Neutrinos and the LHC

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June, 14-19, 2010

Neutrino mass→ New physics beyond SM:

Two generic Issues:

- **New mass scale to explain why** $m_{\nu} << m_{q,l}$ **?**

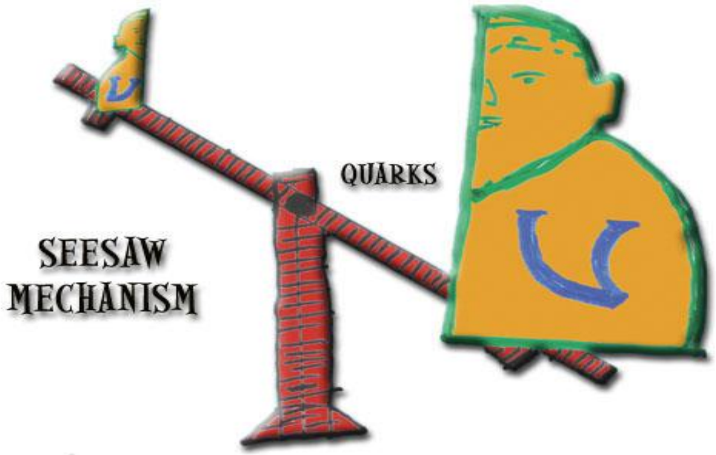
- **How to understand the flavor puzzle** :
Why quark and lepton mixing patterns are so different ?

- **Low energy probes**: Oscillations, $\beta\beta_{0\nu}$, $\mu \to e + \gamma$

- **Probing this new physics at LHC:→This talk**

Scale of new physics

- **Why is** $m_\nu << m_{q,l}$ **? Seesaw Paradigm:**
- **Add heavy right handed neutrinos** N **to SM and play seesaw:**

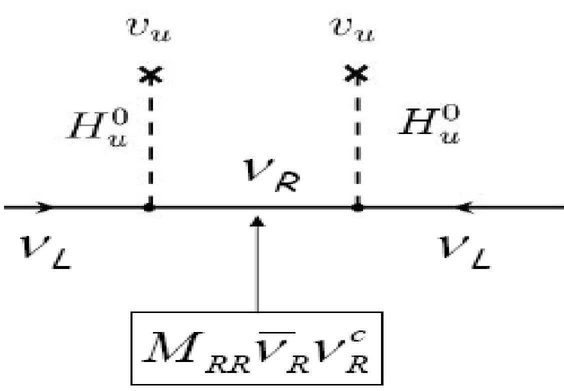


- **Seesaw scale is the new physics scale !!**
- Different experimental signatures depending on N Majorana or Dirac

Type I seesaw

- **Majorana** N

$$L_Y = h_\nu \overline{L} H N_R + M_R N N$$



- M_R New scale

$$m_\nu \cong -\frac{h_\nu^2 v_{wk}^2}{M_R}$$

-Neutrino majorana

→small nu mass natural since $M_R >> h v_{wk}$

$$\frac{m_D}{M_R} \equiv \frac{h_\nu v_{wk}}{M_R}$$ **key parameter to test seesaw** $\sim 10^{-7} - 10^{-10}$

- Minkowski,Gell-Mann, Ramond Slansky,Yanagida, Mohapatra,Senjanovic,Glashow

Inverse Seesaw

- **Mostly Dirac** N **i.e. add another singlet** S

$$L_Y = h_\nu \bar{L} H N_R + M\, S\, N_R + \mu SS \qquad \mu << M$$

$$(\nu_L, \nu_R, S)$$

$$\begin{pmatrix} 0 & hv_{wk} & 0 \\ hv_{wk} & 0 & M \\ 0 & M & \mu \end{pmatrix} \qquad m_\nu \cong -m_D^T M^{-1} \mu M^{-1} m_D$$

(RNM'86; RNM, Valle'86)

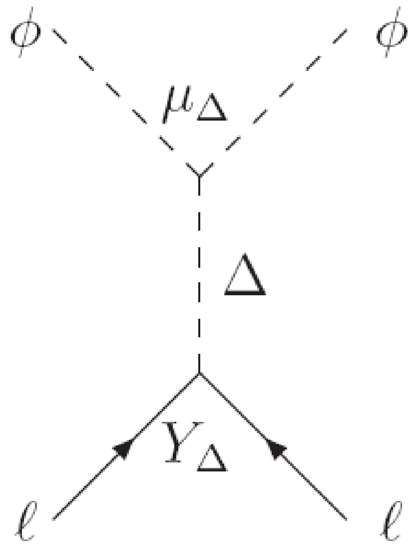
- Seesaw testing parameter $\frac{m_D}{M} \sim 10^{-3}$ or larger;

Seesaws without RH Nus

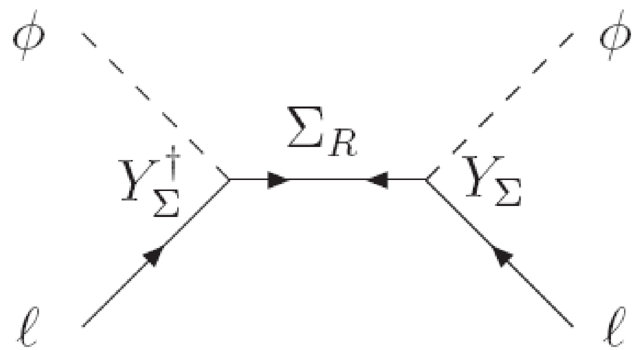
- **Type II** (scalar triplet) **Type III** (fermion triplet)

(Maag, Wetterich, Shafi, Lazaridis; RNM, Senjanovic; Schecter, Valle)

(Foot, He, Lew, Joshi)



$$m_\nu = -2Y_\Delta v^2 \frac{\mu_\Delta}{M_\Delta^2}\,.$$



$$m_\nu = -\frac{v^2}{2} Y_\Sigma^T \frac{1}{M_\Sigma} Y_\Sigma$$

- **Loop models** **(Babu, Zee,…)**

New seesaw related particles: Minimal case

- Type I and Inverse seesaw: **Right handed neutrinos:** N
- Type II: **Scalar bosons** $\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}.$
- Type III: **triplet fermions:** $\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}.$
- Loop models → particles similar to δ^{++}
- **If their masses (seesaw scale) are sub-TeV, LHC is ideal machine for their search:**

Decay modes:

- RH neutrino N : ~Dirac (Inverse) $N \to l^- W^+$
  Majorana (Type I) $N \to l^\pm W^\mp$
- Scalar triplet (Type II) $\Delta = \begin{pmatrix} \delta^+/\sqrt{2} & \delta^{++} \\ \delta^0 & -\delta^+/\sqrt{2} \end{pmatrix}.$ $\delta^{++} \to l^+ l^+, W^+ W^+$
  $\delta^+ \to l^+ \overline{\nu}, W^+ Z$
- Fermion triplet: (Type III) $\Sigma = \begin{pmatrix} \Sigma^0/\sqrt{2} & \Sigma^+ \\ \Sigma^- & -\Sigma^0/\sqrt{2} \end{pmatrix}.$ $\Sigma^0 \to l^+ W^-$
  $\Sigma^+ \to l^+ Z, ...$

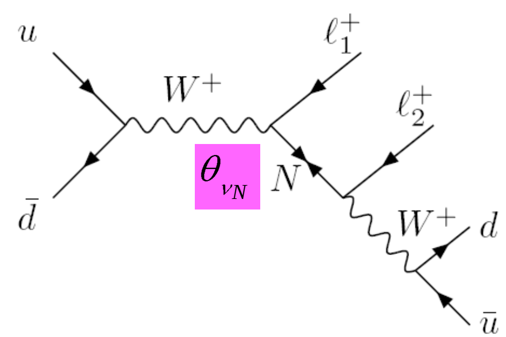
Collider Production:

- **Type II and type III**: New particles **couple** to W, Z and γ and can be produced via

$$q\bar{q} \rightarrow Z^*/\gamma^* \rightarrow \Sigma^+\Sigma^-, \quad \delta^{++}\delta^{--}$$
$$q\bar{q}' \rightarrow W^* \rightarrow \Sigma^+\Sigma^0, \quad \delta^{++}\delta^-$$

- **Type I and Inverse-N-** SM singlets,

do not couple to, W or Z-
Only production mode is via
nu-N mixing.



Testing Type II:

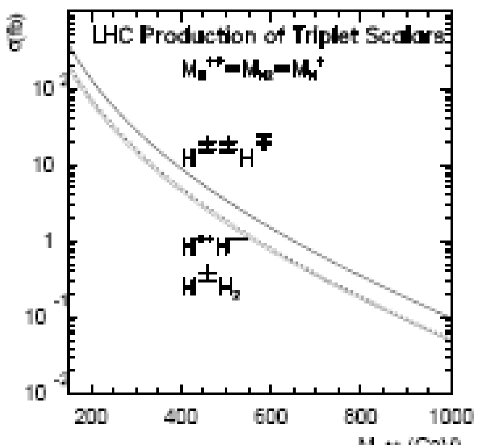
- Doubly charged member →Striking signal

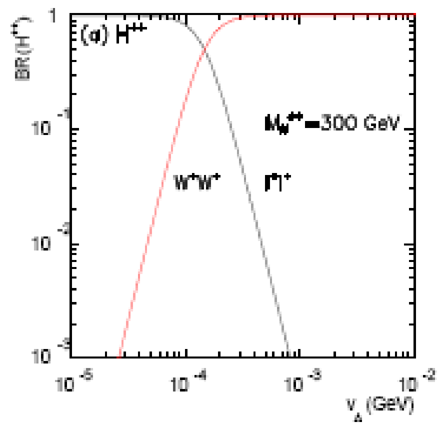
$$u\bar{u} \to \delta^{++}\delta^{--}; u\bar{d} \to \delta^{++}\delta^{-}$$

$$\delta^{++} \to l^+ l^+, W^+ W^+$$

Production

Decay





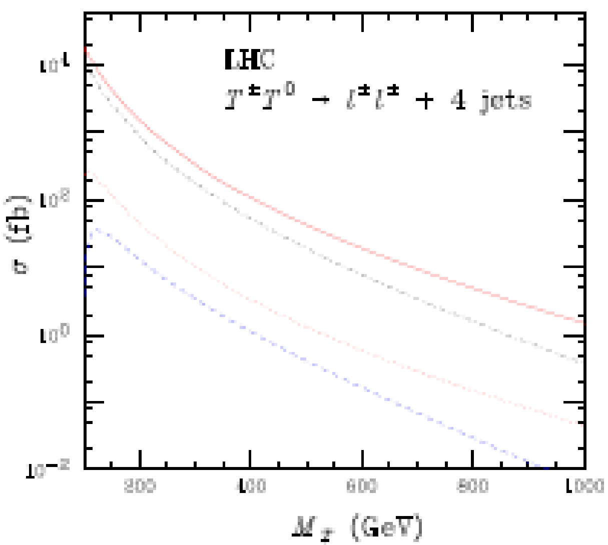
- Final state: $\ell^+\ell^+\ell^-\ell^-$ inv mass can be used to reduce bg.
- LHC reach ~TeV; leptonic couplings give nu mass matrix (roughly) (Han, Perez, Huang, Li, Wang; Akyroid, Aoki; Azuelos, Mukhopadhyay,)

Signals of Type III

- Y=0, fermion triplet: **(Bajc, Senjanovic, Nemesvek,..)**

$$q\bar{q} \rightarrow Z^*/\gamma^* \rightarrow \Sigma^+\Sigma^-$$
$$q\bar{q}' \rightarrow W^* \rightarrow \Sigma^+\Sigma^0$$

$$\Sigma^0 \rightarrow l^+W^-, \quad W^- \rightarrow jj$$



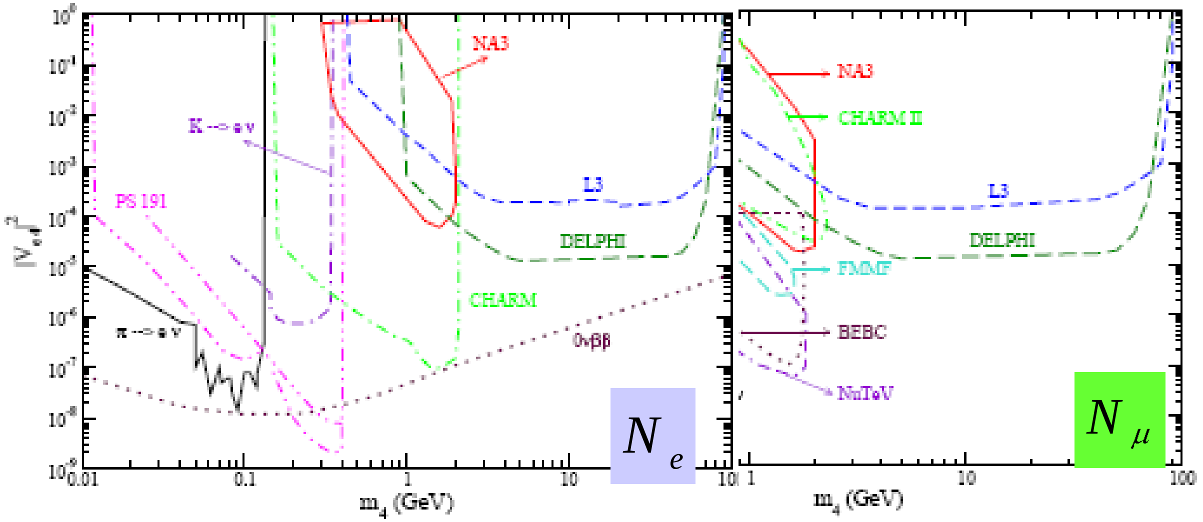
Like sign dileptons+ 4 jets

LHC Reach <TeV

Type I, Inverse: Need $\theta_{\nu N}$

- **Low energy bounds on** $\theta_{\nu N} = \frac{m_D}{M}$ **vs** M_N

FromNA3, CHARM,DELPHI, L3, NOMAD, double beta decay



Type I

$$\theta_{\nu N} \leq 10^{-6}$$

Atre, Han, Pascoli, Zhang

- Only observable for inverse seesaw for M_N< TeV

but does not reveal the Majorana nature ! **(Petcov, Molinaro'10)**

Situation different with new gauge forces

- **How plausible are new gauge forces ?**
- **Type I** : why seesaw scale below Planck scale: **Local B-L** symmetry
- **Inverse seesaw case**:
- **Why** $\begin{pmatrix} 0 & hv_{wk} & 0 \\ hv_{wk} & 0 & M \\ 0 & M & \mu \end{pmatrix}$ **why not** $\begin{pmatrix} 0 & hv_{wk} & h'v_{wk} \\ hv_{wk} & M' & M \\ h'v_{wk} & M & \mu \end{pmatrix}$
- **Case for new Gauge symmetry compelling !!**
- **LHC can see their signals !!**

What Gauge Symmetry ?

- **Standard model: gauge sym.** $SU(2)_L \times U(1)_Y$
- **Fermions:**

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \qquad \begin{matrix} u_R \\ d_R \end{matrix}$$

$$m_\nu = 0 \quad \leftarrow \quad \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad e_R$$

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- **N_R → Gauge group:**

$$SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$$

$$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \overset{P}{\Leftrightarrow} \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$$

$W_L^\pm$ $\quad W_R^\pm$ $\quad Z, Z', \gamma$

- **New** $\quad \uparrow$ ($W_R^\pm$) $\quad \uparrow$ (Z')

Additional motivation: Parity an exact symmetry of nature

- The weak Lagrangian of model:

$$L = \frac{g}{2}[\vec{J}_L^{\;\mu} \cdot \vec{W}_{\mu L} + \vec{J}_R^{\;\mu} \cdot \vec{W}_{\mu R}]$$

- **Weak Lagrangian conserves Parity**
- **Low energy parity violation due to**

$$M_{W_R, Z'} \gg M_{W_L, Z}$$

RNM, Pati, Senjanovic 74-75

Bound on LR scale

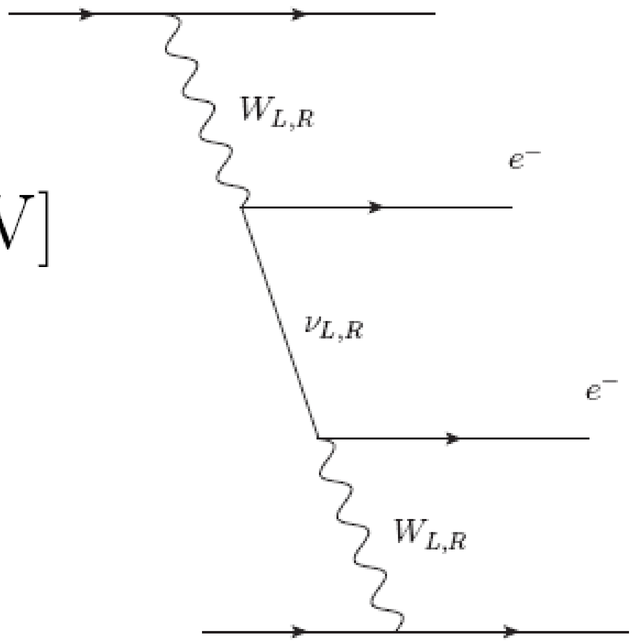
- Most stringent bounds come from CP viol. Observables e.g. $\varepsilon, \varepsilon', d_n^e$ depends on how CP is introduced:

Two minimal scenarios

- **Parity defined as usual:($\psi_L \leftrightarrow \psi_R$) minimal model:**
- $\theta_L^{CKM} = \theta_R$;2 CP phases $M_{W_R} \geq 4TeV$ **(An,Ji,Zhang,RNM '07)**
- **Parity as C (as in SUSY i.e. $\psi \leftrightarrow \psi^c$) $\theta_L^{CKM} = \theta_R$ more CP phases**
  (Maezza, Nesti Nemevsek,Senjanovic'10)
  $M_{W_R} \geq 2.5TeV$
- **With SUSY: bounds weaker: > 1-2 TeV** **(An, Ji, Zhang'08)**
- **Collider (CDF,D0) 640-750 GeV;**

Bounds from Nu-less double beta decay

- New contributions from WR-N exchange **(only for Case I)** (RNM, 86; Hirsch, Klapdor, Panella 96)
- **Diagram:**



$$\rightarrow \quad m_{W_R} \geq 1.1 \left(\frac{\langle m_N^{(V)} \rangle}{1\text{TeV}}\right)^{(-1/4)} [\text{TeV}]$$

From Ge76:

TeV Seesaw signal from $\beta\beta_{0\nu}$

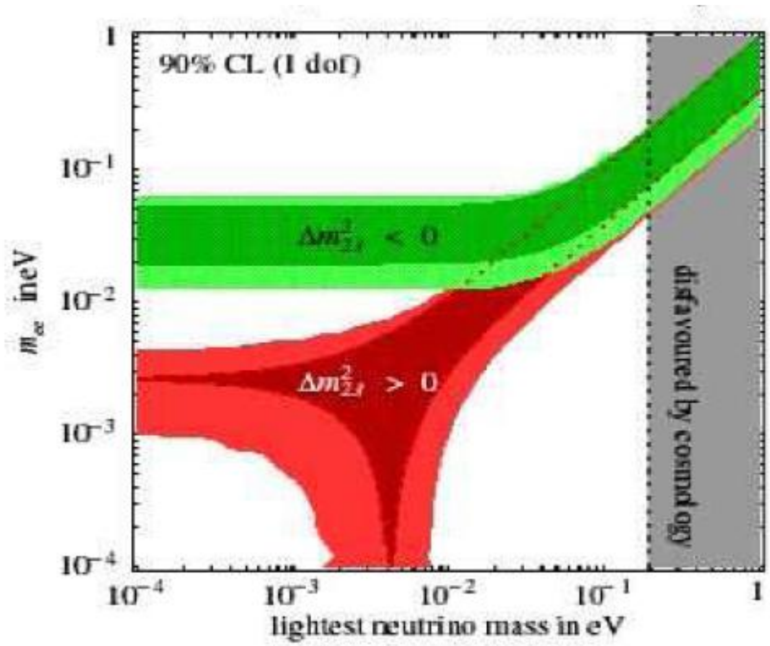
- **Nu contribution**:

  (Feruglio, Strumia, Vissani)

  Inverse hierarchy

  Normal hierarchy

  (Rodejohann's talk)



Punch line:

- **Suppose long baseline** → $\Delta m^2_{31} > 0$
- **and nonzero signal for** $\beta\beta_{0\nu}$ (+ RP if susy)

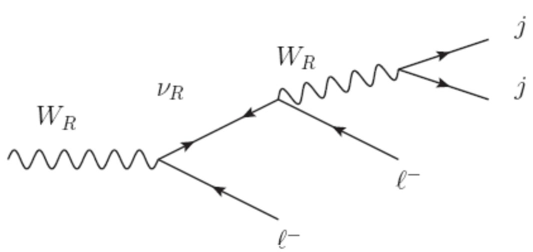
→could be a signal of TeV WR and type I

LR type I seesaw at LHC

- WR and Z': $u\bar{d} \to W_R \to l^+ N$; $u\bar{u} \to Z' \to NN$

(Keung, Senjanovic; Han, Perez,Huang,Li, Wang; Del Aguila, Aguilar-Saavedra; de Blas, Azuelos,

- N-decay: (a) νN mixing and/or (b) W_R exchange
- **type I** $\theta_{\nu N} << 10^{-3}, M_{W_R} < 4TeV$ (a) negligible; $N \to l^{\pm} jj$

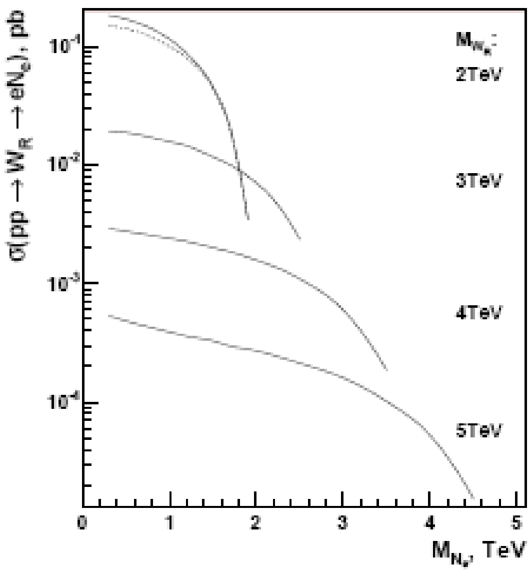


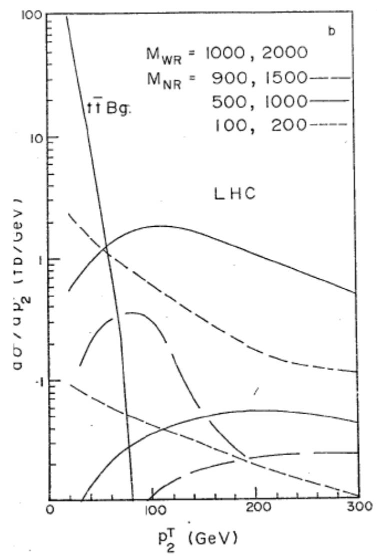
- **Signal: like sign dileptons+jets; no missing E**

Background from $t\bar{t}nj, WZnj, WWnj$,...

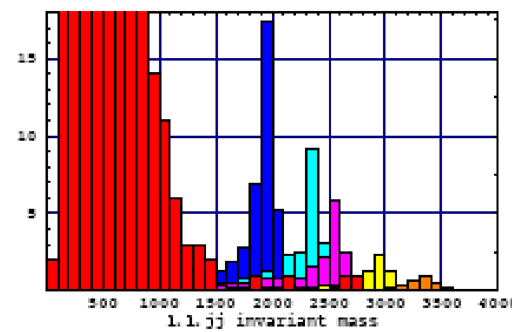
LHC Reach for WR

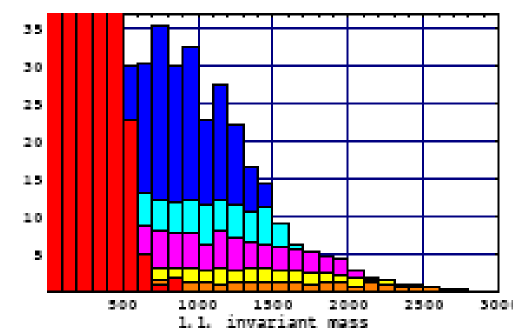
(Ferrari et al’00 ; Gninenko et al, 07) Datta, Guchait, Roy’92





Maleza, Nemevsek,Nesti, Senjanovic

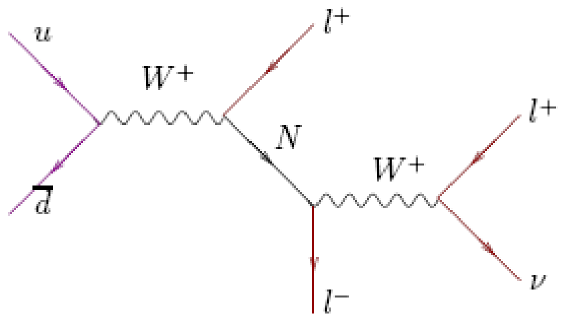




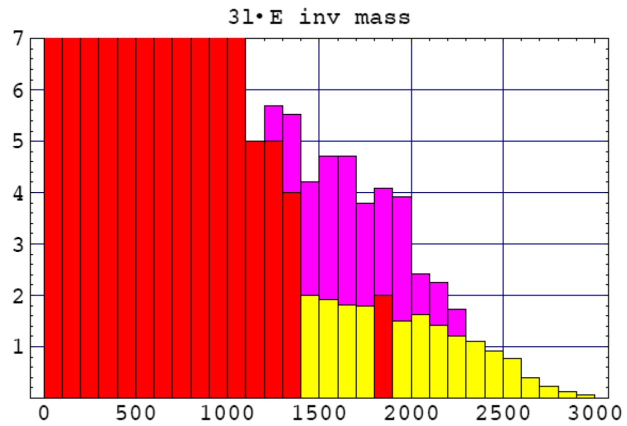
m_{W_R} [TeV]	m_{ν_R} [TeV]	$\int L$	energy
4 (2)	2 (1)	30 /fb	14(7) TeV
2.1 (1.5)	2.1	100/pb	14(10) TeV

Signals of LR Inverse seesaw

- **N mostly Dirac and** $\theta_{\nu N} > 10^{-3}$ $N \to l^- jj, l^- l^+ \nu$



$pp \to l^{\pm}_{\alpha} l^{\pm}_{\beta} l^{\mp}_{\gamma} \nu(\overline{\nu})$+jets



F.Nesti

- Possible displaced vertex

$$\tau_{\nu_R} \gtrsim 1\,\text{cm for } m_{\nu_R} \lesssim 10\,\text{GeV} \quad (m_{W_R} = 2.5\,\text{TeV})$$

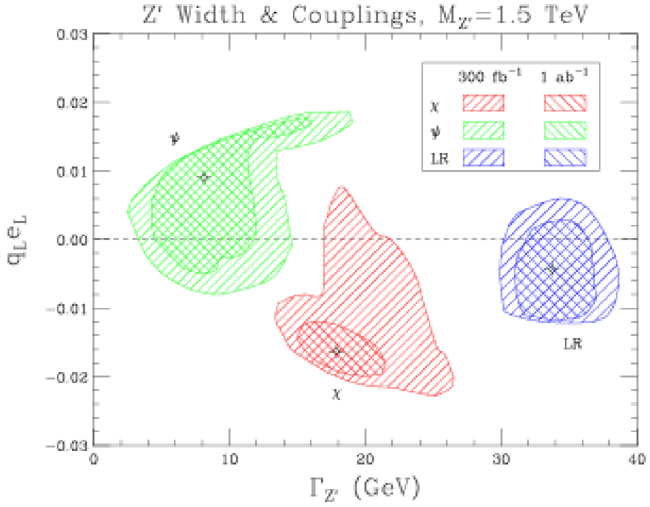
- Distinguishes between Type I and Inverse seesaw;

LR Z' at LHC

- Z' – first to show up at LHC; Current limit~TeV **(Langacker)**
- To tell it is related to neutrino mass (e.g. LR) is hard: couplings needed **(Petriello, Quackenbush'09)**

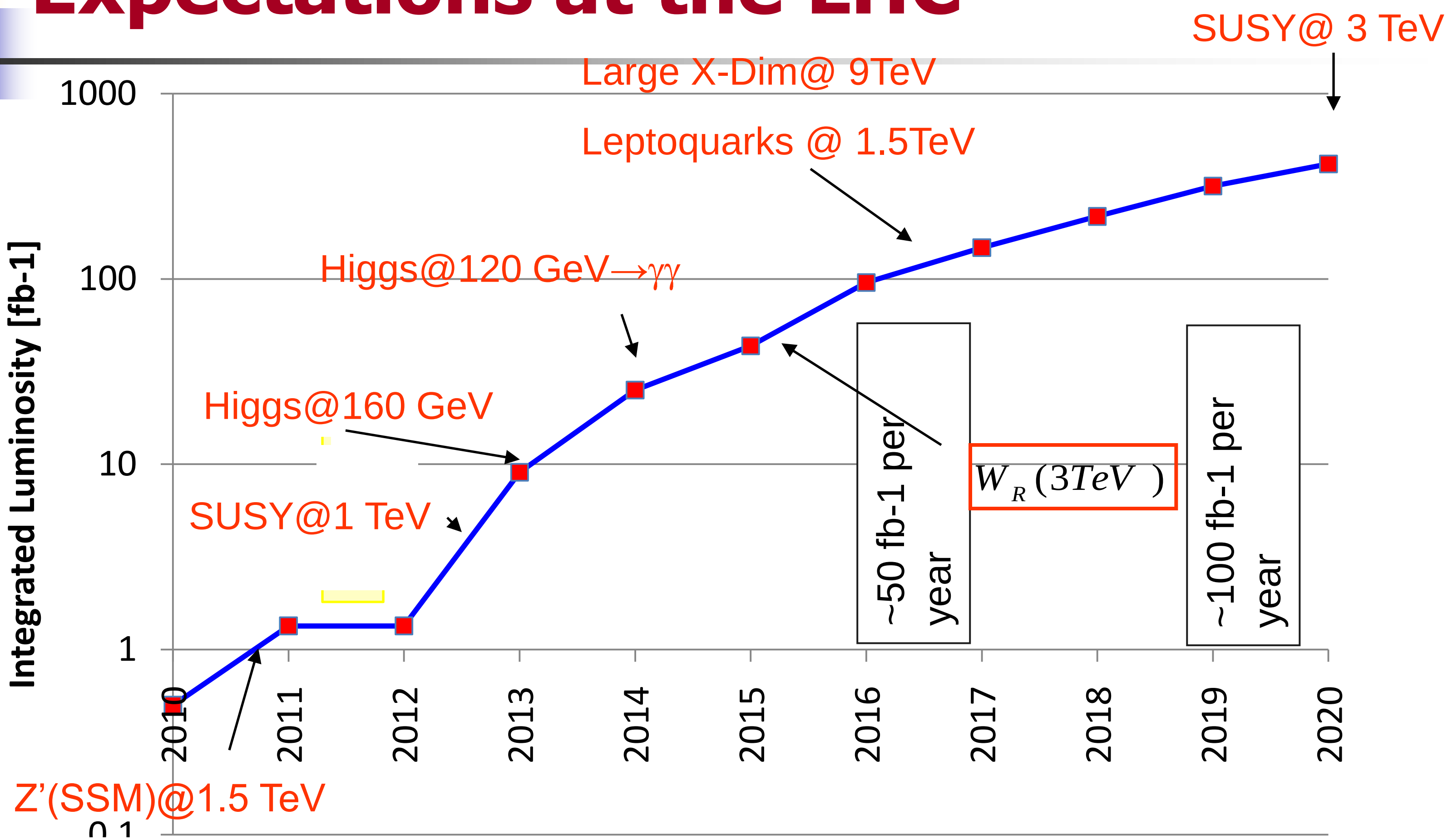
$\sqrt{s} = 10\,TeV\ , M_{Z'} = 1.5 TeV$

300 fb^-1-1000 fb^-1



- **Heavier the Z', the harder it is.**
- In minimal LR models $M_{Z'} > 1.3 - 1.7\, M_{W_R}$

Expectations at the LHC

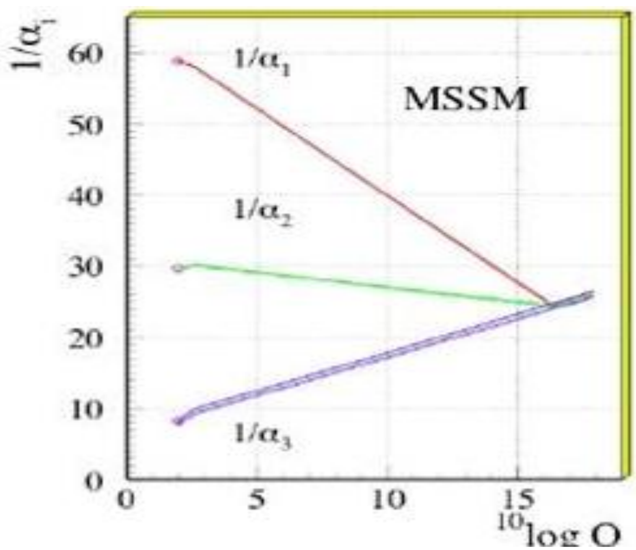


Physics updated from De Roeck

Luminosity projections - Jenni, 3/10 **(Dawson Pheno2010)**

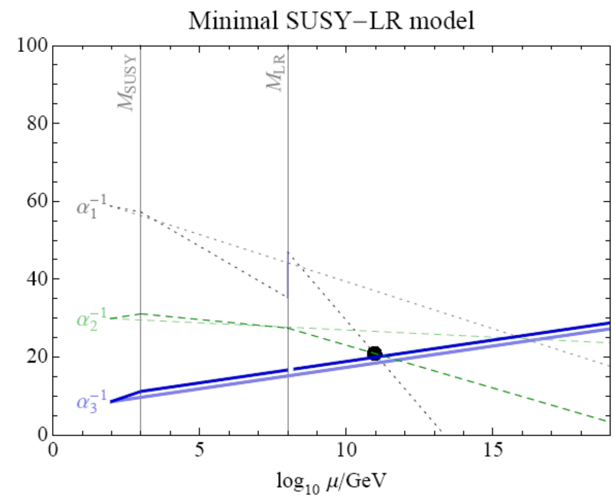
Seesaw at LHC:what can it tell us about Grand unification

- **MSSM**



Type I

seesaw



(Kopp, Lindner, Niro, Underwood'09; Parida, Sarkar, Majee, Raichaudhuri'09)

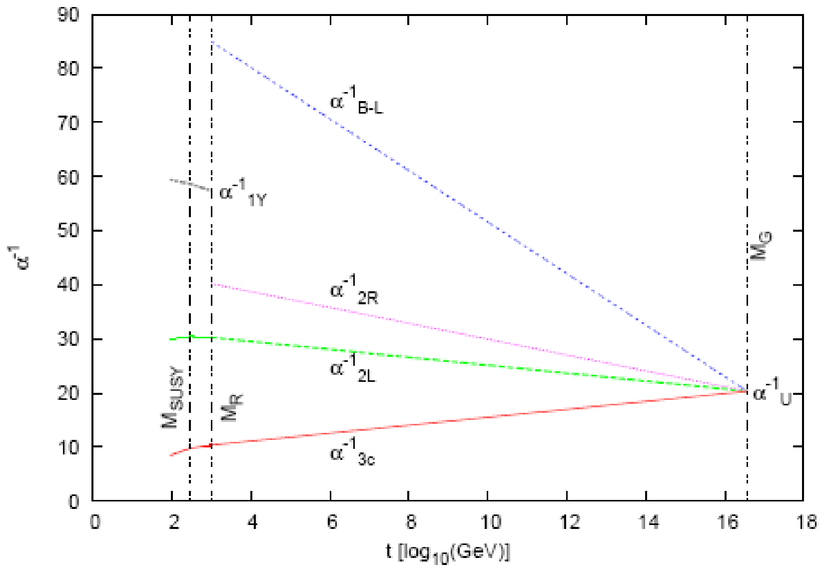
$$M_{U,BL} \cong 2 \times 10^{16}\ GeV$$

<u>**TeV type I seesaw does not grand unify:**</u>

Discovery of doubly charged Higgs or type I signal at LHC will rule out GUTs.

TeV Inverse Seesaw (LR) does unify

- New result! **Inverse seesaw** does unify –TeV WR and Z'



$$m_{\tilde{q}_{1,2}} \geq TeV$$

- $\bullet\ SO(10) \xrightarrow{M_G} 3_c 2_L 2_R 1_{B-L} \xrightarrow{M_R} 3_c 2_L 1_Y (\mathrm{MSSM}) \xrightarrow{M_{SUSY}} 3_c 2_L 1_Y (\mathrm{SM}) \xrightarrow{M_Z} 3_c 1_Q$

$$M_U \cong 10^{16}\ GeV\ ;\ M_{BL,R} \cong TeV$$

(Dev, RNM, 09; PRD; arXiv: 1003:6102);

- **New motivation to search for WR,Z' at LHC !!**

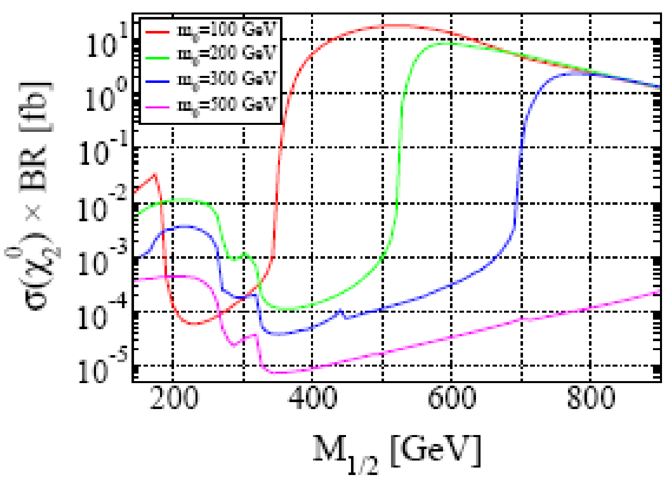
Testing GUT Scale Type I Seesaw

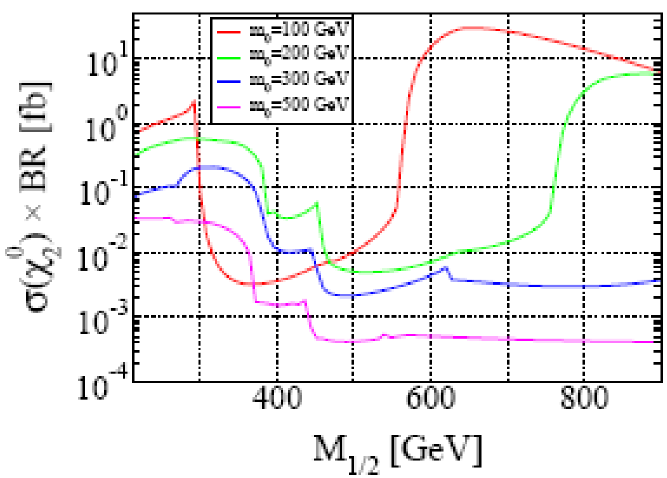
- In GUTs, type I seesaw scale is near GUT scale: no low energy tests.
- **With susy**, LHC tests possible: Neutrino mixing→ lepton superpartners mixing→ flavor violating signals

$$\tilde{\tau} \rightarrow e + \chi_1^0, \mu + \chi_1^0$$

$$\chi_2^0 \rightarrow \chi_1^0 + \mu^- + \tau^+$$

(Porod, Hirsch, Romao, Valle, Moral)





Conclusion:

- Seesaw scale can be in the TeV range in very reasonable class of theories (even SUSY GUTs)
- A likely model of TeV scale seesaw is left-right sym. model - parity restored at TeV.
- Premium channel for probing WR and Z' at LHC are like sign dileptons or trileptons.
- Discovery of TeV seesaw signal will provide an understanding of the origin of the second mass problem in particle physics, that of m_ν **-will surpass in impact the discovery of the Higgs boson !!**