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LHC SIGNATURES OF A VECTOR-LIKE TOP PARTNER AND CHARGED HIGGS BOSON IN THE 2HDM-II

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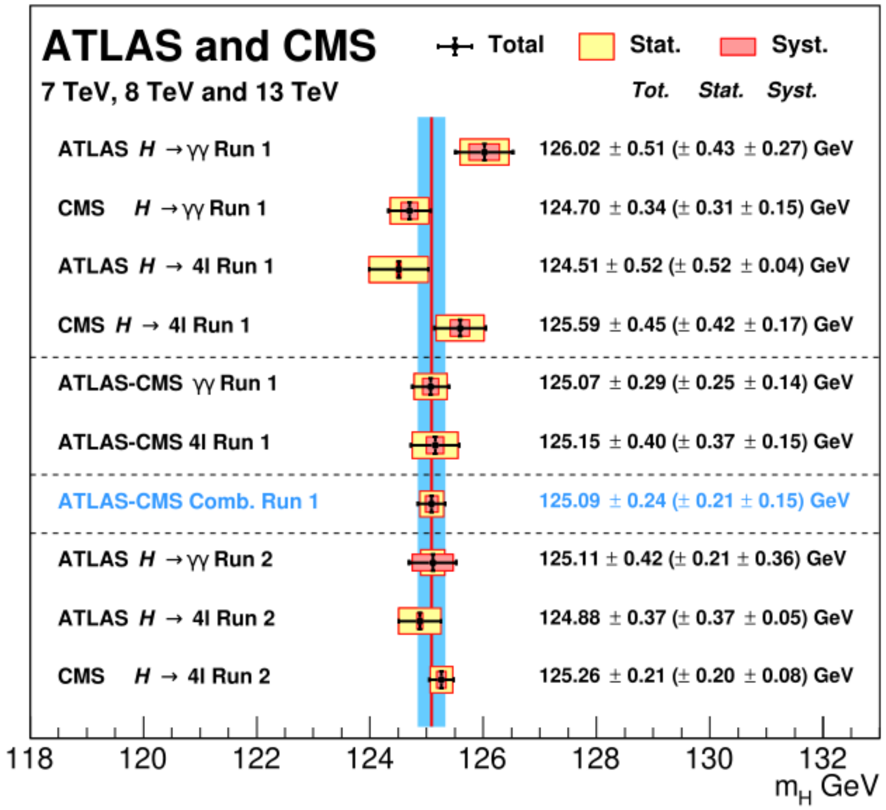
Outline

Motivation: Precision Higgs Physics and Beyond

- Precision measurements from ATLAS and CMS confirm the SM Higgs mass near 125 GeV.
- However, no additional scalars have been observed so far, the nature of the Higgs sector remains an open question.
- The Two-Higgs-Doublet Model (2HDM) is a well-motivated minimal extension of the scalar sector:
  - ★ Provides a richer scalar spectrum: $h, H, A, H^{\pm}$
  - ★ Enables LHC benchmark scenarios for both light and heavy Higgs bosons
- Such frameworks remain consistent with Higgs data and open avenues for discovering new particles.



ATLAS and CMS Higgs mass measurements (Run 1 and 2)

Motivation: Vector-Like Quarks (VLQs)

- VLQs are hypothetical colored fermions where left- and right-handed components transform identically under $SU(2)_L$.
- Their mass term $m\psi\bar{\psi}$ is gauge invariant and independent of electroweak symmetry breaking.
- VLQs can mix with SM quarks and couple to both neutral and charged Higgs bosons in extended Higgs sectors.
- VLQs are among the simplest BSM fermions still allowed by current collider constraints with unique decay signatures:

$$T \to tH,\ tZ,\ bW \qquad B \to bH,\ bZ,\ tW$$

- VLQs can appear in various representations 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

- Electric charges include: $Q_T = \frac{2}{3},\ Q_B = -\frac{1}{3},\ Q_X = \frac{5}{3},\ Q_Y = -\frac{4}{3}$

2HDM PARAMETRIZATION

The most general scalar potential of the 2HDM [Branco, G. et al. Phys.Rept. 516 (2012)] :

$$
\begin{aligned}
V(\Phi_1\Phi_2) = & \boldsymbol{m_{11}^2}\Phi_1^\dagger\Phi_1 + \boldsymbol{m_{22}^2}\Phi_2^\dagger\Phi_2 - \left[\boldsymbol{m_{12}^2}\Phi_1^\dagger\Phi_2 + \text{h.c.}\right] \\
& + \frac{\boldsymbol{\lambda_1}}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\boldsymbol{\lambda_2}}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \boldsymbol{\lambda_3}\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \boldsymbol{\lambda_4}\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) \\
& + \left\{\frac{\boldsymbol{\lambda_5}}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 + \left[\boldsymbol{\lambda_6}\left(\Phi_1^\dagger\Phi_1\right) + \boldsymbol{\lambda_7}\left(\Phi_2^\dagger\Phi_2\right)\right]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\}
\end{aligned}
\tag{1}
$$

with :

$$
\Phi_{1,2} = \begin{pmatrix} \phi_{1,2}^+ + i\varphi_{1,2}^+ \\ \frac{1}{\sqrt{2}}\left(v_{1,2} + \rho_{1,2} + i\eta_{1,2}\right) \end{pmatrix}
\tag{2}
$$

✦ The 10 independent parameters ($\boldsymbol{m_{11}^2},\ \boldsymbol{m_{22}^2},\ \boldsymbol{m_{12}^2},\ \boldsymbol{\lambda_{1,\ldots,7}}$) are assumed to be real. .

2HDM PARAMETRIZATION (Z_2 SYMMETRY)

- Introduced to avoid flavor-changing neutral currents (FCNCs) at tree level.
- Each Higgs doublet transforms under : $\Phi_1 \to \Phi_1$, $\Phi_2 \to -\Phi_2$.
  - **Type I**: One doublet couples to all fermions.
  - **Type II**: One doublet couples to up-type quarks, the other to down-type quarks and leptons.
  - **Lepton-specific (Type X)**: One doublet couples to quarks, the other to leptons.
  - **Flipped (Type Y)**: One doublet couples to up-type quarks and leptons, the other to down-type quarks.
- 2 minimization conditions and the combination $v_1^2 + v_2^2 = v^2 \implies$ **7** free parameters:

m_h, m_H, m_A, $m_{H^\pm}$, $s_{\beta-\alpha}$, $\tan\beta = \frac{v_2}{v_1}$ and $m_{1,2}^2$.

VECTOR-LIKE QUARK PARAMETRIZATION

- In the Higgs basis, the VLQ Yukawa Lagrangian reads:

$$\mathcal{L} \supset -y^u \bar{Q}_L^0 \tilde{H}_2 u_R^0 - y^d \bar{Q}_L^0 H_1 d_R^0 - M_u^0 \bar{u}_L^0 u_R^0 - M_d^0 \bar{d}_L^0 d_R^0 + \text{h.c.}$$

- Considering mixing between the top quark and a new vector-like partner T, the weak-to-mass basis transformation is:

$$\begin{pmatrix} t_{L,R} \\ T_{L,R} \end{pmatrix} = \begin{pmatrix} \cos\theta^u_{L,R} & -\sin\theta^u_{L,R} e^{i\phi_u} \\ \sin\theta^u_{L,R} e^{-i\phi_u} & \cos\theta^u_{L,R} \end{pmatrix} \begin{pmatrix} t^0_{L,R} \\ T^0_{L,R} \end{pmatrix}$$

- The mass Lagrangian (up- and down-type) in the weak basis is:

$$\mathcal{L}_{\text{mass}} = -\begin{pmatrix} \bar{t}_L^0 & \bar{T}_L^0 \end{pmatrix} \begin{pmatrix} y^u_{33}\frac{v}{\sqrt{2}} & y^u_{34}\frac{v}{\sqrt{2}} \\ y^u_{43}\frac{v}{\sqrt{2}} & M^0 \end{pmatrix} \begin{pmatrix} t^0_R \\ T^0_R \end{pmatrix} + \text{h.c.}$$

  (Similar structure applies to the down sector for b–B mixing.)

- The matrix is diagonalized via:

$$U_L^q \, \mathcal{M}^q \, (U_R^q)^\dagger = \mathcal{M}^q_{\text{diag}}$$

- Depending on the VLQ representation:

$$\tan\theta_R^q = \frac{m_q}{m_Q} \tan\theta_L^q \qquad \text{(singlet)}$$
$$\tan\theta_L^q = \frac{m_q}{m_Q} \tan\theta_R^q \qquad \text{(doublet)}$$

Parametrization & Yukawa Sector

- All VLQ representations can be parametrized by only two free parameters, except the TB doublet which requires three:

Representation	T	B	TB	XT	BY	TBY	XTB
Parameters	m_T, s^u_L	m_B, s^d_L	m_T, s^u_R, s^d_R	m_T, s^u_R	m_B, s^d_R	m_T, s^u_L	m_T, s^u_L

- Charged Higgs interactions (H^+tb and H^+Tb):

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

In the 2HDM-II+TB scenario:

$$Z^L_{tb} = c^d_L c^u_L + \frac{s^d_L}{s^u_L}({s^u_L}^2 - {s^u_R}^2)e^{i(\phi_u-\phi_d)}$$

$$Z^R_{tb} = \frac{m_b}{m_t}\left[c^u_L c^d_L + \frac{s^u_L}{s^d_L}({s^d_L}^2 - {s^d_R}^2)e^{i(\phi_u-\phi_d)}\right]$$

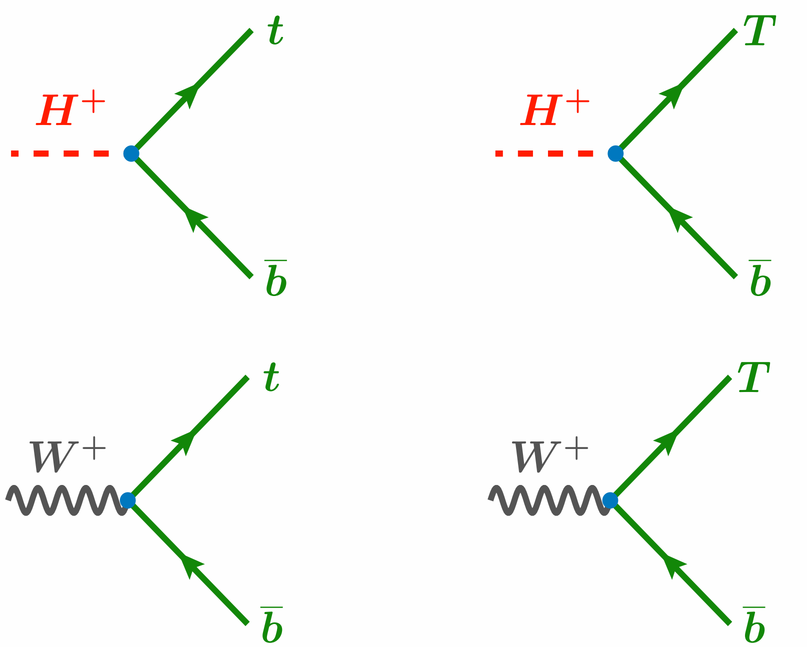
$$Z^L_{Tb} = c^d_L s^u_L e^{-i\phi_u} + ({s^u_L}^2 - {s^u_R}^2)\frac{s^d_L}{c^u_L}e^{-i\phi_d}$$

$$Z^R_{Tb} = \frac{m_b}{m_T}\left[c^d_L s^u_L e^{-i\phi_u} + ({s^d_R}^2 - {s^d_L}^2)\frac{c^u_L}{s^d_L}e^{-i\phi_d}\right]$$

- W^+ boson interaction (W^+Tb):

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}\overline{T}\gamma^\mu(V^L_{Tb}P_L + V^R_{Tb}P_R)bW^+_\mu + \text{h.c.}$$

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



CONSTRAINTS

Theoretical

- **Unitarity** The variety of scattering process must be unitary.
- **Perturbativity** constraints impose the following condition on the quartic couplings of the scalar potential: $|\lambda_i| < 8\pi$
- **Vacuum stability** constraints require the potential to be bounded from below and positive in any direction of the fields Φ_i, consequently, the parameter space must satisfy the following conditions:

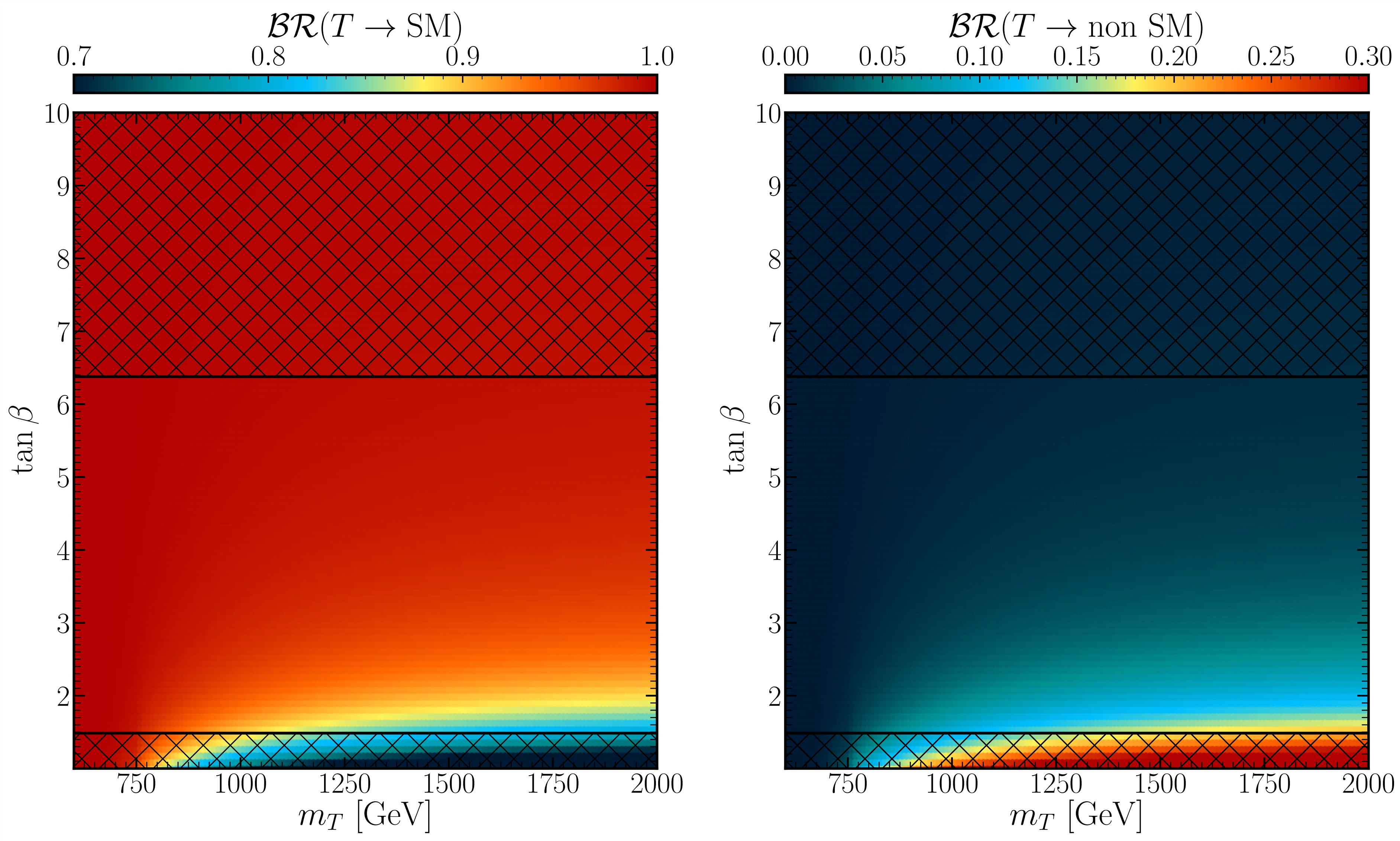
$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2},$$
$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2}.$$

2HDMC-1.8.0 (D. Eriksson, J. Rathsman and O. Stal [0902.0851])

Experimental

- **EWPOs**, implemented through the EW oblique parameters S, T, we require $\Delta\chi^2(S^{VLQ} + S^{2HDM},\ T^{VLQ} + T^{2HDM}) \leq 6.18$.
- **SM-like Higgs boson discovery**: an agreement between selected points in parameter space and the current measurements of the properties of the discovered Higgs boson at 125 GeV is enforced by means of the publicly available code `HiggsSignals-3` via `HiggsTools`.
- **Non-SM-like Higgs boson exclusions**: to check the parameter space points against the exclusion limits from BSM Higgs boson searches at LEP, Tevatron and, the LHC, we apply the public code `HiggsBounds-6` via `HiggsTools` .
- **B-physics observables** are tested against data by resorting to the public code `SuperIso_v4.1`, (mainly $B \to X_s\gamma,\ B_{s,d} \to \mu^+\mu^-$ and $B_s \to \tau\nu$).
- **Direct search constraints from the LHC for VLQs**: The current LHC limits mainly target the SM decay modes of VLQs and are addressed by a dedicated code, which will be publicly available soon: R. Benbrik, M. Boukidi, M. Ech-chaouy, S. Moretti and K. Salime, JHEP 03 (2025)

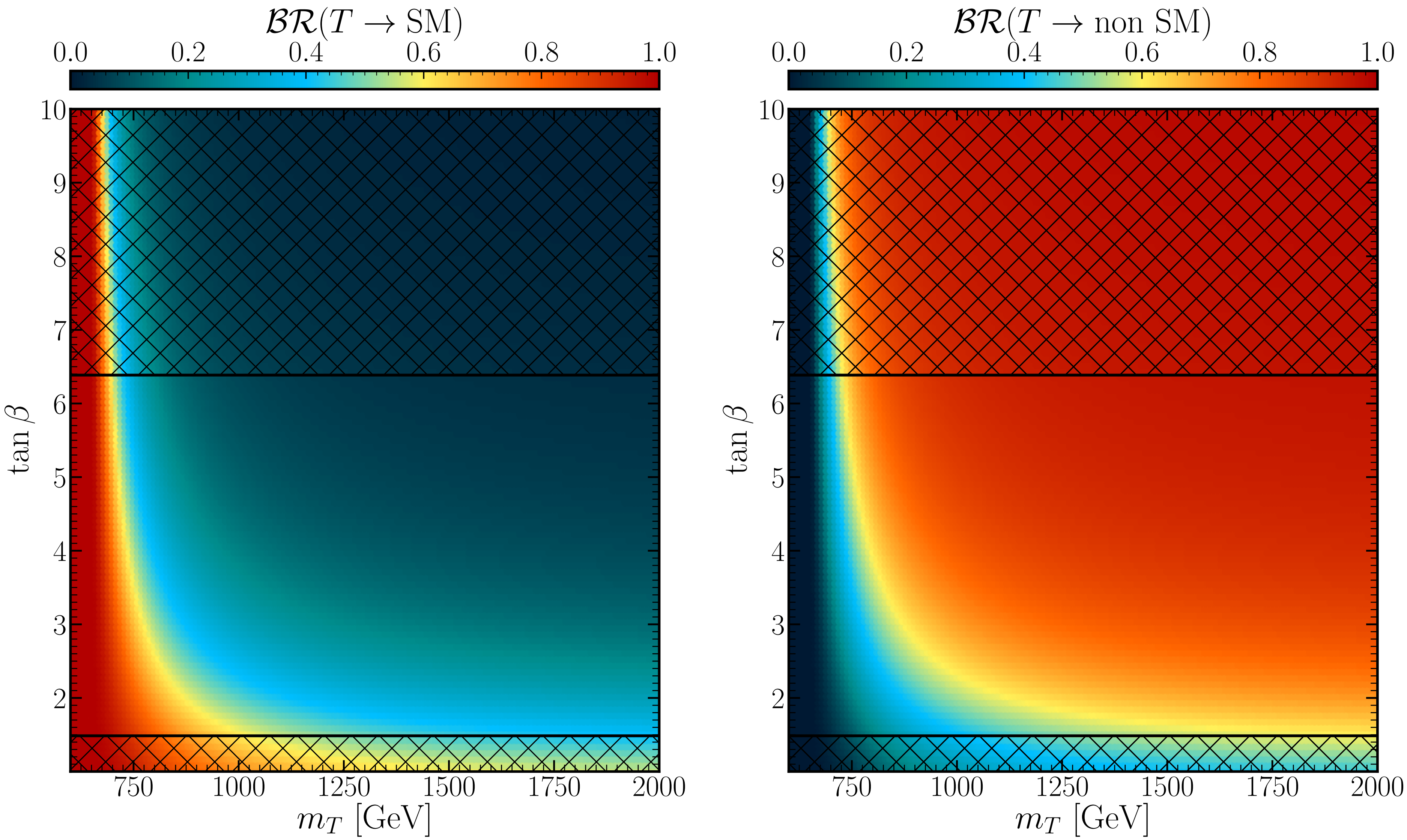
2HDM-II+T Singlet Scenario



- BRs of T in the $(m_T, \tan\beta)$ plane for a singlet T under $SU(2)_L$
- SM channels dominate: $T \to tZ, th, bW$
- Exotic decays are suppressed in this representation

`Arhrib, Benbrik, Boukidi, Manaut, Moretti Eur.Phys.J.C 85 (2025) 1, 2`

2HDM-II+TB DOUBLET SCENARIO



- Same parameter scan, now for a (T, B) doublet
- Dominant decay modes: $T \to Ht$, At, H^+b
- These exotic modes are enhanced due to the doublet Yukawa structure
- LHC searches focused only on SM final states could miss this scenario

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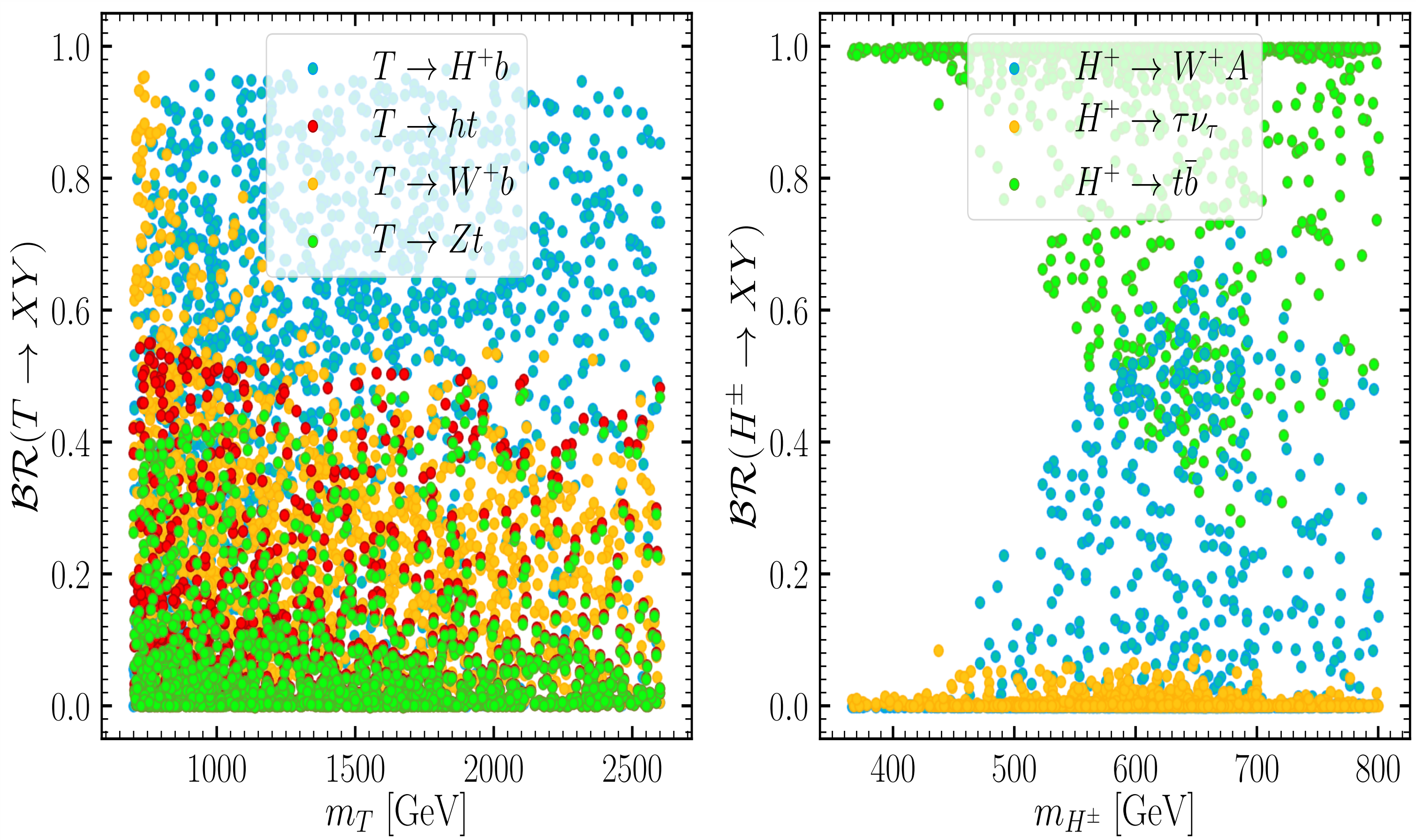
2HDM-II+TB Doublet Scenario

Parameters	Scanned ranges
2HDM	
m_H	$[130, 800]$
m_A	$[80, 800]$
$m_{H^\pm}$	$[80, 800]$
$\tan\beta$	$[0.5, 20]$
$\sin(\beta-\alpha)$	1
2HDM-II+(TB)	
$s_R^{u,d}$	$[-0.5, 0.5]$
m_T	$[750, 2600]$

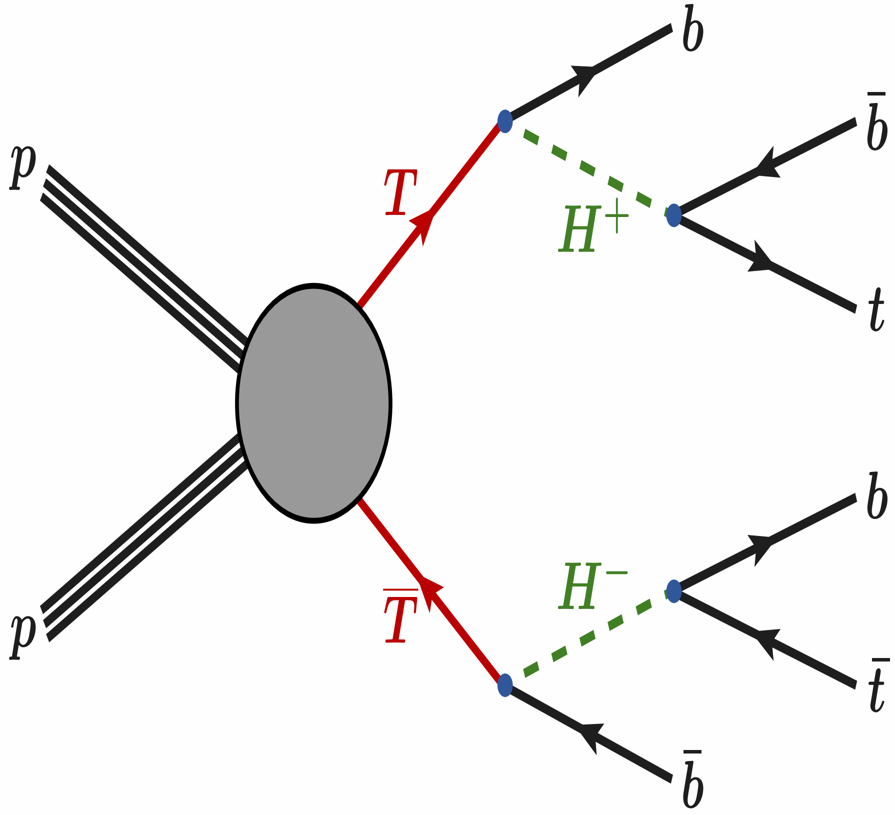


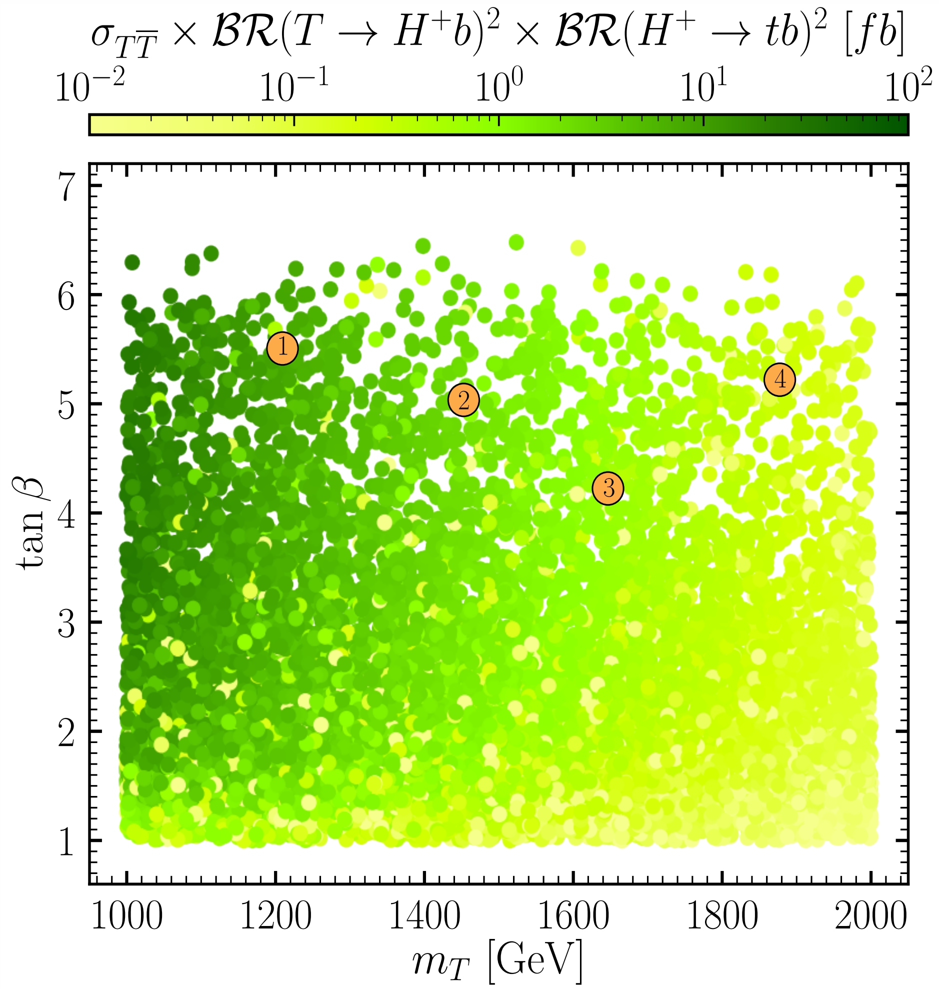
MC SIMULATION

- Two complementary collider studies in this work:
  - ★ Multi–b-jet analyses: $4b$ and $5b$ final states from $T\bar{T} \to H^+ b\, H^- \bar{b}$.
  - ★ Dilepton + multi–b-jet analysis: $l^+ l^- + 6b + \not{E}_T$.

- Simulation pipeline:
  - ★ `MadGraph5@NLO` - Event generation .
  - ★ `Pythia8` - Parton showering and hadronization.
  - ★ `Delphes` - Fast detector simulation.
  - ★ `FastJet` - Jet clustering .
  - ★ `MadAnalysis5` - Cut-based analysiss.

Pair Production of VLT with $T \to H^+ b$ at the LHC





- ✩ Feynman diagrams for $pp \to T\bar{T}$ and decays leading to $4b + 2t$.
- ✩ Signal: $pp \to T\bar{T} \to (bH^+)(\bar{b}H^-) \to (b(tb))(\bar{b}(\bar{t}b))$.
- ✩ Signal regions: $N(b) \geq 4$ and $N(j) \geq 8$, $N(b) \geq 5$ and $N(j) \geq 8$.
- ✩ Main backgrounds: $t\bar{t}t\bar{t}(j)$, $t\bar{t}b\bar{b}j$, $4b\,j$, and $2b$ jets.

- ✩ $\sigma_{TT} \times \mathcal{BR}(T \to H^+ b)^2 \times \mathcal{BR}(H^+ \to t\bar{b})^2$ vs. m_T and $\tan\beta$ in 2HDM-II+TB. Orange circles mark the selected BPs.

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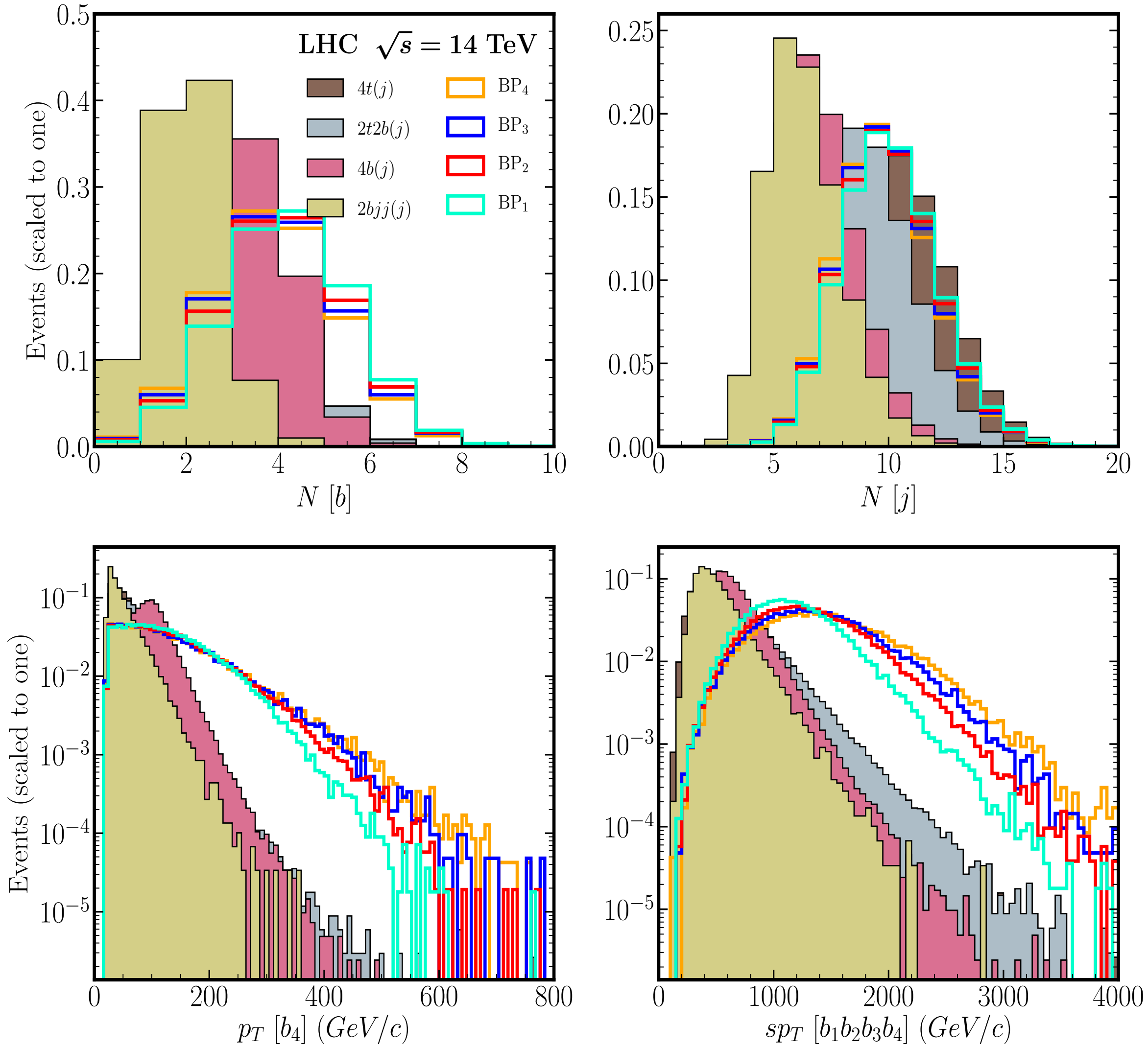


✯ Distributions of $N(b)$, $N(j)$, $p_T(b_4)$, and $sp_T(b_1b_2b_3b_4)$ for BPs (BP_1–BP_4) and backgrounds at $\sqrt{s} = 14$ TeV.

Cuts	Definition
Cut 1	$N(b) \geq 4$, $N(j) \geq 8$
Cut 2	$sp_T > 1400$ GeV
Cut 3	$p_T^{b_4} > 140$ GeV

✯ Cut set for signal/background at $\sqrt{s} = 14$ TeV.

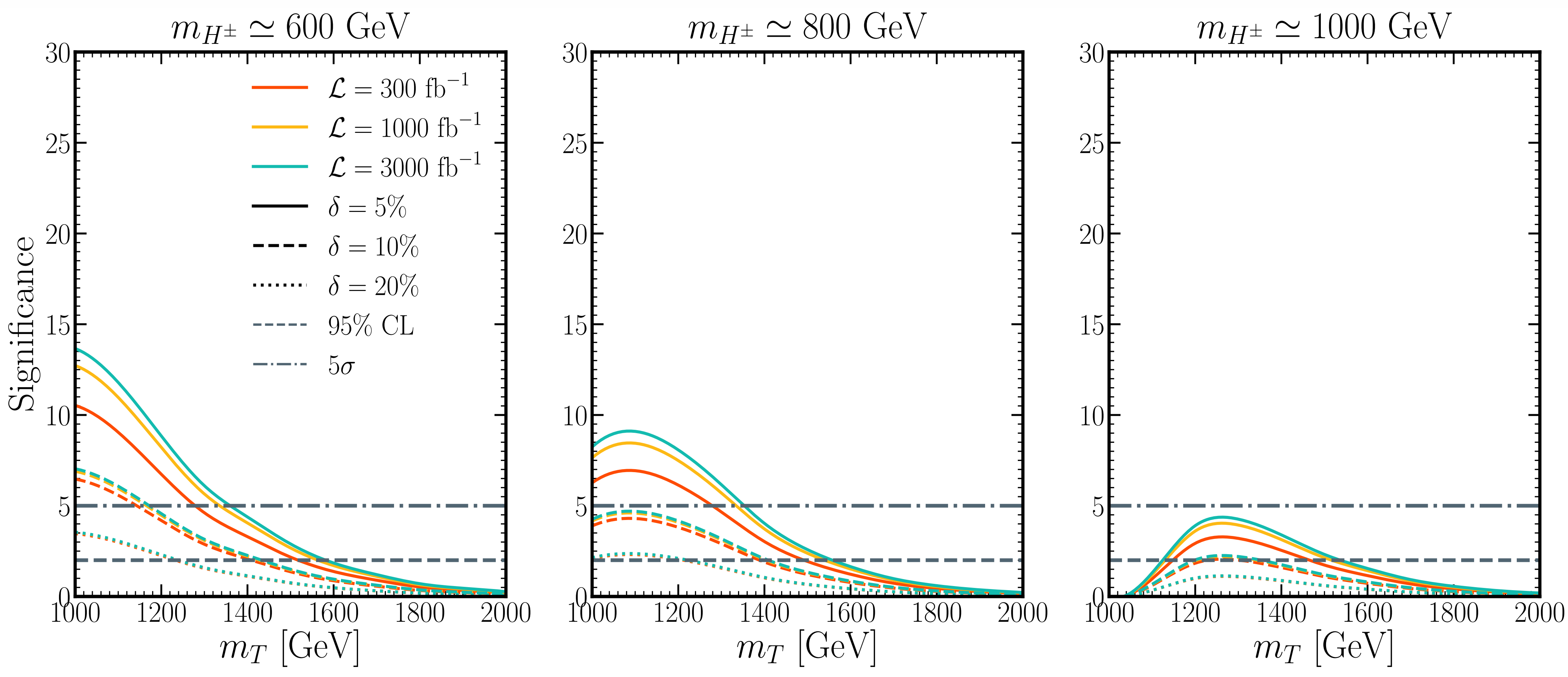
Cuts	Signals				Backgrounds			
	BP1	BP2	BP3	BP4	2bjets	$4bj$	$2t2bj$	$4tj$
Basic	10.36	1.95	0.819	0.28324072577.74			202.56	16.60
Cut 1	4.41	0.760	0.31	0.0931005.2022.9			29.60	3.07
Cut 2	1.00	0.272	0.13	0.045.60		0.33	0.543	0.033
Cut 3	0.67	0.168	0.08	0.026.96		0.179	0.18	0.008
Efficiency	6.48%	8.83%	9.70%	9.74%2.93 ×	10^{-6}	2.45×10^{-4}	9.39×10^{-4}	4.94×10^{-4}

✯ Cutflow of cross sections (fb) for signal and SM backgrounds at $\sqrt{s} = 14$ TeV.

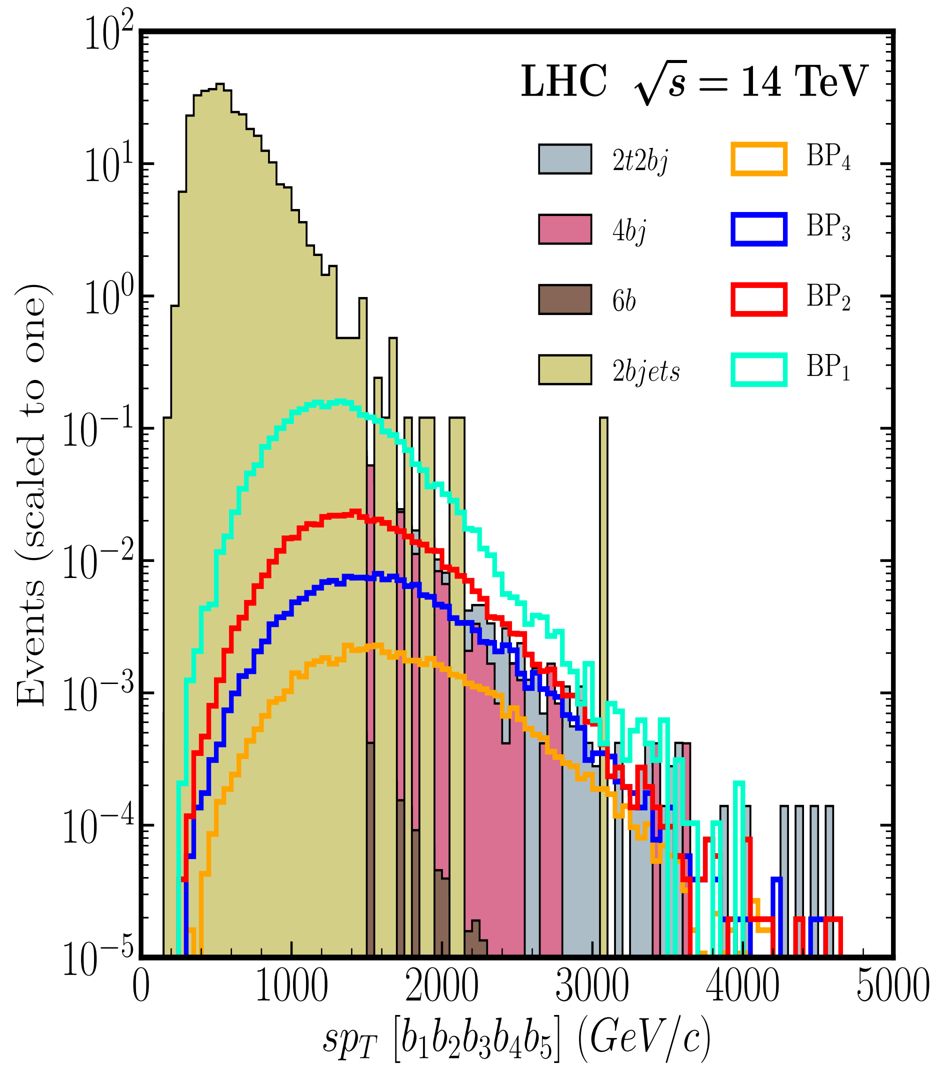
4b Analysis

m_T [GeV]	$\mathcal{L} = 300$ fb^{-1}			$\mathcal{L} = 1000$ fb^{-1}			$\mathcal{L} = 3000$ fb^{-1}		
	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$
1000.0	10.53	6.47	3.47	12.73	6.90	3.53	13.66	7.04	3.55
1100.0	9.05	5.58	2.99	10.97	5.96	3.05	11.79	6.08	3.06
1200.0	6.74	4.18	2.25	8.21	4.47	2.29	8.85	4.56	2.30
1300.0	4.61	2.88	1.55	5.65	3.08	1.58	6.10	3.15	1.59
1400.0	3.30	2.06	1.11	4.05	2.22	1.14	4.38	2.27	1.14
1500.0	2.17	1.36	0.74	2.67	1.46	0.75	2.90	1.50	0.76
1600.0	1.38	0.87	0.47	1.70	0.93	0.48	1.85	0.95	0.48
1700.0	0.90	0.56	0.31	1.11	0.61	0.31	1.20	0.62	0.31
1800.0	0.52	0.33	0.18	0.65	0.36	0.18	0.70	0.36	0.18
1900.0	0.34	0.21	0.12	0.42	0.23	0.12	0.46	0.24	0.12
2000.0	0.20	0.12	0.07	0.24	0.13	0.07	0.26	0.14	0.07

- Discovery significance $\mathcal{Z}_{disc}$ for the 4b analysis shown for different systematics (δ) and integrated luminosities $\mathcal{L} = 300, 1000, 3000$ fb^{-1}.
- Fixed parameters: $m_H = 600.26$ GeV, $m_A = 595.24$ GeV, $m_{H^\pm} = 658.07$ GeV, $\tan\beta = 6$, $s_R^u = 0.05$, $s_R^d = 0.11$.
- Significance vs. m_T for $m_{H^\pm} = 600$ GeV (left), 800 GeV (center), and 1000 GeV (right).



$5b$ Analysis



✩ sp_T distribution for BPs and backgrounds in the $5b$ analysis.

✩ Cut set for signal/background at $\sqrt{s} = 14$ TeV.

Cuts	Definition
Cut 1	$N(b) \geq 5$, $N(j) \geq 8$
Cut 2	$sp_T > 1500$ GeV
Cut 3	$p_T^{b_4} > 120$ GeV

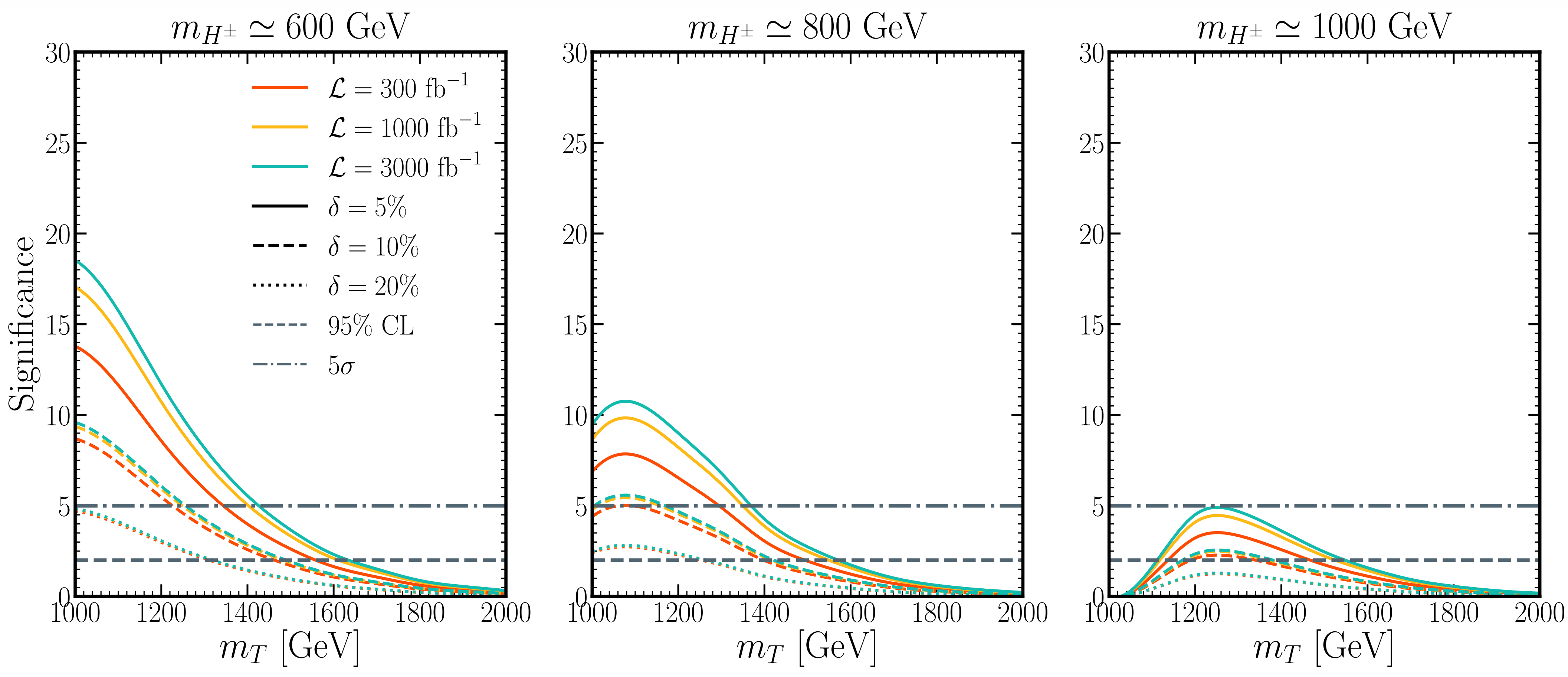
✩ Cutflow of cross sections (fb) for signals and SM backgrounds at $\sqrt{s} = 14$ TeV for the three typical BPs.

Cuts	Signals				Backgrounds			
	BP1	BP2	BP3	BP4	$2b$jets	$4bj$	$2t2bj$	$6b$
Basic	10.36	1.95	0.82	0.28	324073	727.74	202.56	0.14
Cut 1	2.76	0.47	0.18	0.054	241.7	16.4	10.21	0.040
Cut 2	0.84	0.21	0.096	0.032	0.84	0.18	0.28	0.0015
Cut 3	0.73	0.18	0.08	0.026	0.722	0.145	0.18	0.0013
Efficiency	7.09%	9.17%	9.75%	9.73%	2.23×10^{-6}	1.99×10^{-4}	8.81×10^{-4}	9.40×10^{-3}

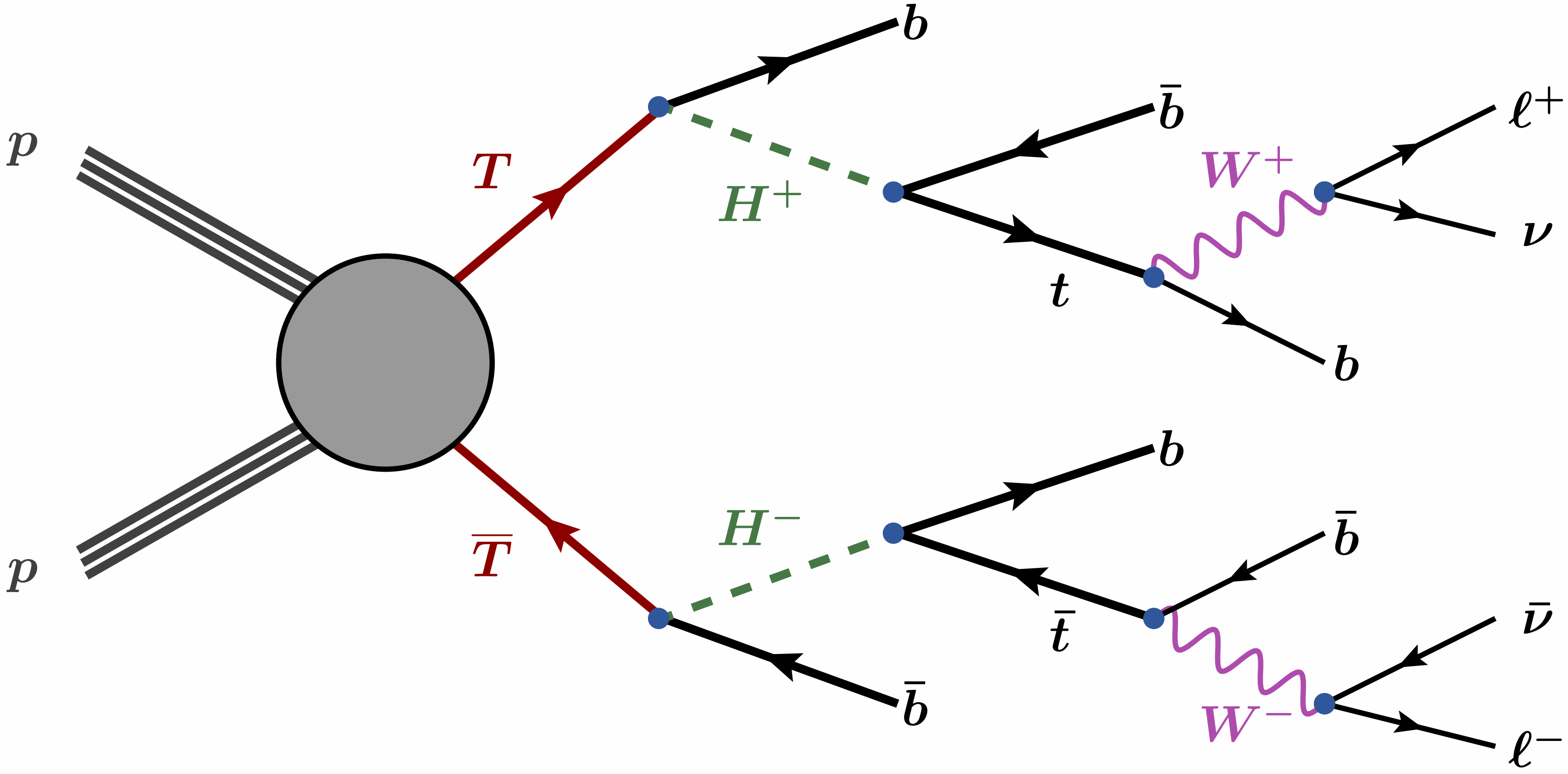
$5b$ Analysis

m_T [GeV]	$\mathcal{L} = 300$ fb^{-1}			$\mathcal{L} = 1000$ fb^{-1}			$\mathcal{L} = 3000$ fb^{-1}		
	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$
1000.0	13.79	8.69	4.71	17.06	9.37	4.81	18.53	9.60	4.84
1100.0	11.65	7.38	4.01	14.47	7.97	4.10	15.75	8.17	4.12
1200.0	8.57	5.47	2.98	10.72	5.93	3.05	11.71	6.08	3.07
1300.0	5.93	3.81	2.09	7.47	4.15	2.14	8.19	4.26	2.15
1400.0	3.99	2.58	1.42	5.05	2.81	1.45	5.55	2.89	1.46
1500.0	2.62	1.70	0.94	3.33	1.86	0.96	3.67	1.91	0.97
1600.0	1.65	1.07	0.59	2.10	1.17	0.61	2.32	1.21	0.61
1700.0	1.07	0.70	0.39	1.37	0.77	0.40	1.51	0.79	0.40
1800.0	0.62	0.41	0.22	0.80	0.45	0.23	0.88	0.46	0.23
1900.0	0.39	0.26	0.14	0.50	0.28	0.15	0.55	0.29	0.15
2000.0	0.22	0.15	0.08	0.29	0.16	0.08	0.32	0.17	0.08

- Discovery significance $\mathcal{Z}_{disc}$ for the $5b$ analysis shown for different systematics (δ) and luminosities ($\mathcal{L} = 300,\ 1000,\ 3000$ fb^{-1}).
- Fixed parameters: $m_H = 600.26$ GeV, $m_A = 595.24$ GeV, $m_{H^\pm} = 658.07$ GeV, $\tan\beta = 6$, $s_R^u = 0.05$, $s_R^d = 0.11$.
- Significance vs. m_T for $m_{H^\pm} = 600$ GeV (left), 800 GeV (center), and 1000 GeV (right).



Final state with multiple b-jets and opposite-sign dilepton



- Feynman diagrams for $T\bar{T}$ pair production with subsequent decays into opposite-sign dileptons, multiple b-jets, and missing transverse energy from neutrinos.

- Signal: $l^+ + l^- + 6b + \not{E}_T$

- Backgrounds: $t\bar{t}b\bar{b}(j)$, $t\bar{t}$+jets, $t\bar{t}W(j)$, $t\bar{t}Z(j)$, $t\bar{t}h(j)$, $t\bar{t}t\bar{t}$

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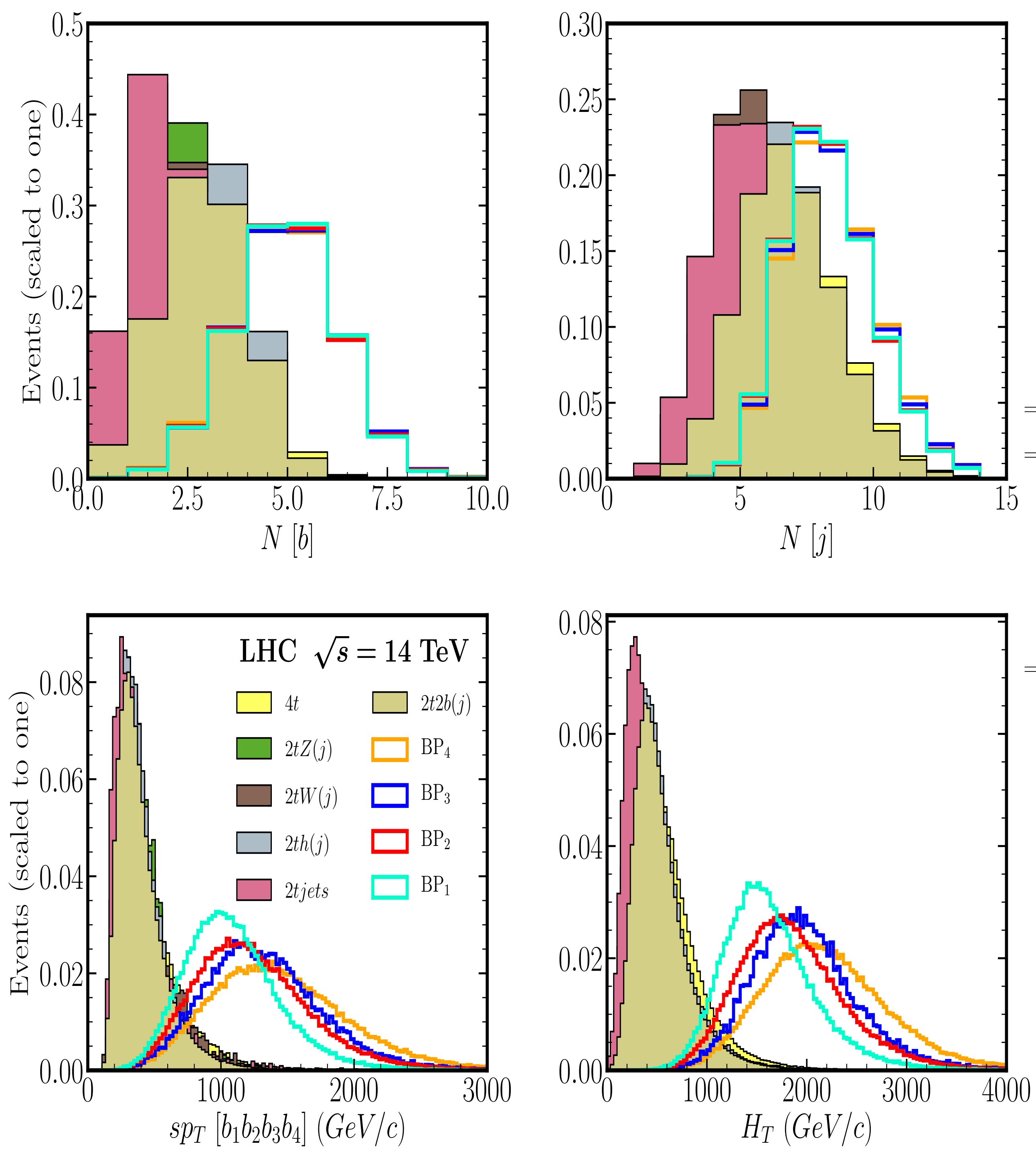
Results



- Distributions of $N(b)$, $N(j)$, $sp_T(b_1b_2b_3b_4)$, and H_T for signal benchmarks (BP_1–BP_4) and backgrounds at $\sqrt{s} = 14$ TeV.
- Event selection cuts applied at $\sqrt{s} = 14$ TeV:

Cuts	Definition
Cut 1	$N(b) \geq 4$, $N(j) \geq 5$, $N(l^-) = 1$, $N(l^+) = 1$
Cut 2	$p_T(l^\pm) > 20$ GeV
Cut 3	$p_T(b_1) > 300$ GeV, $p_T(b_4) > 40$ GeV
Cut 4	$sp_T > 900$ GeV
Cut 5	$H_T > 1500$ GeV

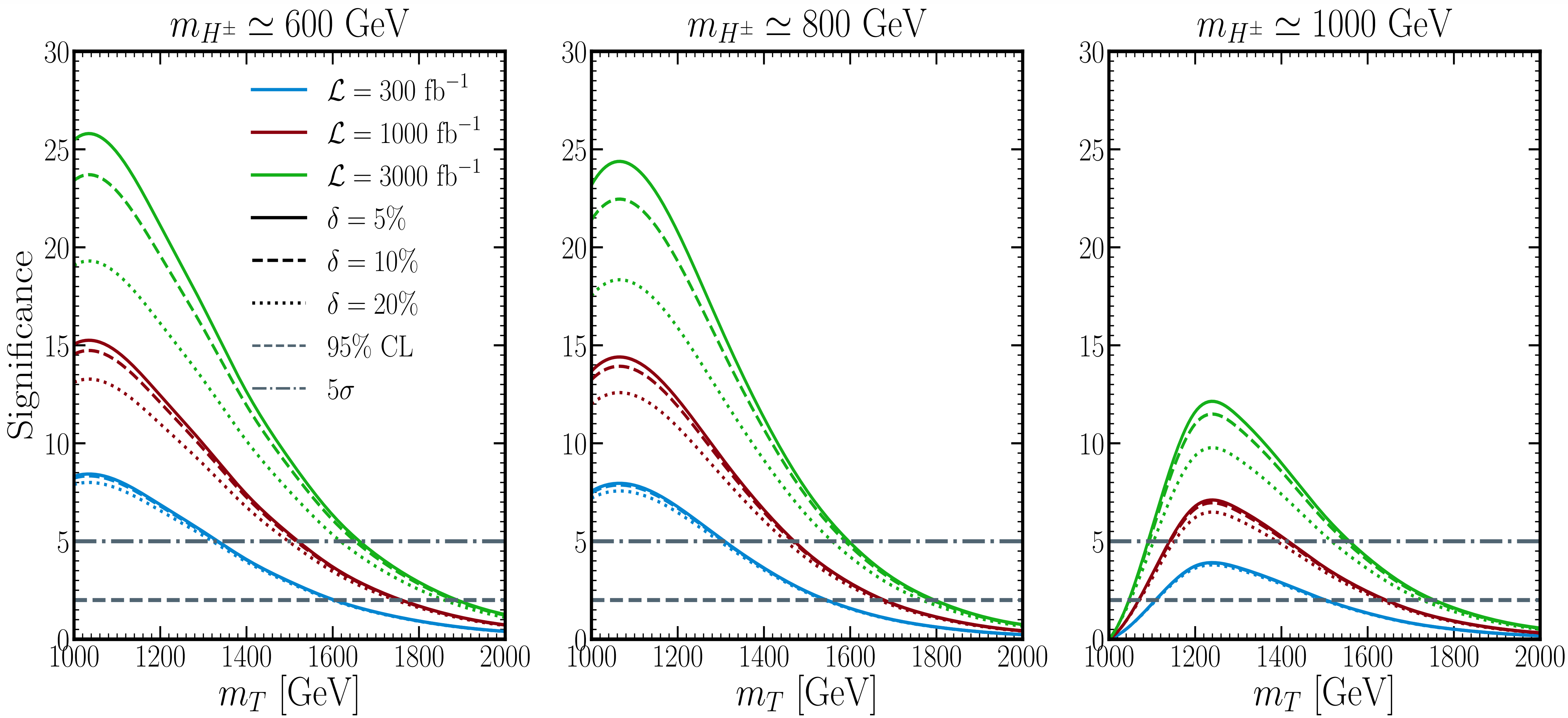
RESULTS

Cuts	Signals				Backgrounds					
	$BP1$	$BP2$	$BP3$	$BP4$	$2t2b(j)$	$2t$+jets	$2tW(j)$	$2tZ(j)$	$2th(j)$	$4t$
Basic	33.8	7.3	6.0	0.84	5828	467702	43621	3463	2419	305
Cut1	7.34	1.59	1.26	0.18	31.3	105.6	0.10	3.13	11.1	3.16
Cut2	6.29	1.36	1.11	0.16	26.5	81.9	0.08	2.48	9.90	2.53
Cut3	5.34	1.25	1.02	0.15	2.37	5.45	0.01	0.21	0.65	0.42
Cut4	4.57	1.12	0.96	0.14	0.53	1.81	0.002	0.09	0.14	0.15
Cut5	3.24	0.95	0.88	0.13	0.14	0	0.002	0	0	0.07
Eff.	9.6%	13.0%	14.7%	15.5%	2.4×10^{-5}	0	4.1×10^{-8}	0	0	1.7×10^{-4}

- ✩ Cutflow for signals and backgrounds at $\sqrt{s} = 14$ TeV; cross sections in 10^{-2} fb.
- ✩ $\mathcal{Z}_{disc}$ shown for several systematics δ and luminosities $300,\ 1000,\ 3000\ fb^{-1}$.
- ✩ $m_H = 600.3$ GeV, $m_A = 595.2$ GeV, $m_{H^\pm} = 658.1$ GeV, $\tan\beta = 6$, $s_R^u = 0.05$, $s_R^d = 0.11$.

m_T [GeV]	$\mathcal{L} = 300$ fb^{-1}			$\mathcal{L} = 1000$ fb^{-1}			$\mathcal{L} = 3000$ fb^{-1}		
	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$	$\delta = 5\%$	$\delta = 10\%$	$\delta = 20\%$
1000.0	8.32	8.22	7.90	15.05	14.54	13.11	25.47	23.41	19.08
1100.0	8.11	8.02	7.71	14.67	14.18	12.80	24.83	22.85	18.65
1200.0	6.87	6.80	6.57	12.44	12.08	10.99	21.12	19.58	16.13
1300.0	5.49	5.45	5.28	9.96	9.71	8.93	16.96	15.86	13.23
1400.0	4.07	4.05	3.95	7.40	7.24	6.74	12.63	11.94	10.13
1500.0	2.95	2.93	2.87	5.36	5.27	4.95	9.18	8.75	7.54
1600.0	2.03	2.02	1.99	3.69	3.64	3.45	6.33	6.08	5.33
1700.0	1.38	1.38	1.36	2.52	2.49	2.38	4.33	4.18	3.72
1800.0	0.93	0.93	0.92	1.69	1.68	1.61	2.91	2.82	2.54
1900.0	0.61	0.61	0.60	1.11	1.10	1.06	1.90	1.85	1.68
2000.0	0.40	0.40	0.40	0.73	0.73	0.70	1.26	1.23	1.12

RESULTS



- Discovery significance $\mathcal{Z}_{disc}$ as a function of m_T for three charged Higgs benchmark masses: $m_{H^\pm} = 600$ GeV (left), 800 GeV (center), 1000 GeV (right).
- Results shown for different systematic uncertainties (δ) and luminosities ($\mathcal{L} = 300, 1000, 3000$ fb^{-1}).
- Parameters fixed to $m_H \simeq m_A \simeq m_{H^\pm}$, $\tan\beta = 5$, $s_R^u = 0.05$, $s_R^d = 0.11$.

CONCLUSIONS

- We studied the pair production of vector-like top quarks (T) in the 2HDM-II+TB scenario, focusing on the decay channel $T \to H^+ b$.
- Two complementary analyses were performed:
  - Hadronic final states with multi-b jets ($4b$, $5b$).
  - Opposite-sign dilepton final states with multiple b jets.
- Discovery significances $\mathcal{Z}_{disc}$ show strong prospects, reaching multi-TeV m_T scales at high luminosities (HL-LHC).
- These results demonstrate that exotic decays of VLQs into charged Higgs bosons provide viable discovery channels beyond the traditional W, Z, and h searches.