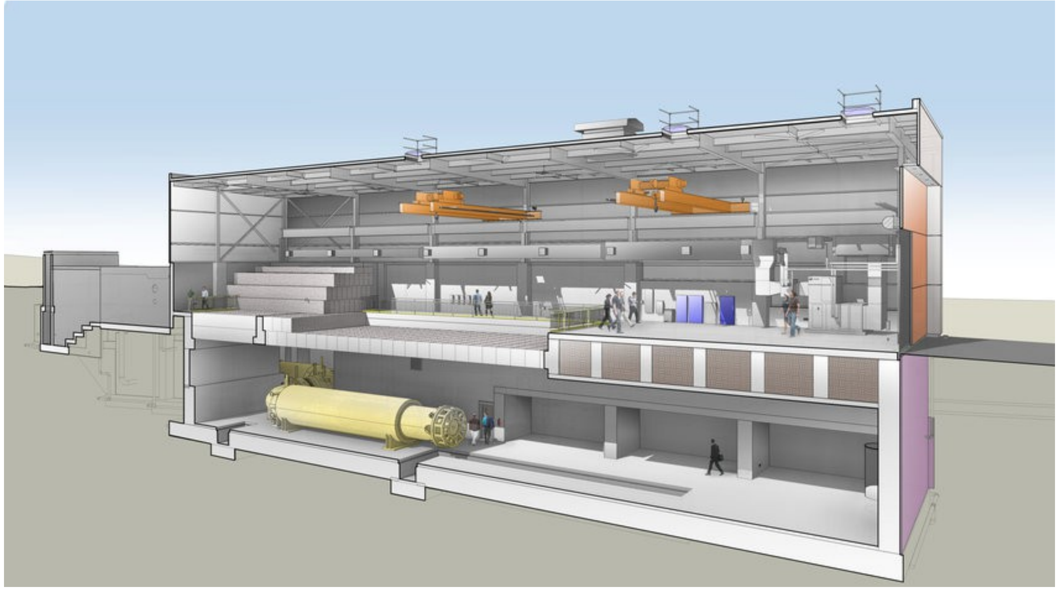
The Mu2e Experiment

A Search for Charged Lepton Flavor Violation



Mu2e Summer Lectures: Introduction

Manolis Kargiantoulakis

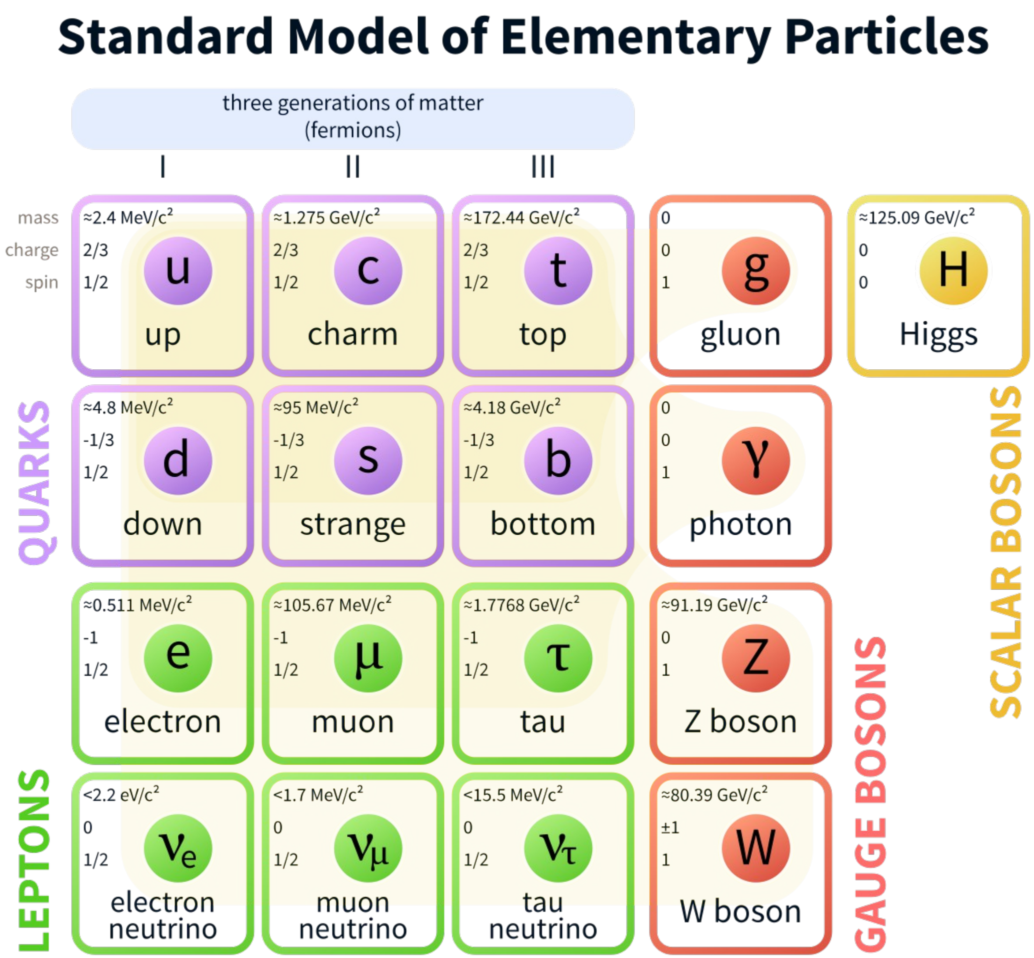
8/10/2018

Outline

- Context and motivation
- The Mu2e experiment
- Backgrounds
- Summary, outlook

- Context and motivation
    - Lepton flavor in the SM
    - Charged lepton flavor violation
    - $\mu \rightarrow e$ conversion
- The Mu2e experiment
- Backgrounds
- Summary, outlook

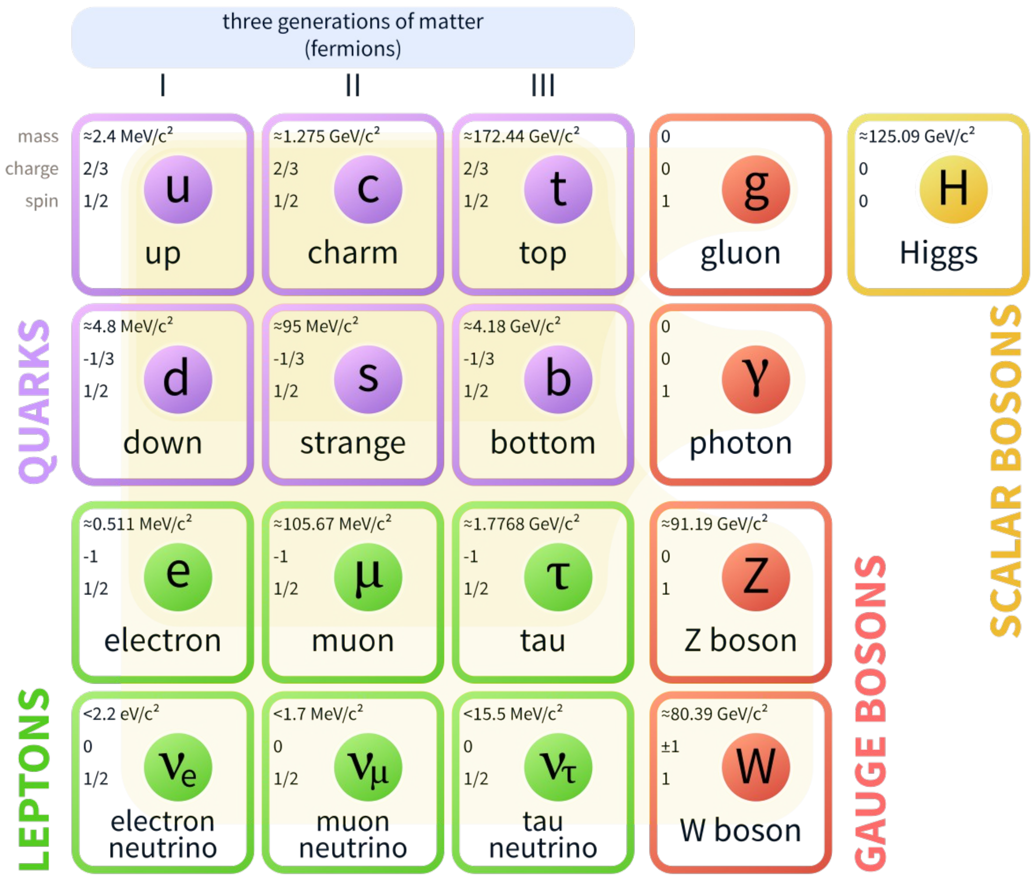
Standard Model



- The Standard Model
  A greatly successful theory
- Crowning triumph:
  Discovery of *SM-like* Higgs particle

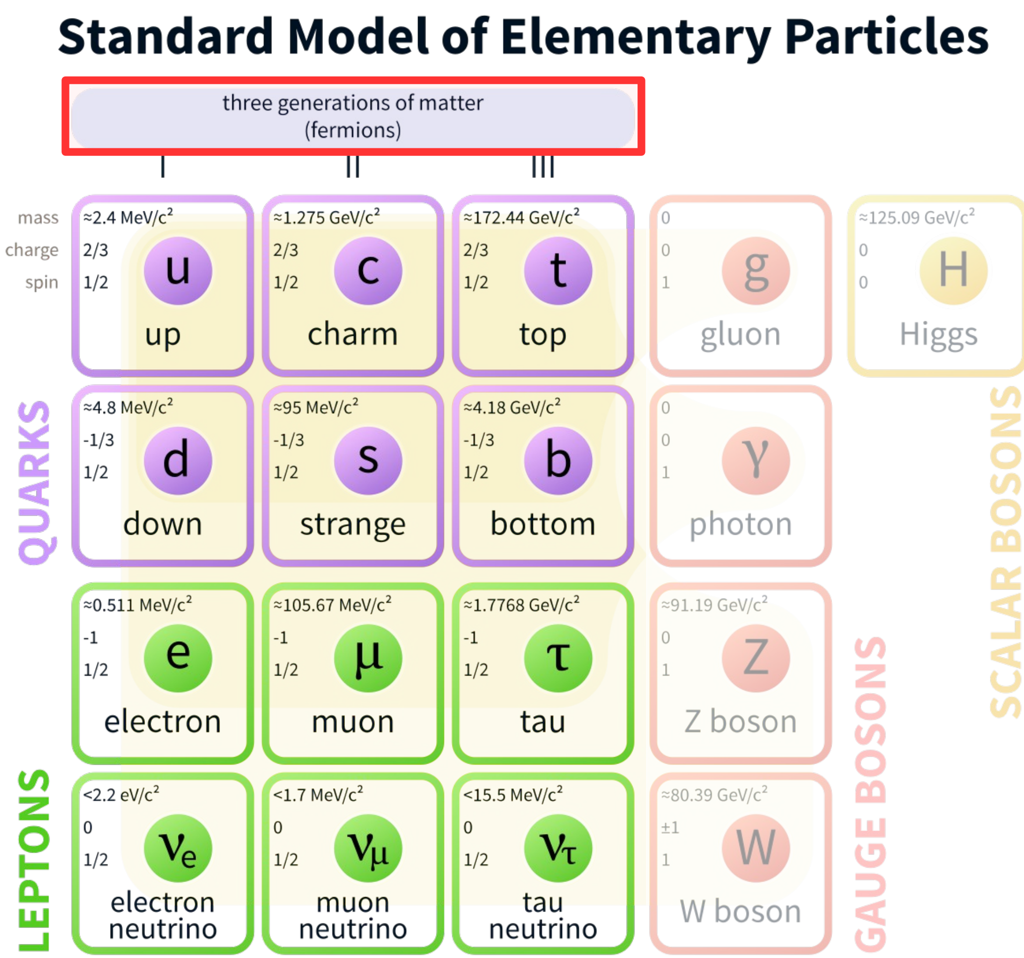
Standard Model

Standard Model of Elementary Particles



- The Standard Model
  A greatly successful theory
- Crowning triumph:
  Discovery of *SM-like* Higgs particle
- And yet...
  Must be incomplete!
  - Gravity, dark matter
  - neutrino oscillations
- Not a complete theory of fundamental interactions
  - Motivated to search for physics *beyond* the SM
  - Address open questions

Lepton Flavor in the SM



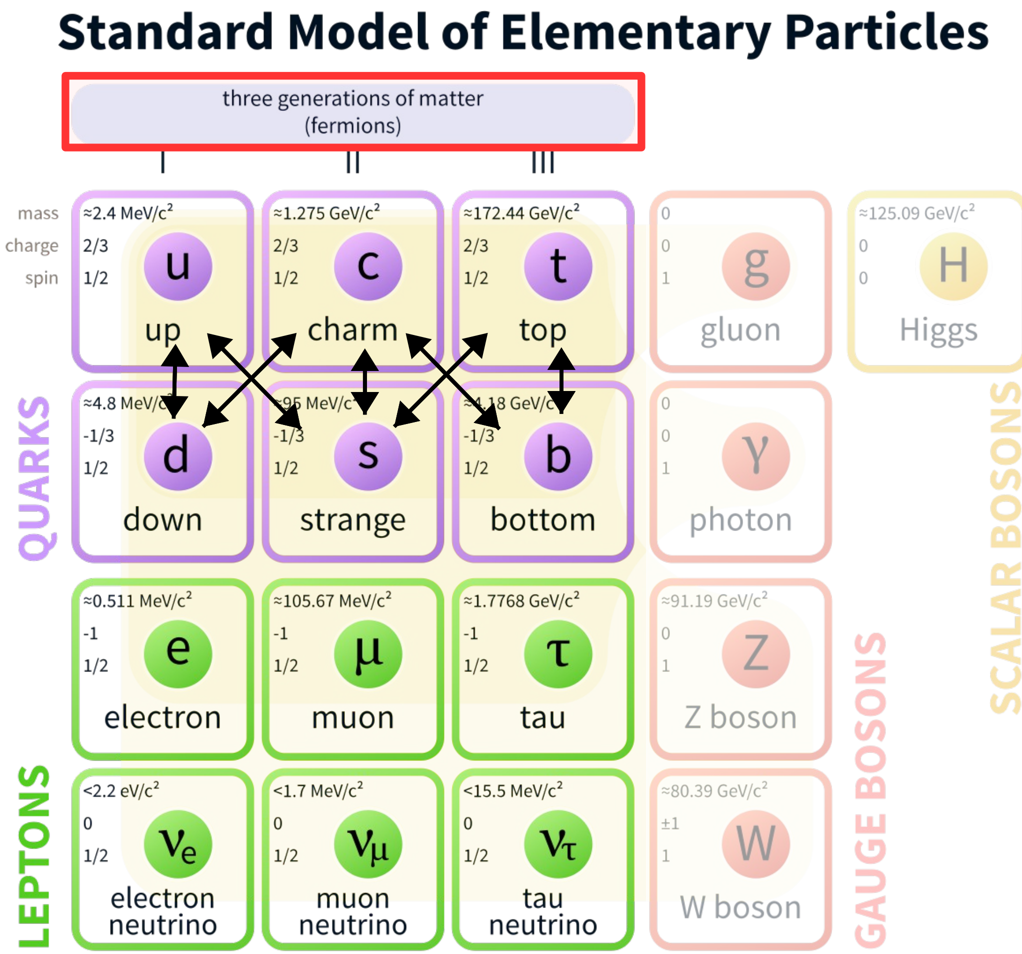
The SM flavor puzzle

- Why are there 3 generations of matter?
  - Rabi encapsulated the issue well..

– R. Harnik

- What defines fermion masses?
- Is mixing allowed between generations/flavors?

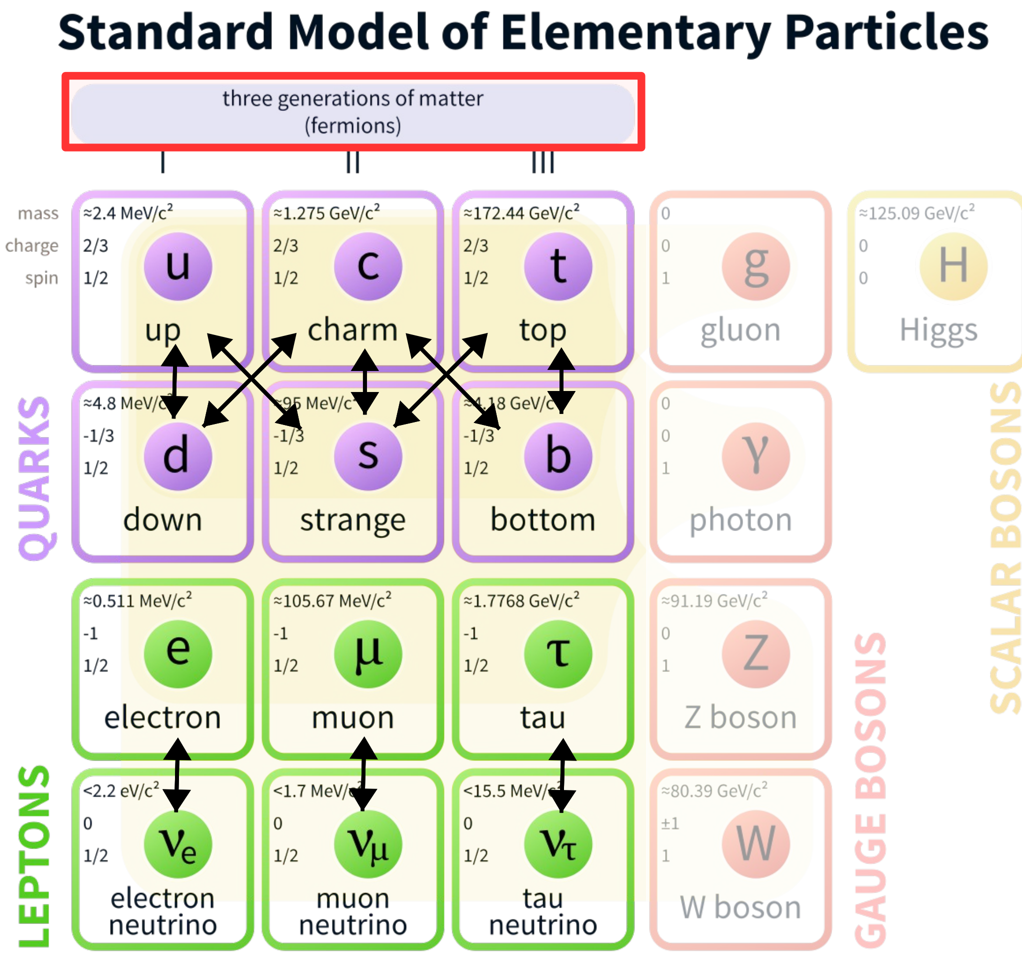
Lepton Flavor in the SM



Mixing between flavors

- Quarks mix through W exchange, CKM mechanism

Lepton Flavor in the SM



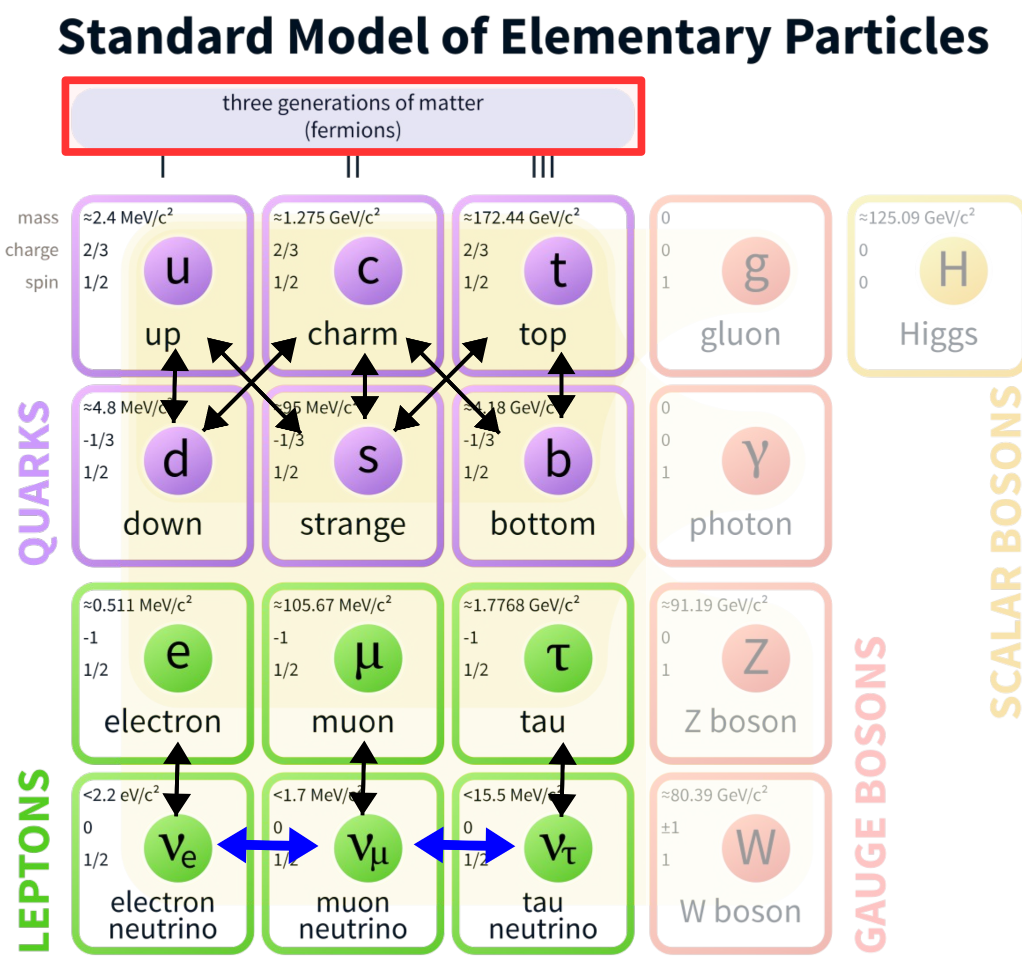
Mixing between flavors

- Quarks mix through W exchange, CKM mechanism
- Leptons weak decay

$$l^{\pm} \rightarrow W^{\pm} \ \nu_l$$

(all in the family)

Lepton Flavor in the SM



Mixing between flavors

- Quarks mix through W exchange, CKM mechanism
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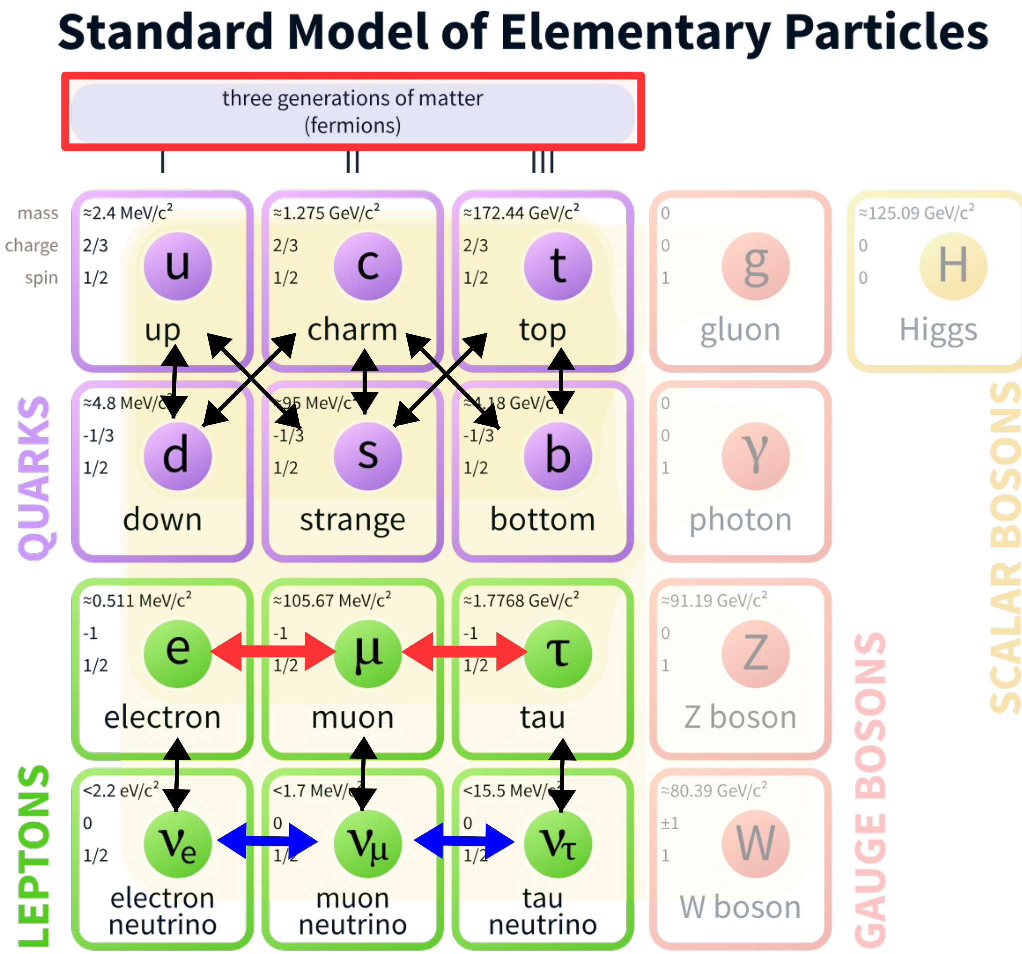
$$l^{\pm} \rightarrow W^{\pm} \; \nu_l$$

(all in the family)

- Neutrino oscillations
  → *Lepton flavor violated!*

Lepton Flavor in the SM



Mixing between flavors

- Quarks mix through W exchange, CKM mechanism
- Leptons weak decay

  $$l^{\pm} \rightarrow W^{\pm} \; \nu_{l}$$

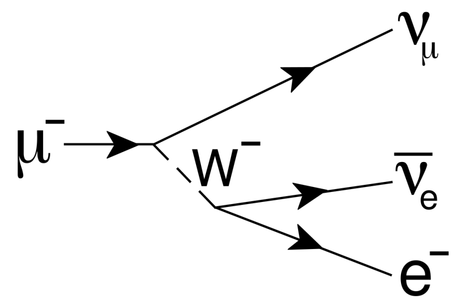
  (all in the family)
- Neutrino oscillations
  → Lepton flavor violated!
- Mixing between charged leptons:
  Never observed!
- Well motivated searches for *violation of charged lepton flavor*
  - A single observation would be evidence of *New Physics*

Charged Lepton Flavor Violation

Ordinary muon decay conserves lepton flavor:

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

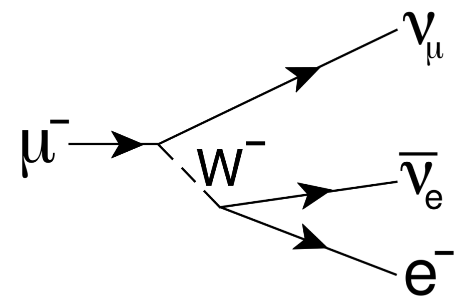
	μ^-	e^-	$\overline{\nu}_e$	ν_μ
L_μ	1	0	0	1
L_e	0	1	-1	0



Violation of charged lepton flavor "*forbidden*" in SM

Charged Lepton Flavor Violation

Ordinary muon decay conserves lepton flavor:



	μ^-	$\rightarrow e^-$	$\overline{\nu}_e$	ν_μ
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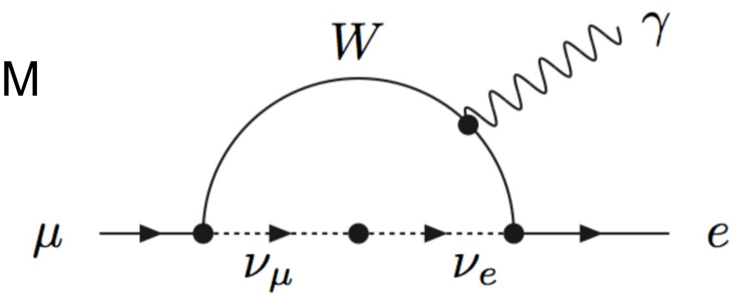
Violation of charged lepton flavor "*forbidden*" in SM



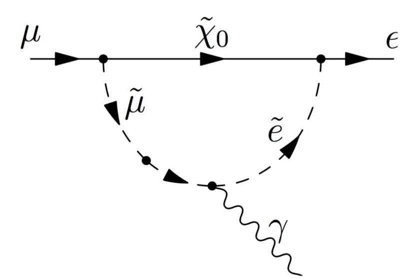
Loophole: neutrino oscillations

- Some CLFV *must occur*
- But rate is vanishingly small, $<10^{-50}$

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

Any CLFV observation would be evidence that rate is enhanced by new physics

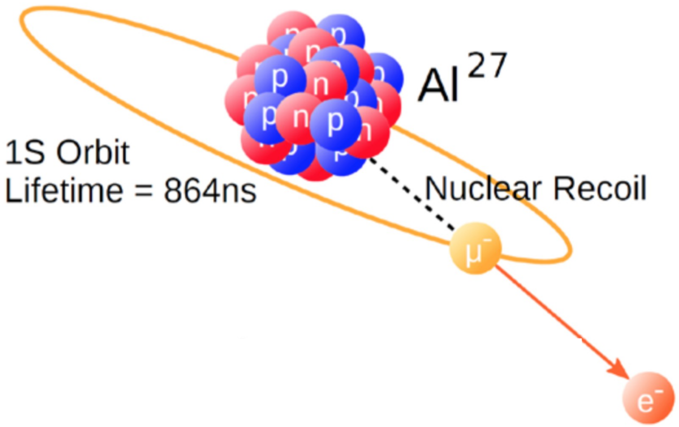
- Intensity Frontier search, complementarity and synergy with LHC
- Connections with: flavor in SM, neutrino mass, lepton flavor universality, g-2, …



$\mu \rightarrow e$ conversion: The Mu2e search

Coherent conversion $\mu \rightarrow e$ in the field of a nucleus

$$\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)$$



Clean experimental signature

- monochromatic e^- – for Al:

$$E_e(\mathrm{Al}) = M_\mu - E_b - E^{\mathrm{Al}}_{\mathrm{recoil}} \approx 104.97\ \mathrm{MeV}$$

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

Conversion process

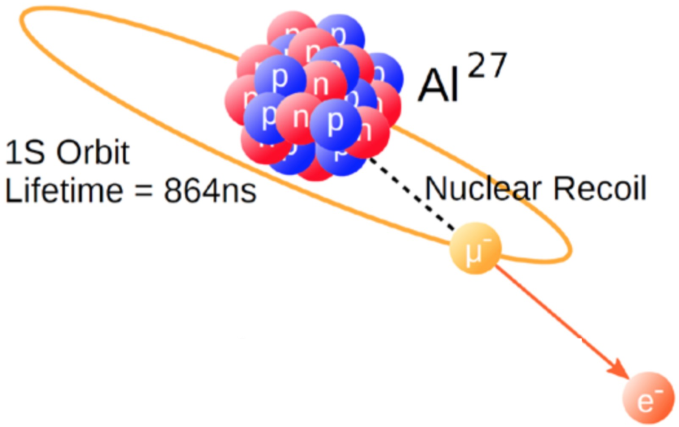
Ordinary muon capture

Current limit: $R_{\mu e} < 7\times10^{-13}$ [SINDRUM II]

$\mu \longrightarrow e$ conversion: The Mu2e search

Coherent conversion $\mu \longrightarrow e$ in the field of a nucleus

$$\mu^- + A(Z,N) \rightarrow e^- + A(Z,N)$$



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Conversion process

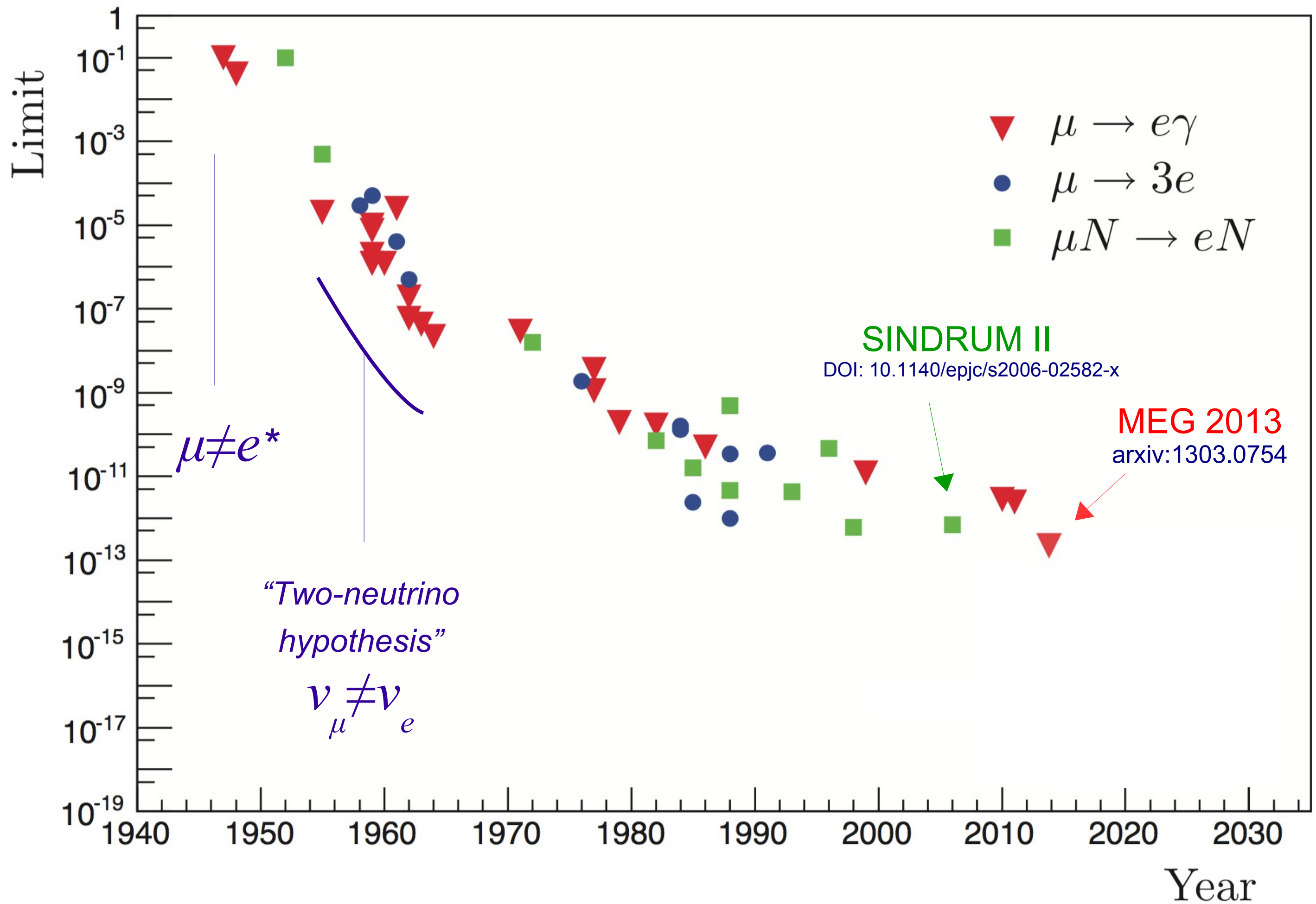
Ordinary muon capture

Current limit: $R_{\mu e} < 7\times10^{-13}$ [SINDRUM II]

The Mu2e experiment will probe $R_{\mu e}$ at the level of ~6×10^{-17} (90% CL)

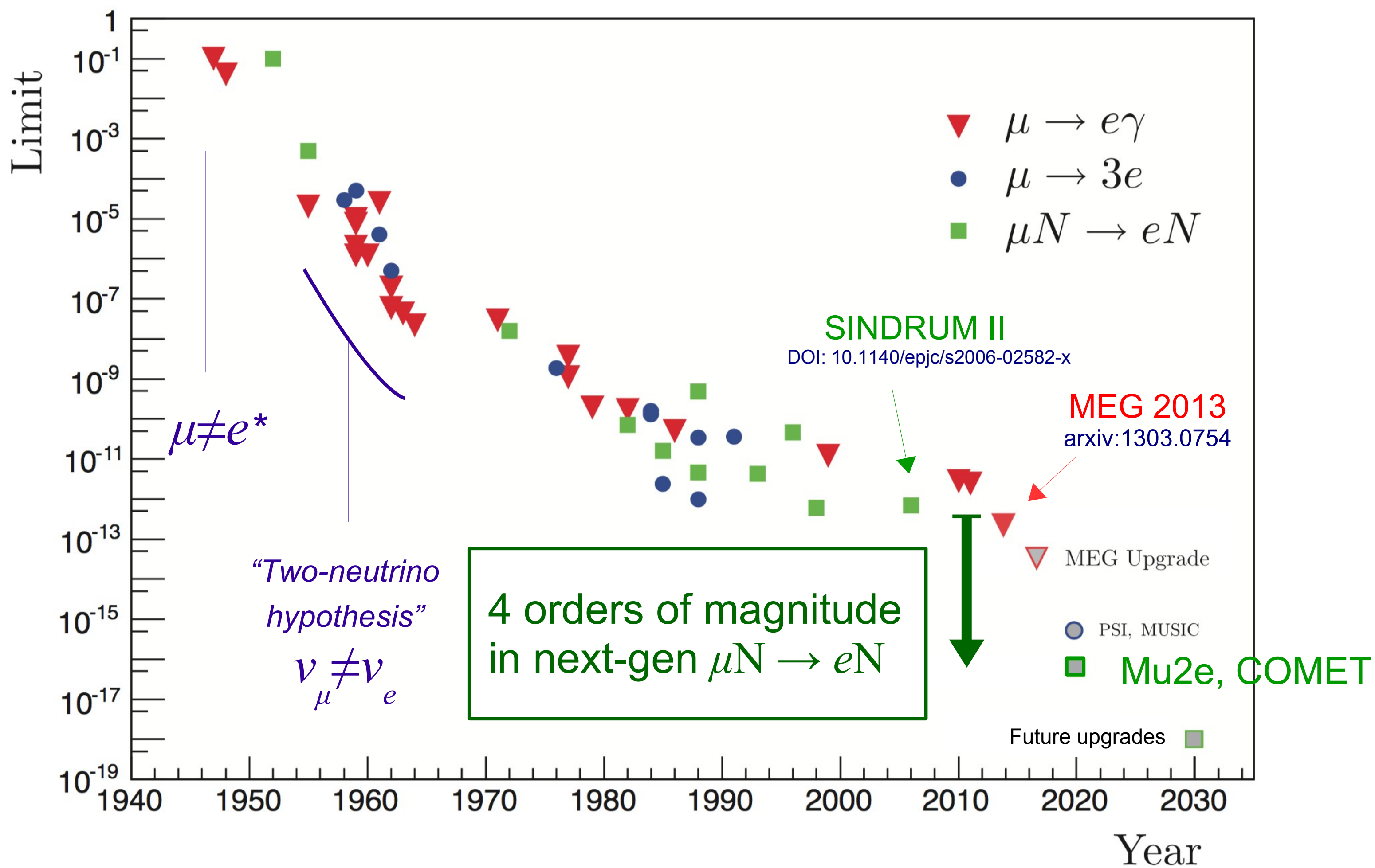
- 4 orders of magnitude improvement – a rare opportunity!

History of CLFV searches



Improvement in sensitivity usually driven by availability of more intense muon beams

History of CLFV searches



- Dramatic improvement in next generation experiments, especially $\mu\mathrm{N} \rightarrow e\mathrm{N}$
- Exploring unconstrained phase space favored by many New Physics models

$\mu \longrightarrow e$ conversion processes

Effective Lagrangian:

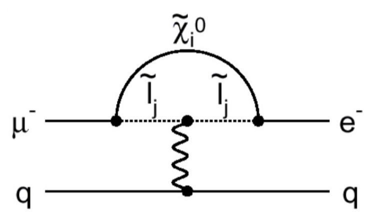
$$\mathcal{L}_{\mathrm{CLFV}} = \underbrace{\frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu}}_{\text{“Loop”}} + \underbrace{\frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)}_{\text{“Contact”}}$$

Λ: effective mass parameter

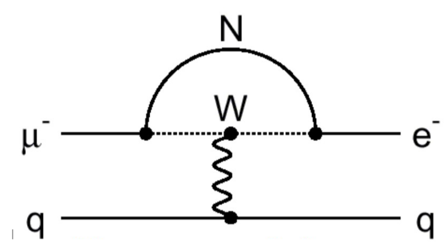
κ: relative strength of loop- and contact-dominated terms

Loop terms:

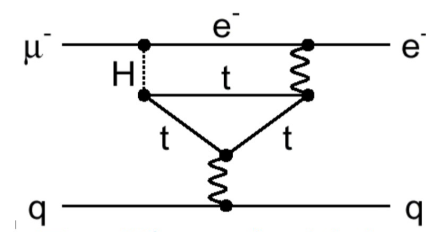
- Also mediate $\mu \longrightarrow e\gamma$



Supersymmetry



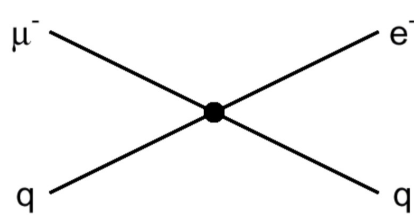
Heavy neutrino



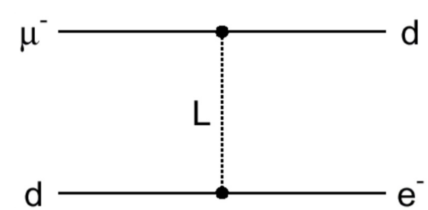
Two Higgs doublets

Contact terms:

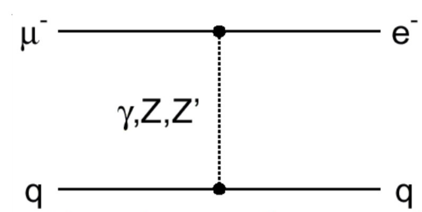
- Only mediate $\mu N \longrightarrow eN$



Compositeness



Leptoquarks



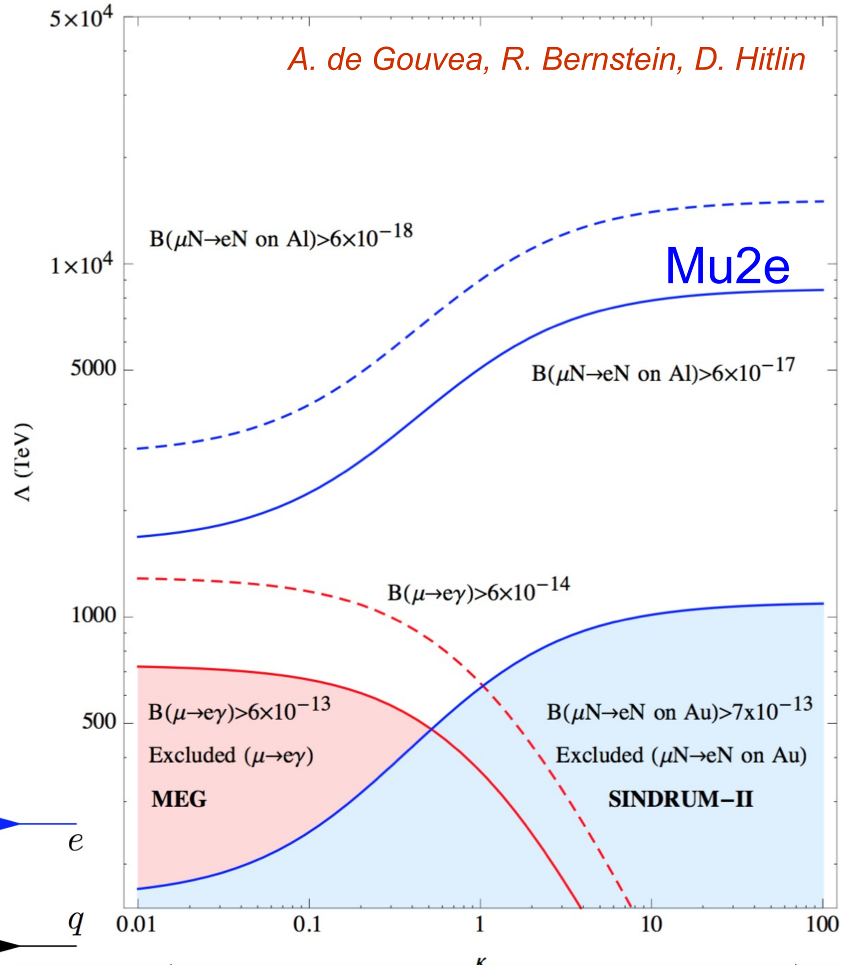
New heavy bosons/ anomalous couplings

Physics Reach

$$\mathcal{L}_{\text{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$

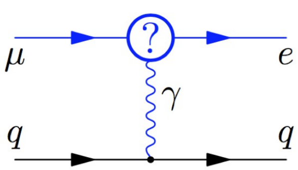
Λ: effective mass parameter

κ: relative strength of loop- and contact-dominated terms

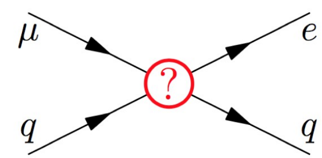


Mu2e improves sensitivity in all New Physics scenarios

Effective mass scale reach up to 10^4 TeV, well beyond the direct reach of current or future colliders



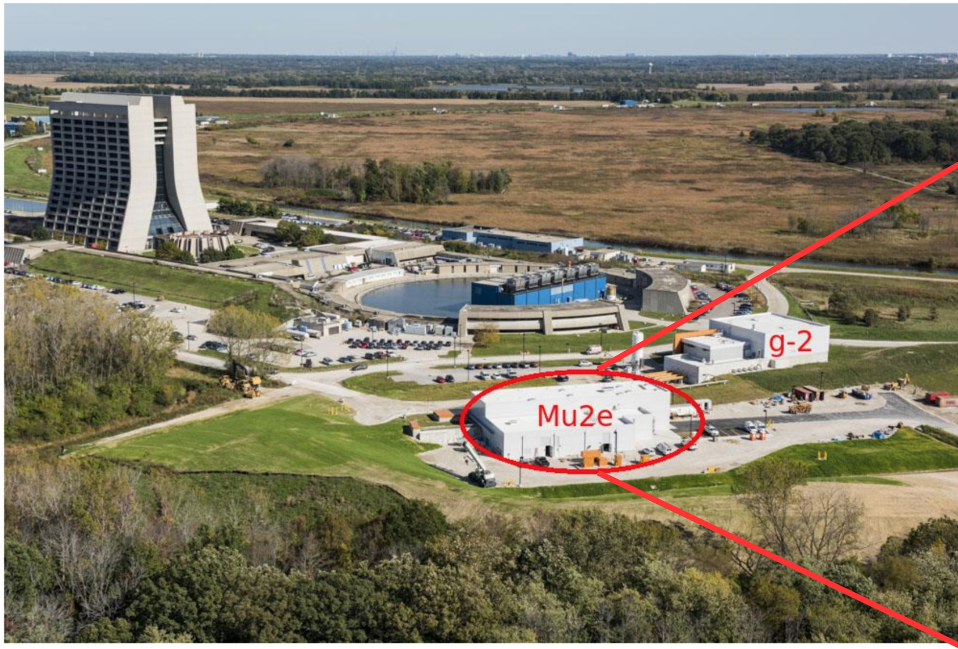
Loop-dominated



Contact-dominated

- Context and motivation
- The Mu2e experiment
    - Apparatus and concept
    - Solenoidal transport
    - Detectors
- Backgrounds
- Summary, outlook

The Fermilab Mu2e experiment



Mu2e will be performed in Fermilab, in the new Muon Campus.

The Mu2e Collaboration

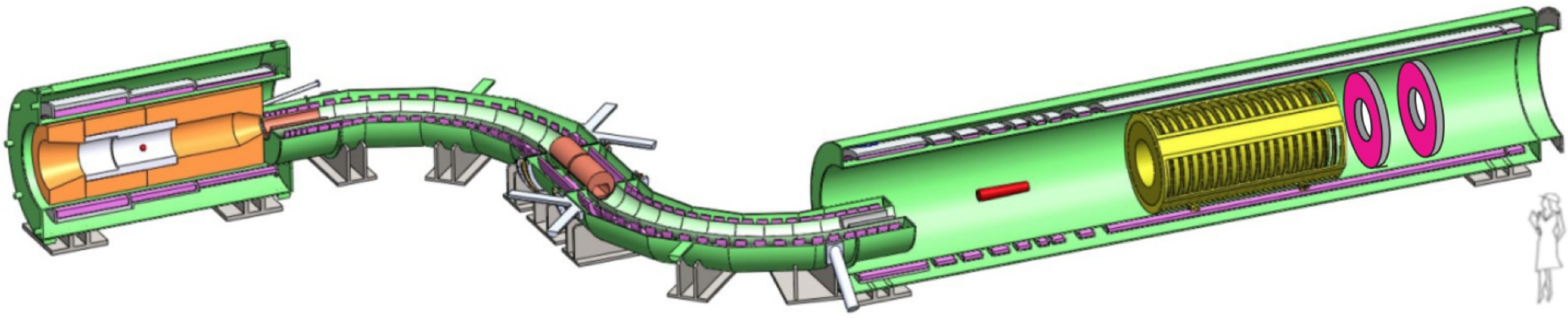
>200 scientists, 37 institutions

Mu2e Experimental Apparatus

Production Solenoid

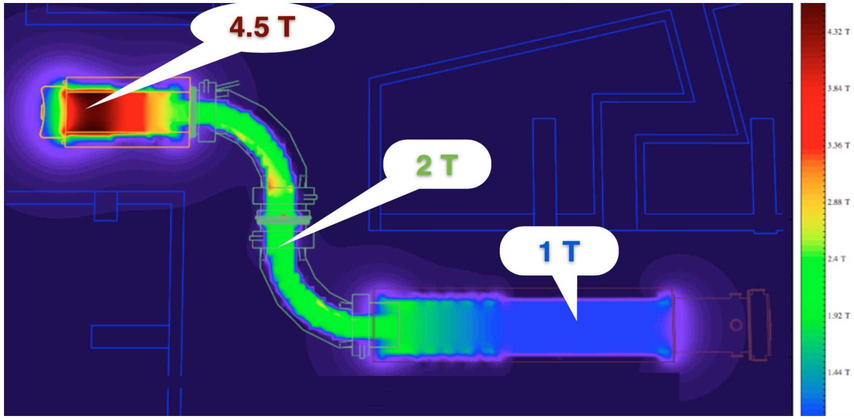
Transport Solenoid

Detector Solenoid

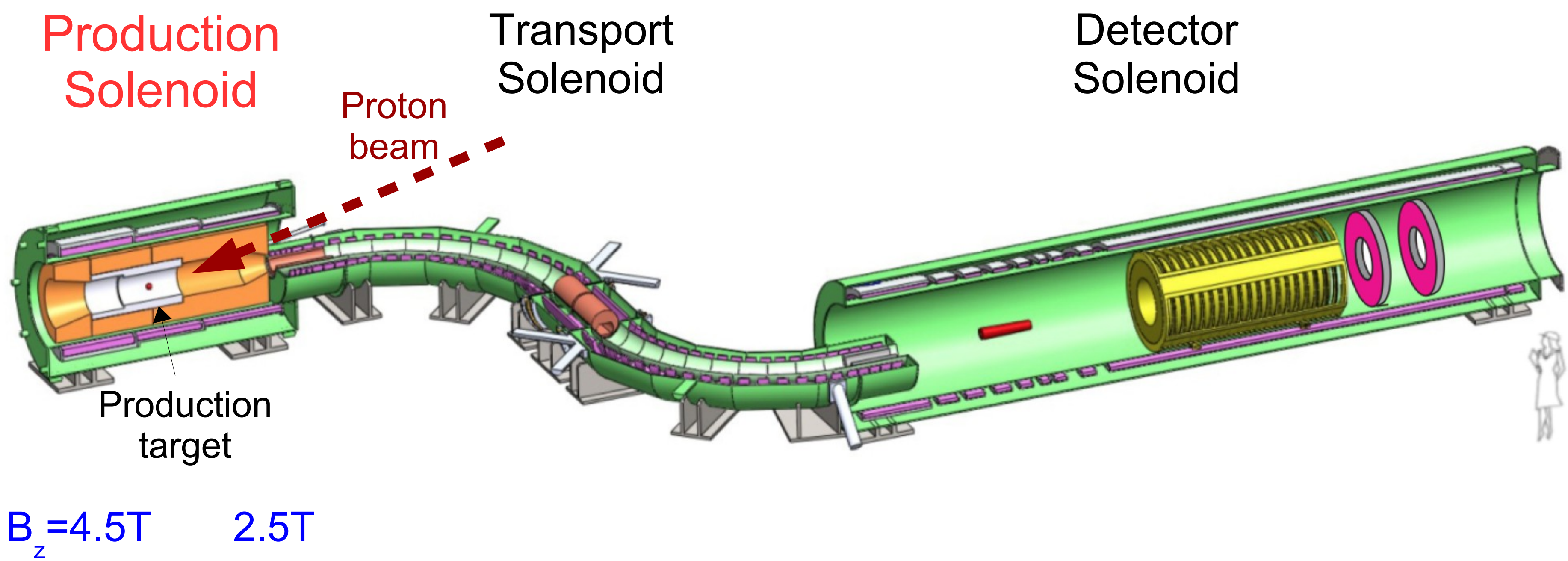


~25 m

- Three functional solenoid units
- Graded fields 4.5 T → 1 T
  - Increase collection efficiency, sweep particles from production to detector

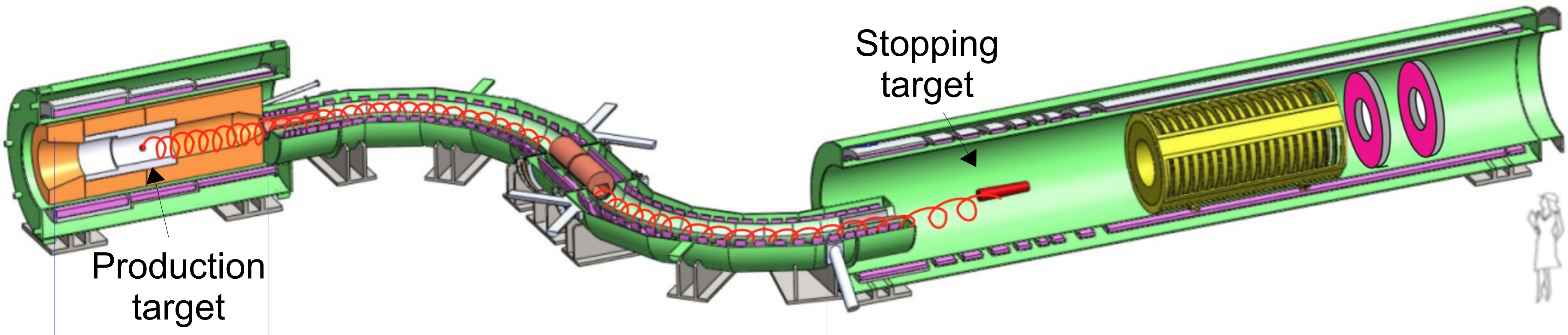


Mu2e Experimental Apparatus: Production



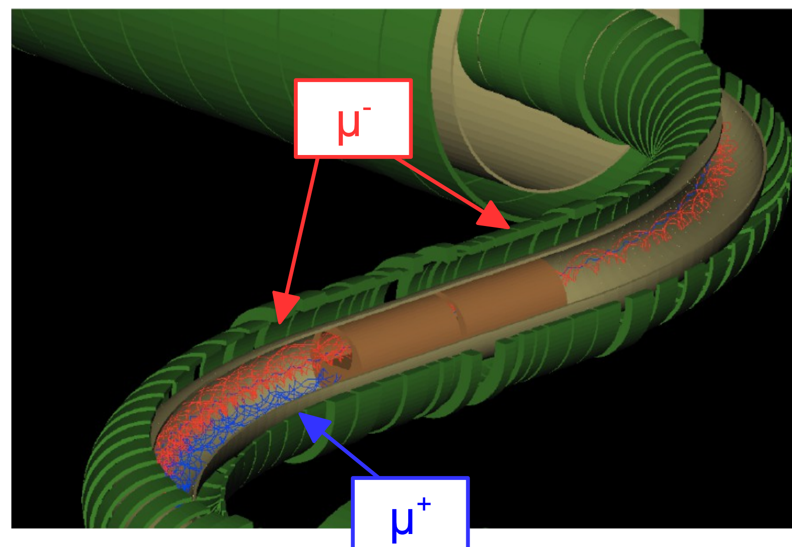
- 8 GeV pulsed proton beam at 8 kW, 1.7 μs between pulses
- ~7×10^{12} protons/s on tungsten production target
- Pions decay to produce secondary muon beam
- Magnetic gradient directs muons to Transport Solenoid

Mu2e Experimental Apparatus: Transport

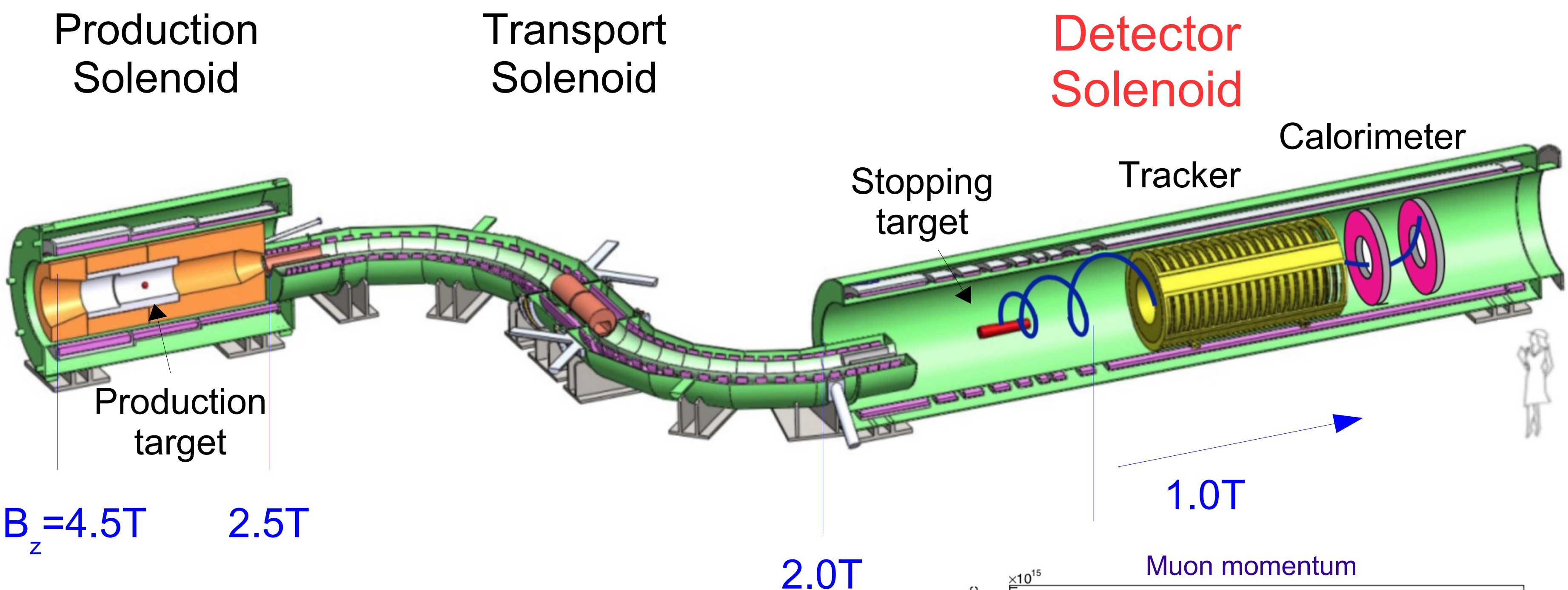


S-shape solenoid eliminates line-of sight backgrounds.

Curvature drift and collimators select sign and momentum of muon beam, transport to stopping target.

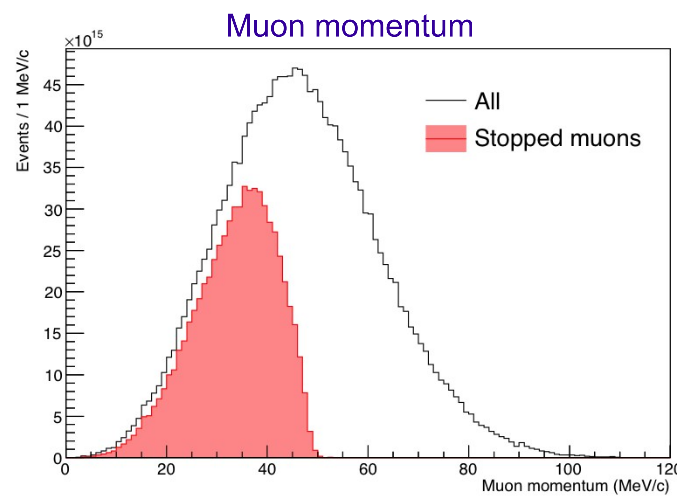


Mu2e Experimental Apparatus: Detector



- Muons with $\langle p_\mu \rangle \approx 35$ MeV/c stopped at Al target
- 10^{10} stopped μ/s, ~10^{18} total over 3 years
  - World's most intense muon beam!

- Detector system must identify and reconstruct a 105 MeV conversion electron, while rejecting backgrounds from conventional processes



Processes at the Stopping Target

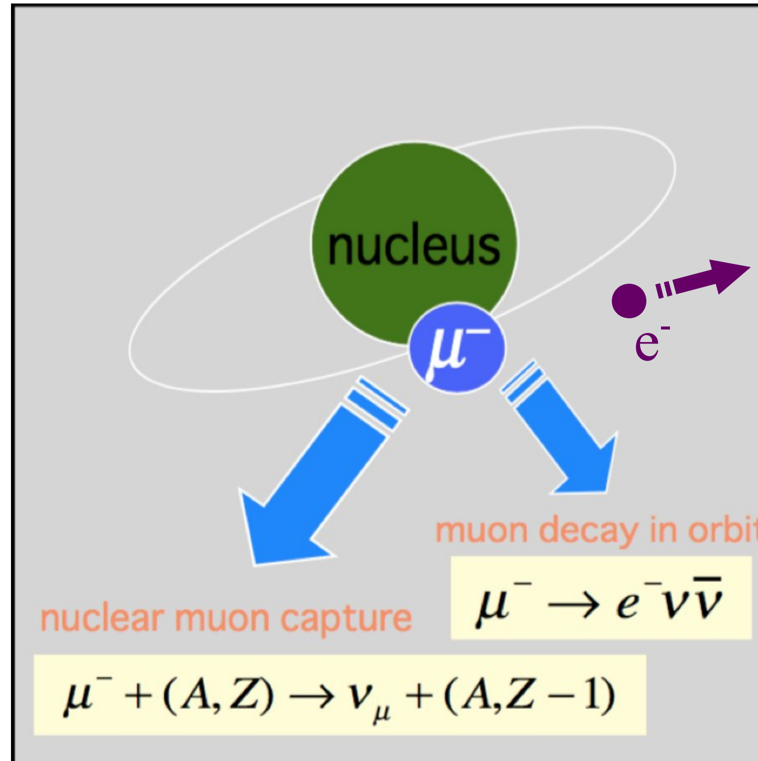
Possibilities for stopped muon at Al atom:

1) Conversion to ~105 MeV electron
- This is the signal of CLFV
- Unfortunately not very often – $R_{\mu e} < 7\times10^{-13}$

2) Muon captured in Al nucleus
- ~60% occurrence
- Process used for rate normalization

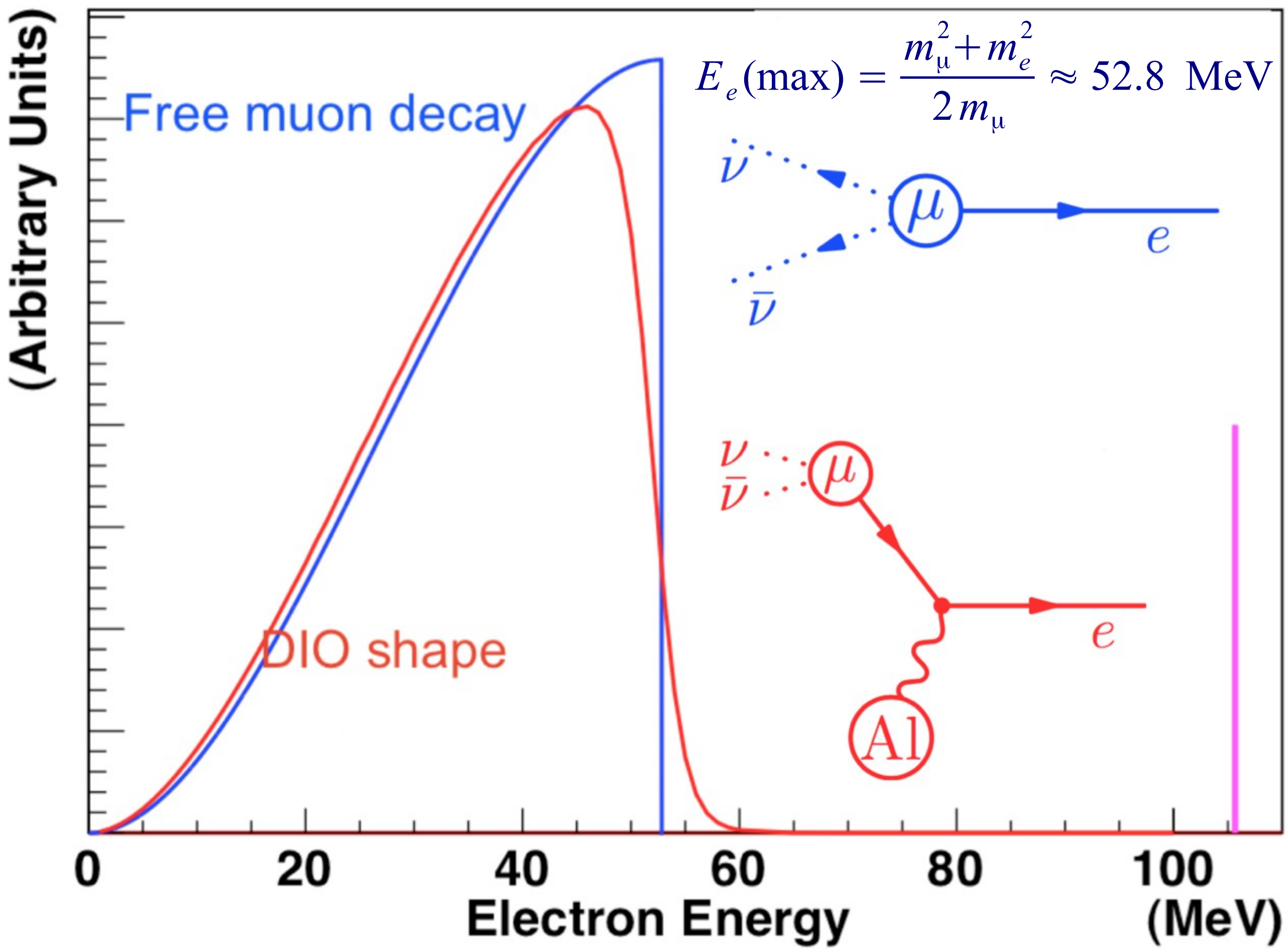
$$R_{\mu e} = \frac{\mu N \to e N}{\mu \, \mathrm{Al}(27,13) \to \nu_\mu \, \mathrm{Mg}(27,12)}$$

3) Decay in orbit (DIO)
- ~40% occurrence
- Background process



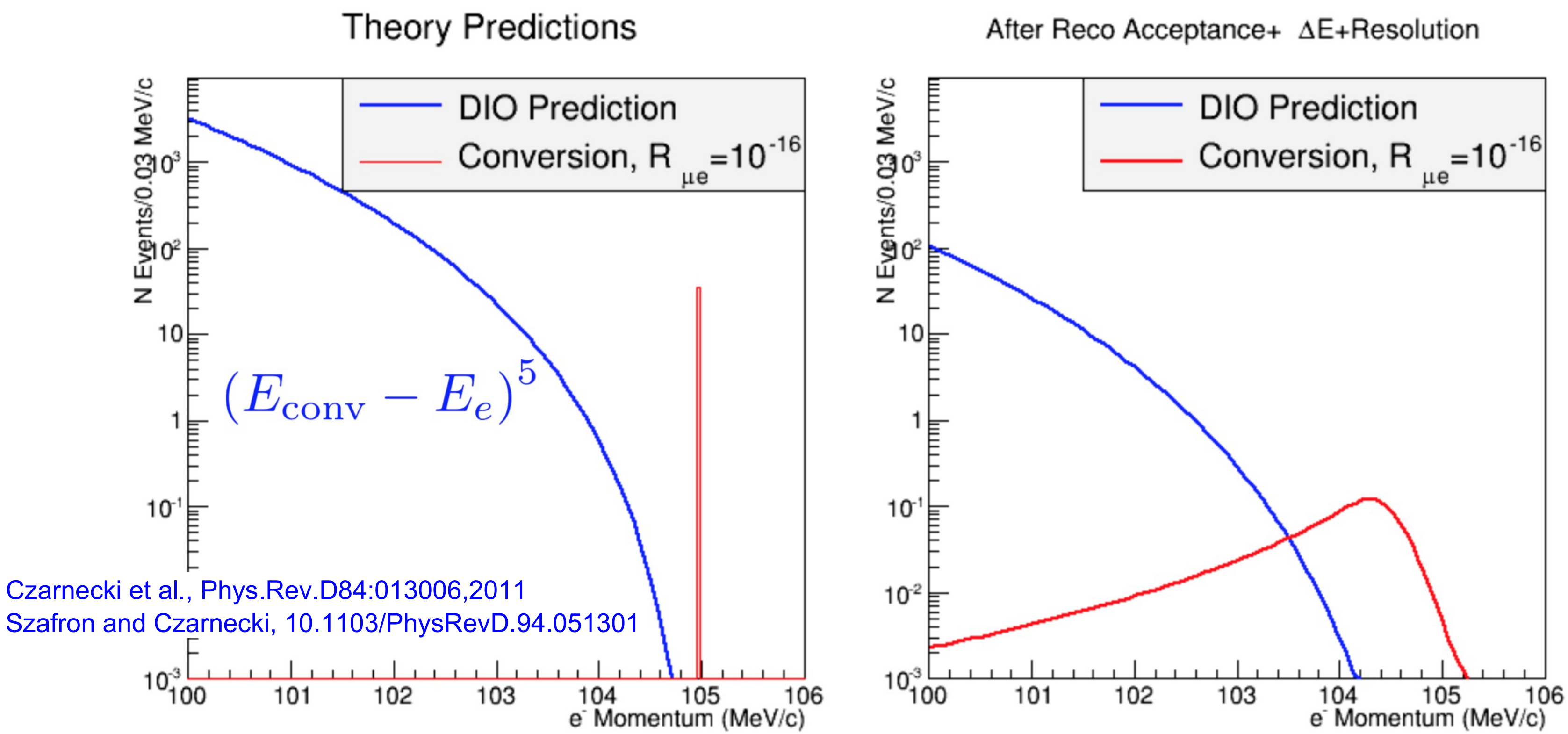
Background Process: Decay in Orbit

Michel spectrum of E_e after free muon decay, or modified in field of nucleus



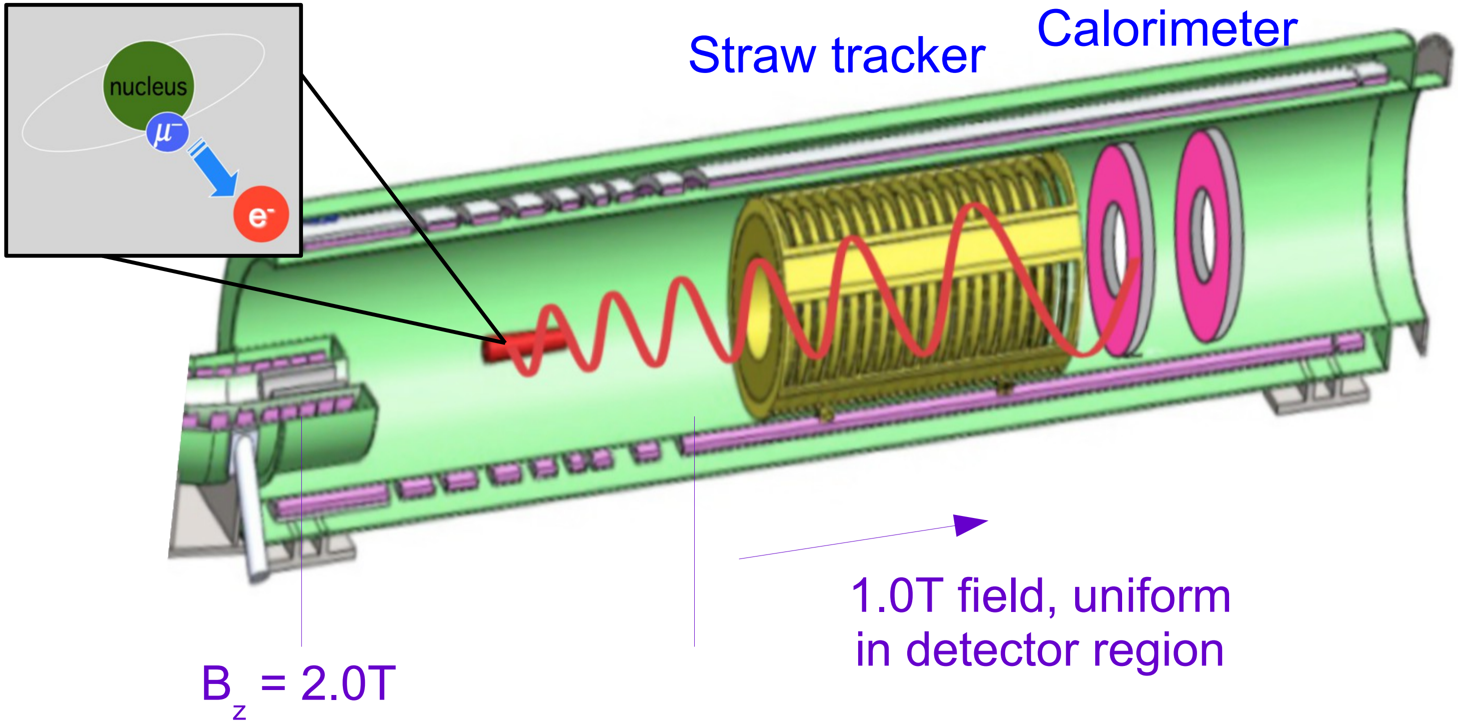
Conversion electron energy far from Michel peak

Background Process: Decay in Orbit



- Nuclear modification pushes DIO spectrum near conversion electron energy
- Overlap after energy loss in material and detector resolution
- DIO electron only differs from signal through its momentum
  → Need low mass detector with high resolution

Detector



Detector immersed in solenoid field → electrons travel in near helical path
- High-rate, time-varying environment, in vacuum

Main detector element: Straw tracker: low-mass straw drift tubes, transverse to axis
- High precision momentum reconstruction of charged particles → separation from DIO
- Hole-in-center design rejects most backgrounds

(Mete's talk)

Followed by Calorimeter: 2 disks of CsI scintillating crystals (Davide's talk)
- Independent measurement of energy, position, time; protection from some backgrounds

- Context and motivation
- The Mu2e experiment
- **Backgrounds**
  - Prompt backgrounds
  - Delayed signal window and extinction
  - Cosmic ray veto
- Summary, outlook

When a single event is evidence of New Physics, all potential backgrounds must be suppressed to an expectation of **zero**

Types of Backgrounds

- Intrinsic (muon induced)
  – Muon decay in orbit (DIO)
  – Radiative muon capture
- Prompt backgrounds
  – Radiative pion capture
  – Muon decay in flight
  – Pion decay in flight
  – Beam electrons
- Slow transit through muon beamline
  – Antiprotons
- Cosmic rays

Suppressed by spectrometer design: minimized occupancy, optimized resolution, track reconstruction

Mu2e Prompt Backgrounds

Prompt event: occurs shortly after particle reaches stopping target

Example: Radiative pion capture
Non-decayed pion reaches stopping target and is radiatively captured, then photon converts.

$$\pi^- \mathrm{N} \rightarrow \gamma\, \mathrm{N}$$

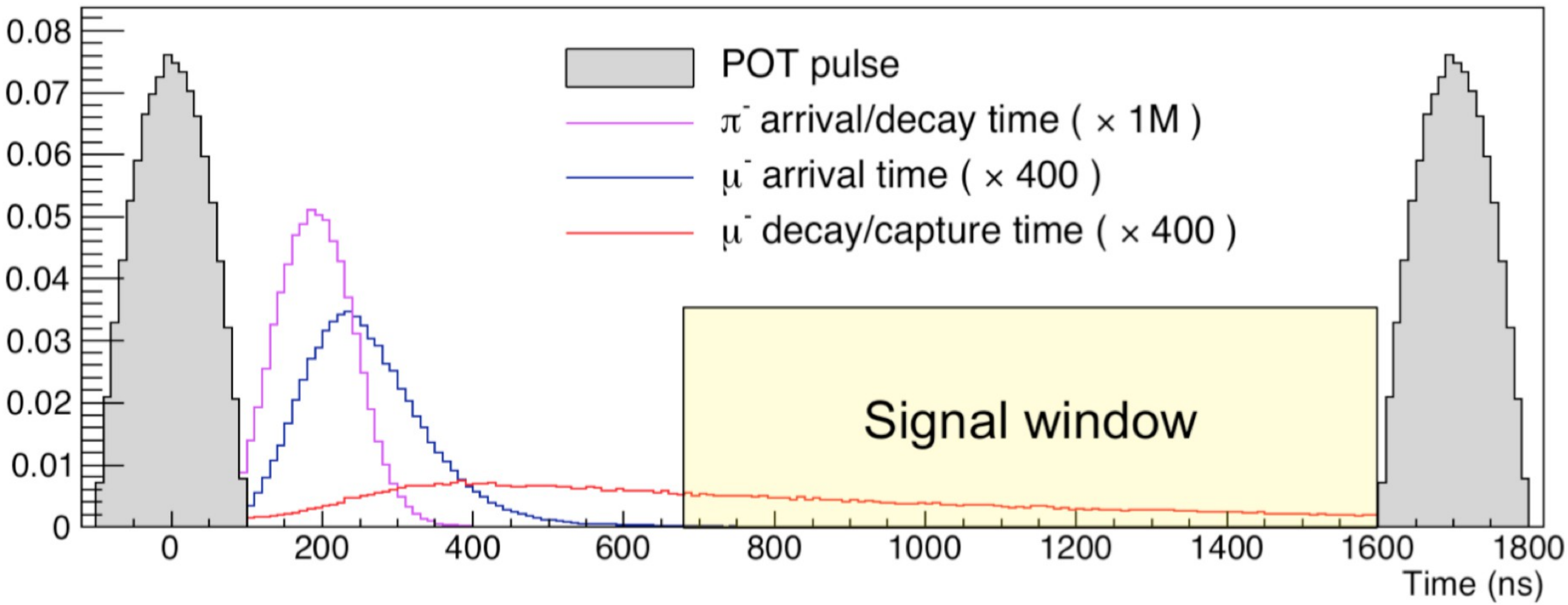
$$\gamma \rightarrow e^- e^+$$

Photon momentum endpoint at m_π.
The electron can have momentum in signal window, and mimic conversion event.

Pion lifetime: only ~26 ns, much shorter than muonic Al (864 ns)
Prompt backgrounds: decay quickly after proton pulse

Concept to suppress prompt backgrounds:
Simply wait until their rates are lowered before initiating live window to look for signal.

Pulsed Beam and Delayed Signal Window



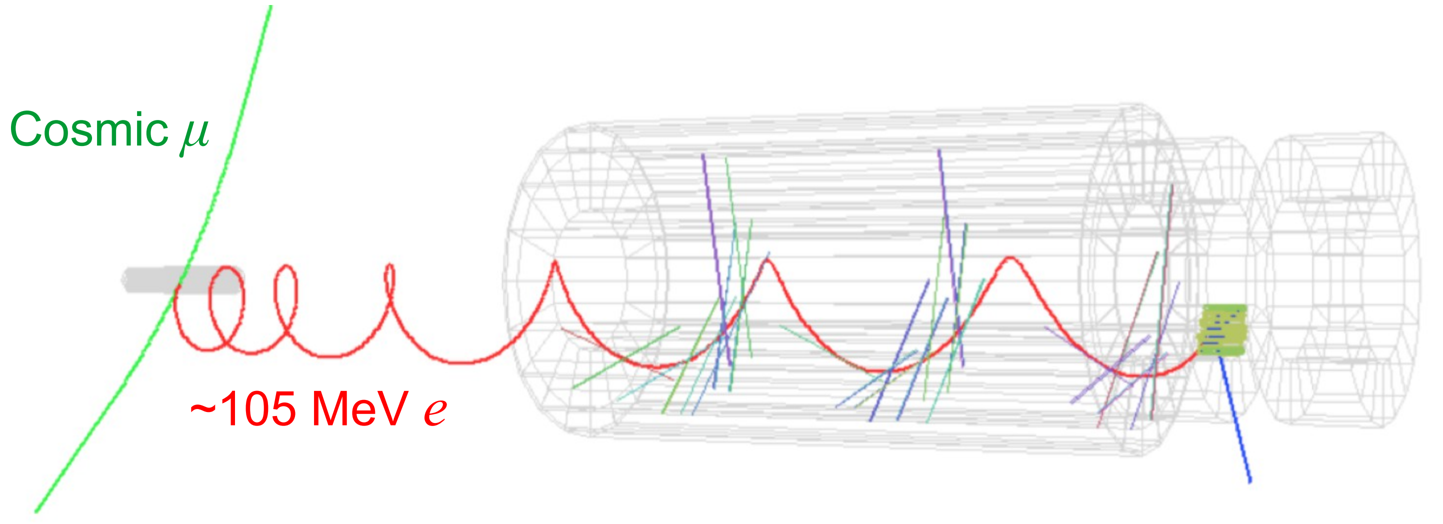
- Proton pulse period: 1695 ns (FNAL Delivery Ring)
  - Beam "flash" in first ~500 ns
- Pion lifetime: 26 ns – prompt backgrounds decay before signal window
- Delayed signal window: 700 → 1600 ns – **Detector is live here**
- Muonic Al lifetime: 864 ns – reason for selecting Al target

Must also eliminate late-arriving protons

Require beam extinction (fraction of beam between pulses): $\varepsilon < 10^{-10}$

Cosmic Ray Backgrounds

- A cosmic muon track can look like a 105 MeV/c electron (mitigated by calorimeter E/p)
- Or, the cosmic muon can decay or knock out electron from material → indistinguishable from conversion electron



- Expect one such event per day
- Crucial to veto cosmic rays → Cosmic Ray Veto system (Yuri's talk)

Types of Backgrounds

• Intrinsic (muon induced) – Muon decay in orbit (DIO)	Separated by electron momentum, low-mass detector, resolution
• Late arriving – Radiative pion capture – Muon decay in flight – Pion decay in flight – Beam electrons	Delayed signal window, simply wait until prompt rates are lowered. Resonant extraction + AC dipole achieve extinction $\varepsilon < 10^{-10}$
• Slow transit through muon beamline – Antiprotons	Absorbed by thin mylar window in transport solenoid
• Cosmic rays	Cosmic ray veto (CRV)

Backgrounds Summary

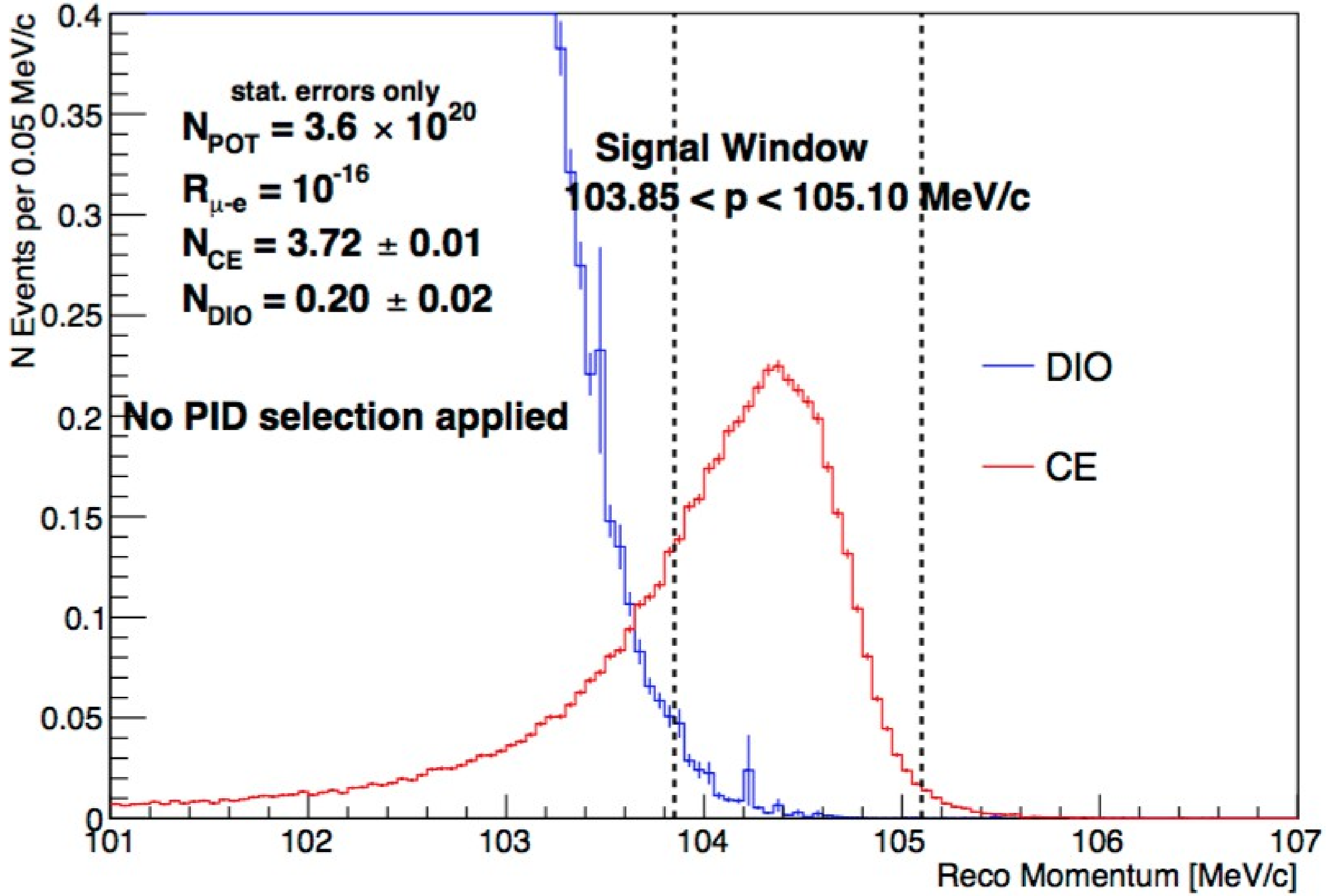
3 years at 1.2×10^{20} protons/year (8 kW beam power)

Category	Background	Expected events
Intrinsic	Muon decay in orbit	0.199 ± 0.092
	Muon capture (RMC)	$0.000^{+0.004}_{-0.000}$
Late arriving	Pion capture	0.023 ± 0.006
	Muon decay in flight	< 0.003
	Pion decay in flight	$0.001 \pm < 0.001$
	Beam electrons	0.003 ± 0.001
Miscellaneous	Antiproton induced	0.047 ± 0.024
	Cosmic rays	0.082 ± 0.018
Total		0.36 ± 0.10

Expect <0.5 background event in 3 years:

Any observation will be evidence of CLFV

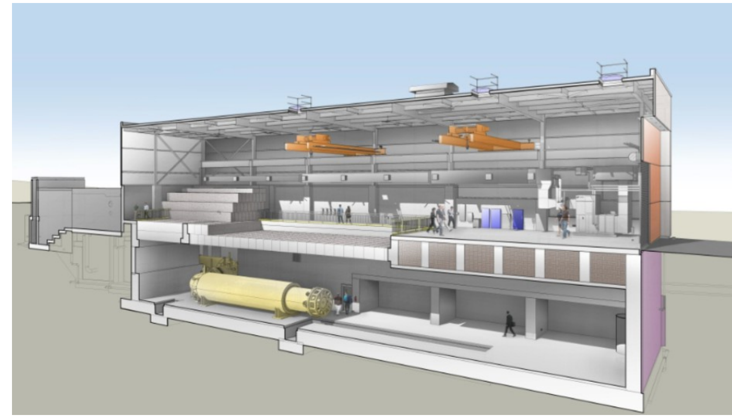
Signal and DIO Background



For $R_{\mu e} \approx 10^{-16}$ we expect:

~4 conversion events, no background contamination

Mu2e Building Status



Mu2e detectors and solenoids in the building stage, installation soon

Summary

The Mu2e experiment

- A search for Charge Lepton Flavor Violation
  - coherent conversion of a muon to an electron in the field of an Al nucleus
- Sensitivity increase by 4 orders of magnitude
  - World's most intense muon beam
  - Extreme suppression of backgrounds
  – any event will be sign of CLFV and New Physics
- Discovery potential over wide range of New Physics models
  – results will shape future directions in physics research
- Data expected in 2022

Backup

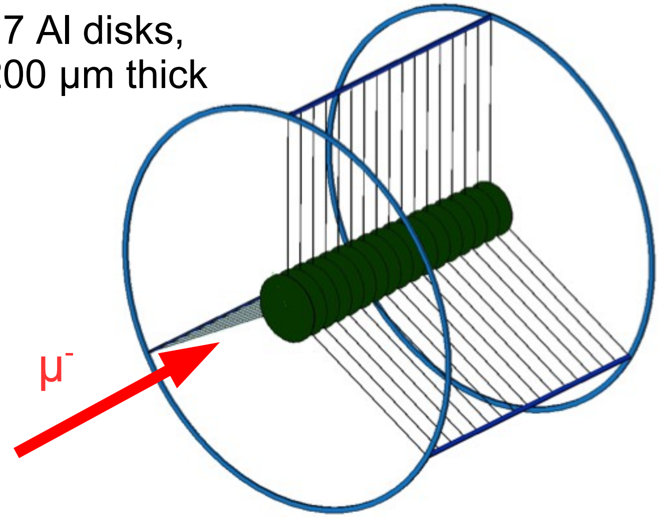
CLFV processes

Broad global interest in CLFV searches:

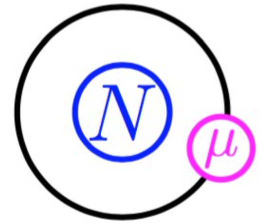
Process	Current limit	Planned Next Gen Experiment
$Z \to e\mu$	$\mathrm{BR} < 7.5 \cdot 10^{-7}$	
$\tau \to eee$	$\mathrm{BR} < 2.7 \cdot 10^{-8}$	10^{-9}, BELLE-II
$\tau \to \mu\mu\mu$	$\mathrm{BR} < 2.1 \cdot 10^{-8}$	
$\tau \to \mu ee$	$\mathrm{BR} < 1.5 \cdot 10^{-8}$	
$\tau \to \mu\eta$	$\mathrm{BR} < 6.5 \cdot 10^{-8}$	
$\tau \to e\gamma$	$\mathrm{BR} < 3.3 \cdot 10^{-8}$	
$\tau \to \mu\gamma$	$\mathrm{BR} < 4.4 \cdot 10^{-8}$	
$K_L \to e\mu$	$\mathrm{BR} < 4.7 \cdot 10^{-12}$	
$K^+ \to \pi^+ e\mu$	$\mathrm{BR} < 1.3 \cdot 10^{-11}$	
$B^0 \to e\mu$	$\mathrm{BR} < 7.8 \cdot 10^{-8}$	
$B^+ \to K^+ e\mu$	$\mathrm{BR} < 9.1 \cdot 10^{-8}$	
$\mu^+ \to e^+\gamma$	$\mathrm{BR} < 4.2 \cdot 10^{-13}$	10^{-14} (MEG)
$\mu^+ \to e^+e^-e^+$	$\mathrm{BR} < 1.0 \cdot 10^{-12}$	10^{-16} (Mu3e)
$\mu^- A \to e^- A$	$\mathrm{R}_{\mu e}^{\mathrm{Au}} < 7.0 \cdot 10^{-13}$	10^{-17} (Mu2e, COMET)

- Most stringent limits come from the muon sector
- The $\mu A \to eA$ process offers greatest potential sensitivity
  - Best control of backgrounds

Stopping Target

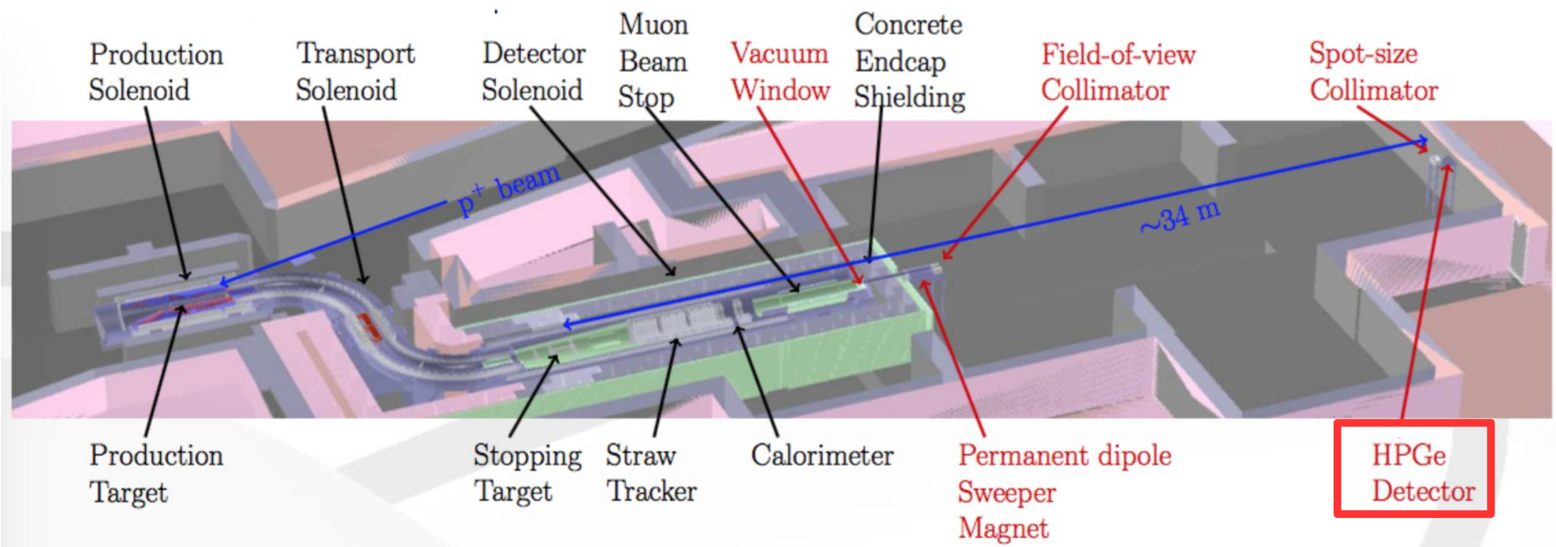


Muons stopped in thin Al target foils.
Quickly cascade to 1s ground state (~1 fs), emitting X-rays at characteristic energies



Fermi radius ~20 fm
Muonic Al lifetime: 864 ns

Muonic atom at rest

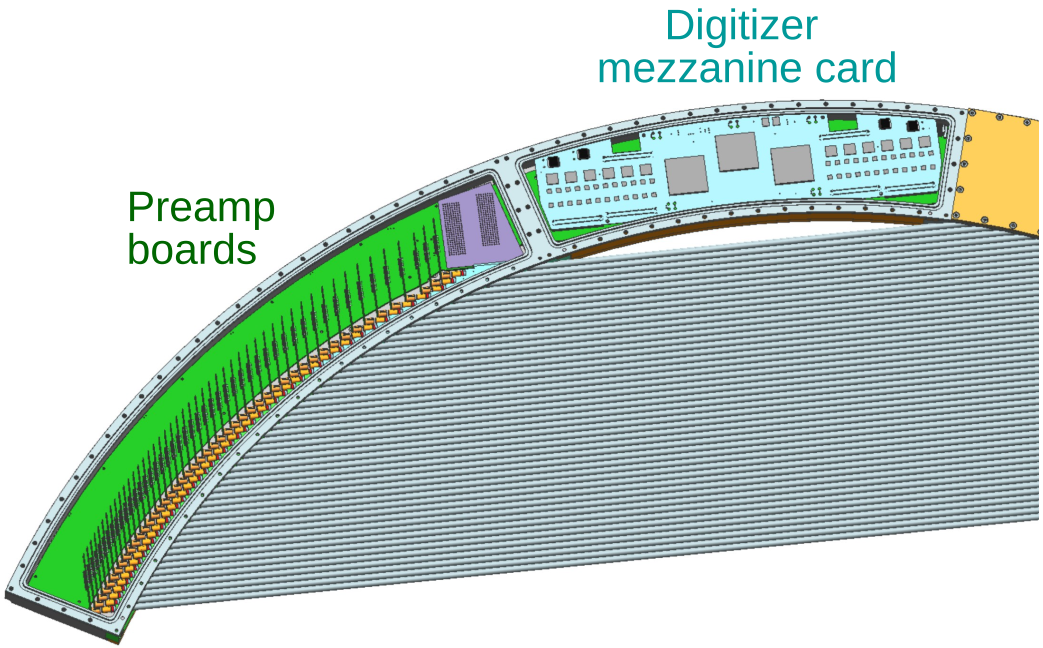


High-purity Ge detector monitors de-excitation X-rays from stopping target

Tracker Front-End Electronics

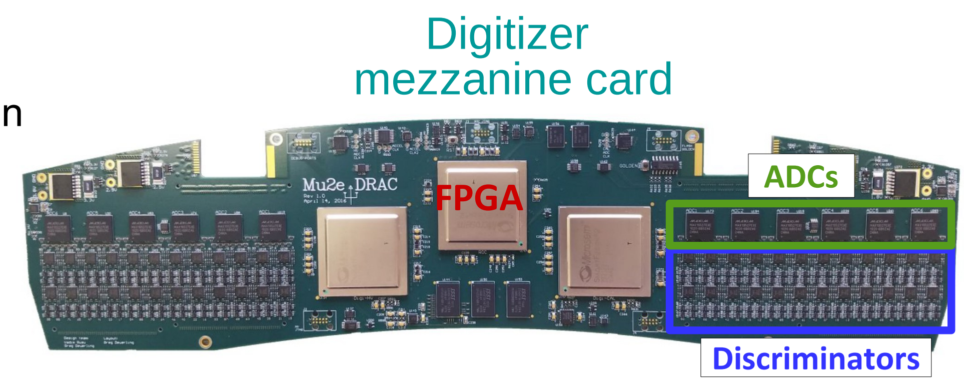
Electronics volume 71<r<80 cm
- on every panel inside cryostat

Readout at both ends of straw, preamp and digitization
- Drift time resolution: 2ns (100μm drift radius)
- Time difference resolution: 4cm along straw axis
- ADC for dE/dx measurement to identify highly-ionizing proton hits

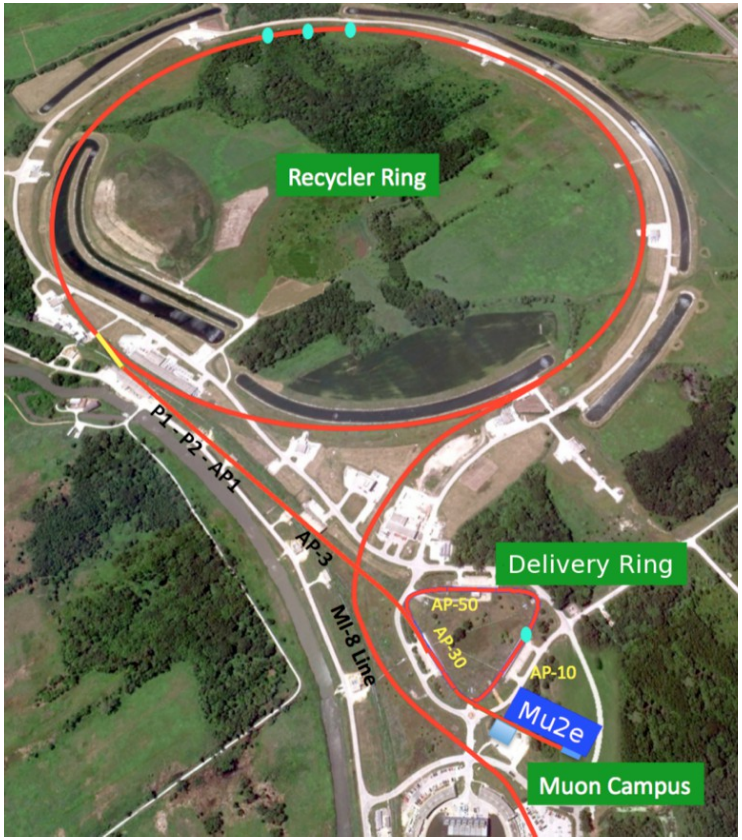


Requirements:

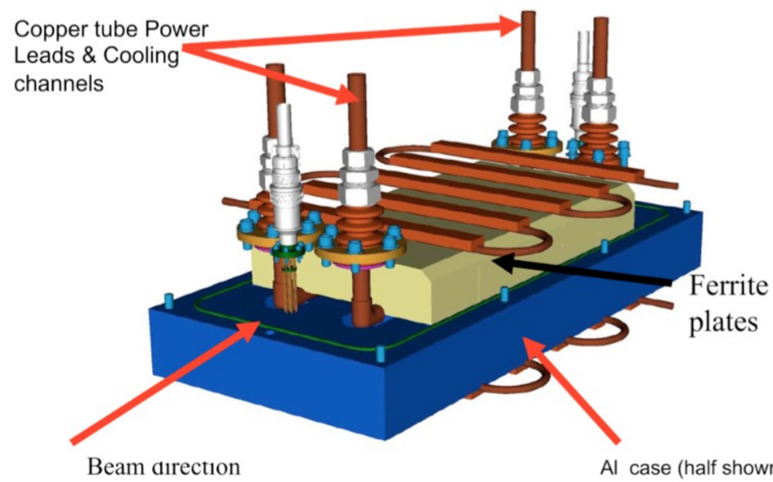
- Supply HV to straws (and remote disconnect)
- B-field perturbation <1G in active detector region
- Low power <10kW within cooling capabilities
- Sustain radiation damage from target
- <12 × 96 dead channels in 5 yrs at 90% CL



Achieving Extinction

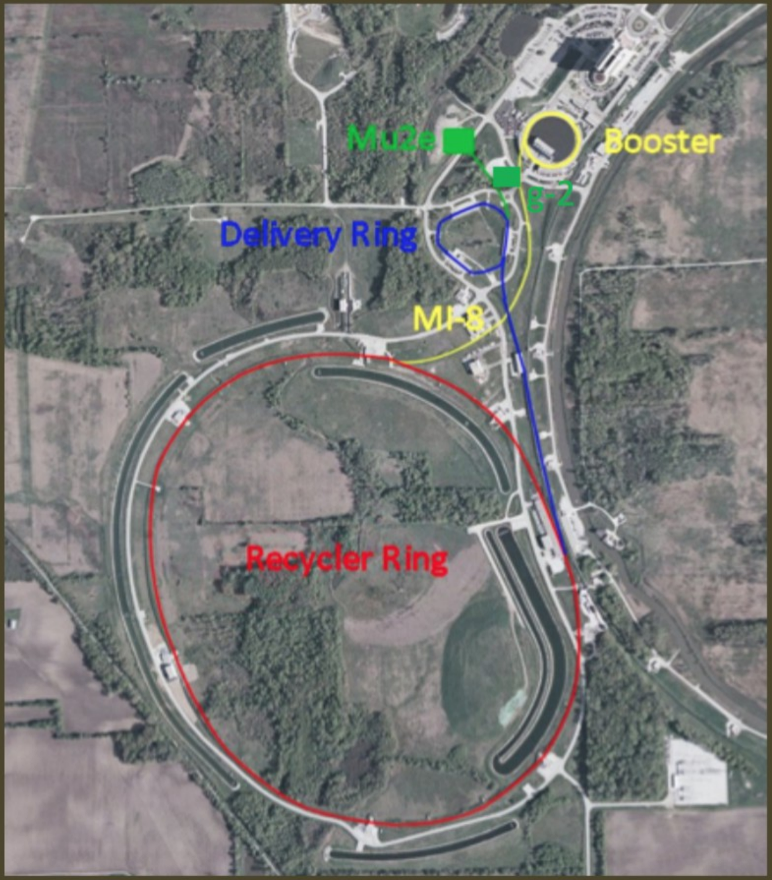


- Single bunch in Delivery Ring at a time – revolution period 1695 ns
- Resonant Extraction peels off proton pulses to Mu2e production target – extracted beam $\varepsilon \approx 2\times10^{-5}$
- Resonant dipole guides out-of-time beam to collimators – extinction factor $\varepsilon = 5\times10^{-8}$



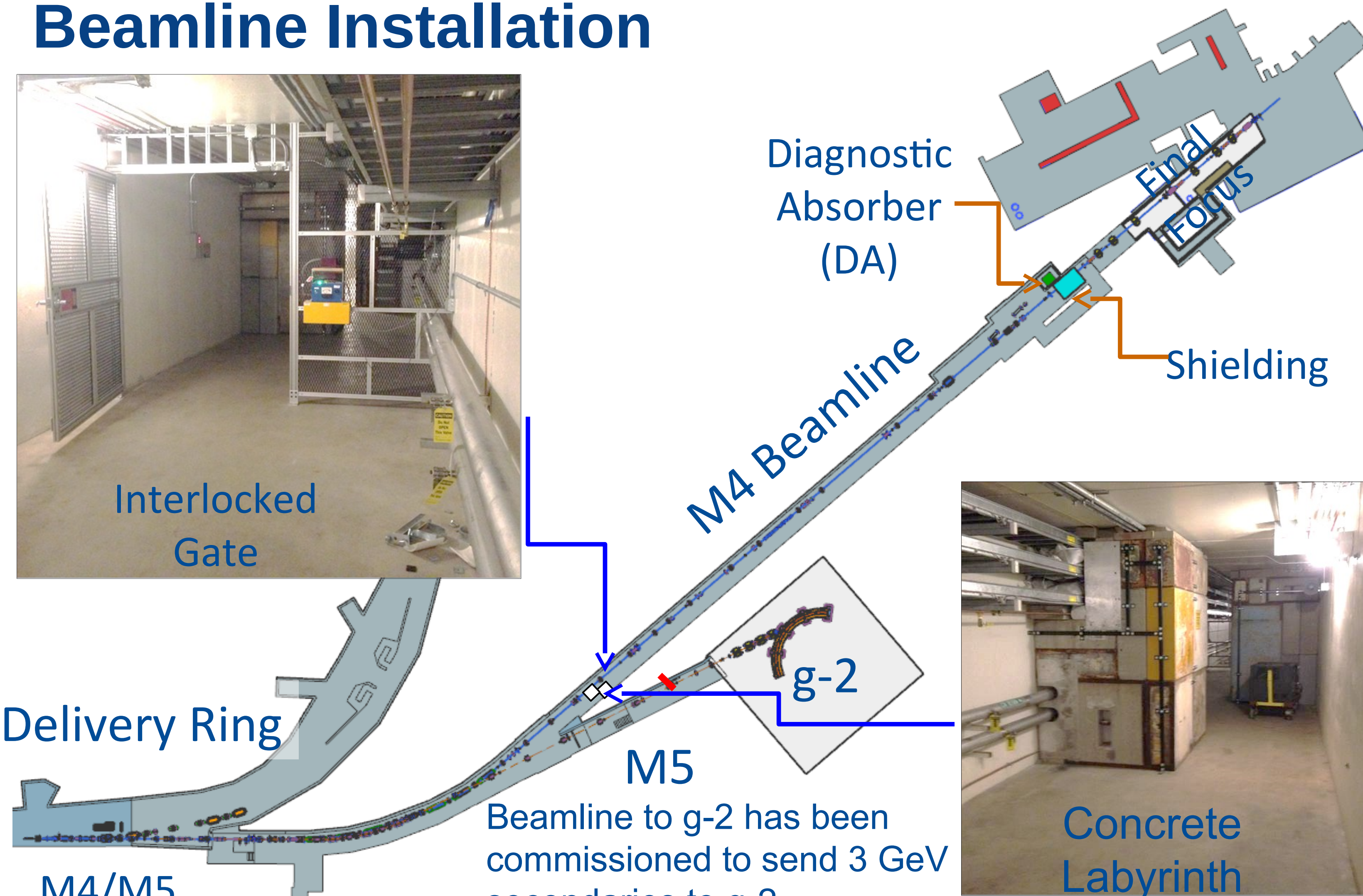
Total expected extinction:
$\varepsilon = 1.1\times10^{-12}$

The Mu2e Proton Beam



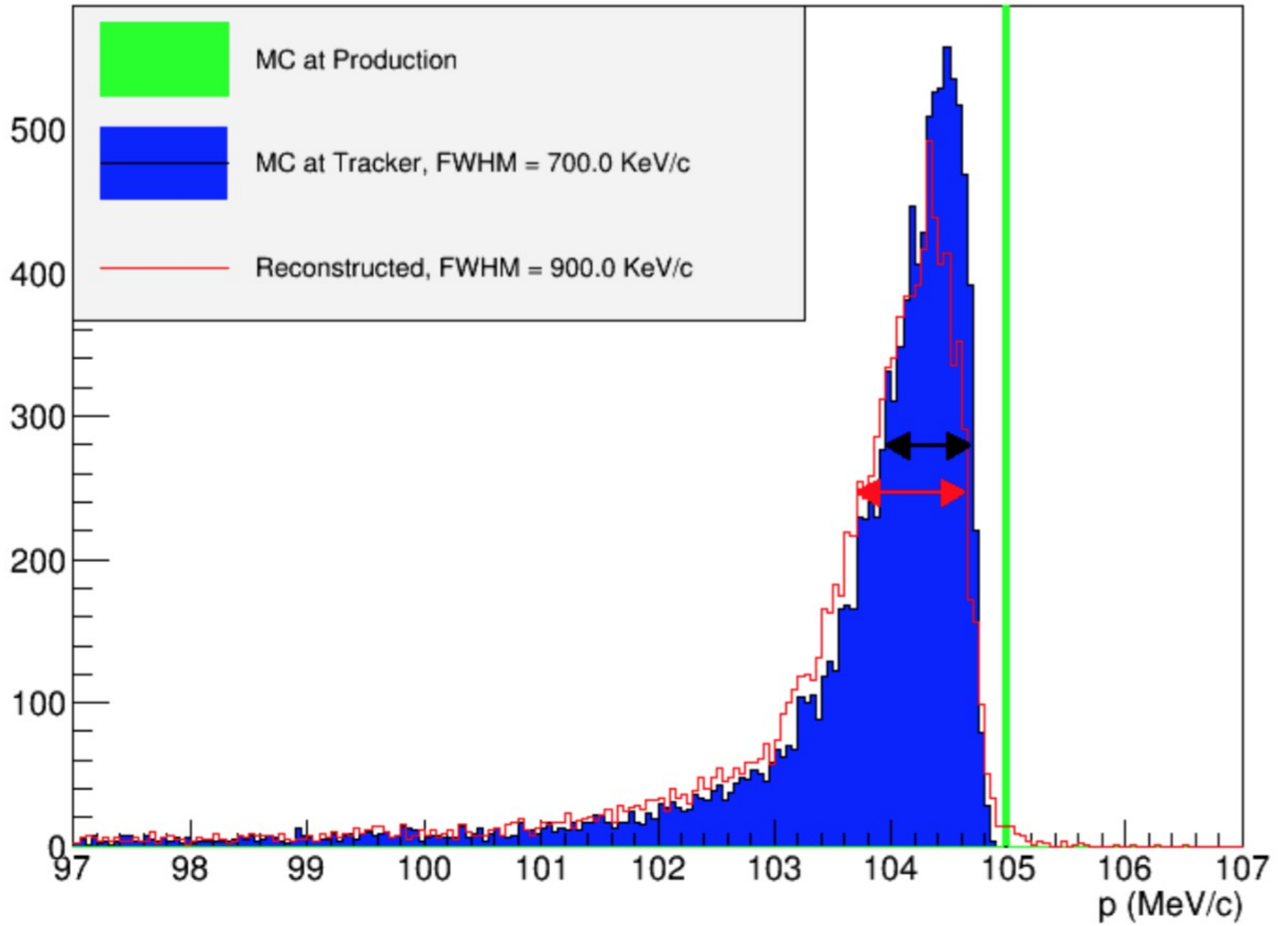
- Mu2e begins by using protons to produce pions
- Mu2e will repurpose much of the Tevatron anti-proton complex to instead produce muons.
- Mu2e can (and will) run simultaneously with NOvA and BNB.

Beamline Installation



Beamline to g-2 has been commissioned to send 3 GeV secondaries to g-2

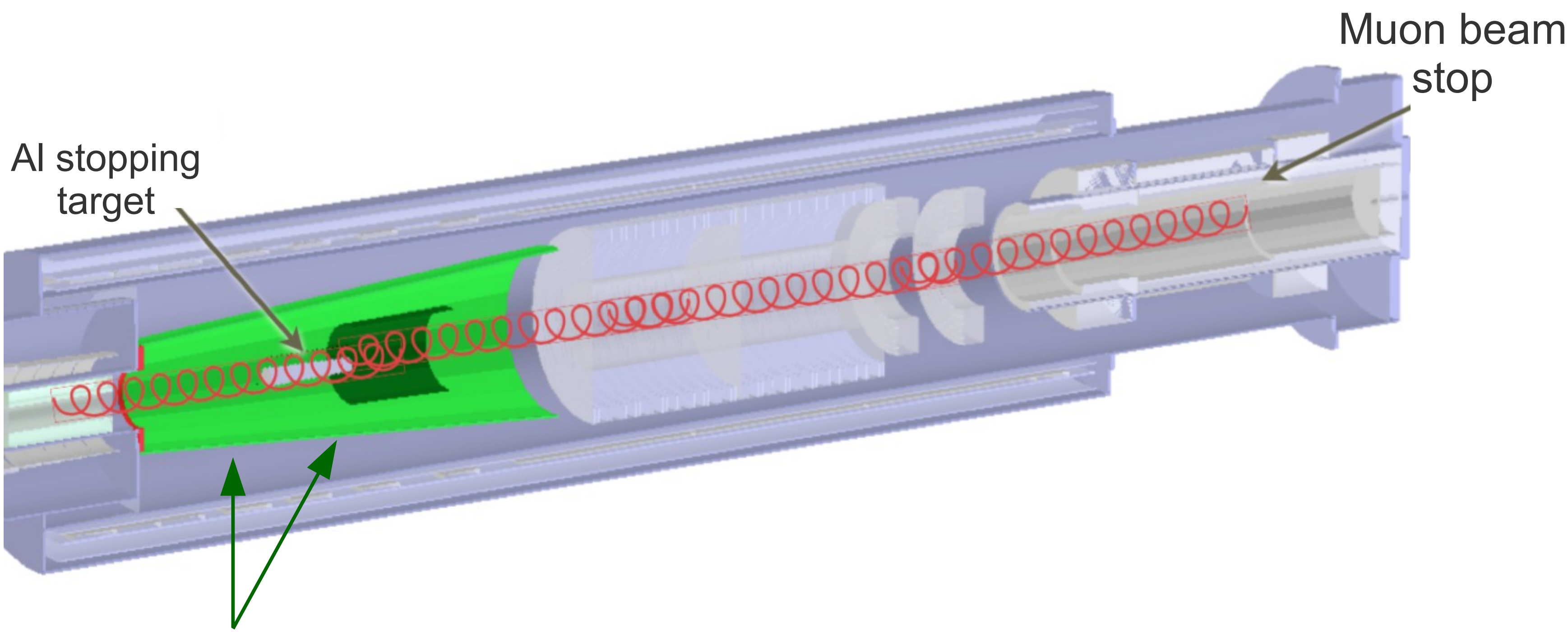
Signal momentum spectrum



Smearing dominated by interactions at the target and at neutron/proton absorbers upstream of the tracker

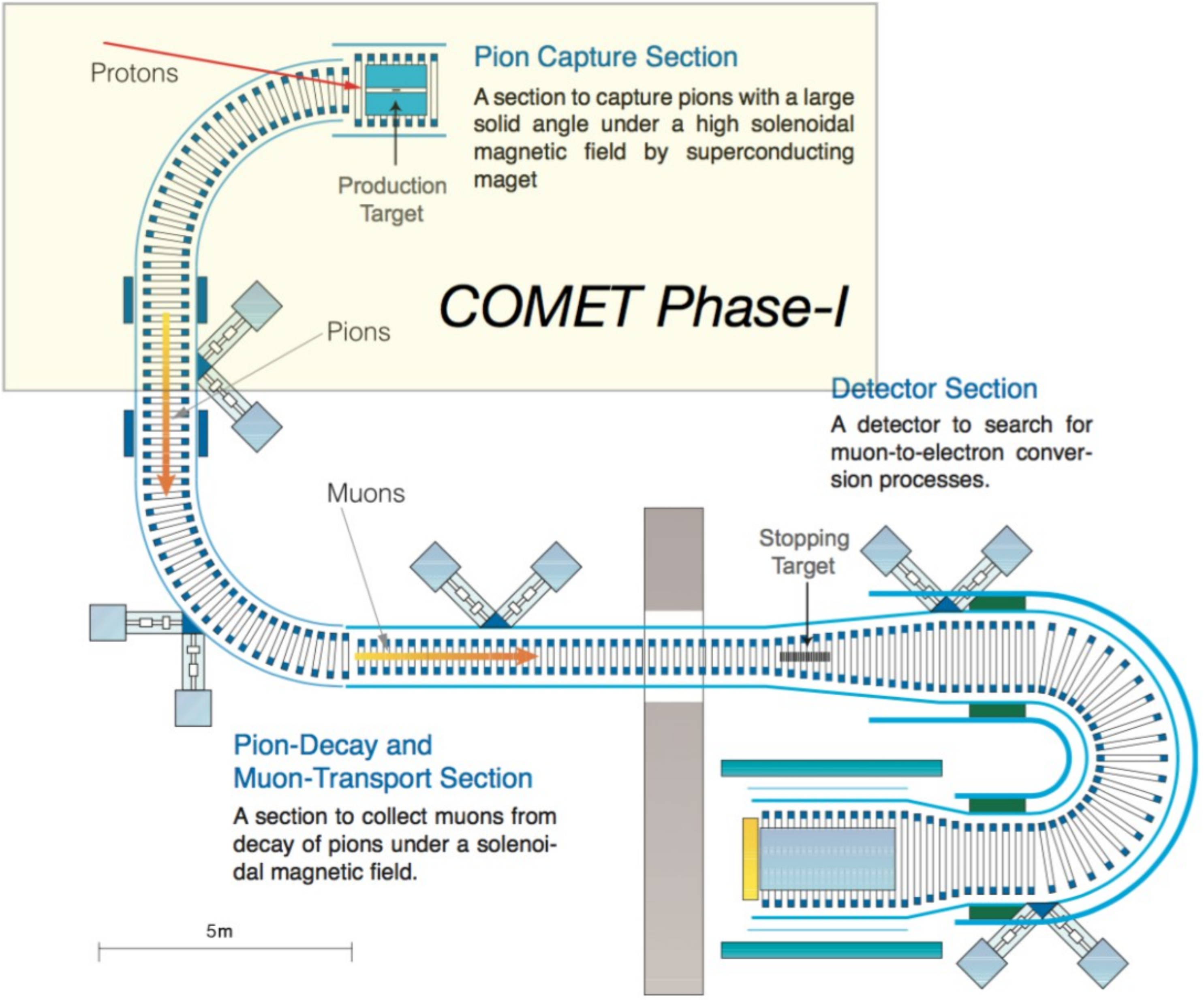
Remnant Beam and Proton Absorbers

Detector is blind to low-momentum particles, beam flash, ...



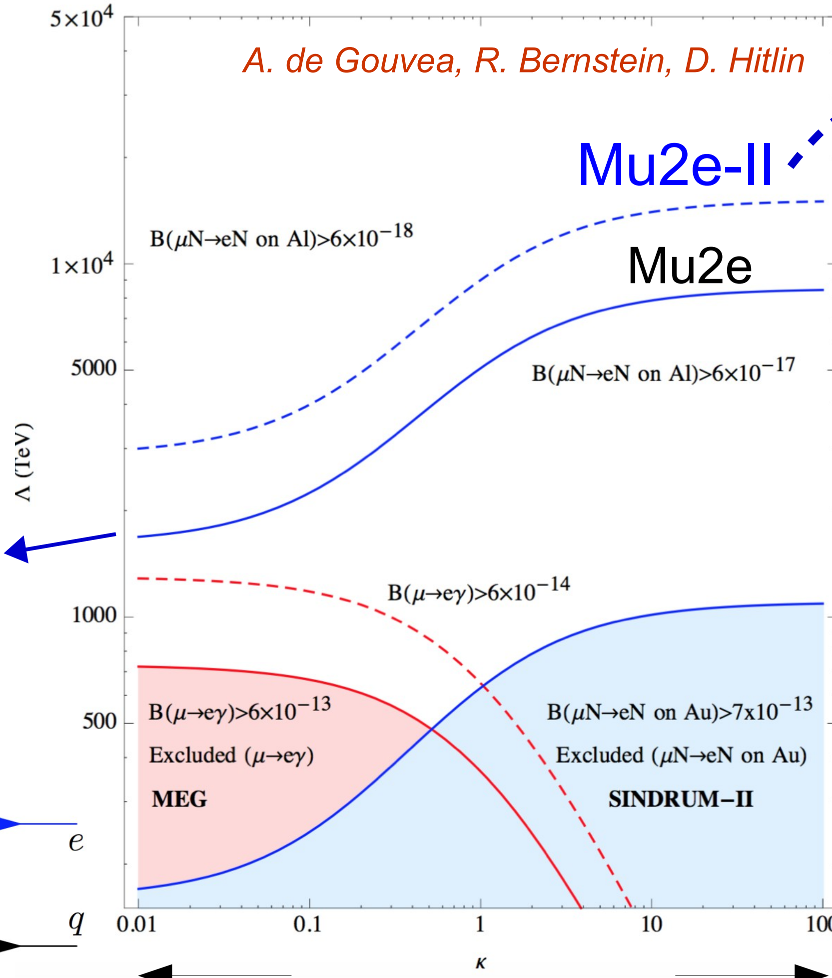
Proton absorbers

Plastic absorbs protons from target (~0.1/muon capture, large dE/dx), protects tracker from high rates and large charge deposition.


Protons
Pion Capture Section
A section to capture pions with a large solid angle under a high solenoidal magnetic field by superconducting maget
Production Target
COMET Phase-I
Pions
Detector Section
A detector to search for muon-to-electron conversion processes.
Muons
Stopping Target
Pion-Decay and Muon-Transport Section
A section to collect muons from decay of pions under a solenoidal magnetic field.
5m

Mu2e-II

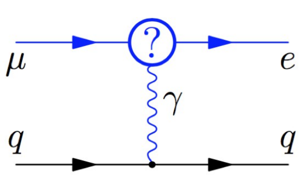
$$\mathcal{L}_{\mathrm{CLFV}} = \frac{m_\mu}{(1+\kappa)\Lambda^2}\bar{\mu}_R\sigma_{\mu\nu}e_L F^{\mu\nu} + \frac{\kappa}{(1+\kappa)\Lambda^2}\bar{\mu}_L\gamma_\mu e_L(\bar{u}_L\gamma^\mu u_L + \bar{d}_L\gamma^\mu d_L)$$



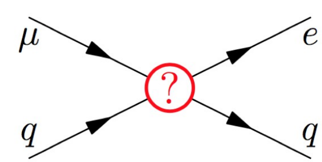
Next generation Mu2e improves $R_{\mu e}$ limit by an extra order of magnitude

- Next-generation Mu2e feasibility study (1307.1168)
- Requires FNAL intensity upgrade (PIP-II)
- Powerful measurement in any scenario

Mu2e improves sensitivity in all NP scenarios



Loop-dominated

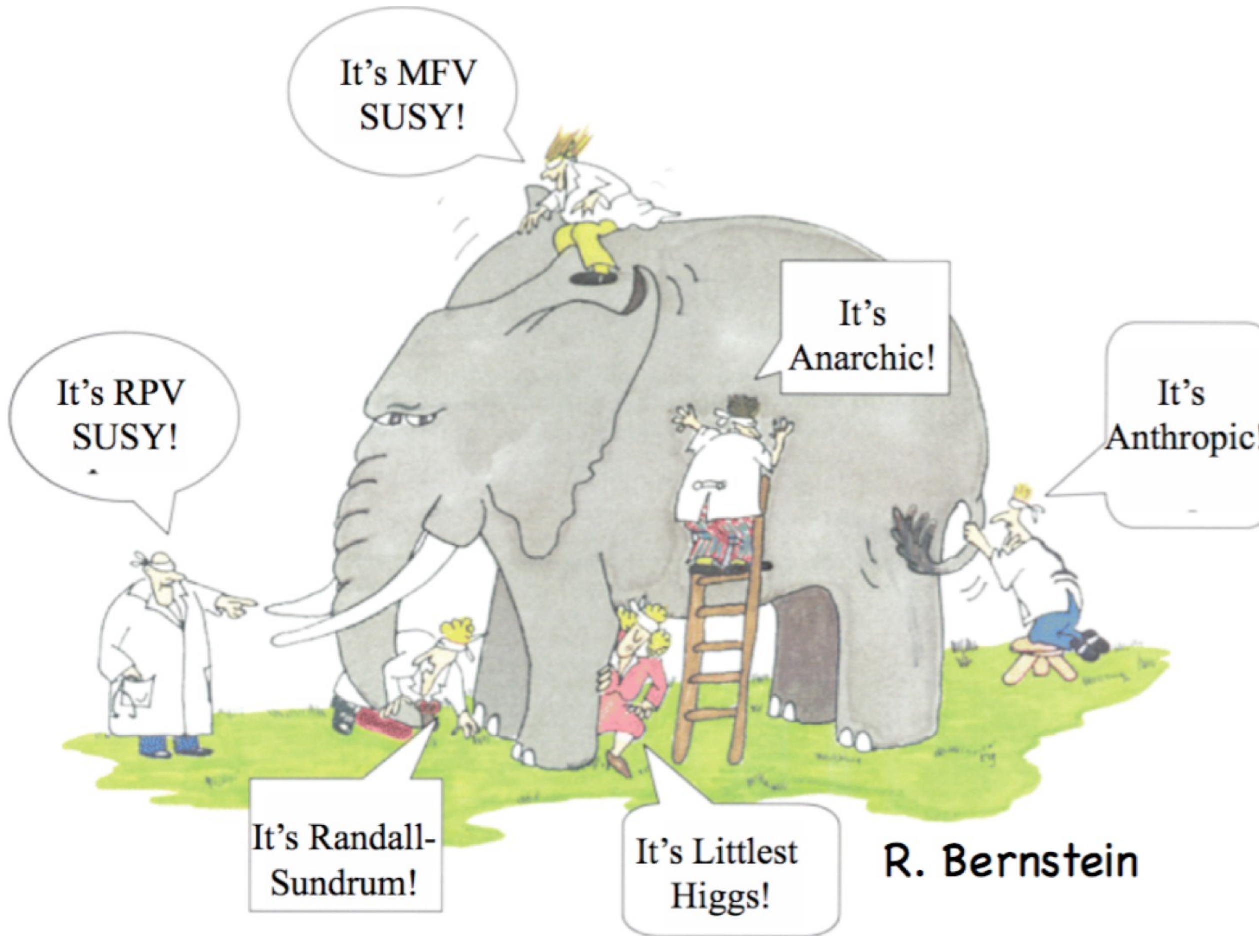


Contact-dominated

Mu2e-II

Next-next-generation Mu2e-II will be powerful even if no signal is observed in Mu2e

If a signal *is* observed in Mu2e..



Model Discrimination

We obtain model discriminating power on underlying physics mechanism by comparing CLFV rates on different stopping targets

V. Cirigliano et al., phys. Rev. **D80** 013002 (2009)