Probing leptonic CP at LHC

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- B. Bajc, G. Senjanović, 06

- B. Bajc, M. Nemevšek, G. Senjanović, 07

- A. Arhrib, B. Bajc, D. Ghosh, T. Han, G.-Y. Huang, I. Puljak, G. Senjanović, to appear soon

The strategy to probe leptonic CP:

- 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 $\to M \lesssim \mathcal{O}(\mathrm{TeV})$

2) strongly enough coupled to our world to be produced $\to$ 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)

Similar examples already in the literature

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

can be found at LHC but have to assume:

1) $M_\Delta \lesssim \mathcal{O}(\text{TeV})$ (of course nothing forbids it to be light, but there is no reason-motivation for it)

2) $v_\Delta \lesssim 10^{-4}$ GeV (otherwise the triplets decay through other modes WW): 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 here 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

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)

Add just one extra fermionic 24_F

1. Gauge coupling unification

Under $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_W \times \mathrm{U}(1)_Y$ 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 typical solution

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

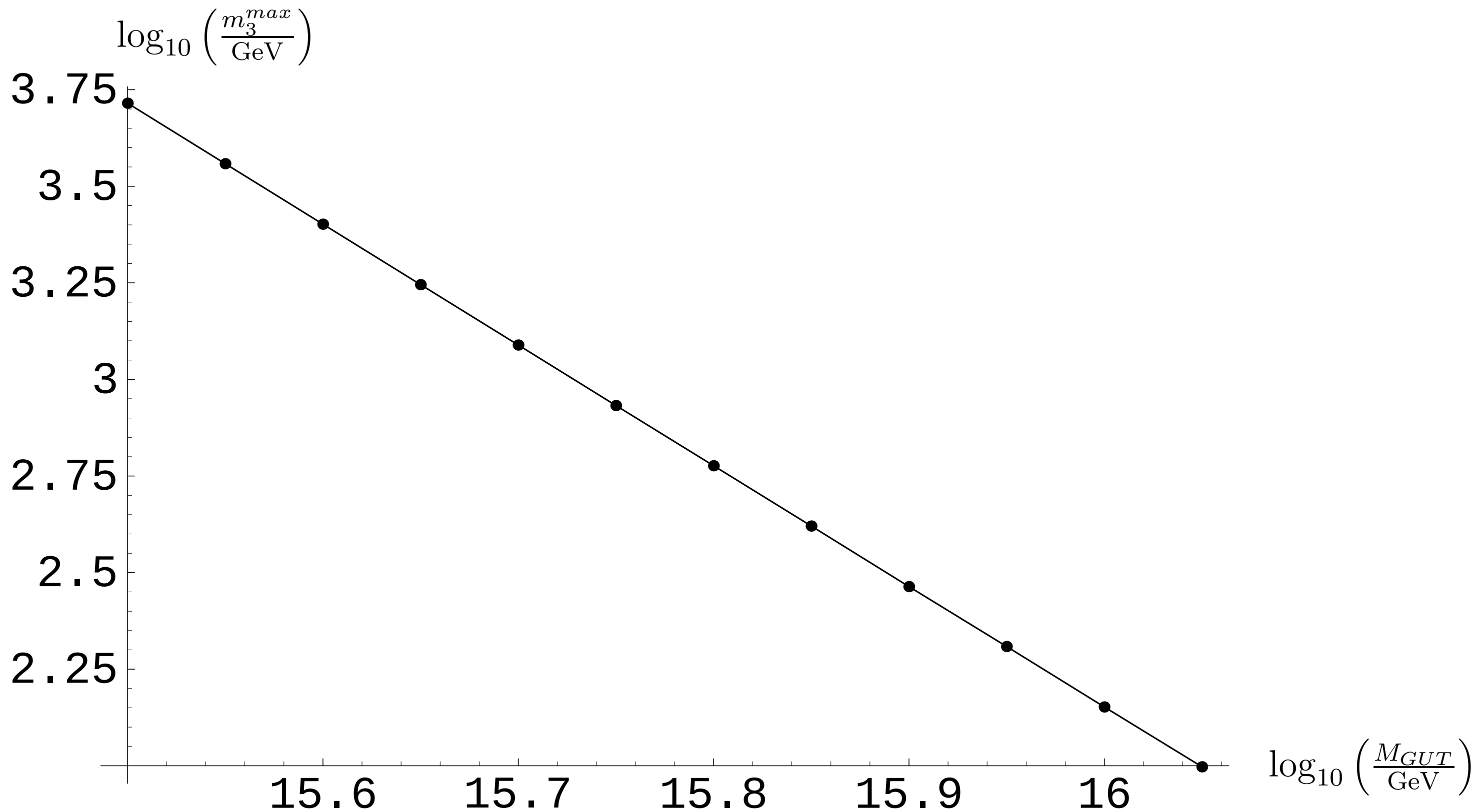
1-loop result:

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

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

Prediction of the model

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



Very important:

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

2. Neutrino mass

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:

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

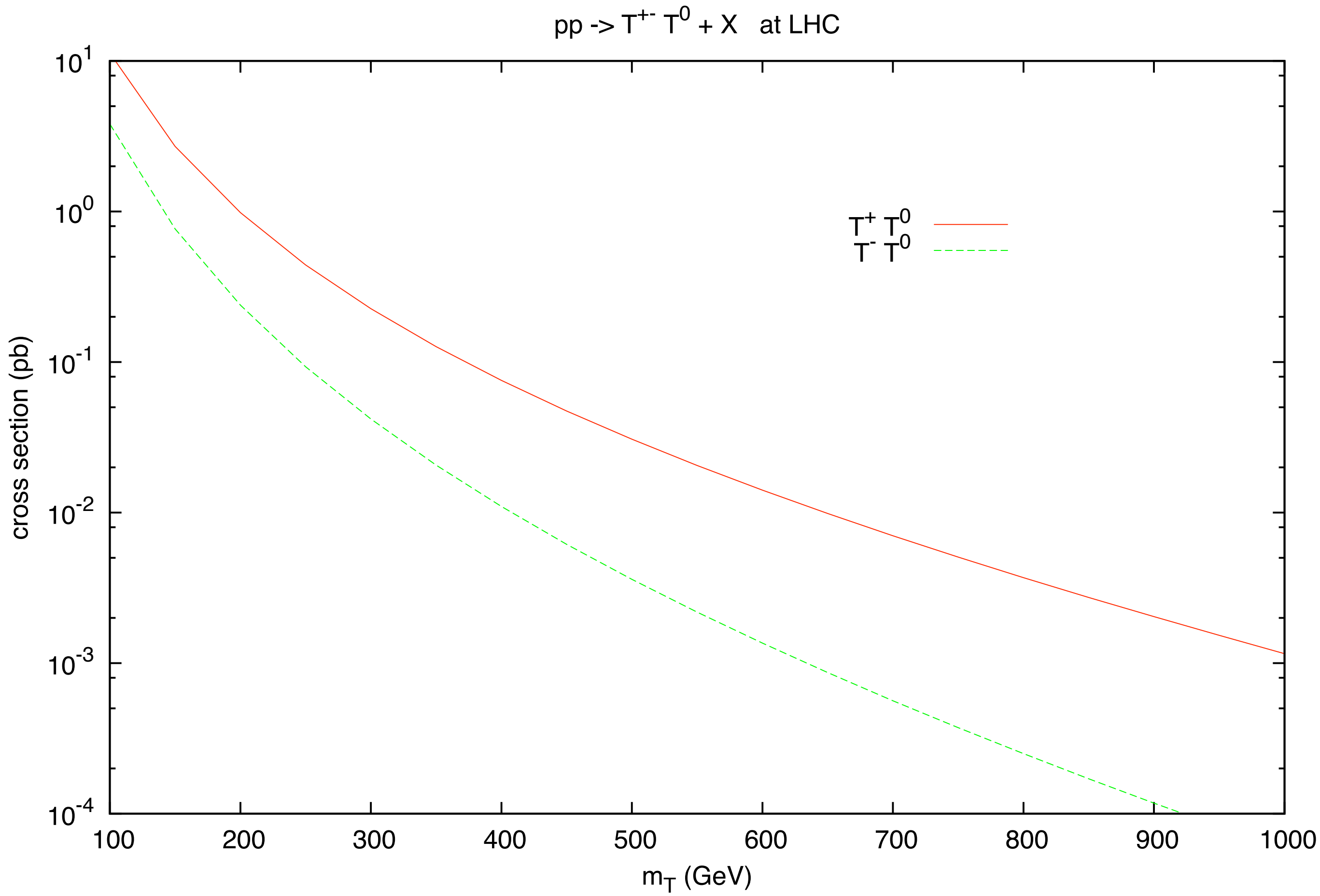
$\rightarrow$ one massless neutrino

How to produce T at LHC ?

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

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

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


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

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.

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

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

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

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

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

Same couplings y_T^i contribute to

- ν mass matrix and
- T decays

Normal hierarchy:

$$\frac{v y_T^{i*}}{\sqrt{2}} = i\sqrt{m_T}\left(U_{i2}\sqrt{m_2^\nu}\cos z \pm U_{i3}\sqrt{m_3^\nu}\sin z\right)$$

Inverse hierarchy:

$$\frac{v y_T^{i*}}{\sqrt{2}} = i\sqrt{m_T}\left(U_{i1}\sqrt{m_1^\nu}\cos z \pm U_{i2}\sqrt{m_2^\nu}\sin z\right)$$

U = PMNS matrix, z = arbitrary complex number

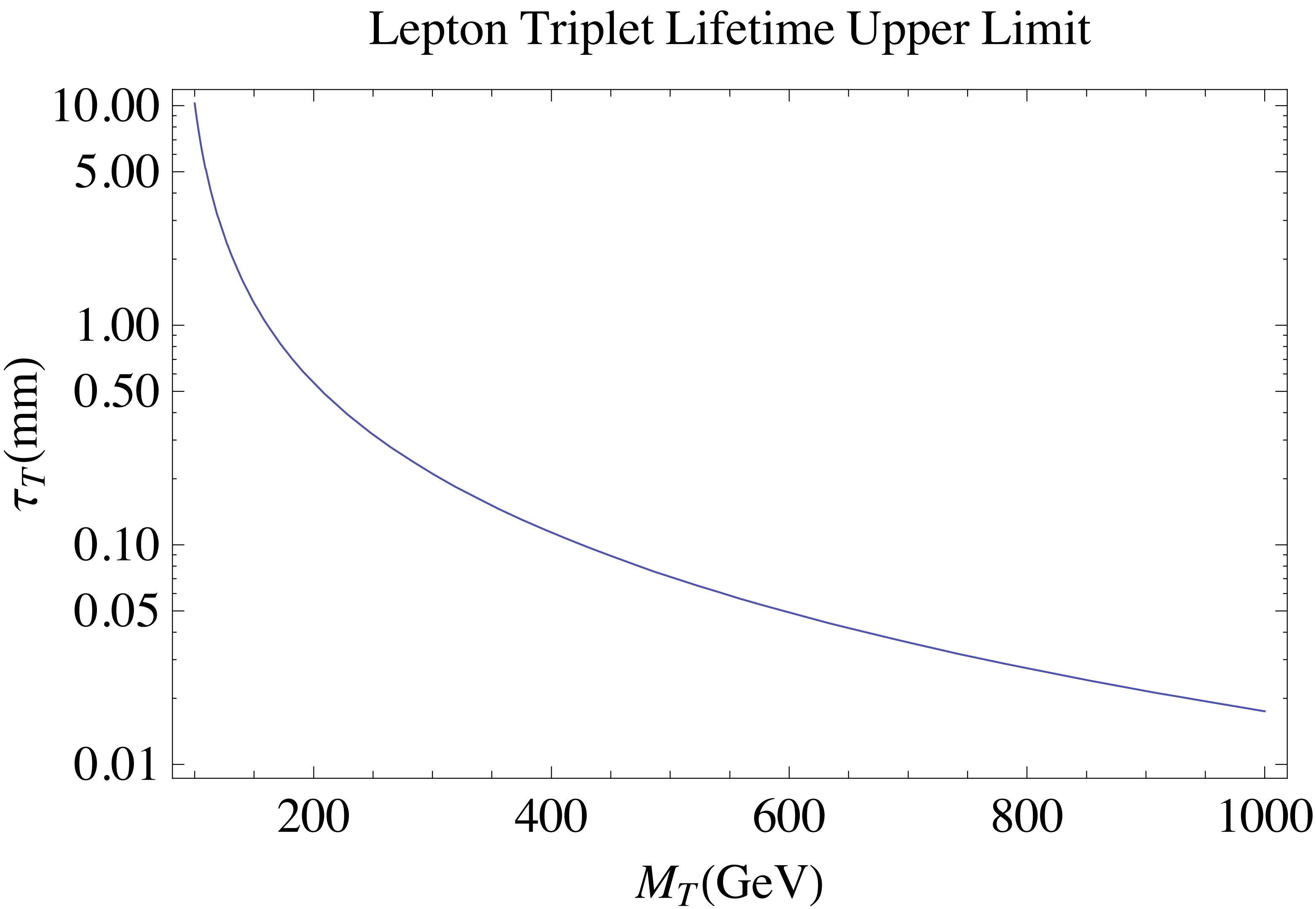
Ibarra, Ross, 03

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



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)

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

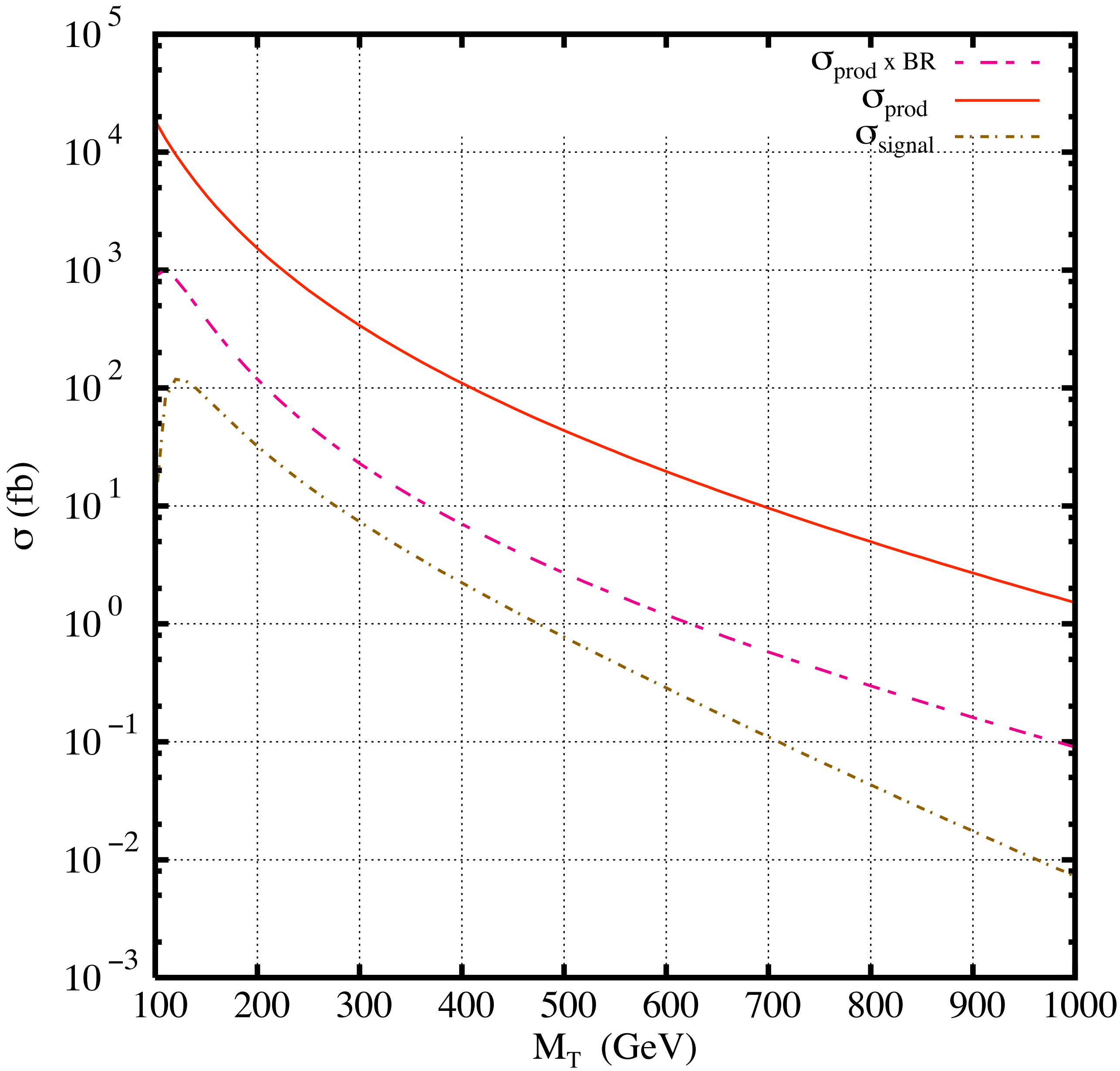
  $p_T^{\text{jets}} > 20 \text{ GeV} \ , \ p_T^{\ell} > 15 \text{ GeV} \ ,$

- 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

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



10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
σ (fb)
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)

Arhrib, Bajc, Ghosh, Han,
Huang, Puljak, Senjanović, to appear soon

Consistent with other estimates of these and other channels:

del Aguila, Aguilar-Saavedra, 07, 08

Franceschini, Hambye, Strumia, 08

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

How to probe CP?

Need to measure leptonic flavour in final states ($l^\pm l'^\pm jjjj$):

$$\underbrace{\sigma_{prod} \times BR}_{\sigma(M_T) f(M_T, M_h)} \quad \times \quad \underbrace{NBR_l}_{|y_T^l|^2 / \left(|y_T^e|^2 + |y_T^\mu|^2 + |y_T^\tau|^2\right)} \quad \times \quad NBR_{l'}$$

Suppose we will measure:

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. $NBR_\mu = |y_T^\mu|^2 / \left(|y_T^e|^2 + |y_T^\mu|^2 + |y_T^\tau|^2\right)$

Case with normal hierarchy

Assume a simplified situation with

$$\theta_{13} = 0$$

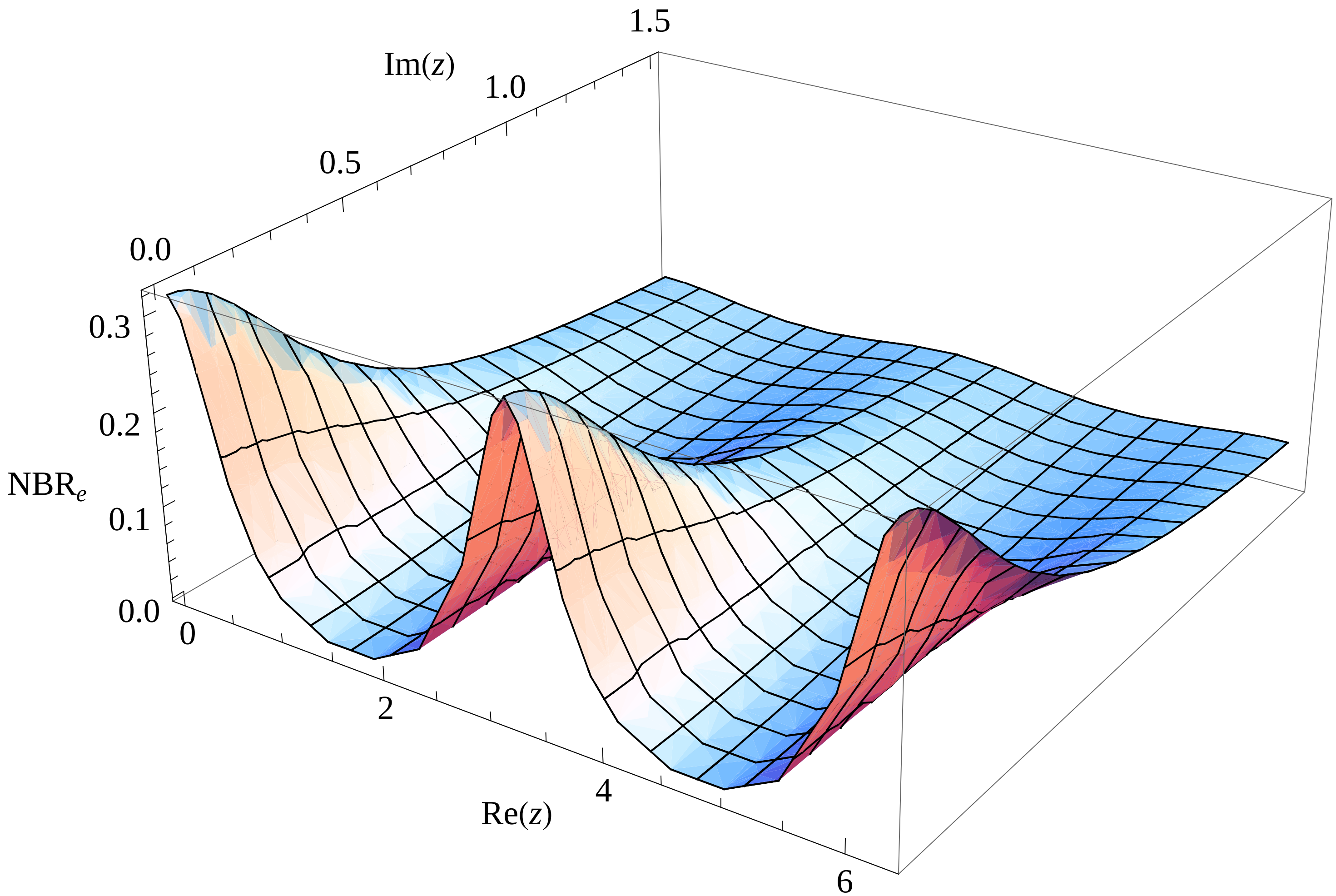
The only unknown parameters (3):

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

This case special:

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

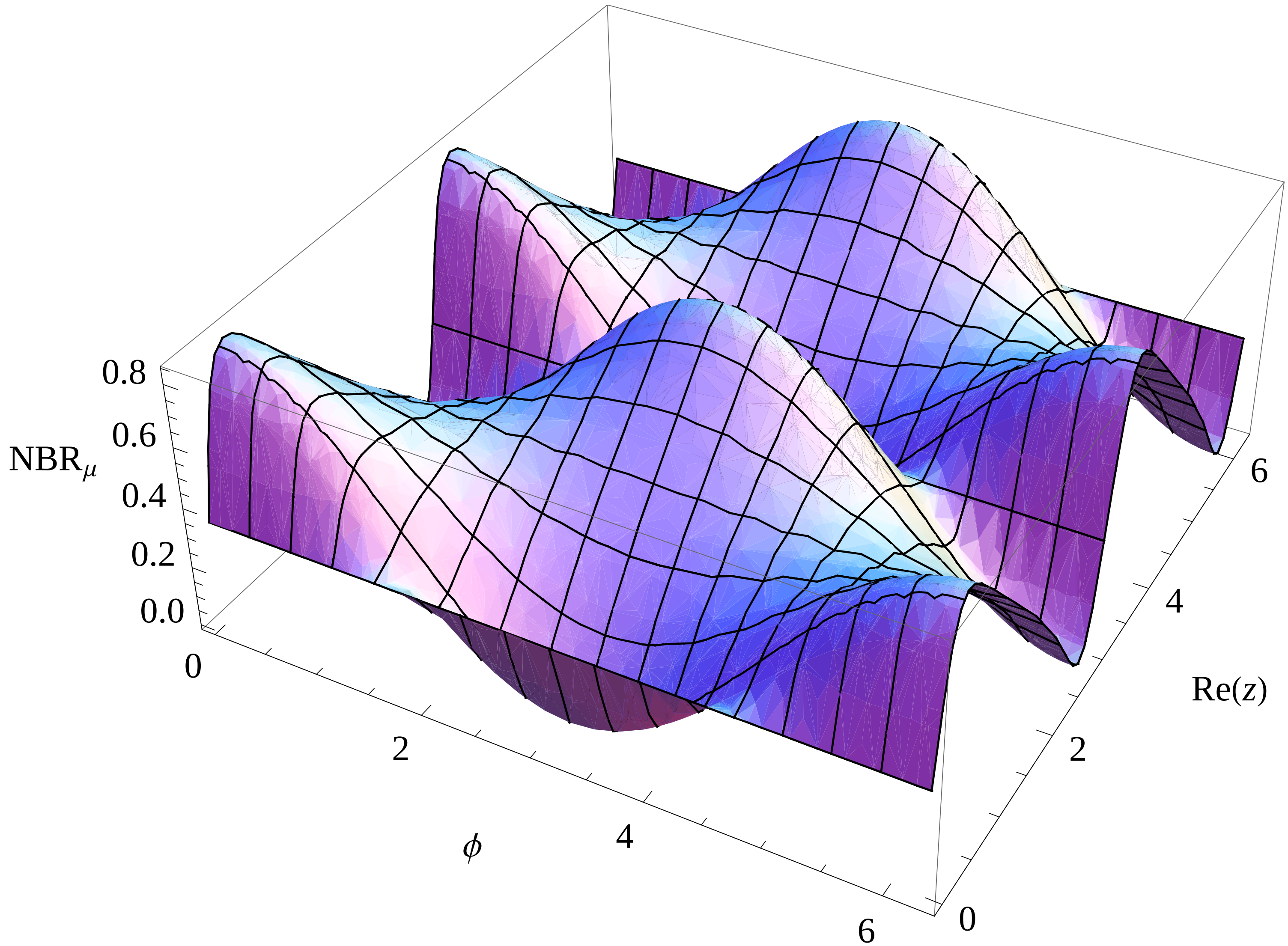
do not depend on Φ


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

Possible to determine Φ from

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

$Im(z) = 0:$



Conclusions

- Shown an explicit example of predictive GUT theory: ordinary minimal SU(5) with extra fermionic adjoint
- weak fermionic triplet predicted in the TeV range
- its decay connected with neutrino mass
- good chances to find it at LHC
- possible to get information on unmeasured (CP) neutrino parameters