Neutrino masses and LHC

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G.-Y.Huang, I.Puljak, G.Senjanović, 09

Outline

- Short introduction to the seesaw mechanism
- The general strategy
- The case of Type I seesaw
- The case of Type II seesaw
- The case of Type III seesaw
- No seesaw at LHC from SO(10) ?

- The minimal non-supersymmetric SU(5)
  - Why is the Georgi-Glashow SU(5) ruled out?
  - Add a fermionic 24_H: light triplet predicted
  - Neutrino masses
  - Triplet decays
  - Triplet production at LHC
  - probing the neutrino parameters at LHC
- Conclusions

Short introduction to the seesaw mechanism

With the degrees of freedom of the SM

ν masses parametrized by Weinberg $d = 5$ effective operator

$$\mathcal{L} = Y_{ij} \frac{L_i H H L_j}{M}$$

In the basis with diagonal charged leptons

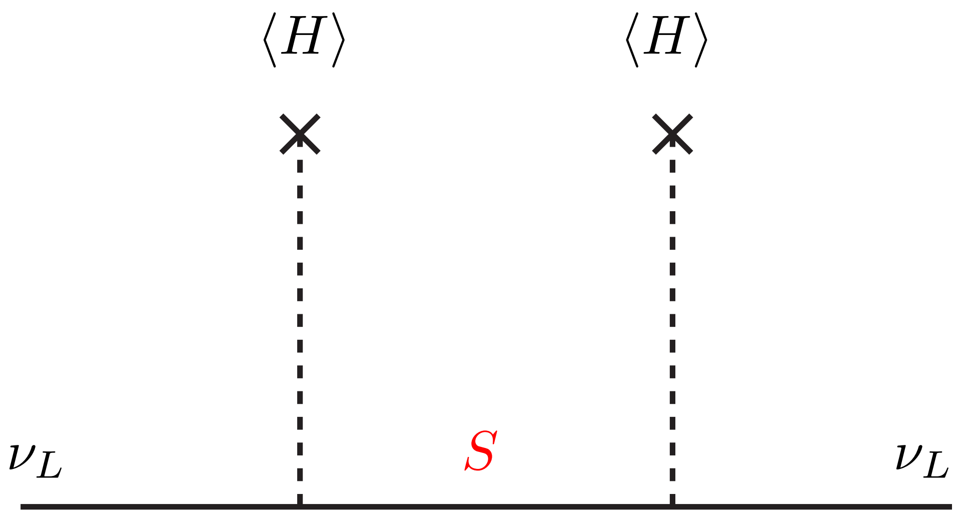
$$\frac{v^2}{M} Y = U_{PMNS}\ m_\nu^{diag}\ U_{PMNS}^T$$

- Y describes flavour structure
- M signals the appearence of new physics

Only 3 ways of producing the Weinberg operator:

by exchange of 3 types of heavy particles fermion singlet $S = (1,1,0)$

TYPE I SEESAW



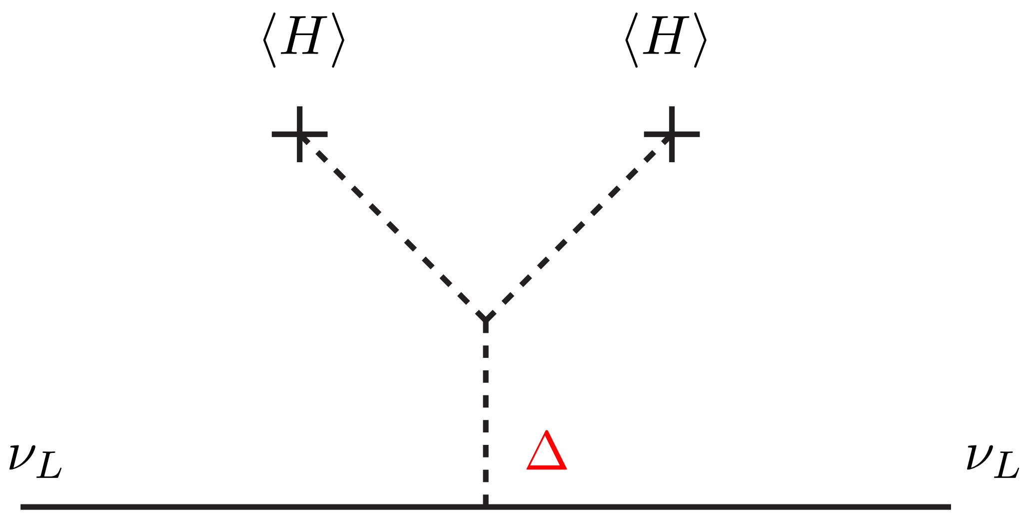
Minkowski, 77

Yanagida; Gell-Mann, Ramond, Slansky;
Glashow; Mohapatra, Senjanović, 79

Very well studied

boson weak triplet $\Delta = (1,3,2)$

TYPE II SEESAW

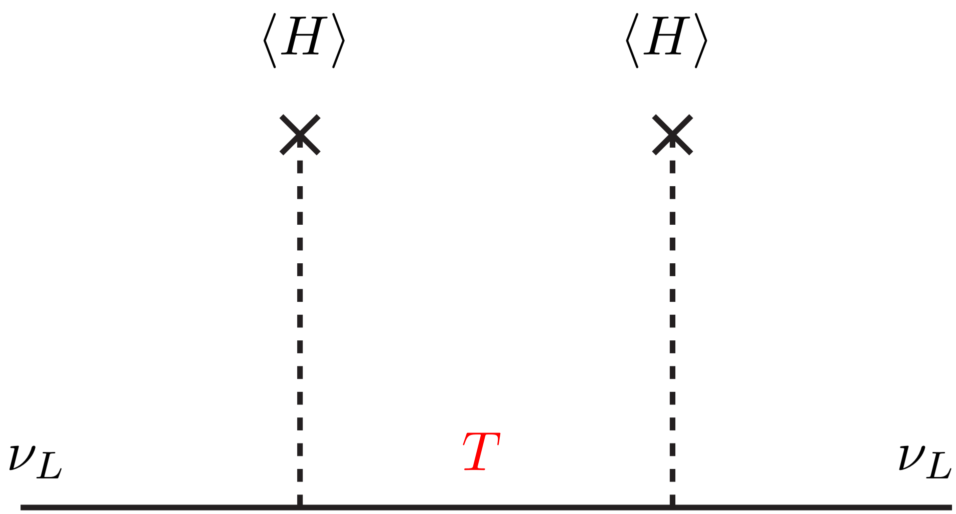


Lazarides, Magg, Wetterich;
Magg, Wetterich; Mohapatra, Senjanović, 80

Quite well studied

fermion weak triplet $T = (1, 3, 0)$

TYPE III SEESAW



Foot, Lew, He, Joshi, 89

Till recently studied only in context of R-parity violating susy

The general strategy

To probe seesaw (at LHC):

- produce seesaw mediators
- measure their decay rates

to suppress SM backgrounds we look for lepton number violating processes

What we need is mediators

1) light enough → $M \lesssim \mathcal{O}(\text{TeV})$

2) coupled strongly enough to our world to be produced → case with gauge nonsinglets a long shot → type II or III seesaw

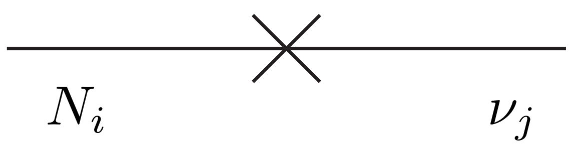
3) its decay must go dominantly through yukawas (that participate in ν mass)

The case of Type I seesaw

type I: mediator = fermionic $N(1,1,0)$ (at least 2 needed)

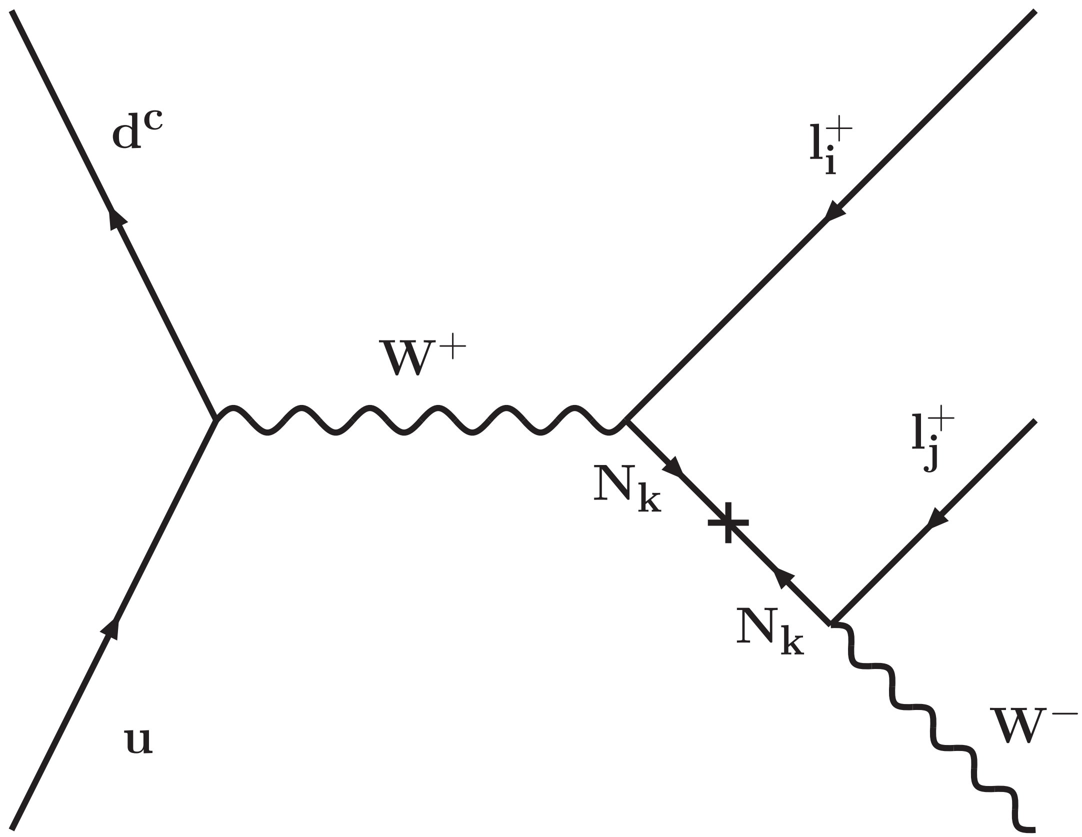
$$
\begin{aligned}
\mathcal{L} &= -\frac{M_{N_i}}{2} N_i N_i + Y_{ij} N_i L_j H + h.c. \\
&\to \quad m_\nu = -v^2 Y^T M_N^{-1} Y
\end{aligned}
$$

Mixing between N_i and ν_j after SU(2) breaking $\langle H \rangle = v$:



... $Y_{ij} \frac{v}{M_{N_i}}$

Through mixing singlets N_i coupled to gauge bosons



Amplitude $\propto Y_{ki} Y_{kj} \times$ Prop$_k$ (or $\propto Y_{ki}$ if N_k on-shell)

GOOD:

flavour in final state determines Y_{1j} (N_1 the lightest singlet)

BAD:

1. N singlet $\rightarrow$ no reason for M_N to be small
2. but even if $M_N = \mathcal{O}(\text{TeV}) \rightarrow$ Yukawa typically small $\rightarrow$ rare processes
   - $Y \approx \mathcal{O}(10^{-6}) \rightarrow$ too small to be produced at LHC
   - Y larger: fine tuning (extra symmetry can stabilize it)

Possible to produce N at LHC if $Y \gtrsim \mathcal{O}(10^{-2})$

Kersten, Smirnov, 07

del Aguila, Aguilar-Saavedra, Pittau, 07

del Aguila, Aguilar-Saavedra, 08

The case of Type II seesaw

type II: mediator = bosonic $\Delta(1,3,2)$ (one is enough)

$$\mathcal{L} = -M_\Delta |\Delta|^2 + Y_{ij} L_i^T \Delta L_j + \mu H^T \Delta^* H + h.c.$$

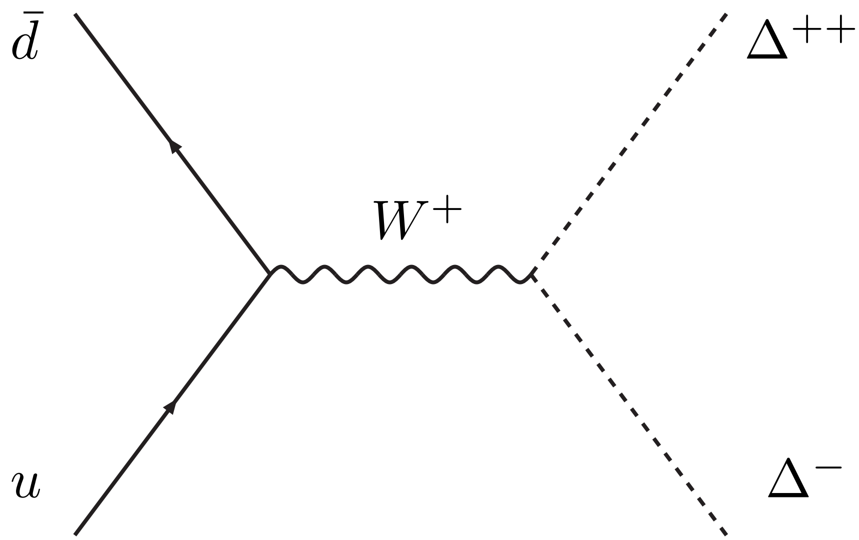
Triplet vev:

$$v_\Delta \equiv \langle \Delta \rangle = \mu v^2 / M_\Delta$$

Neutrino mass:

$$m_\nu = v_\Delta Y$$

Production of mediators in pairs by weak interaction (Drell-Yan)



can be found at LHC but have to (A) assume: $M_\Delta \lesssim \mathcal{O}(\text{TeV})$

On top of that, decay of mediators:

$\Delta^{++} \to l_i^+ l_j^+$ ($\propto M_\Delta |Y_{ij}|^2$) but also into W^+W^+ ($\propto v_\Delta^2 / M_\Delta$)

the lepton mode dominates (B) providing $v_\Delta \lesssim 10^{-4}$ GeV: not predicted but smallness perturbatively stable (if zero→lepton number)

Garayoa, Schwetz, 07

Kadastik, Raidal, Rebane, 07

Akeroyd, Aoki, Sugiyama, 07

Fileviez Perez, Han, Huang, Li, Wang, 08

del Aguila, Aguilar-Saavedra, 08

This case unique: if

(A) light enough triplet bosons and

(B) small enough triplet vev $\rightarrow$

all Yukawas could in principle be measured directly

$$m_\nu = v_\Delta Y = U_{PMNS}\, m_\nu^{diag}\, U_{PMNS}^T$$

Unknowns from neutrino physics: m_ν^1, θ_{13}, δ, $\Phi_{1,2}$ (5)

With 6 measurements $|Y_{ij}|$ one can (in principle) fix them all

But no minimal model known to predict (A) and (B)

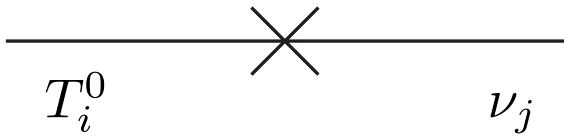
The case of Type III seesaw

type III: mediator = fermionic $T(1,3,0)$ (at least two needed)

$$\begin{aligned} \mathcal{L} &= -\frac{M_{T_i}}{2} T_i T_i + Y_{ij} T_i L_j H + h.c. \\ &\to \quad m_\nu = -v^2 Y^T M_T^{-1} Y \end{aligned}$$

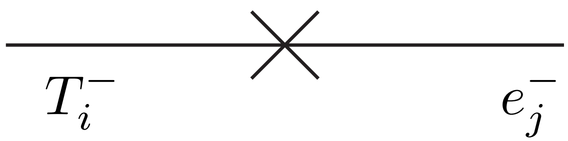
Similar to the type I case, but now the mediator is a gauge nonsinglet (much easier to produce it at the LHC)

As in the type I seesaw, there is mixing between T^0 and ν:



... $Y_{ij}\,\frac{v}{M_{T_i}}$

But now also mixing in the charged sector:



... $\sqrt{2}Y_{ij}\,\frac{v}{M_{T_i}}$

GOOD:

- T gauge triplet, RGE could be a reason for it to be light
- Yukawas enter only in decay, not in production

Recently studied repeatedly:

Possible to produce at LHC provided $M_T \lesssim$ 500 GeV - 1 TeV

Ma, Roy, 02

Franceschini, Hambye, Strumia, 08

del Aguila, Aguilar-Saavedra, 08

Later will see a detailed analysis in a well defined restrictive model

Arhrib, BB, Ghosh, Han, Huang, Puljak, Senjanović, 09

No seesaw at LHC from SO(10) ?

GOOD:

- natural see-saw mechanism, existence of ν_R automatic
- m_ν and $0\nu2\beta$ well described, connected to charged sector
- other processes (proton decay etc) also connected

An examples is the minimal supersymmetric SO(10):

- Field content: $3 \times 16_F$, 10_H, 210_H, $126_H + \overline{126}_H$
- all parameters (26) determined

Aulakh, Mohapatra; Clark, Kuo, Nakagawa, 82

Aulakh, BB, Melfo, Senjanović, Vissani, 03

A lot of analysis done:

the Yukawa sector could be fit

Babu, Mohapatra, 92

Goh, Mohapatra, Ng, 03

Bertolini, Malinsky, 05

Babu, Macesanu, 05

but inconsistent with the Higgs sector (m_ν too small)

Aulakh, Garg, 05

BB, Melfo, Senjanović, Vissani, 05

Bertolini, Malinsky, Schwetz, 06

One can

- add new representations (120)

Aulakh, Garg, 05

Lavoura, Kuhbock, Grimus; Aulakh, Garg, 06

- include susy threshold corrections

Aulakh, Garg, 08

- or allow split supersymmetry

BB, Doršner, Nemevšek, 08

BAD:

no reason for low scale see-saw mechanism (no $\Delta L = 2$ in colliders)

- usually no low scale from running ($M_{\nu_R} \approx M_{GUT}$)
- typically $m_{Dirac} \sim m_{top}$ (and so too large)

What about non-supersymmetric SO(10)?

- LR scale needed to be lower than in susy due to RG
- But not enough, still too high for LHC

BB, Melfo, Senjanović, Vissani, 05

Bertolini, Di Luzio, Malinsky, 09

No convincing SO(10) (or LR) theories for LHC

Any other minimal GUT candidate with measurable seesaw?

The minimal non-supersymmetric SU(5)

We will present a simple model which predicts a seesaw mediator with

1) $\lesssim$ TeV mass

2) gauge quantum numbers (type III seesaw)

3) decays mainly through yukawas

4) neutrino mass rank 2

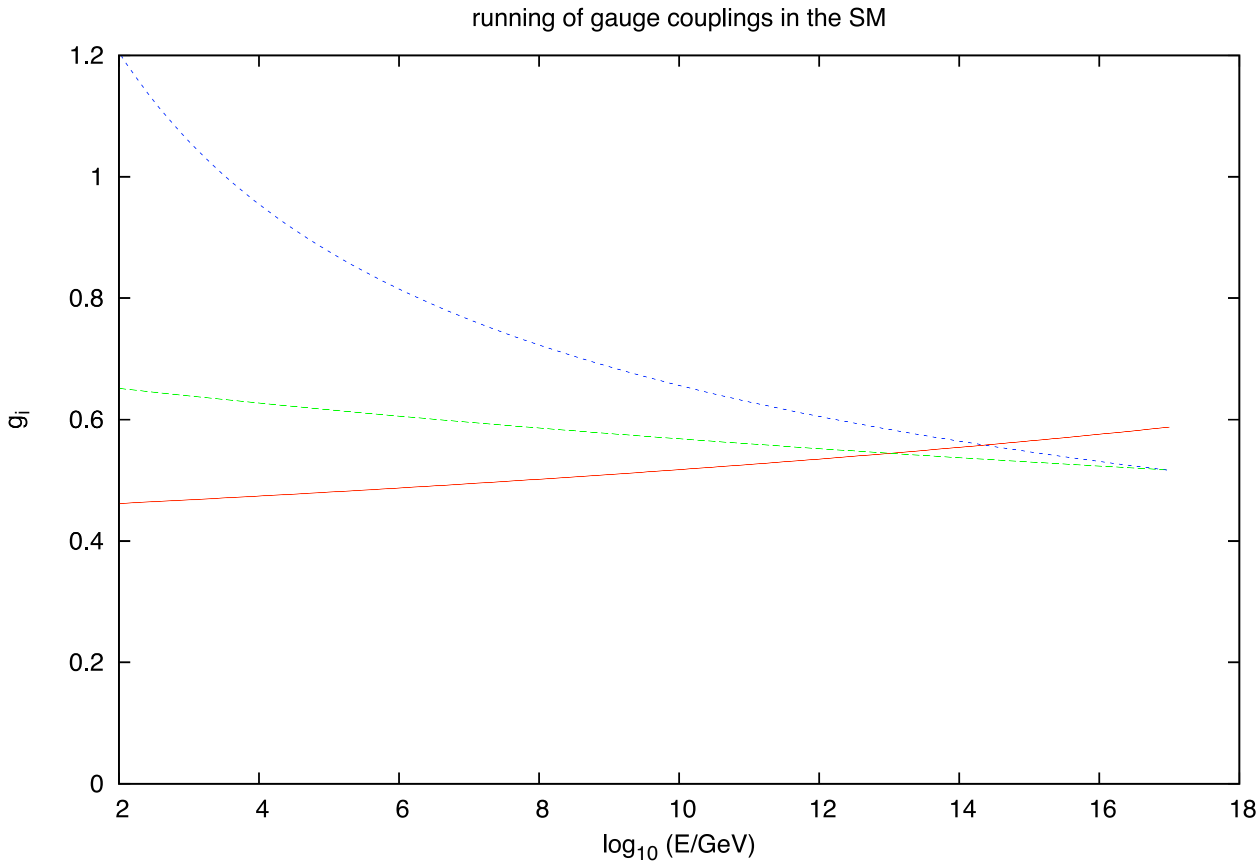
Try with the simplest one, non-supersymmetric SU(5).

Why is the Georgi-Glashow SU(5) ruled out?

nonsupersymmetric with $24_H + 5_H + 3(10_F + \overline{5}_F)$

1. gauge couplings do not unify
2. neutrinos massless (as in the SM)

1. Gauge coupling non-unification



- 2 and 3 meet at $\approx 10^{16}$ GeV (as in susy),

- but 1 meets 2 too early at $\approx 10^{13}$ GeV

2. Neutrino masses

Minimal SU(5) Yukawa terms:

$$\mathcal{L}_Y = 10_F^i Y_1^{ij} 10_F^j 5_H + 5_H^* 10_F^i Y_2^{ij} \bar{5}_F^j + \frac{1}{\Lambda}\left[\bar{5}_F^i 5_H Y_3^{ij} 5_H \bar{5}_F^j + ...\right]$$

Neutrinos can get mass from $1/\Lambda$ term but too small:

$$m^\nu \approx Y_3 \frac{v^2}{\Lambda} \lesssim 10^{-4}\,\mathrm{eV}$$

for $\Lambda \gtrsim 100 \times \mathrm{M_{GUT}} \gtrsim 10^{17}$ GeV (needed for perturbativity)

Neutrino practically massless!

Add a fermionic 24_F: light fermionic triplet predicted

B.B., G.Senjanović, 06

B.B., M.Nemevšek, G.Senjanović, 07

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

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

Extra states $(m_3, m_8, m_{(3,2)})$ with respect to the minimal model

$\rightarrow$ RGE change

$$\exp\left[30\pi\left(\alpha_1^{-1}-\alpha_2^{-1}\right)(M_Z)\right]=\left(\frac{M_{GUT}}{M_Z}\right)^{84}\left(\frac{m_3}{M_Z}\right)^{25}\left(\frac{M_{GUT}}{m_{(3,2)}}\right)^{20}$$

$$\exp\left[20\pi\left(\alpha_1^{-1}-\alpha_3^{-1}\right)(M_Z)\right]=\left(\frac{M_{GUT}}{M_Z}\right)^{86}\left(\frac{m_8}{M_Z}\right)^{25}\left(\frac{M_{GUT}}{m_{(3,2)}}\right)^{20}$$

In spite of many free parameters (m_3, m_8, $m_{(3,2)}$) only one possible pattern:

$$m_3 \ll m_8 \ll m_{(3,2)} \ll M_{GUT}$$

Can these masses be completely arbitrary?

They come from the Lagrangian

$$
\begin{aligned}
\mathcal{L}_F &= m_F Tr\left(24_F^2\right) + \lambda_F Tr\left(24_F^2 24_H\right) \\
&+ \frac{1}{\Lambda}\left[a_1 Tr\left(24_F^2\right) Tr\left(24_H^2\right) + a_2\left(Tr\left(24_F 24_H\right)\right)^2\right. \\
&+ \left. a_3 Tr\left(24_F^2 24_H^2\right) + a_4 Tr\left(24_F 24_H 24_F 24_H\right)\right] \\
&+ \mathcal{O}(1/\Lambda^2)
\end{aligned}
$$

$$m_3 = m_F - \frac{3\lambda_F M_{GUT}}{\sqrt{30}} + \frac{M_{GUT}^2}{\Lambda}\left[a_1 + \frac{3}{10}(a_3+a_4)\right]$$

$$m_8 = m_F + \frac{2\lambda_F M_{GUT}}{\sqrt{30}} + \frac{M_{GUT}^2}{\Lambda}\left[a_1 + \frac{2}{15}(a_3+a_4)\right]$$

$$m_{(3,2)} = m_F - \frac{\lambda_F M_{GUT}}{2\sqrt{30}} + \frac{M_{GUT}^2}{\Lambda}\left[a_1 + \frac{(13a_3-12a_4)}{60}\right]$$

Since

$$m_3 \ll m_8 \ll m_{(3,2)} \ll M_{GUT}$$

possible only by cancellation

$\rightarrow m_F, \lambda_F M_{GUT}, M_{GUT}^2/\Lambda$ must be of the same order

$\rightarrow m_{(3,2)} \lesssim M_{GUT}^2/\Lambda$

we will take $\Lambda = 100\, M_{GUT}$ (perturbativity and $b-\tau$)

A unique (1 loop) solution:

$$m_3 \approx 10^2 \text{GeV}$$

$$m_8 \approx 10^7 \text{GeV}$$

$$m_{(3,2)} \approx 10^{14} \text{GeV}$$

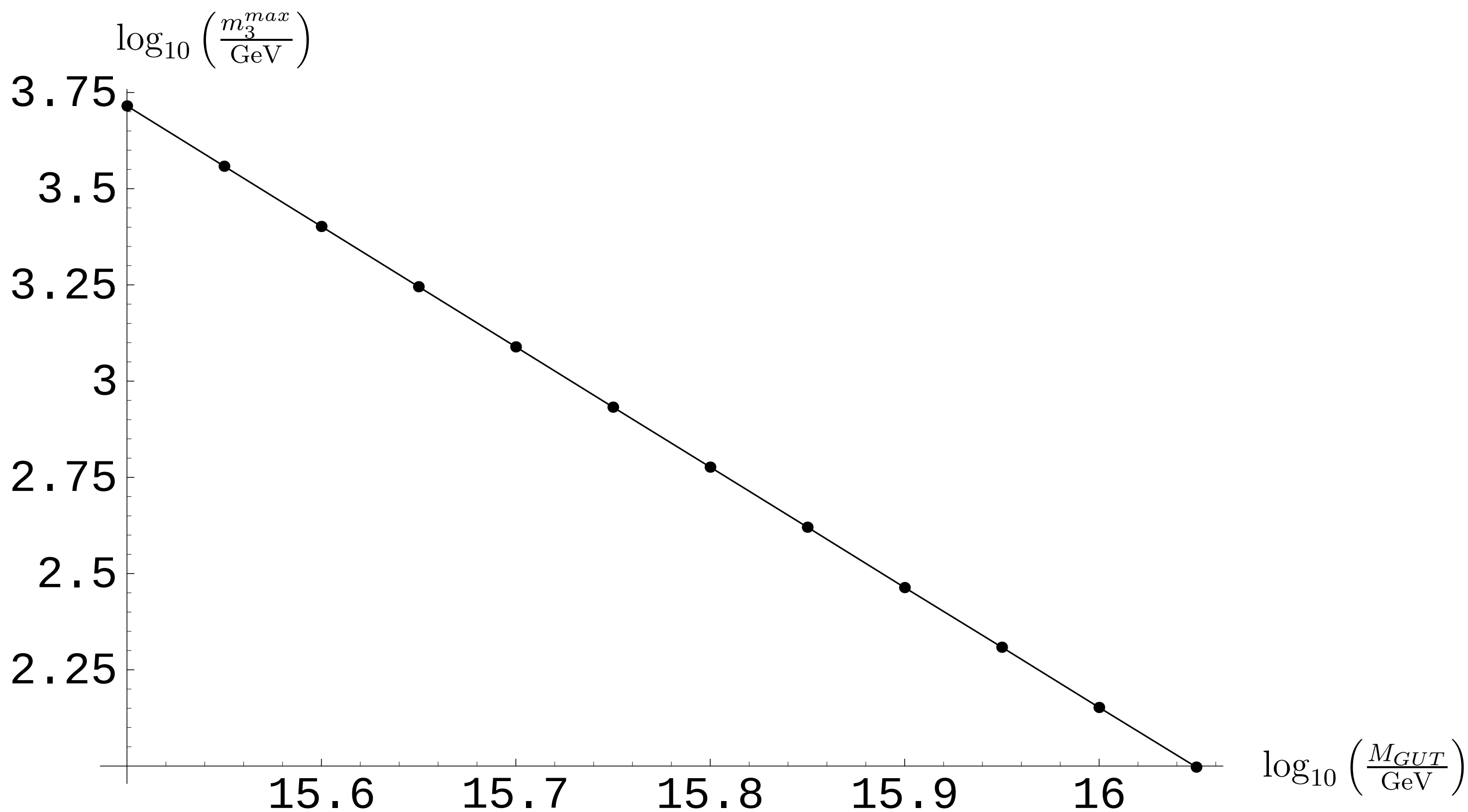
$$M_{GUT} \approx 10^{16} \text{GeV}$$

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

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

Prediction of the model

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



Very important:

- if $m_T \approx 100$ GeV $\to$ proton decay slow (interesting for LHC)
- if $m_T \approx 1$ TeV $\to$ proton decay fast (interesting for next generation proton decay detectors)

B.B., G.Senjanović, 06

B.B., M.Nemevšek, G.Senjanović, 07

Neutrino masses

New Yukawa terms with 24_F

singlet $S = (1,1)_0$
triplet $T = (1,3)_0$

$$\delta\mathcal{L} = L_i \left(y_T^i T + y_S^i S \right) H + m_T TT + m_S SS + h.c.$$

Mixed Type I and Type III seesaw:

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

Neutrino mass matrix rank 2:

$\rightarrow$ one massless neutrino

$\rightarrow$ crucial for probing neutrino parameters from y_T^i

Normal hierarchy:

$$v y_T^i = \sqrt{m_T} \left(U_{i2} \sqrt{m_2^\nu} \cos z + U_{i3} \sqrt{m_3^\nu} \sin z \right)$$

Inverse hierarchy:

$$v y_T^i = \sqrt{m_T} \left(U_{i1} \sqrt{m_1^\nu} \cos z + U_{i2} \sqrt{m_2^\nu} \sin z \right)$$

U = PMNS matrix, z = arbitrary complex number

Ibarra, Ross, 03

The PMNS matrix:

$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

$$\times \quad \mathrm{diag}(1, e^{i\Phi}, 1)$$

Measuring y_T^i

$\rightarrow$ constraints on z, θ_{13}, phases δ, Φ

Triplet decays

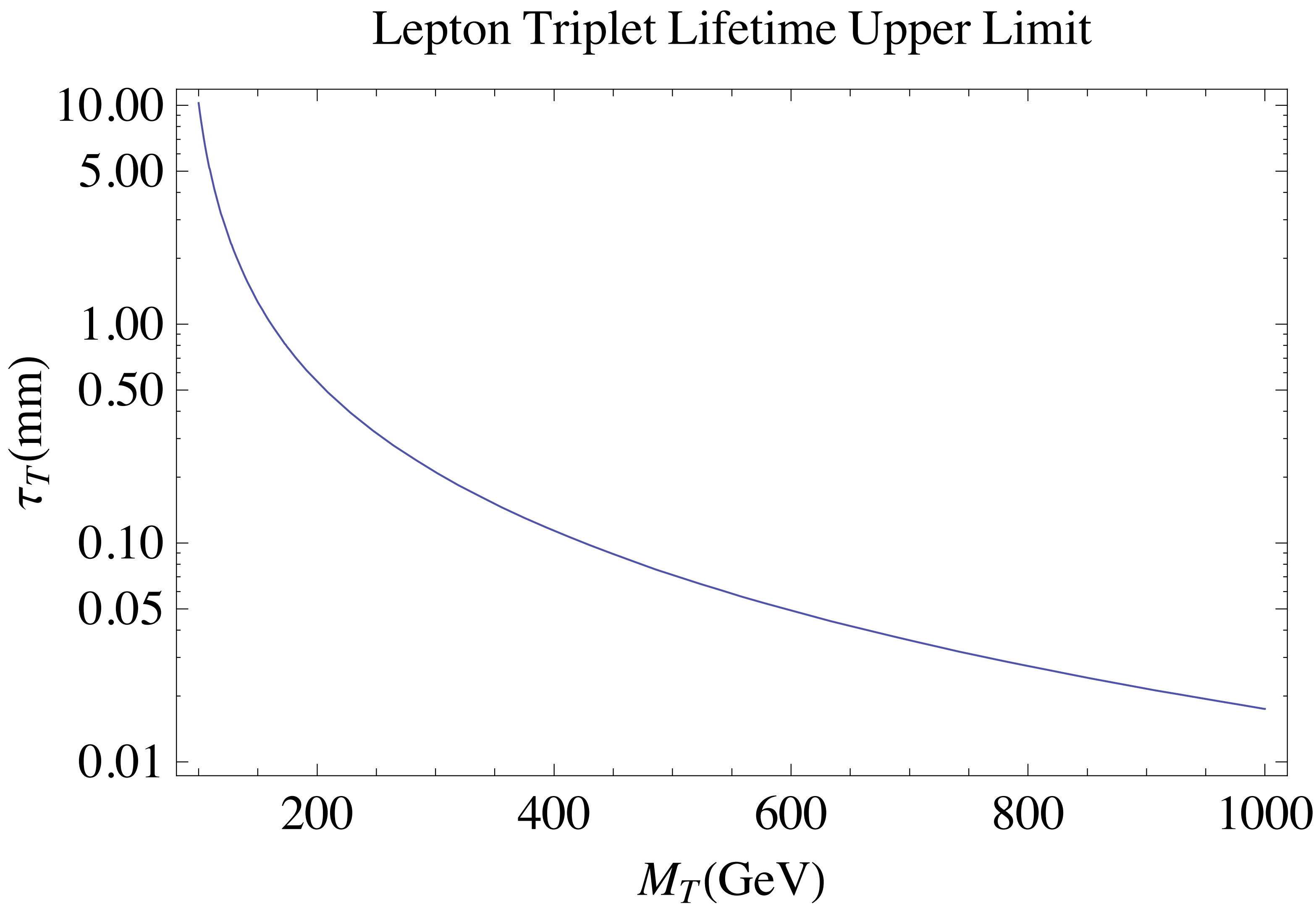
Decays through Yukawas

$$T^\pm \to Z l_k^\pm \qquad T^0 \to Z \nu_k$$
$$T^\pm \to W^\pm \nu_k \qquad T^0 \to W^\pm l_k^\mp$$

Non-Yukawa decay $T^\pm \to T^0 \pi^\pm$ are suppressed by small $\Delta M_T \lesssim 160$ MeV.

$$\Gamma_T \approx m_T |y_T|^2$$

Can measure y_T^k through decays


Lepton Triplet Lifetime Upper Limit
10.00
5.00
1.00
0.50
0.10
0.05
0.01
τ_T(mm)
200
400
600
800
1000
M_T(GeV)

Approximate upper limit on total triplet lifetime ($m_T > 200$ GeV)

$$\tau_T \lesssim 0.5 \left(\frac{200 \text{ GeV}}{m_T} \right)^2 \text{ mm} \qquad \text{(normal hierarchy)}$$

(and $\sqrt{\Delta m_A^2 / \Delta m_S^2} \approx 5$ times smaller for inverse hiearchy)

Here different than the case of 3 triplets:

rank 3 ν mass $\to$

- one T^0 in principle could be stable
- $T^\pm \to \pi^\pm T^0$ could dominate

Triplet production at LHC

$T^{0,\pm}$ weak triplet

$\rightarrow$ produced through gauge interactions (Drell-Yan)

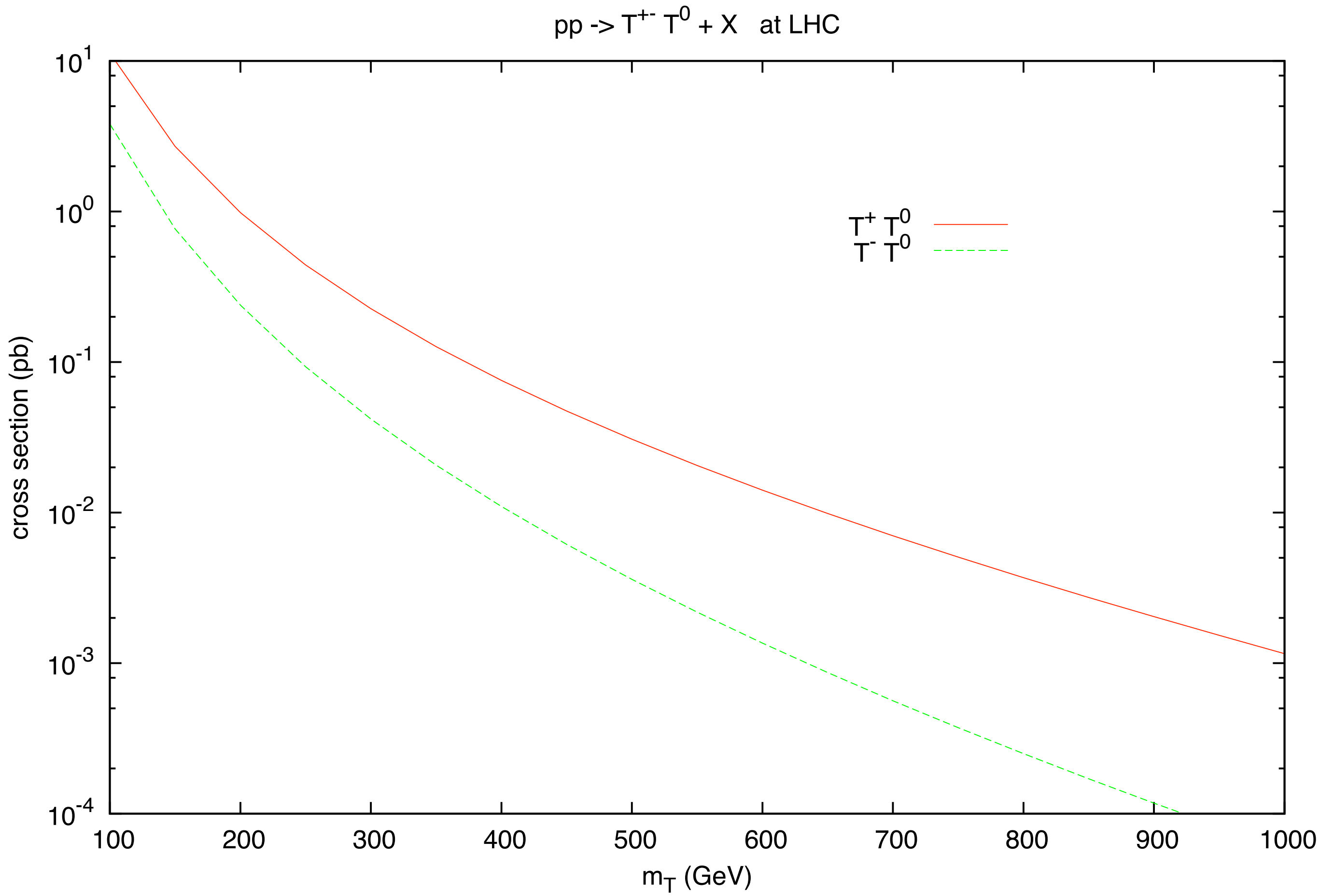
$$pp \rightarrow W^{\pm} \rightarrow T^{\pm} T^{0}$$
$$pp \rightarrow (Z \,\mathrm{or}\, \gamma) \rightarrow T^{+} T^{-}$$

Ma, Roy, 02

del Aguila, Aguilar-Saavedra, 07, 08

Franceschini, Hambye, Strumia, 08

Arhrib, BB, Ghosh, Han, Huang, Puljak, Senjanović, 09


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

If you want to avoid missing energy (no ν)

1. only charged leptons

$$T^{\pm} \to Z l^{\pm} \to l'^{+} l'^{-} l^{\pm}$$

2. charged leptons + jets

$$\begin{aligned} T^{\pm} &\to Z l^{\pm} \to l^{\pm} + 2jets \\ T^{0} &\to W^{\mp} l^{\pm} \to l^{\pm} + 2jets \end{aligned}$$

The best channel is like-sign dileptons + jets

(like in LR models with low W_R mass and $m_{\nu_R} \leq m_{W_R}$)

Keung, Senjanović, 83

$$BR(T^\pm T^0 \to l_i^\pm l_j^\pm + 4 \text{ jets}) \approx \frac{1}{20} \times NBR_i \times NBR_j$$

$$NBR_i = \text{ normalized branching ratio}(i) = \frac{|y_T^i|^2}{\sum_k |y_T^k|^2}$$

Define the following cross sections:

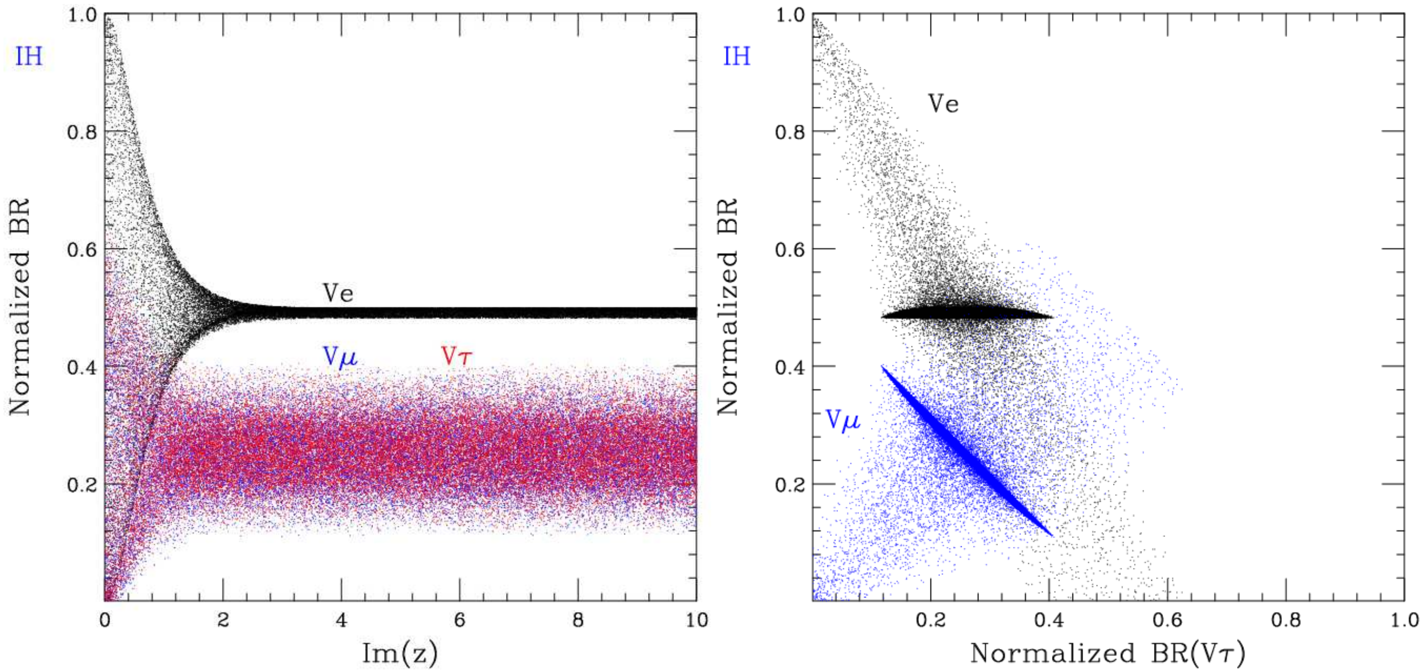
—— σ_{total} for sum over all $l = e, \mu, \tau$ at $E = 14$ TeV

_ · _ · _ σ_{total} for sum over all $l = e, \mu, \tau$ at $E = 10$ TeV

· · · · · σ_{total} (expected) for $l = e, \mu$ (IH case, $\Phi = 0$)

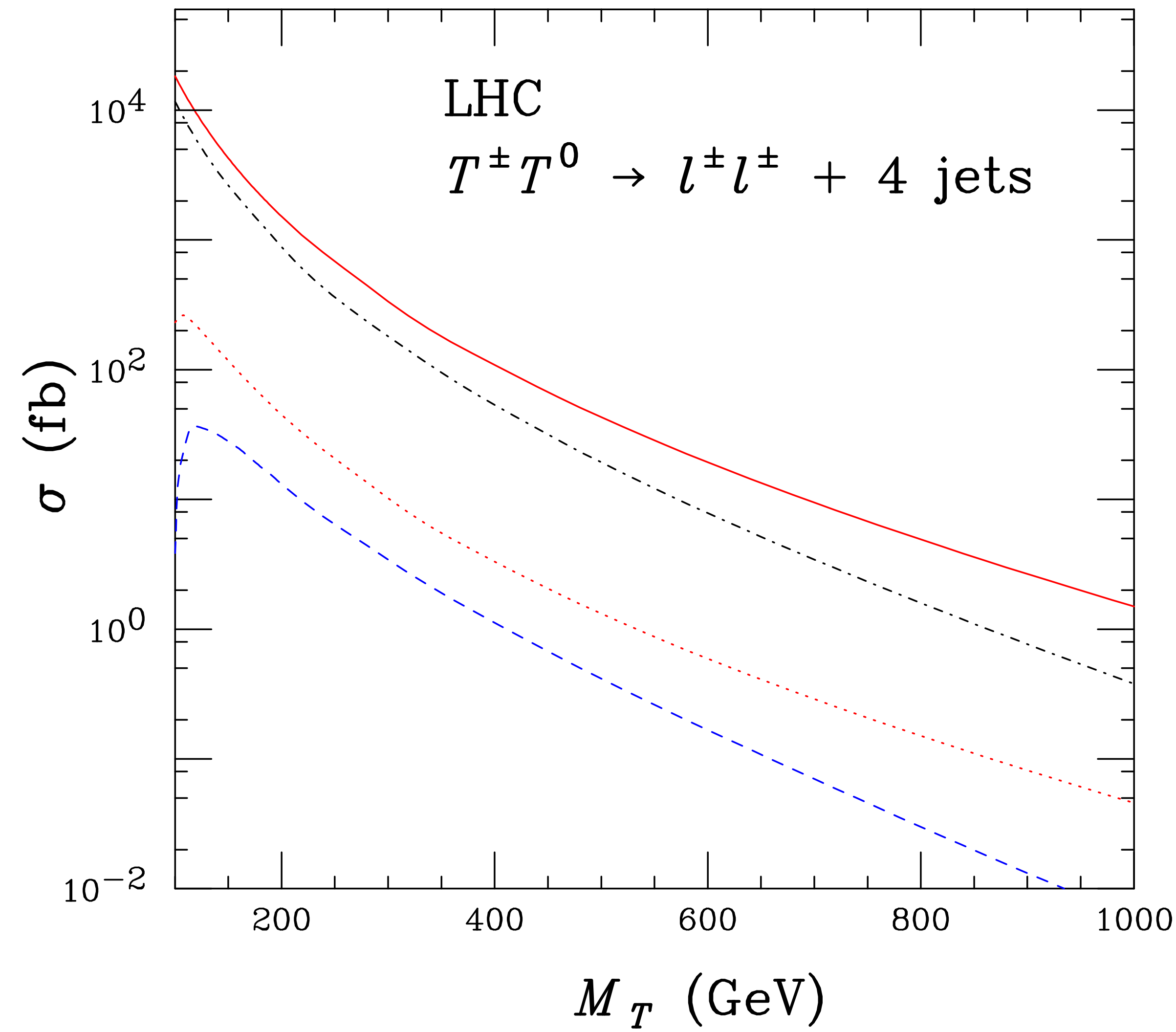
_ _ _ _ σ_{total} (expected) for $l = e, \mu$ (IH case, $\Phi = 0$) after cuts

What does it mean "expected" for inverse hierarchy (IH) case, $\Phi = 0$?



CUTS

- Rapidity coverage for leptons and jets
  $|\eta(\ell)| < 2.5 \;\; , \;\; |\eta(j)| < 3$
- High transverse momentum cuts
  $p_T^{\text{jets}} > 20 \text{ GeV} \;\; , \;\; p_T^{\ell} > 15 \text{ GeV}$
- Particle identification, $\Delta R_{\alpha\beta} \equiv \sqrt{(\Delta\phi_{\alpha\beta})^2 + (\Delta\eta_{\alpha\beta})^2}$
  $\Delta R_{jj} > 0.4 \; , \quad \Delta R_{\ell j} > 0.4 \; , \quad \Delta R_{\ell\ell} > 0.3$
- No significant missing energy
  $\not{E}_T < 25\,\text{GeV}$
- W, Z or h reconstruction:
  $65 \text{ GeV} < m(jj) < 105 \text{ GeV}$ or $100 \text{ GeV} < m(jj) < 140 \text{ GeV}$
- triplet invariant mass:
  $m(jjl) \in M_T \pm 50 \text{ GeV}$


LHC
$T^{\pm}T^{0} \to l^{\pm}l^{\pm}$ + 4 jets
10^4
10^2
10^0
10^{-2}
σ (fb)
200
400
600
800
1000
M_T (GeV)

Background from

$$t\bar{t}W^{\pm}$$
$$W^{\pm}W^{\pm}Vjj$$
$$W^{\pm}W^{\pm}jjjj$$

with $W^{\pm} \to l^{\pm}\nu$ producing final states $\to l^{\pm}l^{\pm}4j+$ missing energy

Small missing energy cut crucial (factor ≈ 20 decrease)

Easily made negligible ($\lesssim 0.1$ fb)

Arhrib, BB, Ghosh, Han, Huang, Puljak, Senjanović, 09

Consistent with other estimates of these and other channels:

del Aguila, Aguilar-Saavedra, 07, 08

Franceschini, Hambye, Strumia, 08

Some numbers from here:

For the signal we would require $\gtrsim 5$ events:

$$\sigma_{min} \approx \frac{5}{\int \mathcal{L}}$$

- From LHC we can probe

  $\rightarrow$ up to $m_T \approx 450$ GeV for $\int \mathcal{L} = 10$ fb^{-1}

  $\rightarrow$ up to $m_T \approx 700$ GeV for $\int \mathcal{L} = 100$ fb^{-1}

- τ identification will only help improving the bounds

- For Tevatron similar analysis (cuts a bit different) give

  $\rightarrow$ up to $m_T \approx 200$ GeV for $\int \mathcal{L} = 8$ fb^{-1}

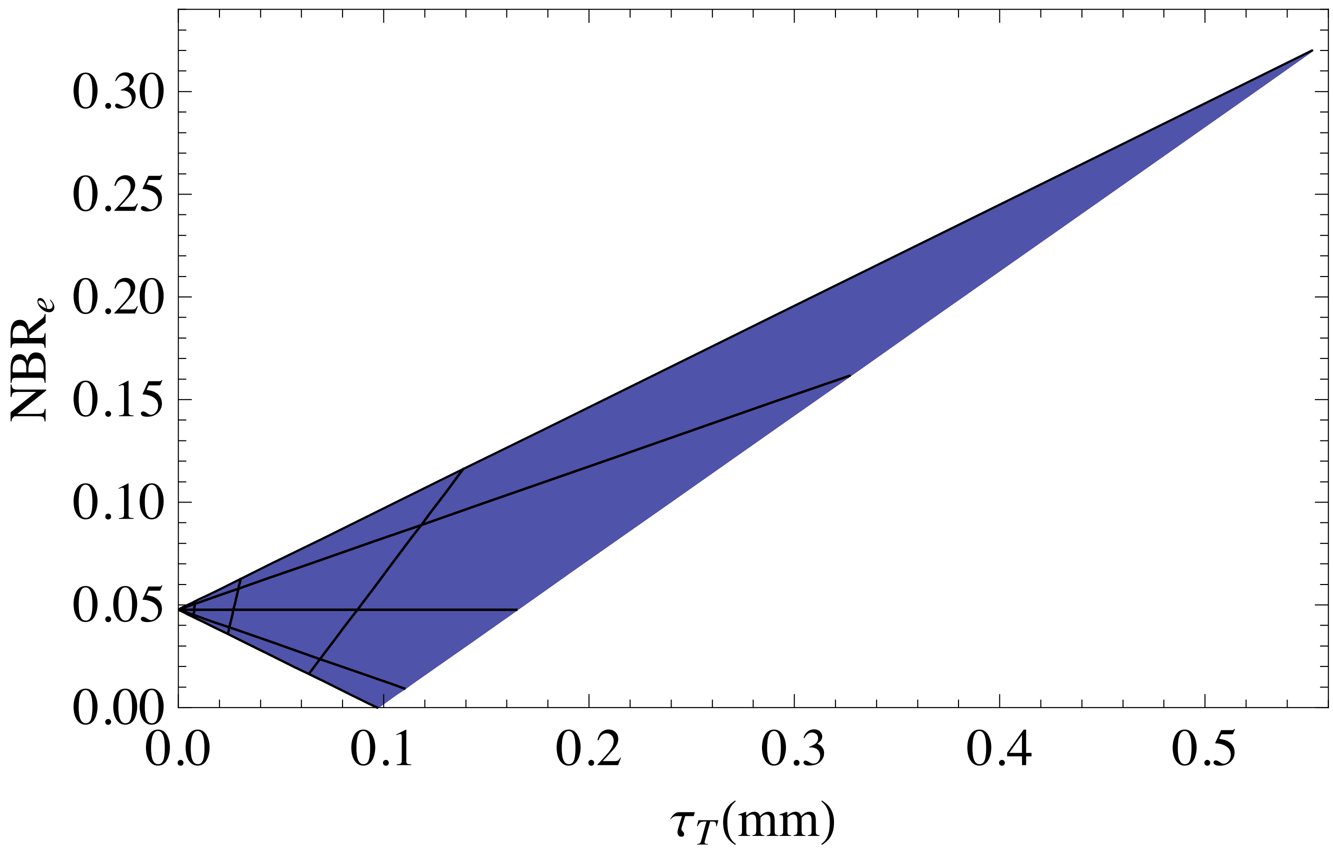
Probing the neutrino parameters at LHC

Seesaw parameters: θ_{13}, δ, Φ

- Imagine we can produce at LHC the light triplet
- Then we can in principle measure the three $|y_T^i|$ $(i = e,\ \mu,\ \tau)$ through
  1. triplet lifetime $\propto \left(|y_T^e|^2 + |y_T^\mu|^2 + |y_T^\tau|^2\right)$
  2. $NBR_e = |y_T^e|^2 / \left(|y_T^e|^2 + |y_T^\mu|^2 + |y_T^\tau|^2\right)$
  3. $NBR_\mu = |y_T^\mu|^2 / \left(|y_T^e|^2 + |y_T^\mu|^2 + |y_T^\tau|^2\right)$

Example 1

Yukawas constrained (rank 2 model) $\rightarrow$ consistency checks possible



Example 2

Case with normal hierarchy

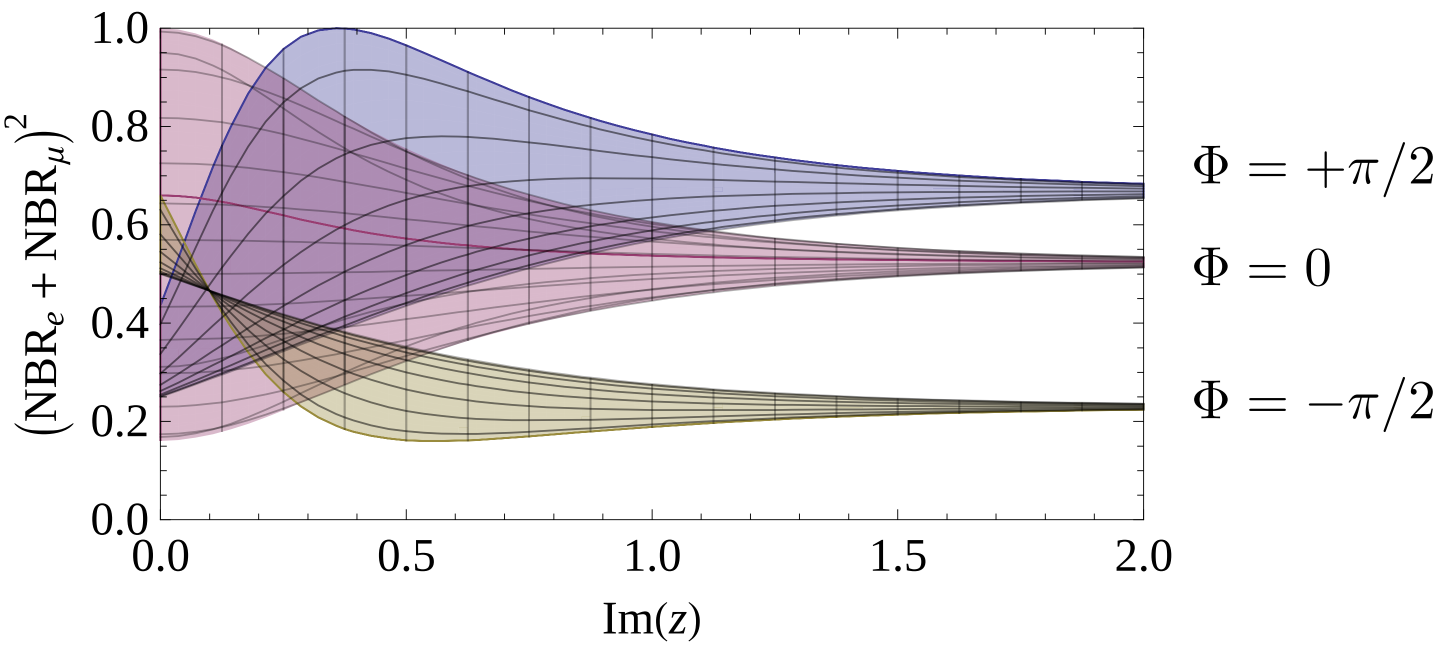
Assume a simplified situation with

$$\theta_{13} = 0$$

The only unknown parameters (3):

$Re(z)$, $Im(z)$, Majorana CP violating phase Φ

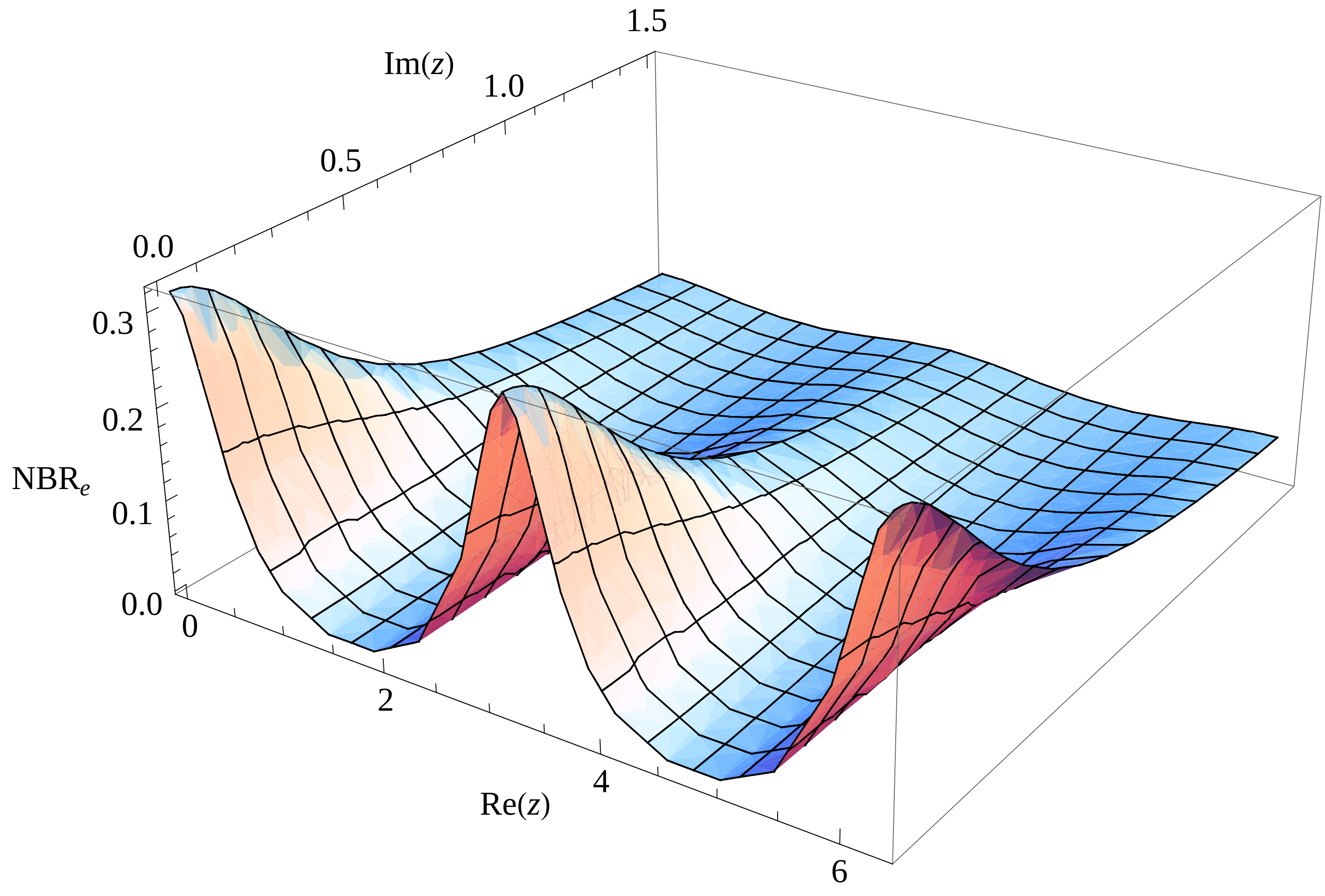
Just by measuring the cross section $\Delta L = 2$ production of same sign dilepton already some info:



$\theta_{13} = 0$ case special:

$$\begin{aligned} \tau &= \tau\left(Re(z), Im(z)\right) \\ NBR_e &= NBR_e\left(Re(z), Im(z)\right) \end{aligned}$$

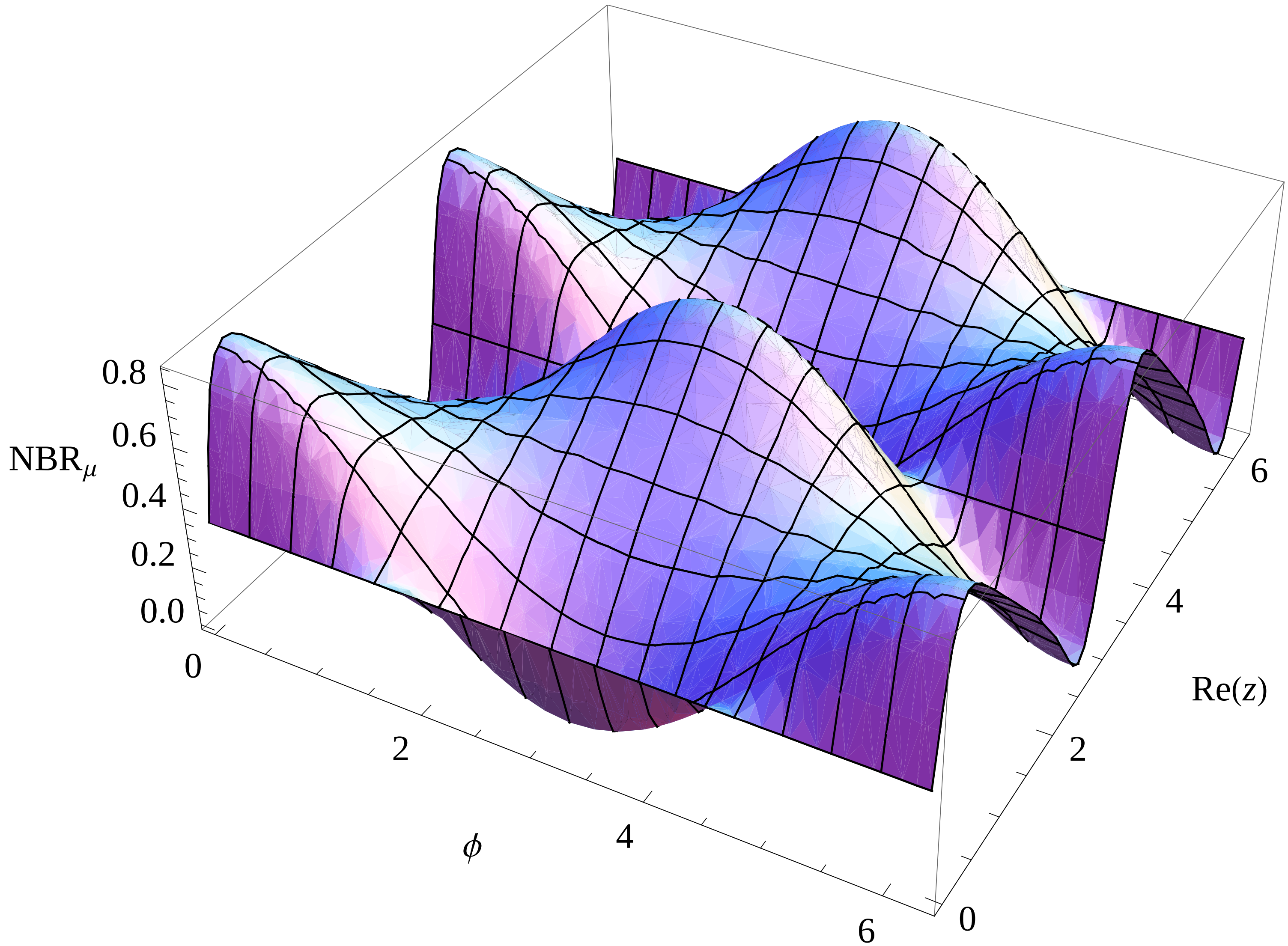
do not depend on Φ


1.5
Im(z)
1.0
0.5
0.0
0.3
0.2
NBR$_e$
0.1
0.0
0
2
4
Re(z)
6

Possible to determine Φ from

$$NBR_\mu(Im(z), Re(z), \Phi)$$

$Im(z) = 0:$



Conclusions

- After 30 years seesaw still the most popular
- LHC a special opportunity to test it directly
- in most models this check unfortunately possible only in small part of parameter space
- type I needs light mediators and large cancellations in the seesaw formula (approximate symmetry ?)
- type II needs light mediators and small triplet vev (extra symmetry again)
- type III needs light mediators and not too small lightest triplet Yukawas

- mixed type I+III the only known example of a predictive and testable seesaw: ordinary minimal SU(5) with extra fermionic adjoint

  1. weak fermionic triplet predicted in the TeV range (good chances to find it at LHC)
  2. its decay connected with neutrino mass
  3. possible to get information on unmeasured (angles, CP) neutrino parameters