Gluonic Operators and Lepton Flavor Violation at the LHC

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Introduction

Non-zero neutrino masses and mixing are now well-established.

- However, processes that violate charged lepton number in the SM are still suppressed by powers of m_ν^2/m_W^2.
- Experiments should be extremely sensitive to BSM physics with CLFV.

Observation of lepton flavor non-universality at LHCb, BaBar, and Belle in measurements of $R_{K^{(\star)}}$ and $R_{D^{(\star)}}$ have renewed interest in this sector.

- CLFV is predicted in many models that resolve these anomalies.

Introduction

If particles mediating CLFV are beyond the direct reach of the LHC, can still study the effects through EFT.

Lowest dimension CLFV operators appear at dim-6.
Gluon-mediated CLFV first appears at dim-8.

Questions for this study:

- Can the large parton luminosity of gluons at the LHC overcome the increased power suppression?
- Dim-6 operators participate in gluon fusion processes through SM quark loops. What can this tell us?

Dimension 8 Gluonic Operators

SM-invariant operators coupling gluons to leptons first appear at dim-8:

$$\mathcal{L}_{\text{eff}}^{(8)} \supset \frac{g_s^2}{\Lambda^4}\left[Y_{ij}\overline{L}_L^i H \ell_R^j G_{\mu\nu}^a G^{a\,\mu\nu} + \widetilde{Y}_{ij}\overline{L}_L^i H \ell_R^j G_{\mu\nu}^a \widetilde{G}^{a\,\mu\nu}\right] + \text{H.c.}$$

After EW symmetry breaking, these operators include:

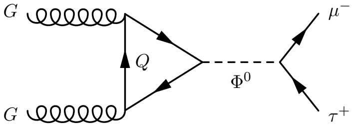
$$\mathcal{L}_{\text{eff}}^{(8)} \supset \frac{v g_s^2}{\sqrt{2}\Lambda^4}\left[y_{ij}\overline{\ell}_L^i \ell_R^j G_{\mu\nu}^a G^{a\,\mu\nu} + \widetilde{y}_{ij}\overline{\ell}_L^i \ell_R^j G_{\mu\nu}^a \widetilde{G}^{a\,\mu\nu}\right] + \text{H.c.}$$

For definitiveness, we will study μ-τ mixing.

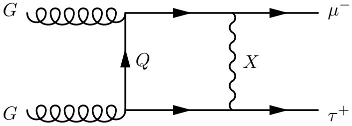
Dimension 8 Gluonic Operators

Example UV theories generating these operators:

- 2HDM without NFC



- Leptoquark



Note: scaling of these operators is not universal!

- One Scale: $Q \sim \Phi^0/X \sim \Lambda$, $\mathcal{M} \propto (16\pi^2\Lambda^4/v)^{-1}$.
- Two Scales: $Q \sim m_q$, $\Phi^0/X \sim \Lambda$, $\mathcal{M} \propto (16\pi^2 m_q \Lambda^2)^{-1}$.

(We'll come back to this later.)

Dimension 8 Gluonic Operators

For this study, we do not consider the effects of possible *CP*-violation. Therefore, we will assume the coefficients are real.

For the sake of model independence, introduce dimension-full Wilson coefficients:

$$\mathcal{L}_{\rm eff}^{(8)} \supset \sum_{i=1}^{4} \mathcal{C}_i^{\mu\tau} \mathcal{O}_i^{\mu\tau} + \text{H.c.}\,,$$

$$\begin{aligned} \mathcal{O}_1^{\mu\tau} &= (\overline{\mu}_L \tau_R)\; G^a_{\mu\nu} G^{a\,\mu\nu}\,, & \mathcal{O}_2^{\mu\tau} &= (\overline{\mu}_L \tau_R)\; G^a_{\mu\nu} \widetilde{G}^{a\,\mu\nu}\,, \\ \mathcal{O}_3^{\mu\tau} &= (\overline{\mu}_R \tau_L)\; G^a_{\mu\nu} G^{a\,\mu\nu}\,, & \mathcal{O}_4^{\mu\tau} &= (\overline{\mu}_R \tau_L)\; G^a_{\mu\nu} \widetilde{G}^{a\,\mu\nu}\,. \end{aligned}$$

LHC Constraints

τ decays promptly, search for μ-e final state.

Backgrounds:

- W^+W^- pair production,
- $Z/\gamma^* \to \tau\tau$,
- $\bar{t}t$ pair production.

Event selection:

Han, Lewis, and Sher [arXiv:1001.0022, JHEP 03 (2010) 090]

- $p_{\mathrm{T}}^{\mu,e} > 20$ GeV, $|\eta^{\mu,e}| < 2.5$, jet veto,
- $\delta\phi(p_{\mathrm{T}}^{\mu}, p_{\mathrm{T}}^{e}) > 2.5$, $\delta\phi(p_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{e}) < 0.6$, $p_{\mathrm{T}}^{\mu} - p_{\mathrm{T}}^{e} > 0$,
- $M_{\mu\tau} > 250$ GeV.

LHC Constraints

Benchmark: $C_i^{\mu\tau} = 4\pi v g_s^2/\sqrt{2}\Lambda^4\,,\ \ \Lambda = 2\ \text{TeV}\,.$

σ (pb)	No cuts	+ Detector	$+\ \delta\phi,\ \Delta p_{\rm T}$	$+\ M_{\mu\tau}$
$WW(\mu\tau)$	1.6	0.024	0.0044	0.0015
$WW(\mu e)$	1.6	0.35	0.014	0.0044
$Z/\gamma^*(\tau\tau)$	2400	1.7	0.26	0.00083
$tt(\mu\tau)$	12	0.043	0.0045	0.0019
$tt(\mu e)$	12	0.53	0.015	0.0081
$\mathcal{O}_i^{\mu\tau}$	0.89	0.030	0.028	0.028

Single operator dominance hypothesis (estimation of scale).

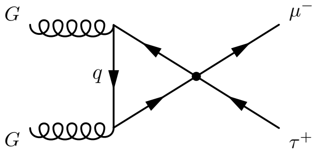
With 100 fb^{-1} integrated luminosity we can expect:

$$\left(\mathcal{C}_i^{\mu\tau}\right)_{2\sigma} \approx (3300\ \text{GeV})^{-3}\,, \qquad \Longrightarrow \qquad \Lambda_{2\sigma} \approx 3000\ \text{GeV}\,,$$
$$\left(\mathcal{C}_i^{\mu\tau}\right)_{5\sigma} \approx (2900\ \text{GeV})^{-3}\,, \qquad \Longrightarrow \qquad \Lambda_{5\sigma} \approx 2800\ \text{GeV}\,.$$

Dimension 6 Operators

As mentioned earlier, these gluonic operators can be produced in a variety of ways.

SM quark loop-induced from dim-6 $\overline{q}q\,\mu\tau$ operators:



$$\mathcal{L}^{(6)}_{\mu\tau} \supset \frac{1}{\Lambda^2}\sum_{i=1}^{4} C_i^{q\mu\tau}\mathcal{O}_i^{q\mu\tau} + \mathrm{H.c.}\,,$$

$$\mathcal{O}_1^{q\mu\tau} = (\overline{\mu}_L\tau_R)(\overline{q}_L q_R)\,, \qquad \mathcal{O}_2^{q\mu\tau} = (\overline{\mu}_L\tau_R)(\overline{q}_R q_L)\,,$$
$$\mathcal{O}_3^{q\mu\tau} = (\overline{\mu}_R\tau_L)(\overline{q}_L q_R)\,, \qquad \mathcal{O}_4^{q\mu\tau} = (\overline{\mu}_R\tau_L)(\overline{q}_R q_L)\,.$$

Dimension 6 Operators

Matching to the dim-8 operators:

$$\mathcal{C}_{1,3}^{\mu\tau} = \frac{g_s^2}{16\pi^2}\frac{F_1(x)}{\Lambda^2 m_q}\left[C_{1,3}^{q\mu\tau} + C_{2,4}^{q\mu\tau}\right]_{C_{1,3}^{q\mu\tau}=C_{2,4}^{q\mu\tau}} ,$$

$$\mathcal{C}_{2,4}^{\mu\tau} = \frac{ig_s^2}{16\pi^2}\frac{F_2(x)}{\Lambda^2 m_q}\left[C_{1,3}^{q\mu\tau} - C_{2,4}^{q\mu\tau}\right]_{C_{1,3}^{q\mu\tau}=-C_{2,4}^{q\mu\tau}} ,$$

with form factors

$$F_1(x) = -\frac{x}{2}\left[4 + (4x-1)\ln^2\left(1 - \frac{1}{2x} + \frac{\sqrt{1-4x}}{2x}\right)\right] ,$$

$$F_2(x) = \frac{x}{2}\ln^2\left(1 - \frac{1}{2x} + \frac{\sqrt{1-4x}}{2x}\right) ,$$

where $x \equiv m_q^2/\hat{s}$.

Dimension 6 Operators

$$m_q^2 \ll \hat{s} \;\; \rightarrow \;\; F_i(x) \propto m_q^2/\hat{s} \quad \text{and} \quad C_i^{\mu\tau} \propto m_q.$$

Most sensitive to the heaviest quark in the loop.

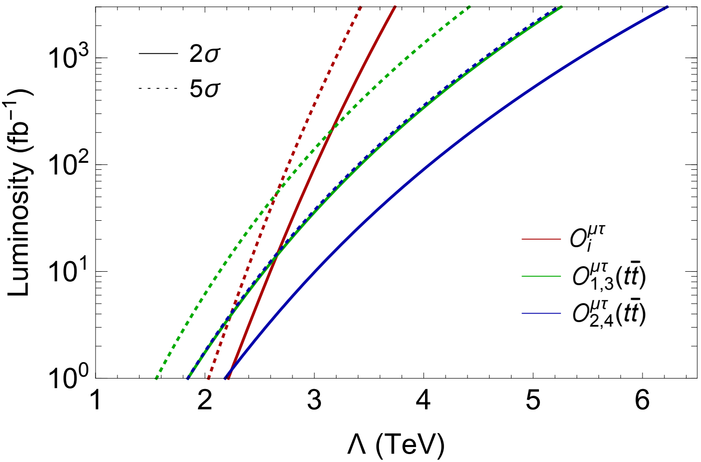
For $|C_i^{t\mu\tau}| = 4\pi$, $L = 100\ \mathrm{fb}^{-1}$, the constraint on the NP scale Λ of $\bar{t}t\,\mu\tau$ operators due to this gluon fusion mechanism is estimated to be:

$$\Lambda_{2\sigma}^{GG} \approx 3400\ \mathrm{GeV} \qquad \Lambda_{2\sigma}^{G\widetilde{G}} \approx 4100\ \mathrm{GeV}$$
$$\Lambda_{5\sigma}^{GG} \approx 2900\ \mathrm{GeV} \qquad \Lambda_{5\sigma}^{G\widetilde{G}} \approx 3400\ \mathrm{GeV}$$

For models that preferentially couple LFV to top quarks, this mechanism can be competitive with direct production from lighter quarks.

Luminosity Scaling

Constraints as a function of luminosity with the benchmarks $|y_{\mu\tau}| = |\widetilde{y}_{\mu\tau}| = 4\pi$ and $|C_i^{t\mu\tau}| = 4\pi$.



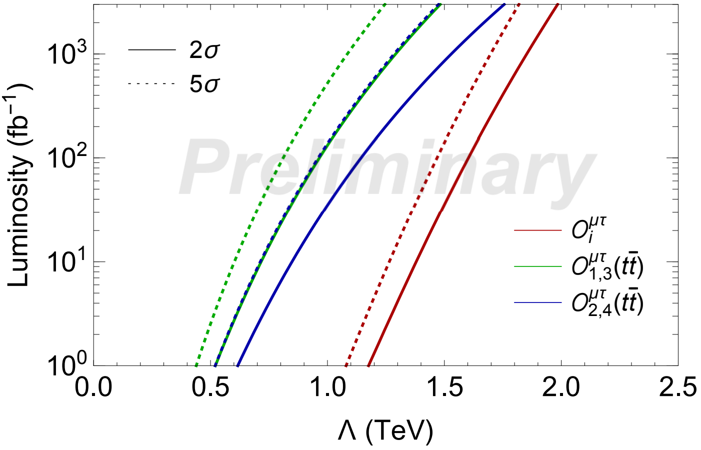
Conclusions

- Constraints on the scale of dimension-8 $GG\,\mu\tau$ operators can be placed at $\sim 3\ \mathrm{TeV}$ with 100 fb^{-1} of data.
  - However, scaling is not favorable with more data, as the operators scale as Λ^{-4}.
- Constraints on the scale of dimension-6 $\bar{t}t\,\mu\tau$ operators can be placed at $\sim 3-4\ \mathrm{TeV}$ from loop-induced gluon fusion.
  - Can be probed further with more data, as the operators scale as Λ^{-2}.
  - May be a significant mechanism for probing CLFV in models with enhanced top-quark couplings relative to lighter quarks.
- Still more work can be done: detailed analysis, CP-violation, and global fits without SOD.

Backup Slides

Rescaled Constraints

Constraints as a function of luminosity with the benchmarks $|y_{\mu\tau}| = |\widetilde{y}_{\mu\tau}| = 1$ and $|C_i^{t\mu\tau}| = 1$.



Low Energy Constraints

τ decay constraints on gluonic operators.

Converted to constraints on Λ from $C_i^{\mu\tau} = 4\pi v g_s^2/\sqrt{2}\Lambda^4$ from: Petrov and Zhuridov [arXiv:1403.5781, PRD89 (2014) 095014]

$$\mathcal{B}(\tau \to \mu\pi^+\pi^-) < 2.1 \times 10^{-8} \quad \Longrightarrow \quad \Lambda^{GG} \approx 1000 \text{ GeV},$$
$$\mathcal{B}(\tau \to \mu K^+K^-) < 4.4 \times 10^{-8} \quad \Longrightarrow \quad \Lambda^{GG} \approx 950 \text{ GeV},$$

$$\mathcal{B}(\tau \to \mu\eta) < 1.3 \times 10^{-7} \quad \Longrightarrow \quad \Lambda^{G\widetilde{G}} \approx 830 \text{ GeV},$$
$$\mathcal{B}(\tau \to \mu\eta') < 1.3 \times 10^{-7} \quad \Longrightarrow \quad \Lambda^{G\widetilde{G}} \approx 760 \text{ GeV}.$$