

Status of the Mu2e experiment

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on behalf of the Mu2e collaboration

28 May 2025 – Venezia (Italy)

Mu2e Collaboration

253 members,
40 institutions, 6 countries ..
~ 25+25
Active number of PhD-Postdocs



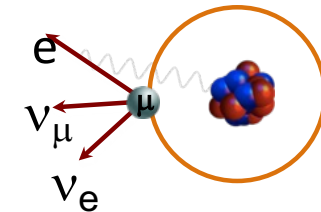
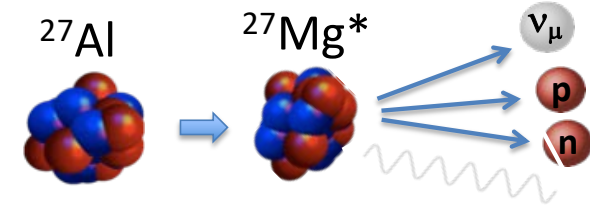
Mu2e goal → x10000 improvements of current sensitivity

- ✓ Mu2e searches for the cLFV conversion of μ^- to e^- in Al nuclei



- ✓ When μ^- are stopped in aluminum a muonic atom is formed

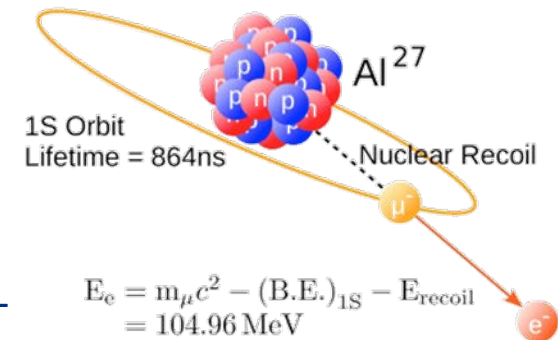
- Prompt cascade to 1s state (0.1 ps)
- 347 keV X-ray emitted – **candidate for normalization**
- Due to high mass, muons circulate in very short radius around nucleus (20 fm)
 - 61% undergo muon nuclear capture, **1.8 MeV line**
 - 39% decay in orbit (**DIO**)
 - few (hopefully 😊) undergo conversion



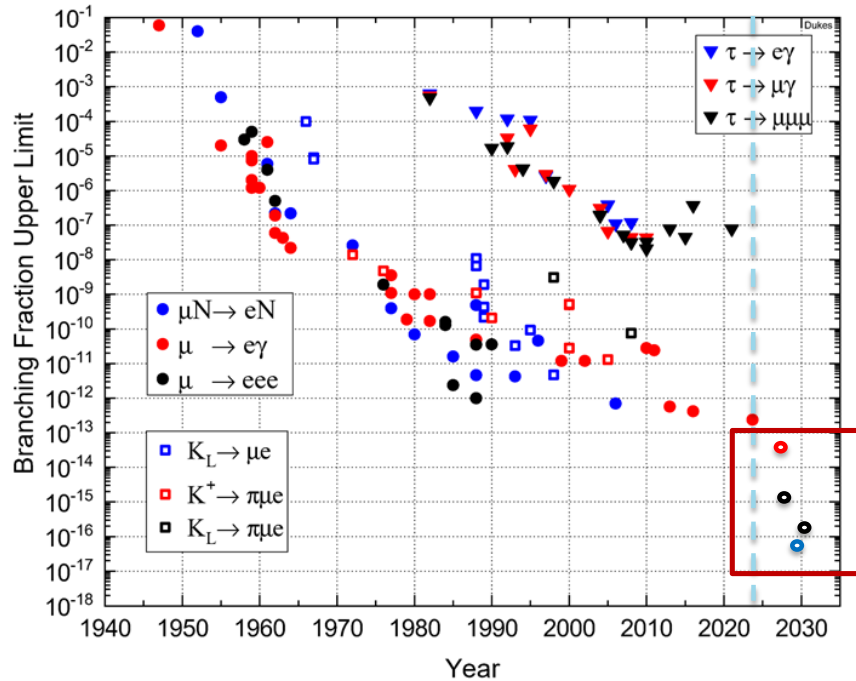
- ✓ Golden signature for conversion is a single monoenergetic electron close to the muon mass
- ✓ Mu2e wants to improve the current sensitivity by four orders of magnitude

$$R_{\mu e} = \frac{\mu^- + N(A, Z) \rightarrow e^- + N(A, Z)}{\mu^- + N(A, Z) \rightarrow \nu_\mu + N(A, Z - 1)} < 8.4 \times 10^{-17}$$

@ 90% CL



Current status of CLFV searches and muon sector relevance



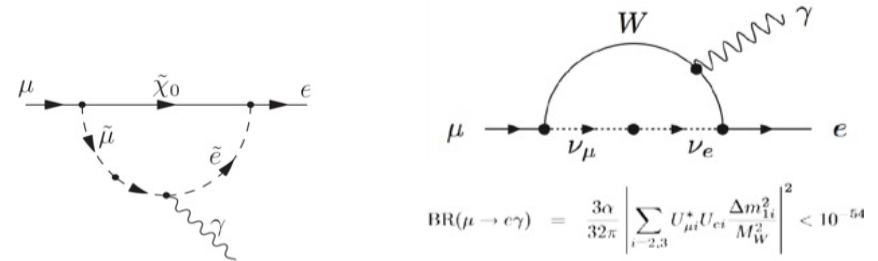
MEG+MEG-2
UL < 1.3E⁻¹³

W. Altmannshofer, *et al*, arXiv:0909.1333 [hep-ph]

	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\phi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \rightarrow X_s \gamma)$	★	★	★	★★★	★★★	★	?
$A_{78}(B \rightarrow K^* \mu^+ \mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \rightarrow K^* \mu^+ \mu^-)$	★	★	★	★	★	★	?
$B \rightarrow K^{(*)} \nu \bar{\nu}$	★	★	★	★	★	★	★
$B_s \rightarrow \mu^+ \mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \rightarrow \pi^+ \nu \bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \rightarrow \pi^0 \nu \bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \rightarrow e \gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \rightarrow \mu \gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \rightarrow e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
d_n	★★★	★★★	★★★	★★	★★★	★	★★★
d_e	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

Table 8: “DNA” of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

- Only SM background is from neutrino oscillations at BR~10⁻⁵²
- Observation of the CLFV events is therefore a clear sign of new physics
- We can explore range of new masses up to 10⁴ TeV
→ an unexplorable land for current (or foreseen) high-energy colliders



$$\text{BR}(\mu \rightarrow e \gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54}$$

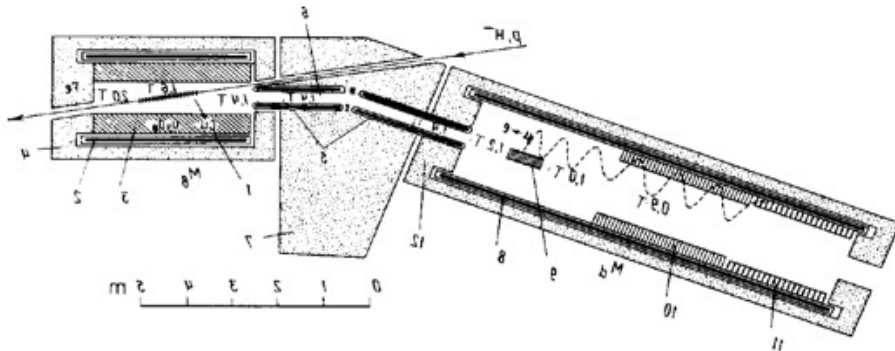
Mu2e how to: x 10000 improvements (1)

1. High statistics: $O(10^{18})$ stopped muons needed in 5 years

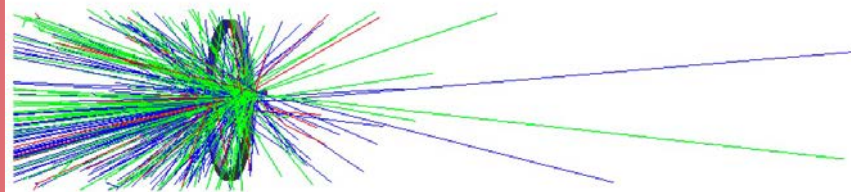
- Highest intensity muon beam in the world (~ 10 GHz on stopping target)
- required x1000 improvement wrt Sindrum-II (PSI, 10^7 muon/sec, 1 MW) \rightarrow **GW beam is excluded**
- Use multi-gradient solenoidal system to produce, transport, focus the muon beam from pion decays generated by a 8 GeV proton beam on a production target

(first proposed in 1989 for the MELC experiment @ Dubna)

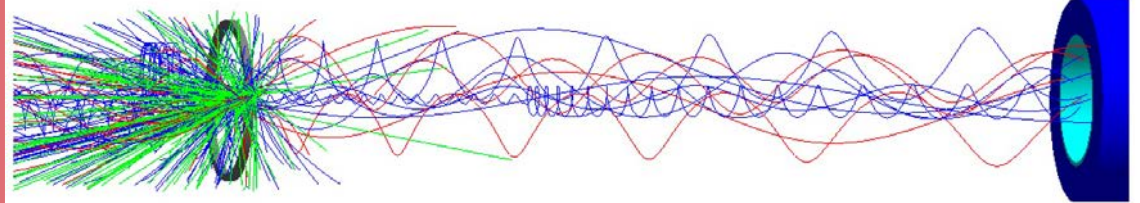
R.M. Dzhilkibaev and V.M. Lobashev
Sov.J.Nucl.Phys. 49, 384 (1989)



Instead of this



Do this



Solenoidal B field confines soft pions. Collect their muons.

Mu2e: $> 10^{10} \mu^-/s$ from only 8 kW of protons!

Mu2e how to: x 10000 improvements (2)

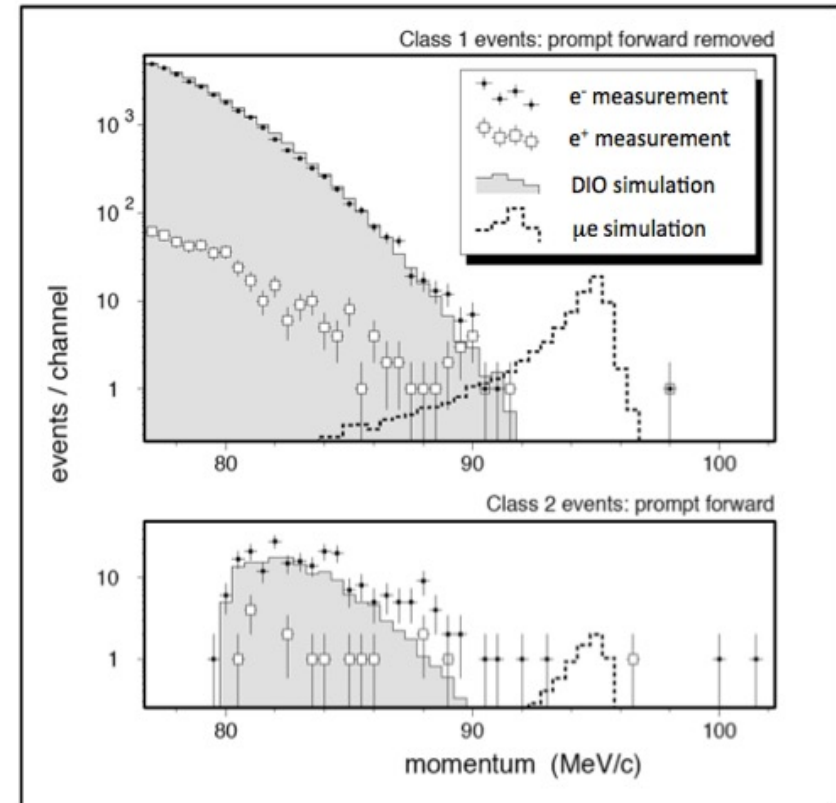
2. High background rejection

- Sophisticated/state of the art detector, TDAQ and reconstruction to isolate signal candidate a reduce irreducible background (DIO) and other backgrounds (CR, ...) to < 0.5 events

3. Pulsed beam

- Need to separate prompt background to satisfy 2nd requirement
- **Radiative pion capture**
(RPC, $\pi^- N \rightarrow \gamma N'$, $\gamma \rightarrow e^+ e^-$; $\pi^- N \rightarrow e^+ e^- N$)
- Main background for the Sindrum-II experiment at PSI

4. Provide proton extinction and measure it



Mu2e how to – background control

Anything that produces 105 MeV/c like-electron signal can be background

▪ Muon DIO:

- Free muon decay has maximum energy of = 52.8 MeV
- Presence of nucleus distorts the DIO spectrum shape;
- reconstruction uncertainties and detector energy loss smear out the monoenergetic peak

➔ MITIGATION: **High Precision Tracking (< 200 keV @ 100 MeV)**

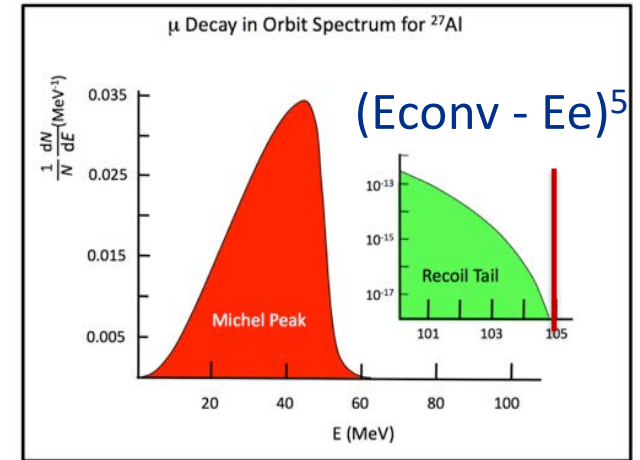
- Primary beam related backgrounds: muon/pion decay in flight, beam e-
- Cosmic rays interacting with detector material

➔ MITIGATION: **Offline Veto of Incoming Cosmic rays (CRV detector)**
PID mu/e (Calo/Tracker)

- Antiproton induced backgrounds
 - Annihilation, various interactions with detector
- MITIGATION: **absorber in muon beamline**

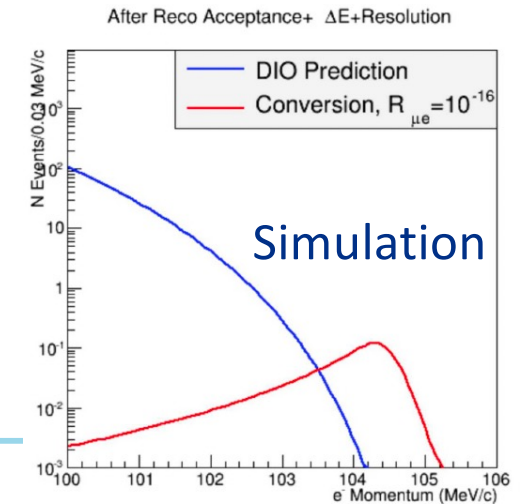
- Accidental activity

➔ MITIGATION: **excellent resolution and fast detectors**



E_e (MeV)

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



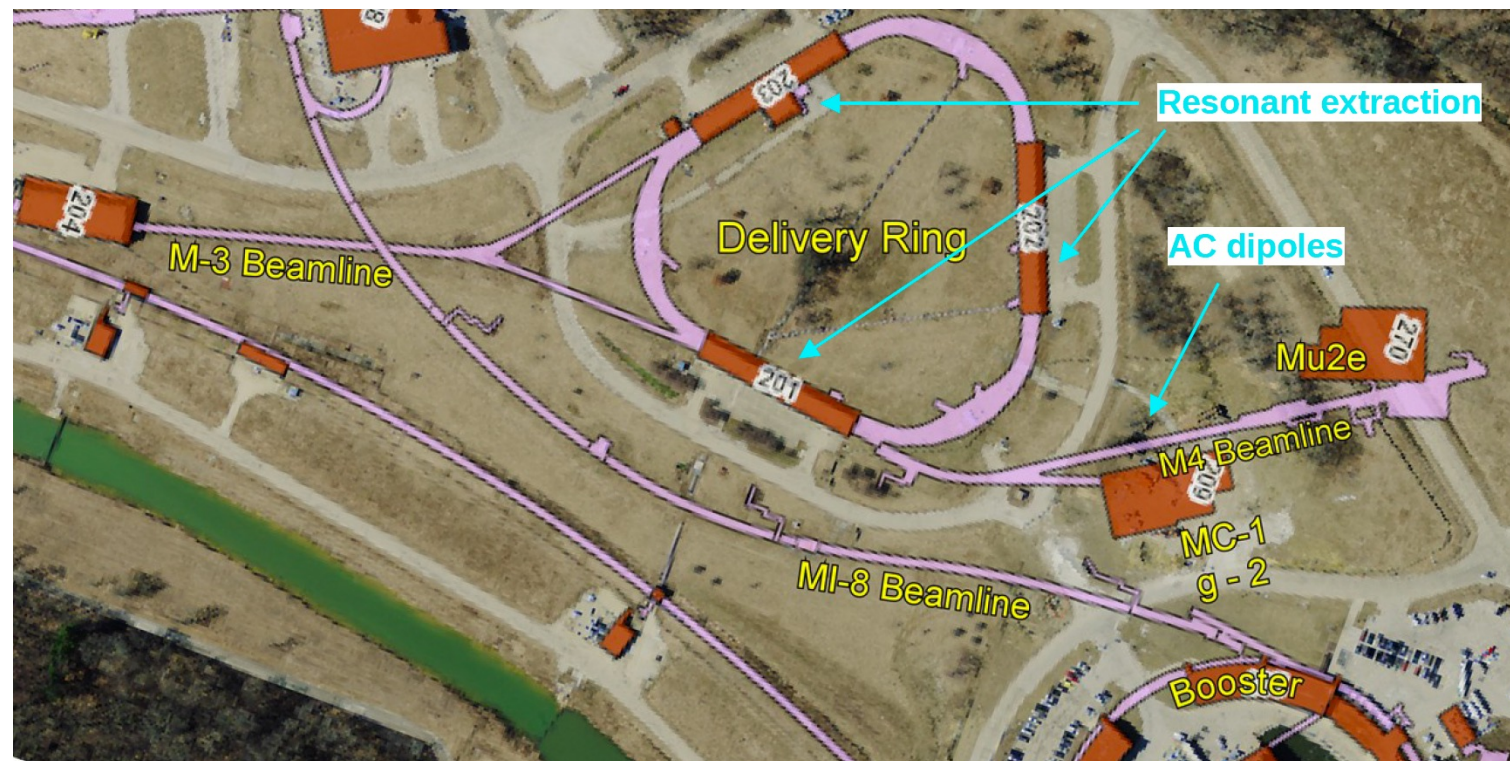
nilab

Accelerator Proton beam

8 GeV protons from the Booster are re-bunched in the Recycler and then stored in the Delivery ring

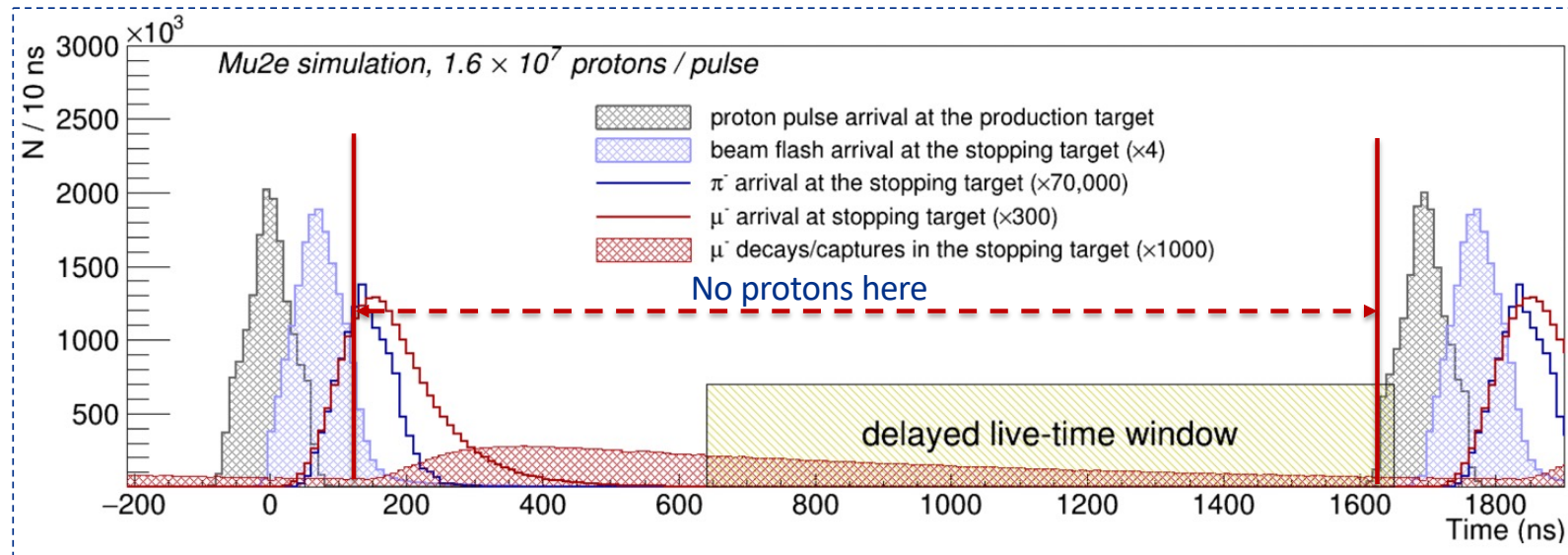


Proton bunches from the Delivery Ring are then slowly extracted to the experiment every $1.7 \mu\text{s}$



Pulsed proton beam and extinction

- Each pulse: 1695 ns ($\sim 2 \tau_{\mu}^{\text{Al}}$)
- High intensity $\rightarrow 3.9 \times 10^7$ protons
- Low intensity running $\rightarrow 1.6 \times 10^7$
- **Inter-bunch proton extinction ratio (fraction out of bunch) $< 10^{-10}$**



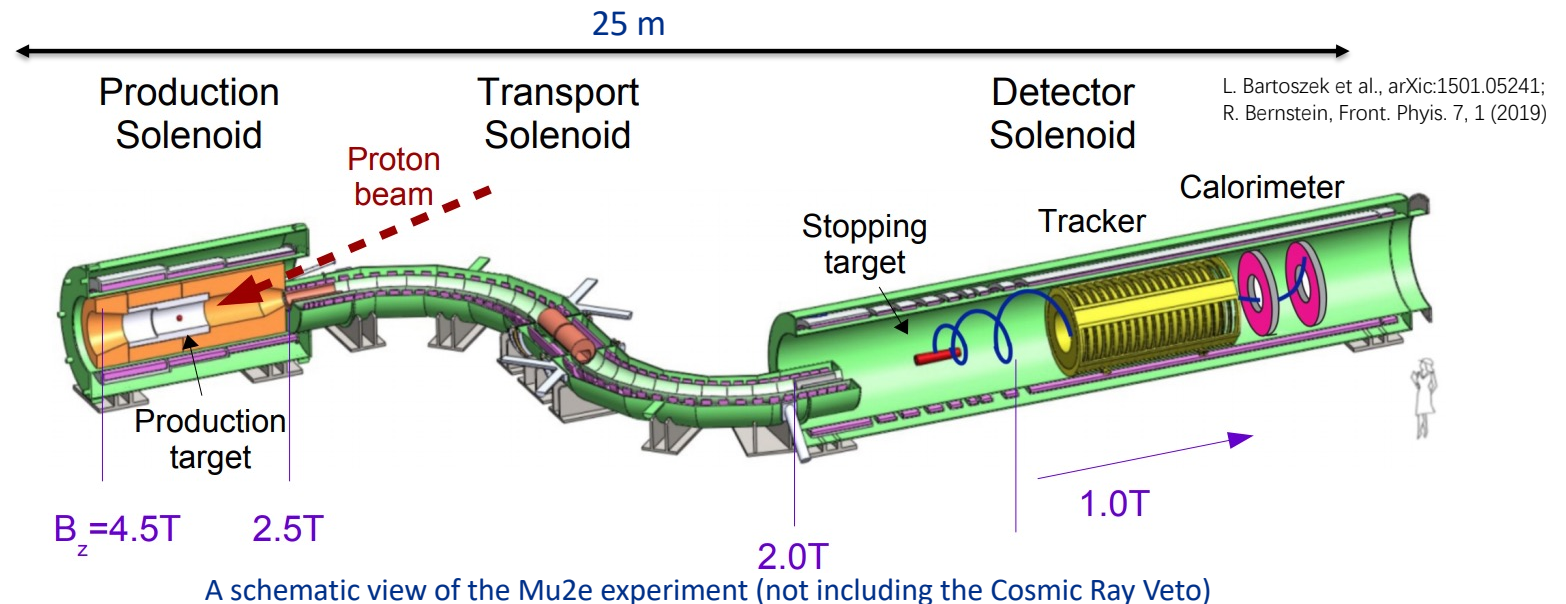
Proton extinction from two sources:

- Bunch formation in recycler (10^{-5})
- AC-dipole sweeping magnets ($10^{-(5-6)}$)

Mu2e experiment layout

- **Production solenoid (PS)**
 - Contains tungsten production target
 - Gradient magnetic field sweeps pions/muons to transport solenoid
- **Transport solenoid (TS)**
 - S-shaped; collimator in the middle selects sign and momentum
 - Absorbers to remove antiprotons at center of S
- **Detector solenoid (DS)**
 - Al muon stopping target
 - Proton absorber to reduce accidental events
 - Straw tube tracker provides momentum measurement, electromagnetic calorimeter differentiates particles through energy deposition
- Searching for 105 MeV electrons, with a 180 keV/c momentum resolution

- Gradient field from 4.5 to 1 T in beamline
- 1T uniform field in Tracker/Calo region
- Muon charge selection With rotating collimator
- Symmetric detector: measure e^- and e^+ simultaneously



Solenoids status – TS

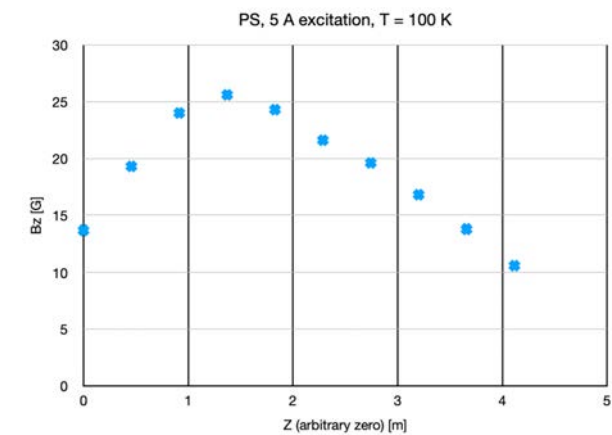
- Transport solenoids delivered: 12/23 (TSU) 2/24 (TSD) & installed in Mu2e hall
- Rotating collimator and Antiproton absorber installed
- Cryogenic system connection well progressing



Solenoids status - PS

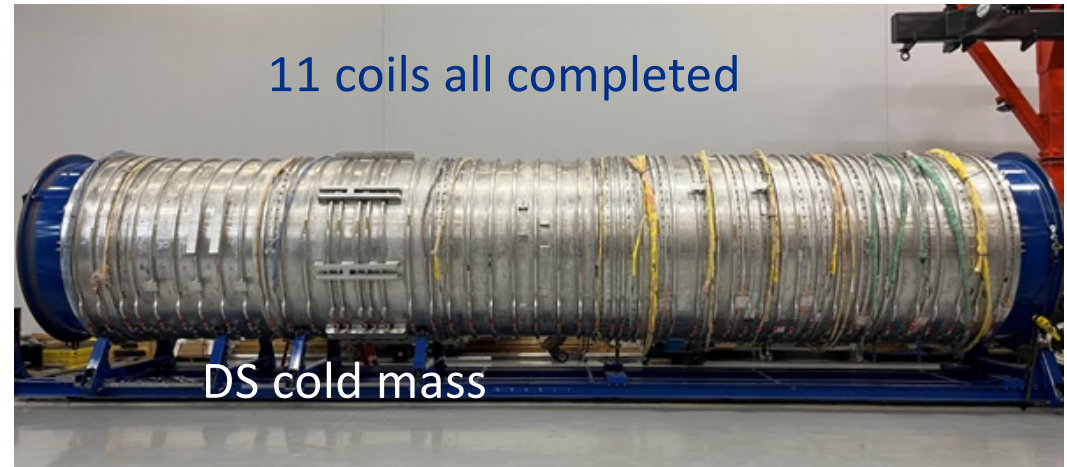
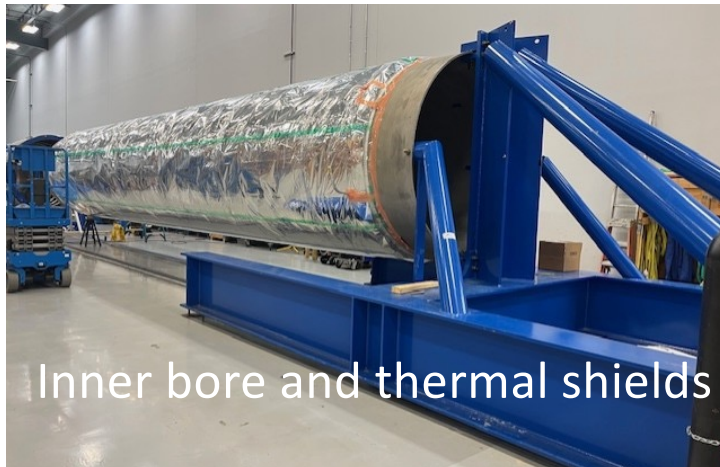
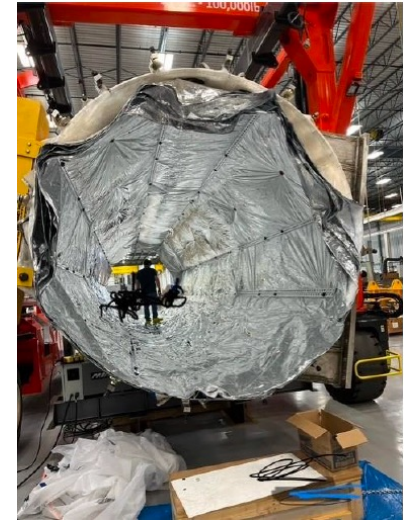


- PS assembly completed in winter 2024
- Successful cooldown + instrumentation tests
- Successful magnetic field and heat load test
- Preparing for shipment from vendor to FNAL
- Current delivery date: July 2025



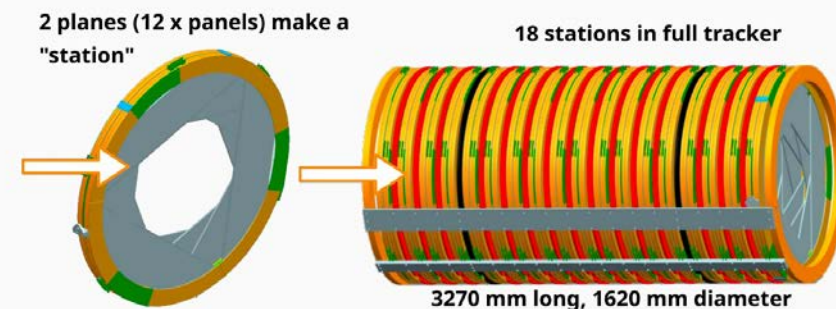
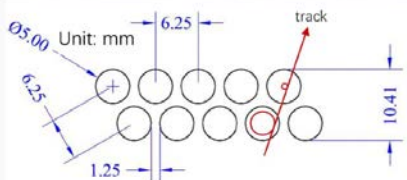
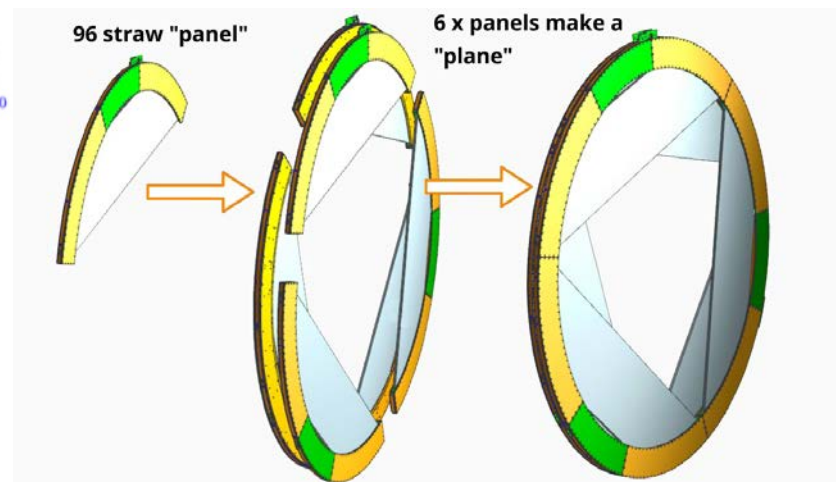
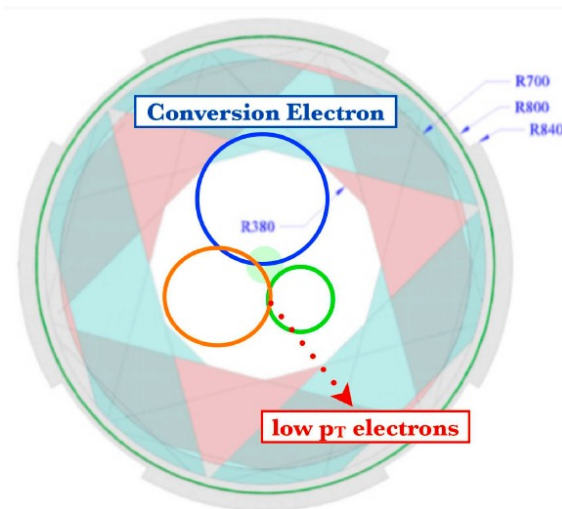
Solenoids status - DS

- Insert inner bore into cold mass and cold mass into vacuum vessel
- Build the chimney
- Close up vacuum vessel
- Perform cold test, leak tests
 - Current “realistic” schedule shows delivery for end of 2025

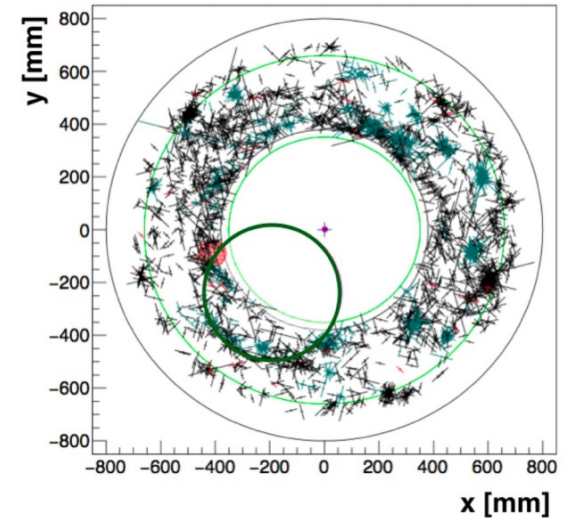
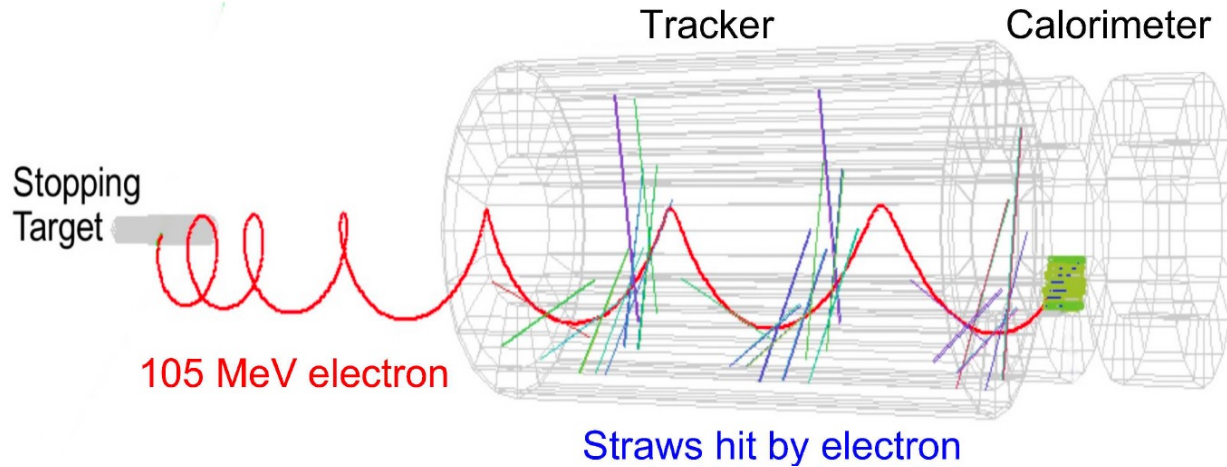


Tracker - design

- Very high precision detector (~ 180 keV for 105 MeV/c CE)
- ~ 21000 mylar straws
- 96/panel x 12(panels) x 18(stations)
- Each straw, 5 mm ϕ , 15 μ m thick Mylar walls, 25 μ m W wire
- 1 Atm of 80/20 Ar/CO₂
- Blind to most of low momentum tracks \rightarrow Annular design

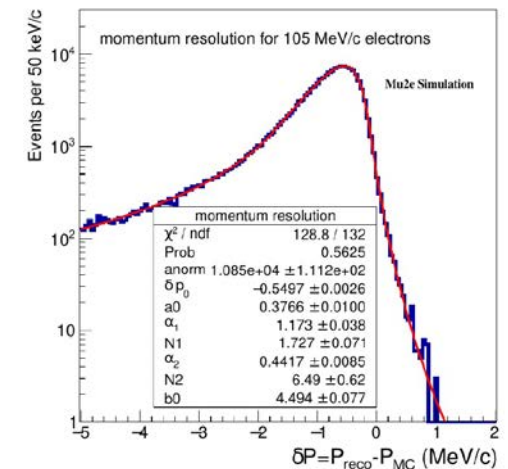
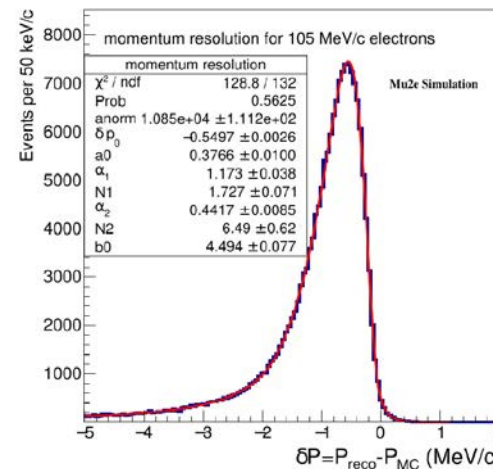


Tracker - performance



- 105 MeV signal makes 1.5-3 turns
 - 40 straw hits
- High pileup rate (100 kHz/straw)
- No external T0 constraint
- Intrinsic mom. resolution < 200 keV

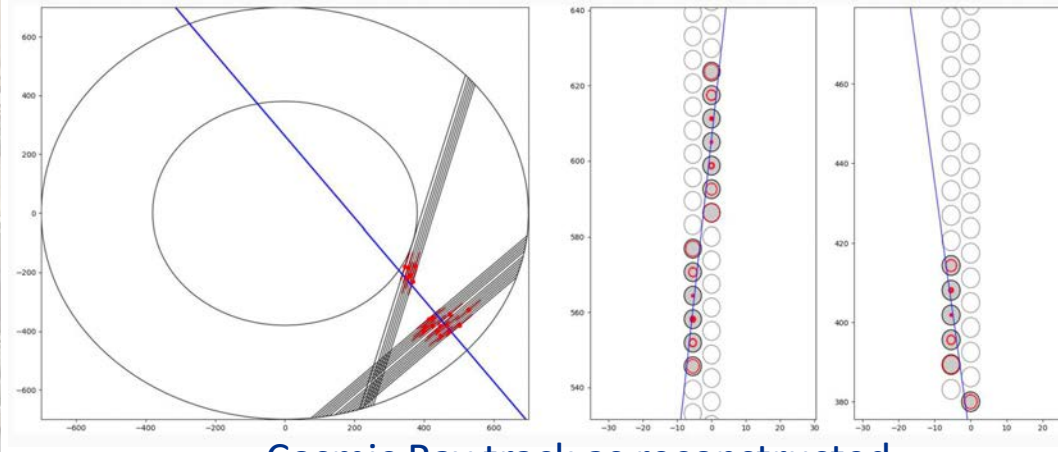
Mu2e simulation*



Tracker – construction status



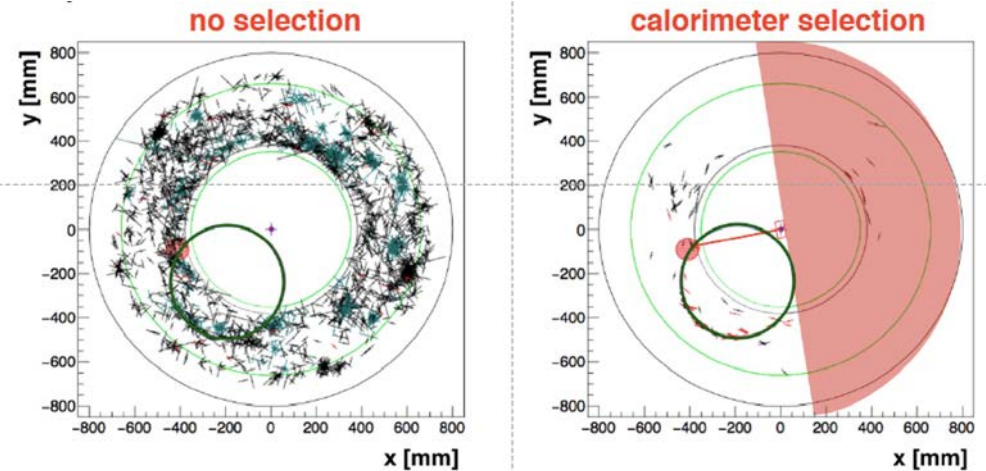
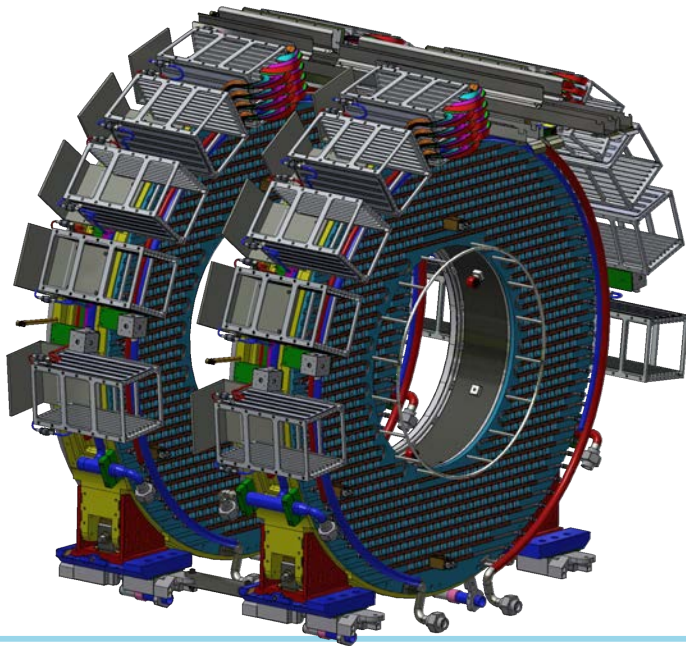
- ✓ 100 % of panels (216) and planes (36) completed.
- ✓ All electronics delivered.
- ✓ Installation of electronics in progress
- ✓ Assembly of stations in progress (3/18)
- ✓ Advanced status for services and infrastructure
- Expect to land in Detector Hall in extracted position – Fall 2025



Cosmic Ray track as reconstructed at the Tracker VST of the station

Calorimeter - design

- 2 disks, each composed of 674 pure CsI crystals with 2 SiPM readout/crystal
- Better than 10% energy resolution at 105 MeV/c
- Better than 500 ps timing resolution at 105 MeV/c
- Keep performances in vacuum and in a high radiation environment

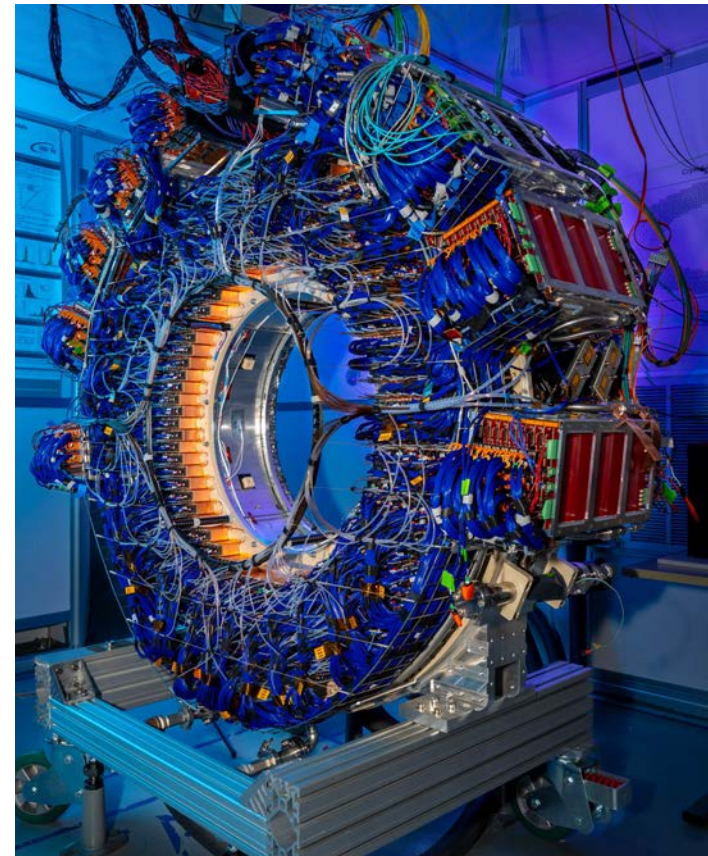
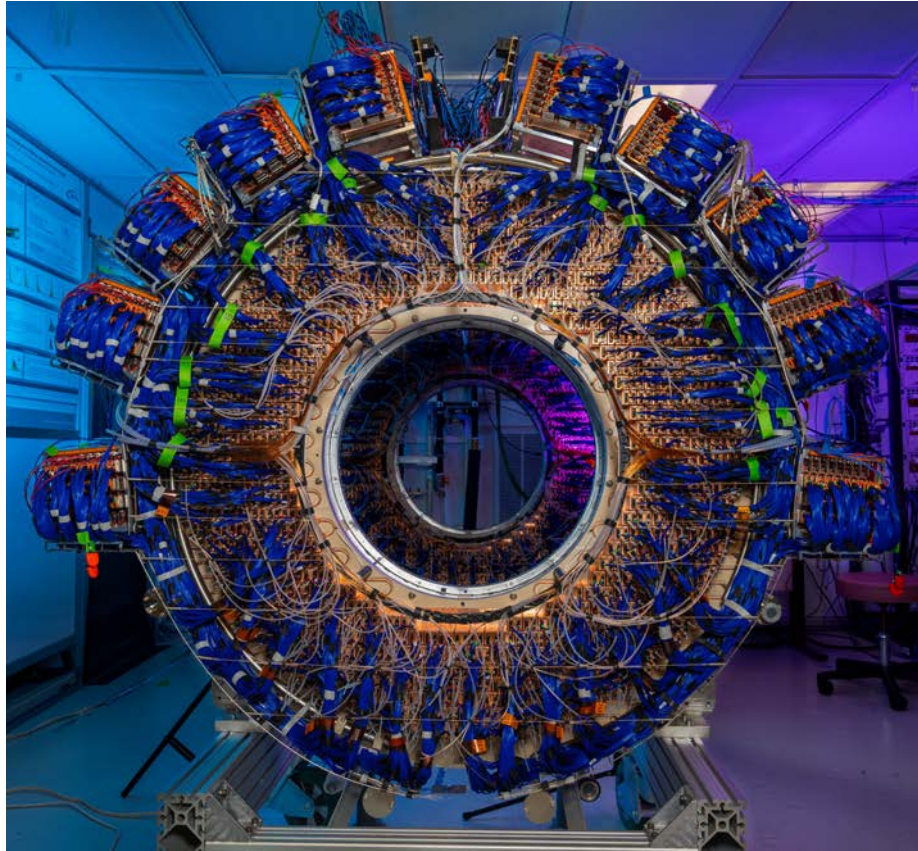


- black crosses = straw hits, red circle = calorimeter cluster, green line = CE track

Calorimeter adds redundancy and complementarity w.r.t. the high precision tracking system:

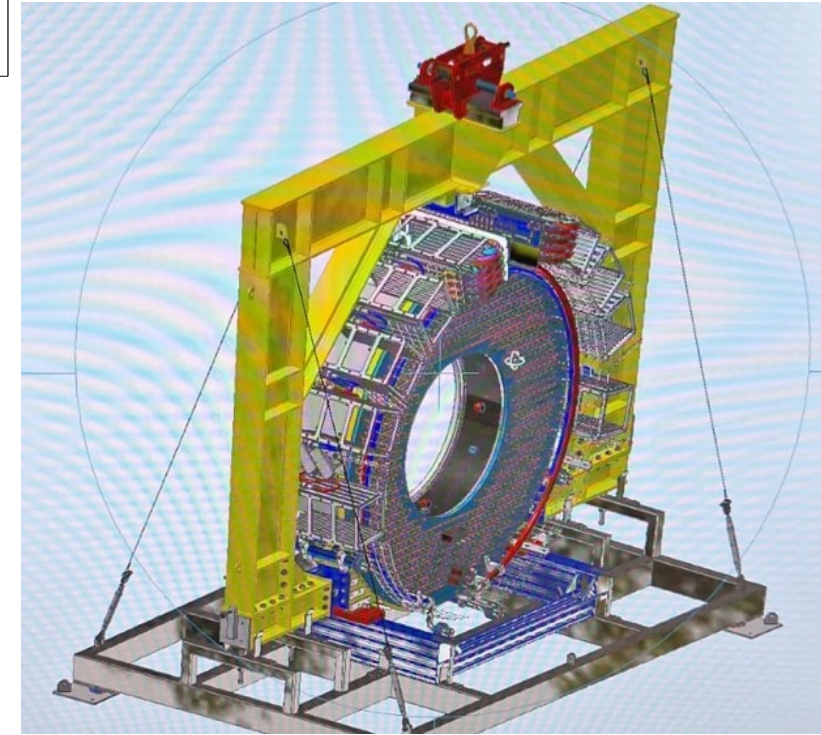
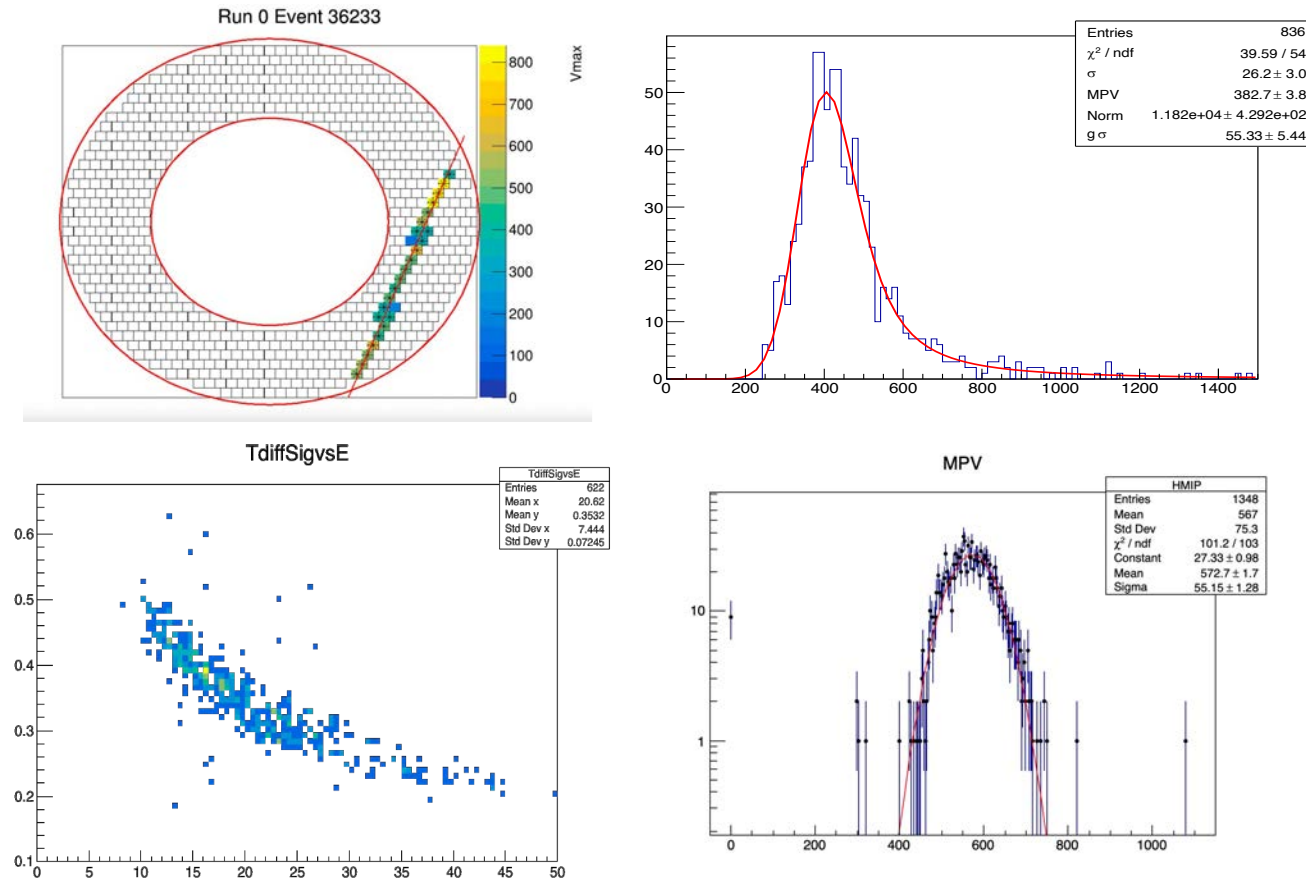
- Large acceptance for mono-energetic conversion electron candidates
- PID with μ/e rejection of 200
- EMC seeded track finder
- Standalone trigger

Calorimeter – construction status



- Disk-0 and Disk-1 fully assembled including all digital electronics and cables from FEE to Digital boards
- TDAQ readout of Disk1 carried out in September/December 2024
- TDAQ readout of Disk0 in progress since February 2025 → Final commissioning runs in May/June

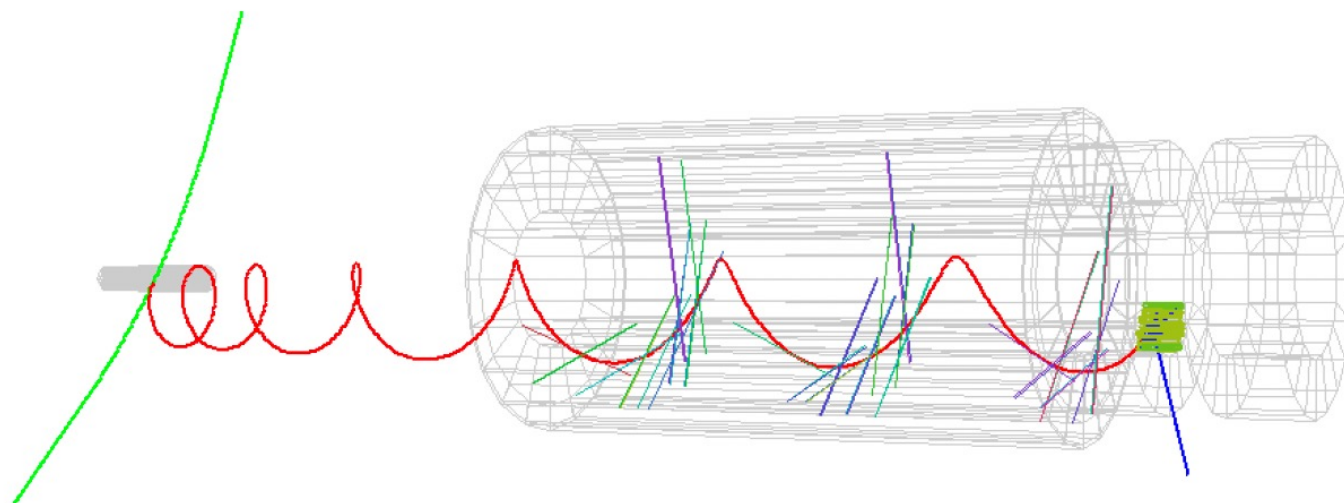
Calorimeter – tests and planning



- ✓ Successful readout of all channels and good data quality.
- ✓ Transportation in Mu2e building planned for middle of June 2025

Cosmic Ray background

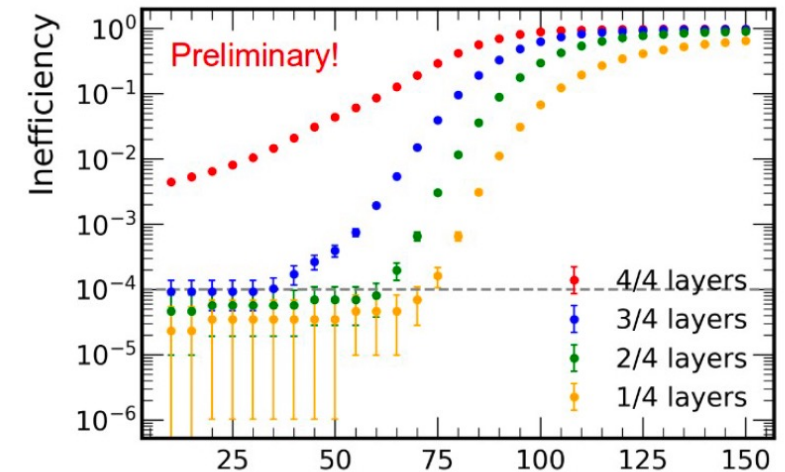
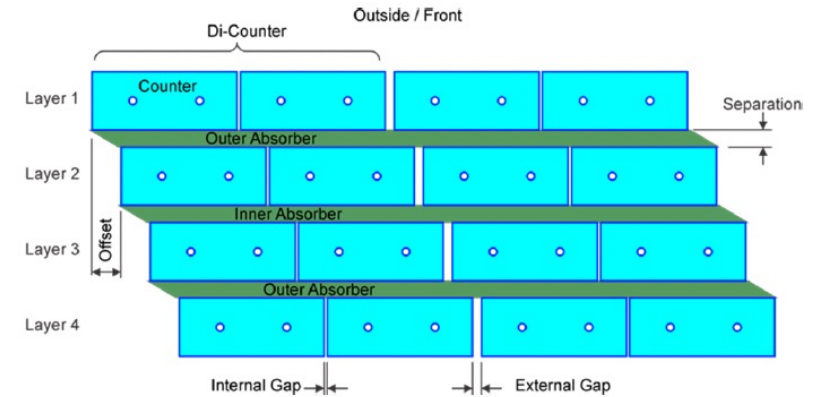
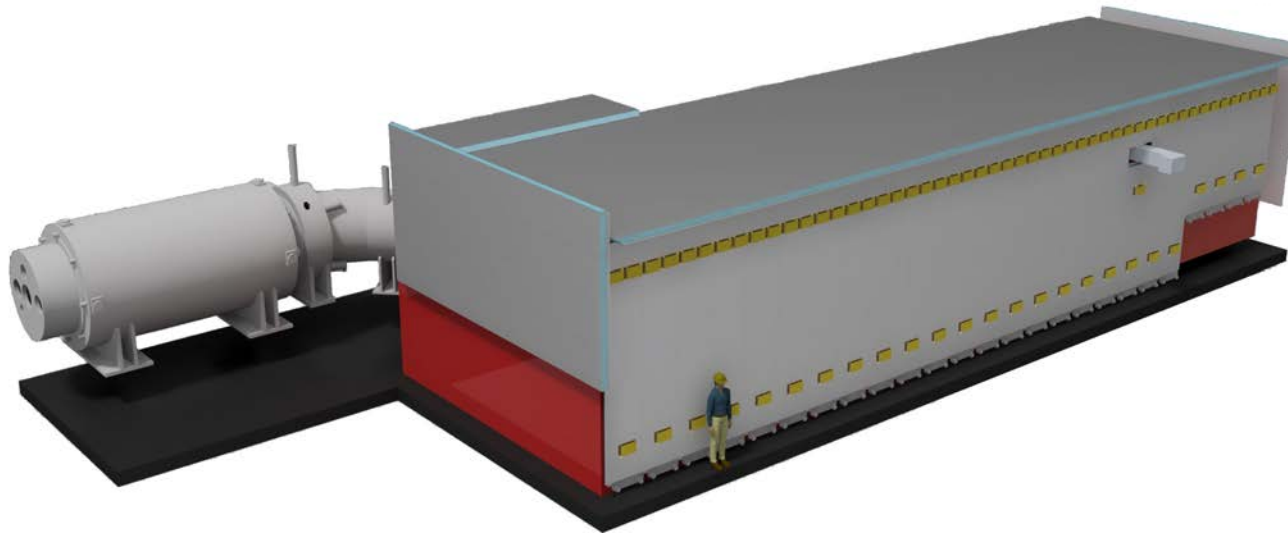
- ❑ Cosmic ray tracks can mimic a 105 MeV/c electron track
- ❑ A cosmic muon can decay or knock out electrons from a detector material



- ➔ Expect 1 CR-related background event/day to produce tracks in signal momentum region
- ➔ Need “offline” VETO for incoming cosmic muons with high efficiency and high coverage
- ➔ Need PID to discriminate muons from electrons

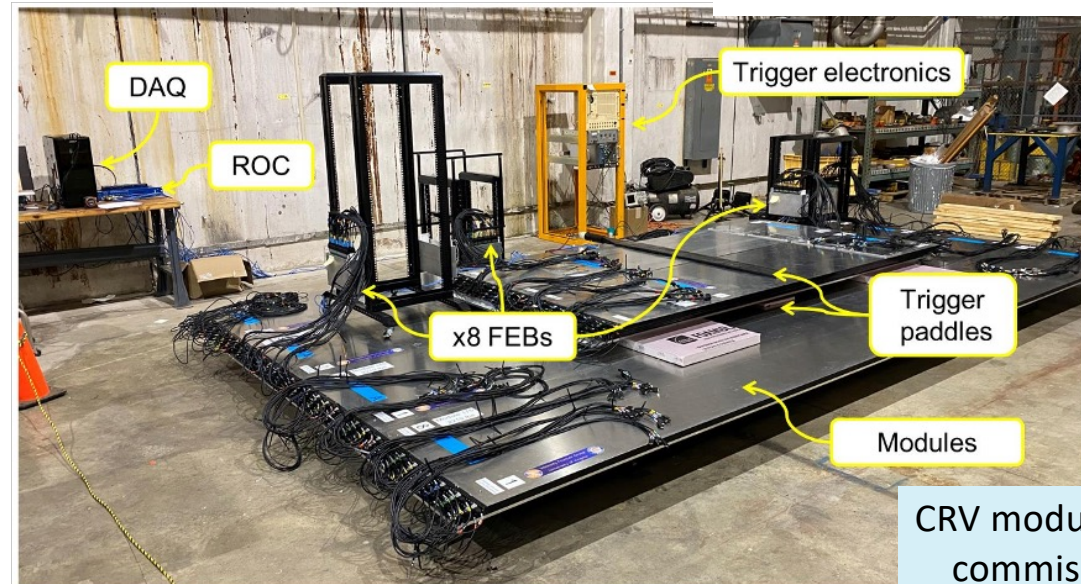
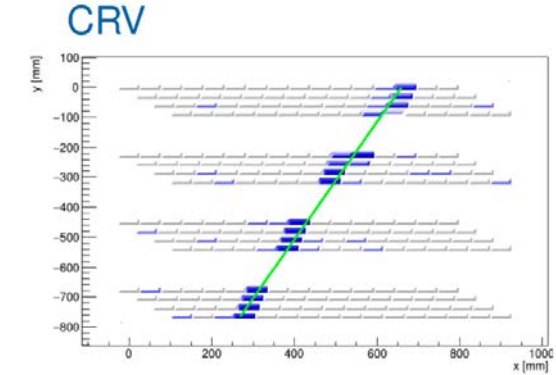
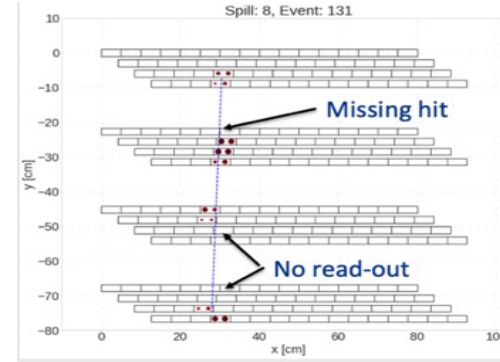
Detectors: Cosmic Ray Veto detector - design

- ✓ **Very high efficiency (> 99.99%) over 300 m²**
for full DS coverage and part of TS
- ✓ Technology: Four layers of extruded polystyrene scintillator with embedded WLS fiber and SIPM readout interleaved with aluminum absorbers
- ✓ 3/4 layers fired for Veto → efficiency demonstrated with current detector



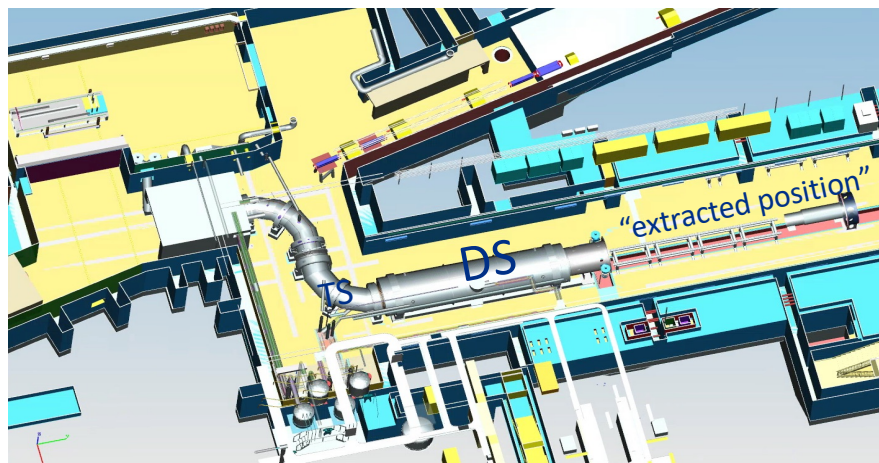
Cosmic Ray Veto detector status

- ❑ Complete procurement of new FEB – ongoing now
- ❑ Complete mechanical structure for CRV installation
- ❑ Installation will proceed after shielding installation
- ❑ VST progressing greatly
- ❑ Modules for Commissioning in the Mu2e hall ready to be delivered

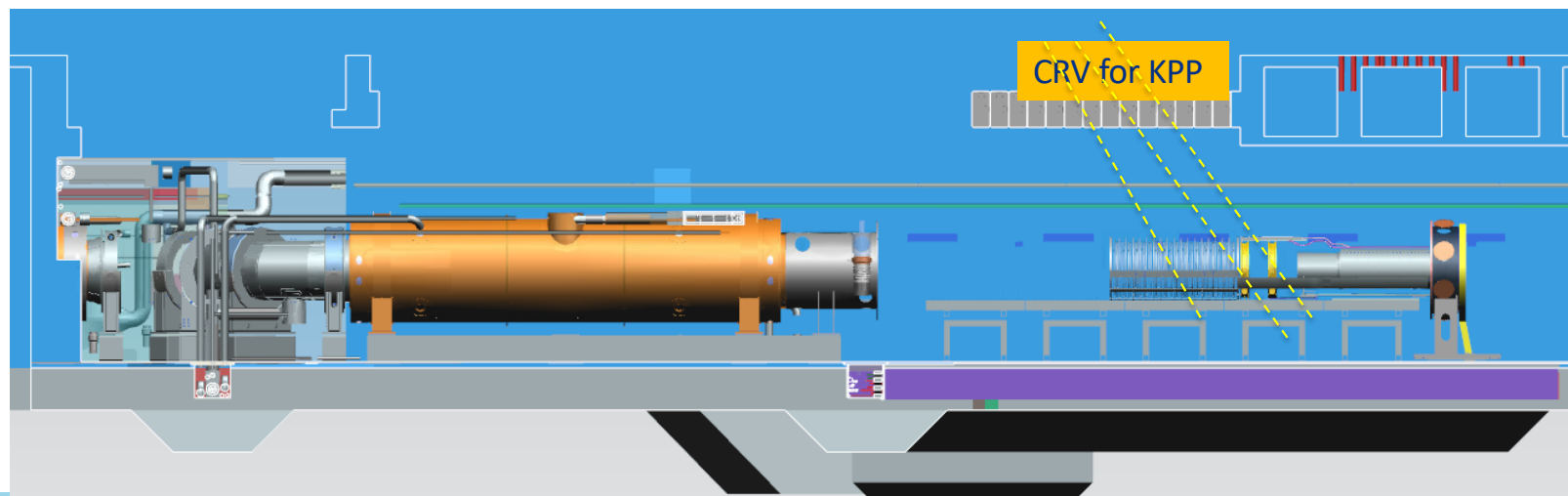


CRV modules for commissioning

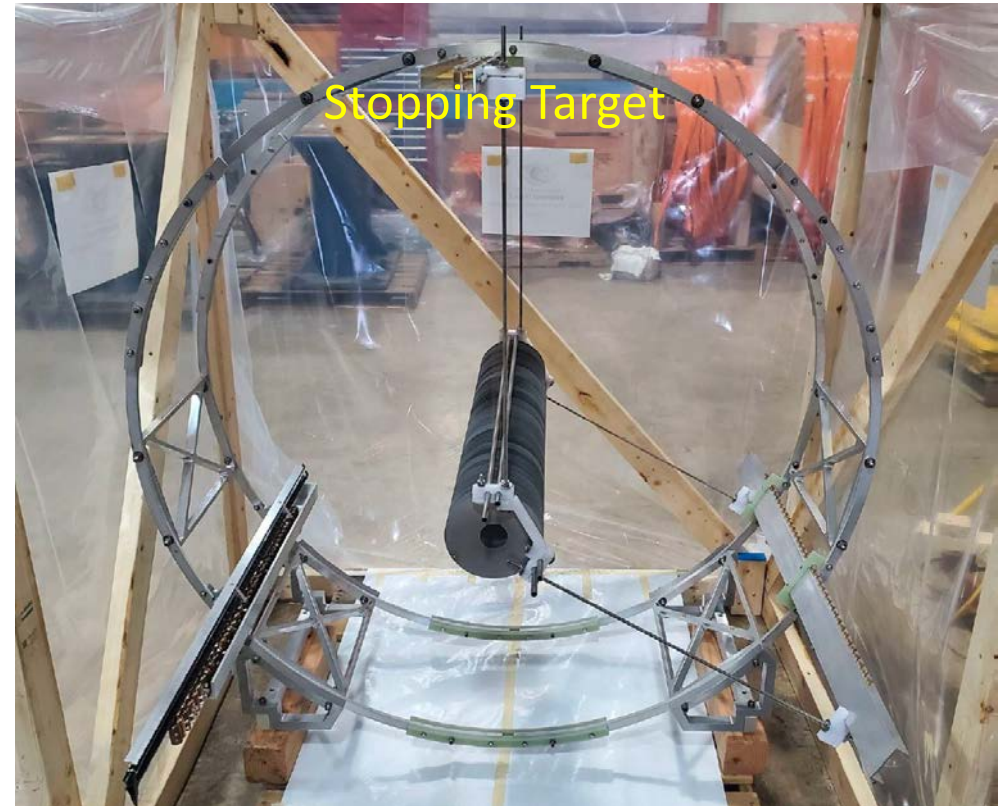
Startup of commissioning –Fall 2025 – extracted position



- ❑ One year+ Cosmic Ray Run with Tracker and Calorimetry & a fraction of CRV in the extracted position (outside the magnet)
- ❑ Exercise TDAQ, online system, and detectors' functionality
- ❑ Calibrate detectors in-situ and perform initial tracker alignment
- ❑ When magnets are ready:
 - insert detectors inside
 - makes test in vacuum
 - run at low temperatures, and with B-Field
- ❑ Keep taking CR data, while waiting for Beam

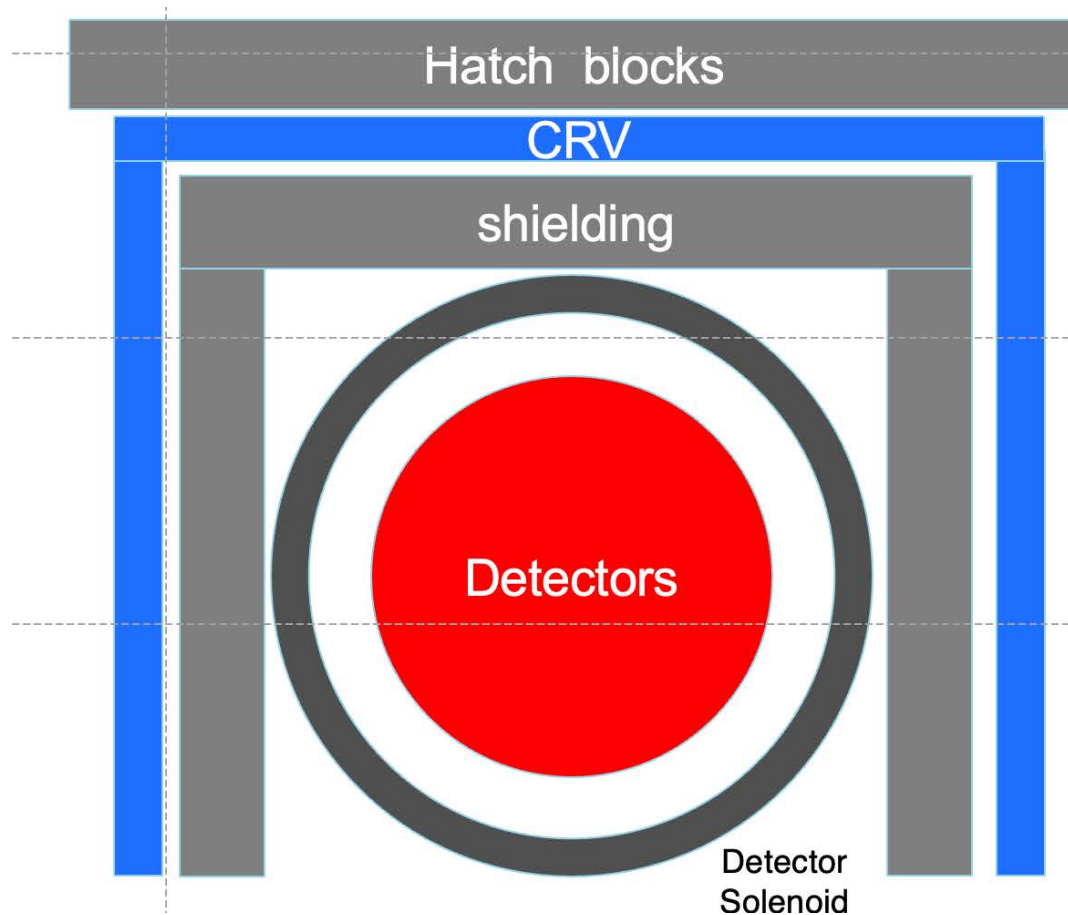


Muon Beam Line



Cumulative experiment effort ongoing to integrate all parts and services for the detectors. Installation sequence now well defined. Preparation for flanges, cabling and vacuum ongoing

Sequence of installation for running with beam

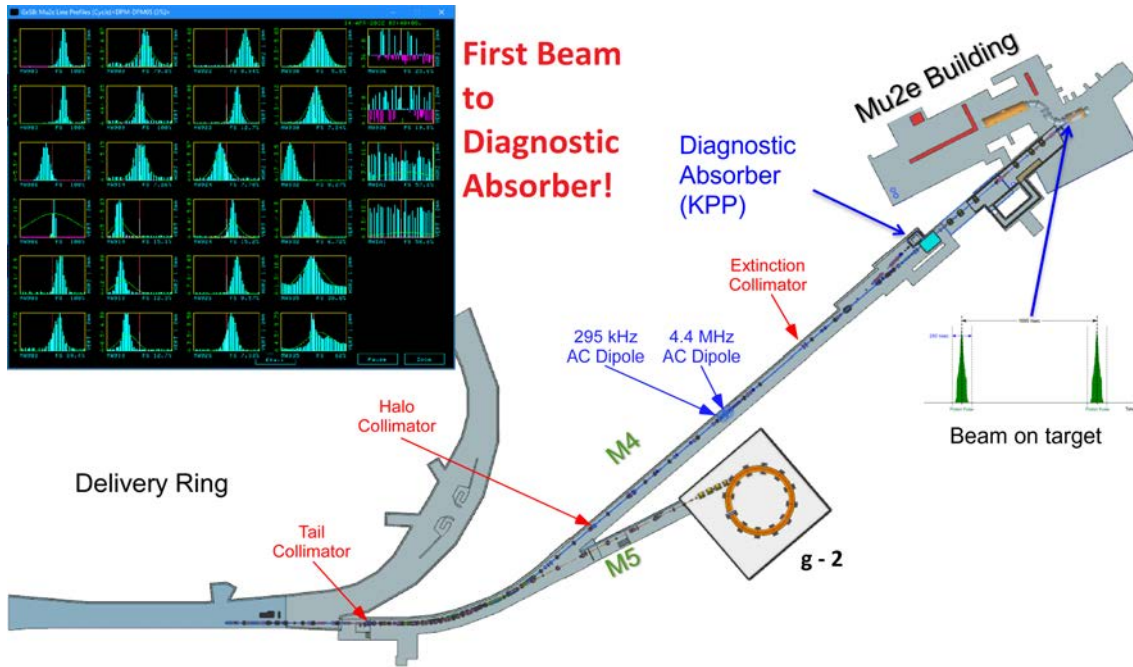


Component	Notes
Detector solenoid	Delivered, installed, cooled and powered
Inner detectors	Inserted into solenoid
External shielding	installation
Final focus	installation
Cosmic ray veto	Construct supports, install
Hatch blocks	Install
Accelerator readiness rev.	Before completion of hatch blocks
Beam to experiment	Soon after completion of hatch blocks

Accelerator achievements – (beam line and beam delivery)

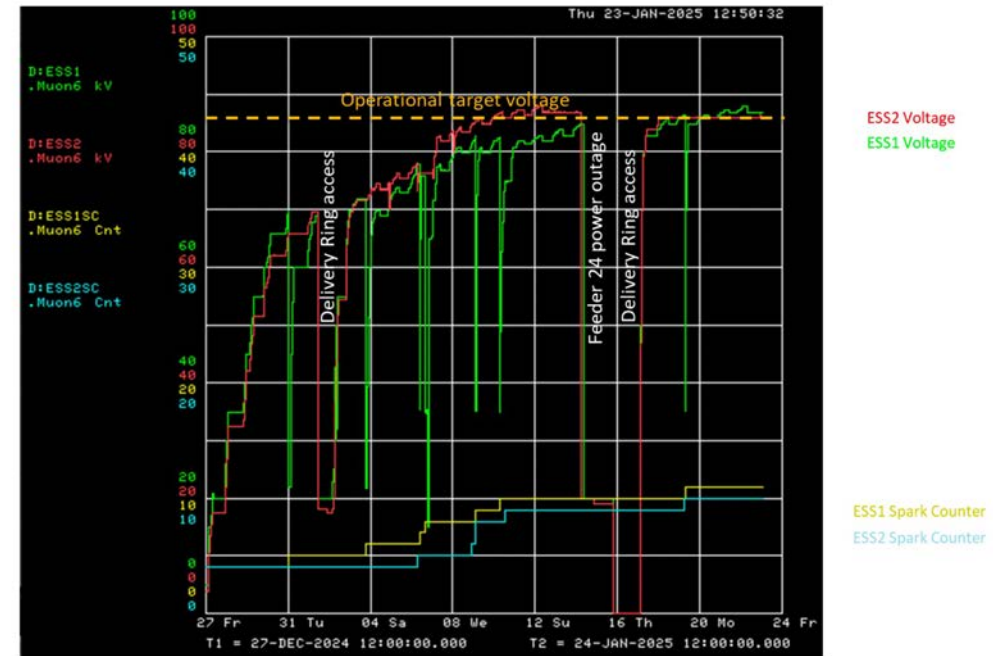
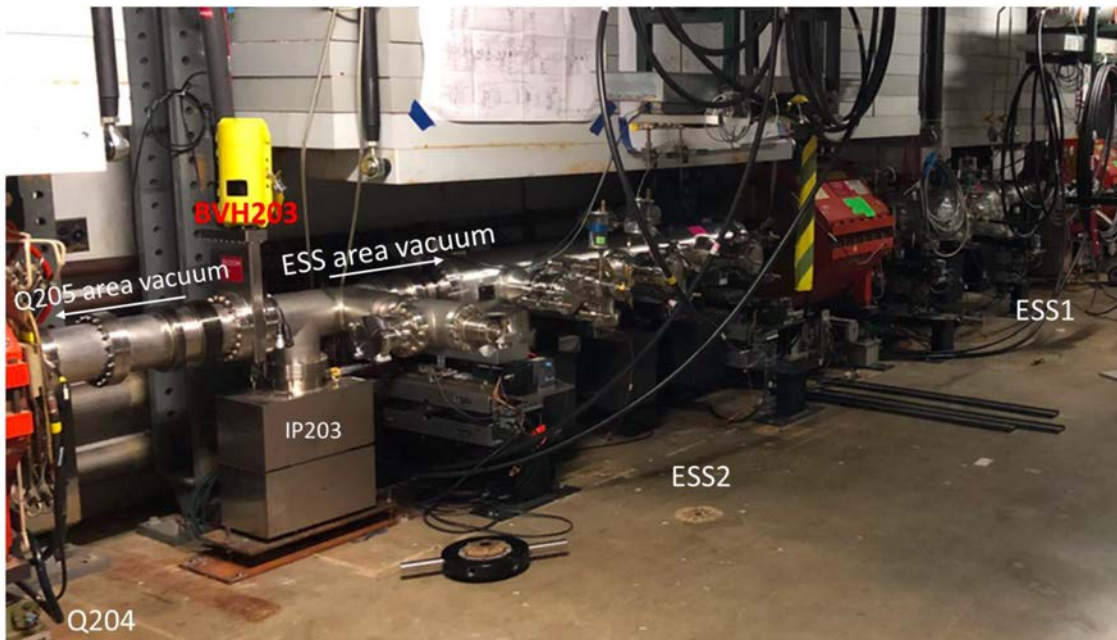
- First **Kicked Beam** to diagnostic absorber – April 2022

✓ beam on the delivery ring slowly- extracted with two ESS (Electrostatic Septa)



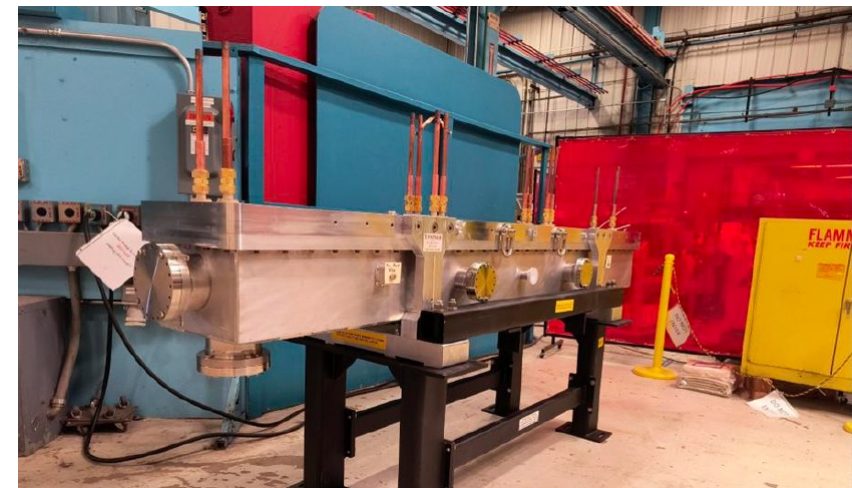
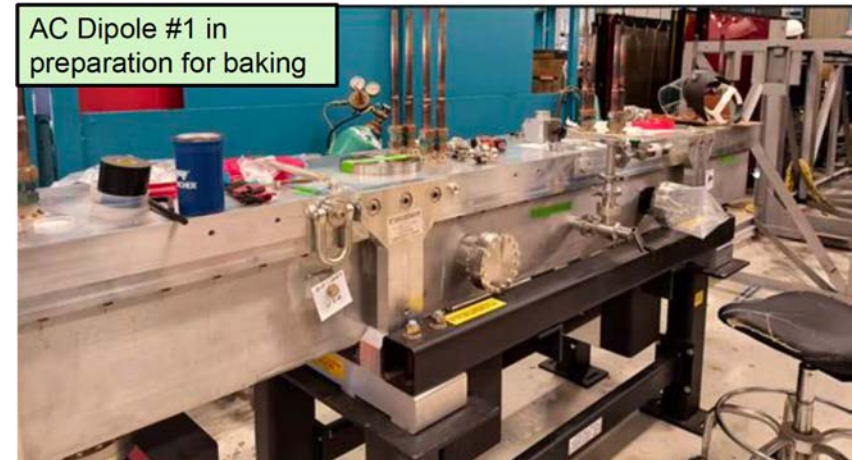
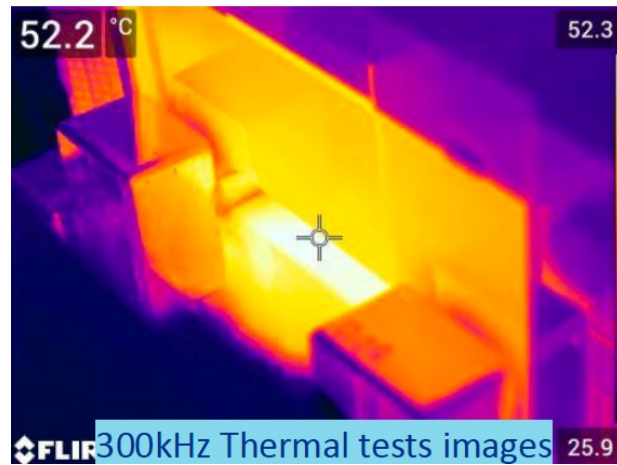
✓ First slow extracted beam with prototype ESS on July 2023

Accelerator achievements: ESS installed



- ❑ ESS1 and ESS2 completed in 2024, tested at full voltage in laboratory
- ❑ ESS1 and ESS2 installed in beam line in June and November 2024
- ❑ Reached full voltage in January 2025
- ❑ Ready for operation with beam

Accelerator achievements – HRS, AC, and final focus

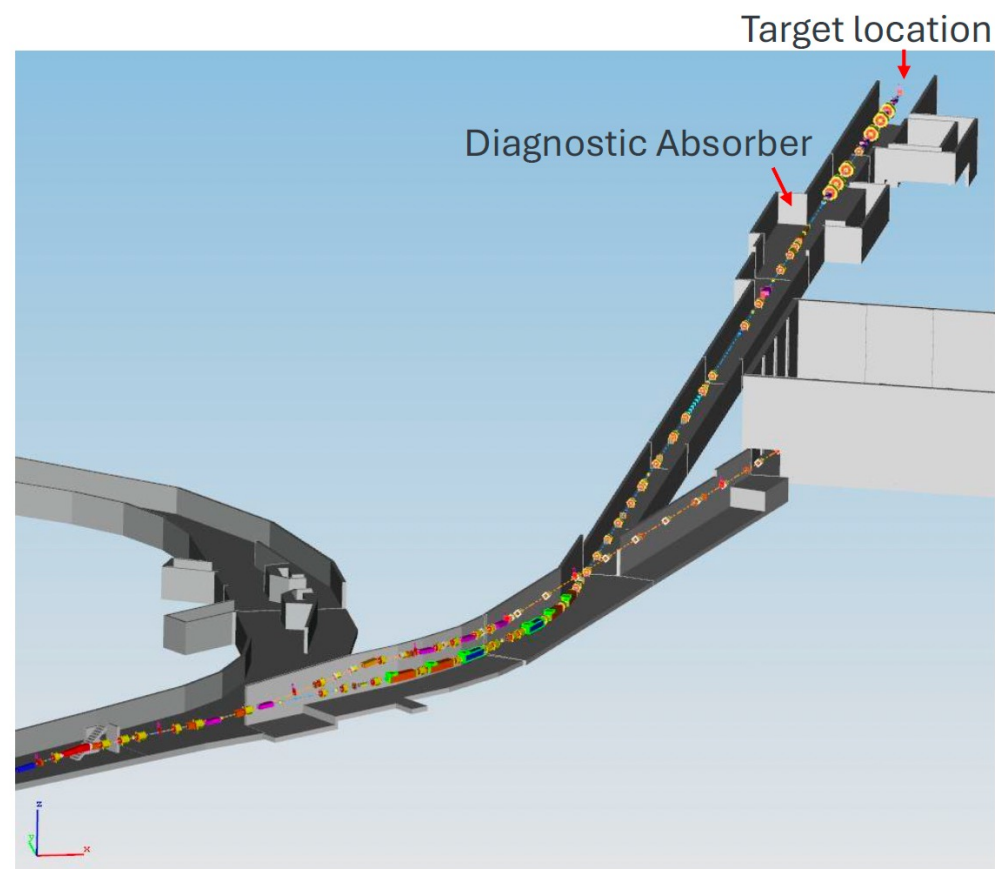


- ✓ HRS (Heat Radiation Shielding) waits for installation inside PS
- ✓ The two “needed” 3m-long AC dipoles completed and under test
- ✓ 1 spare AC dipole in construction
- ✓ Transportation plan in place
- ✓ Next: complete final focus + instrumentation & shielding + study bunch formation

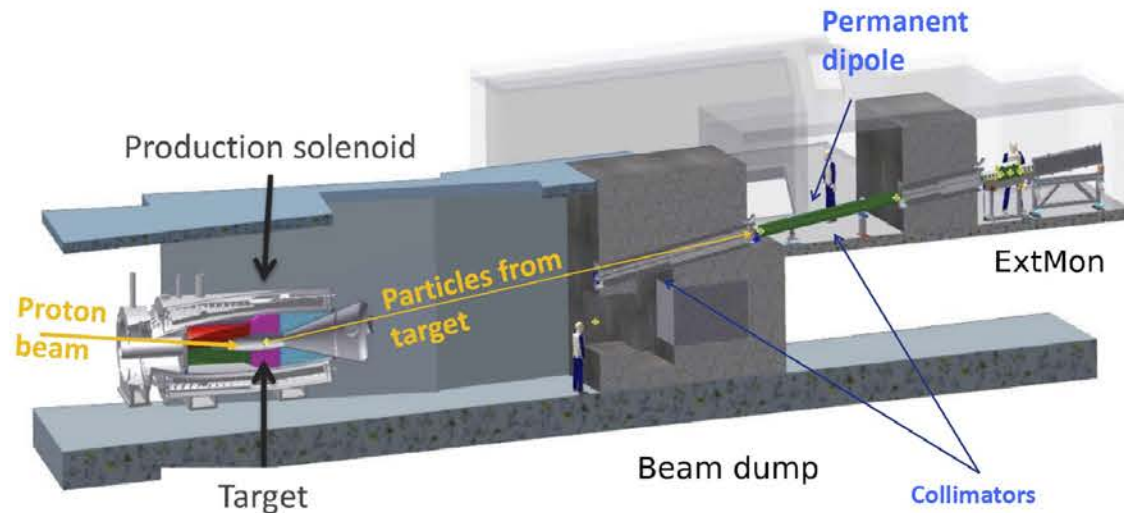
Goals for 2025 beam commissioning run

Beam established on Muon campus at beginning of May, with 2 months commissioning-run underway dedicated to:

- ➔ Establish resonant extraction with full ESS splitting voltage
- ➔ Increase extraction efficiency
- ➔ Advance the spill regulation system commissioning
- ➔ Start measuring upstream extinction



Extinction Monitor (downstream, upstream)



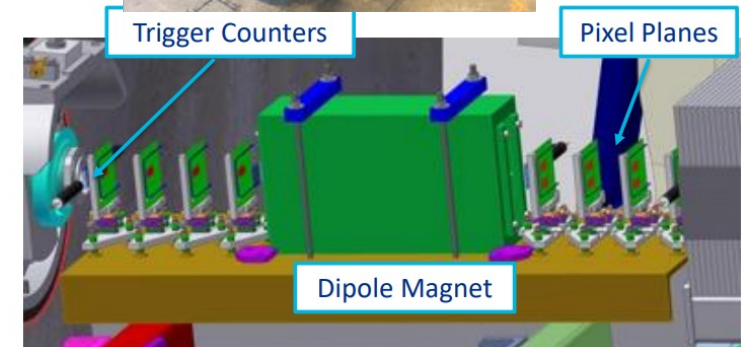
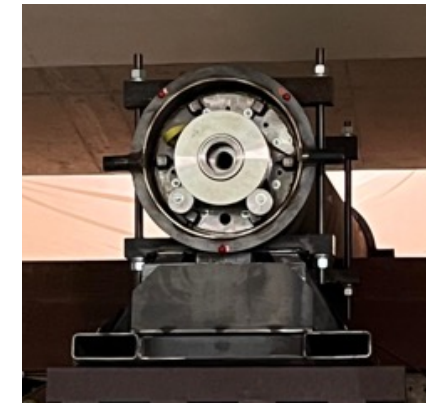
Downstream EXTMON located above and behind the primary beam dump

→ The 2 collimators + 1 dipole select a p/pi beam of $\sim 4 \text{ GeV}/c$

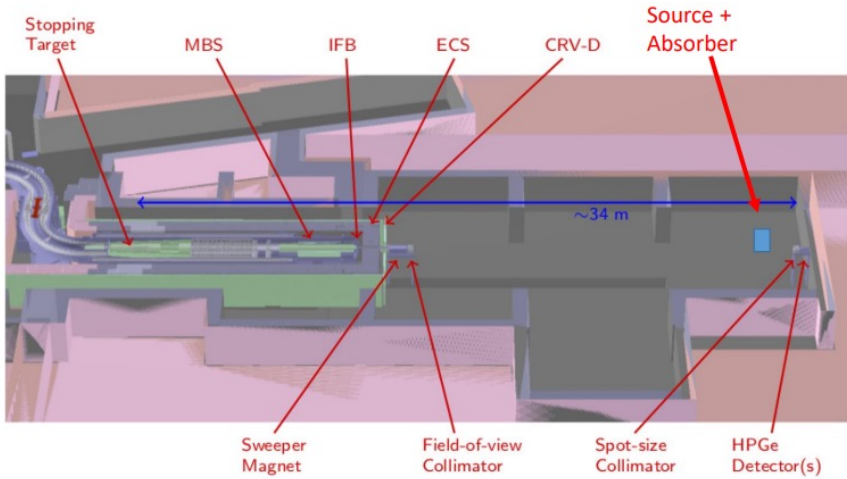
- The detector is based on Trig Scintillators + Pixel Tracker
 - Scintillators : arrival time and between bunch trigger
 - Tracker : reconstruct p, π 's + dipole rough momentum determination

• It provides an average extinction value (not pulse by pulse) over $\sim 8 \text{ hrs}$

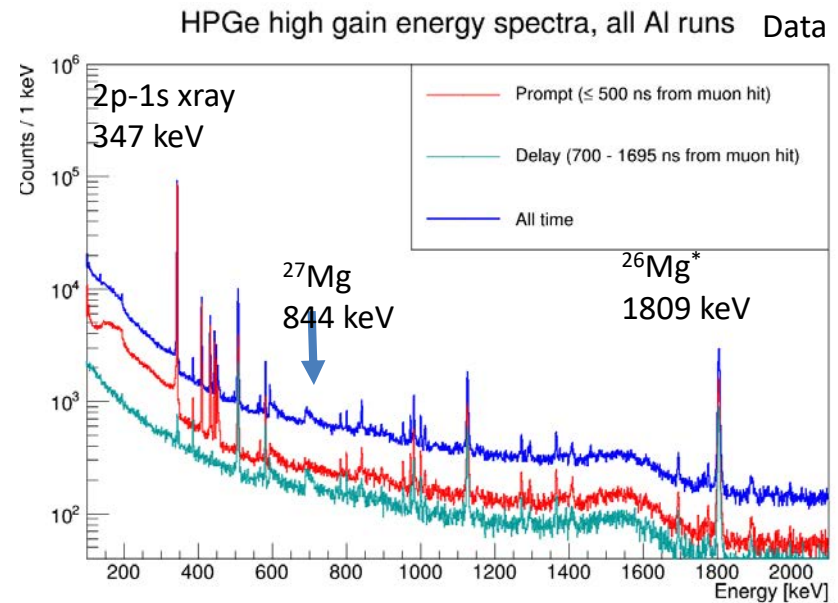
Upstream EXTMON: A completely independent Cherenkov counter detector measures the single pulse extinction from the Recycler by looking at off-axis counts before the AC sweeping dipoles – **under commissioning**



Main normalization detector - STM



- Measure rates of muonic X and g's lines from Stopping Target using high resolution HPGe and lower resolution (but faster) LaBr3
- 34 m away from the target looking for 3 lines 347 keV "prompt", 844 keV delayed, 1809 keV
- 10 % absolute precision in few minutes of data collection

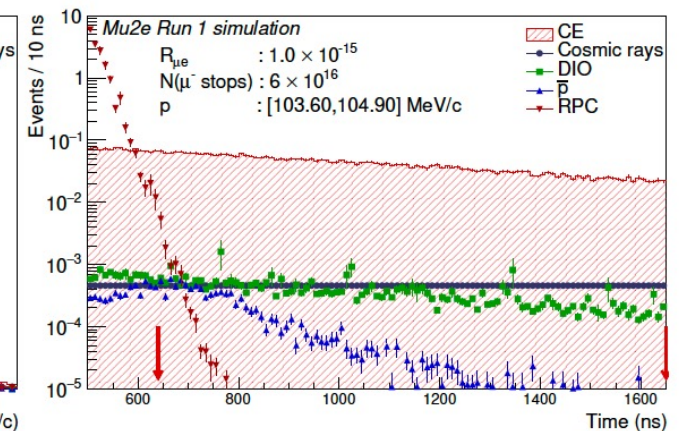
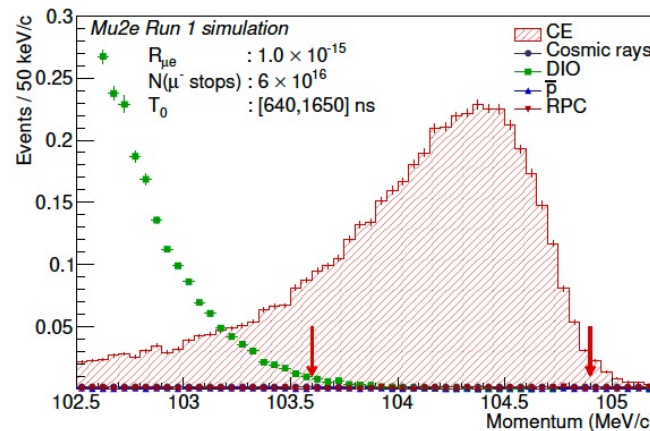


Run-1 physics goals (SU-2020)

Universe 2023, 9(1), 54; <https://doi.org/10.3390/universe9010054>

- In Run1 we plan to start running with beam at low intensity (1 batch mode) and rampup to high intensity (2 batch mode) in a second phase
- **Goal is to reach x 1000 sensitivity in $\mu^- \rightarrow e^-$ (10% of total NPOTs)**
- Run-1 scheduled for few months of running in 2027, before Fermilab Accelerator Long Shutdown for PIP-2 installation (Jan 2028)
- Run-1 will provide a good learning phase and preparation for Run-2 to complete our goals

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



Any further delay in PS/DS delivery could impact our running time

Conclusions

- Observation of **CLFV** processes **directly access physics beyond the Standard Model**
- The **Mu2e** experiment **aims to improve by four orders of magnitude the current sensitivity for $\mu^- \rightarrow e^-$ conversion** as well as to explore new physics in other channels such as **$\mu^- \rightarrow e^+$ or $\mu^+/\pi^+ \rightarrow e^+ X$**
- The **Mu2e project is now on track to deliver the Mu2e detector in the hall** in the next two years and allows the collaboration to:
 - Start a ***1.5 year long Commissioning run in fall 2025***
 - Execute RUN-1 for ***beam physics data collection in middle 2027*** before LS begins
- **RUN 1 optimal goal is to** get up to O(10%) of the total number of Mu2e stopped muons:
 - improve the current sensitivity up to O(1000) to open the road for this new exciting physics program
- This run will be a learning phase to get ready **for reaching our final sensitivity goal in a long extended RUN 2 after LS**

• ADDITIONAL MATERIAL

Other physics channels

- DL=2 channel $\mu^- \rightarrow e^+$ conversion

- It violates both lepton flavour and lepton number

- Complementary to double-beta decay

- Main background is RMC, poorly known near endpoint

- We can measure with photon spectrum and theory extrapolation

- $\mu^- \rightarrow e^- X$

- searches for ALP, new bosons, peak in electron spectrum + could modify the DIO spectrum near endpoint

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

- searches for ALP, new bosons

- require rotating collimators, low intensity, $\frac{1}{2}$ B field

- Search for peak in electrons spectrum

- $\pi^+ \rightarrow e^+ X$

- searches for heavy neutral leptons in π decay

- require same condition of μ^+ search, but more background (especially muon decays in flight)

- RMC, RPC photon spectra

- RMC, RPC bkg shape of electron spectra from positron distribution

Mu+ → e+X, pi+ → e+X from Phys.Rev.D 109, 035025 (2024)

- Exclusion plots for different ALP models (mu+ → e+X) or Heavy neutral leptons (pi+)
- Context: special runs, 1 week low intensity, 1/2 field, rotated collimator sign, degrader for pions
- Acceptance taken from Mu2e PhD thesis - **Main findings: sensitiv reach comparable with mu3e, Meg-II-X, Comet-X**

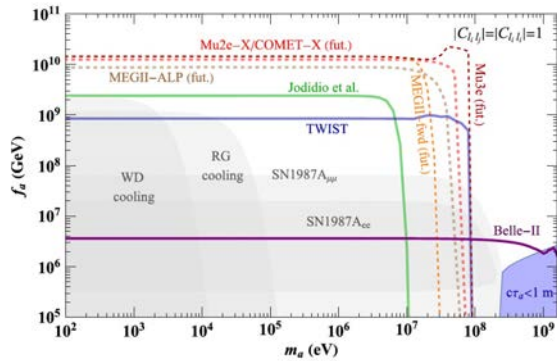


FIG. 1. The 95% C.L. limits on a general ALP with anarchic couplings to all three generations of leptons. The present laboratory

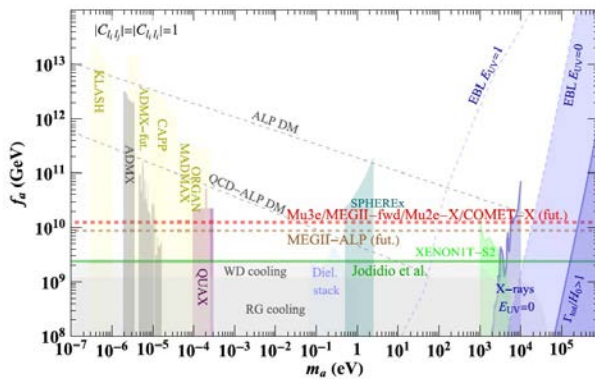


FIG. 2. The 95% C.L. limits on a leptophilic ALP that can be a

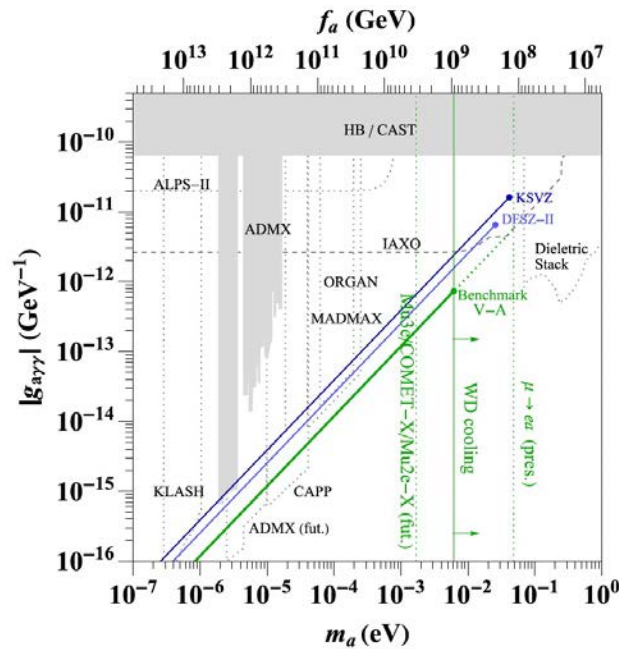


FIG. 3. The 95% C.L. limits on lepton flavor violating QCD axion for the assumed $V - A$ forms of couplings. The mass of the QCD axion, m_a , is inversely proportional to the coupling constant f_a . The vertical axis refers to the axion coupling to photons,

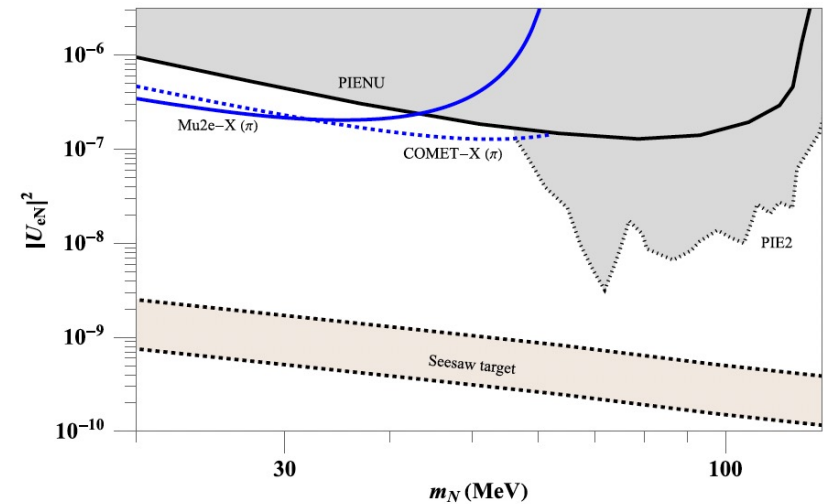
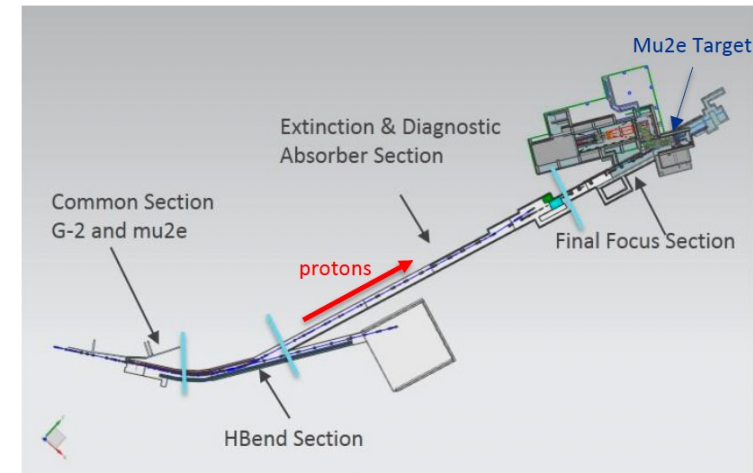


FIG. 4. Projections for mass dependent 90%-C.L. sensitivity to HNL mixing with electron flavor from Mu2e-X in a pion configuration; see Sec. III for details. Existing limits come from

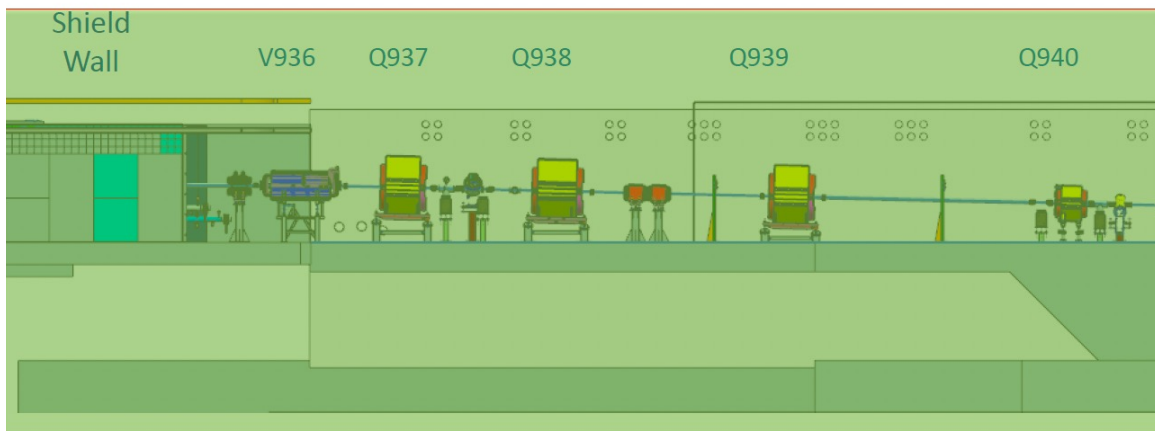
M4 Final Focus Remaining Scope

- Upper-Level component & vacuum installation is complete.
- Lower-Level Remaining requires Vacuum & Trim Magnet Installation.
- Commission all M4 final focus power supply circuits.



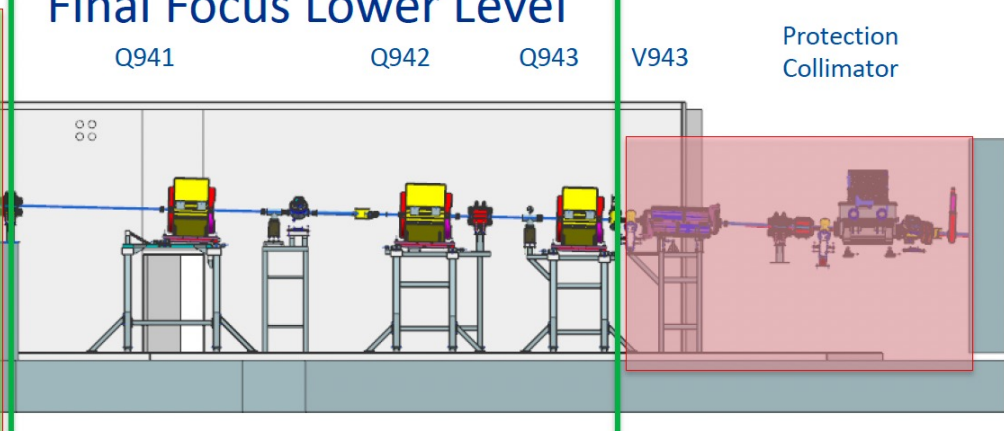
COMPLETE

Final Focus Upper Level



Vacuum Installation in Progress

Final Focus Lower Level

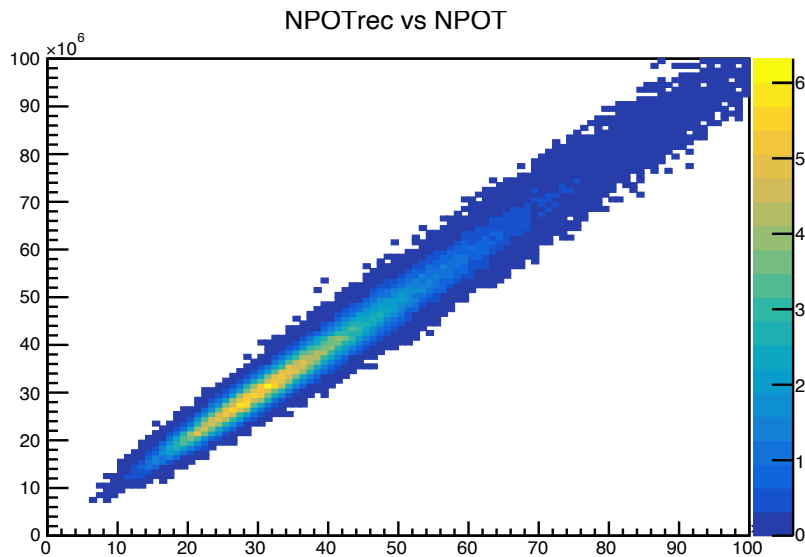


Off Project

Protection Collimator

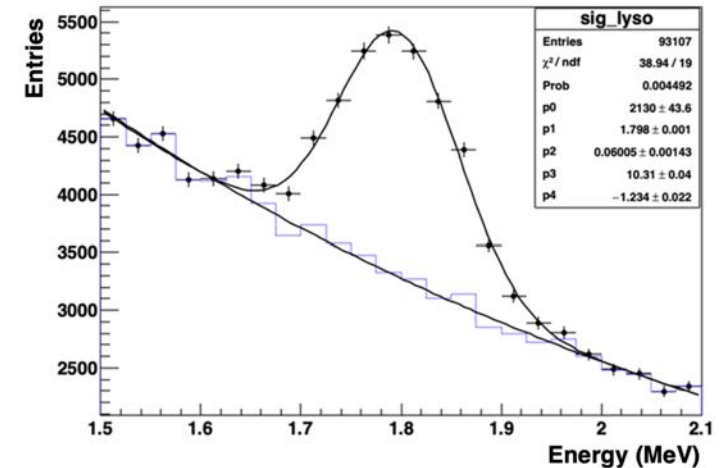
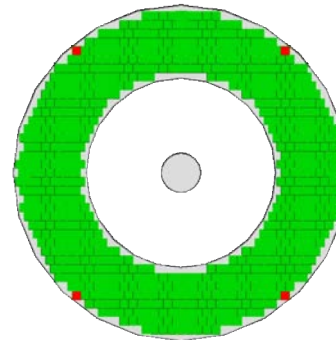
Normalization/beam feedback detector(s)

of tracker/calor hits



Caphri .. installed / tested

- Calorimeter Precision Hi-Reso Intensity Detector
- 4 LYSO counters (ESR wrapped) replaced CsI to measure the 1.8 MeV "golden" line from muon capture in Al nuclei
- **3% counting error per Injection Cycle (1.4 sec)**

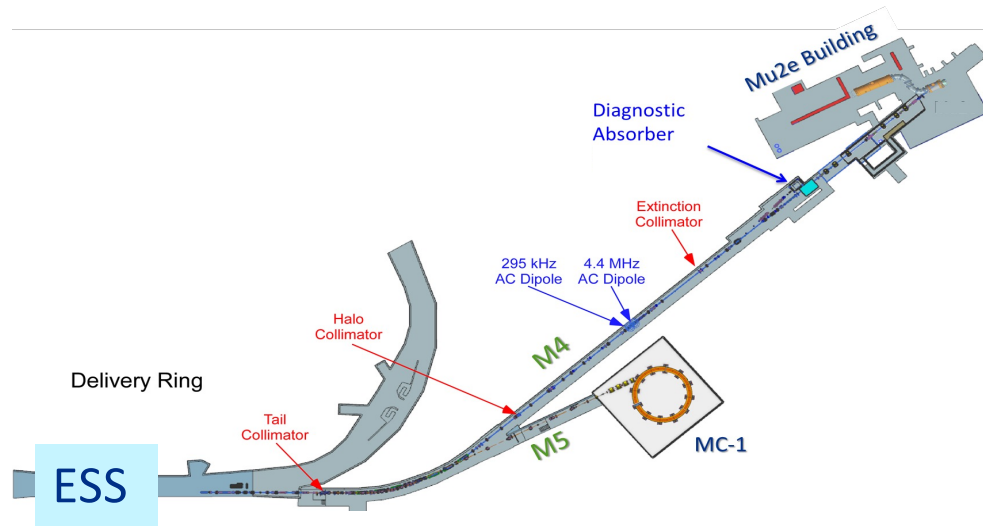


A lot of activity in the collaboration to provide fast feedback to the AD when running beam

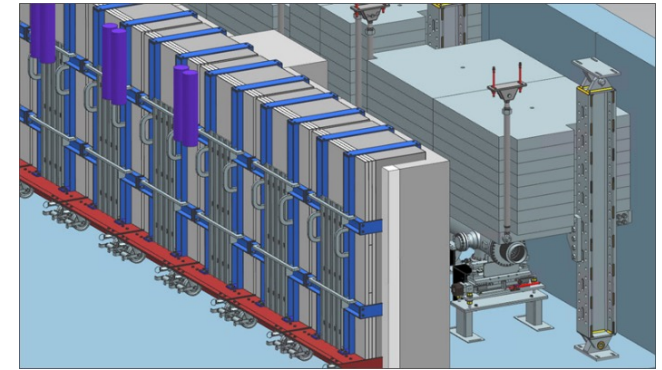
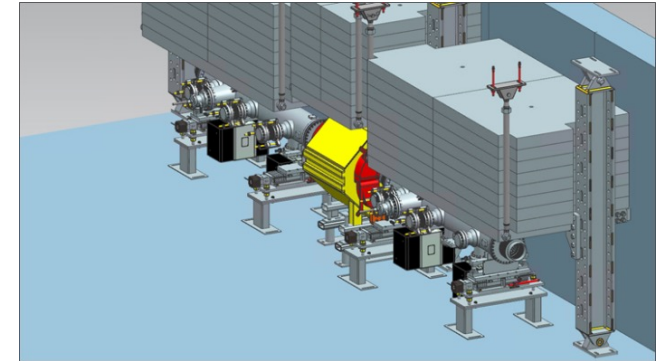
→ flash monitor (tracker hits), PBI variation (Tracker/calor Hits)

→ muon stopping rate (Caphri, proton count) – Spill loss monitor and so on

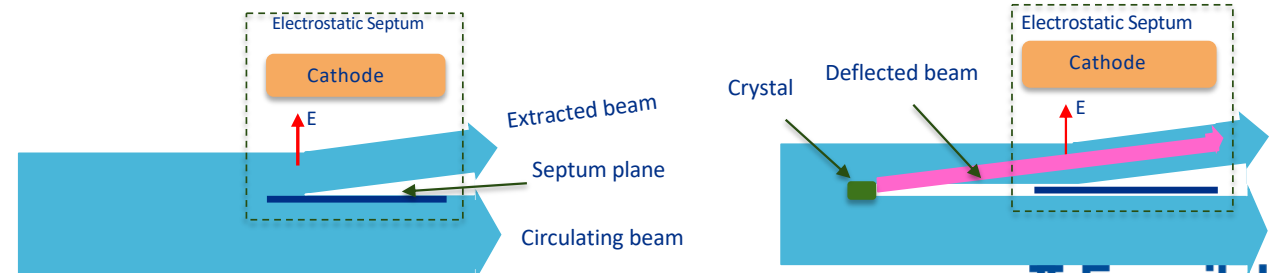
Bent crystals for beam shadowing at Mu2e



Radiation Shielding Around ESS

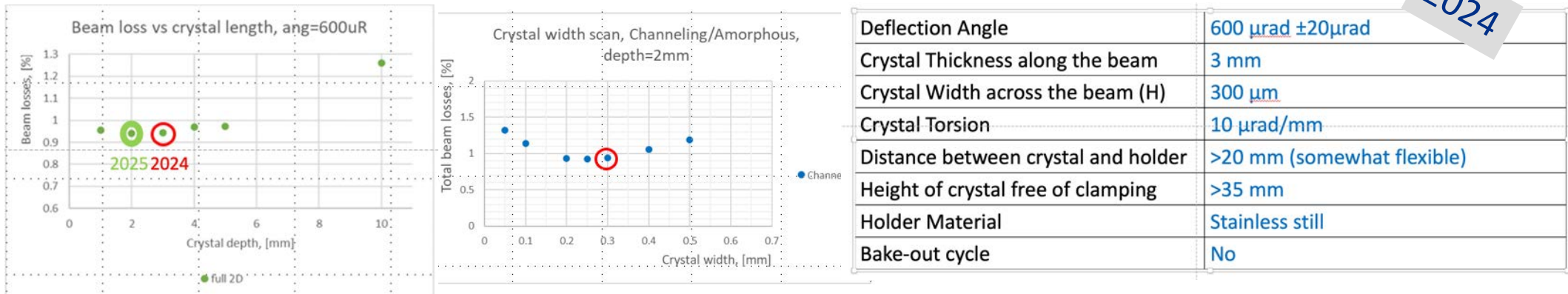


- Slow Extraction is inherently lossy
- Design: Losses < 2%
- Deliver Ring (DR) shieldings are good to run 8 kW beam (design intensity)
- What happens if the shielding is still unable to seal the losses at run startup?
→ We should reduce the beam intensity ...



Bent crystals final optimization – bending angle, dimensions

2024



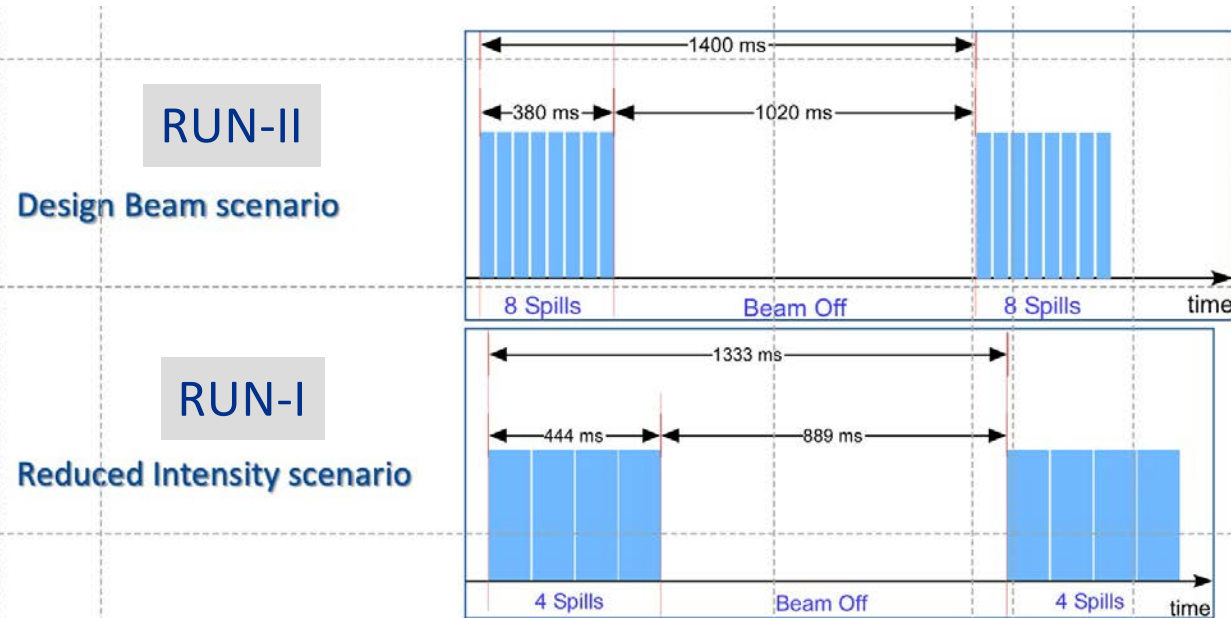
Tables of crystal response by Ferrara's team, computed using G4 extension w Fluka (A.Sytov)

- First set of 2024 crystal production underway + design of holder underway
- Bulk characterization of Si Wafers done @ ESRF- BM05 beamline, OK
- A second set of crystals of 2 mm in length will be produced in 2025

Next plan:

- Full characterization of crystals in Ferrara's lab + planning test beam at Cern in 2025
- Procurement of goniometer on-going
- Procurement/realization of beam station planned
- Installation in beamline 2026

Beam Structure – 1B vs 2 B .. Injection cycles



Parameter	Two Batch	Single Batch	Units
Average Proton Beam Power	7.3	3.8	kW
Main Injector Cycle Time	1.400	1.333	sec
Proton Batches per MI Cycle	2	1	
Mu2e Spills per MI Cycle	8	4	
Spill Duration	43.1	107.3	msec
Number of Proton Pulses per Spill	25,442	63,298	
Proton Intensity per Pulse	3.9×10^7	1.6×10^7	Protons/Pulse
Mu2e Duty Factor	27	32	%
Instantaneous Spill Rate	23×10^{12}	9.3×10^{12}	Protons/sec

- Two Booster batches reduced to one Booster batch per cycle
- MI cycle time reduced from 1.400 s to 1.333 s
- 8 spills reduced to 4 spills
- Length of spill increased – more than doubled

Note: time scales are different