



**Statue of Miguel de Cervantes Saavedra at Peking University**  
**米格尔·德·塞万提斯·萨维德拉 (1547—1616),**  
***author of “Don Quijote de la Mancha”***

# XXXVII INTERNATIONAL CONFERENCE ON HIGH ENERGY PHYSICS ICHEP 2014

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## Spirit of *Don Quijote*

“The impossible dream”

To dream the impossible dream  
To fight the unbeatable foe  
To bear with unbearable sorrow  
To run where the brave dare not go

.....

And the world will be better for this  
That one man, scorned and covered with scars  
Still strove with his last ounce of courage  
To reach the unreachable star

# **Charged Higgs Boson: Tracer of the BSM**

**Shou-hua Zhu**

**ITP, Peking University**

**July, 2014**



# Contents

- **New paradigm and charged Higgs boson**
- **How to discover charged Higgs boson?**
- **How to measure its properties?**

**The role of top quark**

- **Conclusion**

# Changing the angle

- Once upon a time, some of us believed that no scalar at  $O(100 \text{ GeV})$  would be found
- Before the LHC, in the SM,  $\sim 100 \text{ GeV}$  Higgs boson was preferred by precision EW data, though there was a  $\sim 3$  sigma anomaly in bottom forward-backward asymmetry
- However LHC do discover a scalar around 125 GeV
- **It is the time to change the angle!**

# The boring story

- The 125 GeV SM Higgs boson makes the theory valid up to a very high scale ( $10^{10}$  GeV), if one does not care about the fine-tuning problem.
- SM has been tested again and again, from LEP to Tevatron, and to LHC-7/8
- Such boring story would last forever?

# Another boring story

- If one does care about the fine-tuning problem, a natural choice is the Technicolor-like theory which is disfavored in its original form.
- Another popular choice is the supersymmetric (SUSY) theory.
- Realistic SUSY models have even more parameters compared to at least 26 in the SM

*With four parameters I can fit an elephant, and with five I can make him wiggle his trunk.*

Attributed to von Neumann by Enrico Fermi, as quoted by Freeman Dyson in "A meeting with Enrico Fermi" in Nature 427 (22 January 2004) p. 297

- Such boring story would last forever?

# What is the TURE meaning of 125GeV new state?

- Importance of 2012 discovery is not fully understood yet
- Lightness of the new scalar is likely due to a symmetry.
- SUSY? Or other proposed new symmetry like the ones in little Higgs models? Scale invariant?
- We offer alternative way: **Lightness of the new scalar is due to the spontaneously broken of CP symmetry. If CP is conserved, the Higgs would be massless.**

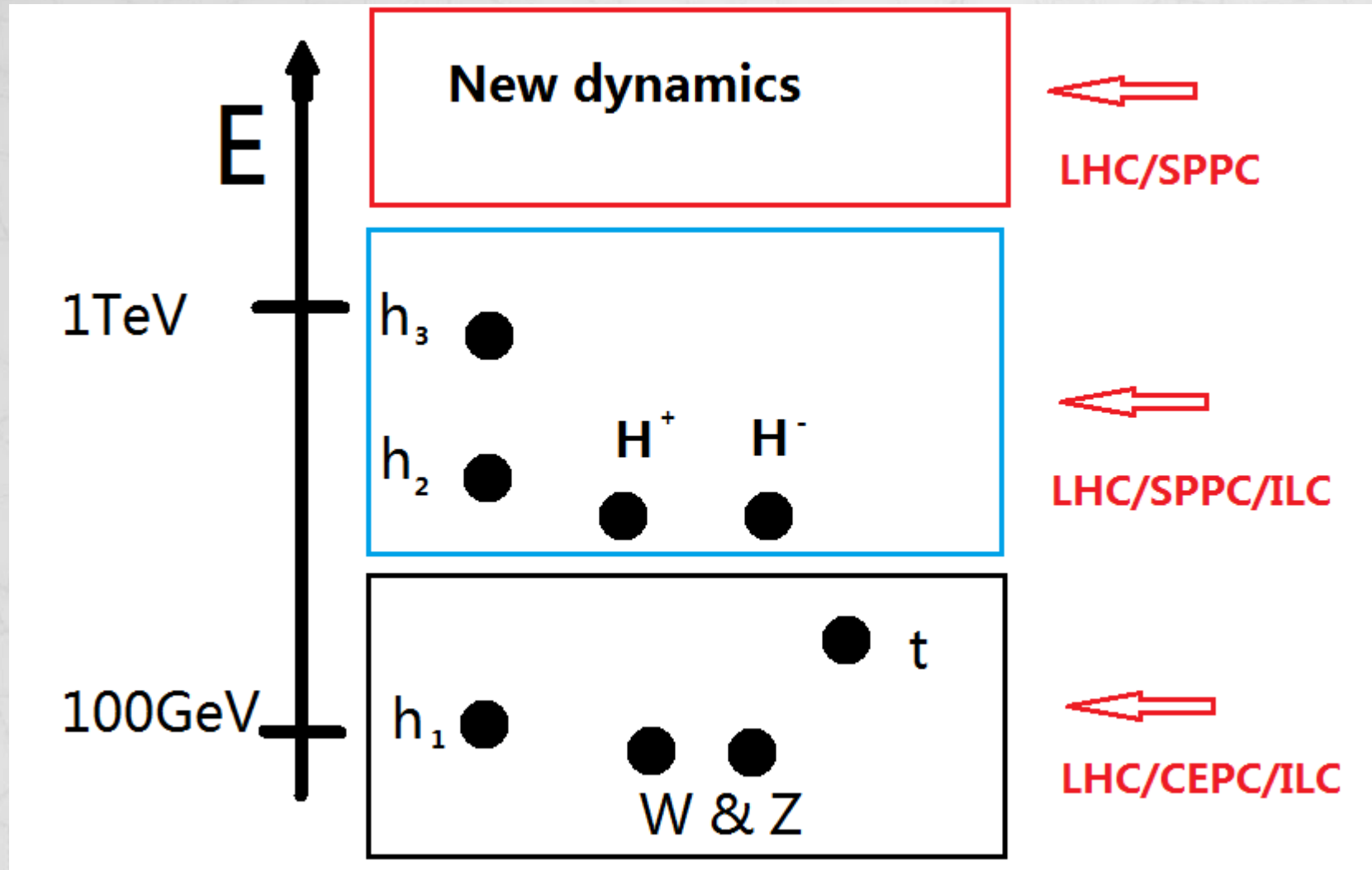
Zhu, 1211.2370,

Hu, Wang, Yin and Zhu, FOP8 (2013) 516

Mao & Zhu, in preparation

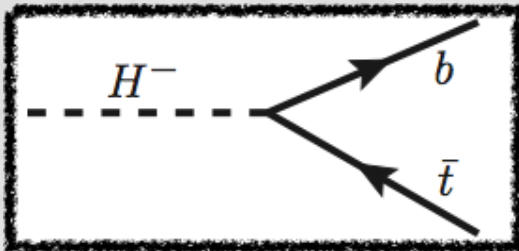


# New paradigm? Postponed mechanism to stabilize EW scale



# Charged Higgs phenomenology and type II 2HDM as the example

Cao, Wan, Wang and Zhu, PhysRevD87.055022  
Wang and Zhu, arXiv:1405.1800

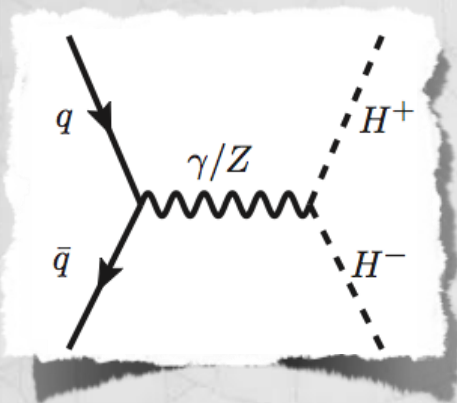


$$\tan \beta = \frac{v_2}{v_1}$$

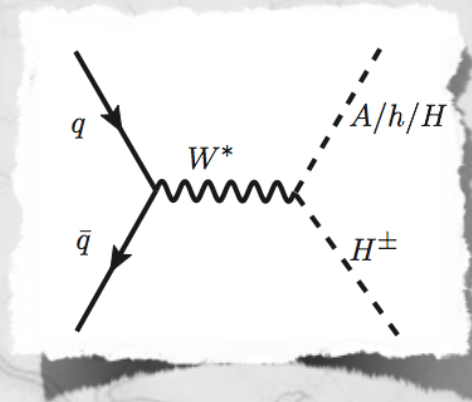
$$g_{H^- t\bar{b}} = \frac{g}{2\sqrt{2}m_W} [m_t \cot \beta (1 + \gamma_5) + m_b \tan \beta (1 - \gamma_5)]$$

# The $H^\pm$ production at LHC

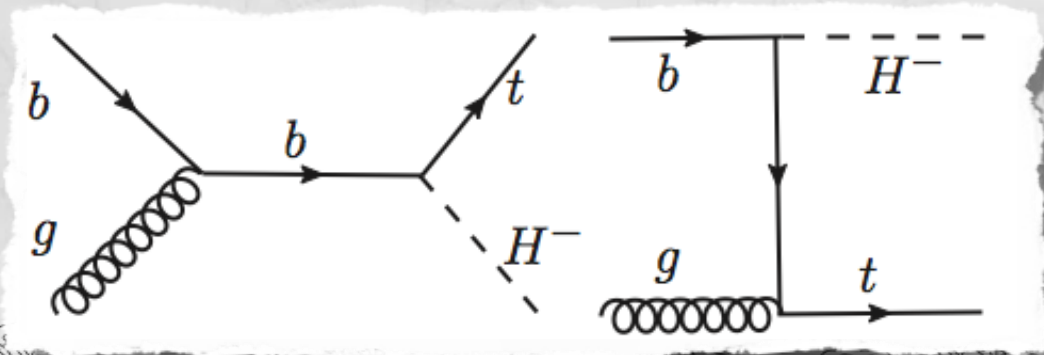
$H^\pm$  pair production



$H^\pm$  H/A/h production

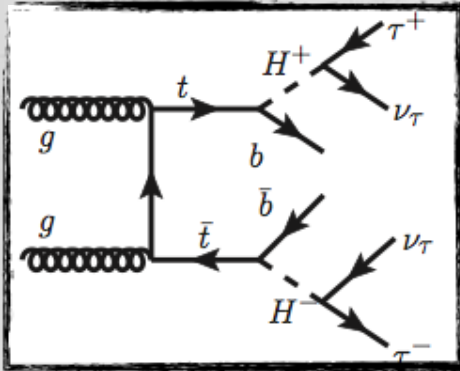


$H^\pm$  t production

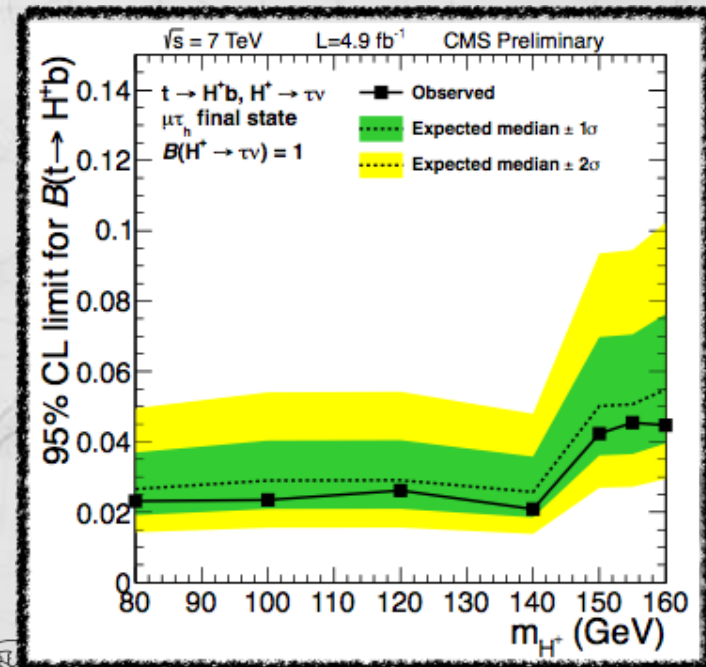
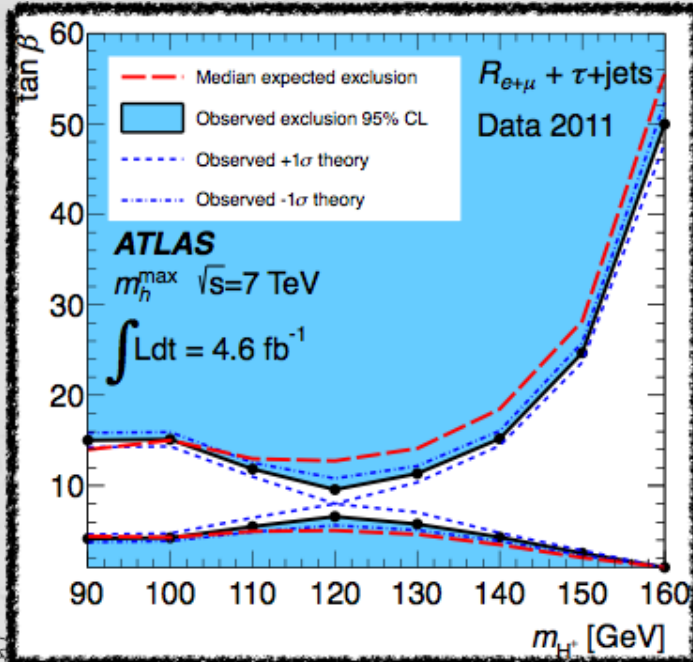


Huang and Zhu, PRD60  
(1999) 075012

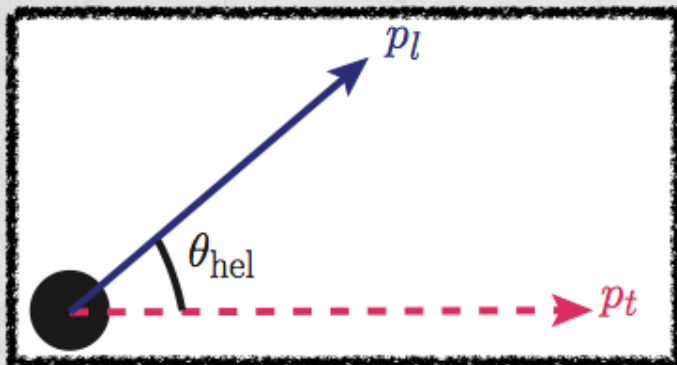
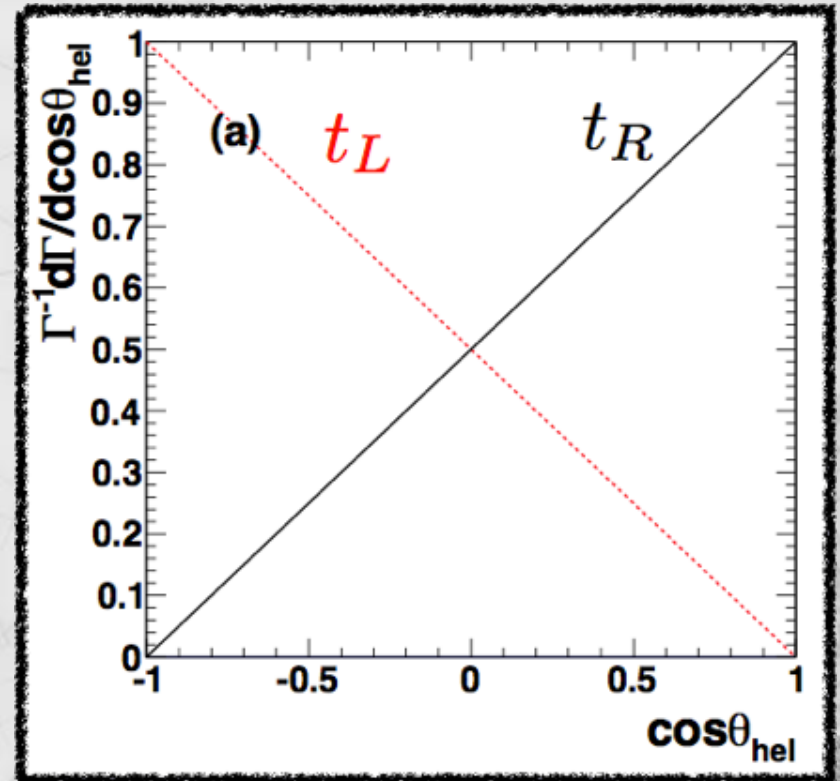
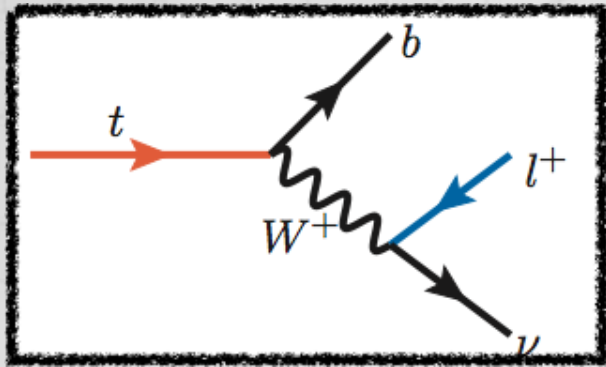
# Light charged Higgs search at LHC



$$\mathcal{N} = \sigma_{t\bar{t}} \times \mathcal{L}[(1 - B)^2 \epsilon_{WW} + B^2 \epsilon_{HH} + B(1 - B)(\epsilon_{H+W-} + \epsilon_{H-W+})] + \mathcal{N}_{\text{others}}$$



# The polarization property of Top

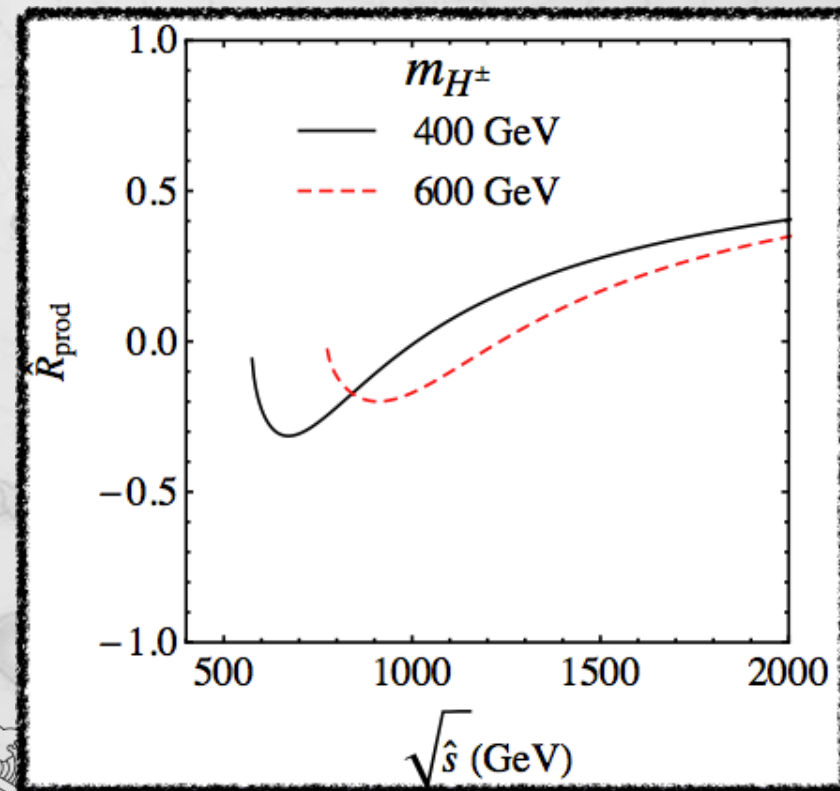


$$\frac{d\Gamma}{\Gamma d\cos\theta_{\text{hel}}} = \frac{1}{2}(1 \pm \cos\theta_{\text{hel}})$$

# The signal process at LHC

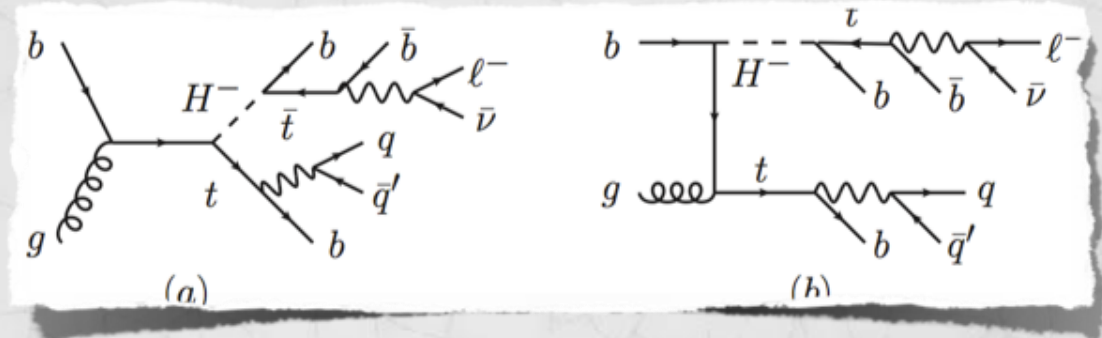
$$D_{\text{decay}} \equiv \frac{\Gamma(\bar{t}_L) - \Gamma(\bar{t}_R)}{\Gamma(\bar{t}_L) + \Gamma(\bar{t}_R)} = \frac{(m_t \cot \beta)^2 - (m_b \tan \beta)^2}{(m_t \cot \beta)^2 + (m_b \tan \beta)^2}$$

$$D_{\text{prod}}(\hat{s}) = \frac{(m_t \cot \beta)^2 - (m_b \tan \beta)^2}{(m_t \cot \beta)^2 + (m_b \tan \beta)^2} \times \hat{R}_{\text{prod}} \cdot D_{\text{decay}}$$

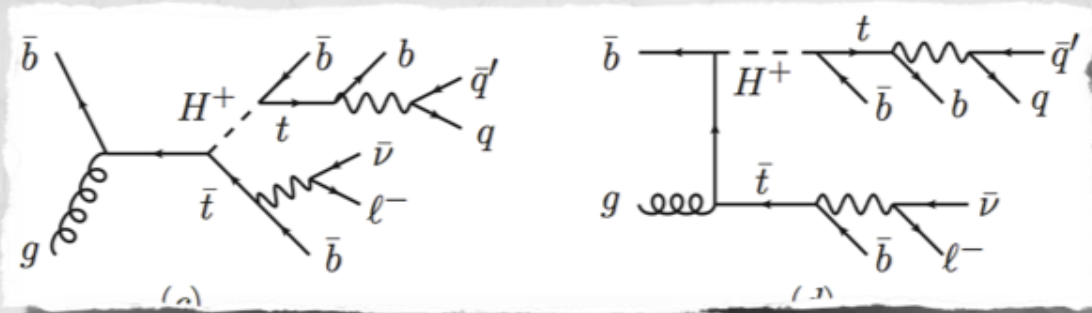


# The signal and background at LHC

## The signal



## The irreducible background



## The SM background

$$t\bar{t}b : pp \rightarrow t\bar{t}j_b \rightarrow bW^+ \bar{b}W^- j_b \rightarrow j_b j_b j_b j_b j_b \ell^- \bar{\nu}$$

$$t\bar{t}j : pp \rightarrow t\bar{t}j \rightarrow bW^+ \bar{b}W^- j \rightarrow j_b j_b j_b j_b j_b \ell^- \bar{\nu}$$

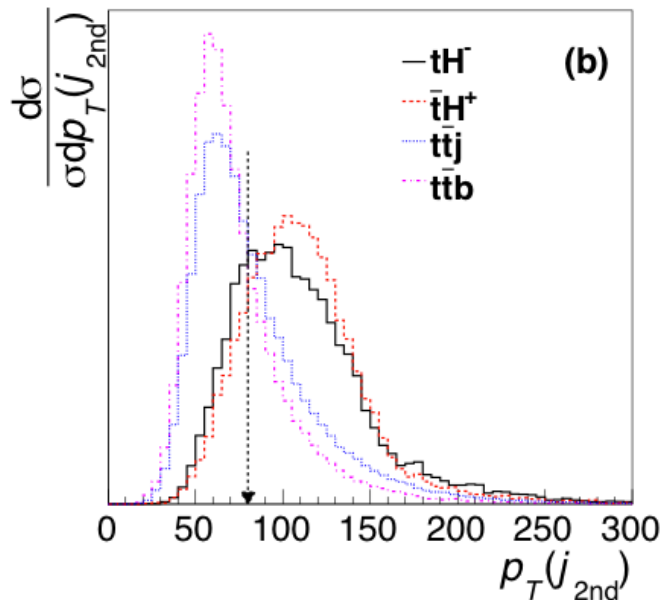
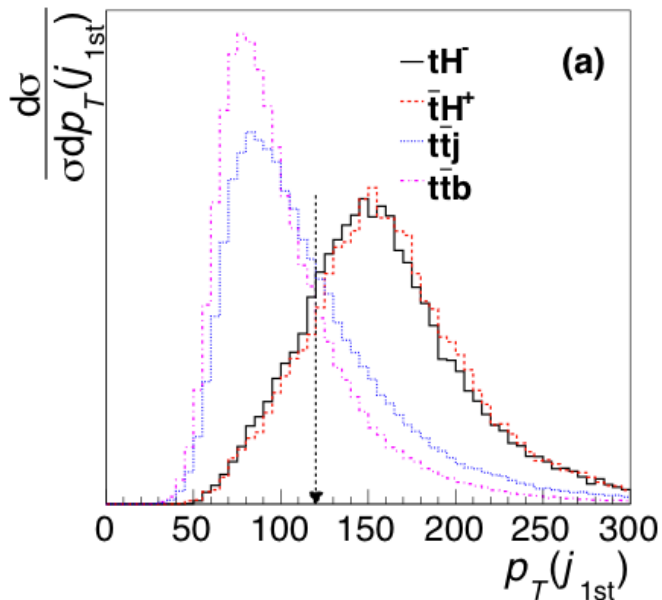
# Detector simulation

Event topology: 3b-jet+2light-jet  
1 charged lepton  
missing energy

$pp \rightarrow tH^- \rightarrow t(\bar{t}b)$

VS

$pp \rightarrow t\bar{t}j$



$p_T(j_{1st}) > 120\text{GeV}$

$p_T(j_{2nd}) \geq 80\text{GeV}$



# Detector simulation

$pp \rightarrow tH^- \rightarrow t(\bar{t}b)$

**VS**

$pp \rightarrow t\bar{t}j$

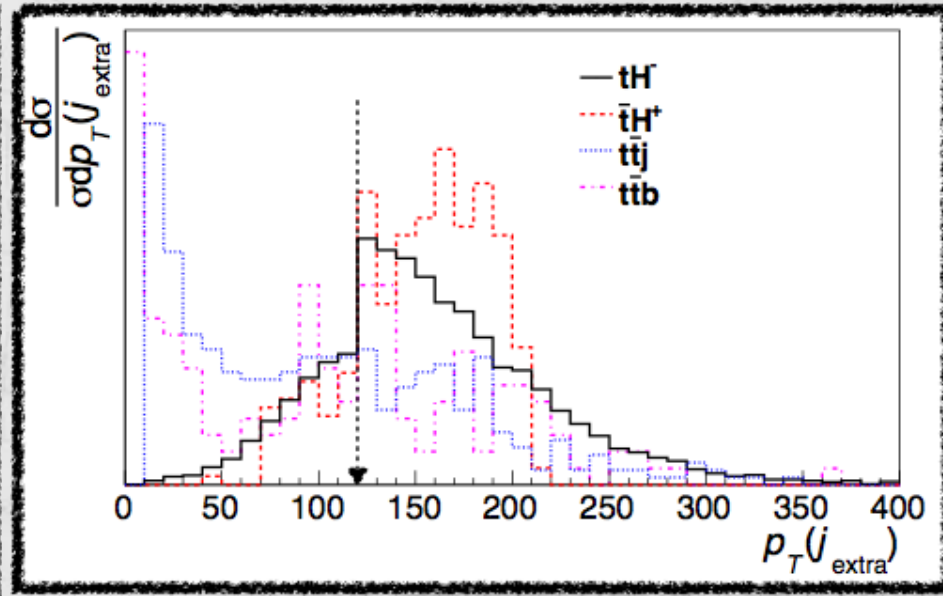
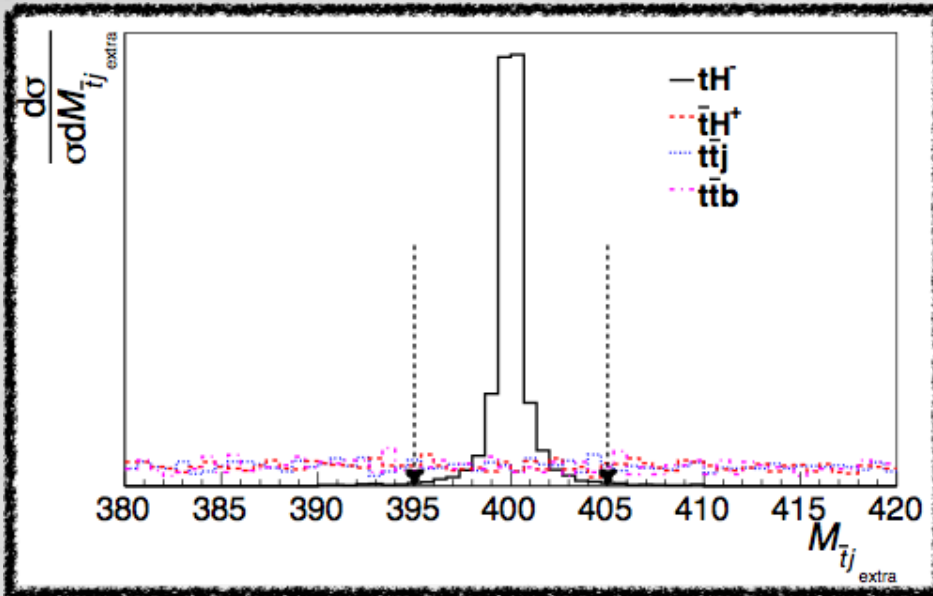
- The W boson on-shell condition

$$p_{\text{sol}} = \frac{1}{2p_{\ell-T}^2} \left[ \left( m_W^2 + 2\vec{P}_{\ell-T} \cdot \vec{E}_T \right) p_{\ell-L} \pm E_{\ell} \sqrt{\left( m_W^2 + 2\vec{P}_{\ell-T} \cdot \vec{E}_T \right)^2 - 4p_{\ell-T}^2 E_T^2} \right]$$

- The minima  $\chi^2$ -template method

$$\chi^2 = \frac{(m_W - m_{jj})^2}{\Delta m_W^2} + \frac{(m_t - m_{j\ell-s})^2}{\Delta m_t^2} + \frac{(m_t - m_{jjj})^2}{\Delta m_t^2}$$

# Detector simulation



$$\Delta M_{\bar{t}j_{\text{extra}}} = |M_{\bar{t}j_{\text{extra}}} - M(H^\pm)| \leq 5\text{GeV}$$

$$p_T(j_{\text{extra}}) \geq 120\text{GeV}$$

# The discovery potential

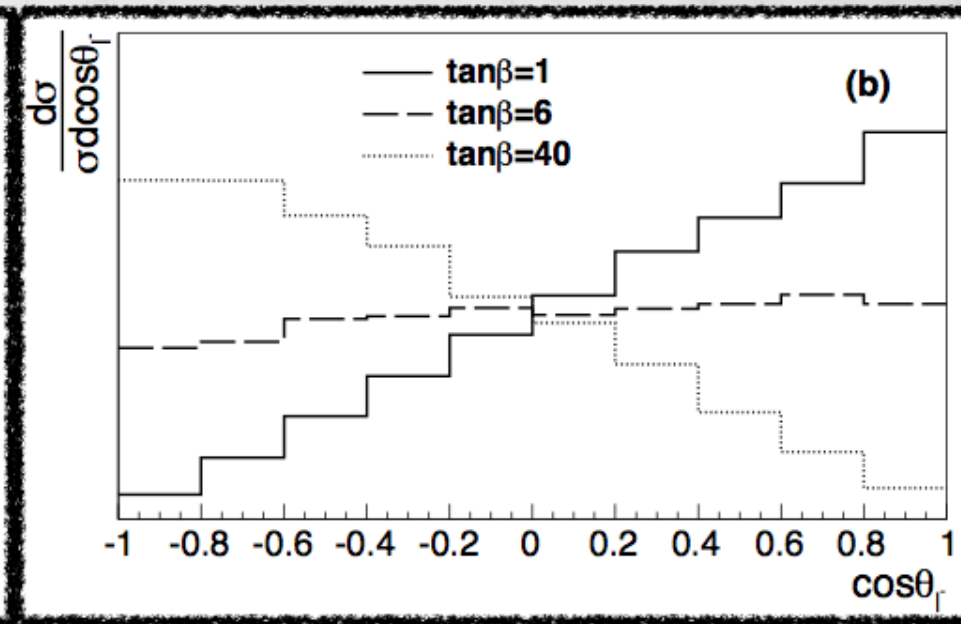
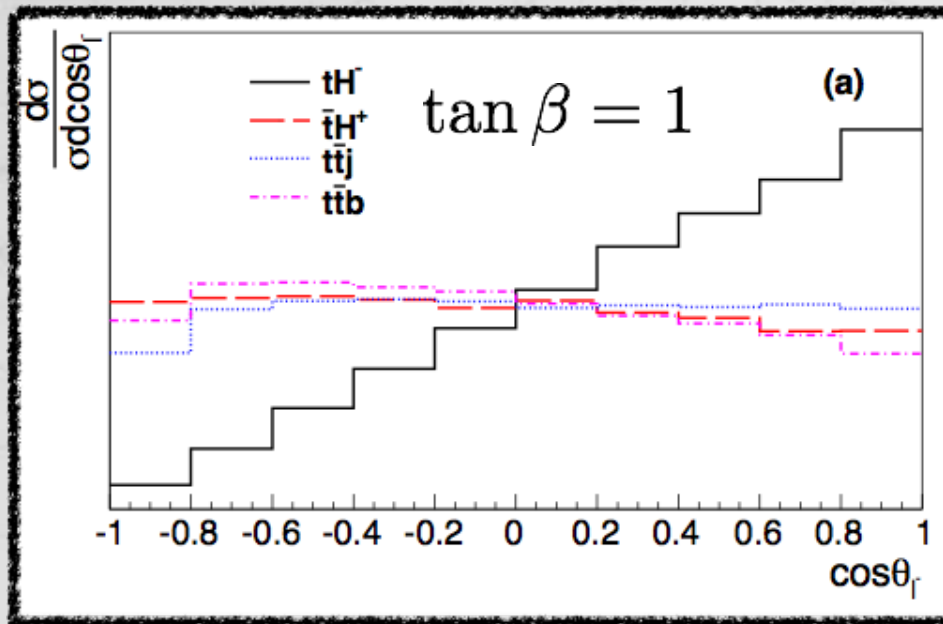
TABLE I: Number of events of the signal and backgrounds at the 14 TeV LHC with an integrated luminosity of  $100 \text{ fb}^{-1}$  for  $m_{H^\pm} = 400 \text{ GeV}$  and three values of  $\tan\beta$ .

$\tan\beta$	1		6		40		SM backgrounds	
	$tH^-$	$\bar{t}H^+$	$tH^-$	$\bar{t}H^+$	$tH^-$	$\bar{t}H^+$	$t\bar{t}j$	$t\bar{t}b$
Inclusive rate	23310	23300	1255	1227	24660	23520	$1.075 \times 10^7$	234000
Hard $p_T$ cuts	11843	13466	687	719	14421	13890	$2.12 \times 10^6$	25052
$\Delta M_{tj_{\text{extra}}}$	4980	368	672	20	5680	383	39238	386
$p_T(j_{\text{extra}})$	3910	305	532	16	4375	310	14942	171
$b$ tagging	2346	183	312	10	2625	186	299	102
Number of events	2529		322		2811		401	
$S/B$	6.3		0.8		7.0		—	
$S/\sqrt{B}$	126.3		16.1		140.3		—	
$\sqrt{S+B}$	54.1		26.9		56.7		—	

# $\tan\beta$ versus top polarization

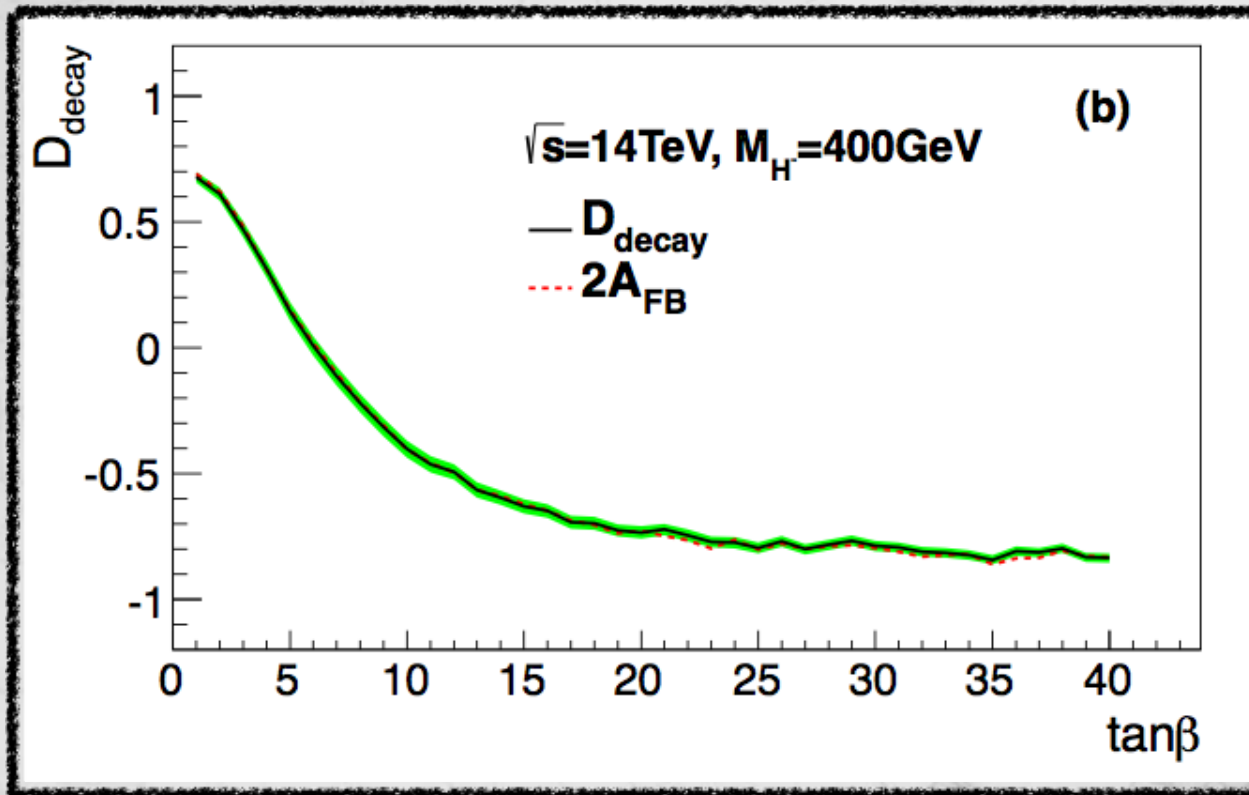
$$\frac{d\Gamma}{\Gamma d\cos\theta_{\text{hel}}} = \frac{1}{2}(1 + D \cos\theta_{\text{hel}})$$

$$D = 3 \sum_{i=1}^{10} \cos\theta_i \left( \frac{d\sigma}{\sigma d\cos\theta} \right)_i \Delta \cos\theta = \frac{3 \sum_{i=1}^{10} \cos\theta_i N_i}{\sum_{i=1}^{10} N_i}$$



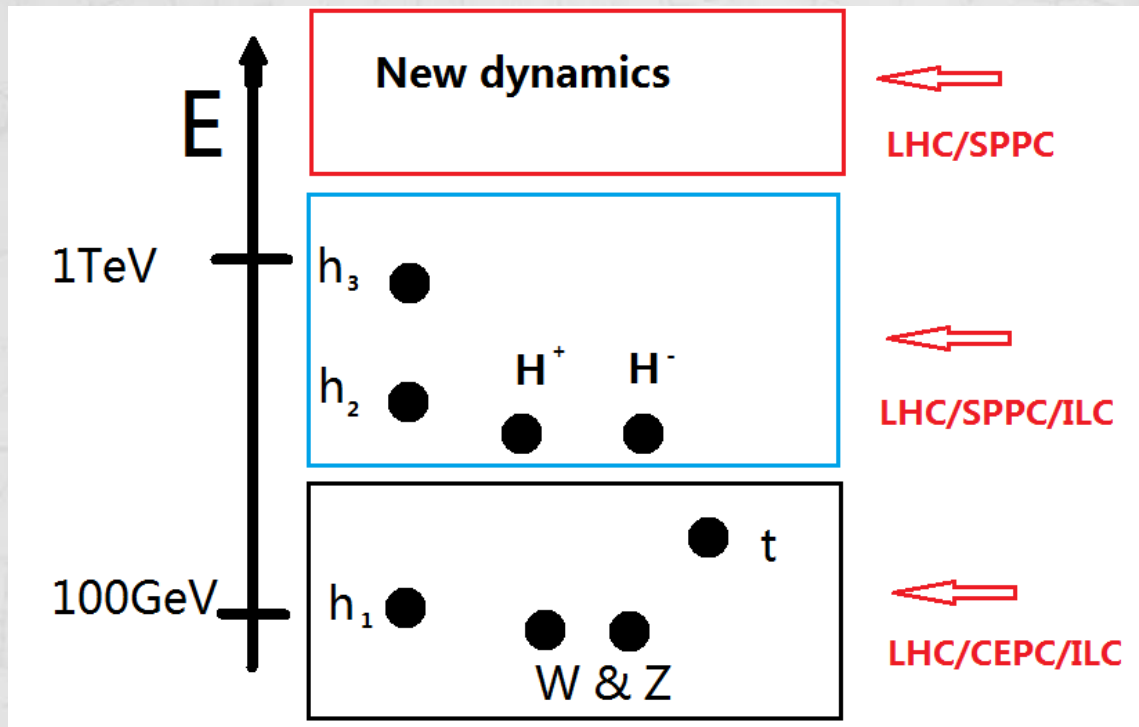
$$m_{H^\pm} = 400\text{GeV}$$

# $\tan\beta$ measurement at LHC



# Conclusion

- The lightness of 125 GeV scalar is likely related to the spontaneous CP symmetry and point to new paradigm
- Charged Higgs bosons can be the tracer of BSM
- Mechanism to stabilize weak scale is postponed





**Thanks!**