Lepton and Baryon number violating tau decays

Workshop on Tau Charm at High Luminosity

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Brief history of leptonic physics

$$-\mathcal{L}_{\text{lep}} = (h_e)_{ij}\bar{e}_{Ri}L_j\phi + \text{h.c.}$$

- Charged leptons massive
- neutrinos massless
- lepton flavour conserved
- total L number conserved

$$U(3)_{e_R} \times U(3)_L \longrightarrow U(1)_e \times U(1)_\mu \times U(1)_\tau$$

$$-\mathcal{L}_{\text{lep}} = (h_e)_{ij}\bar{e}_{Ri}L_j\phi + (h_\nu)_{ij}\bar{\nu}_{Ri}L_j\tilde{\phi} + \text{h.c.}$$

$U(3)_{e_R} \times U(3)_L \longrightarrow U(1)_{\text{lep}}$ Dirac Mass

$$-\mathcal{L}_{\text{lep}} = (h_e)_{ij}\bar{e}_{Ri}L_j\phi + \frac{(\alpha_\nu)_{ij}}{\Lambda}L_i\tilde{\phi}L_j\tilde{\phi} + \text{h.c.}$$

$U(3)_{e_R} \times U(3)_L \longrightarrow \text{nothing}$ Majorana Mass

- Charged leptons massive
- neutrinos massive
- lepton flavour violated – ν oscillations
- total L number conserved or violated

Too bad experimentalists have not found them yet !

$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U^{\star}_{\mu i} U_{ei} \frac{\Delta m^2_{i1}}{m^2_W} \right|^2 < 10^{-54}$$

$$\Delta m^2_{i1} \equiv (m^2_{\nu_i} - m^2_{\nu_1})$$

Is Lepton Flavour Voilation always releted to neutrino mass?

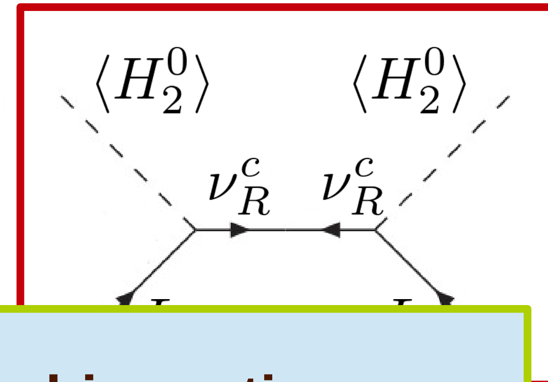
$$-\mathcal{L}_{\rm lep} = (h_e)_{ij} \bar{e}_{Ri} L_j \phi + \frac{(\alpha_\nu)_{ij}}{\Lambda} L_i \tilde{\phi} L_j \tilde{\phi} + \sum_k \frac{\alpha_k}{\Lambda_k^2} \mathcal{O}_k^{D=6} + \text{h.c.}$$

Lepton Number Violation **Lepton Flavour Violation**

- In general, Λ and Λ_k can be different
- For the same suppression Λ, the coefficients of the dimension 5 operator could be much smaller than those of the dimension 6 operators

Example : Type-I SeeSaw

$$W = W_0 - \frac{1}{2}\nu_R^{c\,T}\mathcal{M}\nu_R^c + \nu_R^{c\,T}\mathbf{Y}_\nu L\cdot H_2$$



$$W_{eff} = W_0 + \frac{1}{2}(\mathbf{Y}_\nu L\cdot H_2)^T\mathcal{M}^{-1}(\mathbf{Y}_\nu L\cdot H_2)$$

Model independent predictions for the LFV branching ratios are Not Possible even after having a complete knowledge of the entire neutrino mass matrix elements, as well as the heavy neutrino Majorana mass matrix eigenvalues.

$$D_{\mathcal{M}_\nu} = U^T Y_\nu^T D_{\sqrt{\mathcal{M}^{-1}}} D_{\sqrt{\mathcal{M}^{-1}}} Y_\nu U \langle H_2^0\rangle^2$$

$$[D_{\sqrt{\mathcal{M}^{-1}}} Y_\nu U D_{\sqrt{\mathcal{M}_\nu^{-1}}}\langle H_2^0\rangle]^T[D_{\sqrt{\mathcal{M}^{-1}}} Y_\nu U D_{\sqrt{\mathcal{M}_\nu^{-1}}}\langle H_2^0\rangle] = 1$$

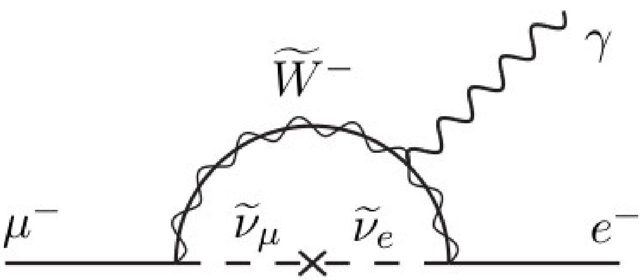
$$Y_\nu = \frac{1}{\langle H_2^0\rangle} D_{\sqrt{\mathcal{M}}} R D_{\sqrt{\mathcal{M}_\nu}} U^\dagger \qquad R^T R = 1$$

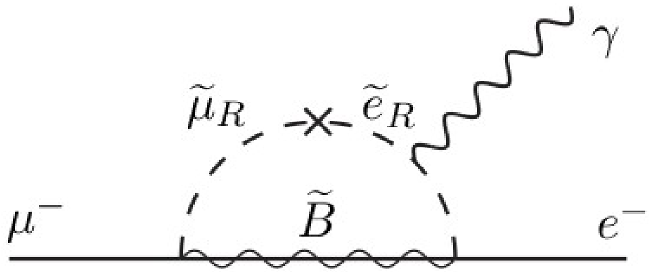
$$l_i \to l_j\gamma : (Y_\nu^\dagger Y_\nu)_{i,j}$$

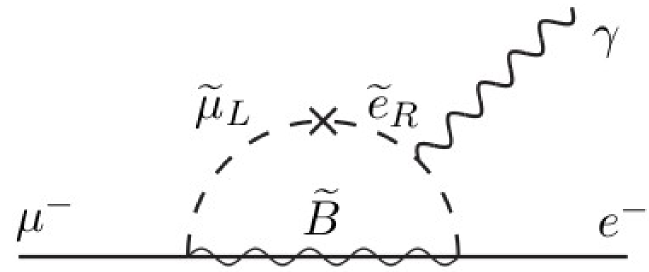
Casas and Ibarra, 2001

MSSM without Neutrino mass :

$$-\mathcal{L}^{\rm lep}_{\rm soft} \;=\; (\mathbf{m}^2_L)_{ij}\widetilde{L}^*_i\widetilde{L}_j \;+ (\mathbf{m}^2_e)_{ij}\widetilde{e}^*_{Ri}\widetilde{e}_{Rj} \;+ \Big(\mathbf{A}_{eij}\widetilde{e}^*_{Ri}\widetilde{L}_j H_d + \text{h.c.}\Big)$$





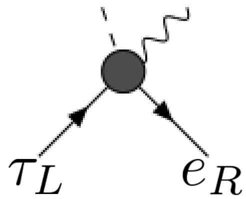


$$\text{Br}(\mu\to e\gamma) \;=\; \left(\frac{|m^2_{\tilde{\mu}^*_R\tilde{e}_R}|}{m^2_{\tilde{\ell}_R}}\right)^2 \left(\frac{100\text{ GeV}}{m_{\tilde{\ell}_R}}\right)^4 10^{-6}\times \begin{cases} 15 & \text{for } m_{\tilde{B}} \ll m_{\tilde{\ell}_R}, \\ 5.6 & \text{for } m_{\tilde{B}} = 0.5 m_{\tilde{\ell}_R}, \\ 1.4 & \text{for } m_{\tilde{B}} = m_{\tilde{\ell}_R}, \\ 0.13 & \text{for } m_{\tilde{B}} = 2 m_{\tilde{\ell}_R}, \end{cases}$$

A Supersymmetry Primer
Stephen P. Martin

Bounds on NP scale :

$$-\mathcal{L} \subset \frac{m_\tau}{\Lambda^2}\,\bar{\tau}\sigma_{\mu\nu}[F_M^{\tau e} + F_E^{\tau e}\gamma_5]e\; F^{\mu\nu}$$



$$BR(\tau \to e\gamma) = \frac{1}{\Gamma_\tau}\frac{m_\tau^3}{8\pi}\;\frac{m_\tau^2}{\Lambda^4}\;4[|F_M^{\tau e}|^2 + |F_E^{\tau e}|^2]$$

$$\Lambda^4 \gtrsim 1.2 \times 10^{11}\;\frac{|F^{\tau e}|^2}{BR_<}\mathrm{GeV}^4$$

$$BR_< \sim 10^{-7}\;,\;\; F^{\tau e} = 1\;,\;\; \Lambda \gtrsim 30 - 40\;\mathrm{TeV}$$

$$BR_< \sim 10^{-7}\;,\;\; F^{\tau e} = 0.1\;,\;\; \Lambda \gtrsim 300 - 400\;\mathrm{GeV}$$

Gauge Invariant dim-6 operators in the SM

	SO(3,1)	SU(3)	SU(2)	$U(1)_{\frac{Y}{2}}$
$L_i \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$(1/2,0)$	1	2	$-1/2$
E	$(0,1/2)$	1	1	-1
$Q_{i\,a} \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$(1/2,0)$	3	2	$1/6$
U_a	$(0,1/2)$	3	1	$2/3$
D_a	$(0,1/2)$	3	1	$-1/3$
H_i	$(0,0)$	1	2	$1/2$

4 Leptons

- $[\bar{L}^i_p \gamma_\mu L_{q\,i}]\,[\bar{L}^j_r \gamma^\mu L_{s\,j}]$
- $[\bar{E}_p \gamma_\mu E_q]\,[\bar{E}_r \gamma^\mu E_s]$
- $[\bar{L}_p \gamma_\mu L_q]\,[\bar{E}_r \gamma^\mu E_s]$

2 Leptons + 2 quarks

- $[\bar{L}_p \gamma_\mu L_q]\,[\bar{Q}_r \gamma^\mu Q_s]$
- $[\bar{L}_p \sigma^I \gamma_\mu L_q]\,[\bar{Q}_r \sigma^I \gamma^\mu Q_s]$
- $[\bar{L}_p \gamma_\mu L_q]\,[\bar{U}_r \gamma^\mu U_s]$
- $[\bar{L}_p \gamma_\mu L_q]\,[\bar{D}_r \gamma^\mu D_s]$
- $[\bar{E}_p \gamma_\mu E_q]\,[\bar{Q}_r \gamma^\mu Q_s]$
- $[\bar{E}_p \gamma_\mu E_q]\,[\bar{U}_r \gamma^\mu U_s]$
- $[\bar{E}_p \gamma_\mu E_q]\,[\bar{D}_r \gamma^\mu D_s]$
- $[\bar{L}_p E_q]\,[\bar{D}_r Q_s]$
- $[\bar{L}^i_p E_q]\epsilon_{ij}[\bar{Q}^j_r U_s]$
- $[\bar{L}^i_p \sigma_{\mu\nu} E_q]\epsilon_{ij}[\bar{Q}^j_r \sigma^{\mu\nu} U_s]$

2 Leptons + Gauge bosons

- $[\bar{L}_p \sigma_{\mu\nu} E_q H]\; B^{\mu\nu}$
- $[\bar{L}_p \sigma_{\mu\nu} E_q \sigma^I H]\; W^{I\,\mu\nu}$
- $[\bar{L}_p \gamma_\mu L_q]\;[H^\dagger D^\mu H]$
- $[\bar{L}_p \sigma^I \gamma_\mu L_q]\;[H^\dagger \sigma^I D^\mu H]$
- $[\bar{E}_p \gamma_\mu E_q]\;[H^\dagger D^\mu H]$

dim-8

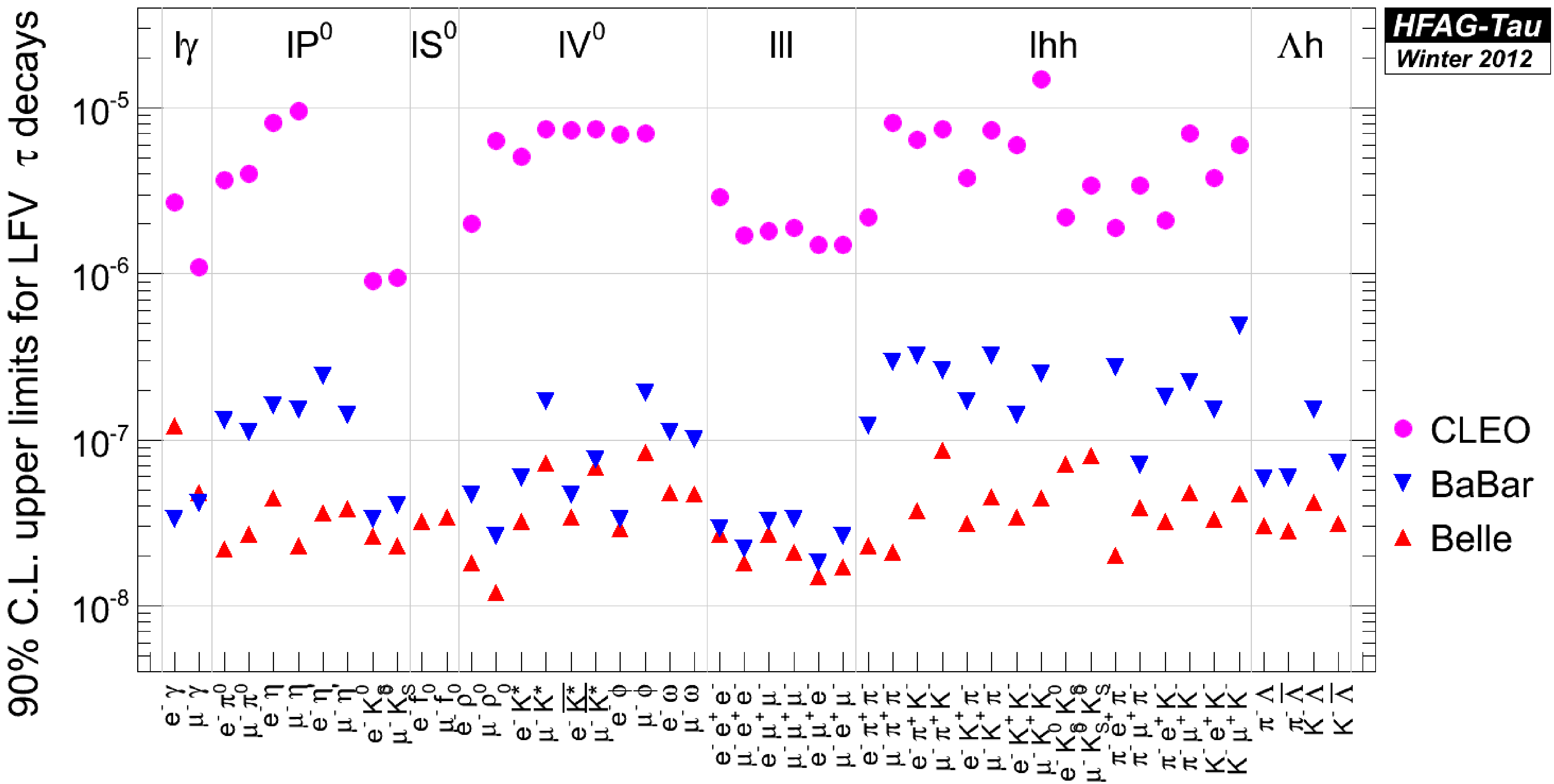
$[\bar{L}_p E_q H][\bar{Q}_r D_s H]$

$[\bar{L}_p \sigma_{\mu\nu} E_q H][\bar{Q}_r \sigma^{\mu\nu} D_s H]$

$[\bar{L}_p E_q H][\bar{U}_r Q_s H]$

R Petronzio et. al. in preparation

Upper limits on tau LFV branching fractions

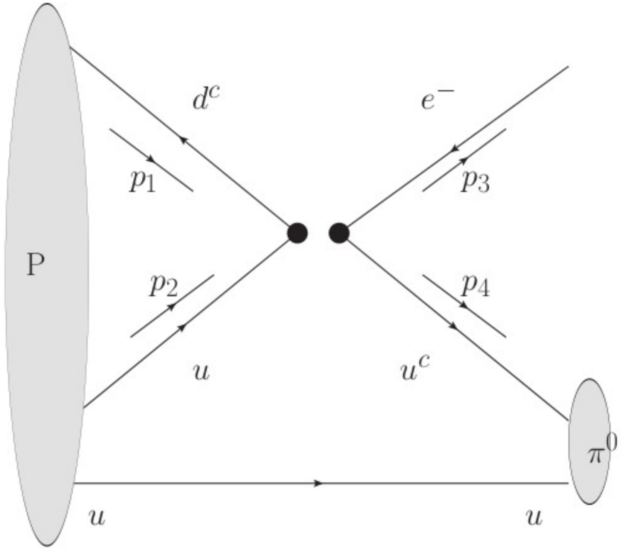


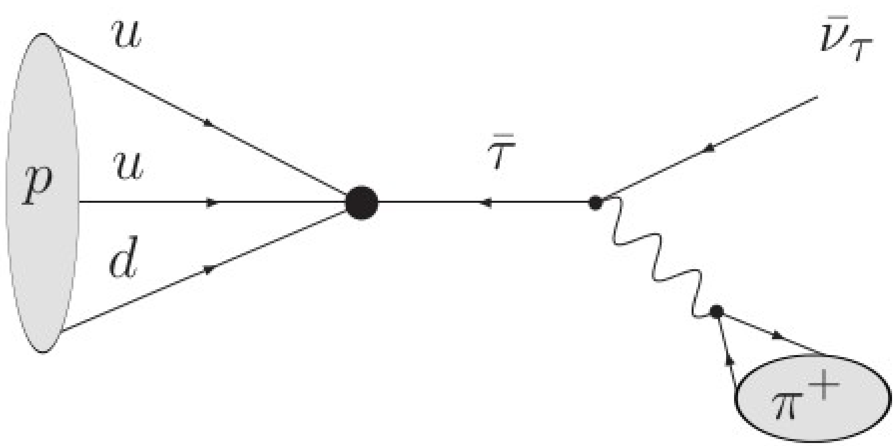
Expectations in various models

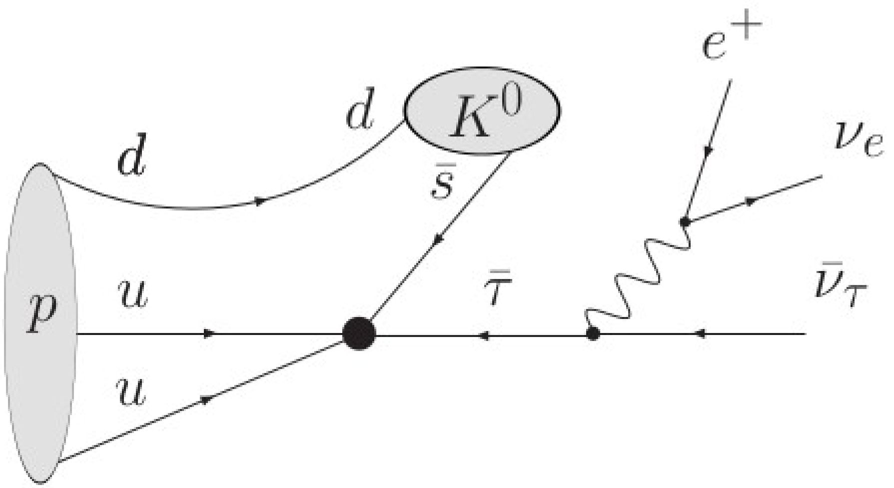
Model	$\tau \to \ell\gamma$	$\tau \to \ell\ell\ell$	Ref.
SM + lepton mixing	10^{-40}	10^{-14}	hep-ph/9810484
SM + left-h. heavy Dirac neutrino	$< 10^{-18}$	$< 10^{-18}$	SJNP25(1977)340
SM + right-h. heavy Majorana neutrino	$< 10^{-9}$	$< 10^{-10}$	PRD66(2002)034008
SM + left and right-h. neutral singlets	$< 10^{-8}$	$< 10^{-9}$	PRD66(2002)034008
mSUGRA + seesaw	$< 10^{-7}$	$< 10^{-9}$	hep-ph/0206110, hep-ph/9911459
SUSY $SU(5)$	$< 10^{-4}$		hep-ph/0303071
SUSY flipped $SU(5)$	$< 10^{-7}$		hep-ph/0304130
SUSY $SO(10)$	$< 10^{-8}$	$< 10^{-10}$	hep-ph/0209303, hep-ph/0304190
SUSY anomalous $U(1)$	$< 10^{-7}$		hep-ph/0308093
neutral SUSY Higgs	$< 10^{-10}$	$< 10^{-7}$	hep-ph/0304081
charged SUSY Higgs triplet		$< 10^{-7}$	hep-ph/0209170
MSSM+nonuniversal soft SUSY breaking	$< 10^{-10}$	$< 10^{-6}$	hep-ph/0305290
Non universal Z' (technicolor)	$< 10^{-9}$	$< 10^{-8}$	PLB547(2002)252
two Higgs doublet III	$< 10^{-15}$	$< 10^{-17}$	hep-ph/0208117
extra dimensions	$< 10^{-11}$		hep-ph/0210021

Baryon Number violating operators :

- $[Q_p^T \mathcal{C} Q_q]\,[Q_r^T \mathcal{C} L_s]$ $\longrightarrow$ $(\overline{d^c} P_L u)(\overline{u^c} P_L e)$
- $[Q_p^T \epsilon \sigma^I \mathcal{C} Q_q]\,[Q_r^T \epsilon \sigma^I \mathcal{C} L_s]$
- $[Q_p^T \mathcal{C} Q_q]\,[U_r^T \mathcal{C} E_s]$
- $[Q_p^T \mathcal{C} L_q]\,[D_r^T \mathcal{C} U_s]$
- $[U_p^T \mathcal{C} E_q]\,[D_r^T \mathcal{C} U_s]$







Hou et.al., 2005

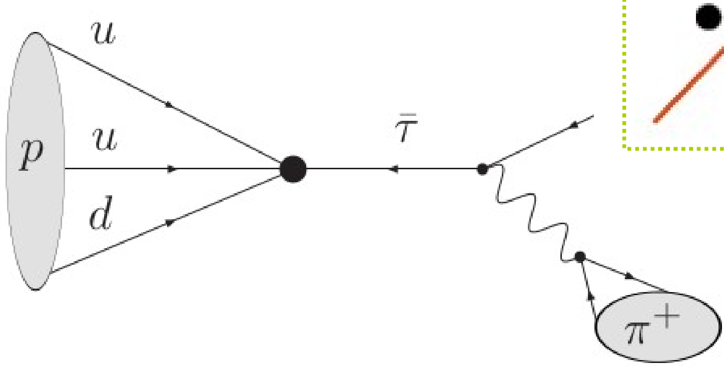
LHCb-CONF-2012-027
24/09/2012

The LHCb collaboration†

A searc … decays … luminos … τ^- lept… D^- mes… to the … consiste… 4.5(3.4)… confider…

…aryon number violating …ponding to an integrated …Cb in 2011. In LHCb, …m decays of B, D_s^- and …ction rate is normalised …d numbers of events are …imits $\mathcal{B}(\tau^- \to \bar{p}\mu^+\mu^-) <$ …^{7} are set at 95% (90%)

- $[Q_p^T C Q_q]\,[Q_r^T C L_s]$
- $[Q_p^T \epsilon\sigma^I C Q_q]\,[Q_r^T \epsilon\sigma^I C L_s]$
- $[Q_p^T C Q_q]\,[U_r^T C E_s]$
- $[Q_p^T C L_q]\,[D_r^T C U_s]$?
- $[U_p^T C E_q]\,[D_r^T C U_s]$



25×10^{30} years

$$BR(\tau \to \bar{p}\gamma) \lesssim 10^{-40}$$

Summary

Lepton Flavour Violation (LFV) occurs in Nature: $\nu_i \rightarrow \nu_j$ oscillation

Well motivated models allow large enhancements in the LFV branching fractions compared to those in the SM and many of them can be reached by a Tau factory

A Tau-Charrm factory has the potential to contribute to our knowledge of LFV tau decays and possibly to our understanding of Lepton Flavour Physics