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

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LHC Higgs Working Group WG3 (BSM): Extended Higgs Sector subgroup meeting

arXiv : 2207.03007

OUTLINE

TRADITIONAL PARAMETRIZATION OF 2HDM

The most general scalar potential of the 2HDM :

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

$\lambda_6 \to 0$, $\lambda_7 \to 0$: $\mathcal{Z}_2$ *Symmetry*

with :

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

- 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 $\lambda_{1,\ldots,5}$
- 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 :

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

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

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

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

- $\cos(\beta-\alpha) \to 0,\ h \equiv H_{SM}$ (J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang and S. Kraml, Phys. Rev. D **92** (2015) no.7, 075004); standard hierarchy
  - with decoupling $m_{H^\pm} \sim m_A \sim m_H \gg v$
  - without decoupling
- $\sin(\beta-\alpha) \to 0,\ H \equiv H_{SM}$ (J. Bernon, J. F. Gunion, H. E. Haber, Y. Jiang and S. Kraml, Phys. Rev. D **93** (2016) no.3, 035027); inverted hierarchy

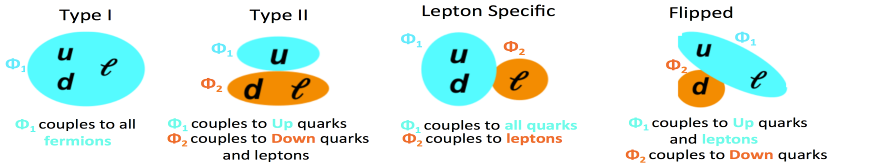
YUKAWA COUPLINGS

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

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

$\Longrightarrow$ **FCNC at tree level**

* $\mathcal{Z}_2$ **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)

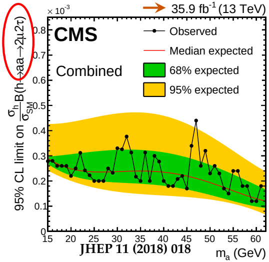
- Constraints of flavour physics observables, namely, $B \to X_s\gamma,\ B_{s,d} \to \mu^+\mu^-$ and $\Delta m_{s,d}$

Search for light pseudoscalars in exotic Higgs decays

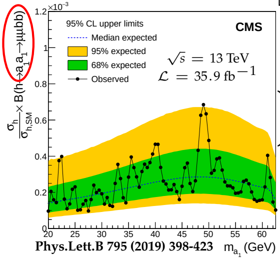
No significant excess is 🧐

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

Limits on
$B(H \to aa \to 2\tau 2\mu)$
$m_a \in [15,\ 60]$ **GeV**



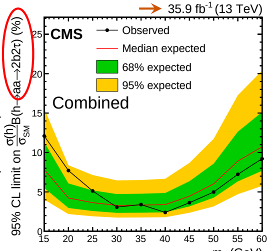
JHEP 11 (2018) 018



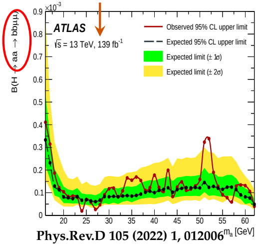
Phys.Lett.B 795 (2019) 398-423

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

$B(H \to aa \to 2b2\tau)$
between 3% and 12%



Phys.Lett.B 785 (2018) 462



Phys.Rev.D 105 (2022) 1, 012006

$B(H \to aa \to 2b2\mu)$
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 ($H_{SM} \to aa(hh) \to 4\gamma$)
    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 $e^+e^- \to ah \to b\bar{b}b\bar{b}$ and $e^+e^- \to (h)Z \to (b\bar{b})Z$.
- 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]
$\tan\beta$	$[0, m_A^2 \sin\beta\cos\beta\,]$

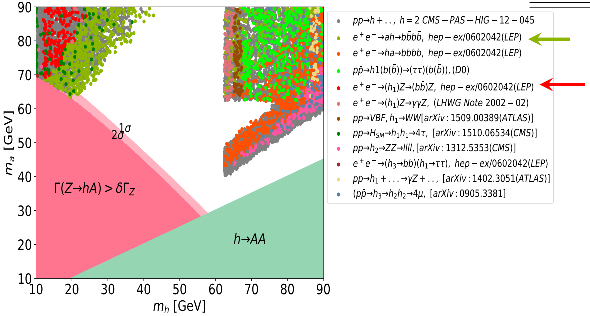
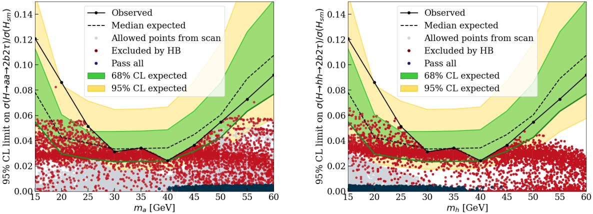


FIGURE – Allowed parameter space in the 2HDM Type-I at 95% C.L. vs. searches to which the relevant (m_h, m_a) regions are sensitive to

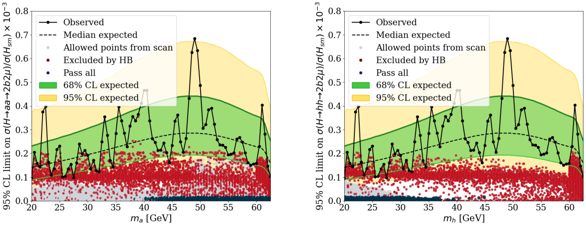
Searches for light BSM Higgses

Phys.Lett.B 785 (2018) 462



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

Phys.Lett.B 795 (2019) 398-423

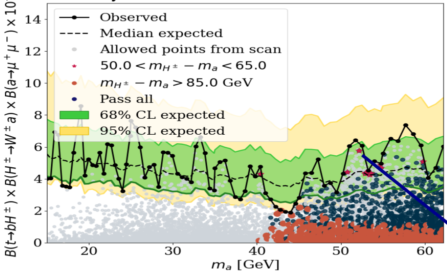


Obs & exp upper limits on $\sigma(H \to aa(hh) \to 2b2\mu)/\sigma_{SM}(H)$ at 95% in type-I

- The recasting of $H \to aa$ in $2b2\tau$, $2b2\mu$ final states for $H \to hh$ 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 $ggF + ISR, VBF, VH \to H \to inv$.
- ATLAS set an upper limit of 0.14 at 95% C.L on $B(H \to inv)$ using data collected for $\mathcal{L} = 139\text{fb}^{-1}$
- The region of parameters is more constrained by $2b2\tau$ search than $H \to aa \to 2b2\mu,\ 2\tau2\mu$.

SEARCH FOR LIGHT CHARGED HIGGS

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



- ATLAS and CMS performed searches for $H^+ \to AW^+$ with $A \to \mu\mu$ at run 2
- Bosonic decay of $H^\pm$ can dominate fermionic channles in BSM when kinematicaly 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}
		$\mathcal{BR}(A\to XY)$		
$\mathcal{BR}(A\to\mu\mu)$	2.36×10^{-4}	2.42×10^{-4}	2.43×10^{-4}	2.43×10^{-4}
		$\mathcal{BR}(H^\pm\to XY)$ in %		
$\mathcal{BR}(H^\pm\to W^+A)$	86.65	90.64	88.47	89.39

New Signature : $gg \to H_{sm} \to Z^* a \to Z^* Z^* h$

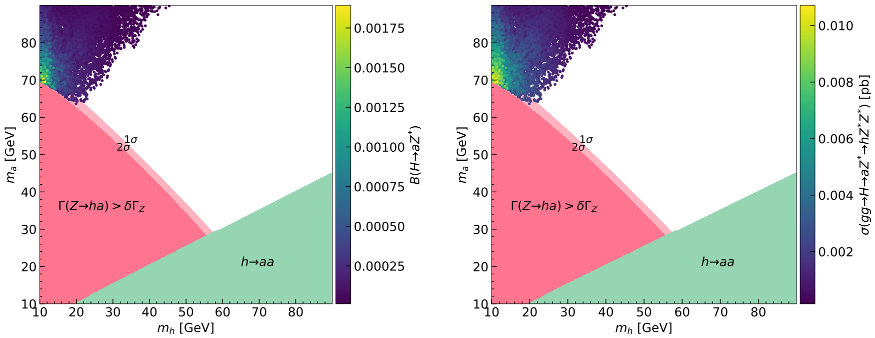
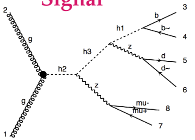


Figure – m_a and m_h vs. $\sigma(gg \to H_{sm} \to Z^* a)$ (left panel) and $\sigma(gg \to H_{sm} \to Z^* a \to Z^* Z^* h)$ (right panel) at 95% C.L in 2HDM Type-I

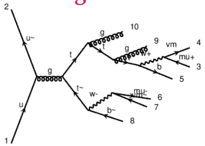
- The subsequent decay of a, when the decay chain $H \to aZ^*$ is open, could lead to $a \to Z^* h$ with Z being off-shell and h decaying to fermions and/or $\gamma\gamma$
- One could look for $Z^*(\to 2\mu)Z^*(\to 2j)h(\to 2b)$ with di-muon trigger & standard $|\eta(\mu)|$
- Watch this space for results!

SIGNAL VS. BACKGROUND : PARTON LEVEL

Signal



Background



- Samples of BPs for the signal given by $H \to aZ^* \to hZ^*Z^* \to \mu^+\mu^- \, jj \, b\bar{b}$ 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)
$pp \to ZZb\bar{b}_{QCD} \to \mu^+\mu^- jjb\bar{b}$	$9.27 \times 10^{-3} \pm 2.4 \times 10^{-5}$
$pp \to ZZb\bar{b}_{QED} \to \mu^+\mu^- jjb\bar{b}$	$2.42 \times 10^{-4} \pm 5.5 \times 10^{-7}$
$pp \to gg t\bar{t} \to gg\mu^+\mu^- jj\nu\bar{\nu}$	2.92 ± 0.008

TABLE – The background cross sections

Toolbox to generate and analyse MC events

`MadGraph-v.9.2.5` is used to generate signal/background events

↓

`PYTHIA8` is used for showering and hadronising parton level events

↓

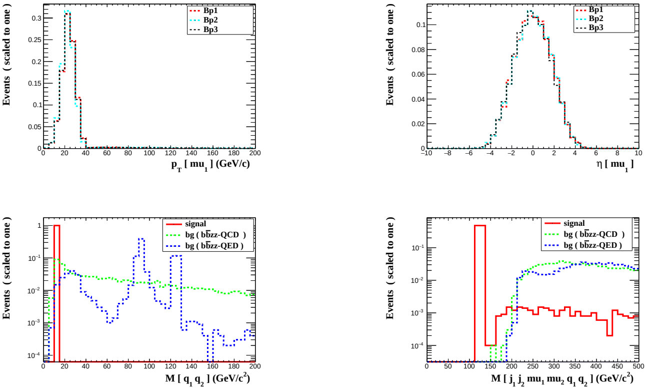
Applying detector simulation via `Delphes-3.5.0` (CMS card)

↓

Applying cuts and carry out analysis using `MadAnalysis`

- 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 $gg \to H \sim 2.6$

Signal vs. Background : Kinematic distributions at Parton Level



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

SIGNAL VS. BACKGROUND : DETECTOR LEVEL

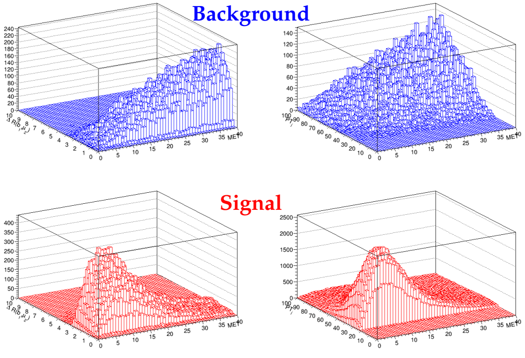
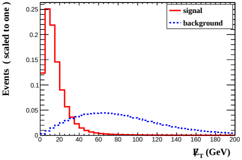


FIGURE – Correlation between $\Delta R(b_1, \mu_2)$ vs. MET (left panel), p_T^j vs. MET (middle panel) and p_T^μ vs. MET (right panel)



- $p_T^{j,\,b} > 20$ GeV, $p_T^l > 10$ GeV, $|\eta(l,b)| < 2.5$, $|\eta(j)| < 5.0$, $\Delta R > 0.4$
- $\not{E}_T$ 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

- $\not{E}_T < 25$ GeV $\Rightarrow$ strongly favour the signal over the background
- $p_T^j < 75$ GeV, $p_T^\mu < 40$ GeV, $m_{\mu\mu} < 40$ 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 $ggt\bar{t}$**

SIGNAL VS. BACKGROUND : DETECTOR LEVEL

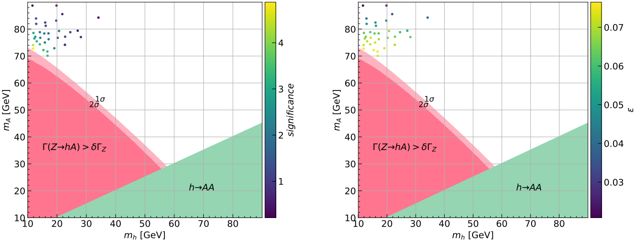


FIGURE – Significance and efficiency (ϵ) of each BP

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 $H \to hh(aa) \to 2b2\tau$ have been excluded by existing searches
- $H^{\pm} \to W^{\pm}a \to W^{\pm}\mu^{+}\mu^{-}$ is a channel with good sensitivity for Run 3
- A substantial $Br(H_{125} \to Z^{*}a \to Z^{*}Z^{*}h)$ 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
- $gg \to H_{SM} \to Z^{*}a \to Z^{*}Z^{*}h \to \mu^{+}\mu^{-}b\bar{b}jj$ is a promising signature to search for light Higgses, with a suppressed background and a large predicted significance
- $gg \to H_{SM} \to Z^{*}a \to Z^{*}Z^{*}h \to \mu^{+}\mu^{-}b\bar{b}jj$ 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	-$\cot\beta$	$\tan(\beta)$	$\tan(\beta)$	-$\cot\beta$

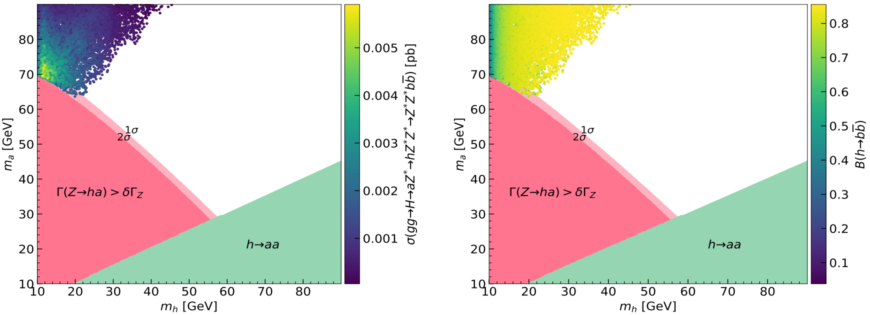


FIGURE – m_h and m_h vs. $B(h \to b\bar{b}))$ (left), and $\sigma(gg \to H \to aZ^* \to hZ^*Z^* \to Z^*Z^*b\bar{b})$ (right) at 95% C.L in 2HDM Type-I

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

At detector level

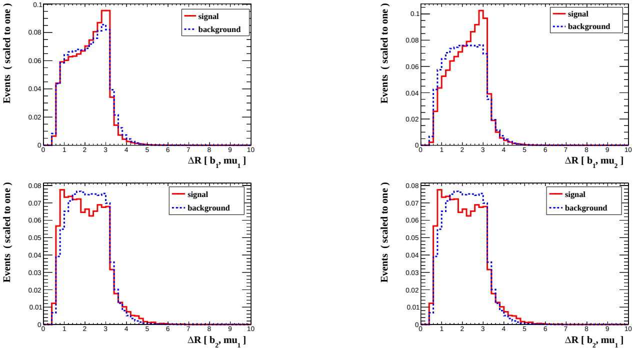


Figure – ΔR distributions between the two (p_T ordered) b-jets and muons, from hardest to softest (clockwise) for signal and background (blue) at detector level.

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

At detector level

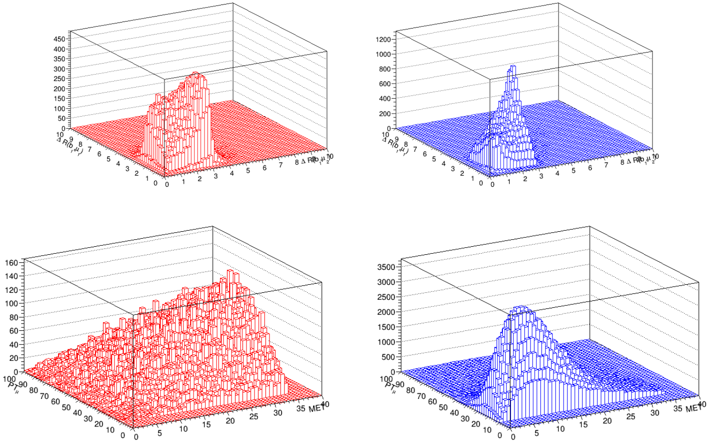


Figure – Correlation between p_T^μ vs. MET for signal (blue) and background (red)