

Detecting Heavy Charged Higgs Boson at the LHC

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MG, Aravind H Vijay, 1806.01317

Higgs and BSM

- 125 GeV Higgs boson, a SM like Higgs.
- It can be the candidate of the BSM, consistent with Higgs data as well.
e.g MSSM, NMSSM can accommodate 125 GeV Higgs.
- So far no signal of BSM is observed.

SM-like Higgs as a candle, probe BSM.

Generic 2 Higgs doublet model(2HDM),
SM Higgs doublet + second Higgs doublet



h, H, A, H^+, H^-

Presence of Charged Higgs is unique.
Discovery of it, an um ambiguous signal of BSM.

Two Higgs Doublet model

Two Higgs Doublet with $Y=+1/2$

ϕ_1 and ϕ_2

$$\begin{aligned} V_{2HDM} = & m_{11}^2 \phi_1^\dagger \phi_1 + m_{22}^2 \phi_2^\dagger \phi_2 \\ & - [m_{12}^2 \phi_1^\dagger \phi_2 + h.c.] \\ & + \frac{1}{2} \lambda_1 (\phi_1^\dagger \phi_1)^2 + \frac{1}{2} \lambda_2 (\phi_2^\dagger \phi_2)^2 \\ & + \lambda_3 (\phi_1^\dagger \phi_1)(\phi_2^\dagger \phi_2) + \lambda_4 (\phi_1^\dagger \phi_2)(\phi_2^\dagger \phi_1) \\ & + \left[\frac{1}{2} \lambda_5 (\phi_1^\dagger \phi_2)^2 + h.c \right] \end{aligned}$$

Minimum of the scalar potential preserves U(1) symmetry:

$$\frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_1 \end{pmatrix} \quad \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v_2 \end{pmatrix}$$

$$v = \sqrt{v_1^2 + v_2^2} \quad \tan \beta = \frac{v_2}{v_1}$$

Higgs Boson States

Five Higgs Boson states: h, H, A, H^+, H^-

$$H^+ = -\phi_1^+ \sin \beta + \phi_2^+ \cos \beta$$

$$A = -Im(\phi_1^0) \sin \beta + Im(\phi_2^0) \cos \beta$$

Masses:

$$M_A^2 = \frac{2m_{12}^2}{\sin 2\beta} - \lambda_5 v^2$$

$$M_{H^\pm}^2 = M_A^2 + \frac{1}{2}v^2(\lambda_5 - \lambda_4)$$

Charged Higgs Couplings

$$\mathcal{L}_Y = \sum_{i=1}^2 \left[\bar{Q}_L \tilde{\phi}_i \eta_i U_R + \bar{Q}_L \phi_i \eta_i^D D_R + \bar{L}_L \phi_i \eta_i^L E_R + h.c \right]$$

Assignment of Z2 charges, determine the pattern: 4types of models

Type	U_R	D_R	L_R	λ_{UU}	λ_{DD}	λ_{LL}
I	+	+	+	$\cot \beta$	$\cot \beta$	$\cot \beta$
II	+	-	-	$\cot \beta$	$-\tan \beta$	$-\tan \beta$
III	+	-	+	$\cot \beta$	$-\tan \beta$	$\cot \beta$
IV	+	+	-	$\cot \beta$	$\cot \beta$	$-\tan \beta$

$$g_{H^+ \bar{u}_i d_j} = \frac{V_{ij}^{\text{CKM}}}{\sqrt{2} M_W} \left[\lambda_{UU} \frac{1 - \gamma_5}{2} + \lambda_{DD} \frac{1 + \gamma_5}{2} \right],$$

$$g_{H^+ \bar{\nu}_\ell \ell} = \frac{1}{\sqrt{2} M_W} \lambda_{LL} \frac{1 + \gamma_5}{2},$$

Type II, MSSM type

Couplings with Fermions

Type I and III

$$g_{H^\pm \bar{t}b} \sim (m_b + m_t) \cot \beta$$

$\tan \beta$ **low enhanced**

Type II and IV

$$g_{H^\pm \bar{t}b} \sim (m_b \tan \beta P_R + m_t \cot \beta P_L)$$

$\tan \beta$ **low and High, both are favoured**

Mass(Type II/SUSY)

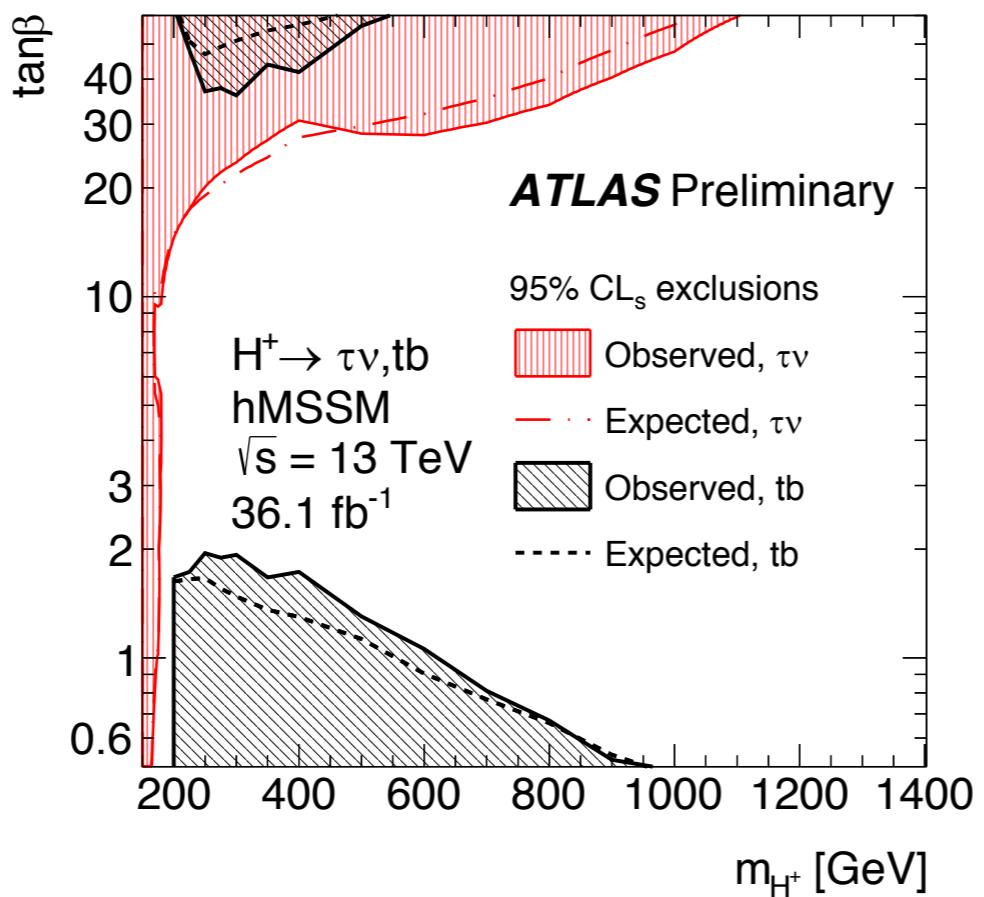
$$M_{H^\pm}^2 = M_A^2 + M_W^2$$

Charged Higgs at the LHC

$$m_{H^\pm} \ll m_t$$

$$m_{H^\pm} > m_t$$

$$H^- \rightarrow \tau\nu, \bar{t}b$$



See Talk by, Laurie, S.H.[CMS]
Mir, Luisa-Maria[ATLAS]

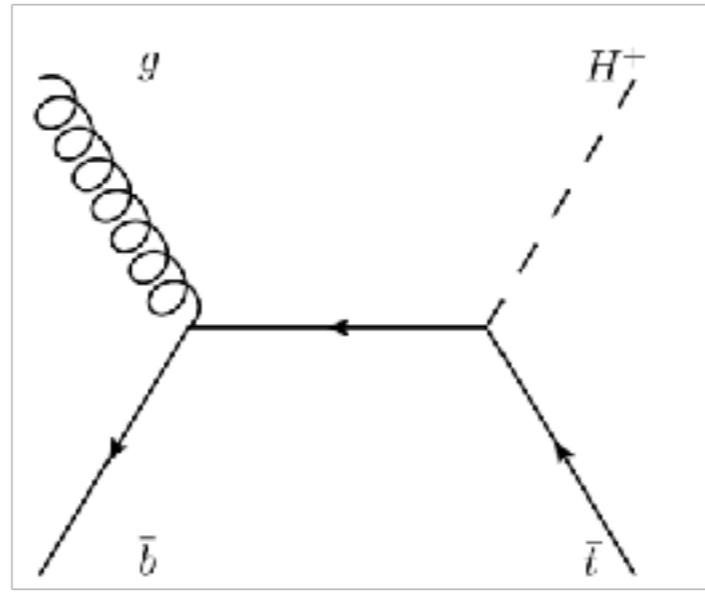
Present study

$$m_{H^\pm} \gg m_t$$

Difficult and challenging, huge backgrounds with same event kinematics

Charged Higgs Boson Production

$gb \rightarrow tH^-$



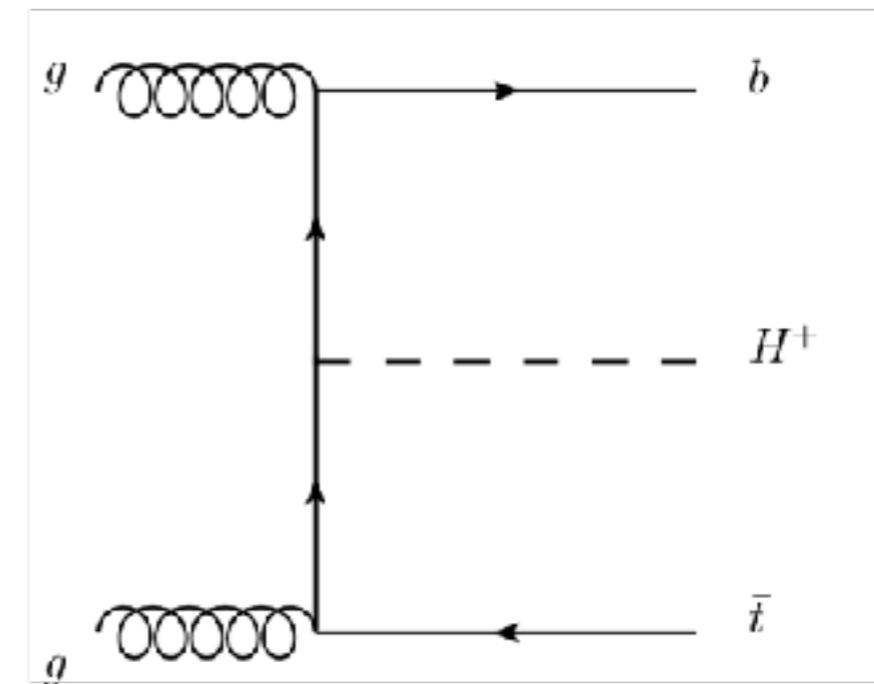
5FS

~ 15-20% Uncertainty, NNLO

Total cross sections, by matching, “Santander Matching”

$$\sigma = \frac{\sigma^{4FS} + w\sigma^{5FS}}{1+w} \quad w = \ln\left(\frac{m_{H^\pm}}{m_b}\right) - 2$$

$gg, q\bar{q} \rightarrow tbH^-$



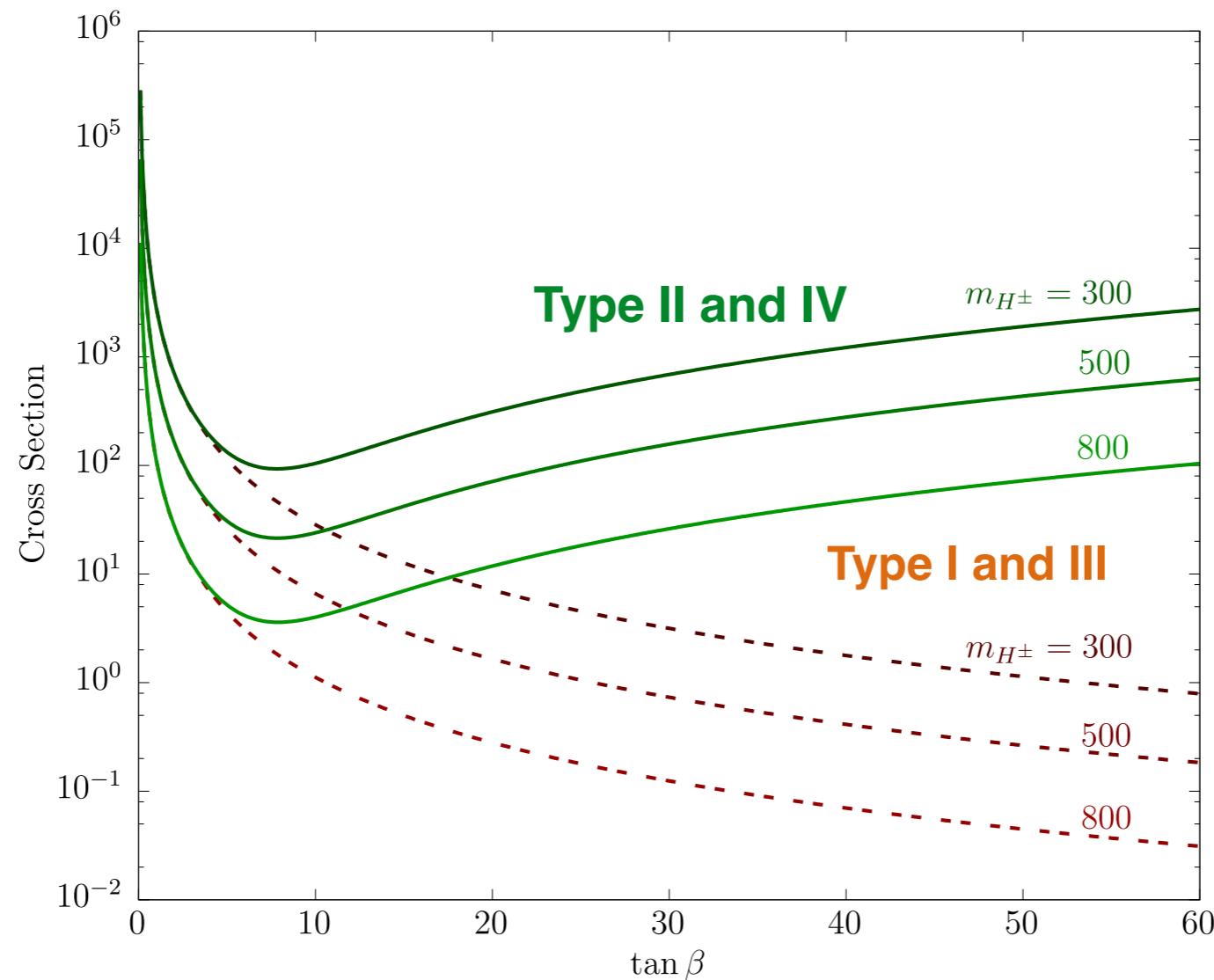
4FS

~ 20% Uncertainty NLO

Harlander et.al 1112.3478

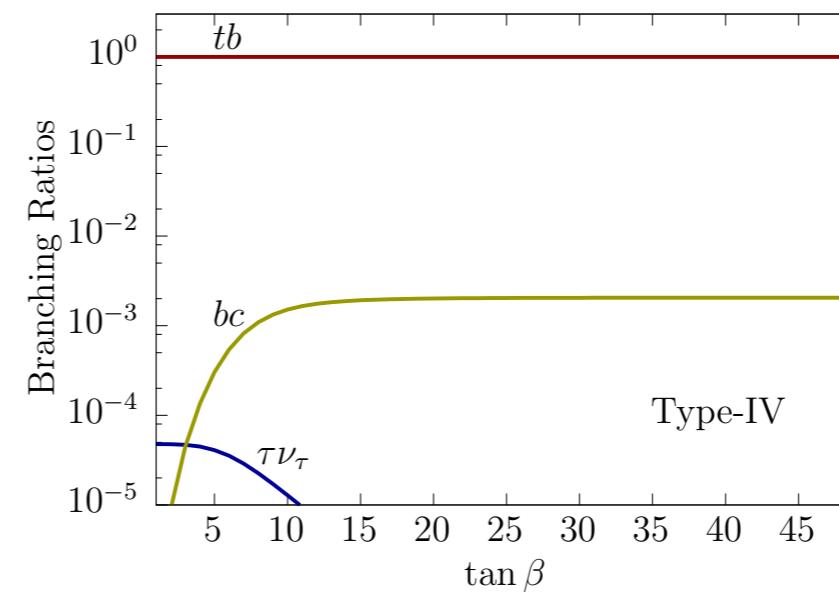
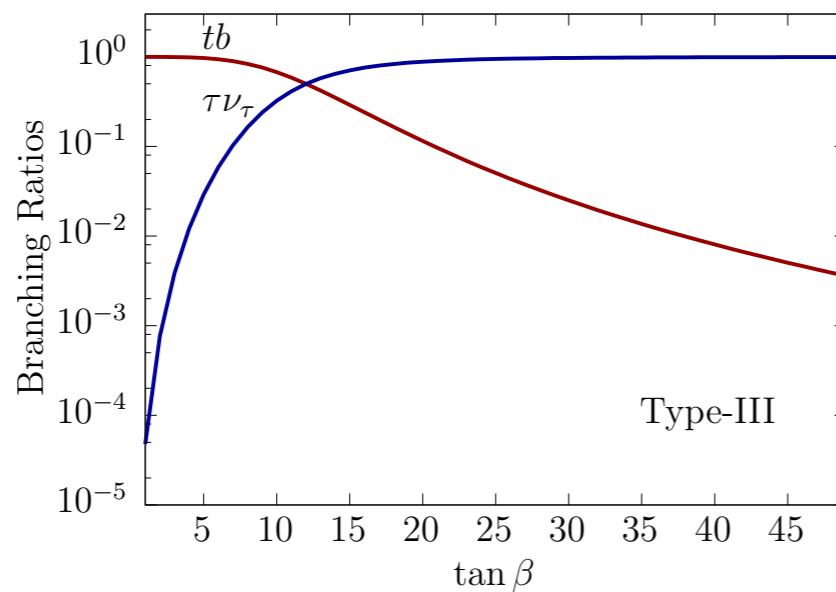
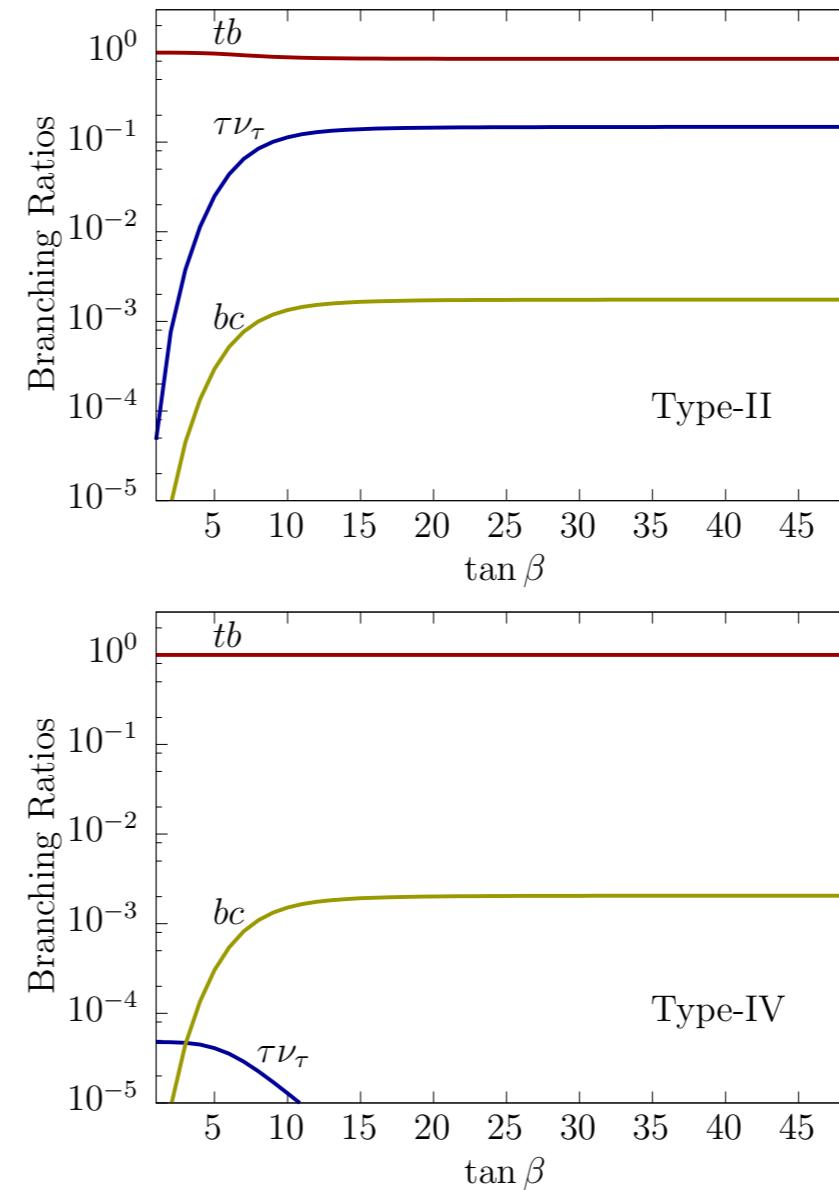
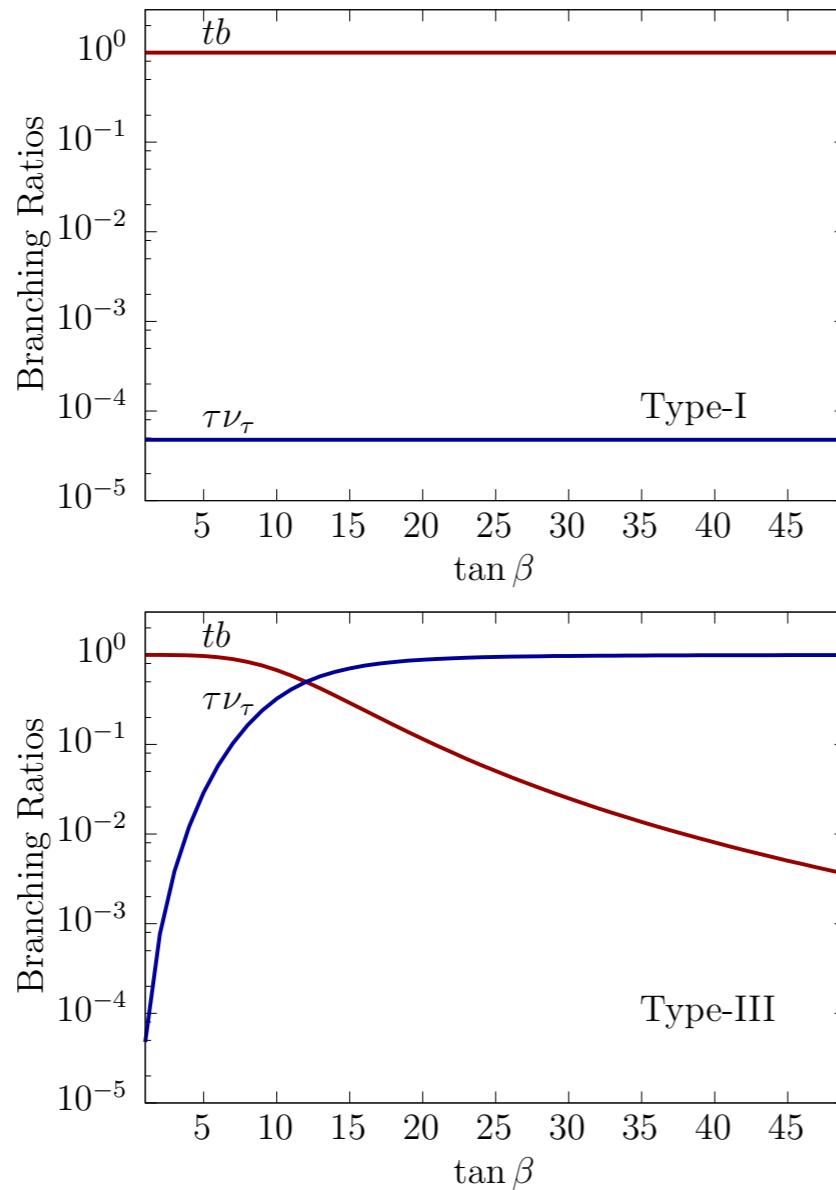
Higgs Production in 4 FS and 5FS

$$\sigma(pp \rightarrow tH^\pm + X)[\text{fb}]$$



Charged Higgs Decays

$m_H = m_A = m_{H^\pm} = 500 \text{ GeV}, \sin(\beta - \alpha) = 1$



$H^- \rightarrow \bar{t}b$ **the dominant decay mode, except in Type III**

Signal and Background

$$pp \rightarrow tH^-(b) \rightarrow t(tb)(b) \rightarrow (bW)(bWb)(b)$$

$\rightarrow 2W + 3b \text{ or } 4b$

$H_{reco} + t_{reco} + b - jets$ **Hadronic**

$H_{reco} + n_\ell (\geq 1) + b - jets$ **Leptonic**

Charged Higgs mass reconstruction: $H_{reco} = m_{tb}$

Top reconstruction: Jet Substructure

Background: $pp \rightarrow t\bar{t} \rightarrow (bW)(bW)$ $\sigma \sim 10^3 pb$

$pp \rightarrow t\bar{t}b\bar{b} \rightarrow (bW)(bW)b\bar{b}$ $\sigma \sim 10 pb$

$pp \rightarrow jets$ **QCD** $\sigma \sim 10^8 pb$

Signal and Background Simulation

$$pp \rightarrow tH^-(b) \rightarrow t(tb)(b) \rightarrow (bW)(bWb)(b)$$

$$H_{reco} + t_{reco} + b - jets$$

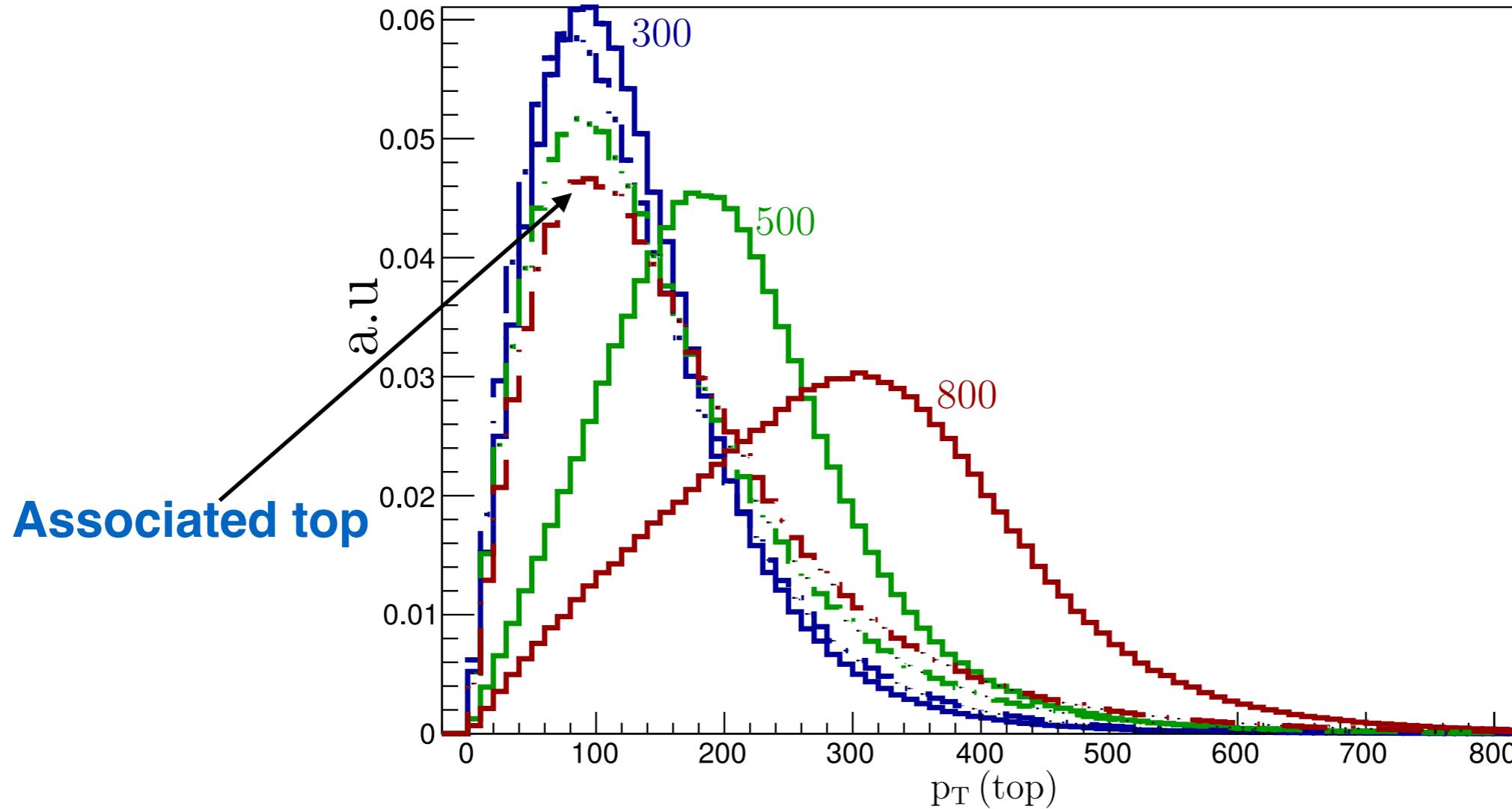
$$H_{reco} + n_\ell (\geq 1) + b - jets$$

MadGraph_aMC@NLO+PYTHIA8
QCD is simulated using PYTHIA8

- **Leptons veto/select**
- **Construct Fatjets, then top tagging**
- **Charged Higgs Mass reconstruction**
- **Select one hard b jet**

Boosted Top

$H^- \rightarrow \bar{t}b$ **Top quark is expected to be boosted**



$$\gamma_t \sim m_{H^\pm} / m_t$$

Reconstruction of Top

$$H^- \rightarrow \bar{t}b$$

HepToptagger is used for top jet reconstruction(MD).

G.P. Salam, et al, 0802.2470, 1503.05921

Top reconstruction efficiency: ~20%

Background(QCD) mis-tag efficiency: ~2-3%

Reconstruction of Top

$$H^- \rightarrow \bar{t}b$$

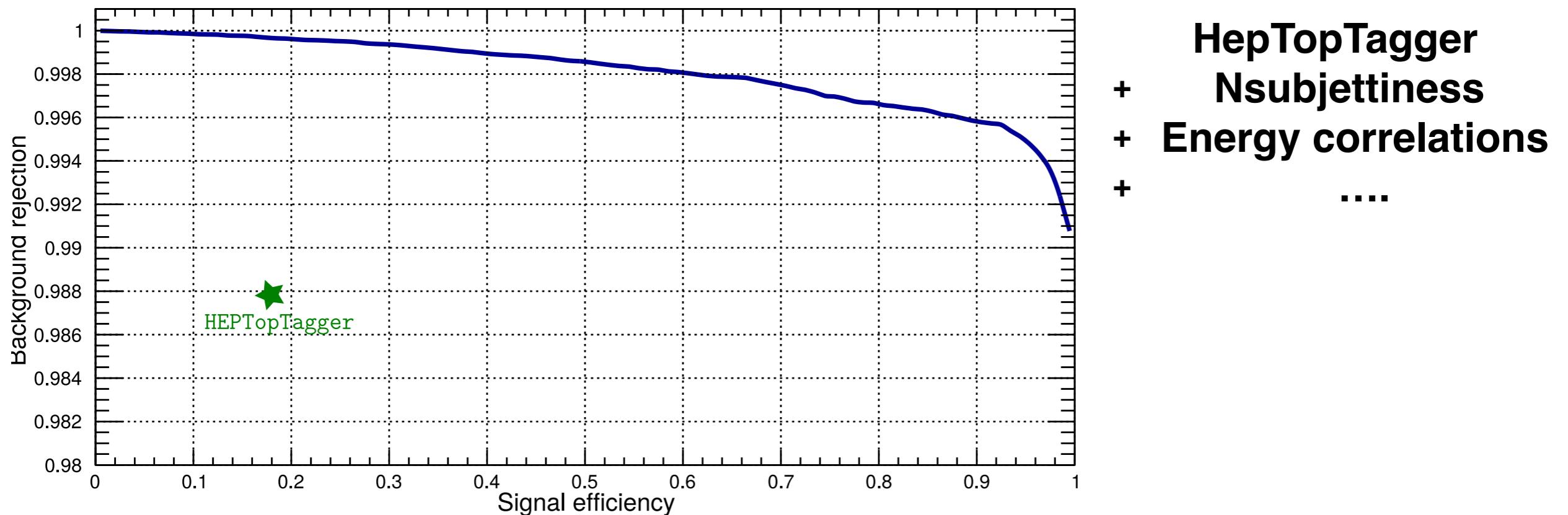
HepTopTagger is used for top jet reconstruction(MD).

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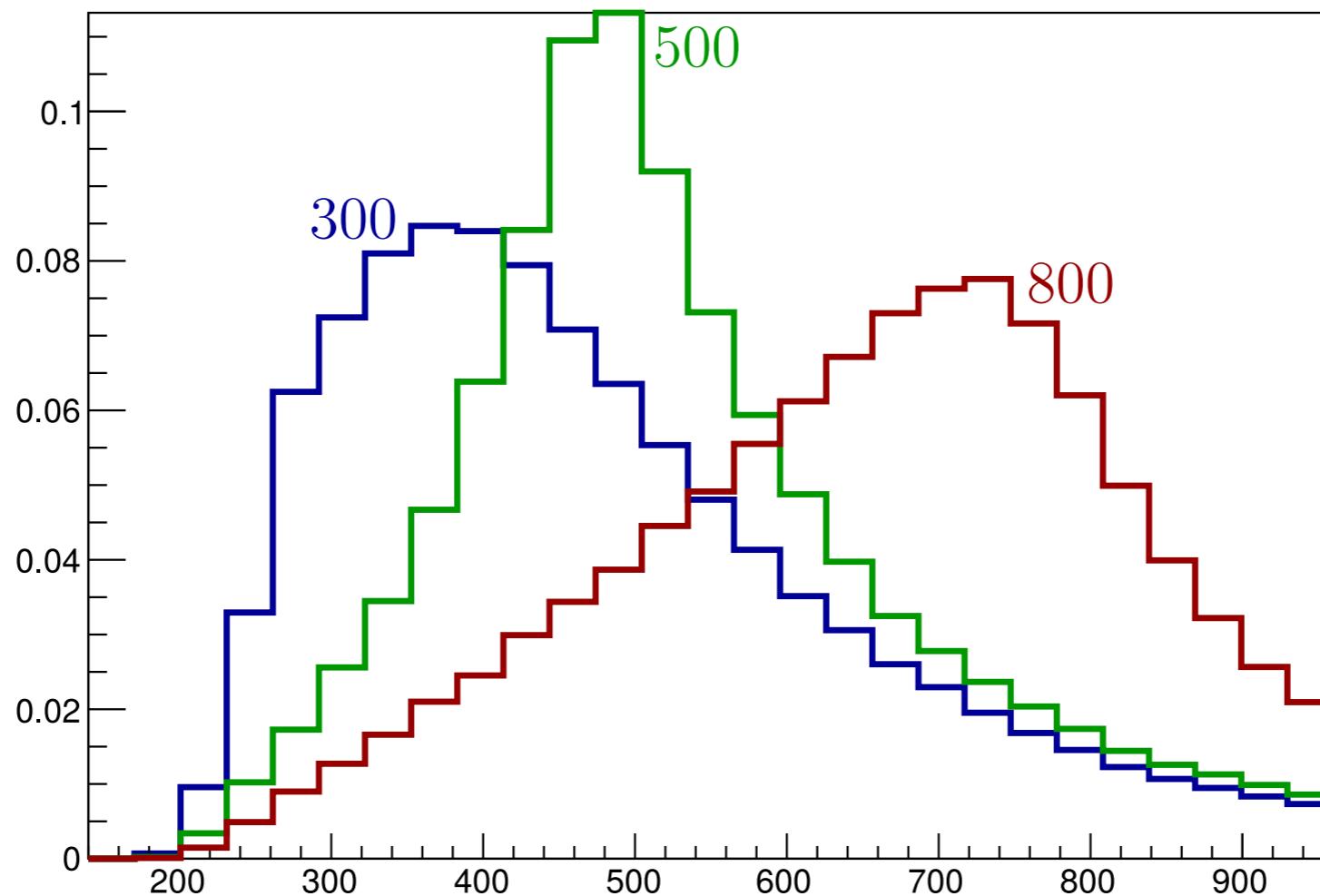
Top Tagging efficiency:MVA



Charged Higgs Mass Reconstruction

$$pp \rightarrow tH^-(b) \rightarrow t(tb)(b) \rightarrow (bW)(bWb)(b)$$

Tagged top jet + leading b jet



Top tagging method helps to avoid combinatorial problem

Events Yield

Hadronic

Selection	5FS×Br	4FS×Br	t̄t	t̄tb̄b	QCD
$\sigma(\text{fb})$	124.9	64.4	8.3×10^5	1.4×10^4	7.2×10^{11}
$N_b \geq 1$ & Lepton Veto	55.8	28.8	4.6×10^5	7.4×10^3	1.2×10^{10}
$N_{\text{FJ}} \geq 1$	44.8	24.2	1.1×10^5	2.6×10^3	9.4×10^6
$N_{t_j} \geq 1$	13.3	7.4	3.2×10^4	790.4	2.5×10^5
$p_T^{\text{b}_1} \geq 50$ GeV	12.3	6.9	2.0×10^4	633.5	9.2×10^4
$m_{t_j b_1} \in [0.7m_{H^\pm}, 1.3m_{H^\pm}]$	8.8	5.2	1.3×10^4	387.6	4.2×10^4
$N_{t_{\text{Associated}}^{\text{Hadronic}}} = 1$	2.2	1.6	364.1	78.8	1.2×10^3
Extra b, $p_T \geq 30$ GeV	0.5	0.5	20.3	15.9	50.2

Leptonic

Selection	5FS×Br	4FS×Br	t̄t	t̄tb̄b	QCD
$\sigma(\text{fb})$	124.9	64.4	8.3×10^5	1.4×10^4	7.2×10^{11}
$N_b \geq 1$ & $N_\ell \geq 1$	39.3	20.3	2.5×10^5	4.2×10^3	5.0×10^6
$N_{\text{FJ}} \geq 1$	29.3	15.8	5.0×10^4	1.3×10^3	3.6×10^3
$N_{t_j} \geq 1$	5.4	3.0	1.0×10^4	276.1	103.1
$p_T^{\text{b}_1} \geq 50$ GeV	4.9	2.8	6.7×10^3	221.8	71.7
$m_{t_j b_1} \in [0.7m_{H^\pm}, 1.3m_{H^\pm}]$	3.4	2.0	4.4×10^3	138.3	20.5
$p_T^{\text{b}_2} \geq 30$ GeV	2.1	1.3	301.0	66.1	$\lesssim 1.0$

Signal Sensitivity

Hadronic(Leptonic)

$m_{H^\pm} \rightarrow$	$\sigma \times \epsilon_{ac}$ (in fb)		
	300 GeV	500 GeV	800 GeV
5FS	0.4 (1.4)	0.5 (2.1)	0.1 (0.51)
4FS	0.3 (0.95)	0.5 (1.3)	0.1 (0.34)
t <bar>t</bar>	5.9 (140.0)	20.3 (301.0)	15.5 (142.3)
t <bar>t>b<bar>b</bar></bar>	5.4 (22.0)	15.9 (66.1)	8.8 (37.6)
QCD	$\lesssim 1.0$ ($\lesssim 1.0$)	50.2 ($\lesssim 1.0$)	21.4 ($\lesssim 1.0$)
Matched Signal cross section(S)	0.4 (1.3)	0.5 (1.9)	0.1 (0.47)
Total Background cross section(B)	11.3 (161.9)	86.4 (367.1)	45.7 (179.9)
\mathcal{L} (fb $^{-1}$)	S/\sqrt{B}		
	300	1.9 (1.73)	0.92 (1.71)
	1000	3.4 (3.16)	1.7 (3.13)
	3000	5.9 (5.48)	2.9 (5.42)

Even for Higher Luminosity,
significances are too low



MVA analysis

MVA: Hadronic

MVA analysis: using TMVA framework, BDT method

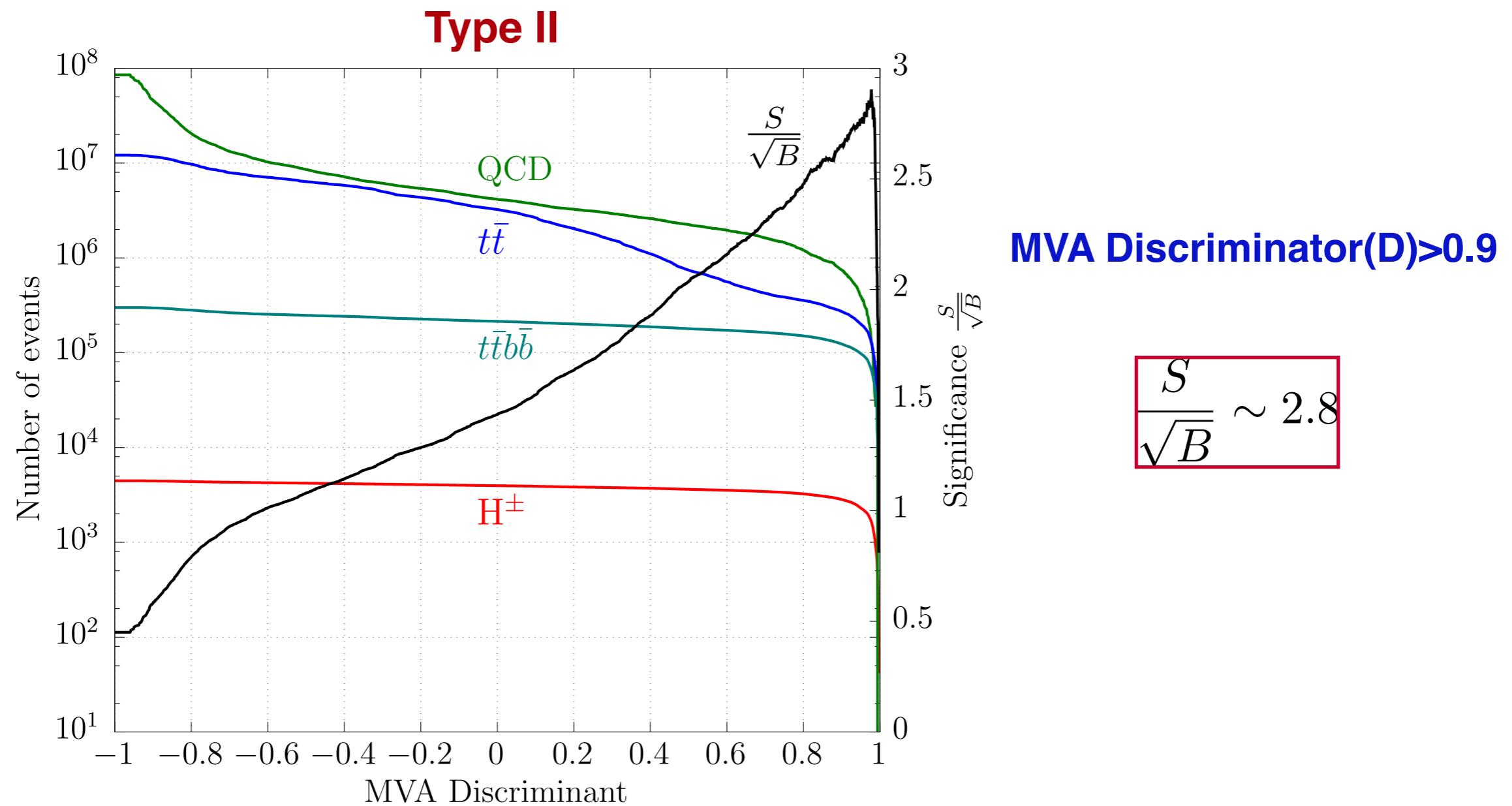
Table 4: Hadronic Kinematic variables..

Rank	Variables	Description
1	$m_{b\bar{b}}^{12}$	Invariant of two b jets
2	p_T^j	p_T of the leading un tagged jet
3	TaggedTopMVADs	MVD Discriminator for Toptagging
4	$m_{b_1 b_2 b_3}$	Invariant mass of 3 b jets
5	$\text{isop}_{T_2}^{bjet}$	p_T of 2nd b jets after top tagging
6	m_{tb}^{reco}	Reconstructed Higgs mass
7	H_T	Scalar sum of p_T of all un-ttaged jets
8	n_j	Number of un tagged
9	$p_{T_3}^{bjet}$	p_T of 3rd b jet
10	H_T^b	Sum of p_T of all b jets

MVA Discriminator: Signal and Background

Hadronic Final state

$$M_H^\pm = 500 \text{ GeV}, \tan \beta = 30, L = 300 fb^{-1}$$



MVA: Leptonic

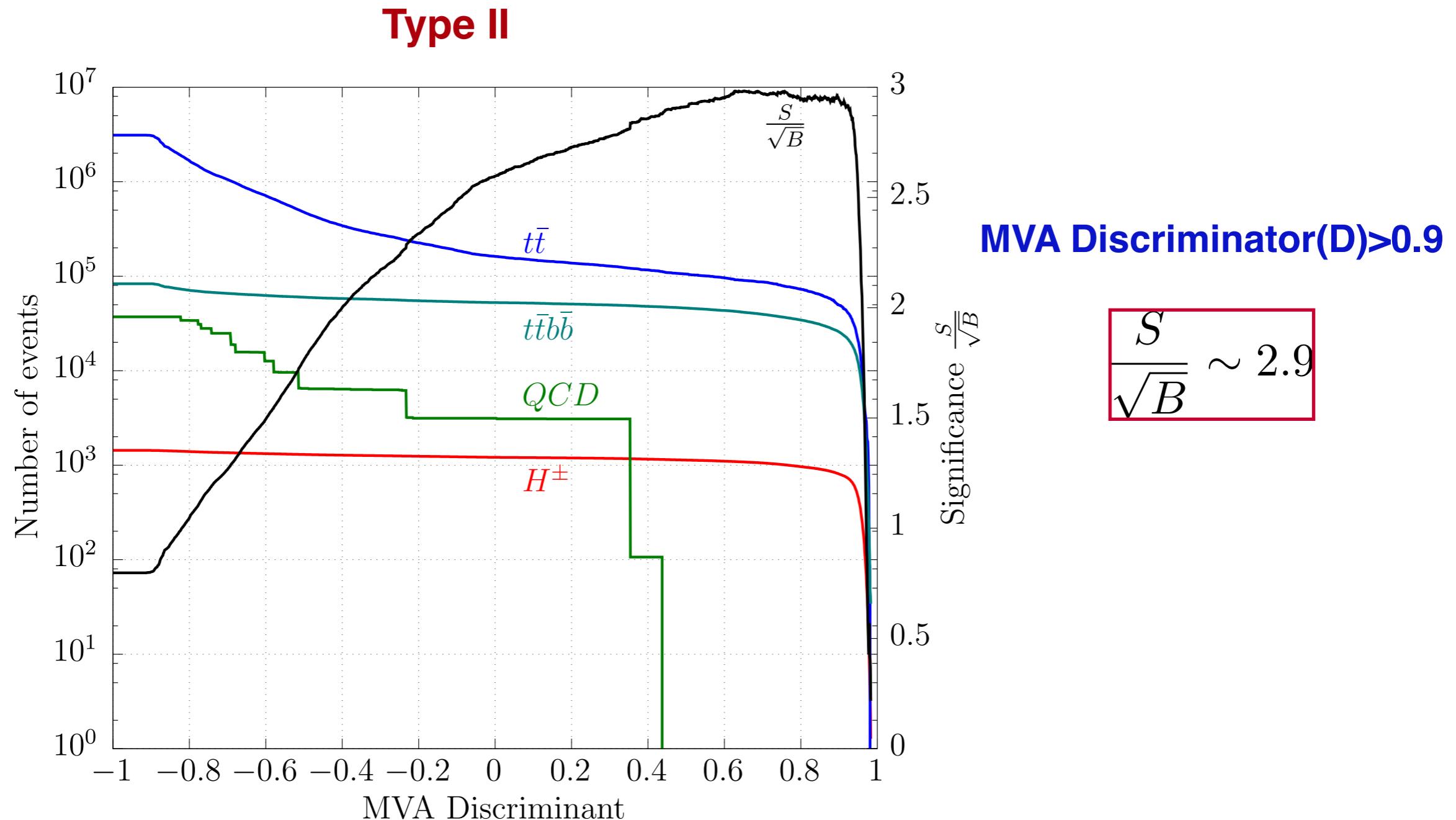
MVA analysis: using TMVA framework, BDT method

Rank	Variables	Description
1	H_T^b	Sum of p_T of all b jets
2	m_{bqq}	Mass of the tagged top jet
3	$m_{b\bar{b}}^{12}$	Invariant of two b jets
4	m_{tb_2}	Invariant mass of tagged top jet and second b jet
5	H_T/MHT	Ratio over H_T and MHT
6	$p_T^{j_1}$	p_T of leading un tagged jet
7	H_T	Scalar sum of p_T of all un-tagged jets
8	p_T^{bjet}	p_T of leading b jet
9	$p_{T_1}^{bjet}$	p_T of 2nd b jet after top tagging
10	MHT	Vector sum of p_T of jets

MVA Discriminator

Leptonic Final state

$M_H^\pm = 500 \text{ GeV}$, $\tan \beta = 30$, $L = 300 fb^{-1}$



Signal Sensitivity(1)

Hadronic(Leptonic)

$$\tan \beta = 30 \quad \sin(\beta - \alpha) = 1$$

Type II

$m_{H^\pm} (GeV) \rightarrow$	S/\sqrt{B}			
	300	500	800	1000
$\mathcal{L} = 300 \text{ fb}^{-1}$	6.1 (5.2)	2.7 (2.94)	0.61 (0.96)	0.22 (0.39)
$\mathcal{L} = 1000 \text{ fb}^{-1}$	11.0 (9.5)	4.8 (5.4)	1.1 (1.7)	0.40 (0.71)
$\mathcal{L} = 3000 \text{ fb}^{-1}$	19.1 (16.5)	8.4 (9.3)	1.9 (3.0)	0.70 (1.2)

**For Type II with high luminosity
Charged Higgs mass $\sim 600 \text{ GeV}$ can be probed**

Signal Sensitivity(2)

Sensitivity for all classes of model

$$\tan \beta = 30 \quad \sin(\beta - \alpha) = 1$$

Hadronic(Leptonic)

m_{H^\pm} (GeV)	\mathcal{L} (in fb^{-1})	Type I	Type II	Type III	Type IV
300	300	0.043 (0.037)	7.4 (6.4)	0.16 (0.14)	0.042 (0.037)
	1000	0.08 (0.07)	13.5 (11.6)	0.30 (0.26)	0.08 (0.07)
	3000	0.14 (0.12)	23.3 (20.1)	0.51 (0.44)	0.14 (0.12)
500	300	0.017 (0.019)	3.1 (3.4)	0.09 (0.10)	0.017 (0.019)
	1000	0.031 (0.034)	5.6 (6.2)	0.17 (0.18)	0.031 (0.034)
	3000	0.053 (0.059)	9.8 (10.8)	0.29 (0.32)	0.053 (0.059)
800	300	0.004 (0.006)	0.71 (1.1)	0.02 (0.03)	0.004 (0.006)
	1000	0.007 (0.011)	1.3 (2.0)	0.04 (0.06)	0.007 (0.011)
	3000	0.01 (0.02)	2.2 (3.5)	0.07 (0.11)	0.01 (0.02)

Type II model promising for mass ~ 600 GeV

Signal Sensitivity(3)

Sensitivity for all classes of model

$$\tan \beta = 3 \quad \sin(\beta - \alpha) = 1$$

Hadronic(Leptonic)

m_{H^\pm} (GeV)	\mathcal{L} (in fb^{-1})	Type I	Type II	Type III	Type IV
300	300	4.3 (3.7)	4.3 (3.7)	4.3 (3.7)	4.3 (3.7)
	1000	7.8 (6.7)	7.9 (6.8)	7.9 (6.8)	7.8 (6.7)
	3000	13.5 (11.7)	13.7 (11.8)	13.7 (11.8)	13.5 (11.7)
500	300	1.7 (1.9)	1.7 (1.9)	1.7 (1.9)	1.7 (1.9)
	1000	3.1 (3.4)	3.1 (3.5)	3.1 (3.5)	3.1 (3.4)
	3000	5.3 (5.9)	5.4 (6.0)	5.4 (6.0)	5.3 (5.9)
800	300	0.39 (0.62)	0.40 (0.63)	0.40 (0.63)	0.39 (0.62)
	1000	0.72 (1.1)	0.73 (1.1)	0.73 (1.1)	0.72 (1.1)
	3000	1.2 (2.0)	1.3 (2.0)	1.3 (2.0)	1.2 (2.0)

**Promising for mass up to ~ 600 GeV
for high luminosity**

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Summary

Discovery potential of charged Higgs of Intermediate to Heavier masses are explored within the framework of 2HDM

Top jet is tagged using jet substructure technique

With HL LHC, charged Higgs mass ~ 600 can be probe

More detailed investigation is required,