Simulation of observed quantities in lepton flavour violation processes in proton-proton collisions

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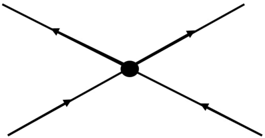
Effective field theory

The process under study:

$$pp \to q\bar{q} \to \mu^{\pm}\tau^{\mp}$$



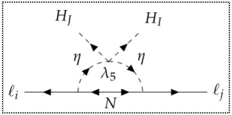
$$\mathfrak{L}_{eff} \sim \sum_{\alpha}\sum_{ijkl}\frac{C_{\alpha}^{ijkl}}{\nu^2}\mathfrak{O}_{\alpha}^{ijkl}. \qquad (1)$$

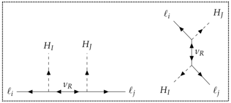
$\nu = (\sqrt{2}G_f)^{-1/2}$ – vacuum expectation value (for the Higgs field $\nu = 246.22GeV$)

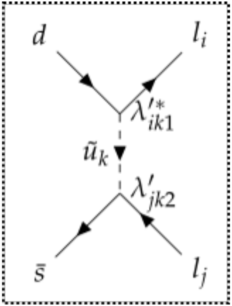
$\mathfrak{O}^{ijkl}$ –semileptonic operators

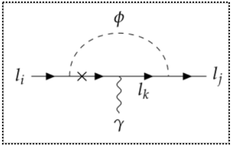
C^{ijkl}– effective coefficients

BSM processes (Ardu and Pezzullo, “Introduction to Charged Lepton Flavor Violation”)

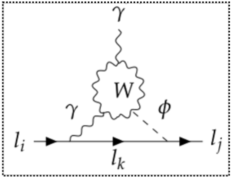


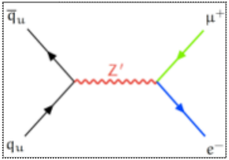


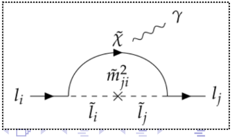




- SUSY
- QBH
- Two Higgs doublet model







Introduction

Table: Operators $\mathfrak{O}_{\alpha}^{ijkl}$, appearing in eq.(1) (Angelescu, Faroughy, and Sumensari, “Lepton flavor violation and dilepton tails at the LHC”)

Eff. coefficients	Operator $\mathfrak{O}_{\alpha}^{ijkl}$	Explicit form of $\mathfrak{O}_{\alpha}^{ijkl}$
$C_{V_{LL}}^{ijkl} = C_1$	$\mathfrak{O}_{V_{LL}}^{ijkl}$	$(\tilde{q}_{Li}\gamma_\mu q_{Lj})(\tilde{l}_{Lk}\gamma^\mu l_{Ll})$
$C_{V_{RR}}^{ijkl} = C_2$	$\mathfrak{O}_{V_{RR}}^{ijkl}$	$(\tilde{q}_{Ri}\gamma_\mu q_{Rj})(\tilde{l}_{Rk}\gamma^\mu l_{Rl})$
$C_{V_{LR}}^{ijkl} = C_3$	$\mathfrak{O}_{V_{LR}}^{ijkl}$	$(\tilde{q}_{Li}\gamma_\mu q_{Lj})(\tilde{l}_{Rk}\gamma^\mu l_{Rl})$
$C_{V_{RL}}^{ijkl} = C_4$	$\mathfrak{O}_{V_{RL}}^{ijkl}$	$(\tilde{q}_{Ri}\gamma_\mu q_{Rj})(\tilde{l}_{Lk}\gamma^\mu l_{Ll})$
$C_{S_R}^{ijkl} = C_5$	$\mathfrak{O}_{S_R}^{ijkl}$	$(\tilde{q}_{Ri} q_{Lj})(\tilde{l}_{Lk} l_{Rl}) + h.c.$
$C_{S_L}^{ijkl} = C_6$	$\mathfrak{O}_{S_L}^{ijkl}$	$(\tilde{q}_{Li} q_{Rj})(\tilde{l}_{Lk} l_{Rl}) + h.c.$
$C_{T}^{ijkl} = C_7$	$\mathfrak{O}_{T}^{ijkl}$	$(\tilde{q}_{Li}\sigma_{\mu\nu} q_{Rj})(\tilde{l}_{Lk}\sigma^{\mu\nu} l_{Rl}) + h.c.$

Table: Eff. coefficients in eq. (1) (Angelescu, Faroughy, and Sumensari, “Lepton flavor violation and dilepton tails at the LHC”)

Eff.coefficient $C_{eff}(\times 10^3)$	$\mu\tau$
$u\bar{u}$	3.0 (0.7)
$d\bar{d}$	4.5 (1.2)

Matrix elements

$$M_1 = C_1 \overline{u}_L^{\tau} \gamma_\nu u_L^{\mu} \frac{1}{\nu^2} \overline{u}_L^{q_1} \gamma^\nu u_L^{q_2} \quad (2)$$

$$M_2 = C_2 \overline{u}_R^{\tau} \gamma_\nu u_R^{\mu} \frac{1}{\nu^2} \overline{u}_R^{q_1} \gamma^\nu u_R^{q_2} \quad (3)$$

$$M_3 = C_3 \overline{u}_R^{\tau} \gamma_\nu u_R^{\mu} \frac{1}{\nu^2} \overline{u}_L^{q_1} \gamma^\nu u_L^{q_2} \quad (4)$$

$$M_4 = C_4 \overline{u}_L^{\tau} \gamma_\nu u_L^{\mu} \frac{1}{\nu^2} \overline{u}_R^{q_1} \gamma^\nu u_R^{q_2} \quad (5)$$

$$M_5 = C_5 \, \overline{u}_L^{\tau} \, u_R^{\mu} \frac{1}{\nu^2} \overline{u}_R^{q_1} \, u_L^{q_2} \quad (6)$$

$$M_6 = C_6 \, \overline{u}_L^{\tau} \, u_R^{\mu} \frac{1}{\nu^2} \overline{u}_L^{q_1} \, u_R^{q_2} \quad (7)$$

$$M_7 = C_7 \, \overline{u}_L^{\tau} \sigma_{\kappa\theta} \, u_R^{\mu} \frac{1}{\nu^2} \overline{u}_R^{q_1} \sigma^{\kappa\theta} \, u_L^{q_2} \quad (8)$$

Square of matrix elements

$$|M_1|^2 = 4\frac{|C_1|^2}{\nu^4}(p_\tau \cdot p_1)(p_\mu \cdot p_2) \approx \frac{4|C_1|^2}{\nu^4}(\frac{m^2 - \hat{t}}{2})(-\frac{\hat{t}}{2}). \quad (9)$$

$$|M_2|^2 = 4\frac{|C_2|^2}{\nu^4}(p_\tau \cdot p_1)(p_\mu \cdot p_2) \approx \frac{4|C_1|^2}{\nu^4}(\frac{m^2 - \hat{t}}{2})(-\frac{\hat{t}}{2}). \quad (10)$$

$$|M_3|^2 = 4\frac{|C_3|^2}{\nu^4}(p_\mu \cdot p_1)(p_\tau \cdot p_2) \approx 4\frac{|C_4|^2}{\nu^4}(\frac{m^2 - \hat{u}}{2})(-\frac{\hat{u}}{2}). \quad (11)$$

$$|M_4|^2 = 4\frac{|C_4|^2}{\nu^4}(p_\mu \cdot p_1)(p_\tau \cdot p_2) \approx 4\frac{|C_4|^2}{\nu^4}(\frac{m^2 - \hat{u}}{2})(-\frac{\hat{u}}{2}). \quad (12)$$

$$|M_5|^2 = 4\frac{|C_5|^2}{\nu^4}(p_\mu \cdot p_\tau)(p_1 \cdot p_2) \approx 4\frac{|C_5|^2}{\nu^4}(\frac{\hat{s} - m^2}{2})\frac{\hat{s}}{2}. \quad (13)$$

$$|M_6|^2 = 4\frac{|C_6|^2}{\nu^4}(p_\mu \cdot p_\tau)(p_1 \cdot p_2) \approx 4\frac{|C_6|^2}{\nu^4}(\frac{\hat{s} - m^2}{2})\frac{\hat{s}}{2}. \quad (14)$$

$$|M_7|^2 = 32|C_7|^2\frac{(\hat{s} + 2\hat{t})^2 - m^2(\hat{s} + 4\hat{t})}{\nu^4} \quad (15)$$

Total square of matrix element

$$|M|^2 = \frac{4}{\nu^4}((|C_1|^2+|C_2|^2)(\frac{m^2-\hat{t}}{2})(-\frac{\hat{t}}{2})+(|C_3|^2+|C_4|^2)(\frac{m^2-\hat{u}}{2})(-\frac{\hat{u}}{2})+ \\ + (|C_5|^2+|C_6|^2)(\frac{\hat{s}-m^2}{2})\frac{\hat{s}}{2}+8|C_7|^2((\hat{s}+2\hat{t})^2-m^2(\hat{s}+4\hat{t}))- \\ -2Re[C_6C_7^\dagger](-m^2\hat{s}+\hat{s}^2+2\hat{t}\hat{s})) \quad (16)$$

Differential cross-section

$$\frac{d\sigma}{d\hat{t}} = \frac{\hat{s}-m_\tau^2}{128\pi\nu^4\hat{s}^2}\Big((|C_1|^2+|C_2|^2)(1-cos\theta)(2m_\tau^2+(\hat{s}-m_\tau^2)(1-cos\theta))+$$
$$+(|C_3|^2+|C_4|^2)(1+cos\theta)(2m_\tau^2+(\hat{s}-m_\tau^2)(1+cos\theta))-$$
$$128|C_7|^2(\hat{s}-(\hat{s}-m_\tau^2)(1-cos\theta))^2-m_\tau^2(\hat{s}-2(\hat{s}-m_\tau^2)(1-cos\theta))\Big)+$$
$$+\frac{\hat{s}(\hat{s}-m_\tau^2)}{32\pi\nu^4\hat{s}^2}\Big((|C_5|^2+|C_6|^2)+8Re[C_6C_7^\dagger]cos\theta\Big). \quad (17)$$

MC simulation of the process

- PYTHIA (ISR, FSR, PDFs);
- FOAM ROOT
- MATGRAPH

$$\sigma = \iint_0^1 \hat{\sigma}(x_1, x_2) f(x_1) f(x_2) dx_1 dx_2 =$$

$$= \iint_0^1 \hat{\sigma}(x_1, x_2) x_1 f(x_1) x_2 f(x_2) dln(x_1) dln(x_2) \quad (18)$$

$$\hat{\sigma} = \int \frac{|M|^2 \lambda(\hat{s}, m_\tau^2, m_\mu^2)}{64\pi^2 \hat{s}^2(x_1, x_2)} dcos\theta \quad (19)$$

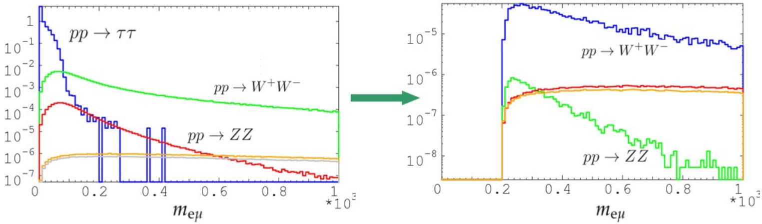
Event selection

Background processes:

- $pp \to WW \to \mu\tau$
- $pp \to ZZ \to \mu\tau$
- $qq \to \mu\tau$

- μ and τ are particles in the final state (don't decay);
- $\eta \leq 2.4\,rad$
- $p_t \geq 10\,GeV$

Figure: Dependence of the cross section σ on the invariant mass for different background processes



Event Selection

Table: Dependence of the number of events per 300 fb^{-1} on the introduced cuts

Cuts	$pp \to WW \to \mu\tau$	LFV(vec)	LFV(scalar)
no cuts	521500	1866.7740	2926.4858
$p_t(\mu^{\pm}\tau^{\mp}) > 10\,GeV$	453000	1854.8267	2911.5607
$\|\eta(\mu^{\pm}\tau^{\mp})\| < 2.4\,rad$	263500	1779.4090	2826.4000
$p_t(\mu^{\pm}\tau^{\mp}) < 30\,GeV$	79230	744.6562	1206.0048
$\varphi(\mu^{\pm}\tau^{\mp}) > 3.0\,rad$	19210	675.0255	1098.6028
$m_{inv}(\mu^{\pm}\tau^{\mp}) > 200\,GeV$	3683	612.4886	988.2743

MC simulation of the process. Results

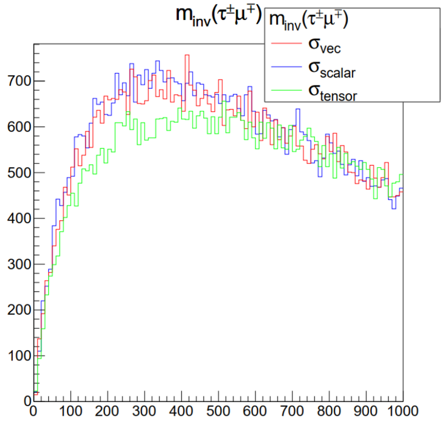


Figure: Dependence of the cross section σ on the invariant mass m_{inv} of a pair of leptons for scalar, vector and tensor signals

MC simulation of the process. Results

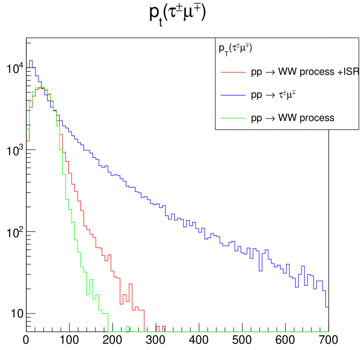


Figure: Dependence of the cross section σ on the total transverse momentum of a pair of leptons (logarithmic scale)

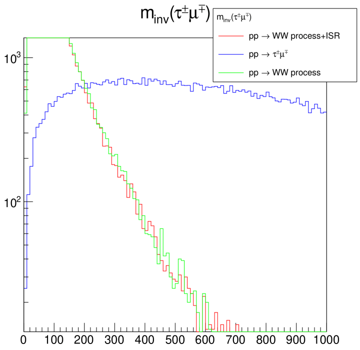


Figure: Dependence of the cross section σ n the invariant mass m_{inv} of a pair of leptons (logarithmic scale)

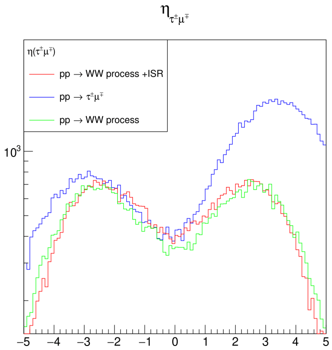


Figure: Dependence of the cross section σ on the pseudorapidity of a pair of leptons (logarithmic scale)

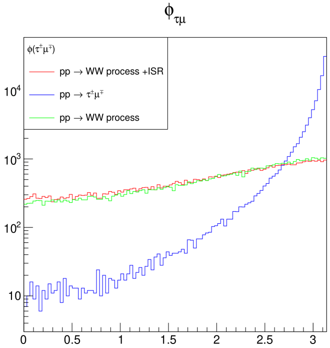
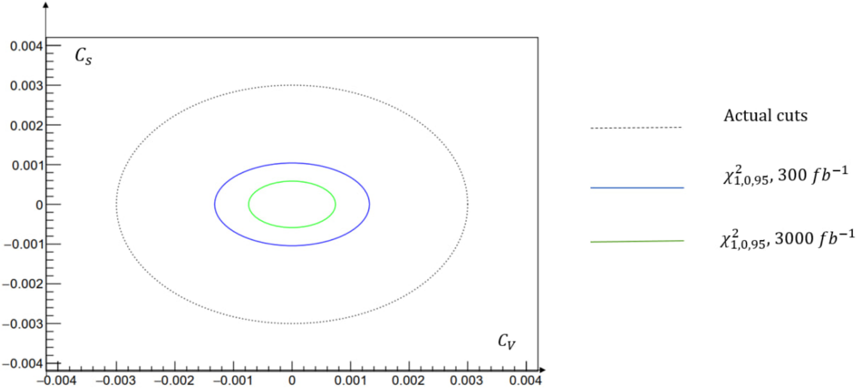


Figure: Dependence of the cross section σ on the azimuth angle (logarithmic scale)

LFV-constants

Figure: Estimation of achievable constraints on the anomalous interaction constants by the χ^2 method

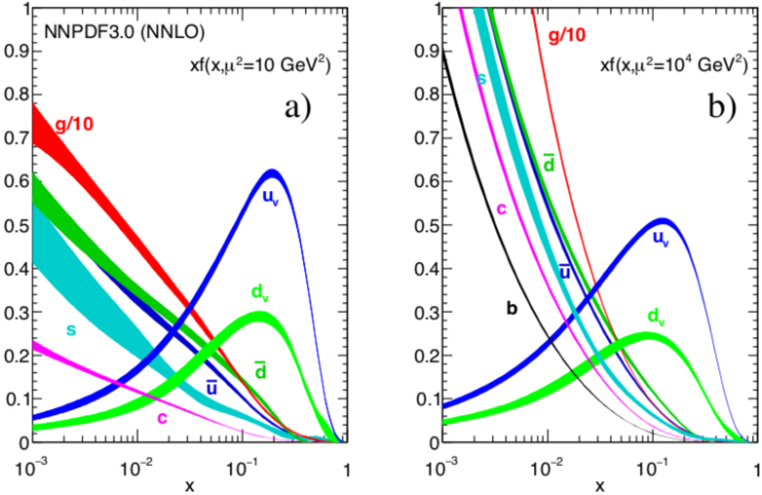


Conclusions

- A MC event generator was created to simulate signal process.
- It was determined that the main contribution to the background is the $pp \to WW \to \mu\tau +$ cancelled MET. Other backgrounds are negligible.
- Using the PYTHIA program for this background process, analysis of signal and background was performed.
- The event selection procedure was proposed for the LFV in $pp \to \mu\tau$ process in the CMS experiment.
- The limit for LFV-constants will be improved at full Run-3.

Thanks for your attention!

Additional slides



Constants (Angelescu, Faroughy, and Sumensari, “Lepton flavor violation and dilepton tails at the LHC”)

$$\mathfrak{B}(\tau^- \to \phi l_l^-) \Longrightarrow \begin{cases} |C_{uu}^{e\tau} + C_{dd}^{e\tau}| < 2 \times 10^{-3} & |C_{ds}^{e\tau}| < 7 \times 10^{-4} \\ |C_{uu}^{\mu\tau} + C_{dd}^{\mu\tau}| < 2 \times 10^{-3} & |C_{ds}^{\mu\tau}| < 10^{-3} \end{cases}$$

$$\mathfrak{B}(B \to K\mu^+ e^-) \Longrightarrow \begin{cases} \sqrt{|C_{sb}^{e\tau}|^2 + |C_{sb}^{\tau e}|^2} < 5 \times 10^{-3} \\ \sqrt{|C_{sb}^{\mu\tau}|^2 + C_{sb}^{\tau\mu}|^2} < 5 \times 10^{-3} \end{cases}$$

$$\mathfrak{B}(B_s \to l_k^{\pm} l_l^{\mp}) \Longrightarrow |C_{sd}^{e\mu}| < 7 \times 10^{-5}, {}^{:} |C_{sd}^{\mu e}| < 5 \times 10^{-5},$$

$$\mathfrak{B}(\mu \to e, N) \Longrightarrow |C_{uu}^{\mu e}| < 1.7 \times 10^{-7}, {}^{:} |C_{dd}^{\mu e}| < 1.5 \times 10^{-7},$$

Experiments

(Ardu and Pezzullo, "Introduction to Charged Lepton Flavor Violation")

$J/\psi \to \mu e$	BESIII	1.5×10^{-7}
$J/\psi \to \tau e$	BESIII	7.5×10^{-8}
$J/\psi \to \tau\mu$	BESII	2.6×10^{-6}
$B^0 \to \mu e$	LHCb	2.8×10^{-9}
$B^0 \to \tau e$	BaBar	2.8×10^{-5}
$B^0 \to \tau\mu$	LHCb	1.4×10^{-5}
$B \to K\mu e$	BaBar	3.8×10^{-8}
$B \to K^*\mu e$	BaBar	5.1×10^{-7}
$B^+ \to K^+\tau e$	BaBar	4.8×10^{-5}
$B^+ \to K^+\tau\mu$	BaBar	3.0×10^{-5}
$B_s^0 \to \mu e$	LHCb	1.1×10^{-8}
$B_s^0 \to \tau\mu$	LHCb	4.2×10^{-5}

$Z^0 \to \mu e$	ATLAS	7.5×10^{-7}
$Z^0 \to \tau e$	OPAL	9.8×10^{-6}
$Z^0 \to \tau\mu$	DELPHI	1.2×10^{-5}
$h \to \mu e$	ATLAS	6.1×10^{-5}
$h \to \tau e$	CMS	2.2×10^{-3}
$h \to \tau\mu$	CMS	1.5×10^{-3}

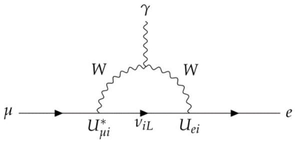
Experiments

(Ardu and Pezzullo, “Introduction to Charged Lepton Flavor Violation”)

$\mu^+ \to e^+\gamma$	MEG	4.2×10^{-13}
$\mu^\pm \to e^\pm e^- e^+$	SINDRUM	1.0×10^{-12}
$\mu^- \mathrm{N} \to e^- \mathrm{N}$	SINDRUM-II	$6.1(7.1) \times 10^{-13}$ Ti (Au)
$\mu^- \mathrm{N} \to e^+ \mathrm{N}'$	SINDRUM-II	5.7×10^{-13}
$\tau\pm \to e^\pm\gamma$	BaBar	3.3×10^{-8}
$\tau^\pm \to \mu^\pm\gamma$	BaBar	4.4×10^{-8}
$\tau \to eee$	Belle	2.7×10^{-8}
$\tau \to \mu\mu\mu$	Belle	2.1×10^{-8}
$\tau \to \mu ee$	Belle	1.8×10^{-8}
$\tau \to e\mu\mu$	Belle	2.7×10^{-8}

$\tau \to e\mu\mu$	Belle	2.7×10^{-8}
$\tau \to \pi^0 e$	Belle	8.0×10^{-8}
$\tau \to \pi^0 \mu$	BaBar	1.1×10^{-7}
$\tau \to \eta e$	Belle	9.2×10^{-8}
$\tau \to \eta \mu$	Belle	6.5×10^{-8}
$\tau \to \rho^0 e$	Belle	1.8×10^{-8}
$\tau \to \rho^0 \mu$	Belle	1.2×10^{-8}
$\pi^0 \to \mu e$	KTeV	3.6×10^{-10}
$K_L^0 \to \pi^0 \mu^+ e^-$	kTeV	7.6×10^{-11}
$K_L^0 \to \mu e$	BNL E871	4.7×10^{-12}
$K^+ \to \pi^+ \mu^+ e^-$	BNL E865	1.3×10^{-11}

SM (Ardu and Pezzullo, “Introduction to Charged Lepton Flavor Violation”)



$$\mathfrak{L}_W = -\frac{g}{\sqrt{2}} W_\alpha^+ \sum U_{ij} e_{iL} \gamma^\alpha \nu_{jL} + h.c.$$

where $i = e, \mu, \tau; j = 1, 2, 3$

$$\mathfrak{B}(\mu \to e\gamma) = 10^{-54} - 10^{-55}$$

Pontecorvo-Maki-Nakagawa-Sakata matrix:

$$U_{PMNS} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times P$$

SMEFT: Bruggisser et al., “The flavor of UV physics”

- Angelescu, Andrei, Darius A. Faroughy, and Olcyr Sumensari. "Lepton flavor violation and dilepton tails at the LHC". In: *The European Physical Journal C* 80.7 (July 2020). DOI: 10.1140/epjc/s10052-020-8210-5. URL: https://doi.org/10.1140%2Fepjc%2Fs10052-020-8210-5.
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