The Mu2e Experiment at Fermilab

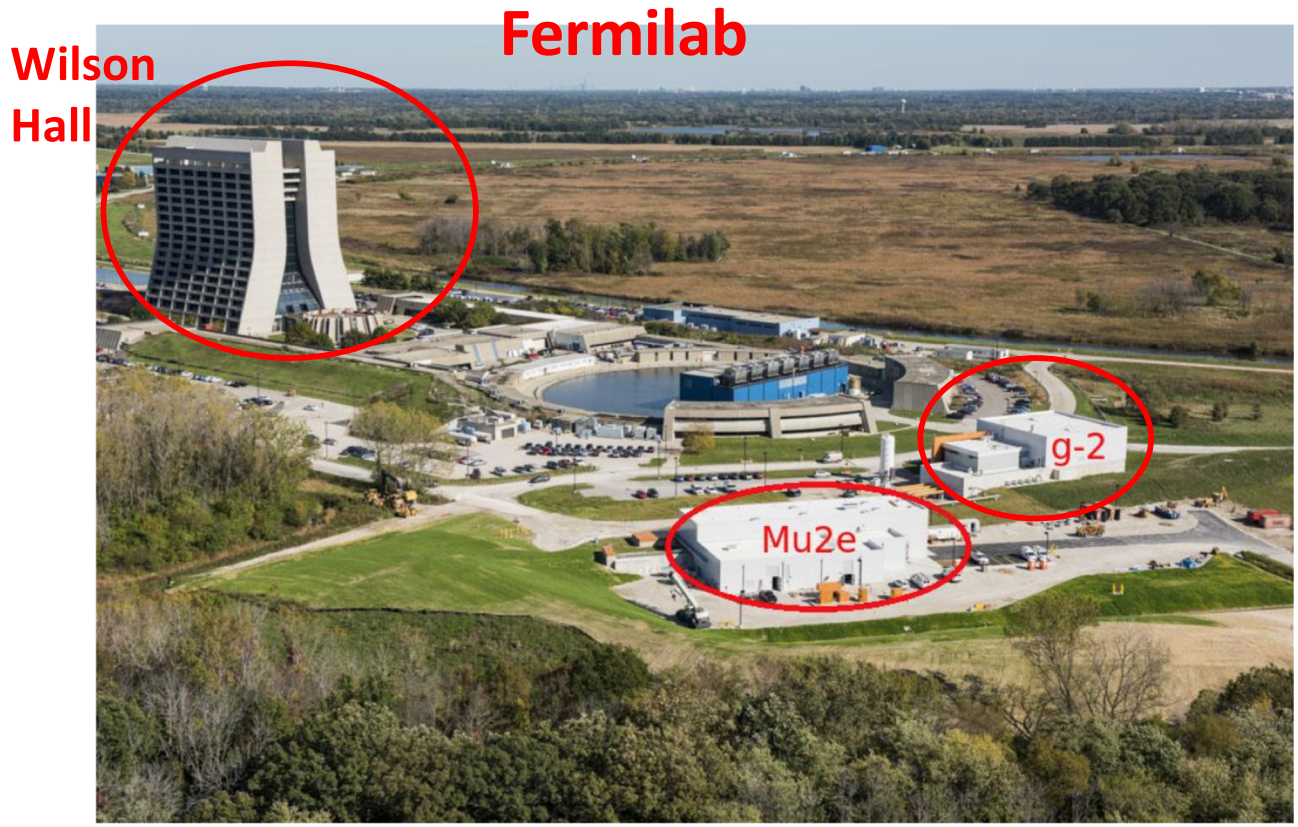
Mu2e IFC Meeting
Dec 5, 2019

Jim Miller, Boston University

Doug Glenzinski, Fermilab

Muon Program: Muon g-2 and Mu2e

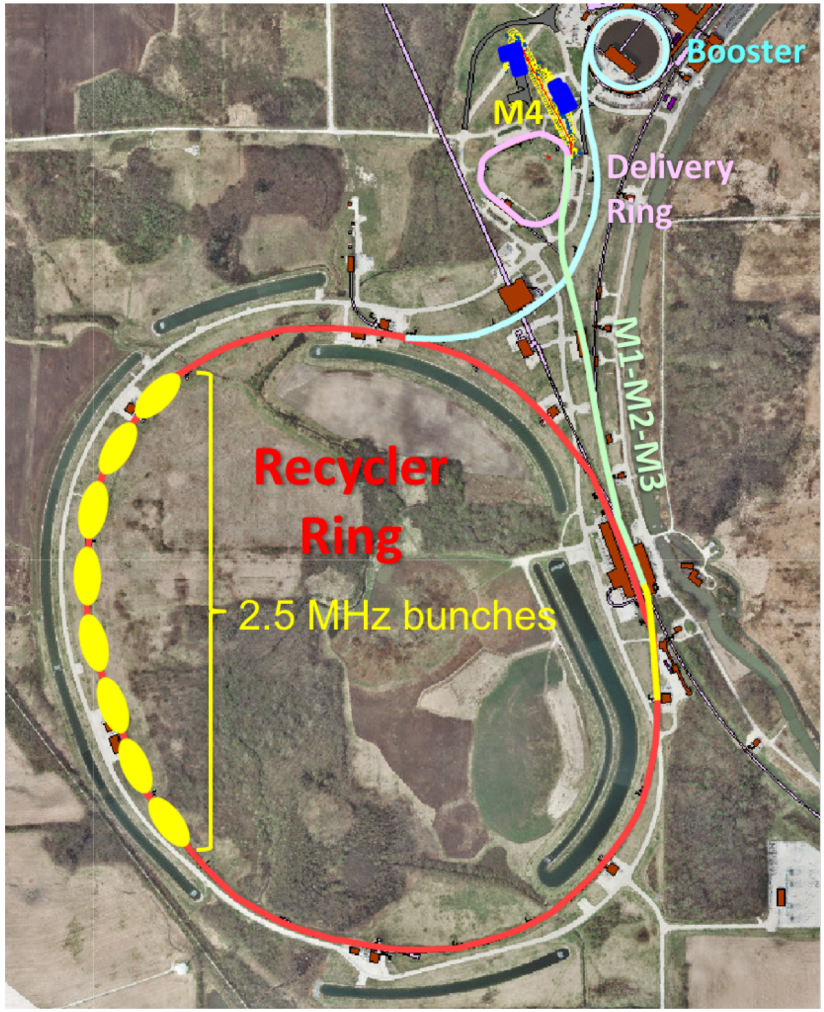
- The Muon Program consists of two experiments and the associated beam line development.
- Mu2e and Muon g-2 experiments share common beam-line elements, partly using repurposed Tevatron facilities.
- Both buildings are complete.
- Muon g-2 is taking data now.
- Mu2e is under construction.
- Both need pulsed beams.
- g-2 needs 3.1 GeV/c muons injected into the g-2 storage ring.
- Mu2e needs a large flux of very low energy negative muons that can stop in a thin target.

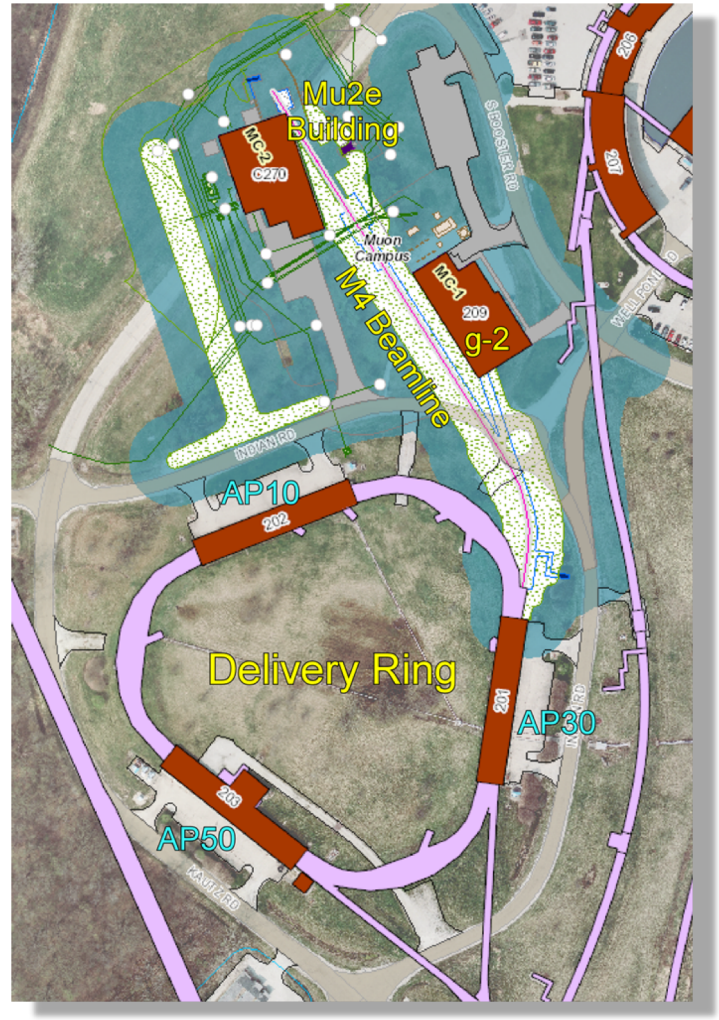


Completed Muon Campus at Fermilab

Mu2e/g-2 beam lines

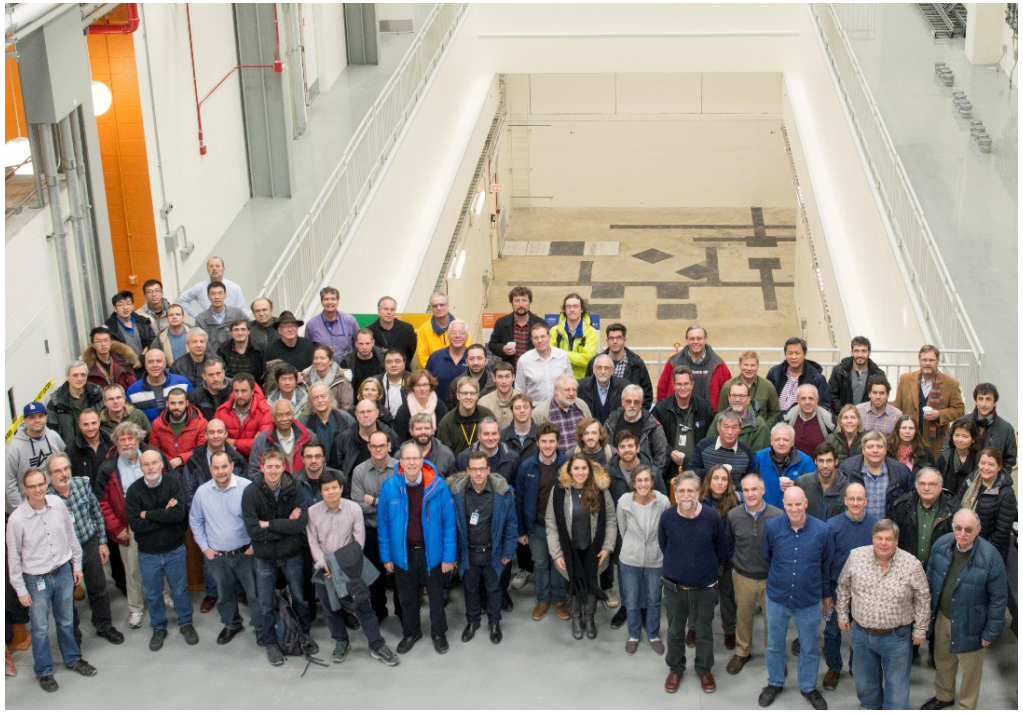
- Mu2e or g-2 run concurrently with the neutrino program
- However Mu2e and g-2 cannot run simultaneously
- g-2 beamline complete and delivering muons since 2017
- Mu2e beamline is complete up to final focus region





The Mu2e Collaboration

Over 200 scientists from 40 institutions



Argonne National Laboratory ● Boston University
Brookhaven National Laboratory
University of California, Berkeley ● University of California, Davis ● University of California, Irvine
California Institute of Technology ● City University of New York ● Joint Institute for Nuclear Research, Dubna ● Duke University ● Fermi National Accelerator Laboratory ● Laboratori Nazionali di Frascati ● INFN Genova ● Helmholtz-Zentrum Dresden-Rossendorf
University of Houston ● Institute for High Energy Physics, Protvino ● Kansas State University ● Lawrence Berkeley National Laboratory ● INFN Lecce and Università del Salento ● Lewis University ● University of Liverpool ● University College London ● University of Louisville ● University of Manchester ● Laboratori Nazionali di Frascati and Università Marconi Roma
University of Michigan ● University of Minnesota
Institute for Nuclear Research, Moscow ● Muons Inc.
Northern Illinois University ● Northwestern University
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 ● University of Washington ● Yale University

Mu2e Collaboration

Tracker – ANL, UC Berkeley, CUNY, Duke , FNAL , Houston, JINR Dubna, LBNL, Michigan, Minnesota

Calorimeter – Caltech, HZDR (Dresden), INFN (Frascati, Lecce, Pisa, Rome, Trieste), JINR Dubna

Cosmic Veto – ANL, JINR Dubna, KSU, NIU, U. South Alabama, Virginia

TDAQ – Caltech, FNAL, KSU, LBNL, Pisa, UCL, Yale

Muon & Proton Monitors – Boston, FNAL, Liverpool, Manchester, NIU, Purdue, University College London, Washington

Solenoids and Field Mapping – ANL, Boston, FNAL, INFN Genova, Northwestern

Stopping Target Monitor- BU, FNAL, HZDR, Liverpool, Manchester, Purdue, UCL, York

Proton Beam Line – CUNY, UC Davis, FNAL, York

Simulations & Software – Boston, UC Berkeley, Caltech, CUNY, FNAL, Frascati, HZDR, LBNL, Louisville, Manchester, Northwestern, NIU, Sun Yat-Sen, Novosibirsk, Pisa, Virginia, Yale

Institutions shown in red are International
Institutions shown in blue are Research supported by DOE and NSF

Mu2e Experiment

Goal:

- Search for muon-to-electron conversion in the field of a nucleus
- Observation would be an example of CLFV and would signal new physics

$$\mathrm{R}_{\mu\mathrm{e}} = \frac{\Gamma\left(\mu^- + \mathrm{N} \rightarrow \mathrm{e}^- + \mathrm{N}\right)}{\Gamma\left(\mu^- + \mathrm{N} \rightarrow \text{all captures}\right)}$$

- Expected sensitivity $R_{\mu e}$ =8x10^{-17}@ 90% CL, x10,000 better than SINDRUM-II
- Discovery at 5σ: 2x10^{-16}

Approach:

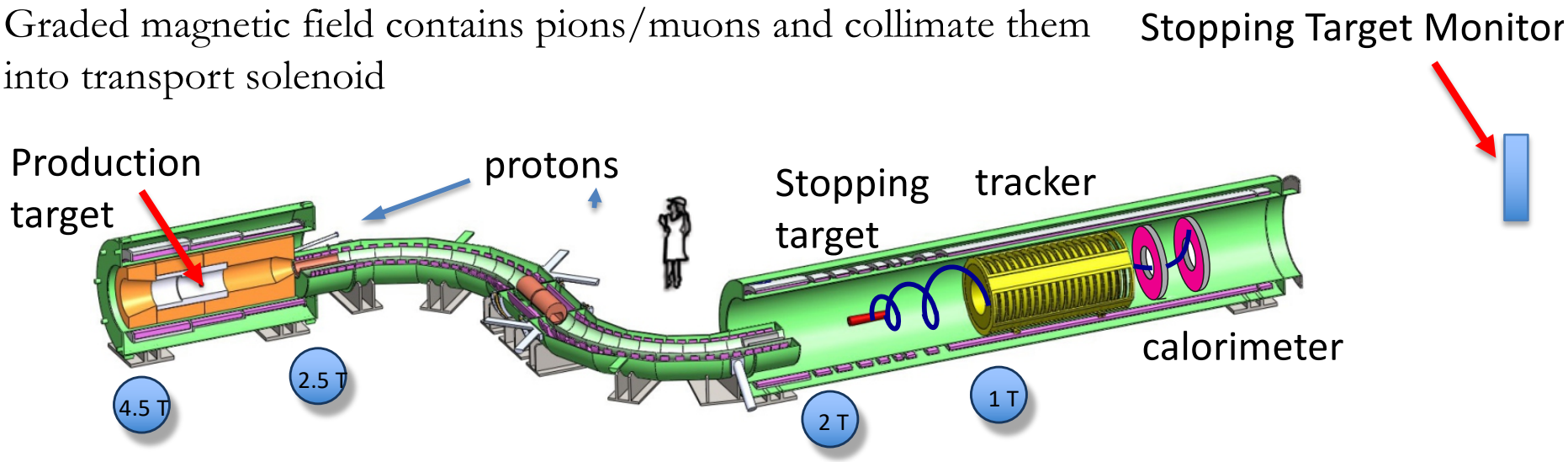
- Form muonic atoms by stopping μ- in an aluminum target
- Search for 105 MeV electron from

$$\mu^- +^{27}_{13} Al \rightarrow e^- +^{27}_{13} Al$$

Mu2e overview

Production Target / Solenoid (PS)

- 8 GeV, 8 kW Proton beam strikes target, producing mostly pions
- Graded magnetic field contains pions/muons and collimate them into transport solenoid



Transport Solenoid (TS)

- Collimator selects low momentum, negative muons
- Antiproton absorber
- The S shape eliminates photons and neutrons

Target, Detector and Solenoid (DS)

- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- Graded field "reflects" downstream conversion electrons emitted upstream, improving efficiency

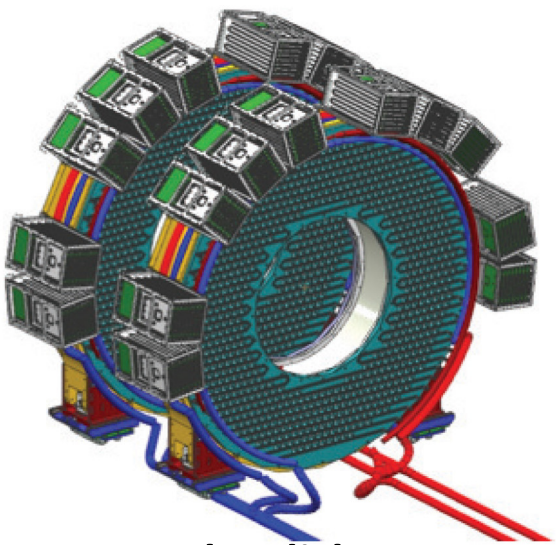
Mu2e Experimental Advances

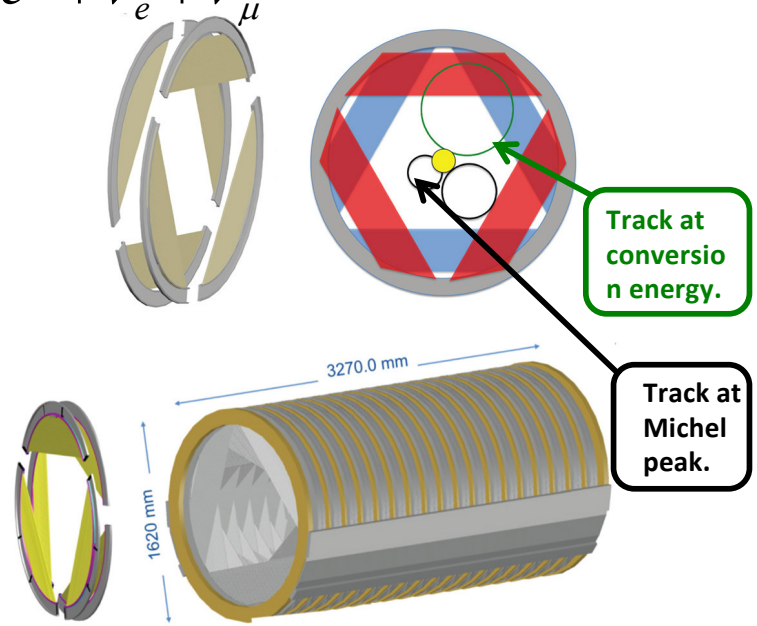
- **Keys to x10,000 better sensitivity**
  - **By placing the production target inside a high-field solenoid, one obtains a highly efficient low-energy muon beam (0.0015 stopped muons/proton)**
    - **This will be the world's hottest stopped-muon source by ~ x100**
    - **10^{10} stopped muons/second**
  - **A pulsed proton beam allows suppression of prompt backgrounds by employing a delayed live gate**
    - **Narrow proton pulses (~250 ns wide) every 1695 ns**
    - **Delay live gate for ~700 ns relative to arrival of protons**
      - **Beam-related 'flash' dissipates early, muonic atoms live long (864 ns)**
    - **Achieves significant suppression of backgrounds from beam electrons and prompt pion interactions in the stopping target**
    - **Time structure is good match to muonic aluminum lifetime (864 ns)**

Trackers and calorimeters are used to reconstruct electron kinematics

Both nearly blind to all DIO electron background due to hole down the middle

DIO electrons: $\mu^- + {}^{27}_{13}Al \rightarrow {}^{27}_{13}Al + e^- + \bar{\nu}_e + \nu_\mu$





- **2 annular disks separated by half a track wavelength gives ~90% acceptance.**
- **Each disk contains ~674 scintillating CsI crystals with SiPMs readout**
- **Resolution ~5% at 105 MeV and ~1 ns.**

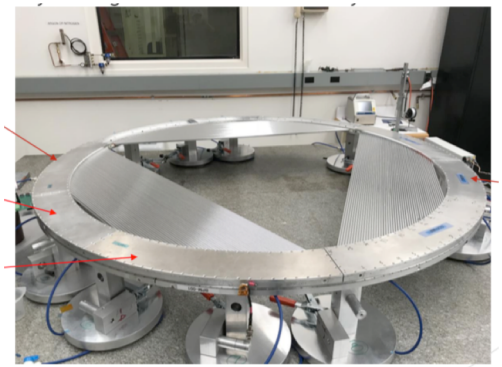
- **5mm diameter straw drift tubes: mylar-epoxy-Au-Al walls and Au-plated W wire.**
- **Operates in a vacuum, Ar/CO2 gas at ~1.45 kV.**
- **Ultra low mass- minimize multiple scattering.**
- **Highly segmented to handle high rates.**
- **Resolution less than 180 keV/c at 105 MeV.**
- **18 stations each having 12 × 120° panels = 216 panels ➔ ~21,000 straws.**

Tracker Progress

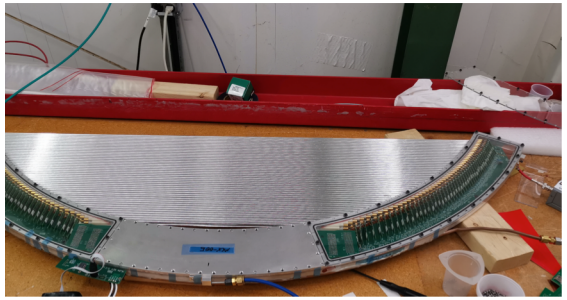
Tracker Panel Construction at University of Minnesota

TDAQ Test Stand for all detectors

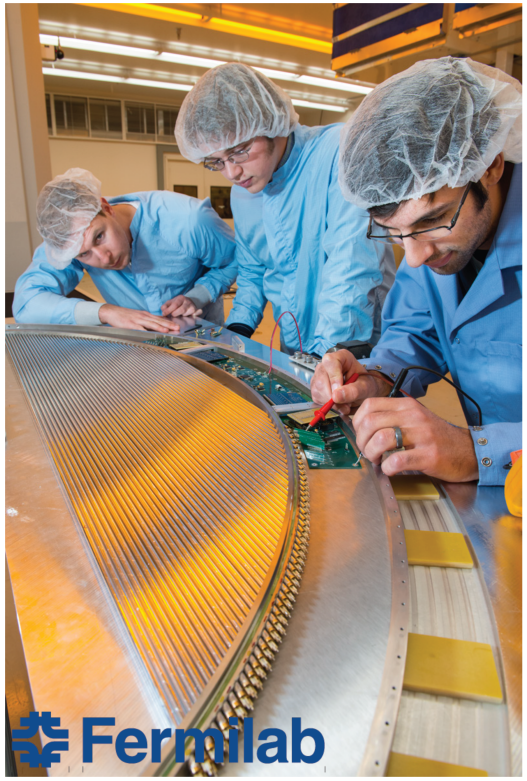
Half Tracker Plane comprised of 3 panels



Instrumented Tracker Panel



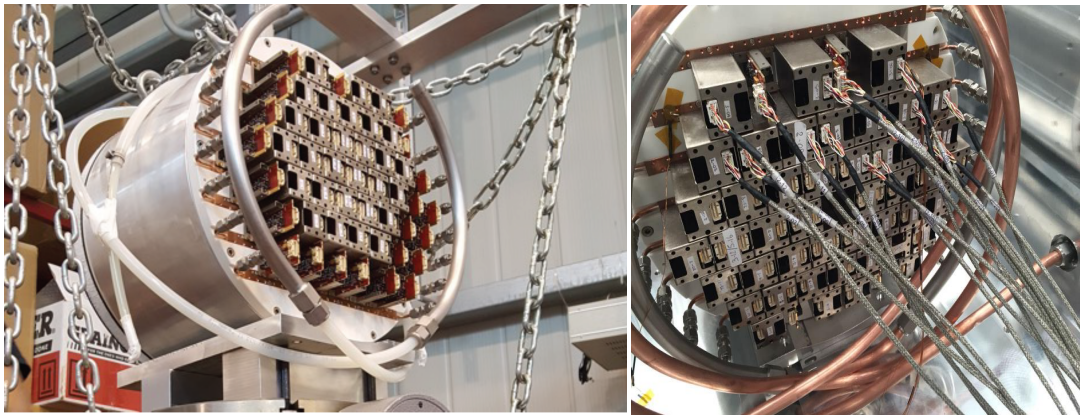
- Panels are being produced at University of Minnesota
- Full production is expected over next few months
- JINR Dubna will join Minn team
- LBNL/UC Berkeley testing electronics
- Panel Component fabrication and QC at Duke and York
- Supports designed at Argonne
- Wires X-rayed at Duke
- Michigan- integration with DAQ
- Houston- panel QC/QA
- Tracker assembled at Fermilab



Calorimeter Progress

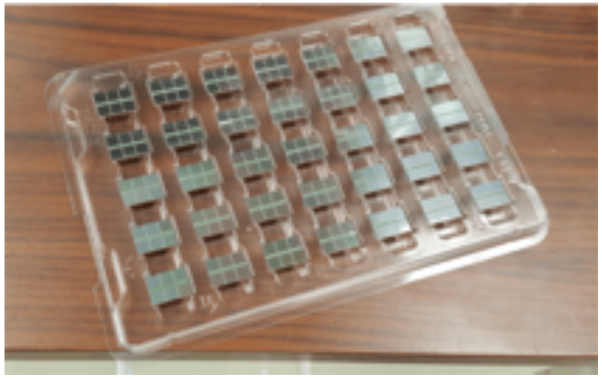
Calorimeter crystals)

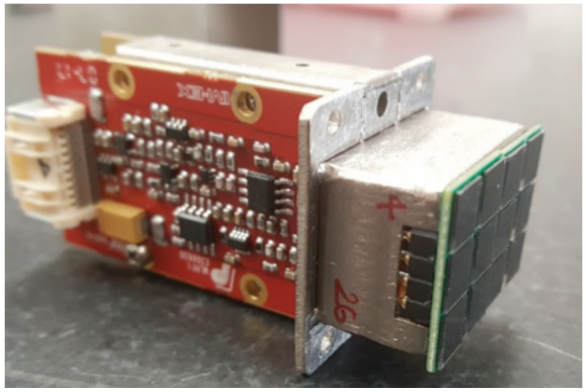
Prototype Calorimeter crystals



- **75% of the CsI crystals received and tested**
- **All SiPM's received & tested**
- **Completion of DAQ and electronics progressing well**
- **Large INFN contribution**
- **Testing- Dubna, HZDR**
- **QA/QC of crystals, calibration system- Caltech**

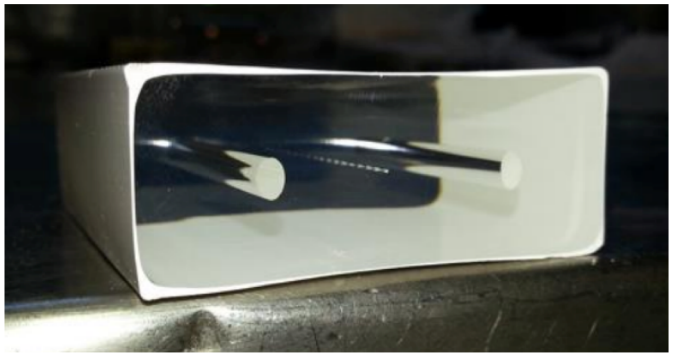
SiPM Array



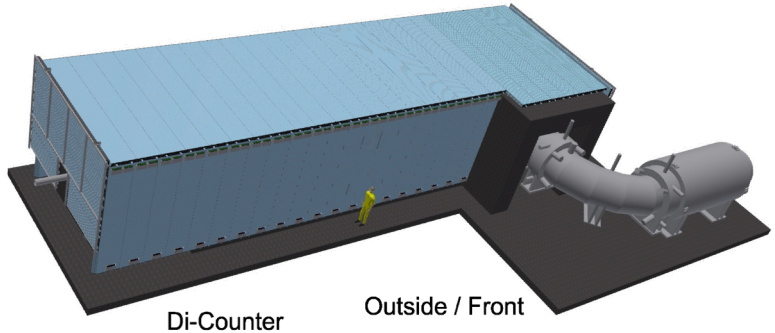


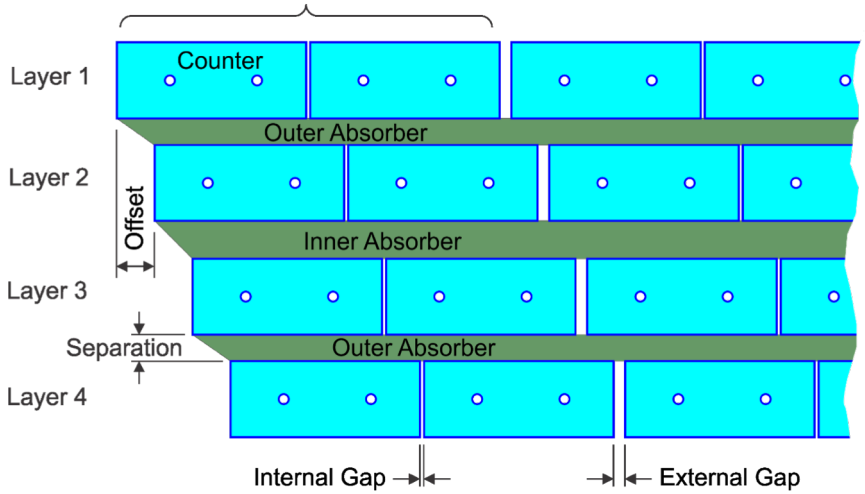
Mu2e Cosmic Ray Veto

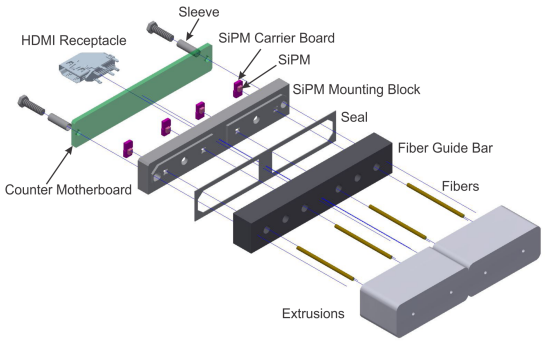
- Covers all of DS, half of TS, better than 10^{-4} inefficiency with 3-fold coincidence
- 4-layers of extruded scintillator bars, wavelength shifting fibers w/SiPM read out
- Scintillator and SiPMs all in hand
- Electronics and DAQ in advanced state
- Virginia, Kansas, Argonne, Dubna



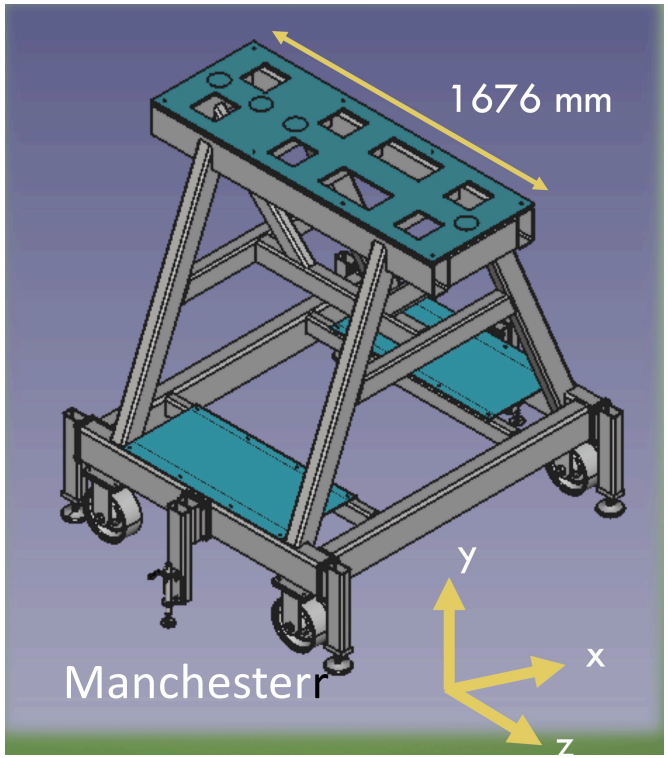
Cosmic Ray Veto Module Construction,University of Virginia

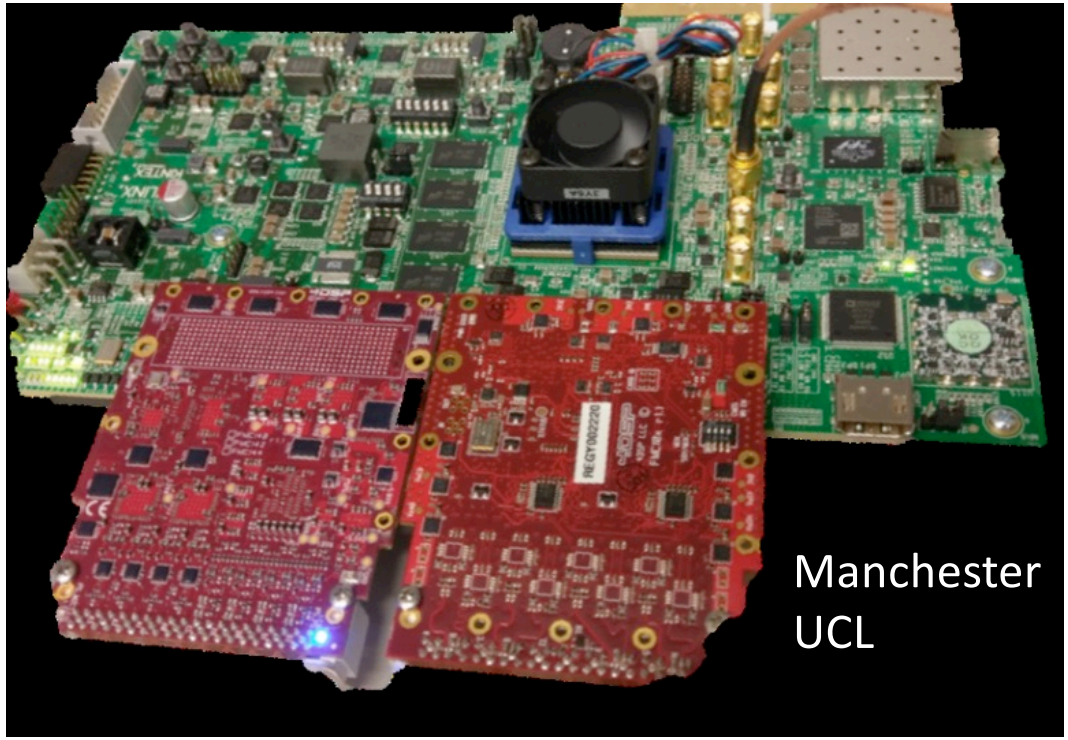


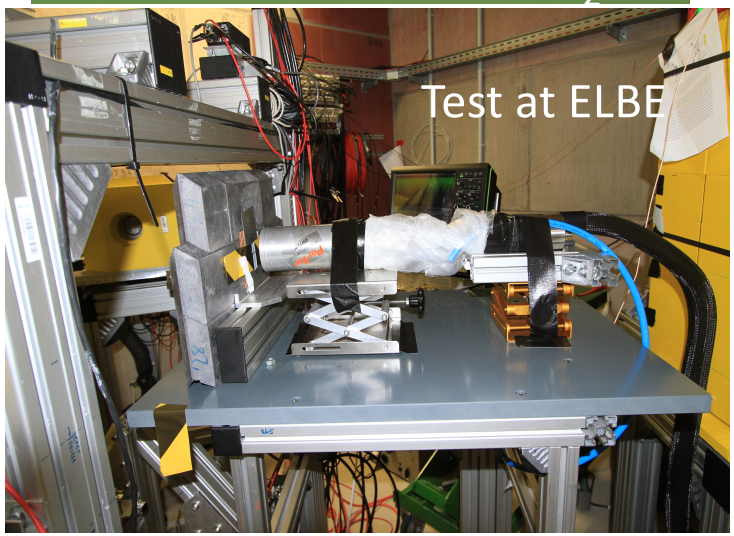




Stopping Target Monitor



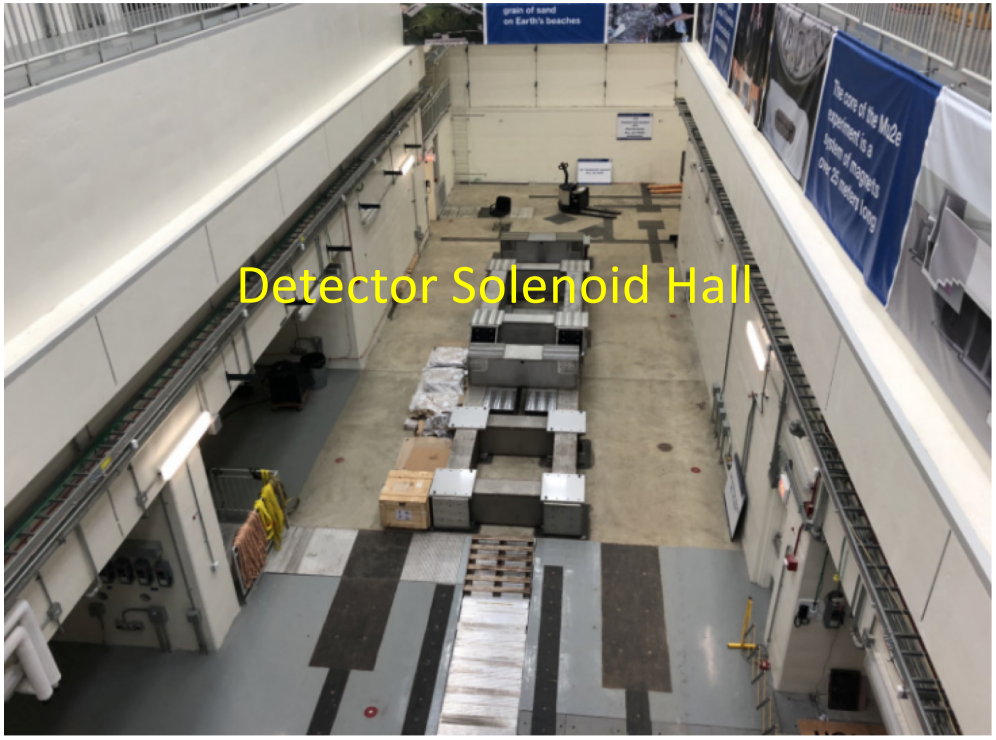


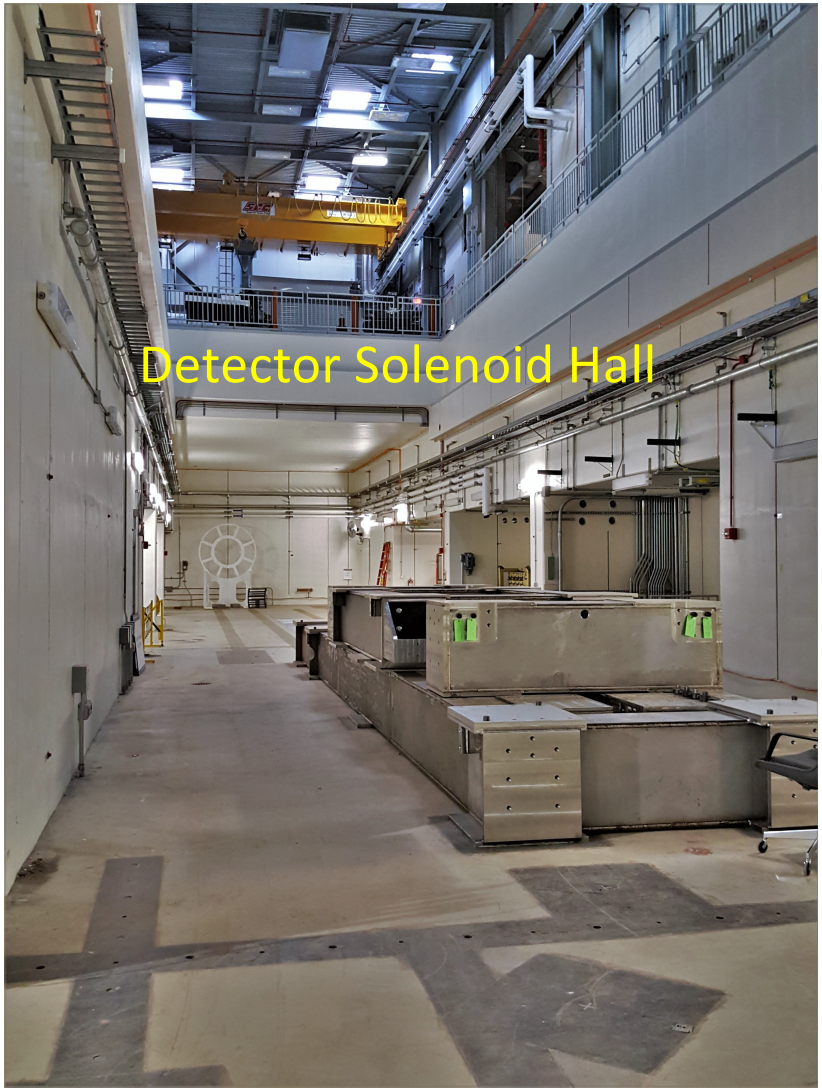


- 2 HPGe detectors acquired (Liverpool)
- Front End electronics in hand (UCL)
- FPGA programming under way (UCL)
- DAQ development under way
- Design on shielding nearing completion
- ELBE beam test done, another planned (HZDR)
- BU, HZDR, Liverpool, Manchester, UCL, Purdue

Mu2e Building is Complete

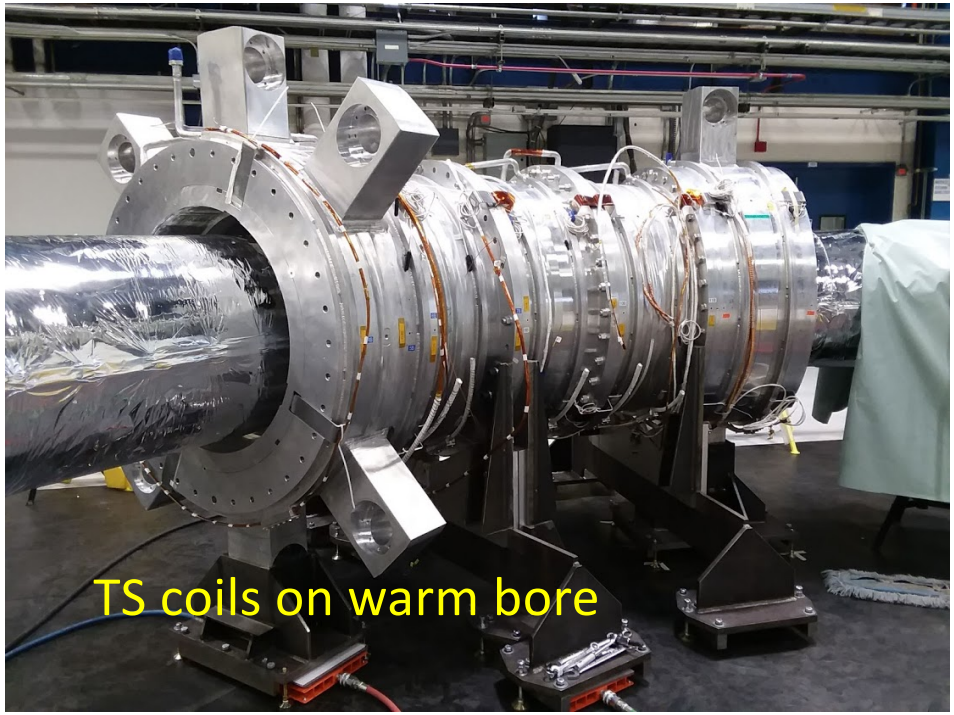
April 2017



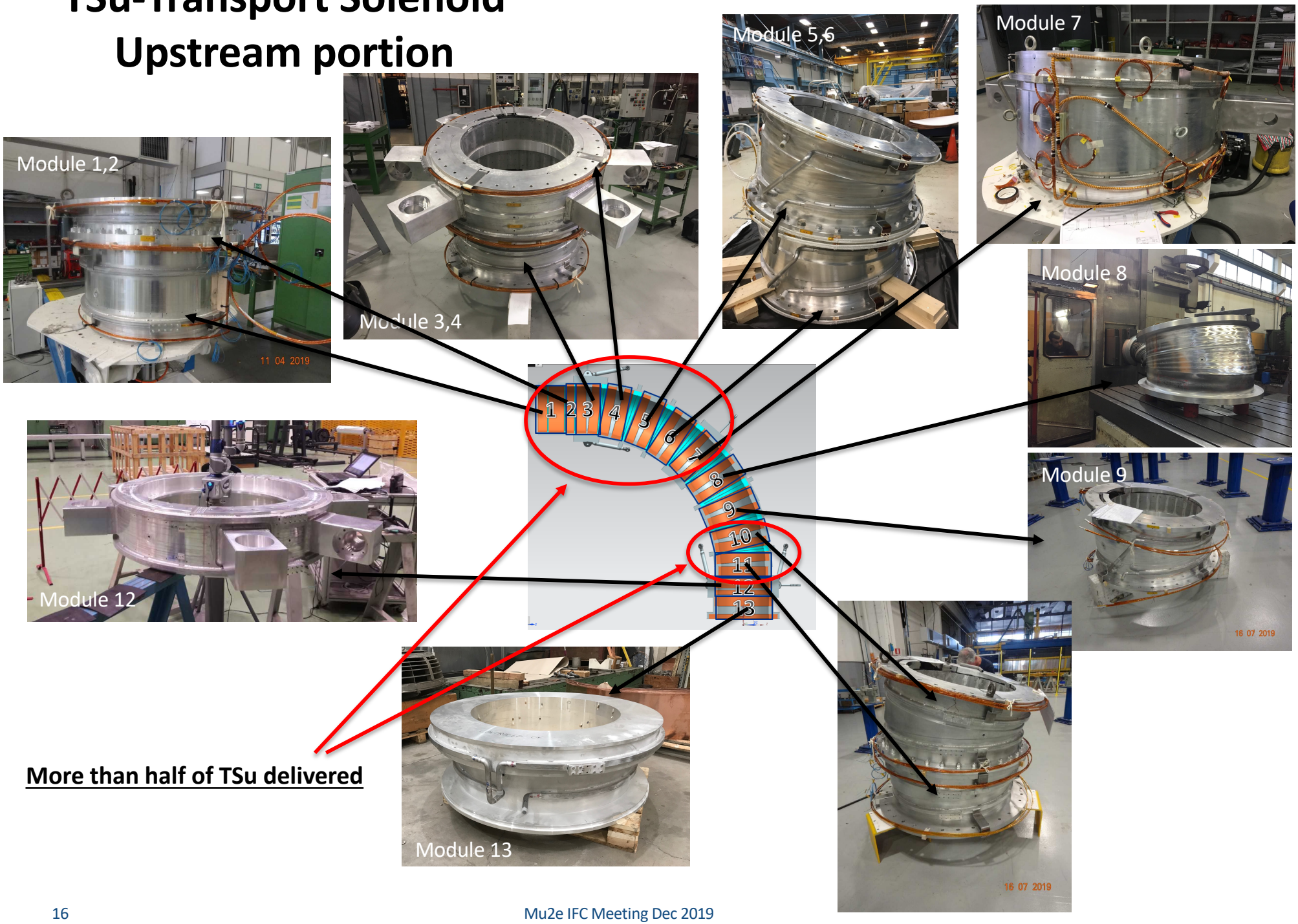


Transport Solenoid Progress

- S-shaped magnet constructed from series of wedge-shaped modules
- Superconducting Coil Modules fabricated in Italian industry
- Delivered modules cooled to Liquid Helium and powered at Fermilab, assembled
- Of 14 total units, 3 units on warm bore, 3 units in house, 2 units ready to ship



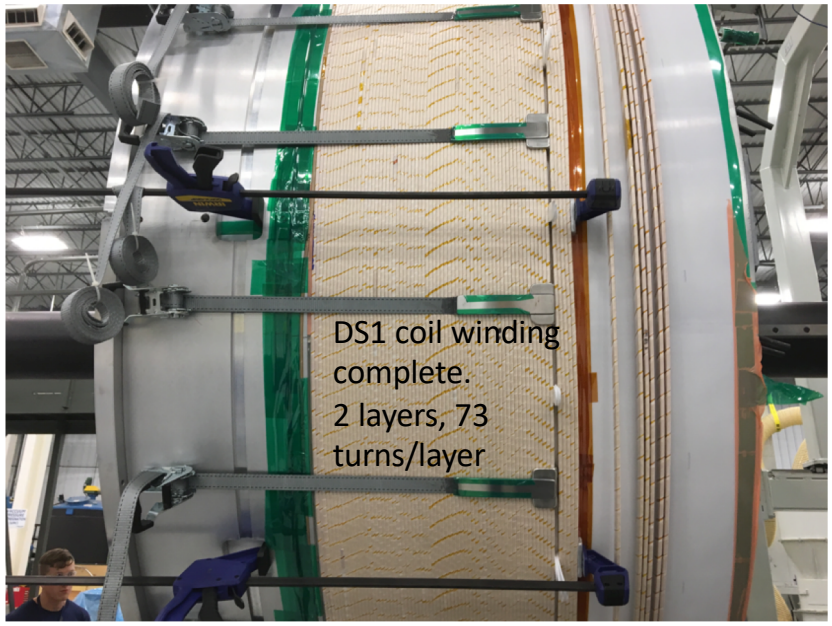
TSu-Transport Solenoid Upstream portion



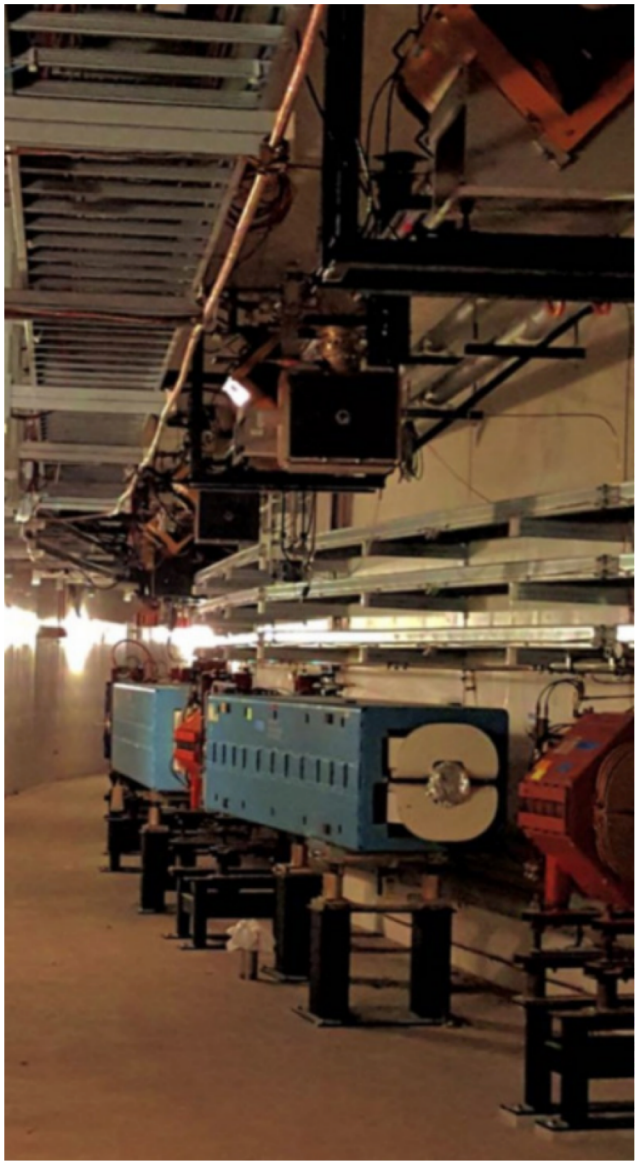
More than half of TSu delivered

Mu2e Status - PS/DS

- Contractor (GA) is manufacturing and assembling Production and Detector Solenoids
- Now successfully winding superconducting coils since early 2019, after initial difficulties which produced delays and cost overruns.
- Working to recover schedule
- 1st of three PS coils on track for completion at end of year
- Completion of solenoids is on the critical path

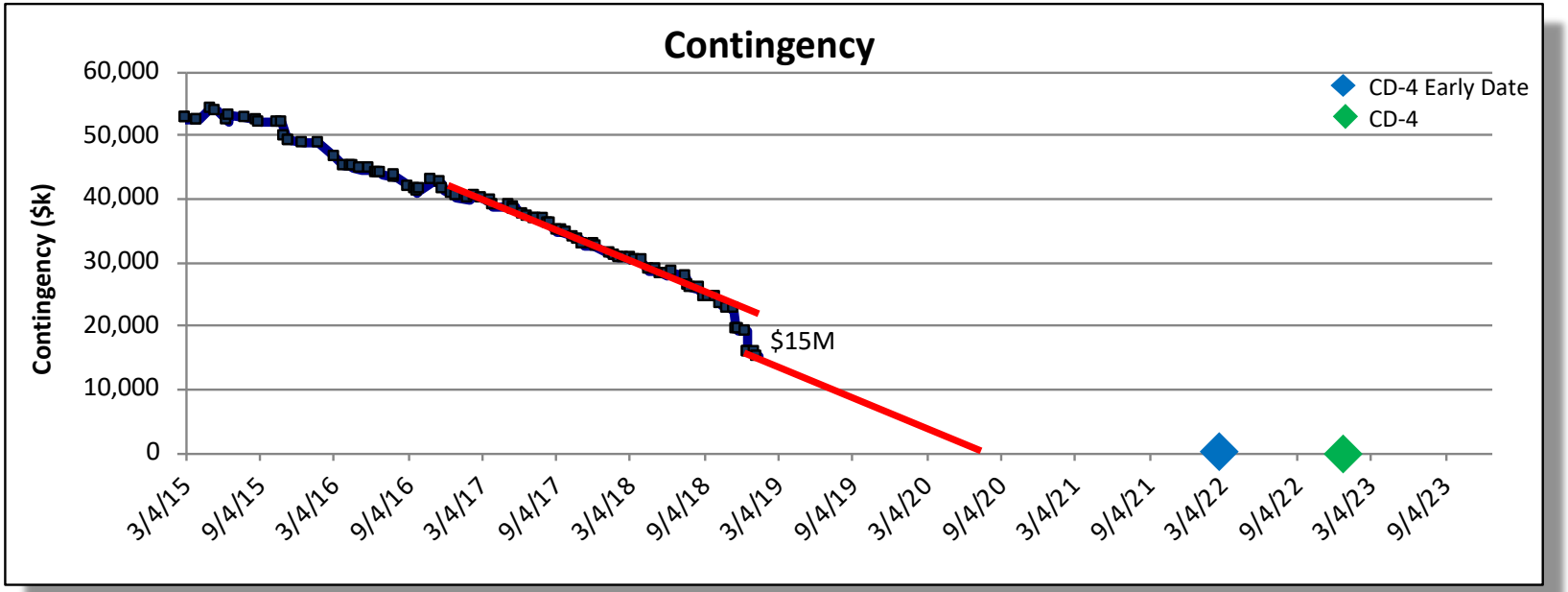


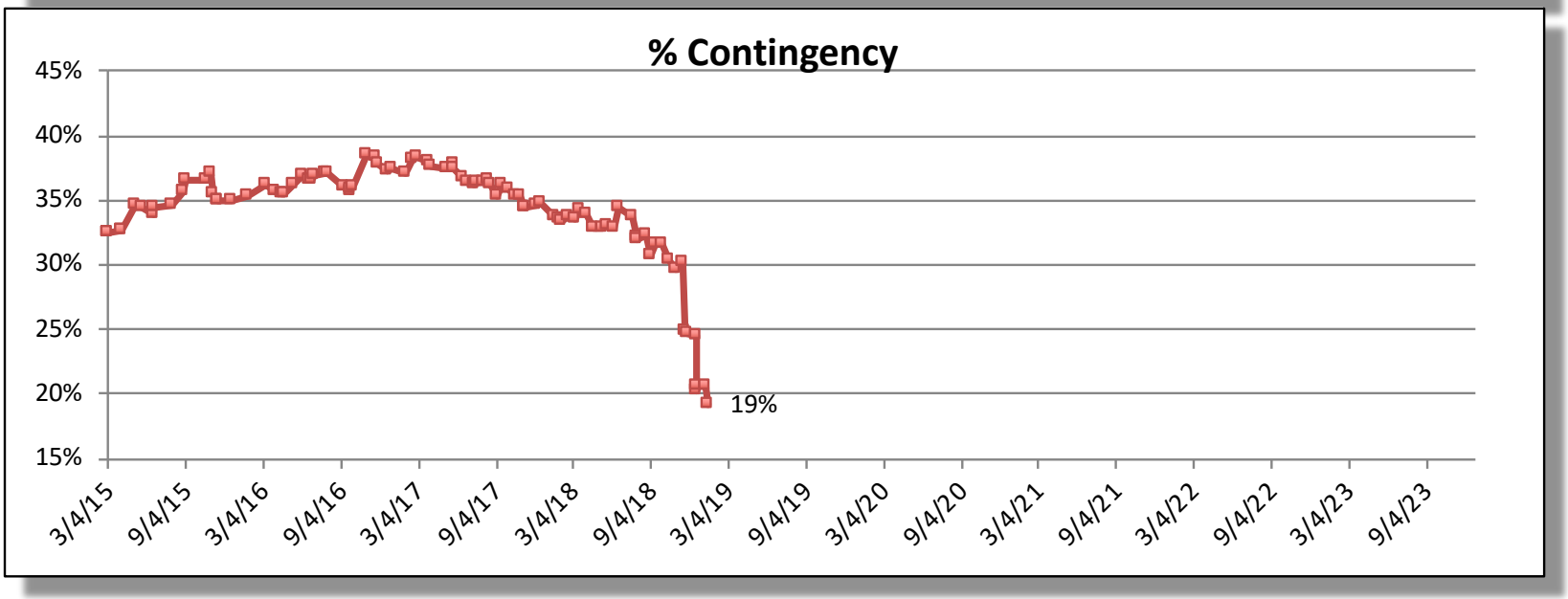
Mu2e Beamline Installation Making Significant Progress



- Most beamline elements are installed up to final focus
- Resonant extraction sextupoles fabricated
- First beam into beamline 2020

Contingency Drawdown – January 2019





Contingency Action Plan

- **Project worked with the Collaboration and Lab to develop a plan**
  - **Identify potential initial de-scopes but *maintain original sensitivity goals***
- **Collaboration evaluated impact of potential descopes on science**
- **Lab appointed a "Red Team" to take an independent look at options**

Prioritized Staging Options for Mu2e

Group	Item	Project Cost Reduction ($k)	Physics Impact		Cost to recover (FY26 $k)	Notes
			Low Intensity	High Intensity		
A	Reduce overhead hatch shielding by 50%	400	none	none	460	Subject to Rad Safety approval. May need full shielding at high intensity running
A	Use regular concrete for external shielding	1700	low	medium	3142	Can use measured rates at low intensity running to optimize required shielding for high intensity running
B	Eliminate the muon stack from the Extinction Monitor	50	low	low	58	Muon stack needed to understand origins of out-of-time beam. Could install during a short shutdown if data shows large out-of-time contributions.
B	Eliminate cold test of completed TSu and TSd cryostats at HAB.	500	low	low	n/a	This would be a permanent de-scope. Increases risk that significant re-alignments would be required in the experimental hall, which could damage the magnets and would cause significant (>3 months) schedule delay - perhaps affecting our ability to meet KPPs. Requires additional simulation studies to help quantify risk.
C	Remove outer layers of calorimeter crystals	<95	low	low	n/a	This would be a permanent de-scope. Strongly disfavored by our international partners (INFN, JINR), who provided much of the calorimeter in-kind.
C	Defer installation of some STM beam line elements	50	low	extreme	58	STM Detector elements already purchased by UK partners (in kind). This would be a reduction in the DOE scope that would limit the capability to only low intensity running.
D	Reduce the number of tracker planes installed by 25%	700	high	extreme	810	Tracker was already value engineered at CD-2, where the number of planes was reduced from 44 to 36, placing it on a performance edge. Further reductions degrade the signal acceptance while causing a sharp increase in the dominant physics background from muon decay-in-orbit.

Group A are determined to have the least impact, Group D significantly compromises science capabilities.

Contingency Action Plan

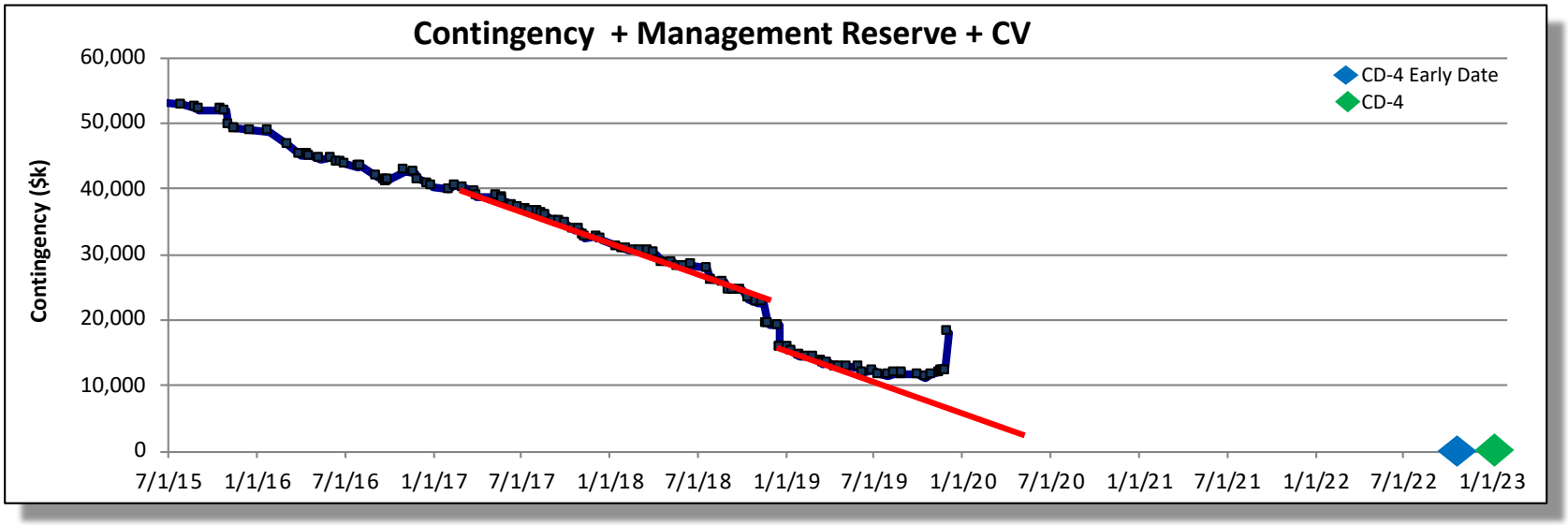
- Response Plan developed using input from Red Team and Collaboration priorities
- Report from the Red team made several recommendations that the Project has accepted and is implementing:
  - Execute BCRs to reduce project scope by about $3.0M
    - Shielding reduction - Done
    - Eliminate cold test of assembled TS at HAB - Done
  - Execute a buy-back of the HAB test facility - $6M
    - Consulting with OHEP on a plan to execute in FY21, FY22
  - Establish a Contingency Task Force to work with project to control costs and solve problems- goal: Deliver required project scope on time and on budget
    - Active, meets monthly, chaired by T. Meyer.
  - Prepare to execute additional buy-backs if necessary
- These actions restore contingency to about 32% on CTG

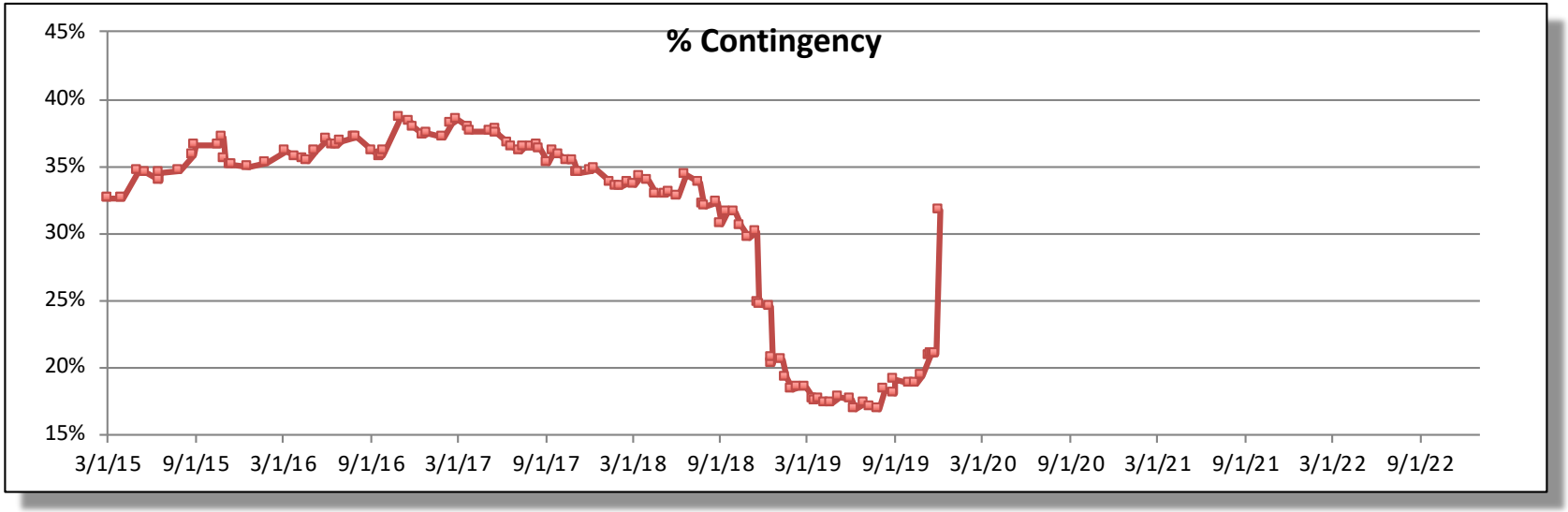
Red Team Membership:

G. Bock, J. Butler, M. Convery, P. Czarapata, P. Derwent, C. Ginsburg, A. Klebaner, M. Lindgren (chair), H. White

Ex officio – J. Frieman, J. Lykken, T. Meyer, R. Tschirhart

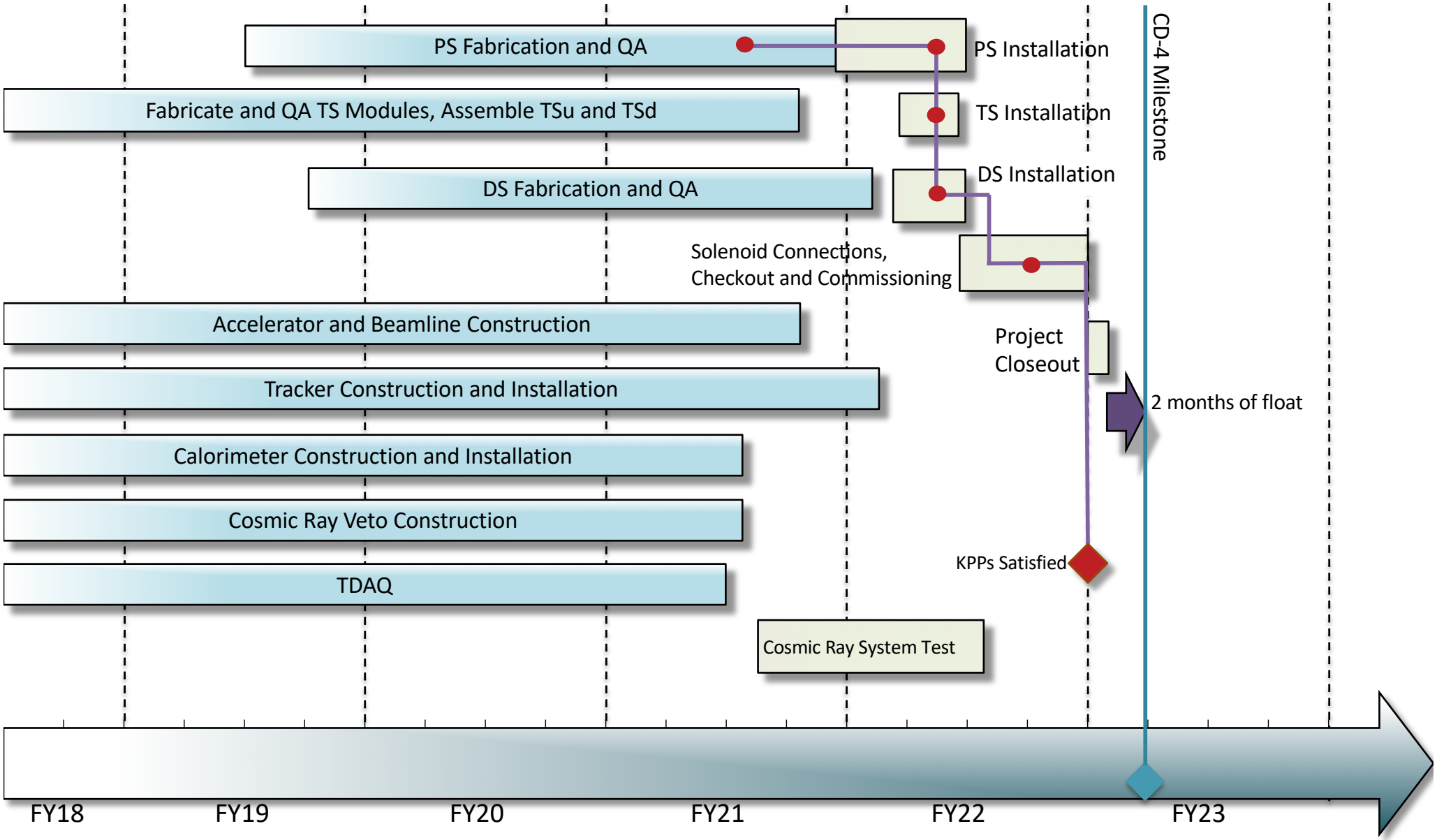
Today





Improved, but remaining risks.

Project Schedule



Transition to Operations

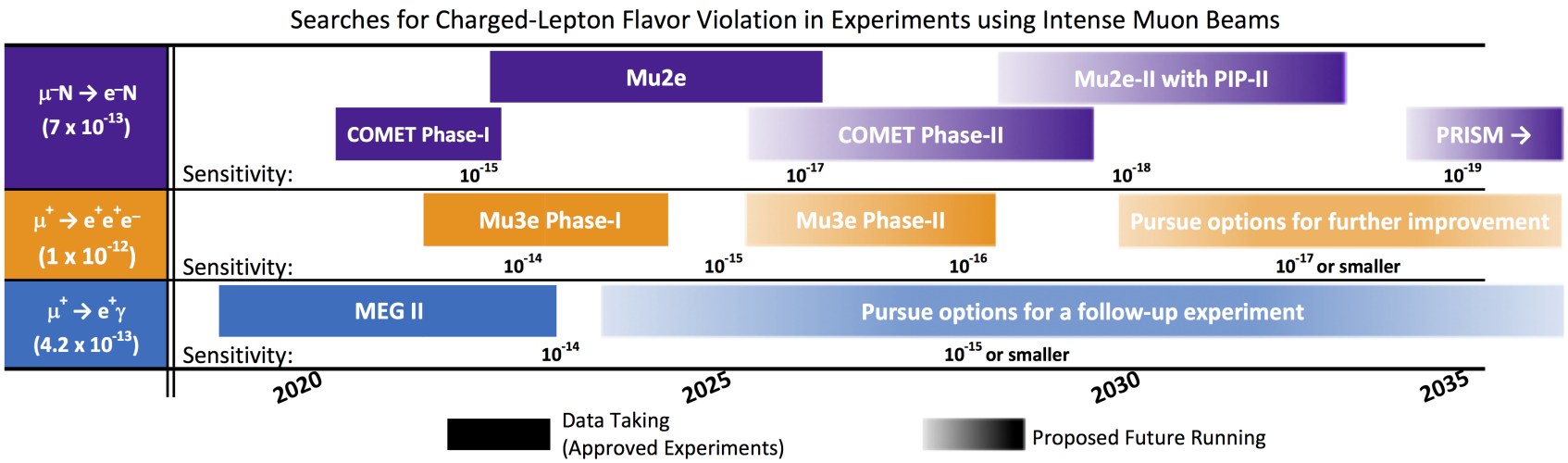
- DOE is formalizing their review of Operations costs.
- A Mu2e working group has been established that has been developing a WBS cost and schedule for operations
- Preliminary Plan is due at DOE in February, reviewed in May.
- We will treat the Common Fund as an “opportunity” for that review.
- It would be great to advertise it as active at the review.

Summary

- Project 77% complete, carefully managing spending
  - Some scope contingency has been exercised – shielding reduction
  - Working closely with lab, DOE, and International Partners to finish on time and on budget
  - Significant contributions from International Partners important Mu2e success
- Schedule is a concern - Solenoids drive the Critical Path completion
  - Pressing vendors to try and advance their schedule
- DOE Operations Review in May 2020
  - Will concentrate on schedule and plan once project is complete
  - Important for us to be able to articulate strong support from our International partners
- Using current schedules, Mu2e data taking will be interrupted by a long shutdown for LBNF and PIP-II beam line construction.
  - In this scenario, Mu2e data taking would finish in late 2020s
  - Mu2e would use long shutdown to address any shielding or performance issues identified with first 2y of data taking
  - The schedule will continue to evolve as the Mu2e, LBNF/DUNE, and PIP-II projects make progress

Backup

CLFV schedule of expts. (European Planning)



[1]

[1] A. Baldini *et al.*, arXiv:1812.06540 [hep-ex] (2018).

P5 Recommendations: Mu2e and g-2

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capability. To meet budget constraints, physics needs, and readiness criteria, large projects are ordered by peak construction time: the Mu2e experiment, the high-luminosity LHC upgrades, and LBNF.

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Muons and Kaons

The Mu2e and muon g-2 projects represent a large fraction of the budget in the early years. These are immediate targets of opportunity in the drive to search for new physics, and they will help inform future choices of direction. The science case is undiminished relative to their earlier prioritization. The programmatic impacts of large changes at this point were also discussed and determined to be generally unwise, although the Mu2e profile could be adjusted by a small amount if needed.

Recommendation 22: Complete the Mu2e and muon g-2 projects.

P5 Recommendation: Mu2e

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- *Rare Muon decays and processes:* Observation of charged lepton flavor violation (*e.g.*, a muon changing to an electron) would be a signature of new physics. In the muon sector, a dramatic order of magnitude increase in sensitivity to the scale of such new physics should come from experiments on the decays $\mu \to e\gamma$, $\mu \to ee^+e^-$, and muon conversion to an electron in the presence of a nucleus. These experiments will be performed at J-PARC, PSI, and Fermilab.

Of these three processes, muon conversion to an electron in the presence of a nucleus will give the greatest increase in mass reach for new physics. Very ambitious next-generation exper-

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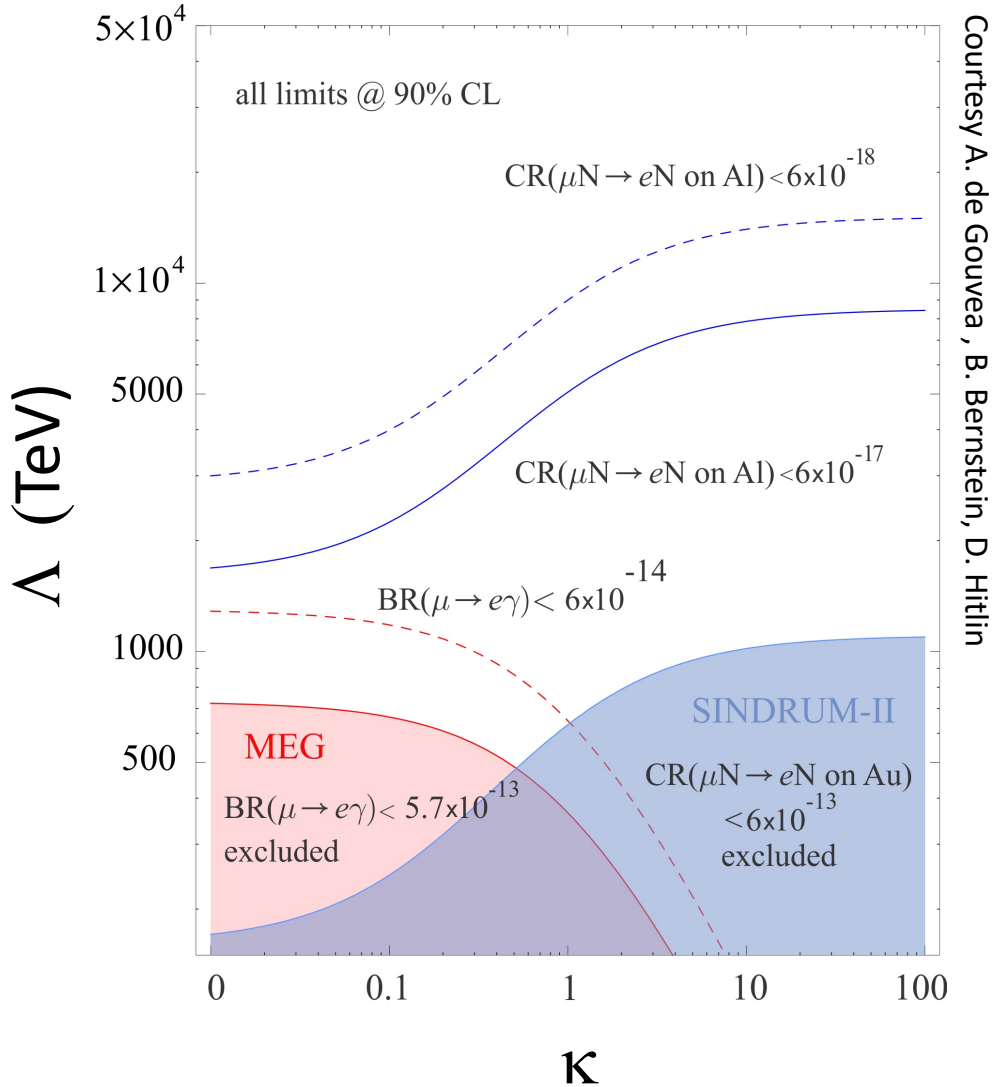
Looking farther into the future, progress in precision physics and rare processes will be shaped partly by what particle physicists learn in the coming decade. Upgrades to the accelerator complex at Fermilab (PIP-II and additional improvements) will offer opportunities to further this program. For example, combined with modest upgrades to Mu2e, improvements in the Fermilab accelerator complex potentially could provide increased sensitivity (by a factor of ten) to muon-to-electron conversion and allow one to search for this very rare process in different nuclei. This will provide crucial clues on the nature of the new physics revealed in the event of an observation in the next-generation experiments.

Mu2e Sensitivity



Courtesy A. de Gouvea , B. Bernstein, D. Hitlin

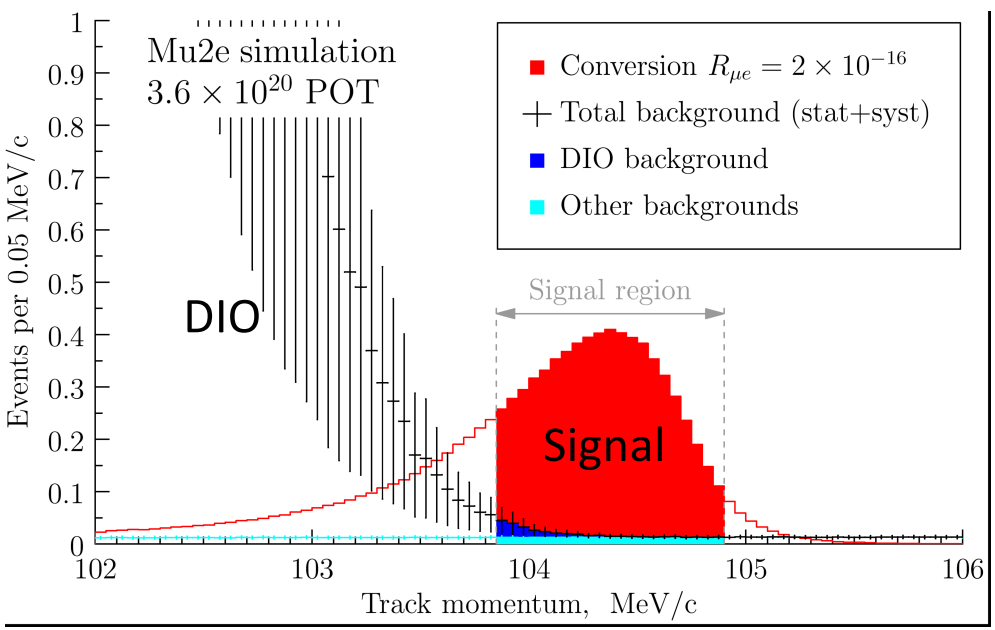
- Mu2e Sensitivity best in all scenarios

Mu2e:Signal and Background

Simulation: Conversion Signal (Red)
+ Background from electrons in tail of distribution of ordinary muon Decay in Orbit(DIO)

$$\mu^- + {}^{27}_{13}Al \rightarrow e^- + \bar{\nu}_e + \nu_\mu + {}^{27}_{13}Al$$

[Simulated signal assumes $R_{\mu e}=2\times10^{-16}$]

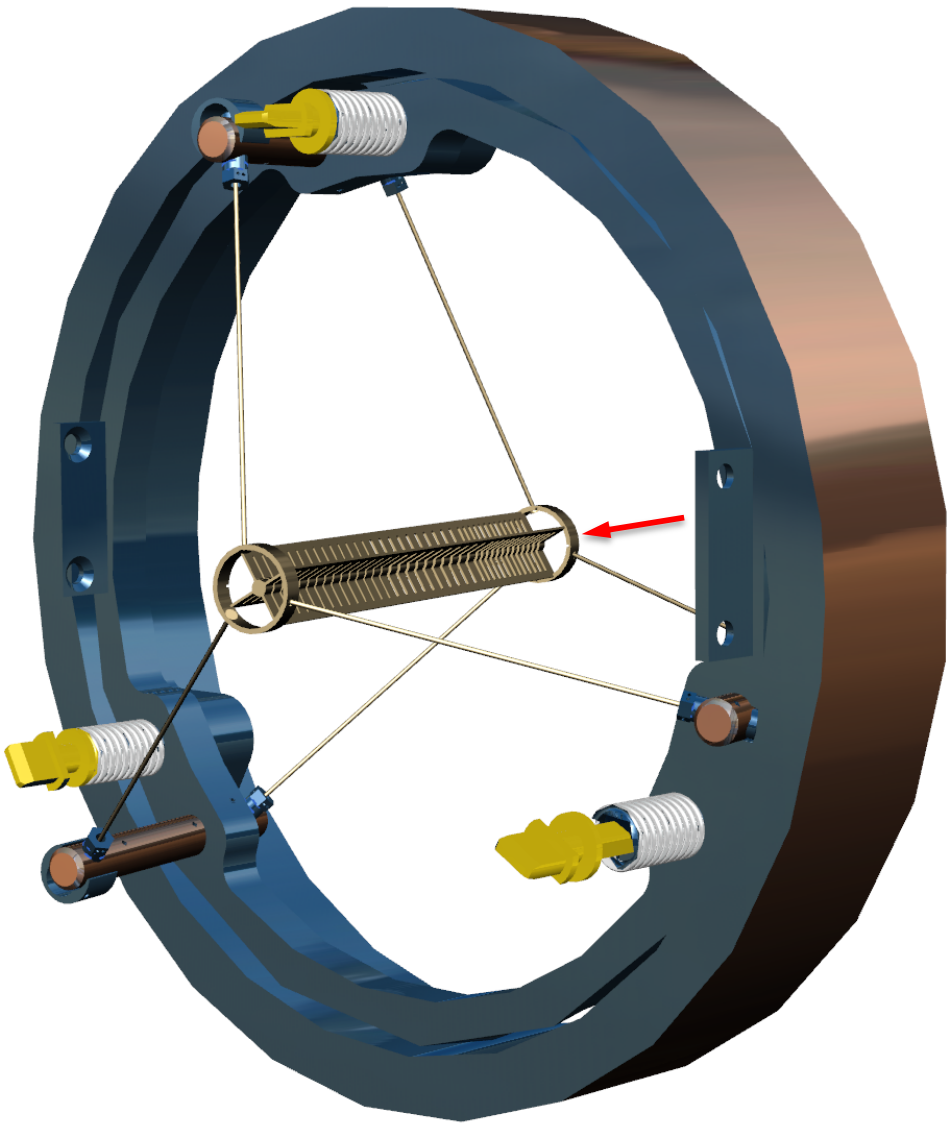


Process	Expected event yield
Cosmic rays	$0.209 \pm 0.022(\text{stat}) \pm 0.055(\text{syst})$
DIO	$0.144 \pm 0.028(\text{stat}) \pm 0.11(\text{syst})$
Antiprotons	$0.040 \pm 0.001(\text{stat}) \pm 0.020(\text{syst})$
Pion capture	$0.021 \pm 0.001(\text{stat}) \pm 0.002(\text{syst})$
Muon DIF	< 0.003
Pion DIF	$0.001 \pm < 0.001$
Beam electrons	$(2.1 \pm 1.0) \times 10^{-4}$
RMC	$0.000^{+0.004}_{-0.000}$
Total	$0.41 \pm 0.13(\text{stat+syst})$

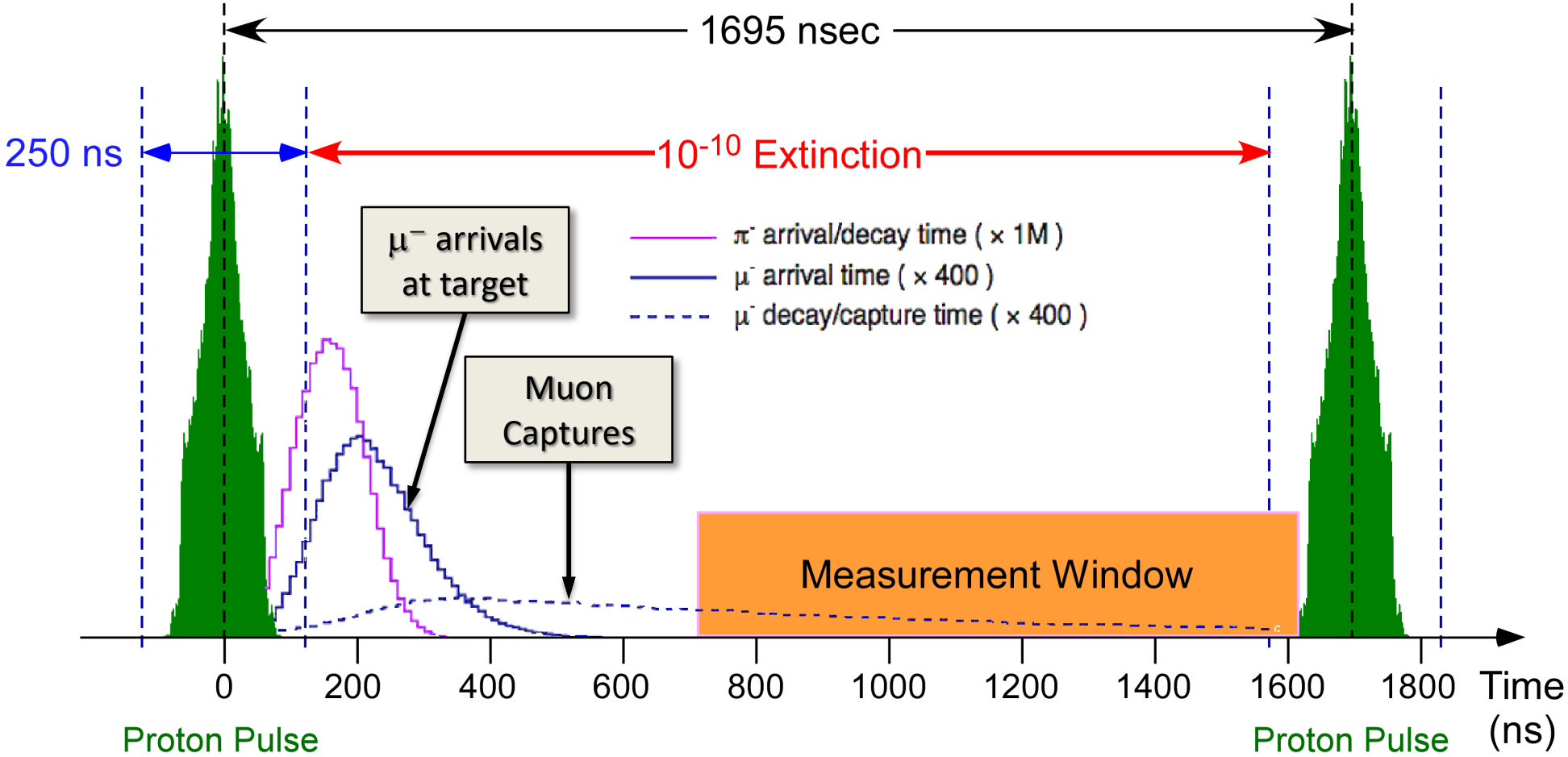
Assumes 6×10^7 seconds running at full intensity

Final Target Design

- Radiatively cooled
- Peak temperature = 1130°C
  (@ 8 kW proton beam power)
- Variable length segmented core and fins to control longitudinal temperature profile
- Four 1mm thick × 13mm tall fins, angled to minimize interference with Extinction Monitor view of target.
- Extended mounting bars on outside ring to minimize bending moment on target
- Stopped muon yield = 0.0015 m/POT
- *Ready to start procurement and fabrication after final reviews*



Reduction of Prompt Backgrounds



- Beam flash decays within 600 ns
- Live gate begins after prompt signal is gone
- $\tau(\mu^-)$ in Al = 864 ns >> prompt background duration
- Out-of-time backgrounds reduced by 10^{-10} extinction factor

Solenoid Power Supply Room

2018: Magnet Power Supplies

Now: Cryo Distribution Box & LHe Dewar installed