# CLFV and Neutrinos

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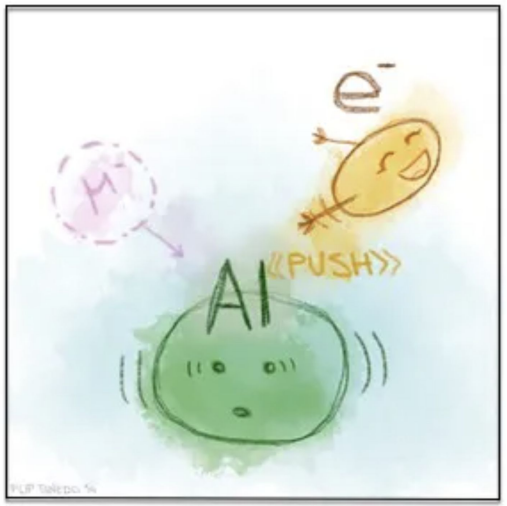
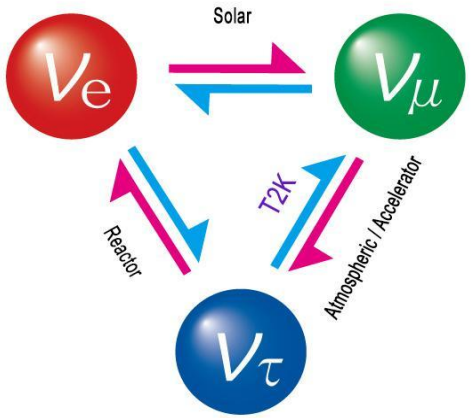


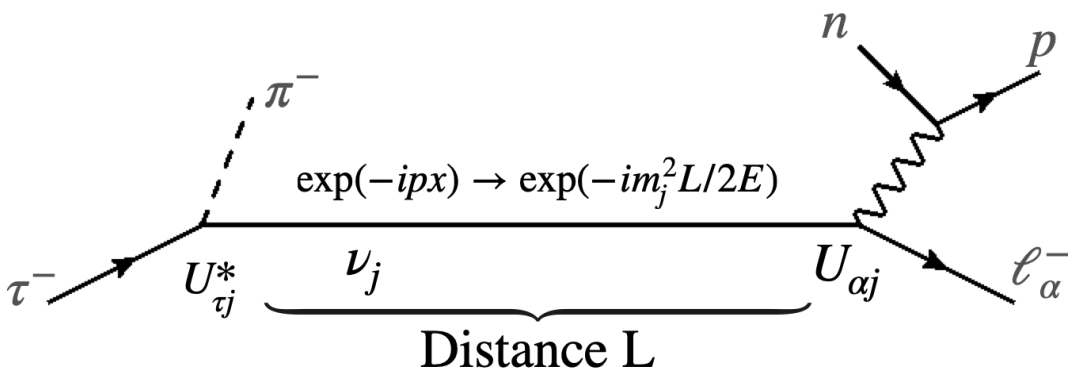

Fermilab Accelerator Complex Evolution (ACE) Workshop, 2023

# Neutrino Physics | Motivations

$$|\nu_\alpha\rangle = \sum_{i=e,\mu,\tau} U_{i\alpha}\,|\nu_i\rangle \Longrightarrow M_\nu \neq 0$$



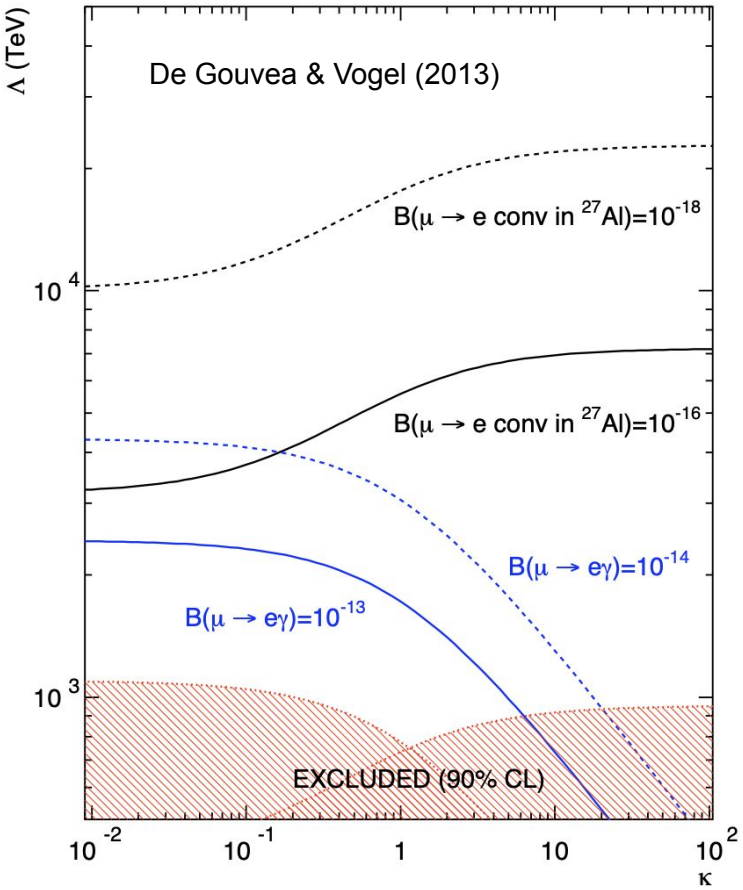
Neutrino oscillation between three generations



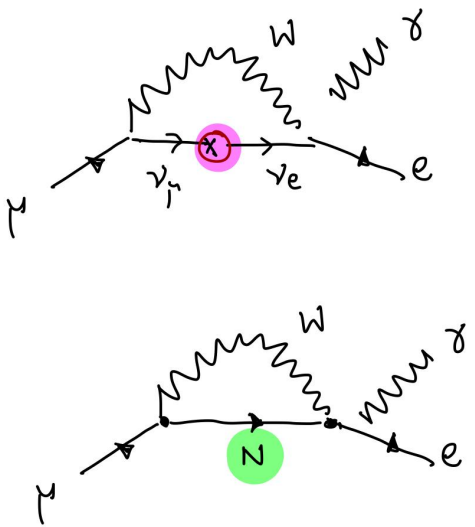

- Neutrinos are a probe of *lepton flavor symmetries.*
- Observed masses imply that there *must exist new physics* below the Planck scale.
- Measurements of mixing angles may supply window into physics beyond the SM that is responsible for the generation of neutrino masses.

# Charged Lepton Flavour Violation | Motivations

- Neutrinos provide *explicit empirical* evidence that $L_{e,\mu,\tau}$ are broken in nature. “
- *A priori* there is no reason to expect physics beyond the SM to obey these symmetries.
- CLFV can probe mass scales up to ~1000 TeV. Strongest constraints on many models.
- Observation of CLFV would constitute a *discovery* of physics beyond the SM.
- Discovery potential is *complementary* to energy frontier (e.g. LHC or muon collider).



# Synergies between CLFV and Neutrino Physics




- SU(2) symmetry in the SM links neutrino and charged lepton

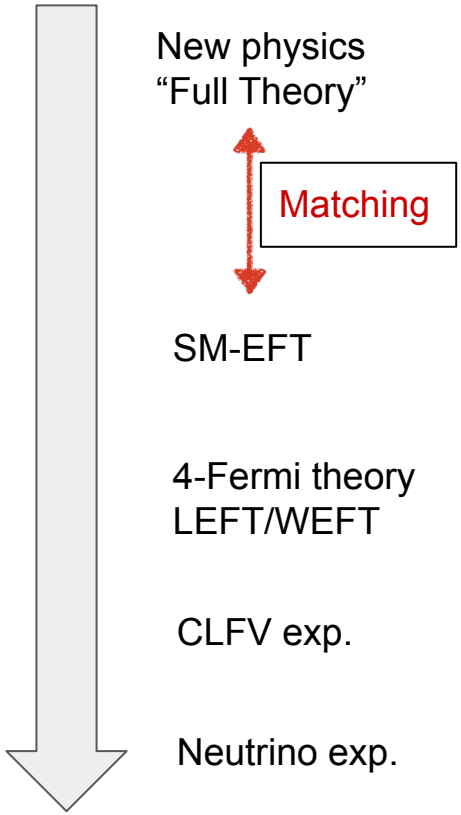
$$L_L \sim \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (1, 2, -1/2)$$

- New physics that mixes neutrinos which "generically" mixes charged leptons as well → *correlated signatures*
- CLFV processes often provide the strongest constraints on models of neutrino mass generation.

CLFV and neutrino experiments provide complementary probes of new physics.

# Context with the SM-EFT

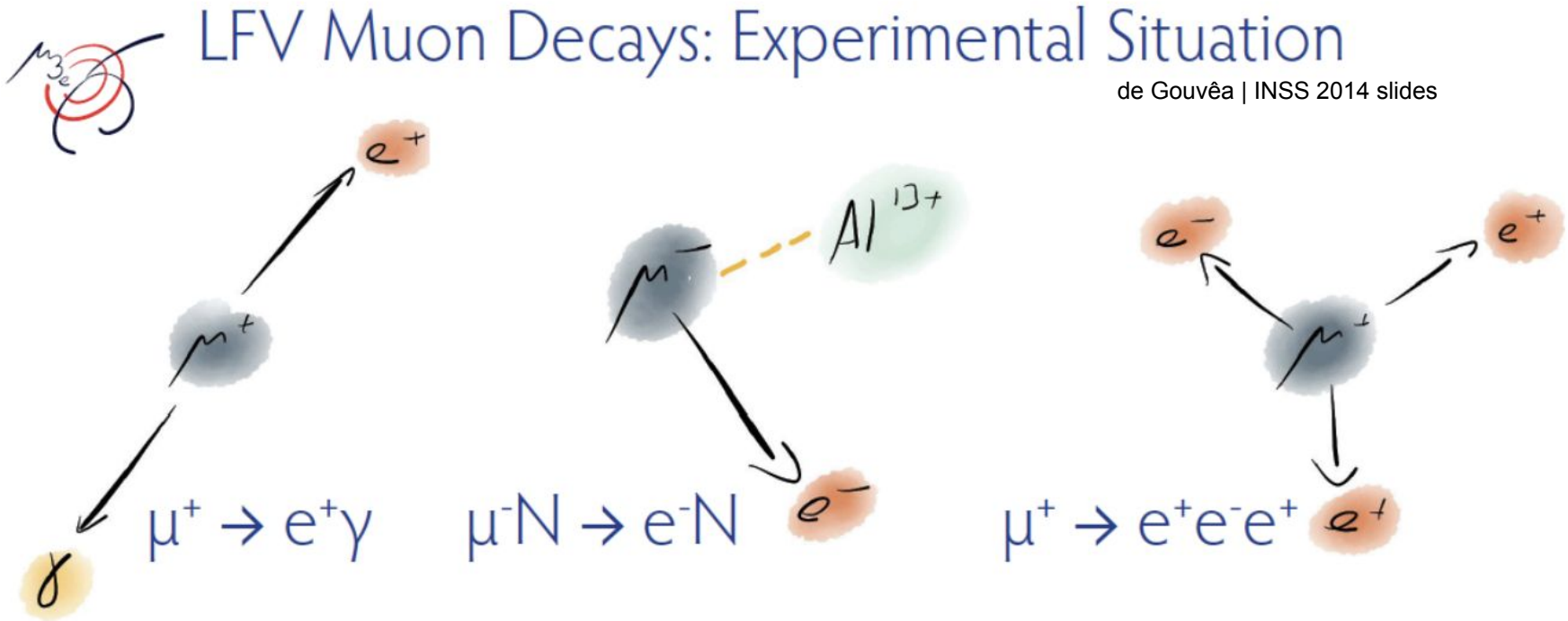
- For new physics heavier than a TeV or so, all effects can be encoded in effective operators built from SM fields.
- Can match observable in “Full Theory” and SM-EFT.
- Provides “Rosetta Stone” between Full Theory & SM-EFT.
- Model-independent constraints on SM-EFT can be converted to new physics model *post facto.*
- CLFV and neutrinos are ***highly sensitive low energy probes*** of low energy EFT ⟶ probe of “Full Theory”.



# Experimental probes of CLFV

Other probes

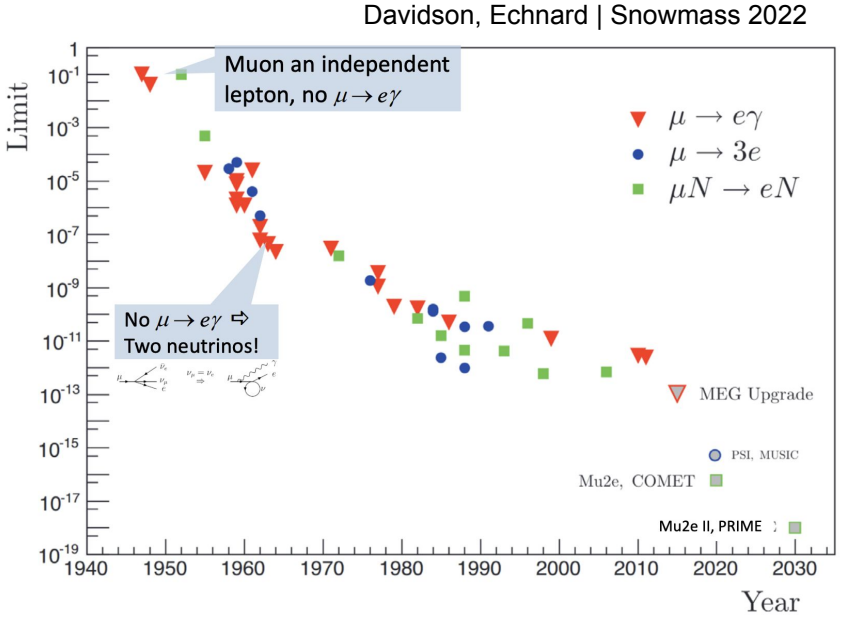
- Tau production at EIC.
- LFV tau decays (BELLE-II, LHCb).
- LFV meson decays.



# Experimental landscape in the near future

## CLFV

Davidson, Echnard | Snowmass 2022




- Four order of magnitude jump

## Neutrino Physics

- Neutrino mass ordering (JUNO)
- CP violating phase (DUNE, T2K)
- LNV (nEXO, CUPID, LEGEND-100).
- Precision frontier for PMNS matrix. (DUNE, HK, JUNO).
- Neutrino astro. (IceCube, KM3NET)

# Connections to FNAL - ACE

| Experiment | Experiment type | Proton Beam | | | Uses existing or new beamline? |
|---|---|---|---|---|---|
| | | Energy [GeV] | Power [kW] | Time Structure | |
| Proton Storage Ring: EDM and Axion Searches | Precision tests Dark Matter | 0.232 | 1e11 polarized protons per fill | Fill the ring every 1000s | new |
| Physics with Muonium | Precision tests | 0.8 | 1e(13+/-1) POT per second | CW | new |
| REDTOP Run I | Precision tests | 1.8 - 2.2 | 0.03-0.05 | slow extraction | Muon Campus |
| REDTOP Run II | Precision tests | 0.8 - 0.92 | 200 | CW, | new |
| REDTOP Run III | Precision tests | 1.7 | >1,000 | CW, | new |
| Ultra-cold Neutron Source for Fundamental Physics Experiments, Including Neutron-Anti-Neutron Oscillations | Precision tests | 0.8-2 | 1,000 | quasi-continuous | new |
| CLFV with Muon Decays | CLFV | Not critical 0.8 to a few GeV | 100 or more | continous beam on the timescale of the muon lifetime i.e. proton pulses separated by a microsecond or less. The more continuous the better | new |
| Mu2e II | CLFV | 1 to 3 | 100 | pulse width 10s of ns or better separated by 200 to 2000 ns. Flexible time structure and minimal pulse-to-pulse variation | new |
| Fixed Target Searches for new physics with O(1 GeV) Proton Beam Dump | Dark Sector, Neutrino | 0.8 to 1.5 GeV | 100 or more | <O(1 micro s) pulse width for neutrino measurements, <O(30 ns) pulse width for dark matter searches, 10^{-5} or better duty factor | new |
| PRISM-like Charged Lepton Flavor Violation | CLFV | 1 -3 GeV | up to 2 MW | 15ns pulses at a rep rate of about 1 kHz | new |
| Proton Irradiation Facility | R&D | Energy is not very important | 1e18 protons in a few hours | Pulsed beam (duty factor not specified) | new |
| SBN | Neutrino | 8 | 32 | 20Hz | BNB |
| Mu2e | CLFV | 8 | 8 | <10^{-10} extinction | Muon Campus |
| Fixed Target Searches for new physics with O(10 GeV) Proton Beam Dump | Dark Sector, Neutrino | 8 | up to 115 | Beam spills less than a few microsec with separation between spills greater than 50 microsec | BNB |
| Muon beam dump | Dark Sector | 8 (producing 3 GeV muons) | 3e14 muons in total on target for the whole run | CW | Muon Campus |
| Muon Collider R&D | R&D | 8 - 16GeV | 4e13 to 1.2e14 protons per bunch | 5 - 20 Hz rep rate and bunch length 1-3 ns | new |
| Muon Missing Momentum | Dark Sector | few 10s of GeV | 10^{10} muons per experimental | Pulsed beam (duty factor not specified) | new |
| High Energy Proton Fixed Target | Dark Sector, Neutrino | O(100 GeV) | 1e12 POT/s therefore ~20 kW | CW via resonant extraction. "IF we could up the duty factor that woul dbe even better"(?) | Switchyard or new |
| Test-Beam Facility | R&D | 120, lower energies would also be beneficial | 10 to 100 kHz on the testing | Pulsed beam (duty factor not specified) | Switchyard or new |
| Tau Neutrinos | Neutrino | 120 | 1200 or higher | MI time structure | LBNF |

# Connections to FNAL - ACE


What can we do with different proton energy targets?

Discussion session

1. CLFV experiments
2. Neutrino experiments
3. Complementarity of 1&2
4. Open floor

# CLFV Experiments

- What interesting targets should CLFV experiments aim for?
- What about related searches for lepton number violation?
- How do accelerator upgrades alter prospects for DUNE? How important is a 3 GeV vs 8 GeV beam for Mu2e-II ?
- What secondary targets are being considered (beyond Al for Mu2e). Titanium vs Vandium for example?
- Can Fermilab be a world leading facility in muon decay searches? What additional infrastructure is needed?
- What about related searches with pions?

# Neutrino Experiments

- What is the value of precision measurements in the neutrino sector?
- Is there a large trade-off between a tau optimized beam from the neutrino oscillation program?
- How long would it take to get  an interesting statistical samples of tau events at the near detector complex (for DUNE).
- What do neutrino cross-section measurements tell us about new physics?
- What about the SBN program?

# Complementarity between CLFV and Neutrinos

- How can experiments probe the lepton flavour and lepton number violation?
- What could we do for neutrino physics with high energy muon sources?
- How do accelerator upgrades alter prospects for DUNE?
- What sort of “parasitic” experiments can be done with muon beam dumps? (Any impact on CLFV?)

# Open floor

Where: Level 13, WH13SW-Disappearance

Also, contribute here →