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"

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

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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 GeV) would be found
- Before the LHC, in the SM, ~100GeV Higgs boson was preferred by precision EW data, though there was a ~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

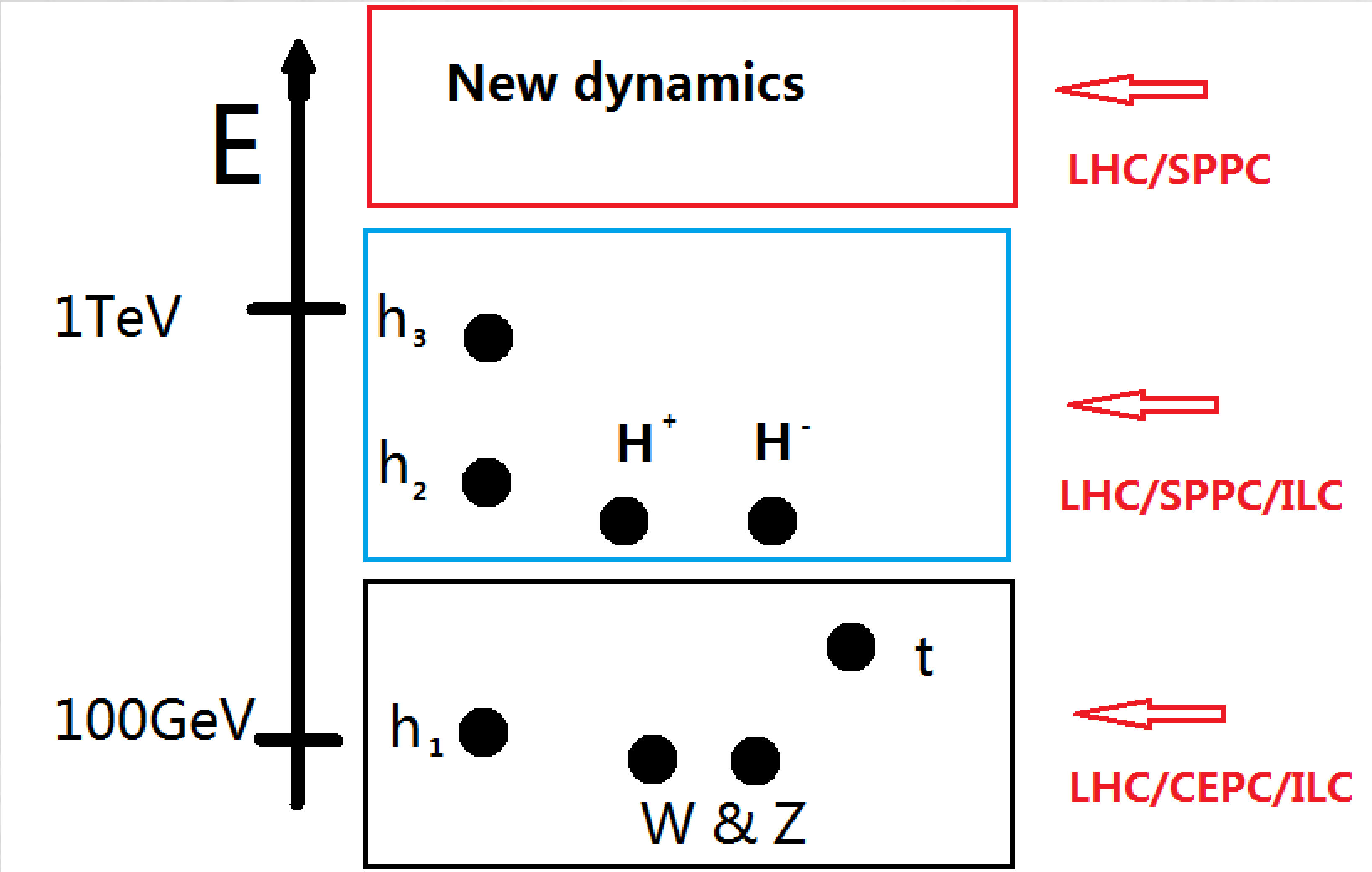
- Such boring story would last forever?

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.

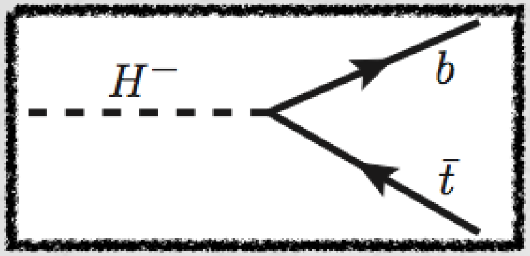
Zhu, 1211.2370,
Hu, Wang, Yin and Zhu, FOP8 (2013) 516
Mao & Zhu, in preparation

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

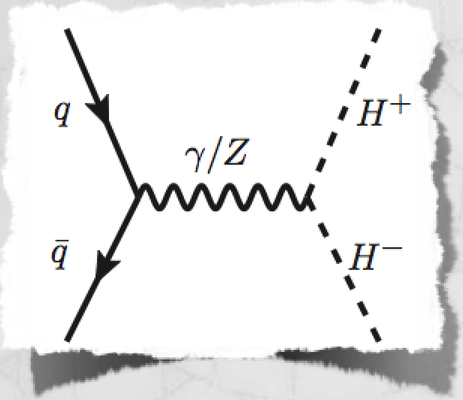


$$\tan\beta = \frac{v_2}{v_1}$$

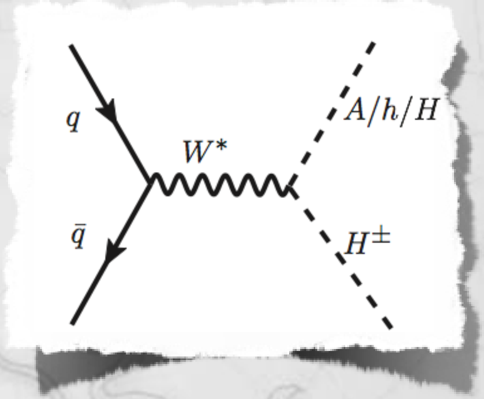
$$g_{H^- t\bar{b}} = \frac{g}{2\sqrt{2}m_W}[m_t \cot\beta\,(1+\gamma_5) + m_b \tan\beta\,(1-\gamma_5)]$$

The $H^{\pm}$ production at LHC

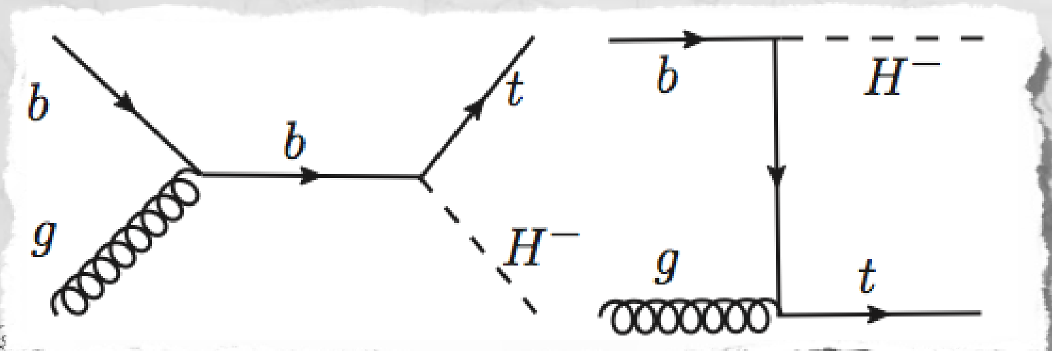
- $H^{\pm}$ pair production



- $H^{\pm}$ H/A/h production

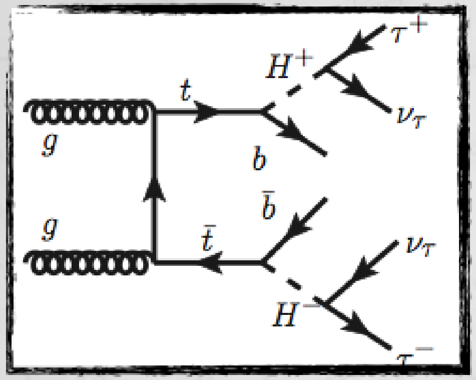


- $H^{\pm}$ t production

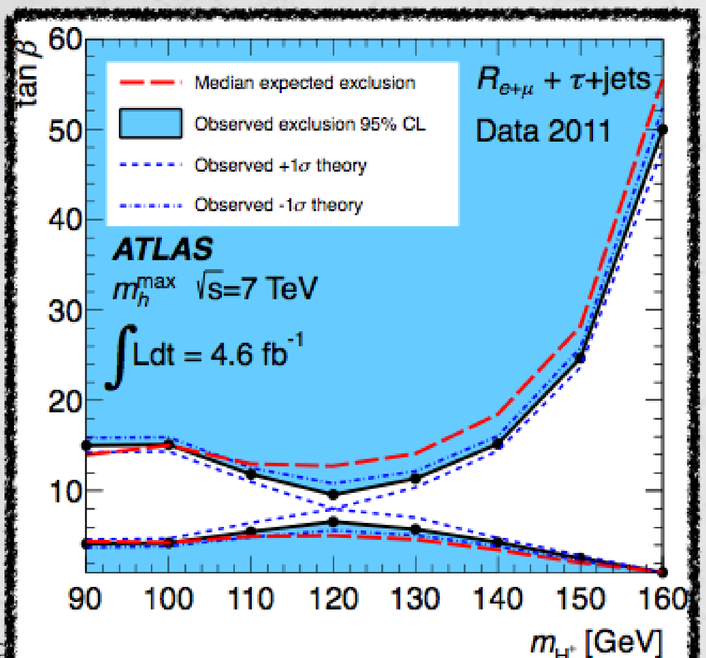


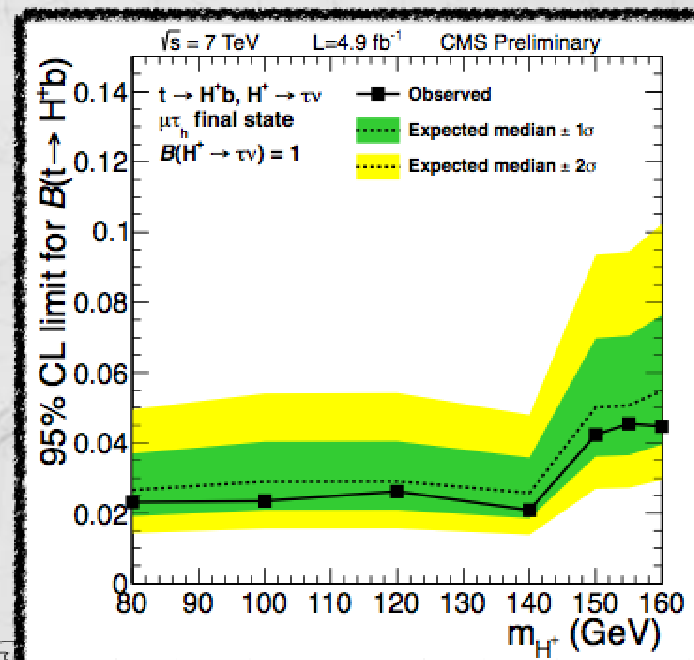
Huang and Zhu, PRD60 (1999) 075012

Light charged Higgs search at LHC

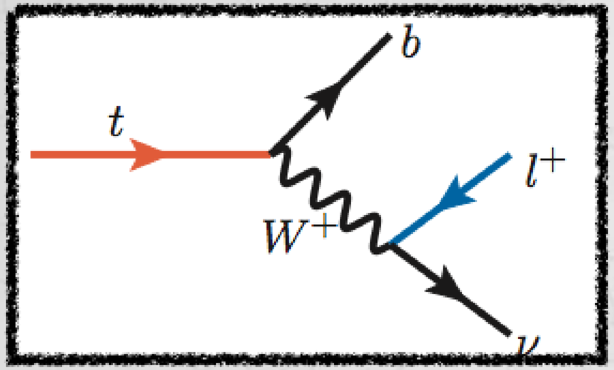


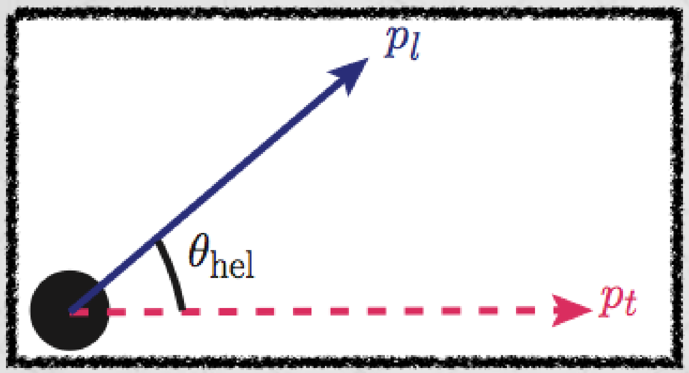
$$\mathcal{N} = \sigma_{t\bar{t}} \times \mathcal{L}[(1-B)^2 \varepsilon_{WW} + B^2 \varepsilon_{HH} + B(1-B)(\varepsilon_{H^+W^-} + \varepsilon_{H^-W^+})] + \mathcal{N}_{\text{others}}$$

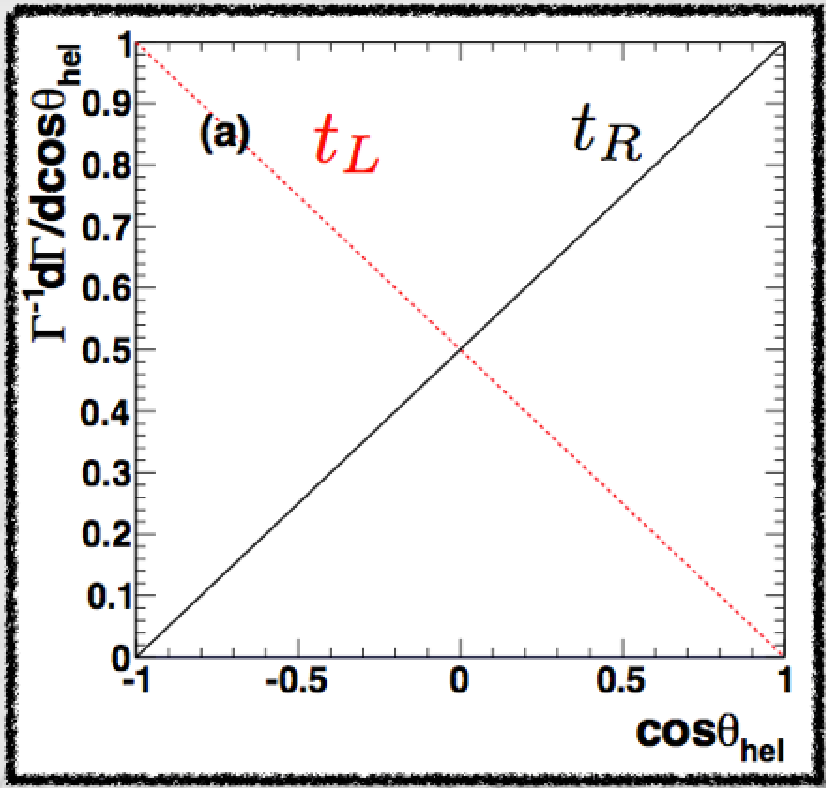




The polarization property of Top







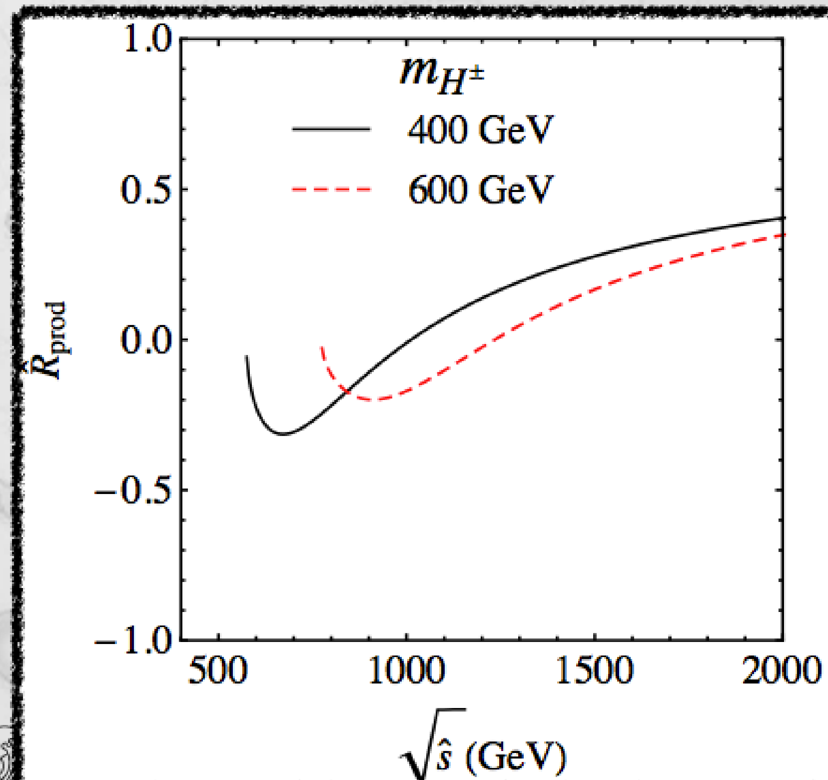
$$\frac{d\Gamma}{\Gamma d\cos\theta_{hel}} = \frac{1}{2}(1 \pm \cos\theta_{hel})$$

The signal process at LHC

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

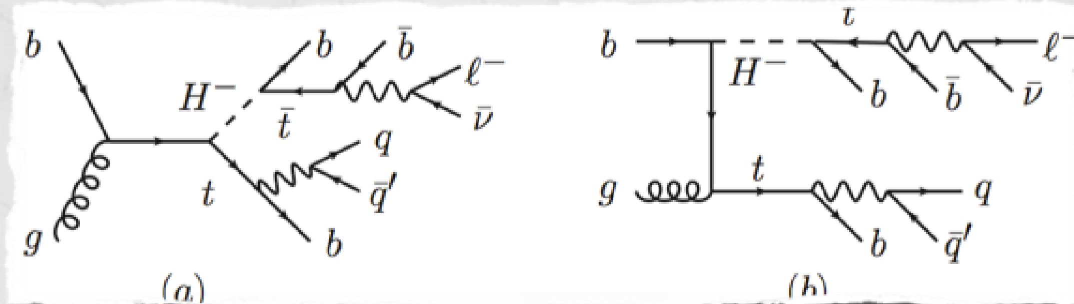
$$D_{\rm prod}(\hat{s}) = \frac{(m_t \cot\beta)^2 - (m_b \tan\beta)^2}{(m_t \cot\beta)^2 + (m_b \tan\beta)^2} \times \hat{R}_{\rm prod}$$

$D_{\rm decay}$

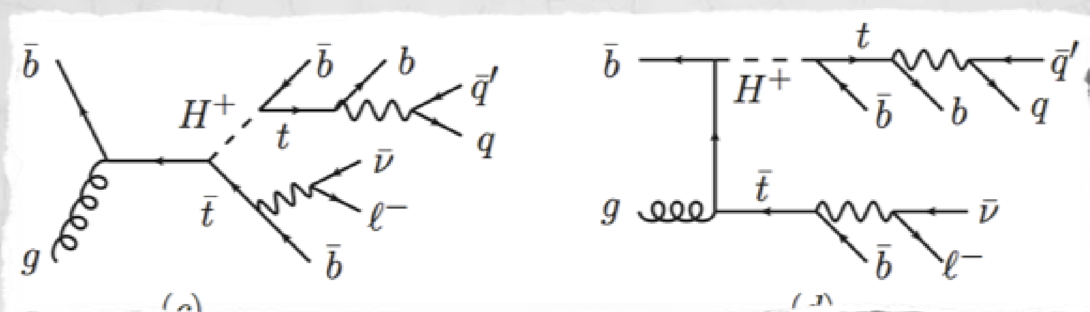


The signal and background at LHC

- The signal



- The irreducible background



- The SM background

$$t\bar{t}b \; : \; pp \to t\bar{t}j_b \to bW^+\bar{b}W^-j_b \to j_bj_bj_bjj\ell^-\bar{\nu},$$

$$t\bar{t}j \; : \; pp \to t\bar{t}j \to bW^+\bar{b}W^-j \to j_bj_bjjj\ell^-\bar{\nu}.$$

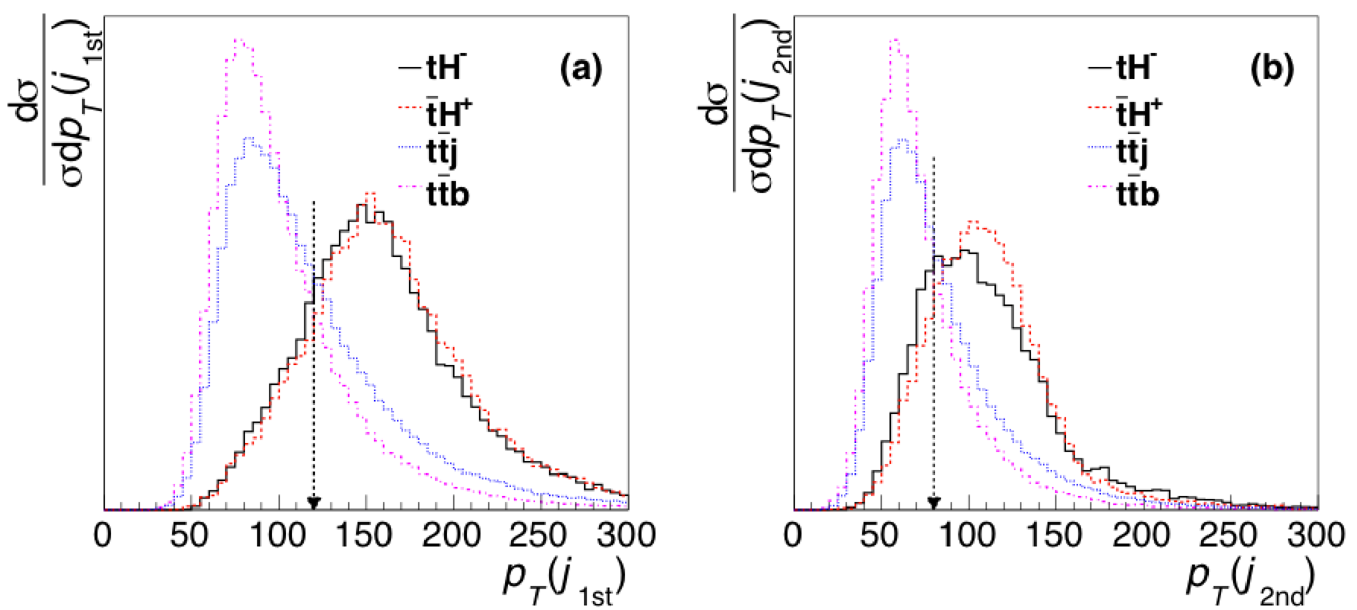
Detector simulation

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

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

VS

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



$p_T(j_{1st}) \geq 120\text{GeV}$ $p_T(j_{2nd}) \geq 80\text{GeV}$

Detector simulation

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

VS

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

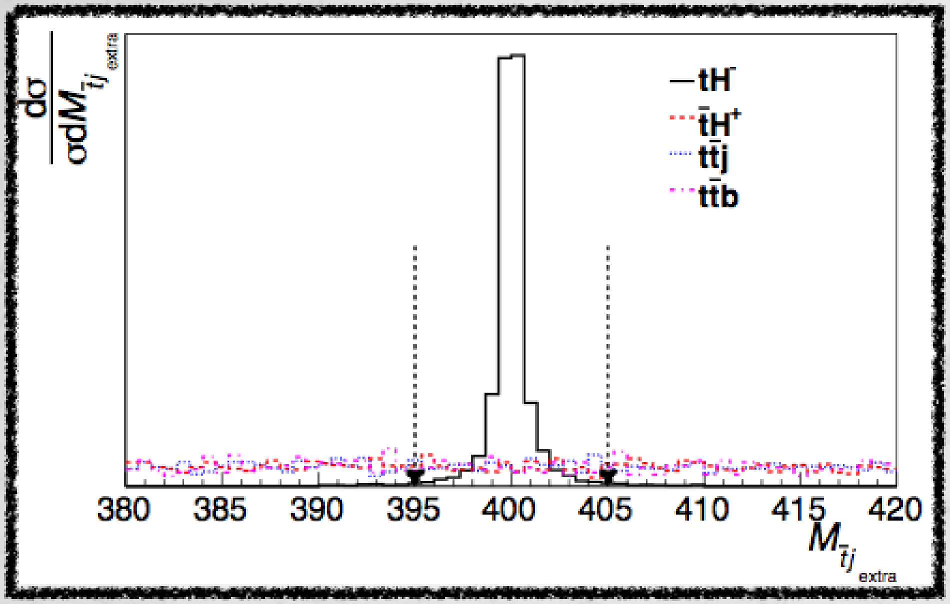
- The W boson on-shell condition

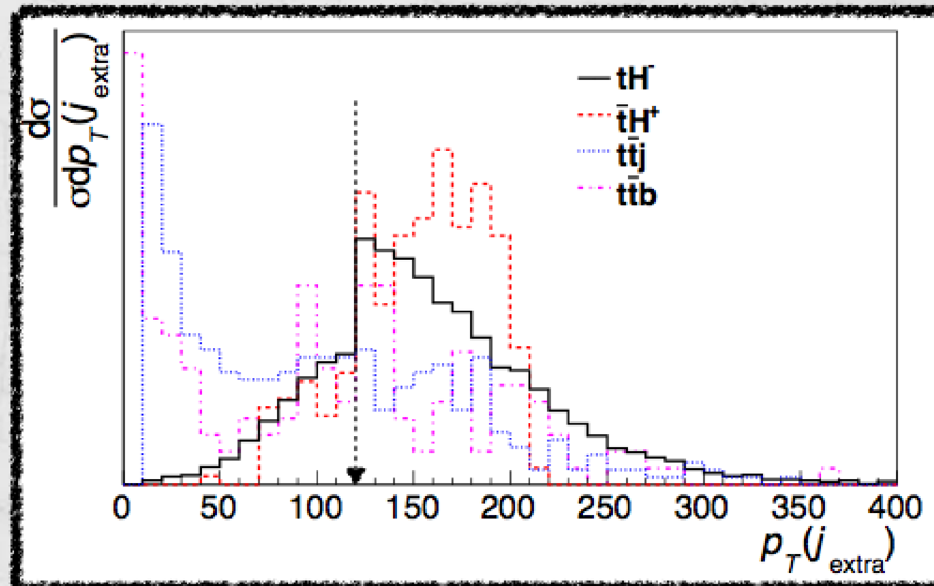
$$p_{\nu L} = \frac{1}{2p^2_{\ell-T}}\left[\left(m_W^2 + 2\vec{P}_{\ell-T}\cdot\vec{\not{E}}_T\right)p_{\ell-L} \pm E_\ell\sqrt{\left(m_W^2 + 2\vec{P}_{\ell-T}\cdot\vec{\not{E}}_T\right)^2 - 4p^2_{\ell-T}\not{E}_T^2}\right]$$

- The minima χ^2 -template method

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

Detector simulation





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

$$p_T\left(j_{\mathrm{extra}}\right) \geq 120\mathrm{GeV}$$

The discovery potential

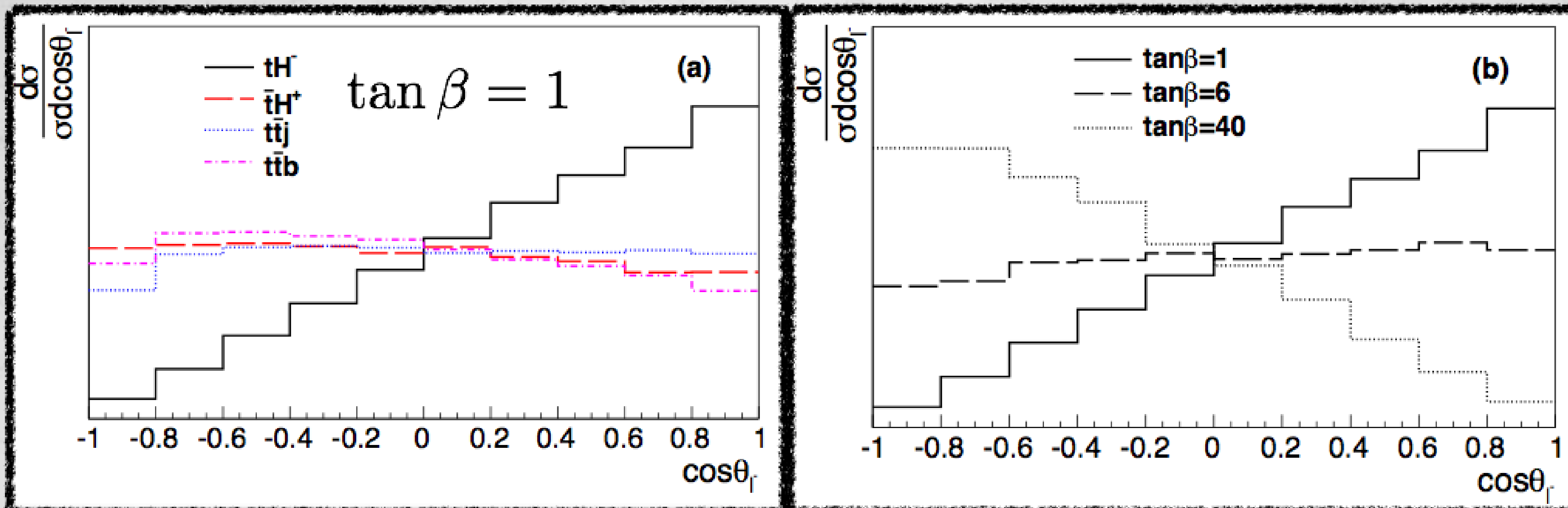
TABLE I: Number of events of the signal and backgrounds at the 14 TeV LHC with an integrated luminosity of 100 fb^{-1} for $m_{H^\pm} = 400$ GeV and three values of $\tan\beta$.

$\tan\beta$	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	1.075×10^7	234000
Hard p_T cuts	11843	13466	687	719	14421	13890	2.12×10^6	25052
$\Delta M_{\bar{t}j_{extra}}$	4980	368	672	20	5680	383	39238	386
$p_T(j_{extra})$	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		–	

tanβ versus top polarization

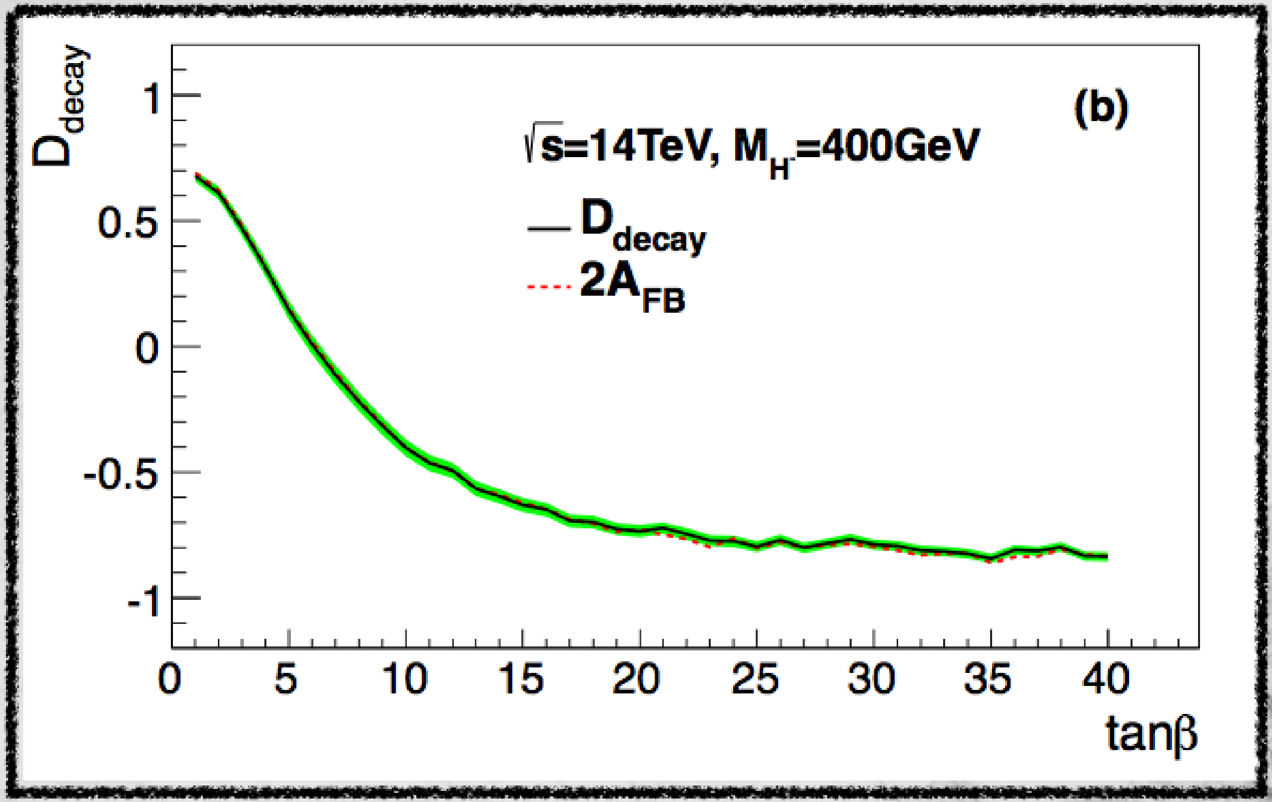
$$\frac{d\Gamma}{\Gamma d\cos\theta_{\rm hel}} = \frac{1}{2}(1 + D\cos\theta_{\rm hel})$$

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



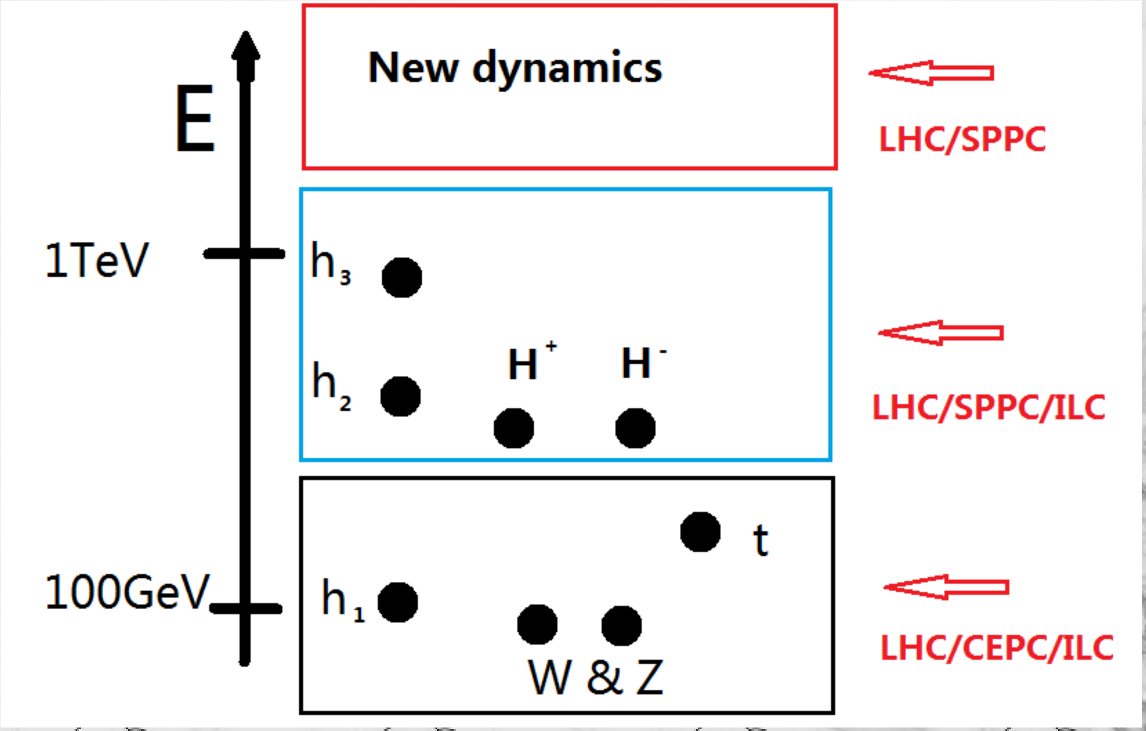
$m_{H^\pm} = 400\text{GeV}$

tanβ 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！