Mu2e: Probing the Frontiers of Physics Using Rare Particle Decays

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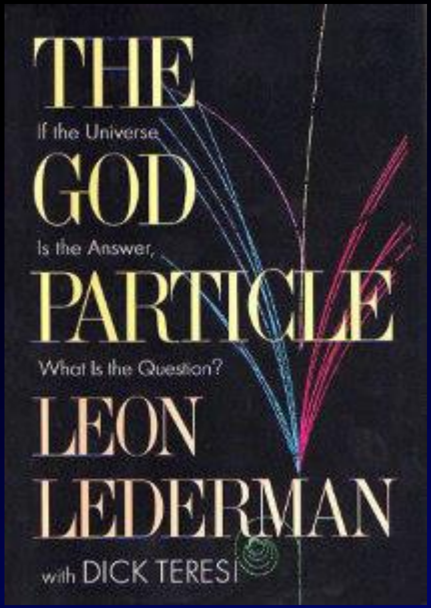
Planning the Future of Particle Physics

Two summers ago about a 1,000 physicists gathered together in Minneapolis for two weeks to plan the future of particle physics in the United States for the next decade.

"Prediction is very hard, especially about the future"

Yogi Berra

Context of Snowmass was Two Profound Discoveries

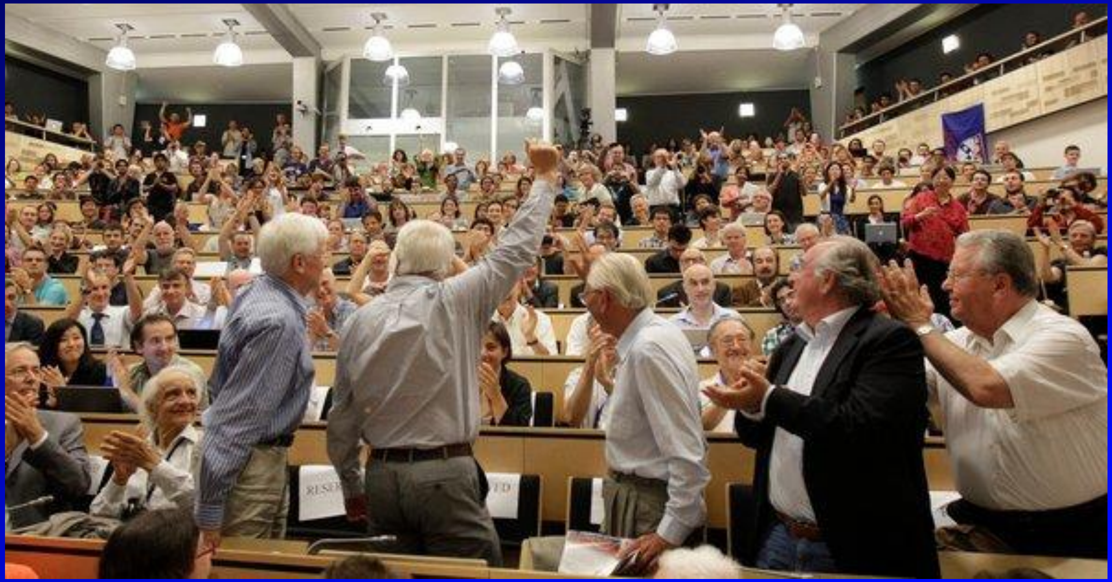


The discovery of the Higgs boson by the LHC

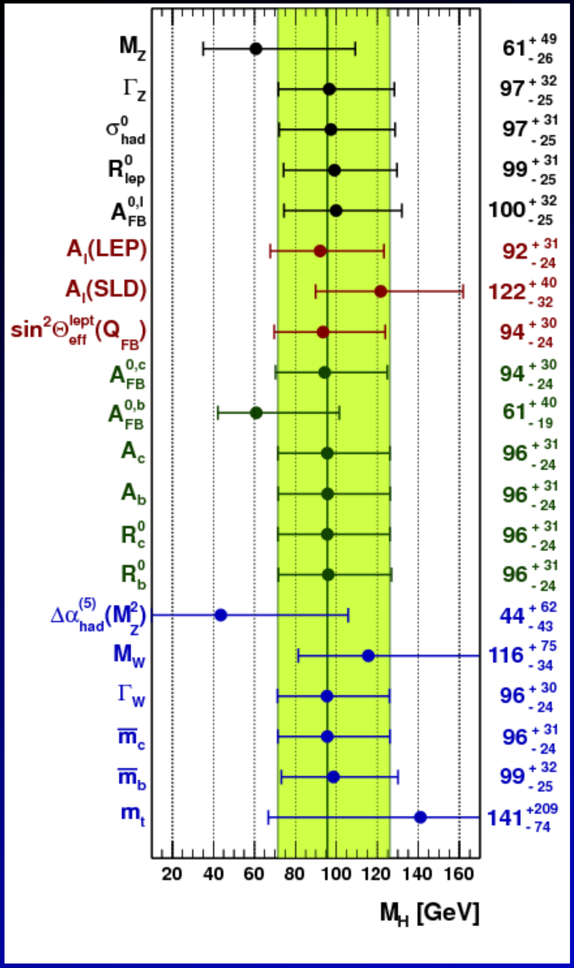
The particle that gives mass to all of the fundamental particles.

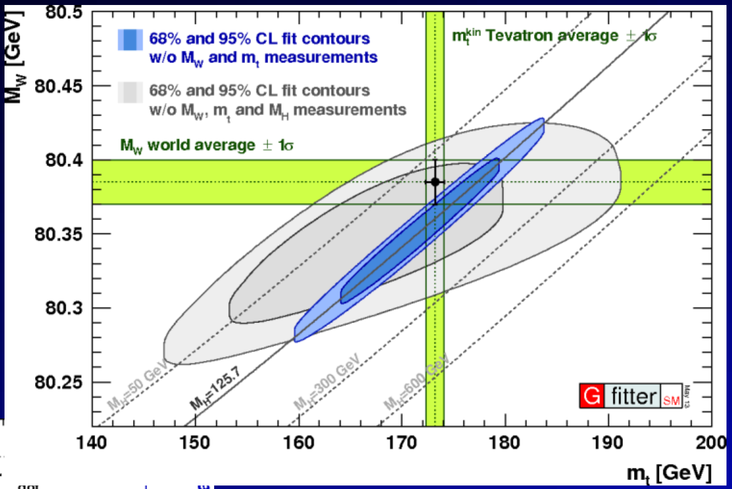
The Standard Model of particle physics is now complete.

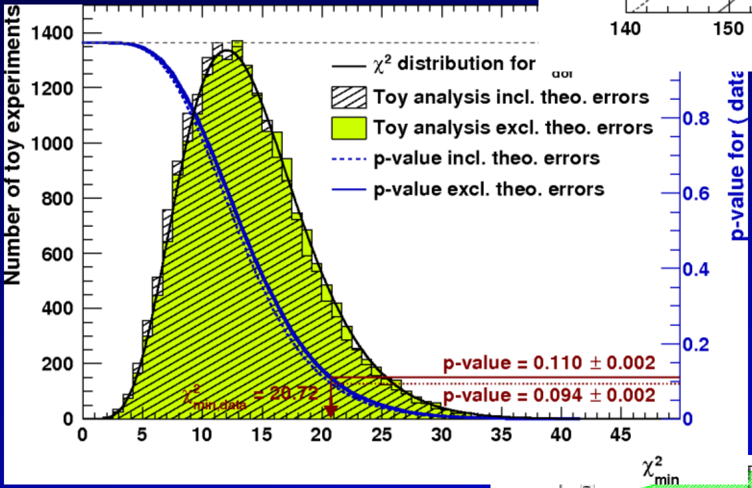
CERN, July 4, 2012

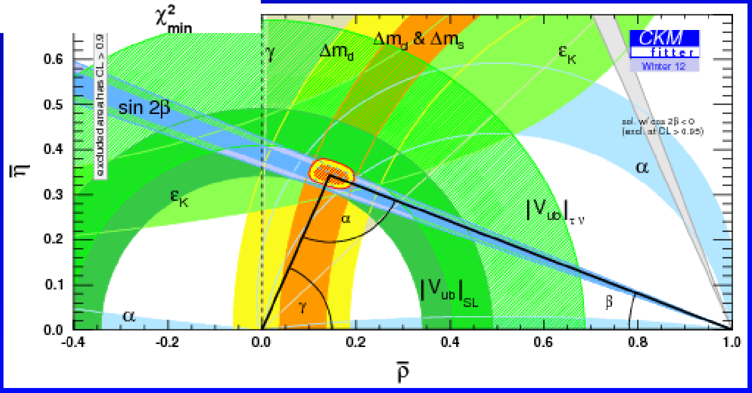


Standard Model and Data Agree Exquisitely Well!



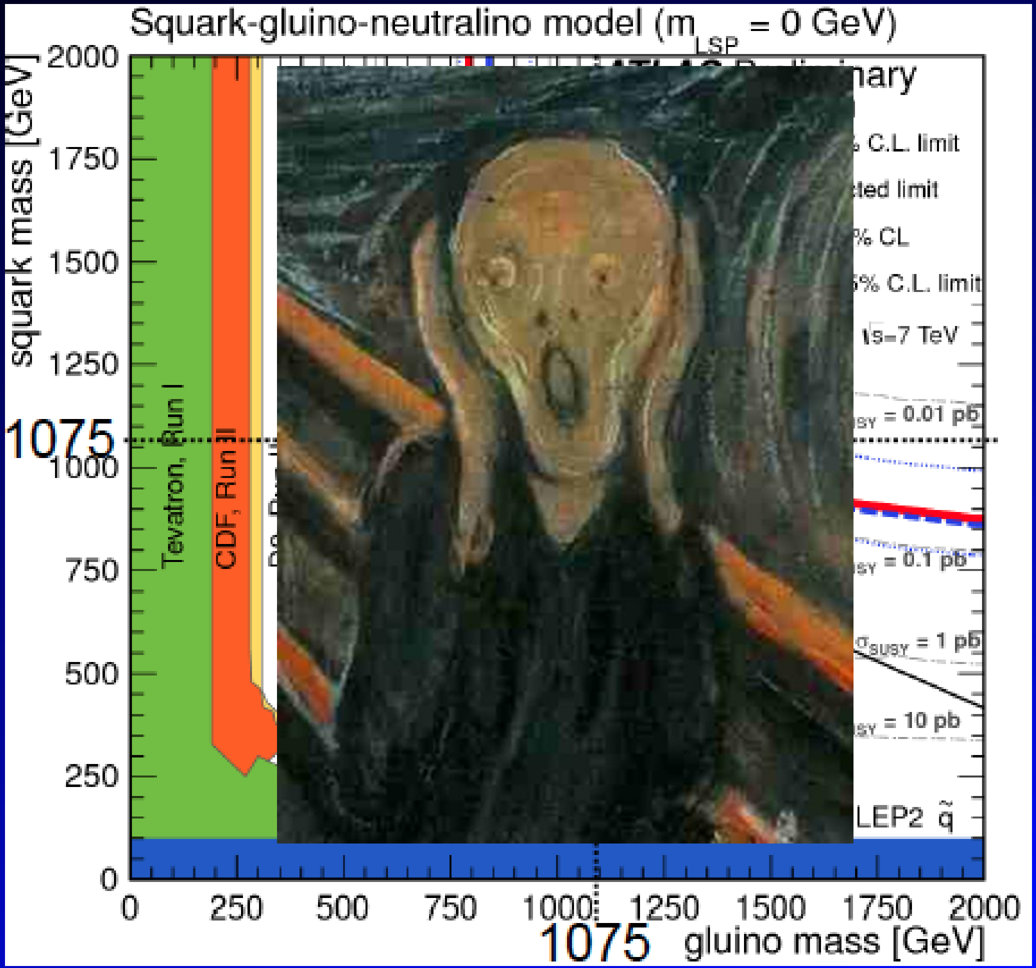






Second Profound Discovery

The non-discovery of Supersymmetry by the LHC



Current State of Theoretical Physics

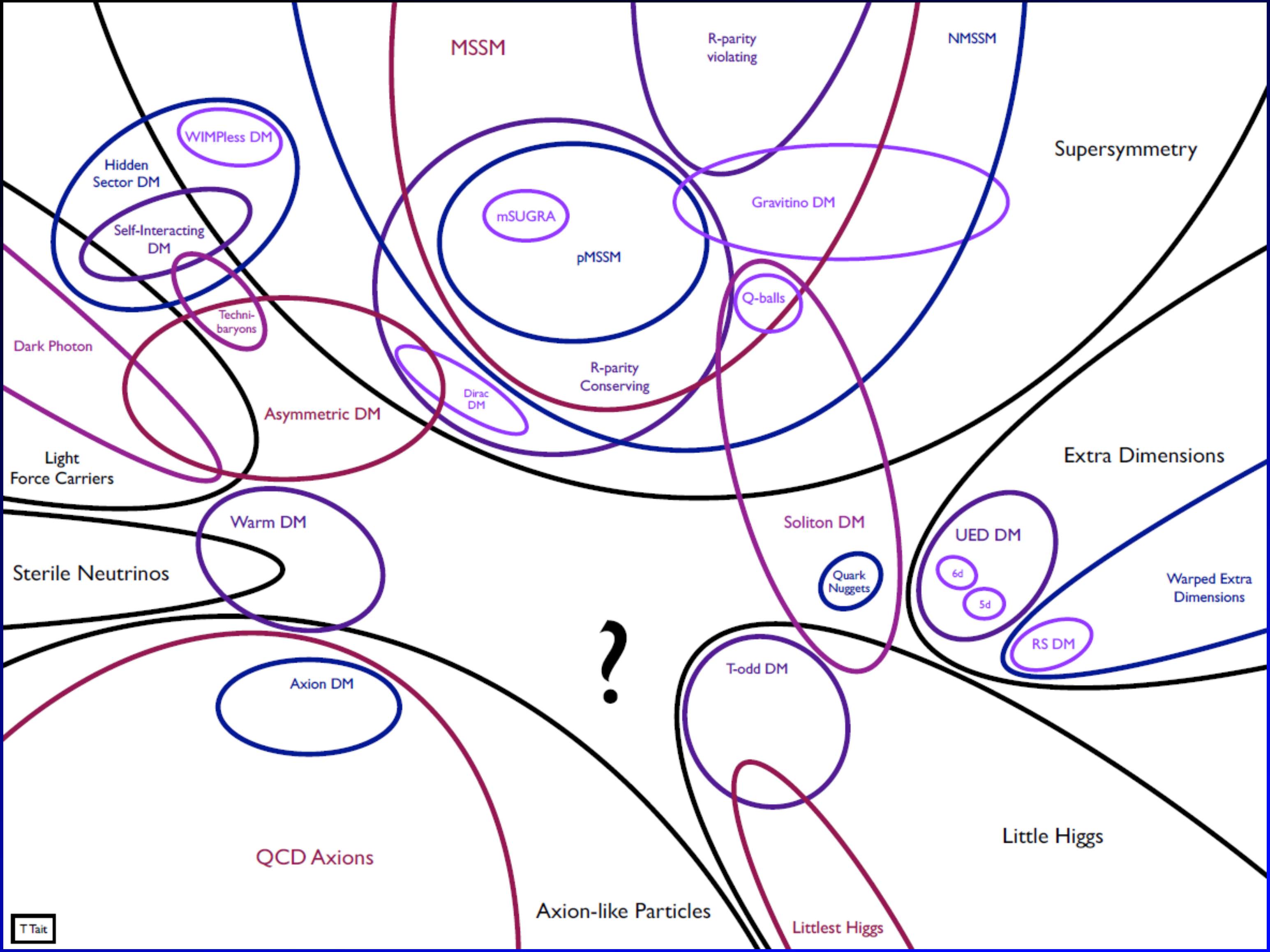
We have a Standard Model that explains (almost) everything we see in our accelerator-based particle experiments.
It does not explain very gross features we unambiguously observe in the universe: dark matter, dark energy, antimatter asymmetry.

"If you ask most theorists working on particle physics, they're in a state of confusion."

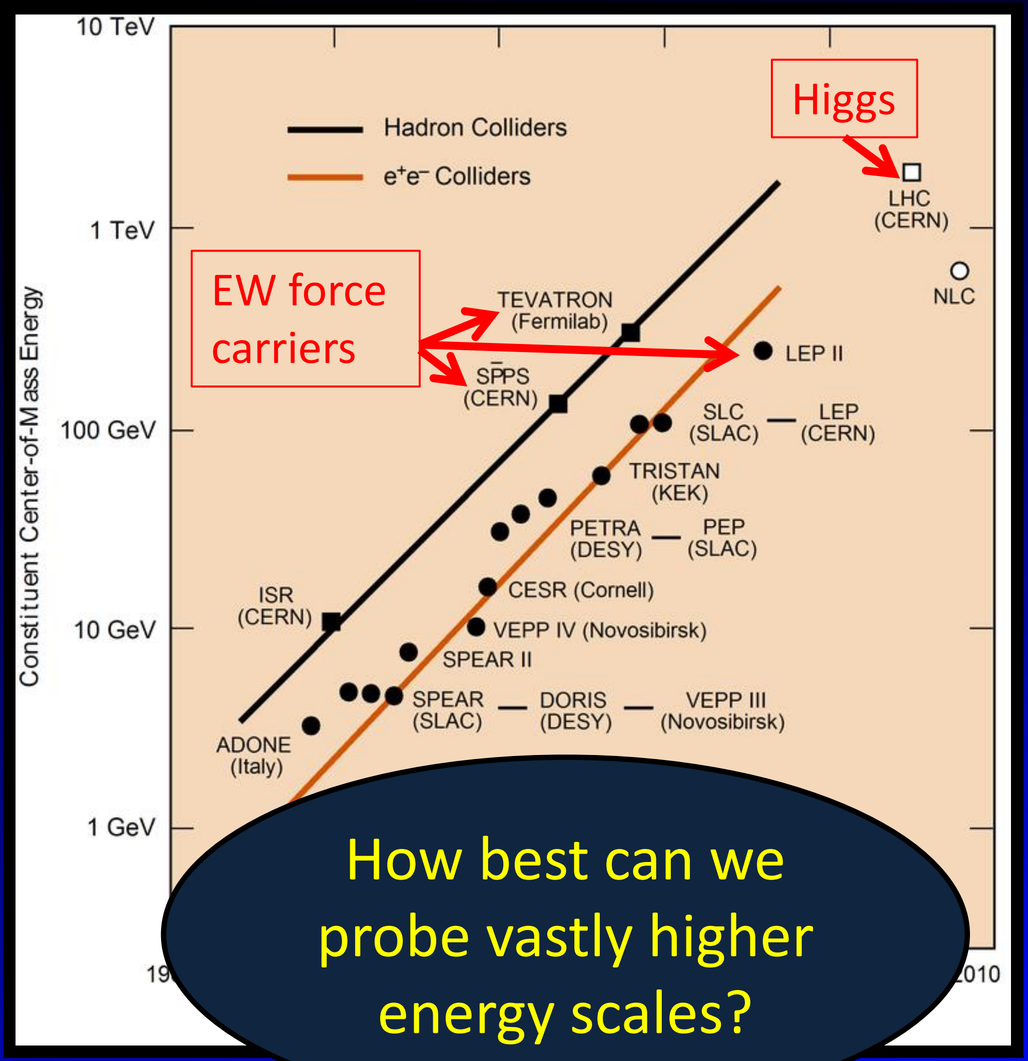
Neil Turok, Director Perimeter Institute

How do we proceed from here?

No Lack of Theoretical Ideas, but Little Guidance



What Energy Accelerator is Needed to Probe New Physics?



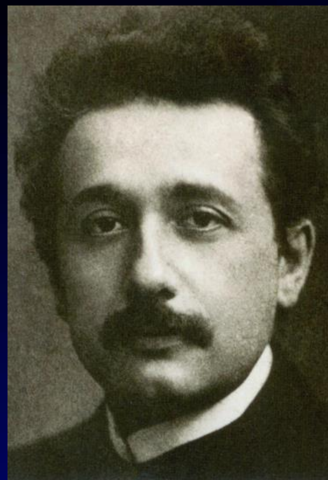
How best can we probe vastly higher energy scales?

We don't know!

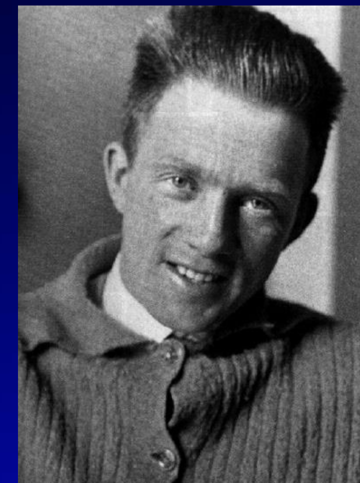
There is no guarantee that a new accelerator 10X or 100X the LHC energy will see anything new: just confirm the Standard Model at a new energy scale.

And accelerators are not cheap: a 10X the LHC energy accelerator would cost tens of billions of dollars.

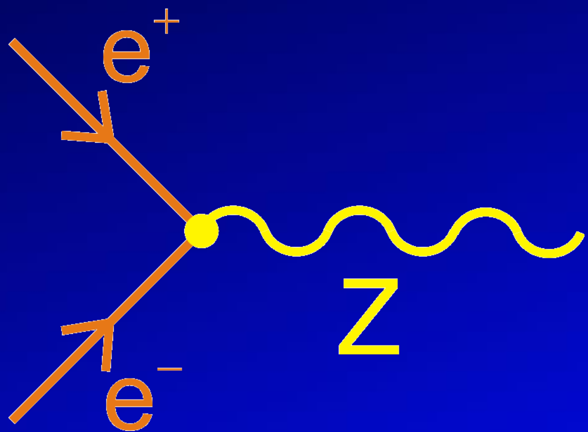
Rather than exploiting Einstein's mass-energy relation, $E=mc^2$, exploit Heisenberg's uncertainty principle, $\Delta E \Delta t \gtrsim \hbar/2$

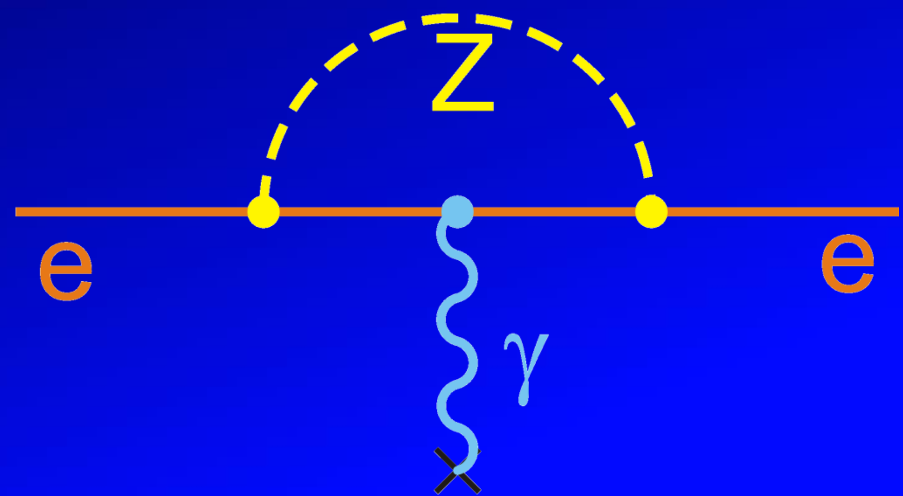


Highest energy crucial



Highest intensities crucial

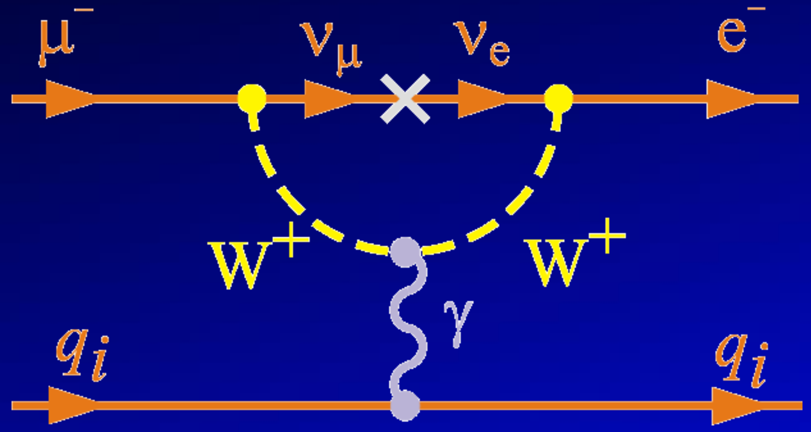




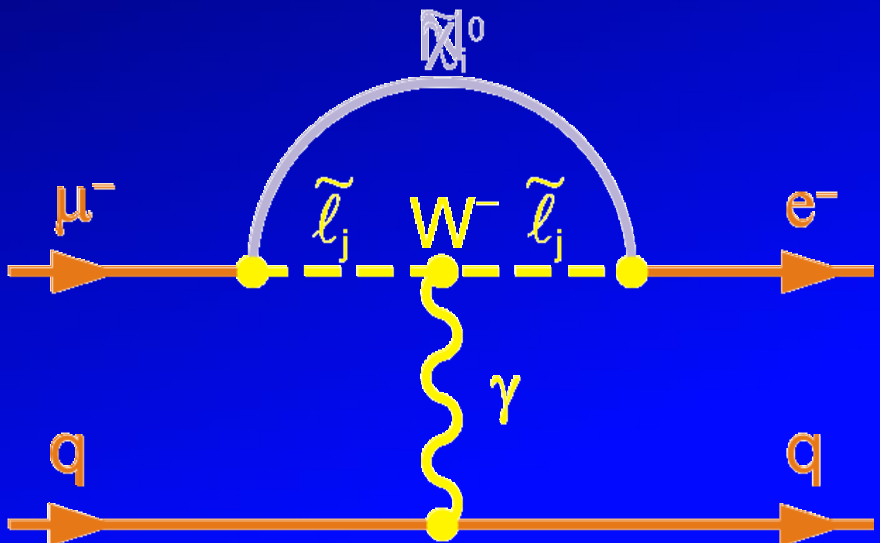
Mu2e: Probe New Physics Charged Lepton Flavor Violation

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

- In Standard Model not there ⇨ neutrino mass discovery implies an unobservable 10^{-52} rate
- Hence, any signal unambiguous evidence of new physics
- Exquisite sensitivities can be obtained experimentally
  - ⇨ sensitivities that allow favored beyond-the-standard-model theories to be tested



Supersymmetry



Why Muon-to-Electron Conversion?

Different SUSY and non-SUSY BSM models

★★★ Large effects

★★ Visible, but small

★ No sizable effect

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

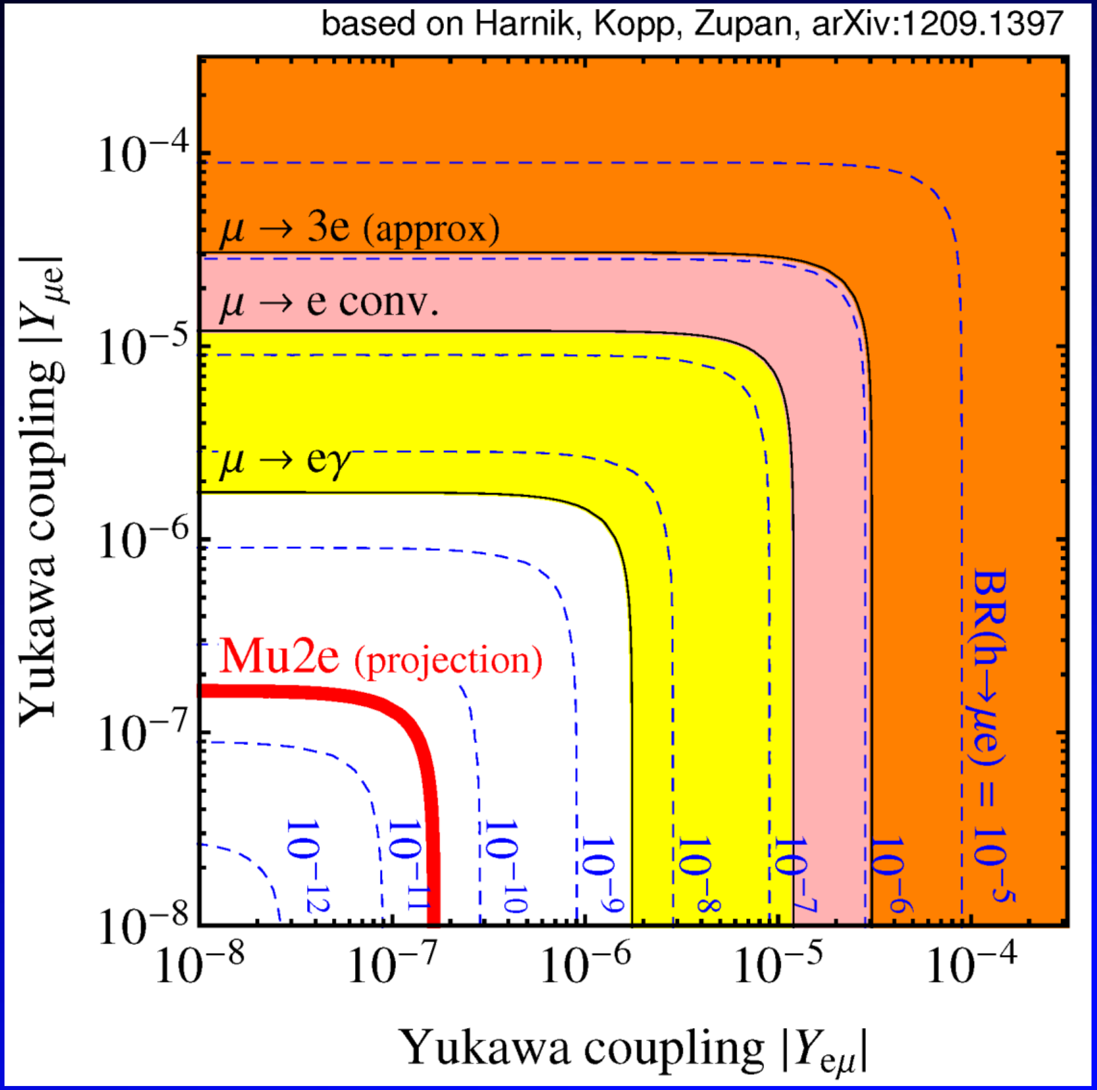
Altmannshofer et al., NPB 830, 17 (2010)

Example: Flavor-Violating Higgs Decays

Flavor violating HIggs couplings: $h \to \mu e$

Mu2e sensitivity:

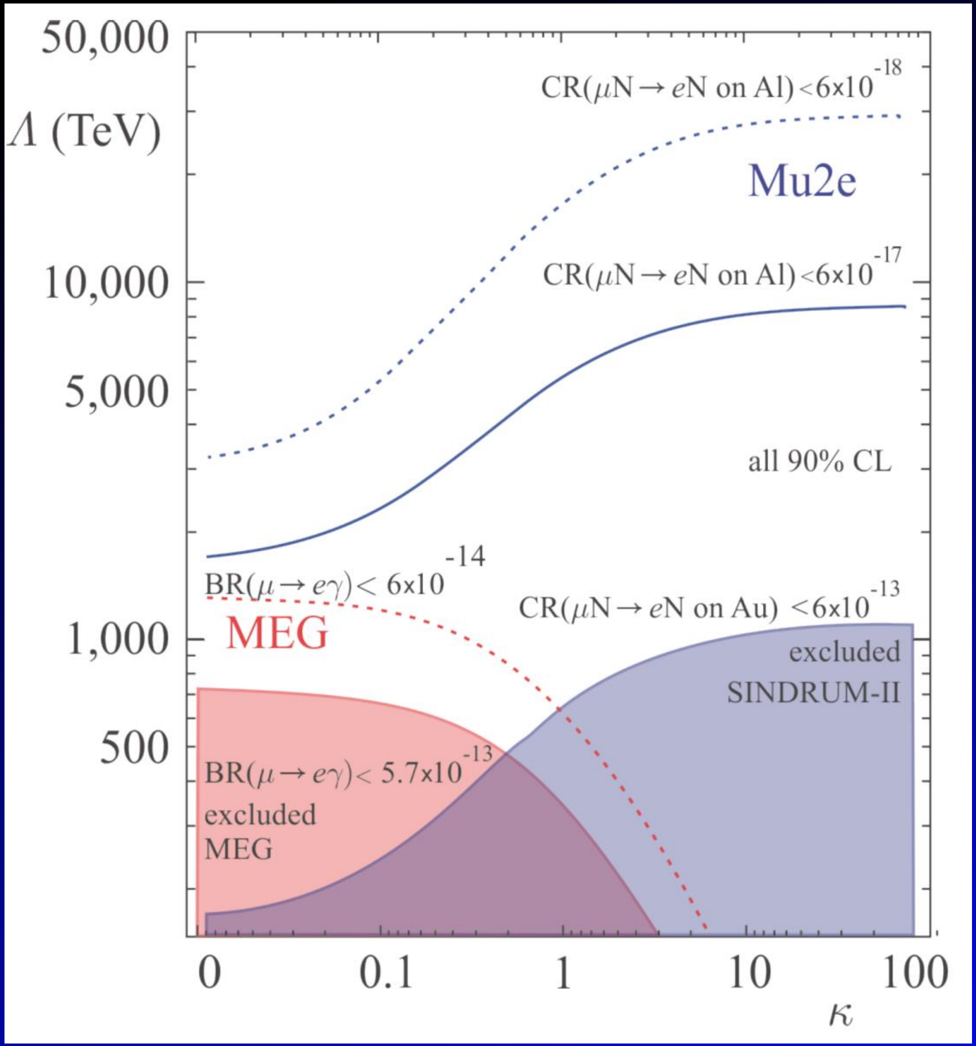
$$\sqrt{|Y_{\mu e}|^2 + |Y_{e\mu}|^2} > \text{few} \times 10^{-7}$$



Mu2e Looking for an Exceedingly Rare Event

To achieve our proposed sensitivity of 3×10^{-17}, a factor of 10,000 better than present limit, the number of muons needed is $\sim 10^{19}$, roughly the number of grains of sand on Earth: $\sim 10^{19}$

Mu2e Will Indirectly Probe Extremely High Mass Scales



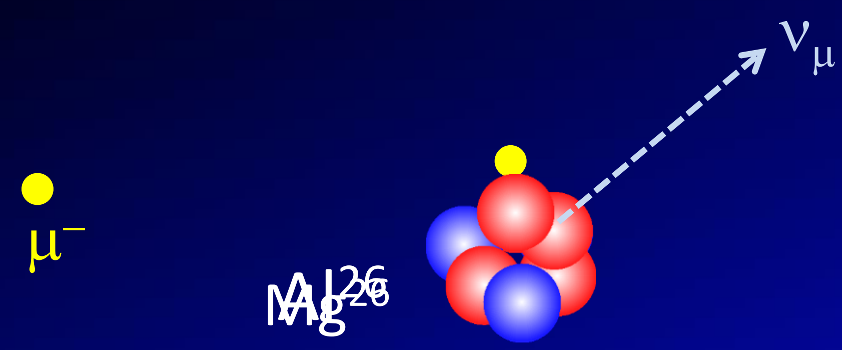
loop dominated

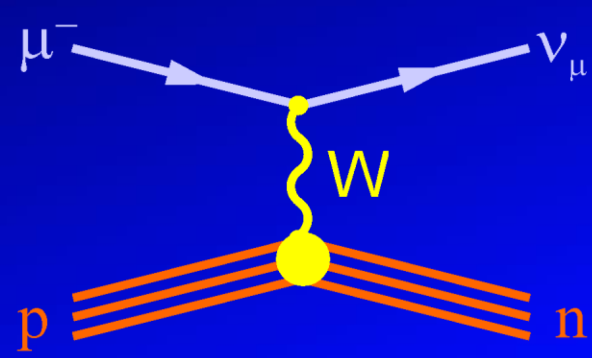
contact dominated

Up to 10,000 TeV or about ~10,000 times that probed directly by the LHC

How to Search for $\mu^- N \to e^- N$

- Stop muon in atom
- Muon rapidly (10^{-16}s) cascades to 1S state
- Circles the nucleus for up to ~2 μs
- Two things most likely happen:
  1. muon is captured by the nucleus: $\mu^- N_{A,Z} \to \nu_\mu N_{A,Z-1}$
  2. muon decays in orbit: $\mu^- N_{A,Z} \to e^- \nu_\mu \nu_e N_{A,Z}$





Muon Capture

How to Search for $\mu^- N \rightarrow e^- N$

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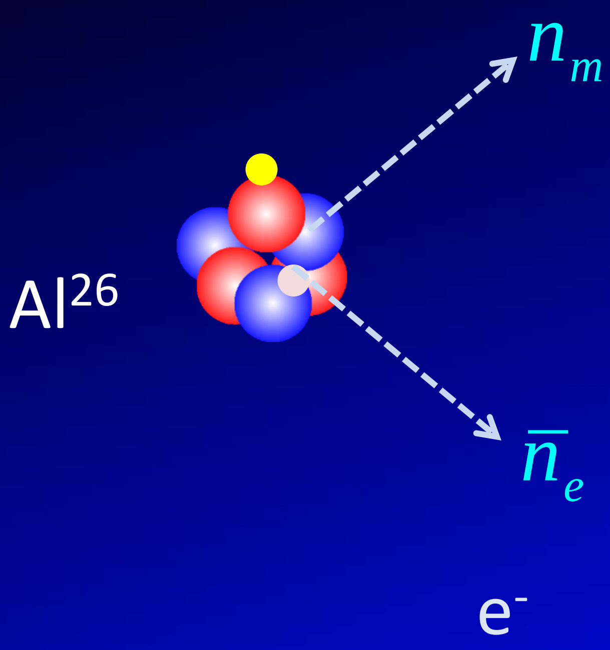
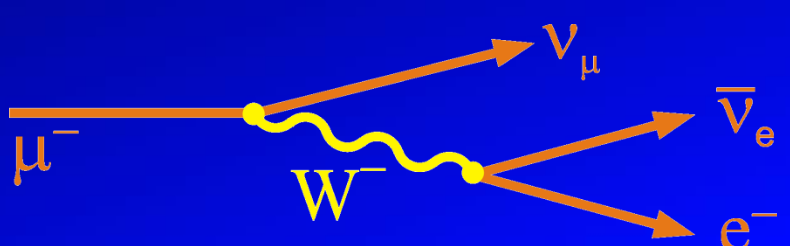




Muon Decay-in-Orbit

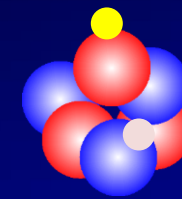
Mu2e Searching for a Third Process: $\mu^- N \rightarrow e^- N$

In $\mu^- N \rightarrow e^- N$ the muon coherently interacts with nucleus leaving it in ground state

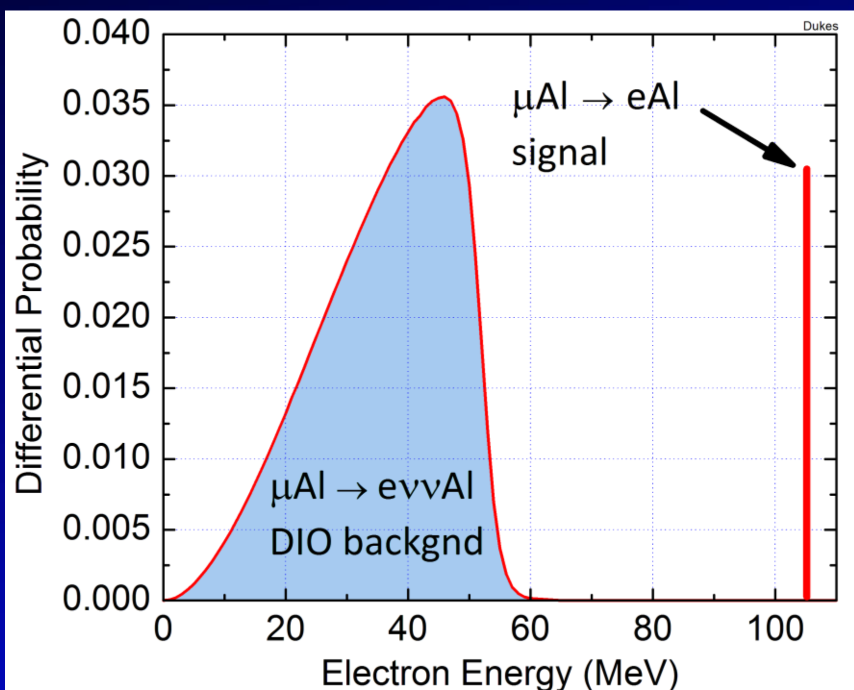
- signature delayed single isolated electron
- Electron energy is rest mass of the muon minus the nucleus recoil + binding energy:

$E_e = m_\mu - E_{NR} - E_b \sim 104.97$ MeV (Al)

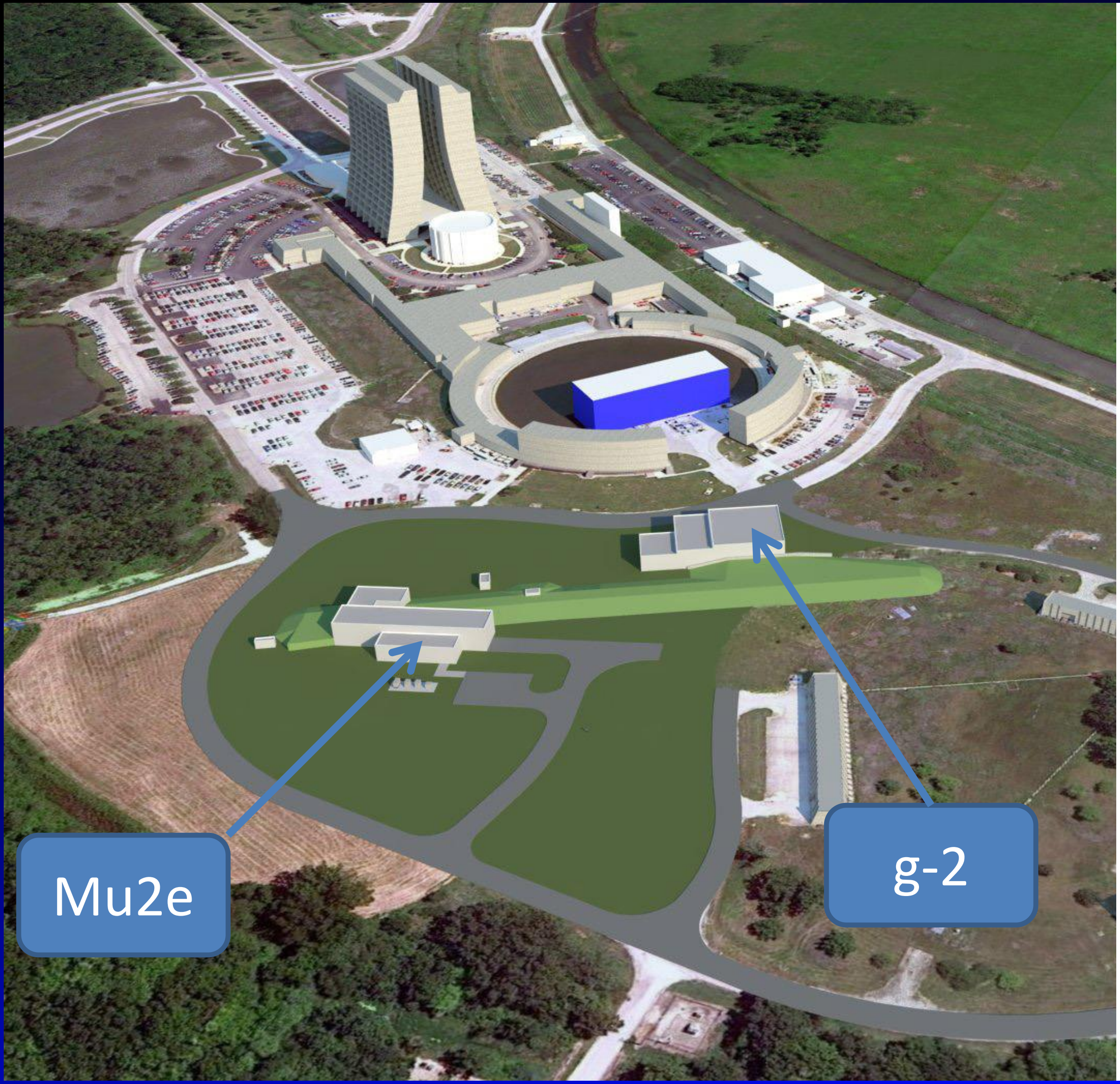
Al^{26}

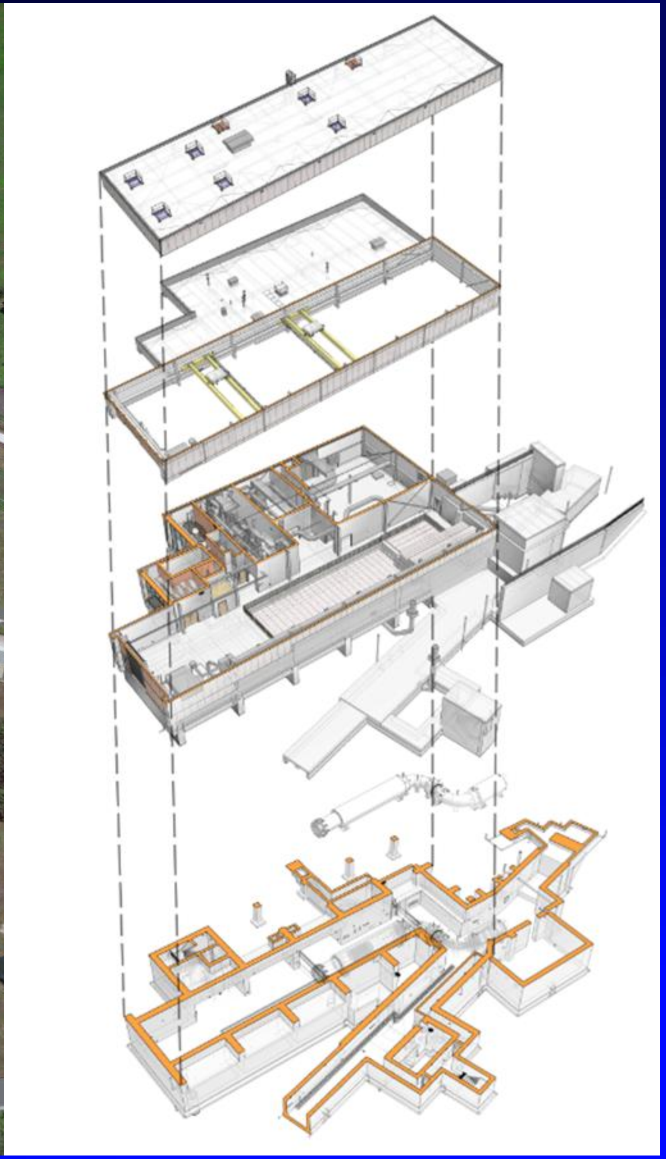


e^-

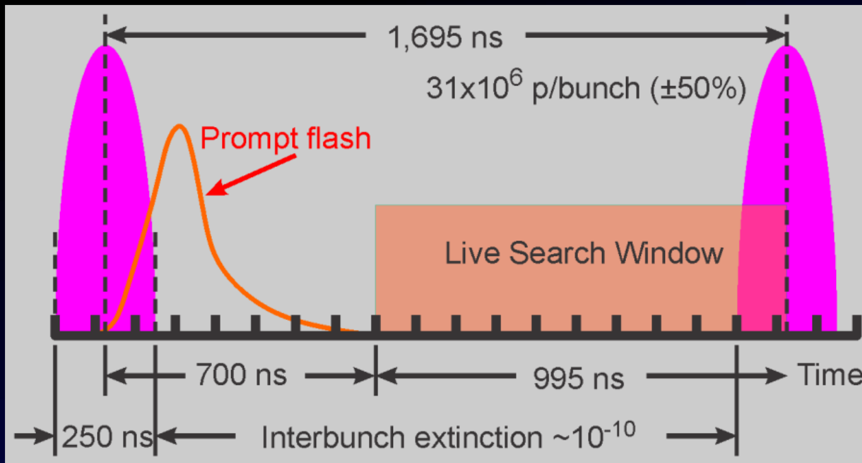


New Beamline and Detector Hall to be Built



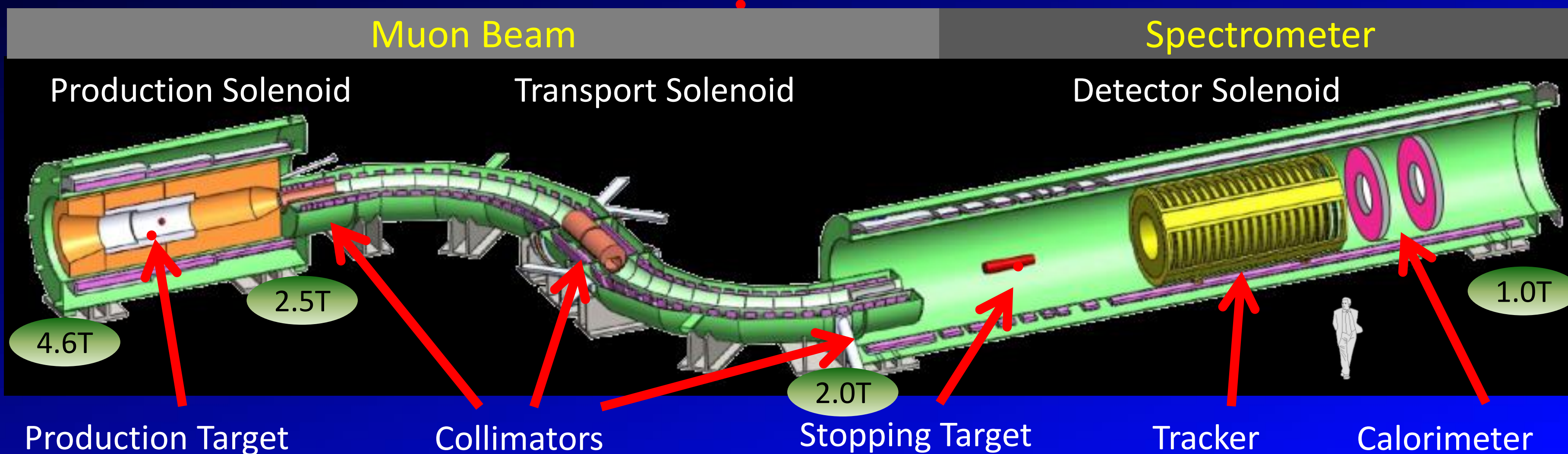


Mu2e Apparatus



Salient Features

- Graded solenoidal field for pion capture
- Muon transport in curved solenoid to eliminate neutral and positive particles
- Pulsed beam to kill prompt backgrounds
- No detector elements in muon beam



$$p + tgt \rightarrow \pi's + X$$
$$\pi^{\pm} \rightarrow \mu^{\pm} + \nu_{\mu}$$

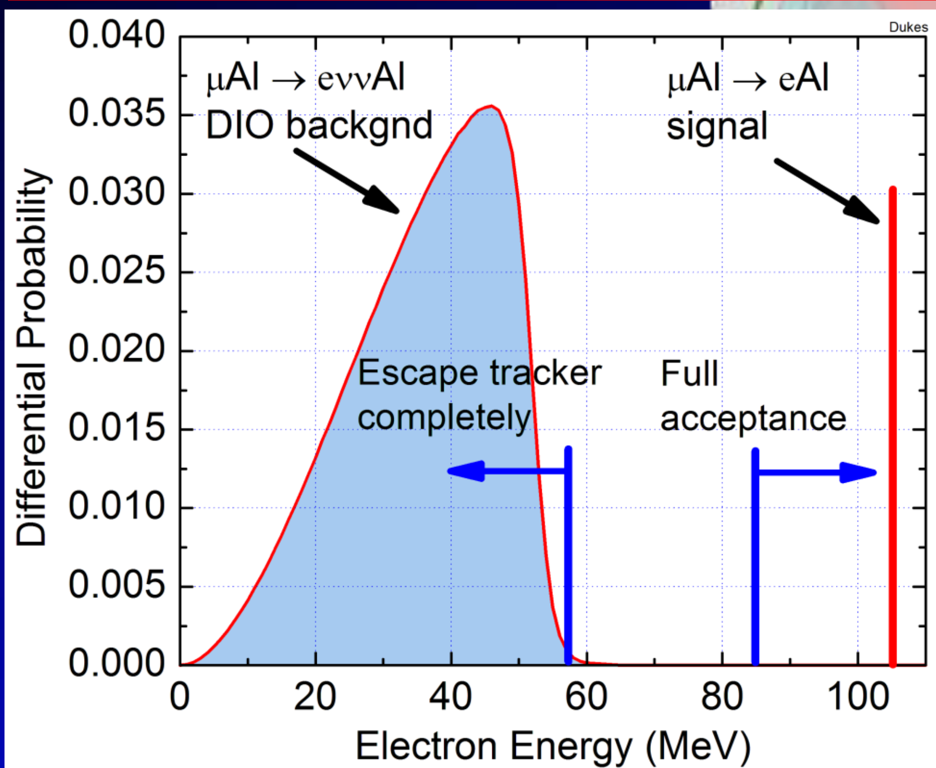
← 25 m →

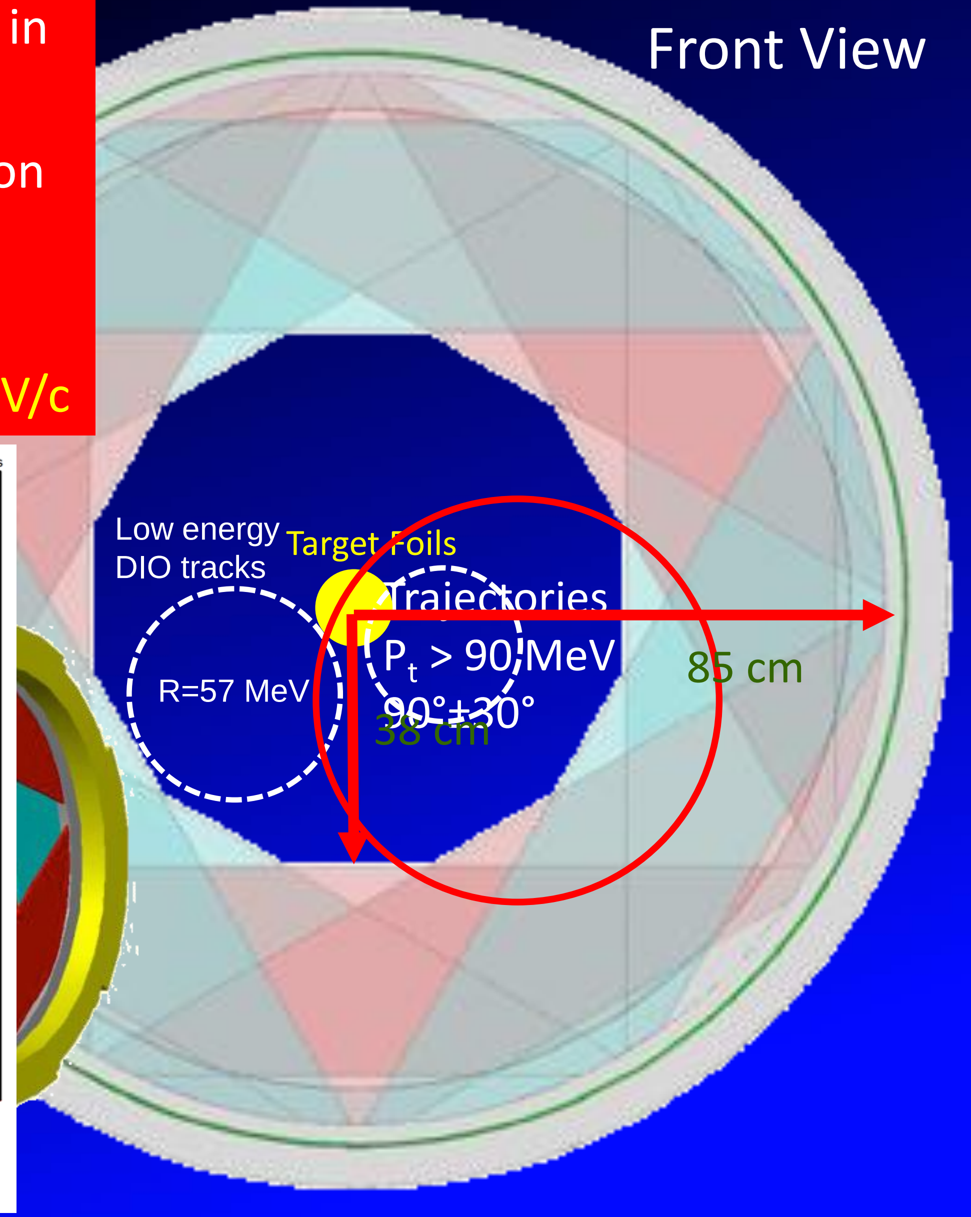
50,000 μ^- stop every 1.7 μs

30 billion μ^- stops/spill-second

Heart of the Spectrometer: Straw Tracker

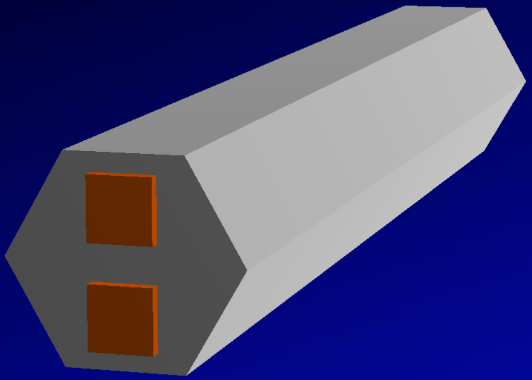
- 23,000 5-mm diameter straws arranged in octangonal geometry
- Center beam region empty: intense muon beam passes freely through
- Signal/DIO acceptance: >20%/<10^{-3}
- Excellent energy resolution: 115/175 KeV/c

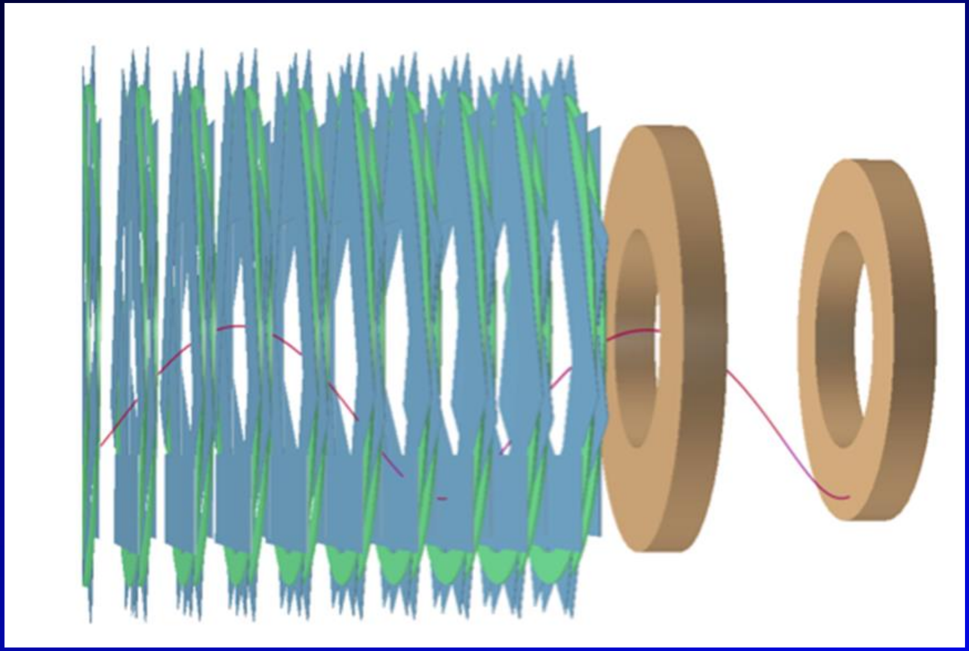


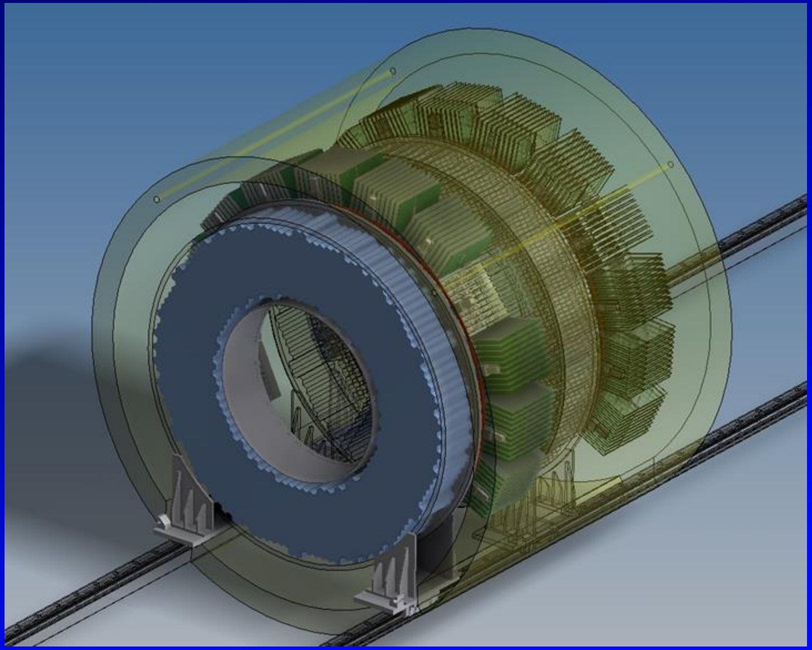


Electromagnetic Calorimeter

- Needed for:
  - Timing
  - Confirmation of tracker energy measurement
  - Particle ID: e vs μ
- 1500 BaF_2 crystals
- Dual APD readout

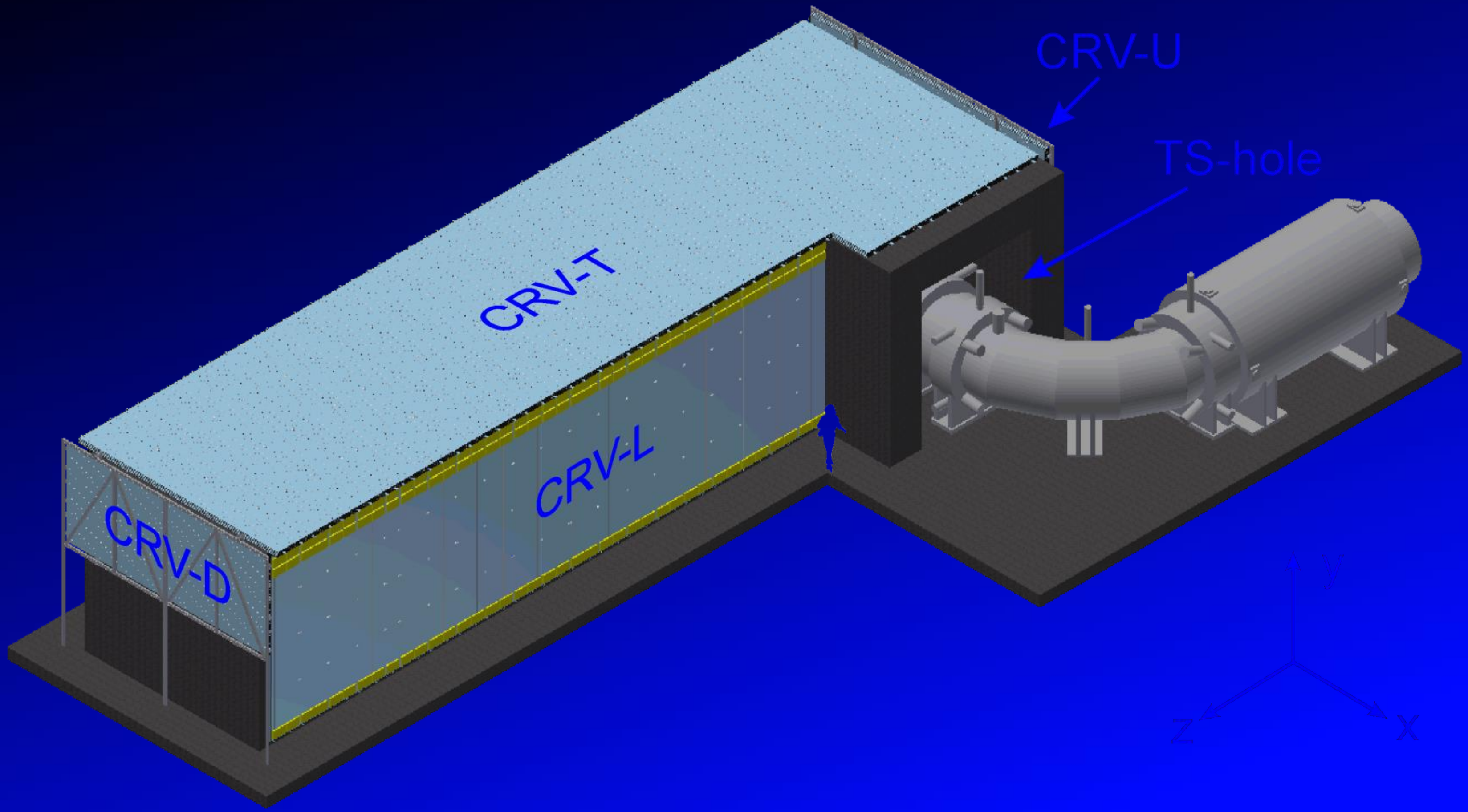






Cosmic Ray Veto

- One fake event/day from cosmic-ray muons
- Hence need 10^{-4} Inefficiency
- Surround Detector Solenoid by 4 layers of scintillator read out by waveshifting fibers, and silicon photomultipliers

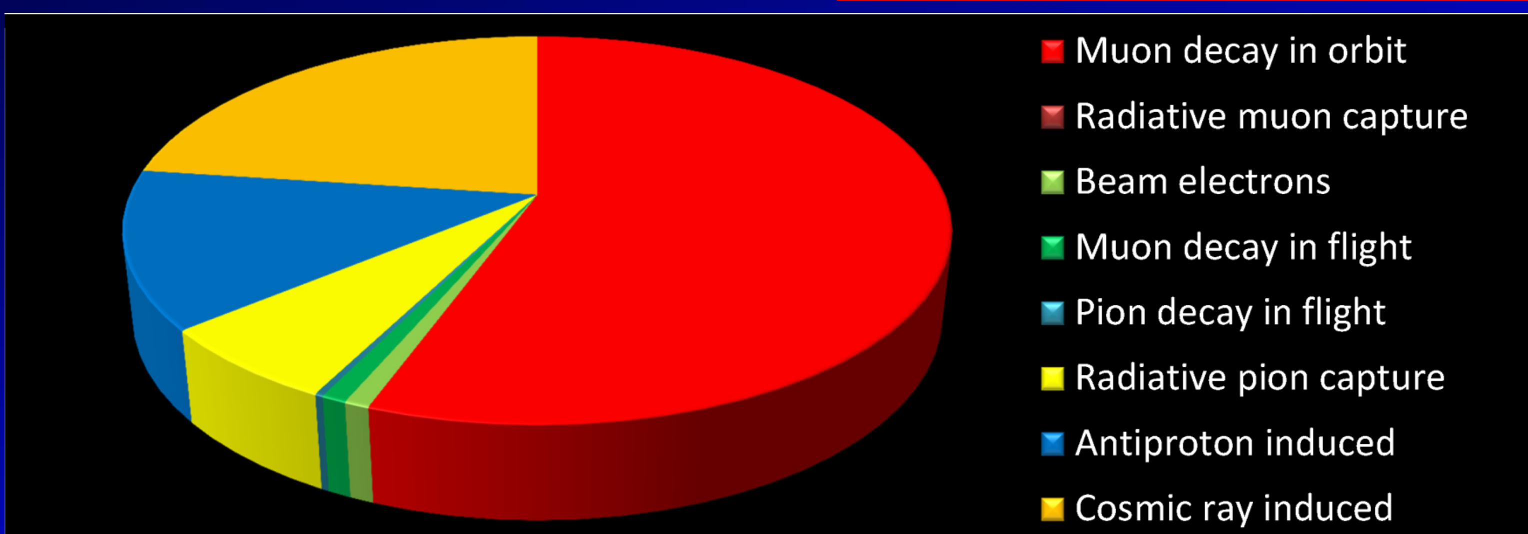


What we Get

$$R_{\mu e} = \frac{\Gamma(\mu N \rightarrow eN)}{\Gamma(\mu N \rightarrow \nu_\mu N^*)}$$

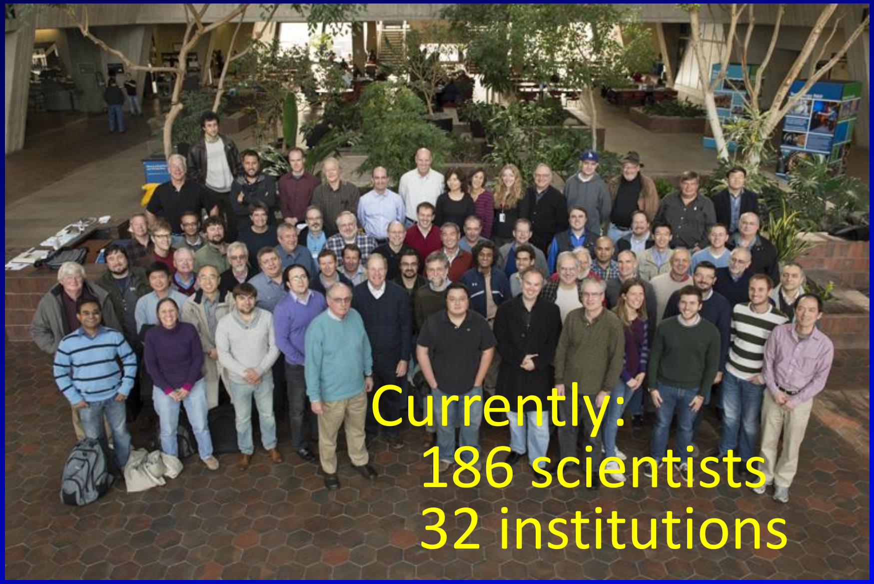
10,000X improvement over present limit (SINDRUM II)

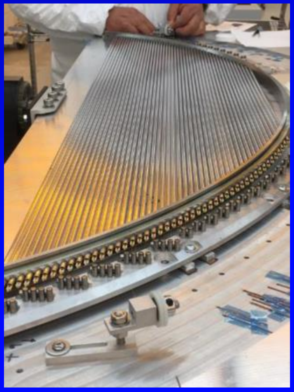
Proton flux	1.9×10^{13} p/s
Running time	6×10^{7} s
Total protons	3.6×10^{20} p
μ^- stops/incident proton	0.0019
μ^- capture probability	0.609
Total acc. and selection eff.	0.085
Single event sensitivity	**2.9×10^{-17}**
Detected events for $R_{\mu e} = 10^{-16}$	3.4
Estimated background events	0.36



Status of Mu2e

- Project a high priority of DOE and Fermilab, with a total project cost of $271M
- Large, vigorous collaboration has been assembled
- Civil and solenoid construction underway
- Detector prototypes have been fabricated
- Beam to detector in 2021





Where Best to Find the New Physics?

"The sense of mystery has never been more acute in our field"

Ian Shipsey, Snowmass 2013

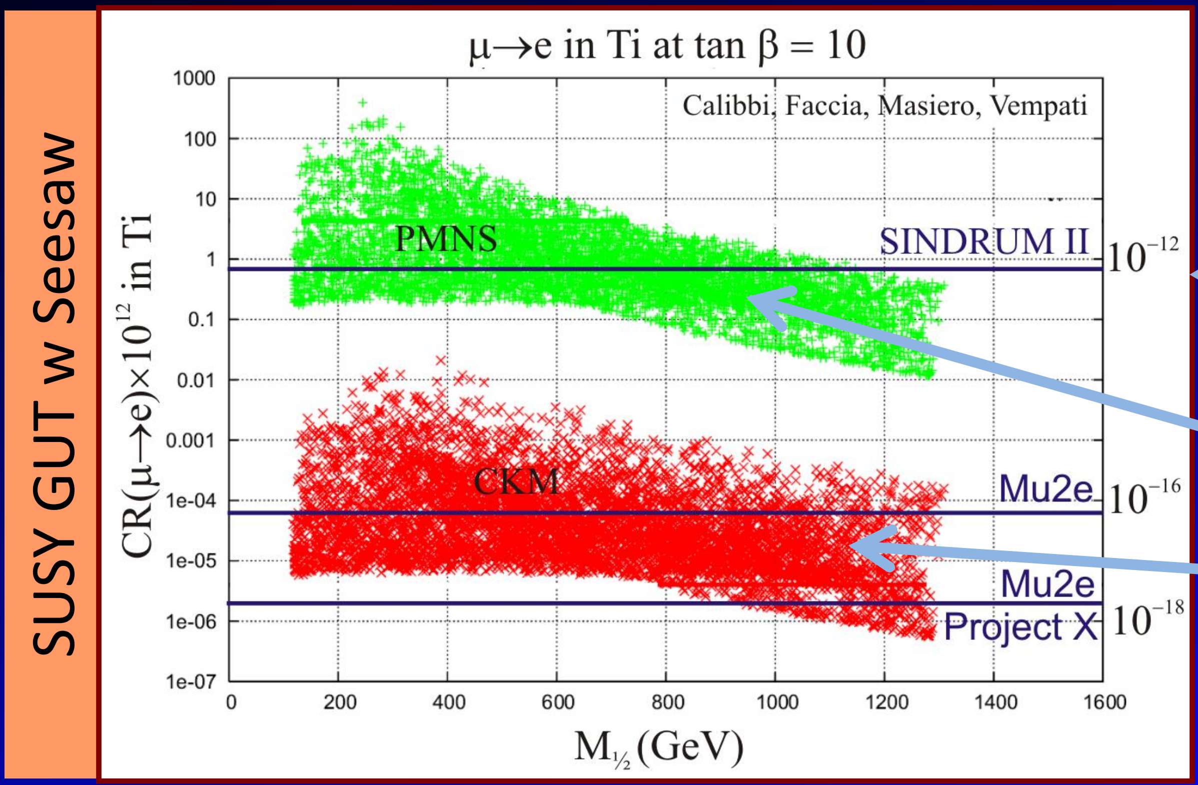
Backup Slides

What Sensitivity is Needed?

Present sensitivity already interesting and constraining!

~10^{-16} removes many models

~10^{-18} extremely difficult for theorists to deal with



Current limit

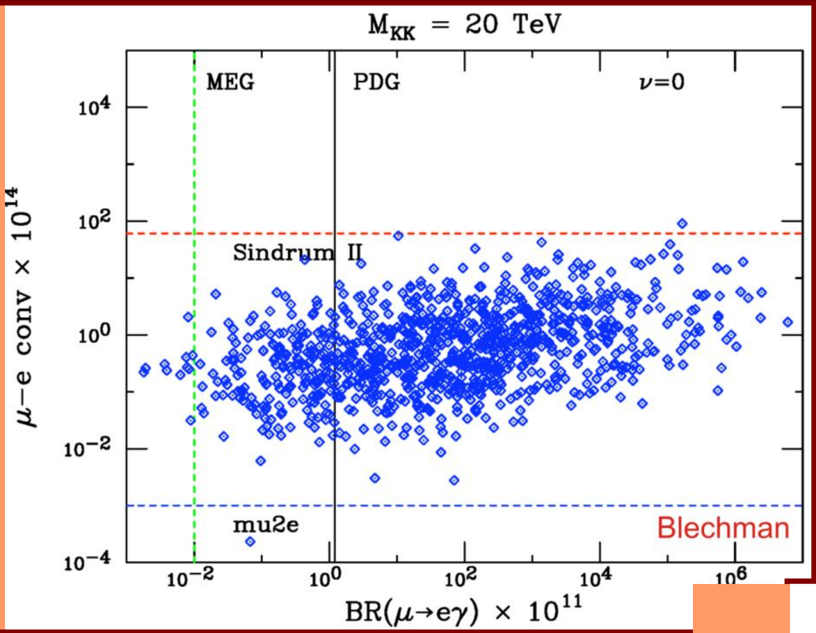
PMNS: neutrino-like mixing

CKM: minimal flavor violation

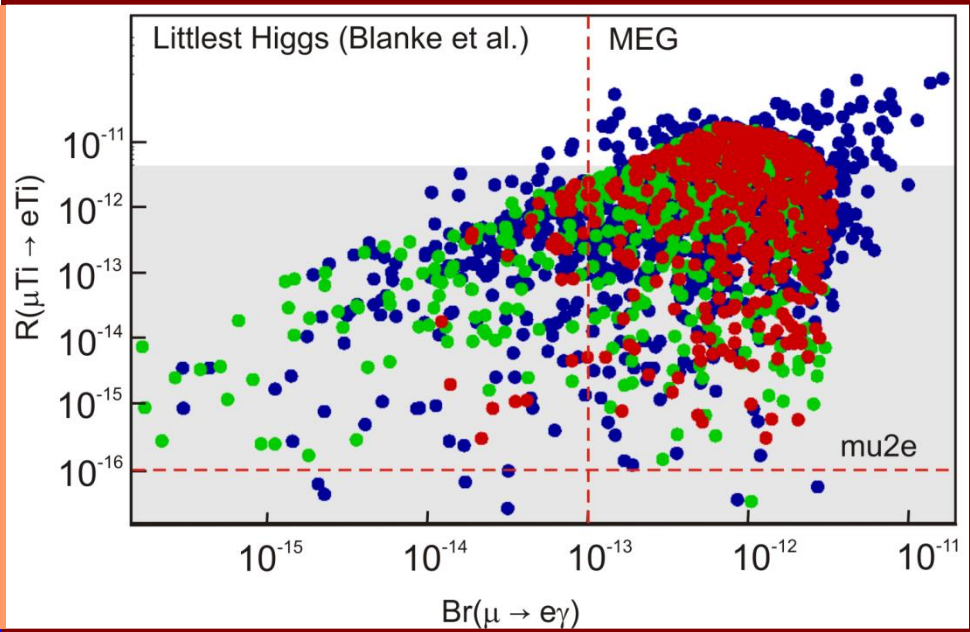
$M_{1/2}$ = gaugino mass

What Sensitivity is Needed?

Randall-Sundrum

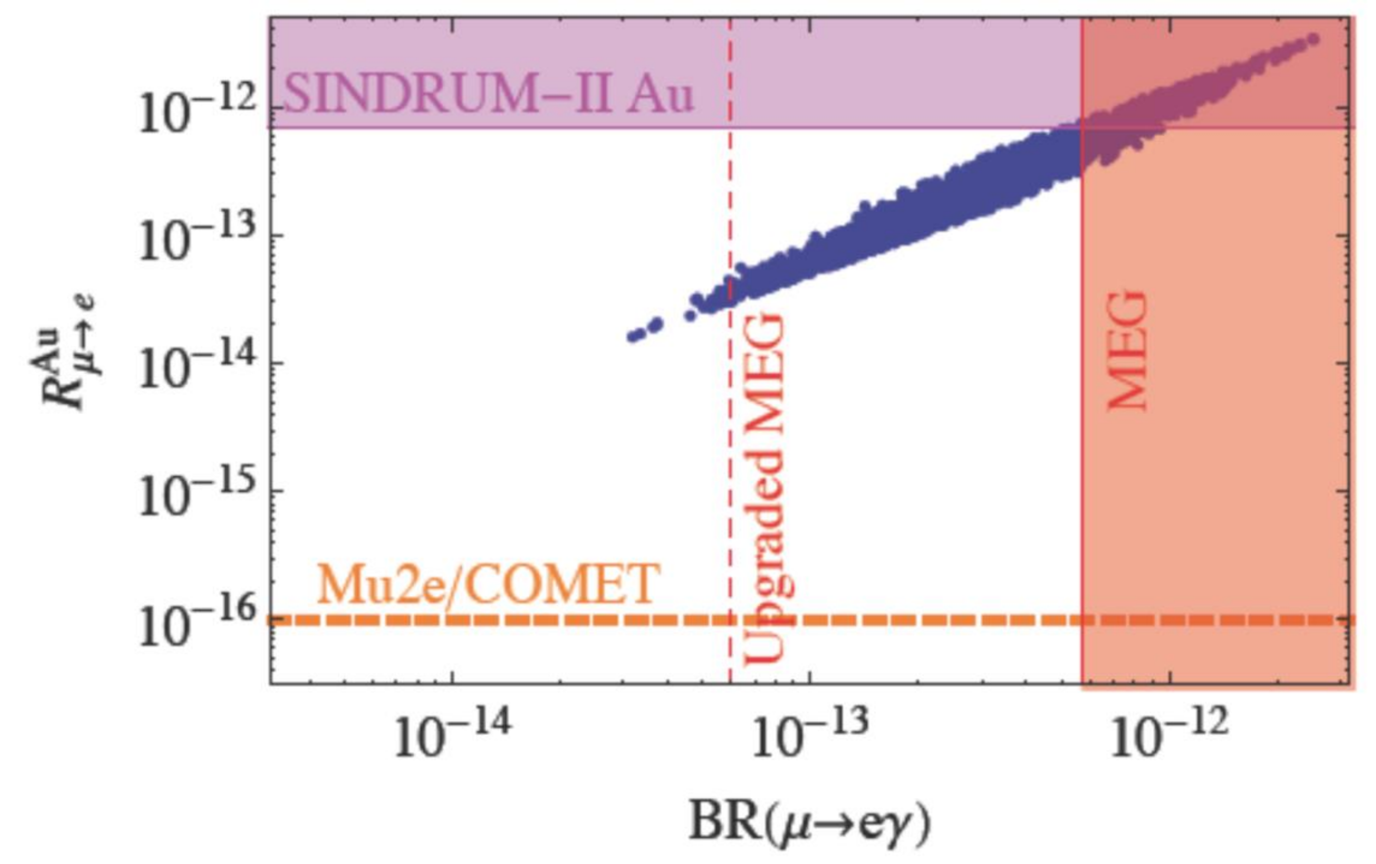


Littlest Higgs



What Sensitivity is Needed?

Left-right symmetric model with Type-I Seesaw



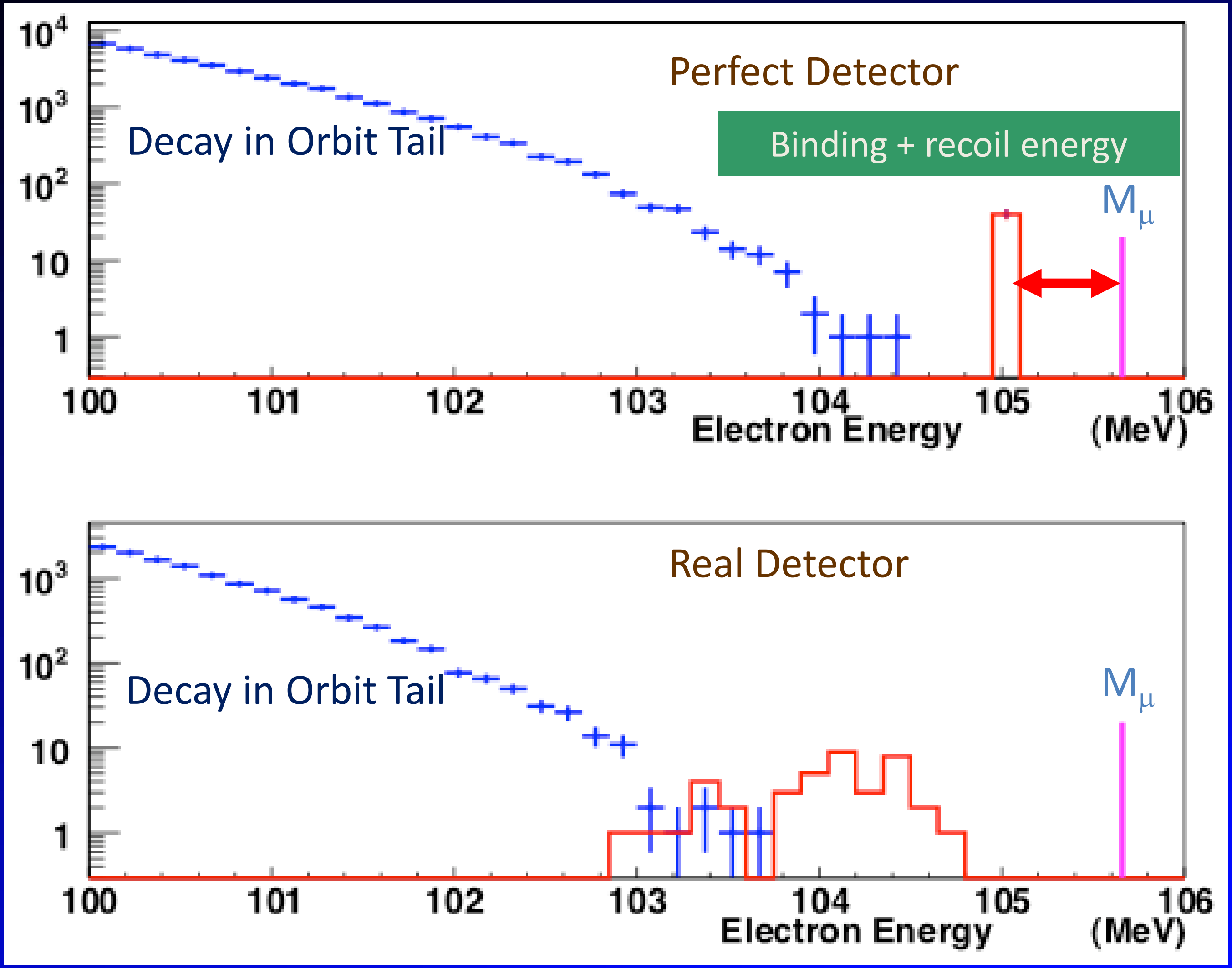
What we Get

Intrinsic tracker energy resolution:

$\sigma(E) \approx 150$ keV

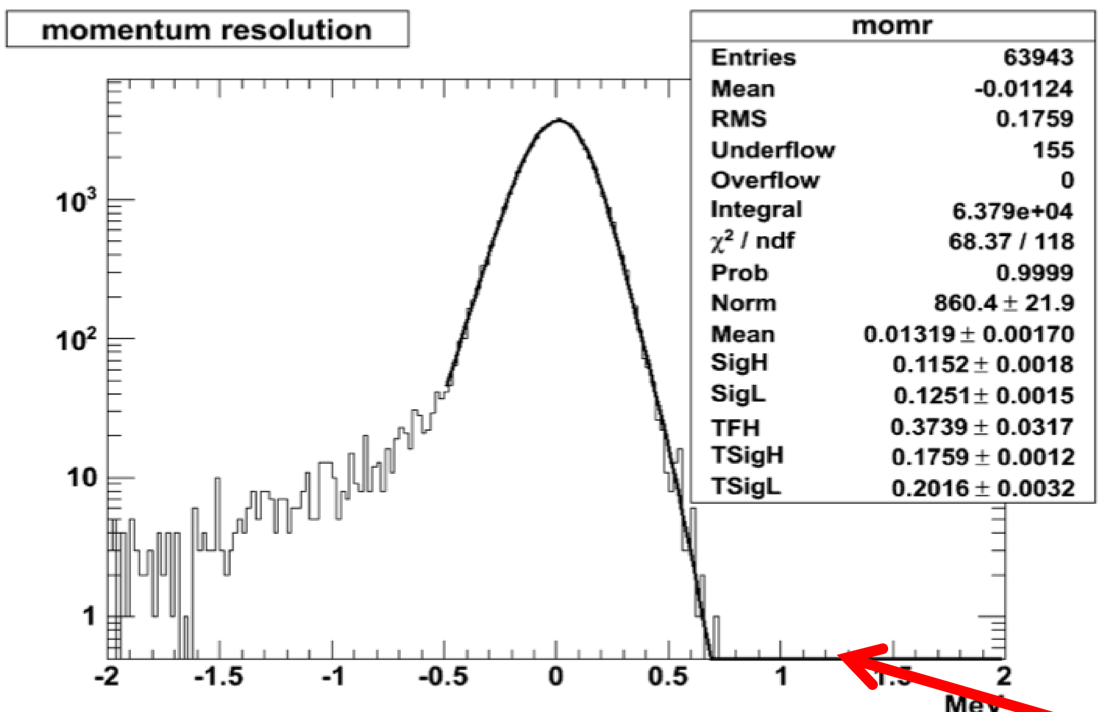
Average energy loss due to spectrometer material:

E(shift) $\approx$ 1 MeV



Tracker Performance

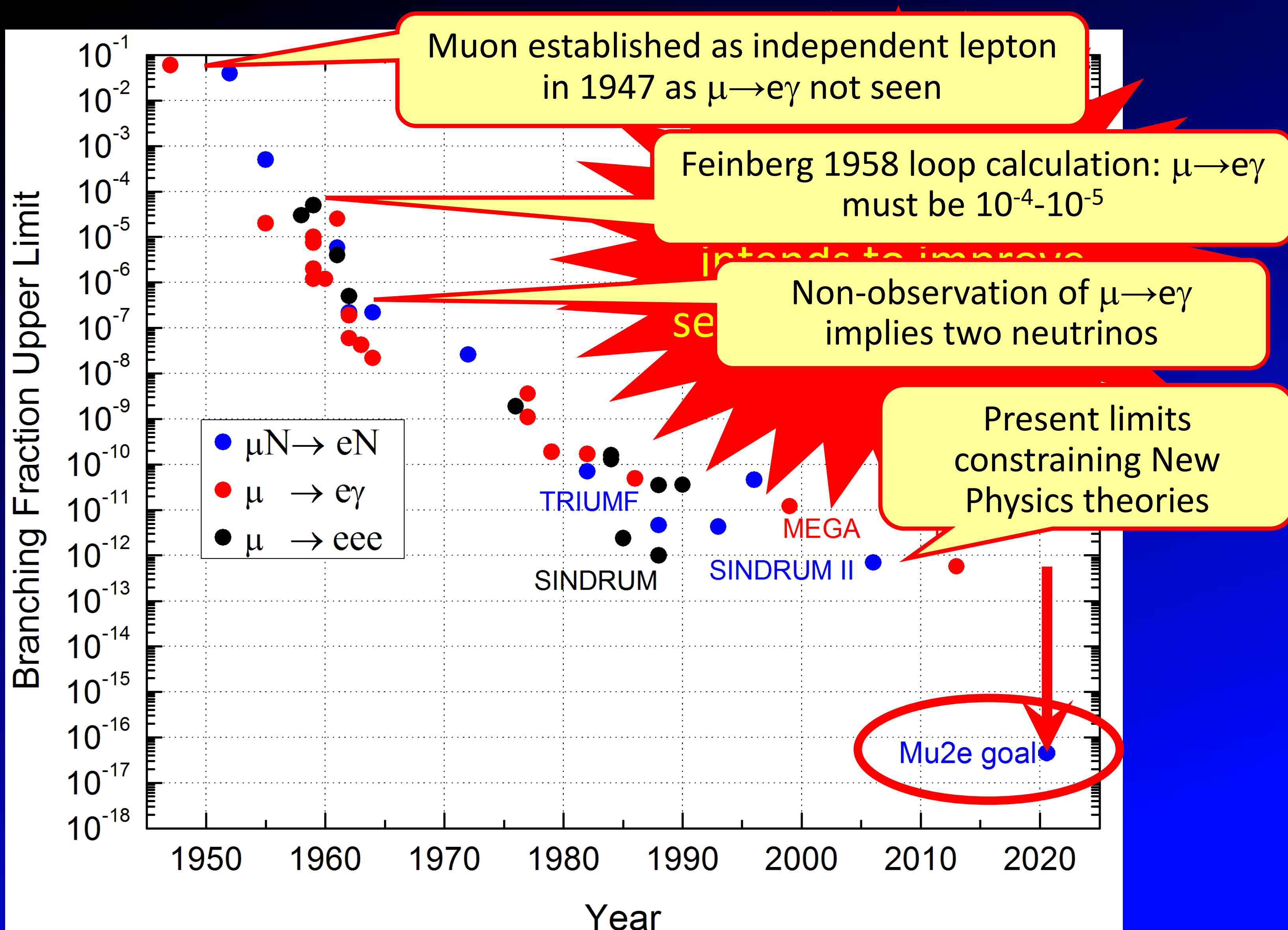
Tracker resolution for 105 MeV/c electrons



SigH	σ of core Gaussian, high side	115 KeV/c
SigL	σ of core Gaussian, low side	125 KeV/c
TFH	Fraction in the tail	37%
TSigH	σ of tail Gaussian, high side	176 KeV/c
TSigL	σ of tail Gaussian, low side	202 KeV/c

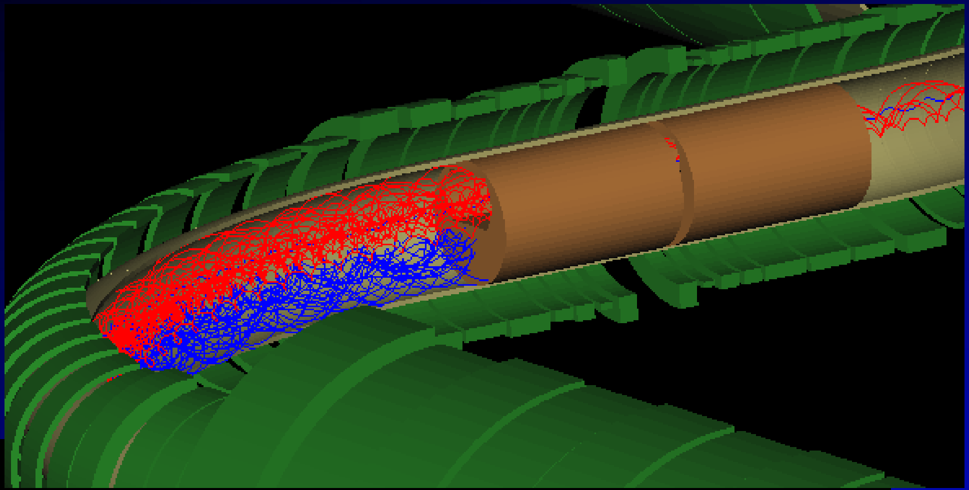
No high-side tail!
Core σ = 115 KeV/c
High-side tail σ = 176 KeV/c

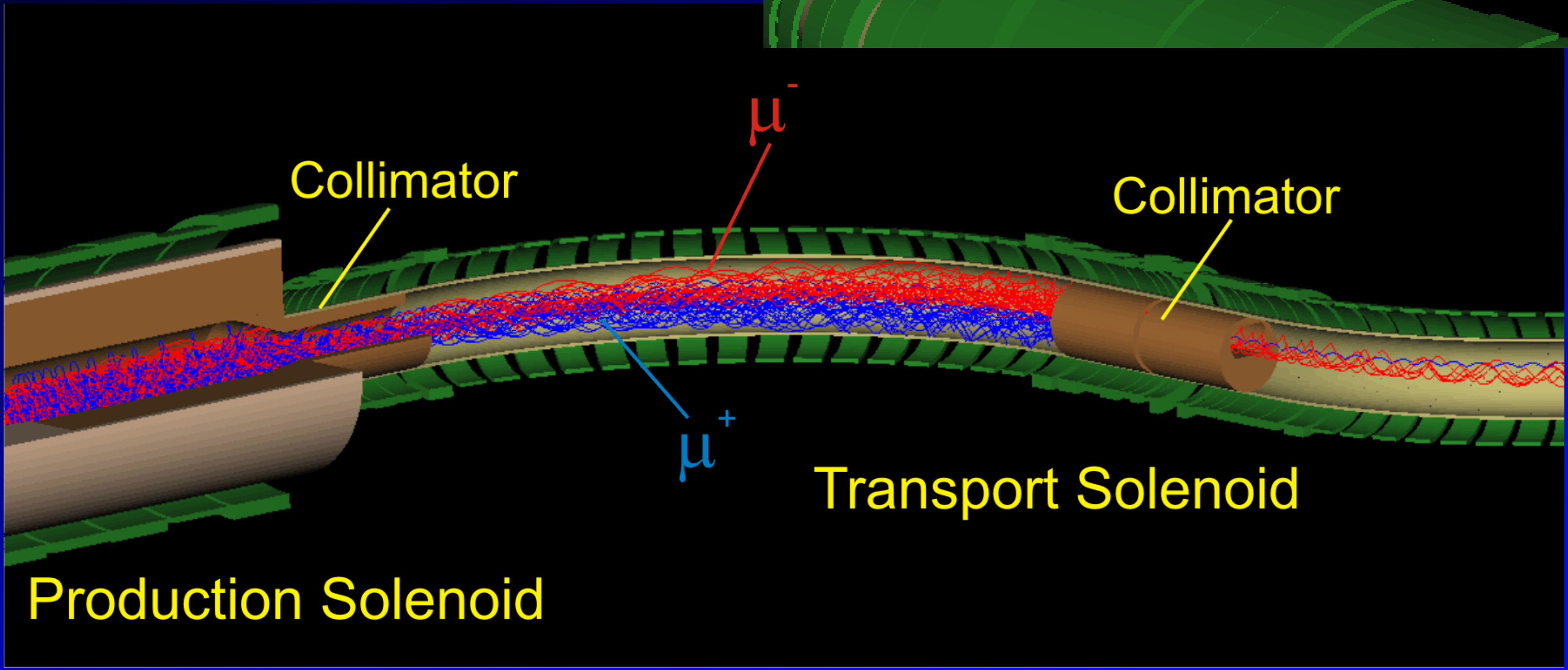
History of Muon Lepton Flavor Violation Searches



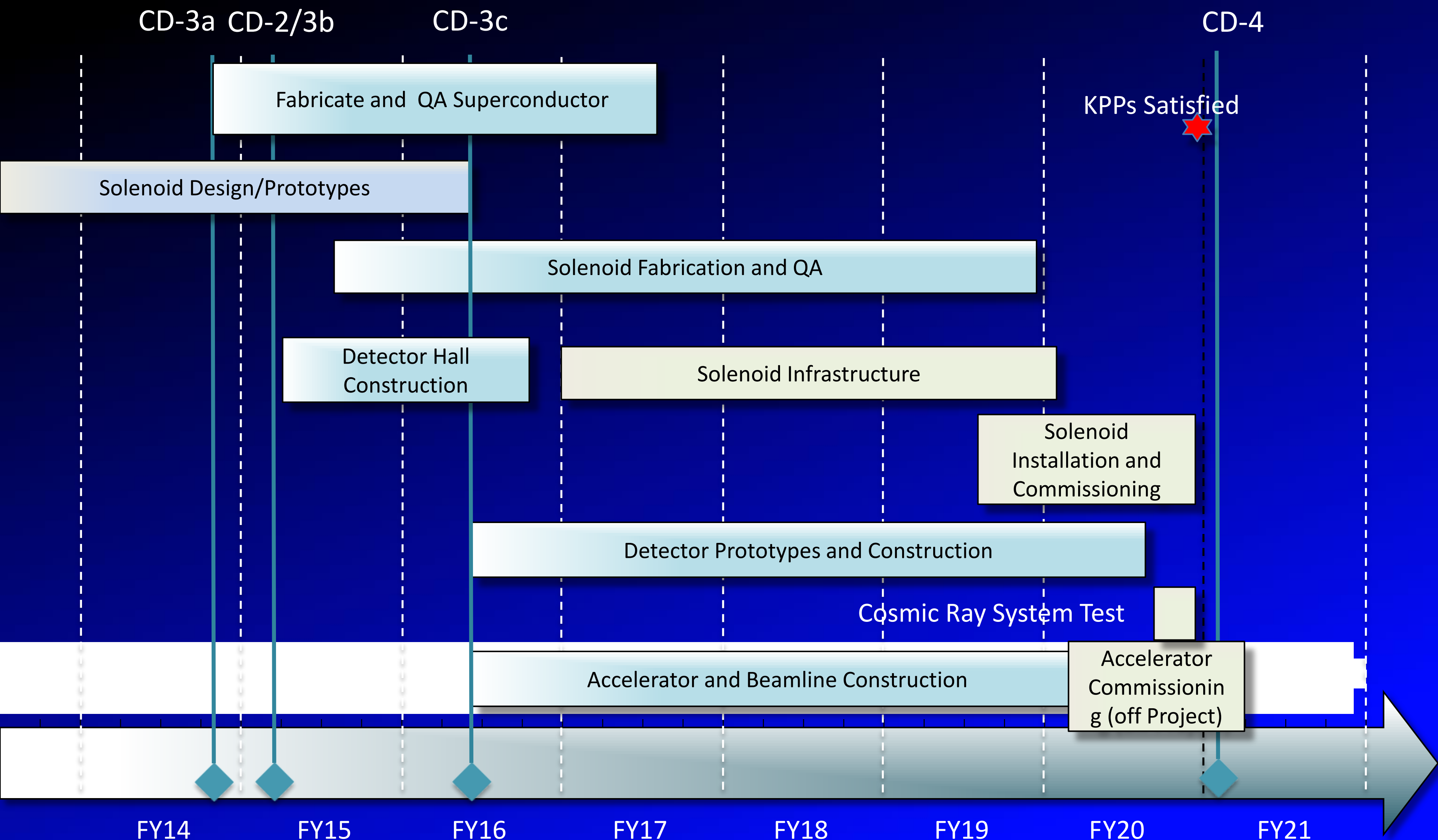
Transport Solenoidal Magnet

- Curved solenoid:
  1. separates charges by charge sign
  2. reduces line-of-sight transport of neutrals
- Collimators eliminate wrong-sign particles and particles with too large momentum

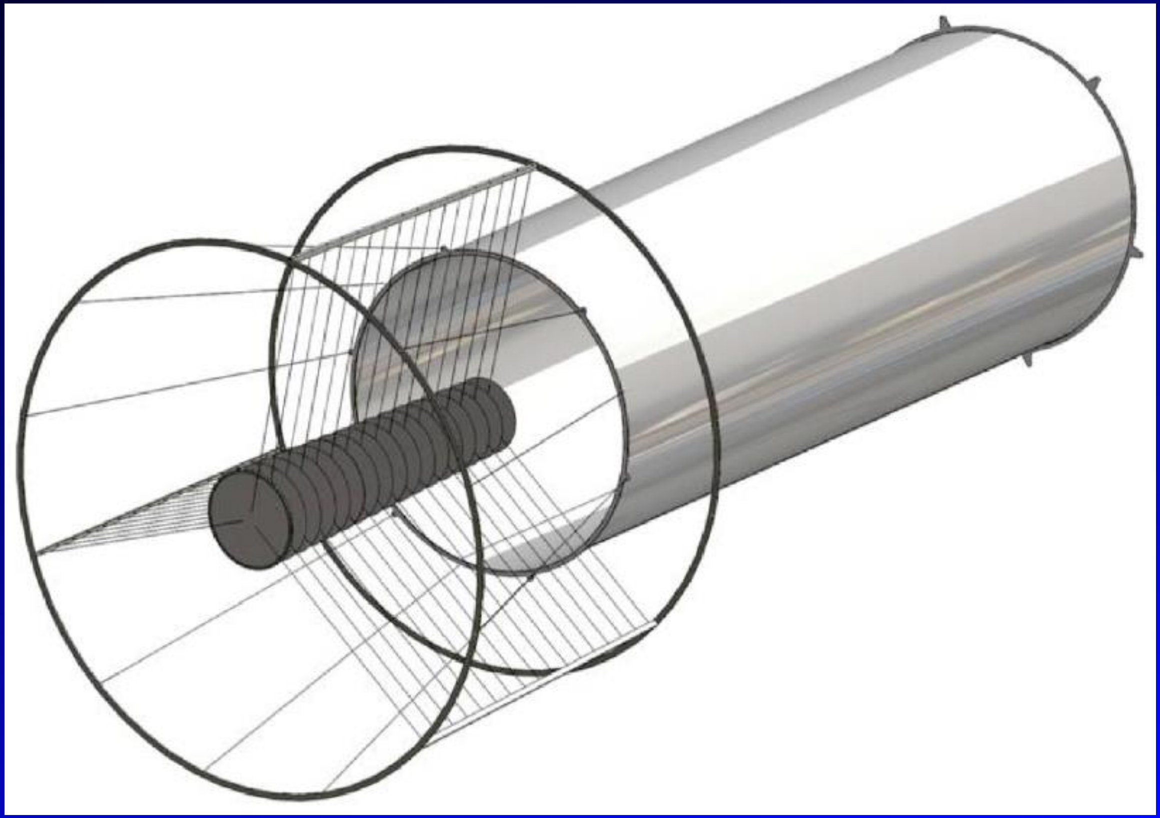




Schedule


CD-3a
CD-2/3b
CD-3c
CD-4
Fabricate and QA Superconductor
KPPs Satisfied
Solenoid Design/Prototypes
Solenoid Fabrication and QA
Detector Hall Construction
Solenoid Infrastructure
Solenoid Installation and Commissioning
Detector Prototypes and Construction
Cosmic Ray System Test
Accelerator and Beamline Construction
Accelerator Commissioning (off Project)
FY14
FY15
FY16
FY17
FY18
FY19
FY20
FY21

Proton Absorber



Choice of StoppingTarget Material

- Large Z:
  - rate $\propto Z|F_n|^2$ (F_n is the form factor)
  - can reveal nature of interaction
- Small Z:
  - longer lifetime
  - higher endpoint energy
- Note: Need $m_{Z-1} > m_Z$ to place max. energy of radiative capture muons below signal electrons