Status and perspectives of CLFV at Mu2e

E. Diociaiuti on behalf of the Mu2e collaboration
Laboratori Nazionali di Frascati dell'INFN

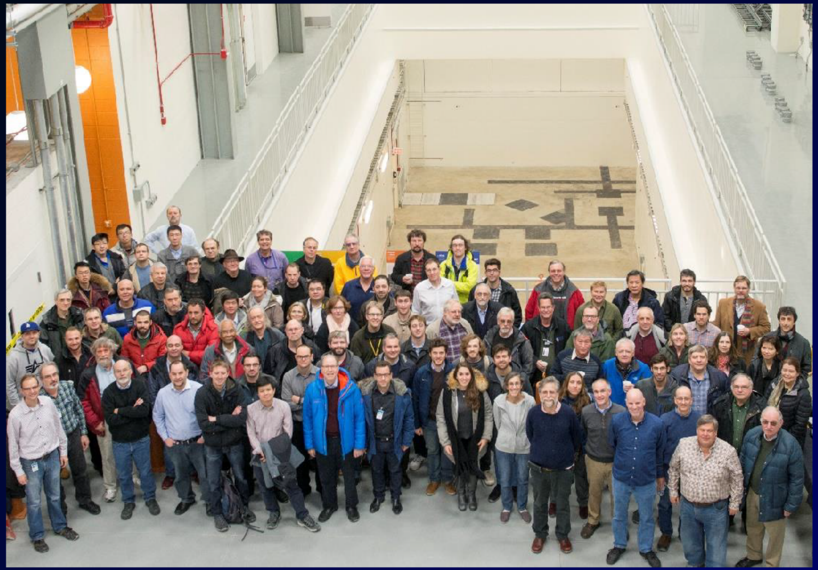
WIFAI 2023, 11/8-10/2023

The collaboration

The Mu2e Collaboration

Over 200 scientists from 38 institutions

The Mu2e Collaboration



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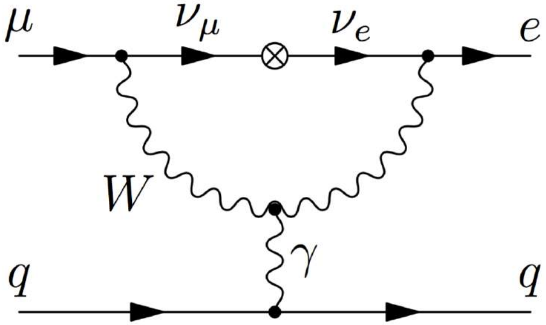
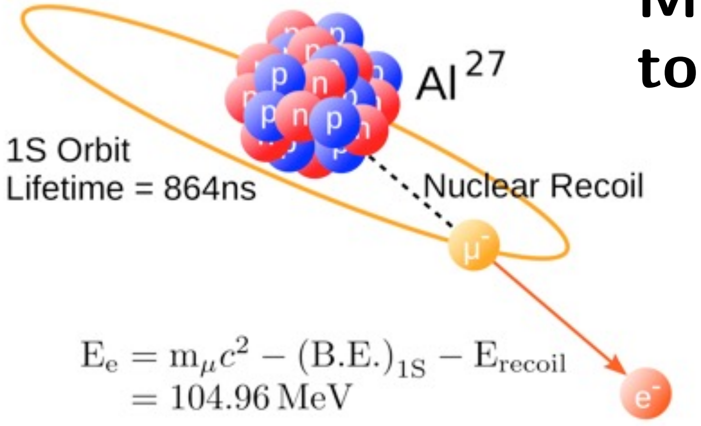
Novosibirsk State University/Budker Institute of Nuclear Physics ● INFN Pisa ● Purdue University ● University of South Alabama ● Sun Yat Sen University ● INFN Trieste
University of Virginia ● Yale University

What is the μ-e conversion ?

Muons converts into electron in presence of a nucleus $\mu^- N \rightarrow e^- N$

- μ-e process is an example of Charged Lepton Flavor Violating (CLFV) process
- CLFV processes are forbidden in the Standard Model
- Assuming neutrino oscillation they are allowed BUT **negligible with BR$\sim 10^{-50}$**
- Many SM extensions enhance the rates to observable values
- **Any observation of a signal will be a clear evidence of New Physics**





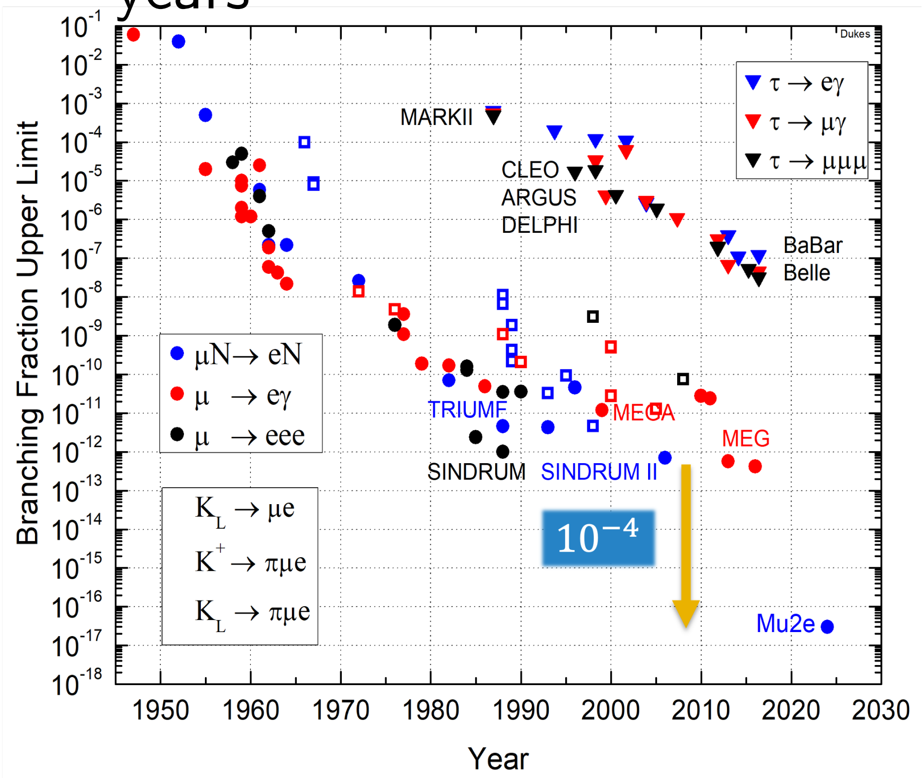
Mu2e measures the rate of μ-e conversion normalized to the μ captures in nuclei:

$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z) \rightarrow e^- + N(A,Z))}{\Gamma(\mu^- + N(A,Z) \rightarrow \nu_\mu + N(A,Z-1))} \leq 8 \times 10^{-17} (@\ 90\%\mathrm{CL})$$

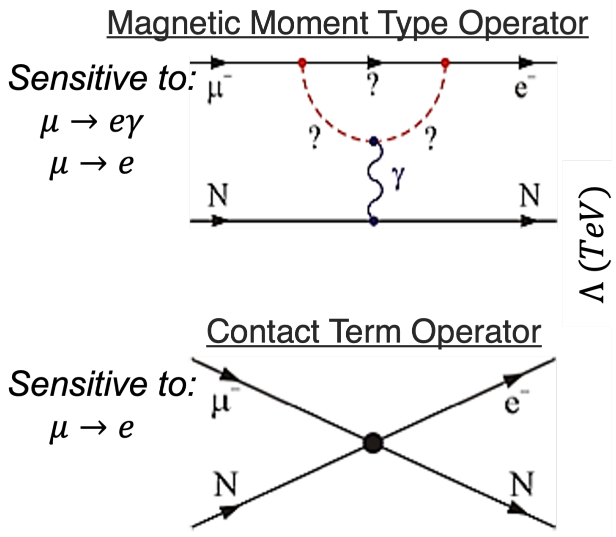
Final Goal: **Improve by 4 orders of magnitude the current best limit set by Sindrum-II ($R_{\mu e} < 7\times10^{-13}$)**

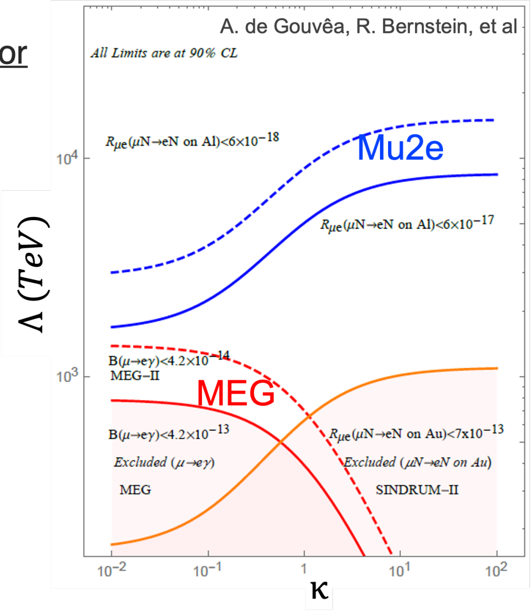
CLFV in muon sector

- Several searches involving different kinds of particles
- **CLFV in μ sector represents the most sensitive probe:**
  - High intensity beams & Clean topologies
- Three different searches in muon CLFV: $\boldsymbol{\mu \rightarrow e\gamma}$**, mu3e and muon conversion**
- Two muon conversion experiments (Mu2e and COMET) will start taking data in few years



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





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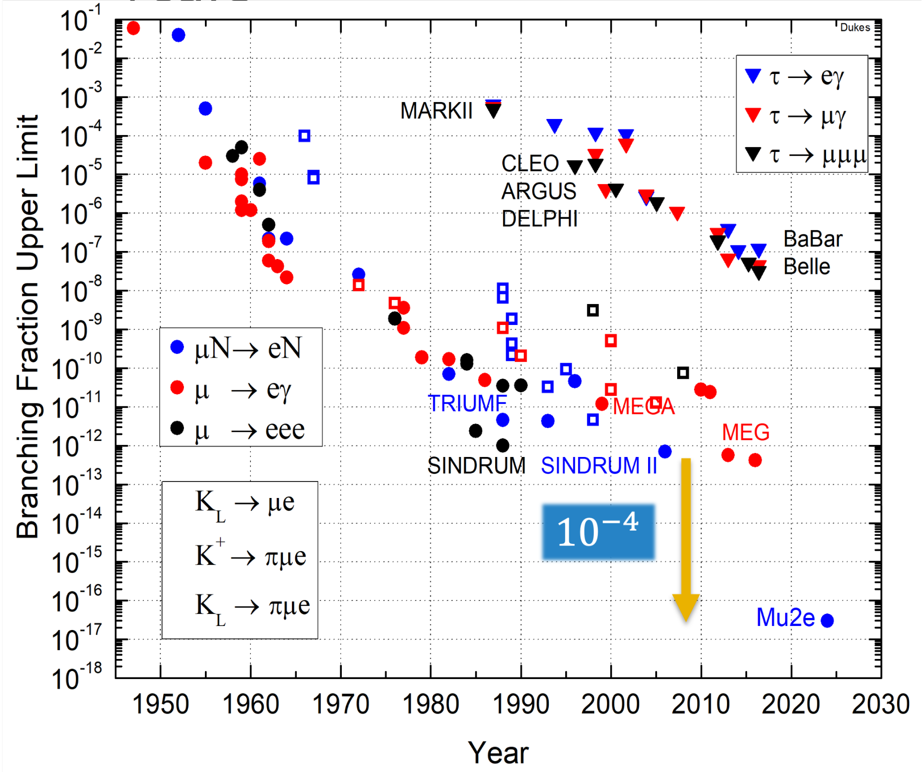

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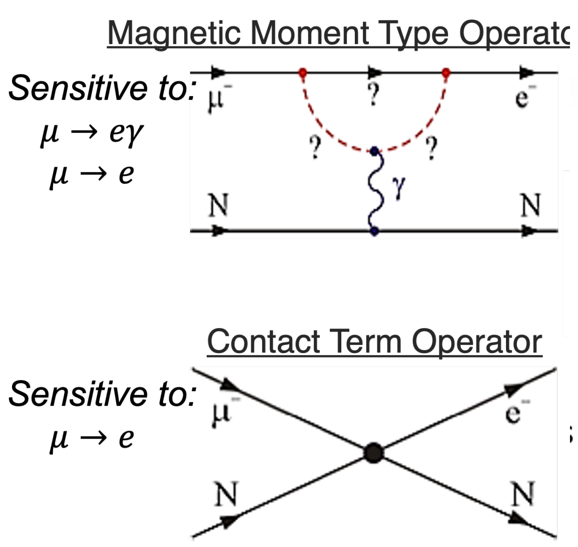
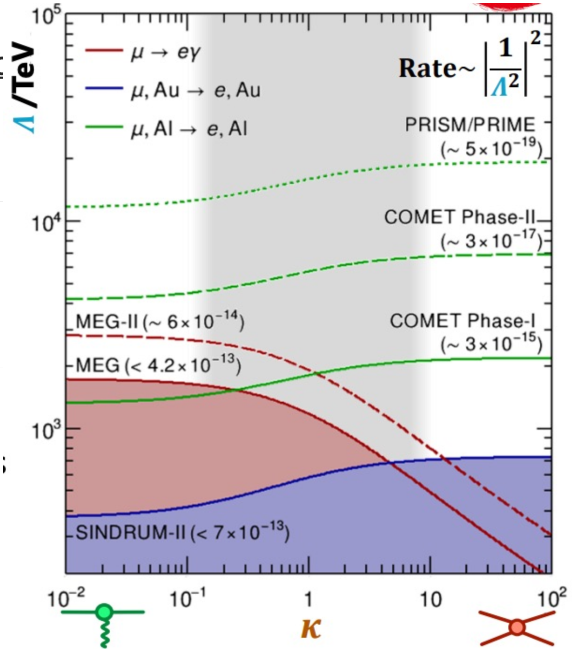




Road for a factor 10000 improvement

- **Production**:
  - High Intensity beam (proton on target)
  - negative muon selection and transport via solenoidal system

- **Pulsed beam**
  - beam pulsed structure comparable to bound muon lifetime

- **extinction requirement**
  - no protons outside of "beam-pulse" , 10^{10} rejection

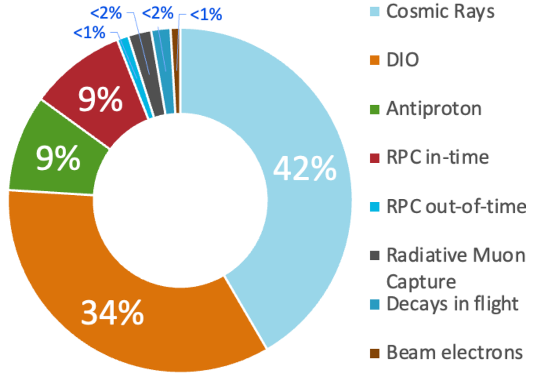
- High momentum resolution detector, PID and Full CR rejection
  → fight DIO falling background .. Identify monoenergetic electrons
  → No CR Fakes

The muon conversion experimental technique

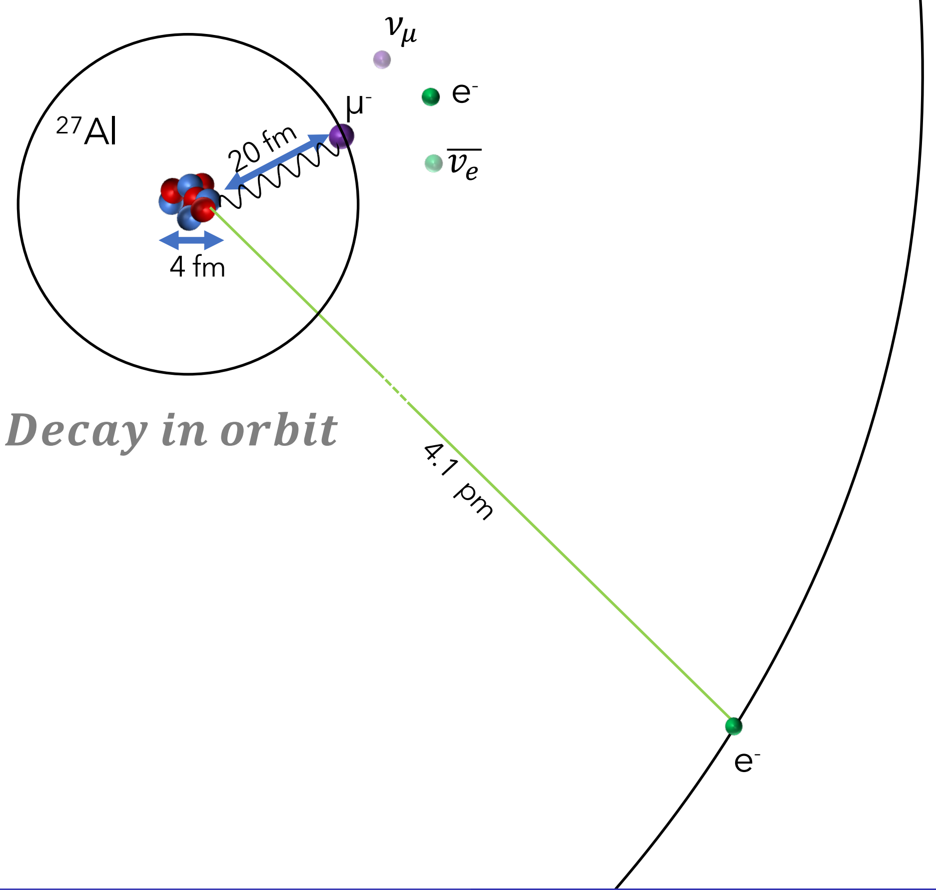
- Low momentum negative μ beam (<100 MeV/c)
- High intensity pulsed rate (10^{10} μ/s stopped)
- Stopped μ is trapped in the atomic orbit and quickly cascades in the 1s state
- μ undergoes 3 processes:
  - ✓ Decay in orbit (39 %) $\mu^- N \rightarrow e^- \nu_\mu \overline{\nu_e}\, N$ **(background)**
  - ✓ Nuclear capture (61%)
  - ✓ Conversion ($<10^{-13}$)

- In the conversion case, monoenergetic electron produced
  → Look for excess at ~105 MeV/c

- background to be kept at sub-event level (~0.1):
  - decay in orbit (DIO),
  - anti-proton processes,
  - conversion-like electrons due to cosmic rays.



Al Muonic atom lifetime : 826 ns



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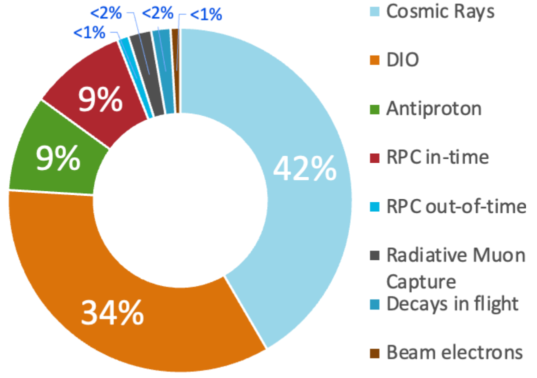

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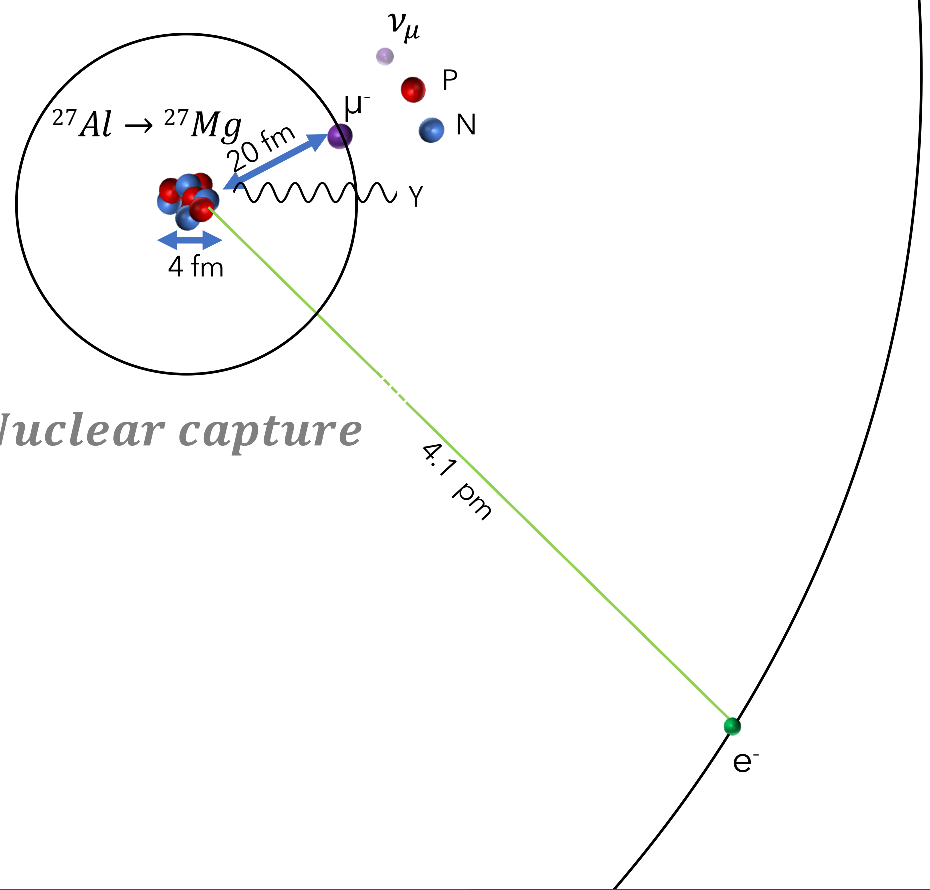

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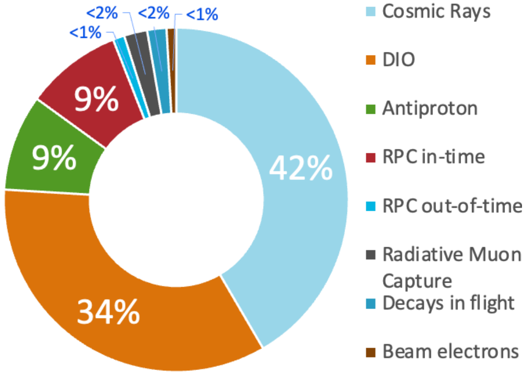

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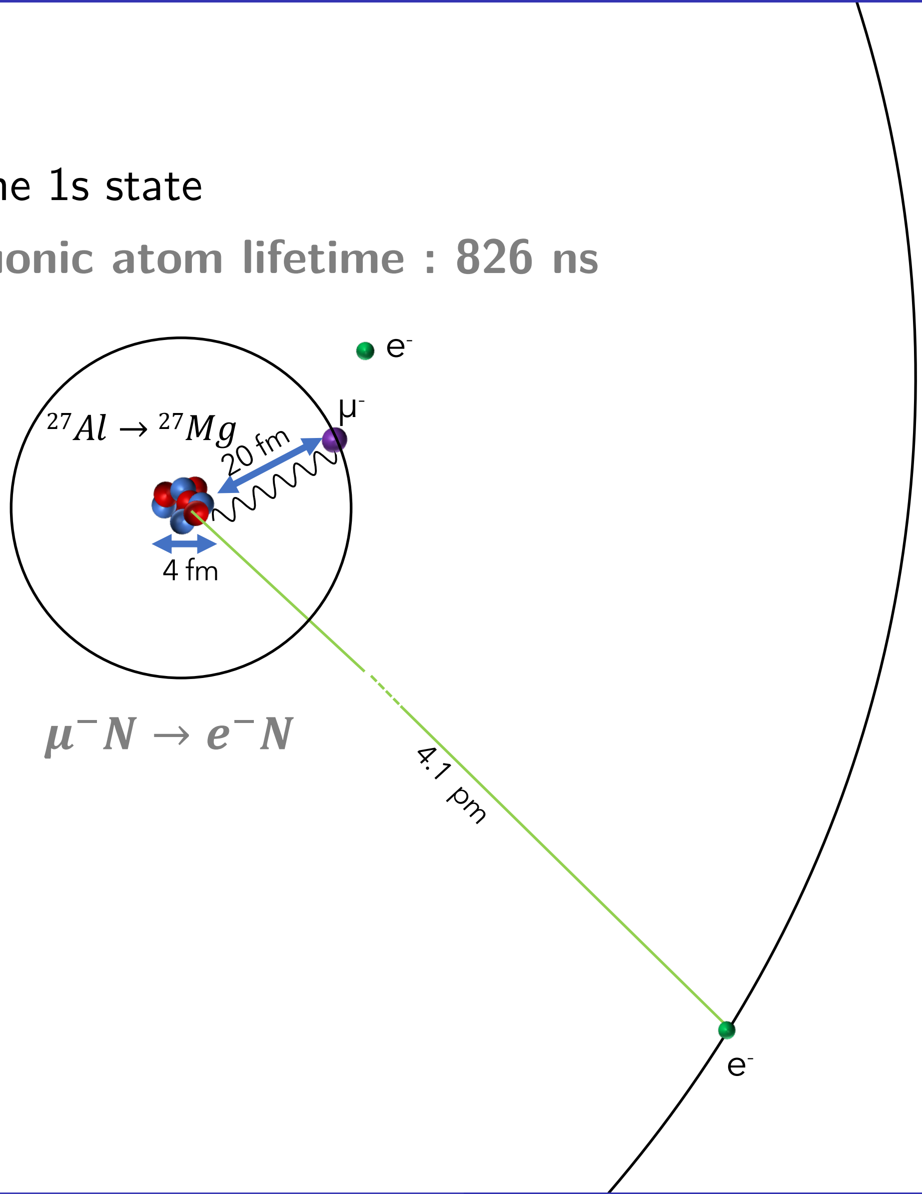
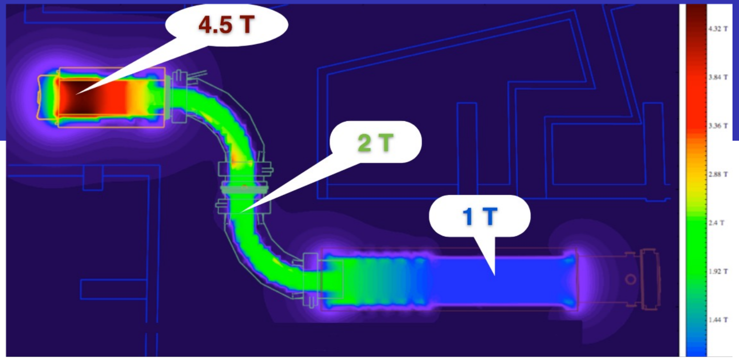


The Mu2e experiment: setup

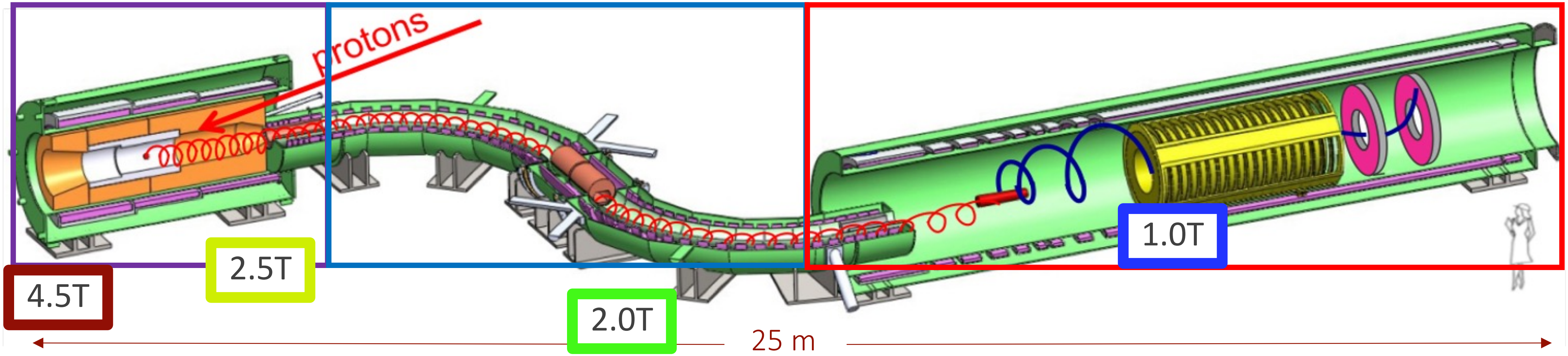


PRODUCTION SOLENOID

- Protons hitting the target and producing mostly π
- Graded magnetic field reflects slow forward π

TRANSPORT SOLENOID

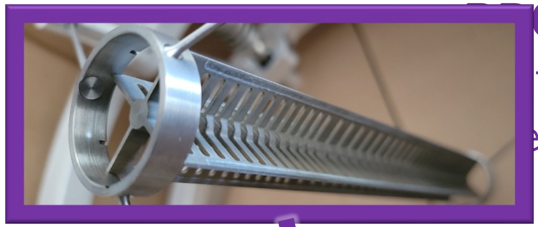
- Selection and transportation of low momentum μ^-



DETECTOR SOLENOID

- Capture μ on the Al target
- High precision momentum measurement in the **tracker** (< 180 keV/c) and energy and timing reconstruction with the **calorimeter**
- **CRV** to veto cosmic rays events

The Mu2e experiment: setup



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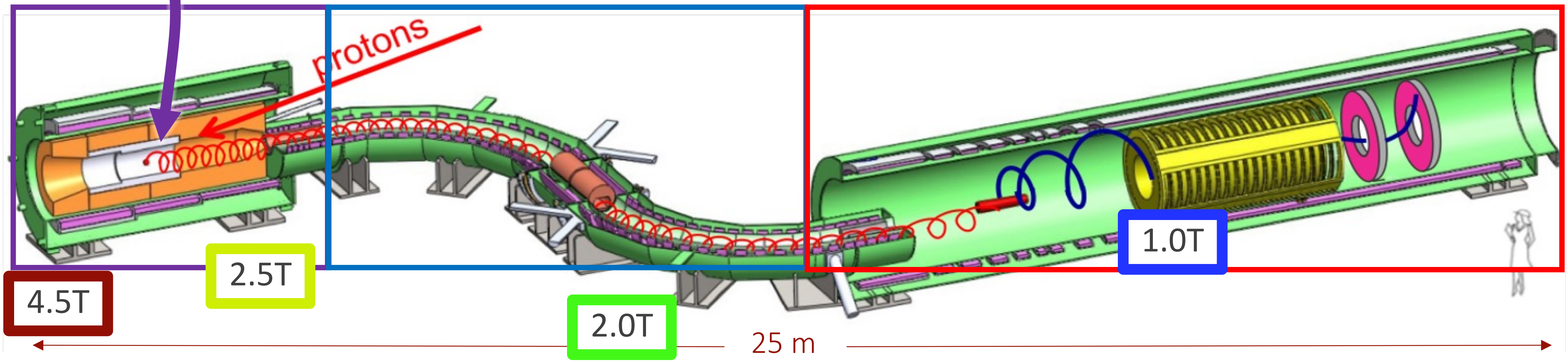

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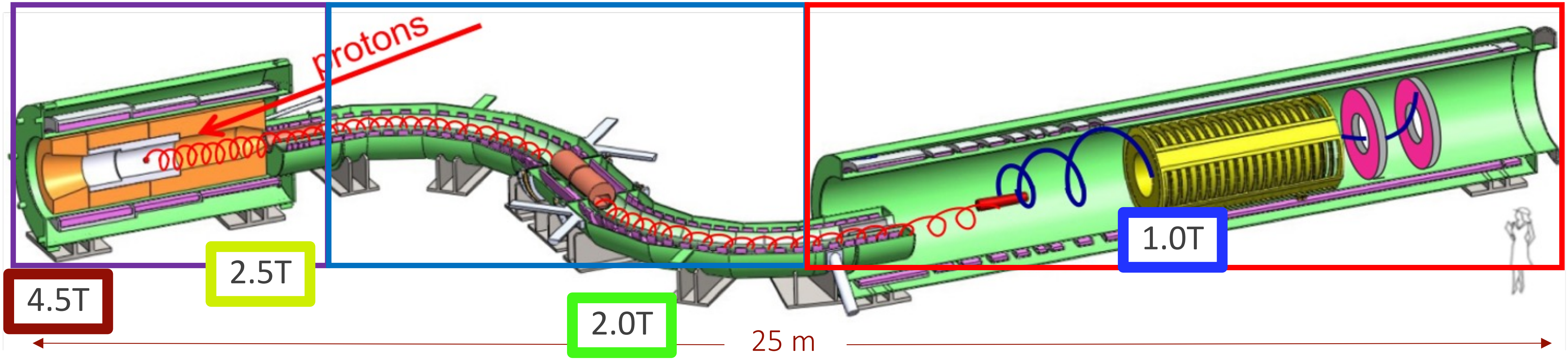

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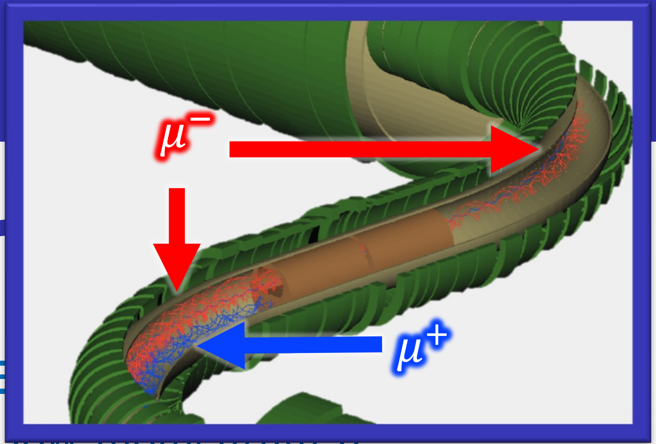

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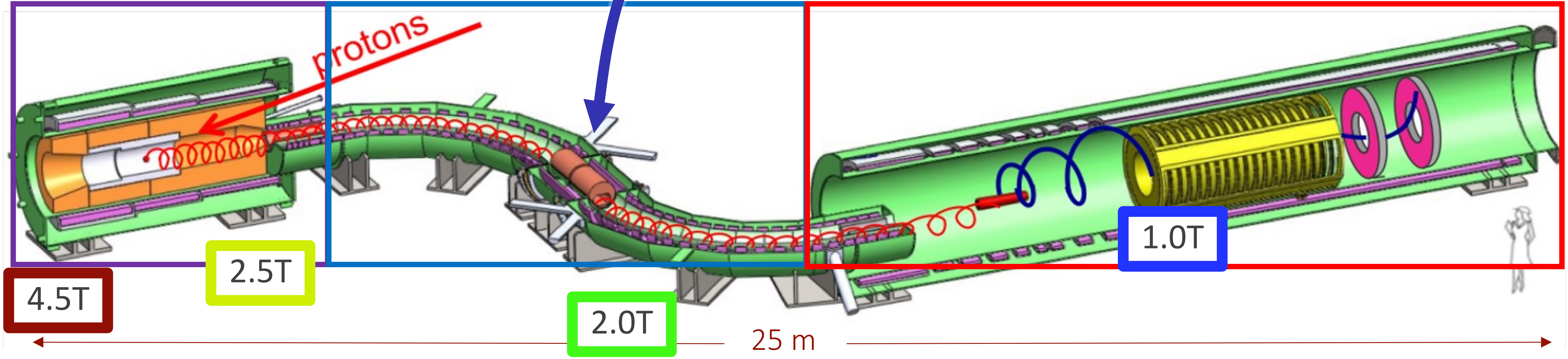

DETECTOR SOLENOID

- Capture μ on the Al target **(rate of 10^{10} /sec)**
- High precision momentum measurement in the **tracker** (< 180 keV/c) and energy and timing reconstruction with the **calorimeter**
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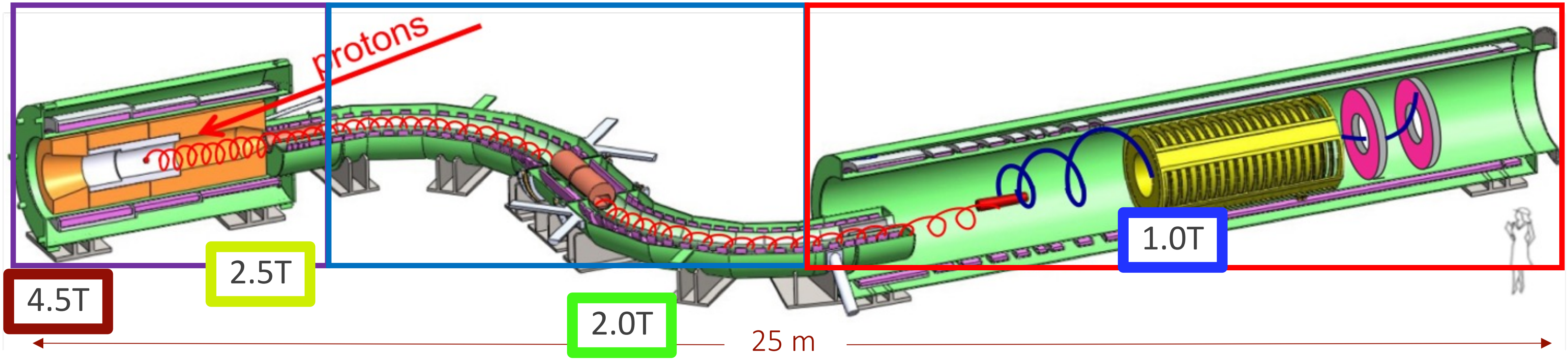

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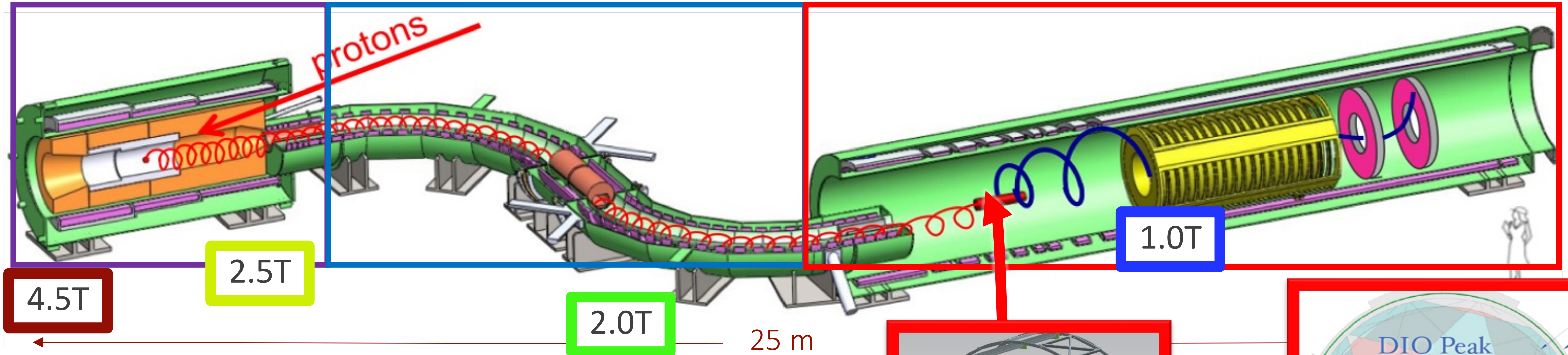

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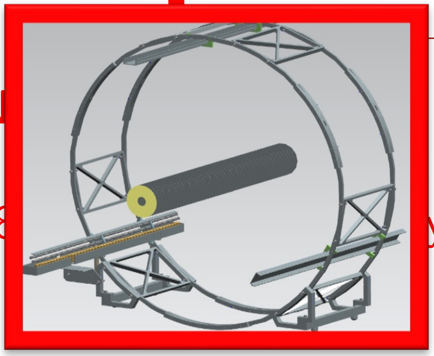

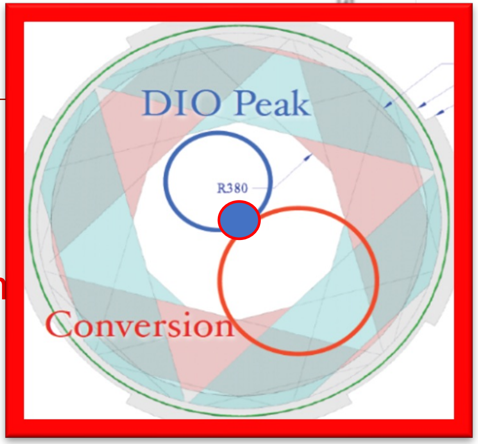

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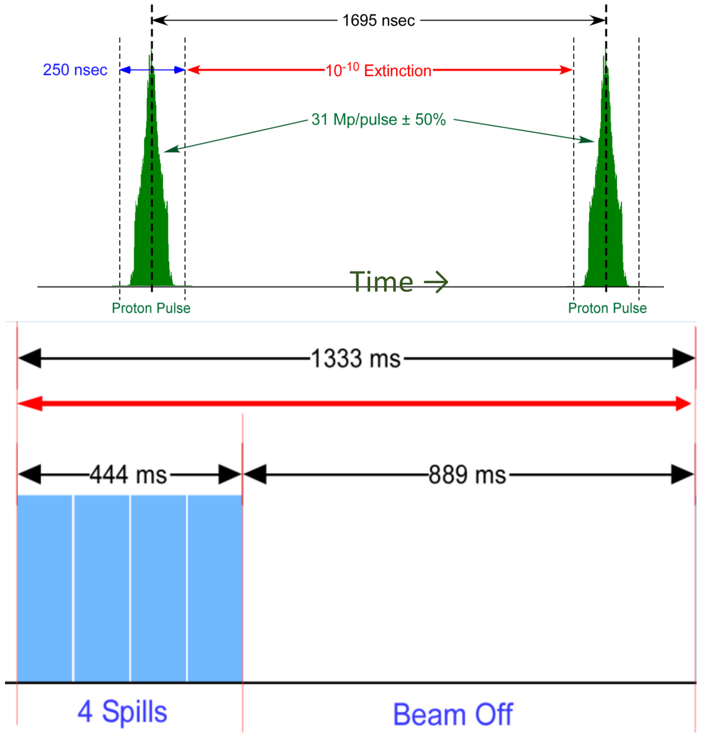
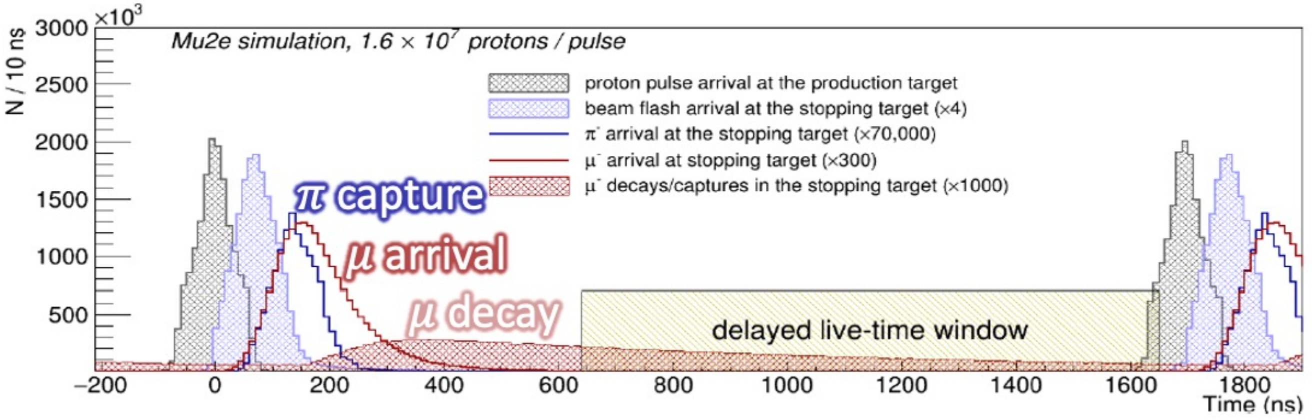
Pulsed beam structure and extinction

- The live window is delayed by 640ns relative to the proton pulse.
  - π reaching and stopping in the stopping target undergo radiative pion capture (RPC). Since the live window is delayed, emission of a conversion-like electron caused by RPC is mitigated.
  - Beam flash is prompt but can blind detector components.
- Protons arriving out of time with respect to the pulses must be kept to a minimum.
  - Can generate additional π, μ that can fake $\mu + N \rightarrow e + N$
  - Require extinction: $\mathbf{10^{-10}}$ **out-of-pulse/in-pulse protons**
  - Measured and monitored throughout the experiment.





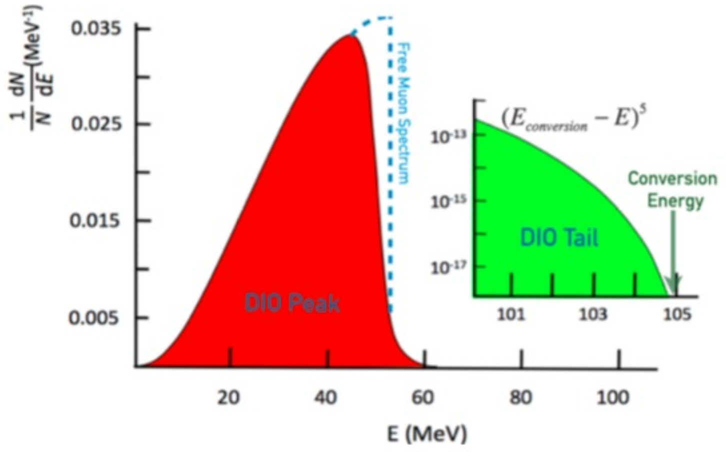
Initial beam condition: μ stopped/s ~ 5 x10⁹

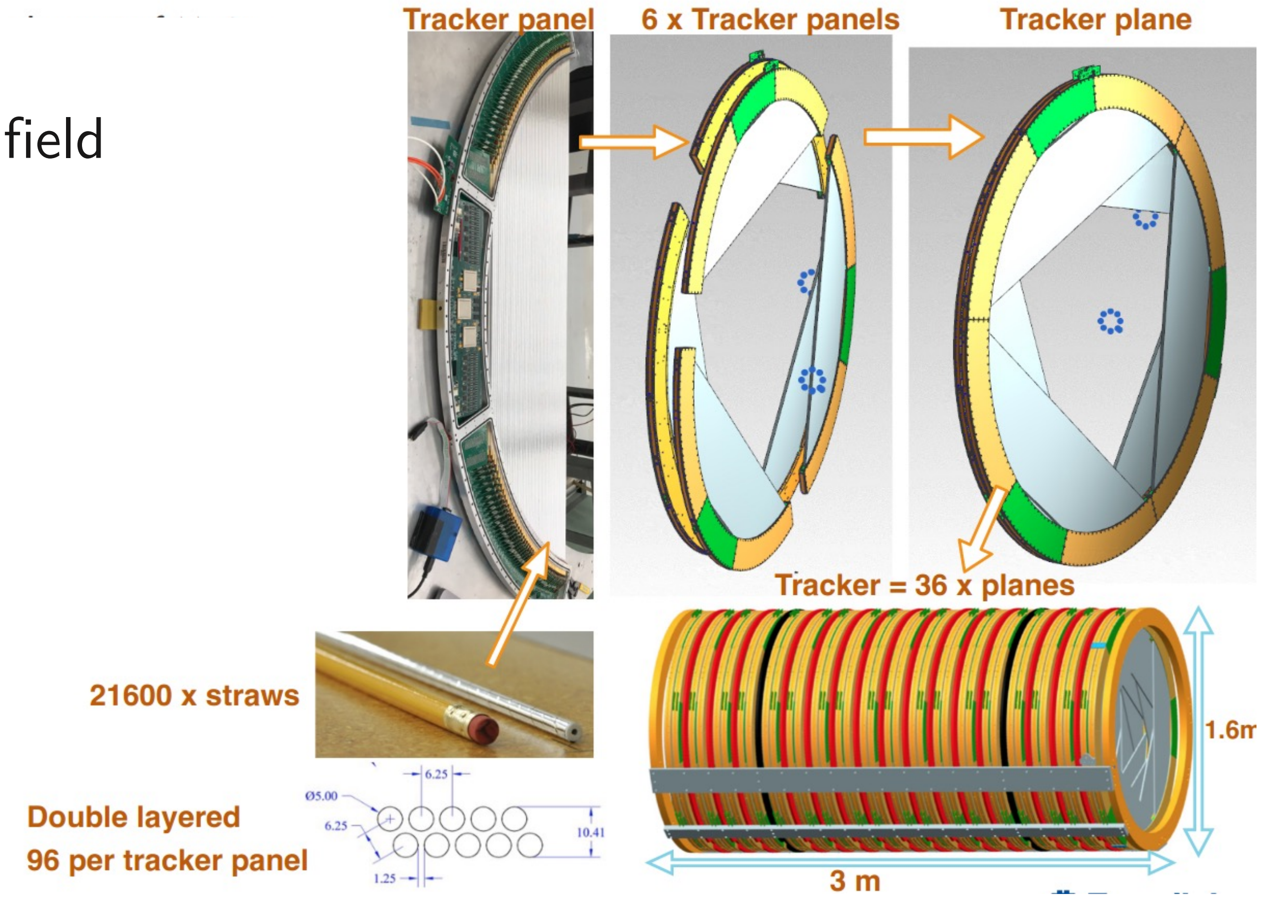
N (protons/pulse)	1.6×10^7
N(pulse/spill)	63289
N(spill/injection cycle)	4
N(μ_{stop}/ proton)	1.5×10^{-3}

The straw tube tracker

Devoted to high-precision measurements of e^- momentum (Momentum Resolution <200KeV/c @ 105MeV)

- 3 m long, 1.4 m diameter in a 1T uniform B field
- Built out of panels, 6 panels per plane,
  2 planes per station, with 18 stations total
- Total of 216 panels and 20k straw
  - 5 mm diameter
  - 12 μm Mylar walls
  - 25 μm Au-plated W sense wire
  - Filled with $Ar:CO_2$

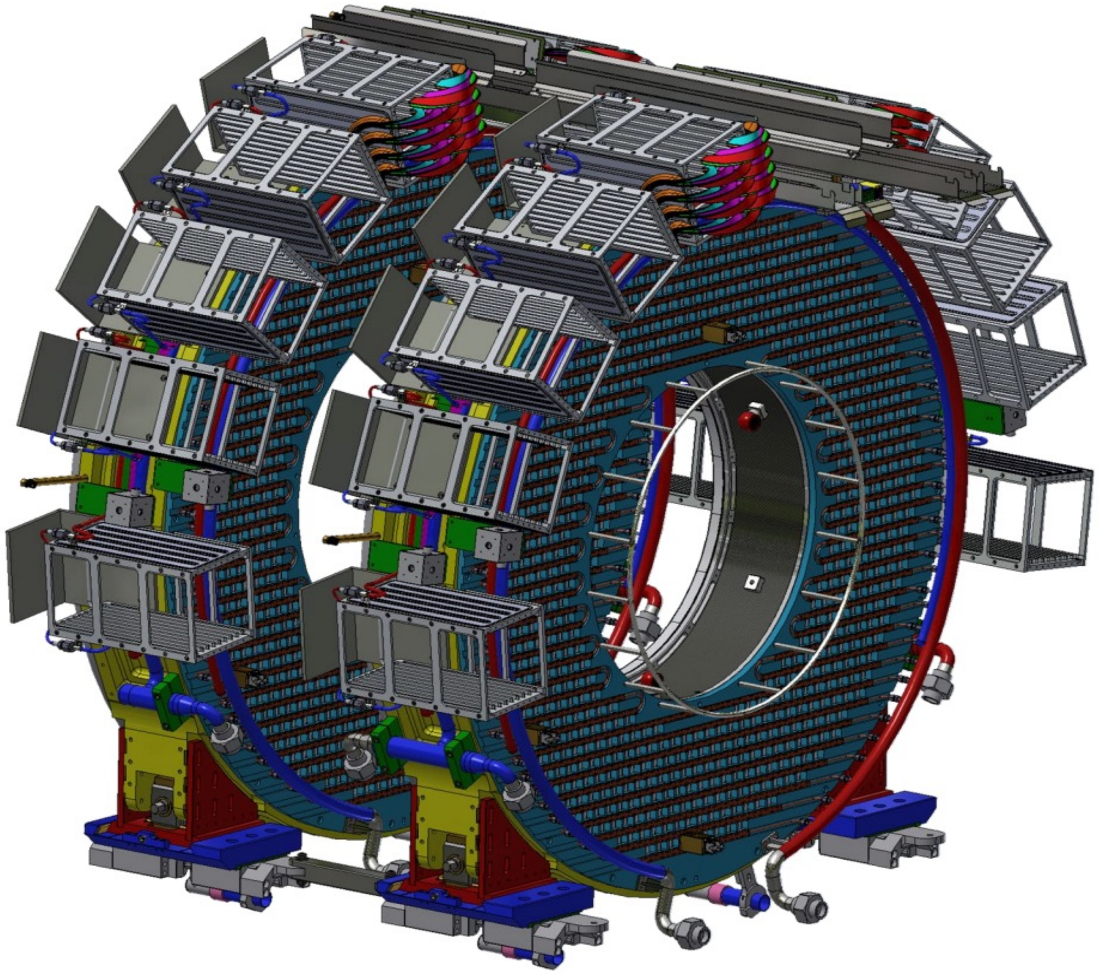




The electromagnetic calorimeter

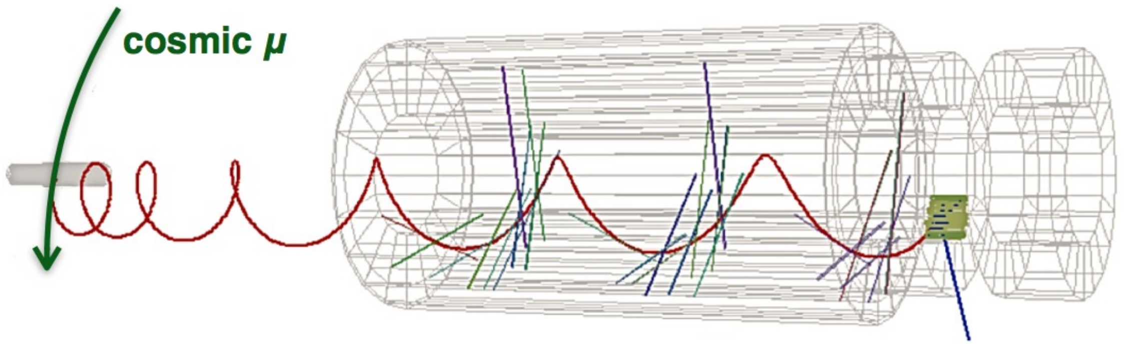
PID: e/μ separation, EMC seed track finder, standalone trigger

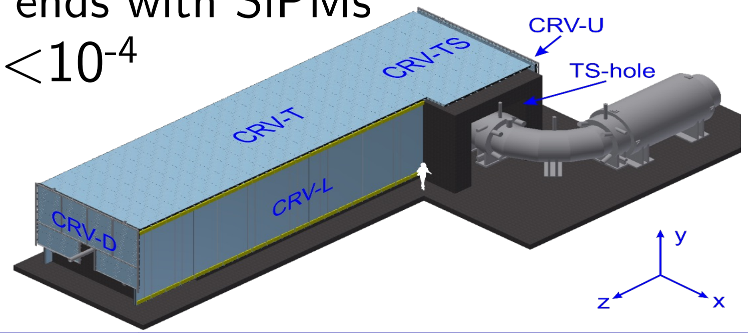
- 2 annular disks filled with 674 pure **CsI crystals** ($34x34x200\ mm^3$) each;
- Each crystal readout by 2 custom array of **UV-extended SiPMs**
- R_{IN} =35.1 cm R_{OUT} = 66 cm
- Depth = 10 X_0 (200 mm), Disk separation ~ 75 cm
- 1 FEE / SiPM , Digital readout on crates
- Radioactive source and laser system provide absolute calibration and monitoring capability
- Work in 1 T field and 10^{-4} Torr
- Radhard up to 100 krad, 10^{12} $n/cm^2/year$
- Good energy resolution $\sigma_E/E \approx$ **5% @ 105MeV**
- Precise timing $\boldsymbol{\sigma_t \sim 100ps}$.

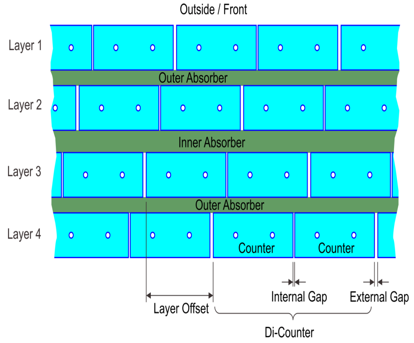


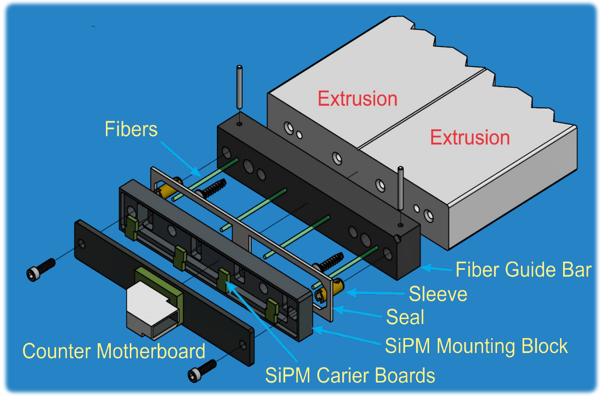
The cosmic ray veto

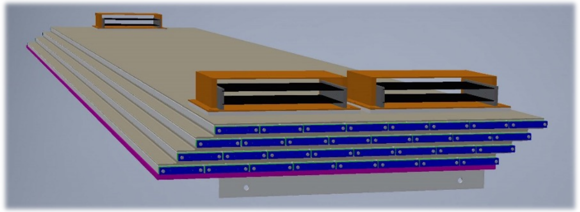
- Cosmic rays have the potential to mimic conversion electrons signal through in-flight decays, as well as secondary interactions and delta-ray production in materials within the apparatus.
- 1 fake CLFV per day w/o CRV
- CRV system covers entire DS and half TS (surface of 327 m^2)
- 4 layers of scintillator counters
  - each bar is 50×20 mm2 extruded scintillator counters of lengths ranging from 1m to 6.9 m.
  - 2 WLS fibers/bar
  - read out at both ends with SiPMs
- Veto inefficiency $<10^{-4}$



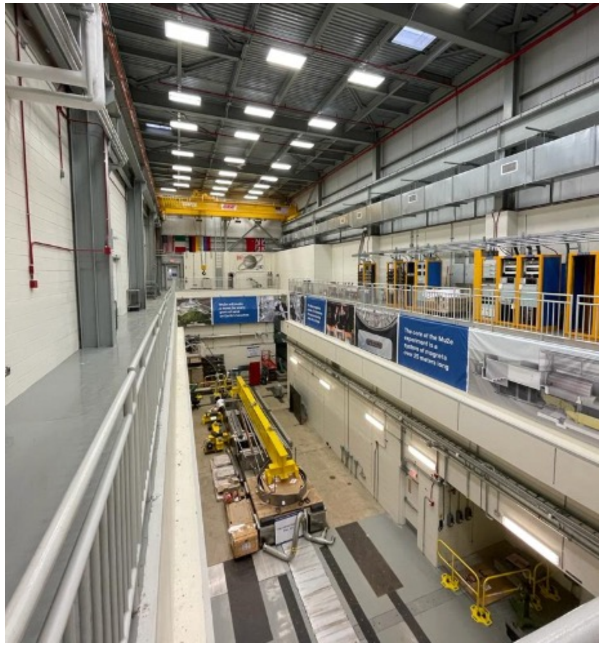




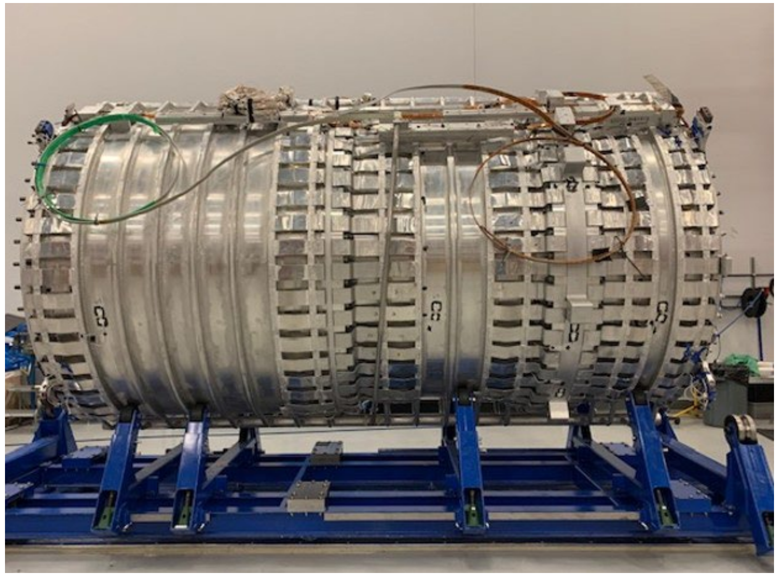




The Muon campus



The solenoids: TS installation start next month



Production Solenoid – cold mass complete

Transport Solenoids: Almost Done

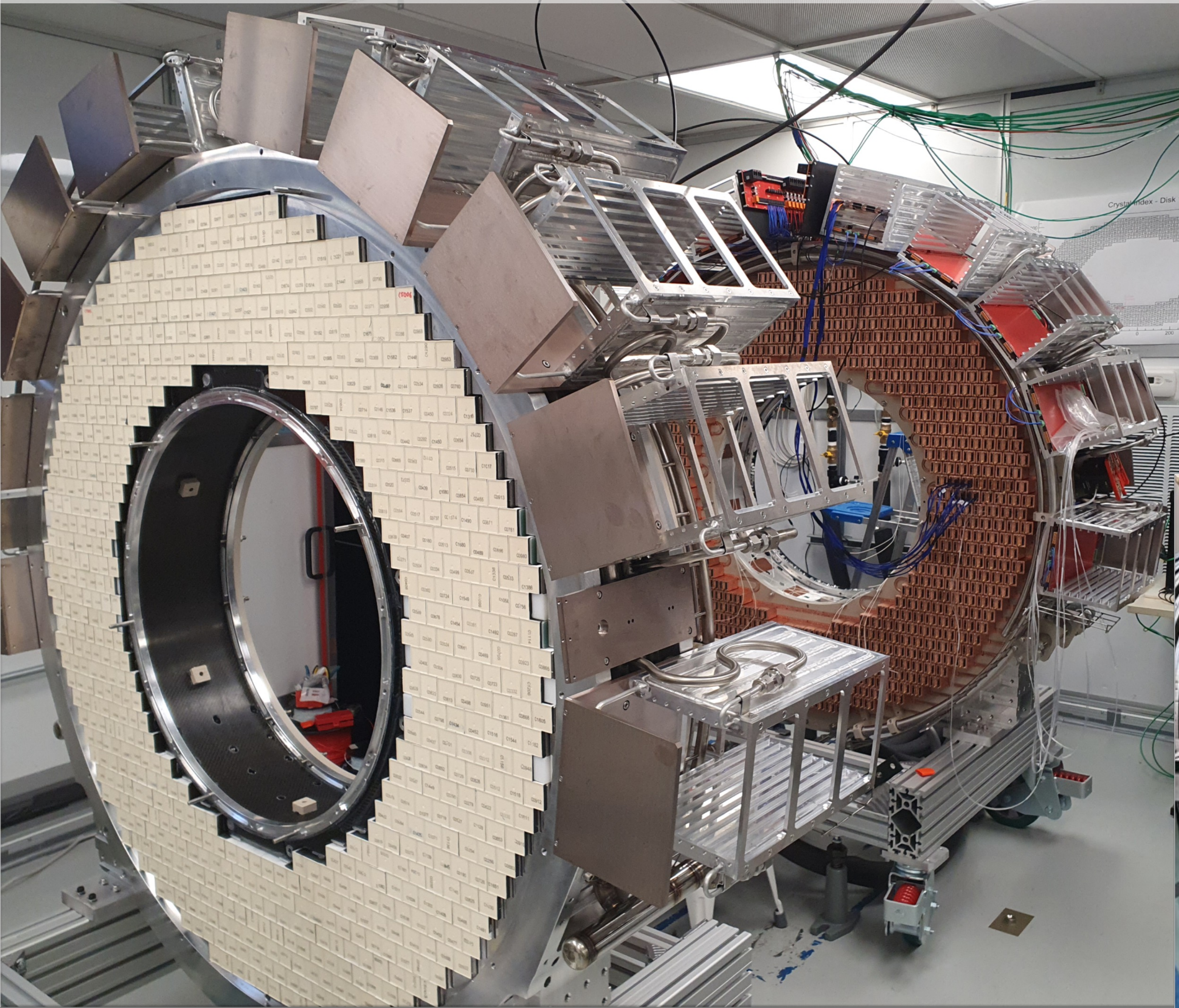
Detector Solenoid
Coils Wound

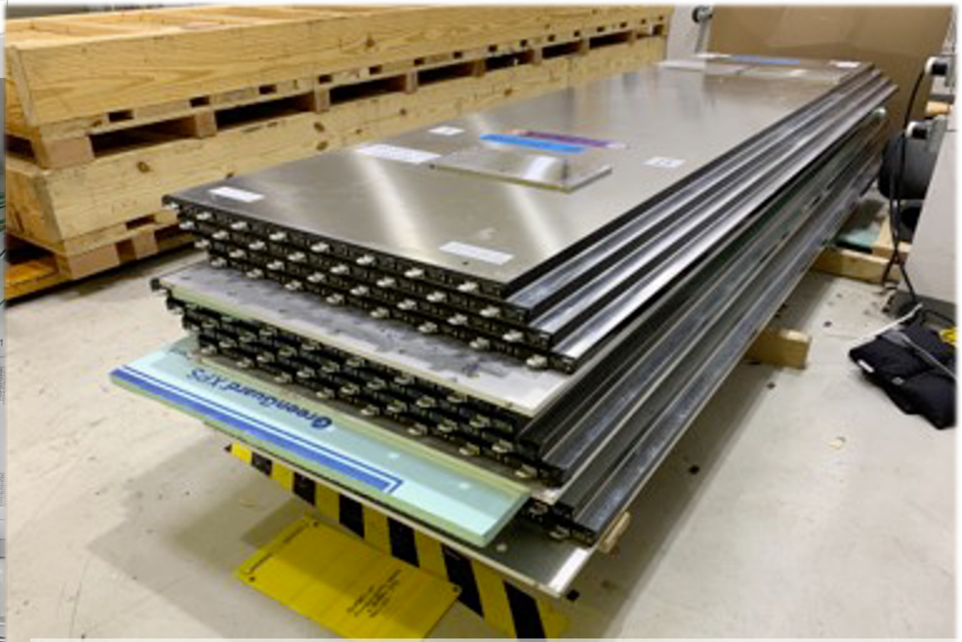
DS-11 coil wound

DS 6/7 Cold Prep Test

Transport Solenoid: First quarter of 2024
Production Solenoid: First half of 2024
Detector Solenoid: Mid 2024

Both disk assembled by the end of 2024

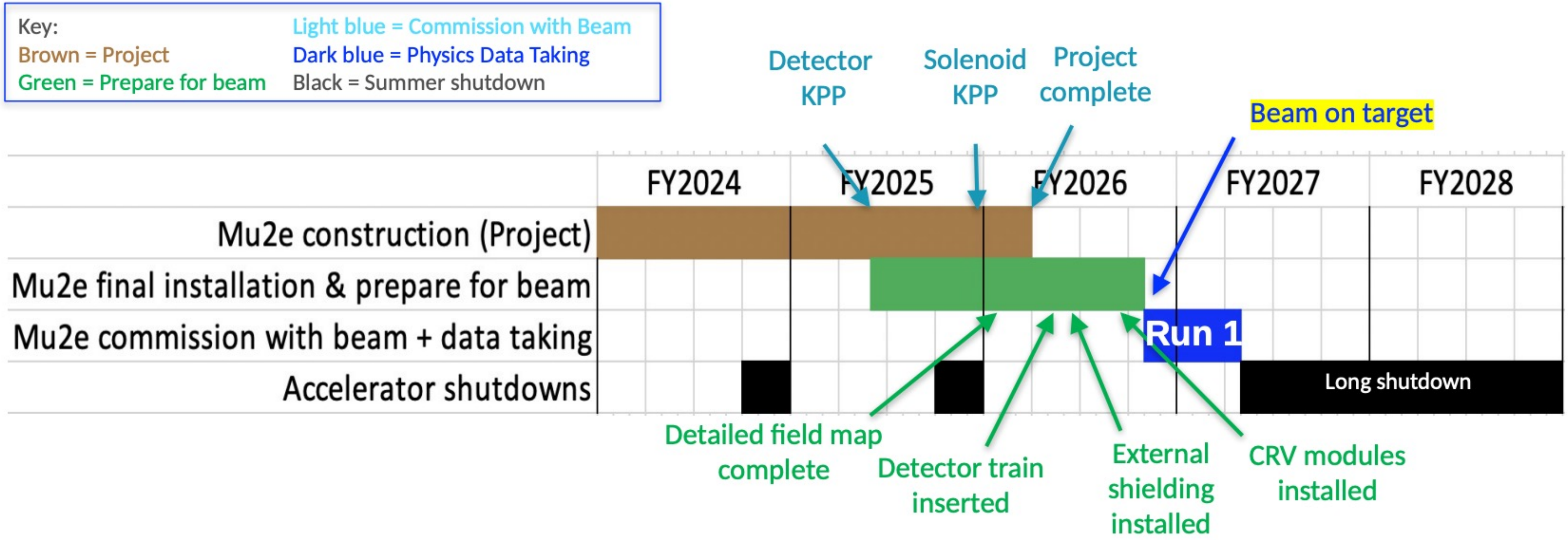




Module assembly completed.

Expect to deliver tracker to Mu2e hall by October 2024

Mu2e Schedule



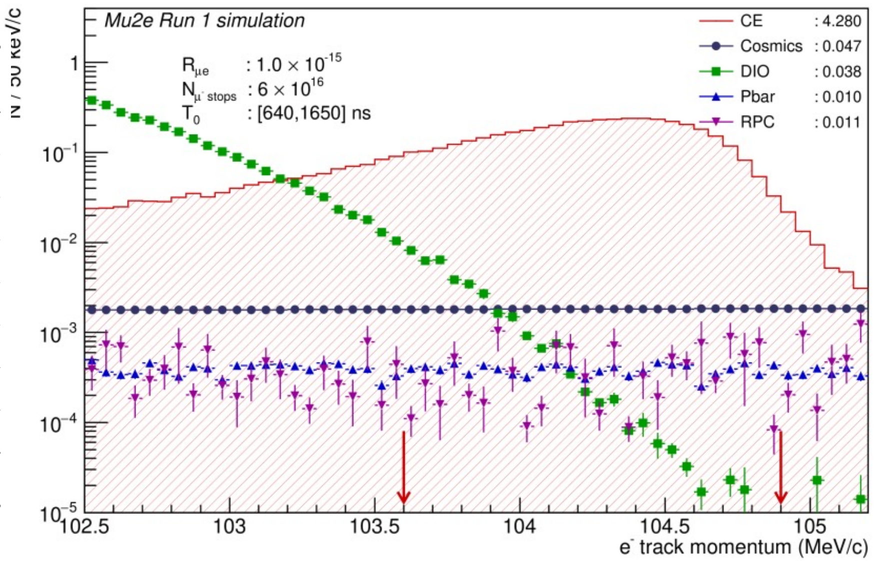
- **Run 1 goal**: get 3x10^{19} POT to improve by x10^3 Sindrum II sensitivity*
- **Run 2 goal**: get 3x10^{20} POT to add an additional factor 10 on sensitivity (longer run, higher average beam intensity, better shielding and CRV, ...)

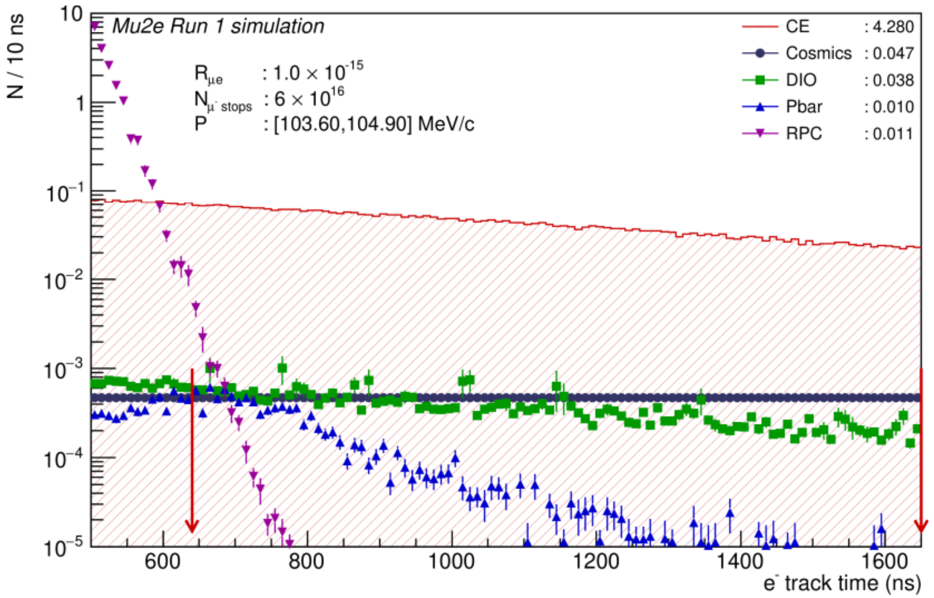
* "Mu2e Run I Sensitivity Projections for the Neutrinoless mu- --> e- Conversion Search in Aluminum", Universe 9 (2023) 1, 54 (38 pages) http://arxiv.org/abs/2210.11380

Run1: the signal background full simulation

- Signal estimate using 10^{16} stopped muons, 1/10 of full RUN
- Assuming a rate of $1{\times}10^{-15}$ for $\mu \rightarrow e$ conversion ~ **5 conversion events expected.**
- Background contributions within the time and momentum selection windows <<1.
  - Selection windows optimized for best discovery sensitivity.

Process	Background (evts)	Statistical	Systematic
Cosmic Rays	0.046	±0.01	±0.009
DIO	0.038	±0.002	$^{+0.025}_{-0.015}$
Antiproton	0.010	±0.003	±0.01
RPC in-time	0.010	±0.002	$^{+0.001}_{-0.003}$
RPC out-of-time	$<1.20{\times}10^{-3}$		
RMC	$<2.40{\times}10^{-3}$		
Decays in flight	$<2.00{\times}10^{-3}$		
Beam electrons	$<1.00{\times}10^{-3}$		
Total	**0.105**	±0.032	





Run- I Physics Run : current schedule is for CY 2026

Other interesting topics at Mu2e

- Another important CLFV and LNV process is:

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

- Muons are captured by a nucleus N(A,Z) into atomic orbits.
- Muon ends up in a ^{1}S state.
- Mono-energetic conversion positron.
- $E_{\mu^- e^+} = m_\mu + M_{N(A,Z)} - [M_{N(A,Z-2)} + 2m_e] - B_\mu(Z) - C(A)$

- Al stopping target: $\boldsymbol{E_{\mu^- e^+} = 92.32}$ **MeV**
- **Not coherent**

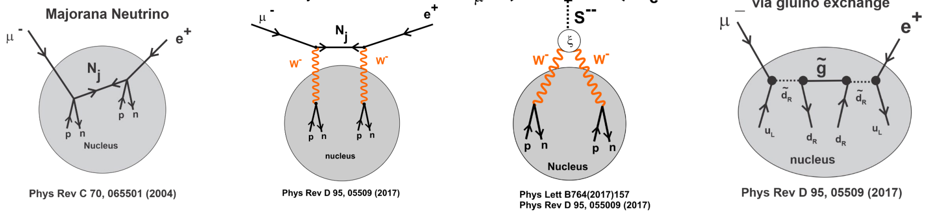
- Large improvement factors expected with respect to Sindrum-II
- Mostly limited by photon conversions from RMC photon spectrum
  → this will be the first Calorimeter related bkg measurement

- Special runs with positive muons or pions being discussed at lower intensity, lower B-Field

search for $\mu^+ \rightarrow e^+X$, $\pi^+ \rightarrow e^+X$

- ✓ A phenomenology paper published 29/9/2023 in arXiv 2310.00043 by Hill, Plestid and Zapan starting from a Mu2e thesis
- ✓ μ^+ search easier and bkg free with respect to p+
- ✓ Search for a "resonance" peak in the momentum spectrum > 20 MeV
- ✓ high sensitivity for ALP, DM (μ^+ eX) and HNL, Z' (π^+eX) in 20-50 MeV mass region

- Double charge exchange process: Involves two nucleons.
- If LNV mediated by light Majorana neutrinos
  - $0\nu\beta\beta$ rates much larger than $\mu^- \rightarrow e^+$ rates
- Other mechanisms could have $\mu^- \rightarrow e^+$ rates > $0\nu\beta\beta$ rates
  - Double charged singlet scalars: S^{--}
  - R-parity Violation SUSY



- Any observation of $\Delta L = 2$ process; the neutrino has a Majorana mass (Black Box Theorem)

- $\dfrac{\Gamma(\mu^- \mathrm{Ti} \rightarrow e^+ \mathrm{Ca}^{GS})}{\Gamma(\mu^- \mathrm{Ti\ Capture})} < 1.7 \times 10^{-12}$ (90% CL)

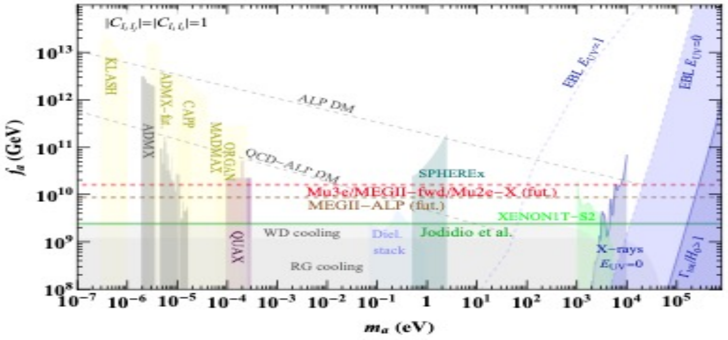


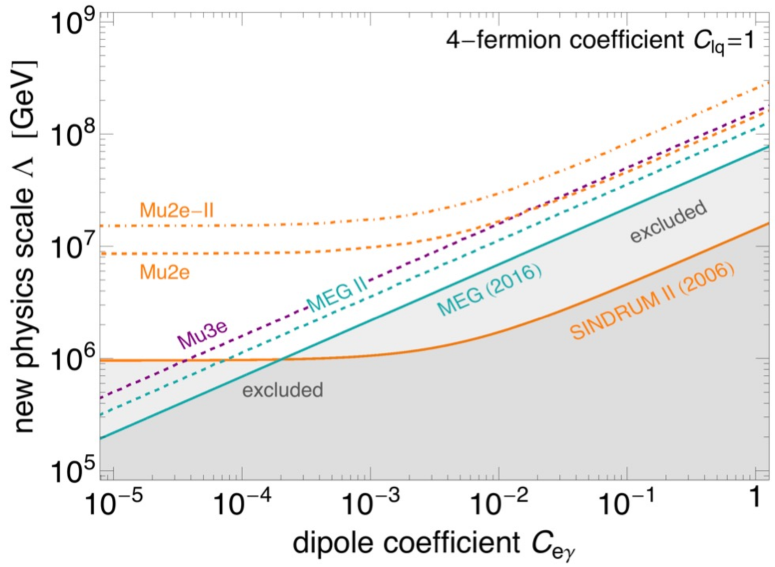
FIG. 2. The 95% C.L. limits on a leptophilic ALP that can be a DM candidate, as well as the reach of a μ^+ run (red dashed line, labeled Mu2e-X), see main text for details. Mu2e-X, MEGII-fwd, and Mu3e have similar projected sensitivities, and we represent all of them with a single line. Adapted from Ref. [61].

What's next after Mu2e Run-II ?

- Two scenarios are possible at the end of the Mu2e data taking (> 2030):

Mu2e does not find a signal:

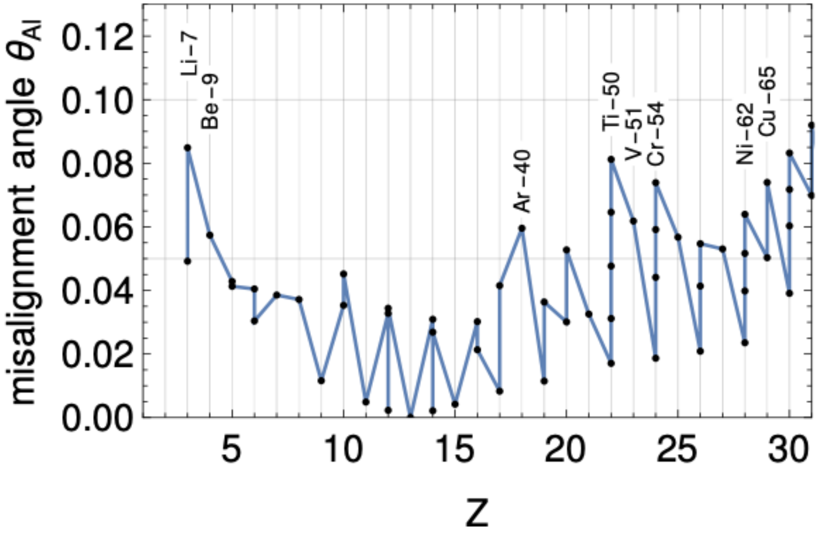
- improve sensitivity
- probe higher mass scales



arXiv:2203.07569

Mu2e discovers CLFV in Al:

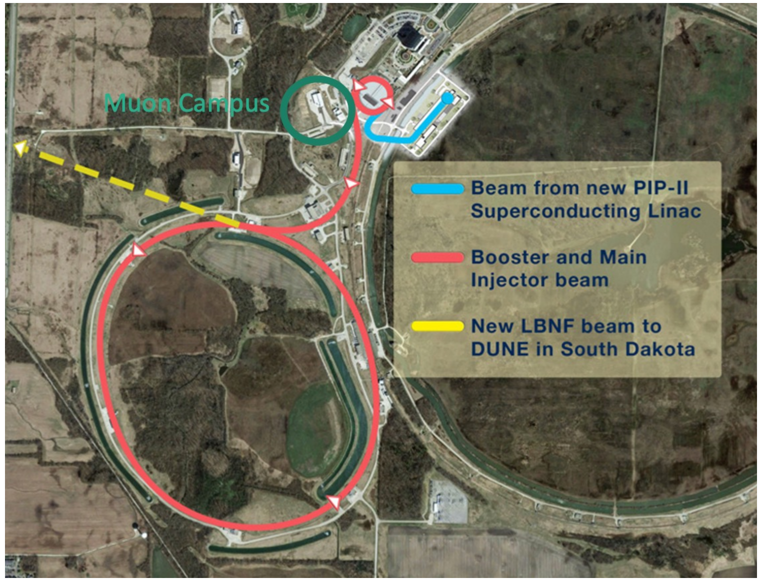
- measure with different target materials
- pin down NP parameters

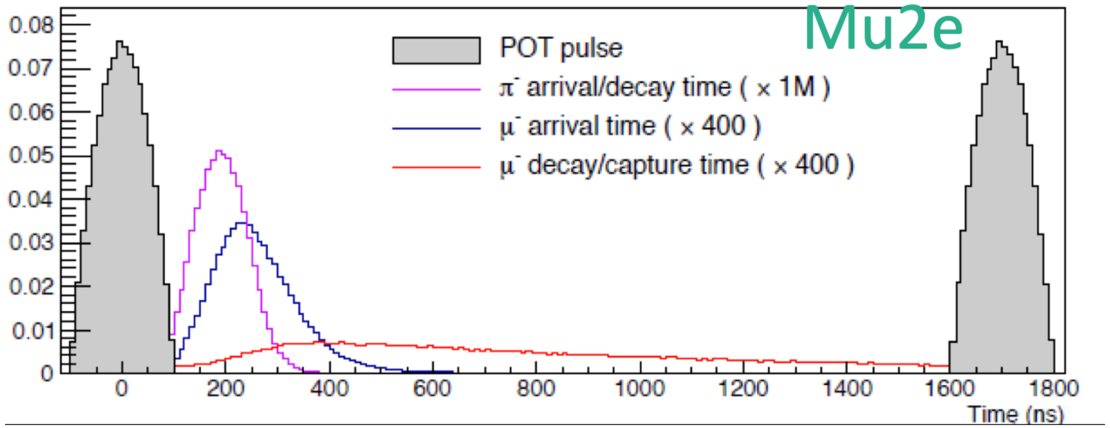


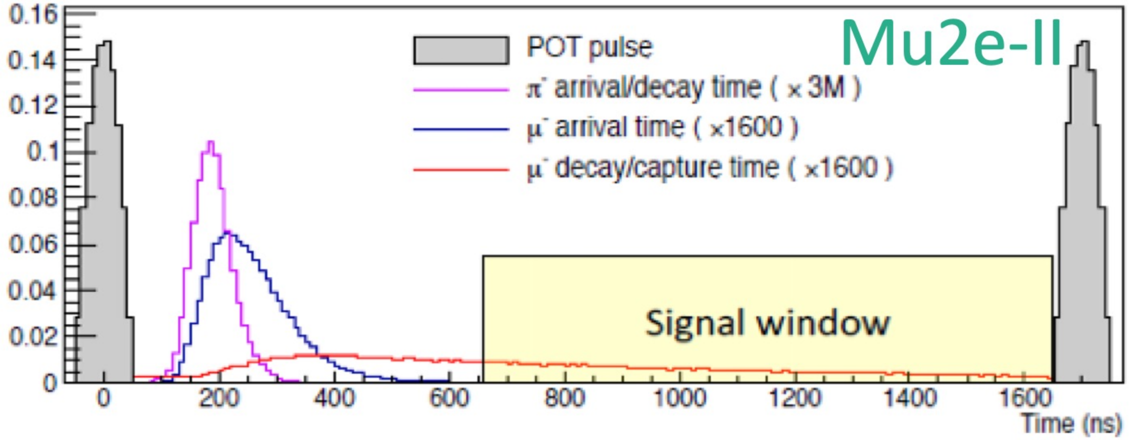
arXiv:2203.00702

Mu2e-II

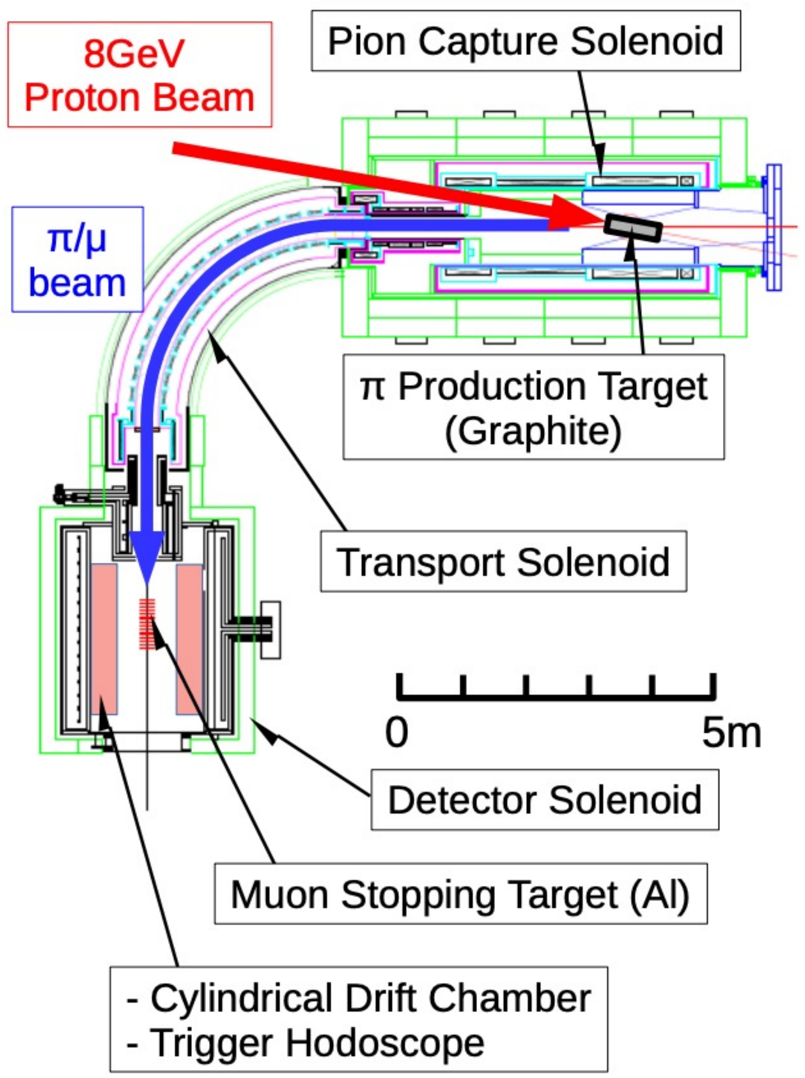
- An additional order of magnitude improvement over Mu2e (10^5)
- Retain as much of Mu2e infrastructure as possible
- Made possible by increased beam intensity from upgrades to PIP-II (8 kW 100 kW)
- Works well at 800 MeV (same muon stops per watt as 8 GeV
- Would benefit from higher muons/watt at 2 GeV
- Needs R&D support to advance conceptual design







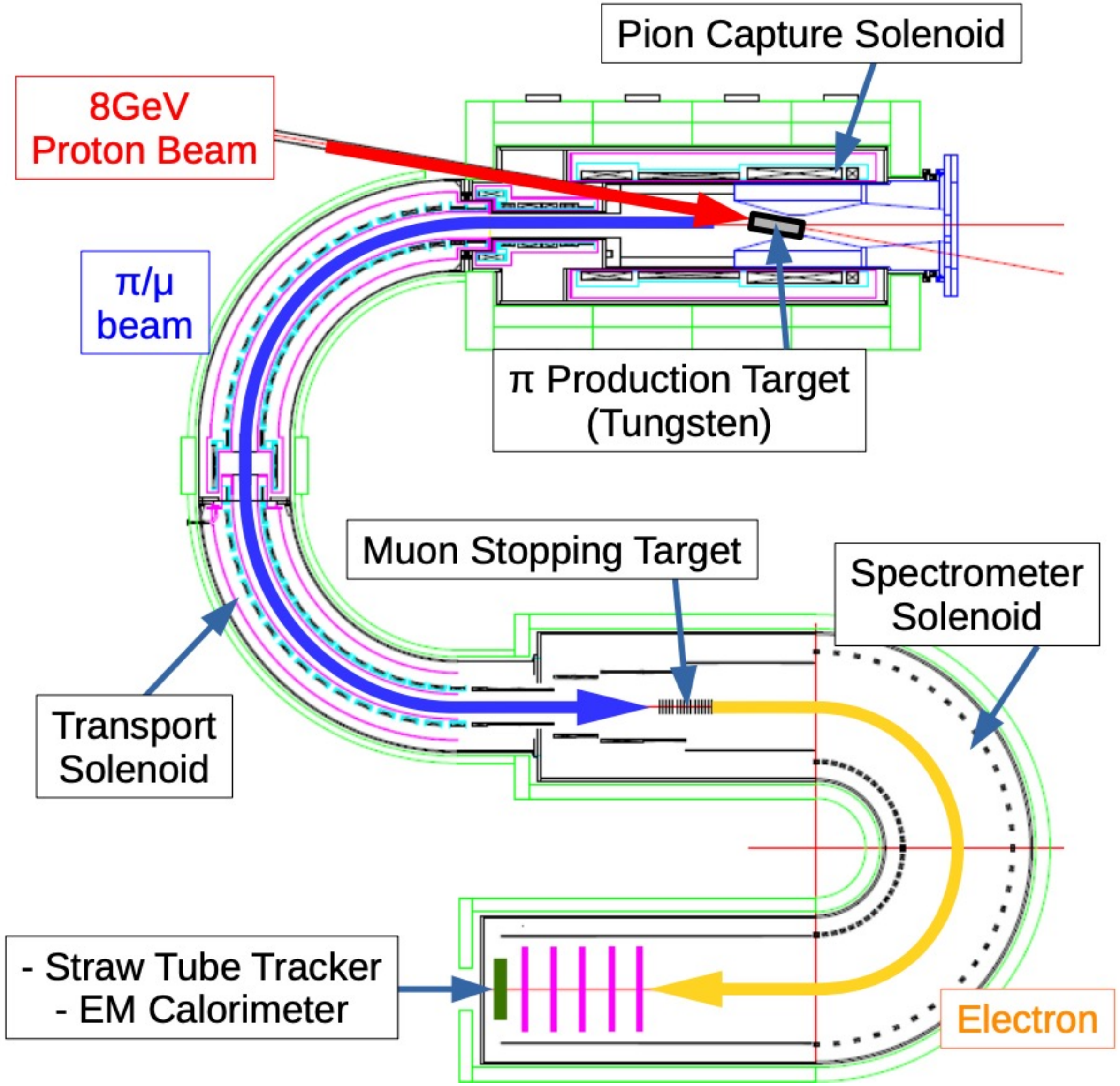
Comet: Phase-I



- J-PARC 8GeV proton beam is injected to Pion Production Target (700mmL graphite), which is installed inside Pion Capture Solenoid.
- Pions decay to muons during transportation in Transport Solenoid.
- Muon are stopped at the aluminum stopping target. Momentum of decay electrons are measured by Cylindrical Drift Chamber (CDC).
- **Expected sensitivity: 7×10^{-15} (x100 improvement)**
- Another program at Phase-I is to study secondary beam itself to evaluate background at Phase-II.
- Muon stopping target and CDC is removed. Instead, Straw Tube Tracker and EM Calorimeter are used.
- Same detector as Phase-II will be used for this study.

Phase- I Physics Run : current schedule is for CY 2025-2027

Comet: Phase-II

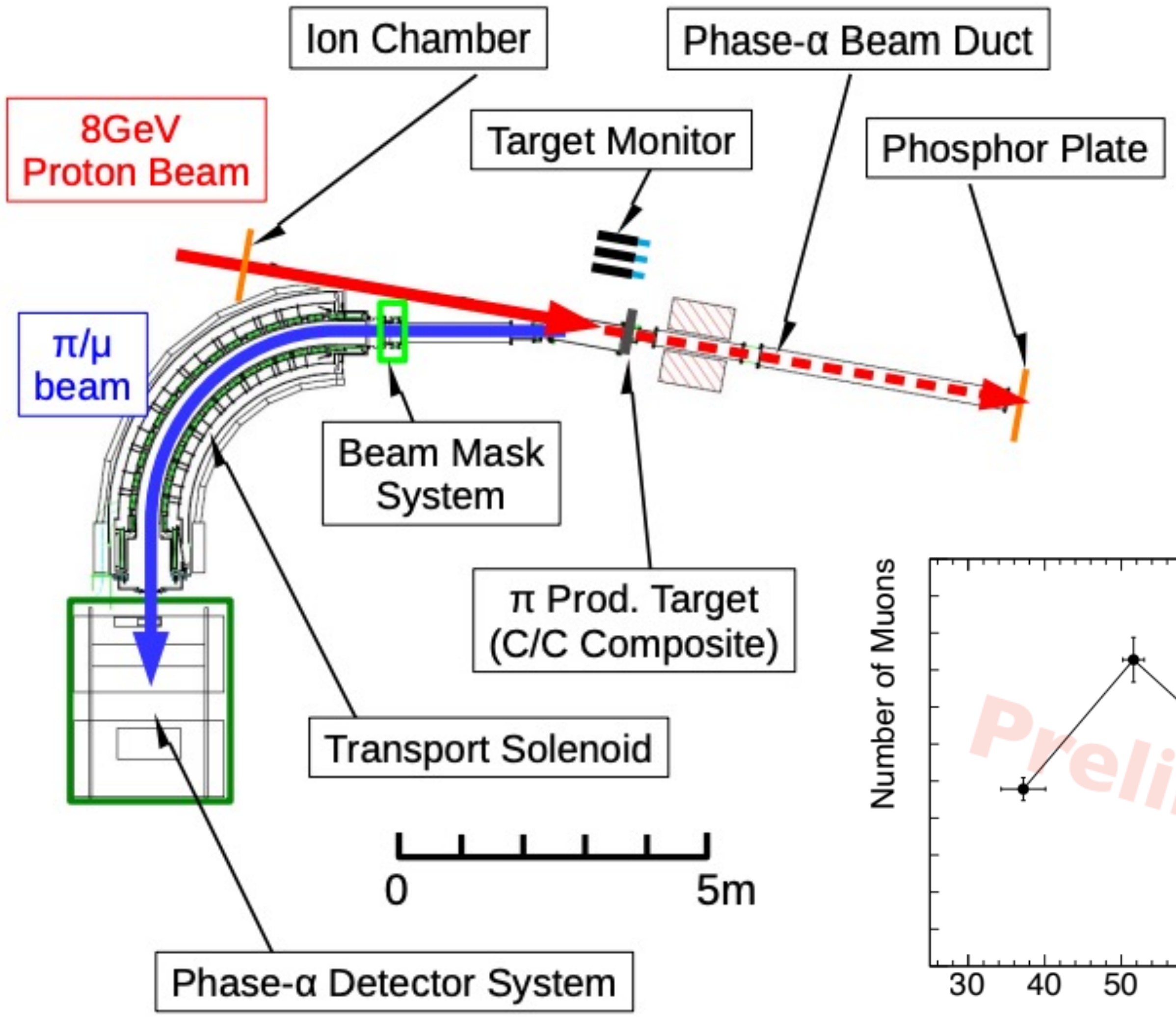


Phase-II→achieve further sensitivity of a factor of 100.

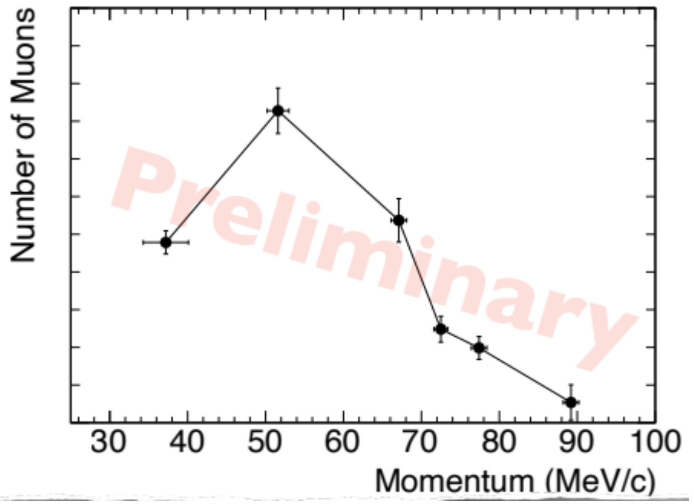
- Proton beam intensity will become 20 times higher.
- Production target will be replaced to tungsten.
- Transport Solenoid will be extended twice longer.
- Electron spectrometer will be installed.
- Straw tube tracker with EM calorimeter will be installed.

Phase- II : current schedule sees installation up to CY 2030

Comet Phase α



- Carried out between February and March 2023
- Investigation of the secondary beam in the experimental area.
  - Comparison between data and simulation, for validation of simulation.



- Proton beam was successfully extracted into the COMET beam hall.
- **Achieved the first observation of beam particles (muons) successfully transported via a 90°-curved Muon Transport Solenoid.**

Summary

- The Mu2e (COMET) experiment is a discovery experiment looking for the CLFV process of a coherent conversion of muon into electron
- Mu2e will improve the sensitivity on conversion experiment of $\sim$ **4 orders of magnitude** up to 10000 TeV mass scale
- It provides discovery capabilities over a wide range on NP model
- With upgrades, we could extend the limit by **one additional order of magnitude**, study the details of new physics, and build a new rare muon process program
  - → Expecting installing the detectors in 2024
  - → Start commissioning the detector in 2025

Mu2e-II is a natural follow-up to the Mu2e experiment

- If Mu2e discovers CLFV in aluminum, Mu2e-II can measure with different target materials to pin down NP parameters
- If Mu2e does not find a signal, repeat the measurement to push limits even further reuse as many components of Mu2e as possible

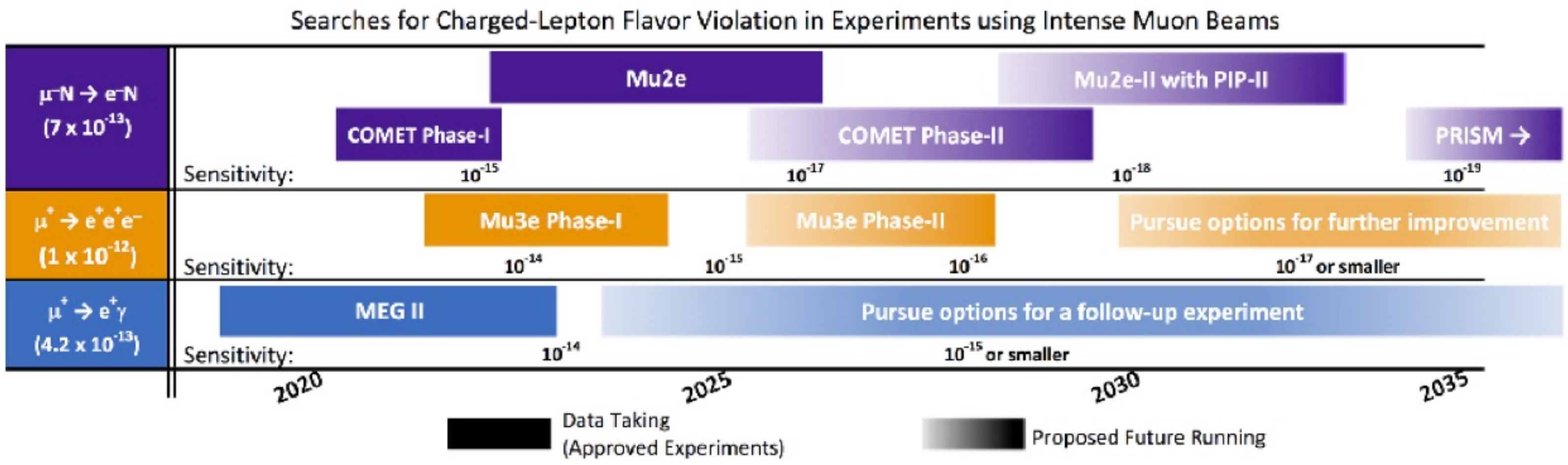
- Still many challenges for Mu2e-II but also many R&D activities already ongoing

SPARE

Peculiarity of the μ-e conversion

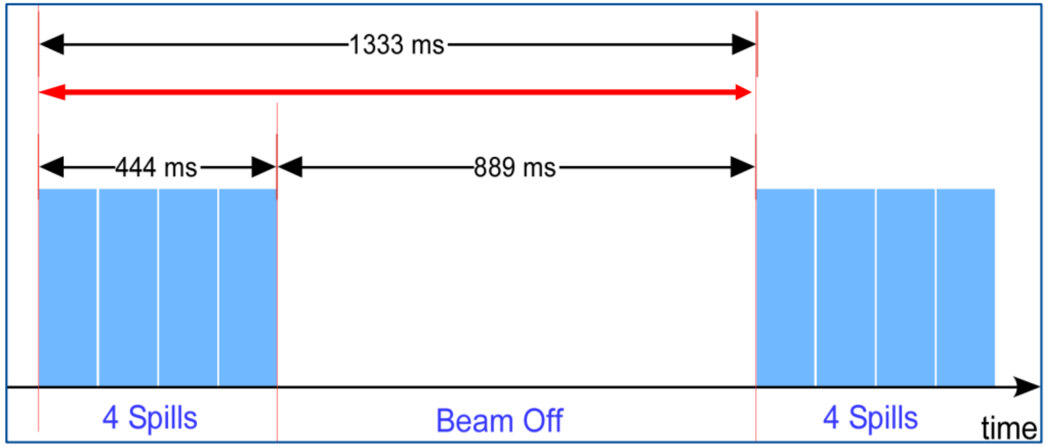
μ-e conversion has a broad sensitivity across several alternative models:

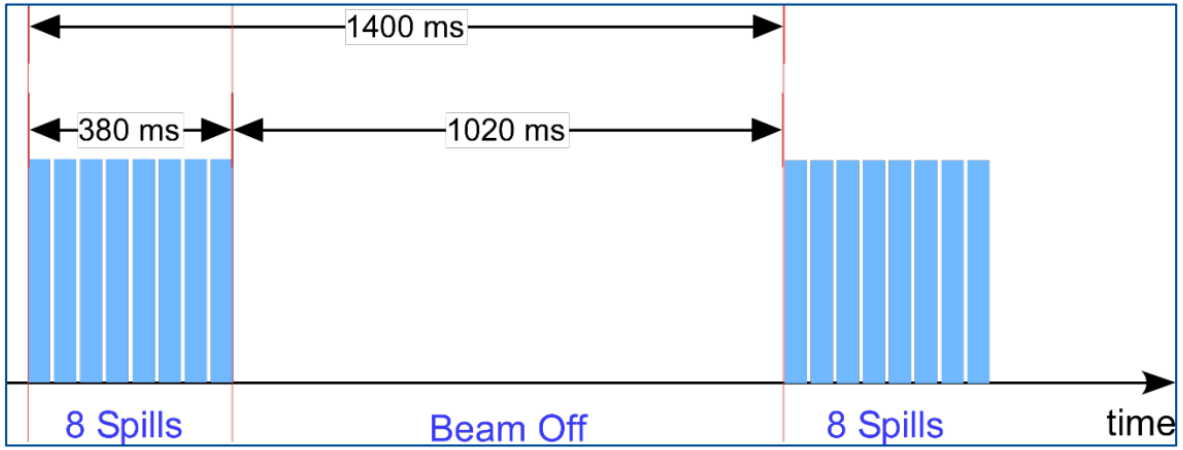
- Sensitivity to the same physics of MEG/Mu3e;
- Sensitivity to physics that MEG/Mu3e are not;
- If MEG/Mu3e observe a signal, Mu2e/COMET will see it also
- If MEG/Mu3e do not observe a signal, Mu2e/COMET have still a reach to do so.



Beam scenario comparison

Reduced Intensity Scenario		Design Beam Scenario	
N (protons/pulse)	1.6×10^7	N (protons/pulse)	3.9×10^7
N(pulse/spill)	63289	N(pulse/spill)	25442
N(spill/injection cycle)	4	N(spill/injection cycle)	8
N(μ_{stop}/ proton)	1.5×10^{-3}	N(μ_{stop}/ proton)	1.5×10^{-3}
N(μ_{stop}/ proton)	$\sim 5 \times 10^9$	N(μ_{stop}/ proton)	$\sim 9 \times 10^9$

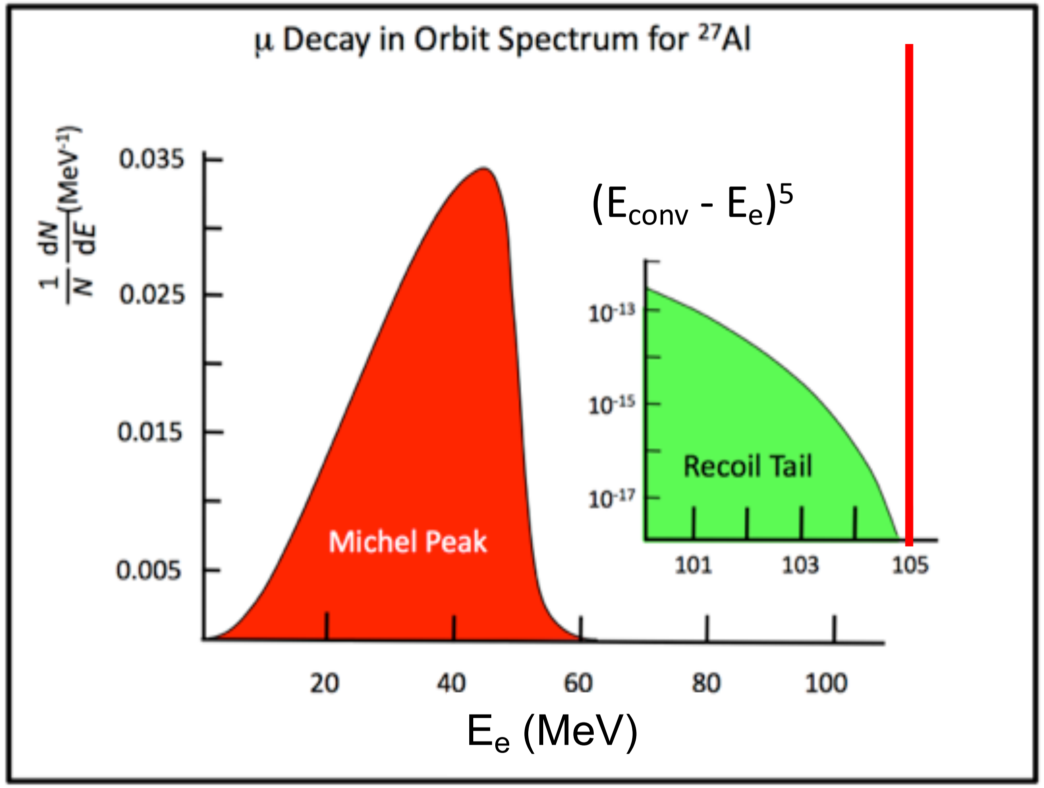




DIO background

$$\mu^- N \rightarrow e^- \nu_\mu \overline{\nu_e} N$$

- Irreducible background
- Michel spectrum of electron from μ decay gets significantly modified by interaction with the nucleus
- Presence of a recoil tail with a fast falling slope close to the μ-e conversion endpoint.
- **To separate DIO endpoint from the CE line we need a high Resolution Spectrometer**



Czarnecki et al., Phys. Rev. D 84, 013006 (2011)
arXiv:1106.4756v2

RPC background

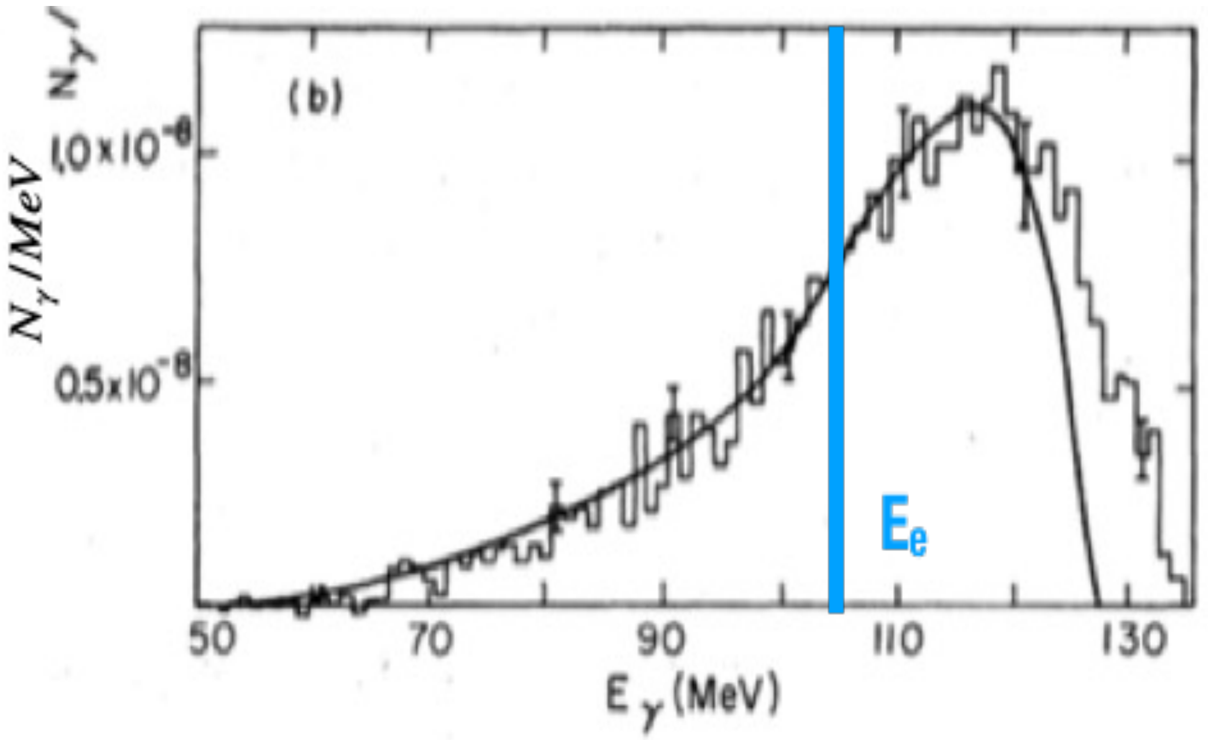
$$\pi^{-}N \rightarrow \gamma N$$

- Non-decayed pions reach the stopping target and are radiatively captured;
- γ can convert (Dalitz or in material)

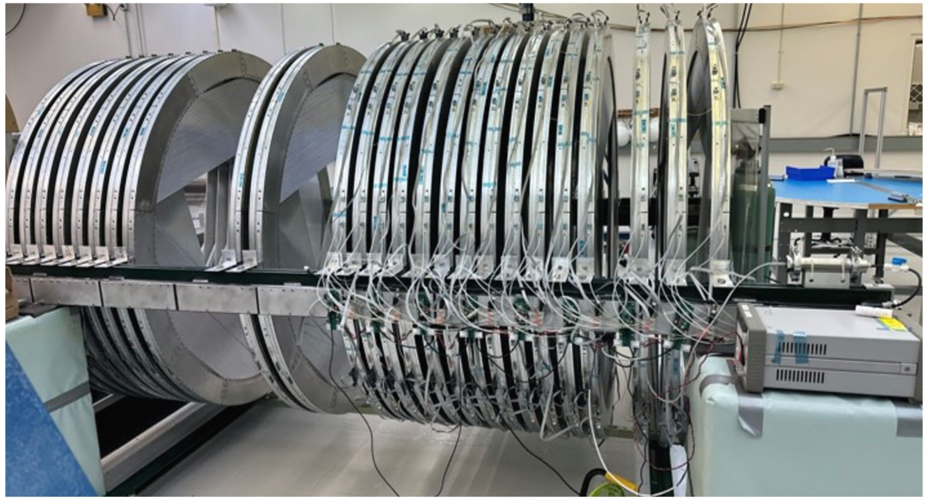
- Electrons can have the momentum in the signal window and mimic a conversion electron when positrons gets not reconstructed.
- The process is prompt:

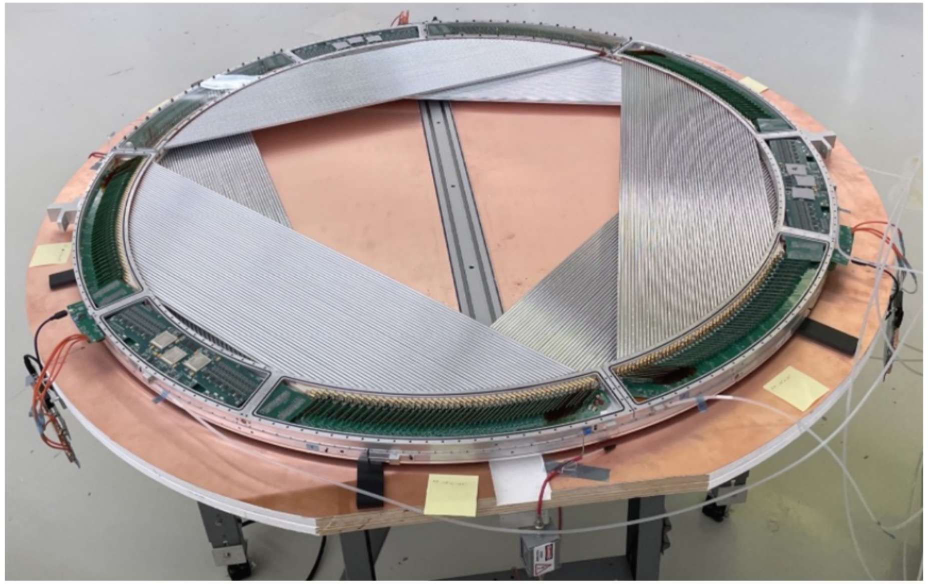
➔ Beam has to be "pulsed"

➔ Beam has to have high extinction



Status of tracker production

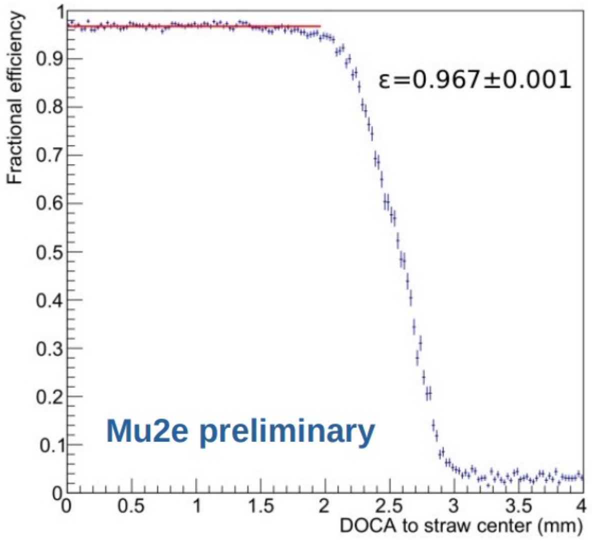


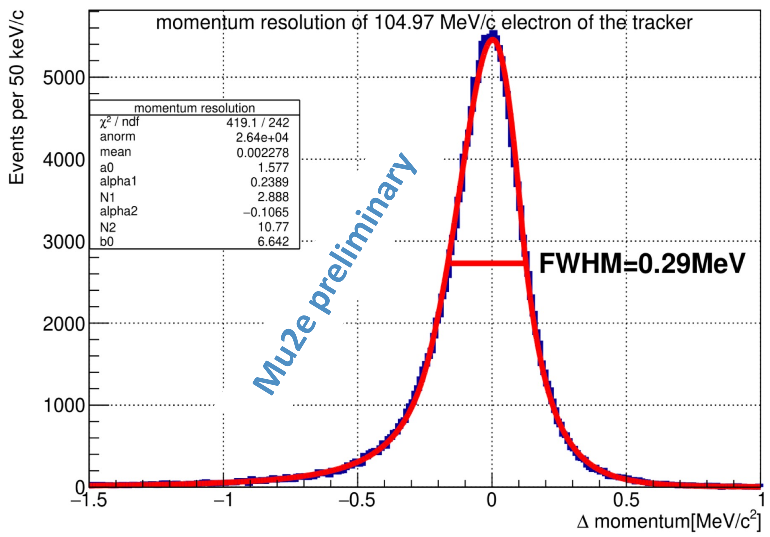


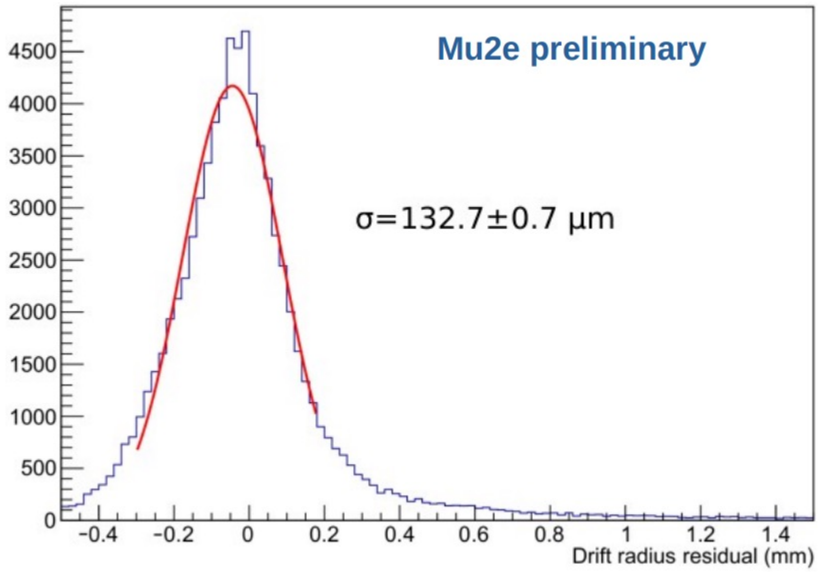
~100 % panels produced
~ 80% planes assembled
~ 1 plane with electronics installed

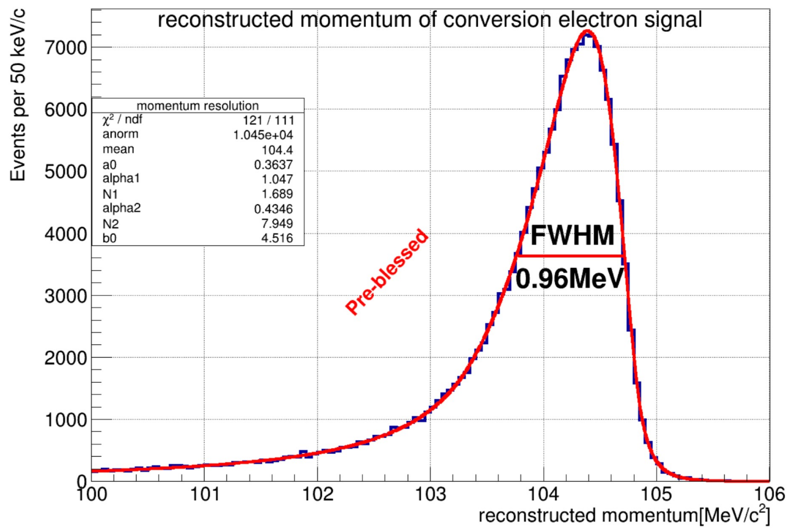
Expect to deliver tracker to Mu2e hall by October 2024

Tracker performance



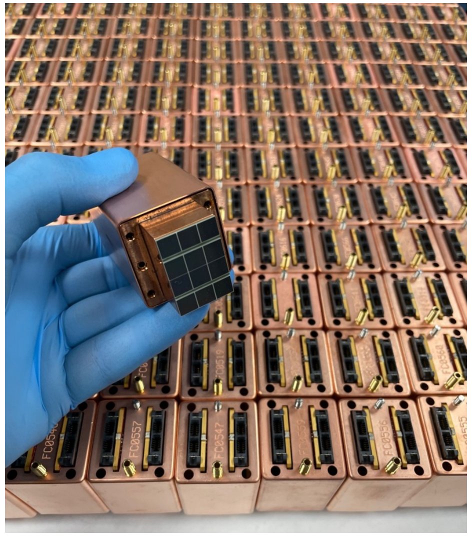


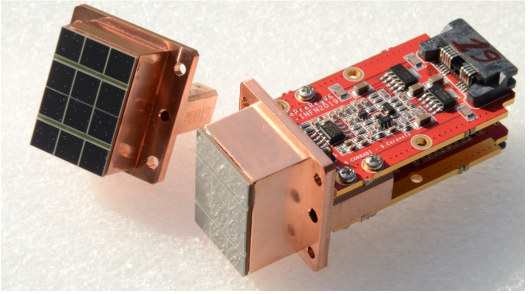


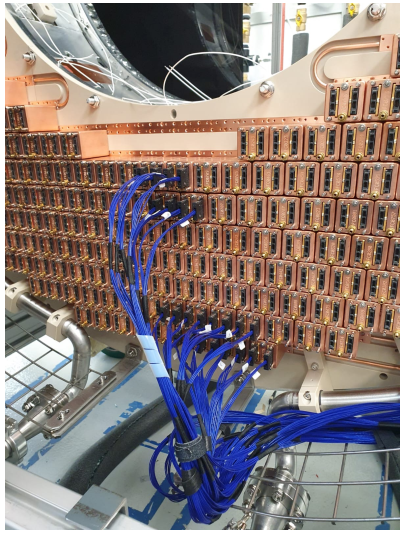


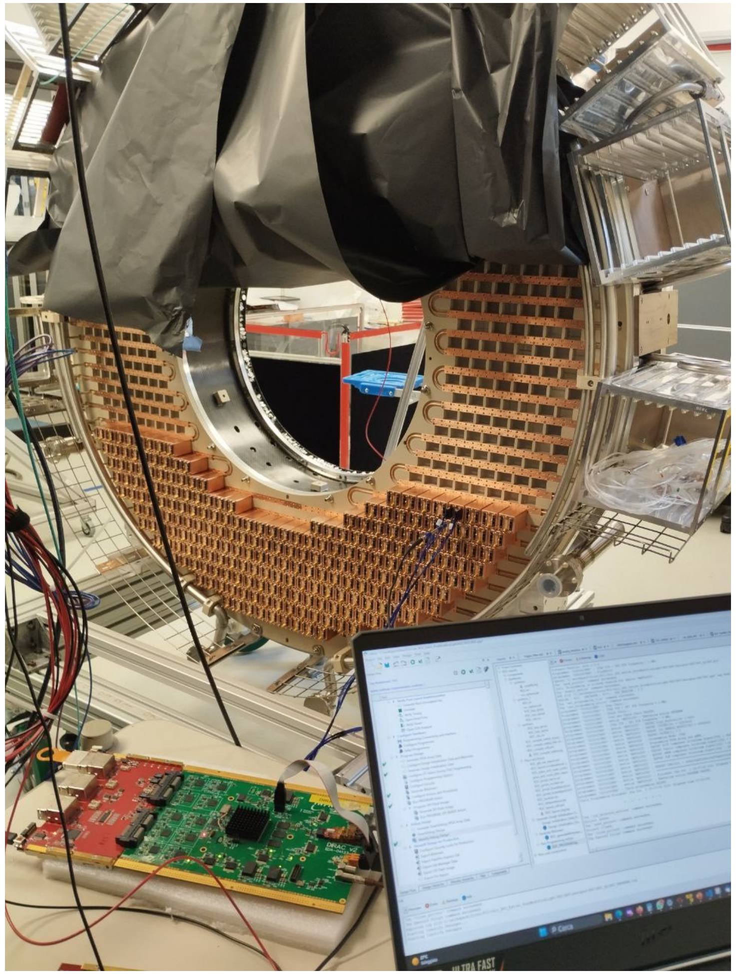
Status of the calorimeter

- All mechanical parts produces
- All crystals, SiPMs produced and tested
- All Front End Electronics produced and tested
- Disk-1 fully assembled (apart digital board)
- Disk-1 fully assembled by end of November 2023
- MZB and digital board production expected to be completed in February 2024



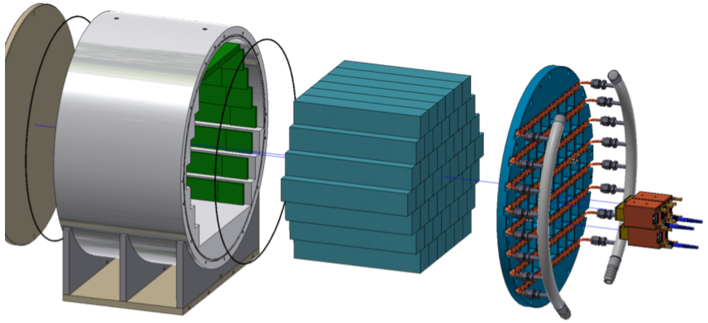


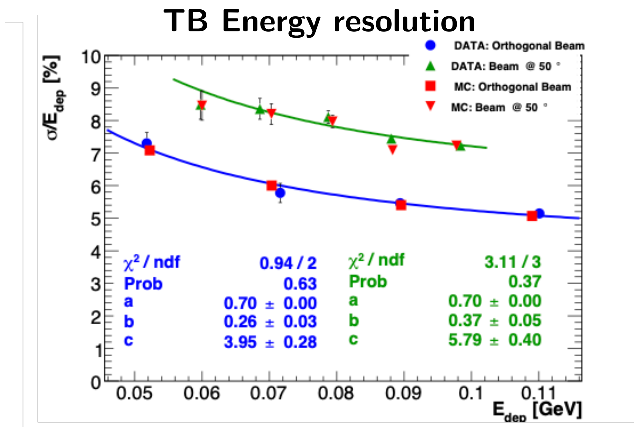


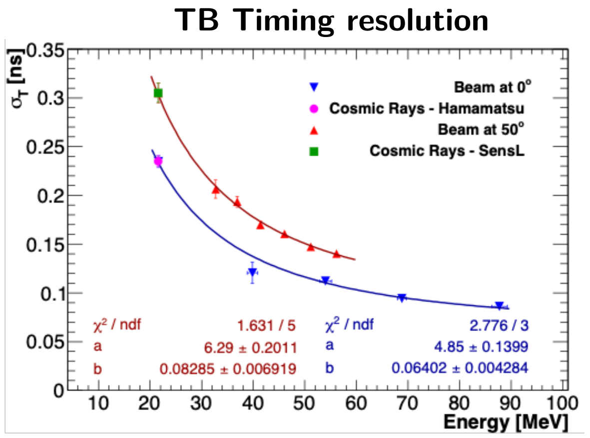


Summary of the calorimeter performance

- Module-0 w/ final readout chain: **Large scale prototype** w/51 crystals matrix
  - Test Beam to check performance
  - Check installation procedure and cooling

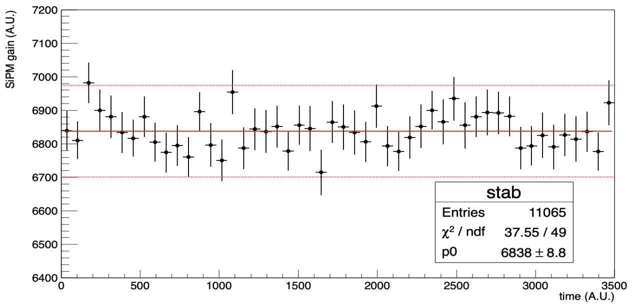




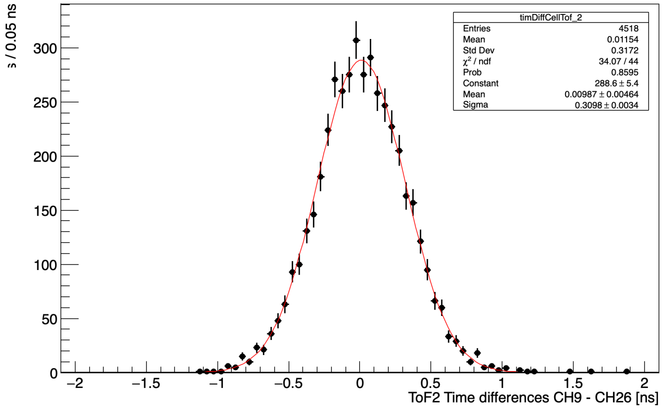


- XY (+ YZ slope) MIP track reconstruction
- Energy equalization on 21 MeV MIP peak
- NPE (from asymmetry) and SiPM gain stability check
  (+1.6 % /°C for SiPM gain)
- Equivalent noise ≈ 200 KeV
- Readout channels timing offset correction trough iterative algorithm to a level < 5 ps RMS
- Cell mean time resolution w/ MIPs ≈ 210 ps

SIPM gain stability over 2 weeks



mean time difference between 2 crystals w/ 2D ToF



Status and performance

- Module production completed
- Vertical Slice Test ongoing on 8 channels
- Aging test ongoing: 3% year → sufficient LY at the end of run-II to achieve designed veto efficiency
- Calibration and monitoring schemes are being developed in preparation for operations.