Intro to Mu2e

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Fermilab Training Lectures

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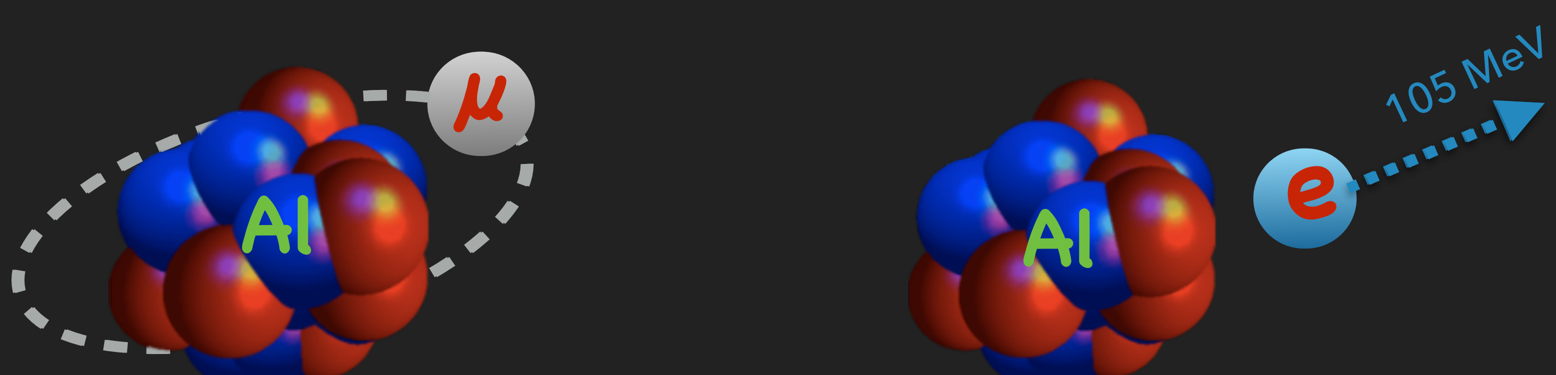
A Search

- Mu2e will search for the neutrino-less conversion of a muon into an electron, within the vicinity of a nucleus, $\mu N \rightarrow eN$
  - *Unprecedented sensitivity: 10,000-fold improvement on the world's best!*
- We will have sensitivity to a multitude of predicted New Physics phenomena with mass scales up to 10,000 TeV
  - *Well beyond the reach of colliders*
- We could discover the violation of Flavor Symmetry within the charged leptons
  - *And thereby provide the first unambiguous evidence of physics beyond the Standard Model*



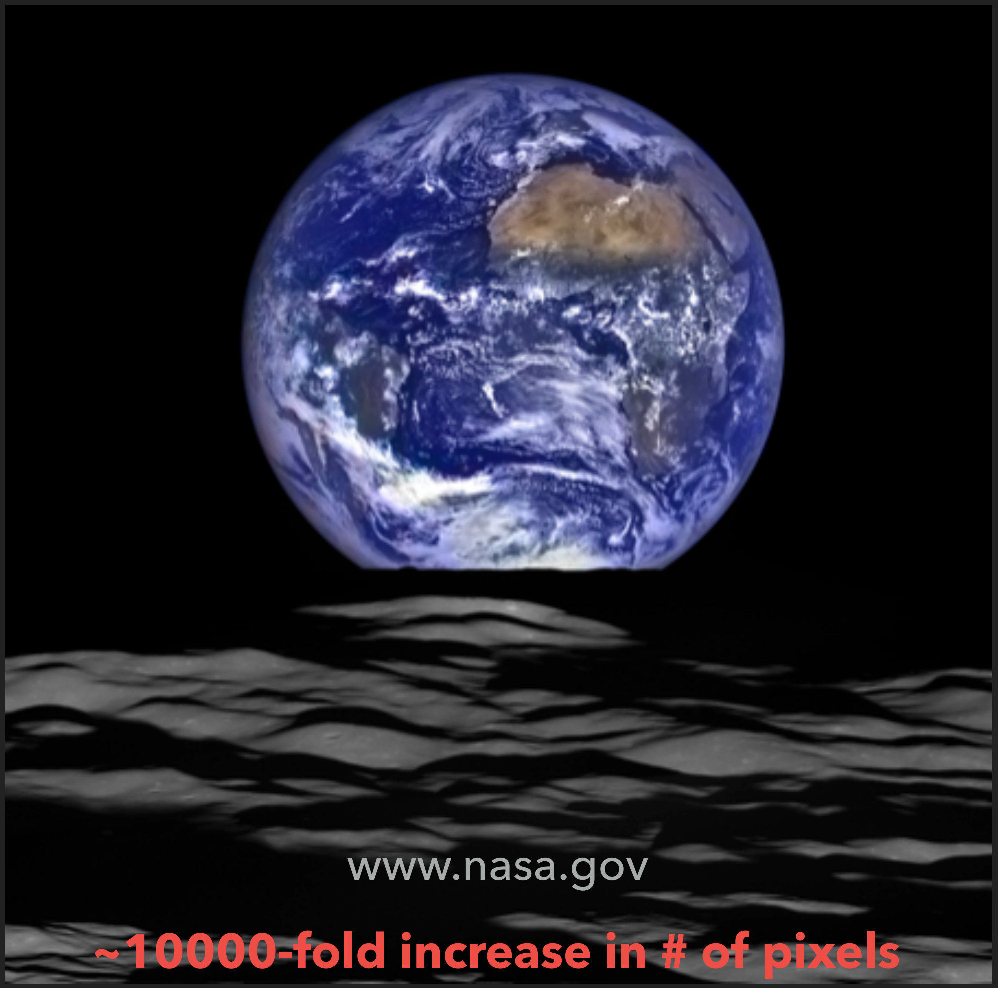
Past Searches

- Despite nearly eight decades of searching, no one has ever observed a Charged Lepton Flavor Violating (CLFV) reaction
  - *Why search again?*

Thanks to Nina Hazen, NYC

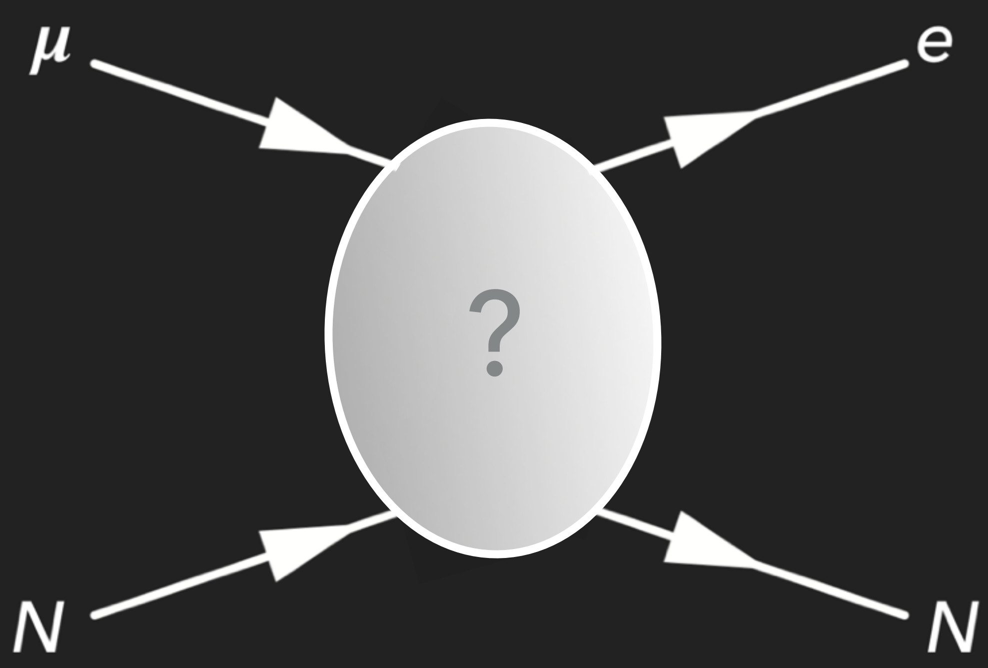
Mu2e's 10000-fold leap in sensitivity will be revealing

- 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 ultimately help guide future experimental and theoretical developments in HEP



We will cover

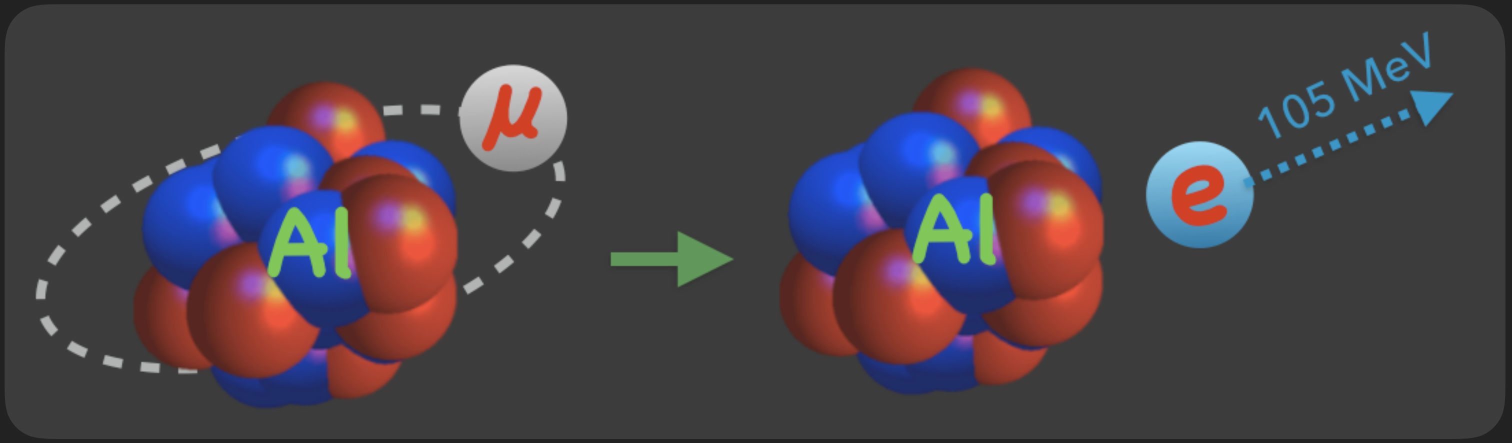
- What will be measured
- Sensitivity & physics reach
- Experimental design
- The future



Mu2e Conversion

- Given a sample of muonic aluminum atoms, how frequently will the muons convert into electrons, without any flavor-conserving neutrinos?
  - We'll quantify this shortly!
- We know from previous experiments that this happens for fewer than 1 in 10^{12} muonic aluminum atoms!

Conversion < 10^{-12}



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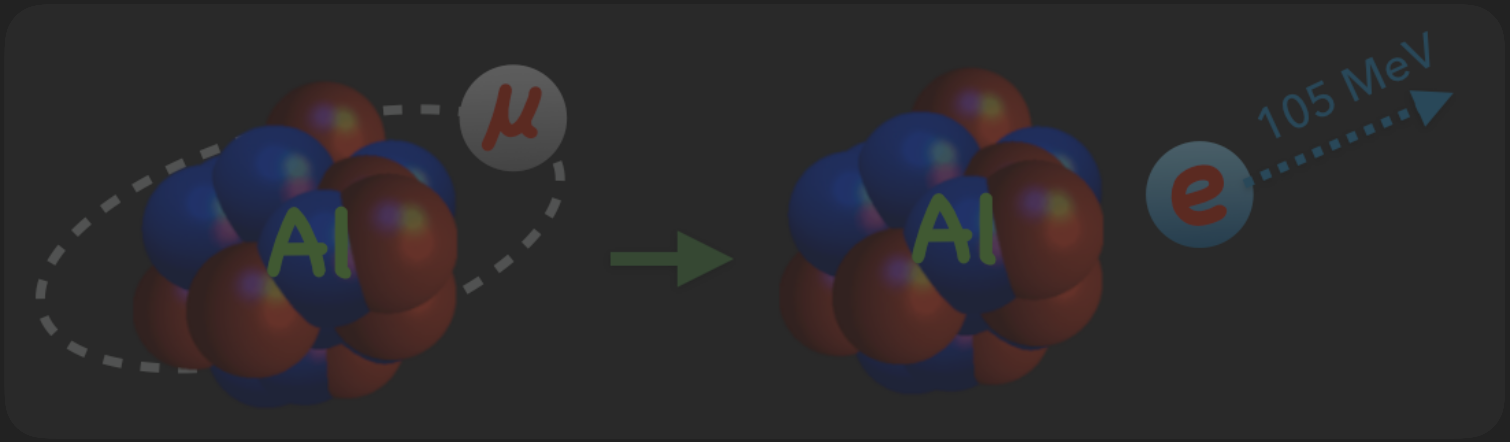
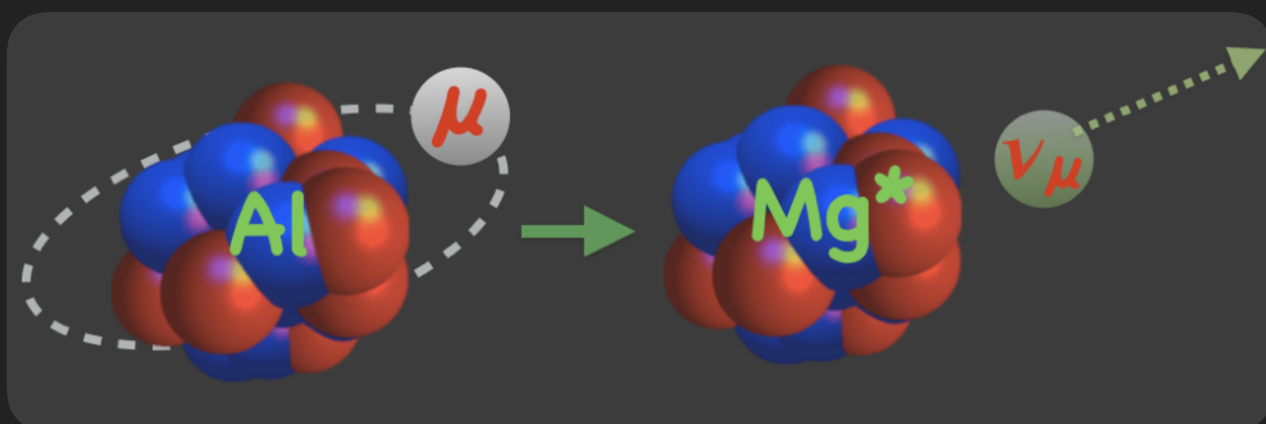
So what else will happen?

Conversion $< 10^{-12}$

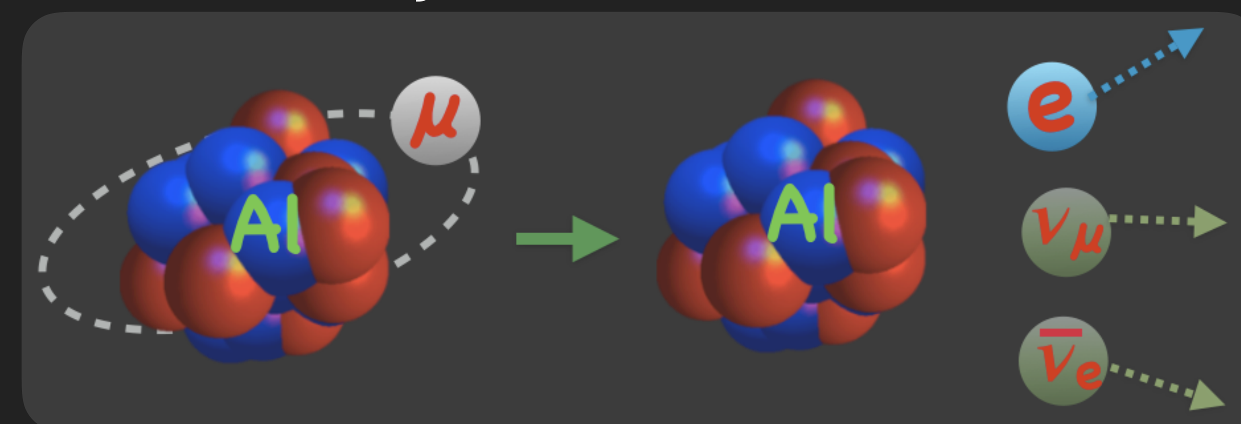


What else will muonic Al do?

Nuclear Capture ~ 61%



Decay In Orbit (DIO) ~ 39%



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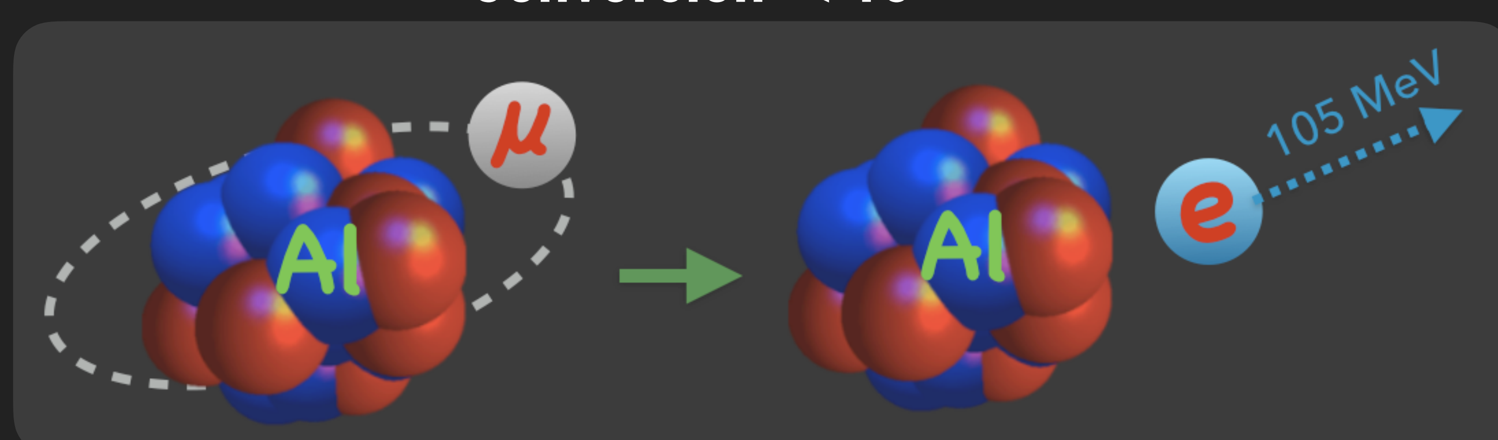

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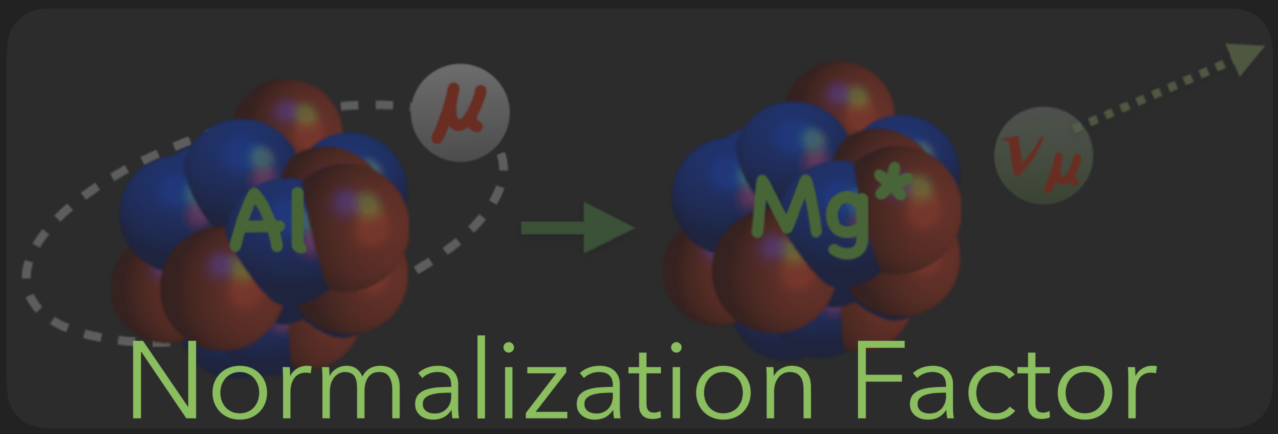

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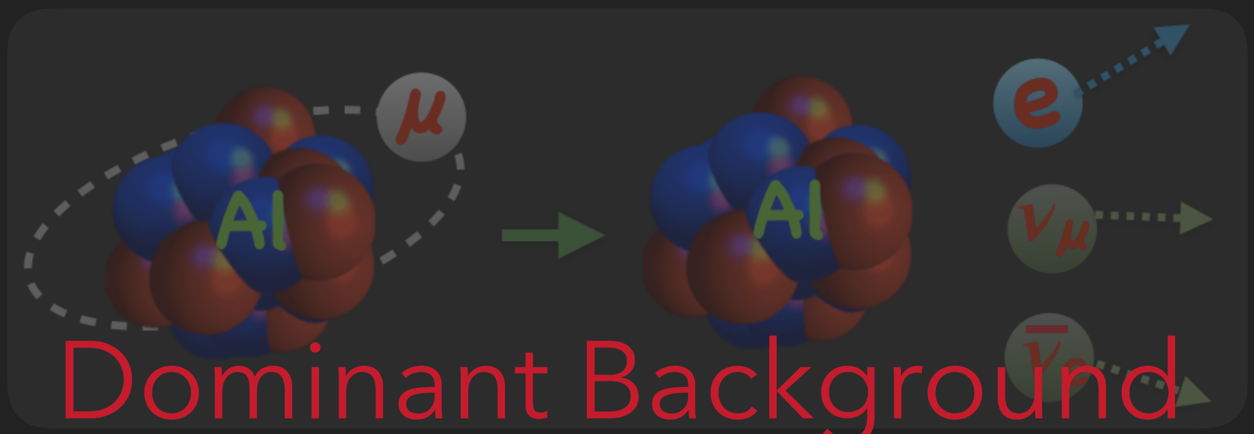

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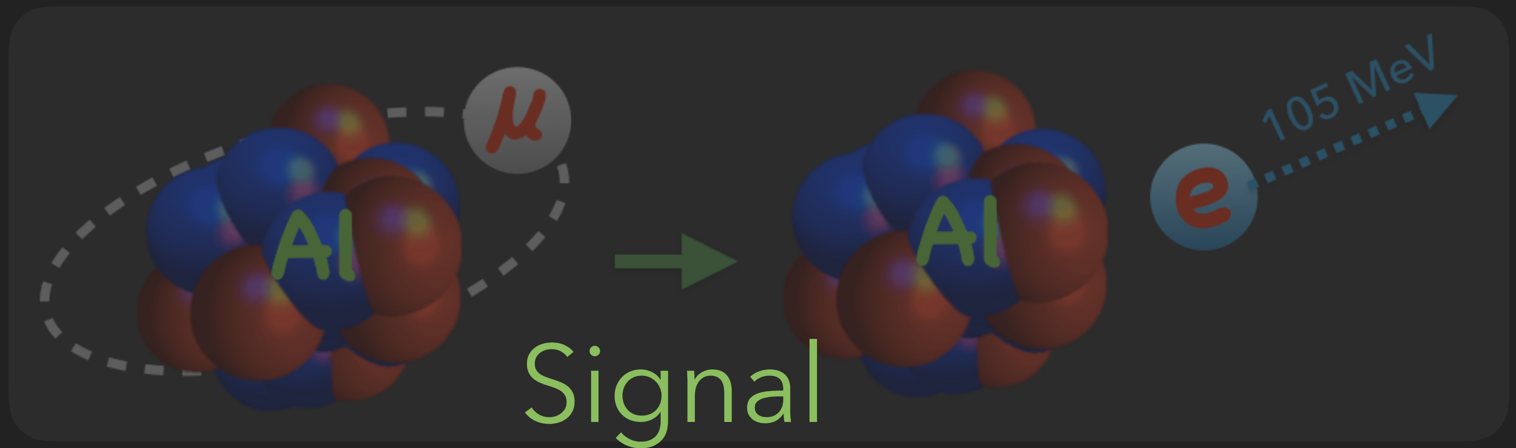
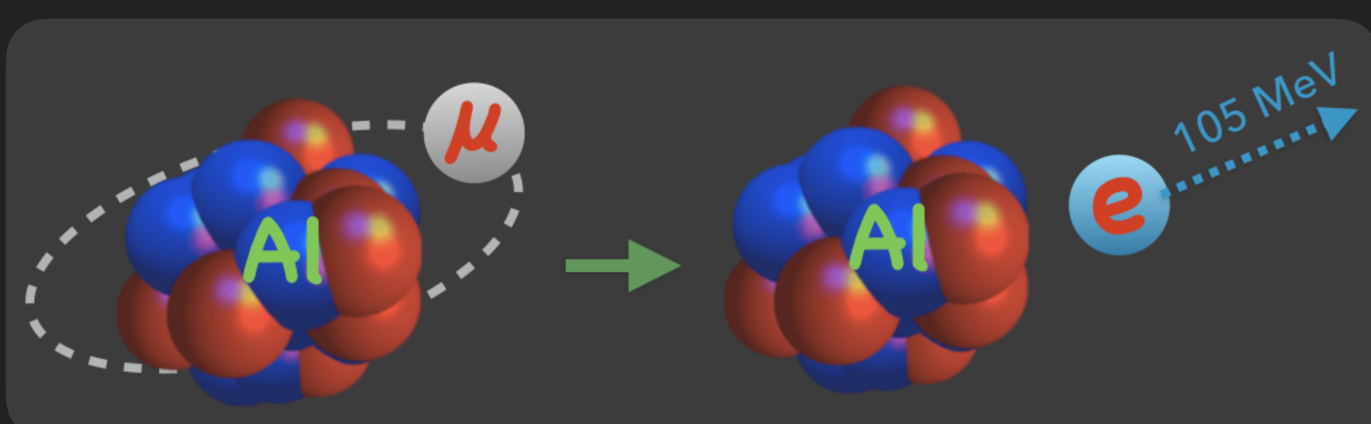


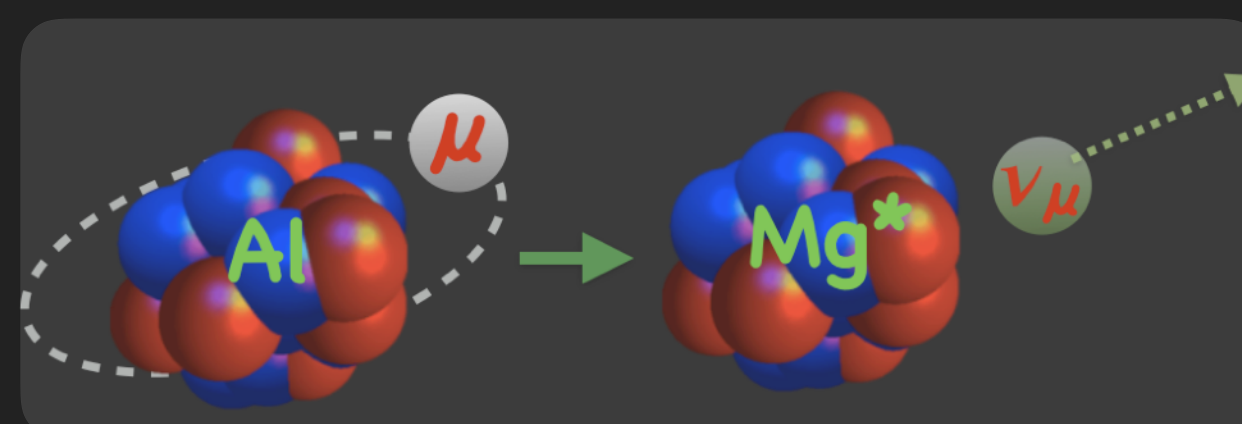
Muon to electron conversion rate: $R_{\mu e}$

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

Numerator: # of conversions



Denominator: # of nuclear captures



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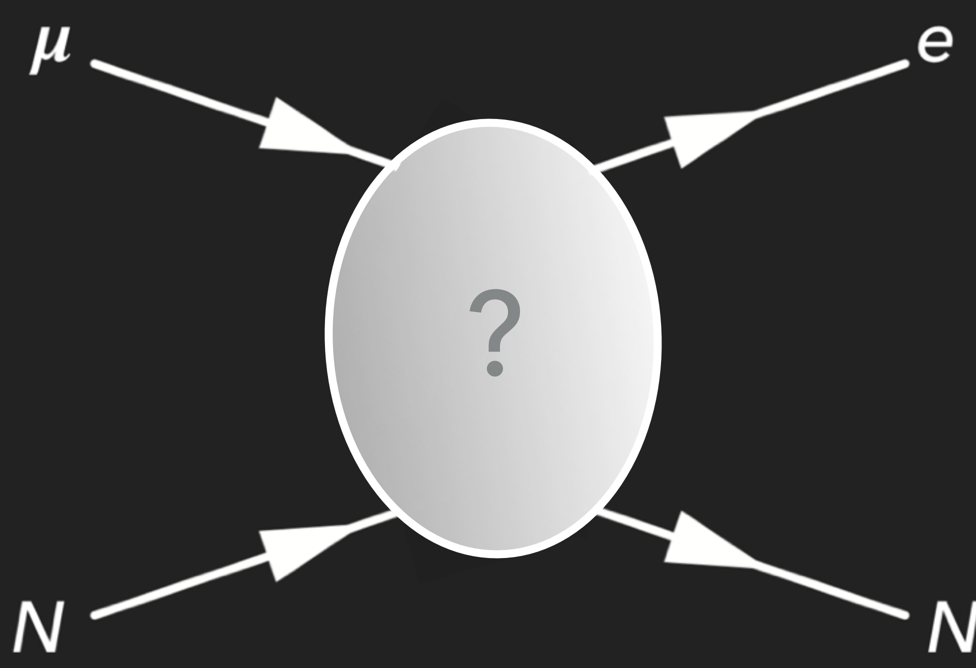
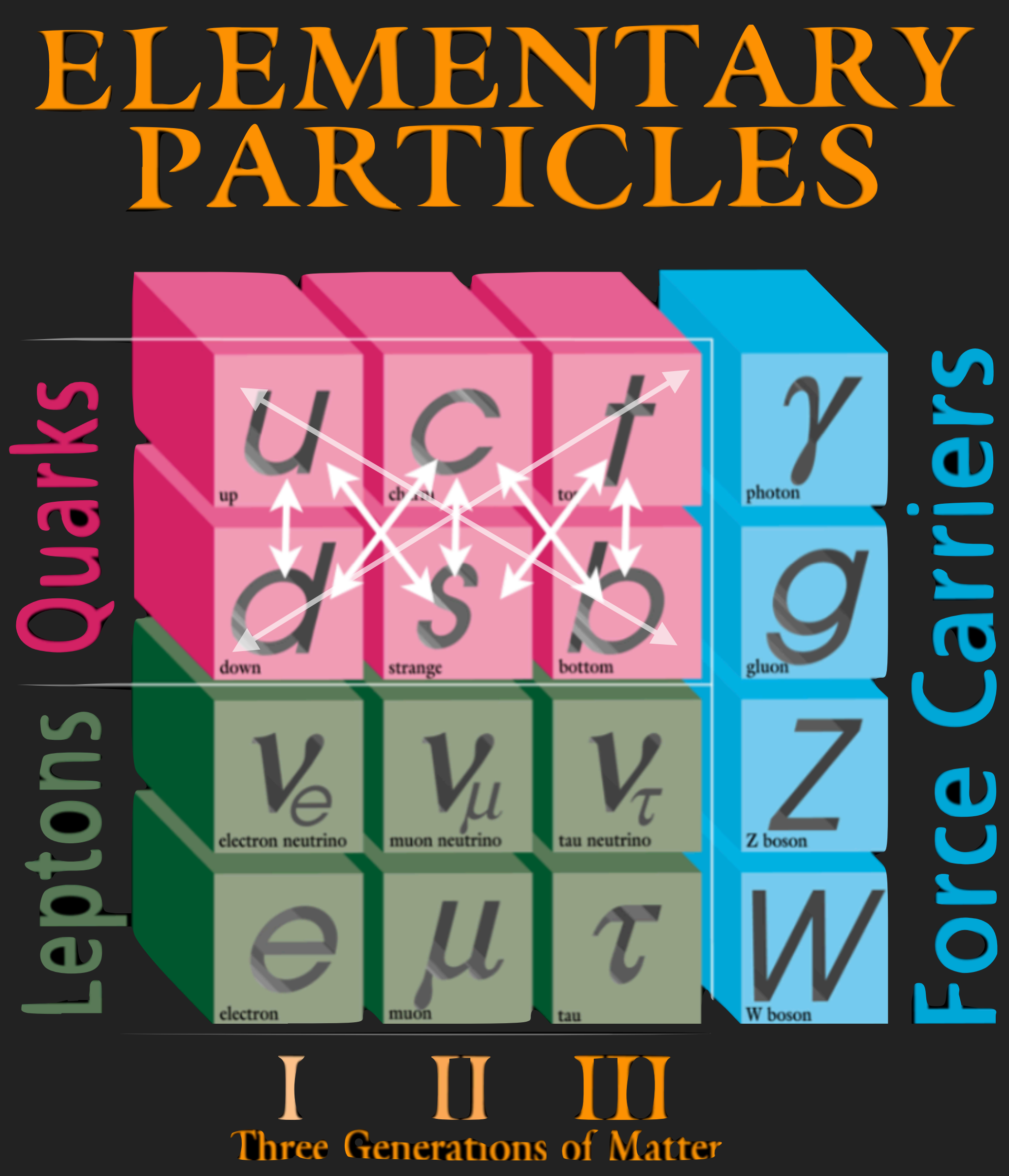


Flavor Violation in the SM

- The quarks commit Flavor Violation
  - They mix via the *W*



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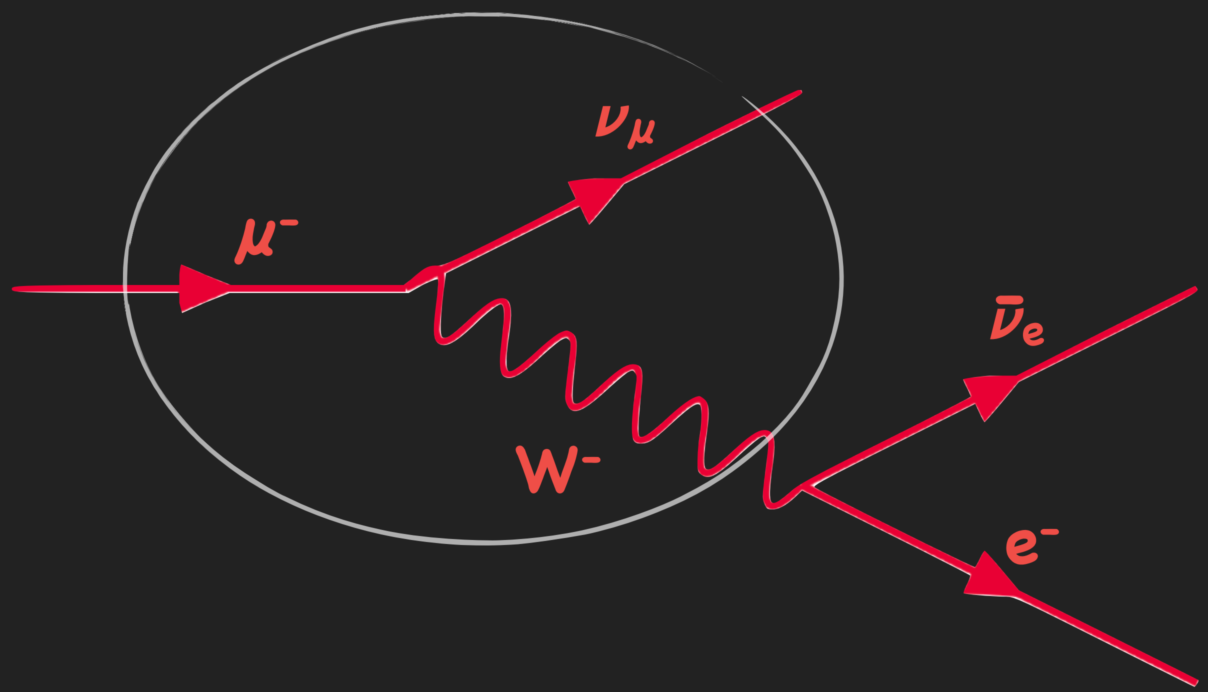

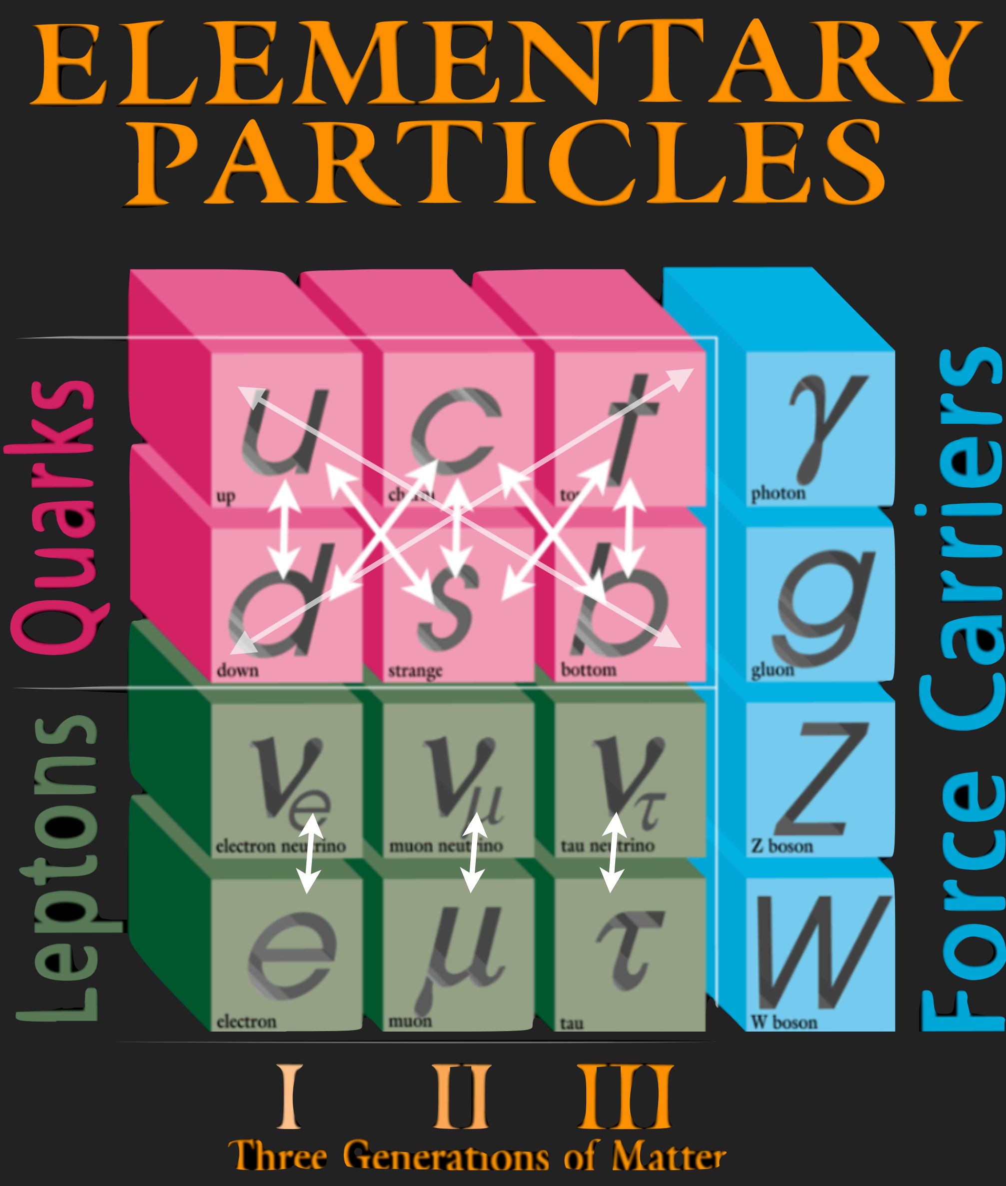

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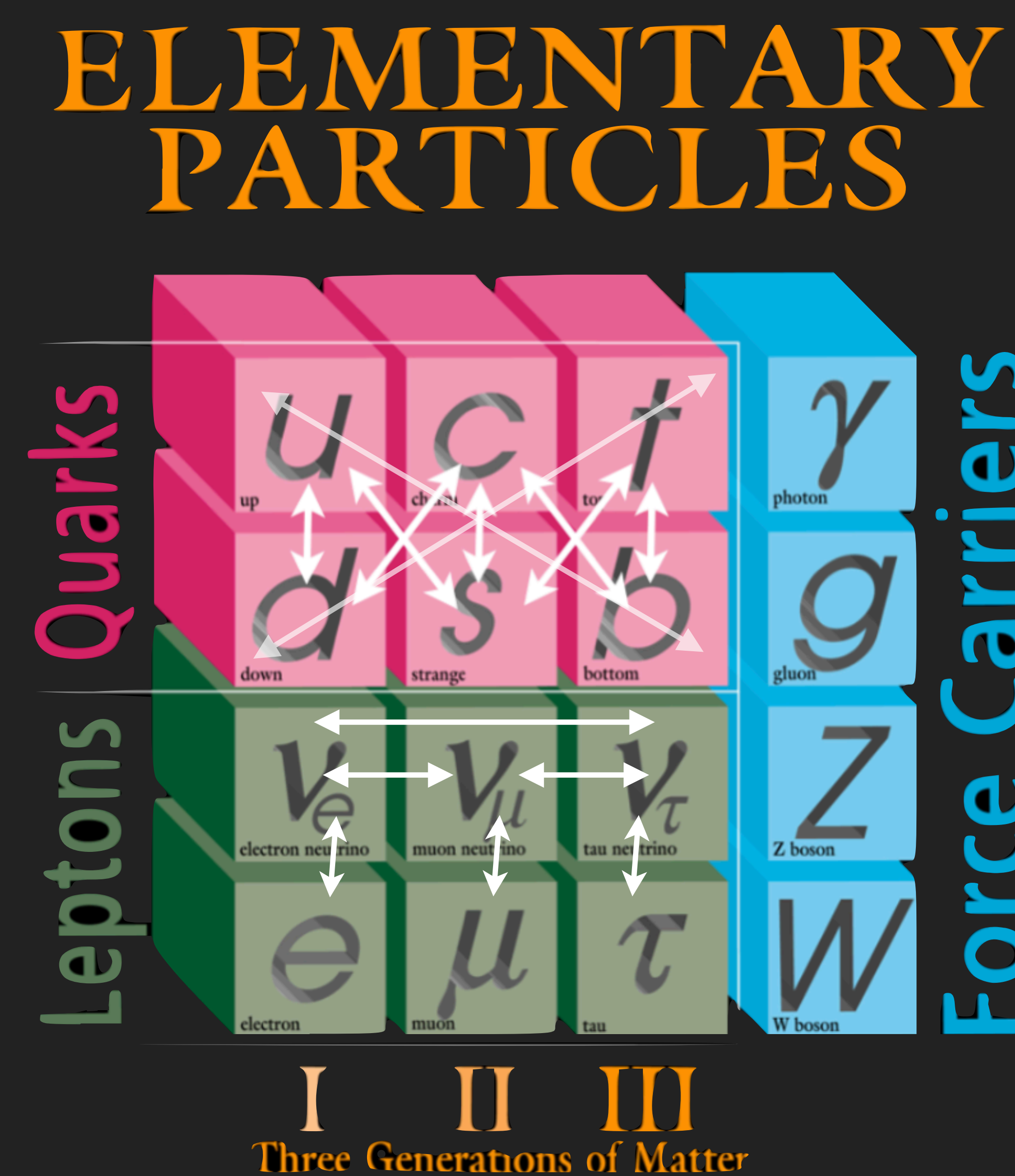

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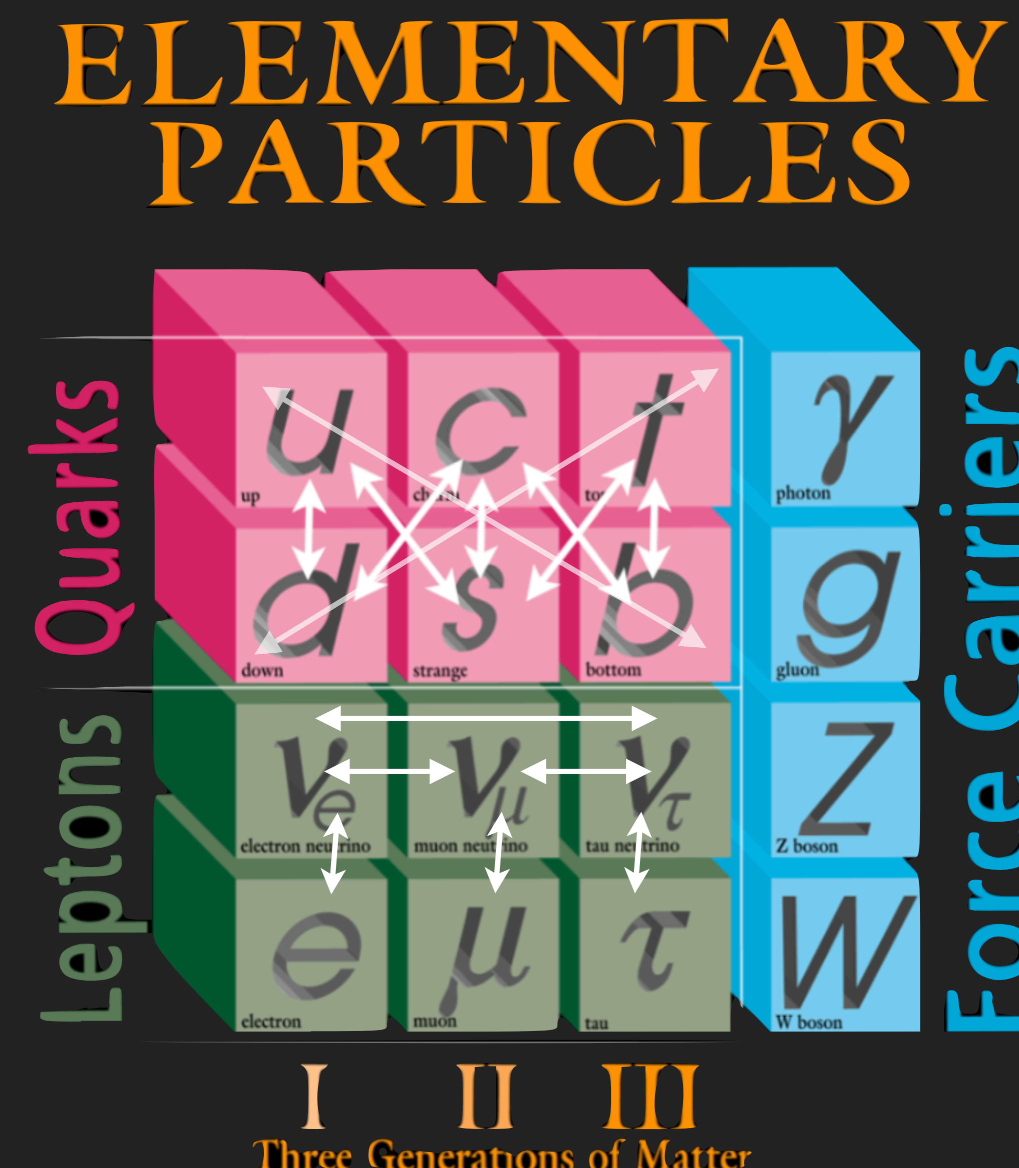
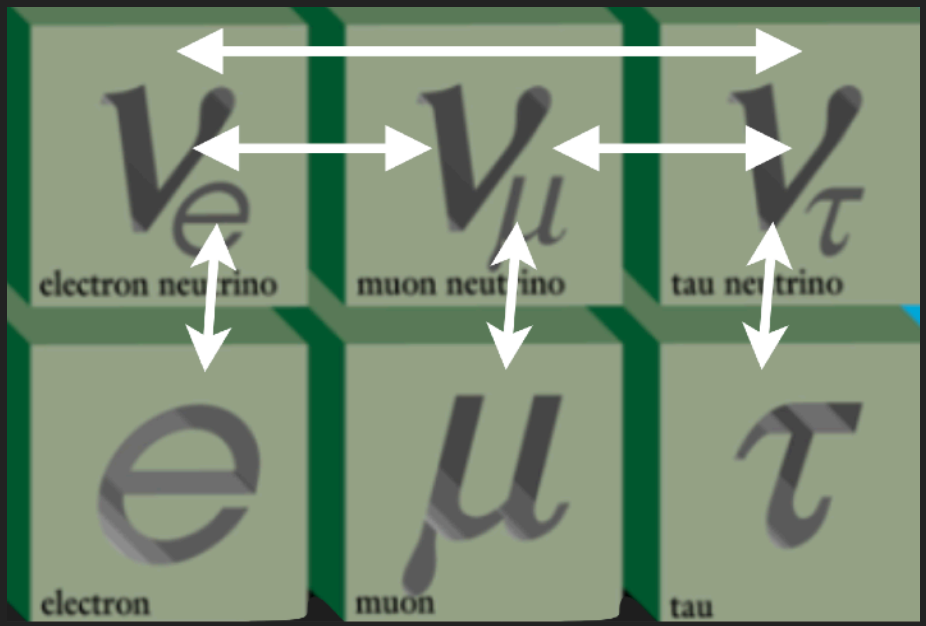


What’s going on with the charged leptons?

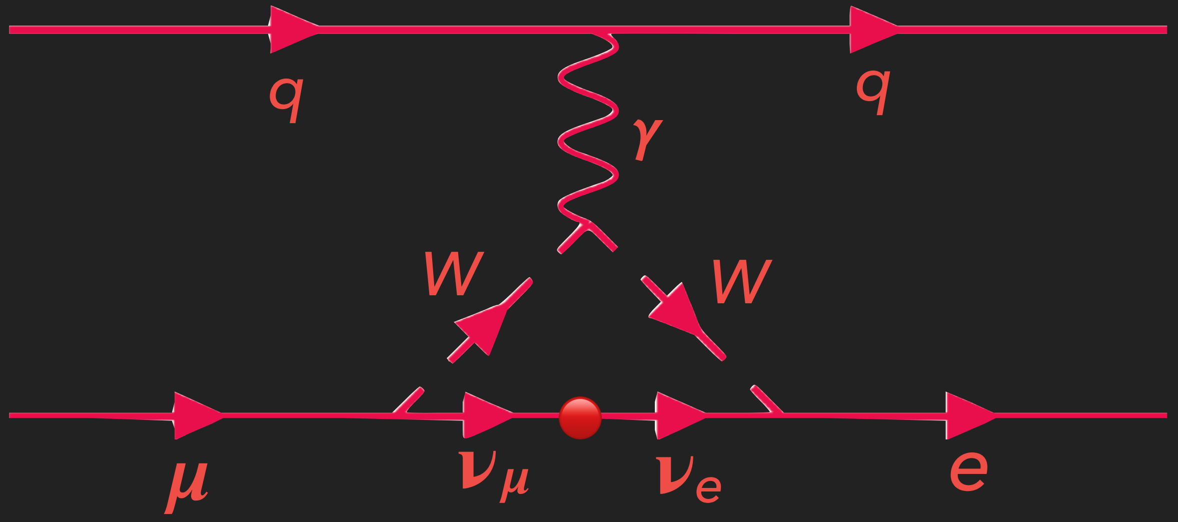
CLFV in the SM

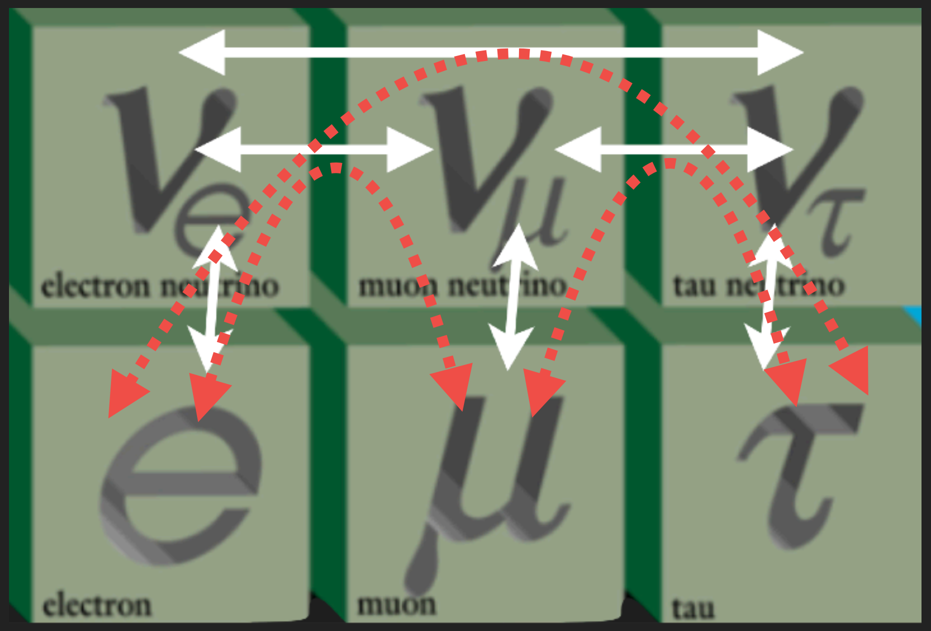
- All CLFV processes are forbidden in the SM
  - i.e. it's impossible to proceed through SM interactions without violating deeper conservation laws
  - But neutrino mixing implies something…



CLVF Must Occur

- Neutrino oscillations *require* CLFV on some level
  - But that level is tiny! ~10^{-50}
  - Because all SM CLFV processes involve loops with *W* and ν
- Science may *never* see this, but therein lies value!
- By the way, we don't understand neutrino mass generation, and the mechanism itself may give rise to *observable* CLFV processes





CLFV Searches

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	
$B^0 \rightarrow e\mu$	BR < 7.8 E-8	
$B^+ \rightarrow K^+ e\mu$	BR < 9.1 E-8	
$\mu^+ \rightarrow e^+\gamma$	BR < 4.2 E-13	10^{-14} (MEG)
$\mu^+ \rightarrow e^+e^+e^-$	BR < 1.0 E-12	10^{-16} (PSI)
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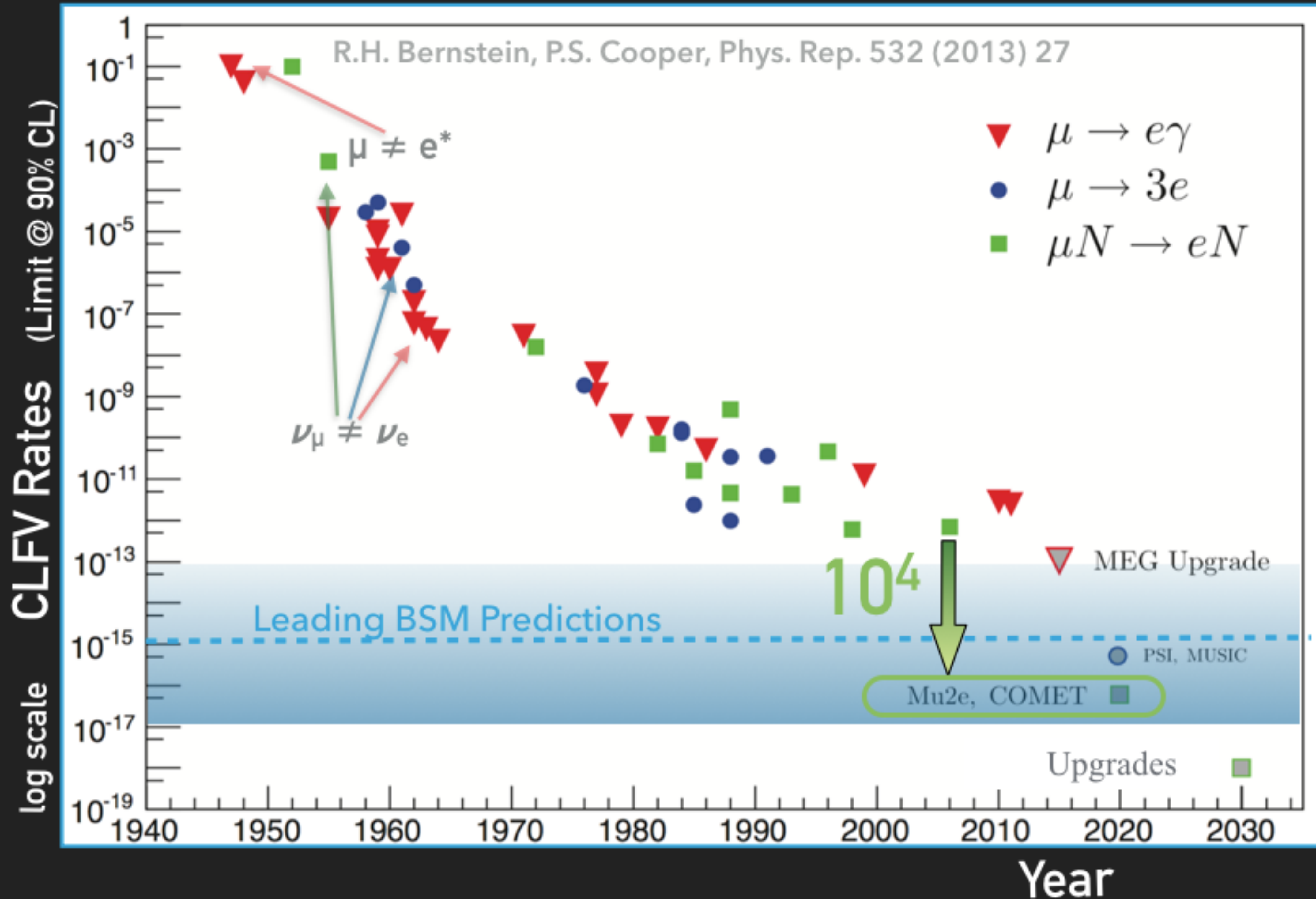
Muons are easy to produce and a have relatively long lifetime, so using them to search for CLFV offers the best combination of New Physics reach and experimental sensitivity

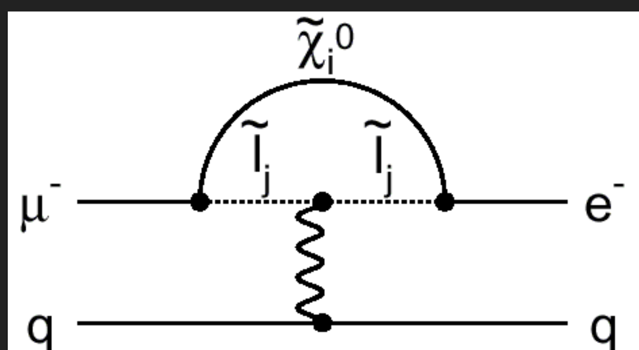
Breaking Through the Plateau… And Beyond the SM?



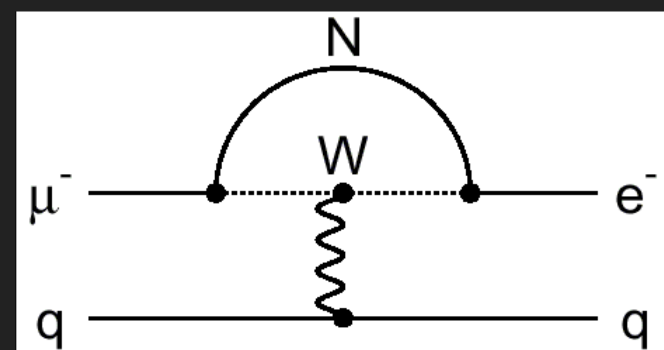
Enhanced $\mu \rightarrow e$ Rates

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

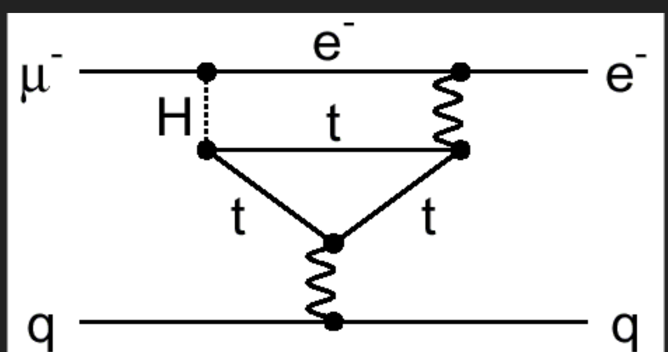
If they are right, we will see ~ 40+ conversions!



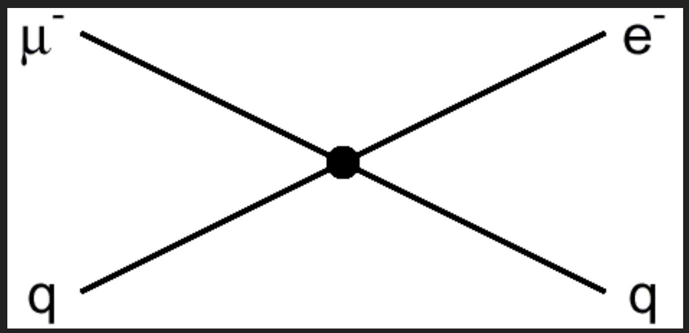
Supersymmetry



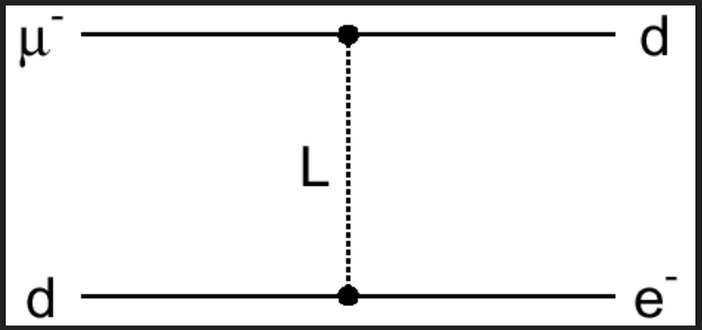
Heavy neutrinos



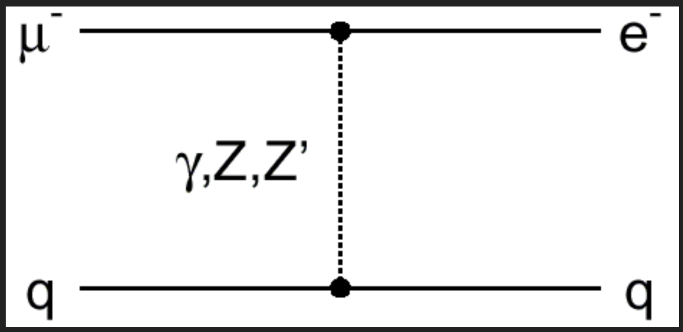
Two Higgs doublets



Compositeness



Leptoquarks



Anomalous coupling

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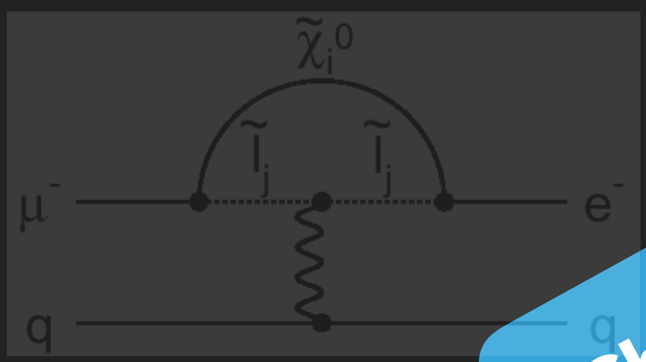
Check out the theory reviews:

Y. Kuno, Y. Okada, 2001

M. Raidal *et al.*, 2008

A. de Gouvêa, P. Vogel, 2013



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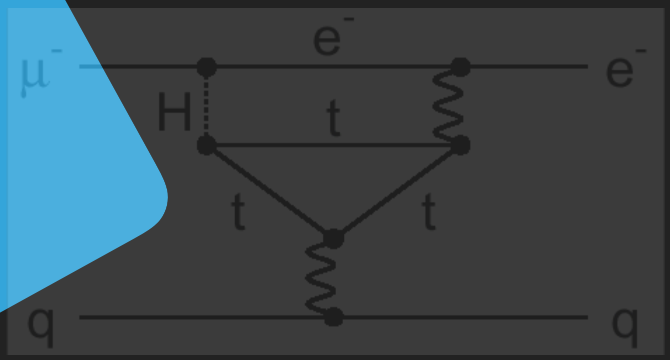

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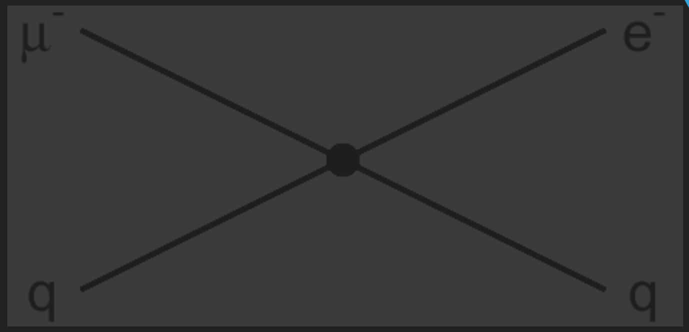

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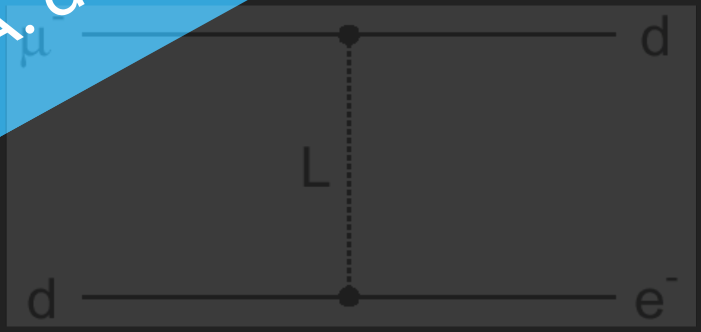

Leptoquarks

Anomalous coupling

Mu2e Sensitivity Summary

- Previous experiments rule out $R_{\mu e} \gtrsim 7 \times 10^{-13}$ @ 90%CL
- Many NP models predict $R_{\mu e} \sim 10^{-14}$ - 10^{-16}
- If $R_{\mu e} \sim 10^{-15}$, we'll will see ~ 40 events
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Experimental details up next!

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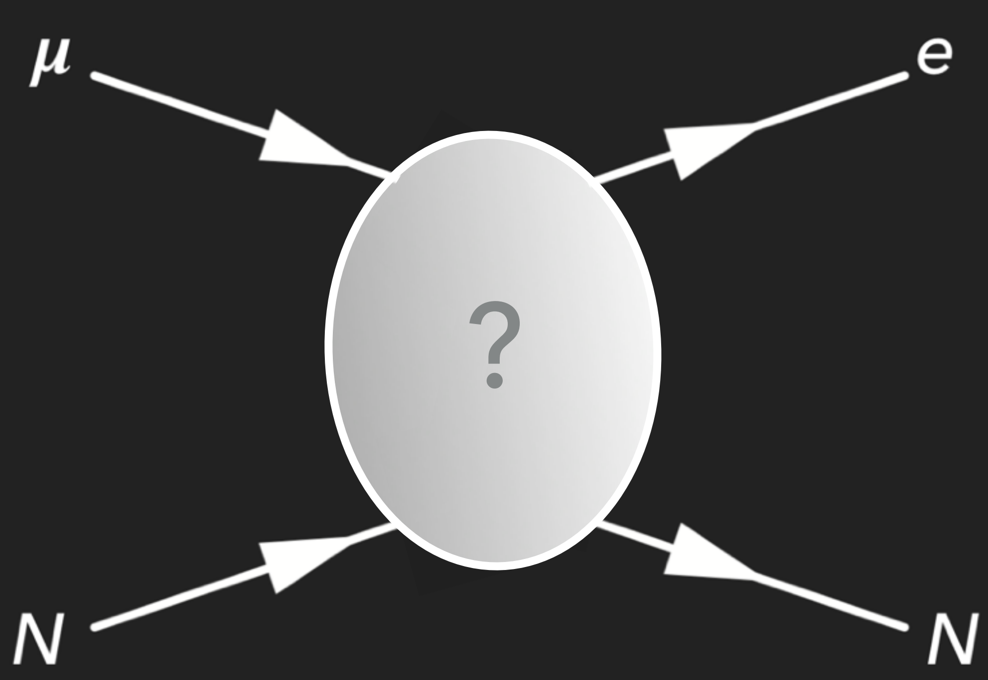
- Sensitivity & physics reach
- Experimental design
- The future

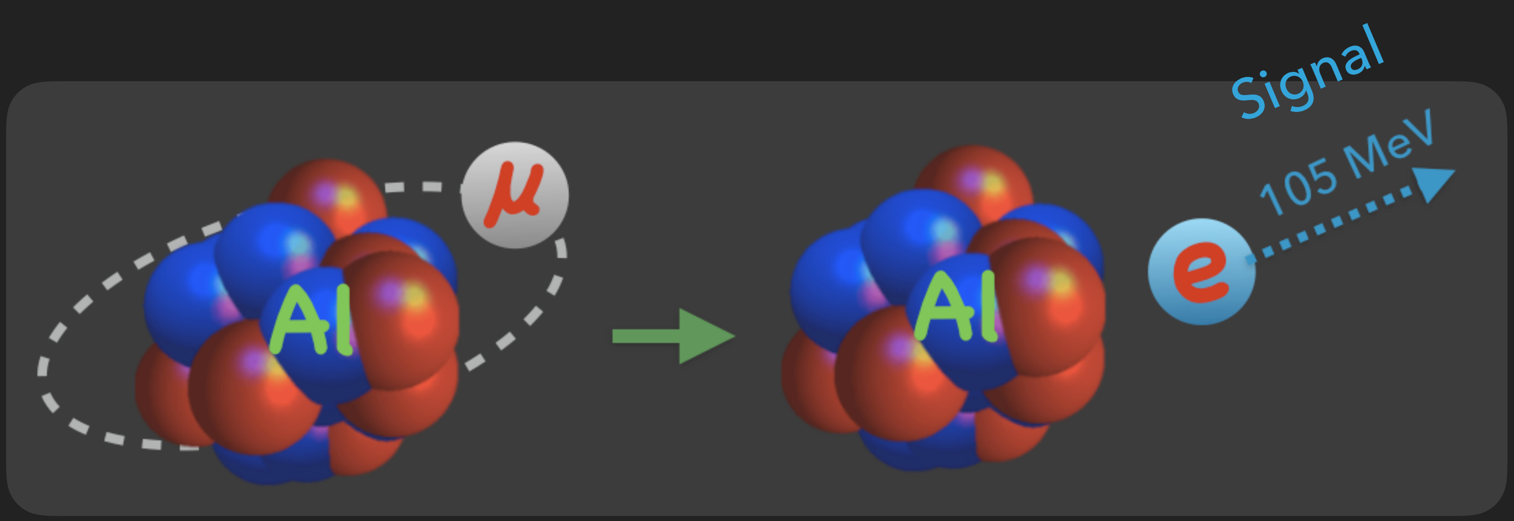


Searching for an ultra rare process

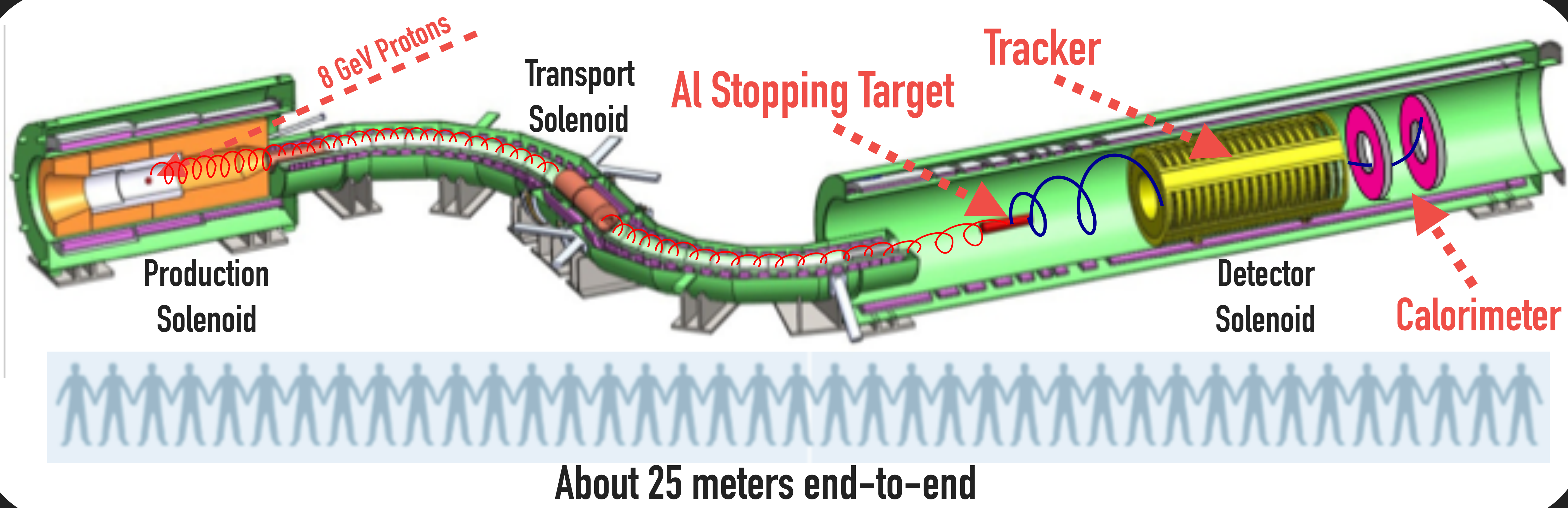
- The conversion we are searching for occurs for fewer than 1 in 10^{13} muonic aluminum atoms
- How can we hope to see this?
  - **Maximize** the number of chances for occurrence
  - Try not to blink! (i.e. **maximize** detection efficiency)
  - **Minimize** false events
  - Count
    - Having no SM background helps!
- Subject to the limitations of resources and ingenuity

The Basic Idea

- Produce **10^{18}** muonic ^{27}Al atoms
  - Irradiate an Al stopping target with a beam of low momentum muons
- Count conversion-like 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 experimental backgrounds



A glance at the detector



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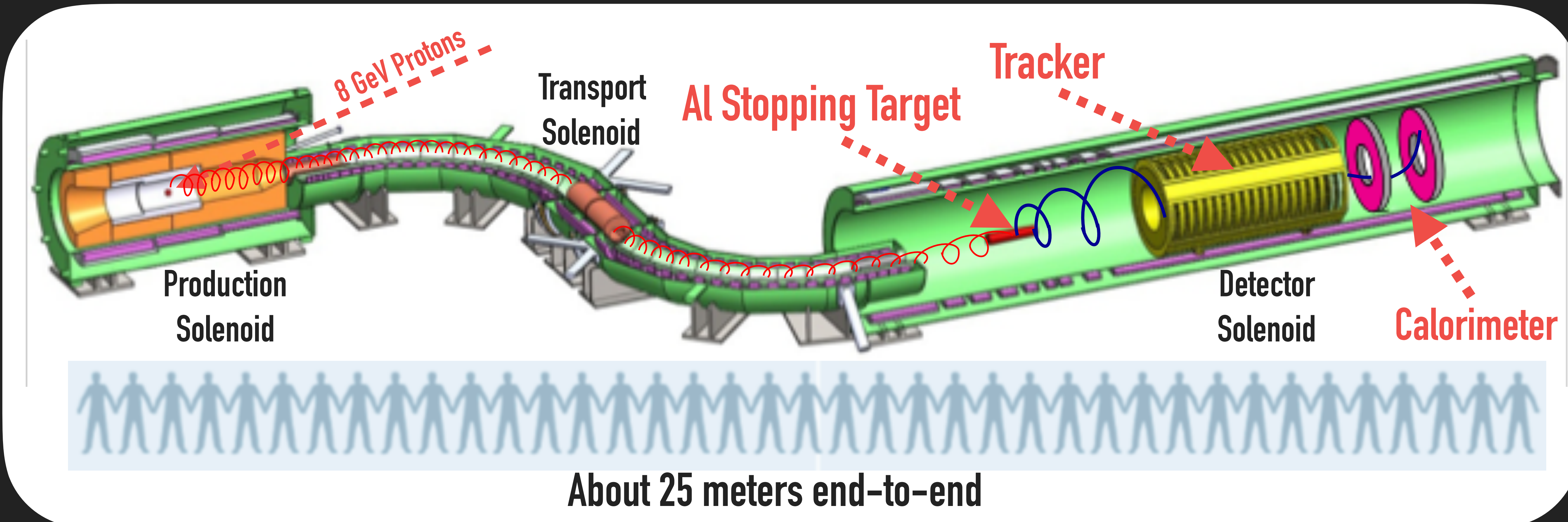
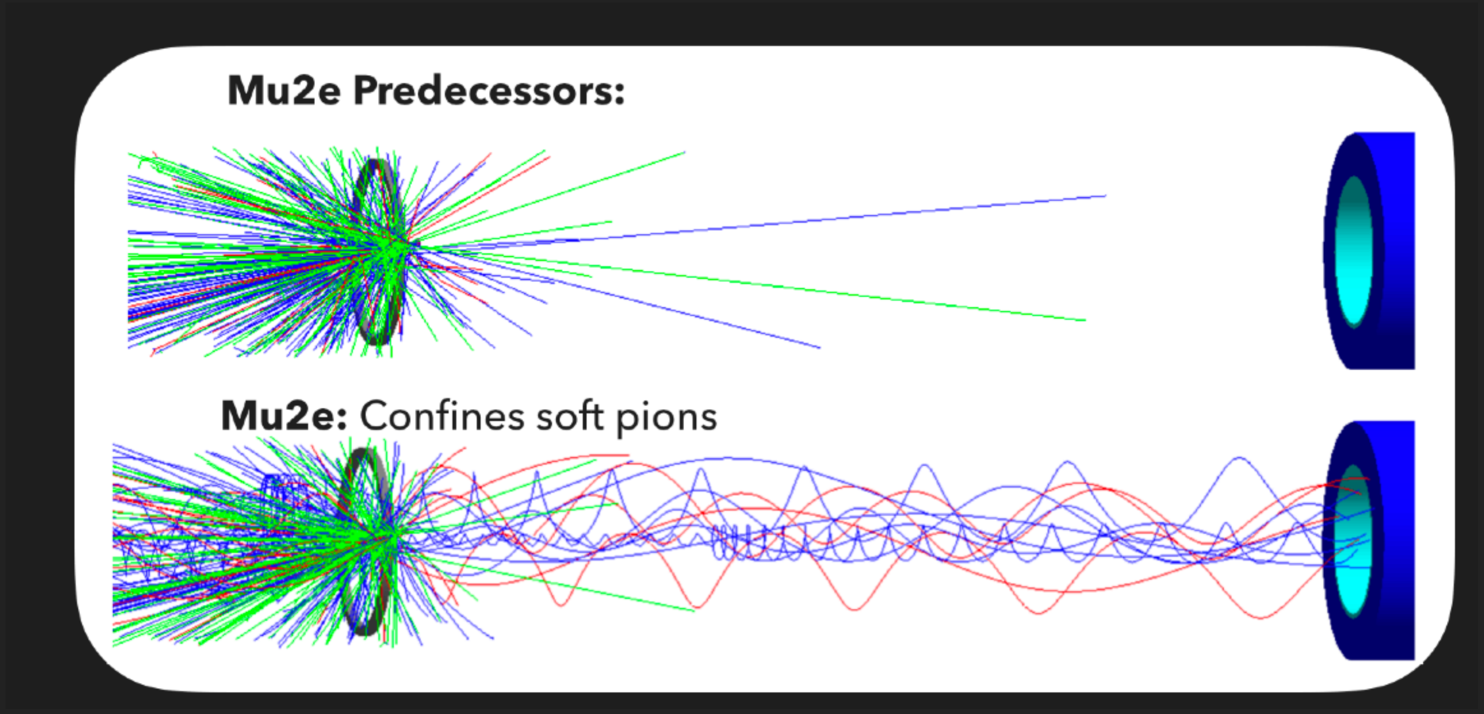


- First issue: scaling from previous experiments, to get 10^{18} muons with an 8 kW proton beam, it seems that we'd have to run for thousands of years
- This brings us to our first big idea

First big idea: the world's hottest muon source

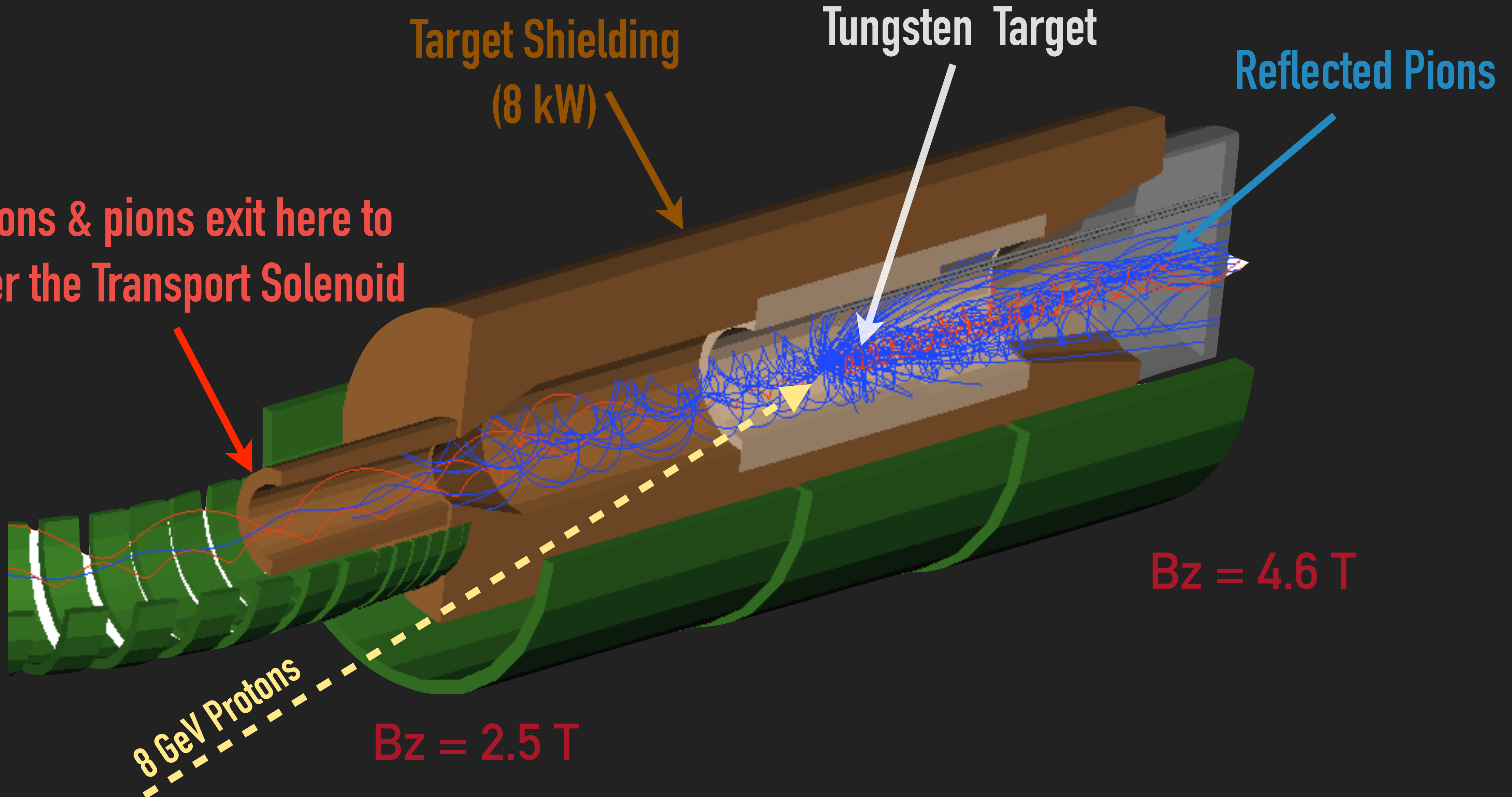
- 8 GeV, 8 kW proton beam Incident on tungsten target
- Confine the soft pions with a solenoidal B-field
- BR($\pi^- \rightarrow \mu^- \nu_\mu$) ~ 99.9%
- Include a strong gradient to increase the yield further through magnetic reflection
- 10^{10} μ/s



Concept originated by R.M. Dzhilkibaev, V.M. Lobashev, Sov.J.Nucl.Phys 49, 384 (1989)

1st incarnation was MELC in Moscow, 2nd was MECO at BNL. Neither ever ran!

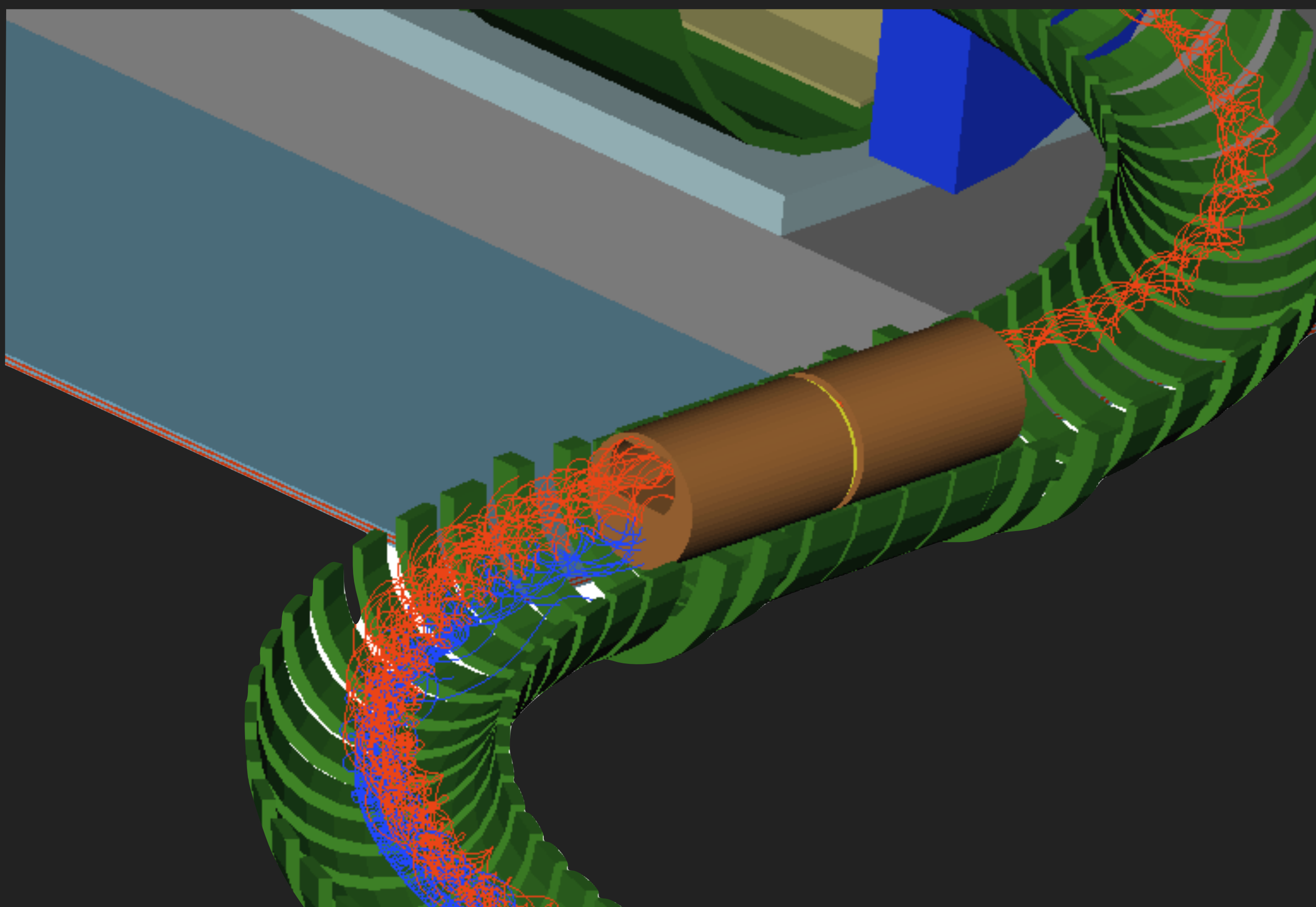
Enter the Production Solenoid



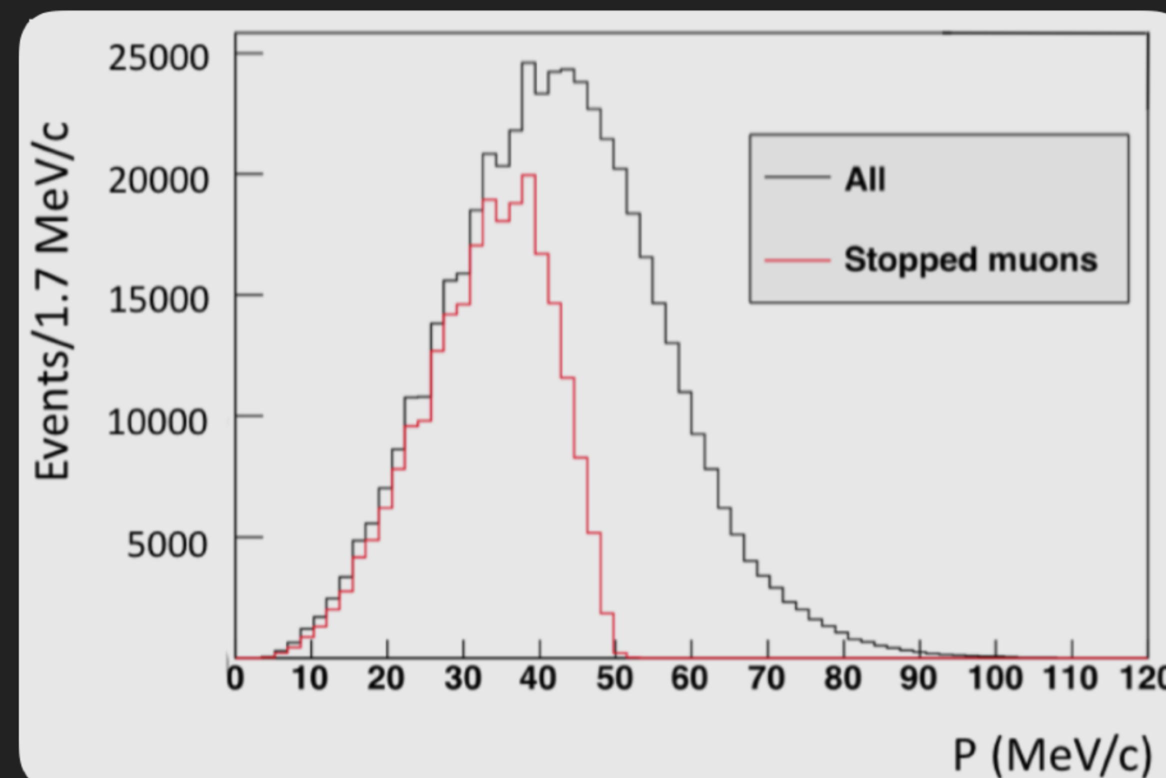
$\tau_{\pi^-} \sim 26$ ns

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

Enter the Transport Solenoid



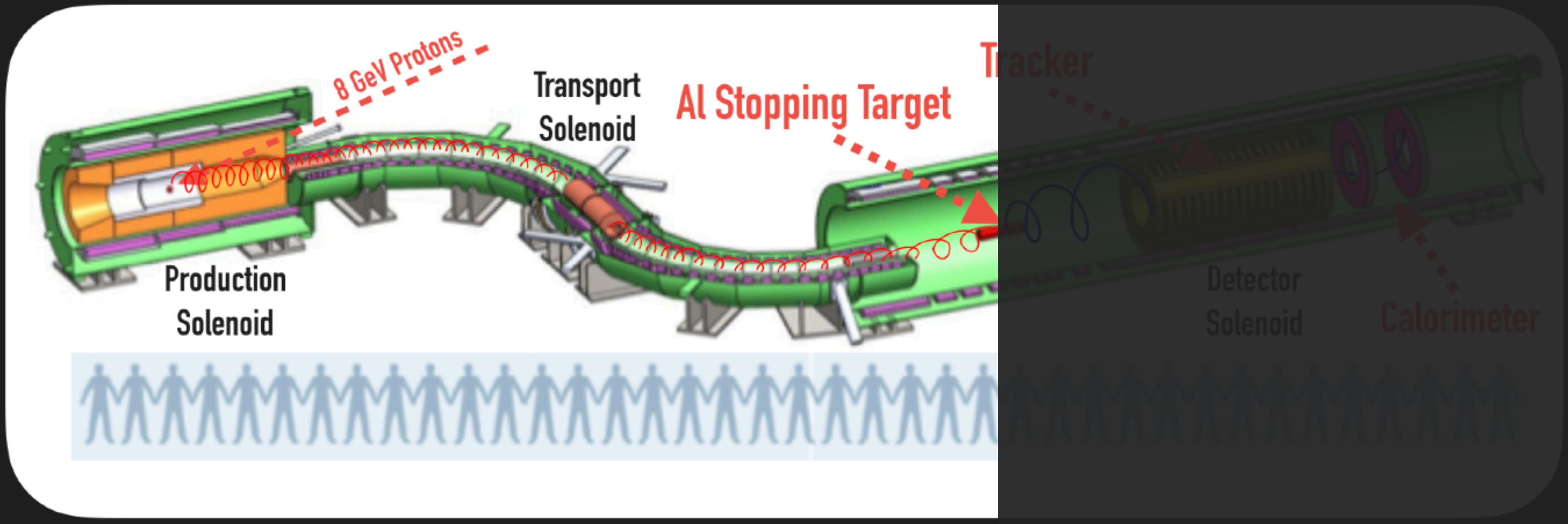
Muon Beam Spectrum

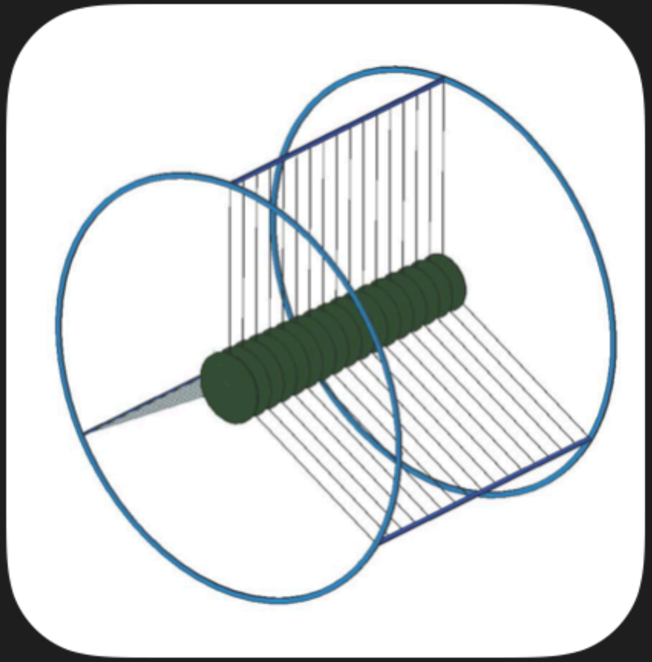


- S-shaped solenoid eliminates line-of-sight transport of photons and neutrons
- Curvature drift and collimators select low-momentum, negative muons

Enter the Detector Solenoid

- Next destination for the beam: the AL stopping target!
- 10^{20} POT in 3 years → 10^{18} stopped μ, as required





Stopping Target

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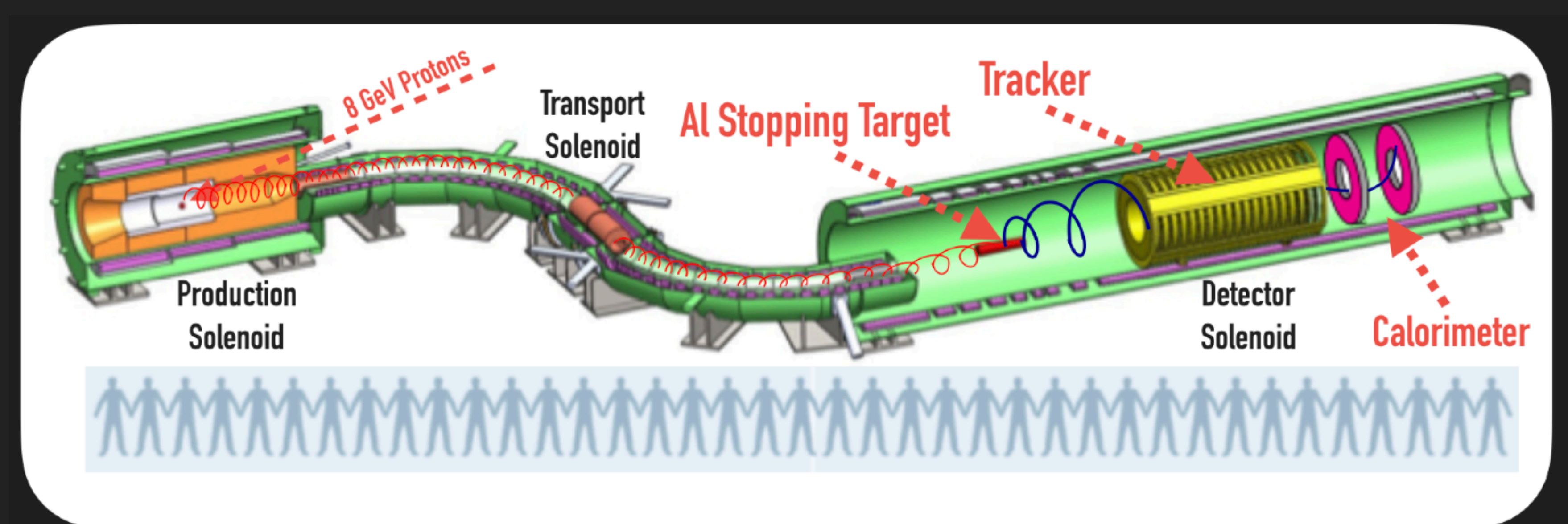

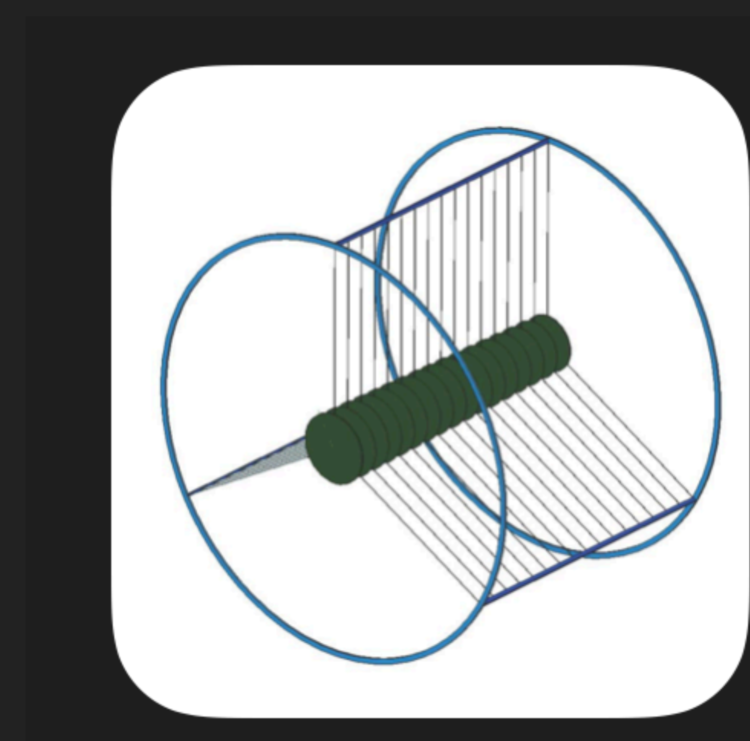

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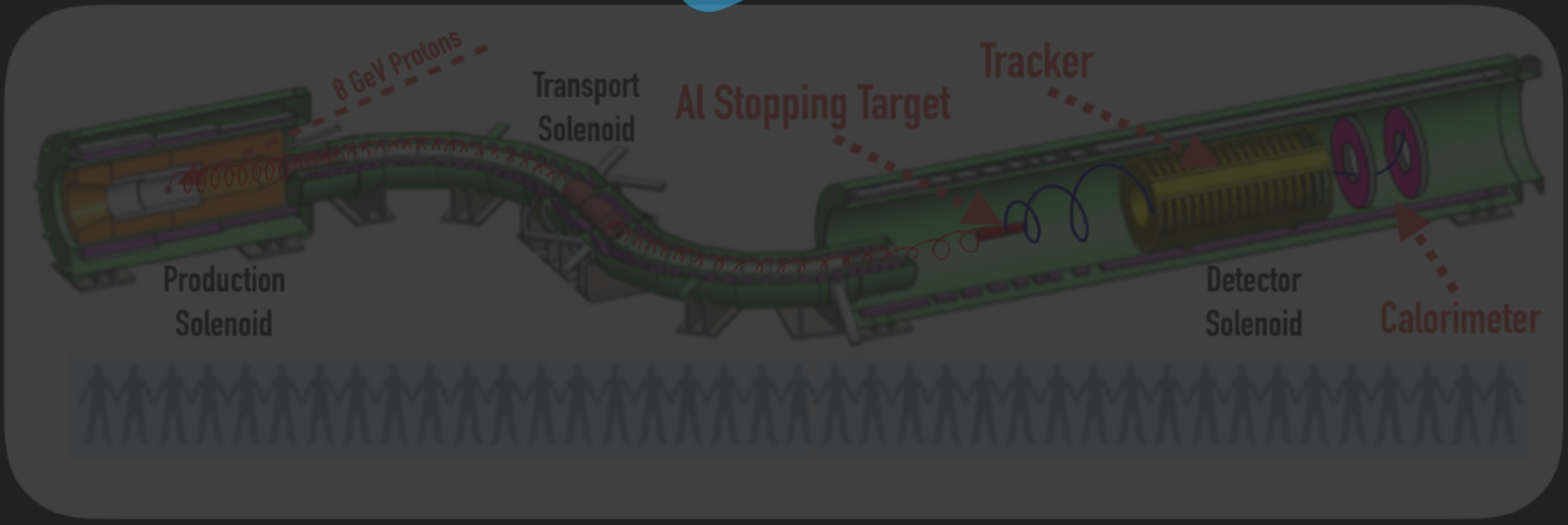
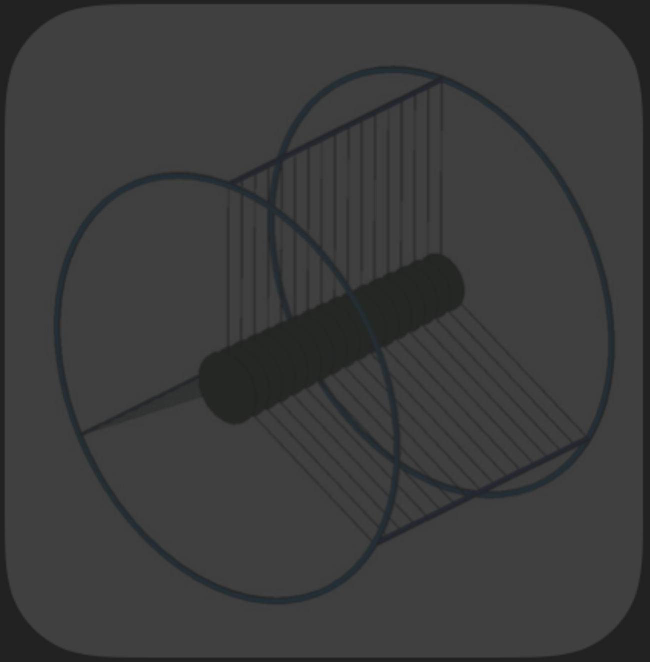
Detection & Backgrounds?

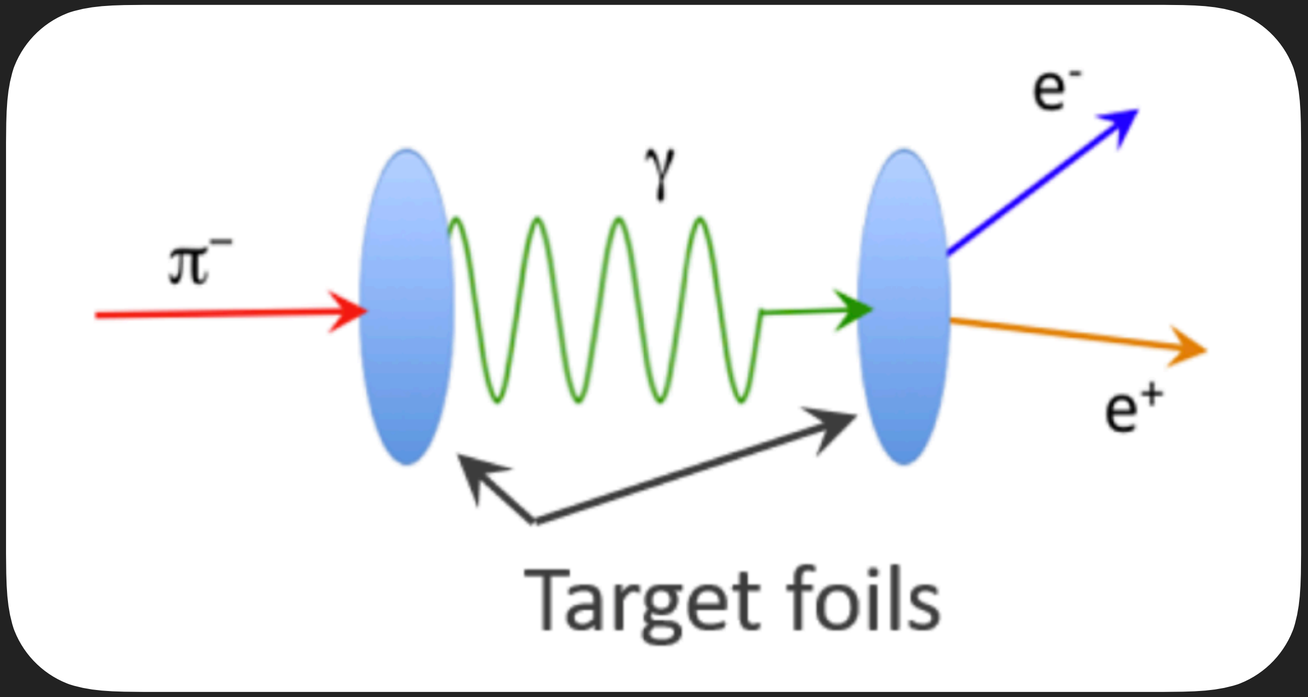




Stopping Target

Prompt Background: Radiative Pion Capture

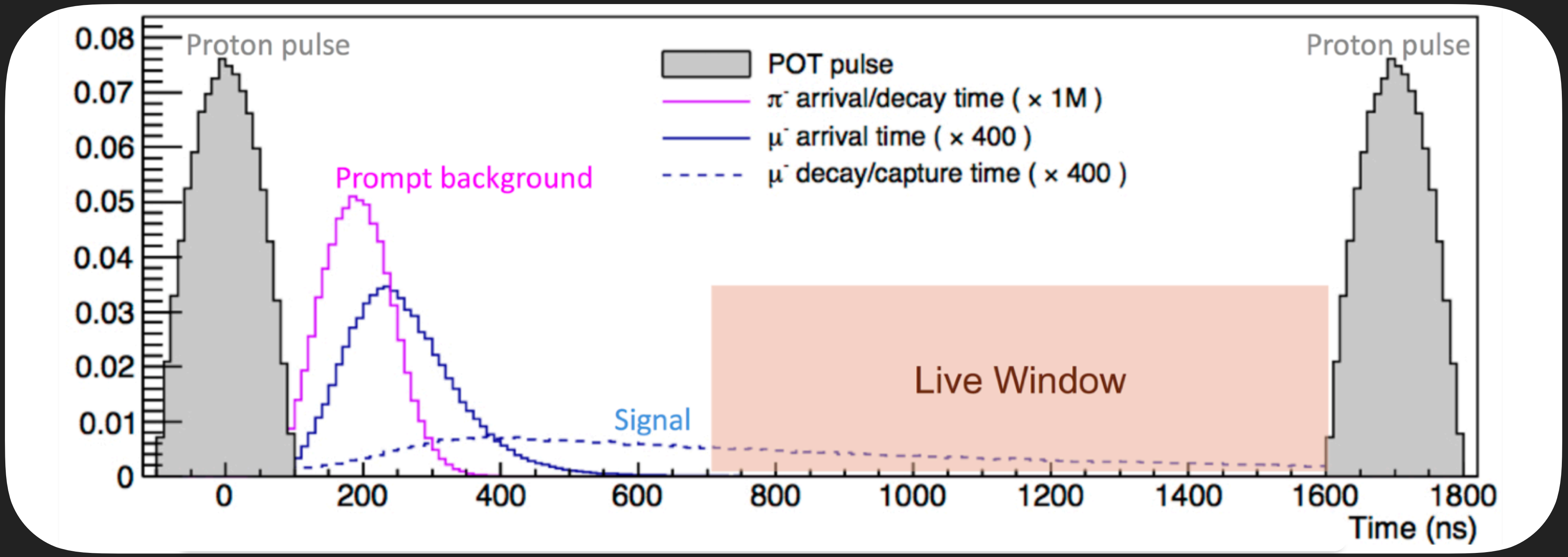
- The muon beam is naturally contaminated with its parent pions
- Some pions are stopped on the Al target, or other parts of the detector
- ~2% of these produce a photon or an e-e pair, and sometimes the e will look like a CE!
- But, the pion lifetime is around 26 ns, while the muon lifetime in Al is 864 ns



This leads us to our second “big idea”

Second big idea: a pulsed proton beam with extinction

- Use a pulsed beam with a long interval between bunches
- Delay the search window
- Muonic aluminum (τ ~ 864 ns) is well optimized for the beam structure!
- 39 M protons / pulse
- Extinction: # of protons outside of 250 ns pulse = 10^{-10}

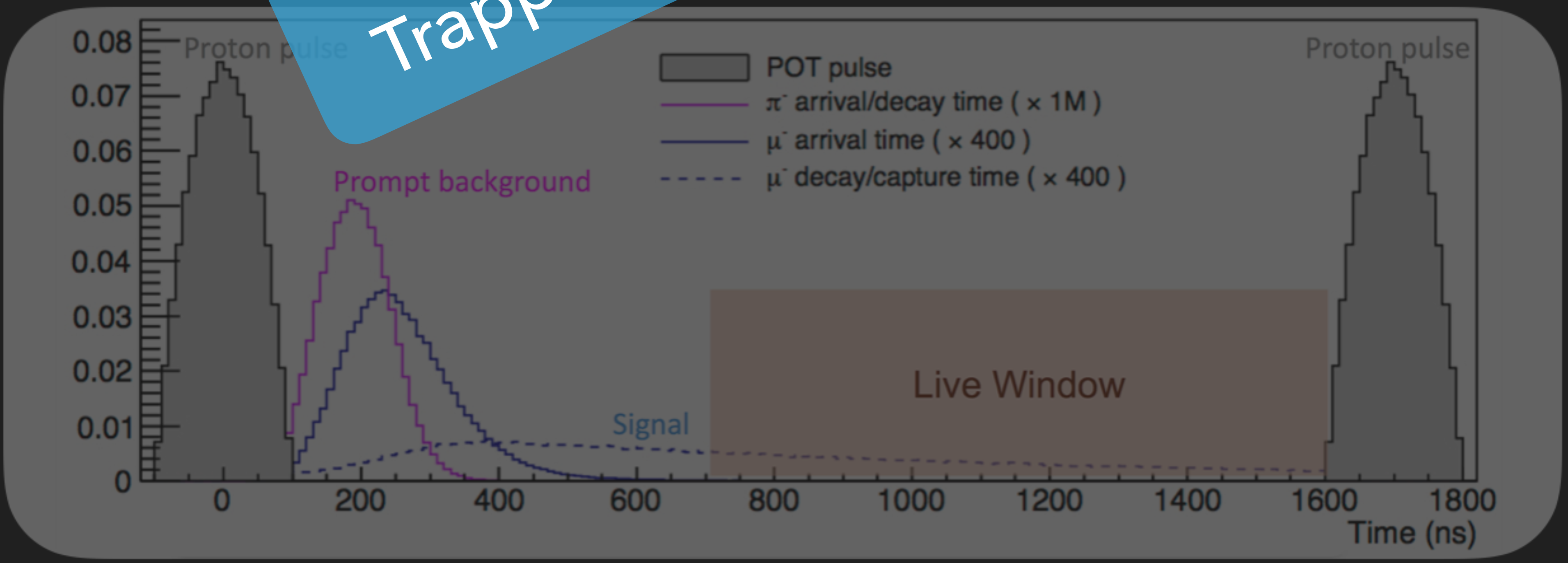


Pion BG reduced by a factor of 10^{-9}!

Second big idea: a pulsed proton beam with extinction

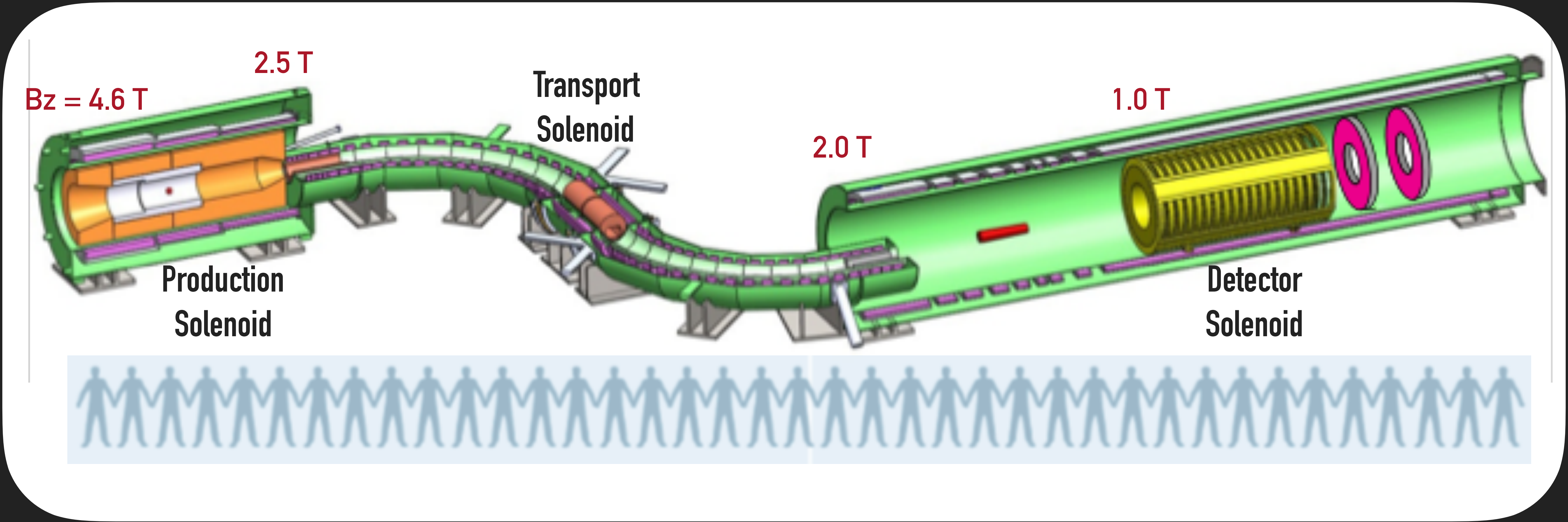
- Use a pulsed beam with a long interval between bunches
- Delay the search window
- Muonic aluminum, τ ~ 864 ns, is well optimized for the beam structure!
- 39 M protons / pulse
- Extinction: # of protons outside of 200 ns pulse = 10^{-10}

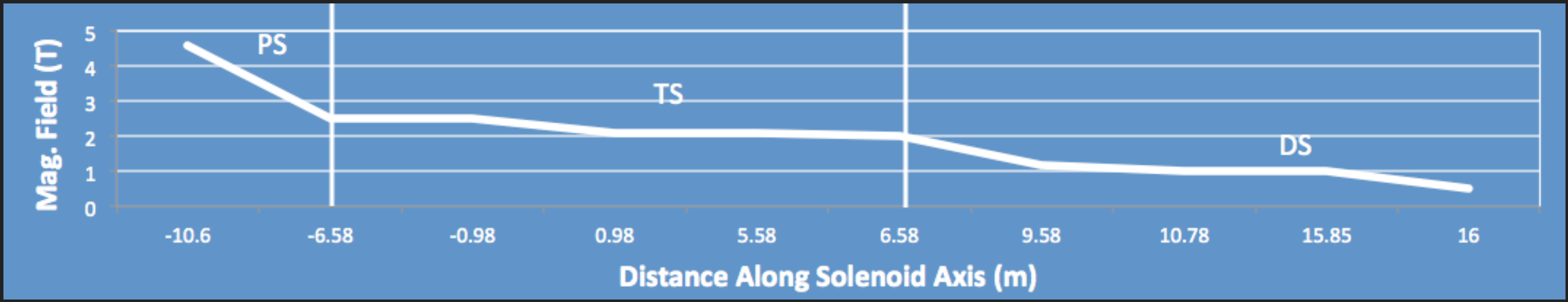
Caveat: Trapped Particles



Pion BG reduced by a factor of 10^{-9}!

Field Design

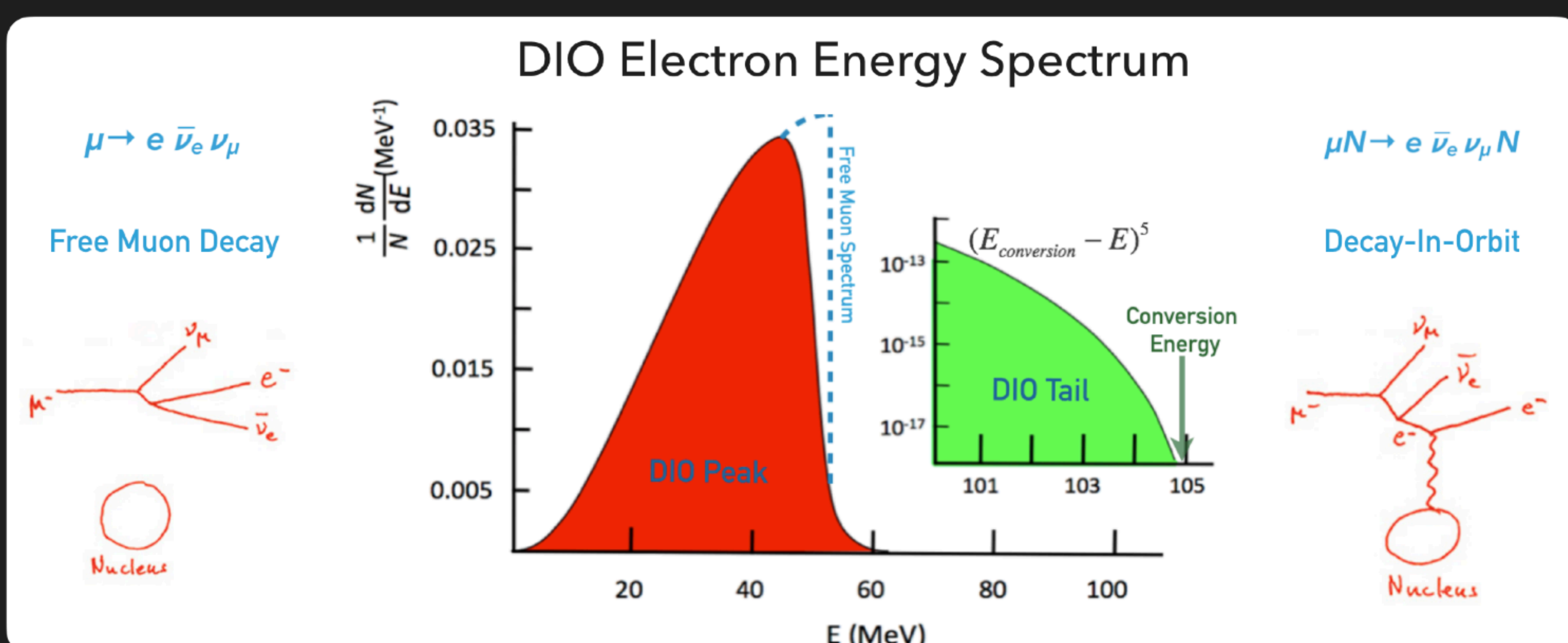




A graded field with no local minima → no trapped particles

Decay in orbit background

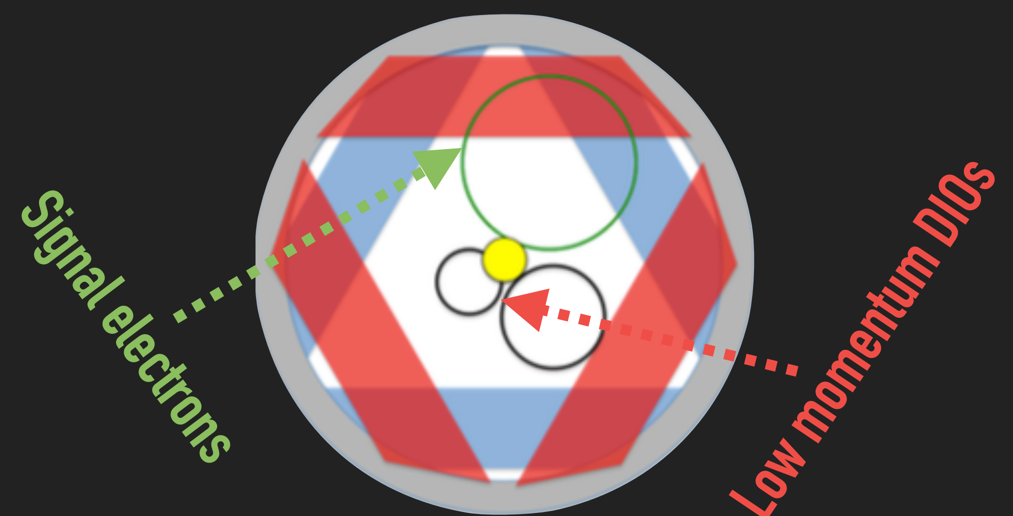
- Other than momentum, there is no way to distinguish DIO from CE
- DIO tail extends all the way out to the muon rest mass, i.e. the signal region
- It's currently our second largest background
- This leads us to our third set of big ideas



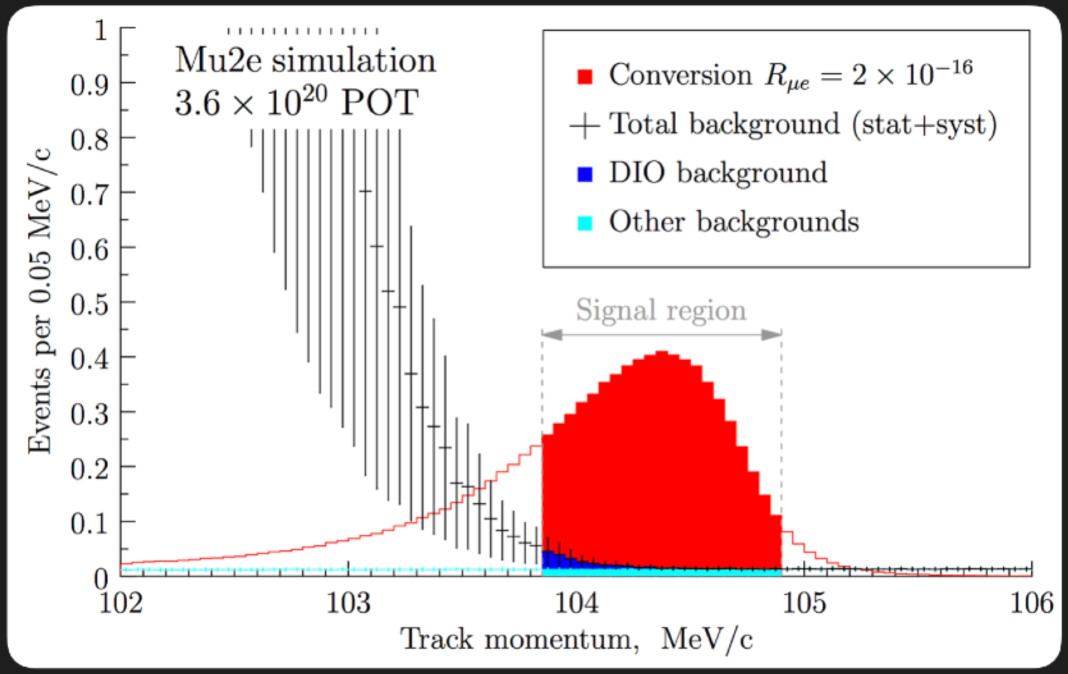
For a theory prediction, see: R.Szafron, A .Czarnecki, Phys. Rev. D**94**(2016)051301

Third big idea: wrestling with DOIs

- Minimize scattering and energy loss
  - Entire Detector Solenoid held under vacuum (~10^{-4} torr)
  - Ultra low mass tracker
  - Optimized target mass and geometry
- Require excellent momentum resolution (σ < 0.2% @ 105 MeV)
- Be blind to, and protect from, low momentum electrons
  - 1T B-field + annular geometry
    - $d\mathbf{p}/dt = q(\mathbf{E} + \mathbf{v}\times\mathbf{B}) \rightarrow R = p_\perp/qB$

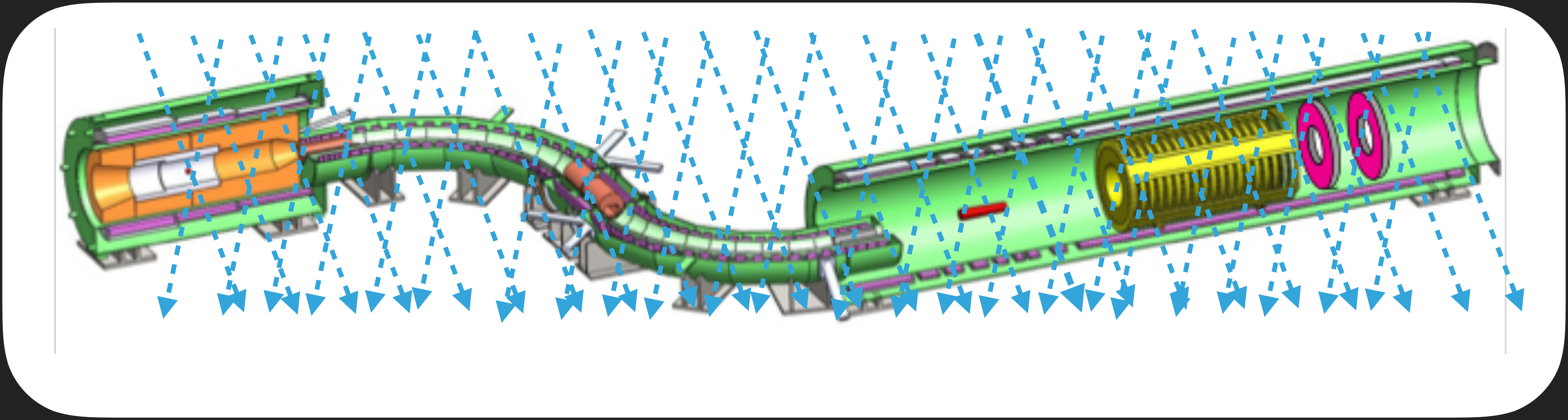


A tracking "plane"



Cosmic Background

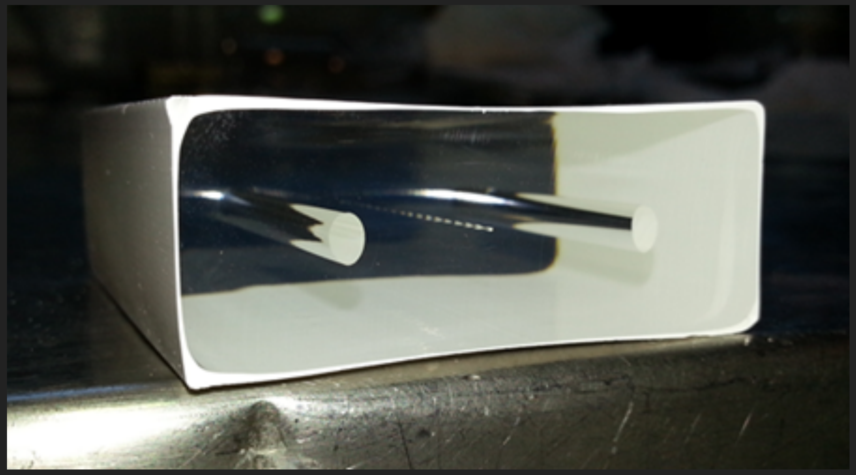
- 10^9 cosmic rays / day
- 1 BG event / day
  - Experiment killer!

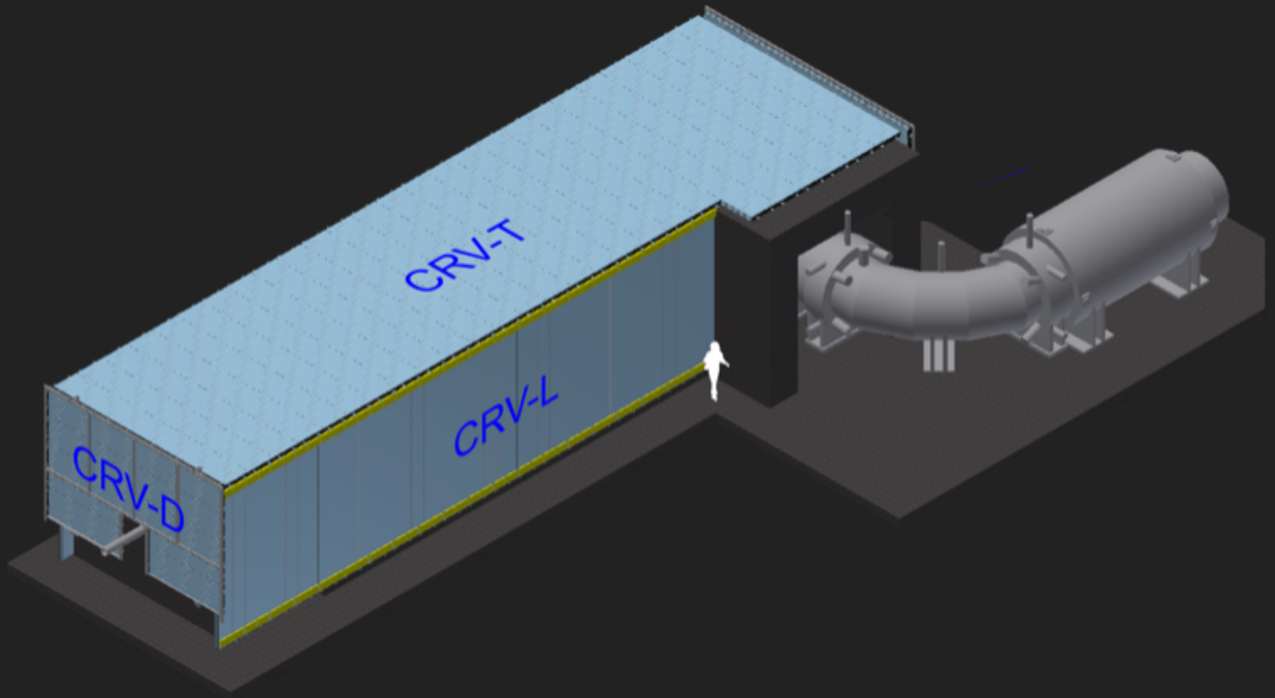


This leads us to our fourth "big idea"

Fourth big idea: a highly efficient Cosmic Ray Vito System

- 4 layers of extruded polystyrene scintillator counter
- Suppresses the spurious detection of conversion-like particles initiated by cosmic-ray muons
- 99.99% efficiency requirement: better not have any holes!
- Minimize false vitos





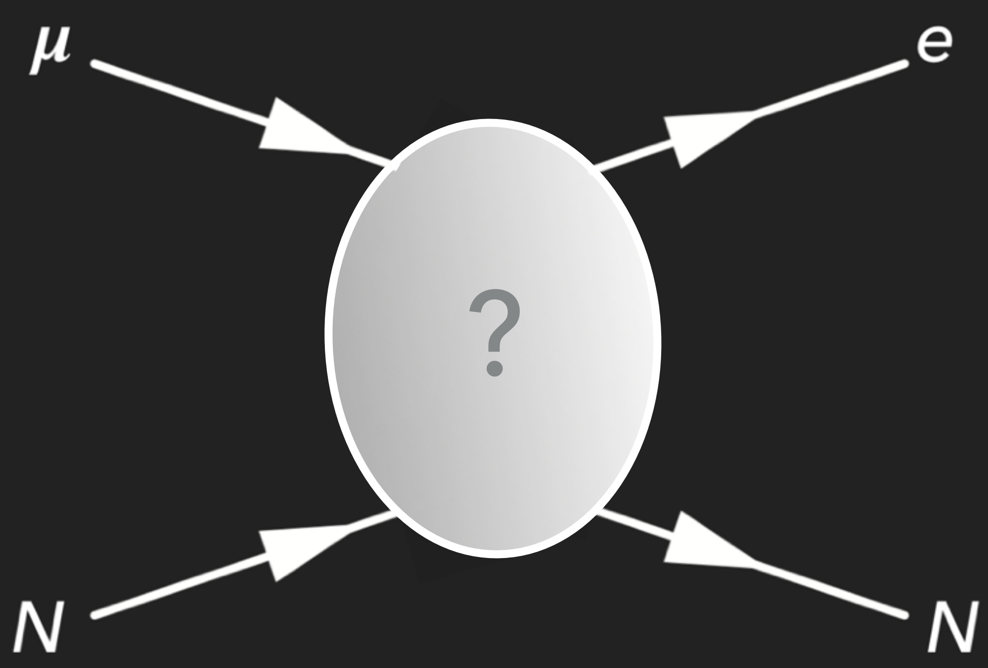
Most Recent Background Estimation

Category	Background Process	Estimated Yield
Intrinsic	Decay In Orbit (DIO)	0.144 ± 0.028(stat) ± 0.11(syst)
	Muon Capture (RMC)	0
Late Arriving	Pion Capture (RPC)	0.021 ± 0.001(stat) ± 0.002(syst)
	Muon Decay in Flight	< 0.003
	Pion Decay in Flight	0.001 ± <0.001
	Beam Electrons	$(2.1 \pm 1.0) \times 10^{-4}$
Miscellaneous	Cosmic Ray Induced	0.209 ± 0.022(stat) ± 0.055(syst)
	Antiproton Induced	0.040 ± 0.001(stat) ± 0.020(syst)
Total		**0.41 ± 0.13(stat + syst)**

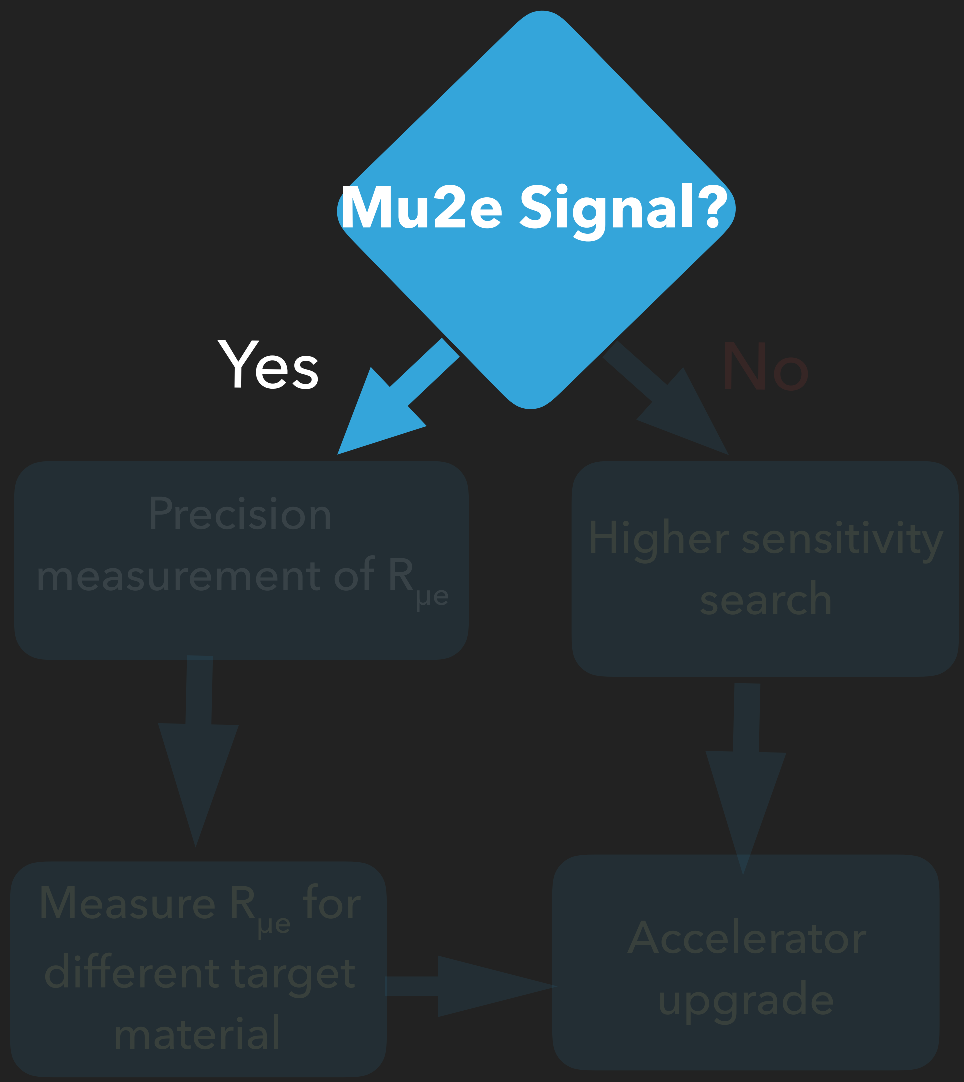
See doc-7464 for further details!

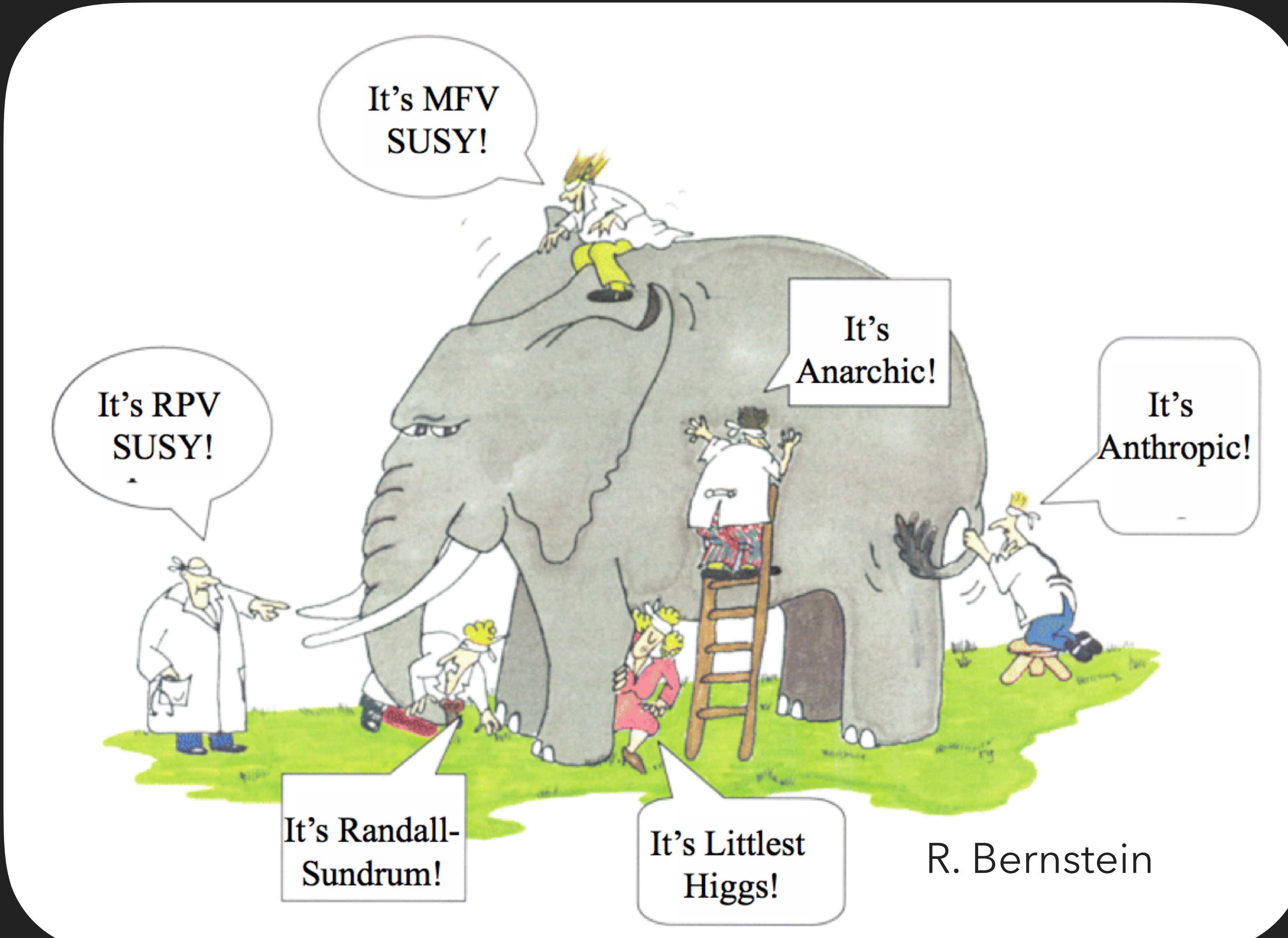
We will cover

- ~~What will be measured~~
- ~~Sensitivity & physics reach~~
- ~~Experimental design~~
- The future



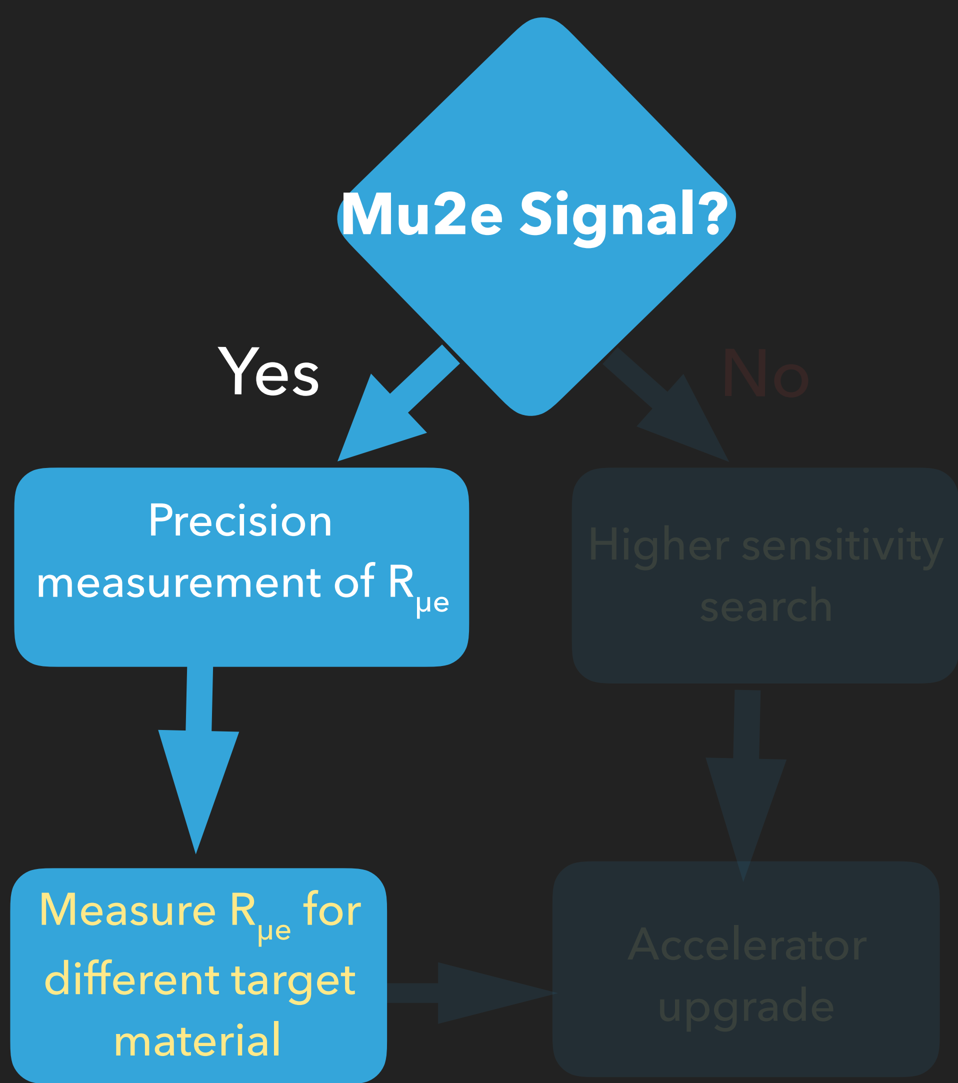
What if we see a signal?



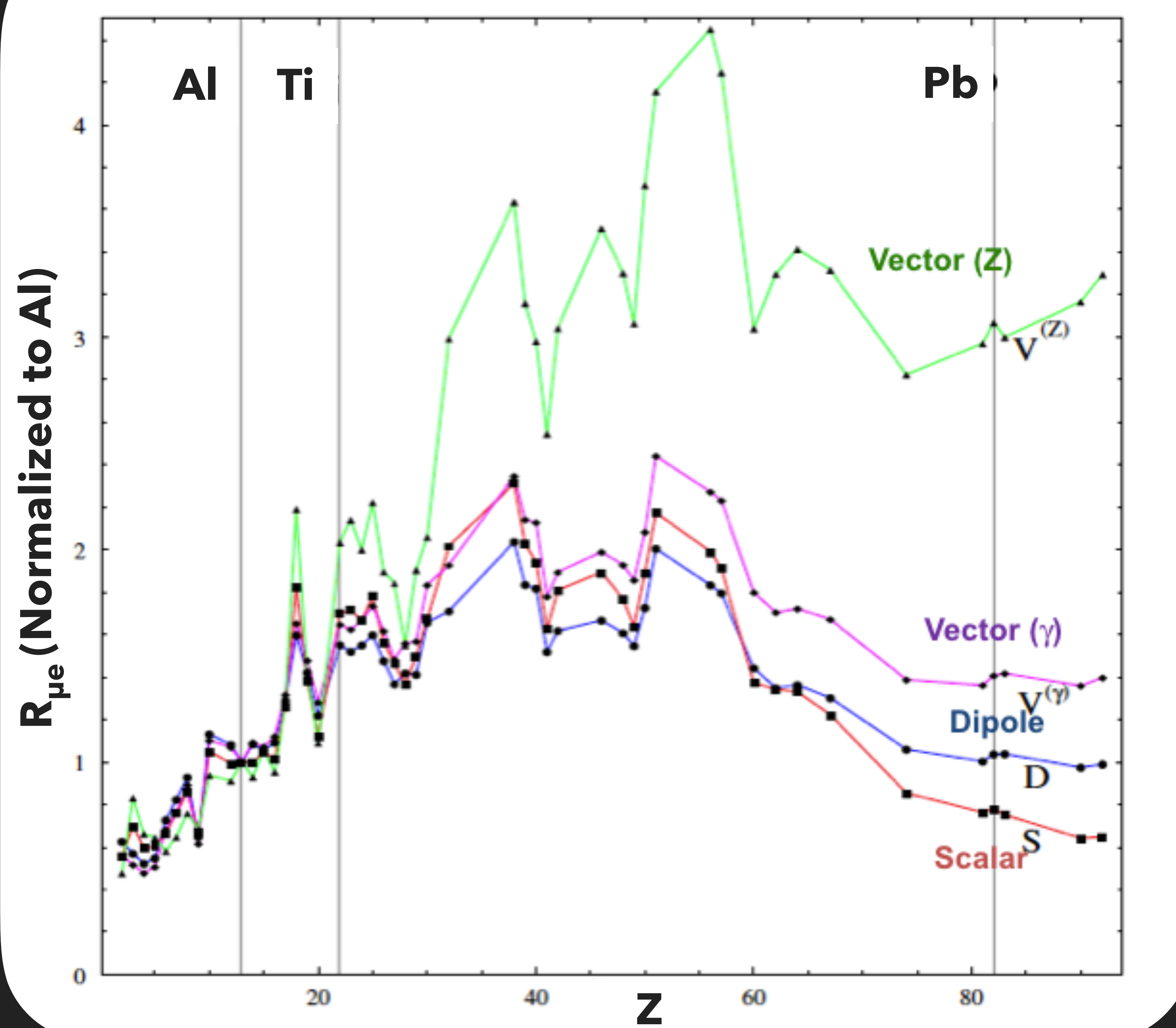


R. Bernstein

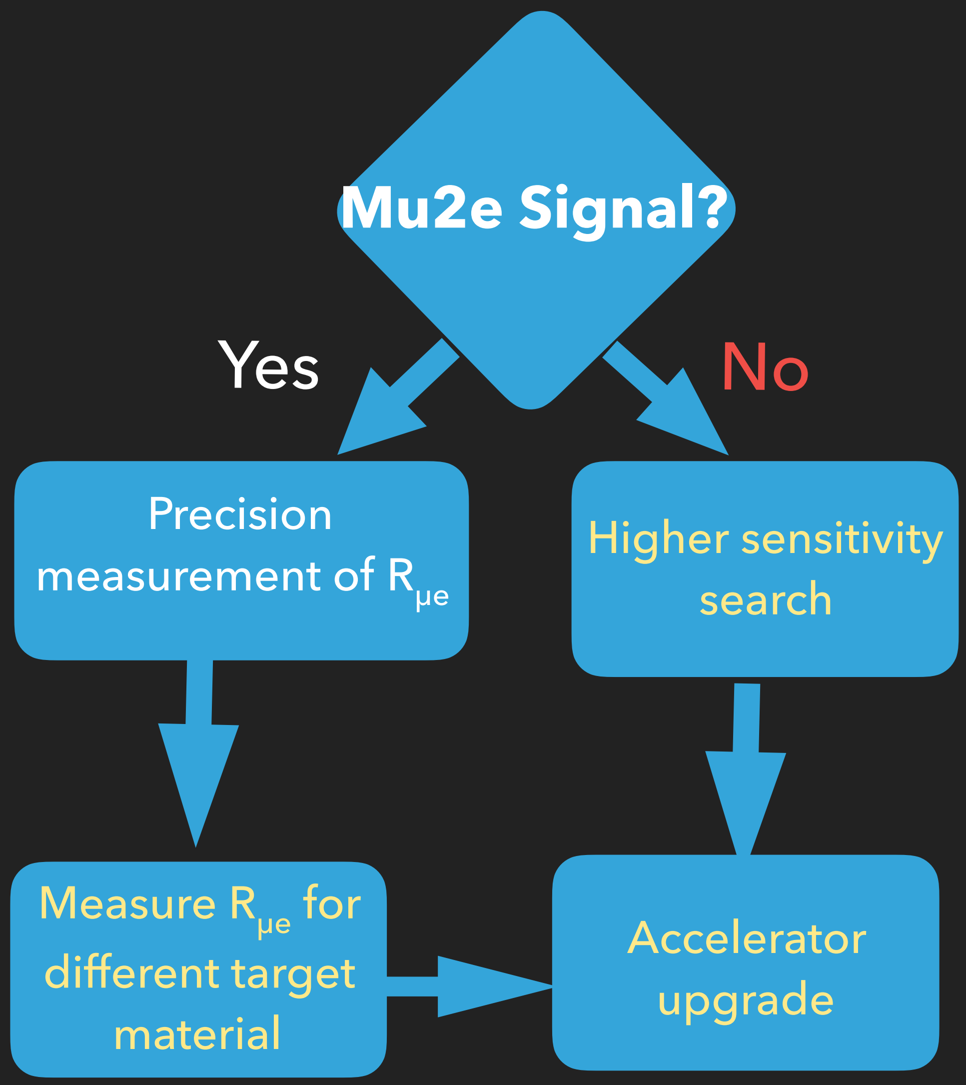
$R_{\mu e}$ in different materials is a powerful model discriminator



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

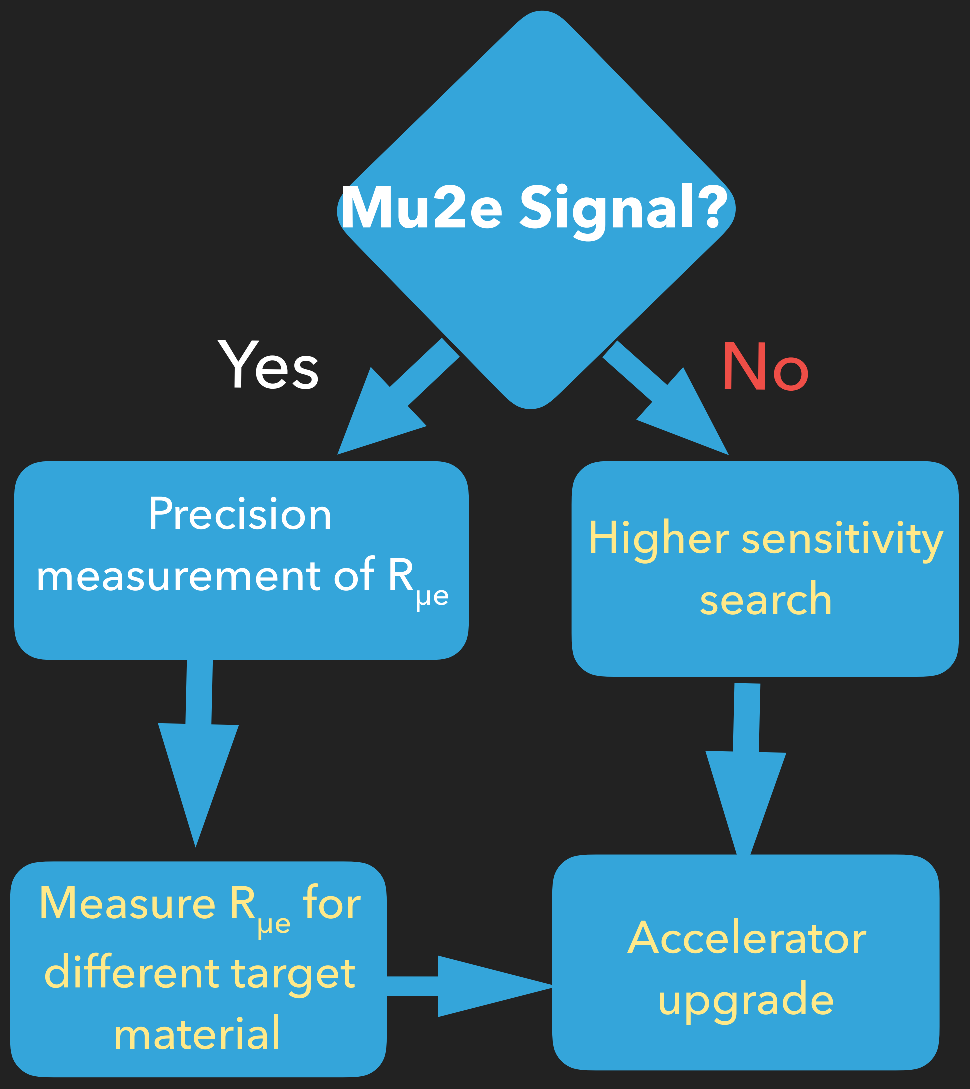


What if we don't see a signal?



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

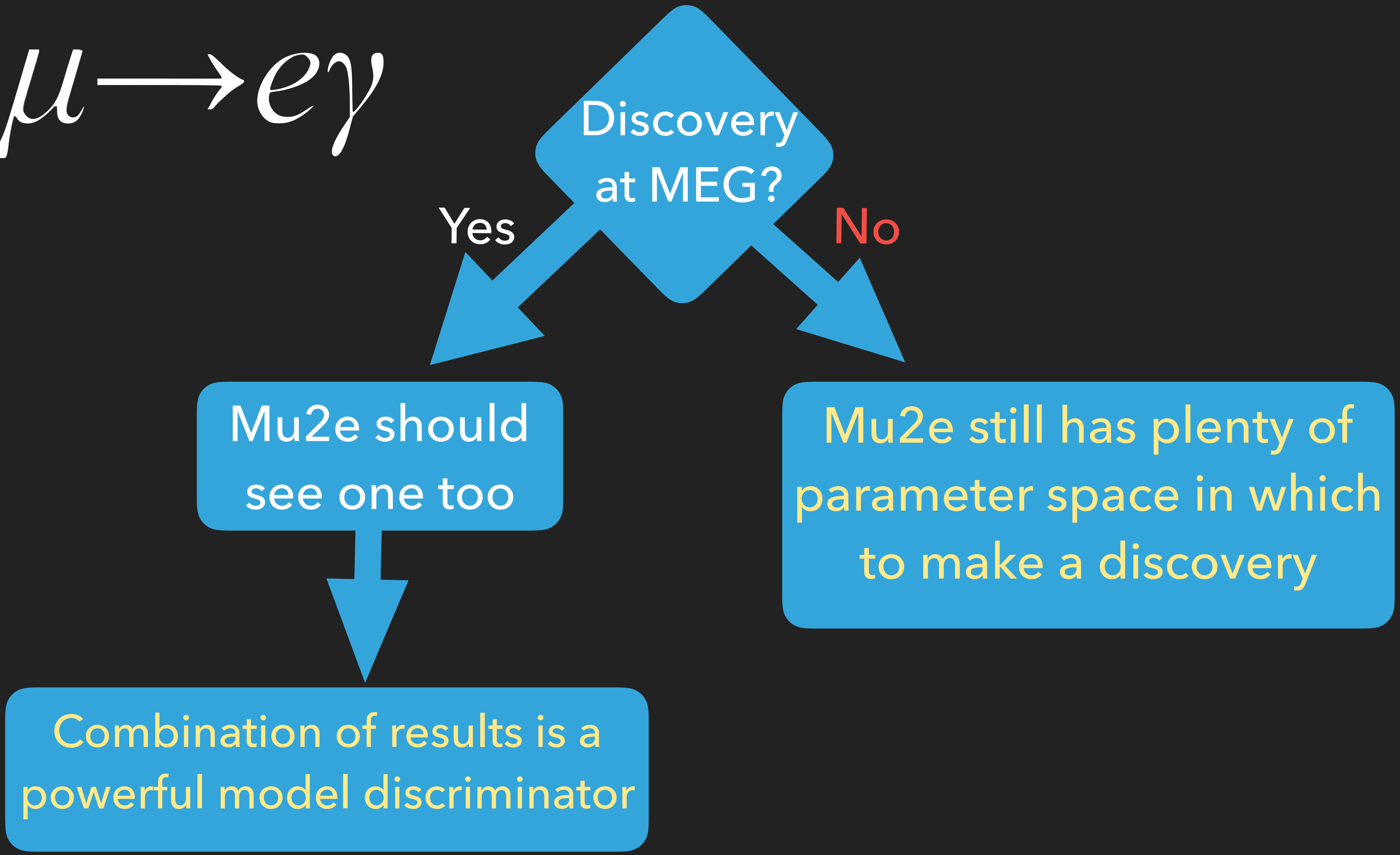
A next generation Mu2e experiment is well motivated in all scenarios

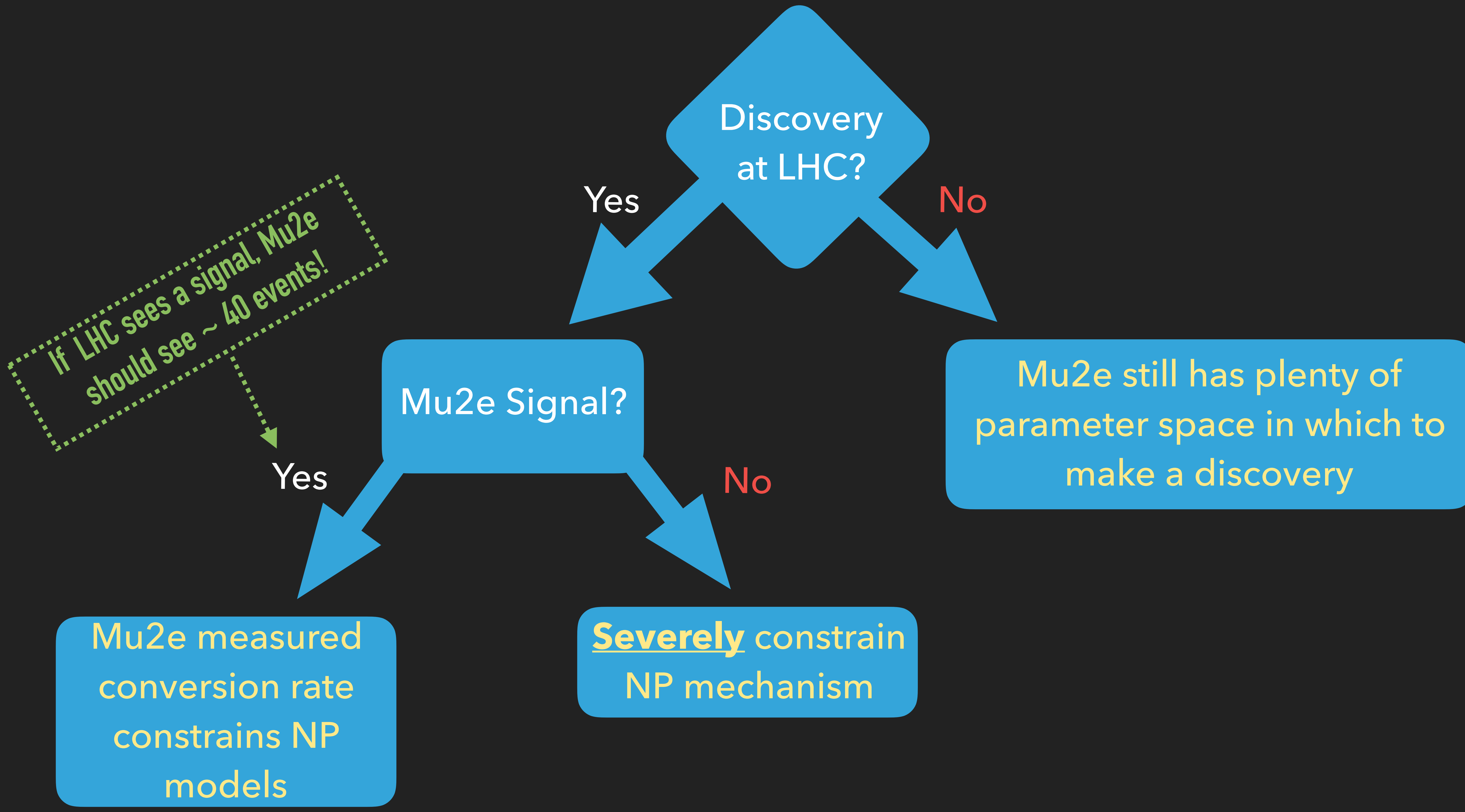


To read about upgrading the Mu2e experiment, see arXiv:1307.1168

Mu2e is a long term project

$$\mu \to e\gamma$$

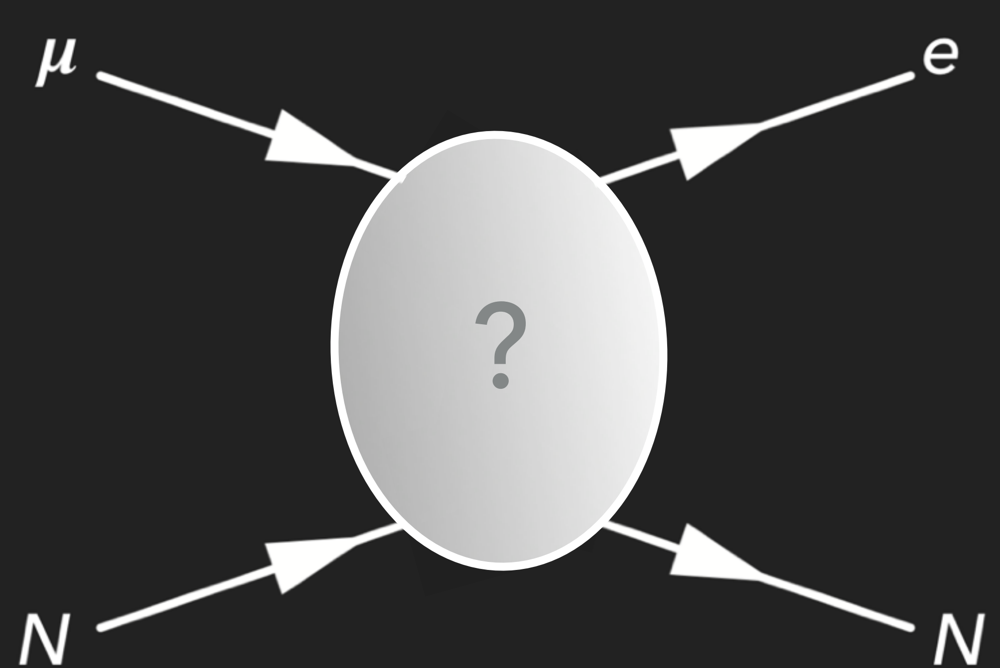

Discovery at MEG?
Yes
No
Mu2e should see one too
Mu2e still has plenty of parameter space in which to make a discovery
Combination of results is a powerful model discriminator



Mu2e is a potential discovery experiment, complementary to the LHC

We will cover

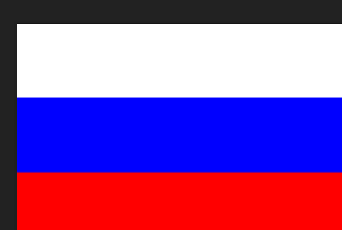
- ~~What will be measured~~
- ~~Sensitivity & physics reach~~
- ~~Experimental design~~
- ~~The future~~



>200 scientists, 37 institutions, 6 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 of Manchester, University of Liverpool, 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







Mu2e
g-2

Mu2e Technical Design Report

October 2014

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INFN

Fermilab

Technical Design Report:

arXiv: 1501.05241 (888 pages)

Conceptual Design Report:

arXiv:1211.7019 (562 pages)

QUESTIONS?