Lepton Flavour Violation in the Littlest Higgs Model with T-Parity

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Outline

Based on:
M. Blanke, A.J. Buras, BD, A. Poschenrieder, C. Tarantino
[JHEP 0705:013,2007]

1. **Sketching the Littlest Higgs Model with T-Parity**
2. **Lepton Flavour Violating Decays**
3. **Conclusions**

Motivation: The Little Hierarchy Problem

Naturalness

- Light Higgs $\Rightarrow \Lambda \sim 1 TeV$
- Higher-dimensional operators $\Rightarrow \Lambda \geq 5-10 TeV$

How to solve this Tension?

A Possible Solution

- Protection of the Higgs mass by an additional symmetry
- Introduction of new particles at the TeV scale
- A popular example: SUSY

Central Ideas of Little Higgs Models

Higgs as a Goldstone Boson

- The Higgs arises as a Goldstone Boson of a spontaneously broken, approximate global symmetry
- massless at tree level
- Higgs potential generated radiatively

Georgi, Pais ’74; Georgi, Dimopoulos, Kaplan ’84

+

Collective Symmetry Breaking

- Global symmetry is only explitly broken by two or more non-vanishing couplings
- Contributions to the Higgs mass involve at least two different couplings
- at one-loop level: logarithmical dependence on the cutoff

Arkani-Hamed, Cohen, Georgi, hep-ph/0105239, hep-th/0104005; Arkani-Hamed, Cohen, Gregoire, Wacker, hep-ph/0202089

The Littlest Higgs Model (without T-Parity)

Spontaneous symmetry breaking of $\boxed{SU(5) \to SO(5)}$

- Symmetry breaking takes places at scale f
- $SU(5) \supset [SU(2) \otimes U(1)]^2 \supset [SU(2) \otimes U(1)]_{SM}$

Particle Content

- SM fields (SM-fermions, SM-bosons)
- a new (T-even) top partner (T_+)
- new heavy partners of EW gauge bosons ($W_H^\pm, Z_H, A_H$)
- 10 scalars
  - a light complex doublet ⇒ Higgs boson h with $\langle h \rangle = v$
  - a heavy complex triplet ⇒ $\Phi^P, \Phi^0, \Phi^\pm, \Phi^{\pm\pm}$ with $\left\langle \Phi^0 \right\rangle \sim v^2/f$

The Littlest Higgs Model with T-Parity

Electroweak precision observables imply $f \sim 2-3\mathrm{TeV}$

Cheng, Low, hep-ph/0308199, hep-ph/0405243

$\Rightarrow$ T-Parity

- Z_2 symmetry exchanging the $[SU(2) \times U(1)]$ gauge factors
- SM particles and T_+ are T-even
- all other new particles are T-odd

Implications

- f can be as low as $\sim$ 500GeV
- heavy photon A_H is a dark matter candidate
- need to introduce mirror fermions

(Note: T-Parity generally anomalous, Hill, Hill, 0705.0697)

Ingredients for LFV in the LHT Model

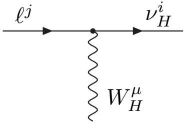
Hubisz, Lee, Paz, hep-ph/0512169; Choudhury et al., hep-ph/0612327;
Blanke, Buras, BD, Poschenrieder, Tarantino, hep-ph/0702136

T-odd Sector

- Mirror leptons $\begin{pmatrix} \nu_H^1 \\ \ell_H^1 \end{pmatrix}, \begin{pmatrix} \nu_H^2 \\ \ell_H^2 \end{pmatrix}, \begin{pmatrix} \nu_H^3 \\ \ell_H^3 \end{pmatrix}$
- to first order in v/f: $m_{Hi}^{\nu} = m_{Hi}^{\ell} \sim \mathcal{O}(TeV)$
- Heavy gauge bosons $W_H^{\pm}, Z_H^0, A_H^0$
- contributions from T-even sector and Φ's negligible

Flavor mixing in the mirror sector ⇒ New mixing matrices $V_{H\ell}$ and $V_{H\nu}$

Mixing matrices are related by $V_{H\nu}^{\dagger} V_{H\ell} = V_{PMNS}^{\dagger}$



$$\rightarrow \quad \frac{ig}{\sqrt{2}} \left(V_{H\ell}\right)_{ij} \gamma^{\mu} P_L$$

Why Study Lepton Flavor Violation?

Most famous LFV decay: $\boxed{\mu \to e\gamma}$

SM + r.h. Dirac neutrinos $\Rightarrow$ $\boxed{Br(\mu \to e\gamma)_{SM} \leq 10^{-54}}$

Experimental upper bound (MEGA): $\boxed{Br(\mu \to e\gamma)_{exp} < 1.2 \cdot 10^{-11}}$

(2007/2008: $\mathcal{O}(10^{-13} - 10^{-14})$ (MEG)

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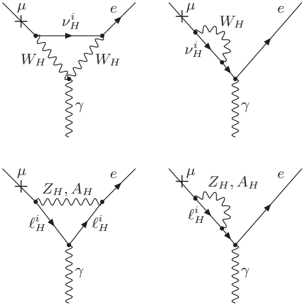
There is plenty of room for new physics!

For example:



Experimental Status and Prospects

- $\mu^- \to e^- e^+ e^-$

$$\boxed{Br(\mu^- \to e^- e^+ e^-)_{exp} < 1.0 \cdot 10^{-12}}$$

- $\mu - e$ - conversion in nuclei (e.g. Ti)

$$\boxed{R(\mu Ti \to e Ti)_{exp} < 4.3 \cdot 10^{-12}}$$

- LFV τ decays (BABAR & BELLE)

$$\boxed{Br(\tau \to \ell\gamma, \tau \to \ell\{\pi, \eta, \eta'\}, \tau \to \ell_i \ell_j \ell_k)_{exp} < \mathcal{O}(10^{-8})}$$

- $(g-2)_\mu$

$$\boxed{a_\mu^{exp} = 11659208.0(63) \cdot 10^{-10}}$$

Lepton Flavour Violating Decays in the LHT

Calculated Processes

$\mu \to e\gamma$
$\tau \to \mu\gamma$
$\tau \to e\gamma$

$\mu^- \to e^- e^+ e^-$
$\tau^- \to \mu^- \mu^+ \mu^-$
$\tau \to e^- e^+ e^-$

μ-e-conversion
in nuclei

$K_L \to \mu e$
$B_{d,s} \to \mu e$
$B_{d,s} \to \tau e$
$B_{d,s} \to \tau\mu$

$\tau^- \to e^- \mu^+ e^-$
$\tau \to \mu^- e^+ \mu^-$

$\tau^- \to \mu^- e^+ e^-$
$\tau \to e^- \mu^+ \mu^-$

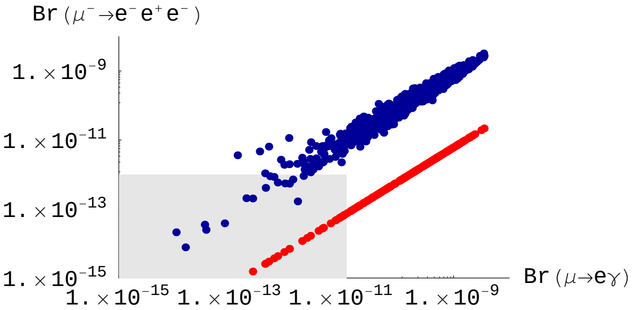
$K_L \to \pi^0 \mu e$

$(g-2)_\mu$

$\tau \to \ell P$
$(P = \pi, \eta, \eta')$

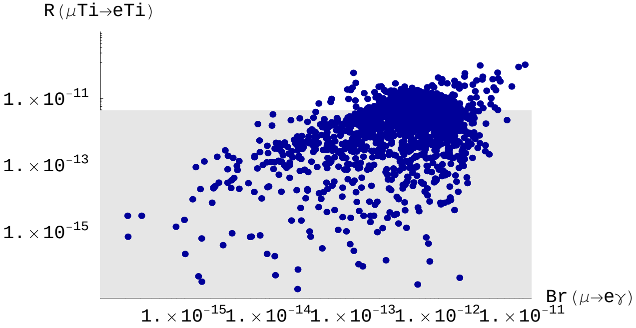
- varied parameters:
  - 300 GeV$\leq m_{Hi} \leq$ 1.5 TeV
  - 0$\leq \theta^\ell_{ij} \leq \pi$
  - $0 \leq \delta^\ell_{ij} \leq 2\pi$
  - $f = 1000$ GeV and $f = 500$ GeV
- several branching ratios can reach present experimental bounds
- $(g-2)_\mu$ negligible
  $\Rightarrow$ LHT can not explain tension between SM and experiment

$\mu \to e\gamma$ vs. $\mu^- \to e^-e^+e^-$



- most points violate experimental bounds
  $\Rightarrow$ hierarchical $V_{H\ell}$ or quasi-degenerate mirror leptons required
- strong correlation between $Br(\mu \to e\gamma)$ and $Br(\mu^{\cdot} \to e^-e^+e^-)$
- dipole contribution negligible - in contrast to the MSSM!

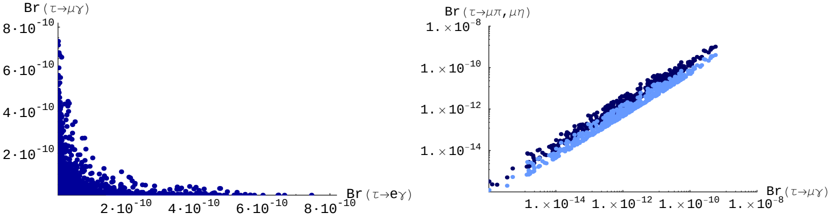
μ-e-Conversion in Nuclei



- poses a strong experimental constraint
- many points close to experimental bound

⇒ Chance of observation at upcoming experiments (e.g. J-PARC)

LFV τ Decays



$(f = 1000 GeV)$

- all $\Delta L = 1$ decays considered can reach the experimental bounds (in particular for low values of f)
- even simultaneously, considerable values are possible
- again, there are interesting correlations
- powerful tool for LHT searches at SuperB-factories

Correlations Allow a Distinction from the MSSM

MSSM: Dipole dominates in the absence of significant Higgs contributions

Ellis, Hisano, Raidal, Shimizu, hep-ph/0206110
Brignole, Rossi, hep-ph/0404211
Arganda, Herrero, hep-ph/0510405
Paradisi, hep-ph/0508054, 0601100

$$\boxed{\begin{aligned}
\frac{Br(\mu^-\to e^-e^+e^-)}{Br(\mu\to e\gamma)} &\simeq \frac{\alpha}{3\pi}\left(\log\frac{m_\mu^2}{m_e^2}-2.7\right)\\
\frac{Br(\tau^-\to \ell^-e^+e^-)}{Br(\tau\to \ell\gamma)} &\simeq \frac{\alpha}{3\pi}\left(\log\frac{m_\tau^2}{m_e^2}-2.7\right)\\
\frac{Br(\tau^-\to \ell^-\mu^+\mu^-)}{Br(\tau\to \ell\gamma)} &\simeq \frac{\alpha}{3\pi}\left(\log\frac{m_\tau^2}{m_\mu^2}-2.7\right)
\end{aligned}}$$

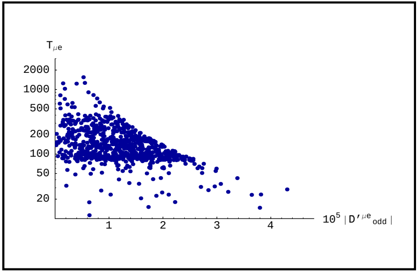
LHT: Dipole negligible compared to boxes and Z^0-penguins

Blanke, Buras, BD, Poschenrieder, Tarantino, JHEP 0705:013,2007

⇒ very different pattern allows for a transparent distinction!

Correlations in the LHT

- Dipole negligible $\Rightarrow$ $T_{ij} = \left| \frac{\bar{Y}^{ij}_{j,odd}}{\bar{D}'^{ij}_{odd}} \right|^2$ is strongly enhanced



boxes
penguins
$\Rightarrow$ Y, Z

electric dipole $\Rightarrow$ D

- ratios of Z and Y loop functions (a_{ij}, b^k_{ij}) are $\sim \mathcal{O}(1)$
  $c_{ij} = c_{ij}(a_{ij}) \sim \mathcal{O}(0.1)$
- finally, ratios between branching ratios are e.g. given by

$$\boxed{\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)} \simeq \frac{2\alpha}{3\pi} \frac{1}{\sin^4\theta_W} T_{\mu e} c_{\mu e}}$$

or

$$\boxed{\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e^- \mu^+ \mu^-)} \simeq 8 \frac{c_{\tau e}}{b^{\mu}_{\tau e}}}$$

- ratios turn out to be mostly parameter independent!

Ratios between Branching Ratios

ratio	LHT	MSSM (dipole)	MSSM (Higgs)
$\frac{Br(\mu^- \to e^- e^+ e^-)}{Br(\mu \to e\gamma)}$	$0.4 \ldots 2.5$	$\sim 6 \cdot 10^{-3}$	$\sim 6 \cdot 10^{-3}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau \to e\gamma)}$	$0.4 \ldots 2.3$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau \to \mu\gamma)}$	$0.4 \ldots 2.3$	$\sim 2 \cdot 10^{-3}$	$0.06 \ldots 0.1$
$\frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau \to e\gamma)}$	$0.3 \ldots 1.6$	$\sim 2 \cdot 10^{-3}$	$0.02 \ldots 0.04$
$\frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau \to \mu\gamma)}$	$0.3 \ldots 1.6$	$\sim 1 \cdot 10^{-2}$	$\sim 1 \cdot 10^{-2}$
$\frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to e^- \mu^+ \mu^-)}$	$1.3 \ldots 1.7$	~ 5	$0.3 \ldots 0.5$
$\frac{Br(\tau^- \to \mu^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- e^+ e^-)}$	$1.2 \ldots 1.6$	~ 0.2	$5 \ldots 10$
$\frac{R(\mu\mathrm{Ti} \to e\mathrm{Ti})}{Br(\mu \to e\gamma)}$	$10^{-2} \ldots 10^{2}$	$\sim 5 \cdot 10^{-3}$	$0.08 \ldots 0.15$

Double-Ratios of Branching Ratios

Dipole operator logarithmically enhanced $\Rightarrow$ breaks $\mu \leftrightarrow e$ symmetry

- In the MSSM: $\mu \leftrightarrow e$ symmetry strongly broken
- In the LHT: $\mu \leftrightarrow e$ symmetry approximately conserved

$\Rightarrow$ Consider quantities of type

$$\boxed{R_1 = \frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to \mu^- \mu^+ \mu^-)} \frac{Br(\tau^- \to \mu^- e^+ e^-)}{Br(\tau^- \to e^- \mu^+ \mu^-)}}$$

$$\boxed{R_2 = \frac{Br(\tau^- \to e^- e^+ e^-)}{Br(\tau^- \to \mu^- \mu^+ \mu^-)} \frac{Br(\tau \to \mu\gamma)}{Br(\tau \to e\gamma)}}$$

$$\boxed{R_3 = \frac{Br(\tau^- \to e^- \mu^+ \mu^-)}{Br(\tau^- \to \mu^- e^+ e^-)} \frac{Br(\tau \to \mu\gamma)}{Br(\tau \to e\gamma)}}$$

- In the MSSM: $R_1 \simeq 20\,, \quad R_2 \simeq 5\,, \quad R_3 \simeq 0.2\,.$
- In the LHT: $0.8 \lesssim R_1 \lesssim 1.3\,, \quad 0.8 \lesssim R_2 \lesssim 1.2\,, \quad 0.8 \lesssim R_3 \lesssim 1.2\,.$

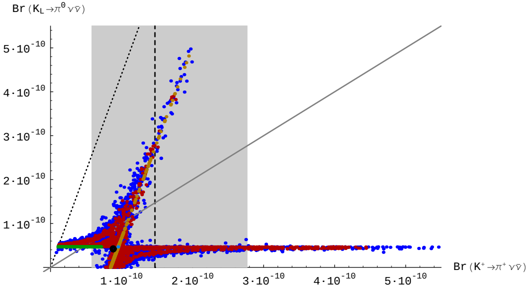
Main Messages

- Contributions from mirror leptons dominate the SM background by more than 40 orders of magnitude
- LFV decays in the LHT can easily reach or even exceed present experimental bounds

  $\Rightarrow$ $\boxed{\text{Chance of observation in upcoming experiments}}$
- Signals of the LHT could show up in LFV decays even before the LHC starts!
- $(g-2)_\mu$ negligible $\Rightarrow$ a problem?
- Correlations between branching ratios allow for a $\boxed{\text{clear distinction from the MSSM}}$ and other models

A Reminder: (Quark-) Flavor Violation in the LHT

Blanke, Buras, Poschenrieder, Tarantino, Uhlig, Weiler, hep-ph/0605214
Blanke, Buras, Poschenrieder, Recksiegel, Tarantino, Uhlig, Weiler, hep-ph/0610298



Upshot

- Large effects (up to factor 10 enhancements) in the K-system
- Smaller effects in the B-system (except for CP violating observables)

Backup: Upper Bounds

decay	$f = 1000\,\mathrm{GeV}$	$f = 500\,\mathrm{GeV}$	exp. upper bound
$\mu \to e\gamma$	$1.2 \cdot 10^{-11}$ $(1 \cdot 10^{-11})$	$1.2 \cdot 10^{-11}$ $(1 \cdot 10^{-11})$	$1.2 \cdot 10^{-11}$
$\mu^- \to e^-e^+e^-$	$1.0 \cdot 10^{-12}$ $(1 \cdot 10^{-12})$	$1.0 \cdot 10^{-12}$ $(1 \cdot 10^{-12})$	$1.0 \cdot 10^{-12}$
$\mu\mathrm{Ti} \to e\mathrm{Ti}$	$2 \cdot 10^{-10}$ $(5 \cdot 10^{-12})$	$4 \cdot 10^{-11}$ $(5 \cdot 10^{-12})$	$4.3 \cdot 10^{-12}$
$\tau \to e\gamma$	$8 \cdot 10^{-10}$ $(7 \cdot 10^{-10})$	$1 \cdot 10^{-8}$ $(1 \cdot 10^{-8})$	$9.4 \cdot 10^{-8}$
$\tau \to \mu\gamma$	$8 \cdot 10^{-10}$ $(8 \cdot 10^{-10})$	$2 \cdot 10^{-8}$ $(1 \cdot 10^{-8})$	$1.6 \cdot 10^{-8}$
$\tau^- \to e^-e^+e^-$	$7 \cdot 10^{-10}$ $(6 \cdot 10^{-10})$	$2 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$	$2.0 \cdot 10^{-7}$
$\tau^- \to \mu^-\mu^+\mu^-$	$7 \cdot 10^{-10}$ $(6 \cdot 10^{-10})$	$3 \cdot 10^{-8}$ $(3 \cdot 10^{-8})$	$1.9 \cdot 10^{-7}$
$\tau^- \to e^-\mu^+\mu^-$	$5 \cdot 10^{-10}$ $(5 \cdot 10^{-10})$	$2 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$	$2.0 \cdot 10^{-7}$
$\tau^- \to \mu^-e^+e^-$	$5 \cdot 10^{-10}$ $(5 \cdot 10^{-10})$	$2 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$	$1.9 \cdot 10^{-7}$
$\tau^- \to \mu^-e^+\mu^-$	$5 \cdot 10^{-14}$ $(3 \cdot 10^{-14})$	$2 \cdot 10^{-14}$ $(2 \cdot 10^{-14})$	$1.3 \cdot 10^{-7}$
$\tau^- \to e^-\mu^+e^-$	$5 \cdot 10^{-14}$ $(3 \cdot 10^{-14})$	$2 \cdot 10^{-14}$ $(2 \cdot 10^{-14})$	$1.1 \cdot 10^{-7}$
$\tau \to \mu\pi$	$2 \cdot 10^{-9}$ $(2 \cdot 10^{-9})$	$5.8 \cdot 10^{-8}$ $(5.8 \cdot 10^{-8})$	$5.8 \cdot 10^{-8}$
$\tau \to e\pi$	$2 \cdot 10^{-9}$ $(2 \cdot 10^{-9})$	$4.4 \cdot 10^{-8}$ $(4.4 \cdot 10^{-8})$	$4.4 \cdot 10^{-8}$
$\tau \to \mu\eta$	$6 \cdot 10^{-10}$ $(6 \cdot 10^{-10})$	$2 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$	$5.1 \cdot 10^{-8}$
$\tau \to e\eta$	$6 \cdot 10^{-10}$ $(6 \cdot 10^{-10})$	$2 \cdot 10^{-8}$ $(2 \cdot 10^{-8})$	$4.5 \cdot 10^{-8}$
$\tau \to \mu\eta'$	$7 \cdot 10^{-10}$ $(7 \cdot 10^{-10})$	$3 \cdot 10^{-8}$ $(3 \cdot 10^{-8})$	$5.3 \cdot 10^{-8}$
$\tau \to e\eta'$	$7 \cdot 10^{-10}$ $(7 \cdot 10^{-10})$	$3 \cdot 10^{-8}$ $(3 \cdot 10^{-8})$	$9.0 \cdot 10^{-8}$
$K_L \to \mu e$	$4 \cdot 10^{-13}$ $(2 \cdot 10^{-13})$	$3 \cdot 10^{-14}$ $(3 \cdot 10^{-14})$	$4.7 \cdot 10^{-12}$
$K_L \to \pi^0\mu e$	$4 \cdot 10^{-15}$ $(2 \cdot 10^{-15})$	$5 \cdot 10^{-16}$ $(5 \cdot 10^{-16})$	$6.2 \cdot 10^{-9}$
$B_d \to \mu e$	$5 \cdot 10^{-16}$ $(2 \cdot 10^{-16})$	$9 \cdot 10^{-17}$ $(9 \cdot 10^{-17})$	$1.7 \cdot 10^{-7}$
$B_s \to \mu e$	$5 \cdot 10^{-15}$ $(2 \cdot 10^{-15})$	$9 \cdot 10^{-16}$ $(9 \cdot 10^{-16})$	$6.1 \cdot 10^{-6}$
$B_d \to \tau e$	$3 \cdot 10^{-11}$ $(2 \cdot 10^{-11})$	$2 \cdot 10^{-10}$ $(2 \cdot 10^{-10})$	$1.1 \cdot 10^{-4}$
$B_s \to \tau e$	$2 \cdot 10^{-10}$ $(2 \cdot 10^{-10})$	$2 \cdot 10^{-9}$ $(2 \cdot 10^{-9})$	—
$B_d \to \tau\mu$	$3 \cdot 10^{-11}$ $(3 \cdot 10^{-11})$	$3 \cdot 10^{-10}$ $(3 \cdot 10^{-10})$	$3.8 \cdot 10^{-5}$
$B_s \to \tau\mu$	$2 \cdot 10^{-10}$ $(2 \cdot 10^{-10})$	$3 \cdot 10^{-9}$ $(3 \cdot 10^{-9})$	—

Backup: Full Particle Content

T-even

- SM fermions, SM bosons, SM Higgs
- T-even top partner T_+

T-odd

vector-like mirror fermions:

$$\begin{pmatrix} u_H^1 \\ d_H^1 \end{pmatrix}, \begin{pmatrix} u_H^2 \\ d_H^2 \end{pmatrix}, \begin{pmatrix} u_H^3 \\ d_H^3 \end{pmatrix}$$

$$\begin{pmatrix} \nu_H^1 \\ \ell_H^1 \end{pmatrix}, \begin{pmatrix} \nu_H^2 \\ \ell_H^2 \end{pmatrix}, \begin{pmatrix} \nu_H^3 \\ \ell_H^3 \end{pmatrix}$$

- to order $\mathcal{O}(v/f)$: mass degenerate doublets
- masses of order $\mathcal{O}(TeV)$

T-odd top partner T_-

heavy gauge bosons:
$W_H^\pm$, Z_H^0, A_H

T-odd scalars:
$\Phi^\pm$, $\Phi^{\pm\pm}$, Φ^0, Φ_P^0

Backup: Additional Parameters in the LHT

Explicit Parameters of the LHT

Symmetry breaking scale f
mixing parameter x_L

mirror quarks
3 mirror quark masses m^q_{Hi}
3 mixing angles θ^d_{ij}
3 mixing phases δ^d_{ij}

mirror leptons
3 mirror quark masses m^ℓ_{Hi}
3 mixing angles θ^ℓ_{ij}
3 mixing phases δ^ℓ_{ij}

$\Rightarrow$ total of 20 new parameters

Paramters from the Unknown UV-Completion

Some amplitudes are formally divergent $\Rightarrow \delta_{div}$

Formally, coefficients of higher dimensional operators have to be included

Backup: Determination of Parameters

Discovery of heavy gauge bosons A_H, $W_H^\pm$, Z_H ⇒ f

Discovery of heavy top partners $T_\pm$ ⇒ x_L

Discovery of mirror leptons ⇒ $m_{H1}^q, m_{H2}^q, m_{H3}^q$
 $m_{H1}^\ell, m_{H2}^\ell, m_{H3}^\ell$

FCNC processes
CP asymmetries ⇒ $\theta_{12}^d, \theta_{13}^d, \theta_{23}^d$
 $\delta_{12}^d, \delta_{13}^d, \delta_{23}^d$

LFV processes ⇒ $\theta_{12}^\ell, \theta_{13}^\ell, \theta_{23}^\ell$
 $\delta_{12}^\ell, \delta_{13}^\ell, \delta_{23}^\ell$