A brief review of Lepton Flavor Violation at the ILC

José I. Illana

CAFPE, U. Granada

1. Motivation
2. Lepton flavor violating processes
3. Lepton Flavor Violation from BSM Physics
4. Probing LFV at the ILC

Motivation

Motivation

- Evidence of LFV: neutrinos oscillate

  ⇒ Neutrinos have a (small) mass and mix:

$$\nu_{L_\alpha} \equiv \mathcal{U}_{\alpha i}\nu_i \qquad \alpha = e,\mu,\tau \qquad i = 1,2,3$$

  ⇒ LFV in the charged sector: negligible (one loop, GIM suppressed) in the SM

$$\ell_\alpha \to \ell_\beta : \qquad \left|\frac{\alpha}{\pi}\sum_i \mathcal{U}^*_{\alpha i}\mathcal{U}_{\beta i}\frac{m^2_{\nu_i}}{M^2_W}\right|^2 \sim \left|\frac{\alpha}{\pi}\sin 2\theta\frac{\Delta m^2_\nu}{M^2_W}\right|^2 \sim 10^{-54}$$

Motivation

- Evidence of LFV: neutrinos oscillate

  ⇒ Neutrinos have a (small) mass and mix:

$$\nu_{L_\alpha} \equiv \mathcal{U}_{\alpha i} \nu_i \qquad \alpha = e, \mu, \tau \qquad i = 1, 2, 3$$

  ⇒ LFV in the charged sector: negligible (one loop, GIM suppressed) in the SM

$$\ell_\alpha \to \ell_\beta : \qquad \left| \frac{\alpha}{\pi} \sum_i \mathcal{U}^*_{\alpha i} \mathcal{U}_{\beta i} \frac{m^2_{\nu_i}}{M^2_W} \right|^2 \sim \left| \frac{\alpha}{\pi} \sin 2\theta \frac{\Delta m^2_\nu}{M^2_W} \right|^2 \sim 10^{-54}$$

- Opportunity for New Physics $\quad [m^2_{\nu_i}/M^2_W \to f(m^2_{\tilde{F}_i}/\Lambda^2_{NP})]$
  - Most NP models suffer the flavor problem: new sources of flavor mixing
  - Lepton sector is more clean
  - Examples: SUSY, Little Higgs, ...

LFV processes

- Where to look for LFV?
  - Rare lepton decays: [μ: MEGA/MEG, SINDRUM (PSI) | τ: Belle, BaBar, LHC]
    – radiative ($\ell_j \to \ell_i \gamma$),
    – leptonic ($\ell_j \to \ell_i \ell_k \bar{\ell}_k$, $\ell_j \to \ell_i \ell_i \bar{\ell}_k$),
    – semileptonic ($\tau \to \mu\eta$, $\tau \to \mu\rho$, $\tau \to \mu\pi\pi$, ...)
  - $\mu - e$ conversion in nuclei [SINDRUM2]
  - Decays of other standard particles:
    – $Z \to \ell_i \bar{\ell}_j$ [..., LEP, GigaZ]
    – $H \to \ell_i \bar{\ell}_j$ [..., LHC, ILC]
    – $D^0 \to \ell_i \bar{\ell}_j$, $B \to \mu e$, ...
  - Decays of non-standard particles: [LHC, ILC]
    e.g. charged sleptons, sneutrinos, charginos, neutralinos

LFV processes

- Present and future limits:

LFV process	Present best UL (90% CL)		Future sensitivity	
$\mathcal{B}(\mu \to e\gamma)$	1.2×10^{-11}	[MEGA 1999]		
	2.8×10^{-11}	[MEG 2010]	$10^{-13} - 10^{-14}$	[MEG]
$\mathcal{B}(\tau \to e\gamma)$	3.3×10^{-8}	[BaBar 2010]	3×10^{-9}	[SuperB]
$\mathcal{B}(\tau \to \mu\gamma)$	4.4×10^{-8}	[BaBar 2010]	2.4×10^{-9}	[SuperB]
$\mathcal{B}(\mu \to ee\bar{e})$	1×10^{-12}	[SINDRUM 1988]	$10^{-13} - 10^{-14}$	[MEG]
$\mathcal{B}(\tau \to ee\bar{e})$	2.7×10^{-8}	[Belle 2010]	$10^{-9} - 10^{-10}$	[SuperB]
$\mathcal{B}(\tau \to \mu\mu\bar{\mu})$	2.1×10^{-8}	[Belle 2010]	$10^{-9} - 10^{-10}$	[SuperB]
$\mathcal{B}(\tau \to e\mu\bar{\mu})$	2.7×10^{-8}	[Belle 2010]	$10^{-9} - 10^{-10}$	[SuperB]
$\mathcal{B}(\tau \to \mu e\bar{e})$	1.8×10^{-8}	[Belle 2010]	$10^{-9} - 10^{-10}$	[SuperB]

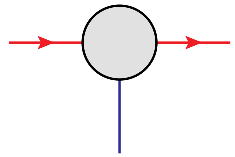
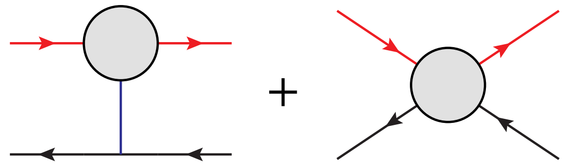
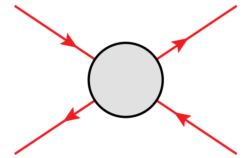
LFV processes

- Present and future limits:

LFV process	Present best UL (90% CL)		Future sensitivity	
$\mathcal{R}(\mu \to e, \mathrm{Au})$	7.0×10^{-13}	[SINDRUM2 2004]	10^{-16}	[Mu2E (Fermilab)]
$\mathcal{R}(\mu \to e, \mathrm{Al})$			10^{-16}	[COMET (J-PARC)]
$\mathcal{R}(\mu \to e, \mathrm{Ti})$	4.3×10^{-12}	[SINDRUM2 2004]	10^{-18}	[PRISM/PRIME (J-PARC)]
$\mathcal{B}(Z \to \mu^\pm e^\mp)$	1.7×10^{-6}	[LEP 1995]	2×10^{-9}	[GigaZ]
$\mathcal{B}(Z \to \tau^\pm e^\mp)$	9.8×10^{-6}	[LEP 1993]	$6.5\kappa \times 10^{-8}$	[GigaZ] $\kappa \in [0.2, 1]$
$\mathcal{B}(Z \to \tau^\pm \mu^\mp)$	1.2×10^{-5}	[LEP 1997]	$2.2\kappa \times 10^{-8}$	[GigaZ]

LFV processes

- NP at 1-loop transitions:

$\Delta F = 1$		$\Delta F = 2$
		
$\mu \to e\gamma$	$\mu \to ee\bar{e}$	
	$\mu - e$ conversion in nuclei	
$\tau \to e\gamma$ $\tau \to \mu\gamma$	$\tau \to ee\bar{e}$ $\quad \tau \to e\mu\bar{\mu}$ $\tau \to \mu\mu\bar{\mu}$ $\quad \tau \to \mu e\bar{e}$	$\tau \to ee\bar{\mu}$ $\tau \to \mu\mu\bar{e}$
$Z \to \mu\bar{e},\ e\bar{\mu}$ $Z \to \tau\bar{e},\ e\bar{\tau}$ $Z \to \tau\bar{\mu},\ \mu\bar{\tau}$	$\Uparrow$	$\Uparrow$
$H \to \mu\bar{e},\ e\bar{\mu}$ $H \to \tau\bar{e},\ e\bar{\tau}$ $H \to \tau\bar{\mu},\ \mu\bar{\tau}$	$\Uparrow$	$\Uparrow$
$e^+e^- \to \ell_i\bar{\ell}_j\,,\quad \gamma\gamma \to \ell_i\bar{\ell}_j$		

Lepton Flavor Violation from BSM Physics

Lepton Flavor Violation | Supersymmetry

- Origin of LFV: misalignment of fermion and sfermion mass matrices

  – Charged sleptons: $\tilde{\ell}_{L_i}$ and $\tilde{\ell}_{R_i}$ superpartners of ℓ_{L_i} and ℓ_{R_i}

$$\mathbf{M}^2_{\tilde{\ell}} = \begin{pmatrix} \mathbf{m}^2_{LL} & \mathbf{m}^{2\dagger}_{LR} \\ \mathbf{m}^2_{LR} & \mathbf{m}^2_{RR} \end{pmatrix} \qquad \begin{aligned} (m^2_{LL})_{ij} &= (m^2_{\tilde{L}})_{ij} + \left[m^2_{\ell_i} + \left(-\frac{1}{2} + \sin^2\theta_W \right) M_Z^2 \cos 2\beta \right] \delta_{ij} \\ (m^2_{RR})_{ij} &= (m^2_{\tilde{e}_R})_{ij} + (m^2_{\ell_i} - M_Z^2 \sin^2\theta_W \cos 2\beta)\delta_{ij} \\ (m^2_{LR})_{ij} &= (A_e)_{ij} v \cos\beta/\sqrt{2} - m_{\ell_i}\mu^* \tan\beta\, \delta_{ij} \end{aligned}$$

Slepton mass eigenstates:

$$\mathbf{S}^{\tilde{\ell}}\, \mathbf{M}^2_{\tilde{\ell}}\, \mathbf{S}^{\tilde{\ell}\dagger} = \mathbf{diag}(m^2_{\tilde{\ell}_X}) \qquad X = 1, \ldots, 6$$

$$\boxed{\tilde{\ell}_X = S^{\tilde{\ell}}_{Xi} \tilde{\ell}_{L_i} + S^{\tilde{\ell}}_{X,i+3} \tilde{\ell}_{R_i}} \qquad X = 1, \ldots, 6 \qquad i = 1, 2, 3$$

- Origin of LFV: misalignment of fermion and sfermion mass matrices

  – Sneutrinos: $\tilde{\nu}_{L_\alpha}$ superpartners of ν_{L_α}

$$(M^2_{\tilde{\nu}})_{\alpha\beta} = (m^2_{\tilde{L}})_{\alpha\beta} + \frac{1}{2} M^2_Z \cos 2\beta \, \delta_{\alpha\beta}$$

  Sneutrino mass eigenstates:

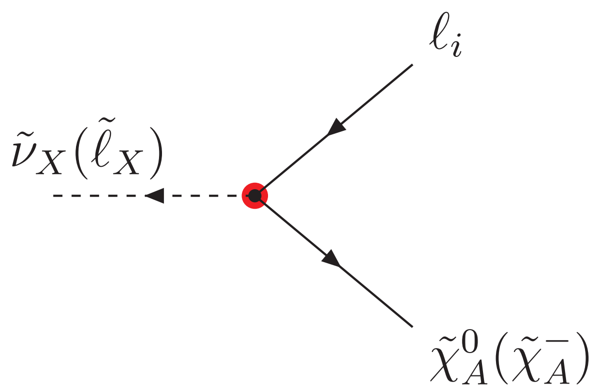
$$\mathbf{S}^{\tilde{\nu}} \, \mathbf{M}^2_{\tilde{\nu}} \, \mathbf{S}^{\tilde{\nu}\dagger} = \mathbf{diag}(m^2_{\tilde{\nu}_X}) \qquad X = 1, 2, 3$$

$$\boxed{\tilde{\nu}_X = S^{\tilde{\nu}}_{X\alpha} \tilde{\nu}_{L_\alpha} = S^{\tilde{\nu}}_{X\alpha} \mathcal{U}_{\alpha i} \tilde{\nu}_i} \qquad X = 1, 2, 3 \qquad \alpha = e, \mu, \tau \qquad i = 1, 2, 3$$

$\Rightarrow$ Off-diagonal terms are responsible for LFV

Lepton Flavor Violation | Supersymmetry

- LFV vertices $ig\ (c^L_{iAX}\ P_L + c^R_{iAX}\ P_R)$ where iAX label mass eigenstates



$$\tilde{\nu}^\dagger_X \bar{\tilde{\chi}}^-_A \ell_i : \qquad c^{L[C]}_{iAX} = -V^*_{A1} S^{\tilde{\nu}}_{X\alpha} \mathcal{U}_{\alpha i}$$

$$c^{R[C]}_{iAX} = \frac{m_{\ell_i}}{\sqrt{2} M_W \cos\beta} U_{A2} S^{\tilde{\nu}}_{X\alpha} \mathcal{U}_{\alpha i}$$

$$\tilde{\ell}^\dagger_X \bar{\tilde{\chi}}^0_A \ell_i : \qquad c^{L[N]}_{iAX} = \frac{1}{\sqrt{2}} (\tan\theta_W N^*_{A1} + N^*_{A2})\ S^{\tilde{\ell}}_{Xi} - \frac{m_{\ell_i}}{\sqrt{2} M_W \cos\beta} N^*_{A3} S^{\tilde{\ell}}_{X,i+3}$$

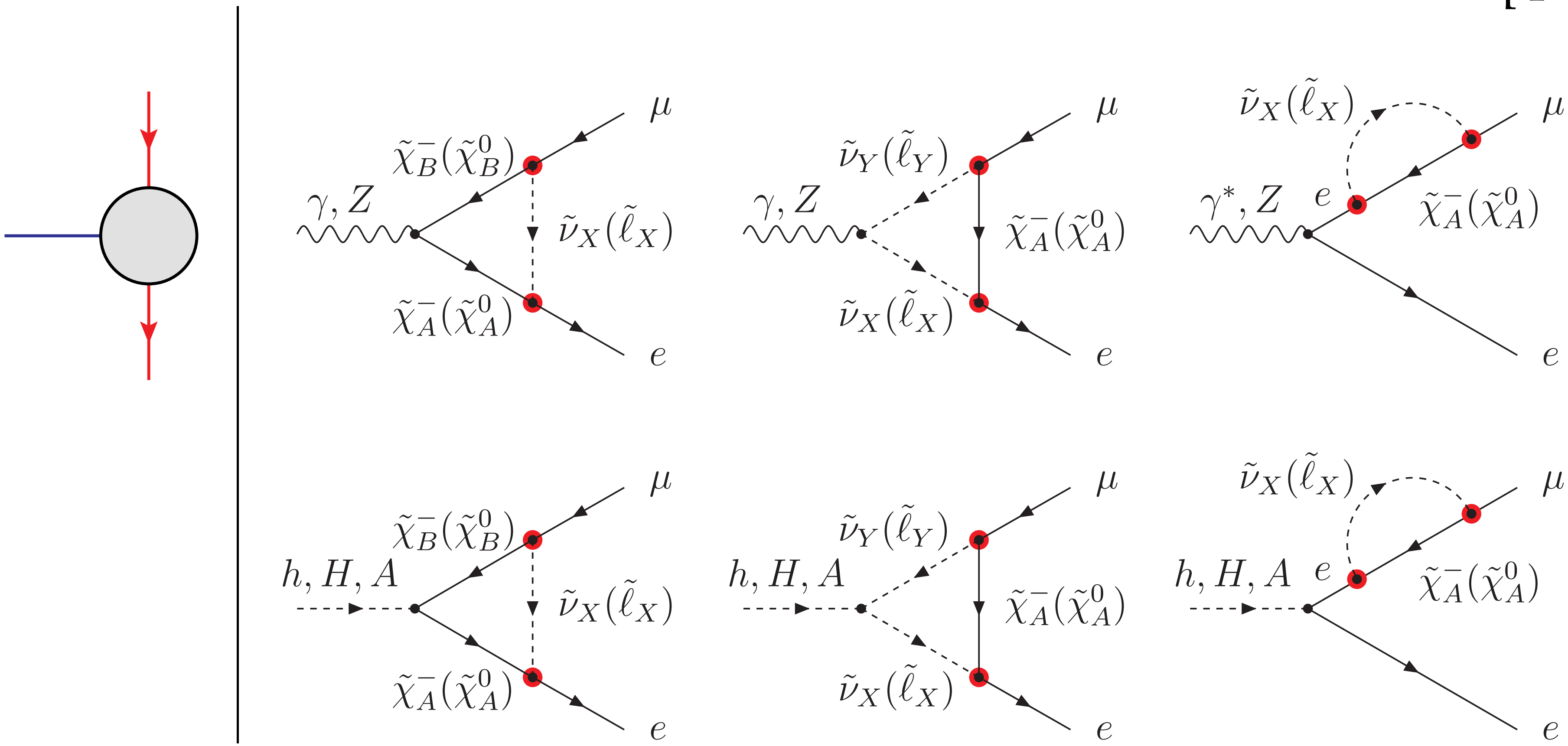
$$c^{R[N]}_{iAX} = -\sqrt{2} \tan\theta_W N_{A1} S^{\tilde{\ell}}_{X,i+3} - \frac{m_{\ell_i}}{\sqrt{2} M_W \cos\beta} N_{A3} S^{\tilde{\ell}}_{Xi}$$

Lepton Flavor Violation | Supersymmetry

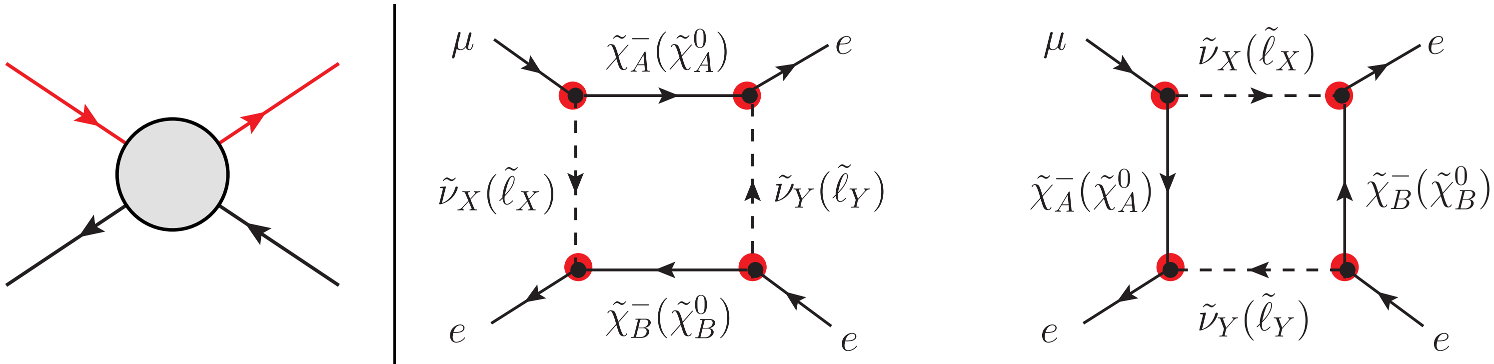
- One-loop transitions: bubbles and triangles ($\Delta F = 1$) $[\mu \to e\gamma]$

$[Z \to e\bar{\mu}]$

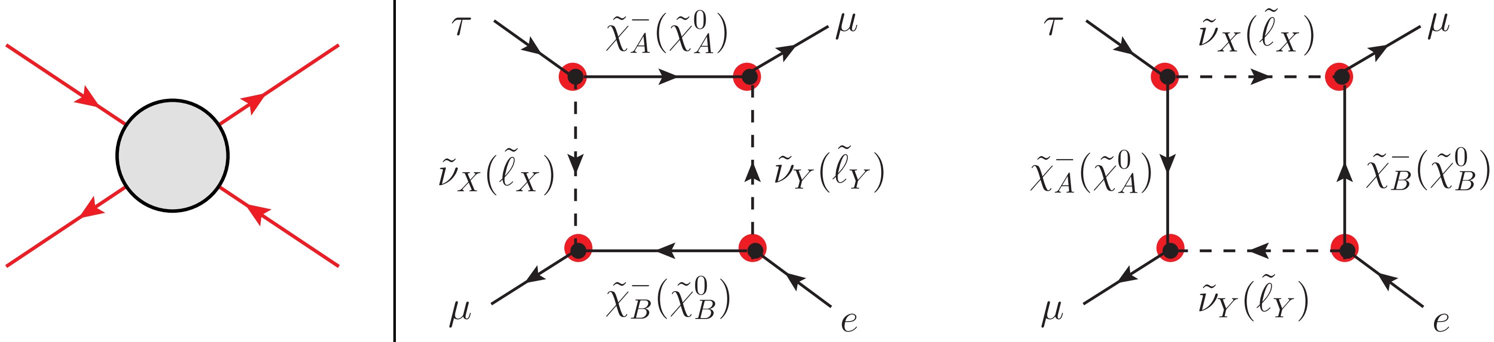
$[\Phi \to e\bar{\mu}]$



- One-loop transitions: boxes ($\Delta F = 1$ and $\Delta F = 2$)



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



$[\tau \to \mu\mu\bar{e}]$

Lepton Flavor Violation | Supersymmetry

- Tree level chain decays:

  Production and decay of charged sleptons, sneutrinos, charginos and neutralinos

$$
\begin{aligned}
e^+e^- \to \quad & \tilde{\ell}^+_X \tilde{\ell}^-_Y && \to \tau^\pm \mu^\mp \tilde{\chi}^0_1 \tilde{\chi}^0_1 \\
& \tilde{\nu}_X \tilde{\nu}_Y && \to \tau^\pm \mu^\mp \tilde{\chi}^+_1 \tilde{\chi}^-_1 \\
& \tilde{\chi}^0_A \tilde{\chi}^0_B && \to \tau^\pm \mu^\mp \tilde{\chi}^0_1 \tilde{\chi}^0_1 \\
& \tilde{\chi}^+_A \tilde{\chi}^-_B && \to \tau^\pm \mu^\mp \tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1
\end{aligned}
$$

Lepton Flavor Violation | Little Higgs

- The model(s)

  – The Higgs is a pseudo-Goldstone boson of an approximate global symmetry broken at a scale f ~TeV

  – The global symmetry (partly gauged) gets explicitly broken by gauge and Yukawa interactions, giving the Higgs a mass and non-derivative couplings, still preserving the cancellation of one-loop quadratic corrections (*collective breaking*)

  – This introduces extra fermions and gauge fields (and extra Higgses): new source of flavor mixing

Lepton Flavor Violation | Littlest Higgs with T Parity

Assume the most popular model: Littlest Higgs with T Parity

The SM spectrum (T-even) is supplemented with:

⋆ T-odd fermion $SU(2)_L$ doublets $l_{HL} \equiv (\nu_{HL}, \ell_{HL})$ and $l_{HR} \equiv (\nu_{HR}, \ell_{HR})$

⋆ T-odd gauge bosons W_H, A_H, Z_H

- Origin of LFV: missalignment of T-even and T-odd fermion mass matrices

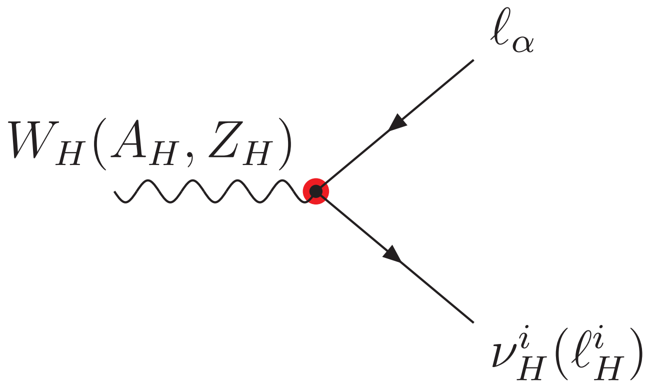
  $\mathcal{L}_{Y_H}$ generates heavy masses inducing heavy-light mixings:

$$\sqrt{2}f\ \bar{l}^0_{HL}\mathbf{Y_H}l^0_{HR} \quad \xrightarrow{\text{diag}} \quad l^0_{HL} = V_H l_{HL} \quad l^0_{HR} = U_H l_{HR}$$

$$\Rightarrow \mathcal{L}_{\text{LHT}} \sim g\ \bar{l}^0_{HL}\not{G}^\dagger_H l^0_L = g\ (\bar{\nu}_{HL}V^\dagger_H,\ \bar{\ell}_{HL}V^\dagger_H)\ \not{G}^\dagger_H \begin{pmatrix} \mathcal{U}\ \nu_L \\ \ell_L \end{pmatrix} \qquad \begin{array}{r} V^\dagger_H\mathcal{U} \equiv V_{H\nu} \\ V^\dagger_H \equiv V_{H\ell} \end{array}$$

$$\Rightarrow \boxed{V^{i\alpha}_{H\ell}\ \bar{\nu}^i_{HL}\not{W}^\dagger_H\ell^\alpha_L}\ \text{CC and}\ \boxed{V^{i\alpha}_{H\ell}\ \bar{\ell}^i_{HL}\{\not{A}_H,\not{Z}_H\}\ell^\alpha_L}\ \text{NC}$$

- LFV vertices $ig\,(g_L\, P_L + g_R\, P_R)$



	$W_H^+ \bar{\nu}_H^i \ell^\alpha$	$A_H \bar{\ell}_H^i \ell^\alpha$	$Z_H \bar{\ell}_H^i \ell^\alpha$
g_L	$\frac{1}{\sqrt{2} s_W} V_{H\ell}^{i\alpha}$	$\left(\frac{1}{10 c_W} - \frac{x_H}{2 s_W} \frac{v^2}{f^2}\right) V_{H\ell}^{i\alpha}$	$-\left(\frac{1}{2 s_W} + \frac{x_H}{10 c_W} \frac{v^2}{f^2}\right) V_{H\ell}^{i\alpha}$
g_R	0	0	0

$\Uparrow$

Identical to SM with heavy neutrinos, replacing $V_{H\ell}$ by $\mathcal{U}$ and W_H by W

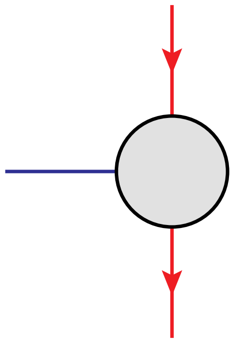
Lepton Flavor Violation | Littlest Higgs with T Parity

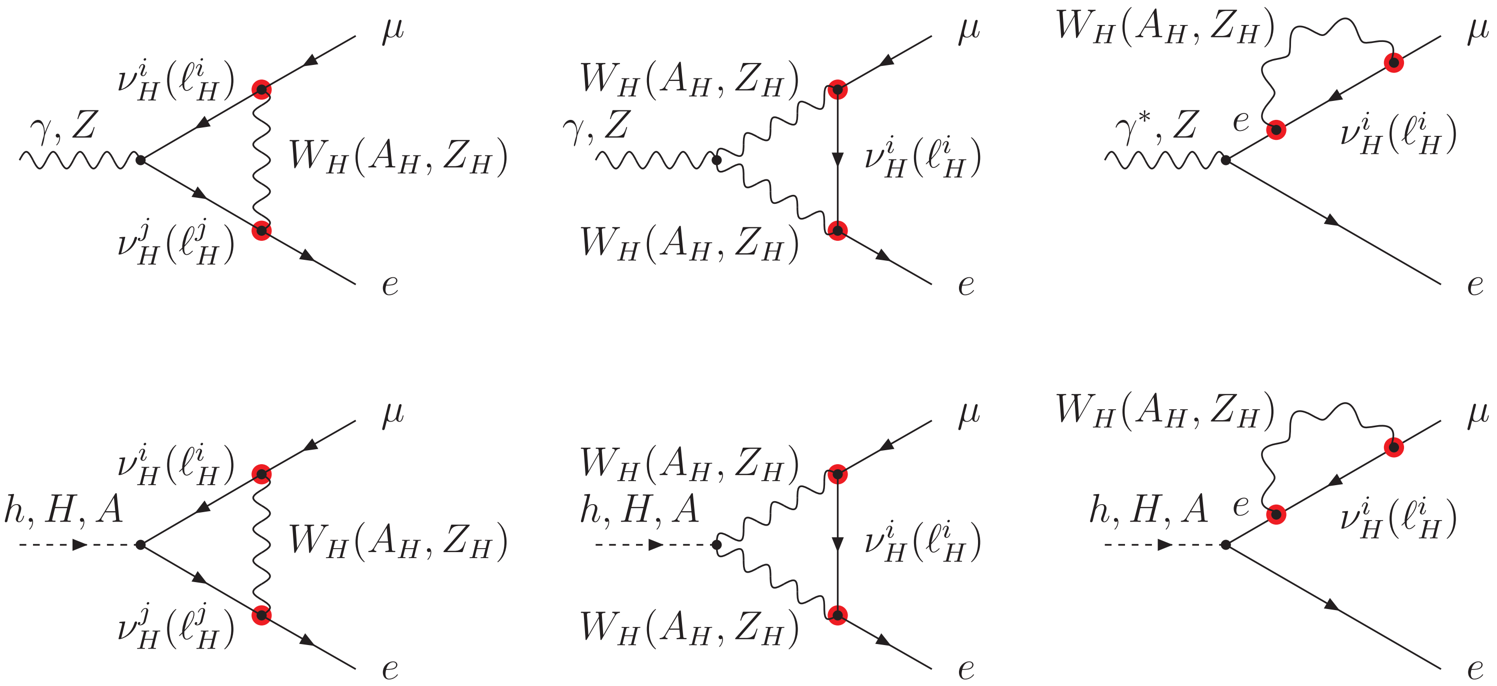
- One-loop transitions: bubbles and triangles ($\Delta F = 1$)

$[\mu \to e\gamma]$

$[Z \to e\bar{\mu}]$

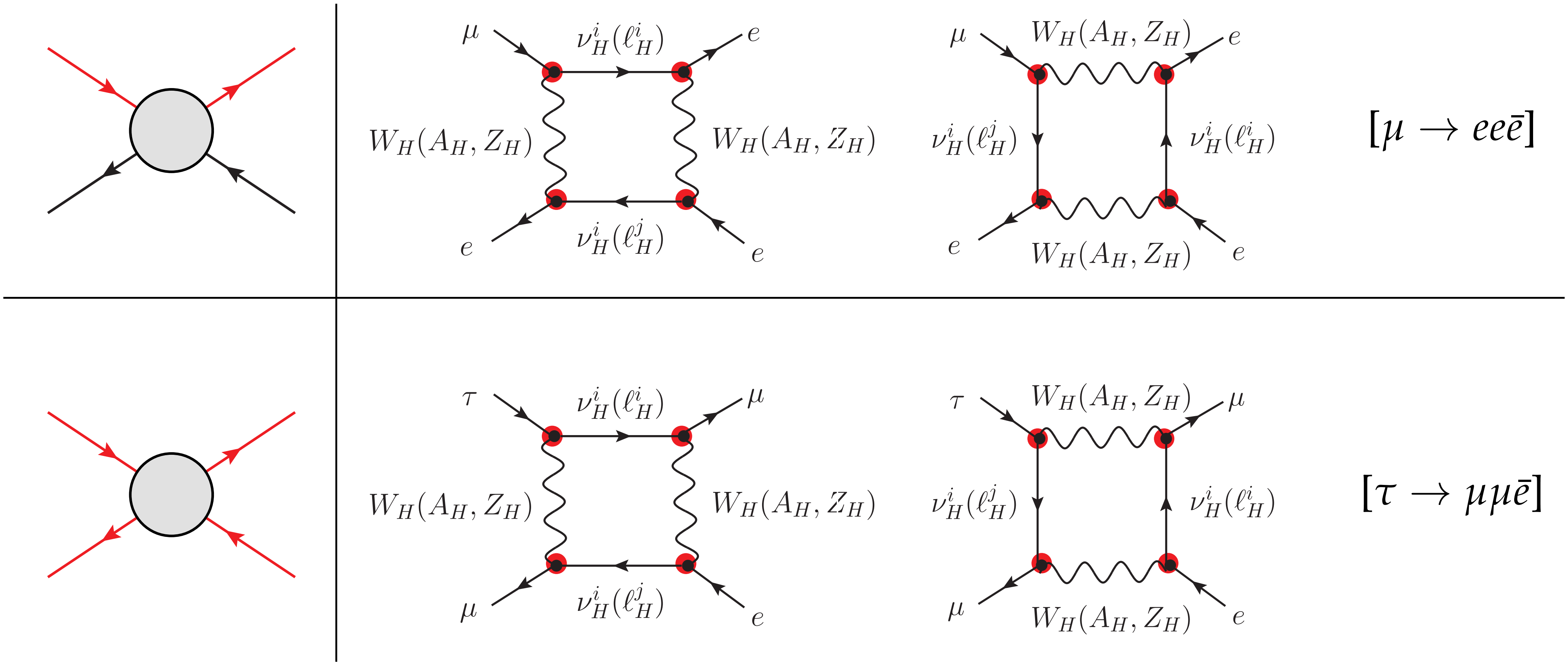
$[\Phi \to e\bar{\mu}]$





Lepton Flavor Violation | Littlest Higgs with T Parity

- One-loop transitions: boxes ($\Delta F = 1$ and $\Delta F = 2$)



Probing LFV at the ILC

Probing LFV at the ILC | Supersymmetry

- Guchait, Kalinowski, Roy [EPJC 21 (2001) 163]

  Deppisch, Päs, Redelbach, Rückl, Shimizu [PRD 69 (2004) 054014]

  Production and decay of sleptons, charginos and neutralinos (SUSY seesaw)

$$
\begin{array}{rrcll}
e^+e^- \to & \tilde{\ell}_i^+\tilde{\ell}_j^- & \to & \ell_\alpha^+\ell_\beta^-\tilde{\chi}_1^0\tilde{\chi}_1^0 & \text{Signal} = \ell_\alpha^+\ell_\beta^- + \not{E}_T \\
 & \tilde{\nu}_i\tilde{\nu}_j^c & \to & \ell_\alpha^+\ell_\beta^-\tilde{\chi}_1^+\tilde{\chi}_1^- & \ell_\alpha^+\ell_\beta^- + 4jets + \not{E}_T \\
 & \tilde{\chi}_a^0\tilde{\chi}_b^0 & \to & \ell_\alpha^+\ell_\beta^-\tilde{\chi}_1^0\tilde{\chi}_1^0 & \ell_\alpha^+\ell_\beta^- + \ell + 2jets + \not{E}_T \\
 & \tilde{\chi}_a^+\tilde{\chi}_b^- & \to & \ell_\alpha^+\ell_\beta^-\tilde{\chi}_1^\pm\tilde{\chi}_1^\mp & \text{(purely leptonic overwhelmed by bkgd)}
\end{array}
$$

  (Background from $e^+e^- \to t\bar{t}g$ reduced by appropriate cuts)

Probing LFV at the ILC | Supersymmetry

- Hohenwater-Sodek, Kernreiter [JHEP 06 (2007) 071]

  Effects of LFV on chargino production

  – $\sigma(e^+e^- \to \chi_a^+ \chi_b^-)$ at $\sqrt{s} = 500$ GeV and assuming beam polarization enhanced up to a factor 2 within limits from $\tau \to \mu\gamma$ due to LFV $\tilde{\nu}_X$ exchange (t-channel)

- Ibarra, Roy [JHEP 05 (2007) 059]

  Sensitivity of future e^+e and e^-e^- colliders to LFV in scenarios with a stau NLSP

  – Signal: two heavily ionizing tracks due to the long-lived staus accompanied by two (LFV in production) or four (LFV in selectron decay) charged leptons

  – Sensitivity (better e^-e^- than e^+e^-) competitive with the present and projected sensitivities to LFV from rare tau decays, although not from $\mu \to e\gamma$

- Kanemura et al [PLB 599 (2004) 2004]

  Search for LFV in Higgs boson decay at a Linear Collider

  $e^+e^- \to Z^* \to Zh^0 \to Z\tau^\pm\mu^\mp$

  – After taking appropriate kinematic cuts, the number of background events is considerably reduced, so that the signal can be visible when the branching ratio of $h^0 \to \tau^\pm\mu^\mp$ is larger than about 10^{-4} (10^{-3} in the 2HDM)
  (Energy tuned to optimize Higgsstrahlung ($\sqrt{s} = M_Z + 2m_h$) and $\mathcal{L} = 1$ ab^{-1})

Probing LFV at the ILC | Supersymmetry

- Canoni, Panella, Kolb [LCWS 04]

  Majorana neutrino and light sneutrino contributions to $e^-e^- \to \mu e, \tau e$

  Majorana $\nu \lesssim 2-3$ TeV feasible, and $\sigma \sim 10^{-2}$ fb in SUSY reachable (polariz.)

Probing LFV at the ILC | Supersymmetry

- JI, Masip [PRD 67 (2003) 035004]

  LFV Z decays from SUSY

  – GigaZ: $Z \to \mu e$ invisible due to $\mu \to e\gamma$ constraint, but $Z \to \mu e$ at reach

Probing LFV at the ILC | Heavy neutrinos

- JI, Riemann [PRD 63 (2001) 053004]

  LFV Z decays from heavy neutrinos

  – GigaZ: $Z \to \ell_i^{\pm}\ell_j^{\mp}$ visible if heavy neutrinos are lighter than the TeV and mix enough to light neutrinos

Probing LFV at the ILC | Little Higgs

- Wei Ma, Chong-Xing Yue, Jiao Zhang, and Yan-Bin Sun [1010.0052]
  Jinzhong Han, Xuelei Wang, Bingfang Yang [1101.3598]
  $e^+e^- \to \ell_i^\pm \ell_j^\mp$ and $\gamma\gamma \to \ell_i^\pm \ell_j^\mp$ and in the LHT at the ILC
  (mediated by LFV in $\gamma\ell_i\ell_j$ and $Z\ell_i\ell_j$ and constrained by rare lepton decays)
  - $\sigma(e^+e^- \to \ell_i^\pm \ell_j^\mp)$ can reach several fb
  - $\sigma(\gamma\gamma \to \ell_i^\pm \ell_j^\mp)$ can reach $0.1 - 1$ fb

Probing LFV at the ILC | Little Higgs

- Chong-Xing Yue and Shuang Zhao [EPJ C50 (2007) 897]

  Signals of the LHT doubly charged scalar triplet Φ from $e^+e^- \to \ell_i^\pm \ell_j^\mp$

  (mediated by the tree level subprocess $e^-e^- \to \Phi^{--} \to \ell_i^- \ell_j^-$)

  – At $\sqrt{s} = 500$ GeV the LFV contribution is small
    but Φ can give a significant contribution to $e^+e^- \to \ell_i^\pm \ell_i^\mp$

Probing LFV at the ILC | Model independent

- Ferreira, Guedes, Santos [PRD 75 (2007) 055015]

  Different LFV decay widths and the cross sections $\sigma(e^+e^- \to \ell_i^\pm \ell_j^\mp)$ are compared using dimension-six effective operators

  - ILC ($\sqrt{s} = 1$ TeV, $\mathcal{L} = 1$ ab^{-1}) explores $\Lambda \lesssim 100$ TeV.
  - Limits from $Z \to \ell_i^\pm \ell_j^\mp$ allow enough events in $e^+e^- \to \ell_i^\pm \ell_j^\mp$ even from future bounds, but if the four-fermion coupling is dominant $\mathcal{B}(\mu \to ee\bar{e}) < 10^{-12}$ already kills $e^+e^- \to e^\pm \mu^\mp$
  - $\sigma(\gamma\gamma \to \ell_i^\pm \ell_j^\mp)$ exceedingly small from constraints on $\ell_j \to \ell_i \gamma$
  - GigaZ will improve the limits on the LFV Z decays but is insensitive to the four-fermion operators