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Targeting Studies for an 800 MeV beam for Mu2e-II

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Lee Teng Internship Presentation

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Outline

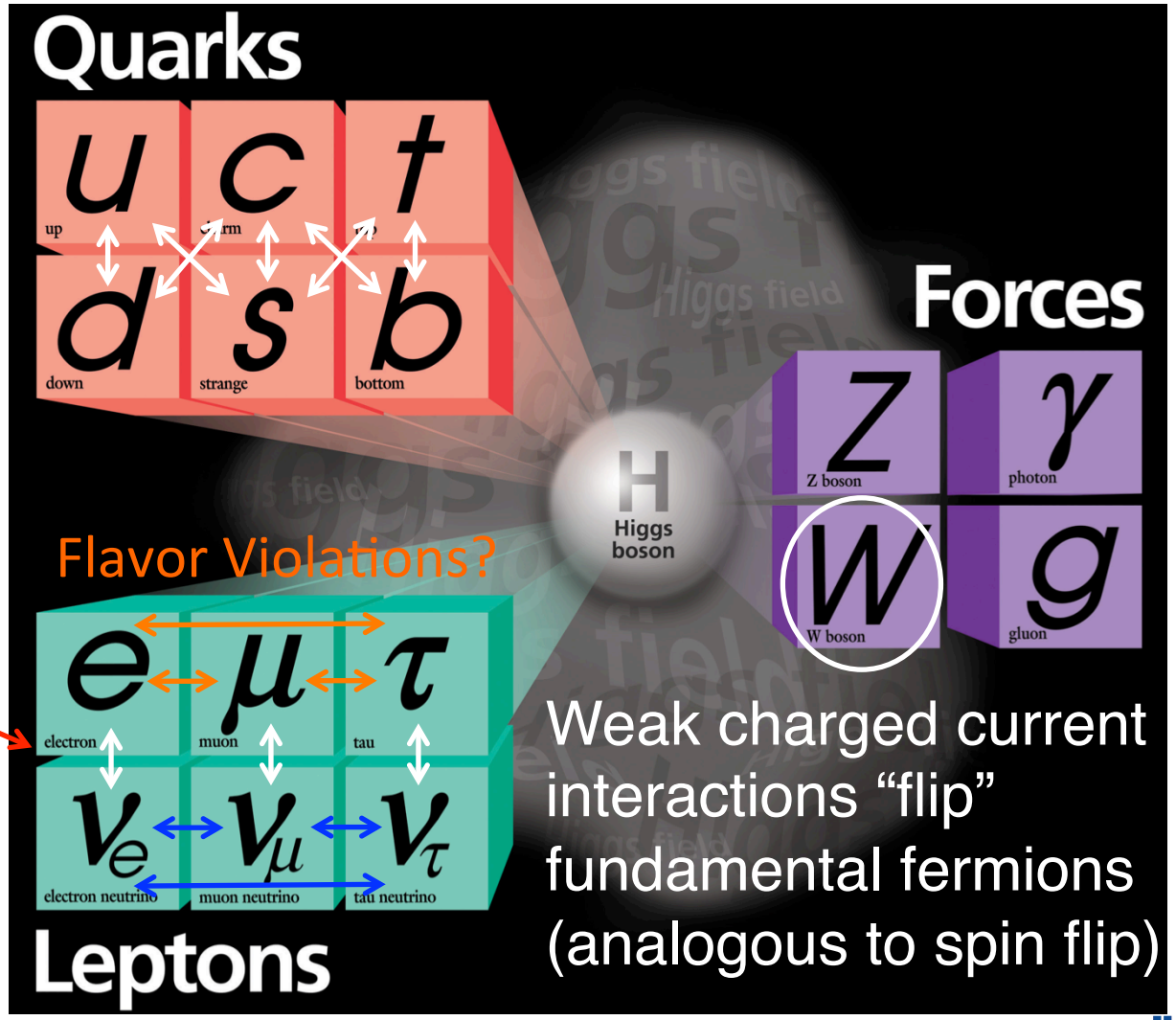
- Overview
  - Motivation for Mu2e
  - Mu2e and Mu2e-II
- Simulation Details
- Simulation Results
- Summary

The Standard Model

Fermions

Bosons

Mixing



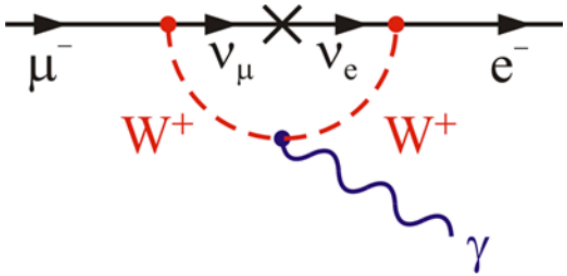
Mixing

Neutrino Oscillations

Weak charged current interactions "flip" fundamental fermions (analogous to spin flip)

Charged-Lepton-Flavor Violation (CLFV)

- CLFV is extremely suppressed in the Standard Model
  e.g.- $\mu \to e\gamma$ Single-event-sensitivity $< 10^{-54}$

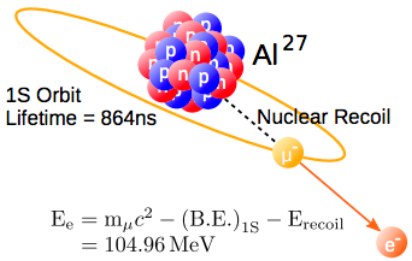


A signal of CLFV → Evidence of *New Physics!*

Mu2e Experiment

- Mu2e searches for muon-to-electron conversion with presence of a nucleus.

$$\mu^- + \mathrm{Al} \rightarrow e^- + \mathrm{Al}$$



- Mu2e measures the single-event-sensitivity:

$$R_{\mu e} \equiv \frac{\Gamma\left(\mu^- N(A,Z) \rightarrow e^- + \mathrm{N(A,Z)}\right)}{\Gamma\left(\mu^- \mathrm{N(A,Z)} \rightarrow \nu_\mu + \mathrm{N'(A,Z\text{-}1)}\right)}$$

- Target sensitivity: 2.87×10^{-17}
  - Current limit: 7×10^{-13} (SINDRUM-II)

- Upgrade: Mu2e-II

Mu2e Upgrade by Proton Improvement Plan-II

Mu2e-II aims to achieve ×10 Mu2e sensitivity

	Mu2e	Mu2e-II
Single-event-sensitivity	2.87×10^{-17}	2.87×10^{-18}
Mean expected background	0.41	<1*

*hopefully achieved by the upgrade

- Hopefully, only modest changes to the Mu2e design are required to pursue Mu2e-II.

After PIP-II is complete,

- Beam power increase from 8 kW to ~100 kW
- Improved duty factor

Why consider Mu2e-II?

Regardless the Mu2e result, Mu2e-II is important:

Mu2e observes CLFV ≥ 5σ

- Switch targets and measure the ratio of rates to further discriminate models of underlying physics

Mu2e observes CLFV at 3σ

- Collect ×10 data to definitely resolve the situation

Mu2e sets stringent new limit on CLFV

- Collect ×10 data and explore new parameter space

Beam Assumption

	Mu2e	Mu2e-II
Beam Kinetic Energy	8 GeV	800 MeV
Beam Power	8 kW	8-100 kW
Protons-On-Target (POT)	3.6×10^{20}	3.6×10^{21} - 4.5×10^{22}
Run Duration	3 years	3 years
Run Time	2×10^{7} sec/year	2×10^{7} sec/year
Duty Factor	0.32	0.90
POT Pulse Full Width	200 ns	-
POT Pulse Spacing	1695 ns	-
POT Extinction	$<1 \times 10^{-10}$	$<1 \times 10^{-12}$?

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Potential of Mu2e-II

A 800 MeV proton beam (8-100 kW) will be available.

- More protons
- No antiproton background
- Less radiation damage to the Production Solenoid / POT
- Less Radiative Pion Capture (RPC) due to the narrower proton pulse
- Improved duty factor

How does the low K.E. beam affect the muon production rate?

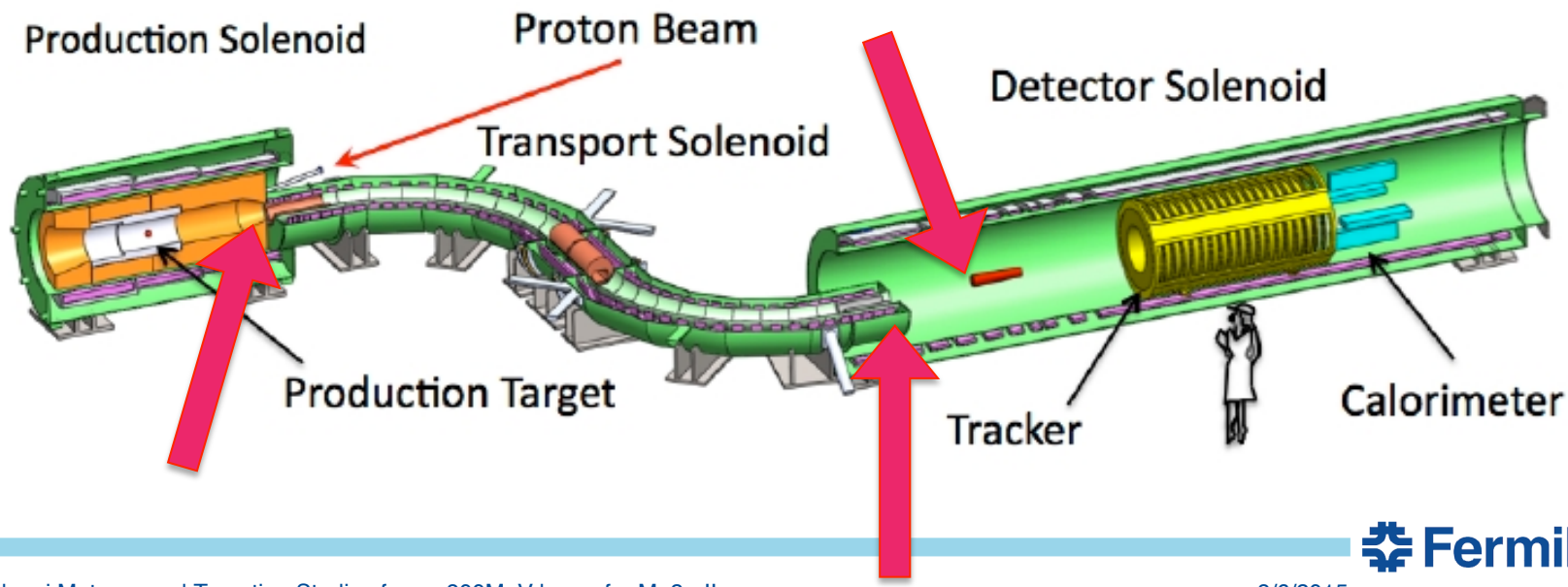
Simulation Details (1)

Software: G4beamline

Kinetic Energy of a beam: 8GeV and 800MeV

Starting position of a beam: 2 mm in front of the production target

Detectors: at the entrance and exit of the transport solenoid, and at the stopping target

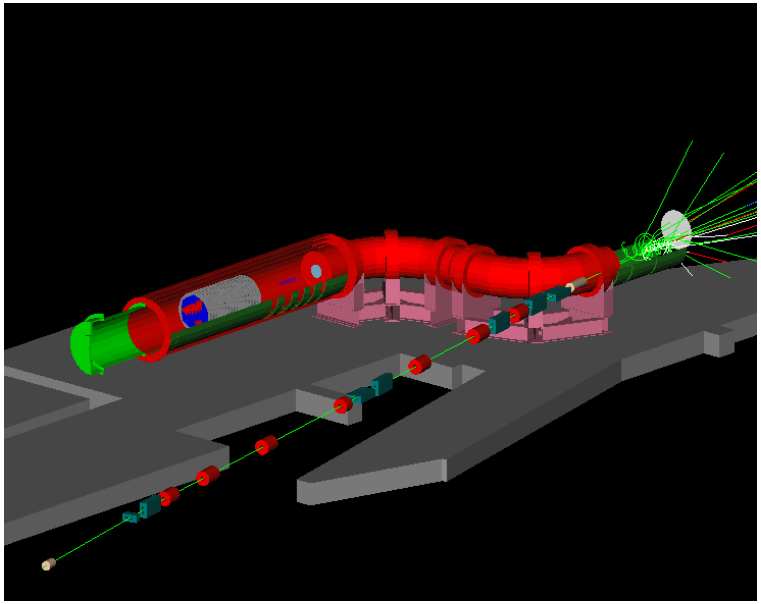


Simulation Details (2)

- Number of Simulated Events

	Kinetic Energy	Momentum	Simulated Events
Mu2e	8 GeV	8.889 GeV/c	40×10^6
Mu2e-II	800 MeV	1.463 GeV/c	300×10^6

- Submit jobs on FermiGrid
  → ~2 days using 100 nodes



Simulation Results (1)

Kinetic Energy	Stops / POT	Stops / kW	Stops / Survived muons after TS
8 GeV	1.690×10^{-3}	7.607×10^{16}	0.3760
800 MeV	1.035×10^{-4}	4.657×10^{16}	0.3795

Simulation Results (2)

Kinetic Energy	Stops / POT	Stops / kW	Stops / Survived muons after TS
8 GeV	1.690×10^{-3}	7.607×10^{16}	0.3760
800 MeV	1.035×10^{-4}	4.657×10^{16}	0.3795

Kinetic Energy	Stops/POT
8 GeV	1.61×10^{-3}

(K. Knoepfel *et al.* 2013)

Simulated Events=100 x 10^6

- The result is consistent with a previous study in 2013.

Simulation Results (3)

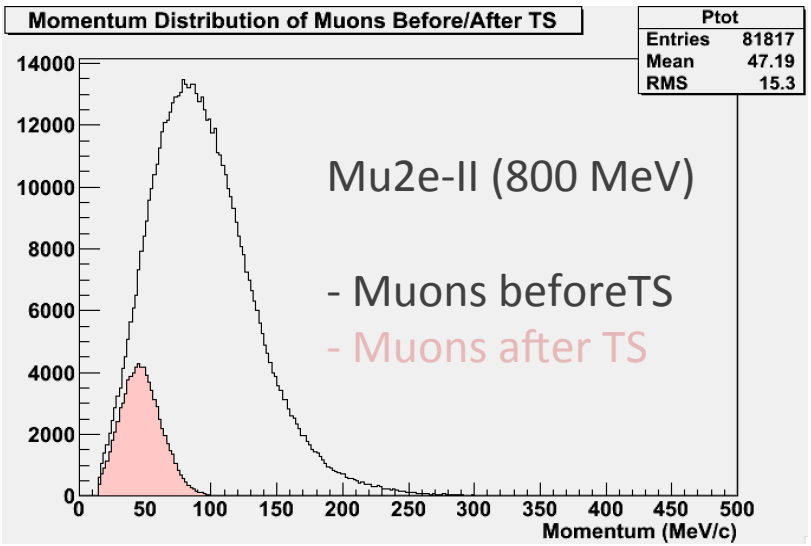
Kinetic Energy	Stops / POT	Stops / kW	Stops / Survived muons after TS
8 GeV	1.690×10^{-3}	7.607×10^{16}	0.3760
800 MeV	1.035×10^{-4}	4.657×10^{16}	0.3795

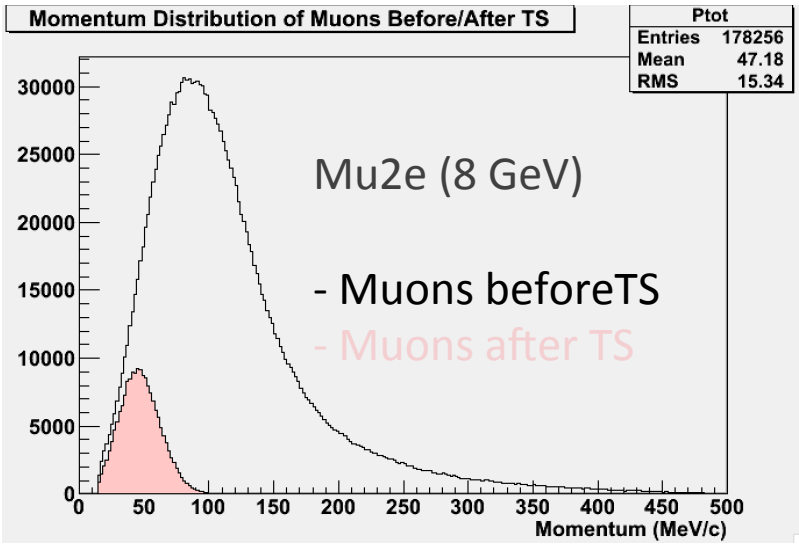
- Muon Production/POT dropped by a factor of 16.3.
- Muon Production/Power dropped by a factor of 1.63.

- Mu2e (8GeV, 8kW): 6.086×10^{17} stops
- Mu2e-II (800 MeV, 100 kW): 4.657×10^{18} stops
  → This is 7.65 times more stopped muons.

Why does it drop by only a factor of 1.63?

Momentum Distribution of muons before TS





- The momentum distribution of 800 MeV has a shorter tail.
- Pions/muons with high momentum are thrown away in the TS.
- Muons with 15-100 MeV/c survive the TS.

Simulation Results (4)

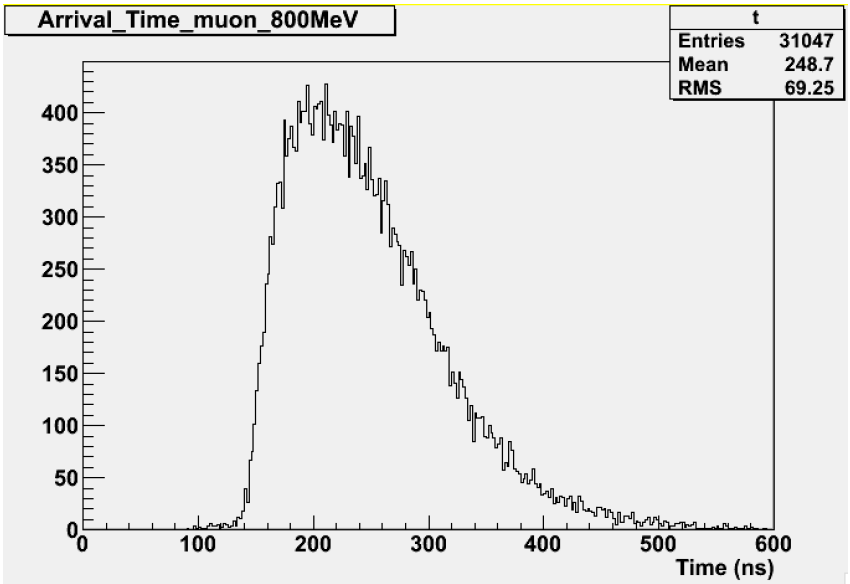
Kinetic Energy	Stops / POT	Stops / kW	Stops / Survived muons after TS
8 GeV	1.690×10^{-3}	7.607×10^{16}	0.3760
800 MeV	1.035×10^{-4}	4.657×10^{16}	0.3795

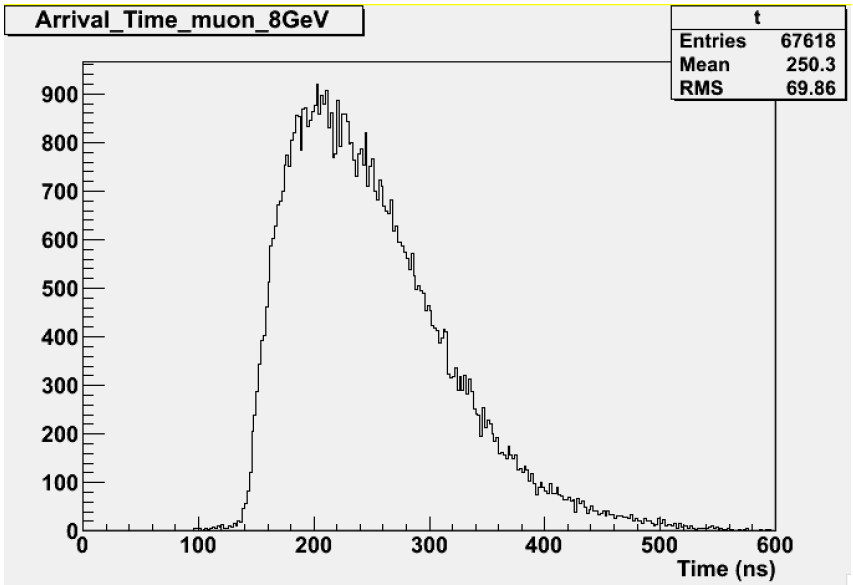
Momentum distributions of survived muons for both scenarios were very alike.

- ~38% of the survived muons are stopped.

Simulation Results (5)

Arrival Time of Muons





The arrival time is independent of proton beam energy.

→ Timing structure of a beam may be retained.

Remaining Questions

- How would we get protons to the primary target?

(On Progress)

- Background study with a PIP-II scenario

- Cosmic Ray Veto considerations
- Hadronic flash

- For PIP-II, we are not constrained to the 1695 ns time cycle.
  – What would be ideal for Mu2e-II?

Summary

Kinetic Energy	Stops / POT	Stops / kW	Stops / Survived muons after TS
8 GeV	1.690×10^{-3}	7.607×10^{16}	0.3760
800 MeV	1.035×10^{-4}	4.657×10^{16}	0.3795

- Mu2e-II targets ×10 better sensitivity.

- Muon Production/Power dropped by a factor of 1.63.
- Mu2e-II may produce 7.65 times more stopped muons than Mu2e during 3 years.

- High power with a low-energy beam would eliminate antiproton background

Acknowledgements

I am very grateful to my mentor, Thomas J. Roberts for his valuable advice, Eric Prebys, and Tanja Waltrip for organizing the internship.

I learnt significant amount of knowledge about accelerator physics at US Particle Accelerator School thanks to William Barletta, Linda Spentzouris, and Elvin Harms.

Finally, I would like thank the Fermi National Accelerator Laboratory, the Illinois Accelerator Institute, and Department of Energy for funding the internship.

Reference

[1] K. Knoepfel et al., “Feasibility Study for a New-Generation-Mu2e Experiment”, 2013, arXiv:1307.1168v2 [physics.ins-det].

[2] Mu2e Collaboration, “Mu2e Technical Design Report”, 2014

[3] T.J. Roberts and D.M. Kaplan, “G4beamline simulation program for matter-dominated beamlines”, Proceedings of the Particle Accelerator Conference, 2007, Albuquerque, NM, USA, PAC.IEEE, 3468.

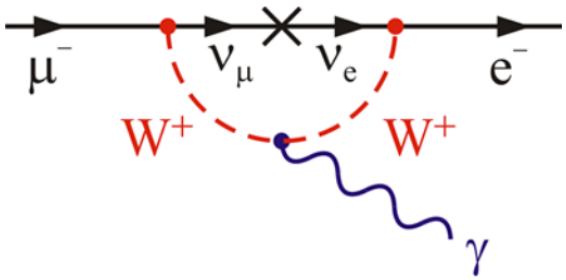
Backup Slides

Charged-Lepton-Flavor Violation (CLFV)

- CLFV is extremely suppressed in the Standard Model

  e.g.- $\mu \to e\gamma$

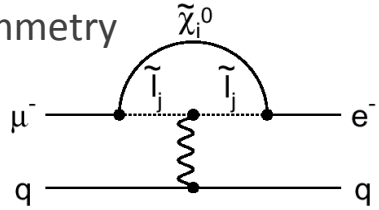
$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$



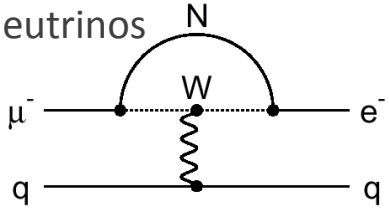
A signal of CLFV → Evidence of *New Physics*!

- Several theories suggest CLFV with higher sensitivities.

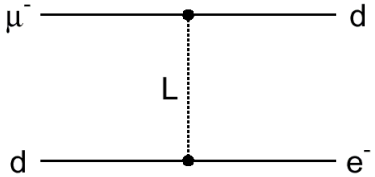
Supersymmetry



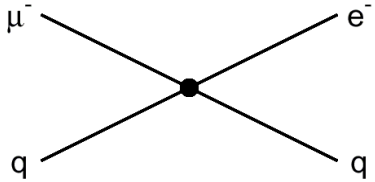
Heavy Neutrinos



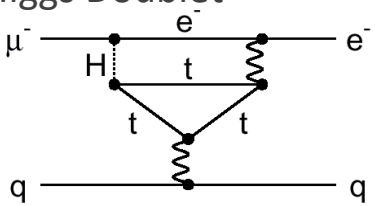
Leptoquarks



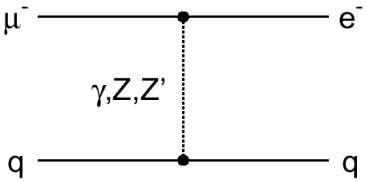
Compositeness



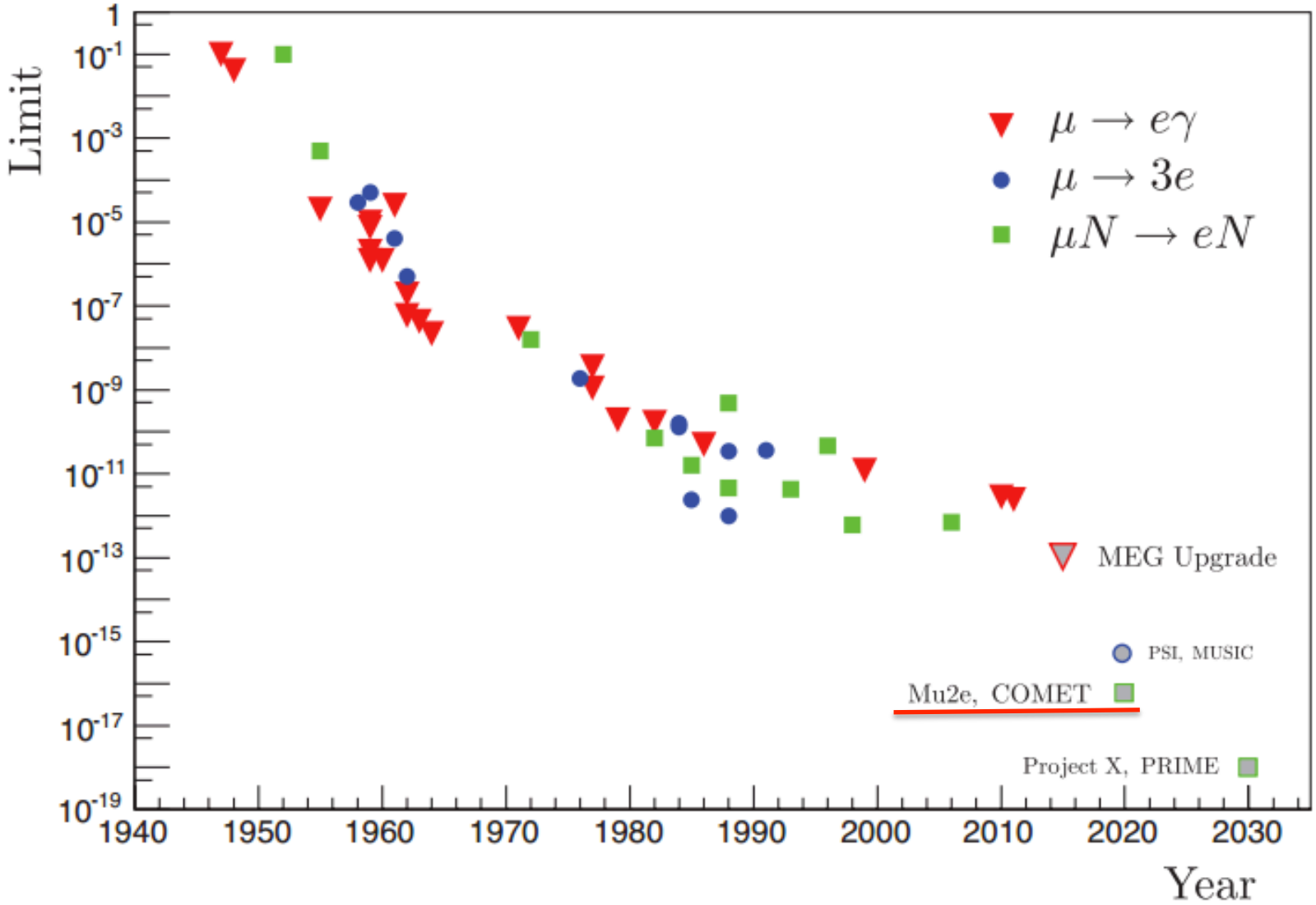
Second Higgs Doublet



Heavy Z' and Anomalous Z Coupling



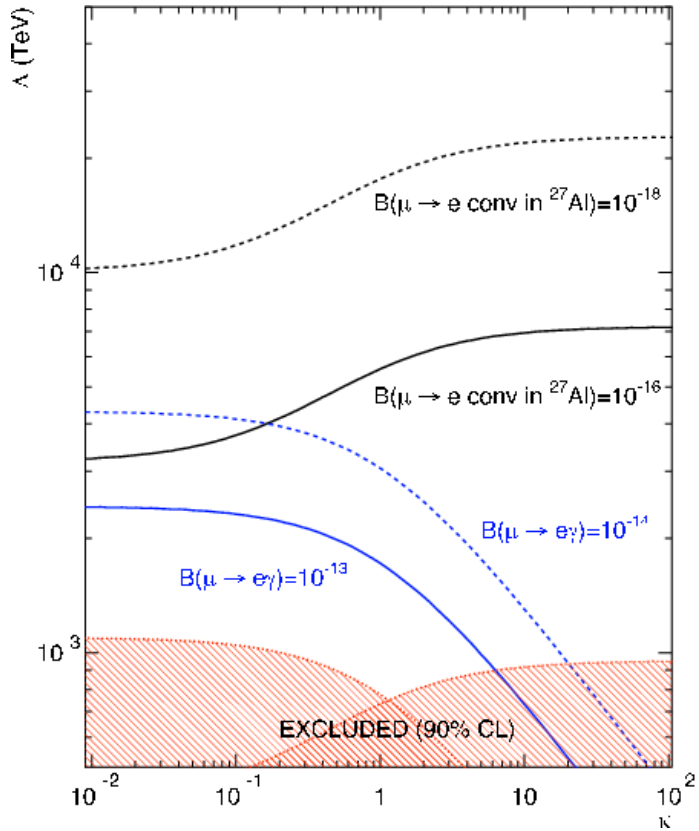
CLFV History



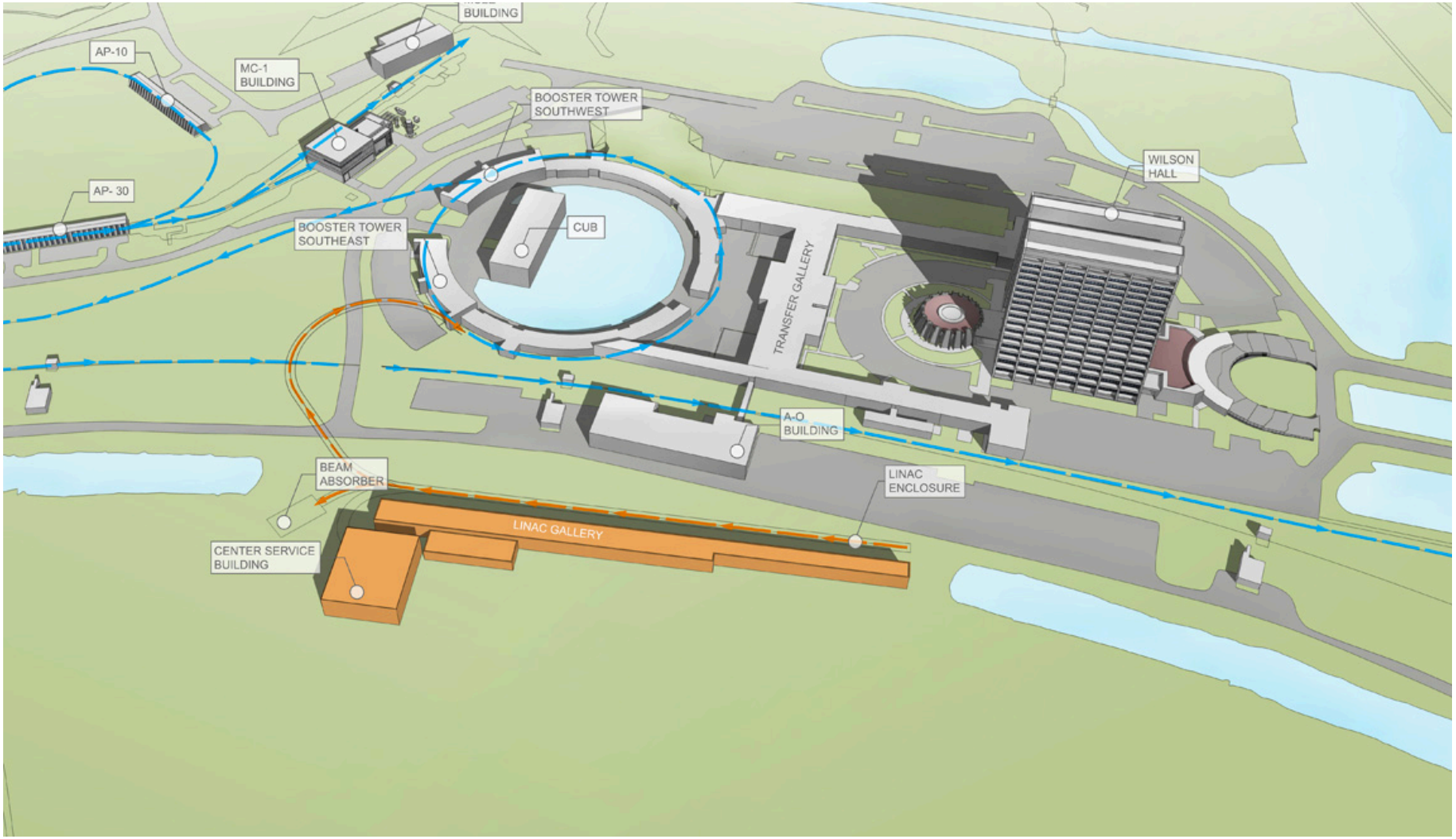
CLFV Parameter Space

- Model-Independent-CLFV Lagrangian

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



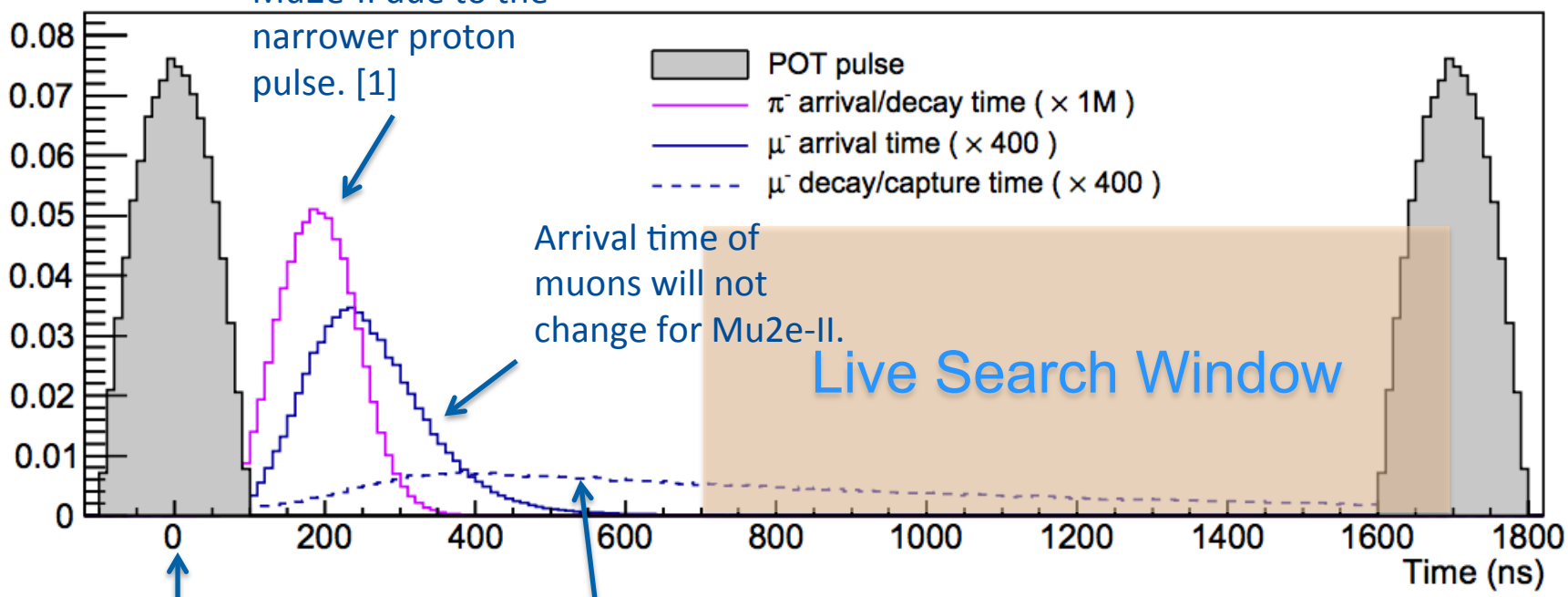
Proton Improvement Plan-II (PIP-II)



Timing Structure

Pion arrival time will be narrower for Mu2e-II due to the narrower proton pulse. [1]

Mu2e (8 GeV)



Arrival time of muons will not change for Mu2e-II.

Live Search Window

(Knopfel et al., 2013)

The width will be halved for Mu2e-II.

DIO has to be studied for Mu2e-II background.

Background of Mu2e

Category	Background process	Estimated yield (events)
Intrinsic	Muon decay-in-orbit (DIO)	55% → 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	13% → 0.047 ± 0.024
	Cosmic ray induced	23% → 0.082 ± 0.018
	Total	0.36 ± 0.10

No antiproton background for Mu2e-II.