# Testing Origin of Neutrino Mass at the LHC

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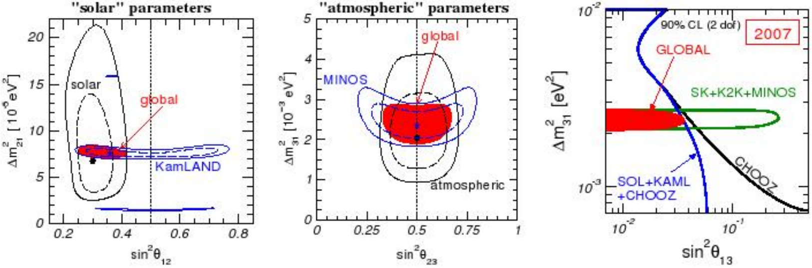
Tao Han, Biswarup Mukhopadhyaya, Zongguo Si and KW
Phys. Rev. D **76**, 075013 (2007) [arXiv:0706.0441 [hep-ph]]
Pavel Fileviez Pére, Tao Han, Guiyu Huang, Tong Li and KW
Phys. Rev. D **78**, 015018 (2008) [arXiv: 0805.3536 [hep-ph]]

# Neutrino Mass: 1st Evidence for Beyond SM




## Global Best Fit at $3\sigma$ level **Schwetz 07**

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

Something to keep in mind: Fermion mass

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

**Challenges:**

- $m_t/m_\nu \sim 10^{12}$
- $\sin^2\theta_{23}$
- 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 will break $U(1)_L$ and generate MAJORANA neutrino mass:

$$\ell\ell H_u H_u/M_{\mathrm{Pl}}; \qquad m_\nu \sim 10^{-5}\ \mathrm{eV}$$

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

**Broken Global Symmetry $U(1)_L$** Chikashige, Mohapatra, Peccei, 80

Majoron, Problem?

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

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

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

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

# Models

**Assumption: SM Higgs**

- 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.......

# Triplet Model (Type II seesaw)

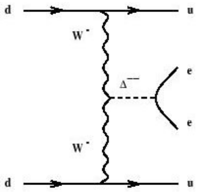
**$Y = 2$ $SU(2)_L$ Triplet, Majorana Neutrino Mass from**

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

$$y_\nu \ell_L^T C^{-1} i\sigma_2 \Delta \ell$$

$$H^{++}W_\mu^- W_\nu^- : i\sqrt{2}g_2^2 v_\Delta g_{\mu\nu} \quad ; H^{++} l_i^- l_j^- : C2\Gamma_{ij}^{++} P_L$$

# 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/Couplings

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

## VEV

$\rho$-parameter **Gunion, *et. al*, 1990**

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

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

Or another real triplet to cancel. **Georgi and Machacek, 1985**

# Triplet Model (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 $U(1)_{\mathrm{B-L}}$

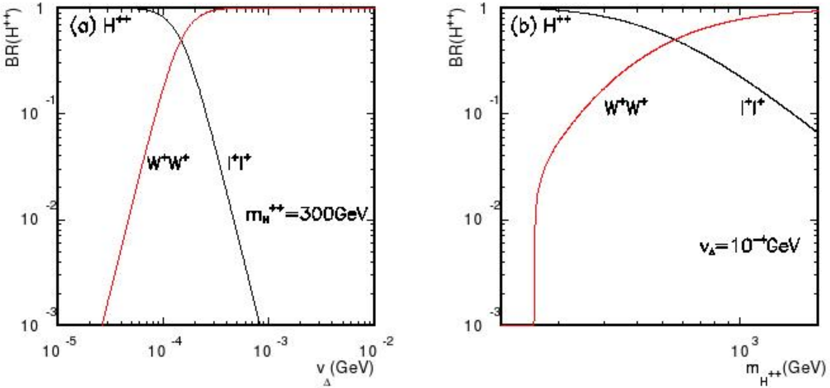
$$y_\nu \ell_L^T C^{-1} i\sigma_2 \Delta \ell + \mu H^T i\sigma_2 \Delta^\dagger H + h.c. + ....$$

$$v_\Delta = \mu \frac{v_0^2}{\sqrt{2} M_\Delta^2}$$

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

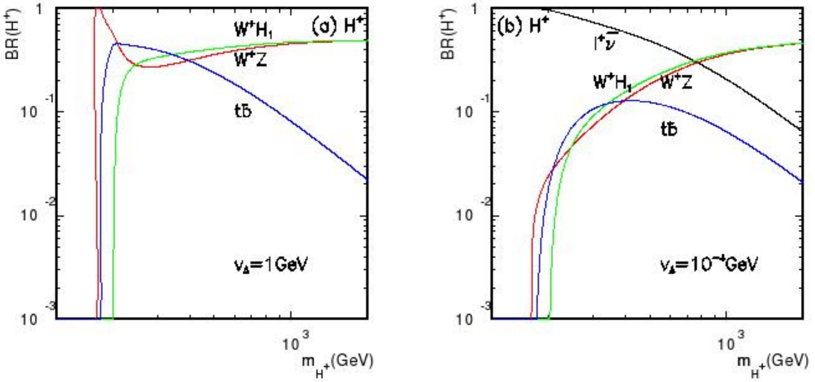
(No tree level mass difference among triplet Higgses. Otherwise $H^{++} \rightarrow H^+W^*, H^+ \rightarrow H_2 W^*$)

# $H^{++}$ Decay BR: $v'$ vs $y_\nu$




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

# $H^+$ Decay BR


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

# Neutrino and Triplet Leptonic Decay

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

No Majorana Phases

$\sin\theta_{23}$

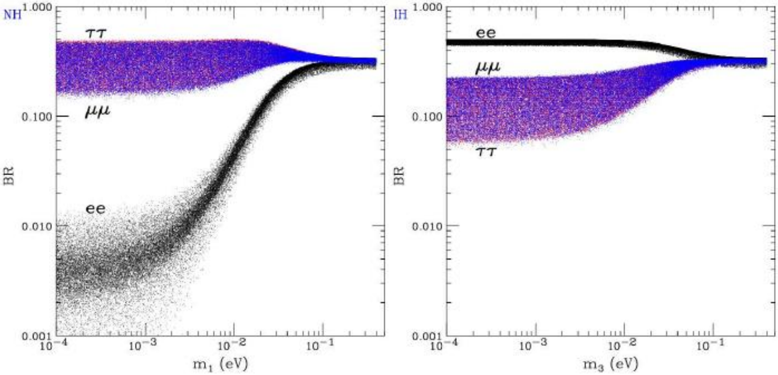
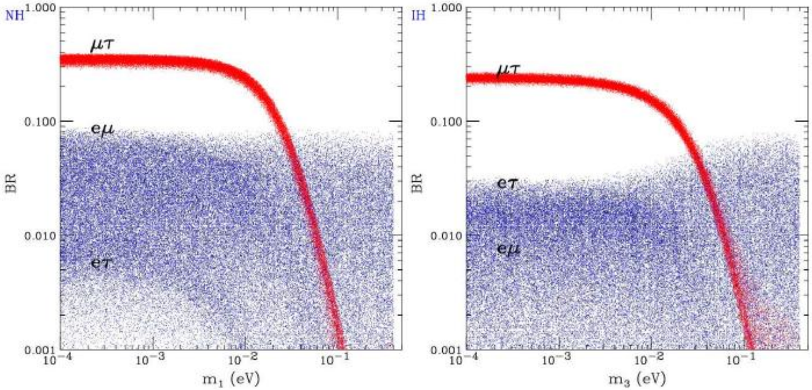
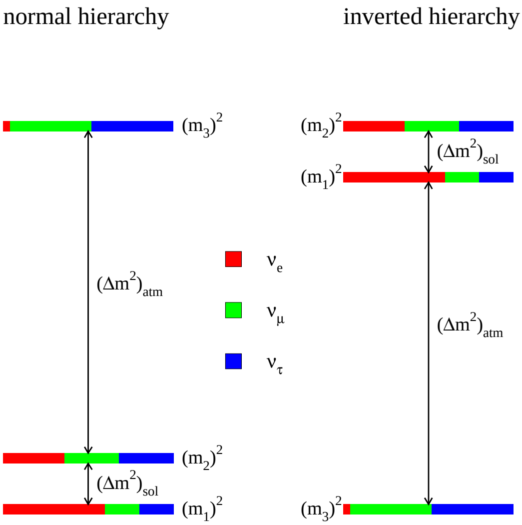



FIG. 12: $\mathrm{Br}(H^{++} \to e_i^+ e_i^+)$ vs. the lowest neutrino mass for NH (left) and IH (right) when $\Phi_1 = 0$ and $\Phi_2 = 0$.

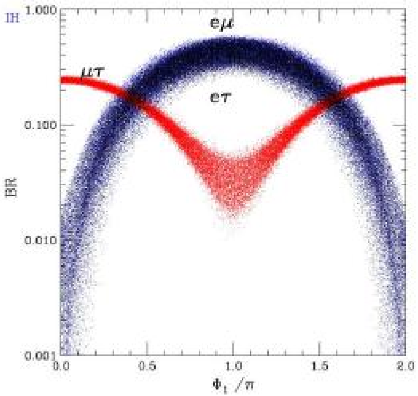
# Doubly Charged (continued)



# Neutrino Spectrum



# Majorana Phase




- Singly Charged Higgs BR is independent of Majorana phases.

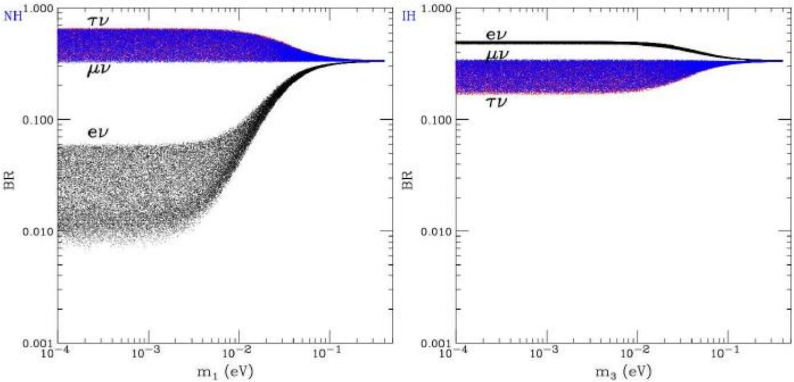
# Majorana Phase: a close look

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

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

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

# Singly Charged



# Decay length of $H^{++}$

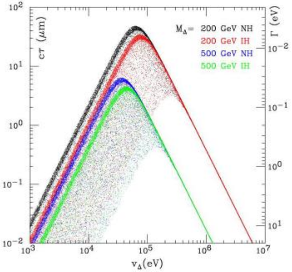



FIG. 14: Decay length and width of doubly charged Higgs ($\Phi_1 = 0$ and $\Phi_2 = 0$).

$v_\Delta \sim 10^{-4}$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

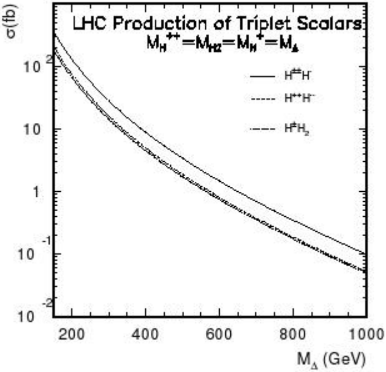
# Phenomenology

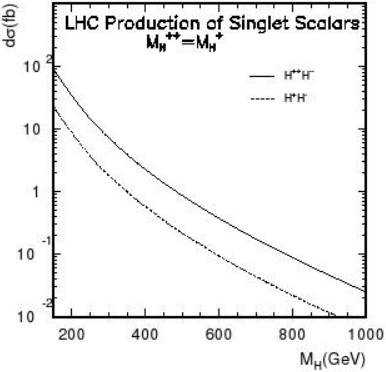
## Searching at the Large Hadron Collider

# Production of Triplet Higgses

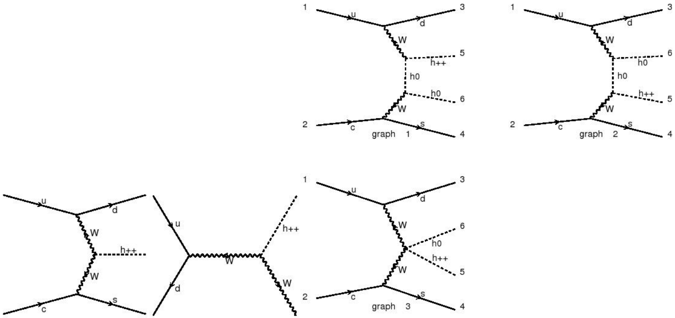
$$
\begin{aligned}
q(p_1) + \bar{q}(p_2) &\rightarrow H^{++}(k_1) + H^{--}(k_2) \\
q(p_1) + \bar{q}'(p_2) &\rightarrow H^{++}(k_1) + H^{-}(k_2) \\
q(p_1) + \bar{q}'(p_2) &\rightarrow H^{+}(k_1) + H_2(k_2)
\end{aligned}
$$

Tree Level Cross-section of Triplet Higgses Production



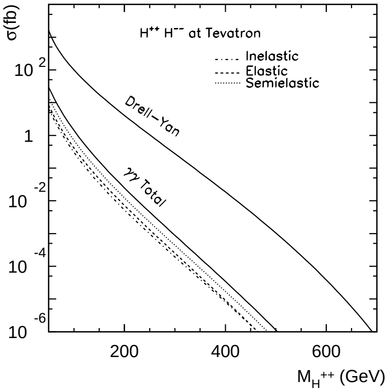
# Remarks on Production

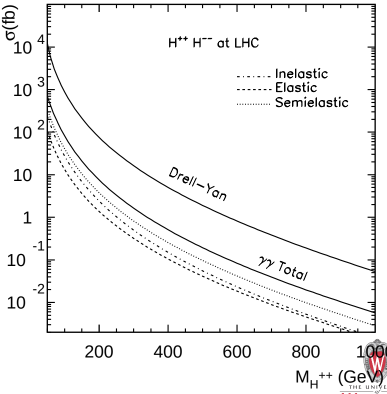



- triplet vev $v_\Delta$ suppresion
- phase space suppression
- Gauge cancellation among diagrams (Longitutinal W)

# Remarks on Production (continued)

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



# Photon-Photon

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

$$\begin{aligned}
\sigma_{\text{elastic}} &= \int_{\tau}^{1} dz_1 \int_{\tau/z_1}^{1} dz_2 f_{\gamma/p}(z_1) f_{\gamma/p'}(z_2)\sigma(\gamma\gamma \to H^{++}H^{--}) \\
\sigma_{\text{inelastic}} &= \int_{\tau}^{1} dx_1 \int_{\tau/x_1}^{1} dx_2 \int_{\tau/x_1/x_2}^{1} dz_1 \int_{\tau/x_1/x_2/z_1}^{1} \\
&\quad dz_2 f_q(x_1) f'_q(x_2) f_{\gamma/q}(z_1) f_{\gamma/q'}(z_2)\sigma(\gamma\gamma \to H^{++}H^{--}) \\
\sigma_{\text{semi-elastic}} &= \int_{\tau}^{1} dx_1 \int_{\tau/x_1}^{1} dz_1 \int_{\tau/x_1/z_1}^{1} dz_2 f_q(x_1) f_{\gamma/q}(z_1) f_{\gamma/p'}(z_2)\sigma(\gamma\gamma \to H^{++}H^{--})
\end{aligned}$$

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

**Drees, Godbole 94**

# Search via Leptonic Decays

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

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

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

- $\mu$,$e$ and $\tau$ respectively
- $H_2 \to \mathrm{invisible}$ and always produced via $H^\pm H_2$, another missing $\nu$ from $H^+$, impossible to reconstruct.

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

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

# 4 Lepton (no $\tau$ final state)

- $p_T(\ell_{\mathrm{max}}) > 30$ GeV and $p_T(\ell)_{\mathrm{min}} > 15$ 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 $\tau$ final state)

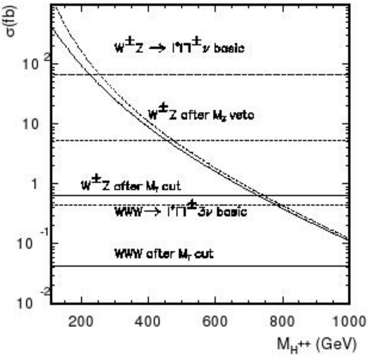
- $p_T(\ell_{\max}) > 30$ GeV and $p_T(\ell)_{\min} < 15$ GeV
- $|\eta(\ell)| < 2.5$
- $\Delta R_{\ell\ell} > 0.4$
- $\not{E}_T > 40$ GeV

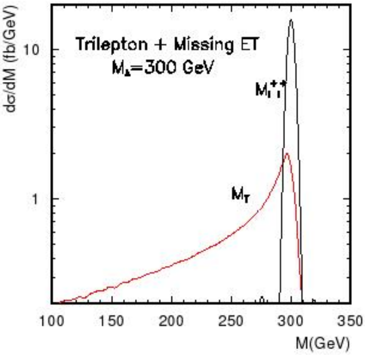
SM Background if there exists same flavor, opposite sign dilepton

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

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

# Trilepton




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

# $\tau$ Reconstruction

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

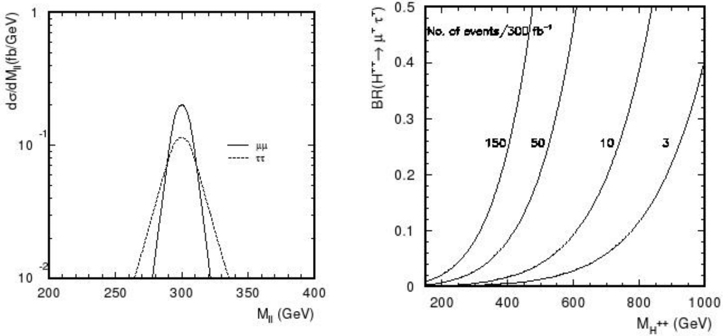
$$pp \to H^{++}H^{--} \to \ell^+\ell^+\tau^-\tau^-, \ell^+\ell^+\mu^-\tau^-, \ell^+\tau^+\tau^-\tau^-$$

## Highly Boosted $\tau$

- $\vec{p}^{\;\text{invisible}} = \kappa\vec{p}^{\;\ell}$; each $\tau$ 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 $\tau$s

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



# $\tau$ Identification

Very different from $\tau^{\pm}$ from Lepton Number Conserving $H^{\pm}$ decay.
$\tau^{\pm}$ behaves just like $\tau^{\pm}$ from SM $W^{\pm}$.

- $H^{-} \rightarrow \tau^{-}\nu$ ($W^{-} \rightarrow \tau^{-}\bar{\nu}_{\tau}$) : $\tau^{-}$ left-handed
- $H^{+} \rightarrow \tau^{+}\bar{\nu}$ ($W^{+} \rightarrow \tau^{+}\nu_{\tau}$): $\tau^{+}$ right-handed

$\tau_R^{+} \rightarrow \pi^{+}\bar{\nu}_{\tau}$
$\tau_L^{-} \rightarrow \pi^{-}\nu_{\tau}$ pions are soft.

# $\tau$ Leptonic decay

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

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

## Lepton $p_T$

- $\ell$ from $H^+$ Jaccobian Peak around $M_H/2$ (may change due to boost)
- $\ell$ from $\tau$, purely boost effect, softer

| $p_T^\ell$ selection (GeV) | 50 | 75 | 100 | 100 | 150 | 200 |
|---|---|---|---|---|---|---|
| $\ell$ misidentification rate | 2.9% | 9.4% | 17.6% | 4.6% | 12.4% | 22.2% |
| $\tau$ survival probability | 57.0% | 69.8% | 78.8% | 62.8% | 75.7% | 83.7% |

$\tau$ selection:

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

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

# Measuring BR

knowns: $N$, $\mathcal{L}$ (Integrate luminosity)
indirect: reconstructed $M_\Delta \to \sigma(H^{++}H^{--})$

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

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

# Once the BRs are measured,...

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

Even the Phase.

# Conclusion

- We propose one scenario that the Triplet models for neutrino mass generation can be directly tested at the LHC.
- It predicts 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!