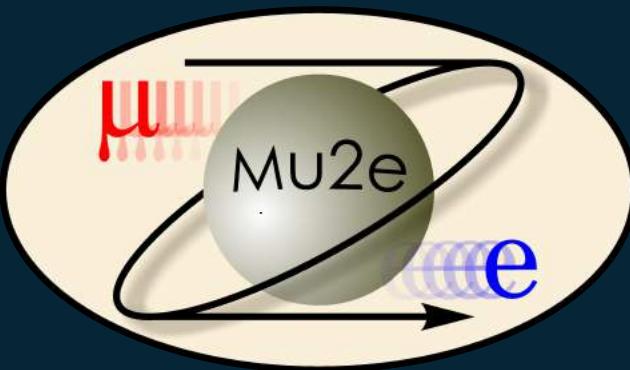


The Mu2e experiment

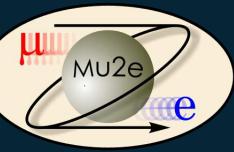


Raffaella Donghia

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

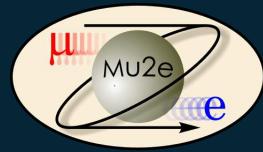


The Mu2e Collaboration



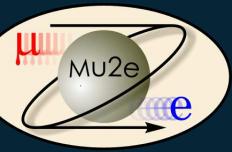
~250 Scientists from 38 Institutions

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

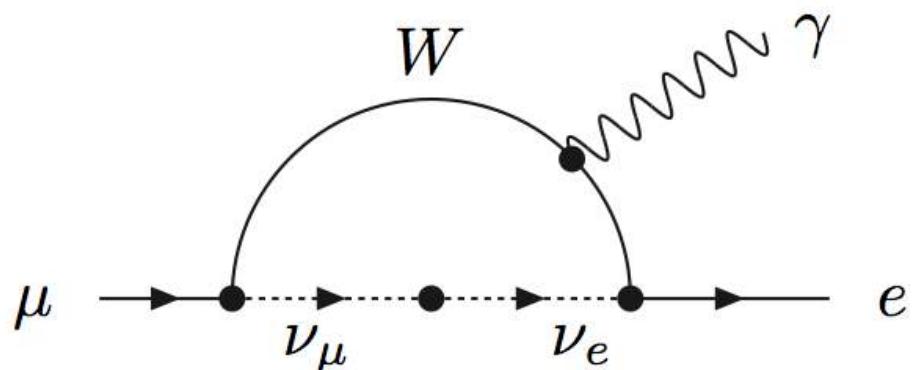


CLFV



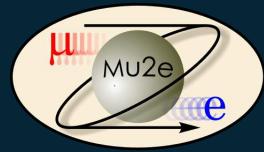
With neutrino mass, we know that lepton flavor is not conserved

The SM CLFV process would be strongly suppressed:

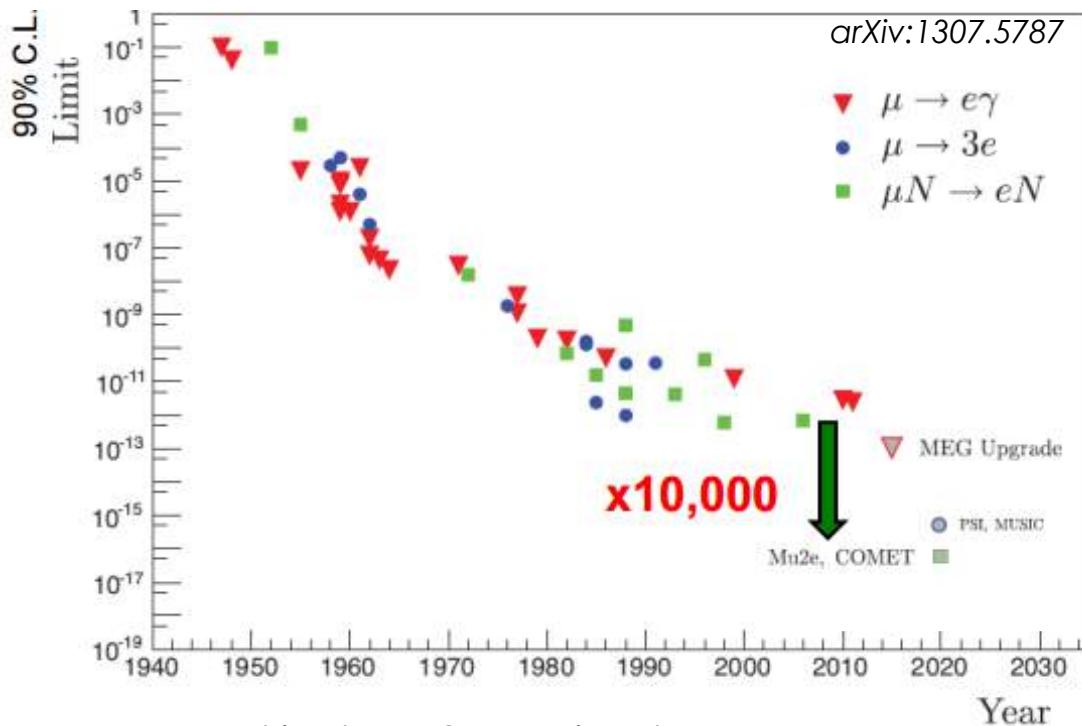
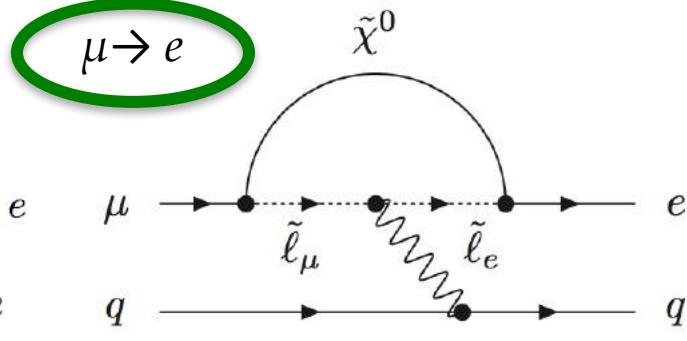
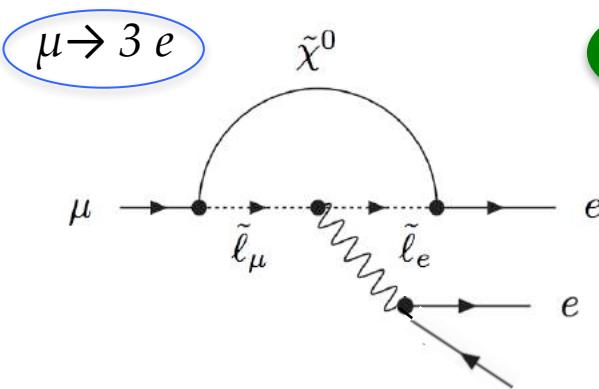
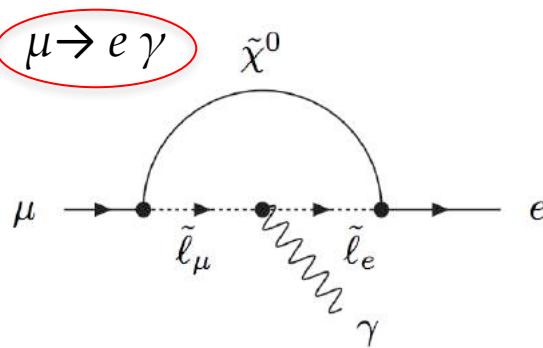


$$\mathcal{B}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{1i}^2}{M_W^2} \right|^2 < 10^{-54}$$

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



Muon CLFV history



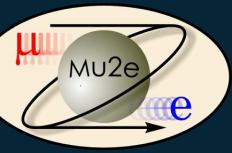
Current best limits:

$BR(\mu \rightarrow e\gamma) < 4.2 \times 10^{-13}$ MEG2016

$BR(\mu \rightarrow 3e) < 1 \times 10^{-12}$ SINDRUM 1988

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

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

| | AC | RVV2 | AKM | δLL | FBMSSM | LHT | RS |
|--|-----|------|-----|-------------|--------|-----|-----|
| $D^0 - \bar{D}^0$ | ★★★ | ★ | ★ | ★ | ★ | ★★★ | ? |
| e_K | ★ | ★★★ | ★★★ | ★ | ★ | ★★ | ★★★ |
| $S_{\psi\phi}$ | ★★★ | ★★★ | ★★★ | ★ | ★ | ★★★ | ★★★ |
| $S_{\phi K_S}$ | ★★★ | ★★ | ★ | ★★★ | ★★★ | ★ | ? |
| $A_{CP}(B \rightarrow X_s\gamma)$ | ★ | ★ | ★ | ★★★ | ★★★ | ★ | ? |
| $A_{7,8}(B \rightarrow K^*\mu^+\mu^-)$ | ★ | ★ | ★ | ★★★ | ★★★ | ★★ | ? |
| $A_9(B \rightarrow K^*\mu^+\mu^-)$ | ★ | ★ | ★ | ★ | ★ | ★ | ? |
| $B \rightarrow K^{(*)}\nu\bar{\nu}$ | ★ | ★ | ★ | ★ | ★ | ★ | ★ |
| $B_s \rightarrow \mu^+\mu^-$ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★ | ★ |
| $K^+ \rightarrow \pi^+\nu\bar{\nu}$ | ★ | ★ | ★ | ★ | ★ | ★★★ | ★★★ |
| $K_L \rightarrow \pi^0\nu\bar{\nu}$ | ★ | ★ | ★ | ★ | ★ | ★★★ | ★★★ |
| $\mu \rightarrow e\gamma$ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| $\tau \rightarrow \mu\gamma$ | ★★★ | ★★★ | ★ | ★★★ | ★★★ | ★★★ | ★★★ |
| $\mu + N \rightarrow e + N$ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ | ★★★ |
| d_n | ★★★ | ★★★ | ★★★ | ★★ | ★★★ | ★ | ★★★ |
| d_e | ★★★ | ★★★ | ★★ | ★ | ★★★ | ★ | ★★★ |
| $(g-2)_\mu$ | ★★★ | ★★★ | ★★ | ★★★ | ★★★ | ★ | ? |

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



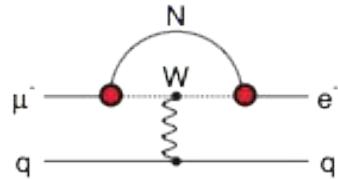
Muon CLFV - BSM



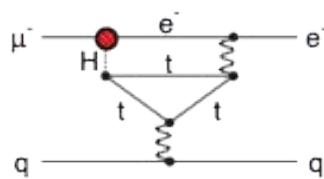
Loop

Heavy Neutrinos

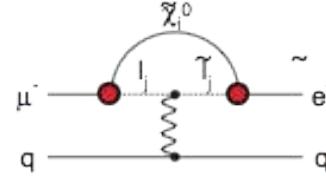
$$|U_{\mu N} U_{e N}|^2 \sim 8 \times 10^{-13}$$

**Second Higgs Doublet**

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

**Supersymmetry**

$$\text{rate} \sim 10^{-15}$$

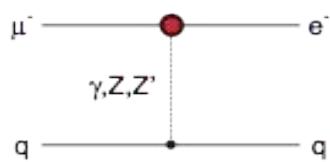


Models which can be probed also by $\mu \rightarrow e \gamma$ searches

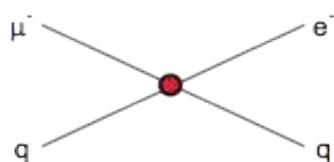
Contact term

**Heavy Z'
Anomal. Z Coupling**

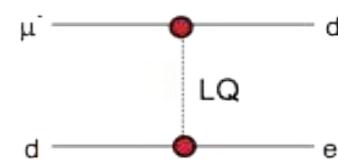
$$M_{Z'} = 3000 \text{ TeV}/c^2$$

**Compositeness**

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

**Leptoquark**

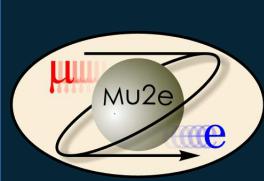
$$M_{LQ} = 3000 (\lambda_{\mu d} \lambda_{e d})^{1/2} \text{ TeV}/c^2$$



Direct coupling between quarks and leptons, better accessed by $\mu N \rightarrow e N$

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?



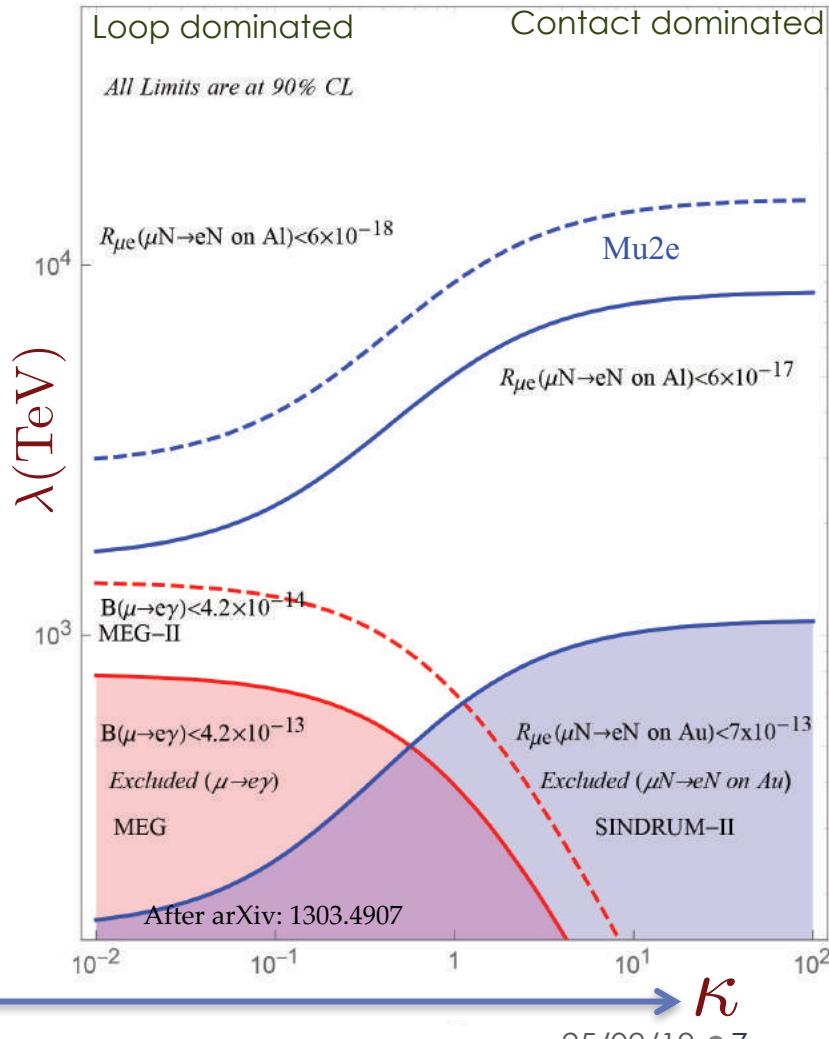
$$L_{\text{CLFV}} = \frac{m_\mu}{(\kappa+1)\Lambda^2} \bar{\mu}_R \sigma_{\mu\nu} e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2} \bar{\mu}_L \gamma_\mu e_L (\bar{u}_L \gamma^\mu u_L + \bar{d}_L \gamma^\mu d_L)$$

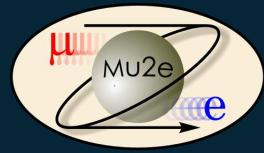
Muon conversion is an unique probe for BSM:

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

$$E_e = 104.97 \text{ MeV}$$

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

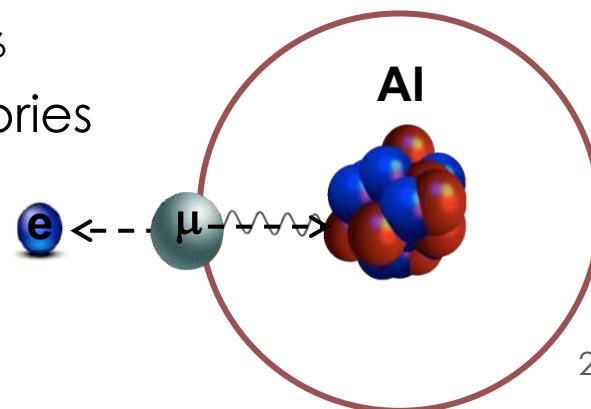
$$R_{\mu e} = \frac{\mu^- + N(A, Z) \rightarrow e^- + N(A, Z)}{\mu^- + N(A, Z) \rightarrow \nu_\mu + N(A, Z - 1)}$$

Nuclear captures of muonic Al atoms

- And set an upper limit:

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

- Discovery sensitivity: all $R_{\mu e} > \text{few} \times 10^{-16}$
Covers broad range of new physics theories

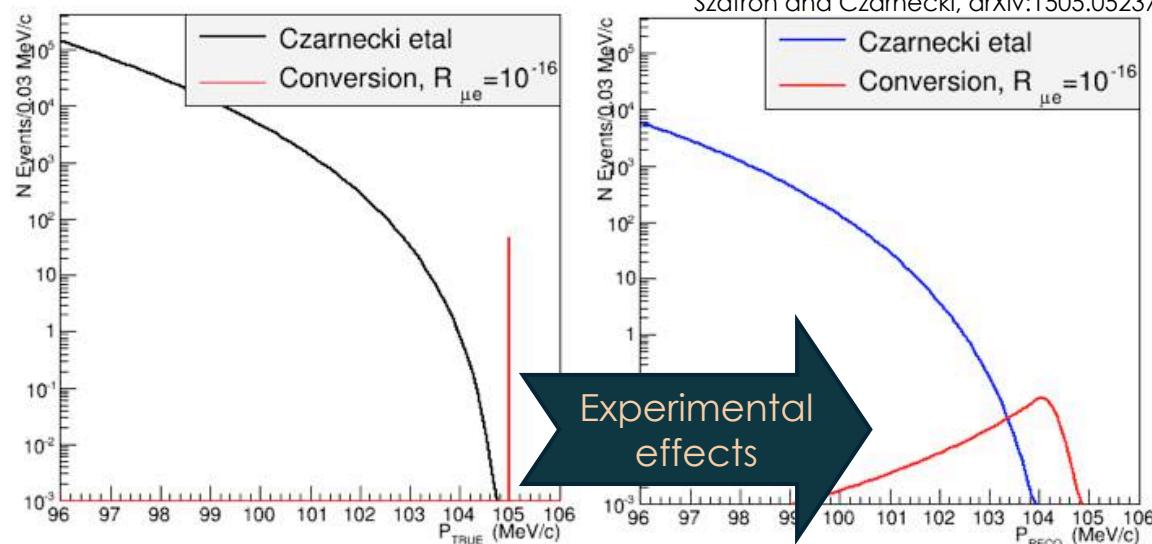




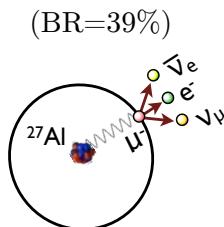
Measurement technique



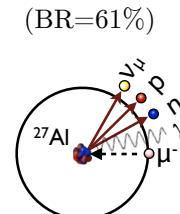
1. Low momentum μ^- beam ($< 100 \text{ MeV}/c$)
2. Stop muons on Al target \rightarrow trapped in orbit around the nucleus
3. Look for an excess around $104.97 \text{ MeV}/c$ in the electron spectrum



Main Backgrounds:

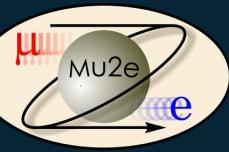


Decay in Orbit (DIO)



Muon Capture Process

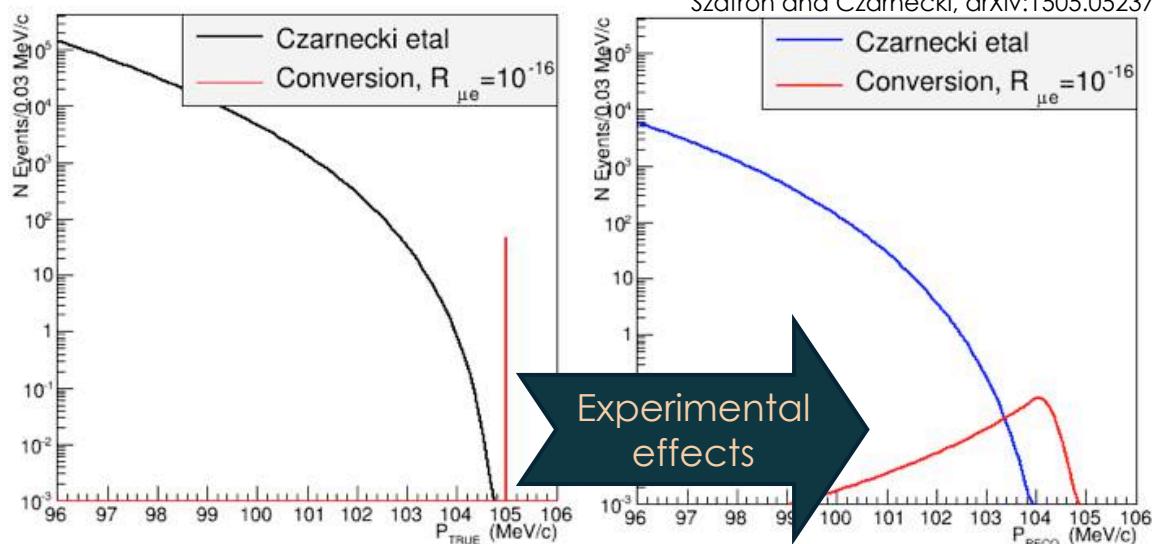
- π/μ decay in flight
- Antiproton annihilation
- Electrons from beam, cosmic rays



Measurement technique



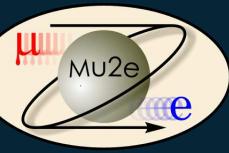
1. Low momentum μ^- beam ($< 100 \text{ MeV}/c$)
2. Stop muons on Al target \rightarrow trapped in orbit around the nucleus
3. Look for an excess around $104.97 \text{ MeV}/c$ in the electron spectrum



Main Backgrounds:



- π/μ decay
 - Antiproton
 - Electrons from cosmic rays
- Pulsed beam
- Antiproton absorber
- CRV+PID

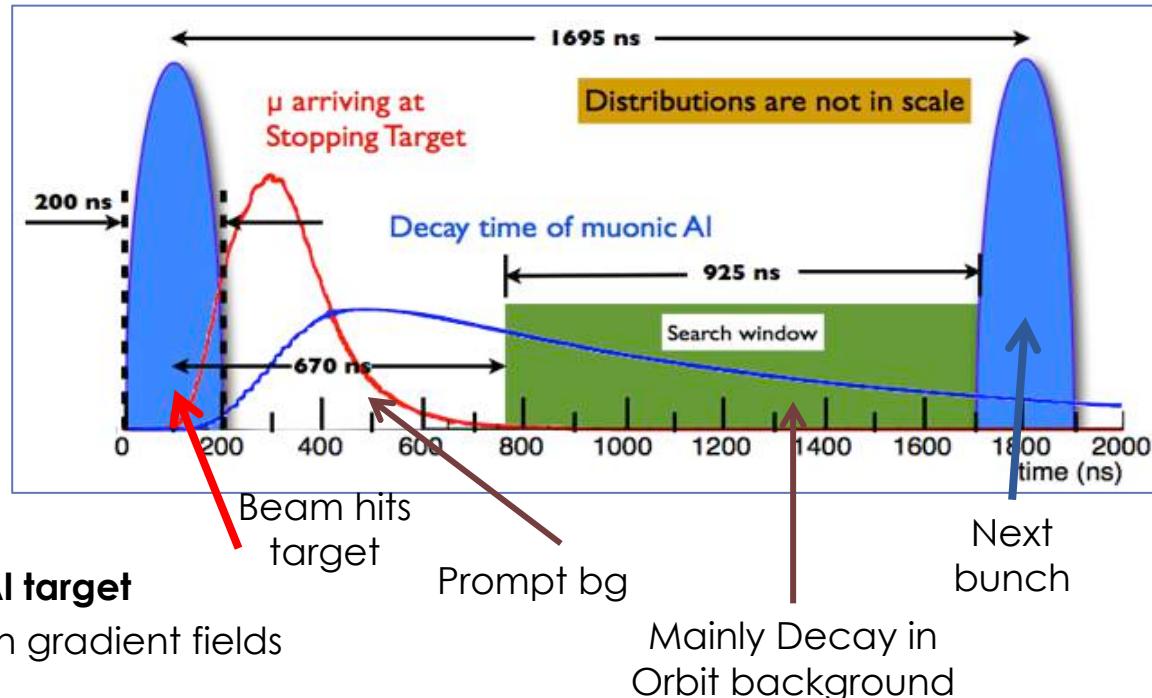


The keys to Mu2e success



High intensity pulsed proton beam

- Narrow proton pulses ($< \pm 125$ 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**



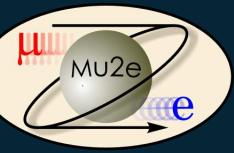
High efficiency in transporting muon to Al target

- Need of a sophisticated magnet with gradient fields

Mainly Decay in Orbit background

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)



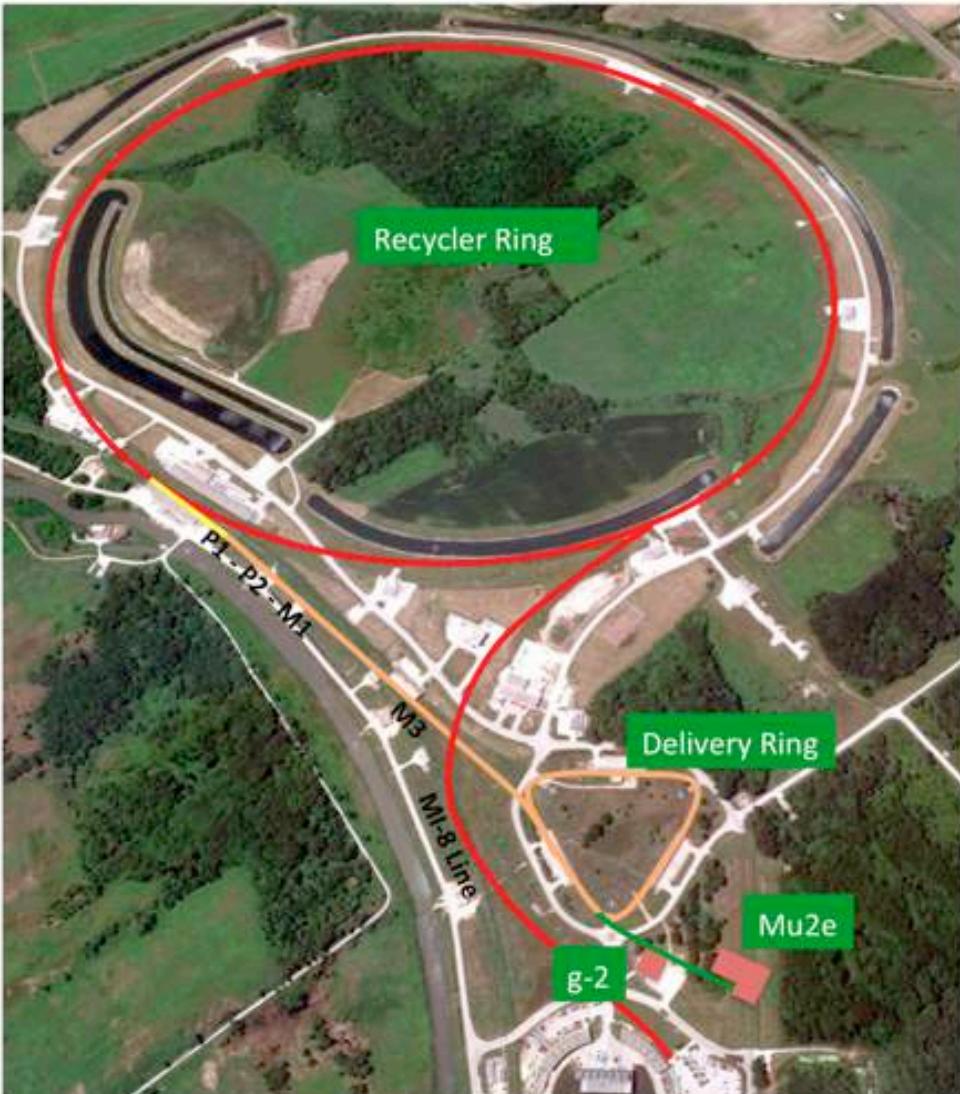
Accelerator scheme for muon beam

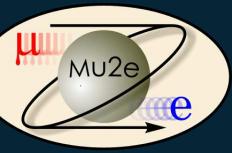


- Booster: batch of 4×10^{12} protons every 1/15th second (8 GeV, 8 kW)
- Booster “batch” injected into the Recycler ring and re-bunched into 4 bunches
- These are extracted one at a time to the Delivery ring (ex De-buncher)
- As a bunch circulates, protons are resonantly extracted to produce the desired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

Bunches of $\sim 3 \times 10^7$ protons each, separated by 1.7 μ s (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



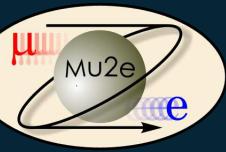
Detector Hall Building

- 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

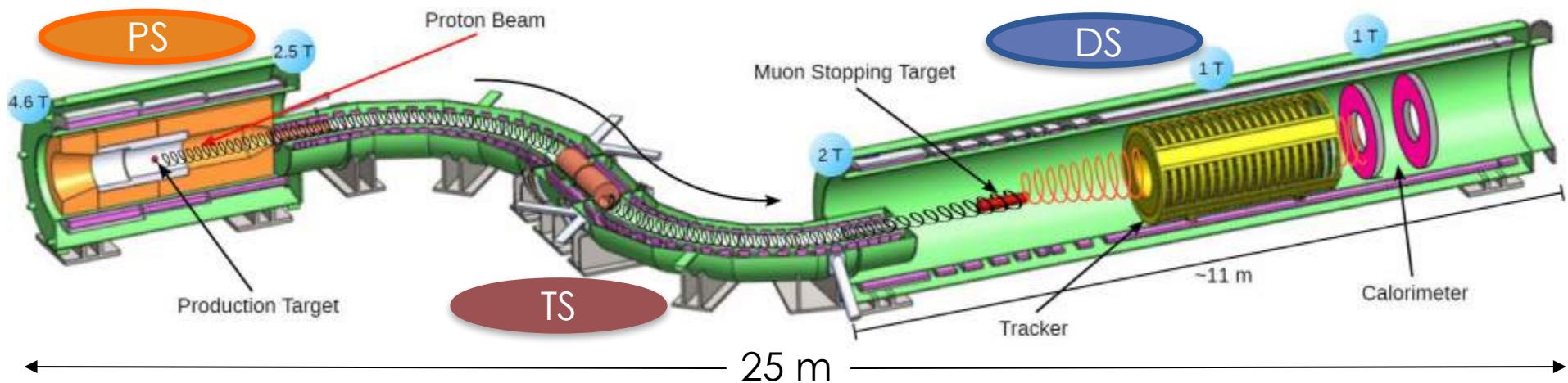


Production Solenoid / Target

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

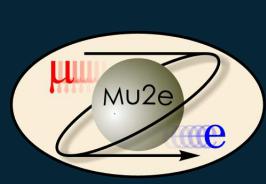
Transport Solenoid

- Selects and transports low momentum μ^-

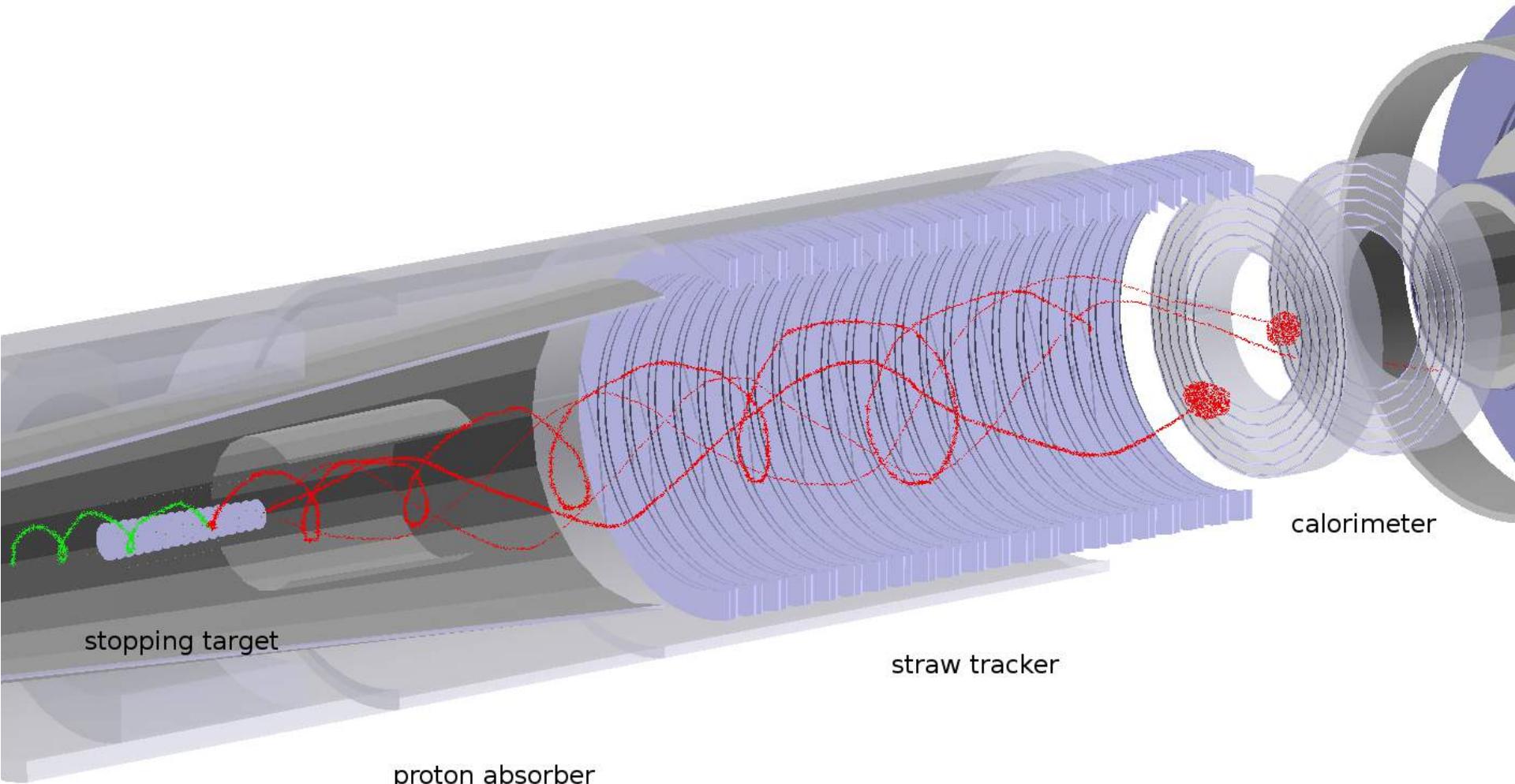


Detector Solenoid: stopping target and detectors

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



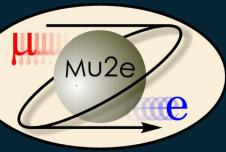
Conversion electron trajectory



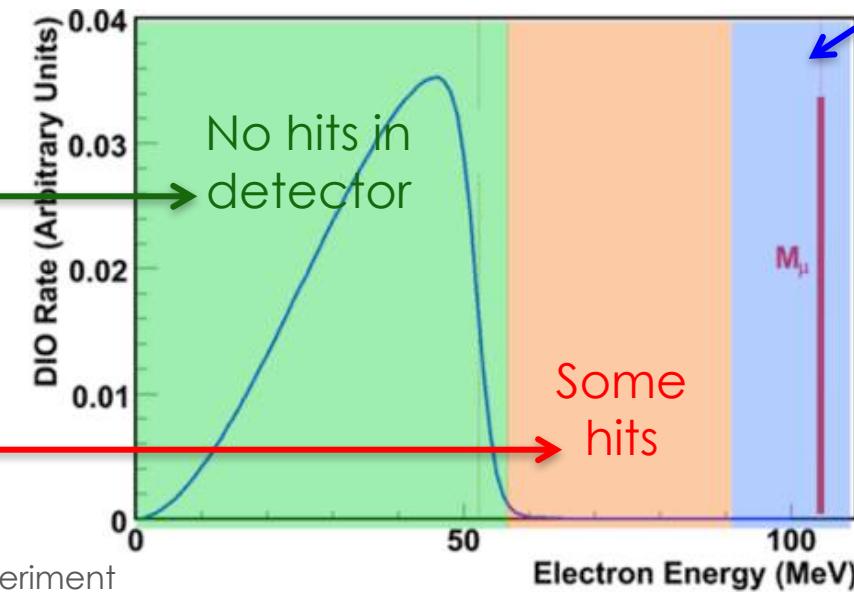
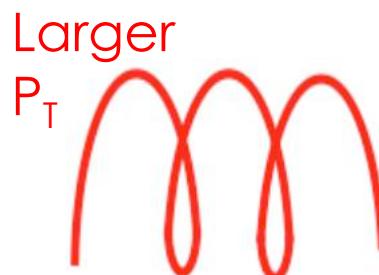
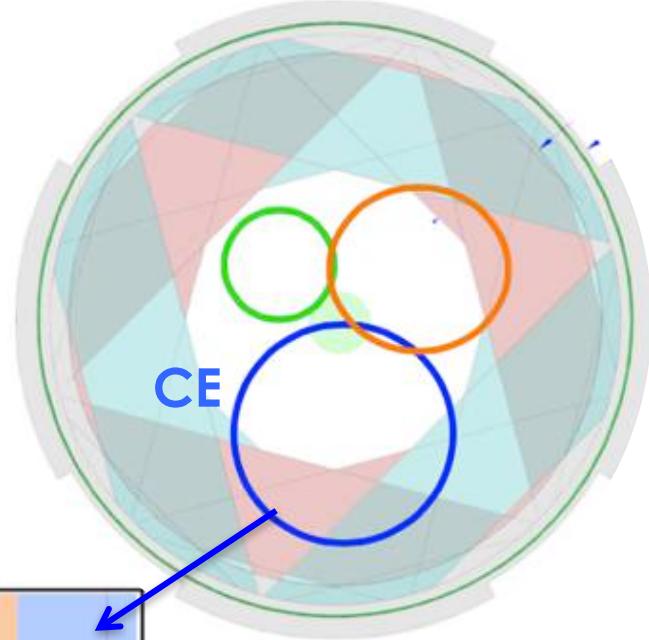
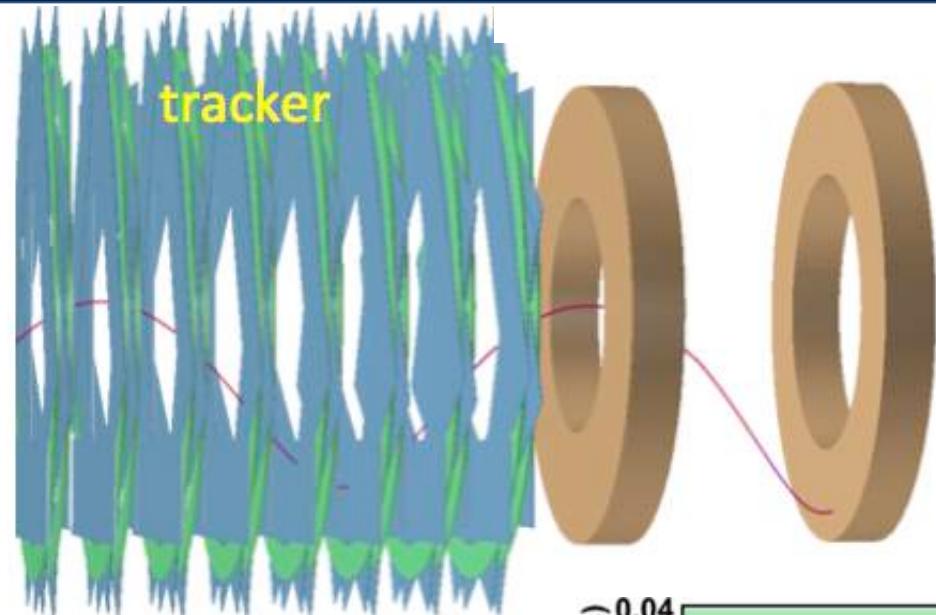
stopping target

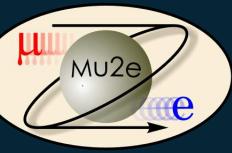
straw tracker

proton absorber



Detectors



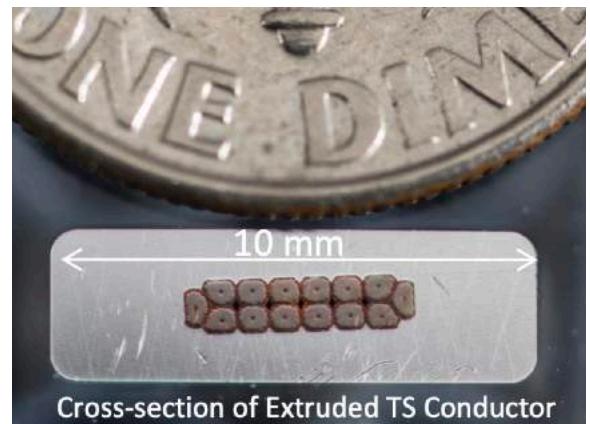


Mu2e solenoids Superconductor

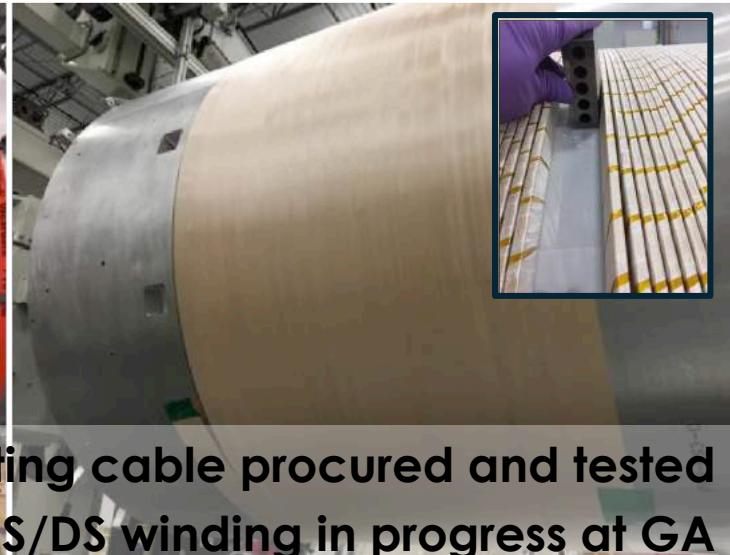
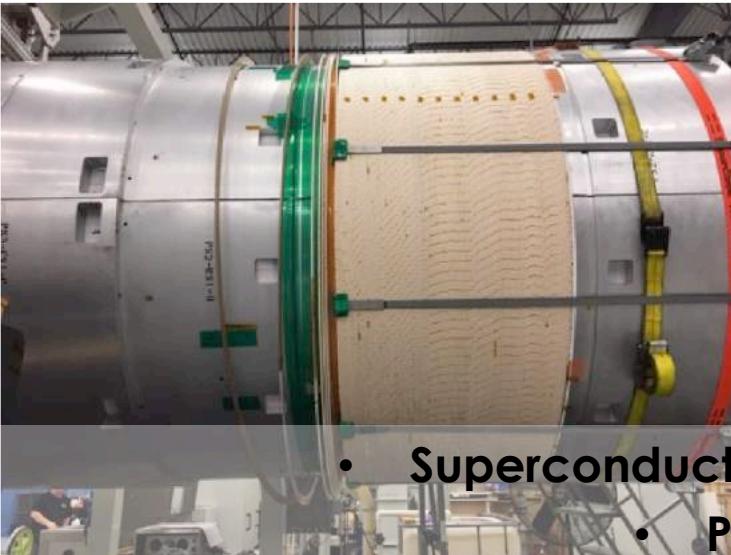


- PS, DS are being built by General Atomics (USA)
- TS is being built by ASG (Italy)
- Conductor production is complete

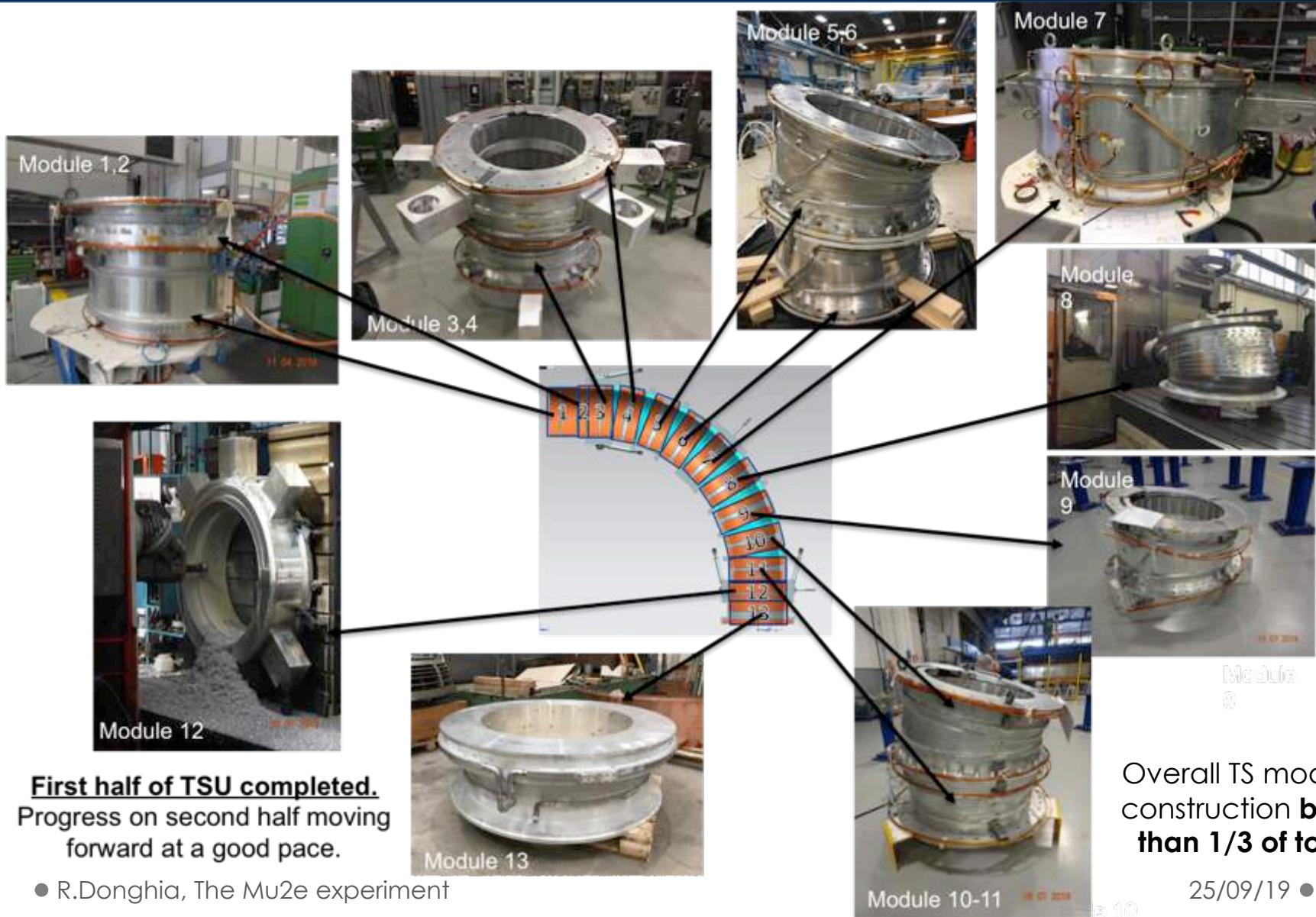
| | Production | Transport | Detector |
|------------------------|------------|-----------|----------|
| Length (m) | 4 | 13 | 11 |
| Diameter (m) | 1,7 | 0,4 | 1,9 |
| Field @ start (T) | 4,6 | 2,5 | 2,0 |
| Field @ end (T) | 2,5 | 2,0 | 1,0 |
| Number of coils | 3 | 52 | 11 |
| Conductor (km) | 14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

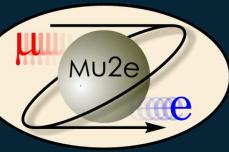


Status of PS/DS

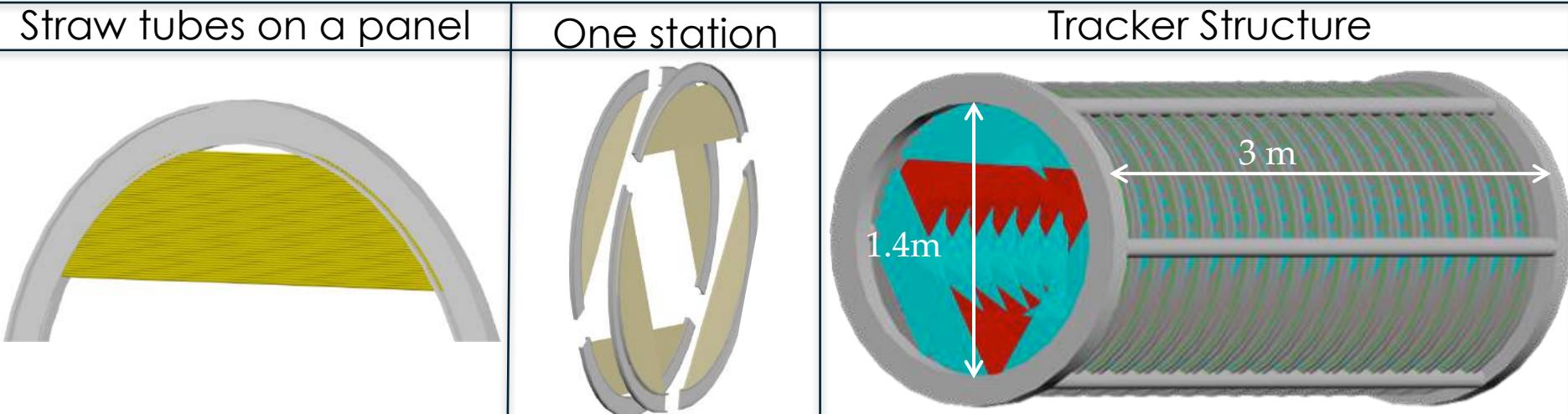


Status of TS





Straw Tracker



Detector requirements:

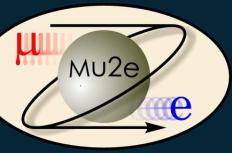


- Small amount of X_0
- **$\sigma_p < 180 \text{ keV} @ 105 \text{ MeV}$**
- Good rate capability:
 - 20 kHz/cm² in live window
 - Beam flash of 3 MHz/cm²
- dE/dx capability to distinguish e-/p
- Operate in $B = 1 \text{ T}$, 10^{-4} Torr vacuum
- Maximize/minimize acceptance for CE/DIO
 - R.Donghia, The Mu2e experiment

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:CO₂ @ 1 atm
- Dual-ended readout with timing (2D/plane)

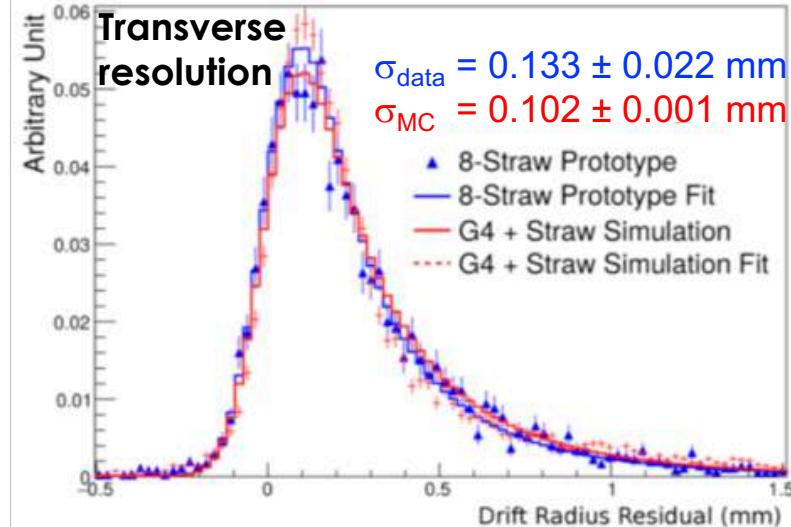
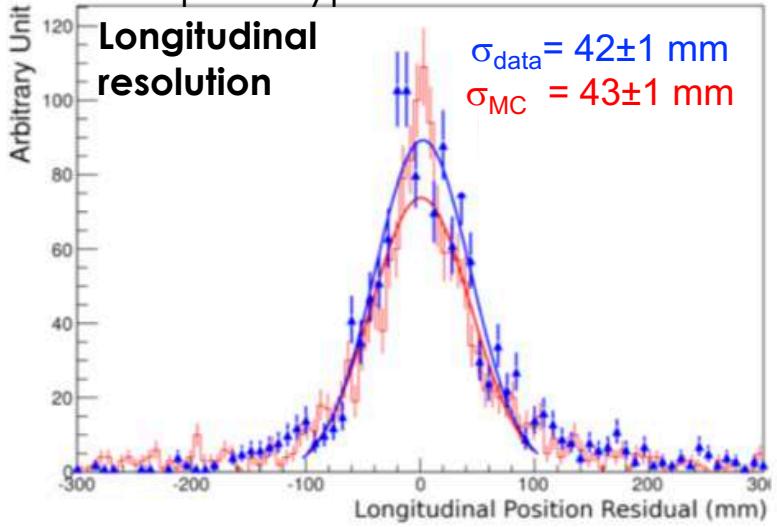




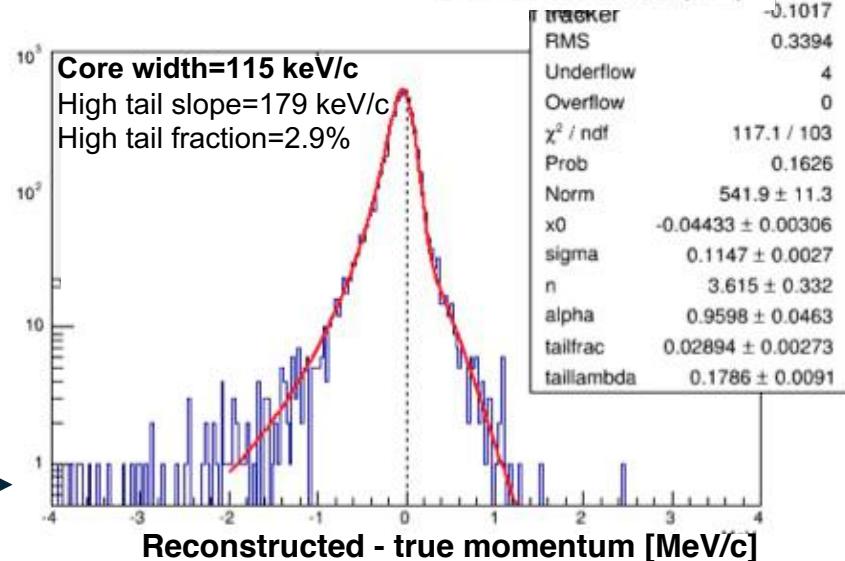
Tracker performance

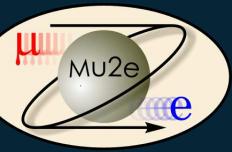


8-channel prototype test with cosmic rays:



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





Tracker Status



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

Panels

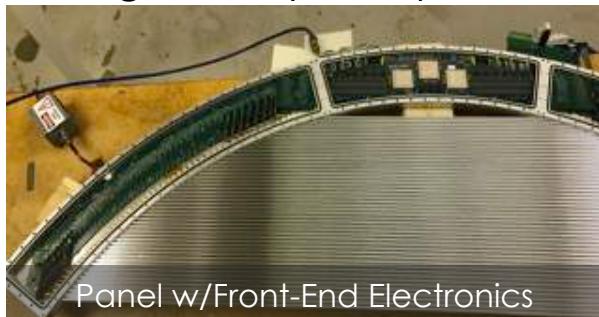
- Design Complete
- Production assembly fixtures being fabricated
- **UMN Panel Factory & QC Station set up**
→ Pre-production panel #12 completed
→ Production will start soon after

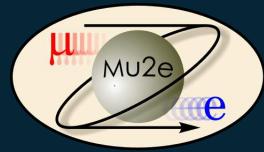
Plane

- Plane assembly tooling fixture design nearly complete

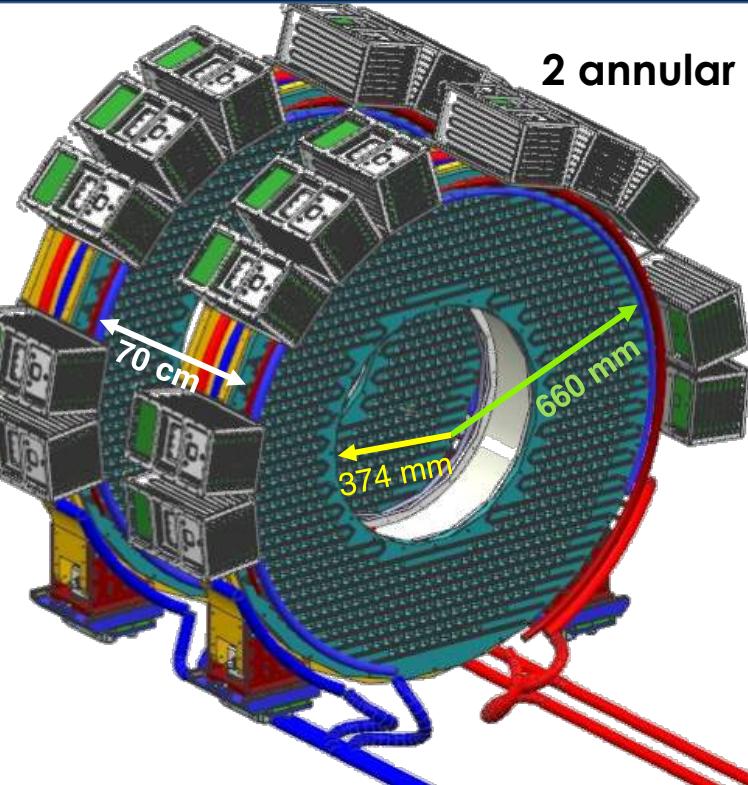
Electronics

- Incorporation of rad hard FPGA in progress





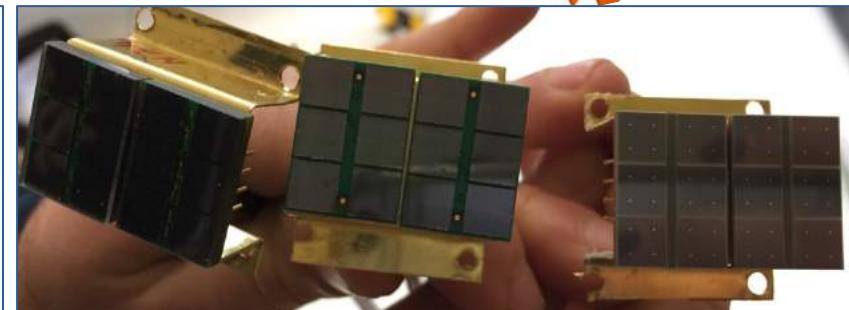
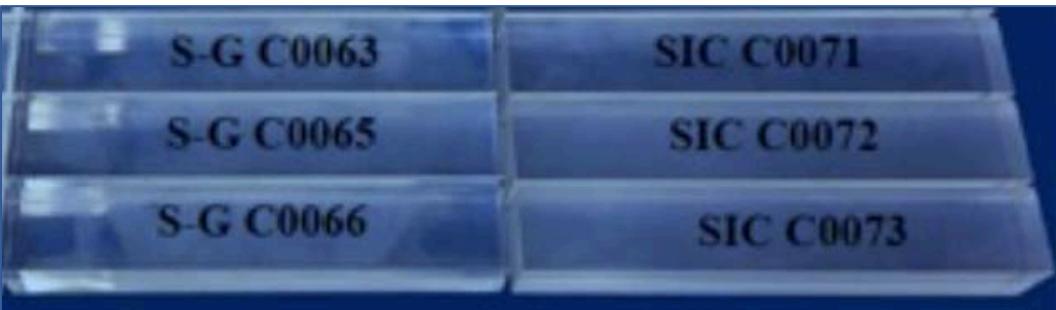
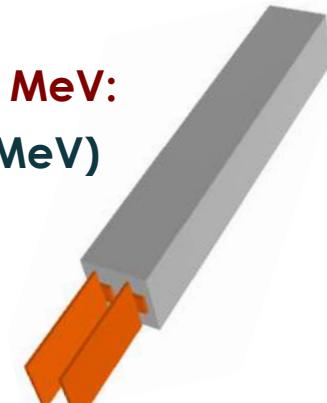
EM Calorimeter

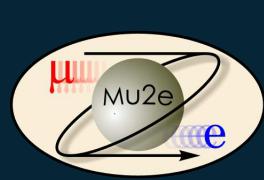


2 annular disks with 674 CsI (30x30x200) mm³ square crystals each

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/cm²/year
- High acceptance for CE signal @ 100 MeV:
 - Energy resolution < 10% (@ 100 MeV)
 - Timing resolution < 0.5 ns
 - Spatial resolution < 1 cm





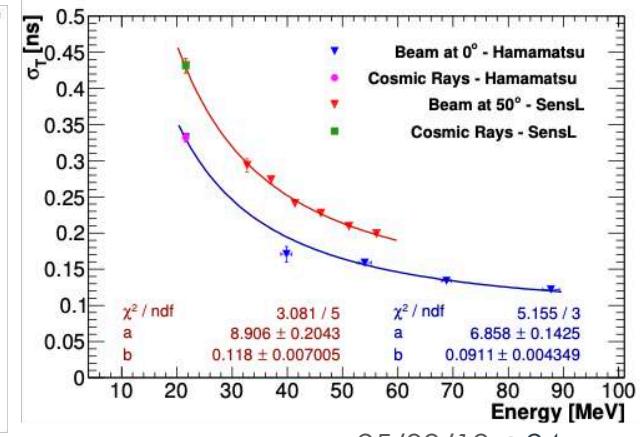
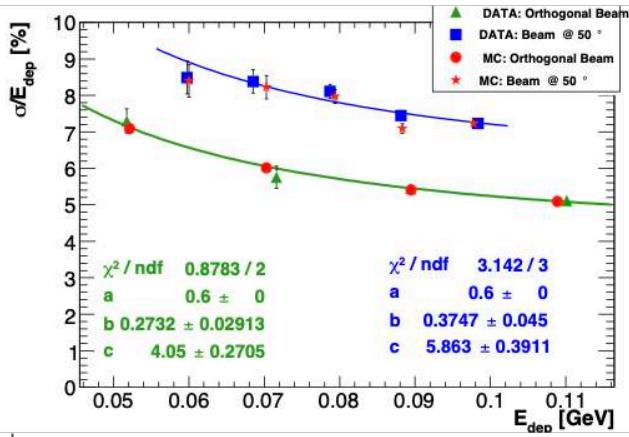
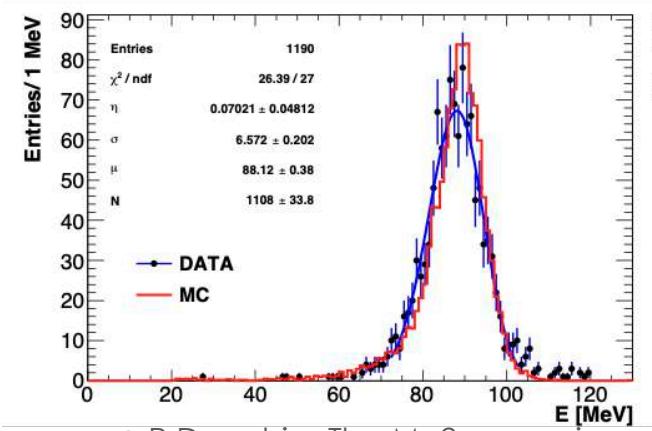
Calorimeter performance

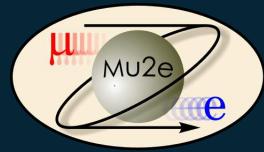


Module-0: 51 crystals, 102 SiPM/FEE channels

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!**

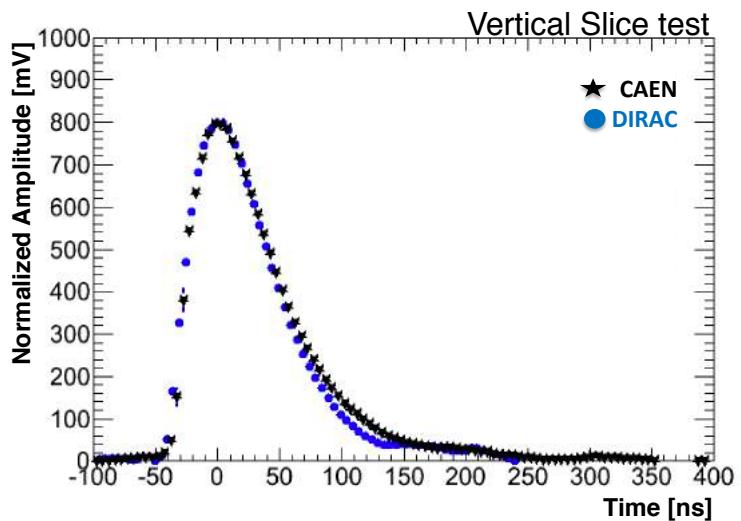
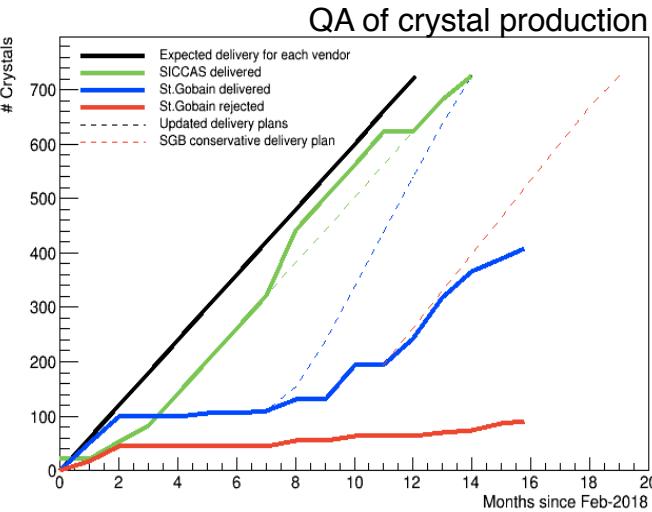


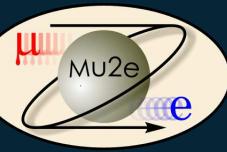


Calorimeter status



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



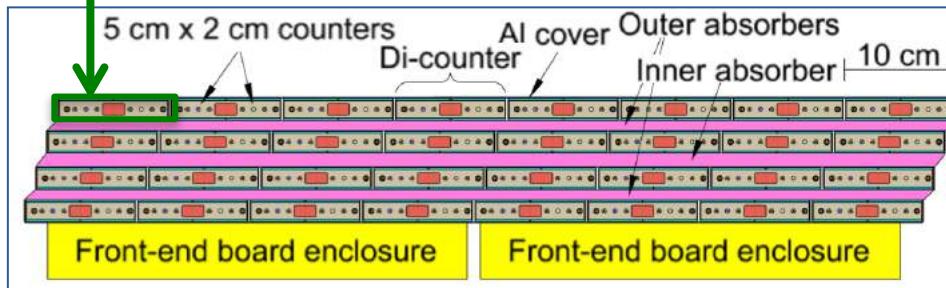
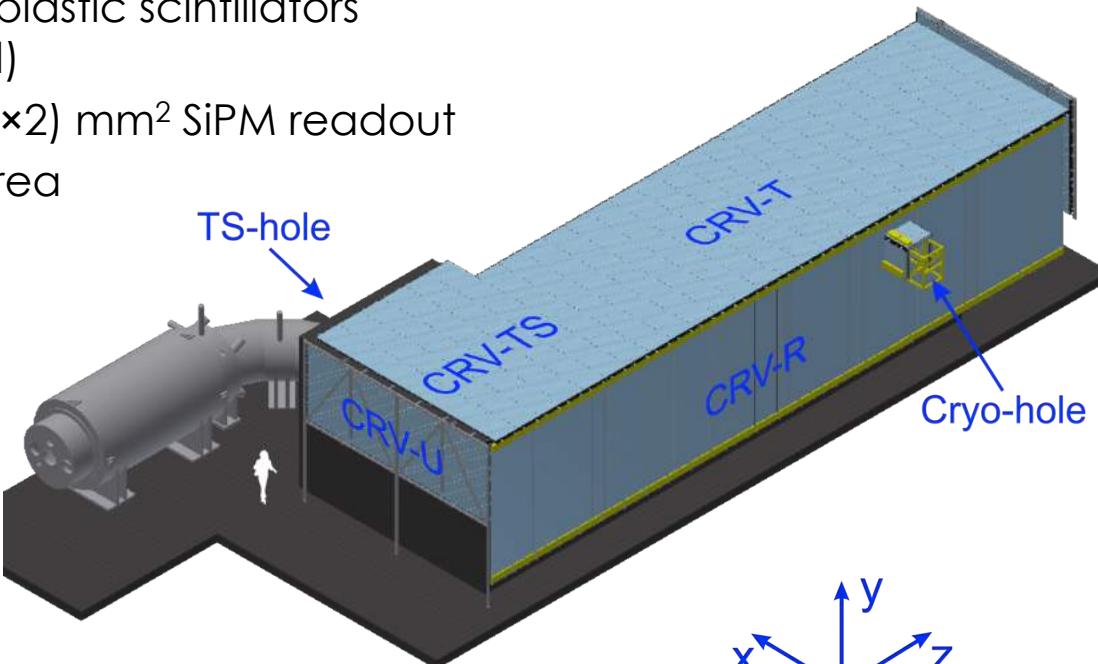
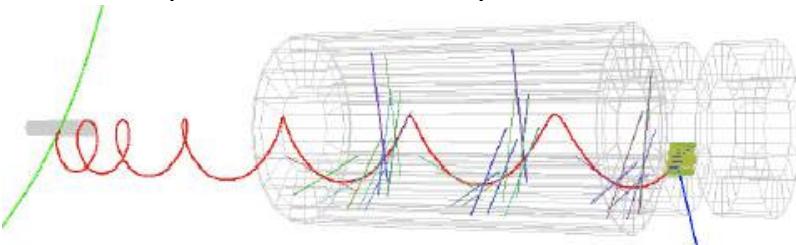


Cosmic Ray Veto



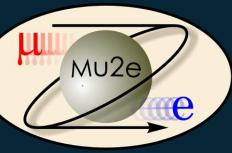
Cosmic ray muons will produce one fake signal event per day without a CRV.

- 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) mm² SiPM readout
- Placed around DS and part of TS area
- Required efficiency: 0.9999



CRV module and electronics design completed:

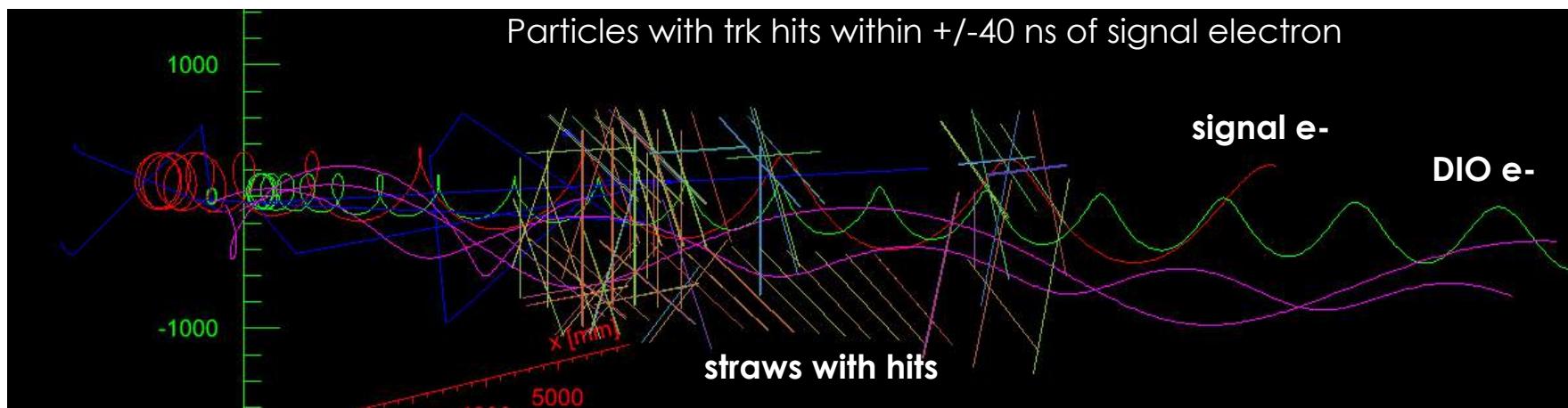
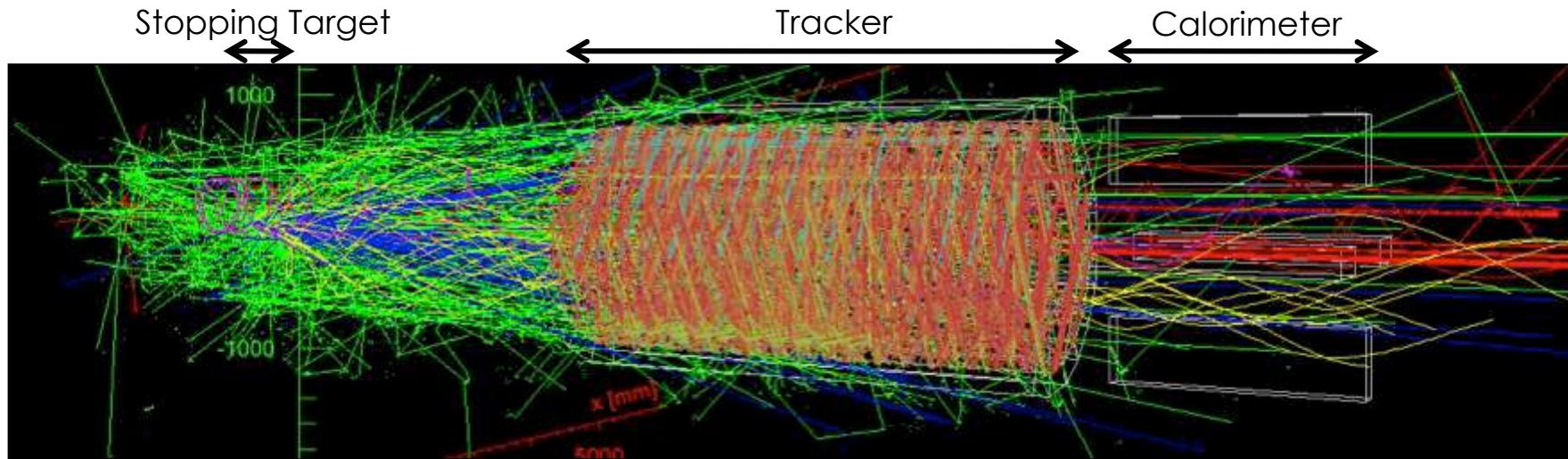
- 4 pilot production modules fabricated
- QA test meet the requirements
- Electronics production underway
~30% of the SiPM tested
- FEE-boards produced @ Kansas State Univ

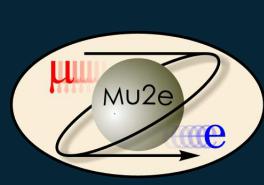


Signal window

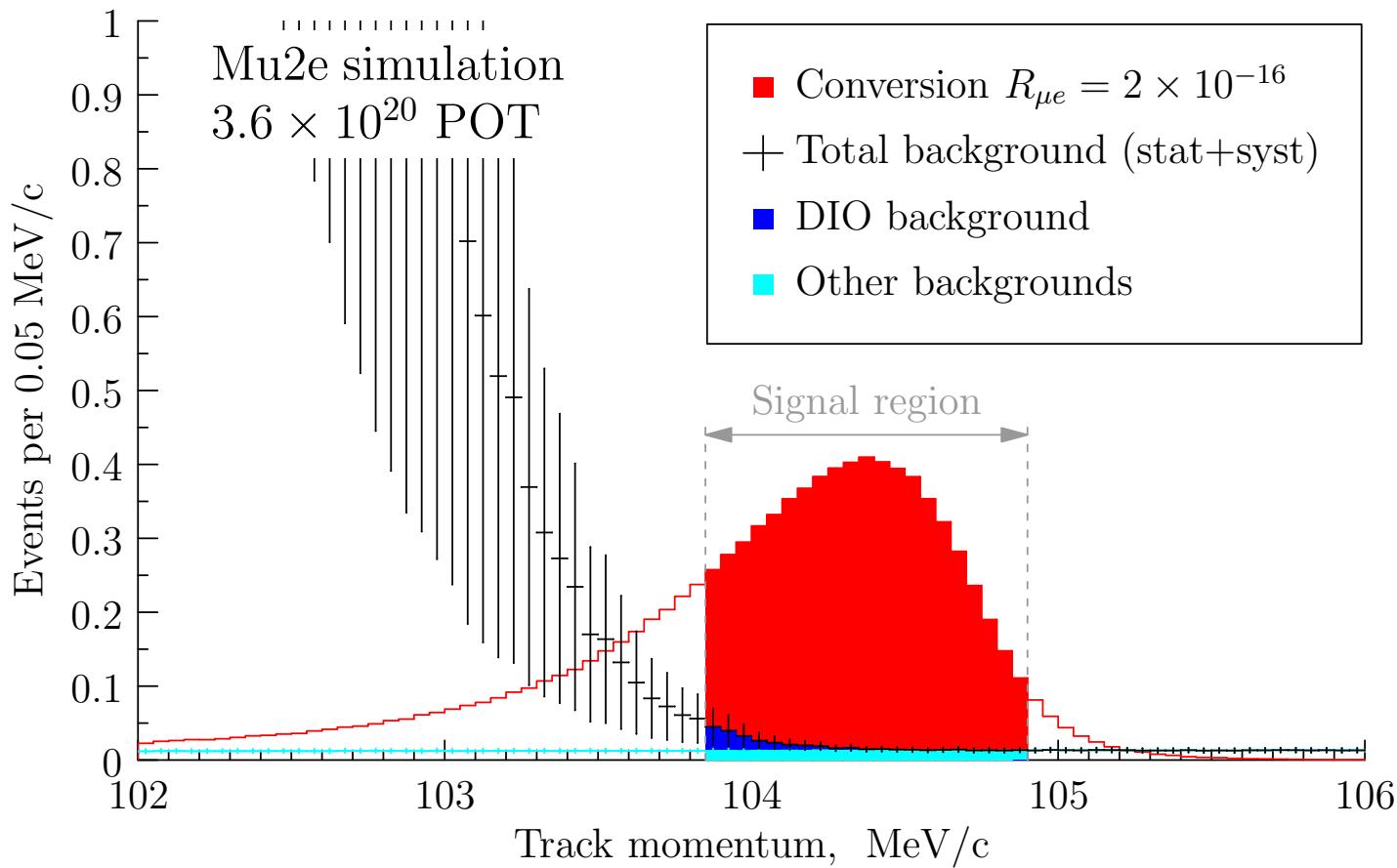


Signal electron, together with all the other hits/tracks occurring simultaneously, integrated over 500-1695 ns window

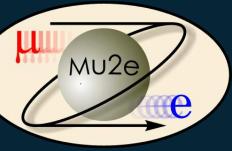




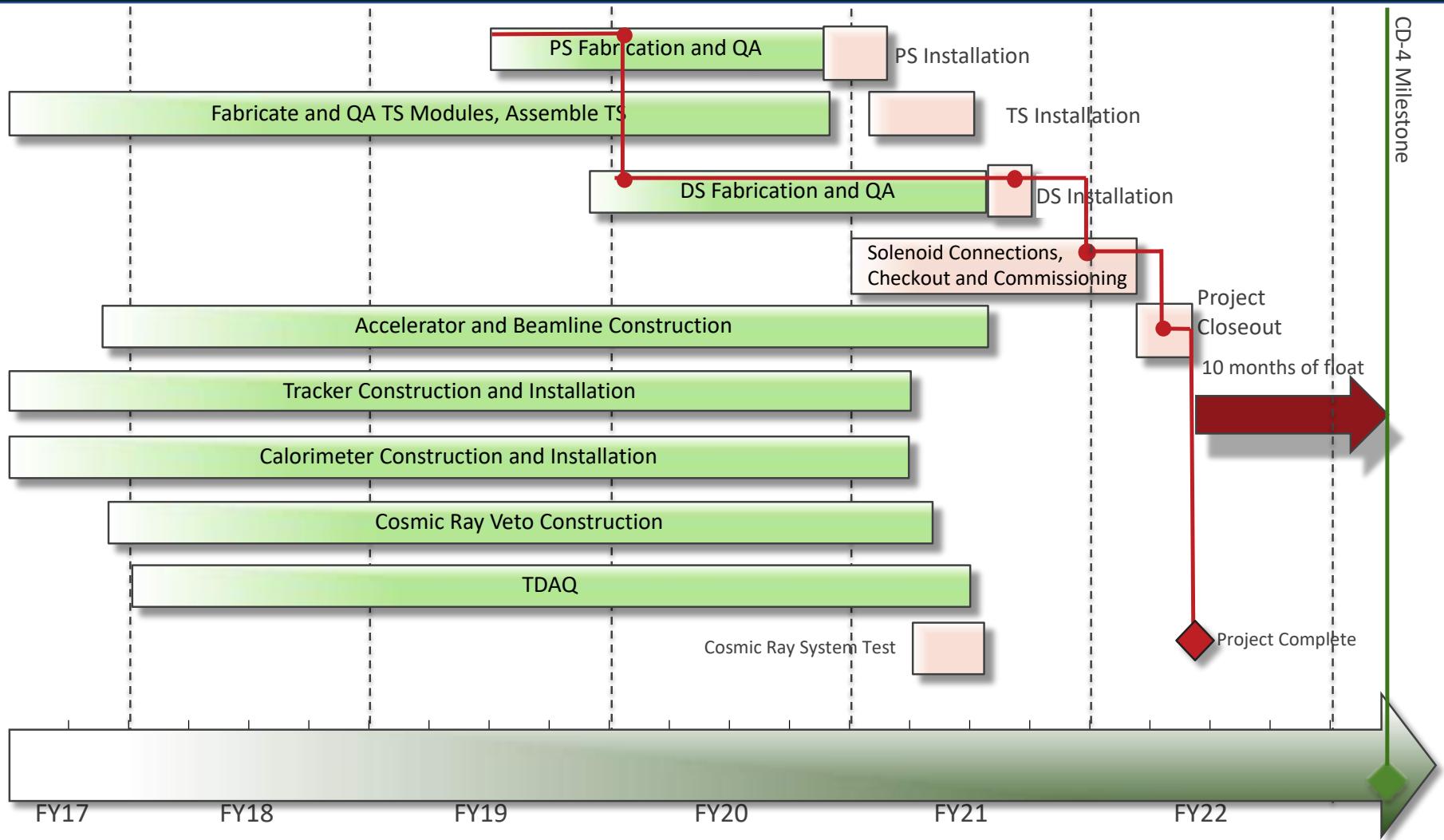
Three years run Expectation by full Simulation

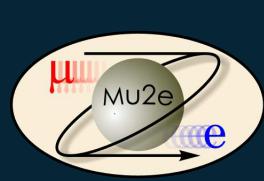


Discovery sensitivity (**7.5 events**) accomplished with three years of running and suppressing **backgrounds to < 0.4** event total (50% cosmics, 35% DIOs)



Project schedule





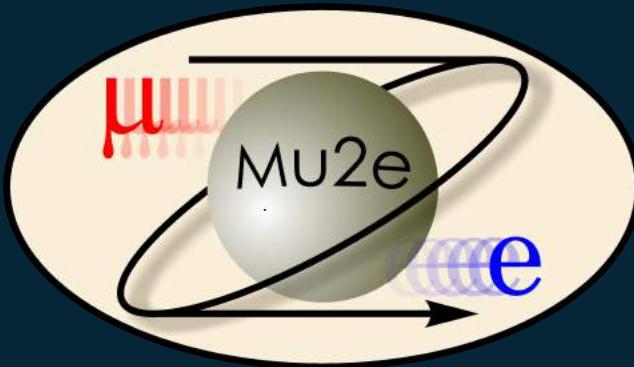
Summary and conclusion



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!

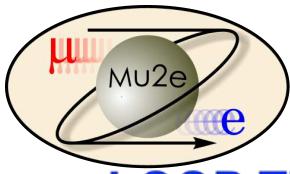
Thanks!



Raffaella Donghia
LNF-INFN

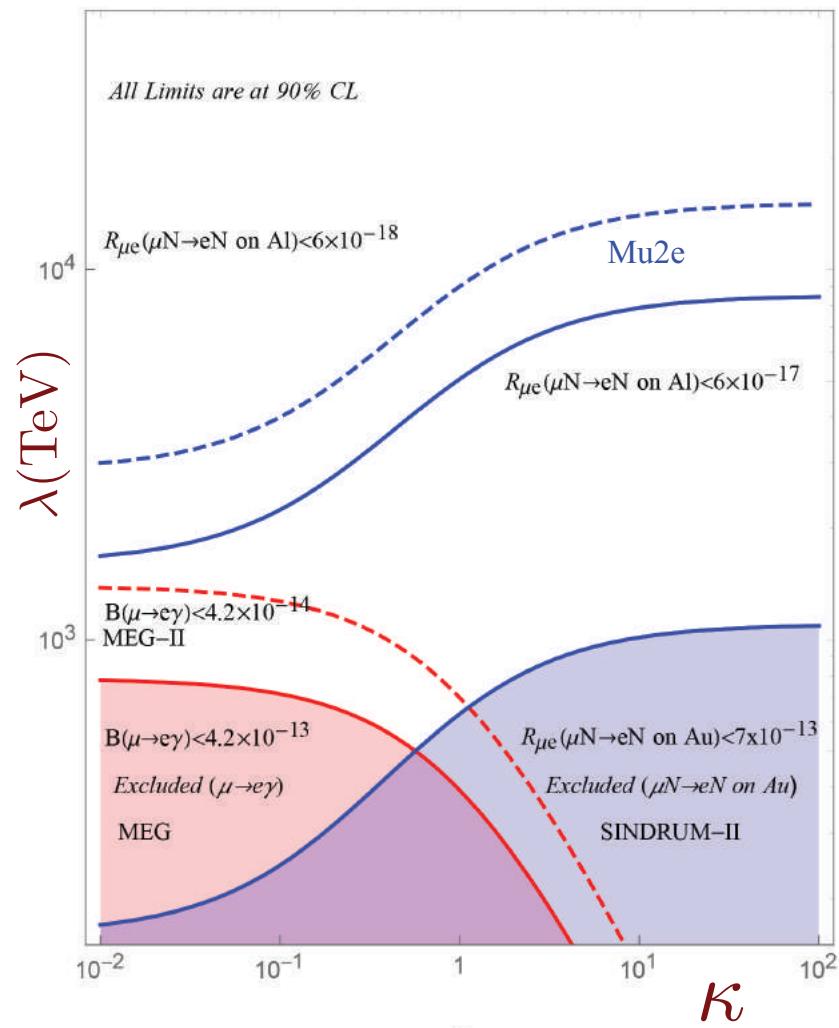
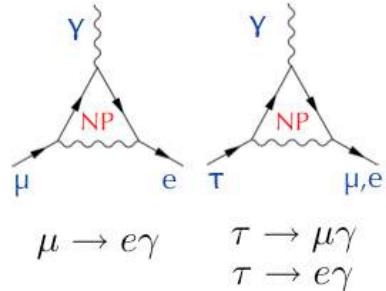
On behalf of the Mu2e collaboration

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



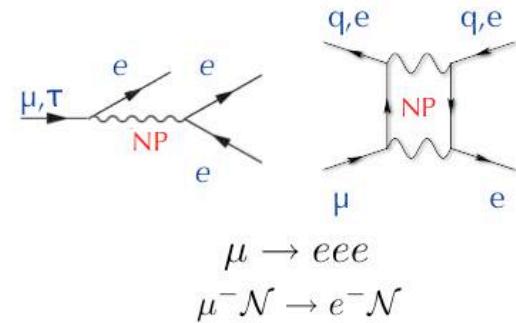
LOOP TERM

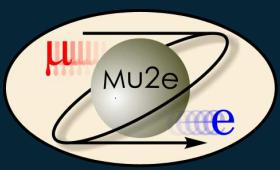
$$\kappa \ll 1$$



CONTACT TERM

$$\kappa \gg 1$$

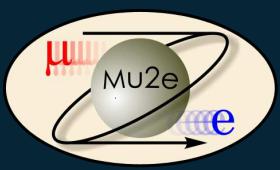




Muon beamline



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

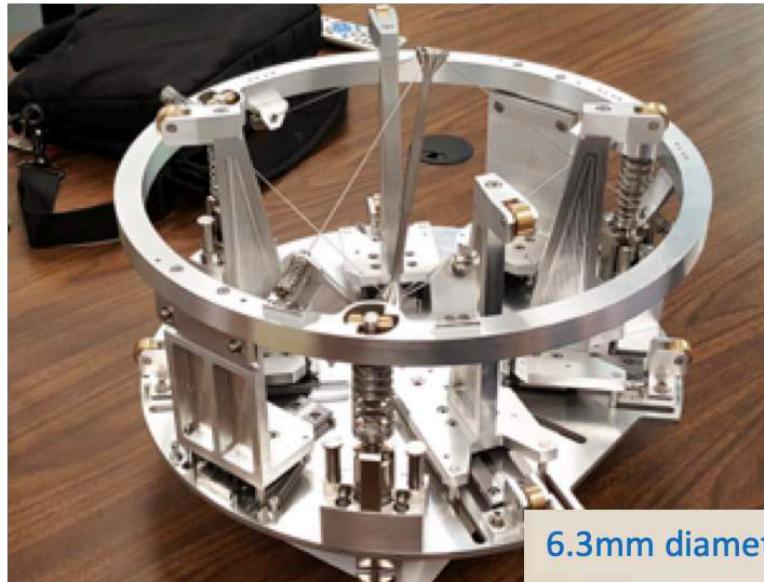


Production target

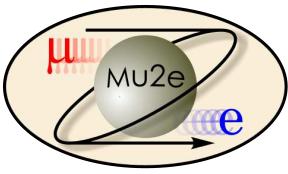
Testing @ Rutherford-Appleton Lab (UK)



Target End-of-Arm tooling @ Fermilab

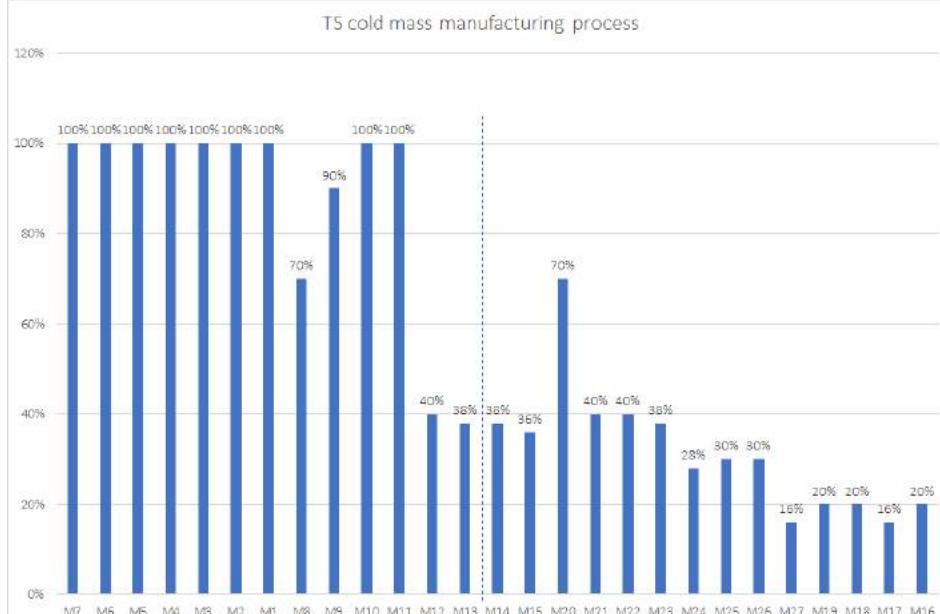


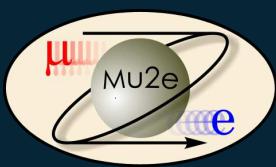
Target design being finalized in the fall



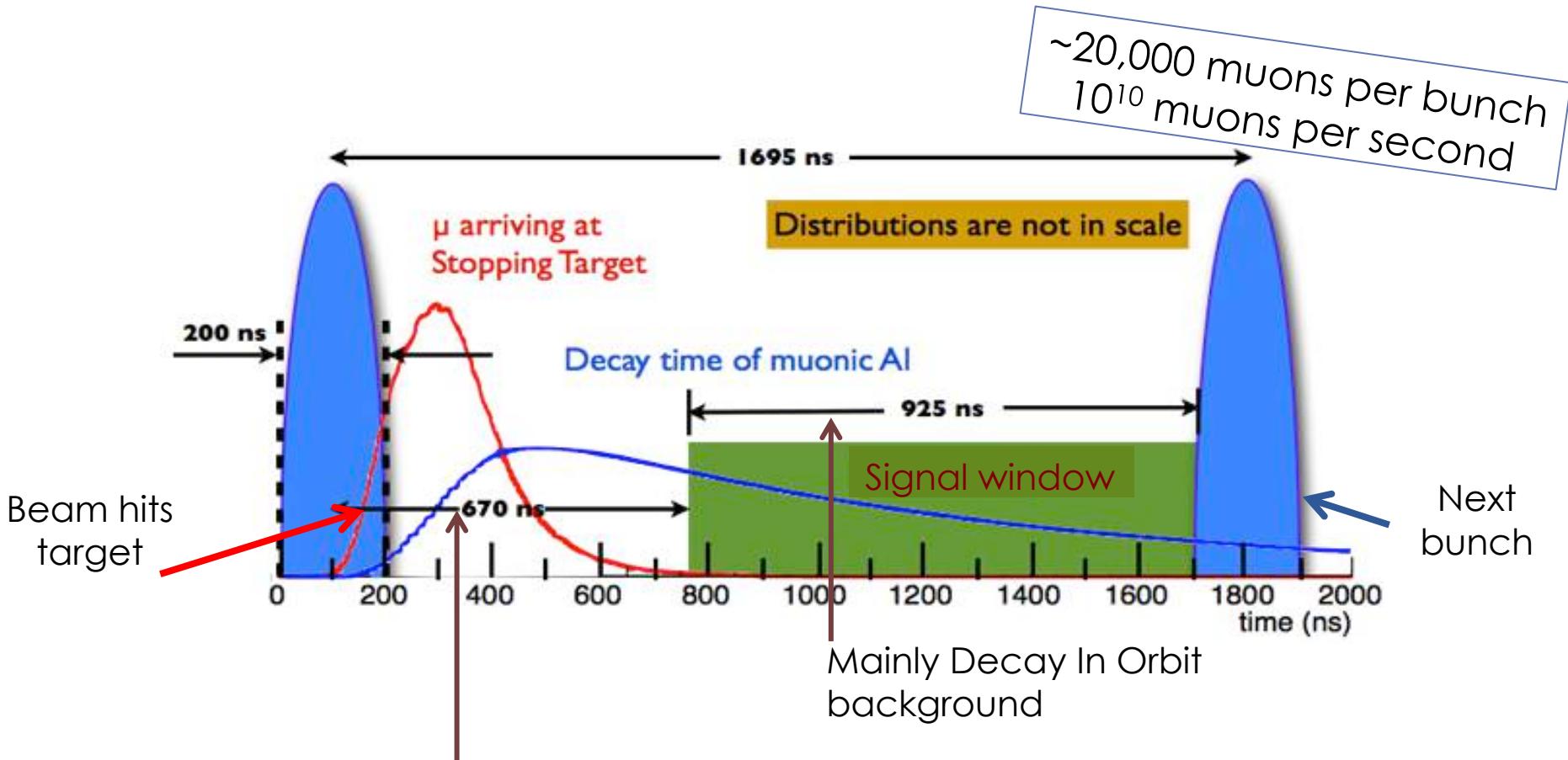
- Construction of TSD also proceeds at full speed in ASG superconducting (Genoa)
- Overall TS modules construction better than 1/3 of total
- Second test unit (M5/M6) assembled on warm bore. Mated together perfectly.

Alignment ongoing.

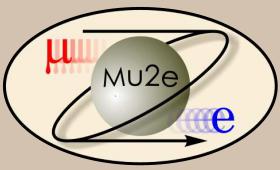




Signal window



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!

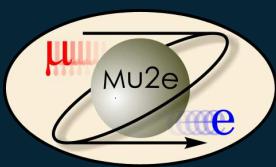
Change the target to study
the underlying NP

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



Weekly di-counter production (full production)

