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

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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**: $A \to \tau^+\tau^-$ [Phys. Rev. Lett. 125, 051801], $A \to HZ^0$ [Eur. Phys. J. C 81, 396 (2021)], $A \to b\bar{b}$ [Phys. Rev. D 102, 112006 (2020)];
- **CP-even scalars**: $H \to \tau^+\tau^-$ [Phys. Rev. Lett. 125, 051801], $H \to b\bar{b}$ [Eur. Phys. J. C 80, 1165 (2020)], $H \to AA$ [JHEP 08, 139 (2020)]
- **Singly-charged scalars** : $H^\pm \to tb$ [JHEP 06, 145 (2021)], $H^\pm \to cs$ [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 $\mathrm{U}(1)'$ flavour symmetry (**Vasileios talk on Thursday**). Yukawa Lagrangian

$$-\mathcal{L}_{\text{Yukawa}} = \overline{q_L^0}\Gamma_a\Phi^a d_R^0 + \overline{q_L^0}\Delta_a\tilde{\Phi}^a u_R^0 + \text{H.c.} + \overline{\ell_L^0}\Pi_a\Phi^a e_R^0 + \overline{\ell_L^0}\Sigma_a\tilde{\Phi}^a\nu_R + \frac{1}{2}\overline{\nu_R^c}\left(\mathrm{A} + \mathrm{B}S + \mathrm{C}S^*\right)\nu_R + \text{H.c.}\,,$$

Scalar potential:

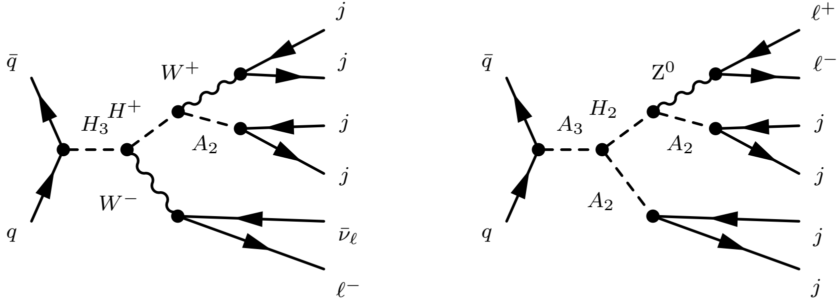
$$\begin{aligned} V_0 = \quad & \mu_a^2|\Phi^a|^2 + \lambda_a|\Phi^a|^4 + \lambda_3|\Phi_1|^2|\Phi_2|^2 + \lambda_4|\Phi_1^\dagger\Phi_2|^2 + {\mu_S}^2|S|^2 + \lambda_1'|S|^4 \\ & + \lambda_2'|\Phi_1|^2|S|^2 + \lambda_3'|\Phi_2|^2|S|^2 \quad (a = 1, 2), \\ V_1 = \quad & \mu_3^2\Phi_2^\dagger\Phi_1 + \frac{1}{2}\mu_b^2 S^2 + a_1\Phi_1^\dagger\Phi_2 S + a_2\Phi_1^\dagger\Phi_2 S^\dagger + a_3\Phi_1^\dagger\Phi_2 S^2 + \text{H.c.}\,, \end{aligned}$$

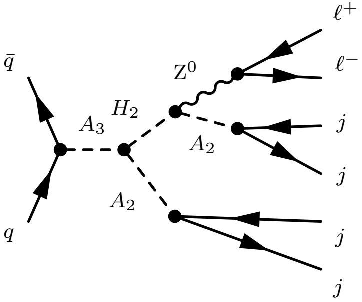
Once the fields develop VEVs, we have **3 CP-even states** (h, H_2, H_3), **2 CP-odd states** (A_2, A_3) and a **singly charged scalar** ($H^\pm$).

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**

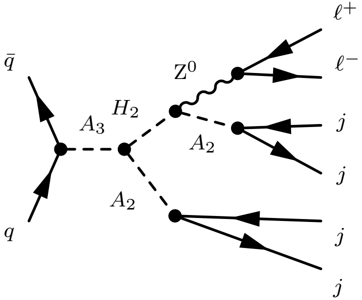




- **Two** opposite charge, same flavour leptons (**muons or electrons**);
- At least **four jets** from 1st/2nd generation quarks (**originate from A_2**);
- Two pairs of jets with identical mass;
- Pre-selection **LO cross-section**: $\mathcal{O}(10^{-1}) - \mathcal{O}(10^{-2})$ fb.

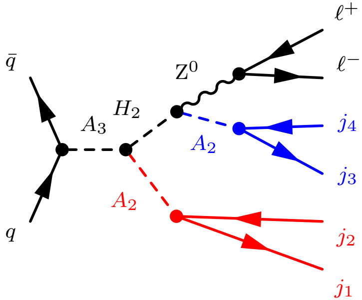
Potentially observable at **run-III** or at the **HL phase** of the LHC. Two pseudoscalars and one CP-even scalar running as internal propagators, **all on-shell** such that

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



- Dominant backgrounds: $\bar{t}t$ and $\mathbf{Z^0 + jets}$;
- 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.

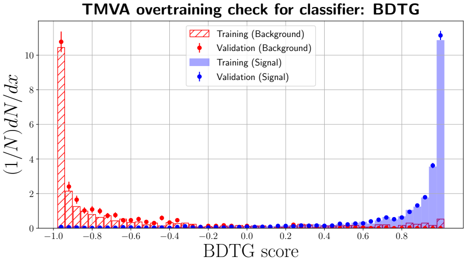


- Mass information can be use to match pairs of jets to original scalars fields;
- $\Delta M = M(j_1, j_2) - M(j_3, j_4) < \varepsilon$:
  - **Signal**: small ε;
  - **Background**: Arbitrary ε;
- Loop over all possible combinations of jets and select the pairs with smallest ε.

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

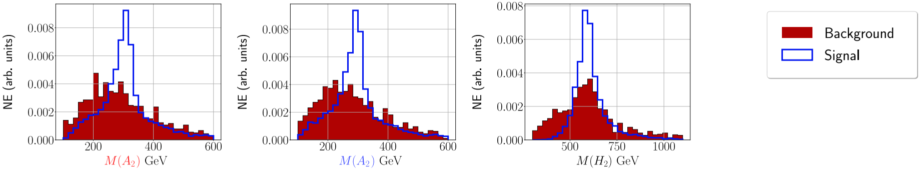
If the minimum is for pair (j_3, j_4), then this is matched to the blue leg and the pair (j_1, j_2) is matched to the red leg.

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



- $p_T(\ell^\pm) > 20$ 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).

	σ (before cuts, in fb)	σ (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
$\mathrm{Z}^0 + \mathrm{jets}$	4.12×10^6	9.64	2891	28915
$t\bar{t}$	9.87×10^5	28.04	8412	84120
Single top	7.38×10^4	14.36	4306	43068
$t\bar{t} + V$	33.41	0.024	7	71
Diboson	7.79×10^4	0.045	13	135

$M(j) > 15$ GeV and $\Delta M < 25$ GeV.

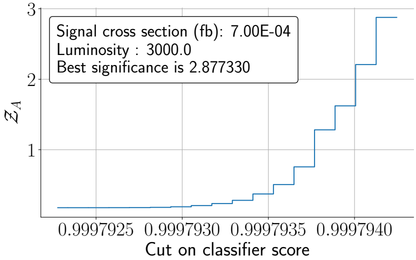
	σ (before cuts, in fb)	σ (after cuts, in fb)	Events at run-III	Events at HL-LHC
Signal (H1)	0.0594	0.029	8	87
Signal (H2)	0.16	0.0048	1	14
$\mathrm{Z}^0 + \mathrm{jets}$	4.12×10^6	92.25	27675	276750
$t\bar{t}$	9.87×10^5	327.82	98346	983460
Single top	7.38×10^4	124.90	37470	374700
$t\bar{t} + V$	33.41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

$M(j) > 10$ GeV and $\Delta M < 35$ GeV.

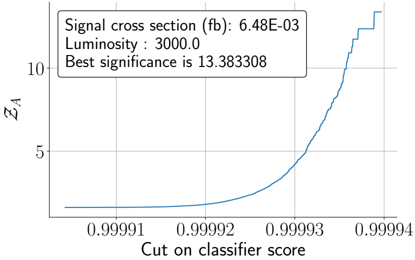
H1: $M_{A_2} = 300$ GeV/ $M_{H_2} = 600$ GeV; **H2:** $M_{A_2} = 215$ GeV/ $M_{H_2} = 400$ GeV;

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

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



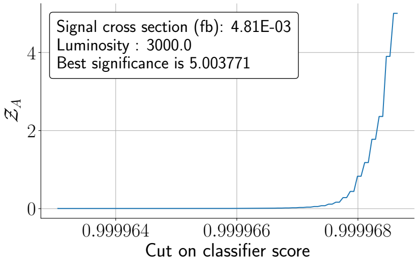
(a) $M_{A_2} = 215$ GeV$/M_{H_2} = 400$ GeV



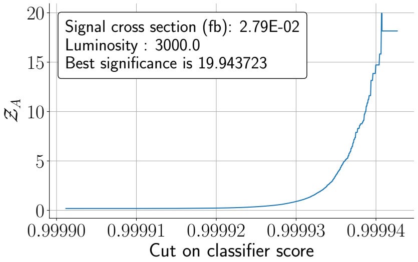
(b) $M_{A_2} = 300$ GeV$/M_{H_2} = 600$ GeV

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

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



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



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

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Thank you for your attention

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