Revisiting $\tau \to 3\mu$ in the Standard Model and Beyond

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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.

We revisit this calculation due to factor logarithmically unbounded as the neutrino masses are taken to be smaller and smaller:

After computing the amplitudes below, [4] gives over s limits:

$$\sin^4 \theta \leq \sin^4 \theta_{\text{max}} = (1+m_\nu \to m_\nu^3)$$

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

We find

$$\begin{align*}
\frac{\Gamma(\tau \to 3\mu)}{\Gamma(\tau \to \mu\gamma)} &= 6\frac{m_\tau}{m_\mu} \sum_{i=1}^{3} U_{\ell i}^2 U_{\nu i}^2 \\
\text{where} \quad U_{\ell i} &= \sum_{j=1}^{3} U_{\ell j}^2 \sin^2 \theta_{\text{max}} \\
\text{Our result:} \quad \frac{\Gamma(\tau \to 3\mu)}{\Gamma(\tau \to \mu\gamma)} &< O(10^{-4})
\end{align*}$$

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

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

- Neutrino Dirac propagator

$$\begin{align*}
\frac{i g V_{\ell i} V_{\nu i}}{p^2 - m_\nu^2}
\end{align*}$$

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

$$\begin{align*}
\frac{i g V_{\ell i} V_{\nu i}}{p^2 - m_\nu^2}
\end{align*}$$

- lepton-neutrino-Goldstone vertex

$$\begin{align*}
\frac{i g V_{\ell i} V_{\nu i}}{p^2 - m_\nu^2}
\end{align*}$$

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References


Current and Future Experimental Bounds

Prospects: Belle II (see plot), HL-LHC ($\tau \to 3\mu$) O(10^-4)

Conclusion

We currently find $Br(\tau \to 3\mu) < O(10^{-4})$ 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.