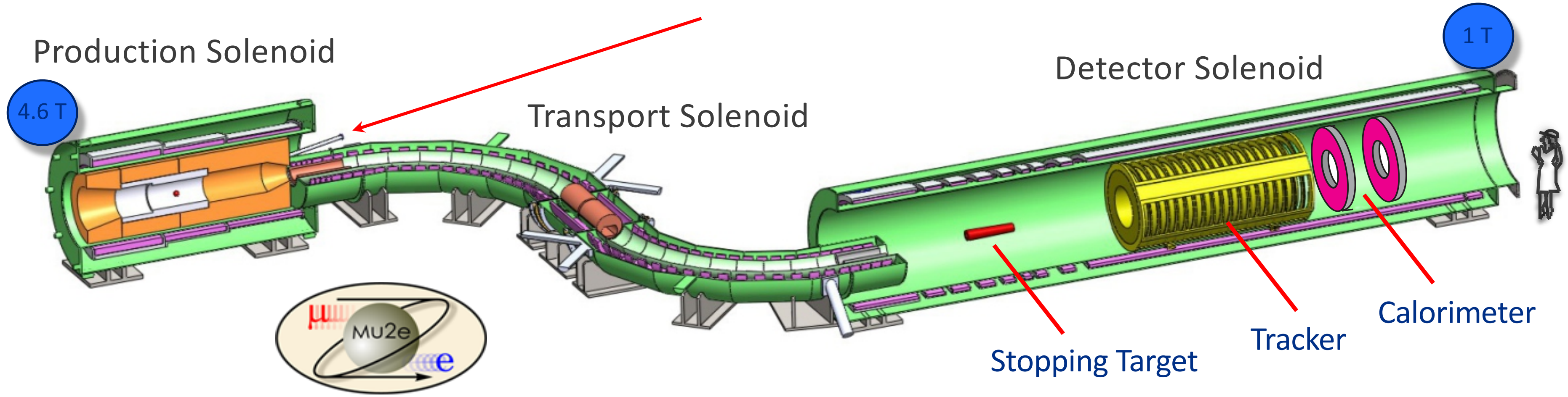


Mu2e Physics and Mu2e experiment status

Stefano Miscetti (LNF INFN Italy)
on behalf of the Mu2e collaboration

Channeling 2024

9 Sept 2024

Riccione - Italy

Talk Layout

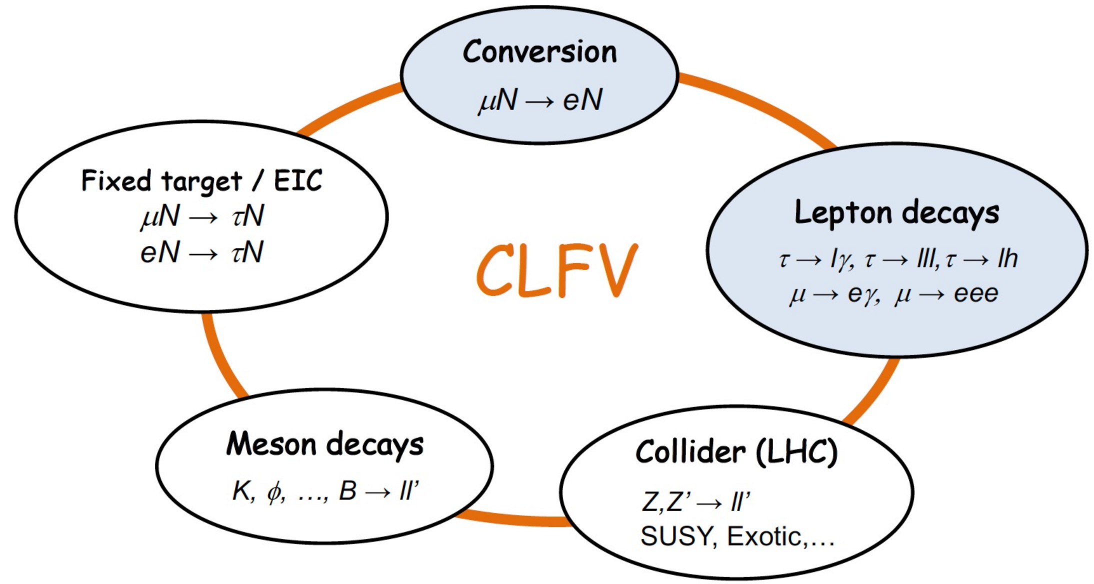
- ✓ What is Mu2e ..
- ✓ Mu2e Physics goal(s)
- ✓ Description of the experiment
  - → explaining the design
  - → where we are now
- ✓ Running plans

Mu2e Collaboration

239 members,
39 istitutions, 6 countries ..
~ 25+25
Active number of PhD-Postdocs

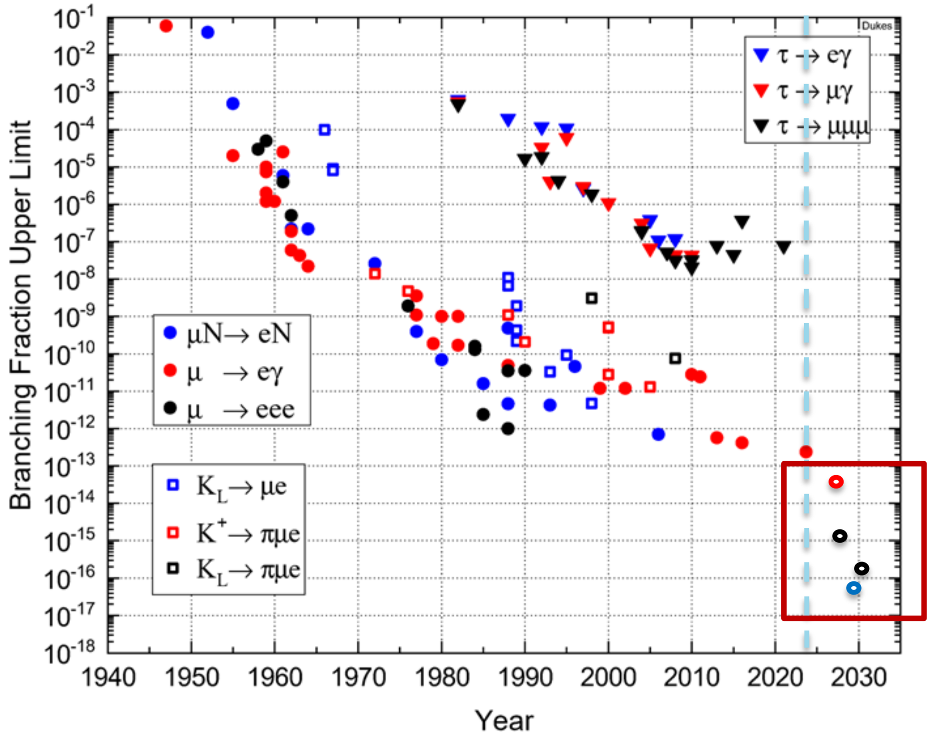
Searching CLFV in the muon sector

- ✓ Charge Lepton Flavour Violation processes are the ones where charge lepton family numbers are not conserved: i.e. a change in e, μ and τ flavour w/o associated neutrinos
- ✓ There is a long history of and plans for CLFV rare decay searches
  - the big bubble here summarizes the different fields
  - while other CLFV processes can be helpful to sort out the underlying physics, **the lepton decays and the conversions** have very high sensitivity reach
  - **The muon sector provides the best sensitivity**
    - → easier to produce
    - → long-lived
    - → clean process w/o hadronic backgrounds



- Muon-to-electron conversion (MU2E and COMET) is similar but complementary to $\mu \to e\gamma$ and $\mu \to 3e$.
- $\mu \to e\gamma$ @ PSI MEG/MEG-2 is currently leading the CLFV search
- $\mu \to 3e$ @ MU3E experiment @ PSI. It will be carried out in two phases for different reach in sensitivity (10^{-15}, 10^{-16})

Current status of CLFV searches and muon sector relevance



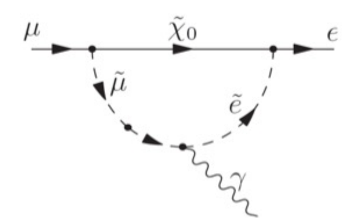
W. Altmannshofer, *et al*, arXiv:0909.1333 [hep-ph]

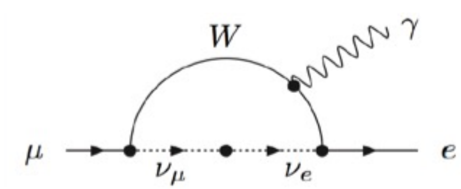
	AC	RVV2	AKM	δLL	FBMSSM	LHT	RS
$D^0 - \bar{D}^0$	★★★	★	★	★	★	★★★	?
ϵ_K	★	★★★	★★★	★	★	★★	★★★
$S_{\psi\phi}$	★★★	★★★	★★★	★	★	★★★	★★★
$S_{\phi K_S}$	★★★	★★	★	★★★	★★★	★	?
$A_{CP}(B \to X_s\gamma)$	★	★	★	★★★	★★★	★	?
$A_{7,8}(B \to K^*\mu^+\mu^-)$	★	★	★	★★★	★★★	★★	?
$A_9(B \to K^*\mu^+\mu^-)$	★	★	★	★	★	★	?
$B \to K^{(*)}\nu\bar{\nu}$	★	★	★	★	★	★	★
$B_s \to \mu^+\mu^-$	★★★	★★★	★★★	★★★	★★★	★	★
$K^+ \to \pi^+\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$K_L \to \pi^0\nu\bar{\nu}$	★	★	★	★	★	★★★	★★★
$\mu \to e\gamma$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
$\tau \to \mu\gamma$	★★★	★★★	★	★★★	★★★	★★★	★★★
$\mu + N \to e + N$	★★★	★★★	★★★	★★★	★★★	★★★	★★★
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 these events is therefore a clear sign of new physics
- We can explore range of new masses up to 10^4 TeV

→ an unexplorable land for current (or foreseen) high-energy colliders

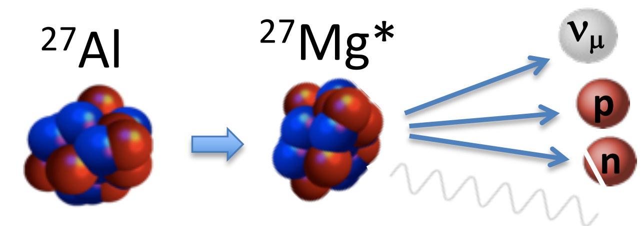




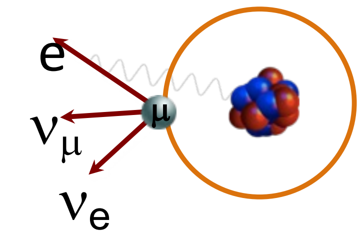
$$BR(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i}U_{ei}\frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

Mu2e goal → x10000 improvements of current sensitivity

- ✓ Mu2e wants to search for the conversion of μ^- to e^- in Al nuclei
  → $\mu^- + {}^{27}_{13}Al \rightarrow e^- + {}^{27}_{13}Al$



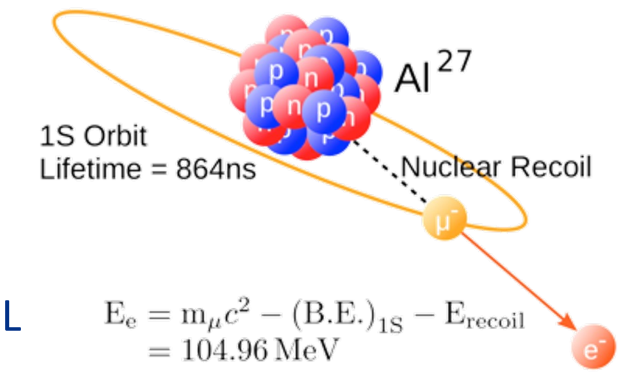
- ✓ When μ^- are stopped in aluminum a muonic atom is formed
  - Prompt cascade to 1s state (0.1 ps)
  - 347 keV X-ray emitted – **candidate for normalization**
  - Due to high mass, muons circulate in very short radius around nucleus (20 fm)
    → 61% undergo muon nuclear capture, **1.8 MeV line**
    → 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

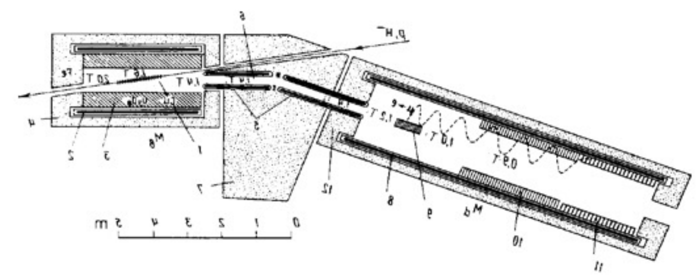


Mu2e how to: x 10000 improvements

The 4 main thrusts to reach this improvement

✓ **1) High statistics:** 10^{18} stopped muons needed in 5 years
- Highest intensity muon beam in the world (~ 10 GHz on stopping target)
- required x100-1000 improvement to current muon/sec rate @ PSI
- 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 by Djilkibaev and Lobashev for the MELC experiment @ Dubna)



✓ **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

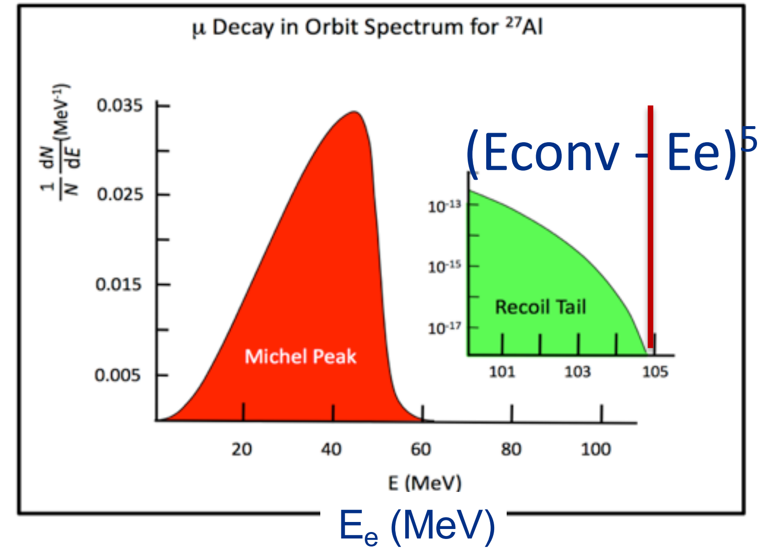
✓ **4) Provide proton extinction and measure it**

Mu2e how to – background control

Anything that produces 105 MeV 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)**



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

- Primary beam related backgrounds:
  - **Radiative pion capture** (RPC, $\pi^- N \rightarrow \gamma N'$, $\gamma \rightarrow e^+e^-$; $\pi^- N \rightarrow e^+e^- N$), pion/muon decay-in-flight, delayed beam electrons, etc.

  ➔MITIGATION : **Pulsed Proton Beam**

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

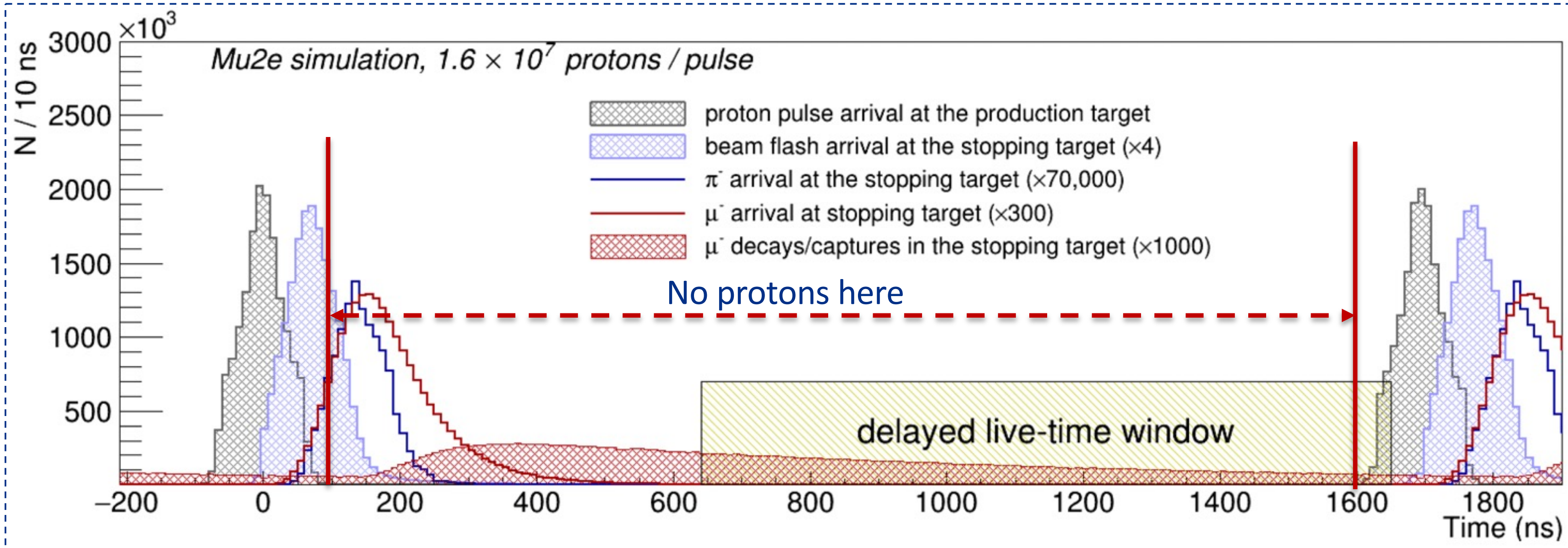
- Antiproton induced backgrounds
  - Annihilation, various interactions with detector materials MITIGATION: **absorber in muon beamline**

- Accidental activities ➔ MITIGATION: **excellent resolution and fast detectors**

Fermilab

Pulsed proton beam and extinction

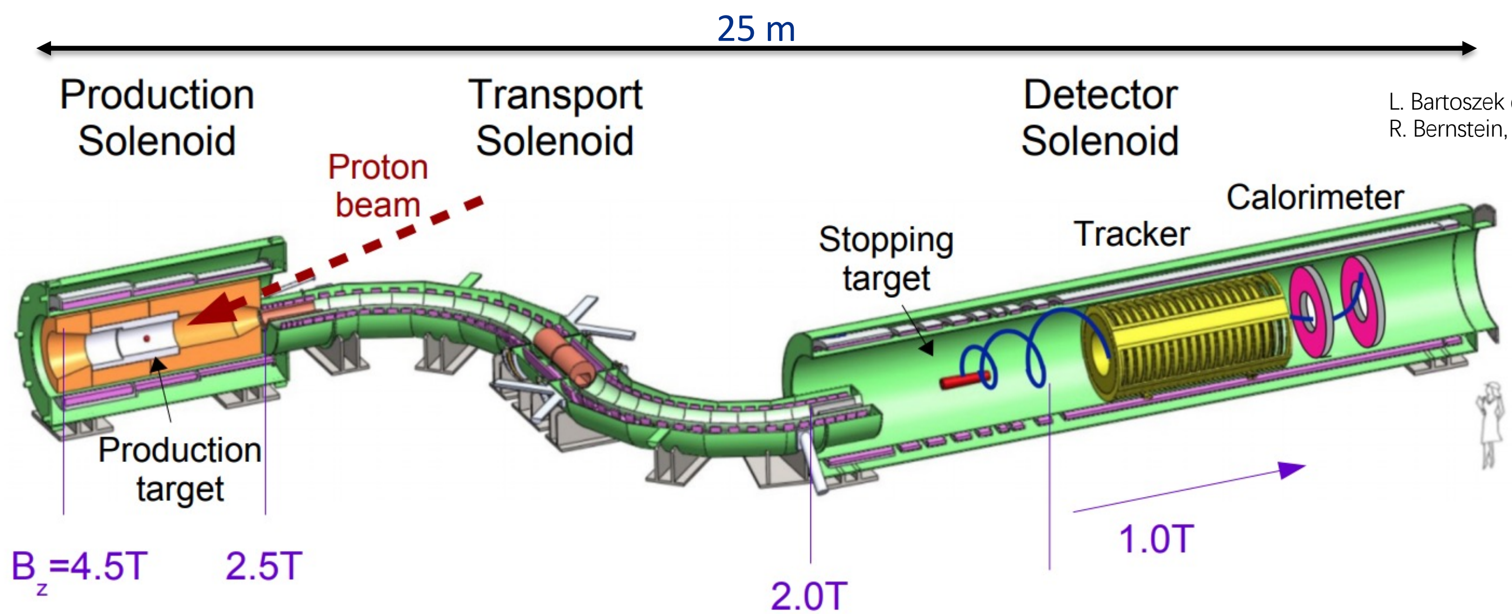
- 8 GeV pulsed proton beam from Fermilab booster, re-bunched in the recycler ring, and then transported to the delivery ring. Extracted through resonant extraction (a.k.a. slow extraction)
- Each pulse: 1695 ns (~2 $\tau_{\mu}^{\rm Al}$), 3.9×10^{7} protons (2 batch), 1.6×10^{7} (1 batch)
- Inter-bunch proton extinction ratio (fraction out of bunch) < 10^{-10}



Proton extinction from two sources:
- Bunch formation in recycler (10^{-5})
- AC-dipole sweeping magnets ($10^{-(5\text{-}6)}$)

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

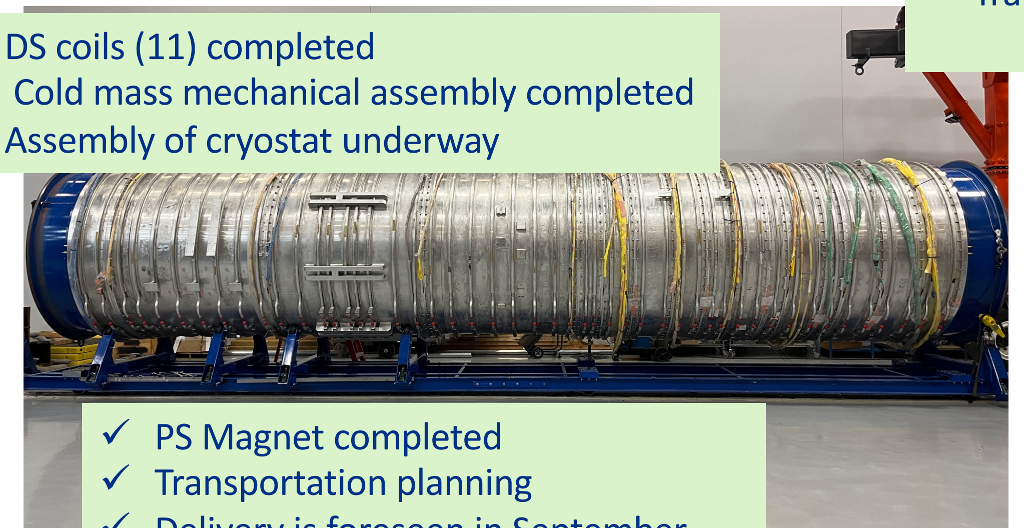


L. Bartoszek et al., arXic:1501.05241;
R. Bernstein, Front. Phyis. 7, 1 (2019)

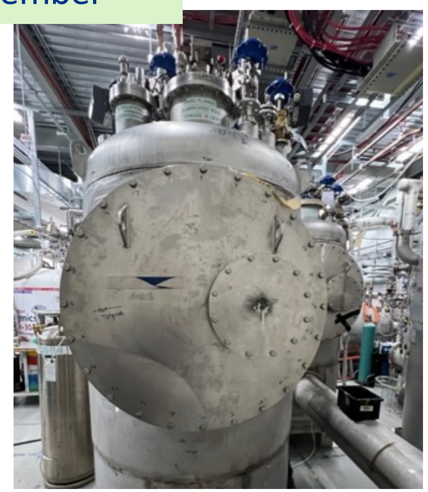
A schematic view of the Mu2e experiment (not including the Cosmic Ray Veto)

Solenoids status

- ✓ DS coils (11) completed
- ✓ Cold mass mechanical assembly completed
- ✓ Assembly of cryostat underway



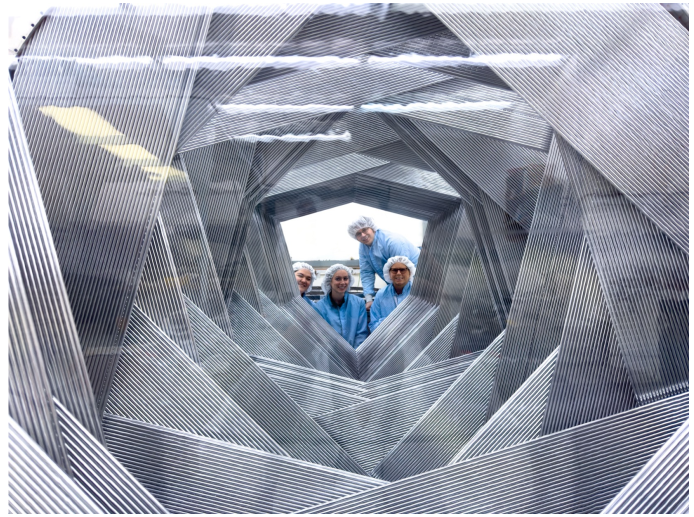
- ✓ PS Magnet completed
- ✓ Transportation planning
- ✓ Delivery is foreseen in September

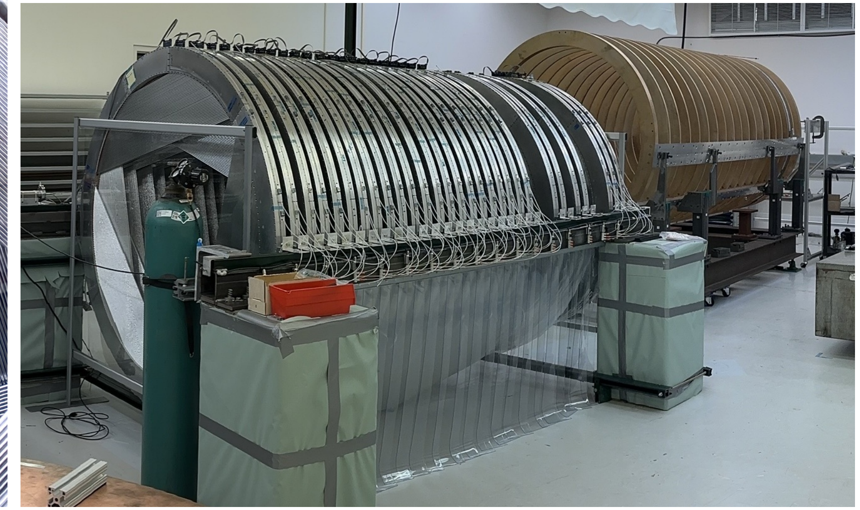


Transport solenoids delivered: 12/23 (TSU)
2/24 (TSD) & installed in Mu2e hall

- DS delivery slippage still drives the project schedule. Delivery is foreseen for beginning of 2025

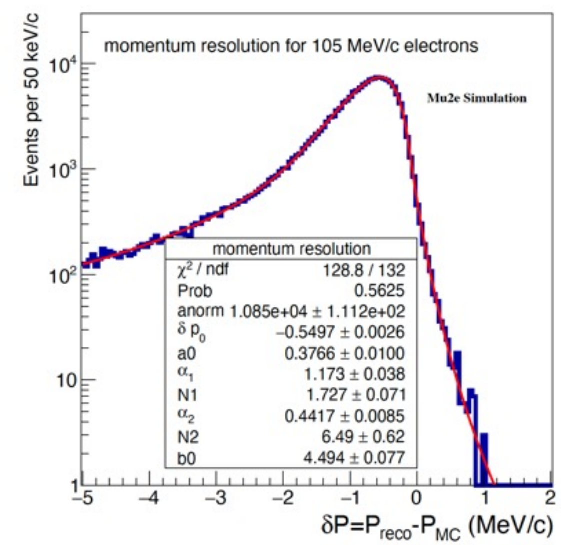
Detectors: tracker





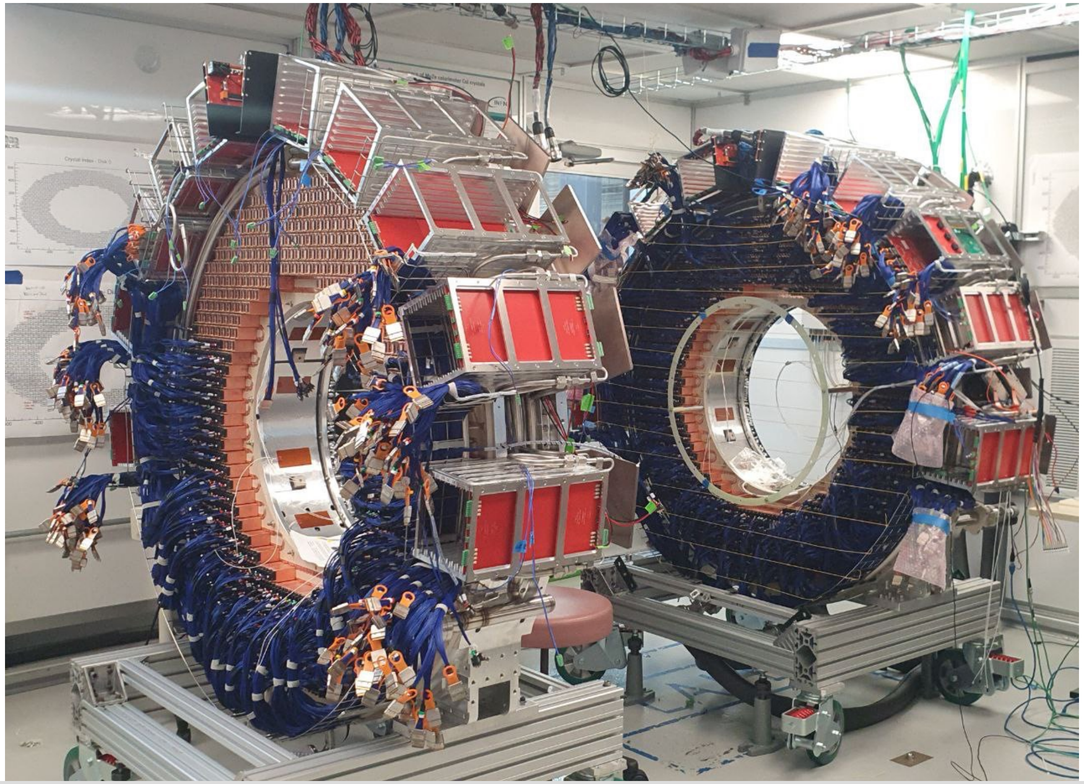
- Very high precision detector (~ 180 keV for CE) with 20 k mylar straws 5 mm ϕ, 15 um thick
- Organized in 18 station. Each station 2 planes, each plane 6 panels

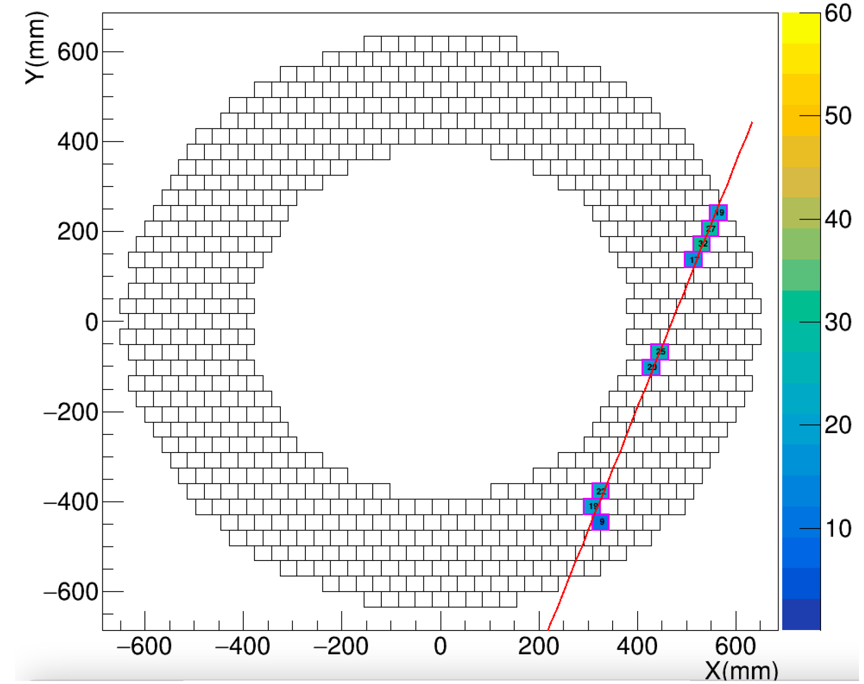
✓ 100 % of panels (216) completed.
✓ Planes preparation almost done (33/36)
✓ All electronics delivered. Installation of electronics in progress
✓ Assembly of stations in progress
✓ Advanced status for services and infrastructure
→ Expect to land in Detector Hall in extracted position – Spring 2025

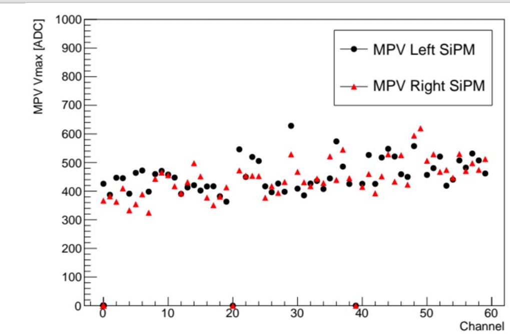


Detectors: Calorimeter

2 disks, each of 674 pure CsI crystals with 2 SiPM readout/crystal



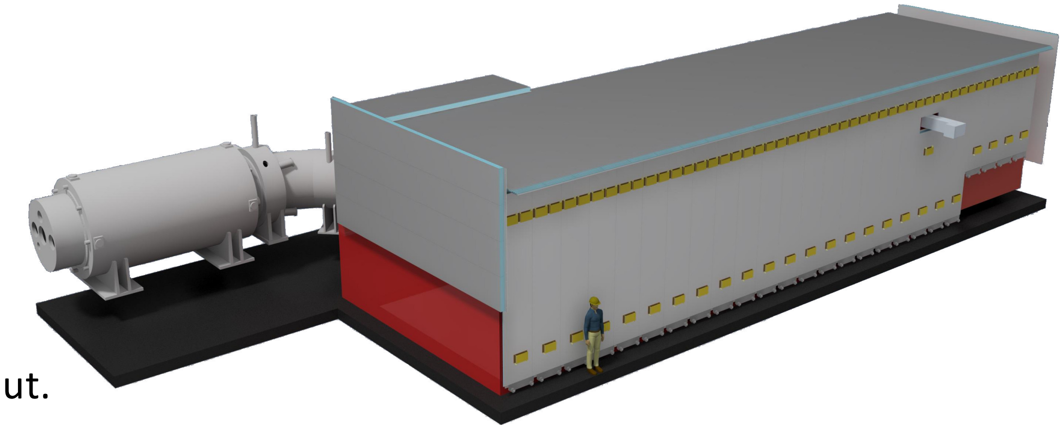




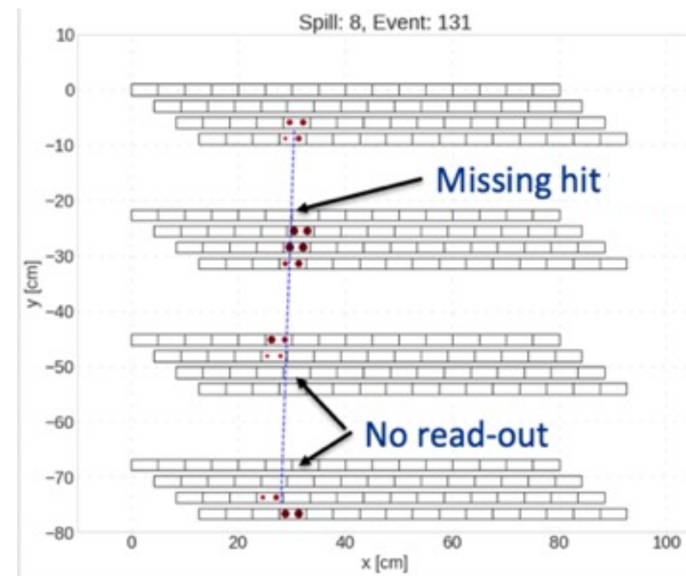
- Components production completed including all digital electronics.
- Installation of boards in progress (50% delivered at FNAL)
- Disk-1 done - Fibers installation (TDAQ/Laser in progress)
- TDAQ readout of ½ disk planned in September
- Expected to be delivered in Mu2e hall in extracted position – Fall 2024

Detectors: CRV

- CRV identifies/veto CR muons that can produce conversion-like backgrounds, at a rate of ~ 1/day
- Very high efficiency (> 99.99%) over 300 m^2 for full DS coverage and part of TS
- Technology: Four layers of extruded polystyrene scintillator with embedded WLS fiber and SIPM readout.

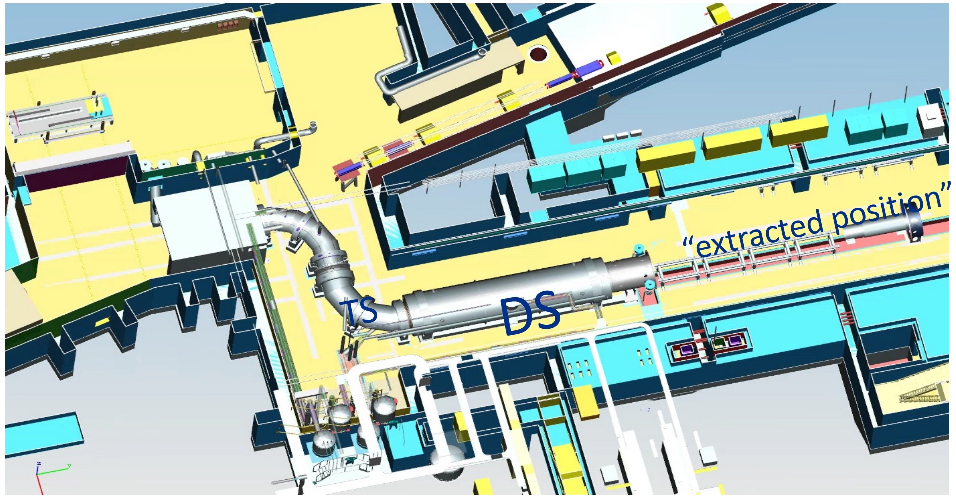


- ❑ Complete procurement of new FEB – foreseen for beginning 2025
- ❑ Complete mechanical structure for CRV installation
- ❑ Installation will proceed after shielding installation

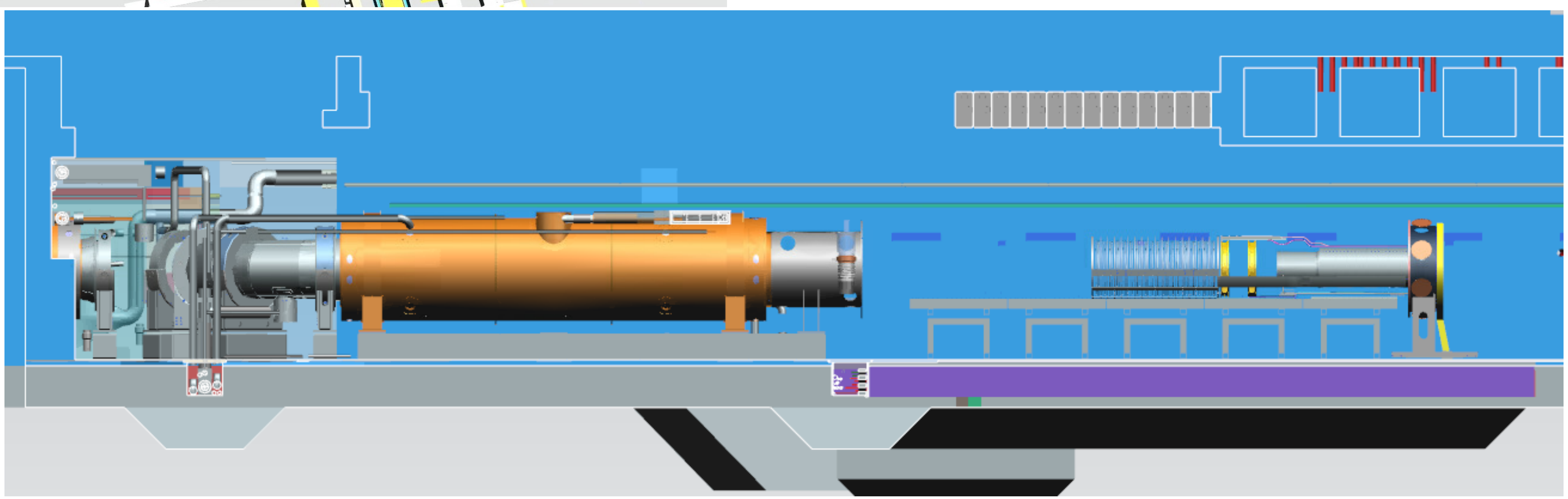


Fermilab

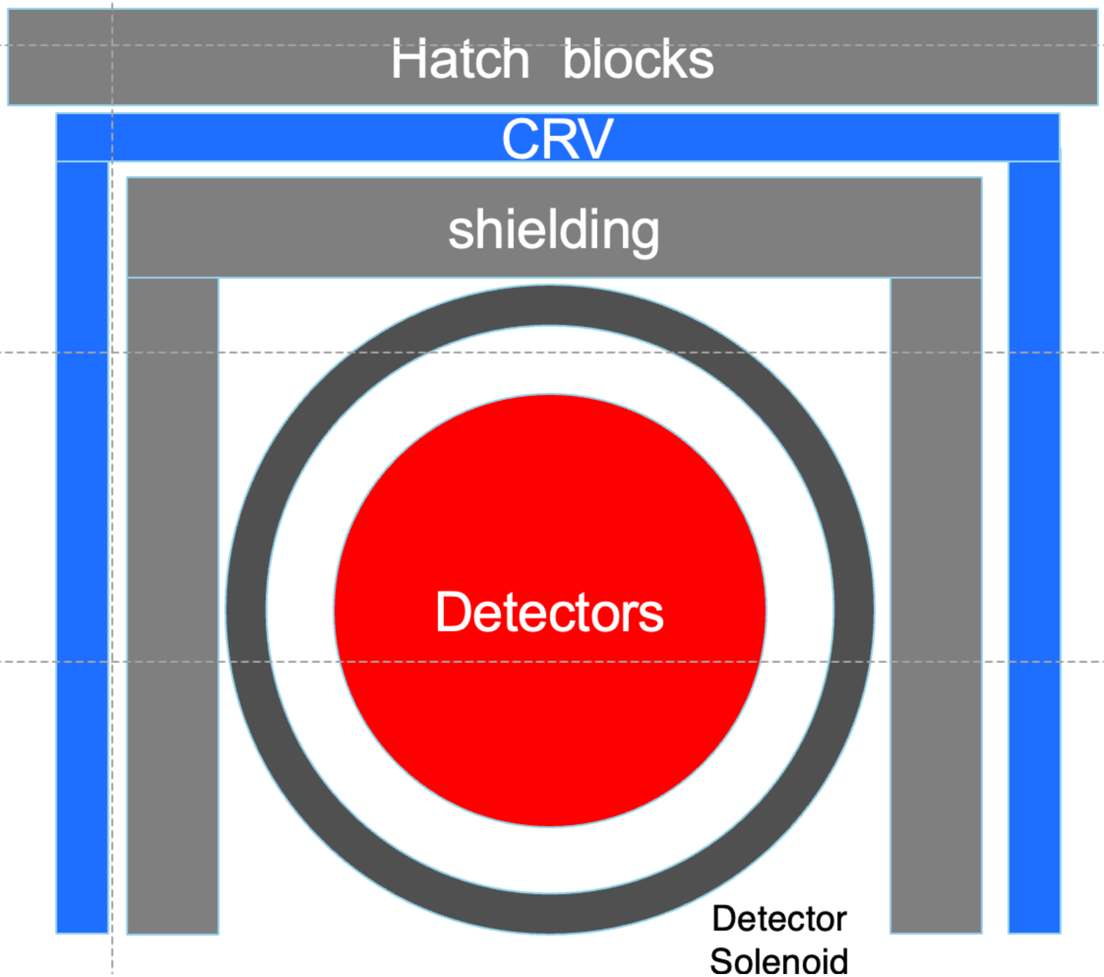
Startup of commissioning – Spring 2025 – extracted position



- ❑ 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



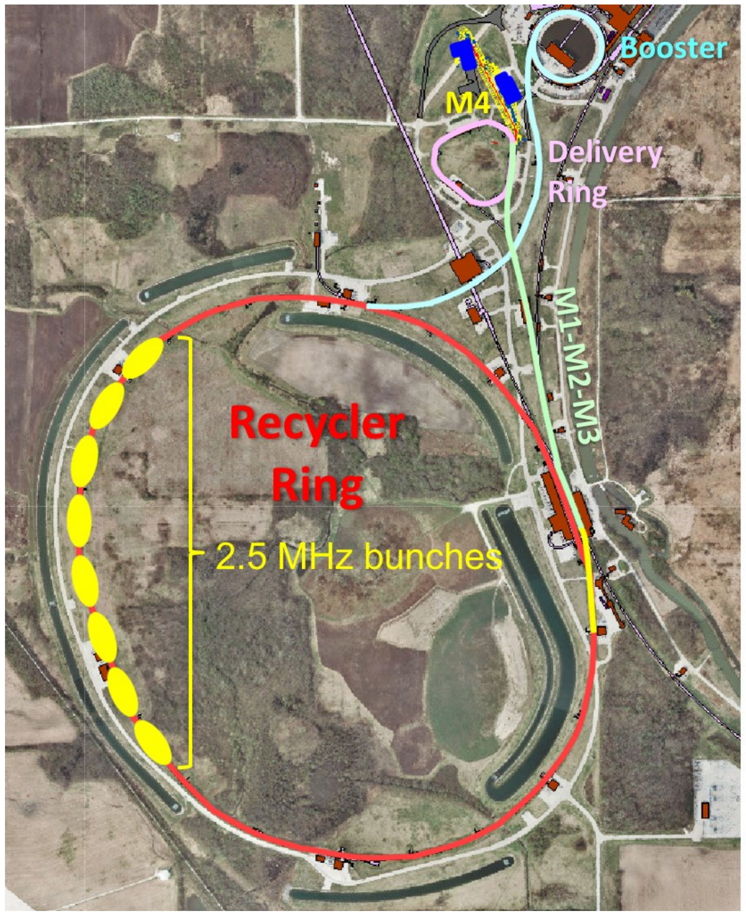
Sequence of installation



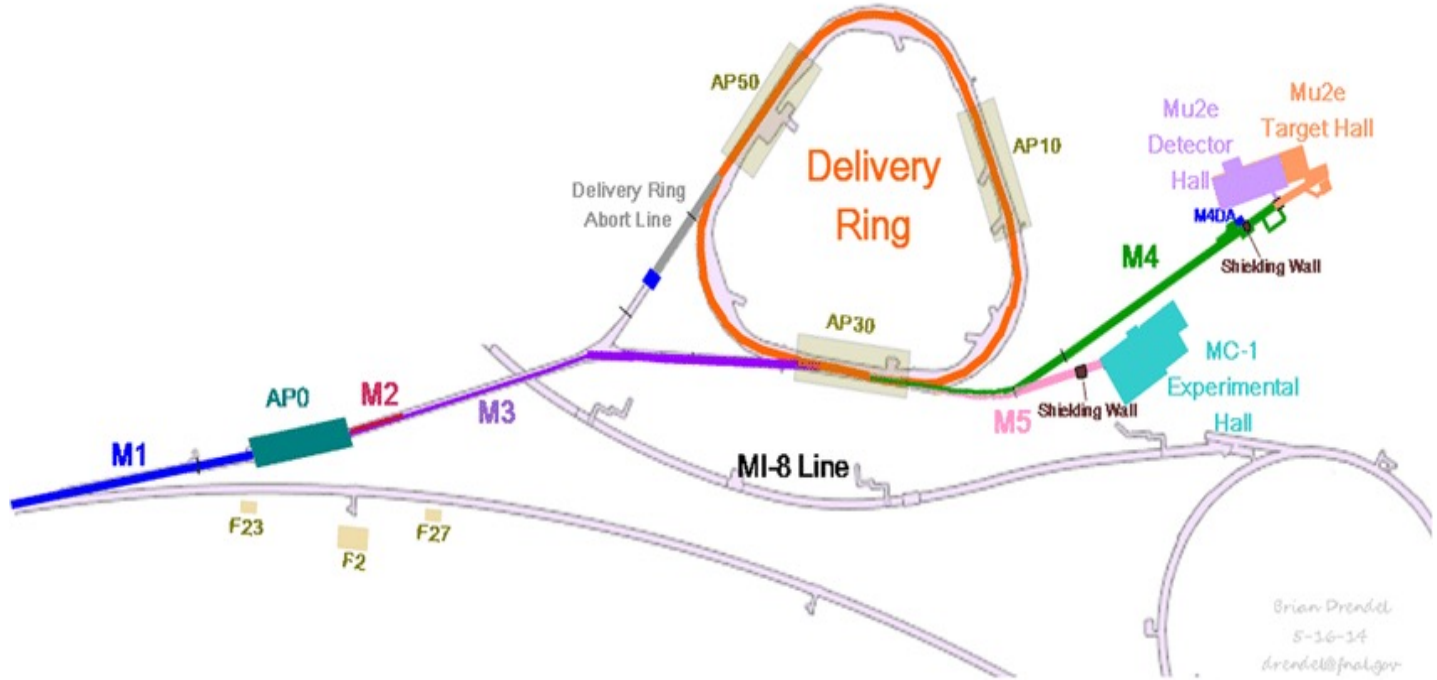
Component	Notes
Detector solenoid	Delivered, installed, cooled and powered
Inner detectors	Inserted into solenoid
External shielding	installation
Final focus	installation
Cosmic ray veto	Construct supports, install
Hatch blocks	Install
Accelerator readiness rev.	Before completion of hatch blocks
Beam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

Accelerator

Booster beam is re-bunched in the Recycler and then stored in the Delivery ring



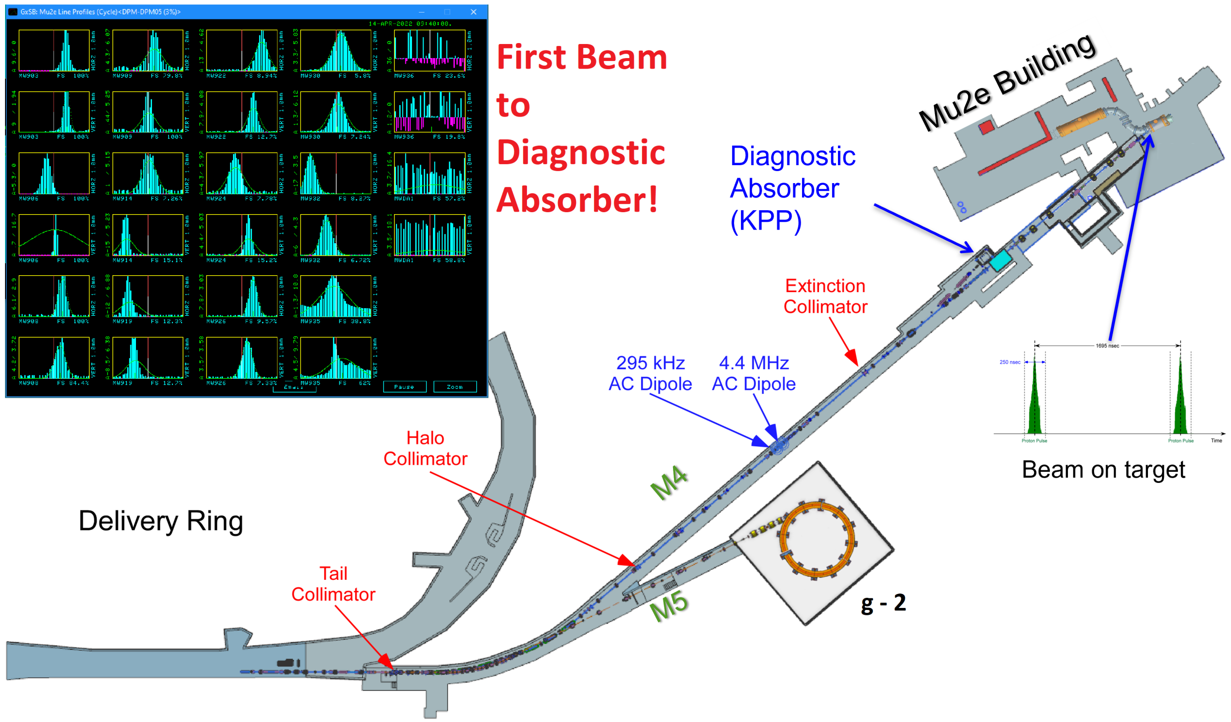
Proton bunches from the Delivery Ring are slowly extracted to the experiment every 1.7 μs



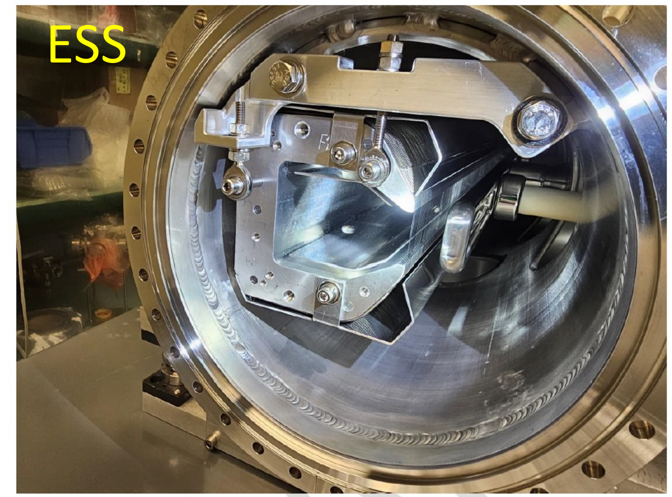
Fermilab

Accelerator achievements – (beam line and beam delivery)

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

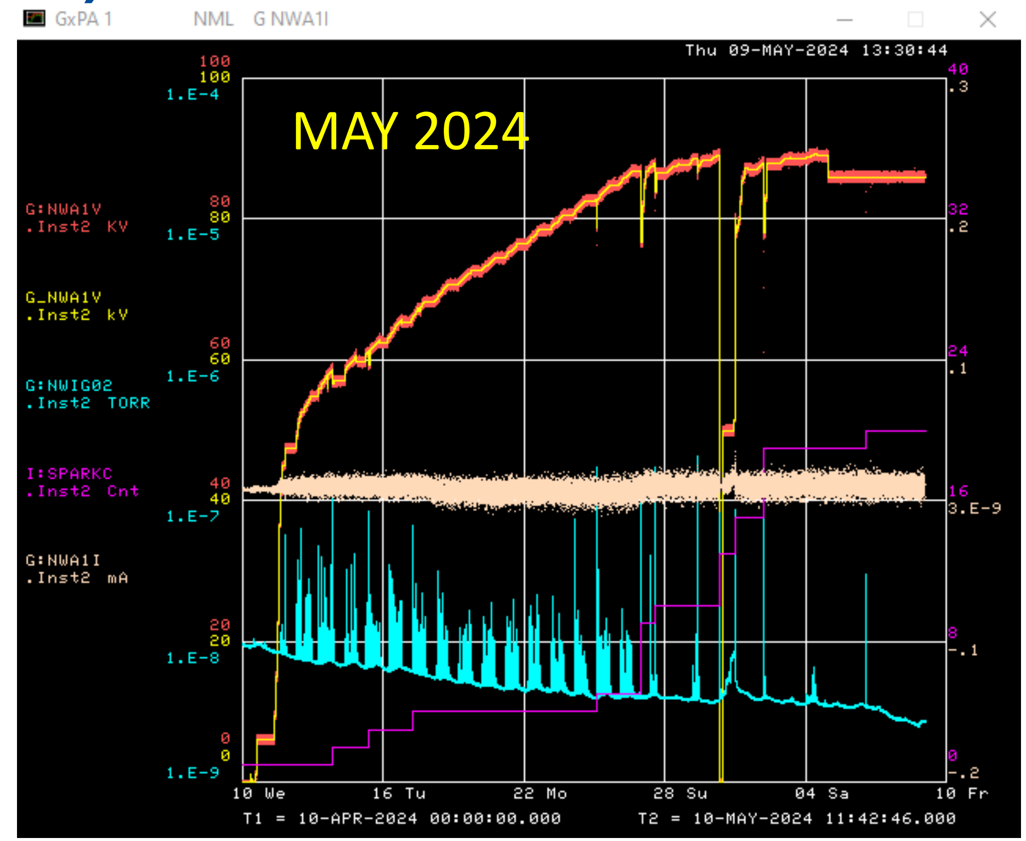


✓ beam on the delivery ring should be slow-extracted with two ESS (Electrostatic Septa) to the Mu2e hall



✓ First slow extracted beam with prototype ESS on July 2023

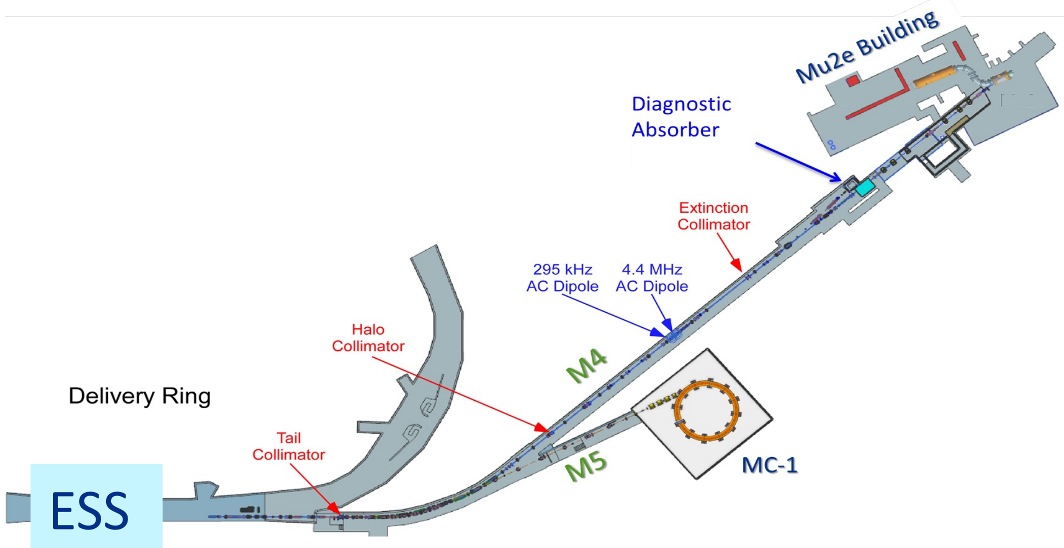
Accelerator achievements – (AC and ESS)



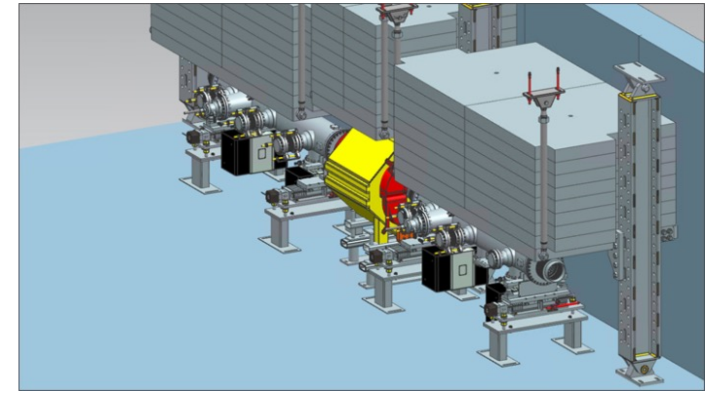
2024 Achievements

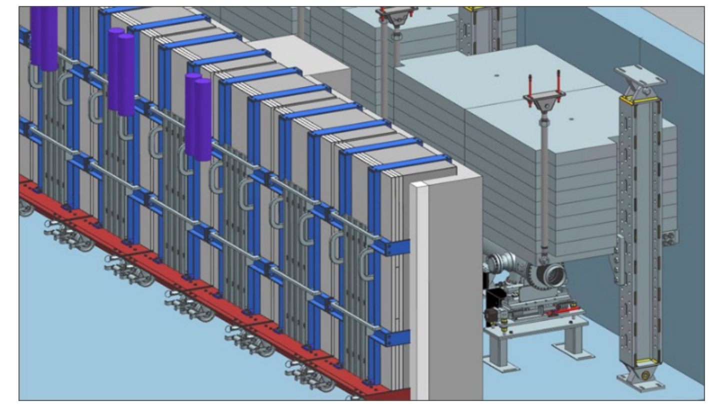
- ✓ HRS (Heat Radiation Shielding) ready for installation inside PS
- ✓ first of 2+1 3m long AC dipoles completed, ESS1 reached full HV → **transition to AD ops OK**
- ✓ beam commissioning underway with Prototype ESS + ESS1
- ✓ Next steps: complete ESS2 + final focus + instrumentation + shielding + study bunch formation

Bent crystals for beam shadowing at Mu2e



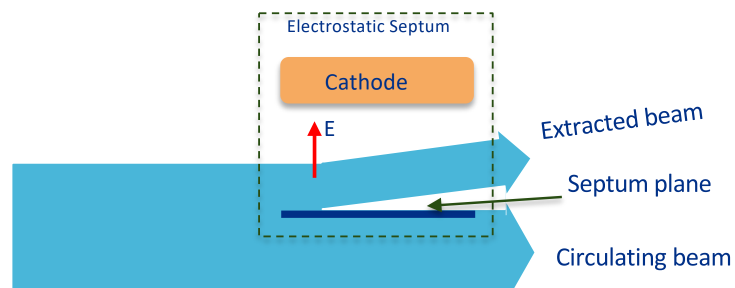
Radiation Shielding Around ESS

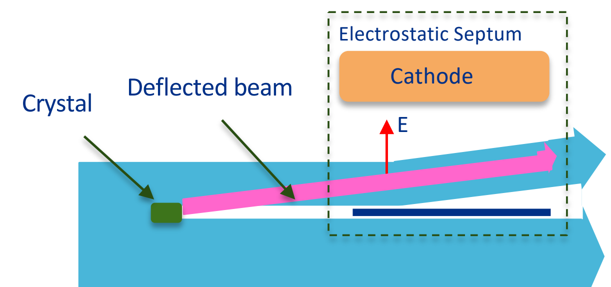




- Slow Extraction is inherently lossy
- Design: Losses < 2%
- Deliver Ring (DR) shieldings are good to run 8 kW beam (design intensity)
- What happens if the shielding is still unable to seal the losses at run startup?

→ We should reduce the beam intensity …





Bent crystal shadowing simulation

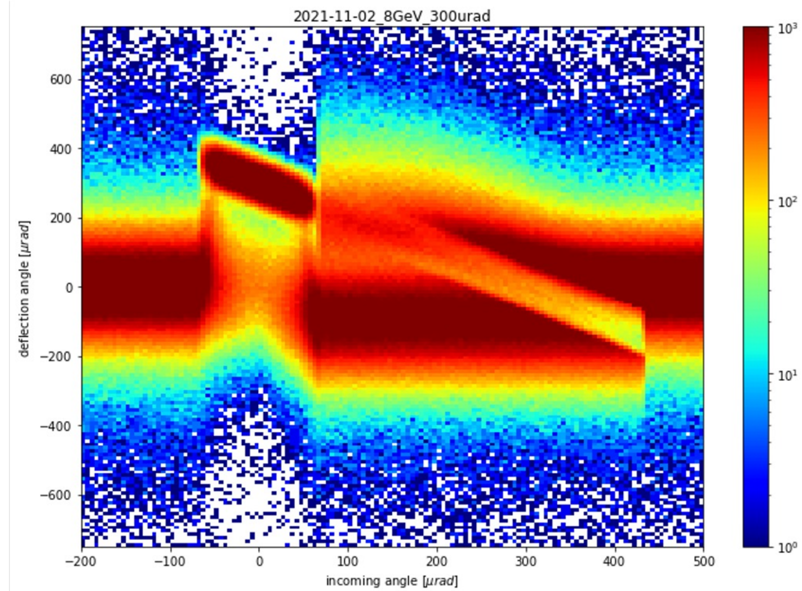
Two steps simulation:

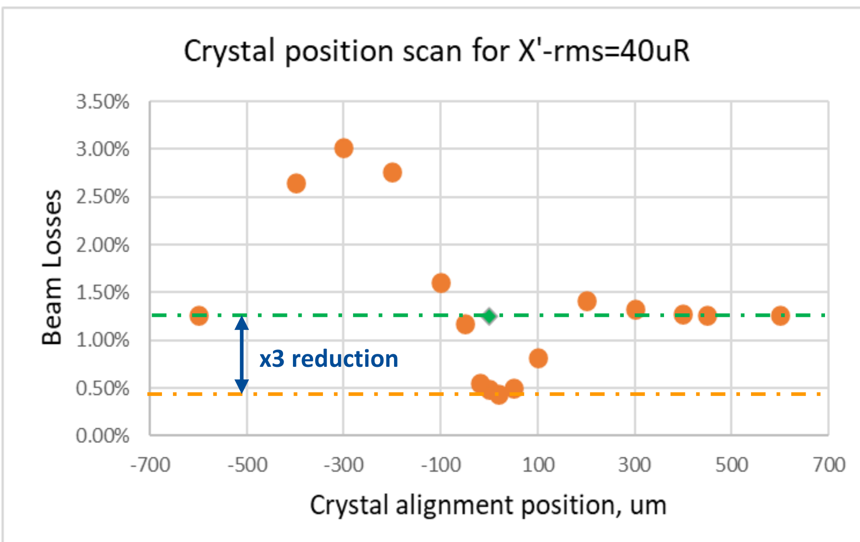
- Transport in the crystal
- Accelerator tracking using Mars

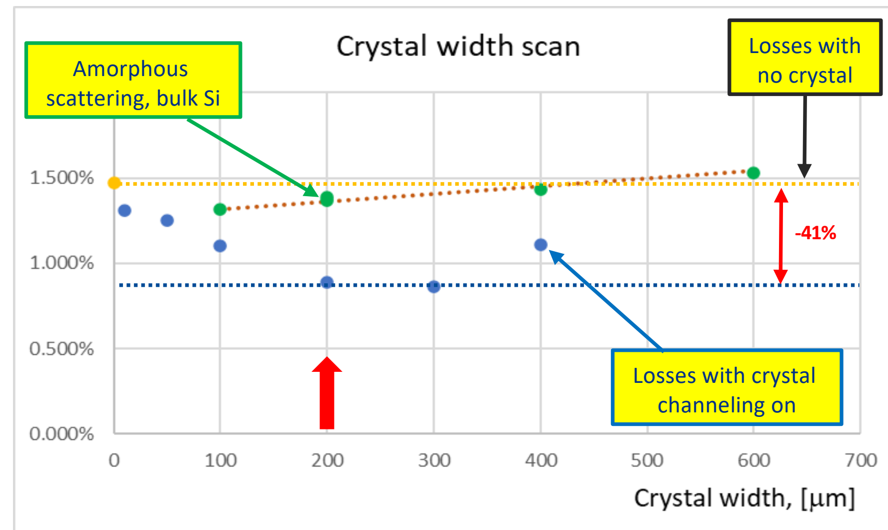
A long story of optimization made short

→ Great sinergy btw FNAL accelerator team and INFN Ferrara's team in Mu2e

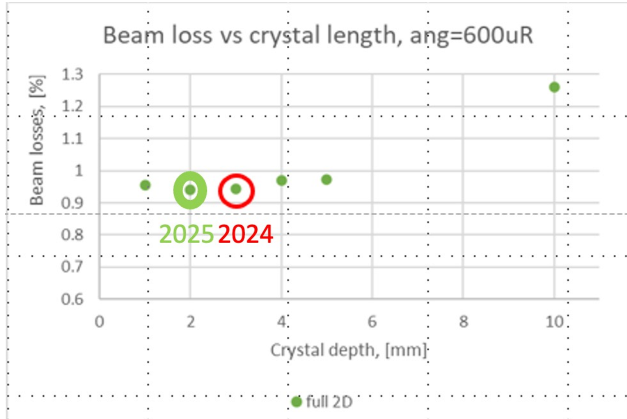
→ Crystals were studied in two configurations of beam quality (standard, conservative)

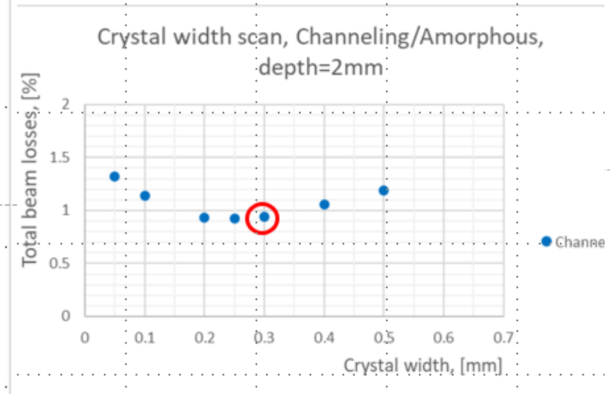






Bent crystals final optimization – bending angle, dimensions





2024

Deflection Angle	600 µrad ±20µrad
Crystal Thickness along the beam	3 mm
Crystal Width across the beam (H)	300 µm
Crystal Torsion	10 µrad/mm
Distance between crystal and holder	>20 mm (somewhat flexible)
Height of crystal free of clamping	>35 mm
Holder Material	Stainless still
Bake-out cycle	No

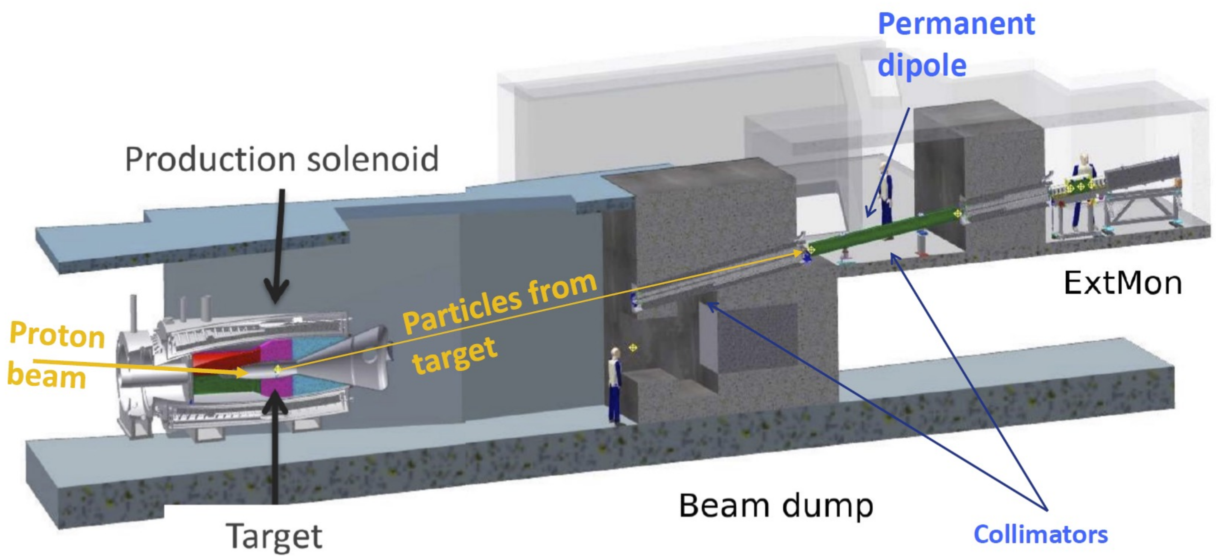
Tables of crystal response by Ferrara’s team, computed using G4 extension w Fluka (A.Sytov)

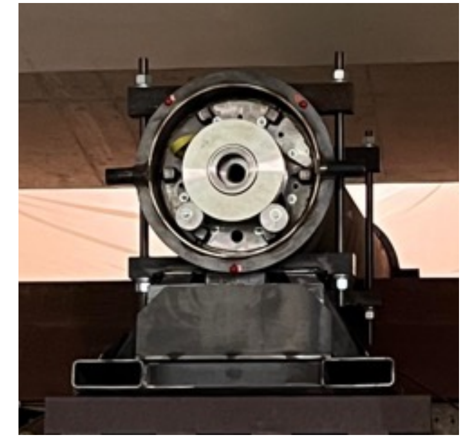
- First set of 2024 crystal production underway + design of holder underway
- Bulk characterization of Si Wafers done @ ESRF- BM05 beamline, OK
- A second set of crystals of 2 mm in length will be produced in 2025

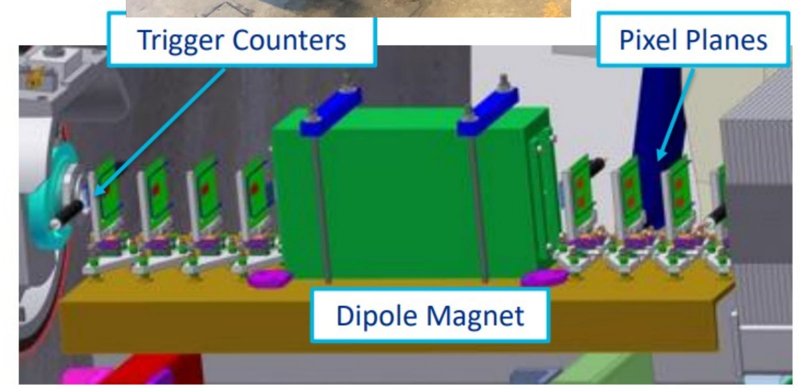
Next plan:

→ 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 ….. end of 2025 /beginning 2026

Extinction Monitor (downstream, upstream)







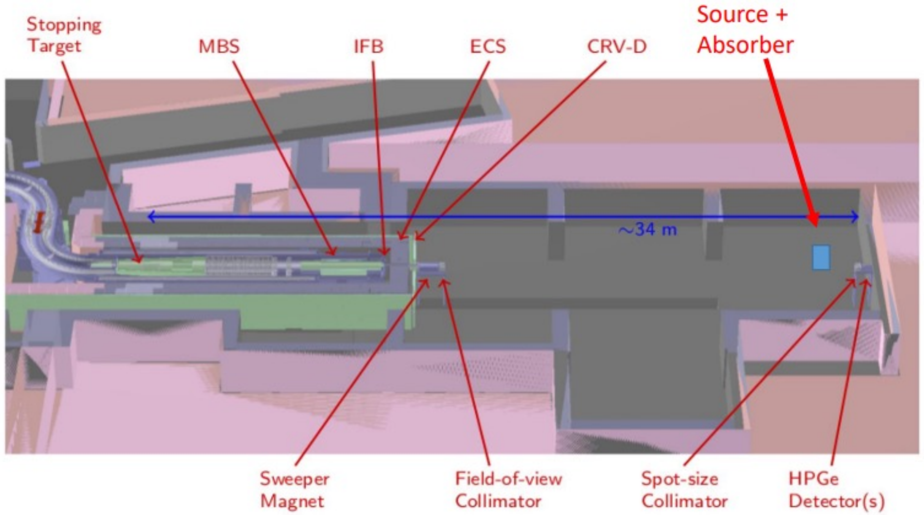
Downstream EXTMON located above and behind the primary beam dump

→ The 2 collimators + 1 dipole select a p/pi beam of ~ 4 GeV/c

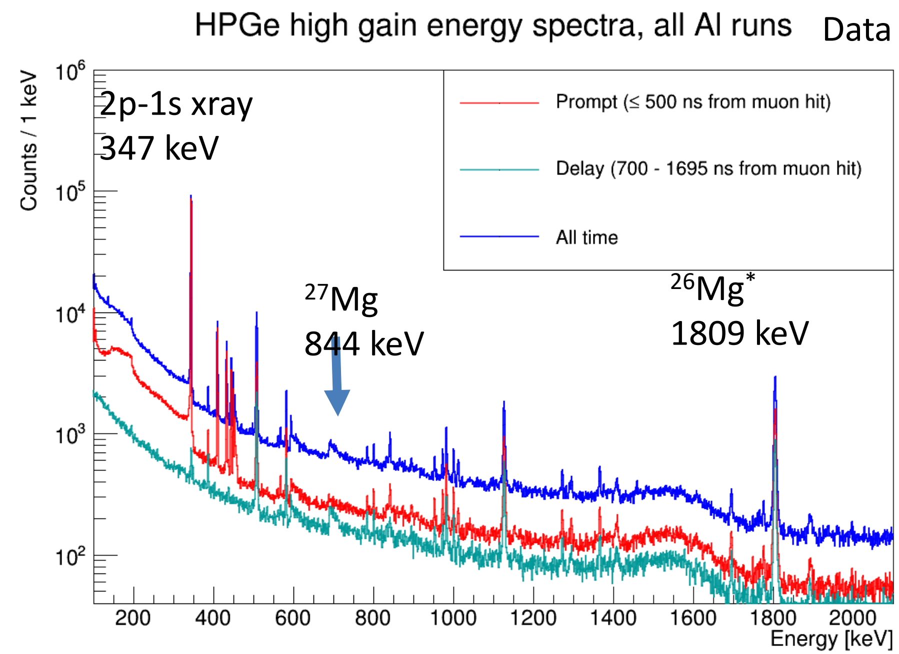
- The detector is based on Trig Scintillators + Pixel Tracker
  - → Scintillators : arrival time and between bunch trigger
  - → Tracker : reconstruct p, π's + dipole rough momentum determination
- It provides an average extinction value (not pulse by pulse) over ~ 8 hrs

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 swiping dipoles – **being commissioned**

Main normalization detector - STM

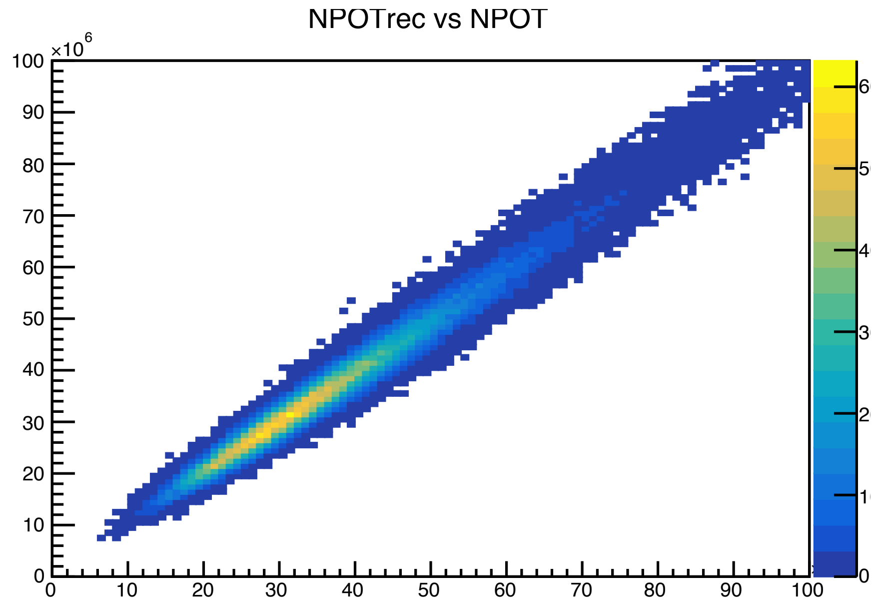


- Measure rates of muonic X and g's lines from Stopping Target using high resolution HPGe and lower resolution (but faster) LaBr3
- 34 m away from the target looking for 3 lines 347 keV "prompt", 844 kev delayed, 1809 keV
- 10 % absolute precision in few minutes of data collection



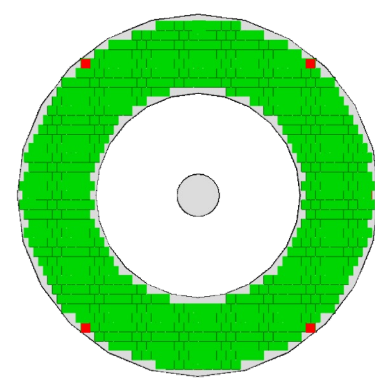
Normalization/beam feedback detector(s)

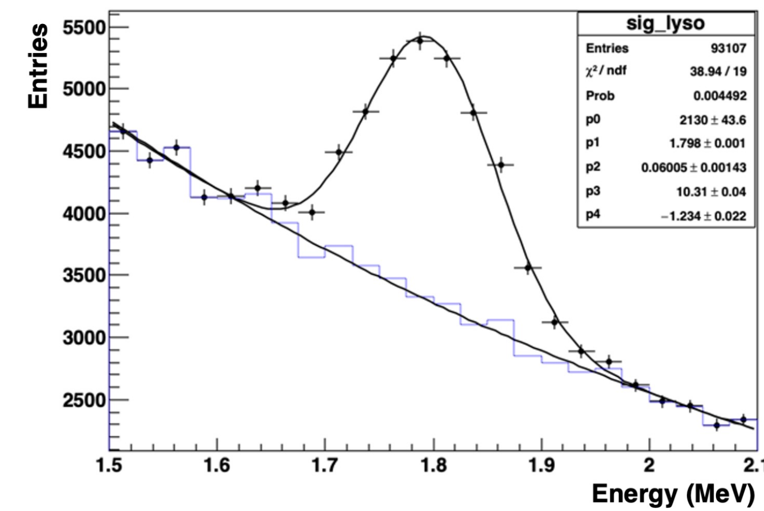
of tracker/calo hits



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

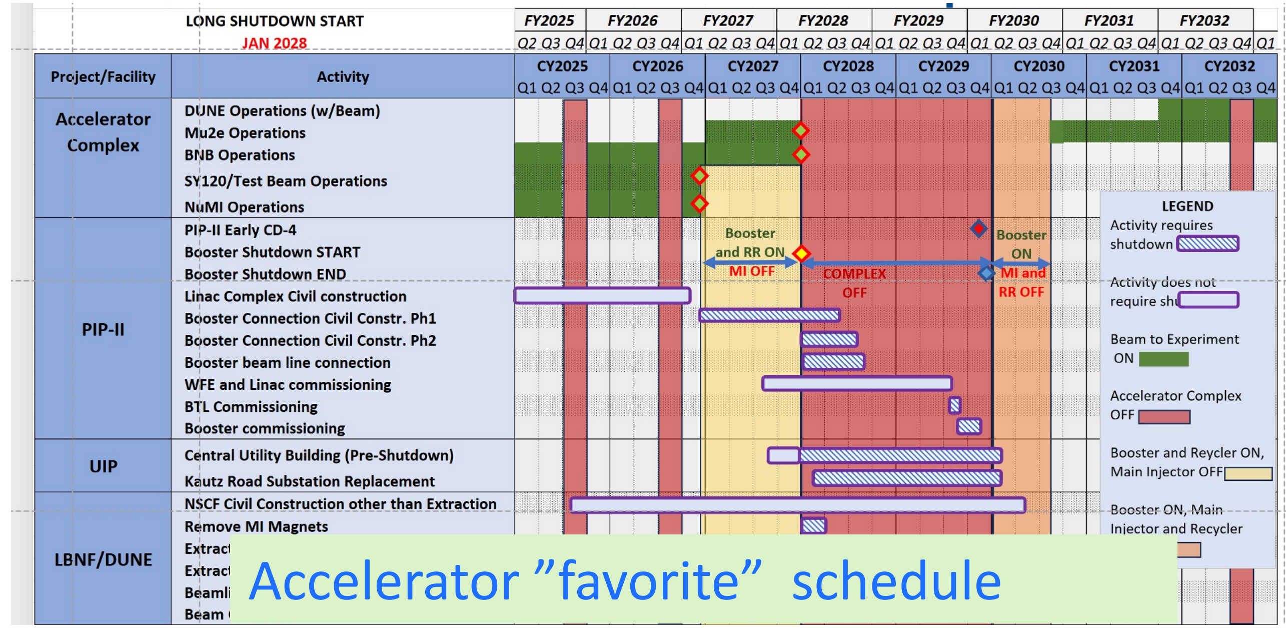
→ flash monitor (tracker hits), PBI variation (Tracker/calo Hits)

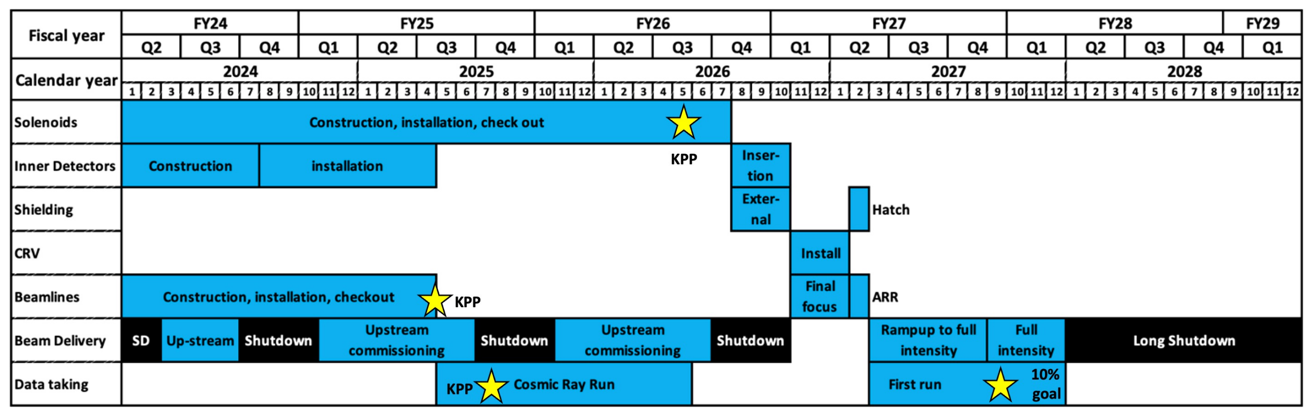
→ muon stopping rate (Caphri, proton count) – Spill loss monitor and so on

Overall schedule for running

- ✓ Mu2e will take advantage of the new “favorite” accelerator scenario from the Lab that foresees us **running in 2027 for ~ 1 year (Run-1)**

- ✓ This year of run includes
  - beam commissioning time,
  - special runs and
  - physics data





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Run-1 physics goals (SU-2020)

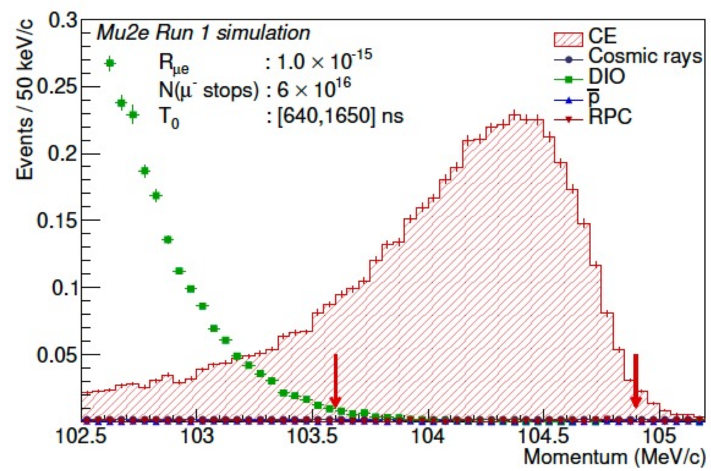
Universe **2023**, *9*(1), 54; https://doi.org/10.3390/universe9010054

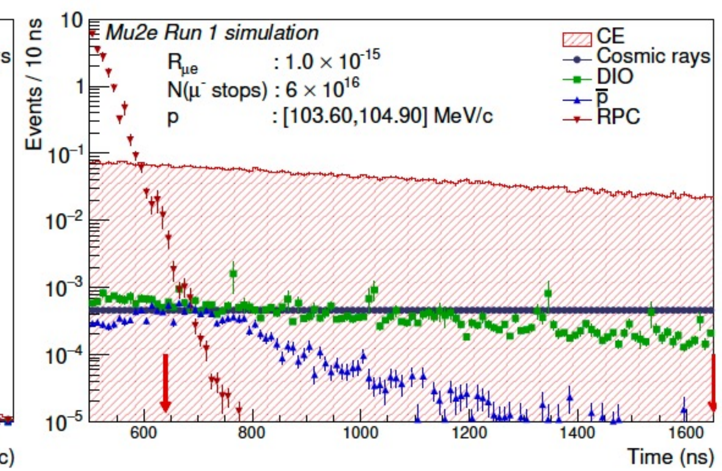
- ✓ In RUN-1 we plan to start at low intensity (1 batch mode) and rampup to 2 batch mode in a second phase
  ➔ Test of background and dead-times related to shielding , adjustment of trigger paths.

- ✓ Goal is to reach x 1000 sensitivity in $\mu^- \rightarrow e^-$ and be x10 ahead of COMET Phase-I (x 100 SINDRUM II in 2026)

- ✓ This will be also a good learning phase and preparation for RUN-2 after LS 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





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 spring 2025***
  - Execute RUN-1 for ***beam physics data collection in 2027*** before LS begins
  - Completing the design***, fabricating, installing, and operating bent-crystals for beam shadowing*** will allow us to reduce losses thus providing margins for operation at higher beam intensity

- **RUN 1 goal is to** get o(10%) of the total number of Mu2e stopped muons:
  - improve the current sensitivity by O(1000) to open the road for this new exciting physics program
  - publish first world's best results in this search

- This will be a learning phase to get ready **for reaching our goal in a long extended RUN 2 after LS**

- ADDITIONAL MATERIAL

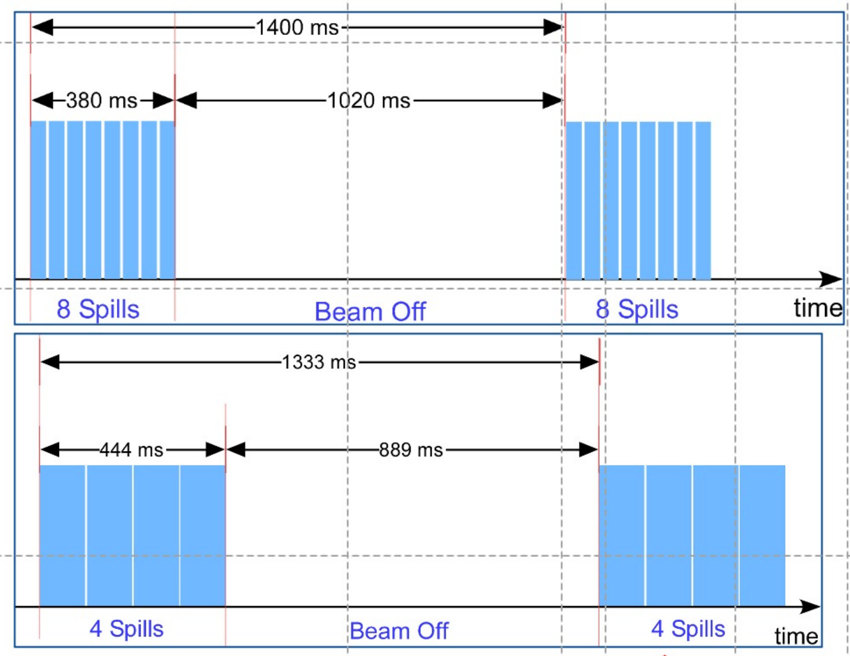
Beam Structure – 1B vs 2 B .. Injection cycles

RUN-II

Design Beam scenario

RUN-I

Reduced Intensity scenario



- 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

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/Puls
Mu2e Duty Factor	27	32	%
Instantaneous Spill Rate	23×10^{12}	9.3×10^{12}	Protons/sec

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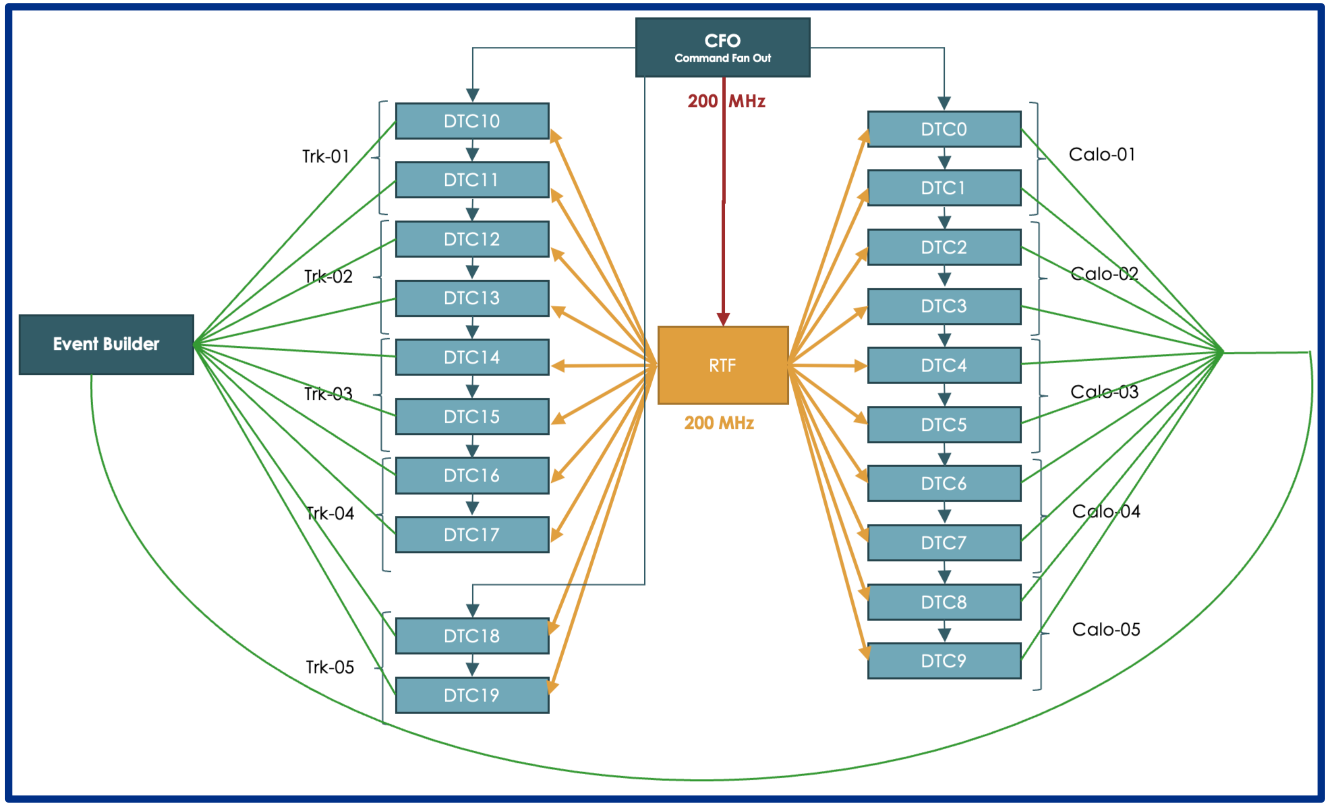
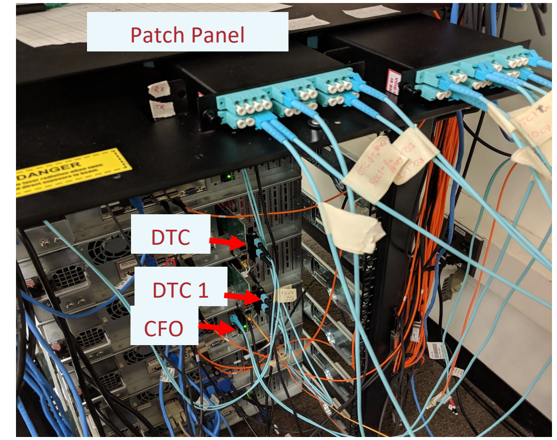
Detectors: TDAQ



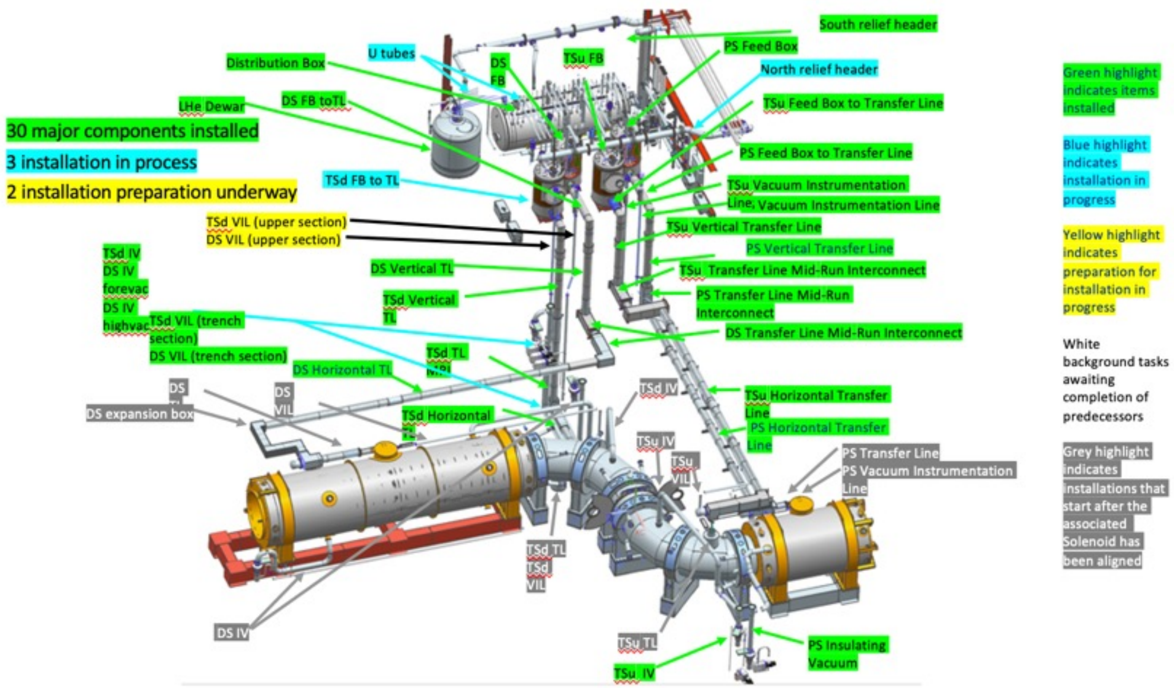


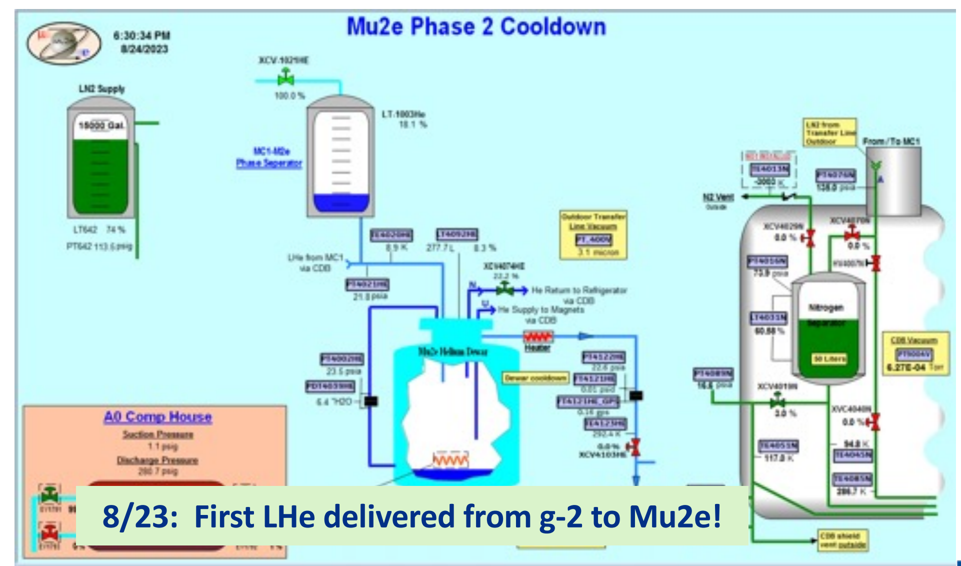
Fiber installation in Trench OK

Institute list
Caltech
KSU
INFN
Yale
U.Michigan
Fermilab

- Support Vertical Slice Test (VST) and Horizontal Slice Test (HST) for detector subsystems
- ¼ scale system in DAQ Room - completed
  - 10 servers arranged in 2 chains, connected to Timing Distribution and EVB network switch.
  - 1st g-2 node installed and tested with no issues.
- Keep up with installation of fibers and PC servers (10 Mu2e+ 24 g-2) to complete (Aug 2024)
- Procurement of feedthroughs and breakouts in progress

Solenoids status – 2 - infrastructures





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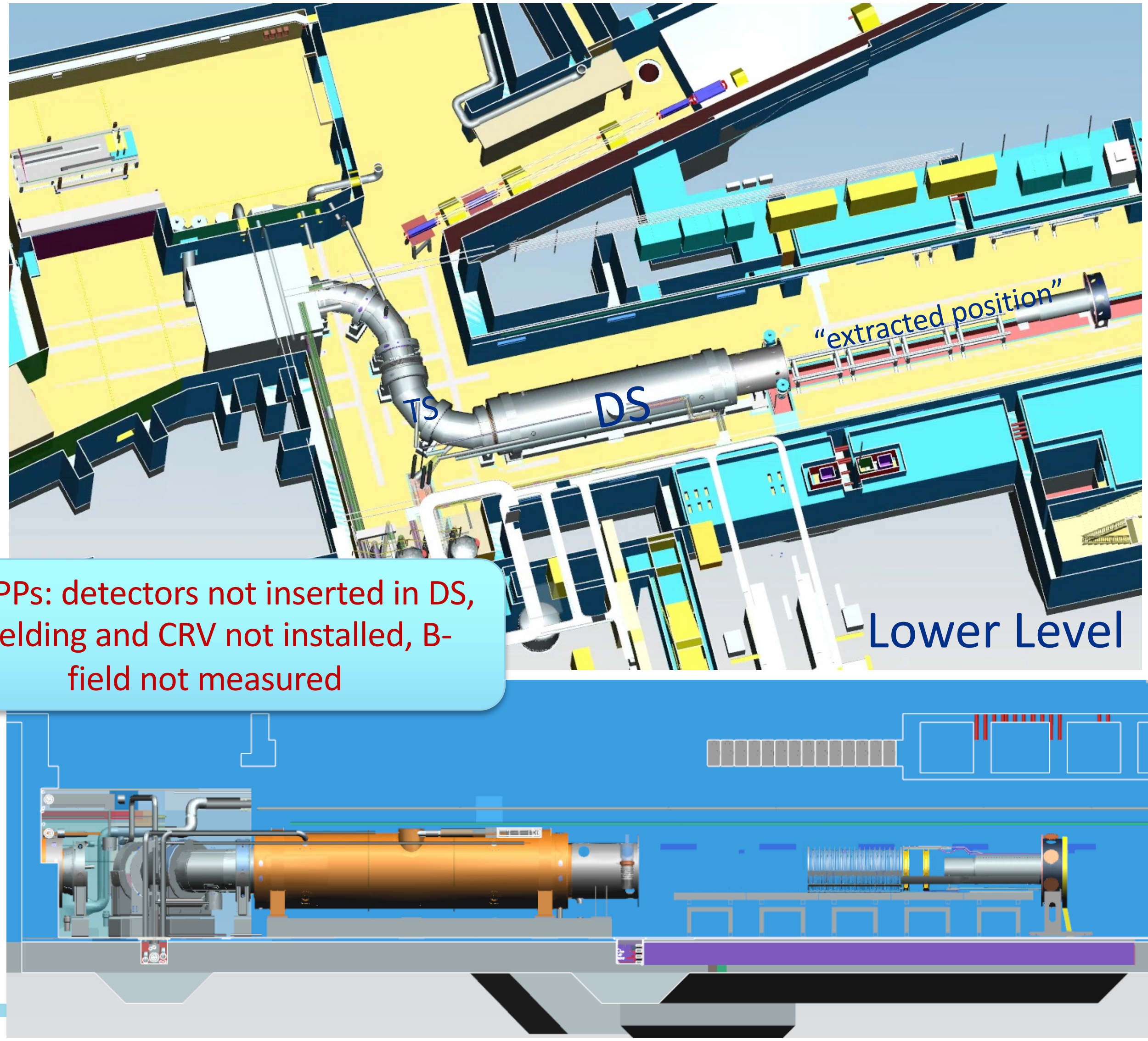
Status of Mu2e experiment @ KPPs



At KPPs: detectors not inserted in DS, shielding and CRV not installed, B-field not measured

KPP’s

Key Param	Threshold Performance	Objective Performance
Acc	Accelerator components are acceptance tested at nominal voltages and currents. Components necessary for single-turn extraction installed.	Protons are delivered to the diagnostic absorber in the M4 beamline.
	Shielding designed for 1.5 kW operation delivered to Fermilab and ready for installation.	Shielding designed for 8 kW operation delivered to Fermilab and ready for installation.
	All target station components are complete, delivered to Fermilab and tested. Heat and Radiation Shield is installed in Production Solenoid. Other components are ready to be installed after field mapping.	
Solenoids	The Production, Transport and Detector Solenoids have been cooled and powered to the settings necessary to take physics data.	The Production, Transport and Detector Solenoids have been cooled and powered to nominal field settings.
Detector	Cosmic ray tracks are observed in the Tracker, Calorimeter and a subset of the Cosmic Ray Veto and acquired by the Data Acquisition System after they are installed in the garage position behind the DS. The balance of the CRV counters are at Fermilab and ready for installation.	The cosmic ray data in the detectors is acquired by the Data Acquisition System, reconstructed in the online processors, visualized in the event display and stored on disk.