

# Collider phenomenology of new neutral scalars in a flavoured multi-Higgs model

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**ICHEP 2022 - International Conference on High Energy Physics  
Bologna (Italy)**



**Multi-Higgs extensions:** Simplest matter extensions. Predicted in various high-scale **GUT and SUSY** models with extensive phenomenological implications:

- Dark Matter and CP violation;
- Muon  $(g - 2)$ , Flavour anomalies  $R_D/R_K$ ;
- Astrophysical consequences e.g. Boson stars, Primordial GWs.

Multiple classes of models (2HDM, 3HDM, C2HDM, etc). Detailed literature on experimental searches on various channels

- **CP-odd scalars:**  $A \rightarrow \tau^+\tau^-$  [Phys. Rev. Lett. 125, 051801],  $A \rightarrow HZ^0$  [Eur. Phys. J. C 81, 396 (2021)],  $A \rightarrow b\bar{b}$  [Phys. Rev. D 102, 112006 (2020)];
- **CP-even scalars:**  $H \rightarrow \tau^+\tau^-$  [Phys. Rev. Lett. 125, 051801],  $H \rightarrow b\bar{b}$  [Eur. Phys. J. C 80, 1165 (2020)],  $H \rightarrow AA$  [JHEP 08, 139 (2020)]
- **Singly-charged scalars :**  $H^\pm \rightarrow tb$  [JHEP 06, 145 (2021)],  $H^\pm \rightarrow cs$  [Phys. Rev. D 102, 072001 (2020)]

Model used in this work first introduced in [Pedro M. Ferreira et al. arXiv:2202.13153]. 2HDM + singlet with a non-trivial  $U(1)'$  flavour symmetry (**Vasileios talk on Friday**). Yukawa Lagrangian

$$\begin{aligned}
 -\mathcal{L}_{\text{Yukawa}} = & \overline{q_L^0} \Gamma_a \Phi^a d_R^0 + \overline{q_L^0} \Delta_a \tilde{\Phi}^a u_R^0 + \text{H.c.} + \overline{\ell_L^0} \Pi_a \Phi^a e_R^0 + \overline{\ell_L^0} \Sigma_a \tilde{\Phi}^a \nu_R \\
 & + \frac{1}{2} \overline{\nu_R^c} (A + BS + CS^*) \nu_R + \text{H.c.},
 \end{aligned}$$

Scalar potential:

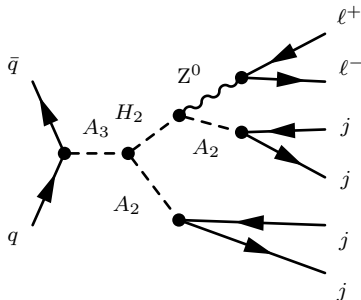
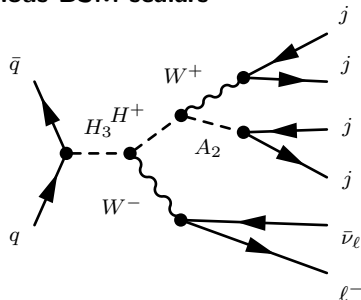
$$\begin{aligned}
 V_0 = & \mu_a^2 |\Phi^a|^2 + \lambda_a |\Phi^a|^4 + \lambda_3 |\Phi_1|^2 |\Phi_2|^2 + \lambda_4 |\Phi_1^\dagger \Phi_2|^2 + \mu_S^2 |S|^2 + \lambda'_1 |S|^4 \\
 & + \lambda'_2 |\Phi_1|^2 |S|^2 + \lambda'_3 |\Phi_2|^2 |S|^2 \quad (a = 1, 2), \\
 V_1 = & \mu_3^2 \Phi_2^\dagger \Phi_1 + \frac{1}{2} \mu_b^2 S^2 + a_1 \Phi_1^\dagger \Phi_2 S + a_2 \Phi_1^\dagger \Phi_2 S^\dagger + a_3 \Phi_1^\dagger \Phi_2 S^2 + \text{H.c.},
 \end{aligned}$$

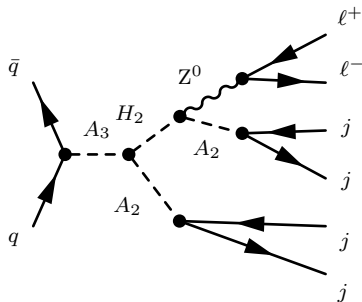
Once the fields develop VEVs, we have **3 CP-even states** ( $h, H_2, H_3$ ), **2 CP-odd states** ( $A_2, A_3$ ) and a **singly charged scalar** ( $H^\pm$ ).

In general (**with some exceptions!**), most searches focus on BSM Higgs decays to heavy SM states

- Limited searches for decays into **1st/2nd gen.** chiral quarks
- Charged Higgs primarily probed in the  $tbH^\pm$  vertex
- Limited searches for decays involving **multiple BSM Higgs**.

Additional parameter space can be probed in more complex final states, involving **various BSM scalars**

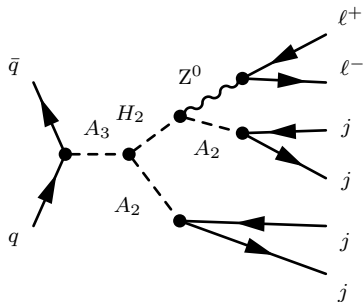




- **Two** opposite charge, same flavour leptons (**muons or electrons**);
- At least **four jets** from 1st/2nd generation quarks (**originate from  $A_2$** );
- Two pairs of jets with identical mass;
- Pre-selection **LO cross-section**:  
 $\mathcal{O}(10^{-1}) - \mathcal{O}(10^{-2})$  fb.

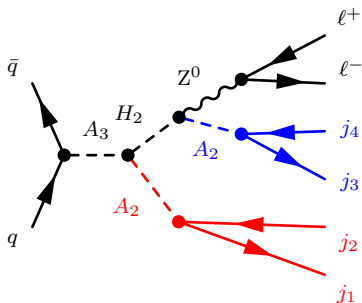
Potentially observable at **run-III** or at the **HL phase** of the LHC. Two pseudoscalars and one CP-even scalar running as internal propagators, **all on-shell** such that

$$M_{A_3} > M_{A_2} + M_{H_2} \quad \text{and} \quad M_{H_2} > M_{Z^0} + M_{A_2}$$



- Dominant backgrounds:  $\bar{t}t$  and  $Z^0 + \text{jets}$ ;
- Sub-leading but relevant: **Single top**,  $\bar{t}t + V$ , **Diboson**;

Leading-order cross-sections with **MadGraph** with MLM jet matching.  
 Hadronization in **Pythia8** and fast detector simulation of the ATLAS detector  
 with **Delphes**. **ROOT** for analysis of distributions.



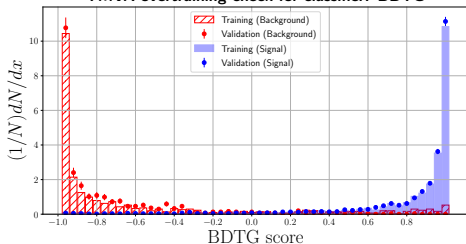
- Mass information can be used to match pairs of jets to original scalar fields;
- $\Delta M = M(j_1, j_2) - M(j_3, j_4) < \varepsilon$ :
  - **Signal**: small  $\varepsilon$ ;
  - **Background**: Arbitrary  $\varepsilon$ ;
- Loop over all possible combinations of jets and select the pairs with smallest  $\varepsilon$ .

Match jets to  $H_2$  scalar:  $\min(|M(j_n, j_m) - M(Z^0) - M(H_2)|)$

If the minimum is for pair  $(j_3, j_4)$ , then this is matched to the **blue leg** and the pair  $(j_1, j_2)$  is matched to the **red leg**.

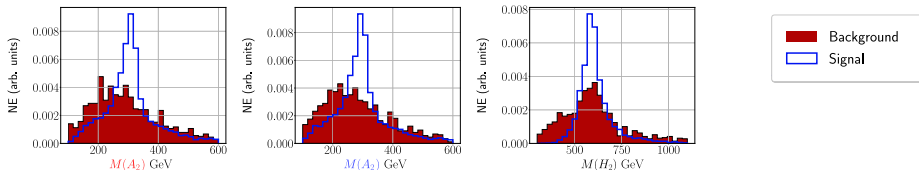
Since  $\varepsilon$  is expected to be arbitrary, the matching procedure can help reduce backgrounds for small values of  $\varepsilon$ .

TMVA overtraining check for classifier: BDTG



- $p_T(\ell^\pm) > 20$  GeV;
- $|\eta(\ell^\pm)| < 2.47$ ;
- $p_T(\text{jet}) > 20$  GeV;
- $|\eta(\text{jet})| < 2.5$ ;
- $M(\text{jet}) > 10/15$  GeV

Jet-matched mass distributions



Well-defined Breit-Wigner mass distributions for all scalar fields in the decay chain ( $M_{A_2} = 300$  GeV and  $M_{H_2} = 600$  GeV).



	$\sigma$ (before cuts, in fb)	$\sigma$ (after cuts, in fb)	Events at run-III	Events at HL-LHC
Signal (H1)	0.0594	0.0064	2	19
Signal (H2)	0.16	0.000699	< 1	2
$Z^0 + \text{jets}$	$4.12 \times 10^6$	9.64	2891	28915
$t\bar{t}$	$9.87 \times 10^5$	28.04	8412	84120
Single top	$7.38 \times 10^4$	14.36	4306	43068
$t\bar{t} + V$	33.41	0.024	7	71
Diboson	$7.79 \times 10^4$	0.045	13	135

$$\underline{M(j) > 15 \text{ GeV and } \Delta M < 25 \text{ GeV.}}$$

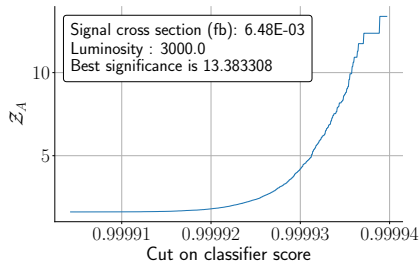
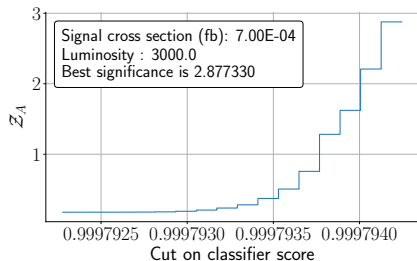
	$\sigma$ (before cuts, in fb)	$\sigma$ (after cuts, in fb)	Events at run-III	Events at HL-LHC
Signal (H1)	0.0594	0.029	8	87
Signal (H2)	0.16	0.0048	1	14
$Z^0 + \text{jets}$	$4.12 \times 10^6$	92.25	27675	276750
$t\bar{t}$	$9.87 \times 10^5$	327.82	98346	983460
Single top	$7.38 \times 10^4$	124.90	37470	374700
$t\bar{t} + V$	33.41	0.25	75	750
Diboson	$7.79 \times 10^4$	13.39	4017	40170

$$\underline{M(j) > 10 \text{ GeV and } \Delta M < 35 \text{ GeV.}}$$

**H1:**  $M_{A_2} = 300 \text{ GeV} / M_{H_2} = 600 \text{ GeV}$ ; **H2:**  $M_{A_2} = 215 \text{ GeV} / M_{H_2} = 400 \text{ GeV}$ ;

Neural networks to separate signal and background and compute statistical significance following methods of [\[Adam Elwood and Dirk Krücker arXiv:1806.00322\]](#)

$$M(j) > 15 \text{ GeV and } \Delta M < 25 \text{ GeV}$$

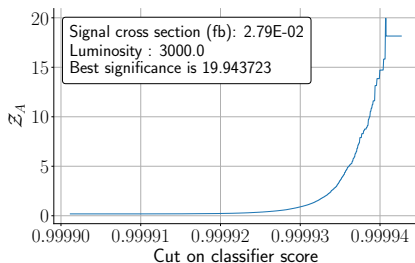
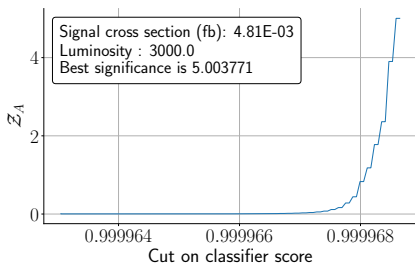


(a)  $M_{A_2} = 215 \text{ GeV}/M_{H_2} = 400 \text{ GeV}$

(b)  $M_{A_2} = 300 \text{ GeV}/M_{H_2} = 600 \text{ GeV}$

Better results for higher cuts on data, therefore **limited by statistics**. This signal can be **potentially** probed at the **HL-LHC**

$$M(j) > 10 \text{ GeV and } \Delta M < 35 \text{ GeV}$$



(a)  $M_{A_2} = 215 \text{ GeV} / M_{H_2} = 400 \text{ GeV}$

(b)  $M_{A_2} = 300 \text{ GeV} / M_{H_2} = 600 \text{ GeV}$

Relaxed constraints on jet mass distributions increases the significance. Particularly helpful for lower mass scalar fields. Still, **high cuts** on data for optimal results.

To finalize . . .

- I have discussed a particular signal topology, involving various BSM scalar fields in the decay chain, and studied its implications on future runs of the LHC.
- I have shown that the combination of kinematic information of the scalar fields can be used to match the original scalars to the outgoing jets;
- Employing neural networks, I have shown that these type of topologies can be probed for at the high-luminosity phase of the LHC.

# Collider phenomenology of new neutral scalars in a flavoured multi-Higgs model

**Thank you for your attention**

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