The Mu2e Experiment at Fermilab

Yuri Oksuzian, DPF 2017

Mu2e

- Quarks and neutrinos mix
  - Do charged lepton flavors mix as well?
- Mu2e will search for neutrino-less, coherent muon conversion into an electron

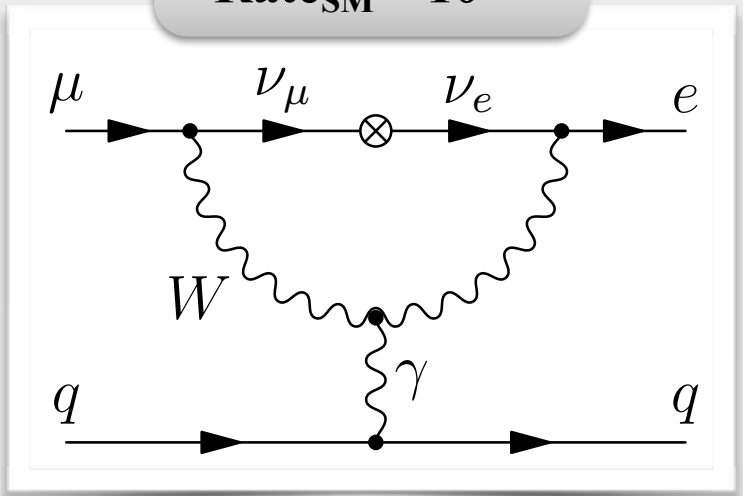
$$\mu^- + N \rightarrow e^- + N$$

- Neutrino-less $\mu \rightarrow e^-$ conversion is Charge Lepton Flavor Violation (CLFV)

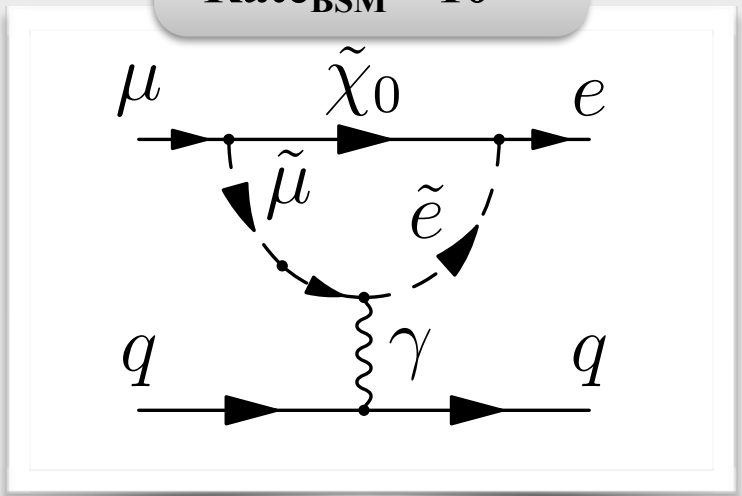
$$\mu \rightarrow e\gamma, \quad \mu \rightarrow 3e, \; \tau \rightarrow e\gamma, \; \tau \rightarrow \mu\gamma ...$$

- In the SM, $\mu \rightarrow e^-$ occurs at the rate of $<10^{-50}$
  - Signal observation at Mu2e is unambiguous sign of new physics

$\text{Rate}_{\text{SM}} < 10^{-50}$



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



What do we measure?

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

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

Numerator

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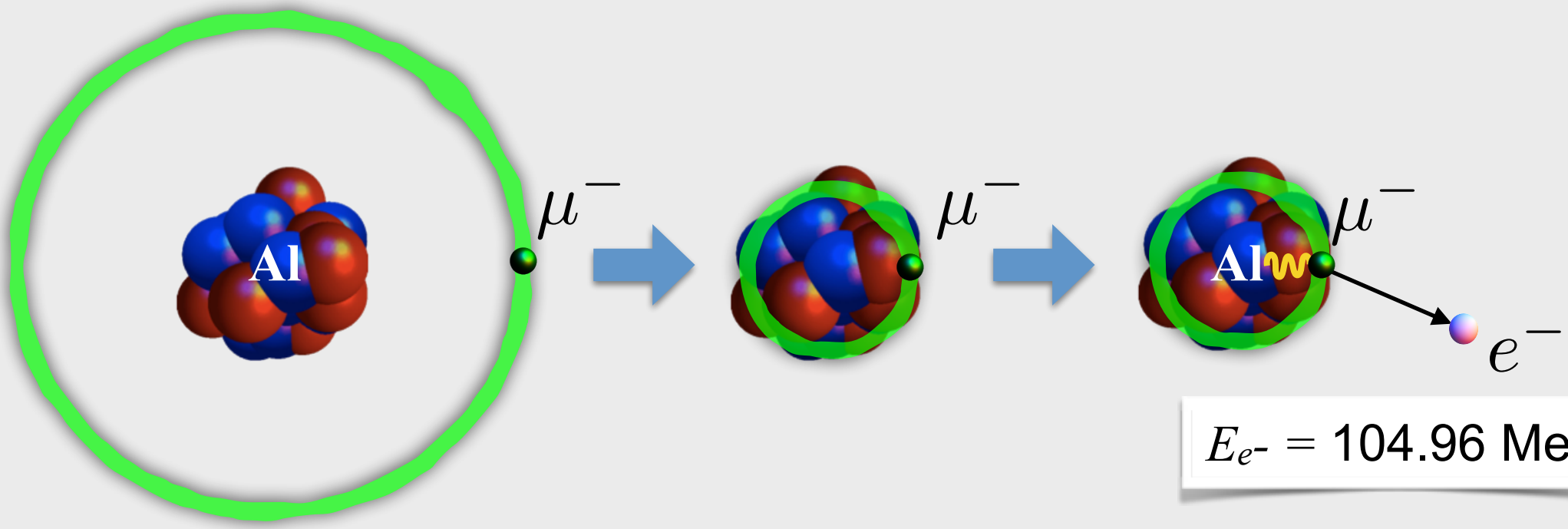

$E_{e^-} = 104.96$ MeV

Denominator

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

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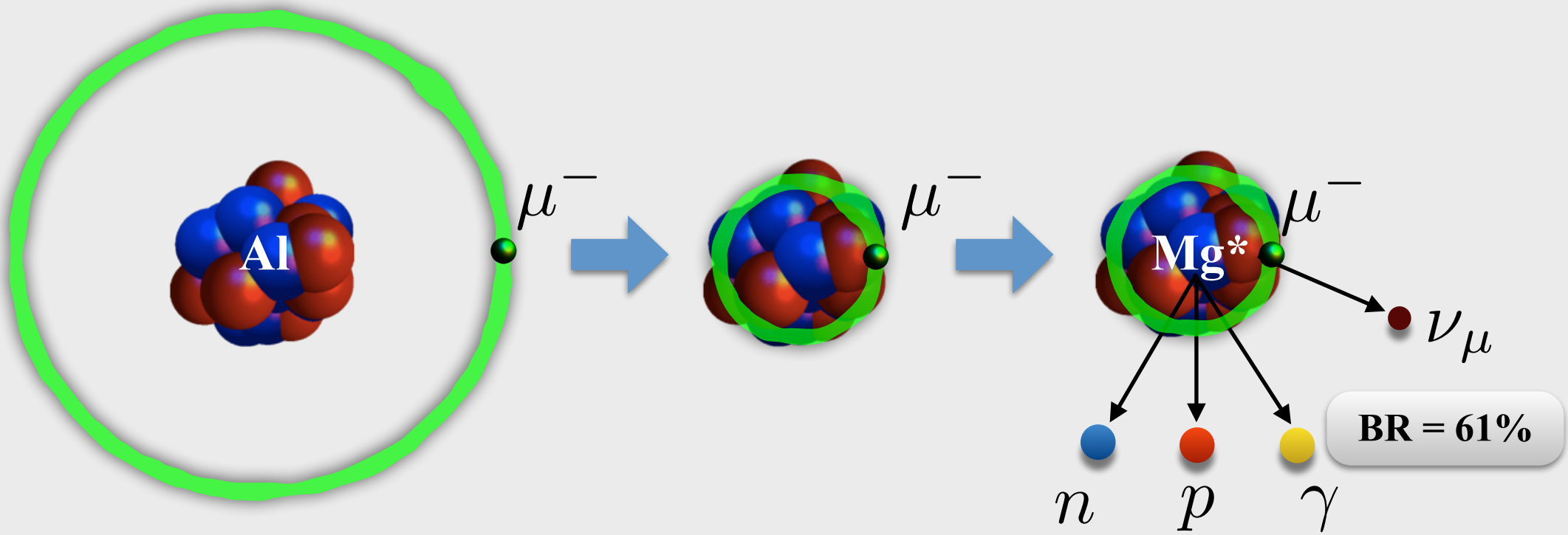

Irreducible background

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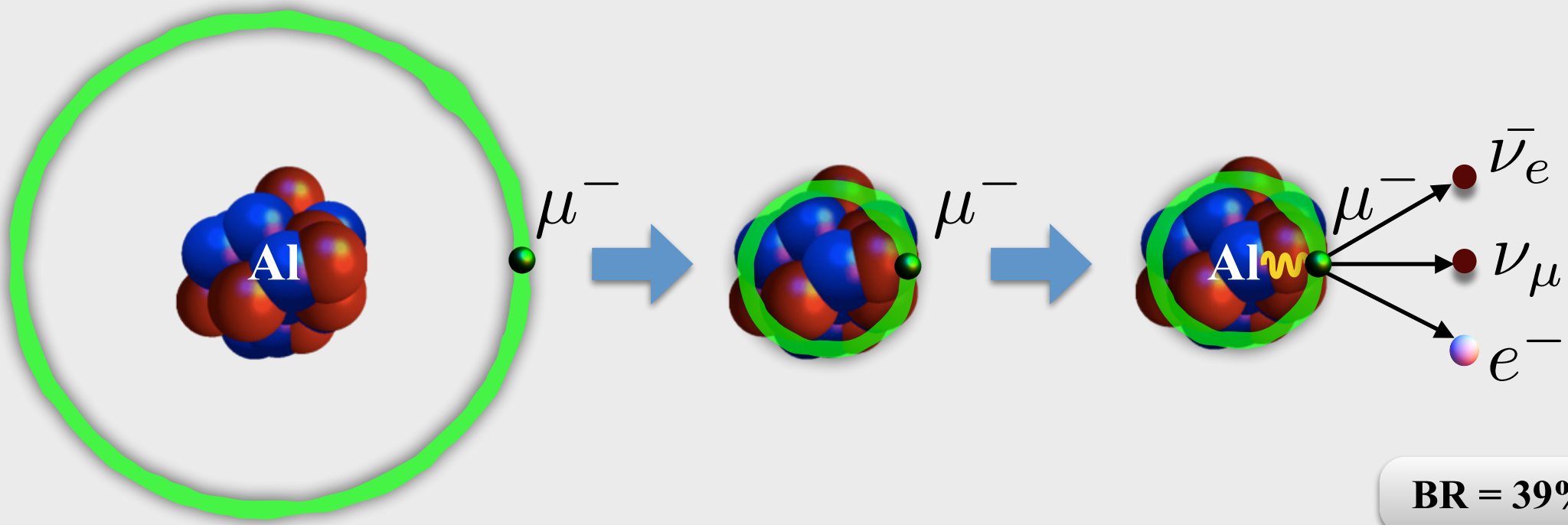

BR = 39%

Mu2e Sensitivity

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

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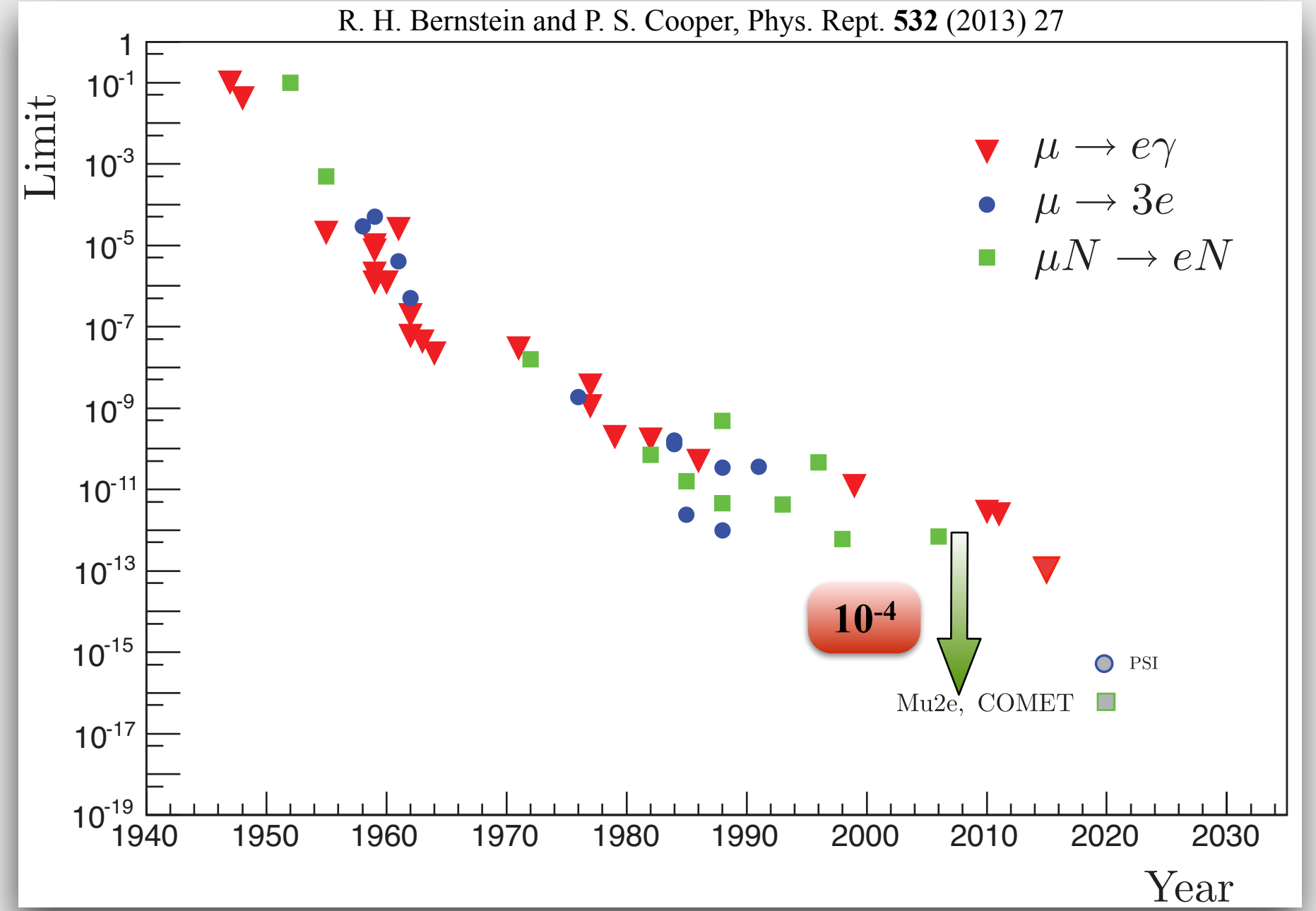
- Mu2e single event sensitivity: $R_{\mu e}$ = 3×10^{-17}
  - Expect 7 events and 5σ discovery sensitivity at $R_{\mu e}$ = 2×10^{-16}
- Expected limit: $R_{\mu e}$ = 8×10^{-17} @ 90% CL
- Mu2e needs to stop ~10^{18} muons
  - 3.6×10^{20} protons on target (POT) over 3 years
- Need to keep background small and well understood
  - Total expected background 0.4 events

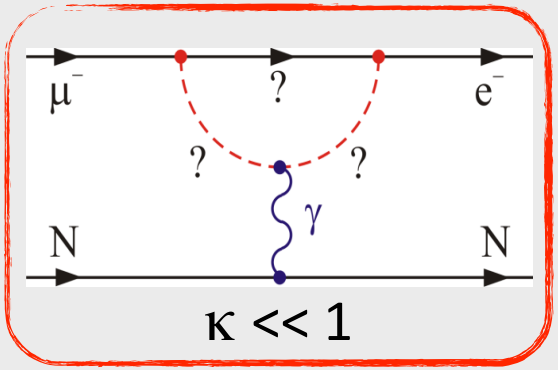
History of CLFV Searches



Mu2e Physics Reach

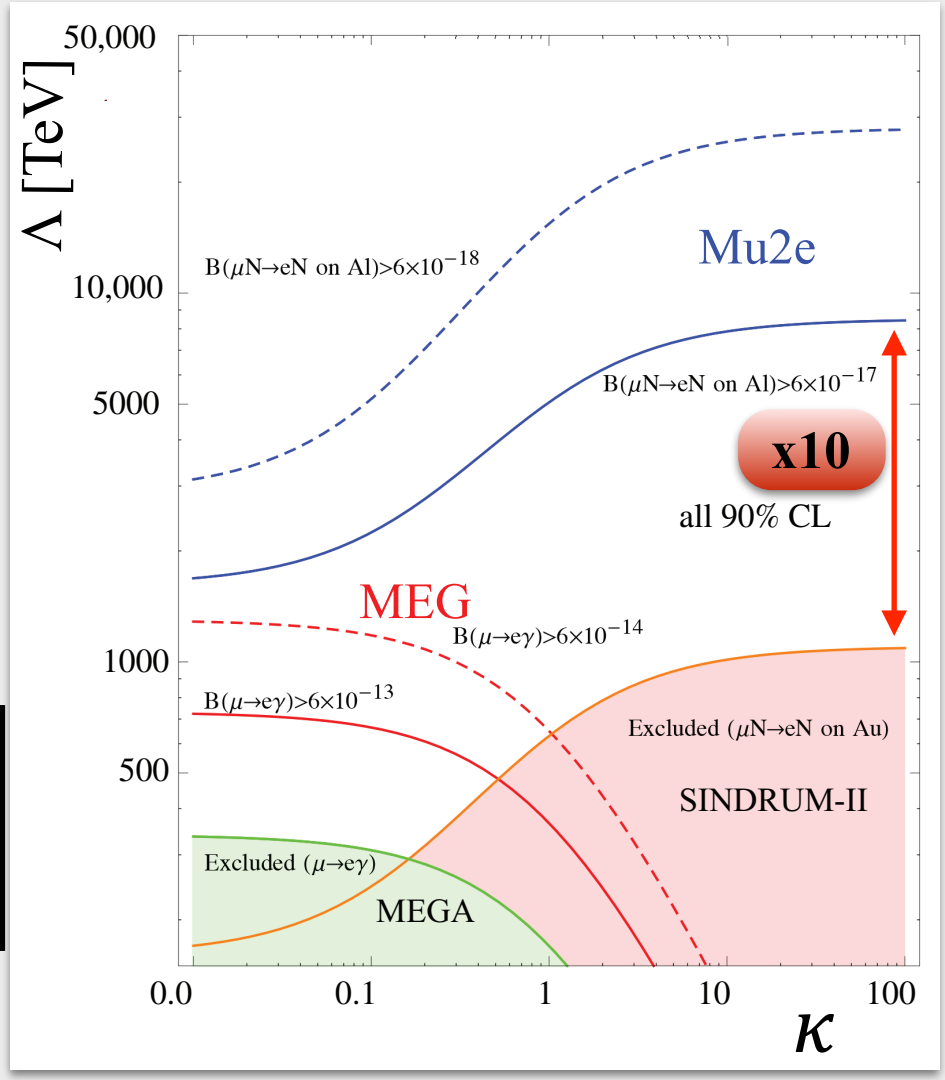
Effective CLFV Lagrangian

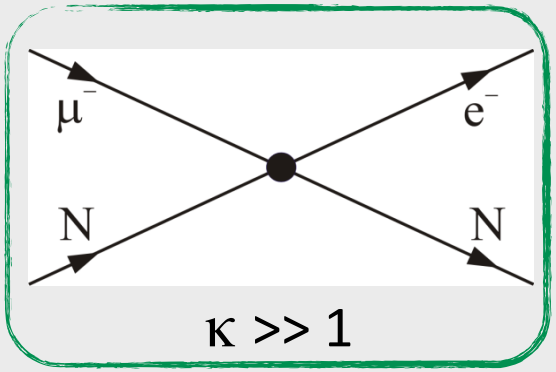
$$L = \frac{m_\mu}{(\kappa+1)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(\kappa+1)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L \sum_{q=u,d}\bar{q}_L\gamma_\mu q_L$$



Magnetic moment type operator

State	μ→eγ	μ→e
Sensitive	Yes	Yes





Contact term operator

State	μ→eγ	μ→e
Sensitive	No	Yes

Mu2e Physics Reach

Effective CLFV Lagrangian

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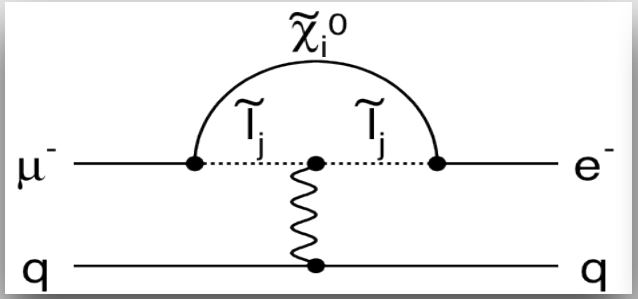
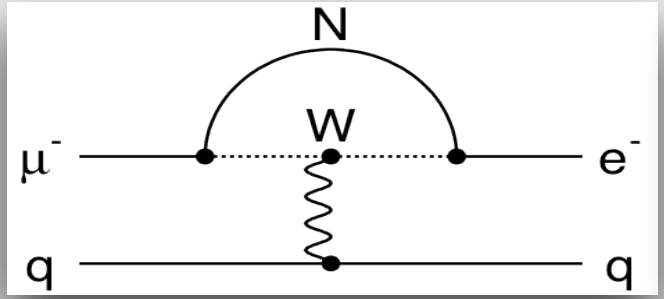
Magnetic moment type operator

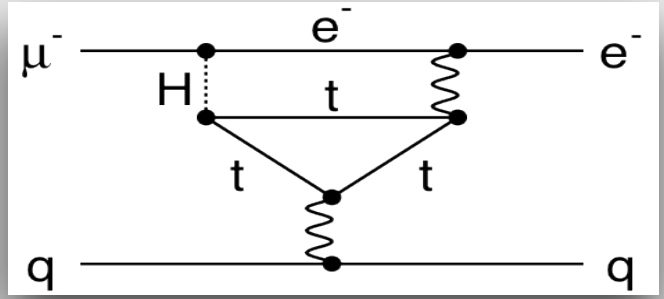
Supersymmetry



Heavy neutrinos

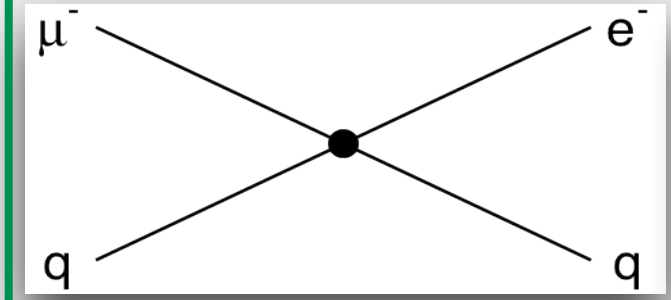


Two Higgs Doublets

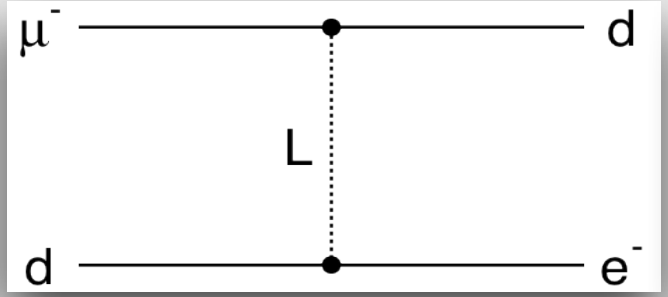


Contact term operator

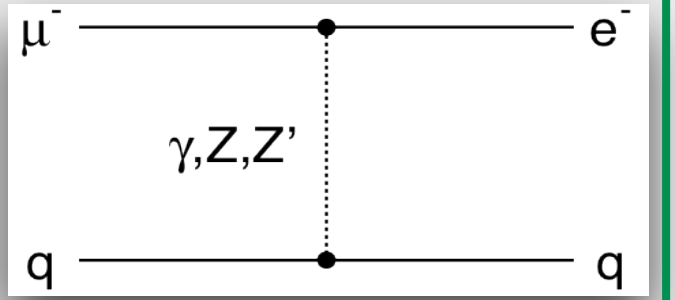
Compositeness



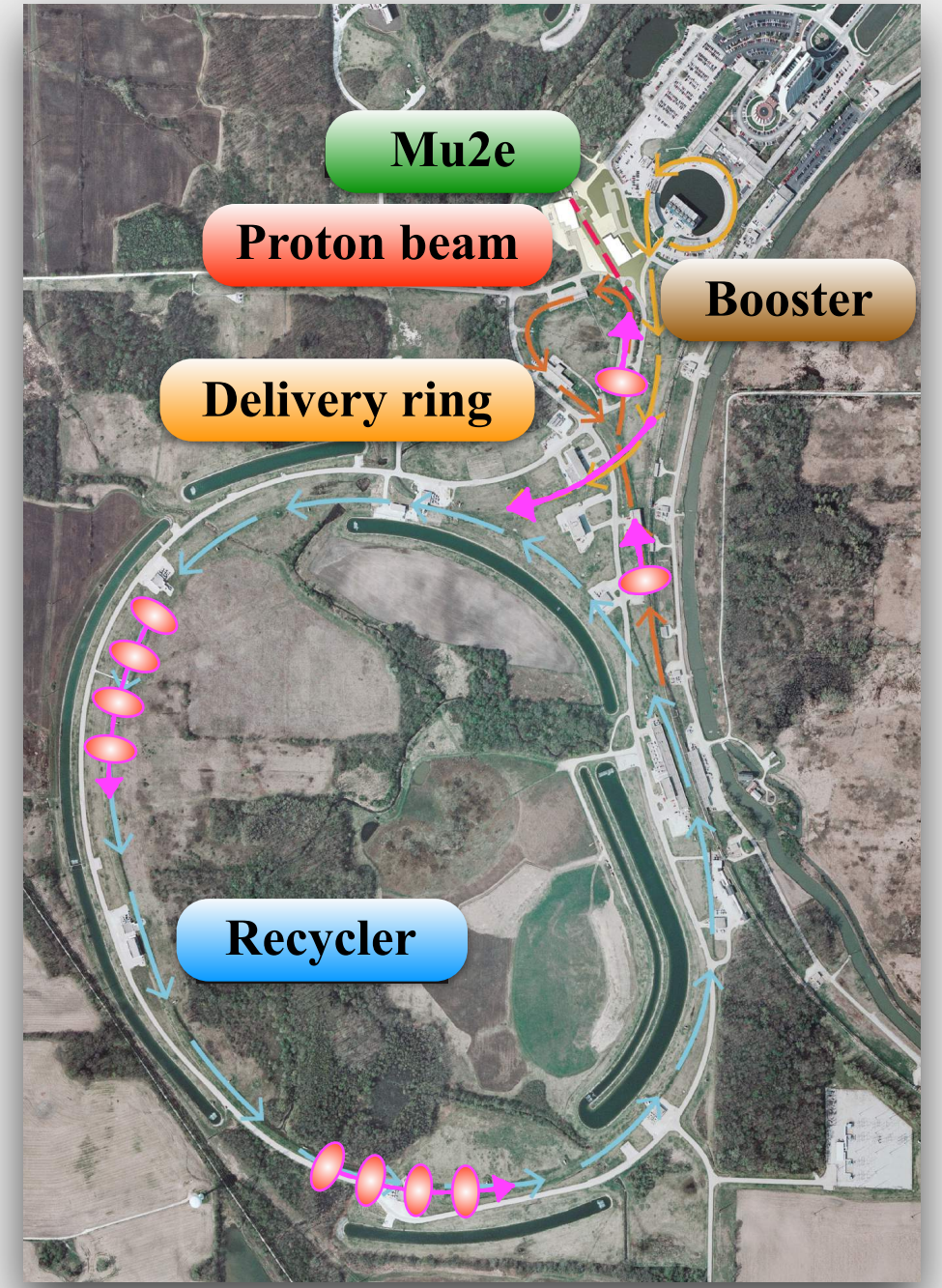
Leptoquarks



Heavy Z'

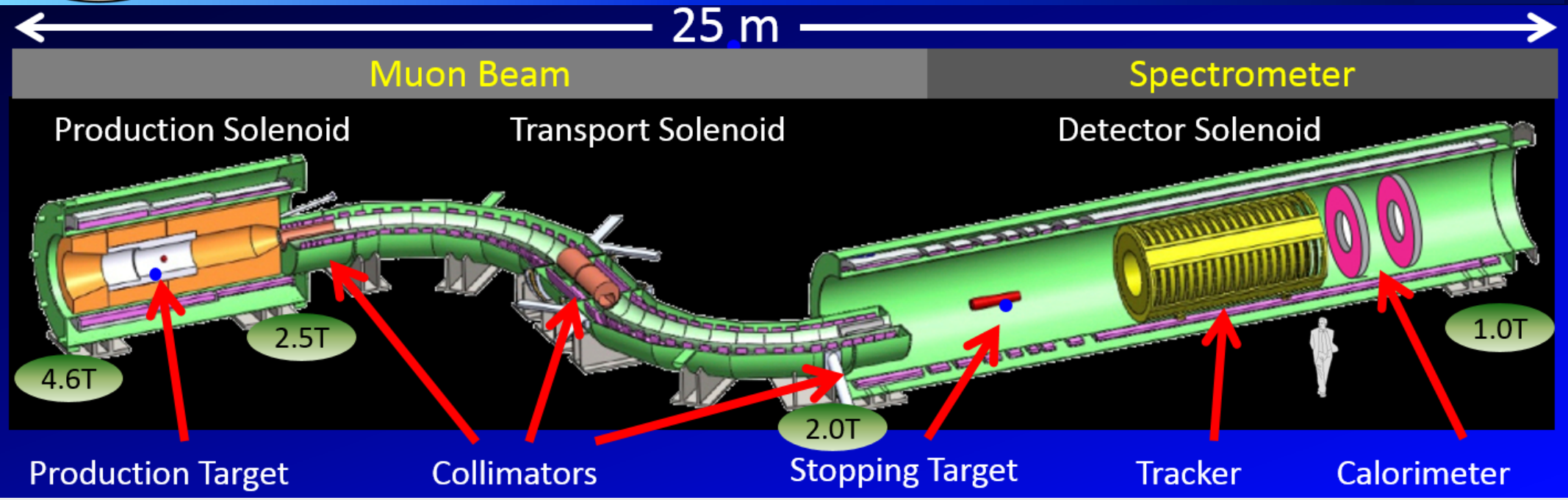


Mu2e proton beam



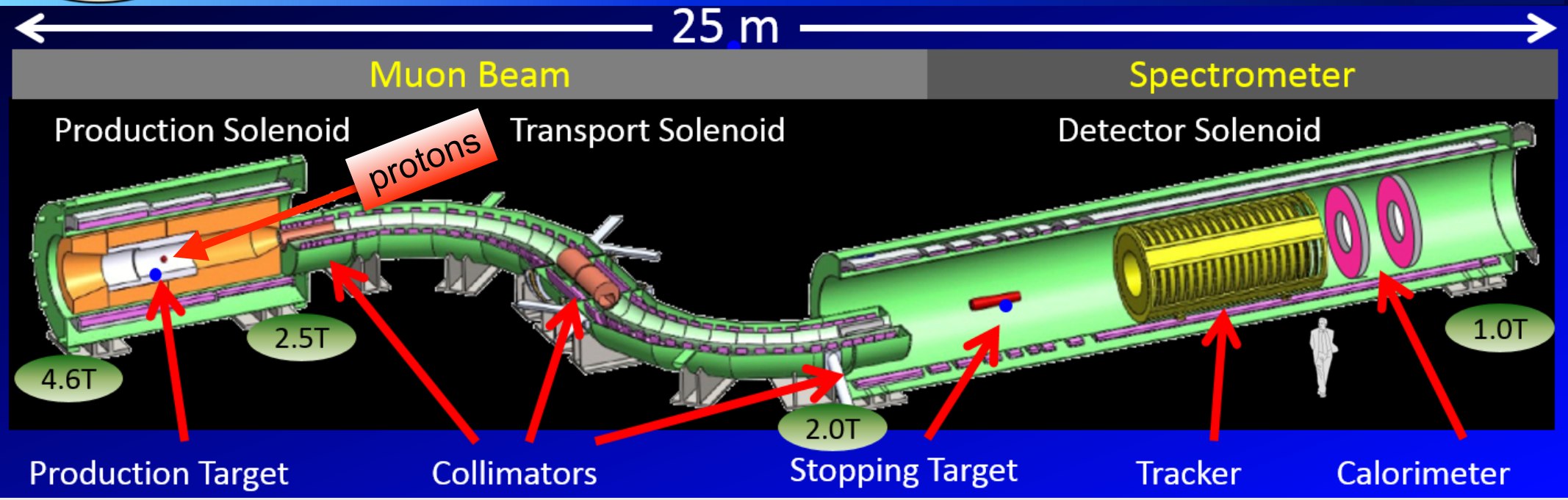
- Mu2e will recycle the existing accelerator infrastructure
- **Booster** provides batches of 8 GeV protons to recycler
- **Recycler** divides proton batches into 8 smaller bunches
- **Delivery ring** gets 1 out of 8 bunches from recycler
- **Mu2e** gets the **proton beam** pulses from delivery ring every 1695 ns

Mu2e apparatus



1. **Every 1695 ns, 8 GeV protons hit production target to produce π^-**
   - π^-/μ^- are reflected toward the transport solenoid
2. **Transport Solenoid delivers π^-/μ^- to Detector Solenoid**
   - Selects particle's momentum and charge
   - Avoids direct line of sight
3. **Muons stop on the Al Stopping Target**
   - 1,000 POT → 4(2) muons reach(stop on) the Al target
   - Conversion electron momentum, energy and timing are measured in the tracker and calorimeter

Mu2e apparatus



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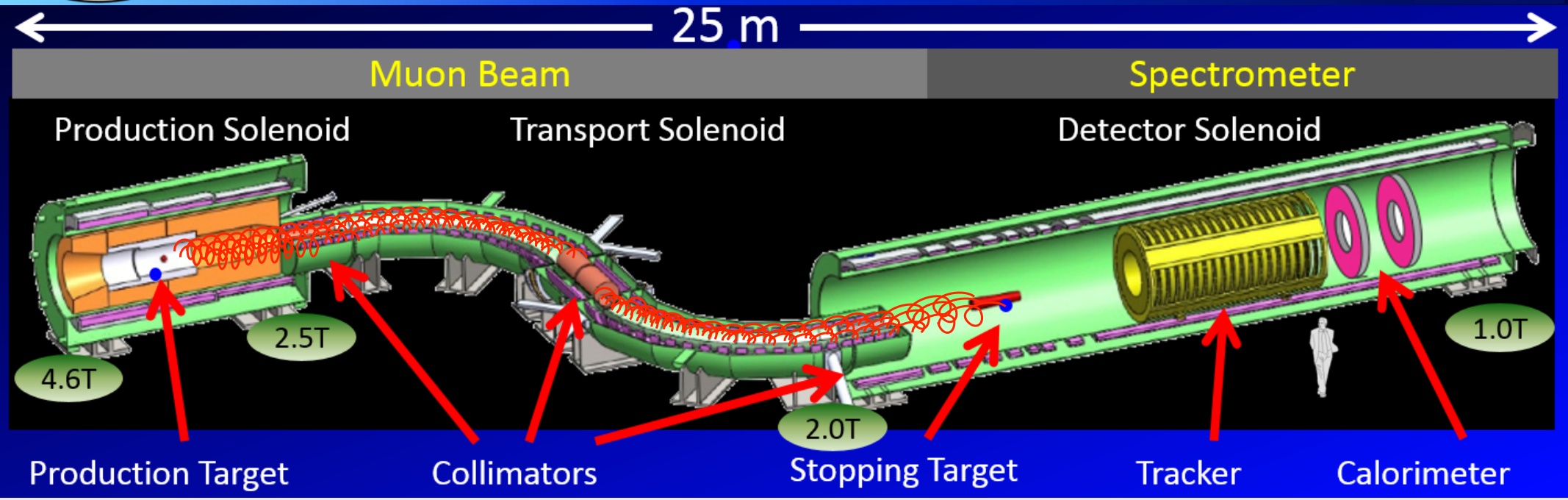

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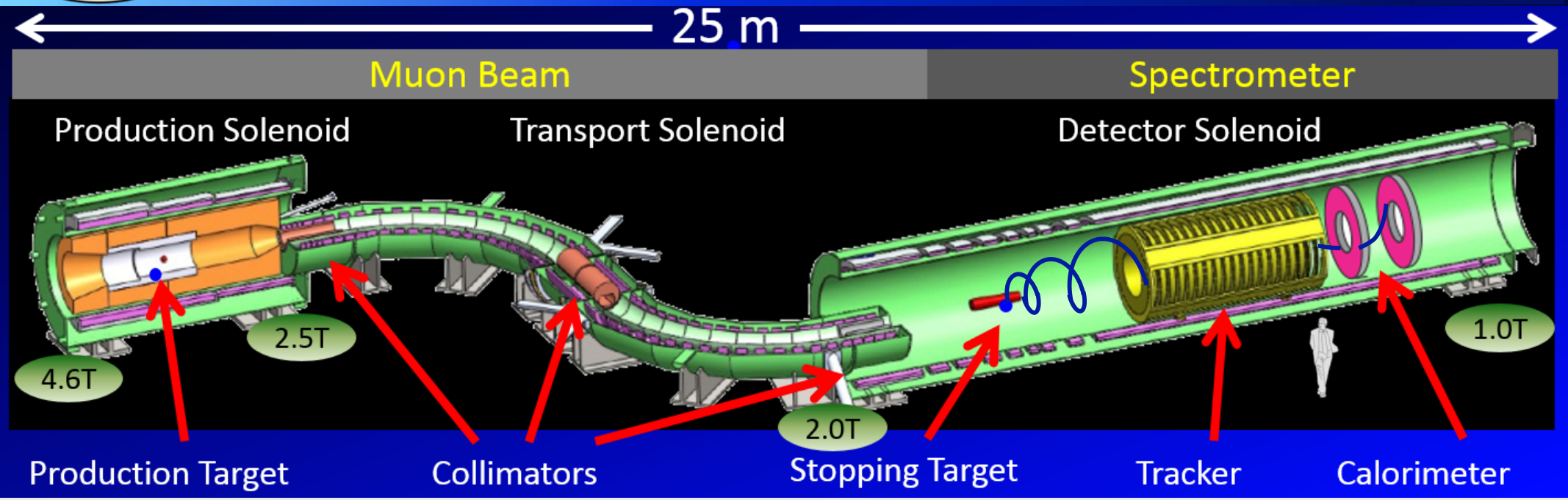

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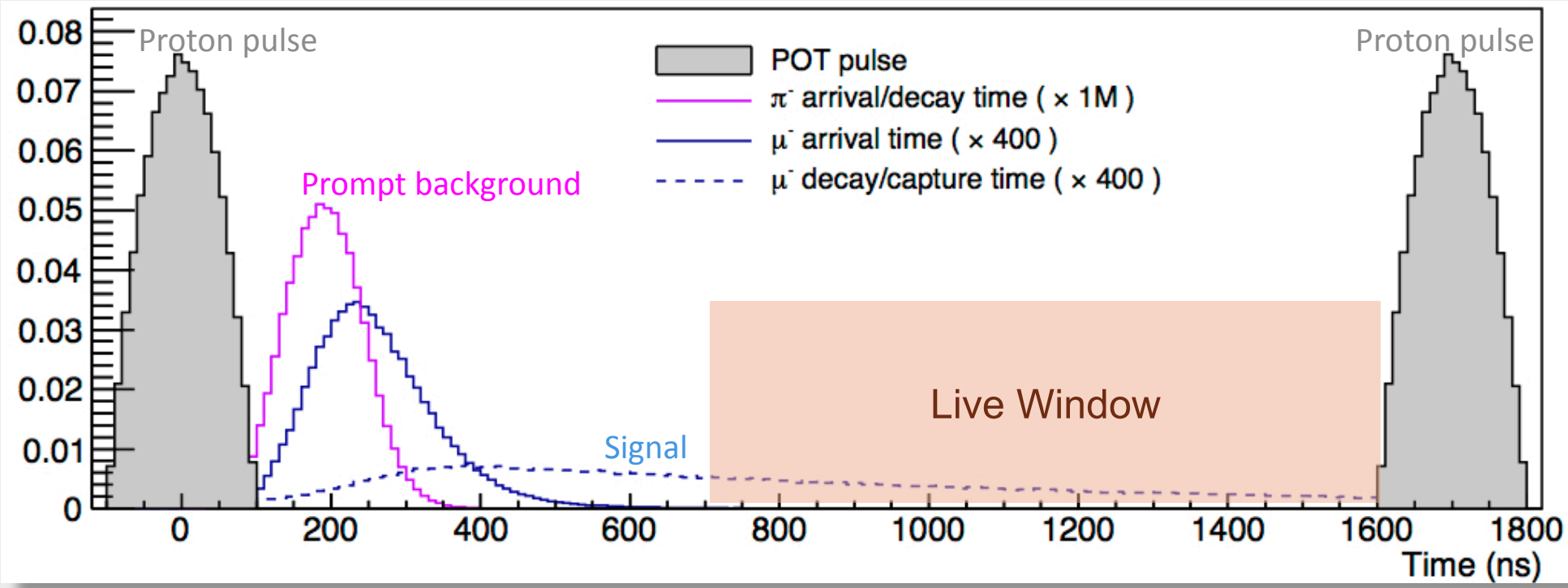
Pulsed beam

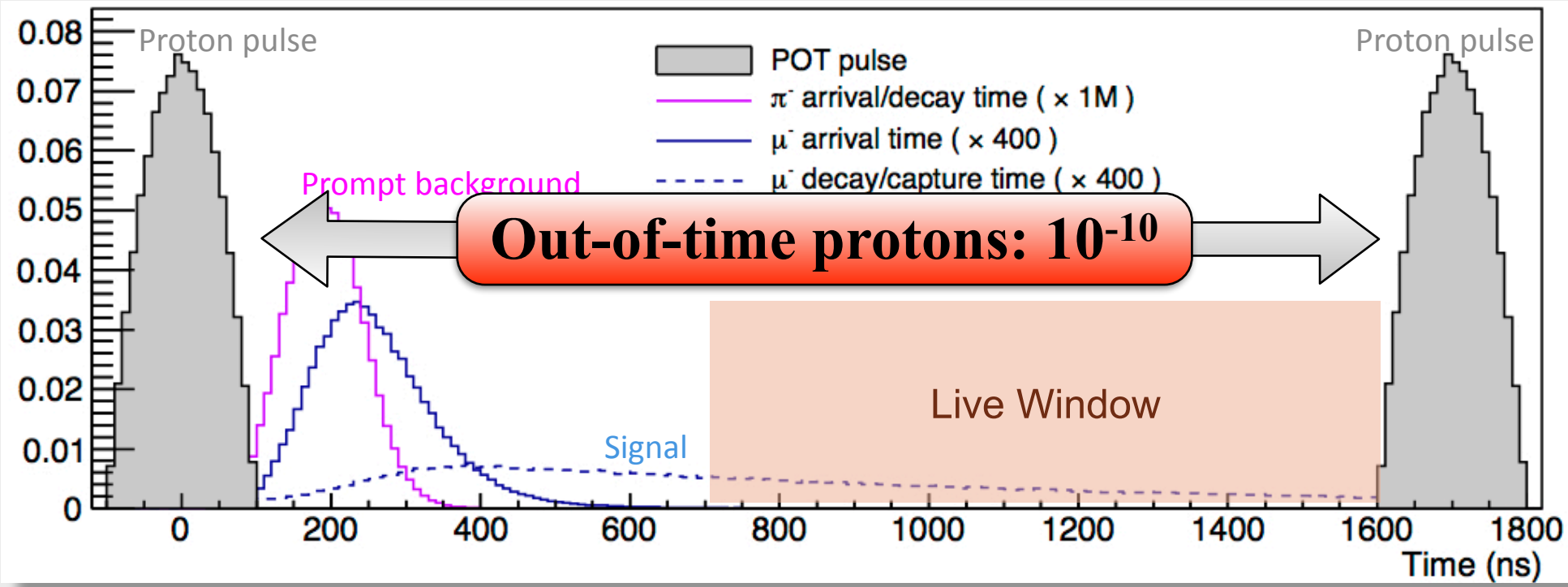


- Prompt background: particles produced by proton pulse which interact almost immediately when they enter the detector
- Muons travel with pions. Pions produce background when captured on target

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

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

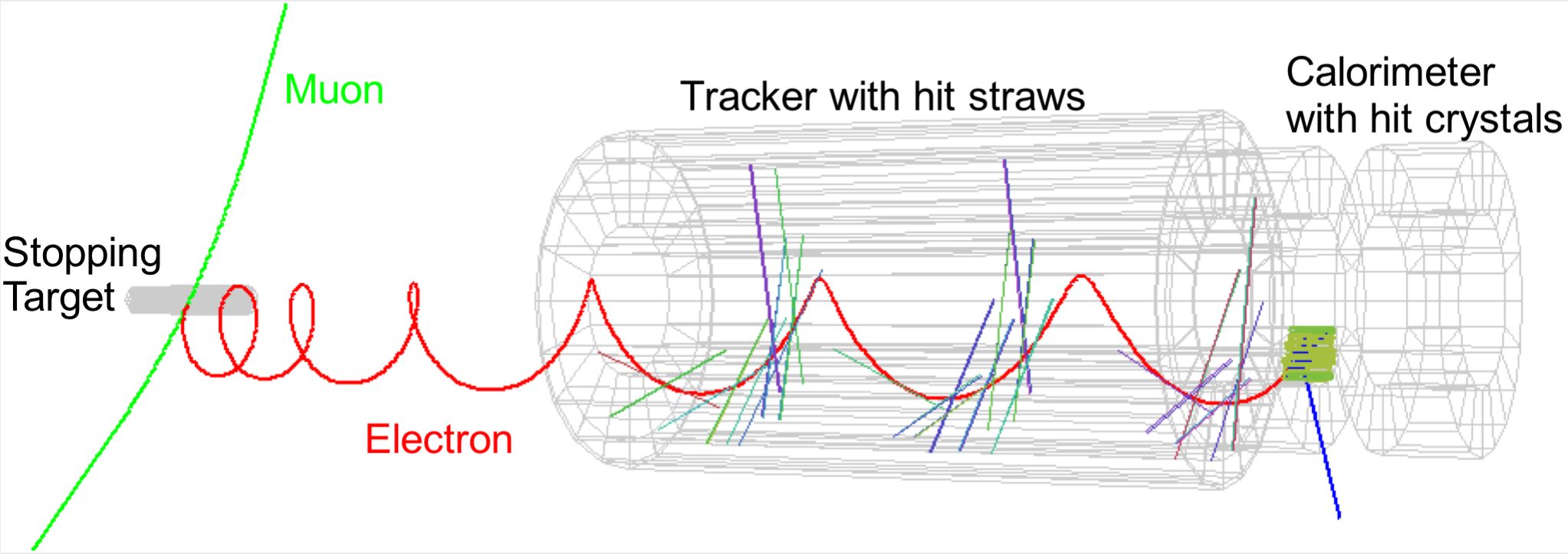
Out-of-time Protons



- 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

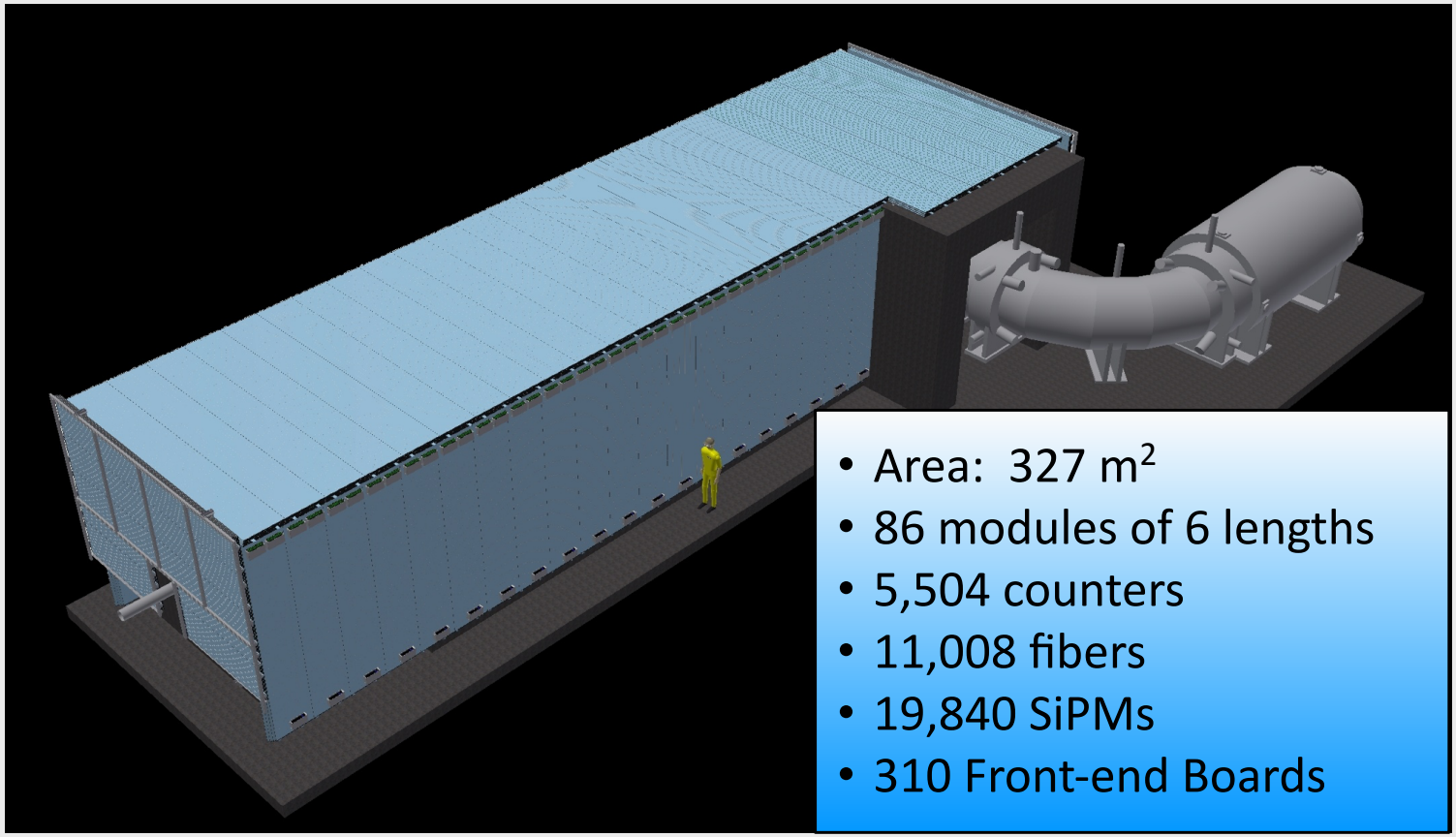
Cosmic Ray Background

- Mu2e expects 1 signal-like event per day induced by cosmic rays
  - Reminder: Total expected background is 0.4 events over 3 years
- Cosmic ray muons produce background though material interactions, decays and muon faking an electron
- To achieve experiment's designed sensitivity, Cosmic Ray Veto detection efficiency is required to be > 99.99%



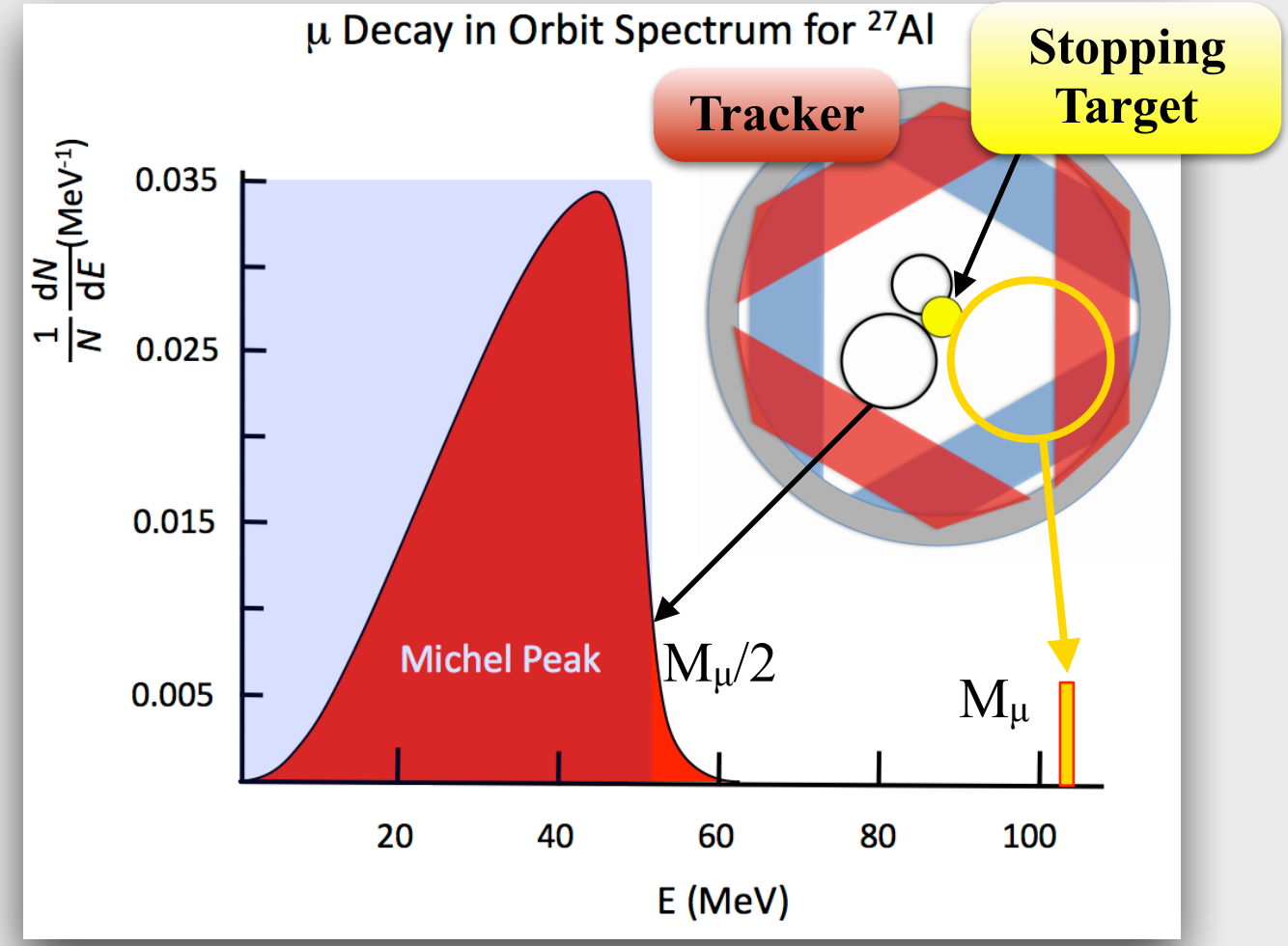
Cosmic Ray Veto

- CRV consists of 4-layer scintillating 5x2 cm^2 counters, read-out through wavelength-shifting fibers by 2x2 mm^2 SiPMs
- Cosmic ray muon detection - hits coincidence in 3/4 layers localized in time and space
- Veto (offline) 125 ns from a signal window after a coincidence in the CRV



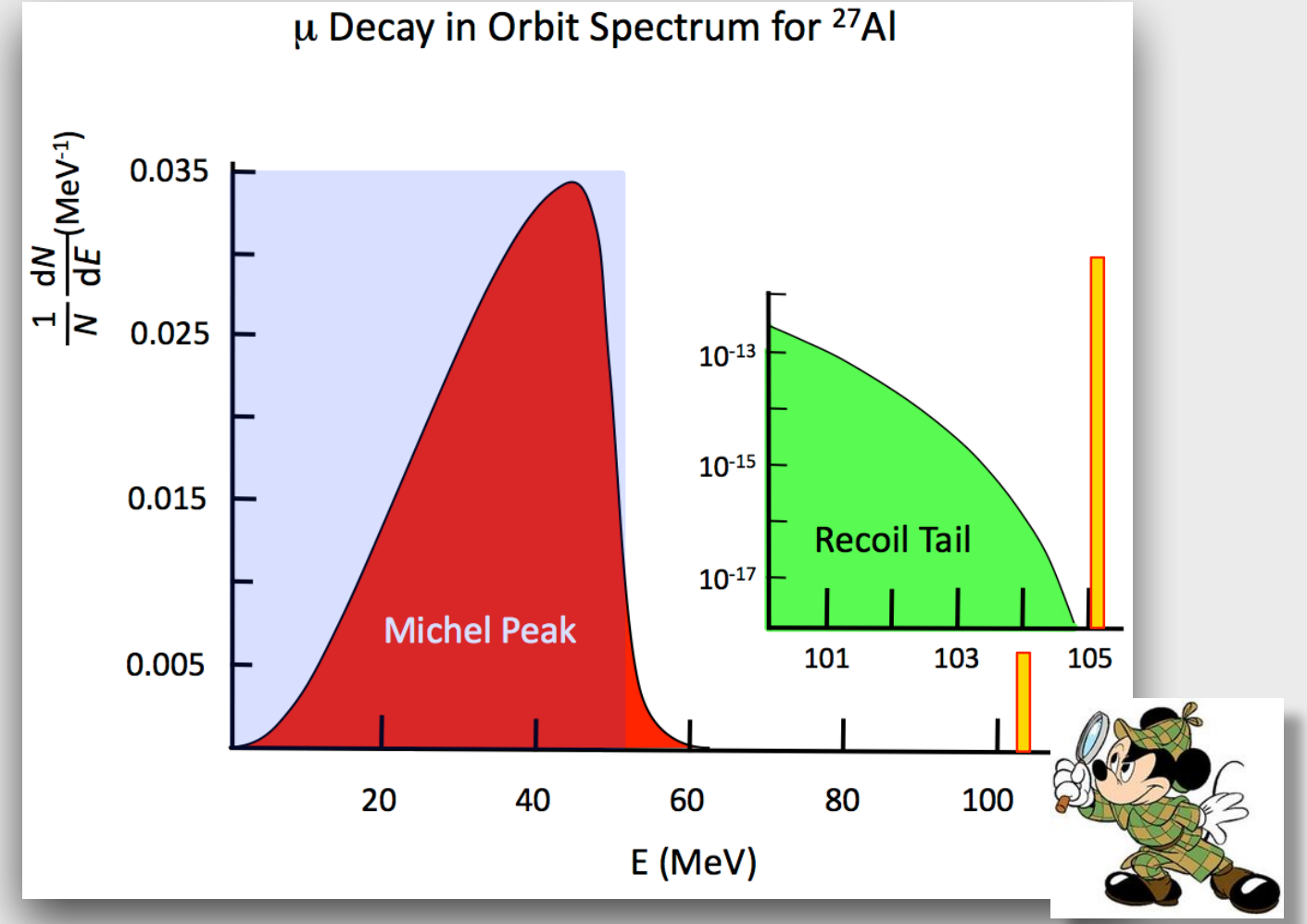
Decay In Orbit

- Muon decays in orbit (DIO) produce irreducible background
- Central part of the tracker is not instrumented
  - blind to 99% of DIO spectrum and beam flash
- Signal electrons travel at higher radii through the tracker fiducial volume



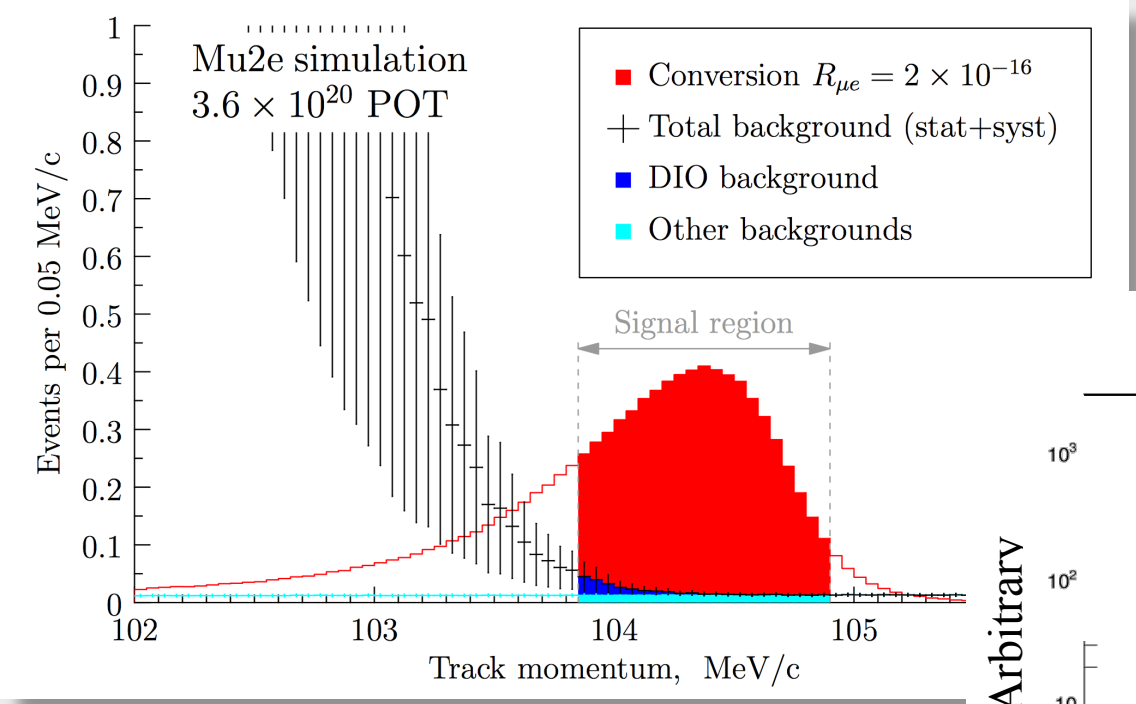
Decay In Orbit

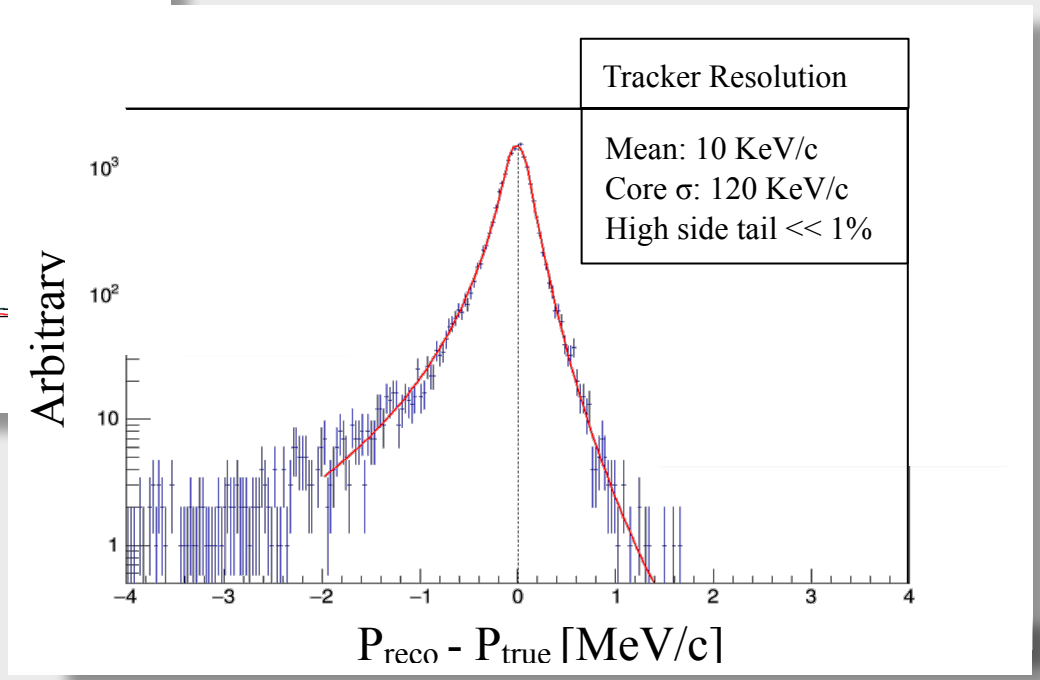
- DIO spectrum spreads to the signal region



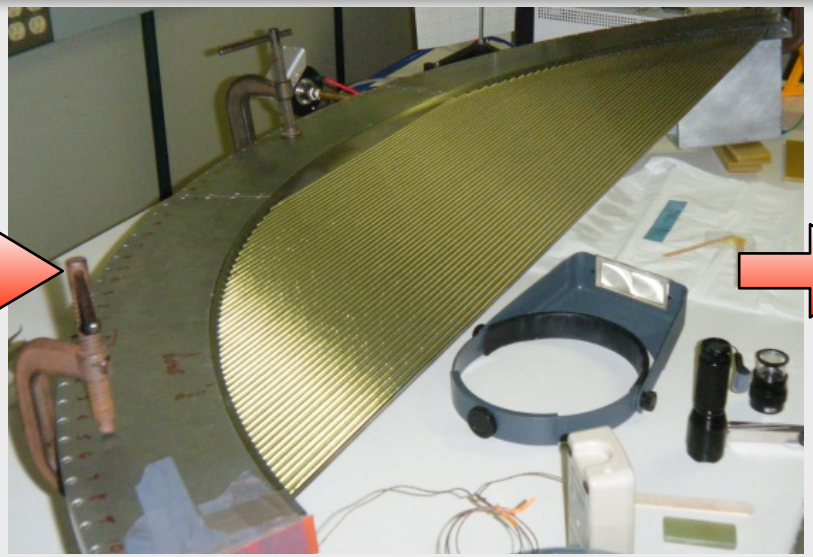
Simulation

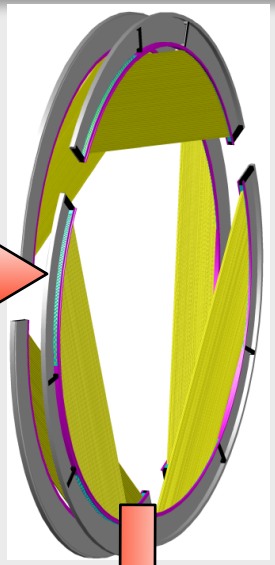
- DIO spectrum spreads to the signal region.
- In addition, signal is smeared due to energy losses
- Need good momentum resolution
  - < 200 KeV/c momentum resolution is achievable

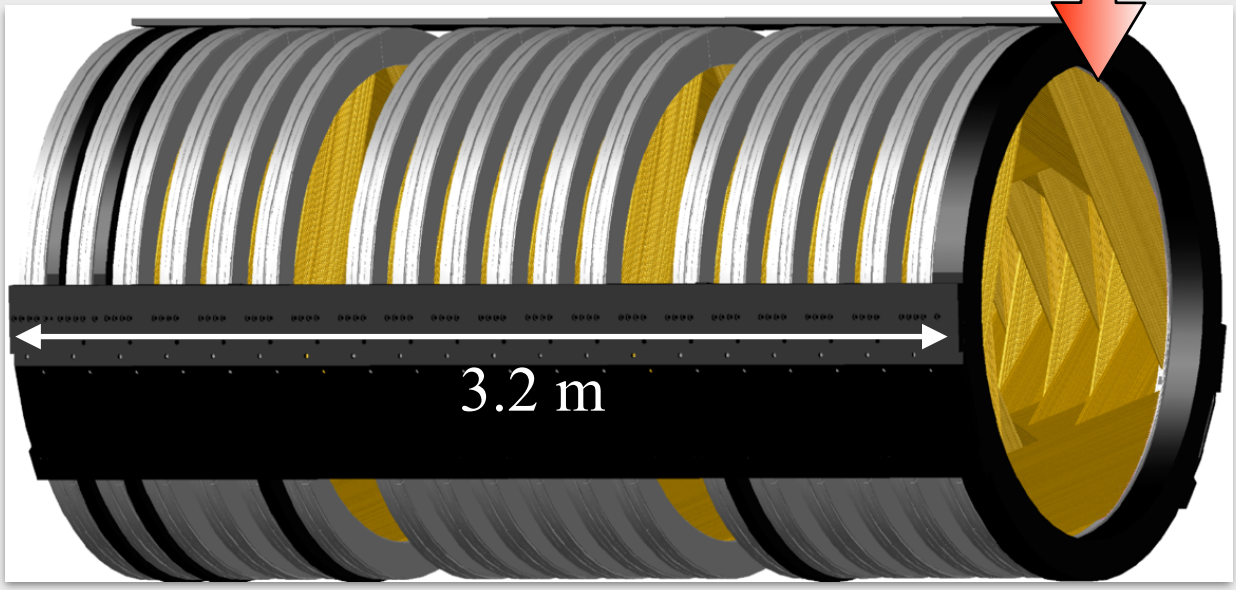




Tracker





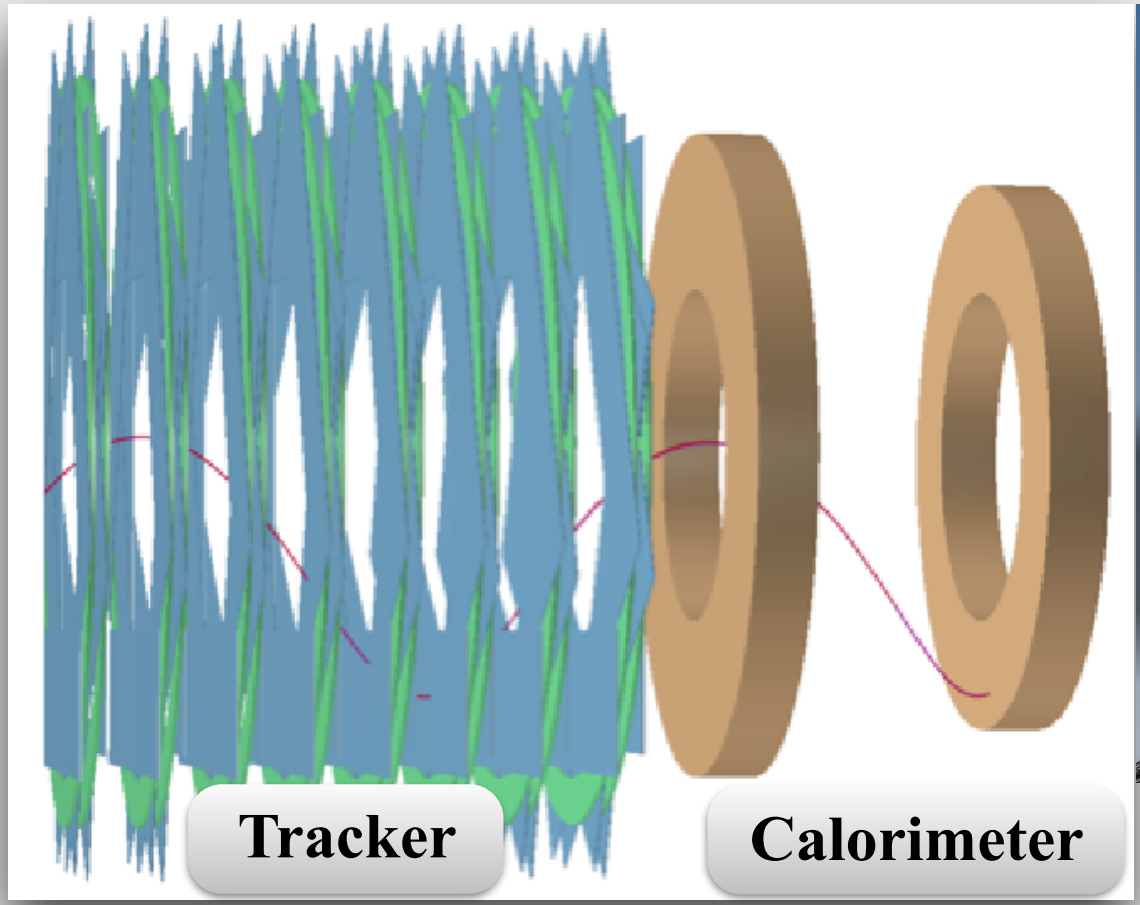


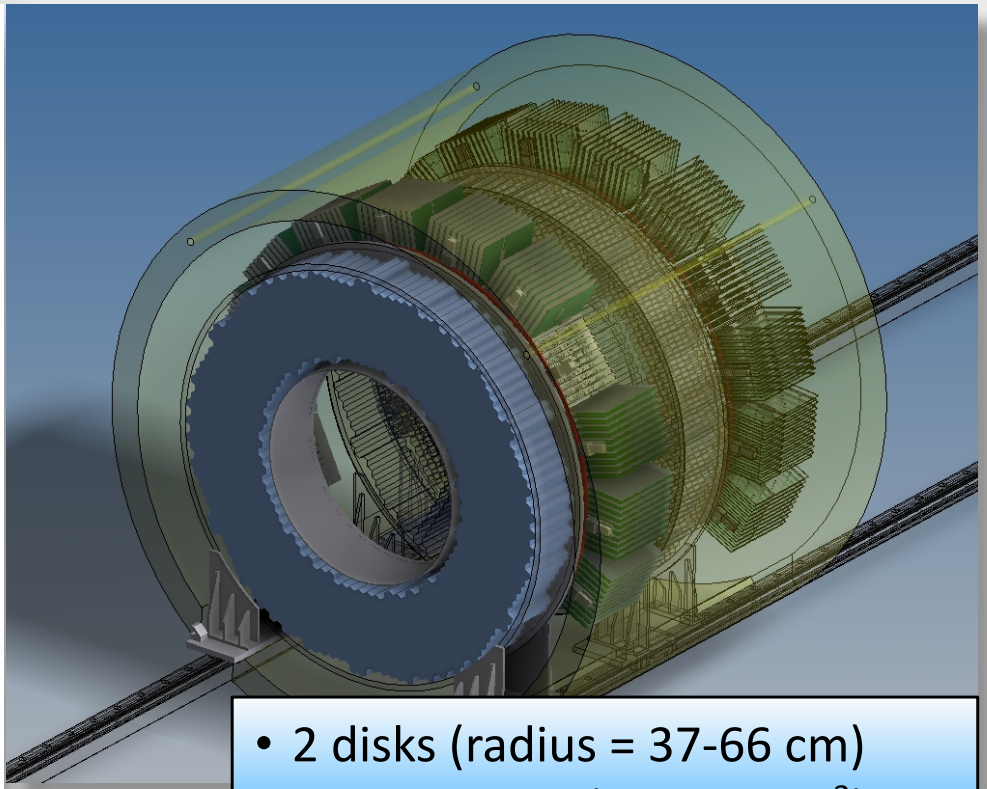
- Low mass straw drift tubes
- 5 mm diameter straws
  - 12 μm Mylar walls
  - Filled with Ar+CO_2
- 25 μm tungsten wires

- 96 Straws = Panel; 6 Panels = Plane; 2 Planes = Station; 18 Station = Tracker. Total number of straws: 22,000

Calorimeter

- Two disks of CsI scintillating crystals
  - Radiation hard, good time (110 ps) and energy (5%) resolution
- Provides precise timing, seed for tracking, triggering and PID
- Muon rejection x200 with 96% electron efficiency





- 2 disks (radius = 37-66 cm)
- 1400 crystals (3x3x20 cm^3)
- 2800 SiPMs

Backgrounds

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

- All the backgrounds can be controlled to the level of <1 event

Mu2e Status

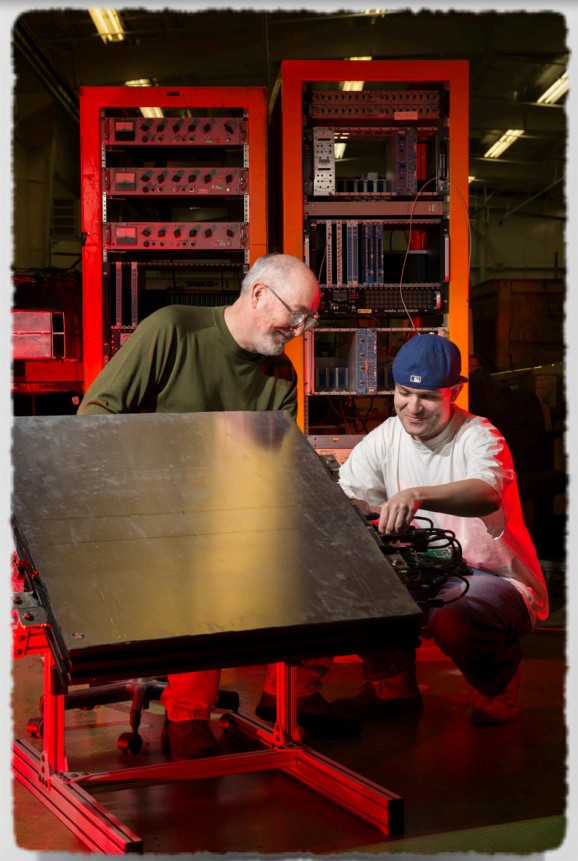
- Detector hall construction is complete
- Detector construction starts next year
- Solenoid installation in 2019
- Beam commissioning begins in 2020
- Physics data taking in 2022

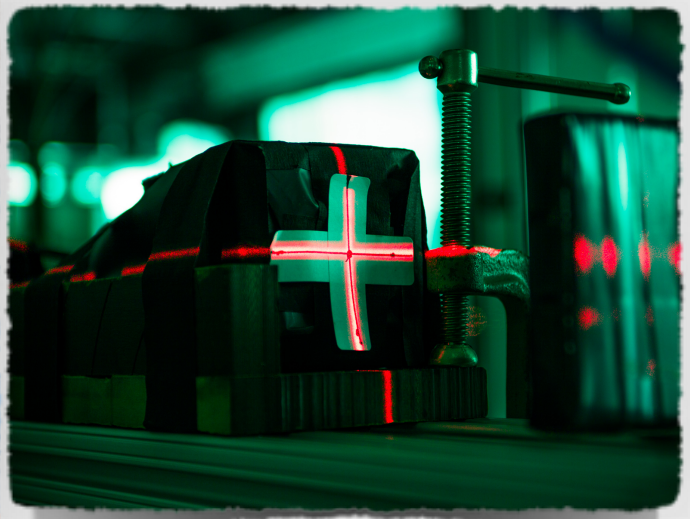
DS Solenoid Bay
04/2016

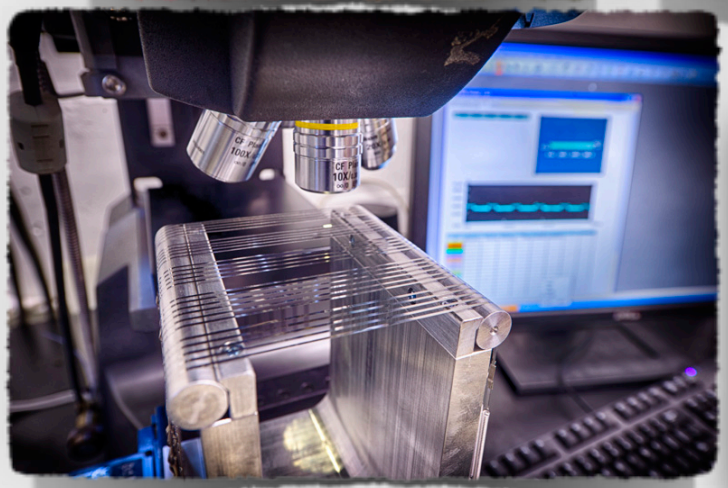
23 talks and posters on Mu2e at DPF:

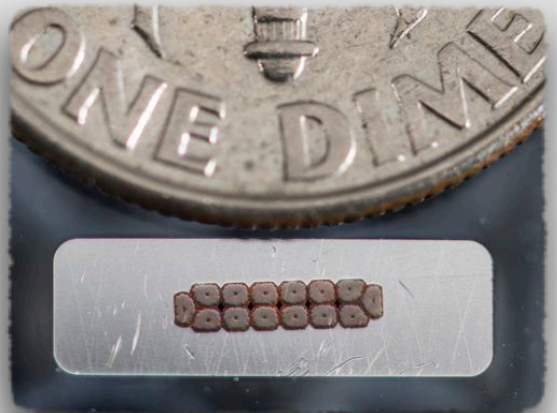
- A Novel Readout System for a High Efficiency Cosmic Ray Veto for the Mu2e Experiment
- Beam Line Extinction in the Mu2e Experiment
- Front-End Electronics Scheme for the Mu2e Straw Tracker
- A High Efficiency Cosmic Ray Veto Detector for the Mu2e Experiment at Fermilab
- Performance of Scintillation Counters with Silicon Photomultiplier Readout
- Studies of Beam Induced Radiation Backgrounds at the Mu2e Experiment and Implications for the Cosmic Ray Veto Detector Operations
- Quality Assurance on Un-Doped CsI Crystals for the Mu2e Experiment
- Mu2e Solenoid Field Mapping System
- Preliminary Results from the AlCap Experiment
- Normalizing to the Number of Stopped Muons in the Mu2e Experiment
- Design and status of the Mu2e crystal calorimeter
- Studies of effect of aging and studies to optimize scintillation counter response for the Mu2e Cosmic Ray Veto System
- Cosmic Ray Backgrounds in the Mu2e Experiment at Fermilab
- Pre-production and quality assurance of the Mu2e Silicon Photomultipliers
- Studies of Radiation Damage to Silicon Photomultipliers
- A Panel Prototype for the Mu2e Straw Tube Tracker at Fermilab
- The Mu2e Solenoid Cold Mass Position Monitor System
- Muon Intensity Increase by Wedge Absorbers
- Mu2e Trigger & DAQ Design and Challenges
- The Mu2e Experiment at Fermilab
- 3D Magnetic Field Calibration
- Studies of scintillation counter response for the Mu2e Cosmic Ray Veto System
- Aging Studies for the Mu2e Cosmic Ray Veto System

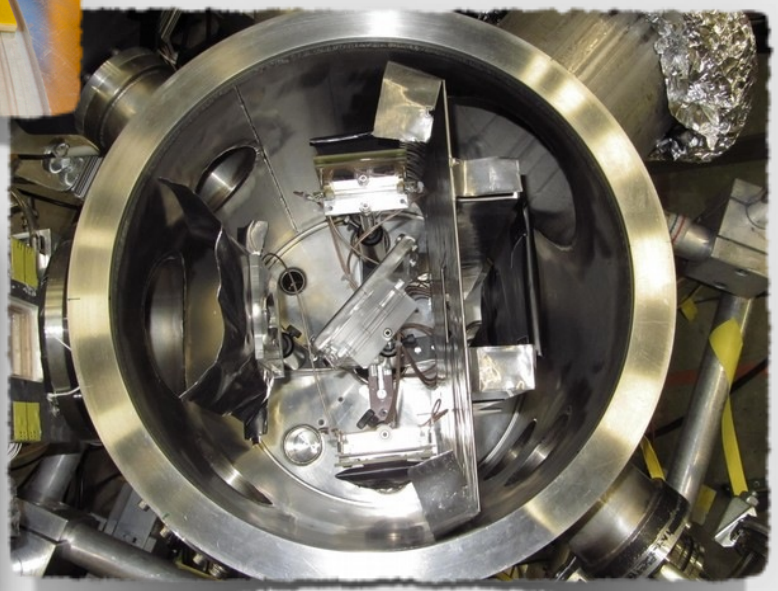
Mu2e R&D/Prototypes Efforts











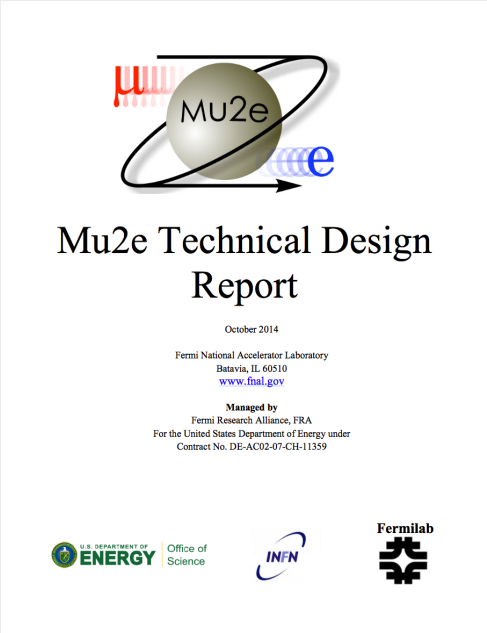
Mu2e Collaboration

200 scientists, 37 institutions

Summary

- Mu2e has a great discovery potential and can reveal new physics
  - Improves over previous conversion experiments by 4 orders of magnitude and probes new physics mass scales of 10^4 TeV/c^2
  - Provides discovery capability over wide range of new physics models
  - Complementary to LHC and other experiments
- Experimental design is mature and on schedule to start commissioning in 2020

- Technical Design Report
  - http://arXiv.org/abs/1501.05241
- Experiment web site
  - http://mu2e.fnal.gov


Mu2e Technical Design Report

October 2014

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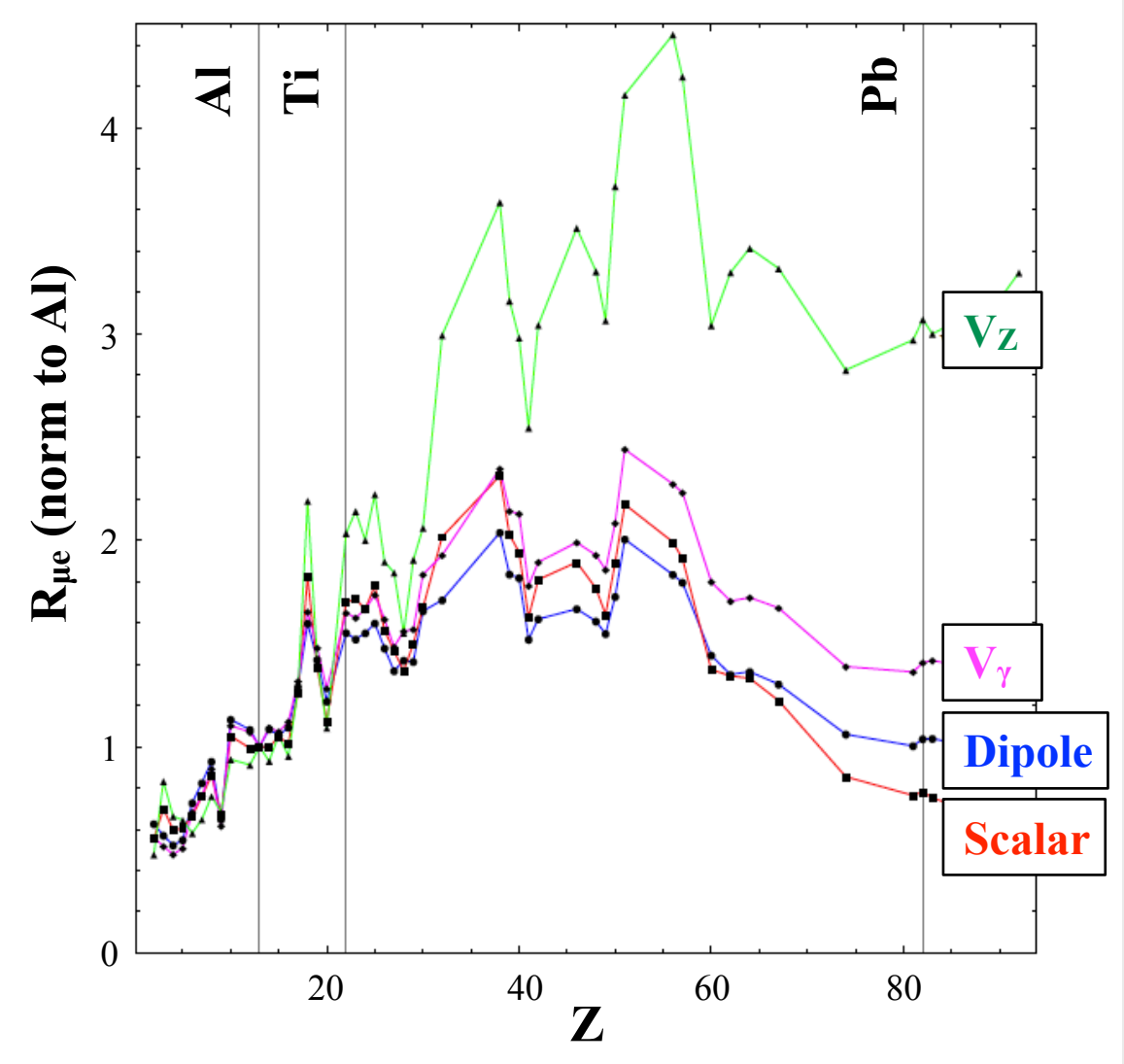
Backup

Target material

- $R_{\mu e}$ is Z-dependent and can distinguish among new physics operators
- Measuring $R_{\mu e}$ for different targets provides discrimination power between new physics model

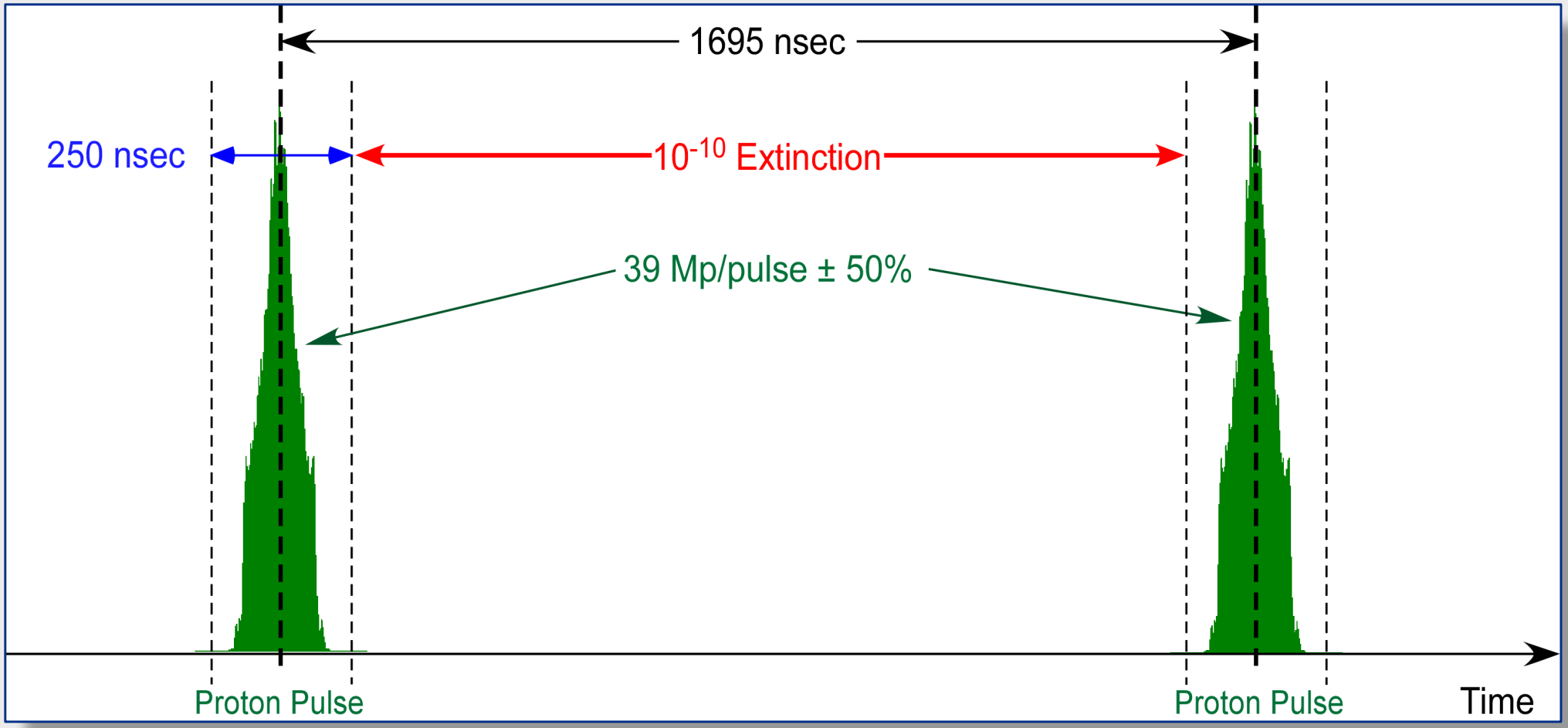


Proton Beam Requirement

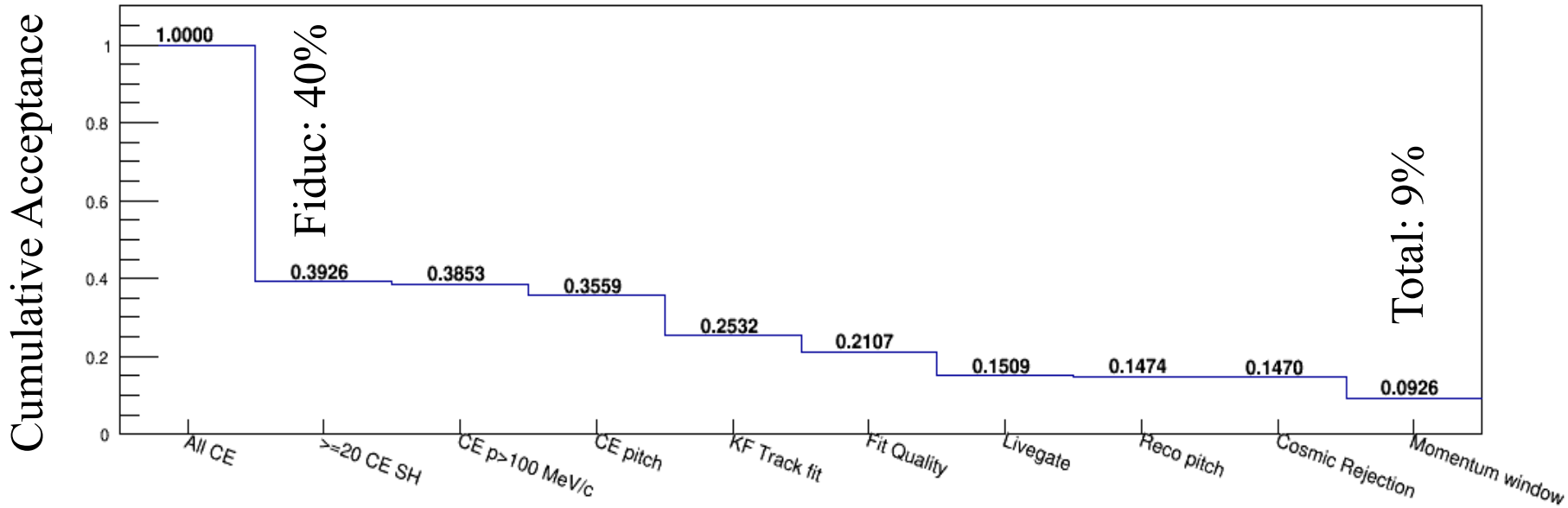
	Parameter	Design Value	Requirement	Unit
	Total protons on target	4.7×10^{20}	$\geq 4.7\times10^{20}$	protons
Time Structure	Time between beam pulses	1695	> 864	nsec
Time Structure	Maximum variation in pulse separation	< 1	10	nsec
Time Structure	Spill duration	43.1	> 20	msec
Time Structure	Beamline Transmission Window	230	< 250	nsec
Time Structure	Transmission Window Jitter (rms)	< 5	<10	nsec
Time Structure	Out-of-time extinction factor	1.6×10^{-12}	$\leq 10^{-10}$	
Intensity	Average proton intensity per pulse	3.9×10^{7}	$< 5.0\times10^{7}$	protons/ pulse
Intensity	Maximum Pulse to Pulse intensity variation	50	50	%
Beam Size	Target rms spot size	1	0.5 – 1.5	mm
Beam Size	Target rms beam divergence	0.5	< 4.0	mrad

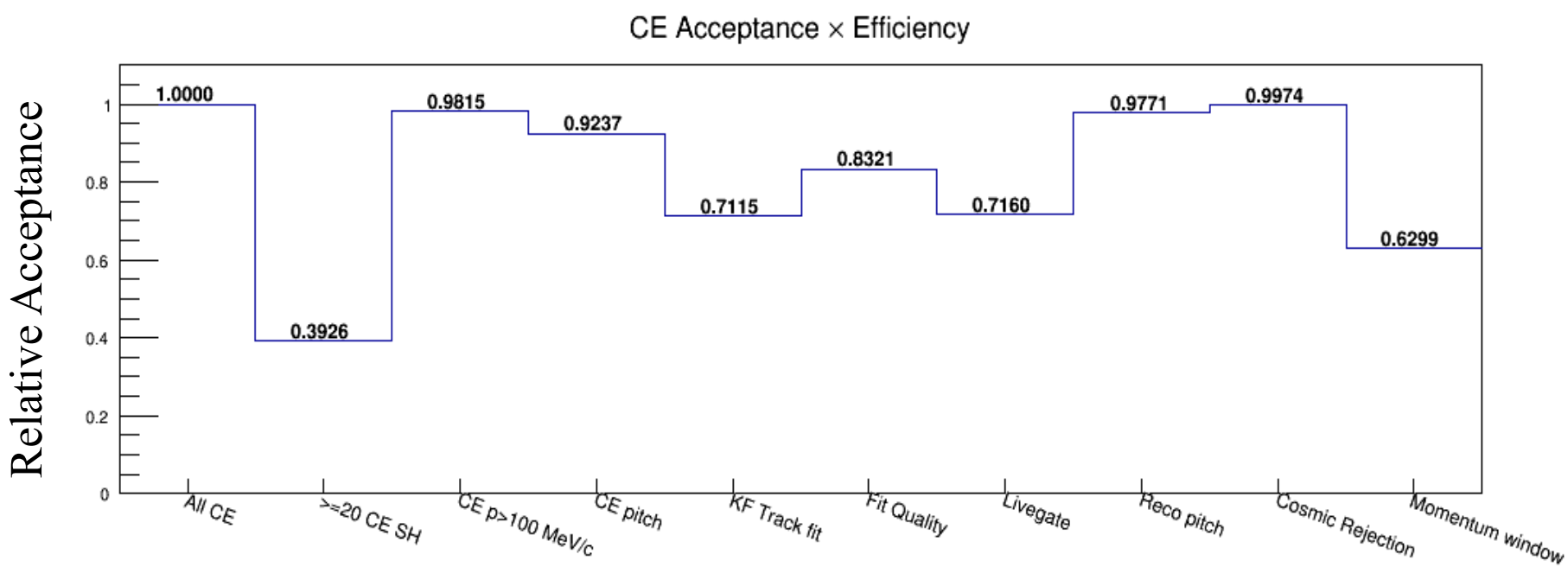
Extinction

- The proton beam on target consists of a train of ~25,000 narrow pulses separated by 1.695 μsec
- Extinction ≡ No. of out-of-time protons / No. of in-time protons

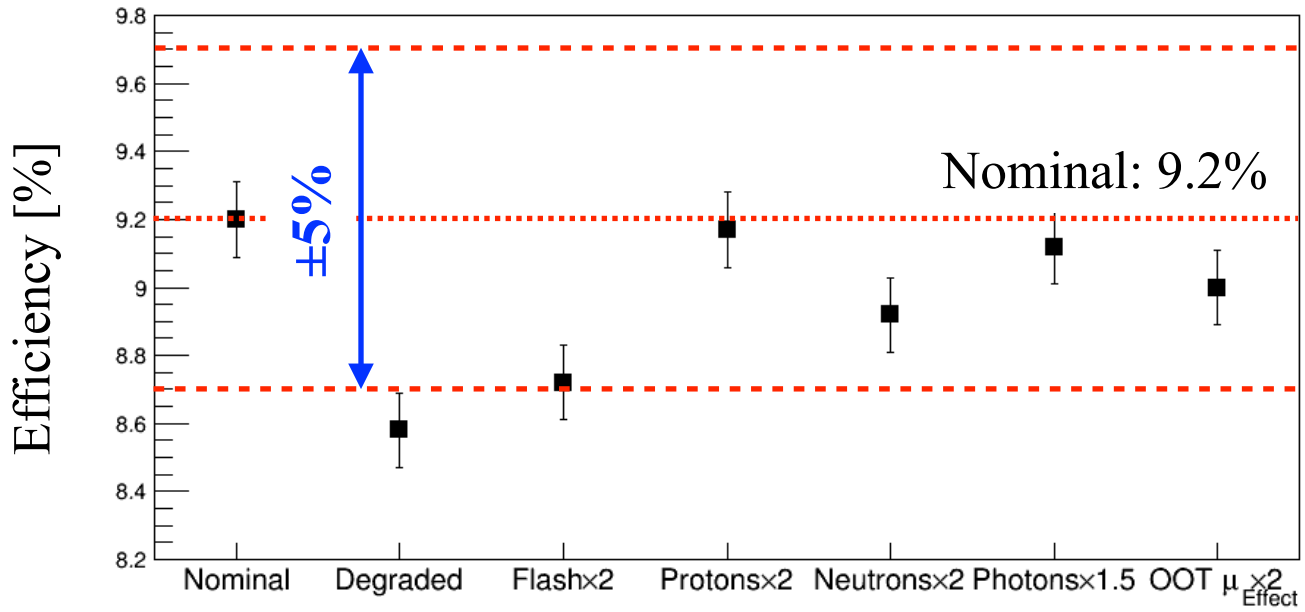


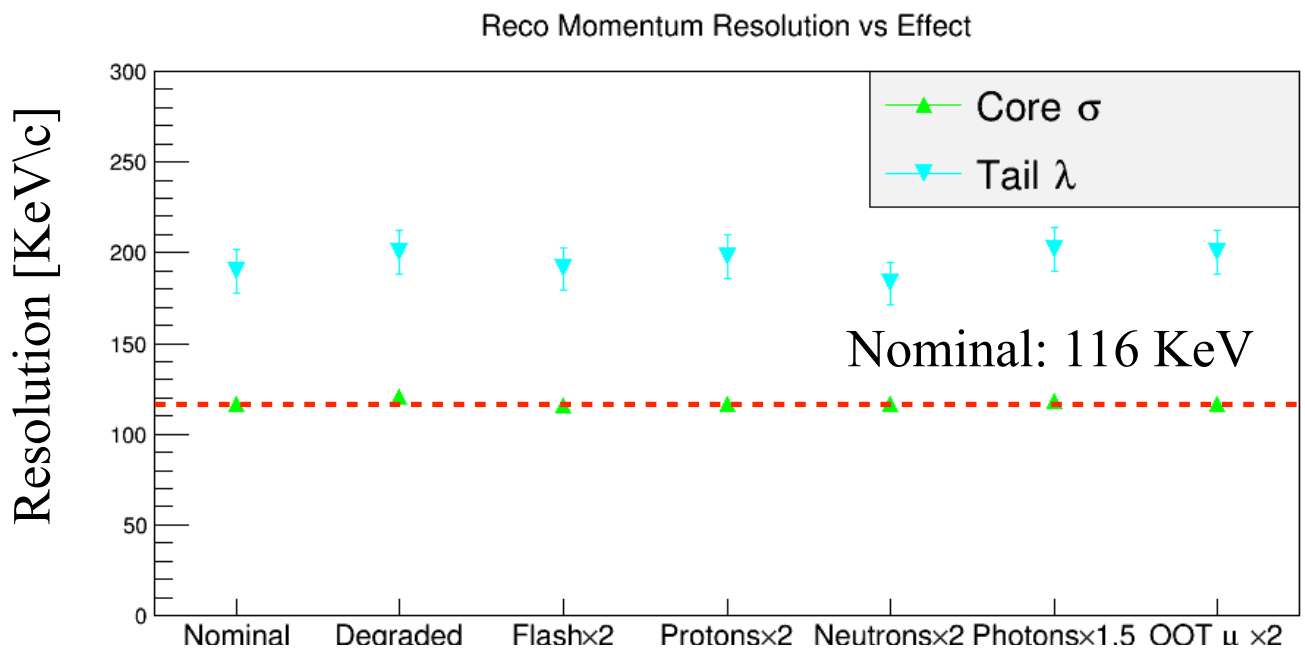
Signal Acceptance





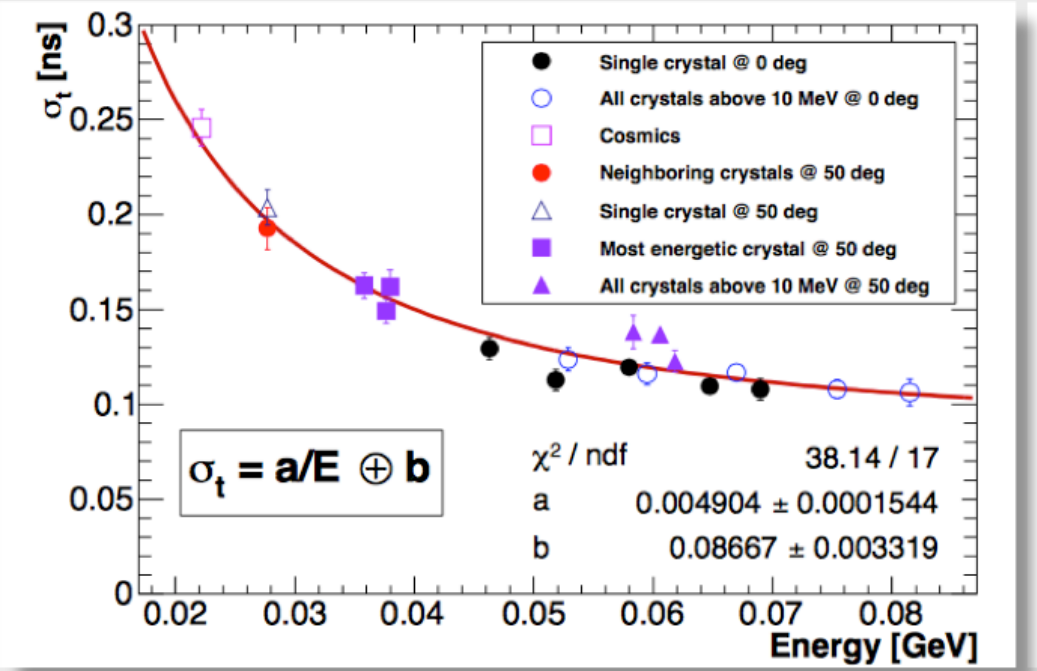
Performance

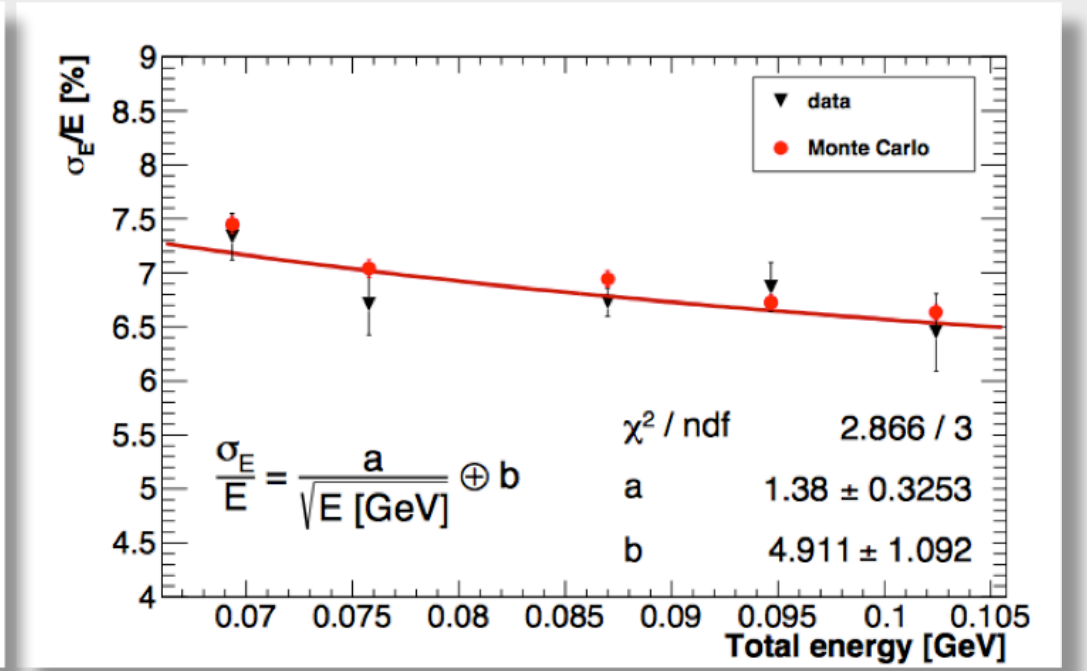


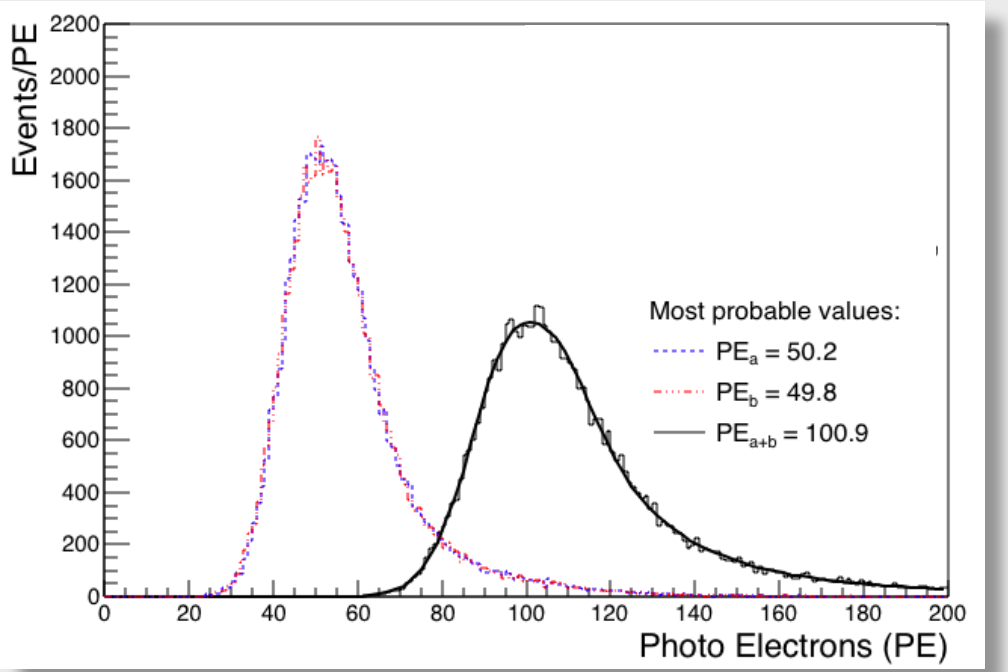
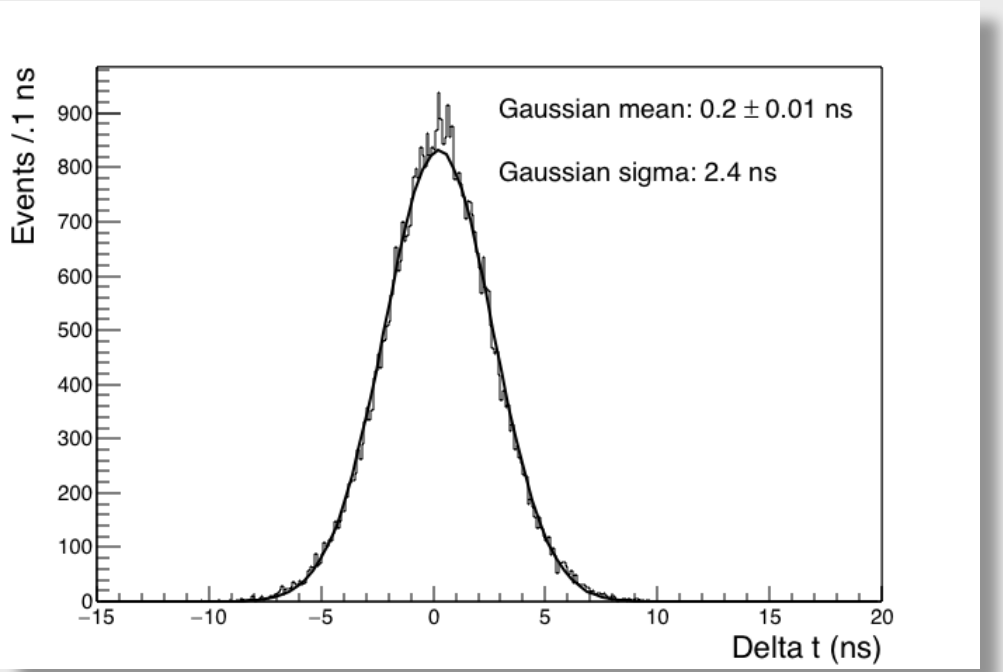


Calorimeter performance

- Test beam results with calorimeter prototype
- Data well described by Monte Carlo
- Energy resolution: ~6.5% at 100 MeV
- Time resolution: 110 ps





CRV performance

- Test beam results with CRV prototype
  - 2x5 scintillating counters, read out through 1.4 mm WLS fibers by 2x2 mm^2 SiPMs
- Light yield: 50 PE/SiPM at 1 m
- Timing resolution: 1.7 ns single channel resolution