LHC and the origin of neutrino mass

Goran Senjanović

ICTP

A. Maiezza, M. Nemevšek, F. Nesti

experiment

$\Downarrow$

tiny neutrino mass: $1/30\,\mathrm{eV} \leq m_\nu \leq 1\,\mathrm{eV}$

$\Downarrow$

$m_\nu \ll m_e$ - interesting puzzle?

window to new physics

Neutrino mass in the standard model

Fermi-like effective: Weinberg $d = 5$ operator

$$\mathcal{L} = Y_{eff} \frac{LHHL}{\Lambda}$$

L - lepton doublet   H - Higgs doublet

$$m_\nu = Y_{eff} \frac{v^2}{\Lambda} \qquad \text{neutrino mass} \; - \text{Majorana}$$

perturbative cut-off: $\Lambda \simeq 10^{14} GeV$

- clue why $m_\nu \ll m_e$?
- case for new physics

Violation of Lepton Number : $\Delta L = 2$

- neutrino-less double beta decay $\nu 0\beta\beta$ a text-book fact

Racah '37; Furry '38

- same sign charged lepton pairs in colliders

Keung, G.S., '83

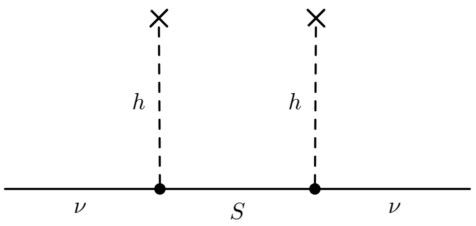
at which scale: Λ=?

Fermi $\rightarrow$ renormalizable W picture

Origin of neutrino mass: seesaw

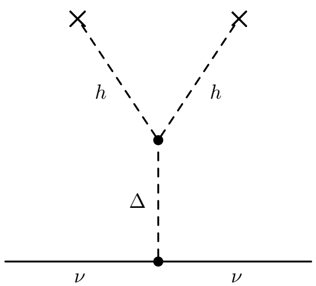
Single set of new particles

- fermion singlet $S_F = N$ $(Y = 0)$: Type I



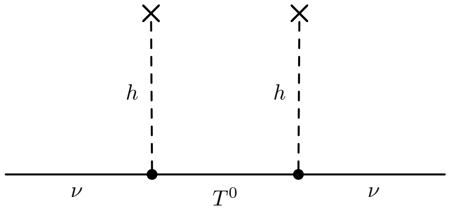
Minkowski, '77; Mohapatra, G.S., '79
Gell-Mann et al, '79; Glashow, '79; 'Yanagida, 79

- boson weak triplet Δ $(Y = 2)$: Type II



Lazarides et al, '80; Mohapatra, G.S., '80

- fermion weak triplet T_F $(Y = 0)$: Type III



Foot et al, '86

standard lore (especially I and II)

More useful than Weinberg d=5 operator?

weak interactions: perturbative cut-off 300 GeV

effective Fermi **V-A theory**

Marshak, Sudarshan; Feynman, Gell-Mann '58

until we had a theory behind → Standard Model

The theory behind seesaw?

L-R symmetry

Pati, Salam; Mohapatra, G.S. '74

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

- $W_L \Rightarrow W_R$: LR at high energy
- $\nu_L \Rightarrow \nu_R$: massive neutrinos
- seesaw: connects m_ν to scale of LR restoration

$$m_N \propto M_{W_R} \quad \Rightarrow \; m_\nu \propto M^2_{W_L}/M_{W_R}$$

Minkowski, Mohapatra, G.S.

V-A limit:

$$M_{W_R} \text{ infinite} \Rightarrow \text{neutrinos massless}$$

idea of P restoration as old as of P violation

Lee, Yang '56

mirror fermions

$$f_{L(R)} \leftrightarrow F_{R(L)}$$

3 more generations: V + A?

Gell-Mann, Minkowski '75

Gell-Mann, Ramond, Slansky '79

Wilczek, Zee '82

G.S., Wilczek, Zee '84

Berezhiani, Mohapatra '90's

L - R theory: neutrino mass and seesaw

(both type I and II)

L number violation

LHC?

Model content: bidoublet $\phi \sim (h_{light}, H_{heavy})$, triplets Δ_L, Δ_R,

$$\langle \Delta_L \rangle = \begin{pmatrix} & \\ v_L & \end{pmatrix}, \qquad \langle \Delta_R \rangle = \begin{pmatrix} & \\ v_R & \end{pmatrix}, \qquad \langle \phi \rangle = \begin{pmatrix} v & \\ & v' \end{pmatrix}$$

spontaneously with $v_L \ll v' < v \ll v_R$.

Mohapatra GS '75 '81

- Quark, Dirac lepton masses from $\bar{\psi}_L (Y_\phi \phi + \tilde{Y}_\phi \tilde{\phi}) \psi_R$

$$M_u = |v| \, Y_\phi + |v'| e^{i\alpha} \tilde{Y}_\phi$$

$$M_d = |v'| \, Y_\phi + |v| e^{i\alpha} \tilde{Y}_\phi$$

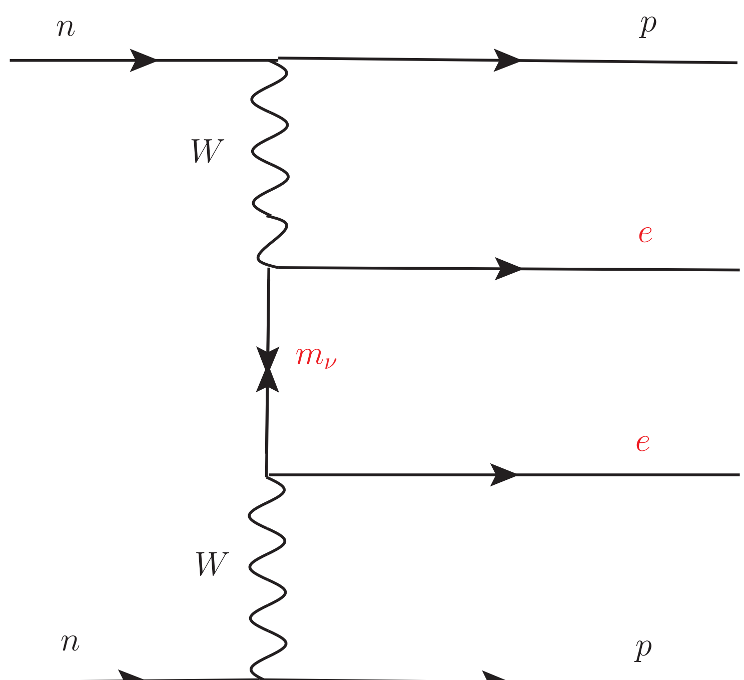
- Majorana neutrino masses, in addition to Dirac

$$m_{LL} = Y_\Delta \langle \Delta_L \rangle \quad \ll \quad m_{RR} = Y_\Delta \langle \Delta_R \rangle$$

- Spectrum: W_R, ν_R, $\Delta_{L,R}$ in the TeV region?
- H should be very heavy (tree-level FC)

Senjanović, GS '80, ..., Zhang et al '07

Neutrino-less double beta decay



$$^{76}\mathrm{Ge} \not\to {}^{76}\,\mathrm{As}\; e\bar{\nu}$$

$$^{76}\mathrm{Ge} \to {}^{76}\,\mathrm{Se}\; ee$$

Racah, '37; Furry, '38

Majorana '37

$$\mathcal{A}_{LL} \propto \frac{m_\nu}{p^2} \leq 10^{-8} GeV^{-1}$$

$$(p \simeq 100 MeV)$$

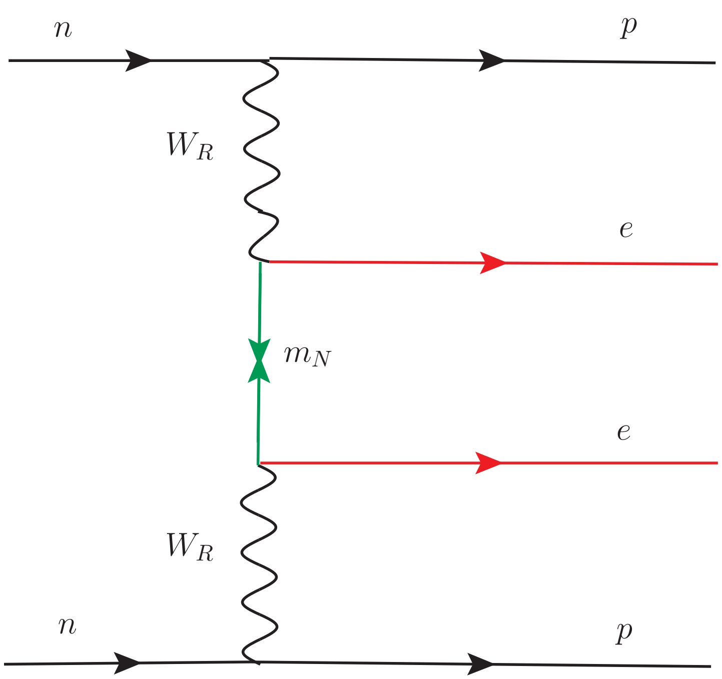
In general m_ν not directly connected to $\nu 0\beta\beta$ decay:

depends on the completion of the SM

Example:

LR symmetry with low W_R, ν_R masses: a nonzero $\nu 0\beta\beta$ decay

even with y_D, $m_\nu \to 0$



$$\mathcal{A}_{RR} \propto \left(\frac{M_L}{M_R}\right)^4 \frac{1}{M_N} \simeq 10^{-8} GeV^{-1}$$

$M_R \simeq 2.5\,\text{TeV}$ & $M_N \simeq 100\,\text{GeV}$

Mohapatra, G.S. '80

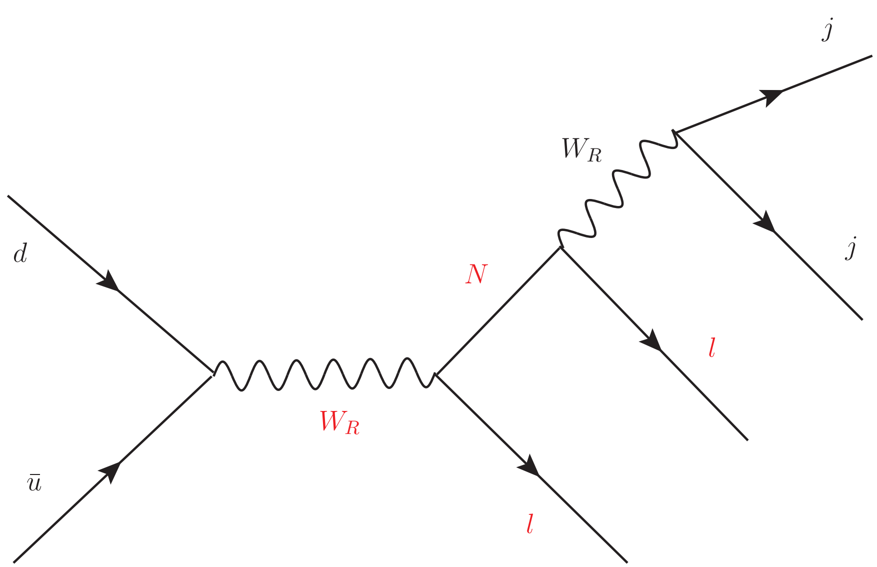
Colliders

To trace see-saw : **measure $\Delta L = 2$ in colliders**

Keung, G.S., '83

produce right-handed neutrinos

through W_R



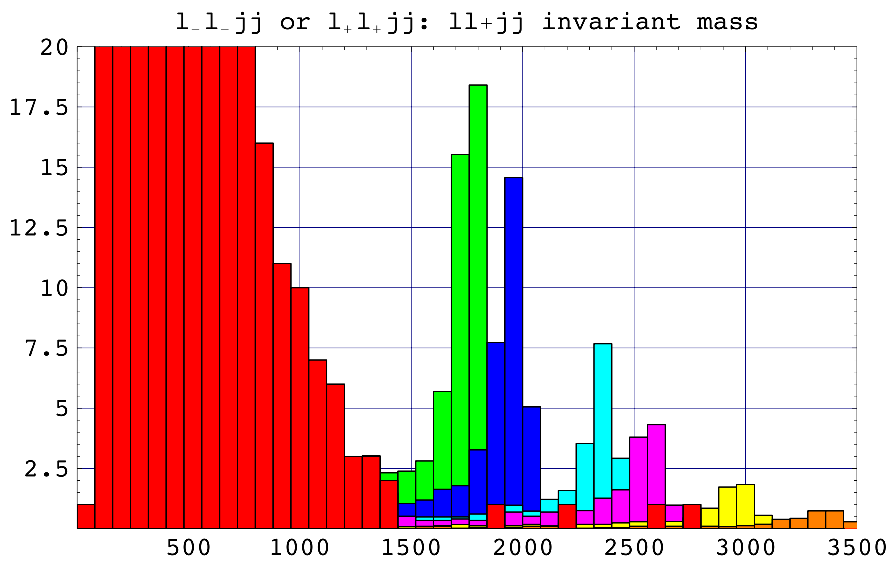
- **direct test of parity restoration**
- **direct test of lepton number violation**
- **determination of W_R and N masses**

Search at LHC

$W_R \to$ **4 (2) TeV** **and** ν_R **in 100 - 1000 GeV**

14 (7) TeV and integrated luminosity of 30 fb^{-1}

Ferrari et al, '99; Gninenko et al, '07

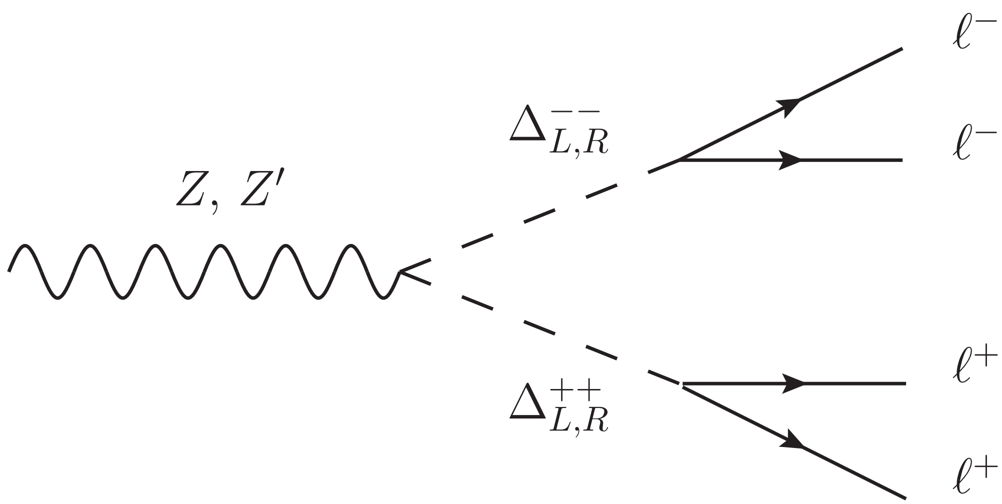


# of events for $\mathrm{L} = 8\mathrm{fb}^{-1}$

$\mathrm{M_R}(TeV)$

$1.8;\ 2,0;\ 2.4;\ 2.6;\ 3.0;\ 3.4$

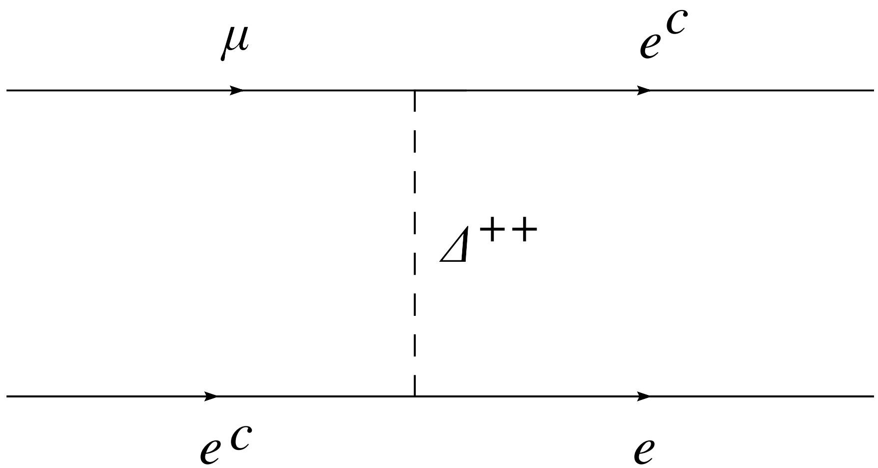
Nesti, talk at CERN Collider meeting '09 and parallel talk



$$\propto (Y_\Delta)_{ij}(Y^*_\Delta)_{kl}$$

$$Y_\Delta = \frac{g_R}{M_{W_R}} V_R^T M_N V_R$$

LFV and $0\nu\beta\beta$



$$B(\mu \to 3e) = \frac{|Y_{e\mu} Y_{ee}^*|^2}{4G_F^2} \left(\frac{1}{M_{\Delta_L}^4} + \frac{1}{M_{\Delta_R}^4} \right)$$

$$Y_\Delta = \frac{g_R}{M_{W_R}} V_R^T M_N V_R$$

No predictions - Requires LHC

Ghosh, Nemevšek, Nesti, Tello, Zhang, GS - in progress

Type II

$$V_R = K_e V_L^*$$

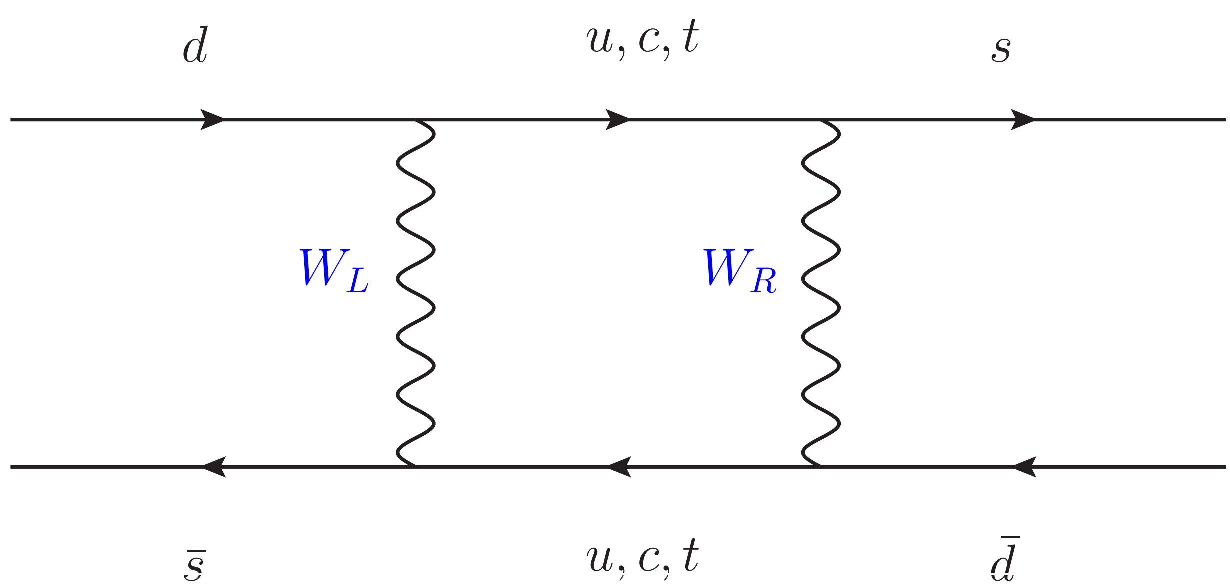
$$\Downarrow$$

predictions

Nemevšek, Nesti, Tello, GS to appear

Limits on M_R

- **direct limit:** $M_R \geq 800\,\mathbf{GeV}$ **(from dijets@DO)**
- **strong sensibility from** $K_L - K_S$ **mass difference**



huge enhancement - around 1000 - over LL

Beall, Bander, Soni '81

Mohapatra, G.S., Tran '83

parallel talk by Nemevšek

depends on LR symmetry

- **LR = P (parity) - canonical**

  hermitian Yukawas: $V_L = V_R$ **- up to phases**

  best limit claimed: combined EDM and ϵ'

$$\boxed{M_{W_R} \gtrsim 4\,\mathbf{TeV}}$$

Zhang, An, Ji, Mohapatra '07

even stronger limit claimed

$M_{W_R} \gtrsim 10\,\mathbf{TeV}$

Xu, An, Ji '09

$\Rightarrow$ **LR NOT@LHC?**

recently revisited:

$$\boxed{M_{W_R} \gtrsim 3\,\mathbf{TeV}}$$

Maiezza, Nemevšek, Nesti, G.S. '10

- **LR = C (charge conjugation)**

symmetric Yukawas: $V_L = V_R^*$ **- up to phases**

best limit from $K_L - K_S$**:**

$$M_{W_R} \geq 2.5\,\textbf{TeV} \qquad M_{Z_R} \geq 4\,\textbf{TeV}$$

Maiezza, Nemevšek, Nesti, G.S. '10

parallel talks by Nesti, Nemevšek

$\Downarrow$

LHC reach

additional motivation:

the tension regarding CP violation in the B_s and B_d systems

disagreement with SM at the level of few sigma, but going up and down

UTfit: Bona et al '08

could be relieved in LR theory - needs more work

it would correlate the W_R and new Higgs masses

parallel talks by Nemevšek, Nesti

Simple predictive GUT with measurable seesaw?

What is the minimal realistic GUT?

Minimal SU(5)

Georgi-Glashow model: $24_H + 5_H$

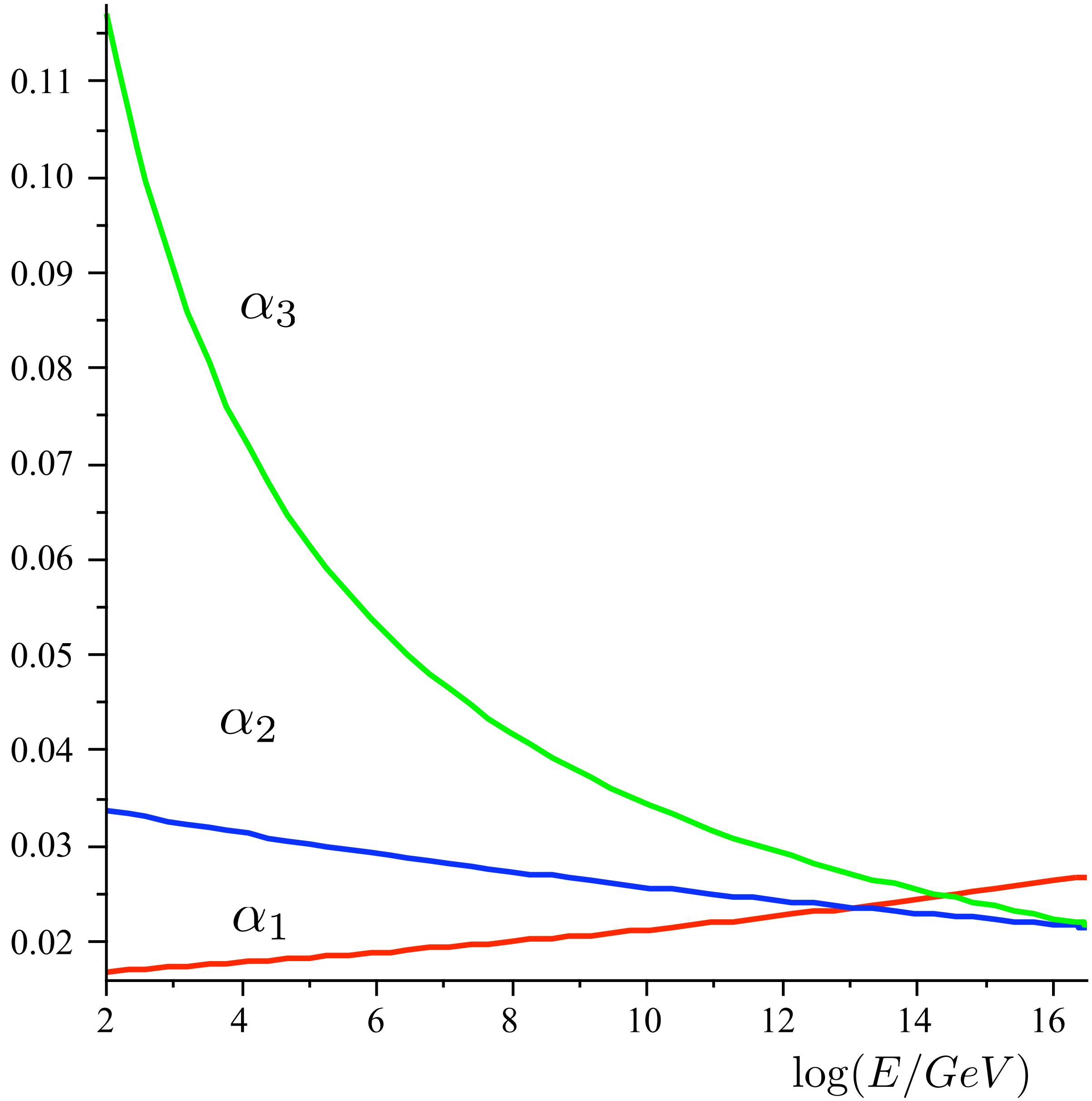
$3(10_F + \overline{5}_F)$

ugly: asymmetric matter, fine-tuning

- but predictive

RULED OUT

1. **gauge couplings do not unify**
   - **2 and 3 meet at 10^{16} GeV (as in susy),**
   - **but 1 meets 2 too early at $\approx 10^{13}$ GeV**
2. **neutrinos massless (as in the SM)**



0.11
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
α_3
α_2
α_1
2
4
6
8
10
12
14
16
$\log(E/GeV)$

Add just one extra fermionic 24_F

Bajc, G.S., '06 ; Bajc, Nemevsek, G.S., '07

maintains the ugliness of the minimal model

asymmetric matter,

even more fine tuning,

$\Rightarrow$ **but also its predictivity**

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

$$24_F = (1,1)_0 + (1,3)_0 + (8,1)_0 + (3,2)_{5/6} + (\bar{3},2)_{-5/6}$$

singlet S **triplet** T

$$\mathcal{L}_{Y\nu} = L_i \left(y_T^i T + y_S^i S \right) H + h.c.$$

Mixed Type I and Type III seesaw:

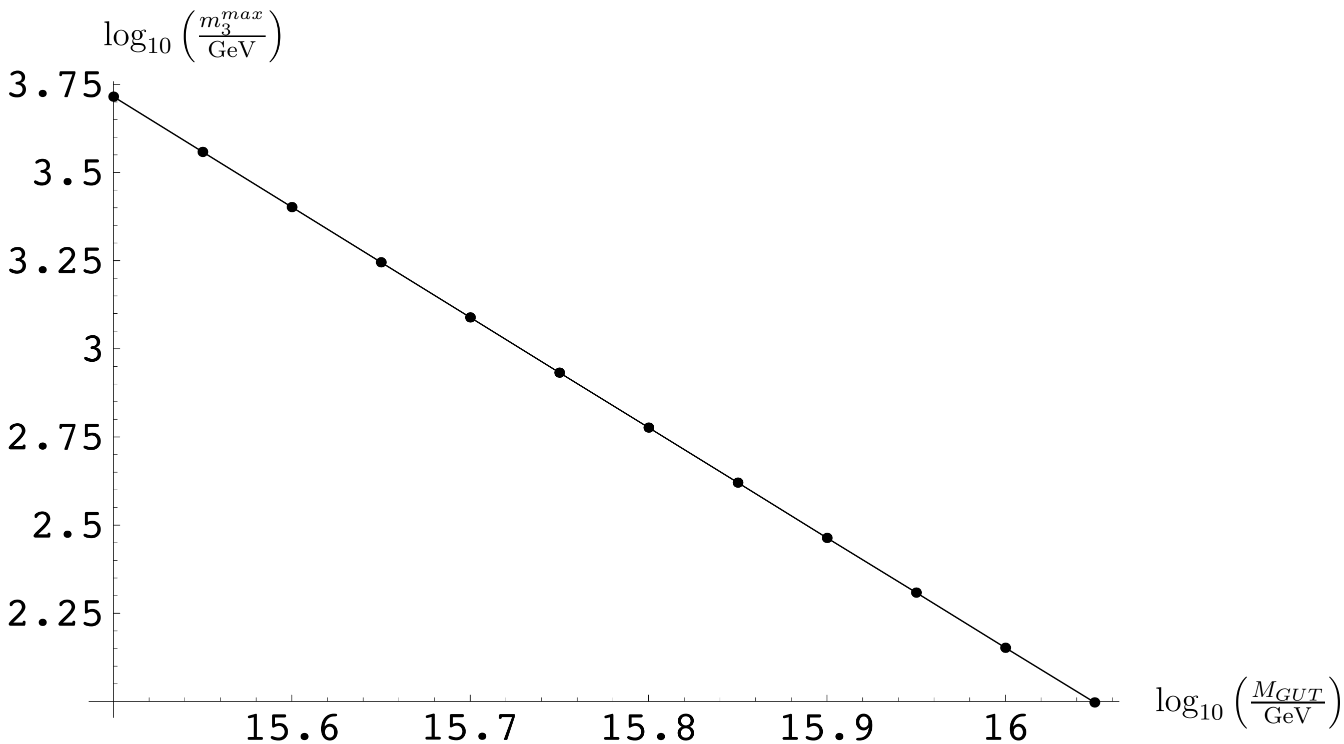
$$M_\nu^{ij} = v^2 \left(\frac{y_T^i y_T^j}{m_T} + \frac{y_S^i y_S^j}{m_S} \right)$$

$\Rightarrow$ **one massless neutrino** $\rightarrow$ **hierarchical spectrum**

$$M_{GUT} \gtrsim 10^{15.5}\ \textbf{GeV}\ \textbf{(p decay)}$$

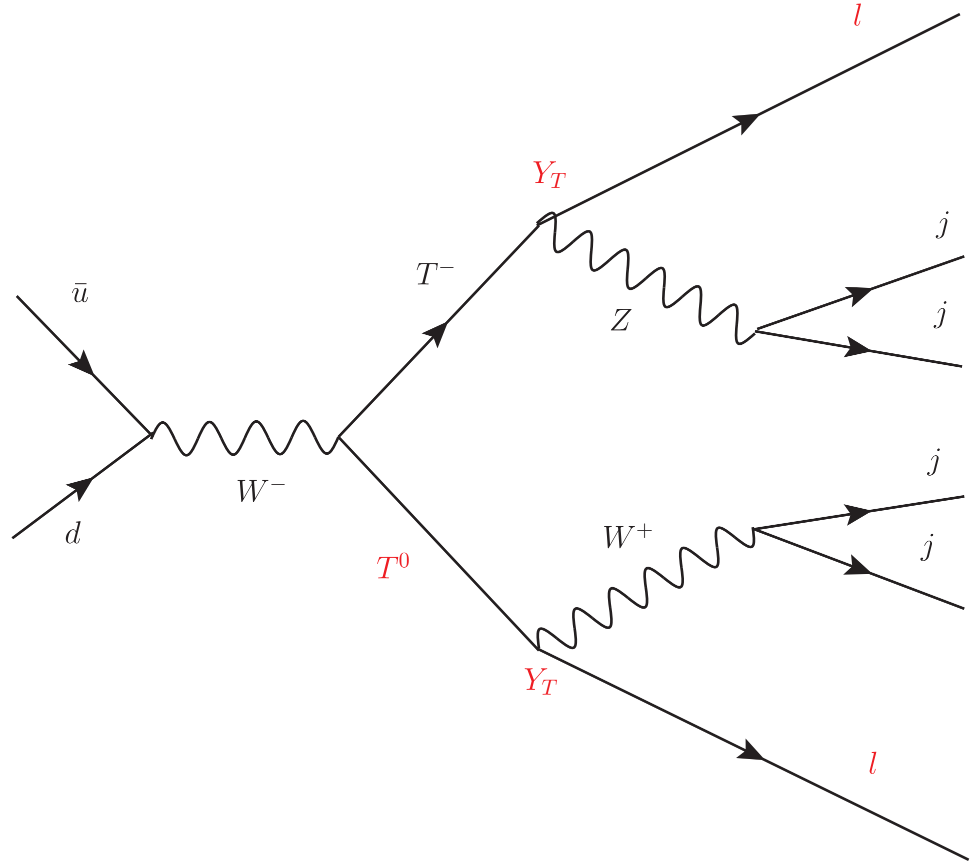
$$\Rightarrow m_3 \lesssim 1\text{TeV}$$

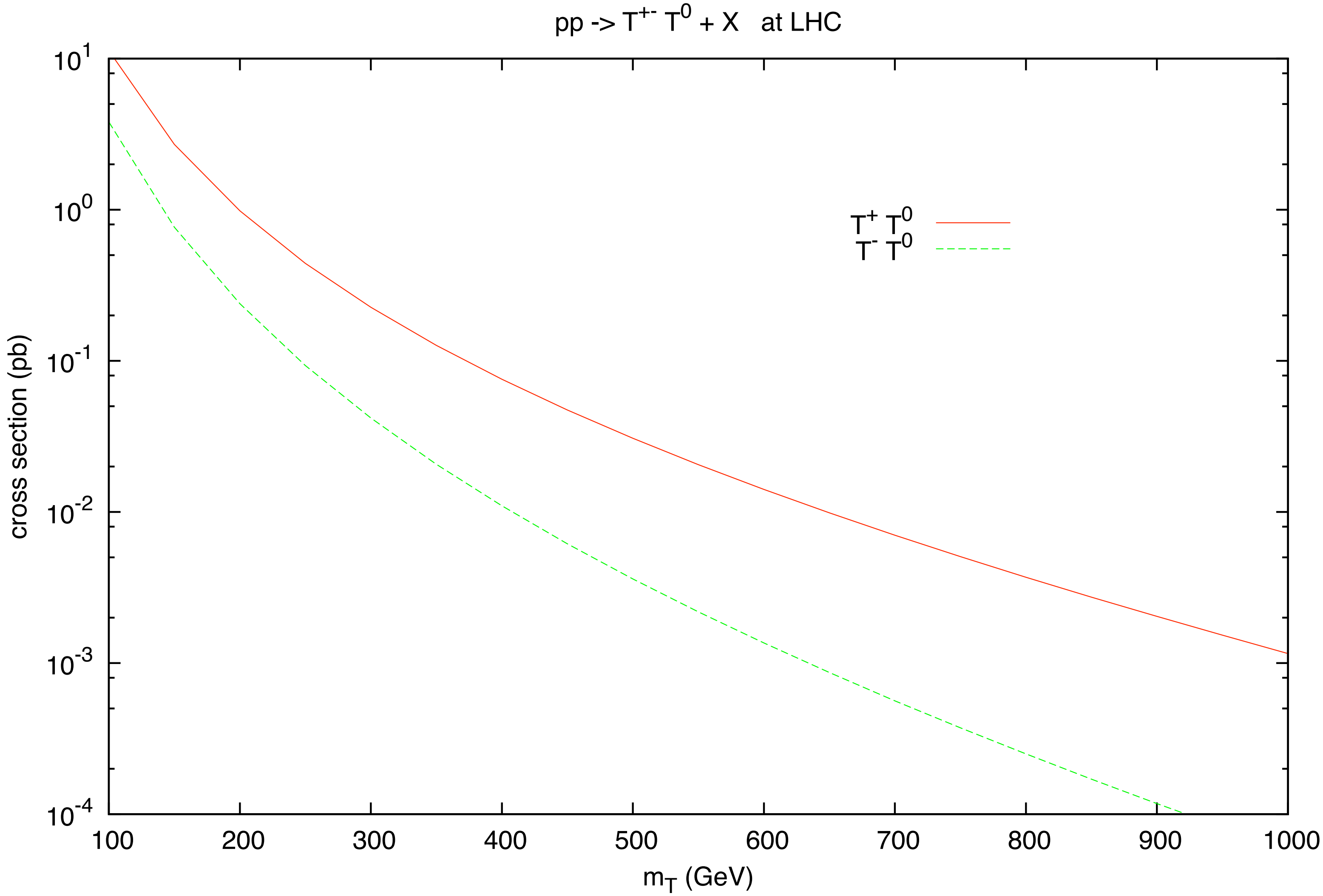
$m_3^{max} - M_{GUT}$ at two loops



Seesaw at LHC

(T^+, T^0, T^-): **weak triplet**




pp -> T+- T0 + X at LHC
cross section (pb)
m_T (GeV)
T+ T0
T- T0
10^1
10^0
10^-1
10^-2
10^-3
10^-4
100
200
300
400
500
600
700
800
900
1000

Probing neutrino parameters

$\Gamma_T \approx m_T |y_T|^2$ $\tau_T \leq \left(\frac{200 GeV}{M_T}\right)^2 0.5\,\mathrm{mm}$

The best channel is like-sign dileptons + jets

$$BR(T^\pm T^0 \to l_i^\pm l_j^\pm + 4\ \mathrm{jets}) \approx \frac{1}{20} \times \frac{|y_T^i|^2 |y_T^j|^2}{(\sum_k |y_T^k|^2)^2}$$

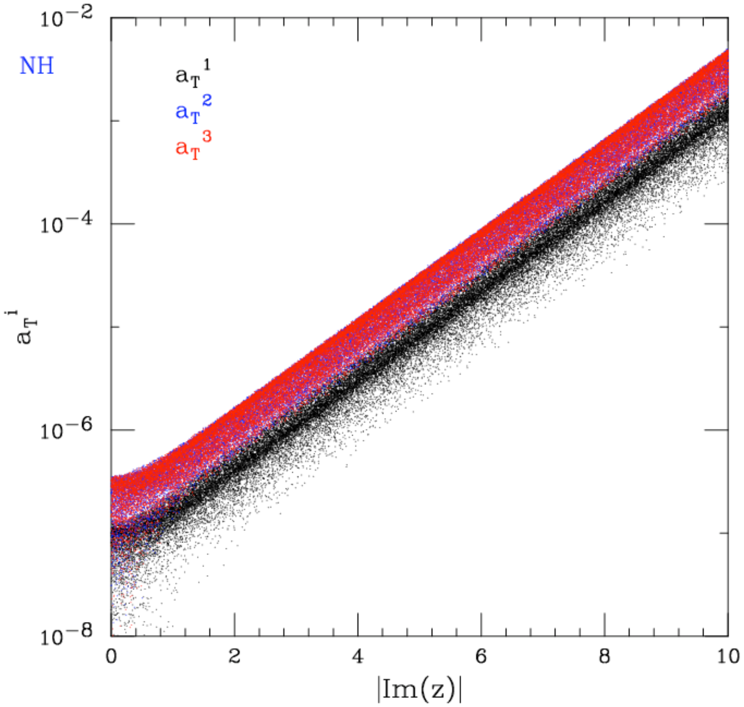
Same couplings y_T^i contribute to

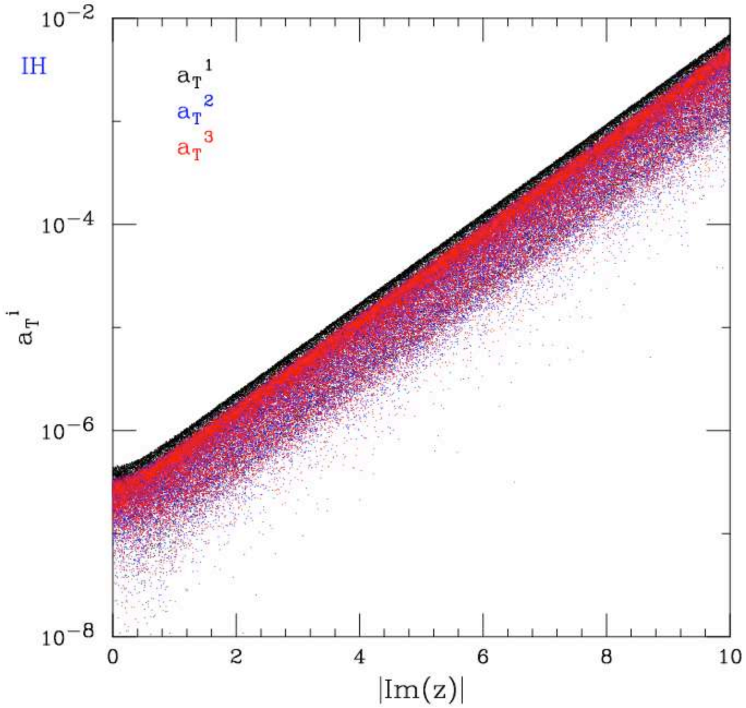
ν mass matrix and T decays

$$v y_T^{i*} = \begin{cases} i\sqrt{M_T}\left(U_{i2}\sqrt{m_2^\nu}\cos z + U_{i3}\sqrt{m_3^\nu}\sin z\right), & \mathrm{NH} \quad (m_1^\nu = 0), \\ i\sqrt{M_T}\left(U_{i1}\sqrt{m_1^\nu}\cos z + U_{i2}\sqrt{m_2^\nu}\sin z\right), & \mathrm{IH} \quad (m_3^\nu = 0). \end{cases}$$

Casas, Ibarra '01; Ibarra, Ross '03

Scanning over whole parameter space

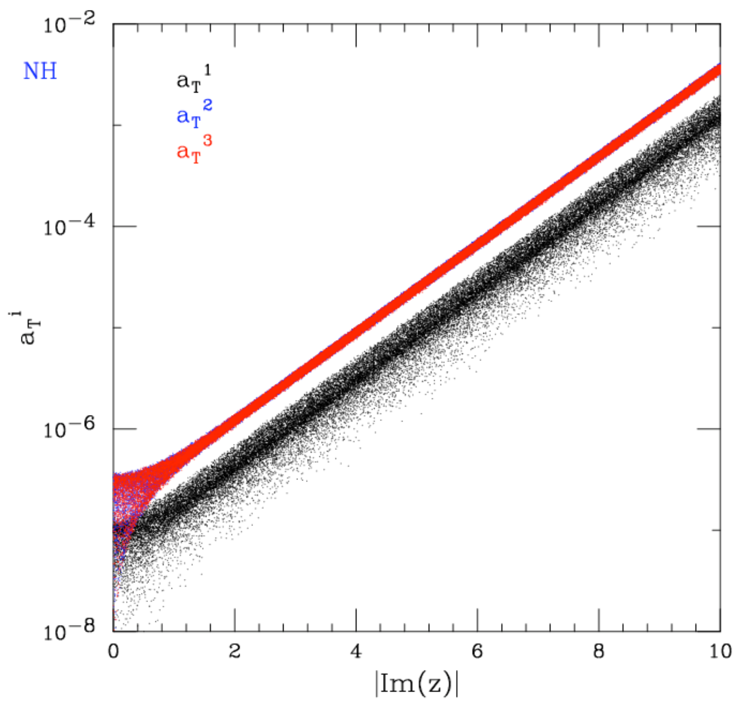


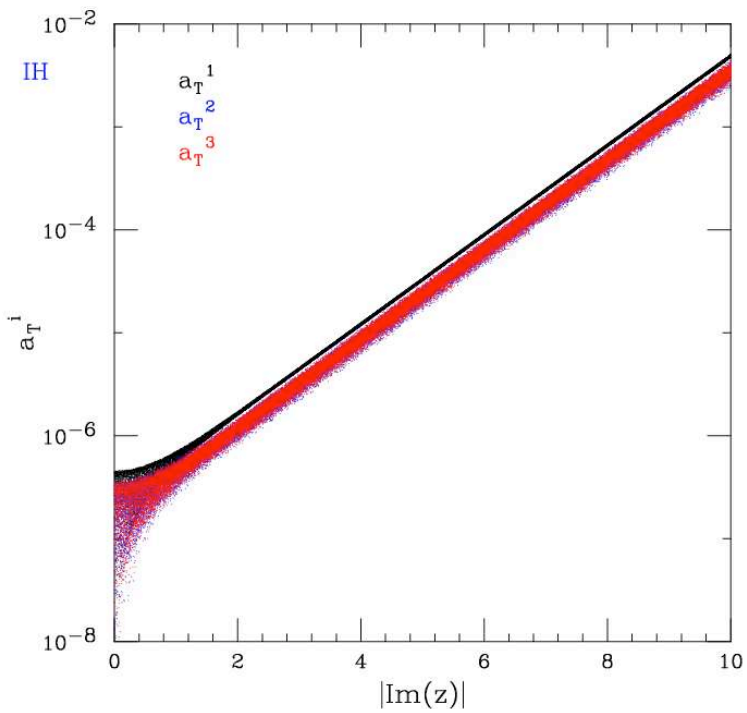


normal hierarchy **inverse hierarchy**

$$a_T^i \equiv \left|y_T^i\right| \sqrt{\frac{v}{2M_T}}$$

Assuming Majorana phase $\Phi = 0$





normal hierarchy **inverse hierarchy**

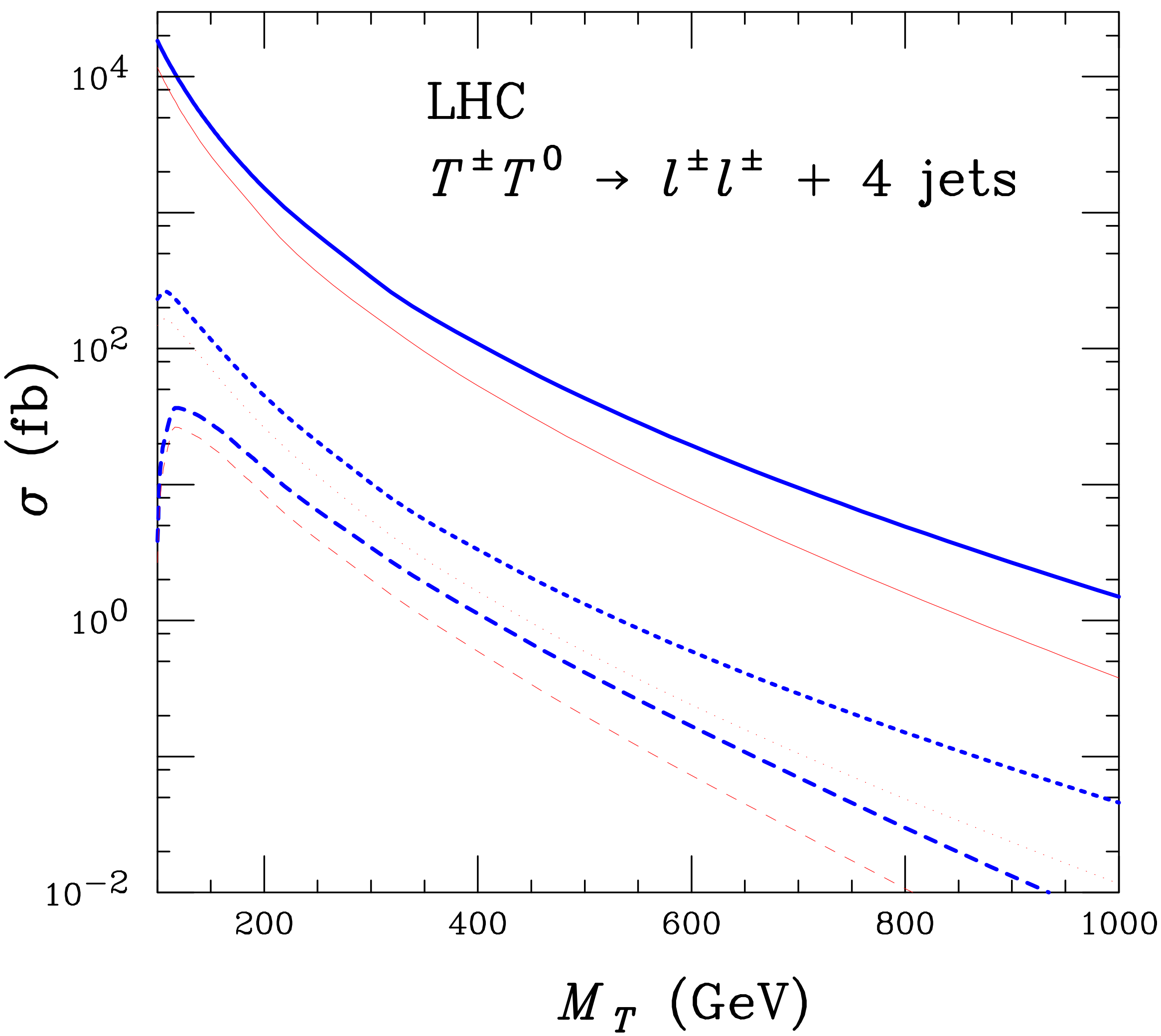
$$a_T^i \equiv \left|y_T^i\right| \sqrt{\frac{v}{2M_T}}$$

Incremental increase of cuts on the signal ($M_T = 200$ GeV):

Cuts $\Downarrow$	$\sigma_{\text{sig.}}$(fb)
$p_T(\ell) > 15$(GeV)	**35**
$p_T(jets) > 20$ (GeV)	**20**
$\mid \eta(\ell) \mid < 2.5$	**16**
$\mid \eta(jets) \mid < 3$	**14**
$\Delta R_{\ell\ell} > 0.3$	**13.8**
$\Delta R_{\ell j} > 0.5$	**12**
$\Delta R_{jj} > 0.5$	**10**

Francheschini, Hambye, Strumia '08; del Aguila, Aguilar-Saveedra '08

Arhrib, Bajc, Ghosh, Han, Huang, Puljak, G.S. '09 '10



14 TeV **10 TeV**

Dotted: branching fraction.

Dashed: selection cuts.

Conclusions

- **experimental probe of Majorana neutrino mass origin**
  lepton number violation at LHC – a high energy analogue of neutrino-less double beta decay
- **L-R theory: possible discovery of $W_R \to 4\,$TeV**
  $\nu_R \to$ TeV through LR restoration and L violation
- **explicit example of a predictive GUT theory**
  SU(5) with a fermionic adjoint
- **weak fermionic triplet predicted in the TeV range**
  LHC@14 TeV $\to$ 450 (700) GeV with $L = 10(100) ft^{-1}$
- **possible to get information on unmeasured neutrino parameters**

R measures separations

$$R = [(\Delta\phi)^2 + (\Delta\eta)^2]^{1/2}$$

where $\Delta\phi$ and $\Delta\eta$ are the azimuthal angular separation and (pseudo) rapidity difference between two particles