

A novel experimental search channel for very light Higgses in the Type-I 2HDM

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arXiv : 2207.03007



OUTLINE

GENERAL 2-HIGGS-DOUBLET MODEL

LHC sensitivity

Conclusion

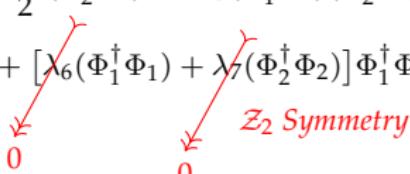
MOTIVATION

- Measurements of Higgs properties at run 1 and run 2 are in a good agreement with the SM, but ...
- Maybe other scalars waiting to be discovered;
- Two Higgs Doublet Model (2HDM) :
 - Minimal extension to the SM
 - Larger scalar sector than SM
 - Rich collider phenomenology
 - LHC benchmark mode
 - Type-II has the same structure as MSSM with much more freedom in the choice of model parameters

TRADITIONAL PARAMETRIZATION OF 2HDM

The most general scalar potential of the 2HDM :

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



 0 0

with :

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

- 5 physical Higgses : 2 CP-even h et H , 1 CP-odd A^0 and 2 Charged Higgs H^\pm
- The scalar potential has 10 independent parameters : $m_{11}^2, m_{22}^2, m_{12}^2, v_1, v_2$ and $\lambda_1, \dots, \lambda_7$
- 2 minimization conditions and the combination $v_1^2 + v_2^2 \Rightarrow 7$ free parameters :
 $m_h < m_H, m_{H^\pm}, m_A, \alpha, \tan \beta = \frac{v_2}{v_1}$ and m_{12}^2

ALIGNMENT LIMIT

The alignment limit is most clearly exhibited in the Higgs-basis :

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

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

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

$$\begin{aligned} H &= (\sqrt{2} \operatorname{Re} H_1^0 - v) \cos(\beta - \alpha) + \sqrt{2} \operatorname{Re} H_2^0 \sin(\beta - \alpha) \\ h &= (\sqrt{2} \operatorname{Re} H_1^0 - v) \sin(\beta - \alpha) + \sqrt{2} \operatorname{Re} H_2^0 \cos(\beta - \alpha) \end{aligned}$$

● $\cos(\beta - \alpha) \rightarrow 0$, $h \equiv H_{SM}$ ([J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang and S. Kraml, Phys.](#)

[Rev. D 92 \(2015\) no.7, 075004](#)); standard hierarchy

- with decoupling $m_{H^\pm} \sim m_A \sim m_H \gg v$
- without decoupling

● $\sin(\beta - \alpha) \rightarrow 0$, $H \equiv H_{SM}$ ([J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang and S. Kraml, Phys.](#)

[Rev. D 93 \(2016\) no.3, 035027](#)); inverted hierarchy

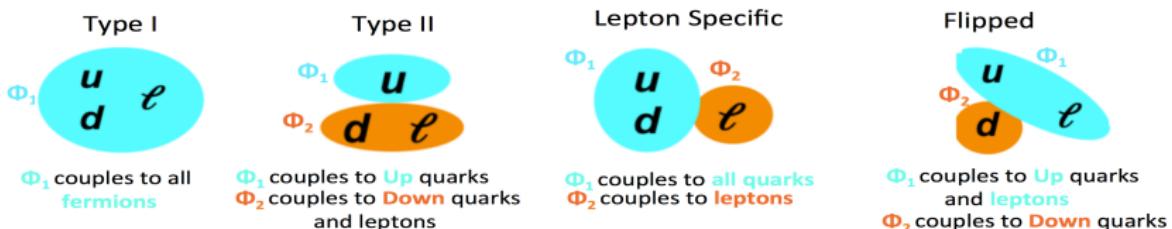
YUKAWA COUPLINGS

The general structure of the Yukawa Lagrangian when both Higgs fields couple to all fermions :

$$\mathcal{L}_Y = \bar{Q}'_L (M'_u \tilde{H}_1 + Y'_u \tilde{H}_2) u'_R + \bar{Q}'_L (M'_d H_1 + Y'_d H_2) d'_R + \bar{L}'_L (M'_l H_1 + Y'_l H_2) l'_R + \text{h.c}$$

\implies FCNC at tree level

* \mathbb{Z}_2 Symmetry :



2HDM	y_u^H	y_d^H	y_ℓ^H	y_u^A	y_d^A	y_ℓ^A
Type-I	s_α/s_β	s_α/s_β	s_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	s_α/s_β	c_α/c_β	c_α/c_β	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-X	s_α/s_β	s_α/s_β	c_α/c_β	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-Y	s_α/s_β	c_α/c_β	s_α/s_β	$\cot\beta$	$\tan\beta$	$-\cot\beta$

$$\frac{s_\alpha}{s_\beta} = \cos(\beta - \alpha) - \cot\beta \sin(\beta - \alpha)$$

$$\frac{c_\alpha}{c_\beta} = \cos(\beta - \alpha) + \tan\beta \sin(\beta - \alpha)$$

THEORETICAL AND EXPERIMENTAL CONSTRAINTS

2HDMC Code (D. Eriksson, J. Rathsman and O. Stål)

- 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

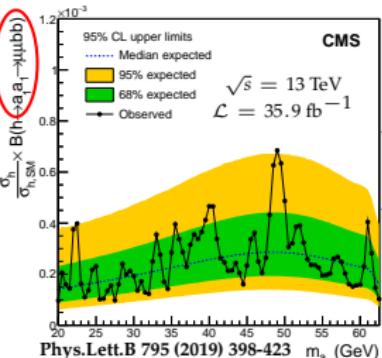
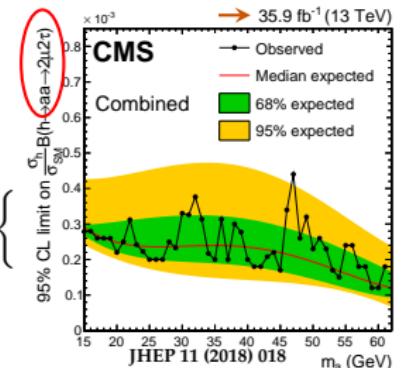
SuperIso (F. Mahmoudi)

- Constraints of flavour physics observables, namely, $B \rightarrow X_s \gamma$, $B_{s,d} \rightarrow \mu^+ \mu^-$ and $\Delta m_{s,d}$

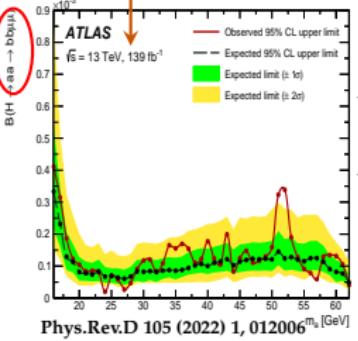
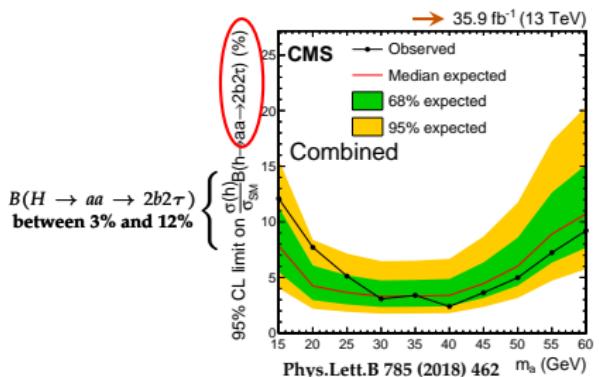
SEARCH FOR LIGHT PSEUDOSCALARS IN EXOTIC HIGGS DECAYS

Upper limits on
 $B(H \rightarrow 2a \rightarrow 2\mu 2b, 2\mu 2\tau, 2b2\tau)$
at 95% C.L.

Limits on
 $B(H \rightarrow aa \rightarrow 2\tau 2\mu)$
 $m_a \in [15, 60] \text{ GeV}$



No significant excess
is 😞



$\sigma_h \times B(H \rightarrow aa \rightarrow 2b2\mu)$
ranging from 5 fb to 33 fb

$B(H \rightarrow aa \rightarrow 2b2\mu)$
in range $[2.0 - 4.0] \times 10^{-4}$

BUT WHY TYPE-I?



Benchmark for **neutral** Higgs

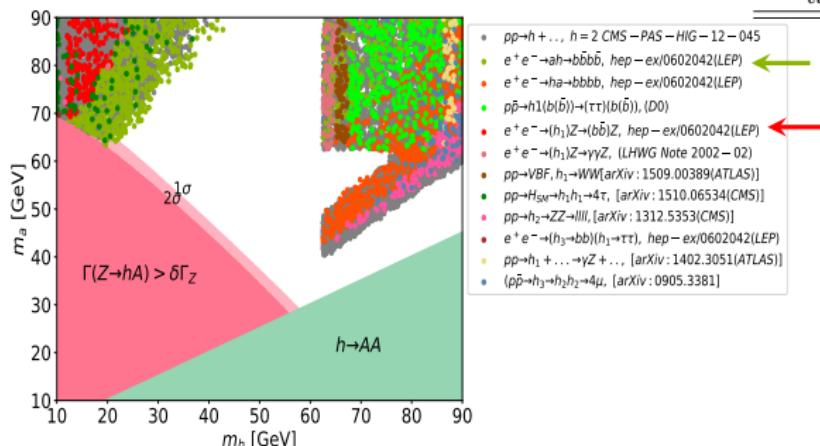
- Multi-photon production in the Type-I 2HDM ($H_{SM} \rightarrow aa(hh) \rightarrow 4\gamma$)
A. Arhrib et al, JHEP 07 (2018) 007
- Observability of 2HDM Neutral Higgs Bosons in fully hadronic decay at future linear collider Ijaz Ahmed, Nadia Kausar, Qasim Shah, arXiv : 2011.12534
- Kinematic corrections and reconstruction methods for neutral Higgs boson decay to $b\bar{b}$ in 2HDM type-I at future lepton colliders
Majid Hashemi and Elnaz Ebrahimi, Phys.Rev.D 103 (2021) 11, 115008

Benchmark for **charged** Higgs H^\pm

- New Discovery Modes for a Light Charged Higgs Boson at the LHC
A. Arhrib et al, JHEP 10 (2021) 073
- Analysis of $W \pm 4\gamma$ in the 2HDM Type-I at the LHC
A. Arhrib et al
- Charged Higgs Observability via Charged Higgs Pair Production at Future Lepton Collider
Ijaz Ahmed, arXiv : 2011.11131
- Signatures of the Type-I 2HDM at the LHC
R. Enberg, W. klemm, S. Moretti and S. Munir, PoS CORFU2018 (2018) 013

REINTERPRETING OF EXOTIC HIGGS DECAYS IN 2HDM TYPE-I

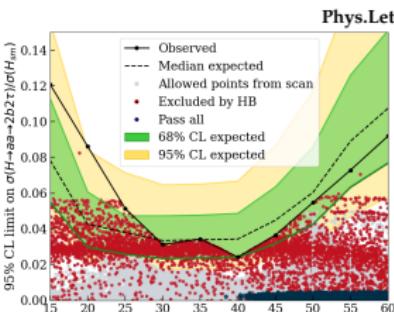
- Interested in $m_h < m_H/2$ and $m_a > m_H/2$
- Sensitivity in this region mainly from LEP searches for processes such as $e^+e^- \rightarrow ah \rightarrow b\bar{b}b\bar{b}$ and $e^+e^- \rightarrow (h)Z \rightarrow (b\bar{b})Z$.
- Updates of LHC ones at Run3 unlikely to rule it out



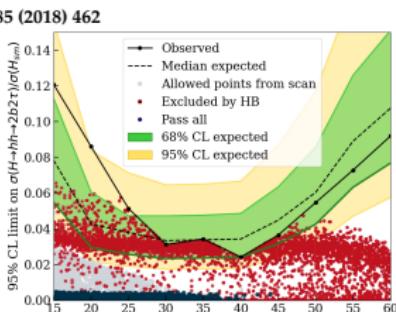
Inverted hierarchy	
parameters	scan
m_h (GeV)	[10, 90]
m_H (GeV)	125
m_a (GeV)	[10, 90]
m_{H^\pm} (GeV)	[100, 160]
$\sin(\beta - \alpha)$	[-0.25, 0]
$\tan \beta$	$[0, m_A^2 \sin \beta \cos \beta]$

FIGURE – Allowed parameter space in the 2HDM Type-I at 95% C.L. vs. searches to which the relevant (m_h, m_a) regions are sensitive to

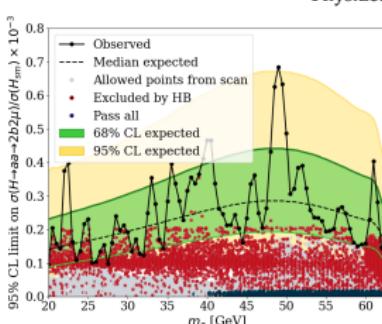
SEARCHES FOR LIGHT BSM HIGGSSES



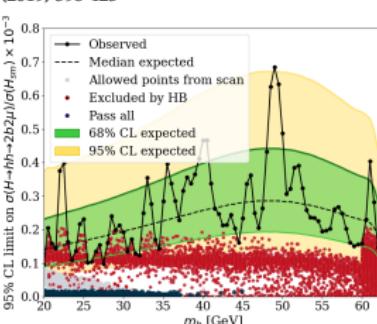
Obs & exp upper limits on $\sigma(H \rightarrow aa(hh) \rightarrow 2b2\tau) / \sigma_{SM}(H)$ at 95% in Type-I



- The recasting of $H \rightarrow aa$ in $2b2\tau$, $2b2\mu$ final states for $H \rightarrow hh$ is possible
- Areas with sensitivity are **excluded** by previous searches.
- CMS placed an upper limit of 0.19 on B_{inv} at 95% C.L., after performing a combination of run 1 & run 2 searches for $ggF + ISR$, VBF , $VH \rightarrow H \rightarrow inv$.
- ATLAS set an upper limit of 0.14 at 95% C.L. on $B(H \rightarrow inv)$ using data collected for $\mathcal{L} = 139\text{fb}^{-1}$
- The region of parameters is more constrained by $2b2\tau$ search than $H \rightarrow aa \rightarrow 2b2\mu$, $2\tau2\mu$.

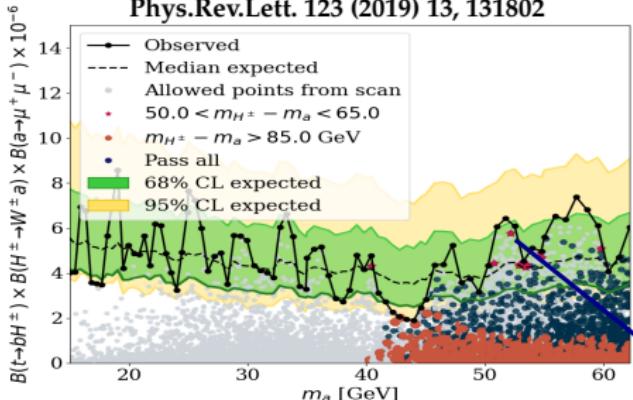


Obs & exp upper limits on $\sigma(H \rightarrow aa(hh) \rightarrow 2b2\mu) / \sigma_{SM}(H)$ at 95% in type-I



SEARCH FOR LIGHT CHARGED HIGGS

Phys.Rev.Lett. 123 (2019) 13, 131802



- ATLAS and CMS performed searches for $H^+ \rightarrow AW^+$ with $A \rightarrow \mu\mu$ at run 2
- Bosonic decay of H^\pm can dominate fermionic channels in BSM when kinematically allowed.
- Type-I offers **sufficient sensitivity**, with an integrated luminosity of 35.9 fb^{-1} (purple stars).

Parameters	BP1	BP2	BP3	BP4
(Masses are in GeV)				
m_h	62.86	75.69	75.58	77.18
m_H	125	125	125	125
m_A	40.37	50.73	52.90	53.44
m_{H^\pm}	105.19	108.15	110.83	111.95
$\tan\beta$	4.82	4.73	4.58	4.57
$\sin(\beta - \alpha)$	-0.203	-0.209	-0.220	-0.0.215
Total decay width in GeV				
$\Gamma(h)$	1.9×10^{-6}	3.00×10^{-6}	1.9×10^{-6}	3.00×10^{-6}
$\Gamma(H)$	4.54×10^{-3}	4.53×10^{-3}	4.47×10^{-3}	4.48×10^{-3}
$\Gamma(A)$	5.39×10^{-5}	6.79×10^{-5}	7.6×10^{-5}	7.7×10^{-5}
$\Gamma(H^\pm)$	3.31×10^{-4}	3.330×10^{-4}	3.339×10^{-4}	3.339×10^{-4}
$\mathcal{BR}(A \rightarrow XY)$				
$\mathcal{BR}(A \rightarrow \mu\mu)$	2.36×10^{-4}	2.42×10^{-4}	2.43×10^{-4}	2.43×10^{-4}
$\mathcal{BR}(H^\pm \rightarrow XY)$ in %				
$\mathcal{BR}(H^\pm \rightarrow W^+ A)$	86.65	90.64	88.47	89.39

NEW SIGNATURE : $gg \rightarrow H_{sm} \rightarrow Z^*a \rightarrow Z^*Z^*h$

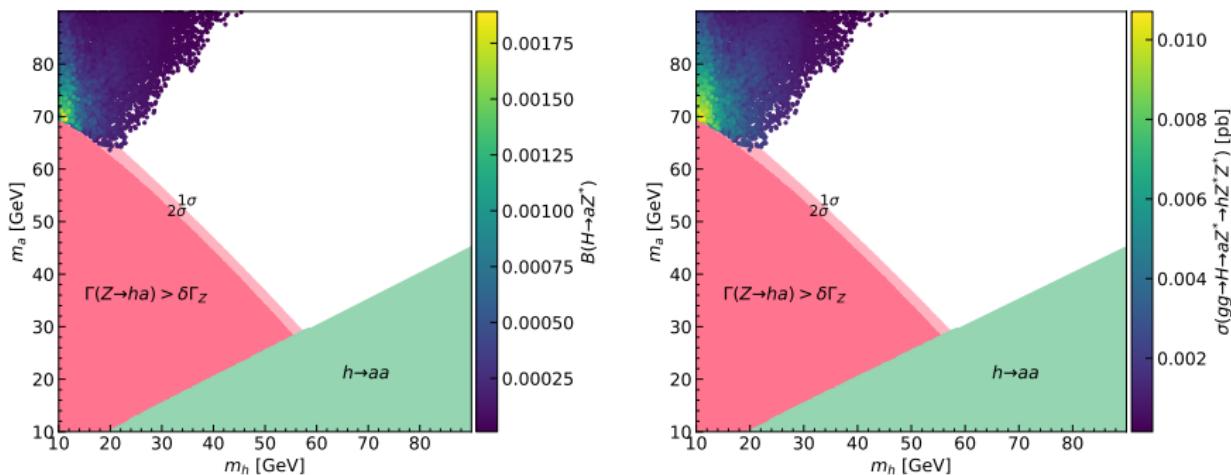
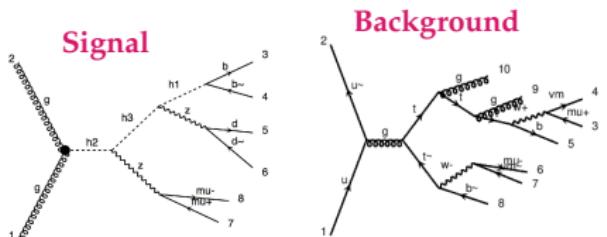


FIGURE – m_a and m_h vs. $\sigma(gg \rightarrow H_{sm} \rightarrow Z^*a)$ (left panel) and $\sigma(gg \rightarrow H_{sm} \rightarrow Z^*a \rightarrow Z^*Z^*h)$ (right panel) at 95% C.L. in 2HDM Type-I

- The subsequent decay of a , when the decay chain $H \rightarrow aZ^*$ is open, could lead to $a \rightarrow Z^*h$ with Z being off-shell and h decaying to fermions and/or $\gamma\gamma$
- One could look for $Z^*(\rightarrow 2\mu)Z^*(\rightarrow 2j)h(\rightarrow 2b)$ with di-muon trigger & standard $|\eta(\mu)|$
- Watch this space for results!

SIGNAL VS. BACKGROUND : PARTON LEVEL

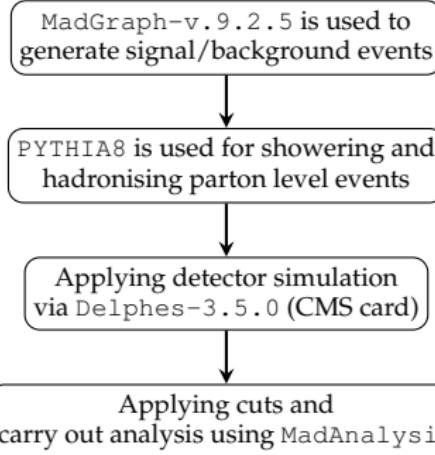


- Samples of BPs for the signal given by $H \rightarrow aZ^* \rightarrow hZ^*Z^* \rightarrow \mu^+\mu^- jj b\bar{b}$ are considered
- Main background processes are :
 - $gg t\bar{t}$ (reducible background)
 - $Z^{(*)}Z^{(*)}$ production in association with $b\bar{b}$ quarks (irreducible background, negligible)

Background	Cross section (pb)
$pp \rightarrow ZZ b\bar{b}_{QCD} \rightarrow \mu^+\mu^- jj b\bar{b}$	$9.27 \times 10^{-3} \pm 2.4 \times 10^{-5}$
$pp \rightarrow ZZ b\bar{b}_{QED} \rightarrow \mu^+\mu^- jj b\bar{b}$	$2.42 \times 10^{-4} \pm 5.5 \times 10^{-7}$
$pp \rightarrow gg t\bar{t} \rightarrow gg\mu^+\mu^- jj\nu\bar{\nu}$	2.92 ± 0.008

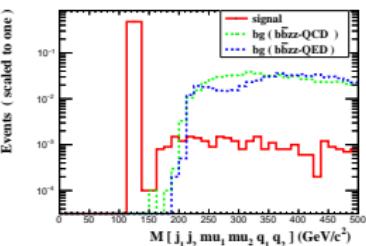
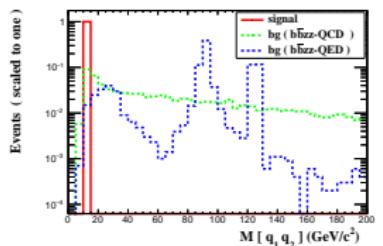
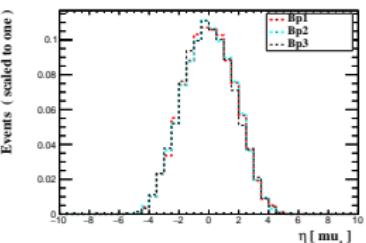
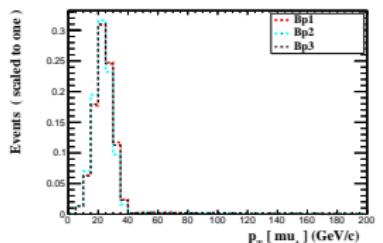
TABLE – The background cross sections

Toolbox to generate and analyse MC events



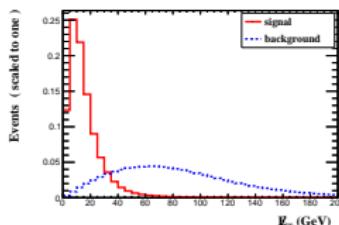
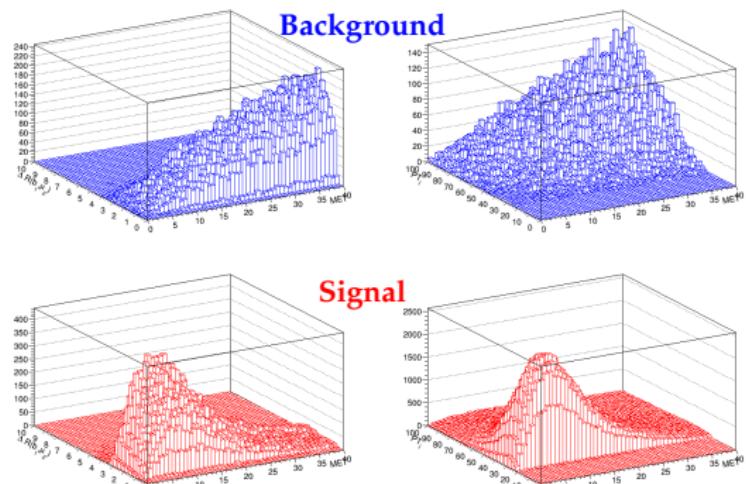
- QCD corrections to signal and background are considered through K-factor,
 - NLO QCD correction to $t\bar{t} + gg \sim -27\%$ Phys.Rev.D 84 (2011) 114017
 - NNLO QCD correction to $gg \rightarrow H \sim 2.6$

SIGNAL VS. BACKGROUND : KINEMATIC DISTRIBUTIONS AT PARTON LEVEL



- The requirement of central pseudorapidity of the muons is generally satisfied
- $p_T^\mu \Rightarrow$ di-muon trigger with $p_T(\mu_{1(2)}) > 17(8)$ GeV
- $m_{b\bar{b}} \sim m_h$ & $m_{\mu^+ \mu^- jj\bar{b}\bar{b}} \sim m_H$ unlike the irreducible background

SIGNAL VS. BACKGROUND : DETECTOR LEVEL



- $p_T^{j, b} > 20 \text{ GeV}, p_T^l > 10 \text{ GeV}, |\eta(l, b)| < 2.5, |\eta(j)| < 5.0, \Delta R > 0.4$
- \cancel{E}_T from simulated samples of background events is mainly from di-leptonic decay of $t\bar{t} + gg$
- The observed MET in signal at detector level is from semi-leptonic B-meson decay

FIGURE – Correlation between $\Delta R(b_1, \mu_2)$ vs. MET (left panel), p_T^j vs. MET (middle panel) and p_T^μ vs. MET (right panel)

- $\cancel{E}_T < 25 \text{ GeV} \Rightarrow$ strongly favour the signal over the background
- $p_T^j < 75 \text{ GeV}, p_T^\mu < 40 \text{ GeV}, m_{\mu\mu} < 40 \text{ GeV}, \Delta R(b_i, \mu_j) < 2.5, \Delta R(\mu_1, \mu_2) < 2.5, \Delta R(j_1, j_2) < 2.5$ and $\Delta R(b_1, b_2) < 2.5 \Rightarrow$ **effective suppression of $gg t\bar{t}$**

SIGNAL VS. BACKGROUND : DETECTOR LEVEL

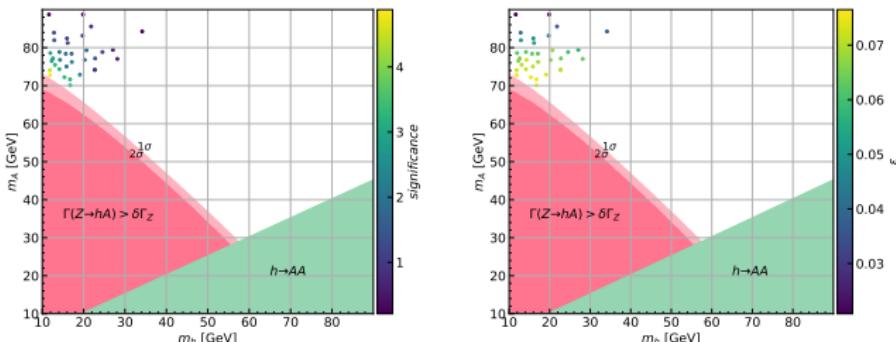


FIGURE – Significance and efficiency (ϵ) of each BP

BP	m_h (GeV)	m_A (GeV)	σ (pb)	k-factor	significance	ϵ
BP1	11.85	72.75	4.82×10^{-4}	2.689	4.88	0.0758
BP2	15.37	72.21	3.28×10^{-4}	2.63	3.20	0.0757
BP3	17.15	76.24	2.54×10^{-4}	2.63	2.29	0.0689
BP4	13.09	75.47	3.538×10^{-4}	2.65	3.31	0.0709
BP5	14.15	74.35	3.458×10^{-4}	2.62	3.29	0.072
BP6	11.96	78.57	3.557×10^{-4}	2.69	2.97	0.062
BP7	12.60	77.17	3.311×10^{-4}	2.66	2.87	0.065
BP9	14.30	76.77	2.423×10^{-4}	2.63	2.31	0.0729
BP10	14.16	78.86	2.572×10^{-4}	2.648	2.11	0.062
BP20	11.83	74.06	4.577×10^{-4}	2.69	4.51	0.073

- Some points on the grid have a significance larger than 3 on the (m_h, m_a) plane for $\mathcal{L} = 300\text{fb}^{-1}$.
- A larger efficiency can be obtained in a parameter space with small m_a .

CONCLUSION

- Most combinations of Type-I for which there is sensitivity for $H \rightarrow hh(aa) \rightarrow 2b2\tau$ have been excluded by existing searches
- $H^\pm \rightarrow W^\pm a \rightarrow W^\pm \mu^+ \mu^-$ is a channel with good sensitivity for Run 3
- A substantial $Br(H_{125} \rightarrow Z^* a \rightarrow Z^* Z^* h)$ in Type-I
- Good case for looking at $Z^* Z^* h$ in the region with high m_a and small m_h which is expected to be available, once Run3 is turned on
- Correlation distributions between kinematic variables for signal & background helped to define such efficient cuts that optimize signal over background
- $gg \rightarrow H_{SM} \rightarrow Z^* a \rightarrow Z^* Z^* h \rightarrow \mu^+ \mu^- b\bar{b}jj$ is a promising signature to search for light Higgses, with a suppressed background and a large predicted significance
- $gg \rightarrow H_{SM} \rightarrow Z^* a \rightarrow Z^* Z^* h \rightarrow \mu^+ \mu^- b\bar{b}jj$ will turn into discovery for HL-LHC

Thank you for listening!

Backup

THE YUKAWA COUPLINGS IN THE ALIGNMENT LIMIT

2HDM	y_u^H	y_d^H	y_ℓ^H	y_u^A	y_d^A	y_ℓ^A
Type-I	s_α/s_β	s_α/s_β	s_α/s_β	$\cot\beta$	$-\cot\beta$	$-\cot\beta$
Type-II	s_α/s_β	c_α/c_β	c_α/c_β	$\cot\beta$	$\tan\beta$	$\tan\beta$
Type-X	s_α/s_β	s_α/s_β	c_α/c_β	$\cot\beta$	$-\cot\beta$	$\tan\beta$
Type-Y	s_α/s_β	c_α/c_β	s_α/s_β	$\cot\beta$	$\tan\beta$	$-\cot\beta$



Couplings	Type-I	Type-II	Type-X	Type-Y
ξ_A^u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ξ_H^u	$-\cot\beta$	$-\cot\beta$	$-\cot\beta$	$-\cot\beta$
ξ_A^d	$-\cot\beta$	$\tan(\beta)$	$-\cot\beta$	$\tan(\beta)$
ξ_H^d	$-\cot\beta$	$\tan(\beta)$	$-\cot\beta$	$-\tan(\beta)$
ξ_A^l	$-\cot\beta$	$\tan(\beta)$	$\tan(\beta)$	$-\cot\beta$
ξ_H^l	$-\cot\beta$	$\tan(\beta)$	$\tan(\beta)$	$-\cot\beta$

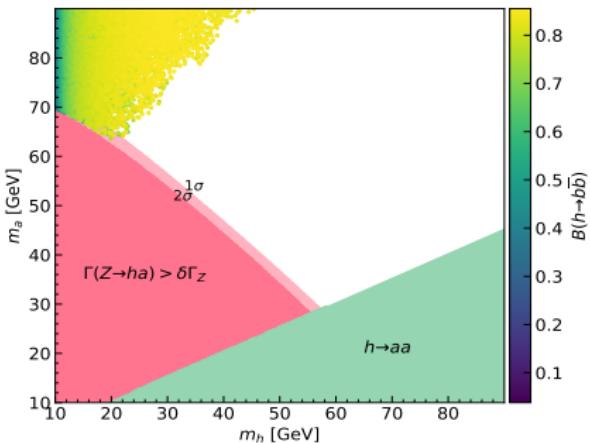
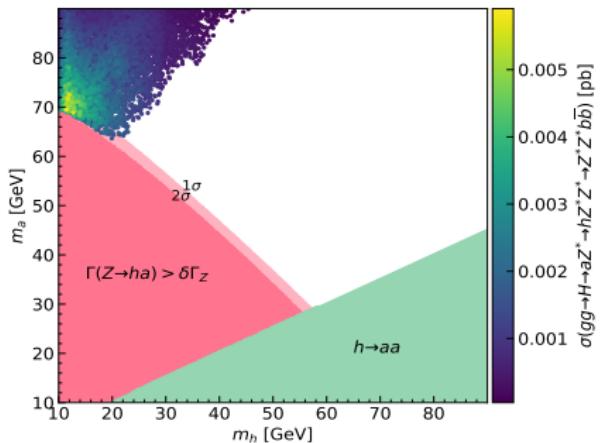


FIGURE – m_h and m_a vs. $B(h \rightarrow b\bar{b})$ (left), and $\sigma(gg \rightarrow H \rightarrow aZ^* \rightarrow hZ^*Z^* \rightarrow Z^*Z^*b\bar{b})$ (right) at 95% C.L in 2HDM Type-I

- The decay width of h is dominated by the decay mode $h \rightarrow b\bar{b}$
- $\sigma(gg \rightarrow H \rightarrow aZ^* \rightarrow hZ^*Z^* \rightarrow Z^*Z^*b\bar{b})$ could reach 0.006 pb

AT DETECTOR LEVEL

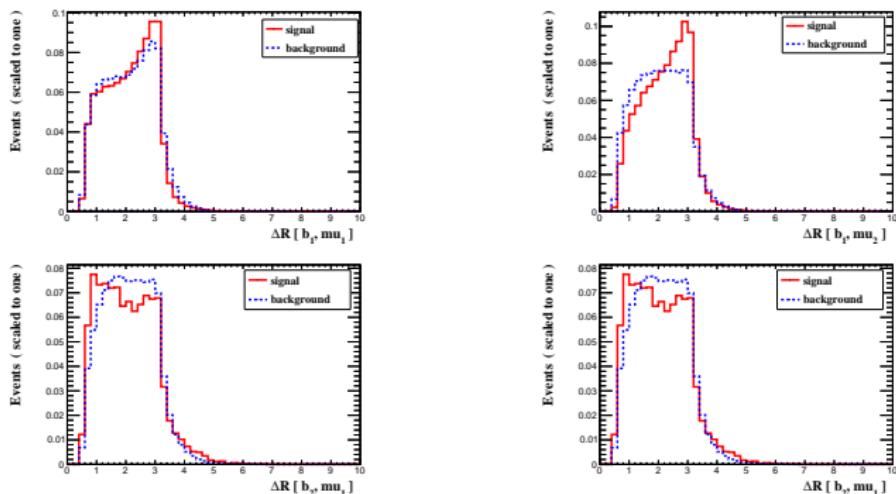
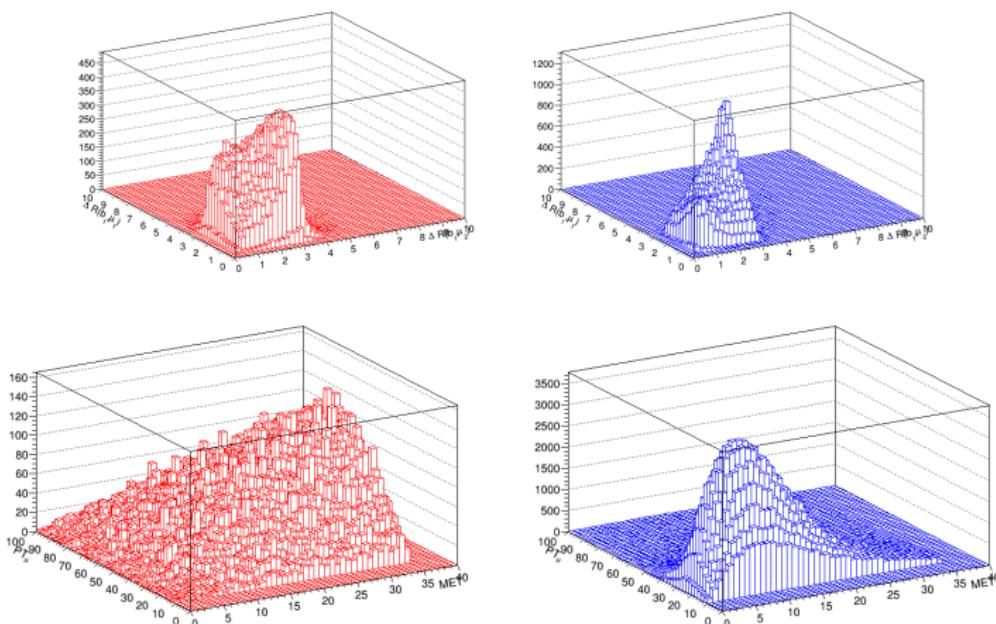


FIGURE – ΔR distributions

- Background has only a minimal component with muons coming from semi-leptonic b -meson decays

AT DETECTOR LEVEL

FIGURE – Correlation between p_T^{μ} vs. MET for signal (blue) and background (red)