



Testing Origin of Neutrino Mass at the LHC

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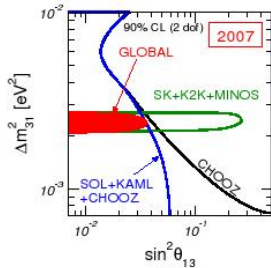
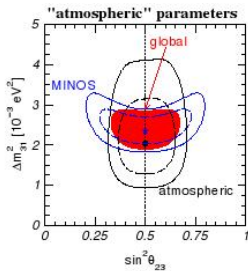
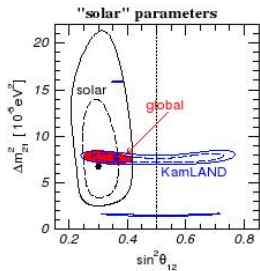
Tao Han, Biswarup Mukhopadhyaya, Zongguo Si and KW
Phys. Rev. D **76**, 075013 (2007) [arXiv:0706.0441 [hep-ph]]
Pavel Fileviez P ere, Tao Han, Guiyu Huang, Tong Li and KW

[arXiv:0803.3450[hep-ph] and *In Preparation*



- Neutrino Masses: First Evidence for BSM Physics
- Triplet Model
- Decay of Triplet Higgses
- Neutrino Spectrum and Δ leptonic decays
- LHC Phenomenology
 - Production of triplet Higgs
 - Leptonic Decay: Reconstruction and BR
 - Testing Doublet/Triplet Mixing
- Conclusion

Neutrino Mass: 1st Evidence for Beyond SM



Global Best Fit at 3σ level Schwetz 07

$$7.1 \times 10^{-5} \text{eV}^2 < \Delta m_{21}^2 < 8.3 \times 10^{-5} \text{eV}^2;$$
$$2.0 \times 10^{-3} \text{eV}^2 < |\Delta m_{31}^2| < 2.8 \times 10^{-3} \text{eV}^2$$
$$0.26 < \sin^2 \theta_{12} < 0.40; 0.34 < \sin^2 \theta_{23} < 0.67; \sin^2 \theta_{13} < 0.050$$
$$\sum_i m_i < 1.2 \text{eV}$$



Challenge: $m_t/m_\nu \sim 10^{12}$, $\sin^2 \theta_{23}$

- Dirac or Majorana nature of neutrino
- Global $U(1)_L$ or $U(1)_{B-L}$

$U(1)_L$ as global symmetry in SM. Quantum gravity effects (wormhole or blackhole) only respects gauge symmetries. Hawking, 87

$$\ell\ell H_u H_u / M_{\text{Pl}}$$

$$m_\nu \sim 10^{-5} \text{ eV}$$



Spontaneously broken $U(1)_L$ Chikashige, Mohapatra, Peccei, 80

Majoron Problem

Once imposing anomaly free condition, upto an overall normalization, $U(1)_Y$ is the uniquely defined.

$U(1)_{B-L}$ is the leading candidate for extra $U(1)$ gauge symmetry.

- No $[SU(3)_C]^2 \times U(1)_{B-L}$ or $[SU(2)_L]^2 \times U(1)_{B-L}$ anomalies
- No $[U(1)_Y]^2 \times U(1)_{B-L}$ or $U(1)_Y \times [U(1)_{B-L}]^2$ anomalies
- ONLY TRACE $\text{Tr}U(1)_{B-L}$ and Cubic $[U(1)_{B-L}]^3$
- $SU(5)$ respect $U(1)_{B-L}$.

One can gauge $U(1)_{B-L}$ by adding just ONE SM singlet!



- Type I seesaw $y_D l \nu^c H_u + M_R \nu^c \nu^c$, $\Delta L = 2$
 $M_R \sim 10^{14} \text{ GeV}$, $m_\nu \sim M_D^2 / M_R$ Yanagida,79; Gell-Man *et al.*,79; Glashow,80; Mohapatra, Senjanovic,80
- Type II seesaw $y_\nu l^T i \sigma_2 \Delta l$, $\Delta L = 2$
 $m_\nu = y_\nu v' \sim 10^{-10} \text{ GeV}$ Minikowski,77; Cheng, Li,80; Mohapatra, Senjanovic,81; Shafi *et al.*, 81
- Zee model, generates neutrino mass at two-loop $\Delta L = 2$ Zee 80, Babu, 88
- Type III seesaw, etc.....

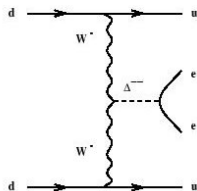


$$\frac{\mu^n \ell \ell H_u H_u}{\Lambda_\chi^{n+1}}$$

Λ_χ must be within collider reach.

$$M_\Delta \sim 100 \text{ GeV} - 1 \text{ TeV}$$

For instance, AMSB Mohapatra et al. 07,08



- $1/M_{W_L}^4 y_\nu v' / M_\Delta^2 \sim 1/M_{W_L}^4 m_\nu / M_\Delta^2$

$$\frac{y_\nu v'}{M_\Delta^2} \leq 5 \times 10^{-8} \text{ GeV}^{-1}$$

$$M_\Delta > 0.1 \text{ GeV}$$



Other Bounds on Triplet Higgs

Masses

- CDF/DØ Search bound: $m_{H^{++}} > 120$ GeV (4 muons/muons+tau)
- Lepton Flavor Violation $\text{Br}(\mu \rightarrow e^- e^+ e^+) < 10^{-12}$
- Unitarity WW scattering: $gM_W \times v_\Delta/v_0$

VEV

ρ -parameter Gunion, et. al, 1990; Chen, Dawson, 2002

Triplet vev breaks $SU(2)_{L+R}$ custodial symmetry

$$\rho = \left(\frac{m_W}{m_Z \cos \theta_W} \right)^2; \quad v_\Delta < 1 \text{ GeV}$$



$Y = 2$ $SU(2)_L$ Triplet

$$\Delta = \frac{1}{2} \begin{pmatrix} H^+ & \sqrt{2}H^{++} \\ \sqrt{2}H^0 & -H^+ \end{pmatrix}$$

Breaking $U(1)_{B-L}$

$$y_{\nu} \ell_L^T C i \sigma_2 \Delta \ell + \mu H^T i \sigma_2 \Delta^\dagger H + h.c. + \dots$$

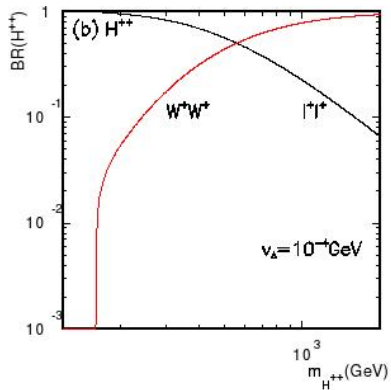
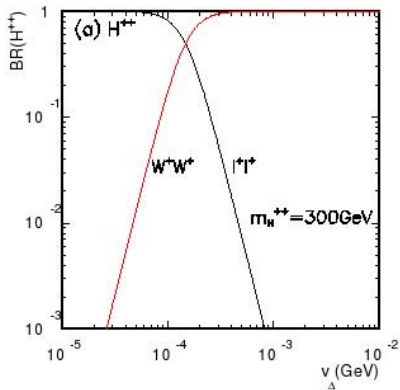
$$H^{++} \rightarrow \ell^+ \ell^+, W^+ W^+$$

$$H^+ \rightarrow \ell^+ \bar{\nu}, W^+ h, W^+ Z, t \bar{b}$$

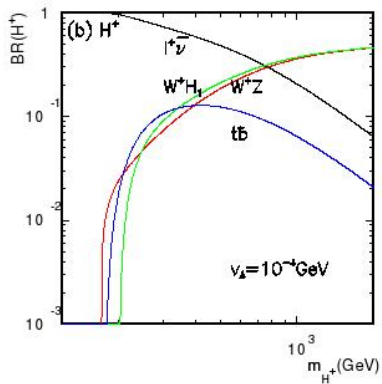
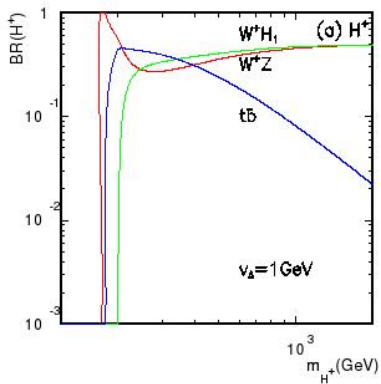
$$H^0 \rightarrow \nu \nu, \bar{\nu} \bar{\nu}, ZZ, W^+ W^-, H_1 H_1$$

(No tree level mass difference among triplet Higgses. Otherwise $H^{++} \rightarrow H^+ W^*, H^+ \rightarrow H_2 W^*$)

H^{++} Decay BR: ν' vs y_ν



$$\Gamma_{WW} \sim M_H^3(\text{longitudinal}); \quad \Gamma_{\ell\ell} \sim M_H$$



$$-Y_{\nu l}^T C i\sigma_2 \Delta l + \text{h.c.}, \quad \text{where } \Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

No Majorana Phases

$\sin \theta_{23}$

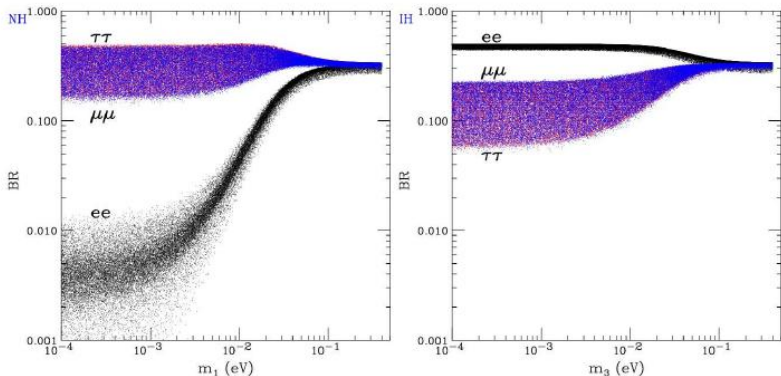
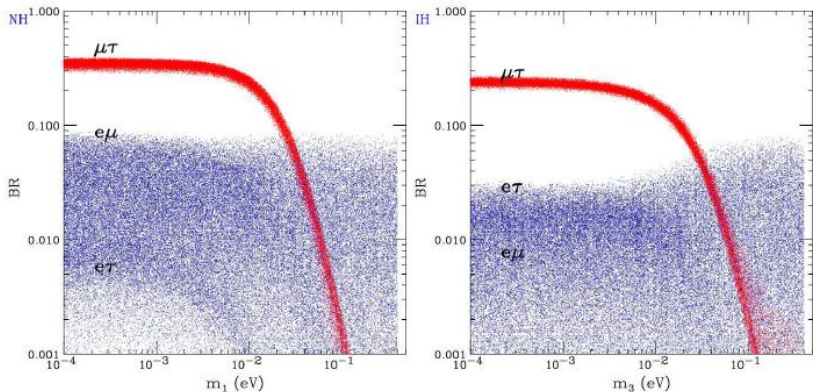
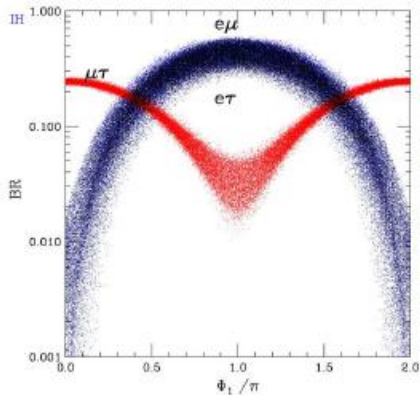


FIG. 12: $\text{Br}(H^{++} \rightarrow e_i^+ e_i^+)$ vs. the lowest neutrino mass for NH (left) and IH (right) when $\Phi_1 = 0$ and $\Phi_2 = 0$.

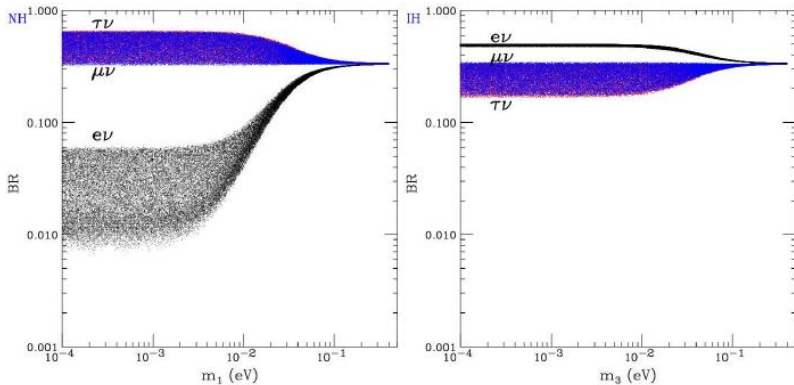


Doubly Charged (continued)





- Singly Charged Higgs BR is independent of Majorana phases.



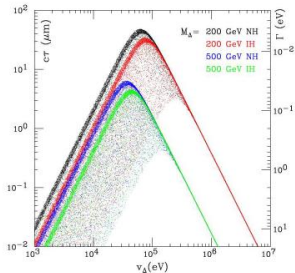


FIG. 14: Decay length and width of doubly charged Higgs ($\Phi_1 = 0$ and $\Phi_2 = 0$).

$v_\Delta \sim 10^{-4}\text{GeV}$: secondary vertex; Not longlived

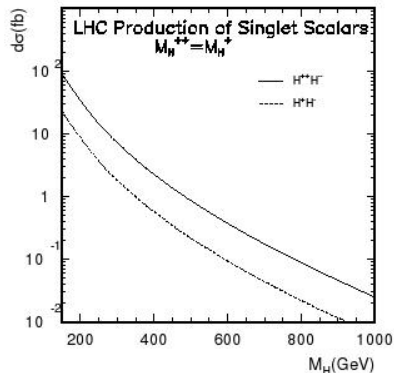
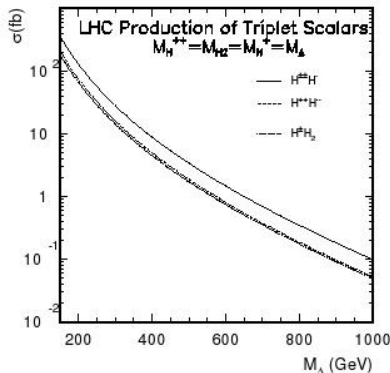
Spectrum	Relations
NH $\Delta m_{31}^2 > 0$	$\text{Br}(\tau^+\tau^+), \text{Br}(\mu^+\mu^+) \gg \text{Br}(e^+e^+)$ $\text{Br}(\mu^+\tau^+) \gg \text{Br}(e^+\tau^+), \text{Br}(e^+\mu^+)$ $\text{Br}(\tau^+\bar{\nu}), \text{Br}(\mu^+\bar{\nu}) \gg \text{Br}(e^+\bar{\nu})$
IH $\Delta m_{31}^2 < 0$	$\text{Br}(e^+e^+) > \text{Br}(\mu^+\mu^+), \text{Br}(\tau^+\tau^+)$ $\text{Br}(\mu^+\tau^+) \gg \text{Br}(e^+\tau^+), \text{Br}(e^+\mu^+)$ $\text{Br}(e^+\bar{\nu}) > \text{Br}(\mu^+\bar{\nu}), \text{Br}(\tau^+\bar{\nu})$
QD	$\text{Br}(e^+e^+) \approx \text{Br}(\mu^+\mu^+) \approx \text{Br}(\tau^+\tau^+)$ $\text{Br}(\mu^+\tau^+) \approx \text{Br}(e^+\tau^+) \approx \text{Br}(e^+\mu^+) \text{ (suppressed)}$ $\text{Br}(e^+\bar{\nu}) \approx \text{Br}(\mu^+\bar{\nu}) \approx \text{Br}(\tau^+\bar{\nu})$

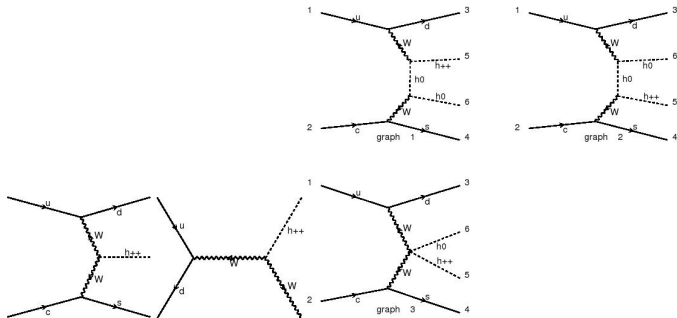
Part II
PHENOMENOLOGY

Searching at the Large Hadron Collider

$$\begin{aligned}
 q(p_1) + \bar{q}(p_2) &\rightarrow H^{++}(k_1) + H^{--}(k_2) \\
 q(p_1) + \bar{q}'(p_2) &\rightarrow H^{++}(k_1) + H^-(k_2) \\
 q(p_1) + \bar{q}'(p_2) &\rightarrow H^+(k_1) + H_2(k_2)
 \end{aligned}$$

Tree Level Cross-section of Triplet Higgses Production



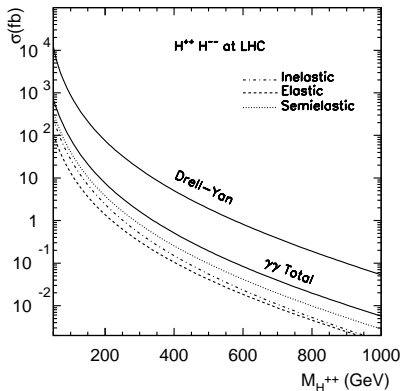
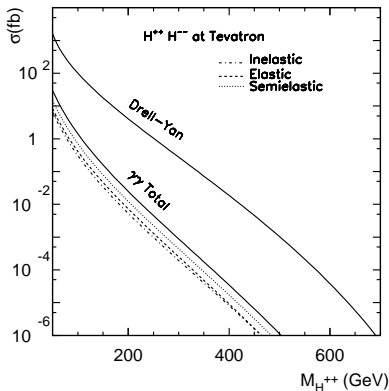


- triplet vev v_Δ suppression
- phase space suppression
- Ward Identity (Longitudinal W , $\epsilon_\mu \rightarrow p_\mu$)

Remarks on Production (continued)



- QCD correction for this mass range 25% (NLO K -factor 1.25)
- real photon emission ($\gamma\gamma \rightarrow H^{++}H^{--}$) 10%



$$\sigma_{\gamma\gamma} = \sigma_{\text{elastic}} + \sigma_{\text{inelastic}} + \sigma_{\text{semi-elastic}}$$

$$\sigma_{\text{elastic}} = \int_{\tau}^1 dz_1 \int_{\tau/z_1}^1 dz_2 f_{\gamma/p}(z_1) f_{\gamma/p'}(z_2) \sigma(\gamma\gamma \rightarrow H^{++}H^{--})$$

$$\sigma_{\text{inelastic}} = \int_{\tau}^1 dx_1 \int_{\tau/x_1}^1 dx_2 \int_{\tau/x_1/x_2}^1 dz_1 \int_{\tau/x_1/x_2/z_1}^1 dz_2 f_q(x_1) f_q'(x_2) f_{\gamma/q}(z_1) f_{\gamma/q'}(z_2) \sigma(\gamma\gamma \rightarrow H^{++}H^{--})$$

$$\sigma_{\text{semi-elastic}} = \int_{\tau}^1 dx_1 \int_{\tau/x_1}^1 dz_1 \int_{\tau/x_1/z_1}^1 dz_2 f_q(x_1) f_{\gamma/q}(z_1) f_{\gamma/p'}(z_2) \sigma(\gamma\gamma \rightarrow H^{++}H^{--})$$

$$\tau = \frac{4m^2}{S}$$

Drees, Godbole 94

Search via Leptonic Decays

Small vev limit $v_{\Delta} < 10^{-4}$ GeV

All LNV, but not observable except for H^{++}

$$H^{++} \rightarrow l^+ l^+; \quad H^+ \rightarrow l^+ \bar{\nu}_l; \quad H_2 \rightarrow \nu \nu$$

- μ, e and τ respectively
- $H_2 \rightarrow$ invisible and always produced via $H^{\pm} H_2$, another missing ν from H^+ , impossible to reconstruct.
- High p_T event, e is better than μ

$$pp \rightarrow H^{++} H^- \rightarrow l^+ l^+ l^- \nu, l^+ l^+ \tau^- \nu \quad (l = e, \mu)$$

$$pp \rightarrow H^{++} H^{--} \rightarrow l^+ l^+ l^- l^-, l^+ l^+ \tau^- \tau^- \quad (l = e, \mu)$$



4 Lepton (no τ final state)

- $p_T(\ell_{\max}) > 30 \text{ GeV}$ and $p_T(\ell)_{\min} > 15 \text{ GeV}$
- $|\eta(\ell)| < 2.5$
- $\Delta R_{\ell\ell} > 0.4$

SM Background if there exists same flavor, opposite sign dilepton

$$ZZ/\gamma^* \rightarrow \ell^+\ell^-\ell^+\ell^-$$

Veto events of $|M_{\ell^+\ell^-} - M_Z| < 15 \text{ GeV}$ After reconstruction,
purely event counting

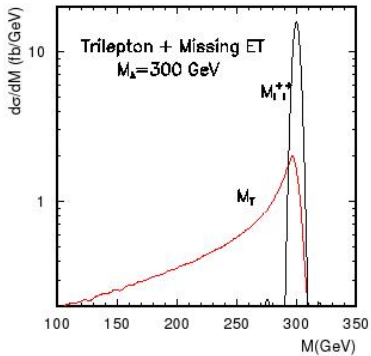
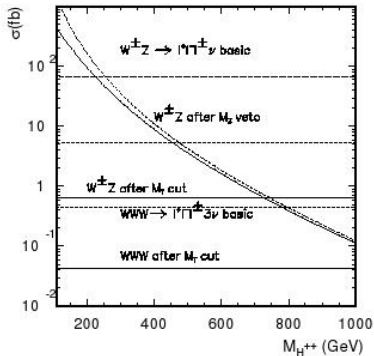


- $p_T(\ell_{\max}) > 30$ GeV and $p_T(\ell)_{\min} > 15$ GeV
- $|\eta(\ell)| < 2.5$
- $\Delta R_{\ell\ell} > 0.4$
- $\cancel{E}_T > 40$ GeV

SM Background if there exists same flavor, opposite sign dilepton

$$W^\pm Z/\gamma^* \rightarrow \ell^\pm \nu \ell^+ \ell^-, W^\pm W^\pm W^\mp \rightarrow \ell^\pm \ell^+ \ell^- + \cancel{E}_T$$

Veto events of $|M_{\ell^+ \ell^-} - M_Z| > 15$ GeV



$$M_T = \sqrt{(E_T^\ell + \cancel{E}_T)^2 - (\vec{p}^\ell + \vec{\cancel{p}}_T)^2}$$

τ Final State

- $\tau \rightarrow \mu\nu\bar{\nu}$ 17.36%
- $\tau \rightarrow e\nu\bar{\nu}$ 17.84%
- $\tau \rightarrow \pi\nu$ 10.9%
- $\tau \rightarrow h^-\pi^0\nu$ 37.0%

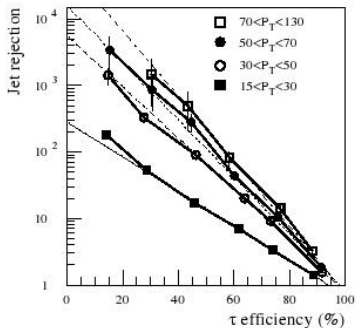


Figure 9-31 Jet rejection as a function of the τ efficiency, as obtained over the region $|\eta| < 2.5$ and in various p_T ranges. Straight-line fits are superimposed.



$$H^+ \rightarrow \tau \nu \rightarrow \ell + \cancel{E}_T$$

$$H^+ \rightarrow \ell + \cancel{E}_T$$

Lepton p_T

- ℓ from H^+ Jacobian Peak around $M_H/2$ (may change due to boost)
- ℓ from τ , purely boost effect, much softer

p_T^ℓ selection (GeV)	50	75	100	100	150	200
ℓ misidentification rate	2.9%	9.4%	17.6%	4.6%	12.4%	22.2%
τ survival probability	57.0%	69.8%	78.8%	62.8%	75.7%	83.7%

τ selection:

$p_T < 100$ GeV (for $M_H^+ = 300$ GeV)

$p_T < 200$ GeV for $M_H^+ = 600$ GeV



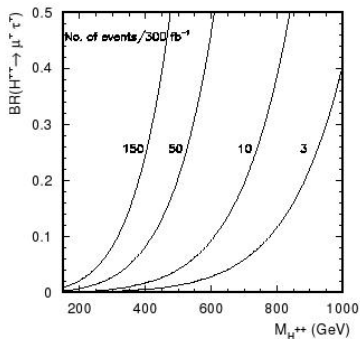
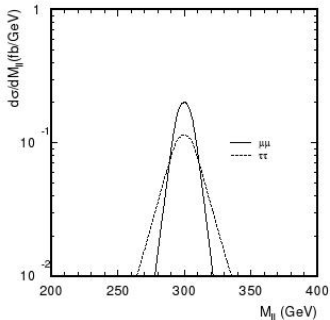
No other \cancel{E}_τ in final state:

$$pp \rightarrow H^{++}H^{--} \rightarrow \ell^+\ell^+\tau^-\tau^-, \ell^+\ell^+\mu^-\tau^-, \ell^+\tau^+\tau^-\tau^-$$

Highly Boosted τ

- $\vec{p}^{\text{invisible}} = \kappa \vec{p}^{\ell}$; each τ corresponds to one unknown
- $\Sigma \vec{p}_\tau^{\text{invisible}} = \vec{p}_T$ 2 independent equations
- $M_{\ell^+\ell^+} = M_{\tau^-\tau^-}^{\text{rec}}$; 1 more equation

UPTO THREE τ S



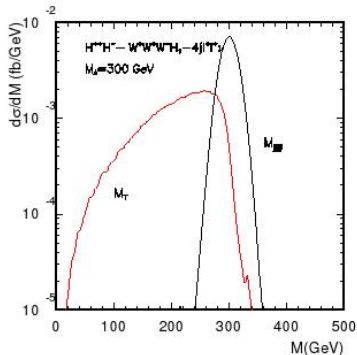
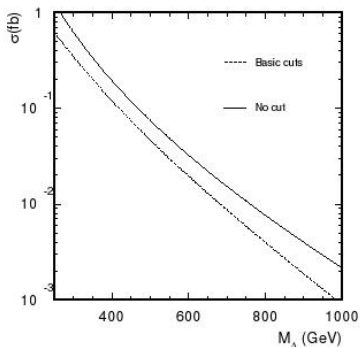


$$N_{4\mu} = \mathcal{L} \times \sigma(pp \rightarrow H^{++}H^{--}) \times \text{BR}^2(H^{++} \rightarrow \mu^+\mu^+)$$

$$N_{3\mu\tau} = \mathcal{L} \times \sigma(pp \rightarrow H^{++}H^{--}) \times \text{BR}(H^{++} \rightarrow \mu^+\mu^+) \text{BR}(H^{++} \rightarrow \mu^+\tau^+)$$

To test doublet-triplet mixing $\mu H^T \Delta H$.
 Both H^+ and H_2 decay will tell this. But $H_2 \rightarrow H_1 H_1$ has at least
 6 jets final state.

$$pp \rightarrow H^{++} H^- \rightarrow W^+ W^+ W^- H_1 / \bar{t} b / W^- Z \rightarrow jjb\bar{b} \ell^+ \ell^+ \cancel{E}_T$$



$\sigma(\text{fb})$ cuts	Basic Cuts	p_T^ℓ cut > 50 GeV	p_T^j cut > 100 GeV	M_{Cluster} > 600 GeV	M_W rec. $M_W \pm 15$ GeV	M_X rec. or M_l veto	M_T < 300 GeV	M_{jjjj} 300 ± 50 GeV
$t\bar{b}$	0.13	0.12	0.12	0.11	0.11	0.094*	0.094	0.092
WH	0.074	0.069	0.065	0.061	0.06	0.046	0.045	0.045
WZ	0.06	0.056	0.053	0.05	0.05	0.038	0.038	0.038
$H^{\pm\pm}H^\mp$ sum	0.26	0.25	0.24	0.22	0.22	0.18	0.18	0.17
$H^{\pm\pm}H^\mp\mp$	0.24	0.23	0.22	0.21	0.21	0.18	0.17	0.17
$t\bar{t}W$	3.1	2.5	1.8	1.4	1.4	0.88*	0.52	0.095
					$(M_H \text{ rec.} \rightarrow)$	0.15	0.097	0.045
					$(M_Z \text{ rec.} \rightarrow)$	0.11	0.071	0.032
					$(M_W \text{ rec.} \rightarrow)$	0.096	0.06	0.026

$\sigma(\text{fb})$ cuts	Basic Cuts	p_T^ℓ cut > 80 GeV	p_T^j cut > 200 GeV	M_{J_1} rec. $M_W \pm 15$ GeV	M_{J_2} rec. $M_X \pm 15$ GeV	M_{JJ} 600 ± 75 GeV
WH	1.1×10^{-2}	9.5×10^{-3}	9.5×10^{-3}	9.4×10^{-3}	9.1×10^{-3}	9.0×10^{-3}
WZ	1.0×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	1.0×10^{-2}	9.9×10^{-3}	9.8×10^{-3}
$H^{\pm\pm}H\mp\mp$	3.3×10^{-2}	3.2×10^{-2}	3.1×10^{-2}	3.1×10^{-2}	3.1×10^{-2}	3.1×10^{-2}
$JJW^\pm W^\pm$	14.95	7.65	4.69	0.24	6×10^{-2}	4.0×10^{-5}
				(M_H rec.→)		
				(M_Z rec.→)		
				(M_W rec.→)	0.1	1.6×10^{-4}



- We propose one scenario that Type II seesaw mechanism can be tested directly at the LHC although it may require high luminosity.
- It has very different phenomenology like doubly charged scalars that can decay into same sign dilepton.
- If the doubly charged Higgs and its LNV decay has been discovered, we will be able to extract information of neutrino mass and mixing from BR of triplet Higgses.

THANK YOU!