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Search for single production of vector-like top partner $T \to H^+ b$ and $H^\pm \to t\bar{b}$ at the LHC Run-III

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Outline

Motivation

- ✭ **LH and RH have the same $SU(2)_L$ transformation.**
- ✭ **VLQs don't get their mass from the Higgs mechanism: .**
- ✭ **VLQs can mix with SM quarks and 2HDM Higgs bosons.**
- ✭ **VLQs are the simplest type of colored fermions still experimentally allowed.**
- ✭ **VLQs could be singlet, doublet or triplet under $SU(2)_L$.**

Component fields	T	B	TB	XT	BY	TBY	XTB
$U(1)_Y$	2/3	-1/3	1/6	7/6	-5/6	-1/3	2/3
$SU(2)_L$	1	1	2	2	2	3	3
$SU(3)_C$	3	3	3	3	3	3	3

- ✭ **VLQs have the electric charges:** $Q_T = \frac{2}{3}, Q_B = -\frac{1}{3}, Q_X = \frac{5}{3}$, **and** $Q_Y = -\frac{4}{3}$.

Lagrangian

- In 2HDM, the Yukawa interaction is given by the Lagrangian as:

$$\mathcal{L}_Y = -Y_u H_u q_L u_R - Y_d H_d q_L d_R - Y_e H_d l_L e_R + h.c.$$

- In the case of 2HDM with VLQs, the Yukawa interaction is given by the Lagrangian :

$$\mathcal{L}_Y = -Y_u H_u Q_L U_R - Y_d H_d Q_L D_R + M_u \bar{U}_L U_R + M_d \bar{D}_L D_R + h.c.$$

- Yukawa interactions that manifest in our signal T:

$$\mathcal{L}_{H^+} = -\frac{g m_t}{\sqrt{2} M_W} \bar{t}(\cot\beta Z^L_{tb} P_L + \tan\beta Z^R_{tb} P_R) b H^+ - \frac{g m_T}{\sqrt{2} M_W} \overline{T}(\cot\beta Z^L_{Tb} P_L + \tan\beta Z^R_{Tb} P_R) b H^+ + H.c.$$

$$Z^L_{tb} = c^d_L c^u_L + \frac{s^d_L}{s^u_L}(s^{u\,2}_L - s^{u\,2}_R) e^{i(\phi_u - \phi_d)}, \qquad Z^R_{tb} = \frac{m_b}{m_t}\left[c^u_L c^d_L + \frac{s^u_L}{s^d_L}(s^{d\,2}_L - s^{d\,2}_R) e^{i(\phi_u - \phi_d)}\right]$$

$$Z^L_{Tb} = c^d_L s^u_L e^{-i\phi_u} + (s^{u\,2}_L - s^{u\,2}_R)\frac{s^d_L}{c^u_L} e^{-i\phi_d}, \quad Z^R_{Tb} = \frac{m_b}{m_T}\left[c^d_L s^u_L e^{-i\phi_u} + (s^{d\,2}_R - s^{d\,2}_L)\frac{c^u_L}{s^d_L} e^{-i\phi_d}\right]$$

- VLQs couplings to W boson ,

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}} \overline{T} \gamma^\mu (V^L_{Tb} P_L + V^R_{Tb} P_R) b W^+_\mu + H.c. \quad (1)$$

- LH Heavy-Light coupling

$$V^L_{Tb} = s^u_L c^d_L e^{-i\phi_u} - c^u_L s^d_L e^{-i\phi_d}$$

- RH Heavy-Light coupling

$$V^R_{Tb} = c^u_R s^d_R e^{-i\phi_d}$$

For more details see : [R. Benbrik, M. Boukidi, S. Moretti: arXiv:2211.07259 [hep-ph]]

THEORETICAL AND EXPERIMENTAL CONSTRAINTS

2HDMC (D. Eriksson, J. Rathsman and O. Stal)

Unitarity, Perturbativity, Vacuum Stability.
EW Precision Observables (S, T), $\Delta\chi^2(S_{VLQ} + S_{2HDM}, T_{VLQ} + T_{2HDM}) \leq 6.18$ is required.

HiggsBounds (P. Bechtle et al)

Exclusion limits at 95% Confidence Level (CL) from Higgs searches at colliders (LEP, Tevatron and LHC).

HiggsSignal (P. Bechtle et al)

Constraints from the Higgs boson signal strength measurements (SM-like Higgs properties).

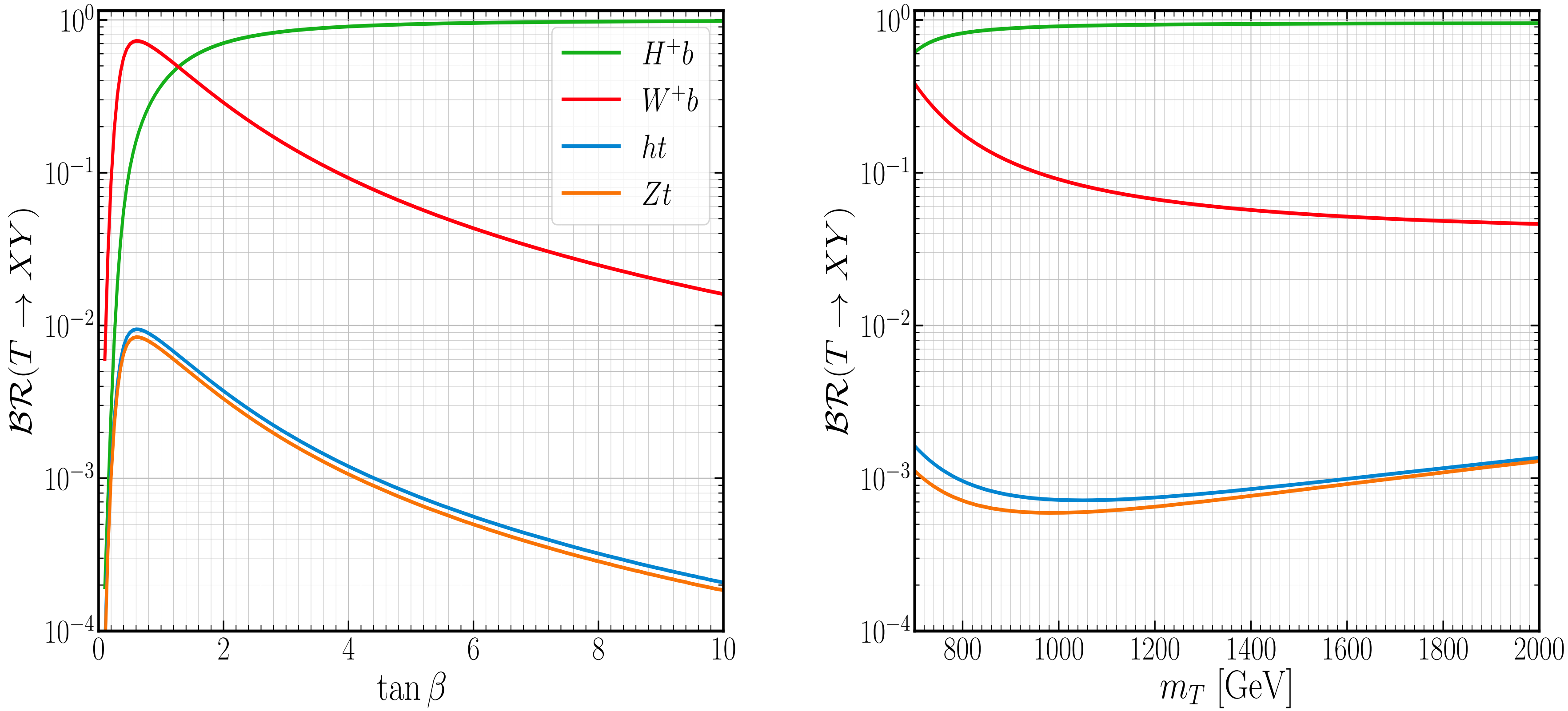
$B_s \to X_s\gamma$ measurement

Charged Higgs boson mass $(m_{H^\pm})$ heavier than 580 GeV.

Parameters	Scanned ranges
m_h	125
m_A	[300, 800]
m_H	[300, 800]
$m_{H^\pm}$	[590, 800]
$\tan\beta$	[0.5, 20]
$\sin\theta_R^{u,d}$	[−0.5, 0.5]
m_T	[700, 2000]

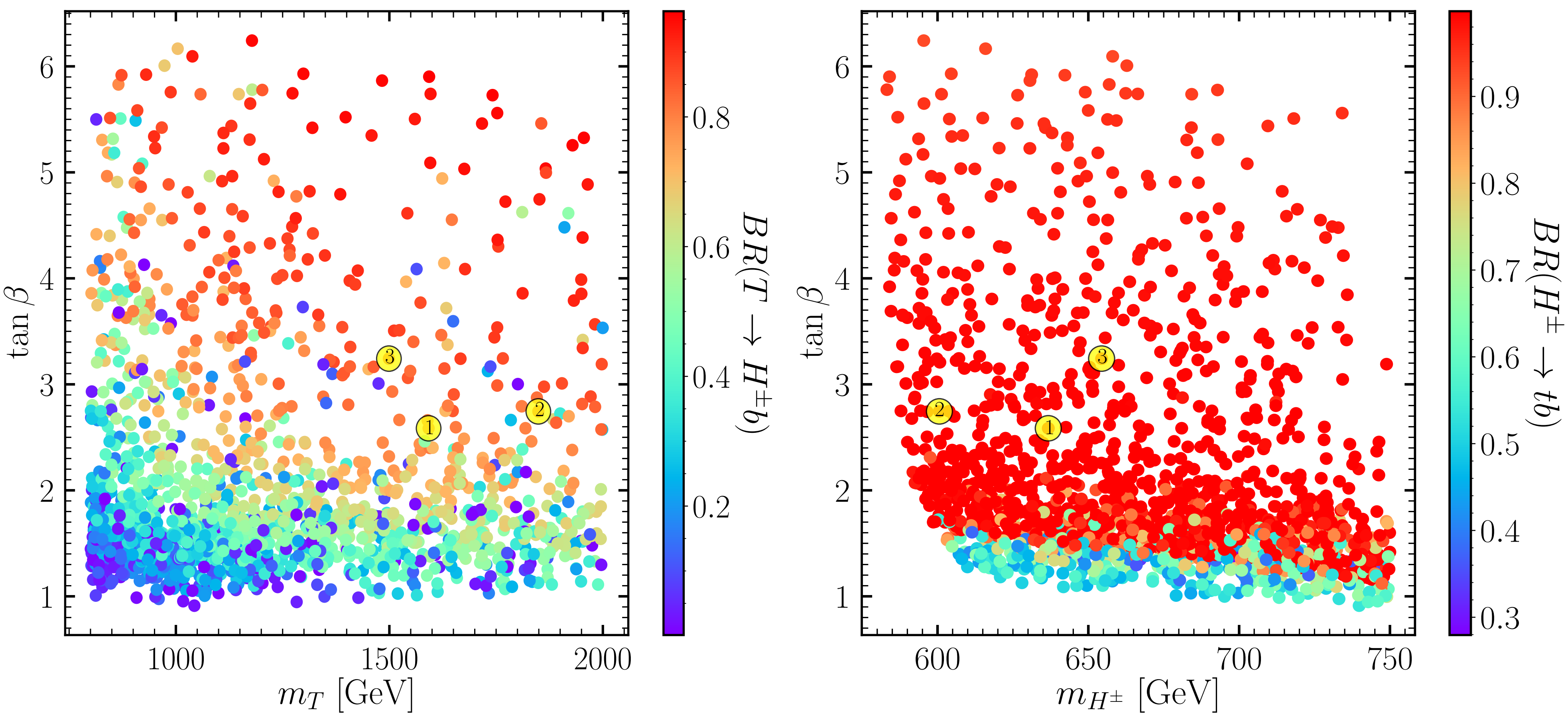
Table: 2HDM & VLQs parameters with their scanned ranges. Masses are in GeV.

BRANCHING RATIOS



- ✩ The branching ratios ($\mathcal{BR}$) for various decay channels of a $TVLQ$: $T \to H^+b$, $T \to W^+b$, $T \to hZ$, and $T \to Zt$.
- ✩ On the left panel,the branching ratios are shown as a function of $\tan\beta$, which is a parameter of the model. It reveals that the $T \to H^+b$ decay mode can dominate for values of $\tan\beta$ above 1.
- ✩ On the right panel,The branching ratios are shown as a function of m_T, which is the mass of the T particle.
- ✩ It is observed that the $T \to H^+b$ decay mode is dominant throughout the mass range of T, .

BENCHMARK POINTS



- $\mathcal{BR}(T \to H^+ b)$ as a function of m_T and $\tan\beta$ (left) and $\mathcal{BR}(H^{\pm} \to t\bar{b})$ (right) plotted over the $(m_{H^{\pm}}, \tan\beta)$ plane.
- In the right panel, for low values of $\tan\beta$, the $\mathcal{BR}(H^{\pm} \to tb)$ can reach 100%.
- In the left panel, the distribution of the $\mathcal{BR}(T \to H^{\pm} + b)$ is shown, where for intermediate values of $\tan\beta$, it may reach 80%, with the remaining 20% going to Standard Model particles.

MC SIMULATION

To generate and analyse MC events:

MadGraph5-aMC-v3.3.1

Is used to generate signal and background events.

Pythia8

Used for showering and hadronising parton level events.

Delphes-3.5.0

detector simulation (HL-LHC card).

MadAnalysis

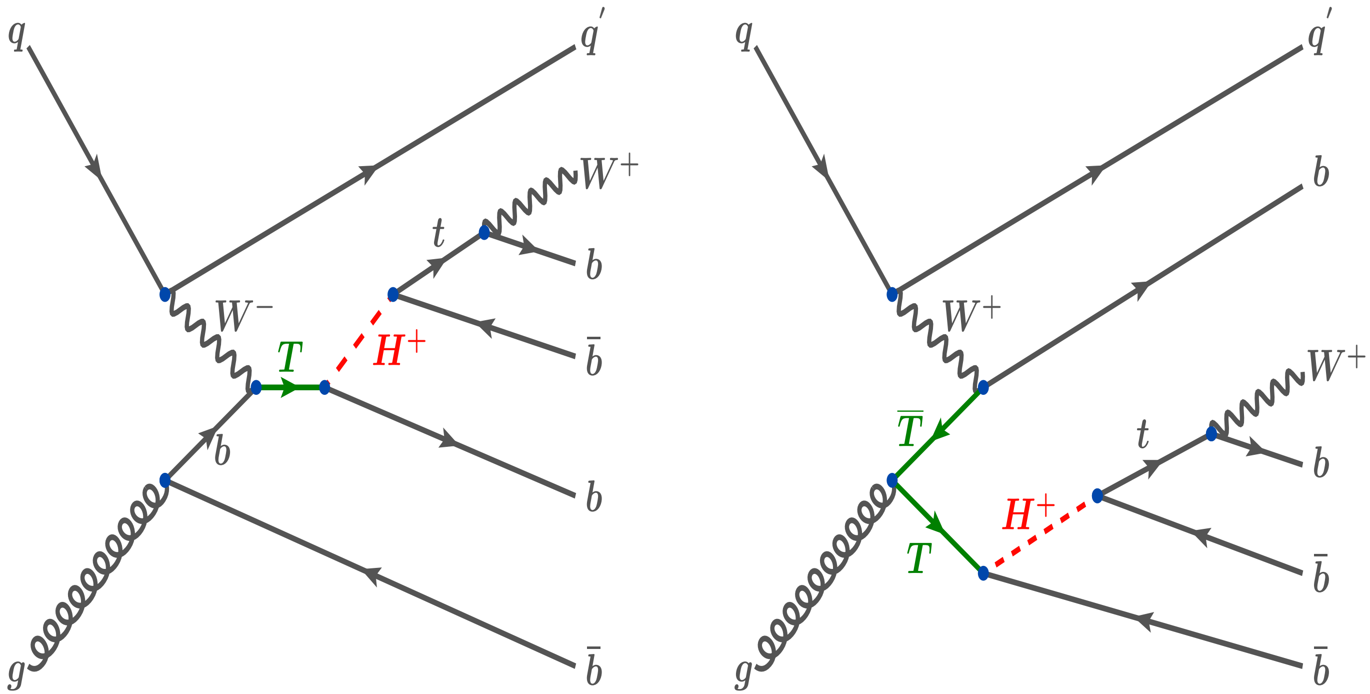
Used for analysis.

Benchmark points:

Parameters	BP_1	BP_2	BP_3
(Masses are in GeV)			
m_h	125	125	125
m_H	629.71	644.33	599.34
m_A	626.62	620.03	586.75
$m_{H\pm}$	654.40	636.73	600.62
$\tan\beta$	3.24	2.59	2.74
$\sin(\beta-\alpha)$	1	1	1
m_T	1498.93	1591.92	1848.90
m_B	1512.33	1612.45	1870.31
$\sin(\theta^u)_L$	0.0035	0.0062	-0.0014
$\sin\left(\theta^d\right)_L$	0.0004	0.0005	0.0004
$\sin(\theta^u)_R$	0.0306	0.0575	-0.0149
$\sin\left(\theta^d\right)_R$	0.1362	0.1688	0.1516

FEYNMAN DIAGRAMS

Feynman diagrams for the production of a single T and its decay into H^+b:

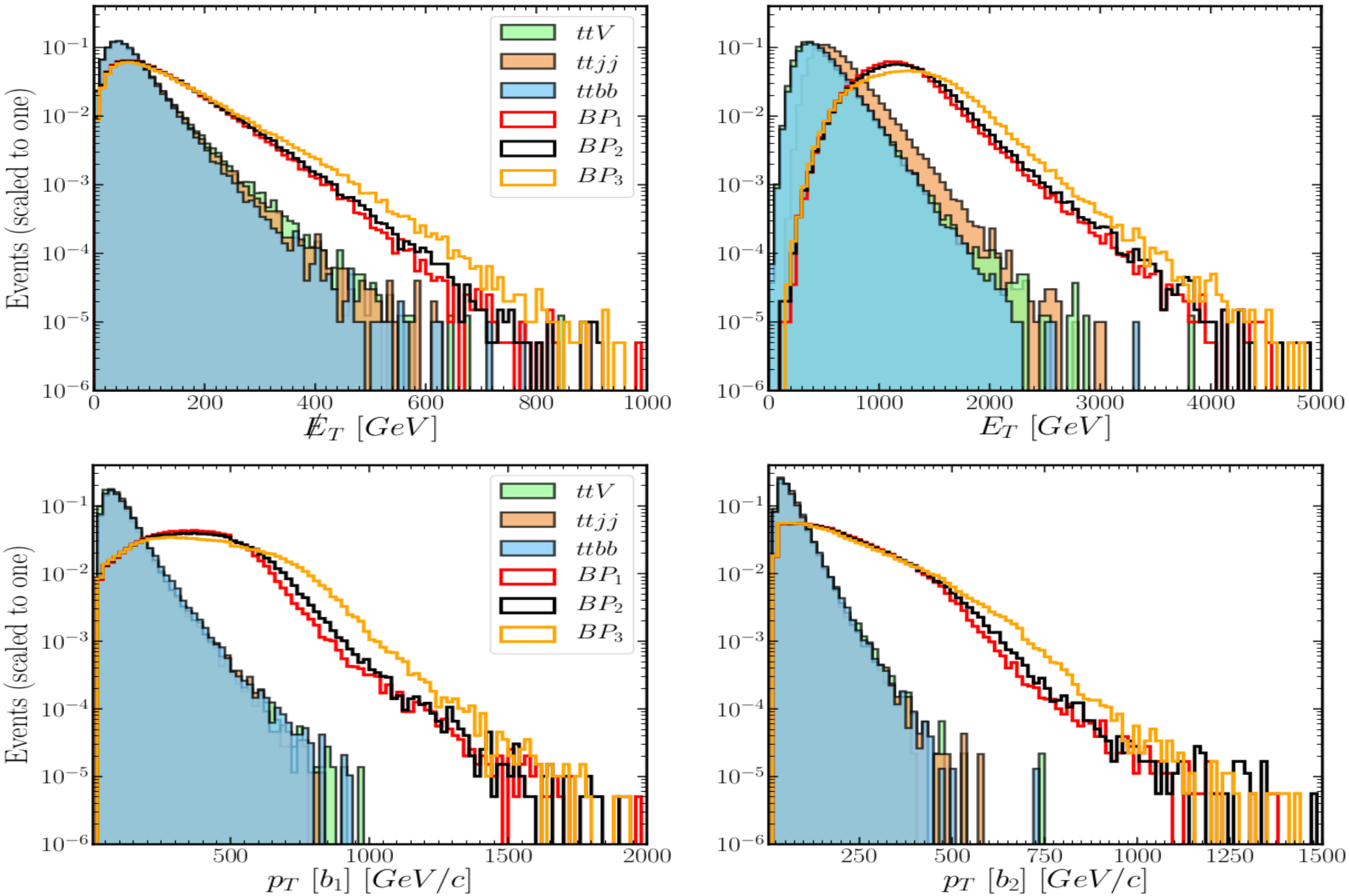


- **Signal:** $pp \to qg \to T\bar{b}j \to H^+b\bar{b}j \to t\bar{b}b\bar{b}j \to W^+b\bar{b}b\bar{b}j \to 1\ell + 4b + 1j + \not{E}_T$
- **Background:**

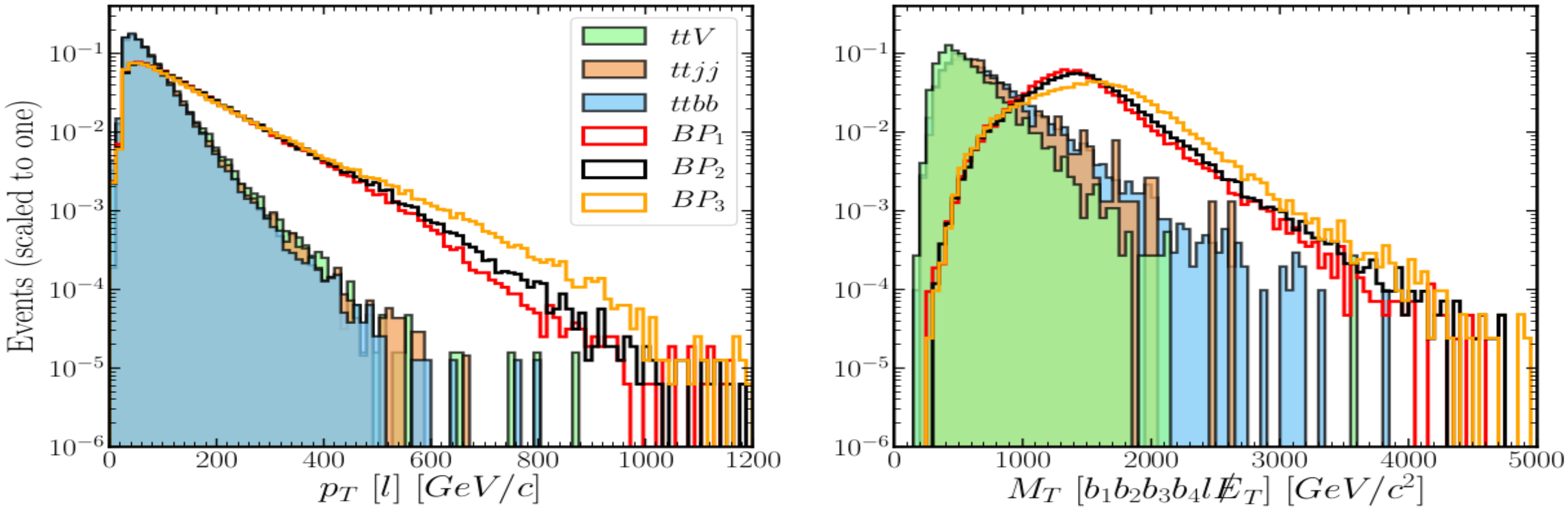
Processes	$t\bar{t}jj$	$t\bar{t}b\bar{b}$	$t\bar{t}Z$	$t\bar{t}W$	$t\bar{t}h$
K factor	1.31	2.37	1.44	1.5	1.28

- The K factors of the QCD corrections for the background processes .

DISTRIBUTIONS @ CUTS



DISTRIBUTIONS @ CUTS



$$M_T^2(b_1b_2b_3b_4l\not{E}_T) = \left(\sqrt{p_T^2(b_1b_2b_3b_4l) + M^2_{b_1b_2b_3b_4}} + \not{E}_T\right)^2 - (\vec{p}_T(b_1b_2b_3b_4l) + \not{E}_T)^2$$

✭ **Set of cuts for the analysis of signal and background events at $\sqrt{s} = 14$ TeV.**

Cuts	Définition
trigger	$N(l) = 1, \quad N(b) \geq 4$
Cut 1	$P_T^l > 50 \quad , \quad \not{E}_T > 30 \quad , \quad E_T > 1000$
Cut 2	$P_T^{b_1} > 450 \; P_T^{b_2} > 220 \quad ,$
Cut 3	$M_T^{b_1b_2b_3b_4l} > 1450 GeV$

ANALYSIS

☆ **Cut flow of the cross sections (in fb) for the signals and SM backgrounds at $\sqrt{s}$ =14 TeV HL-LHC with our three typical BPs.**

Cuts	Signals			Backgrounds		
	BP1	BP2	BP3	$t\bar{t}jj$	$t\bar{t}b\bar{b}$	$t\bar{t}V$
Basic	0.876	1.00155	0.4803	27623	187.5	44.7
Trigger	0.174	0.197	0.0926	257.8	34.05	1.95
Cut1	0.0987	0.117	0.0558	28.01	1.61	0.0923
Cut 2	0.0319	0.0424	0.0245	0.359	0.0672	0.00332
Cut 3	0.0247	0.0352	0.0223	00	0.0318	0.00111
Efficiency	3.51%	4.64%	2.82%	00	$9E^{-5}$	$2.47E^{-5}$

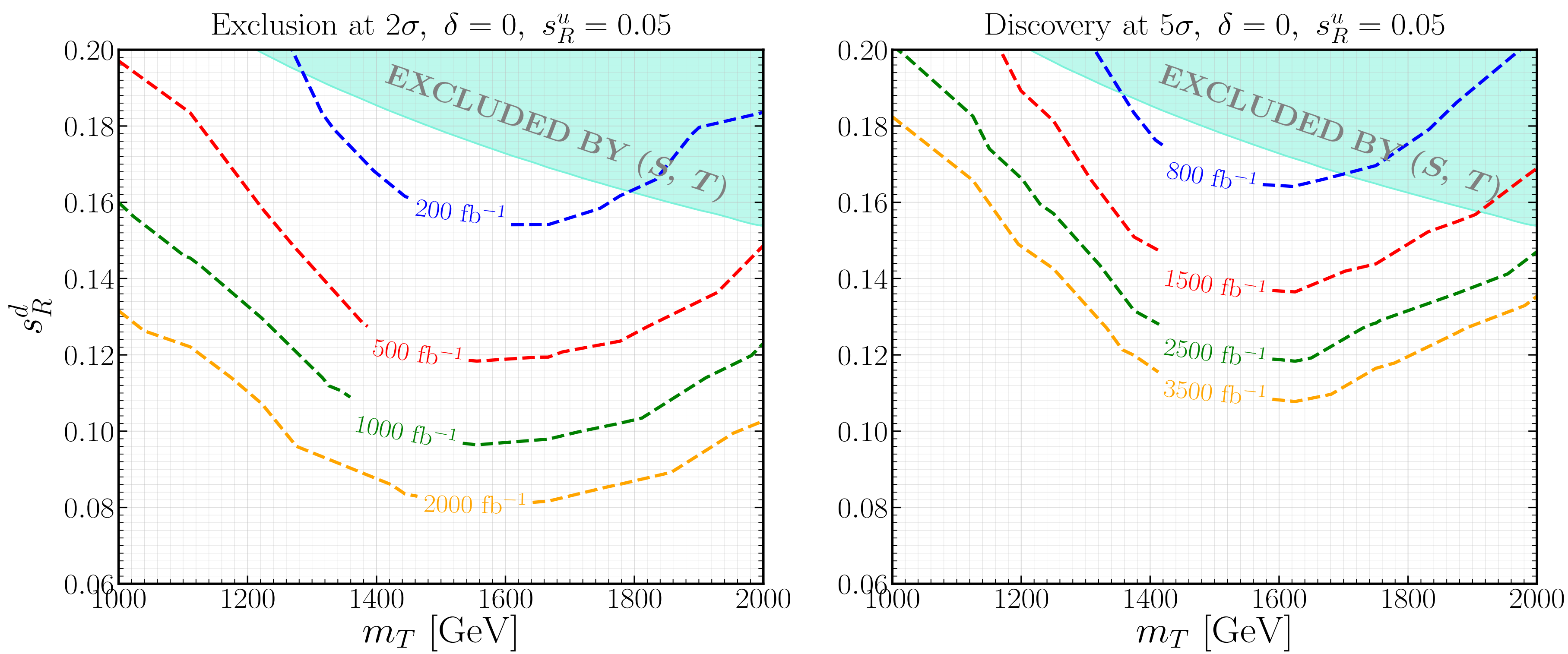
☆ **Significances**

The discovery significance, $\mathcal{Z}_{\rm disc}$, and the exclusion significance, $\mathcal{Z}_{\rm excl}$, are calculated using the following expressions:

$$\begin{aligned}
\mathcal{Z}_{\rm disc} &= \sqrt{2\left[(s+b)\ln\left(1+s/b\right)-s\right]}, \\
\mathcal{Z}_{\rm excl} &= \sqrt{2\left[s-b\ln\left(1+s/b\right)\right]}.
\end{aligned}$$

ANALYSIS

- The discovery prospects (at 5σ) and exclusion limit (at 2σ) contour plots for the signal in $m_T - \sin\theta_R^u$ planes at $\sqrt{s} = 14$ TeV LHC for different integrated luminosities. With $\sin\theta_R^u = 0.05$, $\tan\beta = 2.6$, $m_H \sim m_A \sim m_{H^\pm} = 600$ GeV, and $m_{12}^2 = m_A^2 \tan\beta / \left(1 + \tan\beta^2\right)$



HL-LHC $\sqrt{s} = 14$ TeV, $s_R^u = 0.05$			
$s_R^d(\mathcal{L}\ \text{fb}^{-1})$	2σ Exclusion	$s_R^d(\mathcal{L}\ \text{fb}^{-1})$	5σ Discovery
$s_R^d(200)$	$[0.16, 0.2]$	$s_R^d(800)$	$[0.165, 0.2]$
$s_R^d(500)$	$[0.12, 0.2]$	$s_R^d(1000)$	$[0.155, 0.2]$
$s_R^d(1000)$	$[0.10, 0.16]$	$s_R^d(2000)$	$[0.125, 0.2]$
$s_R^d(2000)$	$[0.08, 0.13]$	$s_R^d(3000)$	$[0.11, 0.19]$

Conclusion

- Contrary to the SM+VLQ, the $\mathcal{BR}$ of new top T may decay into $H^{\pm}b$.
- At $HL-LHC$, the $T \to H^{+}b$ decay mode has the potential to pave the way for new discoveries in physics beyond the Standard Model.

THANK YOU FOR LISTENING!