

The full lepton flavor of little Higgs

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in collaboration with

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-
- Little Higgs: *Littlest* Higgs with T parity (LHT)
 - New sources of flavor mixing
 - Lepton flavor changing processes
 - Conclusions
-

JHEP **07** (2019) 154 [[1705.08827 \[hep-ph\]](#)] JHEP **08** (2017) 028 [[1901.07058 \[hep-ph\]](#)]

+ work in progress

Hierarchy problem: the Higgs mass should be of order v (electroweak scale) but it receives quadratic loop corrections of the order of the theory cutoff (Planck scale?)

Naturalness \Rightarrow New Physics at the TeV scale

[In SUSY: cancellations of quadratic Higgs mass corrections provided by superpartners]

In LH models the Higgs is a pseudo-Goldstone boson

of an approximate global symmetry broken at f (TeV scale)

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(i) Product group

the SM $SU(2)_L$ group from the diagonal breaking of two or more gauge groups

e.g.: *Littlest Higgs*

[Arkani-Hamed, Cohen, Katz, Nelson '02]

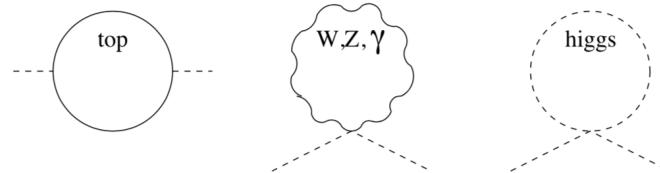
(ii) Simple group

the SM $SU(2)_L$ group from the breaking of a larger group into an $SU(2)$ subgroup

e.g.: *Simplest Little Higgs* ($SU(3)$ simple group)

[Kaplan, Schmaltz '03]

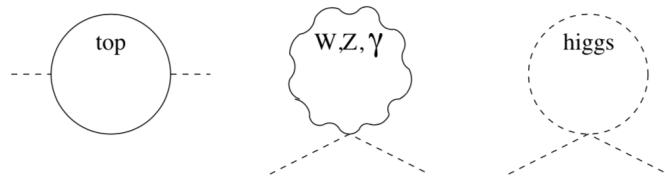
- The low energy *dof* described by a **nonlinear sigma model**, an **effective theory** valid below a **cutoff** $\Lambda \sim 4\pi f$ (order of 10 TeV) since then the loop corrections are



$$\Delta M_h^2 \sim \{y_t^2, g^2, \lambda^2\} \frac{\Lambda^2}{16\pi^2} \lesssim (1 \text{ TeV})^2$$

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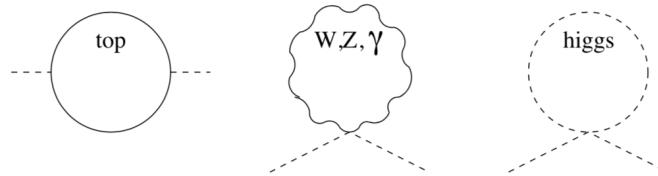


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- The **global symmetry explicitly broken** by gauge and Yukawa interactions, giving the Higgs a mass and non-derivative interactions, **preserving the cancellation of *one-loop quadratic corrections*** thanks to **collective symmetry breaking**:
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LH introduce **extra scalars, fermions and gauge bosons**: new flavor mixing sources

\Rightarrow Enhanced predictions for **lepton flavor changing processes**

$$h \rightarrow \bar{\ell}_1 \ell_2, \quad Z \rightarrow \bar{\ell}_1 \ell_2, \quad \ell_1 \rightarrow \ell_2 \gamma, \quad \mu N \rightarrow e N, \quad \ell \rightarrow \ell_1 \ell_2 \bar{\ell}_3$$

Littlest Higgs

[Arkani-Hamed, Cohen, Katz, Nelson '02]

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$$(1) \quad SU(5) \rightarrow SO(5) \text{ by } \Sigma_0 = \begin{pmatrix} \mathbf{0}_{2 \times 2} & 0 & \mathbf{1}_{2 \times 2} \\ 0 & 1 & 0 \\ \mathbf{1}_{2 \times 2} & 0 & \mathbf{0}_{2 \times 2} \end{pmatrix}, \quad \Sigma(x) = e^{i\Pi/f} \Sigma_0 e^{i\Pi^T/f} = e^{2i\Pi/f} \Sigma_0$$

where $\Pi(x) = \phi^a(x)X^a$ and X^a are the $24 - 10 = 14$ broken generators $\Rightarrow 14$ GB

$$G \equiv SU(5) \supset [SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2 \text{ (gauge)} \xrightarrow{\langle \Sigma \rangle = \Sigma_0} SU(2)_L \times U(1)_Y$$

[unbroken]: $Q_1^a + Q_2^a, Y_1 + Y_2 \Rightarrow 4$ gauge bosons (γ, Z, W^+, W^-) remain massless

[broken]: $Q_1^a - Q_2^a, Y_1 - Y_2 \Rightarrow 4$ gauge bosons (A_H, Z_H, W_H^+, W_H^-) get masses of order f

4 WBGB ($\eta, \omega^0, \omega^+, \omega^-$) eaten by (A_H, Z_H, W_H^+, W_H^-)

10 GB: $\underbrace{H \text{ (complex } SU(2) \text{ doublet)}}_{\text{, }} \Phi \text{ (complex } SU(2) \text{ triplet, PGB)}$

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$$(2) \quad \text{EWSB: } SU(2)_L \times U(1)_Y \xrightarrow{\langle H \rangle} U(1)_{\text{QED}} \Rightarrow H = \sqrt{2} \begin{pmatrix} -i \frac{\pi^+}{\sqrt{2}} \\ \frac{v+h+i\pi^0}{2} \end{pmatrix}$$

3 WBGB (π^0, π^+, π^-) eaten by (Z, W^+, W^-)

1 PGB: h

Littlest Higgs

Goldstones and gauge generators

The matrix of the 14 Goldstone Bosons:

$$\Pi = \begin{pmatrix} -\frac{\omega^0}{2} - \frac{\eta}{\sqrt{20}} & -\frac{\omega^+}{\sqrt{2}} & -i\frac{\pi^+}{\sqrt{2}} & -i\Phi^{++} & -i\frac{\Phi^+}{\sqrt{2}} \\ -\frac{\omega^-}{\sqrt{2}} & \frac{\omega^0}{2} - \frac{\eta}{\sqrt{20}} & \frac{v+h+i\pi^0}{2} & -i\frac{\Phi^+}{\sqrt{2}} & \frac{-i\Phi^0 + \Phi^P}{\sqrt{2}} \\ i\frac{\pi^-}{\sqrt{2}} & \frac{v+h-i\pi^0}{2} & \sqrt{\frac{4}{5}}\eta & -i\frac{\pi^+}{\sqrt{2}} & \frac{v+h+i\pi^0}{2} \\ i\Phi^{--} & i\frac{\Phi^-}{\sqrt{2}} & i\frac{\pi^-}{\sqrt{2}} & -\frac{\omega^0}{2} - \frac{\eta}{\sqrt{20}} & -\frac{\omega^-}{\sqrt{2}} \\ i\frac{\Phi^-}{\sqrt{2}} & \frac{i\Phi^0 + \Phi^P}{\sqrt{2}} & \frac{v+h-i\pi^0}{2} & -\frac{\omega^+}{\sqrt{2}} & \frac{\omega^0}{2} - \frac{\eta}{\sqrt{20}} \end{pmatrix}$$

Littlest Higgs

Gauge generators

Generators of the gauge subgroup $[SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2 \subset SU(5)$:

$$Q_1^a = \frac{1}{2} \begin{pmatrix} \sigma^a & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \mathbf{0}_{2 \times 2} \end{pmatrix} \quad Q_2^a = \frac{1}{2} \begin{pmatrix} \mathbf{0}_{2 \times 2} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -\sigma^{a*} \end{pmatrix}$$

$$Y_1 = \frac{1}{10} \text{diag}(3, 3, -2, -2, -2) \quad Y_2 = \frac{1}{10} \text{diag}(2, 2, 2, -3, -3)$$

Littlest Higgs with T-parity

[Cheng, Low '03]

New particles at TeV scale coupling to SM particles \Rightarrow tension with EW precision tests

\sim T-parity discrete symmetry under which SM (most of new) particles are even (odd)

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Gauge sector

$G_1 \xleftrightarrow{T} G_2$ with $G_j = (W_j^a, B_j)$ gauge bosons of $[SU(2) \times U(1)]_{j=1,2}$

and $g \equiv g_1 = g_2, g' \equiv g'_1 = g'_2$

T-even: $B, W^3(\gamma, Z), W^+, W^- \leftarrow \frac{1}{\sqrt{2}}(G_1 + G_2)$

T-odd: $A_H, Z_H, W_H^+, W_H^- \leftarrow \frac{1}{\sqrt{2}}(G_1 - G_2)$

$$\mathcal{L}_G = \sum_{j=1}^2 \left[-\frac{1}{2} \text{Tr} \left(\tilde{W}_{j\mu\nu} \tilde{W}_j^{\mu\nu} \right) - \frac{1}{4} B_{j\mu\nu} B_j^{\mu\nu} \right]$$

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Scalar sector

$\Pi \xrightarrow{T} -\Omega \Pi \Omega$, where $\Omega = \text{diag}(-1, -1, 1, -1, -1)$

T-even: SM H doublet (h, π^0, π^+, π^-)

T-odd: the others ($\eta, \omega^0, \omega^+, \omega^-, \Phi$)

$$\mathcal{L}_S = \frac{f^2}{8} \text{Tr} \left[(D_\mu \Sigma)^\dagger (D^\mu \Sigma) \right] \supset \text{gauge boson masses}$$

$$\text{with } D_\mu \Sigma = \partial_\mu \Sigma - \sqrt{2}i \sum_{j=1}^2 \left[g W_{j\mu}^a (Q_j^a \Sigma + \Sigma Q_j^{aT}) - g' B_{j\mu} (Y_j \Sigma + \Sigma Y_j^T) \right]$$

Littlest Higgs with T-parity

Fermion (lepton) sector

Fields

Littlest Higgs with T-parity

Fermion (lepton) sector

Fields

(a) Introduce $SU(2)_L$ doublets: l_{1L} , l_{2L} , l_{HR} and \tilde{l}_L^c in

$$\Psi_1[\bar{5}] = \begin{pmatrix} -i\sigma^2 l_{1L} \\ 0 \\ 0 \end{pmatrix} \quad \Psi_2[5] = \begin{pmatrix} 0 \\ 0 \\ -i\sigma^2 l_{2L} \end{pmatrix} \quad \Psi_R = \begin{pmatrix} -i\sigma^2 \tilde{l}_L^c \\ 0 \\ -i\sigma^2 l_{HR} \end{pmatrix}$$

T-even	Standard $l_L = \frac{1}{\sqrt{2}}(l_{1L} - l_{2L}) = (\nu_L \quad \ell_L)^T$	
T-odd	Mirror $l_{HL} = \frac{1}{\sqrt{2}}(l_{1L} + l_{2L}) = (\nu_{HL} \quad \ell_{HL})^T$ $l_{HR} = (\nu_{HR} \quad \ell_{HR})^T$	Mirror partners (decouple?) $\tilde{l}_L^c = (\tilde{\nu}_L^c \quad \tilde{\ell}_L^c)^T$

- ▷ To obtain (heavy) mirror fermion masses *preserving* gauge and T

$$\mathcal{L}_{Y_H} = -\kappa f (\bar{\Psi}_2 \xi + \bar{\Psi}_1 \Sigma_0 \xi^\dagger) \Psi_R + \text{h.c.} \quad \xi = e^{i\Pi/f}$$

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- (b) Introduce (light) standard fermion singlets ℓ_R with mass terms *preserving* gauge and T

[Chen, Tobe, Yuan '06]

$$\mathcal{L}_Y = \frac{i\lambda_\ell}{2\sqrt{2}} f \epsilon_{ij} \epsilon_{xyz} \left[(\bar{\Psi}'_2)_x \Sigma_{iy} \Sigma_{jz} X + \text{T-transformed} \right] \ell_R + \text{h.c.}$$

$$\Psi'_2 = \begin{pmatrix} 0 \\ 0 \\ l_{2L} \end{pmatrix}, \quad X = (\Sigma_{33})^{-\frac{1}{4}}$$

- ▷ So far, masses from Yukawa couplings:

$$\mathcal{L}_Y \supset - \underbrace{\frac{\lambda_\ell}{\sqrt{2}} v}_{\text{lepton masses}} \overline{\ell_L} \ell_R + \text{h.c.}$$

$$\mathcal{L}_{Y_H} \supset - \underbrace{\sqrt{2} \kappa f}_{\text{mirror lepton masses}} \overline{l_{HL}} l_{HR} + \text{h.c.}$$

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(c) To provide **mirror partners** \tilde{l}_L^c (RH) with (heavy) **masses** introduce $\tilde{l}_R^c = (\tilde{\nu}_R^c, \tilde{\ell}_R^c)^T$ (LH) in

$$\Psi_L = \begin{pmatrix} -i\sigma^2 \tilde{l}_R^c \\ 0 \\ 0 \end{pmatrix} \sim \Psi_R \quad \boxed{\mathcal{L}_M = -\mathbf{M} \overline{\tilde{l}_R} \tilde{l}_L + \text{h.c.}}$$

Littlest Higgs with T-parity

Fermion (lepton) sector

Gauge interactions

(d) The **gauge interactions** with fermions are **fixed!**

$$\mathcal{L}_F = i\bar{\Psi}_1 \gamma^\mu D_\mu^* \Psi_1 + i\bar{\Psi}_2 \gamma^\mu D_\mu \Psi_2 + i\bar{\Psi}_R \gamma^\mu \left(\partial_\mu + \frac{1}{2} \xi^\dagger (D_\mu \xi) + \frac{1}{2} \xi (\Sigma_0 D_\mu^* \Sigma_0 \xi^\dagger) \right) \Psi_R + (\Psi_R \rightarrow \Psi_L)$$

$$\text{with } D_\mu = \partial_\mu - \sqrt{2}ig(W_{1\mu}^a Q_1^a + W_{2\mu}^a Q_2^a) + \sqrt{2}ig' (Y_1 B_{1\mu} + Y_2 B_{2\mu})$$

include $\mathcal{O}(v^2/f^2)$ couplings to Goldstones that render one-loop amplitudes
 (vid. Z-penguins) UV finite

[del Águila, JI, Jenkins '09]

(e) The **gauge interactions** of standard right-handed *singlets* (ℓ_R)

$$\mathcal{L}'_F = i\bar{\ell}_R \gamma^\mu (\partial_\mu + ig' y_\ell B_\mu) \ell_R \quad y_\ell = -1$$

enlarging $SU(5)$ with two extra $U(1)$'s to assign proper hypercharges to *all* fermions

[Goto, Okada, Yamamoto '09]

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- ▷ 3 generations: λ_ℓ , κ and M are **matrices** in flavor space

$$\frac{\lambda_\ell}{\sqrt{2}} v = V_L^\ell \text{diag}(m_{\ell i}) V_R^{\ell\dagger}$$

$$\begin{pmatrix} \sqrt{2}\kappa f & 0 \\ 0 & M \end{pmatrix} = \begin{pmatrix} V_L^H & 0 \\ 0 & \tilde{V}_L \end{pmatrix} \begin{pmatrix} \text{diag}(m_{\ell_{Hi}}) & 0 \\ 0 & \text{diag}(m_{\tilde{\ell}_i}) \end{pmatrix} \begin{pmatrix} V_R^{H\dagger} & 0 \\ 0 & \tilde{V}_R^\dagger \end{pmatrix}$$

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- ▷ This leads to **flavor mixings** in both **charged and neutral currents** encoded in

$$\mathbf{V} \equiv V_L^{H\dagger} V_L^\ell$$

$$\mathbf{W} \equiv \tilde{V}_L^T V_R^H$$

misalignment between \mathbf{l}_H and \mathbf{l}

misalignment between $\tilde{\mathbf{l}}^c$ and \mathbf{l}_H

$$\overline{l_{HL}} \mathcal{G}_H l_L \rightarrow \overline{l_{HL}} \mathbf{V} \mathcal{G}_H l_L \quad \overline{\tilde{l}_L^c} \mathcal{G} l_{HR} \rightarrow \overline{\tilde{l}_L^c} \mathbf{W} \mathcal{G} l_{HR} \quad (W^\pm \text{ only})$$

$$\overline{l_{HL}} \lambda_\ell \ell_R \rightarrow \overline{l_{HL}} (\mathbf{V} \lambda_\ell) \ell_R$$

$$\overline{\tilde{l}_L^c} \kappa^\dagger l_{HL} \rightarrow \overline{\tilde{l}_L^c} (\mathbf{W} \kappa) l_{HL}$$

$$\overline{l_{HR}} \kappa^\dagger l_L \rightarrow \overline{l_{HR}} (\kappa \mathbf{V}) l_L$$

$$\overline{\tilde{l}_L^c} \kappa^\dagger l_L \rightarrow \overline{\tilde{l}_L^c} (\mathbf{W} \kappa \mathbf{V}) l_L$$

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 - The complex $SU(2)$ triplet of physical Goldstones Φ ($\Phi^0, \Phi^P, \Phi^\pm, \Phi^{\pm\pm}$) plays a role

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 - The mirror partners \tilde{l}^c decouple!
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- ▷ Study the phenomenology of the full lepton flavor of LHT

LHT

(Lepton) flavor mixing

Parametrization

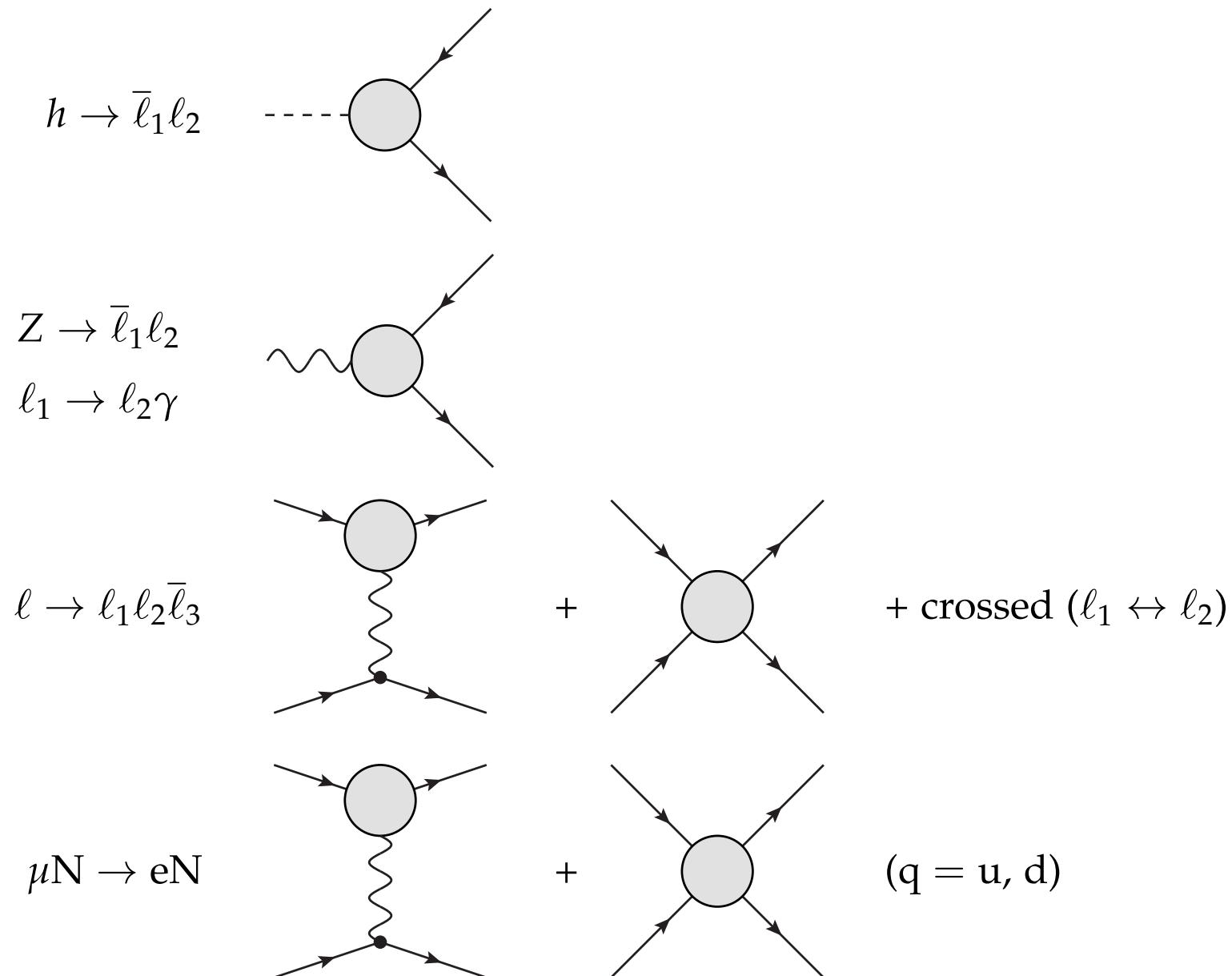
▷ To simplify the discussion consider just **2-family mixing**:

$$\mathbf{V} = \begin{pmatrix} \cos \theta_V & \sin \theta_V \\ -\sin \theta_V & \cos \theta_V \end{pmatrix} \quad \mathbf{W} = \begin{pmatrix} \cos \theta_W & \sin \theta_W \\ -\sin \theta_W & \cos \theta_W \end{pmatrix}$$

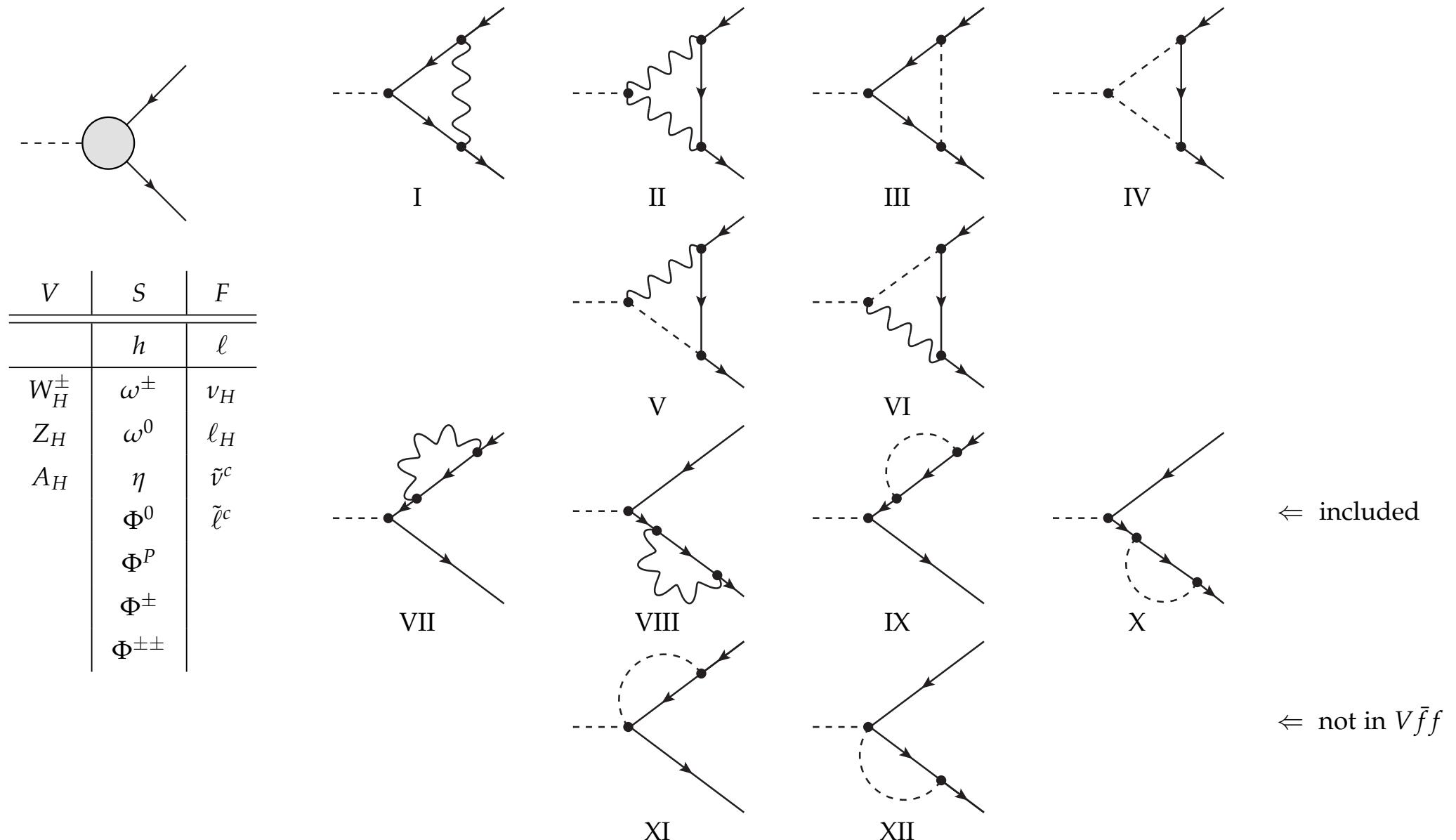
$$m_{\ell_{H1}}, \quad m_{\ell_{H2}} \quad \iff \quad \overline{m}_{\ell_H} \equiv \sqrt{m_{\ell_{H1}} m_{\ell_{H2}}} , \quad \delta_{\ell_H} \equiv \frac{m_{\ell_{H2}}^2 - m_{\ell_{H1}}^2}{\overline{m}_{\ell_H}^2}$$

$$m_{\tilde{\nu}_1^c}, \quad m_{\tilde{\nu}_2^c} \quad \iff \quad \overline{m}_{\tilde{\nu}^c} \equiv \sqrt{m_{\tilde{\nu}_1^c} m_{\tilde{\nu}_2^c}} , \quad \delta_{\tilde{\nu}^c} \equiv \frac{m_{\tilde{\nu}_2^c}^2 - m_{\tilde{\nu}_1^c}^2}{\overline{m}_{\tilde{\nu}^c}^2}$$

▷ LFV effects vanish for zero mixings or degenerate fermions

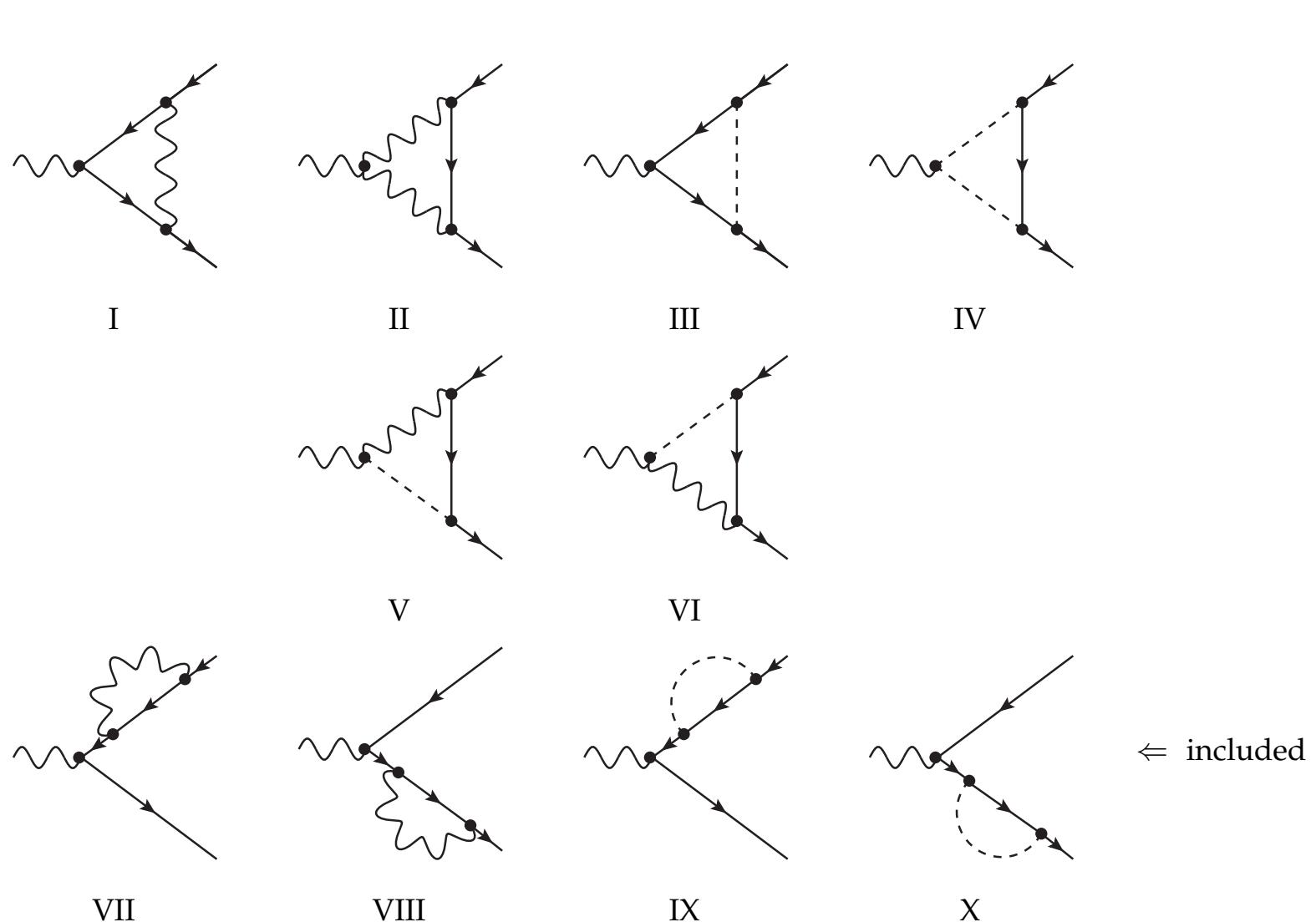


('t Hooft-Feynman gauge)

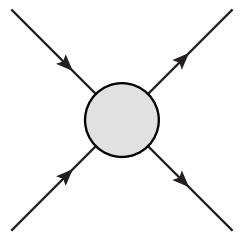


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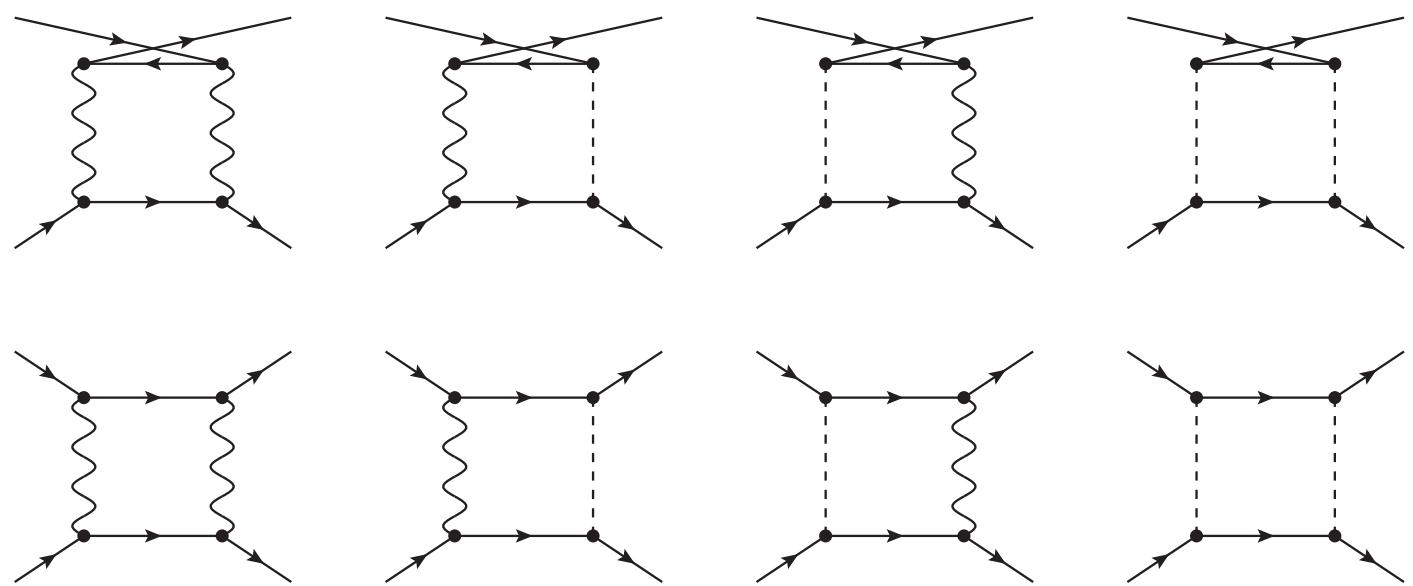
V	S	F
γ, Z, W^\pm		ℓ
W_H^\pm	ω^\pm	ν_H
Z_H	ω^0	ℓ_H
A_H	η	$\tilde{\nu}^c$
Φ^0		$\tilde{\ell}^c$
Φ^P		
Φ^\pm		
$\Phi^{\pm\pm}$		



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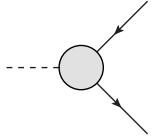


V	S	F
γ, Z, W^\pm		ℓ, u, d
W_H^\pm	ω^\pm	ν_H
Z_H	ω^0	ℓ_H
A_H	η	$\tilde{\nu}^c$
Φ^0	$\tilde{\ell}$	
Φ^P	u_H	
Φ^\pm	d_H	
$\Phi^{\pm\pm}$	\tilde{u} ($Q = 2/3$)	
		\tilde{x} ($Q = 5/3$)



LHT

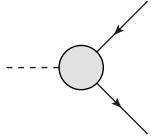
Amplitude

 $h \rightarrow \bar{\tau}\mu$ 

$$\mathcal{M}(h \rightarrow \mu\bar{\tau}) = \bar{u}(p_2) \left(\begin{bmatrix} m_\mu \\ v \end{bmatrix} \begin{bmatrix} \mathcal{C}_L \\ \mathcal{C}_R \end{bmatrix} P_L + \begin{bmatrix} m_\tau \\ v \end{bmatrix} \begin{bmatrix} \mathcal{C}_L \\ \mathcal{C}_R \end{bmatrix} P_R \right) v(p_1)$$

LHT

Amplitude

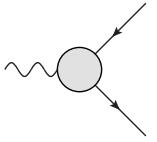
 $h \rightarrow \bar{\tau}\mu$ 

$$\mathcal{M}(h \rightarrow \mu\bar{\tau}) = \bar{u}(p_2) \left(\boxed{\frac{m_\mu}{v}} \boxed{\mathcal{C}_L} P_L + \boxed{\frac{m_\tau}{v}} \boxed{\mathcal{C}_R} P_R \right) v(p_1)$$

$$\begin{aligned} c_{L(R)} = & \boxed{\frac{g^2}{16\pi^2}} \boxed{\frac{v^2}{f^2}} \left\{ \sum_{i=1}^3 V_{\mu i}^\dagger V_{i\tau} \mathcal{F}_h(m_{\ell_{Hi}}, m_{W_H}, m_{A_H}, m_\Phi) \right. \\ & \left. + \sum_{i,j,k=1}^3 V_{\mu i}^\dagger \frac{m_{\ell_{Hi}}}{m_{W_H}} W_{ij}^\dagger W_{jk} \frac{m_{\ell_{Hk}}}{m_{W_H}} V_{k\tau} \mathcal{G}_h(m_{\tilde{\nu}_j^c}, m_{\ell_{Hk(i)}}, m_\Phi) \right\} \end{aligned}$$

(terms of $\mathcal{O}(1)$ cancel!) $\mathcal{G}_h \xrightarrow[m_{\nu_j^c} \rightarrow \infty]{} \ln m_{\nu_i^c}^2 \quad [h\bar{\nu}_H \tilde{\nu}^c]$

$$\begin{aligned} c_{L(R)} \sim & \frac{g^2}{16\pi^2} \frac{v^2}{f^2} \left\{ \boxed{\sin 2\theta_V} [\mathcal{F}_h(m_{\ell_{H1}}) - \mathcal{F}_h(m_{\ell_{H2}})], \underbrace{\frac{\overline{m}_{\ell_H}^2}{M_{W_H}^2} \boxed{\sin 2\theta_W}}_{m_{\tilde{\nu}_i^c} \rightarrow \infty (\theta_V = \delta_{\ell_H} = 0)} \ln \frac{m_{\tilde{\nu}_1^c}^2}{m_{\tilde{\nu}_2^c}^2} \right\} \\ \Rightarrow & \text{non-decoupling of } \tilde{l}_i^c !! \end{aligned}$$



$$i\Gamma_\gamma^\mu = ie [F_L^\gamma(Q^2)\gamma^\mu P_L + iF_M^\gamma(Q^2)(1+\gamma_5)\sigma^{\mu\nu}q_\nu]$$

$$F_L^\gamma \propto \frac{1}{16\pi^2} \frac{Q^2}{f^2}$$

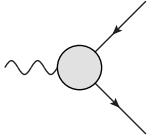
$\overbrace{F_M^\gamma \propto \frac{1}{16\pi^2} \frac{m_\ell}{f^2}}$
UV finite

$$i\Gamma_Z^\mu = ie [F_L^Z(Q^2)\gamma^\mu P_L + iF_M^Z(Q^2)(1+\gamma_5)\sigma^{\mu\nu}q_\nu]$$

$$F_L^Z \propto \frac{g^2}{16\pi^2} \frac{v^2}{f^2}$$

$$F_M^Z \propto \frac{g^2}{16\pi^2} \frac{m_\ell}{f^2}$$

$F_L^\gamma(0) = 0$: $\ell_1 \rightarrow \ell_2 \gamma$ is a dipole transition



$$i\Gamma_\gamma^\mu = ie [F_L^\gamma(Q^2)\gamma^\mu P_L + iF_M^\gamma(Q^2)(1+\gamma_5)\sigma^{\mu\nu}q_\nu]$$

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$\overbrace{F_M^\gamma \propto \frac{1}{16\pi^2} \frac{m_\ell}{f^2}}$ UV finite

$$i\Gamma_Z^\mu = ie [F_L^Z(Q^2)\gamma^\mu P_L + iF_M^Z(Q^2)(1+\gamma_5)\sigma^{\mu\nu}q_\nu]$$

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$$F_M^Z \propto \frac{g^2}{16\pi^2} \frac{m_\ell}{f^2}$$

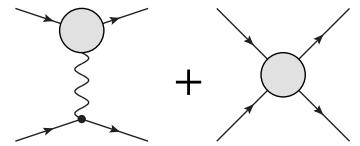
$F_L^\gamma(0) = 0$: $\ell_1 \rightarrow \ell_2 \gamma$ is a dipole transition

$$\begin{aligned} F_{L,M}^{\gamma,Z} \sim & \left\{ \sum_{i=1}^3 V_{\ell_2 i}^\dagger V_{i \ell_1} \mathcal{F}_{L,M}^{\gamma,Z}(m_{\ell_{Hi}}, m_{W_H}, m_{A_H}, m_\Phi) \right. \\ & \left. + \sum_{i,j,k=1}^3 V_{\ell_2 i}^\dagger \frac{m_{\ell_{Hi}}}{m_{W_H}} W_{ij}^\dagger W_{jk} \frac{m_{\ell_{Hk}}}{m_{W_H}} V_{k \ell_1} \mathcal{G}_{L,M}^{\gamma,Z}(m_{\tilde{\nu}_j^c}, m_\Phi) \right\} \end{aligned}$$

(terms of $\mathcal{O}(1)$ cancel!)

$$\mathcal{G}_{L,M}^{\gamma,Z} \xrightarrow{m_{\tilde{\nu}_j^c} \rightarrow \infty} 0 \quad [V \bar{\nu}_H \tilde{\nu}^c]$$

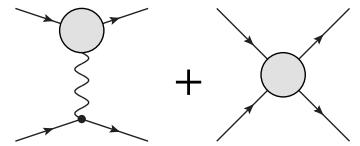
\Rightarrow there is decoupling of \tilde{l}_i^c !!



$$i\mathcal{M}_\gamma = \left(\frac{i}{Q^2}\right) e [\bar{u}(p_1) \Gamma_\gamma^\mu P_L u(p)] [\bar{u}(p_2) \gamma_\mu v(p_3)] - (\ell_1 \leftrightarrow \ell_2)$$

$$i\mathcal{M}_Z = \left(-\frac{i}{M_Z^2}\right) e [\bar{u}(p_1) \Gamma_Z^\mu P_L u(p)] [\bar{u}(p_2) \gamma_\mu (Z_L P_L + Z_R P_R) v(p_3)] - (\ell_1 \leftrightarrow \ell_2)$$

$$i\mathcal{M}_{\text{box}} = ie^2 B_L [\bar{u}(p_1) \gamma^\mu P_L u(p)] [\bar{u}(p_2) \gamma_\mu P_L v(p_3)] - (\ell_1 \leftrightarrow \ell_2)$$



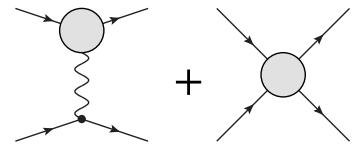
$$i\mathcal{M}_\gamma = \left(\frac{i}{Q^2}\right) e [\bar{u}(p_1) \Gamma_\gamma^\mu P_L u(p)] [\bar{u}(p_2) \gamma_\mu v(p_3)] - (\ell_1 \leftrightarrow \ell_2)$$

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$$i\mathcal{M}_{\text{box}} = ie^2 \mathcal{B}_L [\bar{u}(p_1) \gamma^\mu P_L u(p)] [\bar{u}(p_2) \gamma_\mu P_L v(p_3)] - (\ell_1 \leftrightarrow \ell_2)$$

\triangleright γ -penguins ($Q^2 \rightarrow 0$):

$$\mathcal{A}_L = \frac{F_L^\gamma}{Q^2} \quad \mathcal{A}_R = \frac{2F_M^\gamma}{m_\ell} \propto \frac{1}{16\pi^2} \frac{1}{f^2}$$



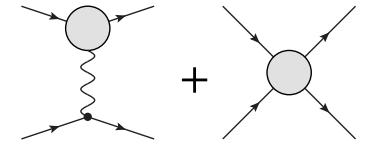
$$i\mathcal{M}_\gamma = \left(\frac{i}{Q^2}\right) e [\bar{u}(p_1) \Gamma_\gamma^\mu P_L u(p)] [\bar{u}(p_2) \gamma_\mu v(p_3)] - (\ell_1 \leftrightarrow \ell_2)$$

$$i\mathcal{M}_Z = \left(-\frac{i}{M_Z^2}\right) e [\bar{u}(p_1) \Gamma_Z^\mu P_L u(p)] [\bar{u}(p_2) \gamma_\mu (Z_L P_L + Z_R P_R) v(p_3)] - (\ell_1 \leftrightarrow \ell_2)$$

$$i\mathcal{M}_{\text{box}} = ie^2 \mathcal{B}_L [\bar{u}(p_1) \gamma^\mu P_L u(p)] [\bar{u}(p_2) \gamma_\mu P_L v(p_3)] - (\ell_1 \leftrightarrow \ell_2)$$

▷ γ -penguins ($Q^2 \rightarrow 0$): $A_L = \frac{F_L^\gamma}{Q^2}$ $A_R = \frac{2F_M^\gamma}{m_\ell}$ $\propto \frac{1}{16\pi^2} \frac{1}{f^2}$

▷ Z -penguins ($Q^2 \rightarrow 0$): $F_{LL} = -\frac{F_L^Z}{M_Z^2} Z_L$ $F_{LR} = -\frac{F_L^Z}{M_Z^2} Z_R$ $\propto \frac{1}{16\pi^2} \frac{1}{f^2}$



$$i\mathcal{M}_\gamma = \left(\frac{i}{Q^2}\right) e [\bar{u}(p_1) \Gamma_\gamma^\mu P_L u(p)] [\bar{u}(p_2) \gamma_\mu v(p_3)] - (\ell_1 \leftrightarrow \ell_2)$$

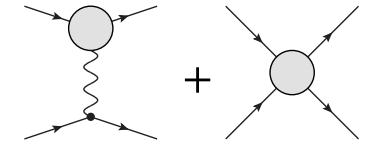
$$i\mathcal{M}_Z = \left(-\frac{i}{M_Z^2}\right) e [\bar{u}(p_1) \Gamma_Z^\mu P_L u(p)] [\bar{u}(p_2) \gamma_\mu (Z_L P_L + Z_R P_R) v(p_3)] - (\ell_1 \leftrightarrow \ell_2)$$

$$i\mathcal{M}_{\text{box}} = ie^2 B_L [\bar{u}(p_1) \gamma^\mu P_L u(p)] [\bar{u}(p_2) \gamma_\mu P_L v(p_3)] - (\ell_1 \leftrightarrow \ell_2)$$

▷ γ -penguins ($Q^2 \rightarrow 0$): $A_L = \frac{F_L^\gamma}{Q^2}$ $A_R = \frac{2F_M^\gamma}{m_\ell}$ $\propto \frac{1}{16\pi^2} \frac{1}{f^2}$

▷ Z -penguins ($Q^2 \rightarrow 0$): $F_{LL} = -\frac{F_L^Z}{M_Z^2} Z_L$ $F_{LR} = -\frac{F_L^Z}{M_Z^2} Z_R$ $\propto \frac{1}{16\pi^2} \frac{1}{f^2}$

▷ Boxes: B_L $\propto \frac{1}{16\pi^2} \frac{1}{f^2}$



$$i\mathcal{M}_\gamma = \left(\frac{i}{Q^2}\right) e [\bar{u}(p_1) \Gamma_\gamma^\mu P_L u(p)] [\bar{u}(p_2) \gamma_\mu v(p_3)] - (\ell_1 \leftrightarrow \ell_2)$$

$$i\mathcal{M}_Z = \left(-\frac{i}{M_Z^2}\right) e [\bar{u}(p_1) \Gamma_Z^\mu P_L u(p)] [\bar{u}(p_2) \gamma_\mu (Z_L P_L + Z_R P_R) v(p_3)] - (\ell_1 \leftrightarrow \ell_2)$$

$$i\mathcal{M}_{\text{box}} = ie^2 B_L [\bar{u}(p_1) \gamma^\mu P_L u(p)] [\bar{u}(p_2) \gamma_\mu P_L v(p_3)] - (\ell_1 \leftrightarrow \ell_2)$$

$$\begin{aligned} B_L \sim & \left\{ \sum_{ij=1}^3 V_{\ell_1 i}^\dagger V_{i \ell} V_{\ell_2 j}^\dagger V_{j \ell_3} \mathcal{F}_B(m_{\ell_{Hi}}, m_{\ell_{Hi}}, \dots) \right. \\ & \left. + \sum_{ijpqrs=1}^3 V_{\ell_1 p}^\dagger \frac{m_{\ell_{Hp}}}{m_{W_H}} W_{pi}^\dagger W_{iq} \frac{m_{\ell_{Hq}}}{m_{W_H}} V_{q \ell} V_{\ell_2 r}^\dagger \frac{m_{\ell_{Hr}}}{m_{W_H}} W_{rj}^\dagger W_{js} \frac{m_{\ell_{Hs}}}{m_{W_H}} V_{s \ell_3} \mathcal{G}_B(m_{\tilde{\nu}_i^c}, m_{\tilde{\nu}_j^c}, \dots) \right\} \end{aligned}$$

(UV finite)

Highly non-trivial cancellations!

$$\left\{ c_{L(R)}, \quad 2s_W c_W F_L^Z, \quad F_L^\gamma \right\} \quad \sim \quad \frac{1}{16\pi^2} \sum_i \textcolor{red}{V}_{\mu i}^\dagger V_{i\tau} \frac{m_{\ell_{Hi}}^2}{f^2} \left(\boxed{\frac{C_{\text{UV}}^{(0)}}{\epsilon}} + \boxed{\frac{C_{\text{UV}}^{(1)}}{\epsilon}} \frac{v^2}{f^2} \right)$$

$$\epsilon = 4 - D$$

$c_{L(R)}$	I	II	III	IV	V+VI	VII+VIII	IX+X	XI+XII	sum
ω, ν_H	–	–	•	•	–	–	1	–1	•
ω^0, ℓ_H	–	–	•	•	–	–	$\frac{1}{2}$	$–\frac{1}{2}$	•
η, ℓ_H	–	–	•	•	–	–	$\frac{1}{10}$	$–\frac{1}{10}$	•
all	–	–	•	•	–	–	$\frac{8}{5}$	$–\frac{8}{5}$	•

$2s_W c_W F_L^Z$	I	II	III	IV	V+VI	VII+VIII	IX+X	sum
W_H, ν_H	0	0	–	–	–	–	0	0
W_H, ω, ν_H	–	–	–	–	0	–	–	0
ω, ν_H	–	–	$\frac{1}{2}$	$–1 + s_W^2$	–	–	$\frac{1}{2} – s_W^2$	•
Z_H, ℓ_H	0	•	–	–	–	–	0	•
ω^0, ℓ_H	–	–	$–\frac{1}{4} + \frac{1}{2}s_W^2$	•	–	–	$\frac{1}{4} – \frac{1}{2}s_W^2$	•
A_H, ℓ_H	0	•	–	–	–	0	–	•
η, ℓ_H	–	–	$–\frac{1}{20} + \frac{1}{10}s_W^2$	0	–	–	$\frac{1}{20} – \frac{1}{10}s_W^2$	•
$\Phi, \tilde{\nu}^c$	–	–	$–\frac{1}{2}$	s_W^2	–	–	$\frac{1}{2} – s_W^2$	•
$\Phi^{++}, \tilde{\ell}^c$	–	–	$1 – 2s_W^2$	$–2 + 4s_W^2$	–	–	$1 – 2s_W^2$	•
all	0	0	$\frac{7}{10} – \frac{7}{5}s_W^2$	$–3 + 6s_W^2$	0	0	$\frac{23}{10} – \frac{23}{5}s_W^2$	•

- also finite part is zero

F_L^γ	all	sum
all	•	•

$c_{L(R)}$	I	II	III	IV	V+VI	VII+VIII	IX+X	XI+XII	sum
W_H, ν_H	0	0	-	-	-	•	-	-	0
W_H, ω, ν_H	-	-	-	-	0	-	-	-	0
ω, ν_H	-	-	$\frac{1}{4}$	$-\frac{1}{8}$	-	-	$-\frac{1}{6}$	$\frac{5}{24}$	$\frac{1}{6}$
Z_H, ℓ_H	•	0	-	-	-	•	-	-	0
Z_H, ω^0, ℓ_H	-	-	-	-	0	-	-	-	0
ω^0, ℓ_H	-	-	•	$-\frac{1}{16}$	-	-	$-\frac{13}{48} + x_H \frac{c_W}{s_W}$	$\frac{7}{16} - x_H \frac{c_W}{s_W}$	$\frac{5}{48}$
A_H, ℓ_H	•	0	-	-	-	•	-	-	0
A_H, η, ℓ_H	-	-	-	-	0	-	-	-	0
η, ℓ_H	-	-	•	$-\frac{1}{16}$	-	-	$-\frac{23}{240} - x_H \frac{s_W}{5c_W}$	$-\frac{17}{240} + x_H \frac{s_W}{5c_W}$	$-\frac{11}{48}$
Z_H, A_H, ℓ_H	-	0	-	-	-	-	-	-	0
ω^0, η, ℓ_H	-	-	-	$\frac{1}{8}$	-	-	-	-	$\frac{1}{8}$
W_H, Φ, ν_H	-	-	-	-	0	-	-	-	0
Φ, ν_H	-	-	•	•	-	-	$-\frac{1}{8}$	$\frac{1}{24}$	$-\frac{1}{12}$
ω, Φ, ν_H	-	-	-	$\frac{1}{6}$	-	-	-	-	$\frac{1}{6}$
ω^0, Φ^P, ℓ_H	-	-	-	$\frac{1}{24}$	-	-	-	-	$\frac{1}{24}$
η, Φ^P, ℓ_H	-	-	-	$-\frac{1}{24}$	-	-	-	-	$-\frac{1}{24}$
$\Phi, \tilde{\nu}^c, \nu_H$	-	-	$-\frac{1}{4}$	$\frac{1}{24}$	-	-	•	$-\frac{1}{24}$	$-\frac{1}{4}$
all	0	0	0	$\frac{1}{12}$	0	•	$-\frac{49}{120}$	$\frac{39}{120}$	0
									\mathcal{M}

 \Rightarrow \Leftarrow

$2s_W c_W F_L^Z$	I	II	III	IV	V+VI	VII+VIII	IX+X	sum
W_H, ν_H	0	0	–	–	–	0	–	0
W_H, ω, ν_H	–	–	–	–	0	–	–	0
ω, ν_H	–	–	$-\frac{1}{8}$	$\frac{1}{8}$	–	–	0	0
Z_H, ℓ_H	0	•	–	–	–	0	–	0
ω^0, ℓ_H	–	–	$\frac{1}{16} - \frac{1}{8}s_W^2 - y_H \frac{c_W}{s_W}$	•	–	–	$-\frac{1}{16} + \frac{1}{8}s_W^2 + y_H \frac{c_W}{s_W}$	0
A_H, ℓ_H	0	•	–	–	–	0	–	0
η, ℓ_H	–	–	$\frac{1}{16} - \frac{1}{8}s_W^2 + y_H \frac{s_W}{5c_W}$	•	–	–	$-\frac{1}{16} + \frac{1}{8}s_W^2 - y_H \frac{s_W}{5c_W}$	0
$\Phi, \tilde{\nu}^c$	–	–	$\frac{1}{8}$	$-\frac{1}{8}$	–	–	•	0
$\Phi^{++}, \tilde{\ell}^c$	–	–	0	0	–	–	•	0
all	0	0	0	0	0	0	0	0

F_L^γ	I	II	III	IV	V+VI	VII+VIII	IX+X	sum
W_H, ν_H	•	0	–	–	–	0	–	0
W_H, ω, ν_H	–	–	–	–	0	–	–	0
ω, ν_H	–	–	•	$\frac{1}{2}$	–	–	$-\frac{1}{2}$	0
Z_H, ℓ_H	0	•	–	–	–	0	–	0
ω^0, ℓ_H	–	–	$\frac{1}{4}$	•	–	–	$-\frac{1}{4}$	0
A_H, ℓ_H	0	•	–	–	–	0	–	0
η, ℓ_H	–	–	$\frac{1}{100} \frac{s_W^2}{c_W^2}$	•	–	–	$-\frac{1}{100} \frac{s_W^2}{c_W^2}$	0
$\Phi, \tilde{\nu}^c$	–	–	•	$\frac{1}{2}$	–	–	$-\frac{1}{2}$	0
$\Phi^{++}, \tilde{\ell}^c$	–	–	–1	2	–	–	–1	0
all	0	0	$-\frac{3}{4} + \frac{1}{100} \frac{s_W^2}{c_W^2}$	3	0	0	$-\frac{9}{4} - \frac{1}{100} \frac{s_W^2}{c_W^2}$	0

LHT flavor phenomenology

LFV decays

- Reference inputs (*natural* values)

$$f = 1.5 \text{ TeV}$$

$$\overline{m}_{\ell_H} = \overline{m}_{\tilde{\nu}^c} = 1.0 \text{ TeV}$$

$$(m_{d_{Hi}} = m_{\tilde{u}_i} = 2.0 \text{ TeV})$$

$$\delta_{\ell_H} = \delta_{\tilde{\nu}^c} = 1$$

$$\theta_V = \theta_W = \frac{\pi}{4}$$

$$\Rightarrow \quad m_{W_H} = m_{Z_H} \approx gf = 960 \text{ GeV}$$

$$m_{A_H} \approx \frac{g' f}{\sqrt{5}} = 230 \text{ GeV}$$

$$m_\Phi = \frac{\sqrt{2}f}{v} m_h = 1080 \text{ GeV}$$

- Current limits

Branching Ratio	90% C.L.	Branching Ratio	90% C.L.
$\mu \rightarrow e \gamma$	4.2×10^{-13}	$\mu \rightarrow e e \bar{e}$	1.0×10^{-12}
Conversion Rate			
$\mu \rightarrow e$ (Au)	7.0×10^{-13}		
$\mu \rightarrow e$ (Ti)	4.3×10^{-12}		
Branching Ratio		Branching Ratio	
$\tau \rightarrow e \gamma$	3.3×10^{-8}	$\tau \rightarrow \mu \mu \bar{e}$	1.7×10^{-8}
$\tau \rightarrow \mu \gamma$	4.4×10^{-8}	$\tau \rightarrow e e \bar{\mu}$	1.5×10^{-8}
		$\tau \rightarrow \mu e \bar{e}$	1.8×10^{-8}
		$\tau \rightarrow e \mu \bar{\mu}$	2.7×10^{-8}
		$\tau \rightarrow e e \bar{e}$	2.7×10^{-8}
		$\tau \rightarrow \mu \mu \bar{\mu}$	2.1×10^{-8}
Branching Ratio	95% C.L.	Branching Ratio	95% C.L.
$Z \rightarrow \mu e$	7.3×10^{-7}	$h \rightarrow \mu e$	3.5×10^{-4}
$Z \rightarrow \tau e$	9.8×10^{-6}	$h \rightarrow \tau e$	6.2×10^{-3}
$Z \rightarrow \tau \mu$	1.2×10^{-5}	$h \rightarrow \tau \mu$	2.5×10^{-3}

- LHT predictions for reference inputs

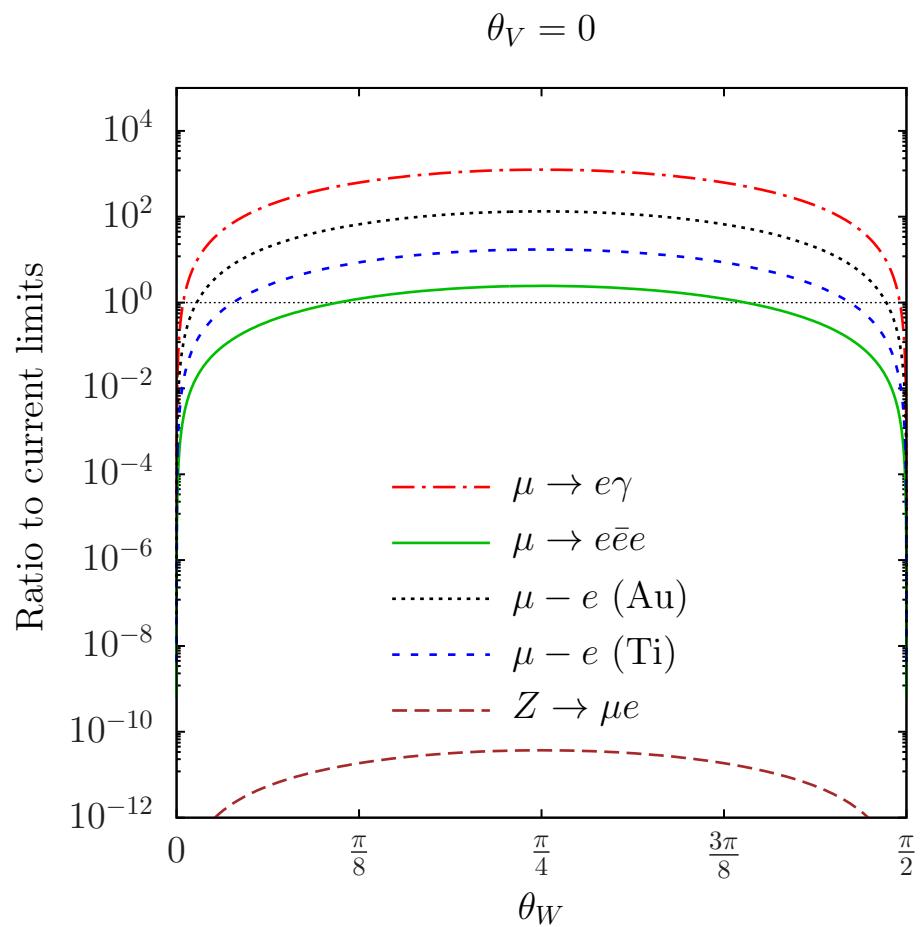
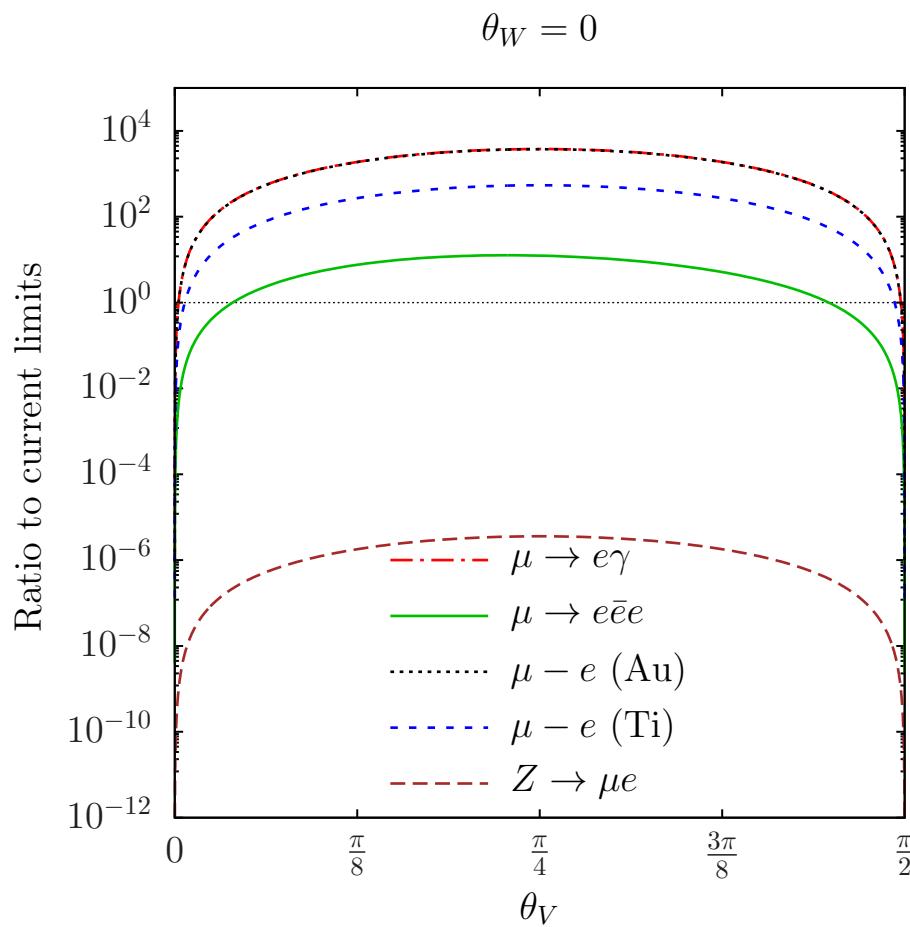
Branching Ratio		Branching Ratio	
$\mu \rightarrow e \gamma$	4.3×10^{-9}	$\mu \rightarrow e e \bar{e}$	2.5×10^{-11}
Conversion Rate			
$\mu \rightarrow e$ (Au)	3.8×10^{-9}		
$\mu \rightarrow e$ (Ti)	3.3×10^{-9}		
Branching Ratio		Branching Ratio	
$\tau \rightarrow e \gamma$	7.3×10^{-10}	$\tau \rightarrow \mu \mu \bar{e}$	0
$\tau \rightarrow \mu \gamma$	7.3×10^{-10}	$\tau \rightarrow e e \bar{\mu}$	0
		$\tau \rightarrow \mu e \bar{e}$	8.2×10^{-12}
		$\tau \rightarrow e \mu \bar{\mu}$	2.2×10^{-12}
		$\tau \rightarrow e e \bar{e}$	7.4×10^{-12}
		$\tau \rightarrow \mu \mu \bar{\mu}$	1.4×10^{-12}
Branching Ratio		Branching Ratio	
$Z \rightarrow \mu e$	2.7×10^{-12}	$h \rightarrow \mu e$	1.2×10^{-15}
$Z \rightarrow \tau e$	2.7×10^{-12}	$h \rightarrow \tau e$	3.2×10^{-13}
$Z \rightarrow \tau \mu$	2.7×10^{-12}	$h \rightarrow \tau \mu$	3.2×10^{-13}

✓ constrained

– unconstrained by current expts

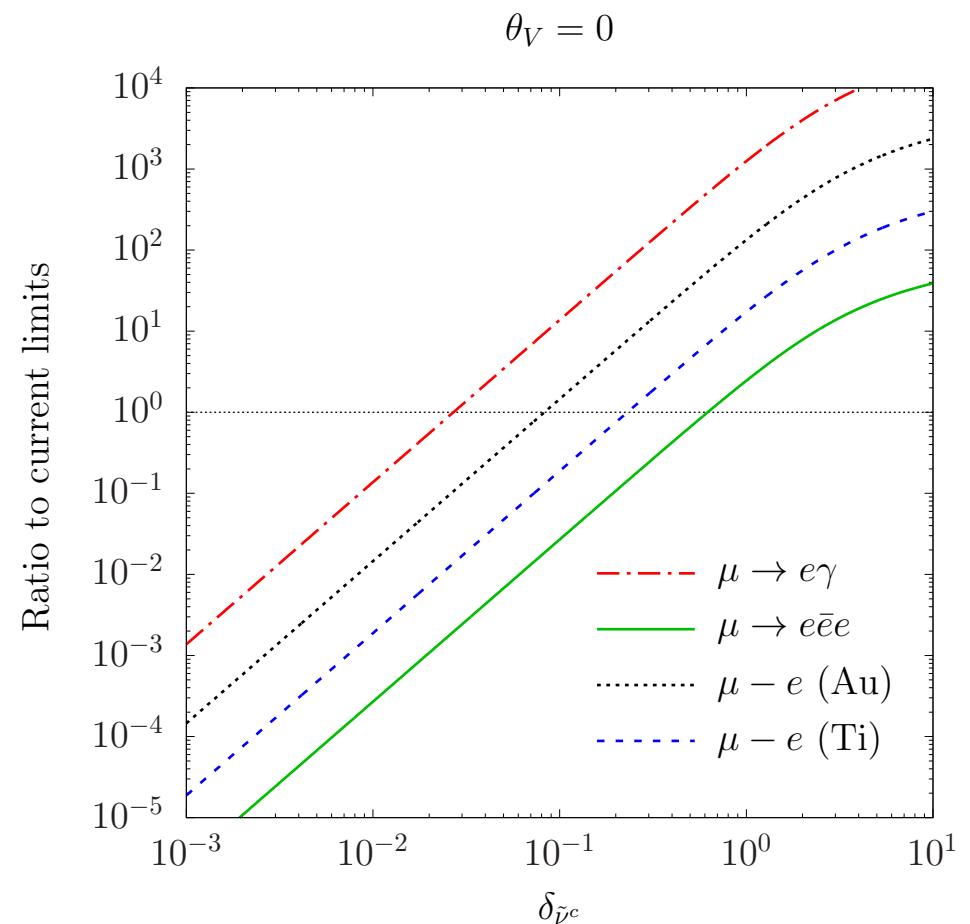
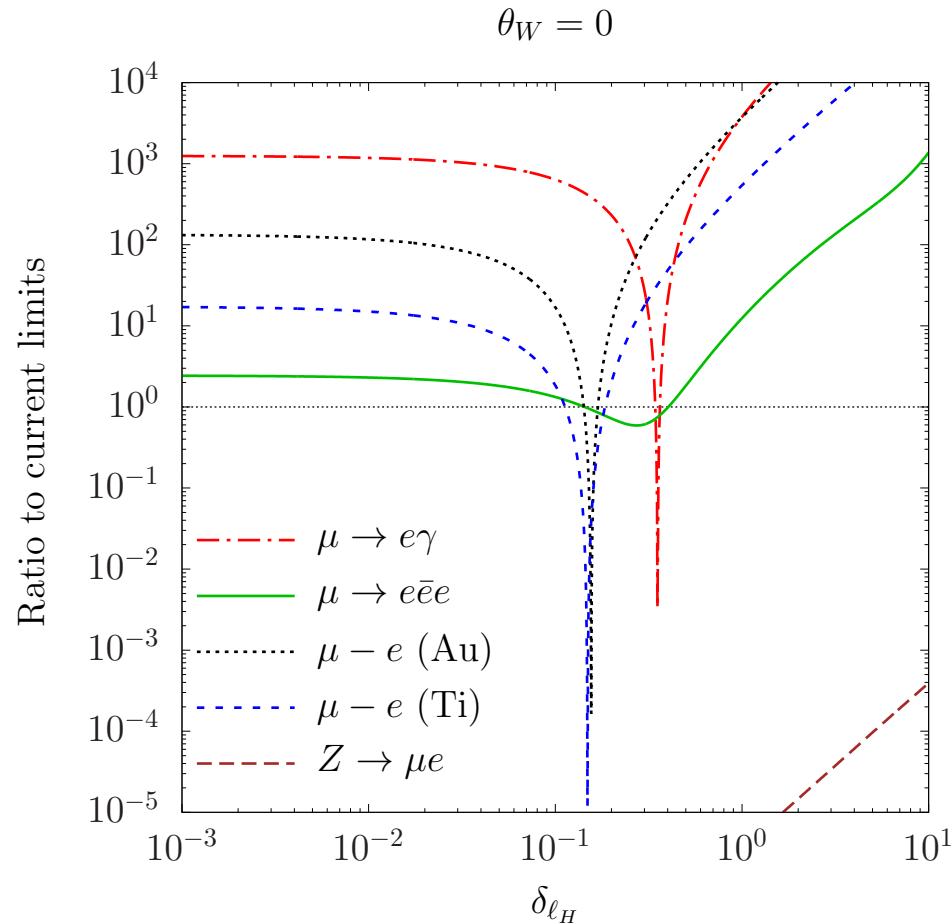
⌚ hopeless

- Parameter scans



- ▷ No LFV for $\theta_V = \theta_W = 0$, maximal for $\theta_{V,W} = \frac{\pi}{4}$
- ▷ Z and h decay rates are very small
- ▷ $\mu \rightarrow e\gamma$ and $\mu - e$ (Au) are most sensitive

- Parameter scans

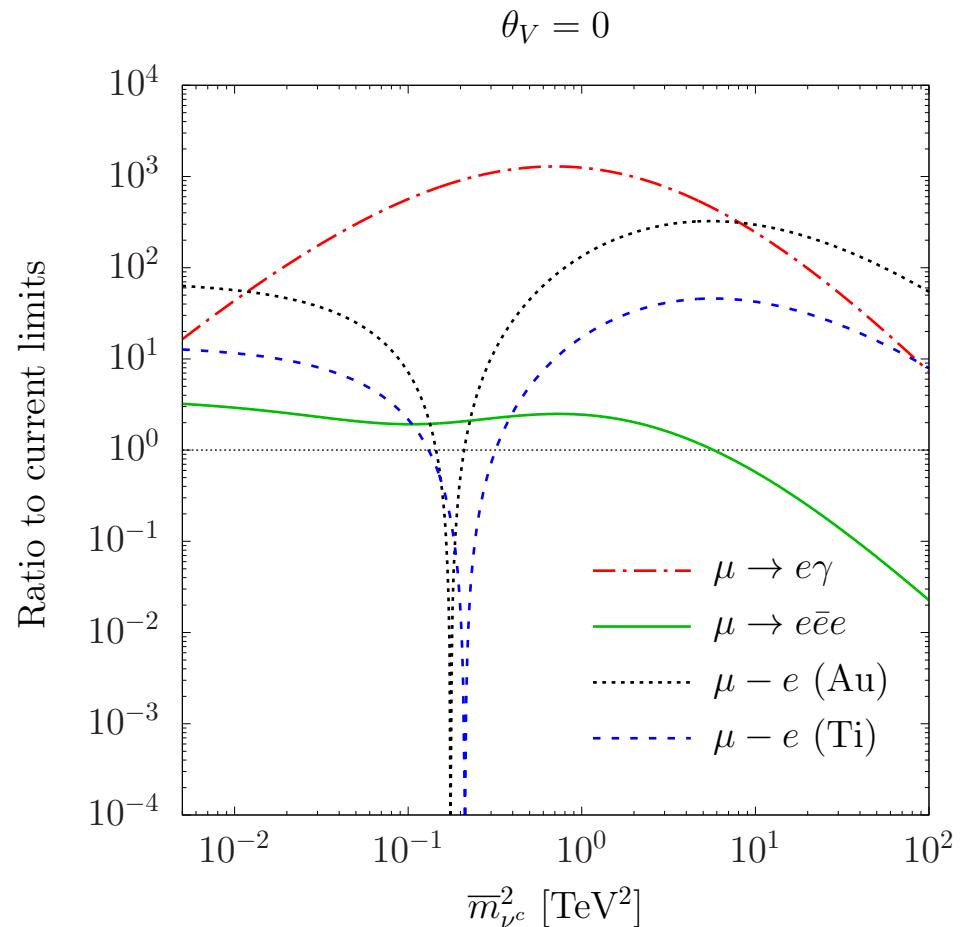
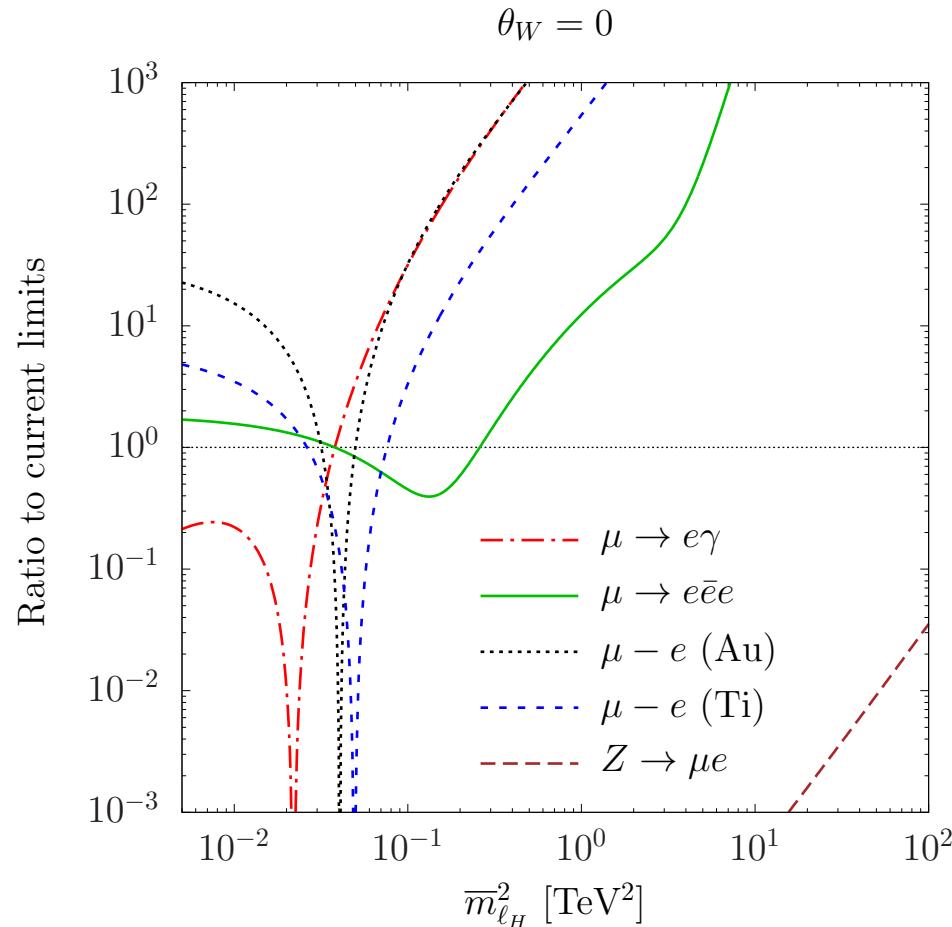
 ∇

$$\lim_{\delta_{\ell_H} \rightarrow 0} \mathcal{M}(\theta_W = 0) \sim \sin 2\theta_V [\mathcal{G}(m_{\nu_1^c}) - \mathcal{G}(m_{\nu_2^c})]$$

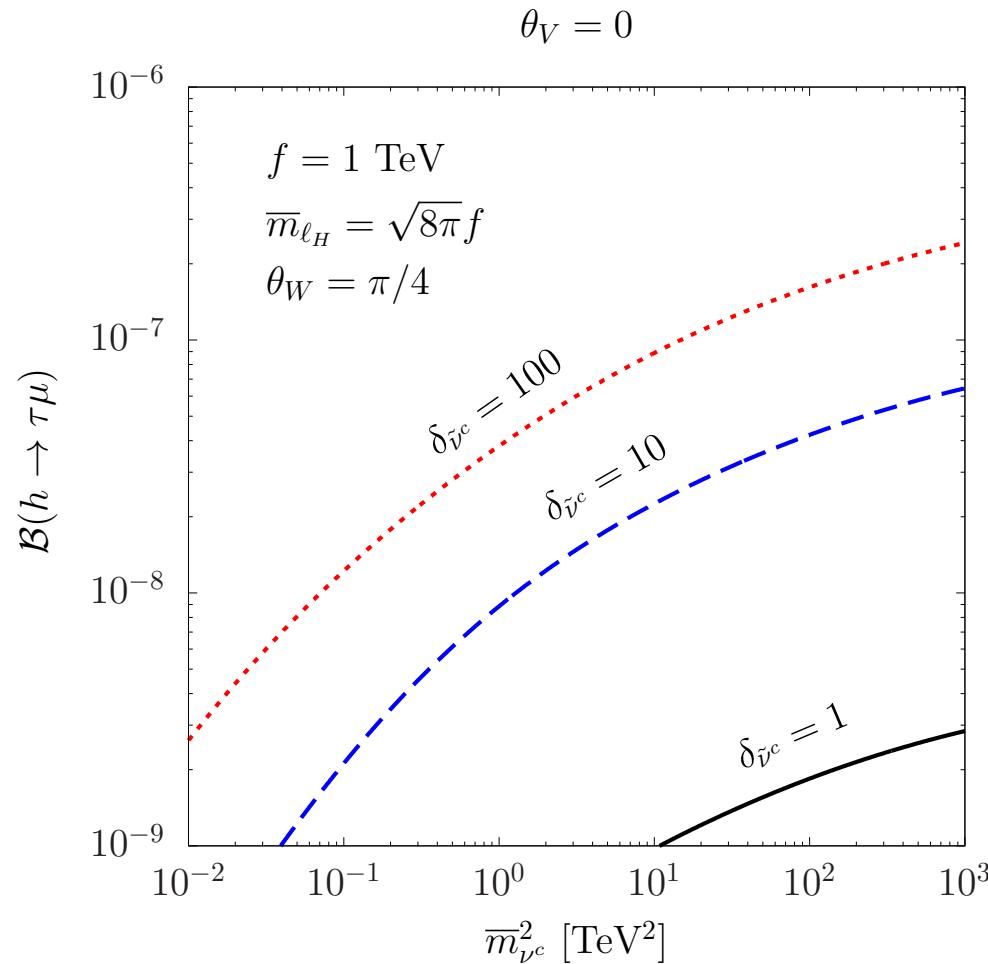
$$\lim_{\delta_{\tilde{\nu}^c} \rightarrow 0} \mathcal{M}(\theta_V = 0) \sim \sin 2\theta_W [\mathcal{G}(m_{\nu_1^c}) - \mathcal{G}(m_{\nu_2^c})] \rightarrow 0$$

 ∇

- Parameter scans

 ∇ ∇

For large $\overline{m}_{\ell_H} = \sqrt{2}\overline{\kappa}f$: non perturbative coupling! For large $\overline{m}_{\tilde{\nu}^c}$: decoupling except h decays

(Current limit [LHC]: $\mathcal{B}(h \rightarrow \tau\mu) < 2.5 \times 10^{-3}$)

$$m_{\tilde{\nu}_1^c}^2 = \overline{m}_{\tilde{\nu}^c}^2 \frac{\sqrt{4 + \delta_{\tilde{\nu}^c}^2} - \delta_{\tilde{\nu}^c}}{2} \xrightarrow{\delta_{\tilde{\nu}^c} \gg 1} \overline{m}_{\tilde{\nu}^c}^2 \times \frac{1}{\delta_{\tilde{\nu}^c}}$$

$$m_{\tilde{\nu}_2^c}^2 = \overline{m}_{\tilde{\nu}^c}^2 \frac{\sqrt{4 + \delta_{\tilde{\nu}^c}^2} + \delta_{\tilde{\nu}^c}}{2} \xrightarrow{\delta_{\tilde{\nu}^c} \gg 1} \overline{m}_{\tilde{\nu}^c}^2 \times \delta_{\tilde{\nu}^c}$$

- Current and Future sensitivities

$$\text{Observables} \propto \frac{\sin^2 2\theta}{f^4}$$

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▷ $\mu - e$ transitions:

*precision = limit/prediction

Process	Experiment	Current precision*	Sensitivity improvement	$[\sin 2\theta = 1]$	$f [\text{TeV}] >$	$[f = 1.5 \text{ TeV}]$	Mixing angle $< \times 10^{-2}$
$\mu \rightarrow e \gamma$	[MEG]	10^{-4}	$10 - 500$	15	$27 - 71$	1	$0.3 - 0.04$
$\mu \rightarrow e e \bar{e}$	[Mu3e]	0.04	$200 - 10^4$	3.4	$13 - 34$	20	$1 - 0.3$
$\mu \rightarrow e$ (Al)	[Mu2e]	10^{-3}	$10^4 - 10^5$	8.4	$84 - 150$	3	$0.03 - 0.01$
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▷ $\tau - e$ and $\tau - \mu$ transitions:

Process	Experiment	Prediction	Current	Future	
$\mathcal{B}(\tau \rightarrow \ell \gamma)$	[BaBar]	7.3×10^{-10}	$\sim 10^{-8}$	$10^{-9} - 10^{-10}$	[BelleII, LHCb] $\Leftarrow \smile$
$\mathcal{B}(\tau \rightarrow \ell \ell' \bar{\ell}'')$	[Belle]	$\sim 10^{-12}$	$\sim 10^{-8}$	$10^{-9} - 10^{-10}$	[BelleII, LHCb]

LHT flavor phenomenology

LFV decays

Comments

SUSY comparison

- When γ dipole contribution ($|A_R|^2$) **dominates** then (kinematics):

$$\frac{\mathcal{B}(\tau \rightarrow \mu\mu\bar{\mu})}{\mathcal{B}(\tau \rightarrow \mu\gamma)} = \frac{\alpha}{3\pi} \left(2 \ln \frac{m_\tau}{m_\mu} - \frac{13}{4} \right) \approx 2 \times 10^{-3}$$

$$\frac{\mathcal{B}(\tau \rightarrow \mu e \bar{e})}{\mathcal{B}(\tau \rightarrow \mu\gamma)} = \frac{\alpha}{3\pi} \left(2 \ln \frac{m_\tau}{m_e} - \frac{7}{2} \right) \approx 10^{-2}$$

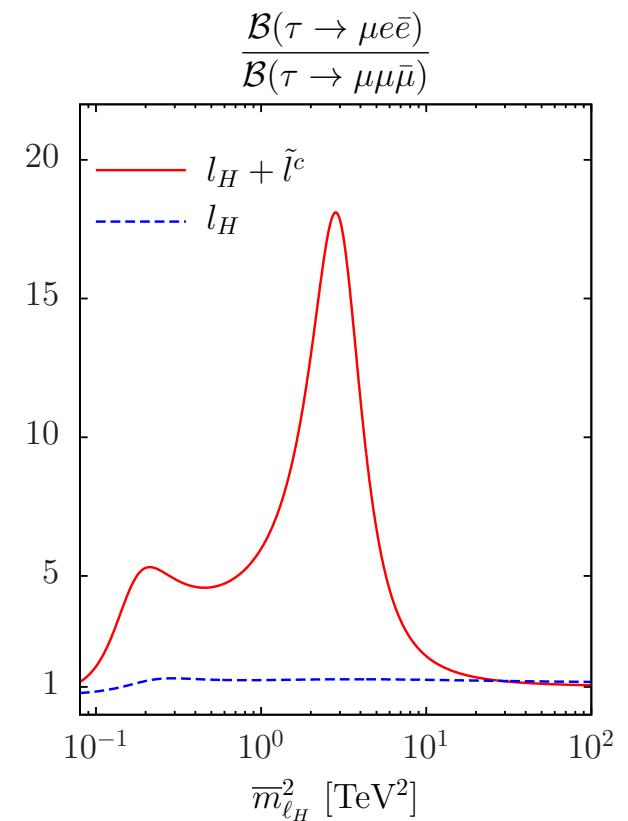
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- ▷ This *tends to happen when both l_H and \tilde{l}^c are included:*
(as in SUSY)

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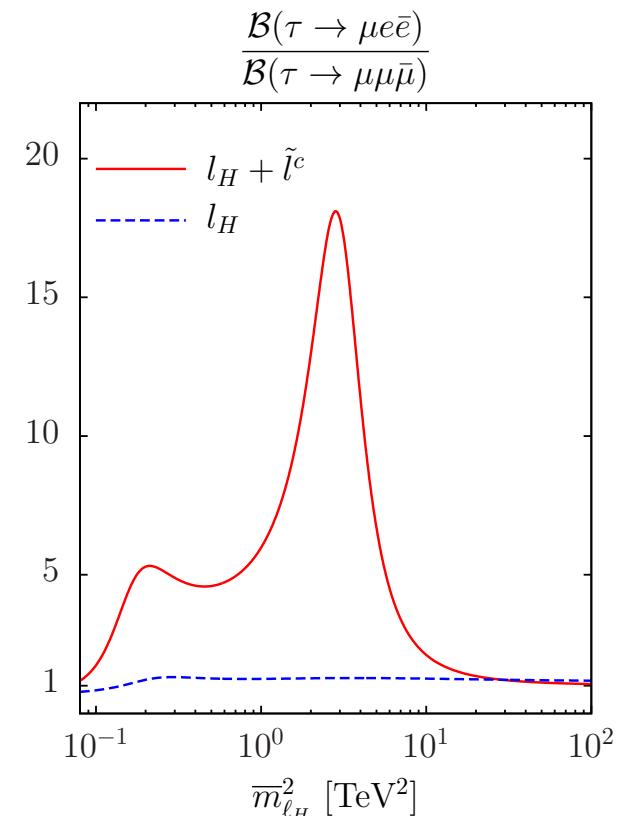
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- When \tilde{l}^c is ignored (decouples) the other terms dominate:
(in contrast to SUSY)

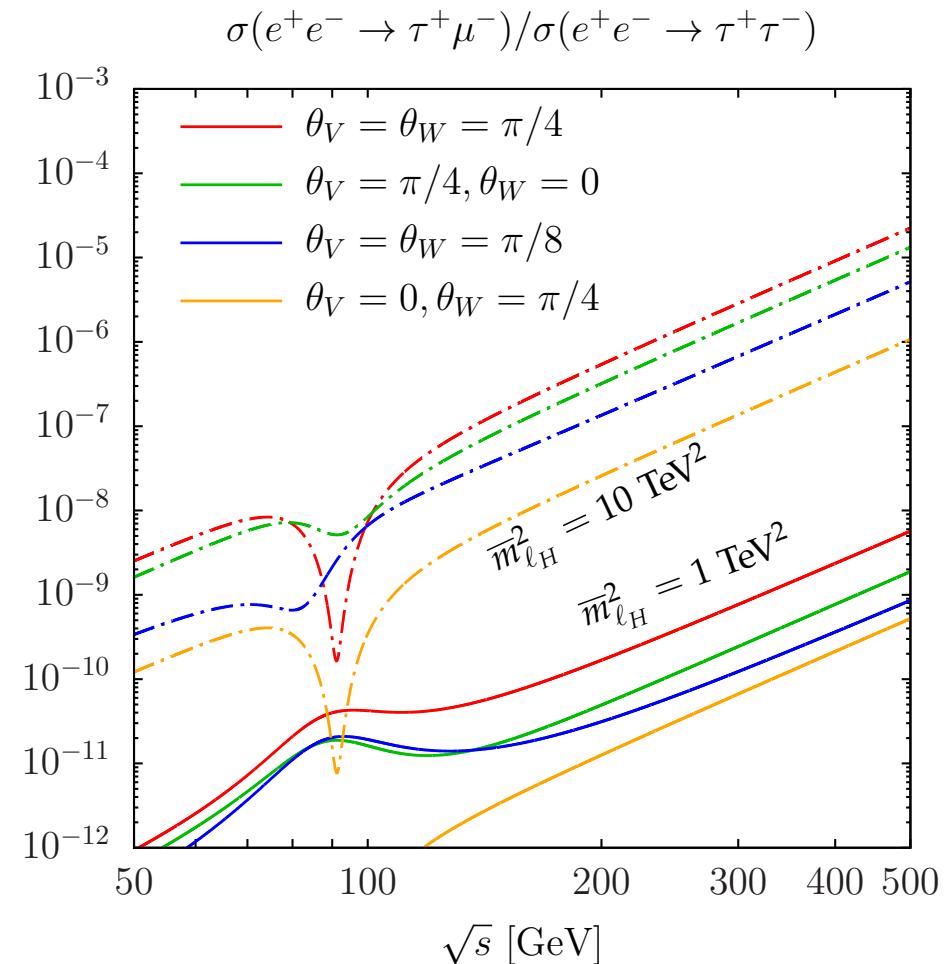
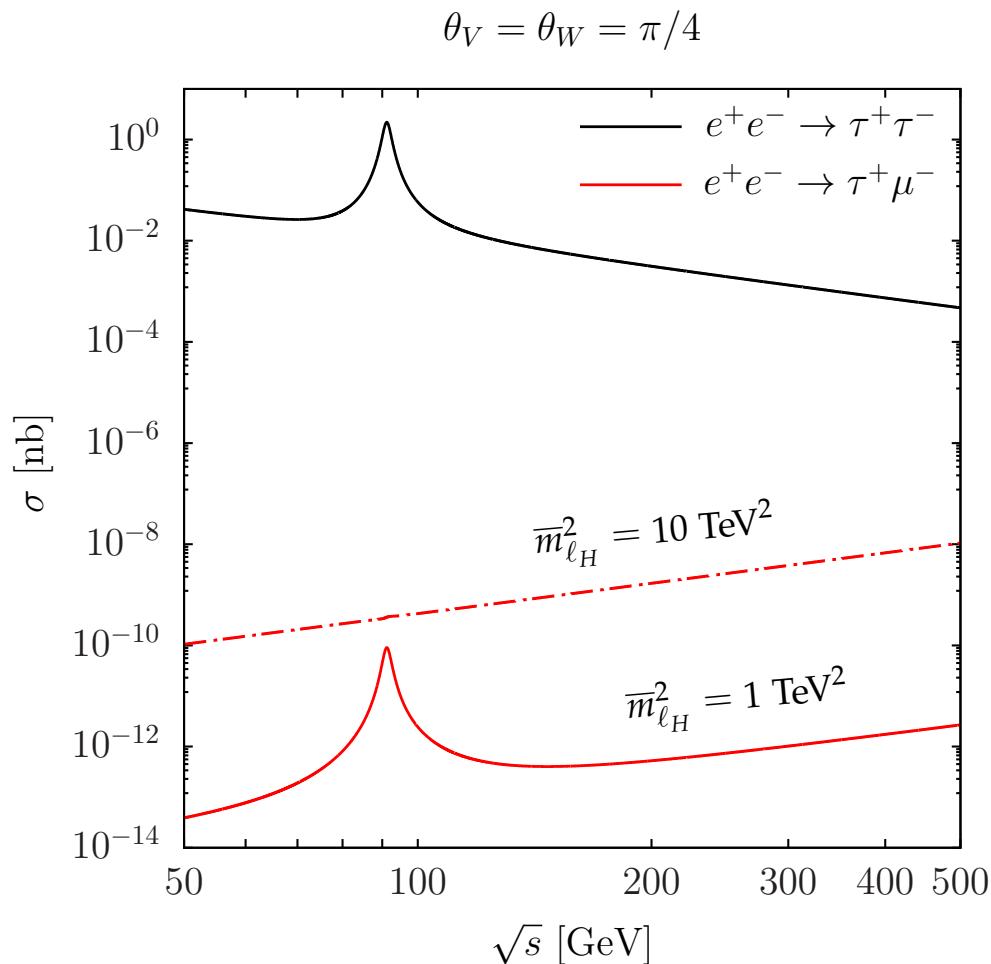
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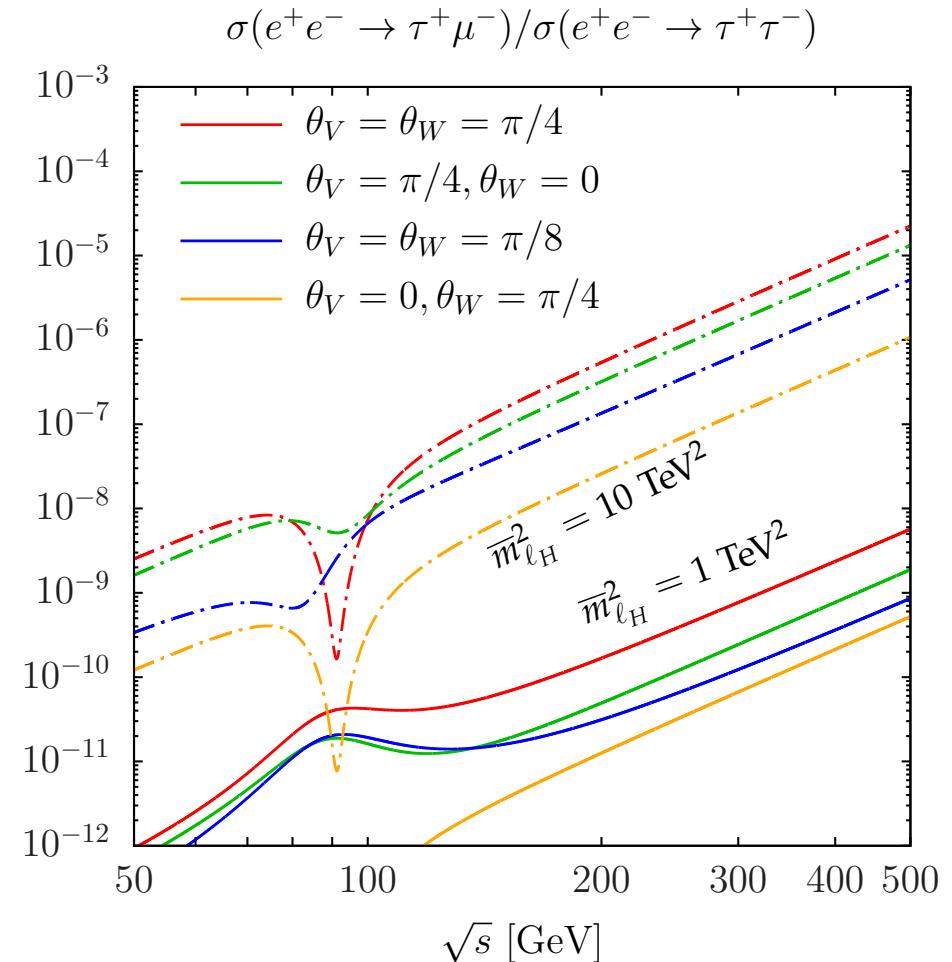
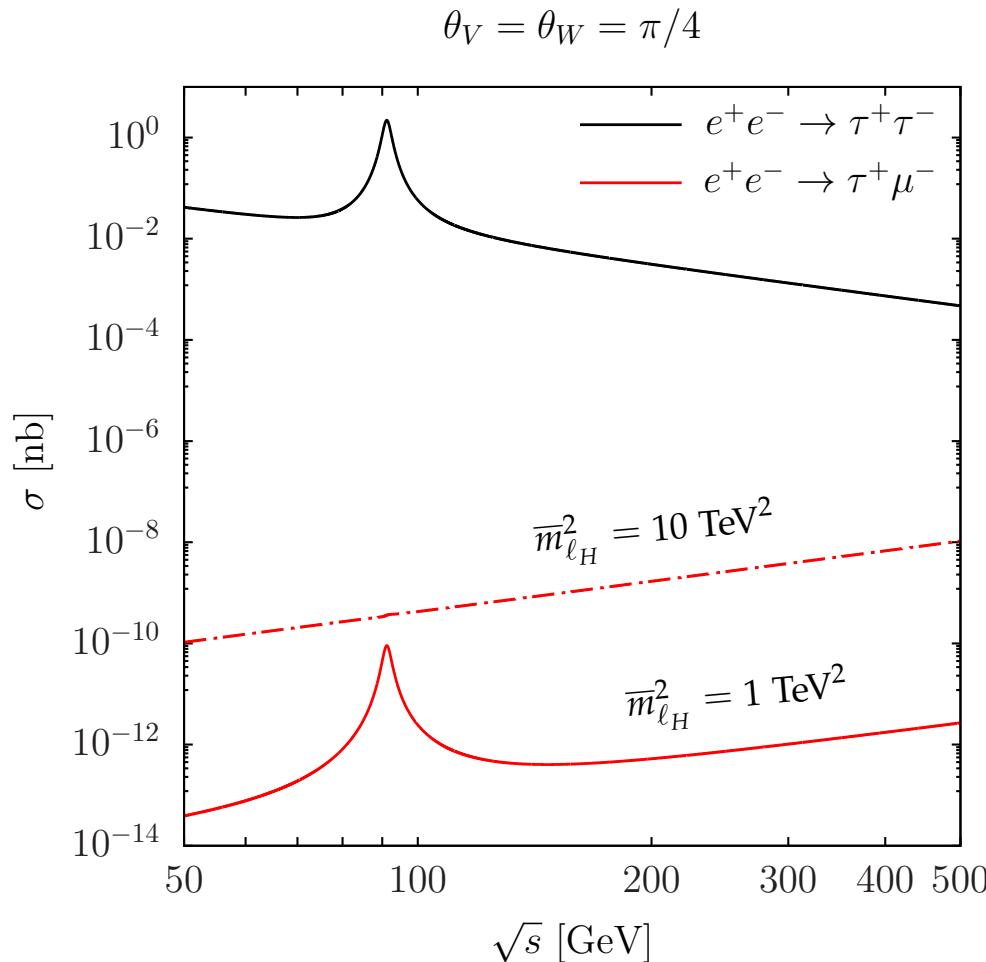


LHT flavor phenomenology

Comments

$e^+e^- \rightarrow \bar{\ell}_1\ell_2$ @ future colliders





- At future FCC-ee or ILC ($\int \mathcal{L} dt \sim 10 \text{ ab}^{-1} = 10^{13} \text{ nb}^{-1}$) one expects $\sim 10^{10} \tau^+\tau^-$ pairs

Conclusions

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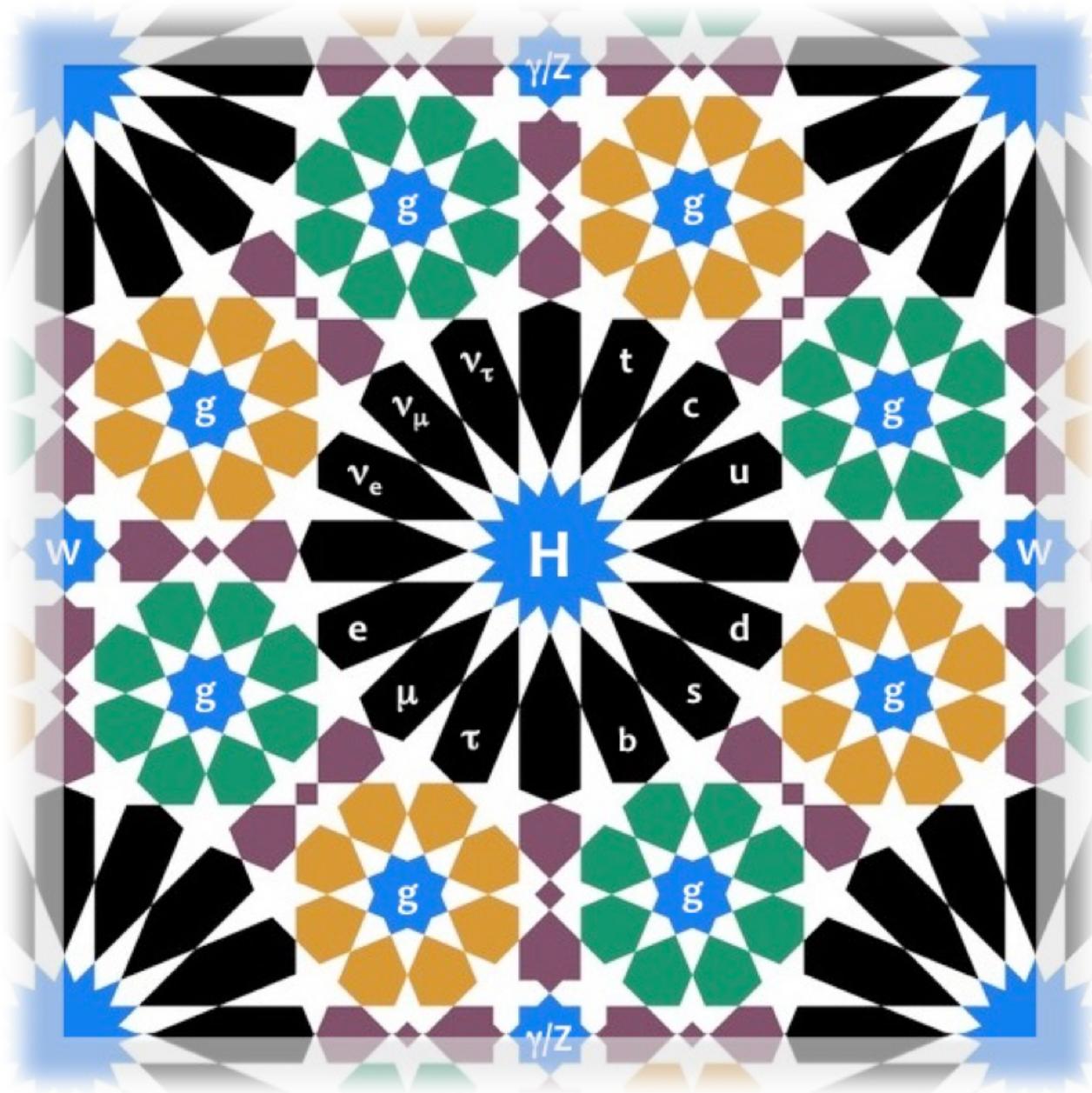
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 - ▷ BUT, if mirror partner masses are of same order as the other T-odd particles, all their contributions have similar size in Higgs and gauge-mediated LFV processes
- Flavor provides complementary constraints to LH models particularly for $\mu - e$ transitions: small misalignment ($\sin 2\theta \lesssim 0.01, \delta \lesssim 0.1$) or heavy scale



Thank You!