Testing the Littlest Higgs Model with T-parity at the LHC

Takeo Moroi (Tohoku)

Reference:

Matsumoto, Moroi & Tobe, arXiv:0806.3837 [hep-ph]

1. Introduction

A recent idea to solve the little-hierarchy problem:

Little Higgs scenario

[Arkani-Hamed, Cohen & Georgi]

Can we find a signal of the Little Higgs scenario?

⇒ Yes

[Azuelos et al.; Matsumoto, Nojiri & Nomura; Nojiri & Takeuchi]

Subject of my talk:

⇒ How we can test the model at the LHC

⇒ An implication to cosmology

We consider the Littlest Higgs model with T-parity (LHT)

[Cheng & Low; Low; Hubisz & Meade; Csaki, Heinonen, Perelstein & Spethmann]

- Higgs: pseudo NG boson for $SU(5)/SO(5)$
- $SU(5) \supset [SU(2) \times U(1)]^2_{\text{Gauged}} \supset [SU(2) \times U(1)]_{\text{SM}}$

Outline:

1. Introduction
2. Model
3. LHC Signals
4. Testing the LHT model
5. Summary

2. Model

The Littlest Higgs model with T-parity

- Parameters in the Higgs sector: f and m_h
- $\Sigma = \exp(2i\Pi/f) \times \langle\Sigma\rangle$

$$\Pi = \begin{pmatrix} 0 & H/\sqrt{2} & \Phi \\ H^\dagger/\sqrt{2} & 0 & H^T/\sqrt{2} \\ \Phi^\dagger & H^*/\sqrt{2} & 0 \end{pmatrix}, \quad \langle\Sigma\rangle = \begin{pmatrix} 0 & 0 & \mathbf{1} \\ 0 & 1 & 0 \\ \mathbf{1} & 0 & 0 \end{pmatrix}$$

All the electro-weak gauge bosons have “T-odd partners”

- A_H, which is (approximately) the partner of $U(1)_Y$ gauge boson, becomes the lightest T-odd particle

$$m_{A_H}^2 \simeq \frac{1}{5} g_1^2 f^2$$

Top-related fermions:

$$Q_1 = \begin{pmatrix} u_{L,1} \\ d_{L,1} \\ U_{L,1} \end{pmatrix}, \quad Q_2 = \begin{pmatrix} u_{L,2} \\ d_{L,2} \\ U_{L,2} \end{pmatrix}, \quad U_{R,1}, \quad U_{R,2}, \quad u_{R+}$$

$$\Rightarrow Q_\pm \equiv \frac{1}{\sqrt{2}} \left(Q_1 \mp Q_2 \right), \quad U_{R,\pm} \equiv \frac{1}{\sqrt{2}} \left(U_{R,1} \mp U_{R,2} \right)$$

Mass terms:

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

Mass eigenstates:

- $(u_{L,+}, U_{L,+}) \oplus (u_{R,+}, U_{R,+}) \rightarrow (t, T_+)$
- $U_{L,-} \oplus U_{R,-} \rightarrow T_-$

Important new particles for my study:

- T_-: colored, T-odd
- T_+: colored, T-even
- A_H: neutral, lightest T-odd (and hence stable)

Parameters

- f and λ_2
- λ_1 is determined once the top mass and λ_2 are given

I study the production processes of T_+ and T_- at the LHC

$\Rightarrow$ Non-trivial test is possible with three observables

$\Rightarrow$ Determination of f and λ_2 is also possible

3. LHC Signals

Sample points for our MC analysis

	Point 1	Point 2
f	570 GeV	600 GeV
λ_2	1.0	1.1
$\sin\beta$	0.20	0.16
m_{A_H}	80.1 GeV	85.4 GeV
m_{T_-}	570 GeV	660 GeV
m_{T_+}	772 GeV	840 GeV
m_h	145 GeV	131 GeV

β: mixing angle (which is determined by f and λ_2)

$$\begin{pmatrix} t_L \\ T_{+L} \end{pmatrix} = \begin{pmatrix} \cos\beta & -\sin\beta \\ \sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} u_{L,+} \\ U_{L,+} \end{pmatrix}$$

Event generation:

- Parton-level events: MadGraph / MadEvent
- Fragmentation and hadronization: PYTHIA
- Detector Simulation: PGS4

Signal processes:

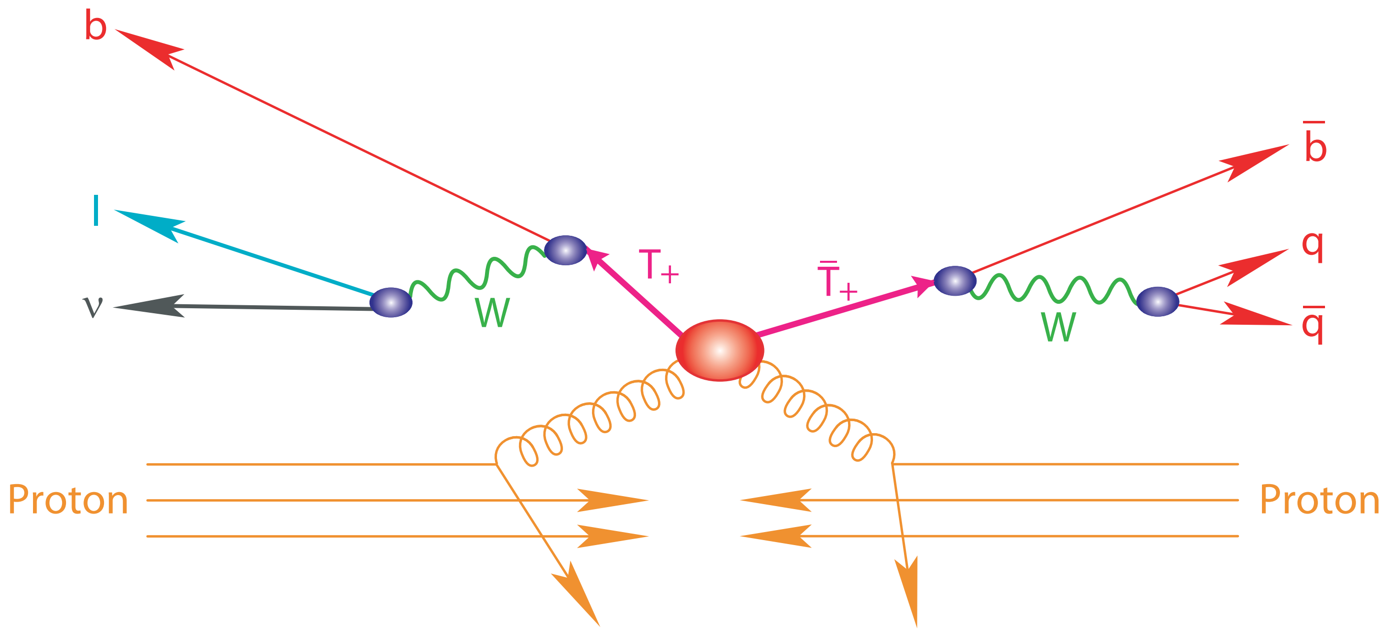
- $pp \to T_+\bar{T}_+$
- $pp \to T_-\bar{T}_-$
- $pp \to jT_+/j\bar{T}_+$

Only the top-related backgrounds are considered

- $pp \to t\bar{t}$
- $pp \to jt/j\bar{t}$

Pair production of T_+: $pp \to T_+\bar{T}_+$

We use $pp \to T_+\bar{T}_+ \to bW^+\bar{b}W^- \to bq\bar{q}'\bar{b}l\nu$



Neutrino momentum can be reconstructed using $\mathbf{p}_T^{(\text{miss})} = \mathbf{p}_T^{(\nu)}$

$\Rightarrow$ T_+ and $\bar{T}_+$ systems can be reconstructed to obtain m_{T_+}

Event shape:

- Several energetic jets
- One isolated lepton

Cuts:

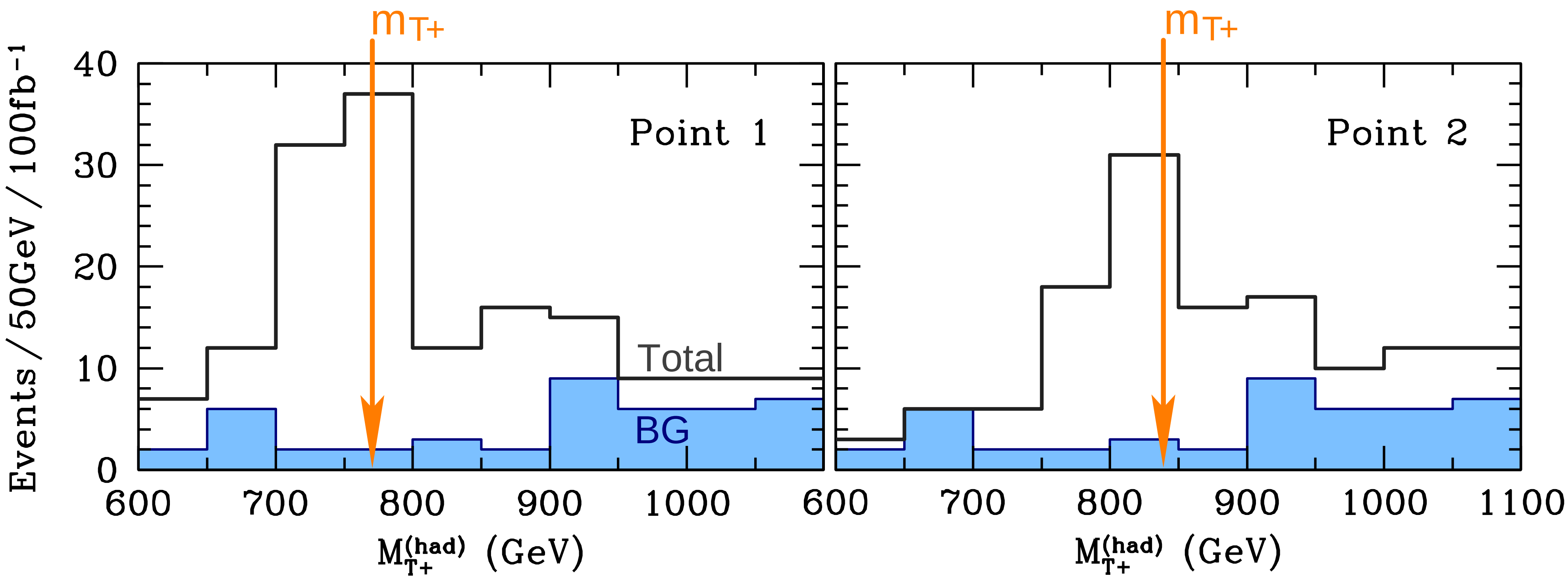
1. Three or more jets with $p_T > 30$ GeV
2. Only one isolated lepton with $p_T > 50$ GeV
3. $M_{\text{eff}} > 1800$ GeV

$$M_{\text{eff}} \equiv \sum_{\text{jets}} p_T + \sum_{\text{leptons}} p_T + \sum_{\text{photons}} p_T + p_T^{(\text{miss})}$$

For jets, $p_T > 30$ GeV is required

4. $|M_{T_+^{(\text{lep})}} - M_{T_+^{(\text{had})}}| < 100$ GeV

Invariant-mass distribution



We can determine m_{T_+} from the position of the peak

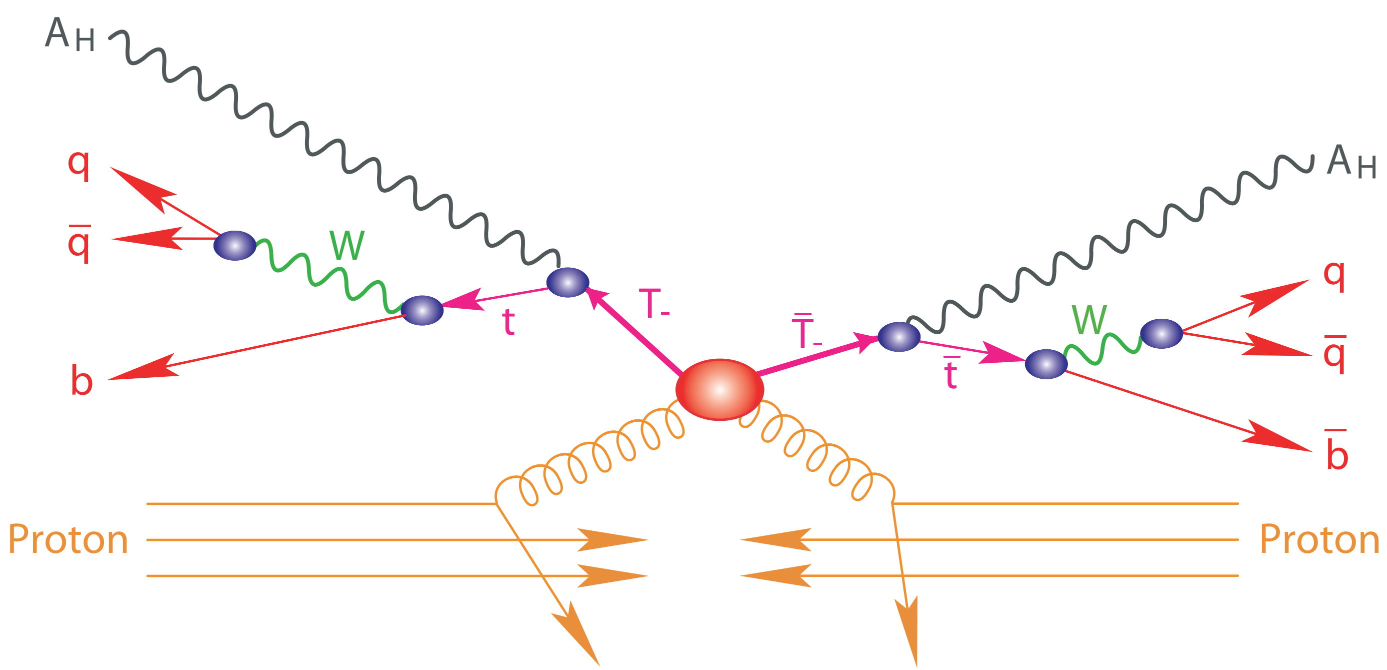
$\Rightarrow \delta M_{T2}^{(\mathrm{max})} \sim 10$ GeV

Pair production of T_-: $pp \to T_-\bar{T}_-$

[Matsumoto, Nojiri & Nomura; Nojiri & Takeuchi]

We have used: $pp \to T_-\bar{T}_- \to tA_H\bar{t}A_H \to \text{jets} + p_T^{(\text{miss})}$

Notice: $Br(T_- \to tA_H) = 100\ \%$



$\Rightarrow$ Missing p_T is due to the emission of A_H

Useful techniques:

- Hemisphere analysis (to separate t and $\bar{t}$ systems)
- M_{T2} analysis (to constrain $m_{T\_}$ and m_{A_H})

M_{T2} variable: a function of the postulated mass of A_H

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

$$M_T(\mathbf{p}_T^t, \mathbf{p}_T^{A_H}; \tilde{m}_{A_H}) = \sqrt{(|\mathbf{p}_T^t|^2 + m_t^2)(|\mathbf{p}_T^{A_H}|^2 + \tilde{m}_{A_H}^2) - \mathbf{p}_T^t \mathbf{p}_T^{A_H}}$$

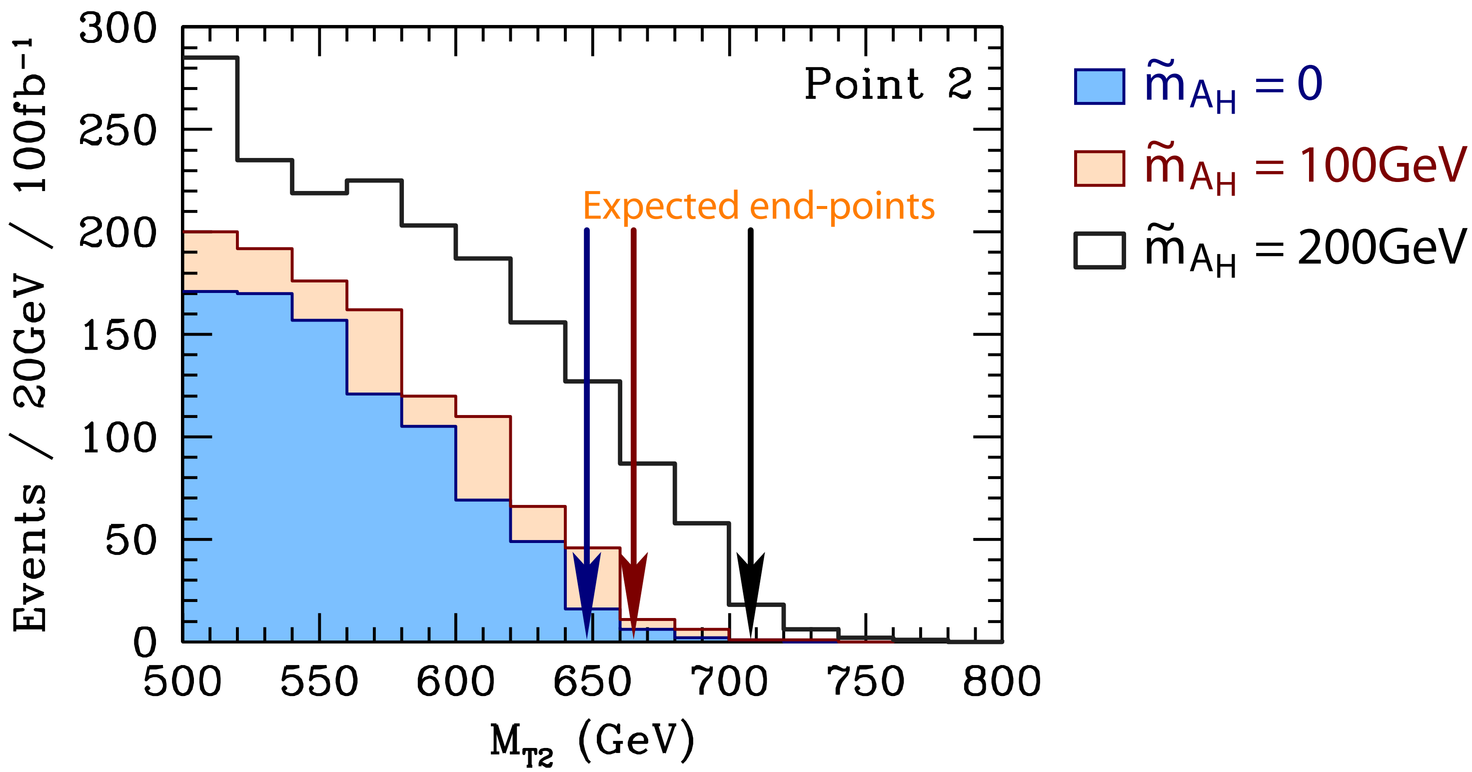
Upper end-point of M_{T2} becomes $m_{T\_}$ if $\tilde{m}_{A_H} = m_{A_H}$

$\Rightarrow$ A constraint on m_{A_H} vs. $m_{T\_}$ plane

$\Rightarrow$ A constraint on f vs. λ_2 plane

Distribution of the M_{T2} variable for several values of $\tilde{m}_{A_H}$

We use kinematical cuts proposed by Nojiri & Takeuchi



$\Rightarrow \delta M_{T2}^{(\text{max})} \sim 10$ GeV (with quadratic fit)

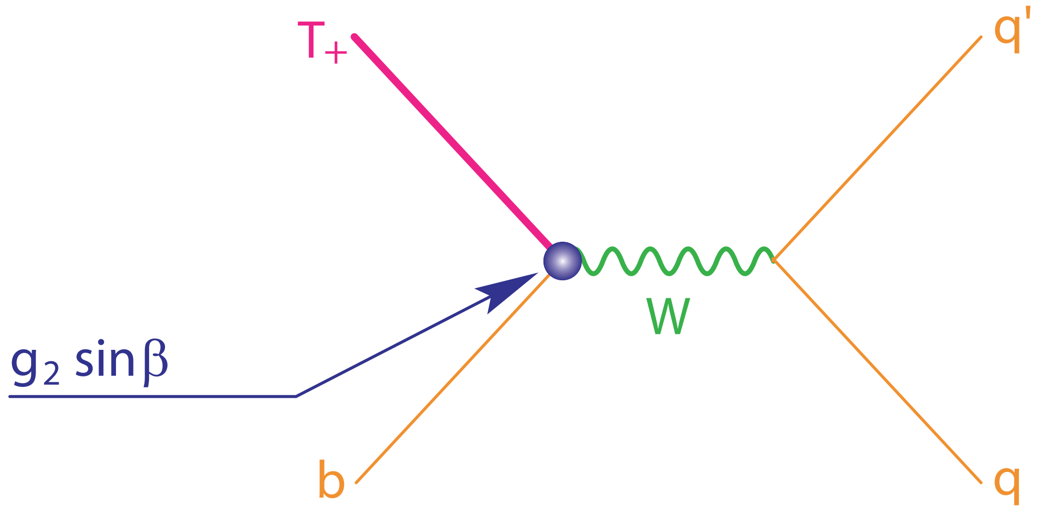
$\Rightarrow$ Some relation between m_{A_H} and m_{T_-}

Single production of T_+: $pp \to jT_+/j\bar{T}_+$

[See also Azuelos et al.]

We use: $pp \to jT_+$ (or $\bar{T}_+$) $\to jbW^+ \to jbl\nu$

Cross section is sensitive to the mixing angle β



$$\sigma_{pp\to jT_+} \propto \sin^2\beta$$

$\Rightarrow$ Determination of the mixing angle in the top sector

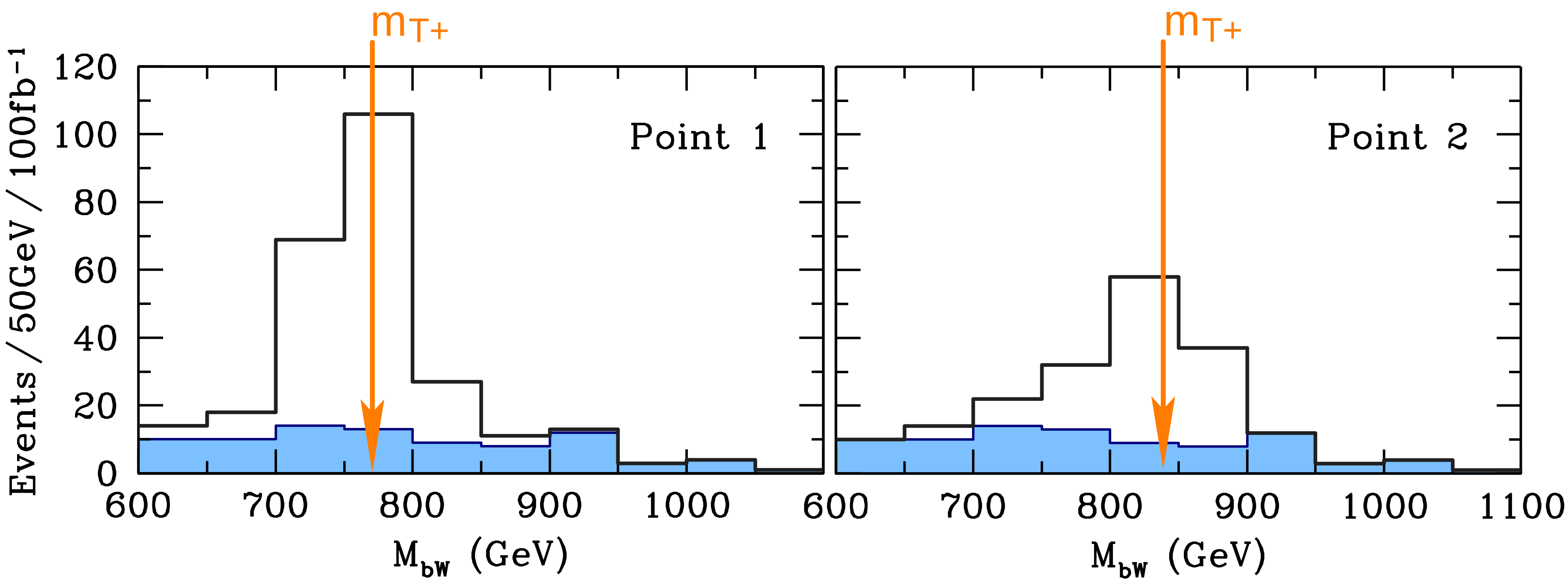
Event shape:

- Two jets, one of which is very energetic
- One isolated lepton
- Sizable missing p_T

Cuts:

0. The number of isolated lepton is 1, the number of jets (with $p_T > 30$ GeV) is 2.
1. $p_{T,l} > 100$ GeV, $p_T^{(\text{miss})} > 100$ GeV,
2. $p_{T,j1} > 300$ GeV, and $M_{j1+j2} > 500$ GeV,
3. $M_{j1} < 50$ GeV (M_{j1}: the jet mass of the first jet)
4. $|M_{bW}^{(1)} - M_{bW}^{(2)}| < 50$ GeV.

Invariant mass distribution



Assumption: $\sigma_{pp\to jT_+}$ is determined from the number of events:

$\Rightarrow$ Number of events in the signal bin ~ 100 (for Point 2)

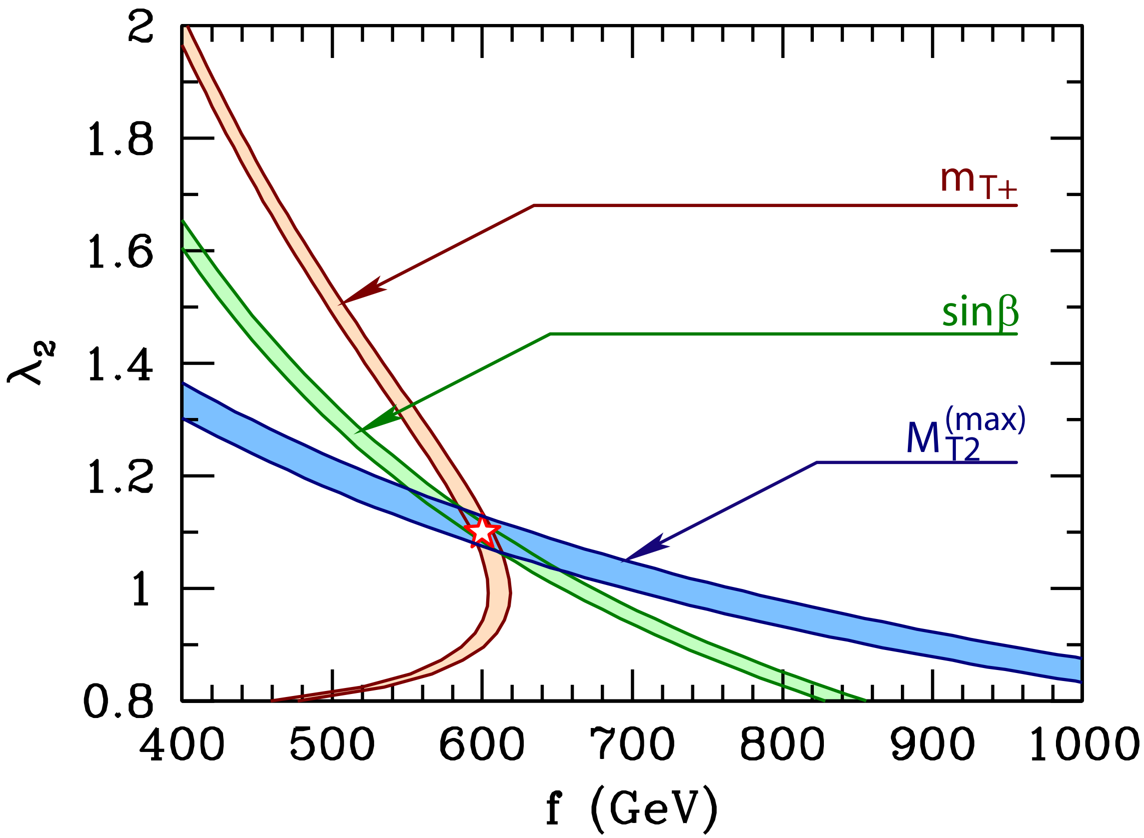
$\Rightarrow$ $\delta \sin\beta / \sin\beta \sim 5$ % (statistical only)

4. Test of the LHT Model

Observables at the LHC:

$$m_{T_+},\ M_{T2}^{(\mathrm{max})},\ \sin\beta$$

Expected constraints on the f vs. λ_2 plane



- $\delta m_{T_+} = 10$ GeV
- $\delta M_{T2}^{(\mathrm{max})} = 10$ GeV
- $\delta \sin\beta / \sin\beta = 5\ \%$

$\Rightarrow$ 584 GeV $< f <$ 613 GeV

$\Rightarrow 1.06 < \lambda_2 < 1.15$

An implication to cosmology:

Reconstruction of the dark matter density

The lightest T-odd particle becomes stable

$\Rightarrow A_H$ is a candidate of the dark matter

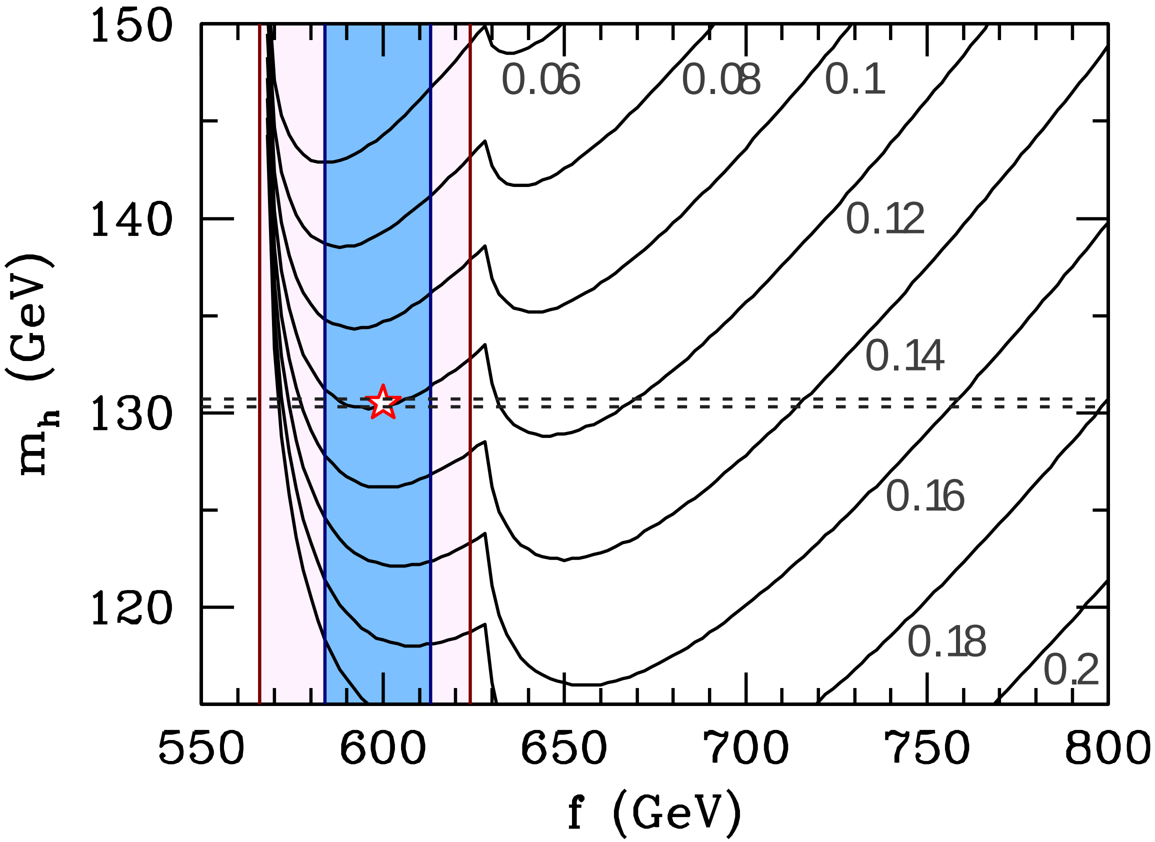
Dominant pair-annihilation process of A_H:

$A_H A_H \to h^* \to W^+ W^- / ZZ$ (if kinematically allowed)

Thermal relic density of A_H depends on f and m_h

- f can be determined with the study of top partners
- m_h will be measured precisely at the LHC ($\delta m_h \sim 200$ MeV)

Reconstruction of $\Omega_{A_H} h^2$ (for Point 2)



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

(underlying parameters: $m_h = 130$ GeV $\Rightarrow \Omega_{A_H} h^2 = 0.120$)

5. Summary

I have discussed a possibility to test the LHT at the LHC

- $pp \to T_+ \bar{T}_+$
- $pp \to T_- \bar{T}_-$
- $pp \to jT_+ / j\bar{T}_+$

We can expect:

- Determinations of mass and mixing parameters
- Reconstruction of $\Omega_{A_H} h^2$

Future works:

- Other processes
- More accurate background estimation