Status of the Mu2e experiment @FERMILAB

S. Miscetti (LNF)

On behalf of the

Mu2e Collaboration

Workshop on "Flavour changing and conserving processes" 2019 (FCCP2019)

29 August 2019

AnaCapri

The Mu2e collaboration

Over 200 Scientists from 38 Institutions (six countries)

Argonne National Laboratory, Boston University, University of California Berkeley, University of California Irvine, California Institute of Technology, City University of New York, Joint Institute of Nuclear Research Dubna, Duke University, Fermi National Accelerator Laboratory, **Laboratori Nazionali di Frascati**, University of Houston, Helmholtz-Zentrum Dresden-Rossendorf**, INFN Genova**, Institute for High Energy Physics, Protvino, Kansas State University, Lawrence Berkeley National Laboratory, **INFN Lecce**, **University Marconi Rome,** Lewis University, University of Liverpool, University College London, University of Louisville, University of Manchester, University of Michigan, University of Minnesota, Muon Inc., Northwestern University, Institute for Nuclear Research Moscow, **INFN Pisa**, **INFN Trieste**, Northern Illinois University, Purdue University, Rice University, Sun Yat-Sen University, University of South Alabama, Novosibirsk State University/Budker Institute of Nuclear Physics, University of Virginia, University of Washington, Yale University

CLFV processes

- Muon-to-electron conversion is a charged lepton flavor violating process (CLFV)

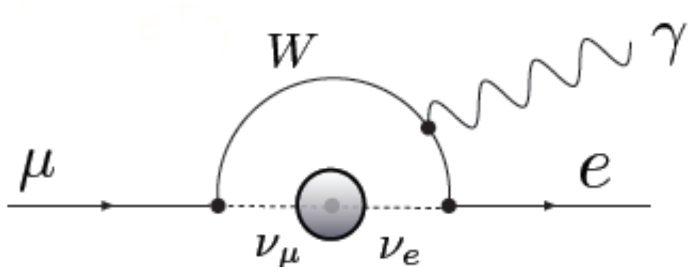
  similar but complementary to other CLFV processes such as:

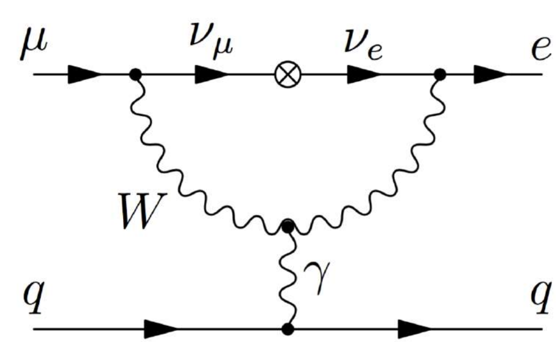
$$\mu^+ \to e^+ + \gamma,\ \mu^+ \to e^+ + e^+ + e^-,\ \tau \to e + \gamma\ ,\ \tau \to \mu + \gamma,\ \tau \to 3e....$$

- The Mu2e experiment searches for muon-to-electron conversion in the coulomb field of a nucleus: $\mu^- Al \to e^- Al$
- **CLFV processes are forbidden in the Standard Model**

  → considering neutrino oscillations (LFV) they **are allowed but their BR is negligible 10^{-52}**

  → **New Physics could enhance CLFV rates to observable values**





Rates and discovery potential

- Most promising CLFV are based on muons:
  - → clean topologies & large rates
  - → the SM contribution is negligible: no SM background
- μ-e conversion covers the BSM on very broad range of models
  - → Three stars signals Discovery potential
  - → Sensitivity across the board

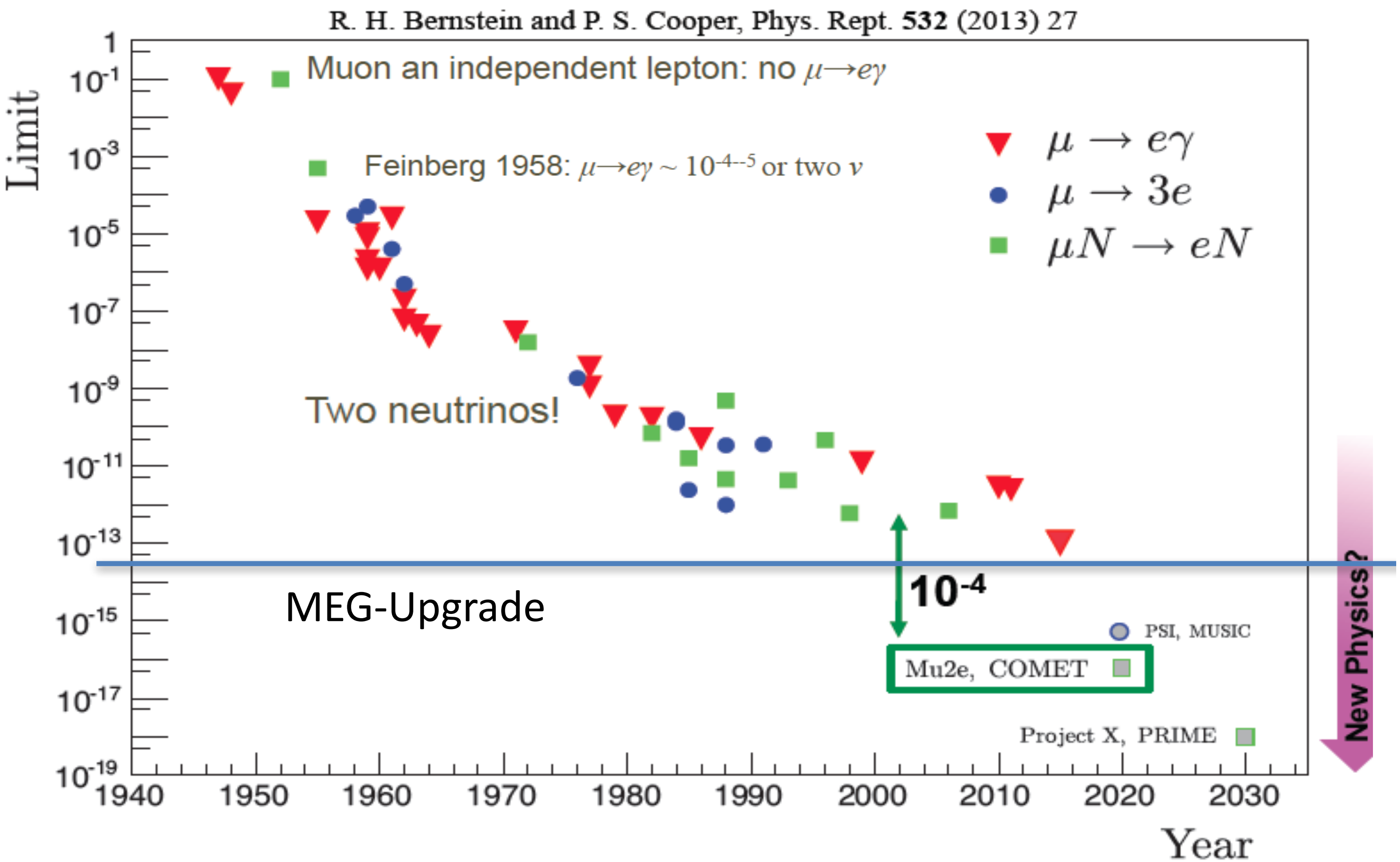
Process	Current Limit	Next Generation exp
$\tau \to \mu\eta$	BR < 6.5 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \to \mu\gamma$	BR < 6.8 E-8	
$\tau \to \mu\mu\mu$	BR < 3.2 E-8	
$\tau \to eee$	BR < 3.6 E-8	
$K_L \to e\mu$	BR < 4.7 E-12	
$K^+ \to \pi^+ e^- \mu^+$	BR < 1.3 E-11	
$B^0 \to e\mu$	BR < 7.8 E-8	
$B^+ \to K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \to e^+\gamma$	BR < 4.2 E-13	10^{-14} (MEG)
$\mu^+ \to e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \to eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

	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.

CLFV history for muons



Current best limits:

MEG-2016
BR(μ→eγ) < 4.2 x 10^{-13}

SINDRUM-1988
BR(μ→3e) < 1 x 10^{-12}

SINDRUM-II 2006
$R_{\mu e}$ < 6.1 x 10^{-13}

MU2E GOAL:
$R_{\mu e}$ = 8 x 10^{-17}

Mu2e (Fermilab) aims to improve by a factor 10^4 the present best limit

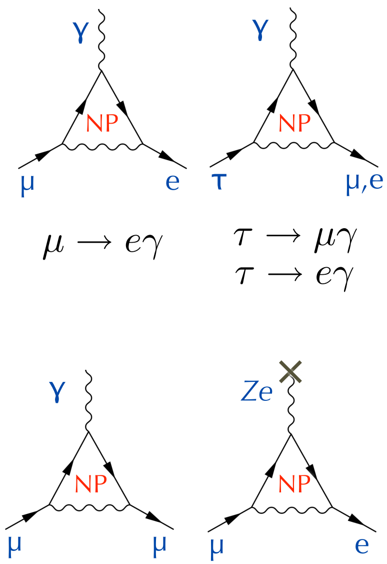
$$R_{\mu e} = \frac{\Gamma(\mu^- + N(A,Z)) \rightarrow e^- + N(A,Z)}{\Gamma(\mu^- + N(A,Z) \rightarrow \text{ all muon capture})} \leq 8 \times 10^{-17} \ (@90\%CL)$$

Mu2e vs MEG in the λ/k plane

$$L_{CLFV} = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

LOOP TERM

$\kappa \ll 1$

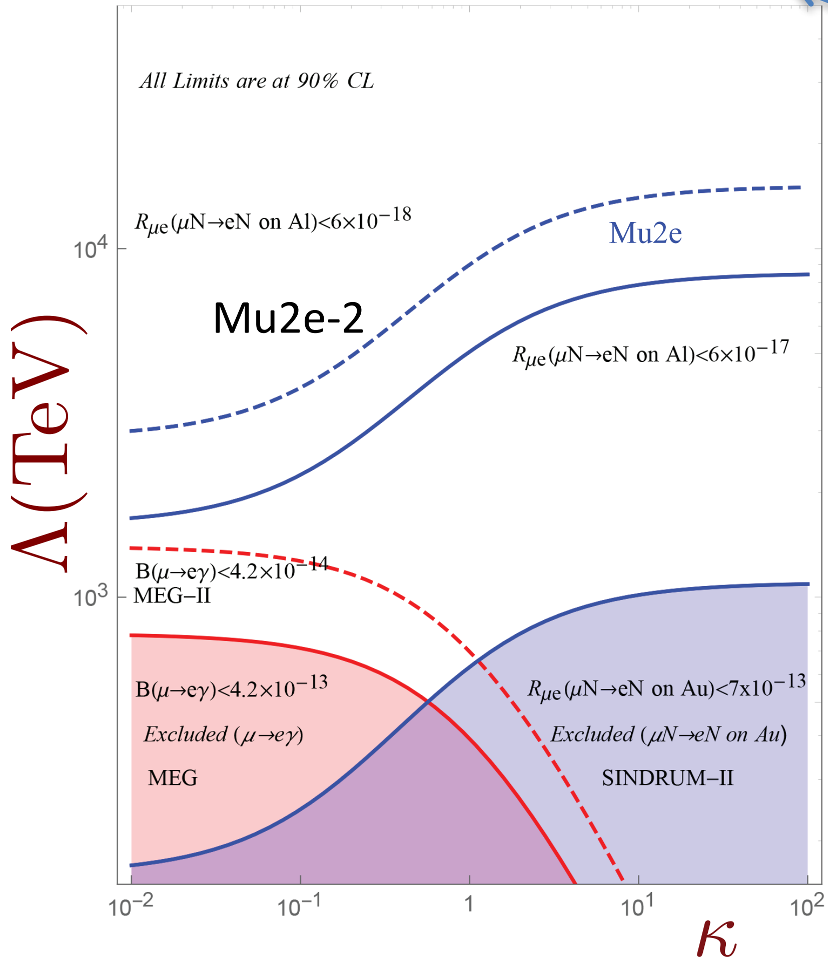


$\mu \to e\gamma$

$\tau \to \mu\gamma$
$\tau \to e\gamma$

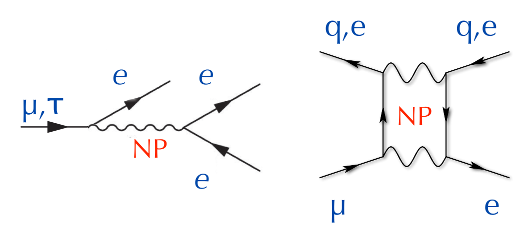
$(g-2)_\mu$

$\mu^- \mathcal{N} \to e^- \mathcal{N}$



CONTACT TERM

$\kappa \gg 1$



$\mu \to eee$

$\mu^- \mathcal{N} \to e^- \mathcal{N}$

If SUSY seen @ LHC
→ rate ~10^{-15}
Implies O(40) signal events
with negligible background

Mass scale discovery up to ~10 k TeV, significantly above the direct LHC reach

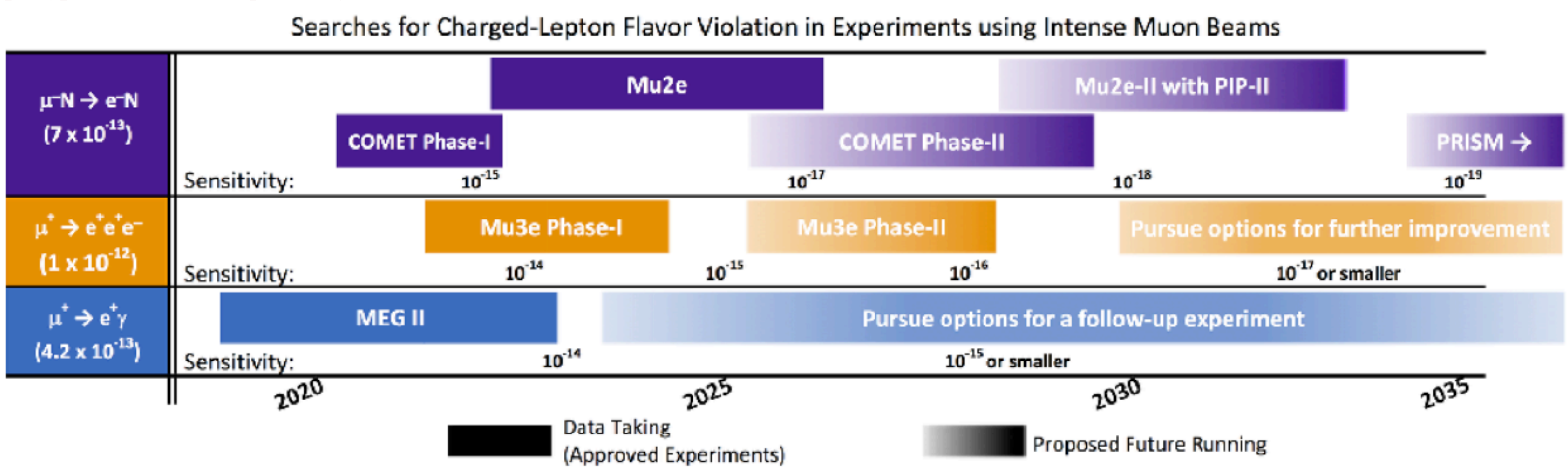
Roughly equal to MEG upgrade in loop-dominated physics

Muon to electron conversion is unique

Muon to electron conversion is a unique probe for BSM:

- **Broad discovery sensitivity across all models:**
  - → Sensitivity to the same physics of MEG/Mu3e with similar mass reach
  - → Sensitivity to physics that MEG/Mu3e are not
  - → If MEG/Mu3e observe a signal, Mu2e/COMET will see it also
    Ratio of the BR allows to pin-down physics model
  - → If MEG/Mu3e do not observe a signal, Mu2e/COMET have still a reach to do so.
    In a long run, sensitivity can also further improve (Mu2e-II) with the proton improvement plan (PIP-2)

- **Sensitivity to Λ (mass scale) up to thousands of TeV beyond any current**

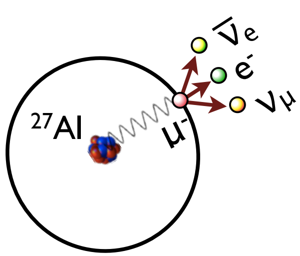


Experimental Technique

- ❑ Low momentum μ beam (< 100 MeV/c)
- ❑ High intensity "pulsed" rate
- → 10^{10}/s muon stop on Al. target
- → 1.7 μsec micro-bunch
- ❑ Formation of muonic atoms that can make a:

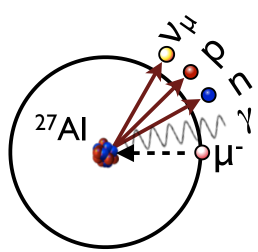
Decay in Orbit (DIO)

(BR=39%)

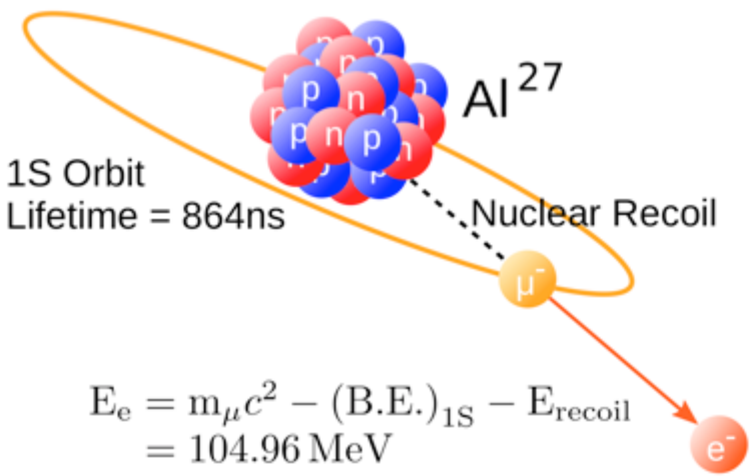


Muon Capture Process

(BR=61%)



Conversion Process



$$E_e = m_\mu c^2 - (B.E.)_{1S} - E_{recoil}$$
$$= 104.96 \text{ MeV}$$

The conversion process results in a clear signature of a single electron, CE, with a mono-energetic spectrum close to the muon rest mass

Mu2e sensitivity and rates

- **Design goal: single-event-sensitivity of 3 x 10^{-17}**
  - Requires about **10^{18} stopped muons**
  - Requires about **10^{20} protons on target**
  - Requires extreme suppression of backgrounds

- **Expected limit: $R_{\mu e}$ < 8 x 10^{-17} @ 90% CL**
  - **Factor 10^4 improvement**

- **Discovery sensitivity: $R_{\mu e}$ > 2 x 10^{-16}**
  - Covers broad range of new physics theories

- **High rate and large number of stopped muons 10^{18}**
  - Needs intense muon source and efficient transport to target

Need to fight a lot of backgrounds

- **Intrinsic – scale with number of stopped muons**
  - μ Decay-in-Orbit (DIO)
  - Radiative muon capture (RMC)

Precise Tracker

- **Late arriving – scale with number of late protons**
  - **Radiative pion capture (RPC)**

    $\pi^- N \rightarrow \gamma N', \gamma \rightarrow e^+e^-$ **and** $\pi^- N \rightarrow e^+e^- N'$
  - **μ and π decay-in-flight (DIF)**

Pulsed Beam + extinction

- **Cosmic rays induced**

CRV+PID

- **Anti-proton induced**

  produce pions when they annihilate in the target ..
  antiprotons are negative and they can be slow!

Proton Absorber

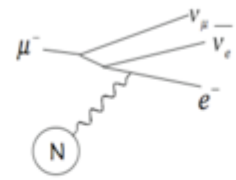
The DIO background

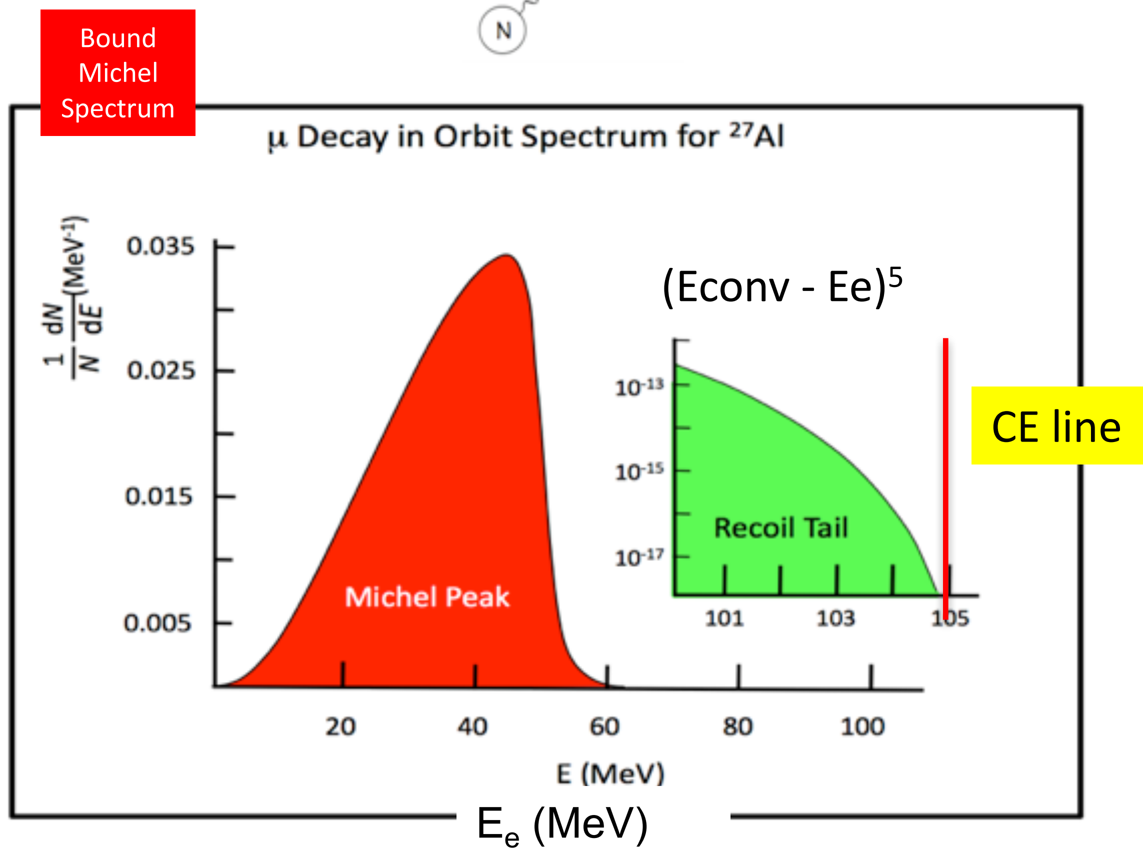
- **The decay in orbit (DIO) is the irreducible background**

- Electron energy distribution from the decay of bound muons is a (modified) Michel spectrum:

→ Presence of atomic nucleus and momentum transfer create a recoil tail with a fast falling slope close to the endpoint

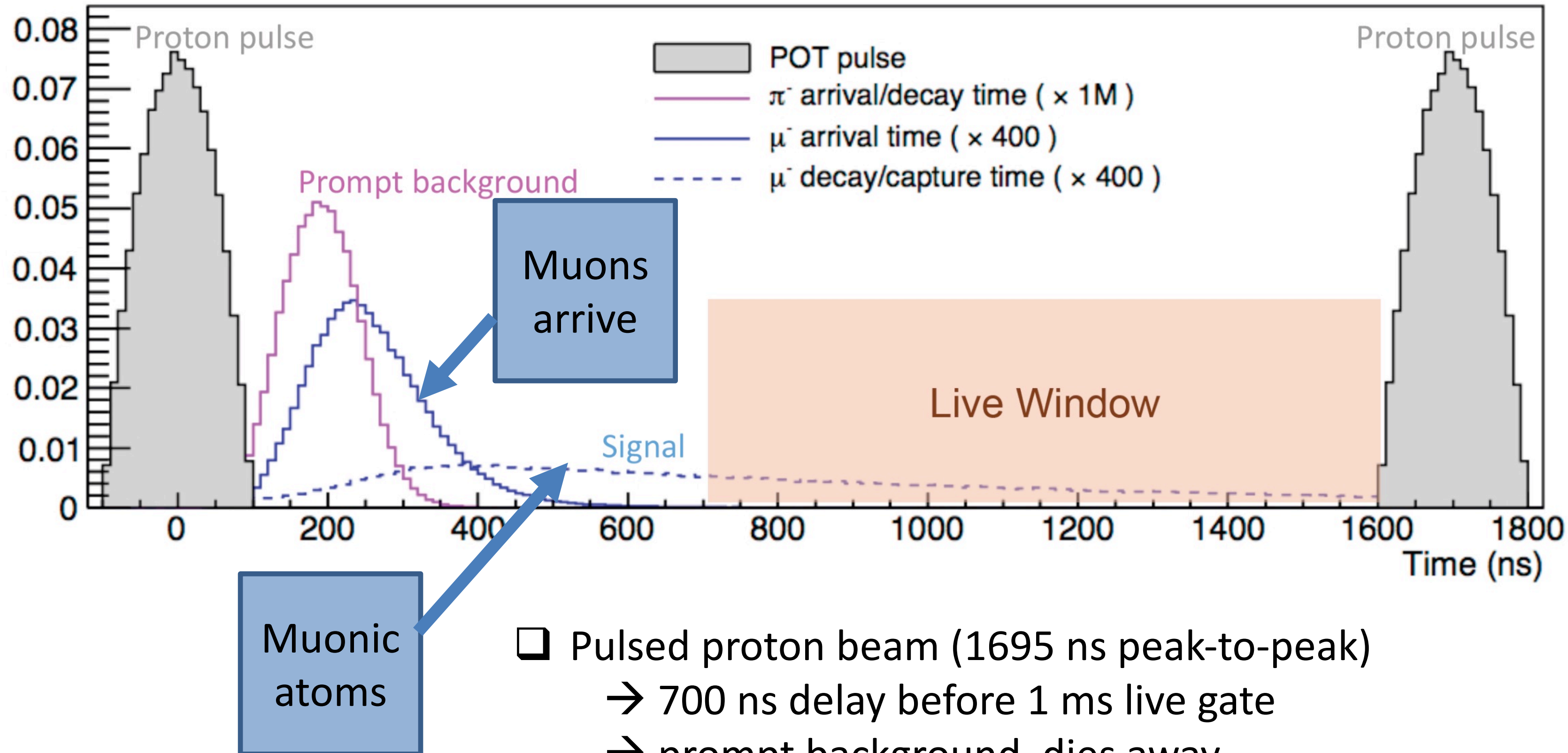
→ To separate DIO endpoint From the CE line we need a high Resolution Spectrometer





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

Beam structure → prompt background



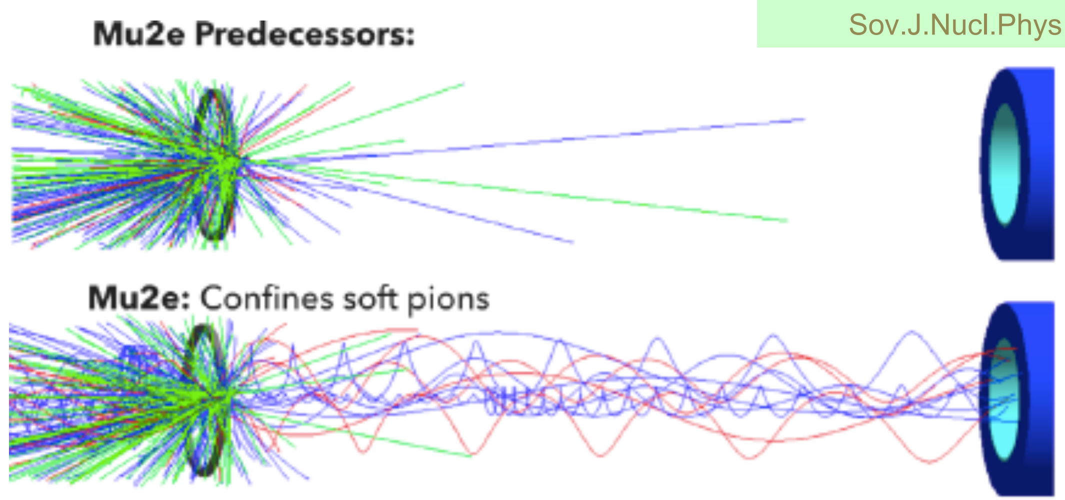
- ❑ Pulsed proton beam (1695 ns peak-to-peak)
  - → 700 ns delay before 1 ms live gate
  - → prompt background dies away
- ❑ Extinction factor (out-of-time/in-time protons) below 10^{-10} is required

The trick here is … muonic atomic lifetime
τ(mu)Al = 864 ns >> prompt background

Summary: the keys to Mu2e Success

- **High intensity pulsed proton beam**
  - Narrow proton pulses (< ± 125 ns)
  - Very few out-of-time protons ($< 10^{-10}$)
  - 3×10^{7} proton/pulse.
- **High efficiency in transporting muon to Al target**
  - Need of a sophisticated magnet with gradient fields
- **Excellent detector for 100 MeV electrons**
  - → Excellent momentum resolution (< 200 keV core)
  - → Calorimeter for PID, triggering and track seeding
  - → High Cosmic Ray Veto (CRV) efficiency (>99.99%)
  - → Thin anti-proton annihilation window(s)

Concept by Lobashev and Djilkibaev
Sov.J.Nucl.Phys. 49, 384 (1989)

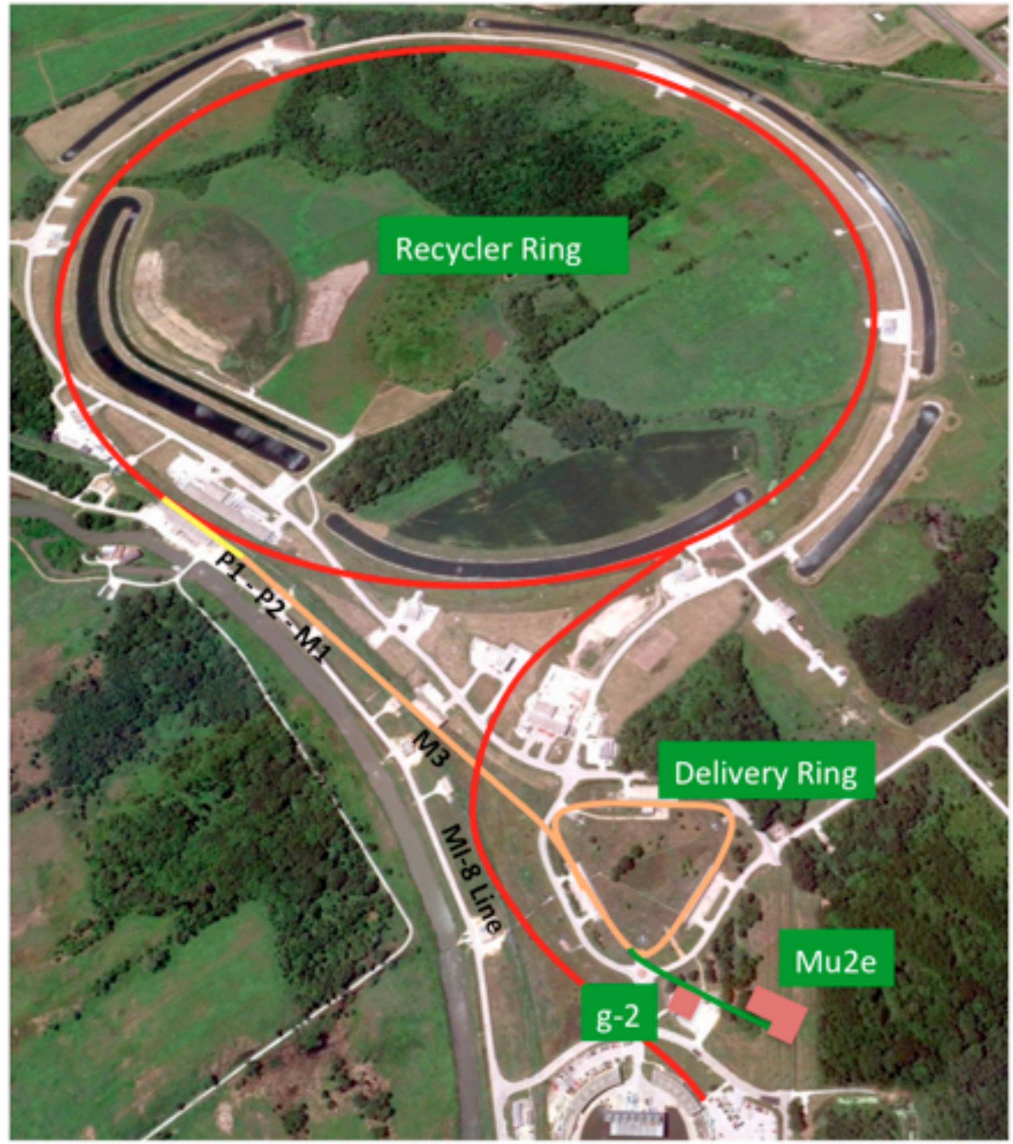


Accelerator Scheme for Mu2e beam

- Booster: batch of 4×10^{12} protons every $1/15^{th}$ second (8 GeV, 8 kW)
- Booster "batch" is injected into the Recycler ring and re-bunched into 4 bunches
- These are extracted one at a time to the Delivery ring (ex Debuncher)
- As a bunch circulates, protons are resonantly extracted to produce the desired beam structure

→ bunches of ~3×10^7 protons each, separated by 1.7 μs (delivery ring period) and then sent to the Mu2e Production Target

- It runs together with neutrino beam for NOVA
- It cannot run together with Muon g-2.



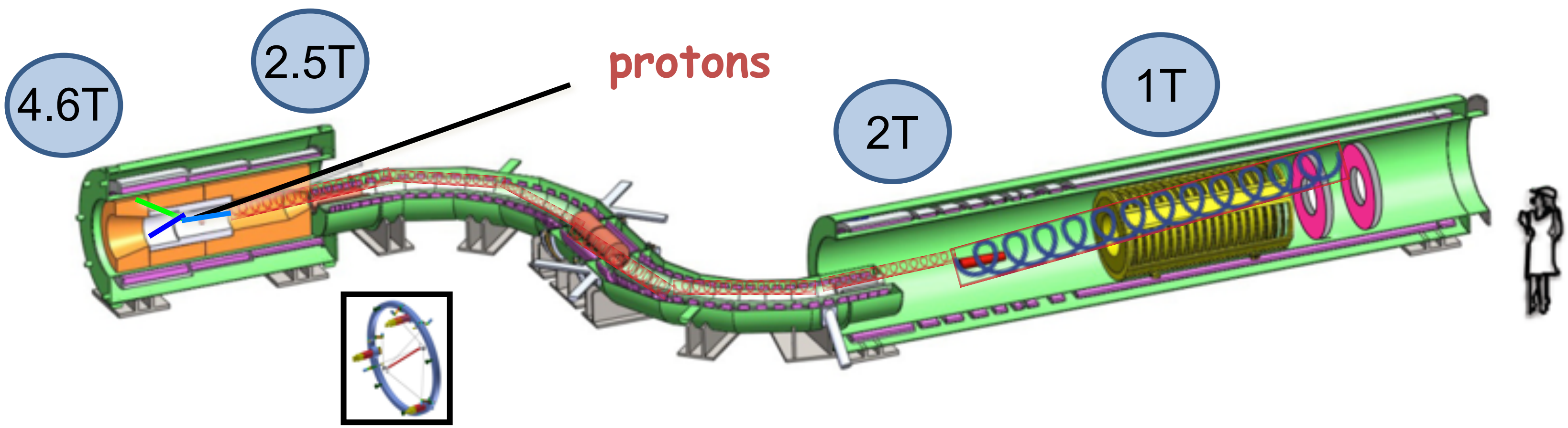
Muon campus & Mu2e Hall status

- Detector Hall Building
  - Broke Ground (April 2015)
  - Building Acceptance (March 2017)
- Infrastructure installation (still on going)
  - LCW pipes, Bus bar, Cable Trays
  - Interlocks, Networking, DAQ infrastructure
  - Cryo Distribution box …

Muon Beam-line

Production Target / Solenoid (PS)

- 8 GeV Proton beam strikes target, producing mostly pions
- Graded magnetic field contains backwards pions/muons and reflects slow forward pions/muons ➔High Muon intensity



→ Heat and radiation shielding
→ Tungsten target.

Target, Detector and Solenoid (DS)

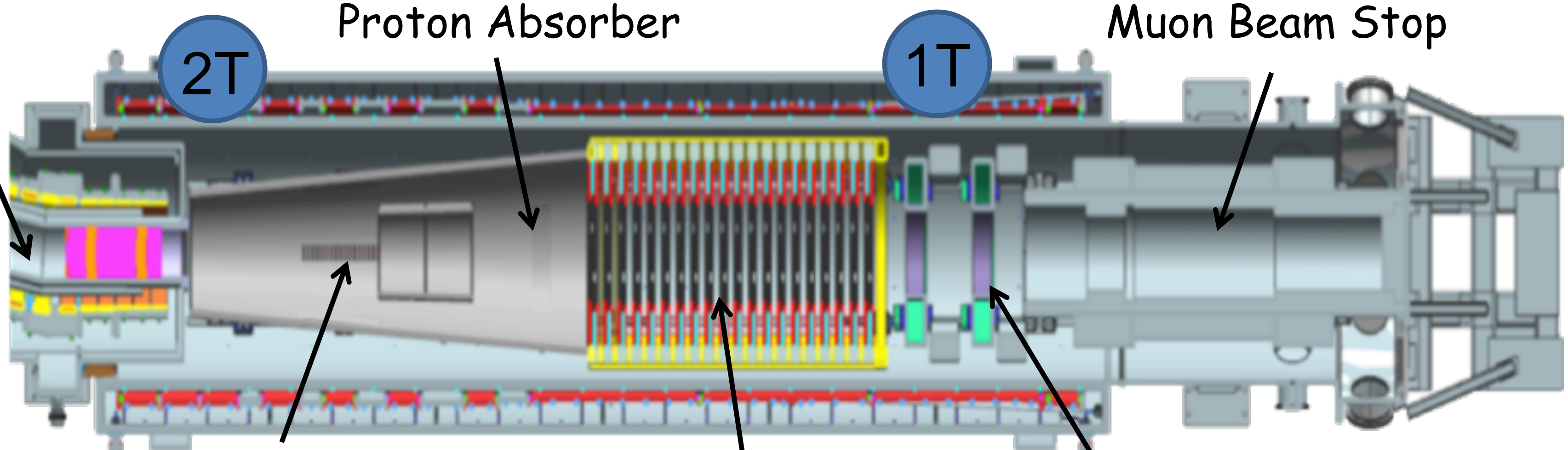
- Capture muons on Al target
- Measure momentum in tracker and energy in calorimeter
- CRV to veto Cosmic Rays event

Transport Solenoid (TS)

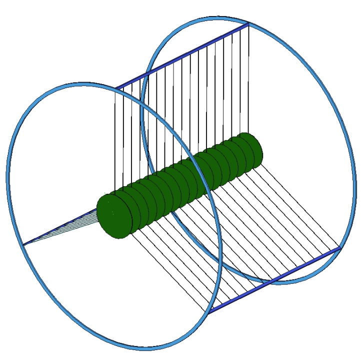
Collimator selects low momentum, negative muons
Antiproton absorber in the mid-section
S-shape eliminates photons andneutrons

Detector Solenoid

Graded field "reflects" downstream a fraction of conversion electrons emitted upstream



34 Al foils; Aluminum choice dictated by the bound muon lifetime (**864 ns**) that nicely matches the the Mu2e pulsed beam structure for prompts' separation



Sensitivity goal →

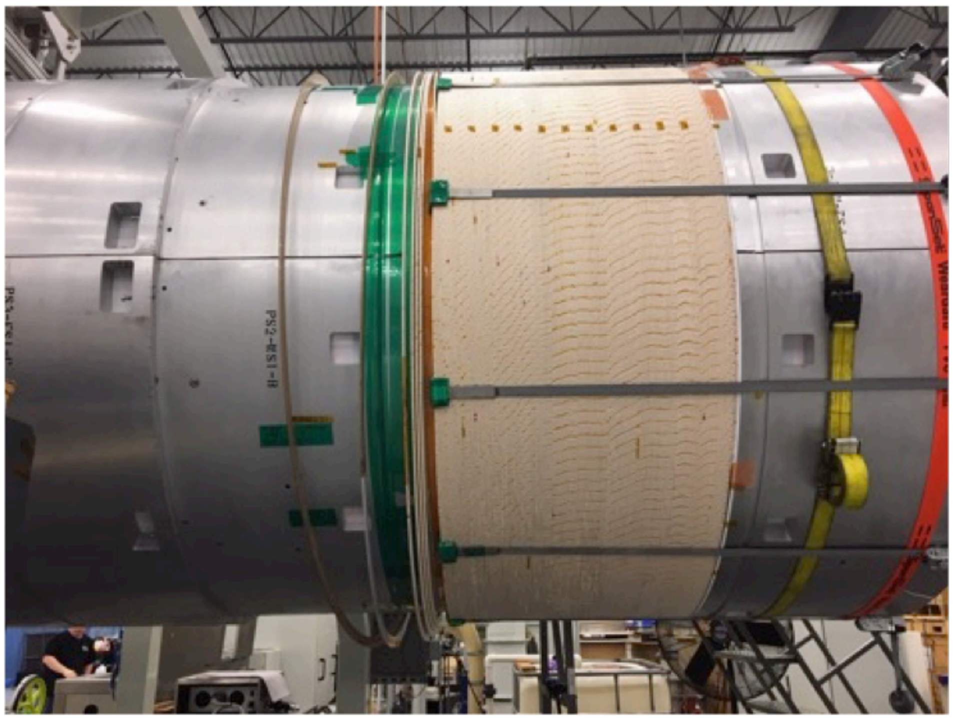
~ 6 x 10^{17} stopped muons

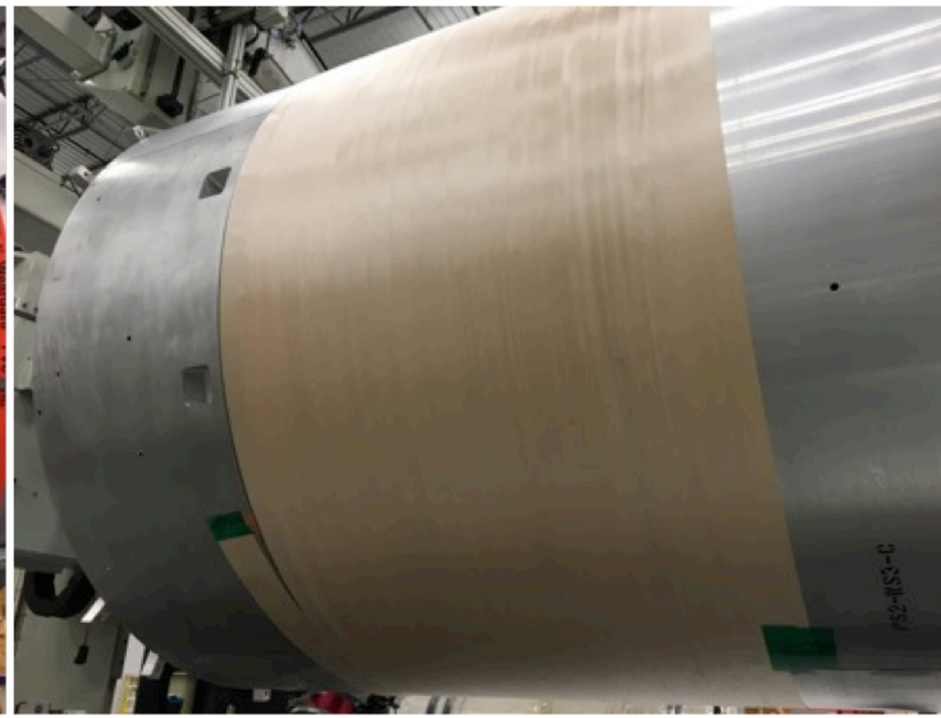
3 year runs , 6 x 10^{7} sec →

10^{10} stopped muon/sec

Status of PS/DS construction

- Superconducting cable procured and tested
- PS/DS winding in progress at GA (Tupelo)

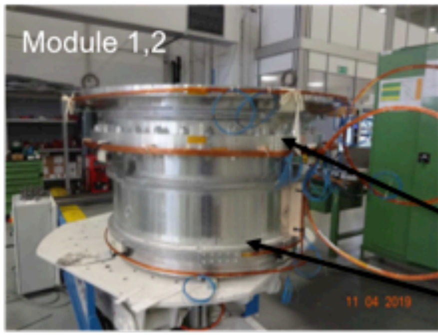


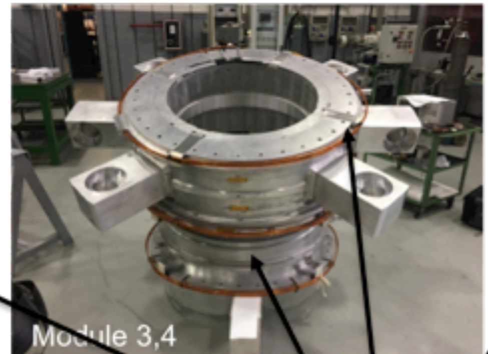


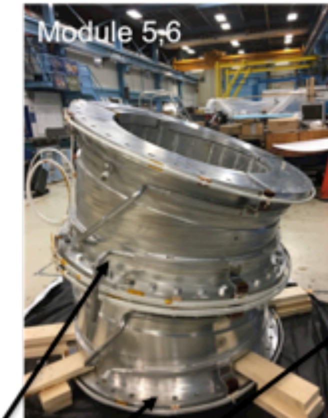
Status of PS/DS construction

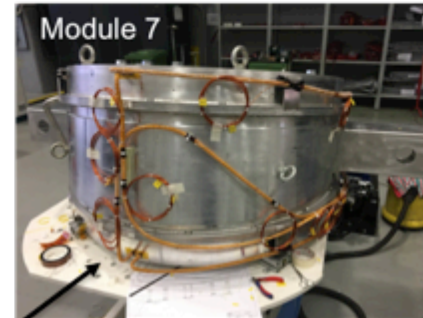
- PS/DS Cryostats being completed @ Joseph Oat (GA Subcontract)

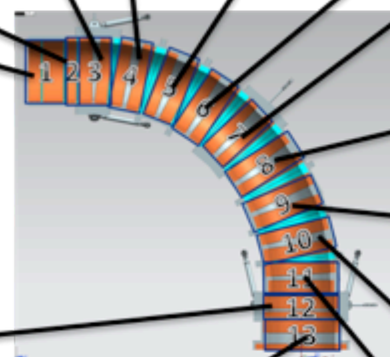
Status of TS construction

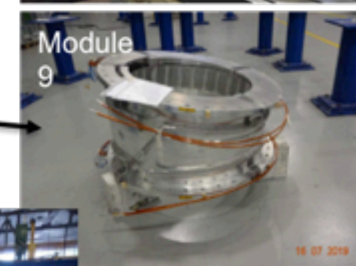








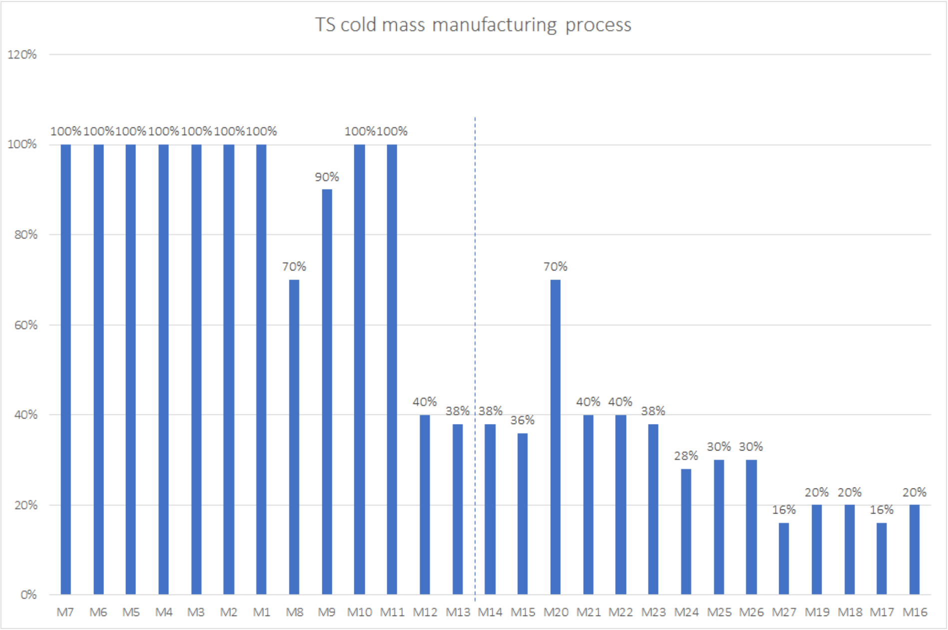


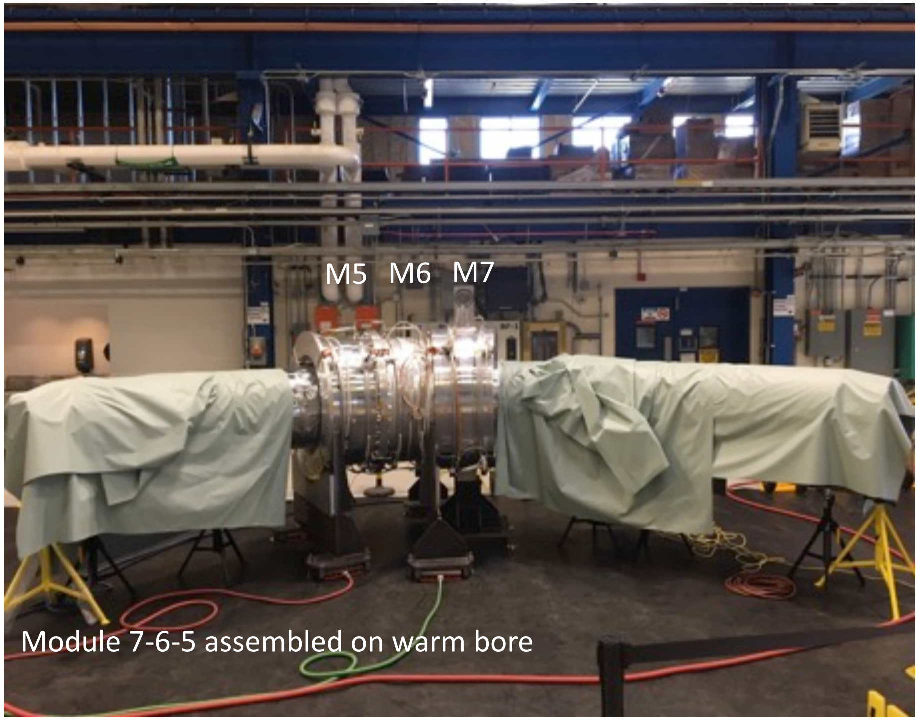


First half of TSU completed.
Progress on second half moving forward at a good pace.

TS construction

- Construction of TSD also proceeds at full speed in ASG superconducting (Genoa)
- Overall TS modules construction better than 1/3 of total
- Second test unit (M5/M6) assembled on warm bore. Mated together perfectly. Alignment ongoing.





The Mu2e Tracker

Detector requirements:

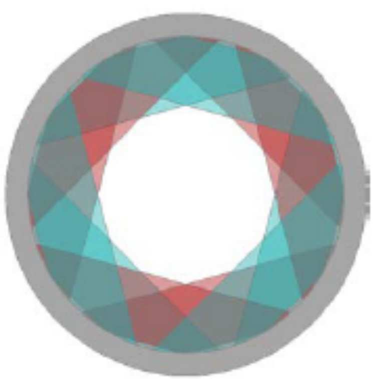
1. Small amount of X_0
2. σ_p < 180 keV @ 105 MeV
3. Good rate capability:
   - 20 kHz/cm^2 in live window
   - Beam flash of 3 MHz/cm^2
4. dE/dx capability to distinguish e^-/p
5. Operate in B = 1 T, 10^{-4} Torr vacuum
6. Maximize/minimize acceptance for CE/DIO

Low mass straw drift tubes design:

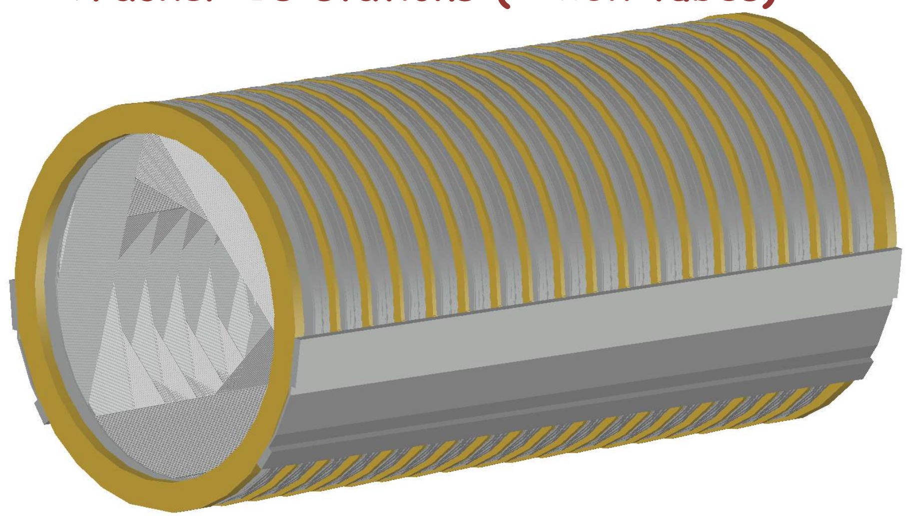
- 5 mm diameter, 33 – 117 cm length
- 15 μm Mylar wall, 25 μm Au-plated W wire
- 80:20 $Ar:CO_2$ @ 1 atm
- Dual-ended readout with timing (2D/plane)

Tracker Plane - 6 panels

Tracker Station: 2 rotated planes

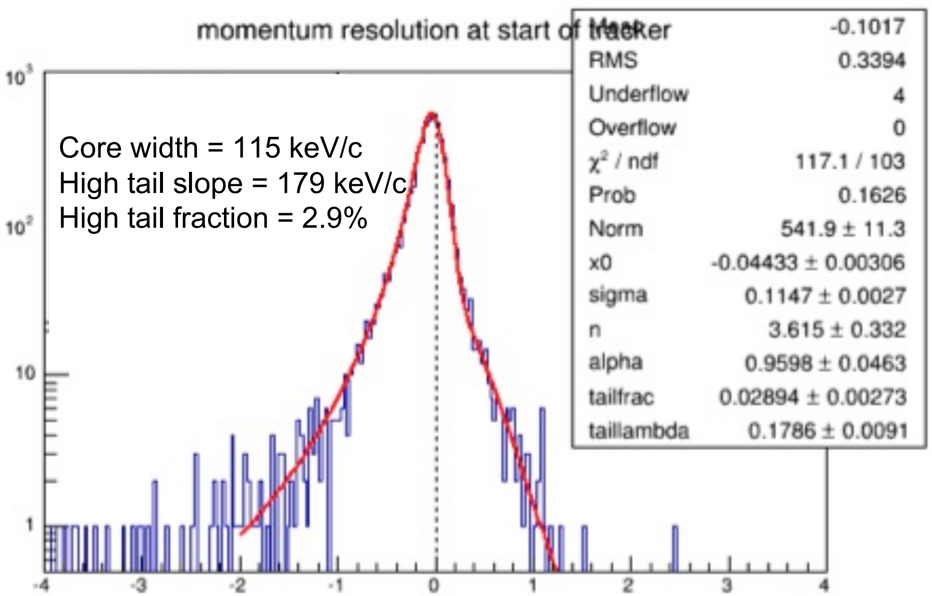


Tracker: 18 stations (> 20k tubes)



Mu2e Tracker Performance

Full simulation

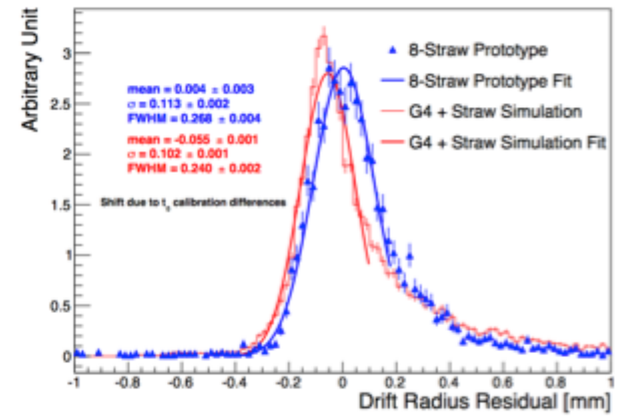


$P_{rec} - P_{tru}$ (MeV/c)

- ✗ Well within physics requirements
- ✗ Robust against increases in rate
- ✗ Inefficiency dominated by geometric acceptance

Cosmics, 8 channel prototype

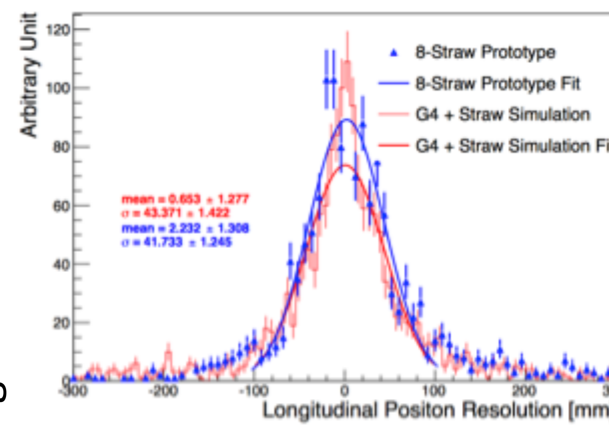
Transverse resolution



σ_{data} = 0.133 ± 0.022 mm

σ_{MC} = 0.102 ± 0.001 mm

Longitudinal resolution



σ_{data} = 42 ± 1 mm

σ_{MC} = 43 ± 1 mm

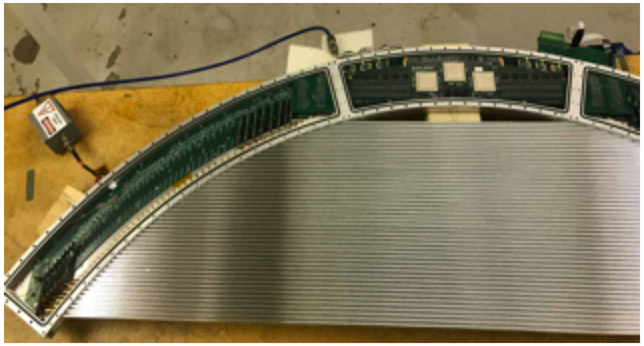
Mu2e Tracker status

- Straw Procurement completed (30k straws)
- Straw production well progressed. Complete fixtures in May 2020

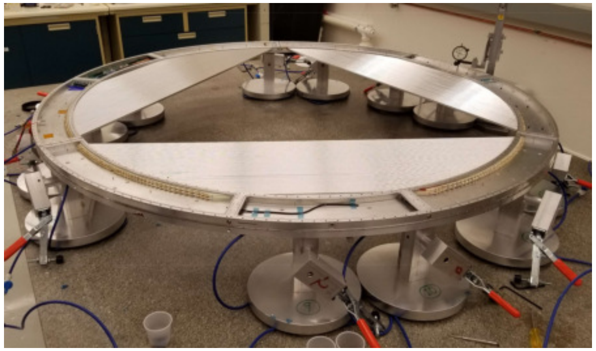
- **Panels**
  - Design Complete
  - Production assembly fixtures being fabricated
  - **UMN Panel Factory & QC Station set up**

  → Now working on the 11th pre-production panel.
  → Production will start after completing Pre-panel #12

- **Plane**
  - Plane assembly tooling fixture design nearly complete
- **Electronics**
  - Incorporation of rad hard FPGA in progress



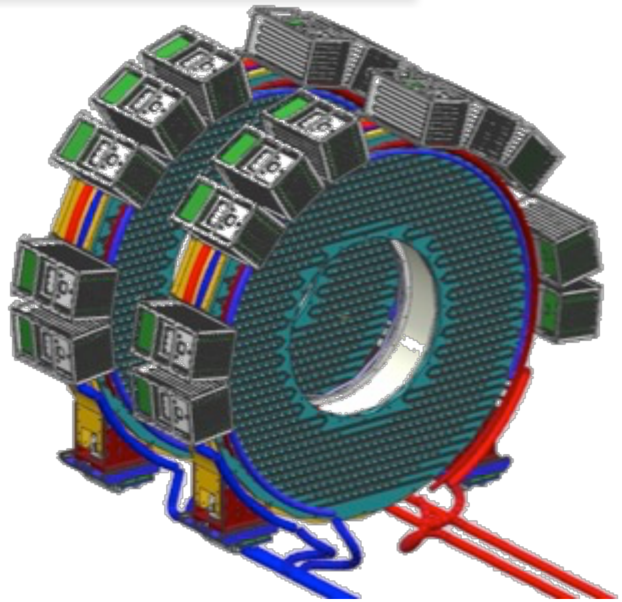
Panel w/Front-End Electronics



Three panels installed in plane

Panel: Straw Installation

Mu2e Calorimeter System



Calorimeter requirements:

→ PID to distinguish e/mu
→ Seed for track pattern recognition
→ Tracking independent trigger
→ Work in 1 T field and 10^{-4} Torr vacuum
→ **RadHard up to 100 krad, 10^{12} n/cm²/year**

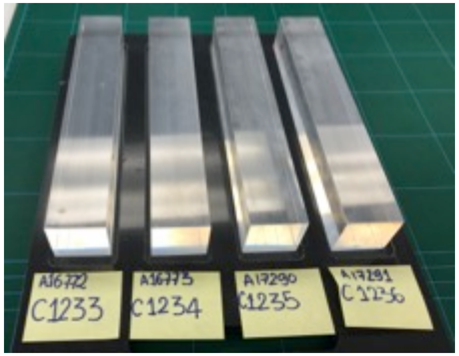
Calorimeter choice:

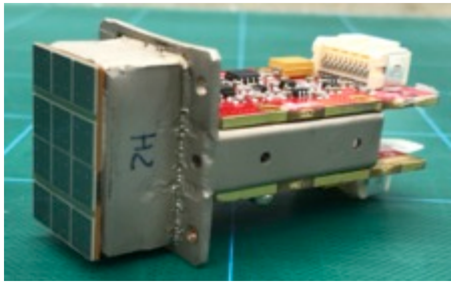
High granularity crystal calorimeter with Large area custom UV extended SiPMs

→ σ/E of O(10%) and Time resolution < 500 ps
→ Position resolution of O(1 cm)
→ High acceptance **for CE signal @ 100 MeV**
→ FEE on SiPM pins, digital electronics on crates
→ Calibration: 6 MeV source and Laser+MIPs

Basic Components:

- Undoped CsI crystals
- Mu2e SiPMs + FEE





Annular disk geometry

- Square crystals 34x34x200 mm³
- Charge symmetric to measure

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

Mu2e Calorimeter performance

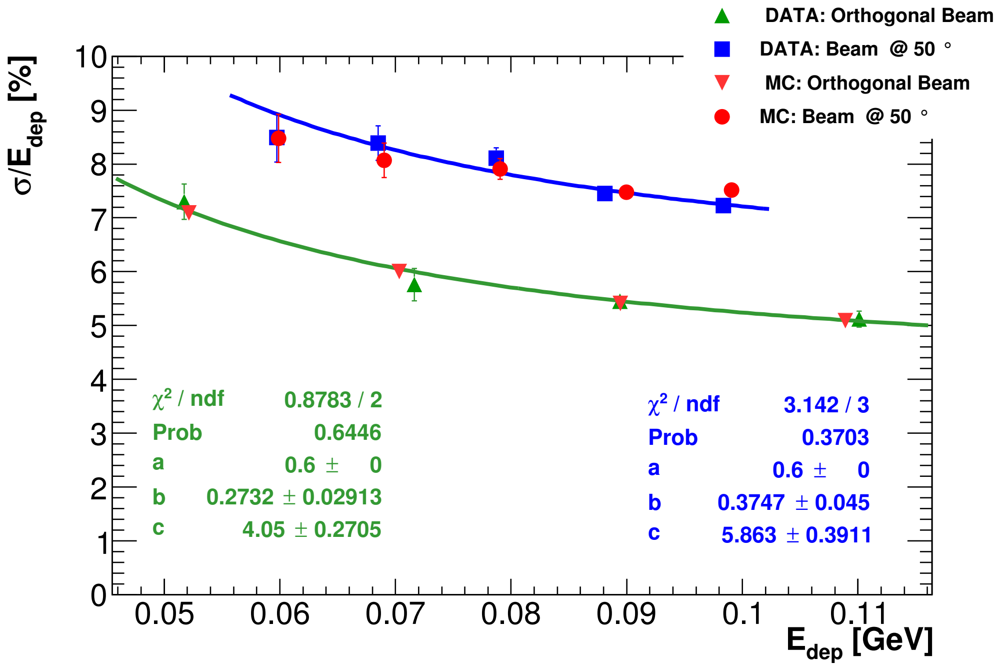
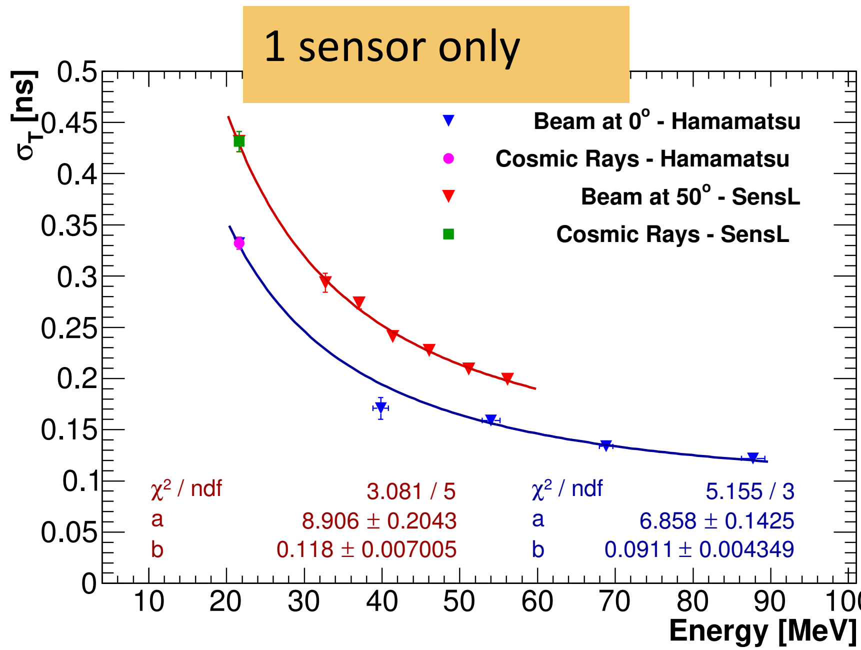


Figure 40: *Energy resolution as a function of the energy deposit in the Module-0 in the orthogonal (blue) and tilted (green) configuration and comparison with the MC expectation.*

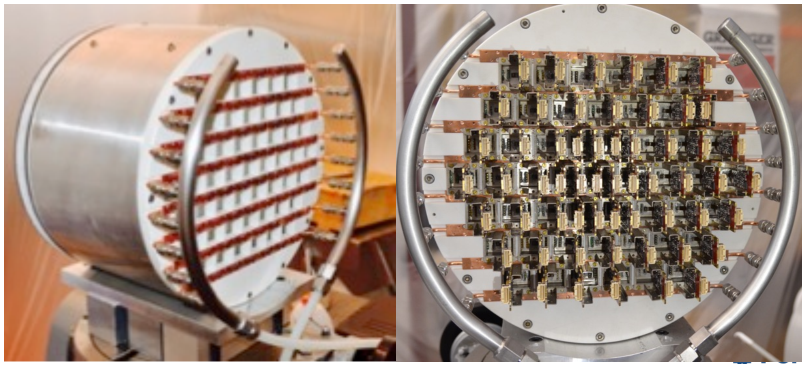


Module-0 51 crystals, 102 SiPM/FEE channels:

➔5.4 % (7.3%) energy resolution @ 100 MeV for 0° (50°) impact angles. Excellent data-MC

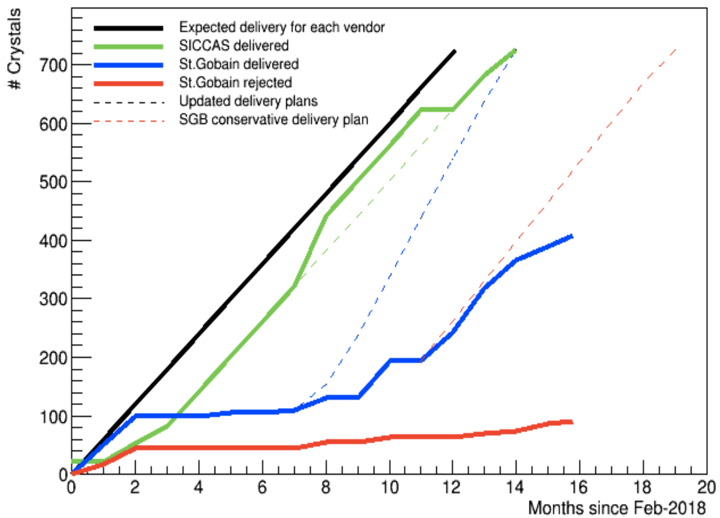
➔Timing resolution < 150 ps with one sensor

➔ Mu2e requirements satisfied



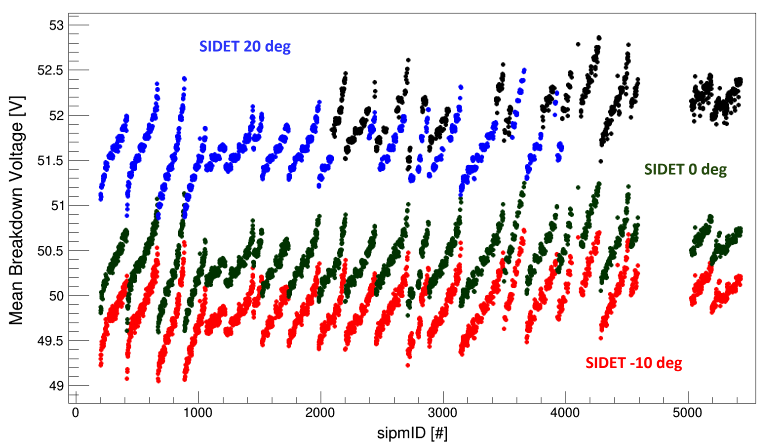
Mu2e Calorimeter status

QA of crystal production



QA of SiPM production

- Results from the 5 tested batches confirmed the sipmID dependance of V_{br}:

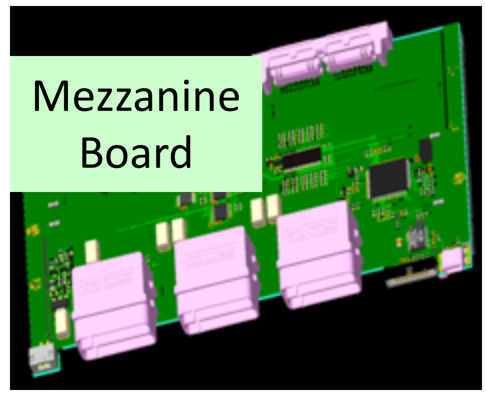


- 1100 out f 1450 crystals produced and tested

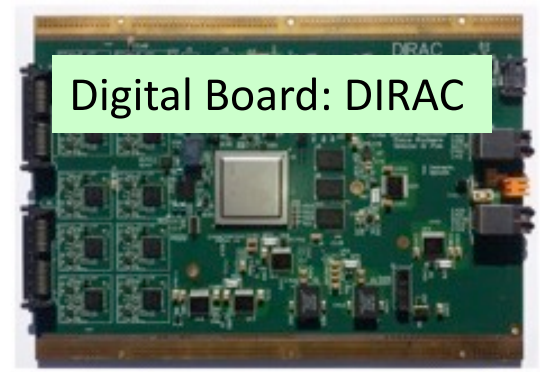
4000/4000 SiPMs produced and tested

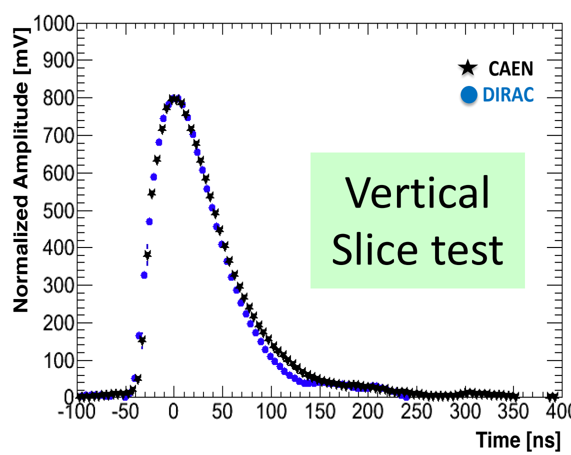
- Radiation hardness test of DEE and DIRAC done
- Vertical slice test done
- Mechanics under construction in Italy

Mezzanine Board



Digital Board: DIRAC



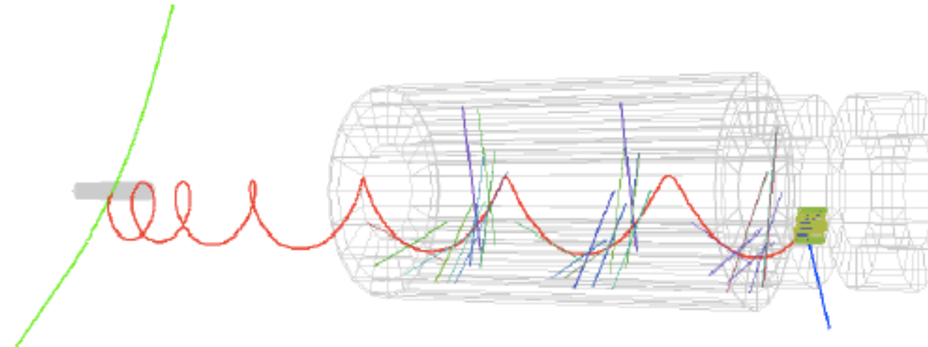


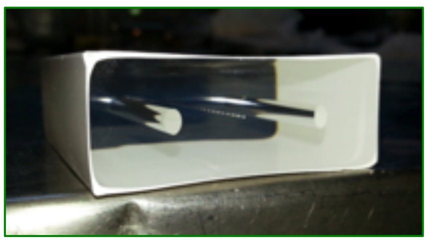
Vertical Slice test

Al Disk Full Size proto

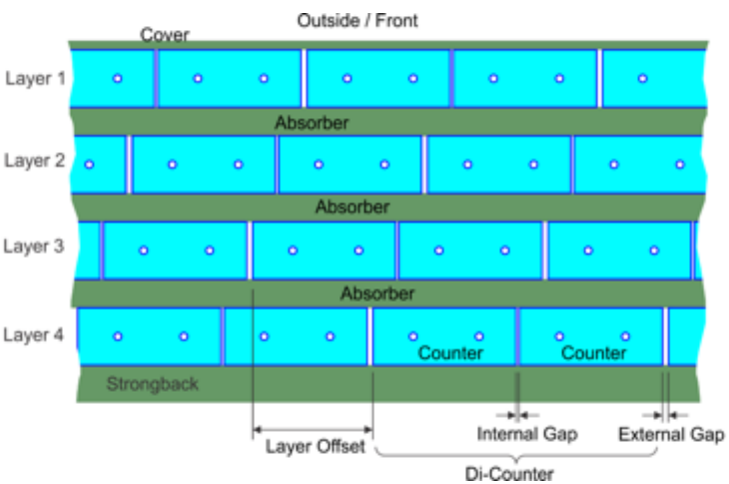
Mu2e Cosmic-Ray Veto

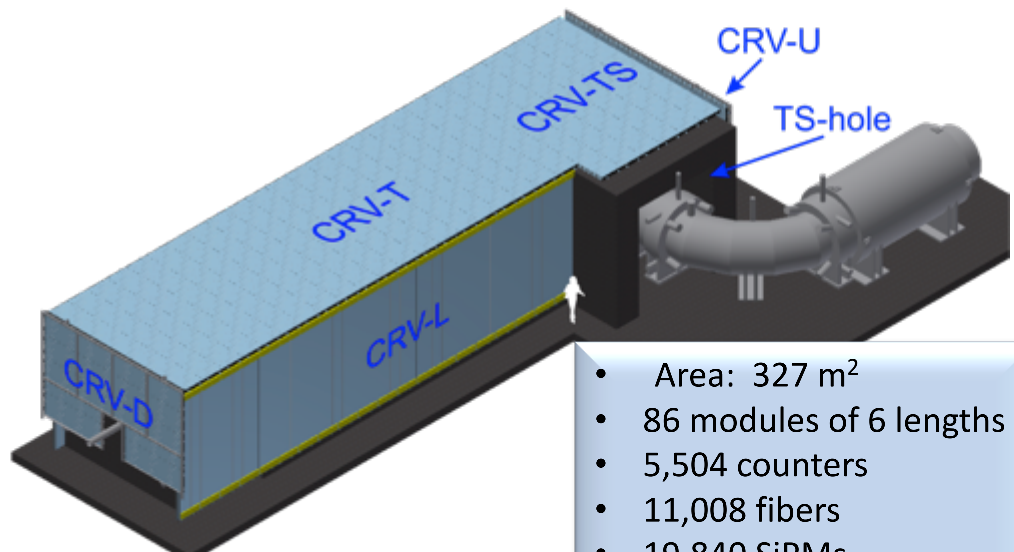
Cosmic ray muons will produce one fake signal event per day without a CRV. The muon itself can fake a 105 MeV e^{-} or it can knock out an e^{-}





- **High efficiency (0.9999) veto needed**
- Four layers of extruded plastic scintillator, (5×2) cm^2
- 2 WLS fibers (1.4 mm diameter) + (2×2) mm^2 SiPM readout
- ¾ layers hit: 125 ns veto

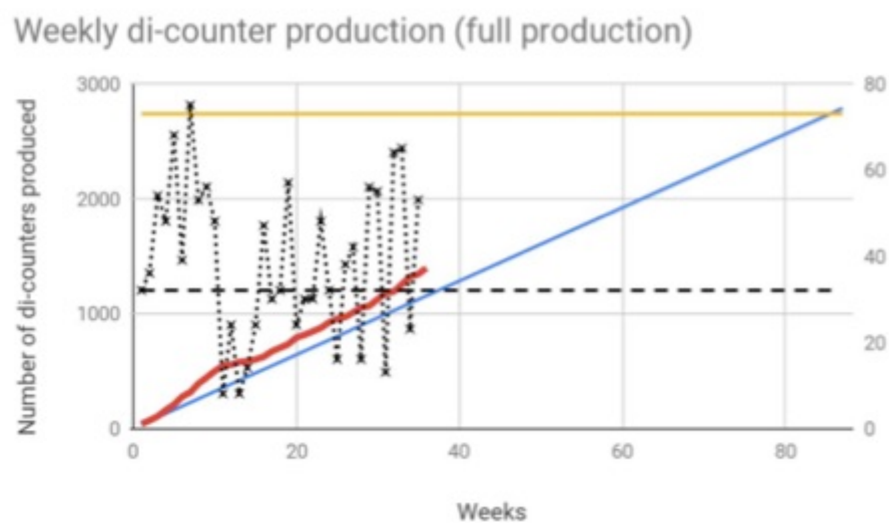


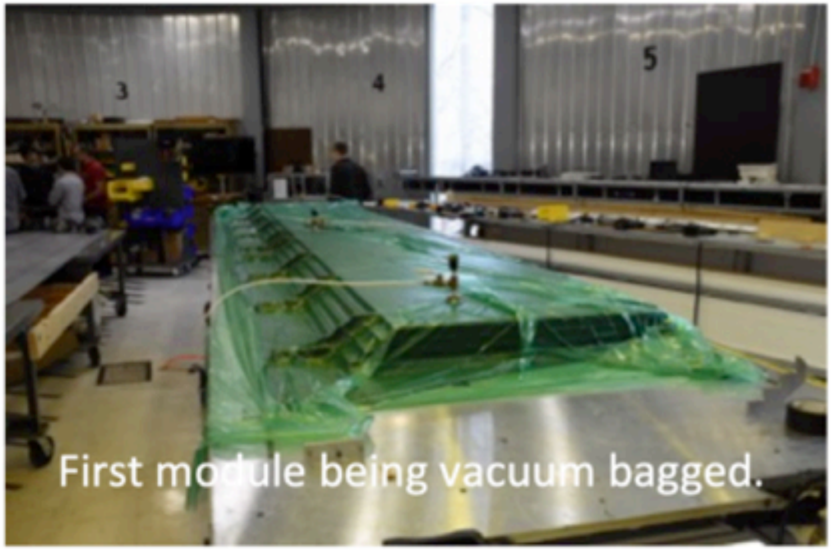


- Area: 327 m^2
- 86 modules of 6 lengths
- 5,504 counters
- 11,008 fibers
- 19,840 SiPMs
- 310 Front-end Boards

CRV status

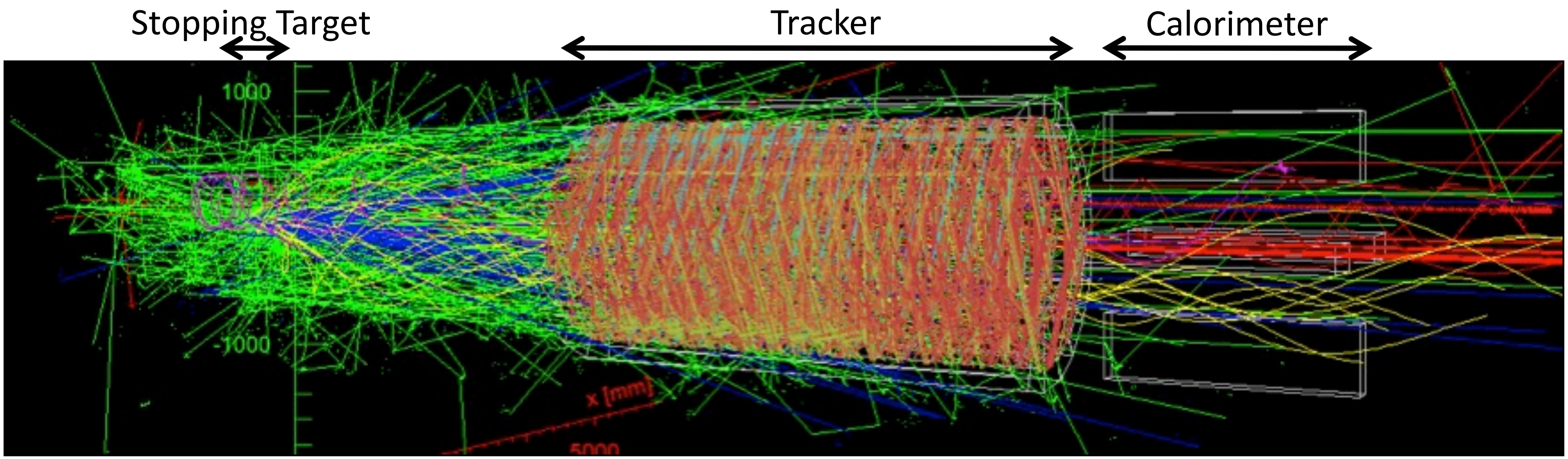
- CRV module and electronics design completed.
- Modules
  - Extrusion fabrication completed
  - Di-counter fabrication at UVA @ 50%
  - 6% of Module fabrication
- Electronics
  - Pre-production FEE Boards completed
- Installation tests underway at ANL

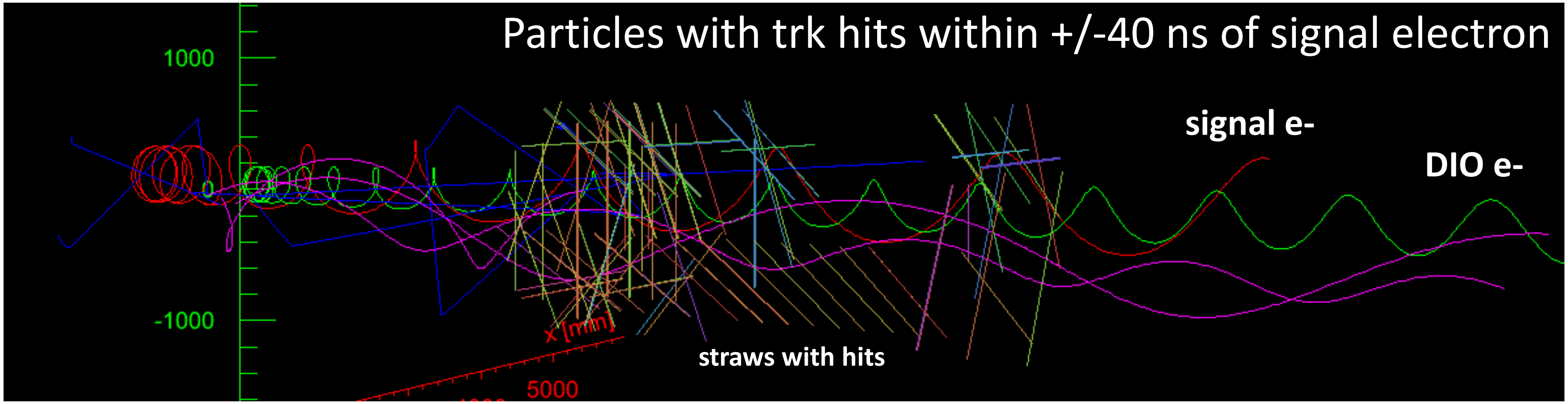




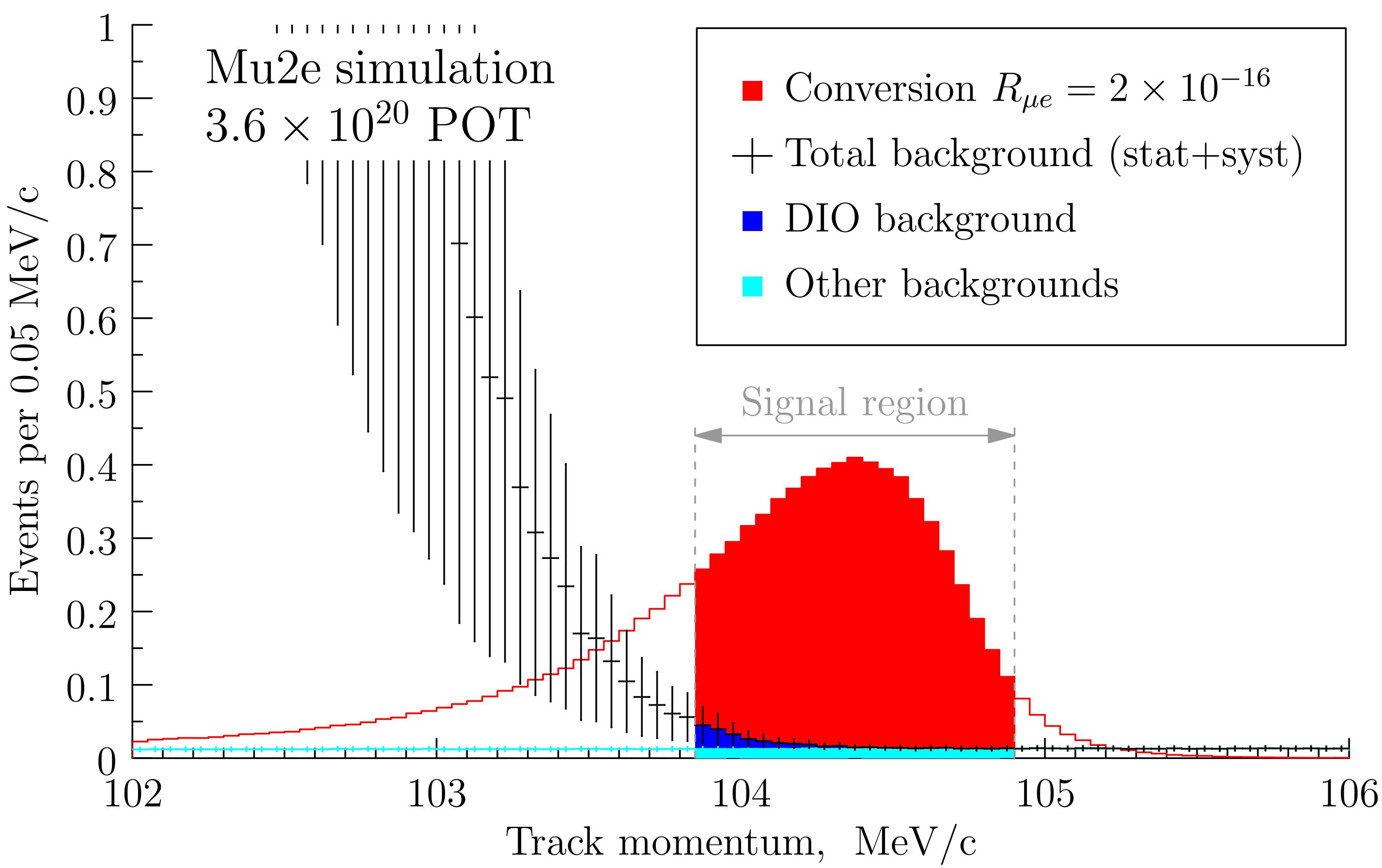
A typical Mu2e signal event

Signal electron, together with all the other hits/tracks occurring simultaneously, integrated over 500-1695 ns window



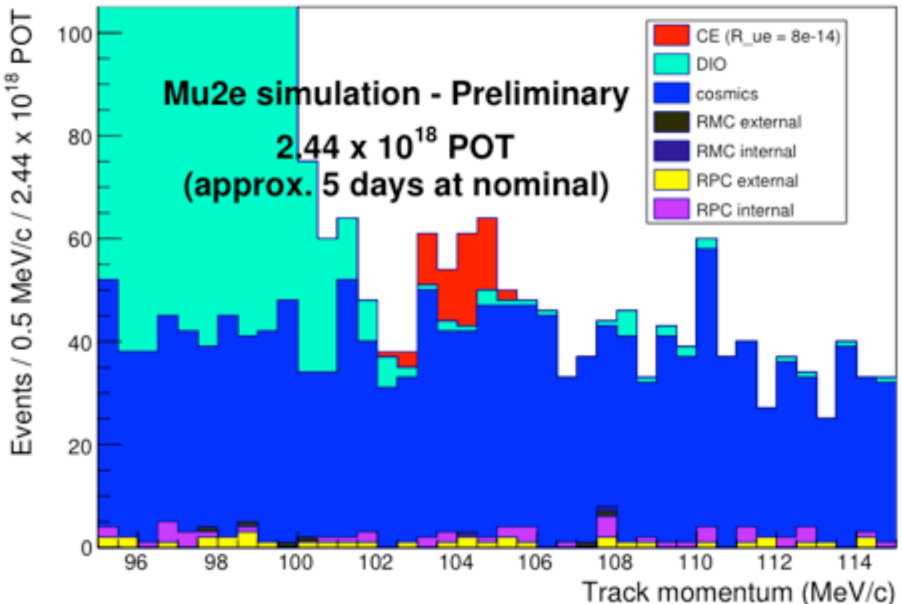


DIO/CE final count with simulation

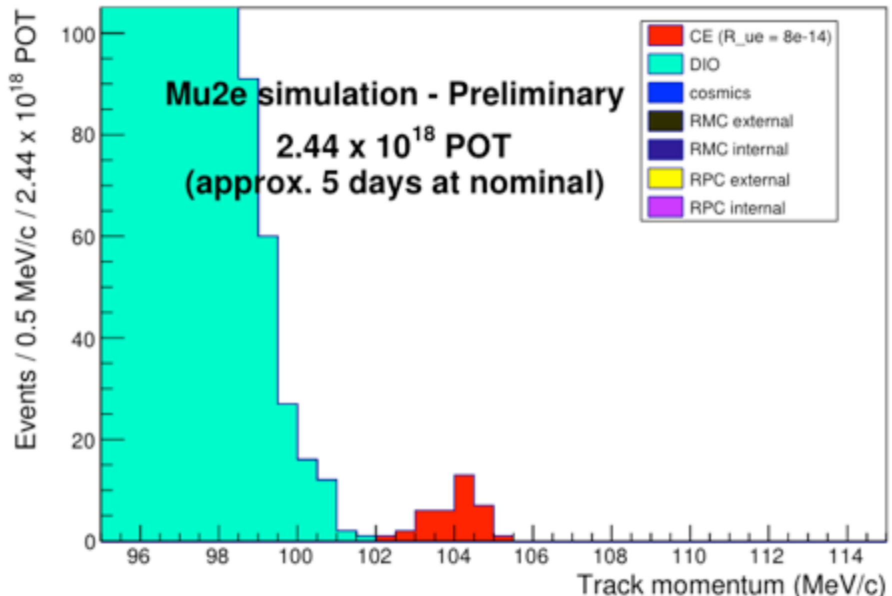


Discovery sensitivity (7.5 events) accomplished with three years of running and suppressing backgrounds to < 0.4 event total (50% cosmics, 35% DIOs)

Mock Data Challenge (1% POT)



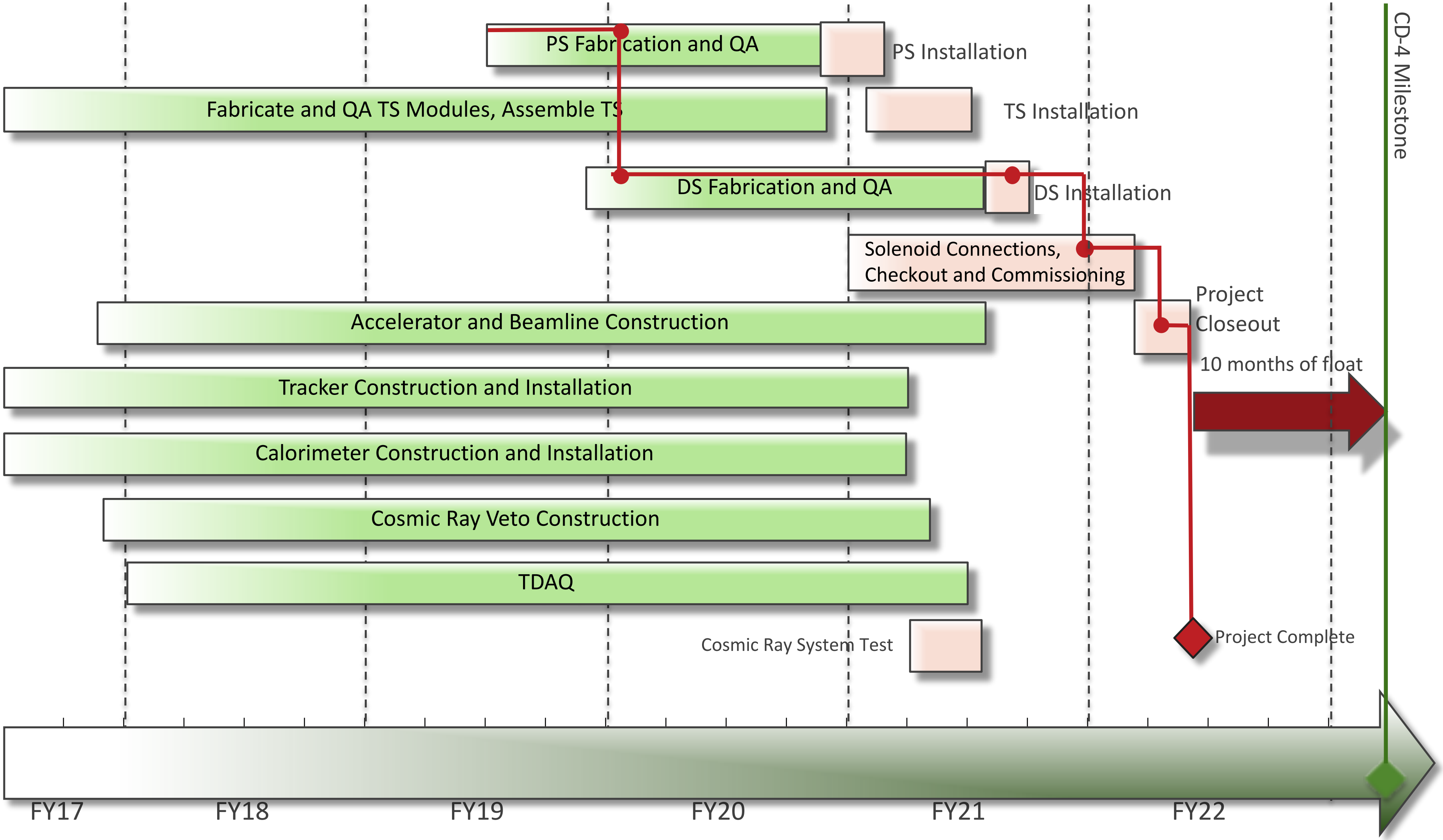
Without analysis cuts



With analysis cuts on time, track, CRV, trigger

- 1 week of data taking simulated (< 1% of POT)
- Rue signal of 8×10^{-14} simulated. 1 order of magnitude below current limit
- Mixed samples created with randomized/hidden parameters to test analysis tools and reconstruction

Mu2e Project Schedule



Installation 2020-2021, Commissioning 2021-2022, Running 2023 →

Summary & conclusions

The Mu2e experiment will exploit the highest intensity muon beams of the Fermilab complex to search for CFLV

- Improves sensitivity on conversion exp. by a factor of 10^4
- Provides *discovery capability* over wide range of New Physics models
- It is complementary to LHC, heavy-flavor, dark matter, and neutrino experiments
- It will begin commissioning in 2021
- Physics running from 2023
- Start discussing about Mu2e-II