New Physics Searches at near detectors of neutrino oscillation experiments

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1 New physics at near detectors

2 Current bounds and prospects

Tau appearance channel @ near detectors

- Why a near ν_τ detector for new physics search?
  - Low background
  - Negligible (or small) neutrino oscillations
- Drawback:
  - No guaranteed signal
- What is the sensitivity needed to compete with current bounds?

See, e.g., Summary report of MINSIS workshop in Madrid, arXiv:1009.0476

Effective field theory approach

- The Standard Model has been extremely successful
- Effective theory approach to beyond SM physics

$$\mathcal{L} = \mathcal{L}_{SM} + \sum_{d \geq 5} \frac{\mathcal{C}_d}{M^{d-4}} \mathcal{O}_d$$

- At $d = 5$, the only effective operator is the Weinberg operator

Weinberg, PRL 43 (1979) 1566

$$\mathcal{O}_5 = \phi\phi LL$$

$\Longrightarrow$ neutrino masses

Dimension 6 operators

- Four-fermion contact operators ($4 \times 1.5 = 6$)
- For near neutrino detectors, two types are of importance
  - Two-quark two-lepton interactions ($2Q2L$)
  - Four-lepton interactions ($4L$)
- Furhtermore, there is a type of $d = 6$ kinetic operator inducing non-unitarity in mixing
- Have to be gauge invariant
- There are $4L$ and kinetic operators that do not give rise to four-charged-fermion interactions
  Bergman, Grossman, PRD 59 (1999) 093005
  Bergman, Grossman, PRD 61 (2000) 053005
  Antusch, Baumann, Fernandez-Martinez, NPB 810 (2009) 369
  Gavela et al., PRD 79 (2009) 013007
- We focus on $2Q2L$

Basis of operators

We use the following basis for first-generation quark operators

Buchmüller, Wyler, NPB 268 (1986) 621

$$
\begin{aligned}
(\mathcal{O}^1_{LQ})_\alpha{}^\beta &= [\overline{L}^\beta \gamma^\rho L_\alpha][\overline{Q}\gamma_\rho Q], \\
(\mathcal{O}^3_{LQ})_\alpha{}^\beta &= [\overline{L}^\beta \gamma^\rho \tau^a L_\alpha][\overline{Q}\gamma_\rho \tau^a Q], \\
(\mathcal{O}_{ED})_\alpha{}^\beta &= [\overline{L}^\beta E_\alpha][\overline{D} Q], \\
(\mathcal{O}_{EU})_\alpha{}^\beta &= [\overline{L}^\beta E_\alpha] i\tau^2 [\overline{Q} U]^T,
\end{aligned}
$$

- Each operator is assumed to be present in the Lagrangian with a coefficient $2\sqrt{2}G_F\mathcal{C}$

Effects on τ decays

- We need to derive the current bounds on the coefficients $\mathcal{C}$
- Naturally, to produce near-detector τs, we need to involve τs in flavor indices
- We use $\tau \to \ell\Pi$ decays, where $\ell = e, \mu$ and Π is a meson
- The involved matrix elements are

$$\mathcal{M} = \langle \ell\Pi \left| \mathcal{L}_{d=6} \right| \tau \rangle$$

Constraining processes $2L2Q$

Process	Prefactor	Relevant combination of coefficients	BR bound
$\tau \to \ell\rho$	1.7	$\left\lvert\mathcal{C}^3_{LQ}\right\rvert^2$	$6.8\cdot10^{-8}$ $6.3\cdot10^{-8}$
$\tau \to \ell\omega$	1.4	$\left\lvert\mathcal{C}^1_{LQ}\right\rvert^2$	$8.9\cdot10^{-8}$ $1.1\cdot10^{-7}$
$\tau \to \ell\phi$	0.84	$\left\lvert\mathcal{C}^1_{LQ'}+\mathcal{C}^3_{LQ'}\right\rvert^2$	$1.3\cdot10^{-7}$ $7.3\cdot10^{-8}$
$\tau \to \ell\pi$	0.69	$\left\lvert\mathcal{C}^3_{LQ}+\frac{\omega_\tau}{2}\left[\mathcal{C}_{ED}-\mathcal{C}_{EU}\right]\right\rvert^2+\frac{\omega_\tau^2}{4}\left\lvert\mathcal{C}^\dagger_{ED}-\mathcal{C}^\dagger_{EU}\right\rvert^2$	$1.1\cdot10^{-7}$ $8.0\cdot10^{-8}$
$\tau \to \ell\eta$	0.20	$\Big\lvert\mathscr{F}_+\mathcal{C}^1_{LQ}-\left[\mathcal{C}^1_{LQ'}+\mathcal{C}^3_{LQ'}\right] + \frac{3m_\eta^2}{4m_s m_\tau}\mathscr{F}_-\left\{\frac{1}{2}\mathscr{F}'\left[\mathcal{C}_{EU}+\mathcal{C}_{ED}\right]-\mathcal{C}_{ES}\right\}\Big\rvert^2 + \left(\frac{3m_\eta^2}{4m_s m_\tau}\right)^2\mathscr{F}_-^2\left\lvert\frac{1}{2}\mathscr{F}'\left[\mathcal{C}^\dagger_{EU}+\mathcal{C}^\dagger_{ED}\right]-\mathcal{C}^\dagger_{ES}\right\rvert^2$	$6.5\cdot10^{-8}$ $9.2\cdot10^{-8}$
$\tau \to \ell\pi^+\pi^-$	0.081	$\left\lvert\mathcal{C}_{ED}-\mathcal{C}_{EU}\right\rvert^2+\left\lvert\mathcal{C}^\dagger_{ED}-\mathcal{C}^\dagger_{EU}\right\rvert^2$	$2.9\cdot10^{-7}$ $1.2\cdot10^{-7}$
$\tau \to \ell K^+K^-$	0.014	$\left\lvert\mathcal{C}_{EU}-\mathcal{C}_{ES}\right\rvert^2+\left\lvert\mathcal{C}^\dagger_{EU}-\mathcal{C}^\dagger_{ES}\right\rvert^2$	$2.5\cdot10^{-7}$ $1.4\cdot10^{-7}$
$\tau \to \ell K^0\bar{K}^0$	0.014	$\left\lvert\mathcal{C}_{ED}+\mathcal{C}_{ES}\right\rvert^2+\left\lvert\mathcal{C}^\dagger_{ED}+\mathcal{C}^\dagger_{ES}\right\rvert^2$	$3.4\cdot10^{-6}$ $2.2\cdot10^{-6}$

BR bounds from PDG

$$\omega_\tau \equiv \frac{m_\pi}{m_\tau}\frac{m_\pi}{m_u+m_d}$$

$$\mathscr{F}_\pm \equiv \frac{F_\eta^8 \pm \sqrt{2}F_\eta^0}{F_\eta^8 - \frac{1}{\sqrt{2}}F_\eta^0}$$

$$\mathscr{F}' \equiv \frac{F_\eta^8 + 2\sqrt{2}F_\eta^0}{F_\eta^8 - \sqrt{2}F_\eta^0}$$

Our appoach

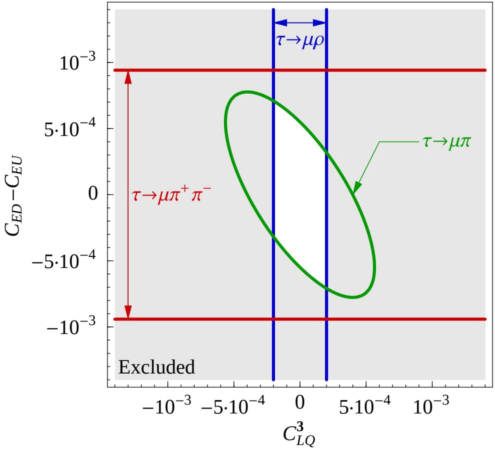
- We make a Markov Chain Monte Carlo (MCMC) to scan the paramter space
- We use the current bounds on LFV τ decays from the PDG as priors

  Amsler et al., PLB 667 (2008) 1

- We use the resulting distributions to derive the bounds on the operator coefficients
- For the MCMC, we use the MonteCUBES software

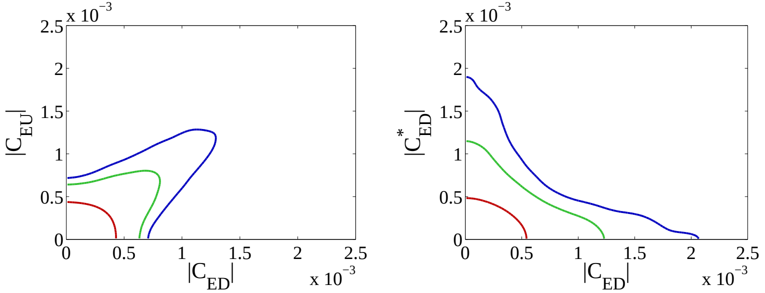
  MB, Fernandez-Martinez, Comput. Phys. Commun. 181 (2010) 227

Illustrative example



- For illustration, assume $\mathcal{C}$ is real and $\mathcal{C}_{EX} = \mathcal{C}_{EX}^T$
- Constraints from decays are ellipsoids in the parameter space

Correlations



Depending on the combinations appearing in the decay formulae, there can be correlations between coefficients

Operator constraints

Operator	$(\mathcal{C}^1_{LQ})_\alpha{}^\tau$	$(\mathcal{C}^3_{LQ})_\alpha{}^\tau$	$(\mathcal{C}_{ED})_\alpha{}^\tau$	$(\mathcal{C}_{EU})_\alpha{}^\tau$	$(\mathcal{C}^\dagger_{ED})_\alpha{}^\tau$	$(\mathcal{C}^\dagger_{EU})_\alpha{}^\tau$
$\alpha = \mu$	$2.1 \cdot 10^{-4}$	$1.7 \cdot 10^{-4}$	$7.2 \cdot 10^{-4}$	$7.2 \cdot 10^{-4}$	$6.2 \cdot 10^{-4}$	$6.2 \cdot 10^{-4}$
$\alpha = e$	$2.4 \cdot 10^{-4}$	$1.6 \cdot 10^{-4}$	$6.9 \cdot 10^{-4}$	$7.1 \cdot 10^{-4}$	$6.0 \cdot 10^{-4}$	$6.1 \cdot 10^{-4}$

- Bounds are generally $\mathcal{O}(10^{-4})$
- Implies reach for probability must generally be $\mathcal{O}(10^{-6}$–$10^{-8})$
- . . . however

Pion chirality enhancement

- Normally, the decay of charged pions is chirality suppressed
- Not the case with $\mathcal{C}^\dagger_{ED}$ and $\mathcal{C}^\dagger_{EU}$

$$\Gamma(\pi^+ \to \nu_\tau \mu^+) = \left| 2(\mathcal{C}^3_{LQ})_\mu{}^\tau + \omega_\mu \left[(\mathcal{C}^\dagger_{ED})_\mu{}^\tau - (\mathcal{C}^\dagger_{EU})_\mu{}^\tau \right] \right|^2 \Gamma(\pi^+ \to \nu_\mu \mu^+)$$

$$\omega_\mu = \frac{m_\pi}{m_\mu} \frac{m_\pi}{m_u + m_d} \simeq 21$$

- Results in

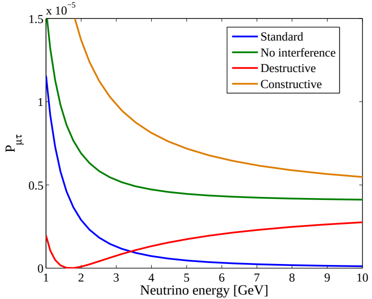
$$\mathcal{R} = \frac{\Gamma(\pi^+ \to \nu_\tau \mu^+)}{\Gamma(\pi^+ \to \nu_\mu \mu^+)} < 7.9 \cdot 10^{-5}$$

- CHORUS: $\mathcal{R} < 1.63 \cdot 10^{-4}$, NOMAD: $\mathcal{R} < 2.2 \cdot 10^{-4}$

Standard oscillation interference

As an example, non-unitarity with $\varepsilon_{\mu\tau} = 10^{-3}$ ($\sim$ upper bound)

Oscillation probability



CP-violation could be observable through interference term

See also Fernandez-Martinez et al., PLB 649 (2007) 427

Probability constraints

- Must consider coherent sum of all possible processes including both source and detector

Beam (channel)	$2L2Q$	$4L$	NU
π $(\mu \to \tau)$	$7.9 \cdot 10^{-5}$	n/a	$4.4 \cdot 10^{-6}$
β $(e \to \tau)$	$< 10^{-6}$	n/a	$1.0 \cdot 10^{-5}$
μ $(\mu \to \tau)$	$< 10^{-6}$	$1.0 \cdot 10^{-3}$ $(3.2 \cdot 10^{-5})$	$4.4 \cdot 10^{-6}$
μ $(e \to \tau)$	$< 10^{-6}$	$1.0 \cdot 10^{-3}$ $(3.2 \cdot 10^{-5})$	$1.0 \cdot 10^{-5}$

Langacker, London, PRD 38 (1988) 886
Langacker, London, PRD 38 (1988) 907
Nardi, Roulet, Tommasini, PLB 327 (1994) 319
Tommasini et al., NPB 444 (1995) 451
Antusch et al., JHEP 10 (2006) 084
Antusch, Baumann, Fernandez-Martinez, NPB 810 (2009) 369

Summary

- We have derived bounds on $2Q2L$ operators
- We have discussed why a near τ detector would be good in the search for new physics
- We have seen that generally the sensitivity to flavor change probability would have to be $\mathcal{O}(10^{-6})$ in order to compete with current bounds
- The exception is when the neutrinos are produced through charged pion decay (chiral enhancement)