THE COLORFUL SEESAW

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12 – April- 2011

The Role of Heavy Fermions in Fundamental Physics

JHEP 1101 (2011) 046: P. Fileviez Perez, T. Han, SS, M. Trenkel

Phys.Rev. D80 (2009) 053006 : P. Fileviez Perez, M. Wise

Quest For BSM

BSM IS ALREADY HERE:

- Neutrino Masses:

$$\Delta m_{21}^2 = m_{\nu_2}^2 - m_{\nu_1}^2 \sim 7.5 \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m_{31}^2 = m_{\nu_3}^2 - m_{\nu_1}^2 \sim 2.3 \times 10^{-3}\ \mathrm{eV}^2$$

$$0.27 < \sin^2\theta_{12} < 0.35$$

$$0.39 < \sin^2\theta_{23} < 0.63$$

$$\sin^2\theta_{12} < 0.04$$

$$s_{ij} \equiv \sin\theta_{ij}$$

- Can be Dirac or Majorana:

$$m_\nu \bar{\nu}_L \nu_R \qquad m_\nu \nu_L \nu_L$$

- Majorana: new heavy particles:

$$\mathcal{L} \supset \frac{1}{M_X} LLHH$$

Very exciting for LHC if $M_X \sim$ TeV

Outline

- Neutrino Mass Models
- The Colorful Seesaw Fields
- The Colorful Seesaw at the LHC
- Conclusion

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Majorana Schemes

- Generically: violates lepton number: $\mathcal{L} \supset \frac{1}{M_X} LLHH$
  - Possible same-sign dilepton signals

- Type I: Fermion $X = \nu_R \sim (1,1,0)$ Minkowski; Yanagida; Gell-Mann et al.; Glashow; Mohapatra & Senjanovic
  - Hard to produce without new interactions
  - $\nu_R \nu_R \to \ell_i^{\pm} \ell_j^{\pm} W^{\mp} W^{\mp}$ Keung & Senjanovic; Han & Zhang; Aguila & Aguilar-Saavedra; Atre et al.; Kersten & Smirnov; Fileviez Perez et al.

- Type II: Scalar $X = \Delta \sim (1,3,1)$ Konetschny & Kummer; Cheng & Li; Lazarides et al.; Schechter & Valle; Mohapatra & Senjanovic
  - Produced via vector bosons Fileviez Perez, Han, Huang, Li & Wang; Chun et al.; Garayoa & Schwetz; Akeroyd et al.; Huitu et al.
  - Exciting signals from pair produced $\Delta^{\pm\pm} \to e^{\pm} e^{\pm}$

- Type III: Fermion $X = \rho \sim (1,3,0)$ Foot Lew, He & Joshi
  - Fermionic also through Drell-Yan
  - $\rho^{+} \rho^{0} \to \ell_i^{+} \ell_j^{+} Z W^{-}$

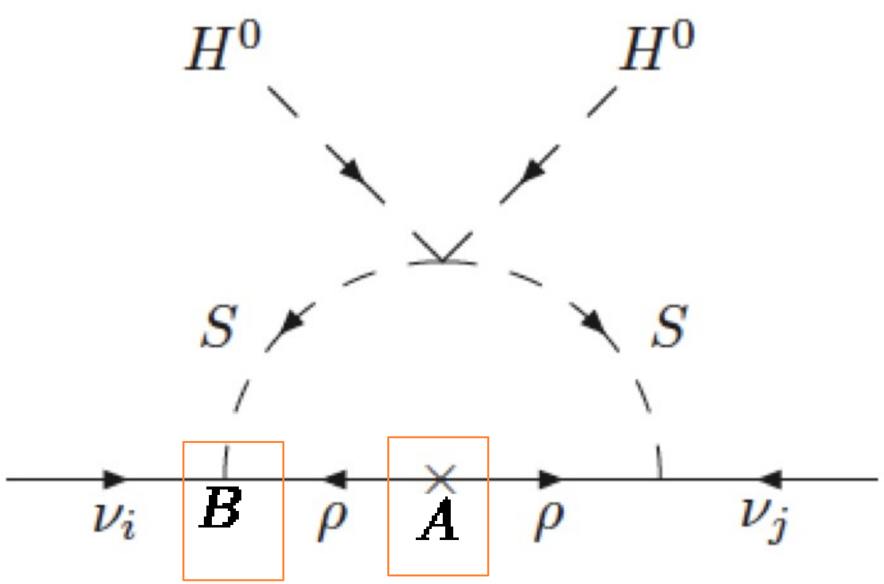
Franceschini et al; Arhrib, Bajc, Ghosh, Han, Huang, Puljak & Senjanovic; Li & He, Aguila & Aguilar-Saavedra

Radiative Seesaw

Zee '80

- Zee Model: Scalar $H' \sim (1, 2, \frac{1}{2})$ and $\delta^+ \sim (1, 1, 1)$
  - $\delta^+ \to e^+ \nu$, LNV not clear

- One type of scalar (S) and one type of fermion (ρ):



$$A: \; M_\rho \rho\rho \to \rho \sim (c_\rho, I_\rho, 0)$$

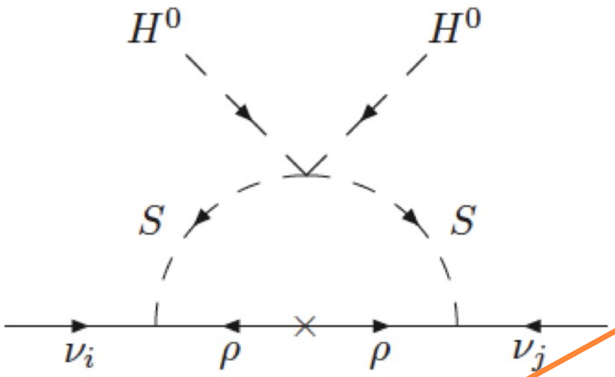
$$B: \; L\rho S \to S \sim \left(c_S, I_S, \frac{1}{2}\right)$$

From $SU(2)$: $|I_S - I_\rho| = 1$

$c_\rho = c_S = 1, 8..$

Fileviez Perez, Wise '09

Choose Colorless Fields



- $I_\rho = 1, \quad I_S = 2$

  $\rho \sim (1,1,0), \quad S = (S^+, S^0)$ → Type I Seesaw

- $I_\rho = 2, \quad I_S = 1$

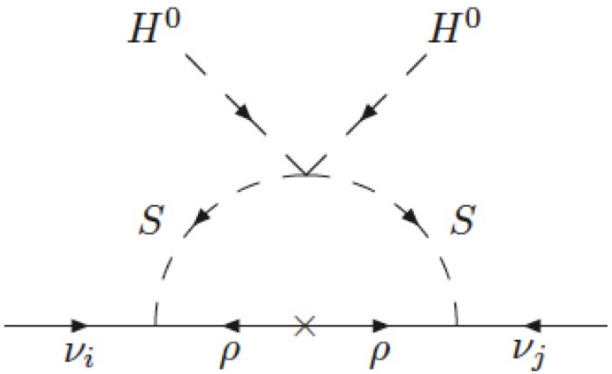
  $\rho = \left(\rho^{\frac{1}{2}}, \rho^{-\frac{1}{2}}\right), \quad S = \left(S^{\frac{1}{2}}\right)$ → Fractionally charged

- $I_\rho = 2, \quad I_S = 3$ → Fractionally charged

- $I_\rho = 3, \quad I_S = 2$

  $\rho = (\rho^+, \rho^0, \rho^-), \quad S = (S^+, S^0)$ → Type III Seesaw

Colorful Fields



$$c_\rho = c_S = 8$$

- $I_\rho = 1, \quad I_S = 2$

  $$\rho \sim (8,1,0)\,, \quad S = (S_A^+, S_A^0)$$

  → ~~Type I Seesaw~~ New

- $I_\rho = 2, \quad I_S = 1$

  $$\rho = \left(\rho_A^{\frac{1}{2}}, \rho_A^{-\frac{1}{2}}\right), \quad S = \left(S_A^{\frac{1}{2}}\right)$$

  → Fractionally charged

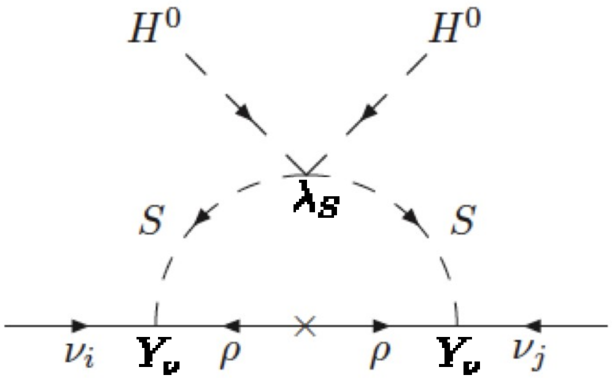
- $I_\rho = 2, \quad I_S = 3$ → Fractionally charged

- $I_\rho = 3, \quad I_S = 2$

  $$\rho = (\rho_a^+, \rho_A^0, \rho_A^-)\,, \quad S = (S_A^+, S_A^0)$$

  → ~~Type III Seesaw~~ New

The Colorful Seesaw



Content:

$$\rho_\alpha \sim (8,1,0)\,; \quad \alpha = 1..2$$

$$S \sim \left(8,2,\frac{1}{2}\right) = \left(S_A^+, S_A^0\right)$$

- One massless neutrino
  - Allows normal hierarchy (NH):

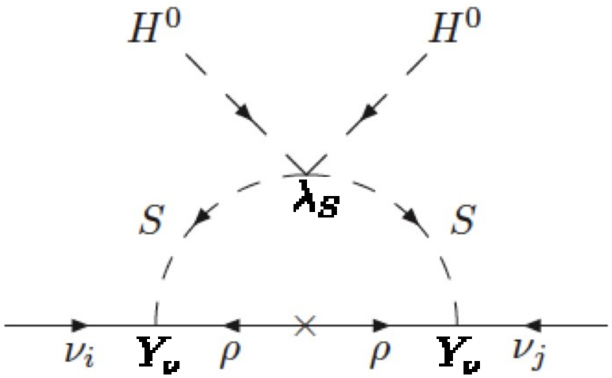
$$m_{\nu_3} = 4.8 \times 10^{-2} \ \text{eV}$$
$$m_{\nu_2} = 8.7 \times 10^{-3} \ \text{eV}$$
$$m_{\nu_1} = 0$$

  - And inverted hierarchy (IH):

$$m_{\nu_1} \sim m_{\nu_2} \sim 4.8 \times 10^{-2} \ \text{eV}$$
$$m_{\nu_3} = 0$$

THE COLORFUL SEESAW

$$\mathcal{L} = Y_\nu^{i\alpha} L_i \rho_\alpha S + m_\rho \rho \rho + \lambda_S H^T S^\dagger S^\dagger H$$



Neutrino Masses:

$$m_\nu^{ij} = \frac{1}{16\pi^2} Y_\nu^{i\alpha} Y_\nu^{j\alpha} \lambda_S v^2 I(m_{\rho_\alpha}, m_S)$$

Loop Function

$$I(m_{\rho_\alpha}, m_S) = m_{\rho_\alpha} \frac{m_S^2 - m_{\rho_\alpha}^2 + m_{\rho_\alpha}^2 \ln(m_{\rho_\alpha}^2 / m_S^2)}{(m_S^2 - m_{\rho_\alpha}^2)^2}$$

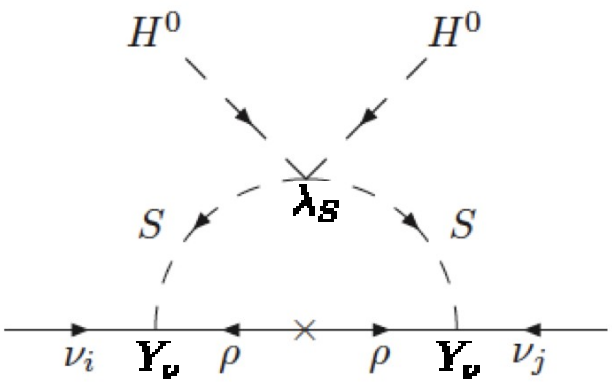
For: $m_S = 2000,\ m_\rho = 200,\ v = 246$ GeV

$$I(m_{\rho_\alpha}, m_S) \sim \frac{m_{\rho_\alpha}}{m_S^2}; \quad m_S \gg m_{\rho_\alpha}$$

$$\boxed{\lambda_S Y_\nu^2 \sim 10^{-8}}$$

Compare to TeV type I seesaw: $(Y_\nu^I)^2 \sim 10^{-10}$

Lepton Number Violation



- Lepton number violation (LNV) requires

$$\lambda_S, Y_\nu \neq 0$$

- Lepton flavor violation (LFV) requires

$$Y_\nu \neq 0$$

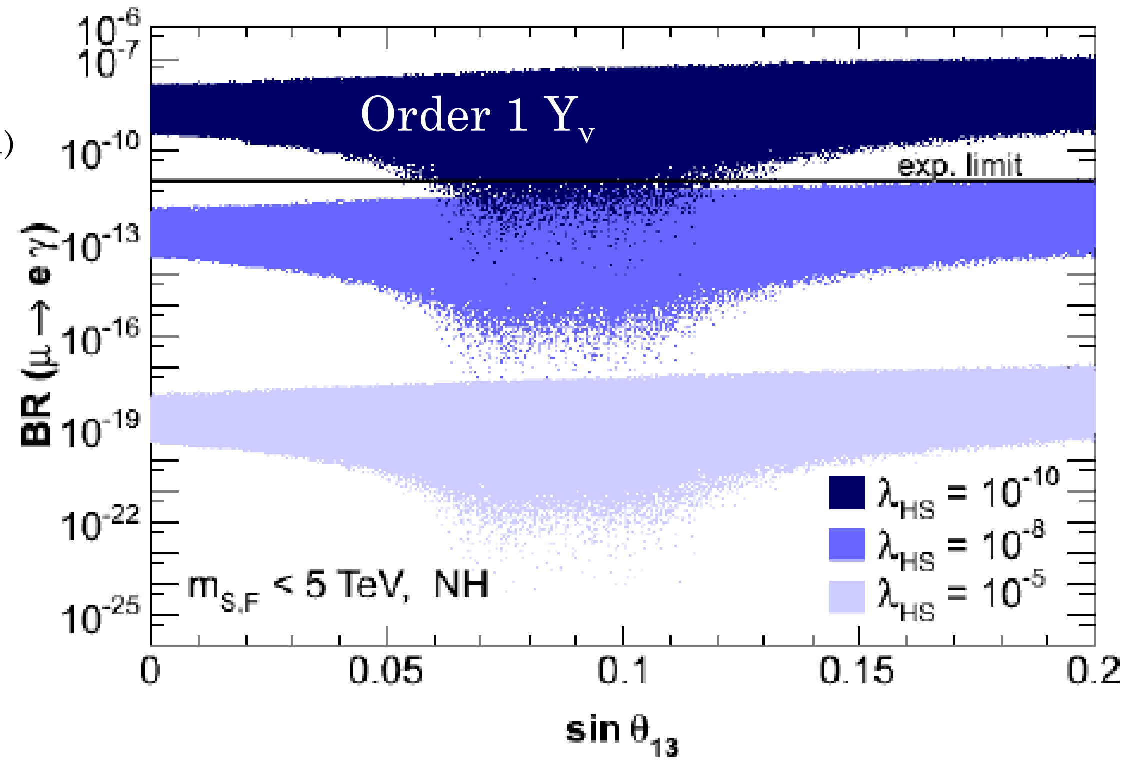
$$\lambda_S Y_\nu^2 \sim 10^{-8}$$

$$\mu \to e\gamma$$

(Liao & Liu '10; Fileviez Perez, SS, Trenkel '11)

$$\mathrm{Br}(\mu \to e\gamma) \sim \frac{3\alpha_{\rm EM}}{4\pi G_F^2 m_S^4} Y_\nu^4$$

Scanned over neutrino parameters.



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Scalar Color Octet

- So called Manohar-Wise ('06)
  - Higgs doublet color adjoint
  - Couples to quarks just like Higgs

$$\mathcal{L} \supset \bar{D}_i \Gamma_D^{ij} S^\dagger Q_j + \bar{U}_i \Gamma_U^{ij} S Q_j$$

- Therefore satisfies minimal flavor violation Ansatz (MFV)
  - Transforms as Higgs under flavor

$$\Gamma_U^{ij} = \eta_U Y_U^{ij}$$

$$\Gamma_D^{ij} = \eta_D Y_D^{ij}$$

- Pheno has been studied

Gresham & Wise; Fileviez Perez, Gavin, McElmurry &Petriell0; Gerbush et al.;

Scalar Color Octet

- Physical states:

$$S \equiv S^A T^A = \begin{pmatrix} S^+ \\ S_R^0 + i S_I^0 \end{pmatrix}$$

- Mass split by Higgs interactions: electroweak
- Mild coupling to down gives $b \to s\gamma$

$$\therefore m_S \gtrsim 1 \text{ TeV}$$

  - S fields fairly degenerate
  - Decays:

$$S^+ \to t\bar{b}$$

$$S^0_{R,I} \to \bar{t}t$$

  - For larger splitting, heavier S decay to W and lighter S, *e.g.*: $S^+ \to W^+ S^0_{R,I}$

Fermionic Octet

- Quantum numbers of gluino (same production)
- Decays governed by Yukawa coupling to Leptons

$$Y_\nu^{i\alpha}\, L_i\, \rho_\alpha\, S$$

- Use Casas-Ibarra ('01) to relate Y_ν and m_ν:

$$Y_\nu = \frac{1}{v} V_{\mathbf{PMNS}}(s_{12}, s_{23}, s_{13})\, m_\nu^{1/2} \Omega\, M_{\mathbf{Eff}}^{1/2}(m_\rho, m_S)$$

  - Ω is a complex matrix with

$$\Omega^T \Omega = 1$$

  - Assumed real, in normal hierarchy:

$$\Omega^{\mathrm{NH}} = \begin{pmatrix} 0 & 0 \\ \sqrt{1-\omega^2} & -\omega \\ \omega & \sqrt{1-\omega^2} \end{pmatrix} \quad 0 \leq \omega \leq 1$$

Fermionic Octet Decays

- For $m_\rho > m_S$

$$\rho \to S^0_{R,I}\,\nu$$
$$\rho \to S^\pm\,\ell^\mp$$

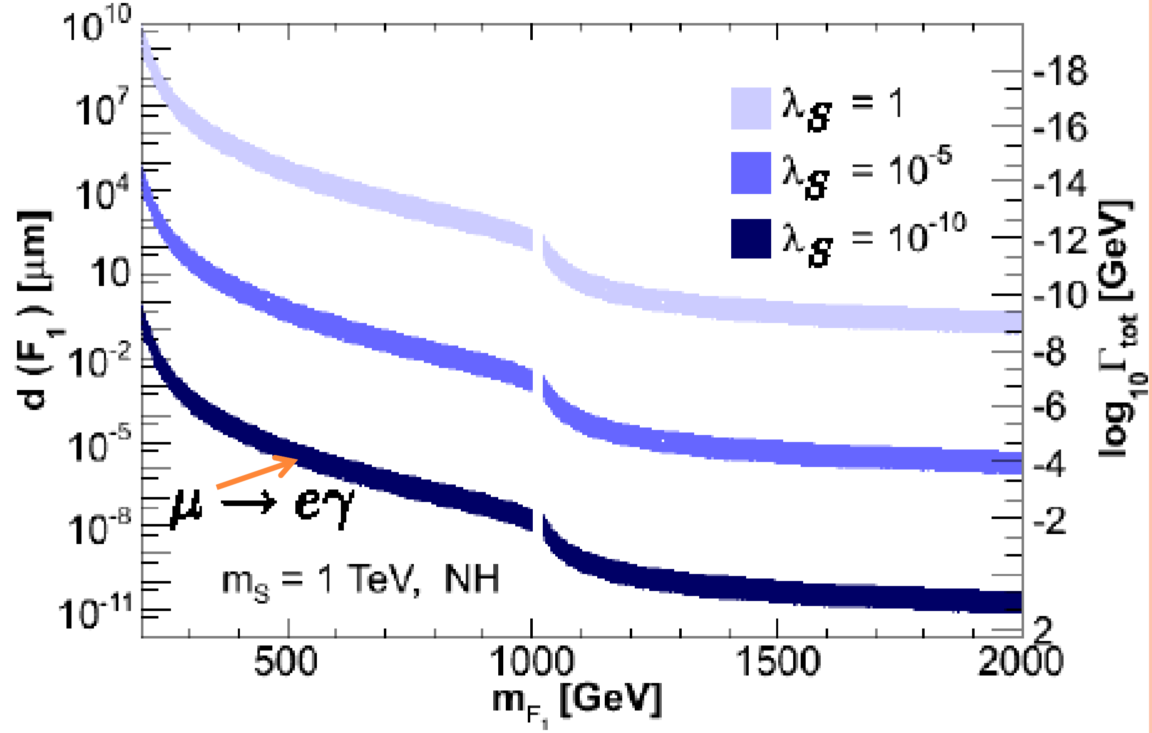
- Or three-body decays

$$\rho \to t\,\bar{t}\,\nu \qquad m_\rho > 2\,m_t$$
$$\rho \to t\,\bar{b}\,\ell^-, \quad \bar{t}\,b\,\ell^+$$

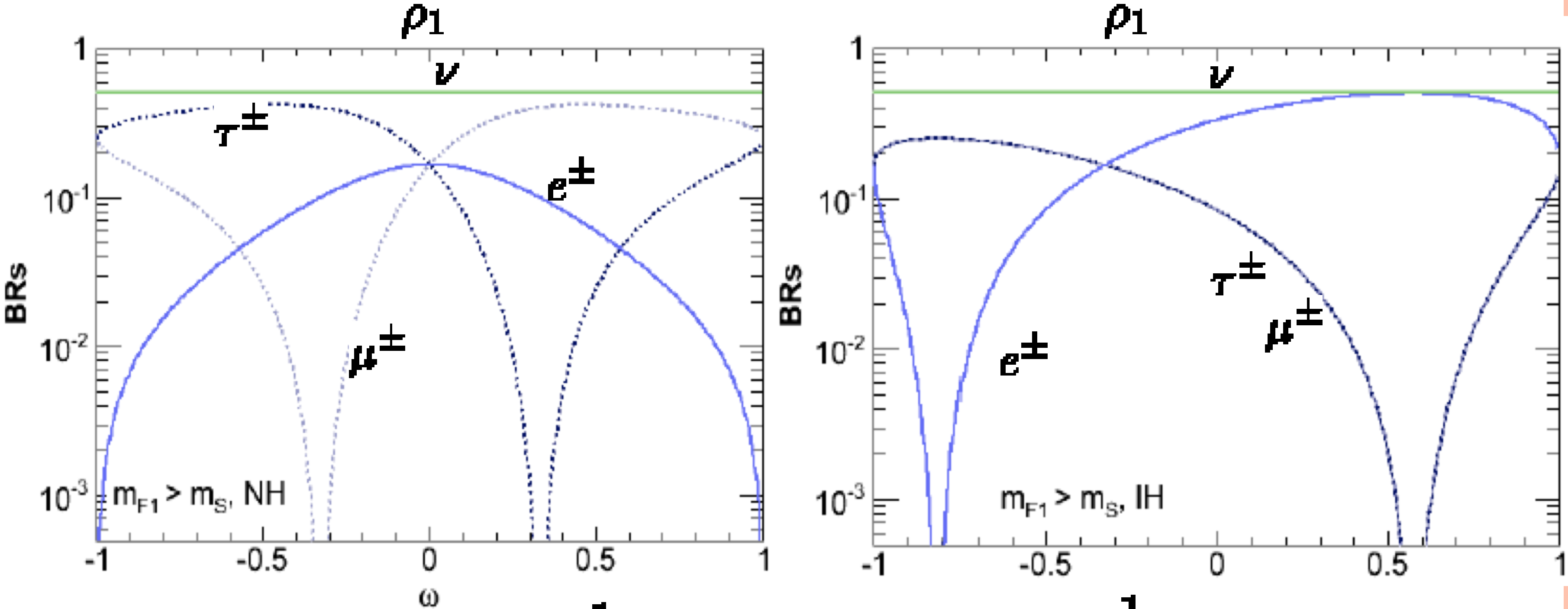
- Decay length: scan over ω and mixings.

$$\lambda_S Y_\nu^2 \sim 10^{-8}$$

Various decay lengths:
Could also be R-hadron.



Decays with Tri-Bimaximal Mixings

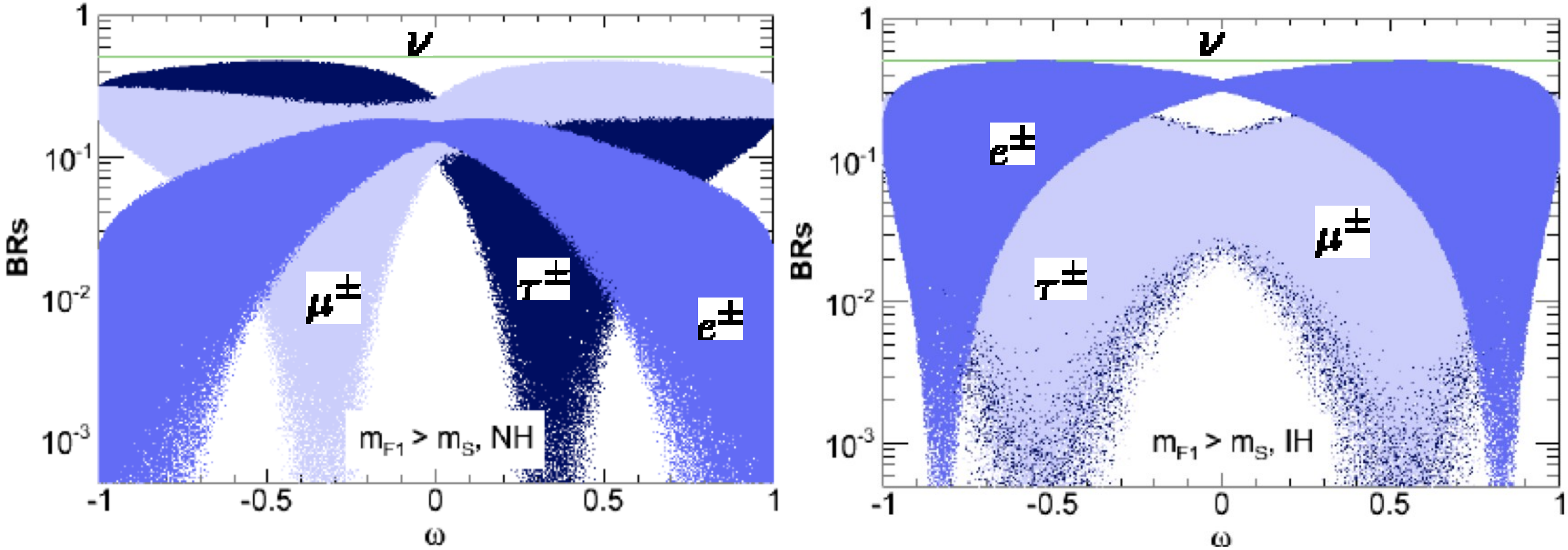


$$s_{12}^2 \sim \frac{1}{3} \qquad s_{13}^2 \sim 0 \qquad s_{23}^2 \sim \frac{1}{2}$$

No Phases

- NH: τ or μ channels always larger than e
- NH: τ and μ coincide

General Mixing



- Scanned over mixing angles and phases
- Not as predictive
  - NH: τ and μ channel still larger then e

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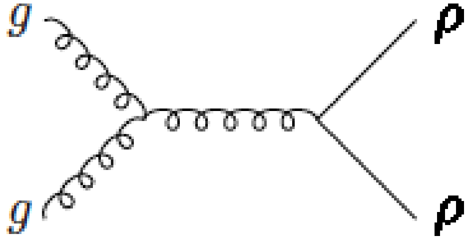
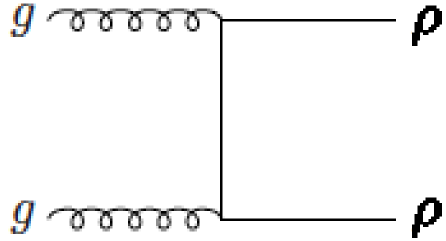
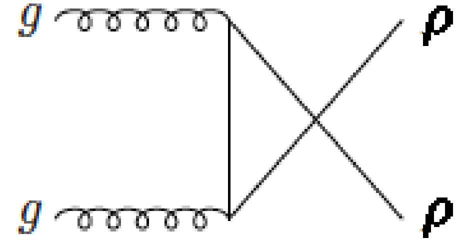
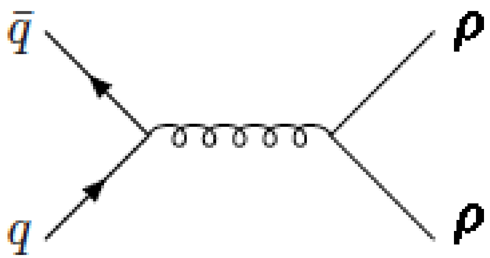
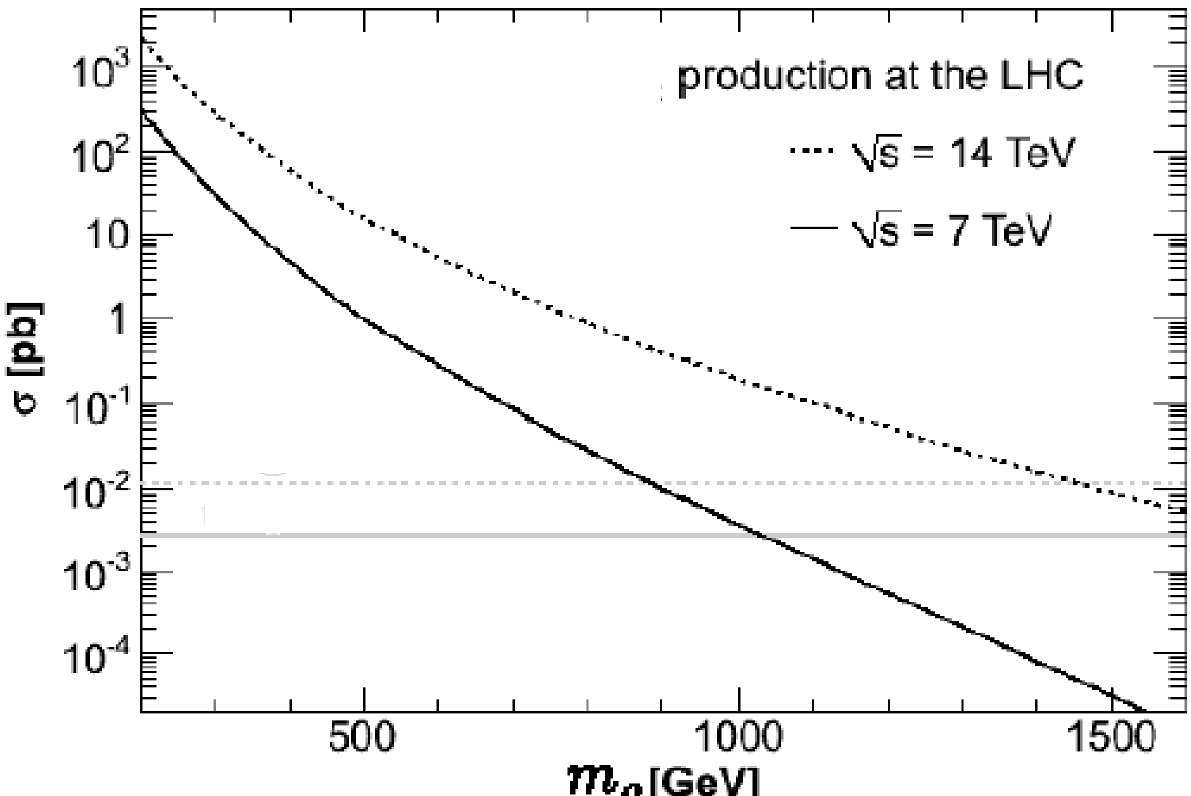
PRODUCTION: SIMILAR TO GLUINO











SIGNALS

- LNV: same-sign dileptons

$$pp \to \rho\,\rho \to \ell_i^{\pm}\ell_j^{\pm}S^{\mp}\,S^{\mp}$$

$$S^{\mp} \to t\,\bar{b}$$

$$t \to b\,2j$$

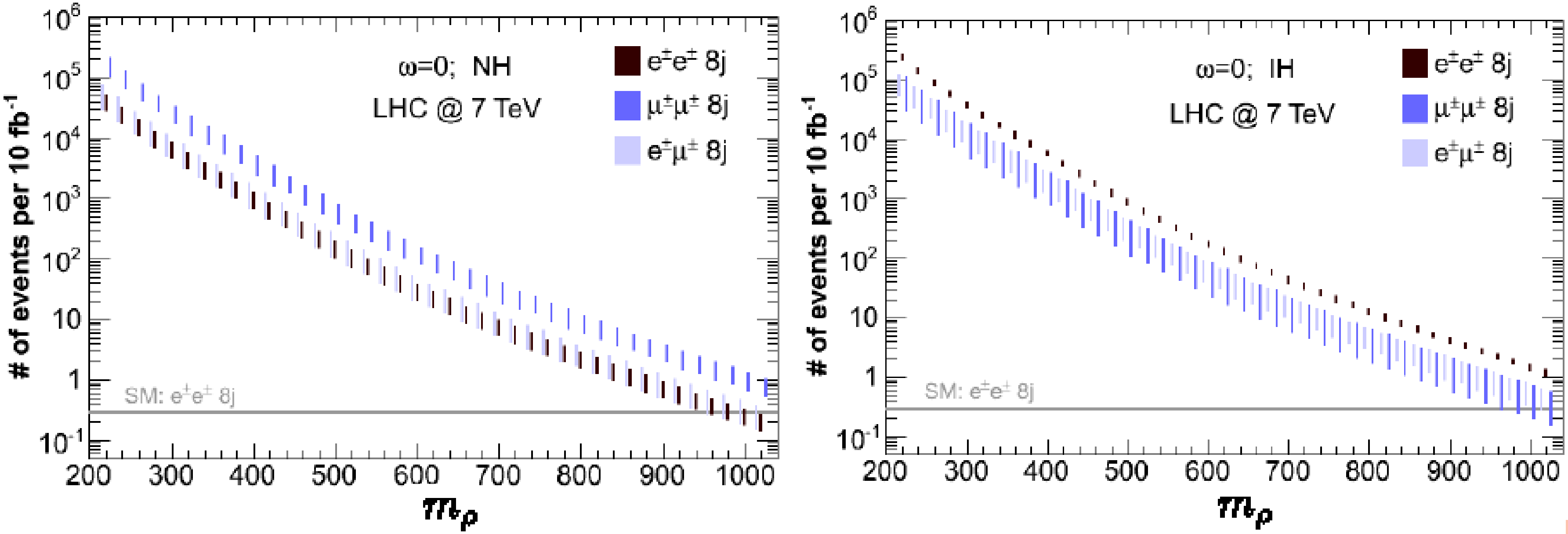
  - Final states of interests: $e^{\pm}\,e^{\pm}\,8j$, $e^{\pm}\,\mu^{\pm}\,8j$, $\mu^{\pm}\,\mu^{\pm}\,8j$

- Leading background: $t\,\bar{t}\,t\,\bar{t}$
  - One pair of like-sign tops decay semi-leptonically

$$\sigma_{\ell^{\pm}\ell^{\pm}8j+\mathrm{MET}} \sim 0.04\ \mathrm{fb} \quad @\ 7\ \mathrm{TeV\ LHC}$$

  - Still before MET cuts

Number of Events for 10 fb^{-1}:



- Scanned over neutrino parameter
- Signal > background even before cuts, up to $m_\rho \sim 800$ GeV
- For 14 TeV, up to $m_\rho \sim 1000$ GeV
- Large particle multiplicity makes reconstruction challenging, but large number of events can make up for it

Conclusion

- Neutrino masses might lead to exciting LHC signals
  - Same-sign dileptons (LNV) with electroweak cross section
- Colorful Seesaw also has same-sign dileptons but **strong** cross sections.
  - One-loop seesaw mechanism
  - Scalar color octet, isospin doublet S
  - Fermionic color octet ρ
- More signal events than background up to $m_\rho \sim 800$ GeV
- With luck, might also discriminate: NH, IH