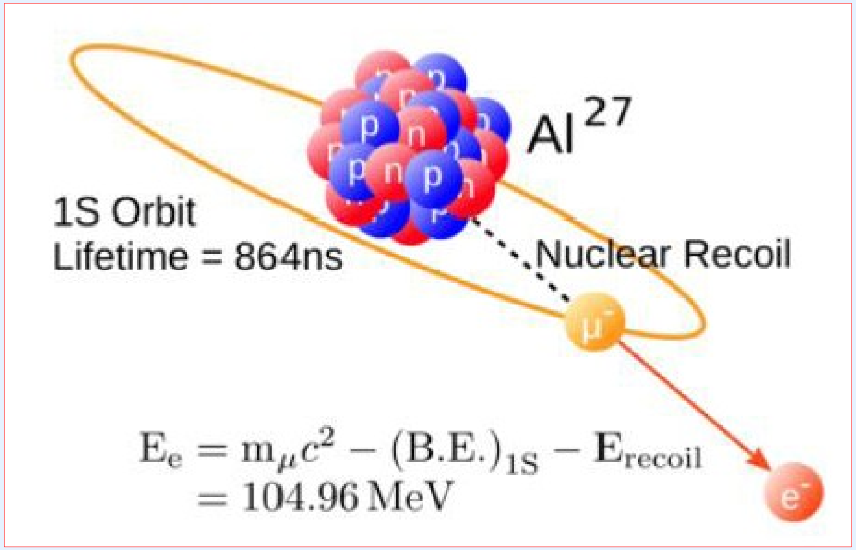
The Mu2e experiment

S. Di Falco (INFN Pisa)

3rd Muon Precision Physics Workshop

Liverpool, 12-14 Nov 2024

$\mu^- N \rightarrow e^- N$ process: current limit and discovery potential



Mu2e looks for the neutrinoless conversion of a μ^- into e^- in the field of an Al atom

Muonic aluminum **lifetime is ~864 ns**

The conversion signal is an almost **monochromatic electron of ~105 MeV**

Experimental observable:

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

90% CL limit (SINDRUM II (2006), Au target*): $\mathbf{R_{\mu e} < 7 \cdot 10^{-13}}$

SM extended for $m_\nu \neq 0$ predicts $\mathbf{R_{\mu e} < 10^{-50}}$ but some **BSM theories** allow for values $\mathbf{O(10^{-15})}$

Mu2e **goal** is to improve by **a factor 10^4** the sensitivity on $\mathbf{R_{\mu e}}$

➡ **Good discovery potential!**

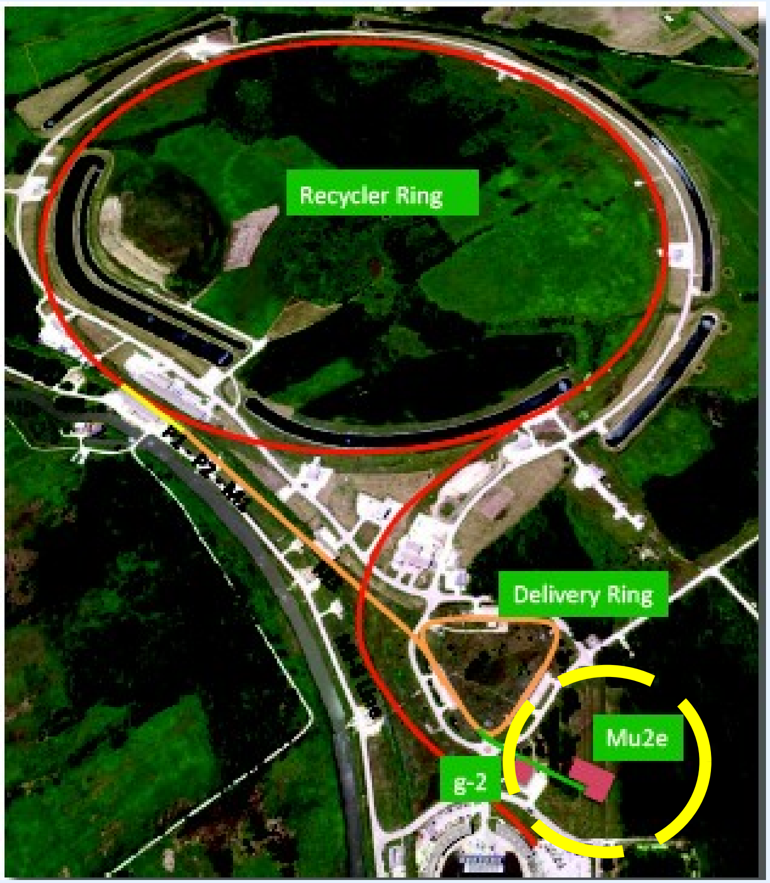
*W. Bertl et al., Eur.Phys.J. C47,337 (2006)

How to get a 10^4 improvement

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

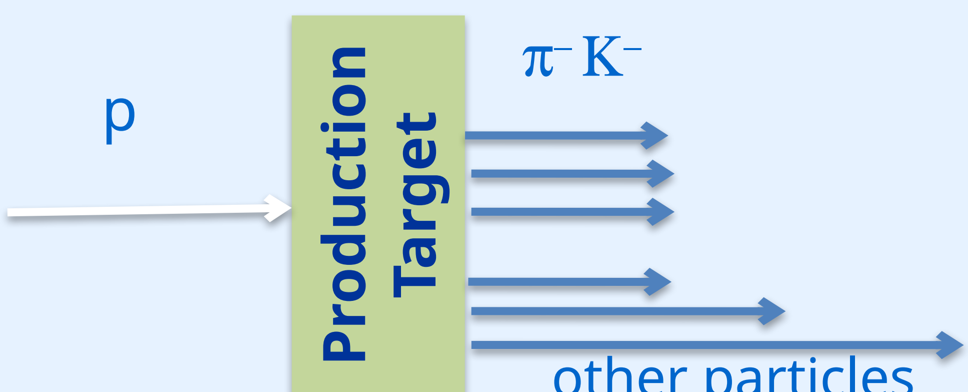
- **SYSTEMATIC ERROR**
  (Improve signal efficiency and background rejection):
  - **Excellent momentum resolution** → **Little material**
  - **Exploit muonic atom lifetime** → **Pulsed p beam**
  - **Reject cosmic rays** → **Veto system**
  - **Particle identification** → **Tracker+ECAL**
  - **Momentum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

How to search for CLFV muon conversion

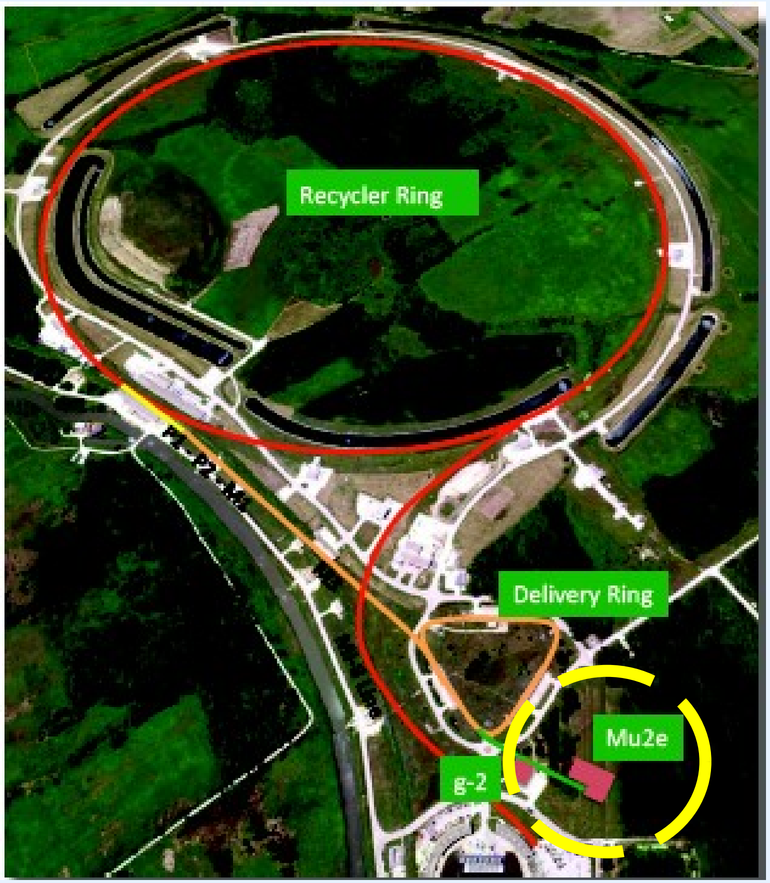


1) Create muon parents smashing an pulsed proton beam on a target

Production

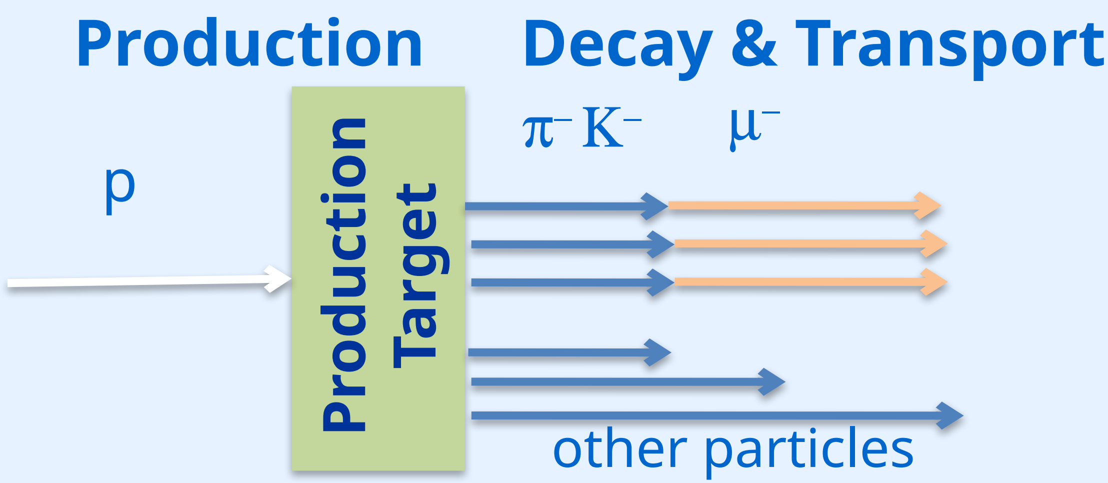


How to search for CLFV muon conversion

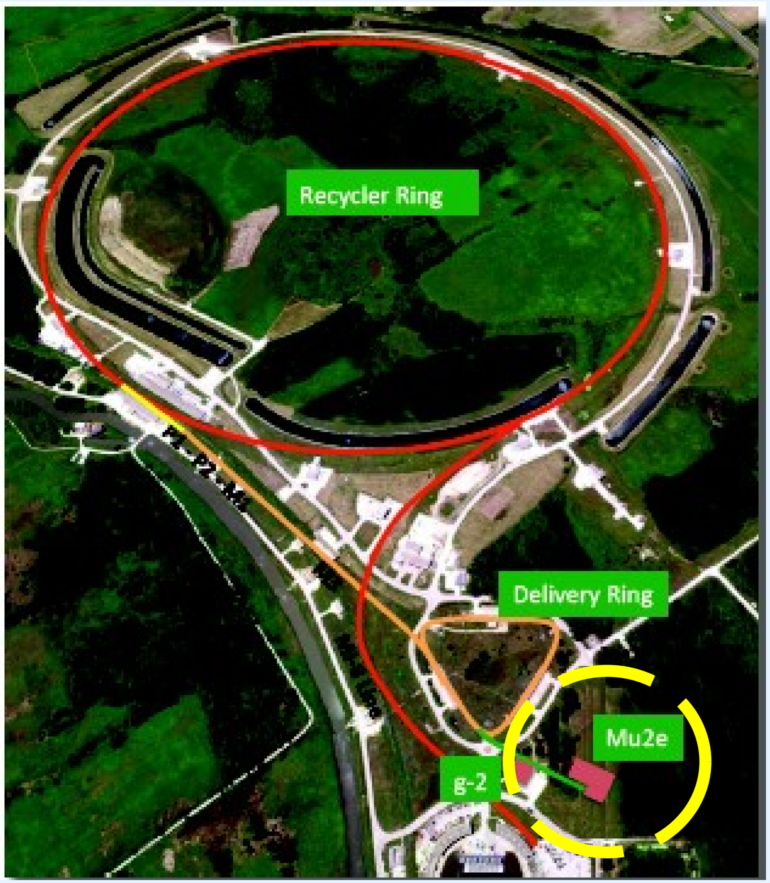


1) Create muon parents smashing an pulsed proton beam on a target

2) Use a magnetic system to select negative particles of wanted charge and momentum



How to search for CLFV muon conversion

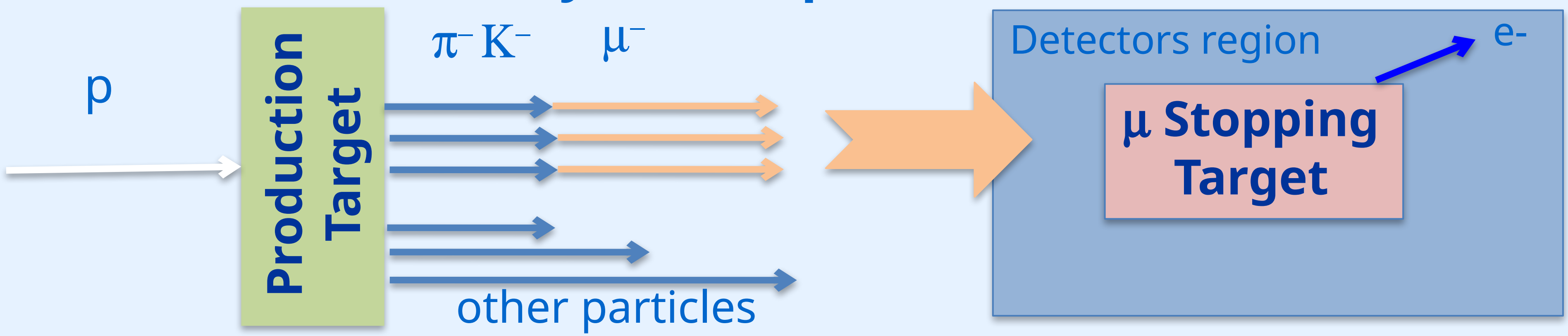


1) Create muon parents smashing an pulsed proton beam on a target

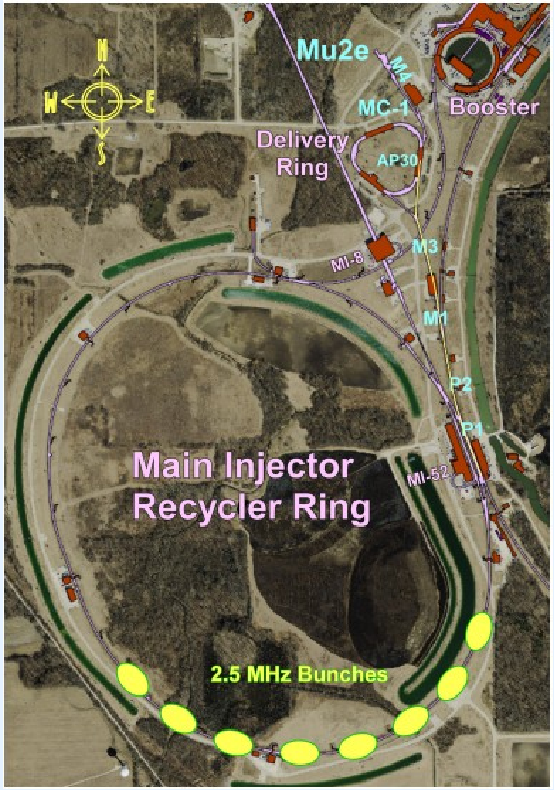
2) Use a magnetic system to select negative particles of wanted charge and momentum

3) Stop μ^- in an Al target and look for monochromatic conversion electrons

Production **Decay & Transport** **Conversion & Detection**



The Mu2e experimental apparatus: the proton beam



The same Fermilab accelerator system used for g-2 provides the protons for Mu2e:

LINAC → booster → Recycler Ring → Delivery Ring → Mu2e

LINAC	booster	Recycler Ring	Delivery Ring	Mu2e
800 MeV	8 GeV	batches 12 for Nova 8 for Mu2e	4 (half Intensity) or 8 bunches	**1.7 μs pulses** **$3.9 \cdot 10^7$ p/pulse** (±50%) **$5.7\ 10^{12}$ p/s**

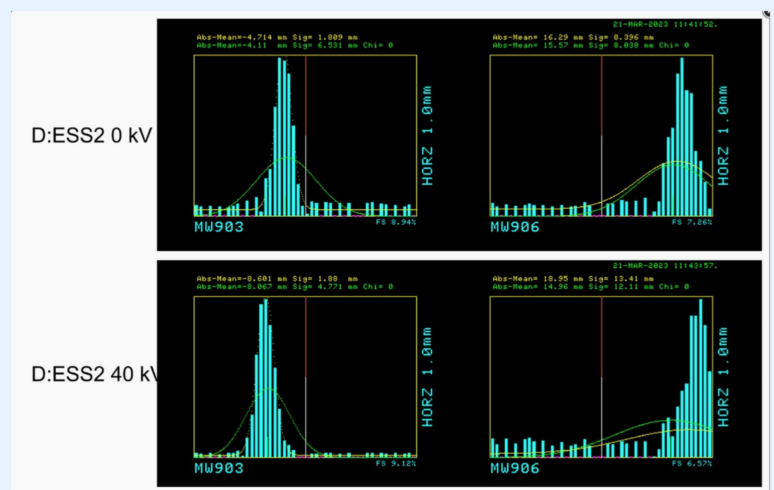
The Mu2e experimental apparatus: the proton beam

The same Fermilab accelerator system used for g-2 provides the protons for Mu2e:

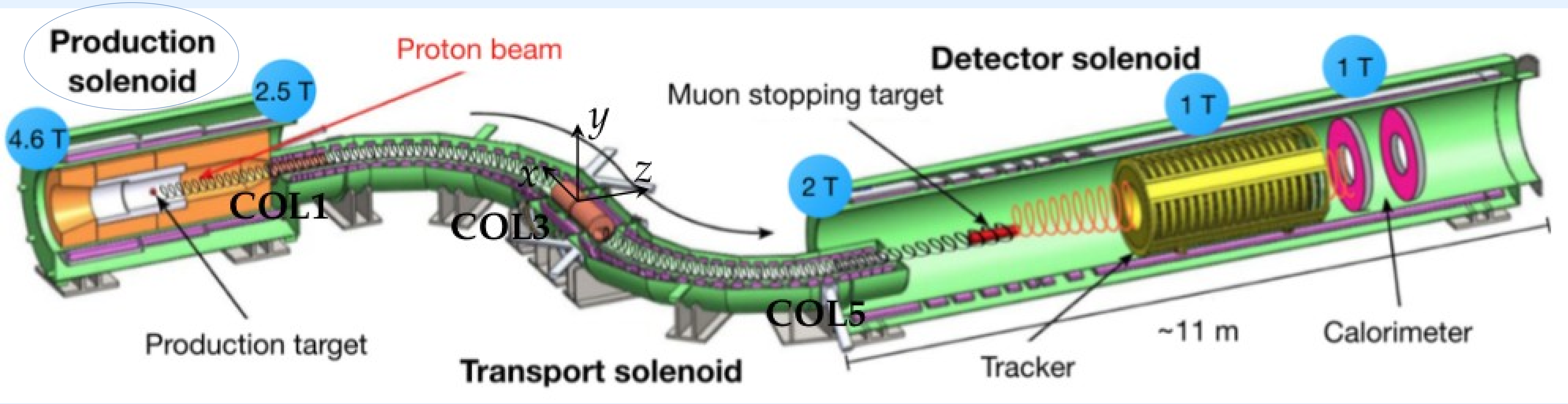
LINAC → **booster** → **Recycler Ring** → **Delivery Ring** → **Mu2e**

LINAC	booster	Recycler Ring	Delivery Ring	Mu2e
800 MeV	8 GeV	batches 12 for Nova 8 for Mu2e	4 (half Intensity) or 8 bunches	**1.7 μs pulses** **3.9 ·10^{7} p/pulse** (±50%) **5.7 10^{12} p/s**

First protons in the last segment of Mu2e beam line in August 2023:

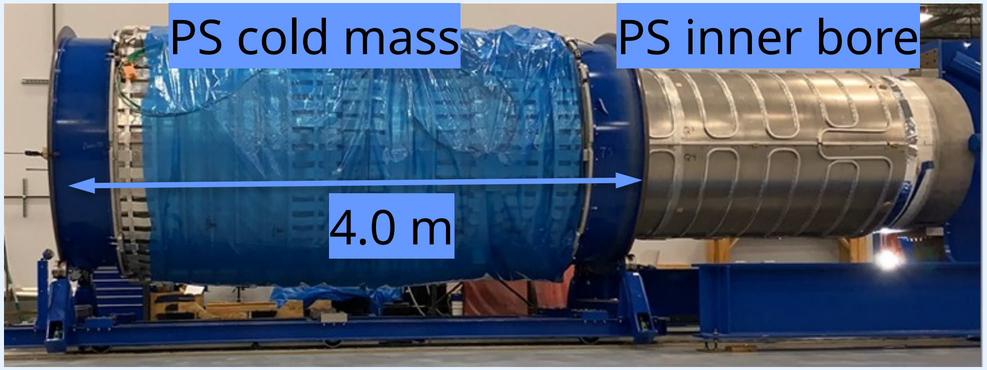


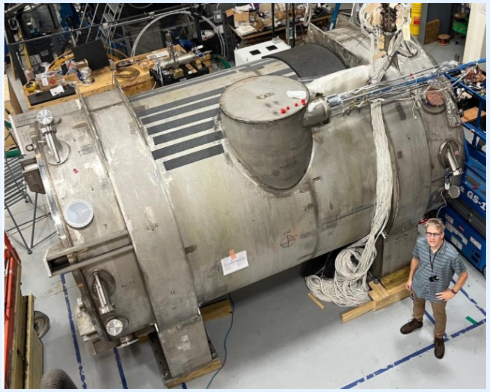
The Mu2e production solenoid (PS)



1) Production Solenoid:

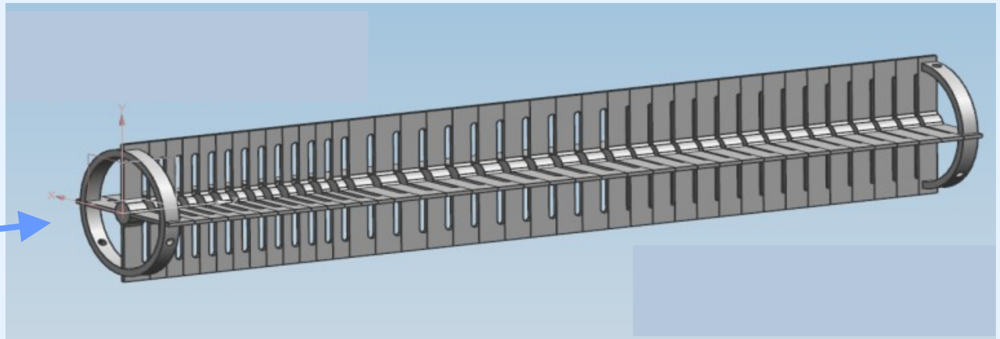
- 8 GeV proton beam from the right
- houses a tungsten target
- a graded magnetic field drives low momentum particles downstream
- Assembly complete
- Cooling test ongoing
- Expected delivery: **December 2024**





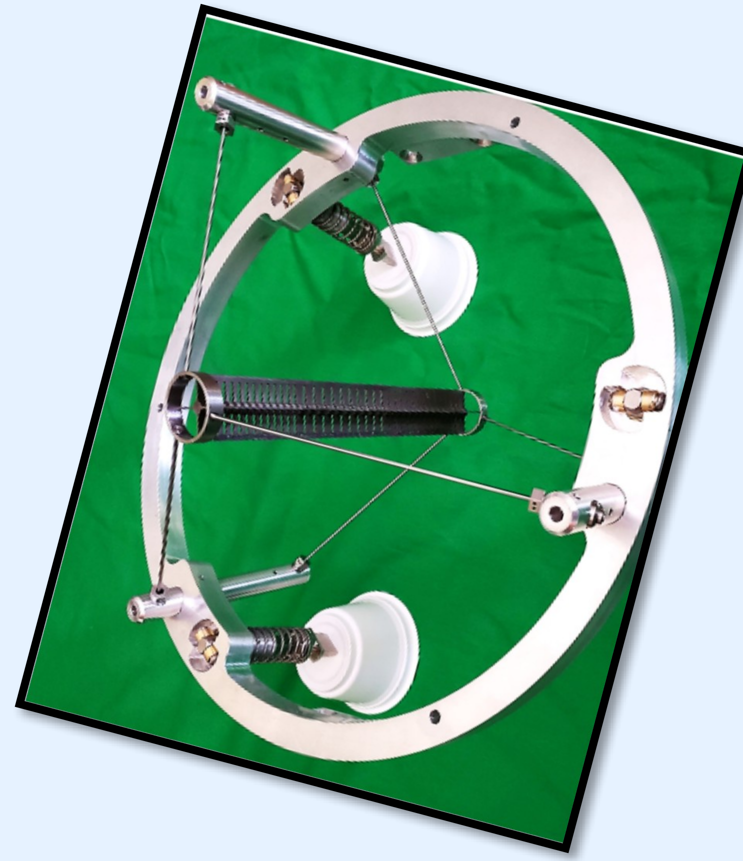
The Tungsten Production target

Beam



Target Geometry

The production target with its support structure

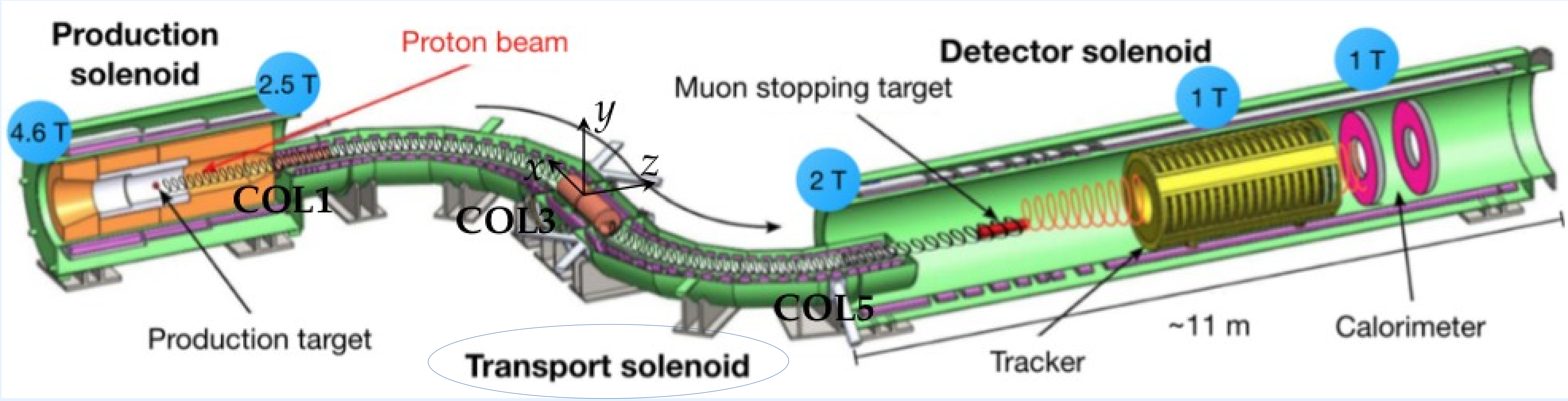


Must resist to $5.7 \cdot 10^{12}$ protons/s

Gaps and fins to help heat dissipation

Maximum T~1100 ^{o}C

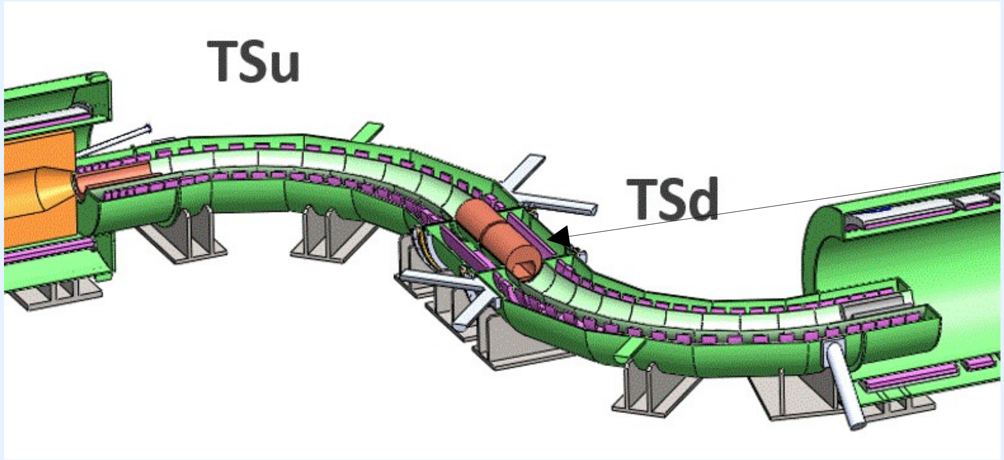
The Mu2e transport solenoid

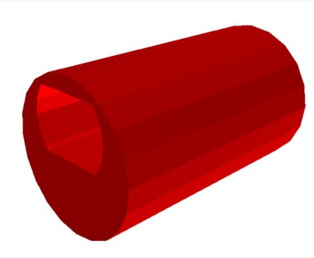


2) Transport solenoid:

- small magnetic field gradient to avoid trapped particles

The Mu2e transport solenoid (TS)



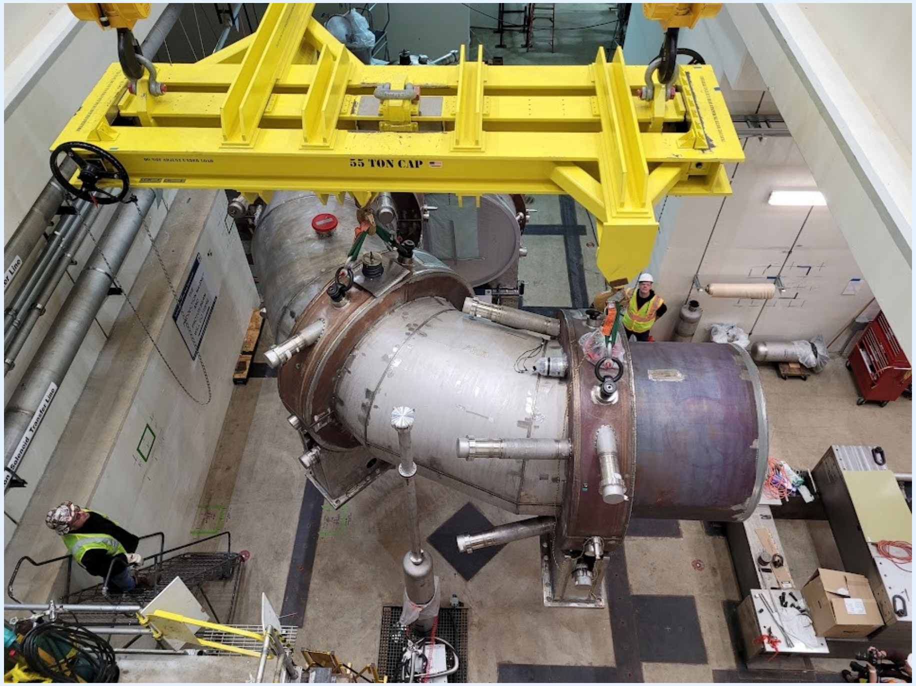


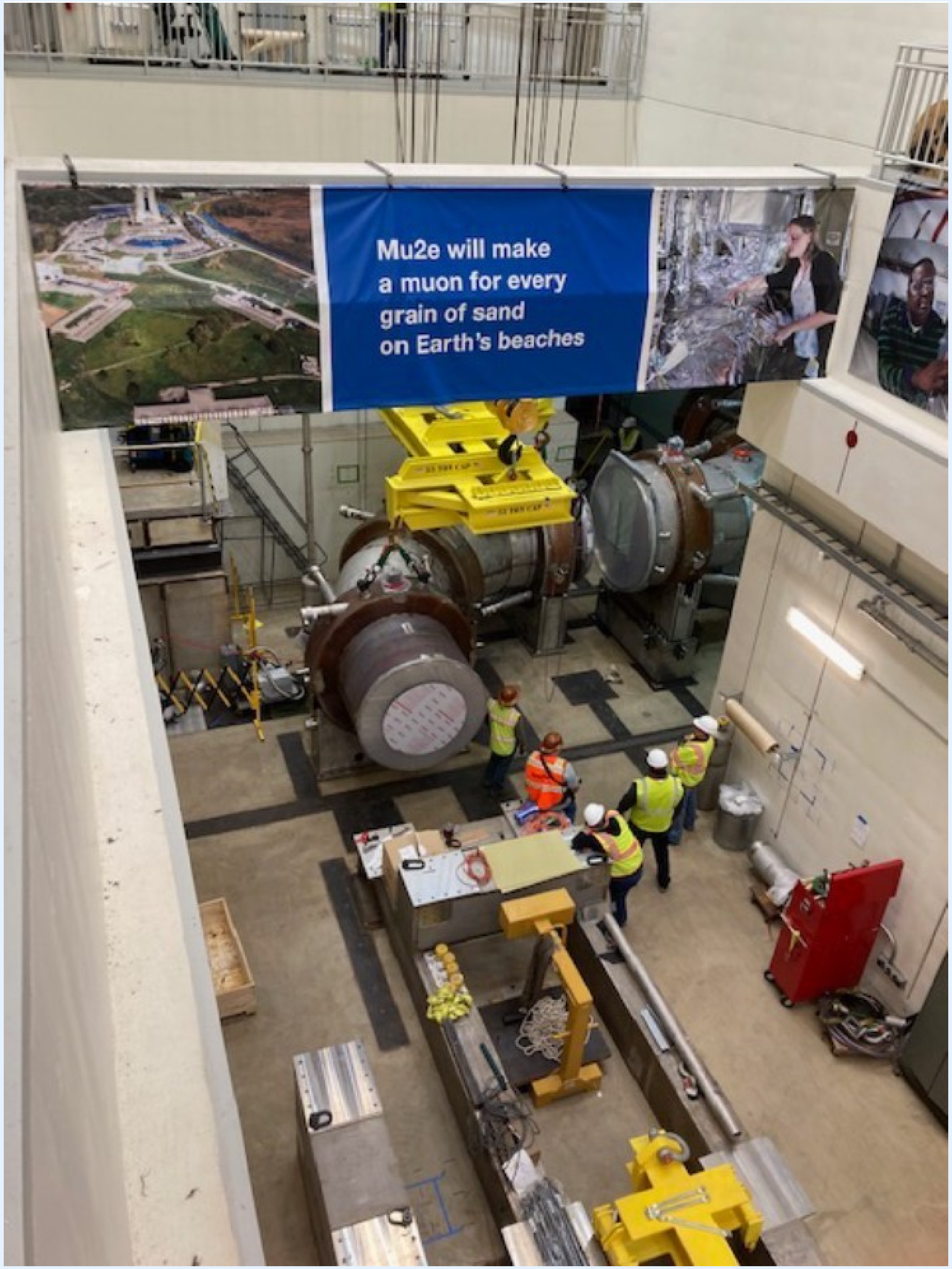
Swivel collimator

2) Transport solenoid:

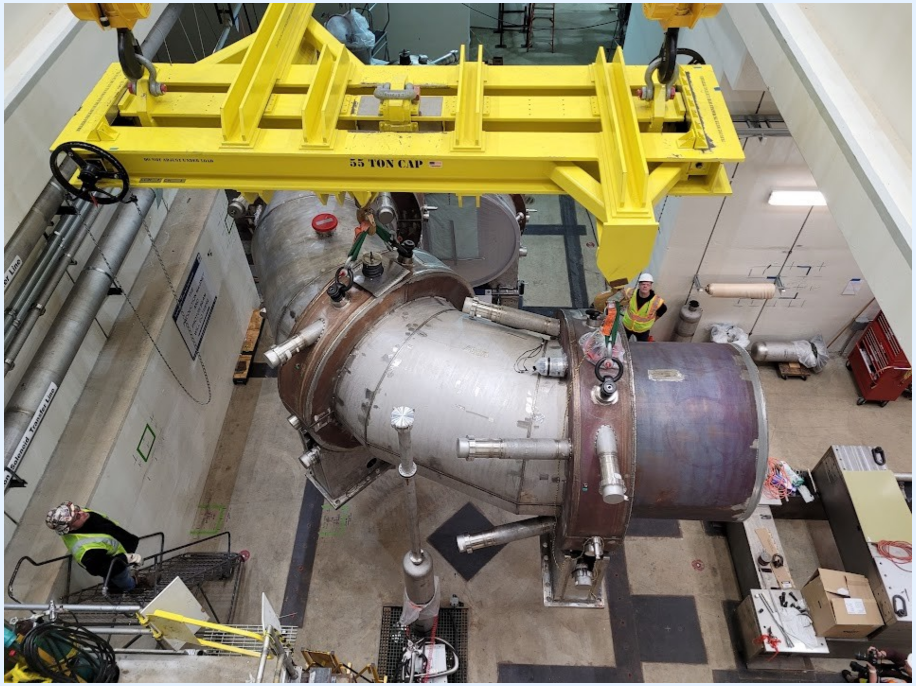
- small magnetic field gradient to avoid trapped particles
- internal swivel collimators to select -/+ particles of wanted momentum
- thin absober windows to reduce antiproton background

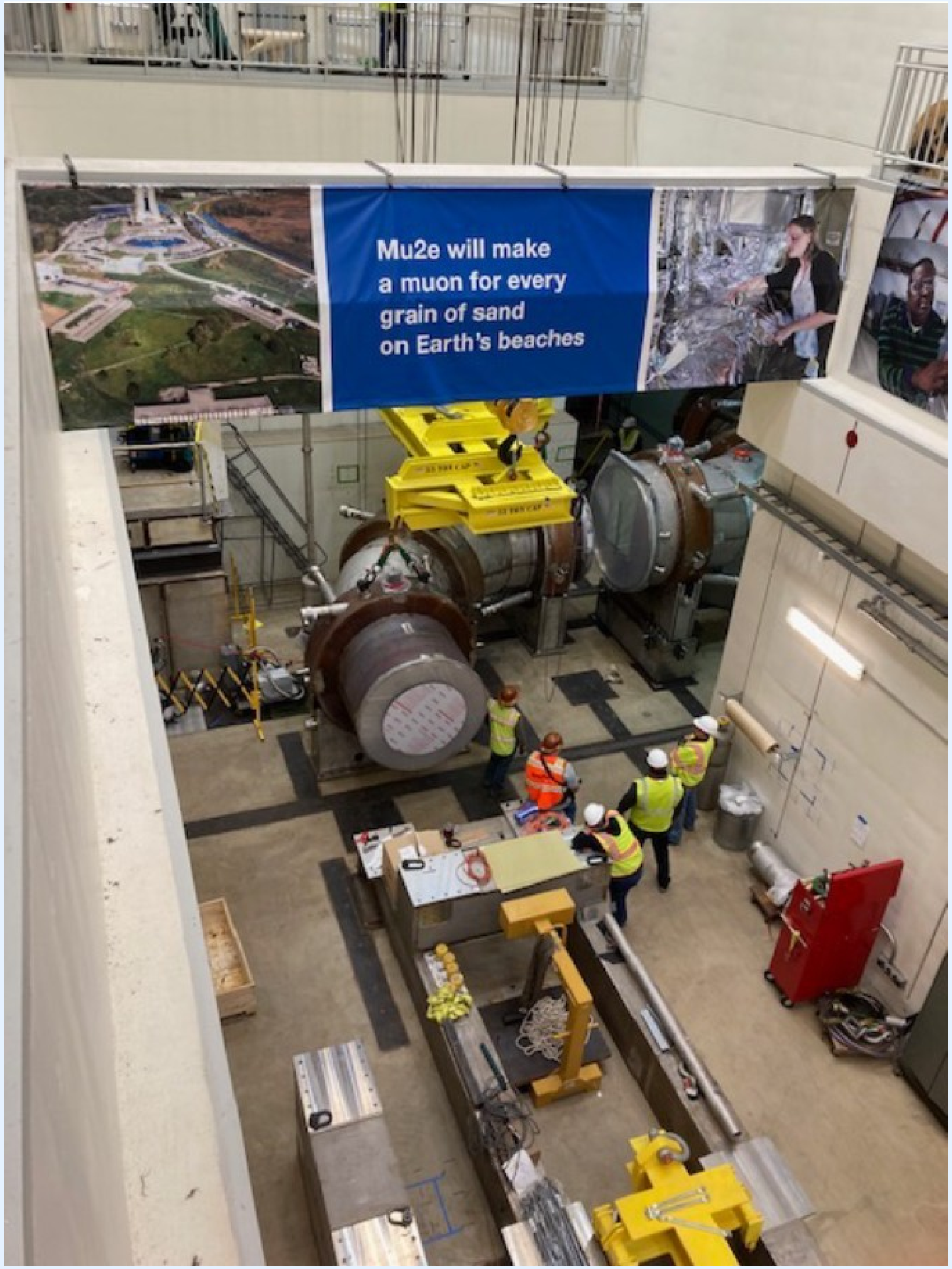
TS installed in Mu2e hall (February 2024)



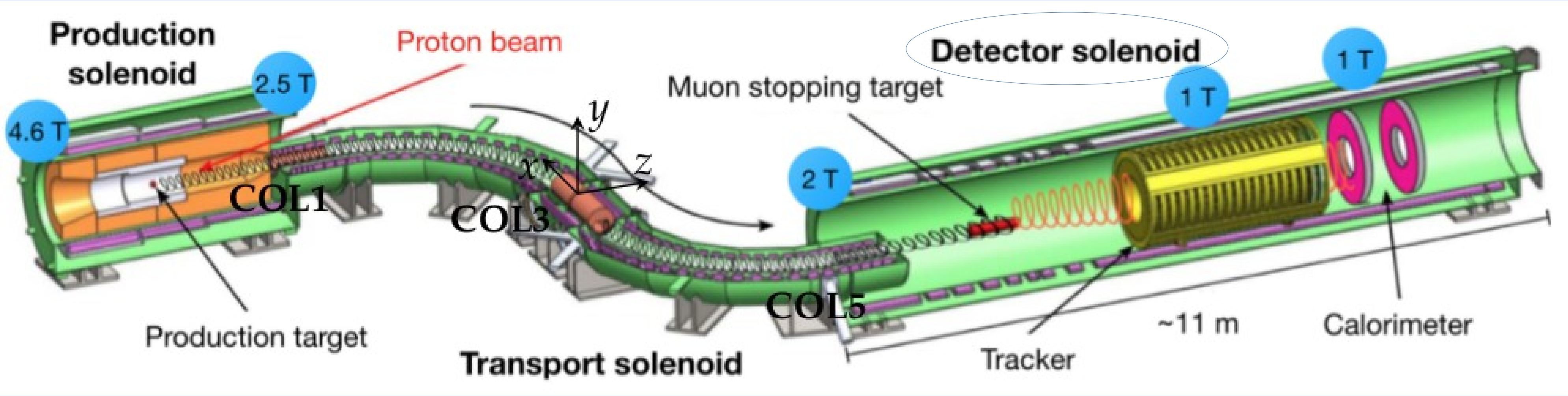


TS installed in Mu2e hall (February 2024)





The Mu2e detector solenoid (DS)



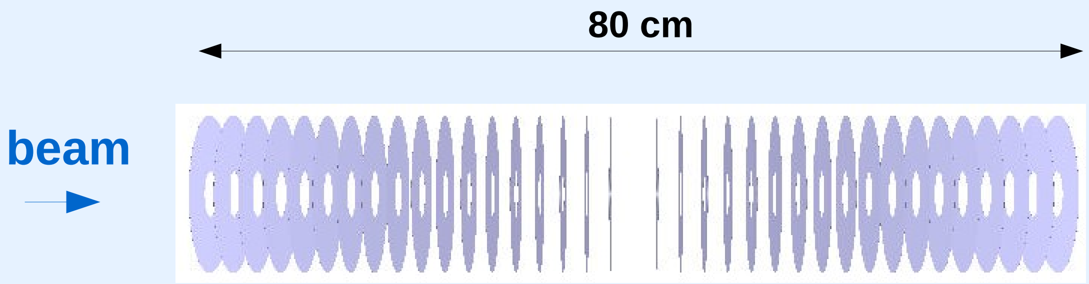
3) Detector Solenoid (11 coils):

- Contains the Al muon stopping target surrounded by proton/neutron absorbers
- field gradient increases acceptance
- 1 T uniform field in detectors region
- cold mass assembled
- thermal shield assembly under way
- expected delivery: **May 2025**

DS cold mass (11 coils)

DS outer shield

The Aluminum muon stopping target



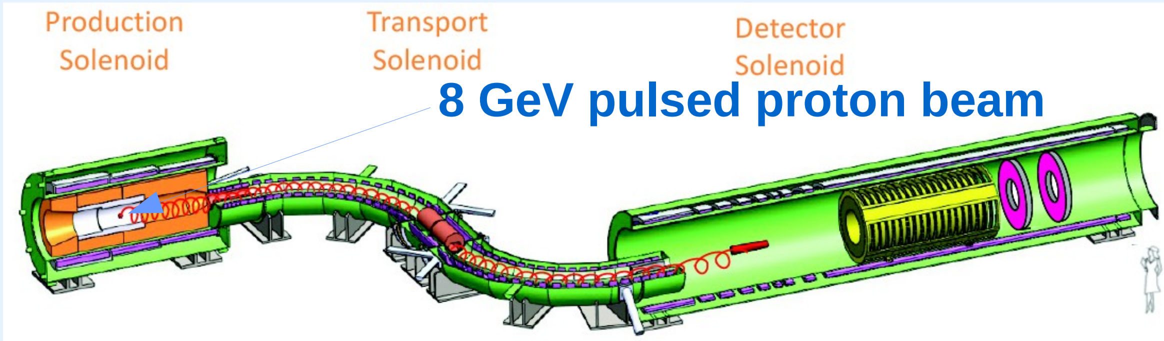
The stopping target:

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

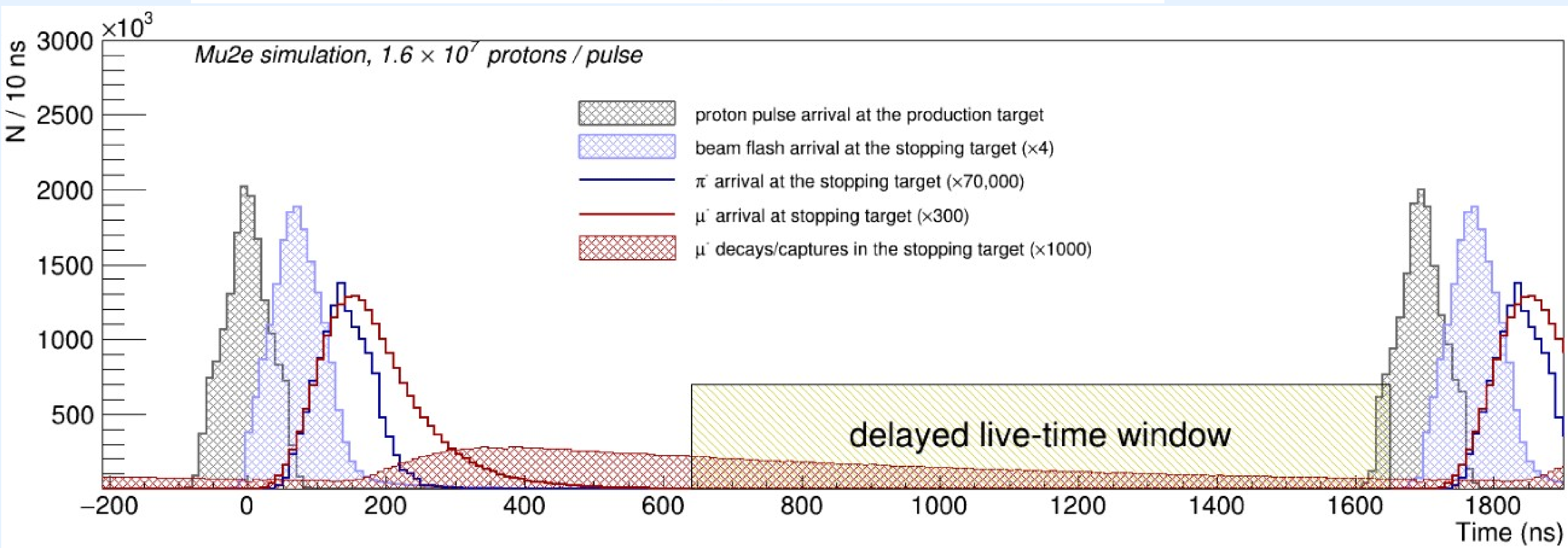
The segmented geometry helps to reduce electron energy losses (improving momentum resolution)

Hollow geometry to reduce radiation in the detector

The pulsed proton beam structure



Full Beam intensity:
3.9 ·10^7 p/pulse
(±50%)



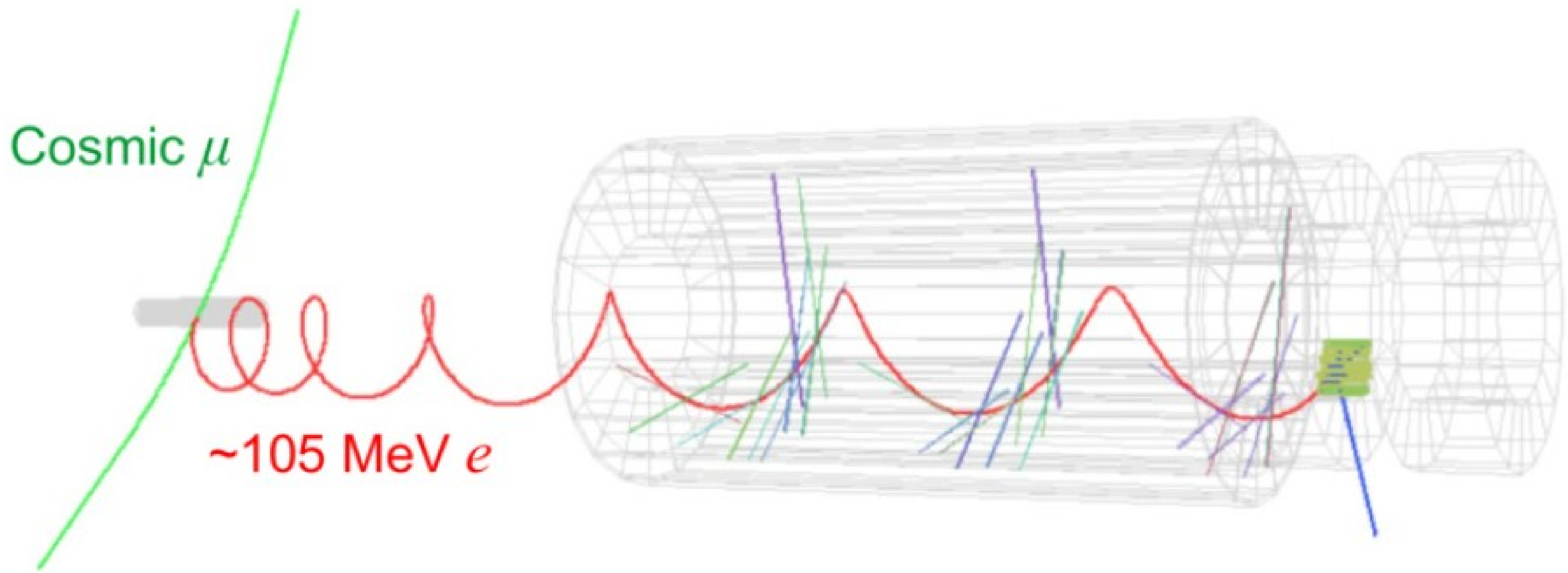
Pulsed Proton Beam Structure:

Proton pulse period: **1.695 μs** ~ $2\tau_\mu^{Al}$ (τ_μ^{Al} = 864 ns)

Delayed analysis window to suppress prompt backgrounds

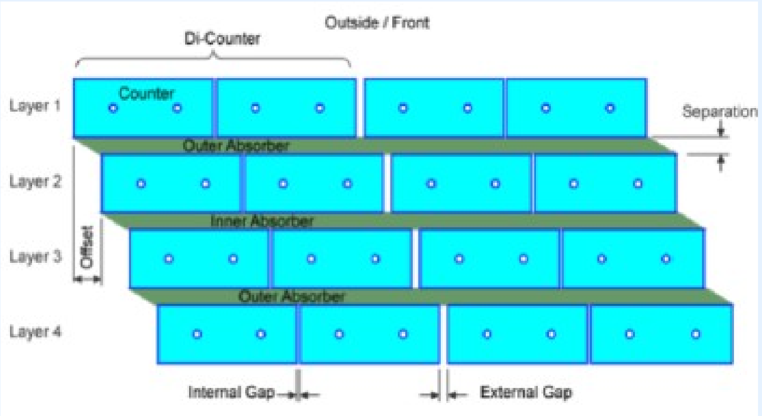
Out of bunch proton fraction ("extinction factor") **< 10^{-10}**
(measured by an extinction monitor downstream of the beam)

The Cosmic Background

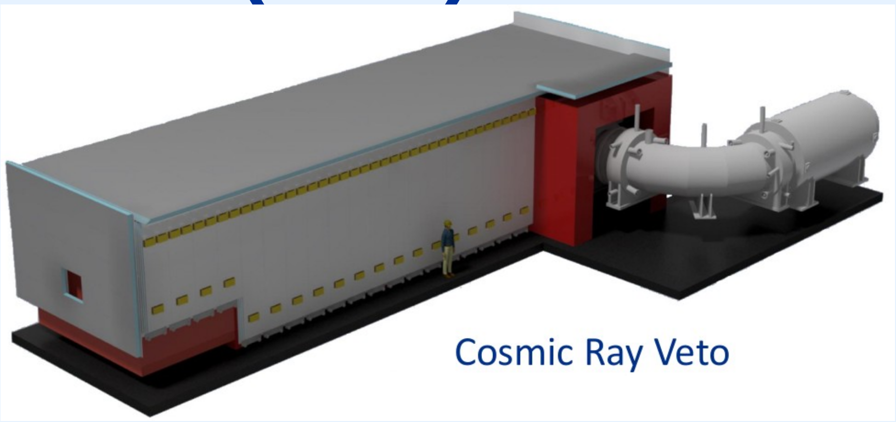


About **1 cosmic event/day** can mimic a 105 MeV electron

Mu2e Cosmic Ray Veto system (CRV)

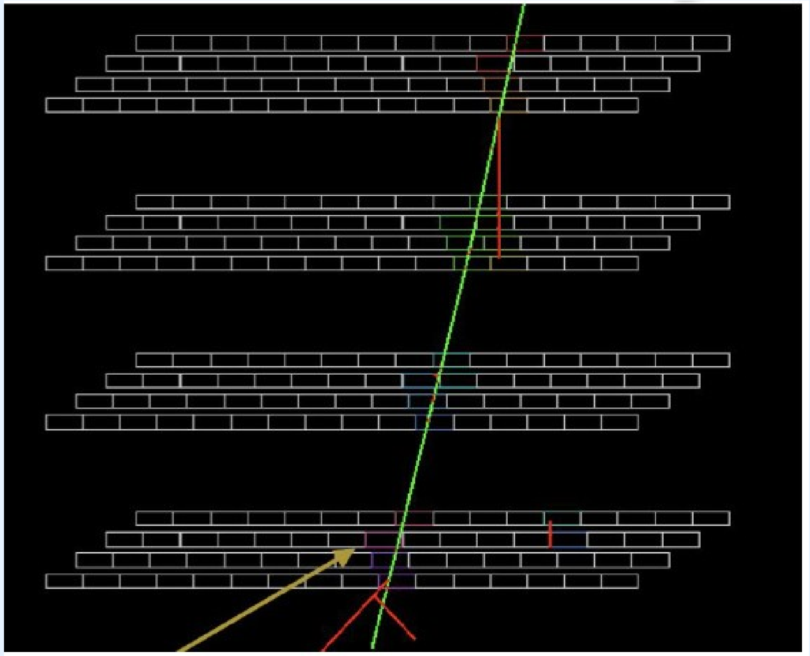


4 layers of scintillator counter modules read by WLS and SiPMs



CRV cover DS and Lower TS

All 83 modules have been built and are under test to determine efficiency and aging rate

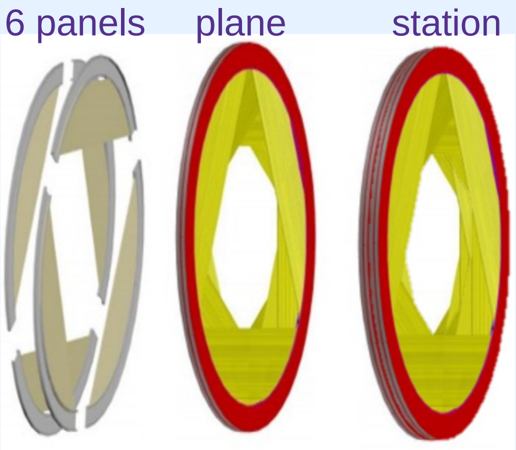


3 out of 4 layers provide a **veto efficiency** on charged partciles **>99.99%**

Mu2e straw tube tracker (STT)

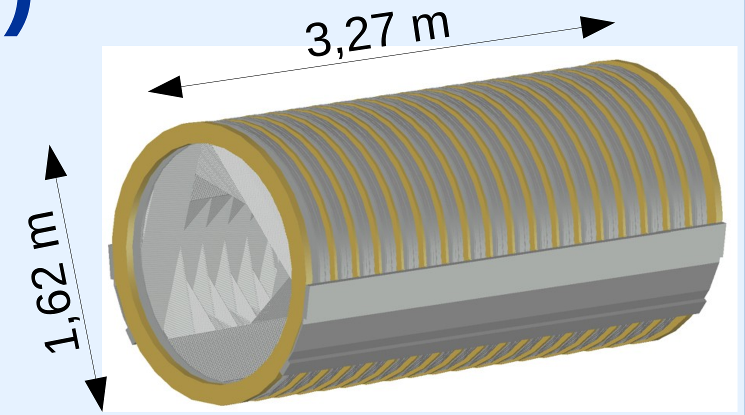
Tracker straw tubes

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



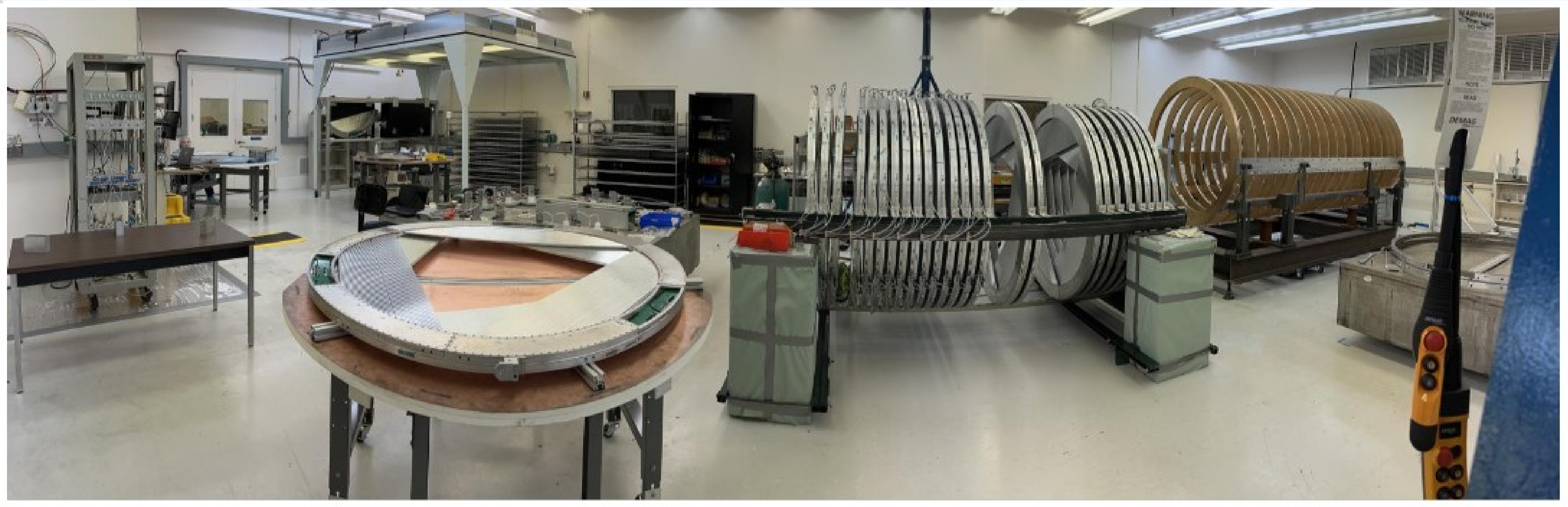
Tracker station assambly

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



Tracker structure

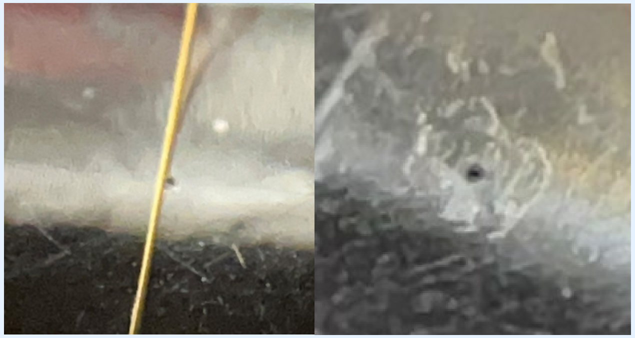
18 stations of 12 panels
(~21000 straw tubes)



All panels and planes assembled. Leakage test ongoing...
Expected completion and installation in Mu2e building: **spring 2025**

An unsupectable source of gas leak

13 pin holes discovered across 7 leaking panels from Oct ‘23 to Jan ‘24

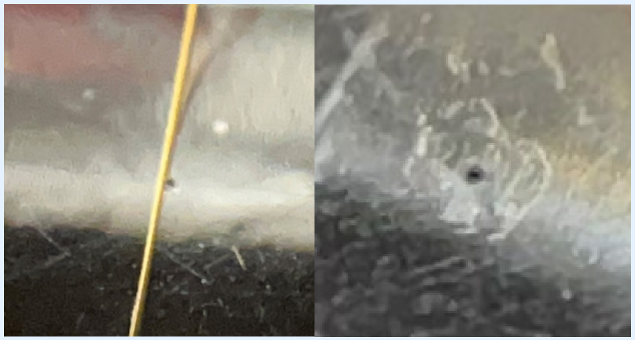


Pin holes

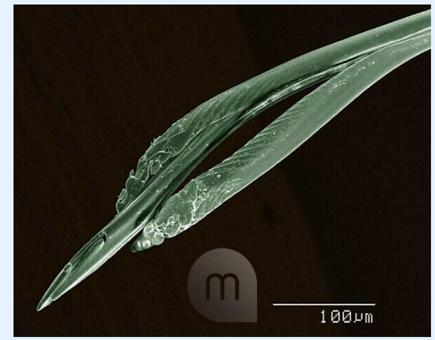
Chemical corrosion excluded...

An unsupectable source of gas leak

13 pin holes discovered across 7 leaking panels from Oct '23 to Jan '24



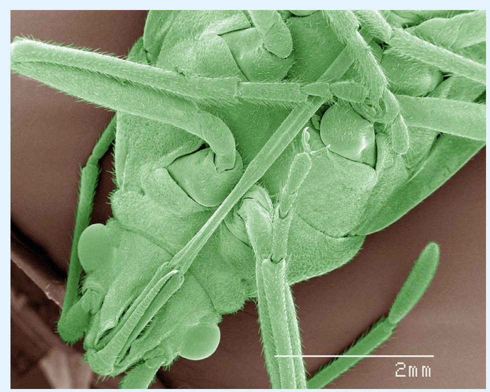
Pin holes



Box bug rostrum

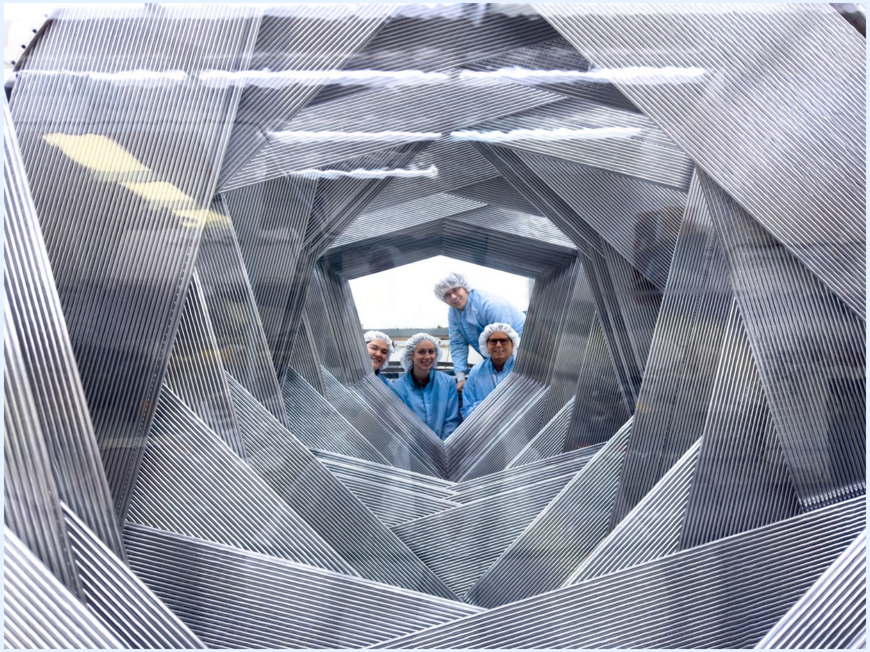
Holes were created by **boxelder bugs**!

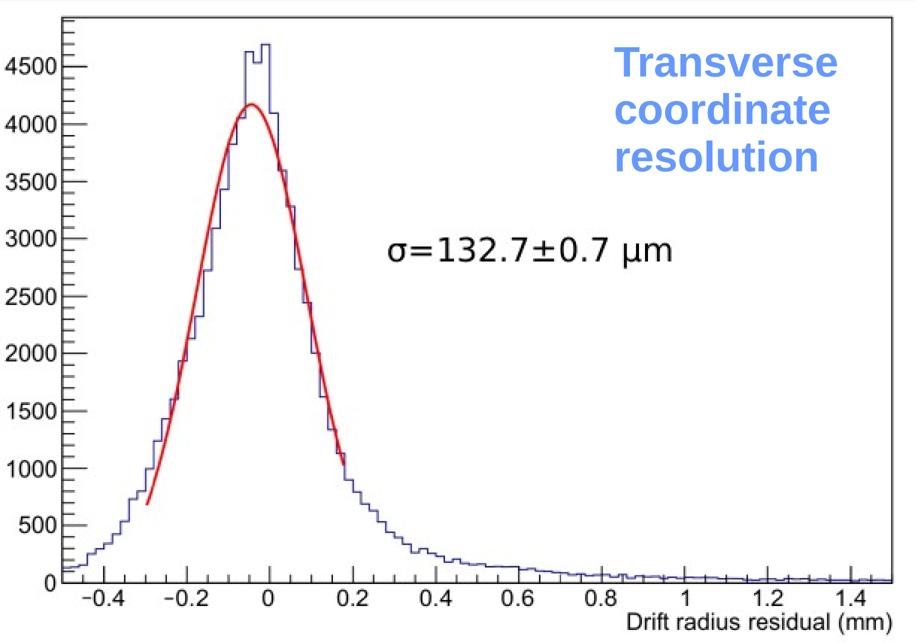
Terrarium setup to reproduce the damage.
Working with Entomologists to protect the clean room and develop protection techniques for Mu2e Hall.

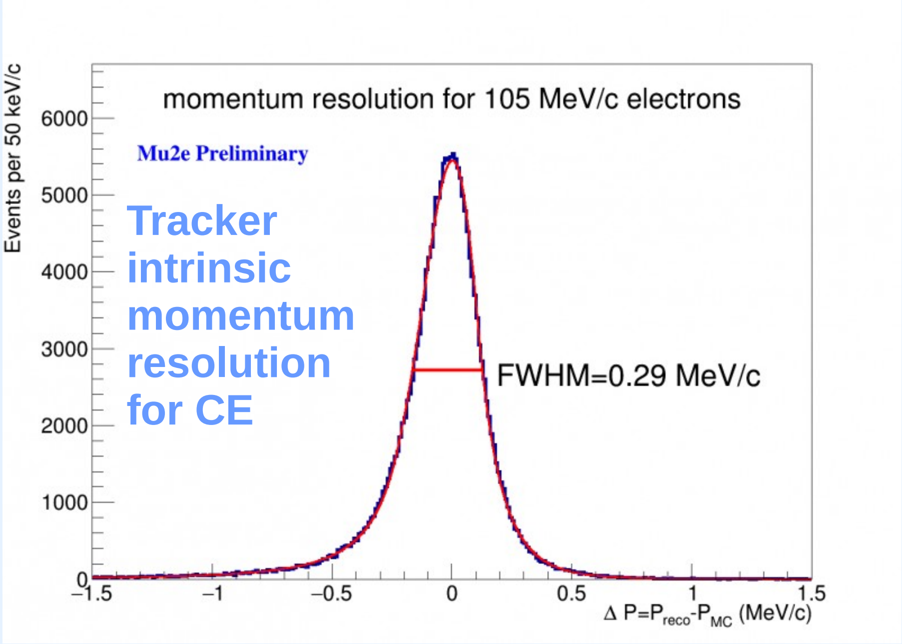


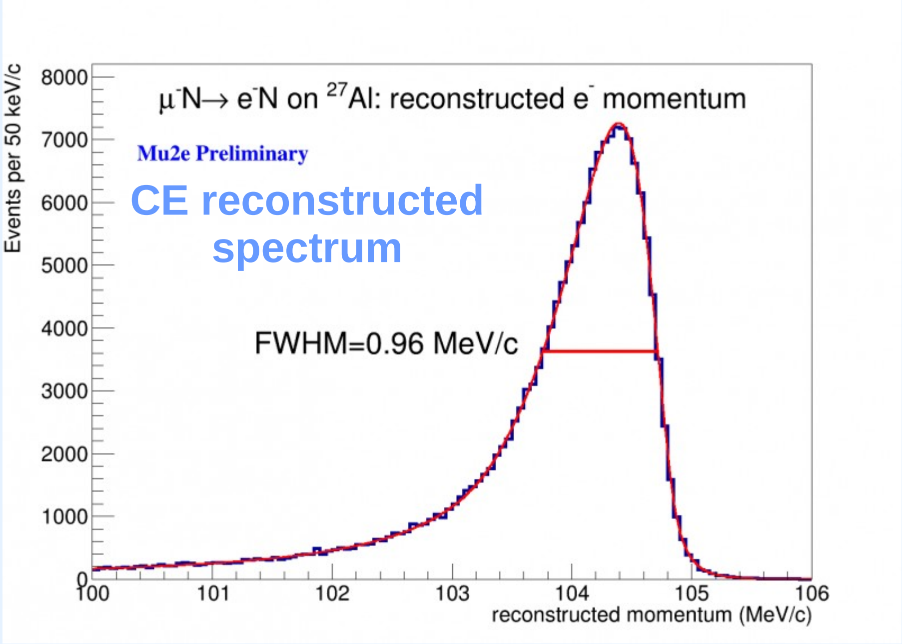
"Terrarium" Setup

Tracker measured and expected performances

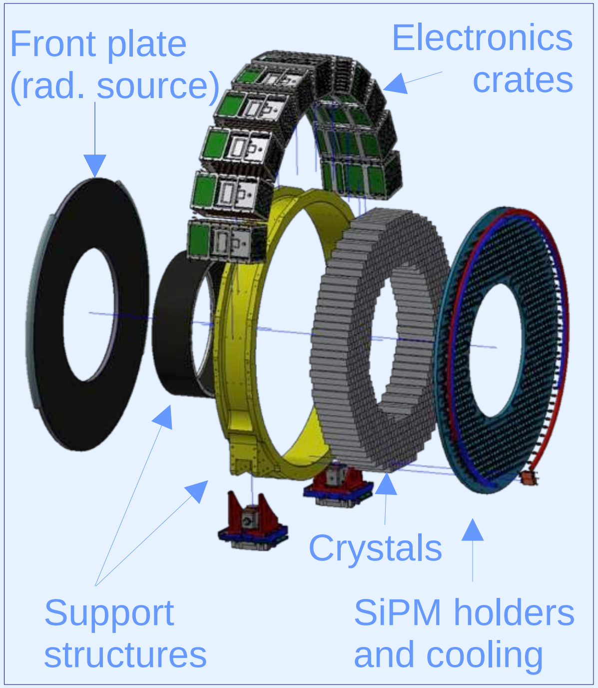








Mu2e electromagnetic calorimeter (ECAL)

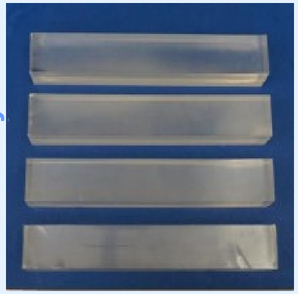


2 disks spaced by 70 cm
374 < radius < 660 mm

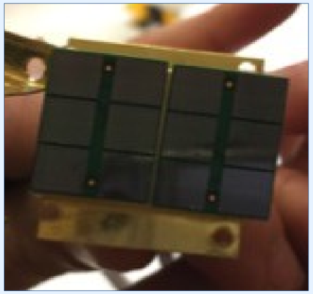
674 pure CsI crystals/disk
2 arrays of 6 SiPMs/crystal

FEE connected to SiPMs

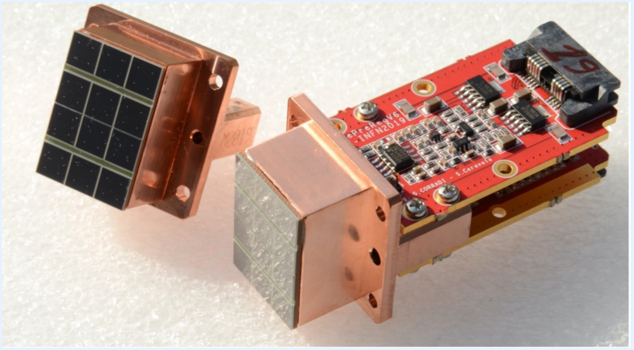
CsI crystals



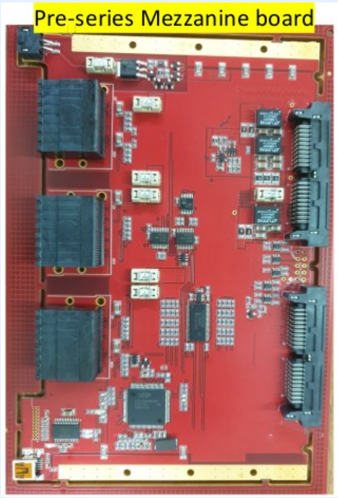
SiPMs



FEE boards



Control and digital electronics
in the crates attached to disks



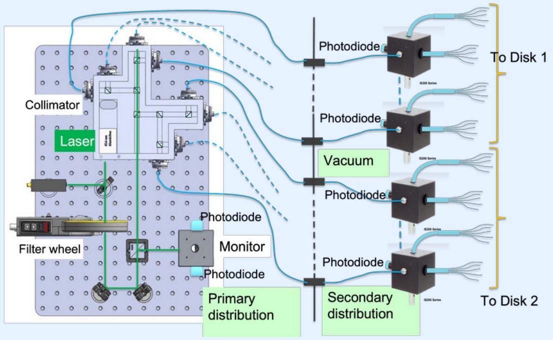
Control board

Digitizer board

Radioactive liquid pipes

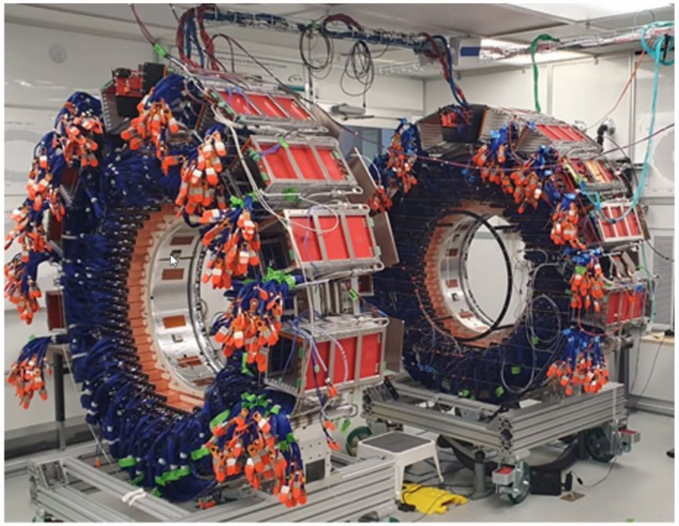
Pipes for radioactive liquid
calibration in front of disks

Laser system

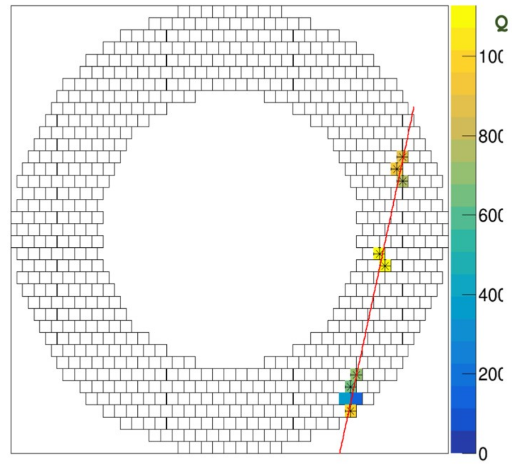


Laser system for energy and
time calibration

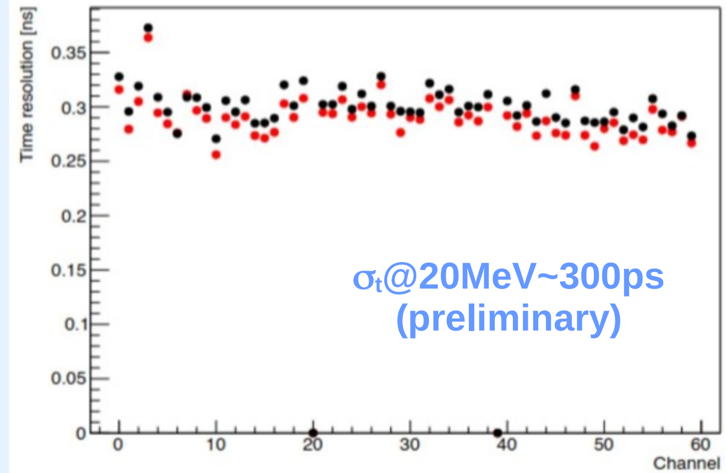
Mu2e electromagnetic calorimeter (ECAL)



First cosmic (August 2024)



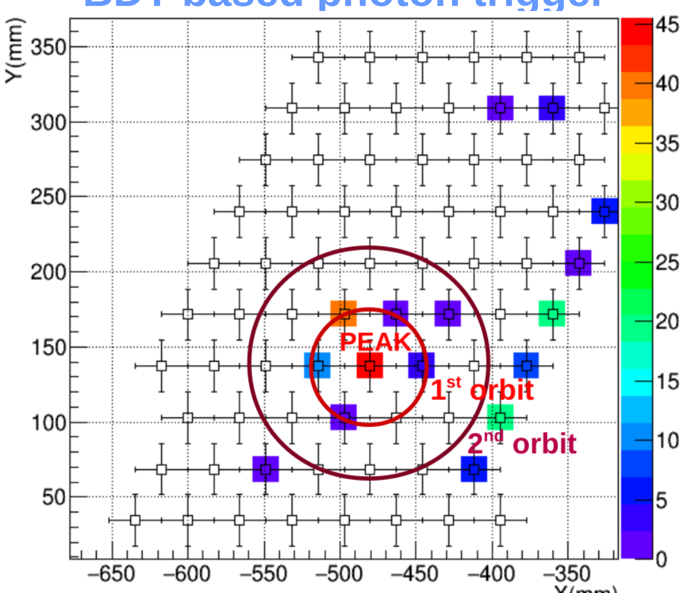
First time calibration



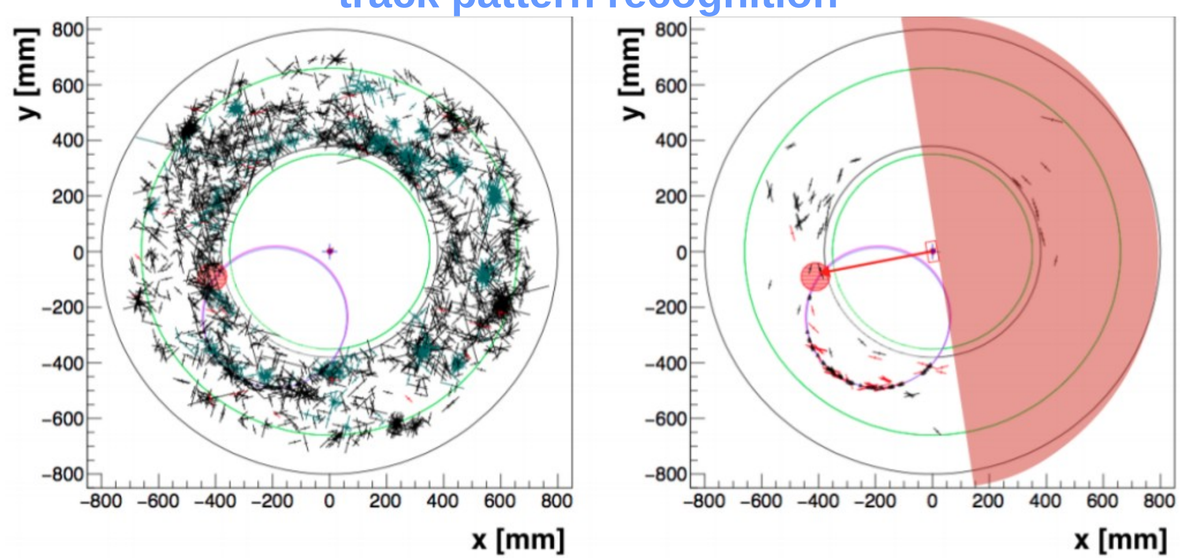
Installation in Mu2e hall: **winter 2024**

<u>Calorimeter tasks:</u>

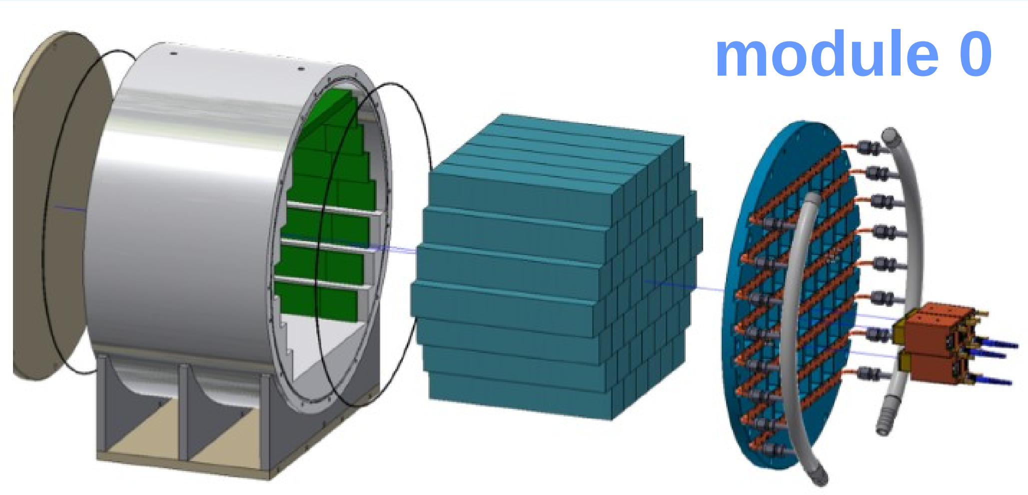
BDT based photon trigger



Simplify and improve
track pattern recognition



ECAL performances

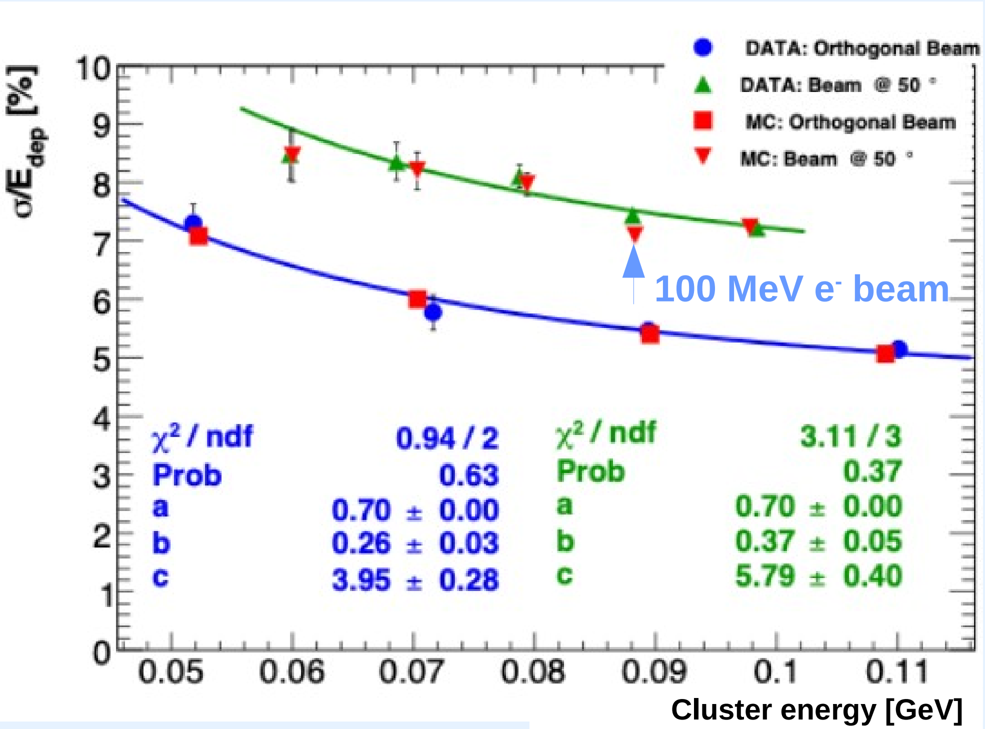


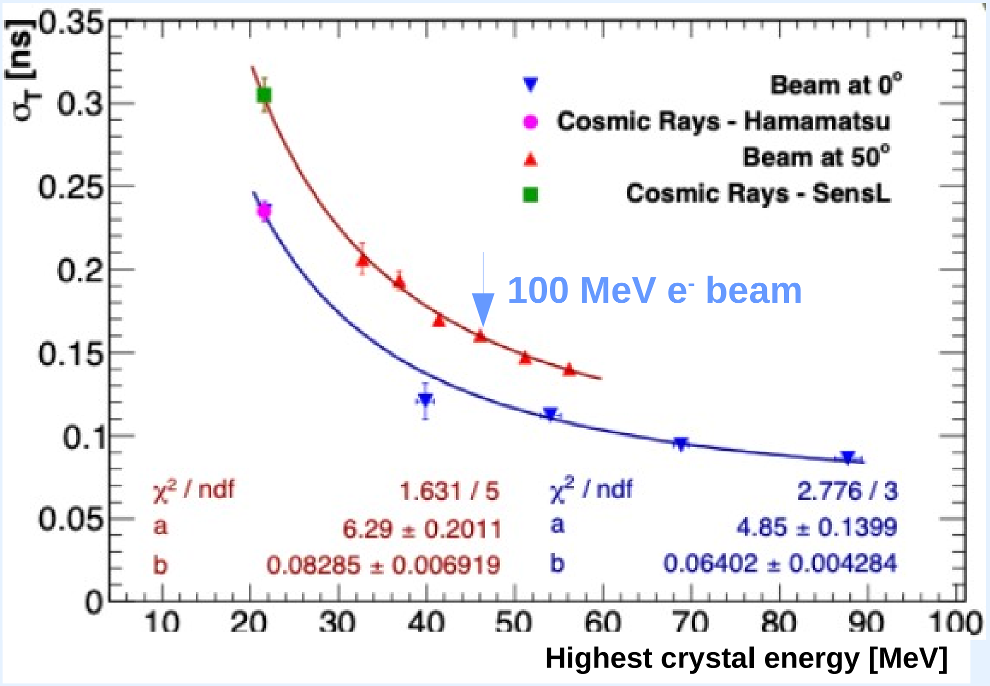
A **module 0** prototype with
- 51 crystals
- 102 SiPMs+FEE boards
- a commercial digitizer
- Cooling lines for SiPMs

The 2017 test with a beam in Frascati has measured for 100 MeV e- with 50^{o} impact angle*:

σ_E/E = 7.3%

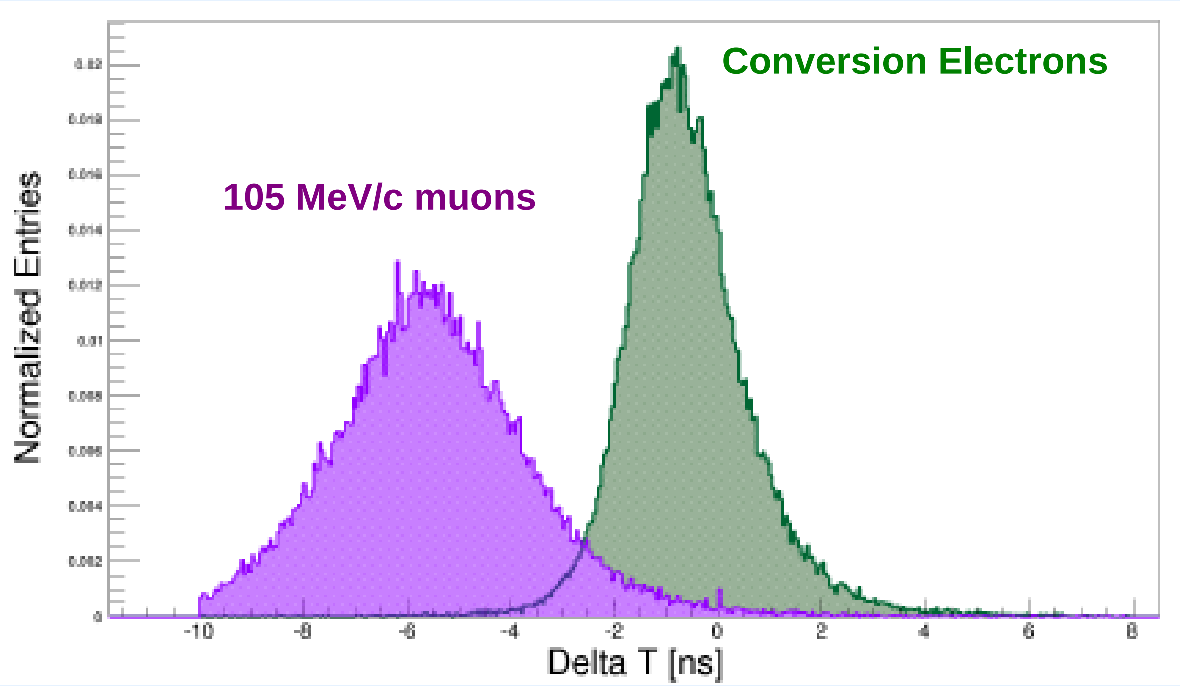
σ_t/t = 230 ps (only 1 sensor)



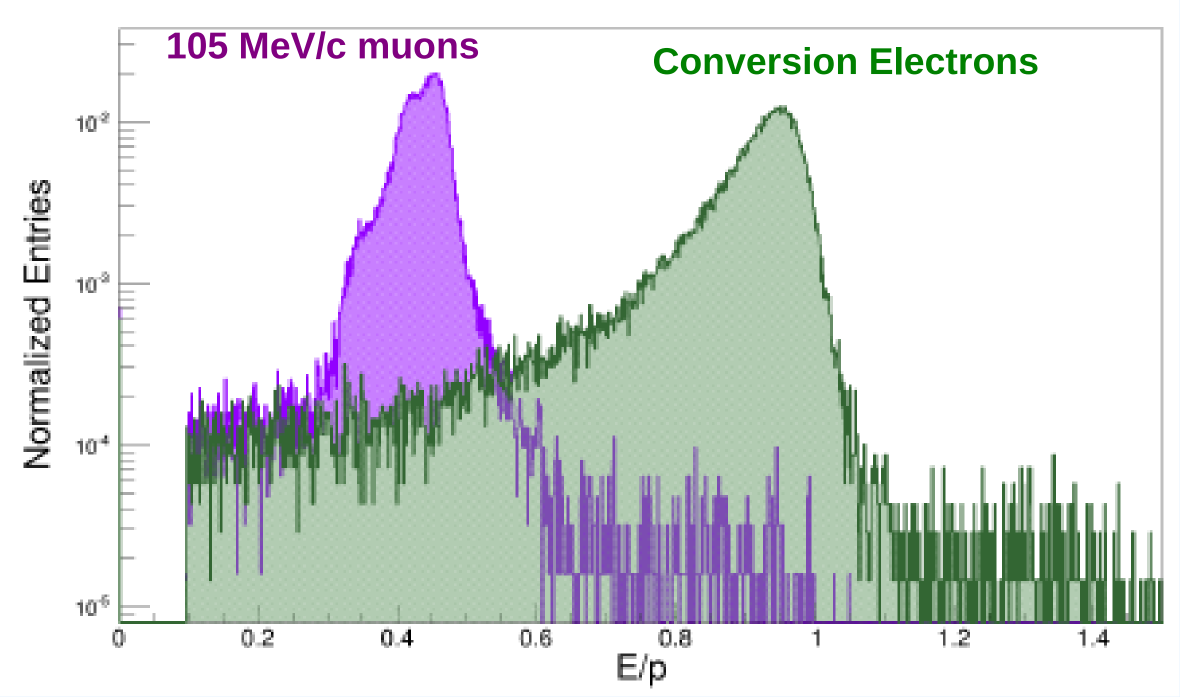


* *"Electron beam test of the large area Mu2e calorimeter prototype", J.Phys.Conf.Ser. 1162 (2019) 1, 012027*

Particle identification (combining Tracker & ECAL)



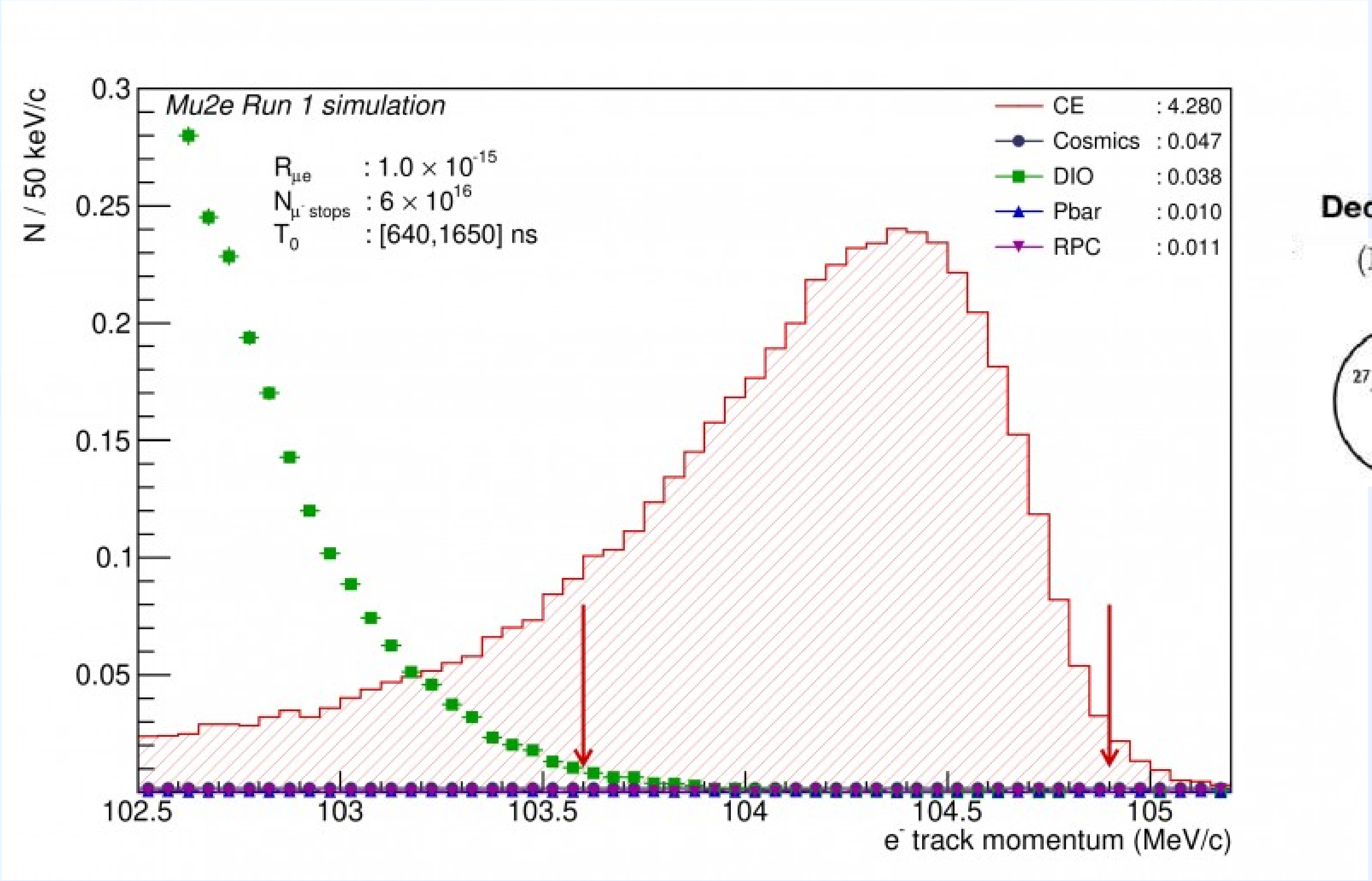
Time of flight:
extrapolated track time (assuming electron mass) – calorimeter cluster time

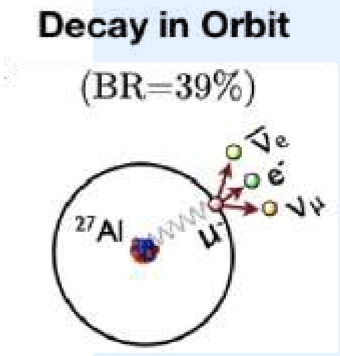


E/p:
Calorimeter cluster energy / track momentum

An **ANN selection** including other topologycal information makes the **cosmic muons** background **negligible** with respect to the irriducible background due to **cosmic generated** e^-

Electron momentum: Decays in Orbit suppression

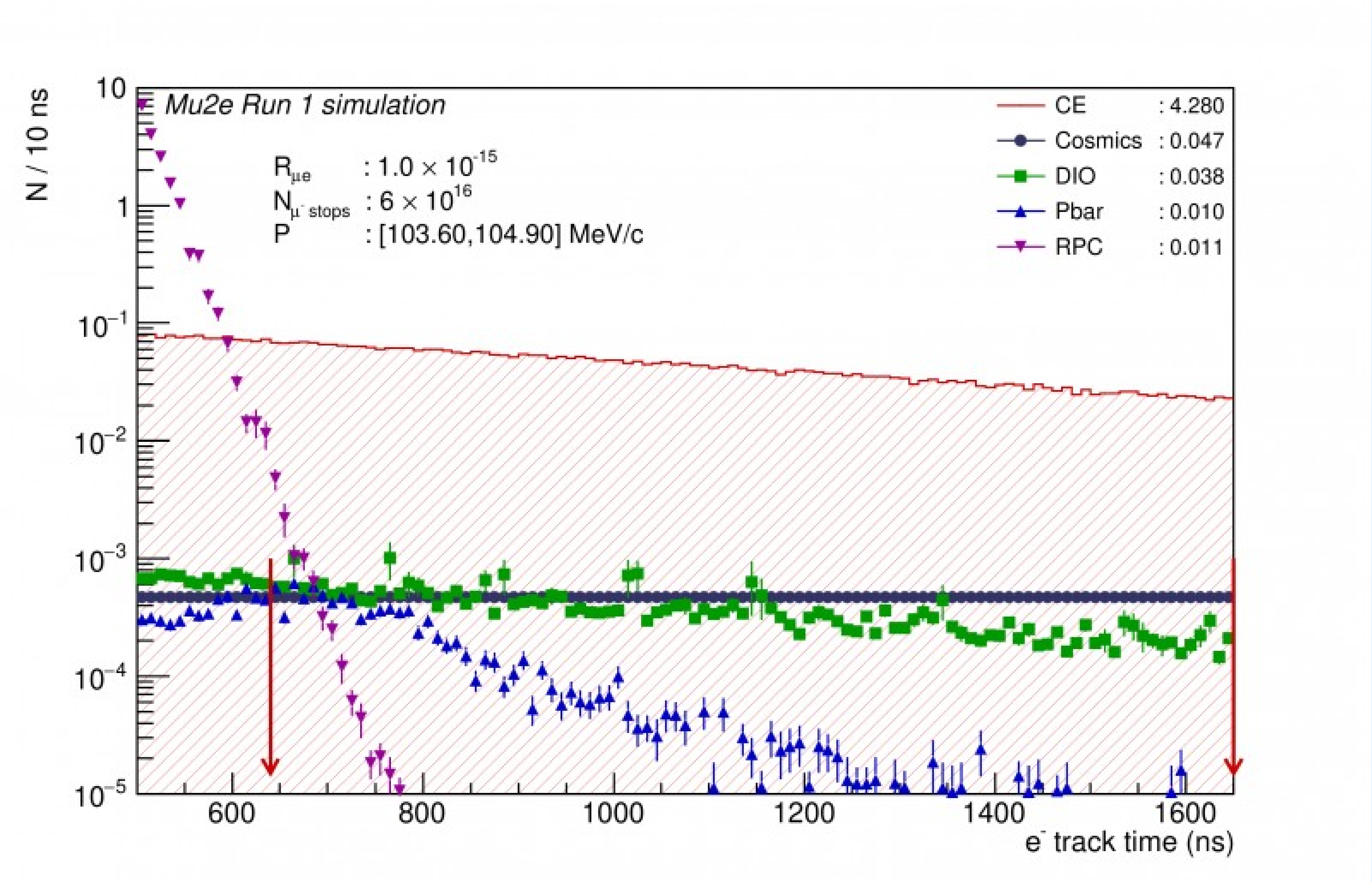




The Decay In Orbit **(DIO)** spectrum falls as $(E_{max}-E)^5$ close to the end point

Can be suppressed by the momentum window cut

Electron time: radiative pion capture suppression



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 have been **optimized** to get the best **discovery sensitivity**

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*

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

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!

Summary and outook

- Mu2e tracker and calorimeter will be installed in the detector hall by spring **2025**. **Detector commissioning** with cosmics will start soon after.

- **Mu2e Run I** is expected to start in **2027** and to improve Sindrum II sensitivity by a factor 10^3.

- **Mu2e Run II** will start after the shutdown for neutrino beam upgrade, presumably in **2029**, aiming to achieve the final 10^4 improvement goal.

- A Mu2e upgrade proposal (**Mu2e II**), inserted in the Snow Mass white paper (*arXiv:2203.07569v2*), aims to exploit the higher intensity and lower energy PIP-II proton beam to obtain a further x10 improvement in sensitivity.

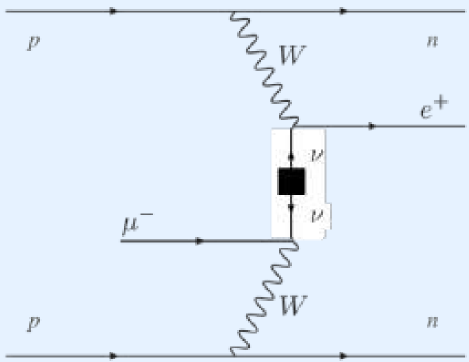
Mu2e Collaboration (February 2024)

Thank you!

BACKUP

μ- → e^+ expected sensitivity

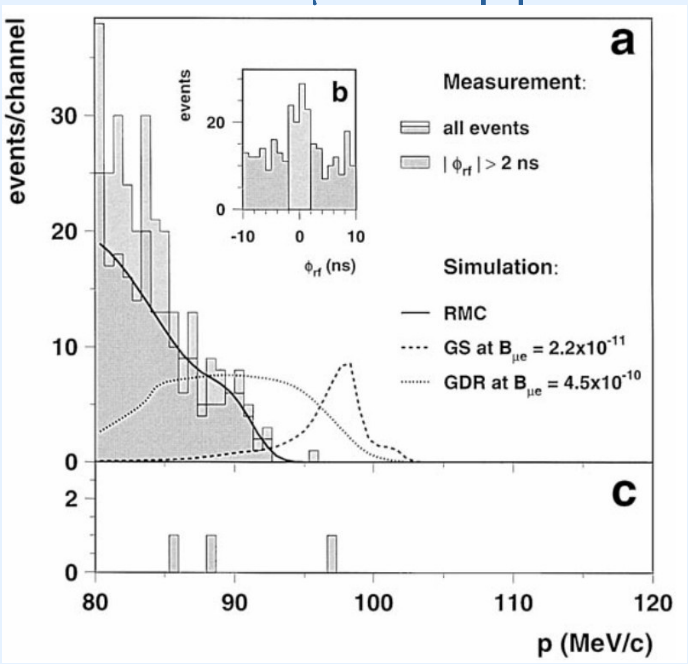
Mu2e will also be able to search for the CLFV and **lepton number violating** (ΔL=2) process:



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

The current limit on $R_{\mu e+}$ is $1.7 \cdot 10^{-12}$ (Sindrum II '98).

Sindrum II μ- → e+ '98 paper



Also for this channel **if the error is dominated by signal statistics** Mu2e should achieve a factor 10^3 improvement in Run 1 and a factor 10^4 after Run 2

μ- → e^+ possible limitation to sensitivity

Sindrum II $\mu^- \rightarrow e^-$ 2006 paper also shows the positron spectrum (not elsewhere published):

Positron spectrum shows an unexpected bump in the signal region

An a posteriori convolution of the signal with the Sindrum II momentum resolution, including energy losses, shows that the bump is not compatible with the signal (arXiv:2009.00214v1)

A possible explanation could be the Radiative Muon Capture (RMC)γ spectrum model.
The commonly used closure approximation:

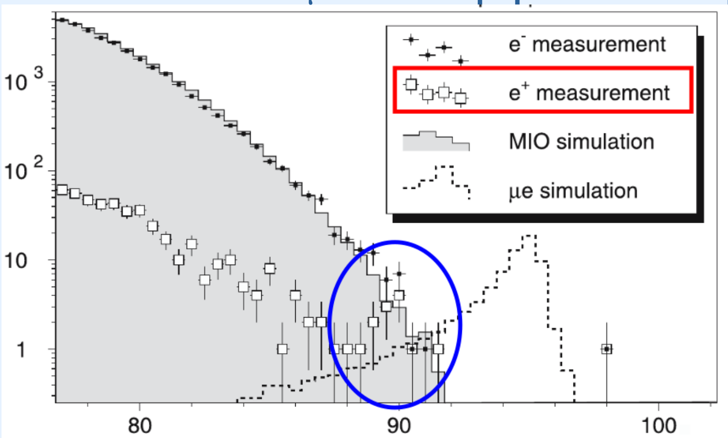
$$dN/dx \sim (1-2x+2x^2)\cdot x\cdot(1-x)^2 \ , \ x = k/k_{max}$$

assumes an end point k_{max}. TRIUMF data fit gives an end point lower than the kinematic limit.

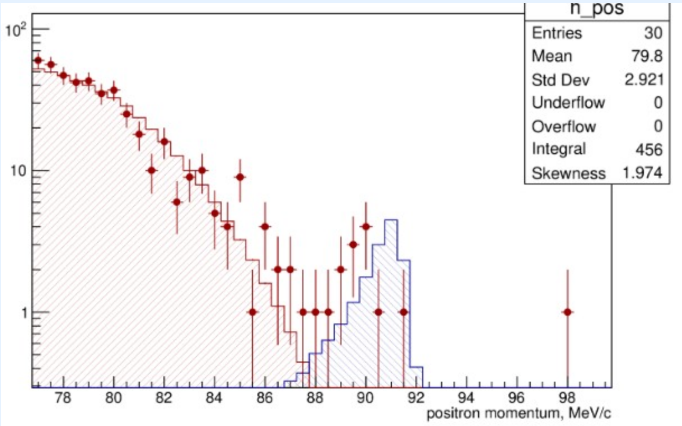
If the photon spectrum extends beyond k_{max}
$\mu^- \rightarrow e^+$ sensitivity could be much worse.

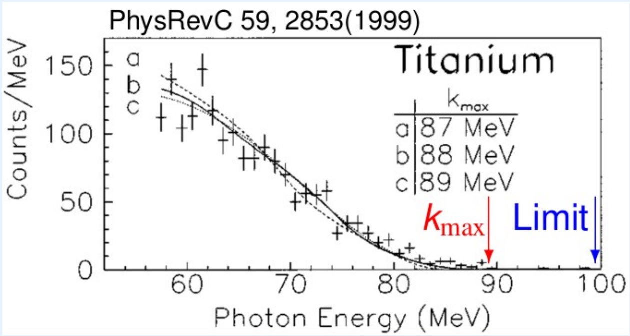
RMC γ photon spectrum will be measured during Mu2e Run I.

Sindrum II $\mu^- \rightarrow e^-$ 2006 paper

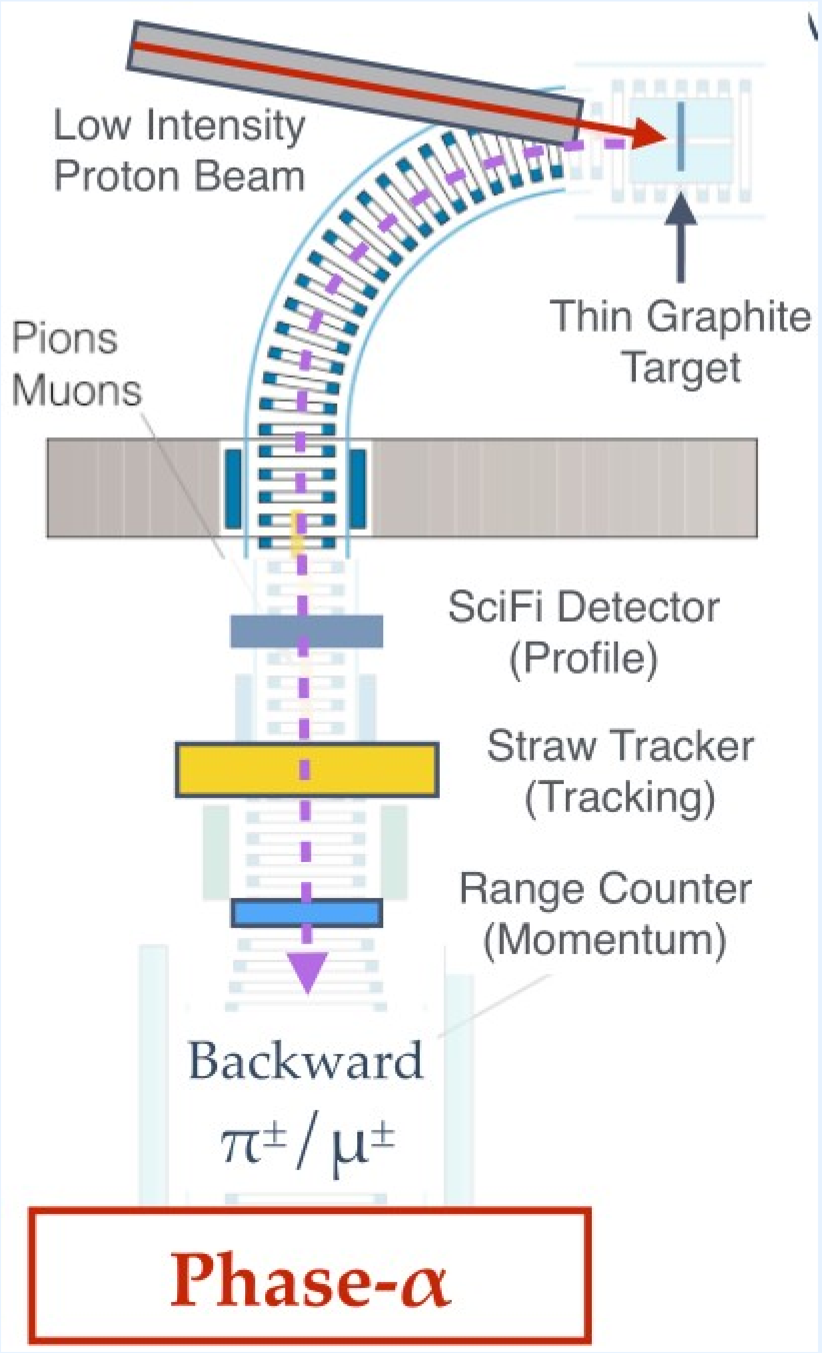


arXiv:2009.00214v1



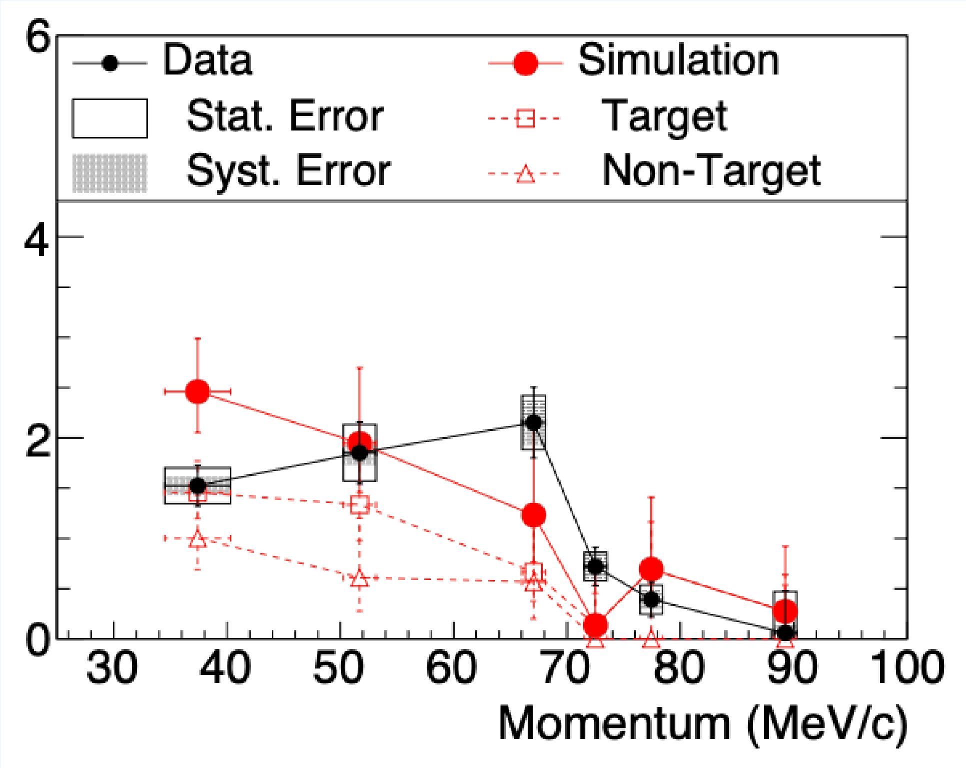


COMET Phase α @ JPARC

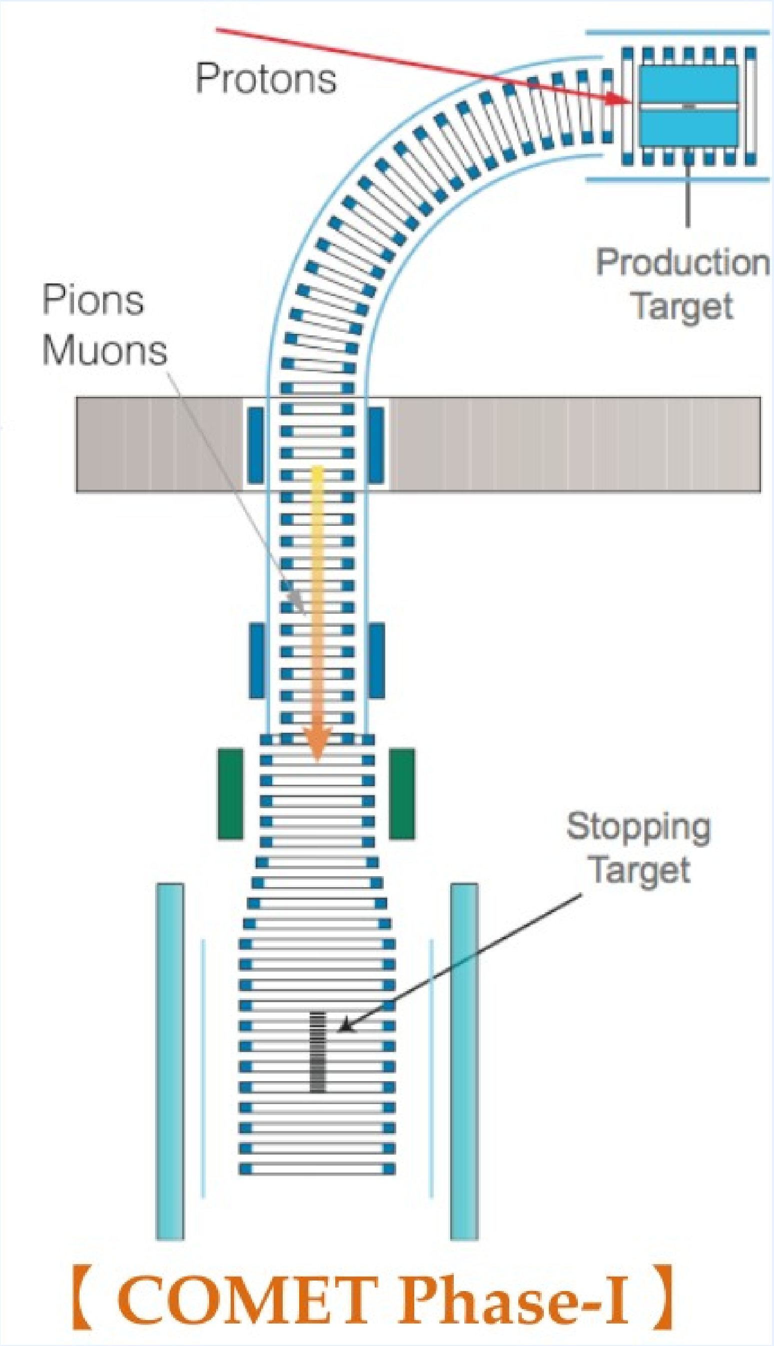


2023:

- Measure π/μ yield
- Validate transported π spectrum



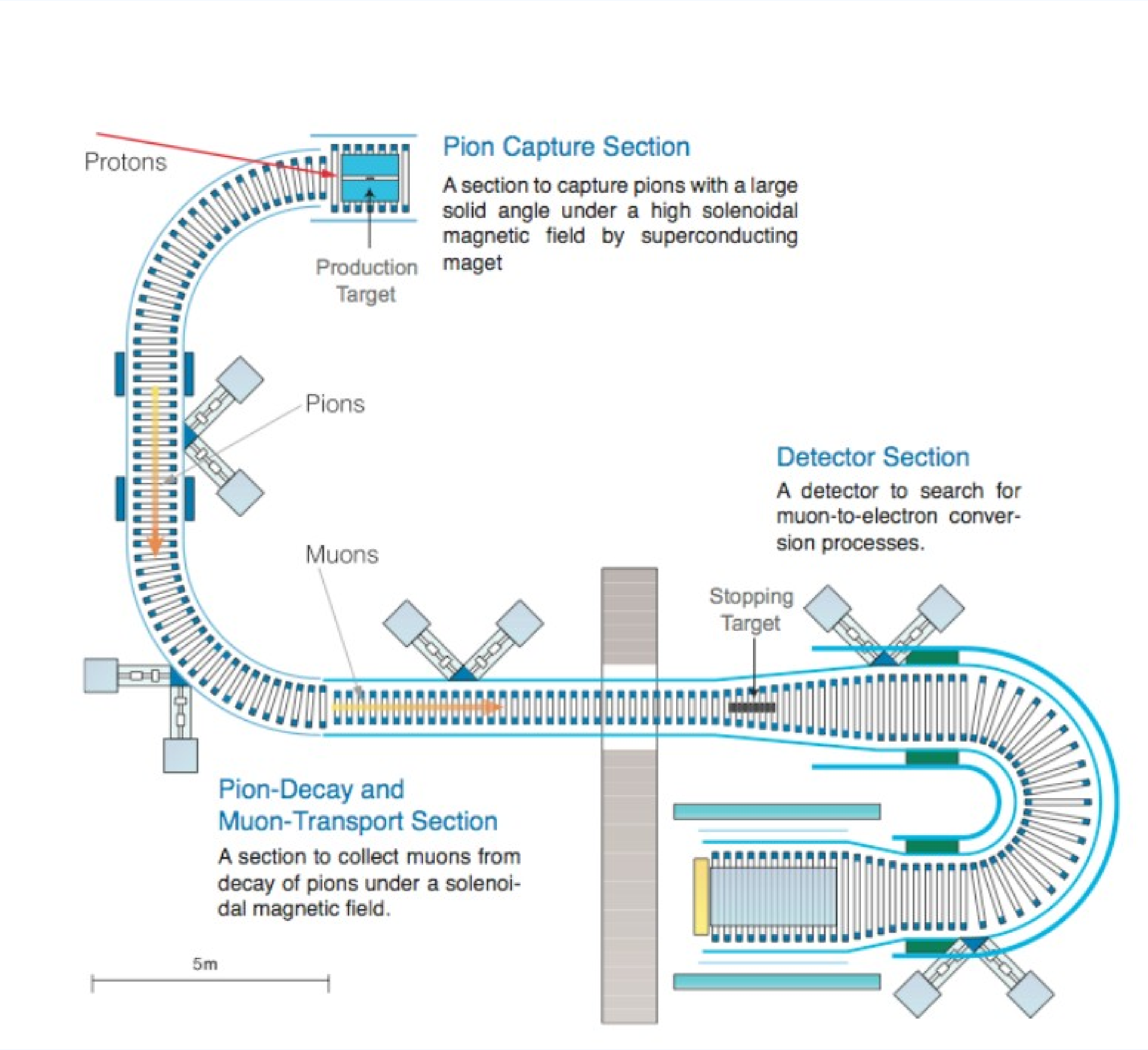
COMET Phase I @ JPARC



2025-2026:

- Construct up to first 90° bend and place detector.
- Perform direct beam measurement:
  - No backward σ_π data so far
  - No real BG data so far
- Perform μ-e Search with an intermediate sensitivity $O(10^{-15})$

COMET Phase II @ JPARC



2029(?):

- Complete all transport
- Perform μ-e search with a full sensitivity $O(10^{-17})$