Fermilab

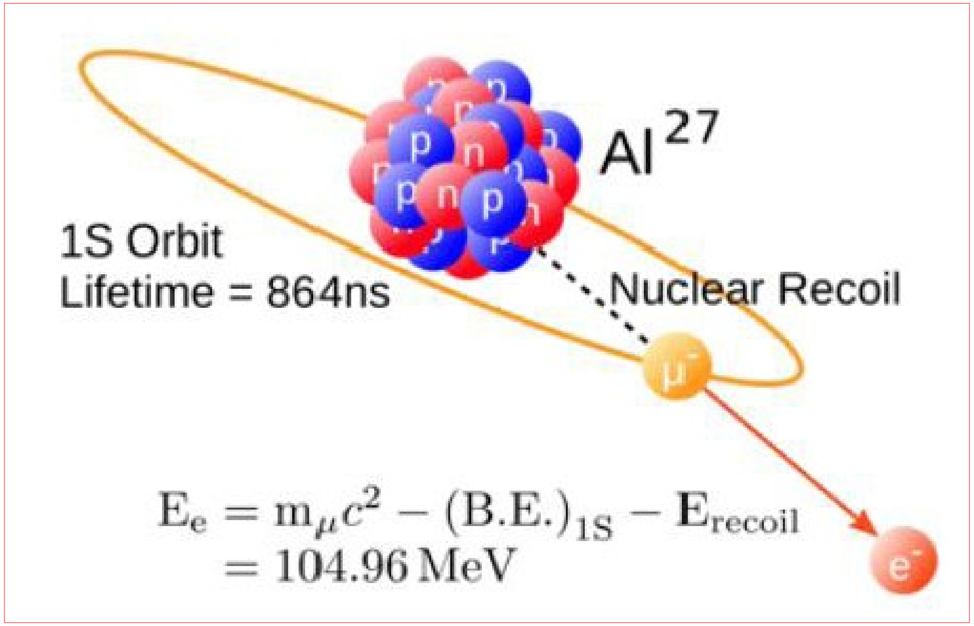
INFN Istituto Nazionale di Fisica Nucleare

The Mu2e experiment

S. Di Falco (INFN Pisa)
on behalf of the Mu2e Collaboration

Physics of fundamental Symmetries and Interactions - PSI2022

Searching for CLFV



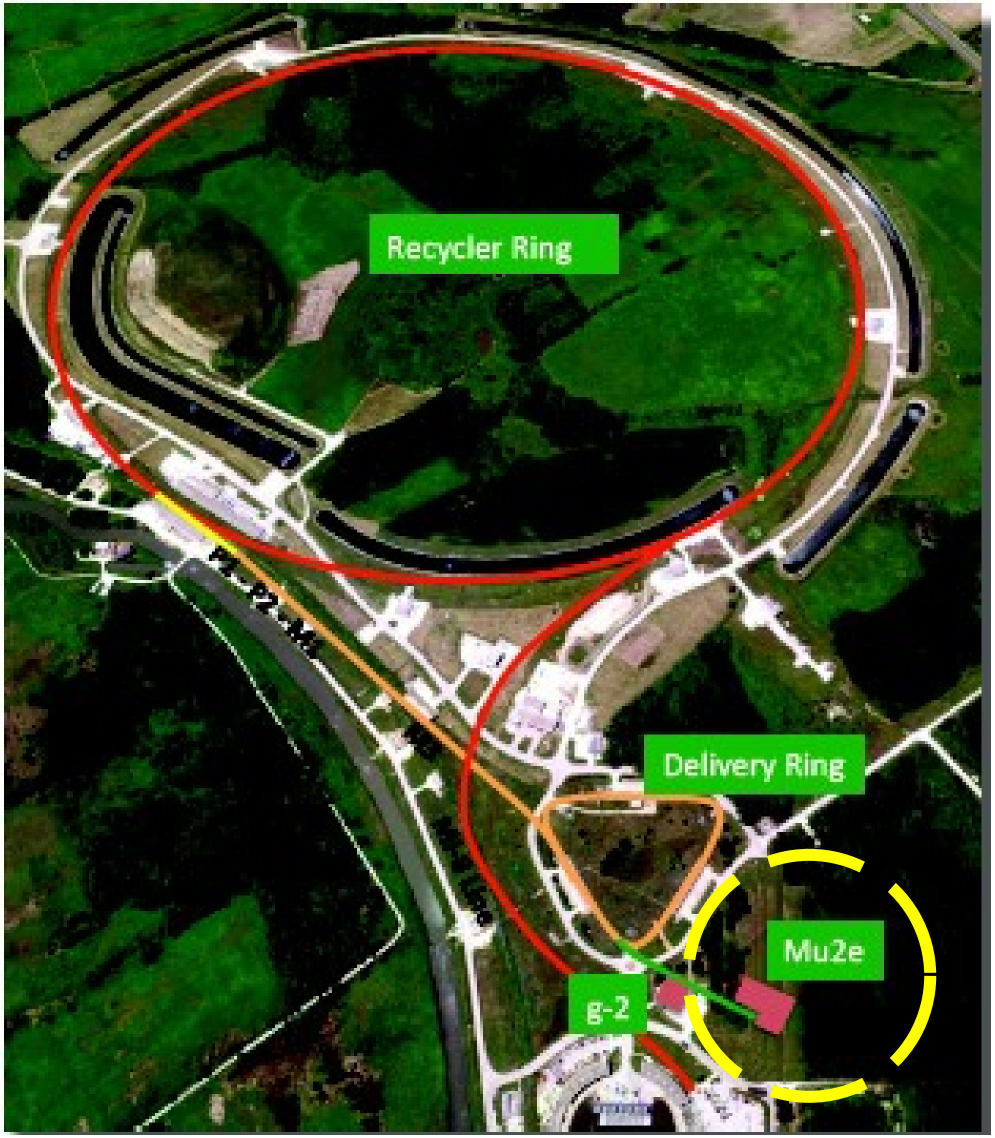
Mu2e searches for **Charged Lepton Flavor Violation (CLFV)** via the coherent conversion:

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

Same channel as COMET, complementary to MEGII and Mu3e

(see nice previous talks for theoretical motivation)

The Mu2e experiment



Mu2e at
Fermilab Muon Campus

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

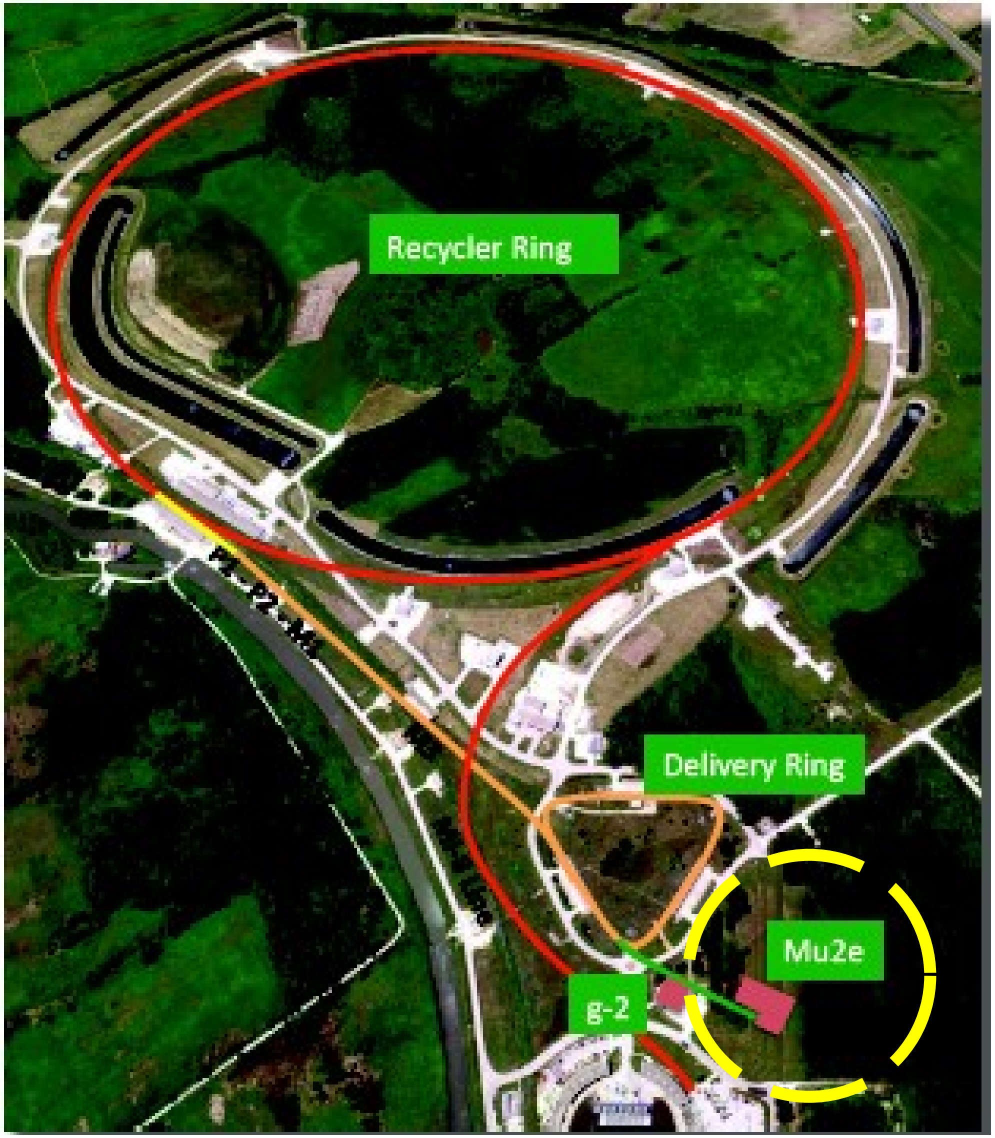
$$R_{\mu e} = \frac{\Gamma(\mu^- + N \to e^- + N)}{\Gamma(\mu^- + N \to \text{all captures})}$$

SINDRUM II @PSI (2006, Au)*:

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

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

The Mu2e experiment



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

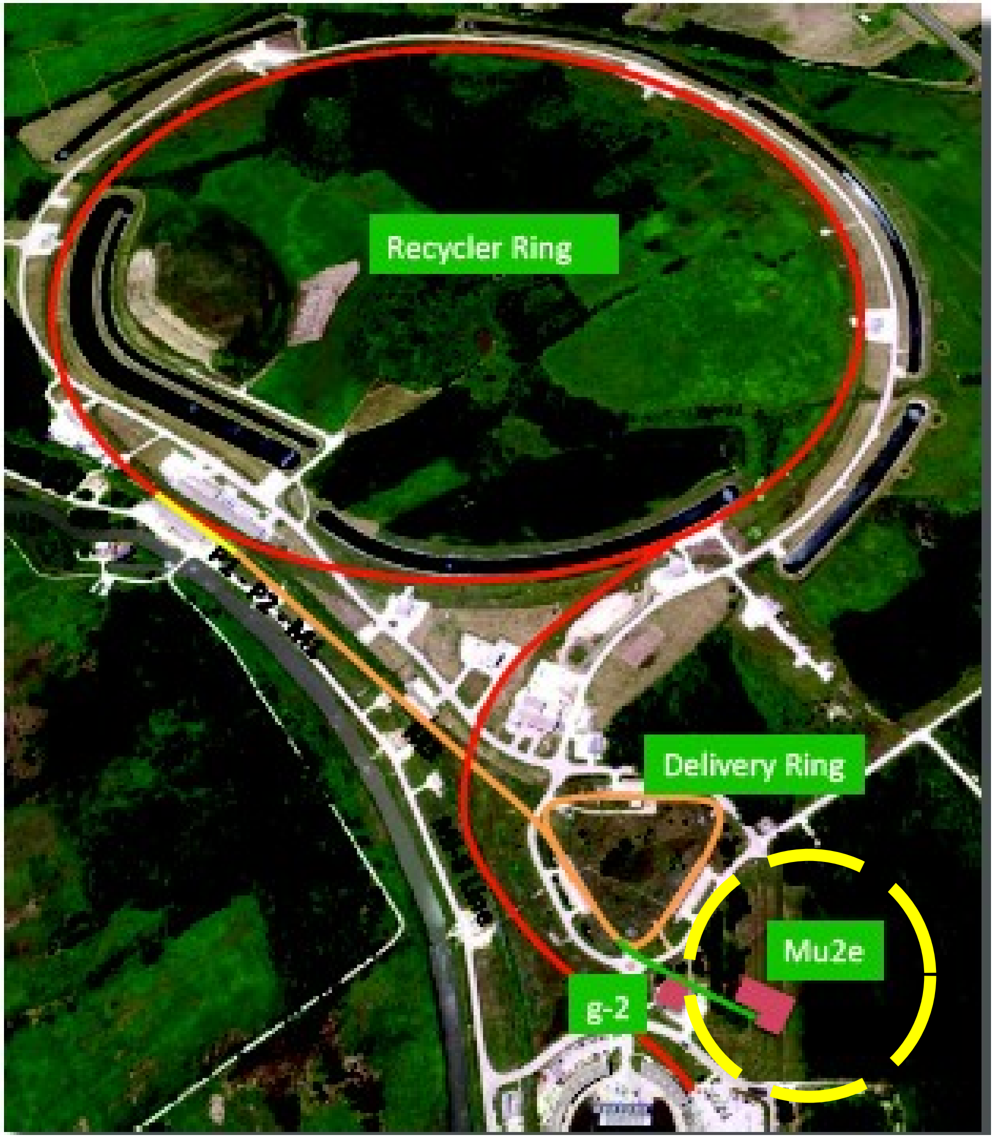
How to compare results for different targets?

Poster 253 (D. Hitlin):

"The (Z,A) Dependence of Muon-to-Electron Conversion"

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

The Mu2e experiment



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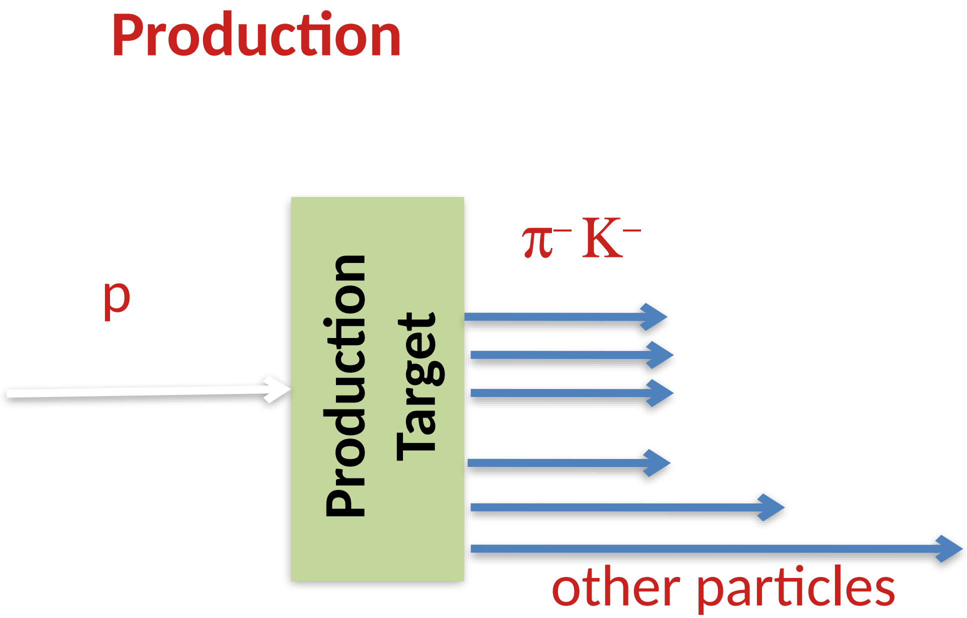
SINDRUM II @PSI (2006, Au)*:

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

Mu2e aims to **observe** some conversion electron.
This would be a clear evidence for **New Physics** since **SM prediction** is $\mathbf{10^{-49}}$-$\mathbf{10^{-52}}$.

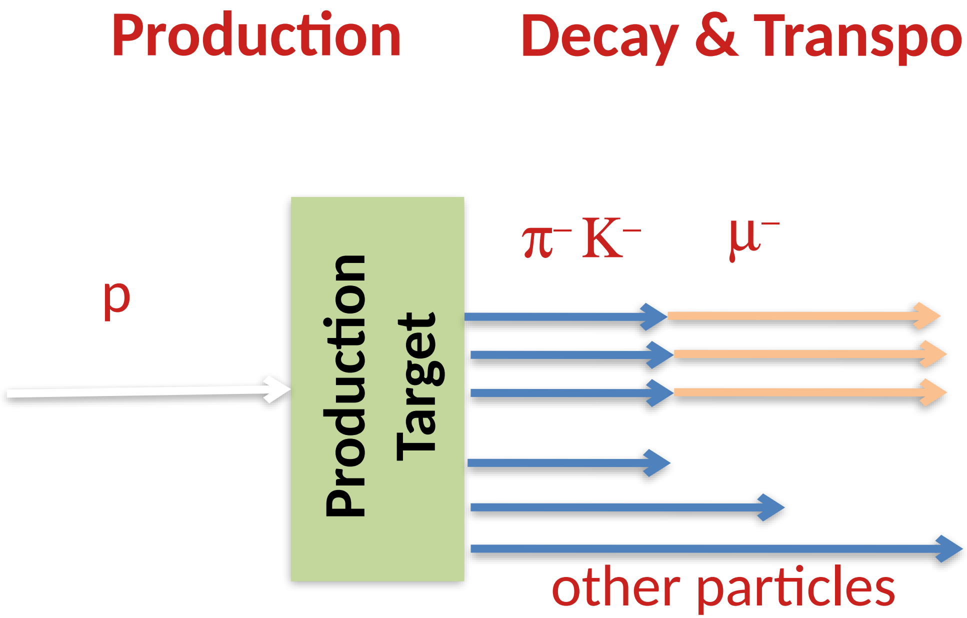
*W. Bertl et al., Eur.Phys.J. C47,337 (2006)

The Mu2e experiment concept



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

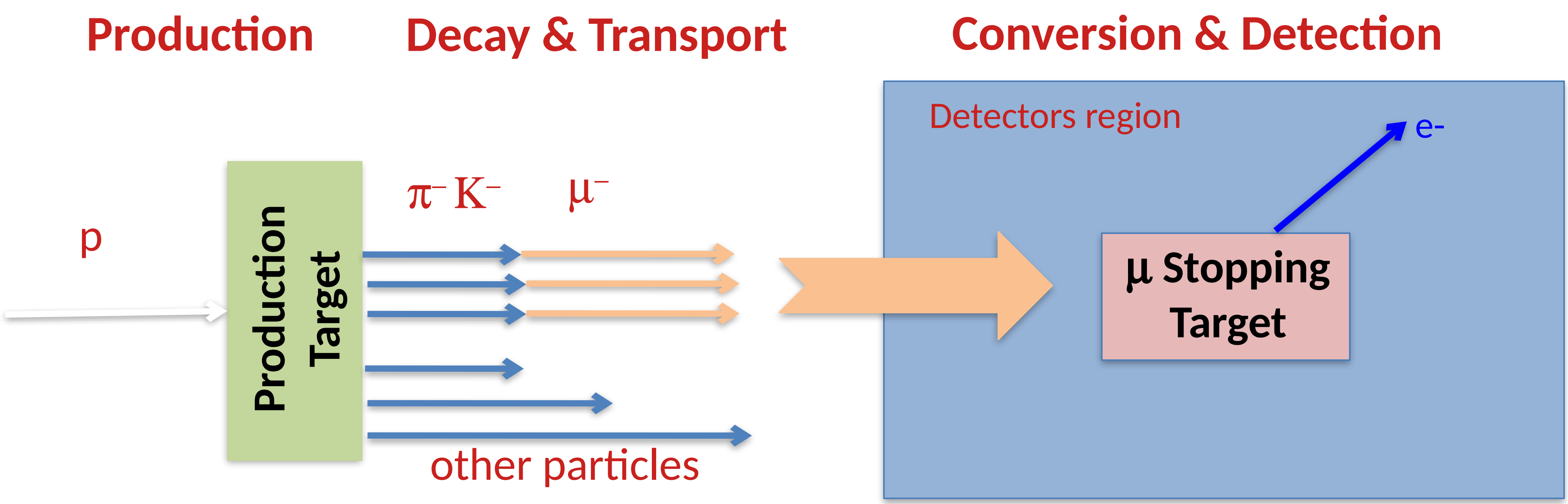
The Mu2e experiment concept



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

2) Transport negative particles of the wanted momentum

The Mu2e experiment concept



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

2) Transport negative particles of the wanted momentum

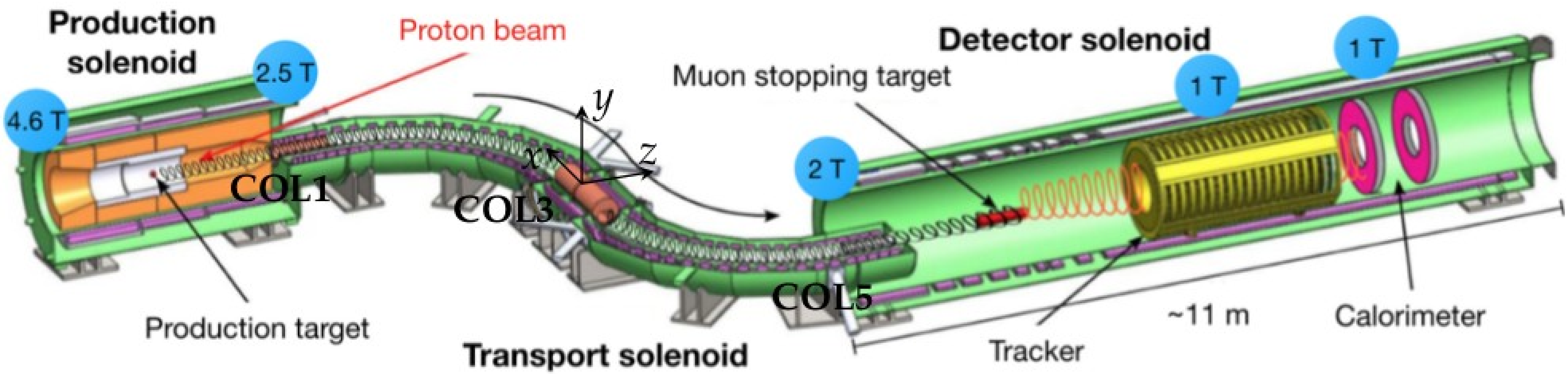
3) Stop muons and search for the monochromatic electron

How to get a 10^4 improvement?

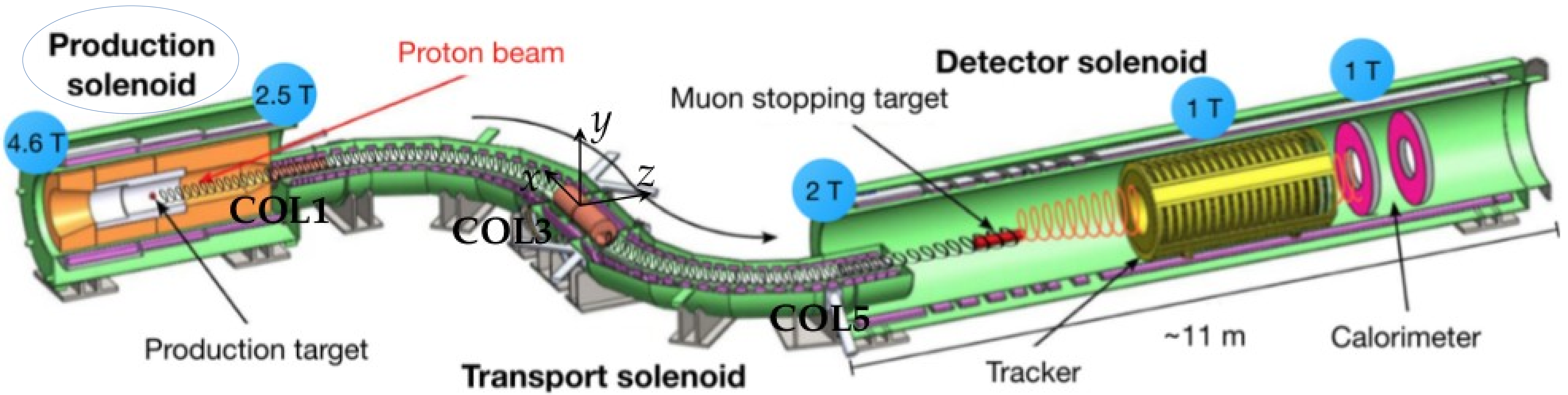
- **STATISTICAL ERROR:**
  (Collect lots of stopped muons):
  - **High intensity proton beam** → **Radiation hardness**
  - **High collection efficiency** → **Magnetic focusing**

- **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**

The Mu2e experimental apparatus: the 3 solenoids

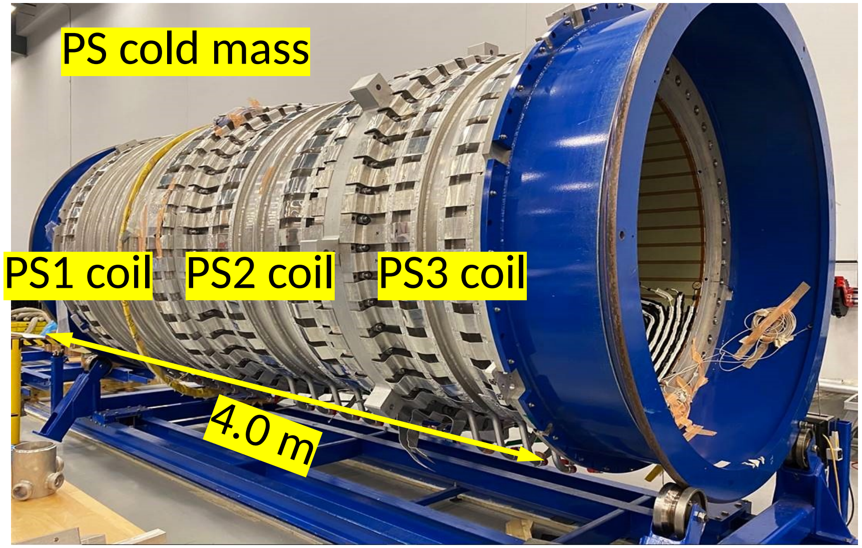


The Mu2e experimental apparatus: the 3 solenoids

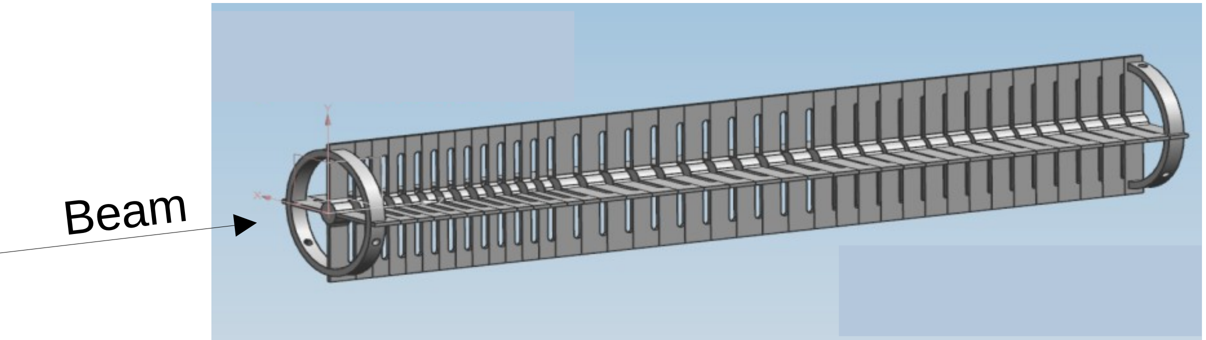


1) Production Solenoid:

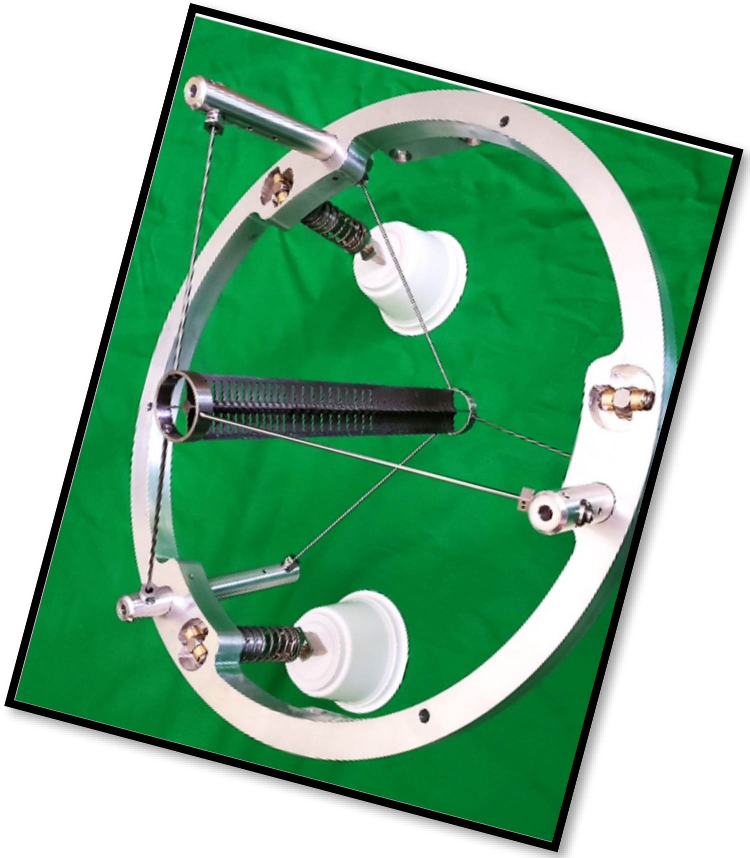
- 8 GeV pulsed proton beam enters from right
  hits the tungsten target
- a graded magnetic field reflects low
momentum particles downstream



The Tungsten Production target



Target Geometry



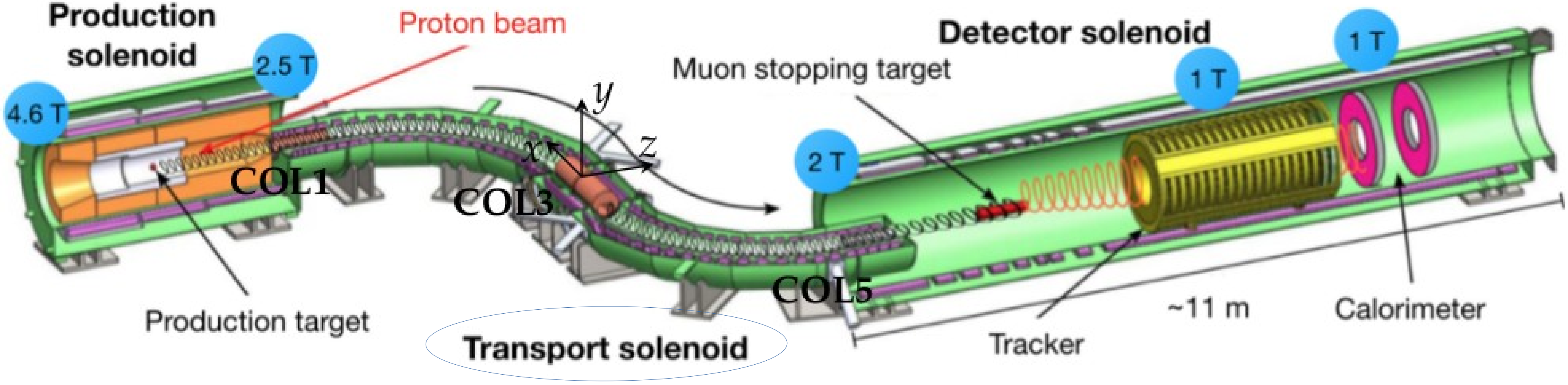
The production target with its support structure

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

Gaps and fins to help heat dissipation

Maximum T~1100 ^{o}C

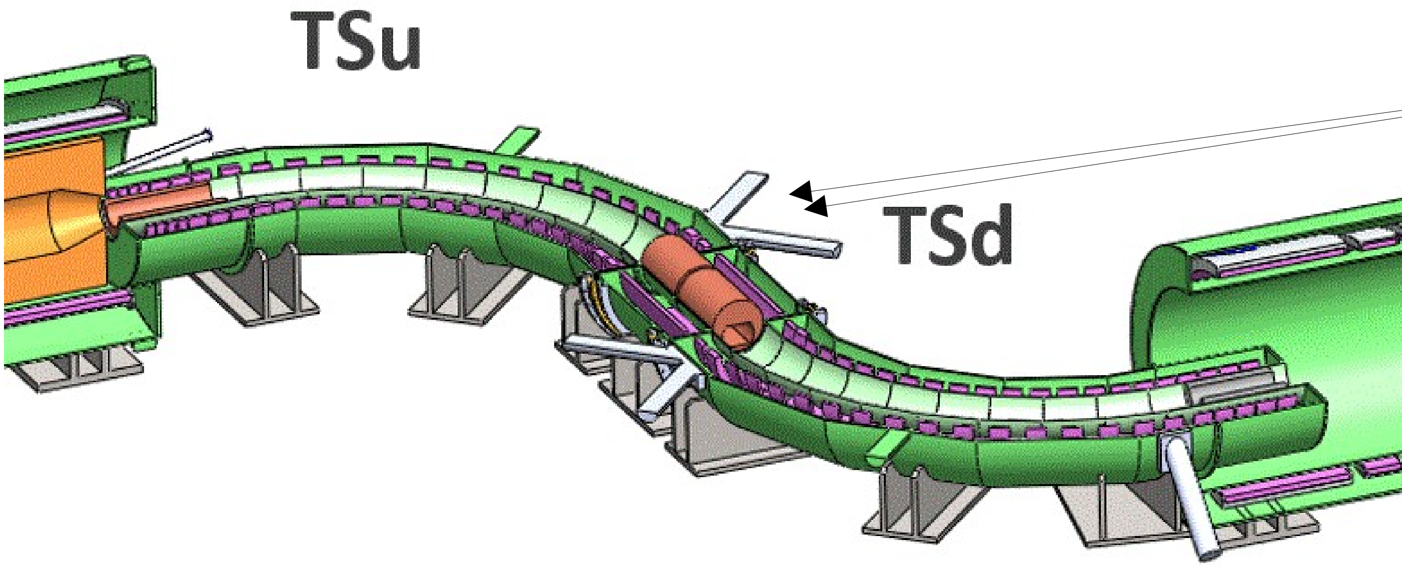
The Mu2e experimental apparatus: the 3 solenoids

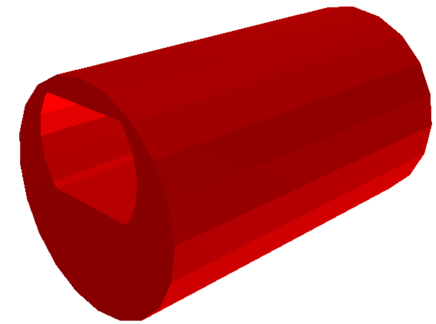


2) Transport solenoid:

- 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



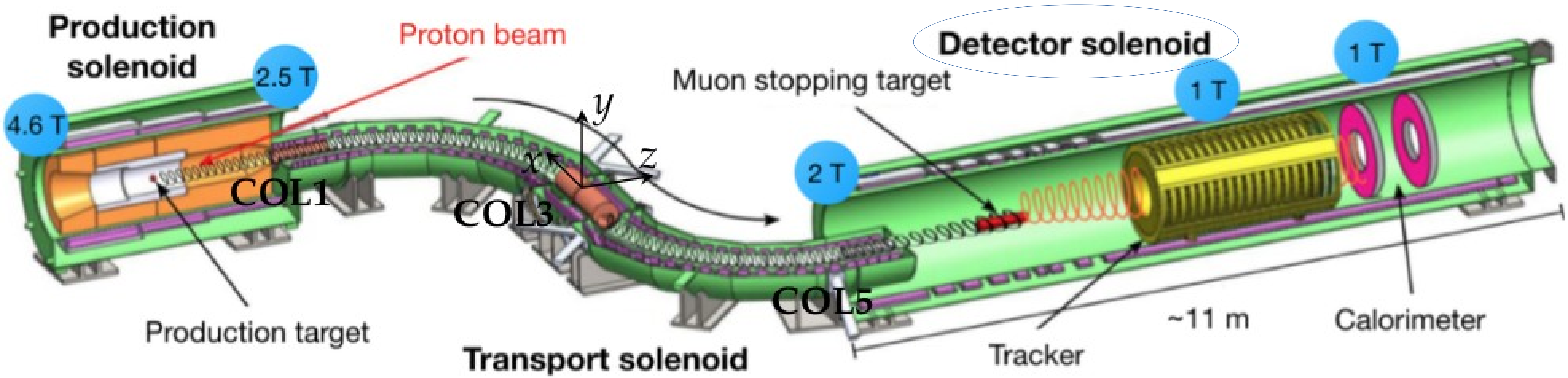


Swivel collimator

Downstream (Tsd) and Upstream (Tsu) cold masses and cryostats

Tsu assembled

The Mu2e experimental apparatus: the 3 solenoids

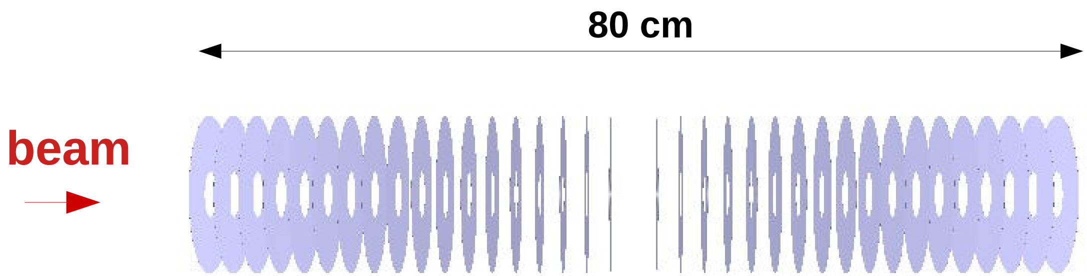


3) Detector Solenoid (11 coils):

- 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

A DS coil ready for cold test

The Aluminum muon stopping target



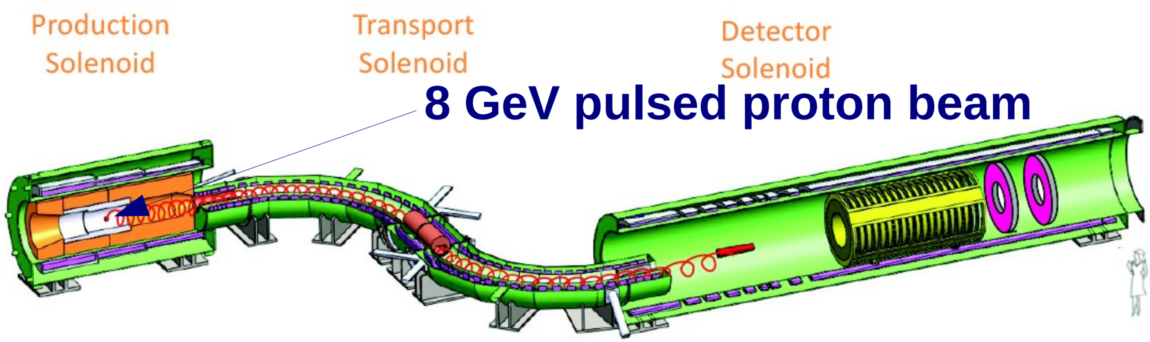
The stopping target:

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

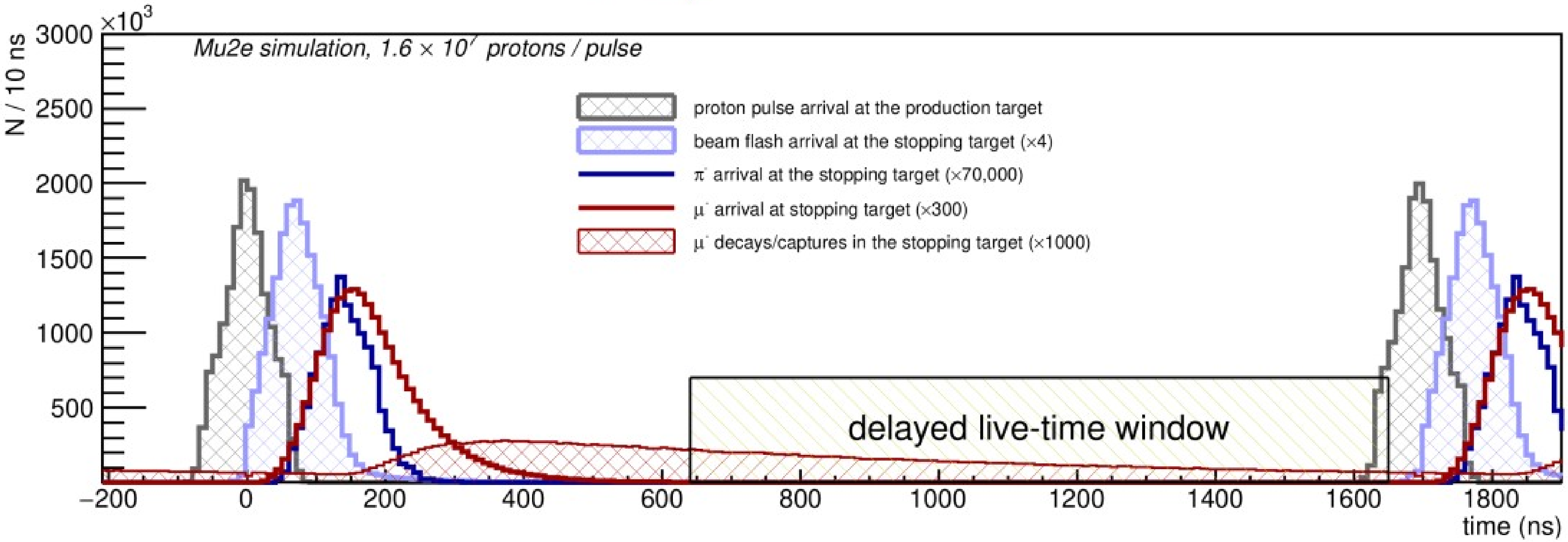
The segmented geometry helps to reduce electron energy losses (improving momentum resolution)

The central hole helps to reduce radiation in the detector

The pulsed proton beam structure



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



Pulsed Proton Beam Structure:

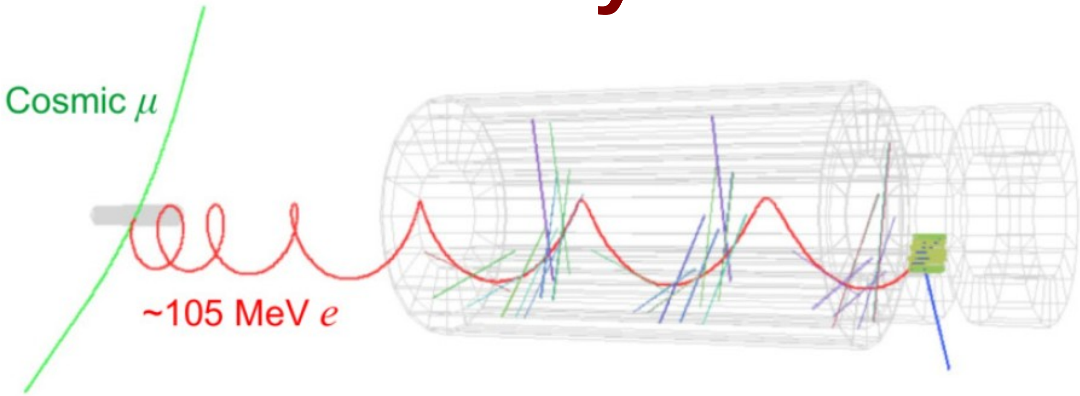
Beam period: 1.695 μs ~ $2\tau_{\mu}^{Al}$ (τ_{μ}^{Al} = 864 ns)

Delayed analysis window to suppress prompt backgrounds

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

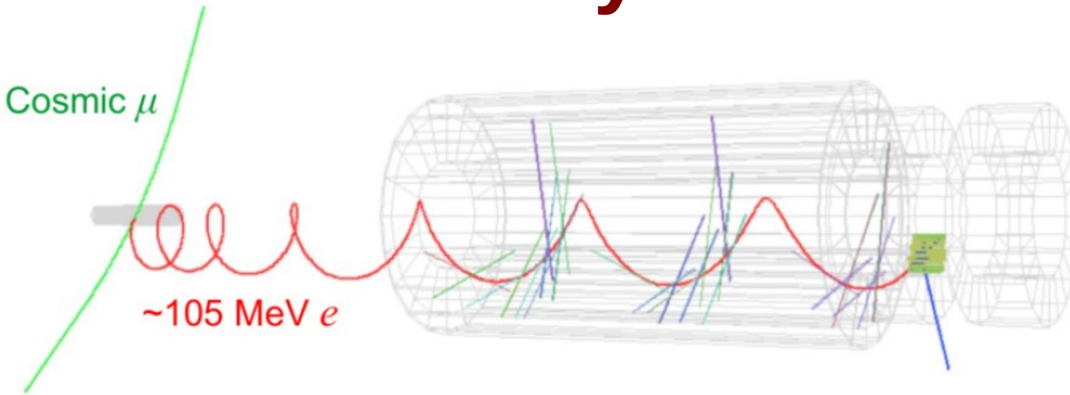
(measured by an extinction monitor downstream of the beam)

The Cosmic Ray Veto



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

The Cosmic Ray Veto



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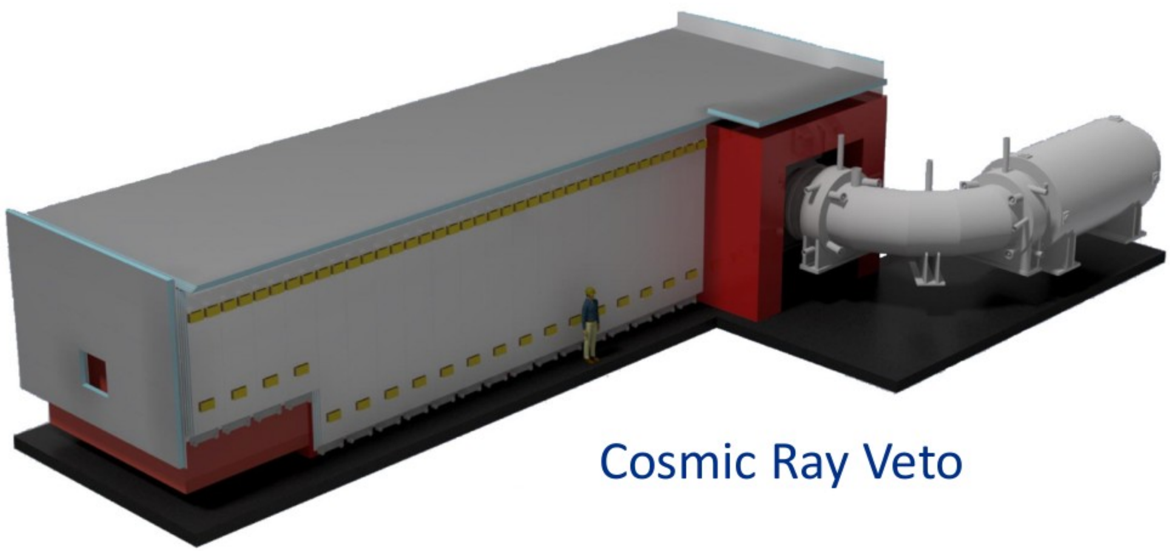
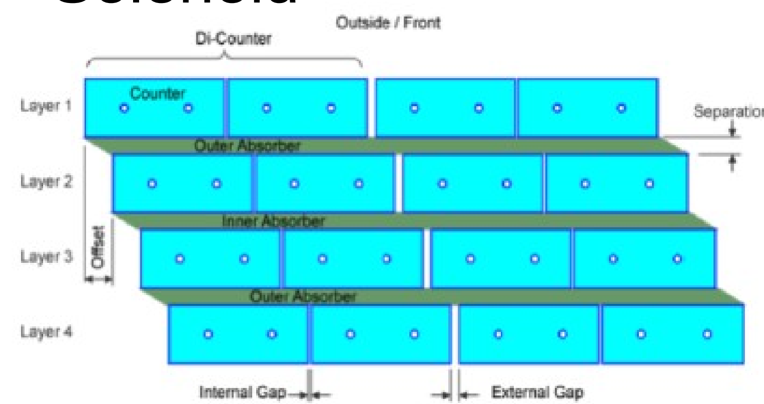


<u>Cosmic Ray Veto:</u>

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

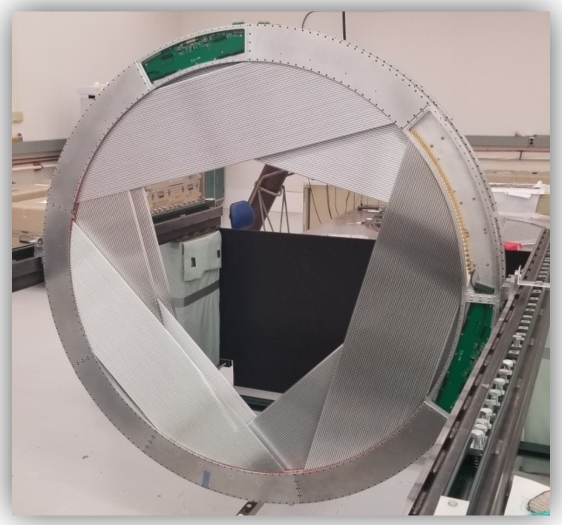


3 of 4 layers provides a veto efficiency >99.99%

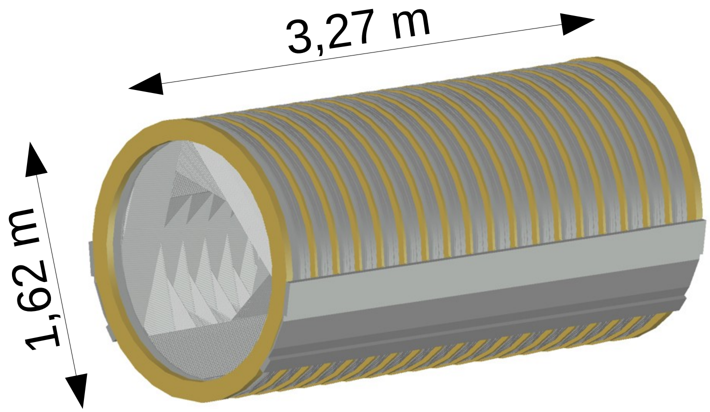
The straw tube tracker

straw tube

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



1 tracker plane
(6 rotated straw panels)



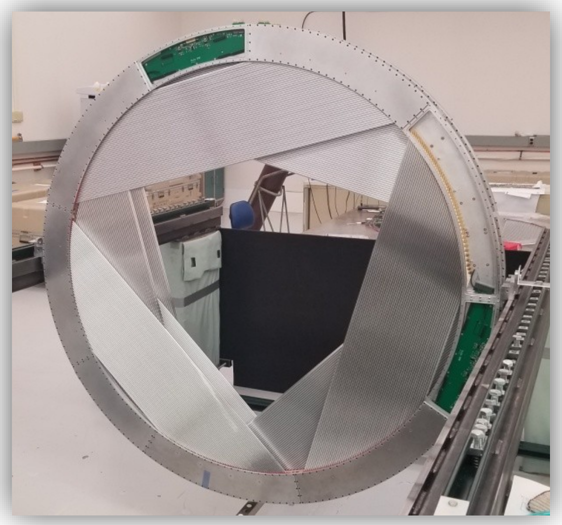
Tracker structure

18 stations of 12 panels
(~21000 straw tubes)

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



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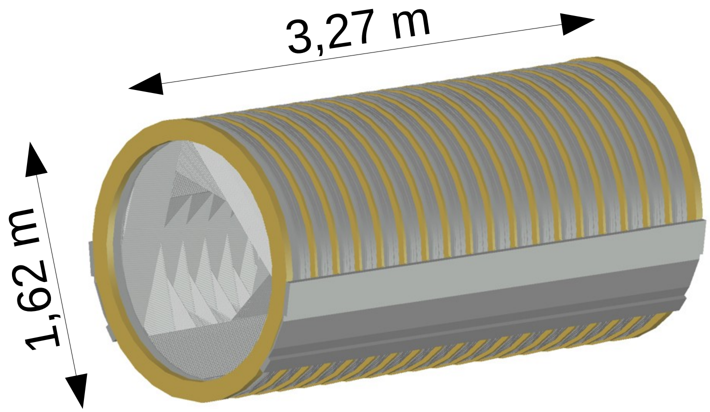

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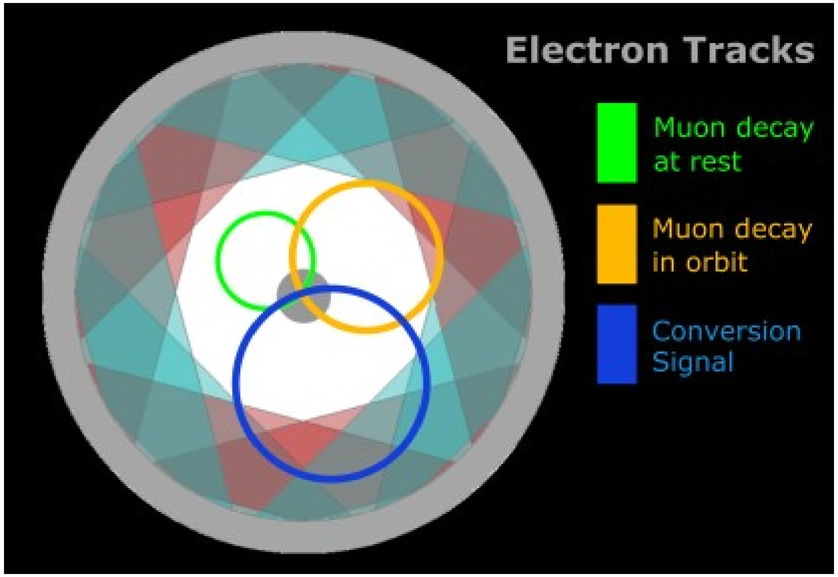
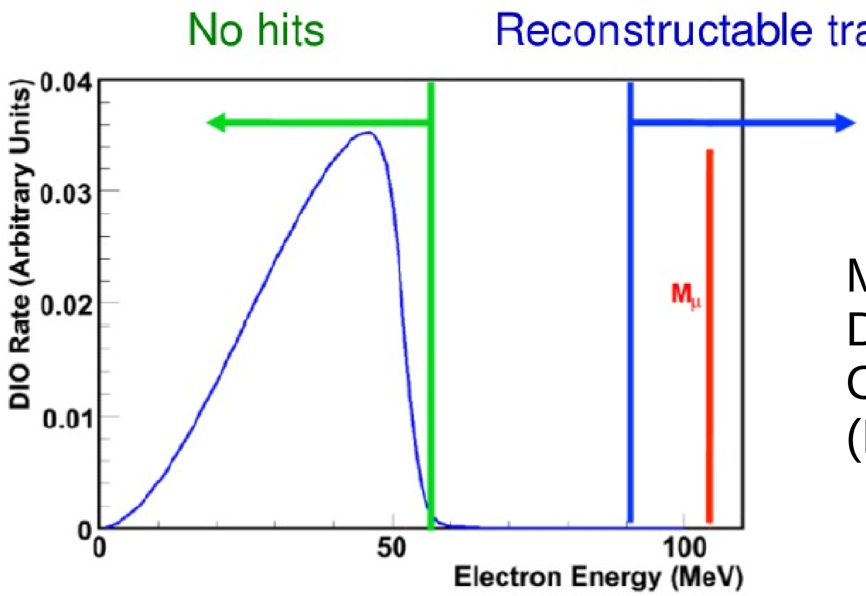
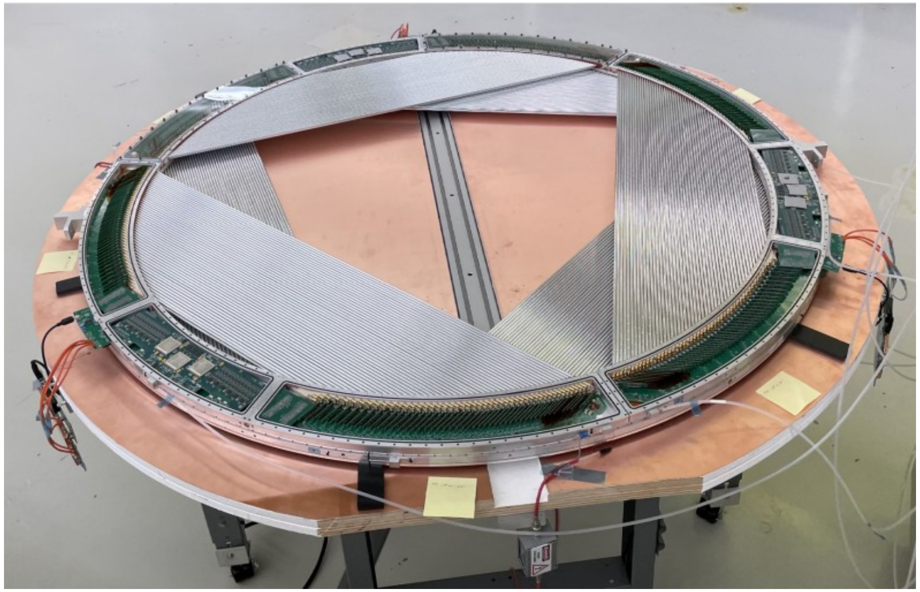


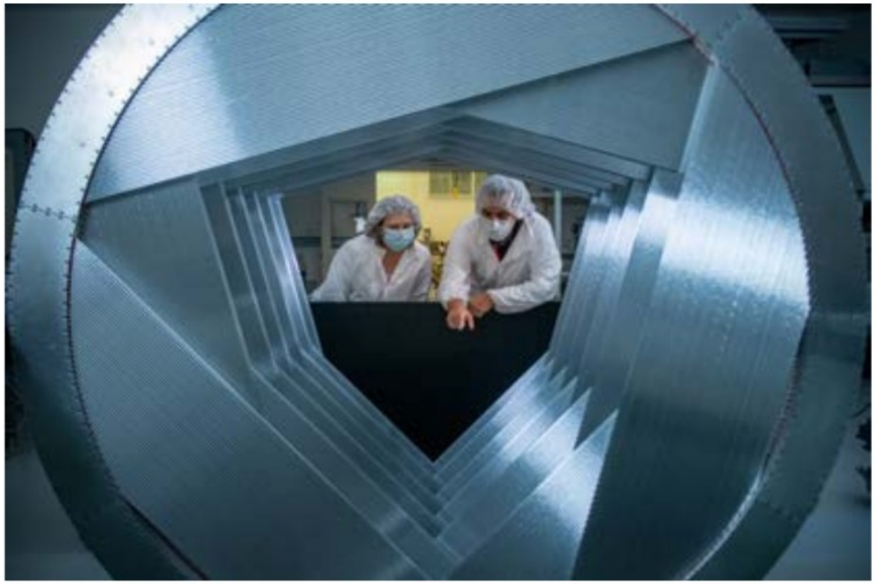


Muon Decays In Orbit (DIO)

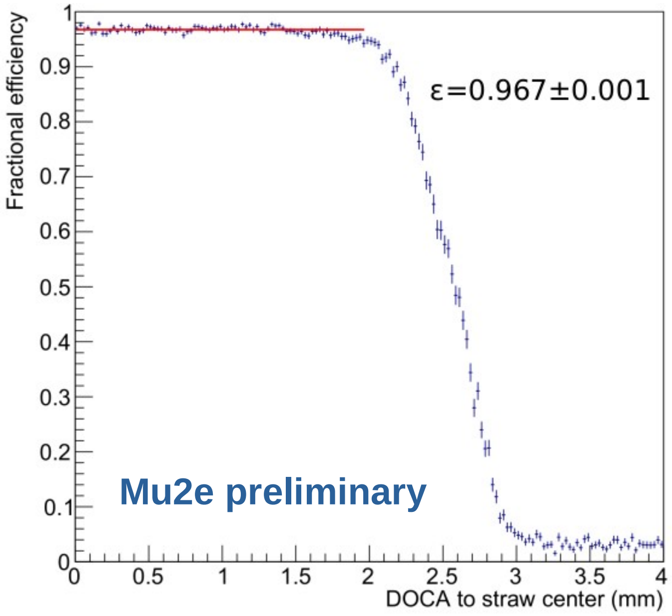
Tracker not sensitive to particles with p_T<80 MeV/c (beam flash and most of DIOs)

Tracker performances from cosmic test



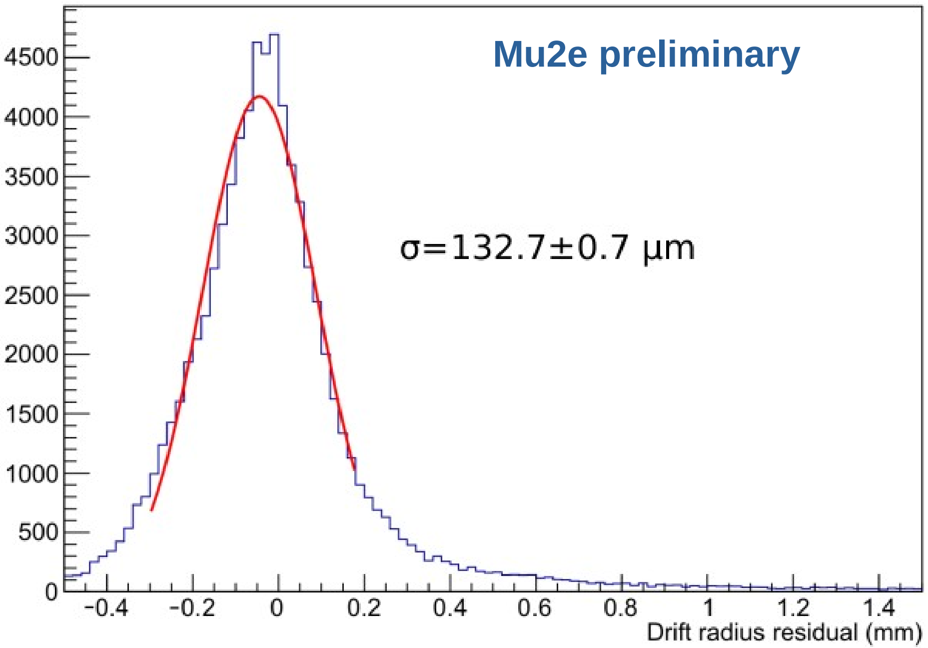


Hit efficiency

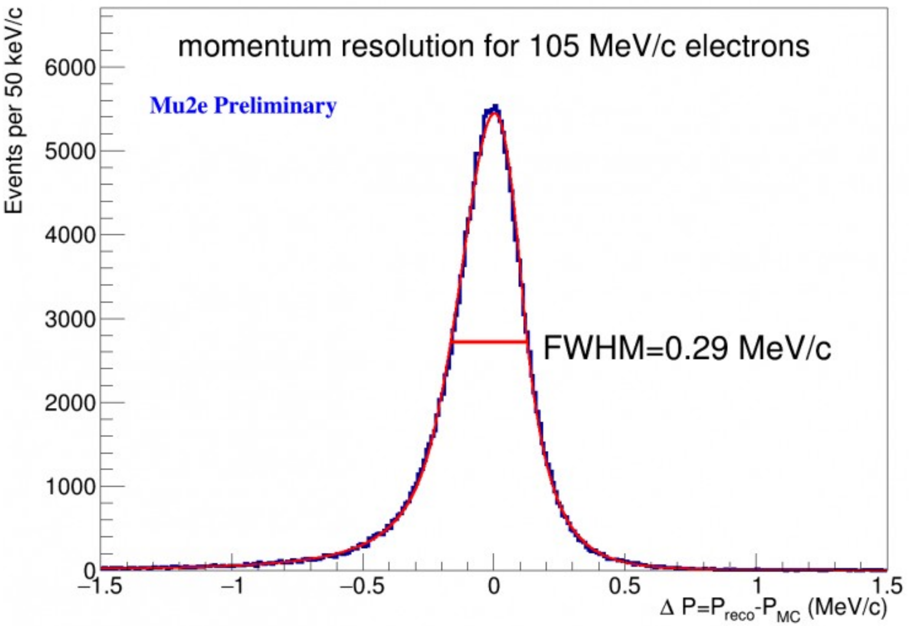


VST straw efficiency

Transverse coordinate resolution

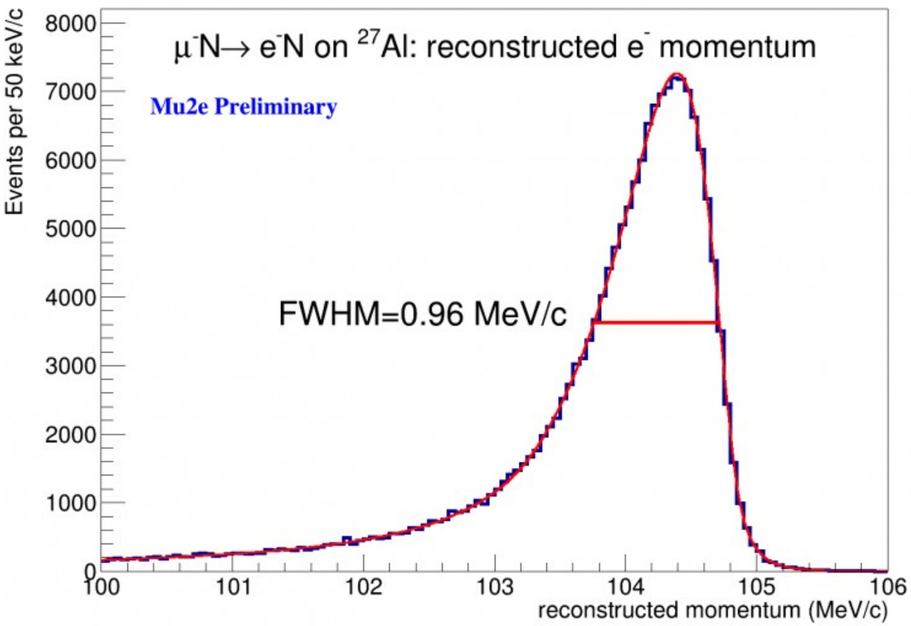


Expected CE reconstructed momentum



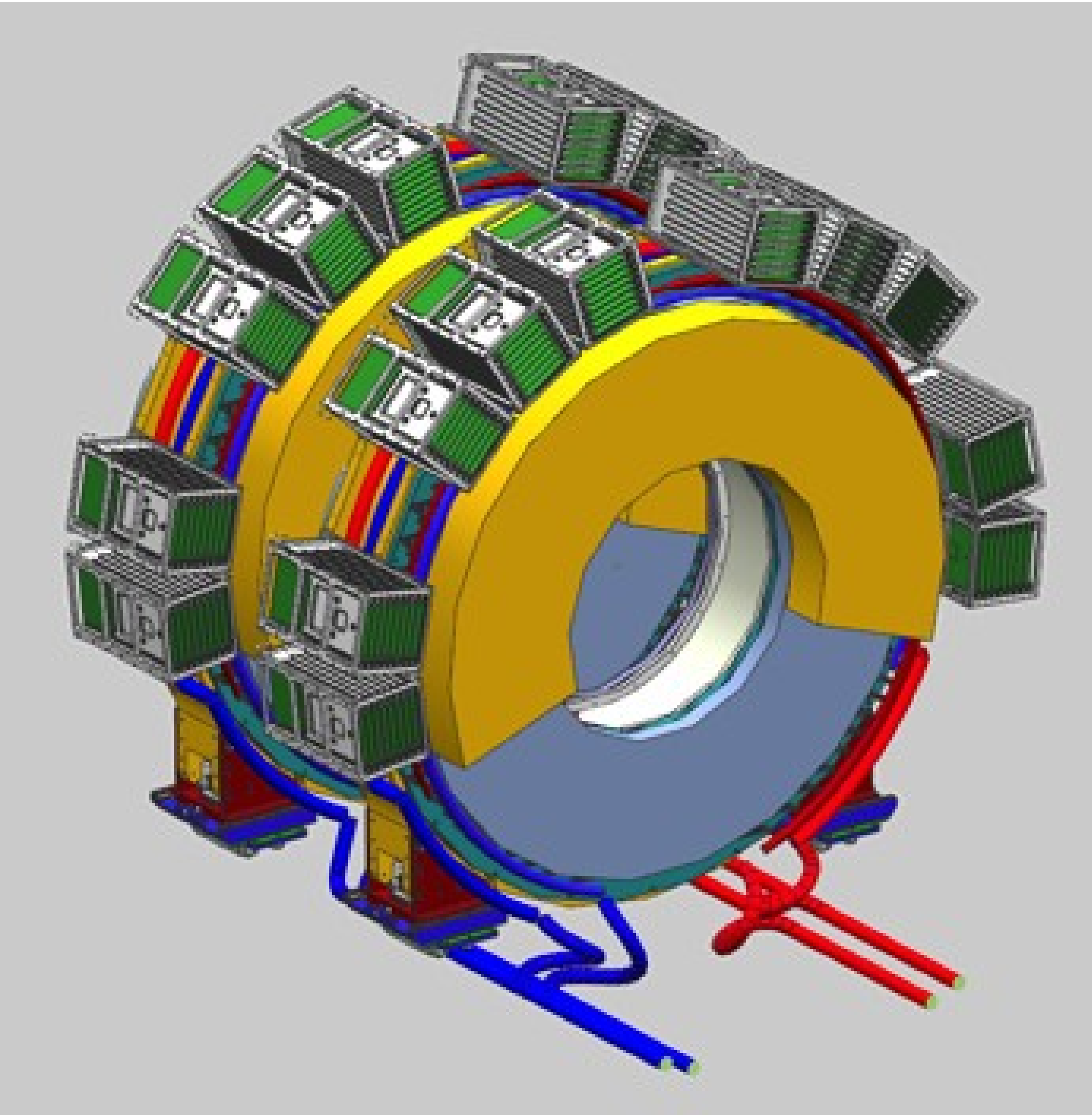
CE: Conversion Electron

Reconstructed-True momentum at tracker entrance

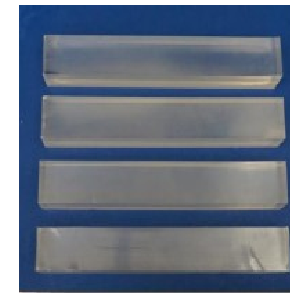


CE reconstructed spectrum: the left tail is due to energy losses

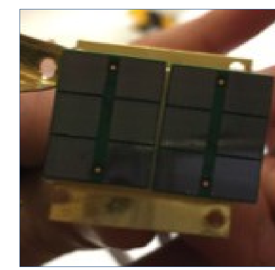
The electromagnetic calorimeter



Geometry
2 disks spaced by 70 cm
inner radius: 37.4 cm
outer radius: 66 cm



Active material:
pure CsI crystals
674 crystals/disk
$3.4 \times 3.4 \times 20\ cm^3$

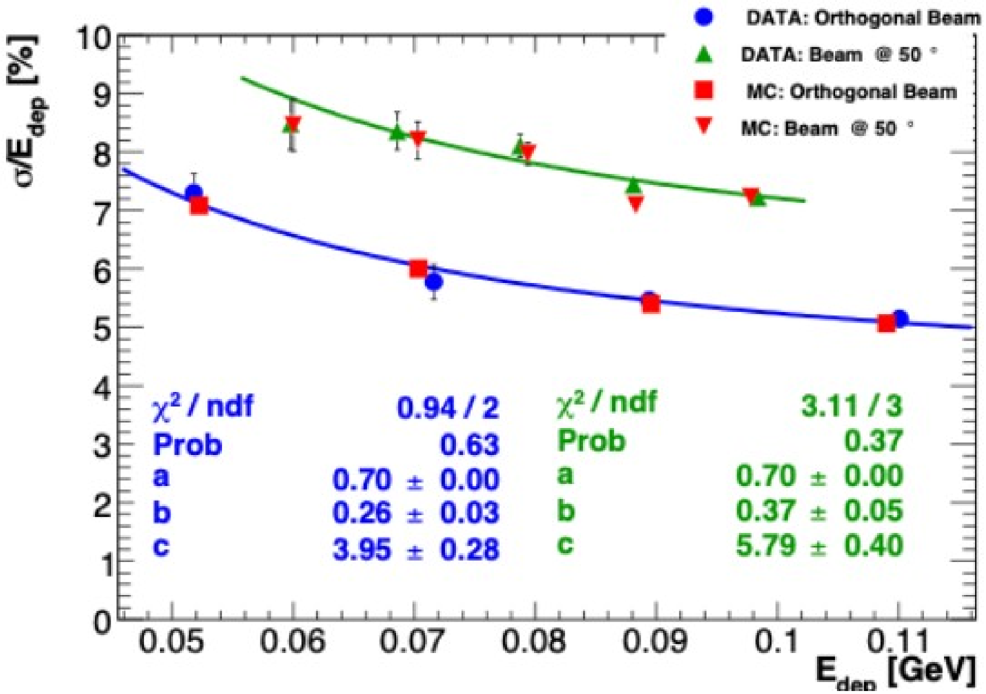


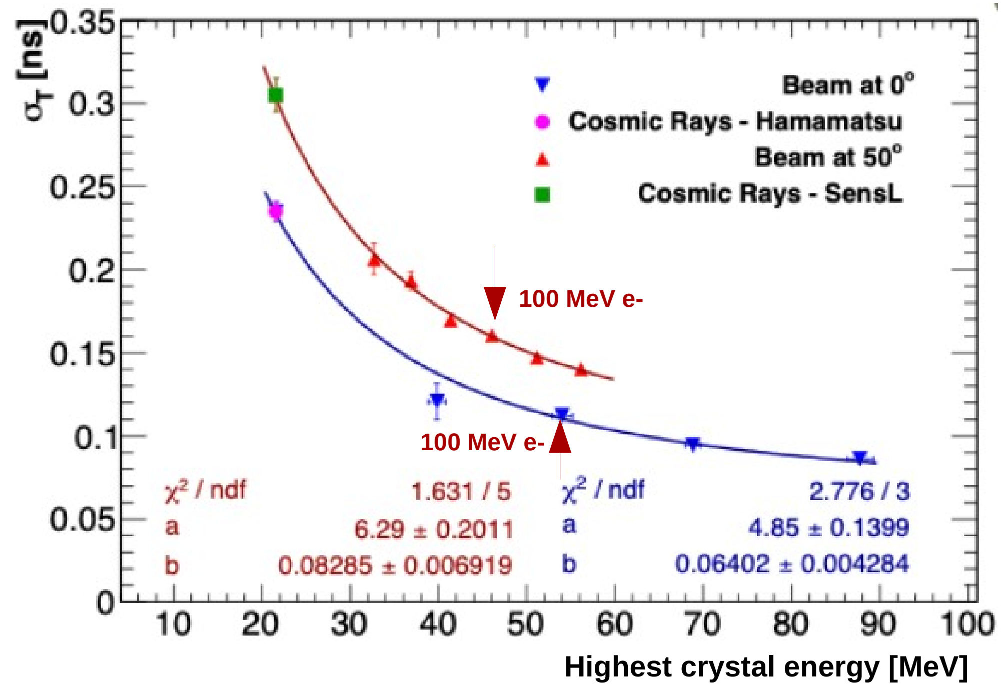
Sensors:
Arrays of 6 SiPMs
2 arrays/crystal
$14 \times 20\ mm^2$ each

Readout electronics:
Preamplifiers on sensors back
Voltage control and Waveform Digitizers in crates around disks

Calibration/monitoring system:
Fluorinert liquid in front of each disk
Laser and electronic pulses

Calorimeter performances

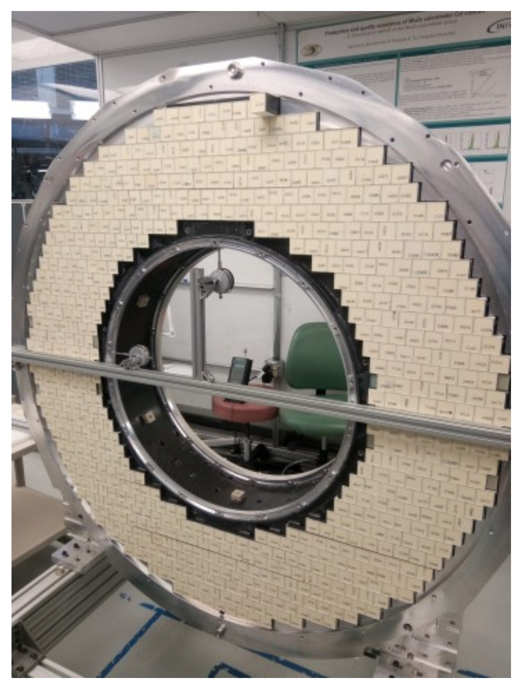




<u>2017 test beam results for 100 MeV e-:</u>

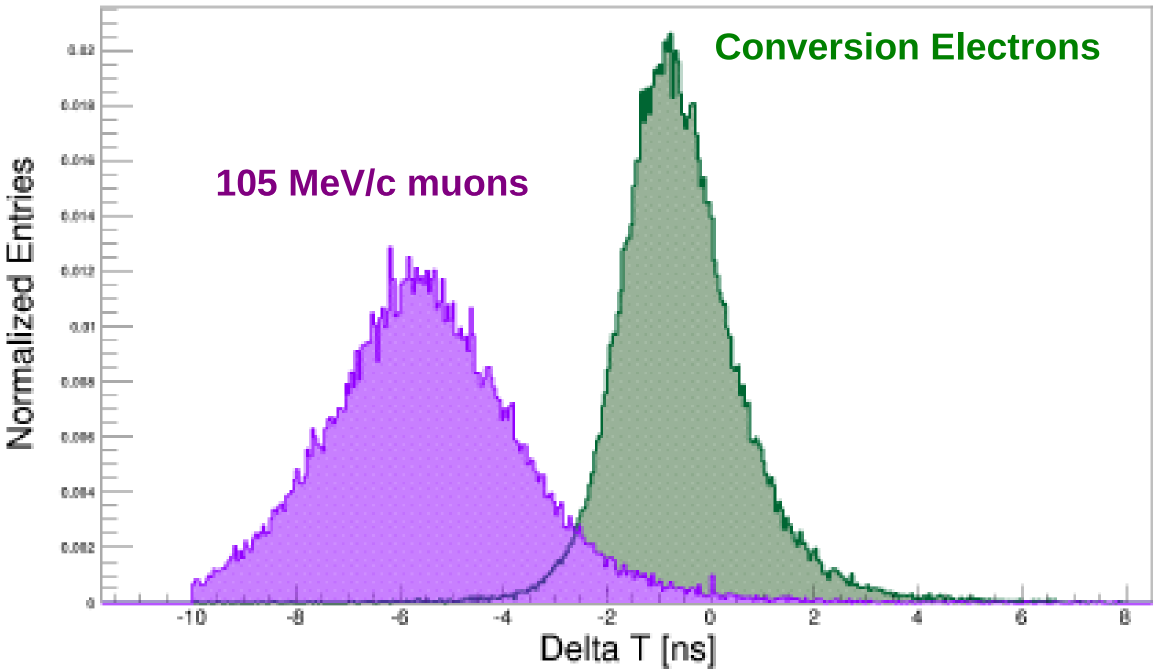
Impact angle:	0°	50° (CE peak)
Energy resolution	5.4%	**7.3%**
Time resolution*	160 ps	**230 ps**

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

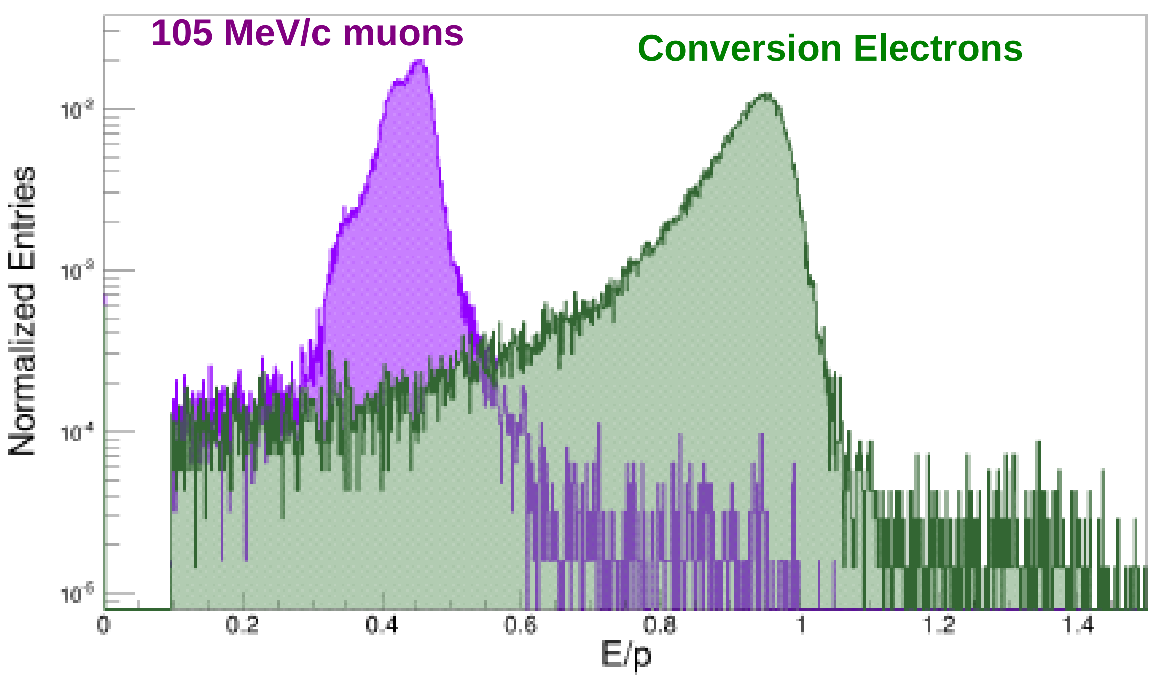


First ECAL disk assembled

Particle identification



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



Calorimeter cluster energy / track momentum

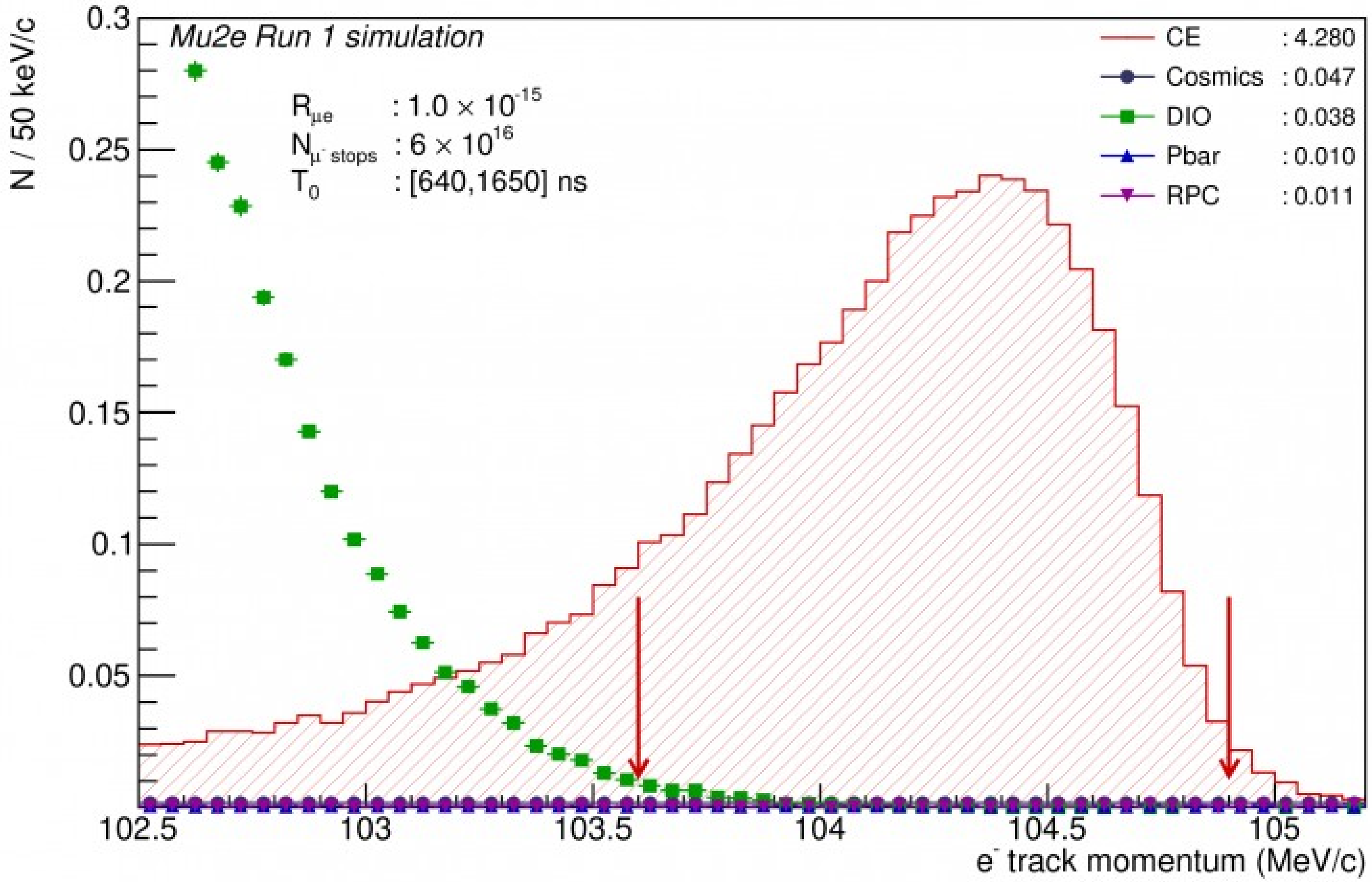
An ANN selection makes the cosmic muons background negligible wrt the cosmic electrons irriducible background

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", submitted to MDPI Universe in October 2022 (38 pages) http://arxiv.org/abs/2210.11380*

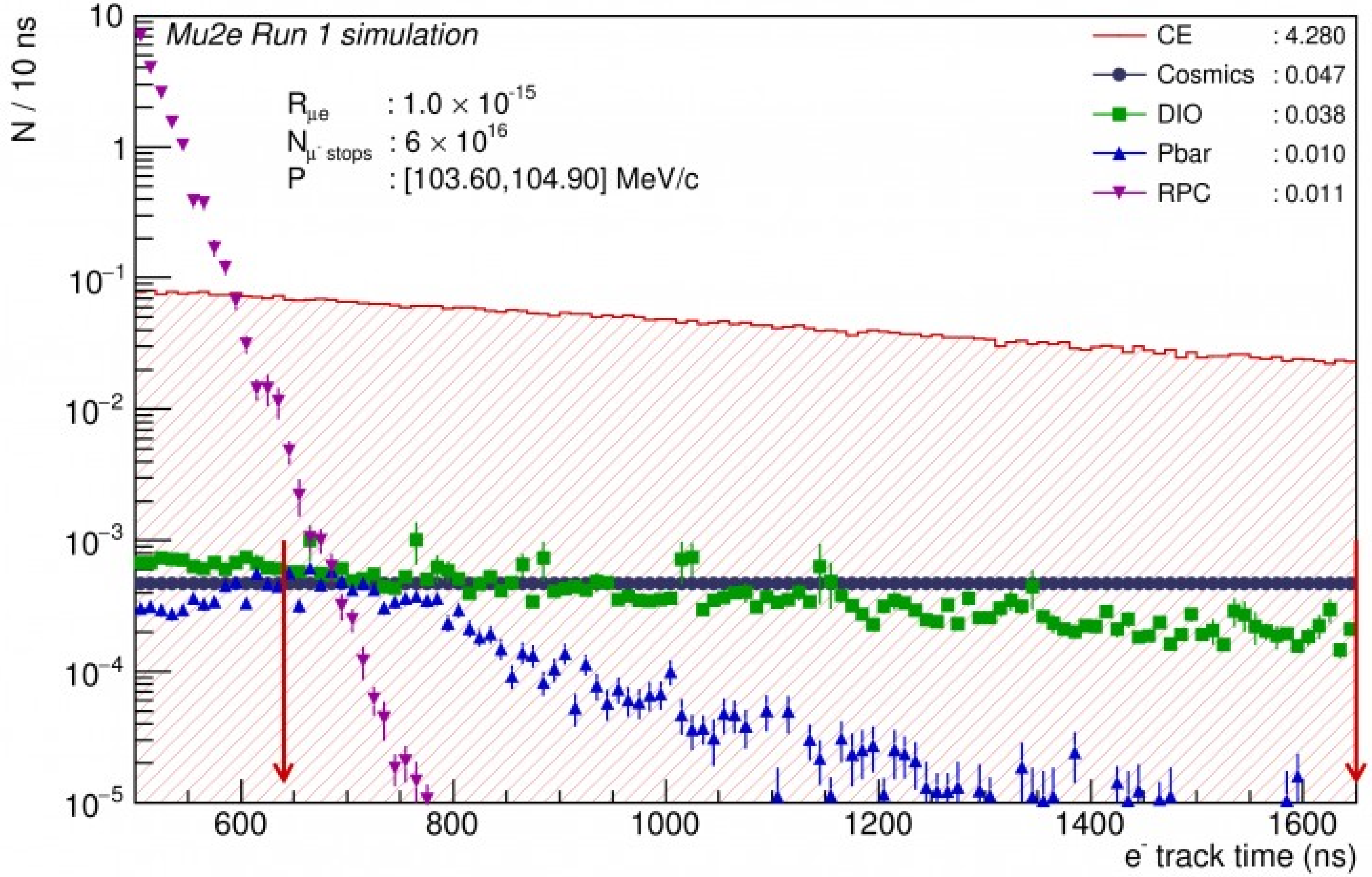
Electron momentum



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!

Summary and outlook

- Mu2e vertical slice tests and simulation are confirming the design detector performances. Construction of the beam line, solenoids and detectors is well under way

- First run in 2026-2027 will allow to improve SINDRUM II limit by x1000

- The second run, starting in 2029 after accelerator shutdown for neutrino beam upgrade, will have an higher beam intensity and then a better signal/cosmic background ratio. The goal will be to improve by x10000 Sindrum II limit.

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

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

  with a Run 1 SES on $R_{\mu e+}$ of $4 \cdot 10^{-16}$ (current limit: $1.7 \cdot 10^{-12}$ (Sindrum II '98))

- Mu2e II experiment is expected to have a sensitivity x10 better using higher intensity and lower energy proton beam