FERMILAB-SLIDES-19-077-E

The Mu2e experiment

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On behalf of the Mu2e collaboration

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INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

Fermilab

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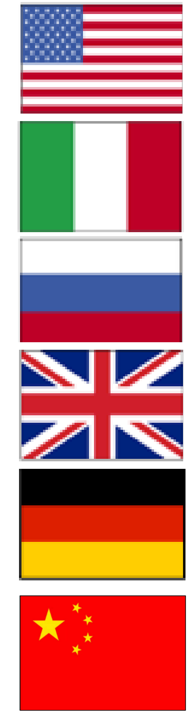
MUSE

The Mu2e Collaboration



~250 Scientists from 38 Institutions

Argonne National Laboratory, Boston University, Brookhaven National Laboratory, 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, University of Illinois, INFN Genova, Lawrence Berkeley National Laboratory, INFN Lecce, University Marconi Rome, Institute for High Energy Physics Protvino, Kansas State University, Lewis University, University of Liverpool, University College London, University of Louisville, University of Manchester, University of Minnesota, Muons Inc., Northwestern University, Institute for Nuclear Research Moscow, Northern Illinois University, INFN Pisa, Purdue University, Novosibirsk State University/Budker Institute of Nuclear Physics, Rice University, University of South Alabama, INFN Trieste, University of Virginia, University of Washington, Yale University

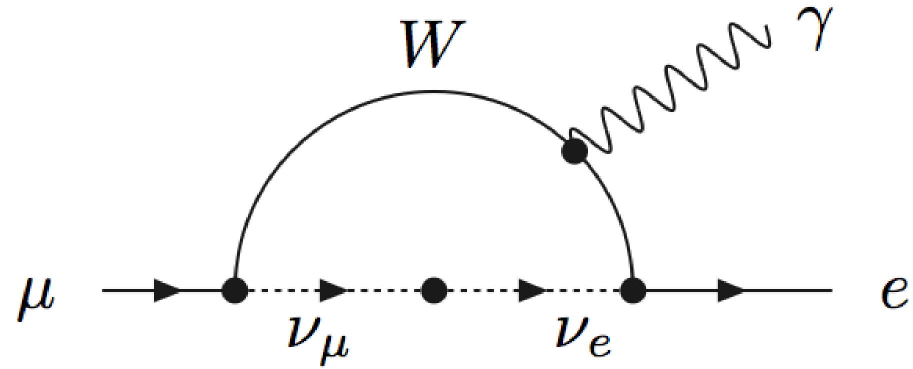
Talk overview

- Charged Lepton Flavor Violation (CLFV)
  - BSM
  - CLFV – Muon sector
  - History
- Muon Conversion
  - Measurement Technique
- Mu2e
  - Goal
  - Design
  - Detectors
- Summary

CLFV

With neutrino mass, we know that lepton flavor is not conserved

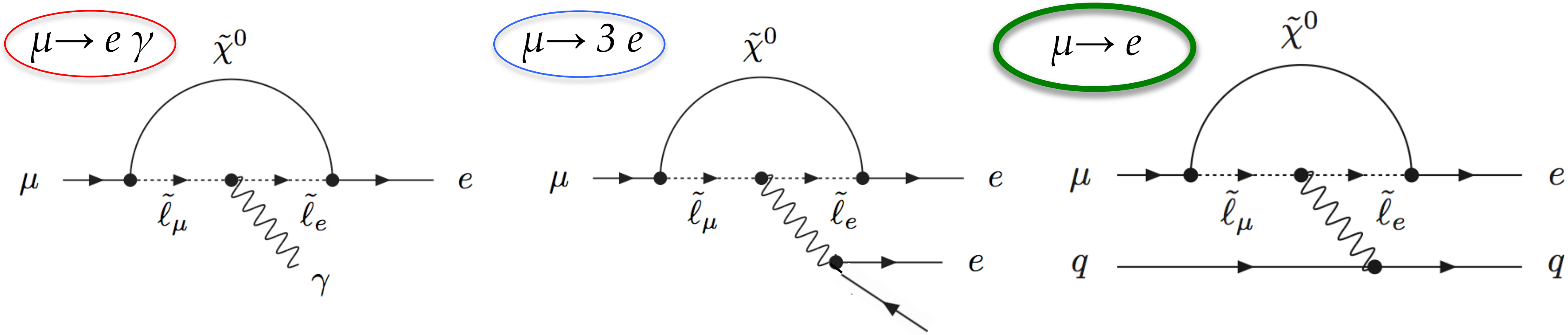
The SM CLFV process would be strongly suppressed:

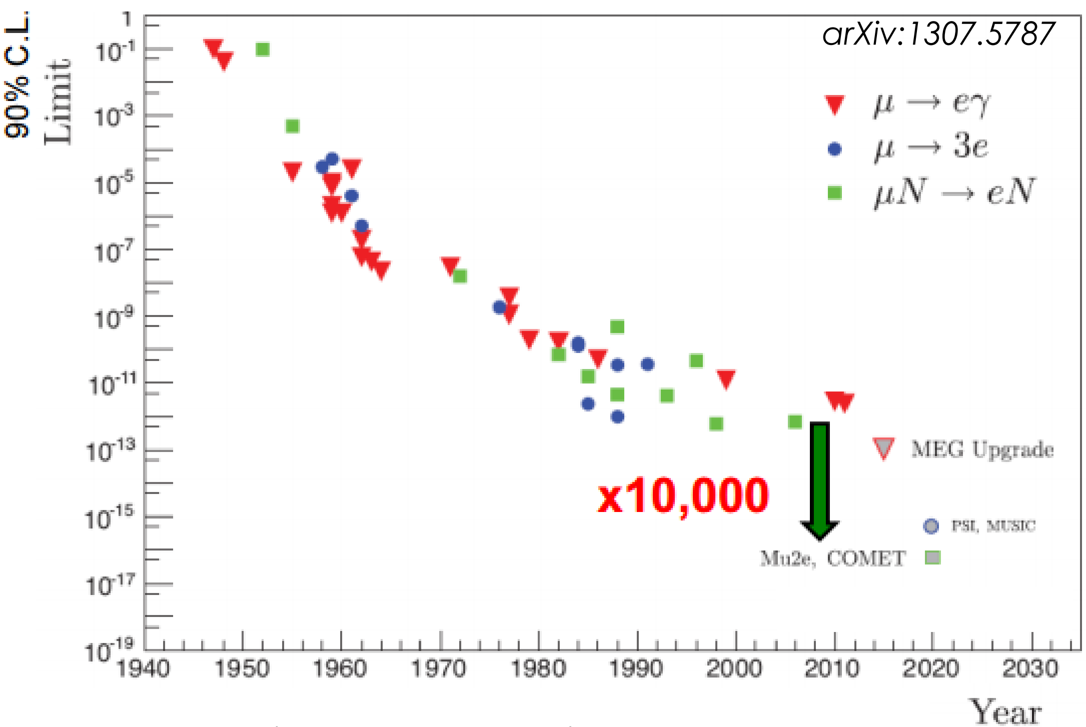


$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M_W^2} \right|^2 < 10^{-54}$$

Any observation of CLFV would be new physics Beyond the Standard Model (BSM)!

Muon CLFV history





Current best limits:

BR(μ→eγ) < 4.2 x 10^{-13} *MEG2016*

BR(μ→3e) < 1 x 10^{-12} *SINDRUM1988*

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

$R_{\mu e}$ < 8 x 10^{-17} Mu2e goal

Why muon conversion is unique?

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	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

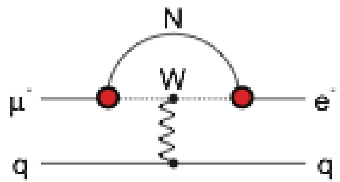
Table 8: "DNA" of flavour physics effects for the most interesting observables in a selection of SUSY and non-SUSY models ★★★ signals large effects, ★★ visible but small effects and ★ implies that the given model does not predict sizable effects in that observable.

Muon CLFV - BSM

Loop

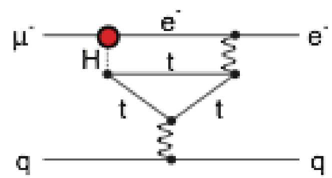
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2 \sim 8\text{x}10^{-13}$



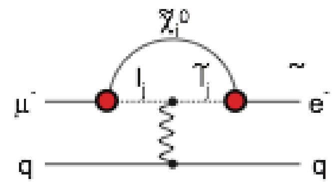
Second Higgs Doublet

$g(H_{\mu e}) \sim 10^{-4} g(H_{\mu\mu})$



Supersymmetry

rate ~ 10^{-15}

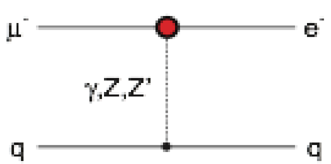


Models which can be probed also by *μ→eγ searches*

Contact term

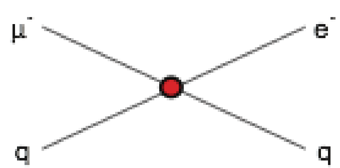
Heavy Z' Anomal. Z Coupling

$M_{Z'} = 3000\ \text{TeV/c}^2$



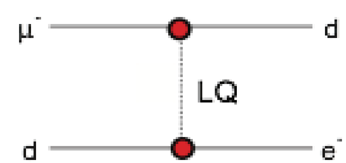
Compositeness

$\Lambda_c \sim 3000\ \text{TeV}$



Leptoquark

$M_{LQ} = 3000\ (\lambda_{\mu d}\lambda_{ed})^{1/2}\ \text{TeV/c}^2$



Direct coupling between quarks and leptons, better accessed by *μN→eN*

also see *Flavour physics of leptons and dipole moments*, arXiv:0801.1826;
Marciano, Mori, and Roney, Ann. Rev. Nucl. Sci. 58, doi:10.1146/annurev.nucl.58.110707.171126

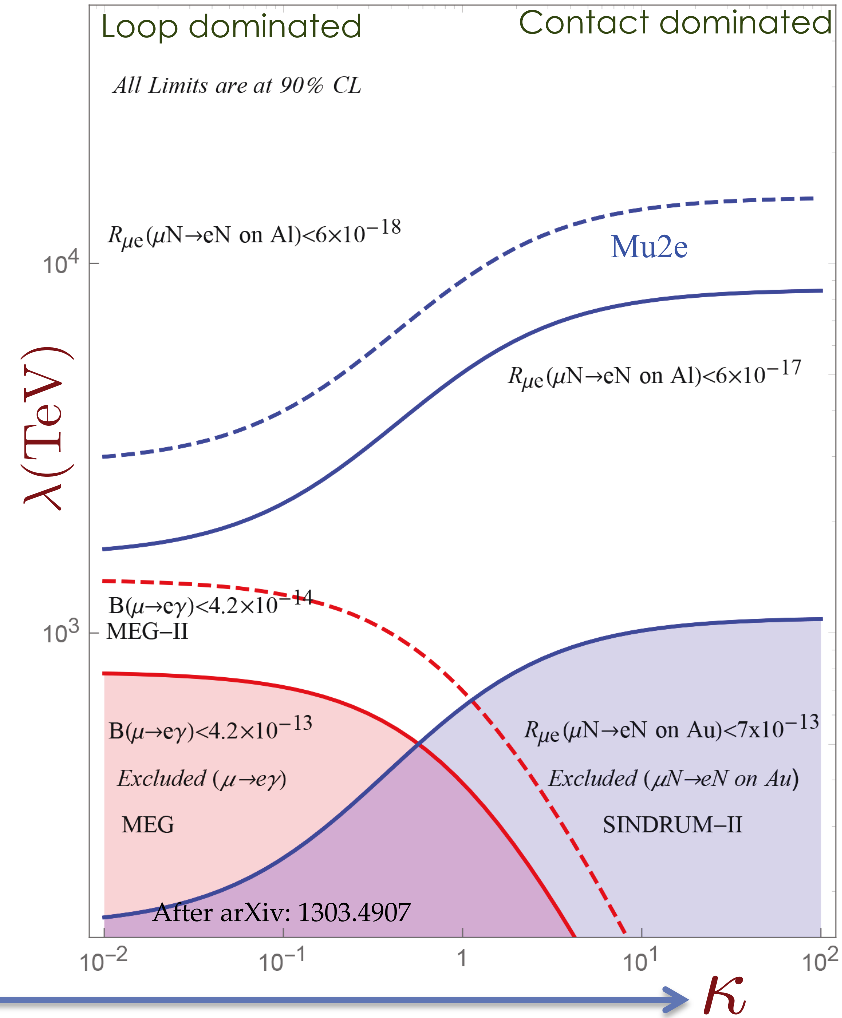
Probe mass scales λ 2000~10000 TeV,
significantly above the direct reach of LHC

Why muon conversion is unique?

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

Muon conversion is an unique probe for BSM:

- Broad discovery sensitivity across all models
- Sensitivity to λ (mass scale) up to thousands of TeV
- Clear experimental signature Neutrinoless and mono-energetic electron
  E_e = 104.97 MeV



Scaling factor between contact and loop interaction

Mu2e goal

- Measure the ratio of μ - e conversions to conventional muon captures

μ-e conversion in the presence of a nucleus

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

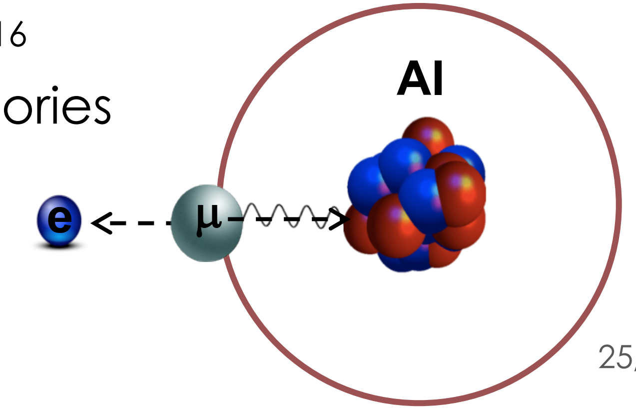
Nuclear captures of muonic Al atoms

- And set an upper limit:

$R_{\mu e}$ < 8 x 10^{-17} (@ 90% CL, with ~ 10^{18} stopped muons in 3 years of running)

- Discovery sensitivity: all $R_{\mu e}$ > few x 10^{-16}

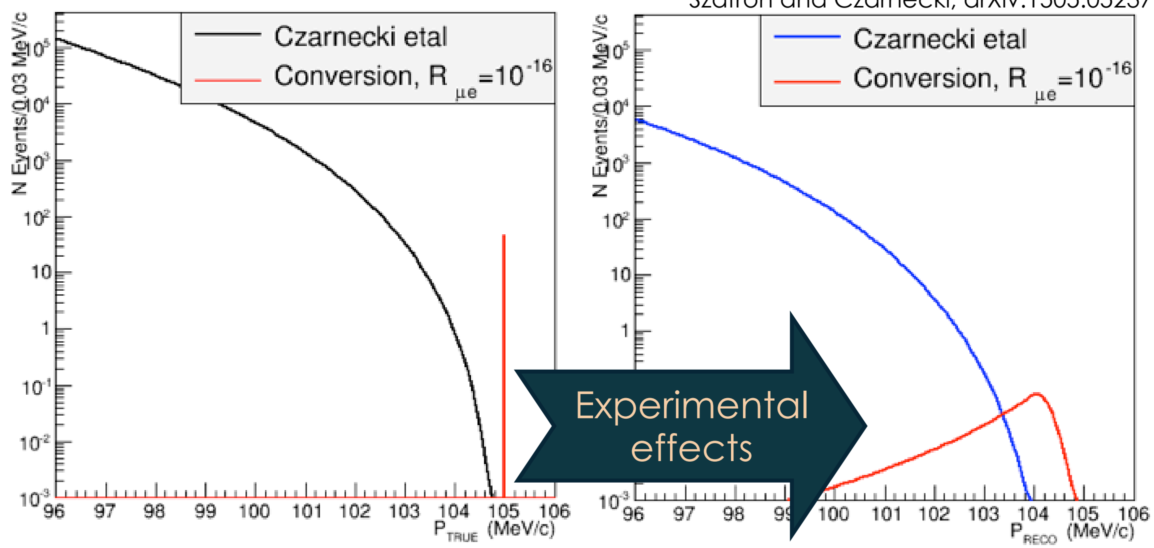
Covers broad range of new physics theories



Measurement technique

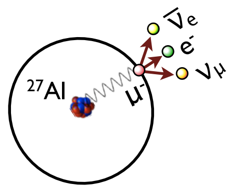
1. Low momentum μ^- beam (< 100 MeV/c)
2. Stop muons on Al target → trapped in orbit around the nucleus
3. Look for an excess around 104.97 MeV/c in the electron spectrum

Szafron and Czarnecki, arXiv:1505.05237



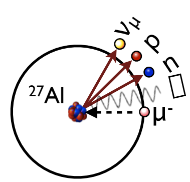
Main Backgrounds:

(BR=39%)



Decay in Orbit (DIO)

(BR=61%)



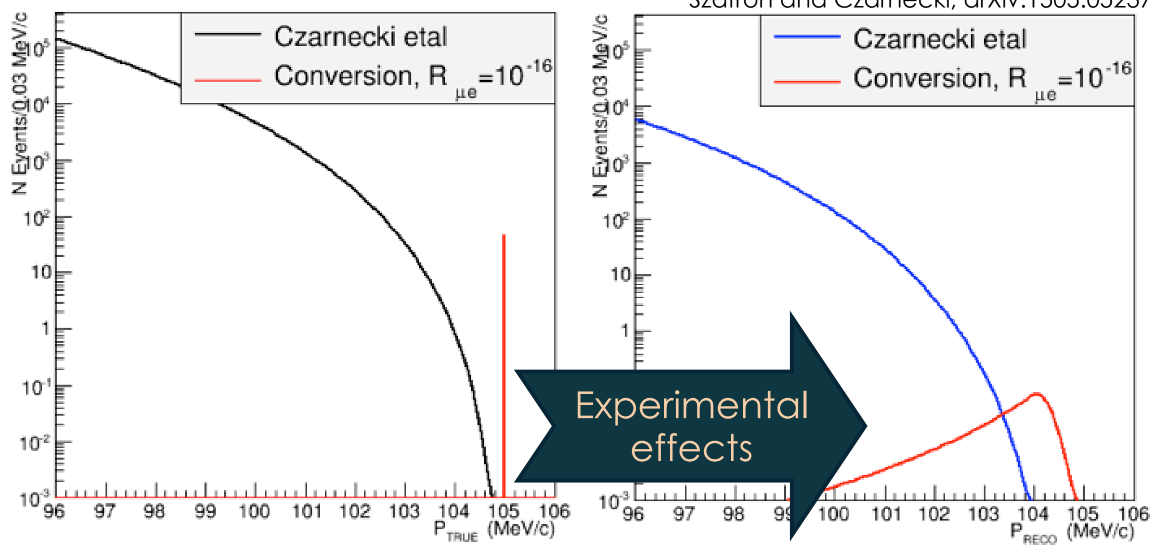
Muon Capture Process

- π/μ decay in flight
- Antiproton annihilation
- Electrons from beam, cosmic rays

Measurement technique

1. Low momentum μ^- beam (< 100 MeV/c)
2. Stop muons on Al target → trapped in orbit around the nucleus
3. Look for an excess around 104.97 MeV/c in the electron spectrum

Szafron and Czarnecki, arXiv:1505.05237



Main Backgrounds:

Decay in Orbit (DIO)   Muon Capture Process

- π/μ de
- Antip
- Electrons fro … mic rays

Pulsed beam

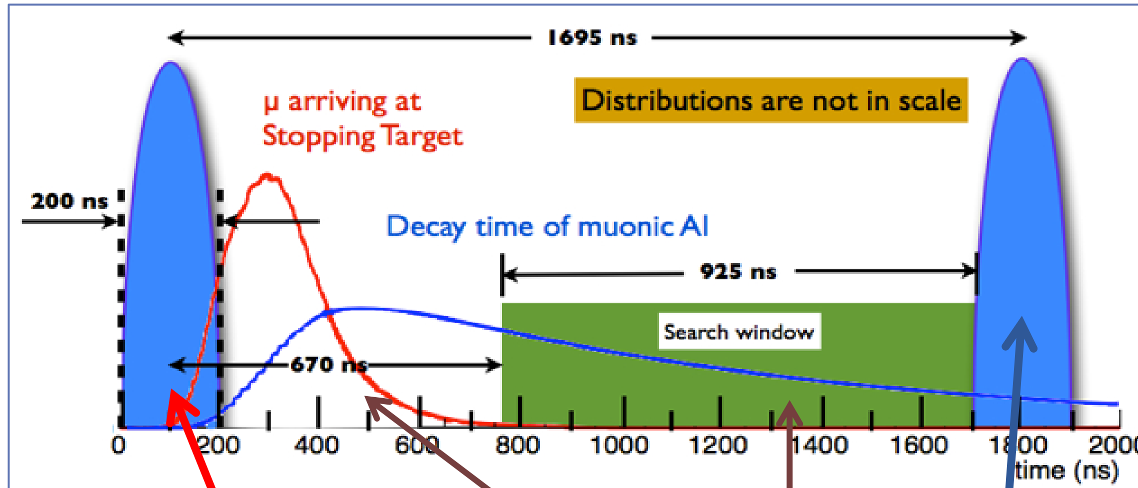
Antiproton absorber

CRV+PID

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
  - ~20,000 muons per bunch
  - 10^{10} muons/second
  - **10 GHz muons stopping rate**



High efficiency in transporting muon to Al target

- Need of a sophisticated magnet with gradient fields

Excellent detector for 100 MeV electrons

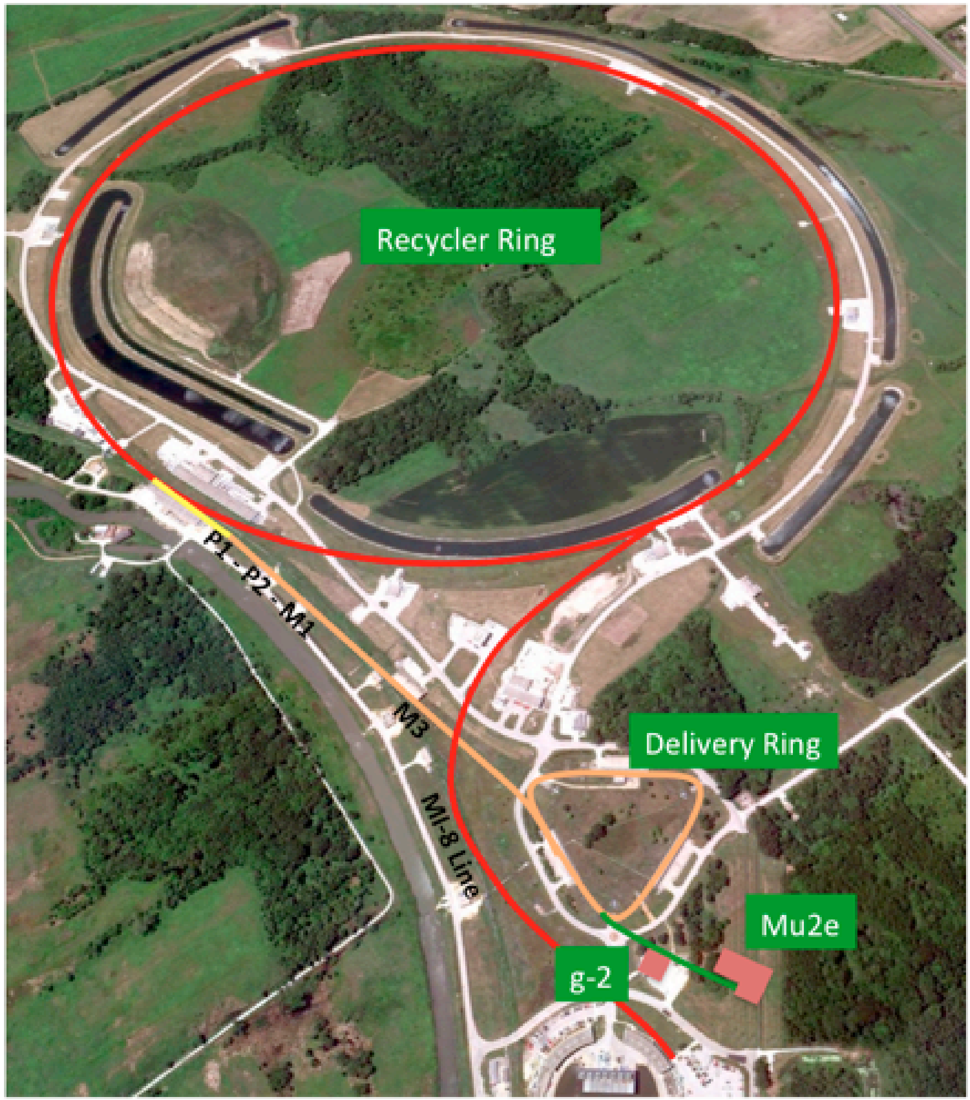
→ Excellent momentum resolution (< 200 keV core)
→ Calorimeter for PID, triggering and track seeding
→ High Cosmic Ray Veto (CRV) efficiency (>99.99%)
→ Thin anti-proton annihilation window(s)

Accelerator scheme for muon beam

- Booster: batch of 4×10^{12} protons every 1/15th second (8 GeV, 8 kW)
- Booster "batch" injected into the Recycler ring and re-bunched into 4 bunches
- These are extracted one at a time to the Delivery ring (ex De-buncher)
- 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 PT

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



Campus and Mu2e hall

Detector Hall Building

- Broke Ground (April 2015)
- Building Acceptance (March 2017)

Infrastructure installation (on going)

- LCW pipes, Bus bar, Cable Trays
- Interlocks, Networking, DAQ
- Cryo Distribution box …

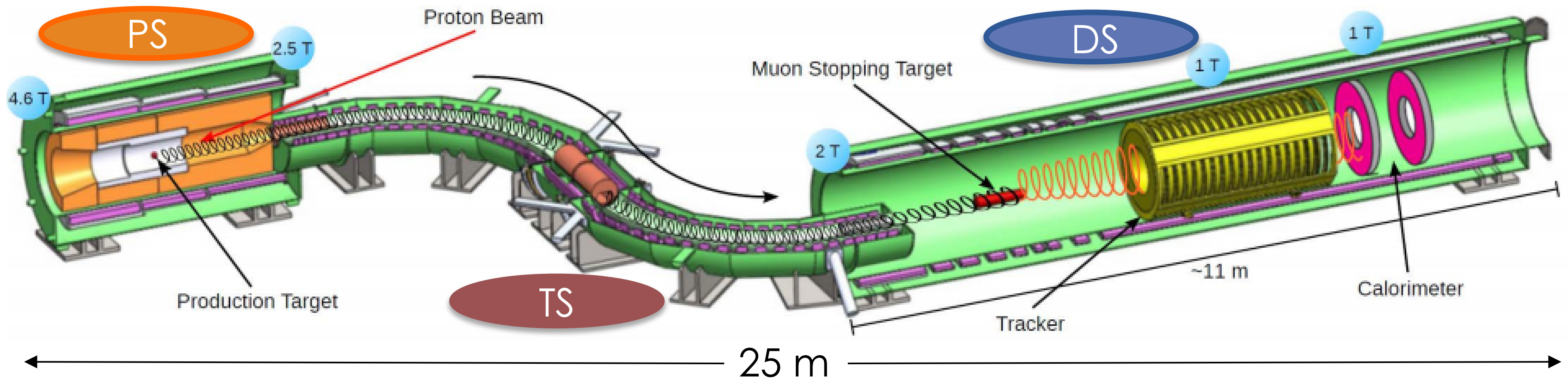
Mu2e design

Production Solenoid / Target

- Protons hitting target and producing mostly π
- Solenoid reflects slow forward μ/π and contains backward μ/π

Transport Solenoid

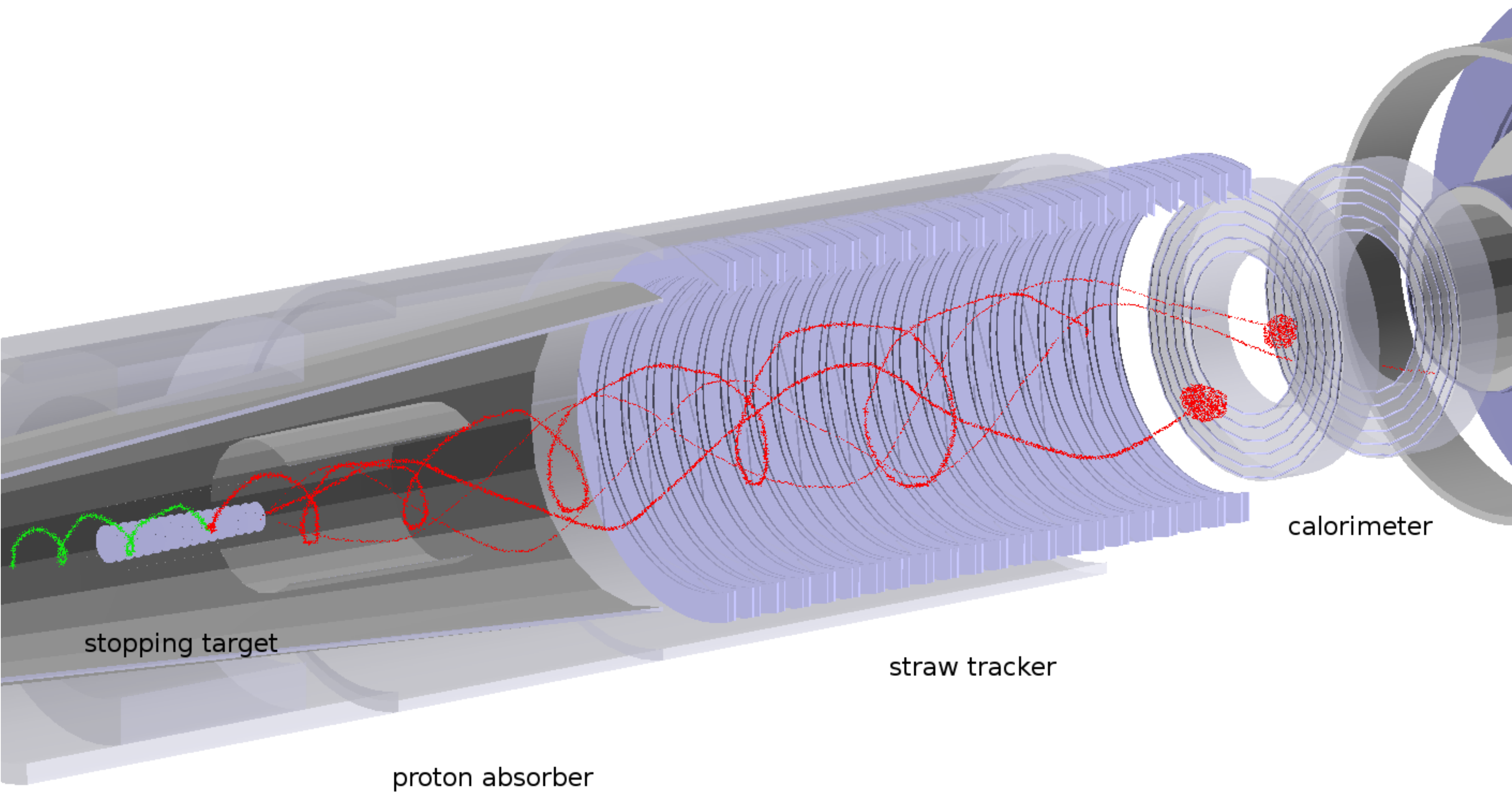
- Selects and transports low momentum μ^-



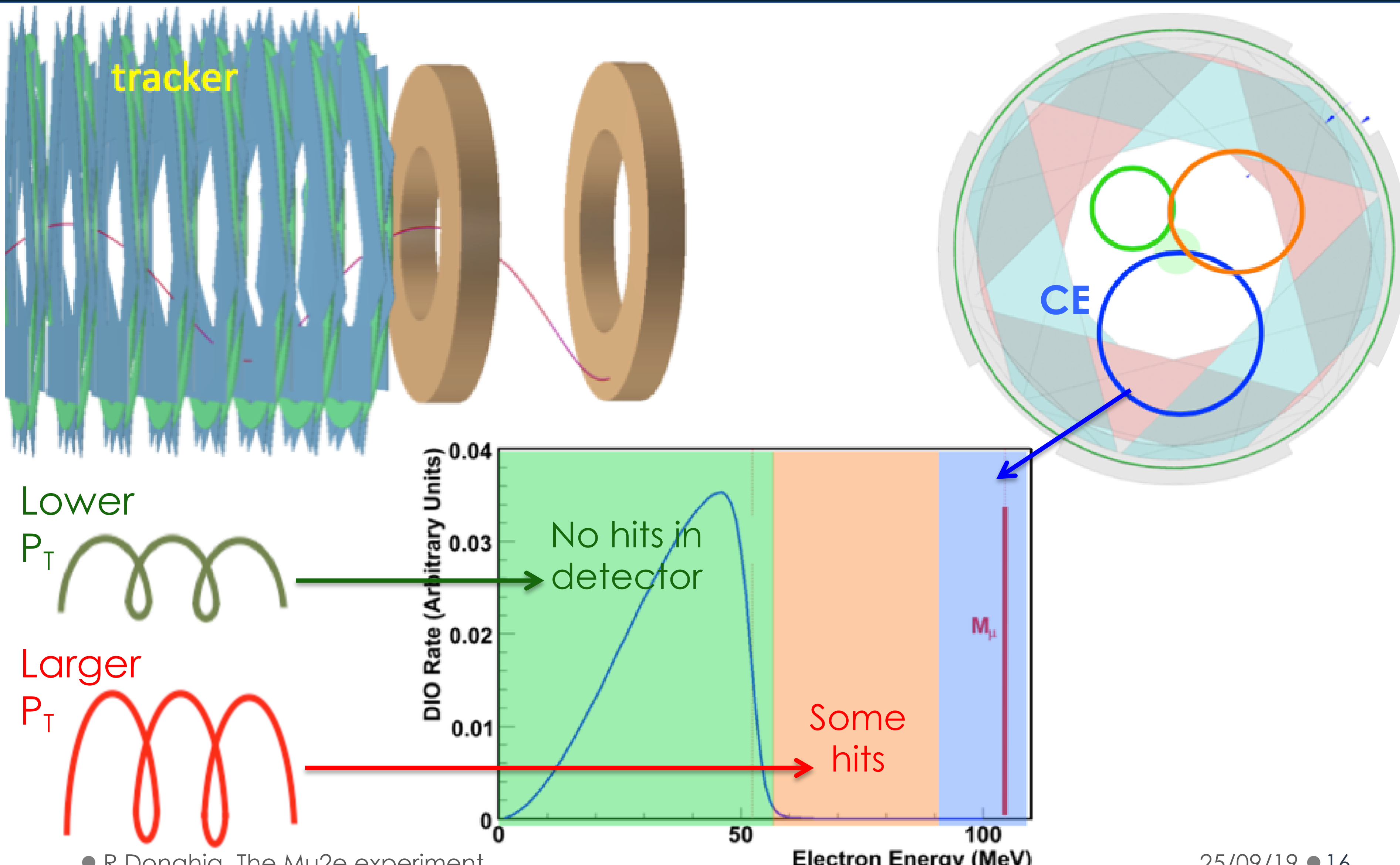
Detector Solenoid: stopping target and detectors

- Stops μ^- on Al foils (decay time ~ 864 ns)
- Events reconstructed by detectors, optimized for 105 MeV momentum

Conversion electron trajectory



Detectors

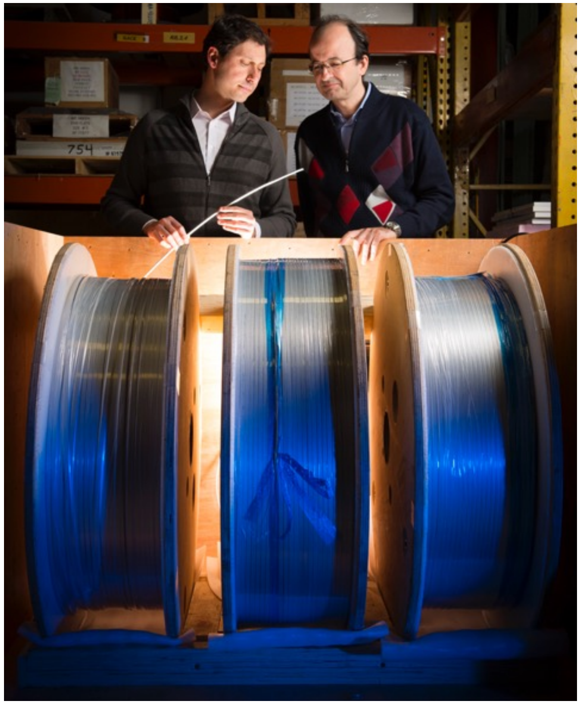


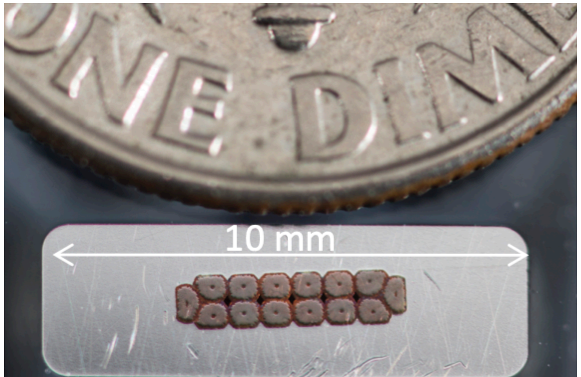
tracker
CE
Lower
P_T
Larger
P_T
No hits in
detector
Some
hits
M_μ
DIO Rate (Arbitrary Units)
0.04
0.03
0.02
0.01
0
0
50
100
Electron Energy (MeV)

Mu2e solenoids Superconductor

- PS, DS are being built by **General Atomics** (USA)
- TS is being built by **ASG** (Italy)
- Conductor production is complete

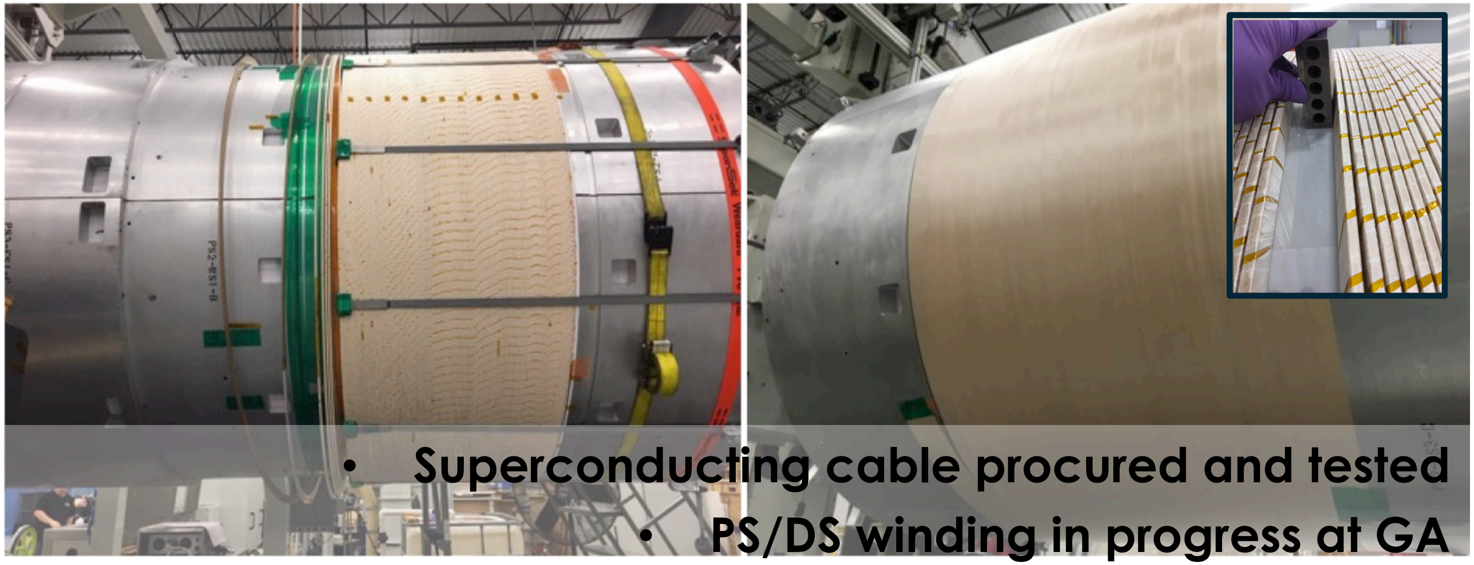
	Production	Transport	Detector
Length (m)	4	13	11
Diameter (m)	1,7	0,4	1,9
Field @ start (T)	4,6	2,5	2,0
Field @ end (T)	2,5	2,0	1,0
Number of coils	3	52	11
Conductor (km)	14	44	17
Operating current (kA)	10	3	6
Stored energy (MJ)	80	20	30
Cold mass (tons)	11	26	8





Cross-section of Extruded TS Conductor

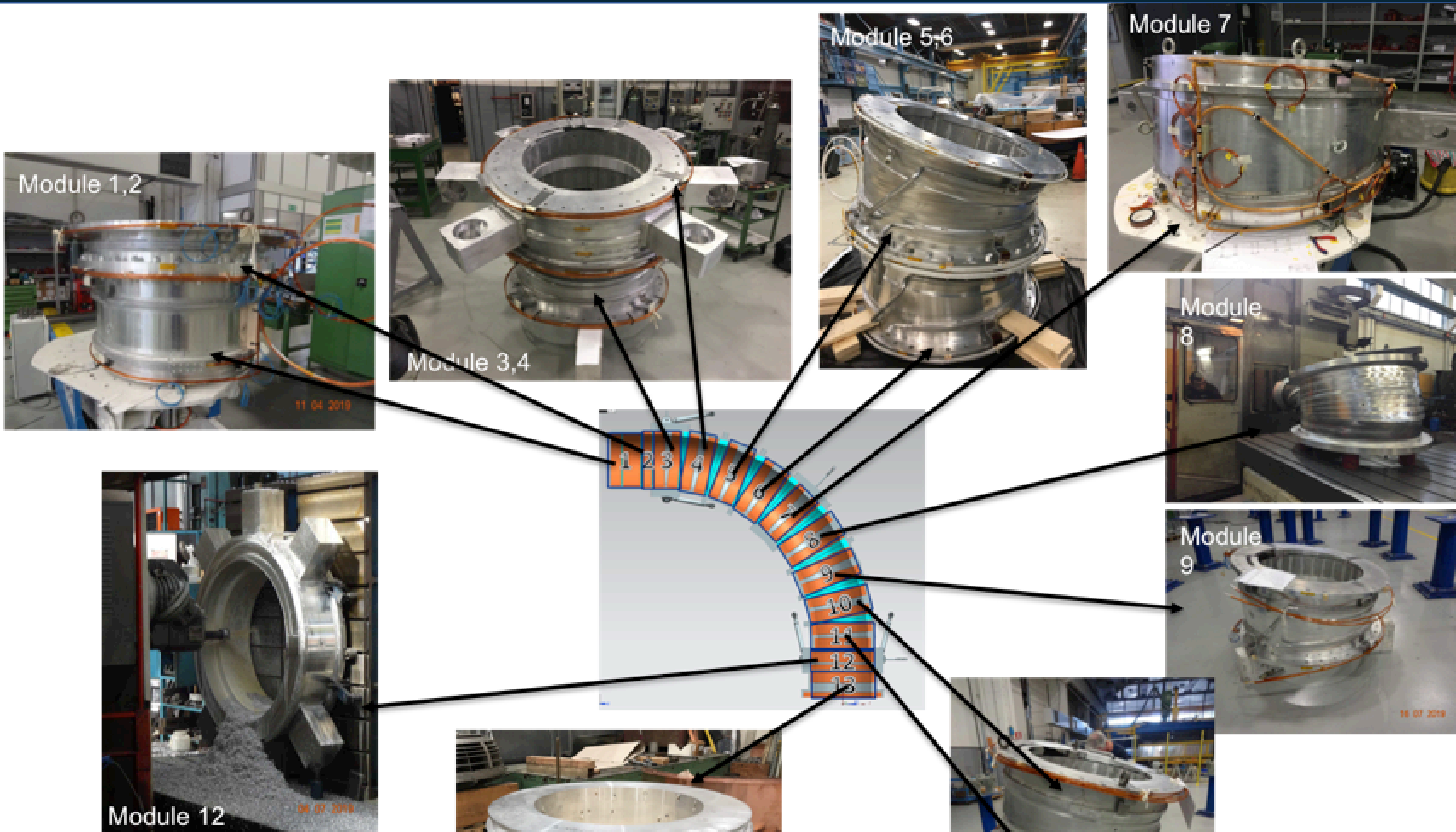
Status of PS/DS



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

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

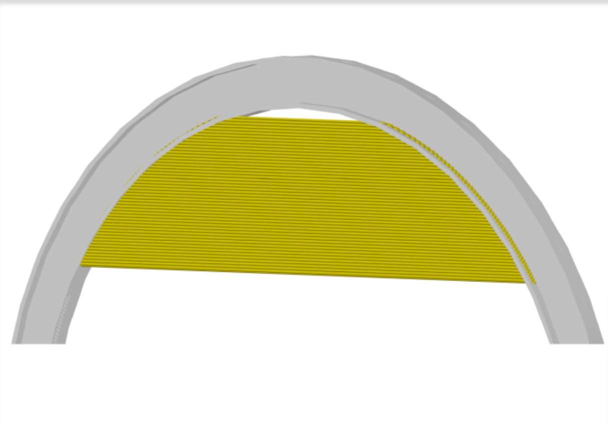
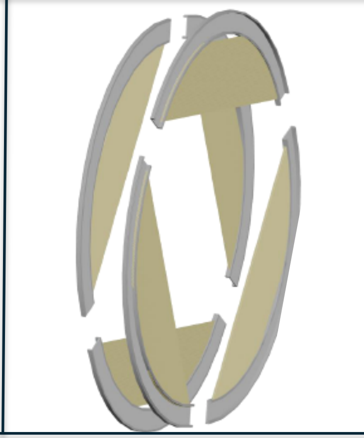
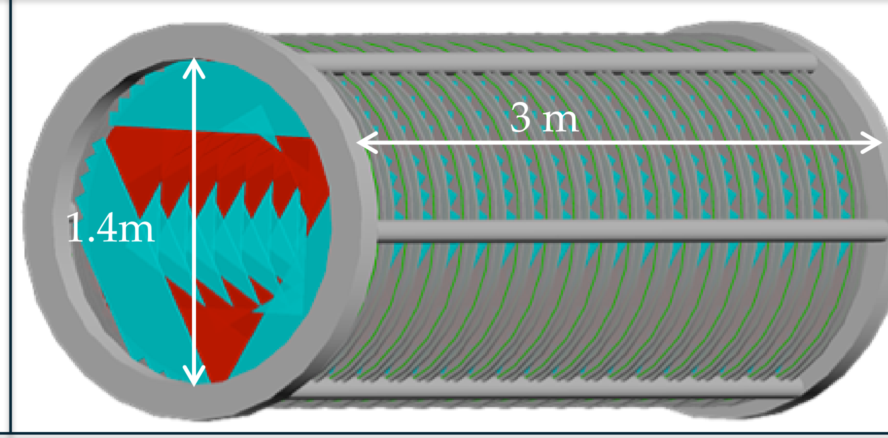
Status of TS



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

Overall TS modules construction **better than 1/3 of total!**

Straw Tracker

Straw tubes on a panel	One station	Tracker Structure
		

Detector requirements:

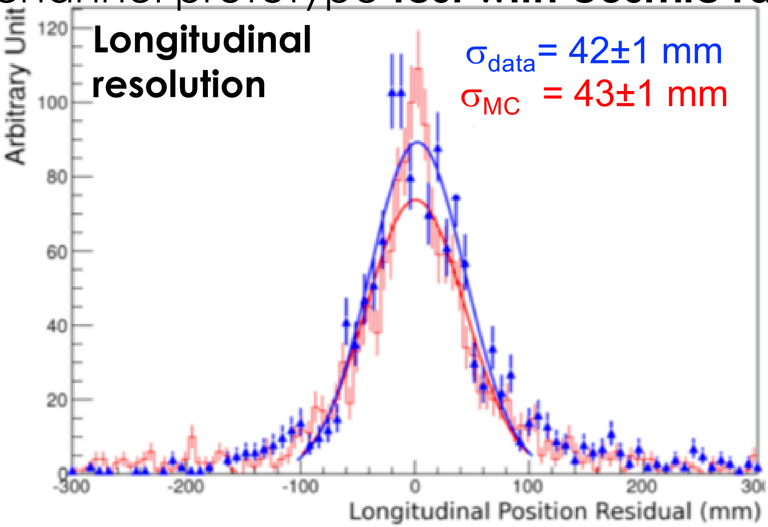
- Small amount of X_0
- **σ_p < 180 keV @ 105 MeV**
- Good rate capability:
  - 20 kHz/cm^2 in live window
  - Beam flash of 3 MHz/cm^2
- dE/dx capability to distinguish e^-/p
- Operate in B = 1 T, 10^{-4} Torr vacuum
- Maximize/minimize acceptance for CE/DIO

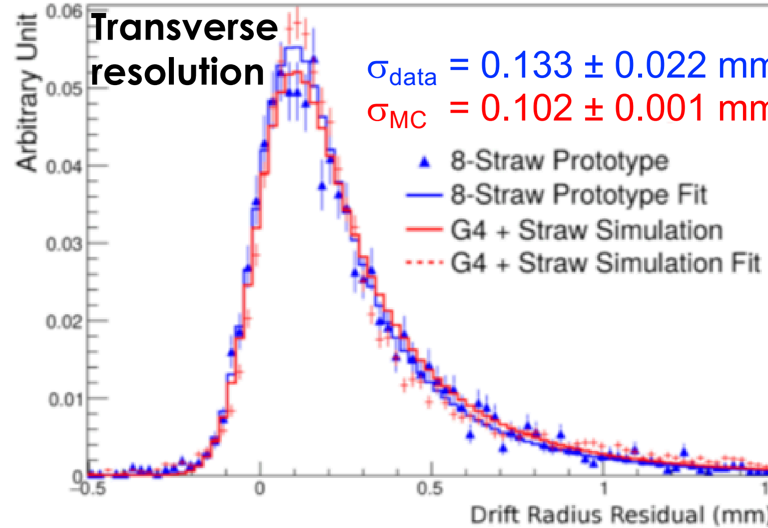
Low mass straw drift tubes design:

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

Tracker performance

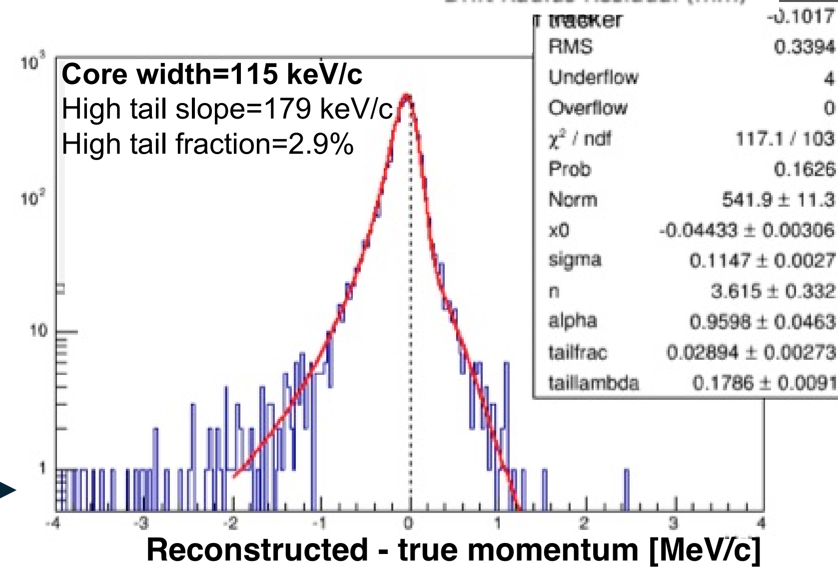
8-channel prototype **test with cosmic rays:**





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

Full simulation of tracker resolution



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**

→Pre-production panel #12 completed

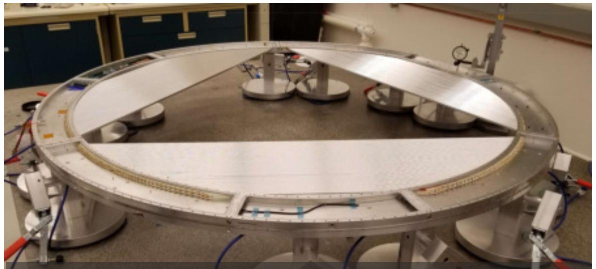
→Production will start soon after

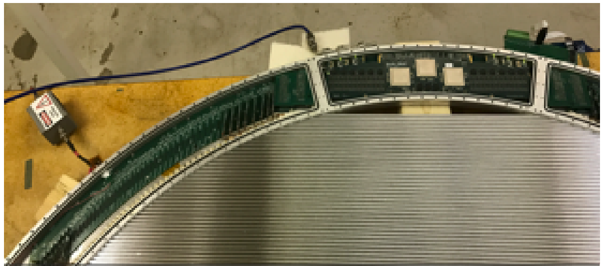
Plane

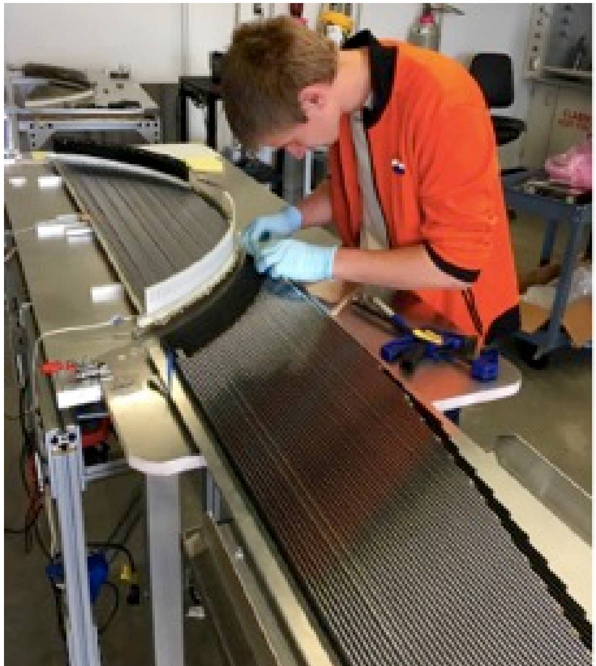
- Plane assembly tooling fixture design nearly complete

Electronics

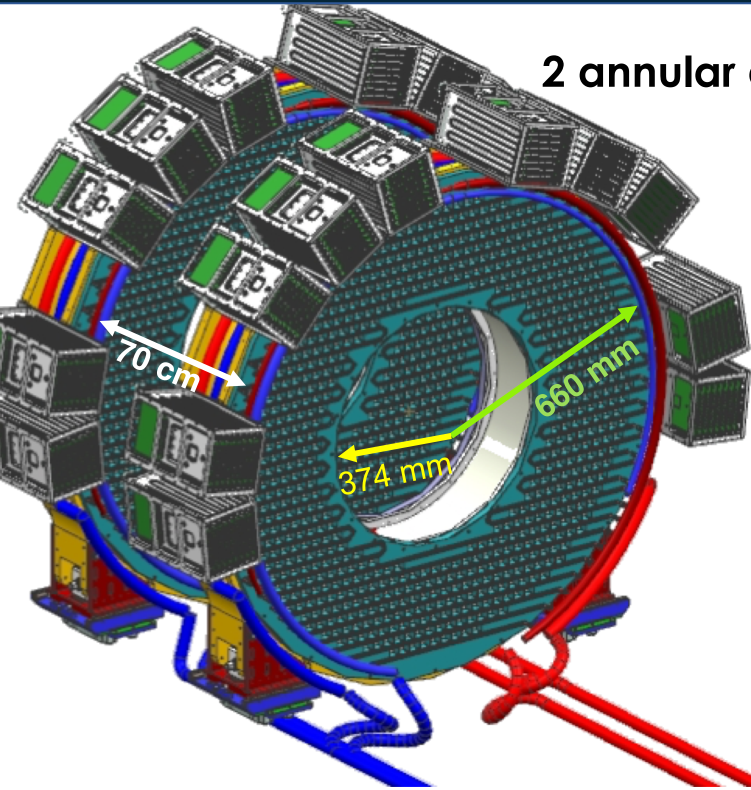
- Incorporation of rad hard FPGA in progress


Three panels installed in plane


Panel w/Front-End Electronics


Panel: Straw Installation

EM Calorimeter



2 annular disks with 674 CsI (30x30x200) mm^3 square crystals each

Requirements

→ **PID to distinguish e/mu**

→ Seed for track pattern recognition

→ Tracking independent trigger

→ Work in 1 T field and 10^{-4} Torr vacuum

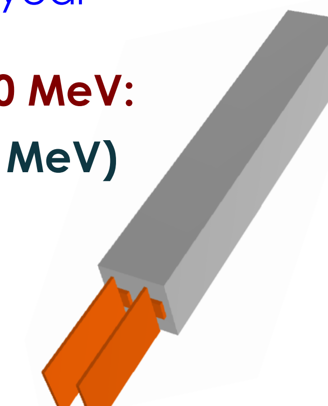
→ RadHard up to 100 krad, 10^{12} n/cm^2/year

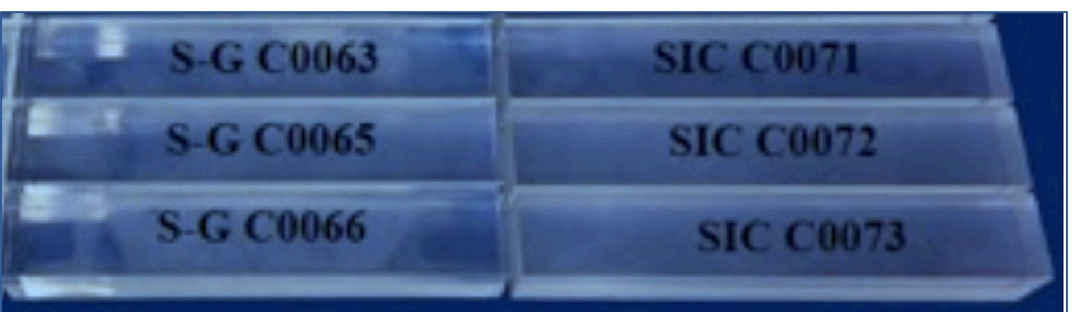
→ High acceptance **for CE signal @ 100 MeV:**

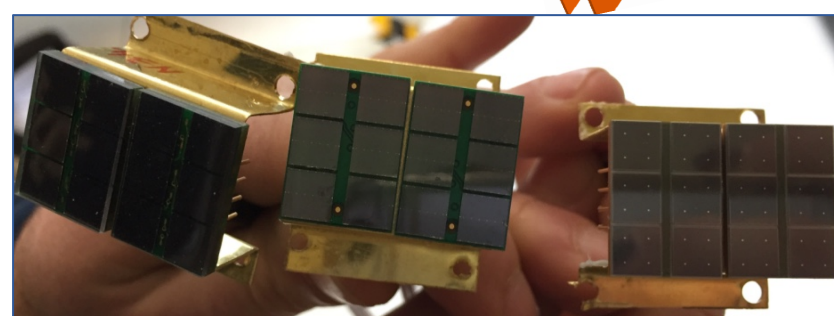
Energy resolution < 10% (@ 100 MeV)

Timing resolution < 0.5 ns

Spatial resolution < 1 cm







Calorimeter performance

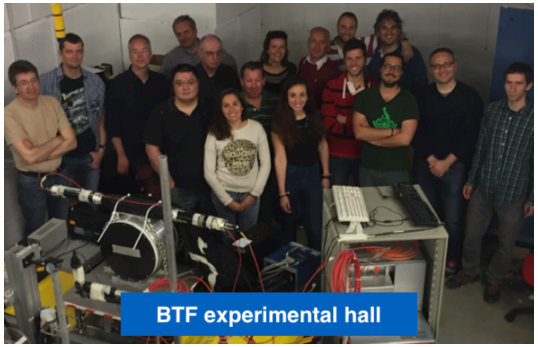
Module-0: 51 crystals, 102 SiPM/FEE channels

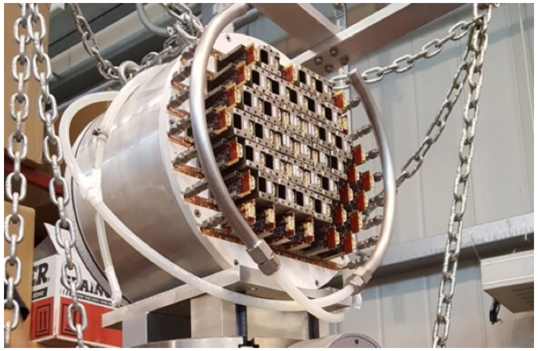
Test @ BTF in Frascati using e- beam [60MeV,120MeV]

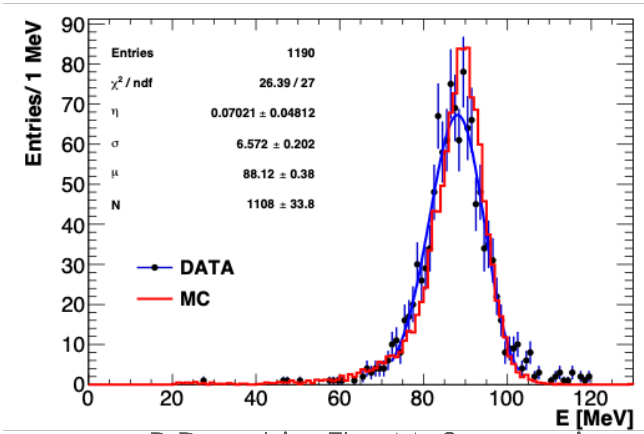
➔ 5.4 % (7.3%) energy resolution @ 100 MeV for 0° (50°) impact angles. Excellent data-MC agreement

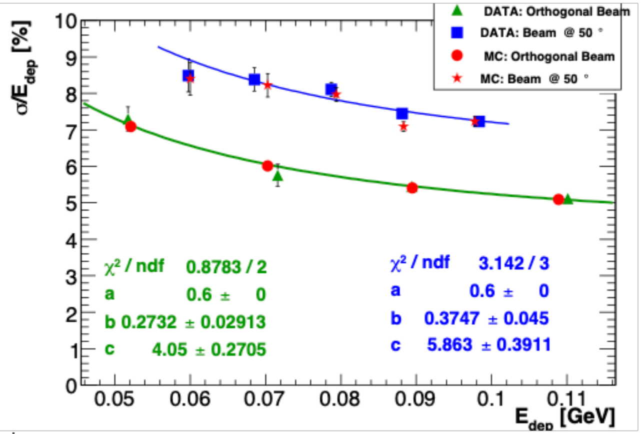
➔ Timing resolution < 150 ps with one sensor

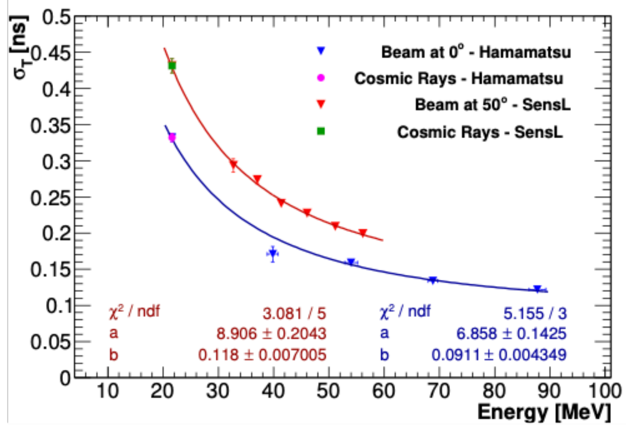
➔ ***Mu2e requirements satisfied!***





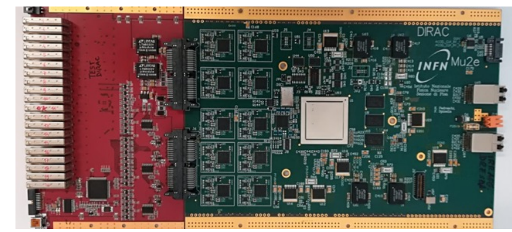


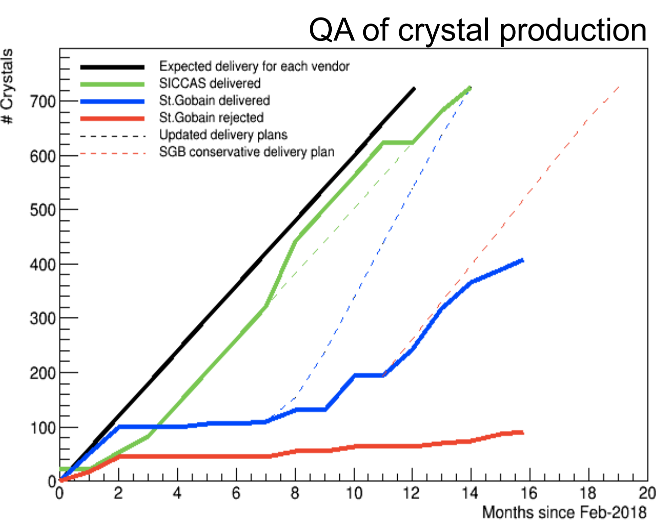


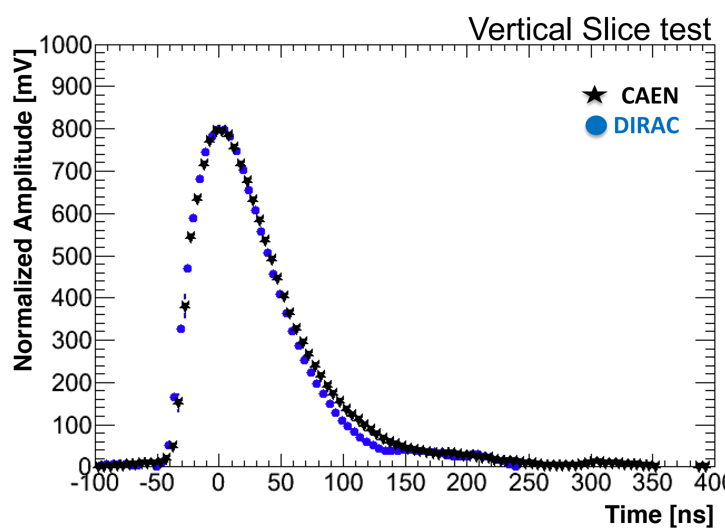


Calorimeter status

- Custom SiPM array (w Hamamatsu), FEE, Readout electronic
  - Radiation hardness test of FEE and DIRAC done
- 1100 out f 1450 crystals produced and tested
- **4000/4000 SiPMs produced and tested**
- Vertical slice test done
- Mechanics under construction in Italy



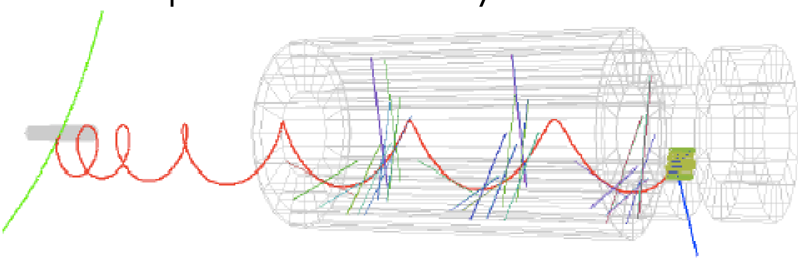


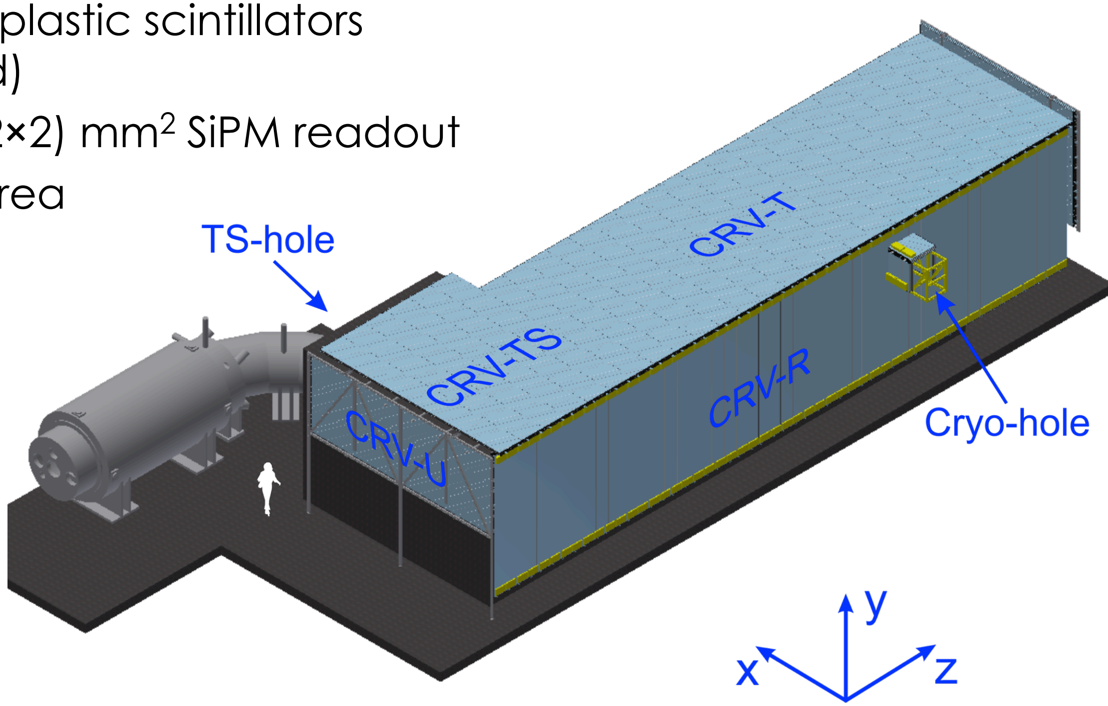


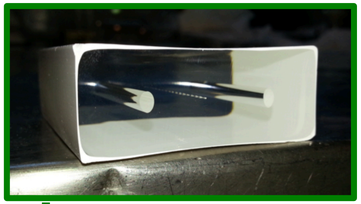
Cosmic Ray Veto

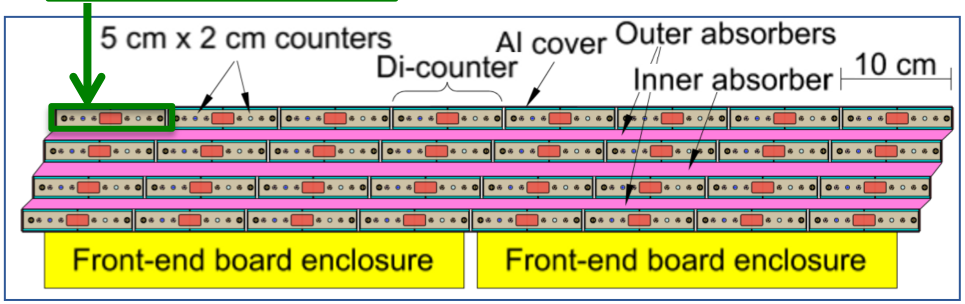
Cosmic ray muons will produce one fake signal event per day without a CRV.

- Composed of 4 layers of extruded plastic scintillators (a coincidence of 3 out of 4 is used)
- 2 WLS fibers (1.4 mm diameter) + (2×2) mm^2 SiPM readout
- Placed around DS and part of TS area
- Required efficiency: 0.9999









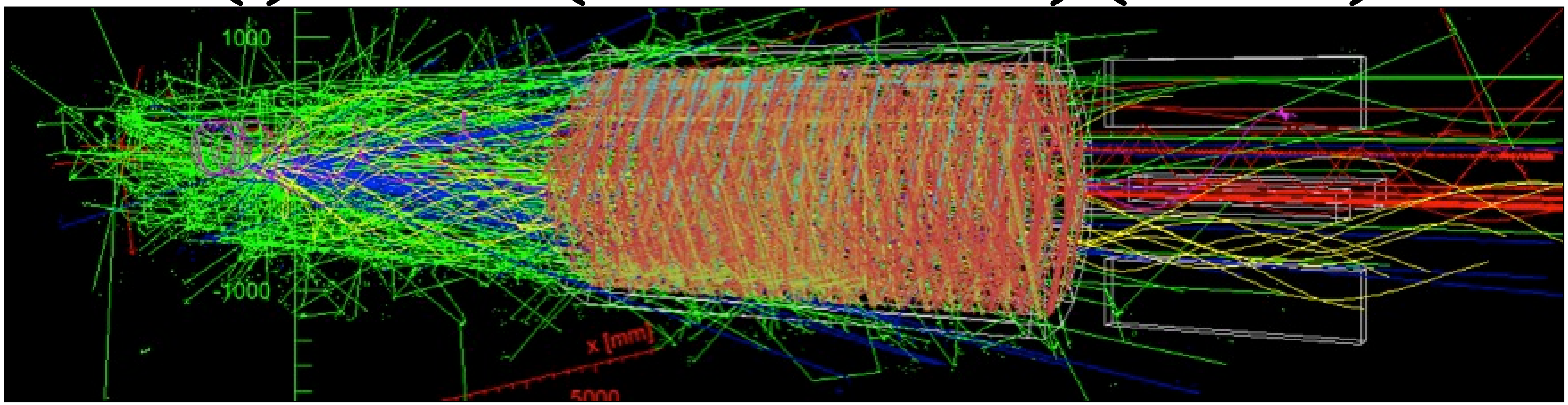
CRV module and electronics design completed:

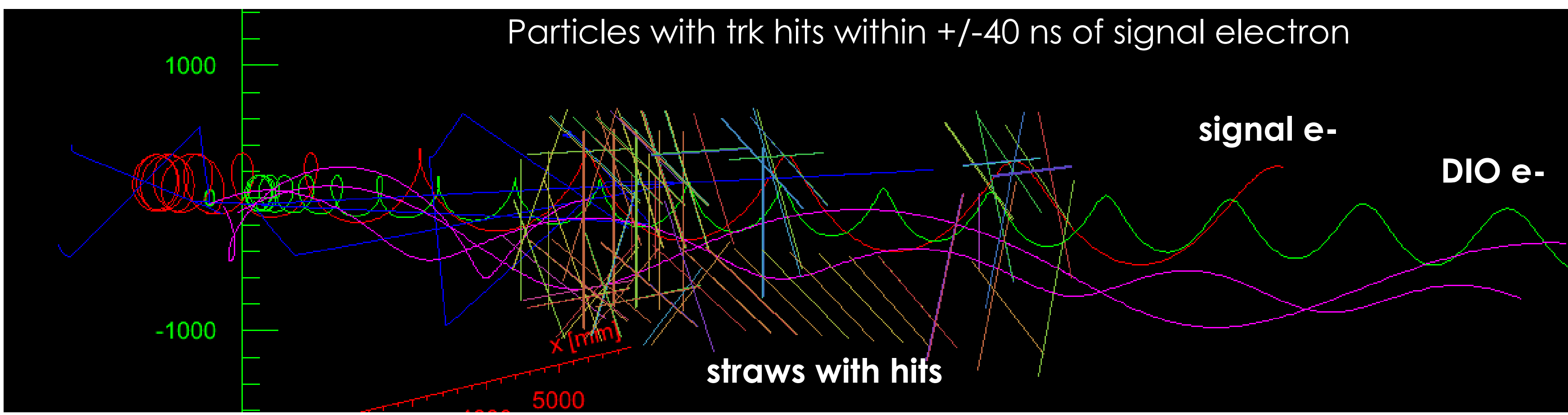
- 4 pilot production modules fabricated
- QA test meet the requirements
- Electronics production underway
  - ~30% of the SiPM tested
  - FEE-boards produced @ Kansas State Univ

Signal window

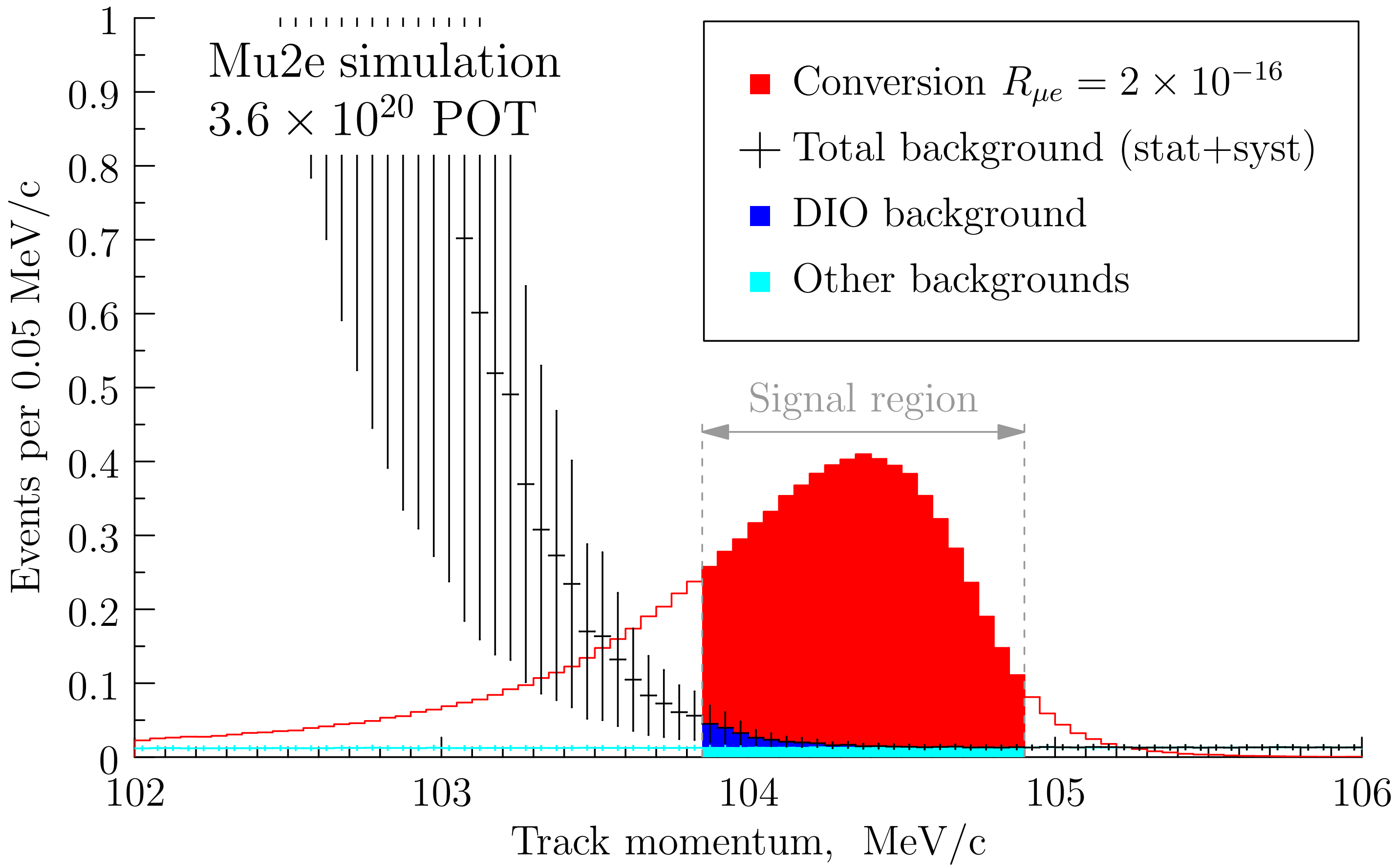
Signal electron, together with all the other hits/tracks occurring simultaneously, integrated over 500-1695 ns window

Stopping Target | Tracker | Calorimeter



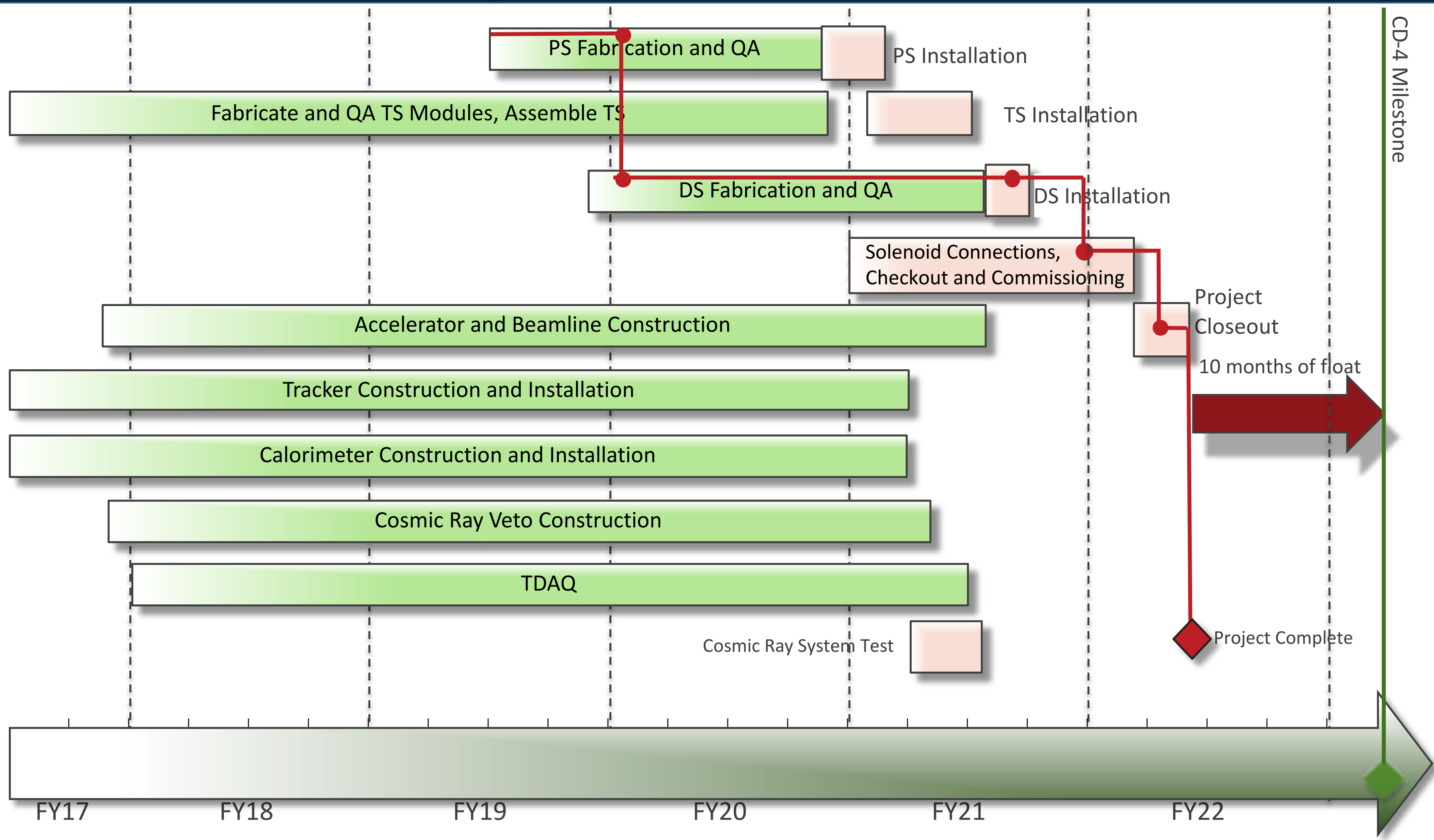


Three years run
Expectation by full Simulation



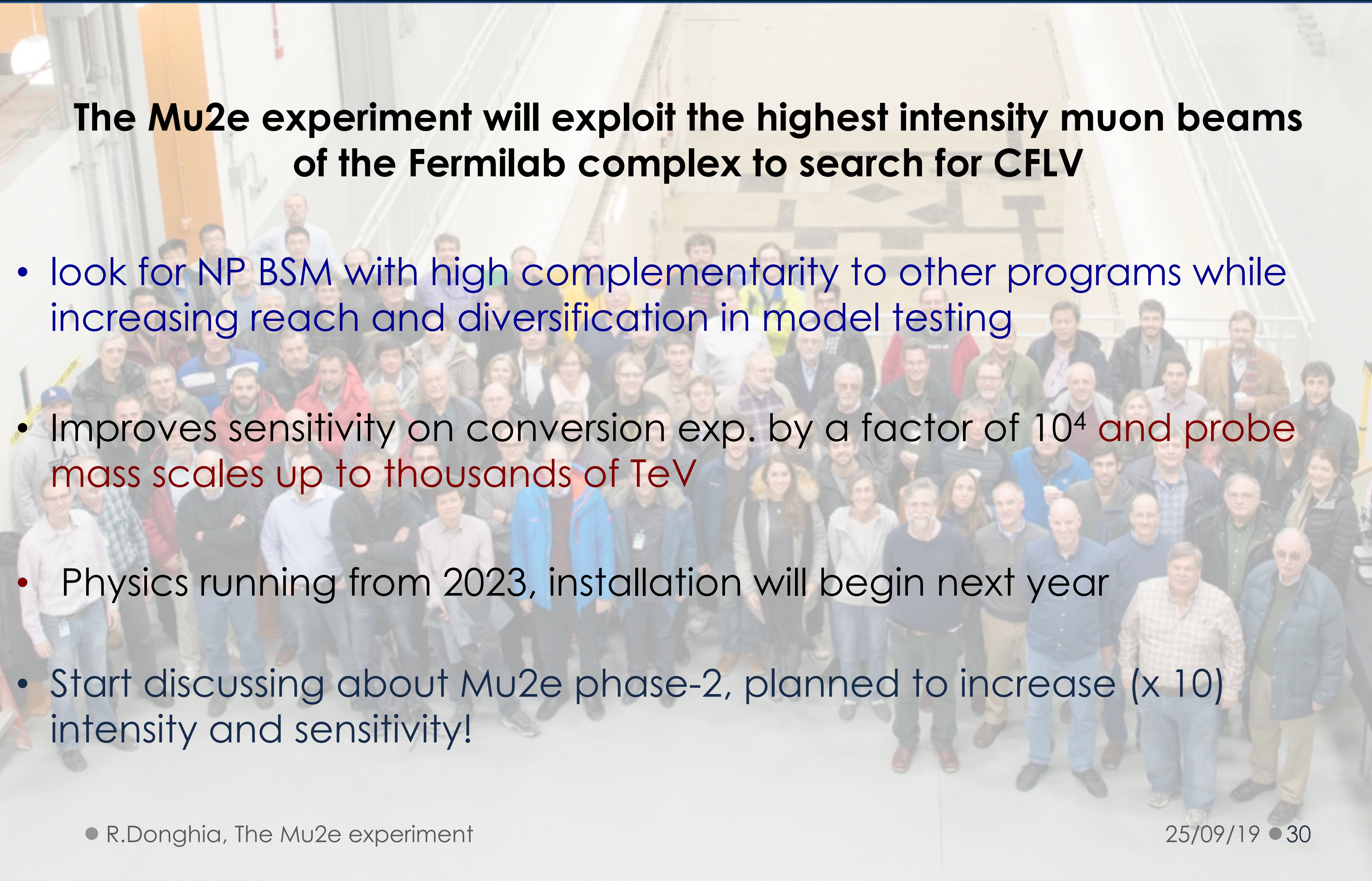
Discovery sensitivity **(7.5 events)** accomplished with three years of running and suppressing **backgrounds to < 0.4** event total (50% cosmics, 35% DIOs)

Project schedule



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

Summary and conclusion



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

- look for NP BSM with high complementarity to other programs while increasing reach and diversification in model testing
- Improves sensitivity on conversion exp. by a factor of 10^4 and probe mass scales up to thousands of TeV
- Physics running from 2023, installation will begin next year
- Start discussing about Mu2e phase-2, planned to increase (x 10) intensity and sensitivity!

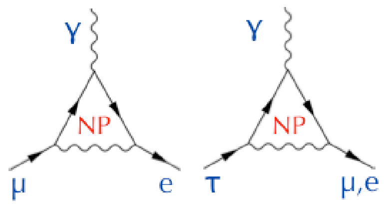
Thanks!

Raffaella Donghia
LNF-INFN
On behalf of the Mu2e collaboration

Gran Sasso Science Institute, L'Aquila, 23-27 Settembre 2019
105° Congresso Nazionale della Società Italiana di Fisica

LOOP TERM

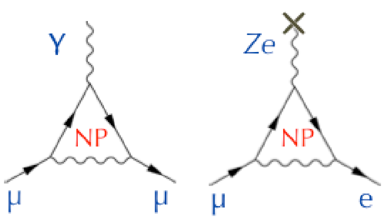
$\kappa \ll 1$



$\mu \to e\gamma$

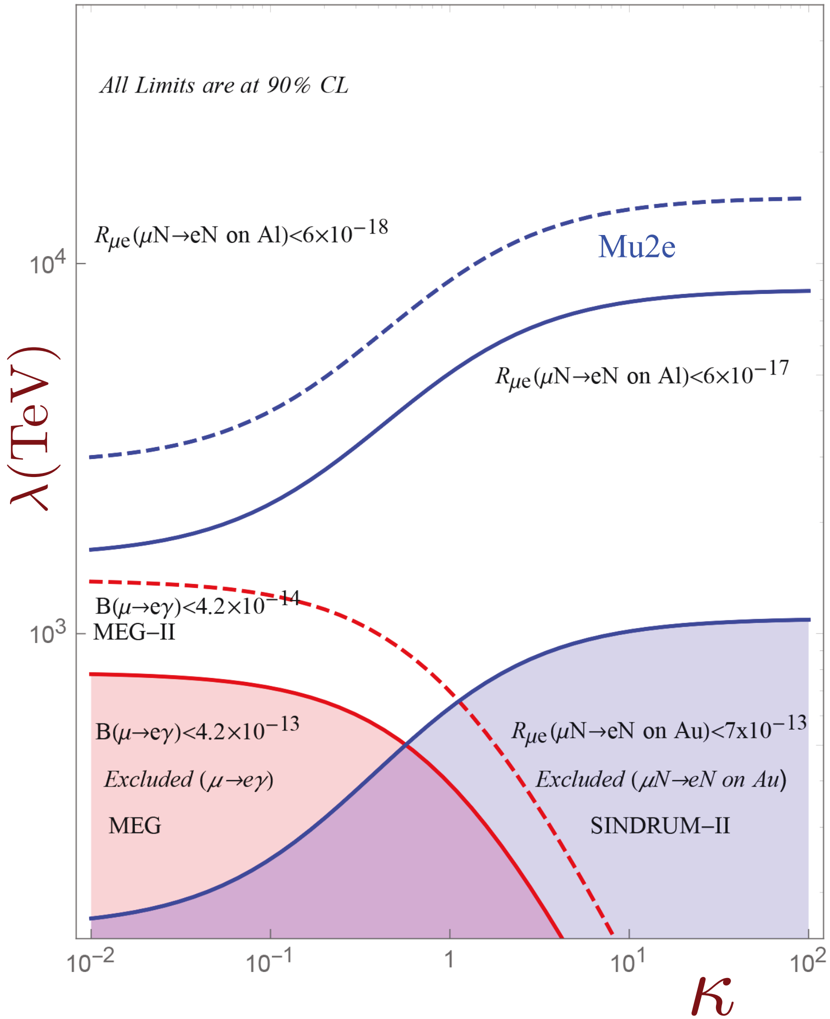
$\tau \to \mu\gamma$

$\tau \to e\gamma$



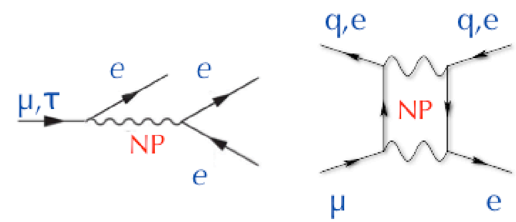
$(g-2)_\mu$

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



CONTACT TERM

$\kappa \gg 1$



$\mu \to eee$

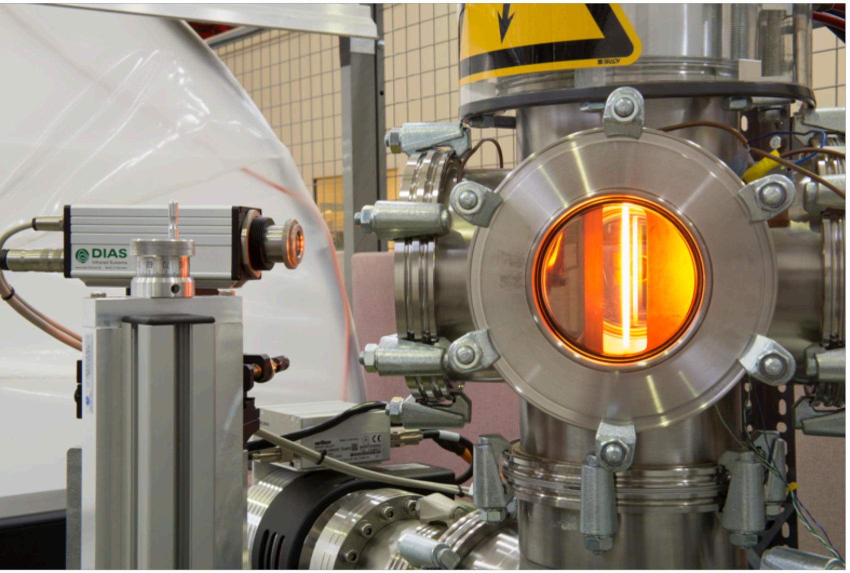
$\mu^- \mathcal{N} \to e^- \mathcal{N}$

Muon beamline

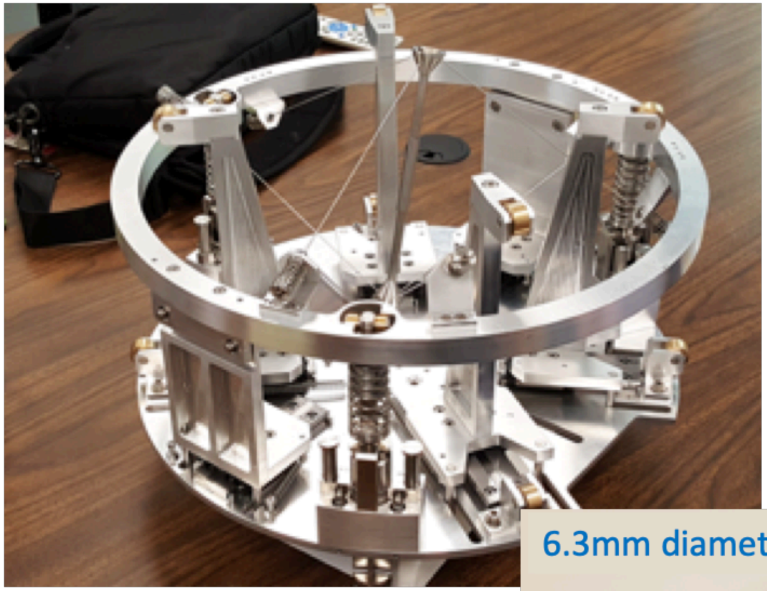
Installation of beam magnets well along:
vacuum system
instrumentation upstream of the diagnostic absorber in progress

Production target

Testing @ Rutherford-Appleton Lab (UK)



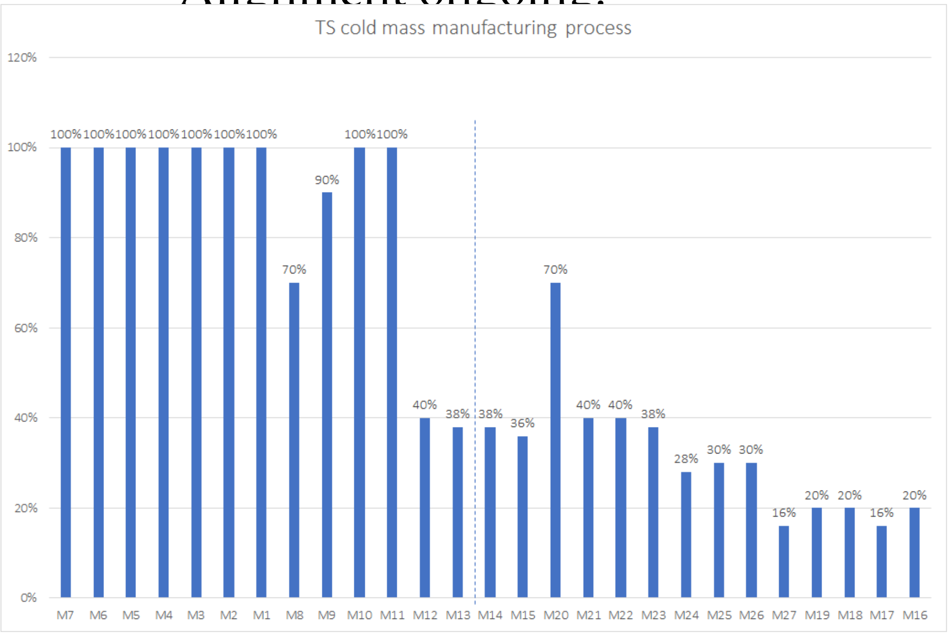
Target End-of-Arm tooling @ Fermilab

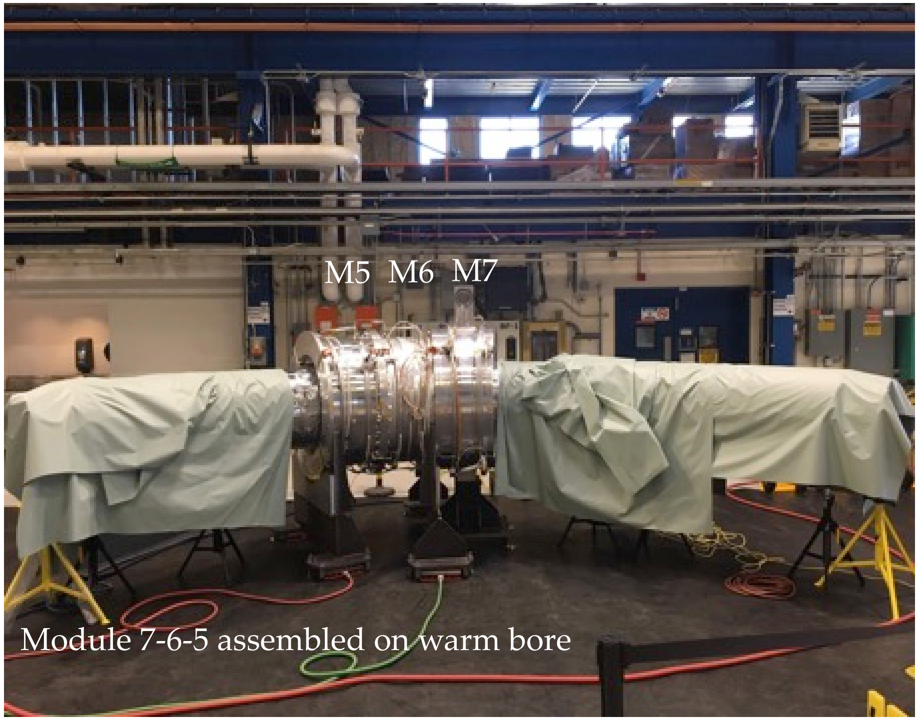


Target design being finalized in the fall

TS construction

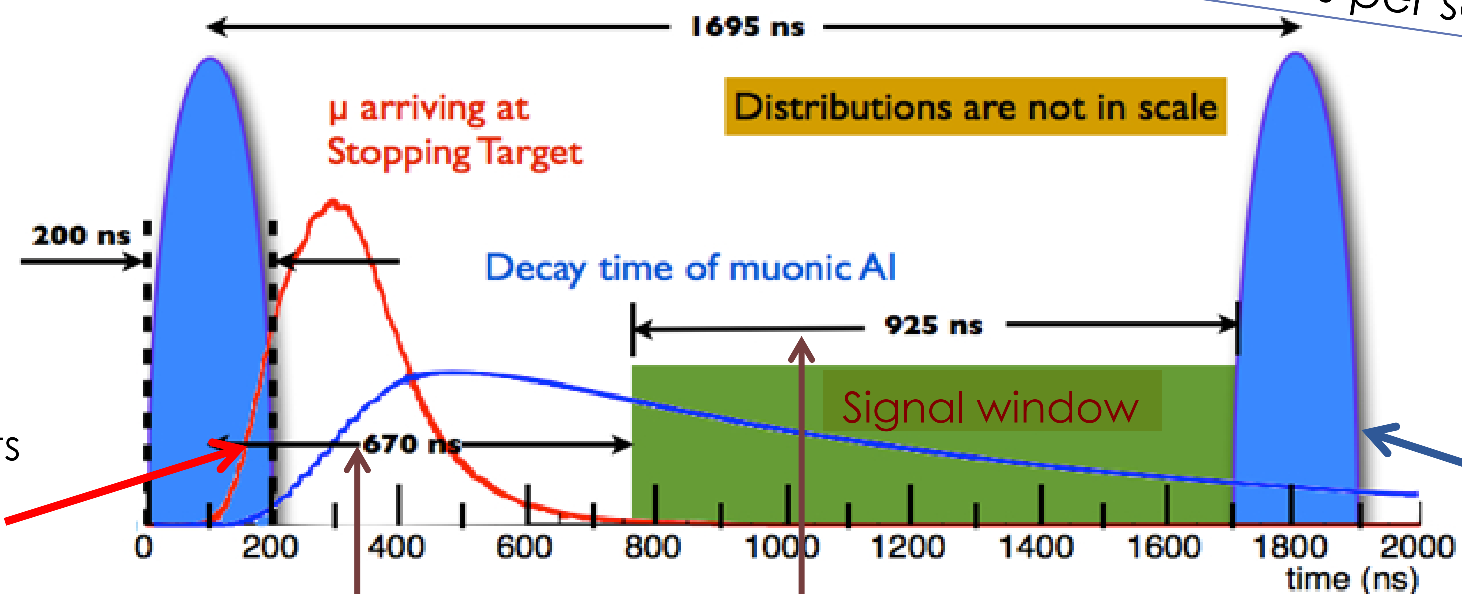
- ❑ Construction of TSD also proceeds at full speed in ASG superconducting (Genoa)
- ❑ Overall TS modules construction better than 1/3 of total
- ❑ Second test unit (M5/M6) assembled on warm bore. Mated together perfectly.
  Alignment ongoing.





Signal window

~20,000 muons per bunch
10^{10} muons per second



Beam hits target

Next bunch

Mainly Decay In Orbit background

Prompt bkg: almost all protons, unstopped muons, stopped and unstopped pions will arrive at the detector before observation window

Possible upgrade

Signal?

Yes

Let's party!

Change the target to study the underlying NP

Upgrade proton source and detector to achieve precision

No

Higher rates, background must decrease to measure $R_{\mu e}$ at 10^{-18}

Upgrade proton source and detector to improve sensitivity

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