DOUBLE CHARGED SCALARS OF THE LITTLEST HIGGS MODEL AT e^+e^- COLLIDERS[1]

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[1] A.Cagil et al: `arXiv:hep-ph/0908.3581`.

DOUBLE CHARGED SCALARS OF THE LITTLEST HIGGS MODEL AT e^+e^- COLLIDERS

- In literature several models contain scalar triplet ranging from Left-Right symmetric models to little Higgs models.
- Appearance of a scalar triplet in a model allows lepton number violation by 2.
- Littlest Higgs model [2]: one of the little Higgs models contain a complex $SU(2)$ scalar.

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

OUTLINE:

In this talk:

- Brief review of Littlest Higgs model
- Lepton number violation in littlest Higgs models
- The production rates of the most dominant processes that could give lepton flavor and number violation in e^+e^- colliders:
    1. $e^+e^- \to Z_L \phi^{++}\phi^{--}$
    2. $e^+e^- \to \phi^{++}\phi^{--}$
- Final state analysis for production processes
- Conclusions

Littlest Higgs model

- **Motivation of LH models:** to overcome hierarchy problem
- LH models differ by their extended symetry groups and represantations of their scalars
- Littlest Higgs model:
  - Global symmetry $SU(5)$ with a weakly gauged group of $(SU(2) \bigotimes U(1))^2$.

- Collective symmetry breaking mechanism
  1. - First $SU(5) \rightarrow SO(5)$ at a scale $f \sim 1TeV$
     - At the same $(SU(2) \bigotimes U(1))^2 \rightarrow SU(2) \bigotimes U(1)$
     - Resulting 14 massless Goldstone bosons,four eaten by vector bosons, vector bosons gain mass.
  2. EWSB occurs at $v = 246GeV$, resulting
     1. SM vector bosons (W_L^+, Z_L and A_L)
        new heavy vector bosons (W_H^+, Z_H and A_H)
     2. SM Higgs scalar: (H)
        new heavy scalars: (ϕ^0, ϕ^P, ϕ^+ and ϕ^{++})
        All degenerate in mass.

- Masses of the gauge bosons:

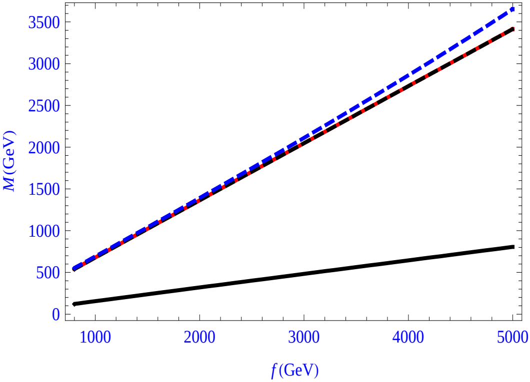
$$
\begin{aligned}
M^2_{W_L^\pm} &= m_w^2\left[1-\frac{v^2}{f^2}\left(\frac{1}{6}+\frac{1}{4}(c^2-s^2)^2\right)+4\frac{v'^2}{v^2}\right], \\
M^2_{W_H^\pm} &= \frac{f^2g^2}{4s^2c^2}-\frac{1}{4}g^2v^2+\mathcal{O}(v^4/f^2)=m_w^2\left(\frac{f^2}{s^2c^2v^2}-1\right), \\
M^2_{A_L} &= 0, \\
M^2_{Z_L} &= m_z^2\left[1-\frac{v^2}{f^2}\left(\frac{1}{6}+\frac{1}{4}(c^2-s^2)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

- s and s' are sines of mixing angles θ and θ' of $SU(2)$ and $U(1)$ 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:
  $\langle h^0 \rangle = v/\sqrt{2} \quad , \qquad v = 246GeV.$
- The vacuum expectation values of ϕ fields:
  $\langle i\phi^0 \rangle = v' \quad , \qquad v' < \frac{v^2}{4f}.$

- The masses of the new vector bosons and heavy scalars vs. f(symmetry breaking scale): $s/s' = 0.8/0.6$ and $v' = 1GeV$. Black line:A_H, Blue dashed:M_ϕ, Red:M_{W_L} and Black dashed:M_{Z_H}.



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 LstHM:

- f, s and s' are not restricted by the model.
- restricted by EWPD, and data from TEVATRON[3].
- TEVATRON constrains the mass of lightst heavy vector boson as: $M_{A_H} \geq 900GeV$.
- This ruled out the original littlest Higgs model for $f < 4TeV$.

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

Two modifications:

1. introduce T parity[4]
2. Fermions are gauged under both $U(1)$ subgroups[5].
   - fermion boson couplings are modified
   - f can be small as $1TeV$.
   - used in this work.
   - parameter space in this modification is:

$$\begin{array}{lclcl} 1TeV \leq f \leq 2TeV & \rightarrow & 0.80 \leq s \leq 0.98 & \text{and} & 0.60 \leq s' \leq 0.70 \\ 2TeV \leq f \leq 3TeV & \rightarrow & 0.65 \leq s \leq 0.99 & \text{and} & 0.40 \leq s' \leq 0.90 \end{array}$$

[4] H. C. Cheng and I. Low; arXiv:hep-ph/0405243.
[5] Csaki et al.; arXiv:hep-ph/0303236

Lepton Flavor Number Violation in Littlest Higgs model

- For light fermions, a Majorana mass term can be implemented in Yukawa lagrangian:

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

  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 [6]:

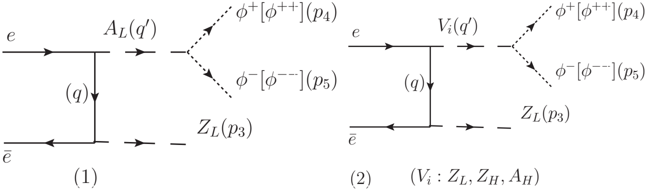
$$\begin{aligned}\Gamma_{\phi^{++}} &= \Gamma(W_L^+ W_L^+) + 3\Gamma(\ell_i^+ \ell_i^+) + 3\Gamma(\ell_i^+ \ell_j^+) \\ &\approx \frac{v'^2 M_\phi^3}{2\pi v^4} + \frac{3}{8\pi}|Y|^2 M_\phi + \frac{3}{4\pi}|Y'|^2 M_\phi \end{aligned} \tag{4}$$

- The last two terms are decays into lepton pairs of same and different generations proportional to Y and Y' respectively.
- As a consequence of this modification, LFV and LNV signals can be seen in littlest Higgs model.

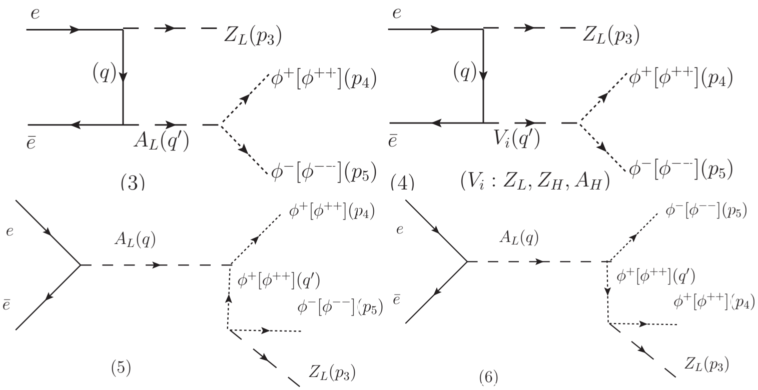
[6] T. Han et al: `arXiv:hep-ph/0505260`

PRODUCTION PROCESSES

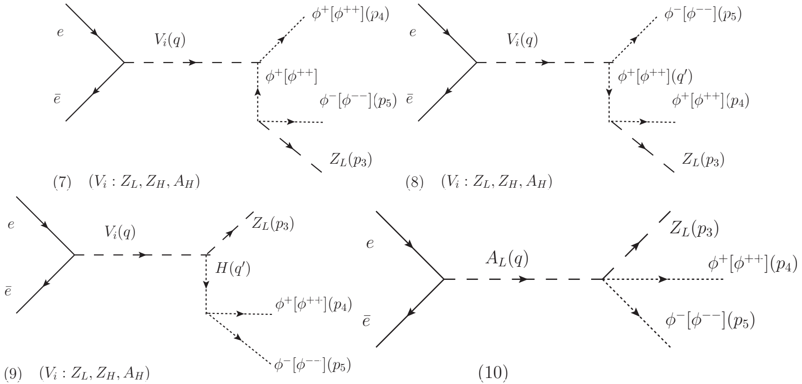
1. $e^+e^- \to Z_L\phi^{++}\phi^{--}$
Feynman diagrams for $e^+e^- \to Z_L\phi^{++}\phi^{--}$ in LstH model(1).



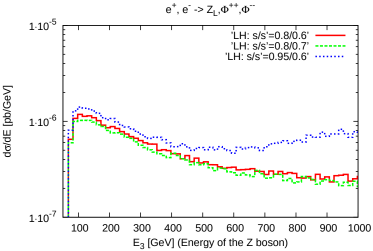
Feynman diagrams for $e^+e^- \to Z_L\phi^{++}\phi^{--}$ in LstH model(2).



Feynman diagrams for $e^+e^- \to Z_L\phi^{++}\phi^{--}$ in LstH model(3).

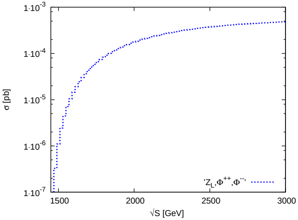


- Differential cross section vs. E_Z graphs for process $e^+e^- \to Z_L\phi^{++}\phi^{--}$ for the fixed value of parameters $s/s' : 0.8/0.6, 0.8/0.7, 0.95/0.6$ at $f = 1000GeV$ at $\sqrt{s} = 3TeV$.



- The production process is not sensitive to mixing angles.
- Differential cross section is at the order of $10^{-6}\,\frac{pb}{GeV}$.

- Total cross section vs. $\sqrt{S}$ graph for the process $e^+e^- \rightarrow Z_L\phi^{++}\phi^{--}$ for the fixed value of parameters $s/s' : 0.8/0.6$ at $f = 1000GeV$.



- The total production cross sections at $f = 1000GeV$ and $\sqrt{s} = 3TeV$ for different values of mixing angles

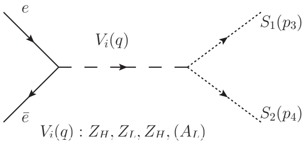
s/s'	$\sigma_{Z_L\phi^{++}\phi^{--}}$
$0.8/0.6$	$0.48 \times 10^{-3}pb$
$0.8/0.7$	$0.44 \times 10^{-3}pb$
$0.95/0.6$	$0.78 \times 10^{-3}pb$

For the process $e^+e^- \rightarrow Z_L\phi^{++}\phi^{--}$:

- For $\sqrt{S} > 2TeV$, Z_L associated double pair production of ϕ^{++} is in the reach for electron colliders.
- For an integrated luminosity of $100fb^{-1}$, there will be $40 \sim 80$ productions via this process.
- The production rate is low, but still accessible.

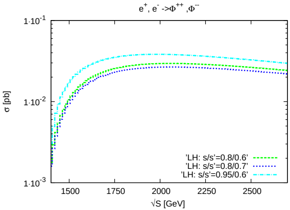
2 $e^+e^- \rightarrow \phi^{++}\phi^{--}$

- Feynman diagrams for $e^+e^- \rightarrow \phi^{++}\phi^{--}$ in LstH model.



- Drell-Yan process

- Total cross section vs. $\sqrt{S}$ graph for the process $e^+e^- \rightarrow \phi^{++}\phi^{--}$ at $f = 1000GeV$.



- The total production cross sections at $f = 1000GeV$ and $\sqrt{s} \geq 1.7TeV$ for different values of mixing angles are about $\sigma \sim 0.03pb$.
- For an electron collider with luminosity of $100fb^{-1}$, there will be 3000 double charged pair can be produced($\sqrt{s} \geq 1.7TeV$).

Final state analysis

- Decays of the double charged scalar[7]:

$$\Gamma_{\phi^{++}} = \Gamma(W_L^+ W_L^+) + 3\Gamma(\ell_i^+ \ell_i^+) + 3\Gamma(\ell_i^+ \ell_j^+)$$
$$\approx \frac{v'^2 M_\phi^3}{2\pi v^4} + \frac{3}{8\pi}|Y|^2 M_\phi + \frac{3}{4\pi}|Y'|^2 M_\phi \quad (5)$$

- $M_{ij} = Y_{ij} v'$ (M_{ij} neutrino mass matrix)
- $Y = Y_{ii}$ and $Y' = Y_{ij(i \neq j)}$
- $10^{-10} GeV < v' < 1 GeV$: allowed region

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

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

1. $v' > 10^{-8} GeV$ ($Y < 0.01$): to bosonic states (no LFV)

   $$\phi^{++}\phi^{--} \longrightarrow W_L^+ W_L^+ W_L^- W_L^-$$

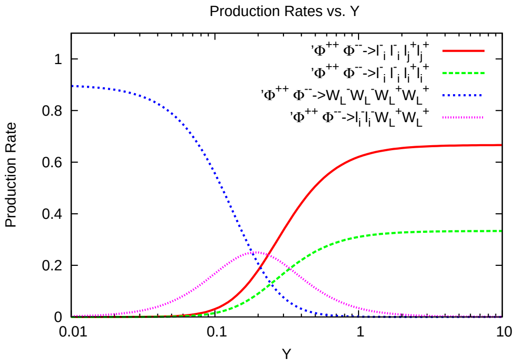
2. $v' \sim 10^{-10} GeV$ ($Y \sim 1$): to leptonic states (LFV)

   - $\phi^{++}\phi^{--} \longrightarrow l_i l_i \bar{l}_j \bar{l}_j$: $BR \simeq 0.67$
   - $\phi^{++}\phi^{--} \longrightarrow l_i l_i \bar{l}_i \bar{l}_i$: $BR \simeq 0.33$

3. $10^{-10} GeV < v' < 10^{-8} GeV$ ($0.01 < Y < 1$): to semileptonic states

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

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



CASE 1: $v' > 10^{-8} GeV$ ($Y < 0.01$)

- For $e^+e^- \to Z_L \phi^{++}\phi^{--}$:
  does not have any significance because of low production rates and high SM background.
- For $e^+e^- \to \phi^{++}\phi^{--}$:
  there is a chance to reconstruct double charged scalars from same charge W_L bosons with a subtraction from SM background.

CASE 2: $v' \sim 10^{-10} GeV$ ($Y \sim 1$)

- For $e^+e^- \longrightarrow Z_L \phi^{++}\phi^{--}$:
  For the decays of double charged scalars into different families(66%); there will be about 50 events of LFV observed free from any SM background.
- For $e^+e^- \longrightarrow \phi^{++}\phi^{--}$:
  For the decays of double charged scalars into different families(66%); there will be about 1800 events of LFV observed free from any SM back ground for $\sqrt{S} \geq 1.7 TeV$. $[l_i l_i \bar{l}_j \bar{l}_j]$
- Explicit **LFV** in both channels.

CASE 3: $10^{-8}GeV > v' > 10^{-10}GeV$ (1>$Y > 0.01$)

when $Y \sim 0.2$

- For $e^+e^- \longrightarrow Z_L\phi^{++}\phi^{--}$:
  There will be about 10 events of LNV observed free from any SM background.
- For $e^+e^- \longrightarrow \phi^{++}\phi^{--}$:
  - There will be about 600 events of LNV observed free from any SM back ground for $\sqrt{S} \geq 1.7TeV$. $[l_i l_i W_L^+ W_L^+]$
  - When both Ws decay into jets (48%): the cleanest signal for **lepton number violation** by 2. There will be about 280 events of $[l_i l_i + \text{jets}]$.
- Explicit **Lepton number violation** in both channels.

Conclusions

- The doubly charged of littlest Higgs model can be produced at linear colliders via $e^+e^- \longrightarrow Z_L\phi^{++}\phi^{--}$ and $e^+e^- \longrightarrow \phi^{++}\phi^{--}$ processes for $\sqrt{S} \simeq 1.7TeV$.
- Depending of the model parameters there will be clean collider signals for lepton flavor and lepton number violation.
- These observations could help in discriminating the Littlest Higgs model from other New Physics realizations at future e^+e^- linear colliders.