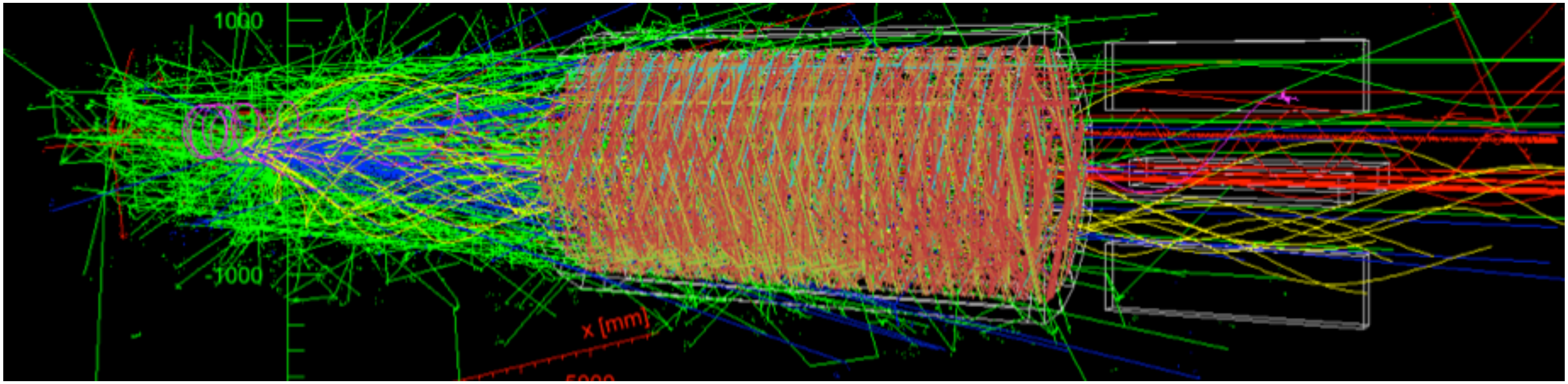
The Mu2e Experiment



Ron Ray
Mu2e Project Manager

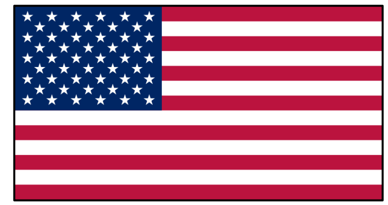
U.S. DEPARTMENT OF ENERGY | Office of Science

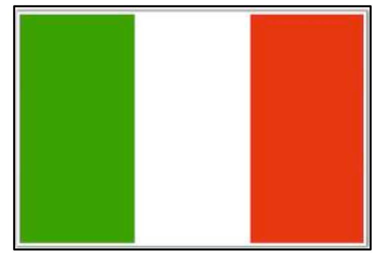
NSF

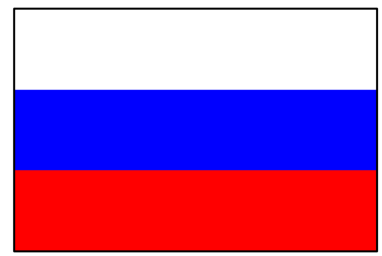
US-Japan

INFN

Mu2e Collaboration







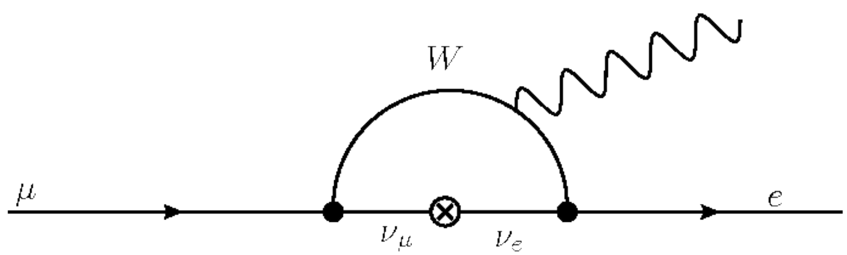
~160 Collaborators, 26 Institutions, 3 Countries

Introduction

- Mu2e is a search for Charged Lepton Flavor Violation (CLFV) via the coherent conversion of $\mu^- N \rightarrow e^- N$
- Target sensitivity has great discovery potential
  - Goal: Single-event-sensitivity of 2 x 10^{-17} (relative to ordinary μ capture)
  - Goal: <0.5 events background
    - Yields Discovery Sensitivity for all rates > few 10^{-16}
- Most new physics models so far postulated provide new sources of flavor phenomena
- Quark flavor is violated. Neutrino flavor is violated.
  - Both implied something profound about the underlying physics
  - Both garnered Nobel Prizes
- What about charged lepton flavor?

Neutrino Oscillations and CLFV

- Neutrinos oscillate, so lepton flavor is not conserved.
- Charged leptons *must* mix through neutrino loops.
  - But the mixing is so small, it's effectively forbidden.



$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_\ell V^\star_{\mu\ell} V_{e\ell} \frac{m^2_{\nu_\ell}}{M^2_W}\right|^2 \leq 10^{-54}$$

- No Standard Model pollution! Observation is unambiguous evidence for new physics.

Charged Lepton Flavor Violation

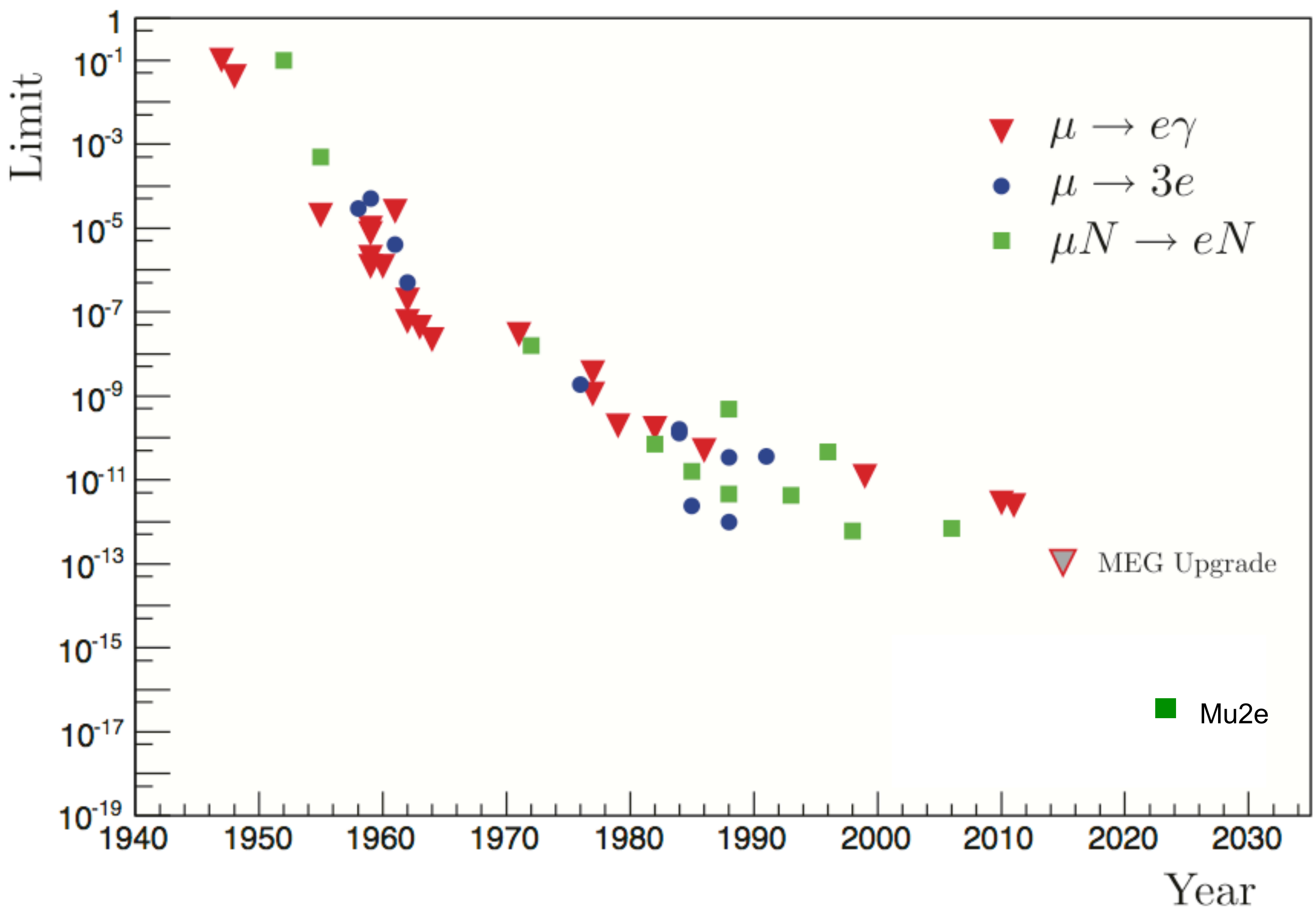
- Significant worldwide interest from Energy and Intensity Frontiers and the theoretical community
  - Rare CLFV decays of μ, τ, K, B-mesons
- Rates negligible in νSM but wide array of new physics models predict rates that are measurable in next generation experiments.
  - Sensitive to new physics well above the TeV scale (10^3 – 10^4 TeV).
- Rates of CLFV processes are model dependent and vary widely depending on the underlying physics.
  - CLFV processes are powerful discriminators.
- The most stringent limits on CLFV come from muons because of the relative "ease" of producing an intense source.
- Muon-to-electron conversion offers excellent discovery potential across a breadth of models and will explore impressive mass scales.

Some CLFV Processes

Process	Current Limit	Next Generation exp
$\tau \rightarrow \mu\eta$	BR < 6.5 E-8	
$\tau \rightarrow \mu\gamma$	BR < 6.8 E-8	10^{-9} - 10^{-10} (Belle II)
$\tau \rightarrow \mu\mu\mu$	BR < 3.2 E-8	
$\tau \rightarrow eee$	BR < 3.6 E-8	
$K_L \rightarrow e\mu$	BR < 4.7 E-12	
$K^+ \rightarrow \pi^+ e^- \mu^+$	BR < 1.3 E-11	NA62
$B^0 \rightarrow e\mu$	BR < 7.8 E-8	Belle II, LHCb
$B^+ \rightarrow K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \rightarrow e^+\gamma$	BR < 5.7 E-13	10^{-14} (MEG)
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
$\mu N \rightarrow eN$	$R_{\mu e}$ < 7.0 E-13	10^{-17} (Mu2e, COMET)

The most sensitive CLFV probes use muons

History of CLFV Searches



Model Independent Evaluation

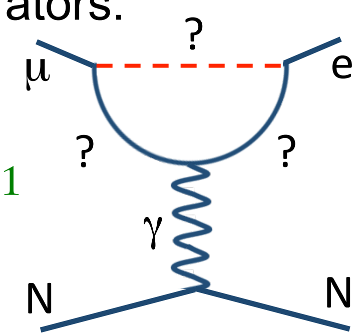
Add CLFV operators to SM Lagrangian.

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

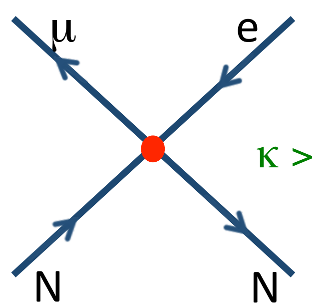
Λ is mass scale of new physics

κ controls relative contribution of two classes of operators:

$\kappa << 1$



Loops



Contact Terms

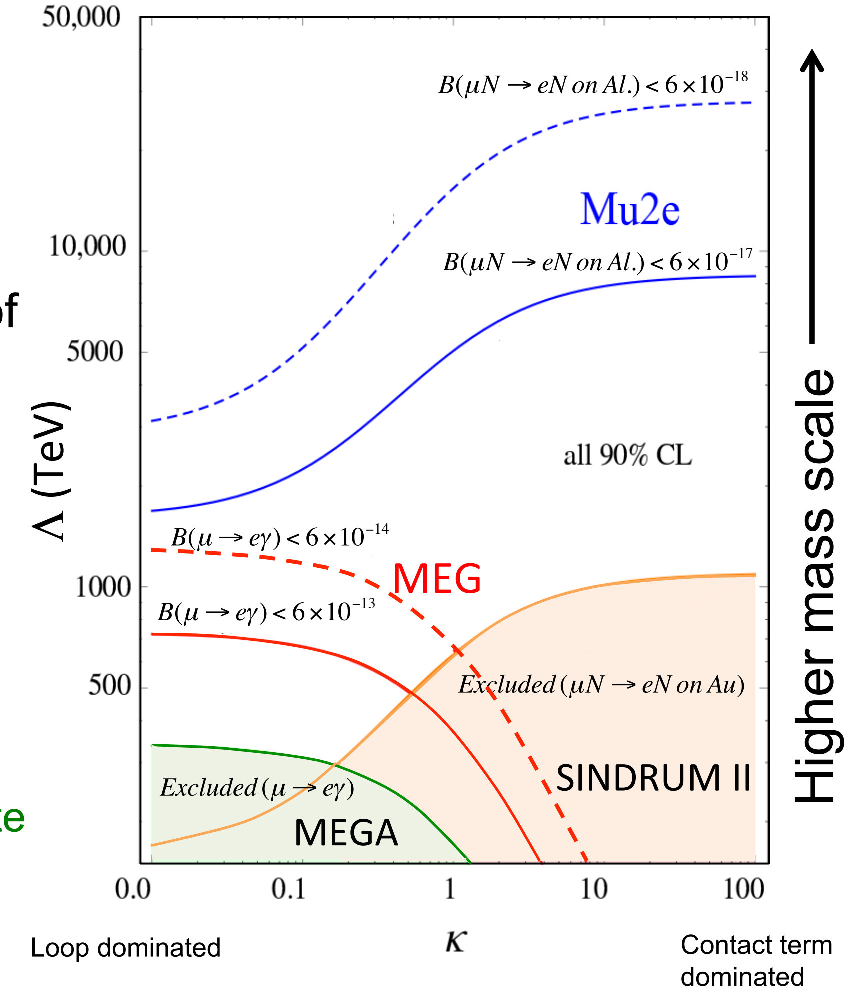
$\kappa >> 1$

Loops with photons contribute to $\mu \rightarrow e\gamma$

Does not contribute to $\mu \rightarrow e\gamma$

Both types of operators contribute to muon-to-electron conversion

A. de Gouvêa, P. Vogel
arXiv:1303.4097 [hep-ph]



Mu2e Physics Reach

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

★★★ = Discovery Sensitivity

	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[hep-ph]

Mu2e Physics Reach

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

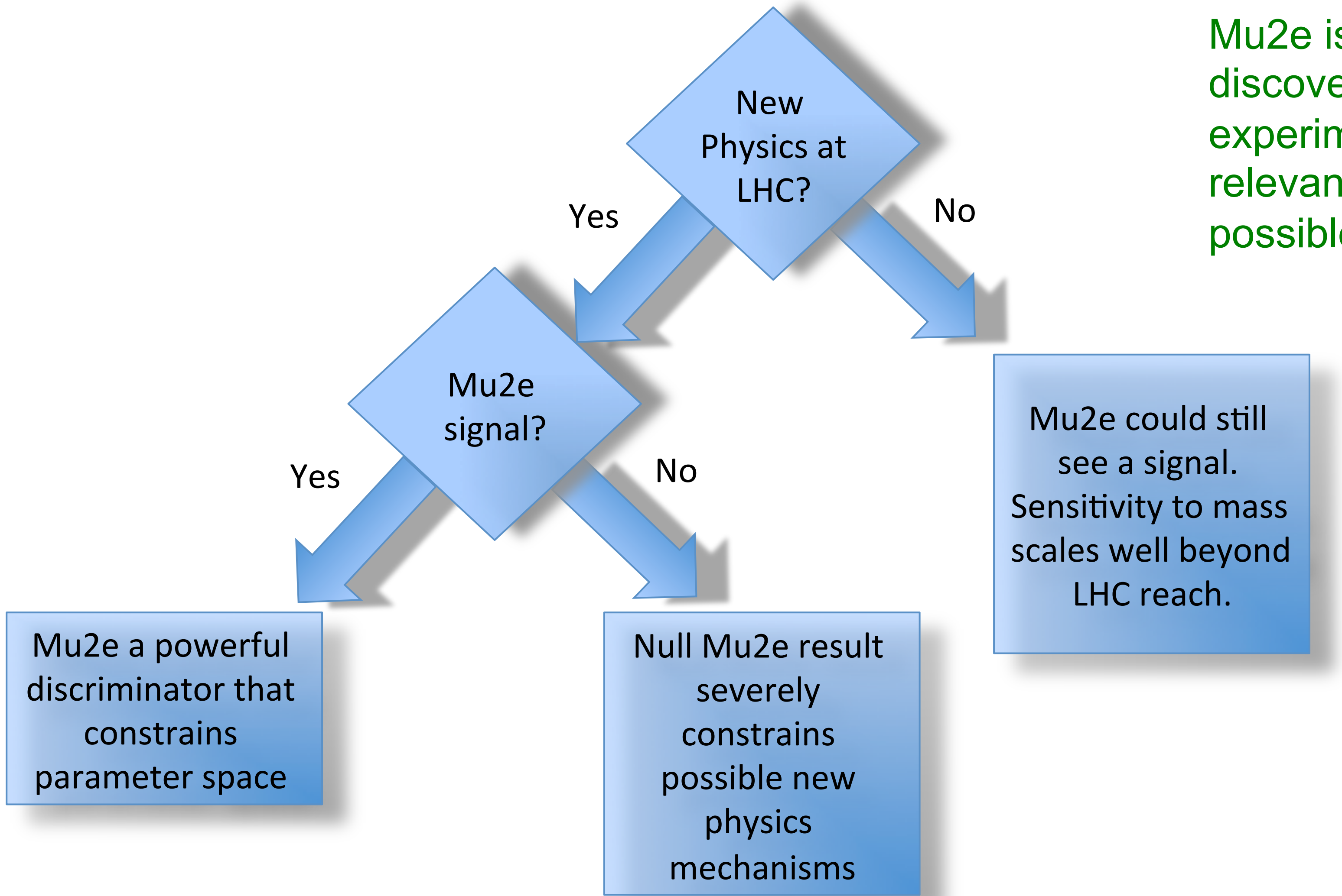
★★★ = Discovery Sensitivity

	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	★★★	★★★	★★	★	★★★	★	★★★
$(g-2)_\mu$	★★★	★★★	★★	★★★	★★★	★	?

arXiv:0909.1333[hep-ph]

Mu2e has discovery sensitivity across the board

Mu2e and the LHC



Mu2e is a potential discovery experiment that is relevant in all possible scenarios.

How does Mu2e work?

Mu2e Concept

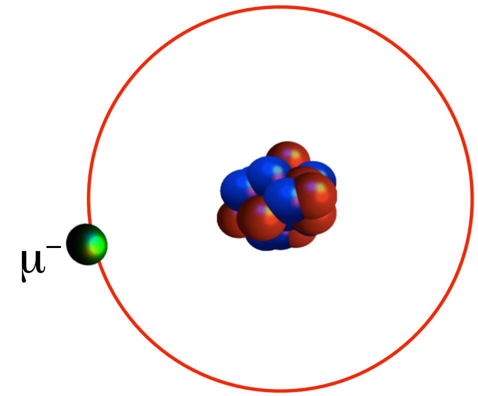
- Generate an intense pulsed beam of low momentum μ^-
  - Use 8 GeV protons from Booster
- Stop muons in orbit around a nucleus
  - $\tau_\mu^{Al} = 864\ ns$
- Wait for prompt backgrounds to go away
  - Pulsed beam
- Measure delayed electron spectrum
  - Signal is a monoenergetic 105 MeV electron

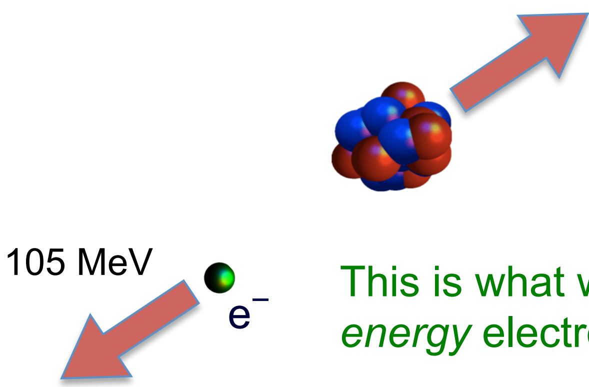
Sounds easy. But achieving 10^{-17} sensitivity is very challenging

Introduction

- Conversion is a two-body process

$$E_e = m_\mu - E_{binding} - E_{recoil} \approx 105\,MeV\ \ for\ Al$$

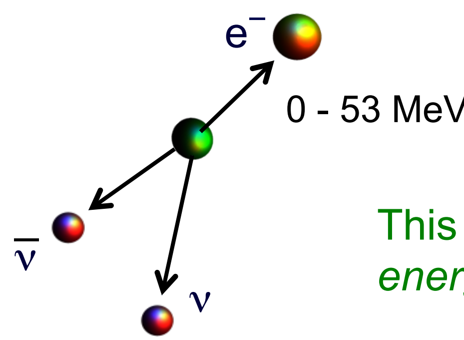




This is what we call a *high energy* electron

- Compare to normal muon decay

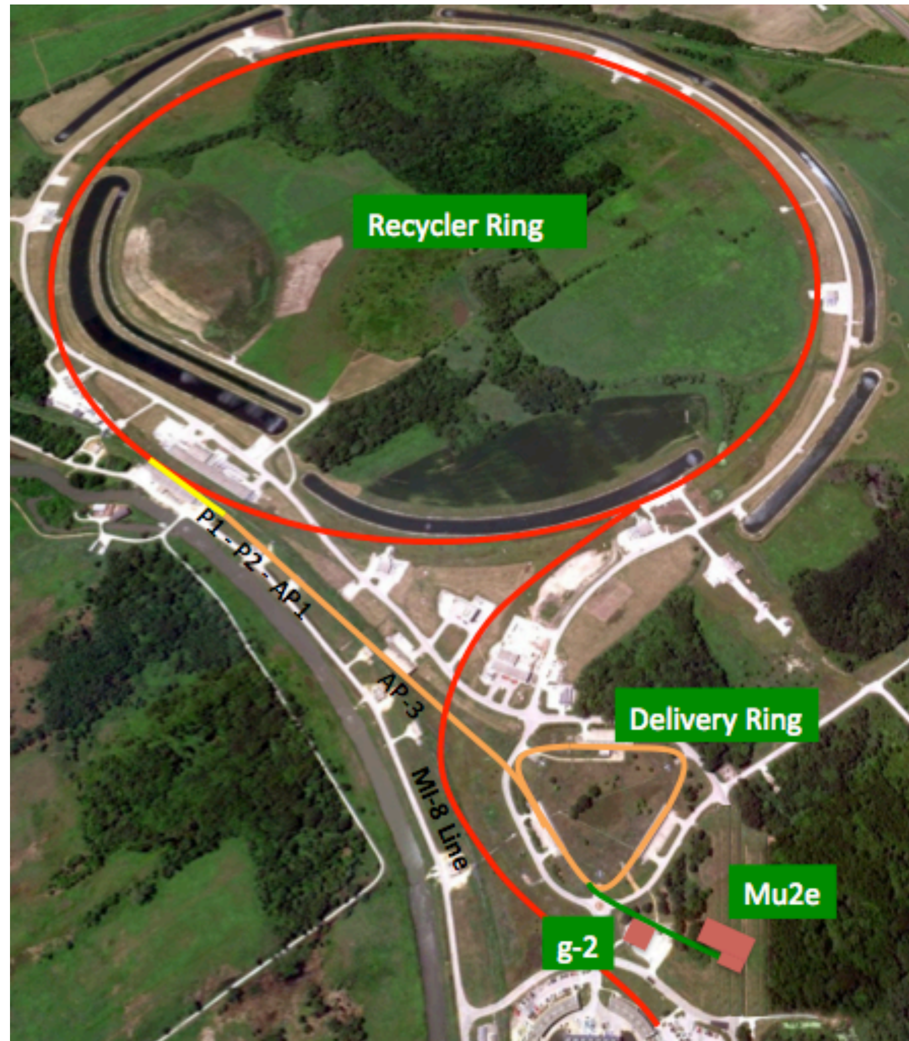
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

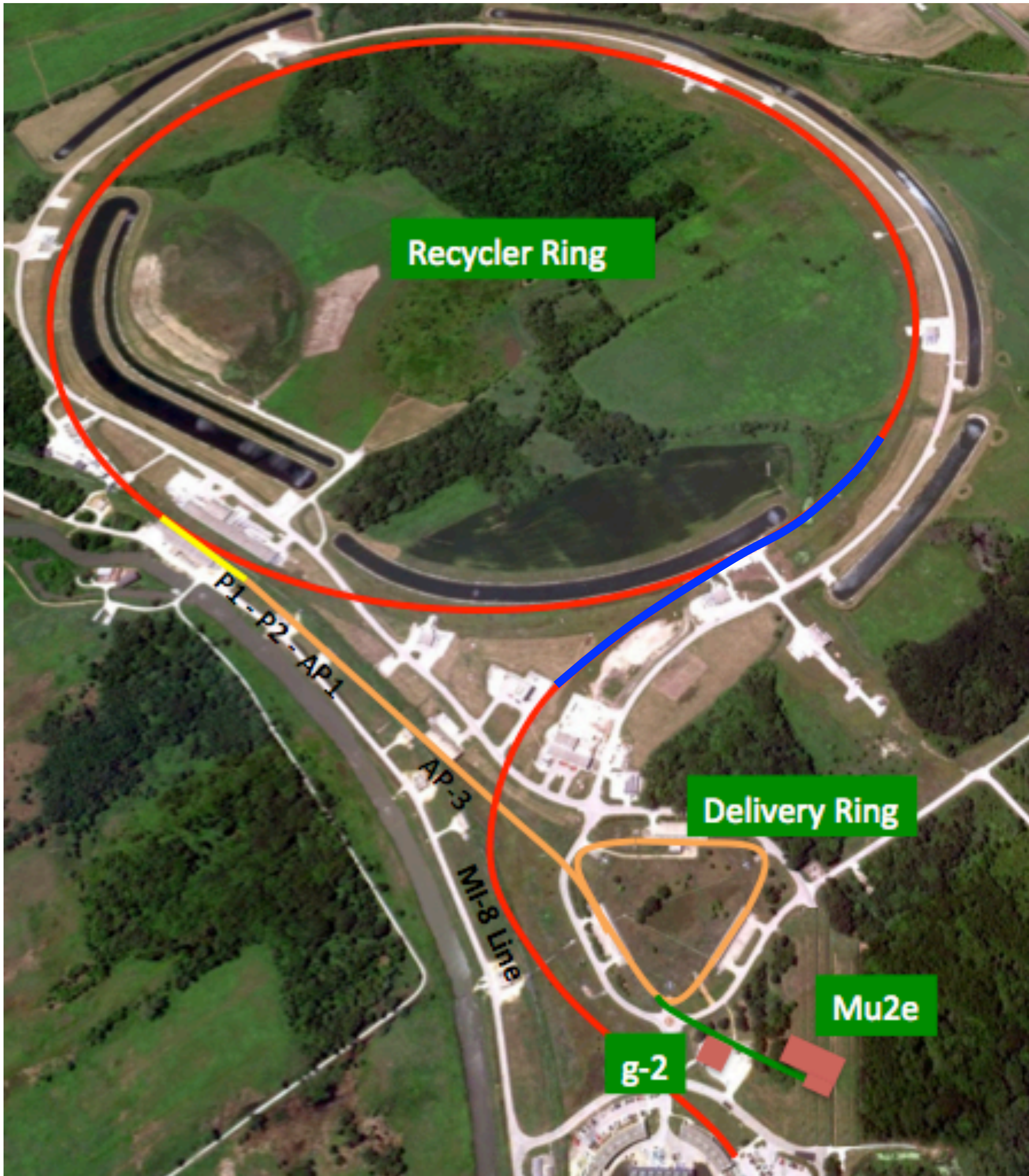


This is what we call *a low energy* electron

Fermilab Accelerator Complex

- Fermilab has a powerful and flexible accelerator complex.
- Multiple machines and multiple rings affords great flexibility and the ability to operate multiple programs simultaneously.
- End of Tevatron program freed up the pbar source and the Recycler Ring for other programs.
- Mu2e can reuse existing rings to package and deliver protons to create the world's most intense muon beam with no impact on the 120 GeV neutrino program (NOvA).

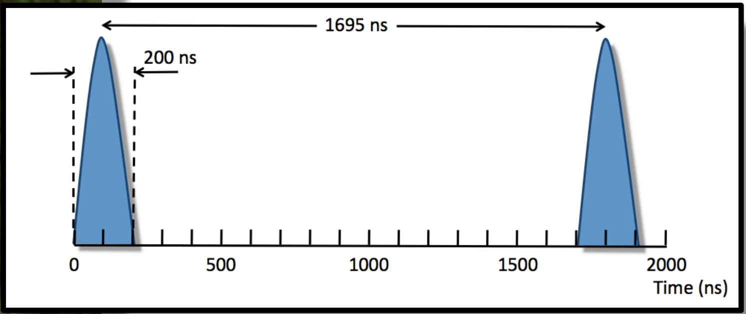




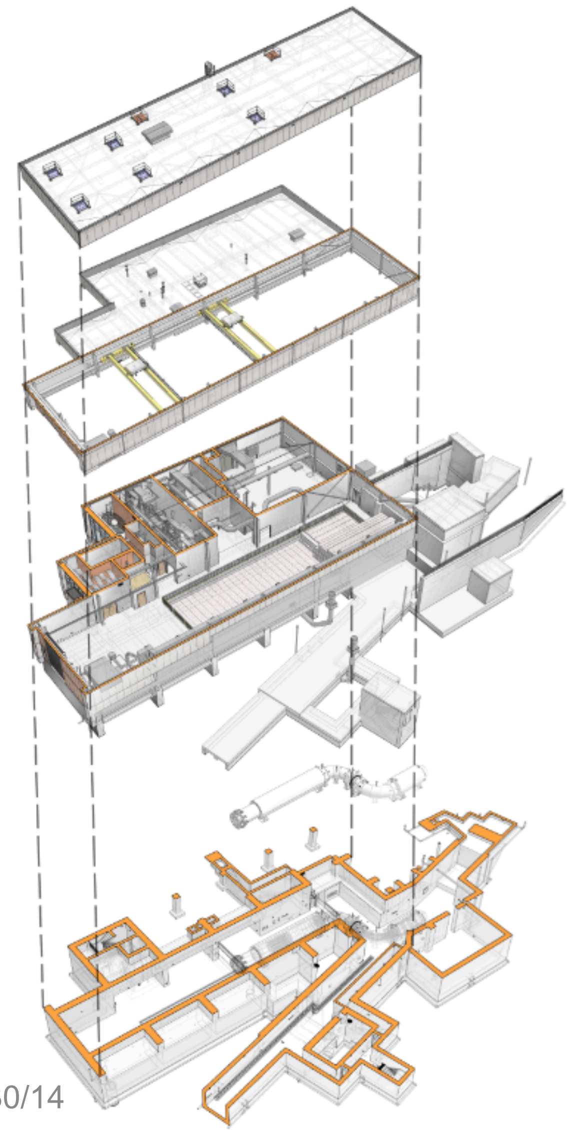
Transfer 2 Booster batches of 8 GeV protons to Recycler ring during Main Injector ramp.

Rebunch into 4 bunches using new 2.5 MHz RF system.

- Transfer 1 bunch at a time to the Delivery Ring.
- Capture with a new 2.4 MHz RF system
- Slow extract micro-bunches of ~ 10^7 protons per revolution to Mu2e.
- Revolution time of 1695 ns is a good match to τ^{Al} = 864 ns.



Experimental Hall

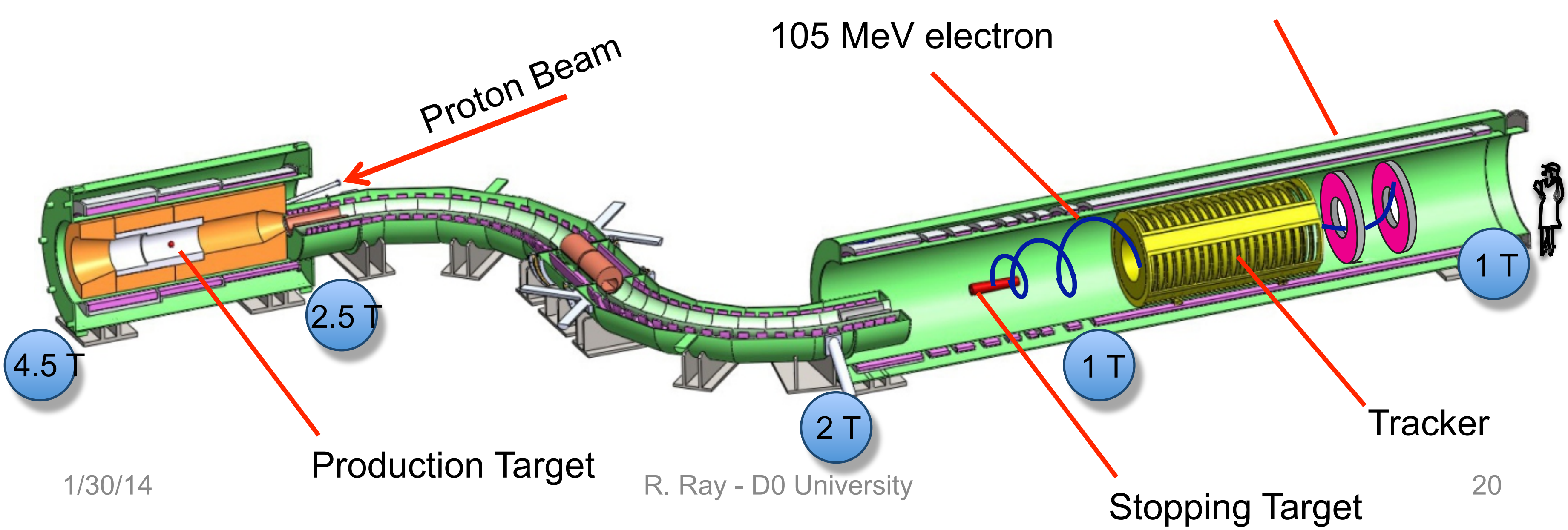


- 100% design from A&E in hand
- Solicit bids in early 2014.
- Bids in hand for CD-2
- Begin site prep work this summer
- Begin building construction on October 1 using FY14 construction funds.

Mu2e Apparatus

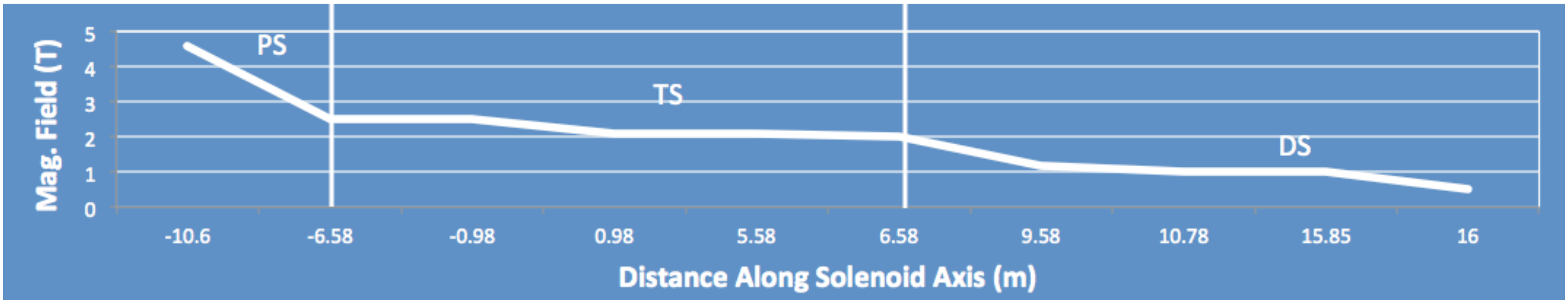
- Solenoids capture pions, form secondary muon beam, preserve timing structure, provide magnetic field for momentum analysis and help to reject backgrounds
  - Most efficient way of producing an intense, low energy muon beam
- 2 targets
- Tracker – Straw tubes
- Calorimeter – BaF2 crystals
- Cosmic Ray Veto – Scintillator, WLS fibers, SiPMs
- Stopping Target Monitor – Crystal
- Warm bore of solenoids evacuated to 10^{-4} to 10^{-5} Torr.

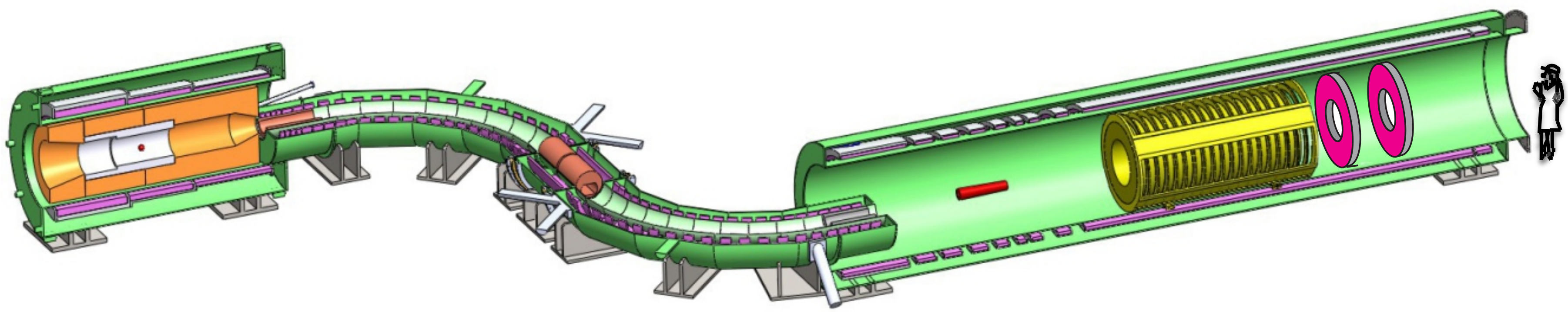
Cosmic Ray Veto and Stopping Target Monitor not shown



Mu2e Apparatus

Magnetic Field Profile – Driven by the science requirements



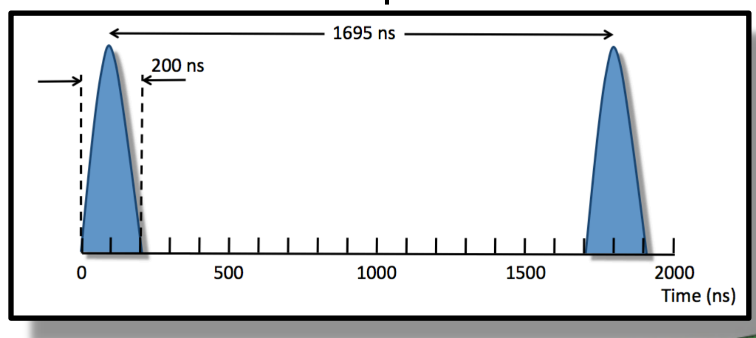


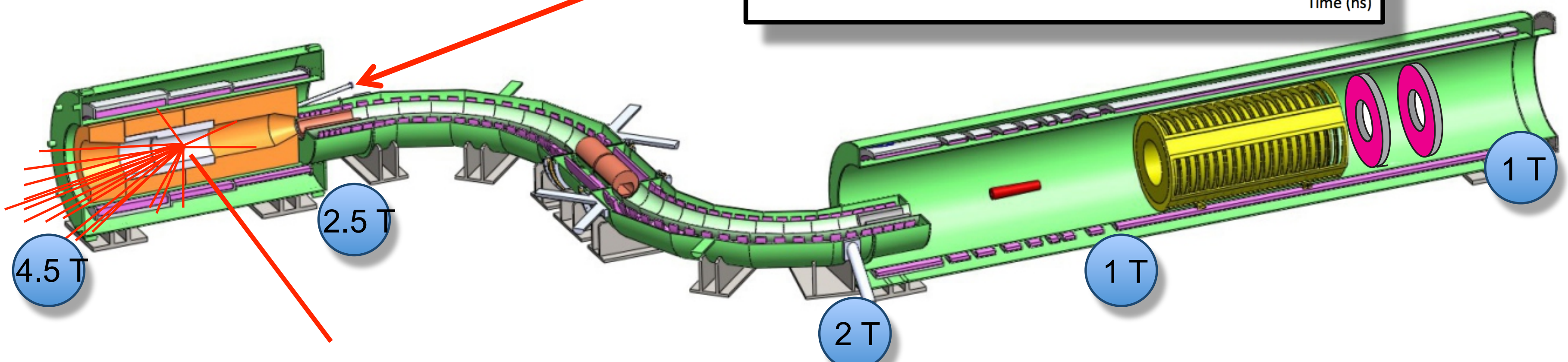
Mu2e Apparatus

Production Solenoid

- Production target
- Graded field
- Captures secondary pions

8 GeV protons



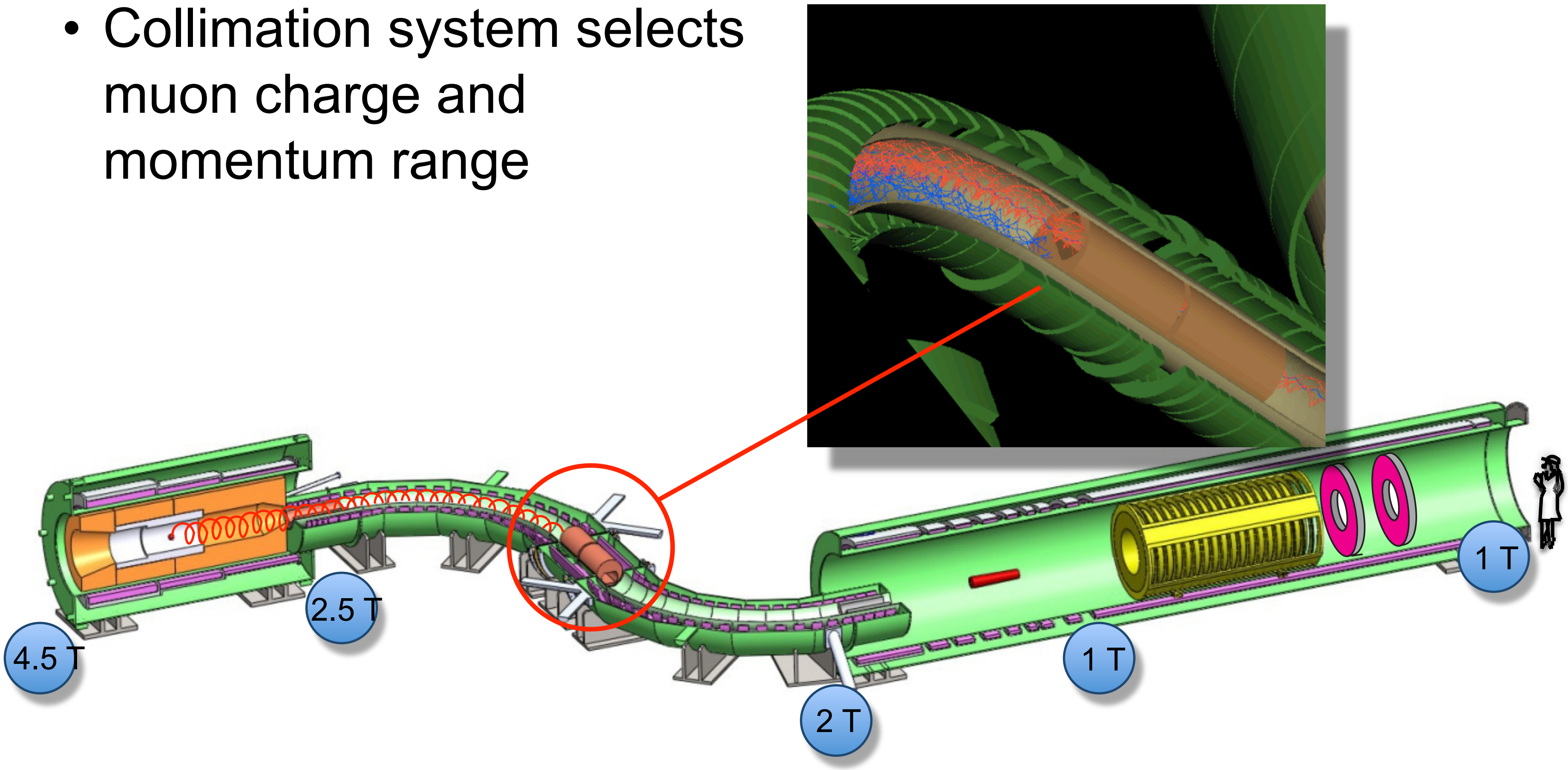


Production Target

Mu2e Apparatus

Transport Solenoid

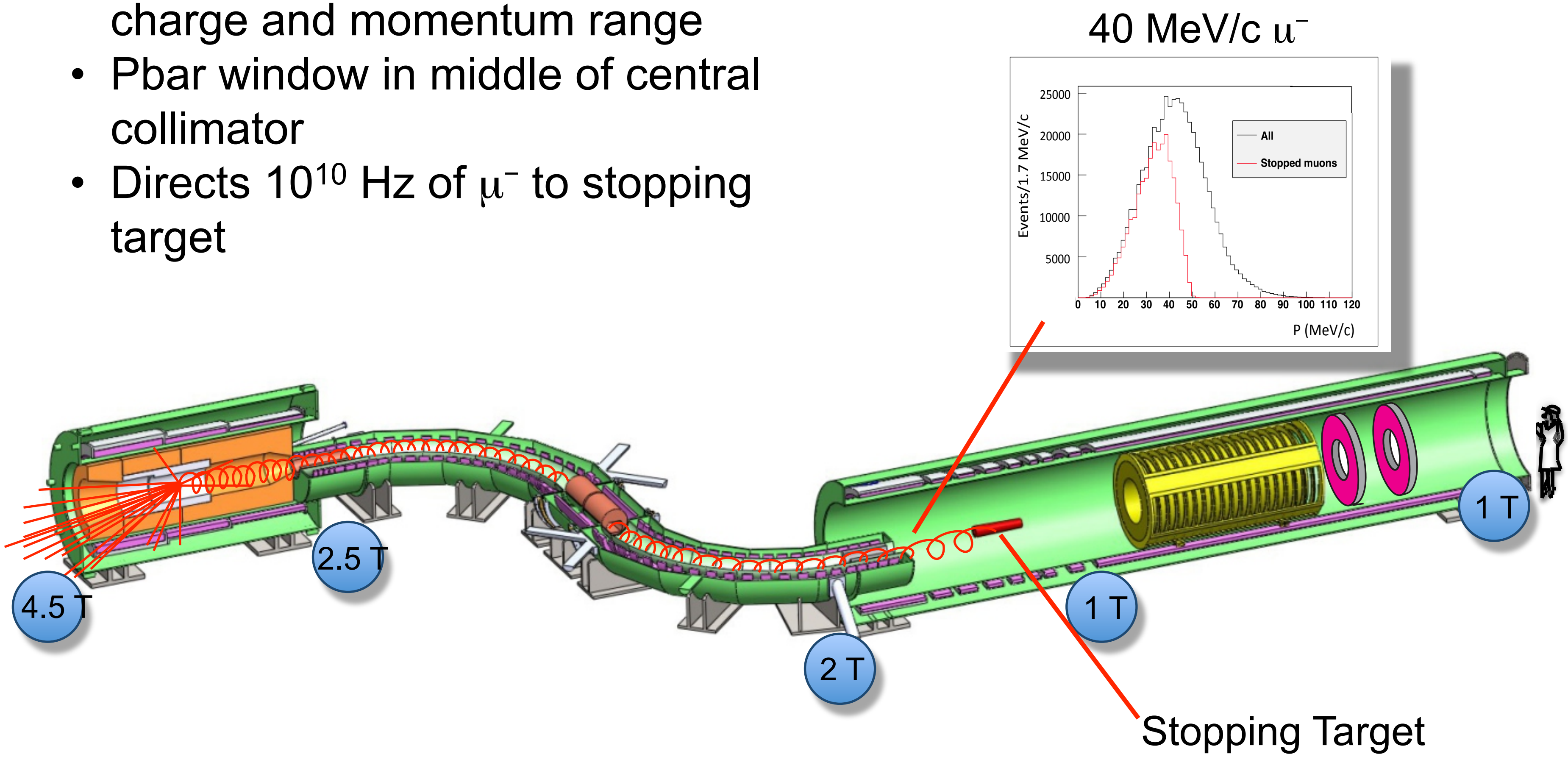
- Collimation system selects muon charge and momentum range



Mu2e Apparatus

Transport Solenoid

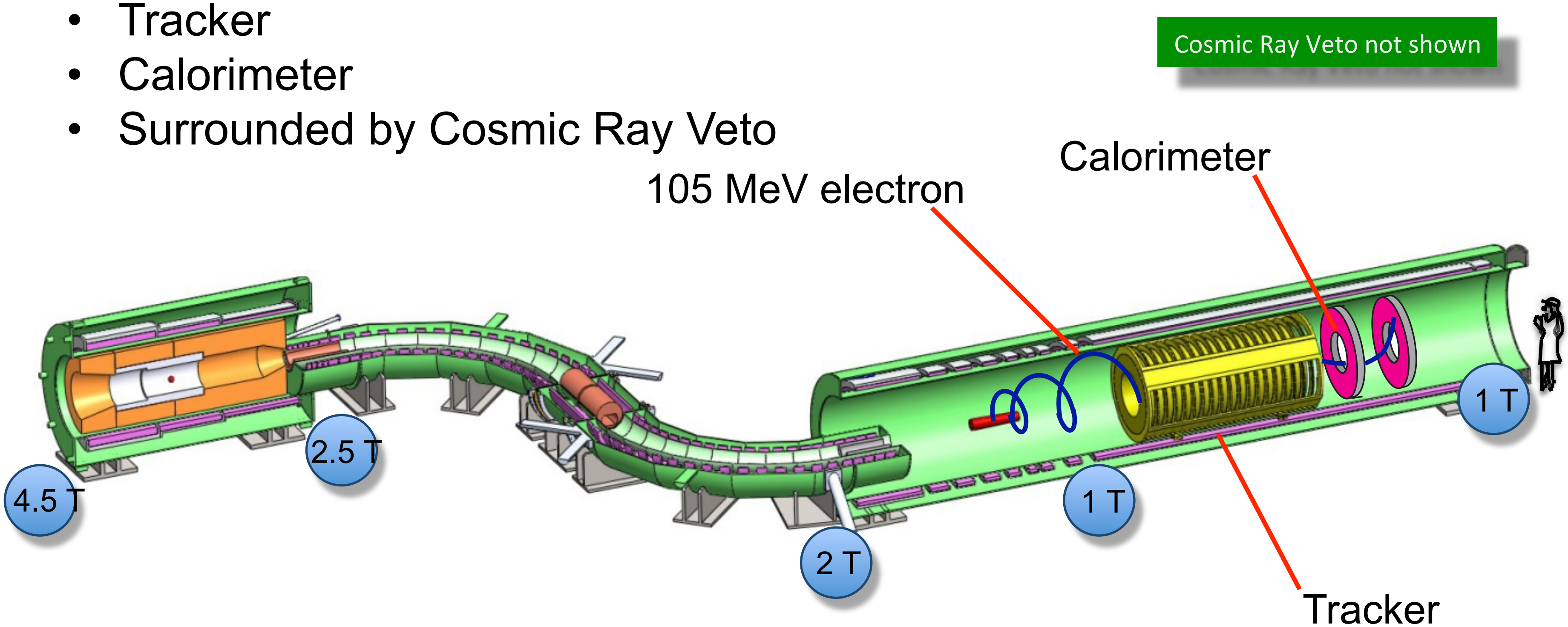
- Collimation system selects muon charge and momentum range
- Pbar window in middle of central collimator
- Directs 10^{10} Hz of μ^- to stopping target



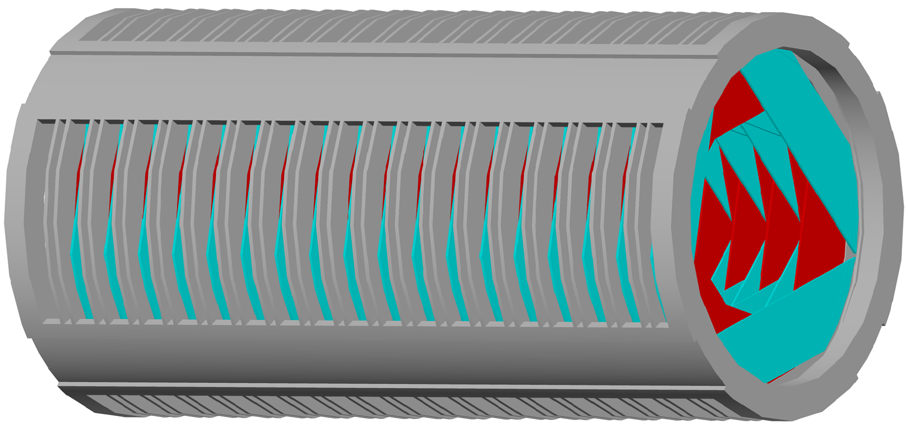
Mu2e Apparatus

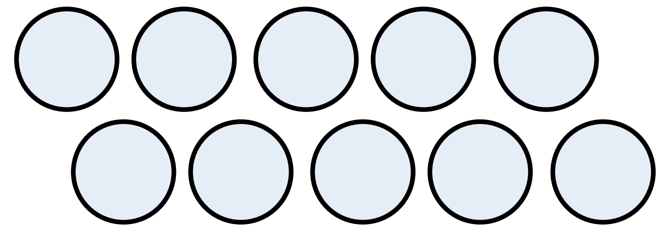
Detector Solenoid

- Graded field upstream for acceptance and background suppression
- Uniform field downstream for momentum analysis
- Muon stopping target
- Tracker
- Calorimeter
- Surrounded by Cosmic Ray Veto



Tracker



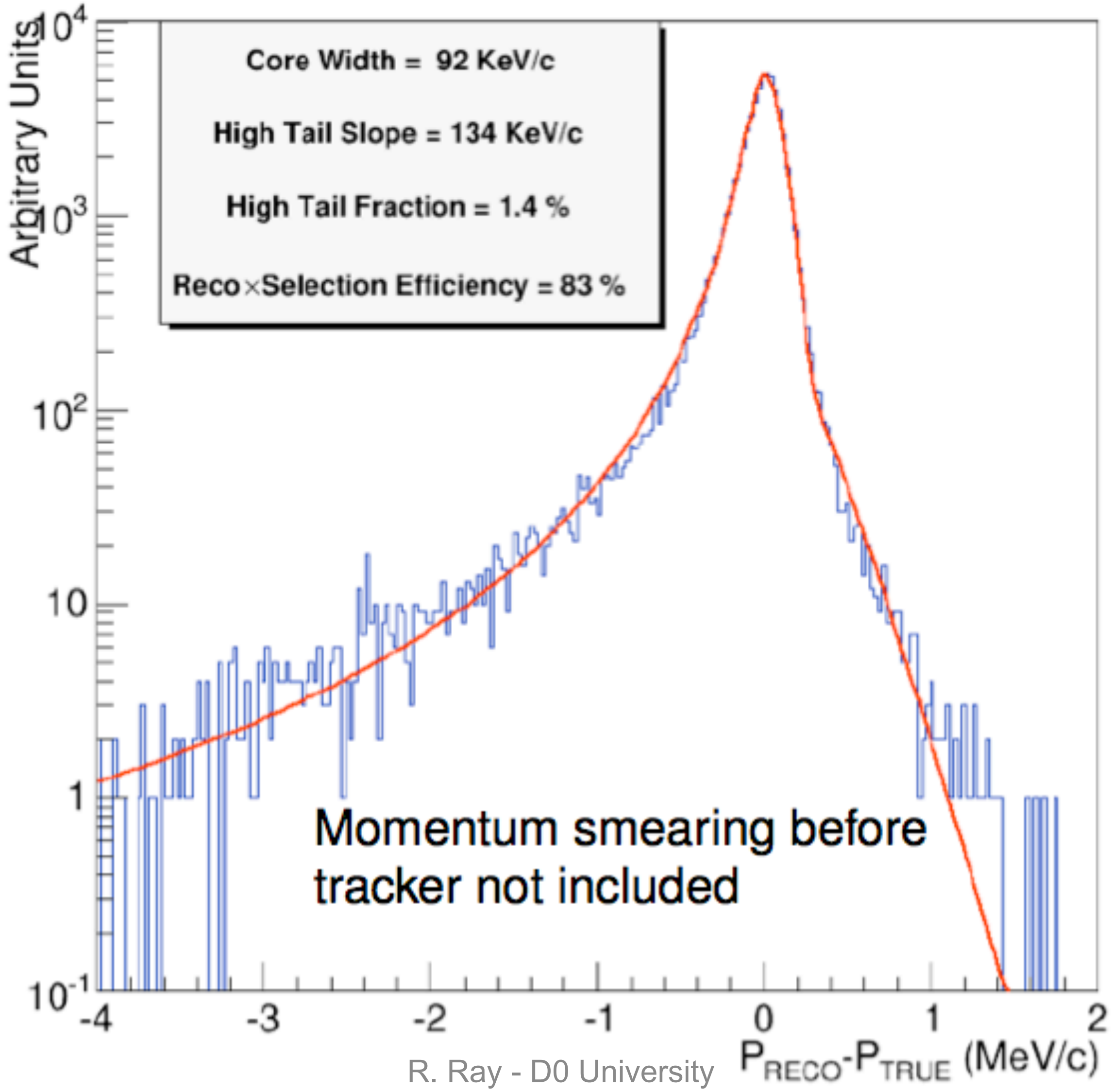


~ 25,000 straw tubes mounted transverse to solenoid axis

- 5 mm diameter
- 15 μm wall thickness
- 25 μm wire
- Good resolution required to control background from muon decay in orbit
- Resolution dominated by multiple scattering and straggling in stopping target.

- ~ 3 m long
- 1 T “uniform” B field
- Operates in 10^{-4} T vacuum
- Good tracks make 2 – 3 turns
- TDC readout at both ends of wire
  - Δt gives position along the wire
- ADC readout for particle ID

Tracker Momentum Resolution

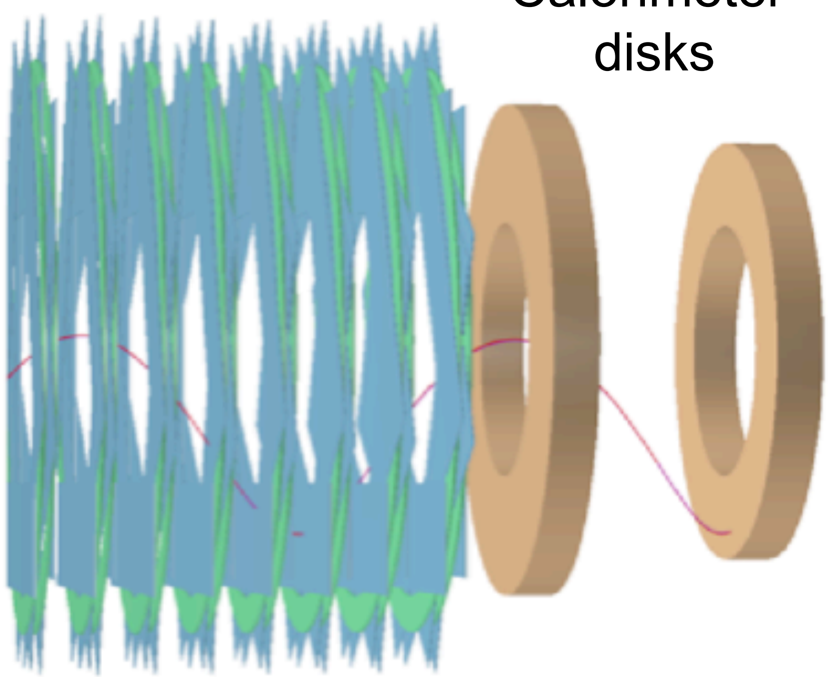


Dave Brown, CLFV2013 (Lecce)

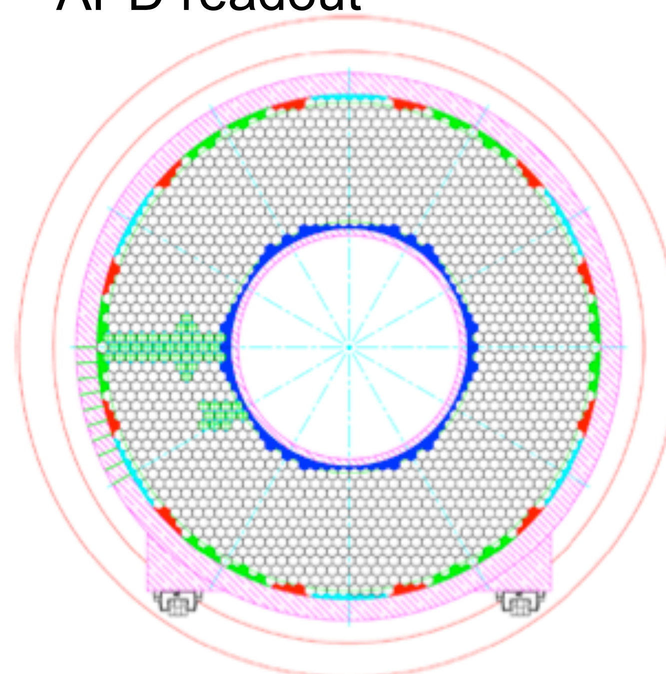
Calorimeter

Tracker

Calorimeter disks



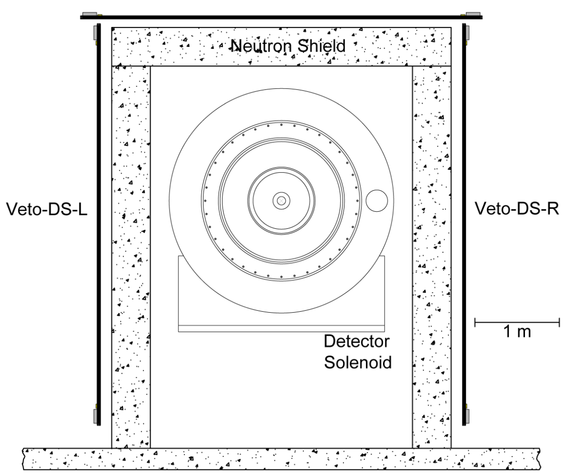
Hexagonal BaF2 crystals
APD readout

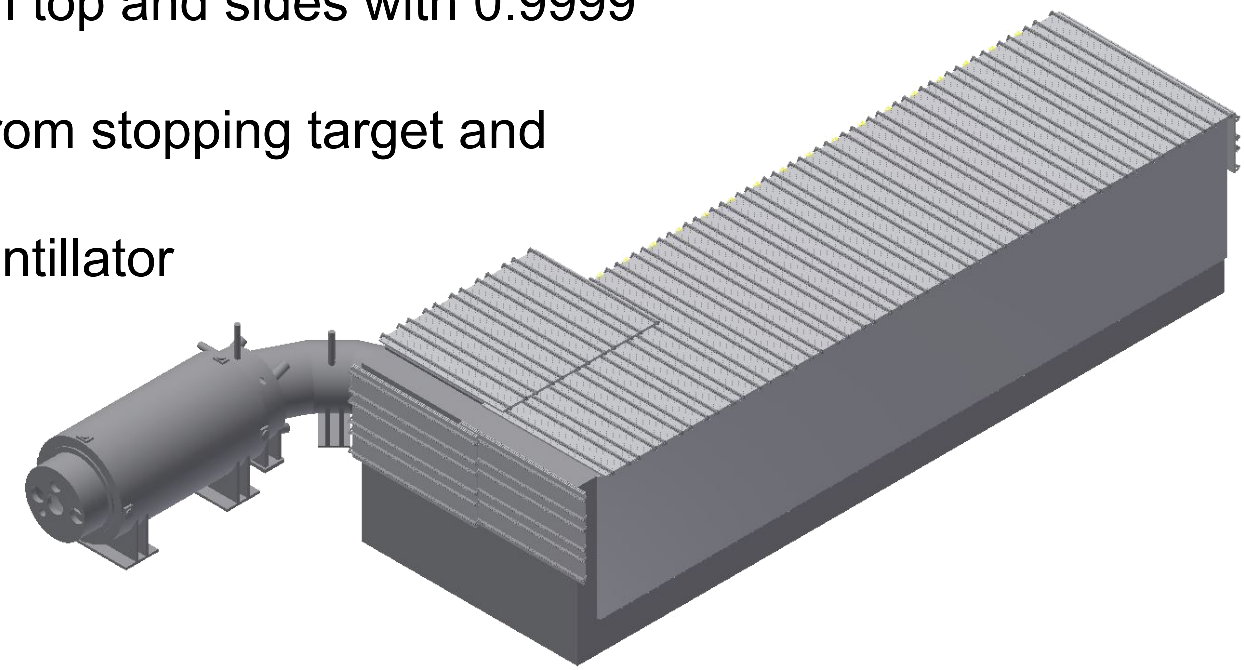


Provides good timing, PID, track seed, trigger.
Corse confirmation of tracker signal events.

Cosmic Ray Veto

- Cosmic Ray Veto covers all of Detector Solenoid and half of Transport Solenoid
- Nearly hermetic veto on top and sides with 0.9999 overall efficiency
- Shielding of neutrons from stopping target and collimators required.
- 4 layers of extruded scintillator
- SiPM readout





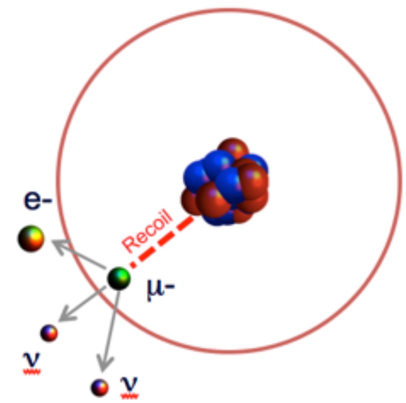
Backgrounds

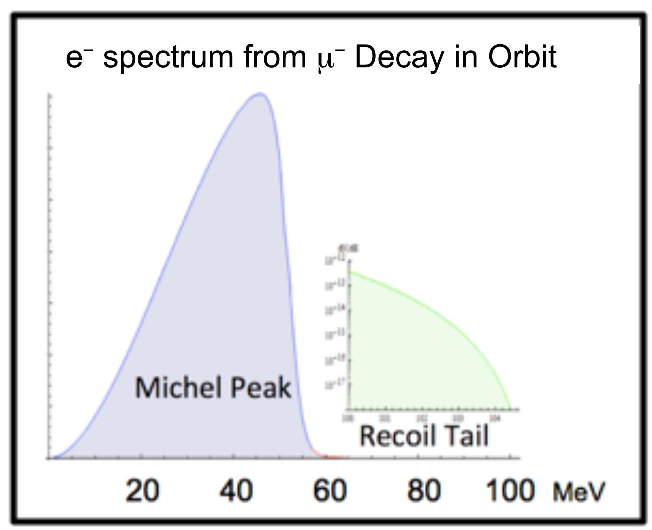
Backgrounds fall into 4 categories:

- Muon decay in orbit
- Prompt processes where an electron is detected shortly after the arrival of a particle at the stopping target
- Cosmic rays
- Antiprotons

Muon Decay in Orbit Background

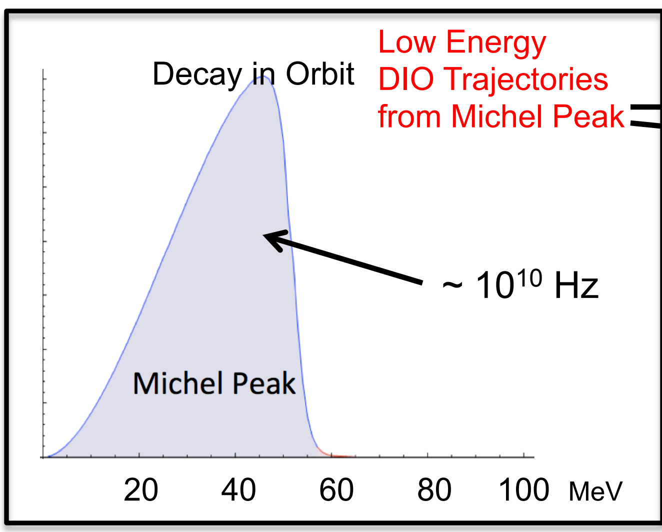
- μ at rest can produce an electron whose energy is at most half of the μ rest mass, the decay of a bound μ can result in an electron with energy approaching that of a conversion electron.
- In kinematic limit where the ν's carry away no energy the electron recoils against the nucleus simulating the two-body conversion process.
- DIO spectrum is a distorted Michel peak and a small recoil tail extending to the conversion energy, falling as $(E_{endpoint} - E_e)^5$ near the endpoint.
  - ~3×10^{-13} of the DIO electrons within 3 MeV of endpoint.
  - Sets the scale for the required energy resolution of the experiment.

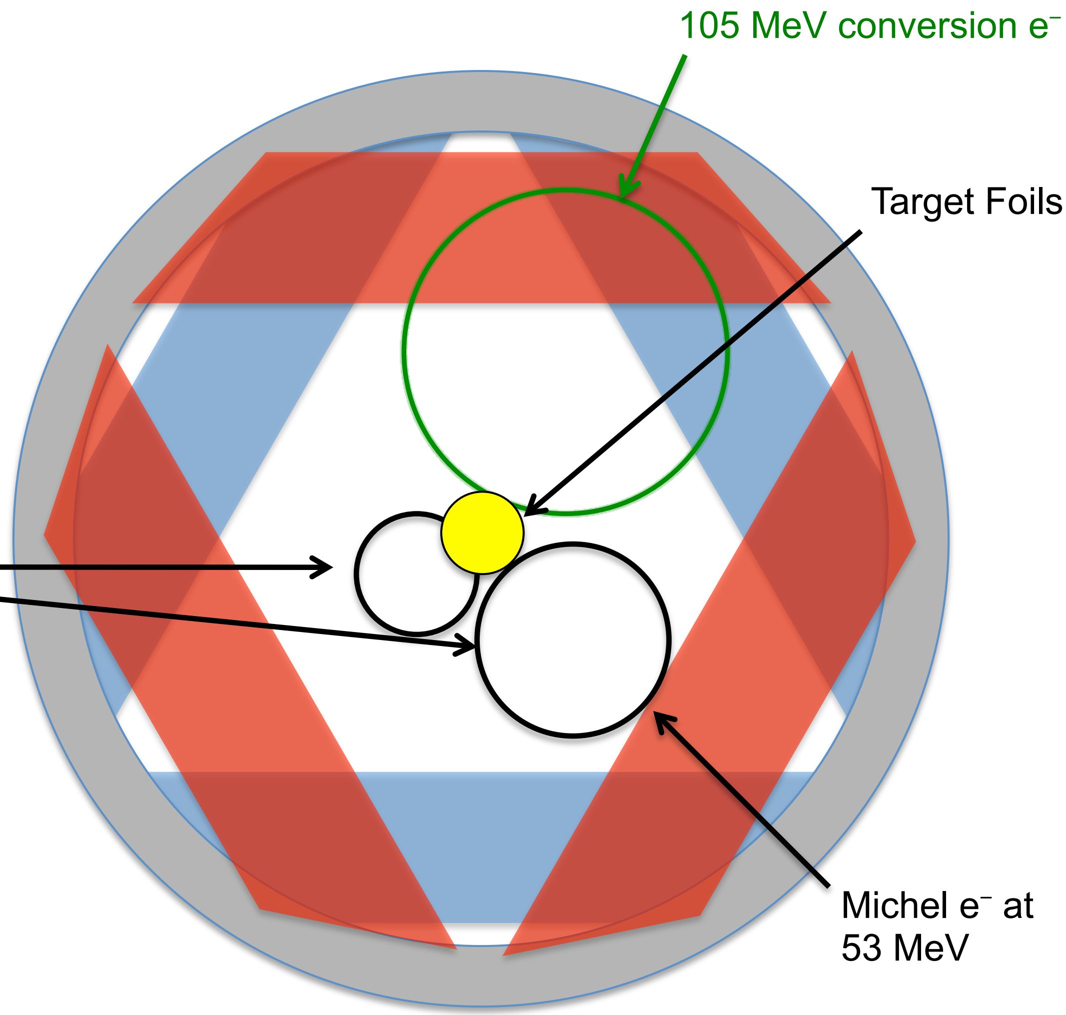




Rate from DIOs

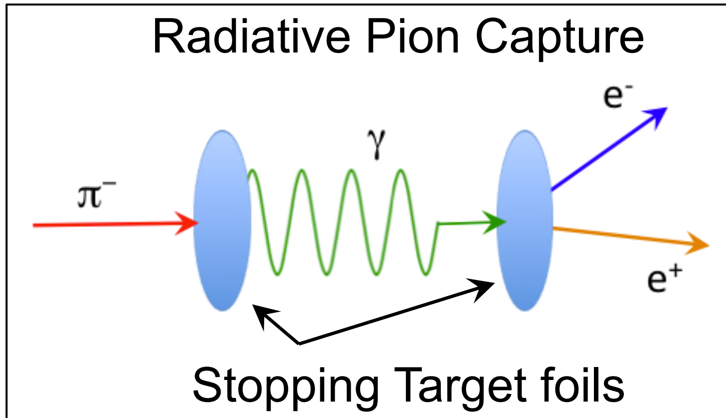
Virtually all of the DIOs pass through the hole in the detector without interacting.

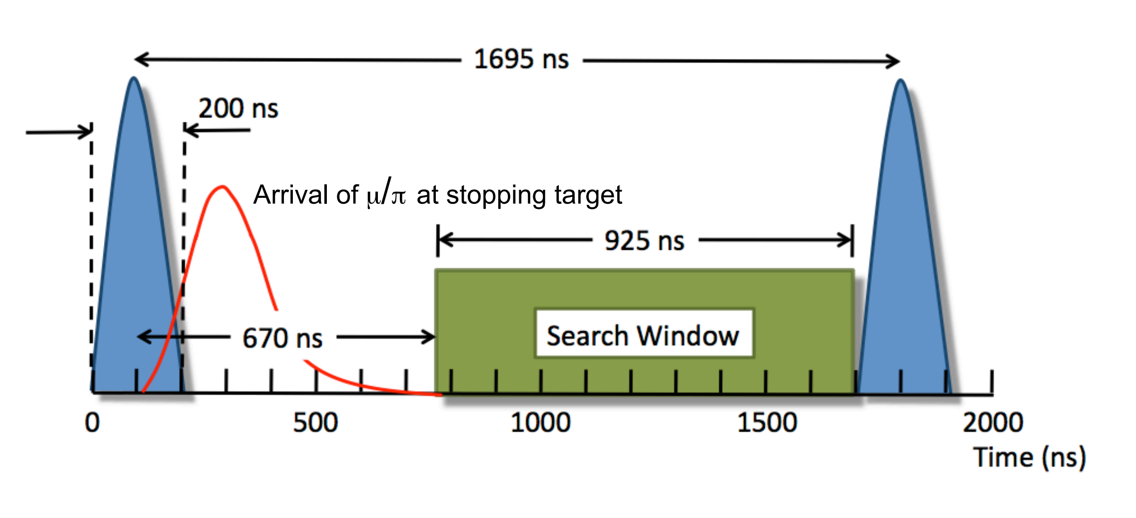




Prompt Backgrounds

Prompt background:
Processes where the detected background electron is nearly coincident in time with the arrival of a beam particle at the muon stopping target.

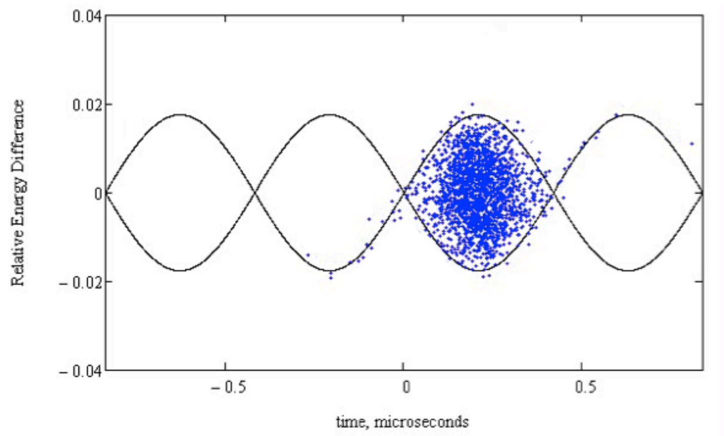




Pulsed beam combined with long τ^{Al}, delayed search window and extinction of beam between pulses reduces prompt backgrounds like Radiative Pion Capture.

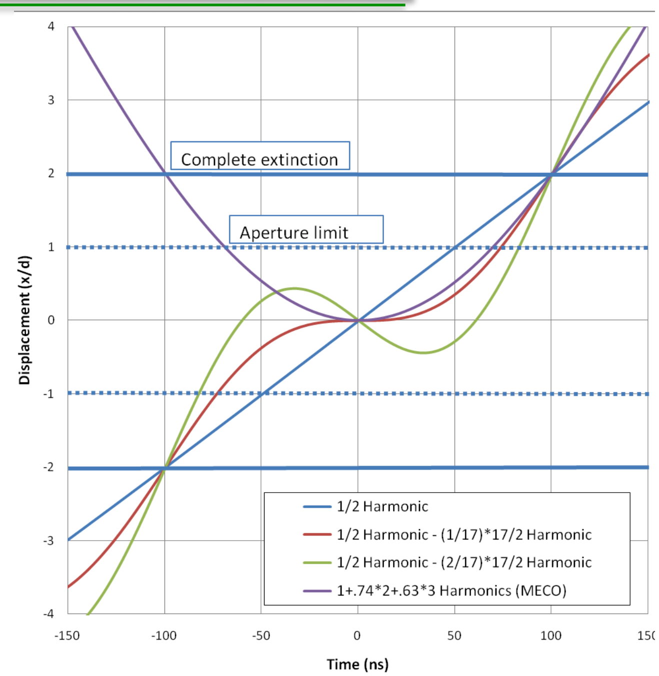
Extinction

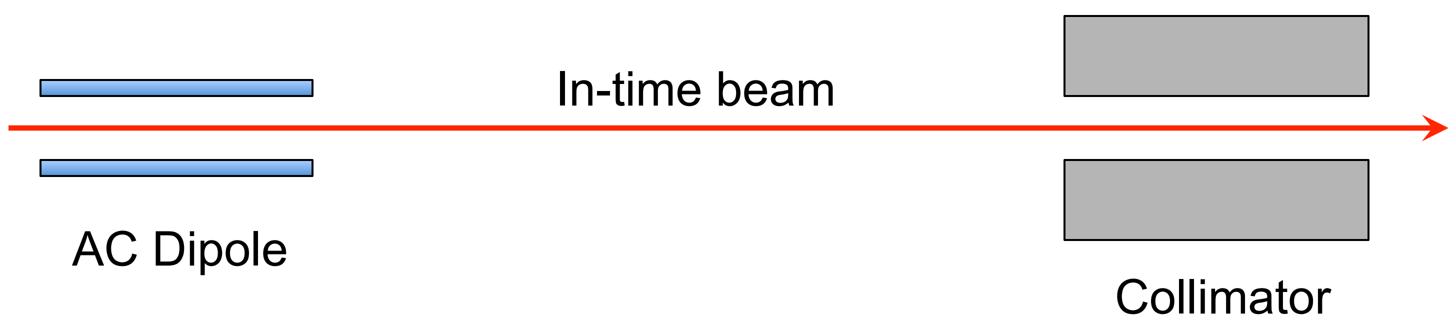
- Extinction requirement of 10^{-10} is not trivial, but can be accomplished through a combination of internal and external extinction.
- Internal
  - We use RF to form and hold tight bunches in both the Recycler and Delivery Rings.
  - $<10^{-5}$ in Recycler Ring
  - Extinction in Delivery Ring $< 10^{-4}$
    - Degrades during slow extraction



Extinction

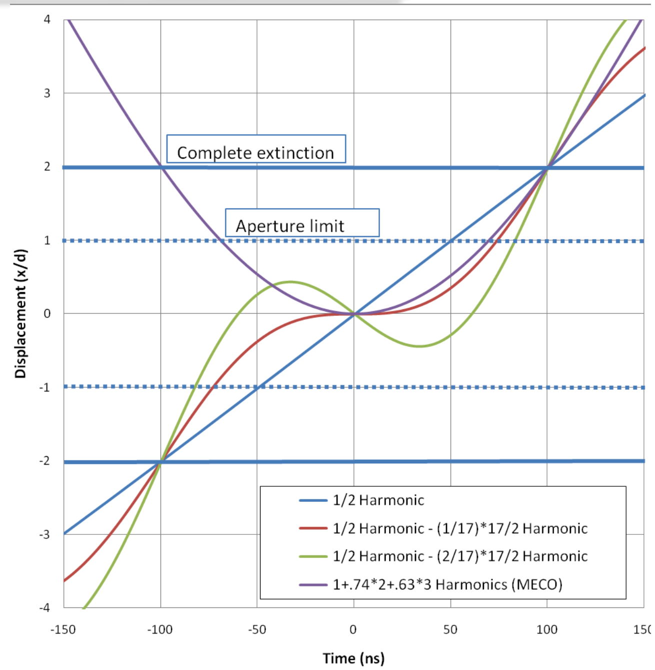
- External extinction is accomplished with a high frequency *AC Dipole* operating at 300 kHz with an admixture of a 5.1 MHz 17th harmonic.
- Unwanted beam swept into collimators.
- MARS simulations indicate this is adequate, but not a trivial magnet to build.
  - Extinction from AC dipole < 10^{-7}

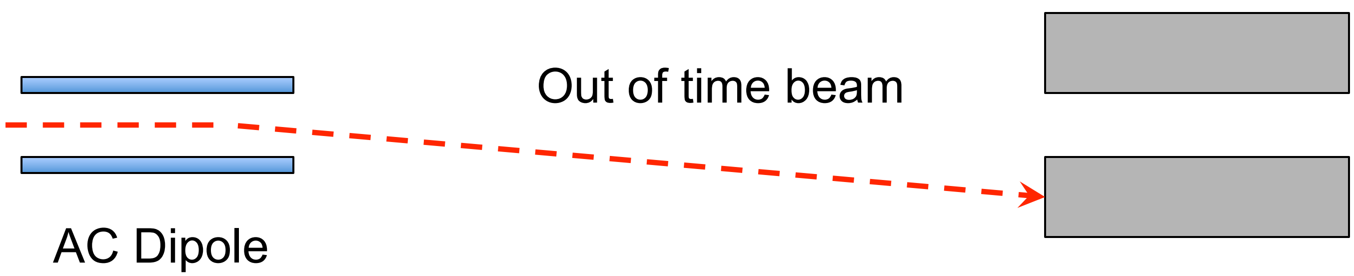




Extinction

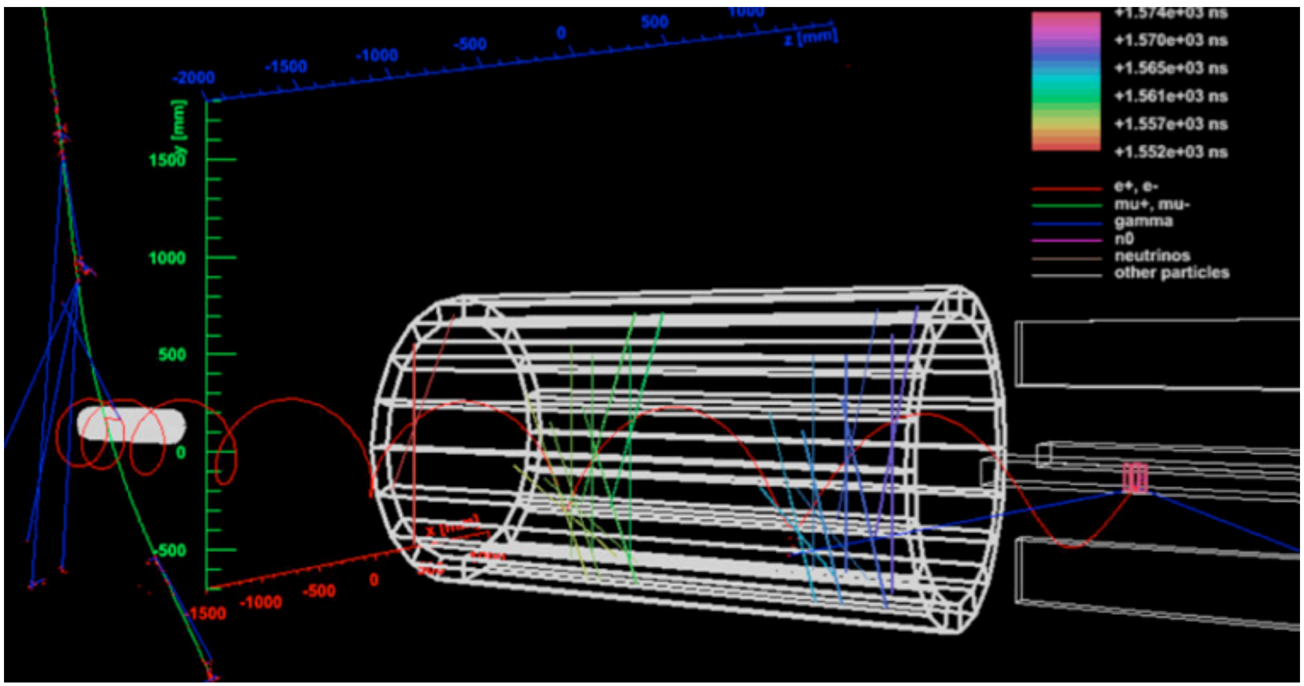
- External extinction is accomplished with a high frequency *AC Dipole* operating at 300 kHz with an admixture of a 5.1 MHz 17th harmonic.
- Unwanted beam swept into collimators.
- MARS simulations indicate this is adequate, but not a trivial magnet to build.
  - Extinction from AC dipole < 10^{-7}
- Bunches at 600 kHz - beyond the state-of-the-art for traditional kickers.





Cosmic Ray Background

- Scales with run time, not POT. Modest improvement from previous experiments all that is required.
- ~1 event/day without CRV



Antiprotons

A source of background

- Negatively charged, so they can be transported to stopping target.
- Do not decay
- Heavy and slow, so they arrive during signal window, even with a perfect extinction system.
- 2 GeV shower

Mitigation

- Thin window in the central collimator
- Reduces muon yield by 15% but effectively annihilates antiprotons

Summary of Backgrounds

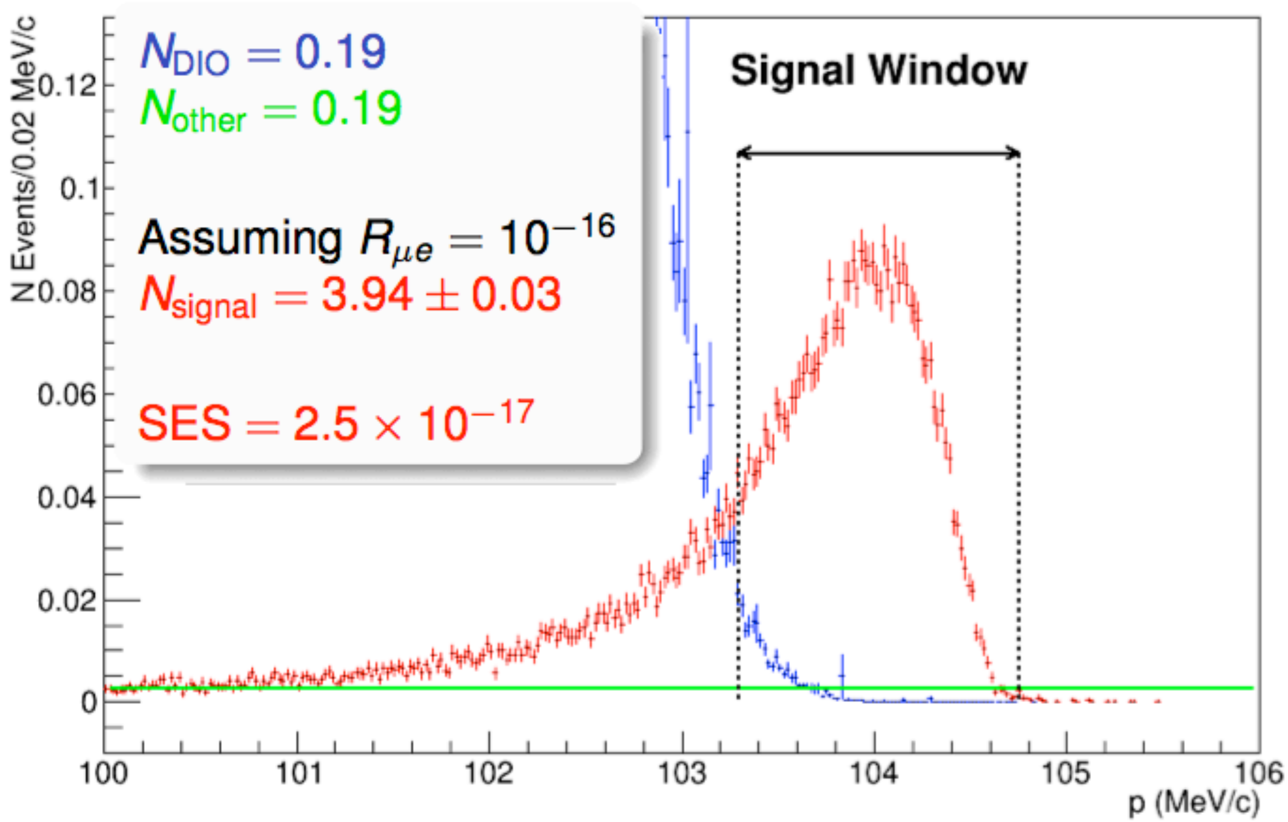
3 years at 1.2 × 10^{20} protons/year (8 kW Beam power)

Background	Expected events
Muon decay in orbit	0.20 ± 0.06
Antiproton induced	0.10 ± 0.06
Radiative pion capture*	0.04 ± 0.02
Cosmic rays**	0.050 ± 0.013
Beam electrons*	0.001 ± 0.001
Muon decay in flight*	0.010 ± 0.005
Total	**0.4 ± 0.1**

* Assumes 10^{-10} beam extinction
** For 10^{-4} cosmic ray veto inefficiency

Signal

3 years at 1.2 × 10^{20} protons/year (8 kW Beam power)

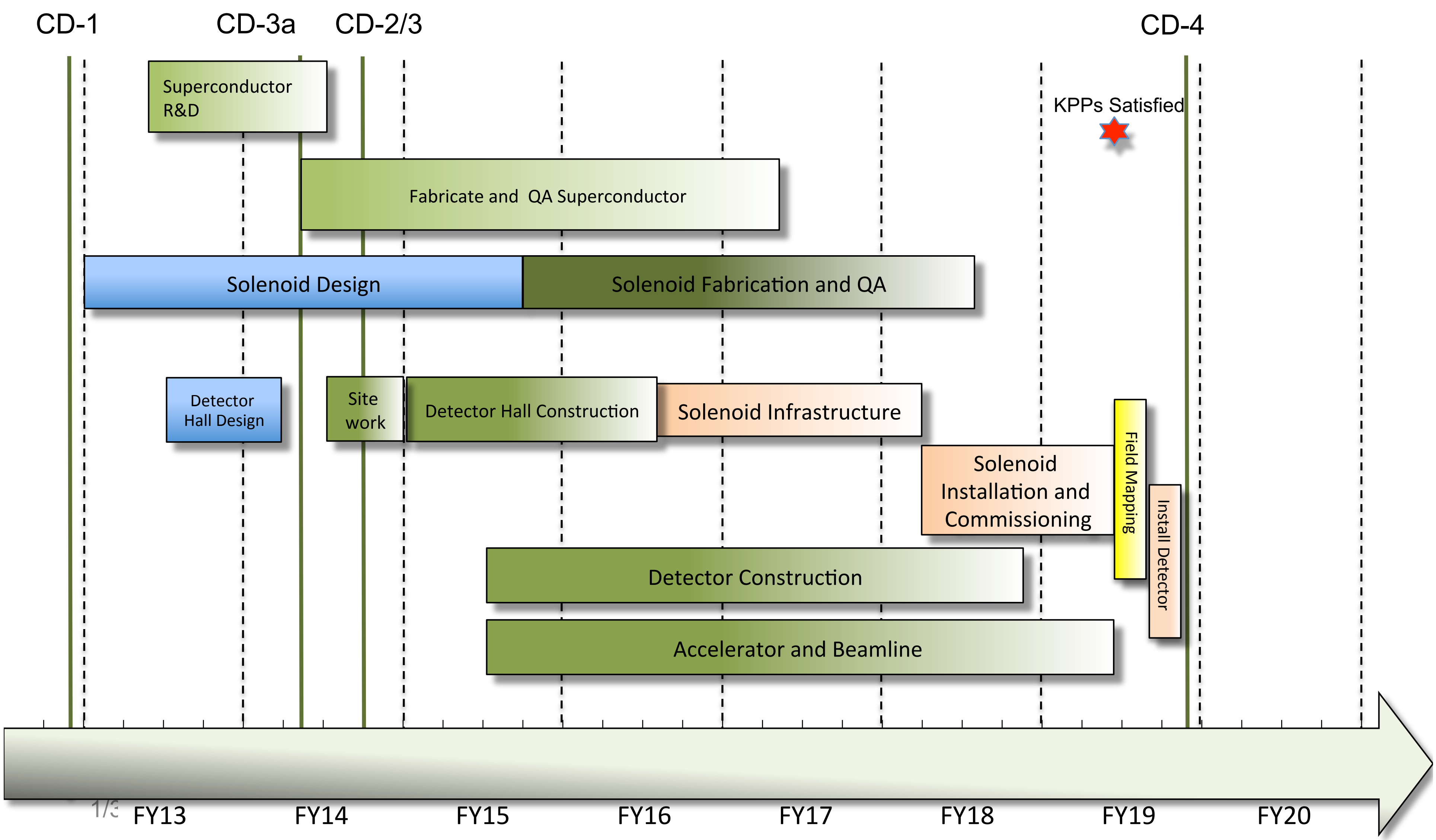


Full G4 and event reconstruction without truth inputs

Project Status

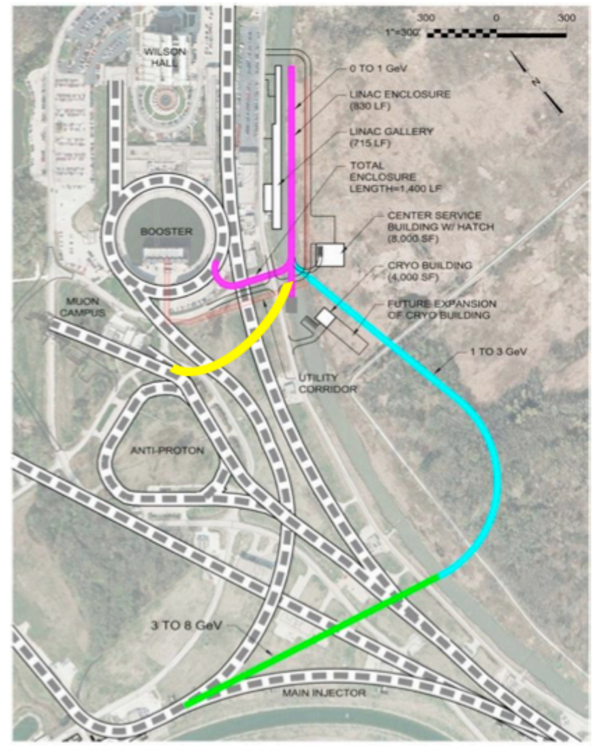
- Mu2e received CD-0 in December 2009
- CD-1 in July 2012
- CD-3a, to authorize long lead solenoid conductor procurement, scheduled for March 2014
- CD-2/3 scheduled for July 2014
- Total Project cost of ~ $250M
  - $40M spent thus far.
- Mu2e Conceptual Design Report can be found at
  - arXiv:1211.7019

Schedule

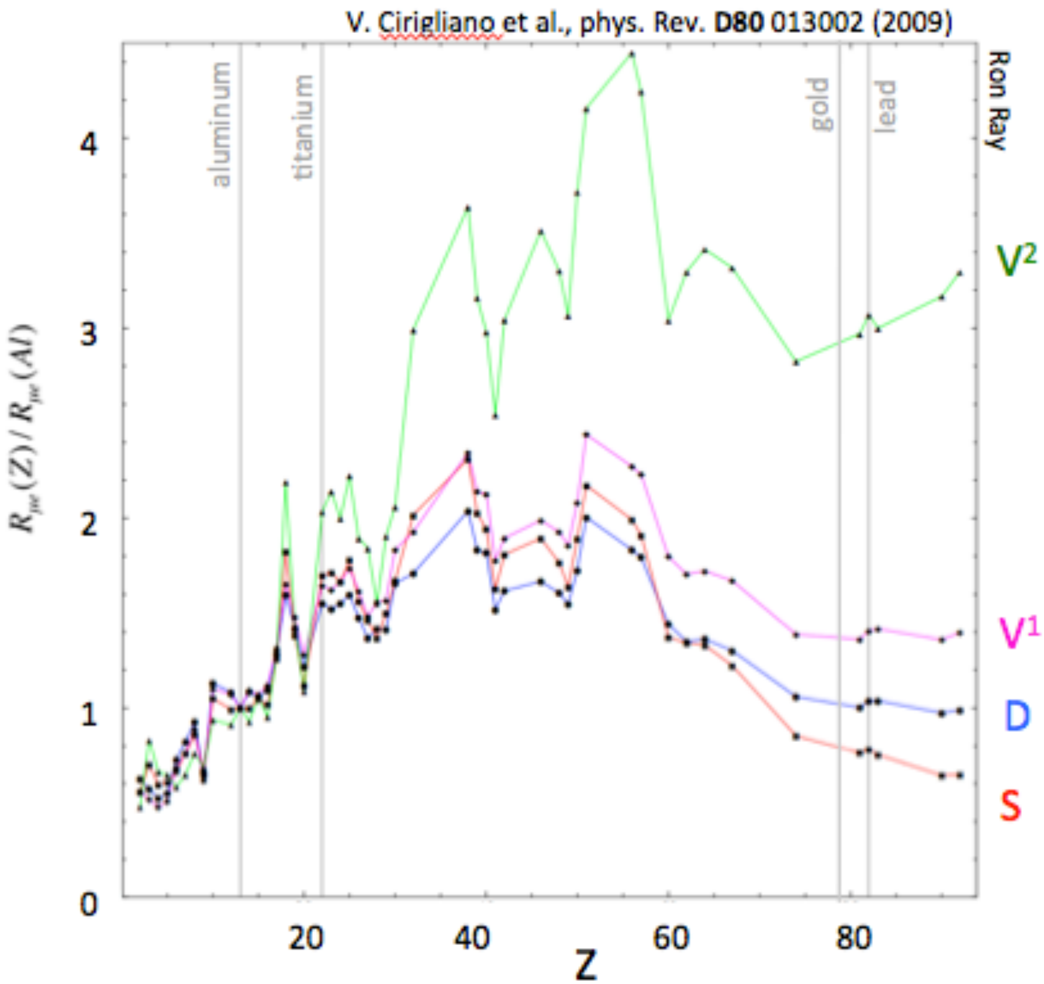

CD-1
CD-3a
CD-2/3
CD-4
Superconductor R&D
KPPs Satisfied
Fabricate and QA Superconductor
Solenoid Design
Solenoid Fabrication and QA
Detector Hall Design
Site work
Detector Hall Construction
Solenoid Infrastructure
Solenoid Installation and Commissioning
Field Mapping
Install Detector
Detector Construction
Accelerator and Beamline
FY13
FY14
FY15
FY16
FY17
FY18
FY19
FY20

Mu2e II

- Mu2e uses 8 kW proton beam from Booster
- PIP II provides an upgrade path to x10 more beam power
  - Narrower proton pulses
  - No pbar background
  - Flexible beam structure
  - Run simultaneously with g-2
  - Requires some modest upgrades to Mu2e apparatus to handle higher beam power.
  - Important physics goals regardless of results from first phase of Mu2e.
    - More beam power for a more sensitive search
    - Flexible time structure of PIP II beam allows access to different stopping target nuclei where model dependent effects vary significantly.



Mu2e II – If we see a signal



Greater discrimination at high Z, but shorter muon lifetimes for higher Z nuclei.

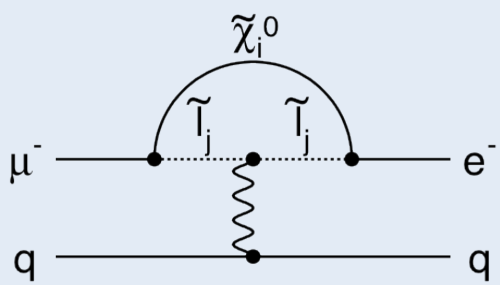
Summary

- Mu2e will either:
  - Reduce the limit for $R_{\mu e}$ by ~ four orders of magnitude ($R_{\mu e} < 6 \times 10^{-17}$ @ 90% C.L.)
  - Discover unambiguous proof of Beyond Standard Model physics and
    - Provide important information either complementing LHC results or probing mass scales up to 10^4 TeV
- With upgrades, we could extend the limit by an order of magnitude or study the details of new physics
- There is plenty of interesting work to do and we are still looking for new collaborators…

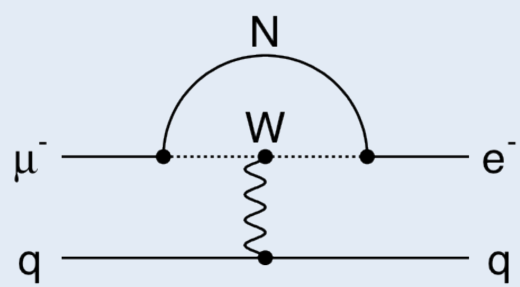
Backup Slides

Discovery Sensitivity

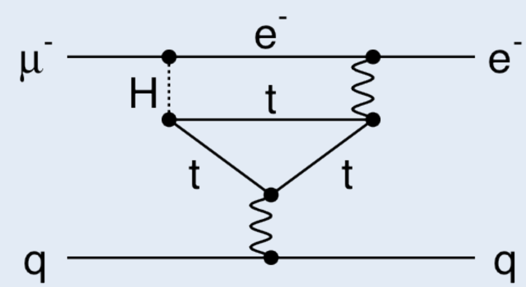
Loops



Supersymmetry

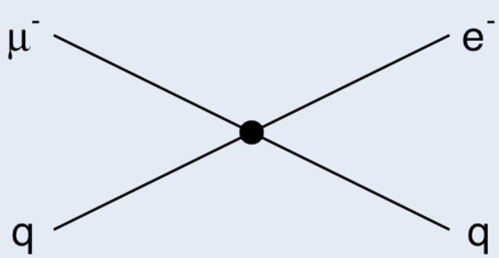


Heavy Neutrinos

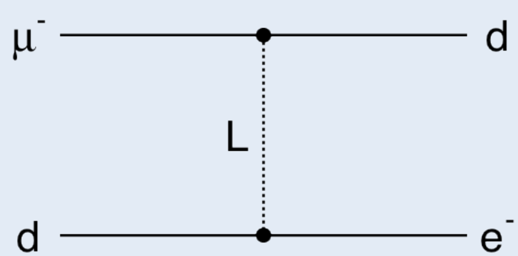


Two Higgs Doublets

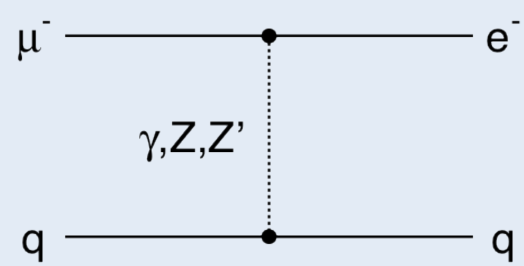
Contact Terms



Compositeness



Leptoquarks



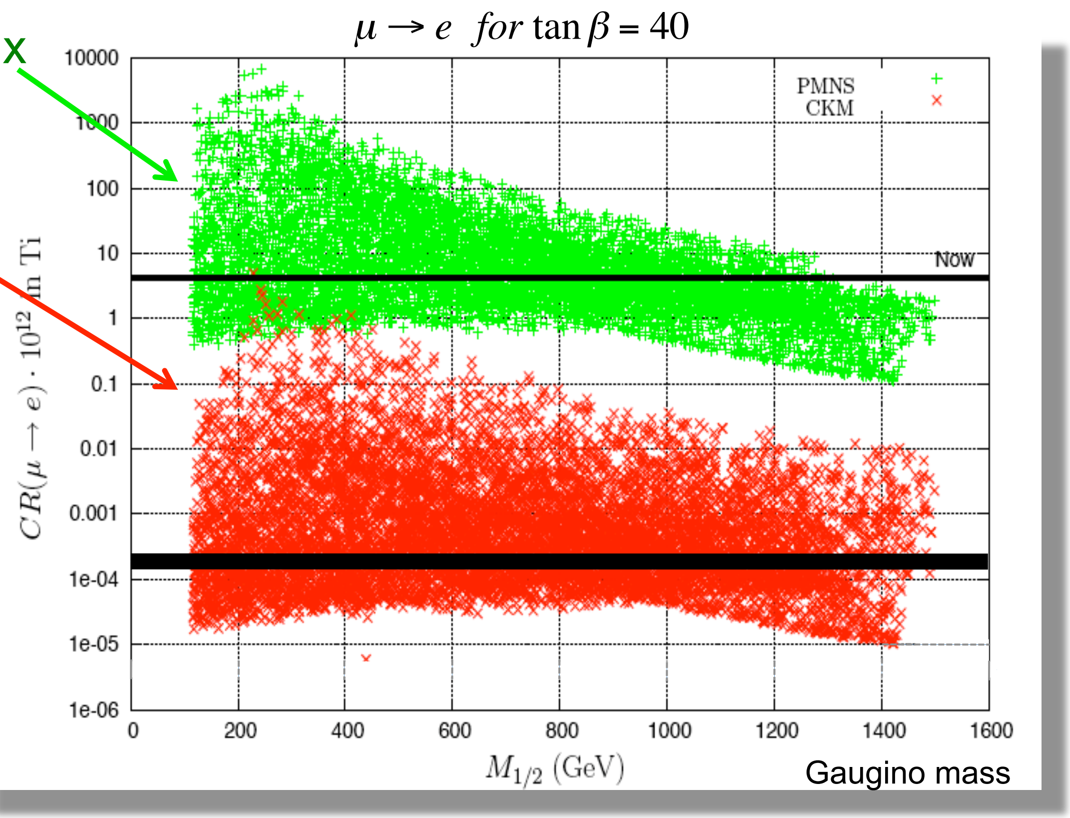
New Heavy Bosons /
Anomalous Couplings

SUSY and μe Conversion

$\mu \longrightarrow e$ Conversion Rate vs. $M_{1/2}$
Scan over LHC accessible SUSY-Gut parameter space.

Neutrino-like mixing matrix for Yukawa ν's(PNMS)

CKM – like mixing matrix for Yukawa ν's (Minimal Flavor Violation)



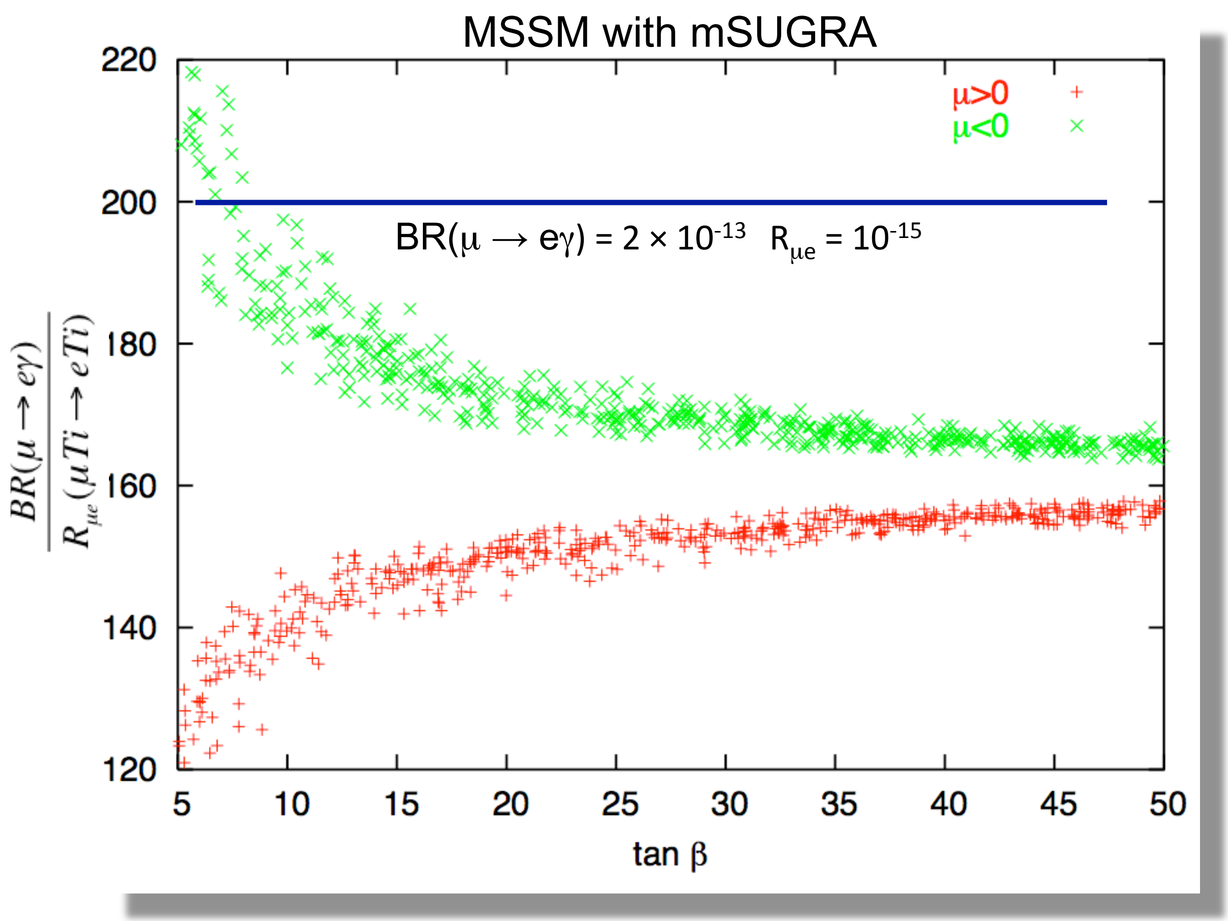
Current

Mu2e

Mu2e can distinguish between PMNS and MFV and help us interpret discoveries at the LHC and provide input to neutrino physics at high mass scales.

Calibbi, Faccia, Masiero, Vempati Phys. Rev. D74:116002 (06)

Pinning down SUSY with CLFV Measurements

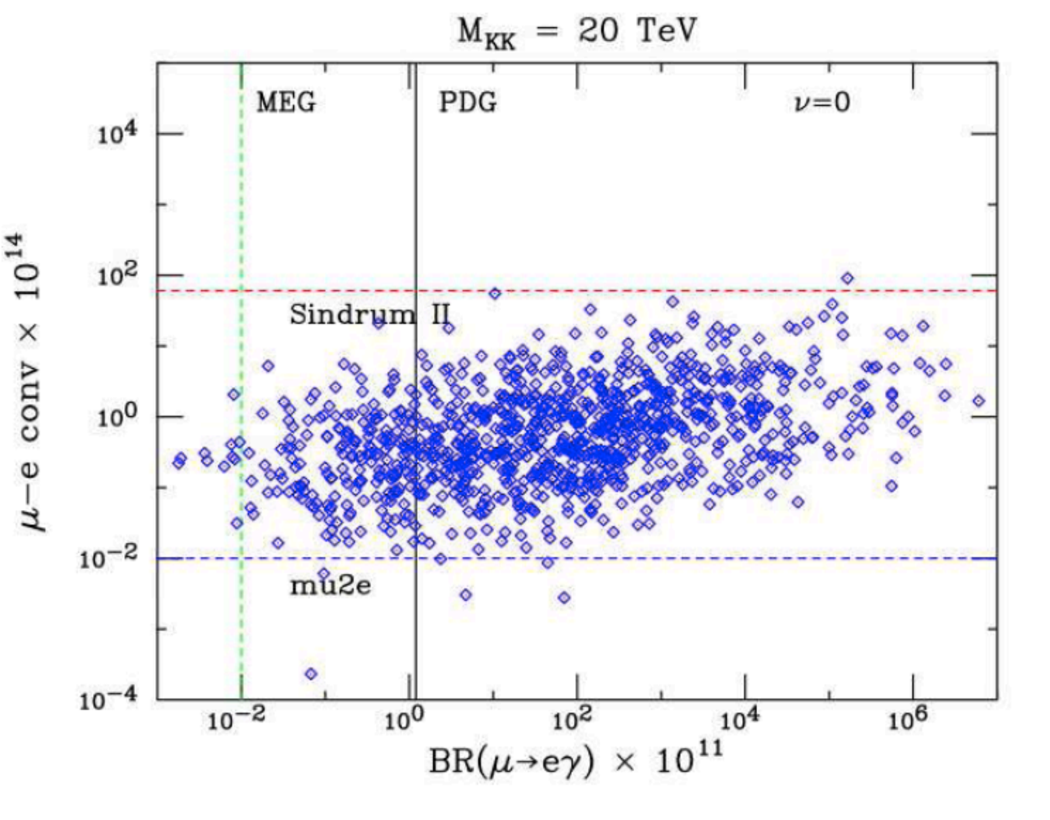


C. E. Yaguna, hep-ph/0502014v2

In the MSSM with msugra boundry conditions, and seesaw induced neutrino masses, BR(μ → eγ) and μ-e conversion constrain msugra parameters.

Effect of Warped Extra Dimensions on Rates

Muon Conversion vs. $\mu \rightarrow e\gamma$



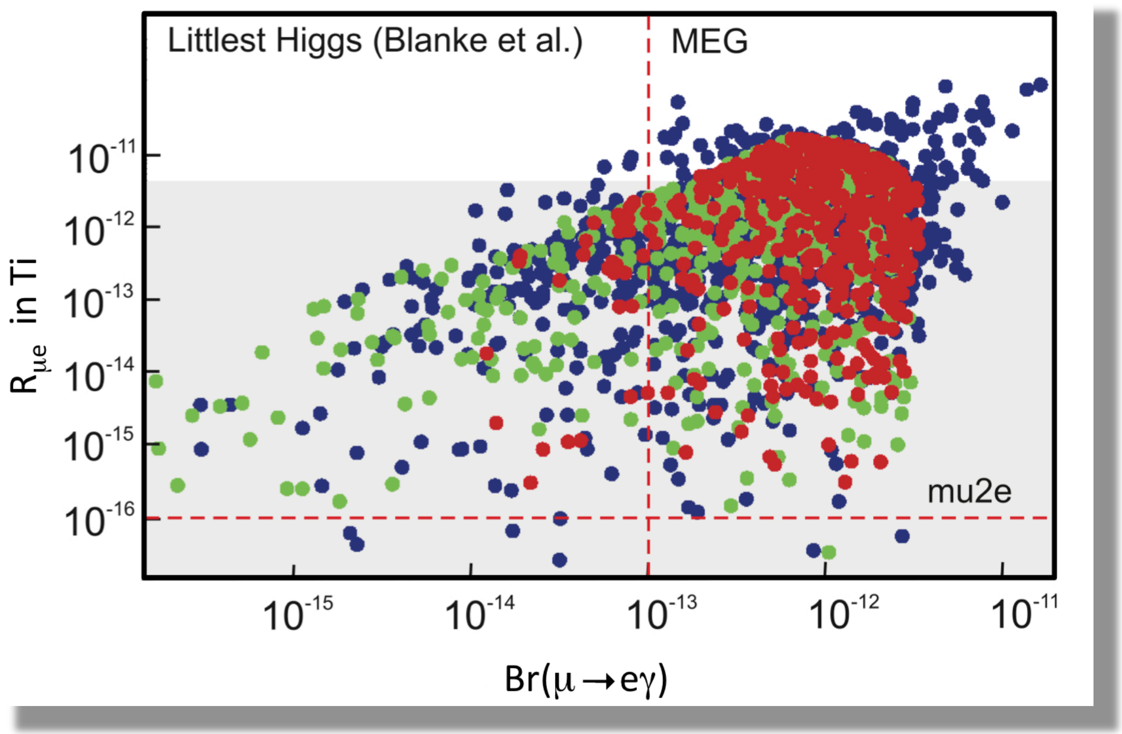
K. Agashe, A. E. Blechman and F. Petriello, Phys. Rev. D 74, 053011 (2006).

μ-e conversion rate as a function of BR($\mu \rightarrow e\gamma$) for RS model with one warped, compact extra dimension in the scenario where the Higgs is allowed to propagate in the bulk.

Mu2e spans nearly the entire parameter space.

Effect of Littlest Higgs Model on Rates

Muon Conversion vs. $\mu \rightarrow e\gamma$

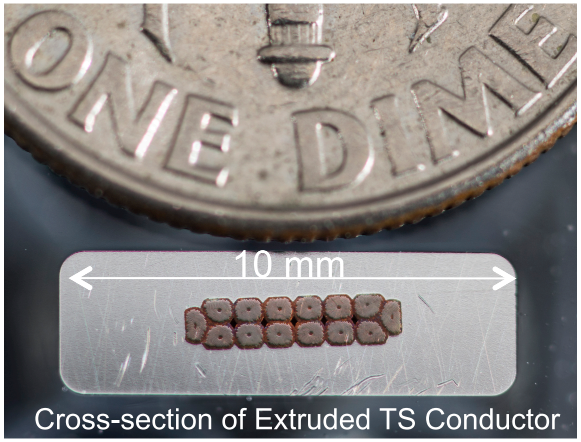


M. Blanke, A. J. Buras, B. Duling, A. Poschenrieder and C. Tarantino, JHEP 0705, 013 (2007).

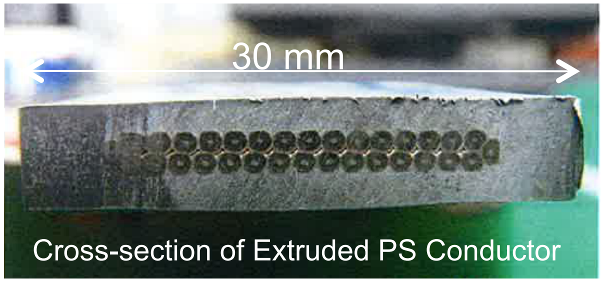
Littlest Higgs Model. The different colored points refer to different choices for the structure of the mirror-lepton mixing matrix that gives rise to the CLFV effects.

Correlations between the two are distinctly different than for SUSY and could be used do differentiate between SUSY and mirror quarks and leptons at the LHC.

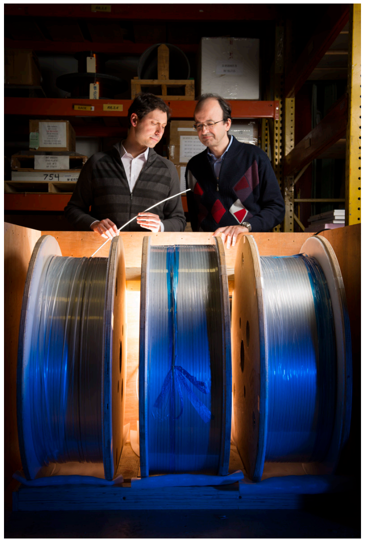
Solenoid Status - Conductor



Cross-section of Extruded TS Conductor



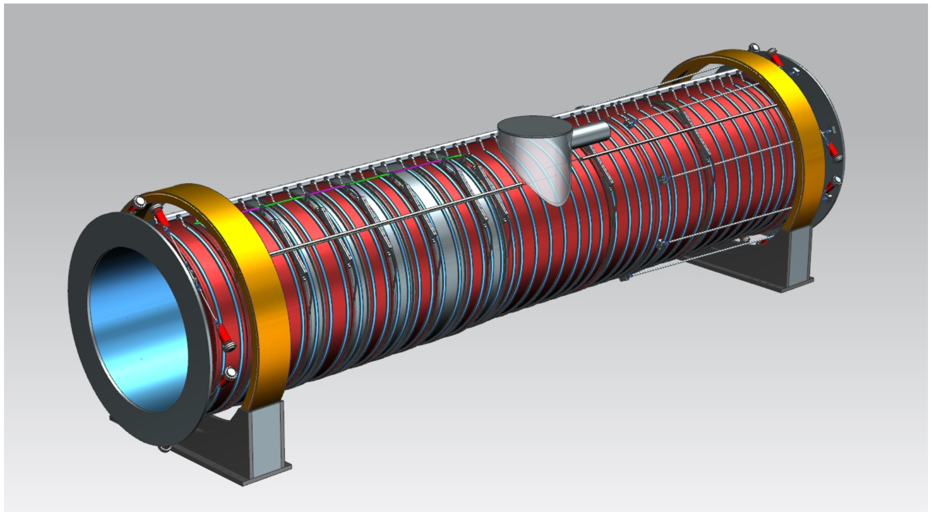
Cross-section of Extruded PS Conductor

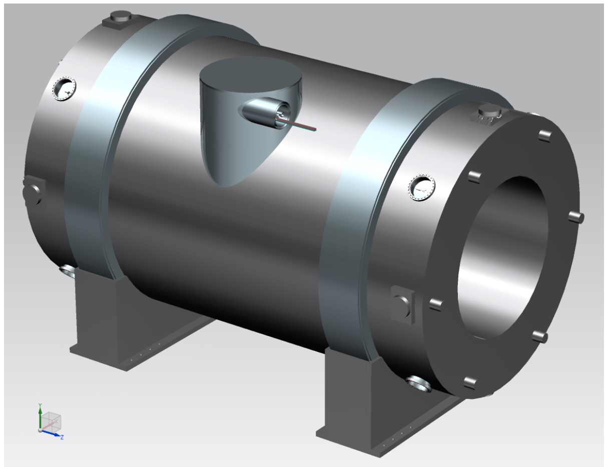


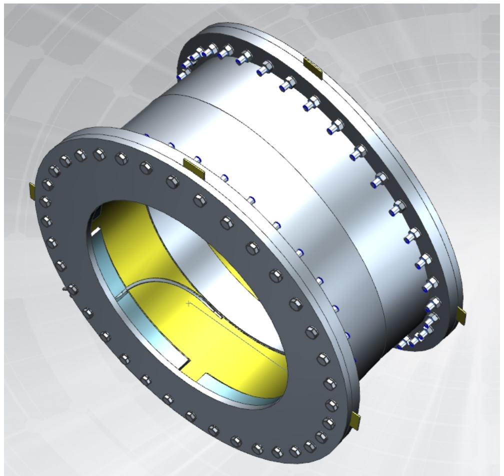
- Magnets are only as good as their conductor
- Solenoid conductor R&D is on the critical path and is nearly complete
- Successful conductor R&D validates decision to develop technically risky conductor in exchange for significantly simpler, cheaper, more robust solenoid designs.

Solenoid Status

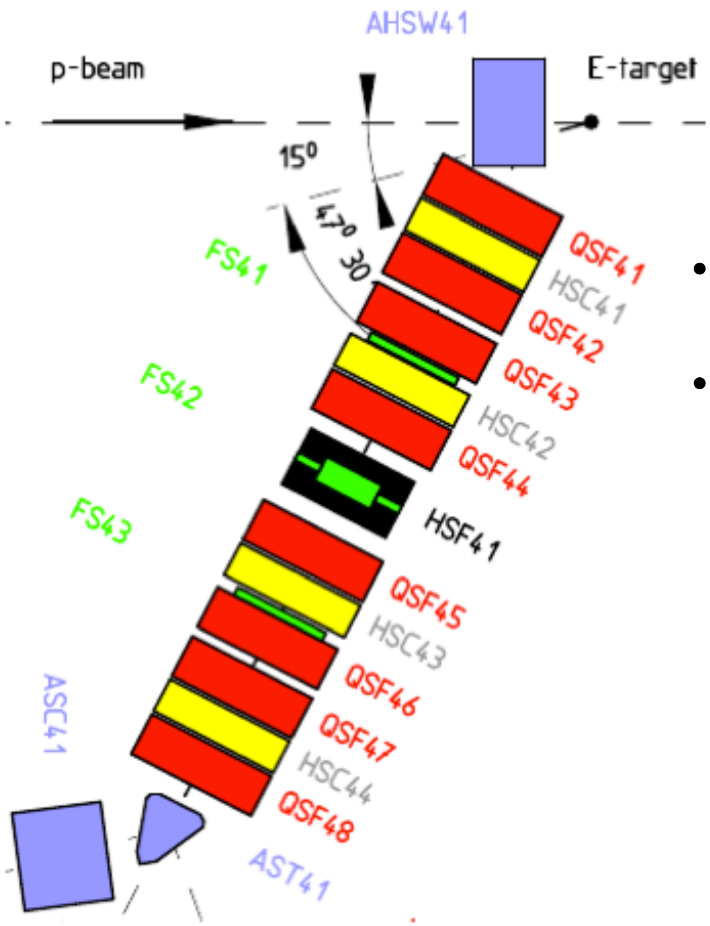
- Solicitation packages for PS/DS sent out this week
- Reference designs completed by Fermilab.
- Vendors complete designs while conductor being fabricated
- Begin solenoid construction in FY15







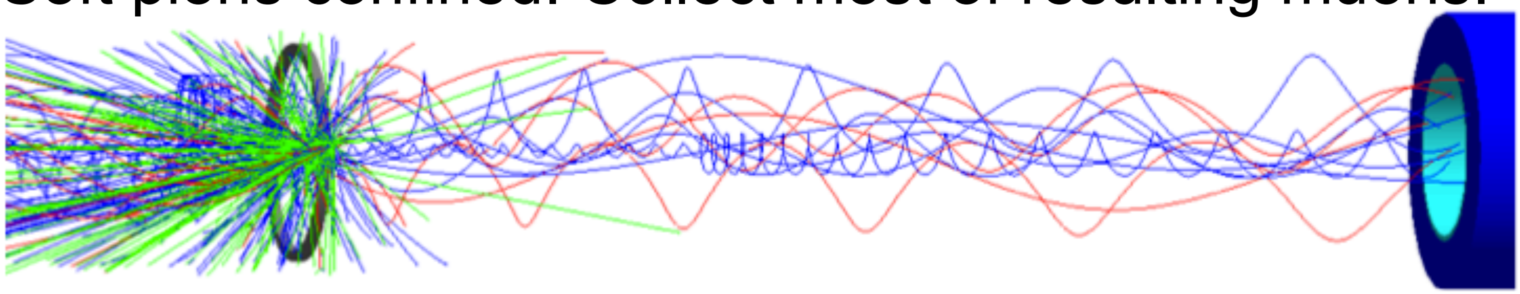
The usual way to collect muons



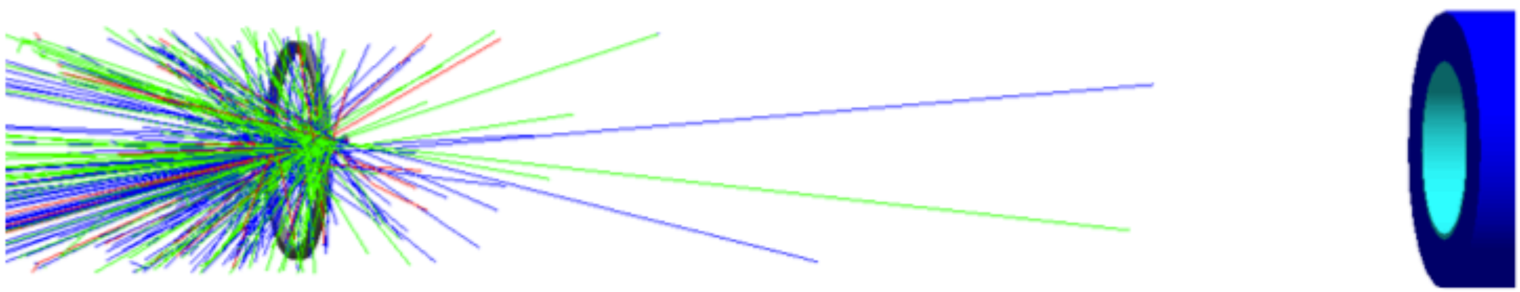
- PSI πE5 beamline used by SINDRUM II
  - 1.3 MW proton beam produces 10^8 μ^+/s
- Mu2e produces 10^{10} μ^-/sec with an 8 kW proton beam.

Mu2e Muon Collection

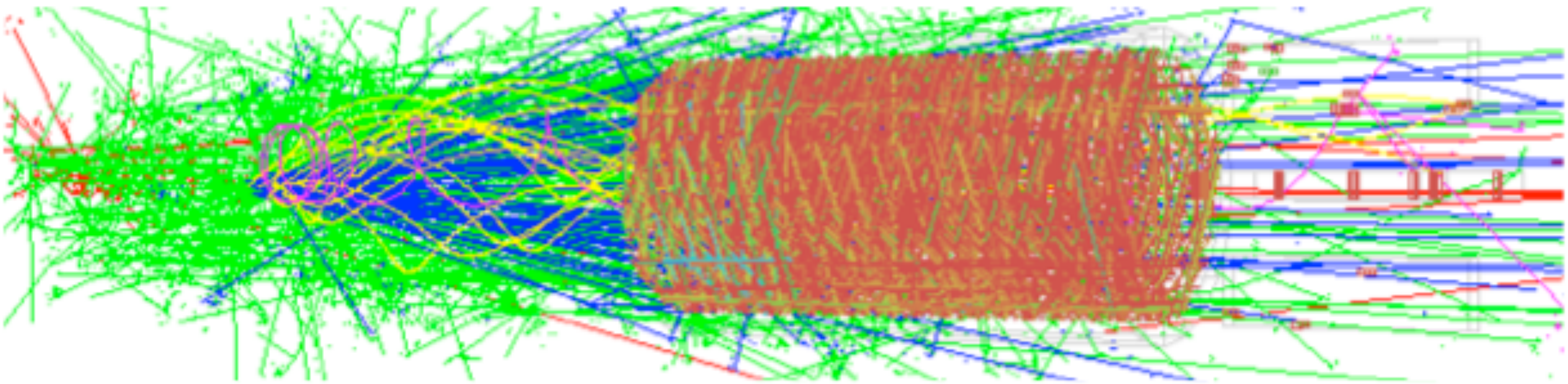
Proton target in solenoidal B field
Soft pions confined. Collect most of resulting muons.



Compare to B = 0

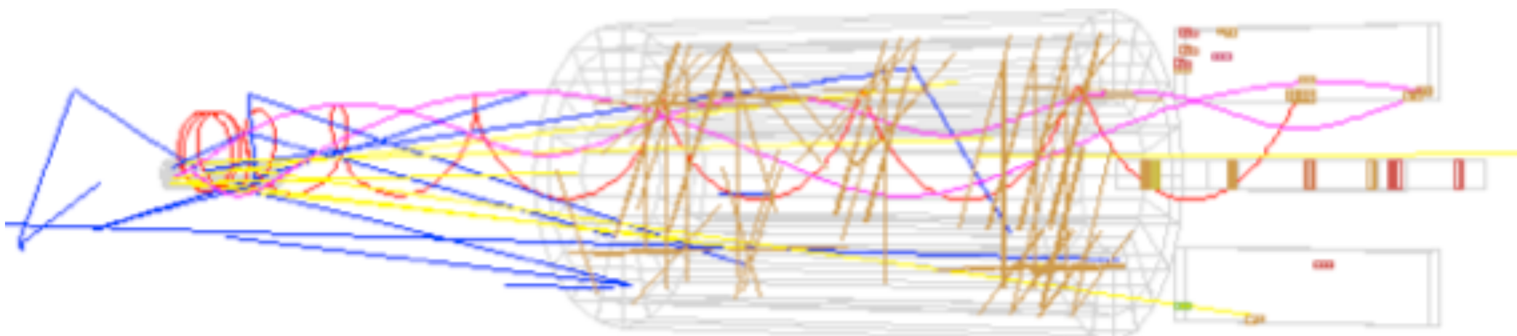


Pattern Recognition



Single proton pulse: particles and hits from 500 – 1694 ns

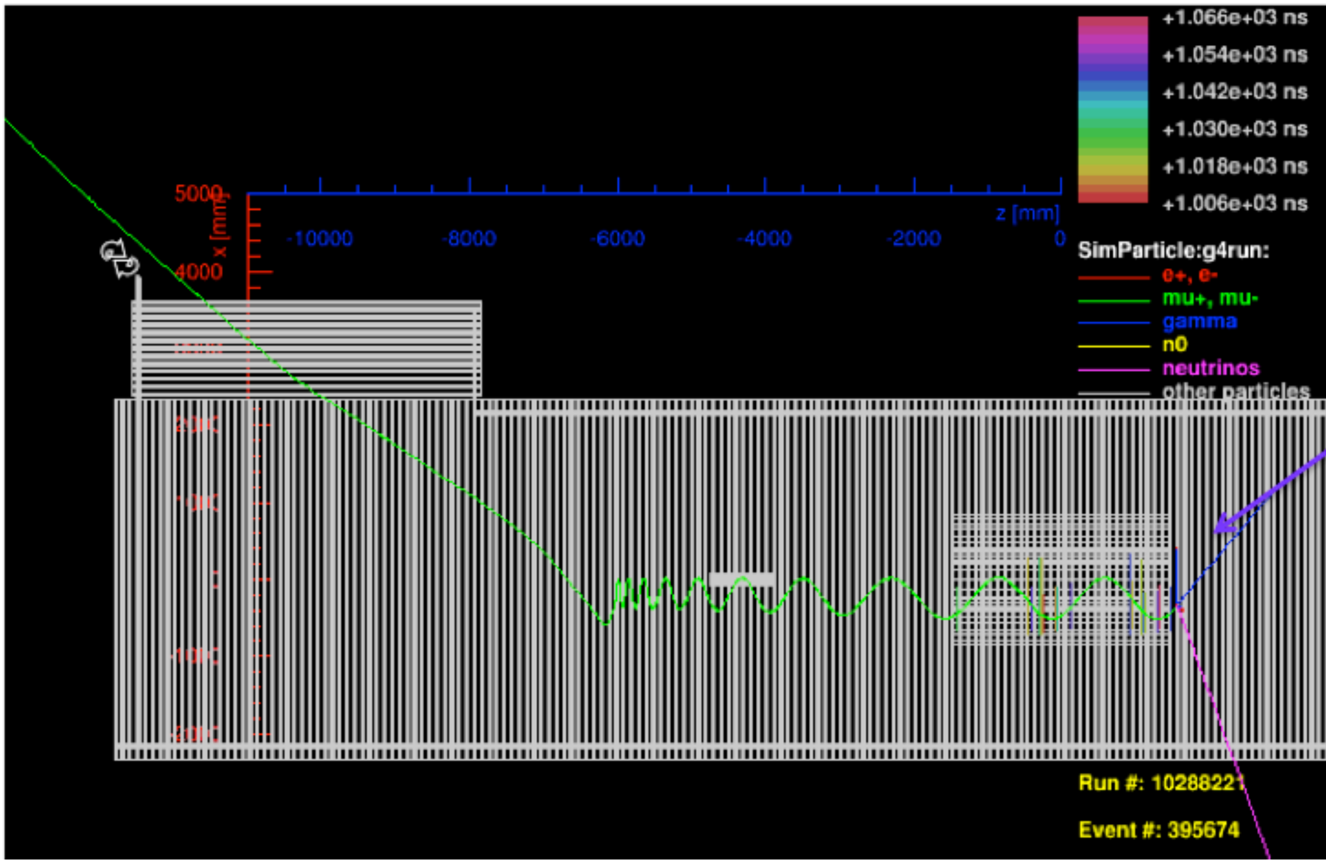
Pattern Recognition



Single proton pulse: Particles and hits in ±50 ns window around conversion

Cosmic Ray Veto

A cosmic ray muon vetoed by the calorimeter



Note: disk calorimeter

DIO Endpoint

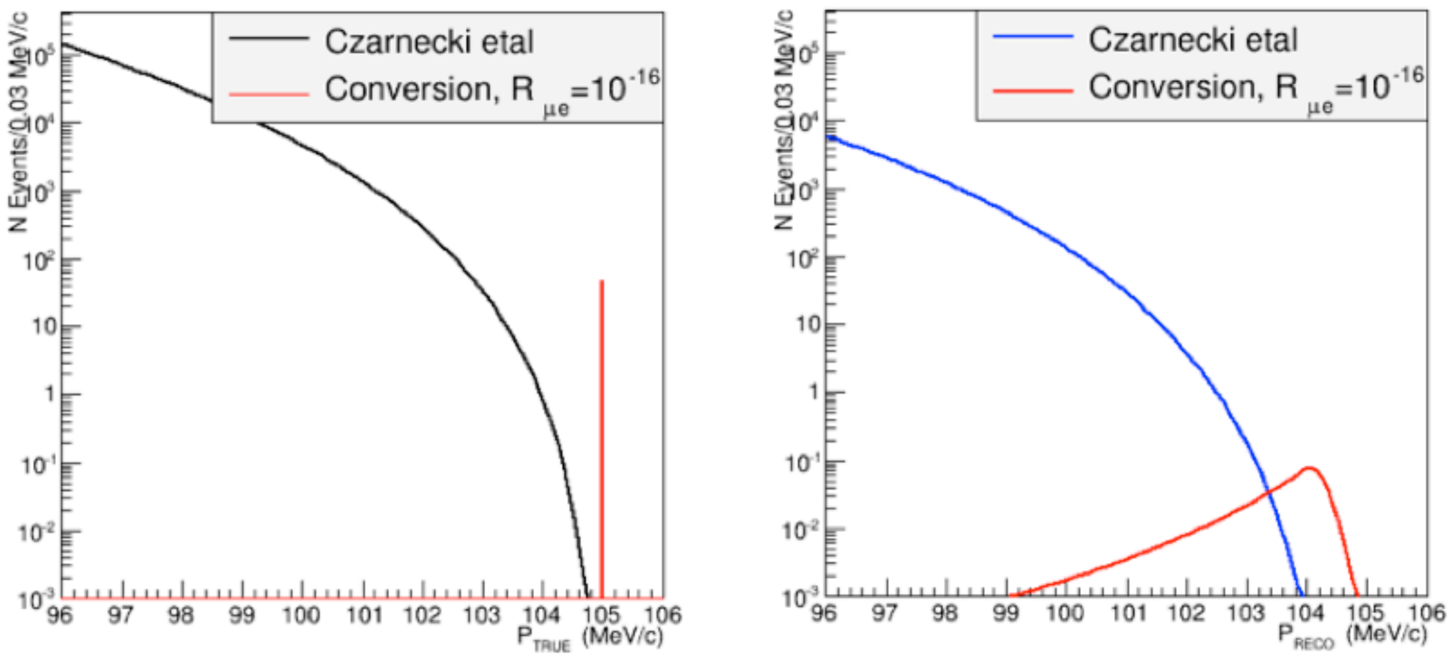
- Latest spectrum computation by Czarnecki, Tormo, Marciano (2011)
- End point expansion

$$\frac{1}{\Gamma_0}\frac{d\Gamma}{dE_e} = B\left(E_\mu - E_e - \frac{E_e^2}{2m_N}\right)^5$$

- Small but steep tail
- DIO electron differs from signal only by its momentum

DIOs

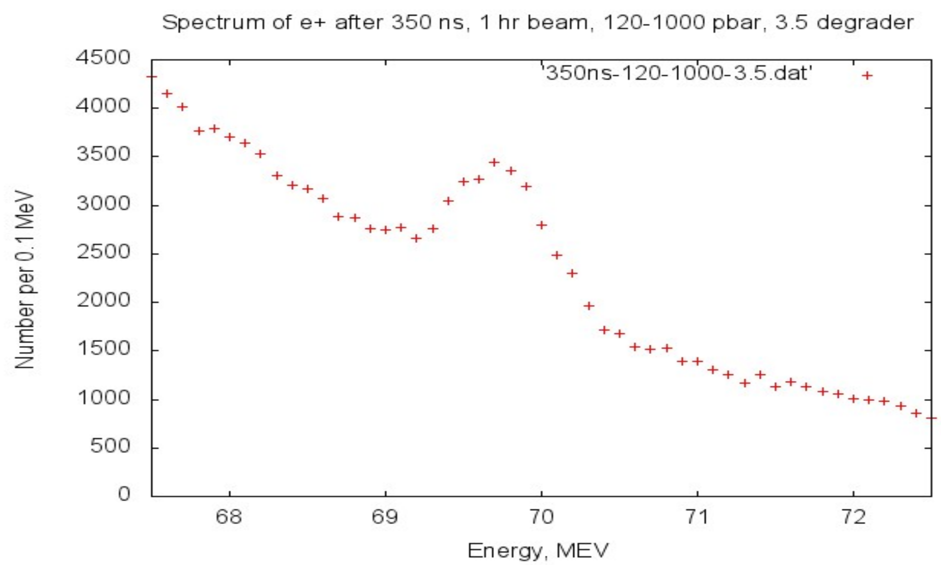
- Momentum resolution is important!
- High side tail pushes DIOs into the signal region

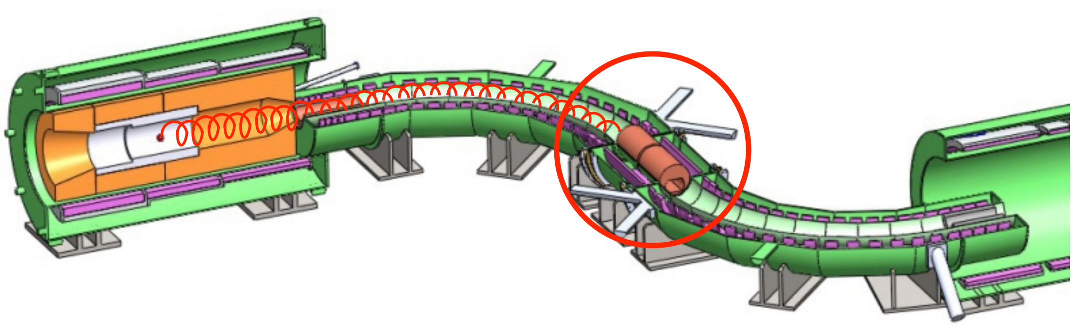


Understanding Resolution

Calibration of this device not easy.

- Use stopped $\pi^+ \rightarrow e^+\nu$ decay for absolute calibration
  - Monochromatic line at ~70 MeV
- Requires lowering the field, lowering the beam intensity, and rotating the central collimator





Resolution Function

- Cosmic muons can spallate electrons from the calorimeter that can reflect in the gradient, allowing the particle to be measured twice
- Measuring the same particle twice allows us to extract the tracker momentum resolution function and understand the tails
- Can also measure energy loss, straggling in upstream material