LEPTON FLAVOR VIOLATING SIGNALS FROM CHARGED SCALARS OF LITTLEST HIGGS MODEL AT LHC

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- Standard Model; SM
  - In agreement with experimental data
  - LHC is running with a big motivation in finding "Higgs Scalar", missing component of SM.
  - If Higgs boson is to be found
    The leading problem: Stabilize its mass against quadratically divergent radiative corrections.
    HIERARCHY PROBLEM

Also SM,

- can not account for neutrino masses
- can not explain CP problem
- no explanation for dark matter
- ...

Obligatory to go beyond SM: Physics BSM.

- Many models have been proposed
- including Little Higgs models
    - Deserves special attention, due to their elegant way to solve the hierarchy problem
    - Littlest Higgs model(LHM)[1]:
    - most economical little Higgs model

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[1] Arkani-Hamed et al:arXiv:hep-ph/0206020

OUTLINE:

In this talk:

- Brief review of Littlest Higgs model
- Lepton flavor violation in littlest Higgs models
- Processes that can give rise to lepton flavor violation at LHC
    1. $p + p \to \phi^{++}\phi^{--}$
    2. $p + p \to \phi^{++}\phi^{-}$
    3. $p + p \to \phi^{+}\phi^{-}$
- Final state analysis for production processes
- Conclusions

Littlest Higgs model

- **Motivation:** to overcome hierarchy problem
- **Approach:** Enlarge the symmetry group of the SM
- then use a collective symetry breaking mechanism.
- Global symmetry $SU(5)$ with a weakly gauged group of $(SU(2) \bigotimes U(1))^2$.

- Collective symmetry breaking mechanism:

1. By choosing a vacuum condansate:
   - $SU(5) \rightarrow SO(5)$ at a scale $f \sim 1TeV$
   - at low energies model can be described by number of degrees of freedom of Nambu-Goldstone bosons(NGB).
   - each broken generator $\rightarrow$ NGBs; 14 NGB.

- Breaking of global symmetry triggers spontaneous breaking of $(SU(2) \otimes U(1))^2 \rightarrow SU(2) \otimes U(1)$ of SM.
- some of the gauge bosons gain masses by eating four NGBs.
- $U(1)_1$ and $U(1)_2$ bosons get mixing;
  mixing angle θ, and $s = \sin\theta$.
- $SU(2)_1$ and $SU(2)_2$ bosons get mixing;
  mixing angle θ', and $s' = \sin\theta'$.
- 4 massive, 4 massless gauge bosons; scalar doublet(h) and the scalar triplet (ϕ) remain physical.

2 standard electroweak symmetry breaking (EWSB) occurs at $v = 246GeV$, resulting

1. gauge bosons gain extra masses and mixings
2. SM vector bosons (W_L^{+}, Z_L and A_L)
   new heavy vector bosons (W_H^{+}, Z_H and A_H)
3. SM Higgs scalar: (H)
   new heavy scalars: (ϕ^0, ϕ^P, ϕ^+ and ϕ^{++})
   All degenerate in mass.

- Masses of the gauge bosons:

$$
\begin{aligned}
M^2_{W_L^\pm} &= m_w^2\left[1-\frac{v^2}{f^2}\left(\frac{1}{6}+\frac{1}{4}(c^2-s^2)^2\right)+4\frac{v'^2}{v^2}\right],\\
M^2_{W_H^\pm} &= \frac{f^2g^2}{4s^2c^2}-\frac{1}{4}g^2v^2+\mathcal{O}(v^4/f^2)=m_w^2\left(\frac{f^2}{s^2c^2v^2}-1\right),\\
M^2_{A_L} &= 0,\\
M^2_{Z_L} &= m_z^2\left[1-\frac{v^2}{f^2}\left(\frac{1}{6}+\frac{1}{4}(c^2-s^2)^2+\frac{5}{4}(c'^2-s'^2)^2\right)+8\frac{v'^2}{v^2}\right],\\
M^2_{A_H} &= \frac{f^2g'^2}{20s'^2c'^2}-\frac{1}{4}g'^2v^2+g^2v^2\frac{x_H}{4s^2c^2}=m_z^2s_w^2\left(\frac{f^2}{5s'^2c'^2v^2}-1+\frac{x_Hc_w^2}{4s^2c^2s_w^2}\right),\\
M^2_{Z_H} &= \frac{f^2g^2}{4s^2c^2}-\frac{1}{4}g^2v^2-g'^2v^2\frac{x_H}{4s'^2c'^2}=m_w^2\left(\frac{f^2}{s^2c^2v^2}-1-\frac{x_Hs_w^2}{s'^2c'^2c_w^2}\right),
\end{aligned}
\tag{1}
$$

- s and s' are mixing angle of $U(1)$ and $SU(2)$ groups respectively, and f is the symmetry breaking scale
- The masses of the scalars are:

$$M_\phi = \frac{\sqrt{2}f}{v\sqrt{1-(\frac{4v'f}{v^2})^2}} M_H, \tag{2}$$

- The vacuum expectation values of h field: $\langle h^0 \rangle = v/\sqrt{2}$.
- The vacuum expectation values of ϕ fields: $\langle i\phi^0 \rangle = v'$

In the model:

- new vector bosons cancel out the divergences coming to Higgs mass from SM vector boson loops.
- new scalars cancel out the quadratic divergences to Higgs mass coming from Higgs self loop.
- a new fermion: T quark; introduced to cancel the quadratic divergences contributing to Higgs mass from t quark loop in SM.

Constraints on the littlest HM:

- f, s and s' are not restricted by the model.
- restricted by EWPD, and data from TEVATRON[2].
- TEVATRON constrains the mass of lightest heavy vector boson as: $M_{A_H} \geq 900GeV$.
- This ruled out the original littlest Higgs model for $f < 4TeV$.

[2] T. Aaltonen, et al, CDF Collaboration, Phys.Rev.Lett.99:171802,2007.

Two modifications:

1. introduce T parity[3]
2. Fermions are gauged under both $U(1)$ subgroups[4].
   - fermion boson couplings are modified
   - f can be small as $0.7 TeV$ ($s \simeq 0.8$ and $s' \simeq 0.6$).
   - used in this work.
   - parameter space in this modification is:

$$\begin{aligned} 0.7TeV \leq f \leq 2TeV \quad &\rightarrow \quad 0.78 \leq s \leq 0.88 \quad \text{and} \quad 0.58 \leq s' \leq 0.70 \\ 2TeV \leq f \leq 3TeV \quad &\rightarrow \quad 0.65 \leq s \leq 0.99 \quad \text{and} \quad 0.40 \leq s' \leq 0.90 \end{aligned}$$

[3] H. C. Cheng and I. Low; arXiv:hep-ph/0405243.

[4] Csaki et al.; arXiv:hep-ph/0303236

Lepton Flavor Violation in Littlest Higgs model

- Remember: LHM has an extre complex scalar $SU(2)$ sector.
- For light fermions, a Majorana mass term can be implemented in Yukawa lagrangian:

$$\mathcal{L}_{LFV} = iY_{ij}L_i^T \, \phi \, C^{-1}L_j + \text{h.c.}, \qquad (3)$$

where L_i are the lepton doublets $\begin{pmatrix} l & \nu_l \end{pmatrix}$.

- Y_{ij} are Yukawa couplings: $Y_{ii} = Y$ and $Y_{ij(i\neq j)} = Y'$.
- by this term neutrinos gain mass without need of right handed neutrinos.
- neutrino masses are given as: $M_{ij} = Y_{ij}v' = 10^{-10}GeV$
- v': vacuum expectation value of scalar triplet has only an upper bound; $v' < \frac{v^2}{4f}$.

- Considering Majorana mass term, decay width of the double charged scalars in the model are [5]:

$$\Gamma_{\phi^{++}} = \Gamma(W_L^+ W_L^+) + 3\Gamma(\ell_i^+ \ell_i^+) + 3\Gamma(\ell_i^+ \ell_j^+)$$
$$\approx \frac{v'^2 M_\phi^3}{2\pi v^4} + \frac{3}{8\pi}|Y|^2 M_\phi + \frac{3}{4\pi}|Y'|^2 M_\phi \qquad (4)$$

[5] T. Han et al:arXiv:hep-ph/0505260

- decay width of the single charged scalar:
- $$\begin{aligned}\Gamma_{\phi^+} &= 3\Gamma(\ell_i^+\bar{\nu}_i) + 6\Gamma(\ell_i^+\bar{\nu}_j) + \Gamma(W_L^+H) + \Gamma(W_L^+Z_L) + \Gamma(t\bar{b}) + \Gamma(T\bar{b}) \\ &\approx \frac{N_c M_t^2 M_\phi}{32\pi f^2} + \frac{v'^2 M_\phi^3}{2\pi v^4} + \frac{3}{8\pi}|Y|^2 M_\phi + \frac{3}{4\pi}|Y'|^2 M_\phi . \end{aligned} \tag{5}$$

- Decays into $T\bar{b}$ are neglected since $M_\phi \sim M_T$.

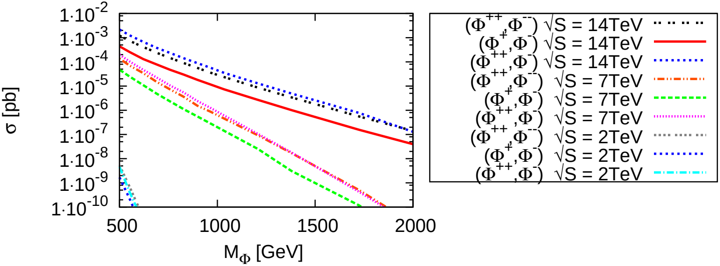
Processes

- Processes that can give rise to lepton flavor violation at LHC
  1. $p+p \to \phi^{++}\phi^{--}$
  2. $p+p \to \phi^{++}\phi^{-}$
  3. $p+p \to \phi^{+}\phi^{-}$
- The scattering amplitudes are calculated by using `Calchep` generator after implementing the models
- For PDF: `CTEQ5L` for protons

Numerical inputs in the calculations

- $M_h = 120GeV$.
- $\sqrt{S} = 2TeV$, $\sqrt{S} = 7TeV$ and $\sqrt{S} = 14TeV$.
- $0.5TeV \leq M_\phi \leq 2TeV$, $0.7TeV \leq f \leq 3TeV$.
- $s = 0.8$ and $s' = 0.6$.

Scattering amplitude of the processes



- Scattering amplitudes of the prduction processes in *pb*s.

	$\phi^{++}\phi^{--}$	$\phi^{++}\phi^{-}$	$\phi^{+}\phi^{-}$
$\sqrt{S} = 2TeV$, $M_\phi = 0.5TeV$	10^{-8}	10^{-8}	10^{-9}
$\sqrt{S} = 7TeV$, $M_\phi = 0.5TeV$	1.4×10^{-4}	2.4×10^{-4}	0.6×10^{-4}
$\sqrt{S} = 14TeV$, $M_\phi = 0.5TeV$	1.2×10^{-3}	2.9×10^{-3}	0.5×10^{-3}
$\sqrt{S} = 14TeV$, $M_\phi = 0.75TeV$	2.3×10^{-3}	3.6×10^{-4}	0.4×10^{-4}

- Productions via both processes are possible for $\sqrt{S} > 7TeV$ at LHC, but very low production rates
- For LHC with luminosity $100fb^{-1}$ (at least 2 more years):
  1. For the process $pp \to \phi^{++}\phi^{--}$, upto hundreds of events can be possible
  2. For the process $pp \to \phi^{++}\phi^{-}$, upto hundreds of events can be possible
  3. For the process $pp \to \phi^{+}\phi^{-}$, number of events can not reach to tens. This process is not contributing.

Final state analysis

- Decays of the charged scalars[6]:

$$\begin{aligned}\Gamma_{\phi^{++}} &= \Gamma(W_L^+ W_L^+) + 3\Gamma(\ell_i^+ \ell_i^+) + 3\Gamma(\ell_i^+ \ell_j^+) \\ &\approx \frac{v'^2 M_\phi^3}{2\pi v^4} + \frac{3}{8\pi}|Y|^2 M_\phi + \frac{3}{4\pi}|Y'|^2 M_\phi \\ \Gamma_{\phi^+} &= 3\Gamma(\ell_i^+ \bar{\nu}_i) + 6\Gamma(\ell_i^+ \bar{\nu}_j) + \Gamma(W_L^+ H) + \Gamma(W_L^+ Z_L) + \Gamma(t\bar{b}) \\ &\approx \frac{N_c M_t^2 M_\phi}{32\pi f^2} + \frac{v'^2 M_\phi^3}{2\pi v^4} + \frac{3}{8\pi}|Y|^2 M_\phi + \frac{3}{4\pi}|Y'|^2 M_\phi .\end{aligned}$$

- $M_{ij} = Y_{ij} v'$ (M_{ij} neutrino mass matrix)
- $Y = Y_{ii}$ and $Y' = Y_{ij(i \neq j)}$
- $10^{-10} GeV < v' < 1 GeV$: allowed region; for $v' < 0.01$ production cross sections are not effected.

[6]T. Han et al:arXiv:hep-ph/0505260

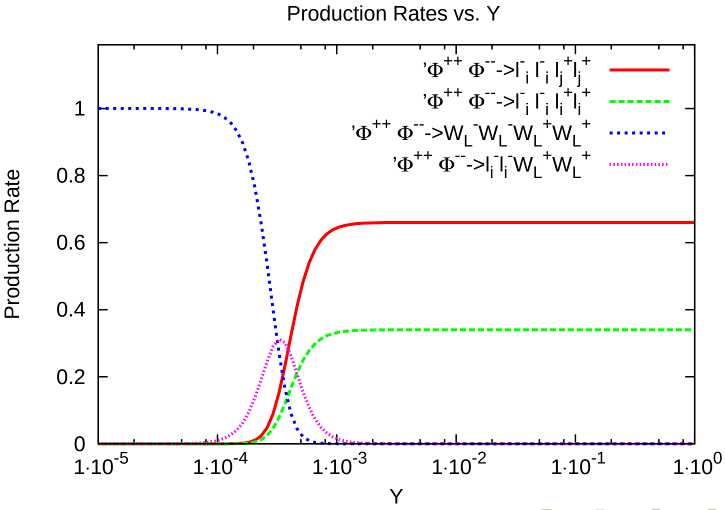
- The decays of the double charged pair $\phi^{++}\phi^{--}$:
  1. $v' > 10^{-6} GeV$ ($Y < 10^{-4}$): to SM bosonic states (no LFV)

     $\phi^{++}\phi^{--} \to W_L^+ W_L^+ W_L^- W_L^-$
  2. $v' < 10^{-7} GeV$ ($Y > 10^{-3}$): to leptonic states (LFV)
     - $\phi^{++}\phi^{--} \to l_i l_i l_j^+ l_j^+$: $BR \simeq 0.66$
     - $\phi^{++}\phi^{--} \to l_i l_i l_i^+ l_i^+$: $BR \simeq 0.33$
  3. $10^{-6} < v' < 10^{-7} GeV$ ($10^{-3} > Y > 10^{-4}$): to semileptonic states (LFV)

     $\phi^{++}\phi^{--} \to W_L^+ W_L^+ l_i l_i$

     W decays into jets with ~ 0.6, in this case LNV by 2.

- Dependance of final decay modes of double charged pairs on Yukawa coupling Y.



- The decays of the charged pair $\phi^{++}\phi^{-}$:

1. $v' \sim 10^{-10} GeV$ ($Y \sim 1$): Lepton Flavor Violation by 1
   - $\phi^{++}\phi^{-} \rightarrow l_i l_i l_j^{+} \bar{\nu}_j$ with rate 0.66
   - $\phi^{++}\phi^{-} \rightarrow l_i l_i l_i^{+} \bar{\nu}_i$ with rate 0.33.

2. $10^{-7} < v' < 10^{-9} GeV$ $(10^{-1} > Y > 10^{-3})$:

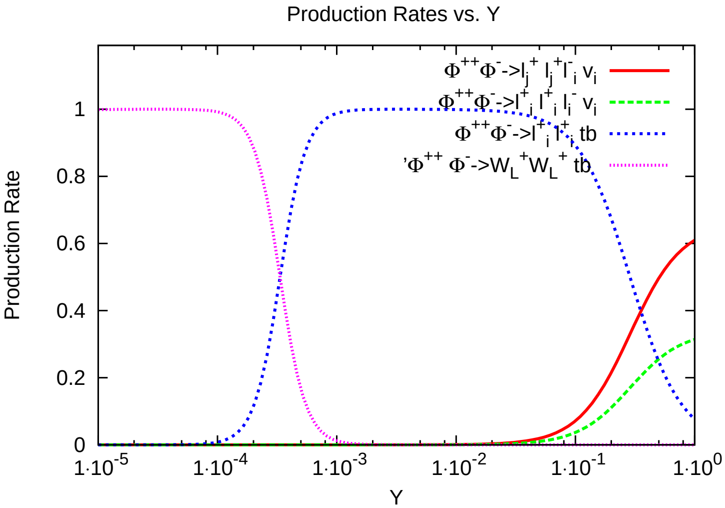
   LEPTON NUMBER VIOLATION by 2

   $\phi^{++}\phi^{-} \rightarrow l_i^{+} l_i^{+} \bar{t} b$:

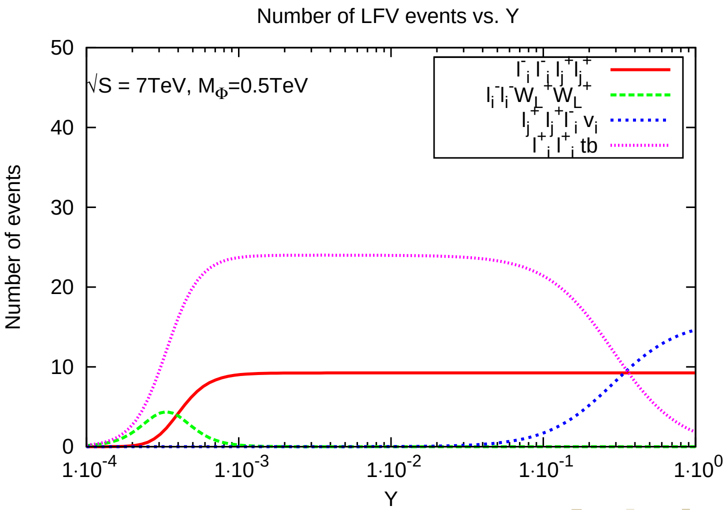
3. $10^{-6} < v'$ $(10^{-3} > Y)$: to SM particles

   $\phi^{++}\phi^{-} \rightarrow W_L^{+} W_L^{+} \bar{t} b$

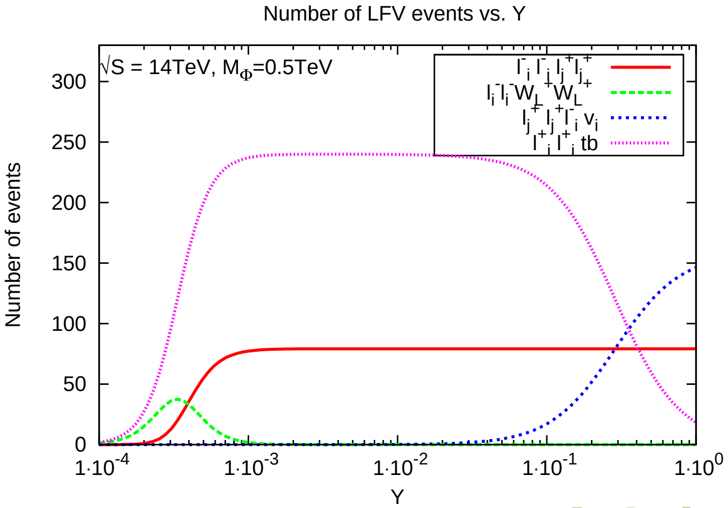
- Dependance of final decay modes of $\phi^{++}\phi^{-}$ pairs on Yukawa coupling Y.



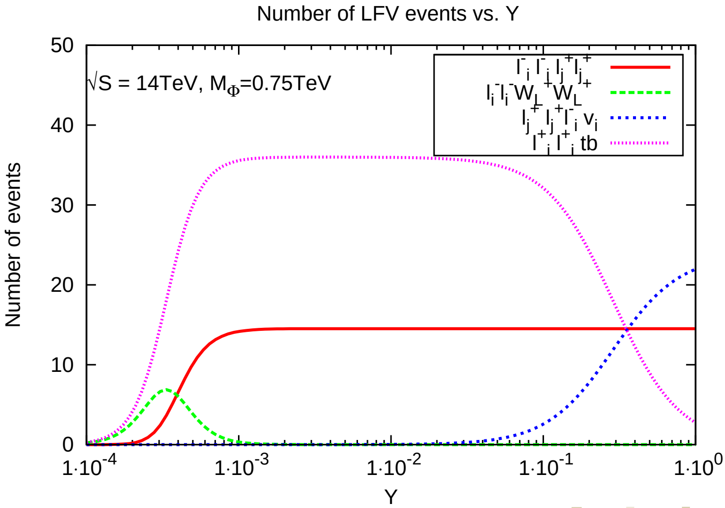
FINAL NUMBER OF LFV EVENTS



FINAL NUMBER OF LFV EVENTS



FINAL NUMBER OF LFV EVENTS



Conclusions

- The charged scalars of littlest Higgs model can be produced via $pp \to Z_L \phi^{++}\phi^{--}$, $pp \to Z_L \phi^{++}\phi^{-}$ and $pp \to Z_L \phi^{+}\phi^{-}$ processes for $\sqrt{S} \simeq 7TeV$ at LHC.
- Since the production rates are low, charged scalars can be detected if there are any distingushing LFV signals.
- Depending of the model parameters the collider signals for lepton flavor and lepton number violation will be free from any SM backgrounds.
  - for $Y \sim 1$, LFV by four in the channel $l_i l_i l_j^+ l_j^+$, and LFV by one in the channel $l_i l_i l_j^+ \nu_j$ are accessable.
  - for $10^-3 < Y < 0.1$ Lepton number violation by two can be observable in the channel $l_i^+ l_i^+ \bar{t} b$ channel

- For $\sqrt{S} = 7TeV$, these observations can be reached if $M_\phi \simeq 0.5TeV$
- For $\sqrt{S} = 14TeV$, these observations can be reached if $M_\phi \leq 1TeV$.
- These observations could help in discriminating the Littlest Higgs model from other New Physics realizations at LHC.