Lepton Flavor Violation in Little Higgs Models

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in collaboration with:

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1. Little Higgs: the hierarchy and the flavor problems
2. Models and lepton flavor mixing:

   [LHT] *Littlest* Higgs with T-parity

   [SLH] *Simplest* little Higgs
3. One-loop contributions to LFV processes: $\mu \to e\gamma$, $\mu \to ee\bar{e}$, $\mu N \to eN$
4. Discussion of results
5. Conclusions

JHEP **01** (2009) 080 [arXiv: 0811.2891 [hep-ph]] and [Work to appear]

Little Higgs

[Arkani-Hamed, Cohen, Georgi '01]

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

[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)

(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]

Little Higgs

– 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

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

Ultraviolet completion (unknown) is required only for physics above Λ

– 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 (collective symmetry breaking)

The sensitivity at two loops to a 10 TeV cutoff is *not unnatural*

LH introduce extra fermions and gauge bosons: new source of flavor mixing

$\Rightarrow$ Obtain and revise predictions for lepton flavor changing processes

Littlest Higgs

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

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

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

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

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

[broken]: $Q_1^i - Q_2^i,\ Y_1 - Y_2 \ \Rightarrow$ 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: H (complex $SU(2)$ doublet), Φ (complex $SU(2)$ triplet)

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

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

1 GB: h

Littlest Higgs with T-parity

[Cheng, Low '03]

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

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

– Gauge sector: $G_1 \stackrel{T}{\longleftrightarrow} G_2$ 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: $A_H, Z_H, W_H^+, W_H^- \leftarrow \frac{1}{\sqrt{2}}(G_1-G_2)$

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

– Scalar sector: $\Pi \stackrel{T}{\longrightarrow} -\Omega\Pi\Omega$, where $\Omega = \mathrm{diag}(-1,-1,1,-1,-1)$

$$\Rightarrow \Sigma \stackrel{T}{\longrightarrow} \widetilde{\Sigma} = \Omega\Sigma_0\Sigma^\dagger\Sigma_0\Omega \qquad\qquad \Sigma \stackrel{G}{\longrightarrow} V\Sigma V^T$$

T-even: SM H doublet $(h, \phi^0, \phi^+, \phi^-)$

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

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

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

Littlest Higgs with T-parity

– Fermion (lepton) sector: (similarly for quark sector)

(a) Introduce $SU(2)_L$ left-handed doublets l_{1L}, l_{2L}, l_{HR} in

$$\Psi_1[\overline{\mathbf{5}}] = \begin{pmatrix} -\mathrm{i}\sigma^2 l_{1L} \\ 0 \\ 0 \end{pmatrix} \quad \Psi_2[\mathbf{5}] = \begin{pmatrix} 0 \\ 0 \\ -\mathrm{i}\sigma^2 l_{2L} \end{pmatrix} \quad \Psi_R = \begin{pmatrix} \tilde{\psi}_R \\ \chi_R \\ -\mathrm{i}\sigma^2 l_{HR} \end{pmatrix}$$

$\Psi_1 \stackrel{\mathrm{T}}{\longleftrightarrow} \Omega\Sigma_0\Psi_2$ new $\qquad \Psi_1 \xrightarrow{G} V^*\Psi_1,\ \Psi_2 \xrightarrow{G} V\Psi_2$

$\Psi_R \xrightarrow{\mathrm{T}} \Omega\Psi_R$ new $\qquad \Psi_R \xrightarrow{G} U\Psi_R$

$\Rightarrow$ T-even: $(\nu_L,\ \ell_L)^T = l_L = \frac{1}{\sqrt{2}}(l_{1L} - l_{2L})\ ,$ $\qquad \chi_R$

T-odd: $(\nu_{HL},\ \ell_{HL})^T = l_{HL} = \frac{1}{\sqrt{2}}(l_{1L} + l_{2L}),\quad (\nu_{HR},\ \ell_{HR})^T = l_{HR}\ ,$ $\qquad \tilde{\psi}_R$

To obtain heavy masses respecting gauge and T symmetries:

$$\mathcal{L}_{Y_H} = -\kappa f\left(\overline{\Psi}_2\xi + \overline{\Psi}_1\Sigma_0\xi^\dagger\right)\Psi_R + \text{h.c.}$$

new

$$\xi = \mathrm{e}^{\mathrm{i}\Pi/f} \xrightarrow{\mathrm{T}} \Omega\xi^\dagger\Omega$$

$$\xi \xrightarrow{G} V\xi U^\dagger \equiv U\xi\Sigma_0 V^T\Sigma_0$$

Littlest Higgs with T-parity

(b) Then the light left-handed and heavy fermion gauge interactions are fixed!

$$\mathcal{L}_F = \mathrm{i}\overline{\Psi}_1\gamma^\mu D^*_\mu\Psi_1 \ + \ \mathrm{i}\overline{\Psi}_2\gamma^\mu D_\mu\Psi_2 + \mathrm{i}\overline{\Psi}_R\gamma^\mu \left(\partial_\mu + \tfrac{1}{2}\xi^\dagger(D_\mu\xi) + \tfrac{1}{2}\xi(\Sigma_0 D^*_\mu\Sigma_0\xi^\dagger)\right)\Psi_R$$

new

with $D_\mu = \partial_\mu - \sqrt{2}\mathrm{i}g(W^a_{1\mu}Q^a_1 + W^a_{2\mu}Q^a_2) + \sqrt{2}\mathrm{i}g'\left(Y_1B_{1\mu} + Y_2B_{2\mu}\right)$

introducing so far ignored $\mathcal{O}(v^2/f^2)$ couplings to Goldstones that render the one-loop amplitudes UV finite [del Águila, JI, Jenkins '09]

(c) Introduce light right-handed singlets (ν_R, ℓ_R) and their gauge interactions

$$\mathcal{L}'_F = \mathrm{i}\overline{\ell}_R\gamma^\mu(\partial_\mu + \mathrm{i}g'y_\ell B_\mu)\ell_R \qquad y_\ell = -1$$

[requires enlarging $SU(5)$]

(d) Introduce masses for light (down-type) fermions from: [Chen, Tobe, Yuan '06]

$$\mathcal{L}_Y = \frac{\mathrm{i}\lambda_\ell}{2\sqrt{2}} f\epsilon_{ij}\epsilon_{xyz}\left[(\overline{\Psi}'_2)_x\Sigma_{iy}\Sigma_{jz}X + \text{T-transformed}\right]\ell_R \qquad \Psi'_2 = (0,0,l_{2L})^T\,, \quad X = (\Sigma_{33})^{-\frac{1}{4}}$$

Littlest Higgs with T-parity

(Lepton) Flavor mixing: (three families)

- In the SM after EWSB, the Yukawa interactions generate masses and mixings (CC):

$$\overline{u}_L^0 M_u u_R^0 + \overline{d}_L^0 M_d d_R^0 + \text{h.c.}$$

$$\text{diag}(m_{q_i}) = V_q^\dagger M_q U_q \Rightarrow q_L^0 = V_q q_L, \quad q_R^0 = U_q q_R$$

$$\Rightarrow \quad \mathcal{L}_{CC} = \frac{g}{\sqrt{2}} \overline{u}_L^0 \not{W}^\dagger d_L^0 + \text{h.c.} = \frac{g}{\sqrt{2}} \overline{u}_L \not{W}^\dagger (V_u^\dagger V_d) d_L + \text{h.c.} \qquad V_{\text{CKM}} \equiv V_u^\dagger V_d$$

- In the LHT, $\mathcal{L}_{Y_H}$ generates heavy masses inducing heavy-light mixings:

$$\sqrt{2} f \; \overline{l}_{HL}^0 \kappa l_{HR}^0 + \text{h.c.}$$

$$\text{diag}(\kappa_i) = V_H^\dagger \kappa U_H \Rightarrow l_{HL}^0 = V_H l_{HL}, \quad l_{HR}^0 = U_H l_{HR}$$

$$\Rightarrow \quad \mathcal{L}_{\text{LHT}} \supset g \; \overline{l}_{HL}^0 \not{G}_H^\dagger l_L^0 + \text{h.c.} = g \; \overline{l}_{HL} \not{G}_H^\dagger \begin{pmatrix} V_H^\dagger V_\nu \, \nu_L \\ V_H^\dagger V_\ell \, \ell_L \end{pmatrix} + \text{h.c.} \qquad \begin{matrix} V_{H\nu} \equiv V_H^\dagger V_\nu \\ V_{H\ell} \equiv V_H^\dagger V_\ell \end{matrix}$$

$$\Rightarrow \boxed{V_{H\ell}^{i\alpha} \; \overline{\nu}_{HLi} \not{W}_H^\dagger \ell_{L\alpha}} \text{ CC} \qquad \boxed{V_{H\ell}^{i\alpha} \; \overline{\ell}_{HLi} \{\not{A}_H, \not{Z}_H\} \ell_{L\alpha}} \text{ NC (tree level!)}$$

Simplest little Higgs

[Kaplan, Schmaltz '03]

(1) $G \equiv [SU(3) \times U(1)]_1 \times [SU(3) \times U(1)]_2 \to [SU(2) \times U(1)]_1 \times [SU(2) \times U(1)]_2$

by $\Phi_1[(\mathbf{3},\mathbf{1})]$, $\Phi_2[(\mathbf{1},\mathbf{3})]$ acquiring *vevs* $\langle\Phi_1\rangle = (0,0,f\cos\beta)^T$, $\langle\Phi_2\rangle = (0,0,f\sin\beta)^T$

$\Rightarrow 18 - 8 =$ 10 broken generators

$$G \supset [SU(3) \times U(1)_\chi] \text{ (gauge) } \xrightarrow{\langle\Phi_1\rangle,\ \langle\Phi_2\rangle} SU(2)_L \times U(1)_Y$$

4 unbroken generators $\Rightarrow$ 4 gauge bosons (γ, Z, W^+, W^-) remain massless

5 broken generators $\Rightarrow$ 5 gauge bosons $(X^+, X^-, Y^0, \overline{Y}^0, Z')$ get masses of order f

5 WBGB: $(x^+,\ x^-,\ y^0,\ y^{0\dagger},\ z')$ eaten by $(X^+, X^-, Y^0, \overline{Y}^0, Z')$

5 GB: H (complex $SU(2)$ doublet), η (real $SU(2)$ singlet)

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

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

1 GB: h

Simplest little Higgs

– Gauge sector: $\mathcal{L}_G = -\frac{1}{2}\mathrm{Tr}\left\{\widetilde{A}_{\mu\nu}\widetilde{A}^{\mu\nu}\right\} - \frac{1}{4}B_{x\mu\nu}B_x^{\mu\nu}$

$$A^a T_a = \frac{A^3}{2}\begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \frac{A^8}{2}\begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix} + \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & W^+ & Y^0 \\ W^- & 0 & X^- \\ Y^{0\dagger} & X^+ & 0 \end{pmatrix}$$

– Scalar sector: $\mathcal{L}_S = |D_\mu \Phi_1|^2 + |D_\mu \Phi_2|^2 \supset$ gauge boson masses $\quad \Phi_{1,2} \sim \mathbf{3}_{-\frac{1}{3}}$

$$D_\mu = \partial_\mu - \mathrm{i}g A^a_\mu T_a + \mathrm{i}g_x Q_x B_{x\mu}\ , \qquad g_x = \frac{g t_W}{\sqrt{1 - t_W^2/3}}$$

gauge boson masses diagonalized by:

$$\begin{pmatrix} A^3 \\ A^8 \\ B_x \end{pmatrix} = \begin{pmatrix} 0 & c_W & -s_W \\ \sqrt{1-t_W^2/3} & s_W t_W/\sqrt{3} & s_W/\sqrt{3} \\ -t_W/\sqrt{3} & s_W\sqrt{1-t_W^2/3} & c_W\sqrt{1-t_W^2/3} \end{pmatrix}\begin{pmatrix} Z' \\ Z \\ A \end{pmatrix} + \mathcal{O}(v^2/f^2)$$

Simplest little Higgs

– Lepton sector:

For each family $m = 1, 2, 3$ introduce the following multiplets:

$$\mathbf{3}_{-\frac{1}{3}} \equiv L_m^T = (\nu_L,\ \ell_L,\ \mathrm{i}N_L)_m \qquad \mathbf{1}_0 \equiv \nu_{Rm} \qquad \mathbf{1}_{-1} \equiv \ell_{Rm} \qquad \mathbf{1}_0 \equiv N_{Rm}$$

Yukawas:

$$\boxed{\mathcal{L}_Y \supset \mathrm{i}\lambda_N^m \overline{N}_{Rm} \Phi_2^\dagger L_m + \frac{\mathrm{i}\lambda_\ell^{mn}}{\Lambda} \overline{\ell}_{Rm} \epsilon_{ijk} \Phi_1^i \Phi_2^j L_n^k + \mathrm{h.c.}}$$

Gauge interactions:

$$\boxed{\mathcal{L}_F \supset \overline{\psi}_m \mathrm{i}\not{D} \psi_m} \qquad \psi_m = \{L_m, \ell_{Rm}, N_{Rm}\}$$

Simplest little Higgs

– Quark sector:

(i) Universal embedding (U):

$$\mathbf{3}_{\frac{1}{3}} \equiv Q_m^T = (u_L,\ d_L,\ \mathrm{i}U_L)_m \qquad \mathbf{1}_{\frac{2}{3}} \equiv u_{Rm} \qquad \mathbf{1}_{-\frac{1}{3}} \equiv d_{Rm} \qquad \mathbf{1}_{\frac{2}{3}} \equiv U_{Rm}$$

Yukawas: $\{u^1_{Rm}, u^2_{Rm}\} \leftrightarrow \{u_{Rm}, U_{Rm}\}$

$$\boxed{\mathcal{L}_Y \supset \mathrm{i}\lambda_1^{um}\overline{u}^1_{Rm}\Phi_1^\dagger Q_m + \mathrm{i}\lambda_2^{um}\overline{u}^2_{Rm}\Phi_2^\dagger Q_m + \frac{\mathrm{i}\lambda_d^{mn}}{\Lambda}\overline{d}_{Rm}\epsilon_{ijk}\Phi_1^i\Phi_2^j Q_n^k + \text{h.c.}}$$

Gauge interactions:

$$\boxed{\mathcal{L}_F \supset \overline{Q}_m \mathrm{i}\not{D}^L Q_m + \overline{u}_{Rm}\mathrm{i}\not{D}^u u_{Rm} + \overline{d}_{Rm}\mathrm{i}\not{D}^d d_{Rm} + \overline{U}_{Rm}\mathrm{i}\not{D}^u U_{Rm}}$$

Simplest little Higgs

– Quark sector:

(ii) Anomaly-free embedding (AF): [Kong '03]

$$
\begin{array}{llllll}
\overline{\mathbf{3}}_0 \equiv Q_1^T = (d_L,\ -u_L,\ \mathrm{i}D_L) & \mathbf{1}_{-\frac{1}{3}} \equiv d_R & \mathbf{1}_{\frac{2}{3}} \equiv u_R & \mathbf{1}_{-\frac{1}{3}} \equiv D_R \\
\overline{\mathbf{3}}_0 \equiv Q_2^T = (s_L,\ -c_L,\ \mathrm{i}S_L) & \mathbf{1}_{-\frac{1}{3}} \equiv s_R & \mathbf{1}_{\frac{2}{3}} \equiv c_R & \mathbf{1}_{-\frac{1}{3}} \equiv S_R \\
\mathbf{3}_{\frac{1}{3}} \equiv Q_3^T = (t_L,\ b_L,\ \mathrm{i}T_L) & \mathbf{1}_{\frac{2}{3}} \equiv t_R & \mathbf{1}_{-\frac{1}{3}} \equiv b_R & \mathbf{1}_{\frac{2}{3}} \equiv T_R
\end{array}
$$

Yukawas: $\{d^1_{R1}, d^2_{R1}\} \leftrightarrow \{d_R, D_R\}$, $\{d^1_{R2}, d^2_{R2}\} \leftrightarrow \{s_R, S_R\}$, $\{u^1_{R3}, u^2_{R3}\} \leftrightarrow \{t_R, T_R\}$

$$
\begin{aligned}
\mathcal{L}_Y \supset\ & \mathrm{i}\lambda_1^t \overline{u}^1_{R3}\Phi_1^\dagger Q_3 + \mathrm{i}\lambda_2^t \overline{u}^2_{R3}\Phi_2^\dagger Q_3 + \frac{\mathrm{i}\lambda_b^m}{\Lambda}\overline{d}_{Rm}\epsilon_{ijk}\Phi_1^i\Phi_2^j Q_3^k \\
& + \mathrm{i}\lambda_1^{dn}\overline{d}^1_{Rn}Q_n^T\Phi_1 + \mathrm{i}\lambda_2^{dn}\overline{d}^2_{Rn}Q_n^T\Phi_2 + \frac{\mathrm{i}\lambda_u^{mn}}{\Lambda}\overline{u}_{Rm}\epsilon_{ijk}\Phi_1^{*i}\Phi_2^{*j}Q_n^k + \mathrm{h.c.}
\end{aligned}
$$

$$
d_{Rm} \in \{d_R, s_R, b_R, D_R, S_R\} \quad u_{Rm} \in \{u_R, c_R, t_R, T_R\} \quad n = 1, 2
$$

Gauge interactions:

$$
\mathcal{L}_F \supset \overline{Q}_m \mathrm{i}\not{D}_i^L Q_m + \overline{u}_{Rm}\mathrm{i}\not{D}^u u_{Rm} + \overline{d}_{Rm}\mathrm{i}\not{D}^d d_{Rm} + \overline{D}_R \mathrm{i}\not{D}^d D_R + \overline{S}_R \mathrm{i}\not{D}^d S_R + \overline{T}_R \mathrm{i}\not{D}^u T_R
$$

Simplest little Higgs

(Lepton) Flavor mixing:

– After EWSB the light and the heavy neutrino of the same family mix at $\mathcal{O}(v/f)$

– If λ_N^m and λ_ℓ^{mn} are not aligned there is also family mixing: (basis where $\ell_{Li} \equiv \ell_{Li}^0$)

$$\begin{pmatrix} \nu_L \\ N_L \end{pmatrix}_i = \begin{pmatrix} \mathbf{1} & -\delta_\nu V_{H\ell} \\ \delta_\nu \mathbf{1} & V_{H\ell} \end{pmatrix}_{im} \begin{pmatrix} \nu_L^0 \\ N_L^0 \end{pmatrix}_m + \mathcal{O}(\delta_\nu^2), \qquad \delta_\nu \equiv -\frac{v}{\sqrt{2} f \tan\beta}$$

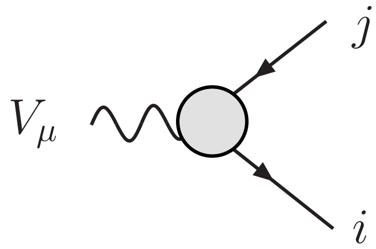
⇒ Heavy-light mixings in CC only: (mixings in $\overline{N}_{Lm}\{Y^0, Z'\}\nu_{Li}$ are irrelevant)

$$\mathcal{L}_{\rm SLH} \supset \underbrace{-\frac{g}{\sqrt{2}}\left(1-\frac{\delta_\nu^2}{2}\right) V_{H\ell}^{im*}\overline{N}_{Lm}\gamma^\mu X_\mu^\dagger \ell_{Li}}_{\mathcal{O}(1)} \underbrace{-\frac{\mathrm{i}g}{\sqrt{2}}\delta_\nu V_{H\ell}^{im*}\overline{N}_{Lm}\gamma^\mu W_\mu^\dagger \ell_{Li}}_{\mathcal{O}(v/f)} \quad +\text{h.c.}$$

[no mixing in NC because there is no heavy charged lepton]

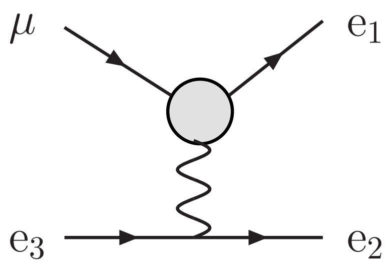
One-loop contributions to Lepton FV processes

$\mu \to e\gamma$:

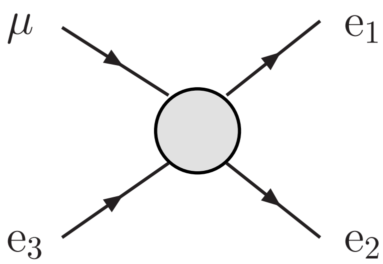


vertex (triangles)

$\mu \to ee\bar{e}$:



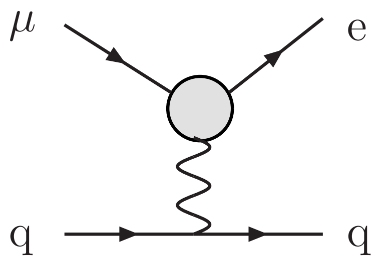
$+$



$+$ crossed ($e_1 \leftrightarrow e_2$)

V-penguins (triangles+SE) e-boxes

$\mu N \to eN$:



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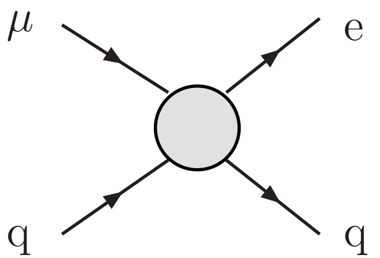
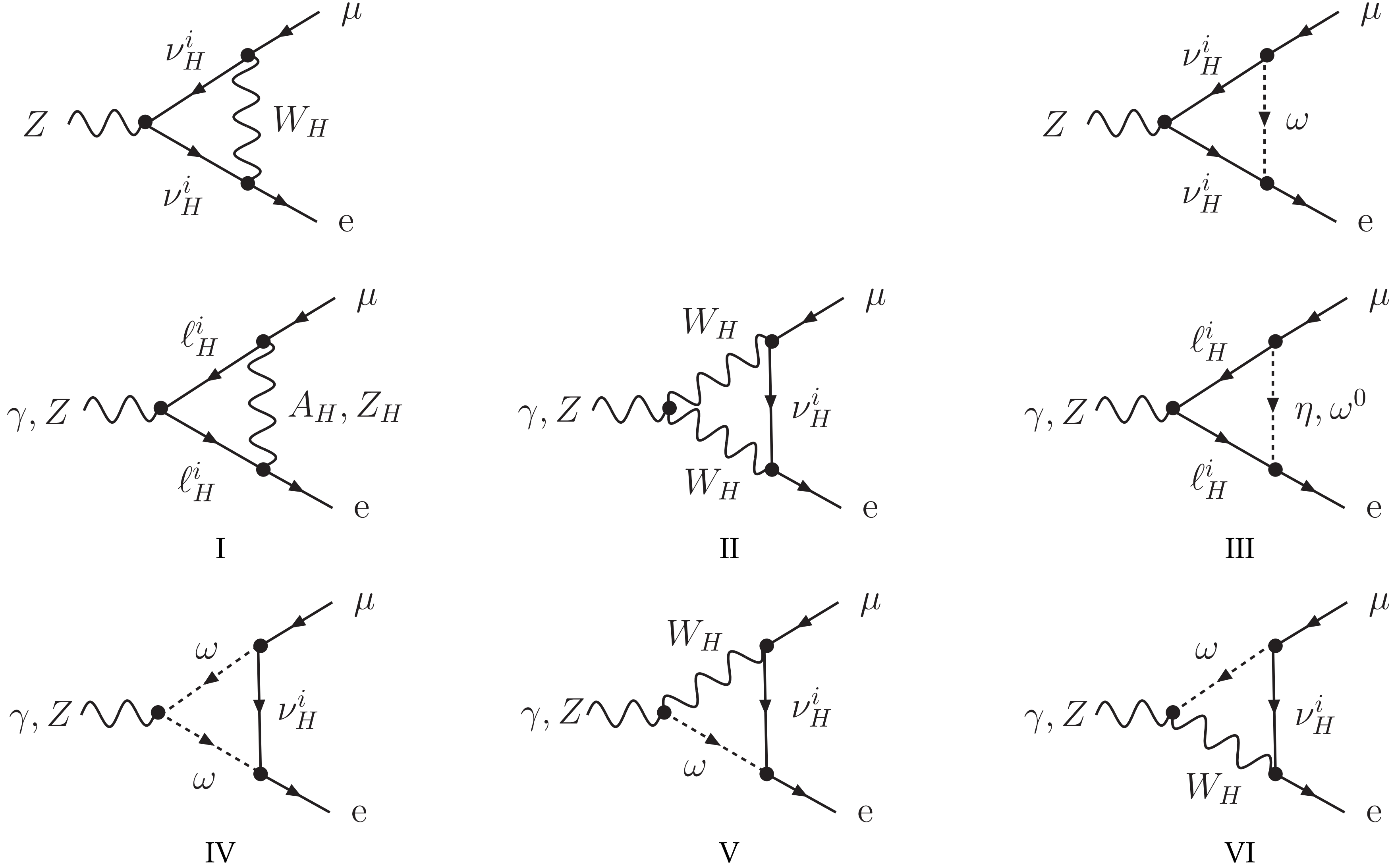


($q = u, d$)

V-penguins (triangles+SE) q-boxes

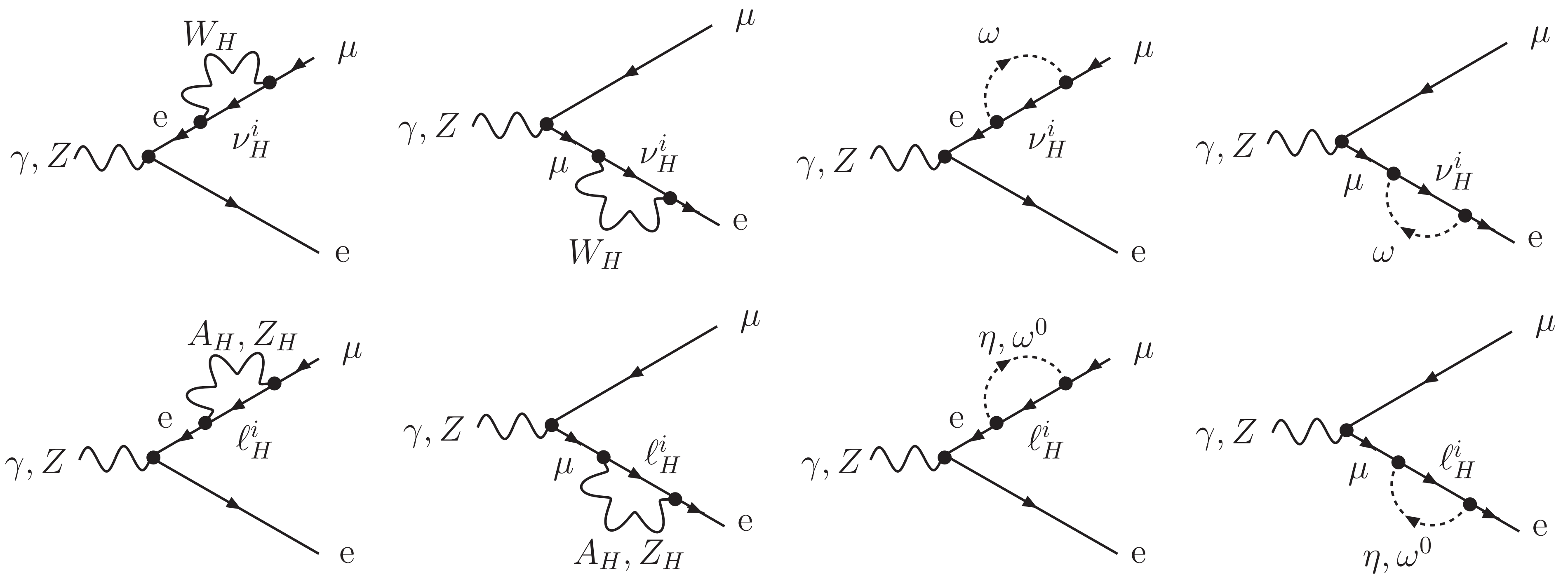
- Triangle diagrams $\Rightarrow$ vertex and penguins



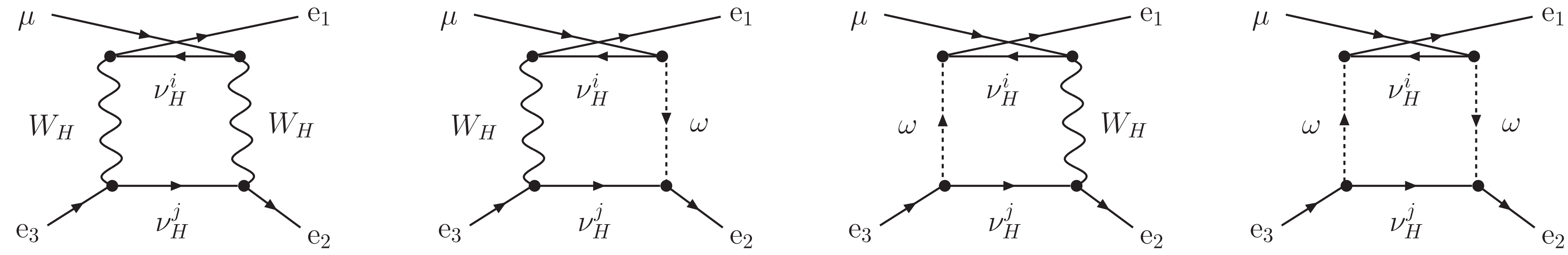
One-loop contributions to Lepton FV processes

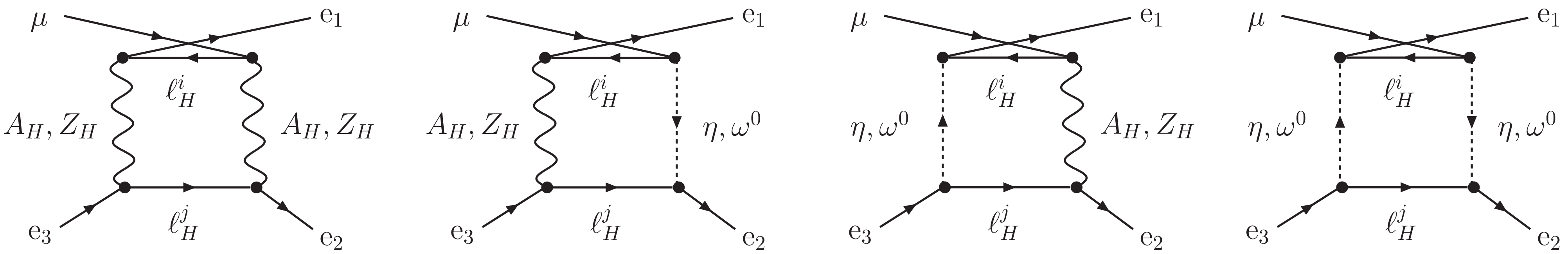
LHT

- Self-energy diagrams ⇒ penguins

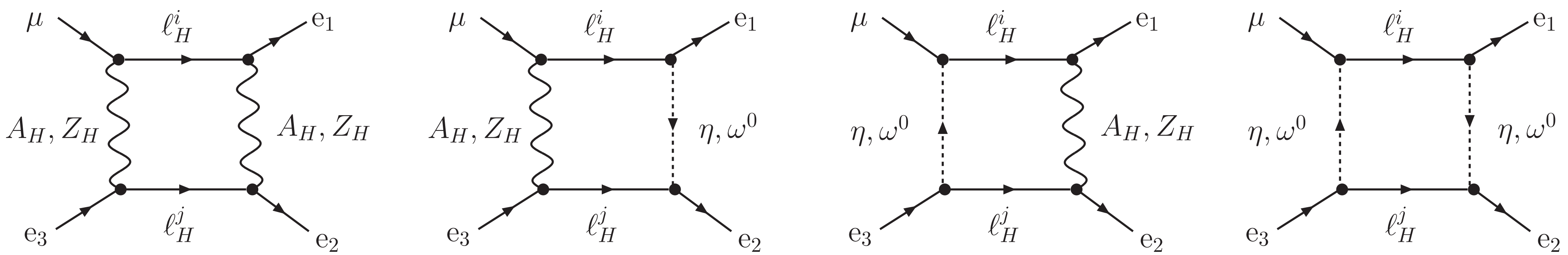


- e-Box diagrams





A1 A2 A3 A4

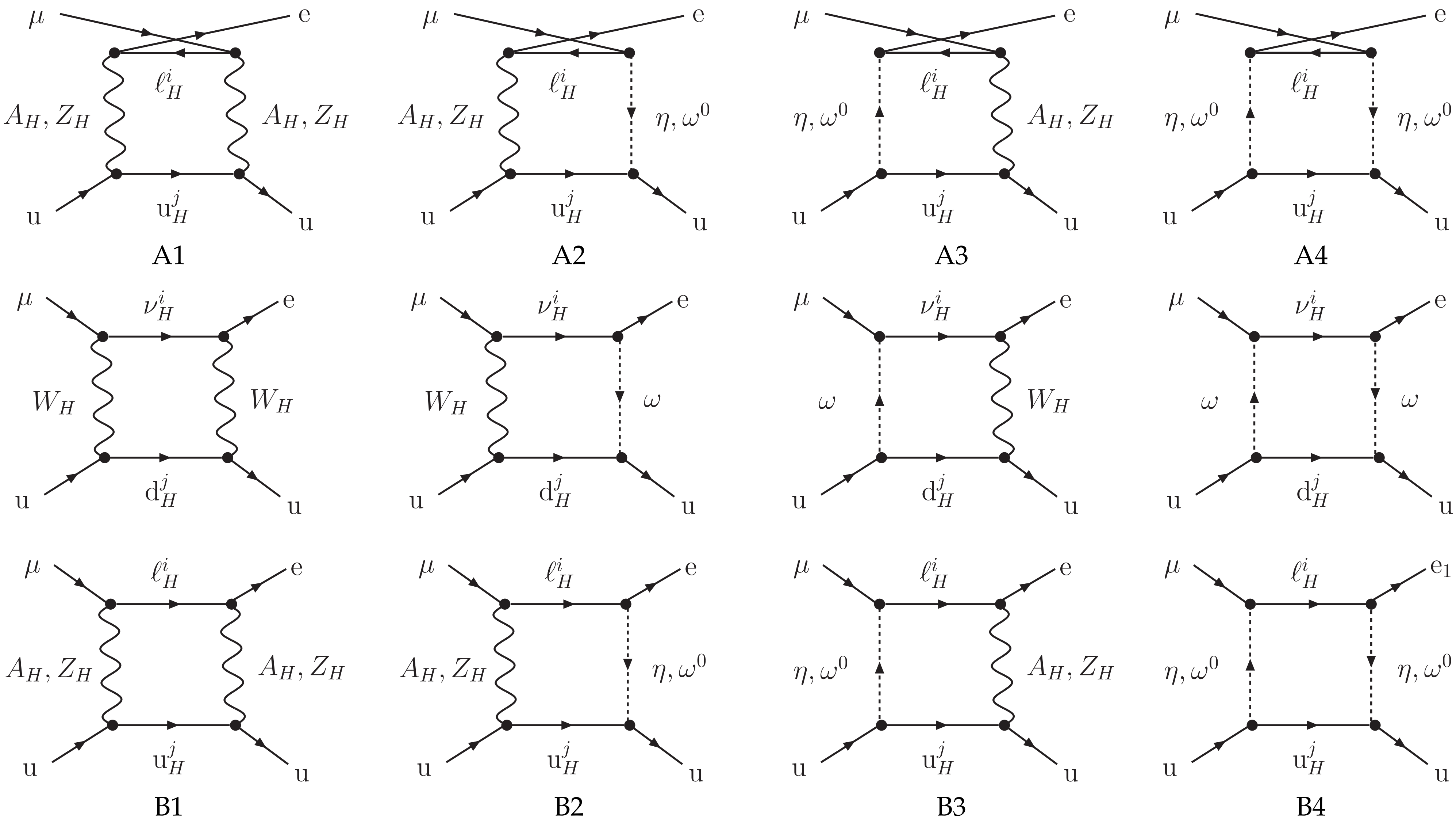


B1 B2 B3 B4

One-loop contributions to Lepton FV processes

LHT

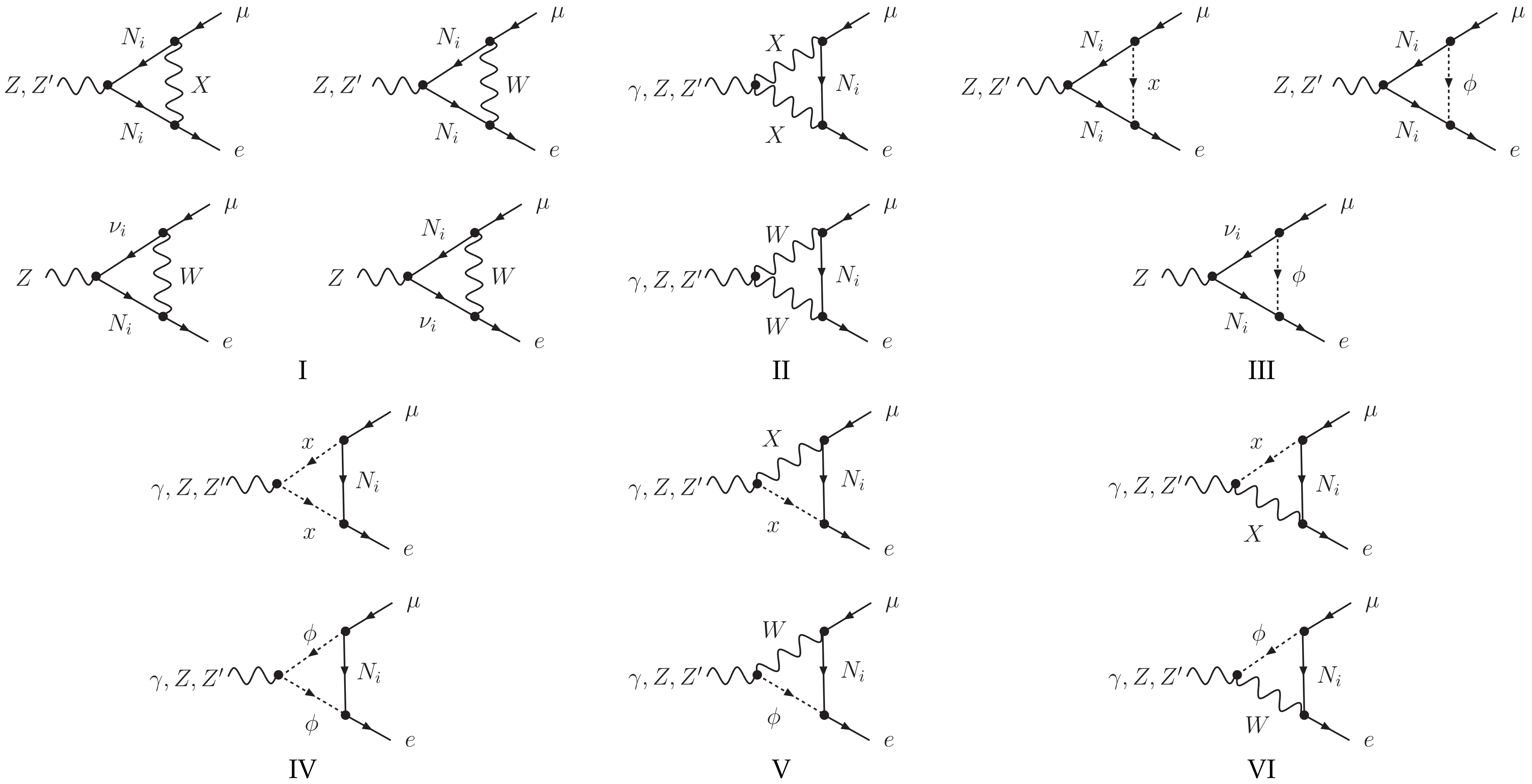
- q-Box diagrams for quark u (similarly for quark d)



One-loop contributions to Lepton FV processes

SLH

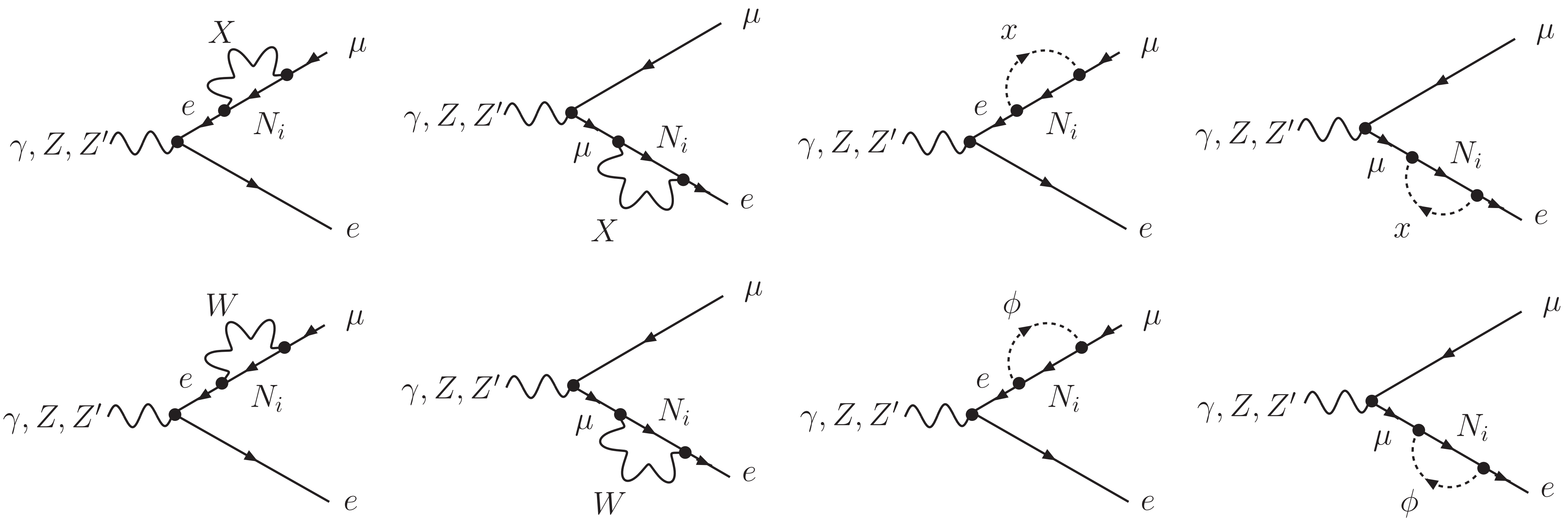
- Triangle diagrams ⇒ vertex and penguins



One-loop contributions to Lepton FV processes

SLH

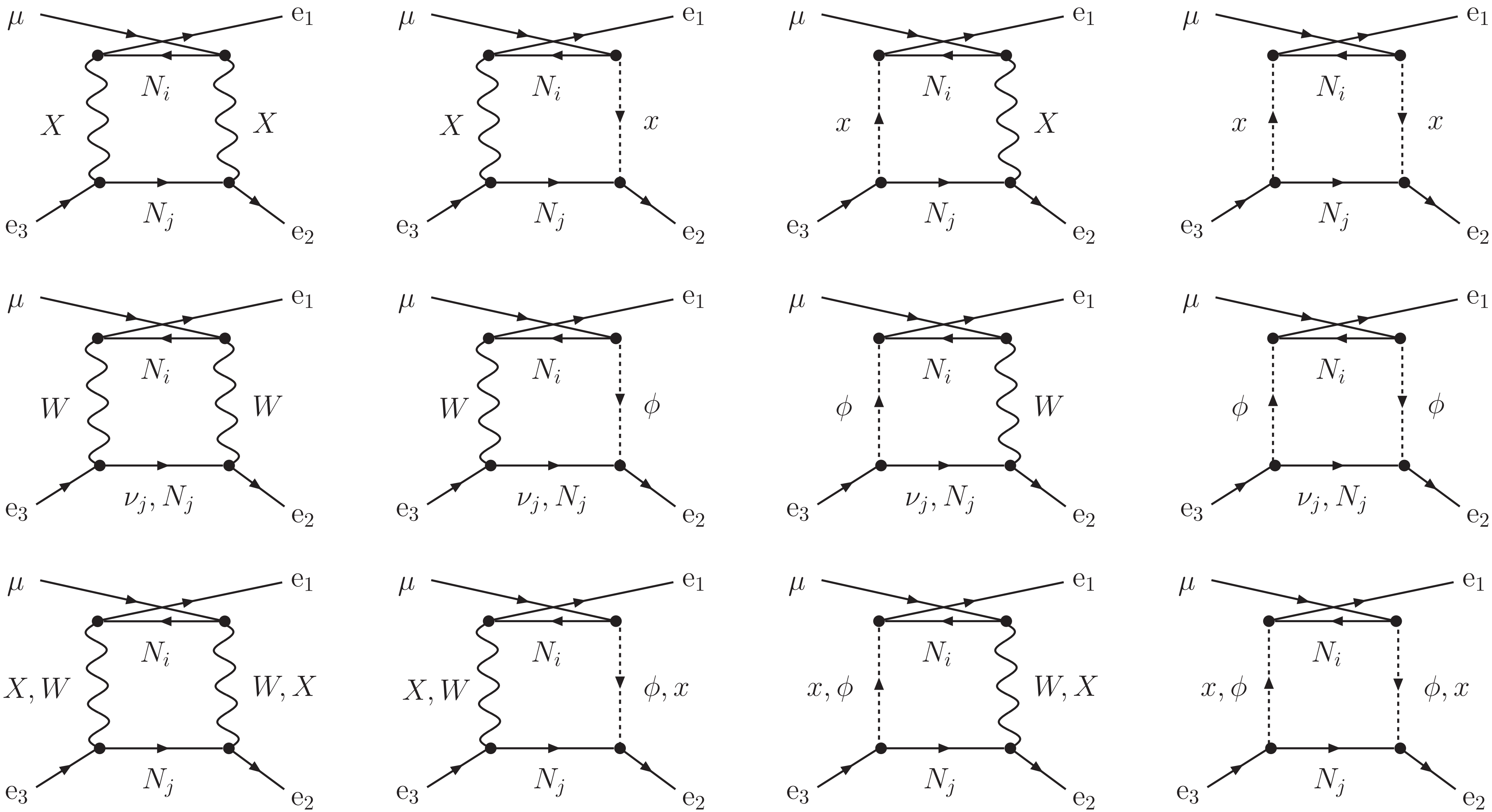
- Self-Energy diagrams $\Rightarrow$ penguins



One-loop contributions to Lepton FV processes

SLH

- e-Box diagrams

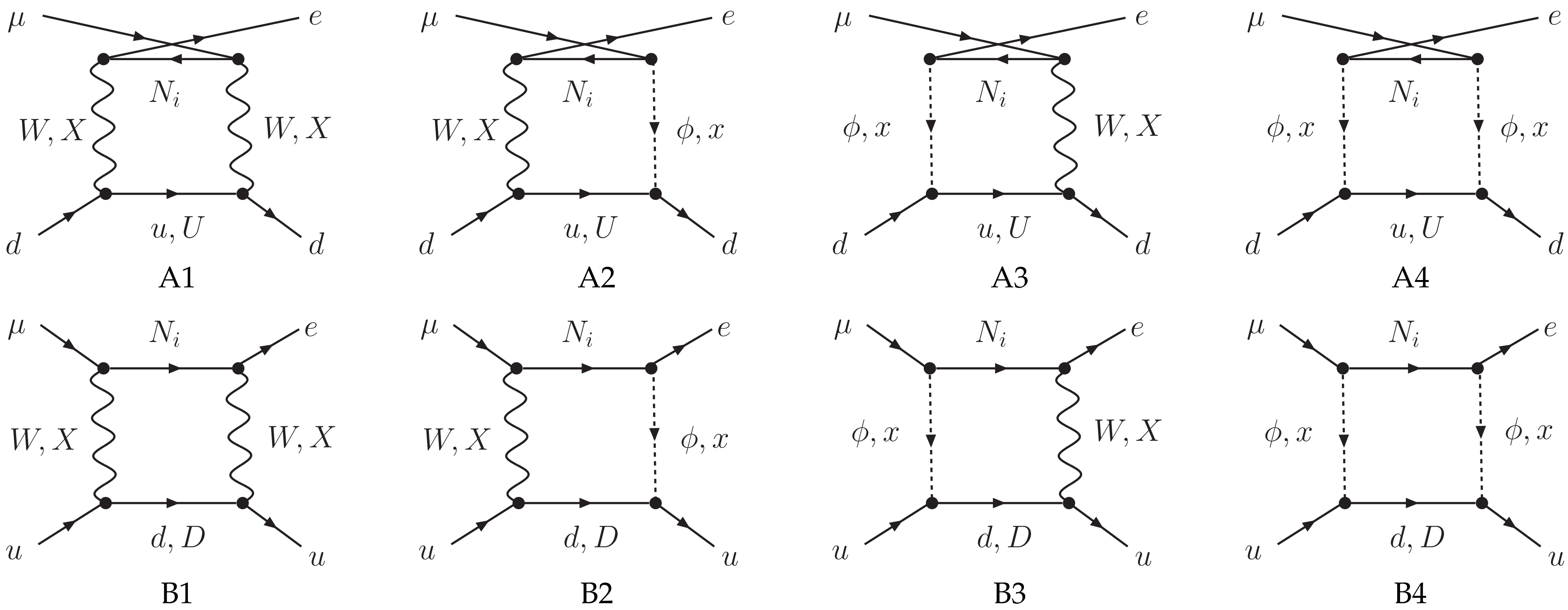


A1 A2 A3 A4

One-loop contributions to Lepton FV processes

SLH

- q-Box diagrams



Discussion

- ✓ FRs including WBGBs ('t Hooft-Feynman gauge) obtained to $\mathcal{O}(v^2/f^2)$
- ✓ All form factors in terms of standard loop integrals computed analytically
- ✓ Amplitudes reduced to exact and simple expressions
- ✓ Ultraviolet finite

– Simplification: just 2-gen lepton mixing with $\{\nu_{Hi}, \ell_{Hi}|N_{Hi}\}$ of $m_{Hi}^2 \equiv y_i M^2_{\{W_H|X\}}$

$$V_{H\ell} = \begin{pmatrix} V_{H\ell}^{1e} & V_{H\ell}^{1\mu} \\ V_{H\ell}^{2e} & V_{H\ell}^{2\mu} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix}, \quad \delta = \frac{m_{H2}^2 - m_{H1}^2}{m_{H1} m_{H2}}, \quad \tilde{y} = \sqrt{y_1 y_2}$$

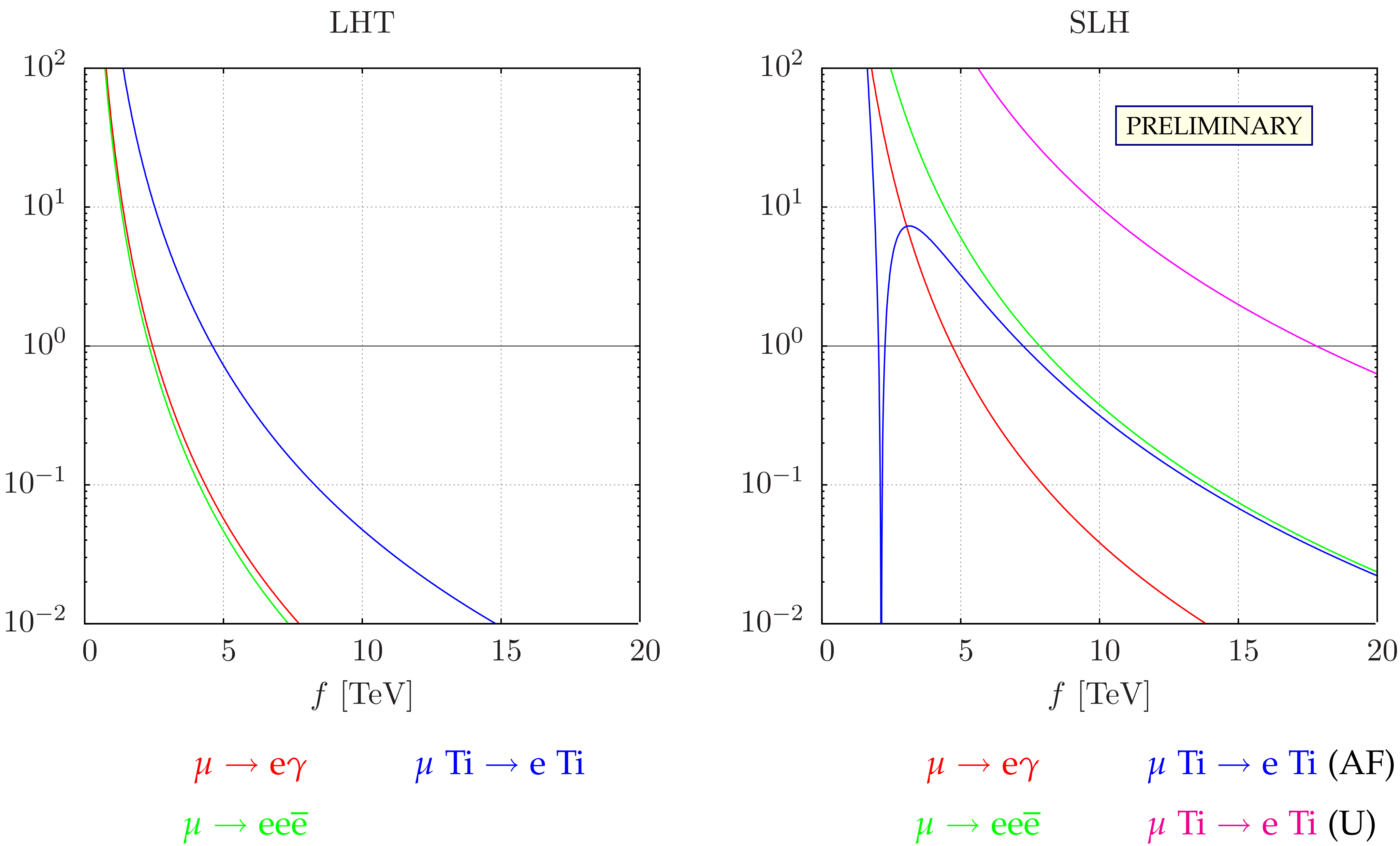
$\rightsquigarrow$ amplitudes approximately scale like $\boxed{\frac{v^2}{f^2}\sin 2\theta\ \delta}$ and vary with $\boxed{\tilde{y}}$

– *Natural* input values: $f \sim 1$ TeV, $\sin 2\theta \sim 1$, $\delta \sim 1$, $\tilde{y} \sim 1$, $(m_{q_{Hi}} = 500$ GeV$)$

[for SLH: $\tan\beta = 1$, $m_U = m_D = 500$ GeV]

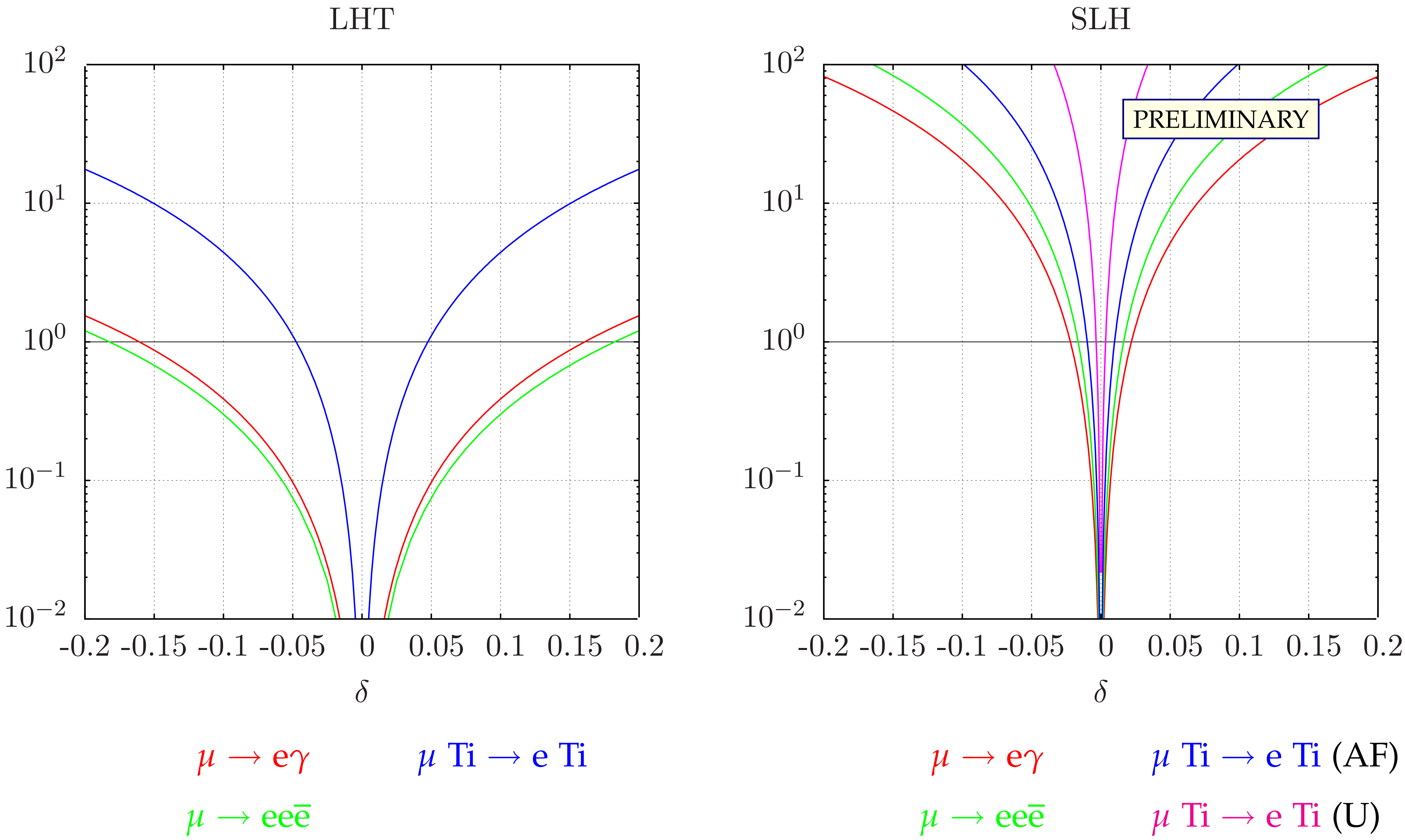
Ratio of expectations to current limits

$\delta = 1 \;\; \sin 2\theta = 1 \;\; \tilde{y} = 1$



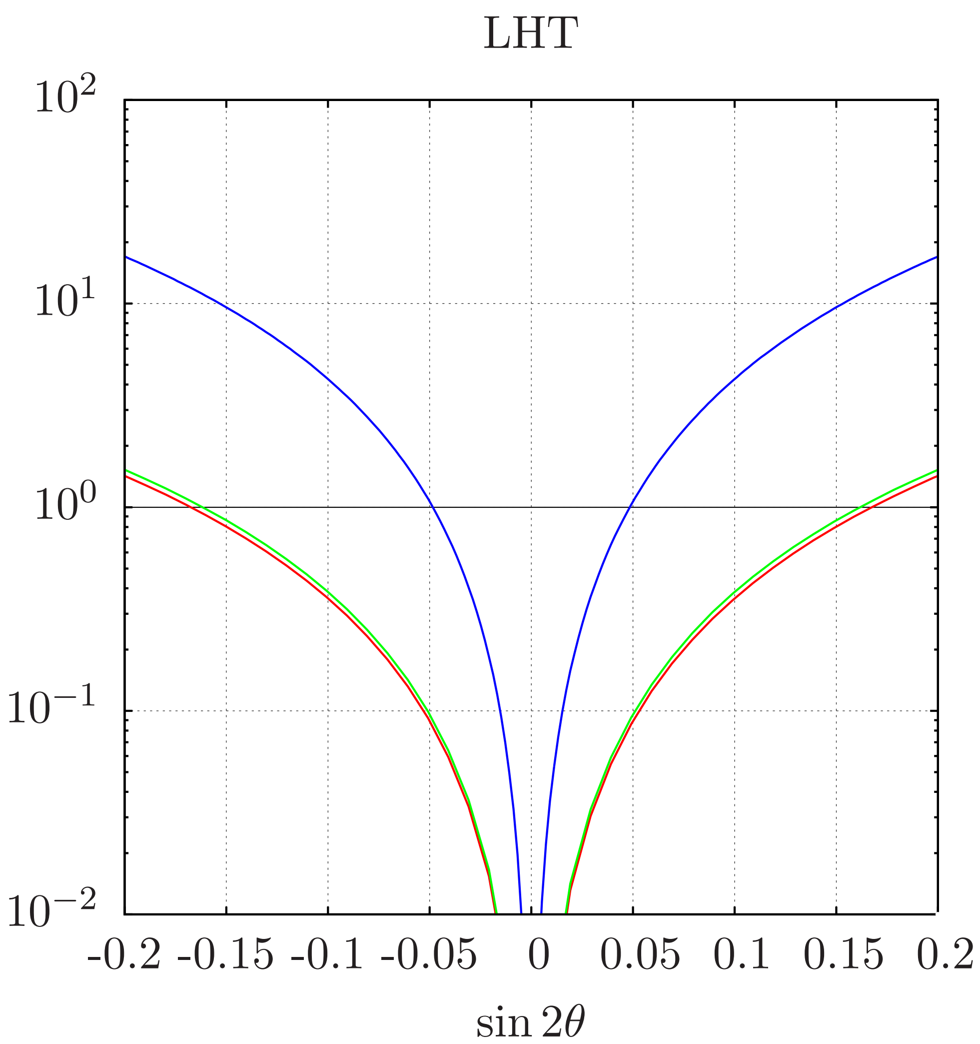
Ratio of expectations to current limits

$f = 1$ TeV $\sin 2\theta = 1$ $\tilde{y} = 1$



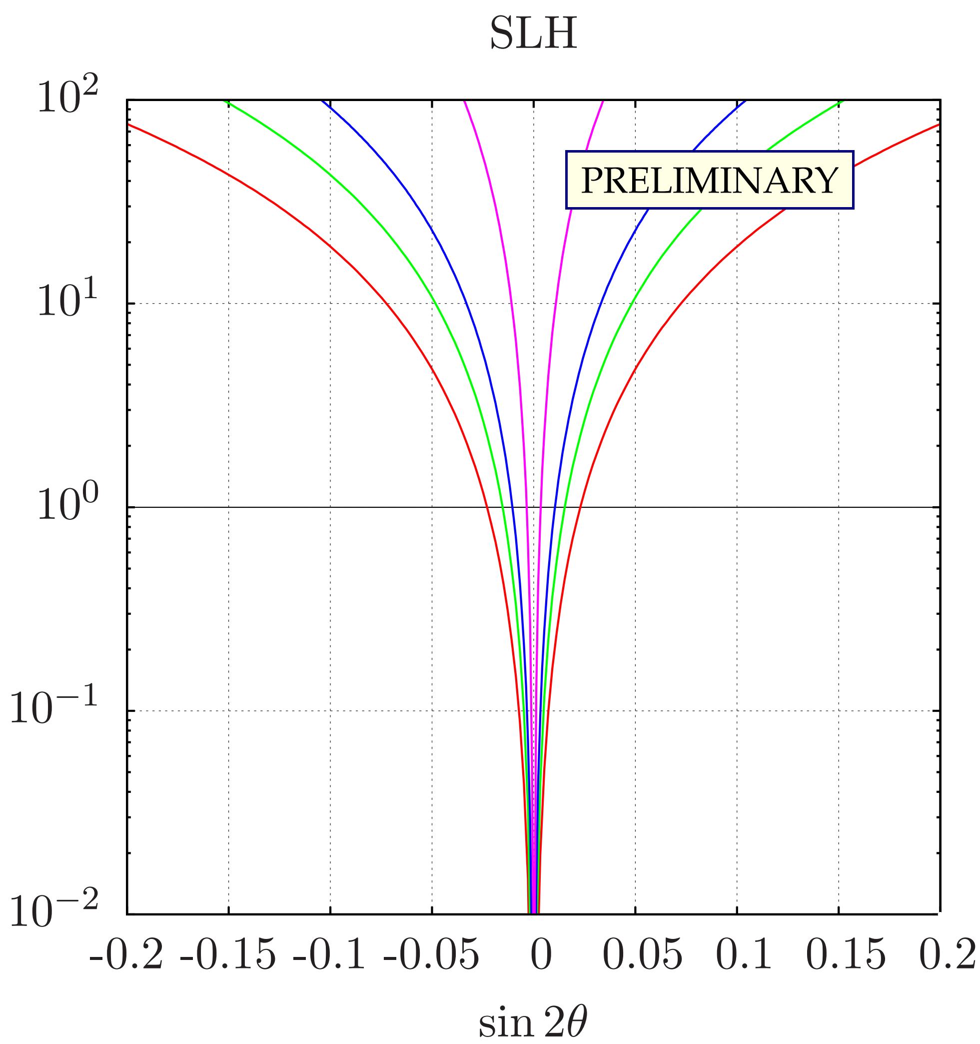
Ratio of expectations to current limits

$f = 1$ TeV $\delta = 1$ $\tilde{y} = 1$



$\mu \to e\gamma$ μ Ti $\to$ e Ti

$\mu \to ee\bar{e}$

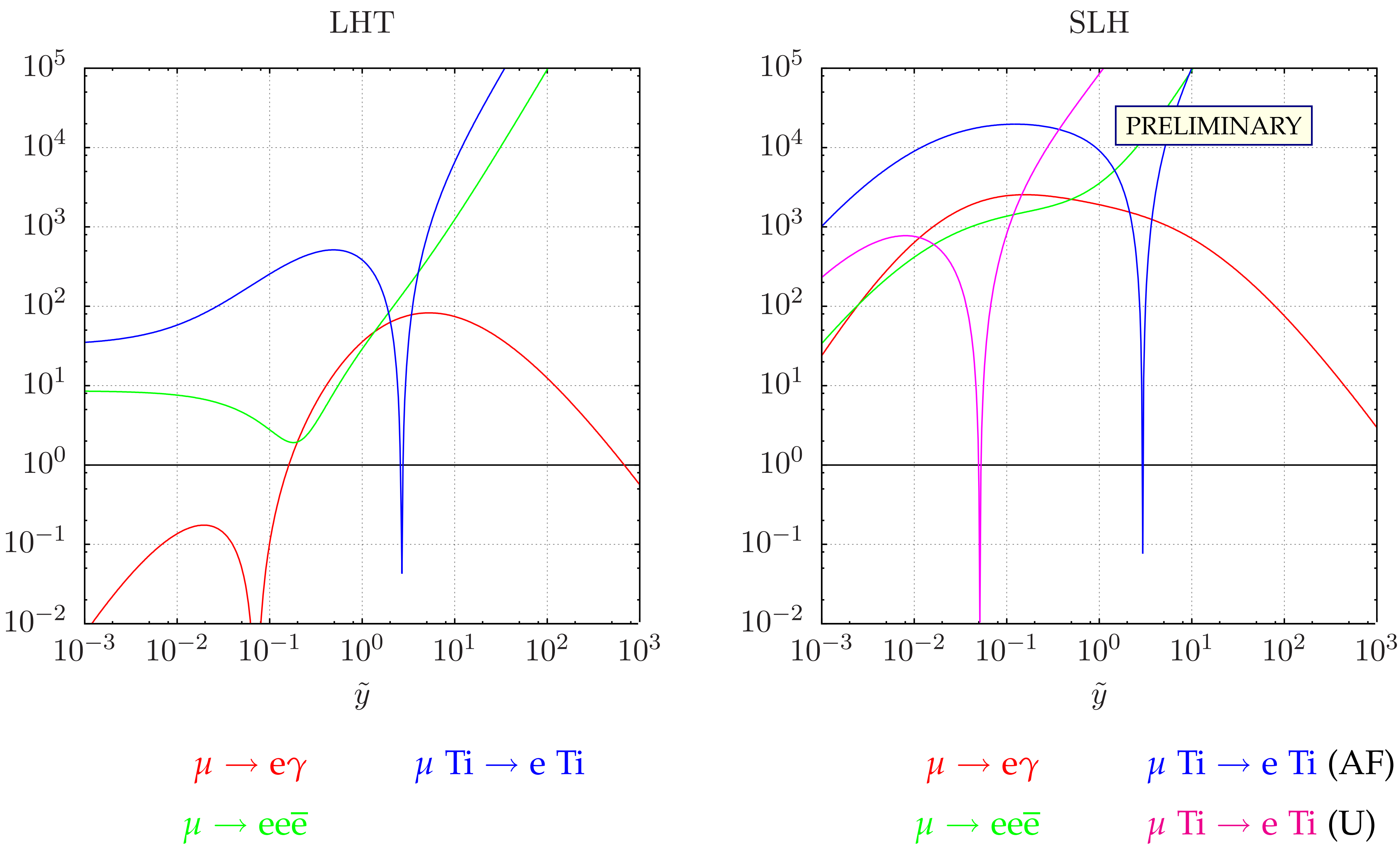


$\mu \to e\gamma$ μ Ti $\to$ e Ti (AF)

$\mu \to ee\bar{e}$ μ Ti $\to$ e Ti (U)

Ratio of expectations to current limits

$f = 1$ TeV $\delta = 1$ $\sin 2\theta = 1$



Results and experimental constraints

LHT

– Present upper limits on $|\delta|$ in the LHT: $(\sin 2\theta = 1,\ m_{q_{Hi}} = 500\ \text{GeV})$

	$\mu \to e\gamma$			$\mu \to ee\bar{e}$			μ Ti $\to$ e Ti		
f [TeV]	$\tilde{y} = \frac{1}{4}$	$\tilde{y} = 1$	$\tilde{y} = 4$	$\tilde{y} = \frac{1}{4}$	$\tilde{y} = 1$	$\tilde{y} = 4$	$\tilde{y} = \frac{1}{4}$	$\tilde{y} = 1$	$\tilde{y} = 4$
0.5	0.131	0.040	0.026	0.161	0.046	0.015	0.011	0.009	0.155
1.0	0.527	0.161	0.106	0.646	0.182	0.061	0.050	0.048	0.067
2.0	2.20	0.665	0.428	2.74	0.737	0.244	0.159	0.190	0.215
4.0	14.0	3.47	1.99	13.4	3.26	0.987	0.570	0.740	0.815

– Comparison with future limits (assuming natural values for the other parameters):

	$\mathcal{B}(\mu \to e\gamma) <$		$\mathcal{B}(\mu \to ee\bar{e}) <$		$\mathcal{R}(\mu\ \text{Ti} \to e\ \text{Ti}) <$	
	1.2×10^{-11}	10^{-13}	10^{-12}	10^{-14}	4.3×10^{-12}	10^{-18}
$f/\text{TeV} >$	2.45	8.09	2.33	7.34	4.61	214
$\sin 2\theta <$	0.167	0.015	0.162	0.016	0.051	0.000
$|\delta| <$	0.161	0.015	0.182	0.018	0.048	0.000

Results and experimental constraints

SLH

– Present upper limits on $|\delta|$ in the SLH: $(\sin 2\theta = 1, \tan\beta = 1, m_U = m_D = 500$ GeV)

	$\mu \to e\gamma$			$\mu \to ee\bar{e}$			μ Ti $\to$ e Ti for AN (U)		
f [TeV]	$\tilde{y} = \frac{1}{4}$	$\tilde{y} = 1$	$\tilde{y} = 4$	$\tilde{y} = \frac{1}{4}$	$\tilde{y} = 1$	$\tilde{y} = 4$	$\tilde{y} = \frac{1}{4}$	$\tilde{y} = 1$	$\tilde{y} = 4$
0.5	0.005	0.004	0.005	0.007	0.005	0.002	0.001 (0.006)	0.001 (0.001)	0.001 (0.000)
1.0	0.019	0.022	0.027	0.023	0.016	0.007	0.007 (0.011)	0.010 (0.003)	0.022 (0.001)
2.0	0.113	0.128	0.140	0.092	0.064	0.027	0.052 (0.032)	0.568 (0.012)	0.026 (0.004)
4.0	0.755	0.682	0.639	0.374	0.256	0.109	0.504 (0.116)	0.423 (0.050)	0.084 (0.018)

– Comparison with future limits (assuming natural values for the other parameters):

	$\mathcal{B}(\mu \to e\gamma) <$		$\mathcal{B}(\mu \to ee\bar{e}) <$		$\mathcal{R}(\mu \text{ Ti} \to \text{e Ti}) <$	
	1.2×10^{-11}	10^{-13}	10^{-12}	(10^{-14})	4.3×10^{-12}	10^{-18}
$f/\text{TeV} >$	4.70	14.5	7.84	24.8	7.25 (17.8)	355 (811)
$\sin 2\theta <$	0.023	0.002	0.015	0.002	0.010 (0.003)	0.000 (0.000)
$\|\delta\| <$	0.022	0.002	0.016	0.002	0.010 (0.003)	0.000 (0.000)

Conclusions

- The one-loop predictions for flavor violating processes in the LHT are finite when *all* Goldstone interactions compatible with gauge and T symmetry included
- EWPT allow f as low as 500 GeV in the LHT model [Hubisz, Meade, Noble, Perelstein '06]
  and dark matter limits on the lightest T-particle set $f \gtrsim 1.8$ TeV [Hubisz, Meade '05]
  but present experimental limits on LFV processes (μN $\to$ eN) require:
  - somewhat heavier scale ($f \gtrsim 4.5$ TeV), or
  - flavor alignment of light and heavy leptons ($\sin 2\theta \lesssim 0.05$), or
  - small splitting of heavy lepton masses ($\delta \lesssim 5\%$)
- The Feynman rules for the SLH in the 't Hooft-Feynman gauge obtained and predictions for LFV processes computed for the first time
- The constraints on the SLH from LFV are even more demanding ($f \gtrsim 8$ TeV, $\sin 2\theta \lesssim 0.01$, $\delta \lesssim 1\%$)