LABORATORY OF FUNDAMENTAL AND APPLIED PHYSICS
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New charged Higgs boson discovery channel at the LHC

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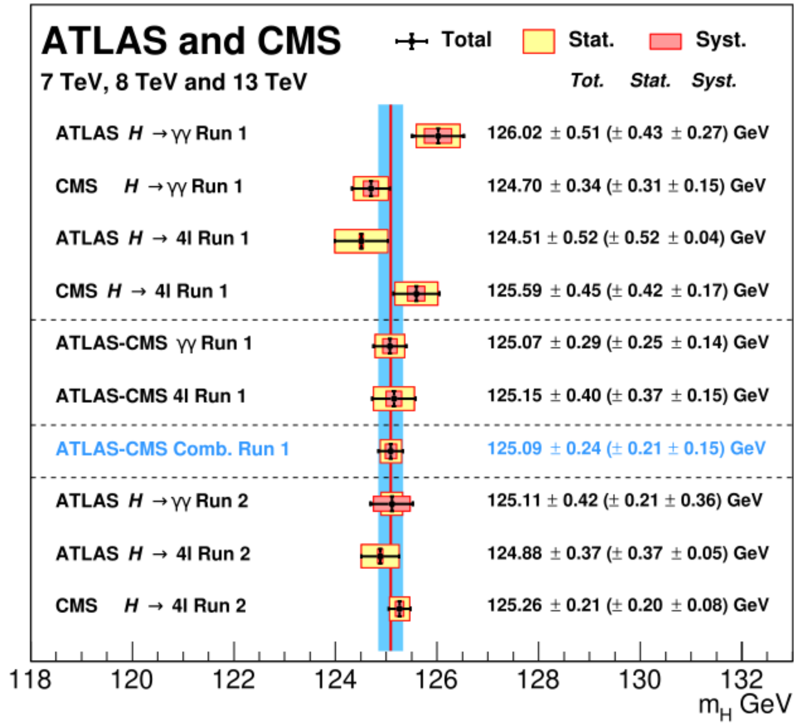
Outline

INTRODUCTION & MOTIVATION

- Higgs properties measurements at run 1 and run 2 are in a good agreement with the SM
- Perhaps other scalars are not yet discovered
- Two Higgs Doublet Model (2HDM)
  - Minimal extension to the SM
  - 2HDM-TypeII ≡ MSSM
  - Rich collider phenomenology
  - LHC benchmark mode
    - Benchmarks for light/heavy charged Higgs
    - Benchmarks for light/heavy neutral Higgses



TWO HIGGS DOUBLET MODEL PARAMETRIZATION

The most general scalar potential of the 2HDM :

$$\begin{aligned} V(\Phi_1\Phi_2) = {} & \boldsymbol{m_{11}^2}\Phi_1^\dagger\Phi_1 + \boldsymbol{m_{22}^2}\Phi_2^\dagger\Phi_2 - \left[\boldsymbol{m_{12}^2}\Phi_1^\dagger\Phi_2 + \text{h.c.}\right] \\ & + \frac{\boldsymbol{\lambda_1}}{2}\left(\Phi_1^\dagger\Phi_1\right)^2 + \frac{\boldsymbol{\lambda_2}}{2}\left(\Phi_2^\dagger\Phi_2\right)^2 + \boldsymbol{\lambda_3}\left(\Phi_1^\dagger\Phi_1\right)\left(\Phi_2^\dagger\Phi_2\right) + \boldsymbol{\lambda_4}\left(\Phi_1^\dagger\Phi_2\right)\left(\Phi_2^\dagger\Phi_1\right) \\ & + \left\{\frac{\boldsymbol{\lambda_5}}{2}\left(\Phi_1^\dagger\Phi_2\right)^2 + \left[\boldsymbol{\lambda_6}\left(\Phi_1^\dagger\Phi_1\right) + \boldsymbol{\lambda_7}\left(\phi_2^\dagger\Phi_2\right)\right]\Phi_1^\dagger\Phi_2 + \text{h.c.}\right\} \end{aligned} \quad (1)$$

with :

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

- ✦ The 10 independent parameters ($\boldsymbol{m_{11}^2},\ \boldsymbol{m_{22}^2},\ \boldsymbol{m_{12}^2},\ \boldsymbol{\lambda_{1,\ldots,7}}$) are asumed to be real.
- ✦ 2 minimization conditions and the combination $v_1^2 + v_2^2 \implies$ **7** free parameters:

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

YUKAWA COUPLINGS

- Tree-level FCNCs allowed $\Longrightarrow$ both doublets can couple to leptons and quarks.
- The associated model is called **2HDM type-III.**
- The Yukawa Lagrangian in terms of physical scalar masses:

$$
\begin{aligned}
-\mathcal{L}_Y^{III} &= \sum_{f=u,d,\ell} \frac{m_j^f}{v} \left[(\xi_h^f)_{ij} \bar{f}_{Li} f_{Rj} h + (\xi_H^f)_{ij} \bar{f}_{Li} f_{Rj} H - i (\xi_A^f)_{ij} \bar{f}_{Li} f_{Rj} A \right] \\
&+ \frac{\sqrt{2}}{v} \sum_{k=1}^{3} \bar{u}_i \left[\left(m_i^u (\xi_A^{u*})_{ki} V_{kj} P_L + V_{ik} (\xi_A^d)_{kj} m_j^d P_R \right) \right] d_j H^+ \\
&+ \frac{\sqrt{2}}{v} \bar{\nu}_i (\xi_A^\ell)_{ij} m_j^\ell P_R \ell_j H^+ + h.c. \,,
\end{aligned} \tag{3}
$$

- To get naturally small **FCNCs**, one can use the ansatz formulated by: $\tilde{Y}_{ij} \propto \sqrt{m_i m_j}/v\ \chi_{ij}$

ϕ	$(\xi_\phi^u)_{ij}$	$(\xi_\phi^d)_{ij}$	$(\xi_\phi^\ell)_{ij}$
h	$\frac{c_\alpha}{s_\beta}\delta_{ij} - \frac{c_{\beta-\alpha}}{\sqrt{2}s_\beta}\sqrt{\frac{m_i^u}{m_j^u}}\chi_{ij}^u$	$-\frac{s_\alpha}{c_\beta}\delta_{ij} + \frac{c_{\beta-\alpha}}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^d}{m_j^d}}\chi_{ij}^d$	$-\frac{s_\alpha}{c_\beta}\delta_{ij} + \frac{c_{\beta-\alpha}}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^\ell}{m_j^\ell}}\chi_{ij}^\ell$
H	$\frac{s_\alpha}{s_\beta}\delta_{ij} + \frac{s_{\beta-\alpha}}{\sqrt{2}s_\beta}\sqrt{\frac{m_i^u}{m_j^u}}\chi_{ij}^u$	$\frac{c_\alpha}{c_\beta}\delta_{ij} - \frac{s_{\beta-\alpha}}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^d}{m_j^d}}\chi_{ij}^d$	$\frac{c_\alpha}{c_\beta}\delta_{ij} - \frac{s_{\beta-\alpha}}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^\ell}{m_j^\ell}}\chi_{ij}^\ell$
A	$\frac{1}{t_\beta}\delta_{ij} - \frac{1}{\sqrt{2}s_\beta}\sqrt{\frac{m_i^u}{m_j^u}}\chi_{ij}^u$	$t_\beta\delta_{ij} - \frac{1}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^d}{m_j^d}}\chi_{ij}^d$	$t_\beta\delta_{ij} - \frac{1}{\sqrt{2}c_\beta}\sqrt{\frac{m_i^\ell}{m_j^\ell}}\chi_{ij}^\ell$

ALIGNMENT LIMIT

In the Higgs-basis the alignment limit is most clearly exhibited :

$$H_1 = \begin{pmatrix} H_1^+ \\ H_1^0 \end{pmatrix} \equiv \Phi_1 \cos\beta + \Phi_2 \sin\beta, \qquad H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix} \equiv -\Phi_1 \sin\beta + \Phi_2 \cos\beta$$

$$H_1 = \begin{pmatrix} G^+ \\ \left(v + S_1 + iG^0\right)/\sqrt{2} \end{pmatrix}, \qquad H_2 = \begin{pmatrix} H^+ \\ \left(S_2 + iS_3\right)/\sqrt{2} \end{pmatrix}$$

The 2 physical Higgs states h et H are as follows:

$$H = (\sqrt{2}\mathrm{Re}H_1^0 - v)\cos(\beta-\alpha) + \sqrt{2}\mathrm{Re}H_2^0 \sin(\beta-\alpha) \tag{4}$$

$$h = (\sqrt{2}\mathrm{Re}H_1^0 - v)\sin(\beta-\alpha) + \sqrt{2}\mathrm{Re}H_2^0 \cos(\beta-\alpha) \tag{5}$$

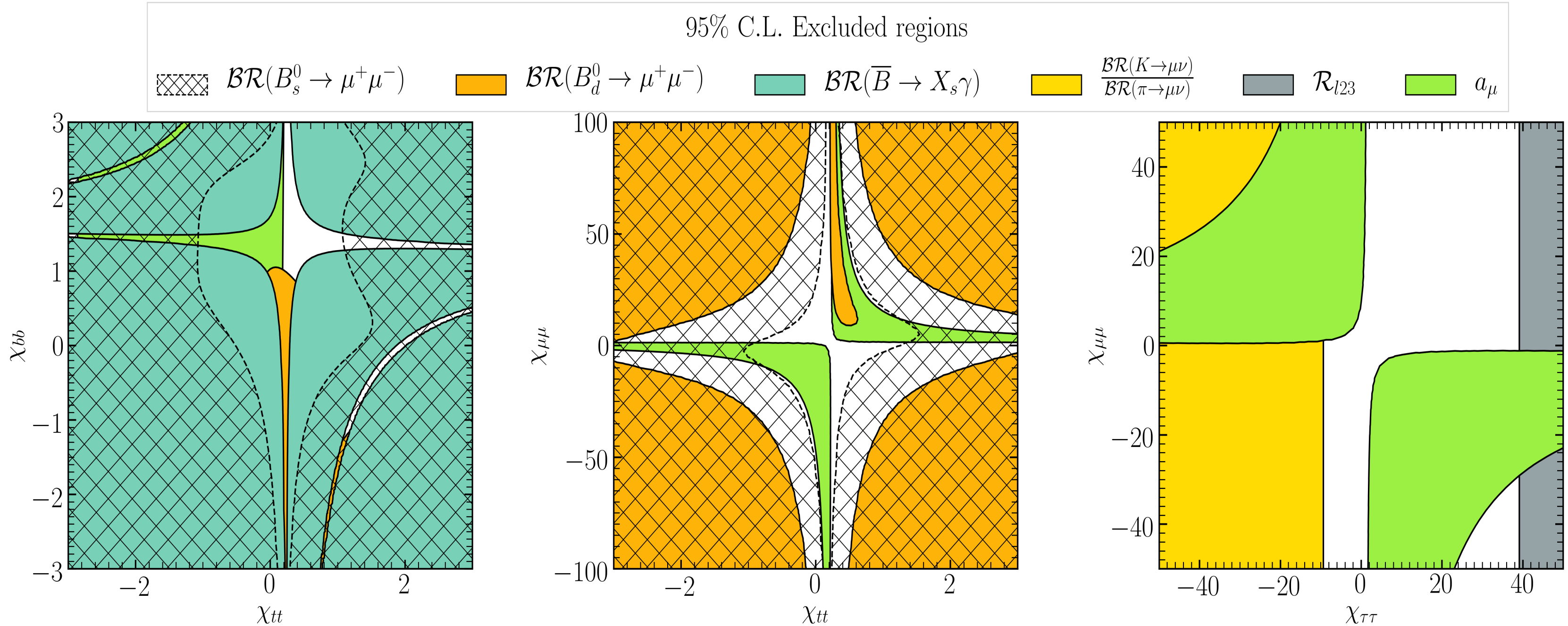
- $\cos(\beta-\alpha) \to 0$, $h \equiv H_{SM}$ (J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang and S. Kraml, Phys. Rev. D 92 (2015) no.7, 075004) ; standard hierarchy
- $\sin(\beta-\alpha) \to 0$, $H \equiv H_{SM}$ (J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang and S. Kraml, Phys. Rev. D 93 (2016) no.3, 035027) ; inverted hierarchy

THEORETICAL AND EXPERIMENTAL CONSTRAINTS

- **2HDMC (D. Eriksson, J. Rathsman and O. Stal)**
  - Unitarity, Perturbativity, Vacuum Stability.
  - EW Precision Observables (S, T and U).
- **HiggsBounds (P. Bechtle et al), and HiggsSignal (P. Bechtle et al)**
  - Exclusion limits at 95% Confidence Level (CL) from Higgs searches at colliders (LEP, Tevatron and LHC).
  - Constraints from the Higgs boson signal strength measurements (SM-like Higgs properties).
- **SuperIso (F. Mahmoudi)**
  - Constraints of flavour physics observables ($B \to X_s\gamma,\ B_{s,d} \to \mu^+\mu^-$ and $B_s \to \tau\nu$).

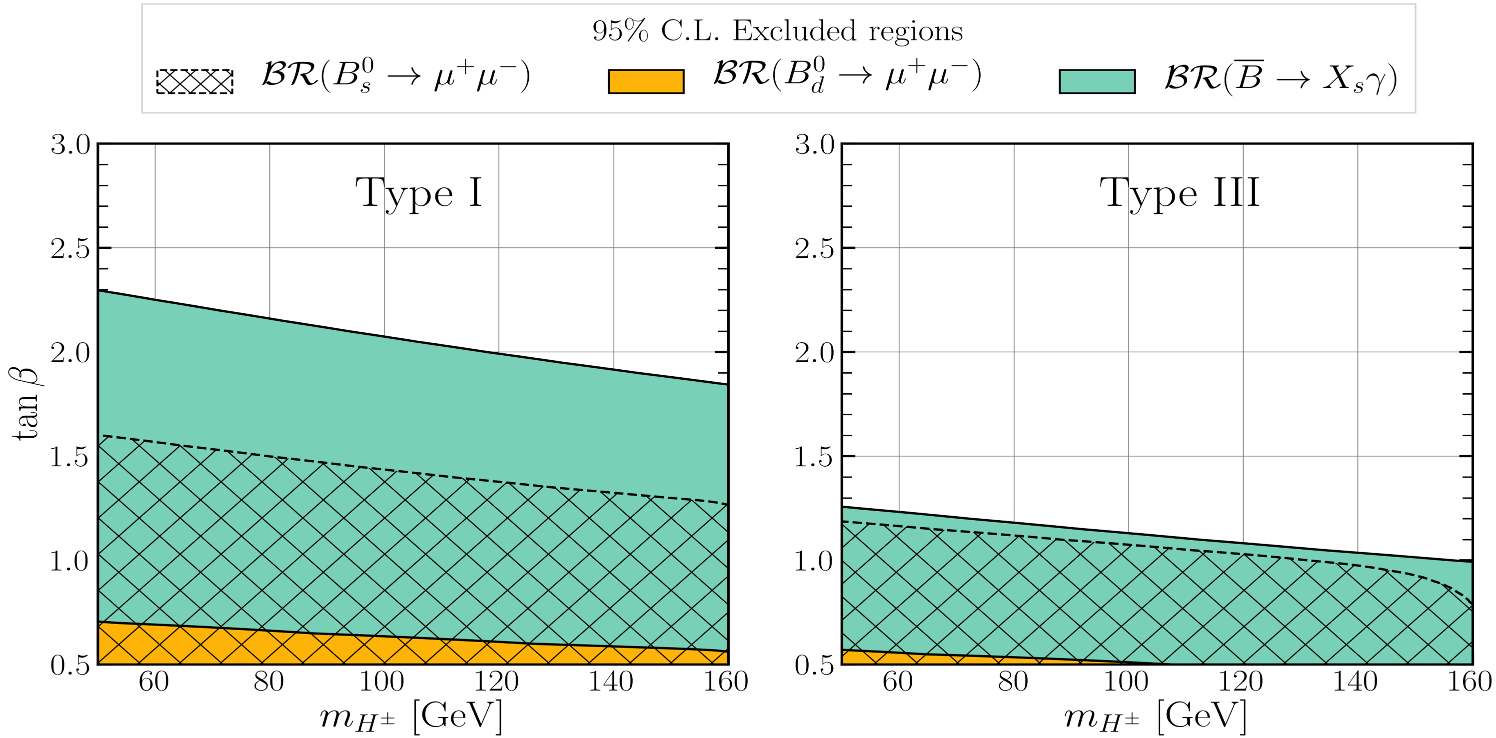
Numerical results

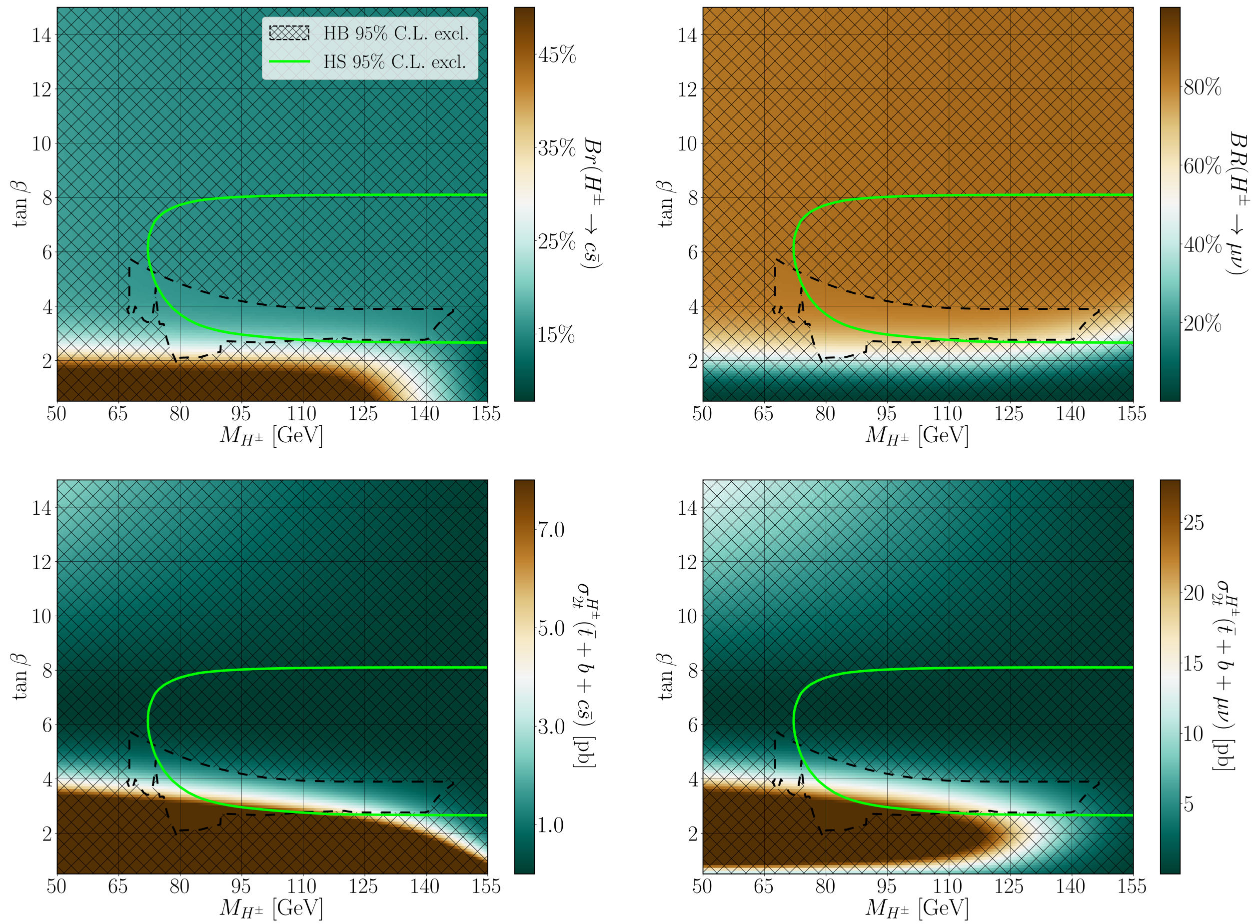
✦ The free parameters $\chi_{ij}^{u,d,l}$ are tested at the current constraints from B-physics observables.



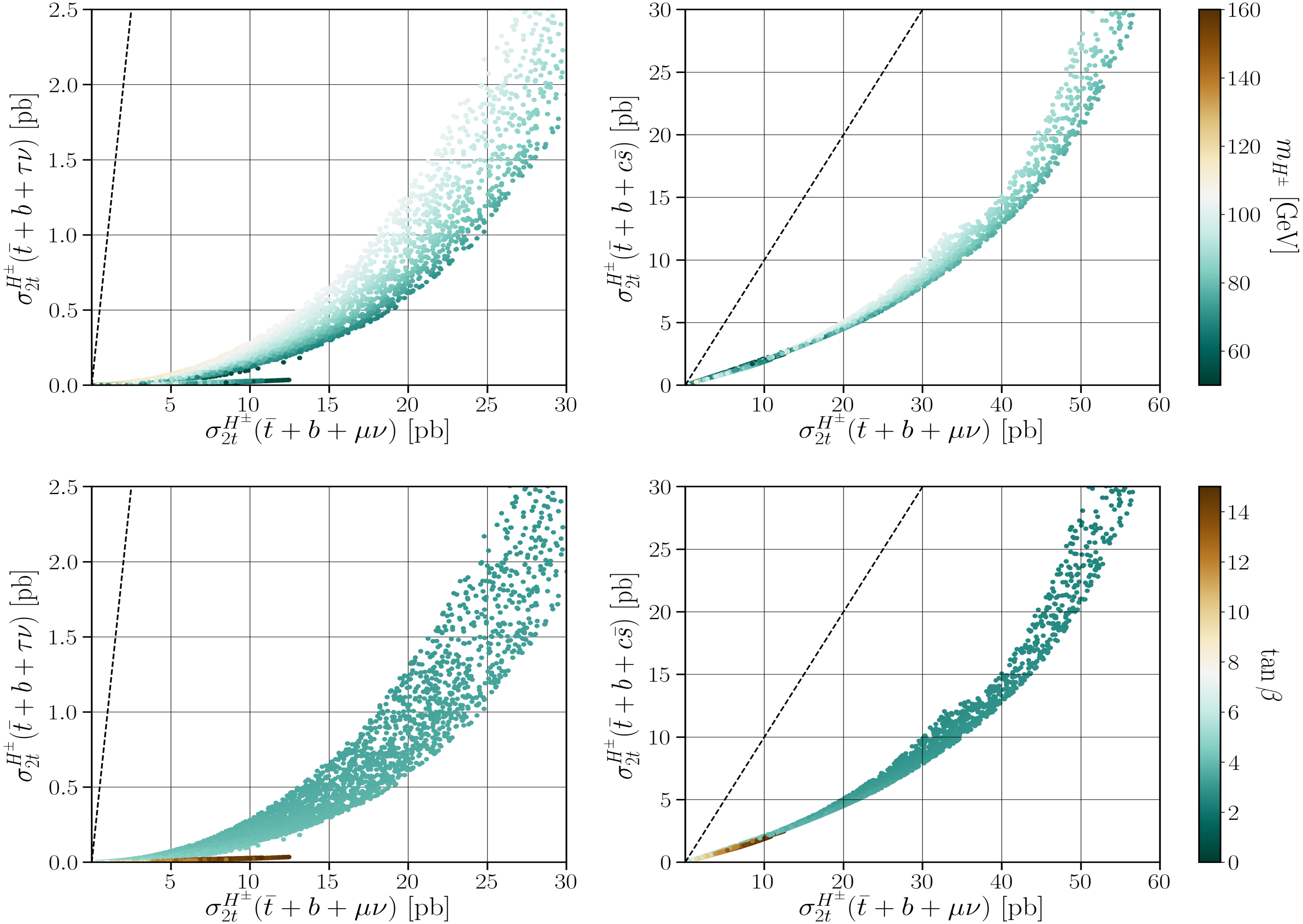
$$\chi^u = \begin{pmatrix} 0.187 & 0 & 0 \\ 0 & 0.254 & 0 \\ 0 & 0 & 0.210 \end{pmatrix}, \chi^d = \begin{pmatrix} -0.553 & 0 & 0 \\ 0 & 2.863 & 0 \\ 0 & 0 & 1.440 \end{pmatrix}, \chi^l = \begin{pmatrix} 0.484 & 0 & 0 \\ 0 & -2.101 & 0 \\ 0 & 0 & 1.400 \end{pmatrix} \quad (6)$$

	m_h $[GeV]$	m_H $[GeV]$	m_A $[GeV]$	$m_{H^\pm}$ $[GeV]$	$s_{\beta-\alpha}$	$\tan\beta$	m_{12}^2
h Scenario	125	135	220	[50; 160]	−0.98	[0.5; 15]	$m_h^2 \tan\beta/(1+\tan^2\beta)$
H Scenario	95	125	177	[50; 160]	−0.05	[0.5; 15]	$m_h^2 \tan\beta/(1+\tan^2\beta)$

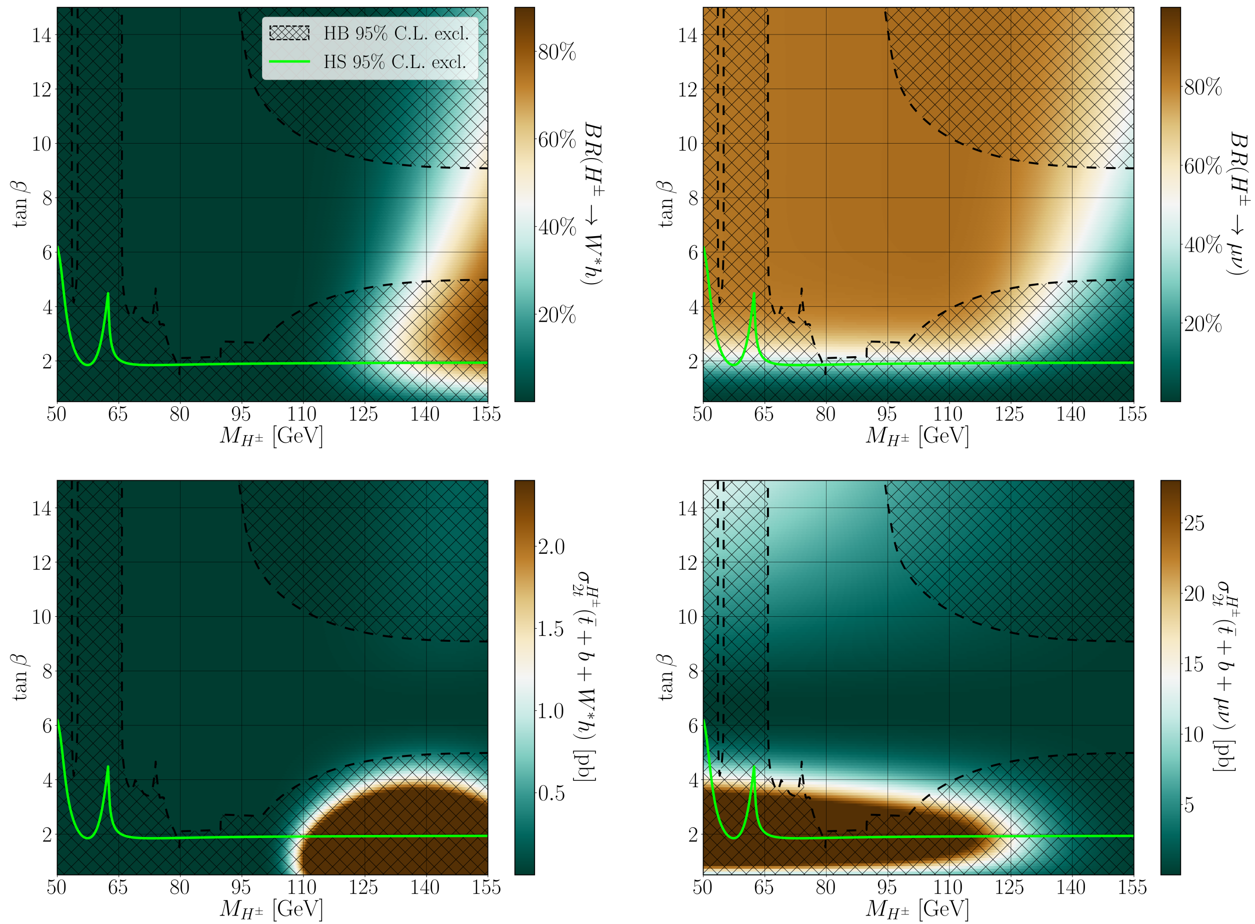




- The decay channel $H^\pm \to \mu\nu$ is dominant over $\tau\nu$, $c\bar{s}$ and W^*h
- $\sigma_{2t}^{H^\pm}(\bar{t} + b + \mu\nu)$ could reach 27 pb in the allowed region

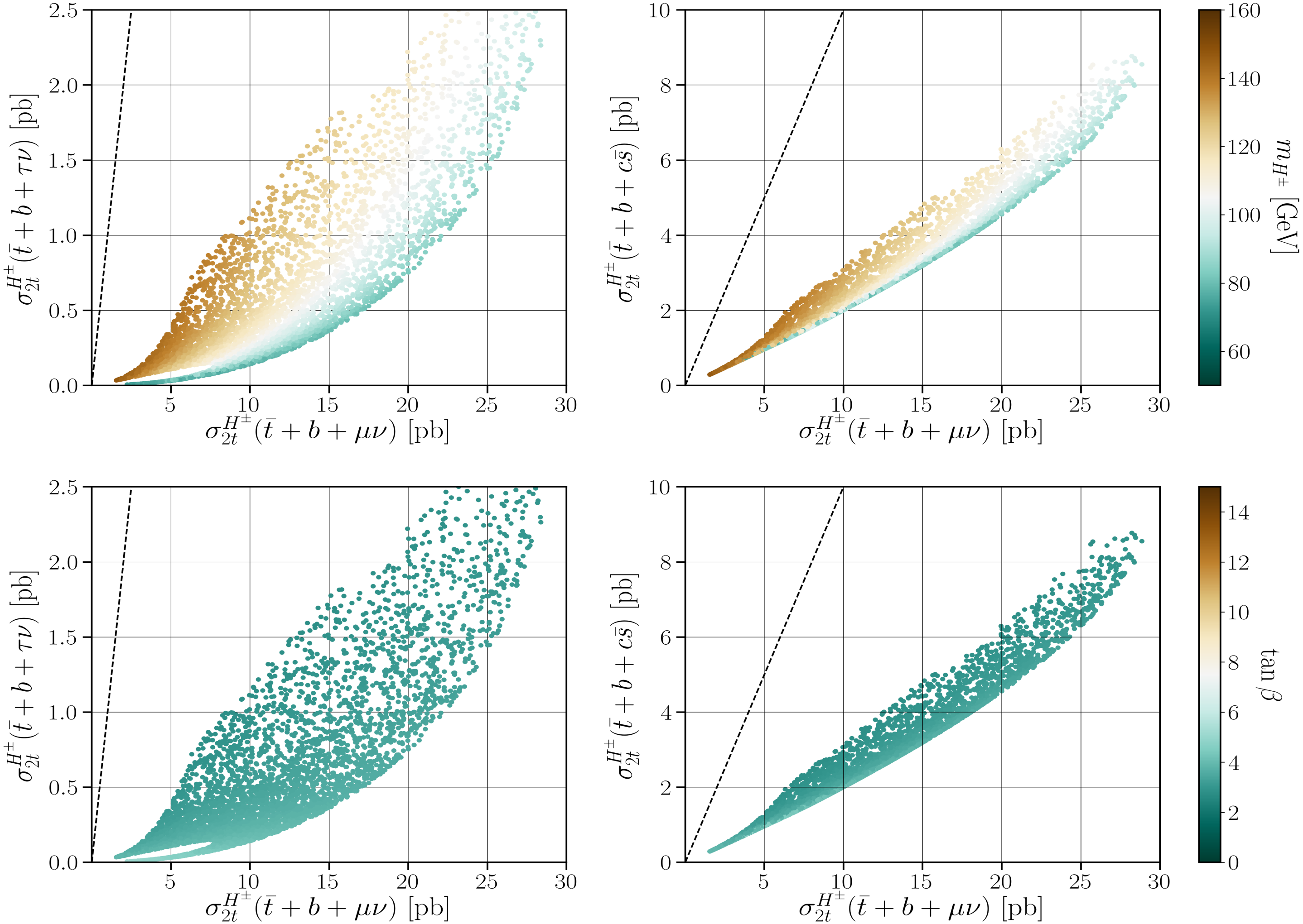

$\sigma_{2t}^{H^\pm}(\bar{t}+b+\tau\nu)$ [pb]
$\sigma_{2t}^{H^\pm}(\bar{t}+b+\mu\nu)$ [pb]
$\sigma_{2t}^{H^\pm}(\bar{t}+b+c\bar{s})$ [pb]
$m_{H^\pm}$ [GeV]
$\tan\beta$
0.0
0.5
1.0
1.5
2.0
2.5
5
10
15
20
25
30
40
50
60
80
100
120
140
160
0
2
4
6
8
12
14

STANDARD HIERARCHY



- The decay channel $H^\pm \to \mu\nu$ is dominant over $\tau\nu$, $c\bar{s}$ and W^*h

- $\sigma_{2t}^{H^\pm}(\bar{t}+b+\mu\nu)$ could reach 23 pb in the allowed region


$\sigma_{2t}^{H^\pm}(\bar{t}+b+\tau\nu)$ [pb]
$\sigma_{2t}^{H^\pm}(\bar{t}+b+\mu\nu)$ [pb]
$\sigma_{2t}^{H^\pm}(\bar{t}+b+c\bar{s})$ [pb]
$m_{H^\pm}$ [GeV]
$\tan\beta$

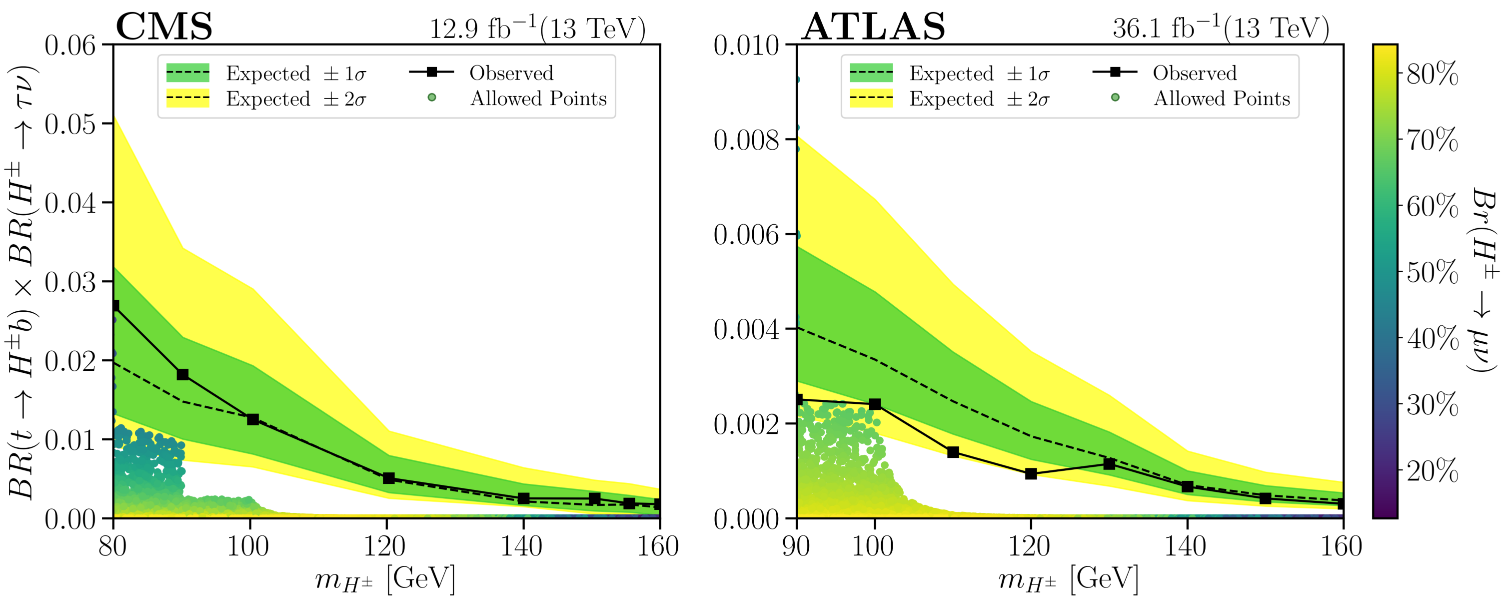
Benchmark Points

Selected BPs in $m_h = 125$ GeV scenario					
Parameters	BP1	BP2	BP3	BP4	BP5
The Higgs masses are in GeV					
m_h	125	125	125	125	125
m_H	135	135	135	135	135
m_A	220	220	220	220	220
$m_{H^\pm}$	110	93.2	99.4	91.4	102
$\cos(\beta-\alpha)$	0.145	0.145	0.145	0.145	0.145
$\tan\beta$	2.9	3.2	3.7	4.3	3
m_{12}^2	4815.35	4448.39	3935.5	3447.28	4687.5
$\sigma_{2t}^{H^\pm}(\bar{t}+b+XY)$ [pb]					
$c\bar{s}$	6.2	5.76	2.48	1.32	6.48
$t^*\bar{b}$	0.2	–	0.002	–	0.04
W^*h	–	–	–	–	–
$\mu\nu$	21.12	11.46	22.92	6.82	23.32
$\tau\nu$	2	1.36	0.34	0.08	1.88

Selected BPs in $m_H = 125$ GeV scenario					
Parameters	BP1	BP2	BP3	BP4	BP5
The Higgs masses are in GeV					
m_h	95	95	95	95	95
m_H	125	125	125	125	125
m_A	177	177	177	177	177
$m_{H^\pm}$	95	90	94	99.6	90.80
$\sin(\beta-\alpha)$	−0.05	−0.05	−0.05	−0.05	−0.05
$\tan\beta$	3	3.5	4.2	3.7	3.2
m_{12}^2	2707.5	2383.96	2033.53	2273.14	2569.39
$\sigma_{2t}^{H^\pm}(\bar{t}+b+XY)$ [pb]					
$c\bar{s}$	7.58	3.98	1.42	2.46	6.06
$t^*\bar{b}$	–	–	–	0.003	–
W^*h	–	–	–	0.00046	–
$\mu\nu$	26.92	17.8	7.36	11.86	23.96
$\tau\nu$	2.18	0.66	0.1	0.34	1.42

Conclusion

- Both configuration, standard and inverted, heirarchy allow for $Br(H^{\pm} \to \mu\nu)$ to reach 80%
- Type-III is a very promising model that can accommodate light charged charged Higgs with $80 < m_{H^{\pm}} < 150$,while satisfying experimenrtal constraints from Higgs data and flavor physics
- Selecting some benchmark points for a further MC simulation promoting a new channel to search for light charged higgs



Thank You For Listening

Back-up

- Allowed regions on $(m_{H^\pm}, \tan\beta)$ in colour (standard & inverted hierarchy)
- Sensitivity in this region mainly from LHC searches