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)

Outline

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

SM @ 14 TeV LHC

- total cross section at LHC : 10^{11} pb
- $b\bar{b}$: 10^7 pb
- $t\bar{t}$: 800 pb
- $W \to e^{\pm}\nu$: 10^4 pb
- $Z \to e^+e^-$: 10^3 pb

Easy Identifiable BSM signature:

- $Z' \to \ell^+\ell^-$ (What can DIS experiments tell us?)
- Blackholes (multi-hard objects, ΔB, ΔL ... but need to be consistent with constraints like proton decay, etc.)

Multijet+Same Sign Dilepton+$\not{E}_T$

SM contributes to enomous background as multijet, jets+$W^\pm$, jets+Z, jets+$W^+W^-/t\bar{t}$, ... One of the most stricking 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) $nj\chi_1^\pm\chi_1^\pm$
- ED: KK-gluon $g'g' \to njW'^\pm W'^\pm$
- 4-th generation: $b'\bar{b}' \to t\bar{t}W^+W^- \to njW^\pm W^\pm$
- Color Octet: $88 \to t\bar{t}t\bar{t} \to njW^\pm W^\pm$

What else?

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

$U(1)$ symmetries

$$
\begin{aligned}
A_{[SU(3)_C]^2\times U(1)} &= \frac{N_g}{2}(2q+u+d)=0\\
A_{[SU(2)_L]^2\times U(1)} &= \frac{N_g}{2}(3q+\ell)=0\\
\mathrm{TrU}(1) &= N_g(6q+3u+3d+2\ell+e)=0\\
A_{[U(1)]^3} &= N_g(6q^3+3u^3+3d^3+2\ell^3+e^3)=0\\
A_{[U(1)_Y]^2\times U(1)} &; \quad A_{[U(1)]^2\times U(1)_Y}=0\\
\mathrm{Yukawa} &: \quad q+u+h=0,\ q+d-h=0,\ \ell+e-h=0
\end{aligned}
$$

- No extra Unbroken $U(1)$ Gauge Symmetry except $U(1)_Y$
- Hypercharge normalization from new physics GUTs
- 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

Testable B/L Violations in BSM:

- R-parity violation in SUSY
  Suppressed coupling; no $B - L$
- Majorana neutrino at the LHC
  tuning dimensionless Yukawa coupling
  Tiny Mixing $\rightarrow$ highly suppressed production
- $\overline{\psi^c}\psi\phi$ in extended scalar models (for instance, Pati-Salam Model)
  may need to tune dimension-1 parameter (can be considered as soft breaking)
  Gauge interaction production with only Resonance $\not{B}/\not{L}$ Decay

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 $\Phi_6 : (6, 1, 4/3)$, $\phi_6 : (6, 1, -2/3)$, $\delta_6 : (6, 1, +1/3)$

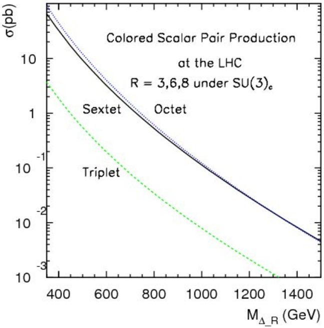
Scalar QCD

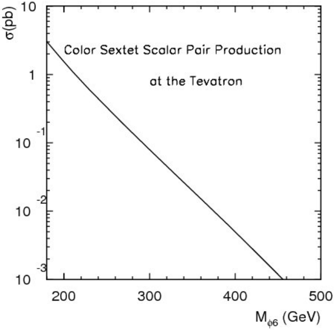
$$
\begin{aligned}
& \mathrm{Tr}[(D_\mu \Delta_6)^\dagger (D^\mu \Delta_6)] - M_\Delta^2 \mathrm{Tr}[\Delta_6^\dagger \Delta_6] + f_\Delta Q_L^T C^{-1} \tau_2 \Delta_6^\dagger Q_L \\
+ \quad & (D_\mu \Phi_6)^\dagger (D^\mu \Phi_6) - M_\Phi^2 \Phi_6^\dagger \Phi_6 + f_\Phi u_R^T C^{-1} u_R \Phi_6^\dagger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

$$D_\mu = \partial_\mu - i g_s G_\mu^a T_r^a$$

QCD Production of Color Sextet Scalar Pair

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





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

Remarks

Sextet	Octet
No $q\bar{q}, gg \to \Phi_6$ but $qq \to \Phi_6$ $gg, q\bar{q} \to \Phi_6\bar{\Phi}_6$	$q\bar{q}, gg \to \Phi_8$ $q\bar{q}, gg \to \Phi_8, \Phi_8$

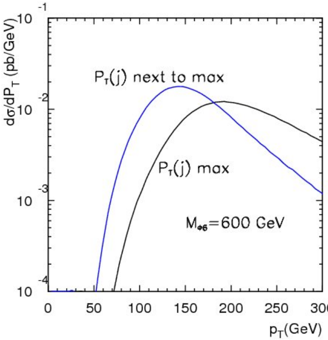
- $D^0 - \overline{D^0}$ mixing from $f_{11} f_{22}$, maybe dominant decaying into top
- $\overline{u^c_R} u_R \Phi_6$ GIM violation. But only coupling to righthanded states.
- $$3 \otimes 3 = 6 \oplus \bar{3}$$

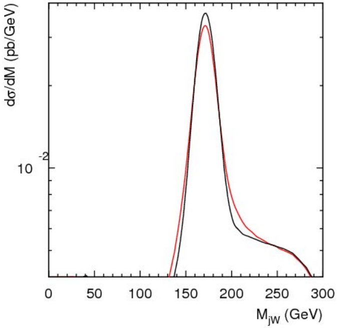
  Squark pair production with R-parity violation decay? only $u^c d^c d^c$

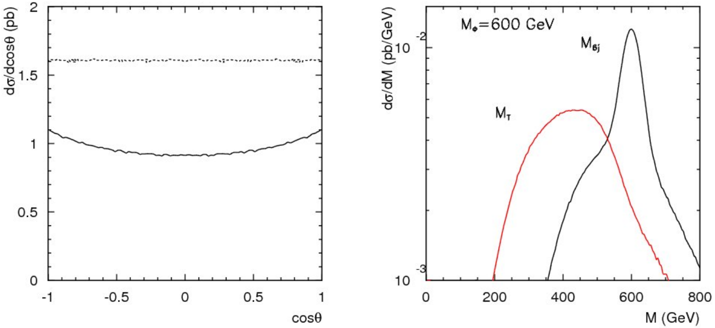
Same Sign Top

$$pp \to \bar{\Phi}_6\Phi_6 \to tt\overline{tt} \to 4b + \ell^{\pm}\ell^{\pm} + \not{E}_T + Nj,$$

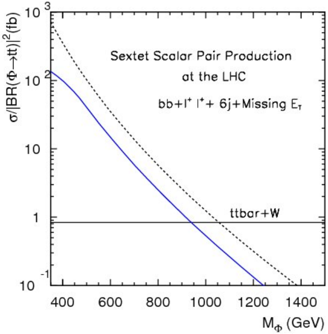
(No radiation included)

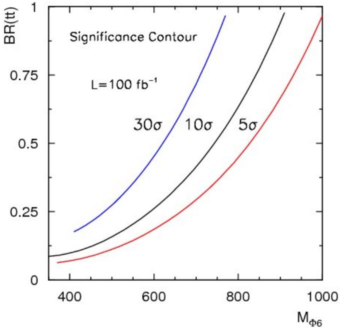






Reconstructed two hadronic Top shows the scalar feature.
Multijet resonance





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

Lepton Number Violation

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

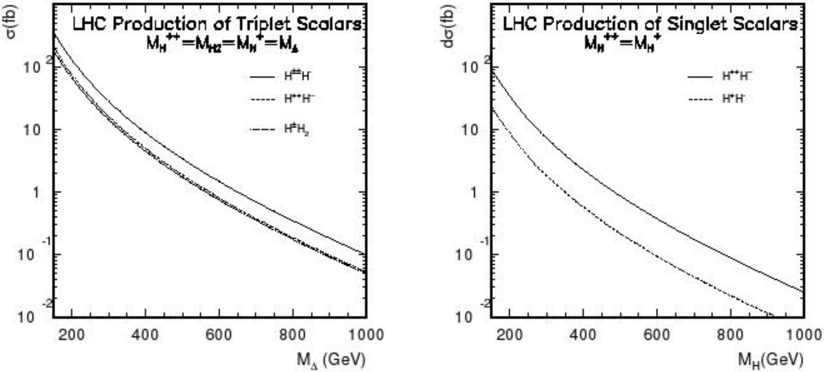
- $SU(2)_L$ adjoint $\Delta : (1,3,1)$
- $SU(2)_L$ singlet $\phi^{--} : (1,1,-2)$

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

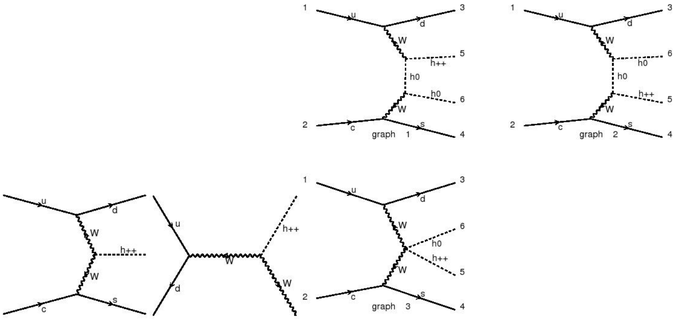
Production of Triplet Higgses

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

Tree Level Cross-section of Triplet Higgses Production



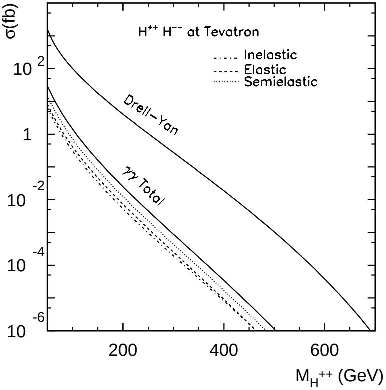
Remarks on Production

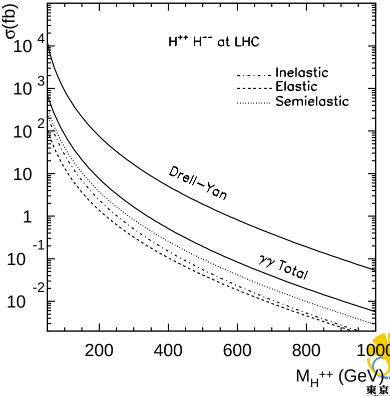


- triplet vev v_Δ suppresion
- phase space suppression
- Ward Identity (Longitutinal W, $\epsilon_\mu \to p_\mu$)

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

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

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

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

Drees, Godbole 94

Search via Leptonic Decays

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

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

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

- 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

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

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

SM background

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

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

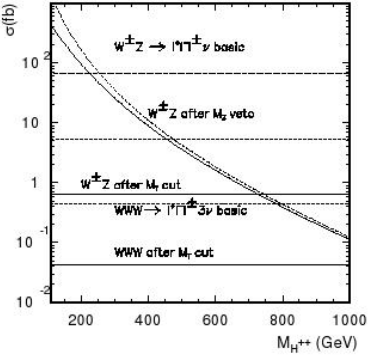
  Veto events of $|M_{\ell^+\ell^-} - M_Z| < 15\ \mathrm{GeV}$ After reconstruction, purely event counting

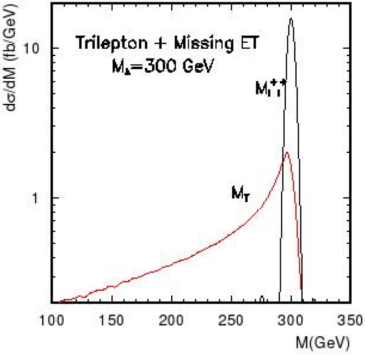
- Trilepton (no τ final state)
  SM Background if there exists same flavor, opposite sign dilepton

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

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

Trilepton





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

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

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τ Reconstruction

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

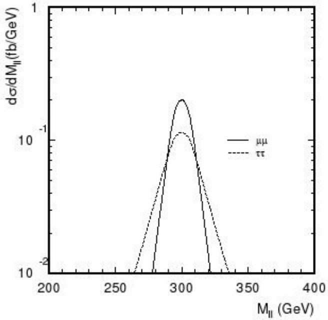
$$pp \to H^{++}H^{--} \to \ell^+\ell^+\tau^-\tau^-, \ell^+\ell^+\mu^-\tau^-, \ell^+\tau^+\tau^-\tau^-$$

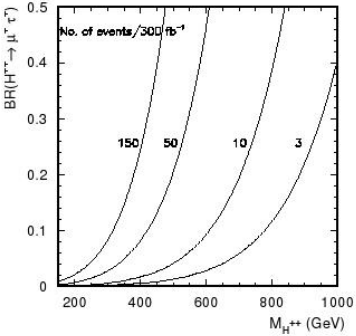
Highly Boosted τ

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





Top-down: Theory Realizations

Color Sextet Scalar

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

$$(3,1,10) : \{(3,1,-2,1) \oplus (3,1,-2/3,3) \oplus (3,1,2/3,6)\}$$

- Adjoint $SU(5)$ (down-type)

SUSY Pati-Salam (Chacko-Mohapatra, 99), Electroweak Baryogenesis(Babu, Mohapatra, 03)

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

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

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

If y_ν is of $\mathcal{O}(0.01)$, $\mu \sim 1$keV. $\lim \mu \to 0$, $U(1)_L$ or $U(1)_{\mathrm{B-L}}$ 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 $\sin\theta_{23}$

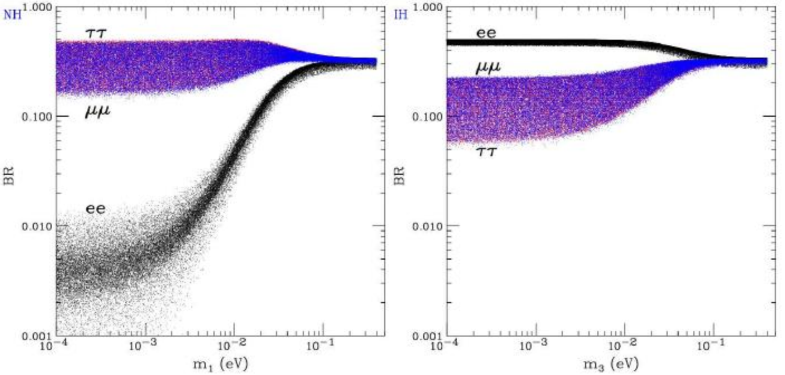
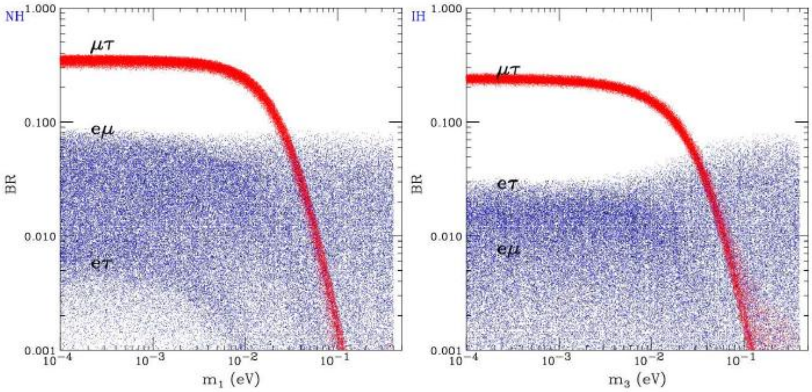
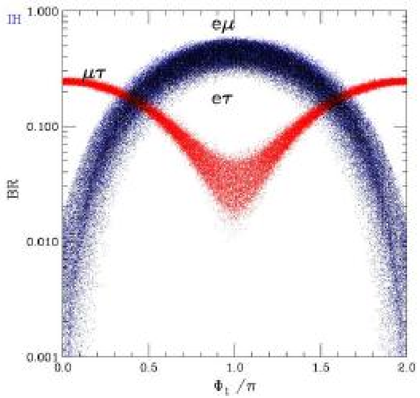


FIG. 12: $\mathrm{Br}(H^{++} \to e_i^+ e_i^+)$ vs. the lowest neutrino mass for NH (left) and IH (right) when $\Phi_1 = 0$ and $\Phi_2 = 0$.

Doubly Charged (continued)

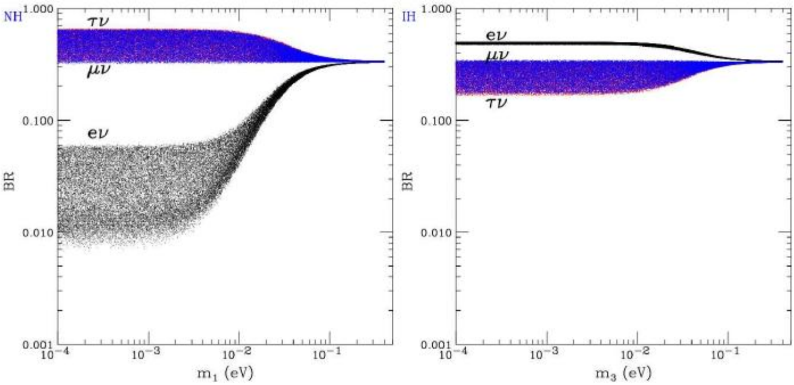


Majorana Phase



- Singly Charged Higgs BR is independent of Majorana phases.

Singly Charged



Majorana Phase: a close look

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

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

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

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

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 $\Phi \to tt$ 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. $H^{++} \to \ell^+\ell^+$ is crucial in testing the model but the $H^+ \to \ell^+\bar{\nu}$ helps to link the triplet Higgs decays with the neutrino mass spectrum even in the presence of Majorana phase.

Thank you.

Backup Slides

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

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

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 $SU(3)$.