Neutrinos in GUTs

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SO(10): Aulakh, Melfo, Senjanović, Vissani, ...

E_6: *Babu, Susič*

SU(5): Nemevšek, Senjanović, ...

Introduction

Main predictions of GUTs:

- charge quantization
- proton decay
- existence of magnetic monopoles

Since leptons and quarks are somehow on the same footing it is expected also some correlation between neutrino and charged matter.

SU(5):

$$\bar{5} = d^c(3) + L(2) \quad , \quad 10 = Q(6) + u^c(3) + e^c(1)$$

SO(10):

$$16 = \bar{5} + 10 + \nu^c(1)$$

E_6:

$$27 = 16 + \underbrace{10}_{\text{extra } 5+\bar{5}} + 1$$

In SO(10) (and E_6) existence of right-handed neutrino automatically provided.

SO(10) seems a better theory on neutrinos.

Supersymmetric SO(10)

Clark, Kuo, Nakagawa, '82

Aulakh, Mohapatra, '83

Aulakh, BB, Melfo, Senjanović, Vissani, '03

1. **The model**:

   - use $126_H + \overline{126}_H$ to break rank and predict R-parity

$$R \equiv (-1)^{3(B-L)+2S}$$

   R-parity is part of SO(10)
   $\langle 126_H \rangle$ has $B - L = 2$

Mohapatra, 86

Aulakh,Benakli,Senjanović,'97

Aulakh,Melfo,Senjanović,'98

Aulakh, Melfo, Rašin, Senjanović, '99

- use 10_H to get *3rd* generation fermion masses

$$m_b \approx m_\tau$$

- use $\overline{126}_H$ (Babu-Mohapatra) to correct bad mass relations (Georgi-Jarskog)
- use 210_H to break SO(10) and connect $\overline{126}_H$ to 10_H

Babu, Mohapatra, '92

2. The Yukawa sector

$$\mathcal{L}_{Yukawa} = 16_F^T \left(Y_{10} 10_H + Y_{126} \overline{126}_H \right) 16_F$$

Relevant vevs (under Pati-Salam $SU(2)_L \times SU(2)_R \times SU(4)_C$):

$$\begin{aligned} 10_H &= \underbrace{(2,2,1)}_{v_{10}^u, v_{10}^d} + \ldots \\ \overline{126}_H &= \underbrace{(2,2,15)}_{v_{126}^u, v_{126}^d} + \underbrace{(1,3,10)}_{v_R} + \underbrace{(3,1,\overline{10})}_{v_L} \ldots \end{aligned}$$

$$
\begin{aligned}
M_U &= v_{10}^u Y_{10} + v_{126}^u Y_{126} \\
M_D &= v_{10}^d Y_{10} + v_{126}^d Y_{126} \\
M_E &= v_{10}^d Y_{10} - 3 v_{126}^d Y_{126} \\
M_N &= \underbrace{-M_{\nu_D}^T M_{\nu_R}^{-1} M_{\nu_D}}_{type\ I} + \underbrace{M_{\nu_L}}_{type\ II}
\end{aligned}
$$

$$
\begin{aligned}
M_{\nu_D} &= v_{10}^u Y_{10} - 3 v_{126}^u Y_{126} \\
M_{\nu_R} &= v_R Y_{126} \\
M_{\nu_L} &= v_L Y_{126}
\end{aligned}
$$

2 Yukawa matrices ($Y_{10,126}$) $\rightarrow$ 4 mass matrices ($M_{U,D,E,N}$)

3. b-tau unification

From Yukawa sector:

$$Y_{126} \propto M_D - M_E$$

On the other side if type II see-saw dominates

$$M_N \propto M_{\nu_L} \propto Y_{126}$$

heaviest 2 generations:

$$M_N \propto M_D - M_E = \begin{pmatrix} \epsilon & \epsilon \\ \epsilon & m_b \end{pmatrix} - \begin{pmatrix} \epsilon & \epsilon \\ \epsilon & m_\tau \end{pmatrix}$$

$b - \tau$ unification $\leftrightarrow$ large atmospheric mixing angle

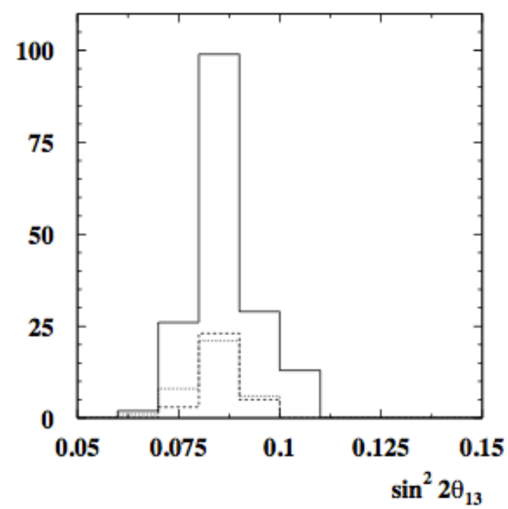
BB, Senjanović, Vissani, '02

4. **Fit to Yukawa sector** (without taking into account the constraints on the Higgs sector) **successful**

   Prediciton (in 2004):

$$\theta_{13}^{l} \approx 0.15 \pm 0.05$$

Bertolini, Malinsky, '04



Babu, Macesanu, '04

5. Full model with $m_{susy} = \mathcal{O}(TeV)$ ruled out

Aulakh, '05

BB, Melfo, Senjanović, Vissani, '05

Bertolini, Malinsky, Schwetz, '06

The problem is that $v_{10,126}^{u,d}$, $v_{L,R}$ not completely free, but constrained by the superpotential. The minimal renormalizable model too constrained:

$$
\begin{aligned}
W &= M_{210}\, 210_H^2 + \lambda\, 210_H^3 \\
&+ M_{126}\, 126\, \overline{126}_H + \eta\, 126_H\, \overline{126}_H\, 210_H \\
&+ M_{10}\, 10_H^2 + \alpha\, 126_H\, 10_H\, 210_H + \bar{\alpha}\, \overline{126}_H\, 10_H\, 210_H
\end{aligned}
$$

6. Split susy **scenario again** (probably) **realistic**

BB, Doršner, Nemevšek, '08

- $m_\lambda \approx 100$ TeV, $m_{\tilde{f}} \approx 10^{14}$ GeV
  $\rightarrow$
  – no $d = 5$ p-decay modes
  – no uncertainties with soft terms
  – no MSSM threshold corrections to fermion masses
- $M_{GUT} \approx 10^{15.8}$ GeV $\rightarrow$ relatively fast $d = 6$ p-decay modes
  – $BR(p \rightarrow \pi^+ \bar{\nu}) = 0.49$
  – $BR(p \rightarrow \pi^0 e^+) = 0.44$
  – $BR(p \rightarrow K^0 \mu^+) = 0.05$
- good fit of fermion masses, prediction (in 2008):

$$\theta^l_{13} \approx 0.1$$

but minimizing χ^2 with a penalty only for $\theta^l_{13} > 0.17$

SO(10) from E_6?

The problem with the minimal SO(10) model was a too constrained Higgs sector.

BB, Susič, 13

Babu, BB, Susič, 15

Can we increase the group keeping the model still minimal?

$$
\begin{array}{rcl}
\mathrm{SO}(10) & & E_6 \\
16_F & \in & 27_F \\
10_H & \in & 27_H \\
126_H & \in & 351'_H \\
\overline{126}_H & \in & \overline{351}'_H \\
 & \ldots &
\end{array}
$$

In all generality for symmetric Yukawas

$$W = 27_i \left(Y^{ij}_{27}\, 27 + Y^{ij}_{\overline{351}'}\, \overline{351}' \right) 27_j$$

$$Y_{27,\overline{351}'} = Y^T_{27,\overline{351}'}$$

Completely analogous to SO(10):

$$W = 16_i \left(Y^{ij}_{10}\, 10 + Y^{ij}_{\overline{126}}\, \overline{126} \right) 16_j$$

$$Y_{10,\overline{126}} = Y^T_{10,\overline{126}}$$

In fact

$$\mathbf{27} = 1 + \mathbf{10} + \mathbf{16}$$

$$\overline{\mathbf{351}}' = 1 + \mathbf{10} + \overline{\mathbf{16}} + 54 + \overline{\mathbf{126}} + \mathbf{144}$$

But now also extra Higgs doublets in **10**, **16** and **144**

$\rightarrow$ mixing between 16_i, 10_i and 1_i in matter 27_i.

$$W = \begin{pmatrix} 16 & 10 & 1 \end{pmatrix} Y_{27} \begin{pmatrix} 10 & 16 & 0 \\ 16 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix} \begin{pmatrix} 16 \\ 10 \\ 1 \end{pmatrix}$$

$$+ \begin{pmatrix} 16 & 10 & 1 \end{pmatrix} Y_{\overline{351}'} \begin{pmatrix} \overline{126} + 10 & 144 & \overline{16} \\ 144 & 54 & 0 \\ \overline{16} & 0 & 1 \end{pmatrix} \begin{pmatrix} 16 \\ 10 \\ 1 \end{pmatrix}$$

- several new Higgs doublets (not only in 10 and $\overline{126}$)
- 16, $\overline{16}$, 144 have large $\mathcal{O}(M_{GUT})$ vevs $\to$
  - mixing between $\bar{5} \in 16$ and $\bar{5} \in 10$ (d^c, L)
  - mixing between $1 \in 1$ and $1 \in 16$ (ν^c)
- $M^U_{3\times 3}$, $M^D_{6\times 6}$, $M^E_{6\times 6}$, $M^N_{15\times 15} \to$ light $(M_{U,D,E,N})_{3\times 3}$

As an example of what happens let's see the down sector:

$$\begin{pmatrix} d^{cT} & d'^{cT} \end{pmatrix} \begin{pmatrix} \bar{v}_2 Y_{27} + \left(\frac{1}{2\sqrt{10}}\bar{v}_4 + \frac{1}{2\sqrt{6}}\bar{v}_8\right) Y_{\overline{351}'} & c_2 Y_{27} \\ -\bar{v}_3 Y_{27} - \left(\frac{1}{2\sqrt{10}}\bar{v}_9 + \frac{1}{2\sqrt{6}}\bar{v}_{11}\right) Y_{\overline{351}'} & \frac{1}{\sqrt{15}} f_4 Y_{\overline{351}'} \end{pmatrix} \begin{pmatrix} d \\ d' \end{pmatrix}$$

$\bar{v}_{2,3,4,8,9,11} = \mathcal{O}(m_Z)$; $c_2, f_4 = \mathcal{O}(M_{GUT})$

$$\left. \begin{array}{l} d^c \in \bar{5}_{SU(5)} \in 16_{SO(10)} \\ d'^c \in \bar{5}_{SU(5)} \in 10_{SO(10)} \end{array} \right\} \text{mix}$$

$$d \in 10_{SU(5)} \in 16_{SO(10)}$$

$$d' \in 5_{SU(5)} \in 10_{SO(10)} \ldots \text{ heavy}$$

The matrix above has the form

$$\mathcal{M} = \begin{pmatrix} m_1 & M_1 \\ m_2 & M_2 \end{pmatrix}$$

with $m_{1,2} = \mathcal{O}(m_Z)$ and $M_{1,2} = \mathcal{O}(M_{GUT})$

All are 3×3 matrices.

the idea is to find a 6×6 unitary matrix $\mathcal{U}$ that

$$\mathcal{U} \begin{pmatrix} M_1 \\ M_2 \end{pmatrix} = \begin{pmatrix} 0 \\ \text{something} \end{pmatrix}$$

The solution is

$$\mathcal{U} = \begin{pmatrix} \left(1 + XX^\dagger\right)^{-1/2} & -\left(1 + XX^\dagger\right)^{-1/2} X \\ X^\dagger \left(1 + XX^\dagger\right)^{-1/2} & \left(1 + X^\dagger X\right)^{-1/2} \end{pmatrix}$$

with

$$X = M_1 \, M_2^{-1}$$

so that

$$\mathcal{U}\mathcal{M} = \begin{pmatrix} \underbrace{\mathcal{O}(m_Z)}_{\text{light sector}} & 0 \\ \mathcal{O}(m_Z) & \mathcal{O}(M_{GUT}) \end{pmatrix}$$

Finally

$$M_D = \left(1 + XX^\dagger\right)^{-1/2} \left(\left(\bar{v}_2 - \bar{v}_3 X\right) Y_{27} + \left(\frac{1}{2\sqrt{10}}\left(\bar{v}_4 - \bar{v}_9 X\right) + \frac{1}{2\sqrt{6}}\left(\bar{v}_8 - \bar{v}_{11} X\right)\right) Y_{\overline{351}'} \right)$$

with

$$X = -3\sqrt{\frac{5}{3}}\,\frac{c_2}{f_4}\,Y_{27}\,Y_{\overline{351}'}^{-1},$$

But if in SO(10) language all

$$\langle 16 \rangle, \langle \overline{16} \rangle, \langle 144 \rangle = 0 \to X = 0$$

$$M_D = \bar{v}_2 Y_{27} + \left(\frac{1}{2\sqrt{10}}\bar{v}_4 + \frac{1}{2\sqrt{6}}\bar{v}_8\right) Y_{\overline{351}'}$$

- no mixing between $\bar{5} \in 16$ and $\bar{5} \in 10$
- R-parity again automatically conserved as in SO(10)

Whether it works better than in SO(10) or not still open

Babu, BB, Susič, work in progress

Non-supersymmetric SU(5)

Simple model which predicts a seesaw mediator with

1) $\lesssim$ TeV mass

2) gauge quantum numbers (type III seesaw)

3) decays mainly through yukawas

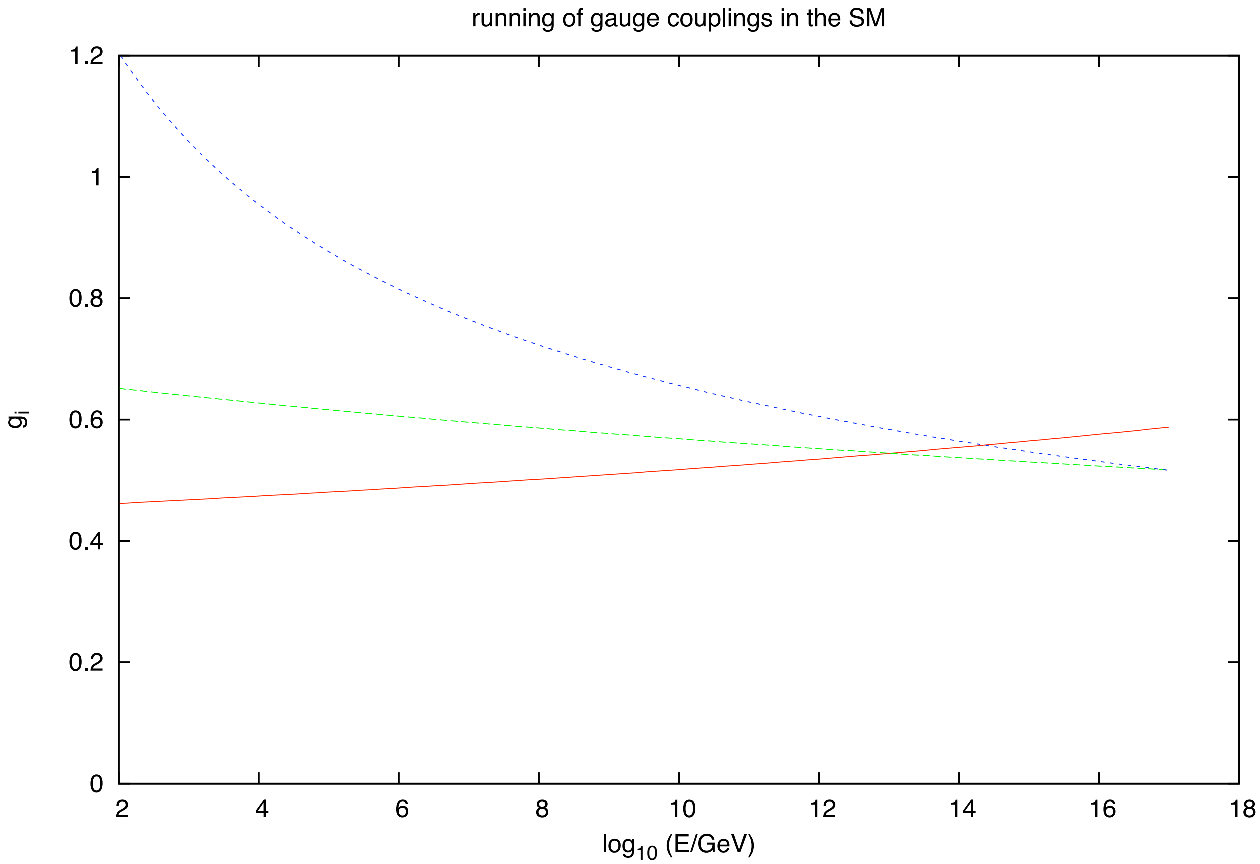
4) neutrino mass rank 2

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

Minimal: $24_H + 5_H + 3(10_F + \overline{5}_F)$

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

1. Non-unification of SM gauge couplings



- 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 just one extra fermionic 24_F

BB, Senjanović, 06

BB, Nemevšek, Senjanović, 07

1. **Gauge coupling unification**

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

The only possible pattern:

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

A unique solution:

$$\begin{aligned} m_3 &\approx 10^2 \mathrm{GeV} \\ m_8 &\approx 10^7 \mathrm{GeV} \\ m_{(3,2)} &\approx 10^{14} \mathrm{GeV} \\ M_{GUT} &\approx 10^{16} \mathrm{GeV} \end{aligned}$$

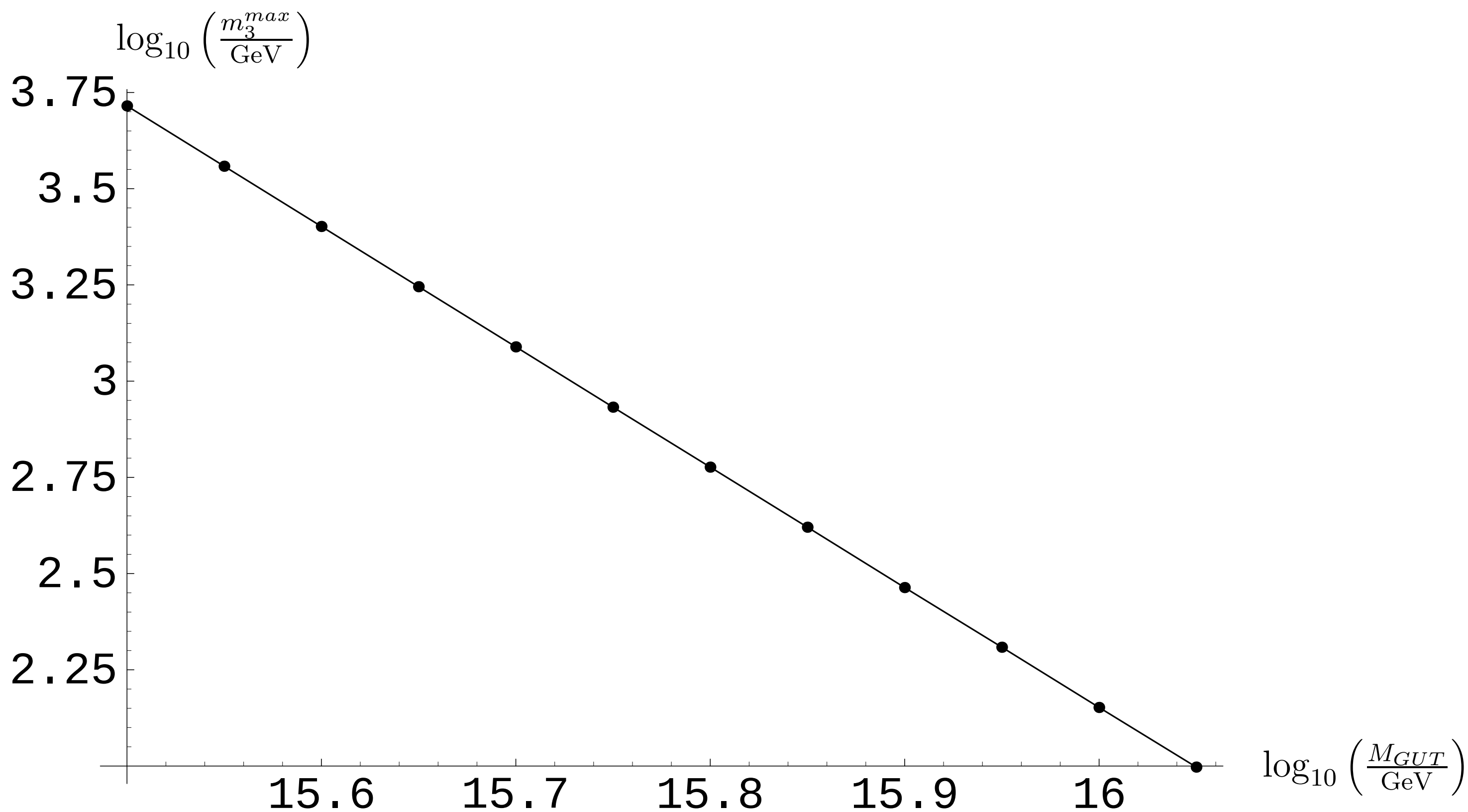
1-loop result:

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



Summary:

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

If LHC does not find the triplet:

$m_T \gtrsim 700$ GeV $\rightarrow \tau_p \lesssim 10^{35}$ yrs (or the model is ruled out)

BB, Senjanović, 06

BB, Nemevšek, Senjanović, 07

2. Neutrino mass

New Yukawa terms with 24_F

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

$$\begin{aligned} \delta\mathcal{L} &= \bar{5}_{Fi} 24_F 5_H \left(Y_i^{(1)} + Y_i^{(2)} \frac{24_H}{\Lambda} + \dots \right) \\ &+ 24_F 24_F \left(m_{24} + \lambda_1 24_H + \lambda_2 \frac{24_H^2}{\Lambda} + \dots \right) \\ &\rightarrow L_i \left(y_T^i T + y_S^i S \right) H + m_T TT + m_S SS + h.c. \end{aligned}$$

Mixed Type I and Type III seesaw:

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

→ one massless neutrino

How to produce T at LHC ?

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

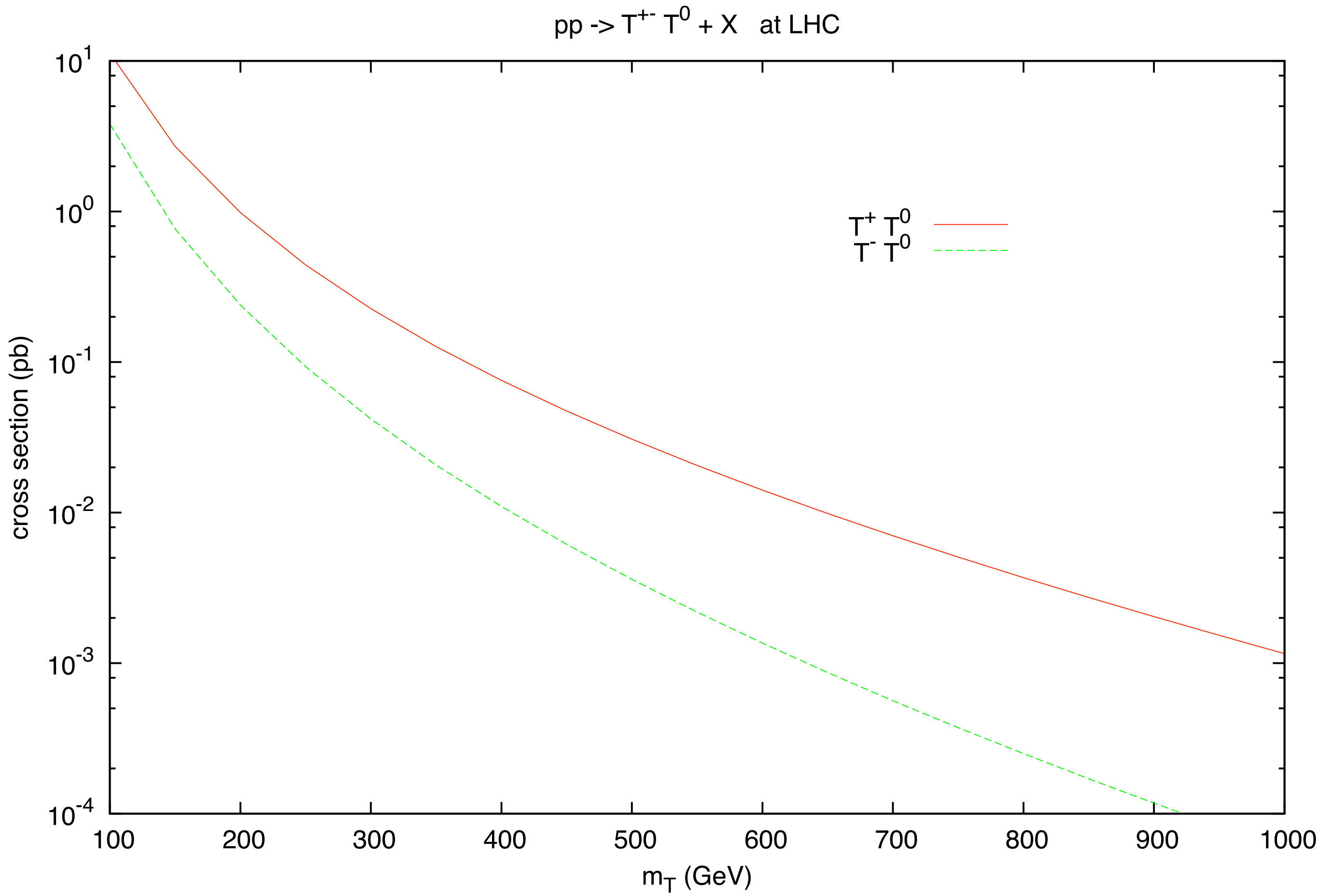
$\rightarrow$ produced through gauge interactions (Drell-Yan)

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

del Aguila, Aguilar-Saavedra, 07, 08

Franceschini, Hambye, Strumia, 08

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


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

Triplet 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

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

$$T^\pm \to Z l^\pm \to l^\pm + 2 jets$$
$$T^0 \to W^\mp l^\pm \to l^\pm + 2 jets$$

The cleanest channel is same-sign dileptons + jets

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

Keung, Senjanović, 83

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

Good chances for discovery with $\int \mathcal{L} \gtrsim 10 \text{ fb}^{-1}$ if $m_T \lesssim 400$ GeV

Experimentalists seem not to care (problems with multi jets):

$$pp \to T^{\pm}T^{0} \quad \to \quad (lZ)(\nu Z, lW) \to 3l + \ldots$$
$$pp \to T^{\pm}T^{0} \quad \to \quad (lW)(\nu W) \to lljj + \text{missing energy}$$

Triplet masses below $m_T \approx (300 - 500)$ GeV excluded

ATLAS, 1506.01291v1

ATLAS, 1506.01839v1

More on Yukawas and PMNS phases

Same couplings y_T^i contribute to

- ν mass matrix and
- triplet T decay

ν mass rank 2 $\rightarrow$

crucial for probing neutrino parameters from y_T^i

For rank 3 ν mass (R complex orthogonal 3×3)

$$v y_T^i = \sqrt{m_T} \sum_{j=1}^{3} U_{ij} \sqrt{m_j^\nu} R_{jT}(z_1, z_2, z_3)$$

Casas, Ibarra, 01

Too many unknowns:

$z_{1,2,3} \to$ 6 real

neutrino mass$\to$ 1 real

$\delta, \Phi_{1,2}$ from U (PMNS)$\to$ 3 real

Hard to disentangle useful information for neutrino parameters from only 3 measurements $|y_T^{1,2,3}|$

Much easier in our rank 2 case:

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:

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

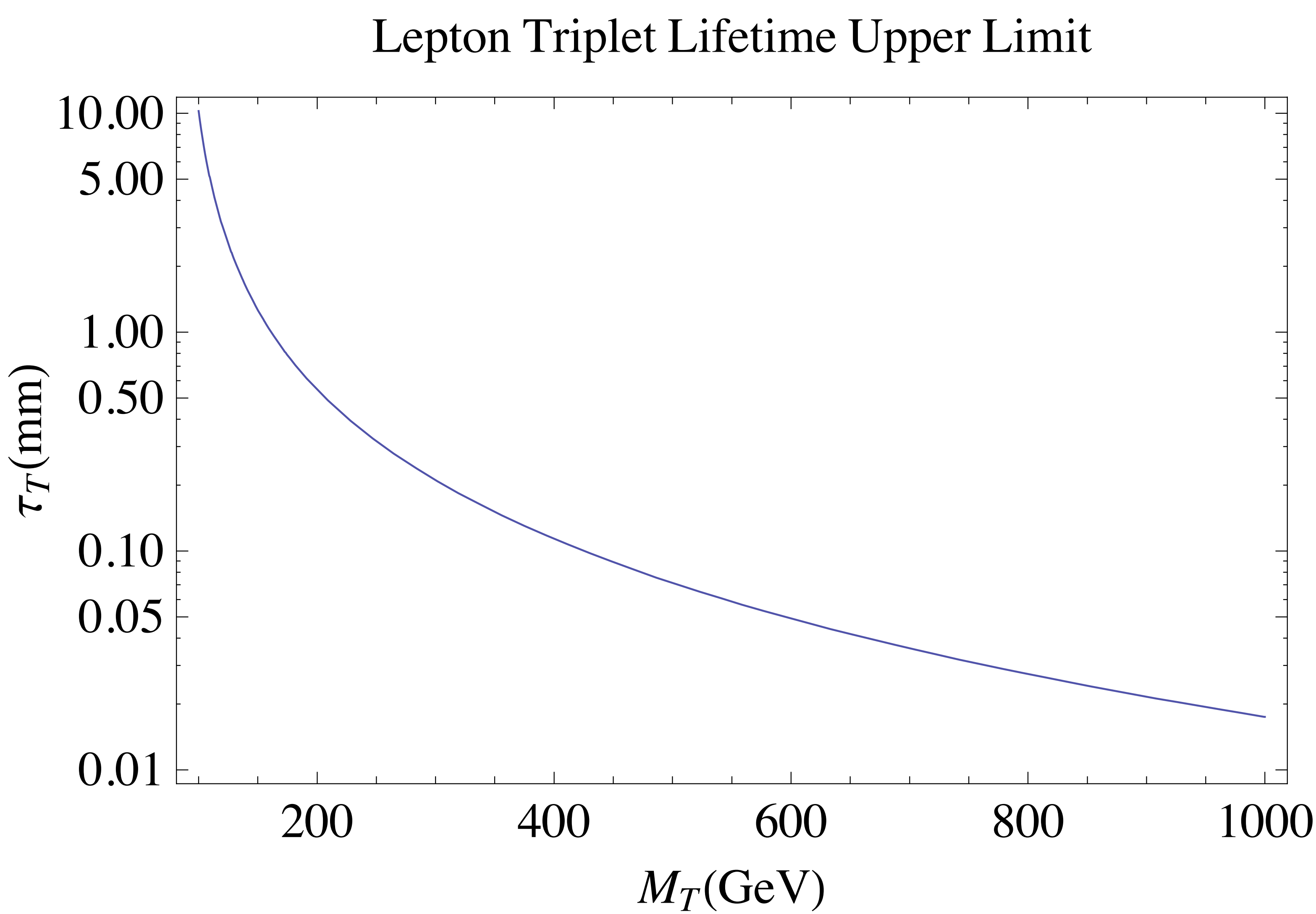
$$\times \quad \mathrm{diag}(1, e^{i\Phi}, 1)$$

Measuring light triplet decays

→ constraints on z, phases δ, Φ

How to probe seesaw parameters (δ, Φ)?

- Imagine we produce at LHC the light fermionic weak triplet T
- 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. $NBR_\mu = |y_T^\mu|^2 / \left(|y_T^e|^2 + |y_T^\mu|^2 + |y_T^\tau|^2\right)$


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)

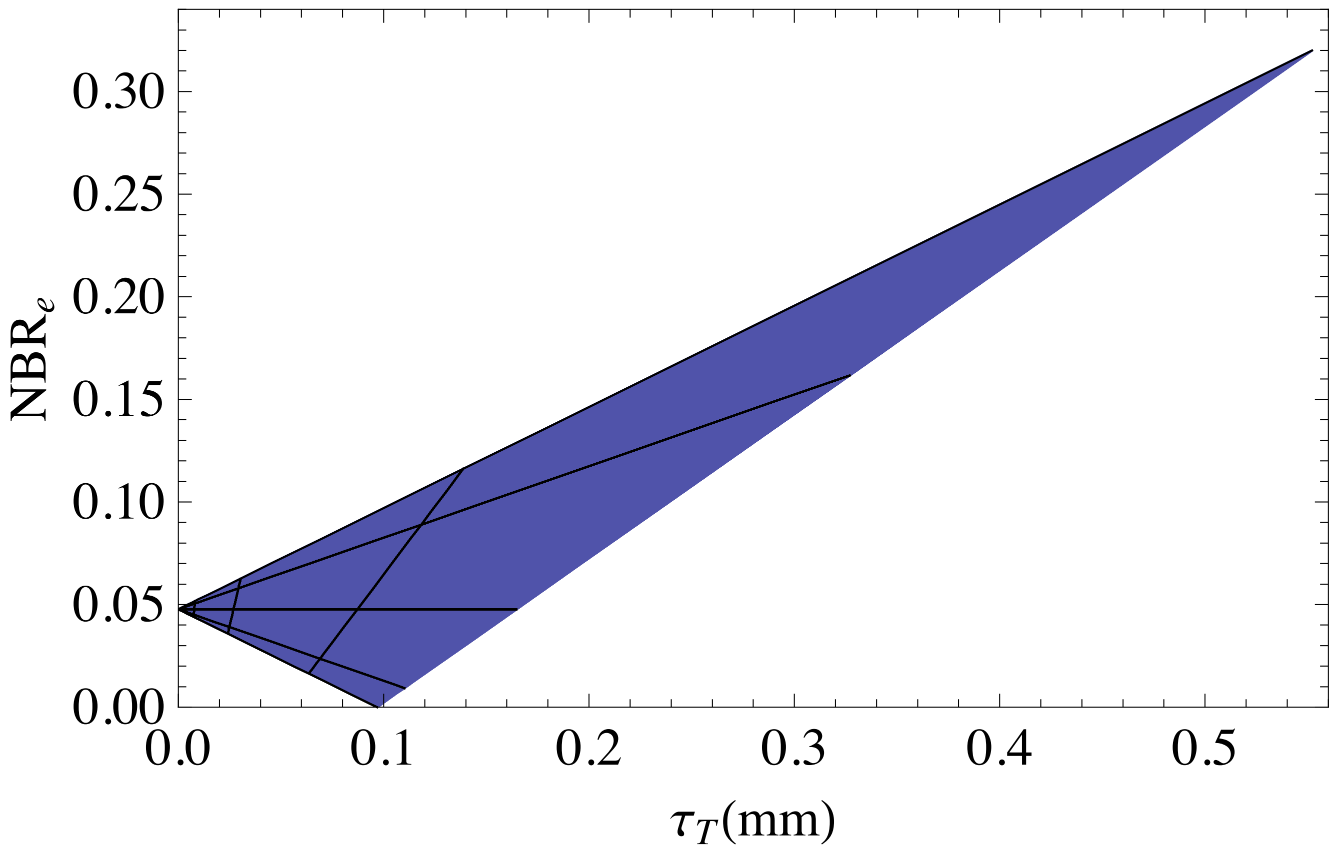
$$\tau_T \lesssim 0.5 \left(\frac{200 \text{ GeV}}{m_T} \right)^2 \text{ mm} \qquad \text{(normal hierarchy)}$$

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

Yukawas constrained in any rank 2 model →

consistency checks possible

Example (normal hierarchy and $M_T = 200$ GeV):



Case with normal hierarchy

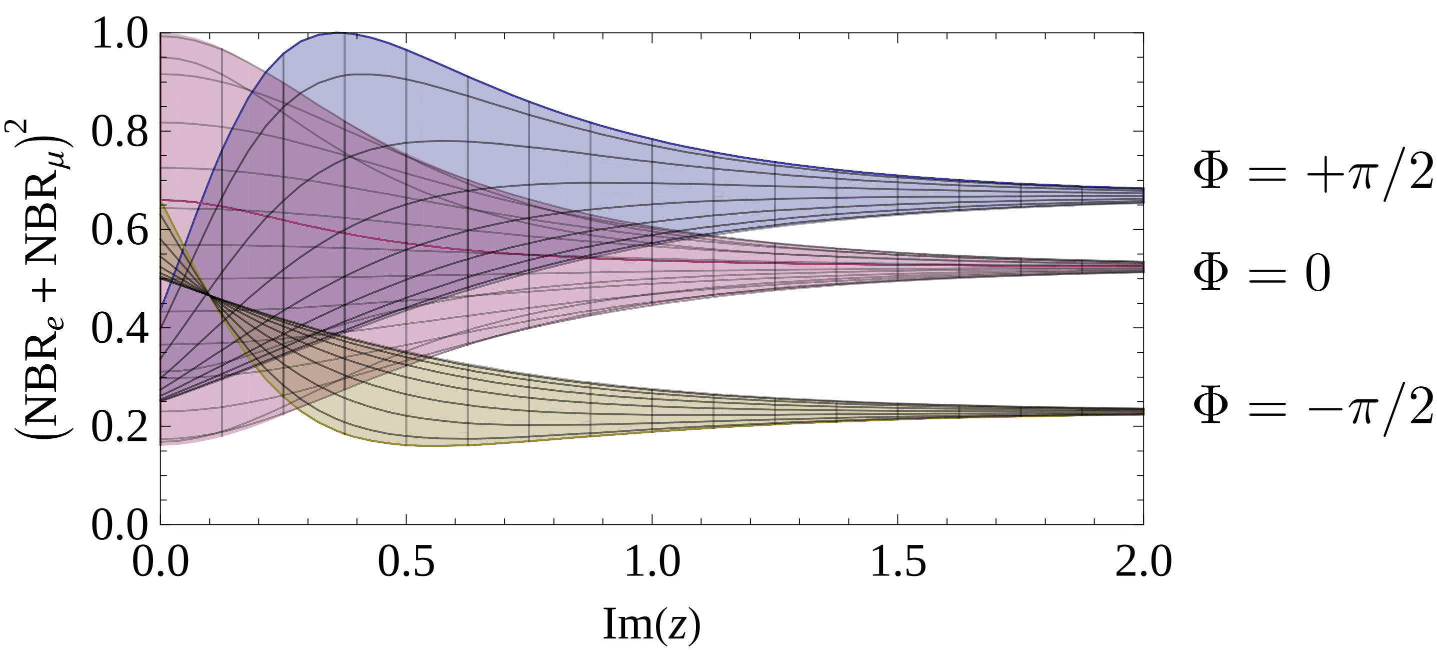
Assume an approximate simplified situation with

$$\theta_{13} \approx 0$$

The only unknown parameters (3):

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

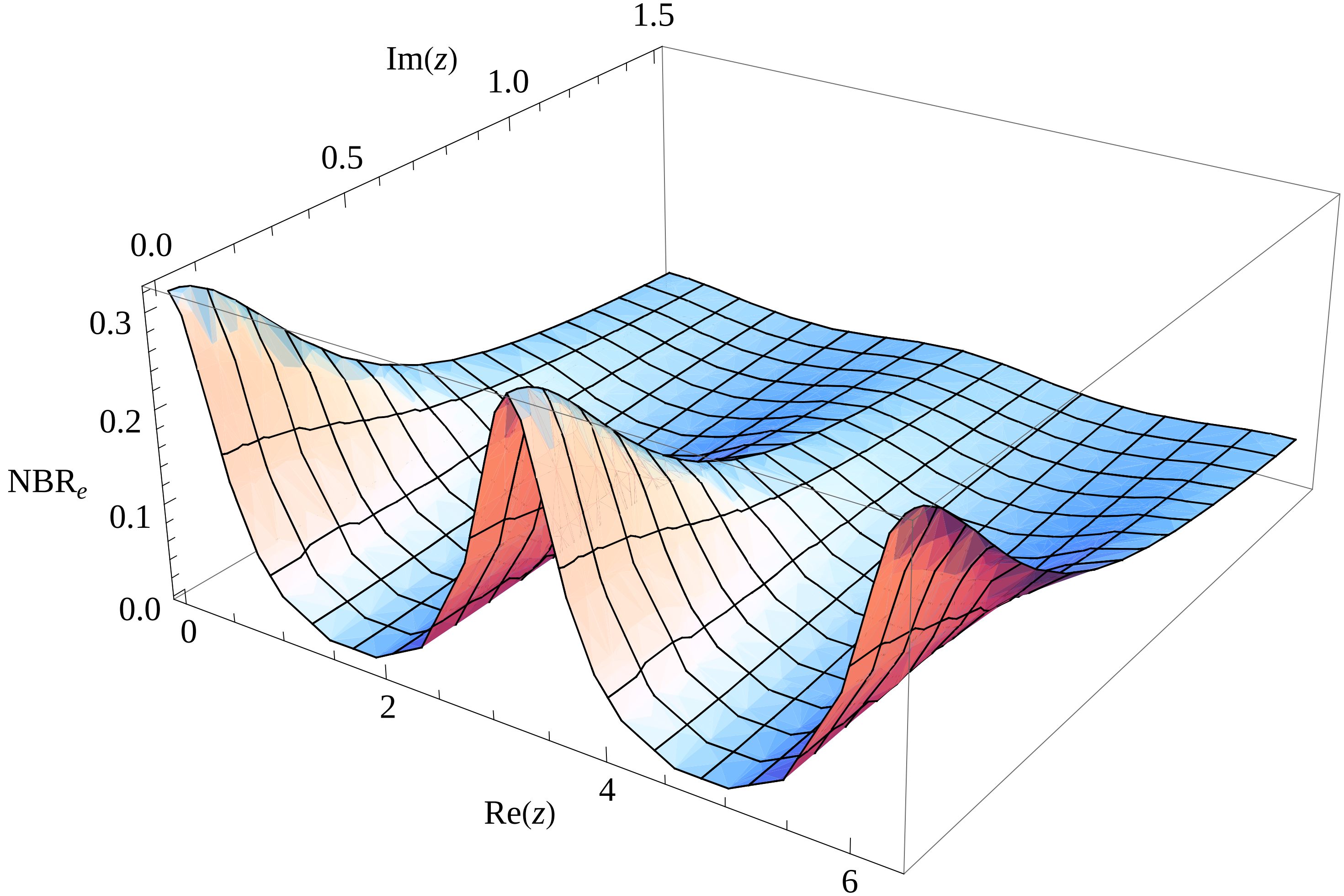
Just by measuring the cross section $\Delta L = 2$ production of same sign dilepton already some info:



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

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

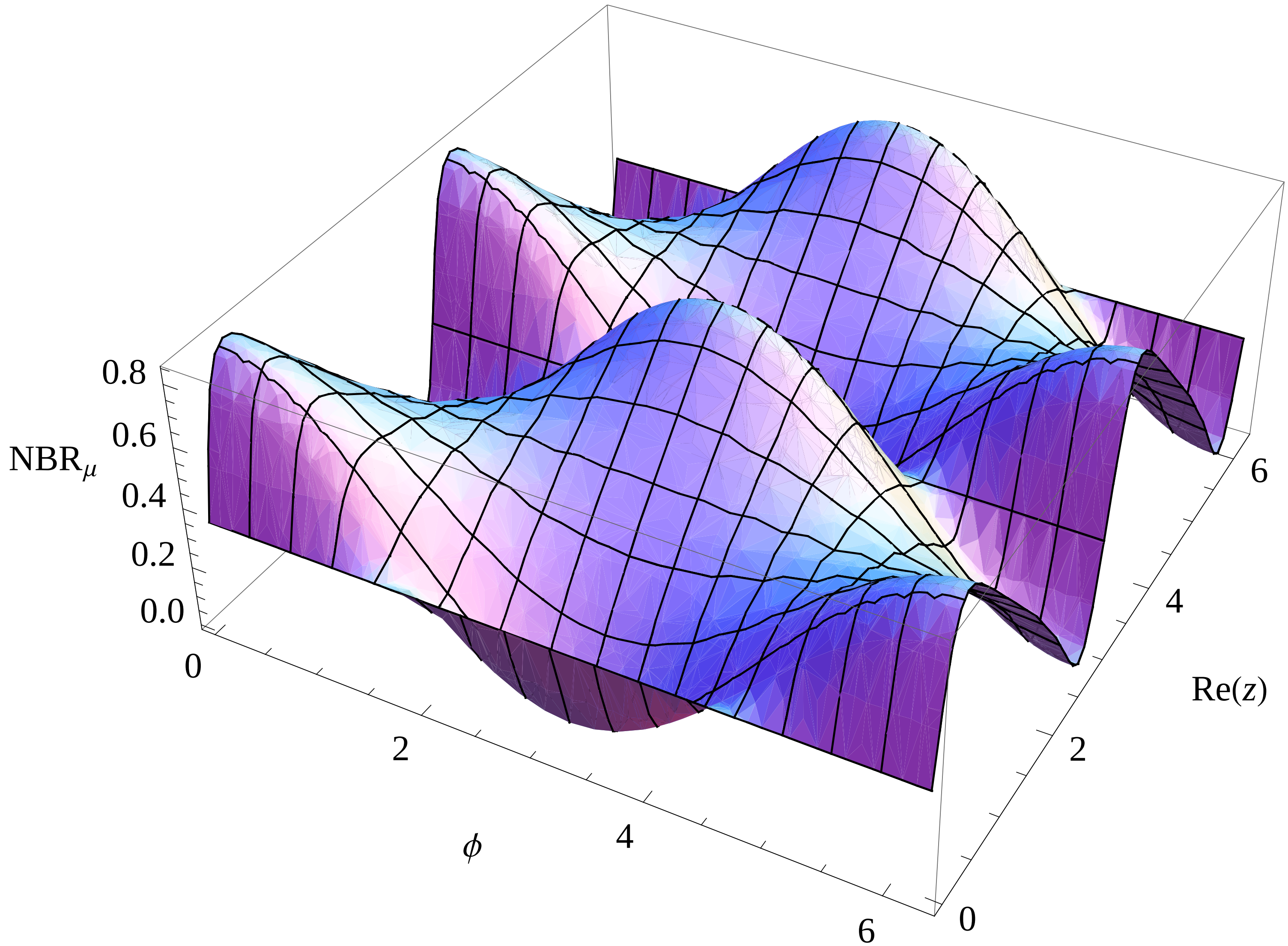
do not depend on Φ


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

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

$Im(z) = 0:$



Conclusion

Leptons and quarks on similar footing in GUTs.

Physical parameters can sometimes be predicted, not only fitted.

Two examples:

- supersymmetric SO(10)
  - $b - \tau$ unification connected with large neutrino mixing
  - large θ_{13} has been predicted
  - (yet unmeasured) phases part of the fit
- non-supersymmetric SU(5)
  - light (TeV) fermionic weak triplet predicted
  - its decay connected to neutrino mass and mixing

Backup slides

More on the triplet production

Define the following cross sections:

$$\begin{aligned}
\sigma_{prod} &\equiv \sigma(pp \to T^{\pm}T^{0}) \\
\sigma_{prod} \times BR &\equiv \sigma(pp \to T^{\pm}T^{0}) BR(T^{\pm} \to l^{\pm}jj) BR(T^{0} \to l^{\pm}jj) \\
&= \underbrace{f(M_T, M_h)}_{\approx 1/20} \sigma(pp \to T^{\pm}T^{0}) \\
\sigma_{signal} &\equiv \sigma_{prod} \times BR \quad \text{after cuts}
\end{aligned}$$

CUTS

- Rapidity coverage for leptons and jets

  $|\eta(\ell)| < 2.5 \ , \ \ |\eta(j)| < 3$

- High transverse momentum cuts

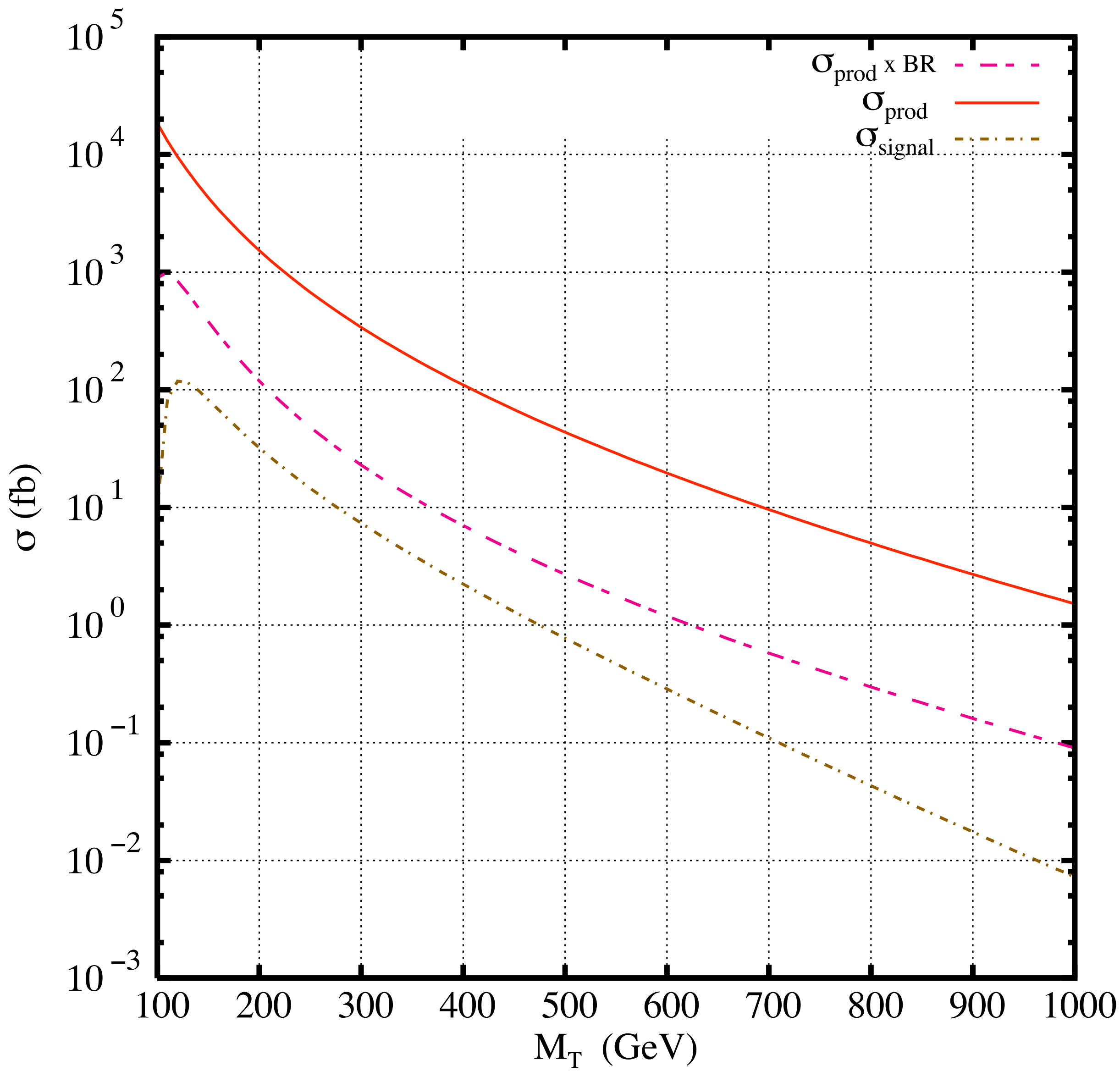
  $p_T^{\text{jets}} > 20 \text{ GeV} \ , \ \ p_T^{\ell} > 15 \text{ GeV} \ ,$

- Particle identification, $\Delta R_{\alpha\beta} \equiv \sqrt{(\Delta\phi_{\alpha\beta})^2 + (\Delta\eta_{\alpha\beta})^2}$

  $\Delta R_{jj} > 0.5 \ , \quad \Delta R_{\ell j} > 0.5 \ , \quad \Delta R_{\ell\ell} > 0.3 \ .$

- No significant missing energy

  $\not{E}_T < 25\,\text{GeV}$



σ (fb)
10^5
10^4
10^3
10^2
10^1
10^0
10^−1
10^−2
10^−3
100
200
300
400
500
600
700
800
900
1000
M_T (GeV)
σ_prod x BR
σ_prod
σ_signal

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)