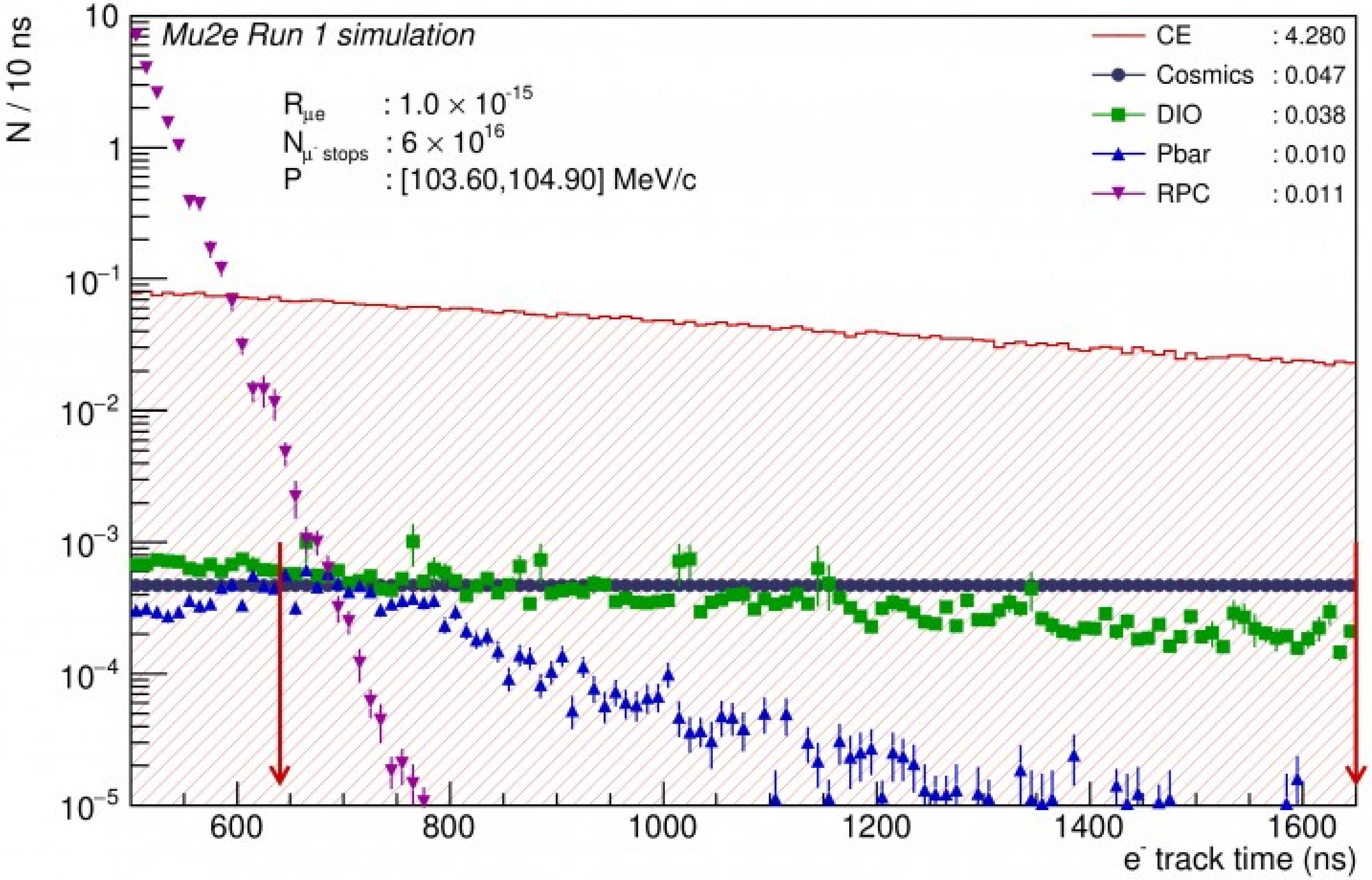
Electron momentum



The **DIO** spectrum falls as $(E_{max}\text{-}E)^5$ close to the end point

Can be suppressed by the momentum window cut

Electron time



Radiative Pion Captures (RPC) in the Al target producing photons converting in e^+e^- pairs can be suppressed by a time window cut
Also delayed pions coming from **antiproton** annihilation can be suppressed

Time and momentum windows **optimized** to get the best **discovery sensitivity**

Mu2e expected sensitivity for Run 1

Given the very low background level a **5σ discovery** will require Mu2e to observe just **5 events** of muon conversion

The $R_{\mu e}$ corresponding to a **5σ discovery** in Run 1 is:

$$R_{\mu e} = 1.1 \cdot 10^{-15}$$

Mu2e Run 1
5σ Discovery reach

If no events will be observed the **90% CL limit** will be:

$$R_{\mu e} = 6.2 \cdot 10^{-16}$$

Mu2e Run 1
90% CL limit

that is more than **x1000** better than current best limit!

Mu2e run 2 and beyond

- The second Mu2e run, starting in 2029 after accelerator shutdown for neutrino beam upgrade, aims to achieve the final x10000 improvement with respect to Sindrum II: it will profit from an improved average beam intensity and a refined detector shielding (using Run I results).

- At the same time Mu2e will look for lepton number violating process:

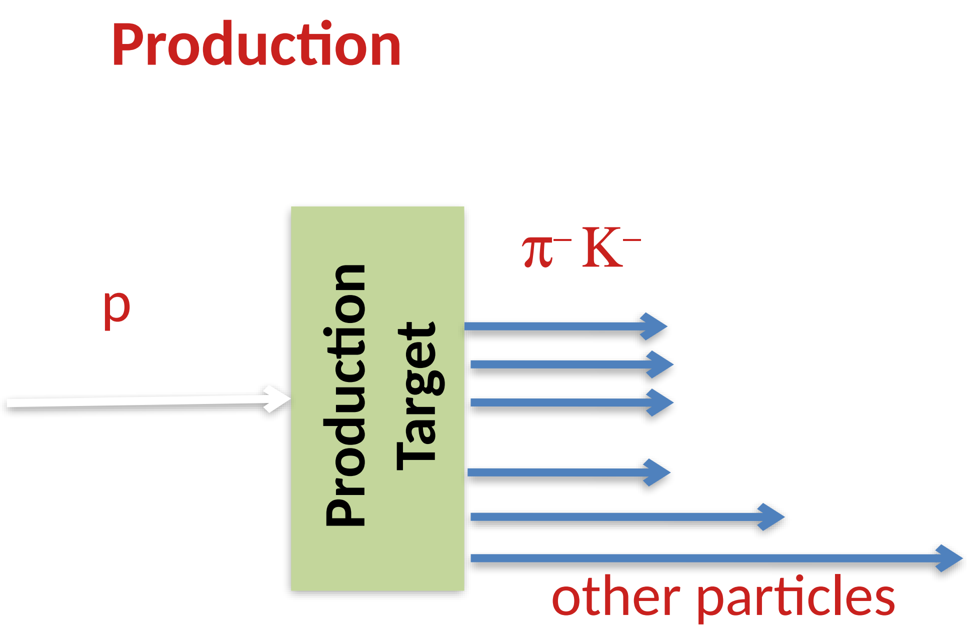
$$\mu^- N(A,Z) \rightarrow e^+ N(A,Z-2)$$

  with a Run 1 SES on $R_{\mu e+}$ of $4 \cdot 10^{-16}$ (current limit: $1.7 \cdot 10^{-12}$ (Sindrum II '98)). In this case the main background comes from Radiative Muon Capture that will be better characterized in Run I.

- A Mu2e upgrade proposal, called Mu2e II, has been inserted in the Snow Mass white paper: it aims to exploit the higher intensity and lower energy PIP-II proton beam to obtain a further x10 in sensitivity to muon conversion

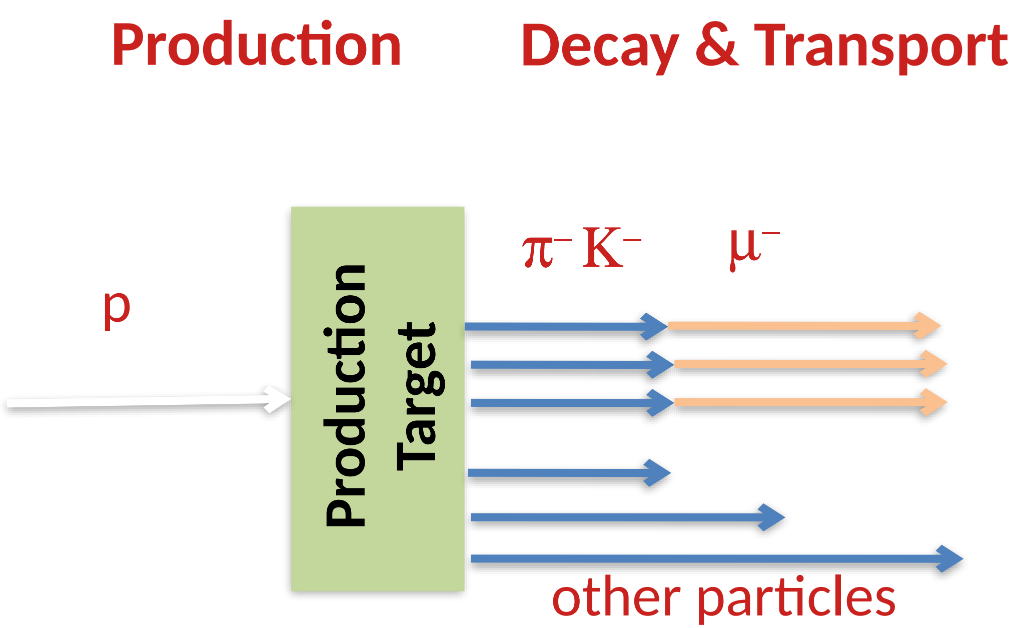
BACKUP

The Mu2e experiment concept



1) A pulsed proton beam hits a tungsten target

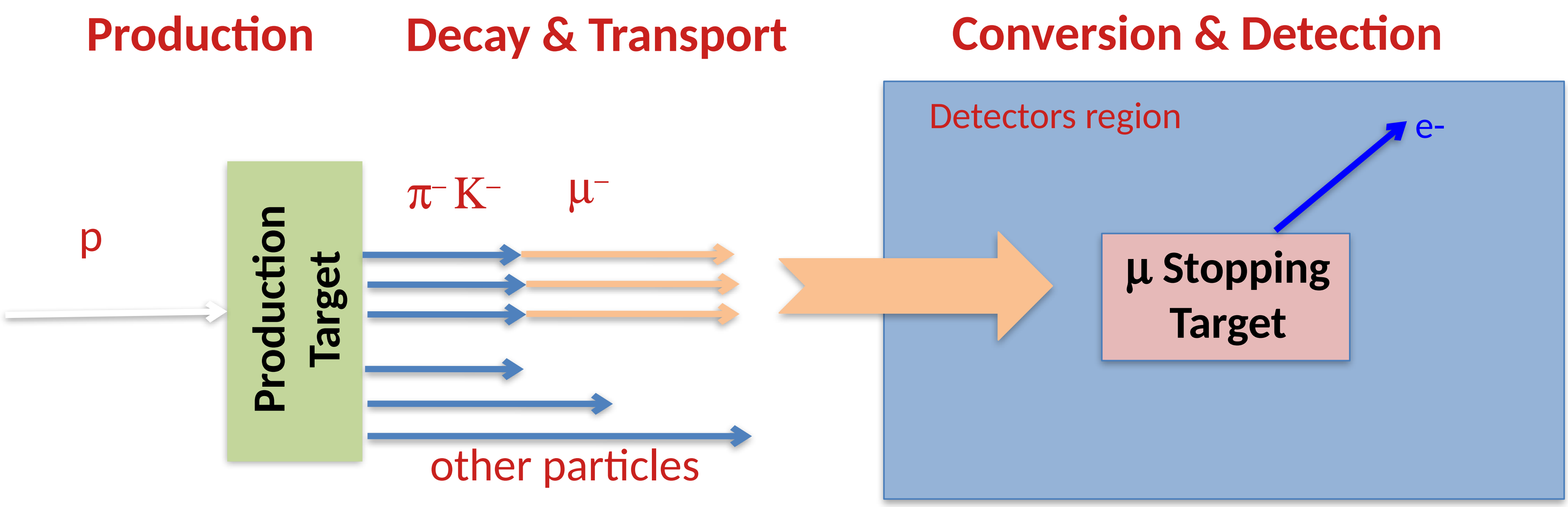
The Mu2e experiment concept



1) A pulsed proton beam hits a tungsten target

2) A magnetic system selects negative particles of wanted momentum

The Mu2e experiment concept

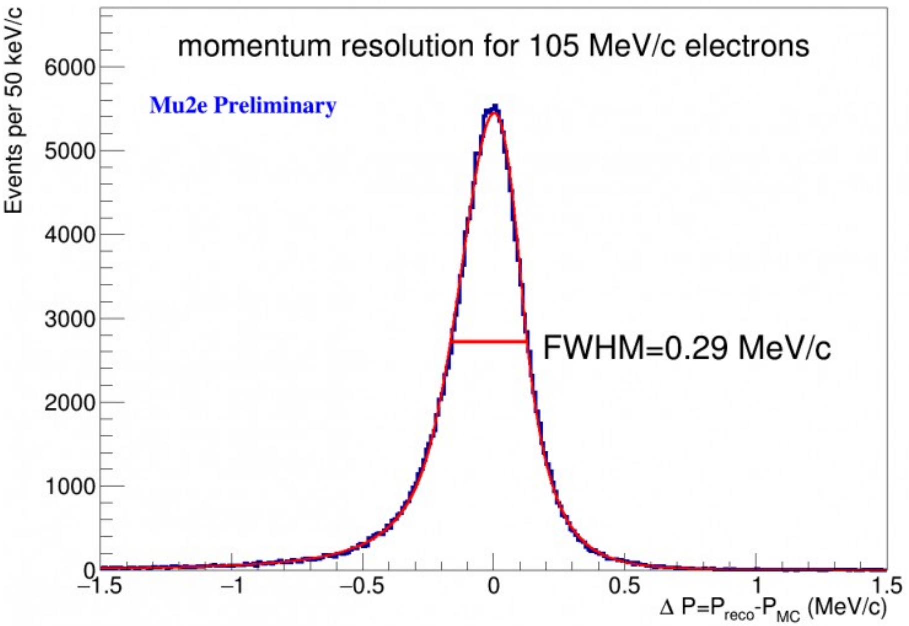


1) Create muon parents using a pulsed proton beam on target

2) A magnetic system selects negative particles of wanted momentum

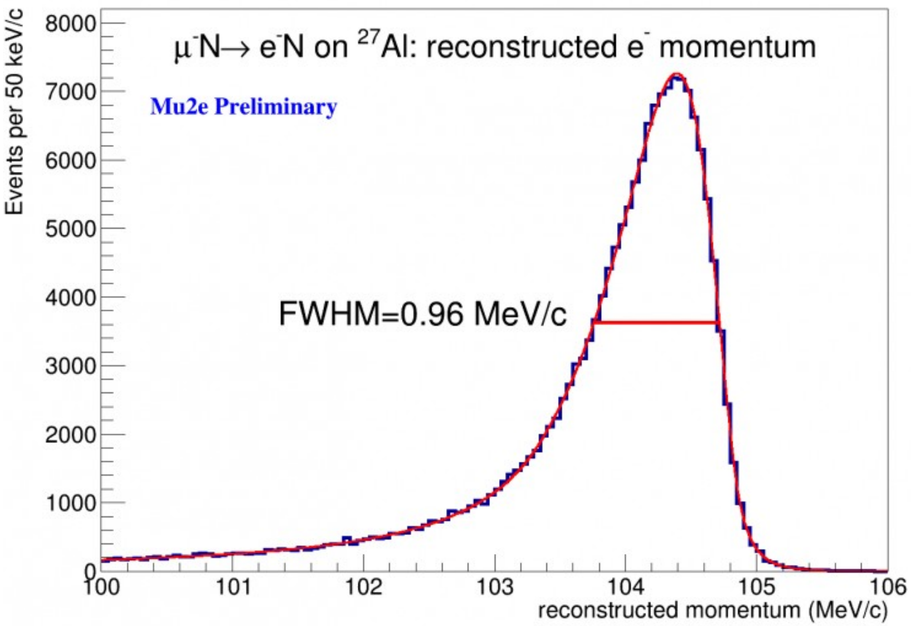
3) Stopped μ^- form muonic Al and eventually convert in e^- that can be detected

Expected CE reconstructed momentum



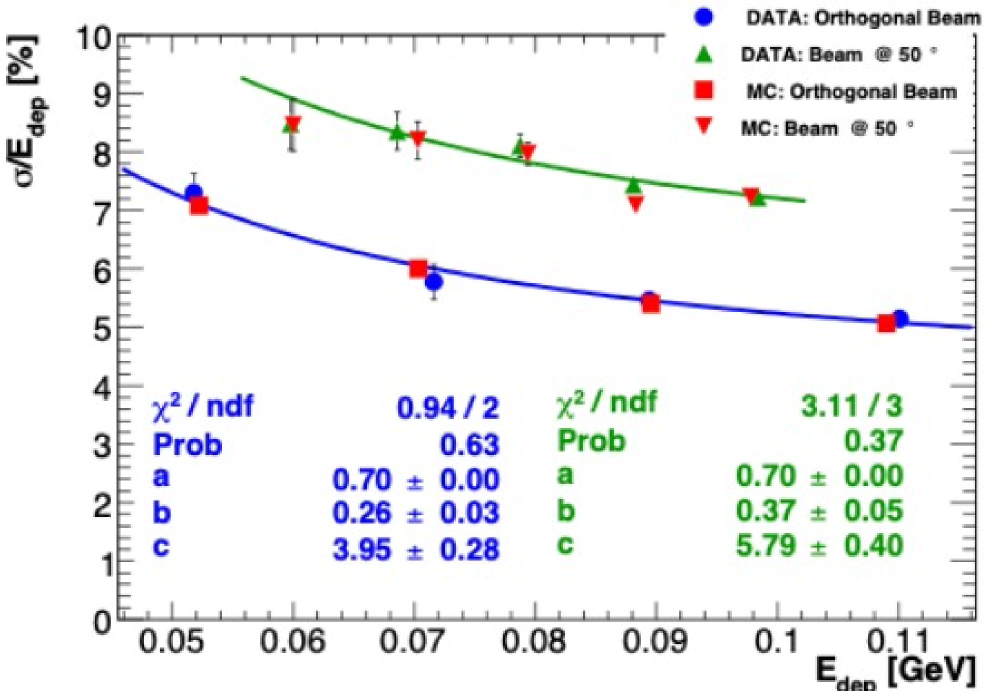
CE: Conversion Electron

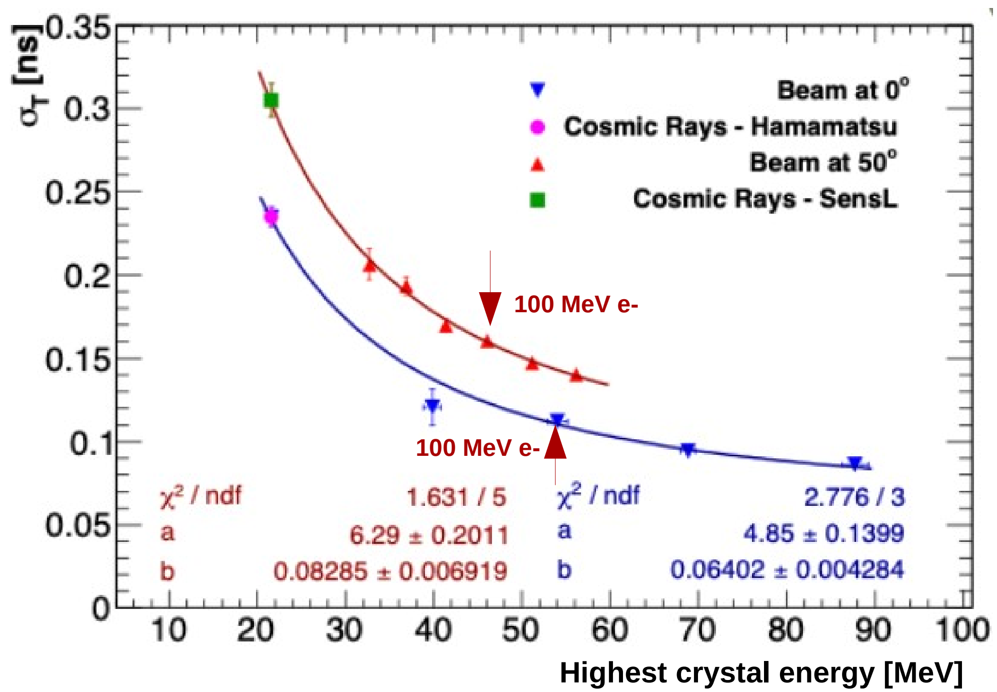
Reconstructed-True momentum at tracker entrance



CE reconstructed spectrum: the left tail is due to energy losses

Calorimeter performances

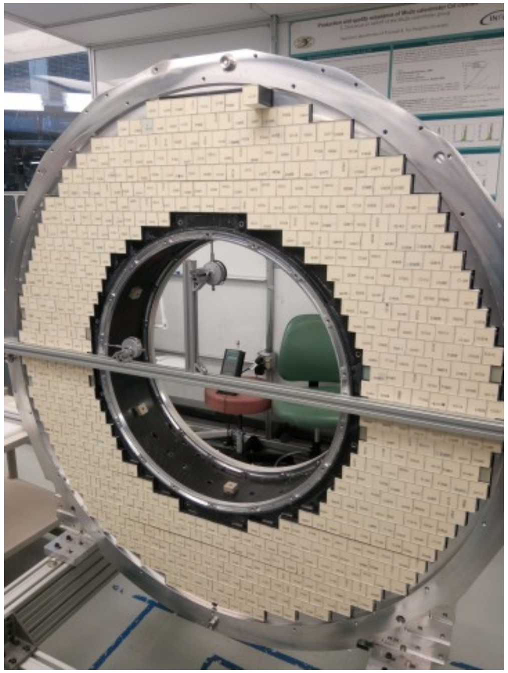




<u>2017 test beam results for 100 MeV e-:</u>

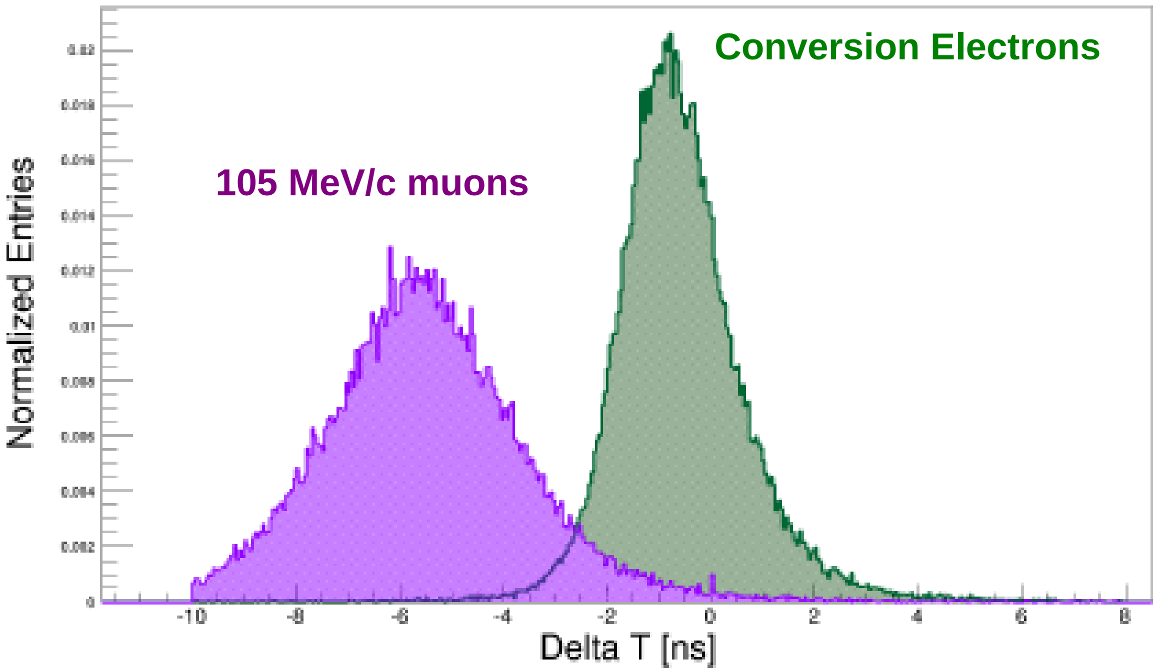
Impact angle:	0°	50° (CE peak)
Energy resolution	5.4%	**7.3%**
Time resolution*	160 ps	**230 ps**

*Obtained for 1 sensor from the time difference of 2 sensors

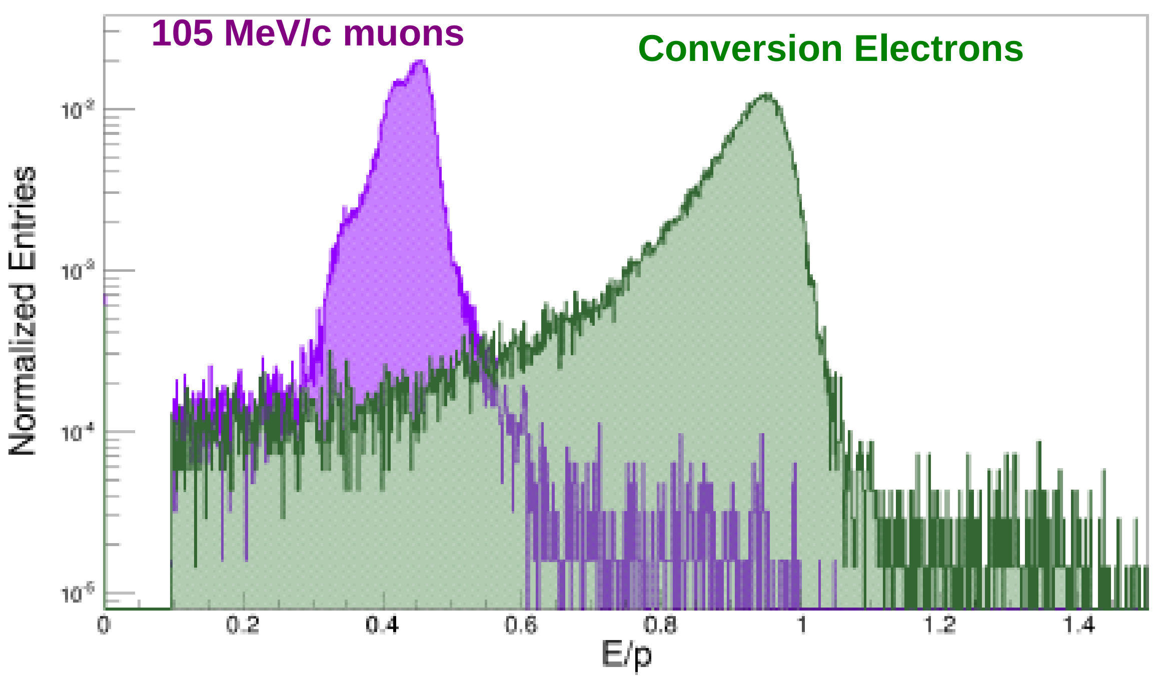


First ECAL disk assembled

Particle identification



Extrapolated track time (assuming electron mass) – calorimeter cluster time



Calorimeter cluster energy / track momentum

An ANN selection makes the cosmic muons background negligible wrt the cosmic electrons irriducible background

How to get a 10^4 improvement?

- **STATISTICAL ERROR:**
  (Collect lots of stopped muons):
  - High intensity proton beam → Radiation hardness
  - High collection efficiency → Magnetic focusing

- **SYSTEMATIC ERROR**
  (Efficient signal-background separation):
  - Excellent momentum resolution → Little material
  - Exploit muonic atom lifetime → Pulsed p beam
  - Reject cosmic rays → Veto system
  - Particle identification → Tracker+ECAL
  - Momentum scale calibration → π+ beam, B map
  - *In situ* background measurement → low intensity runs