

**Probing B/L Violations in Extended Scalar Models
at the CERN LHC**
A Bottom-up Approach

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W Klemm, V. Rentala, Z. Si and KW, in preparation
C. Chen, W. Klemm, V. Rentala and KW; Phys. Rev. D **79**, 054002 (2009)
P. Fileviez Perez, T. Han, G. Huang, T. Li and KW; Phys. Rev. D **78**, 015018 (2008)

- Testing global symmetries $U(1)_B, U(1)_L$ in the SM: proton decay, $n - \bar{n}$ oscillation, $(\beta\beta)_{0\nu}$...how about LHC?
- \cancel{B}, \cancel{L} but not simultaneous breaking (no proton decay, $\Delta B = 2$ or $\Delta L = 2$)
- Exotic signals with large production rate at the LHC, little SM background, easy to identify
- Possible connection with neutrino mass generation
- Probing extended gauge symmetry group
- may need to tune the parameter spaces to be accessible at the LHC (conventional models relevant to 10^{11} GeV physics...) but not necessarily unnatural with soft breaking of symmetry (when the dimensional one parameter vanishes, the symmetry is restored.)



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Outline

- Signatures@LHC
 - Color Sextet Scalar decaying to same-sign diquark
 - Doubly Charged Higgs decaying to same-sign dilepton
- How to accommodate the signatures in theoretical models
 - Pati-Salam Model
 - Type-II seesaw Model/Zee-Babu Model for neutrino mass generation
- Summary



Multijet+Same Sign Dilepton+ \cancel{E}_T

SM contributes to enormous background as multijet, jets+ W^\pm , jets+ Z , $t\bar{t}$,
One of the most striking signals for BSM physics search at the LHC.

Same-sign Dilepton as handle

Irreducible SM background

- $t\bar{t}W^\pm$ $\mathcal{O}(10)$ fb
- jets+ $W^\pm W^\pm$ $\mathcal{O}(10)$ fb

New Physics with large production \mathcal{O} pb

- SUSY: gluino, same-sign squark pair (gluino in t-channel) $n_j \chi_1^\pm \chi_1^\pm$
- ED: KK-gluon $g'g' \rightarrow n_j W'^\pm W'^\pm$
- 4-th generation: $b'\bar{b}' \rightarrow t\bar{t}W^+W^- \rightarrow n_j W^\pm W^\pm$
- Color Octet: $88 \rightarrow t\bar{t}t\bar{t} \rightarrow n_j W^\pm W^\pm$

What else?

our example: the same final with different reconstruction at comparable rate



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$U(1)$ symmetries

$$A_{[SU(3)_C]^2 \times U(1)} = \frac{N_g}{2} (2q + u + d) = 0$$

$$A_{[SU(2)_L]^2 \times U(1)} = \frac{N_g}{2} (3q + \ell) = 0$$

$$\text{Tr}U(1) = N_g (6q + 3u + 3d + 2\ell + e) = 0$$

$$A_{[U(1)]^3} = N_g (6q^3 + 3u^3 + 3d^3 + 2\ell^3 + e^3) = 0$$

$$A_{[U(1)_Y]^2 \times U(1)} ; A_{[U(1)]^2 \times U(1)_Y} = 0$$

$$\text{Yukawa} : q + u + h = 0, q + d - h = 0, \ell + e - h = 0$$

- No extra Unbroken $U(1)$ Gauge Symmetry except $U(1)_Y$
- Hypercharge normalization from new physics GUTs/partial unification/...
- Flavor brings extra degrees of freedom $L_e - L_\mu$
- $B - L$ can be gauged by one extra singlet N_R
- $B + L$ (fermion number in SM): $[SU(2)_L]^2 \times U(1)$ anomaly



B/L Violations

SM gauge invariant non-renormalizable operators:

- $\Delta B = 1, \Delta L = 1$: proton decay
- $\Delta B = 2, \Delta L = 2$: neutrino mass, $n - \bar{n}$ oscillations
- $\Delta B = 3, \Delta L = 3$: highly suppressed, instanton violation

Collider-Testable B/L Violations in BSM:

- R -parity violation in SUSY
Suppressed coupling
- Majorana neutrino at the LHC see T. Han and B. Zhang, 2005; Z. Si and KW, 2009
tuning dimensionless Yukawa coupling; tiny Mixing \rightarrow highly suppressed production (require W_R, Z_{B-L} to enhance production, see Bruce's talk)
- $\overline{\psi}_f^c \psi_f \phi$ in extended scalar models ($\overline{\psi}_f \psi_f \phi$ always $\propto m_f$)
may need to tune dimension-1 parameter (can be considered as soft breaking)
Gauge interaction production with only Resonance B/L Decay



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Bottom-up setup

Color Sextet Scalars under $SU(3)_C \times SU(2)_L \times U(1)_Y$:

- $SU(2)_L$ adjoint $\Delta_6 : (6, 3, 1/3)$
- $SU(2)_L$ singlet $\Phi_6 : (6, 1, 4/3)$, $\phi_6 : (6, 1, -2/3)$,
 $\delta_6 : (6, 1, +1/3)$

Scalar QCD

$$\begin{aligned} & \text{Tr}[(D_\mu \Delta_6)^\dagger (D^\mu \Delta_6)] - M_\Delta^2 \text{Tr}[\Delta_6^\dagger \Delta_6] + f_\Delta Q_L^T C^{-1} \tau_2 \Delta_6^\dagger Q_L \\ & + (D_\mu \Phi_6)^\dagger (D^\mu \Phi_6) - M_\Phi^2 \Phi_6^\dagger \Phi_6 + f_\Phi u_R^T C^{-1} u_R \Phi_6^\dagger \\ & + (D_\mu \phi_6)^\dagger (D^\mu \phi_6) - M_\phi^2 \phi_6^\dagger \phi_6 + f_\phi d_R^T C^{-1} d_R \phi_6^\dagger \\ & + (D_\mu \delta_6)^\dagger (D^\mu \delta_6) - M_{\delta_6}^2 \delta_6^\dagger \delta_6 + f_\delta d_R^T C^{-1} u_R \delta_6^\dagger + V \end{aligned}$$

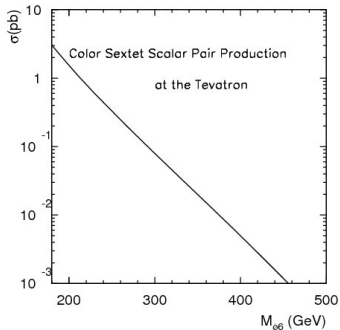
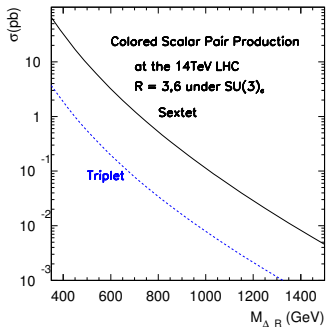
$$D_\mu = \partial_\mu - ig_s G_\mu^a T_r^a$$



QCD Production of Color Sextet Scalar Pair

$$g(p_1) + g(p_2) \rightarrow \bar{\Phi}_6(k_1) + \Phi_6(k_2) \rightarrow \bar{t}t\bar{t}t$$

$$q(p_1) + \bar{q}(p_2) \rightarrow \bar{\Phi}_6(k_1) + \Phi_6(k_2) \rightarrow \bar{t}t\bar{t}t$$



Production of $\bar{\Phi}_6\Phi_6$ at the LHC and Tevatron $\mu_F = \mu_R = \sqrt{\hat{s}}/2$, CTEQ6L

$$\sigma(q\bar{q} \rightarrow \bar{\Phi}_6\Phi_6) = \pi C(3)C(R) \frac{d_8}{d_3^2} \frac{\alpha_s^2}{3s} \beta^3 = \frac{10\pi}{27s} \alpha_s^2 \beta^3$$

$$\begin{aligned} \sigma(gg \rightarrow \bar{\Phi}_6\Phi_6) &= d_R C_2(R) \pi \frac{\alpha_s^2}{6s} \frac{1}{d_8^2} [3\beta(3 - 5\beta^2) - 12C_2(R)\beta(\beta^2 - 2)] \\ &+ \ln\left|\frac{\beta+1}{\beta-1}\right| [(6C_2(R)(\beta^4 - 1) - 9(\beta^2 - 1)^2)] \\ &= \frac{5\pi}{96s} \alpha_s^2 [\beta(89 - 55\beta^2) + \ln\left|\frac{\beta+1}{\beta-1}\right| (11\beta^4 + 18\beta^2 - 29)] \end{aligned}$$

where \sqrt{s} is the total energy, $\beta = \sqrt{1 - 4M_{\Phi_6}^2/s}$ and R is 6 with the normalization factor C and Casimir C_2 as

d_R	3	6	8
$C(R)$	1/2	5/2	3
$C_2(R)$	4/3	10/3	3

Table: Normalization factor $C(R)$ and quadratic Casimir $C_2(R)$ for $d_R = 3, 6, 8$ under $SU(3)$.



Remarks

- $qq \rightarrow \Phi_6$ from f_{11} or f_{22} (valence u quark, LHC is a pp machine)
- $\overline{\psi^c}\psi\phi$, the coupling f_{ij} irrelevant to fermion masses
- tree level $D^0 - \overline{D^0}$ mixing from $f_{11}f_{22}$, maybe dominant decaying into top
- GIM violation. But only coupling to righthanded states.
-

$$3 \otimes 3 = 6 \oplus \overline{3}$$

Squark pair production with R -parity violation decay?
only $u^c d^c d^c$

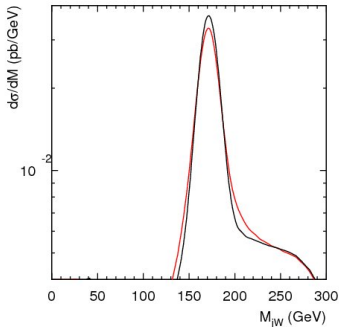
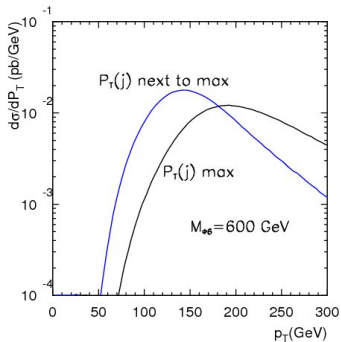
- Sextet Quarks in ETC

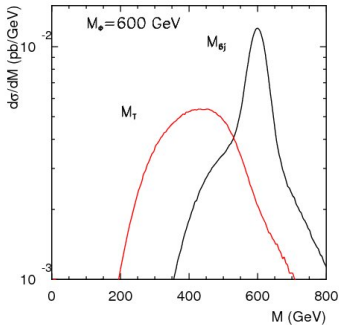
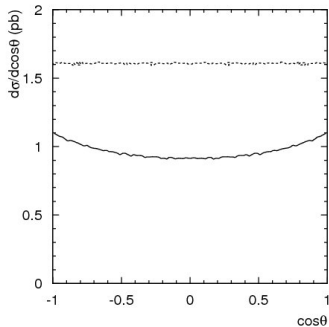


Same Sign Top

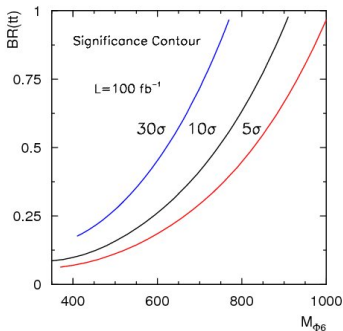
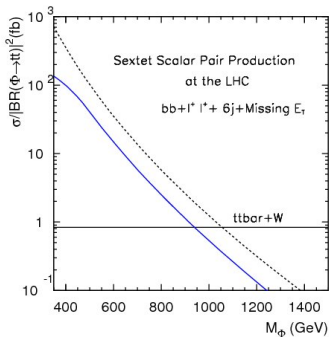
$$pp \rightarrow \bar{\Phi}_6 \Phi_6 \rightarrow t\bar{t}t\bar{t} \rightarrow 4b + \ell^\pm \ell^\pm + \cancel{E}_T + Nj,$$

(No radiation included)





Reconstructed two hadronic Top shows the scalar feature.
Multijet resonance



(background included irreducible only, leading background: $tt\bar{t}W^\pm$)

Lepton Number Violation

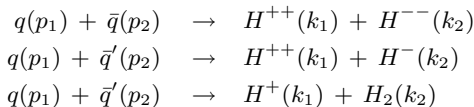
under $SU(3)_C \times SU(2)_L \times U(1)_Y$:

- $SU(2)_L$ adjoint $\Delta : (1, 3, 1)$
- $SU(2)_L$ singlet $\phi^{--} : (1, 1, -2)$

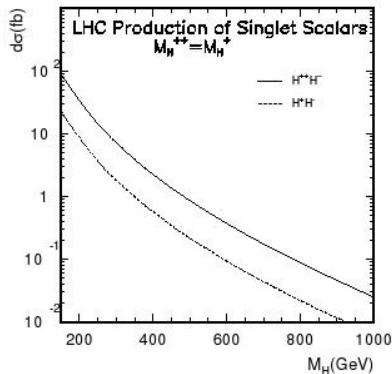
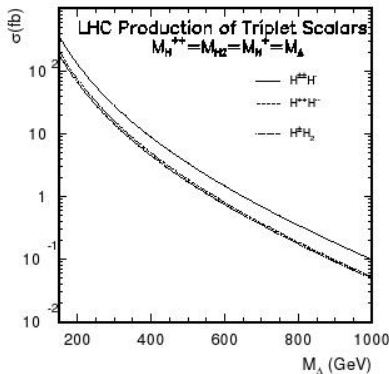
$$\begin{aligned} & \text{Tr}[(D_\mu \Delta)^\dagger (D^\mu \Delta)] - M_\Delta^2 \text{Tr}[\Delta^\dagger \Delta] + y_\nu \ell_L^T C^{-1} \tau_2 \Delta^\dagger \ell_L \\ + & (D_\mu \phi)^\dagger (D^\mu \phi) - M_\Phi^2 \phi^\dagger \phi + y e_R^T C^{-1} e_R \phi^{++} + V \end{aligned}$$



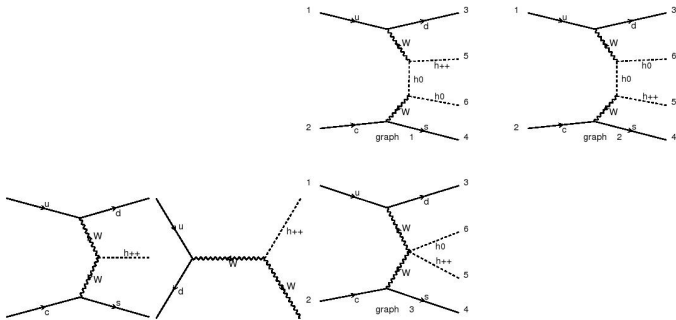
Production of Triplet Higgses



Tree Level Cross-section of Triplet Higgses Production



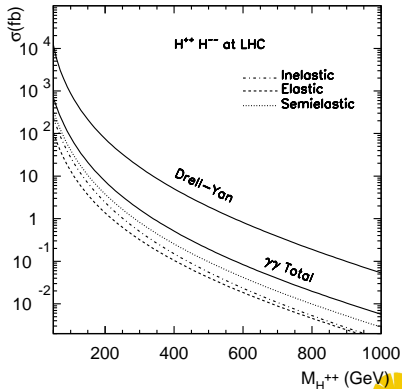
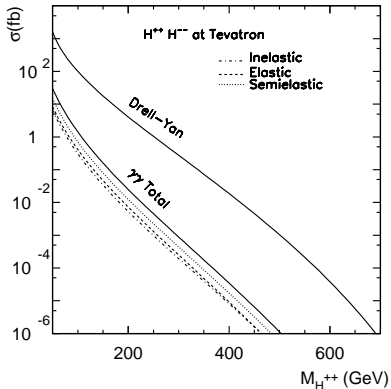
Remarks on Production



- 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% Muhleitner and Spira, 03
- real photon emission ($\gamma\gamma \rightarrow H^{++}H^{--}$) 10%



Photon-Photon

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

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

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

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

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

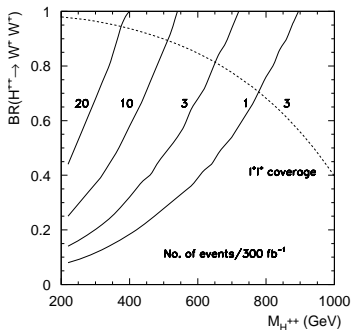
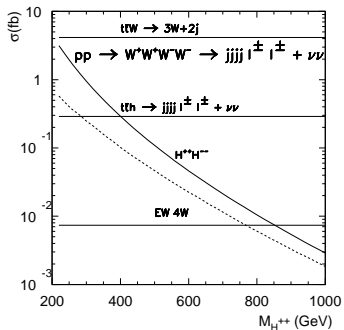
Drees, Godbole 94



Another Example for Multijet + $l^\pm l^\pm + \cancel{E}_T$

$$H^{++} \rightarrow W^+W^+ : \propto v_\Delta$$

$$pp \rightarrow H^{++}H^{--} \rightarrow W^+W^+W^-W^- \rightarrow l^\pm l^\pm + \cancel{E}_T + 4j$$



M_H : boosted hadronic W , W -jet



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

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

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



SM background

- Four Lepton (no τ final state)
SM Background if there exists same flavor, opposite sign dilepton

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

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

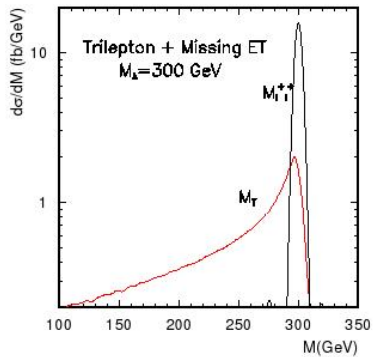
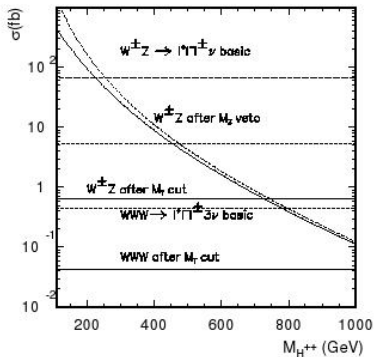
- Trilepton (no τ final state)
SM Background if there exists same flavor, opposite sign dilepton

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

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



Trilepton



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



τ Leptonic decay

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

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

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:

$$p_T < 100 \text{ GeV (for } M_H^+ = 300 \text{ GeV)}$$

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



τ Reconstruction

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

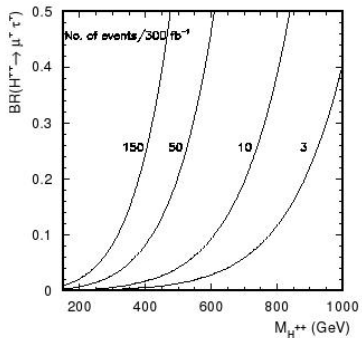
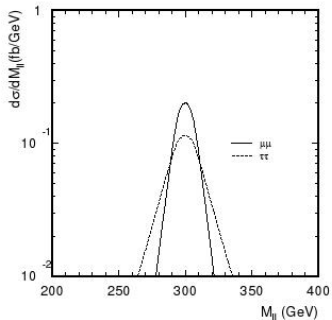
$$pp \rightarrow H^{++} H^{--} \rightarrow \ell^+ \ell^+ \tau^- \tau^-, \ell^+ \ell^+ \mu^- \tau^-, \ell^+ \tau^+ \tau^- \tau^-$$

Highly Boosted τ

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

UPTO THREE τ S

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



Examples of Theory Realization

Pati-Salam Model to Left-Right Model

$$SU(2)_L \times SU(2)_R \times SU(4)_C \rightarrow SU(2)_L \times SU(2)_R \times U(1)_{B-L} \times SU(3)_C$$

$$(3, 1, 10) : \{(\mathbf{3}, \mathbf{1}, -2, \mathbf{1}) \oplus (\mathbf{3}, \mathbf{1}, -2/3, \mathbf{3}) \oplus (\mathbf{3}, \mathbf{1}, 2/3, \mathbf{6})\} + L \leftrightarrow R$$

- $\Delta B = 2$ $n - \bar{n}$ neutron anti-neutron oscillation
- why light? Pati-Salam (Chacko-Mohapatra, 99), Post-Sphelaron Baryogenesis and still consistent with $n - \bar{n}$ constraints
- Neutrino mass:

$$\Delta(\mathbf{3}, \mathbf{1}, -2, \mathbf{1}) : \ell^T C^{-1} i\tau_2 \Delta^\dagger \ell$$



Neutrino Mass and LNV

- $SU(2)_L$ singlet: Zee-Babu Model (two-loop neutrino mass)
- $SU(2)_L$ Triplet: Type-II seesaw

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

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

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

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

If y_ν is of $\mathcal{O}(0.01)$, $\mu \sim 1\text{keV}$. $\lim \mu \rightarrow 0$, $U(1)_L$ or $U(1)_{B-L}$ is restored. can be naturally small. ρ -parameter prefers small μ . (Gunion et al, 90)



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

$\sin \theta_{23}$

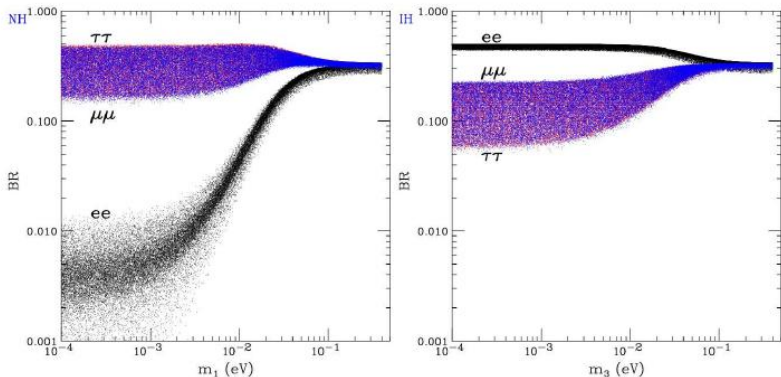
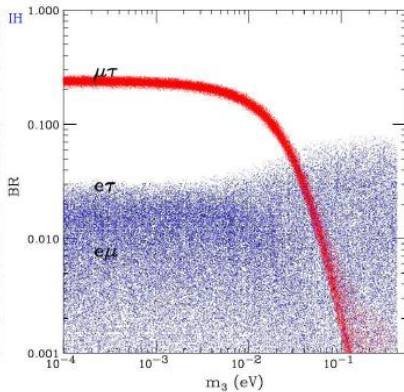
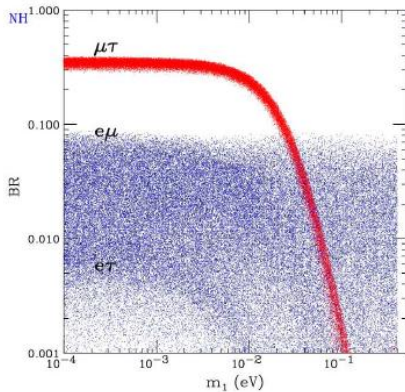


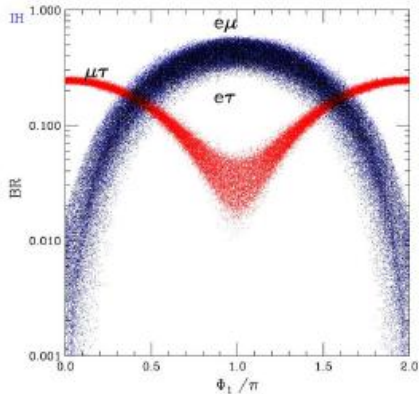
FIG. 12: $\text{Br}(H^{++} \rightarrow e_i^+ e_i^+)$ vs. the lowest neutrino mass for NH (left) and IH (right) when $\Phi_1 = 0$ and $\Phi_2 = 0$.



Doubly Charged (continued)

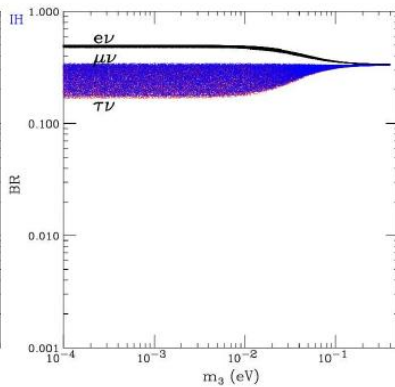
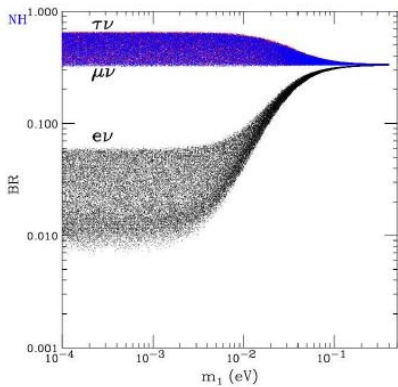


Majorana Phase



- Singly Charged Higgs BR is independent of Majorana phases.

Singly Charged



Majorana Phase: a close look

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

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

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



Distinguish Spectrum via LNV Higgs Decay

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	$\text{Br}(e^+e^+) \approx \text{Br}(\mu^+\mu^+) \approx \text{Br}(\tau^+\tau^+)$ $\text{Br}(\mu^+\tau^+) \approx \text{Br}(e^+\tau^+) \approx \text{Br}(e^+\mu^+) \text{ (suppressed)}$ $\text{Br}(e^+\bar{\nu}) \approx \text{Br}(\mu^+\bar{\nu}) \approx \text{Br}(\tau^+\bar{\nu})$

Summary

We discuss testing the B/L violations in the extended scalar models with the following two examples:

- Color sextet scalar that decays into same-sign diquark. We use the $\Phi \rightarrow tt$ to test its sextet nature and we plan to use the angular correlation in top decay to confirm the sextet only couples to the righthanded states.
- $SU(2)$ triplet Higgs in Type-II seesaw for neutrino mass generation. $H^{++} \rightarrow \ell^+ \ell^+$ is crucial in testing the model but the $H^+ \rightarrow \ell^+ \bar{\nu}$ helps to link the triplet Higgs decays with the neutrino mass spectrum even in the presence of Majorana phase.

Thank you.

