Revisiting τ→3μ in the Standard Model and Beyond

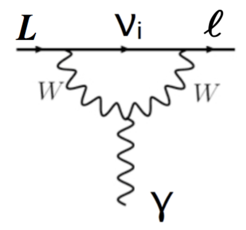
Patrick Blackstone | University of Indiana
Emilie Passemar | University of Indiana / JLab

Grant No.
PHY - 1714253

Background and Motivation

- Neutrino Oscillations suggest lepton flavor is not conserved, opening door to lepton flavor violating (LFV) processes.
- The simplest way to incorporate oscillations into diagrams is by coupling charged leptons not to the associated flavor eigenstate, but to the mass eigenstate. The vertices are then suppressed by an appropriate matrix mixing element.
- In the Standard Model, Branching ratios for these processes are typically calculated to be unobservably small, owing to the GIM-like mechanism of the Pontecorvo-Maki-Nakagawa-Sakata Matrix and typical suppression factor by the neutrino mass.

$$\mathrm{Br}(\mu\to e\gamma) = \frac{3\alpha}{32\pi}\left(\sum_i U^*_{ei}U_{\mu i}\left(\frac{m_i}{M_w}\right)^2\right)^2 < 10^{-40}$$



(Petcov '77, Marciana & Sanda '77, Lee & Shrock '77, Cheng & Li '84)

- It was claimed [1] that Br(τ→3μ) could be as large as 10^{-14}, a surprising result in light the simpler process L →ℓγ being unobservably small. This is reported to be due to factor logarithmically unbounded as the neutrino masses are taken to be smaller and smaller:

$$\sum U^*_{\mu i}U_{\tau i}\log\left(\frac{M_w^2}{m_j^2}\right) \quad (\clubsuit)$$

- We revisit this calculation **in the approximation of neglected external mass and momenta** and using the most recent mixing angle data.

PMNS Matrix and Oscillation Parameters

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}s_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{12}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$\Delta m^2_{12} = (7.4\pm0.2)\times10^{-5}\,\mathrm{eV}^2$ **(KamLAND)**
$\Delta m^2_{23} = (2.5^{+0.2}_{-0.15})\times10^{-5}\,\mathrm{eV}^2$ **(NOvA, T2K, SuperK, IceCube)**
$\sin^2(\theta_{13}) = 0.0221\pm0.0008$ **(Daya Bay)**
$\sin^2(\theta_{12}) = 0.307\pm0.013$ **(SNO, SuperKamiokande)**
$\sin^2(\theta_{23}) = 0.54^{+0.08}_{-0.12}$ **(NOvA, T2K, SuperK, IceCube)**

GIM-like Mechanism (Unitarity):

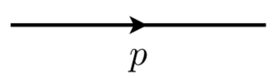
$$\sum_i U^*_{\ell i}U_{\ell' i} = \delta_{\ell\ell'}$$

Feynman Rules modified by PMNS elements in Feynman-'t Hooft Gauge (ξ=1)

Ramão & Silva '12 (diagrams)

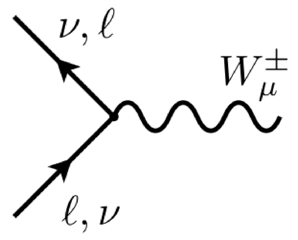
Feynman rules adapted from Cheng & Li '84

- Neutrino Dirac propagator



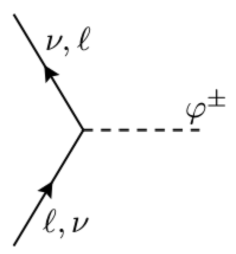
$$\frac{i(\not{p}+m_i)}{p^2-m_i^2}$$

- lepton-neutrino-W vertex: the matrix element has (does not have) a conjugation if the charged lepton is entering (leaving).



$$\left(\frac{ig}{\sqrt{2}}\right)\gamma_\mu P_L U^{(*)}_{\ell i}$$

- lepton-neutrino-Goldstone vertex



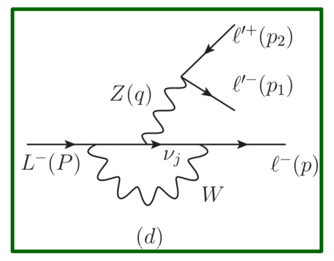
$$\left(\frac{ig}{\sqrt{2}}\right)\frac{U^{(*)}_{\ell i}}{M_W}[m_i P_{L,R} - m_\ell P_{R,L}]$$

Diagrams for τ→3μ

After computing the amplitudes below, [4] gives over s limits: $4m_\mu^2 \le s \le (m_\tau - m_\mu)^2$

$$\frac{d\Gamma}{ds dt} = \int \frac{\overline{|\mathcal{M}|^2}}{256\pi^3 m_\tau^3} \qquad s = (P-p_2)^2,\quad t = (P-p_1)^2$$

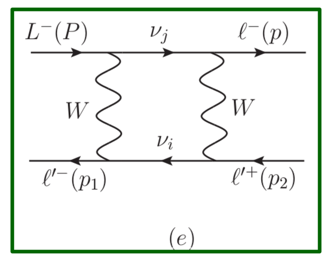
In keeping with the conventions of [1] and [2], we refer to the diagrams of Figure 1 of [2]:



We find

$$\mathcal{T}_d \approx -\frac{G_F^2}{\pi^2}M_W^2\left[\sum_j U^*_{\mu j}U_{\tau j}\left(\frac{m_j^2}{M_W^2}\log\left(\frac{M_w^2}{m_j^2}\right) - \frac{m_j^2}{M_W^2}\right)\right]\overline{u}_\ell(p)\gamma^\lambda(1-\gamma_5)u_L(P)$$
$$\times\left(\frac{1}{8}\overline{u}_{\ell'}(p_1)\gamma_\lambda(1-\gamma_5)v_{\ell'}(p_2) - \frac{\sin^2(\theta_W)}{2}\overline{u}_{\ell'}(p_1)\gamma_\lambda v_{\ell'}(p_2)\right)$$

In [1], the expression in red is replaced by (♣) which lacks the suppressing factor of m_j^2, leading to the extraordinary branching ratio 10^{-14}. [2] suggests that this expression is due to an erroneous approximation of momentum transfer $q^2 \approx 0$. Our result above agrees with Eqn. 2.8 of [2] in the same approximation.

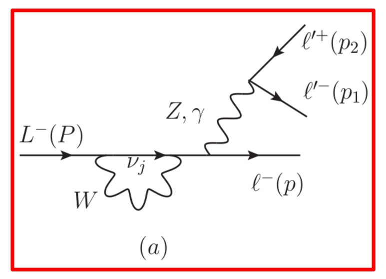


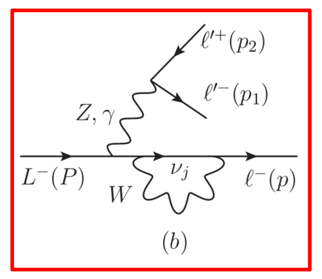
Our result:

$$\mathcal{T}_e \approx -\frac{G_F^2}{32\pi^2}M_W^2\times\sum_{i,j}\left(U^*_{\ell,j}U_{L,j}|U_{\ell',i}|^2[\cdots]_{i,j}\right)\times$$
$$[\overline{u}_\ell(p)\gamma^\mu\gamma^\alpha\gamma_\lambda(1-\gamma_5)u_L(P)][\overline{u}_{\ell'}(p1)\gamma^\lambda\gamma_\alpha\gamma_\mu v_{\ell'}(p2)]$$

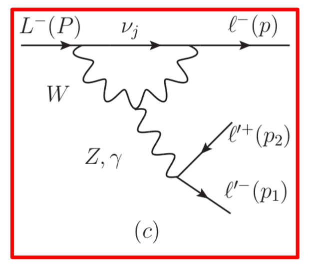
Where

$$[\cdots]_{i,j} = -\frac{1}{(1-x_i)(1-x_j)} + \frac{x_i^2}{(x_i-x_j)(1-x_i)^2}\log(x_i) - \frac{x_j^2}{(x_i-x_j)(1-x_j)^2}\log(x_2)$$





In progress



Should be unobservably small, calculation in progress: Expect that this Br be suppressed by extra factor of α (for the photon) or G_F (for the Z boson), but still potentially comparable to diagrams (d) and (e).

Additionally, diagrams need to be added replacing the W with Goldstone bosons, but all Goldstone diagrams are suppressed by factors of external masses.

Acknowledgements

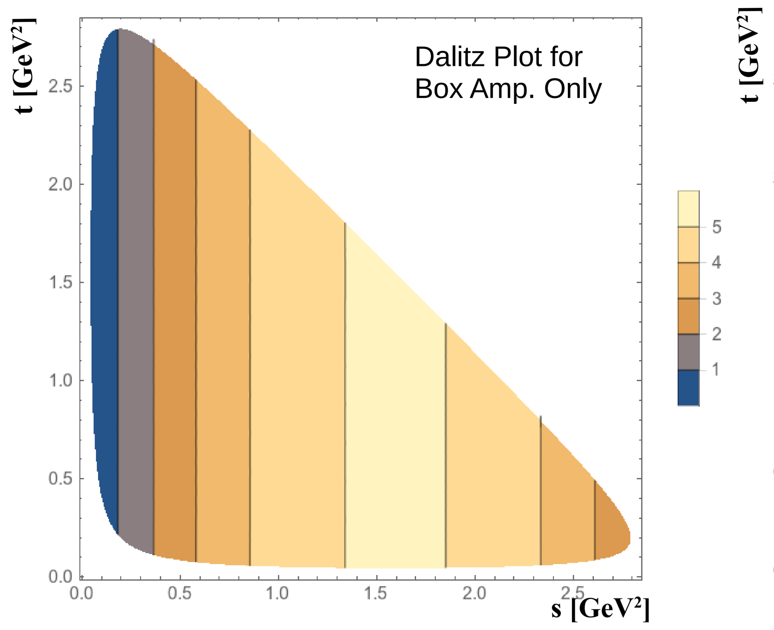
Prof. Swagato Banerjee (University of Louisville)
Dr. Alexander Friedland (SLAC)
Tau 2018 organizers
Indiana University Graduate School

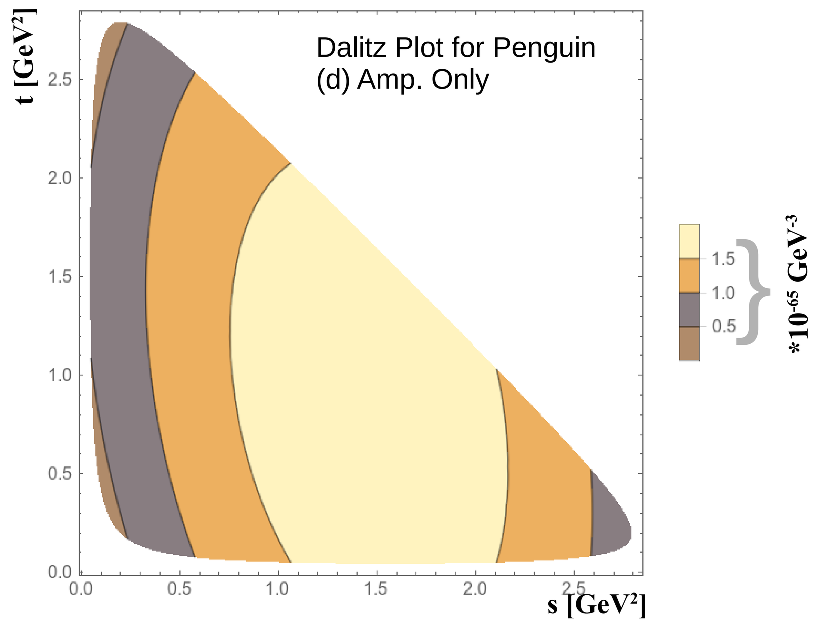
References

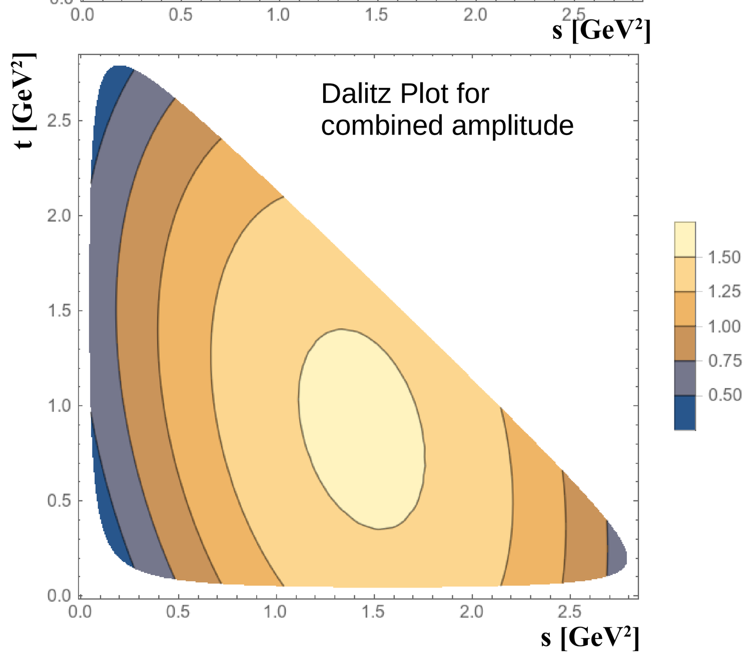
[1] X. Y. Pham, Eur.Phys.J. C8 (1999) 513-516
[2] G. Hernández-Tomé, G. López Castro and P. Roig, arXiv:1807.06050 [hep-ph]
[3] S. T. Petcov, Sov. J. Nucl. Phys. **25** (1977) 340
[4] T. P. Cheng and L. F. Li, "Gauge Theory Of Elementary Particle Physics," Oxford, Uk: Clarendon (1984) 536 P. (Oxford Science Publications)
[5] M. Tanabashi et al. (Particle Data Group), Phys. Rev. D 98, 030001 (2018)
[6] The Belle II Physics Book, 1808.10567

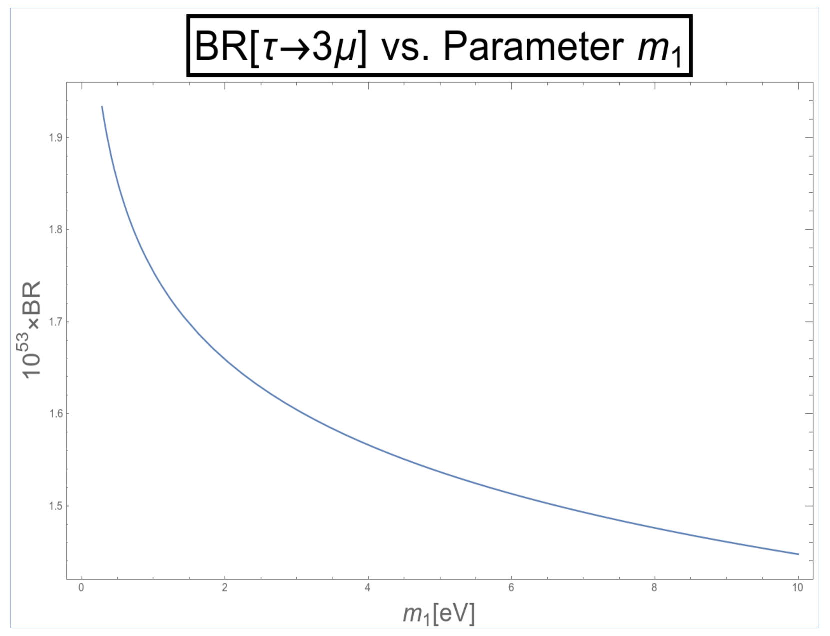
Dalitz and Branching Ratio vs Neutrino Mass for τ→3μ

Preliminary – τ→3e etc. to come



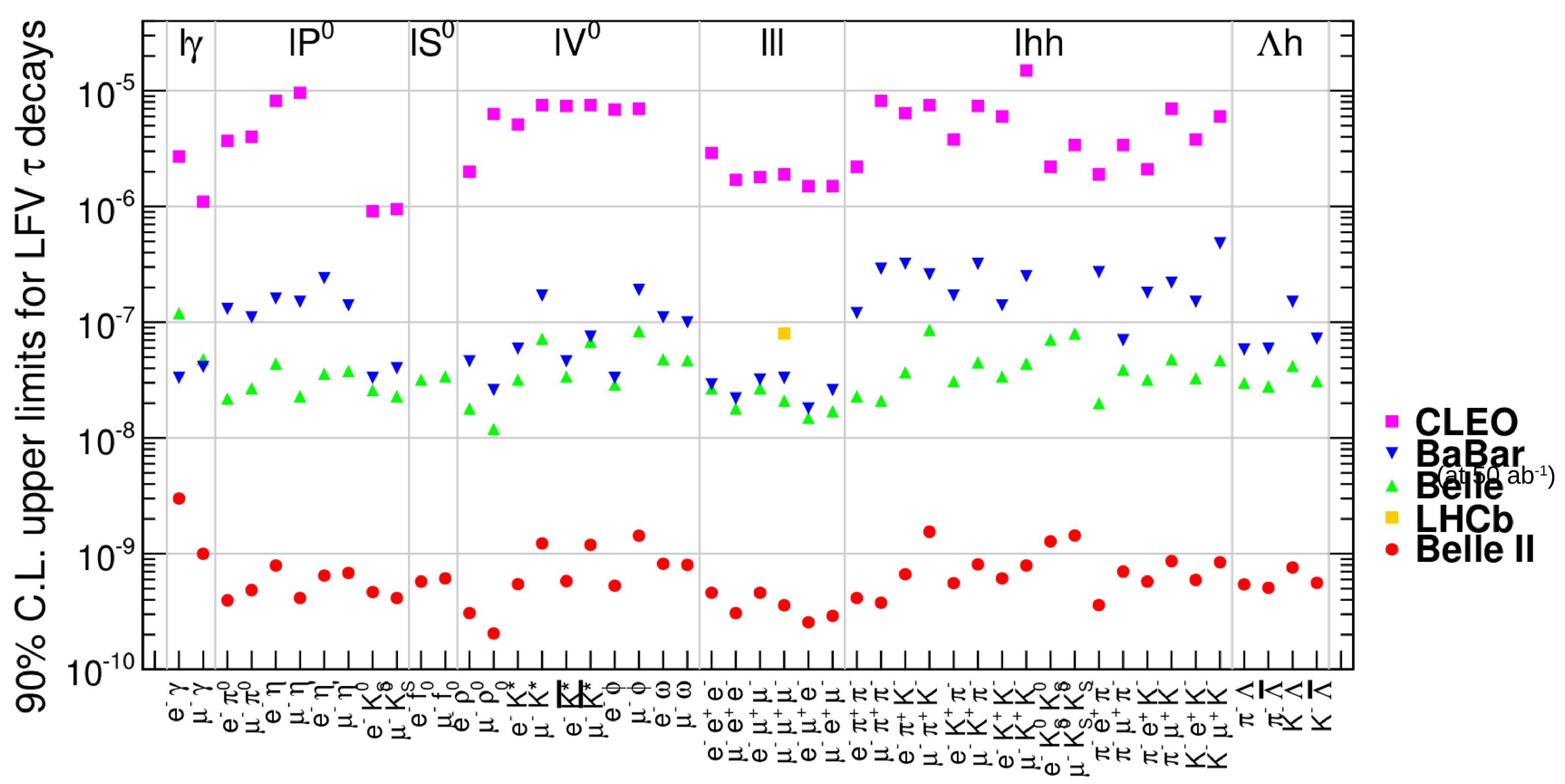






The Branching Ratio in this approximation maximizes when the lightest neutrino mass vanishes: **Br(τ→μ) < 2.3*10⁻⁵³**

Current and Future Experimental Bounds



Prospects: Belle II (see plot), HL-LHC (τ→3μ) O(10^{-9})

Conclusion

We currently find BR(τ→3μ) < O(10^{-53}) due to Dirac neutrino loop correction in accordance with [2, 3], refuting the claim by [1]. Therefore, if neutrinos are Dirac Fermions, observation of these LFV processes will be clear signature of new physics.