Collaboration with Andrea Lami and Jorge Portolés (IFIC, Valencia) Phys.Rev. D**93** (2016) no.7, 076008; **94** no. 5, 056001 (2016).

(Improved analysis presented here)

Lepton Flavor Violation in the Simplest Little Higgs Model

Pablo Roig (Cinvestav Physics Dept., Mexico City)

The 14th International Workshop on Tau Lepton Physics (Tau2016), 19-23 September, 2016, IHEP, Beijing, China

Motivation (LFV)

After the discovery of ν oscillations, flavor violation only remains unmeasured in the charged lepton sector.

See also Emilie's introductory talk

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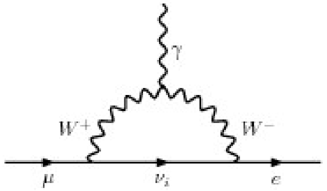

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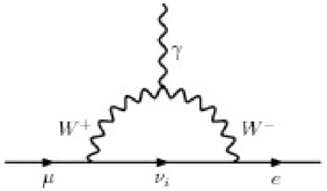

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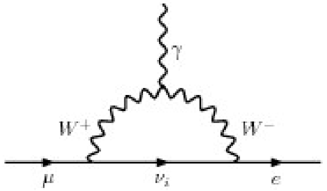

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4.2

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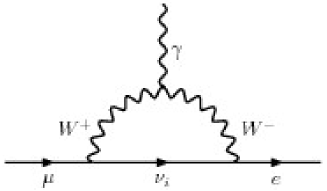

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Hunt of New Physics at MEG, MEGA, SINDRUM (II), Mu2e, Mu3e, COMET, PRISM, Belle-II, ATLAS & CMS, LHCb…

See related talks today and tomorrow

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Motivation (SLH)

LH models are **composite Higgs models** (Georgi-Kaplan ’84, Dugan-Georgi-Kaplan ‘85).

Higgs as a ‘kind’ of π

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Features of LH models:
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II) Tree-level generated quartic coupling (see however Schmalz-Stolarski-Thaler '09).
III) 'Little' particles with masses of O(f), that cancel the main one-loop corrections to the Higgs mass in the SM (consequence of collective symmetry breaking).
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Two **types** of LH models:
I) Product group models $[SU(2)xU(1)]^N$ (needs *T-parity*).
II) Simple group models SU(N)xU(1) (like **SLH**).

See also Moyotl et. al. &
Arroyo et. al., poster session

Motivation (SLH, Schmaltz '04)

- Solves the **hierarchy problem** without T-parity.
- $SU(2)_L x U(1)_Y$ from the breakdown of $SU(3)_X x U(1)$.
- Every fermion family contains a L SU(3) triplet and the corresponding R singlets. We follow the *anomaly-free embedding*:

$$L_k^{-1/3} = (\nu_k, \ell_k, i\boxed{N_k})_L^T, \quad \ell_{kR}^{-1}, \quad \boxed{N_{kR}^0}, \quad k = 1,2,3 \longrightarrow \text{(No } \nu \text{ masses)}$$

$$\begin{aligned} Q_1^0 &= (d, -u, i\boxed{D})_L^T, & d_R^{-1/3}, \quad u_R^{2/3}, \quad & D_R^{-1/3}, \\ Q_2^0 &= (s, -c, i\boxed{S})_L^T, & s_R^{-1/3}, \quad c_R^{2/3}, \quad & S_R^{-1/3}, \\ Q_3^{1/3} &= (t, b, i\boxed{T})_L^T, & b_R^{-1/3}, \quad t_R^{2/3}, \quad & T_R^{2/3}, \end{aligned}$$

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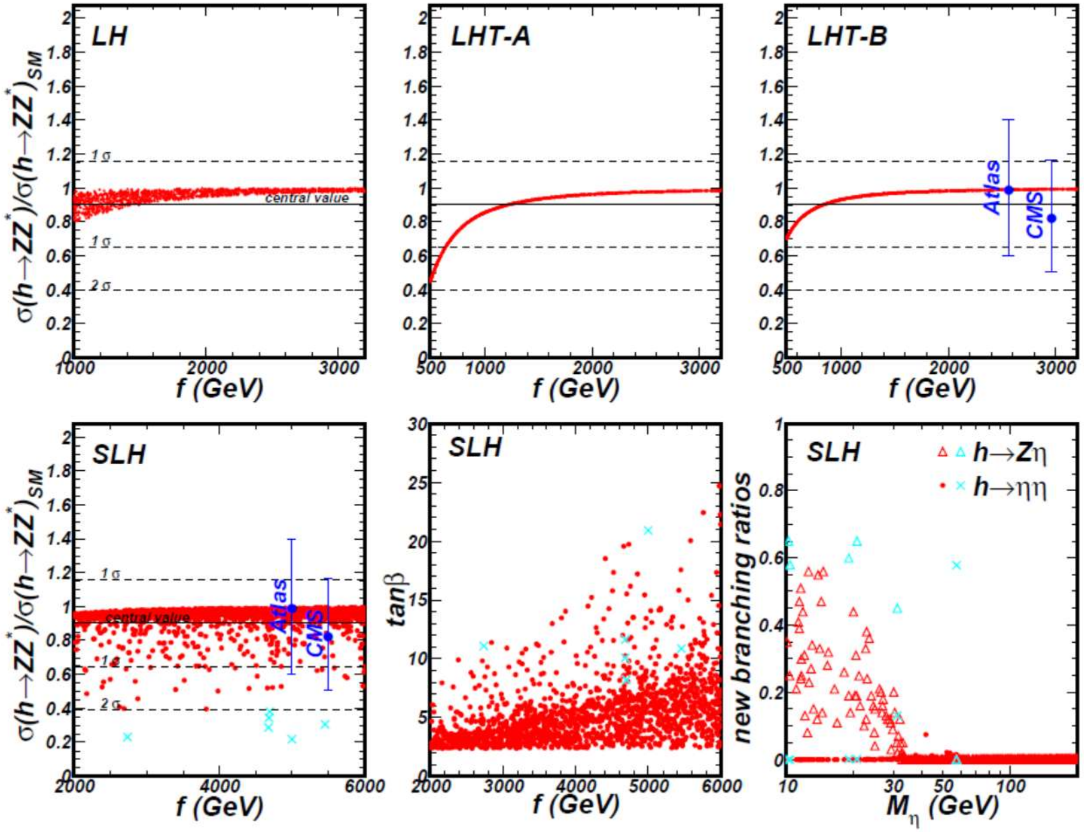

(More complete discussion in additional material)

LH models vs LHC data: Han, Wang, Yang, Zhu ‘13

(See also Kalyniak, Martin, Moats ’15)

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- Scalar potential with $[SU(3)xU(1)]^2$ symmetry, breaking to $[SU(2)xU(1)]^2$ with vevs of order f and NGBs. The (gauged) diagonal subgroup $SU(3)_L xU(1)_X$ breaks down to the SM EW group via the vevs. The scalar multiplets are given by non-linear sigma models (including the SM Higgs and new NGBs):

$[SU(3)xU(1)]^2 \rightarrow [SU(2)xU(1)]^2$

5 additional massive gauge bosons ($W'^{\pm}$, $Y^{0(\dagger)}$, Z')

Only the diagonal part is gauged: SSB of global symmetry & of local gauge symmetry

Higgs d.o.f & η (Cheung, Song et. al. '07, '08)

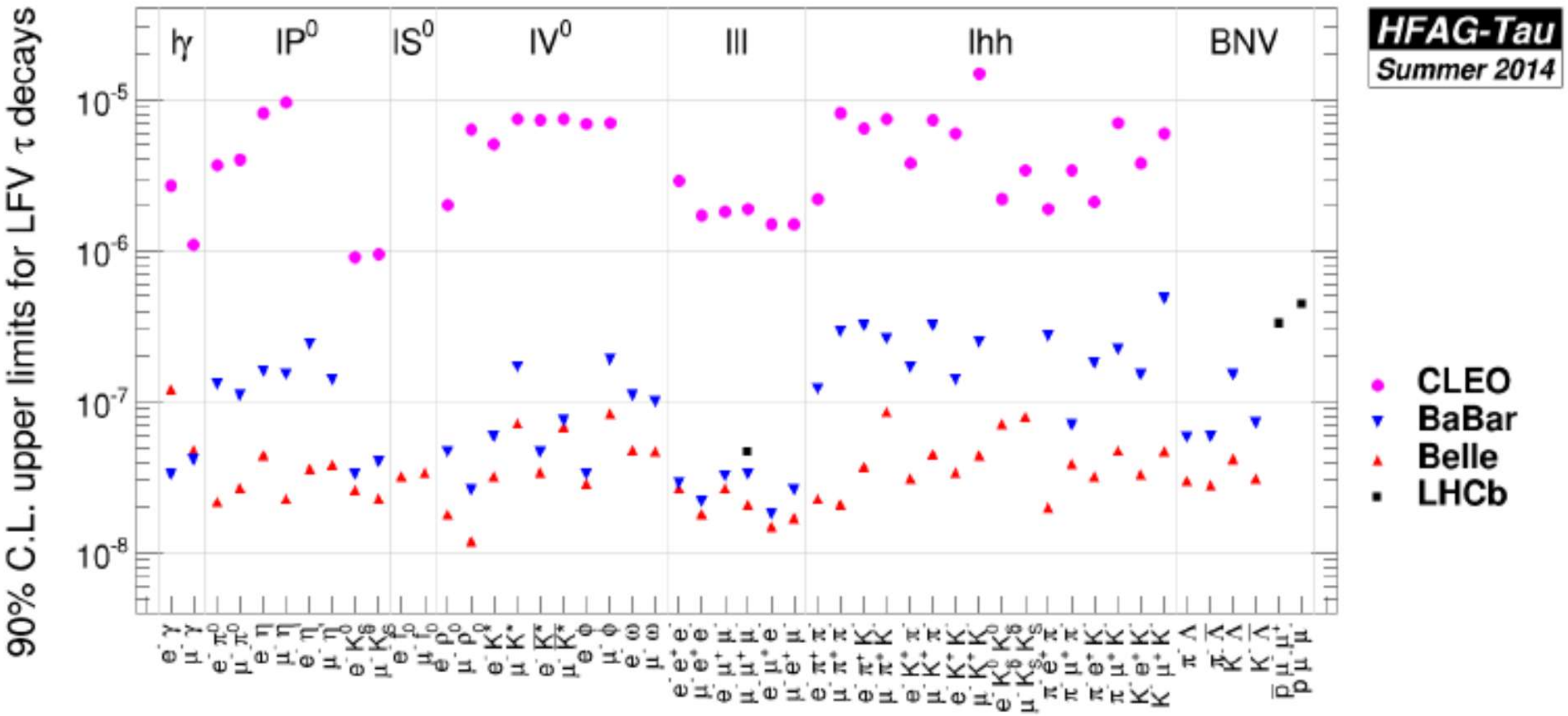
$$t_\beta \equiv \tan\beta = f_1/f_2, \; s_\beta \equiv \sin\beta, \; c_\beta = \cos\beta \text{ and } f^2 = f_1^2 + f_2^2.$$

EWSB

PART I: Semileptonic LFV tau decays

Improved analysis with respect to Phys.Rev. D93 (2016) no.7

Motivation

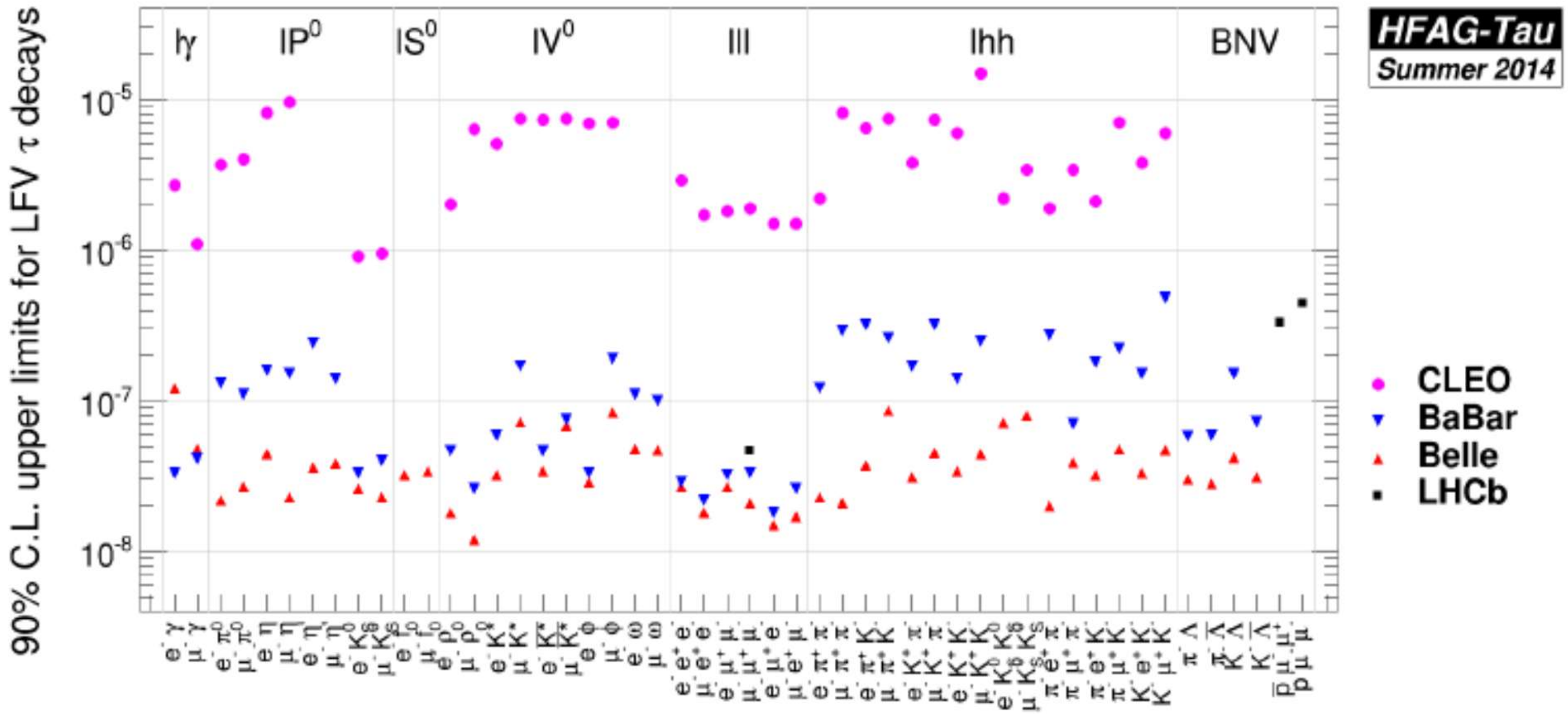


And 2 orders of magnitude improvement expected for Belle-II !!

See also Emilie's introductory talk

See also Toshiki Yoshinobu, poster session

Motivation



But not so much activity on the theory side (but for L→l $\gamma^{(*)}$):

SUSY (Brignole-Rossi '04, Fukuyama-Ilakovic-Kukuchi '08, Arganda-Herrero-Portolés '08, Arganda-Portolés-Rodríguez-Sánchez '09)

LH with T-parity (Liu-Yue-Zhang '10, Goto-Okada-Yamamoto'11)

3-3-1 models (Hua & Yue '14)

EFT (Celis-Cirigliano-Passemar '14)

See also Emilie's introductory talk

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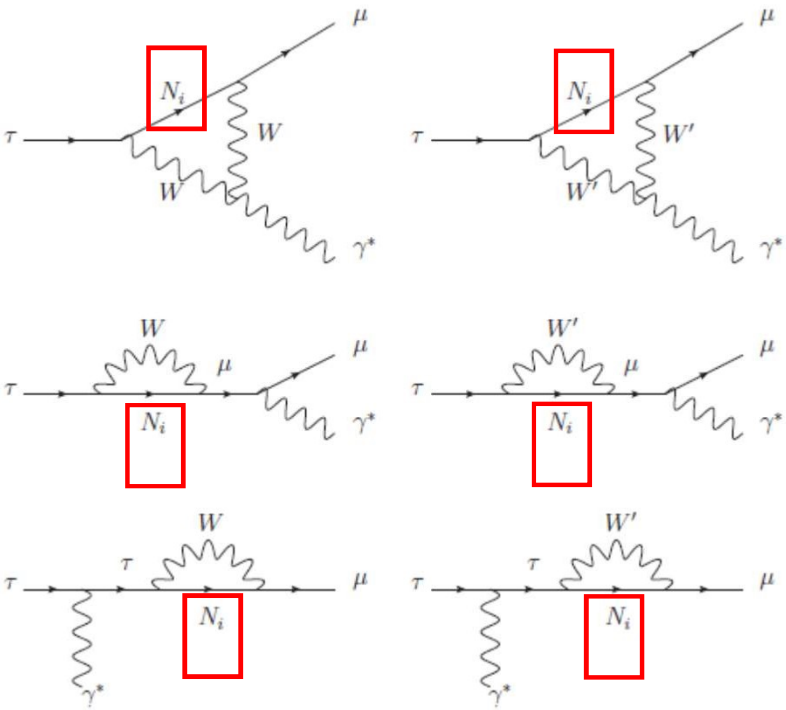
1-loop diagrams $(\gamma, Z, Z')^* \to q\,\bar{q}$ omitted

Unitary gauge throughout!!



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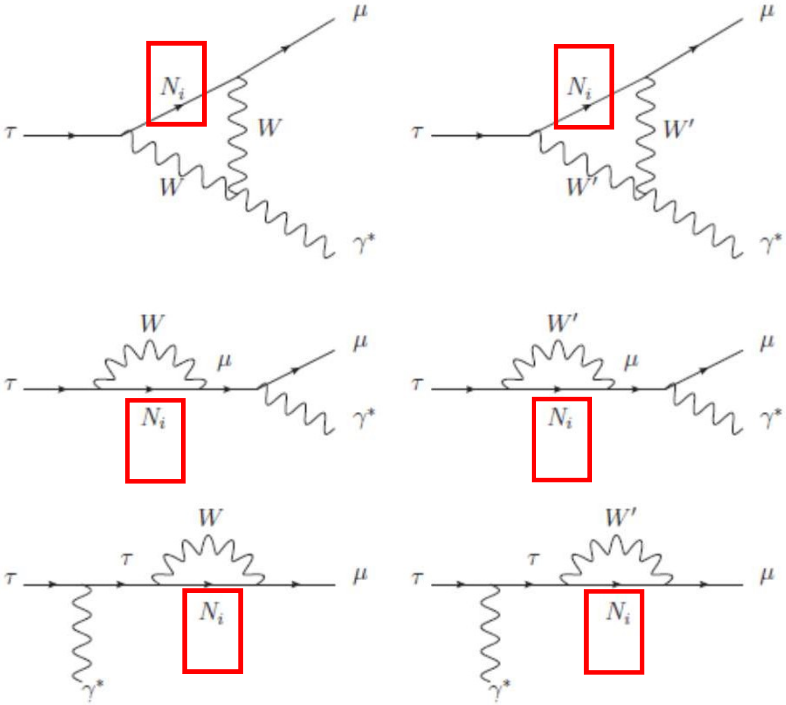

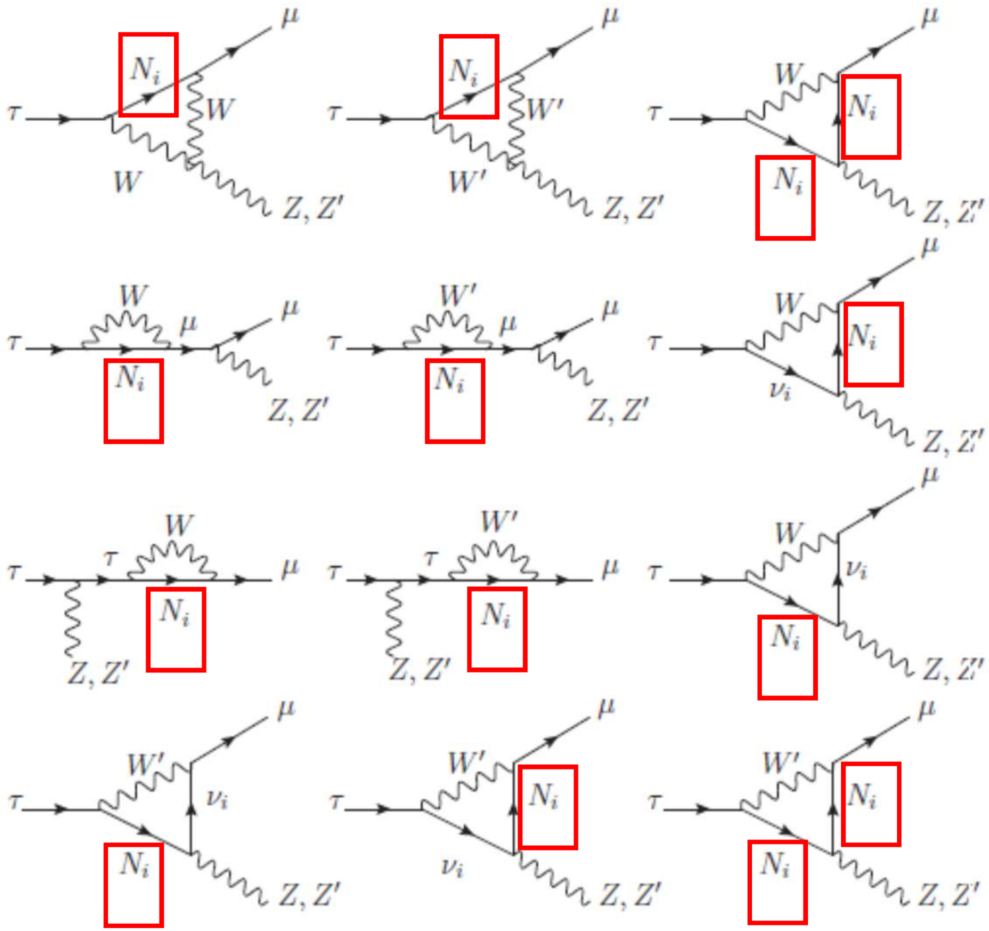

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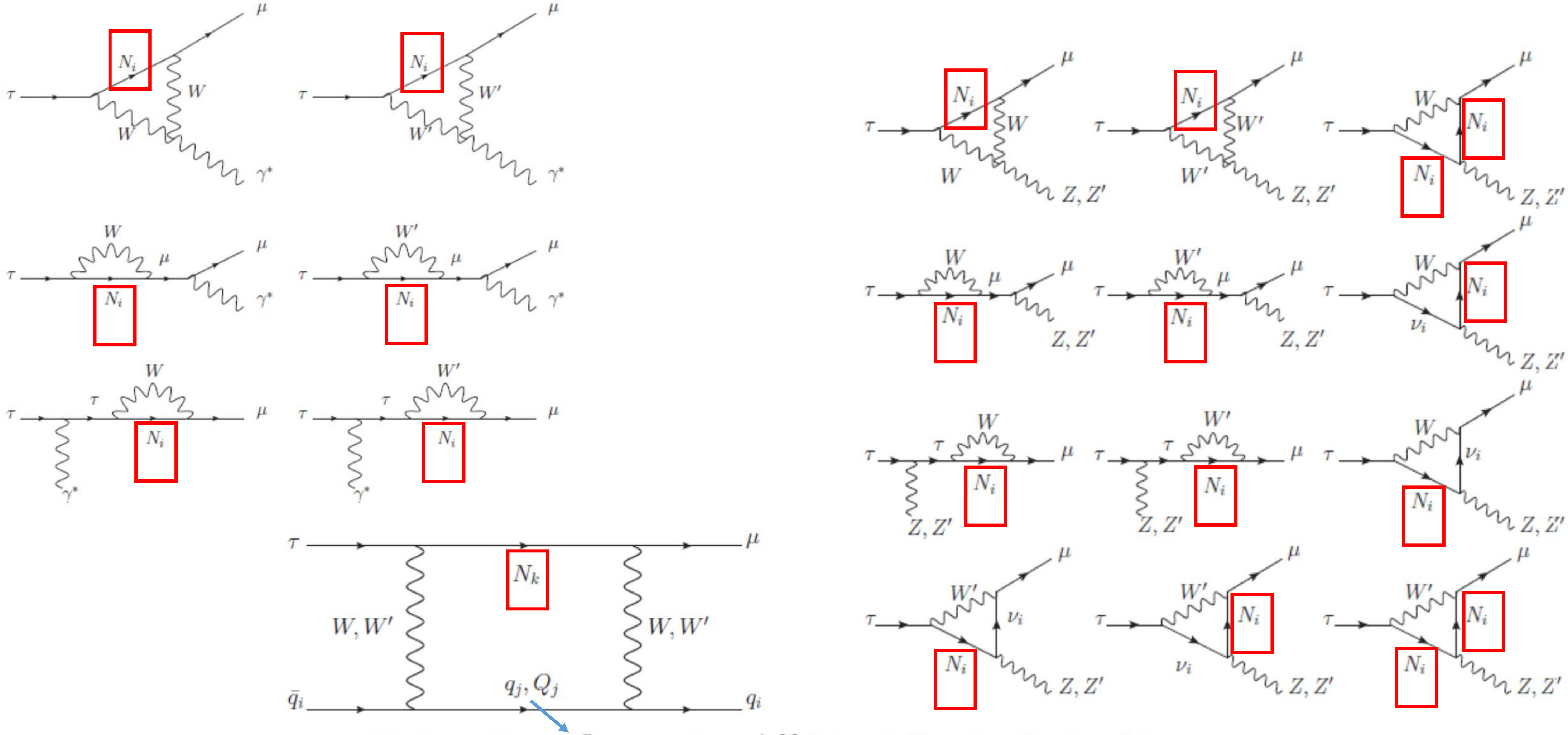

The internal quark states are $(u, \overline{u}) \to \{d, D\}$, $(d, \overline{d}) \to \{u\}$, $(s, \overline{s}) \to \{c\}$.

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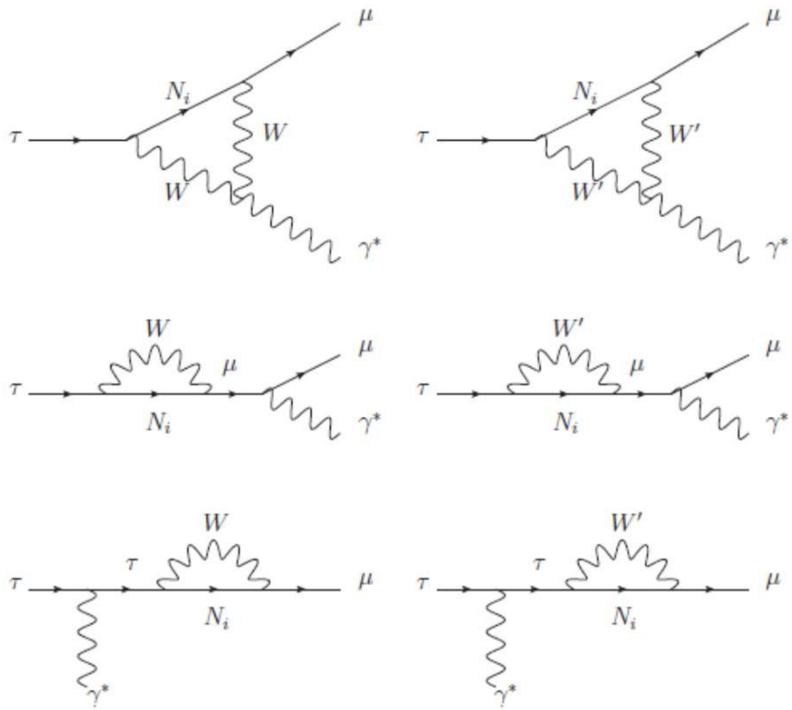
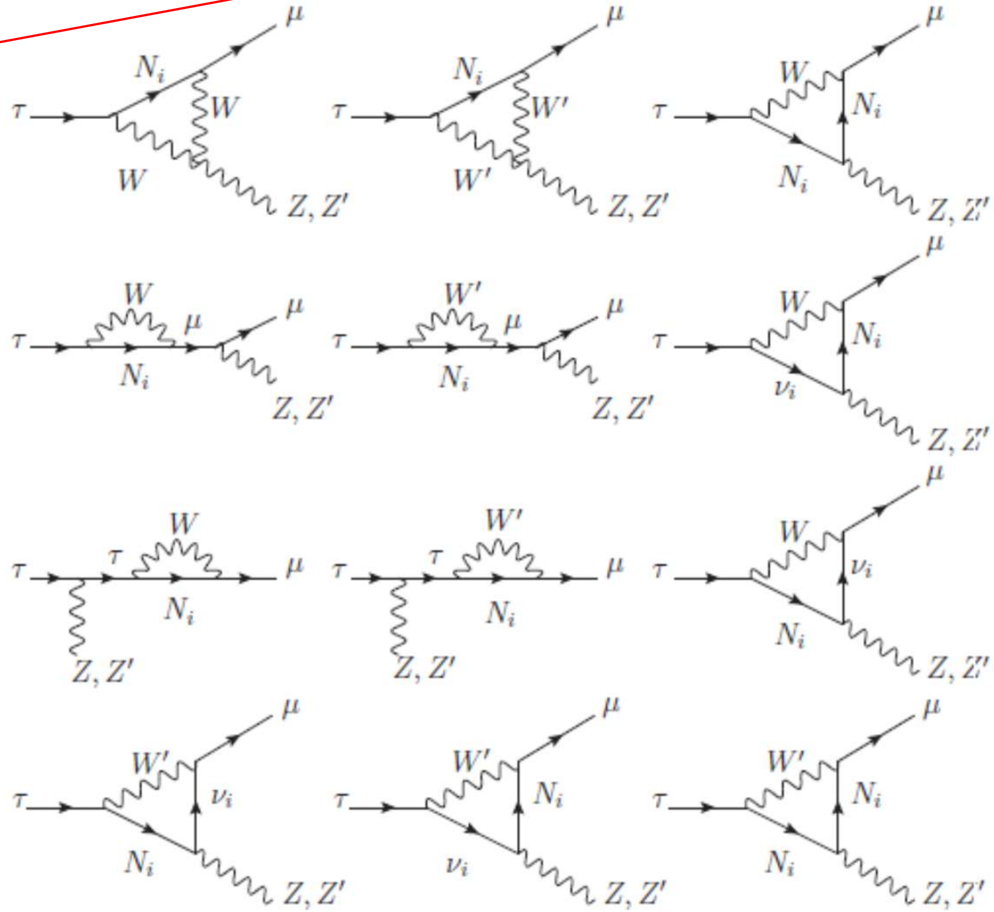
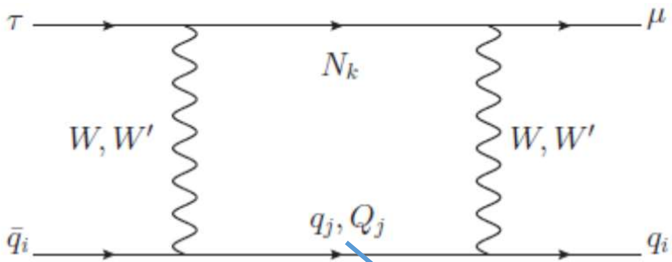


Subtle cancellation of divergences !!





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γ contribution(γ* → q $\bar{\text{q}}$ omitted)

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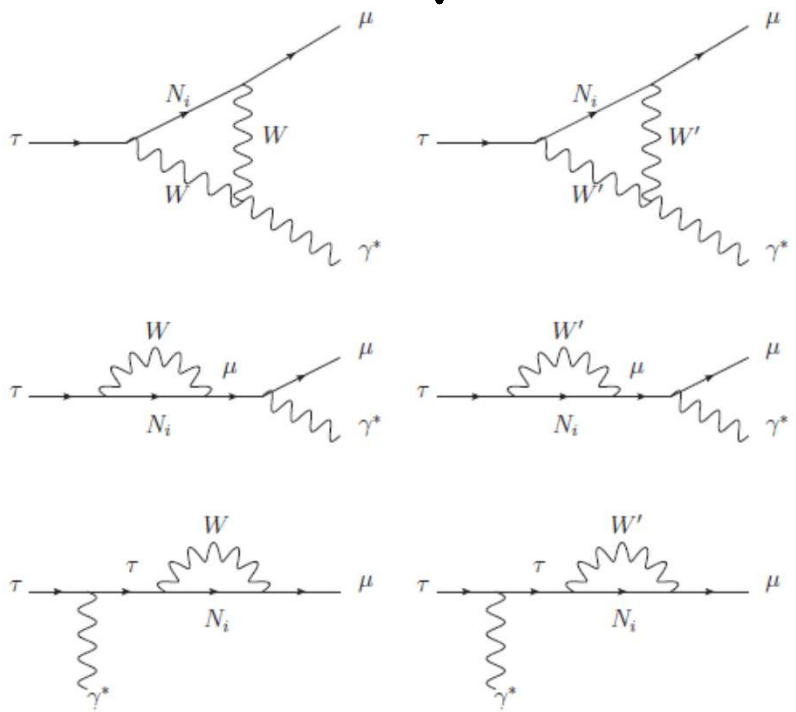


Approximations:

$$\lim_{\frac{v}{f}\to 0} \mathcal{M}_{\tau\to\mu\ hadrons} = 0 \ \Rightarrow\ \mathcal{M}\left(\frac{v^2}{f^2}\right) + \mathcal{O}\left(\frac{v^3}{f^3}\right)$$

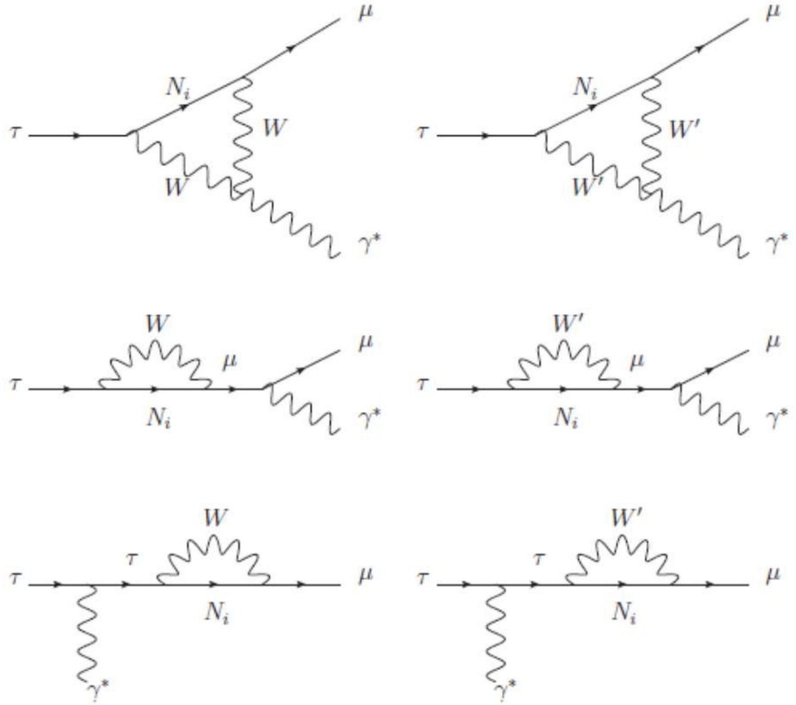
$$\frac{1}{(k-p)^2 - M^2} \approx \frac{1}{k^2 - M^2}\left[1 - \frac{p^2 - 2k\cdot p}{k^2 - M^2} + \frac{(p^2 - 2k\cdot p)^2}{(k^2 - M^2)^2}\right]$$

$$m_{\nu_i} = m_\mu = m_q = 0 \quad ; \quad \frac{m_\tau^2}{M_N^2} \simeq \frac{m_\tau^2}{M_W^2} \simeq \frac{m_\tau^2}{{M_{W'}}^2} \simeq \frac{m_\tau^2}{M_Z^2} \simeq \frac{m_\tau^2}{{M_{Z'}}^2} \simeq 0$$

External momenta set to zero in the computation of boxes

Unitary gauge throughout!!

γ contribution($\gamma^* \to q\,\bar{q}$ omitted)



$$\mathcal{T}_\gamma = \frac{e^2}{Q^2}\frac{v^2}{f^2}\sum_j V_\ell^{j\mu *} V_\ell^{j\tau}\,\overline{\mu}(p')\left[Q^2\gamma_\lambda\left(\boxed{F_L^j}P_L + \boxed{F_R^j}P_R\right)\right.$$
$$\left. + i m_\tau \sigma_{\lambda\nu} Q^\nu \left(\boxed{G_L^j}P_L + \boxed{G_R^j}P_R\right)\right]\tau(p)\;\overline{q}(p_q) Q_q \gamma^\lambda q(p_{\overline{q}})$$

$$Q_q = \frac{1}{3}\begin{pmatrix} 2 & & \\ & -1 & \\ & & -1 \end{pmatrix}$$

Unitary gauge throughout!!

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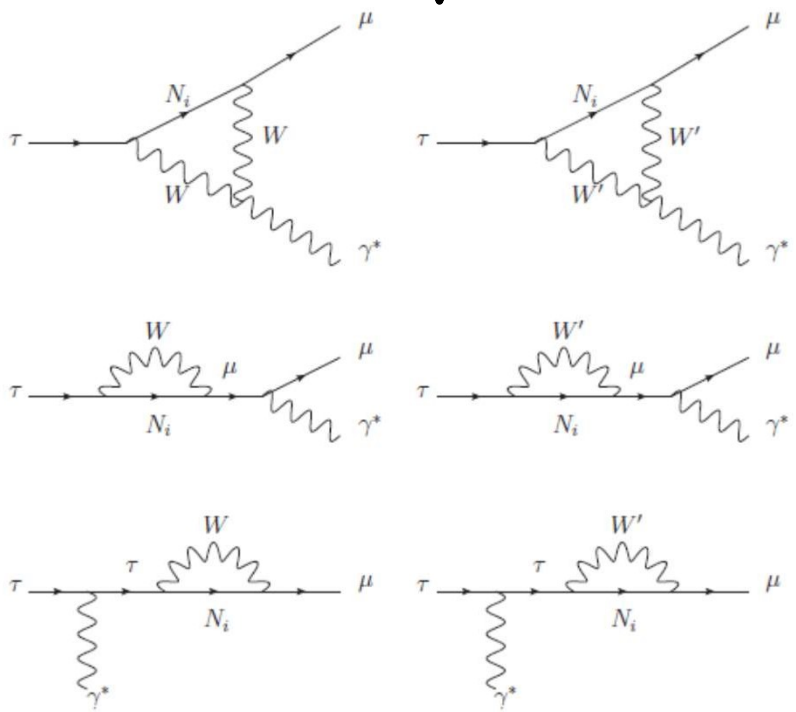

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$$\underline{F_R^j} = \mathcal{O}(m_\tau^2/M_Z^2),\ \underline{G_L^j} = 0$$

$$\underline{F_L^j} = \frac{\alpha_W}{4\pi}\frac{1}{16M_W^2}\left[\left(\frac{\chi_j^3\left(\chi_j^2 - 8\chi_j + 13\right)}{\left(\chi_j - 1\right)^4} - 4\,\delta_\nu^2\frac{M_{W'}^2}{M_W^2}\right)\ln\chi_j + \frac{4\chi_j^5 - 19\chi_j^4 + 29\chi_j^3 + 5\chi_j^2 - 95\chi_j + 40}{6\left(\chi_j - 1\right)^3}\right],$$

$$\underline{G_R^j} = \frac{\alpha_W}{4\pi}\frac{1}{8M_W^2}\left[\left(\frac{\chi_j^3\left(2\chi_j + 1\right)}{\left(\chi_j - 1\right)^4} + 2\,\delta_\nu^2\frac{M_{W'}^2}{M_W^2}\right)\ln\chi_j + \frac{6\chi_j^5 - 15\chi_j^4 - 35\chi_j^3 + 72\chi_j^2 - 66\chi_j + 20}{6(\chi_j - 1)^3}\right]$$

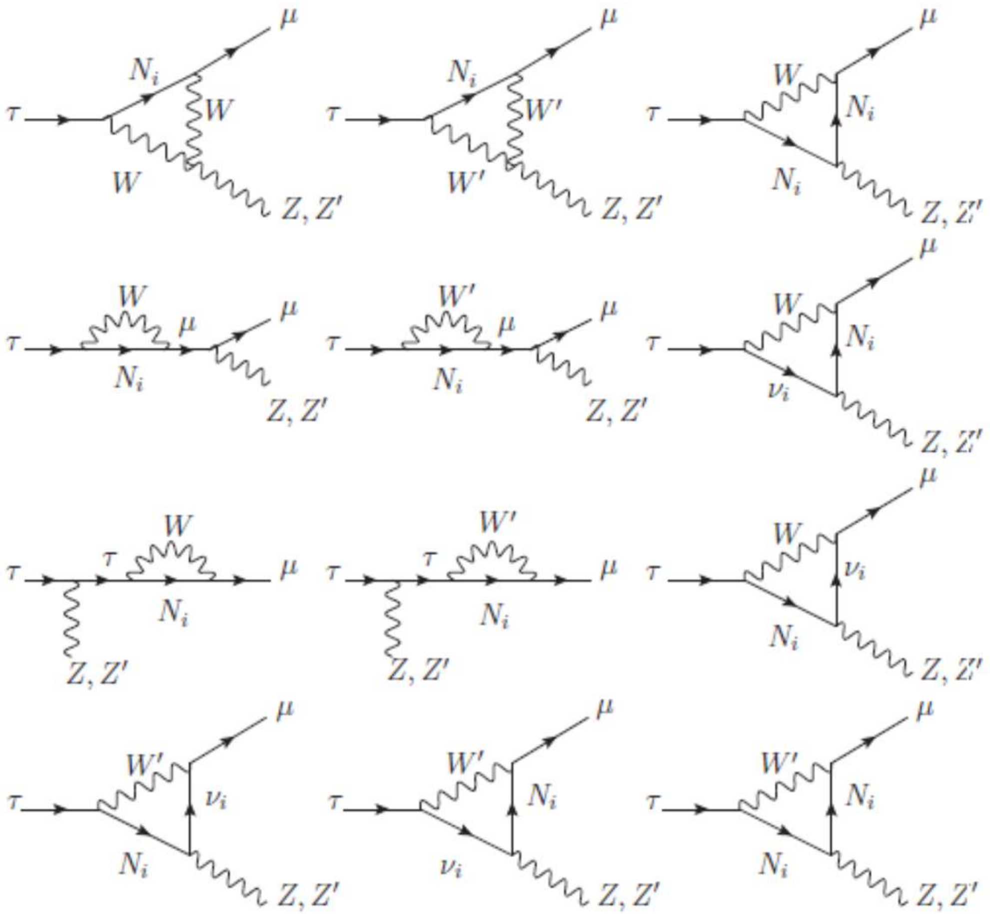
$$\alpha_W \equiv \alpha/s_W^2\ .$$

$$O(1) \longrightarrow \chi_j = M_{N_j}^2/M_{W'}^2$$

$$\delta_\nu = \frac{-1}{\sqrt{2}\tan\beta}\frac{v}{f}$$

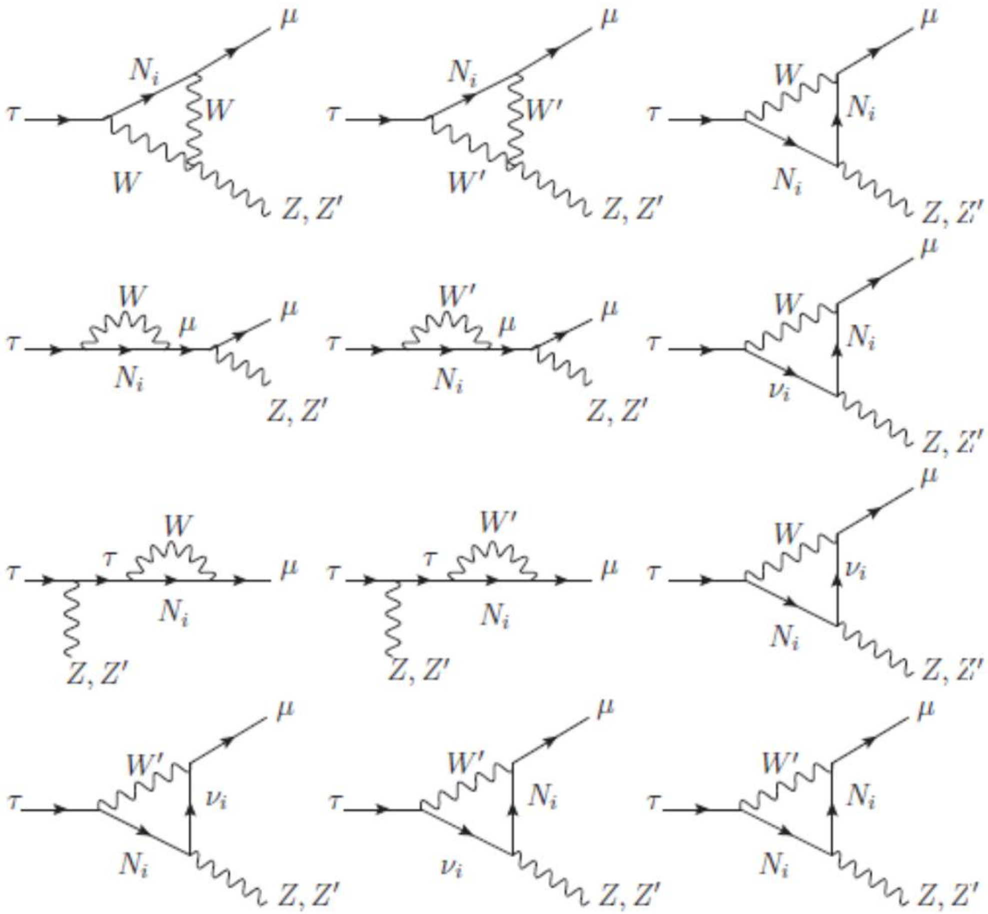
Z & Z' contributions($Z^{(\prime)*} \to q\,\bar{q}$ omitted)

Unitary gauge throughout!!



$$\mathcal{T}_Z = \frac{g}{M_Z^2} \sum_j V_\ell^{j\mu *} V_\ell^{j\tau}\, \overline{\mu}(p') \left[\gamma_\mu \left(\boxed{H_L^j} P_L + \boxed{H_R^j} P_R\right)\right] \tau(p)$$
$$\times \overline{q}(p_q) \left[\gamma^\mu \left(\underline{Z_L} P_L + \underline{Z_R} P_R\right)\right] q(p_{\overline{q}}),$$
$$\mathcal{T}_{Z'} = \frac{g}{M_{Z'}^2} \sum_j V_\ell^{j\mu *} V_\ell^{j\tau}\, \overline{\mu}(p') \left[\gamma_\mu \left(\boxed{\widetilde{H}_L^j} P_L + \boxed{\widetilde{H}_R^j} P_R\right)\right] \tau(p)$$
$$\times \overline{q}(p_q) \left[\gamma^\mu \left(\underline{Z'_L} P_L + \underline{Z'_R} P_R\right)\right] q(p_{\overline{q}}),$$

Z & Z' contributions($Z^{(\prime)*} \to q\,\bar{q}$ omitted)



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$$\times \overline{q}(p_q) \left[\gamma^\mu \left(Z'_L P_L + Z'_R P_R\right)\right] q(p_{\overline{q}}),$$

$\mathcal{O}(m_\tau^2/M_Z^2)$

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(Explicit expressions in additional material)

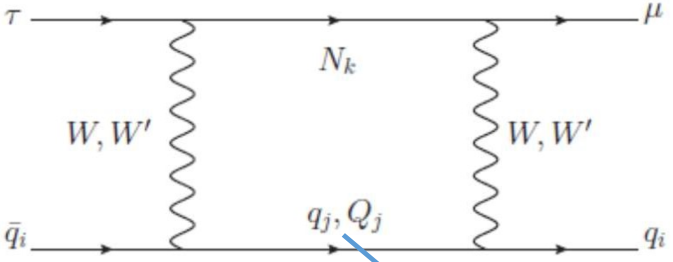
$$Z_L = \frac{g}{c_W}\left(T_3^q - s_W^2 Q_q\right),$$
$$Z_R = -\frac{g}{c_W} s_W^2\, Q_q\,,$$
$$Z'_L = \frac{g}{6}\sqrt{3 - t_W^2}\, \mathbb{1}_{3\times 3}\,,$$
$$Z'_R = -\frac{g t_W^2}{\sqrt{3 - t_W^2}}\, Q_q\,.$$

$$Q_q = \frac{1}{3}\begin{pmatrix} 2 & & \\ & -1 & \\ & & -1 \end{pmatrix}$$

$$T_3^q = \frac{1}{2}\begin{pmatrix} 1 & & \\ & -1 & \\ & & -1 \end{pmatrix}.$$

Unitary gauge throughout!!

Box contributions



(Del Águila-Illana-Jenkins '11)

The internal quark states are $(u, \overline{u}) \to \{d, D\}$, $(d, \overline{d}) \to \{u\}, (s, \overline{s}) \to \{c\}$.

$$\boxed{B_q^j} = \frac{\alpha_W}{64\pi}\left[\alpha_q^j \ln \chi_j + \beta_q^j \ln \delta + \gamma_q^j\right]$$

(Explicit expressions in additional material)

$$\delta = m_D^2/M_{W'}^2$$

$$\delta_d \simeq \delta_s \simeq -\delta_\nu$$

(small mixing for q_d)

$$\delta_\nu = \frac{-1}{\sqrt{2}\tan\beta}\frac{v}{f}$$

$$\alpha_W \equiv \alpha/s_W^2 .$$

$$O(1) \to \chi_j = M_{N_j}^2/M_{W'}^2$$

$$\mathcal{T}_B = g^2 \sum_q^{u,a,s} \sum_j V_\ell^{j\mu *} V_\ell^{j\tau} \boxed{B_q^j}$$
$$\times\, \overline{\mu}(p')\gamma_\mu P_L \tau(p) \cdot \overline{\psi_q}(p_q)\gamma^\mu P_L \psi_q(p_{\overline{q}})$$

$\psi_q = \{u, d, s\}$

Box contributions relevant (essential in decay channels with only one pseudoscalar meson)

Hadronization

$$V_\mu^i = \overline{q}\,\gamma_\mu\,\frac{\lambda^i}{2}\,q \quad , \qquad A_\mu^i = \overline{q}\,\gamma_\mu\,\gamma_5\,\frac{\lambda^i}{2}\,q\,, \qquad q = (u,d,s)^T$$

$$\mathcal{J}_\mu^{\text{em}} = \overline{q}\,Q_q\,\gamma_\mu q = V_\mu^3 + \frac{1}{\sqrt{3}}V_\mu^8$$

$$\overline{u}\,\gamma_\mu\,P_L\,u = J_\mu^3 + \frac{1}{\sqrt{3}}V_\mu^8 + \frac{2}{\sqrt{6}}J_\mu^0\,,$$

$$\overline{d}\,\gamma_\mu\,P_L\,d = -\,J_\mu^3 + \frac{1}{\sqrt{3}}V_\mu^8 + \frac{2}{\sqrt{6}}J_\mu^0\,, \qquad J_\mu^i = (V_\mu^i - A_\mu^i)/2$$

$$\overline{s}\,\gamma_\mu\,P_L\,s = -\frac{2}{\sqrt{3}}V_\mu^8 + \frac{2}{\sqrt{6}}J_\mu^0$$

$$V_\mu^i = \left.\frac{\partial\mathcal{L}_{\text{R}\chi\text{T}}}{\partial v_i^\mu}\right|_{j=0}, \qquad A_\mu^i = \left.\frac{\partial\mathcal{L}_{\text{R}\chi\text{T}}}{\partial a_i^\mu}\right|_{j=0}$$

Hadronization

$$V_\mu^i = \overline{q}\,\gamma_\mu \frac{\lambda^i}{2} q \quad , \quad A_\mu^i = \overline{q}\,\gamma_\mu\,\gamma_5 \frac{\lambda^i}{2} q\,, \qquad q = (u,d,s)^T$$

$$\mathcal{J}_\mu^{\rm em} = \overline{q}\,Q_q\,\gamma_\mu q = V_\mu^3 + \frac{1}{\sqrt{3}} V_\mu^8$$

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Chiral symmetry + **Dispersion relations** (unitarity, analyticity, crossing symmetry) + **Brodsky-Lepage behaviour** + **Accurate data**

See also
Sergi González-Solís &
Rafel Escribano talks

(Dumm-Roig ‘12, Shekhovtsova-Przedzinski-Roig-Was ’12, …)

Hadronization

$$V_\mu^i = \overline{q}\,\gamma_\mu \frac{\lambda^i}{2} q \quad , \quad A_\mu^i = \overline{q}\,\gamma_\mu \gamma_5 \frac{\lambda^i}{2} q \,, \qquad q = (u,d,s)^T$$

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1. $\tau \to \mu P \qquad P = \{\pi^0, \eta, \eta'\}$

Basically only f_P decay constant

	$P=\pi^0$	$P=\eta$	$P=\eta'$
$Z(P)$	1	$\frac{1}{\sqrt{6}}\left(\sin\theta_\eta + \sqrt{2}\cos\theta_\eta\right)$	$\frac{1}{\sqrt{6}}\left(\sqrt{2}\sin\theta_\eta - \cos\theta_\eta\right)$
$Z'(P)$	$\sqrt{3}t_{\mathrm{W}}^2$	$\cos\theta_\eta t_{\mathrm{W}}^2 - \sqrt{2}\sin\theta_\eta\left(3 - t_{\mathrm{W}}^2\right)$	$\sin\theta_\eta t_{\mathrm{W}}^2 + \sqrt{2}\cos\theta_\eta\left(3 - t_{\mathrm{W}}^2\right)$
$B_j(P)$	$\frac{1}{2}\left(B_d^j - B_u^j\right)$	$\frac{1}{2\sqrt{3}}\left[\left(\sqrt{2}\sin\theta_\eta - \cos\theta_\eta\right)B_u^j + \left(2\sqrt{2}\sin\theta_\eta + \cos\theta_\eta\right)B_d^j\right]$	$\frac{1}{2\sqrt{3}}\left[\left(\sin\theta_\eta - 2\sqrt{2}\cos\theta_\eta\right)B_d^j - \left(\sin\theta_\eta + \sqrt{2}\cos\theta_\eta\right)B_u^j\right]$

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(Dumm-Roig ‘12, Shekhovtsova-Przedzinski-Roig-Was ’12, …)

Hadronization

2. $\tau \to \mu P P$ $\quad P\overline{P} = \left\{\pi^+\pi^-, K^+K^-, K^0\overline{K^0}\right\}$.

$$\langle P_1(p_1)P_2(p_2)|\mathcal{J}_\mu^{\text{em}}|0\rangle = (p_1 - p_2)_\mu \boxed{F_V^{P_1 P_2}(Q^2)} \qquad Q = p_1 + p_2$$

(Explicit expressions in additional material)

Chiral symmetry + **Dispersion relations** (unitarity, analyticity, crossing symmetry) + **Brodsky-Lepage behaviour** + **Accurate data**

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(Explicit expressions in additional material)

3. $\tau \to \mu V \qquad V = \rho, \phi$

$$B(\tau \to \mu\rho) = B(\tau \to \mu\pi^+\pi^-)\Big|_\rho,$$
$$B(\tau \to \mu\phi) = B(\tau \to \mu K^+K^-)\Big|_\phi + B(\tau \to \mu K^0\overline{K^0})\Big|_\phi,$$

$$s_\pm = M_\rho^2 \pm \frac{1}{2} M_\rho \Gamma_\rho(M_\rho^2).$$

$$s_\pm = M_\phi^2 \pm \frac{1}{2} M_\phi \Gamma_\phi(M_\phi^2),$$

See also
Sergi González-Solís &
Rafel Escribano talks

Numerical results

$2\,\mathrm{TeV} < f < 10\,\mathrm{TeV}$ 2 heavy neutrinos (GIM-like) $1 < t_\beta < 10$ $\delta_d \simeq \delta_s \simeq -\delta_\nu$ (small mixing for q_d)

Previous work within SLH in Del Águila-Illana-Jenkins '11: μ → e γ, μ → eee & μ → e in nuclei

$ft_\beta > 3.48\ \mathrm{TeV}$

$\delta_\nu = \frac{-1}{\sqrt{2}\tan\beta}\frac{v}{f}$

Allowed heavy neutrino mass hierarchies

Numerical results

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$$ft_\beta > 3.48\ \text{TeV}$$

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Allowed heavy neutrino mass hierarchies

All low-E constraints taken into account for our analyses of τ **→ l (P/PP/V) & H → l l'**

Numerical results

$2\,\text{TeV} < f < 10\,\text{TeV}$ 2 heavy neutrinos (GIM-like) $1 < t_\beta < 10$ $\delta_d \simeq \delta_s \simeq -\delta_\nu$ (small mixing for q_d)

Process	$\mathcal{B} \times 10^8$ (90 % C.L.) [1]	
	$\ell = \mu$	$\ell = e$
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$\tau \to \ell\pi^0$	< 11.0	< 8.0
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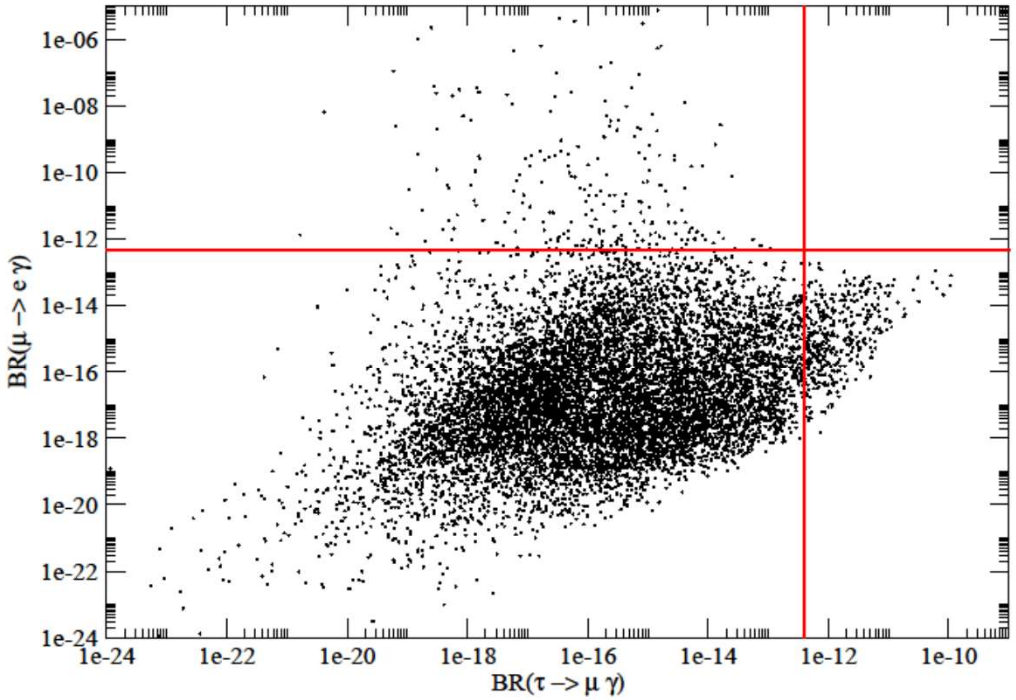
And 2 orders of magnitude improvement expected for Belle-II !!



Scatter plot for reasonable values of model parameters

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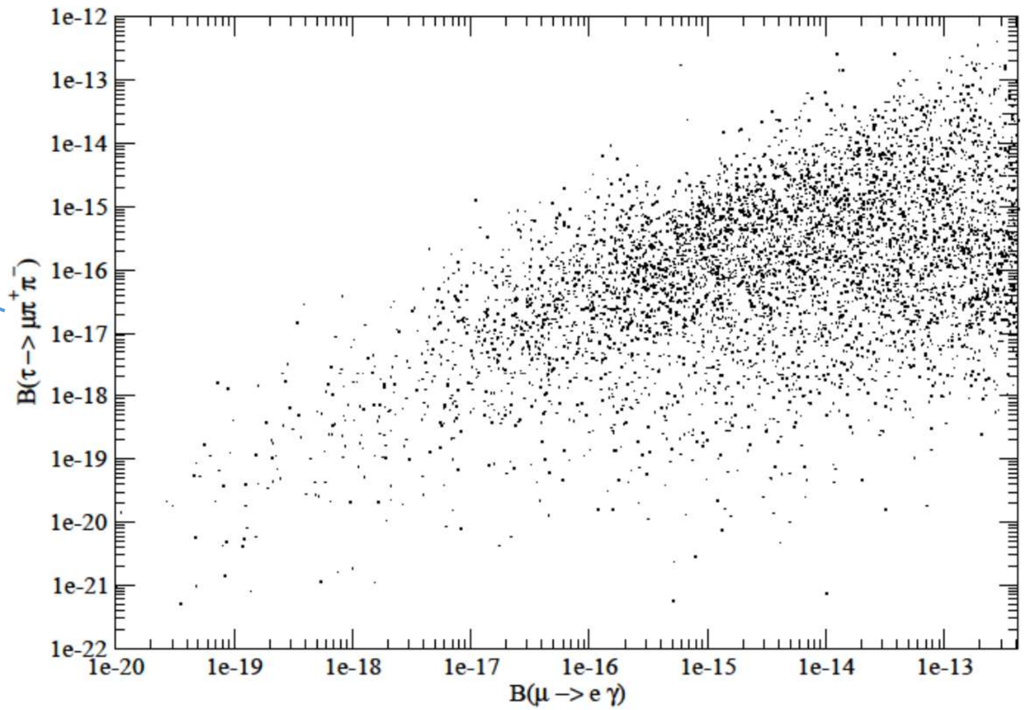

Scatter plot for reasonable values of model parameters

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Numerical results

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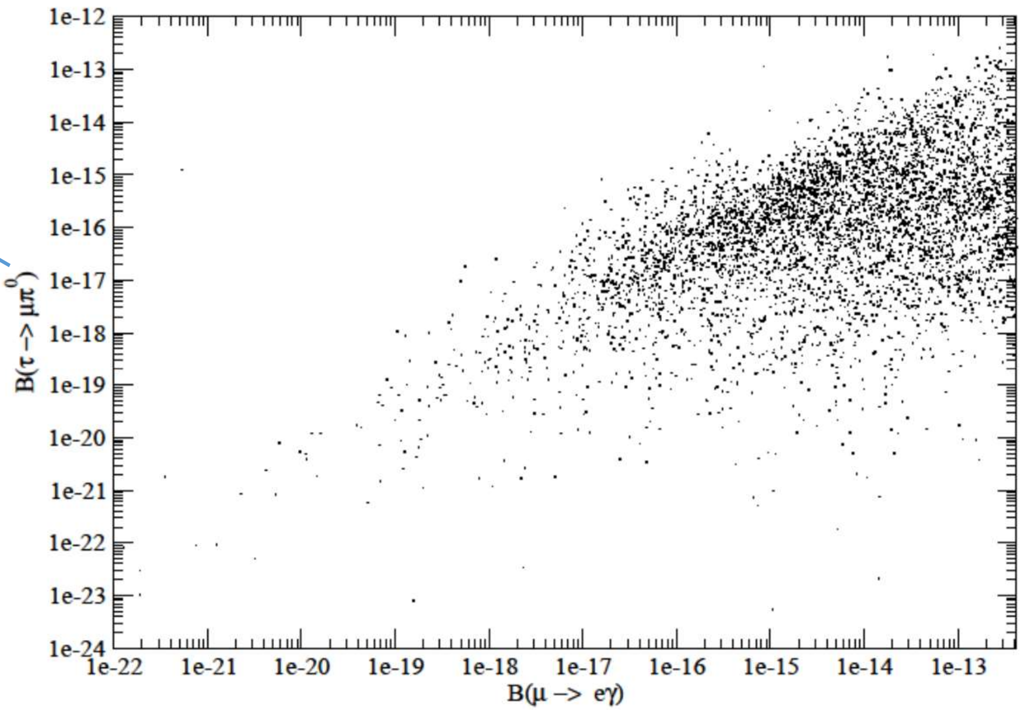

Scatter plot for reasonable values of model parameters

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Numerical results

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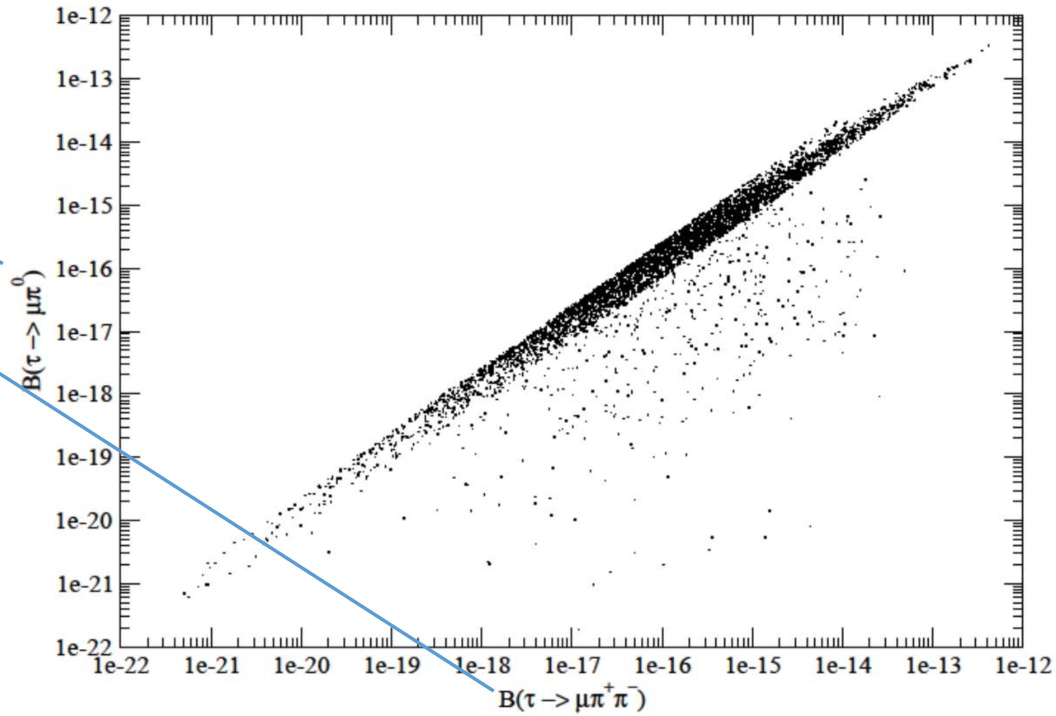

Scatter plot for reasonable values of model parameters

Numerical results

$2\,\text{TeV} < f < 10\,\text{TeV}$ ~~(GIM-like)~~ **3** heavy neutrinos $1 < t_\beta < 10$ $\delta_d \simeq \delta_s \simeq -\delta_\nu$ (small mixing for q_d)

Process	$\boxed{B \times 10^8}$ (90 % C.L.) [1]	
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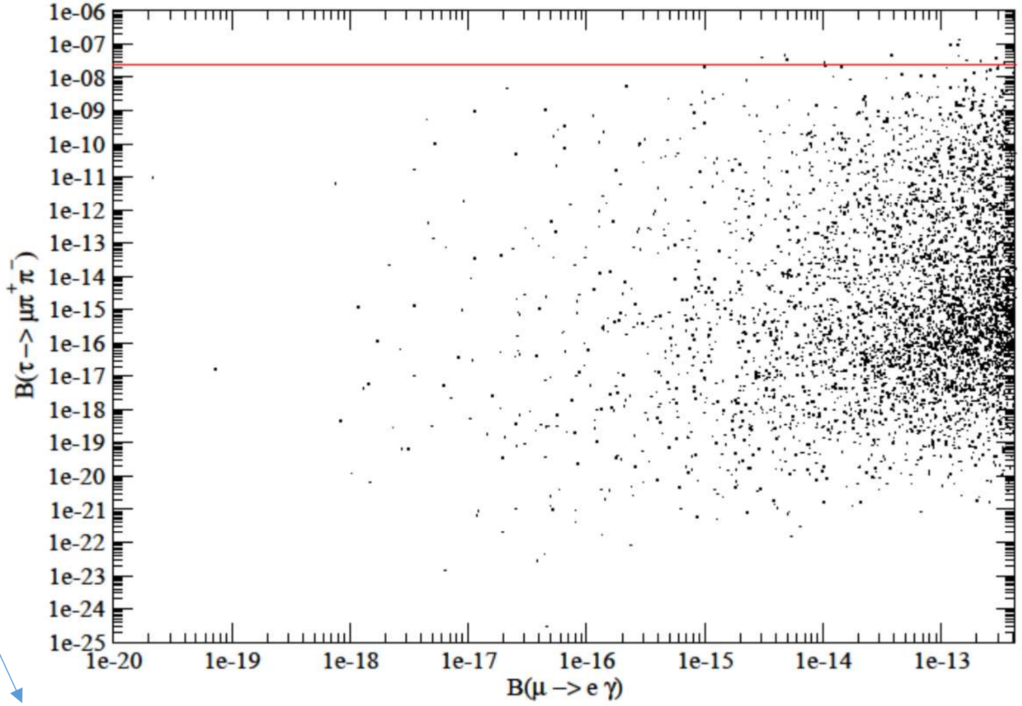

And 2 orders of magnitude improvement expected for Belle-II !!

(Vanishing CPV phase for simplicity)

$$V_\ell^{if} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$, $i = 1, 2, 3$ and $f = e, \mu, \tau$.

Numerical results

$2\,\text{TeV} < f < 10\,\text{TeV}$ ~~(GIM-like)~~ **3** heavy neutrinos $1 < t_\beta < 10$ $\delta_d \simeq \delta_s \simeq -\delta_\nu$ (small mixing for q_d)

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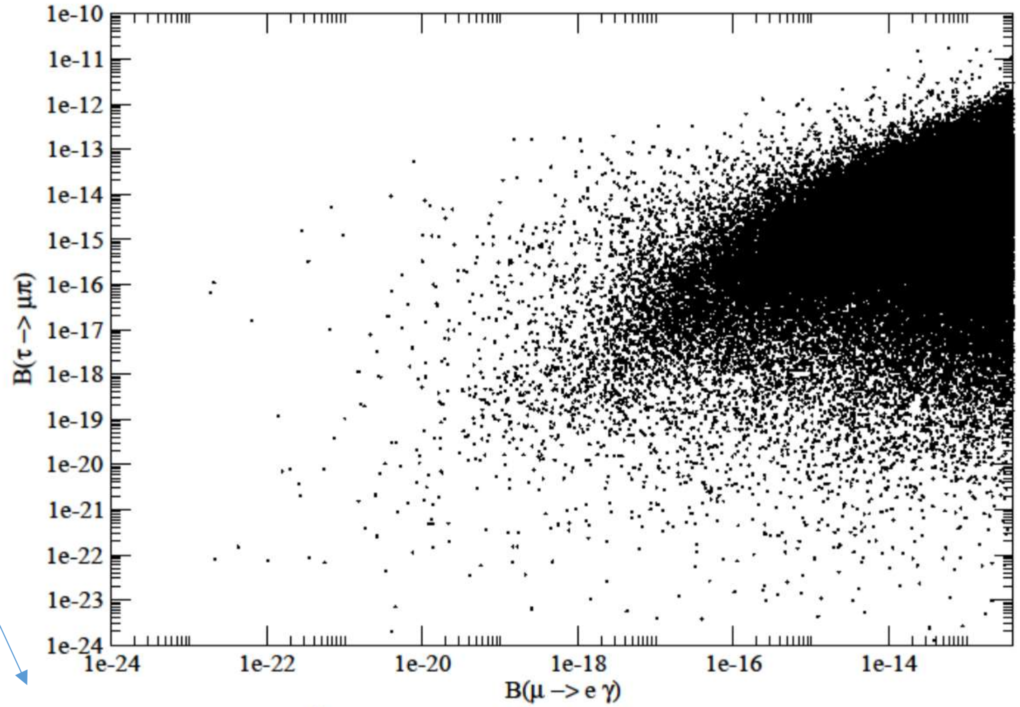

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Numerical results

$2\,\text{TeV} < f < 10\,\text{TeV}$

2 heavy neutrinos

(GIM-like)

$1 < t_\beta < 10$

$\delta_d \simeq \delta_s \simeq -\delta_\nu$ (small mixing for q_d)

Process	$\mathcal{B} \times 10^8$ (90 % C.L.) [1]	
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Respect to the UL

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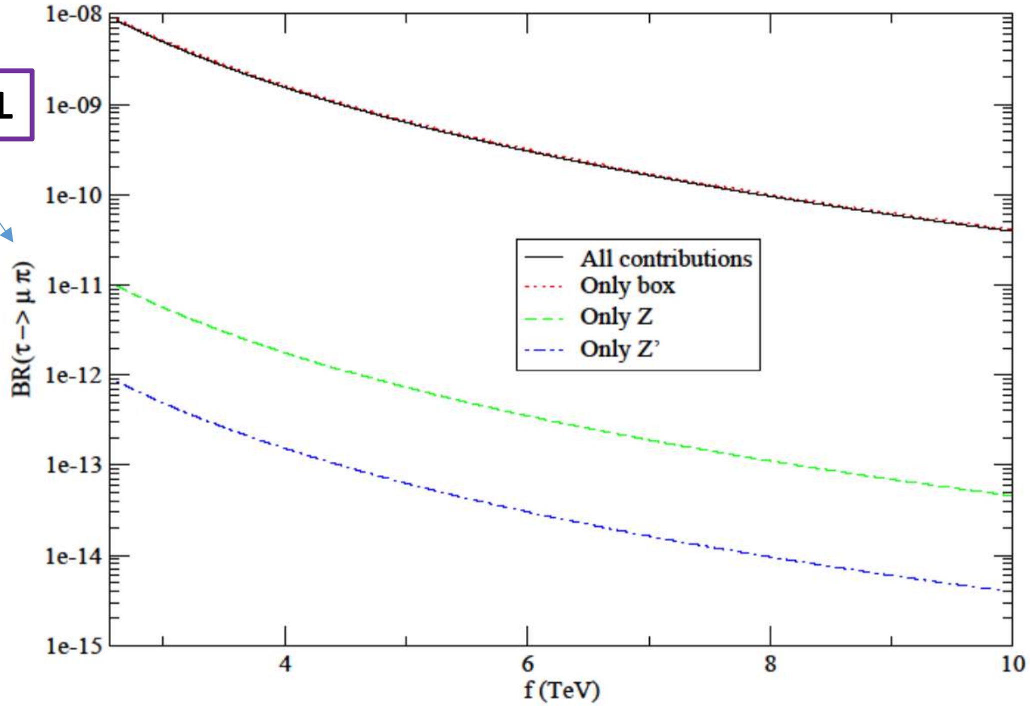

Fixed (average) values of model parameters

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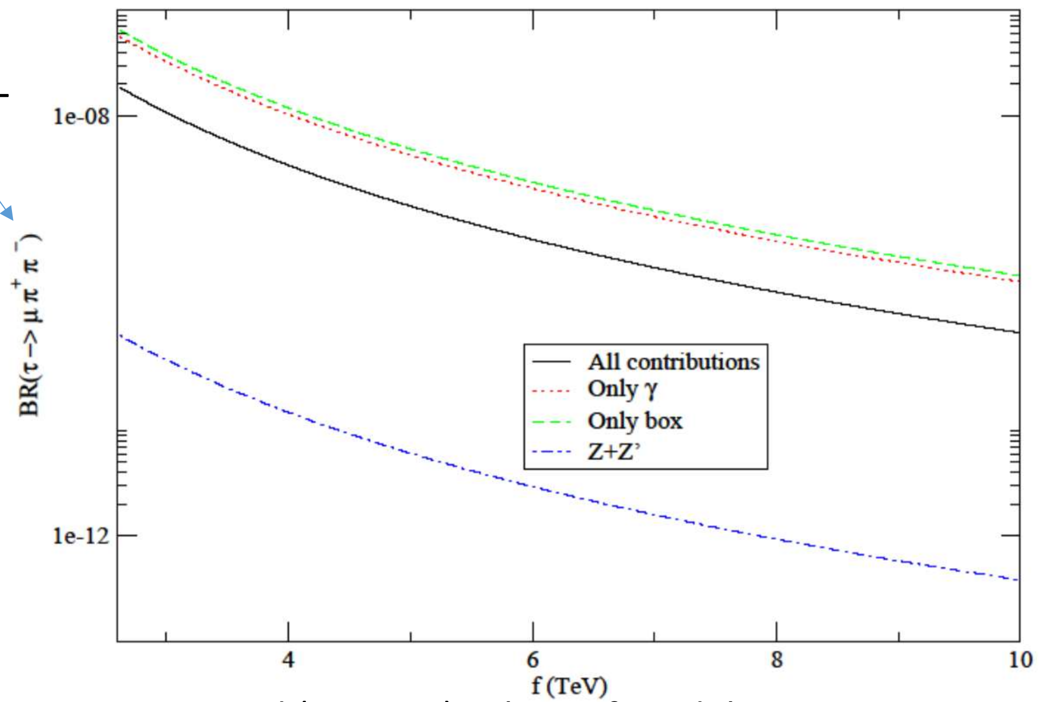

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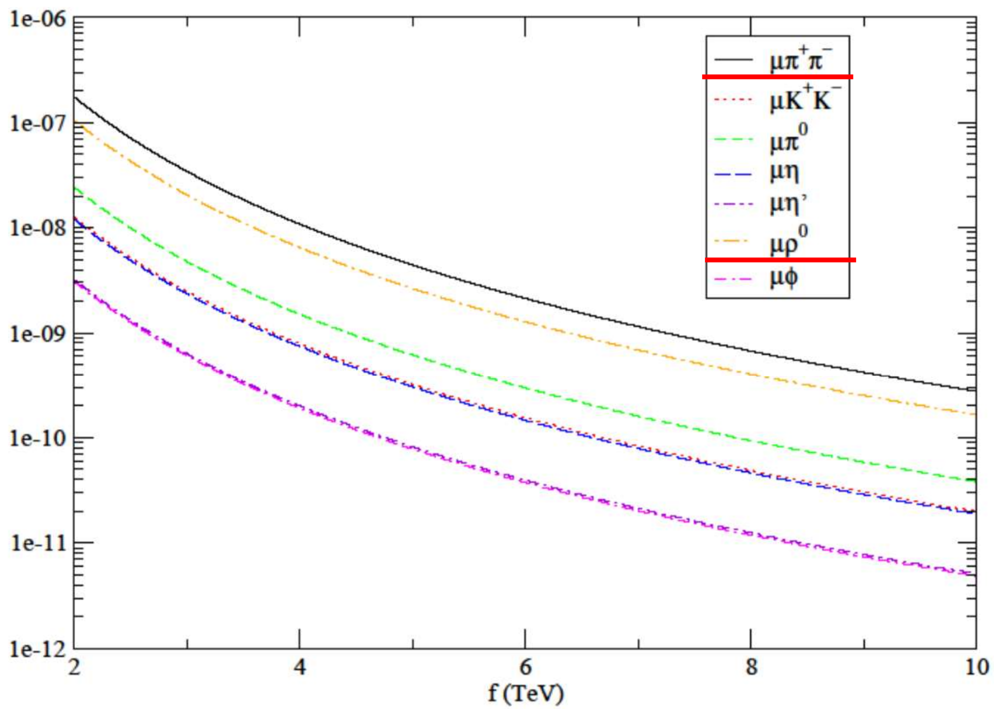
Respect to the ULs



Fixed (average) values of other parameters

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Numerical results

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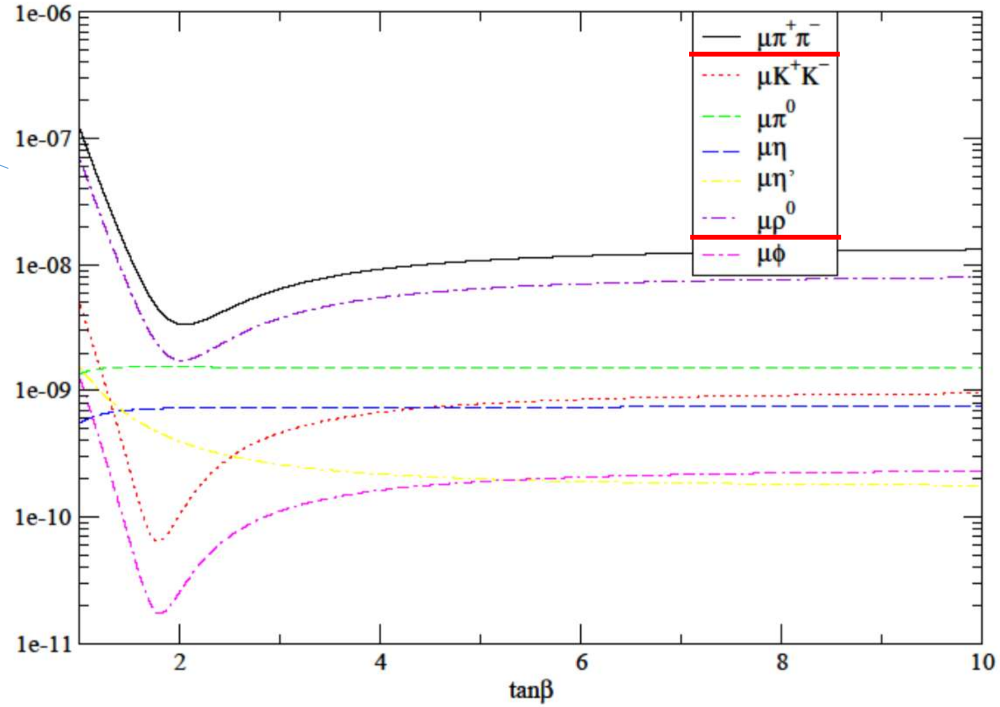
Respect to the ULs



Fixed (average) values of other parameters

And 2 orders of magnitude improvement expected for Belle-II !!

Numerical results

$2\,\mathrm{TeV} < f < 10\,\mathrm{TeV}$ 2 heavy neutrinos (GIM-like) $1 < t_\beta < 10$ $\delta_d \simeq \delta_s \simeq -\delta_\nu$ (small mixing for q_d)

Process	$\boxed{B \times 10^8}$ (90 % C.L.) [1]	
	$\ell = \mu$	$\ell = e$
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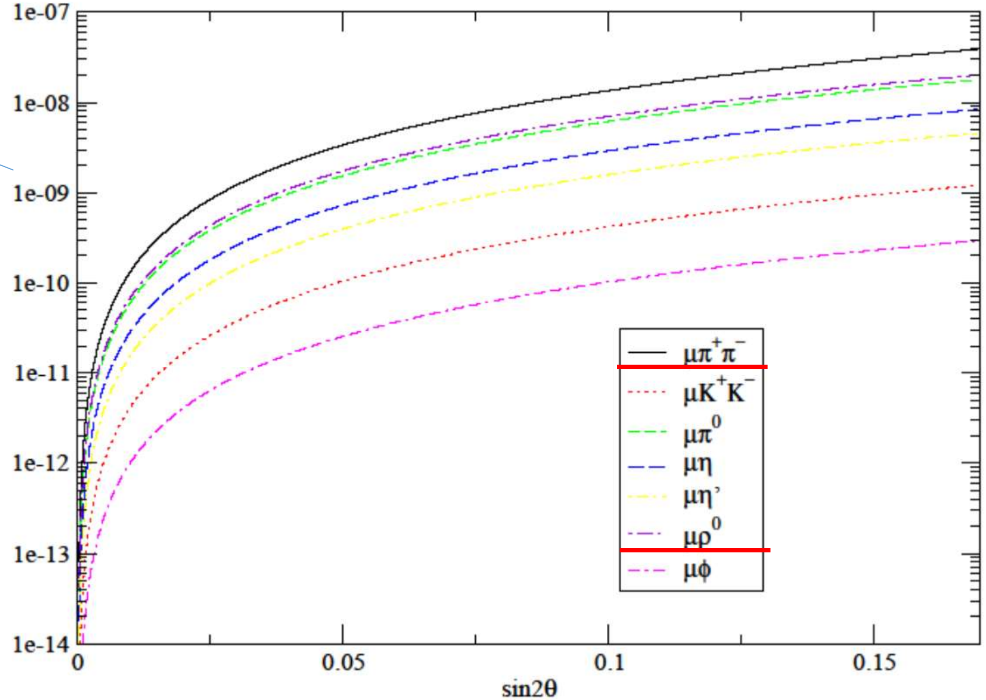

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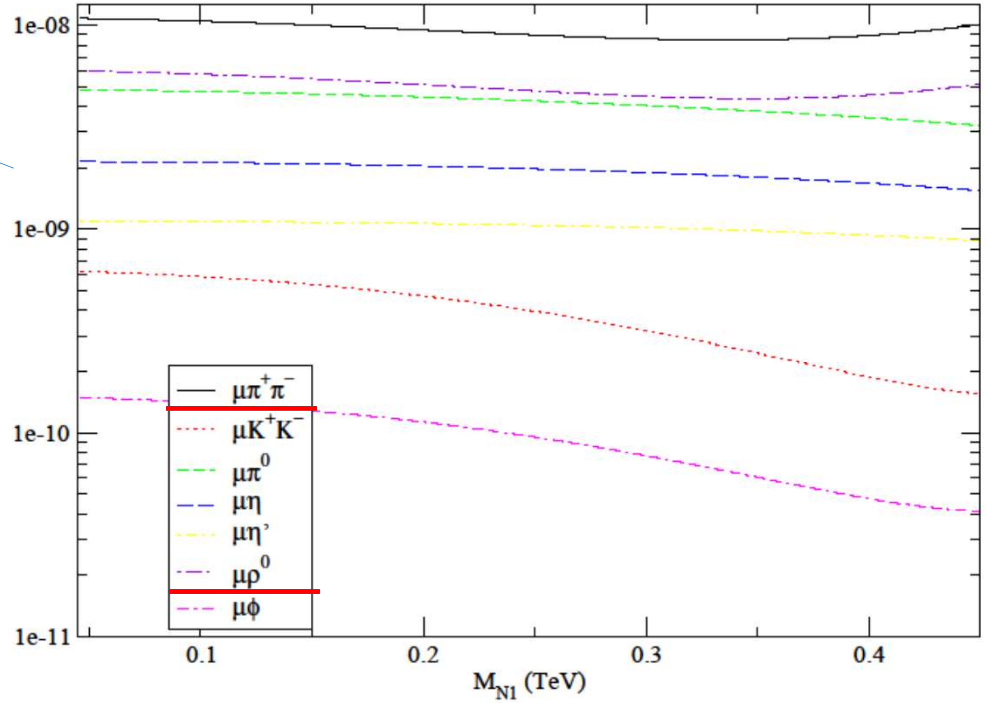
Respect to the ULs

Large splitting case for the heavy neutrinos



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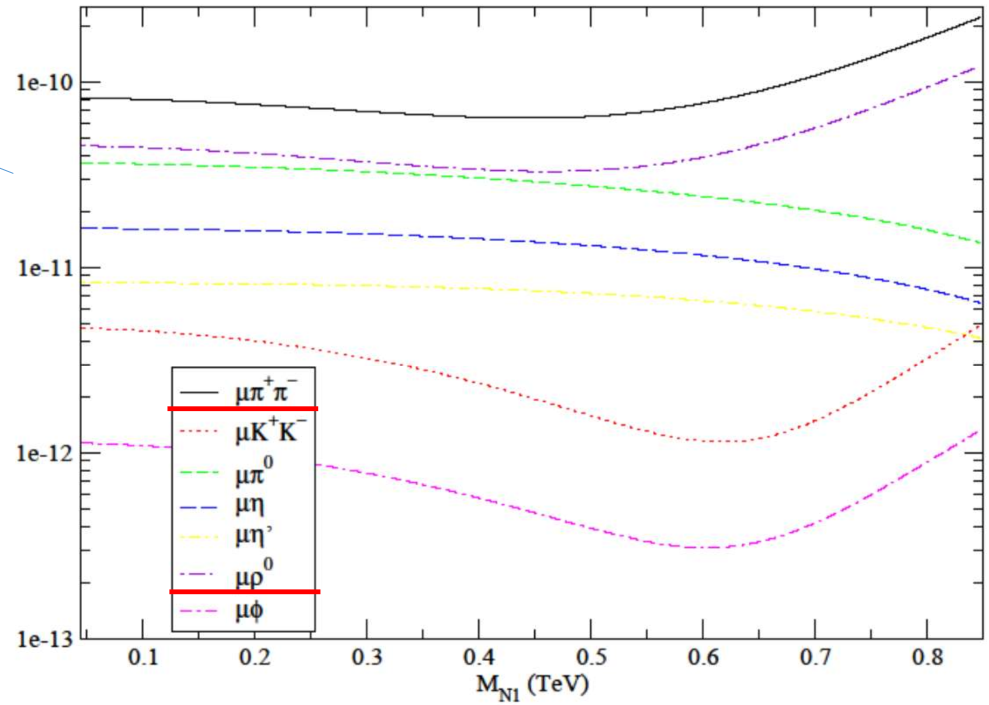

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(GIM-like)

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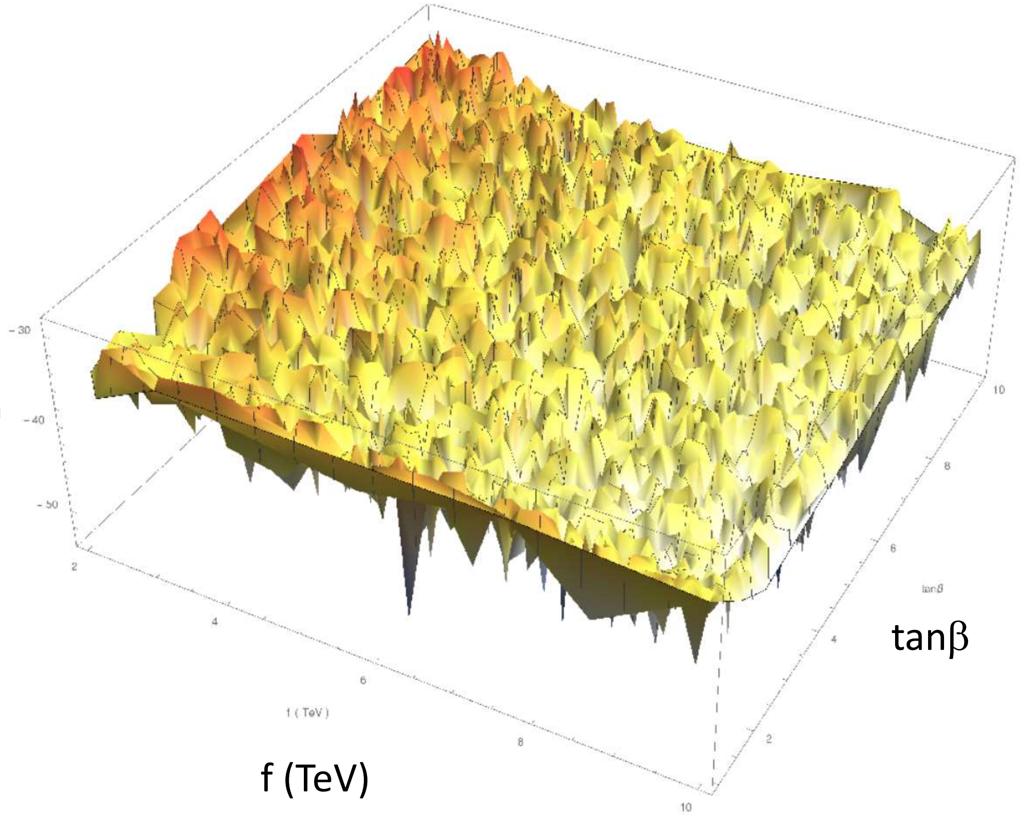
Log[BR($\mu\pi\pi$)]



Scatter plot for reasonable values of model parameters

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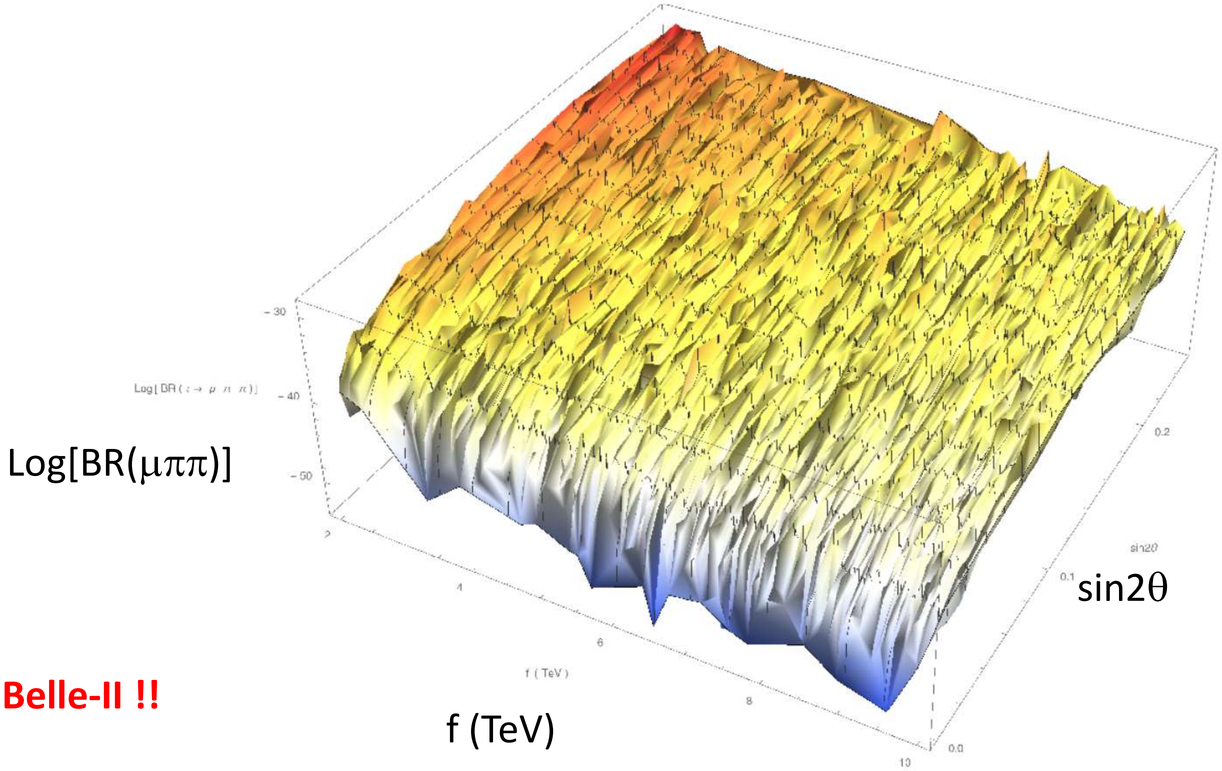

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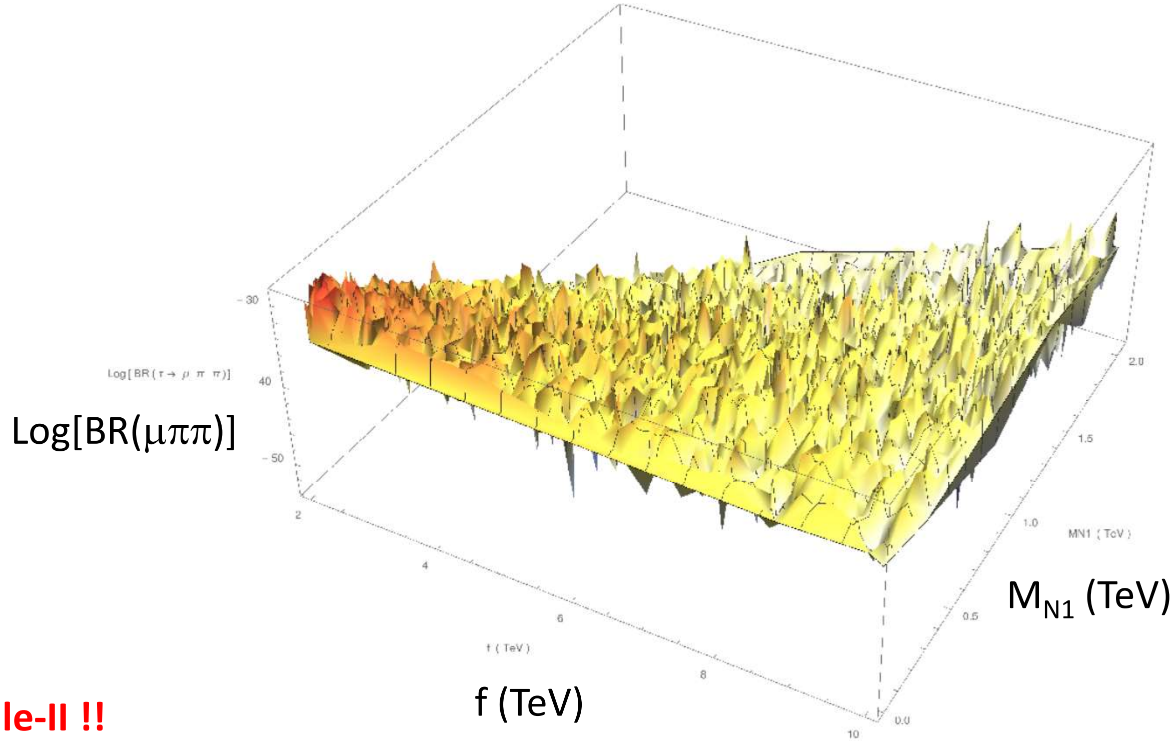

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Numerical results

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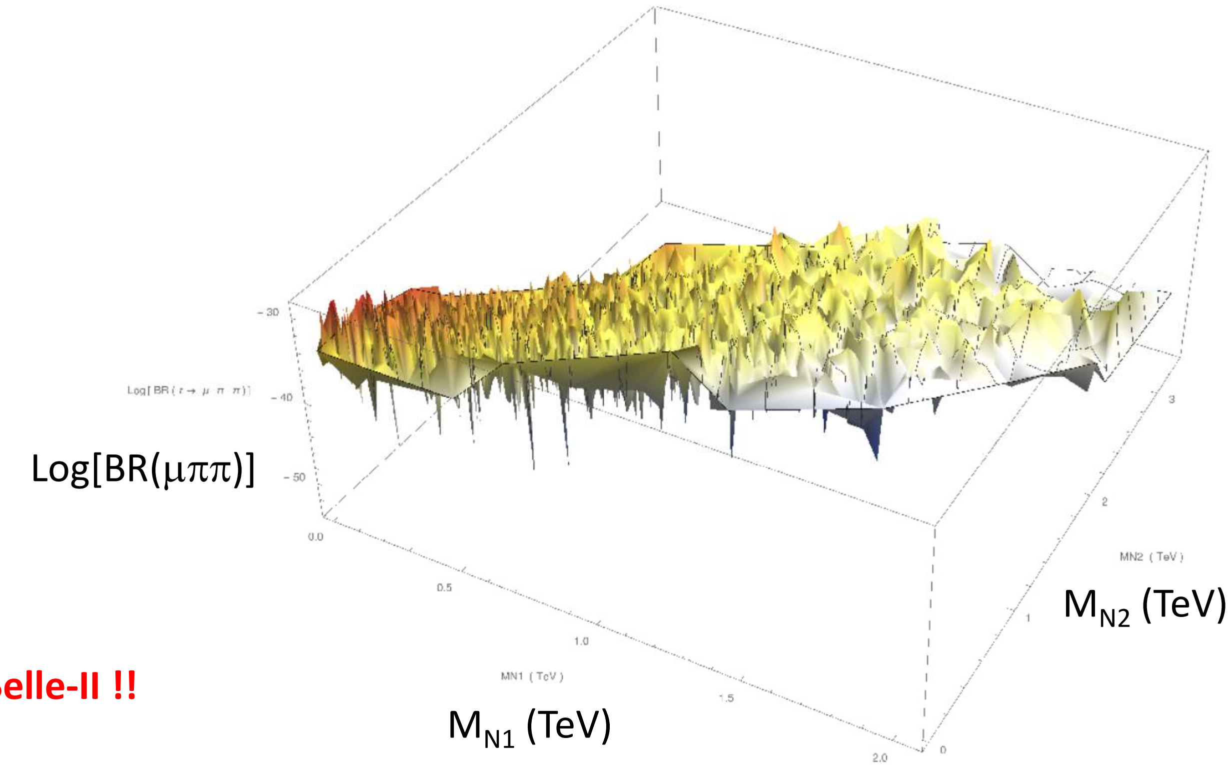

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PART II: LFV Higgs decays

Phys.Rev. D**94** no. 5, 056001 (2016)

Motivation

At the end of last century $H \to \tau\,\mu$ was proposed as a promising channel to discover flavor violation of charged leptons: Pilaftsis '92, Korner-Pilaftsis-Schilcher '93, Díaz-Cruz & Toscano '00, Han-Marfatia '00, Díaz-Cruz '03, Arganda-Curiel-Herrero-Temes '05, …

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Renewed interest in this process was motivated by the improved limits on LFV decays obtained by the B-factories and by the 2015 CMS hint of LFV Higgs decays at a rate of ~ 1 %: Kanemura et. al. '06, Díaz-Cruz et. al. '09, Bhattacharyya et. al. '11, Blakenburg et. al. '12, Harnik et. al. '13, Davidson et. al. '12, Arana-Catania et. al. '13, Celis et. al. '14, Falkowski et. al. '14, Dery et. al. '14, Aristizábal et. al. '14, Arganda et. al. '15-'16, Lee et. al. '15, Heeck et. al. '15, Crivellin et. al. '15-'16, Dorsner et. al. '15, He et. al. '15, Aloni et. al. '16, Botella et. al. '15, Baek et. al. '16, Bizot et. al. '16, Herrero-García et. al. '16, …

CMS '15: $BR(H \to \tau\mu) = \left(0.84^{+0.39}_{-0.37}\right)\% \ (< 1.51\% \text{ at } 95\% \text{ CL})$

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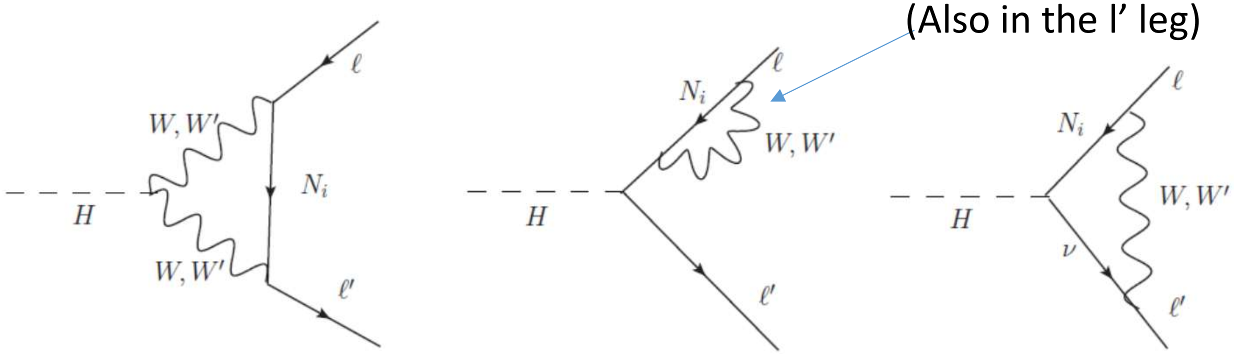
Unitary gauge throughout!!

1-loop diagrams

(Also in the l' leg)



$$\frac{M_H^2}{M_{N_j}^2} \sim \frac{M_W^2}{M_{N_j}^2} \sim \frac{M_H^2}{M_{W'}^2} \sim \frac{M_W^2}{M_{W'}^2} = \omega \sim \frac{v^2}{f^2} << 1 \qquad \frac{M_W^2}{M_H^2} \sim \frac{M_{N_j}^2}{M_{W'}^2} = \chi_j \sim \mathcal{O}(1) \qquad \delta_\nu \sim \frac{v}{f}$$

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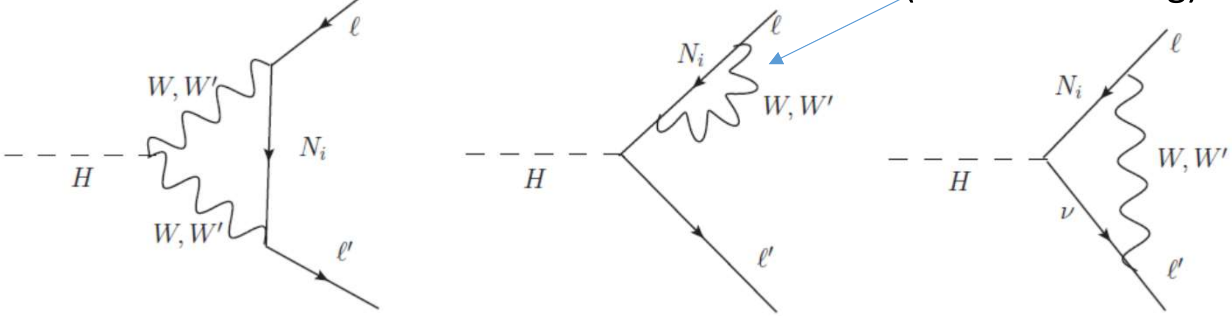

(GIM-like)

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2 heavy neutrinos

$1 < t_\beta < 10$

(3 heavy neutrino case also considered)

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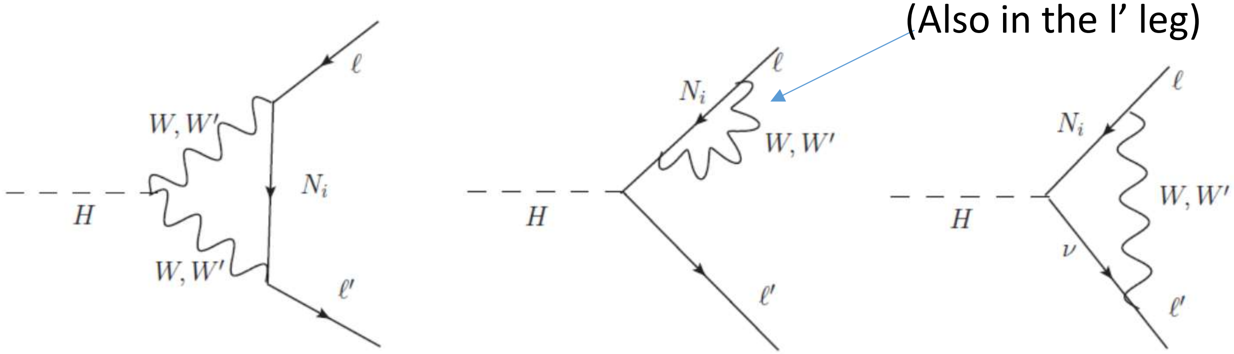

No ω-dependence in the 2 N case

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$$\mathcal{M}_H = -\frac{iv\alpha^2\delta_\nu m_\tau \sum_j V_{\tau j}V^*_{\mu j}}{s_w^3 M_W^2}\left[O\log\chi_j - P(\chi_j)\right]\bar{u}(p')P_R u(q,m_\tau)$$

$$O = \frac{\delta_\nu}{16}\frac{M_H^2 - 13M_W^2}{M_W^2}$$

$$P(\chi_j) = \cot(2\beta)\frac{M_H^2\left(3\chi_j^3 - 9\chi_j^2 + 8\chi_j - 2\right) + M_W^2\chi_j\left(12\chi_j^2 - 23\chi_j + 10\right)}{8M_{W'}M_W\chi_j\left(\chi_j - 1\right)} + \frac{\omega\left(2\chi_j^4 + 20\chi_j^3 - 74\chi_j^2 + 35\chi_j - 1\right)}{48\left(\chi_j - 1\right)^2} + \frac{\delta_\nu\chi_j}{24M_W^2\sin^2(2\beta)}\left[-5M_H^2 + 3\cos(4\beta)\left(4M_W^2 - M_H^2\right)\right]$$

$$\frac{M_H^2}{M_{N_j}^2} \sim \frac{M_W^2}{M_{N_j}^2} \sim \frac{M_H^2}{M_{W'}^2} \sim \frac{M_W^2}{M_{W'}^2} = \omega \sim \frac{v^2}{f^2} << 1 \qquad \frac{M_W^2}{M_H^2} \sim \frac{M_{N_j}^2}{M_{W'}^2} = \chi_j \sim \mathcal{O}(1) \qquad \delta_\nu \sim \frac{v}{f}$$

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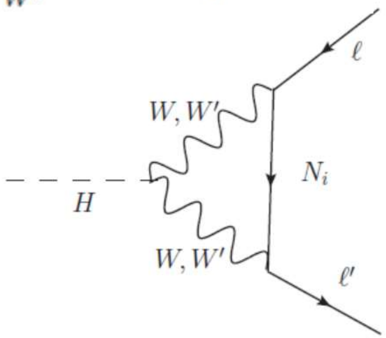

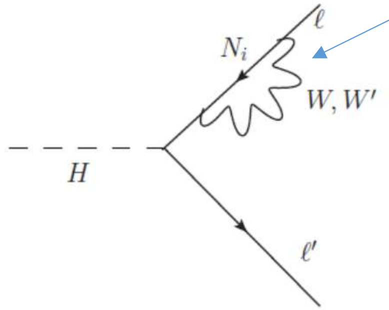

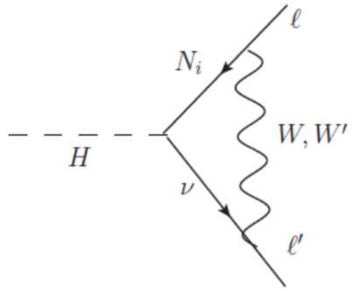

$$\frac{M_W^2}{M_H^2} \sim \frac{M_{N_j}^2}{M_{W'}^2} = \chi_j \sim \mathcal{O}(1)$$

No ω-dependence in the 2 N case

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(3 heavy neutrino case also considered)

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$$BR(H \to \tau\mu) = \frac{(M_H^2 - m_\tau^2)^2\alpha^4 v^2\delta_\nu^2 m_\tau^2}{16\pi M_H^3\Gamma_H M_W^4 s_w^6}\left(\frac{\sin 2\theta}{2}\right)^2\left[O\log\left(\frac{\chi_1}{\chi_2}\right) + P(\chi_2) - P(\chi_1)\right]^2$$

Unitary gauge throughout!!

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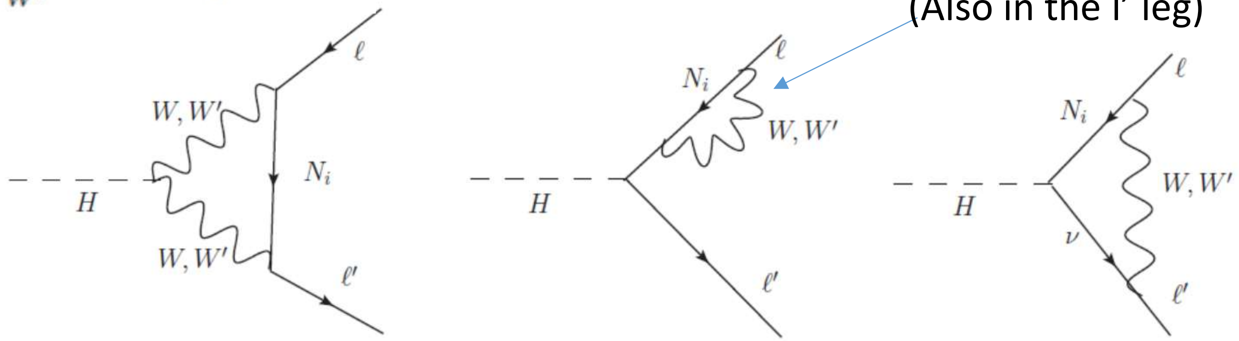

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ω-dependence in the 3 N case

$$2\,\mathrm{TeV} < f < 10\,\mathrm{TeV}$$

3 heavy neutrinos

~~(GIM-like)~~

$$1 < t_\beta < 10$$

$$V_\ell^{if} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13} & c_{12}c_{23} - s_{12}s_{23}s_{13} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{12}s_{23} - s_{12}c_{23}s_{13} & c_{23}c_{13} \end{pmatrix}$$

(Vanishing CPV phase for simplicity)

$c_{ij} \equiv \cos\theta_{ij}$, $s_{ij} \equiv \sin\theta_{ij}$, $i = 1, 2, 3$ and $f = e, \mu, \tau$.

2 heavy neutrinos → 3 heavy neutrinos: $\left(\frac{\sin 2\theta}{2}\right)^2 \left[O \log\left(\frac{\chi_1}{\chi_2}\right) + P(\chi_2) - P(\chi_1)\right]^2 \to \sum_{i=1}^{3} V_\ell^{i\mu} V_\ell^{i\tau} \left[O \log\left(\frac{\chi_i}{\omega}\right) + P(\chi_i)\right]^2$

Numerical results

$2\,\mathrm{TeV} < f < 10\,\mathrm{TeV}$ 2 & 3 heavy neutrinos $1 < t_\beta < 10$

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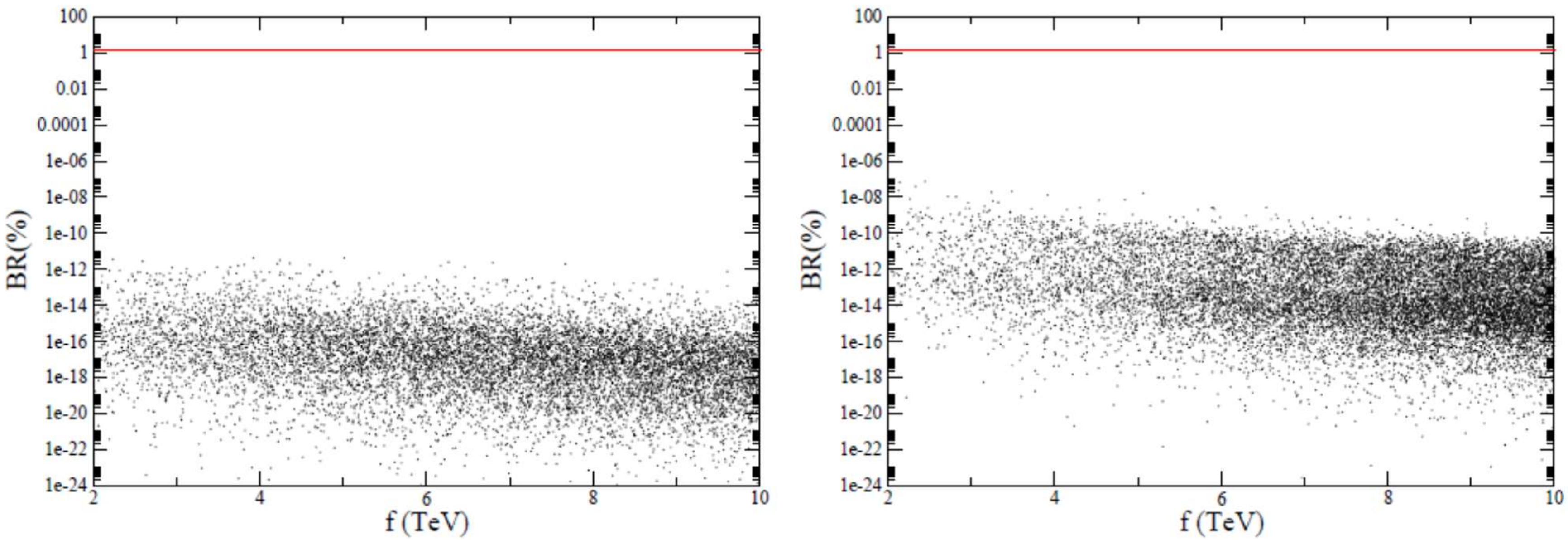

~~(GIM-like)~~

Figure 2: Dependence of the scale of compositeness, f, of the branching ratio (%) of the $H \to \tau\ell$ decays in the SLH model with two (left) and three (right) heavy neutrinos. The red line shows the 95% CL upper bound by CMS.

Numerical results

$2\,\text{TeV} < f < 10\,\text{TeV}$ 2 & 3 heavy neutrinos $1 < t_\beta < 10$

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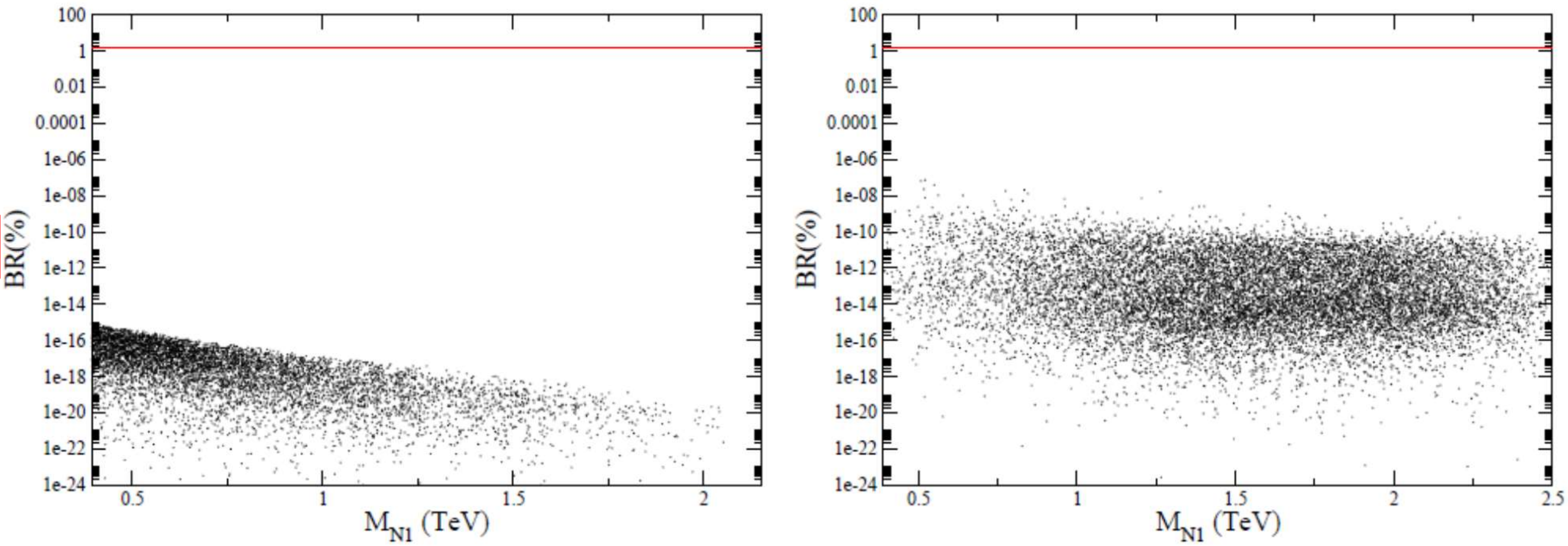


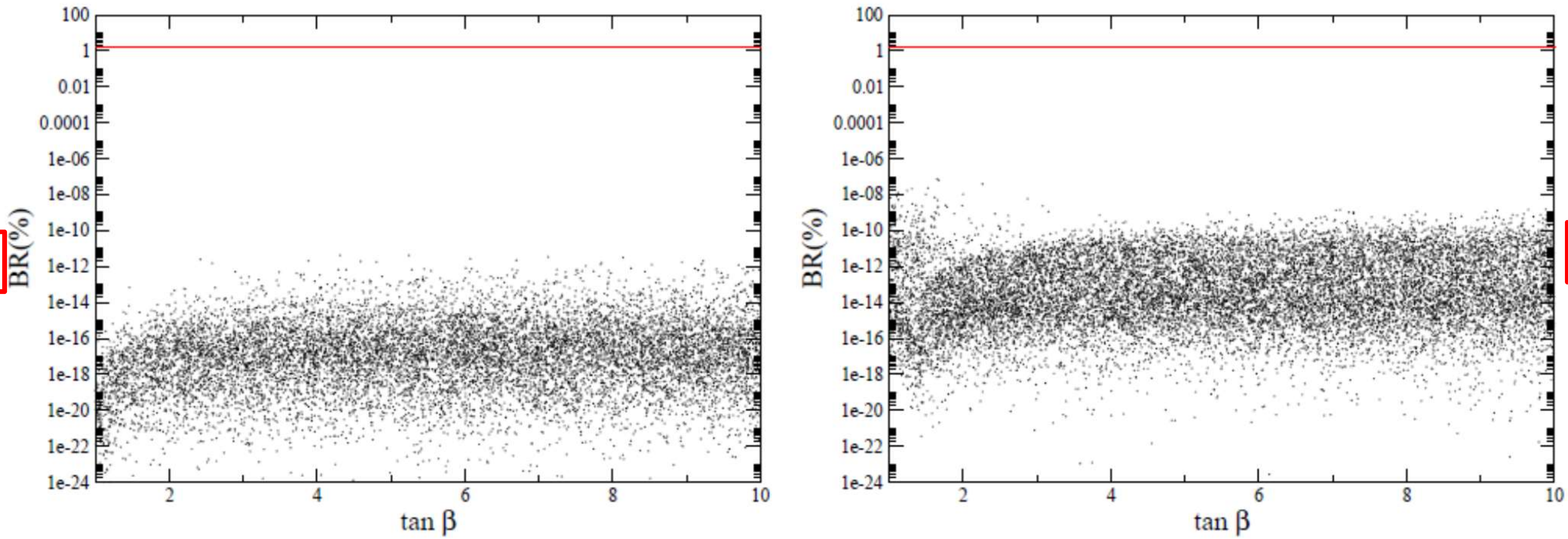
~~(GIM-like)~~

Figure 3: Dependence on the lightest mass of the heavy neutrinos, M_{N_1}, of the branching ratio (%) of the $H \to \tau\ell$ decays in the SLH model with two (left) and three (right) heavy neutrinos. The red line shows the 95% CL upper bound by CMS.

Numerical results

$2\,\mathrm{TeV} < f < 10\,\mathrm{TeV}$ 2 & 3 heavy neutrinos $1 < t_\beta < 10$

(GIM-like)



~~(GIM-like)~~

Figure 4: Dependence on the ratio of the two vevs, $\tan\beta$, of the branching ratio (%) of the $H \to \tau\ell$ decays in the SLH model with two (left) and three (right) heavy neutrinos. The red line shows the 95% CL upper bound by CMS.

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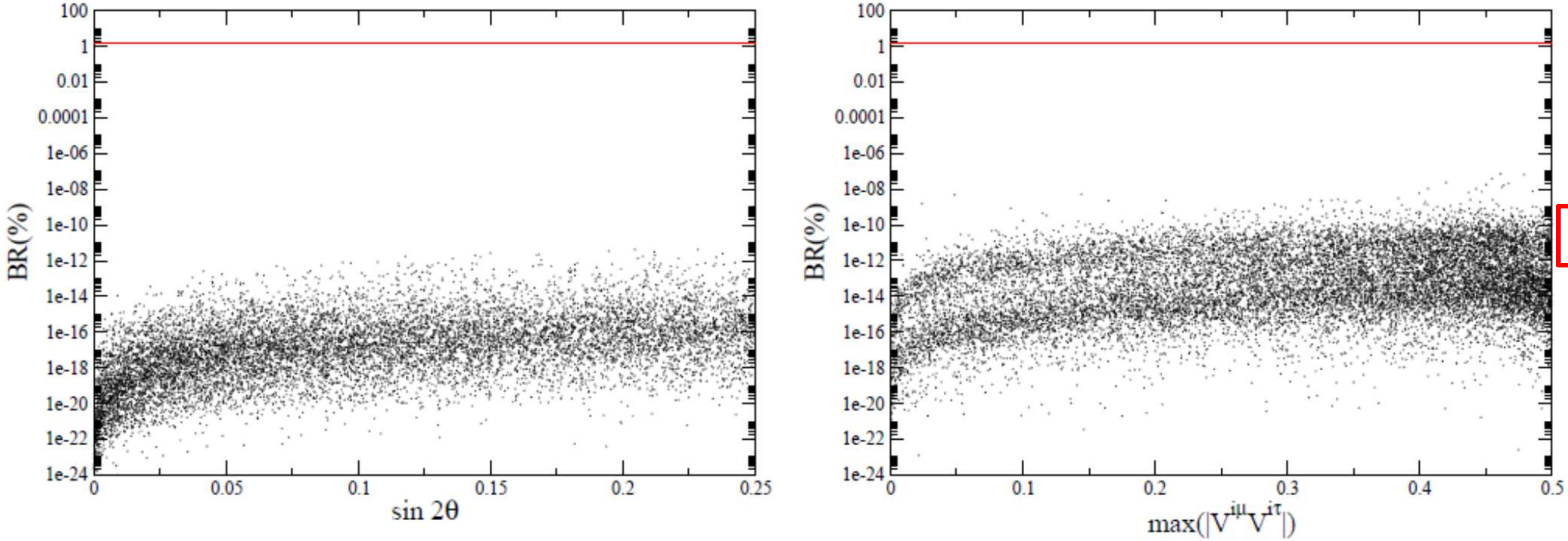

~~(GIM-like)~~

Figure 5: Left plot: Dependence of the mixing angle between the two heavy leptons, $\sin 2\theta$, of the branching ratio (%) of the $H \to \tau\ell$ decays in the SLH model. The red line shows the 95% CL upper bound by CMS. Right plot: Analogous representation for the largest mixing among heavy neutrinos, $|V_\ell^{i\mu} V_\ell^{i\tau}|$.

Numerical results

$2\,\mathrm{TeV} < f < 10\,\mathrm{TeV}$ 3 heavy neutrinos $1 < t_\beta < 10$

Small BRs for LFV Higgs decays in agreement with B. Yang et. al. '16 (LH-T)

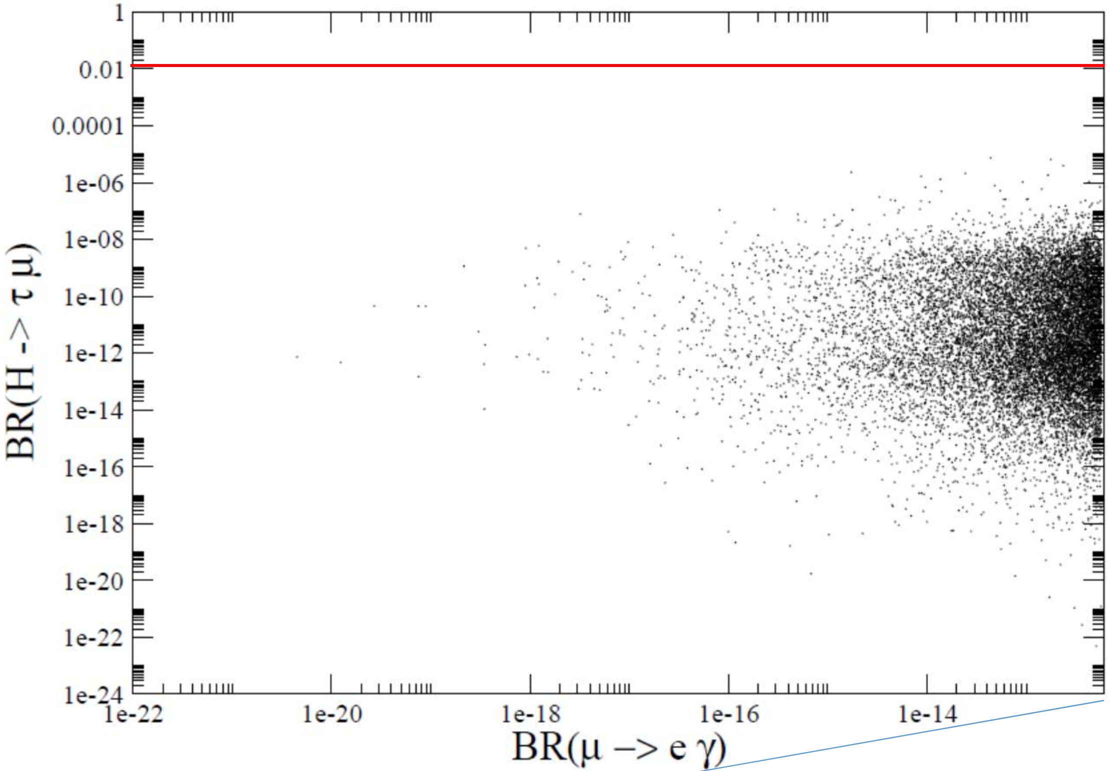

Figure 6: The correlation between the $H \to \tau\ell$ and $\mu \to e\gamma$ decays is illustrated within the SLH model in the case with three heavy neutrinos, N_k. The x-axis is cut at the current upper limit (UL) at 90% C.L. of $BR(\mu \to e\gamma)$, $5.7 \cdot 10^{-13}$ [23].

See also Moyotl et. al., poster session

~~(GIM-like)~~

Conclusions

Little Higgs models (particularly SLH) remain as elegant candidates to alleviate the hierarchy problem on the Higgs mass, respecting all experimental bounds.

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(S)LH models predict small LFV decay rates which could escape detection at Belle-II and (specially) at LHC.

Within SLH, LFV detection would be easier with 3 heavy neutrinos and for τ/μ decays

$\boxed{\text{(GIM-like)}}$

ADDITIONAL

MATERIAL

Motivation (SLH, Schmaltz '04)

- Solves the **hierarchy problem** without T-parity.
- $SU(2)_L xU(1)_Y$ from the breakdown of $SU(3)_X xU(1)$.
- Every fermion family contains a L SU(3) triplet and the corresponding R singlets. We follow the anomaly-free embedding:

$$L_k^{-1/3} = (\nu_k, \ell_k, i\boxed{N_k})_L^T\,, \qquad \ell_{kR}^{-1}, \qquad \boxed{N_{kR}^0,} \qquad k = 1,2,3$$

$$\begin{aligned} Q_1^0 &= (d, -u, i\boxed{D})_L^T\,, & d_R^{-1/3},\ u_R^{2/3},\ & \boxed{D_R^{-1/3},} \\ Q_2^0 &= (s, -c, i\boxed{S})_L^T\,, & s_R^{-1/3},\ c_R^{2/3},\ & \boxed{S_R^{-1/3},} \\ Q_3^{1/3} &= (t, b, i\boxed{T})_L^T\,, & b_R^{-1/3},\ t_R^{2/3},\ & \boxed{T_R^{2/3},} \end{aligned}$$

- Gauge part: $D_\mu = \partial_\mu - i\,g\,A_\mu + i\,g_x\,y_x\,B_\mu^x \qquad g_x = g\,t_W/\sqrt{1-t_W^2/3}$

$$A_\mu = A_\mu^3 \frac{\lambda^3}{2} + A_\mu^8 \frac{\lambda^8}{2} + \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & W^+ & Y^0 \\ W^- & 0 & W'^- \\ Y^{0\dagger} & W'^+ & 0 \end{pmatrix}_\mu$$

$$M_{W'} \simeq \frac{g\,f}{\sqrt{2}} \left(1 - \frac{v^2}{4f^2}\right),$$

$$M_{Z'} = g\,f\sqrt{\frac{2}{3-t_W^2}} \left(1 - \frac{3-t_W^2}{c_W^2}\,\frac{v^2}{16f^2}\right)$$

- Two complex scalar fields, triplets under SU(3):

$$\mathcal{L}_\Phi = (D_\mu \Phi_1)^\dagger D^\mu \Phi_1 + (D_\mu \Phi_2)^\dagger D^\mu \Phi_2$$

- Scalar potential with $[SU(3)xU(1)]^2$ symmetry, breaking to $[SU(2)xU(1)]^2$ with vevs of order f and NGBs. The (gauged) diagonal subgroup $SU(3)_L xU(1)_X$ breaks down to the SM EW group via the vevs. The scalar multiplets are given by non-linear sigma models (including the SM Higgs and new NGBs):

$$\Phi_1 = \exp\left(i\frac{\Theta'}{f}\right) \exp\left(i t_\beta \frac{\Theta}{f}\right) \begin{pmatrix} 0 \\ 0 \\ f\,c_\beta \end{pmatrix}$$

$$\Phi_2 = \exp\left(i\frac{\Theta'}{f}\right) \exp\left(-\frac{i}{t_\beta}\frac{\Theta}{f}\right) \begin{pmatrix} 0 \\ 0 \\ f\,s_\beta \end{pmatrix}$$

$$t_\beta \equiv \tan\beta = f_1/f_2,\ s_\beta \equiv \sin\beta,\ c_\beta = \cos\beta \text{ and } f^2 = f_1^2 + f_2^2.$$

SLH model

SU(3)

$$Z' \to Z' + \delta_Z Z,\; Z \to Z - \delta_Z Z'$$

$$\delta_Z = \frac{1-t_W^2}{8c_W}\sqrt{3-t_W^2}\,\frac{v^2}{f^2}$$

$$\mathcal{L}_V + \mathcal{L}_\psi = -\frac{1}{2}Tr\,(G_{\mu\nu}G^{\mu\nu}) + \overline{\psi}_k\, i\,\not{D}\,\psi_k\,,$$

$$G_{\mu\nu} = (i/g)\,[D_\mu, D_\nu] \text{ and } \psi_k = \{L_k, \ell_{kR}, N_{kR}\}$$

$$\mathcal{L}_q = \overline{Q}_k\, i\not{D}_k\, Q_k + \overline{q_u}_R\, i\not{D}^u\, q_{uR} + \overline{q_d}_R\, i\not{D}^d\, q_{dR} + \overline{T}_R\, i\not{D}^u\, T_R + \overline{D}_R\, i\not{D}^d\, D_R + \overline{S}_R\, i\not{D}^d\, S_R\,,$$

$$q_u = \{u,c,t\},\; q_d = \{d,s,b\}$$

$$D_{\{1,2\}\,\mu} = \partial_\mu + i\,g\,A_\mu^*\,,$$

$$D_{3\,\mu} = \partial_\mu - i\,g\,A_\mu + \frac{i}{3}\,g_x\,B_\mu^x\,,$$

$$D_\mu^u = \partial_\mu + i\,\frac{2}{3}\,g_x\,B_\mu^x\,,\quad D_\mu^d = \partial_\mu - \frac{i}{3}\,g_x\,B_\mu^x$$

$$\mathcal{L}_Y = i\,\lambda_N^k\,\overline{N}_{kR}\Phi_2^\dagger\,L_k + i\,\frac{\lambda_\ell^{kl}}{\Lambda}\,\overline{\ell}_{kR}\,\varepsilon_{m\,n\,p}\,\Phi_1^m\,\Phi_2^n\,L_l^p + h.c.\,,$$

$$\begin{pmatrix}\nu_i\\ N_i\end{pmatrix}_L \longrightarrow \begin{pmatrix}1-\frac{\delta_\nu^2}{2} & -\delta_\nu\\ \delta_\nu & 1-\frac{\delta_\nu^2}{2}\end{pmatrix}\begin{pmatrix}V_\ell^{ij}\nu_j\\ N_i\end{pmatrix}_L$$

$$\delta_\nu = -\frac{1}{\sqrt{2}\,t_\beta}\,\frac{v}{f}$$

$$m_{N_i} = f\,s_\beta\,\lambda_N^i$$

$$P_L \to P_L + \delta_p p_L \text{ and } p_L \to p_L - \delta_p P_L \text{ for } P = \{T,D,S\} \text{ and } p = \{t,d,s\}$$

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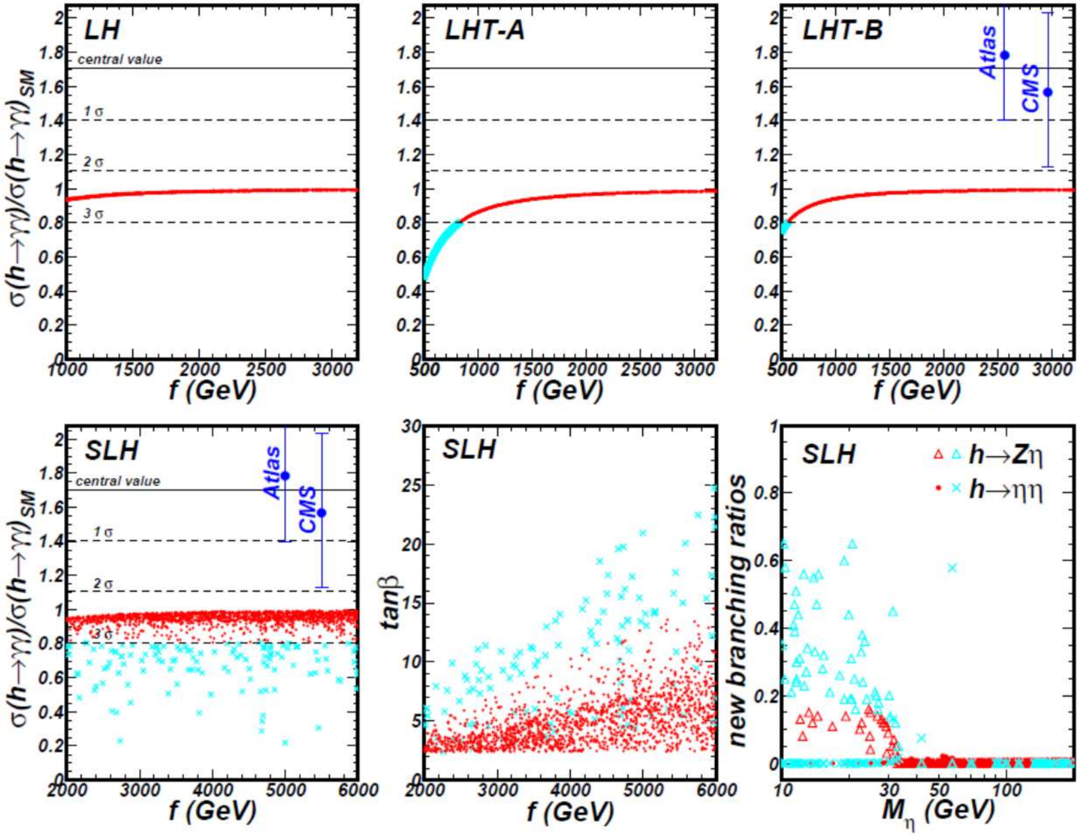

LH models vs LHC data: Han, Wang, Yang, Zhu '13

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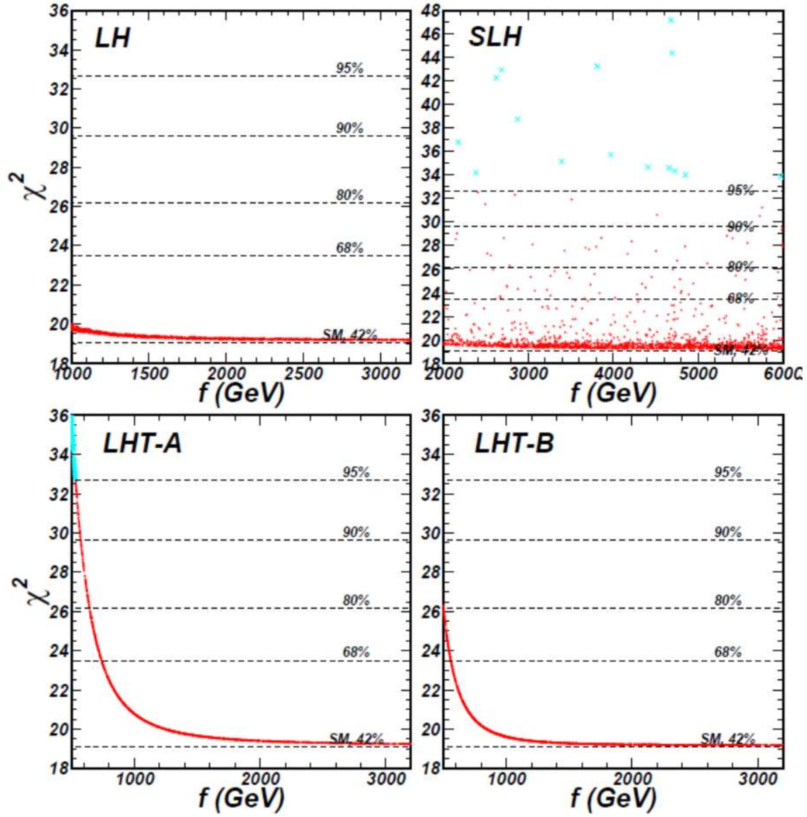

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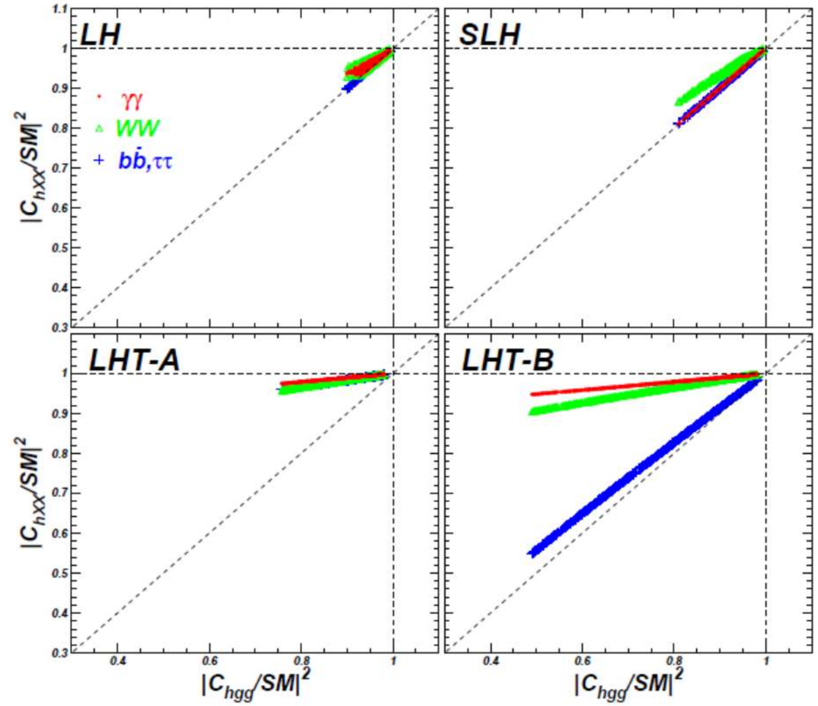

FIG. 4: The scatter plots of the parameter space showing the Higgs couplings normalized to the SM values. These samples satisfy the conditions: (i) within the 3σ range of the diphoton data; (ii) within the 2σ range of the ZZ^* data; (iii) $\chi^2 \leq 32.7$ (corresponding to 95% C.L.).

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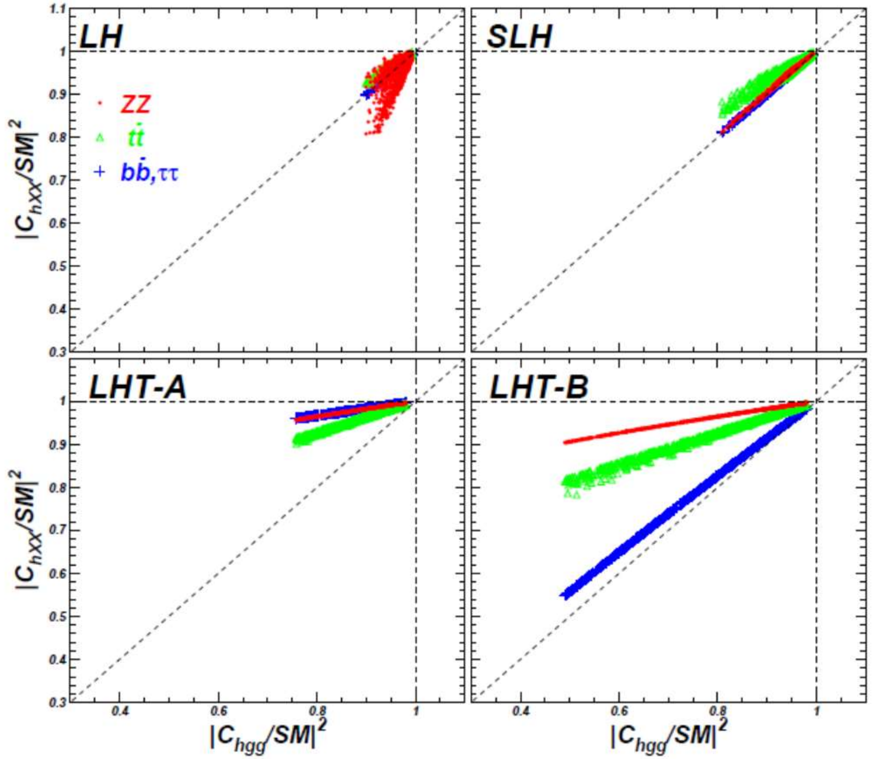
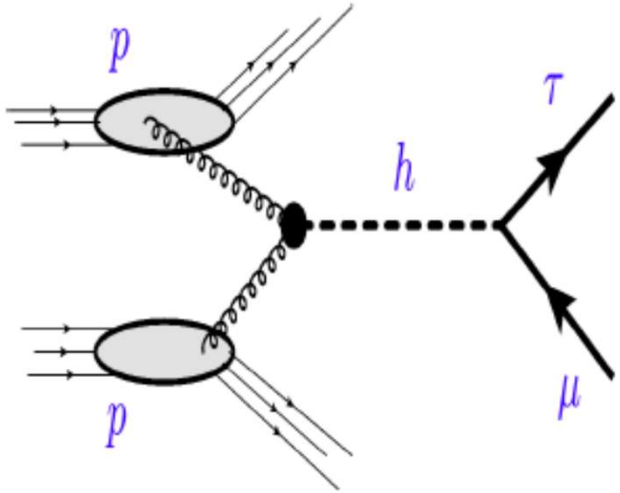


FIG. 5: Same as Fig. 4, but showing different couplings.

(Celis, Cirigliano, Passemar, '14)

Higgs contribution to semileptonic LFV tau decays



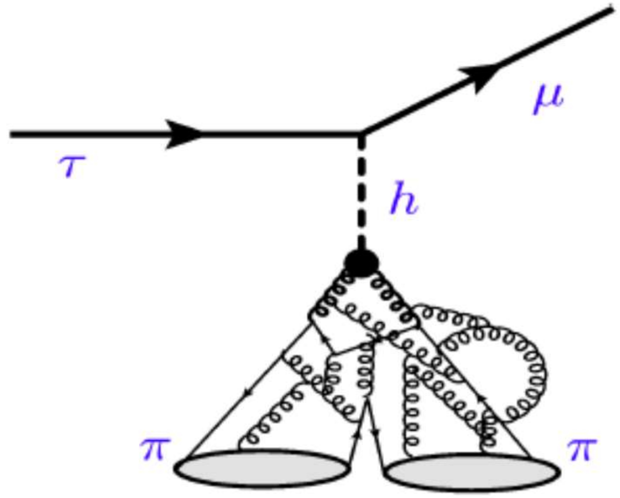


Figure 1: *Relation between the LHC process $pp(gg) \to h \to \tau\mu$ (left figure) and the semileptonic decay $\tau \to \mu\pi\pi$ (right figure): the effective Higgs coupling to gluons enters in both processes.*

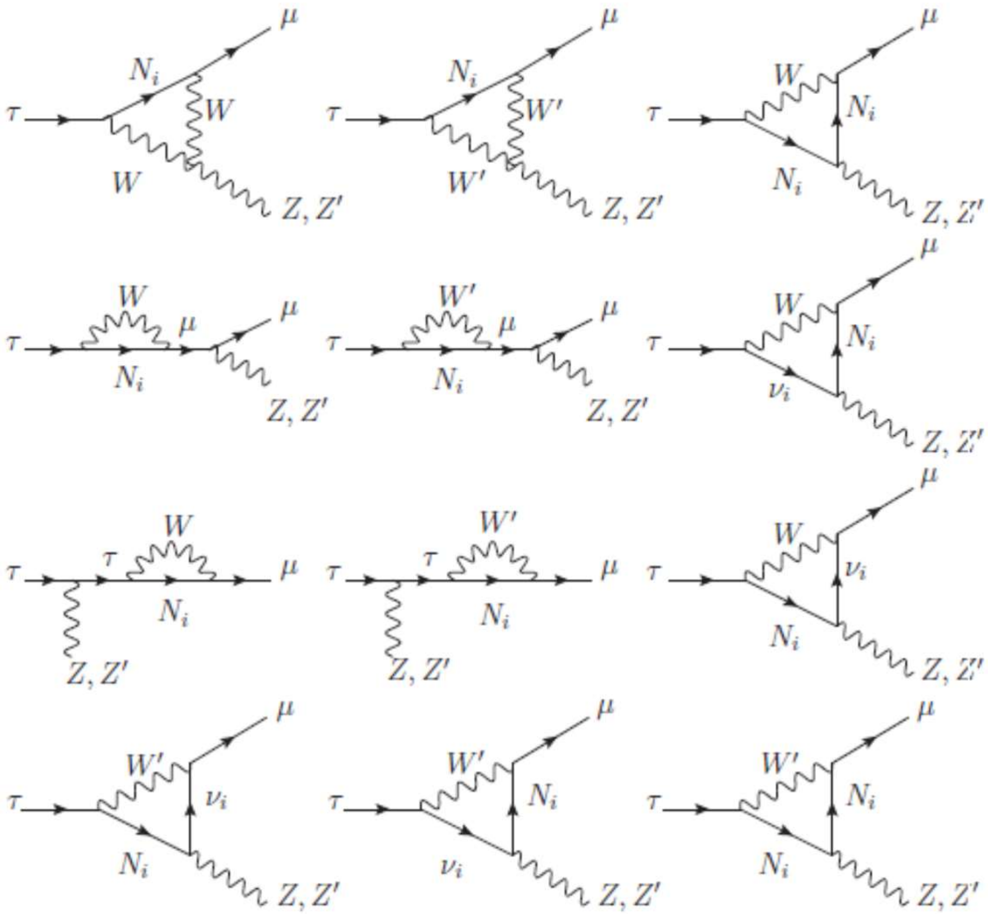
$$\begin{aligned}\langle \pi^+(p_{\pi^+})\pi^-(p_{\pi^-})|m_u\bar{u}u + m_d\bar{d}d|0\rangle &\equiv \Gamma_\pi(s)\\ \langle \pi^+(p_{\pi^+})\pi^-(p_{\pi^-})|m_s\bar{s}s|0\rangle &\equiv \Delta_\pi(s)\\ \langle \pi^+(p_{\pi^+})\pi^-(p_{\pi^-})|\theta^\mu_\mu|0\rangle &\equiv \theta_\pi(s)\end{aligned}$$

$$\theta^\mu_\mu = -9\frac{\alpha_s}{8\pi}G^a_{\mu\nu}G^{\mu\nu}_a + \sum_{q=u,d,s} m_q\bar{q}q$$

General contribution: Independent of LFV model used !!

Z & Z’ contributions

Unitary gauge throughout!!



$\mathcal{O}(m_\tau^2/M_Z^2)$

$$\mathcal{T}_Z = \frac{g}{M_Z^2}\sum_j V_\ell^{j\mu *} V_\ell^{j\tau}\,\overline{\mu}(p')\left[\gamma_\mu\left(H_L^j P_L + H_R^j P_R\right)\right]\tau(p)$$
$$\times\overline{q}(p_q)\left[\gamma^\mu\left(Z_L P_L + Z_R P_R\right)\right]q(p_{\overline{q}}),$$
$$\mathcal{T}_{Z'} = \frac{g}{M_{Z'}^2}\sum_j V_\ell^{j\mu *} V_\ell^{j\tau}\,\overline{\mu}(p')\left[\gamma_\mu\left(\widetilde{H}_L^j P_L + \widetilde{H}_R^j P_R\right)\right]\tau(p)$$
$$\times\,\overline{q}(p_q)\left[\gamma^\mu\left(Z'_L P_L + Z'_R P_R\right)\right]q(p_{\overline{q}}),$$

$\mathcal{O}(m_\tau^2/M_Z^2)$

$$H_L^j = \frac{\alpha_W}{32\pi}\left\{\frac{\delta_Z}{c_W^2\sqrt{3-t_W^2}}\times\right.$$
$$\left[\left(3\chi_j(\chi_j-2) - 2c_W^2(7\chi_j^2 - 14\chi_j + 4)\right)\frac{\chi_j\ln\chi_j}{(\chi_j-1)^2}\right.$$
$$\left.+\frac{-5\chi_j^2 + 5\chi_j + 6 + 6c_W^2\left(3\chi_j^2 - \chi_j - 4\right)}{2(\chi_j-1)}\right]$$
$$\left.-\delta_\nu^2\,\frac{2\chi_j^2 - 5\chi_j + 3}{c_W(\chi_j-1)}\right\},$$
$$\widetilde{H}_L^j = \frac{\alpha_W}{32\pi}\frac{1}{c_W^2\sqrt{3-t_W^2}}\times$$
$$\left[\left(3\chi_j(\chi_j-2) - 2c_W^2(7\chi_j^2 - 14\chi_j + 4)\right)\frac{\chi_j\ln\chi_j}{(\chi_j-1)^2}\right.$$
$$\left.+\frac{-5\chi_j^2 + 5\chi_j + 6 + 6c_W^2\left(3\chi_j^2 - \chi_j - 4\right)}{2(\chi_j-1)}\right].$$

$$\delta_Z = \frac{1-t_W^2}{8c_W}\sqrt{3-t_W^2}\,\frac{v^2}{f^2}$$

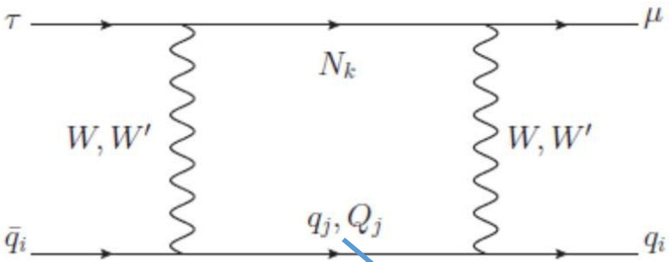
$$\alpha_W \equiv \alpha/s_W^2\,.$$

$$\text{O(1)} \longrightarrow \chi_j = M_{N_j}^2/M_{W'}^2$$

$$\delta_\nu = \frac{-1}{\sqrt{2}\tan\beta}\frac{v}{f}$$

Unitary gauge throughout!!

Box contributions



(Del Águila-Illana-Jenkins '11)

The internal quark states are $(u, \overline{u}) \to \{d, D\}$, $(d, \overline{d}) \to \{u\}, (s, \overline{s}) \to \{c\}$.

$$B_q^j = \frac{\alpha_W}{64\pi}\left[\alpha_q^j \ln\chi_j + \beta_q^j \ln\delta + \gamma_q^j\right]$$

$$\alpha_u^j = \frac{1}{M_W^2(\chi_j-\delta)}\left\{\frac{3\chi_j\delta\delta_\nu(\delta_d^*+\delta_d)}{(\chi_j-1)} - \delta^2\delta_\nu(\delta_d^*+\delta_d) + \frac{\chi_j(6-13\chi_j)}{(\chi_j-1)^2}\frac{M_W^2}{M_{W'}^2} + (\delta^2-6\delta)\frac{M_W^2}{M_{W'}^2} + \delta^2\delta_d^2\delta_\nu^2\frac{M_{W'}^2}{M_W^2}\right\},$$

$$\alpha_d^j = \frac{3\,\delta_\nu}{M_W^2(\chi_j-1)}\,(\delta_d^*+\delta_d)\,,$$

$$\alpha_s^j = \frac{3\,\delta_\nu}{M_W^2(\chi_j-1)}\,(\delta_s^*+\delta_s)\,,$$

$$\underline{\delta = m_D^2/M_{W'}^2}$$

$$\delta_d \simeq \delta_s \simeq -\delta_\nu$$

(small mixing for q_d)

$$\delta_\nu = \frac{-1}{\sqrt{2}\tan\beta}\frac{v}{f}$$

$$\alpha_W \equiv \alpha/s_W^2\,.$$

O(1) → $\chi_j = M_{N_j}^2/M_{W'}^2$

$$\delta_Z = \frac{1-t_W^2}{8c_W}\sqrt{3-t_W^2}\,\frac{v^2}{f^2}$$

$$\mathcal{T}_B = g^2\sum_q^{u,d,s}\sum_j V_\ell^{j\mu *}V_\ell^{j\tau}\,B_q^j \times \overline{\mu}(p')\gamma_\mu P_L\tau(p)\cdot\overline{\psi_q}(p_q)\gamma^\mu P_L\psi_q(p_{\overline{q}})$$

$\psi_q = \{u, d, s\}$

$$\beta_u^j = \frac{\delta^2}{M_W^2(\delta-\chi_j)}\left\{\delta_d^2\delta_\nu^2\frac{M_{W'}^2}{M_W^2} + \frac{\delta(\delta-8)}{(\delta-1)^2}\frac{M_W^2}{M_{W'}^2} - \delta_\nu(\delta_d^*+\delta_d)\frac{\delta^2-5\delta+4}{(\delta-1)^2}\right\},$$

$$\beta_d^j = \beta_s^j = 0\,,$$

$$\gamma_u^j = -\frac{1}{2M_W^2}\left\{3\,\delta_\nu^2\,\delta_d^2\,\chi_j\frac{M_{W'}^2}{M_W^2} + \frac{\delta(3\chi_j^2-16\chi_j+13)-3\chi_j^2+13\chi_j+4}{(\delta-1)(\chi_j-1)}\frac{M_W^2}{M_{W'}^2}\right\},$$

$$\gamma_d^j = \frac{3}{2M_W^2}\,\delta_\nu\,(\delta_d^*+\delta_d)\,\chi_j\,,$$

$$\gamma_s^j = \frac{3}{2M_W^2}\,\delta_\nu\,(\delta_s^*+\delta_s)\,\chi_j\,.$$

Hadronization

$$V^i_\mu = \overline{q}\,\gamma_\mu \frac{\lambda^i}{2} q \quad , \quad A^i_\mu = \overline{q}\,\gamma_\mu \gamma_5 \frac{\lambda^i}{2} q\,, \qquad q = (u,d,s)^T$$

$$\mathcal{J}^{\rm em}_\mu = \overline{q}\,Q_q\,\gamma_\mu q = V^3_\mu + \frac{1}{\sqrt{3}} V^8_\mu$$

$$\overline{u}\,\gamma_\mu P_L\,u = J^3_\mu + \frac{1}{\sqrt{3}} V^8_\mu + \frac{2}{\sqrt{6}} J^0_\mu\,,$$
$$\overline{d}\,\gamma_\mu P_L\,d = -J^3_\mu + \frac{1}{\sqrt{3}} V^8_\mu + \frac{2}{\sqrt{6}} J^0_\mu\,, \qquad J^i_\mu = (V^i_\mu - A^i_\mu)/2$$
$$\overline{s}\,\gamma_\mu P_L\,s = -\frac{2}{\sqrt{3}} V^8_\mu + \frac{2}{\sqrt{6}} J^0_\mu$$

$$V^i_\mu = \left.\frac{\partial \mathcal{L}_{\rm R\chi T}}{\partial v^\mu_i}\right|_{j=0}, \qquad A^i_\mu = \left.\frac{\partial \mathcal{L}_{\rm R\chi T}}{\partial a^\mu_i}\right|_{j=0}$$

1. $\tau \to \mu P \qquad P = \{\pi^0, \eta, \eta'\}$

$$\mathcal{T}_Z(P) = -i\frac{g^2}{2c_{\rm W}}\frac{F}{M^2_{\rm Z}} Z(P) \sum_j V^{j\mu *}_\ell V^{j\tau}_\ell \times \overline{\mu}(p') \left[\not{Q} \left(H^j_L P_L + H^j_R P_R \right) \right] \tau(p),$$
$$\mathcal{T}_{Z'}(P) = i\frac{g^2}{4\sqrt{9-3t^2_{\rm W}}}\frac{F}{M^2_{\rm Z'}} Z'(P) \sum_j V^{j\mu *}_\ell V^{j\tau}_\ell \times \overline{\mu}(p') \left[\not{Q} \left(\widetilde{H}^j_L P_L + \widetilde{H}^j_R P_R \right) \right] \tau(p),$$
$$\mathcal{T}_B(P) = -ig^2 F \sum_j V^{j\mu *}_\ell V^{j\tau}_\ell \times B^j(P)\, \overline{\mu}(p') \left[\not{Q} P_L \right] \tau(p).$$

Chiral symmetry + Dispersion relations (unitarity, analyticity, crossing symmetry) + Brodsky-Lepage behaviour + Accurate data

(Dumm-Roig ‘12, Shekhovtsova-Przedzinski-Roig-Was ’12, …)

Hadronization

1. $\tau \to \mu P \qquad P = \{\pi^0, \eta, \eta'\}$

$$\mathcal{T}_Z(P) = -i\frac{g^2}{2c_W}\frac{F}{M_Z^2}\,Z(P)\sum_j V_\ell^{j\mu *}V_\ell^{j\tau} \times \overline{\mu}(p')\left[\not{q}\left(H_L^j P_L + H_R^j P_R\right)\right]\tau(p),$$

$$\mathcal{T}_{Z'}(P) = i\frac{g^2}{4\sqrt{9-3t_W^2}}\frac{F}{M_{Z'}^2}\,Z'(P)\sum_j V_\ell^{j\mu *}V_\ell^{j\tau} \times \overline{\mu}(p')\left[\not{q}\left(\widetilde{H}_L^j P_L + \widetilde{H}_R^j P_R\right)\right]\tau(p),$$

$$\mathcal{T}_B(P) = -ig^2 F\sum_j V_\ell^{j\mu *}V_\ell^{j\tau} \times B^j(P)\,\overline{\mu}(p')\left[\not{q}P_L\right]\tau(p).$$

	$P = \pi^0$	$P = \eta$	$P = \eta'$
$Z(P)$	1	$\frac{1}{\sqrt{6}}\left(\sin\theta_\eta + \sqrt{2}\cos\theta_\eta\right)$	$\frac{1}{\sqrt{6}}\left(\sqrt{2}\sin\theta_\eta - \cos\theta_\eta\right)$
$Z'(P)$	$\sqrt{3}t_W^2$	$\cos\theta_\eta t_W^2 - \sqrt{2}\sin\theta_\eta\left(3-t_W^2\right)$	$\sin\theta_\eta t_W^2 + \sqrt{2}\cos\theta_\eta\left(3-t_W^2\right)$
$B_j(P)$	$\frac{1}{2}\left(B_d^j - B_u^j\right)$	$\frac{1}{2\sqrt{3}}\left[\left(\sqrt{2}\sin\theta_\eta - \cos\theta_\eta\right)B_u^j + \left(2\sqrt{2}\sin\theta_\eta + \cos\theta_\eta\right)B_d^j\right]$	$\frac{1}{2\sqrt{3}}\left[\left(\sin\theta_\eta - 2\sqrt{2}\cos\theta_\eta\right)B_d^j - \left(\sin\theta_\eta + \sqrt{2}\cos\theta_\eta\right)B_u^j\right]$

Hadronization

P = π^0, η, η'

1. $\tau \to \mu P \qquad P = \{\pi^0, \eta, \eta'\}$

$$\mathcal{T}_Z(P) = -i\frac{g^2}{2c_W}\frac{F}{M_Z^2}\,Z(P)\sum_j V_\ell^{j\mu *}V_\ell^{j\tau}$$
$$\times\,\overline{\mu}(p')\left[\not{Q}\left(H_L^j P_L + H_R^j P_R\right)\right]\tau(p),$$
$$\mathcal{T}_{Z'}(P) = i\frac{g^2}{4\sqrt{9-3t_W^2}}\frac{F}{M_{Z'}^2}\,Z'(P)\sum_j V_\ell^{j\mu *}V_\ell^{j\tau}$$
$$\times\,\overline{\mu}(p')\left[\not{Q}\left(\widetilde{H}_L^j P_L + \widetilde{H}_R^j P_R\right)\right]\tau(p),$$
$$\mathcal{T}_B(P) = -ig^2F\sum_j V_\ell^{j\mu *}V_\ell^{j\tau}$$
$$\times\,B^j(P)\,\overline{\mu}(p')\left[\not{Q}P_L\right]\tau(p).$$

$$B(\tau\to\mu P) = \frac{\lambda^{1/2}(m_\tau^2, m_\mu^2, m_P^2)}{4\pi\, m_\tau^2\,\Gamma_\tau}\,\frac{1}{2}\sum_{i,f}|\mathcal{T}(P)|^2$$

$$\sum_{i,f}|\mathcal{T}(P)|^2 = \frac{1}{2m_\tau}\sum_{k,l}\left[\left(m_\tau^2+m_\mu^2-m_P^2\right)\left(a_P^k a_P^{l*} + b_P^k b_P^{l*}\right)\right.$$
$$\left. +2m_\mu m_\tau\left(a_P^k a_P^{l*} - b_P^k b_P^{l*}\right)\right], \qquad k,l = Z, Z', B.$$

$$\Delta_{\tau\mu} = m_\tau - m_\mu,\ \Sigma_{\tau\mu} = m_\tau + m_\mu$$

$$a_P^Z = -\frac{g^2\,F}{4c_W M_Z^2}\,\Delta_{\tau\mu}\,Z(P)\sum_j V_\ell^{j\mu *}V_\ell^{j\tau}\left(H_R^j + H_L^j\right)$$
$$a_P^{Z'} = \frac{g^2\,F}{8\sqrt{9-3t_W^2}M_{Z'}^2}\,\Delta_{\tau\mu}\,Z'(P)\sum_j V_\ell^{j\mu *}V_\ell^{j\tau}\left(\widetilde{H}_R^j + \widetilde{H}_L^j\right),$$
$$a_P^B = -\frac{g^2\,F}{2}\,\Delta_{\tau\mu}\sum_j V_\ell^{j\mu *}V_\ell^{j\tau}B_j(P),$$
$$b_P^Z = \frac{g^2\,F}{4c_W M_Z^2}\,\Sigma_{\tau\mu}\,Z(P)\sum_j V_\ell^{j\mu *}V_\ell^{j\tau}\left(H_R^j - H_L^j\right),$$
$$b_P^{Z'} = -\frac{g^2\,F}{8\sqrt{9-3t_W^2}M_{Z'}^2}\,\Sigma_{\tau\mu}\,Z'(P)\sum_j V_\ell^{j\mu *}V_\ell^{j\tau}\left(\widetilde{H}_R^j - \widetilde{H}_L^j\right)$$
$$b_P^B = -\frac{g^2\,F}{2}\,\Sigma_{\tau\mu}\sum V_\ell^{j\mu *}V_\ell^{j\tau}B_j(P).$$

Hadronization

2. $\tau \to \mu P P \qquad P\overline{P} = \left\{\pi^+\pi^-, K^+K^-, K^0\overline{K^0}\right\}$

$$\langle P_1(p_1)P_2(p_2)|\mathcal{J}_\mu^{\rm em}|0\rangle = (p_1 - p_2)_\mu \, F_V^{P_1P_2}(Q^2) \qquad Q = p_1 + p_2$$

$$\mathcal{T}_\gamma^P = \frac{e^2}{Q^2}\frac{v^2}{f^2} F_V^{P\overline{P}}(Q^2) \times \sum_j V_\ell^{j\mu *} V_\ell^{j\tau}\, \overline{\mu}(p') \Big[Q^2 (\not{p}_q - \not{p}_{\overline{q}}) \left(F_L^j P_L + F_R^j P_R\right) + 2 i m_\tau p_q^\lambda \sigma_{\lambda\nu} p_{\overline{q}}^\nu \left(G_L^j P_L + G_R^j P_R\right)\Big] \tau(p)$$

$$\mathcal{T}_Z^P = g^2 \frac{2 s_{\rm W}^2 - 1}{2 c_{\rm W} M_Z^2} F_V^{P\overline{P}}(Q^2) \times \sum_j V_\ell^{j\mu *} V_\ell^{j\tau}\, \overline{\mu}(p') (\not{p}_q - \not{p}_{\overline{q}}) \left(H_L^j P_L + H_R^j P_R\right) \tau(p)$$

$$\mathcal{T}_{Z'}^P = -g^2 \frac{t_{\rm W}^2}{4 M_{Z'}^2 \sqrt{3 - t_{\rm W}^2}} F_V^{P\overline{P}}(Q^2) \times \sum_j V_\ell^{j\mu *} V_\ell^{j\tau}\, \overline{\mu}(p') (\not{p}_q - \not{p}_{\overline{q}}) \left(\widetilde{H}_L^j P_L + \widetilde{H}_R^j P_R\right) \tau(p)$$

$$\mathcal{T}_B^P = \frac{g^2}{2} F_V^{P\overline{P}}(Q^2) \times \sum_j V_\ell^{j\mu *} V_\ell^{j\tau} \left(B_u^j - B_d^j\right) \overline{\mu}(p') (\not{p}_q - \not{p}_{\overline{q}}) P_L \tau(p)$$

$$B(\tau \to \mu P P) = \frac{\cancel{\kappa}\; 1}{64 \pi^3 m_\tau^2 \Gamma_\tau} \int_{s_-}^{s_+} ds \int_{t_-}^{t_+} dt \, \frac{1}{2} \sum_{i,f} |\mathcal{T}^P|^2,$$

$$t_-^+ = \frac{1}{4s}\left[(m_\tau^2 - m_\mu^2)^2 - \left(\lambda^{1/2}(s, m_P^2, m_P^2) \mp \lambda^{1/2}(m_\tau^2, s, m_\mu^2) \right)^2 \right],$$

$$s_- = 4 m_P^2,$$

$$s_+ = (m_\tau - m_\mu)^2 .$$