COLLIDER SIGNALS FOR AN INVERSE SEESAW MODEL OF NEUTRINOS

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May 10, 2011

PHENO 2011

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OUTLINE

INTRODUCTION

- A very attractive mechanism that can account for the small neutrino masses is the seesaw mechanism.

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D \\ m_D & M_R \end{pmatrix}$$

  - small neutrino mass $\sim m_D^2/M_R$ but also small mixing angle $\tan\theta \sim m_D/M_R$
  - TeV scale seesaw but with un-naturally small Yukawa couplings.
- Large mixing angle possible for inverse seesaw models of neutrino

- With a singlet Dirac fermion $N = N_L + N_R$ one can write the mass matrix in the $(\bar{\nu}_L, N_R, \bar{N}_L)$ basis

$$\mathcal{M}_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D & \epsilon_R & m_N \\ 0 & m_N & \epsilon_L \end{pmatrix}$$

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- For $\epsilon_{L,R} \ll m_D, m_N$, gives a small neutrino mass $\sim m_D^2 \epsilon_L / m_N^2$ with a $\mathcal{O} \sim 10^{-1}$ mixing angle.
  - much better but still hard to produce at colliders.
  - does an underlying model give enhanced production of these heavy leptons ?
- An extra neutral gauge boson at the TeV scale that couples to both SM fermions and the heavy neutrino can give enhanced production cross section.

- Many extensions to the Standard Model have an extra $U(1)$ and predict an additional neutral gauge boson.
  - Left-Right symmetric models, $SO(10)/E_6$ GUT models, etc.

- Many extensions to the Standard Model have an extra $U(1)$ and predict an additional neutral gauge boson.
    - Left-Right symmetric models, $SO(10)/E_6$ GUT models, etc.
- The inverse seesaw model can be naturally obtained in an E_6 model.
- We have used the E_6 model where one linear combination of the two $U(1)$ groups survives to the TeV scale.

MODEL

- The particle content and the charges in the decomposition of the E_6 fundamental representation:

$$E_6 \to SO(10) \times U(1)_\psi \to SU(5) \times U(1)_\psi \times U(1)_\chi$$

Quantum numbers

$SO(10)$	$SU(5)$	$2\sqrt{10}Q_\chi$	$2\sqrt{6}Q_\psi$	$2\sqrt{15}Q_s$
16	$10\ (u, d, \bar{u}, \bar{e})$	-1	1	-1/2
	$\bar{5}(\bar{d}, \nu, e)$	3	1	4
	$1(\bar{N})$	-5	1	-5
10	$5(D, H_u)$	2	-2	1
	$\bar{5}(\bar{D}, H_d)$	-2	-2	-7/2
1	$1(S_L)$	0	4	5/2

where Q_s is the charge under the unbroken $U(1)$ symmetry at the TeV scale.

- To realize the inverse seesaw we need a term $N^c S S_H$ which gives the unbroken symmetry as $U(1)_s \equiv \psi - \frac{9}{5}\chi$.
- Thus in the neutral lepton basis of $(\nu, N^c, S, \omega, \omega^c)$

$$\begin{pmatrix} 0 & y_\nu < H_u > & 0 & 0 & 0 \\ y_\nu < H_u > & 0 & y_{\nu S} < S_H > & 0 & 0 \\ 0 & y_{\nu S} < S_H > & 0 & y_{S\omega} < H_u > & y_{S\omega^c} < H_d > \\ 0 & 0 & y_{S\omega} < H_u > & 0 & y_\omega < S_H > \\ 0 & 0 & y_{S\omega^c} < H_d > & y_\omega < S_H > & 0 \end{pmatrix}$$

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which gives for 1-family:

$$m_\nu \simeq \frac{y_\nu^2 y_{S\omega} y_{S\omega^c} v_u^3 v_d}{m_N^2 m_\omega} \sim \frac{m_D^4}{m_N^2 m_\omega}$$

- S_L mixes with ν_L

$$N_L \equiv \frac{m_D \nu_L + m_N S_L}{\sqrt{m_D^2 + m_N^2}}$$

which forms a Dirac fermion with N^c.

COLLIDER SIGNALS

- Already strong constraints from LEP and Tevatron on additional neutral gauge bosons (Z') which couple to SM fermions.
- Present Tevatron bound on Z' in our model $\sim$ 800 GeV.
- The $U(1)$ gauge boson can be produced on-shell at LHC and will decay to SM fermions which for massless final states is

$$\Gamma_{Z' \to f\bar{f}} = \frac{g_s^2 M_{Z'}}{24\pi} (Q_L^2 + Q_R^2)$$

- Bump hunting in the dilepton invariant mass and direct search limits can be obtained at LHC: [Kang, Langacker 2005]

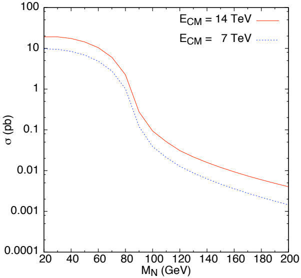
$$pp \to Z' \to e^+ e^- / \mu^+ \mu^-$$

- The Z' decay probabilities are modified in our model as $M_N < M_{Z'}/2$.

Heavy neutrino at colliders

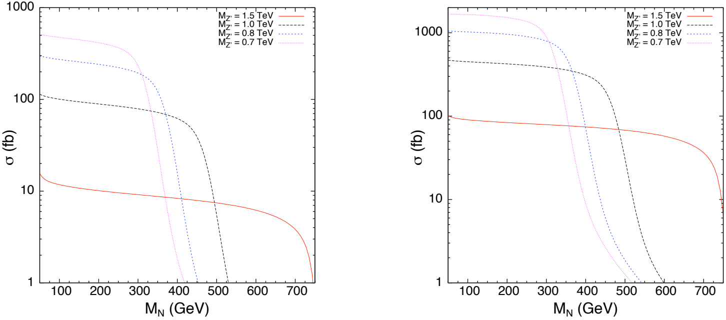
- The heavy Dirac neutrino in the inverse seesaw model mixes with the light neutrinos with large mixing angle
  - Constraints from weak decays of mesons and leptons.
  - mass dependent constraints from LEP : $\tan\theta < 0.06$ for $M_N \leq 100 GeV$
- Single production cross section depends on the mixing angle [Han, Zhang 2006]

$$pp \longrightarrow Z^* \longrightarrow \bar{\nu}_e N / \nu_e \bar{N} \qquad pp \longrightarrow W^{\mp} \longrightarrow \bar{N} e^- / e^+ N$$



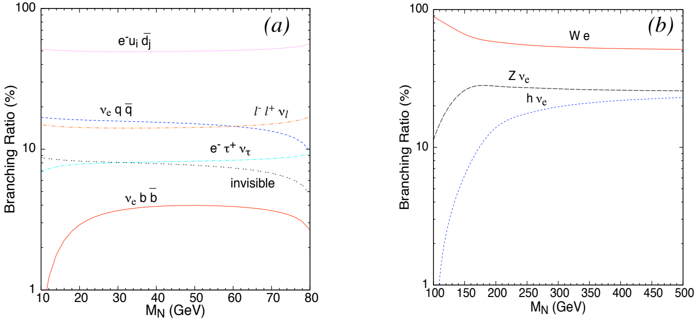
- The extra Z' in our model enhances the pair production cross section of the heavy neutrinos

$$pp \longrightarrow Z' \longrightarrow \bar{N}N$$



BRANCHING RATIOS OF N

- Final states depend on the decay probabilities of N which is independent of the mixing angle



- Signal with multi-lepton final states.
- No like-sign dilepton signal.

FINAL STATES

$$pp \to N\overline{N} \to \begin{cases} (\ell W)(\ell W) & \Longrightarrow 4\ell + \not{E}_T,\ 2\ell + 4j + \not{E}_T, 3\ell + 2j + \not{E}_T \\ (\ell W)(\nu Z) & \Longrightarrow 4\ell + \not{E}_T,\ 2\ell + 2j/0j + \not{E}_T, 3\ell + 2j + \not{E}_T \\ (\ell W)(\nu H) & \Longrightarrow 2\ell + 2W/2b + \not{E}_T \\ (\nu Z)(\nu Z) & \Longrightarrow 4\ell + \not{E}_T,\ 2\ell + 2j/0j + \not{E}_T \\ (\nu H)(\nu Z) & \Longrightarrow 2\ell + 2W/2b + \not{E}_T \\ (\nu H)(\nu H) & \Longrightarrow 4W + \not{E}_T,\ 2W + 2b + \not{E}_T \end{cases}$$

SIGNALS AND DETECTION

- Interesting multi lepton final states

$$\overline{N}N \to \begin{cases} 4\ell + \not{E}_T + X \\ 3\ell + 2j + \not{E}_T + X \end{cases}$$

- Small SM background for 4 lepton final states from $pp \to ZZ$.
- Dominant SM background for 3 lepton signal from $t\bar{t} + X, WZ$ and ZZ.
- Kinematic selection cuts where we demand that there are atleast 2 electrons in the final state.

$$\begin{array}{llll} p_T^e > 20 \text{ GeV} & & |\eta^\ell| < 2.5 & \Delta R_{\ell\ell} > 0.2 \\ p_T^\mu > 10 \text{ GeV} & & |\eta^j| < 3.0 & \Delta R_{\ell j} > 0.4 \\ p_T^j > 40 \text{ GeV} & \Delta R_{jj} > 0.7 & & 80 \text{ GeV} < M_{\ell^+\ell^-} > 100 \text{ GeV} \\ \not{E}_T > 20 GeV & & & \end{array}$$

- We have used CalcHEP+Pythia to generate the signal and background events for the final states using the CTEQ6L1 leading-order PDF's.

Signals and detection

Final state cross sections (fb)

	SM background	$M_N = 200$ GeV		$m_N = 300$ GeV	
		$M_{Z'} = 800$ GeV	$M_{Z'} = 1.0$ TeV	$M_{Z'} = 800$ GeV	$M_{Z'} = 1.0$ TeV
$\sqrt{s} = 14$ TeV					
$4\ell + \not{E}_T + X$	0.3	10.1	5.1	7.6	4.4
$3\ell + 2j + \not{E}_T + X$	17.8	76.3	36.6	56.1	30.2
$\sqrt{s} = 7$ TeV					
$4\ell + \not{E}_T + X$	0.09	2.72	1.2	2.33	1.02
$3\ell + 2j + \not{E}_T + X$	7.4	21.0	8.24	15.6	6.7

- The final states have large signal, small SM background
- We find that for $M_N = 500$ GeV and $M_{Z'} = 1.5$ TeV, the signal cross sections are still comparable to the SM background at $\sqrt{s} = 14$ TeV at LHC.

SUMMARY

- We have presented a model for neutrino mass generation through the inverse seesaw mechanism in the E_6 framework.
- We predict an extra neutral gauge boson at the TeV scale and heavy Dirac type neutrinos at the EW scale.
- We show that the heavy neutrinos can lead to clean multi-lepton final states at LHC with very little SM background.
- These heavy neutrinos can also effect Higgs signals at LHC.
- Absence of like-sign dilepton signal will distinguish these heavy states from models with EW scale Majorana type neutral leptons.