Lecture III

TESTING NEUTRINO PHYSICS AT LHC AND OTHER EXPERIMENTS
LHC Physics from the Neutrinos

- While high scale seesaw is most appealing, it is hard to test it directly by experiments!!

- Alternative lower seesaw scale is quite conceivable and have been considered and have direct LHC signatures!!

  - TeV scale seesaw and left-right symmetry;

- They lead to physics motivated by neutrinos that can be seen at LHC ?

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Three kinds of neutrino related LHC signals

• Possibility of Low Seesaw scale- TeV scale $W_R, Z'$, new Higgs etc.

• Sub-TeV scale doubly charged Higgs bosons in intermediate seesaw models

• Sparticle spectrum shift in high scale seesaw models.
Low Scale Parity Restoration and Left-right models

Details

Gauge group $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$

Matter: $SU(2)_L$ Doublets: $Q_L \equiv \begin{pmatrix} u_L \\ d_L \end{pmatrix}$; $\psi_L \equiv \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$;

$SU(2)_R$ doublets: $Q_R \equiv \begin{pmatrix} u_R \\ d_R \end{pmatrix}$; $\psi_R \equiv \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$

Higgs: $\phi(2, 2, 0) \equiv \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix}$;

$\Delta_R(1, 3, +2) \equiv \begin{pmatrix} \Delta^+ / \sqrt{2} & \Delta^{++} \\ \Delta^0 & -\Delta^+ / \sqrt{2} \end{pmatrix}$

$\mathcal{L}_Y = h_u \bar{Q}_L \phi Q_R + h_d \bar{Q}_L \bar{\phi} Q_R + h_e \bar{\psi}_L \bar{\phi} \psi_R + h.c.$

$+ f (\psi_R \psi_R \Delta_R + L \leftrightarrow R)$
Fermion masses

Masses arise from symmetry breaking

\[ < \phi^0 > = \begin{pmatrix} \kappa & 0 \\ 0 & \kappa' \end{pmatrix} \quad \text{and} \quad < \Delta^0_R > = v_R \]

\[ < \phi > \] gives masses to quarks and charged leptons only

\[ m_\nu \neq 0 \] arises from the seesaw matrix (coming up).
Limits on $W_R$ mass

No limit from beta and muon decays if $\nu_R$ is heavy and Majorana !!

Why? New process mediated by $W_R$ is:
$n \rightarrow p + e + \nu_R$; but $n\nu_R$ is heavy - so this does not occur.

Indirect effects:
Limit comes from $K_L - K_S$ mass difference, $\epsilon_K$ and $d_n$, all of which get new contributions from $W_R$ sector; these limits are based on assumptions and can be avoided !:

**Bottom-line:** One should search actively for TeV scale $W_R$ and $Z'$ in both LHC and possible ILC.
Collider signature of $W_R$ production with Majorana right handed neutrino

$\sigma_{pp \rightarrow W_R \rightarrow lN} \sim pb$ at $M_{W_R} \sim 800$ GeV;

Distinguishing signal- $pp \rightarrow jj\mu^-\mu^- + X$ from RH Majorana neutrino decay. Present collider limits from D0 and CDF collaborations: $M_{W_R} \geq 720$ GeV for the two jet two lepton mode.

Figure 17: like sign dileptons with two jets and no missing energy is a signature of $W_R$ production
New contribution to neutrinoless double beta decay

\[ W_L^{-} \quad U_{ei} \quad \nu_i \quad W_R^{-} \quad \nu_i \quad V_{ei} \quad e^- \]

**Bound on** $M_R$: $M_{WR} \geq 1.3 \text{ TeV} \left( \frac{M_N}{1 \text{ TeV}} \right)^{-1/4}$

**Usual nuclear matrix element uncertainty makes this bound reliable only within a factor of $\sim 2$ or so.**
LFV in TeV scale seesaw models

- One loop diagram mediated by $W_R$ and $M_R$:

\[
A(\mu \rightarrow e + \gamma) \simeq \frac{e G_F m_\mu m_e m_{N_R}^2}{\pi^2 m_{W_R}^2} \mu_B
\]

Figure 18: $\mu \rightarrow e + \gamma$ in non-SUSY nu-SM with low scale $M_R$
Leads to \( B(\mu \rightarrow e + \gamma) \sim \alpha \left( \frac{M_{WL}}{M_{WR}} \right)^4 \left( \frac{M_N}{M_{WR}} \right)^4 \sim 10^{-11} \) for \( M_{WR} \sim 3.2 \text{ TeV} \) and \( M_N \sim M_{WR} \sim 1/3 \)
Low $W_R$ at LHC

\[ \sigma_{pp \rightarrow W_R \rightarrow N} \sim \text{picobarn for } M_{W_R} \sim \text{TeV}; \text{ it goes down as } M_{W_R} \text{ increases; } 10^{-4} \text{ pb for 5 TeV mass.} \]

LHC search limit 5-6 TeV; Collot et al; ATLAS study group; few events in a year.
Light doubly charged Higgs Bosons

- A clear difference between SM, MSSM and LR sym. models is the presence of doubly charged Higgs bosons;

They can be light ($\sim 100$ GeV) if $W_R$ scale is low;

They can also be low if Seesaw scale is $10^{11}$ GeV but there is supersymmetry.

So one should look for them in colliders!!

- Decay modes: \( \Delta^{++} \rightarrow e^+e^+, \mu^+\mu^+, e^+\mu^+ \);  

Bounds from OPAL, CDF, DO searches: \( M_{\Delta^{++}} \geq 133, 136, 115 \) GeV’s for different modes.

- Constraints on couplings

  \( \Delta^{++} \rightarrow e^+e^+, \mu^+\mu^+, e^+\mu^+ \);

  PSI expt. has limit \( M_{\mu^+e^-\mu^-e^+} \leq G_F \times 10^{-3} \)

  \( \rightarrow \frac{f_{ee\mu\mu}}{M_{\Delta^{++}}} \leq 10^{-8} \) GeV.

  \( (g - 2) \) of muon \( f_{\mu\mu}^2 \frac{m_\mu^2}{M_{\Delta^{++}}^2} \leq 10^{-8} \)
Figure 19: Production cross section of $\Delta^{++}$ Higgs bosons in Tevatron.
SUSY $\rightarrow$ doubly charged fermions

![Graph showing production cross section for doubly charged Higgsinos at Tevatron.](image)

Figure 20: Production cross section for doubly charged Higgsinos at Tevatron.

$$\tilde{\Delta}^{++} \rightarrow \mu^+ + \tilde{\mu}^+ \rightarrow \mu^+ \mu^+ + \text{missing } E.$$
Neutrino mass and neutron-anti-neutron oscillation

Seesaw requires Majorana mass for RH neutrinos i.e. $\Delta L = 2$.

But the true symmetry is $(B - L)$; so $\Delta L = 2$ implies $\Delta (B - L) = 2$.

For processes involving hadrons, $\Delta (B - ) = 2$ implies $\Delta B = 2$ or $N - \bar{N}$ oscillation.

Two questions are:

(i) How to search for $N - \bar{N}$ oscillation?

(ii) Are there any decent theories where $N - \bar{N}$ oscillation time is measurable?
Experimental search for $\tau_{N-\bar{N}}$

Phenomenology of $N - \bar{N}$

$$i\hbar \frac{\partial}{\partial t} \begin{pmatrix} N \\ \bar{N} \end{pmatrix} = \begin{pmatrix} E_n & \delta m \\ \delta m & E_{\bar{n}} \end{pmatrix} \begin{pmatrix} N \\ \bar{N} \end{pmatrix}$$

(1)

$$P_{N\to\bar{N}} \sim \left( \frac{\delta m}{\Delta E_n} \right)^2 \sin^2 \Delta E_n t$$

Two cases

- Case (i): $\Delta E_n t \ll 1$: $P_{N\to\bar{N}} \sim (\delta m \cdot t)^2 = \left( \frac{t}{\tau_{N-\bar{N}}} \right)^2$
  - corresponds to free neutron oscillation;

- Case (i): $\Delta E_n \cdot t \gg 1$: $P_{N\to\bar{N}} \sim \frac{1}{2} \left( \frac{\delta m}{\Delta E_n} \right)^2$
  - corresponds to bound neutrons.
Curious coincidence

Stability of Nuclei to $\Delta B \neq 0$ should give a limit on $\tau_{N-\bar{N}}$:

To see what this is, note that for nuclei,

$$E_N - E_{\bar{N}} \sim 100 \text{ MeV; so}$$

$$\tau_{\text{Nucl.}} \sim \left(\frac{\delta m}{2\Delta E_n}\right)^{-2} 10^{-23} \text{ sec. This should be } \geq 10^{32} \text{ yrs.}$$

$$\rightarrow \delta m \leq 10^{-29} \text{ MeV or } \tau_{N-\bar{N}} \geq 10^8 \text{ sec.}$$

We will see that present reactor neutron fluxes are precisely in the right range to probe these values of $\tau_{N-\bar{N}}$. 
Reactor Search Expt. set-up: ILL (1994)

Key Formula for doing an expt.

\[ \text{\# of events} = N \left( \frac{t}{\tau_{N-N}} \right)^2 \times T \sim 1 \]

where \( N \) = reactor flux; \( v_N t \) = distance to detector; \( T \) running time.
Feasibility of further improvement

Maximum available reactor fluxes (100 MW reactor) $\sim 10^{13} - 10^{14}$ N/cm$^2$ sec.; for $t = 0.1$ sec. and $T \sim 3$ years can yield a limit of $10^{10}$ sec.

Need to ensure that there is a magnetic shielding to the level of $10^{-5}$ Gauss which is achieved by $\mu$-metal shielding.

Present limit from ILL, 1994- Baldoceolin et al.:
$\tau_{N-\bar{N}} \geq 8.6 \times 10^7$ sec.

New search effort and proposal by Y. Kamyshkov, M. Snow, A. Young et al., hep-ex/0211006 but no concrete site yet.
Comparison of free-neutron and bound-neutron methods

\[ \tau \text{ (free neutron), seconds} \]

\[ T \text{ (intraneutron transition), years} \]

- HFIR GOAL
- Super-K reach
- SNO reach
- Soudan II '02
- Kamiokande '86
- Grenoble '94
- UCN

Future N-Neutron Prospects

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Expectations for $\tau_{N-\bar{N}}$ in SUSY seesaw models

**Operator analysis**

No Supersymmetry and SM field content:

Effective operator: $\mathcal{O}_{\Delta B=2} = \frac{u^c d^c d^c u^c d^c d^c}{M^5}$;

\[ \delta m_{N\bar{N}} \sim \mathcal{O} \Lambda^6_{QCD} \]

and

\[ \delta m_{N-\bar{N}} = \frac{1}{\tau_{N\bar{N}}} \ (h\text{-bar}=1); \]

Present limit of $\tau_{N\bar{N}} \geq 10^8$ sec $\rightarrow$

$M \sim 10^{5.5}$ TeV.

Does it mean that $N - \bar{N}$ can only probe 100 TeV range scales?

Yes, if there is no supersymmetry; but things change drastically, if there is SUSY
SUSY and effective operator for $N - \bar{N}$

Supersymmetry introduces a new $\Delta B = 2$ operator that has lower dimension $(u^c d^c \tilde{u}^c \tilde{d}^c \tilde{d}^c / M^3)$ than the nonsusy case.

If the TeV scale theory has a scalar field of type $\Delta_{u^c u^c}$, then the effective operator is: $\Delta_{u^c u^c} d^c d^c \tilde{d}^c \tilde{d}^c / M^2$.

The combination of these two effects reduce the dependence on $M_{\text{seesaw}}$ making $N - \bar{N}$ observable even for high seesaw scale $\sim 10^{11} \text{ GeV.}$
Seesaw, $N - \bar{N}$ connection

- Neutrino mass is pure L-violation whereas $N - \bar{N}$ is baryon violating; how could they be related in an actual theory?

The connection is there once quarks and leptons are unified e.g. in a model with Pati-Salam $SU(4)_c$ or if there are interactions that connect quarks to leptons (unlike in the standard model).

- $SU(4)_c$ example:

$$F_{L,R} \equiv \begin{pmatrix} u & u & u & \nu \\ d & d & d & e \end{pmatrix}_{L,R}.$$

Recall seesaw mass arises from a B-L=2 multiplet which has quantum number of type $\Delta_{ll}$.

$$\Delta_R(1,3,+2) \equiv \begin{pmatrix} \Delta^+ / \sqrt{2} \\ \Delta^0 \\ -\Delta^+ / \sqrt{2} \end{pmatrix}.$$ 

In a quark-lepton unified theory, this has companions of type- $\Delta_{ql}$ and $\Delta_{qq}$;

The Feynman diagram responsible for $N - \bar{N}$ oscillation next page:
Diagram for $N - \bar{N}$ oscillation in $SU(4)_c$ models

- yields $\tau_{N-\bar{N}} \propto M_{\Delta qq}^5$; For $M_{\Delta qq} = 100$ TeV, $\tau_{N-\bar{N}} \sim 10^7 - 10^8$ sec. which is measurable

Since $M_{\Delta qq} \sim M_{\text{seesaw}}$, in a non-supersymmetric theories, $N - \bar{N}$ is observable in the low scale (i.e., 100 TeV) models.
Supersymmetric enhancement of $N - \bar{N}$

In SUSY $SU(4)_c$ models, some diquarks $\Delta_{ucuc}$ become 100 GeV scale even with high seesaw scale due to large accidental symmetries; e.g. suppose there is a B-L=2 triplet under SU(2). $W = S(\Delta\bar{\Delta} - M^2)$ has a global symmetry $SU(3, c)$; when SU(2) breaks down, more Goldstone bosons appear! This effect gets magnified when there is $SU(4)_c$. 
SUSY diagrams for $N - \tilde{N}$

New diagrams for $N - \tilde{N}$ appear and weaken the power dependence on the seesaw scale to $M^{-2}$ from $M^{-5}$.

$$G_{N-\tilde{N}} \sim \frac{f^3_{11}}{\lambda^2 M_{\text{seesaw}}^2 v_{\text{wk}}^3}$$

$$M_{\text{seesaw}} \sim 10^{11} \text{ GeV, typical } f, \lambda, \tau_{N-\tilde{N}} \sim 10^{10} \text{ sec.}$$
Diquarks are observable at LHC.

$\Delta^*_w u_c \rightarrow tt$ is the interesting mode since $t$ quarks are “easier” to observe at LHC.

**Signature:** $\Delta^*_w u_c \rightarrow tt, \ t_c, \ldots$

$tt \rightarrow jj\ell + missingE$
References for $N - \bar{N}$ oscillation

Nonsusy $SU(4)_c$ model: Marshak, RNM, PRL, 44 1316 (1980)

SUSY $SU(4)_c$:
(Chacko, RNM, 1999); Dutta, Mimura and RNM, (2005)
Babu, Nasri and RNM, PRL (2007).
Conclusions

Many interesting hints of new physics in neutrino data
Detailed nature of this new physics is still work in progress, although some things are becoming clear:

- Almost sure: Seesaw mechanism and right handed neutrinos!
- Seesaw scale still not completely clear-although the case for SO(10) like theory quite compelling
- Also strong hints of possible family symmetries e.g. $\mu - \tau$ exchange or $S_3$ symmetry to explain tri-bi-maximal mixing in data.
- Not clear whether it is symmetries or a dynamical mechanism doing large neutrino mixings (as in SO(10) models) !! Far deviations from maximality will point to a dynamical mechanism.
- searching for CP violation in the leptonic sector will clarify our understanding of one of the fundamental mysteries of cosmology i.e. origin of matter;
- we must be alert to any sterile neutrino effects.
Future is bright

New Era of Precision Neutrino Measurement Science –PNMS era– about to be lunched will determine neutrinos’ Majorana nature, $\theta_{13}$, mass ordering and create a new road-map for flavor physics beyond the standard model.
Extra stuff

\begin{itemize}
\item Limit on $W_R$ mass
\end{itemize}

Beall, Bender, Soni (82);

\begin{figure}[h]
\includegraphics{diagram}
\caption{Lower limit on $W_R$ in the minimal non-supersymmetric LR model. Red points from $\epsilon_K$ and Green and Blue points from $d_n$ for different values of $W_L - W_R$ mixing. From a recent analysis by Zhang, An, Ji, RNM (2007)}
\end{figure}

which gives a lower limit of 2.5 TeV in the minimal LR models with no supersymmetry.

Include SUSY or expand the Higgs sector, the limit goes Sub-TeV.