Charged Higgs Search at LHC and Future Colliders

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Introduction (1)

[G.C. Branco et al., Phys. Rep. 516 (2012) 1]

Both scalar SU(2) doublets and singlets are compatible with ρ=1. One of the simplest extension is the 2 Higgs Doublet Model (2HDM):

SUSY requires 2 Higgs: MSSM

Peccei-Quinn model to remove CPV term in QCD Lagrangian

Baryogenesis with CPV can be realized in 2HDM

The general CP and flavor conserving double Higgs Lagrangian:

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

The potential minimum is given by the following VEV:

$$
\langle \Phi_1 \rangle_0 = \begin{pmatrix} 0 \\ \frac{v_1}{\sqrt{2}} \end{pmatrix}, \quad \langle \Phi_2 \rangle_0 = \begin{pmatrix} 0 \\ \frac{v_2}{\sqrt{2}} \end{pmatrix}
$$

Three scalars are eaten by the W/Z bosons, with 5 remaining (2 charged, 1 CP odd, and 2 CP even)

Introduction (2)

Both the two charged scalars and two pseudoscalars ($\eta_{1,2}$) have the mass matrix form:

$$\begin{pmatrix} v_2^2 & -v_1 v_2 \\ -v_1 v_2 & v_1^2 \end{pmatrix}$$

After diagonalization, the zero-mass Goldstone scalars are eaten, and a massive $H^{\pm}$ and A^0 remain. This give an important parameter: $\tan\beta = v_2/v_1$

Another important angular parameter, α, diagonalizes the masses of 2 scalars ($\rho_{1,2}$). Thus, we have

$$A = \eta_1 \sin\beta - \eta_2 \cos\beta$$

$$\begin{aligned} h &= \rho_1 \sin\alpha - \rho_2 \cos\alpha \\ H &= -\rho_1 \cos\alpha - \rho_2 \sin\alpha \end{aligned}$$

$$\begin{aligned} H^{\rm SM} &= \rho_1 \cos\beta + \rho_2 \sin\beta \\ &= h \sin(\alpha - \beta) - H \cos(\alpha - \beta) \end{aligned}$$

In the alignment limit, $\alpha-\beta \sim -\pi/2$, h is SM like and H decouples

To avoid FCNC at tree-level, with terms like $y^1_{ij}\bar{\psi}_i\psi_j\Phi_1 + y^2_{ij}\bar{\psi}_i\psi_j\Phi_2$, impose the discrete symmetry:

$\Phi_1 \rightarrow -\Phi_1$ for type I, and $\Phi_1 \rightarrow -\Phi_1, d_R^i \rightarrow -d_R^i$ for type II

Charged Higgs production

The general flavor-conserving Yukawa coupling for charged Higgs:

$$-H^{+}\left(\frac{\sqrt{2}V_{ud}}{v}\bar{u}(m_u P_L X + m_d P_R Y)d + \frac{\sqrt{2}}{v}m_L Z \bar{\nu}_L l_R\right) + H.c.$$

For type II:
X=cotβ,
Y=Z=-tanβ

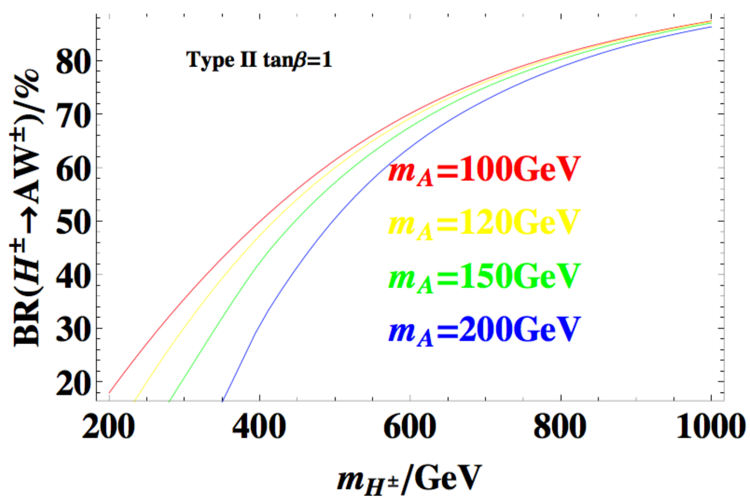
The s-channel $H^{\pm}$ production matrix element is

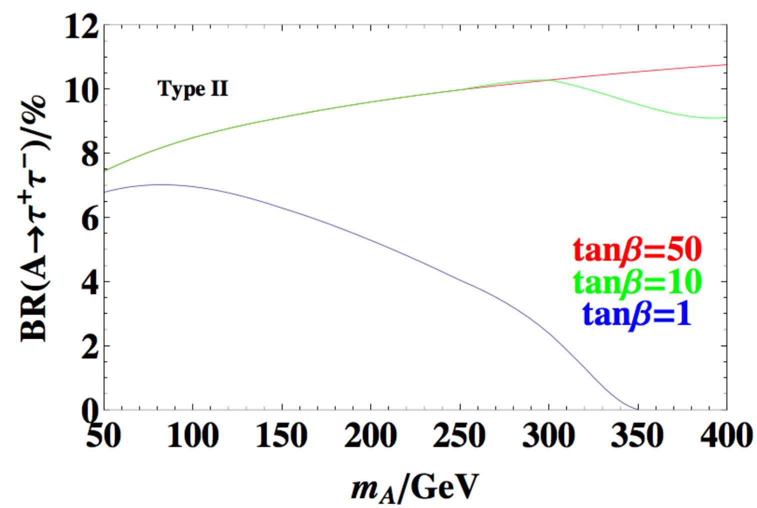
$$\overline{|\mathcal{M}|^2} = \frac{V_{ud}^2}{v^2}(m_u^2 X^2 + m_d^2 Y^2)$$

The largest matrix element corresponds to u=**c**, d=**s/b** (Heavy Quark Fusion), and $\tan\beta = \sqrt{m_u / m_d}$. In the alignment limit and assuming H^0 is heavier than $H^{\pm}$, the main decay modes for $H^{\pm}$ are

$$H^{+} \to t\bar{b}, \quad H^{+} \to W^{+}A$$

In very high tanβ, $H^{+} \to \tau\nu$ is also important





Charged Higgs production

The more interesting FCNC case is type III: in the Higgs basis, the two doublets can be rotated such that $\langle\Phi_1\rangle = \left(0, \upsilon/\sqrt{2}\right)^T, \langle\Phi_2\rangle = (0,0)^T$. The quark sector Yukawa:

$$-\mathcal{L}_Y^q = \frac{\sqrt{2}}{v}\left[M_{ij}^U \overline{Q_{iL}}\widetilde{\Phi}_1 u_{jR} + M_{ij}^D \overline{Q_{iL}}\Phi_1 d_{jR}\right] + \left[Y_{ij}^U \overline{Q_{iL}}\widetilde{\Phi}_2 u_{jR} + Y_{ij}^D \overline{Q_{iL}}\Phi_2 d_{jR}\right] + \text{h.c.}$$

In general, it is impossible to diagonalize M and Y simultaneously. The charged sector reads

[H.J. He, C.P. Yuan, PRL 83 (1999) 28]

$$H^+[\overline{t_R}\ (\widehat{Y}_U^\dagger V)_{tb}\ b_L - \overline{t_L}\ (V\widehat{Y}_D)_{tb}\ b_R] + H^+[\overline{c_R}\ (\widehat{Y}_U^\dagger V)_{cb}\ b_L - \overline{c_L}\ (V\widehat{Y}_D)_{cb}\ b_R\ ] + \text{h.c.}$$

V is CKM matrix

Of course all $H^\pm$ couplings are flavor changing, but we can have the flavor mixing scenario of $H^\pm$-c-b coupling, which is closely related to FCNC H^0-t-c:

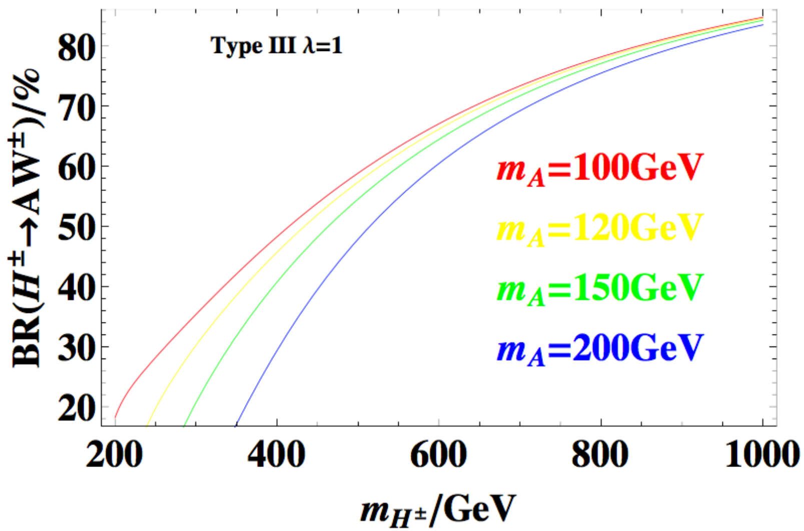
$$(\widehat{Y}_U^\dagger V)_{cb} \simeq \widehat{Y}_{tc}^{U*} V_{tb} + \widehat{Y}_{cc}^{U*} V_{cb} \simeq \widehat{Y}_{tc}^{U*}$$

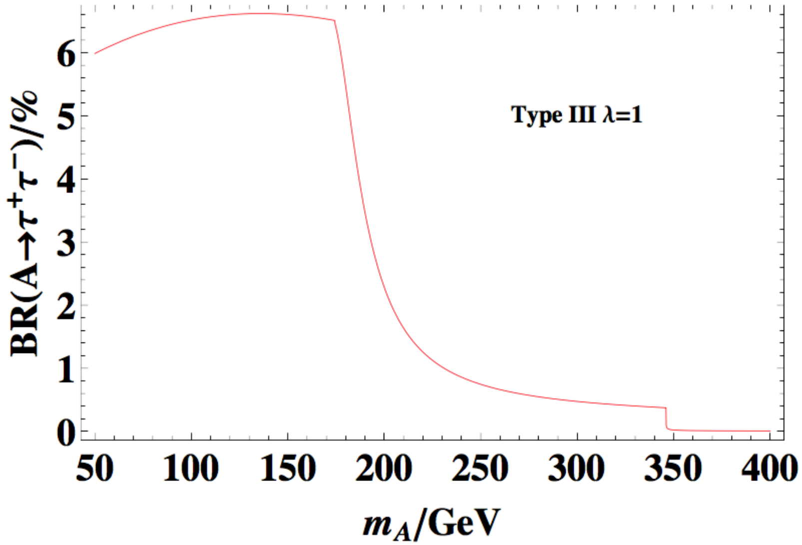
According to Cher-Sher Ansatz: $\hat{Y}^F = \lambda_{ij}^F \sqrt{2m_i m_j}/\upsilon$, we have the matrix element for type III $c\bar{b} \rightarrow H^+$ production:

$$\overline{|\mathcal{M}|^2} \approx \frac{\lambda_{ct}^2 m_c m_t}{v^2}$$

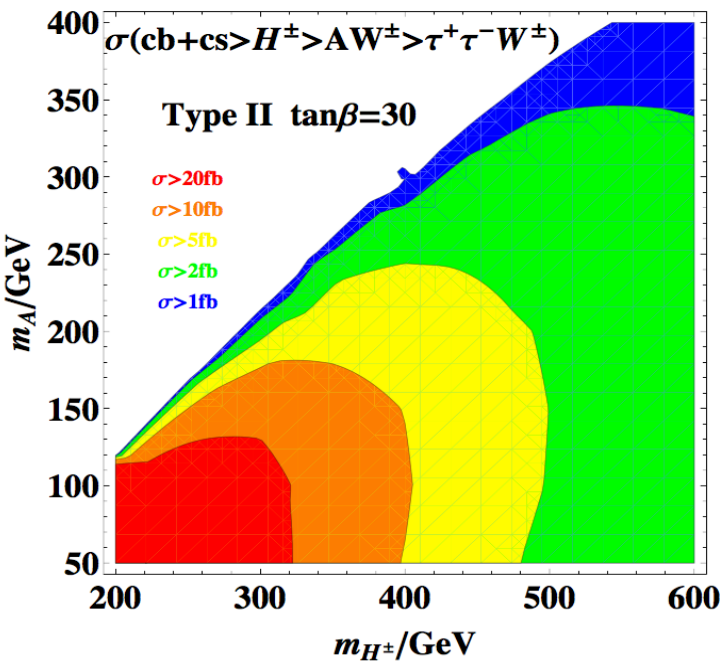
Charged Higgs through HQF

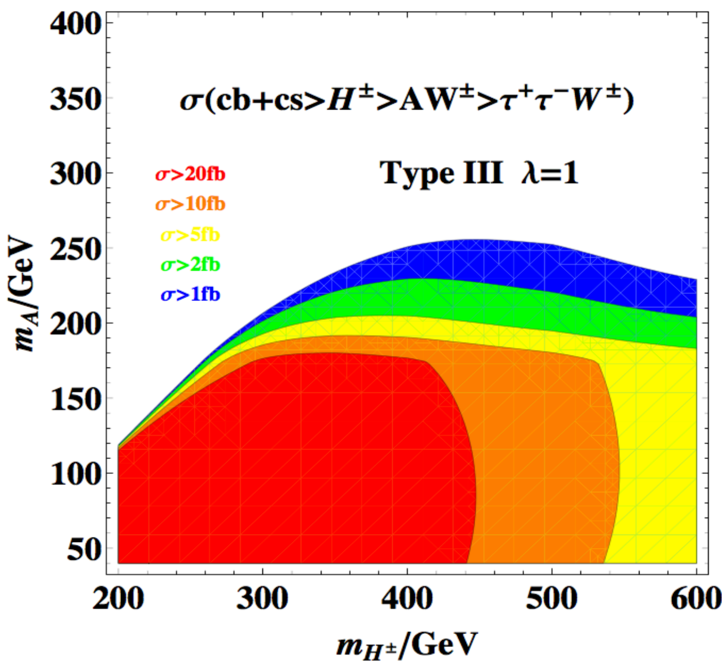
[X. Chen, H.J. He, R.Q. Xiao, C. Zhang, work to be submitted]





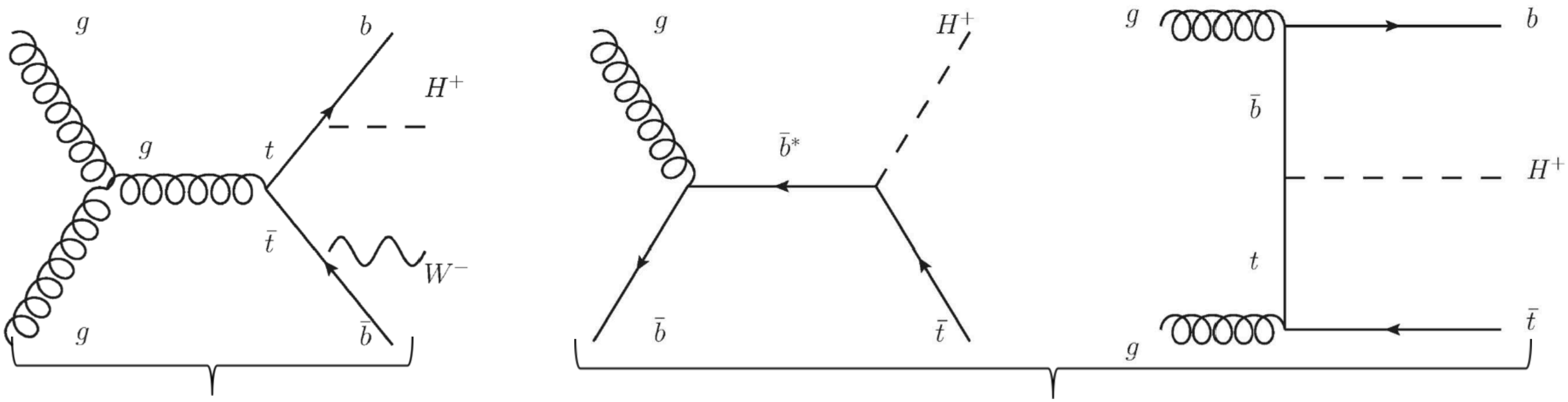
When $A \to t\bar{c}, \bar{t}c$ opens, the BR of $A \to \tau\tau$ drops significantly





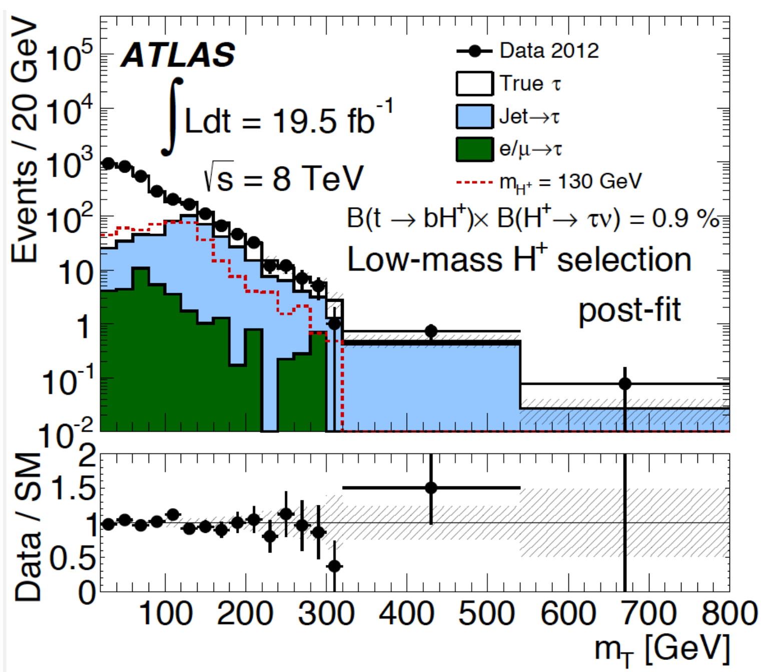
Charged Higgs search in ATLAS (H->τν)

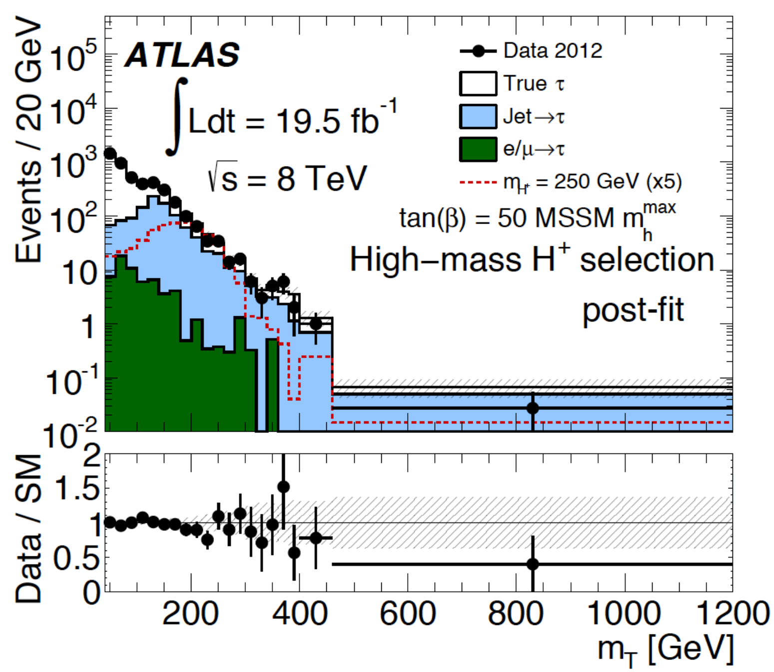
[JHEP03 (2015) 088]



Low-mass

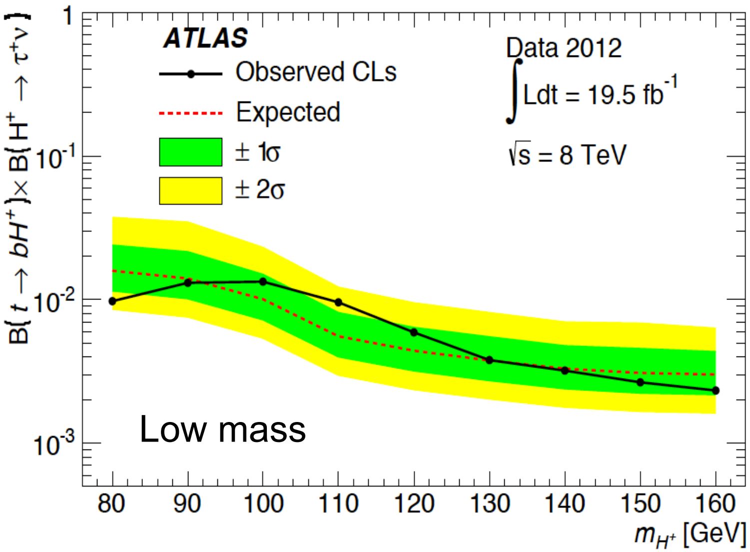
High-mass

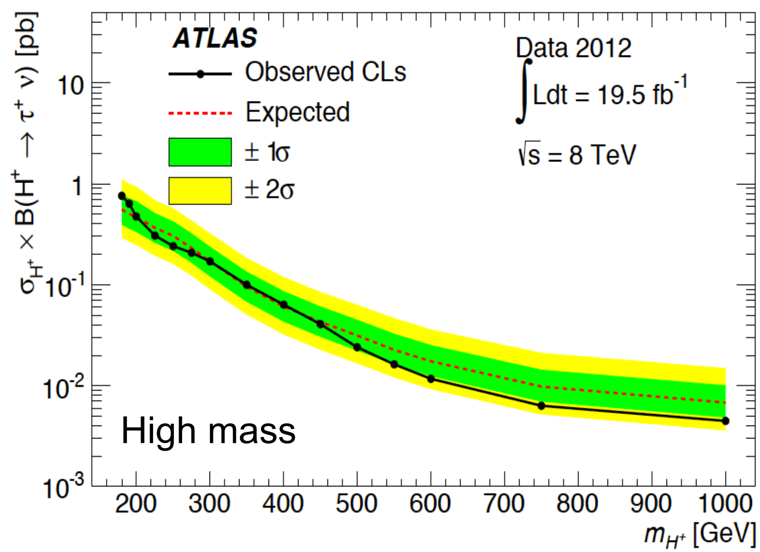




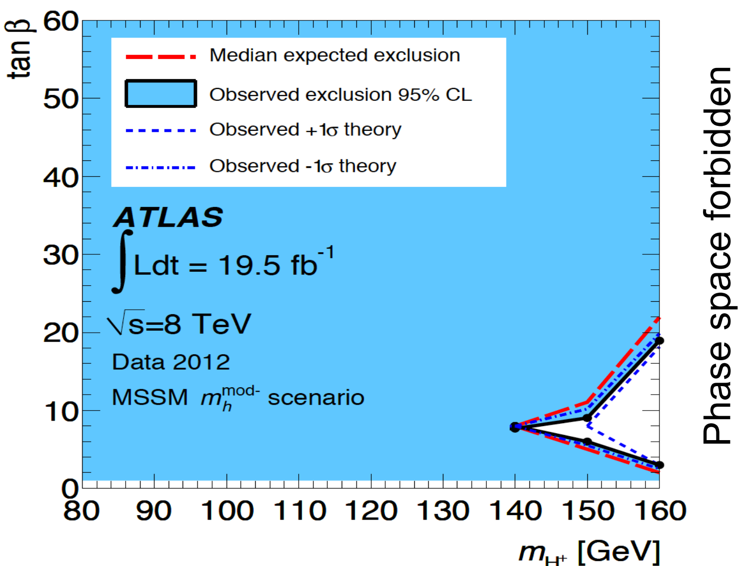
Charged Higgs search in ATLAS (H->τν)

- Model independent and MSSM (m_h^{mod}) search limits:

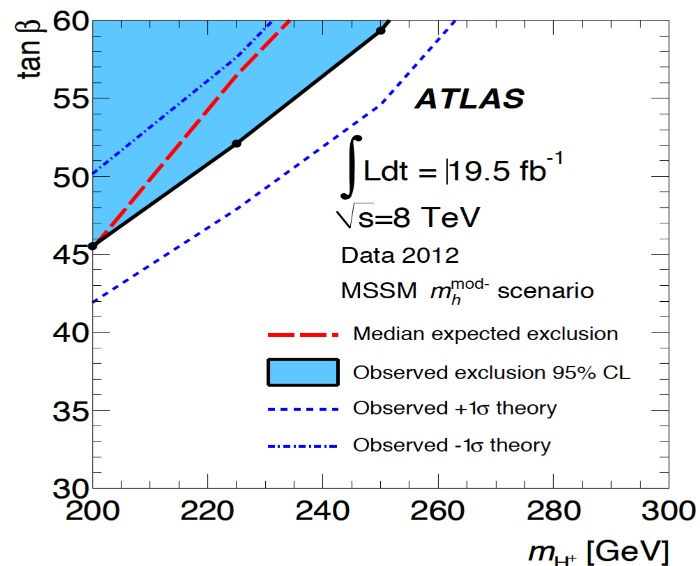




m_h^{mod-}



Low mass

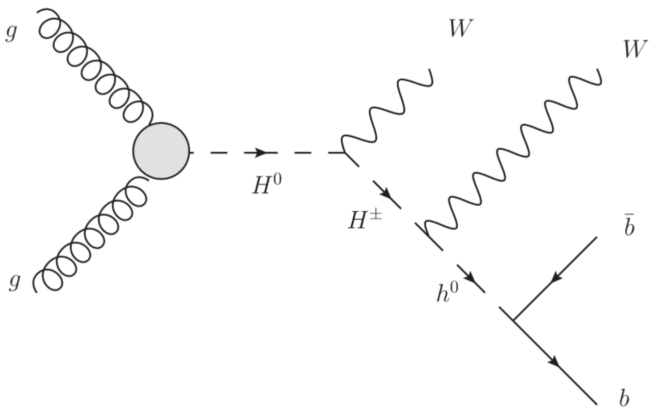


High mass

Charged Higgs search in ATLAS (H^0->W^+H^-)

[PRD 89, 032002 (2014)]

Charged Higgs search has also been carried out in the cascade decays:

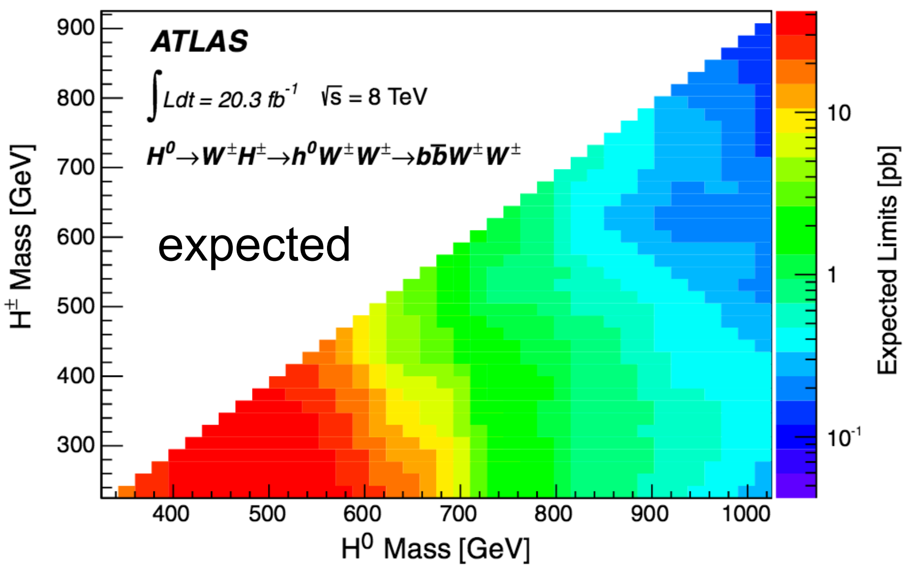


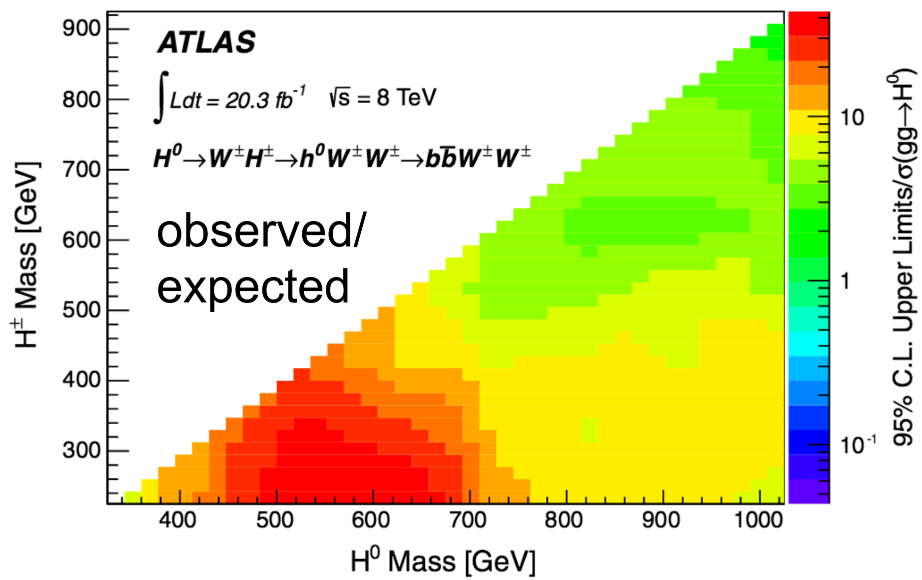
$$gg \to H^0 \to W^\mp H^\pm \to W^\mp W^\pm h^0 \to W^\mp W^\pm b\bar{b}$$

One W decays leptonically, and one hadronically

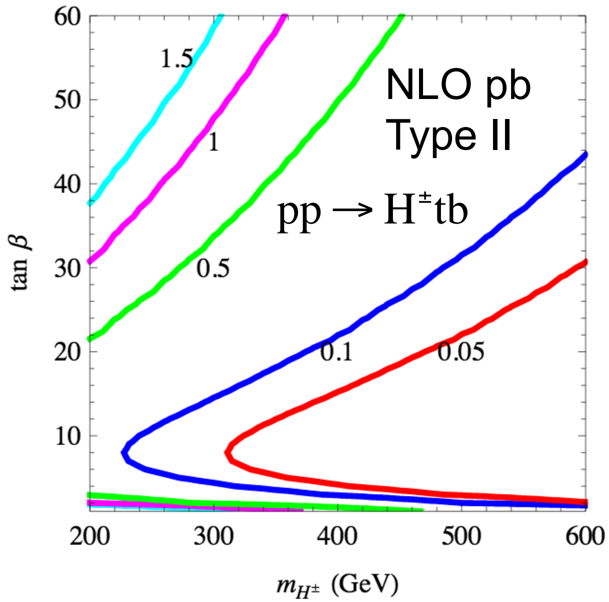
BDT analysis with input varianles m(bb), m(bbW), m(bbWW), ΔR_{bb}, m_T

Different BDT for different signal mass points





Search in pp->tbH$^{\pm}$->tbAW$^{\pm}$



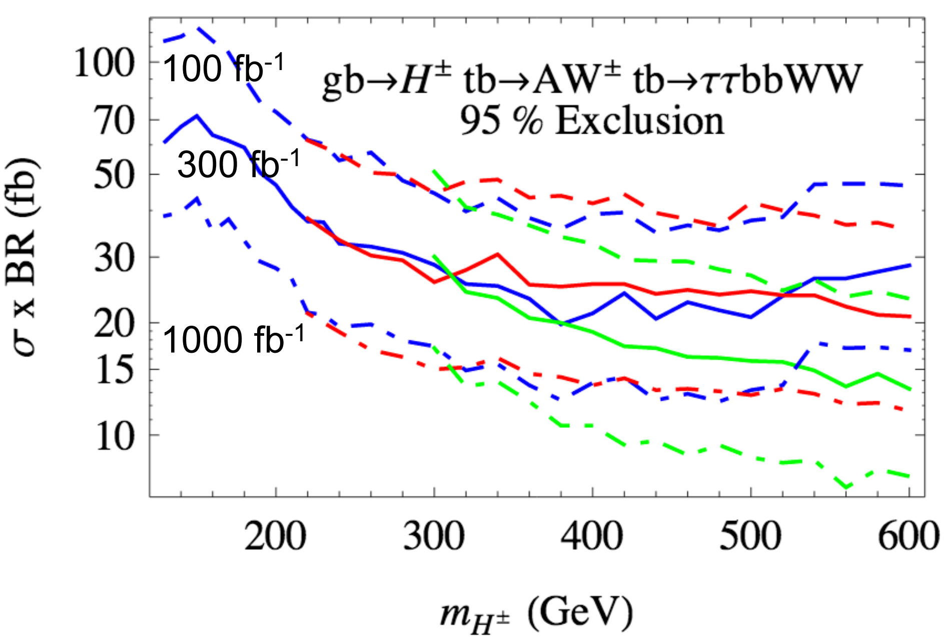
[B. Coleppa, F. Kling, S. Su, JHEP12 (2014) 148]

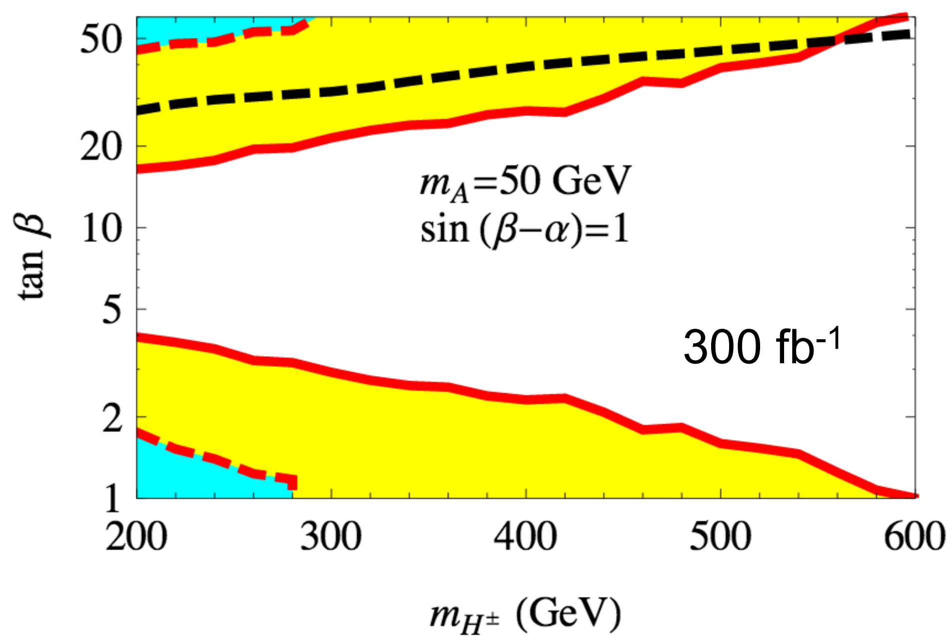
Look at $pp \to H^{\pm}tb \to AW^{\pm}tb \to \tau\tau bbWW$

One W decays hadronically, one leptonically

Divide into 0/1/2 lepton (e/μ) signal regions

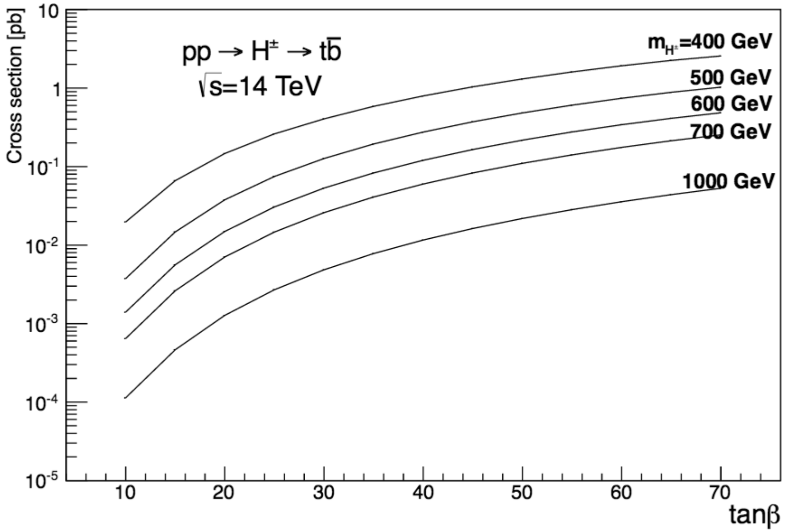
Main background $t\bar{t}, t\bar{t}\tau\tau, W\tau\tau$. Signal xsec is at sub-fb level after cuts

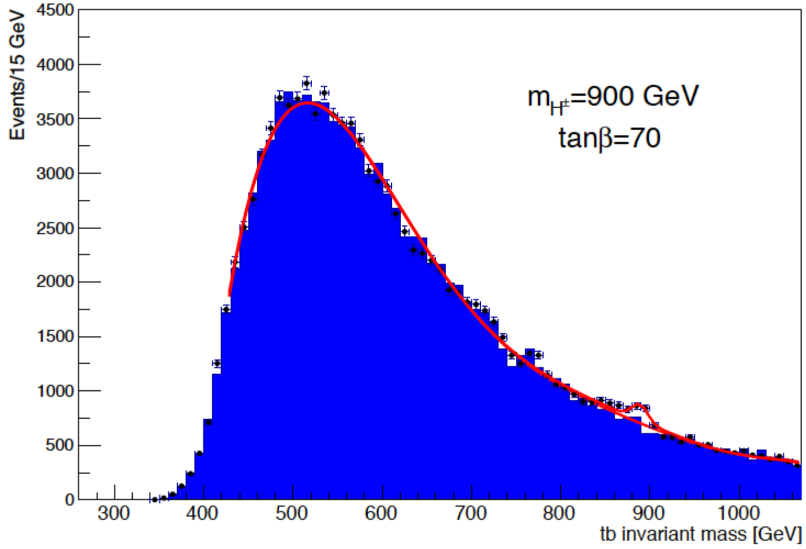


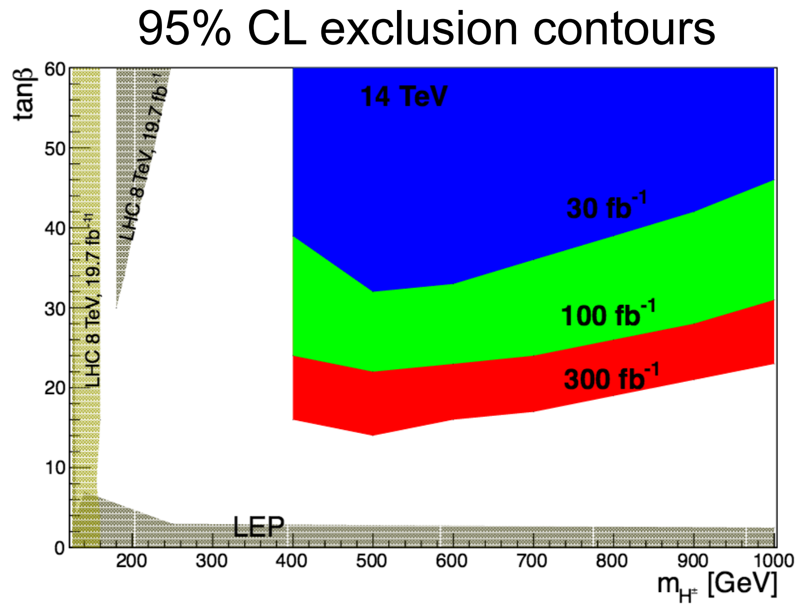


The s-channel search in pp->H$^{\pm}$->tb

[M. Hashemi, G. Haghighat, arXiv:1511.00874]







MSSM m_h^{max} scenario signal

Very large background from ttbar and single top

Use the boosted topology of top from H$^{\pm}$ decay – use HepTopTagger

tb mass bump hunting – able to detect charge Higgs at ~1 TeV

Charged Higgs through HQF

[X. Chen, H.J. He, R.Q. Xiao, C. Zhang, work to be submitted]

Our main search channels are s-channel $H^{\pm}$ production with

$H^{\pm} \to W^{\pm}A \to l\nu\tau\tau$: trilepton channel, $H^{\pm} \to W^{\pm}A \to jj\tau\tau$: dilepton channel

In the trilepton channel, to fight background, we only take the 3-lepton (e/μ) , in which there is no Opposite-Sign-Same-Flavor pair (3l-no-OSSF), and 2-lepton+τ_h where the leptons are of Same-Sign (SS-2l+τ_h). A jet veto ($N_{jet}\leq1$) is required in 3l-no-OSSF (SS-2l+τ_h) is required to suppress the top

3l-no-OSSF:

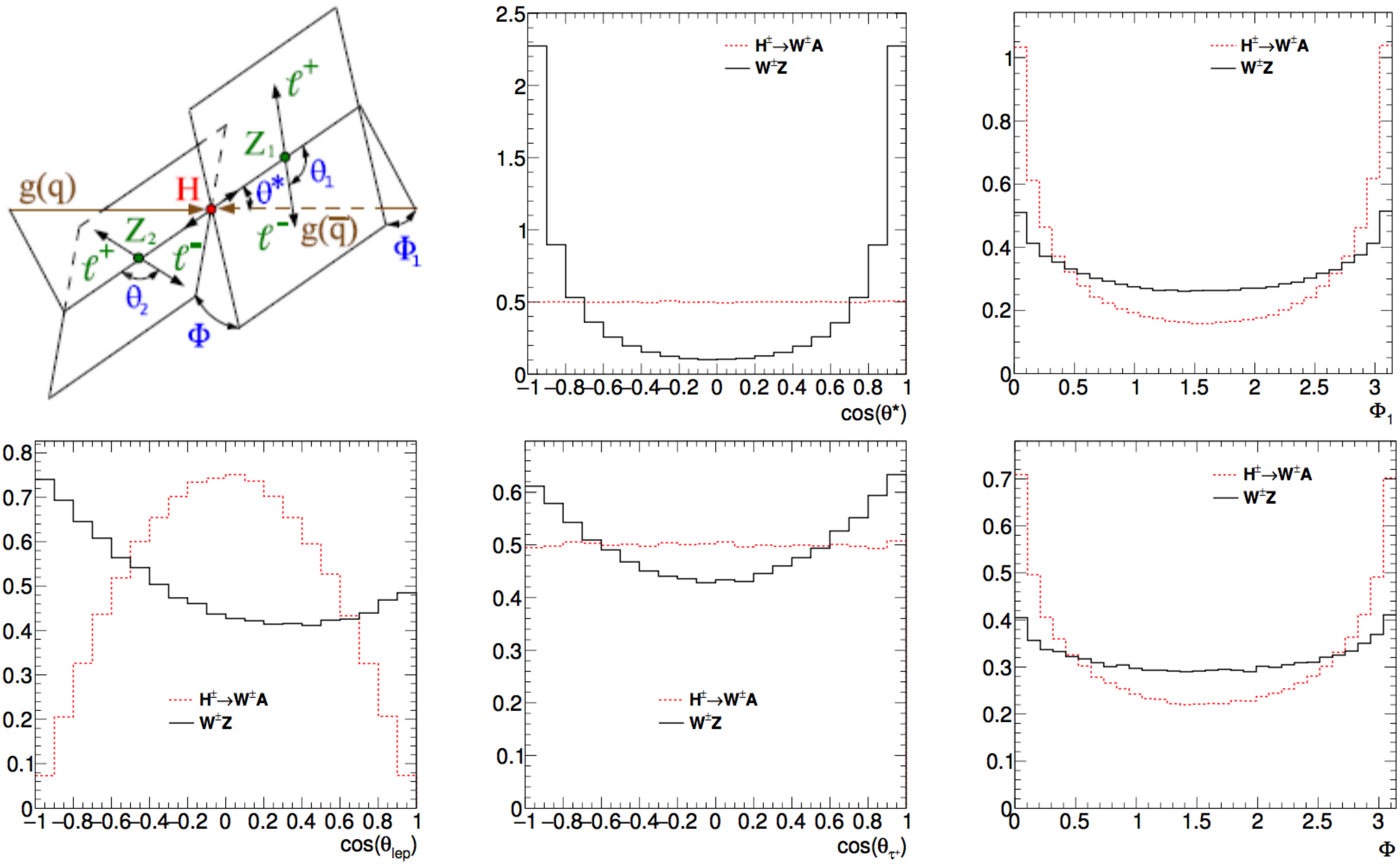
	$WZ \to l\nu 2\tau$	WWW	$ZZ \to 4\tau$	$ZZ \to 4l/2l2\tau$	WH/ZH	signal
no cut	198.7	1.341	11.57	92.8	100.7	1.000
exactly $3l$	1.0657	0.0127	0.0362	16.2653	0.7197	0.0188
net charge ±1	1.0657	0.0127	0.0362	16.2653	0.7197	0.0188
no SFOS	0.2669	0.0031	0.0092	0.0442	0.1186	0.0046
jet veto	0.2030	0.0022	0.0053	0.0247	0.0849	0.0029

SS-2l+τ_h:

	$WZ \to l\nu 2\tau$	WWW	$ZZ \to 4\tau$	$ZZ \to 4l/2l2\tau$	WH/ZH	signal
no cut	198.7	1.341	11.57	92.8	100.7	1.000
exactly $2l + \tau_h$	2.5507	0.0035	0.1295	3.8200	0.6656	0.0420
net charge ±1	2.5368	0.0035	0.1292	3.8034	0.6626	0.0418
SS-$2l$	1.2623	0.0011	0.0439	0.2443	0.2005	0.0206
$N_{jet} \geq 1$ veto, and b-jet veto	1.2095	0.0010	0.0403	0.2230	0.1849	0.0184

$\sigma_{H^{\pm}} \times BR(H^{\pm} \to W^{\pm}A \to l\nu\tau\tau) = 1$ fb is assumed in the table

Angular variables

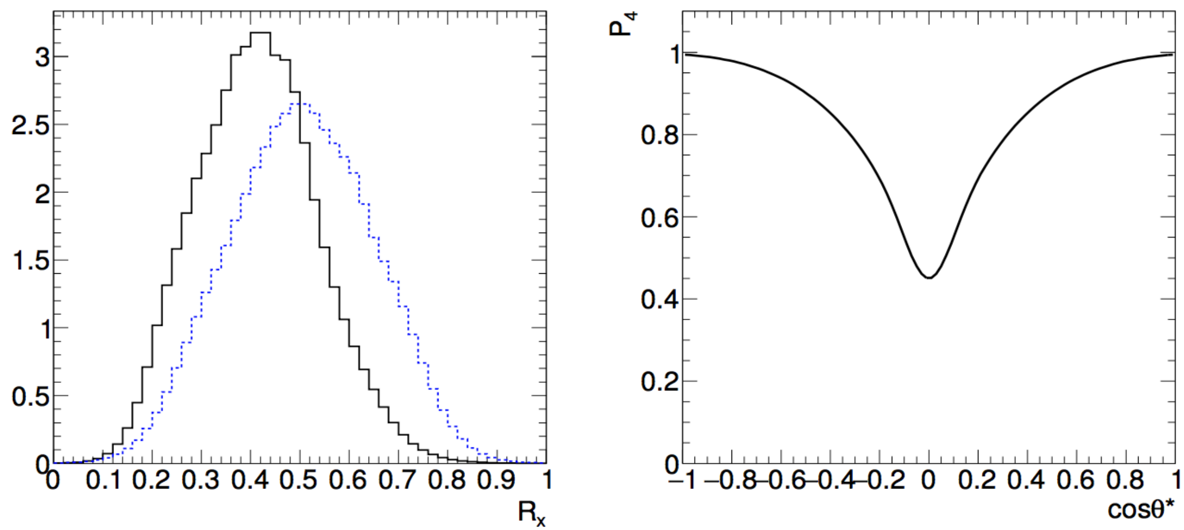


Five angular variables. Can be used for both mass reco. and background reduction

Mass reconstruction

To reconstruct the A and $H^{\pm}$ mass, a χ^2 is minimized per event:

$$\chi^2 = -2\ln\mathcal{P}_1(R_x) - 2\ln\mathcal{P}_2(\Phi) - 2\ln\mathcal{P}_3(\theta_l) - 2\ln\mathcal{P}_4(\theta^*) + \left(\frac{E^{mis}_{x,fit} - E^{mis}_x}{\sigma_{mis}}\right)^2 + \left(\frac{E^{mis}_{y,fit} - E^{mis}_y}{\sigma_{mis}}\right)^2.$$

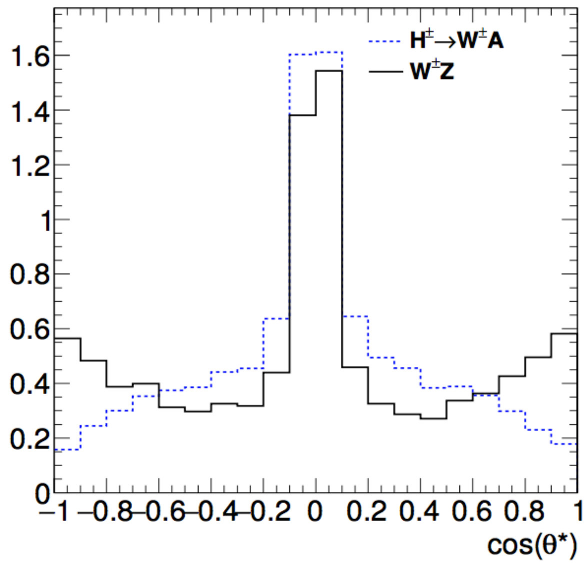


R_x is the ratio $x_1/(x_1+x_2)$, where $x_{1,2}$ are the fractional variables used in the di-tau collinear mass reconstruction

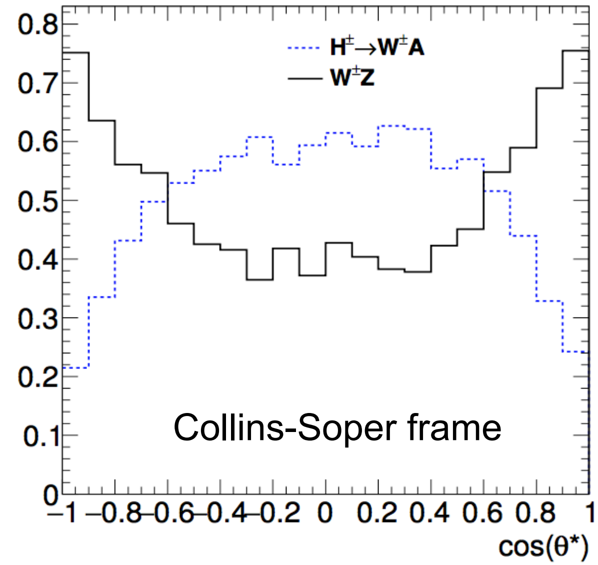
P_4 is a penalty term to correct for the cases where the wrong solution of p_z^{mis} from W decay is picked, as its solution is two-fold

Mass reconstruction

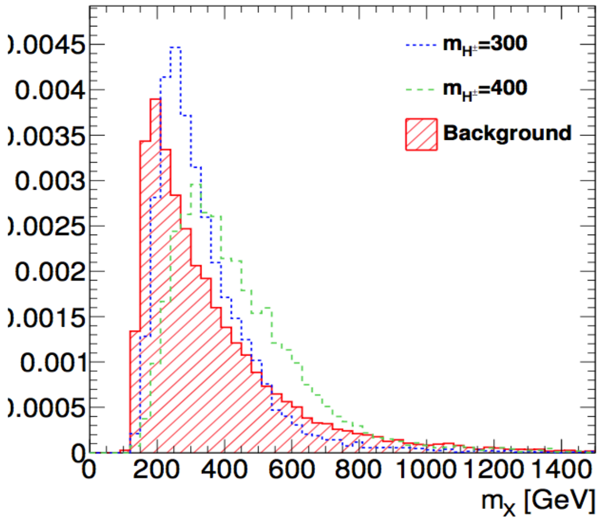
without penalty term

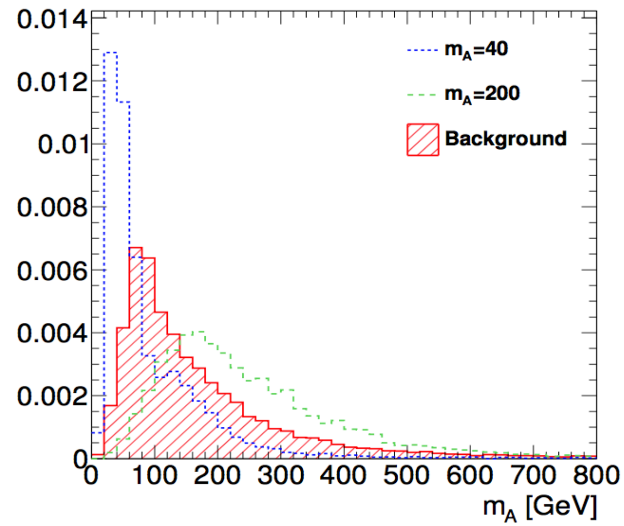


with penalty term



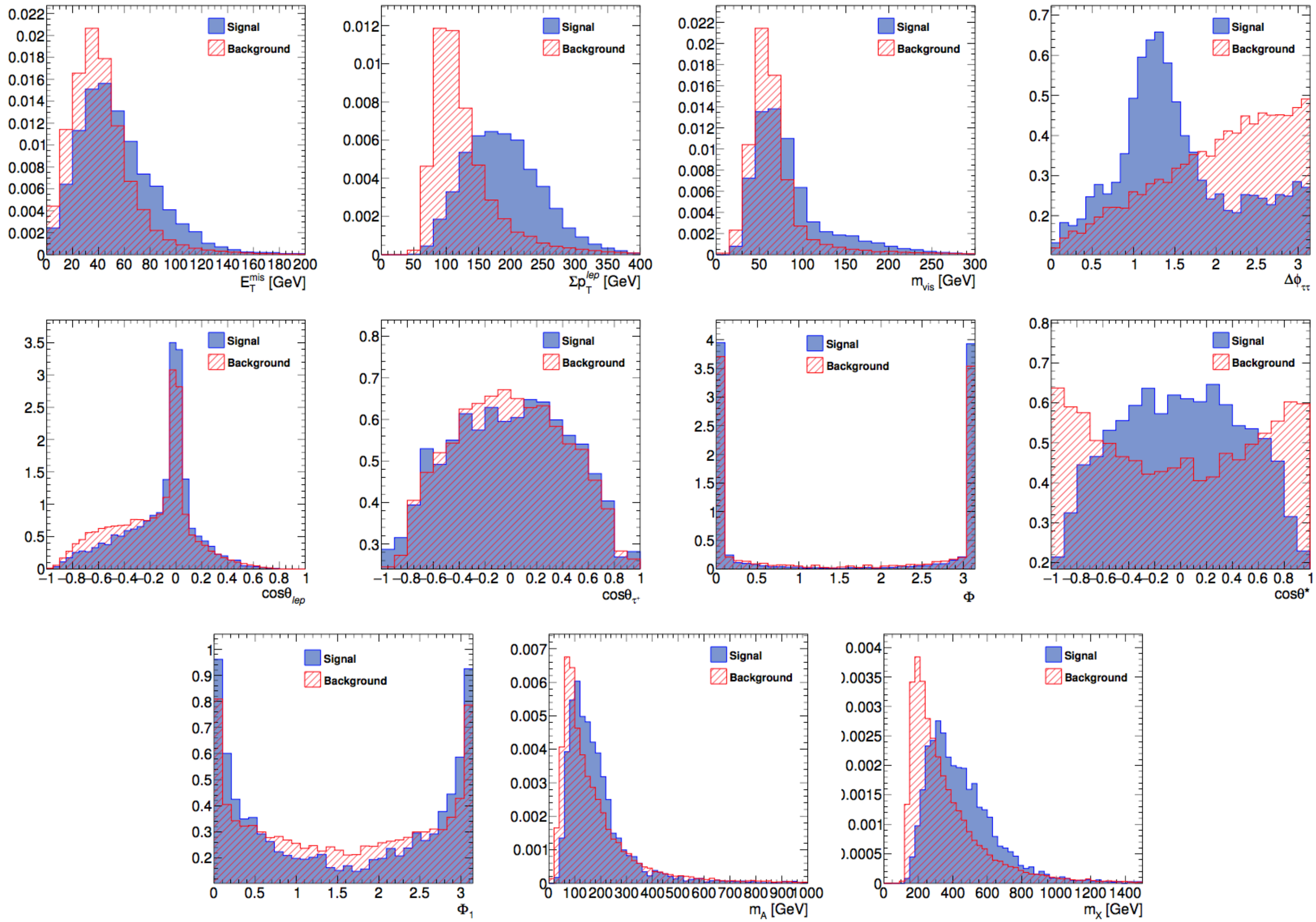
There is still a two-fold ambiguity in assigning the two SS leptons to W and A decay – determined by the minimization as well. The reconstructed mass:





Multi-Variant Analysis

The angles and other kinematic variables can be used together in a MVA algorithm, such as Boosted Decision Trees (BDT), for the best signal-background separation

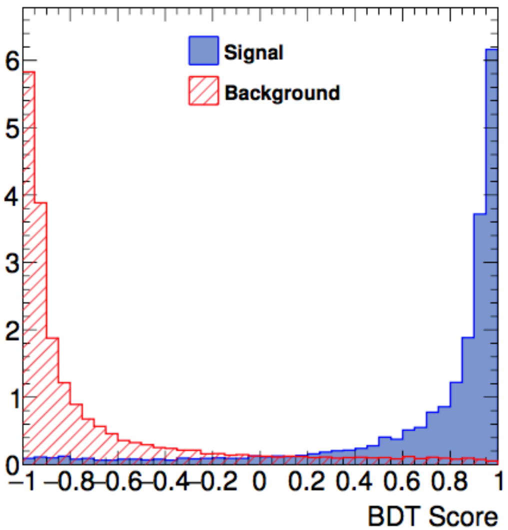


BDT output

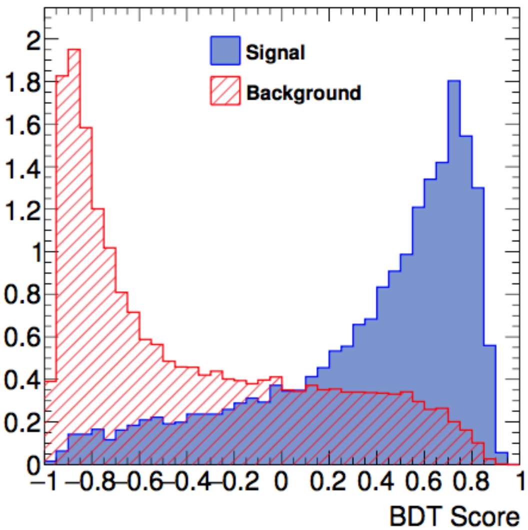
The signal-background separation is evident in the BDT output distributions. However, as we don't know the new scalar masses a priori, the analysis is mass dependent (one BDT training for each mass point) – analogous to the mass bump hunting

Separate the simulation samples into two halves, one for training and the other for testing. The results are always based on the test samples

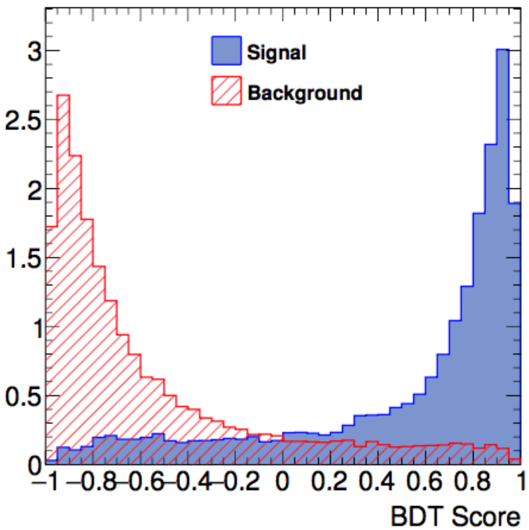
Specifically, gradient BDT is used. Overtraining is controlled by the MaxDepth parameter – we try to avoid the BDT being sensitive in the statistical fluctuation in the training sample, but try to avoid sacrificing discriminations if being too coarse



$(m_{H^\pm}, m_A) = (300, 40)$ GeV



$(m_{H^\pm}, m_A) = (400, 120)$ GeV



$(m_{H^\pm}, m_A) = (400, 280)$ GeV

Dilepton search channel

Although the $H^{\pm} \to W^{\pm} A \to jj\tau\tau$ channel suffers from larger background, it also has the advantage of A, H± mass reconstruction without ambiguity. The dilepton channel is further divided into $\tau_l\tau_l, \tau_l\tau_h, \tau_h\tau_h$ subchannels

$\tau_l\tau_l$

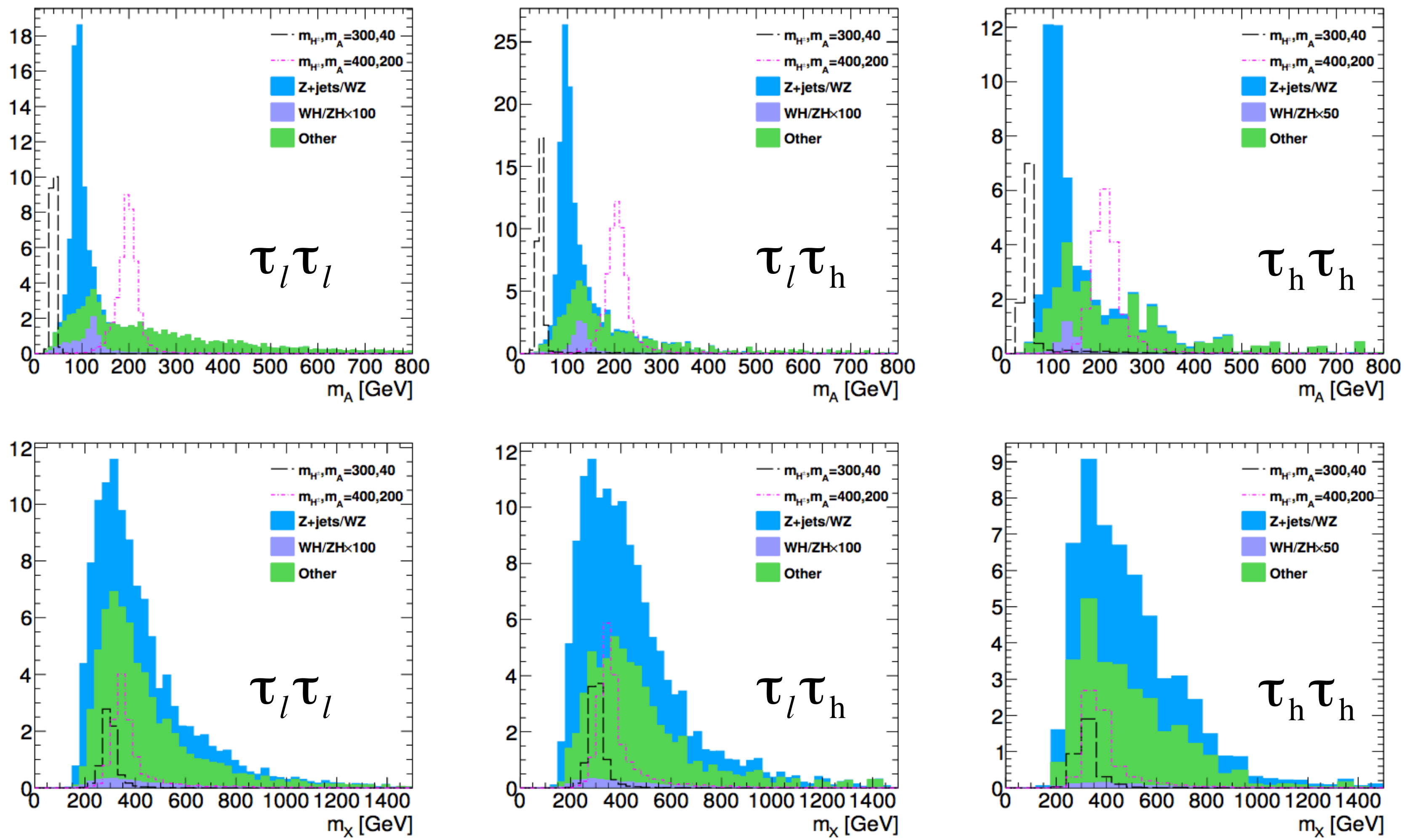
	$Z \to \tau\tau$	$WZ \to jj\tau\tau$	$t\bar{t}$	WH/ZH	signal
no cut	6.641×10^5	596.0	5.442×10^5	100.7	1.000
$\tau_l\tau_l$ p_T cut, $Z \to ll$ veto	3.748×10^3	4.603	9.554×10^3	4.160	0.0223
E_T^{mis}	822.8	2.081	7.859×10^3	2.911	0.0205
b-jet veto	807.5	1.987	2.151×10^3	2.747	0.0187
W jet cut	50.70	0.6186	166.8	0.5043	0.0110
$C_{mis} > 0.3$	49.28	0.6115	61.98	0.3082	0.0109

$\tau_l\tau_h$

	$Z \to \tau\tau$	$WZ \to jj\tau\tau$	$t\bar{t}$	$W \to l\nu$	WH/ZH	signal
no cut	6.641×10^5	596.0	5.442×10^5	8.001×10^6	100.7	1.000
$\tau_l\tau_h$ p_T	5.924×10^3	6.484	3.939×10^3	1.067×10^4	2.933	0.0428
E_T^{mis}	1.453×10^3	2.845	3.245×10^3	6.909×10^3	2.020	0.0365
b-jet veto	1.429×10^3	2.723	1.155×10^3	6.832×10^3	1.904	0.0334
W jet cut	86.23	0.8427	191.7	211.8	0.3296	0.0181
$C_{mis} > 0.2$	81.58	0.8201	95.66	79.10	0.2937	0.0178
$m_{T,1} < 40$	73.64	0.7581	35.06	31.64	0.2357	0.0151

Dilepton search channel

The ditau mass reconstruction is according to the Missing Mass Calculator (MMC):



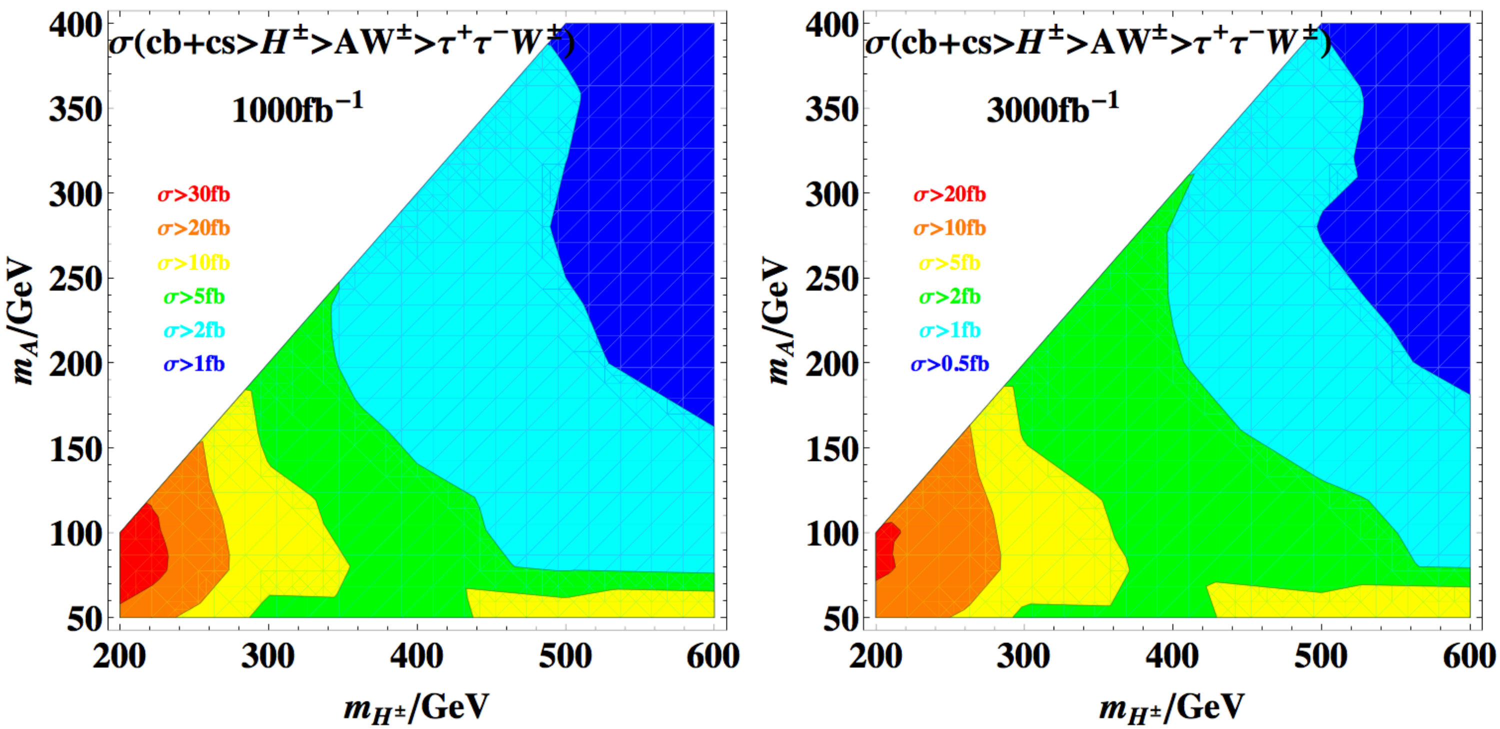
$$m_X = \sqrt{m_{H\pm}^2 - m_A^2}$$

Combined sensitivity

Cut-and-count analysis in each sub-channel based on the BDT output. The combined exclusion is through the following asymptotic formulas:

$$\mathrm{CL} = \frac{1}{2}\mathrm{erfc}\left(-\frac{Z}{\sqrt{2}}\right), \text{ with } Z = \sqrt{\sum_i Z_i^2}, \quad \text{and } Z_i = \sqrt{2s_i - 2b_i \ln\left(1 + \frac{s_i}{b_i}\right)}$$

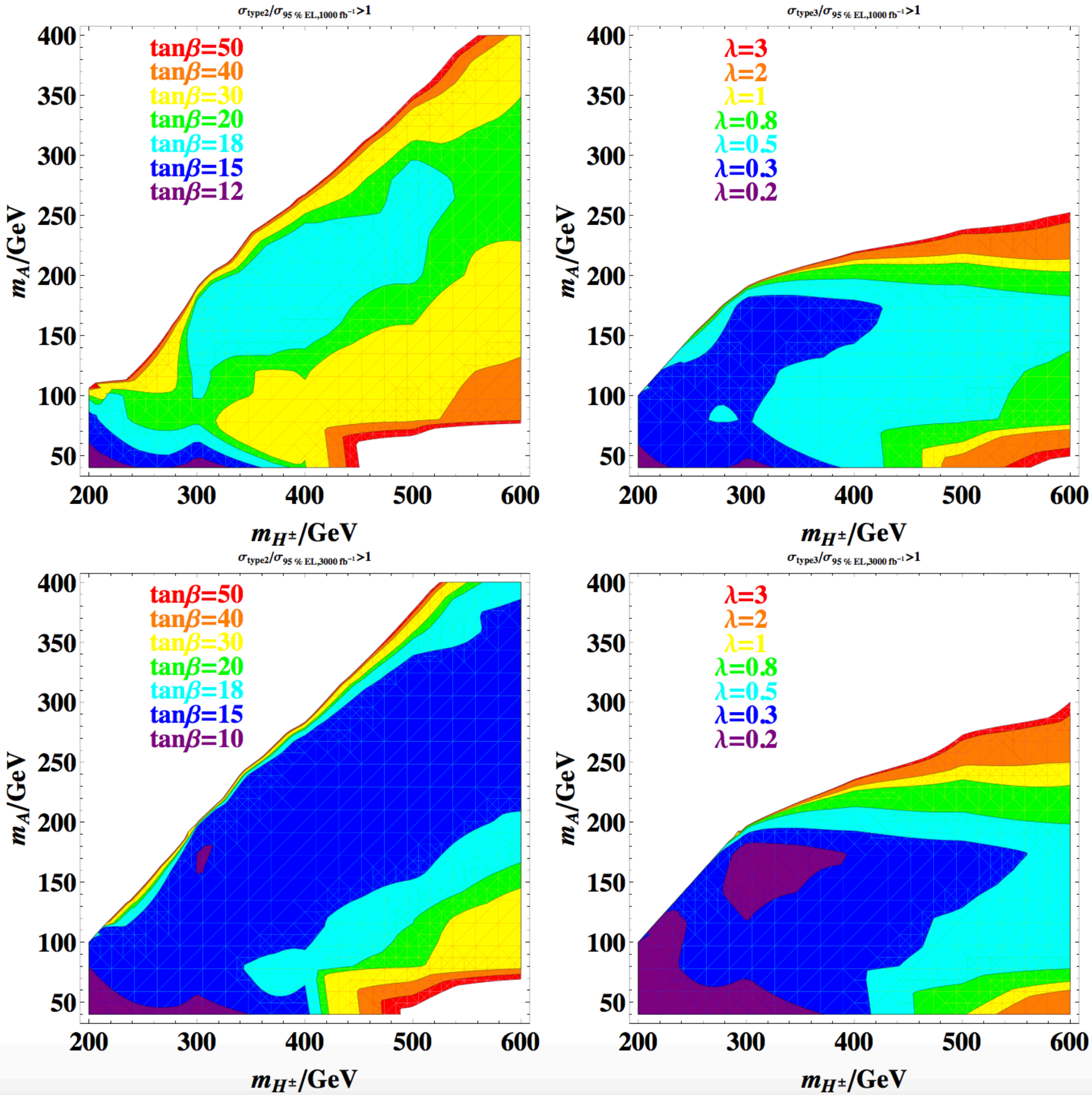
Model independent 95% CL limit on $\sigma_{H^\pm} \times \mathrm{BR}(H^\pm \to W^\pm A \to W^\pm \tau\tau)$:



Model dependent limits

Type II

Type III

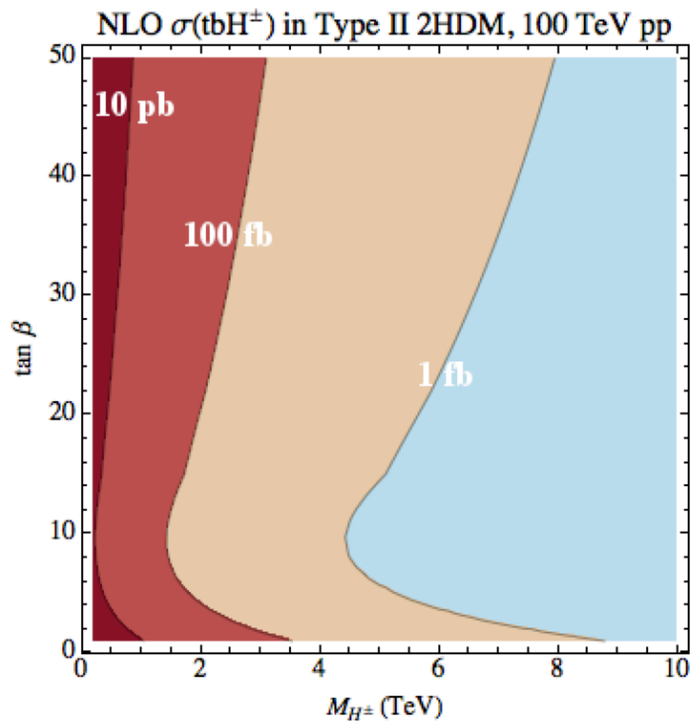


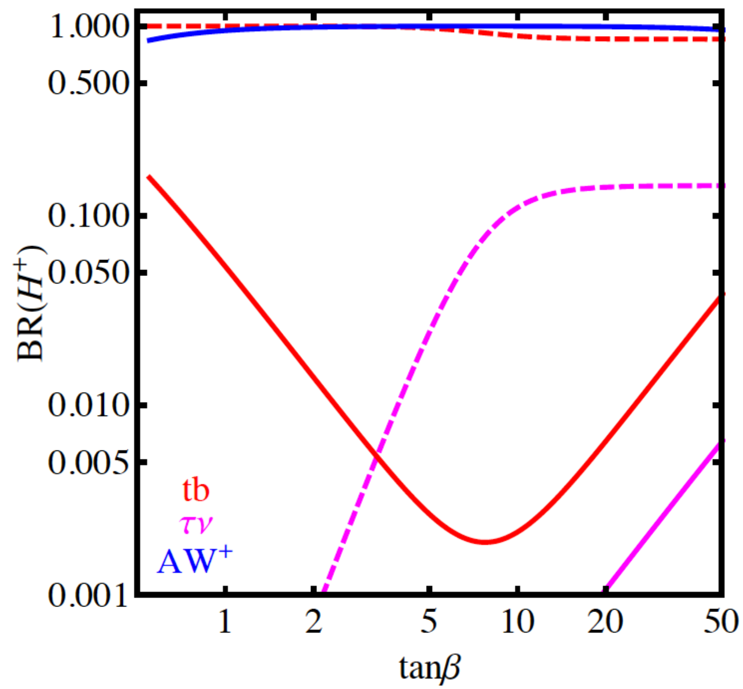
Type II

Type III

Charged Higgs in SppC

At 100 TeV pp collision SppC, the main production channel is still $tbH^{\pm}$. For charged Higgs with a mass of 500 GeV, the enhancement factor is about 90 and even higher for larger masses





MSSM is the most studied case. Compared to the generic 2HDM type II:

- No upper bound on the lightest Higgs
- Higgs self-coupling is arbitrary
- Mixing angle α is arbitrary (dependent on scalar masses and tanβ in MSSM)
- Decay of $H^{\pm} \rightarrow W^{\pm}A$ is allowed (kinematically forbidden in MSSM)

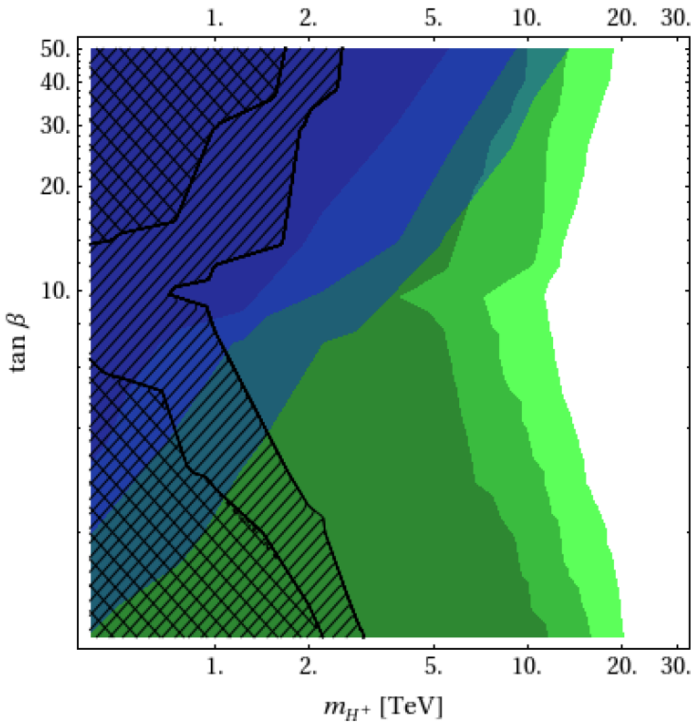
Charged Higgs in SppC

Main search channels for charged and neutral Higgs at SppC:

	$\tan\beta$	Channels
Neutral Higgs H^0, A	High	$pp \to bbH^0/A \to bb\tau\tau, bbbb$
	Intermediate	$pp \to bbH^0/A \to bbtt$
	Low	$pp \to H^0/A \to tt$
Charged Higgs $H^\pm$	High	$pp \to tbH^\pm \to tbtb, tb\tau\nu_\tau$
	Low	$pp \to tbH^\pm \to tbtb$

When H^0 is lighter than $H^\pm$, the following decays are also important:

$$H^\pm \to H^0 W, AW$$



The blue and green excluded regions corresponds to

$pp \to tbH^\pm \to tb\tau_h\nu_\tau$: blue

$pp \to tbH^\pm \to t_h bt_l b$: green

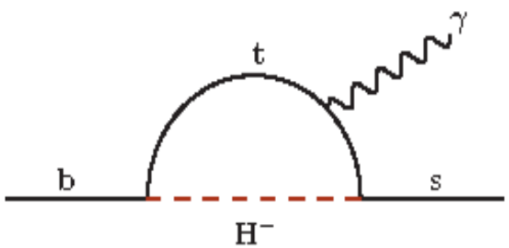
The cross-hatched and dashed regions correspond to expected LHC excluded regions with 300 and 3000 fb^{-1}

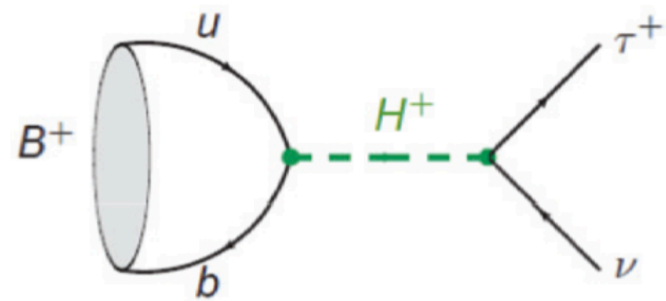
The two channel are complementary and extend the LHC reach significantly

Charged Higgs via flavor searches

[Charged 2012]

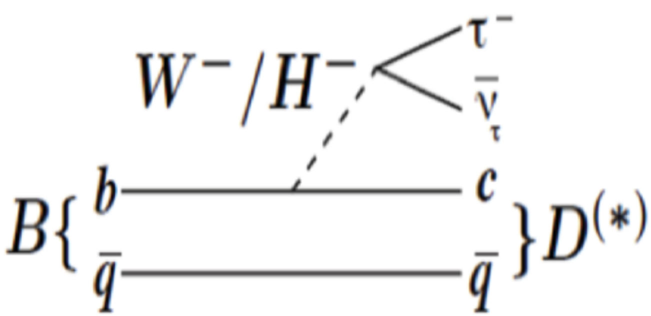
$B \to X_s \gamma$





$$\mathcal{B}(B^+ \to \tau^+ \nu) = \mathcal{B}_{SM} \times \left(1 - \frac{m_B^2}{m_{H^+}^2} \tan^2\beta\right)^2$$

$$\frac{B \to D^{(*)}\tau\nu}{B \to D^{(*)} l \nu}$$



Indirect search for charged Higgs can be carried out at LHCb and future SuperB

- $B_{u/d}$ physics: $B \to \tau\nu$
- τ physics: $\tau \to \mu\gamma$
- B_s physics
- Mixing parameters

The interest in charged Higgs is large enough for the formation of dedicated conference series in Uppsala: Charged 2006, 2008, …, 2014

Summary

Charged Higgs is a benchmark of the 2HDM. Searching for a charged Higgs is being carried out directly at LHC

Apart from the traditional search channels of associated charged Higgs production and $H^+ \to t\bar{b}, \tau\nu$ decays, the production through s-channel Heavy Quark Fusion and/or the decay $H^+ \to W^+A$ can provide a clean signal and extra sensitivity

Our study in the HQF channel shows that a changed Higgs with $\sigma \times BR$ at sub-fb level can be achieved with HL-LHC runs

Although direct searches are hard, the reach for charged Higgs can be significantly extended in future high energy colliders, such as SppC

Charged Higgs can be searched indirectly via precision flavor physics