Remarks for Panel on Possible Future Experiments at Fermilab Muon Campus

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Workshop on Potential Fermilab Muon Campus and Storage Ring Experiments, May 24-27, 2021

CFLV and Searches for Rare Muon Decays

Fermilab has a strong current muon campus program and it is worthwhile to investigate whether this program could be expanded with additional future experiments. Currently:

- Muon $g-2$ experiment E989 [first results: PRL 126, 14 (2021)] with μ^+, which will continue running and might also run with μ^-, as the BNL E821 exp. did.
- Mu2e experiment E973 (TDR: arXiv:1501.05241) that will search for the charged lepton flavor violation (CLFV) muon conversion in the field of a nucleus, $\mu^- + {}^{27}_{13}\mathrm{Al} \to e^- + {}^{27}_{13}\mathrm{Al}$, planning to reach an initial single-event sensitivity of 2.5×10^{-17} in the ratio

$$R_{\mu e} = \frac{\sigma(\mu^- + (Z,A) \to e^- + (Z,A))}{\sigma(\mu^- + (Z,A) \to \nu_\mu + (Z-1,A)^*)}$$

  The Mu2e II EOI (arXiv:1802.02599) plans an upgrade to reach to $R_{e\mu} \sim O(10^{-18})$. The current best upper limit on this from SINDRUM II at PSI (with ${}^{197}_{79}$Au): $R_{\mu e} < 7 \times 10^{-13}$ (90 % CL). Mu2e II also plans to search for $\Delta L = -2$ conversion $\mu^- + (Z,A) \to e^+ + (Z-2,A)$.

Possible new experiments include (i) searches for CLFV μ decays; (ii) a test of $e-\mu$ universality via measurement of $BR(\pi^+_{e2})/BR(\pi^+_{\mu 2})$; (iii) searches for heavy neutrino emission in π^+_{e2} and $\pi^+_{\mu 2}$ decays, etc. Fermilab experiments of this type would be in competition with dedicated programs probing this physics at PSI and TRIUMF.

In the Standard Model (SM), as extended to include neutrino masses and lepton mixing (νSM), rare CLFV μ decays have extremely small BRs, far below levels detectable in current or foreseen experiments, so these CLFV processes are tests for physics beyond the νSM (BSM).

Recall theory: neutrino weak eigenstates ν_ℓ, in terms of mass eigenstates, are: $|\nu_\ell\rangle = \sum_{j=1}^{3+n_s} U_{\ell j}\,|\nu_j\rangle$, where $\ell = e,\ \mu,\ \tau$, and n_s refers to possible additional mass eigenstates occurring as small admixtures in $|\nu_\ell\rangle$ but as mass eigenstates with substantial admixtures in electroweak-singlet (sterile) neutrinos.

From neutrino oscillation data, we know values of $\Delta m^2_{ij} = m^2_{\nu_i} - m^2_{\nu_j}$:

$$|\Delta m^2_{32}| \simeq |\Delta m^2_{31}| = 2.5 \times 10^{-3}\ \mathrm{eV}^2$$
$$\Delta m^2_{21} = 0.74 \times 10^{-4}\ \mathrm{eV}^2\ ,$$

and from cosmology, for effectively stable neutrinos,

$$\sum_j m_{\nu_j} \lesssim 0.15 \text{ eV}$$

so m_{ν_j}, $j = 1, 2, 3$ have sub-eV masses. Calculation in νSM:

$$BR(\mu \to e\gamma) = \frac{3\alpha_{em}}{32\pi} \Big| \sum_{j=1}^{3+n_s} U^*_{ej} U_{\mu j} \Big(\frac{m^2_{\nu_j}}{m^2_W}\Big) \Big|^2$$

(Marciano-Sanda 1977, Petcov 1977, B. W. Lee, Pakvasa, Sugawara, RS 1977).
In the minimal νSM, $BR(\mu \to e\gamma) \sim 10^{-52}$. Similarly $BR(\mu \to ee\bar{e})$ and $R_{e\mu}$ are far below observable levels.

The suppression arises due to a leptonic GIM mechanism operating at the one-loop level. Necessary and sufficient conditions are that leptons of the same chirality and charge have the same weak isospin I and I_3 (B. W. Lee and RS 1977).

With a mostly sterile neutrino, denoted ν_4, having, e.g., $m_{\nu_4} \simeq 0.35$ GeV, $(m_{\nu_4}/m_W)^4 \simeq 3.6 \times 10^{-12}$ and searches for emission in $K^+_{\ell 2}$, $\ell = e, \mu$ in NA62 at CERN yield $|U_{e4}|^2 \lesssim 10^{-9}$ and $|U_{\mu 4}|^2 \lesssim 10^{-8}$, so $|U_{\mu 4} U_{e4}|^2 \lesssim 10^{-17}$, and hence $BR(\mu \to e\gamma) \lesssim 10^{-32}$, still far below detectable BR.

BSM physics that could yield CLFV at observable level includes, e.g.,

- Supersymmetry (SUSY), which could stabilize the Higgs sector against quadratic sensitivity to ultraviolet mass scales and give gauge coupling unification. In SUSY, $BR(\mu \to e\gamma)$ could get substantial contributions from loop diagrams with virtual scalar neutrinos $\tilde{\nu}_i$ and charginos $\tilde{\chi}$ on internal lines (Hall, Suzuki 1984; I-H. Lee, 1984; Barbieri et al. 1995; Hisano et al., 2009; many others).

  This is one of many flavor-changing neutral current (FCNC) processes that could be large in SUSY. But no superpartners have been discovered yet at the Tevatron or LHC, and there are tight constraints on SUSY contributions to FCNC processes.

- Dynamical electroweak symmetry breaking (EWSB) models such as (extended) technicolor (ETC) also yielded substantial FCNC and could yield $\mu \to e\gamma$ etc. at observable levels (e.g., Appelquist, Piai, RS 2004 and others), Although quasi-conformal TC could yield a Higgs-like particle as a quasi dilaton (Yamawaki, Appelquist,...), the observed Higgs properties are in good agreement with minimal SM predictions;

- Z' with flavor-nondiagonal (as well as diagonal) couplings, etc.

Some current results of searches for CLFV:

$BR(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$ from MEG exp. at PSI (EPJC 76, 434 (2016)).

$BR(\mu^+ \to e^+e^+e^-) < 1 \times 10^{-12}$ from SINDRUM II experiment (Nucl. Phys. B 299, 1 (1988)).

Construction and commissioning of MEG II underway at PSI, planning to achieve sensitivity to 10^{-14} range and improve existing limit by a factor of ~ 10 or see a signal (EPJC 78, 380 (2018); arXiv:1912.08656).

Mu3e Experiment at PSI will search for $\mu^+ \to e^+e^+e^-$, anticipating factor 10^2 improvement in sensitivity compared with the old SINDRUM II experiment, eventually achieving an upper limit $BR(\mu^+ \to e^+e^+e^-) \lesssim 10^{-14}$ or seeing a signal (arXiv:2009.11690),

PSI has a very intense muon beam, but the MEG experiment was not able to take the full intensity beam because of backgrounds. So having an intense source of muons is not sufficient to achieve a better limit; one must also have a sufficiently good rejection of backgrounds.

Test of $e-\mu$ Universality in $\pi^+_{\ell 2}$ Decays

Historically, the measurement of the ratio of branching ratios

$$R^{(\pi)}_{e/\mu} = \frac{BR(\pi^+ \to e^+\nu_e)}{BR(\pi^+ \to \mu^+\nu_\mu)}$$

has provided a very stringent test of $e-\mu$ universality. This probes for (i) possible BSM pseudoscalar contributions, (ii) possible heavy neutrino emission, and (iii) other possible BSM contributions, such as Z' bosons with flavor-nondiagonal couplings.

In the SM (and νSM, since m_{ν_i} are negligible for $i = 1, 2, 3$) the ratio is

$$R^{(\pi)}_{e/\mu,SM} = \frac{m_e^2}{m_\mu^2}\left[\frac{1-\frac{m_e^2}{m_\pi^2}}{1-\frac{m_\mu^2}{m_\pi^2}}\right]^2 (1+\delta_{RC}) \ ,$$

where δ_{RC} is the radiative correction (Berman, Kinoshita and Sirlin 1959; Marciano and Sirlin 1993; Cirigliano and Rosell 2007), giving
$R^{(\pi)}_{e/\mu,SM} = (1.2352 \pm 0.0002) \times 10^{-4}$ with fractional accuracy of the SM prediction is 2×10^{-4}. The most accurate measurement, by the TRIUMF PIENU experiment [PRL 115, 071801 (2015)], is (with fractional accuracy 2×10^{-3})

$$R^{(\pi)}_{e/\mu,SM} = (1.2344 \pm 0.0023_{\rm stat} \pm 0.0019_{\rm syst}) \times 10^{-4}$$

The PIENU experiment expects to improve this accuracy to 1×10^{-3}. A similar effort is underway with the PEN experiment at PSI (arXiv:1812.00782).

The TRIUMF PIENUX experiment (TRIUMF doc. 2127 and Snowmass LOI) is a planned upgrade of PIENU at TRIUMF which will use a liquid Xe detector and anticipates achieving an order of magnitude improvement in precision.

With a successful running of PIENUX, the experimental accuracy in the measurement will match the accuracy in the theoretical prediction and the result will serve as a very valuable test of $e - \mu$ universality.

There are some current hints of a possible violation of $e - \mu$ universality from LHCb in $b \to s e^+ e^-$ versus $b \to s \mu^+ \mu^-$ [JHEP 08 (2017) 055; PRL 122, 191801 (2019); arXiv:2103.11769), but recent Belle result consistent with $e - \mu$ universality (JHEP 03 (2021) 105).

There are also hints of possible violation of first-row Cabibbo unitarity, $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$ (V_{ub} contrib. is negligible); Seng, Gorchtein, Patel, Ramsey-Musolf, PRL 121, 241804 (2018); Seng et al., arXiv:2103.04843, others.

So a a new measurement of the ratio $R^{(\pi)}_{e/\mu}$ might probe BSM effects.

Searches for Heavy Neutrino Emission in $\pi^+_{\ell 2}$ Decays

A heavy, mostly sterile, neutrino mass eigenstate, ν_j, $j \geq 4$, could occur as a decay product in particle and nuclear decays.

- via the coefficients U_{ej} in nuclear beta decay and $\pi^+ \to e^+ \nu_e$

- via the coefficients $U_{\mu j}$ in $\pi^+ \to \mu^+ \nu_\mu$

- as well as the decays $M^+ \to \ell^+ \nu_\ell$, where $M^+ = K^+$, D^+, D_s^+, and B^+

This search was suggested in 1980 (RS, PLB 96, 159 (1980); Phys. Rev. D 24, 1232, 1275 (1981) and was used to set bounds on such decays.

The signature is a monochromatic peak in the charged lepton momentum/energy of the charged lepton at a value below the value for a neutrino of negligible mass.

A key to the sensitivity of the search is that the helicity suppression in $BR(M^+ \to e^+ \nu_e)$ for $M^+ = \pi^+,\ K^+$, etc. is removed for a heavy neutrino. This gains a factor of $\sim 10^4$ sensitivity in the search for heavy neutrino emission in π^+_{e2} and $\sim 10^5$ in K^+_{e2}. Little phase space suppression for moderate m_{ν_4}.

From 1981 to present this test has been applied in a series of experiments on $\pi^+_{\ell 2}$ decay at TRIUMF and SIN/PSI, and $K^+_{\ell 2}$ decay at KEK, BNL, and CERN to set very stringent upper bounds on $|U_{ej}|^2$ and $|U_{\mu j}|^2$ as function of m_{ν_j} for a heavy neutrino. Recent results from:

PIENU experiment at TRIUMF in PRD 97, 072012 (2018) (π^+_{e2}); PLB 798, 134980 (2019) ($\pi^+_{\mu 2}$)

NA62 experiment at CERN in PLB 772, 712 (2017) ($K^+_{\mu 2}$); PLB 778, 137 (2018) ($K^+_{\ell 2}$), $\ell = e, \mu$; PLB 807, 135599 (2020) ($K^+_{\ell 2}$), $\ell = e, \mu$; PLB 816, 136259 (2021) ($K^+_{\mu 2}$).

A recent analysis: Bryman and RS, Phys. Rev. D 100, 053006, 073011 (2019).

More generally, there has been considerable interest in heavy neutrinos (neutral heavy leptons) in recent years, e.g. Gorbunov and Shaposhnikov 2007; Kusenko, Pascoli, and Semikoz 2008; Kusenko 2009; Boyarsky, Ruchayskiy, Shaposhnikov, 2009; Helo, Kovalenko, Schmidt 2011; Abada et al. 2014; SHIP Proposal at CERN (Alekhin et al., 2016) de Gouvêa and Kobach 2016; Fernandez-Martinez et al. 2016; Drewes and Garbrecht 2017; Batell et al. 2018; Bondarenko, Boyarsky, Gorbunov, Ruchayskiy 2018; Bondarenko et al. 2021 (arXiv:2101.09255)...

In the SM

$$\Gamma(\pi^+ \to \ell^+\nu_\ell)_{SM} = \frac{G_F^2|V_{ud}|^2 f_\pi^2 m_\pi m_\ell^2}{8\pi}\left(1 - \frac{m_\ell^2}{m_\pi^2}\right)^2$$

For the decay to a ν_4 of non-neglible mass,

$$\Gamma(\pi^+ \to \ell^+\nu_4) = \frac{G_F^2|V_{ud}|^2|U_{\ell 4}|^2 f_\pi^2 m_\pi^3}{8\pi}\rho(\delta_\ell^{(\pi)}, \delta_{\nu_4}^{(\pi)}) \ ,$$

where

$$\rho(x,y) = [x + y - (x-y)^2]\,[1 + (x-y)^2 - 2(x+y)]^{1/2} \ ,$$

and

$$\delta_\ell^{(\pi)} = \frac{m_\ell^2}{m_\pi^2} \ , \quad \delta_{\nu_4}^{(\pi)} = \frac{m_{\nu_4}^2}{m_\pi^2} \ ,$$

For a massless neutrino, $\rho(x,0) = x(1-x)^2$ with $x = \delta_\ell^{(\pi)}$. Thus,

$$\frac{\Gamma(\pi^+ \to \ell^+\nu_4)}{\Gamma(\pi^+ \to \ell^+\nu_\ell)_{SM}} = |U_{\ell 4}|^2 \bar\rho(\delta_\ell^{(\pi)}, \delta_{\nu_4}^{(\pi)})$$

where

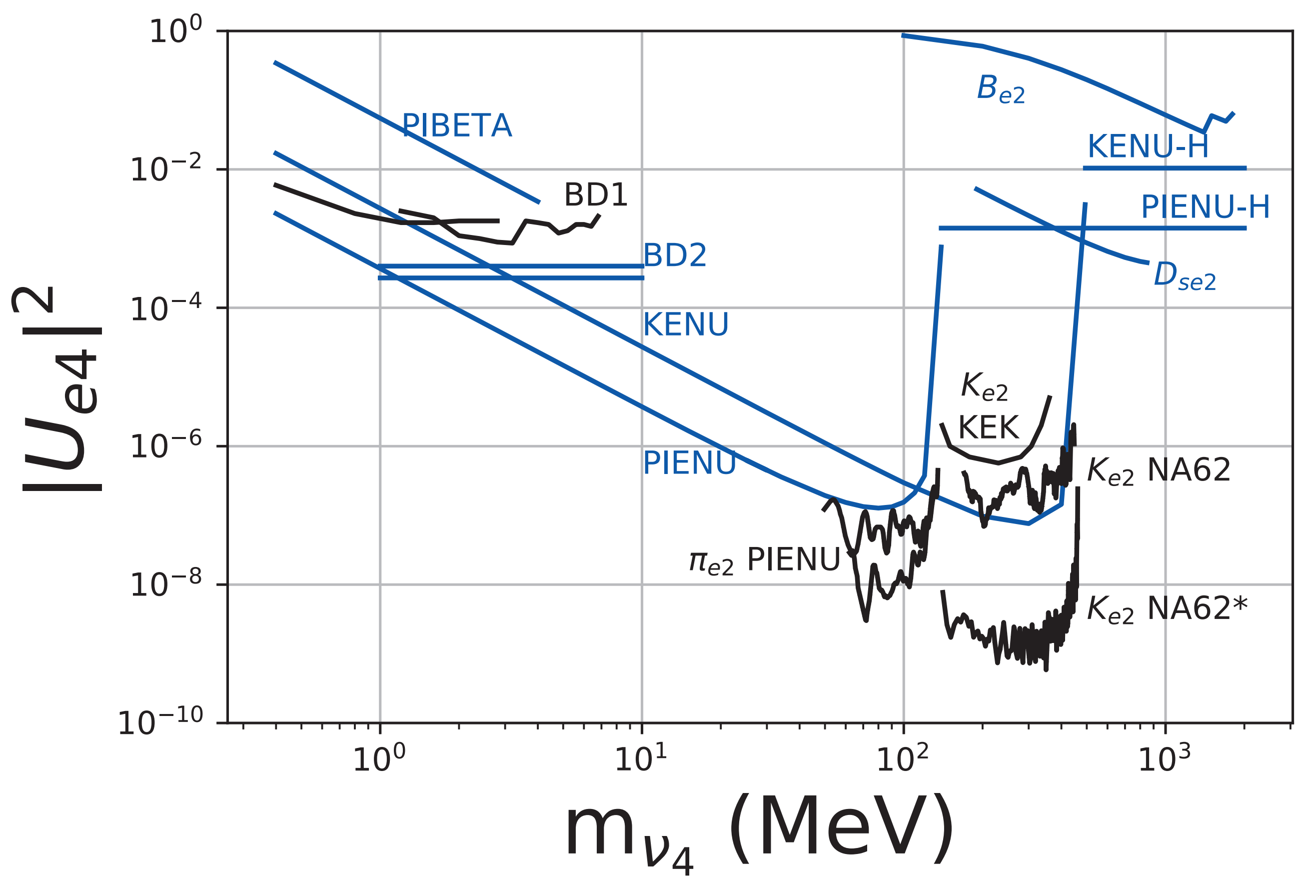
$$\bar\rho(x,y) = \frac{\rho(x,y)}{\rho(x,0)} = \frac{\rho(x,y)}{x(1-x)^2} \ .$$

The function $\bar{\rho}(\delta_e^{(\pi)}, \delta_{\nu_4}^{(\pi)})$ reaches a maximum of 1.1×10^4 at $m_{\nu_4} = 81$ MeV.

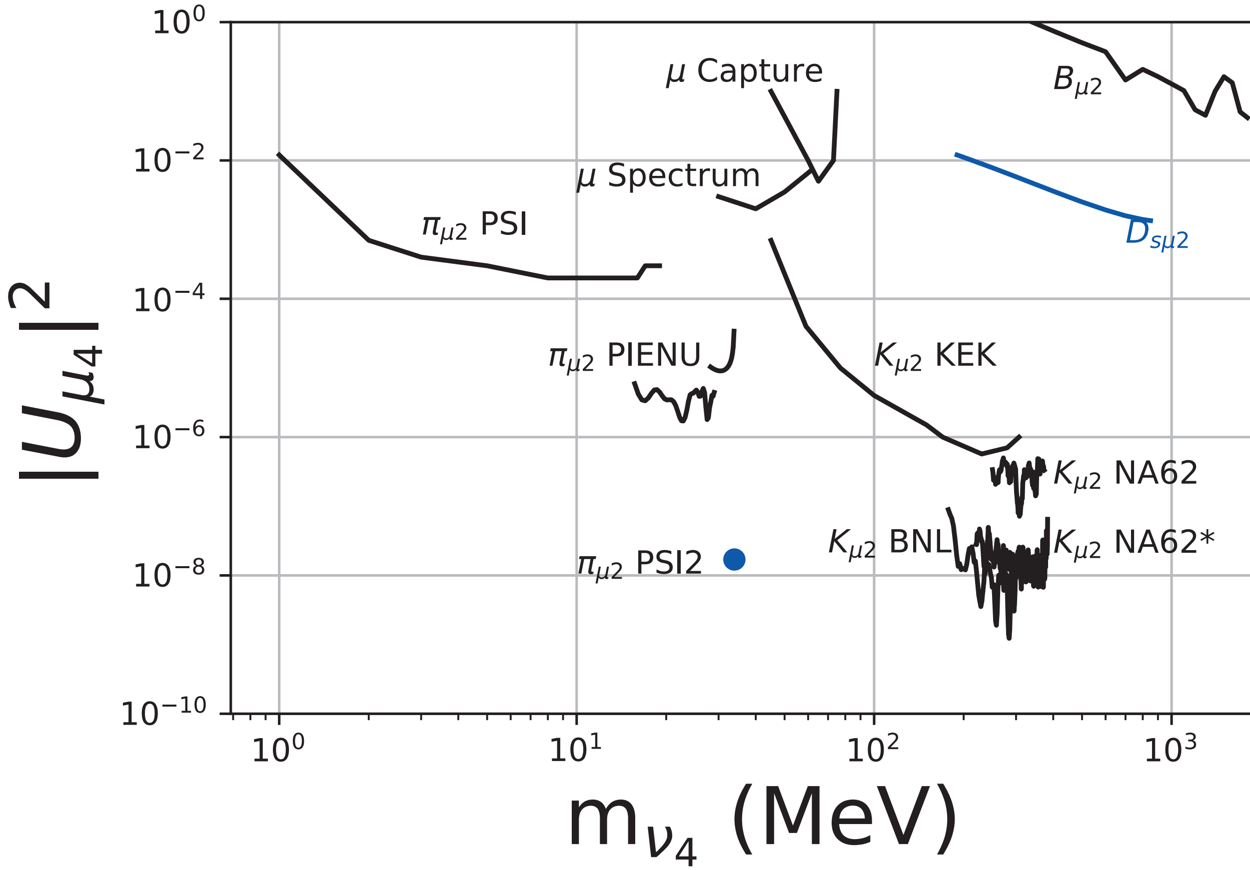
If $m_{\nu_4} > m_\pi - m_\ell$, then the emission is kinematically forbidden, and the decay rate is commensurately reduced.

In general, massive neutrino emission changes the ratio $R_{e/\mu}^{(\pi)}$ from its SM value, and this was used as a constraint on $|U_{e4}|^2$ (RS, 1980, 1981; Bryman 1983)

Recent bounds (Bryman and RS, 2019) in figures:



10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^0
10^1
10^2
10^3
$|U_{e4}|^2$
m_{ν_4} (MeV)
PIBETA
BD1
BD2
KENU
PIENU
π_{e2} PIENU
B_{e2}
KENU-H
PIENU-H
D_{se2}
K_{e2}
KEK
K_{e2} NA62
K_{e2} NA62*



10^{0}
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^{0}
10^{1}
10^{2}
10^{3}
$|U_{\mu_4}|^2$
m_{ν_4} (MeV)
μ Capture
$B_{\mu 2}$
μ Spectrum
$\pi_{\mu 2}$ PSI
$D_{s\mu 2}$
$\pi_{\mu 2}$ PIENU
$K_{\mu 2}$ KEK
$K_{\mu 2}$ NA62
$K_{\mu 2}$ BNL
$K_{\mu 2}$ NA62*
$\pi_{\mu 2}$ PSI2

See talk by P. Cushman for a related proposed search that is sensitive to neutrino mass effects in $\pi^+_{\ell 2}$ decay.

The successful predictions from primordial nucleosynthesis for H, He abundances suggest an upper bound on the lifetime $\tau_{\nu_4} \lesssim 1$ sec (since BBN starts at $t \sim O(1)$ sec.) and hence a lower bound on $|U_{e4}|^2 \gtrsim 10^{-6}$ for $m_{\nu_4} = 100$ MeV.

The advantage of an experimental search is that it is direct and does not depend on assumptions about ν_4 decays or early universe history.

Similar argument that KATRIN experiment and its upper limit (PRL 123, 221802 (2020); arXiv:2105.08533) $m_\beta = [\sum_{j=1}^3 |U_{ej}|^2 m^2_{\nu_j}]^{1/2} < 0.8$ eV are worthwhile, although the cosmological upper limit on $\sum_{j=1}^3 m_{\nu_j} < 0.15$ eV is below the current KATRIN sensitivity.

Another CLFV decay is $\mu \longrightarrow eX$, where X is a neutral weakly interacting boson (familon, majoron,... - recent discussions, e.g. Cornella et al. arXiv:1911.06279; Calibbi et al., 2006.04795; talk by Koltick).

If X does not decay in the detector, the signature is an anomalous peak in the e energy/momentum spectrum. A TRIUMF exp. searched for this for m_X in the range 48-95 MeV and set upper bounds on $BR(\mu^+ \longrightarrow e^+X) \lesssim 10^{-5}$ (PRD 101, 052014 (2020)).

There are also limits from searches for $\mu \longrightarrow eX$ where X decays in the detector, e.g., $X \longrightarrow e^+e^-$ or $X \longrightarrow \gamma\gamma$.

BSM effects can also be present in regular μ decay, $\mu \to e\nu_\mu\bar{\nu}_e$, which is, operationally, $\mu \to e+$ (undetected neutral weakly interacting particles that do not decay in the detector). Examples of BSM physics effects:

- In early supersymmetry models, gauginos were viewed as possibly being light. Then, for example, $\mu \to e\tilde{\gamma}\tilde{\gamma}$ ($\mu \to e\tilde{\chi}^0\tilde{\chi}^0$ in modern notation) could occur (Barber and RS 1984). This would mean that the measured G_μ is larger than the true G_F.

- Possible massive neutrino emission in μ decay would have the opposite effect, that the measured G_μ would be smaller than the true G_F, and would also affect the spectral parameters in μ decay. These effects were used to provide constraints on massive ν emission in μ decay (RS, PRD 24, 1275 (1981); Bryman and RS 2019).

MuLan experiment at PSI measured τ_μ to 10^{-6} accuracy (PRD 87, 0522003 (2013)).

Other Possible Experiments

Other possible experiments could also be of interest, e.g., (i) muon EDM, d_μ (Semertzidis talk); (ii) proton EDM (Morse talk); (iii) muonium-antimuonium oscillations $(\mu^- e^+) - (\mu^+ e^-)$ (Petrov talk); (iv) radiative muon decay (Khaw talk); (v) charged pion lifetime (Gorringe talk), etc.

So, in summary, there are many possible extensions of the Fermilab muon campus experimental program.

Some of these would be in competition with dedicated experimental programs at PSI and TRIUMF, such as searches for CLFV muon decays $\mu \longrightarrow e\gamma$, $\mu \longrightarrow ee\bar{e}$, searches for massive neutrino emission in $\pi^+_{\ell 2}$ decay, and measurement of $BR(\pi^+ \longrightarrow e^+\nu_e)/BR(\pi^+ \longrightarrow \mu^+\nu_\mu)$.

These would also require work on accelerator beamlines, targets, etc., (J. Morgan talks).

However, it is certainly worthwhile to investigate what an extended Fermilab muon campus program might contribute to this physics.