CIPANP 2015

The Mu2e Experiment at Fermilab

Craig Group

(University of Virginia and Fermilab)

...on behalf of the Mu2e collaboration.

CIPANP

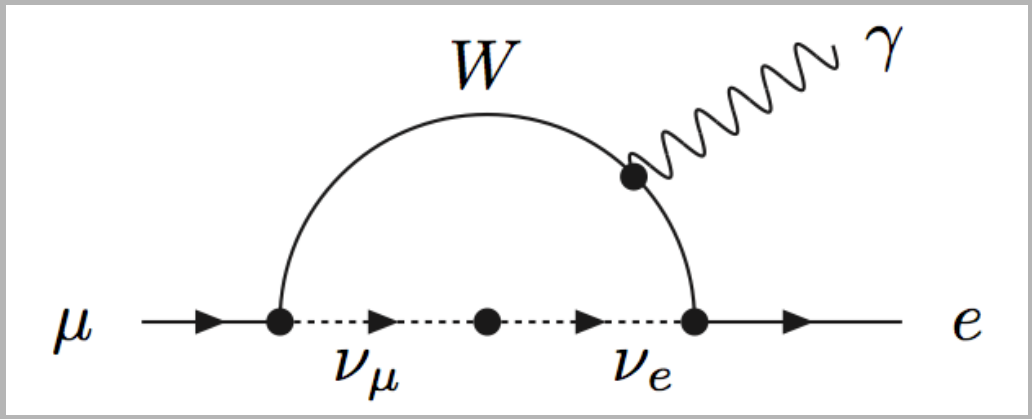
- **Mu2e should be a poster child for Intersections of Particle and Nuclear Physics!**
- **Many topics (muon capture, muonic atoms, low-energy electrons, …) are closer to Nuclear Physics, while the physics goals are of high interest to Particle Physics.**
- **One Spokesperson, Jim Miller of BU, is primarily a nuclear physicist.**
- **At UVA we have Mu2e collaborators from both the Nuclear and HEP groups.**
- **Mu2e is a great opportunity for collaboration between nuclear and particle physicists.**

The Intensity Frontier

- One can probe the properties of the universe by looking for extremely rare processes
- Complementary alternative to using higher energies
  - Crucial component of the future of HEP…
- The medium-term future of accelerator-based particle physics on US soil is the Intensity Frontier:
  - Neutrino experiments (NOvA, SBN, DUNE…)
  - Precision measurements (g-2)
  - Rare decays (Mu2e)

Charged Lepton Flavor Violation (CLFV)

- Neutrinos have mass
- Individual lepton numbers are not conserved
- Therefore, Lepton Flavor Violation occurs in Charged Leptons



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

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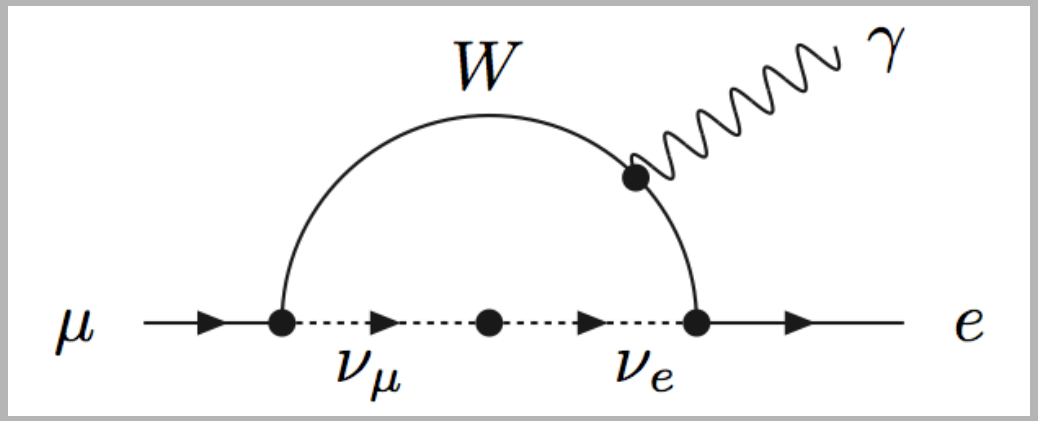
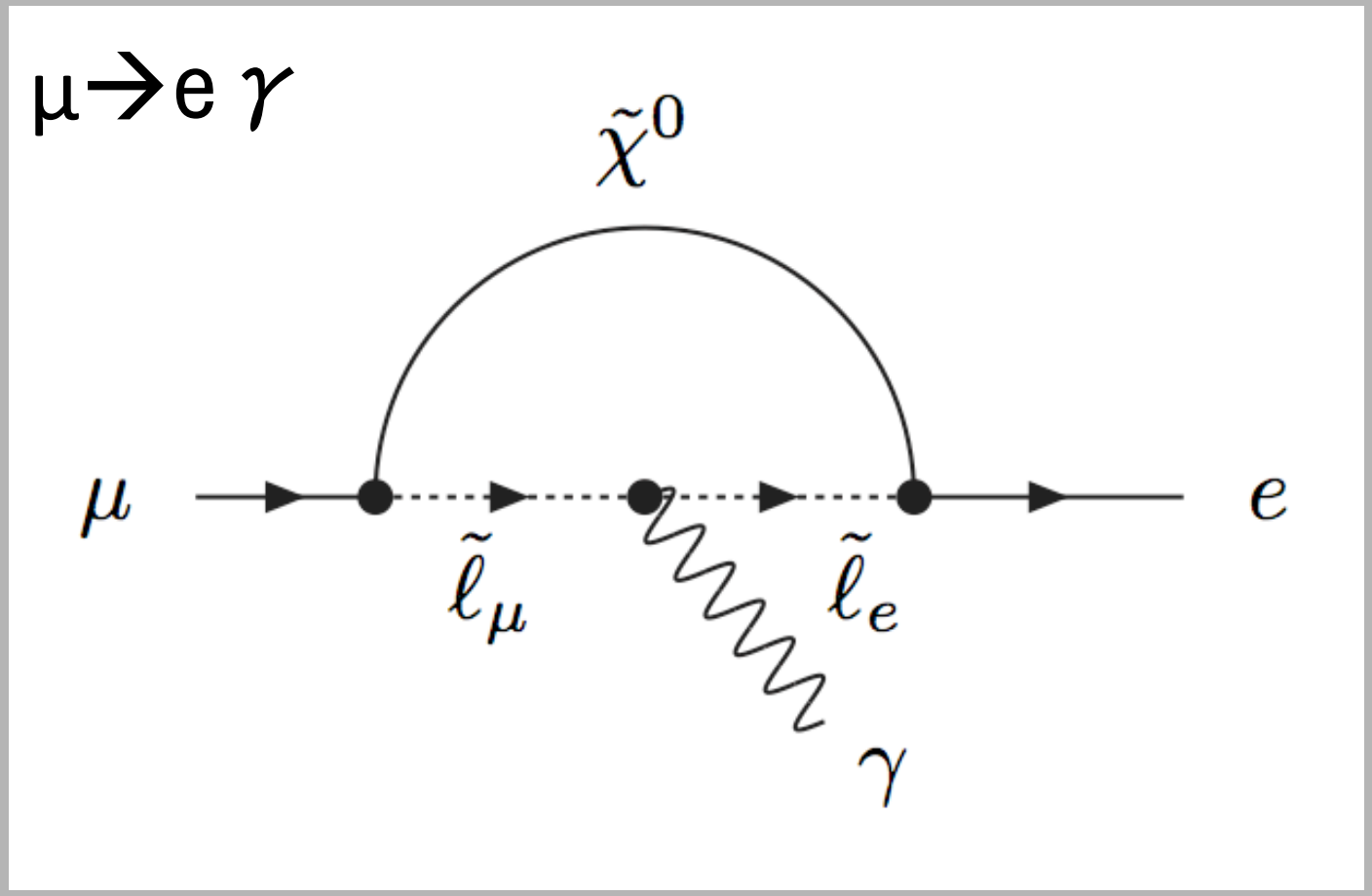


NO SM PHYSICS BACKGROUND! Observation is unambiguous sign of new physics!

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

Searching for CLFV

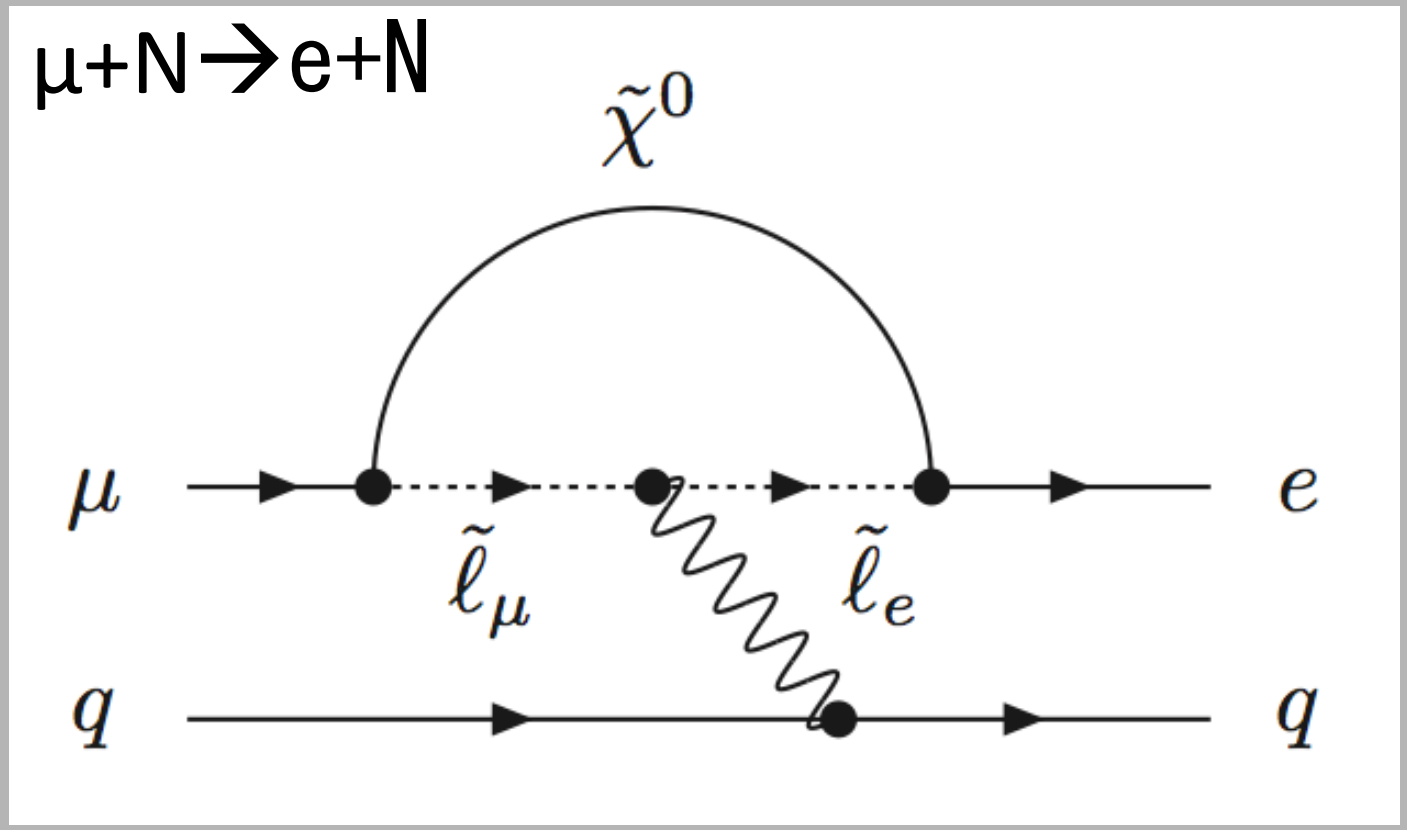
Can look for muon decaying into an electron plus a photon:



Experiments: MEGA, MEG, and others…

Searching for CLFV

Or, conversion in the presence of a nucleus (N):



Experiments: Mu2e, SINDRUM II, COMET, and others…

Mu2e

Experiment with CD2/3 approval that is proposed to begin commissioning in 2020 at Fermilab.

- Goal: Search for $\mu^- N \rightarrow e^- N$
  - Measure ratio:

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

  - With sensitivity to R at 90% C.L. of $6*10^{-17}$

    →4 orders of magnitude better than current limits

    -- $R_{\mu e} < 7 \times 10^{-13}$ @ 90% CL (on Au)

    -- SINDRUM II (W. Bertl et al., Eur. Phys. J. C 47, 337–346 (2006))

    →Need ~10^{18} stopped muons!

    -- ~10^{20} protons on target (3 year run)

    →Need to keep background small and well understood

Experimental Signature

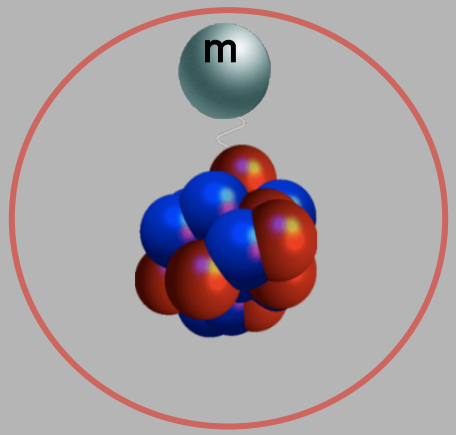
$$\mu^- N \rightarrow e^- N$$

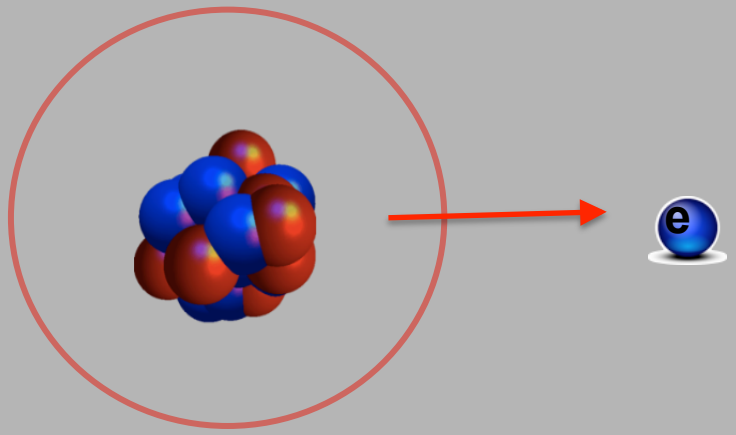
- A single monoenergetic electron
- If N = Al, E_e = 105. MeV

(Electron E depends on Z)

$$\begin{aligned} E_{\mu e} &= m_\mu c^2 - E_b - E_{\text{recoil}} \\ &= 104.973 \text{ MeV} \quad (\text{for Al}) \end{aligned}$$

- Nucleus coherently recoils off outgoing electron, no breakup





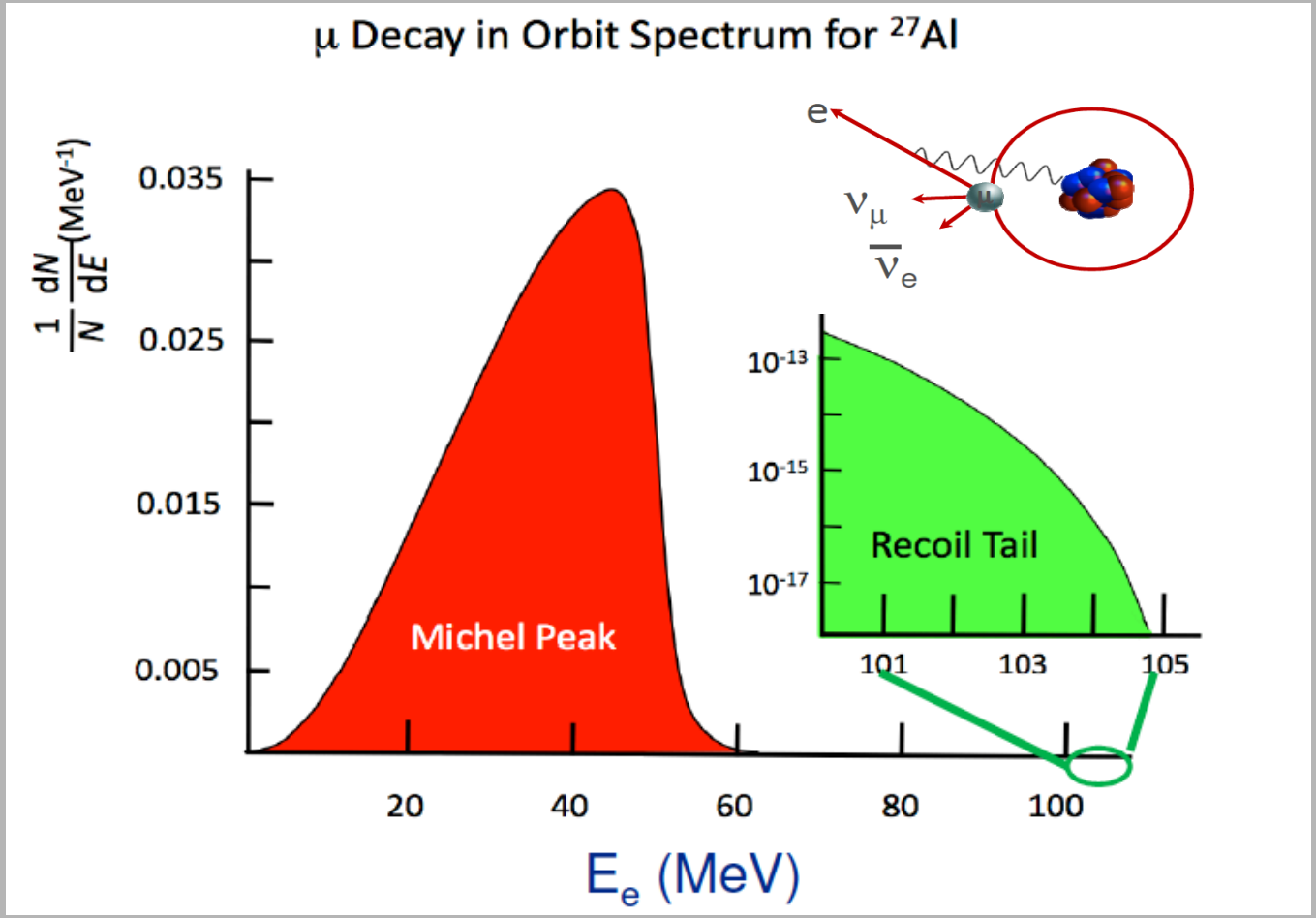
Background Processes

- Signal is a single ~105 MeV e-.
- Many possible sources of background events:
  - Intrinsic (~55%) – scale with number of stopped muons
    - Muon decay in Coulomb orbit (DIO is ~55% of total background)
    - Radiative muon capture (photon can convert asymmetrically)
  - Late arriving (~10%) – scale with number of late protons
    - Radiative pion capture
    - Muon/pion decay in flight
  - Miscellaneous (~35%):
    - Antiprotons and other late arriving particles
    - Cosmic-ray-induced electrons

These can all be controlled
and none produce a sharp peak at 105 MeV!

Background Processes

DIO is the largest component of the background.

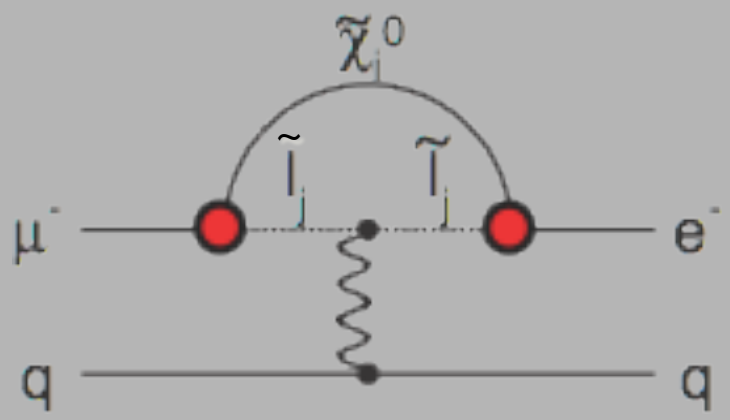


CLFV from SUSY

Access to SUSY through loops.

Supersymmetry

rate ~ 10^{-15}



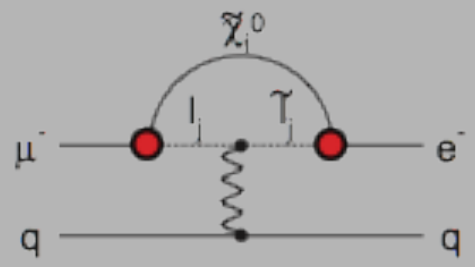
In Mu2e, a signal TeV-scale discovery at LHC implies:

$$\sim \frac{\textit{40 signal events}}{\textit{<1 background event}}$$

Other "new physics" also provide Mu2e signal

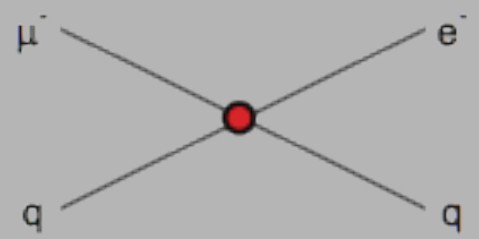
Supersymmetry

rate ~ 10^{-15}



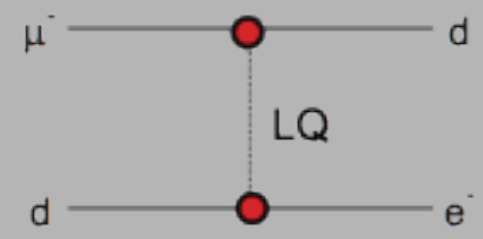
Compositeness

Λ_c ~ 3000 TeV



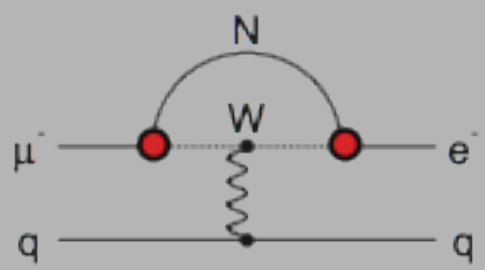
Leptoquark

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



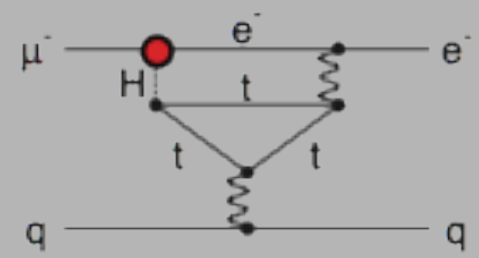
Heavy Neutrinos

$|U_{\mu N}U_{eN}|^2$ ~ 8×10^{-13}



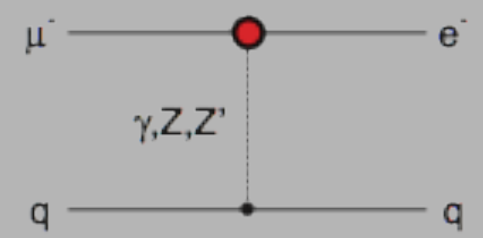
Second Higgs Doublet

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



Heavy Z' Anomal. Z Coupling

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



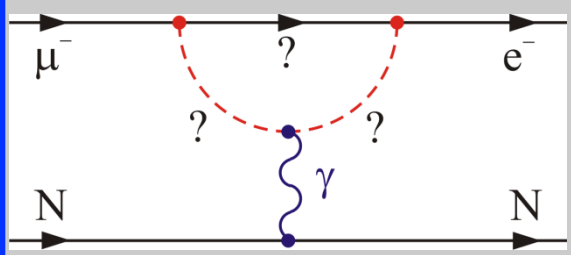
Marciano, Mori, and Roney , Ann. Rev. Nucl. Sci. 58

CLFV in $\mu^+ \rightarrow e^+\gamma$ and $\mu^- N \rightarrow e^- N$

Model-independent effective CLFV Lagrangian

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

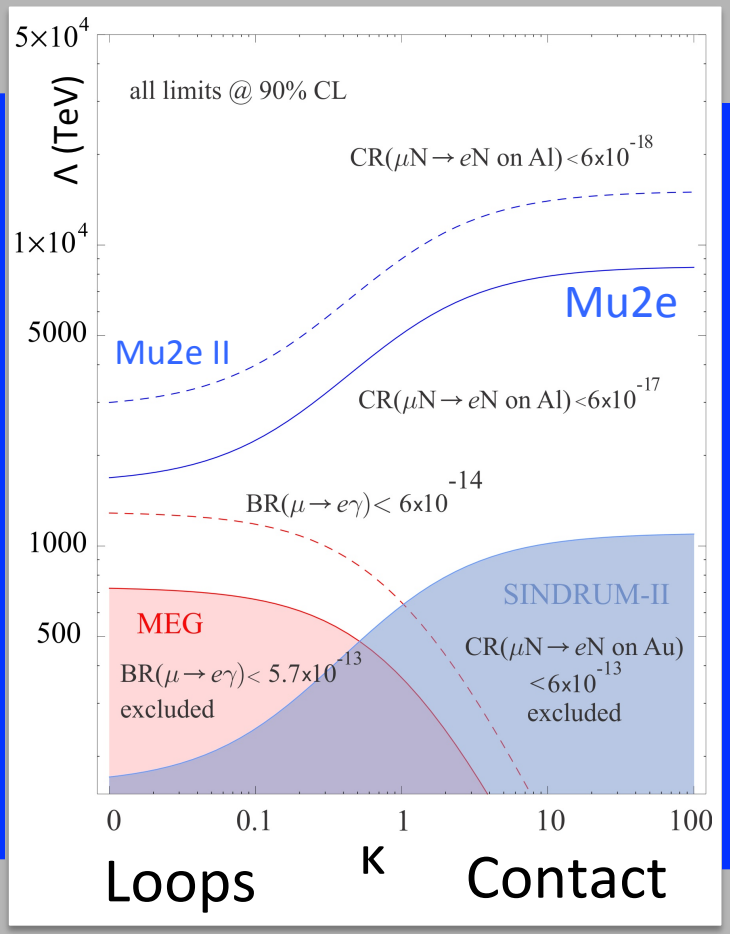
Loops



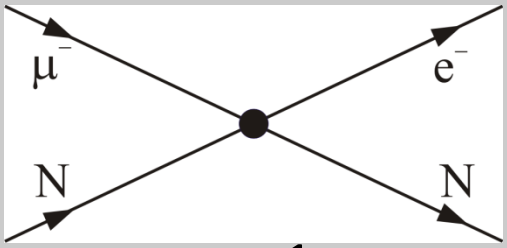
κ<< 1

magnetic moment type operator

μ→ eγ rate ~300X μN → eN rate



Contact Interactions



κ>> 1

four-fermion interaction

μN→ eN rate >> μ→ eγ rate

A. de Gouvea and P. Vogel
Prog.Part.Nucl.Phys. 71 (2013) 75-92

CLFV in $\mu^+ \rightarrow e^+\gamma$ and $\mu^- N \rightarrow e^- N$

Model-independent effective CLFV Lagrangian

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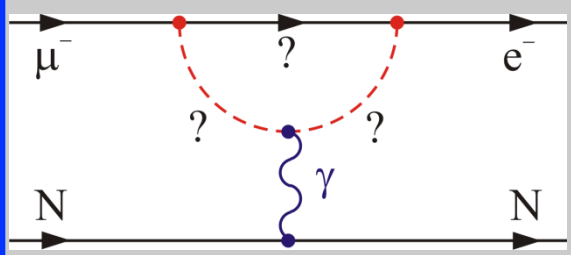
Mu2e is most sensitive over the full range of κ!

Loops



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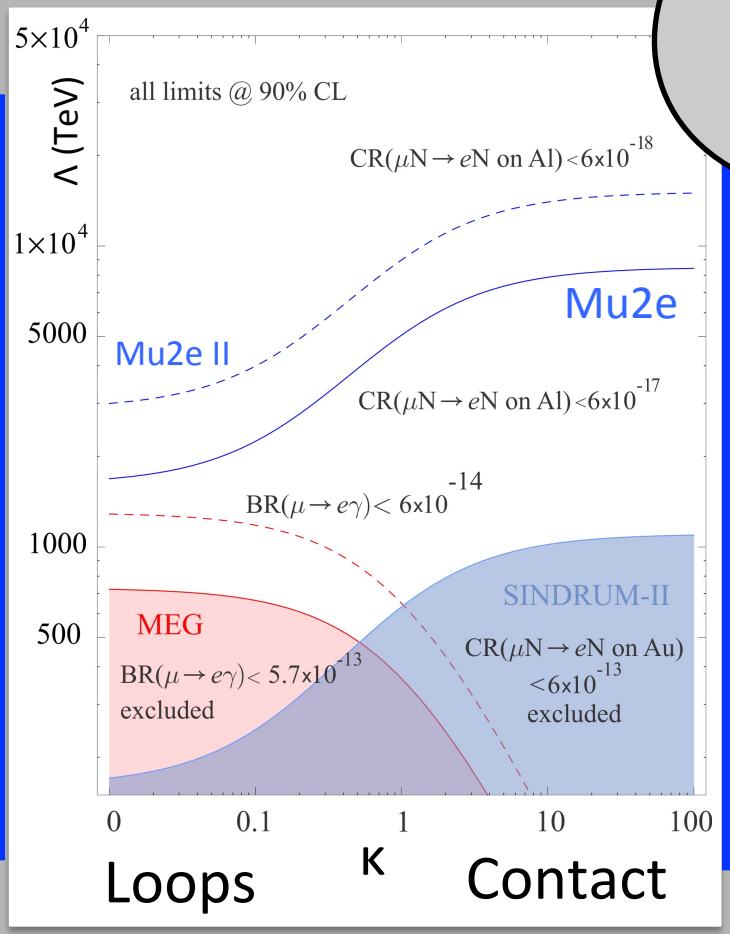

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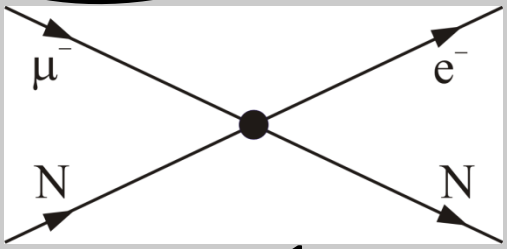

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Mu2e Discovery Potential

Provides information about flavor structure of new physics even if it is not easily accessible at the LHC.

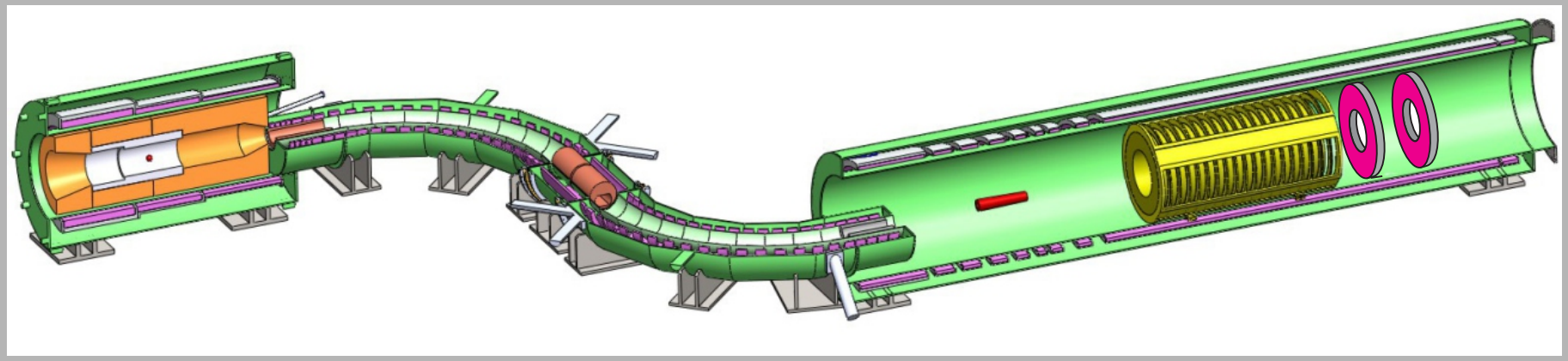
A null Mu2e result at the proposed sensitivity will severely constrain new physics models.

Discovery potential is high -- CLFV is predicted at observable rates for Mu2e in many models of new physics.

Mu2e can probe mass scales up to 10^4 TeV.

The Mu2e Experiment

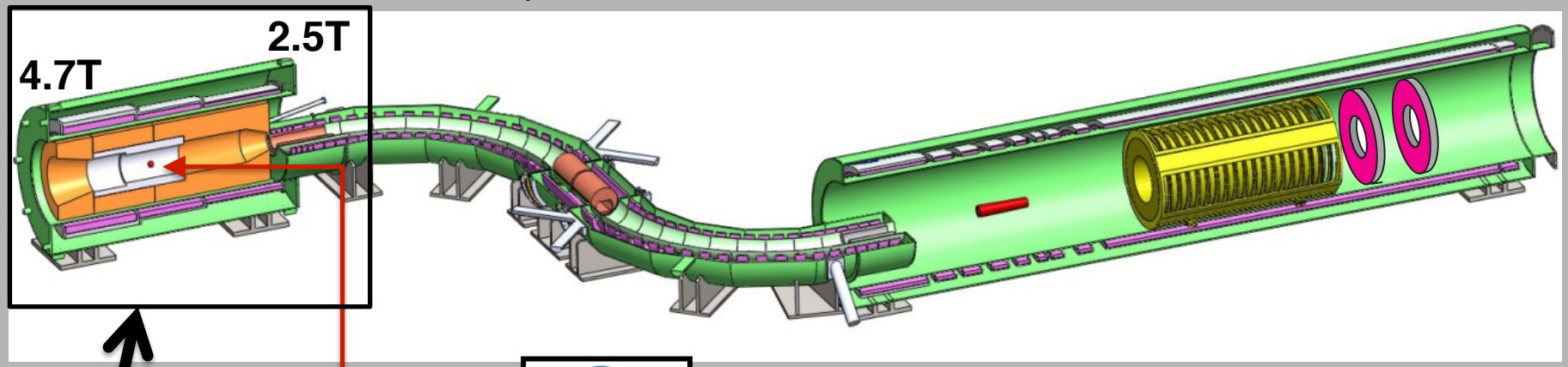
Production Solenoid Transport Solenoid Detector Solenoid

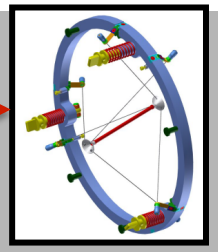


(about 25 meters end-to-end)

The Mu2e Experiment

Production Solenoid Transport Solenoid Detector Solenoid





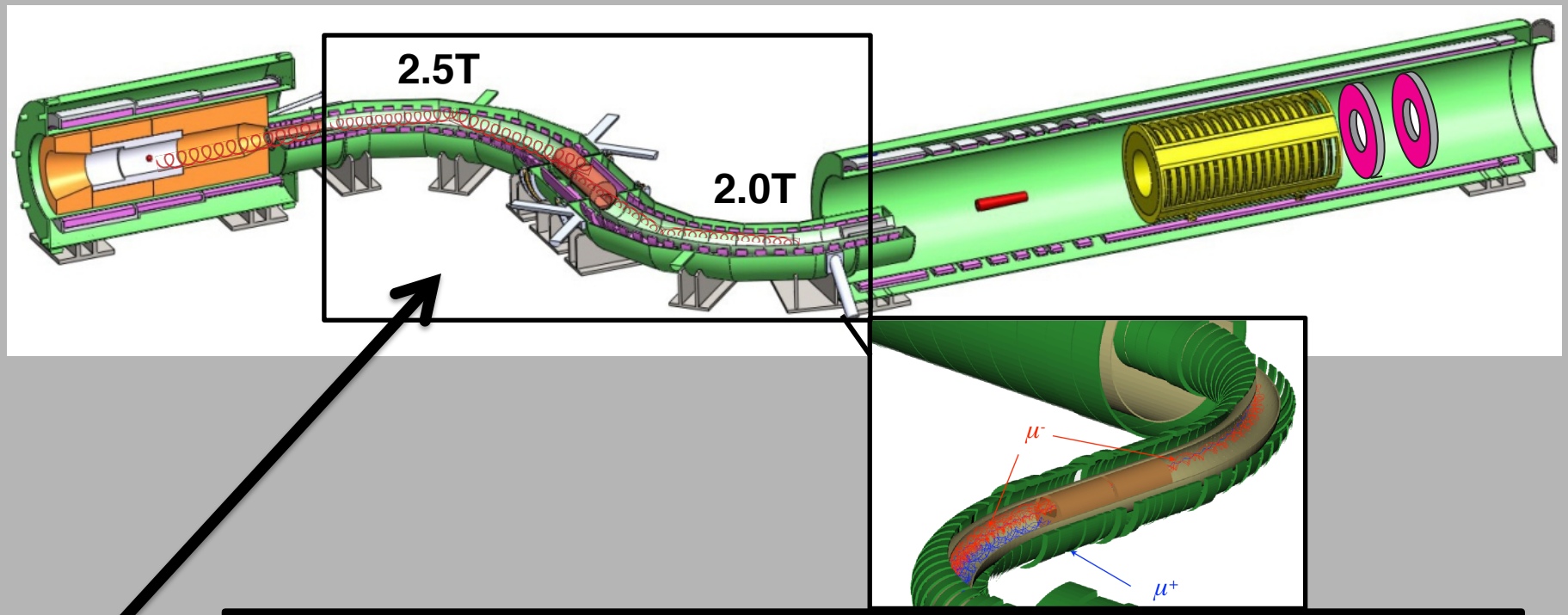
Production Target
(Tungsten, size of a pencil)

1)

- 8 GeV proton beam hits Production Target in Production Solenoid.
- Pions captured and pushed towards Transport Solenoid by graded field.
- Pions decay to muons.

The Mu2e Experiment

Production Solenoid **Transport Solenoid** Detector Solenoid

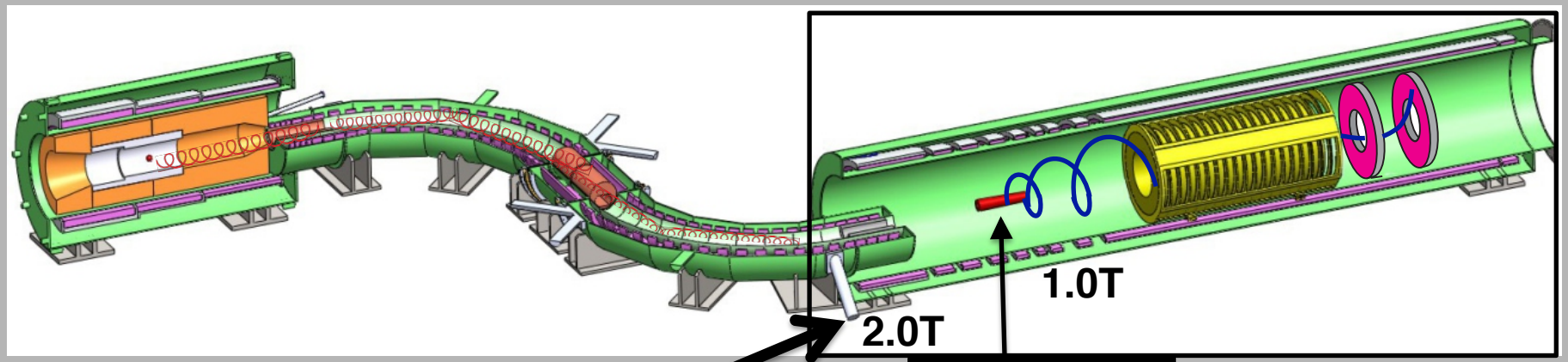


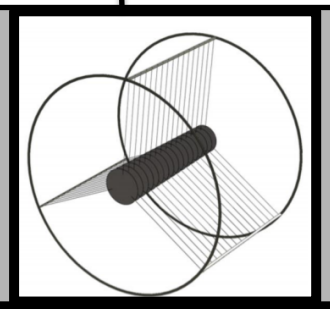
2)

- Transport solenoid performs sign and momentum selection.
- Collimators eliminate high energy negative particles, positive particles, and line-of-sight neutrals.

The Mu2e Experiment

Production Solenoid Transport Solenoid **Detector Solenoid**





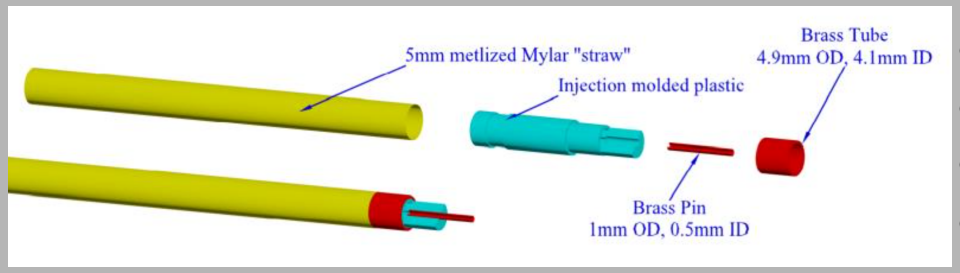
Stopping Target
(Aluminum foils)

3)

- Muons captured in stopping target foils.
- Conversion electron trajectory measured in tracker, validated in calorimeter.
- Cosmic Ray Veto surrounds Detector Solenoid.

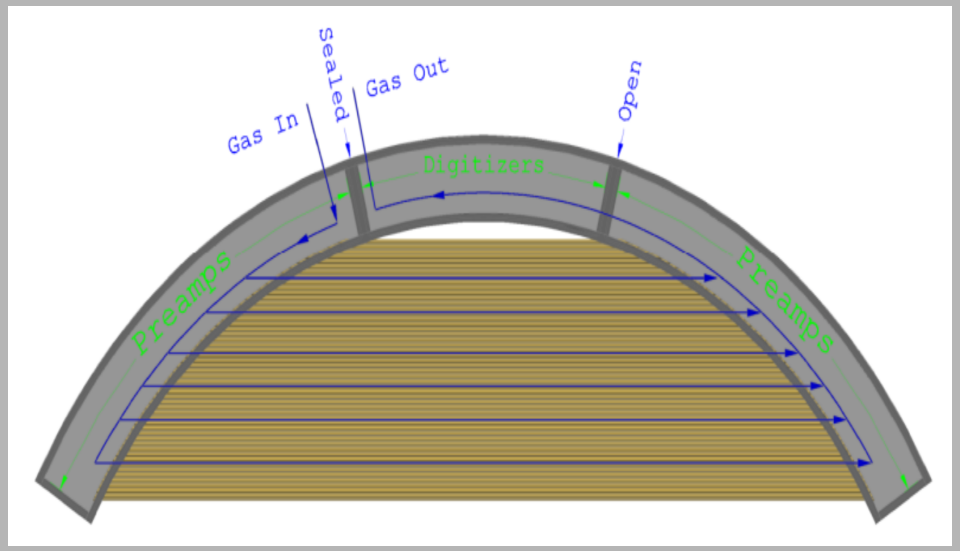
The Mu2e Tracker

straw tube

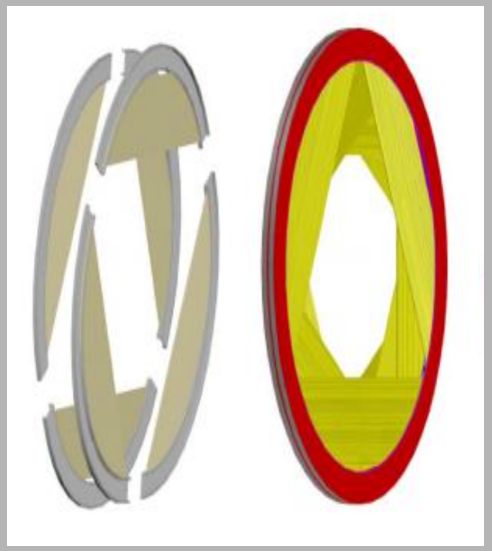


- 5 mm diameter straw, spiral wound
- Al, Au-coated, 15 µm Mylar
- 334 – 1174 mm active length
- 80/20 Ar/CO2 with HV < 1500 V
- 100 µm hit resolution

panel = 96 straw tubes



plane = 6 panels



station = 2 planes

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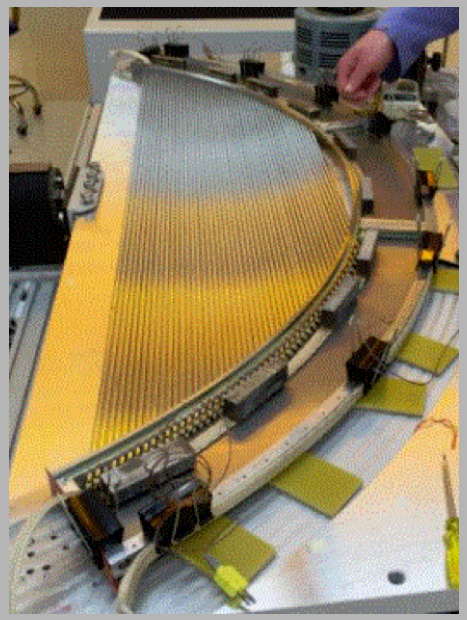

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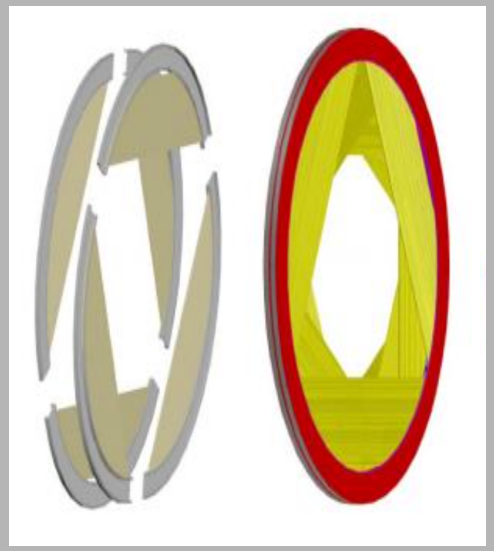
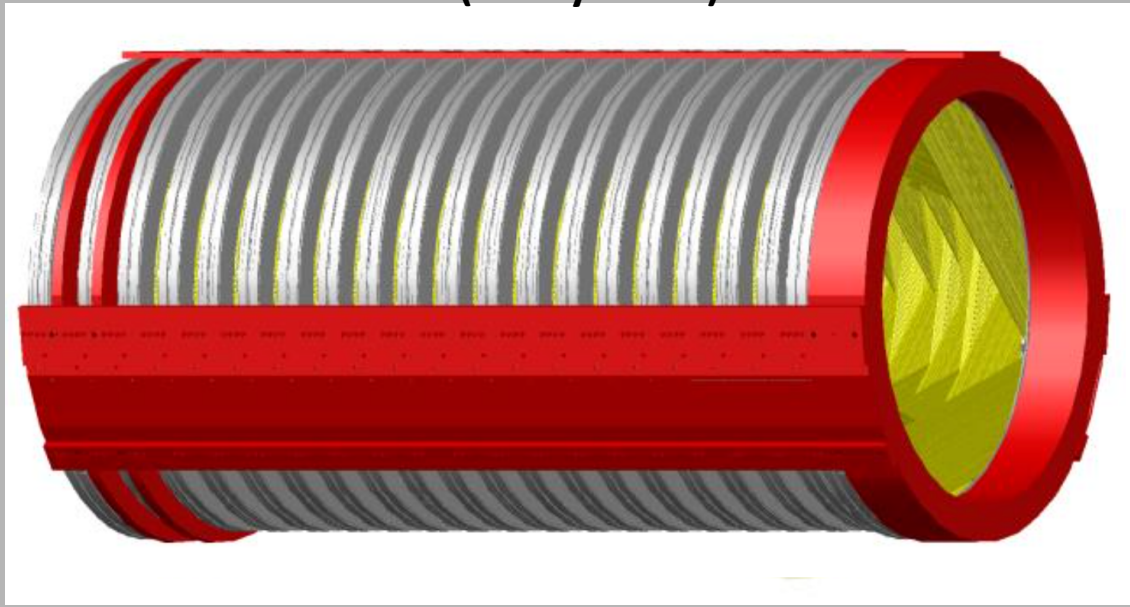
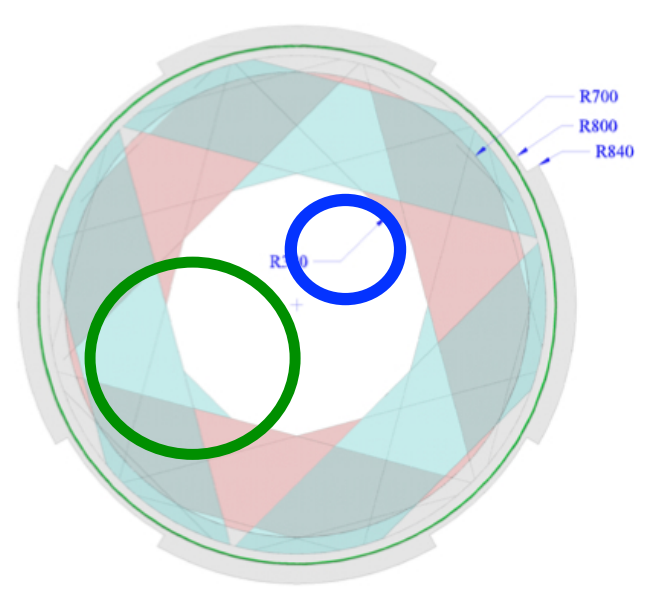


station = 2 planes

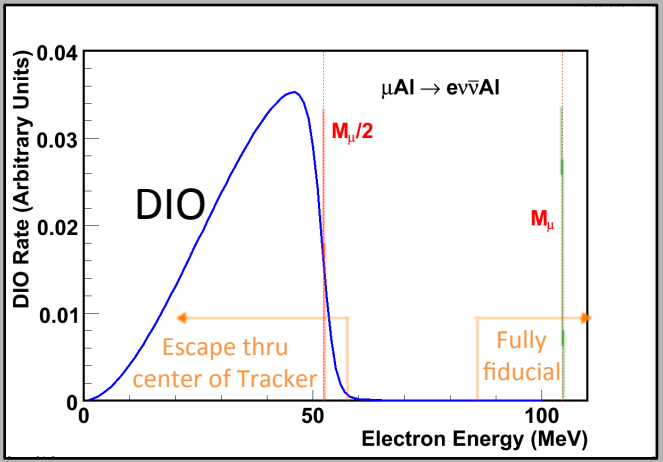
The Mu2e Tracker

detector= 18 stations (3m cylinder)





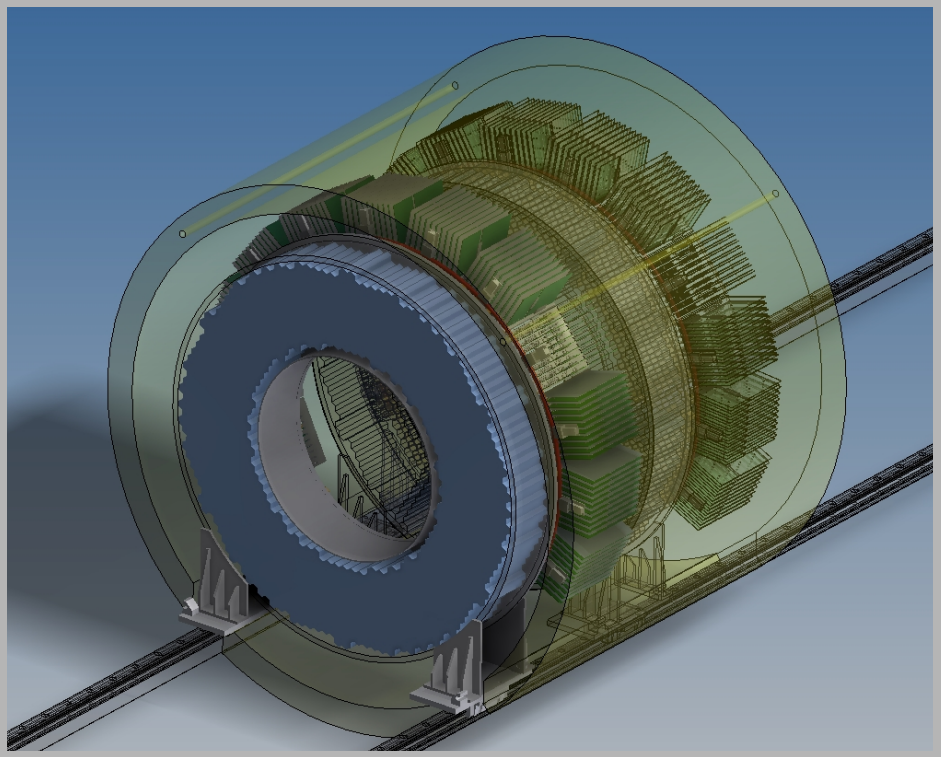
- Detector is in vacuum and inner 38 cm is purposefully un-instrumented
  - Blind to beam flash
  - Blind to >99% of DIO spectrum
- Active tracking region from 38 cm to 70 cm
- Services and structure beyond 70 cm



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

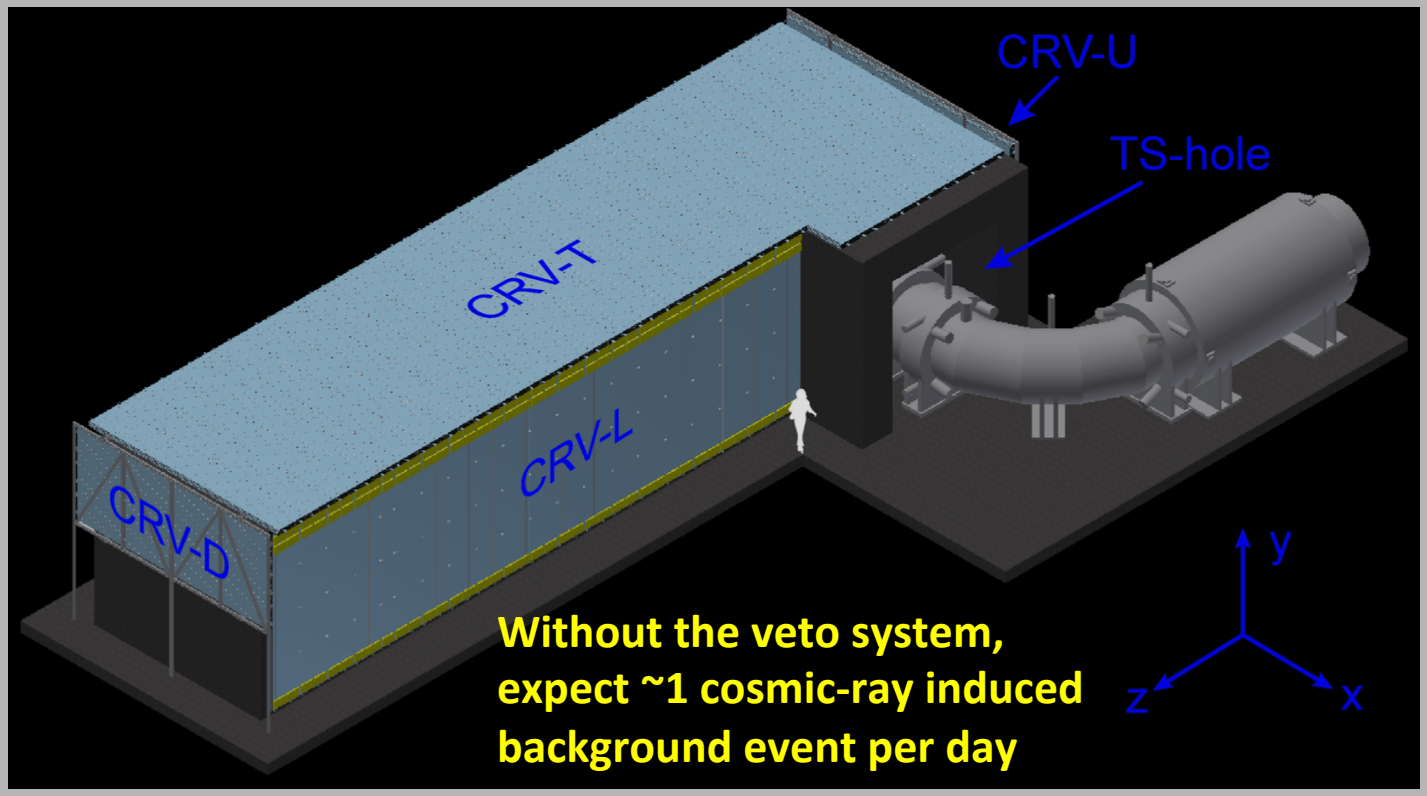
  (radius = 36-70 cm)



~2000 BaF_2 crystals with hexagonal cross-section ~3 cm diameter, ~20 cm long ($10X_0$)

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

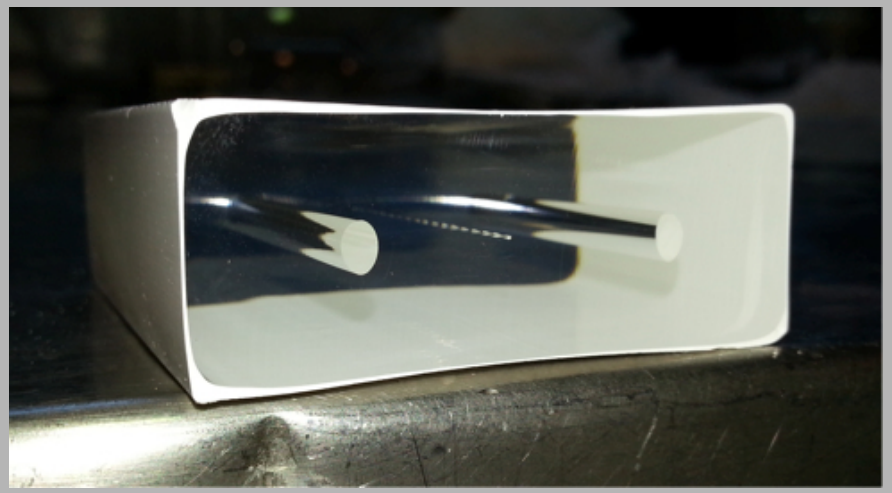
The Mu2e Cosmic-Ray Veto

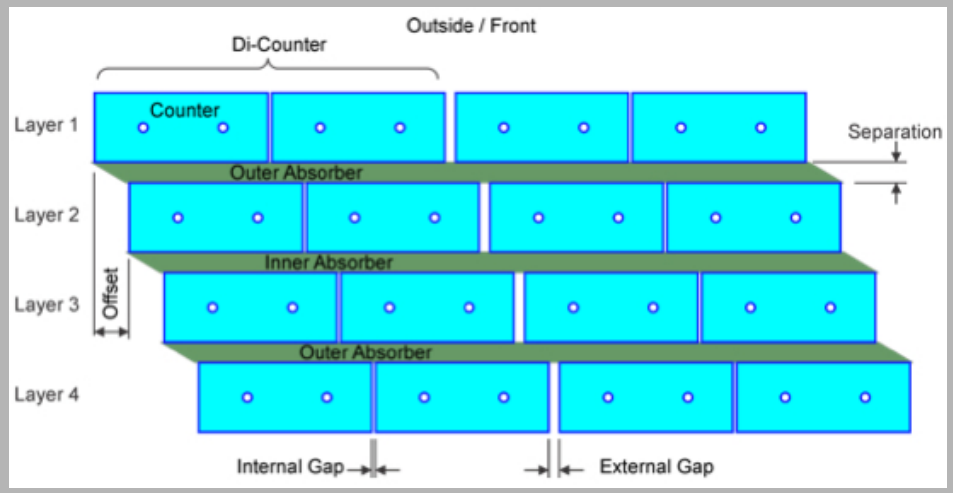


Cosmic ray muons can generate background events via decay, scattering, or material interactions.

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 Eff > 99.4% (per layer) in test beam

Sensitivity Goal

Current limits: $R_{\mu e} = \frac{\mu^- Au \rightarrow e^- Au}{\mu^- Au \rightarrow \text{capture}} < 7\text{x}10^{-13}$ (SINDRUM II)

Mu2e goal: $R_{\mu e} = \frac{\mu^- Al \rightarrow e^- Al}{\mu^- Al \rightarrow \text{capture}} < 6\text{x}10^{-17}$ (90% c.l.)

X10000 improvement over current best limit!

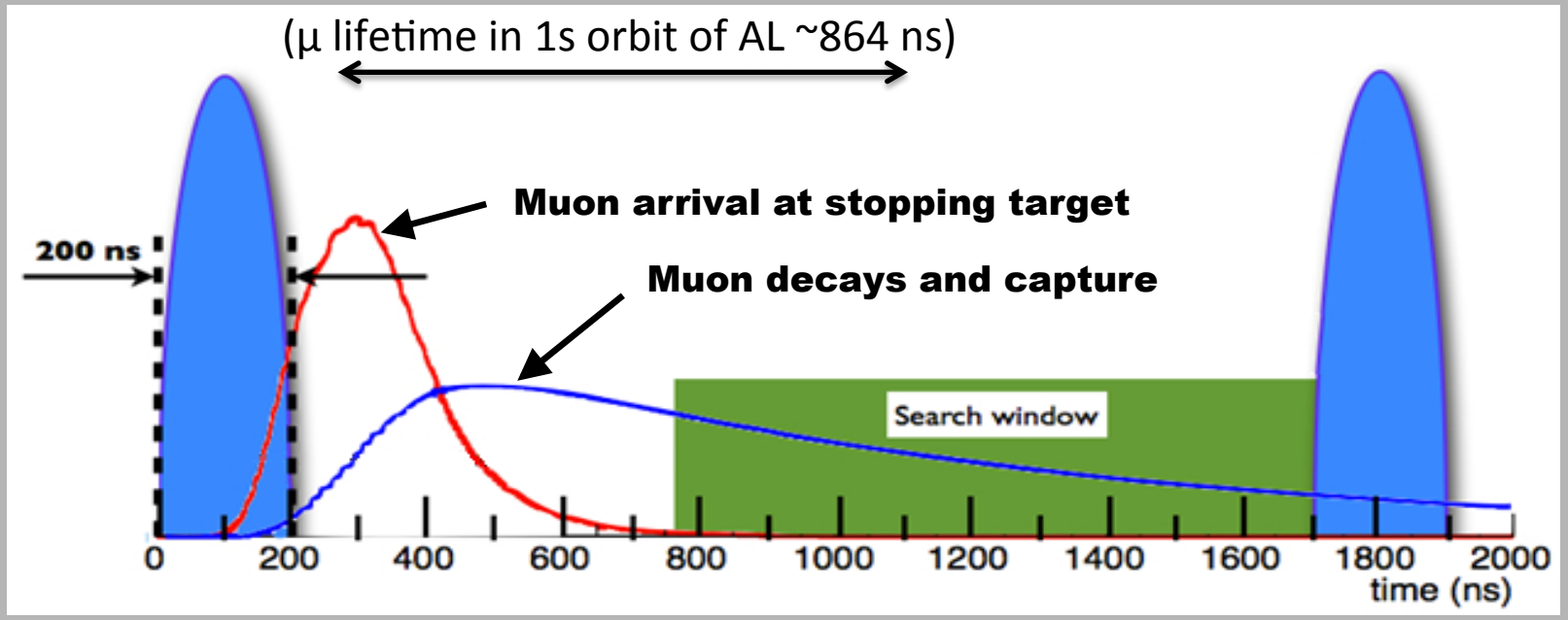
How:

- Improved efficiency for producing and stopping muons
  - Production target in gradient field*
  - Mu2e will stop ~10 billion muons per second!
  - Expect to stop ~21 muons per 10,000 proton on target.
- Reduced backgrounds and detector occupancy due to pulsed beam
- Single event sensitivity! 0.4 bkg events expected in 3-year run

* Djilkibaev, Lobashev *et al.*

How to get 4 orders of magnitude

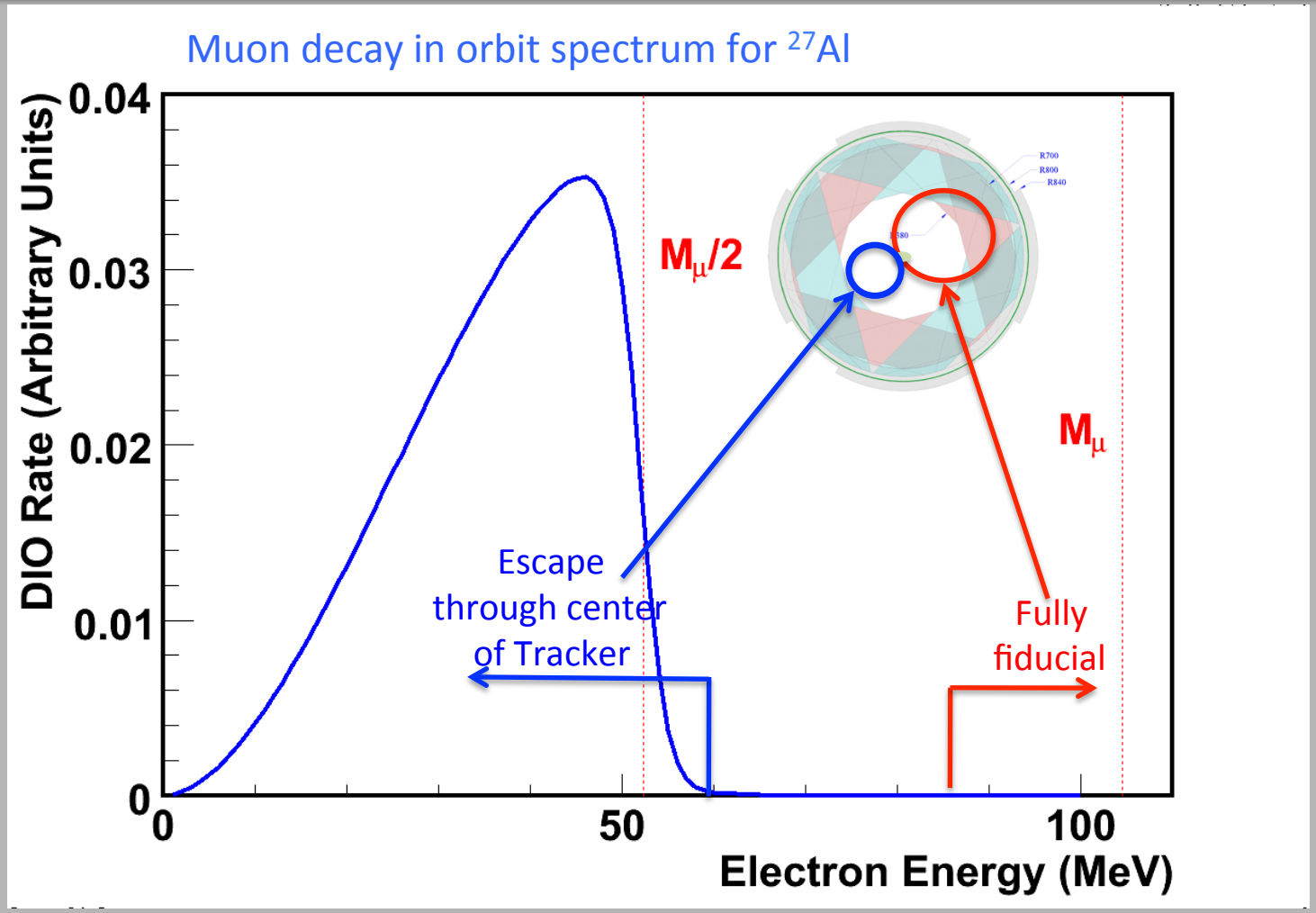
- We have the best accelerator setup in the world for this measurement! Ideal pulse spacing…
- Pulsed beam:
  - beam on target – produce and stop muons (detector blinded)
  - observe stopped muon decays



Extinction level of 10^{-10} between bunches is crucial!

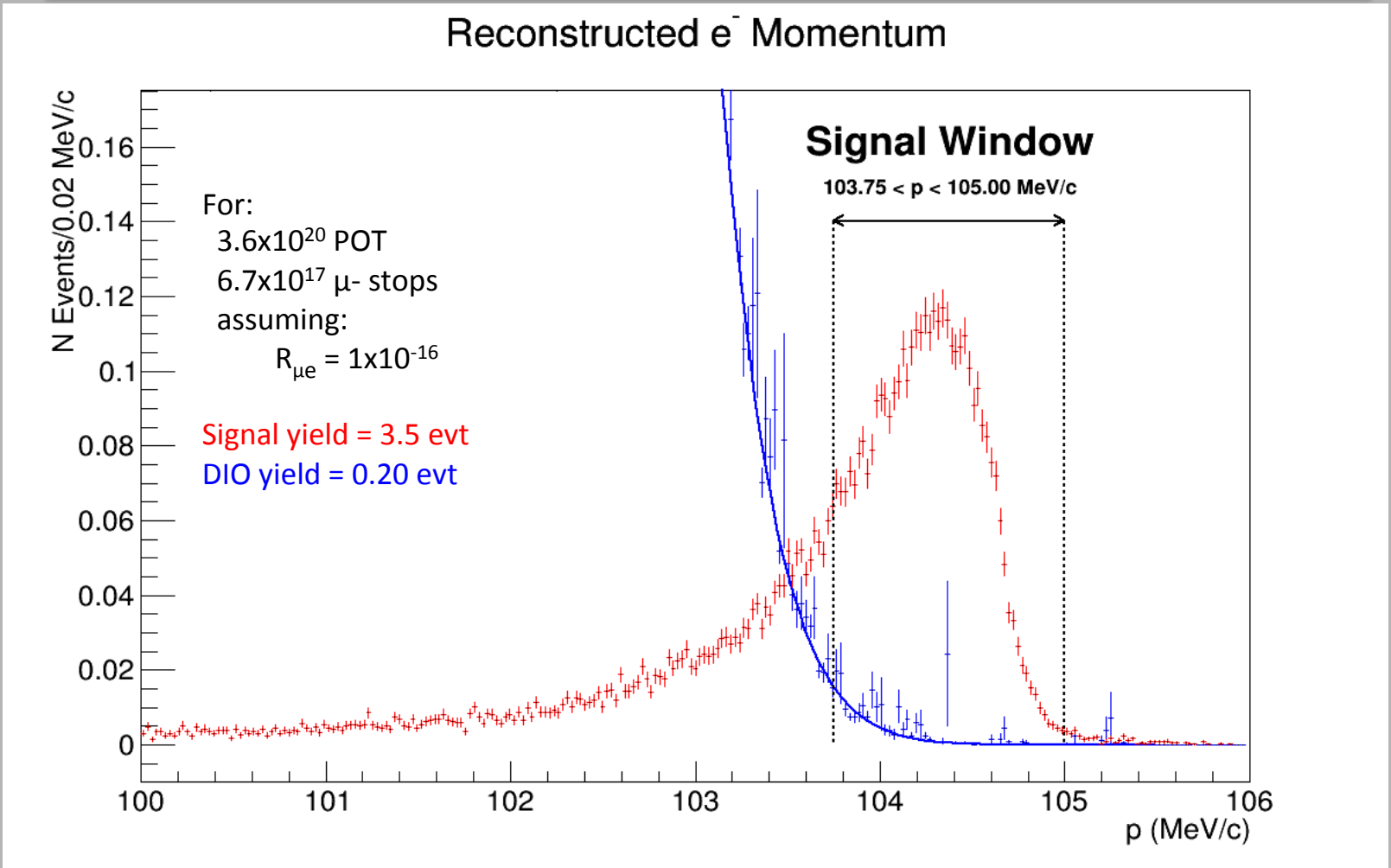
(Removes 'prompt' backgrounds!)

How to get 4 orders of magnitude



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

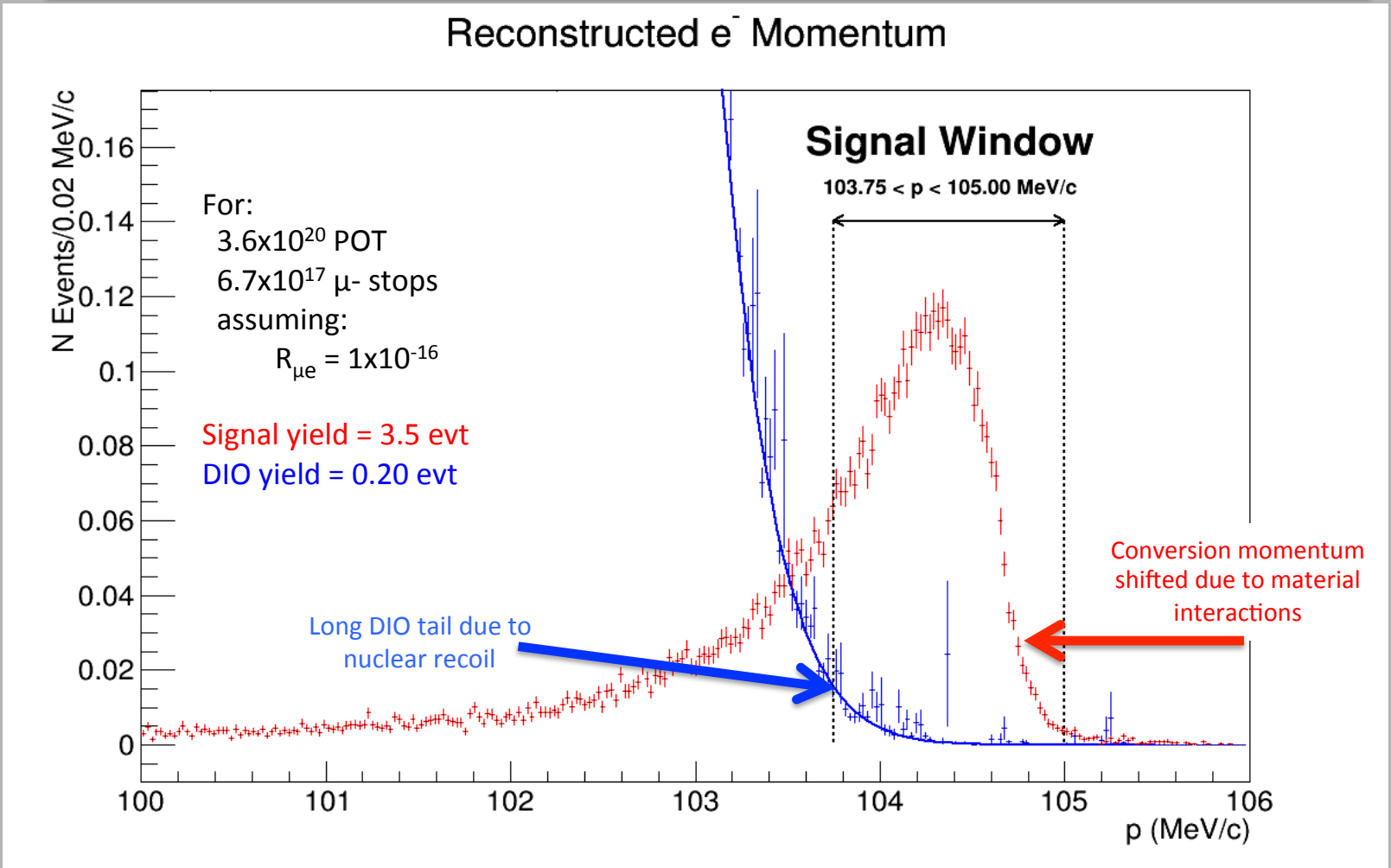
Expected Sensitivity



Single-event-sensitivity = 2.9×10^{-17}

Total background < 0.5 events

Expected Sensitivity



Single-event-sensitivity = 2.9×10^{-17}

Total background < 0.5 events

Magnets are the heart of Mu2e

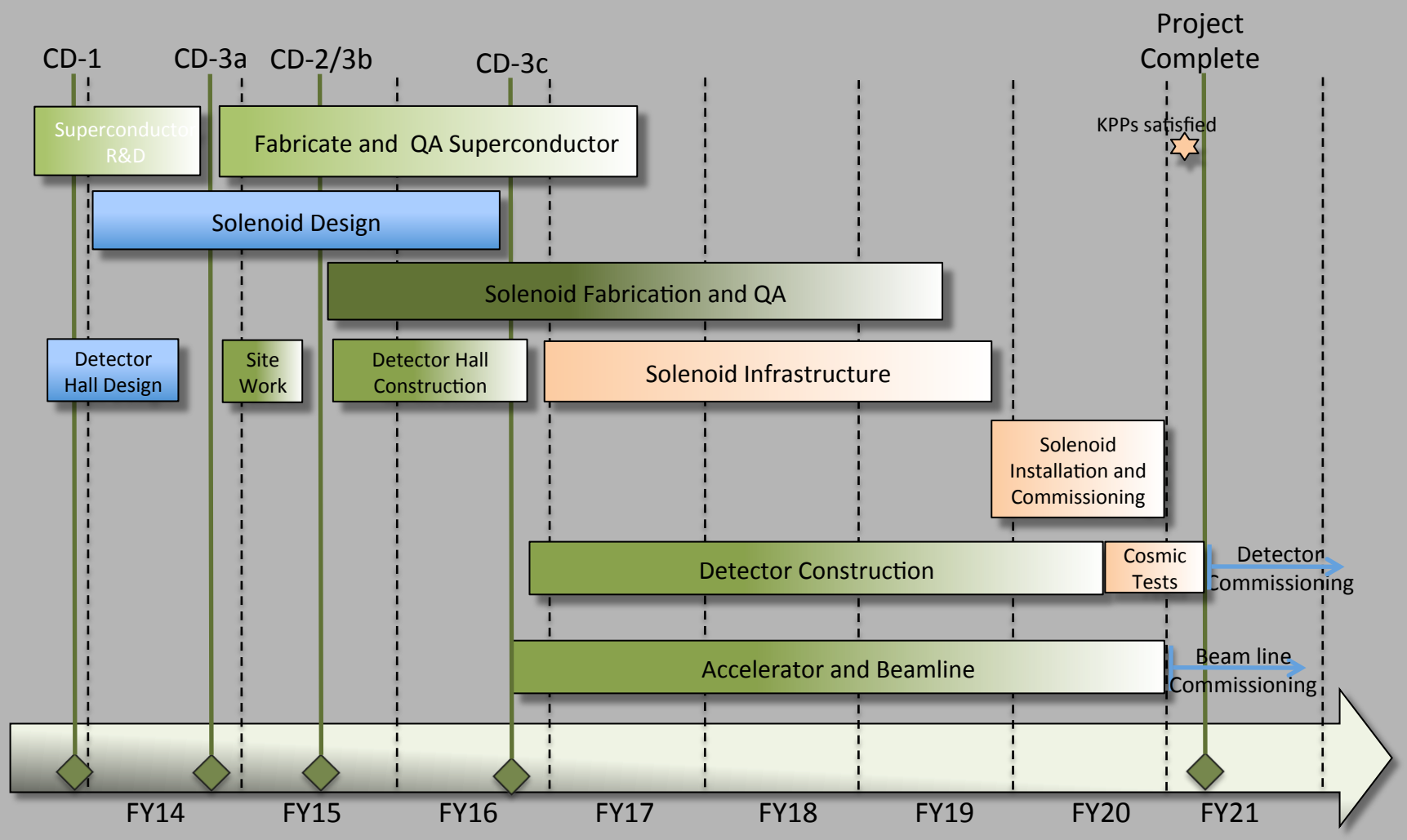
First Transport Solenoid prototype module is being tested…

Note: Full TS is 27 of these modules.

Buildings

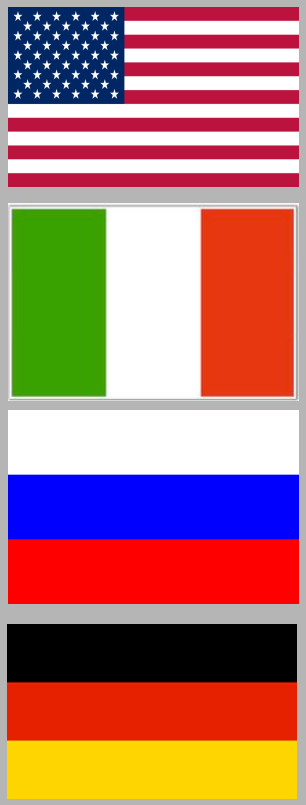
- Beamline is under construction.
- Broke ground on the detector building last month!

Mu2e Schedule



Schedule produced February 2015

The Mu2e Collaboration



~160 People, 32 Institutions, 4 Countries

Additional information

- Technical Design Report

arXiv.org > physics > arXiv:1501.05241

- Experiment web site

http://mu2e.fnal.gov

Mu2e Technical Design Report

October 2014

Fermi National Accelerator Laboratory
Batavia, IL 60510
www.fnal.gov

Managed by
Fermi Research Alliance, FRA
For the United States Department of Energy under
Contract No. DE-AC02-07-CH-11359

Summary

- The intensity frontier and flavor physics may well reveal a sign of exotic physics!
- Mu2e will improve sensitivity by 4 orders-of-magnitude relative to past CLFV searches.
- Mu2e will provide complementary information relative to the LHC and is sensitive to mass scales many orders of magnitude higher than can be directly probed at colliders.
- Much recent progress, and hoping for a discovery in 2021!

Thank you

Possible Scenarios

- We see something the first year!
  - Change target to better constrain the new physics rule out some backgrounds.
- See something with two years of data:
  - Plan for intensity upgrade
  - New targets…
- Don't see anything:
  - Intensity upgrade for sensitivity improvement of two additional orders-of-magnitude.

(See arXiv:1307.1168 for upgrade studies)

Backgrounds

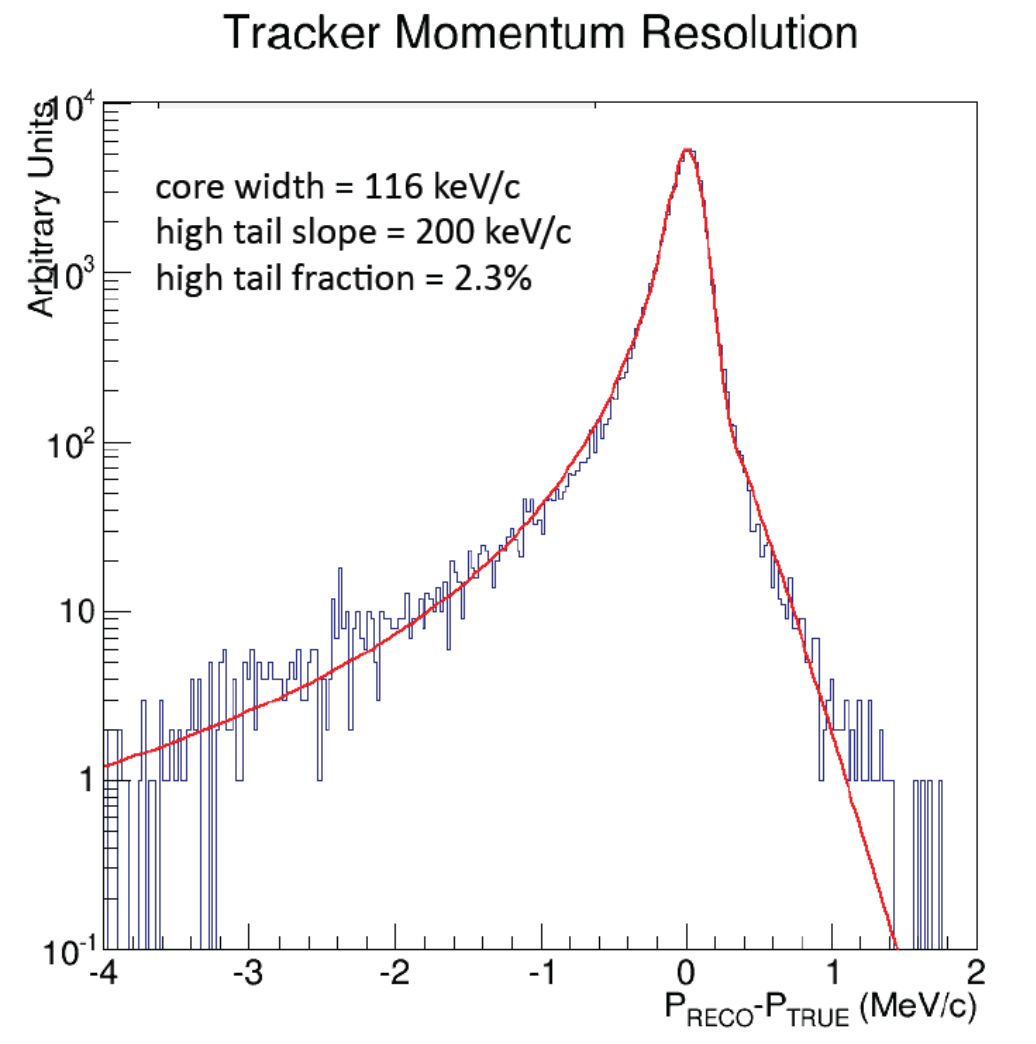
- Background counts expected in 3.6×10^{20} POT

Category	Background process	Estimated yield (events)	
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092	54%
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$	
Late Arriving	Pion capture (RPC)	0.023 ± 0.006	
	Muon decay-in-flight (μ-DIF)	<0.003	
	Pion decay-in-flight (π-DIF)	$0.001 \pm <0.001$	
	Beam electrons	0.003 ± 0.001	
Miscellaneous	Antiproton induced	0.047 ± 0.024	13%
	Cosmic ray induced	0.092 ± 0.020	25%
	Total	0.37 ± 0.10	

- DIO must be managed!
- What does this look like in the detector?

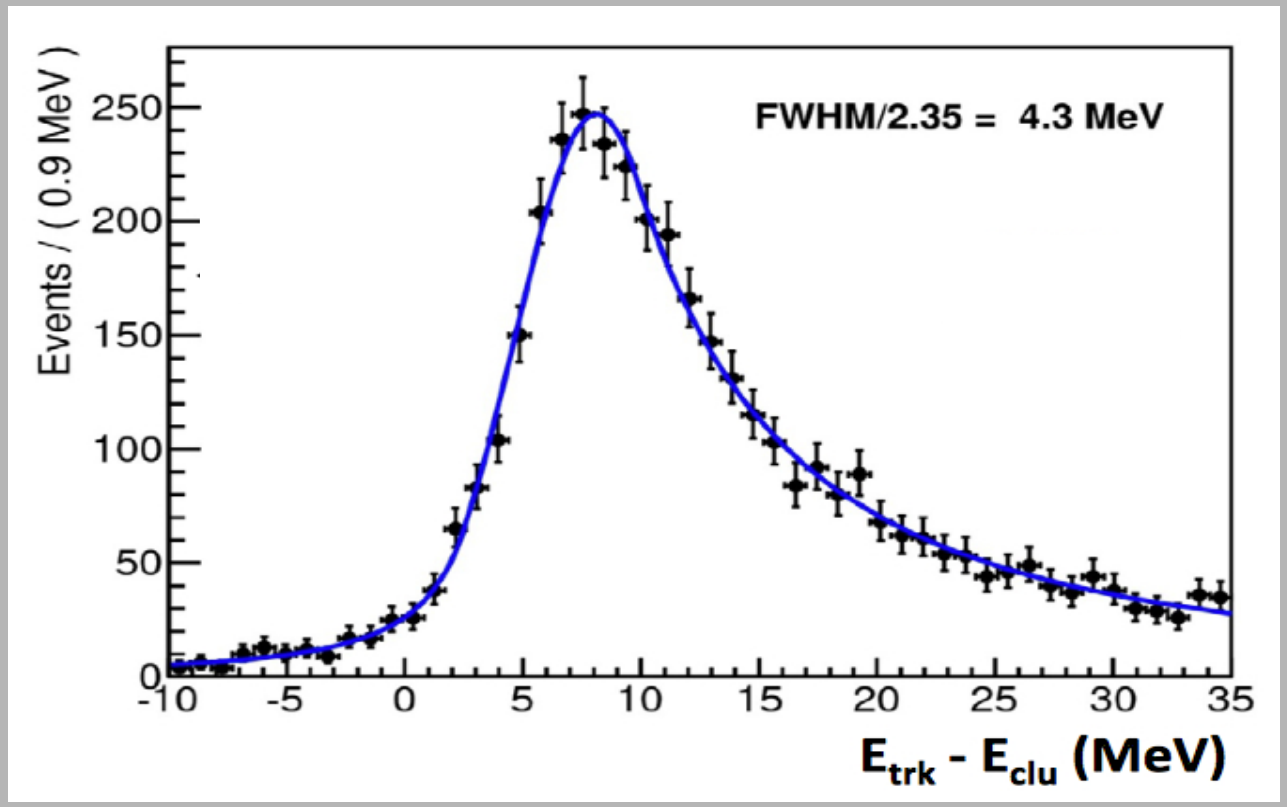
Tracker Performance

- Meets all physics requirements
- Total efficiency 9.2%
  - mostly acceptance
- Resolution 116 keV
- Robust against rate increases
- Low end is energy loss (lowers efficiency)
- High end tail smears DIO into signal region

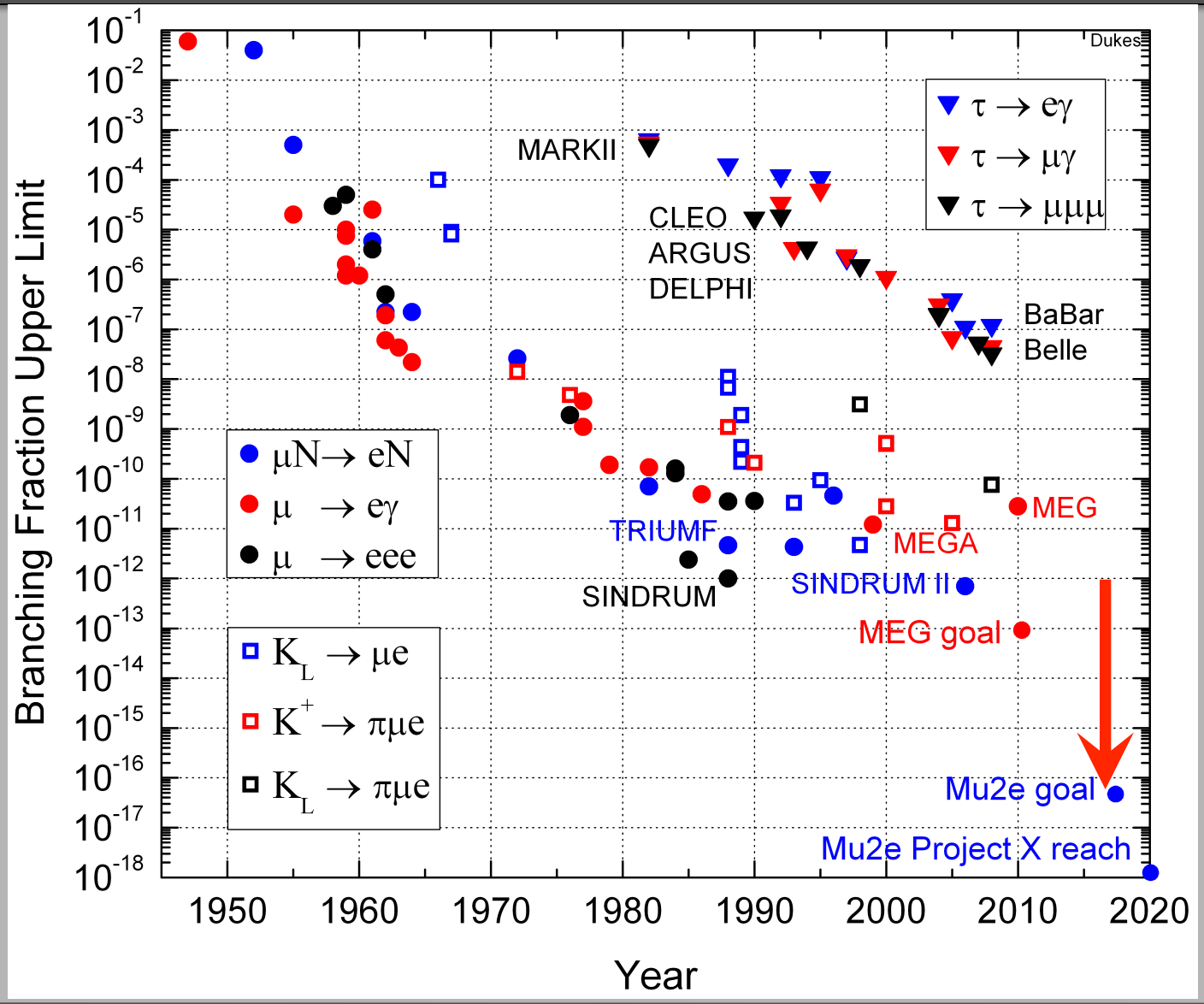


Calorimeter Performance

- Provides independent
  - Timing (0.5ns)
  - Energy (5%)
- Rejects
  - Pions, muons
  - Cosmic rays



History of CLFV Searches



Why this Experiment

It can happen in **many** New Physics scenarios

W. Altmannshofer, A.J.Buras, S.Gori, P.Paradisi, D.M.Straub

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

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

arXiv:0909.1333

Constraints on new physics

L. Calibbi, A. Faccia, A. Masiero, S. Vempati hep-ph/0605139

Neutrino-Matrix Like (PMNS)

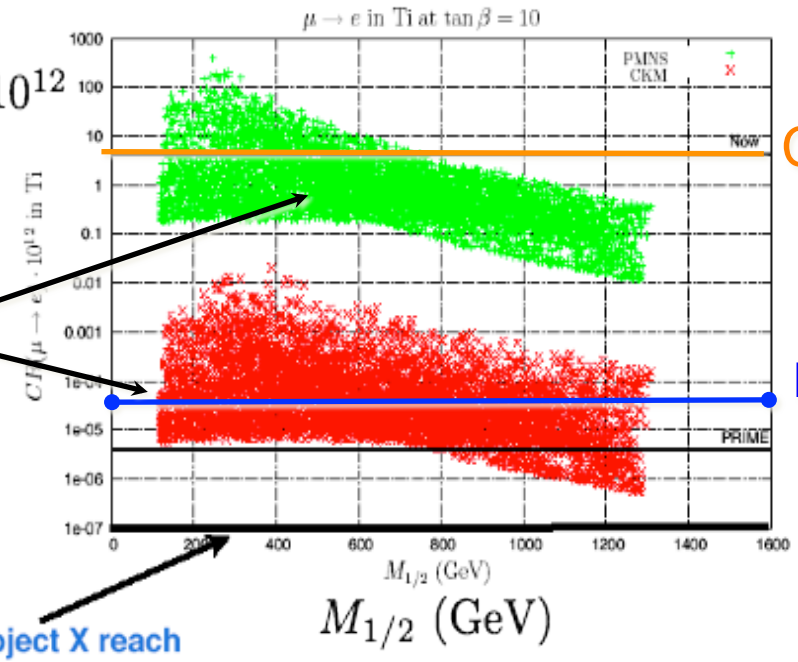
Minimal Flavor Violation(CKM)

$\tan\beta = 10$

$\mathrm{BR}(\mu \to e) \times 10^{12}$

Current limits

Can distinguish between PMNS and MFV

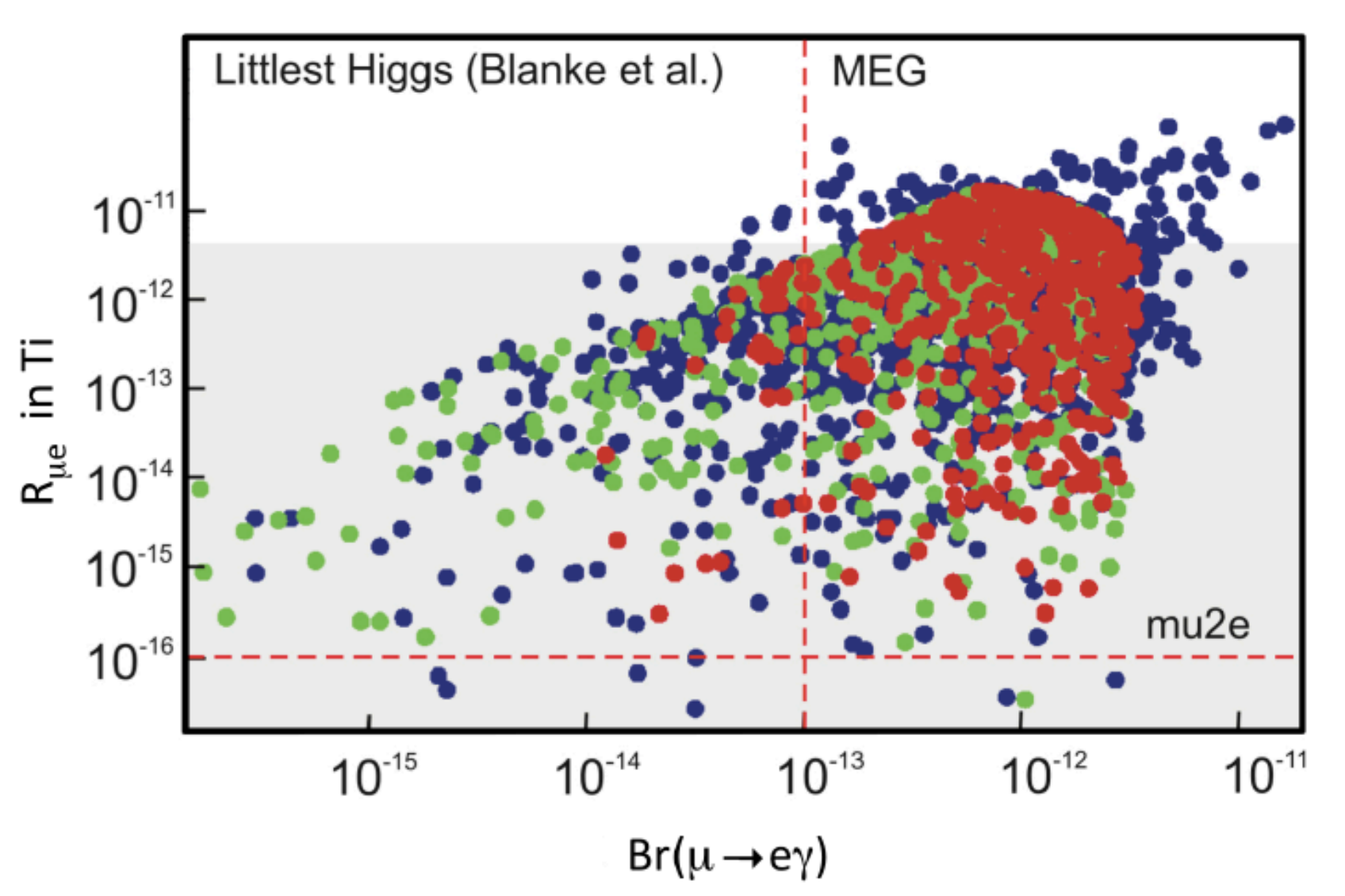


Mu2e

Project X reach

$M_{1/2}$ (GeV)

L. Calibbi, A. Faccia, A. Masiero, S. Vempati, hep-ph/0605139

Complementarity between Lepton Flavor Violation (LFV) and LHC experiments

Constraints on new physics