Mu2e

Jason Bono on behalf of the Mu2e Collaboration

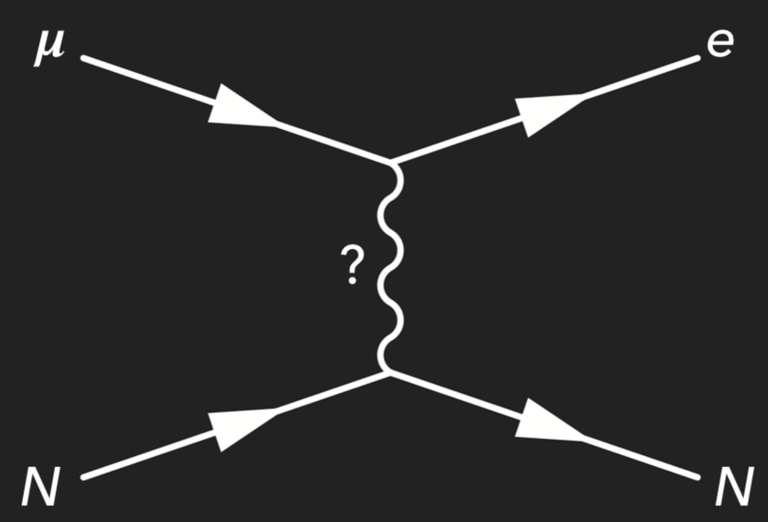
Fermilab Users' Meeting

June 16, 2016

RICE
Fermilab

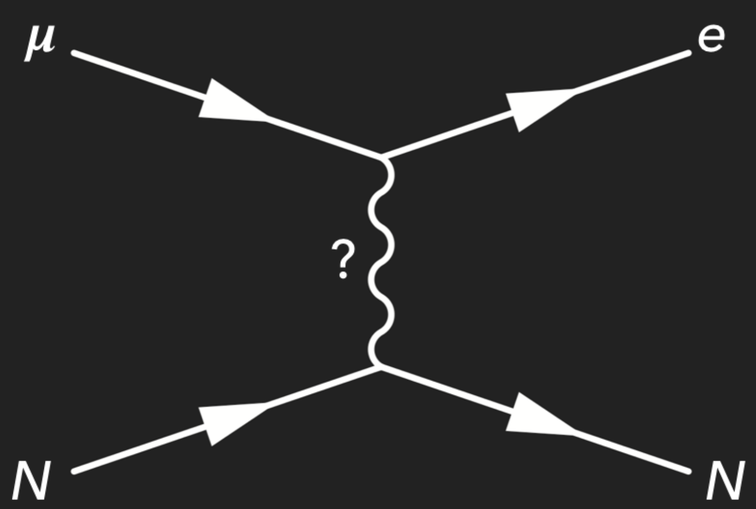
Mu2e

- Mu2e will search for $\mu N \rightarrow eN$ with unprecedented sensitivity, $\mathcal{O}(10^{-17})$
- μ→e conversion is Charged Lepton Flavor Violating (CLFV) Reaction
- The SM rate (from neutrino mixing) is unobservably small, $\mathcal{O}(10^{-52})$
    - An observation is unambiguously New Physics
- Mu2e is sensitive to BSM phenomena on mass scales up to 10,000 TeV!



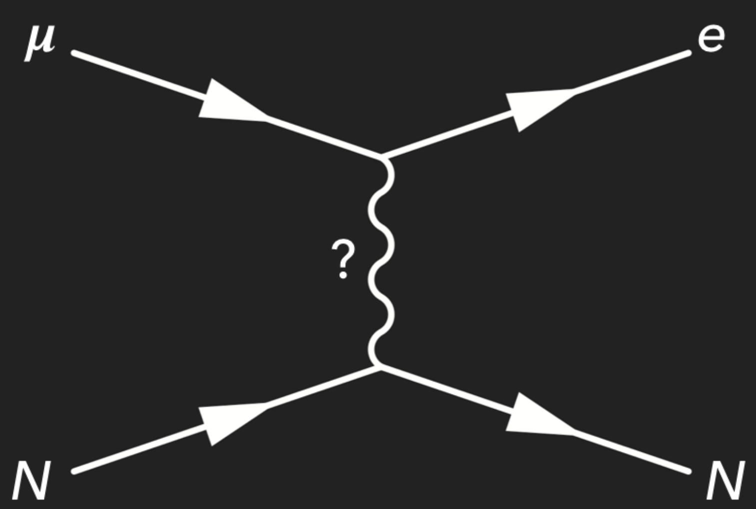
CLFV

- Despite nearly eight decades of searching, no one has ever observed CLFV
- Why search again?



Why Search Again?

- Leading New Physics models predict rates for μN → eN conversion to be within Mu2e's discovery sensitivity but out of reach of all previous experiments!
- The Mu2e measurement, with its revolutionary sensitivity, will strongly constrain theory, regardless of the outcome

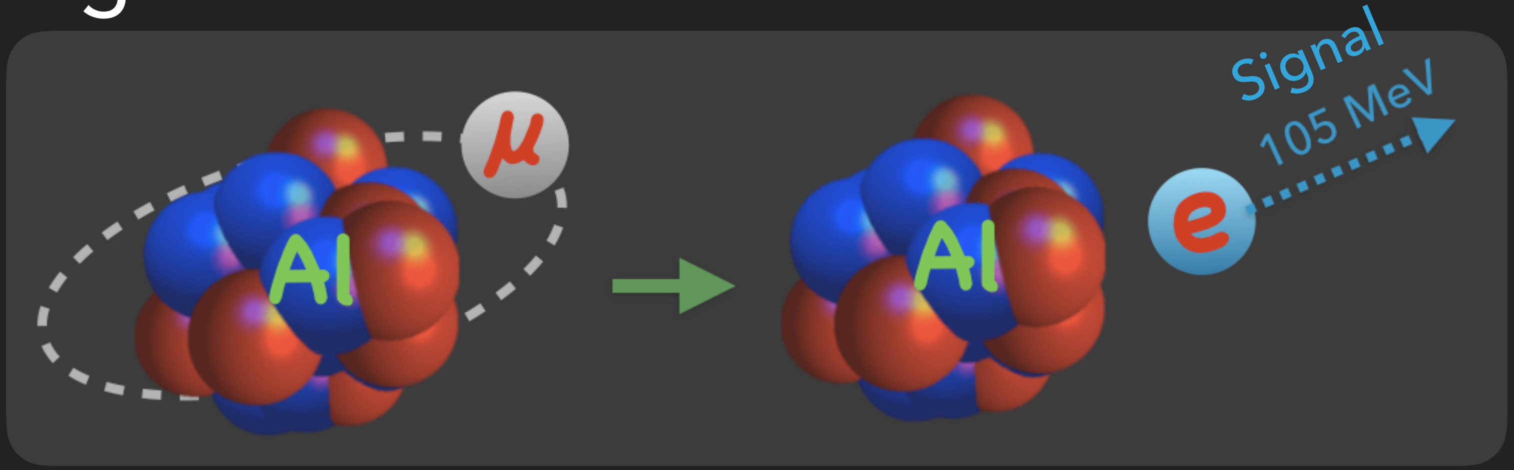


We will cover

- What will be measured
- Design aspects of Mu2e
- Mu2e sensitivity & physics reach

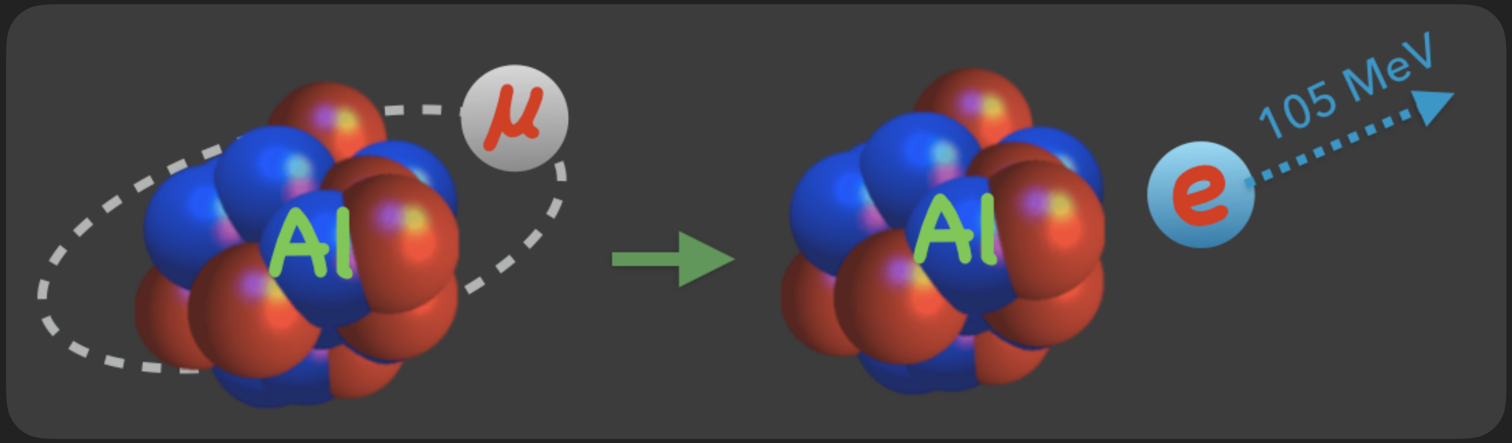
The basic idea

- Produce 10^{18} muonic ^{27}Al atoms
  - Overlap of muon and Al wave function
- Count "conversion electrons" with tracking and calorimetry
  - Mono-energetic electrons emanating from the Al target
  - $E_e = m_\mu c^2 - E_b - E_{recoil} = 104.96$ MeV
- Suppress background



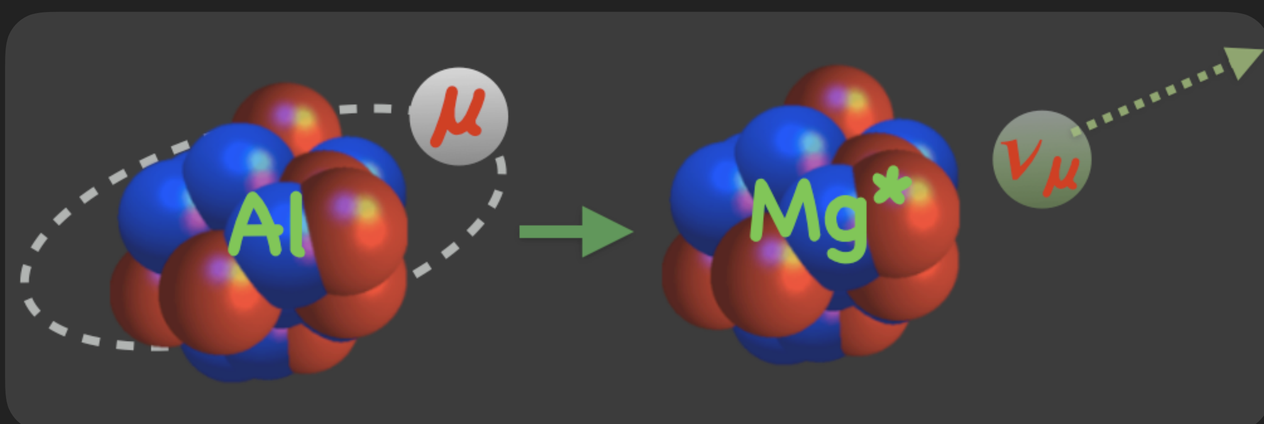
What else will muonic Al do?

Conversion < 10^{-12}

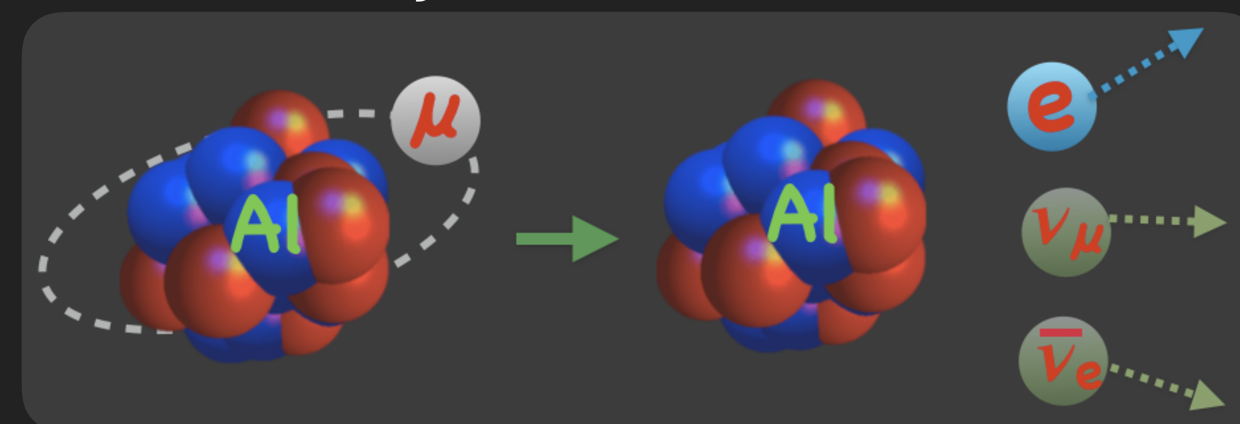


What else will muonic Al do?

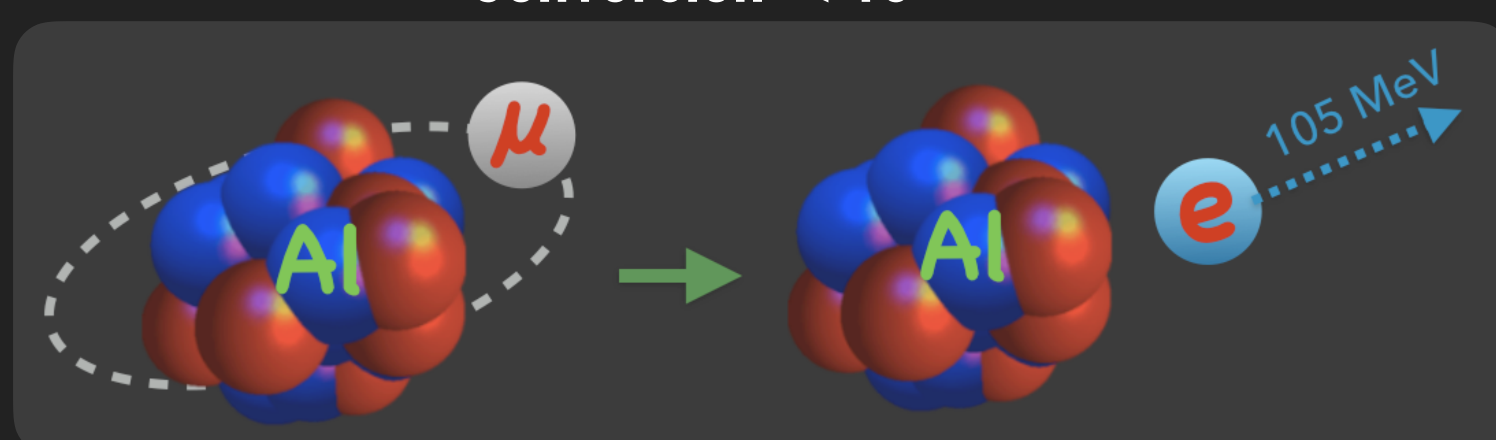
Nuclear Capture ~ 61%



Decay In Orbit (DIO) ~ 39%

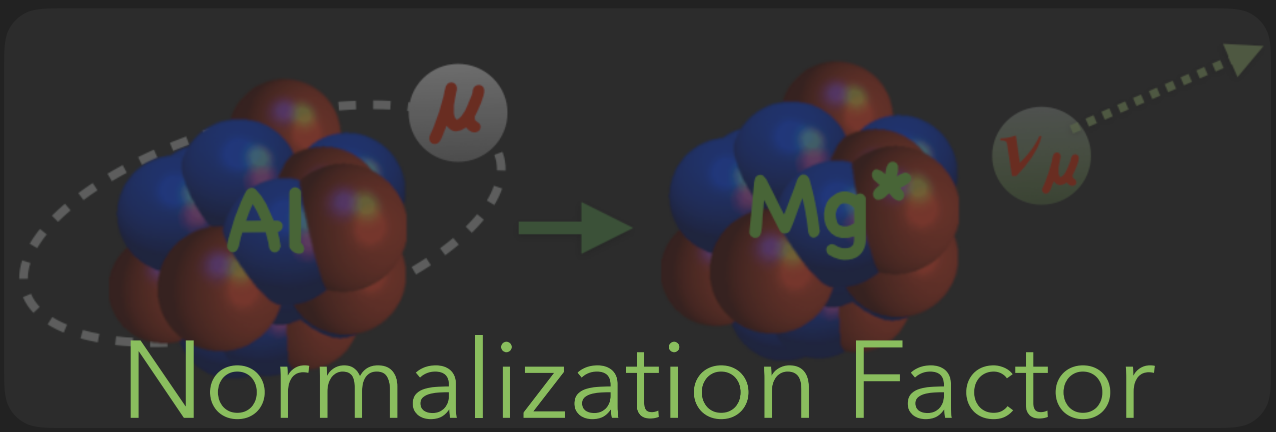


Conversion < 10^{-12}

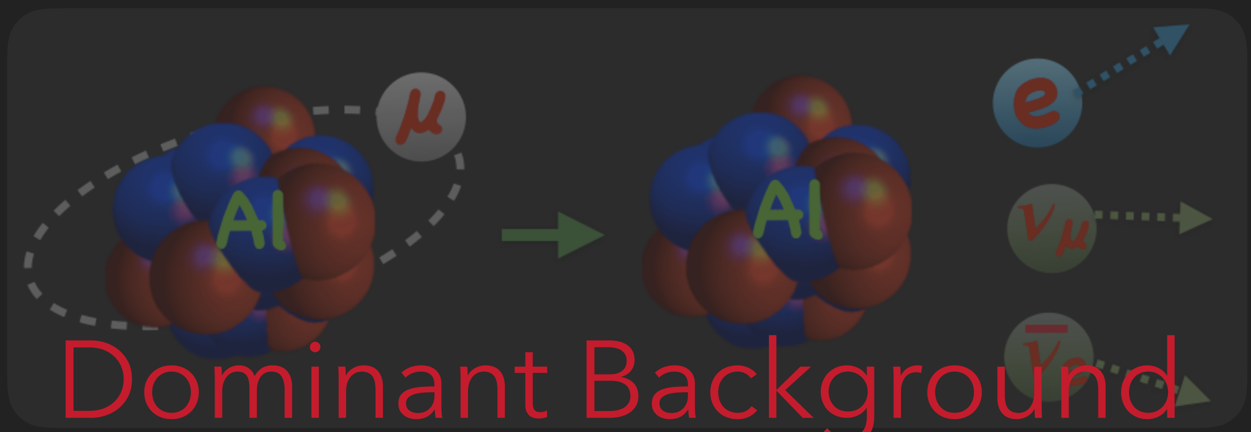


What else will muonic Al do?

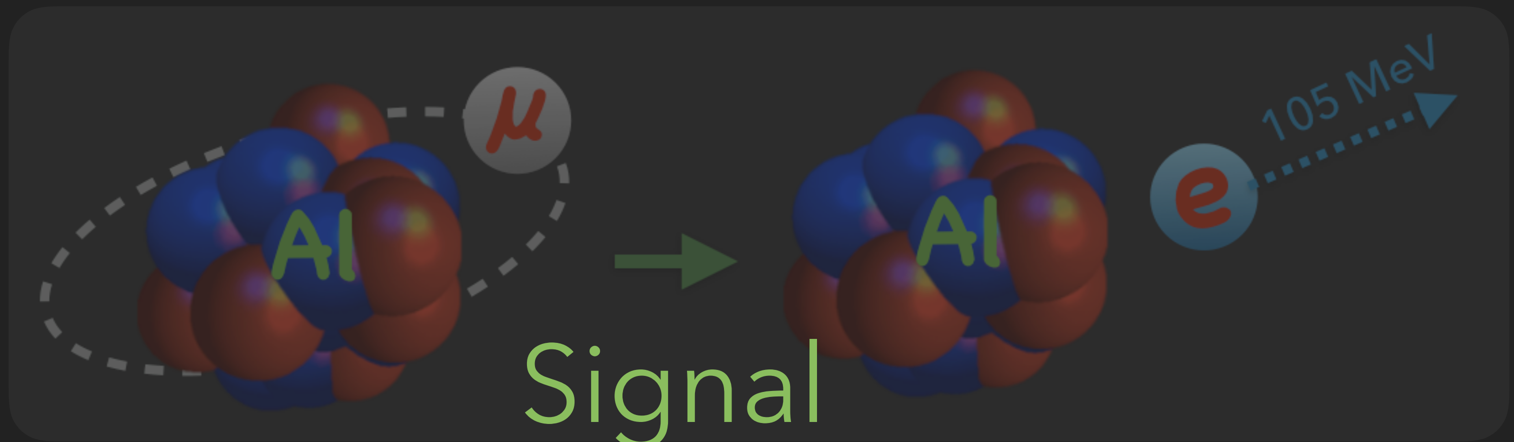
Nuclear Capture ~ 61%



Decay In Orbit (DIO) ~ 39%



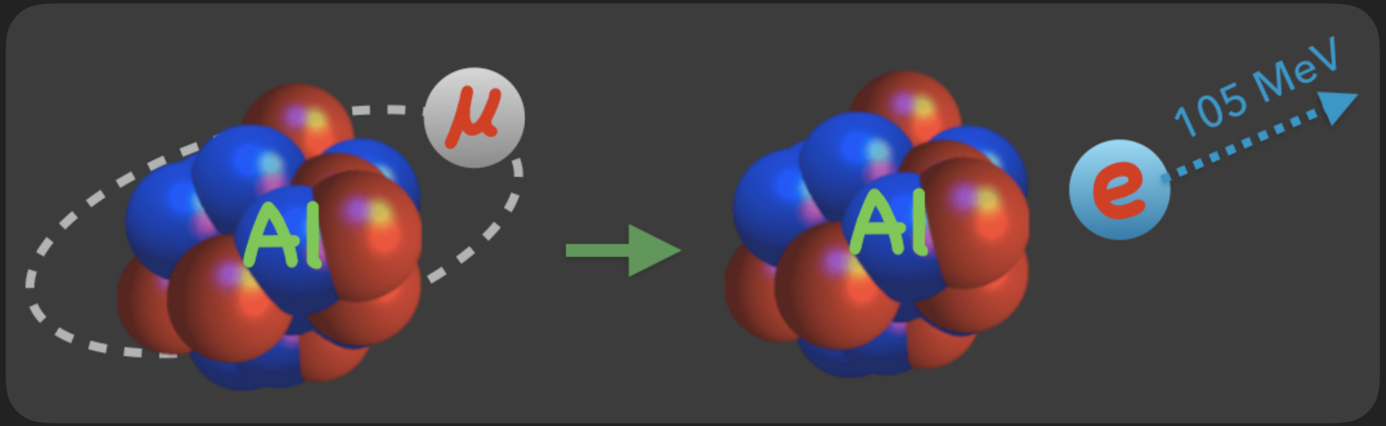
Conversion < 10^{-12}



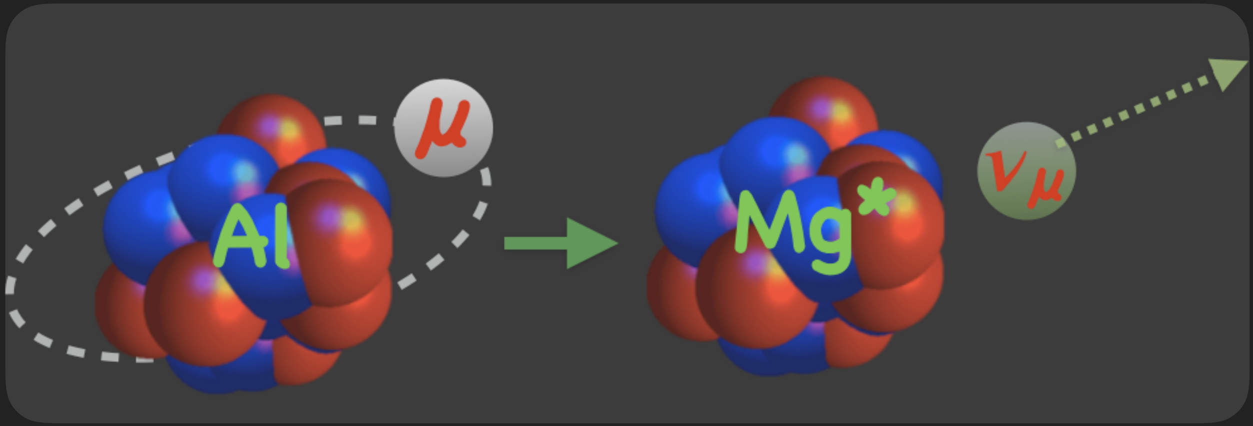
Muon to electron conversion rate: $R_{\mu e}$

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

Numerator: # of conversions

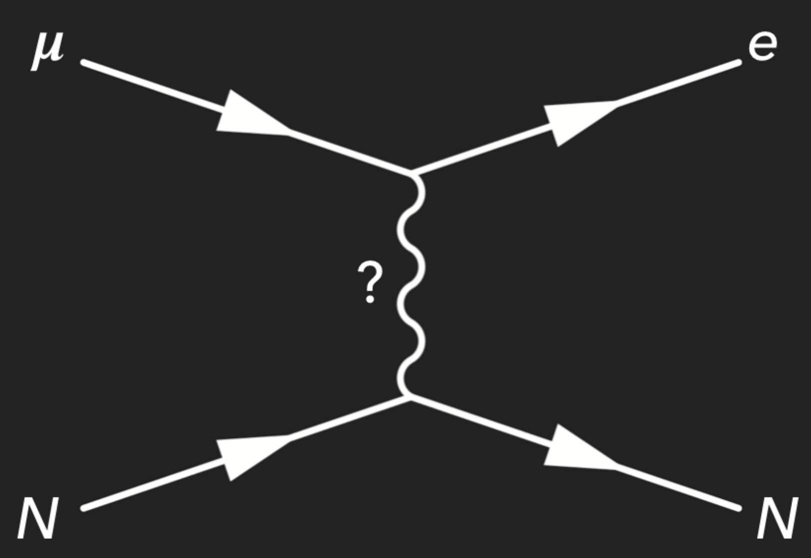


Denominator: # of nuclear captures

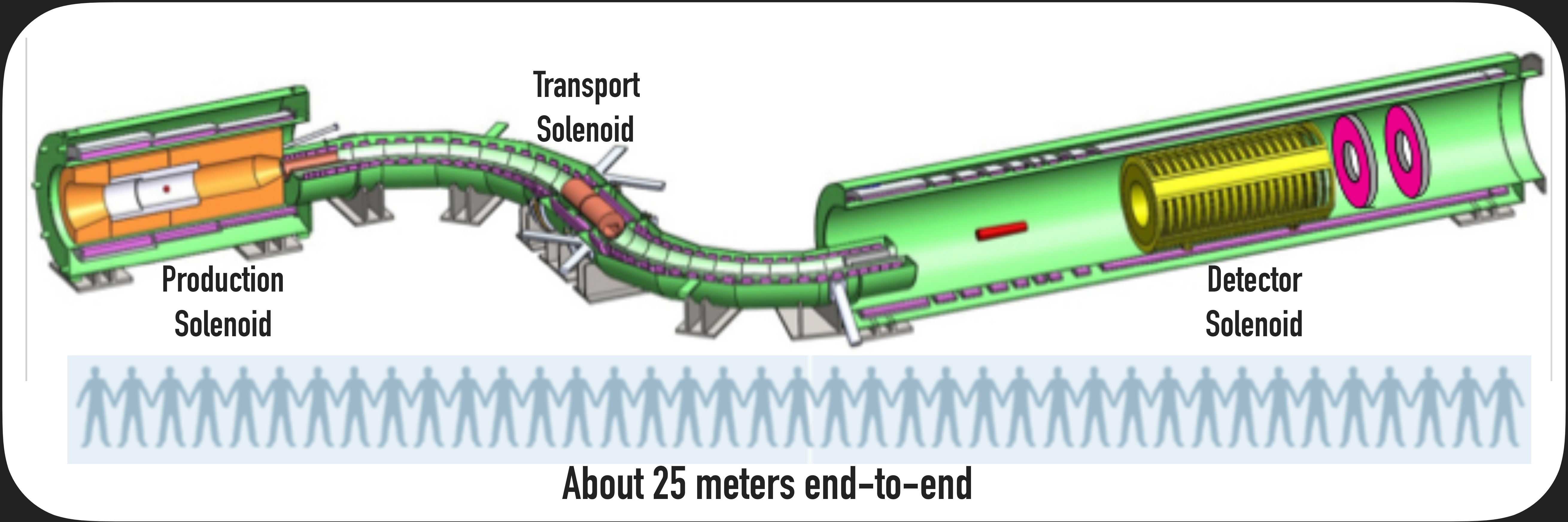


We will cover

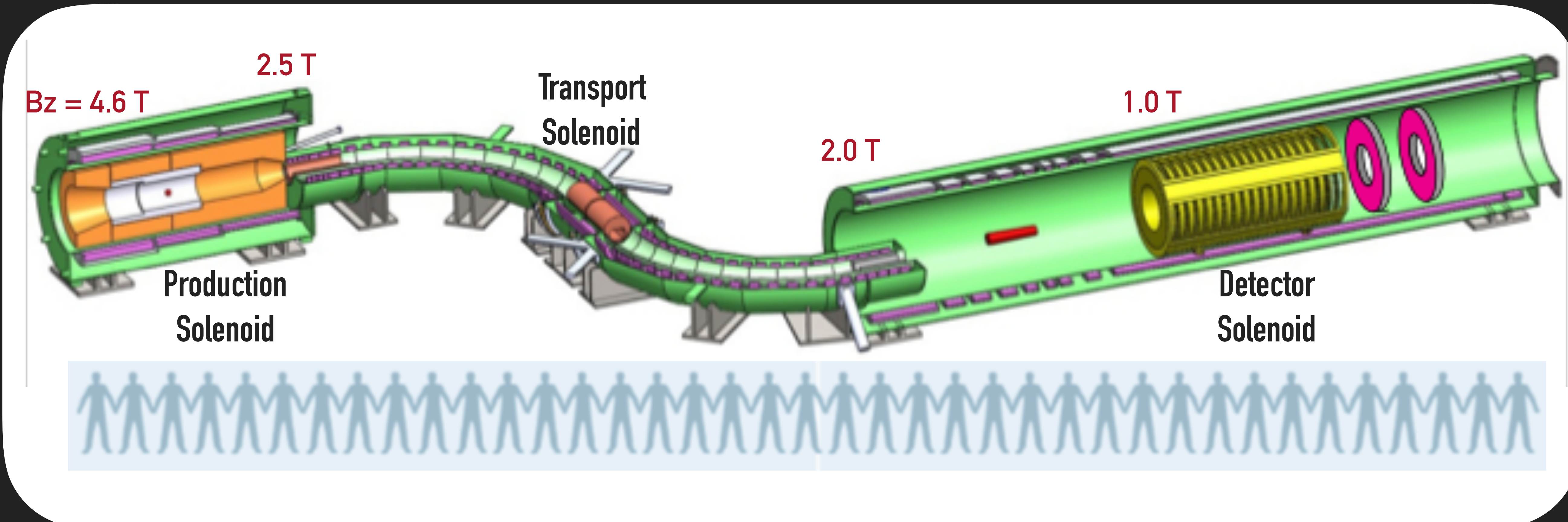
- ~~What will be measured~~
- Design aspects of Mu2e
- Mu2e sensitivity & physics reach

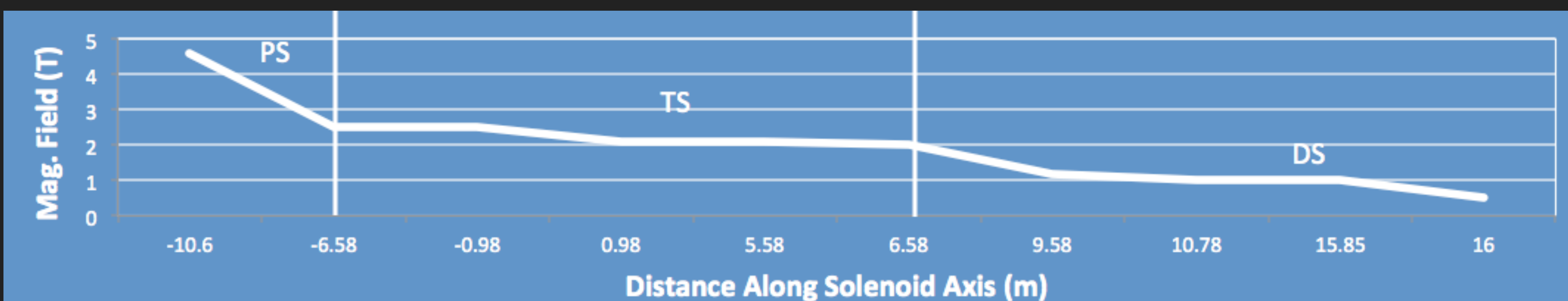


Mu2e consists of 3 solenoids

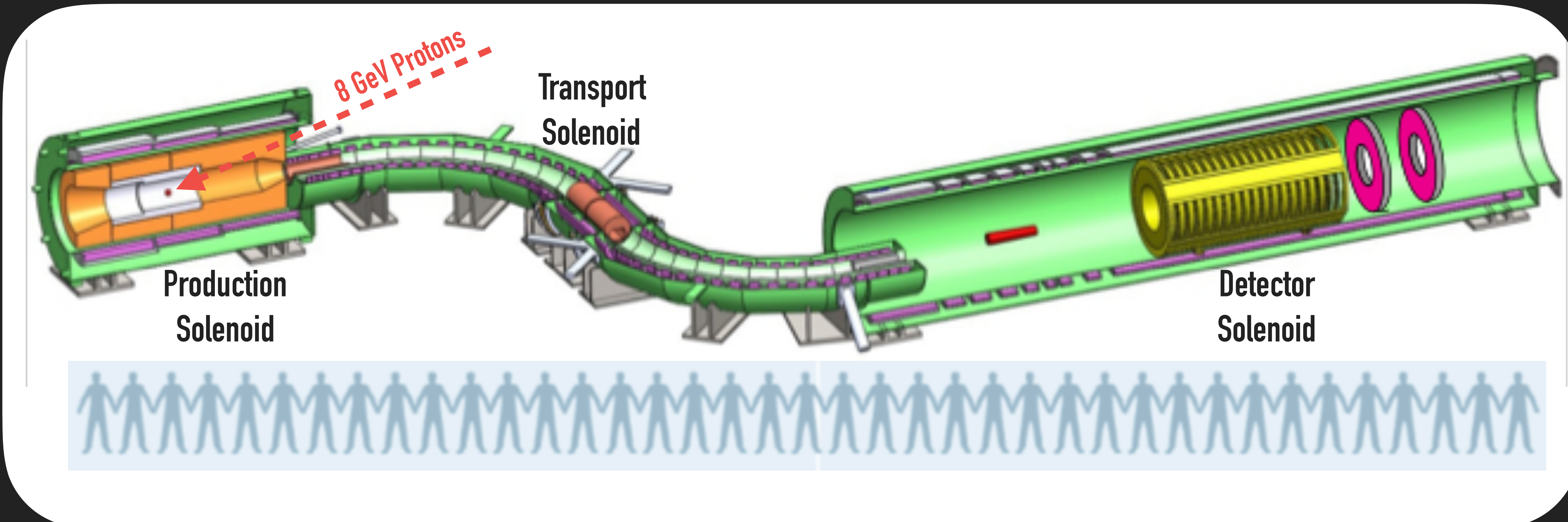


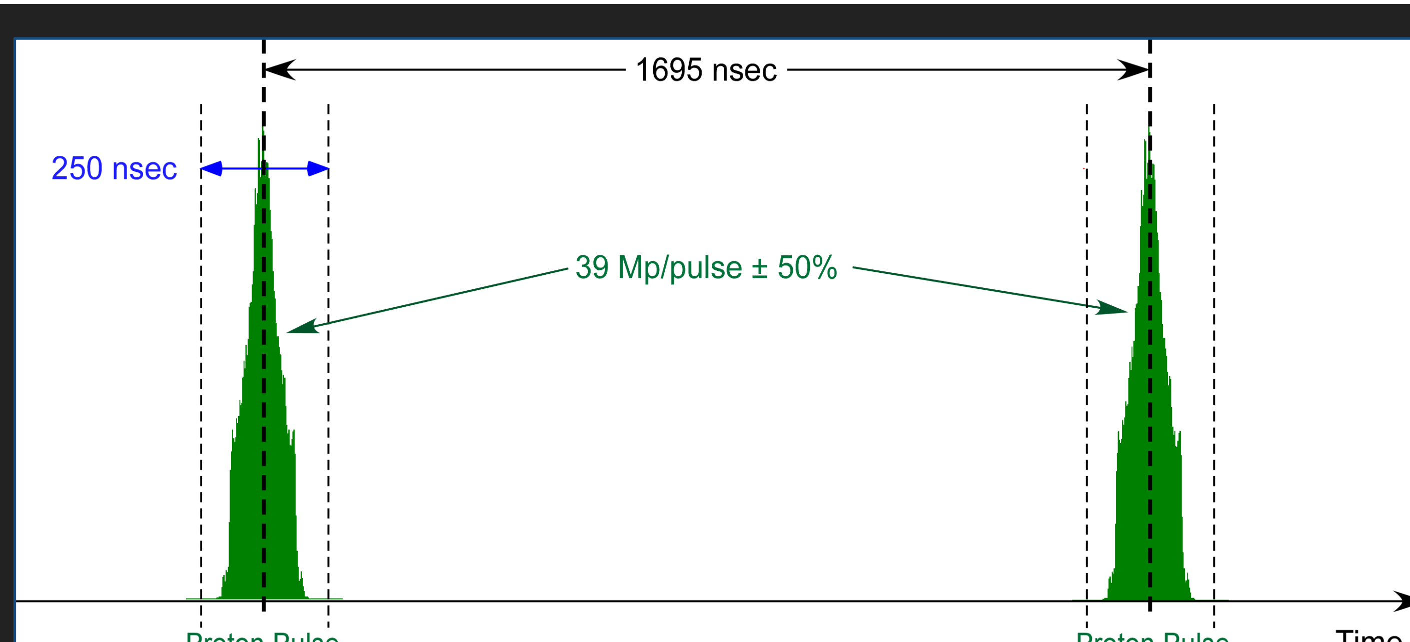
Graded field



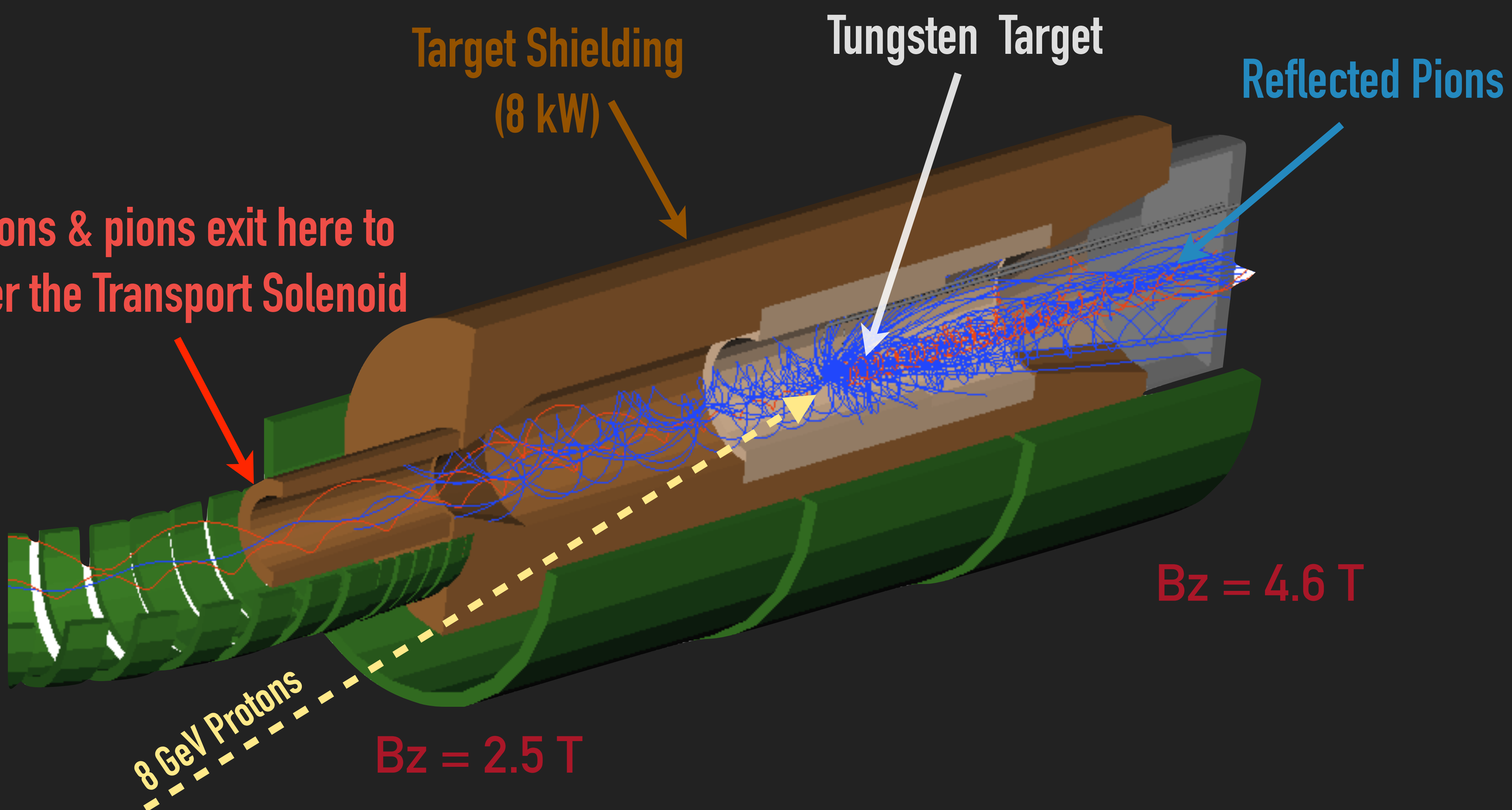


Enter the Production Solenoid





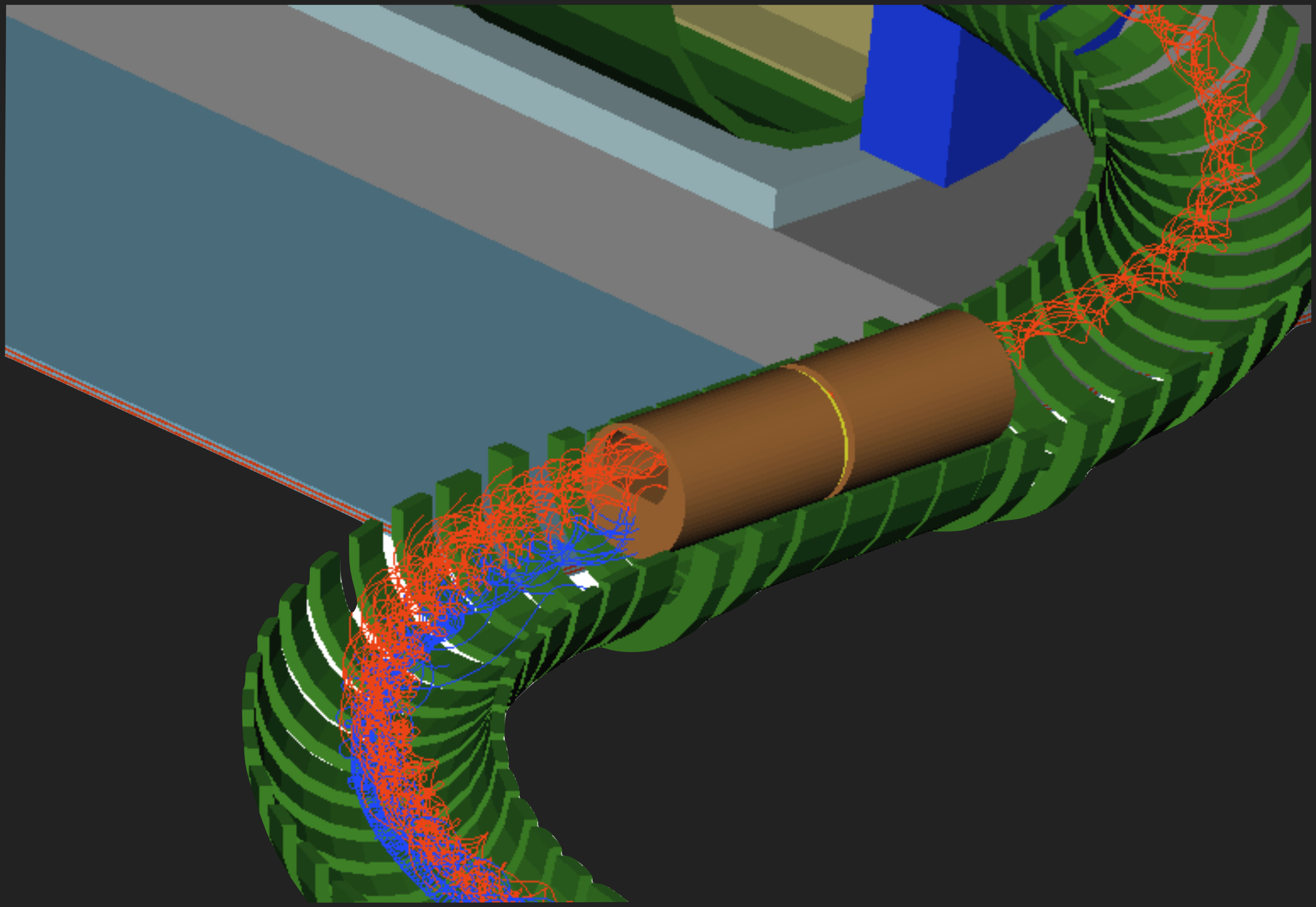
Enter the Production Solenoid



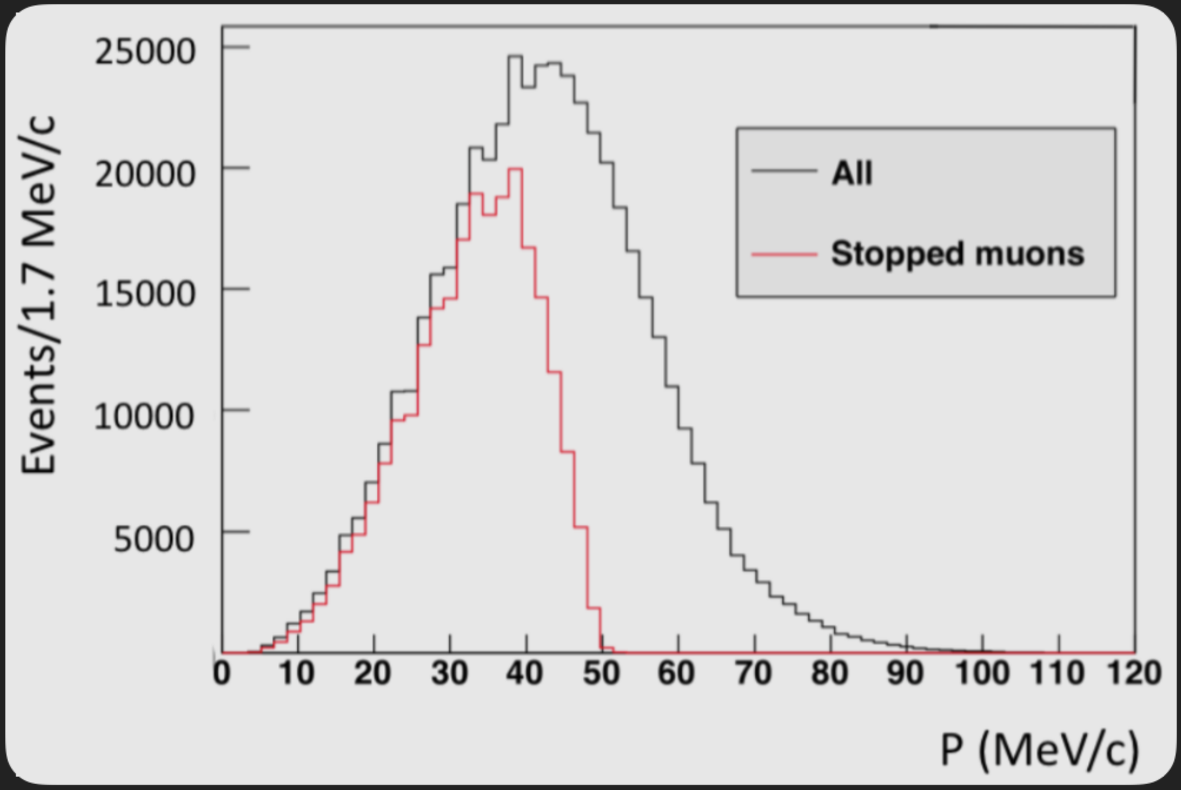
$\tau_{\pi^-} \sim 26$ ns

$BR(\pi^- \rightarrow \mu^- \bar{\nu}_\mu) \sim 99.9\%$

Enter the Transport Solenoid

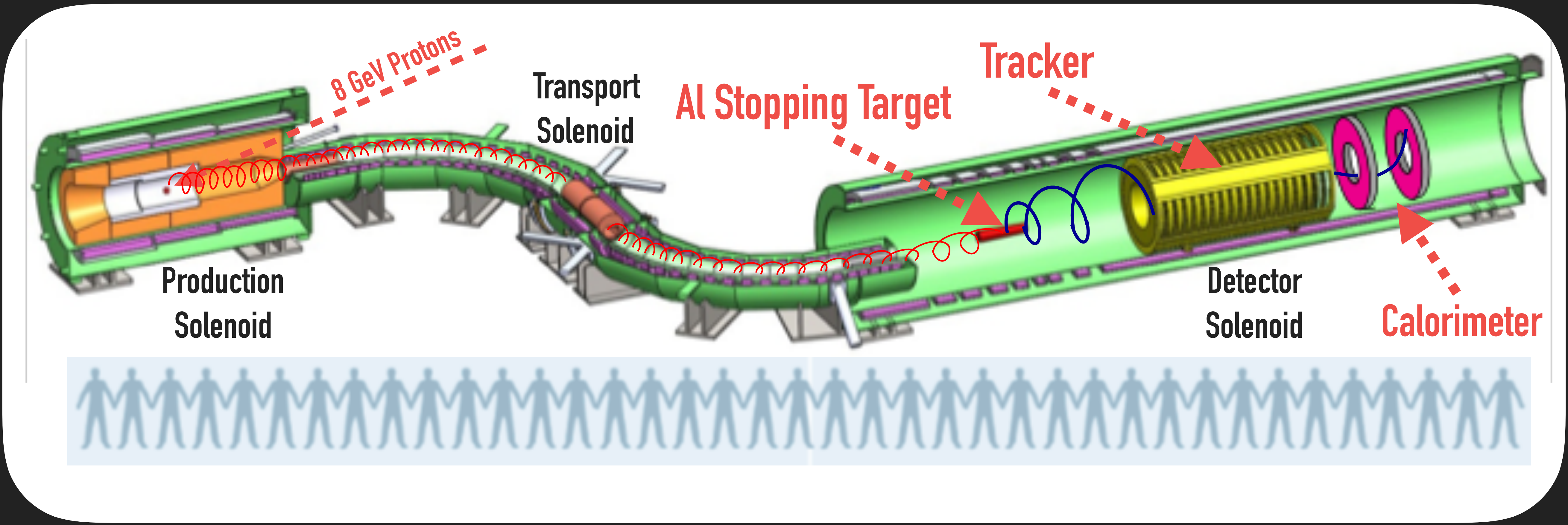


Muon Beam Spectrum



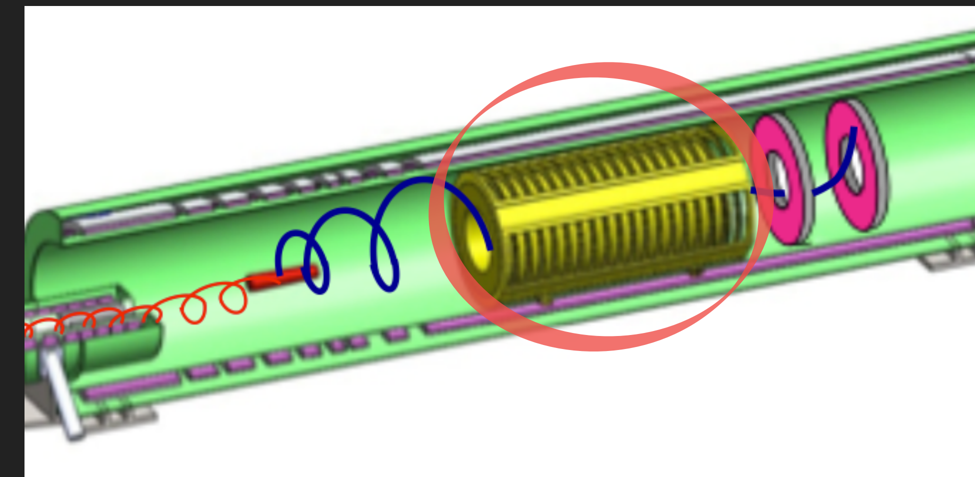
- S-shaped solenoid eliminates line-of-sight transport of photons and neutrons
- Curvature drift and collimators select low momentum negative muons

Enter the Detector Solenoid

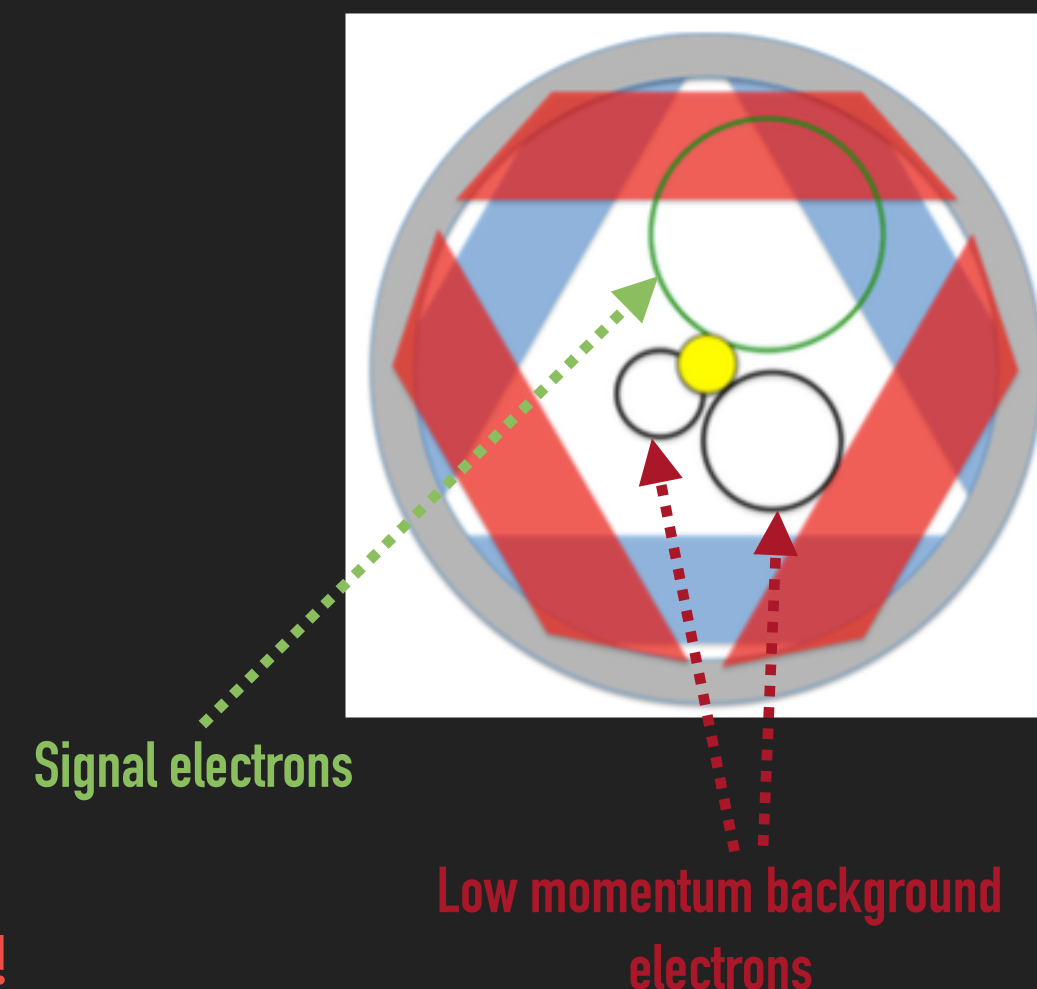


After three years of running, 10^{18} muons will be stopped!

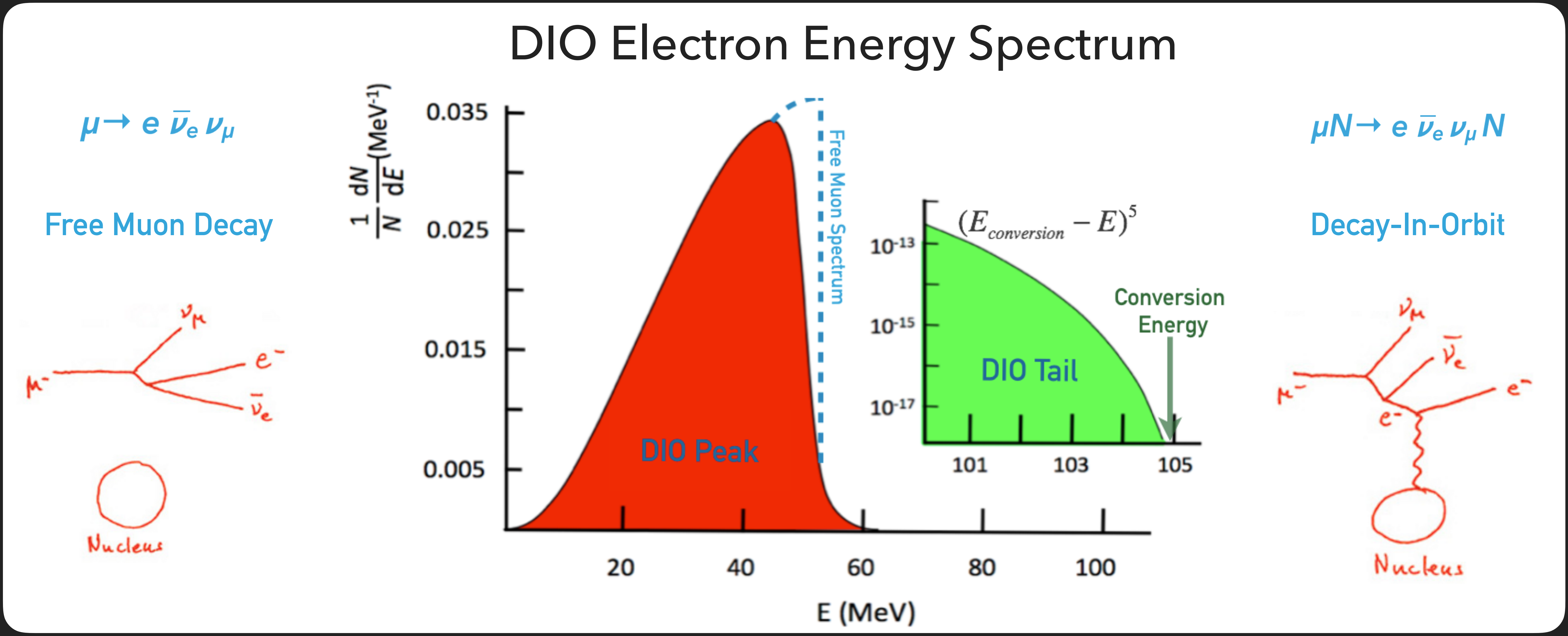
The Tracker



- Primary method of detection
- ~20000 metalized mylar straw drift tubes transverse to detector solenoid
  - 15 um wall thickness, filled with drift gas + sense wire
- Blind to low momentum background
- 180 KeV resolution @ 105 MeV
- Ultra low mass & can operate in vacuum
  - Unprecedented requirements, but essential!

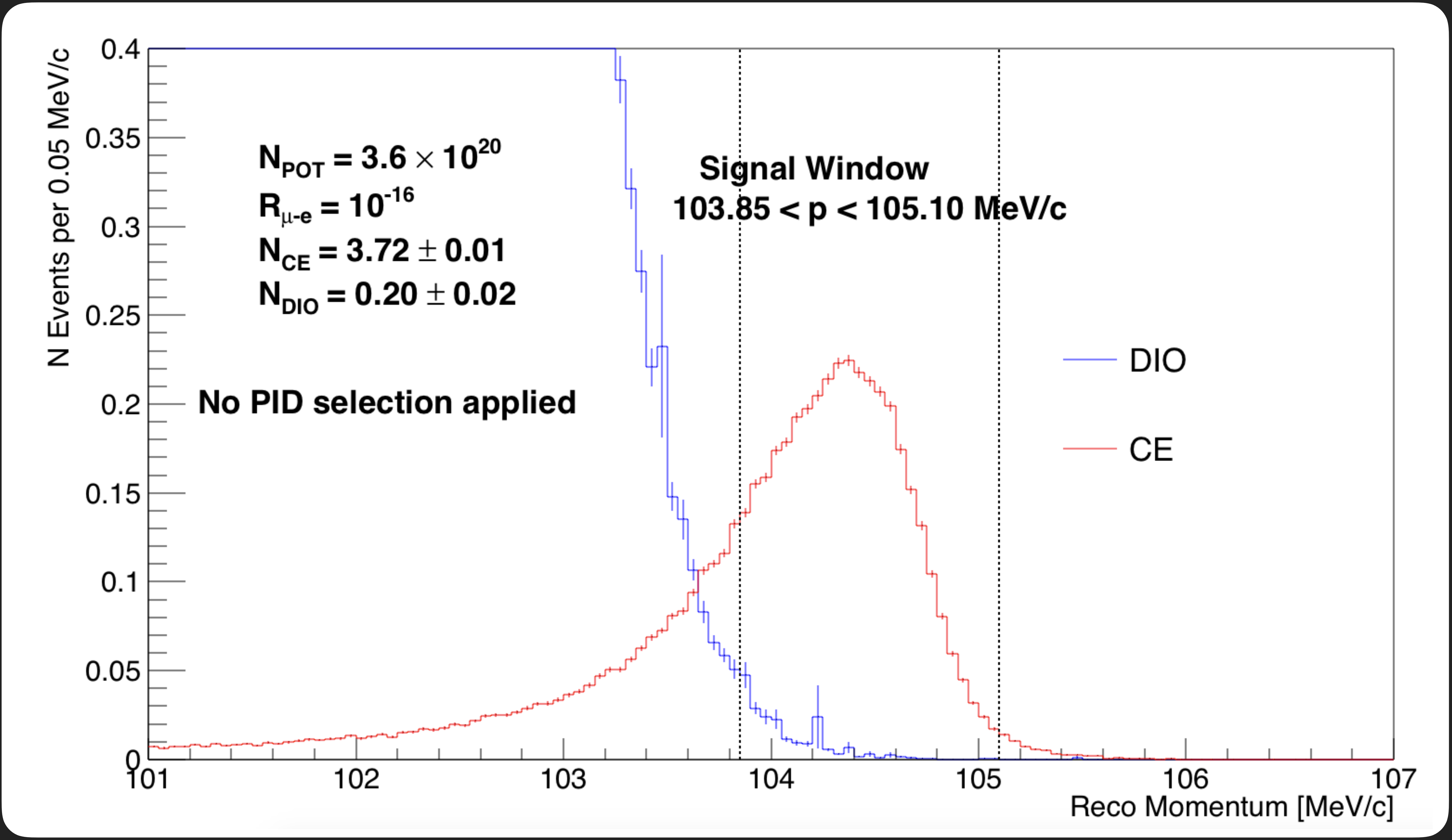


Decay in orbit background



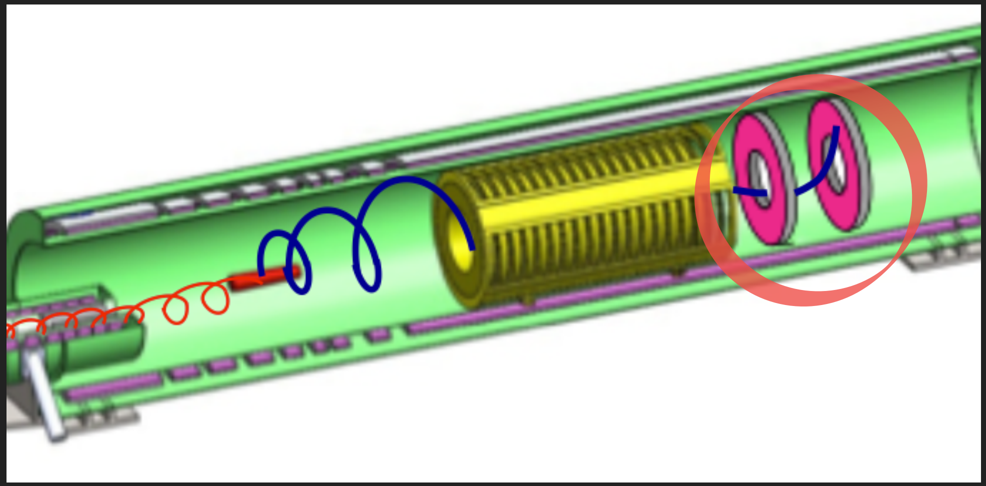
DIO tail extends near the muon rest mass & accounts for ~55% of the total background

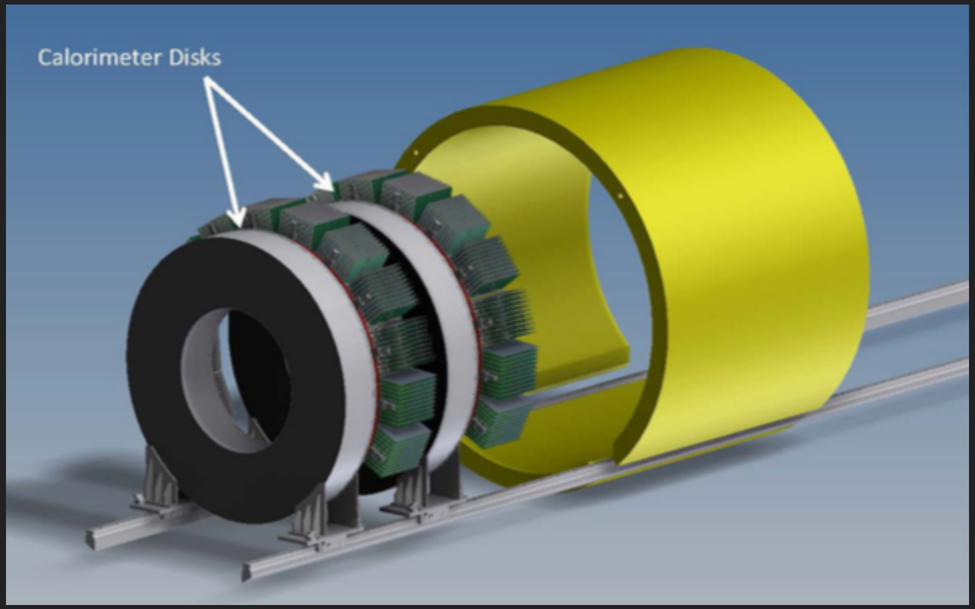
Decay in orbit background

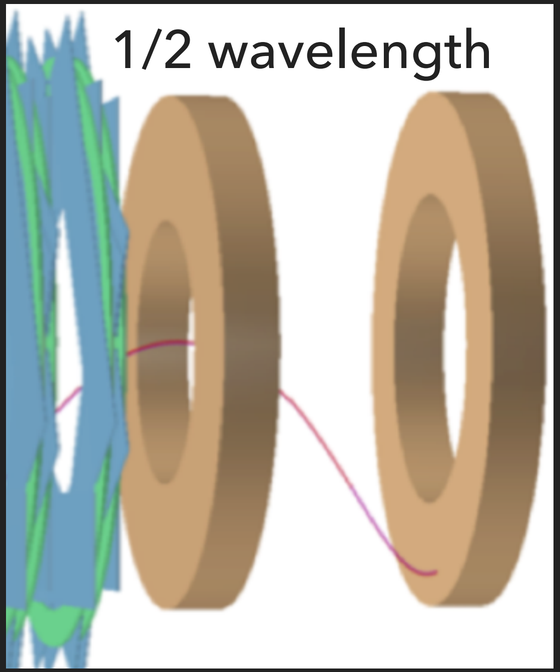


The Calorimeter

- To distinguish muons from electrons, cross check tracker
- ~ 1350 pure Cesium Iodide Crystals within two annular disks (IR = 37 cm, OR = 66 cm)
  - Blind to low momentum background

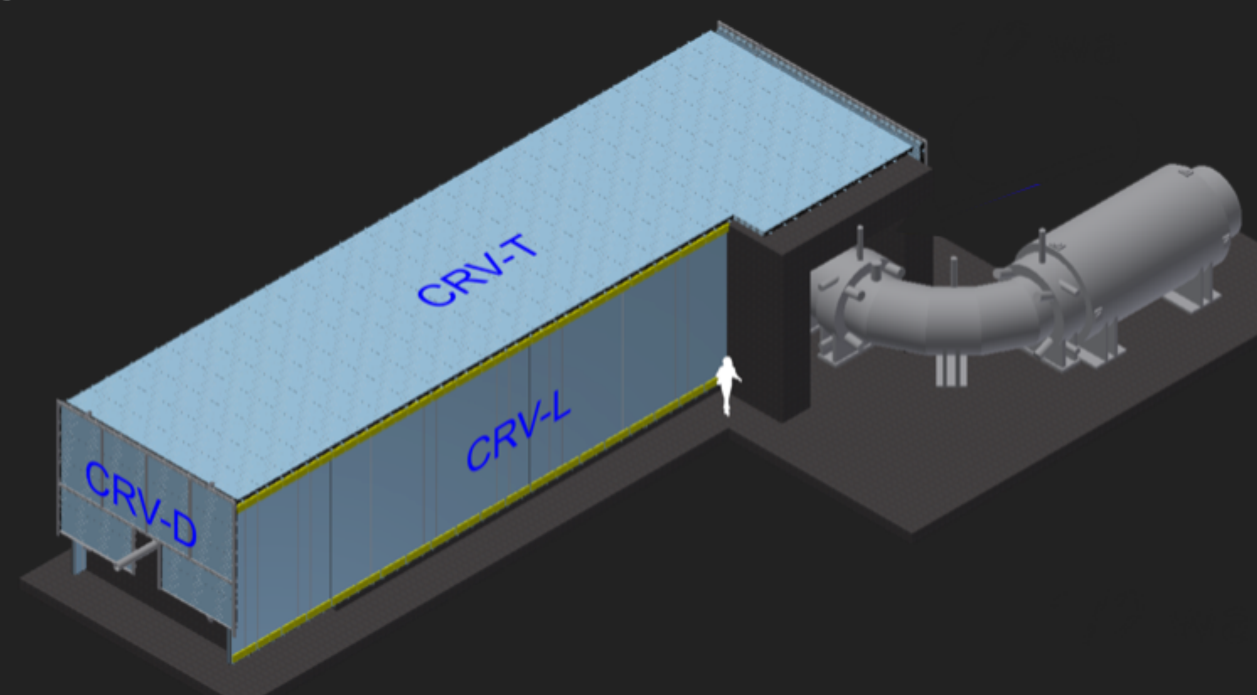






The Cosmic Ray Veto System

- The CRV suppresses the spurious detection of conversion-like particles initiated by cosmic-ray muons
- Without the CRV, we would see 1 such event per day!
  - 99.99% efficiency requirement
- 4 layers of extruded polystyrene scintillator counter

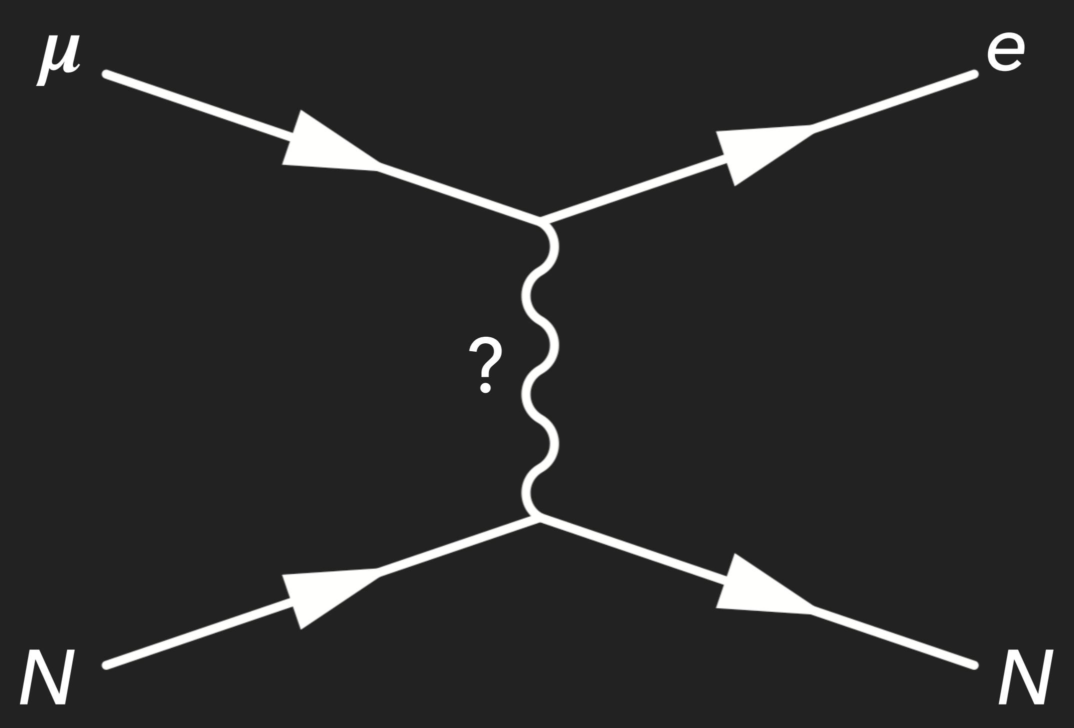


Total Background

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	0.199 ± 0.092
	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
	Cosmic ray induced	0.082 ± 0.018
	Total	0.36 ± 0.10

We will cover

- ~~What will be measured~~
- ~~Design aspects of Mu2e~~
- Mu2e sensitivity & physics reach



Mu2e Sensitivity

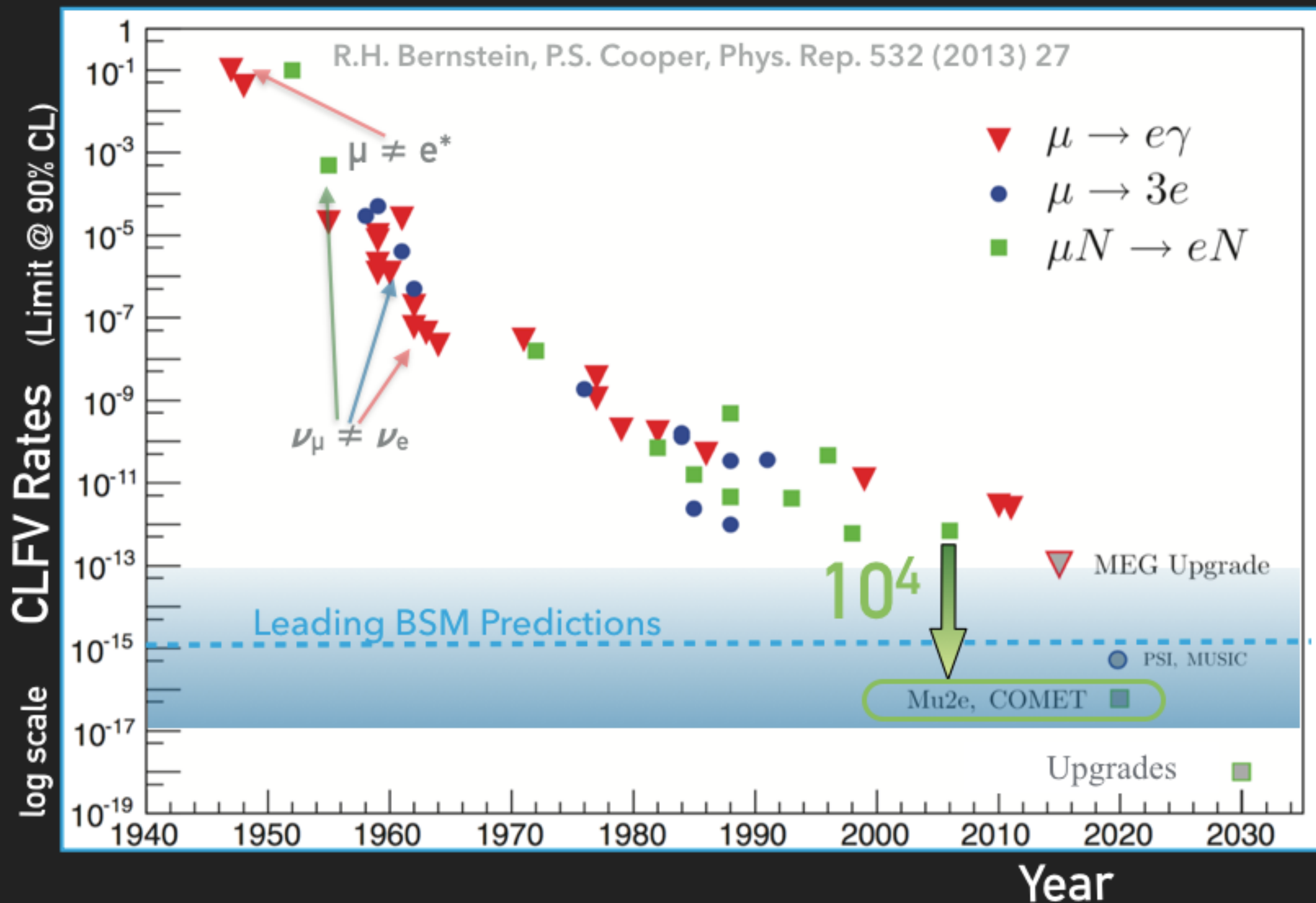
- Previous experiments rule out $R_{\mu e} > 7 \times 10^{-13}$ @ 90%CL
- Most New Physics models predict conversion rates of $R_{\mu e} \sim 10^{-14} - 10^{-16}$
  - If $R_{\mu e} \sim 10^{-15}$, we'll will see ~ 40 events!
  - If $R_{\mu e} = 3 \times 10^{-17}$, we should see 1 event
- Expected background is ~ 0.5 an event
- Mu2e will be sensitive to $R_{\mu e} > 6 \times 10^{-17}$ @ 90%CL!

Mu2e Sensitivity

- Previous experiments rule out $R_{\mu e} > 7 \times 10^{-13}$ @ 90%CL
- Most New Physics models predict conversion rates of $R_{\mu e} \sim 10^{-14} - 10^{-16}$
    - If $R_{\mu e} \sim 10^{-15}$, we'll will see ~ 40 events!
    - If $R_{\mu e} = 3 \times 10^{-17}$, we should see 1 event
- Expected background is ~ 0.5 an event
- Mu2e will be sensitive to $R_{\mu e} > 6 \times 10^{-17}$ @ 90%CL!

10,000 times beyond previous experiments

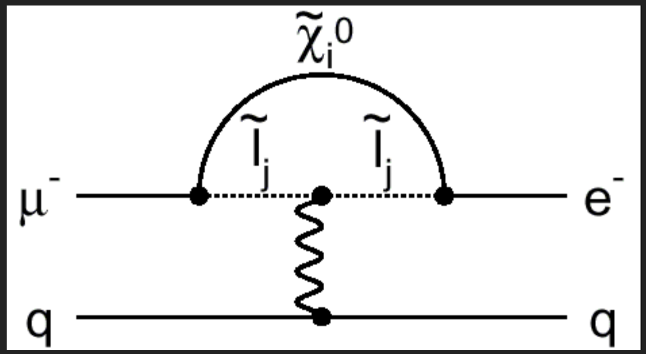
Breaking Through the Plateau… And Beyond the SM?



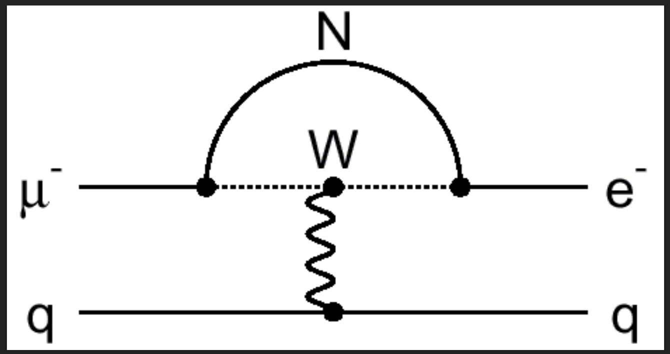
Enhanced $\mu \rightarrow e$ Rates

A multitude of models predict $R_{\mu e} \sim 10^{-15}$ or higher

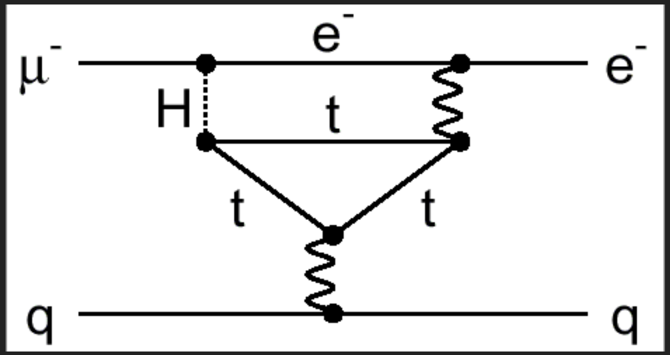
If they are right, we will see ~ 40+ conversions!



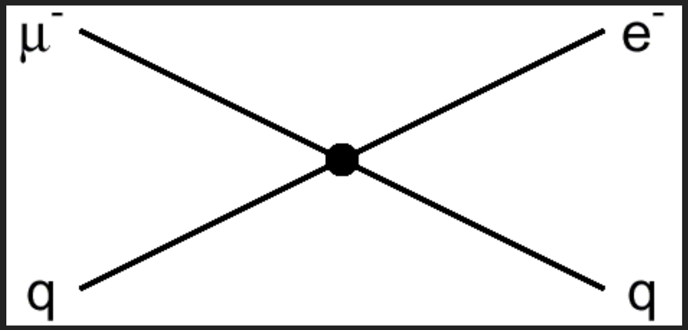
Supersymmetry



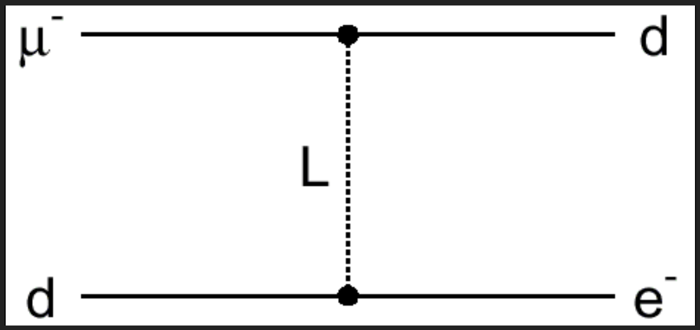
Heavy neutrinos



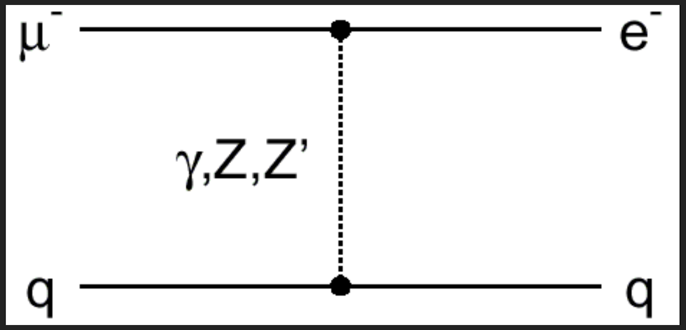
Two Higgs doublets



Compositeness



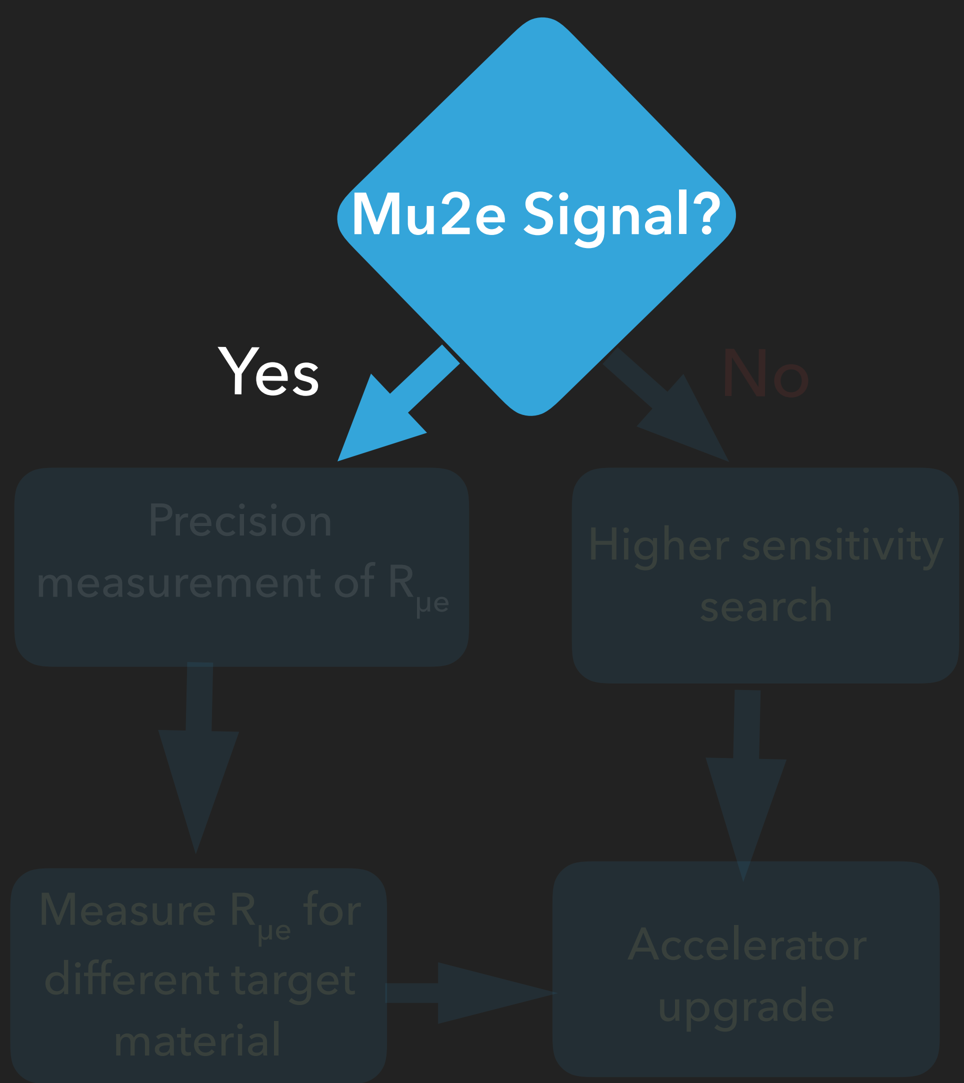
Leptoquarks

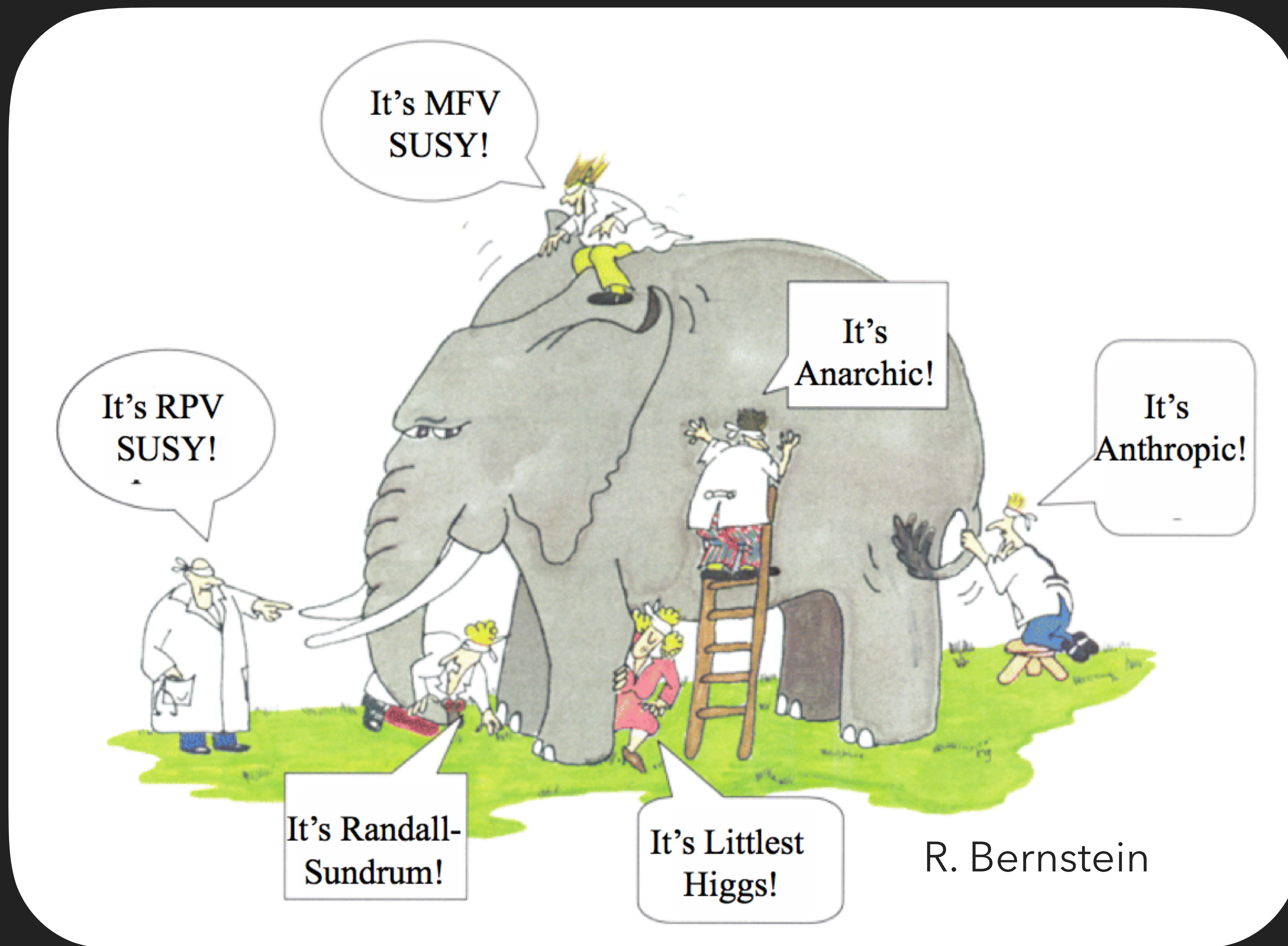


Anomalous coupling

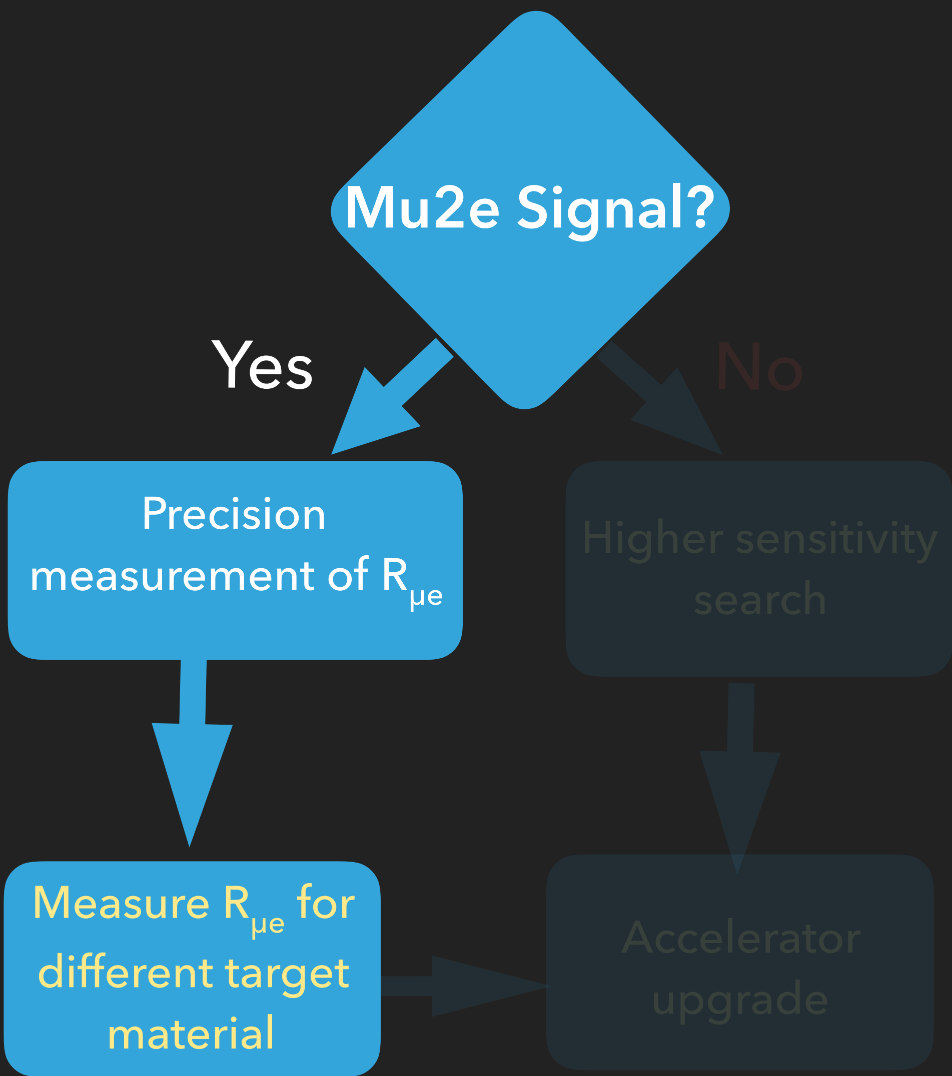
Theory Reviews: Y. Kuno, Y. Okada, 2001; M. Raidal et al., 2008; A. de Gouvea, P. Vogel, 2013

What if we see a signal?

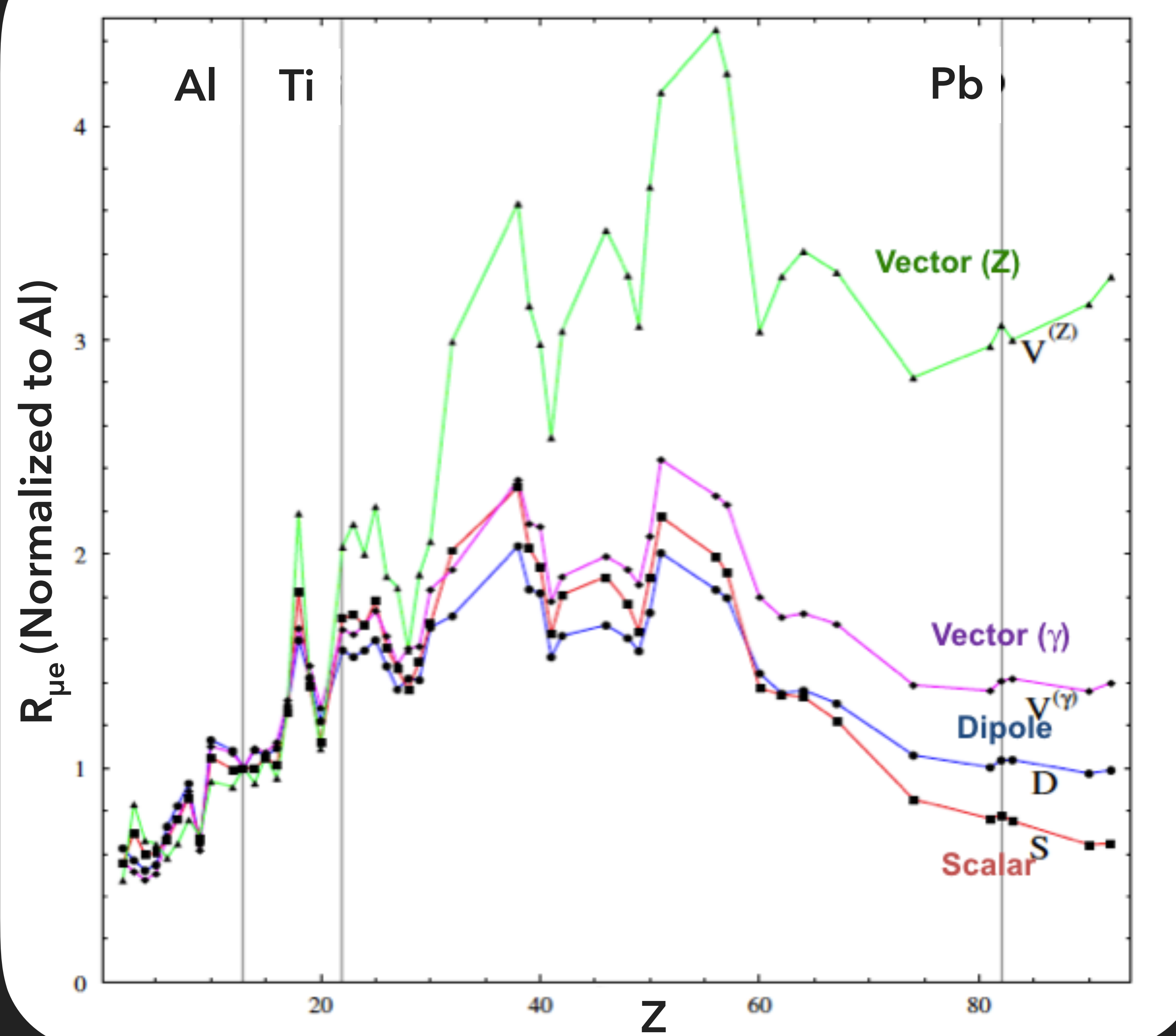




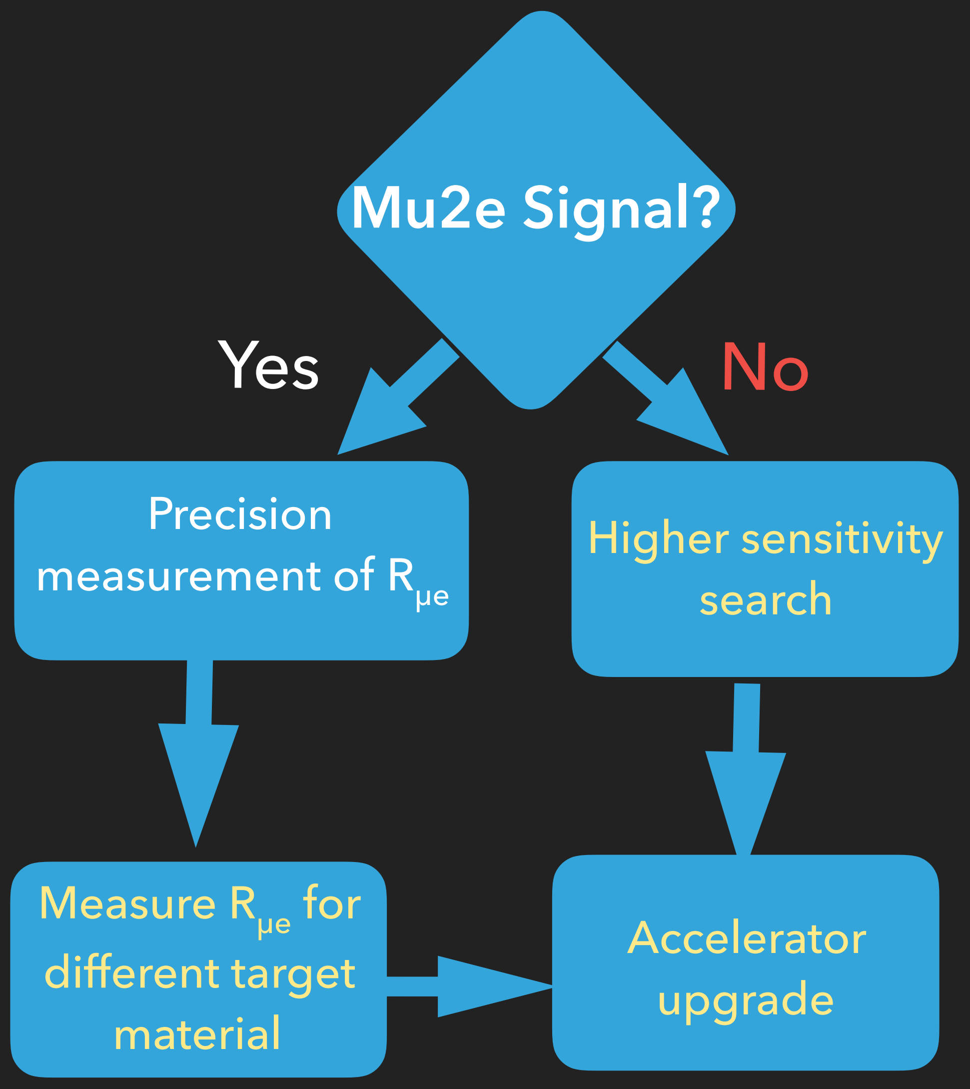
$R_{\mu e}$ in different materials is a powerful model discriminator



Cirigliano, V., R. Kitano, Y. Okada, and P. Tuzon (2009), Phys. Rev. D 80, 013002, arXiv:0904.0957 [hep-ph]

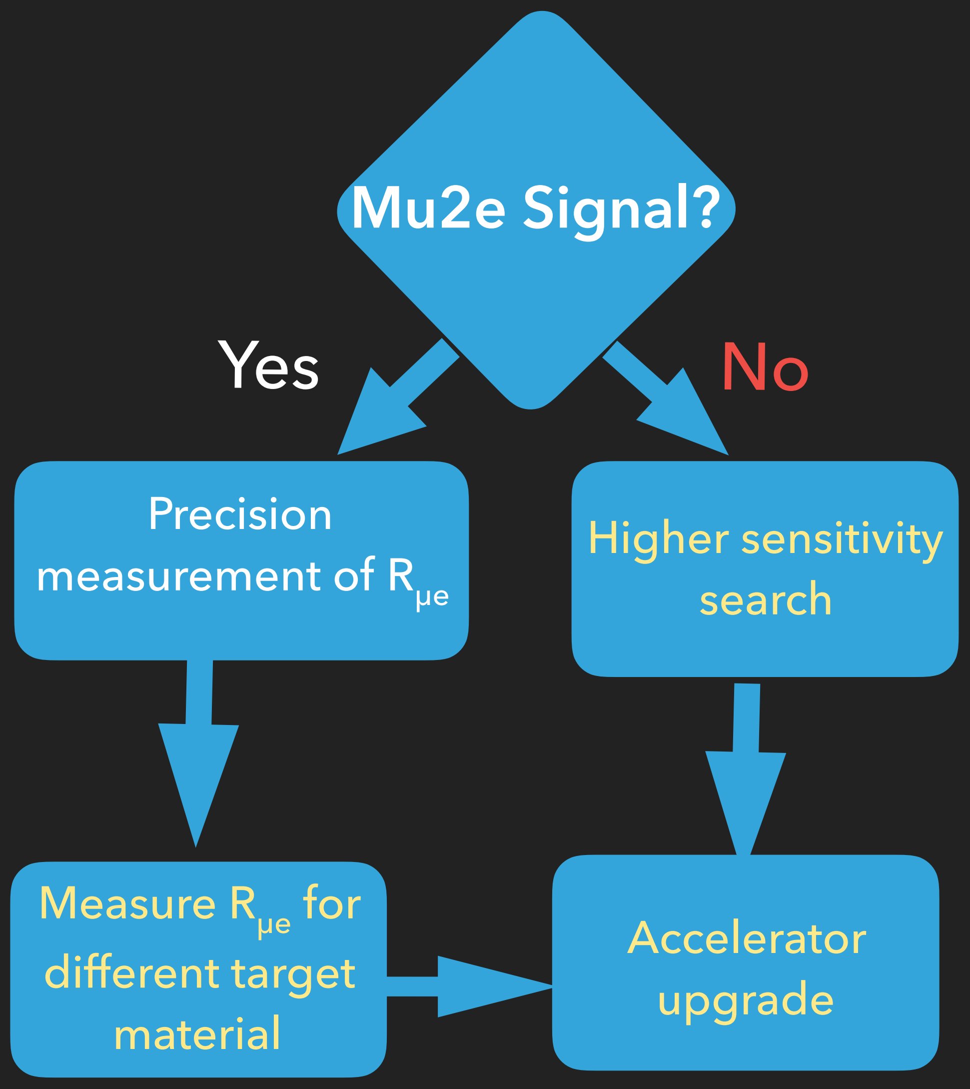


What if we don't see a signal?



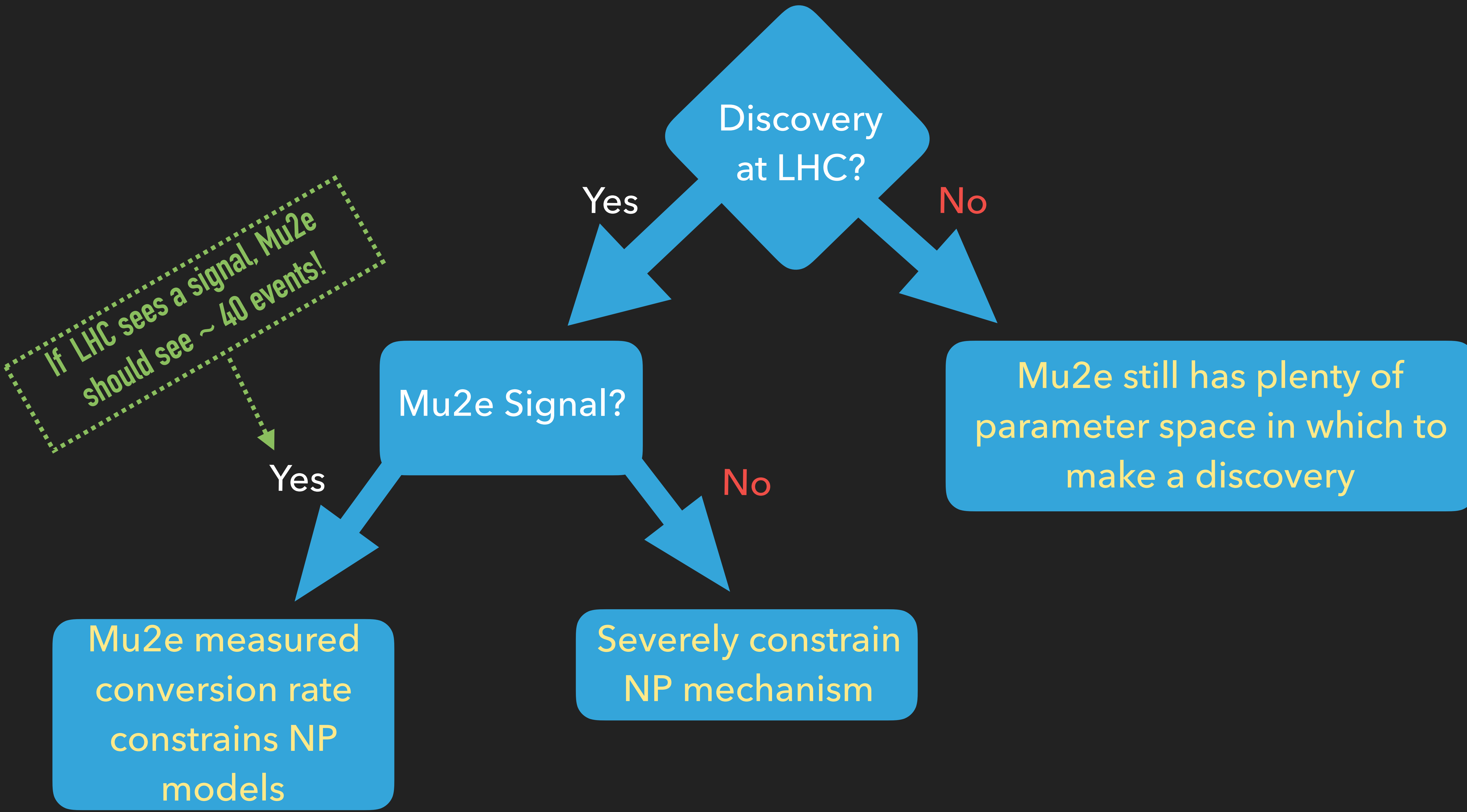
- $R_{\mu e} < 6 \times 10^{-17}$ will strongly constrain models
- Conduct next-generation search with higher sensitivity

A next generation Mu2e experiment is well motivated in all scenarios



To read about upgrading the Mu2e experiment, see arXiv:1307.1168

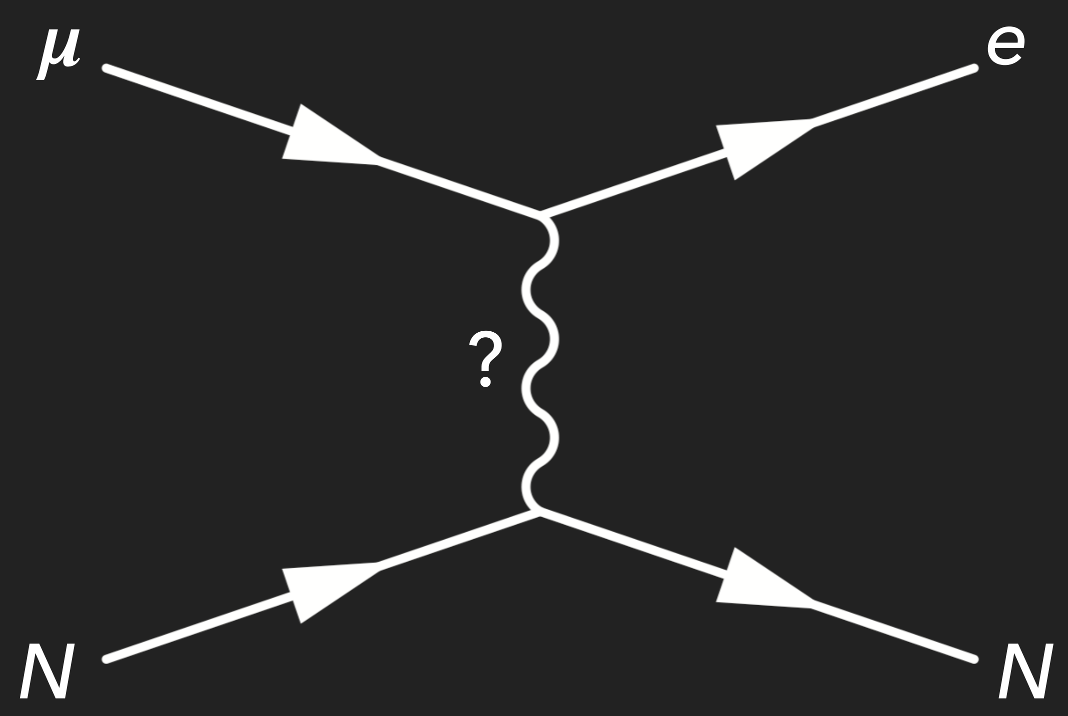
Mu2e is a long term project



Mu2e is a potential discovery experiment, complementary to the LHC

We have covered

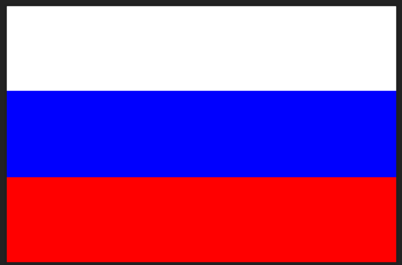
- ~~What will be measured~~
- ~~Design aspects of Mu2e~~
- ~~Mu2e sensitivity & physics reach~~



Active R&D program, mature design, ready for data collection in 2021

~200 scientists, 35 institutions, 5 countries

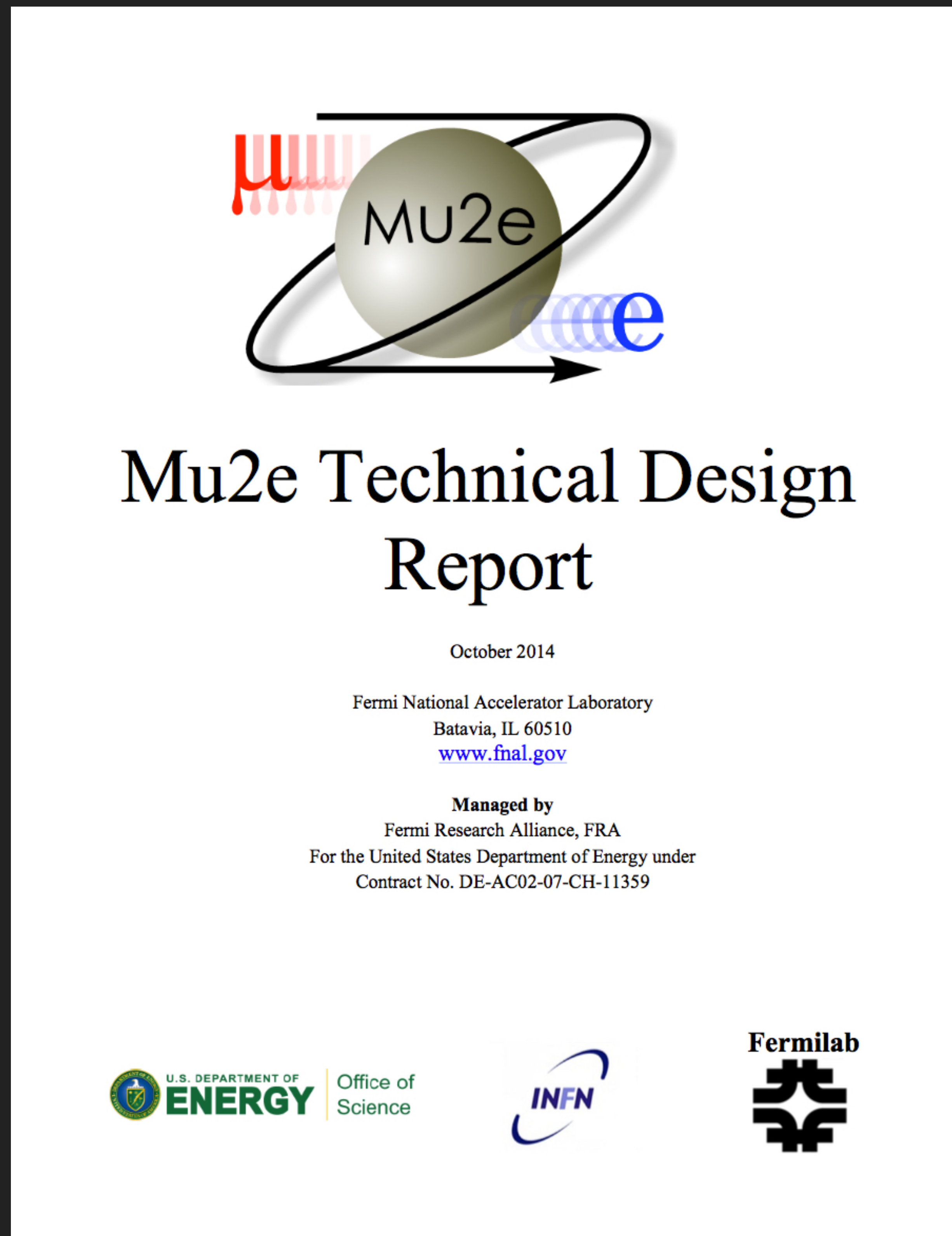
Argonne National Laboratory, Boston University, Brookhaven National Laboratory, University of California Berkeley, University of California Irvine, California Institute of Technology, City University of New York, Joint Institute of Nuclear Research Dubna, Duke University, Fermi National Accelerator Laboratory, Laboratori Nazionale di Frascati, Helmholtz-Zentrum Dresden-Rossendorf, University of Houston, University of Illinois, INFN Genova, Lawrence Berkeley National Laboratory, INFN Lecce, Kansas State University, Lewis University, University of Louisville, University Marconi Rome, University of Minnesota, Muons Inc., Northwestern University,Institute for Nuclear Research Moscow, Northern Illinois University, INFN Pisa, Purdue University, Sun Yat-Sen University, Novosibirsk State University/Budker Institute of Nuclear Physics, Rice University, University of South Alabama, University of Virginia, University of Washington, Yale University

CIVIL CONSTRUCTION

Thought becoming real

LEARN MORE



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

U.S. DEPARTMENT OF ENERGY | Office of Science

INFN

Fermilab

Technical Design Report:

arXiv: 1501.05241 (888 pages)

Conceptual Design Report:

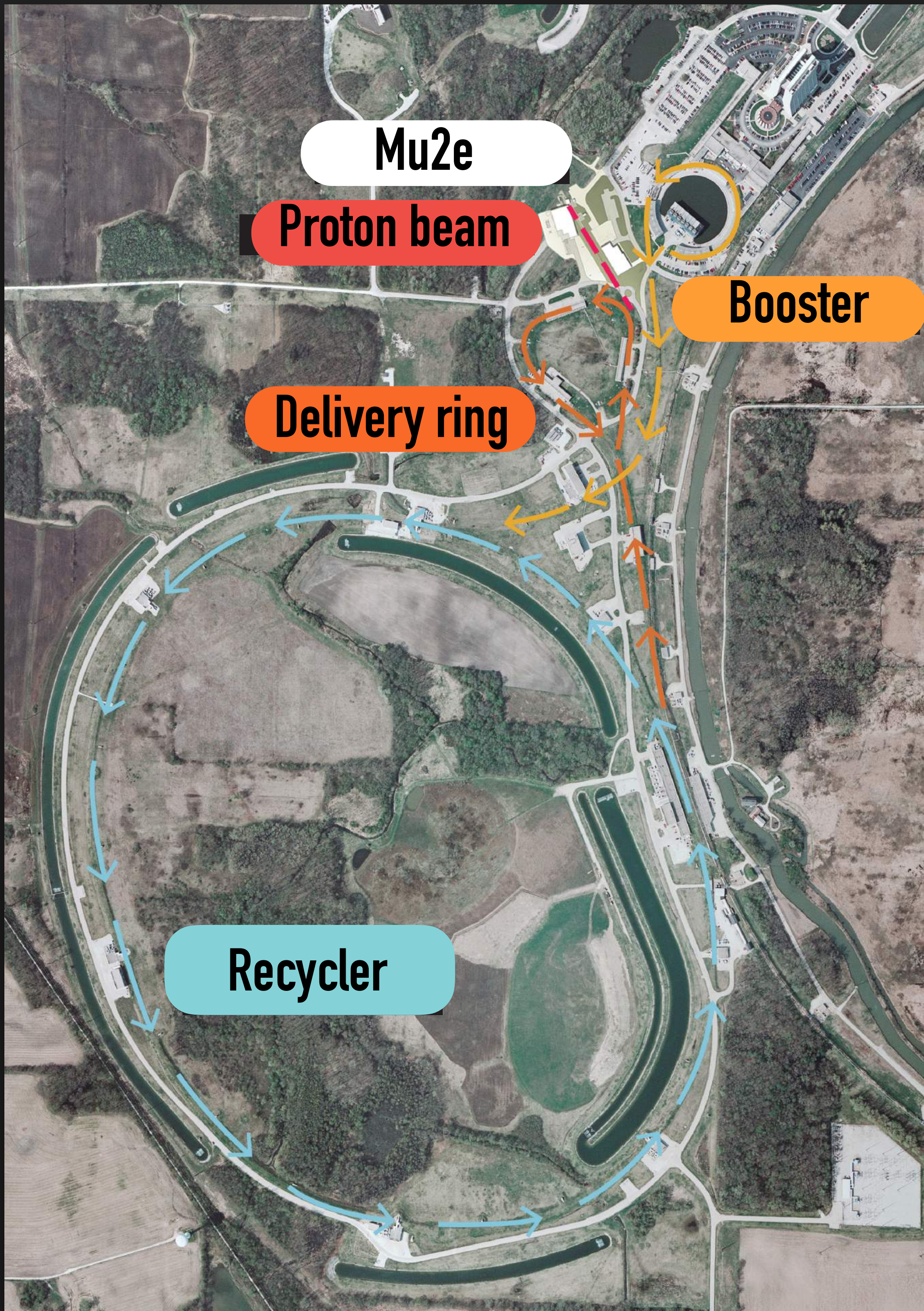
arXiv:1211.7019 (562 pages)

- Mu2e will search for the $\mu N \to eN$
- The goal is to discover CLFV, thereby providing unambiguous evidence of BSM physics
- Unprecedented sensitivity to a multitude of BSM phenomena with mass scales up to 10,000 TeV
- Push the current sensitivity limit by a factor of 10,000
- Under any outcome, a next-generation Mu2e experiment is well motivated
- R&D is mature with data collection scheduled for 2021
- Mu2e will be among the most sensitive probes to BSM physics of its time

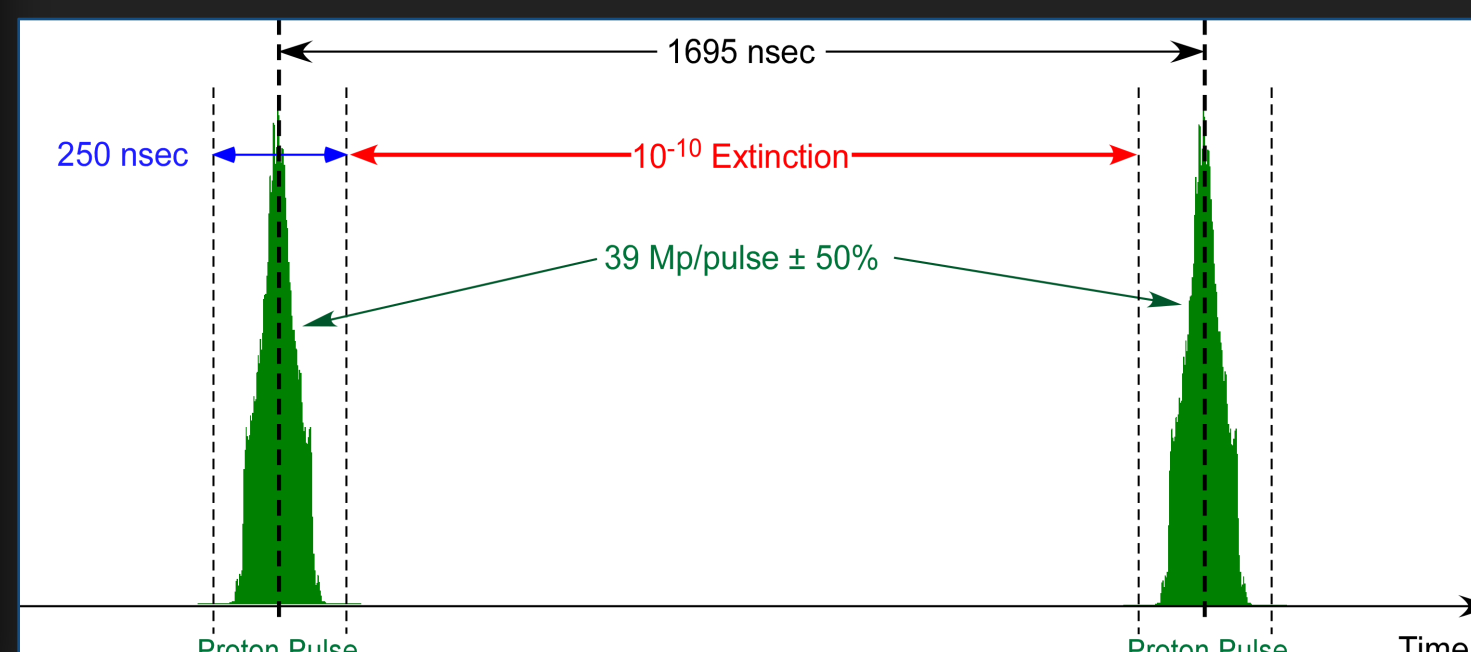

Mu2e
μ
e
Muon-to-Electron
Conversion Experiment
Fermilab
ENERGY
Office of Science

QUESTIONS?

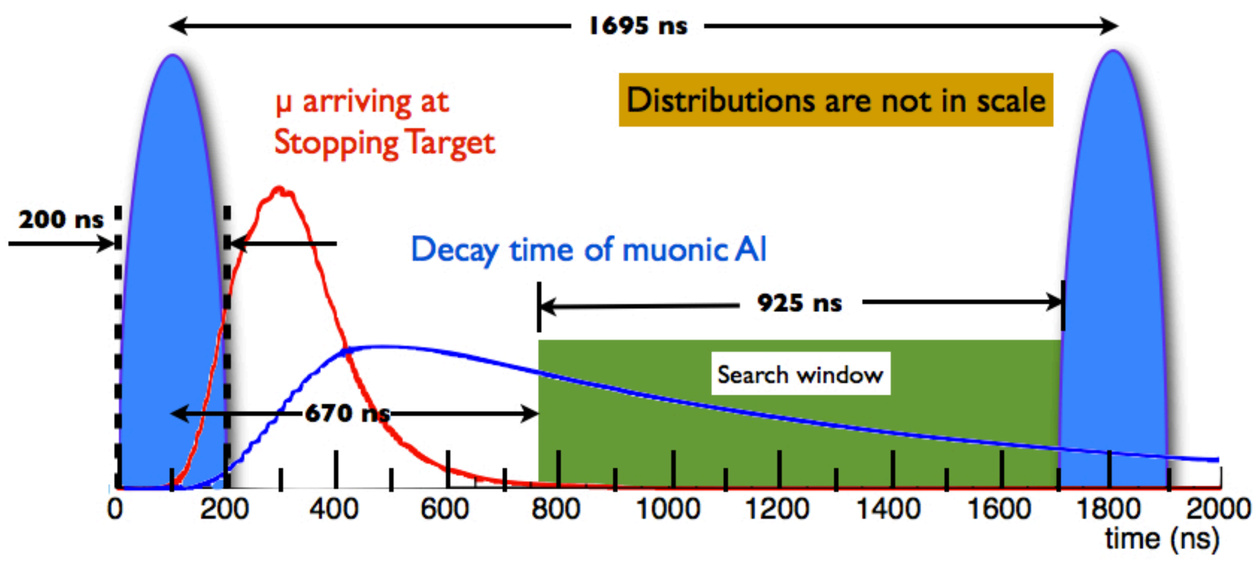
BACKUPS



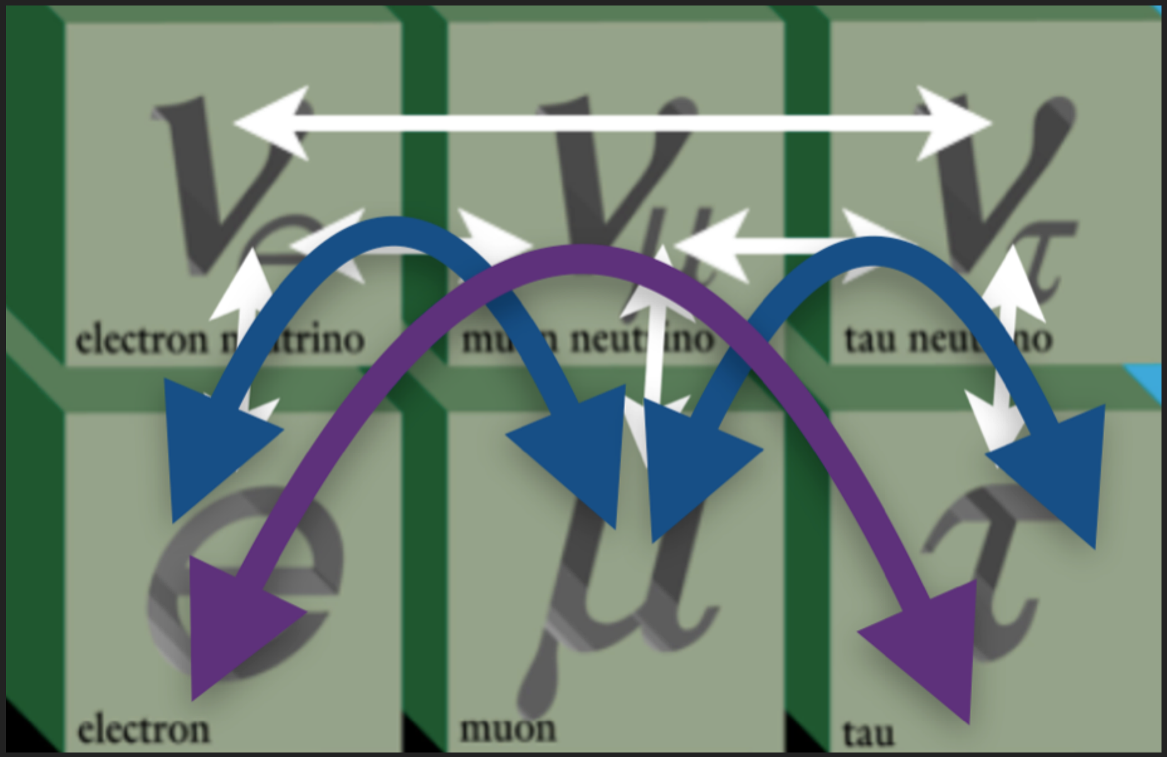
- Booster provides batches of 8 GeV protons to recycler
- Recycler divides proton batches into 4 smaller bunches
- Delivery ring gets 1 out of 4 bunches from recycler
- Mu2e gets the Proton beam pulses from delivery ring every 1695 ns
- Mu2e runs simultaneously with NOvA
  - Using spare Booster batches
  - NOvA POT is unaffected by Mu2e



choose Z based on tradeoff between rate and lifetime: longer lived reduces prompt backgrounds

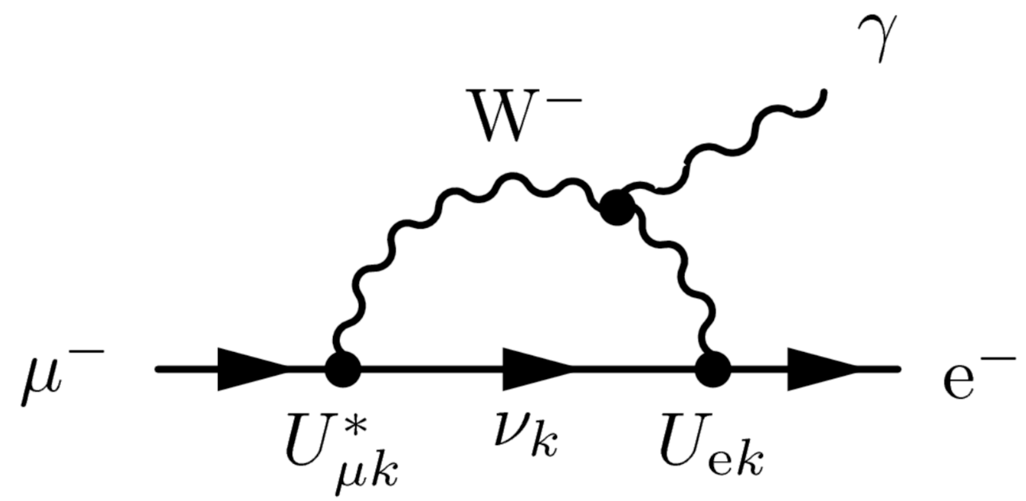


Nucleus	$R_{\mu e}(Z) / R_{\mu e}(Al)$	Bound Lifetime	Conversion Energy
Al(13,27)	1	864 nsec	104.96 MeV
Ti(22,~48)	1.7	328 nsec	104.18 MeV
Au(79,~197)	~0.8-1.5	72.6 nsec	95.56 MeV



Neutrino mixing implies tiny but non-zero CLFV rates…

In principle, how much can we suppress the background?



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

Unobservable

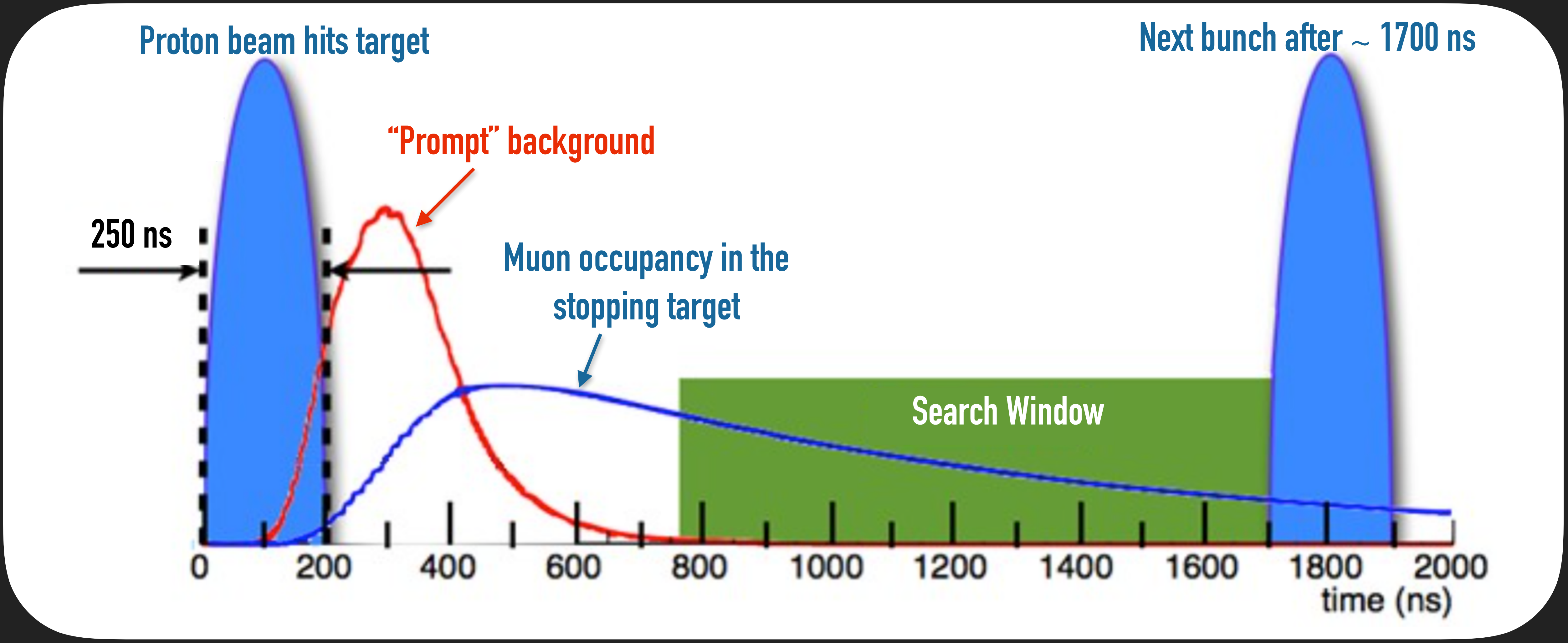
Neutrino mixing implies tiny but non-zero CLFV rates…

- Example above: BR($\mu \to e\gamma$) ≈ 10^{-54}
- Similarly, SM prediction for $R_{\mu e} \approx 10^{-54}$, compare to SES = $\mathcal{O}(10^{-17})$
  - There is effectively no SM background!

Process	**Upper limit**
$\mu^+ \to e^+\gamma$	$< 5.7 \times 10^{-13}$
$\mu^+ \to e^+e^-e^+$	$< 1.0 \times 10^{-12}$
$\mu^-\mathrm{Ti} \to e^-\mathrm{Ti}$	$< 1.7 \times 10^{-12}$
$\mu^-\mathrm{Au} \to e^-\mathrm{Au}$	$< 7 \times 10^{-13}$
$\mu^+e^- \to \mu^-e^+$	$< 3.0 \times 10^{-13}$
$\tau \to e\gamma$	$< 3.3 \times 10^{-8}$
$\tau^- \to \mu\gamma$	$< 4.4 \times 10^{-8}$
$\tau^- \to e^-e^+e^-$	$< 2.7 \times 10^{-8}$
$\tau^- \to \mu^-\mu^+\mu^-$	$< 2.1 \times 10^{-8}$
$\tau^- \to e^-\mu^+\mu^-$	$< 2.7 \times 10^{-8}$
$\tau^- \to \mu^-e^+e^-$	$< 1.8 \times 10^{-8}$
$\tau^- \to e^+\mu^-\mu^-$	$< 1.7 \times 10^{-8}$
$\tau^- \to \mu^+e^-e^-$	$< 1.5 \times 10^{-8}$

Process	**Upper limit**
$\pi^0 \to \mu e$	$< 8.6 \times 10^{-9}$
$\mathrm{K}^0_\mathrm{L} \to \mu e$	$< 4.7 \times 10^{-12}$
$\mathrm{K}^+ \to \pi^+\mu^+e^-$	$< 2.1 \times 10^{-10}$
$\mathrm{K}^0_\mathrm{L} \to \pi^0\mu^+e^-$	$< 4.4 \times 10^{-10}$
$\mathrm{Z}^0 \to \mu e$	$< 1.7 \times 10^{-6}$
$\mathrm{Z}^0 \to \tau e$	$< 9.8 \times 10^{-6}$
$\mathrm{Z}^0 \to \tau\mu$	$< 1.2 \times 10^{-6}$

The FNAL beam structure is well optimized to Muonic Al



τ_{Al} ~ 864 ns: τ_{π} ~ 26 ns:

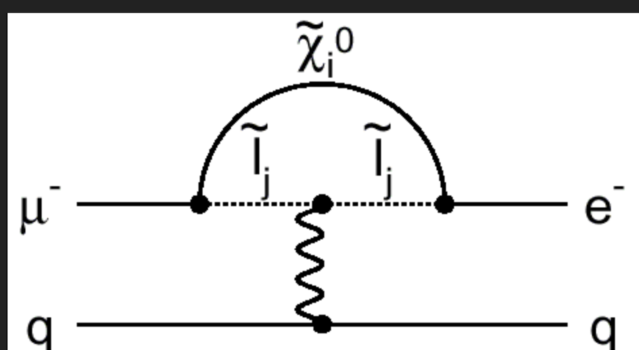
Only 1 in 10 Billion POT will be outside of the pulse window

Prompt background from pion capture is virtually eliminated

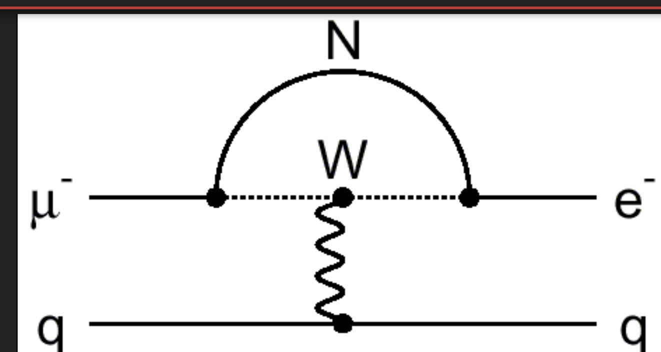
Effective CLFV Lagrangian

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

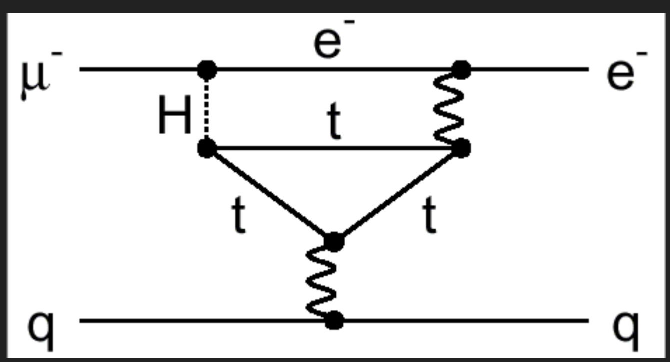
Magnetic moment type operator



Supersymmetry

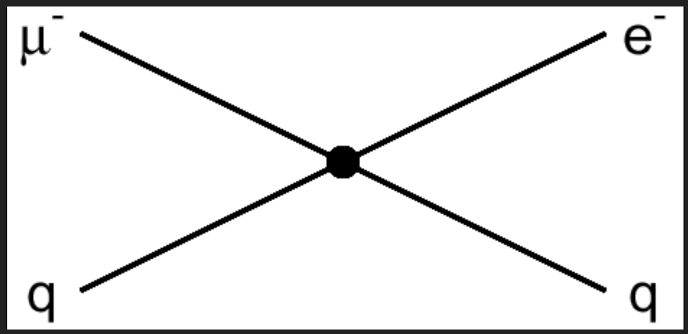


Heavy neutrinos

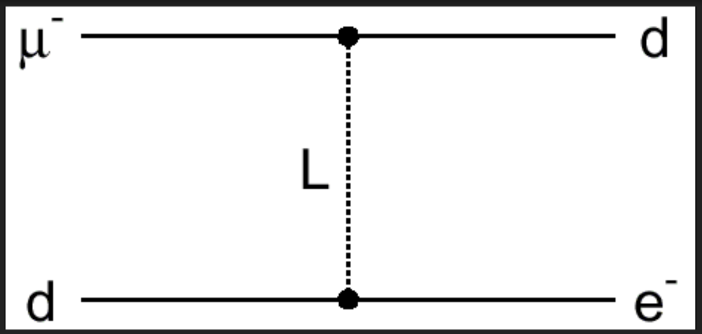


Two Higgs doublets

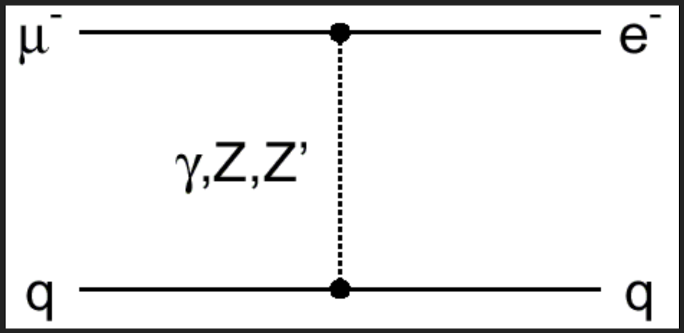
Contact term operator



Compositeness



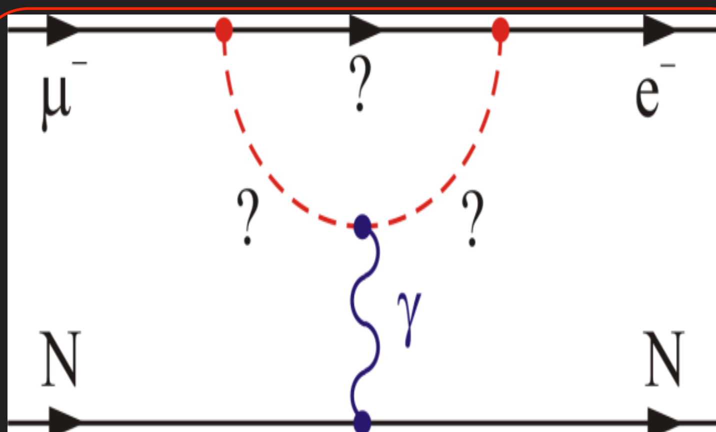
Leptoquarks



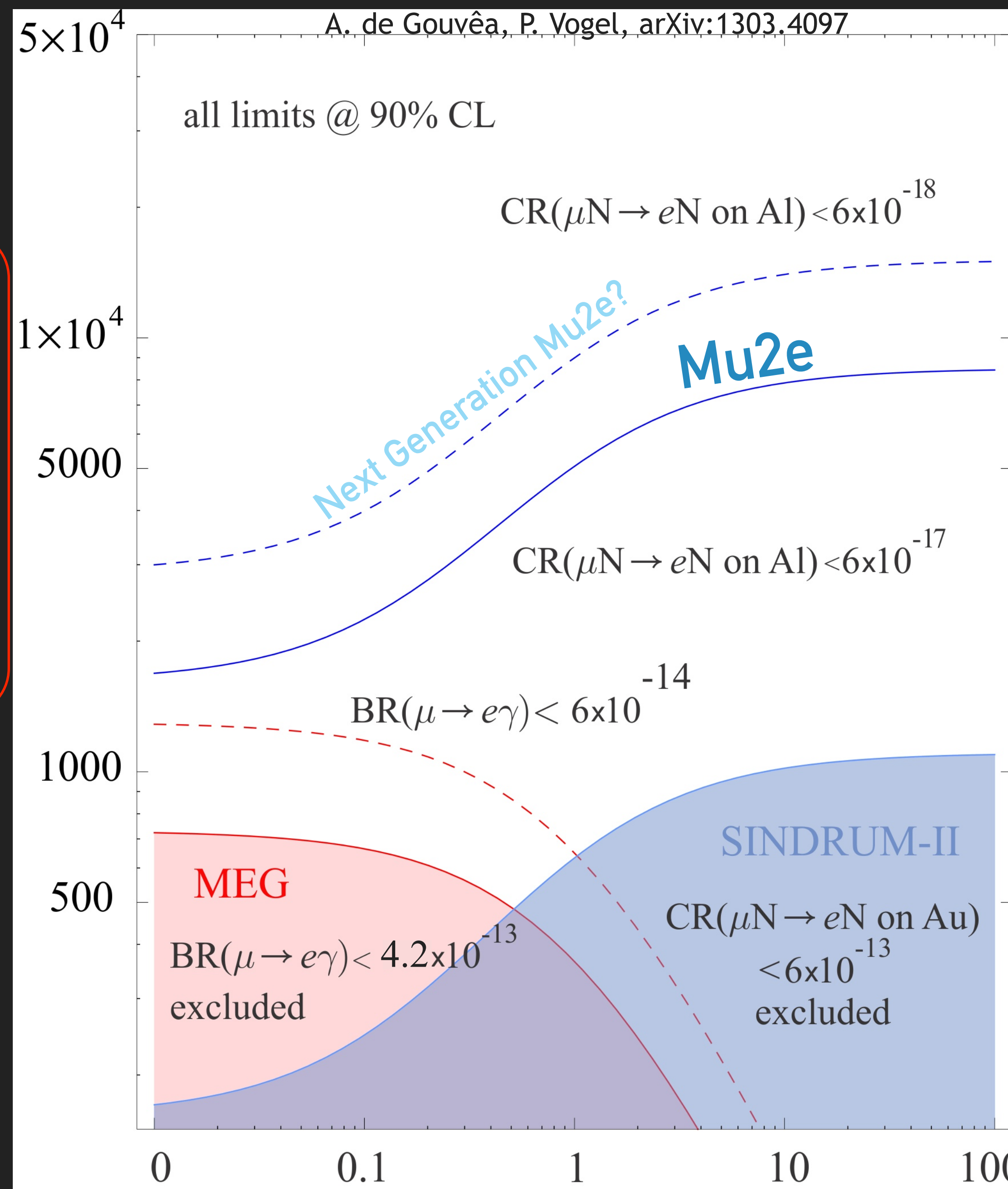
New heavy bosons / anomalous coupling

Effective CLFV Lagrangian

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



κ << 1



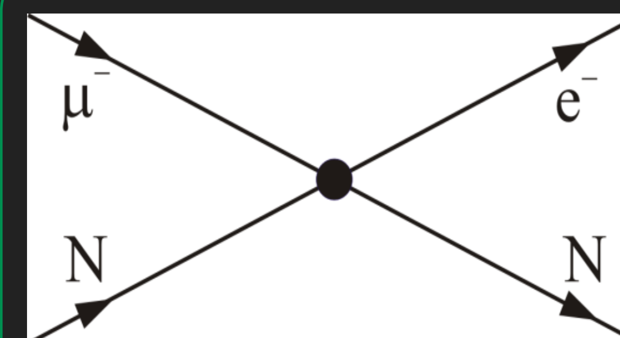
Λ(TeV)

A. de Gouvea, B. Bernstein, D. Hitlin

Loop dominated

K

Contact dominated



κ >> 1

SUSY Sensitivity

★ Vanishingly small effects

★★ Moderate, but visible effects

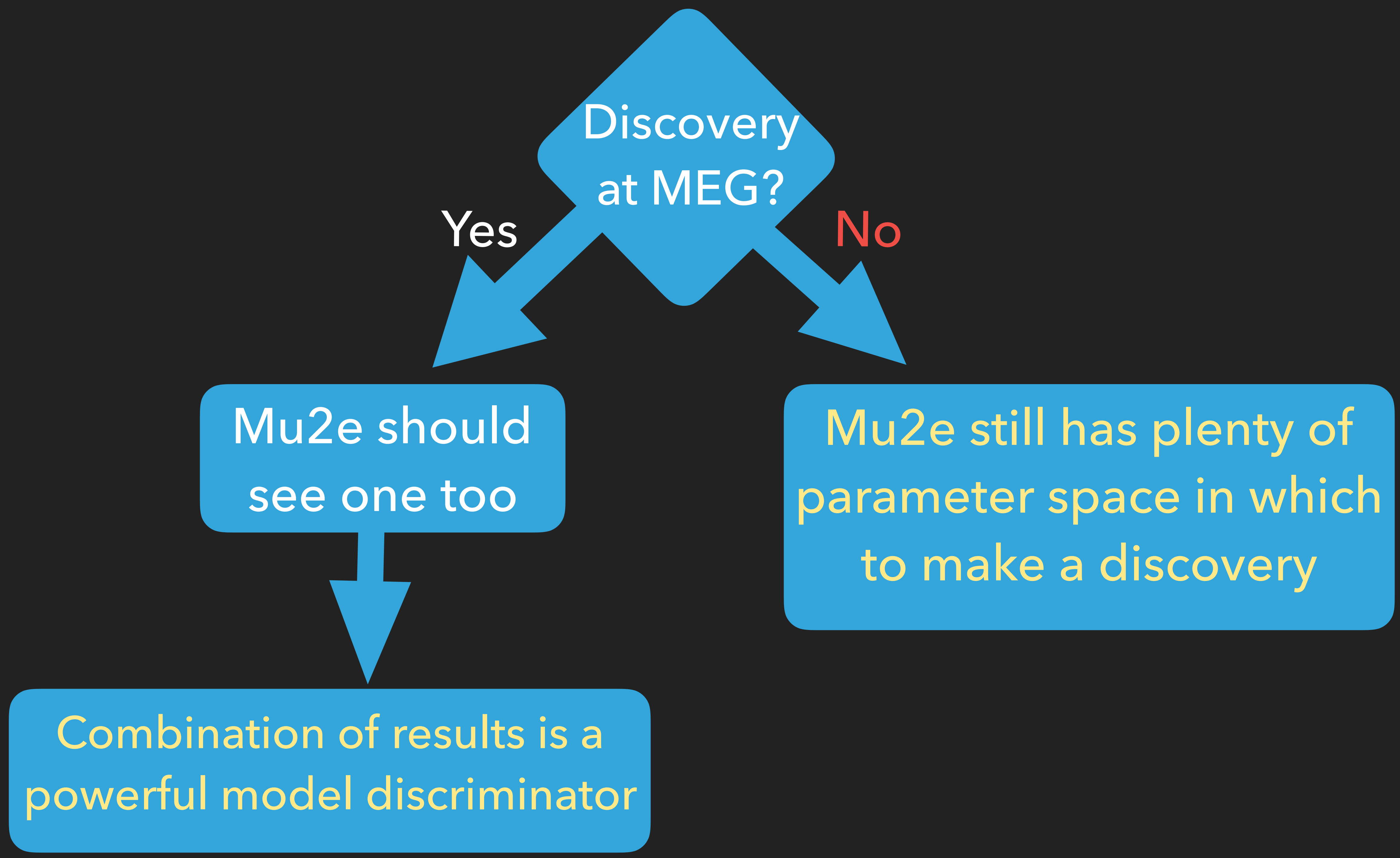
★★★ Large effects

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

Altmannshofer, Buras, *et al*,

Nucl.Phys.B830:17-94, 2010

POSSIBLE SCENARIOS



Mu2e is a potential discovery experiment, relevant in all possible scenarios

END OF BACKUPS