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

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THE 22ND WORKSHOP OF THE LHC HIGGS WORKING GROUP

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Outline

1 Introduction

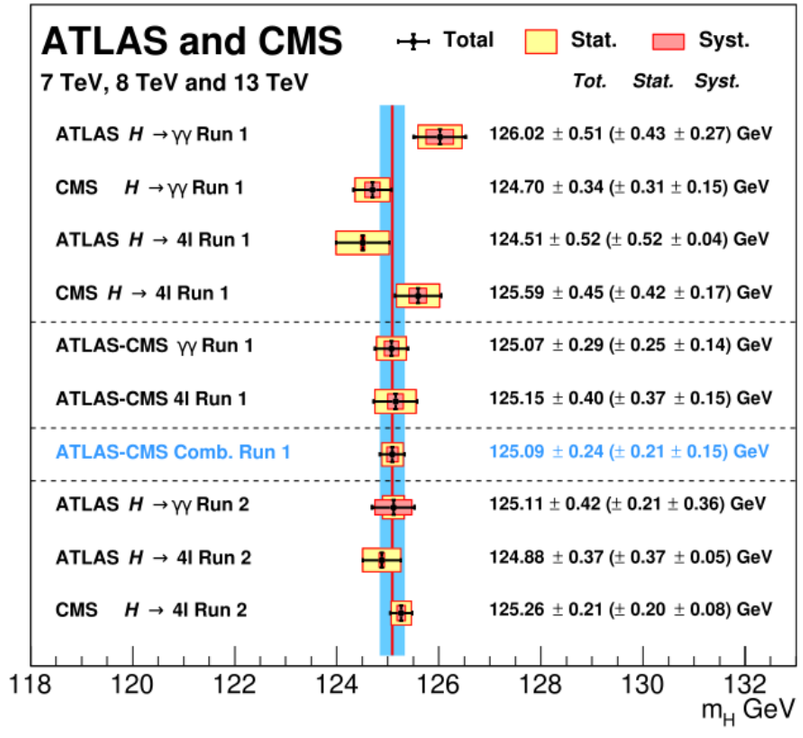
2 Framework

3 Numerical results

4 Conclusions

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)

2HDM SETUP

✦ We extend the SM scalar sector by two $SU(2)_L$ doublets:

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ \frac{1}{\sqrt{2}}(v_i + \rho_i + i\eta_i) \end{pmatrix}, \qquad i = 1, 2, \qquad v^2 = v_1^2 + v_2^2 = (246\ GeV)^2, \quad \tan\beta = \frac{v_2}{v_1}.$$

✦ **General scalar potential** [Branco *et al.*, Phys.Rept. 516 (2012)]

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

★ Throughout this talk we work in the CP-conserving setup, hence all parameters are taken real.

★ At this stage the potential contains **10 real inputs**: $\{m_{11}^2, m_{22}^2, m_{12}^2, \lambda_{1\ldots7}\}$.

YUKAWA STRUCTURE & Z_2 SYMMETRY

- A generic 2HDM Yukawa sector induces tree-level FCNCs if both Φ_1 and Φ_2 couple to the same fermion species.
- We impose Natural Flavour Conservation through a discrete symmetry

$$\Phi_1 \to \Phi_1, \qquad \Phi_2 \to -\Phi_2,$$

  which sets $\lambda_{6,7} = 0$ and allows only a **soft** breaking via m_{12}^2.
- This leads to the standard Yukawa types (I, II, X, Y); **here we adopt Type-II:**

$$\Phi_2 \text{ couples to up-type quarks}, \qquad \Phi_1 \text{ to down-type quarks and leptons}.$$

- After EWSB and using the minimization conditions, a convenient physical parametrization is

$$\boxed{m_h,\ m_H,\ m_A,\ m_{H^\pm},\ \tan\beta,\ \sin(\beta-\alpha),\ m_{12}^2}\,.$$

- **Assumption (alignment):** the observed Higgs is the **light CP-even state,**

$$\sin(\beta-\alpha) = 1, \qquad h \equiv h_{125}, \qquad m_h \simeq 125\ GeV,$$

  so we scan $(m_H, m_A, m_{H^\pm}, \tan\beta, m_{12}^2)$ (and VLQ parameters later).

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

PARAMETRIZATION OF VLQS

- 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:

$$\begin{pmatrix} t_{L,R} \\ T_{L,R} \end{pmatrix} = \begin{pmatrix} \cos\theta_{L,R}^u & -\sin\theta_{L,R}^u e^{i\phi_u} \\ \sin\theta_{L,R}^u e^{-i\phi_u} & \cos\theta_{L,R}^u \end{pmatrix} \begin{pmatrix} t_{L,R}^0 \\ T_{L,R}^0 \end{pmatrix}$$

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

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

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

- The matrix is diagonalized via:

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

- 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_L^u	m_B, s_L^d	m_T, s_R^u, s_R^d	m_T, s_R^u	m_B, s_R^d	m_T, s_L^u	m_T, s_L^u

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

$$\mathcal{L}_{H^+} = -\frac{gm_T}{\sqrt{2}M_W}\overline{T}(\cot\beta Z_{Tb}^L P_L + \tan\beta Z_{Tb}^R P_R)bH^+ - \frac{gm_t}{\sqrt{2}M_W}\bar{t}(\cot\beta Z_{tb}^L P_L + \tan\beta Z_{tb}^R P_R)bH^+ + \text{h.c.}$$

2HDM-II + TB scenario

$$Z_{tb}^L = c_L^d c_L^u + \frac{s_L^d}{s_L^u}(s_L^{u\,2} - s_R^{u\,2})e^{i(\phi_u-\phi_d)}$$

$$Z_{tb}^R = \frac{m_b}{m_t}\left[c_L^u c_L^d + \frac{s_L^u}{s_L^d}(s_L^{d\,2} - s_R^{d\,2})e^{i(\phi_u-\phi_d)}\right]$$

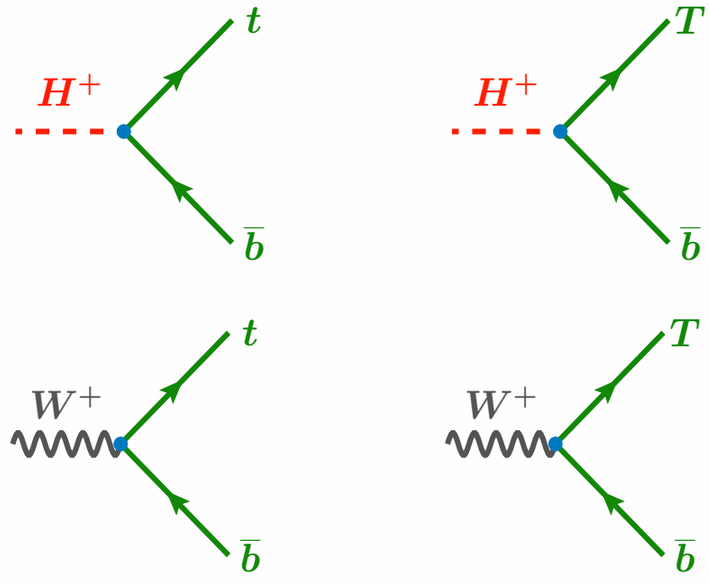
$$Z_{Tb}^L = c_L^d s_L^u e^{-i\phi_u} + (s_L^{u\,2} - s_R^{u\,2})\frac{s_L^d}{c_L^u}e^{-i\phi_d}$$

$$Z_{Tb}^R = \frac{m_b}{m_T}\left[c_L^d s_L^u e^{-i\phi_u} + (s_R^{d\,2} - s_L^{d\,2})\frac{c_L^u}{s_L^d}e^{-i\phi_d}\right]$$

✯ W^+ boson interaction (W^+Tb):

$$\mathcal{L}_W = -\frac{g}{\sqrt{2}}\overline{T}\gamma^\mu(V_{Tb}^L P_L + V_{Tb}^R P_R)bW_\mu^+ + \text{h.c.}$$

$$V_{Tb}^L = s_L^u c_L^d e^{-i\phi_u} - c_L^u s_L^d e^{-i\phi_d}$$
$$V_{Tb}^R = -c_R^u s_R^d e^{-i\phi_d}$$



CONSTRAINTS

Theoretical Constraints

- **Unitarity** The full scalar-scalar scattering matrix (including VLQ-induced corrections to quartics) must satisfy:

$$|a_0| < \tfrac{1}{2}.$$

- **Perturbativity** All scalar and Yukawa couplings satisfy:

$$|\lambda_i| < 8\pi, \qquad |y_{ij}^{u,d}| < \sqrt{4\pi}.$$

- **Vacuum stability** The scalar potential must remain bounded from below:

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2},$$

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

`2HDMC-1.8.0`

D. Eriksson, J. Rathsman, O. Stål (0902.0851)

Experimental Constraints

- **Electroweak Precision Observables (EWPO)** The combined (2HDM + VLQ) contributions to the oblique parameters must satisfy:

$$\Delta\chi^2\left(S^{2HDM} + S^{VLQ},\ T^{2HDM} + T^{VLQ}\right) \leq 6.18,$$

corresponding to a 95% CL ellipse.

- **SM-like Higgs measurements** Compatibility with LHC Run 2 and Run 3 signal-strength data is enforced via:

`HiggsSignals-3` (through `HiggsTools`).

- **BSM Higgs searches** Exclusion limits from LEP, Tevatron and LHC for H, A and $H^{\pm}$ are applied using:

`HiggsBounds-6` (via `HiggsTools`).

- **Flavour Observables** Including $B \to X_s\gamma$, $B_{s,d} \to \mu^+\mu^-$, $B \to \tau\nu$, ΔM_{B_s}, etc., evaluated using:

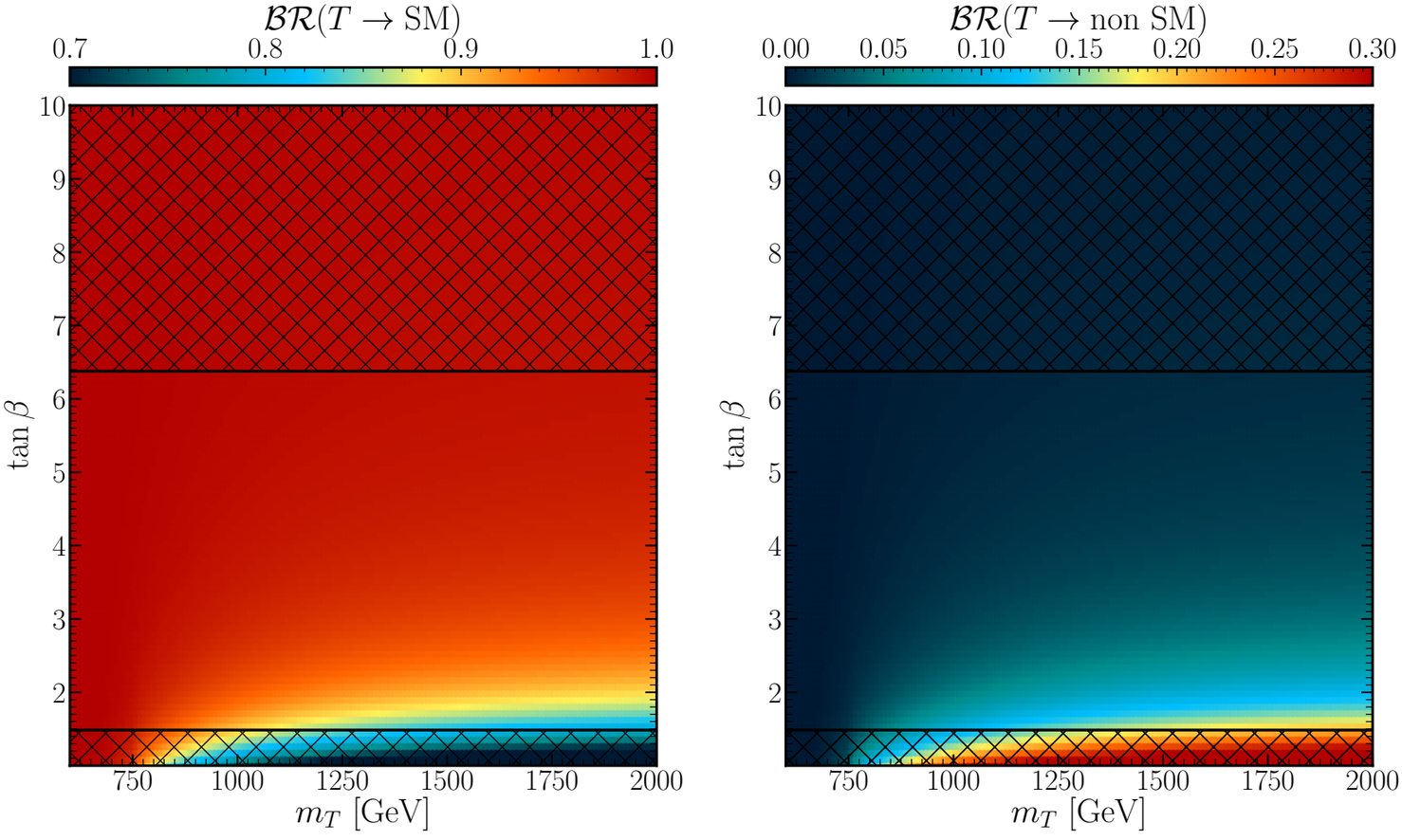
`SuperIso-v4.1`.

- **Direct VLQ searches (LHC)** Current ATLAS/CMS limits primarily target SM-like decay channels:

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

Benbrik, Boukidi, Ech-chaouy, Moretti, 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

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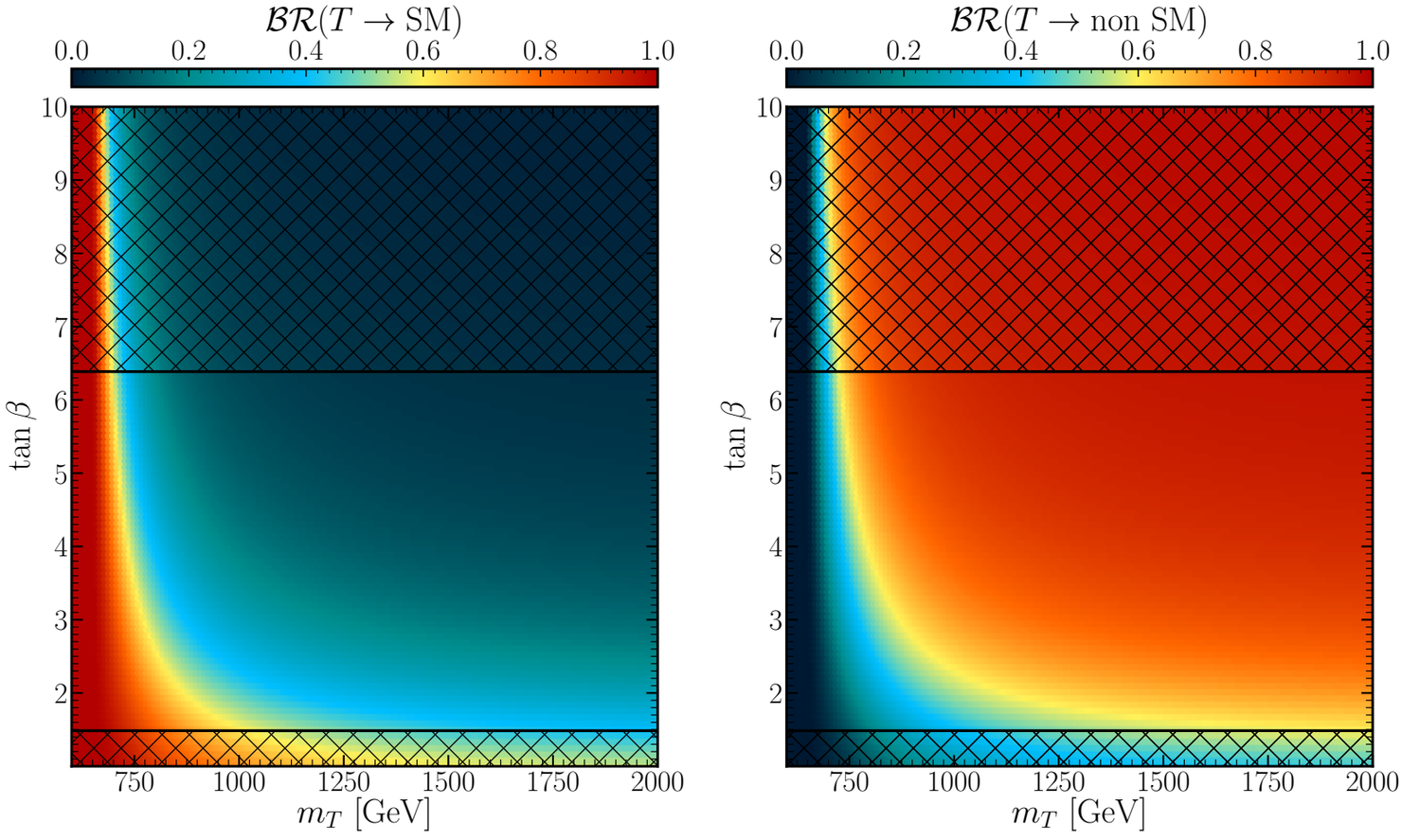
2HDM-II+TB Doublet Scenario



- 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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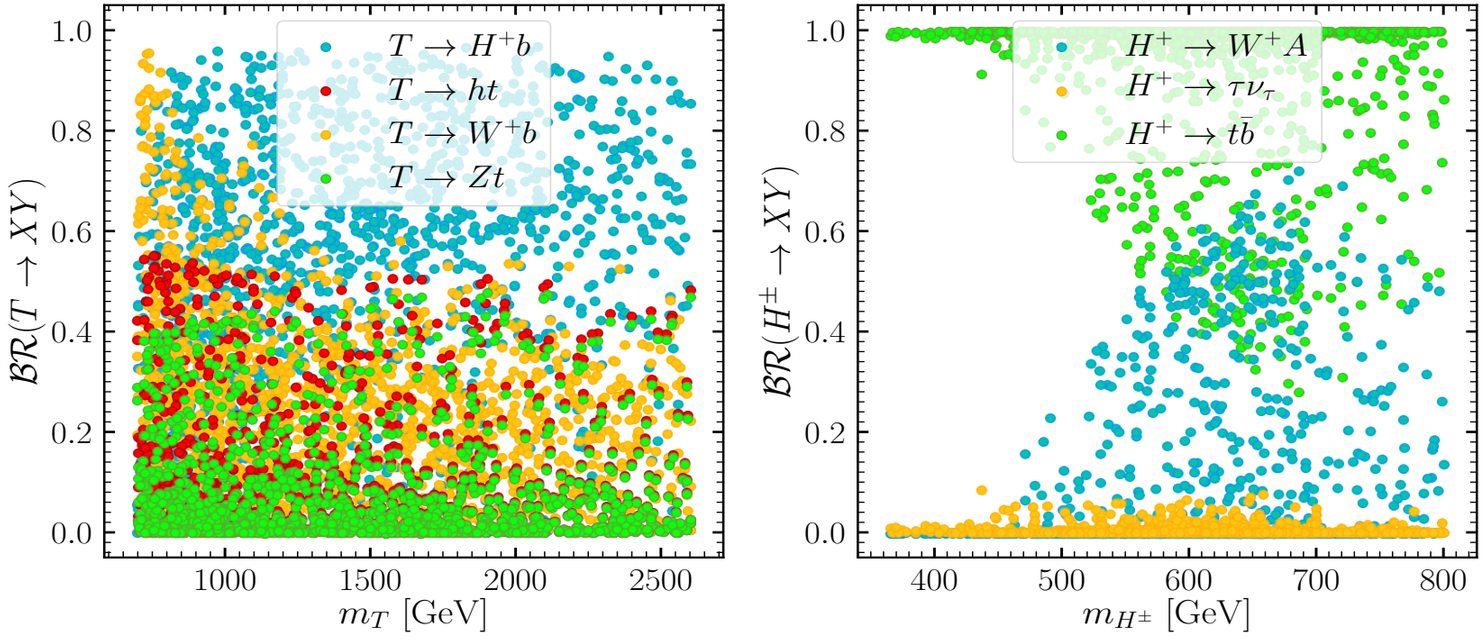
2HDM-II+TB Doublet Scenario

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]



- $\mathcal{BR}(T \to H^+b)$ is the dominant decay over most of the parameter space.
- H^+ decays mainly via $H^+ \to t\bar{b}$ whenever kinematically open.
- Dominant cascade: $T \to H^+b \to t\bar{b}\,b$.

MC Simulation

➥ **Collider analyses performed in this work:**

★ **Fully hadronic analysis** (multi-b):

$$pp \to T\bar{T} \;\to\; (H^+b)(H^-\bar{b}) \;\Rightarrow\; 2t4b \quad (4b,\; 5b \,\text{final states}).$$

★ **Semi-leptonic analysis**:

$$pp \to T\bar{T} \;\to\; (H^+b)(H^-\bar{b}) \;\Rightarrow\; \ell^+\ell^- + 6b + \not{E}_T.$$

➥ **Simulation pipeline:**

★ `MadGraph5_aMC@NLO` hard-scattering event generation.

★ `Pythia8` parton showering and hadronisation.

★ `Delphes` detector response.

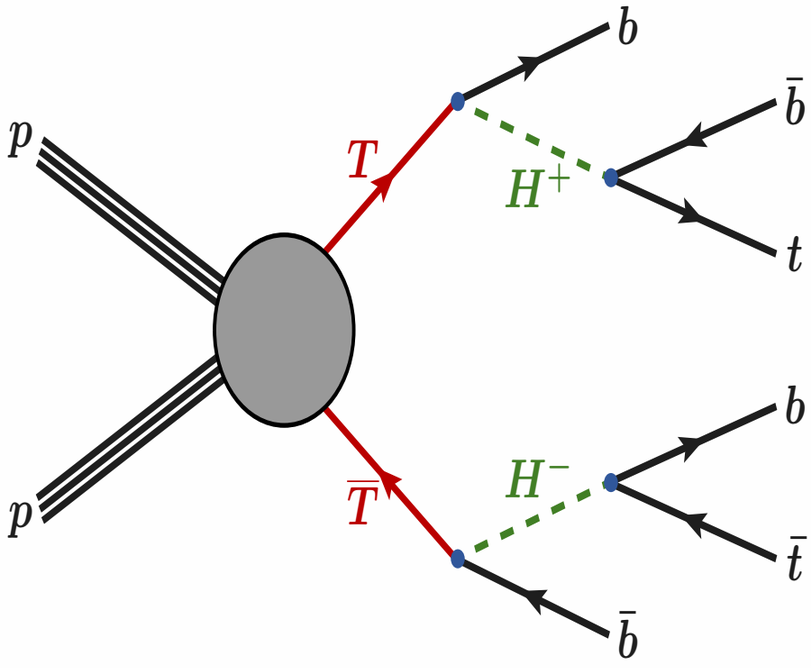
★ `FastJet` anti-k_T jet clustering.

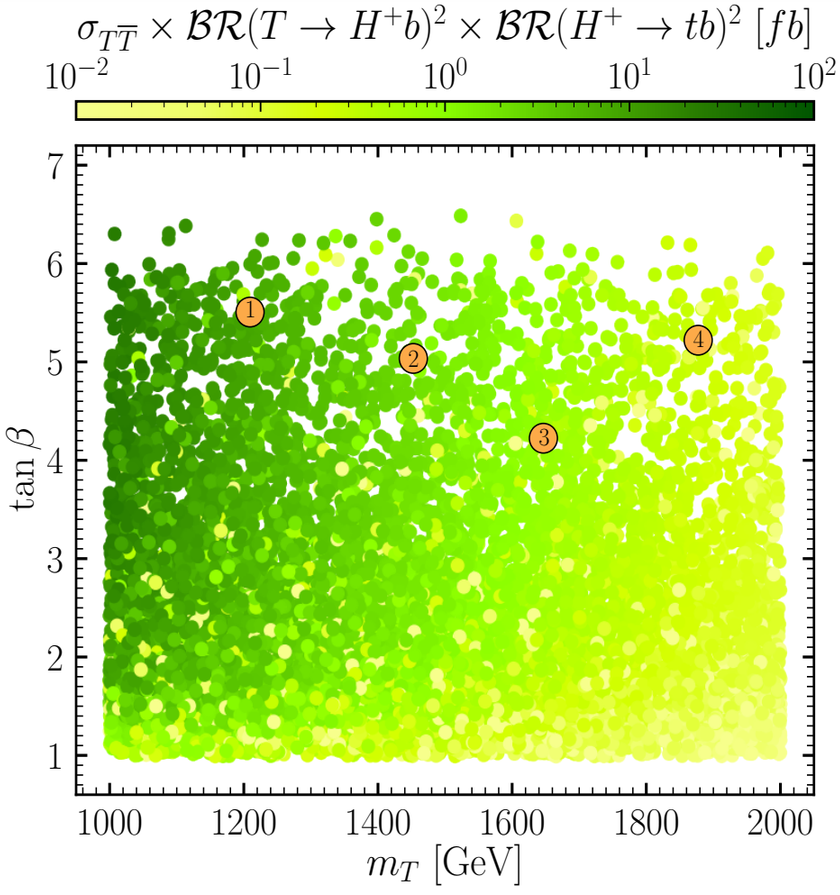
★ `MadAnalysis5` cutflow and event selection.

➥ **Discovery significance including systematics (δ):**

$$\boxed{\mathcal{Z}_{disc} = \sqrt{2\left[(s+b)\ln\left(\frac{(s+b)(1+\delta^2 b)}{b+\delta^2 b(s+b)}\right) - \frac{1}{\delta^2}\ln\left(1+\frac{\delta^2 s}{1+\delta^2 b}\right)\right]}}$$

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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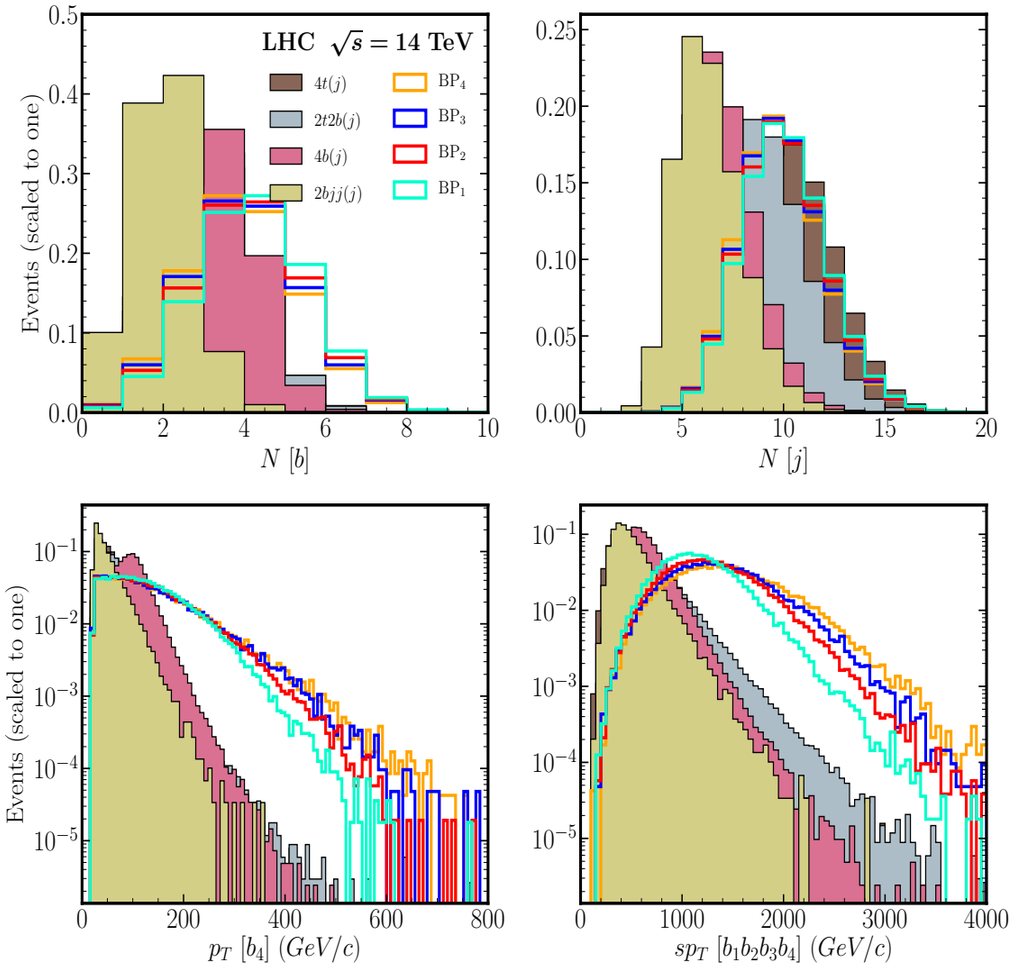
$4b$ Analysis



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

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

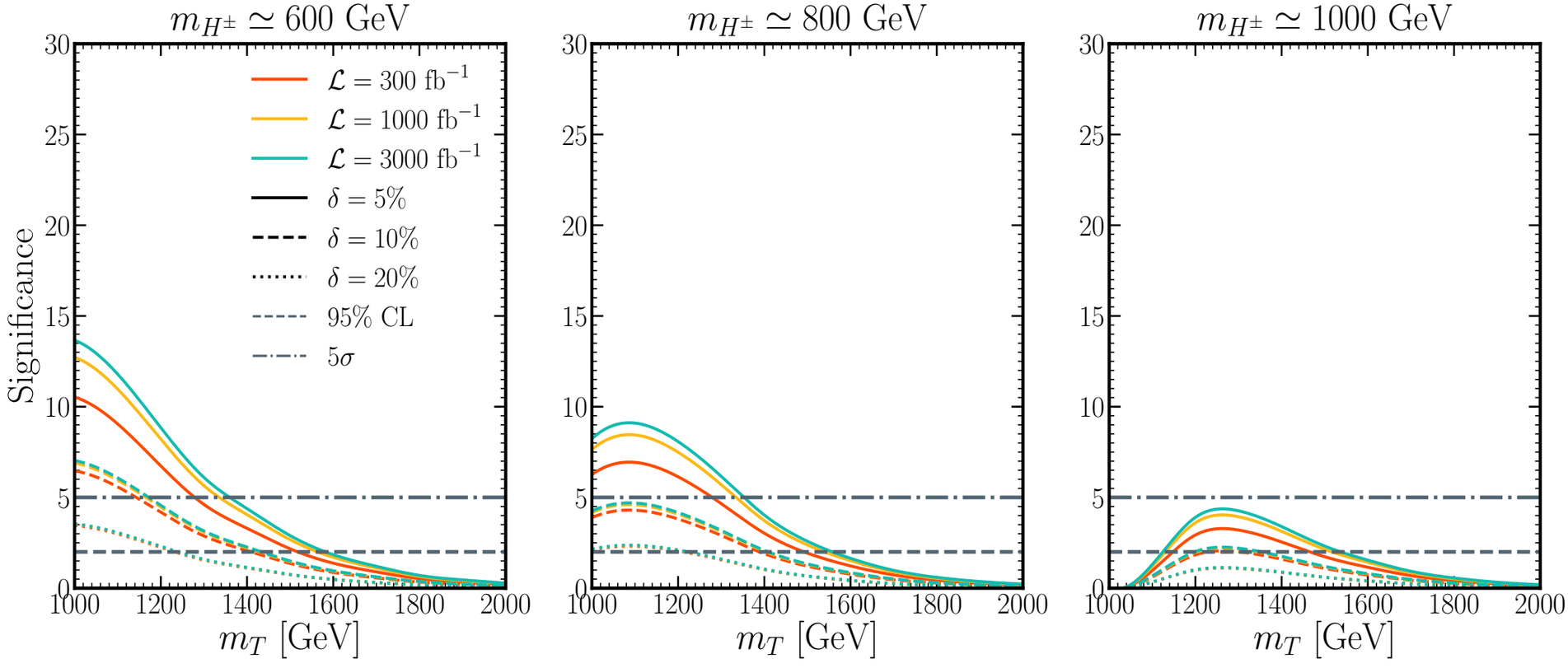
Cuts	Signals				Backgrounds			
	BP1	BP2	BP3	BP4	$2bjets$	$4bj$	$2t2bj$	$4tj$
Basic	10.36	1.95	0.819	0.28	324075	727.74	202.56	16.60
Cut 1	4.41	0.760	0.31	0.093	1005.20	32.9	29.60	3.07
Cut 2	1.00	0.272	0.13	0.045	3.60	0.33	0.543	0.033
Cut 3	0.67	0.168	0.08	0.026	0.96	0.179	0.18	0.008
Efficiency	6.48%	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.

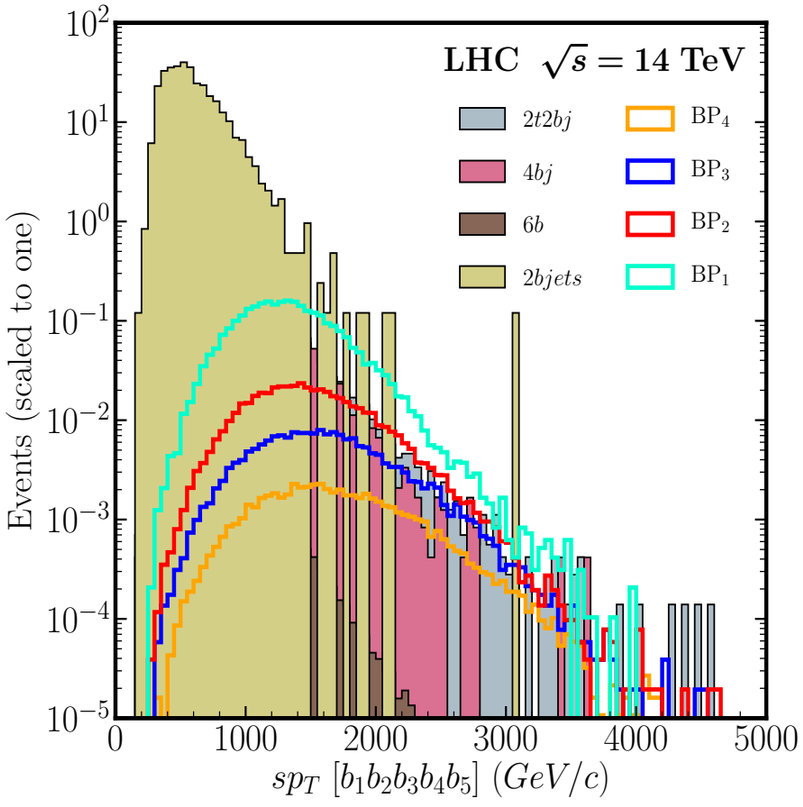
$4b$ Analysis

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

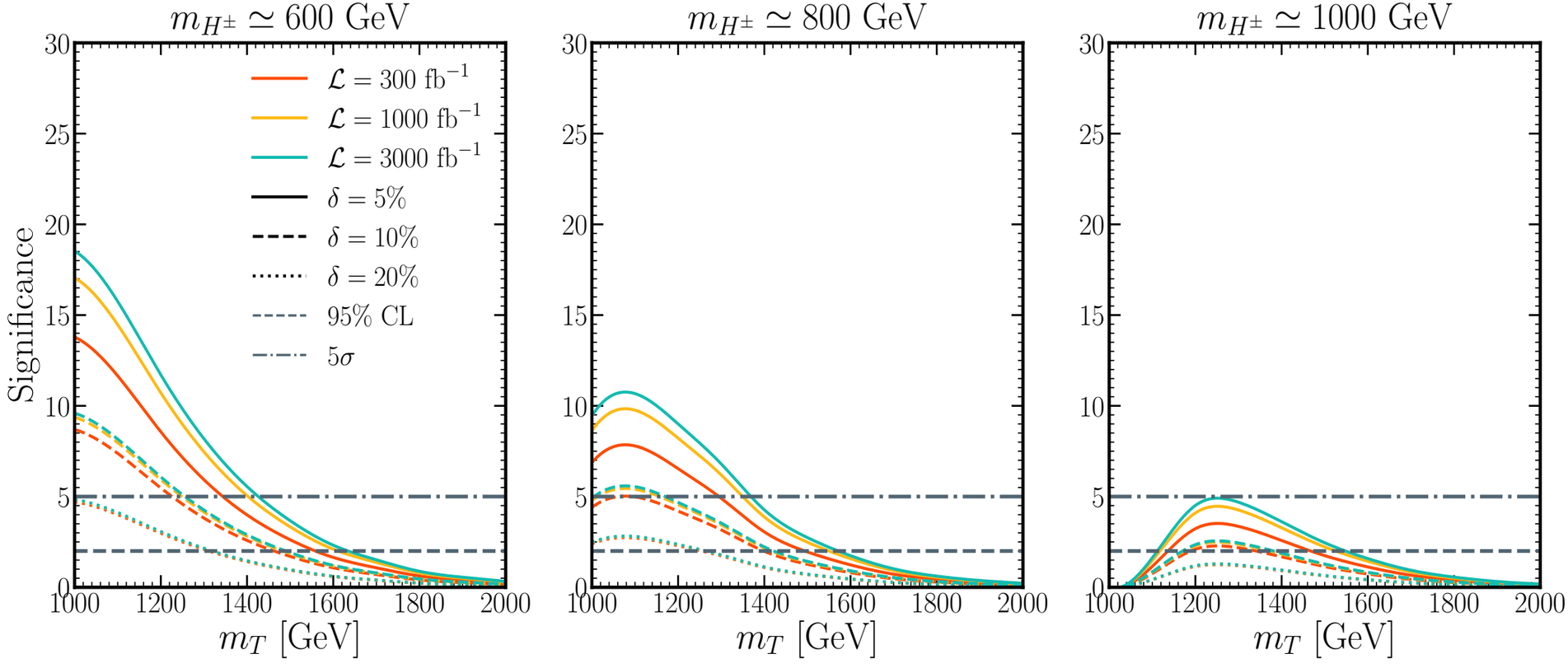
✯ Cutflow of cross sections (fb) for signal and SM backgrounds at $\sqrt{s} = 14$ TeV.

Cuts	Signals				Backgrounds			
	BP1	BP2	BP3	BP4	$2b$jets	$4bj$	$2t2bj$	$6b$
Basic	10.36	1.95	0.82	0.28	324075	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}

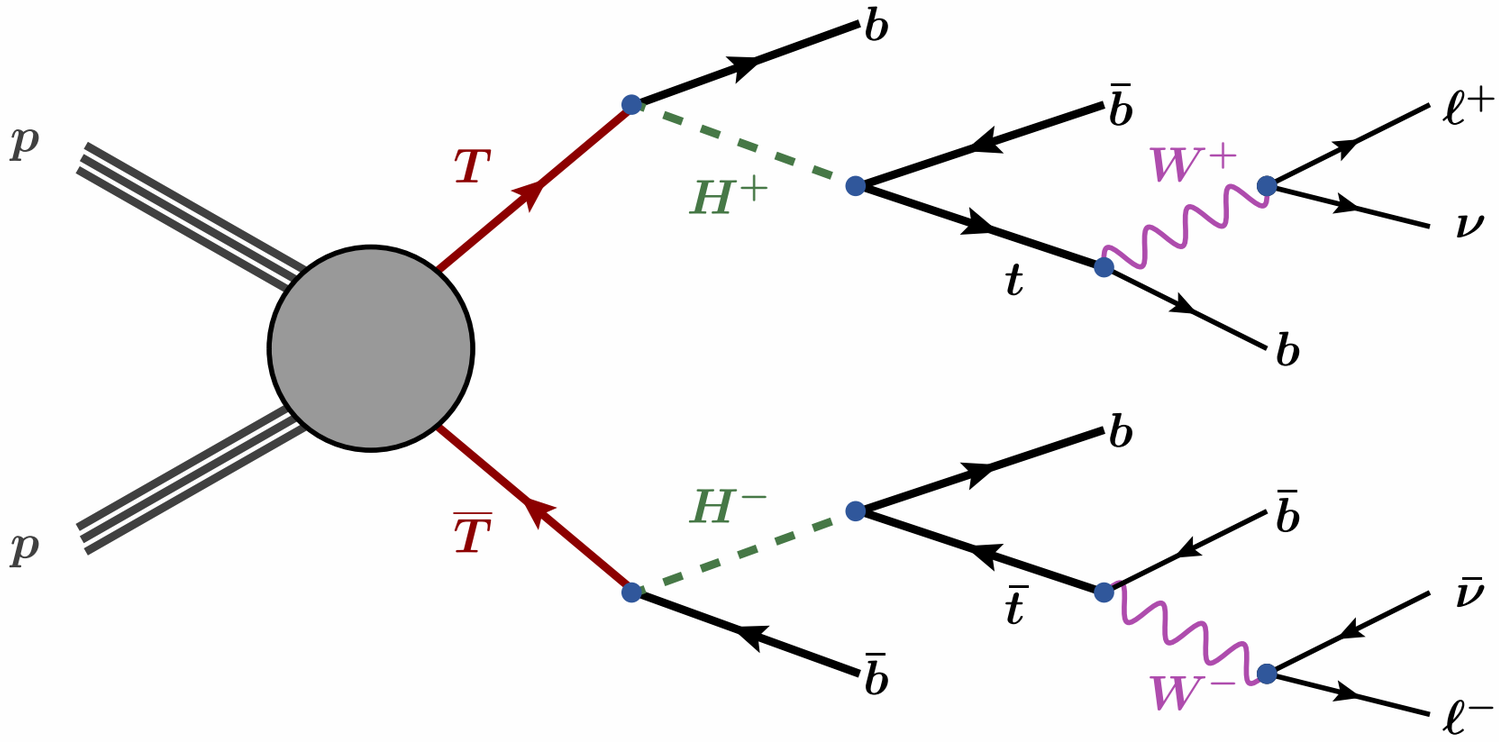
$5b$ Analysis

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 $\mathcal{Z}_{disc}$ of the $5b$ final state, evaluated for different systematic uncertainties (δ) and luminosities ($\mathcal{L} = 300,\ 1000,\ 3000$ fb^{-1}).
- Benchmark point fixed at: $m_H = 600.26$ 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 shown as a function of m_T for three charged Higgs masses: $m_{H^\pm} = 600$ 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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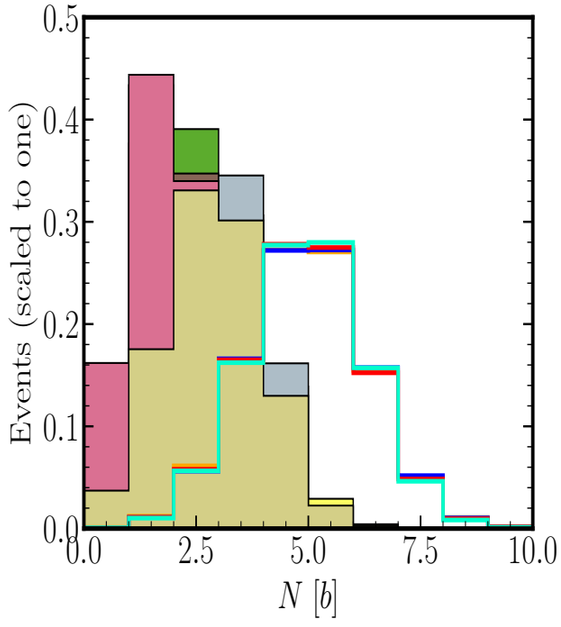
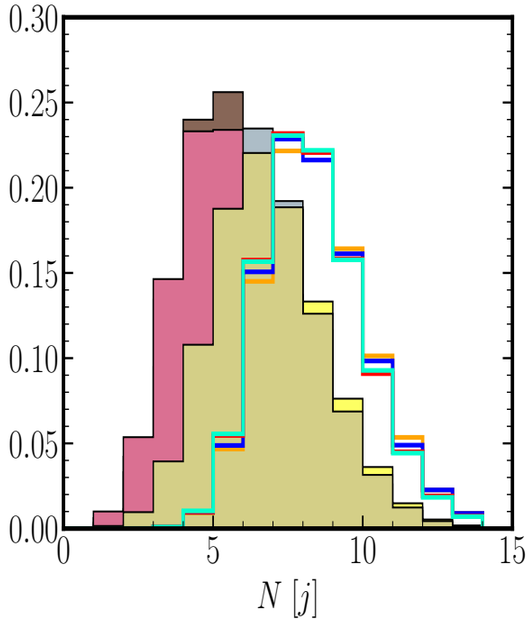
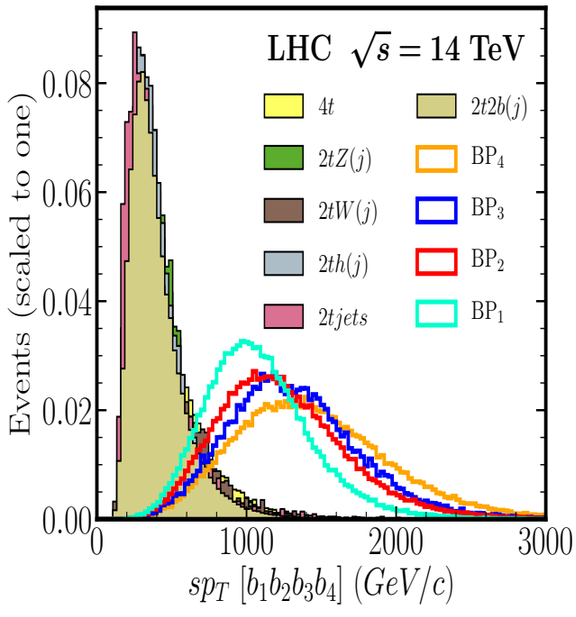
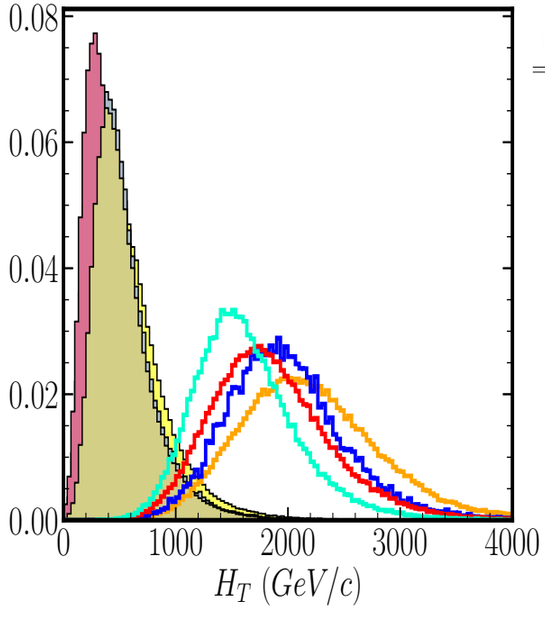
OS Dilepton + Multi-b Final State









- 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

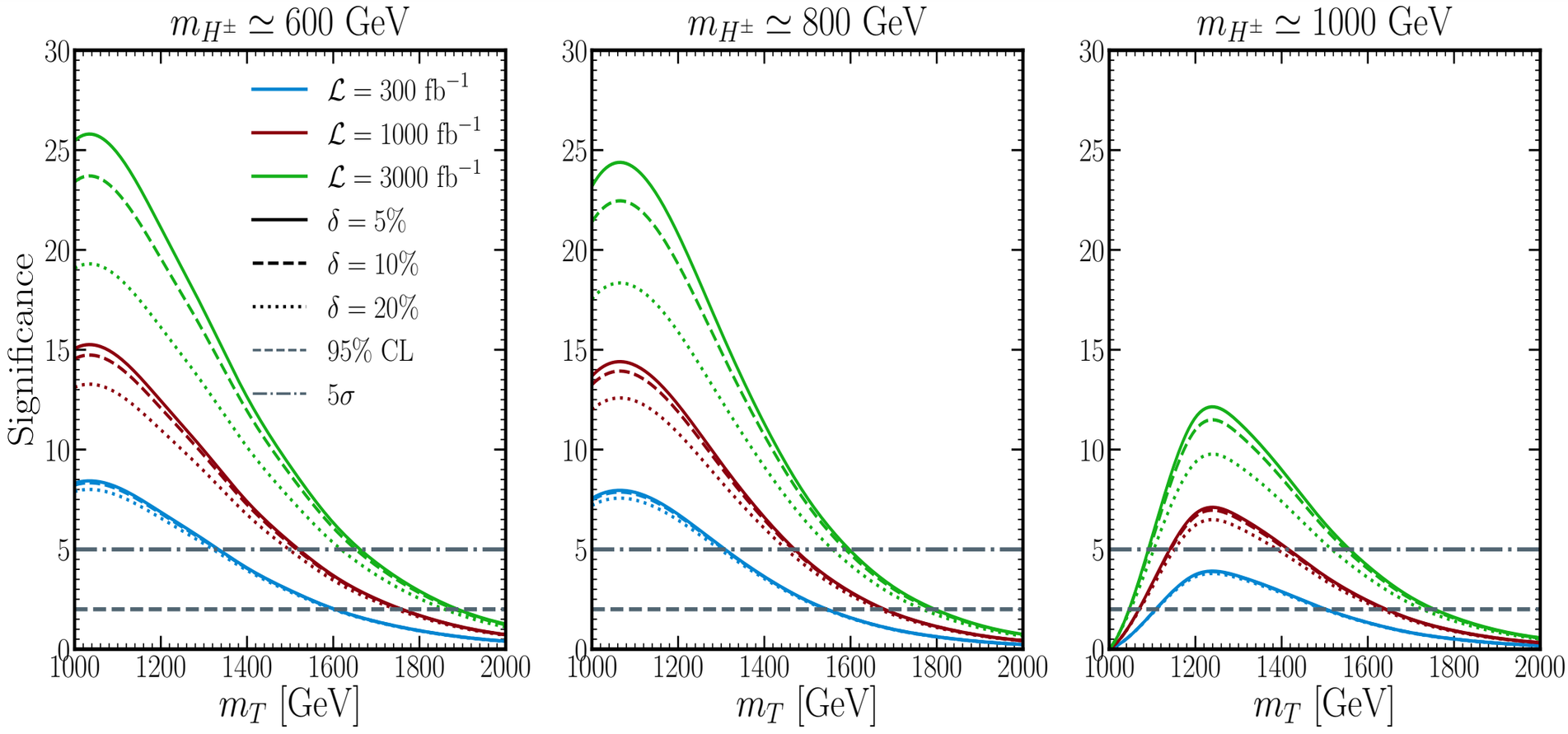
OS DILEPTON + MULTI-b FINAL STATE

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

OS DILEPTON + MULTI-b FINAL STATE



- 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 investigated vector-like quarks in the 2HDM-II+TB scenario, concentrating on the top partner (T) and its decay into a charged Higgs boson, $T \to H^+ b$.
- 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).
- The $T \to H^+ b$ decay is a well-motivated channel, as it allows us to probe both the vector-like top partner and the charged Higgs boson.