Testing the littlest Higgs model with T-parity at the LHC

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Phys. Rev. D78, 055018 (2008)

Outline

- Introduction
- Littlest Higgs model with T-parity (LHT)

  Key particles

  heavy top quark (T):
  Cancellation of quadratic divergence

  heavy photon (A_H):
  Dark matter candidate

- LHT at LHC
- Test of the LHT
- Summary

Introduction

★ Problem of Higgs boson (Naturalness problem)

To solve the naturalness problem,...
we expect TeV-scale new physics.

We have a chance to discover such a TeV-scale new physics at LHC!

But is it SUSY? Little Higgs (LH)?
Or others?

★ Problem of Higgs boson (Naturalness problem)

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Or others?

In this talk,

What is important processes for LH?

(Difference between SUSY and LH?)

Can we test the LH at the LHC?

Little Higgs model

Little Higgs mechanism (collective symmetry breaking)

- Higgs boson is a pseudo Nambu-Goldstone boson which is light because of approximate global symmetries. Georgi and Kaplan

- Global symmetries are broken explicitly by two sets of interactions.

Arkani-Hamed, Cohen, Georgi

$$\mathcal{L} = \mathcal{L}_0 + \lambda_1 \mathcal{L}_1 + \lambda_2 \mathcal{L}_2$$

$$\delta m_H^2 \sim \left(\frac{\lambda_1^2}{16\pi^2} \right) \left(\frac{\lambda_2^2}{16\pi^2} \right) \Lambda^2$$

$$\sim O(100)\mathrm{GeV} \ \text{ for } \Lambda \sim 10 \ \mathrm{TeV}$$

The Higgs is a massless when either set of the interactions is absent.

Littlest Higgs model with T-parity

Arkani-Hamed, Cohen, Katz, Nelson hep-ph/0206021

Cheng, Low hep-ph/0308199

Hubisz et al, hep-ph/0506042

SU(5)/SO(5) non-linear sigma model

SM Higgs boson:

Pseudo Nambu-Goldstone boson of SU(5) ⟶ SO(5) breaking

$$\Sigma = \exp(i\Pi/f)\Sigma_0$$

$$\Pi = \begin{pmatrix} 0 & \frac{H}{\sqrt{2}} & \Phi \\ \frac{H^\dagger}{\sqrt{2}} & 0 & \frac{H^T}{\sqrt{2}} \\ \Phi^\dagger & \frac{H^*}{\sqrt{2}} & 0 \end{pmatrix}$$

$$\underline{\mathbf{1}_0 \oplus \mathbf{3}_0} \oplus \underline{\mathbf{2}_{\pm 1/2}} \oplus \mathbf{3}_{\pm 1}$$

SM Higgs boson

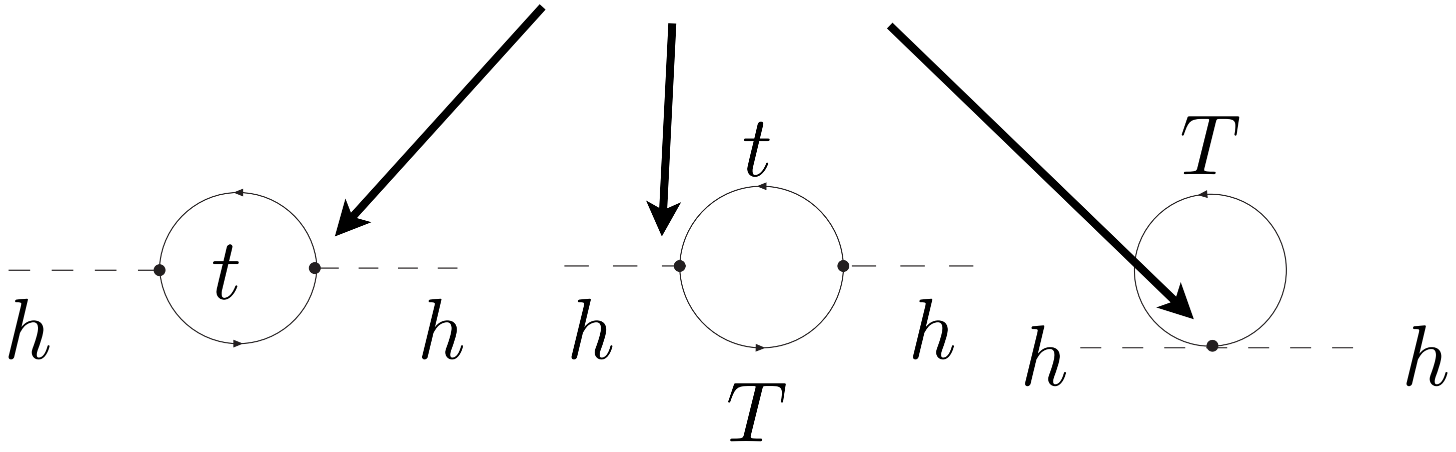
eaten by heavy gauge bosons

Gauge symmetry:

$$SU(5) \supset \ [SU(2) \times U(1)]^2 \xrightarrow{f} SU(2)_L \times U(1)_Y$$

heavy gauge bosons $A_H, \ Z_H, \ W_H^\pm$

Top sector



These couplings are related because of the collective symmetry breaking

Quadratic divergence is cancelled!

Existence of T is very important.

Top sector: T-parity: $SU(2)_1 \leftrightarrow SU(2)_2, \ U(1)_1 \leftrightarrow U(1)_2$

$$Q_{iL} = \left(\begin{array}{c} q_{iL} \\ U_{iL} \end{array} \right), \ U_{iR} \ (i = 1, 2), \ u_R^{(+)}$$

q_{iL} :SU(2) doublet

$U_{iX} \ (X = L, R)$:SU(2) singlet

$$q^{(\pm)} = \frac{1}{\sqrt{2}}(q_{1L} \mp q_{2L}), \ U_{R(L)}^{(\pm)} = \frac{1}{\sqrt{2}}(U_{1R(L)} \mp U_{2R(L)})$$

$(+)$:T-parity even (T-even)

$(-)$:T-parity odd (T-odd)

Mass terms

$$\mathcal{L}_{\rm mass} = -\lambda_1 \left[f \bar{U}_L^{(+)} + v \bar{u}_L^{(+)} \right] u_R^{(+)} - \lambda_2 f \left[\bar{U}_L^{(+)} U_R^{(+)} + \bar{U}_L^{(-)} U_R^{(-)} \right]$$

Mass eigenstates

T-even $$\left(\begin{array}{c} t_L \\ T_L \end{array} \right) = \left(\begin{array}{cc} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{array} \right) \left(\begin{array}{c} u_L^{(+)} \\ U_L^{(+)} \end{array} \right), \ \left(\begin{array}{c} t_R \\ T_R \end{array} \right) = \left(\begin{array}{cc} \cos\alpha & -\sin\alpha \\ \sin\beta & \cos\beta \end{array} \right) \left(\begin{array}{c} u_R^{(+)} \\ U_R^{(+)} \end{array} \right)$$

T-odd $$T_- = U_L^{(-)} + U_R^{(-)}$$

New heavy particles in Littlest Higgs model with T-parity

Gauge sector

dark matter candidate

$$A_H, \ W_H, \ Z_H$$

Higgs sector

$$\Phi \ (\text{triplet})$$

Fermion sector

$$T_-, \ T$$

T-even. All others are T-odd.

$$u_-, \ d_-, \ t_-, \ b_-$$

Masses of particles

$$m_t \simeq \frac{\lambda_1 \lambda_2 v}{\sqrt{\lambda_1^2 + \lambda_2^2}}$$

$$M_{T_-} = \lambda_2 f$$

$$M_T \simeq \sqrt{\lambda_1^2 + \lambda_2^2} \ f$$

$$\sin\beta \simeq \frac{\lambda_1^2}{\lambda_1^2 + \lambda_2^2} \frac{v}{f}$$

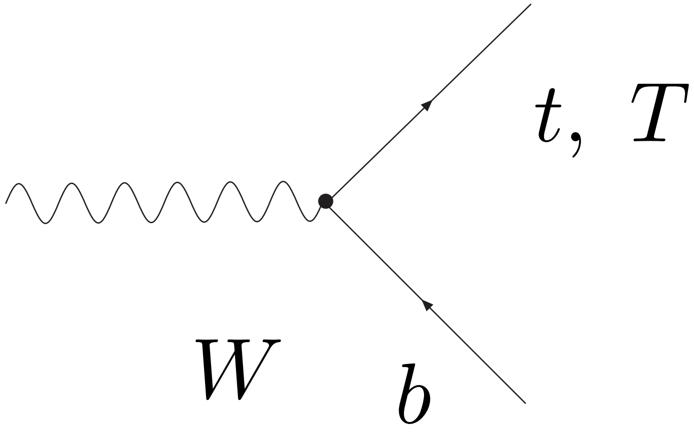
$$m_{A_H} \simeq \frac{g' f}{\sqrt{5}}$$

There are two parameters ($f, \ \lambda_2$) once top mass is fixed.

Important difference between SUSY and Little Higgs

Heavy (T-even) T can mix with SM top quark

(SUSY particles can not mix with any SM particles)



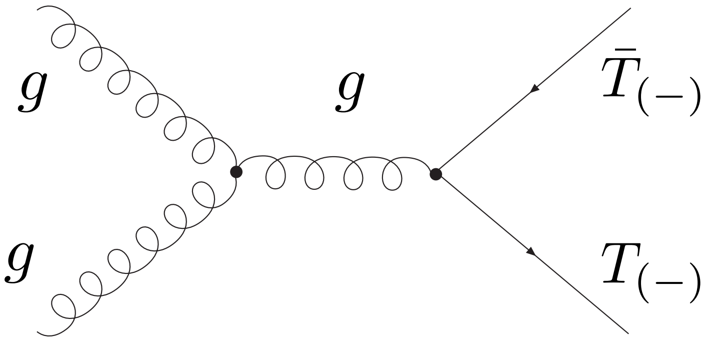
Study of the heavy T is very important to understand the solution to the naturalness problem in the Little Higgs model, and to know the difference between SUSY and Little Higgs.

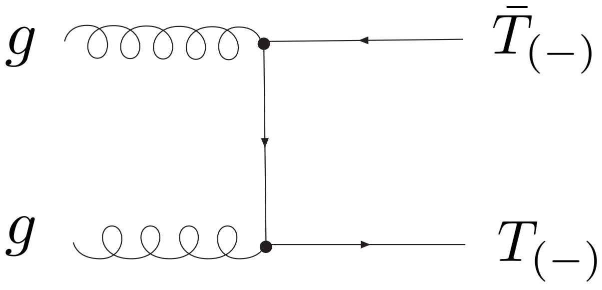
LHT at LHC

★ Production of heavy T-quarks at the LHC

Pair production

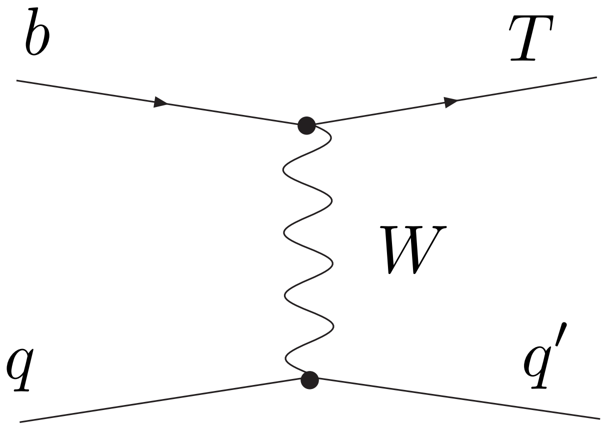
Heavy T-quarks have QCD interaction same as the top quarks.





Single production

Heavy T-quark can be singly produced.



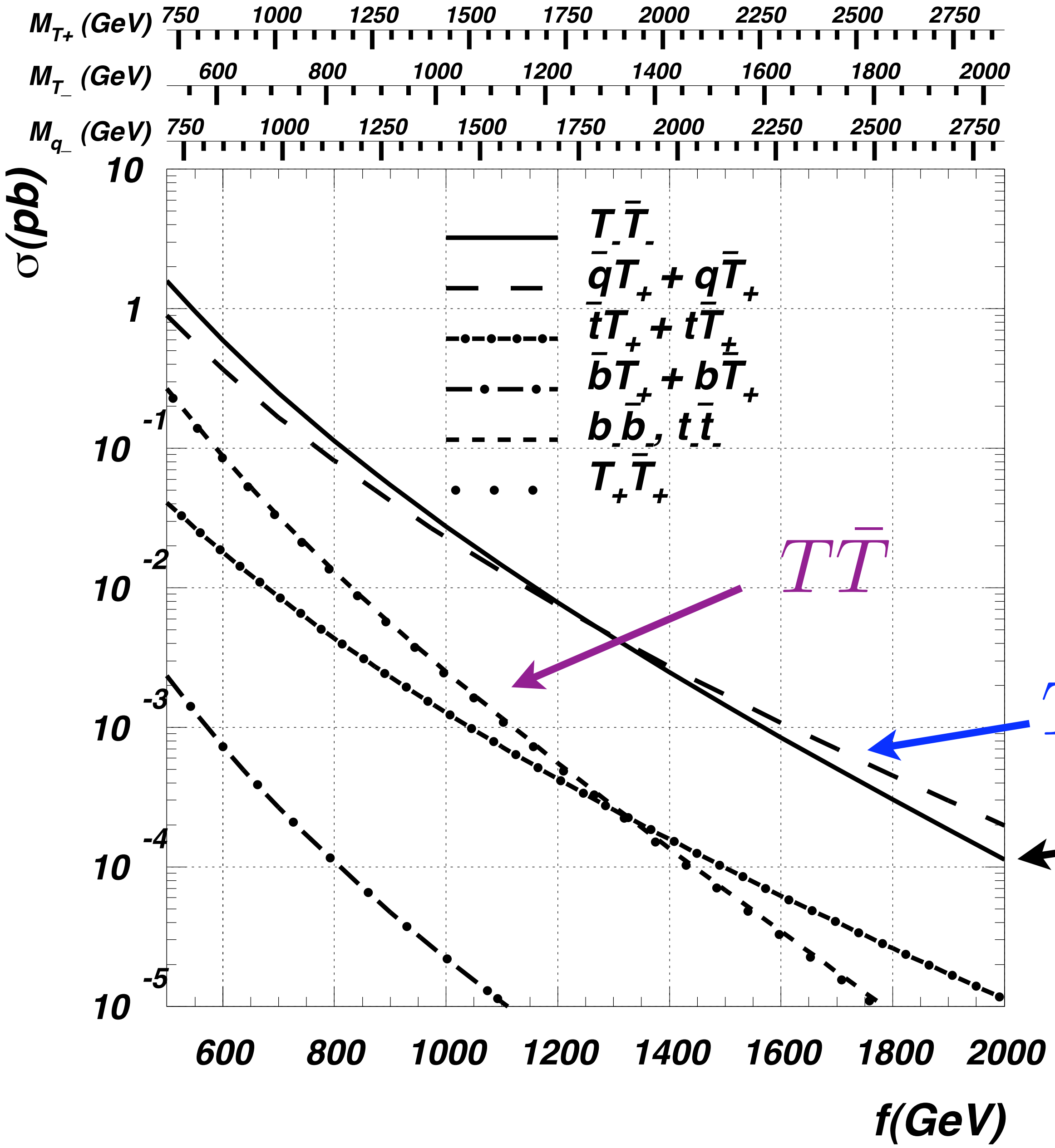
Background

$$pp \longrightarrow t\bar{t},\ \ jt, j\bar{t}$$

We consider these processes as the background.

★ Production of heavy T-quarks at the LHC

Belyaev, Chen, Tobe, Yuan



$T\bar{T}$

The single production cros section is larger than that of the pair production

Tq'

$T_-\bar{T}_-$

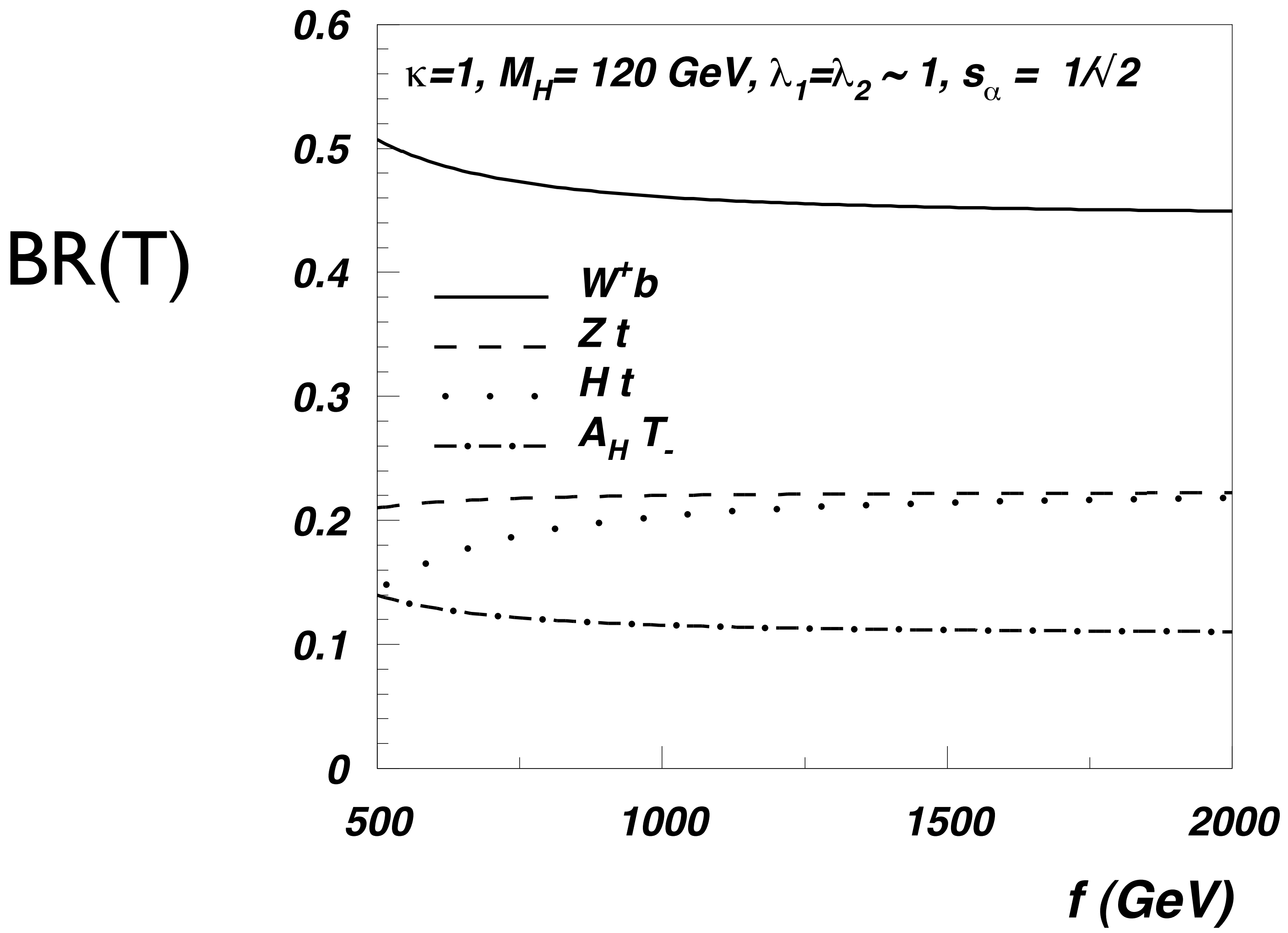
$$M_T > M_{T_-}$$

$$\sigma(t\bar{t}) \simeq 400 \text{ pb}$$

FIG. 7: The third generation heavy T-odd and T-even quark production cross sections at the LHC.

Decay of heavy T-quark

Belyaev, Chen, Tobe, Yuan



The main decay mode is “W+b” same as the top quark.

Decay of heavy T-odd T-quark

$$\mathrm{BR}(T_- \to t A_H) \simeq 100\ \%$$

Representative points for our analysis

	Point 1	Point 2	Point 3
f (GeV)	570	600	570
λ_2	1.0	1.1	1.4
$\sin\beta$	0.20	0.16	0.11
m_h (GeV)	145	131	145
m_{A_H} (GeV)	80.1	85.4	80.1
m_{T_-} (GeV)	570	660	798
m_{T_+} (GeV)	772	840	914
$\sigma(pp \to T_- \bar{T}_- + X)$ (pb)	1.26	0.54	0.17
$\sigma(pp \to T_+ \bar{T}_+ + X)$ (pb)	0.21	0.13	0.07
$\sigma(pp \to T_+ + X)$ (pb)	0.29	0.15	0.05
$\sigma(pp \to \bar{T}_+ + X)$ (pb)	0.14	0.07	0.02
$\mathrm{Br}(T_+ \to W^+ b)$	50.8 %	50.8 %	53.3 %
$\mathrm{Br}(T_+ \to Zt)$	21.1 %	21.8 %	23.6 %
$\mathrm{Br}(T_+ \to ht)$	15.8 %	17.4 %	19.1 %
$\mathrm{Br}(T_+ \to T_- A_H)$	12.3 %	10.0 %	4.03 %

$$\mathcal{L} = 100\ \mathrm{fb}^{-1}$$

Tools for the event generation

MadGraph/MadEvent: (Parton-level event generation)

Pythia: (Hadronization)

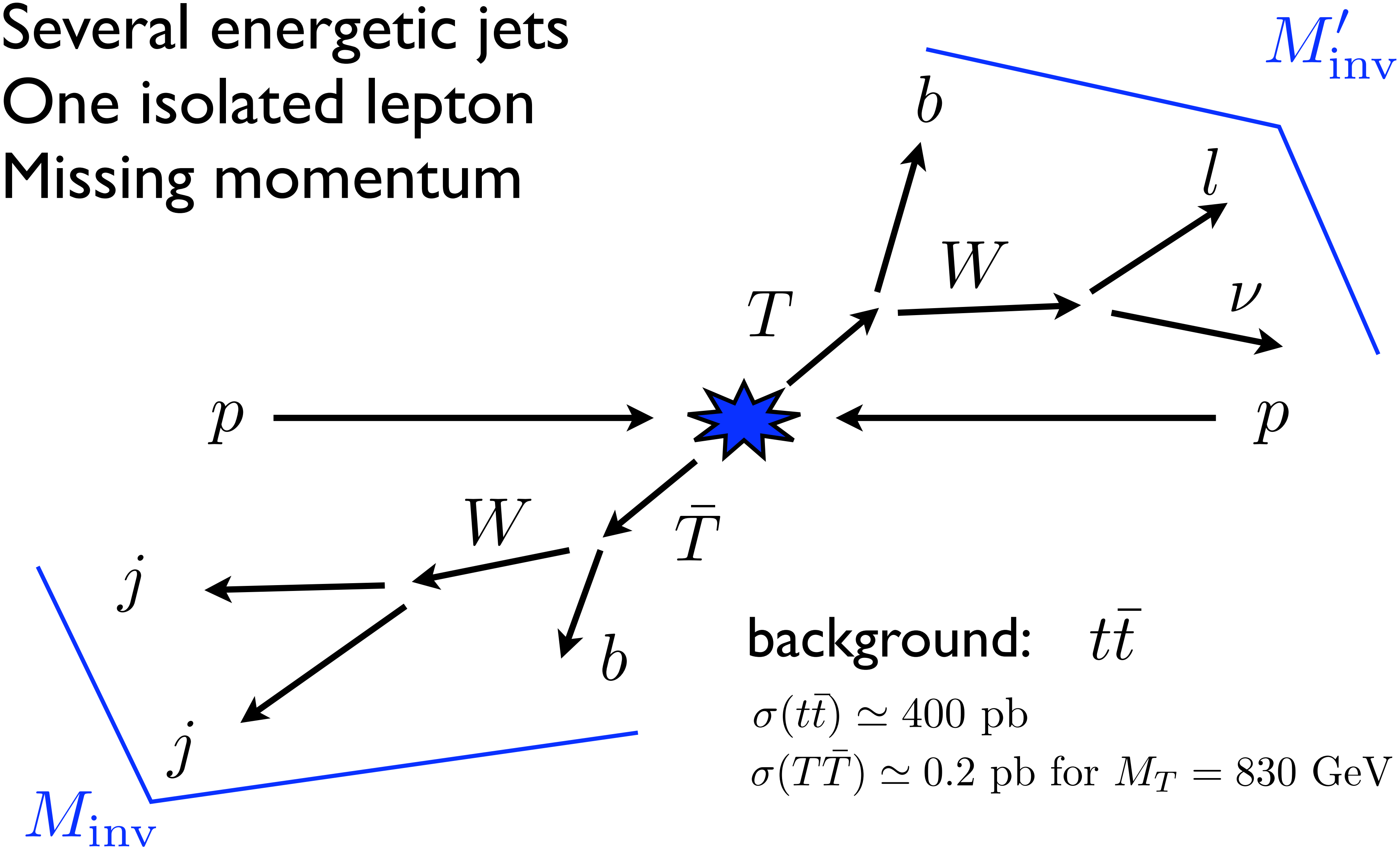
PGS4: (Detector simulation)

Pair production of heavy T-quarks at the LHC

by Matsumoto, Moroi and Tobe

Signal:

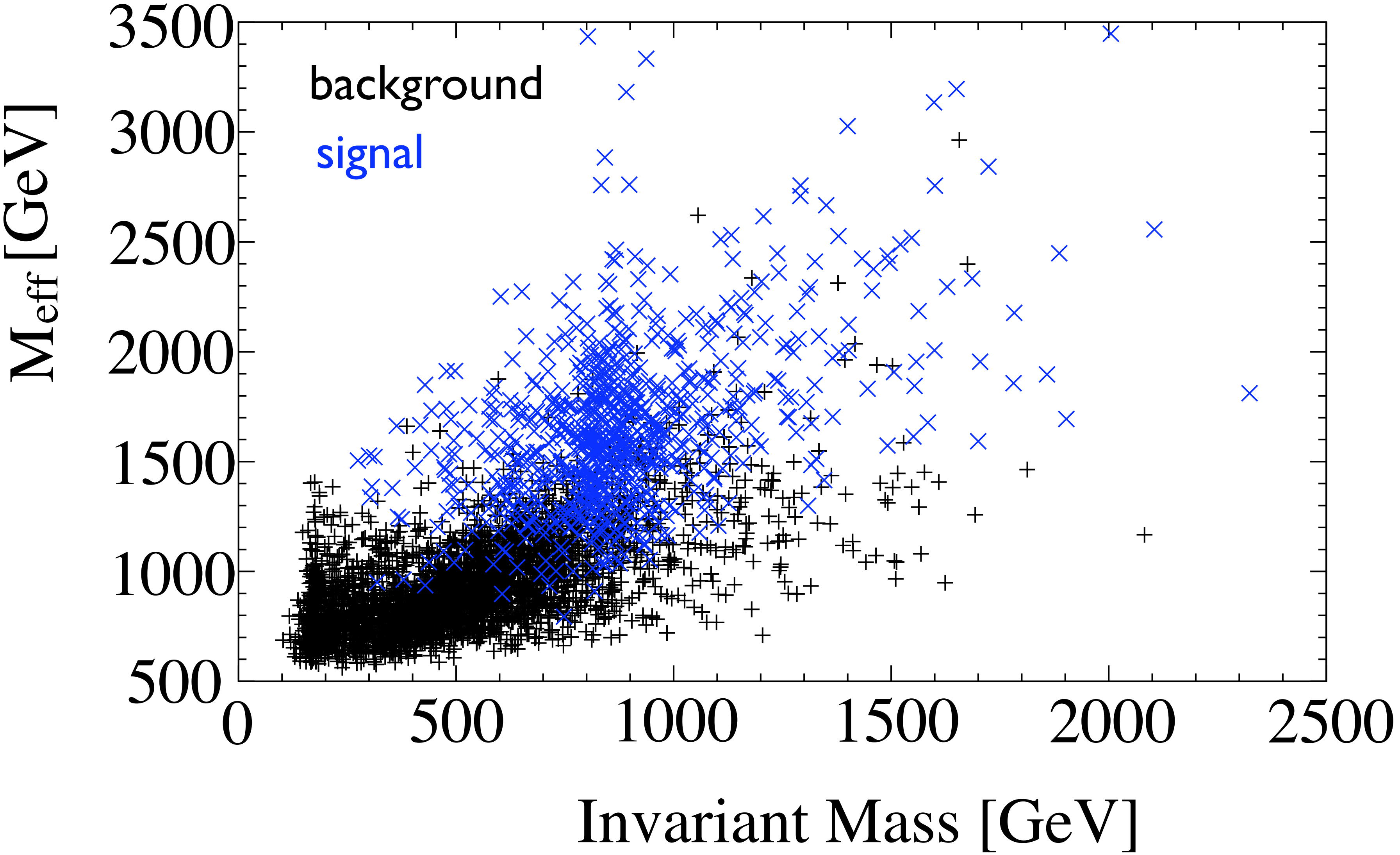
- Several energetic jets
- One isolated lepton
- Missing momentum



background: $t\bar{t}$

$\sigma(t\bar{t}) \simeq 400 \text{ pb}$

$\sigma(T\bar{T}) \simeq 0.2 \text{ pb for } M_T = 830 \text{ GeV}$



$$M_{\mathrm{eff}} = \sum_{\mathrm{jets}} p_T + \sum_{\mathrm{lepton}} p_T + \sum_{\mathrm{photon}} p_T + p_T^{\mathrm{miss}}$$

Signal events tend to have larger “effective mass”.
So we use a cut for the effective mass:

Cuts:

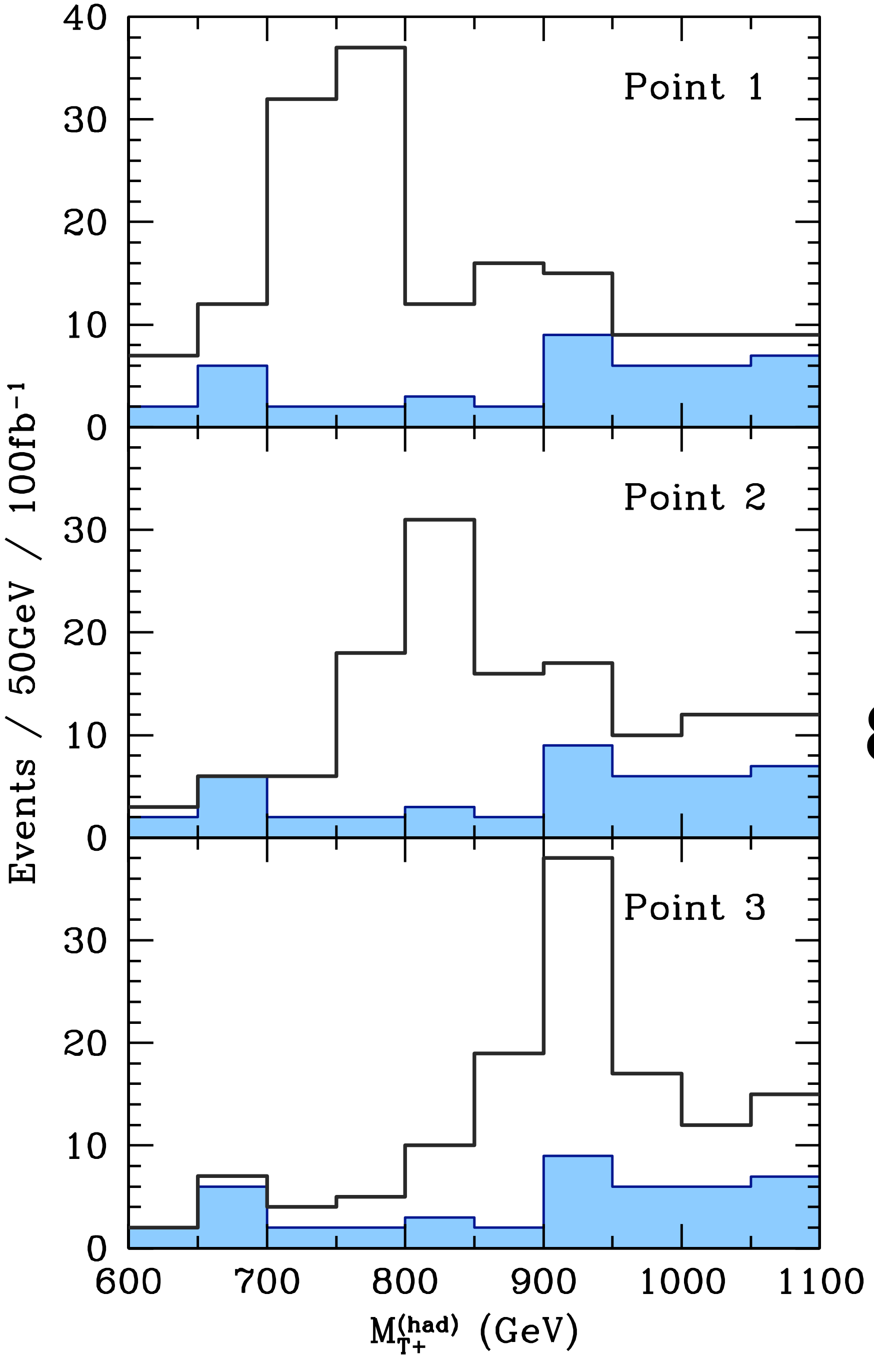
- Only one isolated lepton with $p_T > 50\ \mathrm{GeV}$
- Three or more jets with $p_T > 30\ \mathrm{GeV}$
- $M_{\mathrm{eff}} > 1800\ \mathrm{GeV}$
- $|M_{\mathrm{inv}} - M'_{\mathrm{inv}}| < 100\ \mathrm{GeV}$

Distribution of M_{inv}

M_T

🟦 background

☐ total



772 GeV

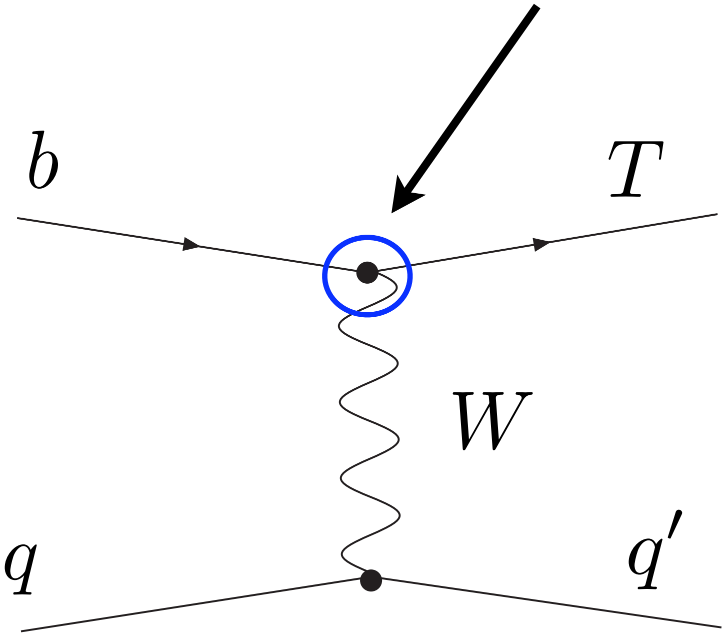
840 GeV

914 GeV

The heavy T-quark mass can be reconstructed.

$$M_T \simeq \sqrt{\lambda_1^2 + \lambda_2^2}\ f$$

Single production of heavy T-quarks at the LHC



mixing $\sin\beta$

$$T \to bW \to bl\nu$$

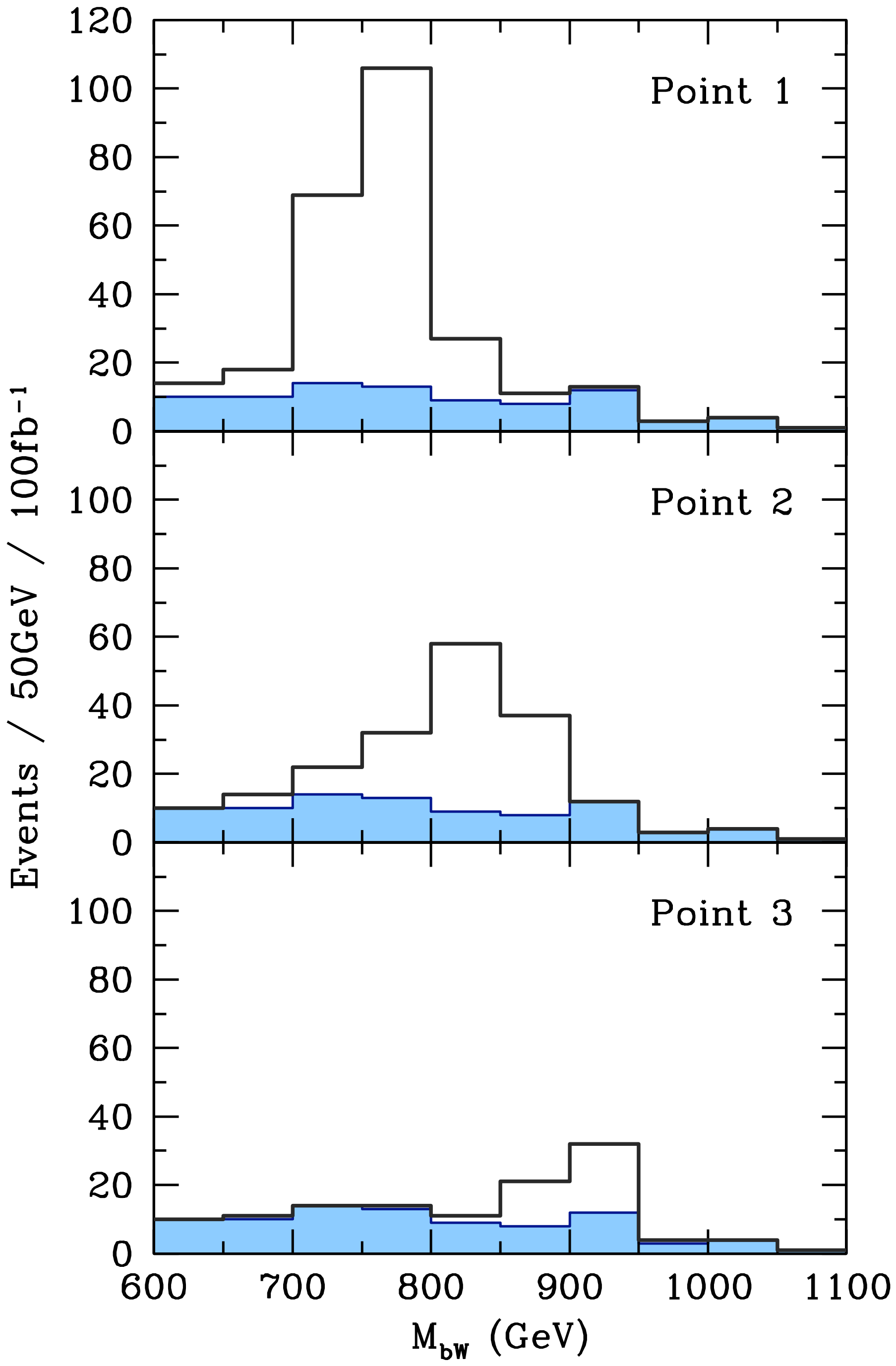
Signal:

- Two (or more) jets
- One isolated lepton
- Missing momentum due to neutrino

Cuts:

- One isolated lepton with $p_T > 100$ GeV
- Two jets with $p_T > 30$ GeV
- $p_T^{(\mathrm{miss})} > 100$ GeV
- $p_{T,j_1} > 300$ GeV and $M_{j_1+j_2} > 500$ GeV
- $M_{j_1} < 50$ GeV (M_{j_1} : the jet mass of the leading jet)
- $|M_{bW}^{(1)} - M_{bW}^{(2)}| < 50$ GeV

Distribution of M_{bW}



🟦 background

☐ total

Assuming that the cross section can be obtained from the number of events in the signal region.

⇩

determination of $\sin\beta$

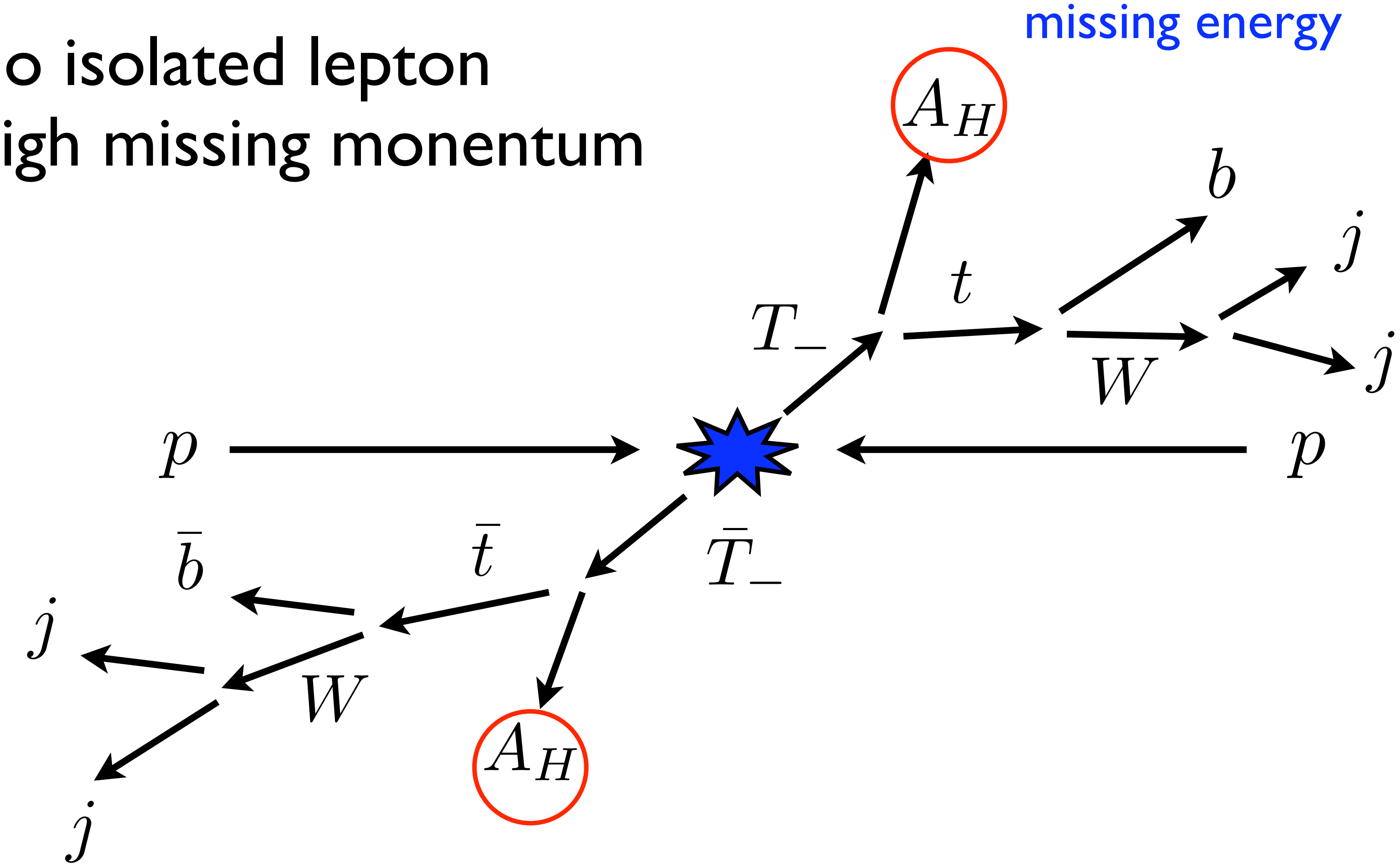
$$\sin\beta \simeq \frac{\lambda_1^2}{\lambda_1^2+\lambda_2^2}\,\frac{v}{f}$$

Pair production of heavy T-odd T-quarks (T_-) at the LHC

Matsumoto, Nojiri, Nomura; Nojiri, Takeuchi

Signal:

- No isolated lepton
- High missing monentum



To obtain a constraint on $M_{T\_}$ and m_{A_H} .....

Hemishere analysis

Reconstruction of t and $\bar{t}$ systems, separately

M_{T2} analysis

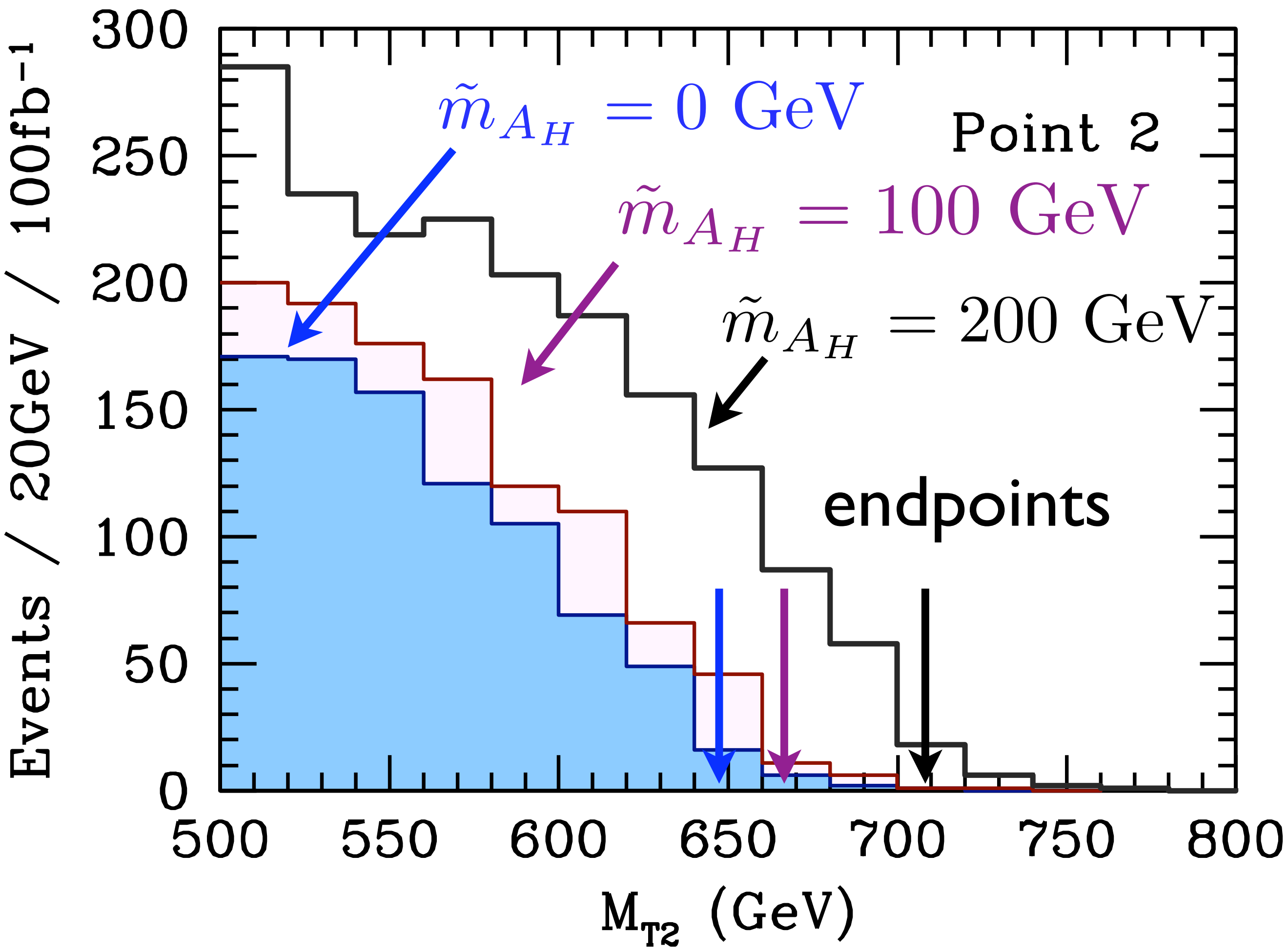
$$M_{T2}^2(\tilde{m}_{A_H}) = \min_{\mathbf{p}_{\mathrm{T}}^t + \mathbf{q}_{\mathrm{T}}^{\bar{t}} + \mathbf{p}_{\mathrm{T}}^{A_H} + \mathbf{q}_{\mathrm{T}}^{A_H} = 0} \left[\max \left\{ M_T^2(\mathbf{p}_{\mathrm{T}}^t, \mathbf{p}_{\mathrm{T}}^{A_H}), M_T^2(\mathbf{q}_{\mathrm{T}}^{\bar{t}}, \mathbf{q}_{\mathrm{T}}^{A_H}) \right\} \right]$$

$$M_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^t, \mathbf{p}_{\mathrm{T}}^{A_H}) = \sqrt{(|\mathbf{p}_{\mathrm{T}}^t|^2 + m_t^2)\,(|\mathbf{p}_{\mathrm{T}}^{A_H}|^2 + \tilde{m}_{A_H}^2) - \mathbf{p}_{\mathrm{T}}^t \mathbf{p}_{\mathrm{T}}^{A_H}}$$

$\tilde{m}_{A_H}$: postulated mass of A_H

Upper end-point of M_{T2} is given by $M_{T\_}$ if $\tilde{m}_{A_H} = m_{A_H}$

Distribution of the M_{T2} variable



$$m_{A_H} \simeq \frac{g' f}{\sqrt{5}}$$

$$M_{T\_} = \lambda_2 f$$

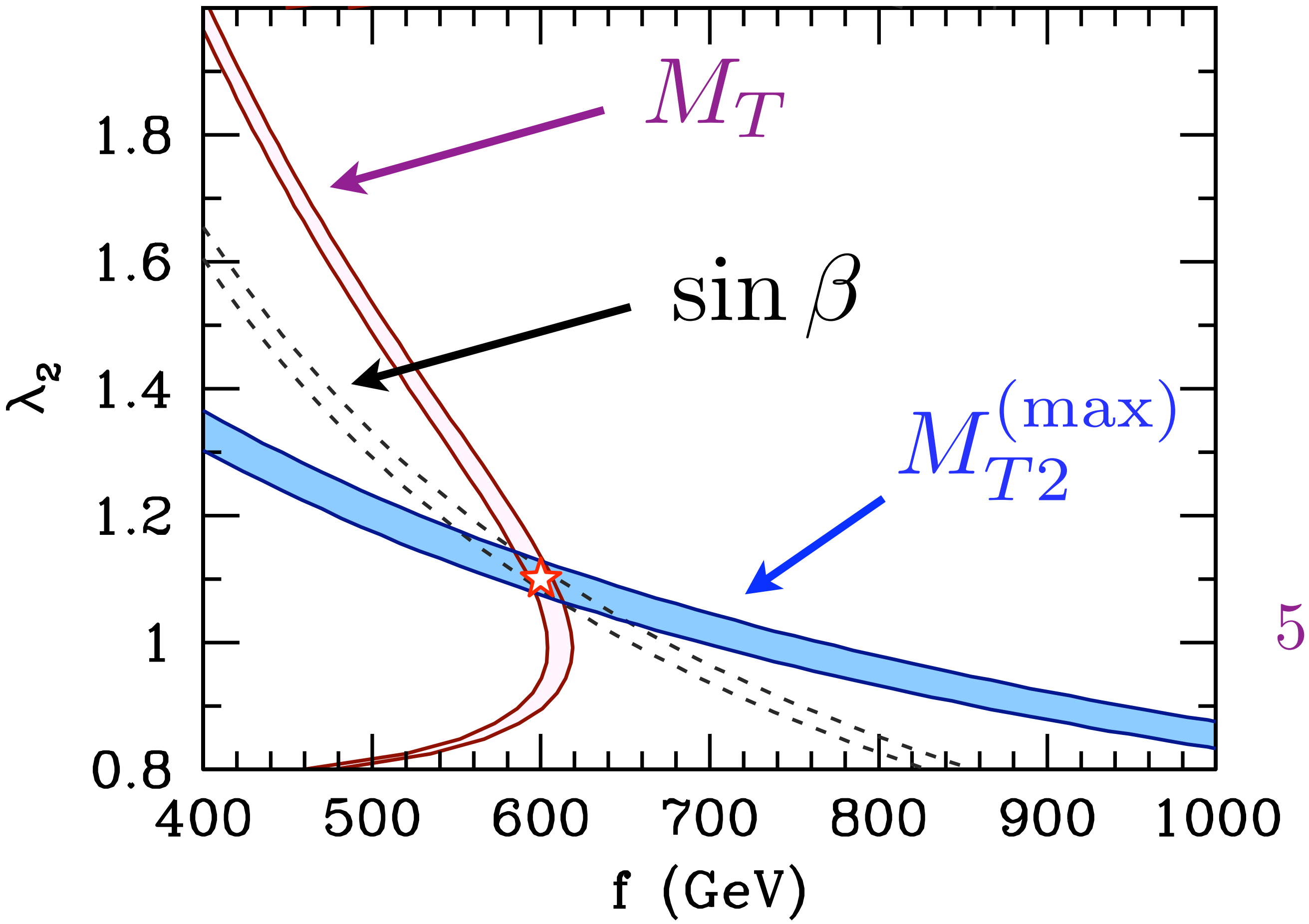
$M_{T2}^{(\max)}$ can be determined from the endpoint.

→ We can obtain the correlation between m_{A_H} and $M_{T\_}$ (or λ_2 and f)

Test of the LHT

From the heavy T-quark analysis at the LHC, $M_T, \ \sin\beta, \ M_{T2}^{(\max)}$ can be measured

Expected constraints on the f vs. λ_2



$$\delta M_T = 10 \text{ GeV}$$

$$\delta \sin\beta / \sin\beta = 5 \ \%$$

$$\delta M_{T2}^{(\max)} = 10 \text{ GeV}$$

$$584 \text{ GeV} < f < 613 \text{ GeV}$$

$$1.06 < \lambda_2 < 1.15$$

parameter determination!

Implication to cosmology

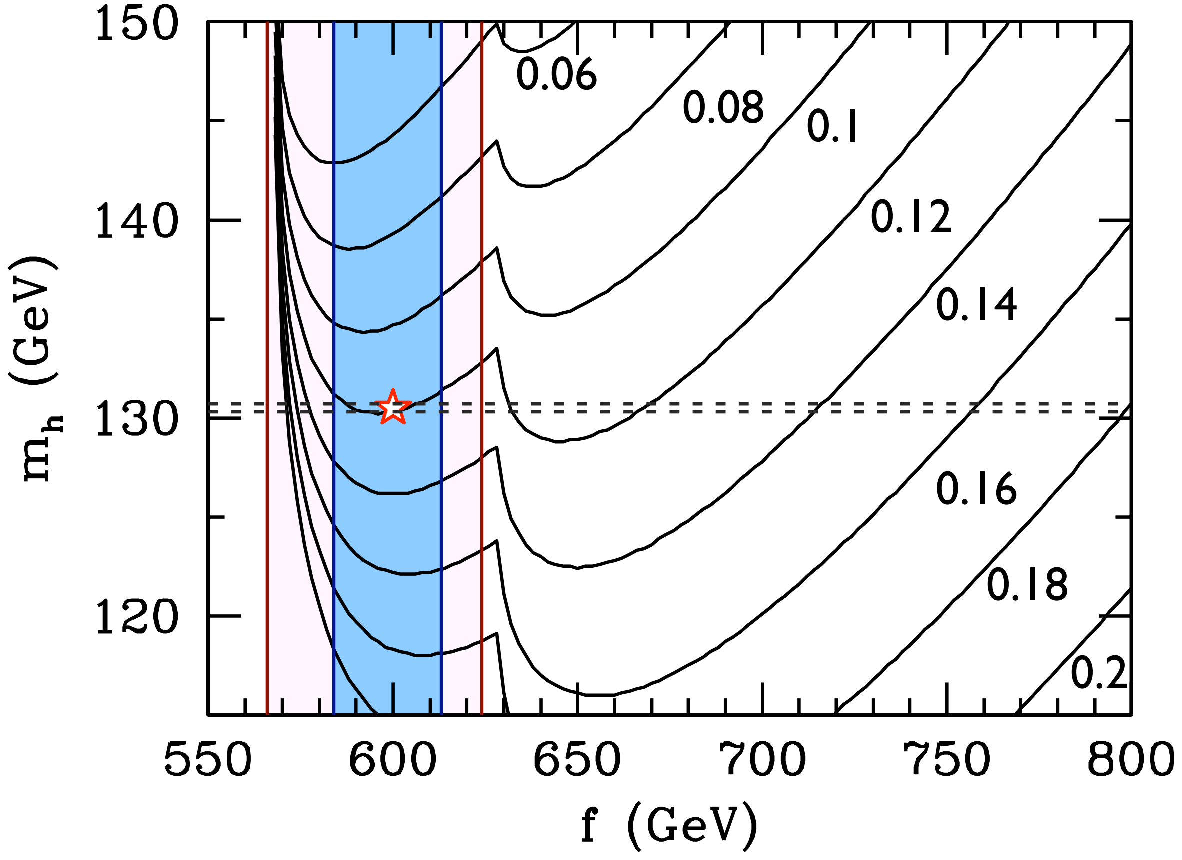
The lightest T-odd particle A_H is a viable candidate of dark matter.

The thermal relic density of A_H depends on the pair annihilation cross section.

The dominant mode is $A_H\ A_H \to h^* \to WW/ZZ$

The thermal relic density can be determined by $m_{A_H}(\mathrm{or}\ f)$ and m_h

$$\Omega_{A_H} h^2$$



$$0.118 < \Omega_{A_H} h^2 < 0.126$$

This kind analysis provides an important test of the cosmological scenario in the LHT.

Summary

- Littlest Higgs model with T-parity is one of interesting candidates for physics beyond the SM.

Key particles

heavy top quark (T):
Cancellation of quadratic divergence

heavy photon (A_H):
Dark matter candidate

- LHC can study the pair and single productions of heavy T-quarks, and measure some parameters.

$$pp \to T\bar{T},\ T_-\bar{T}_-,\ jT,\ j\bar{T}$$

$$M_T \qquad M_{T2} \qquad \sin\beta$$

- Using the measurements at the LHC, we show that the non-trivial test of the LHT can be performed.

- It is difficult to study the heavy gauge bosons of the LHT at the LHC.

ILC will be a good place to study them.

Cao, Chen, PRD76,075007 (2007)

Asakawa et al, arXiv:0901.1081

Backup slides

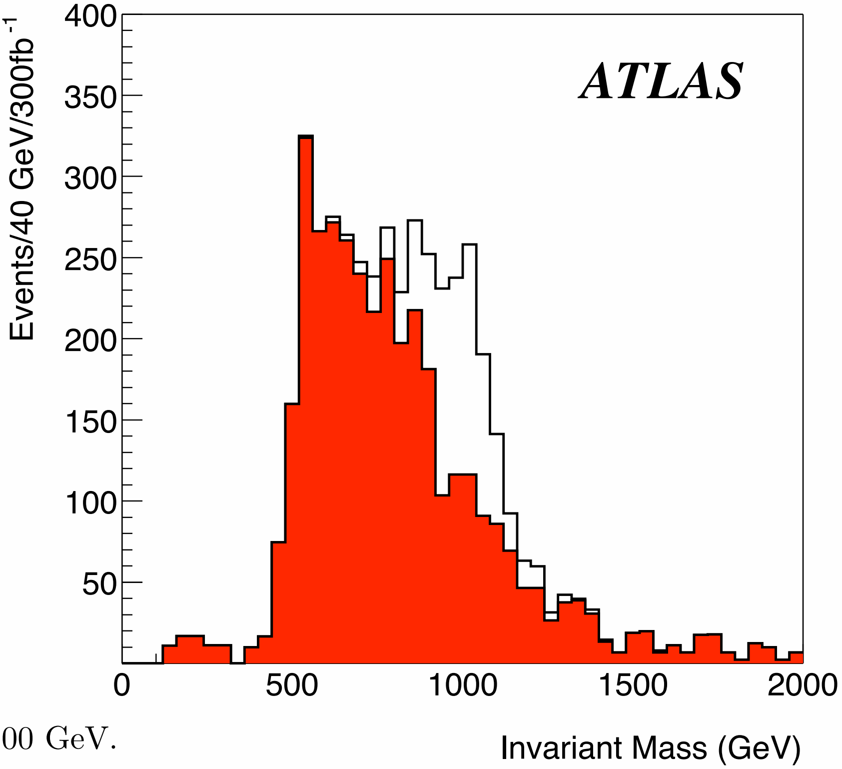
ATLAS study for the single T production $qb \rightarrow q'T$

1. $T \rightarrow Wb \rightarrow l\nu b$

Azuelos et al. Eur.Phys.J.C39S2, 13 (2005)

Background

$t\bar{t}$, single top, $Wb\bar{b}$



Event selection

- At least one charged lepton with p_T >100 GeV.
- One b-jet with $p_T > 200$ GeV.
- No more than 2 jets with $p_T > 30$ GeV.
- Mass of the pair of jets with the highest p_T is greater than 200 GeV.
- $\not{E}_T$ >100 GeV.

Figure 3: Reconstructed mass of the W (inferred from the measured lepton and $\not{E}_T$) and tagged $b-$jet. The signal arises from the decay $T \rightarrow Wb$ and is shown a for mass of 1000 GeV. The background, shown separately as the filled histogram, is dominated by $t\bar{t}$ and single top production (the former is larger). The signal event rates correspond to $\lambda_1/\lambda_2 = 1$ and a $BR(T \rightarrow Wb)$ of 50%. More details can be found in Ref [17].

$2.\ T \to Zt \to l^+l^-l\nu b$

Background $WZ,\ tbZ$

Event selection

- Three isolated leptons (either e or μ) with $p_T > 40$ GeV and $|\eta| < 2.5$. One of these is required to have $p_T > 100$ GeV.
- No other leptons with $p_T > 15$ GeV.
- $\not{E}_T > 100$ GeV.
- At least one tagged $b-$jet with $p_T > 30$ GeV.

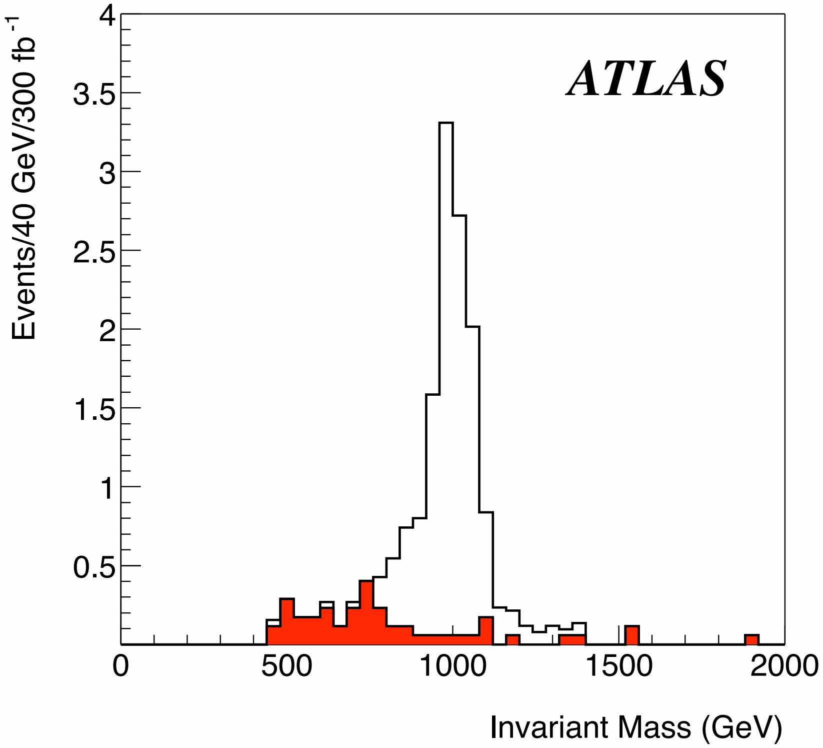


Figure 2: Reconstructed mass of the Z and t (inferred from the measured lepton, $\not{E}_T$, and tagged $b-$jet). The signal $T \to Zt$ is shown for a mass of 1000 GeV. The background, shown as the filled histogram, is dominated by WZ and tbZ (the latter is larger) production. The signal event rates correspond to $\lambda_1/\lambda_2 = 1$ and a $BR(T \to ht)$ of 25%. More details can be found in Ref [17].

3. $T \to ht \to b\bar{b}bl\nu$

Background $t\bar{t}$

Event selection

- One isolated e or μ with $p_T > 100$ GeV and $|\eta| < 2.5$.
- Three jets with $p_T > 130$ GeV.
- At least one jet tagged as a $b-$jet.

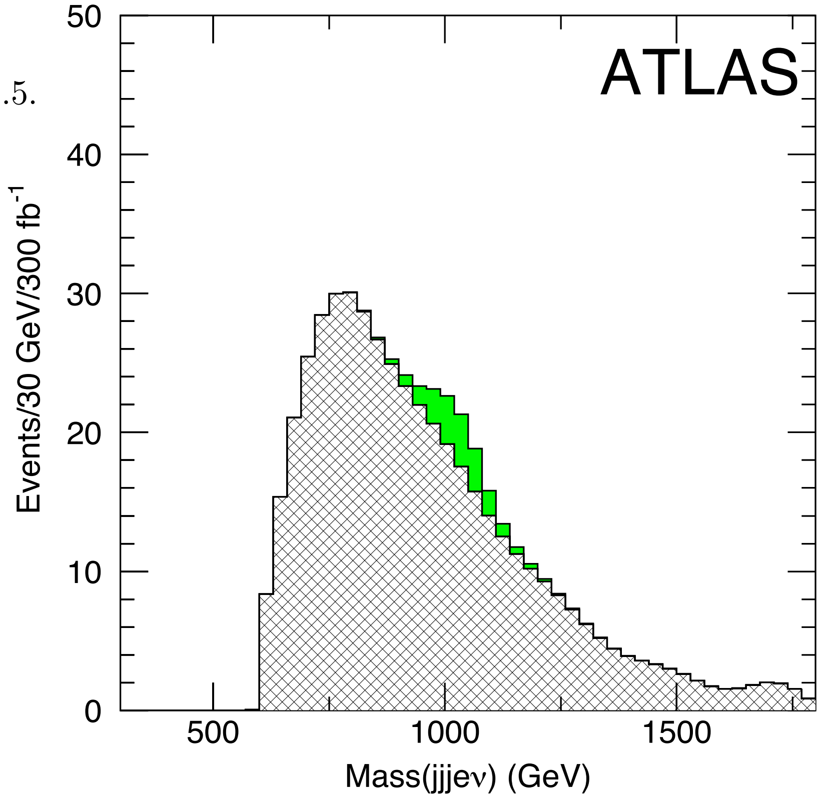


Figure 5: Reconstructed mass of the W (inferred from the isolated lepton and missing transverse energy) and three jets, two of which are required to have an invariant mass consistent with the Higgs mass. The signal arises from the decay $T \to ht$ and is shown for a mass of 1000 GeV. The background, shown in cross-hatching, is dominated by $t\bar{t}$ production. The signal event rates correspond to $\lambda_1/\lambda_2 = 1$ and a $BR(T \to ht)$ of 25%.