# A Proposed Sensitivity Upgrade for the Mu2e Experiment

Craig Group
(University of Virginia)

# Mu2e-II?

## Expression of Interest for Evolution of the Mu2e Experiment

Mu2e Collaboration (F. Abusalma *et al.*) *Show all 128 authors*

Feb 7, 2018 - 17 pages

FERMILAB-FN-1052
e-Print: arXiv:1802.02599 [physics.ins-det] | PDF
Experiment: FNAL-E-0973

**Abstract** (arXiv)
We propose an evolution of the Mu2e experiment, called Mu2e-II, that would leverage advances in detector technology and utilize the increased proton intensity provided by the Fermilab PIP-II upgrade to improve the sensitivity for neutrinoless muon-to-electron conversion by one order of magnitude beyond the Mu2e experiment, providing the deepest probe of charged lepton flavor violation in the foreseeable future. Mu2e-II will use as much of the Mu2e infrastructure as possible, providing, where required, improvements to the Mu2e apparatus to accommodate the increased beam intensity and cope with the accompanying increase in backgrounds.

- Recent Expression of Interest.
- Upgrade to Mu2e – improve sensitivity by a factor of 10.
- Utilize the increased proton intensity afforded by PIP-II upgrade.
- Use as much Mu2e infrastructure as possible.
- Upgrade apparatus where needed to handle improved beam intensity.

# Mu2e-II?

## More past Mu2e-II Work:

**Feasibility Study for a Next-Generation Mu2e Experiment**

K. Knoepfel[3], V. Pronskikh[3], R. Bernstein[3], D.N. Brown[5], R. Coleman[3], C.E. Dukes[7], R. Ehrlich[7], M.J. Frank[7], D. Glenzinski[3], R.C. Group[3,7], D. Hedin[6], D. Hitlin[2], M. Lamm[3], J. Miller[1], S. Miscetti[4], N. Mokhov[3], A. Mukherjee[3], V. Nagaslaev[3], Y. Oksuzian[7], T. Page[3], R.E. Ray[3], V.L. Rusu[3], R. Wagner[3], and S. Werkema[3]

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Submitted as part of the APS Division of Particles and Fields Community Summer Study

(dated: July 5, 2013)

We explore the feasibility of a next-generation Mu2e experiment that uses Project-X beams to achieve a sensitivity approximately a factor ten better than the currently planned Mu2e facility.

arXiv:1307.1168v1 [physics.ins-det] 3 Jul 2013

- A background & sensitivity study was performed assuming a 1 or 3 GeV proton beam
  - arXiv:1307.1168
- Studies of $\mu$ and $\pi$ yields and solenoid radiation damage vs proton beam energy
  - arXiv:1612.08931
- Preliminary targeting studies
  - Internal documents
- Workshops
  - IF Workshop (ANL, 04/2013)
  - Snowmass (UM, 08/2013)
  - Mu2e (FNAL, 02/2016)
  - Mu2e II Workshop (ANL, 12/2017)
- Part of PIP-II planning process

# Mu2e-II?

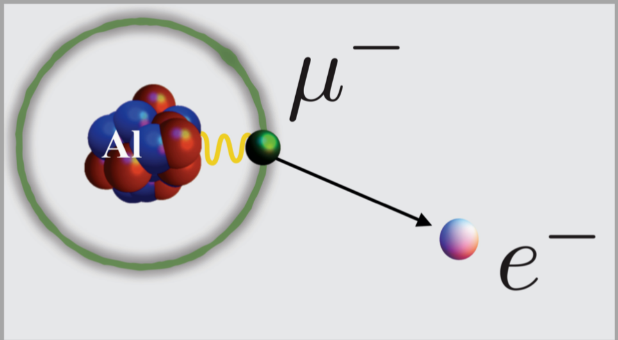
Another factor of ten in sensitivity over Mu2e is compelling regardless of its outcome:

- If signal in Mu2e
  - <5 $\sigma$, improve statistical accuracy
  - >5 $\sigma$, use different targets to sort out nature of interaction
- If no signal in Mu2e
  - Extend sensitivity to find signal or set new limits
- Either way, BSM theories strongly constrained!

# Mu2e Experimental Concept

## Mu2e-II must improve all aspects of Mu2e:

- Generate an intense beam of low momentum muons ($\mu^-$)
- Stop the muons in a thin target
  - Mu2e plans to use aluminum
- The stopped muons are trapped in 1S atomic orbit around the nucleus
  - In muonic aluminum, lifetime 864 ns




$$\mu^- + {}^{27}_{13}Al \rightarrow e^- + {}^{27}_{13}Al + \nu_\mu + \bar{\nu}_e \text{ (decay 39\%)}$$

$$\mu^- + {}^{27}_{13}Al \rightarrow \nu_\mu + X + an + bp + c\gamma \text{ (capture 61\%)}$$

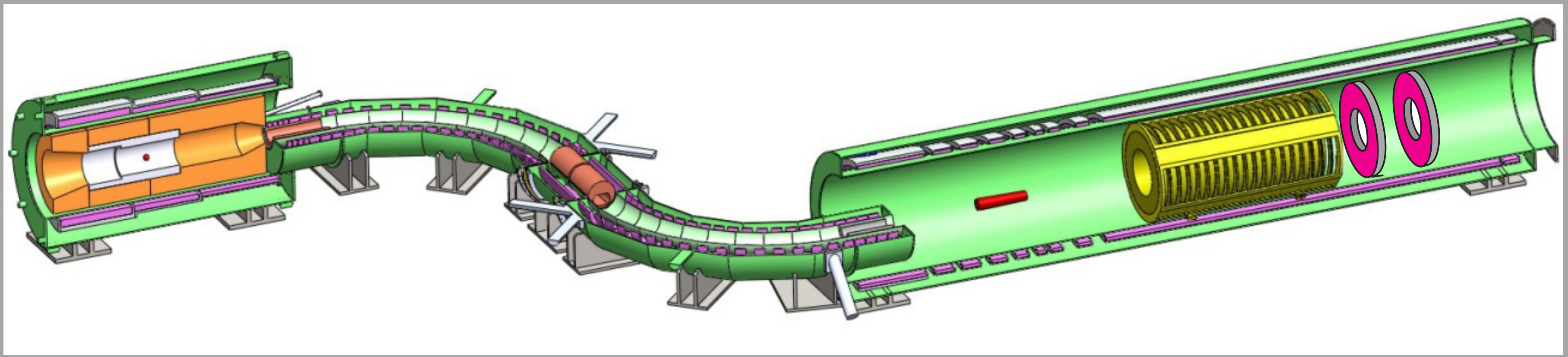
$$\mu^- + {}^{27}_{13}Al \rightarrow e^- + {}^{27}_{13}Al^* \text{ (conversion, } < 6\times 10^{-13}\text{)}$$

  - Large lifetime important for suppressing backgrounds
- Look for monochromatic electron at 105 MeV, from the coherent conversion process

$$\mu^- + {}^{27}_{13}Al \rightarrow e^- + {}^{27}_{13}Al$$

# The Mu2e Experiment

Production Solenoid  Transport Solenoid  Detector Solenoid



(about 25 meters end-to-end)

# Mu2e (and Mu2e-II) Key Advances

- By placing the **production target inside a high-field solenoid**, we obtain a highly efficient low-E muon beam (0.002 stopped muons/proton)

It will be at least 100x more intense than current beams!

- By using a **pulsed proton beam** we can suppress prompt backgrounds by employing a delayed live gate
  - SINDRUM II used a veto counter against beam pions
    - limits rates, statistical power
  - Narrow proton pulses (~250 ns wide) every 1695 ns
  - Delay live gate for ~700 ns relative to arrival of protons
  - Achieves significant suppression of backgrounds from beam electrons and prompt pion interactions in the stopping target
  - Time structure: good match to muonic aluminum lifetime

# Backgrounds

- Radiative Pion Capture: solution is pulsed beam and high extinction

$\pi^- + {}^{27}_{13}Al \rightarrow {}^{27}_{12}Mg^* + \gamma$, $(BR \sim 2\%)$, gamma (<140 MeV) can convert in target to $e^+e^-$

  - Occurs immediately when pions stop in target
  - $e^-$ energy can be 105 MeV, looking just like a conversion electron
  - Major background problem, major reason to use pulsed beam
  - Wait until pions have almost all disappeared before taking data
  - Extinction requirement: avoid between pulse protons to level of $10^{-10}$

- Muon decay in orbit (DIO): solution is excellent energy resolution

$$\mu^- + {}^{27}_{13}Al \rightarrow e^- + \nu_\mu + \bar{\nu}_e + {}^{27}_{13}Al$$

  - Endpoint electron energy equals conversion electron energy (when neutrinos carry no energy)
  - Distribution falls very rapidly near endpoint: suppress background with excellent electron energy resolutions, ~ 1 MeV FWHM.

# Backgrounds

- Antiprotons can stop in the target, annihilate, and can produce a fake conversion electron. Solution: **place thin absorbers in muon beamline to stop antiprotons well upstream of the stopping target.**
- Cosmic Rays;  Solution: highly efficient veto counter surrounding detectors
  - Requires large, surrounding veto detector with 99.99% efficiency
  - Without veto detector one false conversion electron per day
- Flash
  - Initial intense bunch of electrons from production target with width equal to proton pulse
    - Produces bremsstrahlung in target, leads to high rates and radiation damage in detectors
    - Detectors must recover in time for beginning of measurement period
- When muons capture on the nucleus, they produce protons, neutrons, gammas via

$$\mu^- + {}^{27}_{13}Al \rightarrow \nu_\mu + X + an + bp + c\gamma \text{ (capture 61\%)}$$

  - Low energy particles can cause significant noise hit rates and radiation damage in the detectors.

# Backgrounds

- ~~Antiprotons can stop in the target, annihilate, and can produce a fake conversion electron. Solution: place thin absorbers in muon beamline to stop antiprotons well ups~~

Can be eliminated by running p beam E below p-bar threshold.

- Cosmic Rays; Solution: highly efficient veto counter surrounding detectors
  - Requires large, surrounding veto detector with 99.99% efficiency
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# Background Table Mu2e-II (from Snowmass)

Mu2e-II assumes 3 years: $3x10^{22}$ protons on target, $6x10^{18}$ stopped muons, SES< $3x10^{-18}$

| Category | Source | Mu2e | Mu2e-II (Al) | Mu2e-II (Ti) |
|---|---|---|---|---|
| Intrinsic | μ decay in orbit | 0.144 | 0.26 | 1.19 |
| | Radiative μ capture | <0.01 | <0.01 | <0.01 |
| Late Arriving | Radiative π capture | 0.02 | 0.04 | 0.05 |
| | Beam electrons | <0.01 | <0.01 | <0.01 |
| | μ decay in flight | <0.01 | <0.01 | <0.01 |
| | π decay in flight | <0.01 | <0.01 | <0.01 |
| Miscellaneous | Anti-proton induced | 0.04 | -- | -- |
| | Cosmic ray induced | 0.21 | 0.63* | 0.63* |
| **Total Background:** | | 0.41 | 0.93 | 1.86 |

* Quoted as 0.16 in Snowmass note
Duty factor ~3x Mu2e

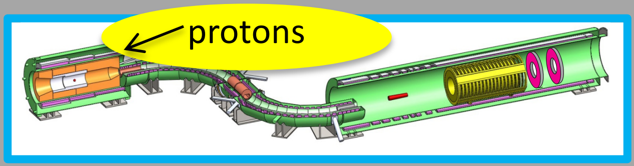
Mu2e-II goal: < 1 event background.

Not optimized for Ti target. 8 μm-walled straws assumed for tracker.

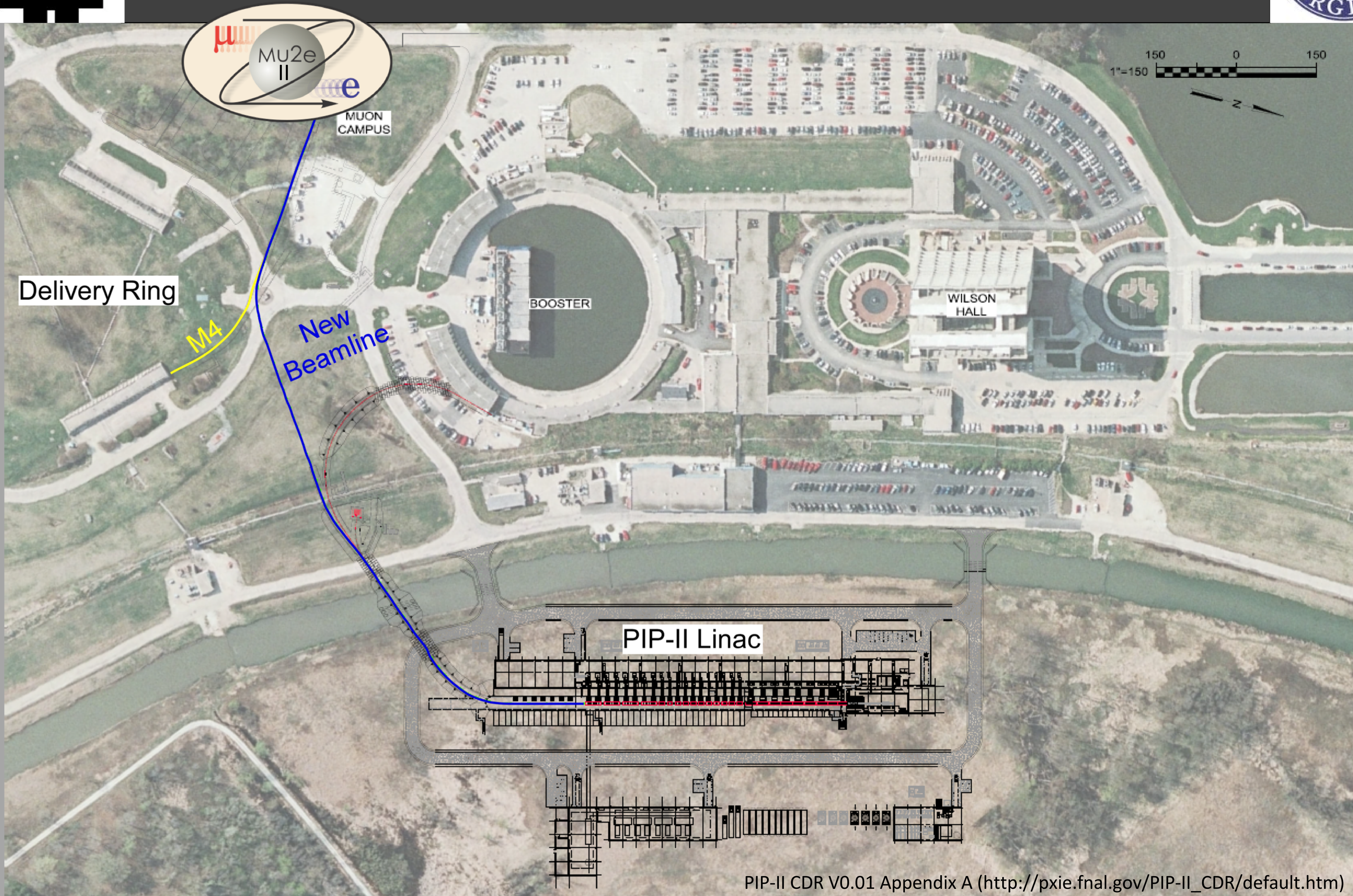
# PIP-II: Proton Beam

## PIP-II linac will replace the present linac:

- Designed to deliver 800 MeV $H^-$ beam to the Booster.
- Use upstream end of transfer line to Booster. Switching magnet directs Mu2e beam.
- Optics of the new beamline is designed to match that of the existing M4 line where the two lines merge.
- A new beam enclosure must be built connecting the Linac to Booster enclosure and the M4 enclosure.
- Recent CD1 approval from DOE.



# New Beamline Required



# Mu2e-II Beam Requirements

- Pulsed proton beam
  - Sufficient beam power to achieve few x $10^{18}$ stopped muons in about 3 years of full intensity running (>100 kW)
  - Pulsed with spacing of ~1700 ns
    (tunable spacing in the range 800-1700 ns even better)
  - Full width ~100 ns (ie. +/- 50 ns around center)
  - Suppress out-of-time protons by $10^{-11}$ or better
  - Duty factor ~90% or better
  - Preferences
    - To avoid using Delivery Ring
    - Kinetic energy < 4 GeV to avoid antiprotons in beam

**PIP-II capable of meeting all of these requirements**

# Beam Parameters

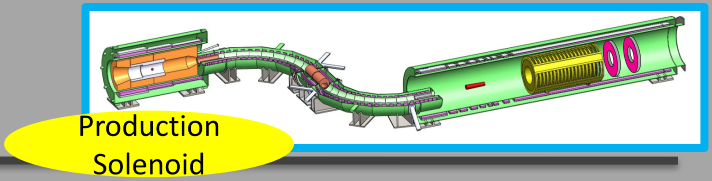
| Parameter | Mu2e | Mu2e II | Units |
|---|---|---|---|
| Total Protons on Target (3 yr) | $4.7\times10^{20}$ | $4.4\times10^{22}$ | protons |
| Pulse Repetition Rate | 590 | 500 - 1250 | kHz |
| Time Between Pulses | 1695 | 800 - 2000 | nsec |
| Pulse Base Width | 250 | 100 | nsec |
| Extinction Level | $10^{-10}$ | $10^{-11}$ | |
| Average Intensity per Pulse | $3.9\times10^{7}$ | $5.6 – 14 \times10^{8}$ | protons |
| Pulse-to-Pulse Intensity Variation | <50 | <10 | % |
| Beam Kinetic Energy | 7946 | 800 | MeV |
| Beam Power | 7.3 | 100 | kW |
| Duty Factor | 25 | 90 | % |

NOTE:

- Blue numbers are calculated from the other parameters (Require 10x stopped muons).
- Total POT assumes 67% accelerator up-time.

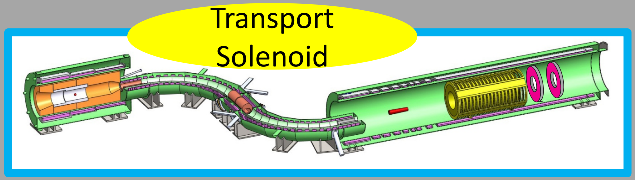
# Production Solenoid

- Mu2e radiatively cooled target will not be adequate for x10 more beam power.
  - Liquid-cooled, gas-cooled…?
  - Rotating target?
  - ?
- Need to aim proton beam so that it hits the target- not so simple in Mu2e-II configuration due to bending in B field, but likely possible.
- Heat and Radiation Shield (Bronze) for protection of superconducting coils is adequate for Mu2e, inadequate for Mu2e-II
  - Replace bronze with tungsten: sufficient?
  - Go to a larger PS that allows thicker HRS?
  - ?
- Mu2e proton flux is currently limited by radiological hazard from delivery ring- but Mu2e-II will not use it.
- Servicing/modifying the radioactive PS and shield will be a challenge.
- Primary target may need additional shielding due radiological hazard.



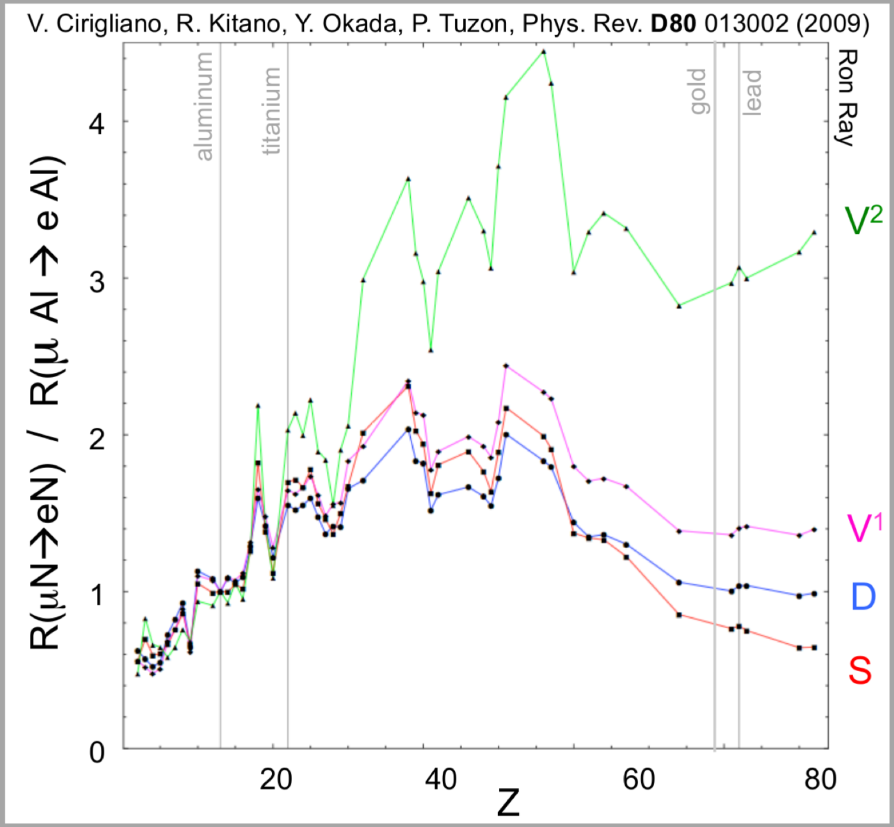
# Transport Solenoid

- There might be issues with radiation and heat loads in the upstream coils (need simulations). First estimate looks OK.
- Otherwise, should be good for Mu2e-II.
- Note that Mu2e-II will not need the antiproton absorbers.

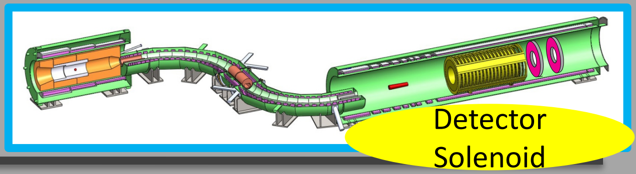


# Target

- Thinner targets are needed to improve energy resolution of the outgoing electron.
- New physics depends on target Z. If signal observed varying target material will probe the new physics properties.

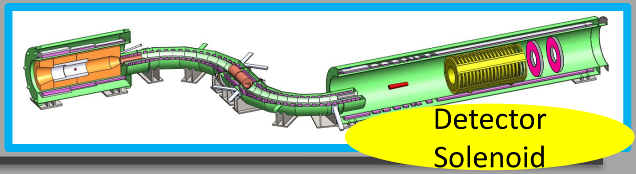



Note: the different color lines represent different interaction classes for the new physics.



# Detector Solenoid

- Front end electronics may be challenged by radiation damage.
- Reduce material in the tracker to improve energy resolution.
  - Are 8 micron straws feasible? (vs 15 microns in Mu2e)
  - Need to understand aging for current tracker.
- The calorimeter likely needs an upgrade to a crystal faster than CsI
  - Prime R&D candidate: BaF2
  - Has a fast UV component but much stronger and slower visible light component.
- The cosmic ray veto system will need to handle higher flux of neutrons (3-4). More shielding?
  - Need to understand aging for CRV.
  - Alternative for upstream region where background rates are very high?



# Mu2e-II Timescale and Other Measurements

- Mu2e-II Timescale:
  - Assume (3+1)yr of Mu2e data taking at full intensity
  - Assume 2-3yr from End-Mu2e to Start-Mu2e-II
  - Mu2e-II could begin data taking on 2030 timescale
- Other CLFV Probes:
  - $\mu^- N \rightarrow e^- N$, $\mu^+ \rightarrow e^+ \gamma$, $\mu^+ \rightarrow e^+ e^+ e^-$ all probe $\mu \rightarrow e$ CLFV transition
  - Provide complementary information regarding underlying NP

# Summary

- Mu2e II can improve sensitivity by an order of magnitude beyond Mu2e if:
  - PIP-II is realized – high-intensity proton beam.
  - New transfer line from PIP-II is constructed.
  - Heat and radiation load increases can be handled.
  - Moderate detector improvements/upgrades:
    - Tracker resolution can be improved –thinner straws?
    - Faster calorimeter crystals
    - Facelift for cosmic ray veto
- R&D is required to develop sub-systems capable of enabling Mu2e-II physics goals.
- Working to identify high-priority R&D so that work can begin soon: Mu2e workshop in two weeks at Northwestern – join us!

  https://indico.fnal.gov/event/17536/

# Bibliography


- 2013 Snowmass White Paper: arXiv:1307.1168
- Mu2e-II Expression of Interest: arXiv:1802.02599
- Mu2e-II Workshop: https://indico.fnal.gov/event/ANLHEP1258/
  - Doug Glenzinski and Jim Miller: Mu2e and Mu2e-II
  - Steve Werkema: Accelerator R&D for Mu2e-II
- PIP-II CDR Appendix A (http://pxie.fnal.gov/PIP-II_CDR/default.htm)
- http://mu2e.fnal.gov/public/project/reviews/ACCCRR/

# Backup

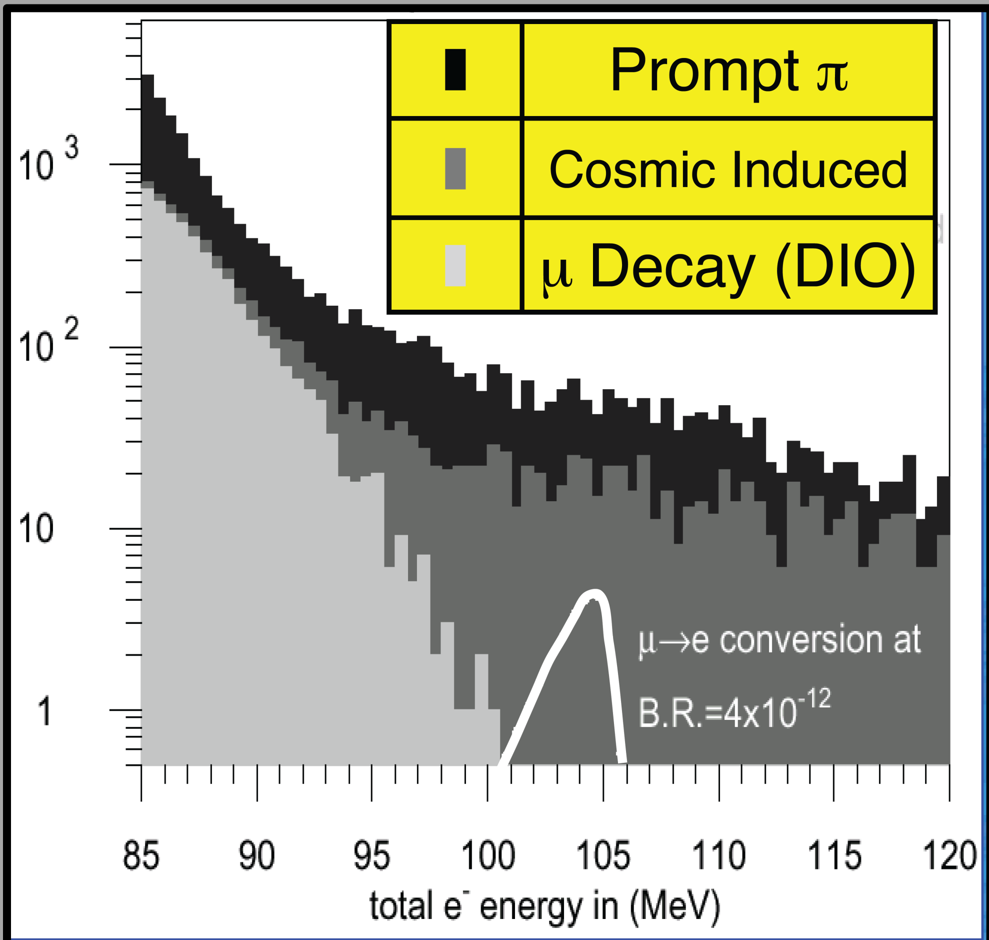
# Accelerator Issues Approximately Ordered by Difficulty

1. **Primary beam transport into and through the PS – How do we hit the target, dump, and extinction monitor?**
2. **Radiological issues – Can shielding be augmented to accommodate 100 kW?**
3. **Target and target handling upgrades required for 100 kW beam.**
4. Heat and Radiation Shield upgrades
5. Extinction – Can chopper + beamline extinction system achieve the required $10^{-11}$ extinction?
6. Where to strip $H^-$ to *p* – Can we transport and target $H^-$ ?

Steve Werkema: Accelerator R&D for Mu2e-II

# Previous Measurements of $\mu N \rightarrow eN$

SINDRUM-II

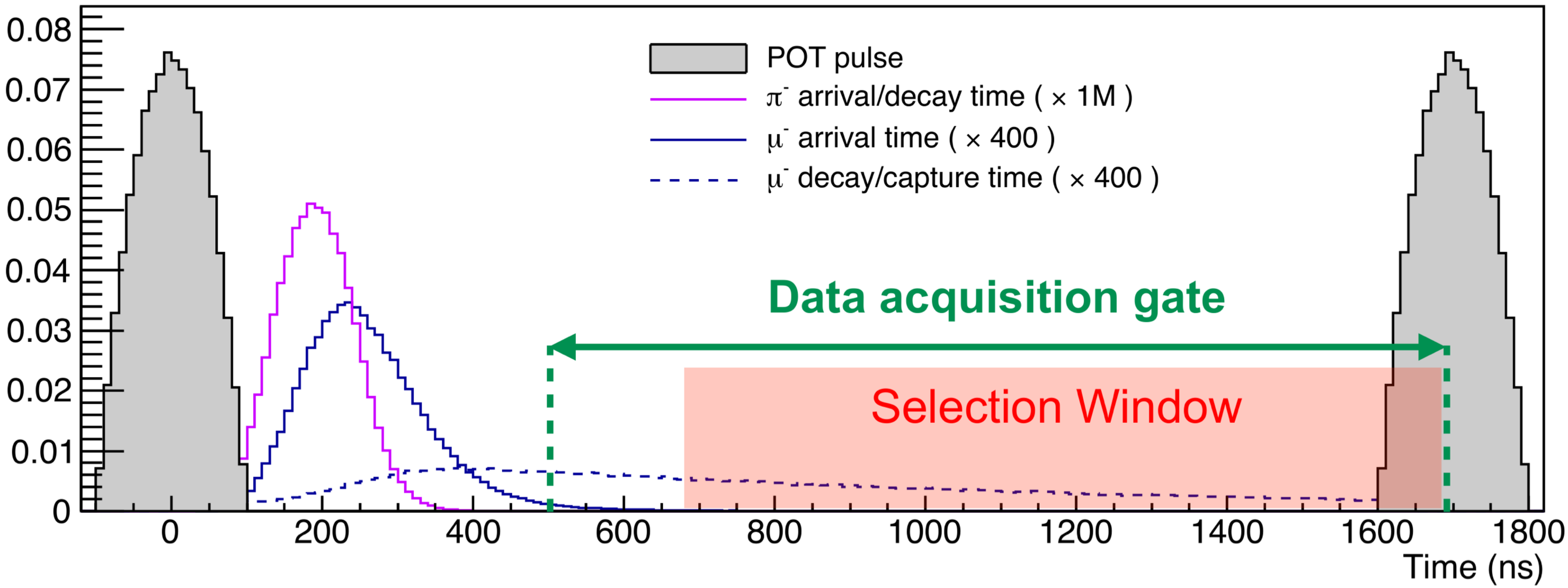



- DC muon beam
- Dominant background was from beam $\pi^-$
  - Radiative Pion Capture (RPC)
  - Reduce with absorbers, veto counter
- Cosmic Rays were also a significant background

$$R_{\mu e}(Au) < 7\text{x}10^{-13}$$

$$R_{\mu e}(Ti) < 4.3\text{x}10^{-12}$$

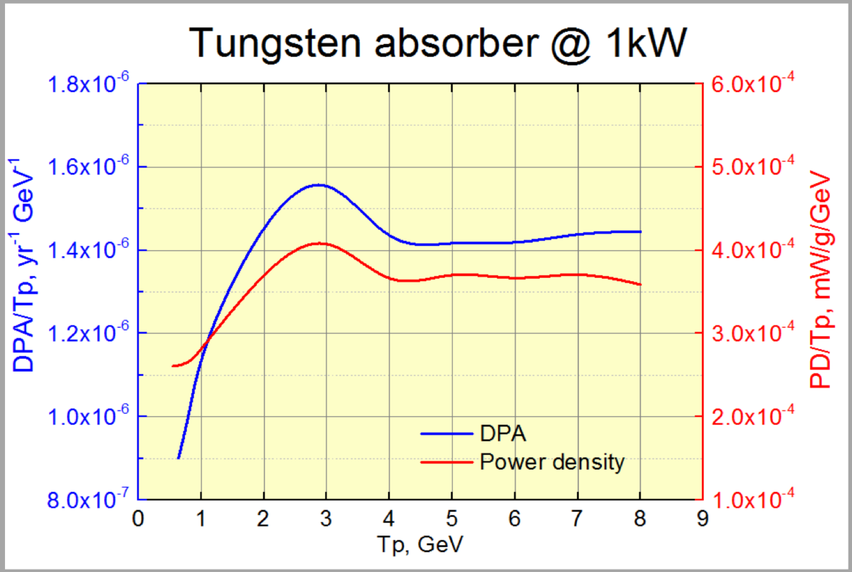
- Muon decays in orbit (DIO) also important



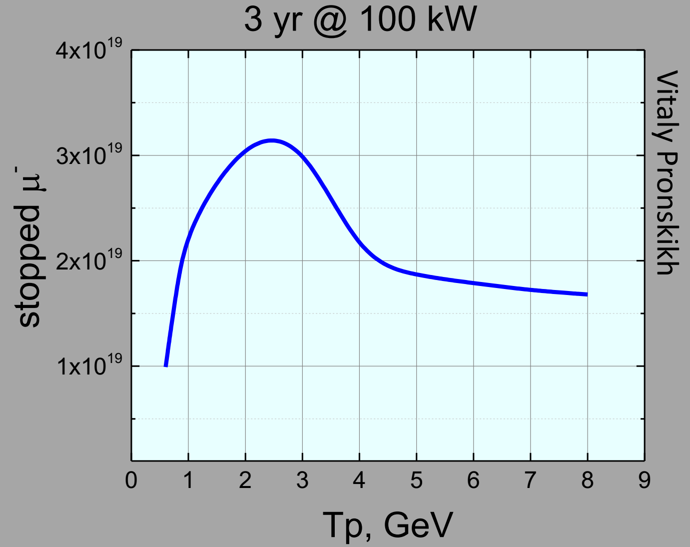

- Large acceptance beam line for negative particles up to 70 MeV/c
- Suppress $\pi$ background by utilizing pulsed proton beam
  - Employ delayed live gate to allow prompt backgrounds to disappear
  - Must suppress out-of-pulse protons by $>10^{10}$ ($10^{11}$) relative to in-pulse protons (out-of-time proton "extinction")

# Studies of coil damage and $\mu$ yields vs $E_{Beam}$

(from arXiv:1612.08931)




(nb. PS conductor can tolerate ~5x10$^{-4}$ DPA/yr and ~3 x 10$^{-2}$ mW/g Peak Power density)

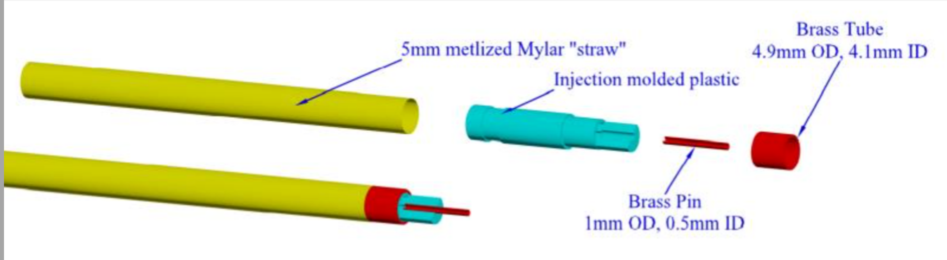



(assuming no change in HRS geometry or production target)

- Optimal beam energy is 1-3 GeV
- Strongly prefer an energy below pbar production threshold ($T_p$ < 4 GeV)
- 800 MeV beam of PIP-II can be made to work

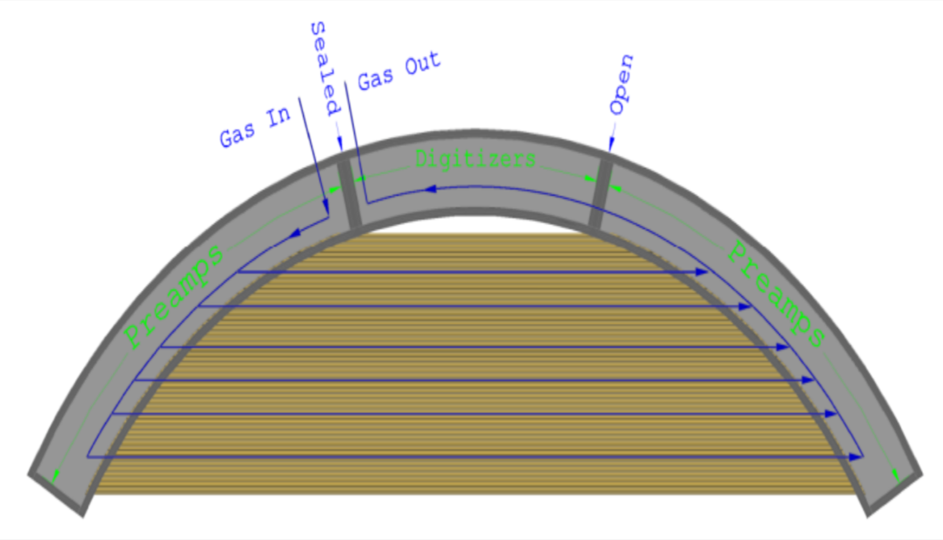
# The Mu2e Tracker

**straw tube**

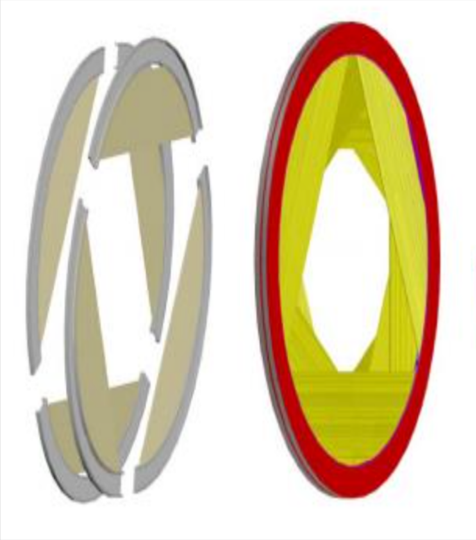



- 5 mm diameter straw, spiral wound
- Al, Au-coated, 15 μm Mylar
- 334 – 1174 mm active length
- 80/20 Ar/CO2 with HV < 1500 V
- 100 μm hit resolution

**panel = 96 straw tubes**




**plane = 6 panels**



**station = 2 planes**

# The Mu2e Tracker

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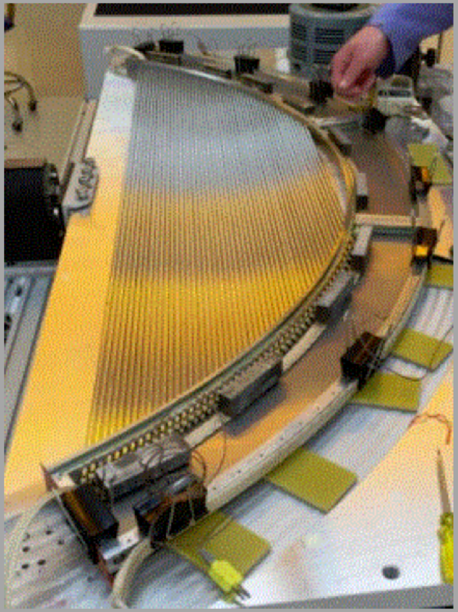

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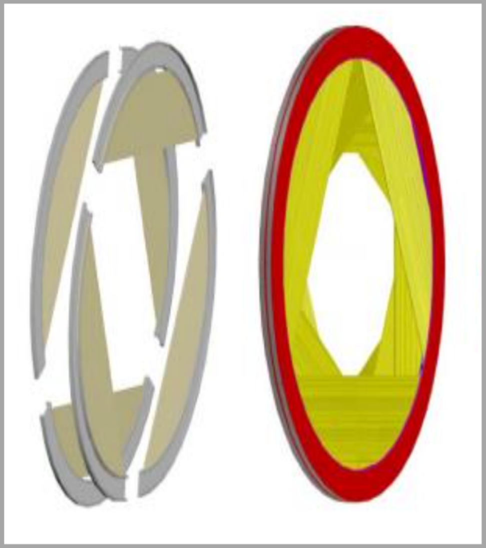
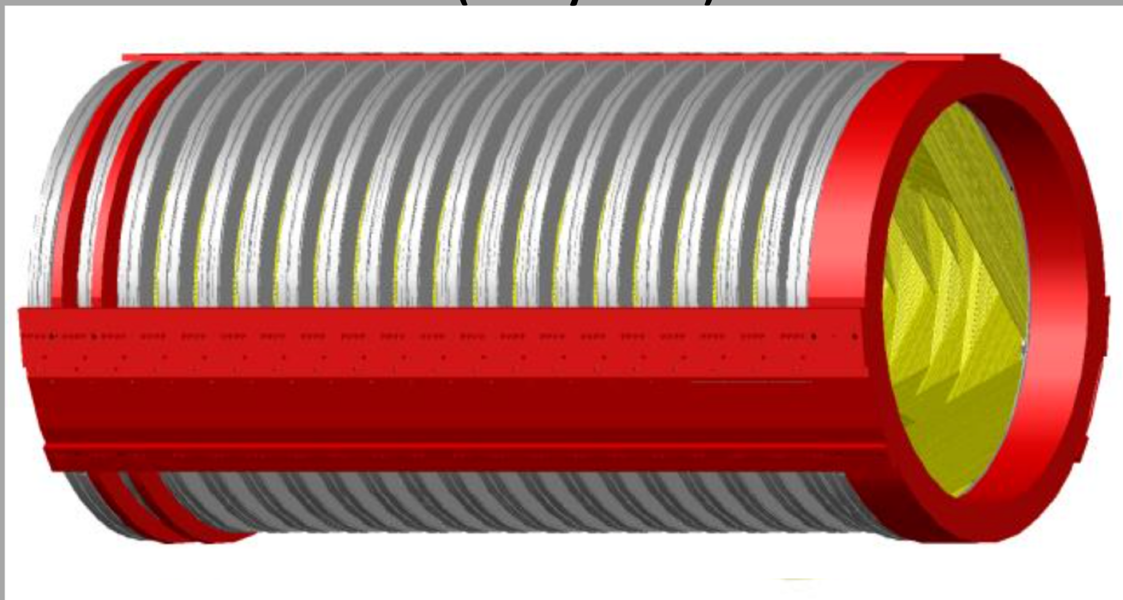
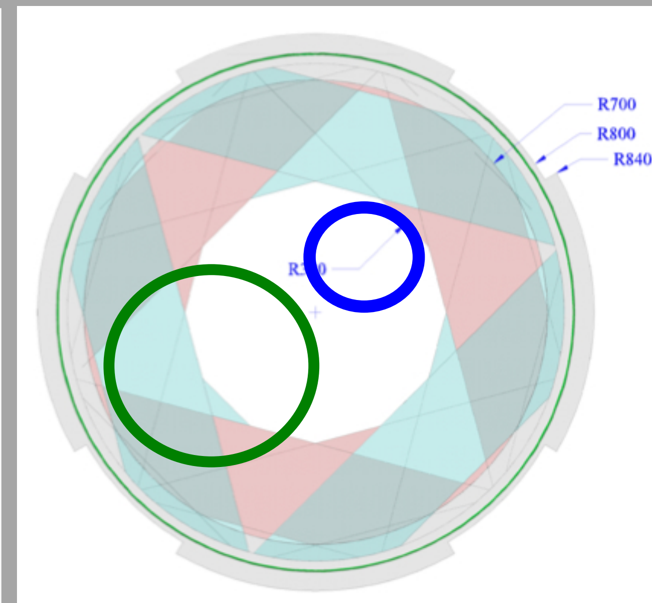


**station = 2 planes**

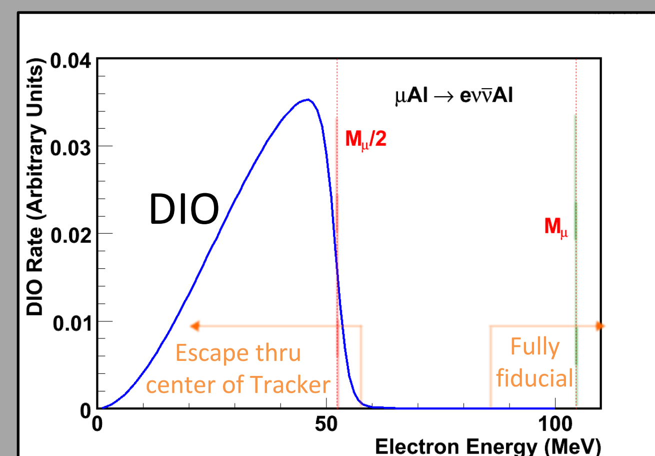
# The Mu2e Tracker

**detector= 18 stations (3m cylinder)**





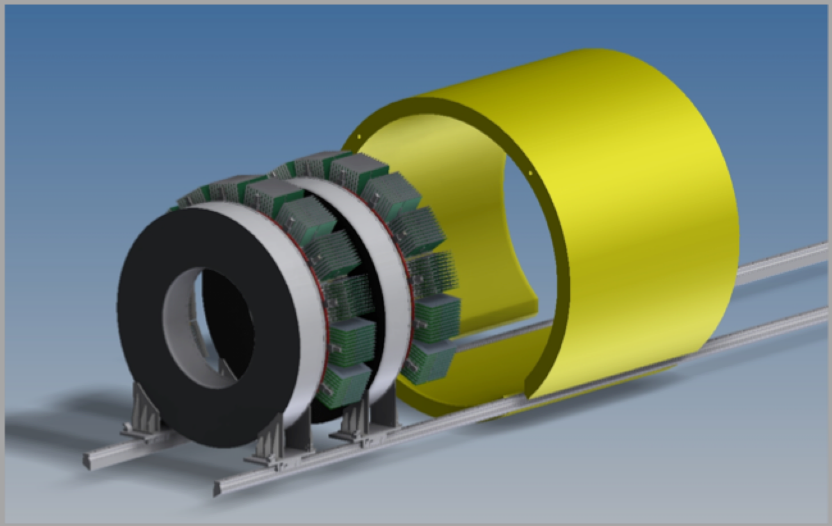

- Detector is in vacuum and inner 38 cm is purposefully un-instrumented
  - Blind to beam flash
  - Blind to >99% of DIO spectrum
- Active tracking region from 38 cm to 70 cm
- Services and structure beyond 70 cm



# The Mu2e Calorimeter

- Role of calorimeter
  - Particle ID
  - Cosmic ray rejection
- Crystal calorimeter
  - Compact
  - Radiation hard
  - Good timing (<1 ns) and energy resolution (5%)
- Will employ 2 disks

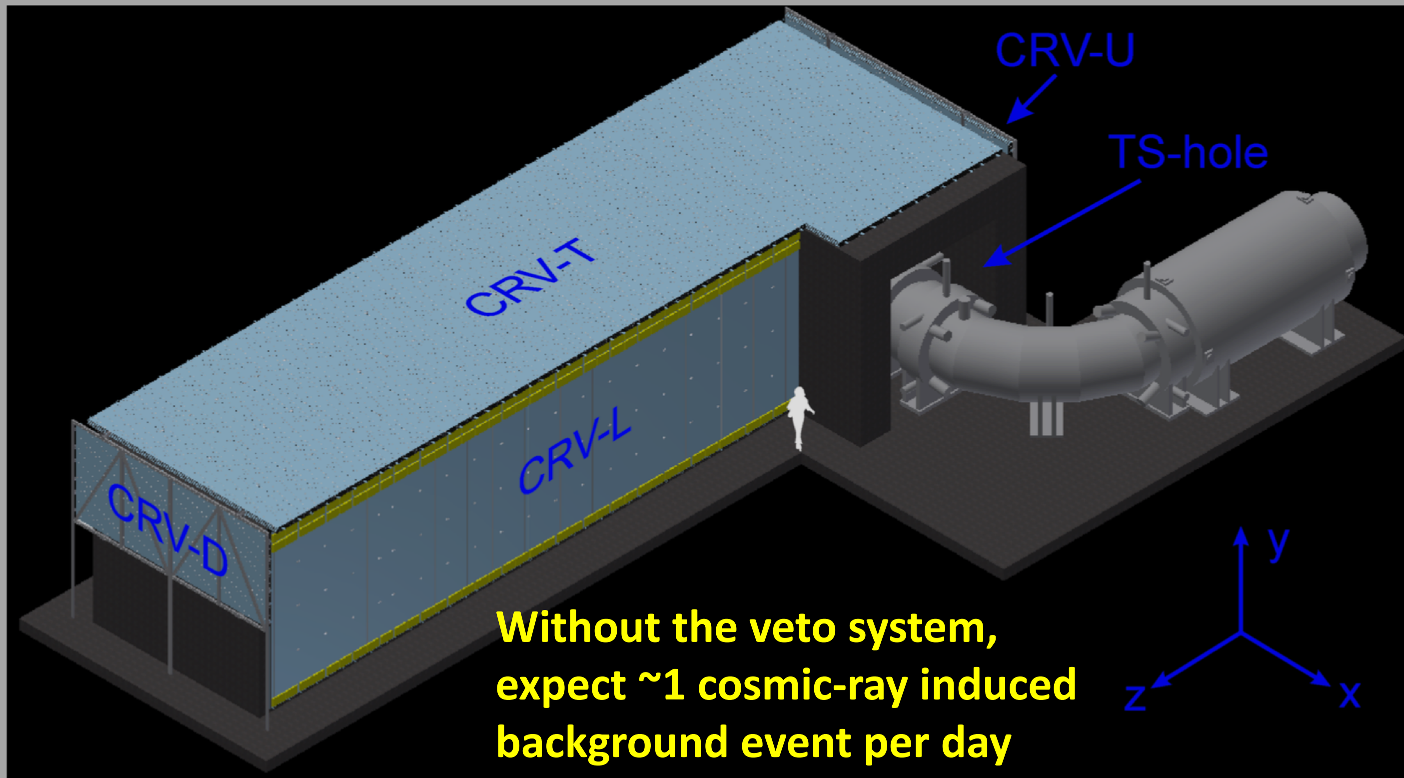
  (radius = 36-70 cm)



~Each disk has 860 CsI crystals with hexagonal cross-section ~3 cm diameter, ~20 cm long ($10X_0$)

Two photo-sensors/crystal on back (APDs or SiPMs)

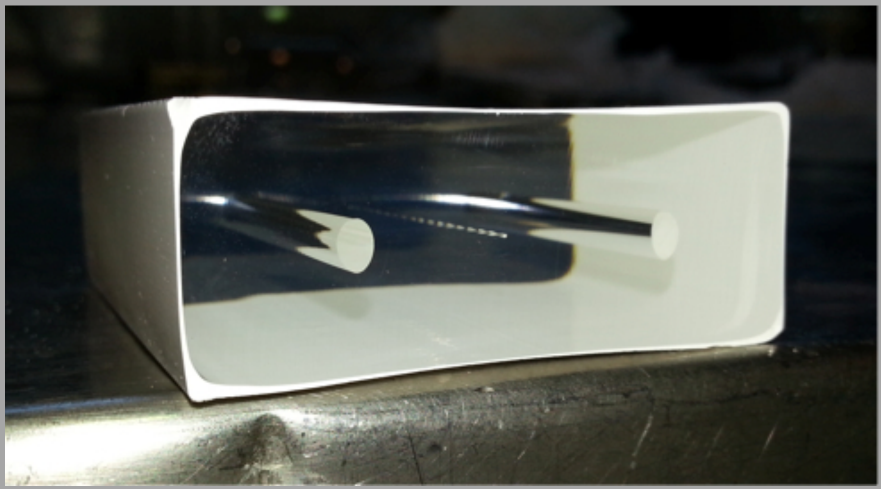
# The Mu2e Cosmic-Ray Veto

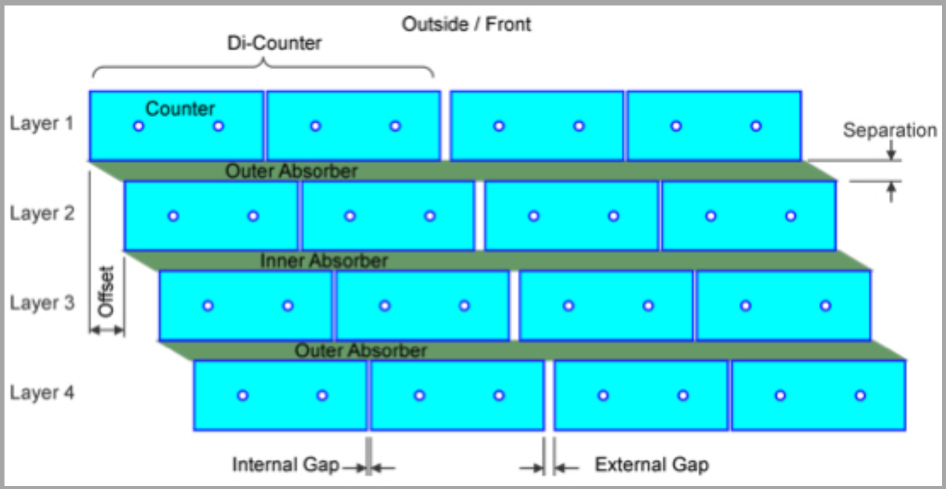



Cosmic ραψ μυονσ can generate background events via decay, scattering, or material interactions.

Veto system covers entire DS and half TS.

# The Mu2e Cosmic-Ray Veto

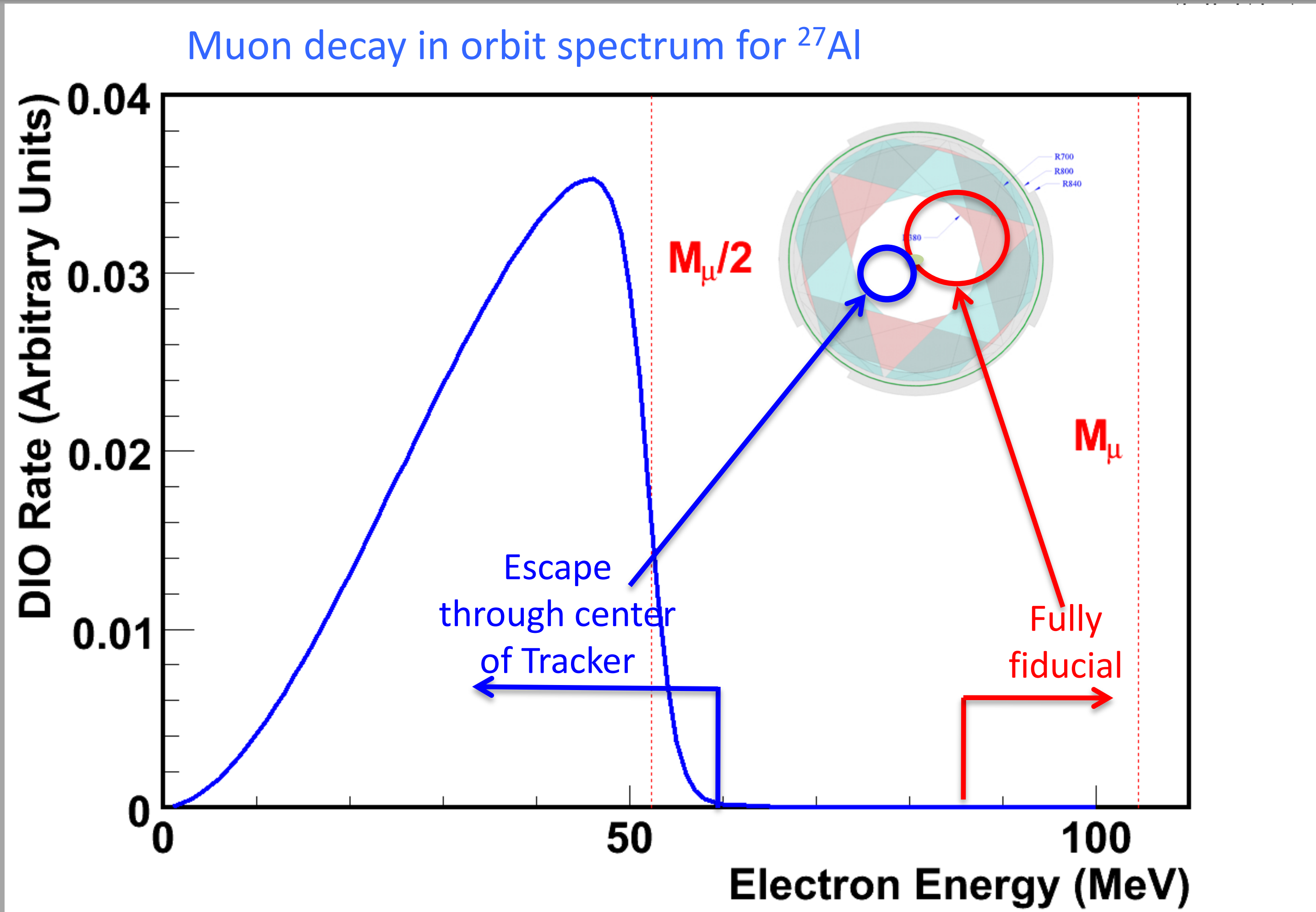





Will use 4 overlapping layers of scintillator bars separated by ~ 10 mm absorber

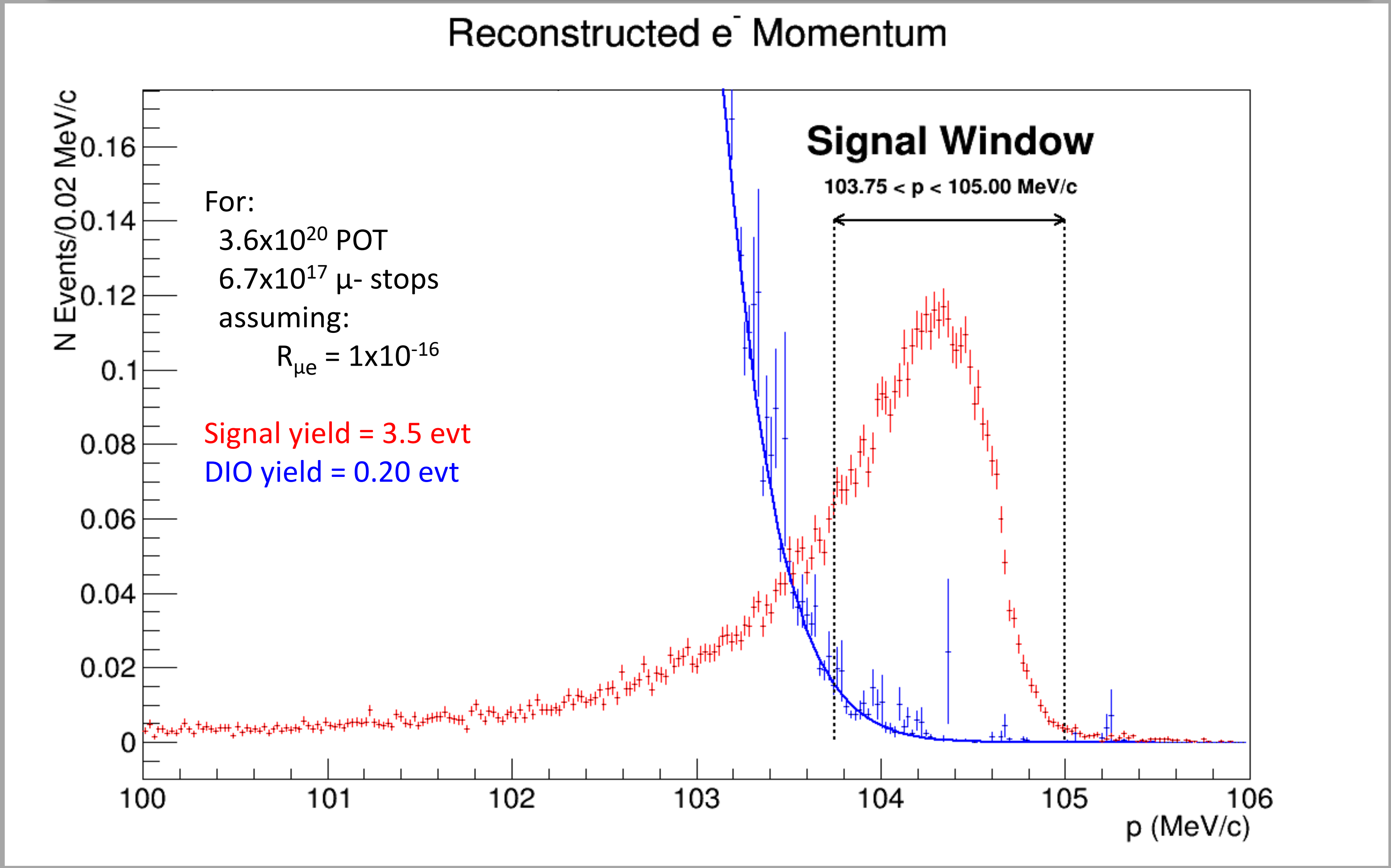
- Each bar is 5 x 2 x (300 - 660) $cm^3$
- 2 wavelength shifting fibers / bar
- Read-out both ends of each fiber with SiPM
- Have achieved Eφφ > 99.4% (per layer) in test beam

# How to get 4 orders of magnitude




→ Straw tracker designed such that no acceptance for lower-energy electrons from muon decay in orbit.

# Expected Sensitivity




Single-event-sensitivity = $2.9 \times 10^{-17}$

Total background < 0.5 events

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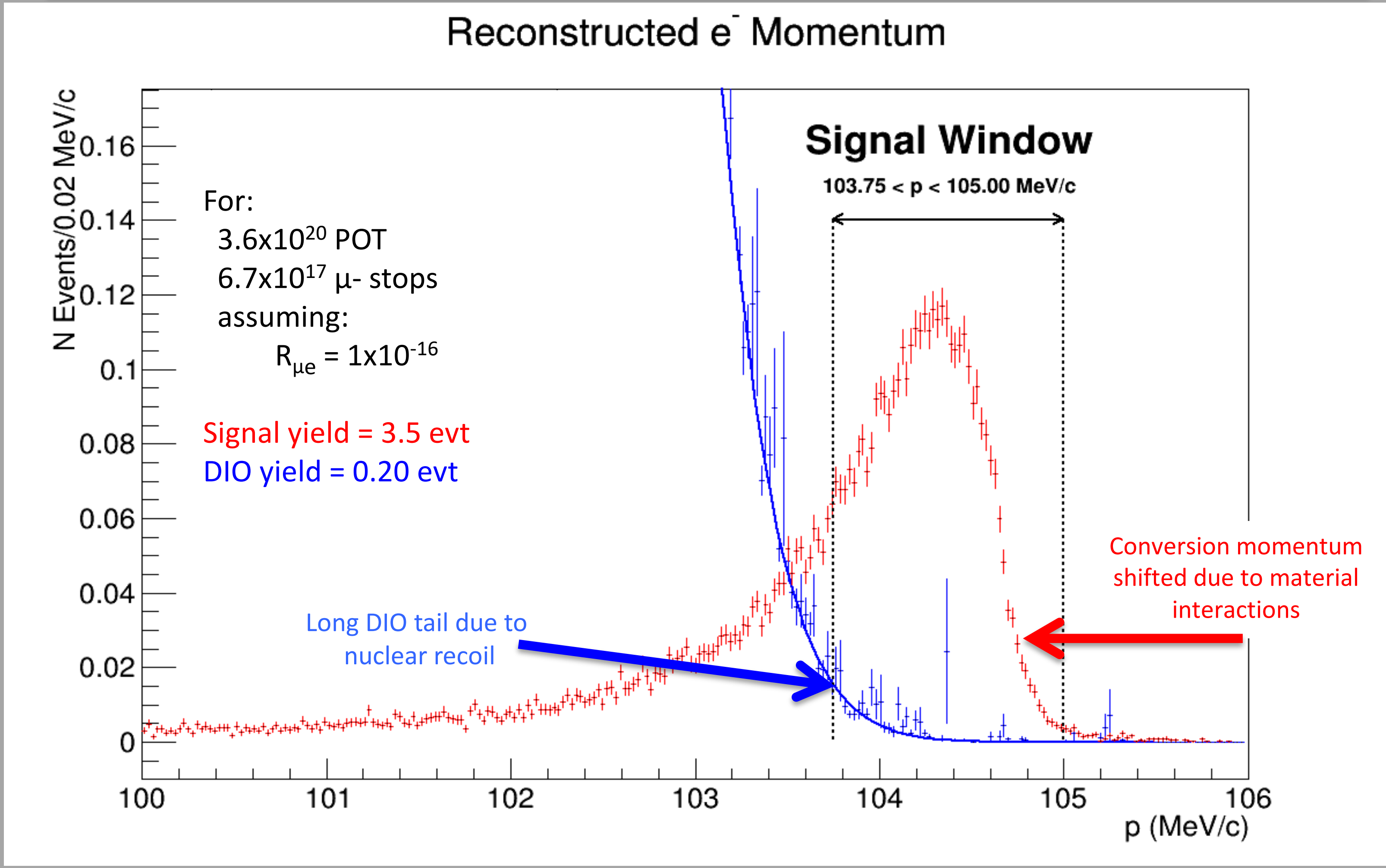


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