The Mu2e Experiment

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BEACH 2018 Peniche, Portugal

Jason Bono, June 21, 2018

A Search for CLFV Using Muons

- In 2021, Mu2e will search for coherent neutrinoless conversion of muon into an electron, within the vicinity of a nucleus, $\mu N \rightarrow e N$
 - ▶ 3-years of data collection
 - ▶ 10,000-fold improvement over existing limits
 - ▶ Access to virtual effects on an effective mass scale of up to 10,000 TeV
 - ▶ Could discover CLFV
 - Proving the existence of new phenomena, and their experimental accessibility
 - ▶ We're complementary to other CLFV searches
 - MEG, Mu3e
 - Higgs decays, Tau decays, meson decays

Mu2e

- CLFV
- Experimental Details
- The Future

Flavor Violation in the SM

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

ELEMENTARY PARTICLES

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We're looking for the same thing, but with charged leptons

ELEMENTARY PARTICLES

CLFV in the Standard Model

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 - ▶ Dynamical suppression: an accidental symmetry
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 - ▶ But CLFV in the ν MSM is too small to see
 - The observation of CLFV unambiguously indicates new physics

$$\text{e.g.} \quad \mathcal{B}(\mu \rightarrow e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{il}^2}{M_W^2} \right|^2 \sim 10^{-54}$$

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- Neutrino mass generation beyond ν MSM often enhances CLFV to observable levels

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Magnetic moment type operator

Supersymmetry

Heavy neutrinos

Two Higgs doublets

Contact term operator

Compositeness

Leptoquarks

New heavy bosons /
anomalous coupling

CLFV's Long Search History

Mu2e

- ~~CLFV~~
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Muonic Aluminum

- Negative muons are stopped and captured by Al
 - ▶ They cascade to the 1S state quickly! $\mathcal{O}(\text{fs})$
 - X-ray emission can give an estimate the number of captures
 - ▶ Bohr radius $\sim 10 \text{ fm}$
 - Large degree of overlap (Al nucleus $\sim 3 \text{ fm}$)
- Wait for a muon to convert into an electron
 - ▶ Coherent process
 - Mono energetic signal
 - $E_e = m_\mu c^2 - E_b - E_{\text{recoil}} = 104.96 \text{ MeV}$

What else will muonic Al do?

Nuclear Capture $\sim 61\%$

Decay In Orbit (DIO) $\sim 39\%$

Conversion $< 10^{-12}$

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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

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
- If $R_{\mu e} \sim 3 \times 10^{-17}$, we should see 1 event (Single Event Sensitivity)
- Expected background is ~ 0.4 an event
- Discovery reach (5σ): $R_{\mu e} \gtrsim 2 \times 10^{-16}$
- Exclusion power (90%CL) : $R_{\mu e} \gtrsim 8 \times 10^{-17}$

The Basic Idea

- Produce 10^{18} muonic ^{27}Al atoms
 - ▶ Irradiate Al target with low energy μ
 - ▶ Only reconstruct $\sim 100\text{K}$ μ decays

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- Count conversion-like electrons
 - ▶ Tracking and calorimetry
- Suppress experimental backgrounds

A Glance at the Experiment

About 25 meters end-to-end

A Glance at the Experiment

- 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
- $BR(\pi^- \rightarrow \mu^- \nu_\mu) \sim 99.9\%$
- Include a strong gradient to increase the yield further through magnetic reflection

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

Enter the Detector Solenoid

- Next destination for the beam: the Al stopping target!
- 10^{20} POT in 3 years $\rightarrow 10^{18}$ stopped μ , as required
 - 10^{10} stopped μ /s!

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 ($1.7\ \mu\text{s}$) between bunches
- Delay the search window
- Muonic aluminum ($\tau \sim 0.864\ \mu\text{s}$) is well optimized for the beam structure!
- 39 M protons / pulse
- Extinction: out-of-time protons / in-time protons = 10^{-11}

Pion BG reduced by a factor of 10^{-11} !

Cosmic Background

- 10^9 cosmic rays / day

Cosmic Background

- 10^9 cosmic rays / day
- Fiducial cuts help, but we still get 1 BG event/day
 - ▶ Experiment killer!

This leads us to our third "big idea"

Third Big Idea — An Efficient Cosmic Ray Veto System

- 4 layers of extruded polystyrene scintillator counter with wavelength shifting fibers
 - readout 2 mm X 2 mm SiPMs
 - Coincidence (15 ns, 30 cm) in 3 of the 4 layers
- 99.99% efficiency requirement: better not have any holes!
 - Currently the largest background in the experiment
- Minimize false veto
 - Require $< 10\%$ dead-time

- Area: 327 m²
- 86 modules of 6 lengths
- 5,504 counters
- 11,008 fibers
- 19,840 SiPMs
- 310 Front-end Boards

Decay In Orbit Background

DIO Electron Energy Spectrum

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

Decay In Orbit Background

- Other than momentum, there is no way to distinguish DIO from CE
 - Fiducial cuts don't help

DIO Electron Energy Spectrum

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Fourth Big Idea — Wrestling With DIOs via Tracking

- Be blind to, and protect from, low momentum electrons
 - Have an annular geometry + operate in a 1T field
 - $d\mathbf{p}/dt = q(\mathbf{E} + \mathbf{v} \times \mathbf{B}) \rightarrow R = p_{\perp}/qB$
- Require excellent resolution & acceptance
 - $\sigma < 0.2\%$ @ 105 MeV
 - (Acceptance)x(Reco efficiency) ~ 20%
- Minimize scattering and energy loss
 - Ultra low mass
 - Operate in vacuum ($\sim 10^{-4}$ torr)

~20,000 straw-tubes running perpendicular the B-field

- 5 mm diameter, metalized mylar straws
 - ▶ 15 μm wall thickness
 - ▶ ~1.2 m to ~0.5 m in length
- Modular design
 - ▶ Tracking region: $38 < r < 70$ cm
- Will be the largest, lowest density, straw-tube detector ever to be held in vacuum
 - ▶ The drift gas alone is ~7% of the mass

8-Straw
Prototype

Full Panel V1.5

Rectangular
Prototype 2

Full Panel V2.5

Early 2015

Completion Date

Mid 2017

Module production has begun

8-Straw
Prototype

Full Panel V1.0

Prototype 2

Full Panel V2.5

.....
Early 201

- Discovery reach (5σ): $R_{\mu e} \approx 2 \times 10^{-16}$
- Exclusion power (90%CL) : $R_{\mu e} \approx 8 \times 10^{-17}$

Realistic MC: includes tracker straw & gas properties

Mu2e

- ~~CLFV~~
- ~~Experimental Details~~
- The Future

What if Mu2e sees a signal?

$R_{\mu e}$ in multiple nuclei 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]

A Mu2e upgrade is well motivated in any scenario

- $R_{\mu e} < 8 \times 10^{-17}$ will strongly constrain models
- Conduct next-generation search with higher sensitivity
- See expression of interest for Mu2e-II
 - ▶ [arxiv.1802.02599](https://arxiv.org/abs/1802.02599)

Expression of Interest for Evolution of the Mu2e Experiment[†]

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Abstract

We propose an evolution of the Mu2e experiment, called Mu2e-II, that would leverage advances in detector technology and utilize the increased proton intensity provided by the Fermilab PIF-II upgrade to improve the sensitivity for neutrinoless muon-to-electron conversion by one order of magnitude beyond the Mu2e experiment, providing the deepest probe of charged lepton flavor violation in the foreseeable future. Mu2e-II will use as much of the Mu2e infrastructure as possible, providing, where required, improvements to the Mu2e apparatus to accommodate the increased beam intensity and cope with the accompanying increase in backgrounds.

Mu2e

- ~~CLFV~~
- ~~Experimental Details~~
- ~~The Future~~

- Improve limit on $\mu N \rightarrow e N$ by four-orders of magnitude
 - ▶ A signal = discovery of new physics
- Many NP models predict $R_{\mu e} \sim 10^{-14} - 10^{-16}$
 - ▶ Discovery reach (5σ): $R_{\mu e} \gtrsim 2 \times 10^{-16}$
 - ▶ Exclusion power (90%CL) : $R_{\mu e} \gtrsim 8 \times 10^{-17}$
- R&D is mature, with physics data collection beginning in 2021
- Not mentioned: alternate searches are possible
- An upgraded experiment is planned

Thank you!