2HDM-I @ LHC

Tanmoy Mondal

BITS Pilani

based on
PRL 131, 231801 (2023),
PRD 109 (2024) 3, 033002

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Introduction

- No trace of BSM yet.
- However, DM, EWPT, CP-Violation, ν Oscillation etc.
- Scalar extension: new charged and neutral scalars may exist
- Detecting these new states complements the Higgs precision studies
- The existing LHC searches for 2HDM are motivated by the Yukawa structure of type-II (SUSY)
- These searches can not explore an extensive part of 2HDM phenomenology

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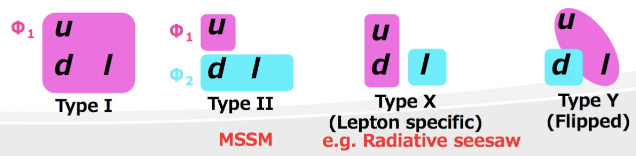
- These searches can not explore an extensive part of 2HDM phenomenology

I will talk about the following:

- 2HDM-I and scalar spectrum
- Charged Higgs searches at the LHC
- EW multi-Higgs production: A smoking gun for the Type-I 2HDM

The 2HDM

- Physical Scalars: $h(125), H, A, H^{\pm}$
- Four types of Yukawa interaction to avoid FCNC

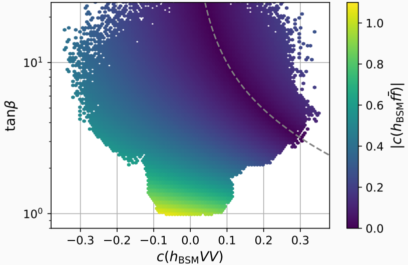


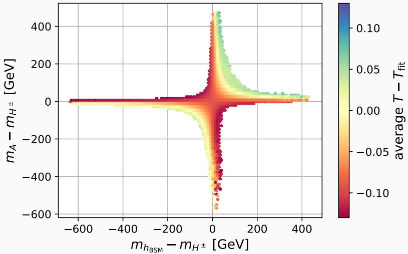
- I will talk about type-I. Yukawa couplings are modified as follows:

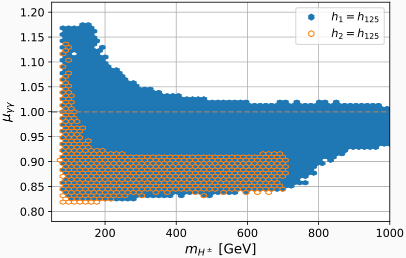
ξ_h^u	ξ_h^d	ξ_h^ℓ	ξ_H^u	ξ_H^d	ξ_H^ℓ	$\xi_{A,H^\pm}^u$	$\xi_{A,H^\pm}^d$	$\xi_{A,H^\pm}^\ell$
$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{c_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\frac{s_\alpha}{s_\beta}$	$\cot\beta$	$-\cot\beta$	$-\cot\beta$

- Fermiophobic H: When $s_\alpha = 0 \to \tan\beta = \frac{s_{\beta-\alpha}}{c_{\beta-\alpha}}$
- Higgs measurement: $s_{\beta-\alpha} \simeq 1$ when $M_H > M_h$
- Then $\xi_H^f \to 1/\tan\beta$: Fermiophobic $H, H^\pm$ & A

Indirect Limits on 2HDM-I







The forgotten channels: charged Higgs boson decays to a $W^\pm$ and a non-SM-like Higgs boson

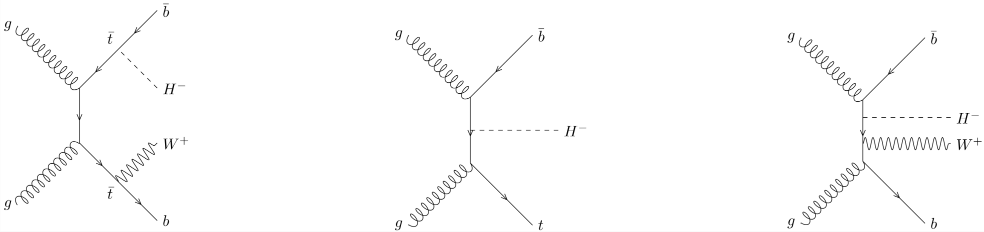
Henning Bahl[*1], Tim Stefaniak[†1], and Jonas Wittbrodt[‡2]

JHEP 06 (2021) 183

Direct Search for BSM scalars in type-I 2HDM

LHC searches for charged Higgs

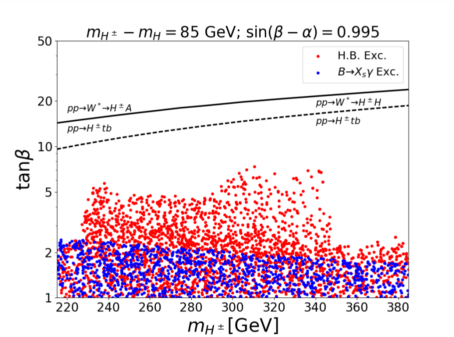
- Production channel explored:

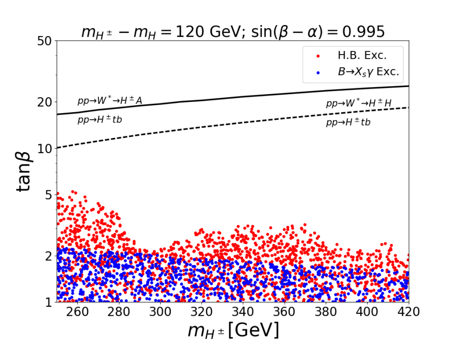


- 4 Decay channels:
  [A] $H^\pm \to \tau^\pm \nu$, [B] $H^\pm \to t\bar{b}$
  [C] $H^\pm \to c\bar{s}$, [D] $H^\pm \to c\bar{b}$
- But in 2HDM-I all these couplings are $\tan\beta$ suppressed.

Experimental Limits

- $m_H \in [130-300]\mathrm{GeV}$, $s_{\beta-\alpha} = 0.995$, $\tan\beta \in [1,50]$ & $m_{12}^2 \in [0, m_H^2\, s_\beta\, c_\beta]$
- LHC: $H^\pm$ searches via top associated production
- LHC: Neutral Higgs searches: $A \to Zh(H)$, $A/H \to \tau\tau$, $H \to ZZ(\gamma\gamma)$



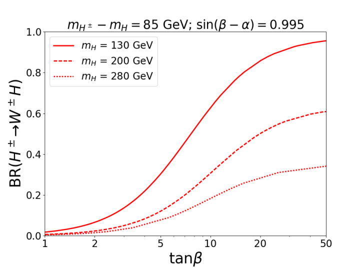


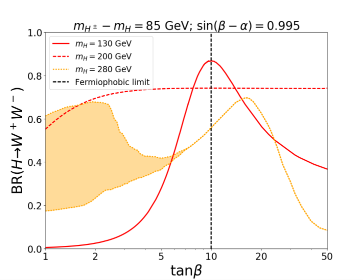
- Anything above $\tan\beta = 5$ is mostly allowed
- Our work: SS3L via bosonic production and decay as a complementary probe at large $\tan\beta$.

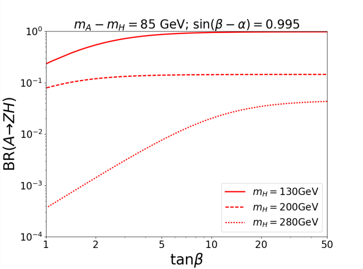
Tanmoy Mondal, & Prasenjit Sanyal, JHEP05(2022)040

Scalar spectrum and Decay

- The T-parameter constraint requires $H^\pm$ to be almost degenerate with either A or H
- We assumed $H^\pm$ and A degenerate while H is lighter
- This allows $H^\pm \to W^\pm H$ and $A \to ZH$ decay

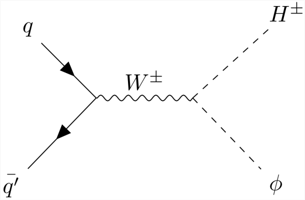






SS3L Signal

- $\tan\beta$ ⇧ $\Longrightarrow H^{\pm}t\bar{b}$ coupling ⇩
- Drell-Yan production becomes dominant



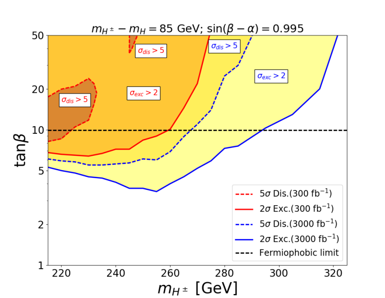
Signal:

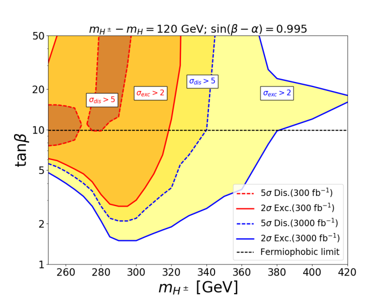
$$pp \to W^{*\pm} \to H^{\pm}H \to (W^{\pm}H)(W^{+}W^{-}) \to (W^{\pm}W^{+}W^{-})(W^{+}W^{-}) \to 3\ell^{\pm}\not{E}_T + X$$

$$pp \to W^{*\pm} \to H^{\pm}A \to H^{\pm}A \to (W^{\pm}H)(ZH) \to (W^{\pm}W^{+}W^{-})(ZW^{+}W^{-}) \to 3\ell^{\pm}\not{E}_T + X$$

Background: • WZ + jets • $Z\ell^{\pm}\ell^{\mp}$ + jets • $t\bar{t}V$ + jets • ZZW

Result


$m_{H^\pm} - m_H = 85$ GeV; $\sin(\beta-\alpha) = 0.995$
$\sigma_{dis} > 5$
$\sigma_{dis} > 5$
$\sigma_{exc} > 2$
$\sigma_{dis} > 5$
$\sigma_{exc} > 2$
5σ Dis.(300 fb^{-1})
2σ Exc.(300 fb^{-1})
5σ Dis.(3000 fb^{-1})
2σ Exc.(3000 fb^{-1})
Fermiophobic limit
$\tan\beta$
$m_{H^\pm}$ [GeV]


$m_{H^\pm} - m_H = 120$ GeV; $\sin(\beta-\alpha) = 0.995$
$\sigma_{dis} > 5$
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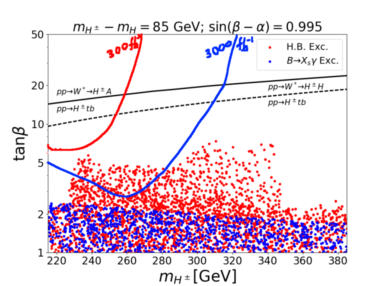
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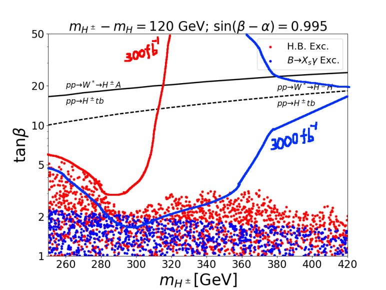
300fb^{-1}
3000 fb^{-1}
H.B. Exc.
$B \to X_s\gamma$ Exc.
$pp \to W^* \to H^\pm A$
$pp \to H^\pm tb$
$pp \to W^* \to H^\pm H$
$pp \to H^\pm tb$
$\tan\beta$
$m_{H^\pm}$ [GeV]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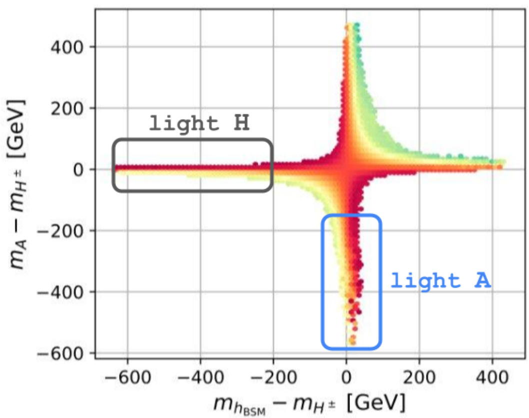
$pp \to W^* \to H^\pm H$
$pp \to H^\pm tb$
$\tan\beta$
$m_{H^\pm}$ [GeV]

Other End: One light Pseudo-Scalar



What happens if H/A is light?

2HDM type-I at the LHC

- Light H has already been studied
  - Multi-Photon Final state : $PP \to H^{\pm}\ H \to W^{\pm}\ H\ H \to \ell^{\pm}\ +\ 4\gamma$
    `A Arhrib, R Benbrik, S Moretti, et.al., JHEP 07 (2018) 007, JHEP 12 (2021) 021`
  - H is lighter than 125 GeV Higgs
- We focus on light pseudoscalar case
  - No CPV: No multi-γ final state
  - Dominant decay : $A \to b\bar{b}$
  - Simultaneous reconstruction of all the BSM scalars.
- BP must pass `HiggsBounds`, `HiggsSignals`, $b \to s\gamma$, STU and other theoretical constraints

Multi pseudoscalar(A) final state via EW production

BP	m_A	$m_{H^\pm}$	m_H	t_β	$s_{\beta-\alpha}$	m_{12}^2	BR(AA)	BR(AZ)
1	70	169.7	144.7	7.47	0.99	2355	0.99	0.006

Neutral

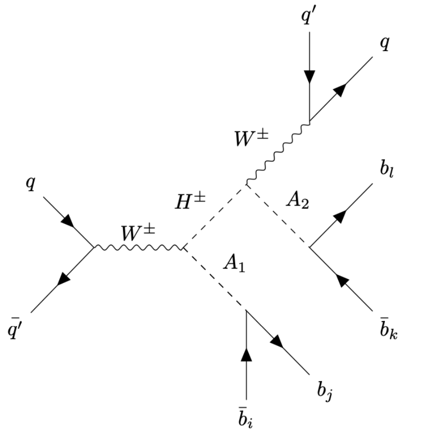
$$AAA \;:\; q\bar{q} \to H(\to AA)A \to 4b + X\,,$$
$$AAZ \;:\; q\bar{q} \to H(\to AZ)A \to 4b + X\,,$$
$$AAWW \;:\; q\bar{q} \to H^+(\to AW)H^-(\to AW) \to 4b + X\,,$$

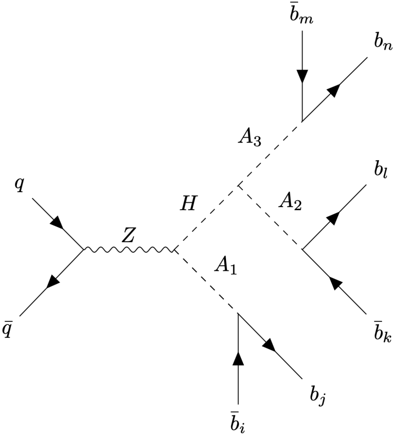
Charged

$$AAW \;:\; q\bar{q}' \to H^\pm(\to AW)A \to 4b + X\,,$$
$$AAAW \;:\; q\bar{q}' \to H^\pm(H^\pm \to AW)H(\to AA) \to 4b + X\,,$$
$$AAZW \;:\; q\bar{q}' \to H^\pm(H^\pm \to AW)H(\to AZ) \to 4b + X\,.$$

Background : QCD multijets. $\sigma \sim 9 \times 10^6 pb$

Heavy scalars





Reconstruction of the pseudoscalar A

$$\texttt{MG5} \rightarrow \texttt{Pythia8} \rightarrow \texttt{Delphes},\ \ p_T(j) > 25\texttt{GeV},\ \ |\eta| < 2.5,\ \ R = 0.4$$

- ≥ 4 b-jets. Possible combinations of b-jet pairs :

  (a,b; c,d): (1,2; 3,4), (1,3; 2,4) & (1,4; 2,3)

- Minimization condition: $\Delta R = |(\Delta R_1 - 0.8)| + |(\Delta R_2 - 0.8)|$

$$\Delta R_1 = \sqrt{(\eta_a - \eta_b)^2 + (\phi_a - \phi_b)^2}\,,$$
$$\Delta R_2 = \sqrt{(\eta_c - \eta_d)^2 + (\phi_c - \phi_d)^2}\,,$$

- b-jets coming from a resonance (A) are expected to be close together compared to unrelated jets.
  CMS EXO-21-010: Search for resonant and nonresonant production of pairs of dijet resonances in proton-proton collisions at $\sqrt{s}$ = 13 TeV

- Asymetry cut: $\bar{\alpha} = \dfrac{|m_1 - m_2|}{m_1 + m_2} < 0.2$

Reconstruction of the Heavy Scalars

$H^{\pm}$

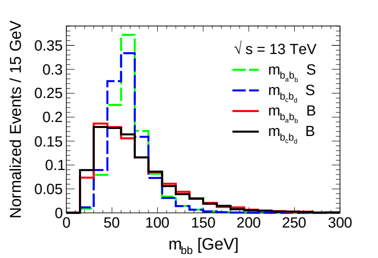
- Dominant Process : $q\bar{q}' \to A_1 H^{\pm} \to A_1\, A_2\, W^{\pm} \to 4b + jj$
- Leading jj pair: $(m_W - 25) < m_{jj} < (m_W + 25)$
- The four b–jets were combined into two b–jet pairs $(A_{1,2})$ as before.
- $p_T(A_1) > p_T(A_2)$
- Inv mass of $A_2\, j\, j$ system gives $H^{\pm}$ mass

H

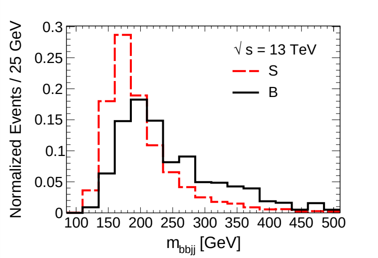
- The dominant signal : $q\bar{q} \to A_1 H \to A_1 A_2 A_3 \to 6b\ (6b/5b + j)$
- If multiple b-pair satisfy A reco, we maximize $\Delta R(A_1, A_2 A_3)$
- $m_{A_2 A_3} = m_H$

Reconstruction of the Heavy Scalars

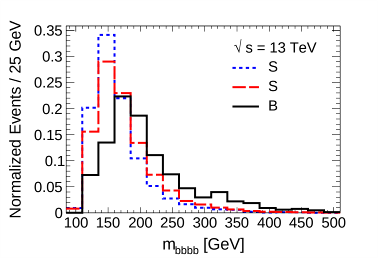
A



$H^{\pm}$



H



Tanmoy Mondal, Stefano Moretti, Shoaib Munir, & Prasenjit Sanyal, Phys. Rev. Lett. 131, 231801 (2023)

Summary

- 2HDM is well studied at the LHC.
- These studies generally focus on a QCD-induced single/multiple production, followed by a specific decay channel.
- In some 2HDM scenarios (for e.g. type-I), EW production dominates and produce uniques signatures
- A EW production of $\phi H^{\pm}$ leads to $5W$ production
- A clean signature of such process is SS3L
- If a BSM scalar is light, with EW production, we can reconstruct all the scalars $(A.H, H^{\pm})$
- We advocate systematic investigations of the EW-induced processes alongside the QCD-initiated ones.

Back Up

BP

Parameters	Pre-selection cross section (fb)	Reconstructed Higgs σ_S (fb)	σ_B (fb)	$S/\sqrt{B}$
$m_{H^\pm} = 169.7$	AAA: 171.6	A		
$m_H = 144.7$	AAZ: 0.76	15.4	8864	8.9σ
$t_\beta = 7.47$	$AAWW$: 25.2	$H^\pm$		
$s_{\beta-\alpha} = 0.99$	AAW: 142.3	2.22	482	5.5σ
$m_{12}^2 = 2355$	$AAAW$: 79.7	H		
$\text{BR}(AA) = 0.99$	$AAZW$: 0.35	2.55	309	7.9σ

Low m_A, different $BR(H \to ZA)$

Parameters	Pre-selection cross section (fb)	Reconstructed Higgs		
		σ_S (fb)	σ_B (fb)	$S/\sqrt{B}$
$m_{H^\pm} = 169.8$	AAA: 101.3	A		
$m_H = 150.0$	AAZ: 79.3	10.4	10175	5.7σ
$t_\beta = 17.1$	$AAWW$: 27.7	$H^\pm$		
$s_{\beta-\alpha} = 0.98$	AAW: 198.0	1.33	491	3.3σ
$m_{12}^2 = 1275$	$AAAW$: 37.1	H		
$\text{BR}(AA) = 0.48$	$AAZW$: 29.0	1.06	256	3.6σ

BG simulation was also a limiting factor

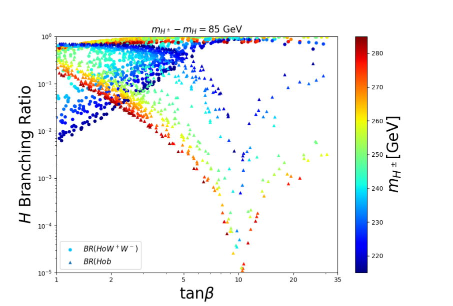
Tanmoy Mondal, Stefano Moretti, Shoaib Munir, & Prasenjit Sanyal, Phys. Rev. Lett. 131, 231801 (2023)

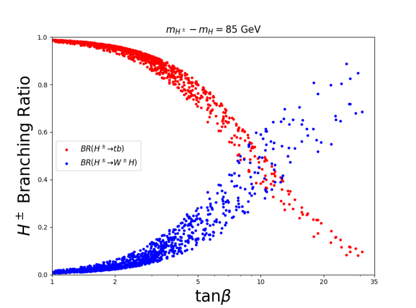
Scalar Trilinear

The scalar trilinear coupling which governs the decay of heavy Higgs to a pair of SM Higgs bosons is

$$\lambda_{Hhh} = -\frac{\cos(\beta-\alpha)}{v\ \sin(2\beta)^2}\left[\left(2m_h^2 + m_H^2\right)\sin 2\alpha \sin 2\beta - \left(2\sin 2\alpha - \sin 2\beta\right) m_{12}^2\right]$$

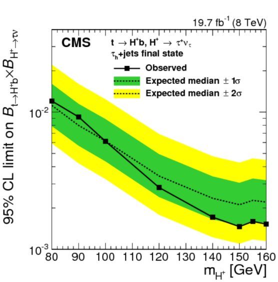
Branching comparison



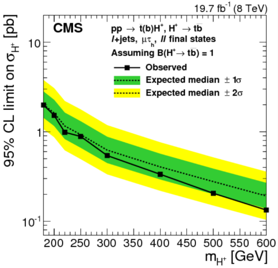


CMS plots

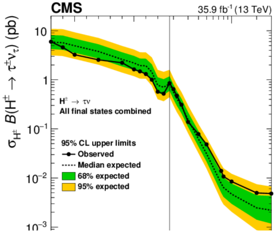
JHEP11(2015) 018,[1508.07774]



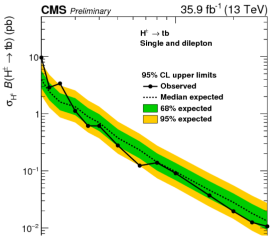
JHEP11(2015) 018,[1508.07774]



JHEP 07 (2019) 142,[1903.04560]



CMS PAS HIG-18-004



Light H vs light A

Hhh

$$\lambda_{Hhh} = \frac{1}{2vc_\beta s_\beta}\{(3M^2 - 2m_h^2 - m_H^2)s_{2\alpha} - M^2 s_{2\beta}\}$$
$$\rightarrow 0, \qquad \text{for } \sin(\beta-\alpha)\rightarrow 1$$

HAA

$$\lambda_{HAA} = \frac{1}{4vc_\beta s_\beta}\{(4M^2 - 2m_A^2 - 3m_H^2)s_{\alpha+\beta} - (m_H^2 - 2m_A^2)s_{\alpha-3\beta}\}$$
$$\rightarrow \frac{2}{vt_{2\beta}}(m_H^2 - M^2), \qquad \text{for } \sin(\beta-\alpha)\rightarrow 1$$

hAA

$$\lambda_{hAA} = \frac{1}{4vc_\beta s_\beta}\{(4M^2 - 2m_A^2 - 3m_H^2)c_{\alpha+\beta} + (2m_A^2 - m_h^2)s_{\alpha-3\beta}\}$$
$$\rightarrow \frac{1}{-}(2M^2 - 2m_A^2 - m_h^2), \qquad \text{for} \sin(\beta-\alpha)\rightarrow 1$$

Analysis

- Three same-sign isolated leptons is a clean channel and can be crucial

Signal cross-sections at $\sqrt{s} = 13$ TeV		
Parameter		σ[fb]
$\Delta m = 60$ GeV	Signal 1	0.0007
	Signal 2	0.0000406
$\Delta m = 85$ GeV	Signal 1	0.0131
	Signal 2	0.00276
$\Delta m = 120$ GeV	Signal 1	0.0260
	Signal 2	0.0113

Background cross-sections at $\sqrt{s} = 13$ TeV		
Backgrounds	Production σ [fb]	Selection σ[fb]
WZ+jets	1360.80	0.0061
$Z\ell^+\ell^-$+jets	246.55	0.00061
ZZW+jets	0.781	0.00155
$h(\to ZZ)W$+jets	0.218	0.00041
$h(\to WW)t\bar{t}$+jets	20.51	0.000123
$t\bar{t}W$+jets	62.57	0.0018
$t\bar{t}Z$+jets	92.08	0.00092

2HDM : Gauge interactions

- Gauge-Higgs sector :

$$g_{hVV} = s_{\beta-\alpha}\, g^{\rm SM}_{hVV}, \quad g_{HVV} = c_{\beta-\alpha}\, g^{\rm SM}_{hVV}, \quad g_{AVV} = 0,$$

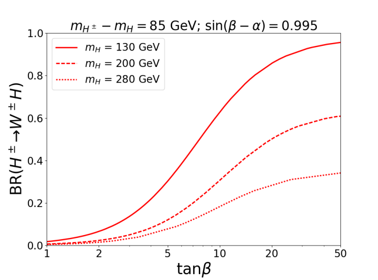
- Other relevant vertices

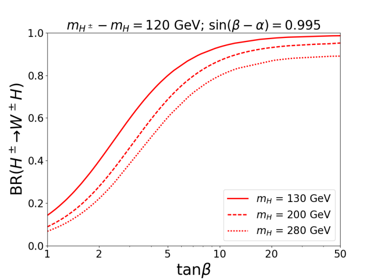
$$(A)\ hAZ_\mu : \frac{g_2}{2c_W} c_{\beta-\alpha}(p+p')_\mu, \quad HAZ_\mu : -\frac{g_2}{2c_W} s_{\beta-\alpha}(p+p')_\mu,$$

$$(B)\ hH^\pm W^\mp_\mu : \mp i\frac{g_2}{2} c_{\beta-\alpha}(p+p')_\mu, \quad HH^\pm W^\mp_\mu : \pm i\frac{g_2}{2} s_{\beta-\alpha}(p+p')_\mu,$$

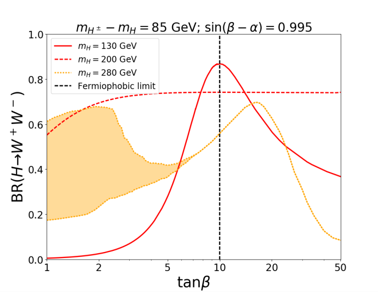
$$(C)\ H^\pm A W^\mp_\mu : \frac{g}{2}(p+p')_\mu$$

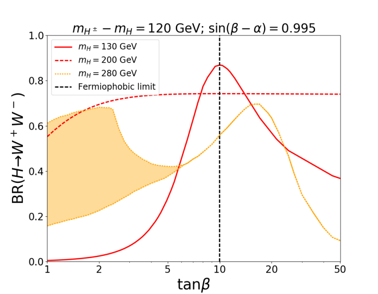
$H^{\pm}$ Mostly decays to HW



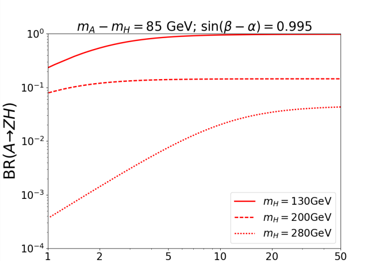


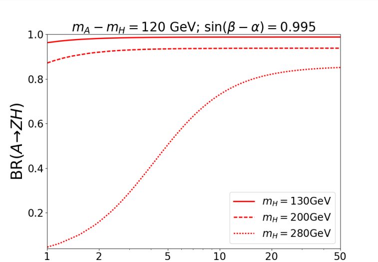
H Mostly decays to WW



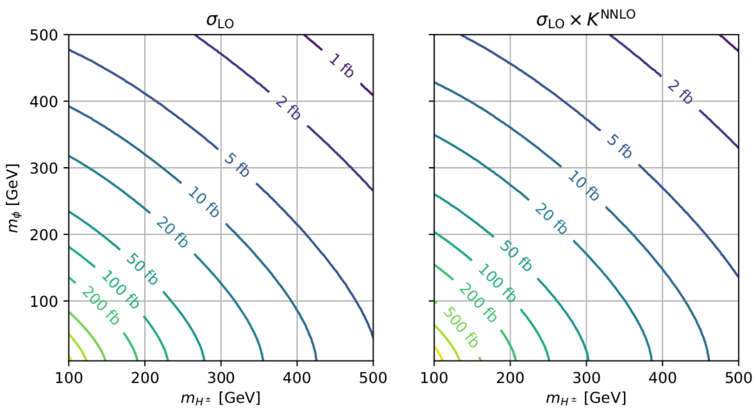


A (degenerate with $H^\pm$) decays to HZ



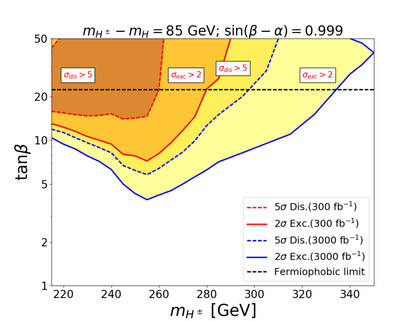


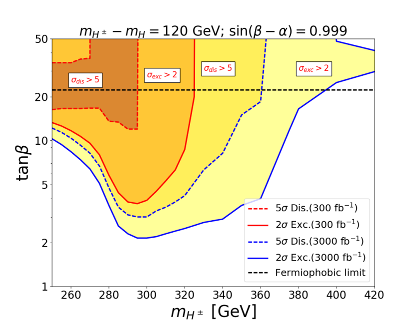
Signal is not very large



- Also SM Background is very small due to lack of b-jet in the signal

Result for $s_{\beta-\alpha} = 0.999$





Tanmoy Mondal, & Prasenjit Sanyal, JHEP05(2022)040