Same-sign Tetra-leptons from Type II Seesaw

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Introduction

- An SU(2) doublet boson (Y=1/2) responsible for the masses of quarks and charged leptons as well as for the electroweak symmetry breaking.
- What about neutrino masses? Maybe due to an "SU(2) triplet boson (Y=1)", $\Delta = (\Delta^{++}, \Delta^{+}, \Delta^{0})$: Type II Seesaw
- Conventional search: $pp \to \Delta^{++}\Delta^{--} \to l^{+} l^{+} l^{-} l^{-}$
- A novel phenomenon of the triplet-antitriplet oscillation leading to $pp \to \Delta^{++}\Delta^{++} + X \to l^{+} l^{+} l^{+} l^{+} + X$

EJC, Sharma, 1206.6278

- Implications for vacuum stability & Higgs-to-diphoton.

EJC, Lee, Sharma, 1209.1303
EJC, Sharma, 1301.1407

Type II Seesaw

- Introduce Higgs doublet (Y=1/2) & triplet (Y=1):

$$\Phi = (\Phi^+, \Phi^0) \qquad \Delta = \begin{pmatrix} \Delta^+/\sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+/\sqrt{2} \end{pmatrix}$$

- Triplet VEV generates neutrino mass matrix:

$$\mathcal{L}_Y = f_{\alpha\beta}\, L_\alpha^T C i\tau_2 \Delta L_\beta + \frac{1}{\sqrt{2}} \mu\, \Phi^T i\tau_2 \Delta \Phi + h.c.$$

$$v_\Delta = \mu \frac{v_\Phi^2}{M_\Delta^2} \;\Rightarrow\; \mathbf{m}^\nu_{\alpha\beta} = \mathbf{f}_{\alpha\beta} \mathbf{v}_\Delta \;\Leftarrow\; \boxed{f_{\alpha\beta} \frac{v_\Delta}{v_\Phi} \sim 10^{-12}} \; ?$$

- ρ parameter constraint on $\xi = v_\Delta / v_\Phi$:

$$\rho = (1+2\xi^2)/(1+4\xi^2) \rightarrow \xi < 0.03$$

- We will work in the limit of $\xi \ll 0.01$, neglecting the tree-level $\Delta\rho$ contribution.

Higgs sector

- Higgs potential of type II seesaw:

$$\begin{aligned}V(\Phi,\Delta) = {} & m^2\Phi^\dagger\Phi + \underline{M}^2\mathrm{Tr}(\Delta^\dagger\Delta) \\ & + \lambda_1(\Phi^\dagger\Phi)^2 + \lambda_2[\mathrm{Tr}(\Delta^\dagger\Delta)]^2 + 2\lambda_3\mathrm{Det}(\Delta^\dagger\Delta) \\ & + \underline{\lambda_4(\Phi^\dagger\Phi)}\mathrm{Tr}(\Delta^\dagger\Delta) + \underline{\lambda_5(\Phi^\dagger\tau_i\Phi)}\mathrm{Tr}(\Delta^\dagger\tau_i\Delta) \\ & + \frac{1}{\sqrt{2}}\mu\Phi^T i\tau_2\Delta\Phi + h.c.\end{aligned}$$

- Five mass eigenstates: $\Delta^{++}, \Delta^{+}, \Delta^{0}$

$$\Phi^{+}, \Phi^{0} \quad \Rightarrow \quad h^0, H^0, A^0, H^+, H^{++}$$

- Doublet-triplet mixing controlled by $\xi = v_\Delta/v_\Phi$:

$$\phi_I^0 = G^0 - 2\xi A^0 \qquad \phi^+ = G^+ + \sqrt{2}\xi H^+ \qquad \phi_R^0 = h^0 - a\xi\, H^0$$

$$\Delta_I^0 = A^0 + 2\xi G^0 \qquad \Delta^+ = H^+ - \sqrt{2}\xi G^+ \qquad \Delta_R^0 = H^0 + a\xi\, h^0$$

Triplet boson spectrum

- Large mass gap among triplet components: EJC, Lee, Park, 0304069

$$
\begin{aligned}
M^2_{H^{\pm\pm}} &= M^2 + 2\frac{\lambda_4-\lambda_5}{g^2}M^2_W \\
M^2_{H^{\pm}} &= M^2_{H^{\pm\pm}} + 2\frac{\lambda_5}{g^2}M^2_W \\
M^2_{H^0,A^0} &= M^2_{H^{\pm}} + 2\frac{\lambda_5}{g^2}M^2_W\,.
\end{aligned}
$$

$$\boxed{\Delta M^2 = 2\frac{\lambda_5}{g^2}M^2_W}$$

- Small mass gap between H⁰ & A⁰:

$$\mathcal{L}_{\Delta} = \frac{1}{\sqrt{2}}\mu\Phi^T i\tau_2\Delta^\dagger\Phi + h.c. \Rightarrow -\mu v_\Phi h^0 H^0$$

$$v_\Delta = \frac{\mu v_\Phi^2}{\sqrt{2}M^2_{H^0}}$$

$$\boxed{\delta M_{HA} \approx 2M_{H^0}\frac{v_\Delta^2}{v_\Phi^2}\frac{M^2_{H^0}}{M^2_{H^0}-m^2_{h^0}}}$$

Triplet decay channels

- Two mass hierarchies:

$$\boxed{M_{H^{++}} < M_{H^+} < M_{H^0/A^0} \quad \text{if} \quad \lambda_5 > 0}$$

$$M_{H^{++}} > M_{H^+} > M_{H^0/A^0} \quad \text{if} \quad \lambda_5 < 0$$

|ΔM| <~ 40 GeV from EWPD
(EJC, Lee, Sharma, 1209.1303)

- Gauge decays for non-vanishing ΔM (λ_5):

$$\boxed{H^0/A^0 \to H^\pm W^* \to H^{\pm\pm} W^* W^*}$$

$$H^{++} \to H^\pm W^* \to H^0/A^0\, W^* W^*$$

$\Leftarrow \Delta M(\lambda_5)$

- Di-lepton (same-sign) decays through $f_{\alpha\beta}$:

$$H^{++} \to l^+_\alpha l^+_\beta;\ H^+ \to l^+_\alpha \nu_\beta;\ H^0/A^0 \to \nu_\alpha \nu_\beta$$

$\Leftarrow f_{\alpha\beta}$

$\sim 10^{-12}/\xi$

- Di-quark/di-boson decays through ξ:

$$H^{++} \to W^+ W^+;\ H^+ \to t\bar{b}; \qquad H^0/A^0 \to t\bar{t},\, b\bar{b}$$
$$\to ZW, hW \qquad \to ZZ, hh/Zh$$

$\Leftarrow \xi \equiv \dfrac{v_\Delta}{v_\Phi}$

Triplet–antitriplet oscillation

- Triplet (lepton) number is conserved in the production:

$$pp \longrightarrow \Delta\bar{\Delta}$$

- Triplet number breaking by doublet-triplet mixing:

$$\mathcal{L}_{\not{\Delta}} = \frac{1}{\sqrt{2}}\mu \Phi^T i\tau_2 \Delta^\dagger \Phi + h.c.$$

- It induces a tiny mass splitting:

$$\mathcal{L}_{\not{\Delta}} = -\mu v_\Phi h^0 H^0 \Rightarrow \boxed{\delta M_{HA} \approx 2M_{H^0}\frac{v_\Delta^2}{v_0^2}\frac{M_{H^0}^2}{M_{H^0}^2 - m_{h^0}^2}}$$

- Oscillation probability of Δ → Δ or $\bar{\Delta}$:

$$\boxed{\chi_\pm = \begin{cases} \frac{2+x^2}{2(1+x^2)} \\ \frac{x^2}{2(1+x^2)} \end{cases}} \qquad \boxed{x \equiv \frac{\delta M}{\Gamma} = \frac{\tau_{dec}}{\tau_{osc}}}$$

Same-Sign Tetra-Leptons

- Lepton number violating processes:

$$\begin{aligned} pp \to \Delta^0\bar{\Delta}^0 \Rightarrow \Delta^0\Delta^0 &\to H^+H^+2W^- \to H^{++}H^{++}4W^- \\ \Delta^+\bar{\Delta}^0 \Rightarrow \Delta^+\Delta^0 &\to H^{++}H^+2W^- \to H^{++}H^{++}3W^- \end{aligned}$$

- Production cross-section:

$$\begin{aligned} \sigma\left(4\ell^\pm + 3W^{\mp^*}\right) &= \sigma\left(pp \to H^\pm H^0 + H^\pm A^0\right)\left[\frac{x_{HA}^2}{1+x_{HA}^2}\right]\mathrm{BF}(H^0/A^0 \to H^\pm W^{\mp^*}) \\ &\times \left[\mathrm{BF}(H^\pm \to H^{\pm\pm}W^{\mp^*})\right]^2\left[\mathrm{BF}(H^{\pm\pm} \to \ell^\pm\ell^\pm)\right]^2; \\ \sigma\left(4\ell^\pm + 4W^{\mp^*}\right) &= \sigma\left(pp \to H^0A^0\right)\left[\frac{2+x_{HA}^2}{1+x_{HA}^2}\frac{x_{HA}^2}{1+x_{HA}^2}\right]\mathrm{BF}(H^0 \to H^\pm W^{\mp^*})\mathrm{BF}(A^0 \to H^\pm W^{\mp^*}) \\ &\times \left[\mathrm{BF}(H^\pm \to H^{\pm\pm}W^{\mp^*})\right]^2\left[\mathrm{BF}(H^{\pm\pm} \to \ell^\pm\ell^\pm)\right]^2. \end{aligned}$$

Same-Sign Tetra-Leptons

- Is this observable?

i) H^{++} is the lightest and $f_{\alpha\beta} > \xi$.

ii) ΔM sufficiently large to allow $\Delta^0 \to H^+ W^- \to H^{++} 2W^-$.

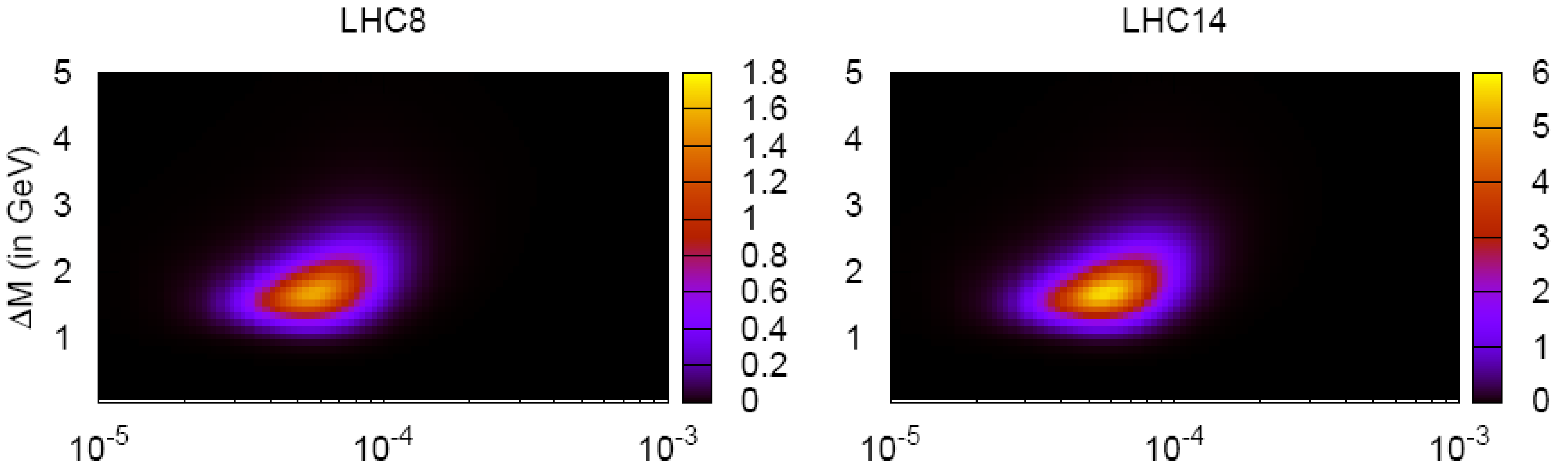
iii) Sizable oscillation parameter: x~1.

$$\delta M_{HA} \sim 2\frac{v_\Delta^2}{v_\Phi^2} M_{H^0} \qquad \Gamma_{H^0/A^0} \sim \frac{G_F^2 \Delta M^5}{\pi^3}$$

$$\boxed{v_\Delta \sim 10^{-4}\mathrm{GeV}, \quad \Delta M \sim 2\mathrm{GeV} \quad \Rightarrow \delta M_{HA} \sim \Gamma_{H^0/A^0} \sim 10^{-11}\mathrm{GeV}}$$

SS4L cross-section

- SS4L production including the oscillation factor:

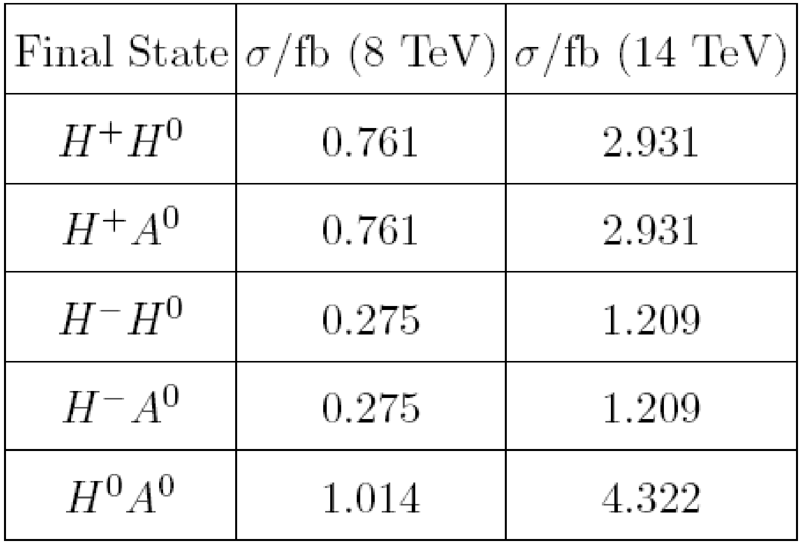


$M_{H^{\pm\pm}} = 400\text{GeV}$

- Benchmark point:

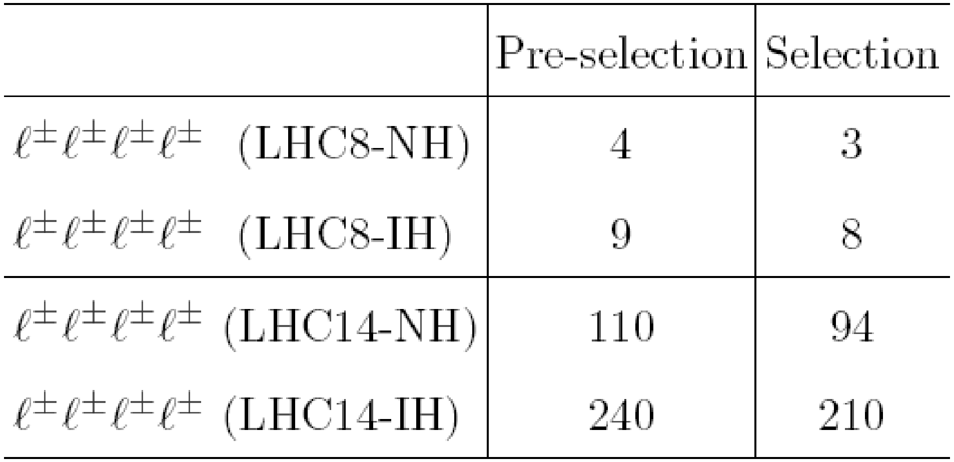
  v_Δ=7x10^{-5} GeV, ΔM=1.5 GeV.

Event numbers



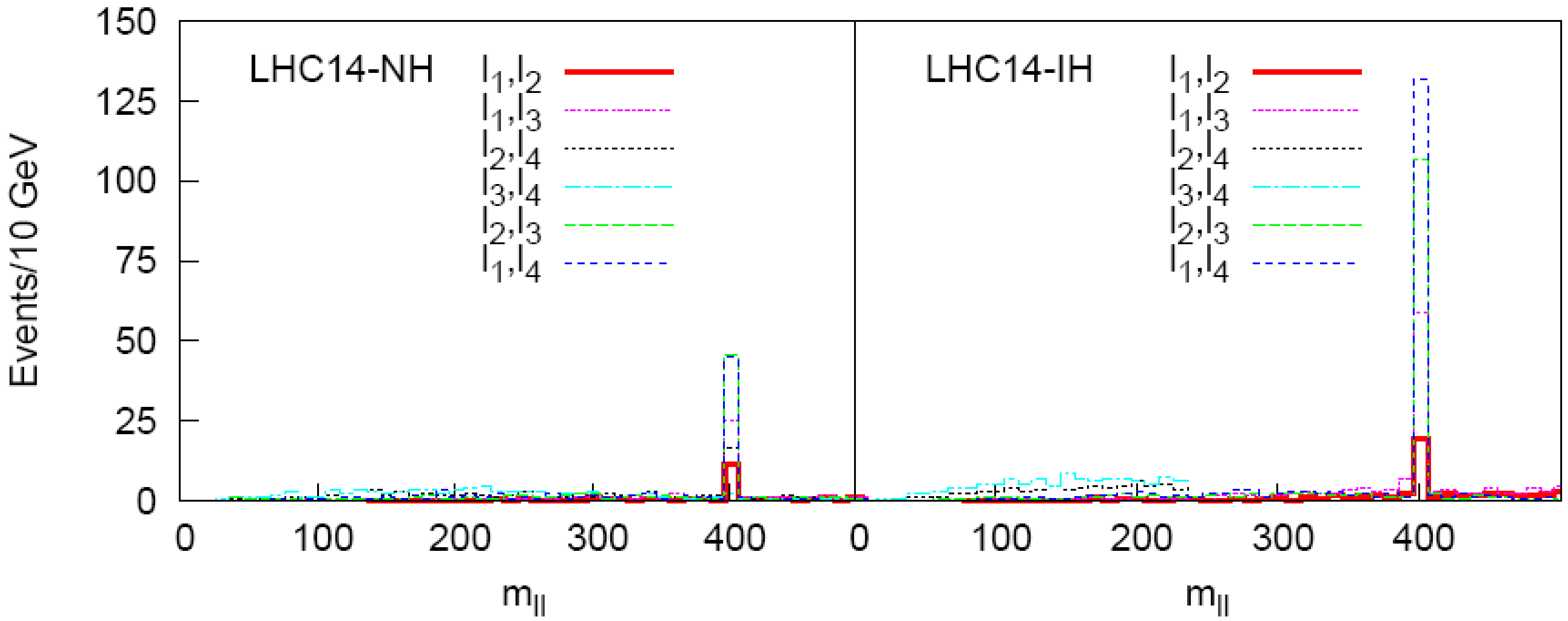
Final State	σ/fb (8 TeV)	σ/fb (14 TeV)
H^+H^0	0.761	2.931
H^+A^0	0.761	2.931
H^-H^0	0.275	1.209
H^-A^0	0.275	1.209
H^0A^0	1.014	4.322

No background
Lepton selection cuts only



		Pre-selection	Selection
$15 fb^{-1}$	$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC8-NH)	4	3
	$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC8-IH)	9	8
$100 fb^{-1}$	$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC14-NH)	110	94
	$\ell^\pm\ell^\pm\ell^\pm\ell^\pm$ (LHC14-IH)	240	210

Mass reconstruction



Conclusion

- Neutrino mass may indicate the presence of an SU(2) triplet boson: Type II seesaw.
- It predicts a novel signature of same-sign tetra-leptons due to the triplet—antitriplet oscillation.
- With 100/bf at LHC14, SS4L signals can be observed up to the triplet boson mass 600-700 GeV in the best case.
- Observation of SS4L is a direct probe of the type II seesaw mechanism confirming the presence of a tiny triplet VEV and mass gaps of the triplet.