IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Testing Origin of Neutrino Mass at the LHC

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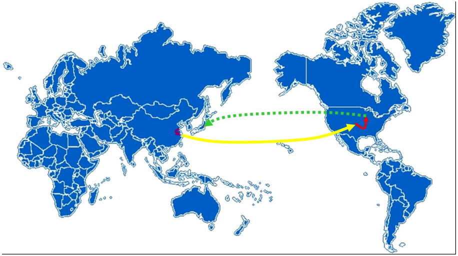
IPMU HEP Seminar

柏の葉2008-9-10

work completed at University of Wisconsin, Madison
Tao Han, Biswarup Mukhopadhyaya, Zongguo Si and KW
Phys. Rev. D 76, 075013 (2007) [arXiv:0706.0441 [hep-ph]]
Pavel Fileviez Pére, Tao Han, Guiyu Huang, Tong Li and KW
[arXiv:0803.3450[hep-ph] and Phys. Rev. D 78, 015018 (2008) 0805.3536 [hep-ph]]



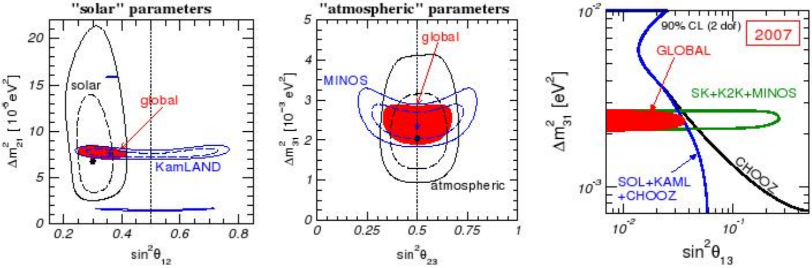
Biographical Sketch

- from Lianyungang, CHINA
  中国江蘇省連雲港市(秦の徐福の故郷;佐賀市,堺市の友好都市)
- 1996-2000, B.S. Zhejiang University, Hangzhou, CHINA
  杭州市–浙江大学(ニュートリノの有名人:王淦昌,李政道)
- 2000-2004, M.S. Oklahoma State University, Stillwater (advisor: Kaladi S. Babu)
- 2005-2008, Ph.D. University of Wisconsin,Madison (advisor: Tao Han)
- 2008- IPMU Postdoc

Outline

- 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: 1^{st} Evidence for Beyond SM



Global Best Fit at 3σ level Schwetz 07

$$7.1\times10^{-5}\,\mathrm{eV}^2 < \Delta m^2_{21} < 8.3\times10^{-5}\,\mathrm{eV}^2;$$
$$2.0\times10^{-3}\,\mathrm{eV}^2 < |\Delta m^2_{31}| < 2.8\times10^{-3}\,\mathrm{eV}^2$$
$$0.26 < \sin^2\theta_{12} < 0.40;\ 0.34 < \sin^2\theta_{23} < 0.67;\ \sin^2\theta_{13} < 0.050$$
$$\textstyle\sum_i m_i < 1.2\ \mathrm{eV}$$

Lepton Number Violation (LNV) $\not{L}$

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

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

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

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

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

Global $U(1)_L$ or $U(1)_{\mathrm{B-L}}$

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.

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

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

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

Models

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

Light Triplet accessible at the LHC

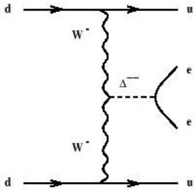
$$\frac{\mu^n \ell\ell H_u H_u}{\Lambda_{\not{L}}^{n+1}}$$

$\Lambda_{\not{L}}$ must be within collider reach.

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

For instance, AMSB Mohpatra *et al.* 07,08

LNV Direct Test: $0\nu\beta\beta$



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

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

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

Other Bounds on Triplet Higgs

Masses

- CDF/DØ Search bound: $m_{H^{++}} > 120~\mathrm{GeV}$ (4 muons/muons+tau)
- Lepton Flavor Violation $\mathrm{Br}(\mu \to e^- e^+ e^+) < 10^{-12}$
- 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

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

Type II seesaw

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

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

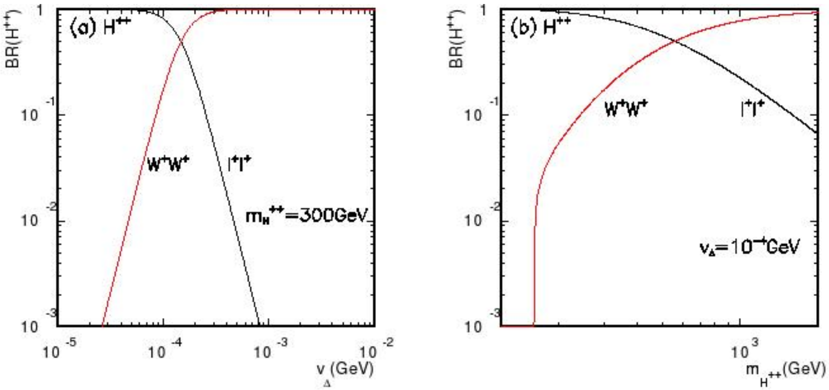
Breaking $U(1)_{\mathrm{B-L}}$

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

$$\begin{aligned} H^{++} &\to \ell^+\ell^+, W^+W^+ \\ H^+ &\to \ell^+\bar{\nu}, W^+h, W^+Z, t\bar{b} \\ H^0 &\to \nu\nu, \bar{\nu}\bar{\nu}, ZZ, W^+W^-, H_1H_1 \end{aligned}$$

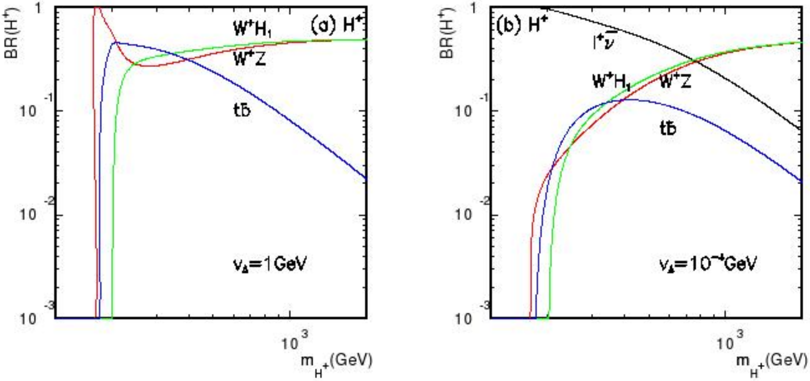
(No tree level mass difference among triplet Higgses. Otherwise $H^{++} \to H^+W^*$,$H^+ \to H_2W^*$)

H^{++} Decay BR: v' vs y_ν



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

H^+ Decay BR


BR(H+)
1
10^-1
10^-2
10^-3
10^3
m_H+(GeV)
(a) H+
W+H1
W+Z
tb̄
v_Δ=1GeV
(b) H+
l+ν̄
W+H1
W+Z
tb̄
v_Δ=10^-4GeV

Neutrino and Triplet Leptonic Decay

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

No Majorana Phases

$\sin\theta_{23}$

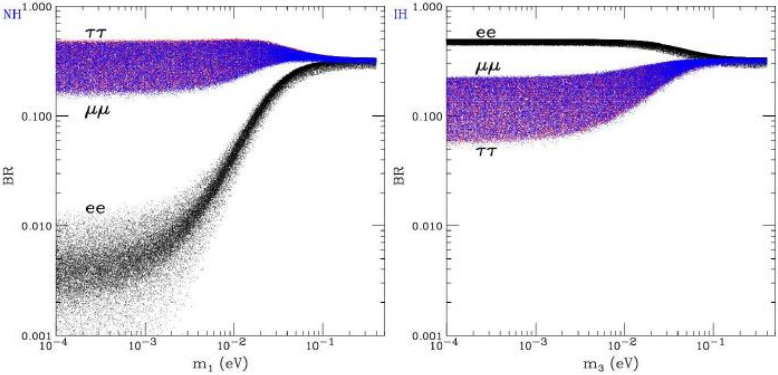
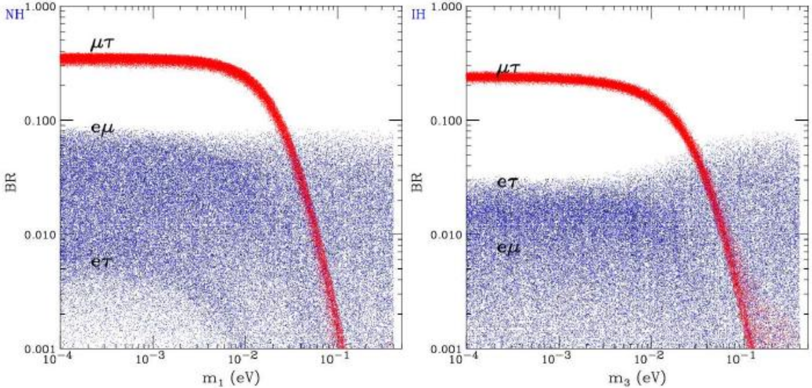
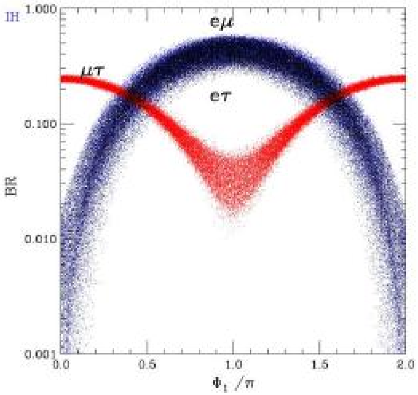


FIG. 12: Br($H^{++} \to e_i^+ e_j^+$) vs. the lowest neutrino mass for NH (left) and IH (right) when $\Phi_1 = 0$ and $\Phi_2 = 0$.

Doubly Charged (continued)



Majorana Phase



- Singly Charged Higgs BR is independent of Majorana phases.

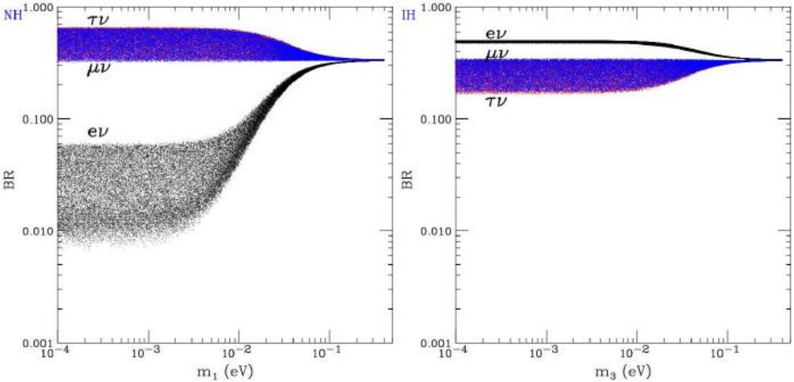
Majorana Phase: a close look

$$\Gamma_+ = \cos\theta_+ \; \frac{m_\nu^{diag} \;\; V_{PMNS}^\dagger}{v_\Delta}, \qquad \Gamma_{++} = \frac{V_{PMNS}^* \;\; m_\nu^{diag} \;\; V_{PMNS}^\dagger}{\sqrt{2}\; v_\Delta}$$

$$Y_+^j = \sum_{i=1}^{3} |\Gamma_+^{ij}|^2 \times v_\Delta^2, \qquad Y_{++} = \sqrt{2} v_\Delta \times \Gamma_{++}$$

$$V_{PMNS} = \begin{pmatrix} c_{12}\, c_{13} & c_{13}\, s_{12} & e^{-i\delta}\, s_{13} \\ -c_{12}\, s_{13}\, s_{23}\, e^{i\delta} - c_{23}\, s_{12} & c_{12}\, c_{23} - e^{i\delta}\, s_{12}\, s_{13}\, s_{23} & c_{13}\, s_{23} \\ s_{12}\, s_{23} - e^{i\delta}\, c_{12}\, c_{23}\, s_{13} & -c_{23}\, s_{12}\, s_{13}\, e^{i\delta} - c_{12}\, s_{23} & c_{13}\, c_{23} \end{pmatrix} \times \mathrm{diag}(e^{i\Phi_1/2}, 1, e^{i\Phi_2/2})$$

Singly Charged



Decay length of H^{++}

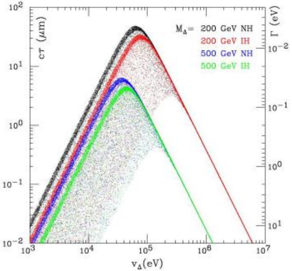
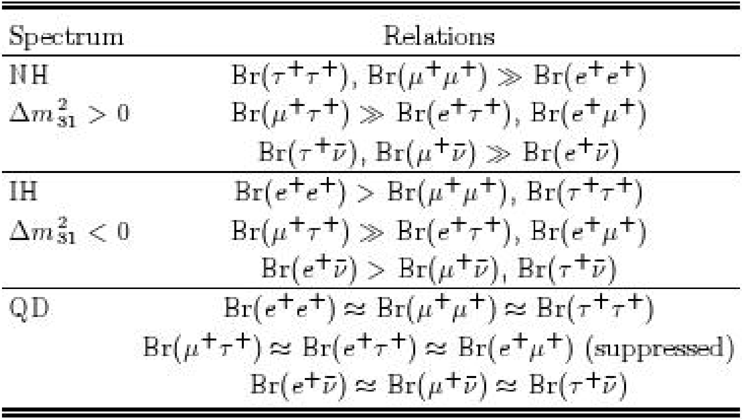


FIG. 14: Decay length and width of doubly charged Higgs ($\Phi_1 = 0$ and $\Phi_2 = 0$).

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

Distinguish Spectrum via LNV Higgs Decay



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

Part II

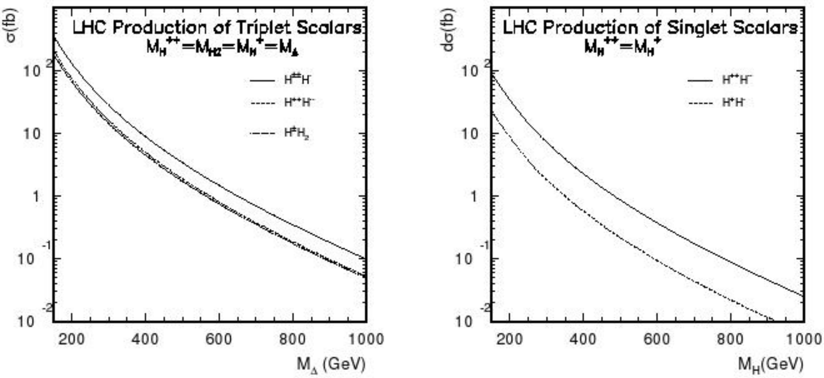
Phenomenology

Searching at the Large Hadron Collider

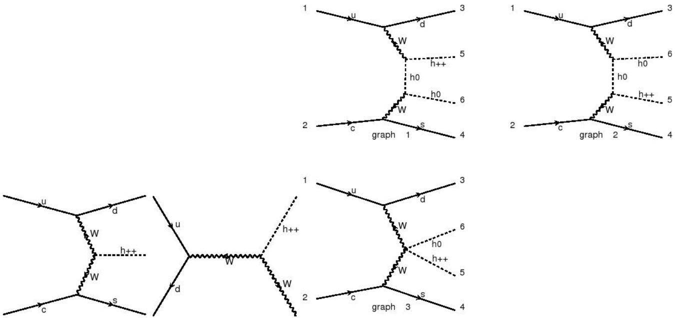
Production of Triplet Higgses

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

Tree Level Cross-section of Triplet Higgses Production



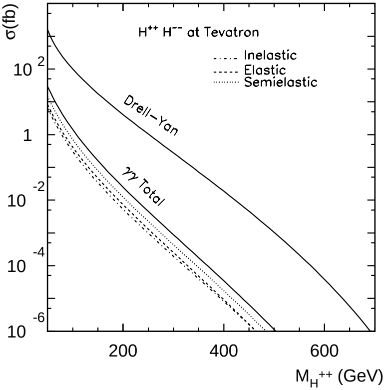
Remarks on Production

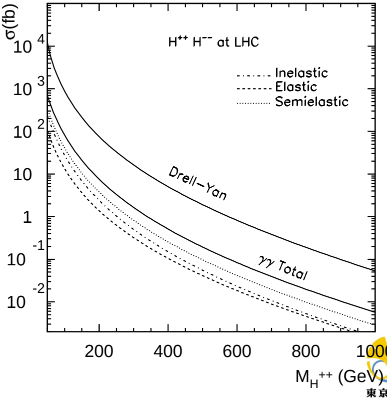


- triplet vev v_Δ suppresion
- phase space suppression
- Ward Identity (Longitutinal W, $\epsilon_\mu \longrightarrow p_\mu$)

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%





Photon-Photon

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

$$\begin{aligned}
\sigma_{\rm elastic} &= \int_{\tau}^{1} dz_1 \int_{\tau/z_1}^{1} dz_2 f_{\gamma/p}(z_1) f_{\gamma/p'}(z_2)\sigma(\gamma\gamma \to H^{++}H^{--}) \\
\sigma_{\rm inelastic} &= \int_{\tau}^{1} dx_1 \int_{\tau/x_1}^{1} dx_2 \int_{\tau/x_1/x_2}^{1} dz_1 \int_{\tau/x_1/x_2/z_1}^{1} \\
& dz_2 f_q(x_1) f_q'(x_2) f_{\gamma/q}(z_1) f_{\gamma/q'}(z_2)\sigma(\gamma\gamma \to H^{++}H^{--}) \\
\sigma_{\rm semi-elastic} &= \int_{\tau}^{1} dx_1 \int_{\tau/x_1}^{1} dz_1 \int_{\tau/x_1/z_1}^{1} dz_2 f_q(x_1) f_{\gamma/q}(z_1) f_{\gamma/p'}(z_2)\sigma(\gamma\gamma \to H^{++}H^{--}) \\
\tau &= \frac{4m^2}{S}
\end{aligned}$$

Drees, Godbole 94

Search via Leptonic Decays

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

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

$$H^{++} \to \ell^+\ell^+; \quad H^+ \to \ell^+\bar{\nu}_\ell; \quad H_2 \to \nu\nu$$

- μ,e and τ respectively
- $H_2 \to \mathrm{invisible}$ 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

$$pp \to H^{++}H^- \to \ell^+\ell^+\ell^-\nu, \ell^+\ell^+\tau^-\nu \qquad (\ell = e, \mu)$$

$$pp \to H^{++}H^{--} \to \ell^+\ell^+\ell^-\ell^-, \ell^+\ell^+\tau^-\tau^- \qquad (\ell = e, \mu)$$

4 Lepton (no τ final state)

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

SM Background if there exists same flavor, opposite sign dilepton

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

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

Trilepton (no τ final state)

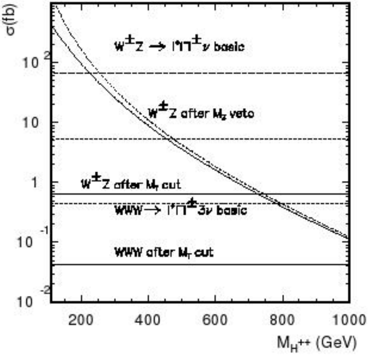
- $p_T(\ell_{\max}) > 30$ GeV and $p_T(\ell)_{\min} > 15$ GeV
- $|\eta(\ell)| < 2.5$
- $\Delta R_{\ell\ell} > 0.4$
- $\not{E}_T > 40$ GeV

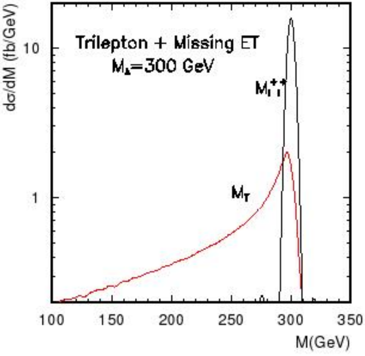
SM Background if there exists same flavor, opposite sign dilepton

$$W^{\pm}Z/\gamma^{*} \rightarrow \ell^{\pm}\nu\ell^{+}\ell^{-}, W^{\pm}W^{\pm}W^{\mp} \rightarrow \ell^{\pm}\ell^{+}\ell^{-} + \not{E}_T$$

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

Trilepton





$$M_T = \sqrt{(E_T^{\ell} + \not{E}_T)^2 - (\vec{p}^{\ell} + \not{\vec{p}})_T^2}$$

τ Final State

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

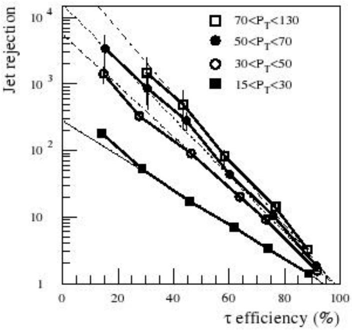


Figure 9-31 Jet rejection as a function of the τ efficiency, as obtained over the region $|\eta| < 2.5$ and in various p_T ranges. Straight-line fits are superimposed.

Atlas TDR

τ Leptonic decay

$$H^+ \to \tau\nu \to \ell + \not{E}_T$$

$$H^+ \to \ell + \not{E}_T$$

Lepton p_T

- ℓ from H^+ Jaccobian 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

τ Reconstruction

No other $\not{E}_T$ in final state:

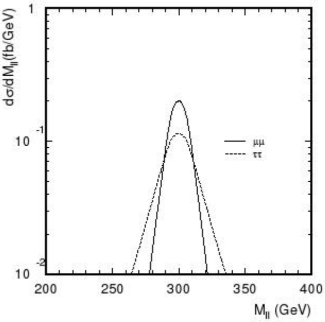
$$pp \to H^{++}H^{--} \to \ell^+\ell^+\tau^-\tau^-, \ell^+\ell^+\mu^-\tau^-, \ell^+\tau^+\tau^-\tau^-$$

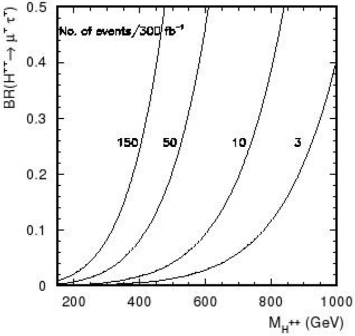
Highly Boosted τ

- $\vec{p}^{\text{ invisible}} = \kappa\vec{p}^{\ \ell}$; each τ corresponds to one unknown
- $\Sigma\vec{p}_T^{\text{ invisible}} = \vec{\not{p}}_T$ 2 independent equations
- $M_{\ell^+\ell^+} = M^{\text{rec}}_{\tau^-\tau^-}$; 1 more equation

UPTO THREE τs

$\mu\mu\tau\tau$ and $\mu\mu\mu\tau$





Measuring BR

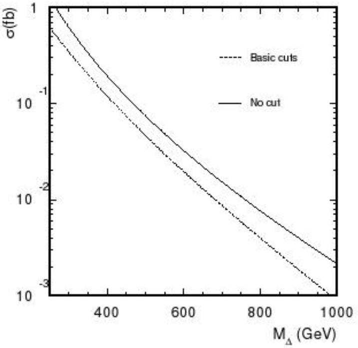
$$N_{4\mu} = \mathcal{L} \times \sigma(pp \to H^{++}H^{--}) \times \mathrm{BR}^2(H^{++} \to \mu^+\mu^+)$$

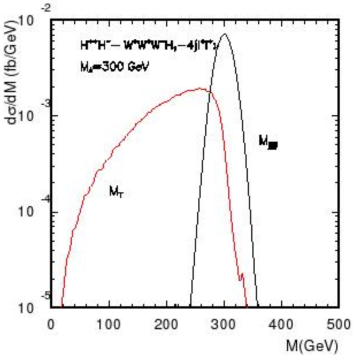
$$N_{3\mu\tau} = \mathcal{L}\times\sigma(pp \to H^{++}H^{--})\times\mathrm{BR}(H^{++} \to \mu^+\mu^+)\mathrm{BR}(H^{++} \to \mu^+\tau^+)$$

Large vev limit

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

$$pp \to H^{++}H^{-} \to W^{+}W^{+}W^{-}H_1/\bar{t}b/W^{-}Z \to jjb\bar{b}\ell^{+}\ell^{+}\not{E}_T$$

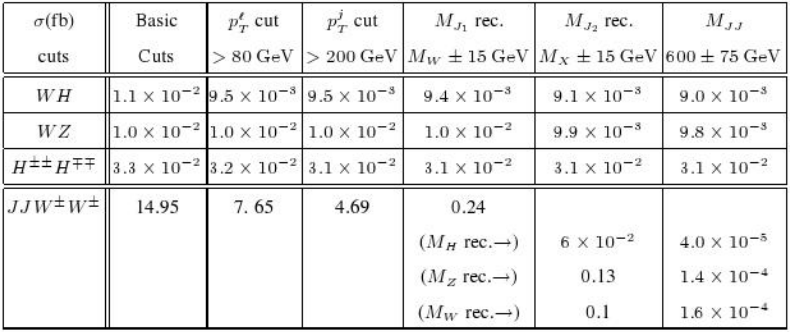




300 GeV-$jjjj\ell^+\ell^+\not{E}_T$

σ(fb)	Basic	p_T^ℓ cut	p_T^j cut	$M_{\rm Cluster}$	M_W rec.	M_X rec.	M_T	M_{jjjj}
cuts	Cuts	> 50 GeV	> 100 GeV	> 600 GeV	$M_W \pm 15$ GeV	or M_t veto	< 300 GeV	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 rec.→)	0.15	0.097	0.045
					(M_Z rec.→)	0.11	0.071	0.032
					(M_W rec.→)	0.096	0.06	0.026

600 GeV-$JJ\ell^+\ell^+\not{E}_T$



σ(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		
				(M_H rec.$\rightarrow$)	6×10^{-2}	4.0×10^{-5}
				(M_Z rec.$\rightarrow$)	0.13	1.4×10^{-4}
				(M_W rec.$\rightarrow$)	0.1	1.6×10^{-4}

Conclusion

- 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!