See-saw signals at the LHC

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B. Bajc, G. Senjanović, 06

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

Various works in progress with A. Arhrib, D. Ghosh, T. Han, G.-Y. Huang, M. Nemevšek, I. Puljak, G. Senjanović

See also tomorrow's plenary talk by Goran Senjanović

With the degrees of freedom of the SM

ν masses parametrized by

Weinberg $d = 5$ effective operator

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

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

M signals the appearence of new physics

Only 3 ways of producing the Weinberg operator

By exchange of heavy

- fermion singlet $(1,1,0)$ TYPE I SEESAW

  Minkowski, 77

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

  Mohapatra, Senjanović, 80

- boson weak triplet $(1,3,1)$ TYPE II SEESAW

  Magg, Wetterich, 80

  Lazarides, Magg, Wetterich; Mohapatra, Senjanović, 81

- fermion weak triplet $(1,3,0)$ TYPE III SEESAW

  Foot, Lew, He, Joshi, 89

I and II very well studied, III almost ignored in the past

All this by itself not more useful than just Weinberg operator

Interesting for LHC only if

1) the mediators have a small enough mass M

2) they are coupled with our world (photons, W, Z, Higgses, fermions) strongly enough to be produced

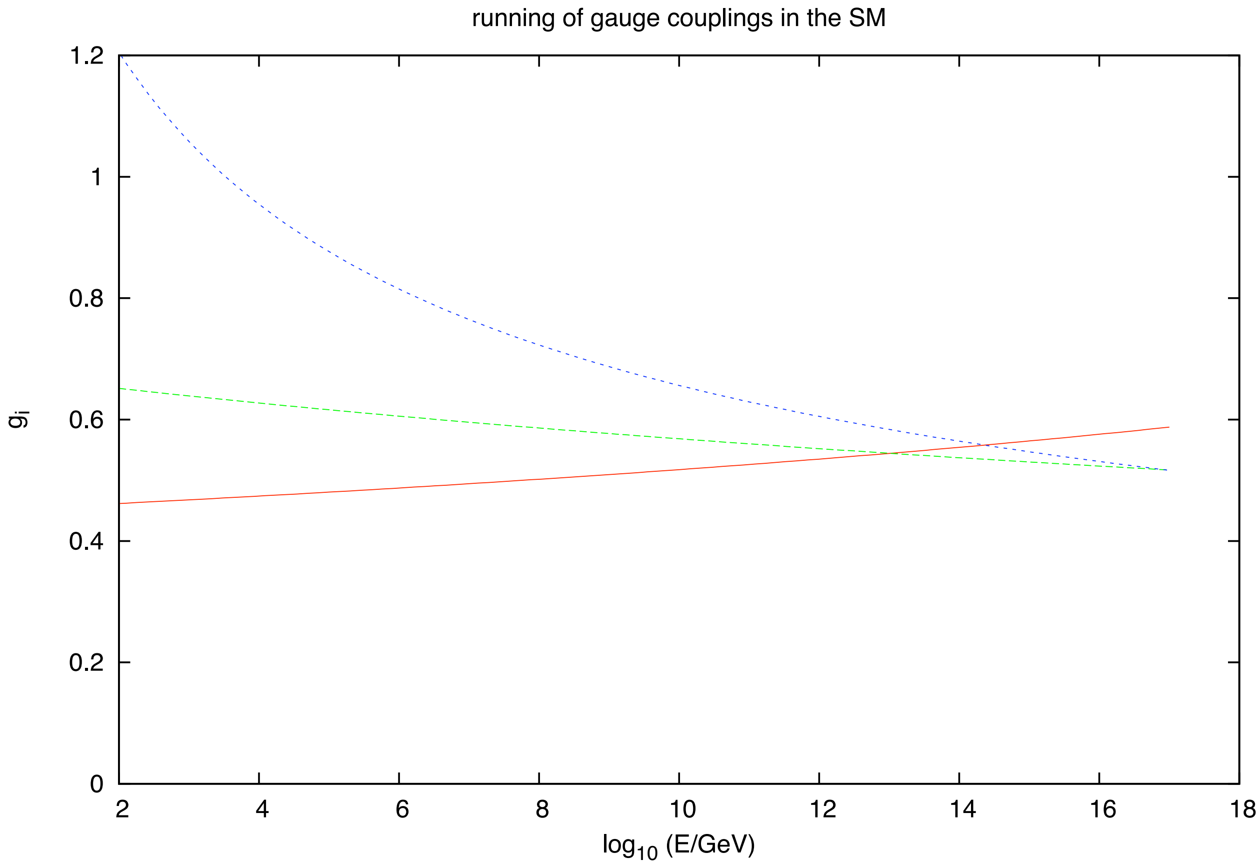
I will present in the following the only known (to my knowledge) model which predicts both: the minimal non-supersymmetric SU(5) with extra adjoint fermionic 24_F

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. Guage 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 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:

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

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

The only possible pattern:

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

A typical solution

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

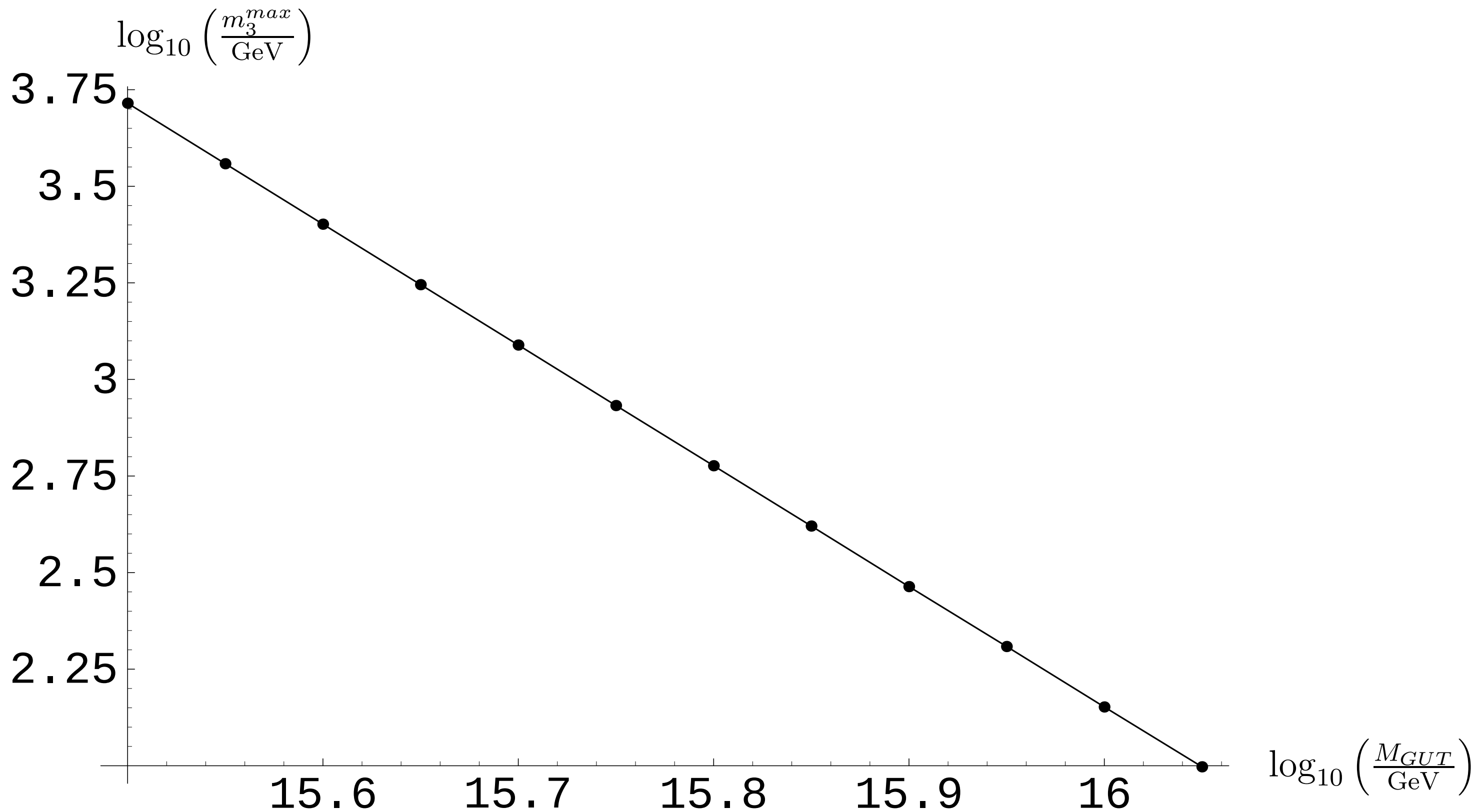
1-loop result:

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

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

Prediction of the model !

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



Very important:

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

2. Neutrino mass

New Yukawa terms

$$\mathcal{L}_{Y\nu} = Y_0^i \bar{5}_F^i 24_F 5_H + \frac{1}{\Lambda} \bar{5}_F^i \left({Y_1}^i 24_F 24_H + ... \right) 5_H + h.c.$$

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

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

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

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

Mixed Type I and Type III seesaw:

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

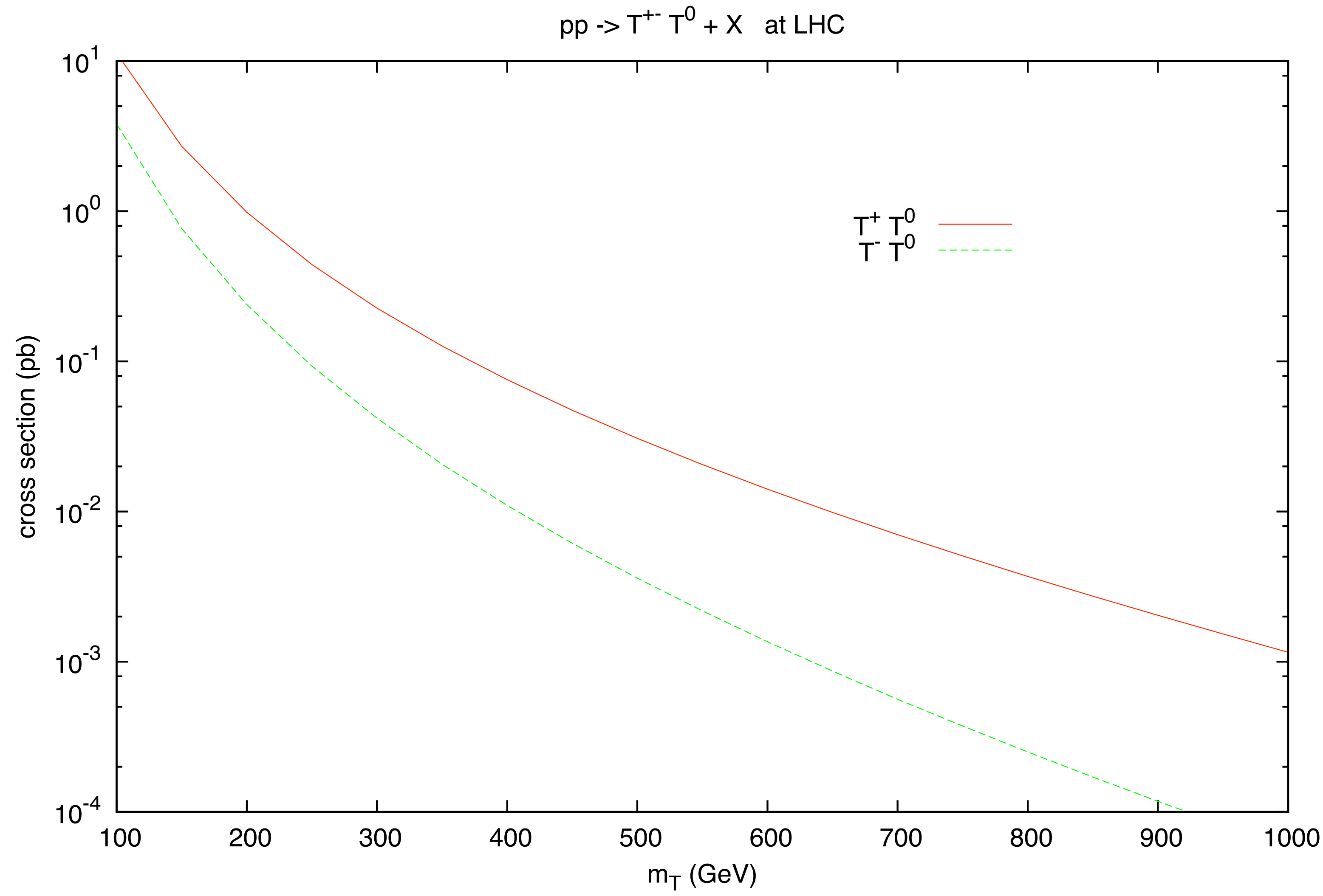
$\rightarrow$ one massless neutrino !

How to produce T at LHC ?

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

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

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


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

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

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

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

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

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

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

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:

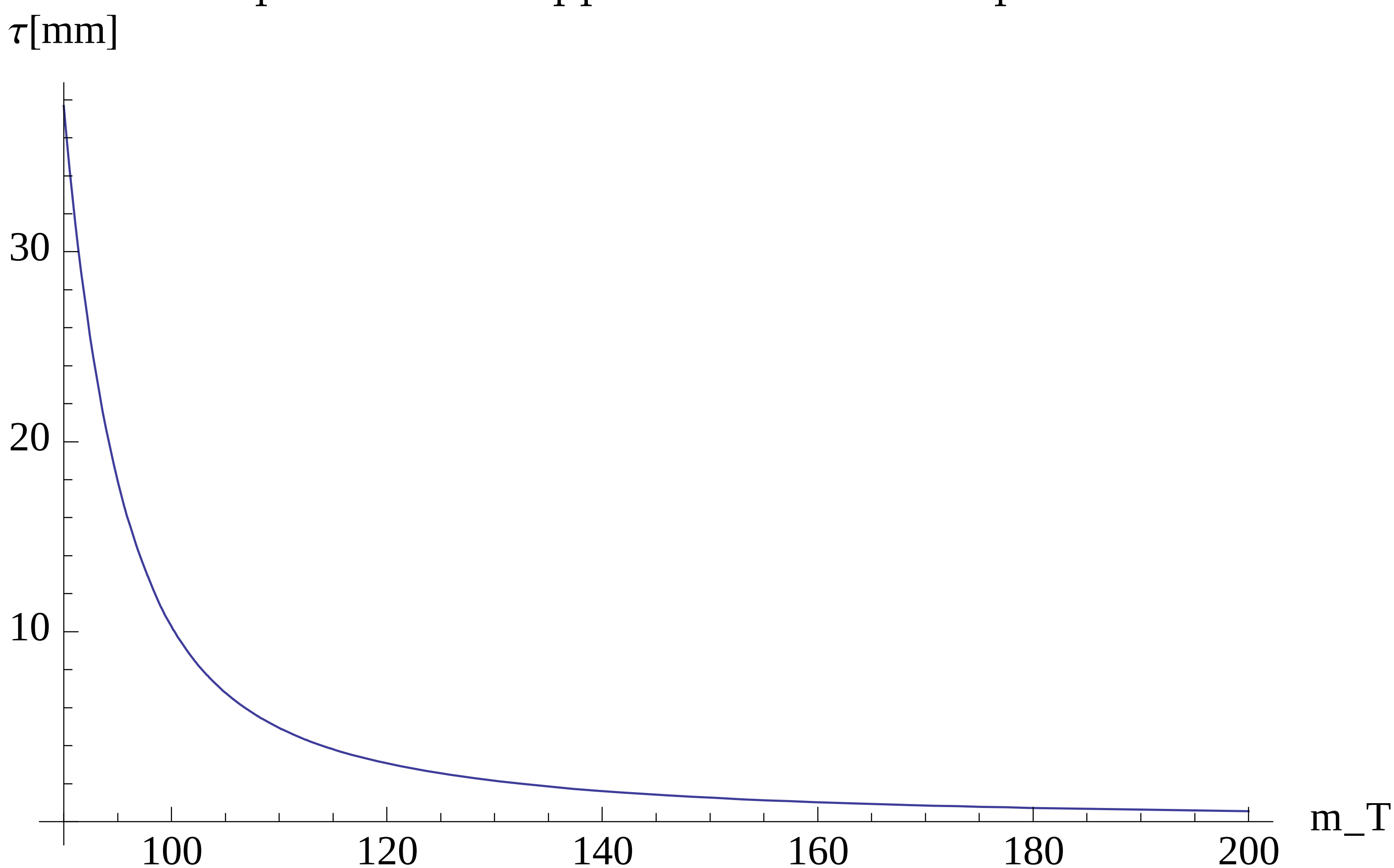
$$\frac{v y_T^{i*}}{\sqrt{2}} = i\sqrt{m_T}\left(U_{i1}\sqrt{m_1^\nu}\cos z \pm U_{i2}\sqrt{m_2^\nu}\sin z\right)$$

U = PMNS matrix, z = arbitrary complex number

Ibarra, Ross, 03

Measuring T decays → constraints on z (θ_{13}, phases)

Triplet lifetime upper limit for low triplet mass:



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

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

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

May be hard to measure lifetime

But should be easier to measure

- slower decay modes
- branching ratios

$|y_T^k|$ from $\tau(T \to l_k jj)$ are partially correlated (connected by unknown complex z and not yet measured θ_{13} and phases δ, Φ in U_{PMNS})

$$a_T^i \equiv y_T^i \sqrt{\frac{v}{2m_T}}$$

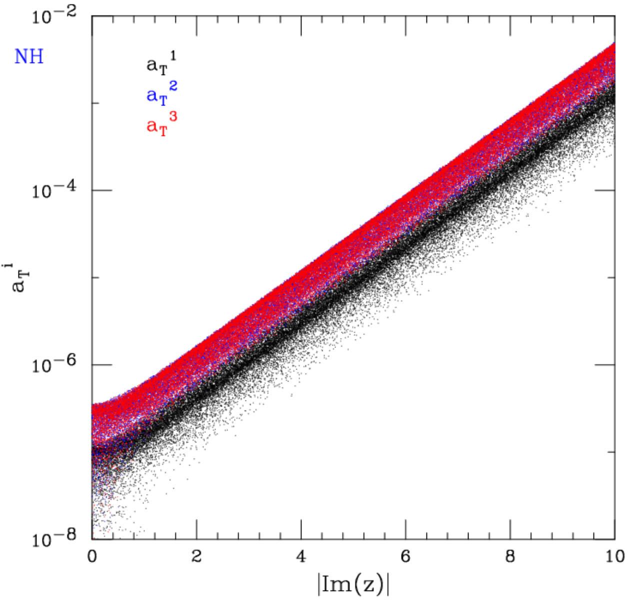
Normal hierachy: $a_T^1 < a_T^2 \approx a_T^3$

Inverse hierachy: $a_T^1 > a_T^2 \approx a_T^3$

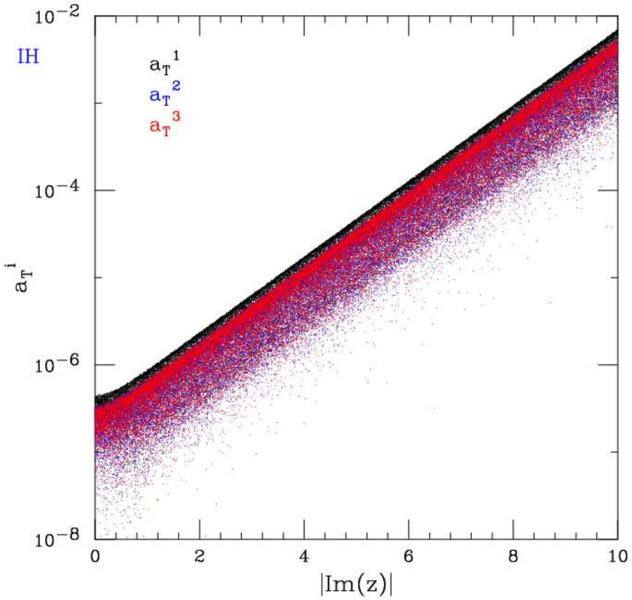
Arhrib, Bajc, Ghosh, Han, Huang, Puljak, Senjanović, to appear

$\tau\tau$ final states never dominates

Scanning over whole parameter space

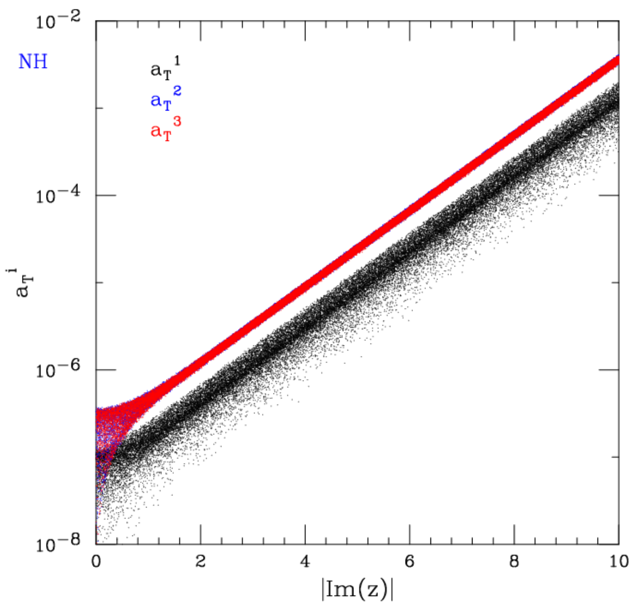


normal hierarchy

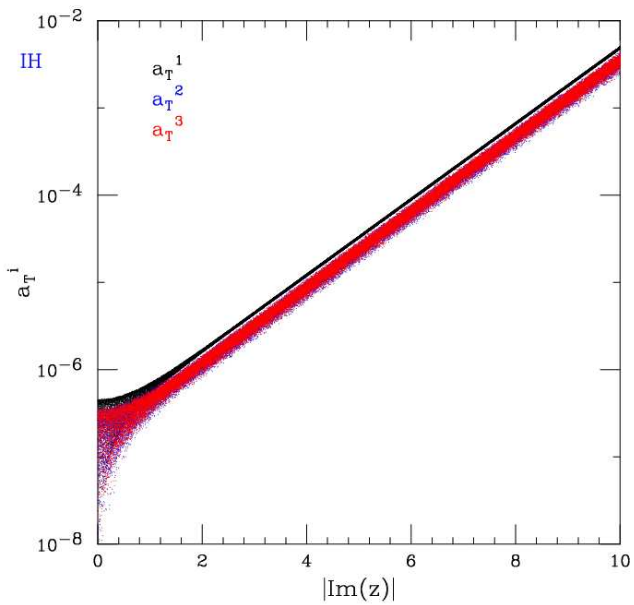


inverse hierarchy

Assuming Majorana phase $\Phi = 0$



normal hierarchy



inverse hierarchy

Define the following cross sections:

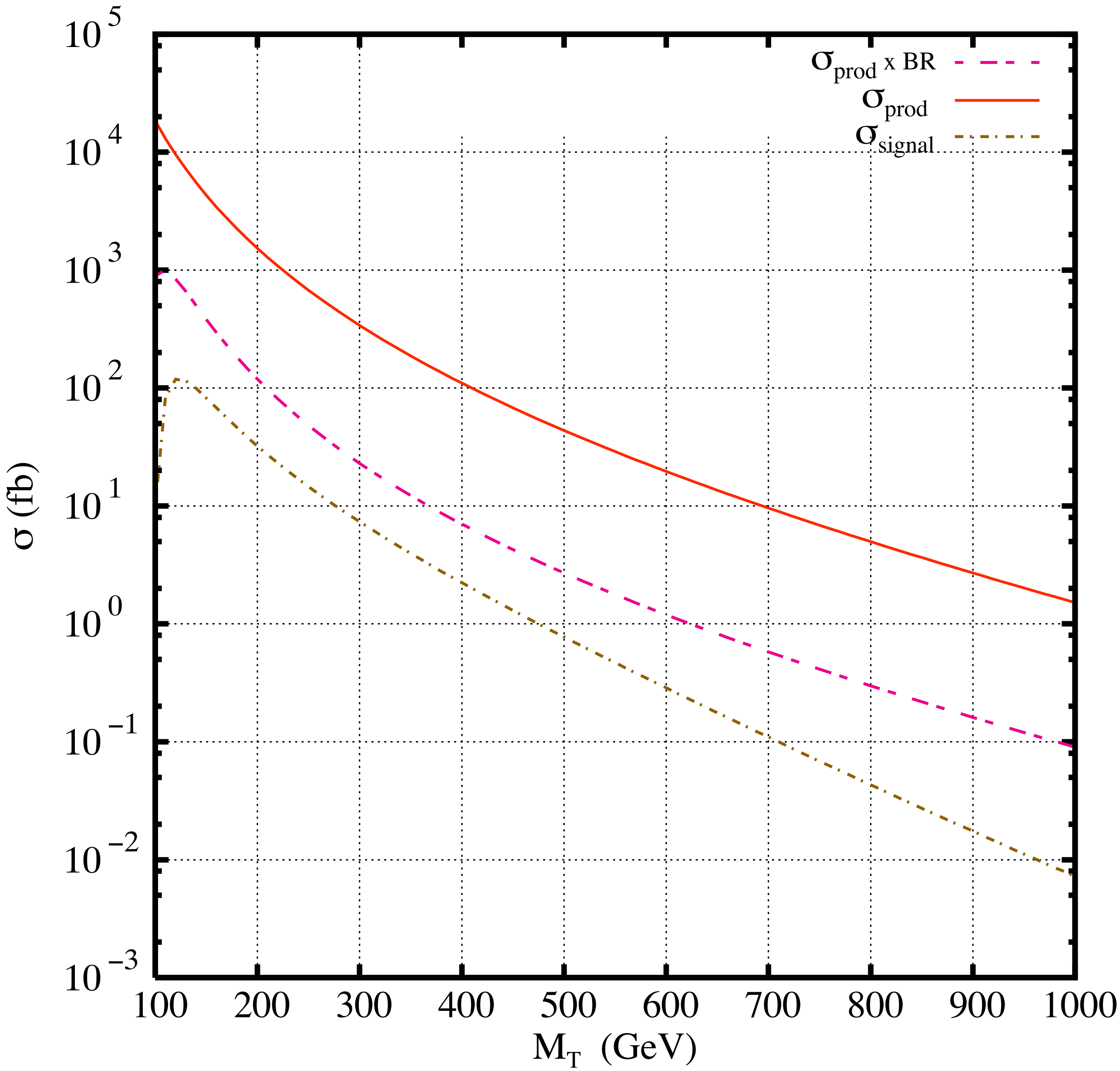
$$
\begin{aligned}
\sigma_{prod} &\equiv \sigma(pp \to T^{\pm}T^{0}) \\
\sigma_{prod} \times BR &\equiv \sigma(pp \to T^{\pm}T^{0}) BR(T^{\pm} \to l^{\pm}jj) BR(T^{0} \to l^{\pm}jj) \\
\sigma_{signal} &\equiv \sigma_{prod} \times BR \quad \text{after cuts}
\end{aligned}
$$

where

$$
BR(T \to ljj) \equiv \sum_{a=1}^{3} BR(T \to l_a jj)
$$

CUTS

- Rapidity coverage for leptons and jets
  $|\eta(\ell)| < 2.5 \ , \ \ |\eta(j)| < 3$
- High transverse momentum cuts
  $p_T^{\text{jets}} > 20 \text{ GeV} \ , \ \ p_T^{\ell} > 15 \text{ GeV} \ ,$
- No significant missing energy
  $\not{E}_T < 25\,\text{GeV}$
- Particle identification, $\Delta R_{\alpha\beta} \equiv \sqrt{(\Delta\phi_{\alpha\beta})^2 + (\Delta\eta_{\alpha\beta})^2}$
  $\Delta R_{jj} > 0.5 \ , \quad \Delta R_{\ell j} > 0.5 \ , \quad \Delta R_{\ell\ell} > 0.3 \ .$


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}

Quite substantial decrease due to cuts (factor ≈ 6)

For $M_T = 200$ GeV and initial $\sigma_{prod} \times BR = 119$ fb:

Cuts $\Downarrow$	$\sigma_{\rm sig.}$(fb)
$p_T(\ell) > 15\,\mathrm{GeV}$	114.92
$p_T(jets) > 20\,\mathrm{GeV}$	63.92
$\mid \eta(\ell) \mid < 2.5$	49.81
$\mid \eta(jets) \mid < 3$	48.43
$\Delta R_{\ell\ell} > 0.3$	44.69
$\Delta R_{\ell j} > 0.5$	37.25
$\Delta R_{jj} > 0.5$	32.80
$\not{p}_T < 25\,\mathrm{GeV}$	21.51

Background mainly from

- $t\bar{t}nj$:

$$
\begin{aligned}
t &\rightarrow W^+ b \\
\bar{t} &\rightarrow W^- (\bar{b} \rightarrow W^+ \bar{q})
\end{aligned}
$$

- $b\bar{b}nj$:

$$
\begin{aligned}
b &\rightarrow W^- (q \rightarrow W^+ q') \\
\bar{b} &\rightarrow W^+ \bar{q}''
\end{aligned}
$$

$W^+ \rightarrow l^+ \nu$ produce final states $\rightarrow l^+ l^+ 4j +$ missing energy

Cross sections huge (QCD), but phase space fortunately small

Other important non-QCD modes

- W^+W^+nj
- W^+Znj

$$Z \quad \longrightarrow \quad q(\bar{q} \rightarrow W^+\bar{q}')$$

Some estimates:

with just very loose cuts: $\sigma_{background} \approx 25$ fb

Different for different final states (e, μ or τ)

Del Aguila, Aguilar-Saavedra, 07, 08

Seems under control ($\sigma_{background} \lesssim 1$ fb) with better cuts

Franceschini, Hambye, Strumia, 08

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

Triplet mass reconstruction:

Finite resolution of measured energy in the detector simulated by Gaussian smearing

$$\frac{\delta E_j}{E_j} = \left[\frac{1\mathrm{GeV}}{E_j} + (0.05)^2\right]^{1/2}$$

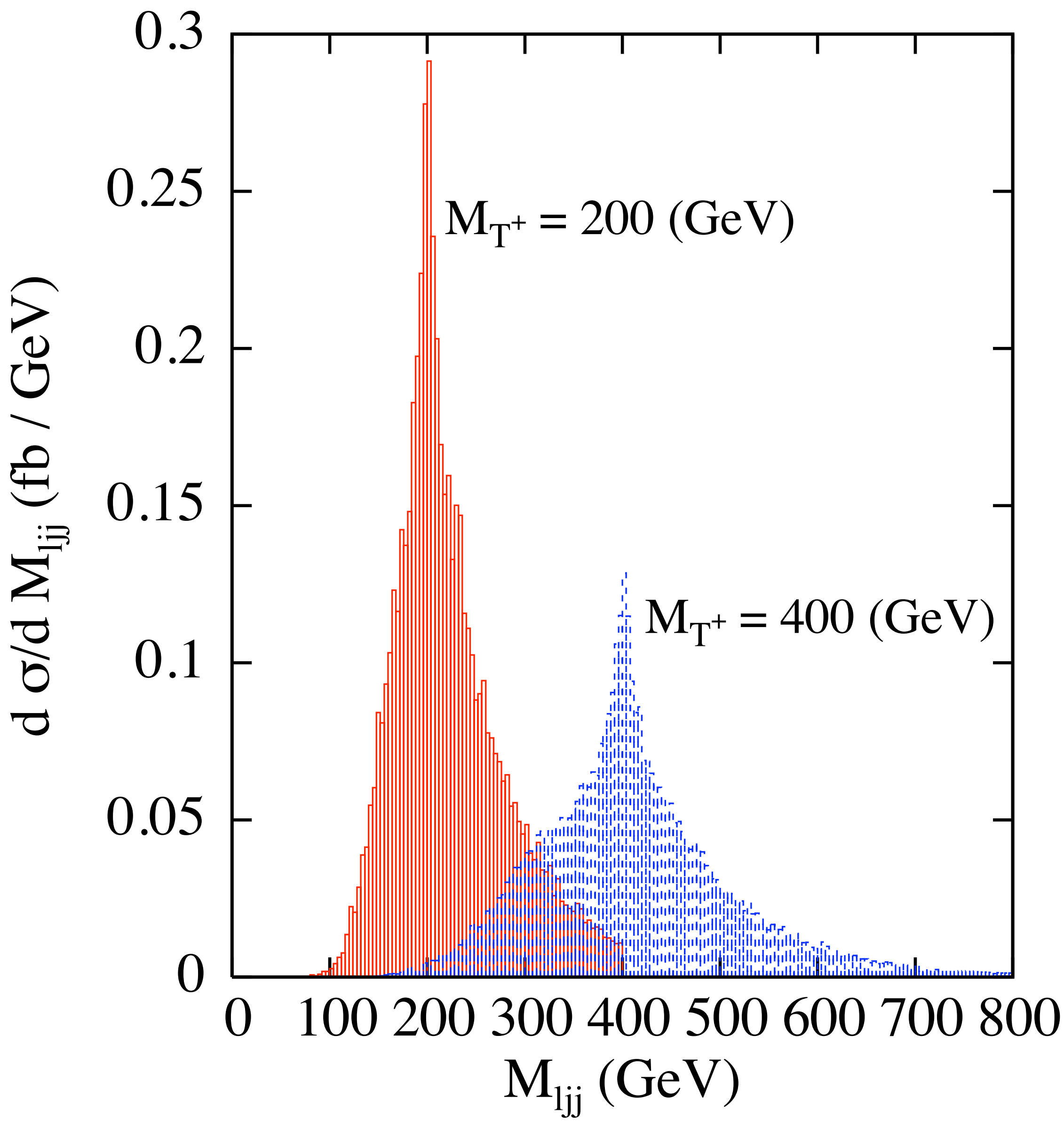
$$\frac{\delta E_\ell}{E_\ell} = \left[\frac{(0.05)^2\mathrm{GeV}}{E_\ell} + (0.0055)^2\right]^{1/2}$$

Triplet invariant mass:

6 ways to partition each $lljjj$ event into $(ljj)_1$ $(ljj)_2$ clusters, with invariant masses m_1, m_2

The best reconstruction has a minimal $|m_1 - m_2|$ and an invariant mass $(m_1 + m_2)/2$

Barger, Keung, Phillips, 95


0.3
0.25
0.2
0.15
0.1
0.05
0
d σ/d M_ljj (fb / GeV)
M_T+ = 200 (GeV)
M_T+ = 400 (GeV)
0 100 200 300 400 500 600 700 800
M_ljj (GeV)

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 even to get information on unmeasured neutrino parameters