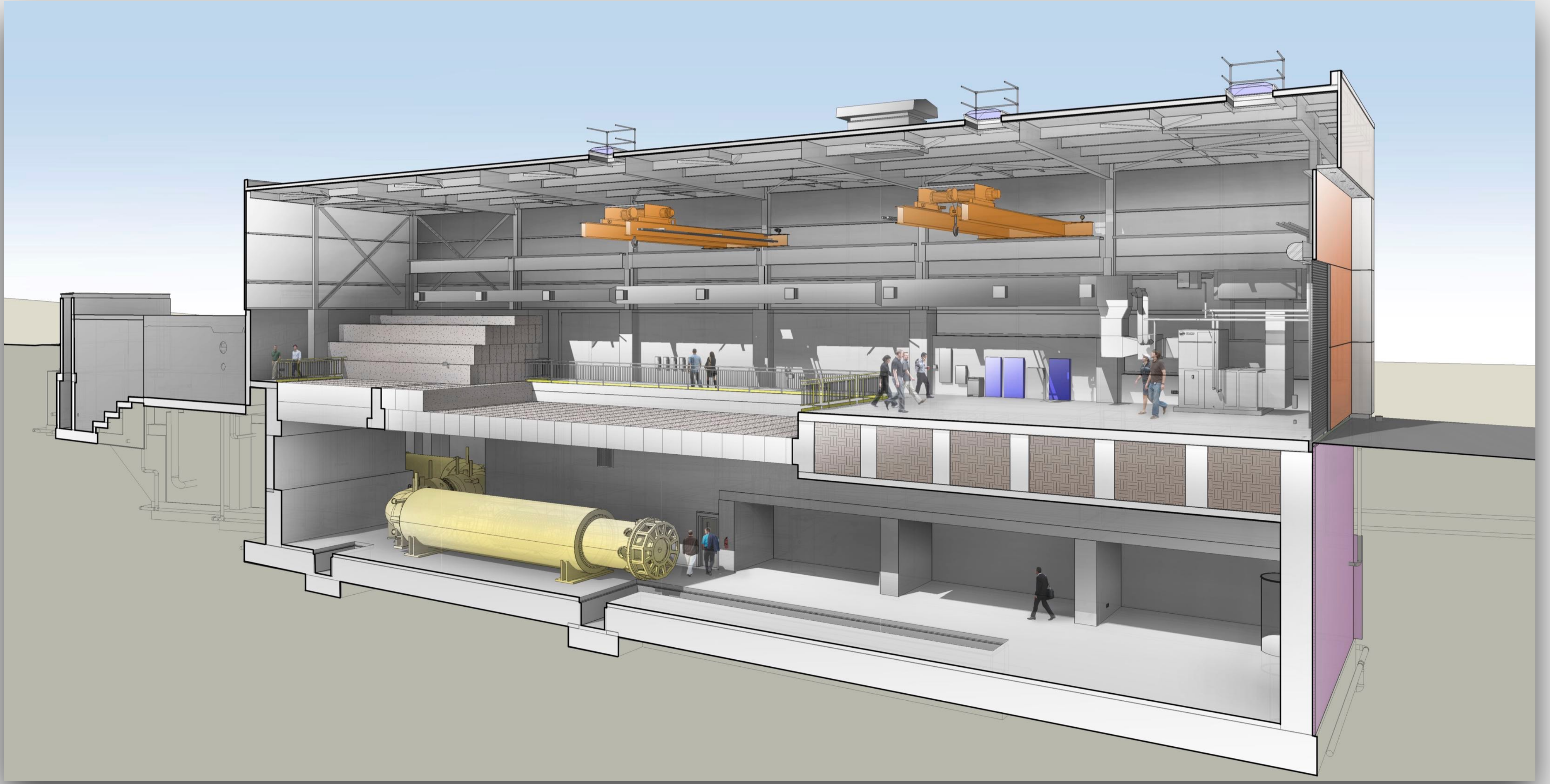
# Mu2e Experiment at Fermilab

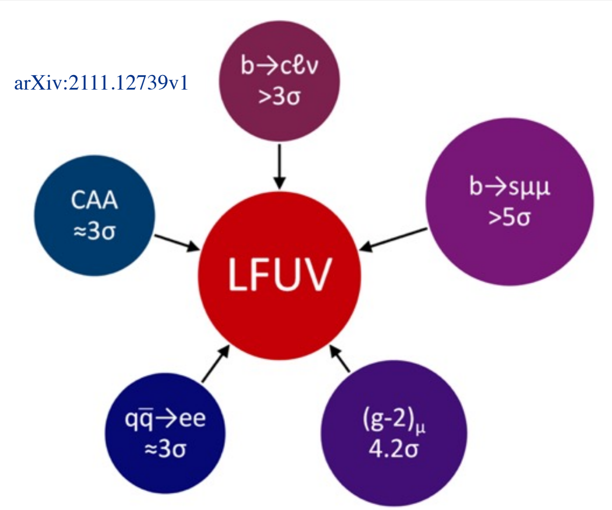


**Yuri Oksuzian on behalf of the Mu2e collaboration**

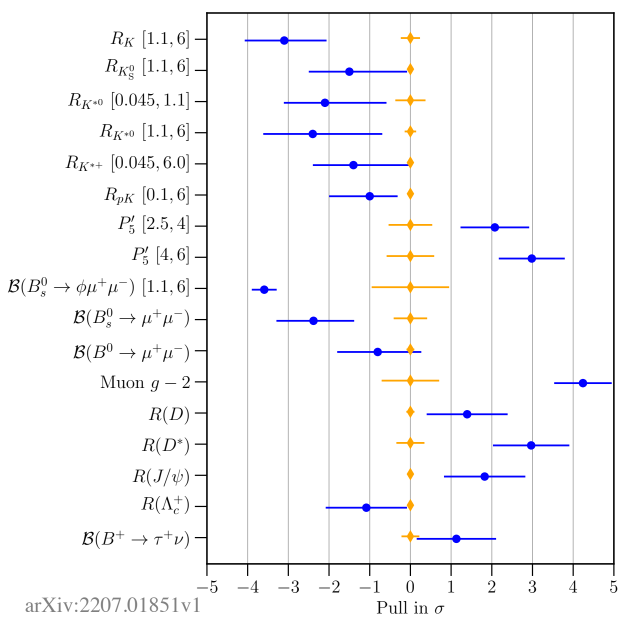
IPA2020, Sep 8, 2022

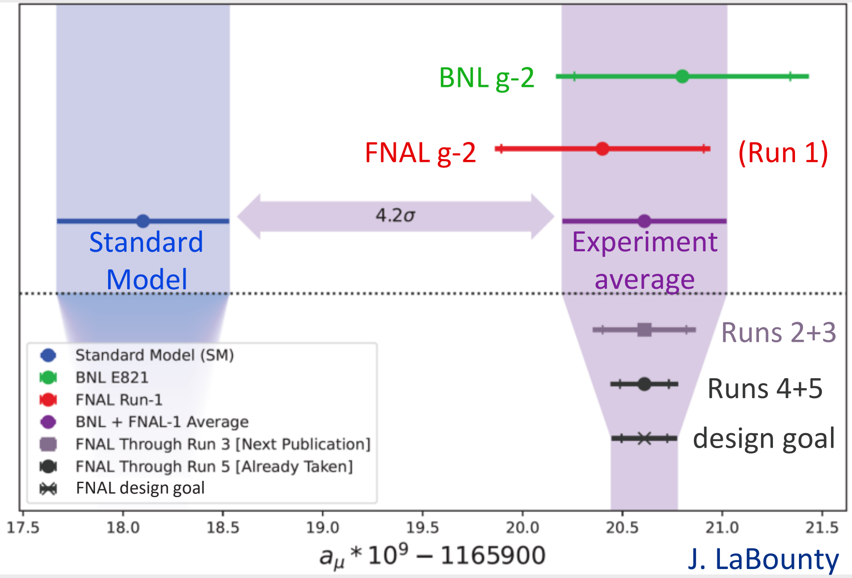
# Motivation

- Standard Model is incomplete: $\nu$-oscillations, dark matter, baryon asymmetry
- We know flavor is not conserved in quark and neutrino sectors
  - Can the *charged* flavor be violated in the muon sector?
  - Are neutral and Charged Lepton Flavor Violation (CLFV) related?
  - Does CLFV arise from neutrino-mass generation mechanism?
- Muons are intriguing and abundantly available:
  - Muon g-2 and B-meson anomalies




Mounting Evidence for the Violation of Lepton Flavor Universality



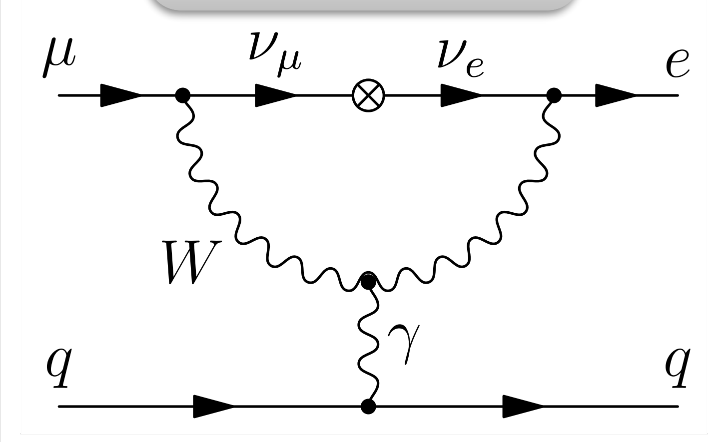
# Mu2e

- Mu2e will search for a neutrino-less $\mu^{-}Al \rightarrow e^{-}Al$ conversion
- Improve the current limit on $R_{\mu e}$ by **four orders** of magnitude:

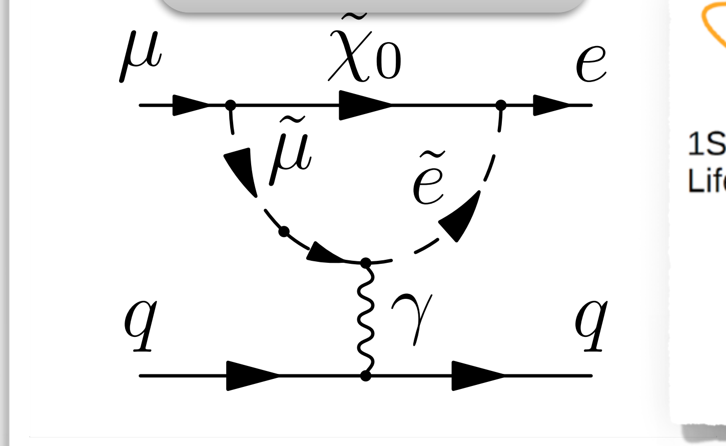
$$R_{\mu\rightarrow e} = \frac{\Gamma\left(\mu^{-} + N(Z,A) \rightarrow e^{-} + N(Z,A)\right)}{\Gamma\left(\mu^{-} + N(Z,A) \rightarrow \nu_{\mu} + N(Z-1,A)\right)} < 6\times 10^{-17} \text{ (90\% CL)}$$

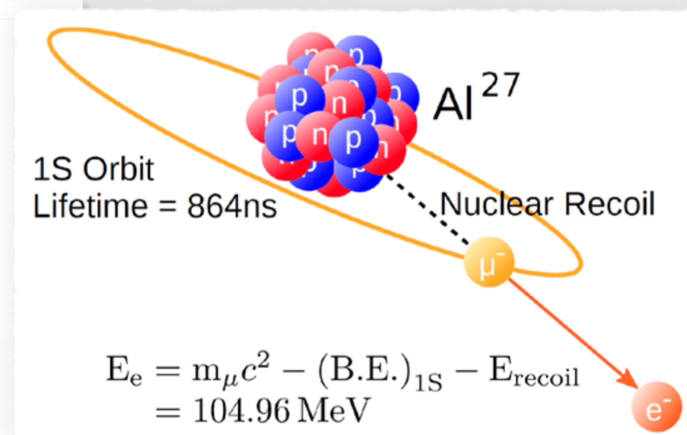
- Mu2e will produce, stop and analyze $7\times 10^{18}$ muons on aluminum foils
  - Searching for $\sim 105$ MeV electrons originating from the stopping target
  - In SM, $\mu^{-}N \rightarrow e^{-}N$ is *practically* forbidden ($R_{\mu e} \sim 10^{-54}$)
- **Signal observation at Mu2e is unambiguous sign of New Physics**

**$\text{Rate}_{\text{SM}} \sim 10^{-54}$**




**$\text{Rate}_{\text{BSM}} \sim 10^{-15}$**

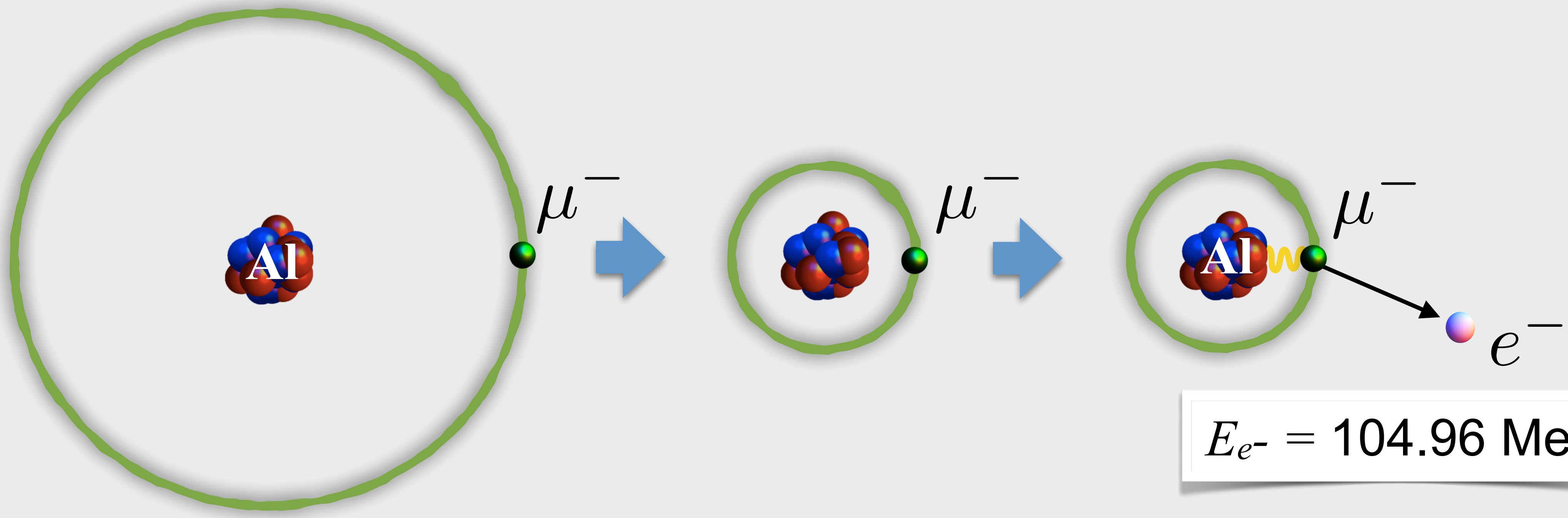


# Numerator

Mu2e will measure the ratio of $\mu \to e^-$ **conversions** to the number of muon captures by Al nuclei:

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




$E_{e^-}$ = 104.96 MeV

Mu2e will measure the ratio of $\mu \to e^-$ conversions to the number of **muon captures by Al nuclei**:

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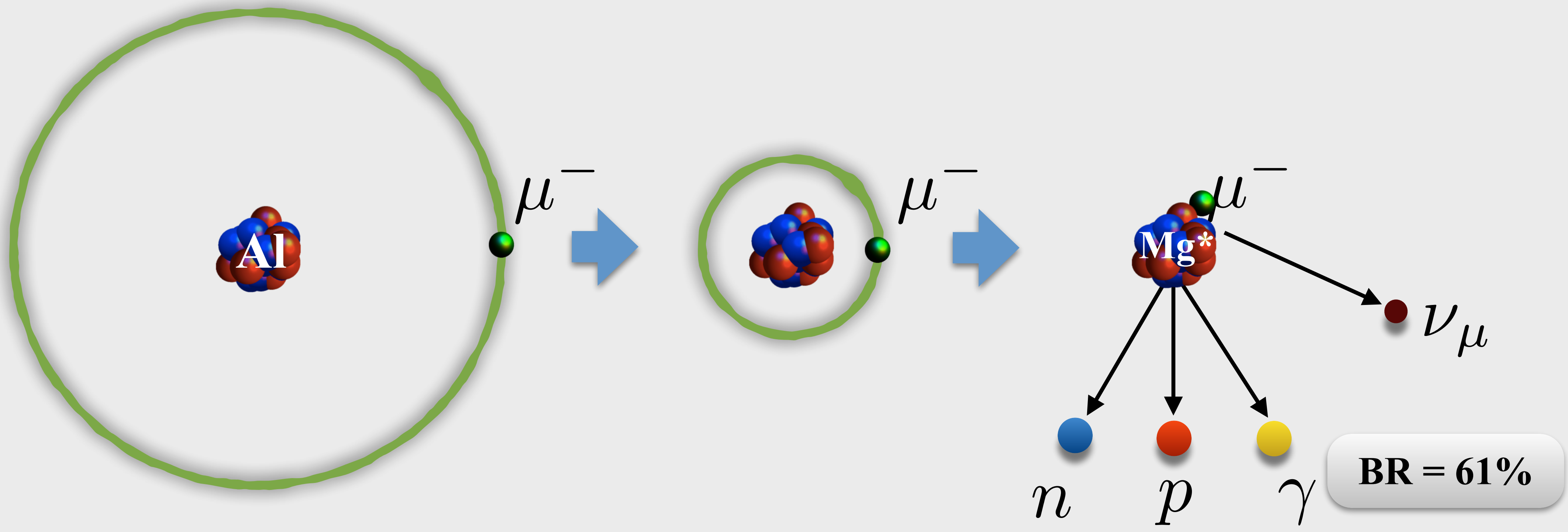

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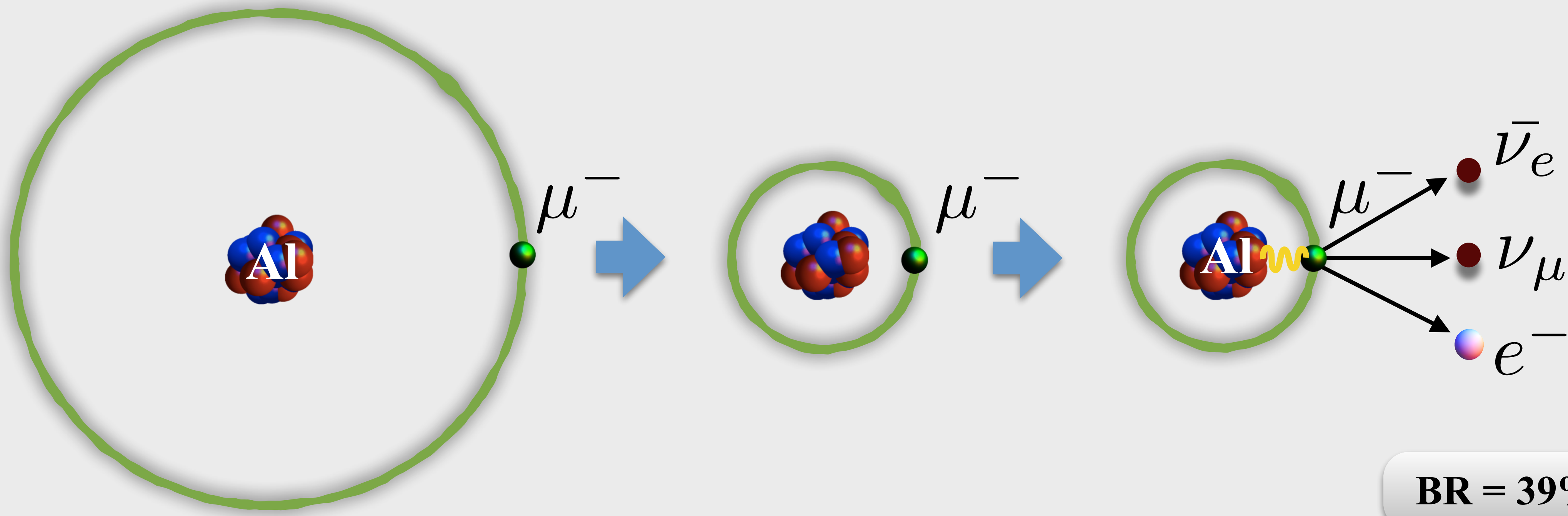
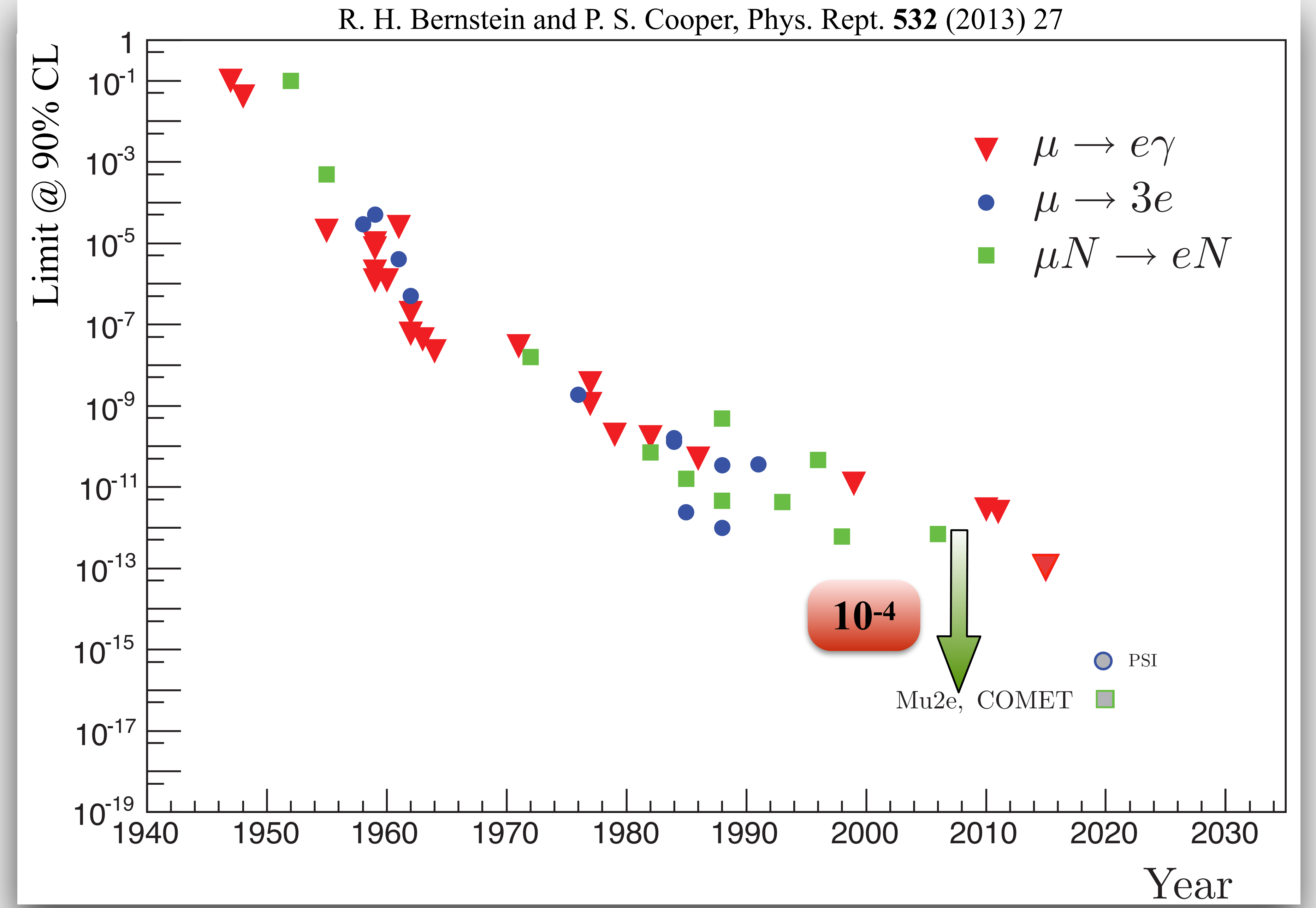



**BR = 39%**

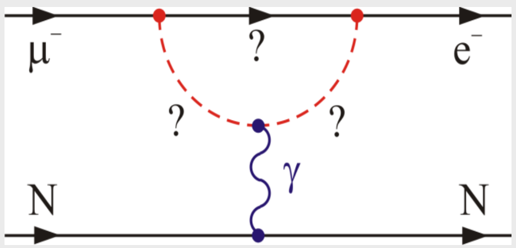
# History of CLFV Searches



# Mu2e Physics Reach

## Effective CLFV Lagrangian

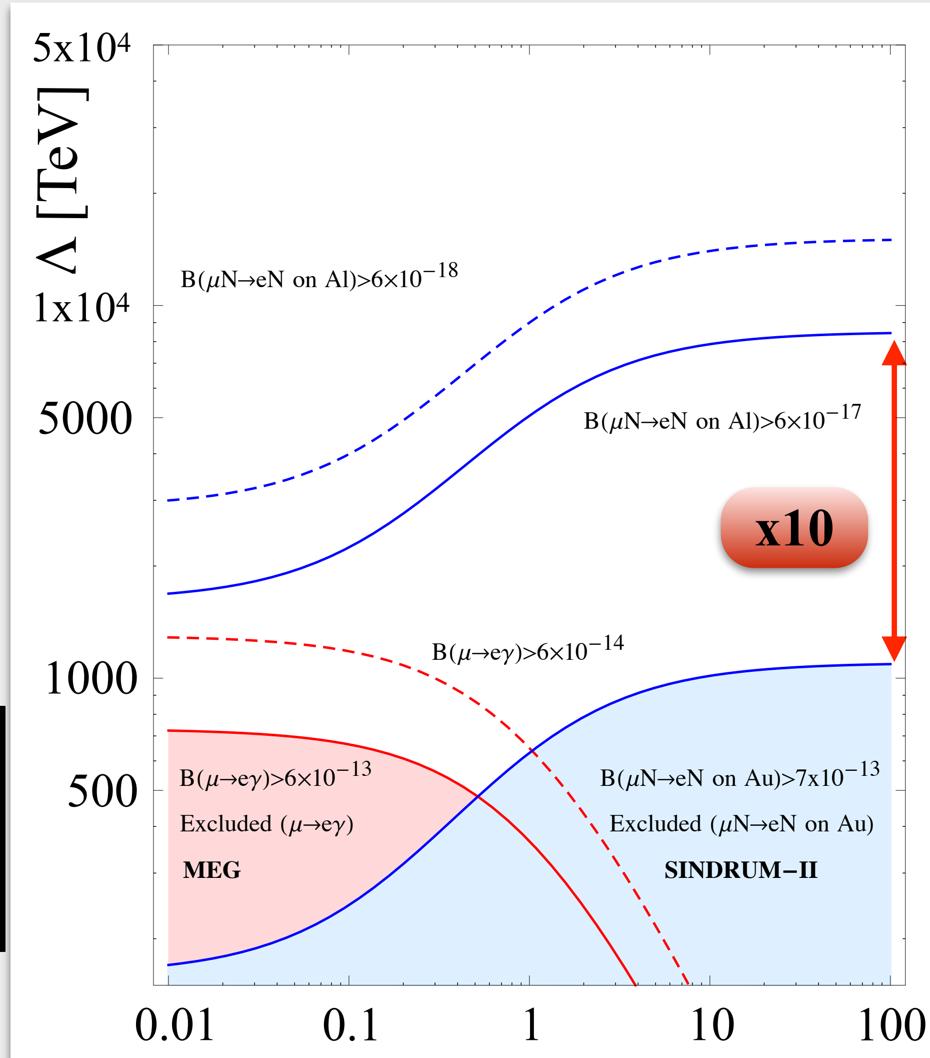
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma_\mu q_L$$

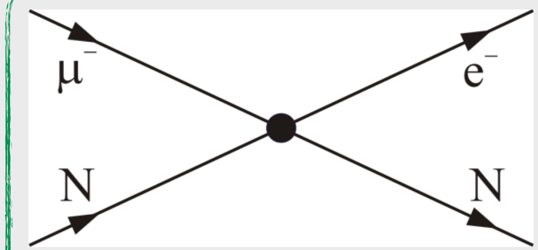



κ << 1

Magnetic moment type operator

| State | μ→eγ | μ→e |
|---|---|---|
| Sensitive | **Yes** | **Yes** |




κ >> 1

Contact term operator

| State | μ→eγ | μ→e |
|---|---|---|
| Sensitive | **No** | **Yes** |

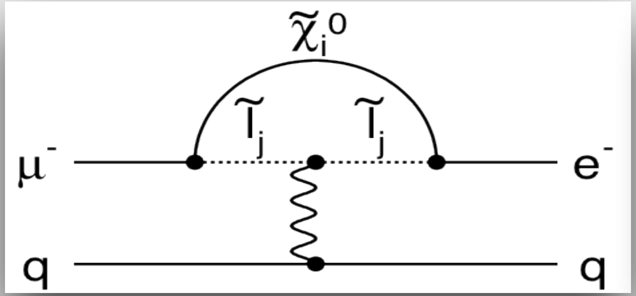
# Mu2e Physics Reach

## Effective CLFV Lagrangian

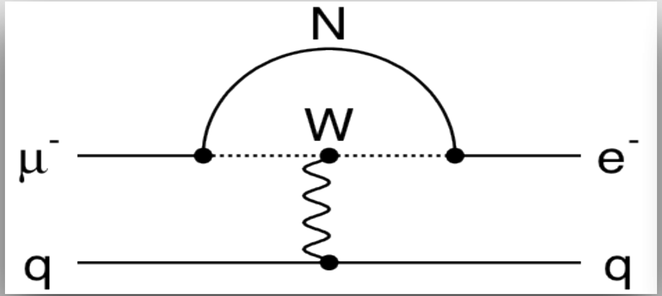
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma_\mu q_L$$

## Magnetic moment type operator

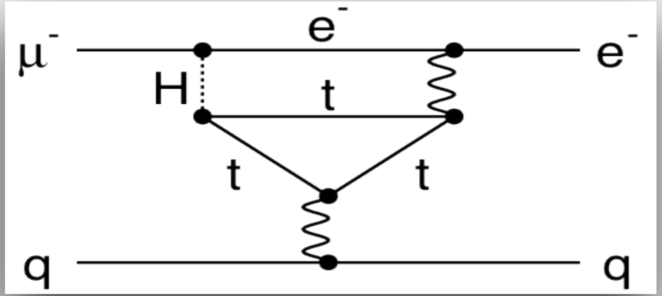
### Supersymmetry




### Heavy neutrinos

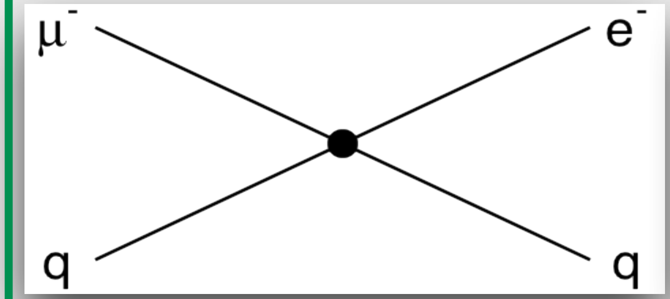



### Two Higgs Doublets

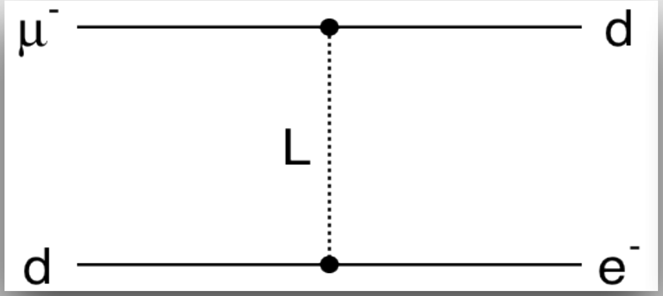



## Contact term operator

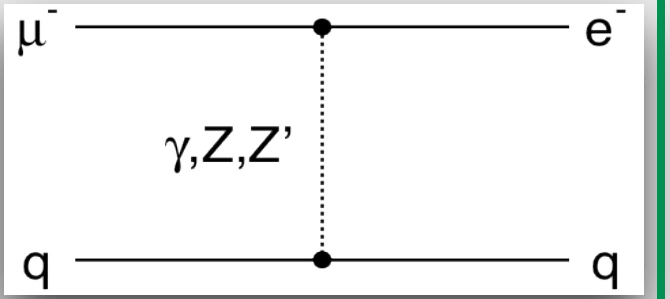
### Compositeness



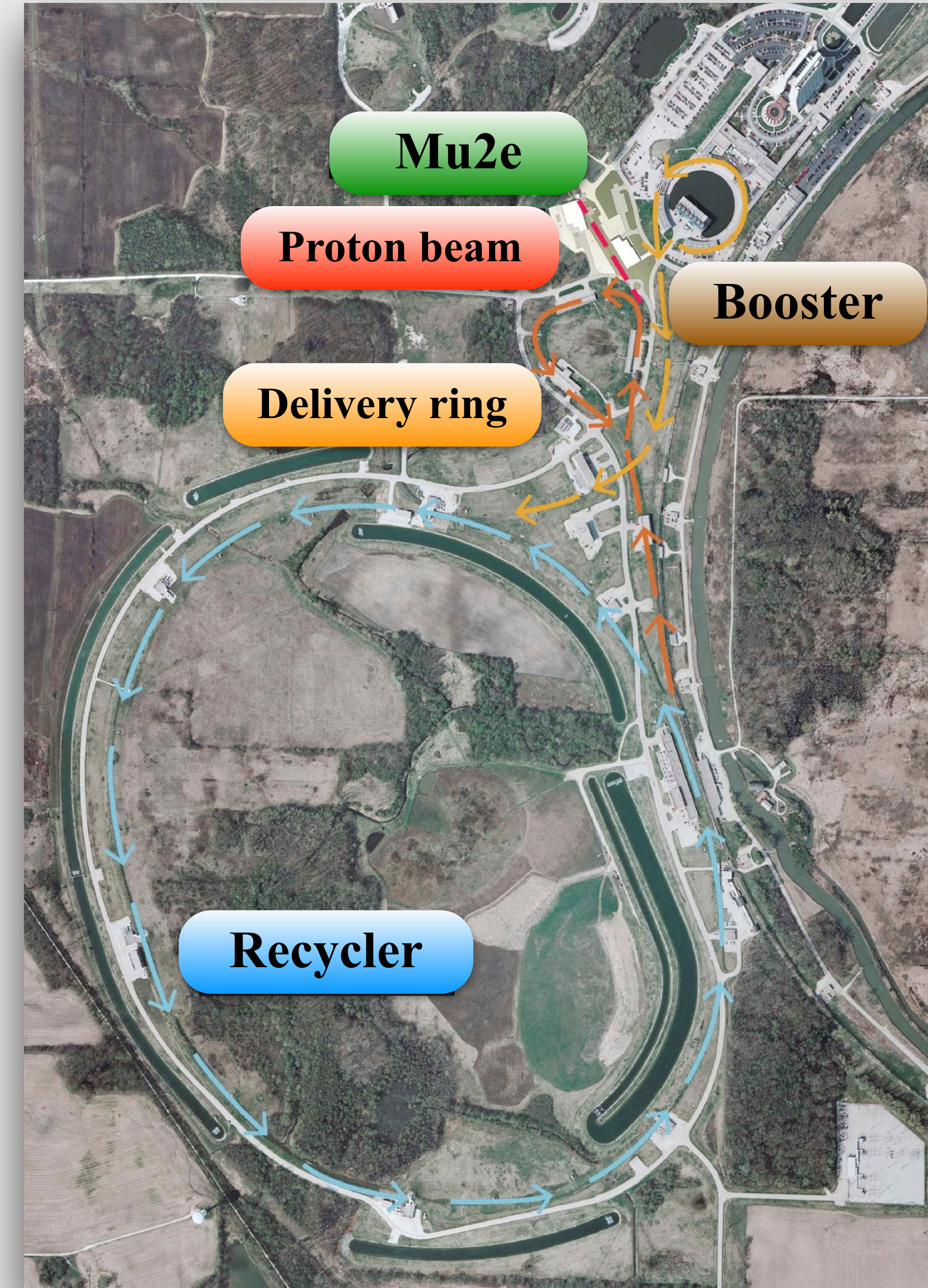

### Leptoquarks




### Heavy Z'



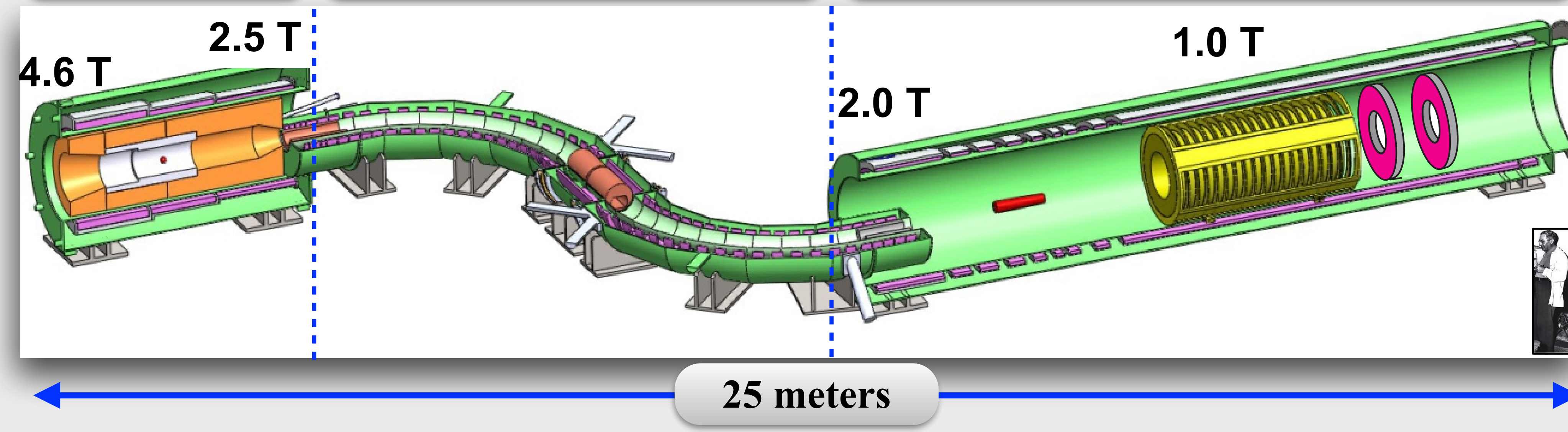
# Mu2e proton beam



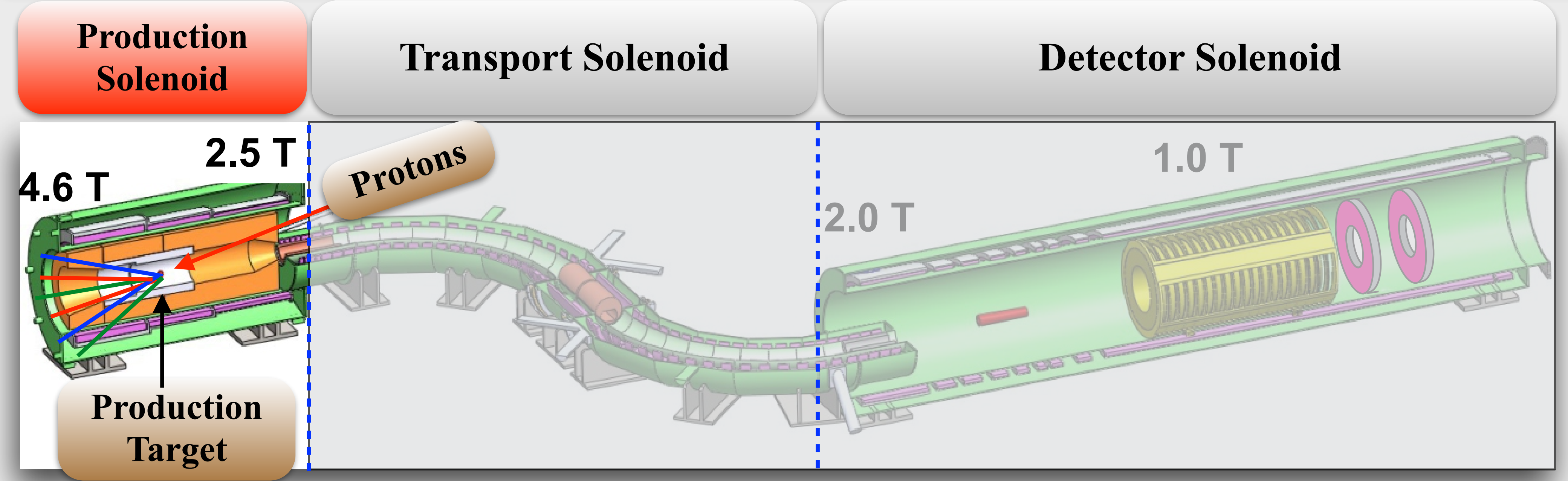

- Mu2e will recycle the existing accelerator infrastructure
- **Booster** provides batches of 8 GeV protons to recycler
- **Recycler** divides proton batches into 4 smaller bunches
- **Delivery ring** gets 1 out of 4 bunches from recycler
- **Mu2e** gets the **proton beam** pulses from delivery ring every 1695 ns
- Mu2e runs simultaneously with neutrino program (NOvA, SBN)
  - Minor impact on neutrino program

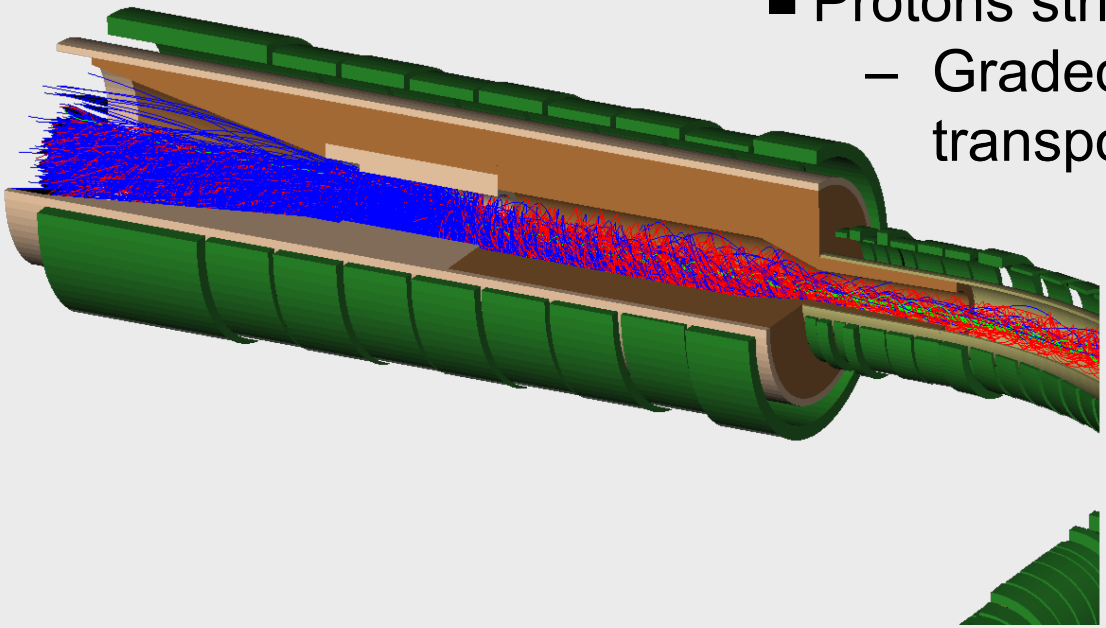
# Mu2e apparatus

| Production Solenoid | Transport Solenoid | Detector Solenoid |
| --- | --- | --- |



# Mu2e apparatus

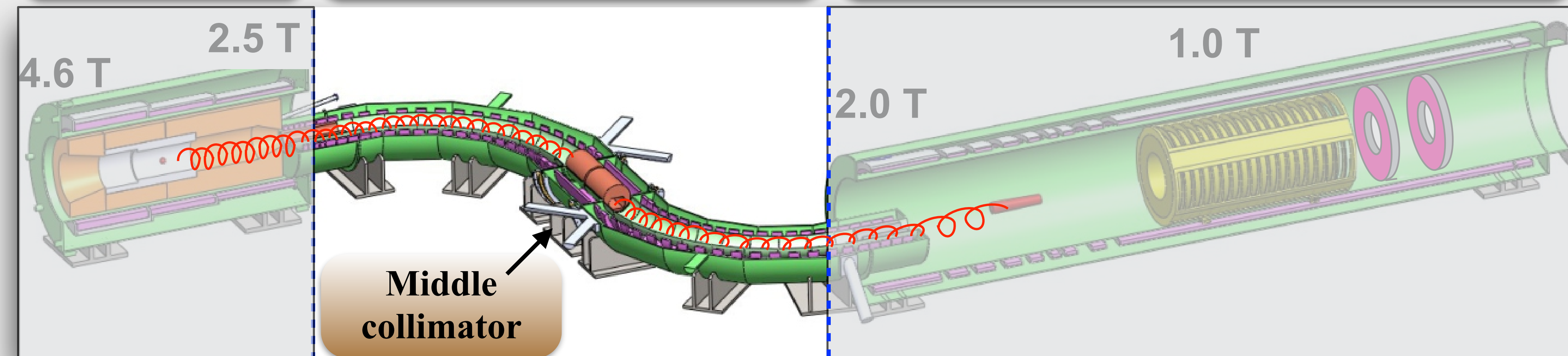


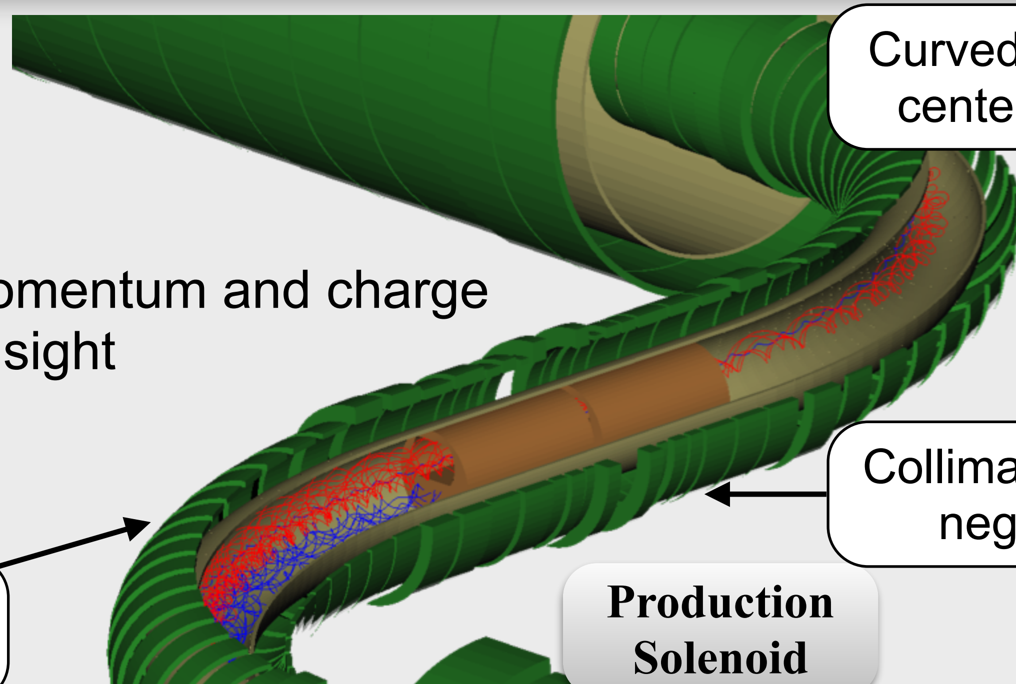
- Protons strike production target to produce $\pi^-$
  - Graded B-field reflects pions toward the transport solenoid

# Mu2e apparatus

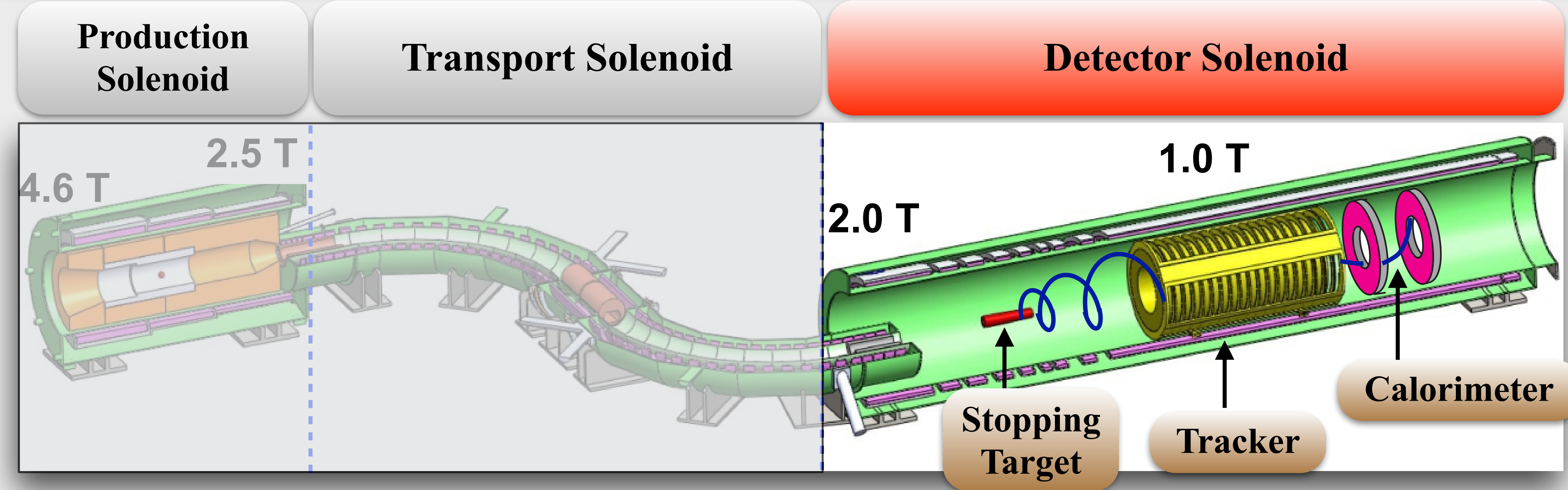
| Production Solenoid | Transport Solenoid | Detector Solenoid |
|---|---|---|




- Trasport solenoid:
  - Transports $\pi^-/\mu^-$
  - Selects particle's momentum and charge
  - Avoids direct line of sight

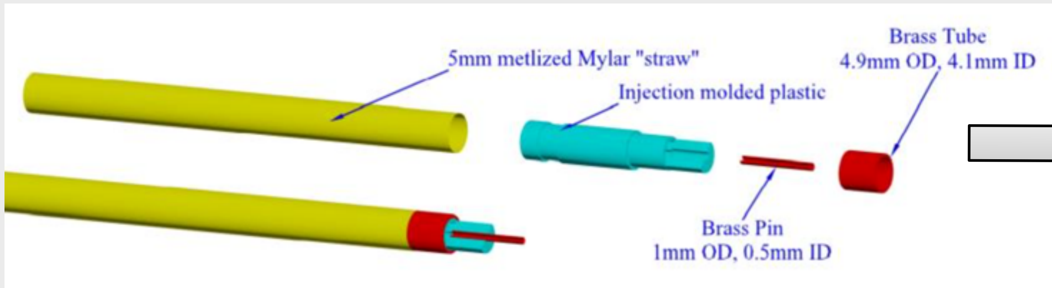


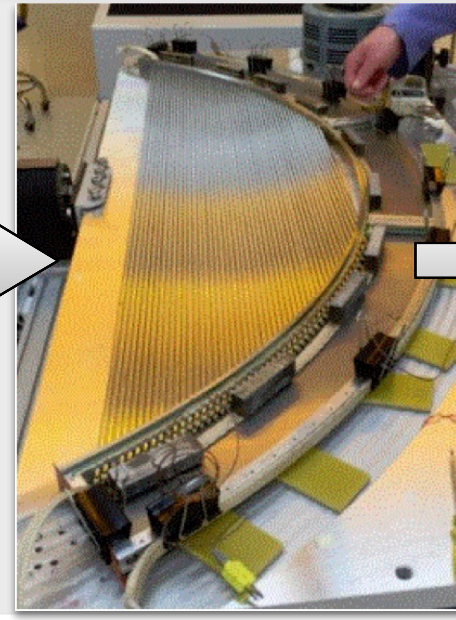
# Mu2e apparatus

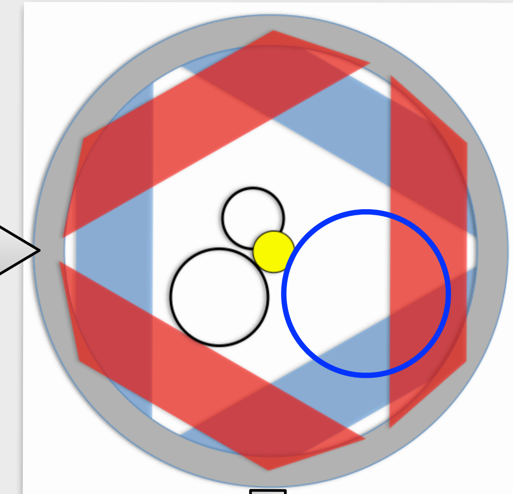


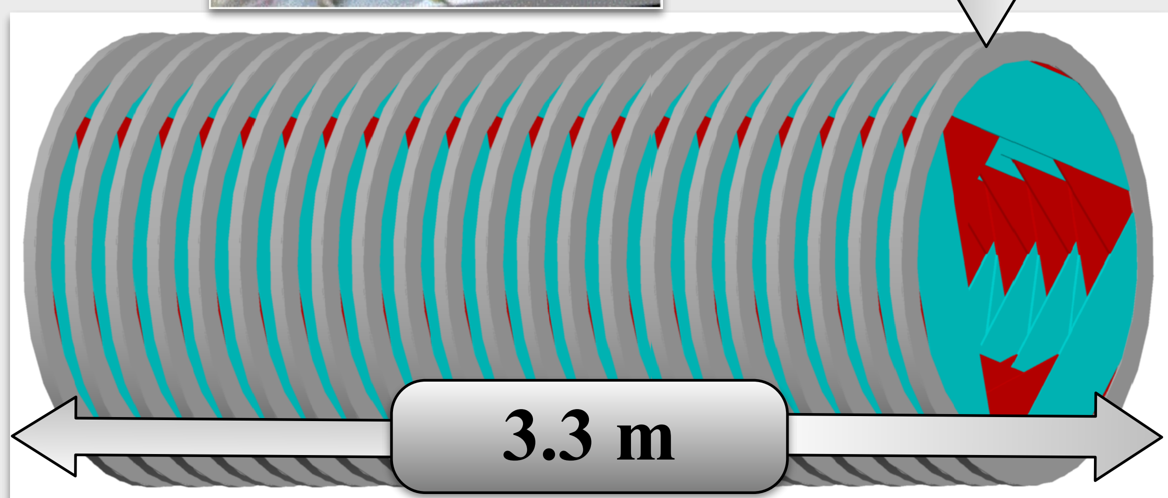

- Muons stop on Al stopping target
  - 50% of $\mu^-$ stop on the target
  - 1,000 POT → 2 stopped muons
  - Graded magnetic field reflects conversion electrons toward the tracker
- Conversion electron momentum and energy are measured in the tracker and calorimeter

# Tracker



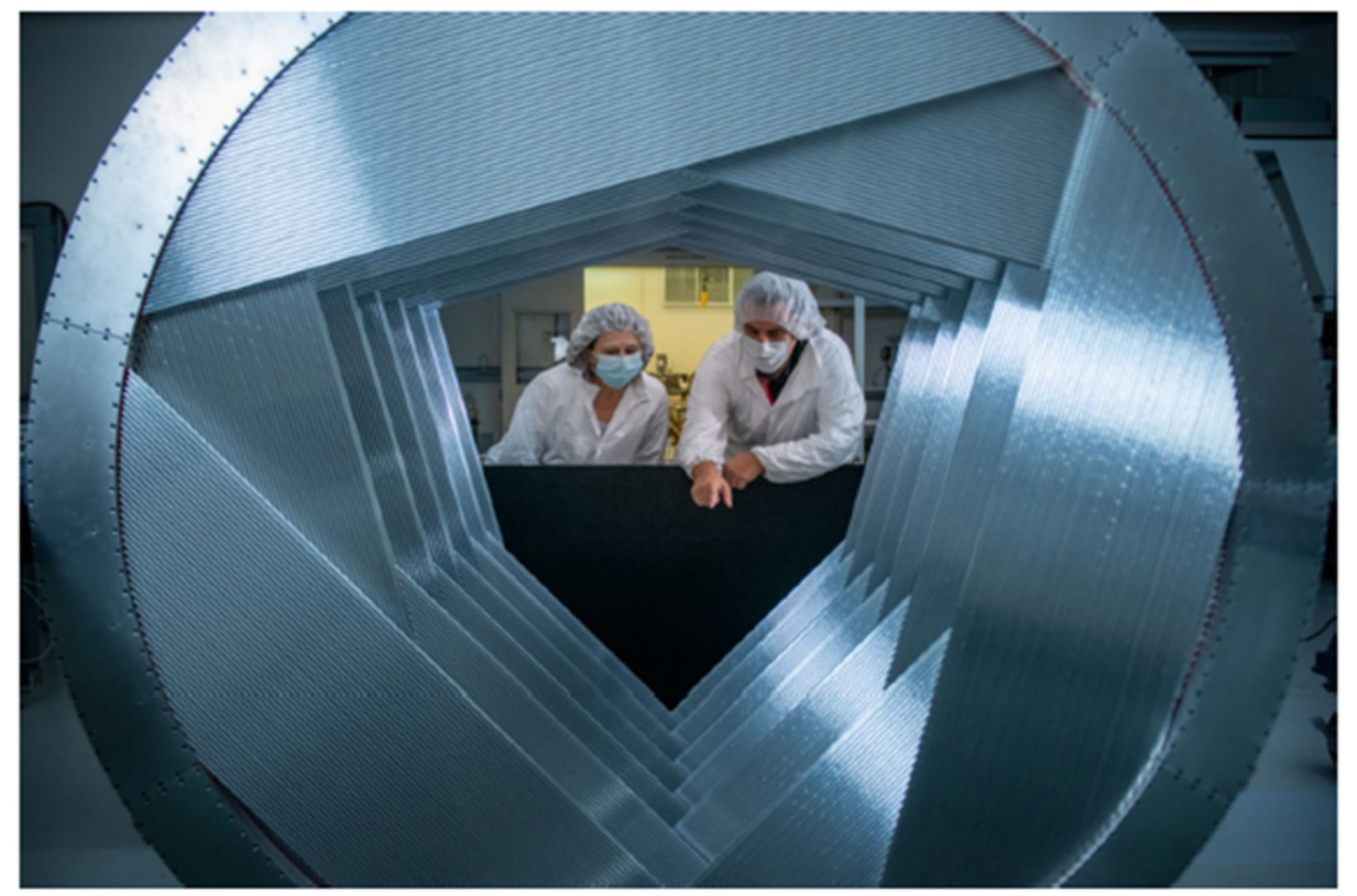





- Low mass straw drift tubes
- 5 mm diameter straws
  - 15 $\mu$m Mylar walls
  - Filled with 80/20 $Ar/CO_2$
- 25 $\mu$m gold-plated tungsten sense wires
- 100 Straws = Panel; 6 Panel = Plane; 2 Planes = Station; Tracker = 18 Station

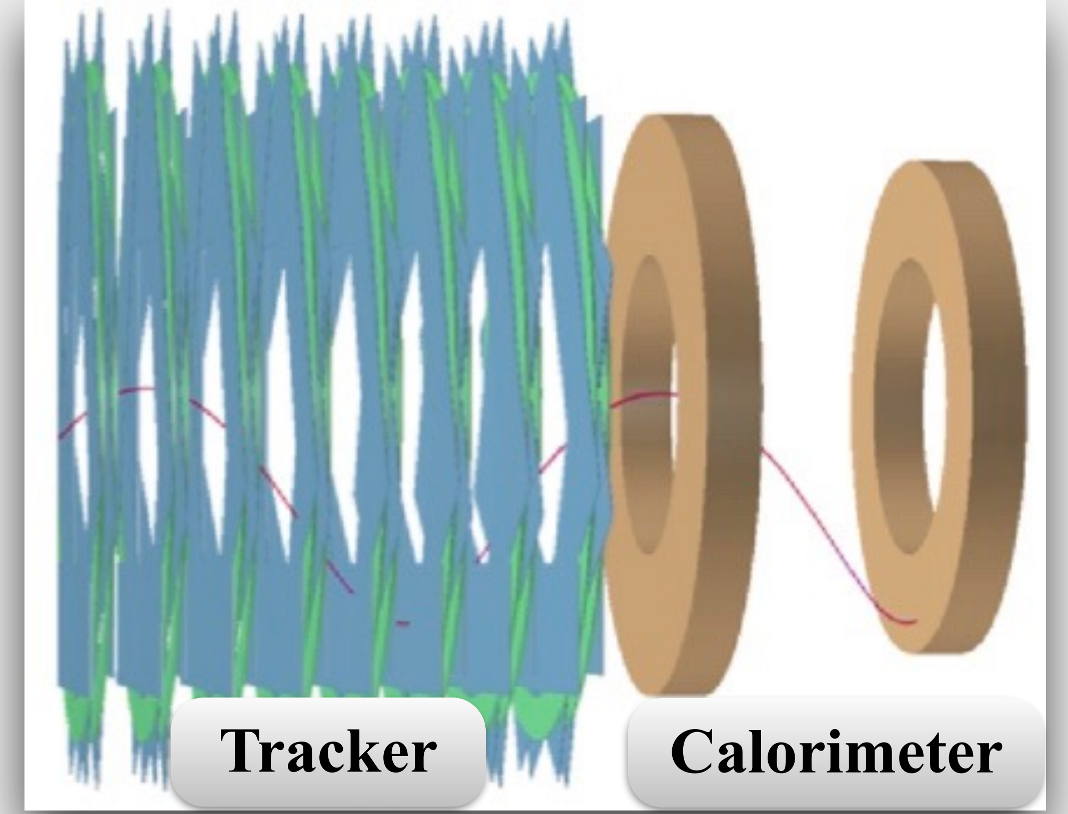
# Tracker Status

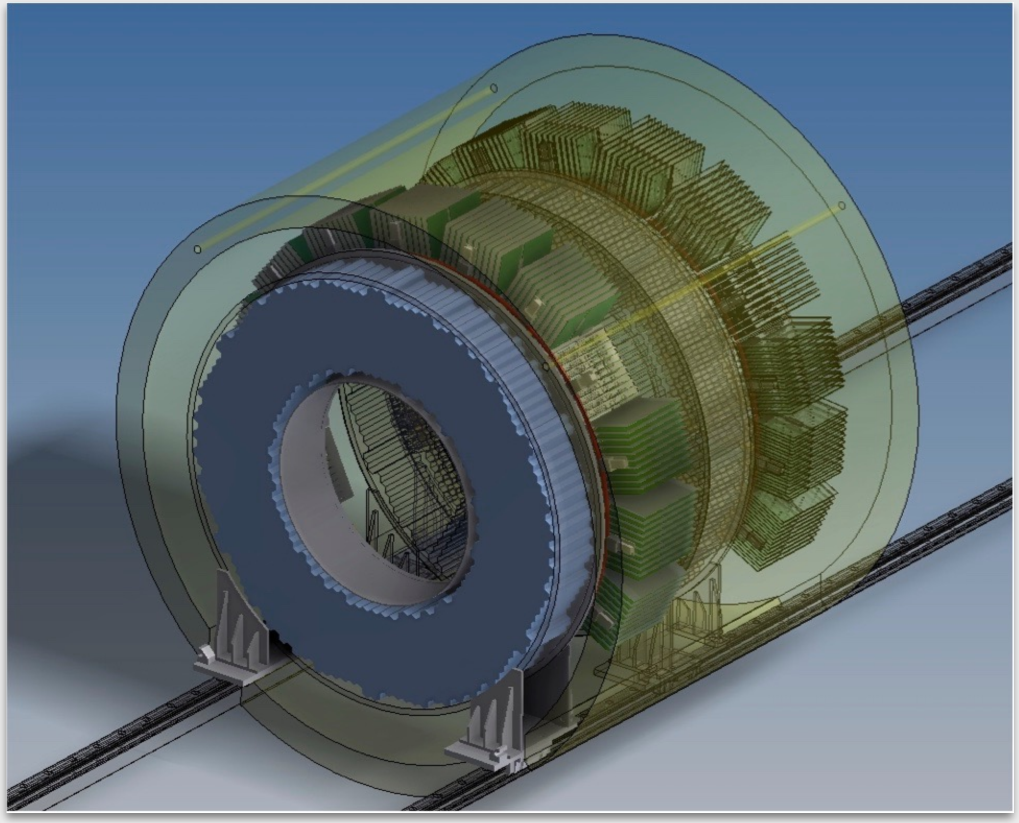
- Produced 92% of Tracker Panels
- Produced 56% of Tracker Planes
- Completed electronics designs
- Demonstration of KPP quality cosmic tracks in Vertical Slice Test



# Calorimeter

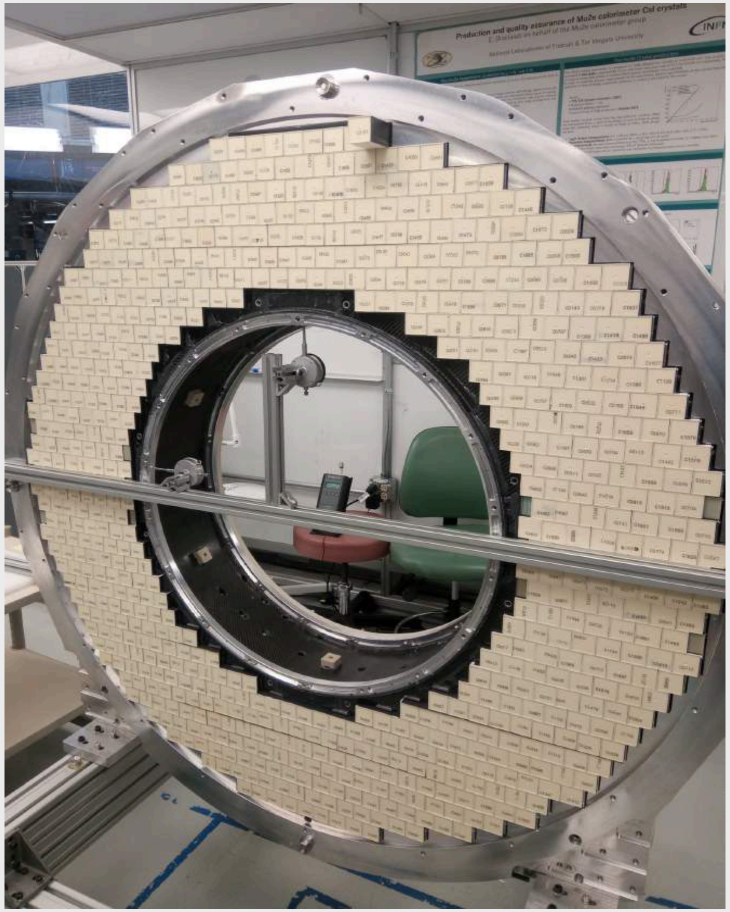
- Two disks of 700 CsI crystals
  - $\sigma_E/E < 10\,\%$ and $\sigma_t < 1\ ns$ at 100 MeV
- Provides precise timing, PID, seed for tracking and triggering



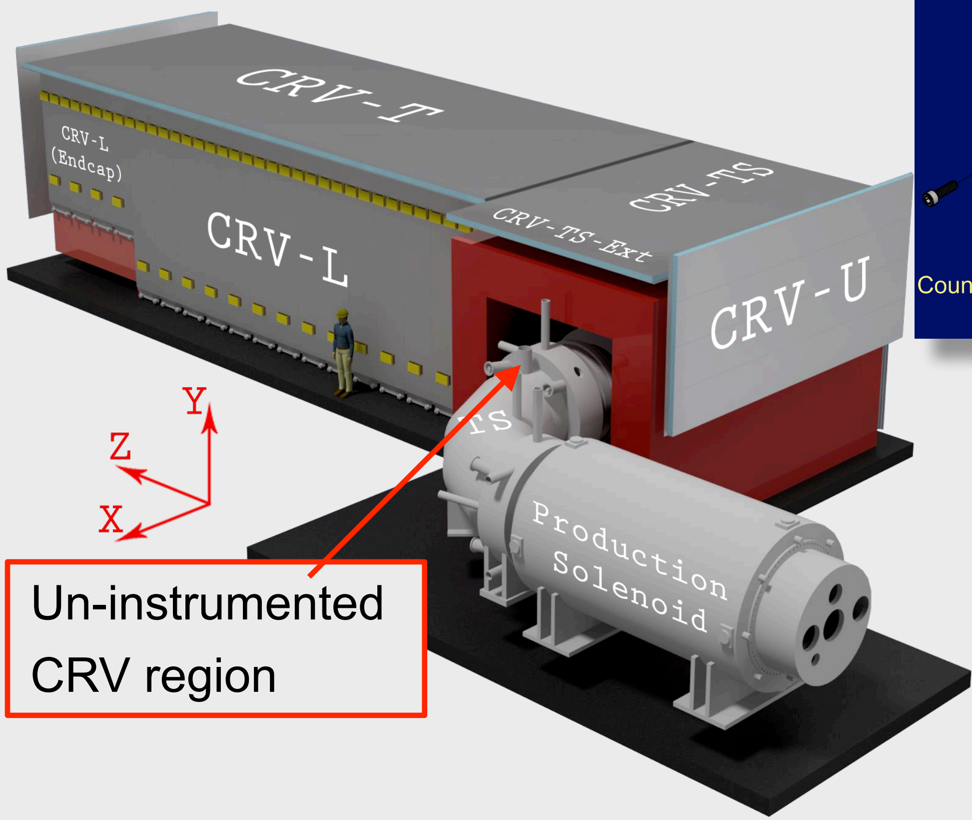
# Calorimeter status

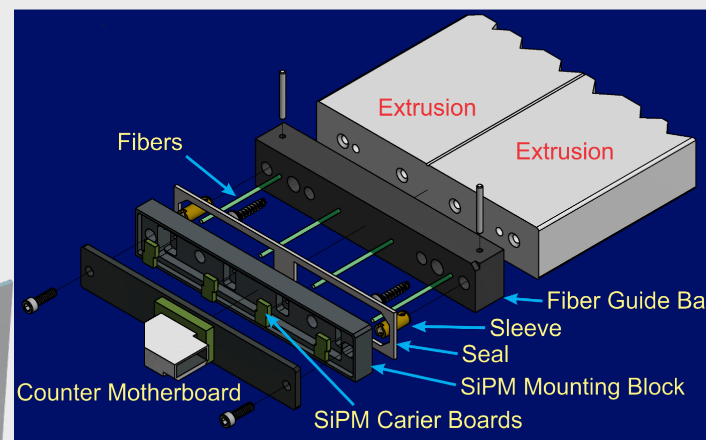
- All crystals, SiPMs, and FEEs produced
- All mechanical parts in hand to build the first disk
  - Finished stacking crystals!
- Cosmic ray test underway with subset of crystals

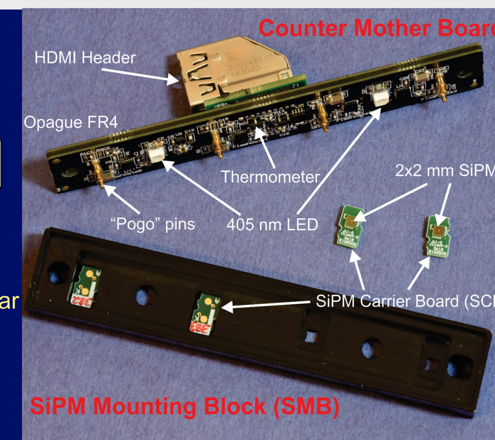


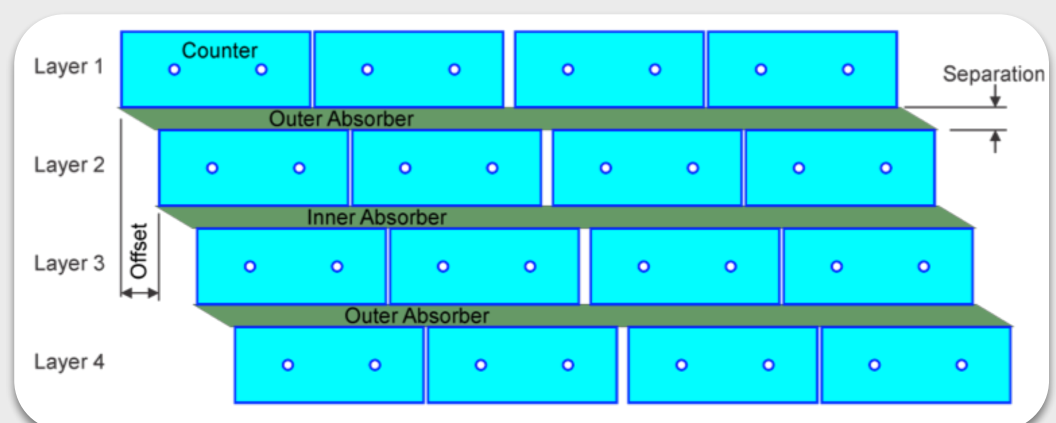
# Cosmic Ray Veto (CRV)

- Mu2e expects 1 signal-like event per day induced by cosmic rays
- Cosmic Ray Veto(CRV) consists of 4-layer scintillating counters
  - Read-out by SiPM through wave-shifting fibers
- CRV will reject 99.99% of cosmic rays, covering 300 m$^2$ of detector solenoid



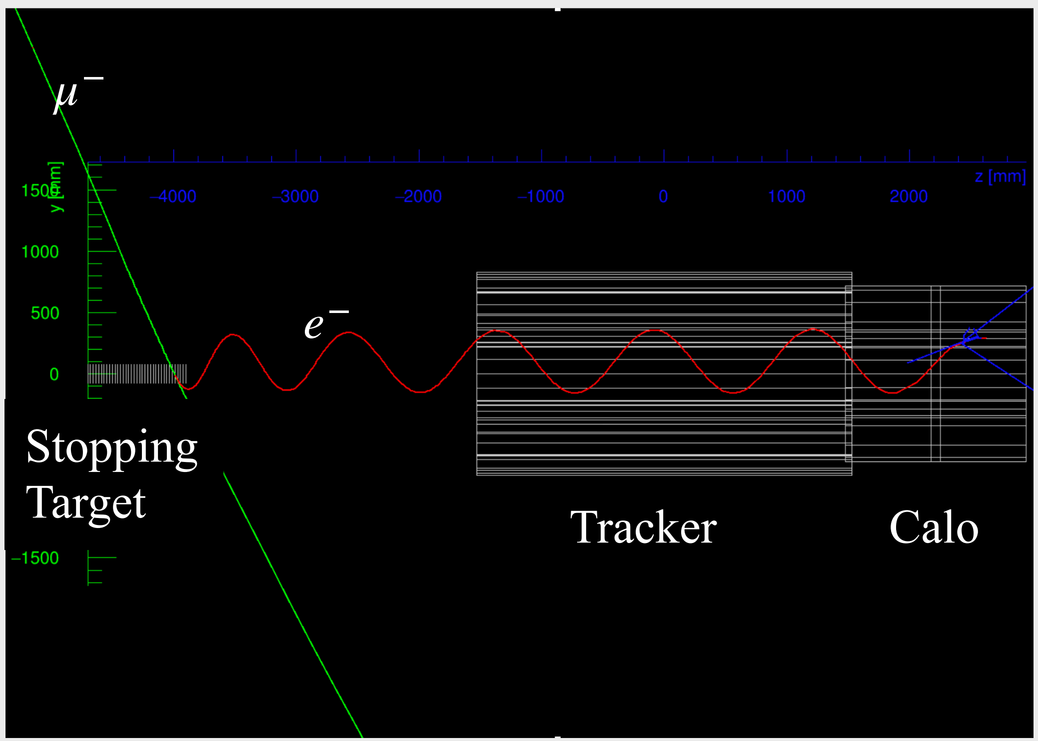



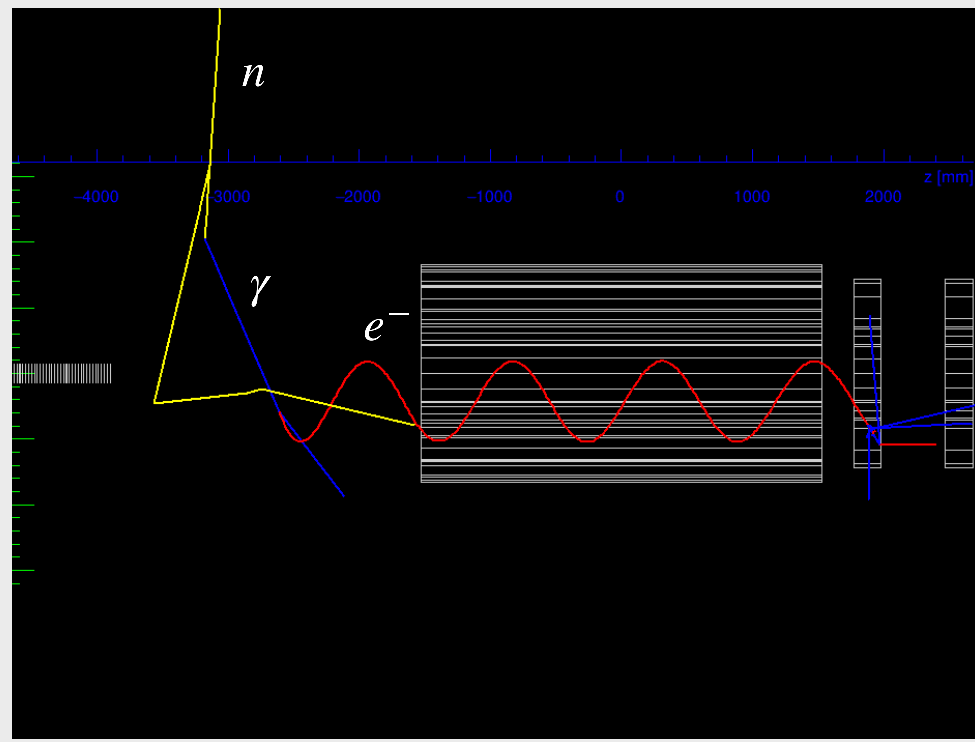
# CRV status

- 2500 / 2700 di-counters produced
- 68 / 83 modules produced and received at Fermilab
- Cosmic ray tests underway at Fermilab

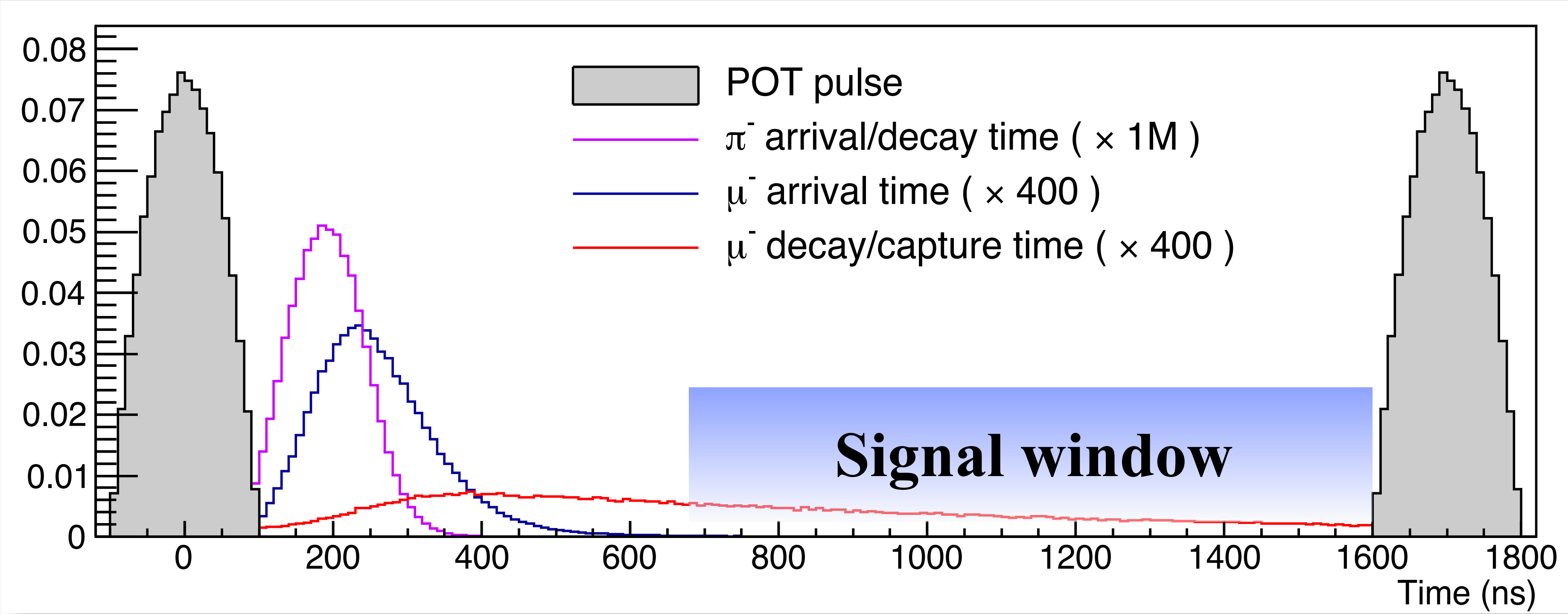
# Cosmic background

- Mu2e will observe ~500 cosmic events over the Mu2e live-time
  - Cosmic ray background component is mostly induced by muons
  - Needs to be suppressed by 4 orders with CRV
- Neutrally charged cosmic hadron escape detection by CRV
  - Rare background, but we're looking for a rare signal…



# Pulsed beam

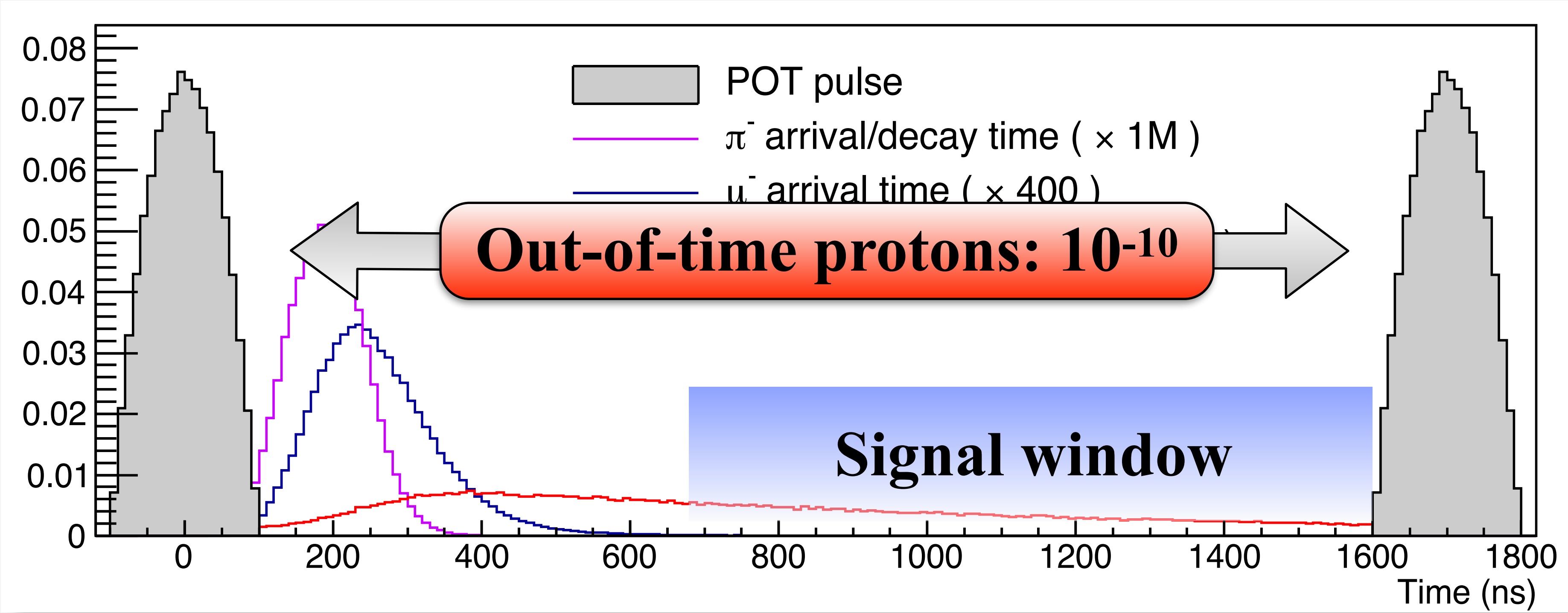



- Prompt background: particles produced by proton pulse which interact almost immediately when they enter the detector
- Muons travel with pions. Pions produce background when captured on target

$$\pi^- N \to \gamma N^* \to e^+ e^- N^*$$

- Other sources of prompt backgrounds: beam electrons, $\mu^-/\pi^-$ decay in flight
- Solution: Suppress prompt backgrounds by employing a delayed signal window
- Delivery ring revolution period of 1695 ns is well matched for $\tau^{Al}$ = 864 ns
  - 50% of muons decay/captured in the signal window

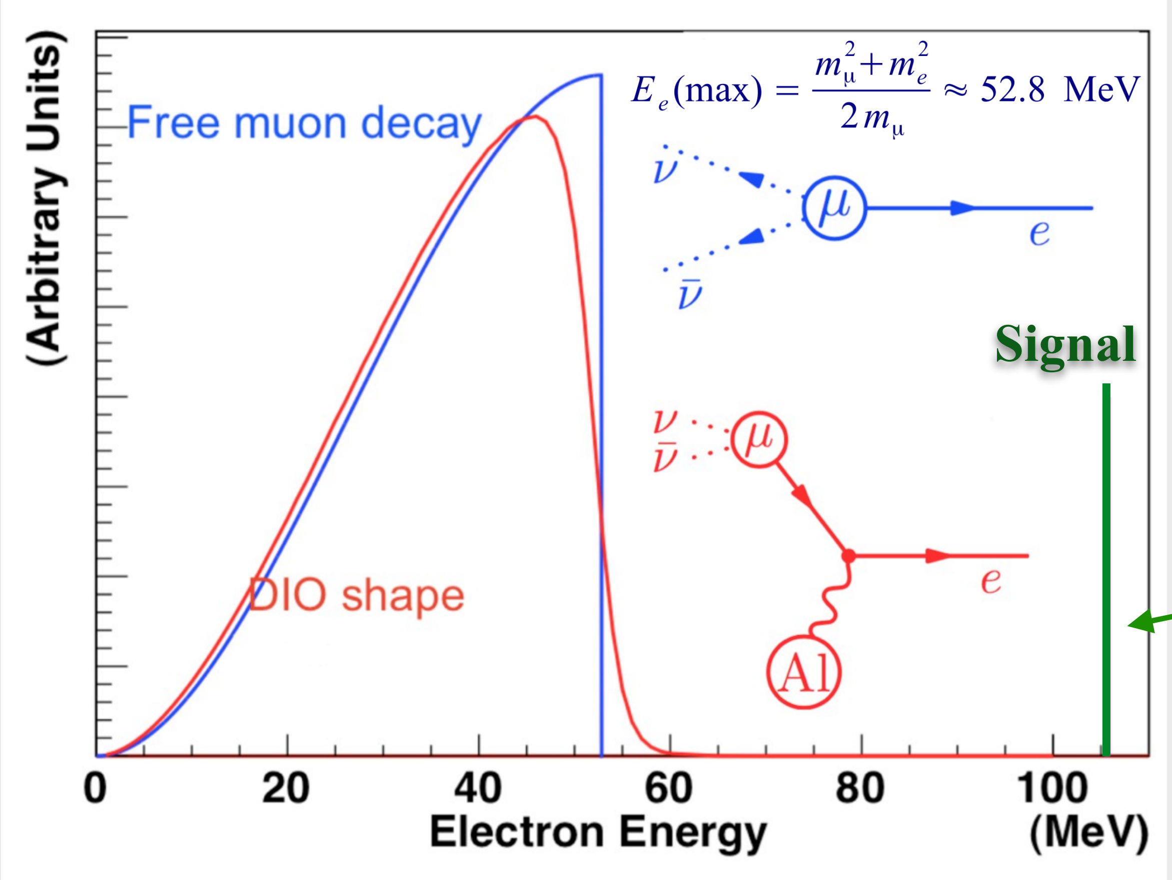
# Out-of-time Protons

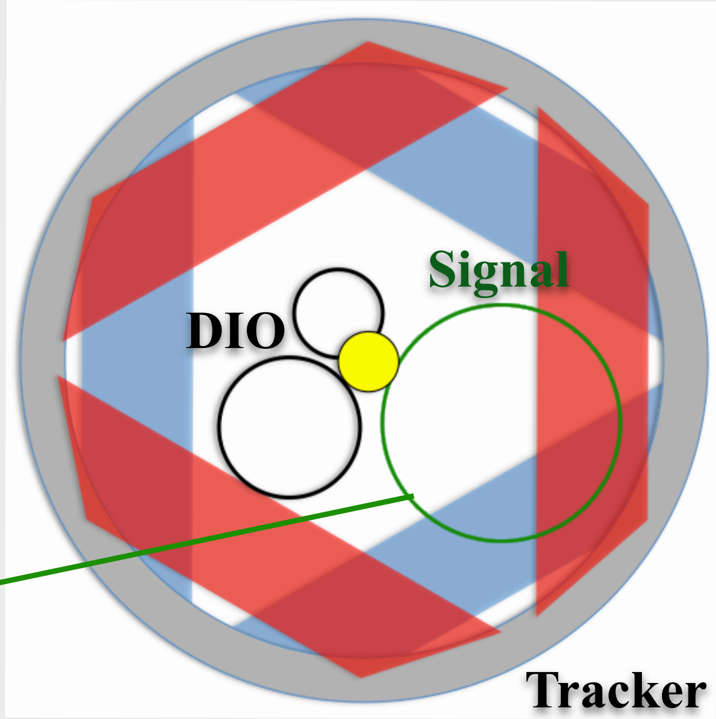



- Out-of-time protons can give rise to prompt backgrounds in the signal window
- RF structure in Delivery ring and sweeping AC dipole in front of PS will suppress out-of-time protons by $>10^{-10}$
- Only 1 in 10 billion POT will be outside of the main pulse

# Decay In Orbit (DIO)

- When muons stop on Al foils, they Decay In Orbit (DIO) 40% of the time
  - $\mu^- \to e^- \nu_\mu \bar{\nu}_e$
- Nuclear recoil modifies energy spectrum:
  - peaks at ~50 MeV, but
  - extends up to the signal region
- Tracker is blind to ~95% of DIO spectrum



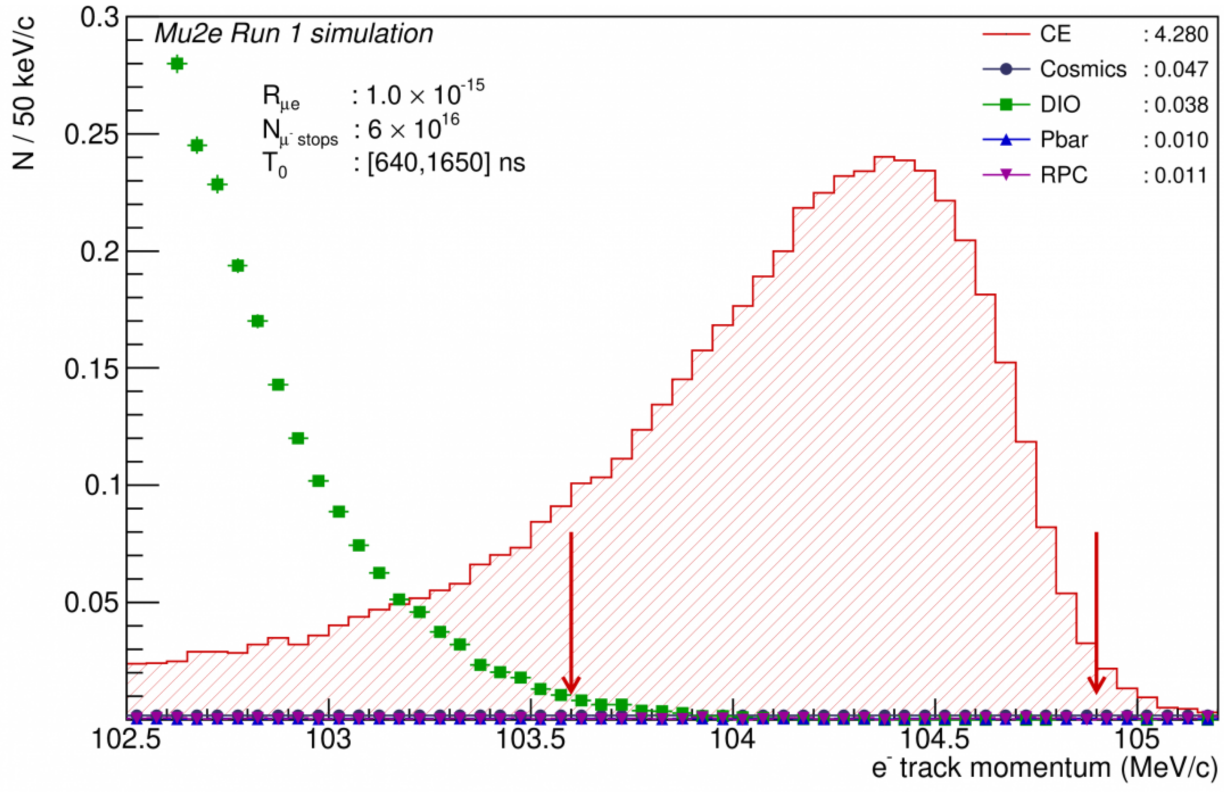
# Run-I sensitivity



- Run-I data-taking in 2025/6:
  - 5σ discovery $R_{\mu e} = 1.1 \times 10^{-15}$
  - 90% CL $R_{\mu e} < 5.9 \times 10^{-16}$
  - 1,000x improvement over SINDRUM-II
- Run-II data-taking starts in 2029 to reach 10,000x improvement

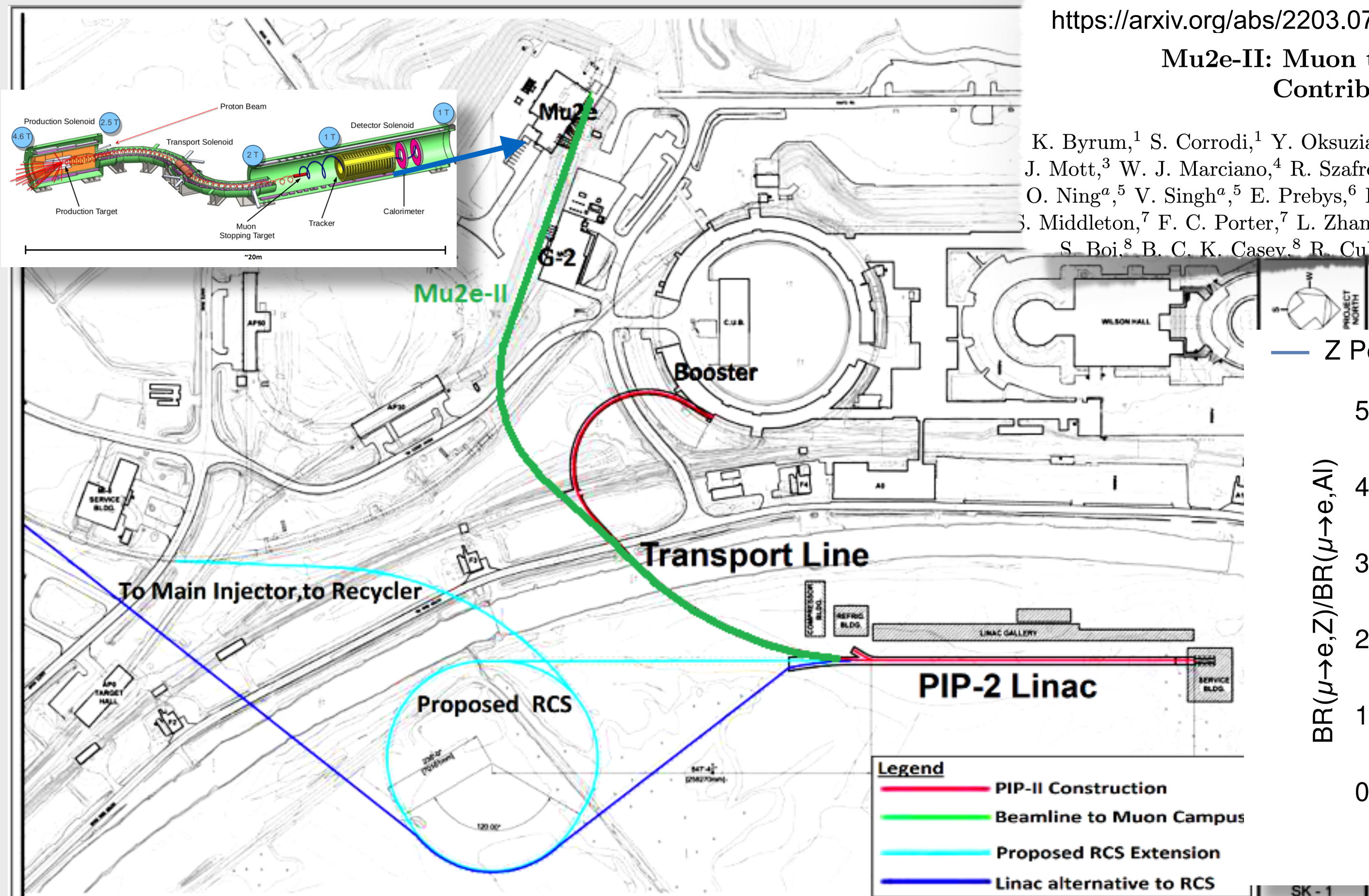
Signal and Background PDFs for $R_{\mu e} = 10^{-15}$

Total background: 0.11 ± 0.03 (stat.+syst.) events



# Mu2e-II@PIP-II

- If approved, Mu2e-II will improve $R_{\mu e}$ sensitivity by $\times 10$ beyond Mu2e limits
  - Refurbish as much of Mu2e infrastructure as possible
  - Upgrade Mu2e components to handle higher beam intensity
  - Expected 5 years of physics run in the next decade
- Mu2e will use 100kW 800 MeV protons from Proton Improvement Plan-II (PIP-II)




https://arxiv.org/abs/2203.07569 March 17, 2022

**Mu2e-II: Muon to electron conversion with PIP-II**
**Contributed paper for Snowmass**

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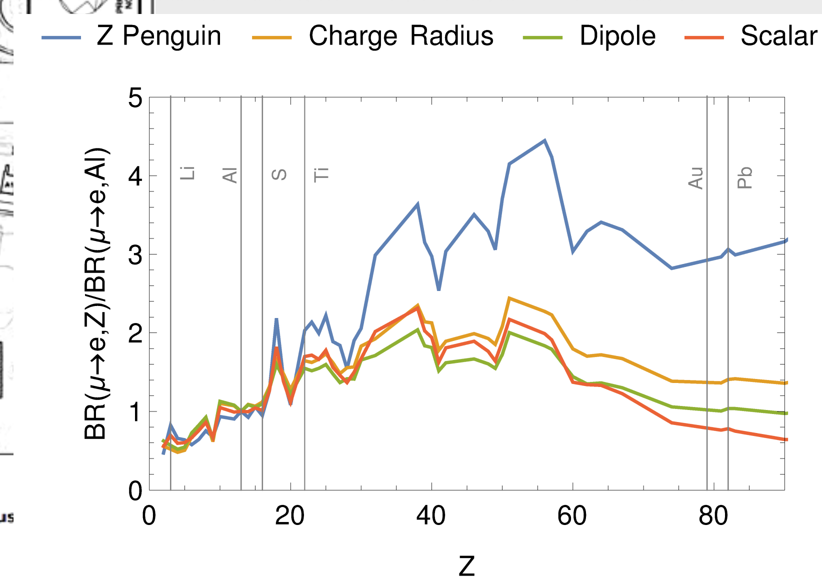
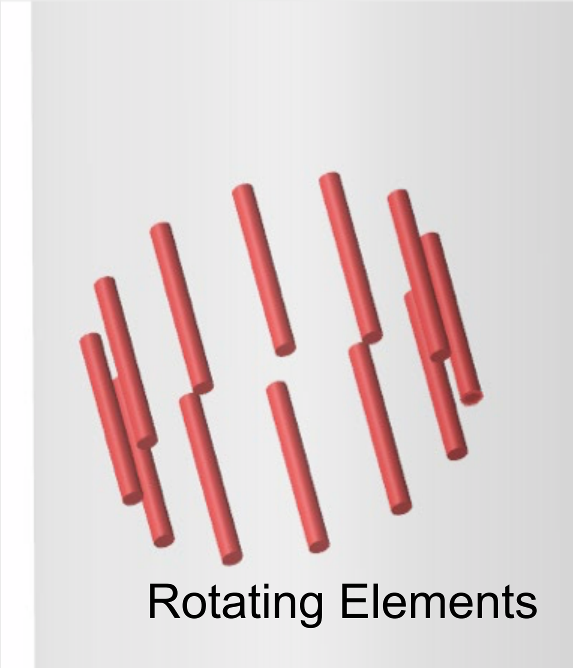
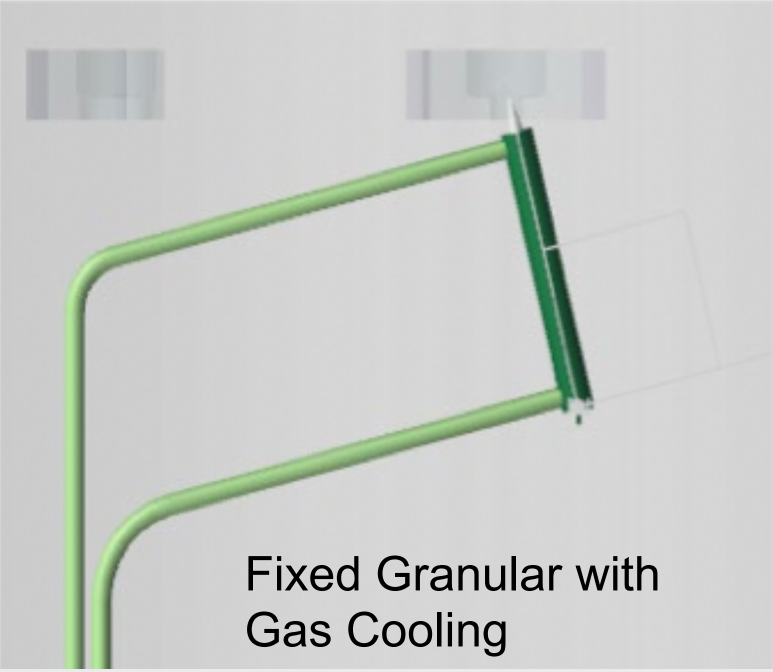
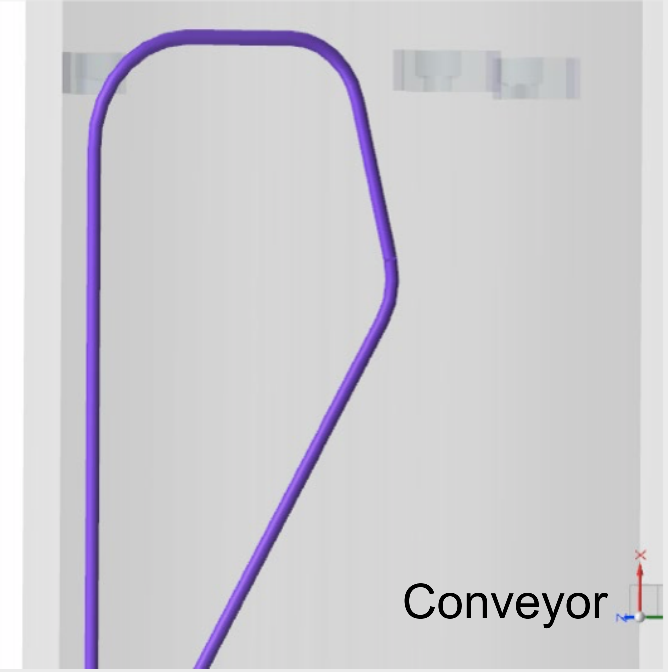


# Mu2e-II: production target

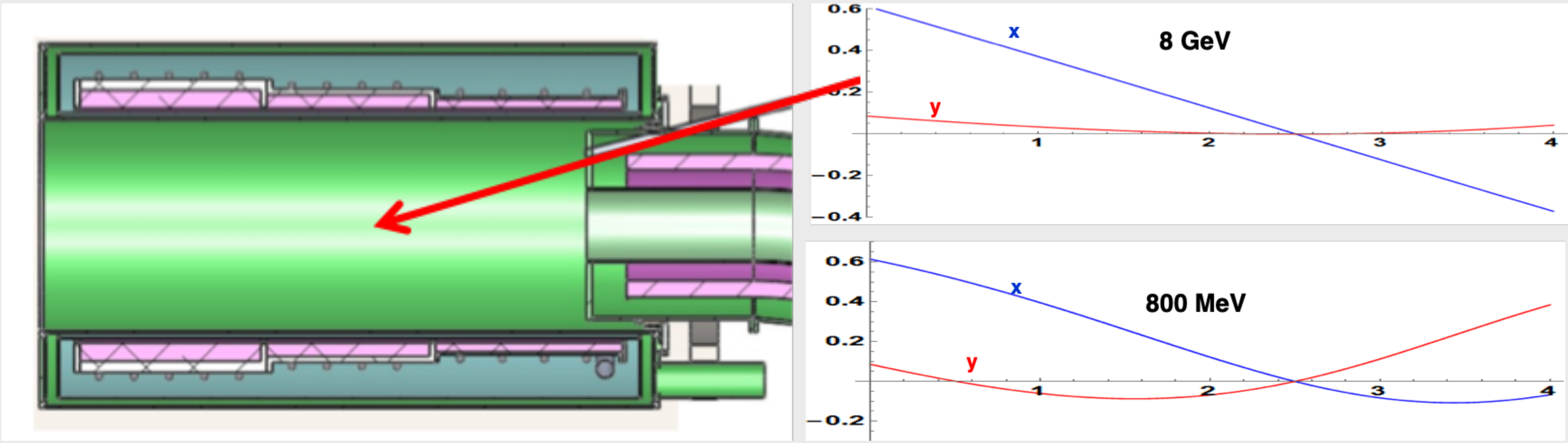
- Fermilab's LDRD project investigates production targets that survive Mu2e-II beam intensities: rotating, granular, conveyor concepts
- Simulation of: muon yield, thermal stress, radiation damage, residual activation, radiation loads
- In out Mu2e-II sensitivity study, we have considered conveyor type production target with carbon spheres
  - Early prototype has been fabricated



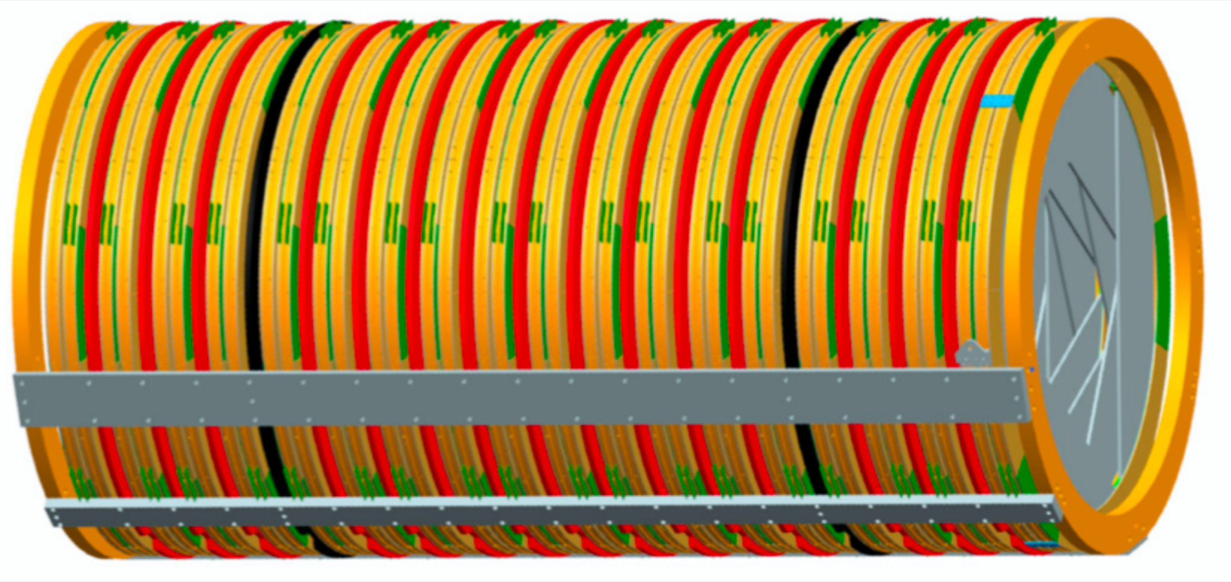



- Aiming the beam on target: 0.8 GeV (Mu2e-II) vs 8 GeV (Mu2e)
  - It also impacts the position of beam dump and extinction monitor position
- To hit the target Mu2e-II will optimize the following parameters
  - Vertical and horizontal incoming angles
  - Production target location
  - Production Solenoid magnetic field

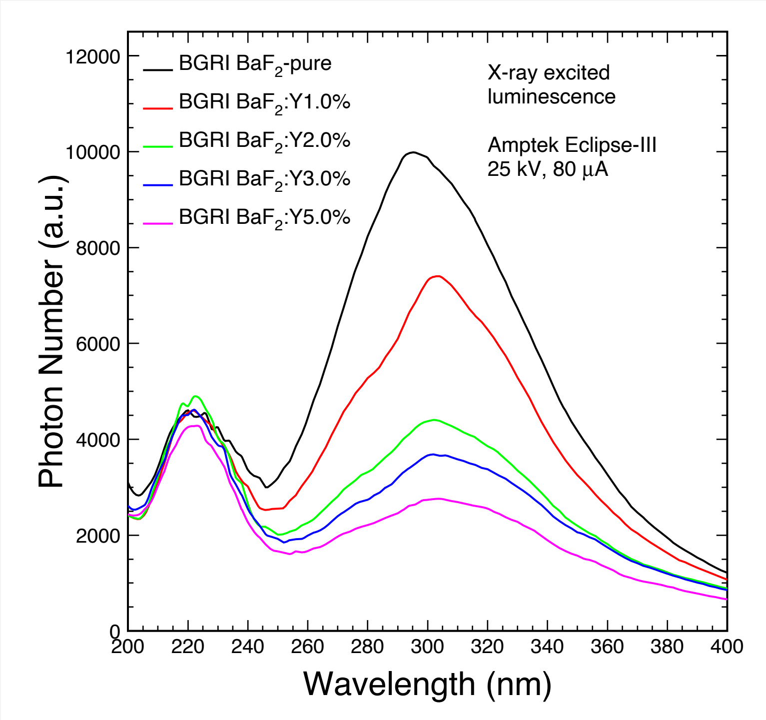


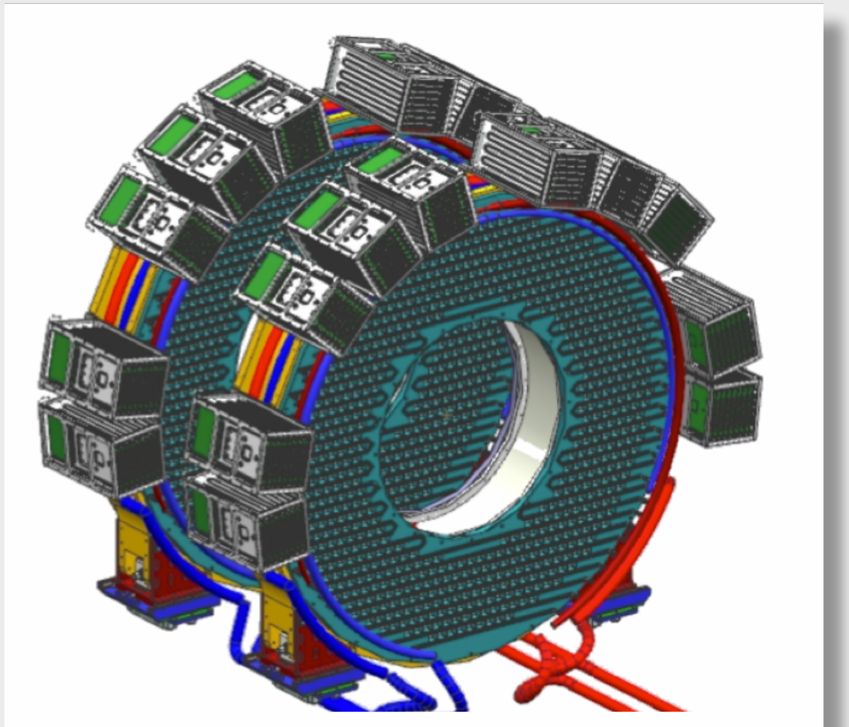
- Conversion electron momentum at Mu2e is reconstructed using straw tracker
- Expected Decay In Orbit (DIO) background at Mu2e: 0.144 events
  - DIO background would increase 10x at Mu2e-II, linear to the number of stopped muons
- Improve momentum resolution to suppress DIO by reducing straws thickness: $15\ \mu m \rightarrow 8\ \mu m$
  - In this study, we also reduced the momentum window $1.05\ MeV \rightarrow 0.85 MeV$ to further suppress DIO



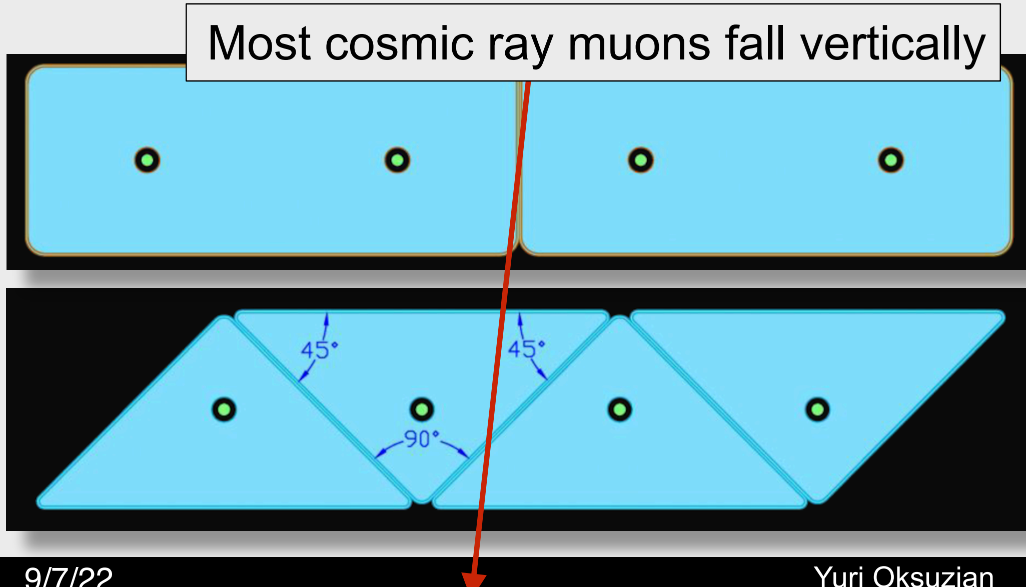
| | Mu2e | Mu2e-II |
|---|---|---|
| Wall thickness (μm) | 18.1 | 8.2 |
| Al thickness (μm) | 0.1 | 0.2 |
| Au thickness (μm) | 0.02 | 0.0 |
| Linear Density (g/m) | 0.35 | 0.15 |
| Pressure limits (atm) | 0–5 | 0–3 |
| Elastic Limit (gf) | 1600 | 500 |

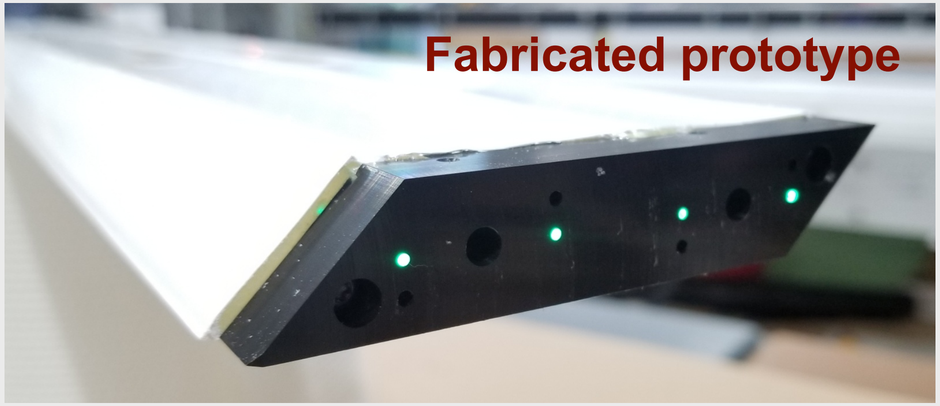
- Requirements: $\sigma_E/E < 10\,\%\ @\,100MeV$ and $\sigma_t < 500\ ps\,@\,100MeV$
- CsI can't handle rad doses and crystals occupancy at Mu2e-II
  - $< Mrad,\ 10^{13}\ n_{1MeV-eq}/cm^2$
- $BaF_2$ is an excellent candidate: rad hard (< 100 Mrad)
  - Challenge: slow component can cause pileup
  - Suppress the slow scintillation component by doping $BaF_2$ with (Y)ttrium, (La)nthanum...
  - Develop solar-blind photosensor: SiPMs with an external filter or UV-sensitive photocathodes



- Expected live-time and hence cosmic ray background is >3x higher at Mu2e-II
  - Use alternative CRV design to enhance the detection efficiency
- Higher (>x3) rad doses: higher DAQ rates, dead-time, rad damage
  - Promising results with enhanced shielding: tungsten PS and boron doped heavy concrete
- Cosmic ray background sources undetectable by CRV:
  - Cosmic ray neutrons is a significant (~0.6) source, if not addressed with enhanced shielding
  - Muons entering through un-instrumented CRV region is small (<0.1), but challenging to suppress contribution



# Summary

- Mu2e has a great discovery potential and can reveal New Physics
- Mu2e will improve over previous conversion experiments by 4 orders of magnitude and will probe new physics mass scales of $10^4$ TeV
- Mu2e will provide complimentary information to the LHC and test the existence of new particles that are too heavy to be produced directly at colliders
- Plan to start data-taking in 2025(6)