LFV: Polarized $\tau^- \to \mu^-\mu^-\mu^+$ decay

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IS VIOLATING LEPTON FLAVOUR IN COLLABORATION WITH:

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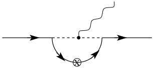
DFG: FOR 1873

QFET workshop, Siegen, 08. December 2014

Introduction

- Neutrino oscillation allows for Lepton Flavour Violation (LFV)



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albeit at tiny $BF \sim 10^{-40..-50}$ level.

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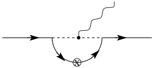

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Bottom-up approach: SM = EFT

Effective Hamiltonian mediating $\tau \to \ell, \ell', \ell''$: Choose helicity structure

$$H_{\rm lept}^{(LL)(LL)} = \frac{g_V^{(LL)(LL)}}{\Lambda^2}(\bar\ell_L\gamma_\mu\tau_L)(\bar\ell'_L\gamma^\mu\ell''_L)$$

$$H_{\rm lept}^{(RR)(RR)} = \frac{g_V^{(RR)(RR)}}{\Lambda^2}(\bar\ell_R\gamma_\mu\tau_R)(\bar\ell'_R\gamma^\mu\ell''_R)$$

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$$H_{\rm rad}^{(LR)} = \underbrace{\alpha_{\rm em}\frac{v}{\Lambda^2}g_{\rm rad}^{(LR)}}_{\rho_1 m_\tau}\left(\bar\ell_L\frac{(-i)}{q^2}q^\eta\sigma_{\mu\eta}\tau_R\right)(\bar\ell\gamma^\mu\ell)$$

$$H_{\rm rad}^{(RL)} = \underbrace{\alpha_{\rm em}\frac{v}{\Lambda^2}g_{\rm rad}^{(RL)}}_{\rho_2 m_\tau}\left(\bar\ell_R\frac{(-i)}{q^2}q^\eta\sigma_{\mu\eta}\tau_L\right)(\bar\ell\gamma^\mu\ell)$$

(only photon at leading power)

[Dassinger, Feldmann, Mannel, Turczyk (2007)]

Decay modes, Dalitz analysis

decay modes

$$\tau^- \longrightarrow e^- e^- e^+ \quad , \quad \tau^- \longrightarrow \mu^- \mu^- \mu^+ \; ,$$
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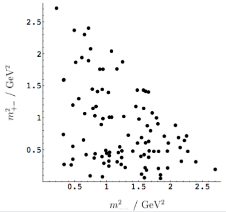
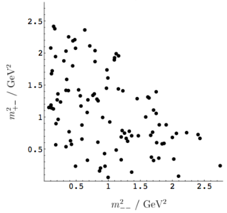
- First and third line contain identical particles in the final state.
- Third line does not receive contributions from radiative operators.

Let's say a few such events are found... [Mannel (2013)]

With one hundred events, can we disentangle the helicity structure, i.e. the couplings of the operators? **Dalitz-Plots:**



$(LL)(LL)$ versus



$(LL)(RR)$.

Why polarized τ?

- It will be hard to extract information on the couplings from sparsely populated phase space.
- **Integrated** (not differential) quantities will be more feasable, e.g. **asymmetries**
- A number of asymmetries can be constructed with the help of the **spin-vector** $\vec{s}$. [Mannel (2013)]

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Spin information

$$u^{\uparrow} = \sqrt{m_\tau}\begin{pmatrix}\xi^{\uparrow}\\ \xi^{\uparrow}\end{pmatrix} \qquad \Rightarrow \qquad u^{\uparrow}\bar{u}^{\uparrow} = (\not{p}_\tau + m_\tau)\frac{1+\gamma_5 \not{s}}{2}$$

Three independent invariant scalars for $\tau^-(p_\tau; s) \to \ell^-(p_1)\ell^-(p_2)\ell^+(p_3)$:

$$\begin{aligned} t &= s\cdot p_2 = -\vec{s}\cdot\vec{p}_2 && \text{in rest frame of } \tau^- \\ u &= s\cdot p_3 = -\vec{s}\cdot\vec{p}_3 \\ v &= \varepsilon_{\alpha\beta\gamma\delta}\, p_\tau^\alpha s^\beta p_2^\gamma p_3^\delta = m_\tau \vec{s}\cdot(\vec{p}_2\times\vec{p}_3) \end{aligned}$$

- $\left[|\mathcal{M}(t,u,v,\ldots)|^2 = J_0(\ldots) + tJ_t(\ldots) + uJ_u(\ldots) + vJ_v(\ldots)\right]$ is at most linear in t, u, v.

Angular decomposition

- In the rest frame of the τ: decay products momenta lie in a plane: $\vec{p}_1 + \vec{p}_2 + \vec{p}_3 = \vec{p}_\tau = 0$.
- We use an Euler rotation $\vec{p}_i' = R_z(\alpha)R_y(\beta)R_z(\gamma)\vec{p}_i$ to transform into the decay plane (defined as the $x' - z'$ plane). Then

$$
\begin{aligned}
t &= s \cdot p_2 = -\vec{s} \cdot \vec{p}_2 \quad = -A \cos\alpha \, \sin\beta - B \cos\beta \\
u &= s \cdot p_3 = -\vec{s} \cdot \vec{p}_3 \quad \propto \cos\beta \\
v &= \varepsilon_{\alpha\beta\gamma\delta} p_\tau^\alpha s^\beta p_2^\gamma p_3^\delta = m_\tau \vec{s} \cdot (\vec{p}_2 \times \vec{p}_3) \quad \propto \sin\alpha \, \sin\beta
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Full angular dependence

$$|\mathcal{M}|^2 = J_1(E_2, E_3) + J_2(E_2, E_3)\cos\beta + J_3(E_2, E_3)\cos\alpha\sin\beta + J_4(E_2, E_3)\sin\alpha\sin\beta$$

and $\phi = \sphericalangle(\vec{p}_2, \vec{p}_3) = \phi(E_2, E_3)$,

$$d\Gamma = \frac{|\mathcal{M}|^2}{2m_\tau} \frac{d\alpha\, d\cos\beta\, d\gamma}{(2\pi)^5} \frac{dE_2 dE_3}{8}\,.$$

Goal

- We aim at a **phenomenological study** of observables with **few events**.

- Example: with $I_i = \int dE_2 dE_3\, J_i(E2, E3)$ we find in the sector of leptonic operators:

Leptonic squared contributions

$$\Delta I_1 = [\lambda_{11} + \lambda_{22}]\,\frac{m_\tau^6}{6}\left(1 - 24\left(\frac{m}{m_\tau}\right)^2\right) + [\lambda_{33} + \lambda_{44}]\,\frac{m_\tau^6}{12}\left(1 - 28\left(\frac{m}{m_\tau}\right)^2\right)$$

$$\Delta I_2 = [\lambda_{11} - \lambda_{22}]\,\frac{m_\tau^6}{6}\left(1 - 36\left(\frac{m}{m_\tau}\right)^2\right) + [\lambda_{44} - \lambda_{33}]\,\frac{m_\tau^6}{36}\left(1 - 12\left(\frac{m}{m_\tau}\right)^2\right)$$

$$\Delta I_3 = 0\,,$$

$$\Delta I_4 = 0\,.$$

Leptonic mixed contributions

$$\Delta I_1 = [\lambda_{34}^R - 2\lambda_{14}^R - 2\lambda_{23}^R]\, m_\tau^6 \frac{1}{3}\left(\frac{m}{m_\tau}\right) + [\lambda_{13}^R + \lambda_{24}^R]\, m_\tau^6 \frac{4}{3}\left(\frac{m}{m_\tau}\right)^2\,,$$

$$\Delta I_2 = [\lambda_{23}^R - \lambda_{14}^R]\, m_\tau^6 \frac{2}{3}\left(\frac{m}{m_\tau}\right) + [\lambda_{24}^R - \lambda_{13}^R]\, m_\tau^6 \frac{2}{3}\left(\frac{m}{m_\tau}\right)^2\,,$$

$$\Delta I_3 = 0\,,$$

$$\Delta I_4 = 0\,.$$

- Without the radiative contributions yet, an asymmetry

$$\frac{\Gamma(\cos\beta > 0) - \Gamma(\cos\beta < 0)}{\Gamma(\cos\beta > 0) + \Gamma(\cos\beta < 0)} \quad \text{is sensitive to} \quad (|g_V^{(LL)(LL)}|^2 - |g_V^{(RR)(RR)}|^2) \quad , \ldots$$

- Many other observables can be constructed from partial rates like $\Gamma(\sin\alpha > 0, \cos\beta > 0, \cos\phi < 0)$, etc.

Status of this subproject

- Fully differential decay rate at tree-level: ✓
- Integrate over energies E_2 and E_3:
  - leptonic sector: ✓
  - radiative sector: ✍
  - mixed sector: ✍ (likely easier than radiative)
- Technical difficulties: Phase-space logarithms ✓

$$\ln^n \frac{m}{m_\tau}$$

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- Timeframe:
  - all integrals solved: before Christmas.
  - Observables and Pheno: January?
  - Wrap up: February?

Outlook

"The field of lepton flavour violation (LFV) is about to begin a golden era, with great expectations in several experimental projects."

[A. Vicente (2014) at CKM conference.]

- On dim. 6 terms in the SM [Grzadkowski, Iskrzynski, Misiak, Rosiek (2010)]
- LFV with hadrons? $\tau^- \to \pi^0 \mu^-$
- LFV in B decays? $B \to K\ell^-\ell'^+$, $B_s \to \ell^-\ell'^+$ [Glashow, Guadagnoli, Lane (2014)]
- LNV and BNV, but $(B - L)$ conserving dim. 6 operators?
  $n \to \pi^0\bar{\nu}$, $n \to \ell^+\pi^+\pi^-\pi^-$, $B^0 \to \Lambda^+\ell^-$ [Hou, Nagashima, Soddu (2005)]