Testing Origin of Neutrino Mass at the LHC

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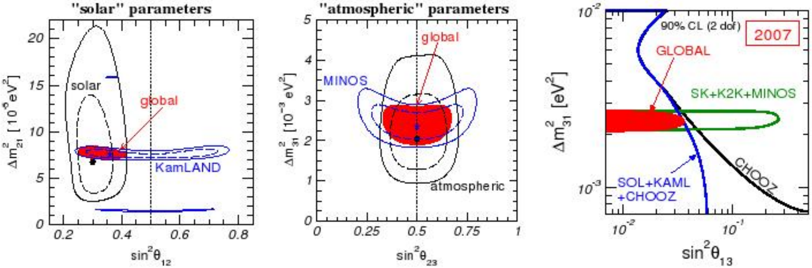
Neutrino Mass: 1$^{\rm st}$ Evidence Beyond SM



Global Fit at 2σ level Schwetz 07

$$7.3\times 10^{-5}\mathrm{eV}^2 < \Delta m^2_{21} < 8.1\times 10^{-5}\mathrm{eV}^2;$$
$$2.1\times 10^{-3}\mathrm{eV}^2 < |\Delta m^2_{31}| < 2.7\times 10^{-3}\mathrm{eV}^2$$
$$0.28 < \sin^2\theta_{12} < 0.37;\ 0.38 < \sin^2\theta_{23} < 0.63;\ \sin^2\theta_{13} < 0.033$$
$$\sum_i m_i < 1.2\ \mathrm{eV}$$

Theoretical Models

- Type I seesaw $y_D \ell \nu^c H_u + M_R \nu^c \nu^c$, $\Delta L = 2$
  $M_R \sim 10^{14-15}\mathrm{GeV}$, $m_\nu \sim M_D^2/M_R \approx 1\mathrm{eV}$

  Yanagida 79; Gell-Man *et al.* **79; Glashow 80; Mohapatra,Senjanovic 80**
- Type II seesaw $y_\nu \ell^T i\sigma_2 \Delta \ell$, $\Delta L = 2$
  $M_\Delta \sim 10^{14-15}\mathrm{GeV}, m_\nu = y_\nu v' \sim 10^{-10}\mathrm{GeV}$

  Cheng,Li 80; Mohapatra,Senjanovic 80; Shafi *et al.* **81**
- Zee-Babu model, generates neutrino mass at two-loop $\Delta L = 2$
- Type III seesaw, etc.......

Type II seesaw

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

$$\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}$$

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

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

$$v_\Delta = \frac{\mu v_0^2}{\sqrt{2} M_\Delta^2}, M_\nu \sim \sqrt{2} v_\Delta y_\nu$$

Bounds on Triplet Higgs

Masses

- LNV Direct Test $0\nu\beta\beta$:
  $\frac{y_\nu v_\Delta}{M_\Delta^2} \leq 5 \times 10^{-8}\ \mathrm{GeV}^{-1}$, $M_\Delta > 0.1\ \mathrm{GeV}$
- CDF/DØ Search bound: $m_{H^{++}} > 120\ \mathrm{GeV}$

VEV

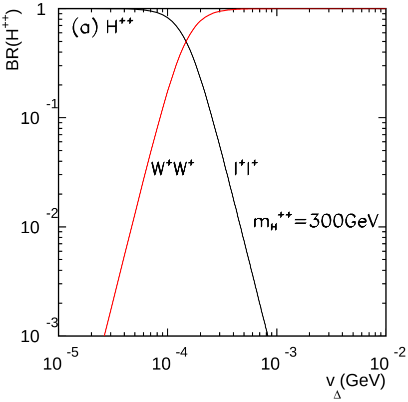
- ρ-parameter **Gunion, *et. al* 90;Chen, Dawson 02**

$$\rho = (m_W/(m_Z \cos\theta_W))^2; \quad v_\Delta \lesssim 1\ \mathrm{GeV}$$

- Lepton Flavor Violation $\mathrm{Br}(\mu \to e^- e^+ e^+) < 10^{-12}$

$$v_\Delta^2 > 0.2 \times 10^5 |M_\nu^{11} M_\nu^{12}| \times \left(\frac{1\ \mathrm{TeV}}{M_\Delta}\right)^2, v_\Delta \gtrsim 10\ \mathrm{eV}$$

H^{++} Decay BR: y_ν vs v_Δ



$$M_\nu \sim \sqrt{2} v_\Delta y_\nu, \quad \frac{\Gamma(\ell\ell)}{\Gamma(WW)} \approx \left(\frac{M_\nu}{M_\Delta}\right)^2 \left(\frac{v_0}{v_\Delta}\right)^4$$

Distinguish Neutrino Spectrum in Triplet LNV Decay

Taking into account the experimental constraints on the neutrino masses and mixing but no Majorana phases

Normal Hierarchy(NH): $\Delta m^2_{31} > 0$

Inverted Hierarchy(IH): $\Delta m^2_{31} < 0$

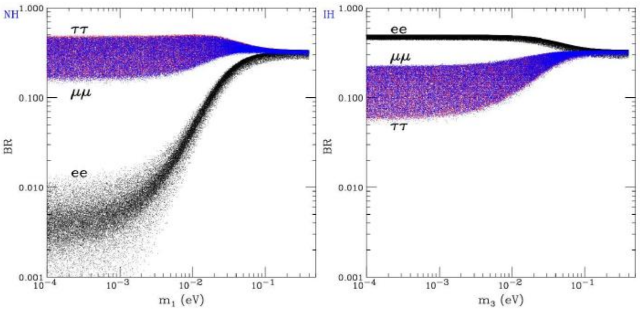
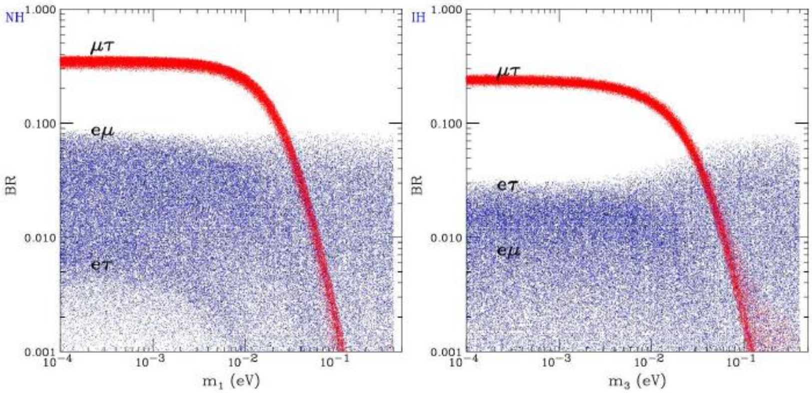


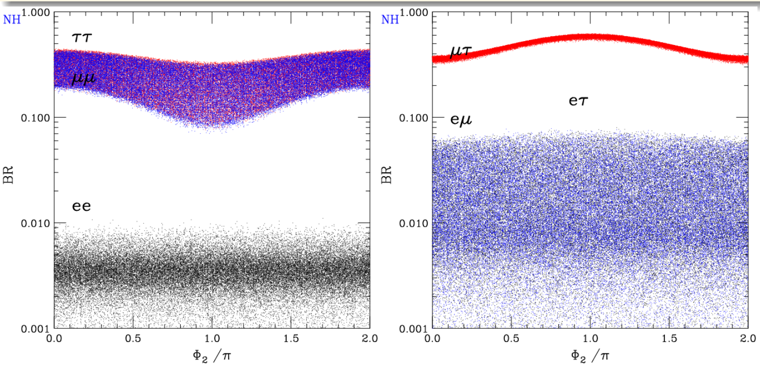
FIG. 12: $\mathrm{Br}(H^{++} \to e_i^+ e_i^+)$ vs. the lowest neutrino mass for NH (left) and IH (right) when $\Phi_1 = 0$ and $\Phi_2 = 0$.

Doubly Charged (continued)

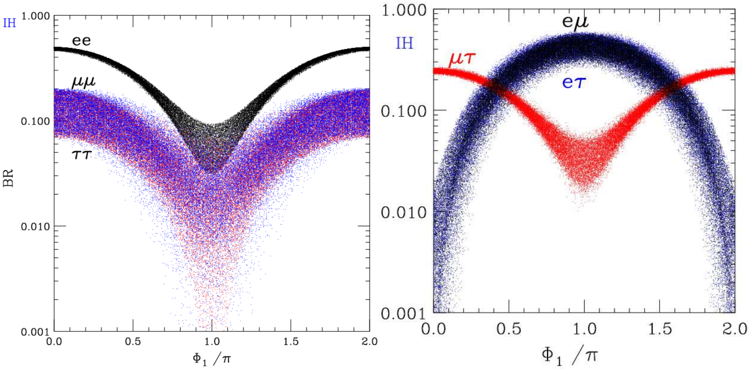


Impact of Majorana Phases in Triplet LNV Decay

The decay of $H^{\pm\pm}$ is only dependent of Majorana phase Φ_2 or Φ_1, in NH or IH case respectively.

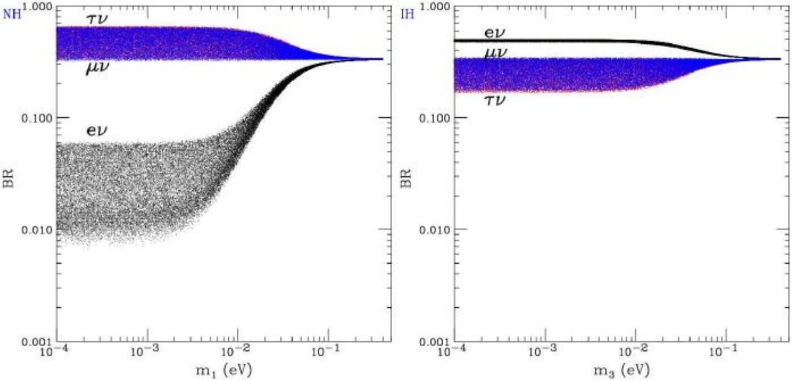


Impact of Majorana Phases (continued)



Singly Charged

The decay of $H^{\pm}$ is independent of Majorana phases.



Leading Leptonic Channels

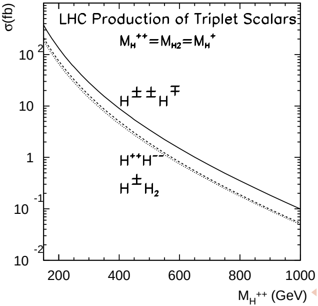
Channels	Modes and BR's Normal Hierarchy	Modes and BR's Inverted Hierarchy
$H^{++}H^{--}$		
$\Phi_1, \Phi_2 = 0$	$\mu^+\mu^+\mu^-\mu^-$ $(40\%)^2$ $\mu^+\mu^+\mu^-\tau^-$ $40\% \times 35\%$ $\mu^+\mu^+\tau^-\tau^-$ $(40\%)^2$ $\mu^+\tau^+\mu^-\tau^-$ $(35\%)^2$ $\mu^+\tau^+\tau^-\tau^-$ $35\% \times 40\%$	$e^+e^+e^-e^-$ $(50\%)^2$ $e^+e^+\mu^-\tau^-$ $50\% \times 25\%$ $\mu^+\tau^+\mu^-\tau^-$ $(25\%)^2$
$\Phi_1 \approx \pi$	same as above	$ee, \mu\tau \to e\mu, e\tau$ $(50\%)^2$
$\Phi_2 \approx \pi$	$\mu\mu, \tau\tau : \times 1/2,\ \mu\tau : \times 2$	same as above
$H^{\pm\pm}H^{\mp}$		
$\Phi_1, \Phi_2 = 0$	$\mu^+\mu^+\mu^-\nu$ $40\% \times 60\%$ $\mu^+\mu^+\tau^-\nu$ $40\% \times 60\%$	$e^+e^+e^-\nu$ $(50\%)^2$
$\Phi_1 \approx \pi$	same as above	$ee \to e\mu, e\tau$ $60\% \times 50\%$
$\Phi_2 \approx \pi$	$\mu\mu : \times 1/2$	same as above

LHC Phenomenology

Production of Triplet Higgses

Tree Level Cross-section of Triplet Higgses Production

$$
\begin{aligned}
q + \bar{q} &\rightarrow H^{++} + H^{--} \\
q + \bar{q}' &\rightarrow H^{\pm\pm} + H^{\mp} \\
q + \bar{q}' &\rightarrow H^{\pm} + H_2
\end{aligned}
$$



Search via Leptonic Decays

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

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

$$\begin{aligned} pp \to H^{++}H^{--} \quad \to \quad & \ell^{+}\ell^{+}\ell^{-}\ell^{-}, \ell^{+}\ell^{+}\ell^{-}\tau^{-}, \ell^{+}\ell^{+}\tau^{-}\tau^{-}, \\ & \ell^{+}\tau^{+}\ell^{-}\tau^{-}, \ell^{+}\tau^{+}\tau^{-}\tau^{-} \ (\ell = e, \mu) \end{aligned}$$

- μ,e and τ respectively
- $H_2 \to$ invisible and always produced via $H^{\pm}H_2$, another missing ν from $H^{\pm}$, impossible to reconstruct.

$\ell^+\ell^+\ell^-\ell^-$ Han,Mukhopadhyaya,Si,Wang 07

Basic Cuts

- $p_T(\ell_{\max}) > 30$ 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

$\ell^\pm \ell^\pm \ell^\mp \nu$ $(\ell = e, \mu)$

Basic Cuts

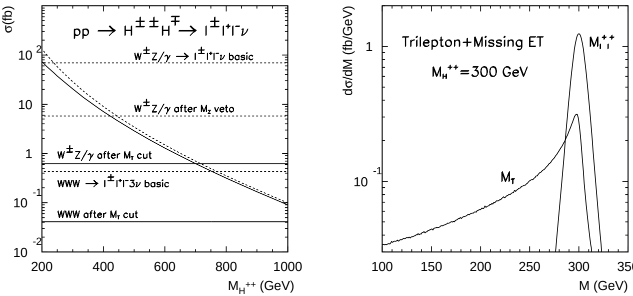
- $p_T(\ell_{\max}) > 30$ GeV and $p_T(\ell_{\min}) > 15$ GeV
- $|\eta(\ell)| < 2.5$
- $\Delta R_{\ell\ell} > 0.4$
- $\not{E}_T > 40$ GeV

SM Background

if there exists same flavor, opposite sign dilepton

$$W^\pm Z/\gamma^* \to \ell^\pm \nu \ell^+ \ell^- \sim 100\ \mathrm{fb},\ W^\pm W^\pm W^\mp \to \ell^\pm \ell^+ \ell^- + \not{E}_T \sim 1\ \mathrm{fb}$$

$\ell^\pm \ell^\pm \ell^\mp \nu$ (continued)



Cuts and Mass reconstruction

- Veto events of $|M_{\ell^+\ell^-} - M_Z| > 15$ GeV
- $M_T = \sqrt{(E_T^\ell + \not{E}_T)^2 - (\vec{p}_T^\ell + \not{p}_T)^2} > 200$ GeV
- $M_{\ell^\pm \ell^\pm}$

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%

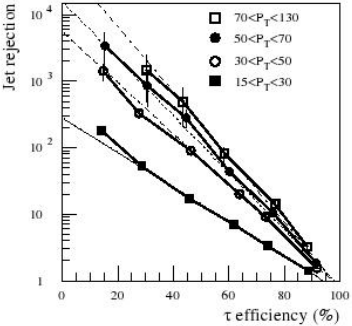


Figure 9-31 Jet rejection as a function of the τ efficiency, as obtained over the region |η| < 2.5 and in various p_T ranges. Straight-line fits are superimposed.

Atlas TDR

$\ell^\pm \ell^\pm \tau^\mp \nu$

τ Leptonic decay: $H^\pm \to \tau^\pm \nu \to \ell^\pm + \not{E}_T$

- ℓ from H^+ Jaccobian Peak around $M_H/2$
- 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:

$$p_T < 100 \text{ GeV for } M_{H^+} = 300 \text{ GeV}$$

$$p_T < 200 \text{ GeV for } M_{H^+} = 600 \text{ GeV}$$

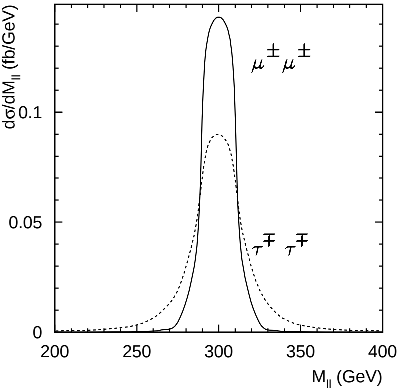
$\ell^+\ell^+\ell^-\tau^-, \ell^+\ell^+\tau^-\tau^-, \ell^+\tau^+\ell^-\tau^-, \ell^+\tau^+\tau^-\tau^-$

Highly Boosted τ

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

UPTO THREE τs

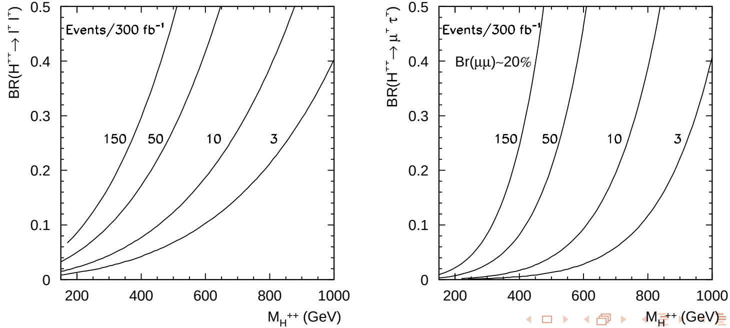
Reconstruction Example: $\mu\mu\tau\tau$



Measuring BR

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

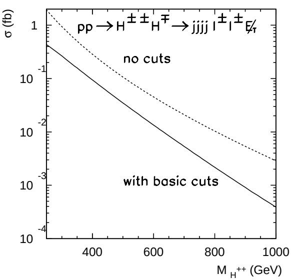
$$N_{3\mu\tau} = \mathcal{L}\times\sigma(pp \to H^{++}H^{--})\times\mathrm{BR}(H^{++} \to \mu^+\mu^+)\mathrm{BR}(H^{++} \to \mu^+\tau^+)$$

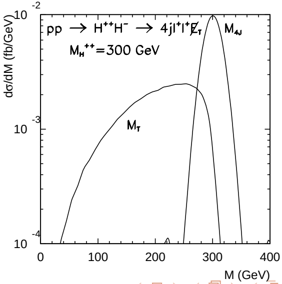


Gauge Bosonic Channels

Large vev limit 10^{-4} GeV $\ll v_\Delta \lesssim 1$ GeV

- 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
- $H^{\pm\pm} H^{\mp} \to W^{\pm} W^{\pm} + W^{\mp} H_1 / \bar{t} b (t \bar{b}) / W^{\mp} Z \to 4j 2\ell^{\pm} \not{E}_T$





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

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

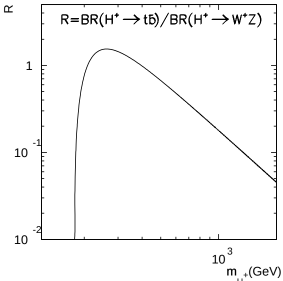
600 GeV-$JJ\ell^+\ell^+\not{E}_T$

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}

Extract μ parameter

$$\Gamma(H^+ \to W^+ H_1) \sim \frac{\mu^2}{M_{H^+}}, \quad \Gamma(H^+ \to t\bar{b}) \sim \frac{\mu^2 m_t^2}{M_{H^+}^3},$$

$$\Gamma(H^+ \to W^+ Z) \sim \left(g_1^2 \, \frac{\mu v_0^2}{M_\Delta^2} - \sqrt{2}(2g_1^2 \; + \; g_2^2) \; v_\Delta \right)^2 \; \frac{M_{H^+}^3}{v_0^4}$$



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!