Recent developments in LHC Higgs WG3 subgroup "Extended Higgs Sector"

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Snowmass 2021, EF10 DM@Colliders, topical meeting
17.11.21

Disclaimer

- will provide a **brief overview on some of the models** which have been discussed at our subgroup meetings

> **https://indico.cern.ch/event/1050919/**
> **https://indico.cern.ch/event/1091117/**
>
> **[egroup: lhc-higgs-neutral-extended-scalars]**

- obviously, **much more going on in WG3**
- also interesting: LHC DM Working Group
- cannot cover everything $\Rightarrow$ **personal selection**

WG 3 Extended Higgs Scalar Meetings

Focus on 3 different topics

$\Rightarrow$ **Overlooked signatures**

$\Rightarrow$ **Width and interference effects in BSM searches**

$\Rightarrow$ **Recasts**

- first point might be of interest
- **"typical": some 2HDM/ 3HDM variety, few contain DM candidates**

3HDM with dark CPV   DM ✓, CPV ✓

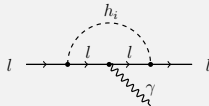DM is protected by a Z_2 symmetry $(-, -, +)$:

$$\phi_1 \rightarrow -\phi_1, \quad \phi_2 \rightarrow -\phi_2, \quad \text{SM fields} \rightarrow \text{SM fields}, \quad \phi_3 \rightarrow \phi_3$$

Z_2 symmetry respected by the vacuum $(0, 0, v)$:

$$\phi_1 = \begin{matrix} H_1^+ \\ \frac{H_1 + iA_1}{\sqrt{2}} \end{matrix} \quad , \quad \phi_2 = \begin{matrix} H_2^+ \\ \frac{H_2 + iA_2}{\sqrt{2}} \end{matrix} \quad , \quad \phi_3 = \begin{pmatrix} G^+ \\ \frac{v + h + iG^0}{\sqrt{2}} \end{pmatrix}$$
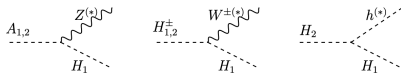
<u>DM candidate:</u> the lightest state among $S_{1,2,3,4}$ (mixture of $H_{1,2}, A_{1,2}$)

Only ϕ_3 can couple to fermions $\phi_u = \phi_d = \phi_e = \phi_3$ and $h_i = h$

$$-\mathcal{L}_{Yukawa} = Y_u \bar{Q}_L' i\sigma_2 \phi_u^* u_R'$$
$$+ Y_d \bar{Q}_L' \phi_d d_R'$$
$$+ Y_e \bar{L}_L' \phi_e e_R' + \text{h.c.}$$

No contributions to electric dipole moments (EDMs)

[JHEP 12, 014 (2016)], [Phys. Rev. D 101, 073007 (2020)]

Inert cascade decays at the LHC
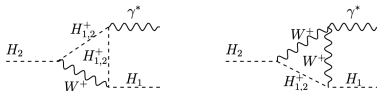
Tree level process: $q\bar{q} \to Z^* \to H_1 A_{1,2} \to H_1 H_1 Z^* \to H_1 H_1 f\bar{f}$

(may be possible in 2HDM)

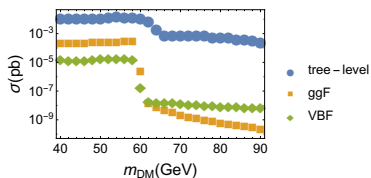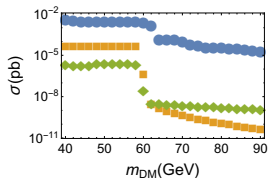Loop level ggF process: $gg \to h \to H_1 H_2 \to H_1 H_1 \gamma^* \to H_1 H_1 f\bar{f}$

Loop level VBF process: $q_i q_j \to H_1 H_2 \to H_1 H_1 \gamma^* \to H_1 H_1 f\bar{f}$

(smoking gun signature of 3HDM)

Benchmark	$m_{H_2} - m_{H_1}$	$m_{A_1} - m_{H_1}$	$m_{A_2} - m_{H_1}$	$m_{H_1^\pm} - m_{H_1}$	$m_{H_2^\pm} - m_{H_1}$
A50	50	75	125	75	125
I5	5	10	15	90	95

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LHC cross section for $\not{E}_T \bar{l}l$ and $\not{E}_T q\bar{q}$ for scenario I5

Decay channels	BR($H_2 \to H_1 X$)	tree-level	ggF	VBF
$H_2 \to s\bar{s}H_1$	2.22e-01	5.71e-03	9.70e-04	7.93e-06
$H_2 \to c\bar{c}H_1$	1.63e-01	1.52e-03	7.12e-05	5.82e-06
$H_2 \to d\bar{d}H_1$	2.28e-01	3.74e-03	9.96e-05	8.14e-06
$H_2 \to u\bar{u}H_1$	2.28e-01	4.80e-03	9.96e-05	8.14e-06
$H_2 \to \tau^+\tau^-H_1$	7.55e-03	1.13e-03	3.30e-06	2.70e-07
$H_2 \to \mu^+\mu^-H_1$	7.54e-02	7.47e-04	3.30e-05	2.69e-06
$H_2 \to e^+e^-H_1$	7.59e-02	1.73e-03	3.32e-05	2.71e-06

[JHEP 05, 030 (2018)]

Production thresholds of $S_i S_j$ at $e^+ e^-$ colliders

The $e^+ e^- \to Z^* \to S_i S_j$ cross section for A, B and C scenarios
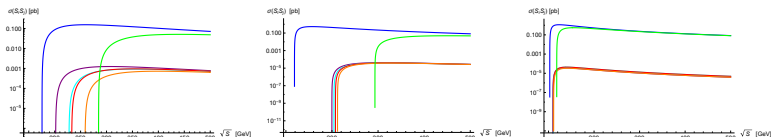
	Point-A	Point-B	Point-C	Point-D
m_{S_1}	72.3	55.4	50.9	63.2
m_{S_2}	103.3	63.2	51.7	78.0
$m_{S_1}^{\pm}$	106.2	79.1	99.1	106.3
m_{S_3}	129.4	144.3	58.5	185.0
m_{S_4}	155.1	148.8	59.4	213.1
$m_{S_2}^{\pm}$	157.5	159.2	111.1	204.3

a smoking gun signature of CP-violation in 3HDMs

IDM and TRSM - mini-introduction

- both models **extend scalar sector of SM, lead to novel particle states and non-SM signatures**
- **IDM: Inert Doublet Model**, Two-Higgs-Doublet Model with an exact Z_2 symmetry $\Rightarrow H, A, H^{\pm}$ **states**, one of these is dark matter
- **signatures: electroweak gauge bosons and** $\not{E}_{\perp}$
- **TRSM: model introducing 2 real scalar fields**, mixing $\Rightarrow$ **3 scalar states** $h_{1,2,3}$ (one $= h_{125}$)
- **signatures: many**, including multiscalar production and decays $p\,p \rightarrow h_i \rightarrow h_j\,h_k,\ i, j, k \in \{1, 2, 3\}$, ...
- **can lead to** $h_1 h_1 h_1$ **and** $h_1 h_1 h_1 h_1$ **final states**

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IDM and TRSM
WG3 Extended Higgs
WG3 Extended Higgs Meeting, 6.7.21
EF10, 17.11.21

Production and decay

- Z_2 symmetry:

  only pair-production of dark scalars $H, A, H^\pm$

- production modes:

  $$pp \to HA,\ HH^\pm,\ AH^\pm, H^+H^-$$
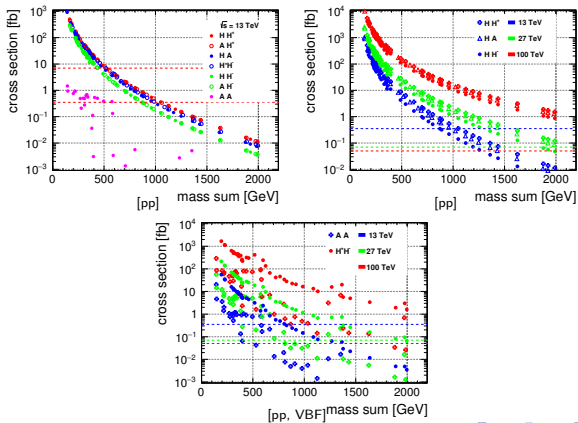
  $+$ dijet: VBF-type production

- decays:

  $$A \to Z\,H : 100\%,\ H^\pm \to W^\pm H : \text{dominant}$$

  signature: electroweak gauge boson(s) + MET

Production cross sections [Symmetry 13 (2021) 6, 991]

lines: 1000 events for design luminosity

Others models with dark matter candidates

- one example: **NMSSM: MSSM + pseudoscalar**
- contains **1 DM candidate**
- people interested in the **multiscalar sector: 3 CP-even, 2 CP-odd scalars**
- ⇒ **long multi-scalar decay chains possible**

$$\Longrightarrow \textbf{dedicated NMSSM subgroup} \Longleftarrow$$

Other Final States - Continued

NHSSM

$A_1 A_1 \to 4b$ ($H_1 = H^{SM}$) 357 fb

$A_1 A_1 \to 4t$ ($H_1 = H^{SM}$) 22.50 fb

$A_1 H_2 \to A_1 A_1 A_1 \to bb A_1 A_1$ 20.58 fb ($H_1 = H^{SM}$)

$H_3 H_3 \to A_1 A_1 A_1 A_1$ ($H_1 = H^{SM}$) 62.32 fb (Cool!)

$H_3 H_3 \to H_1 H_1 t\bar{t}$ ($H_1 = H^{SM}$) 136.55 fb

$H_3 H_3 \to H_1 H_1 H_1 H_1$ ($H_1 = H^{SM}$) 98.25 fb (Cool!)

$H_3 H_3 \to H_1 H_1 H^+ W^-$ ($H_1 = H^{SM}$) 111.16 fb (Cool!)

$H_3 H_3 \to H_1 H_2 t\bar{t}$ ($H_1 = H^{SM}$) 233.57 fb

$H_3 H_3 \to H_1 H_2 A_1 Z$ ($H_1 = H^{SM}$) 118.52 fb

$H_3 H_3 \to H^+ W^- H^+ W^-$ ($H_1 = H^{SM}$) 125.76 fb (Cool!)

$H_3 H_3 \to H^+ W^- t\bar{t}$ ($H_1 = H^{SM}$) 264.26 fb

$H_3 H_3 \to Z A_1 H^+ W^-$ ($H_1 = H^{SM}$) 134.10 fb

$H_3 H_3 \to t\bar{t} t\bar{t}$ ($H_1 = H^{SM}$) 2.8pb !

$H_3 H_3 \to t\bar{t} WW$ ($H_1 = H^{SM}$) 421.73 fb

$H_3 H_3 \to Z A_1 t\bar{t}$ ($H_1 = H^{SM}$) 353.18 fb

$H_3 H_3 \to WW \to H_1 H_1$ ($H_1 = H^{SM}$) 14.51 fb

$H_3 H_3 \to 4W$ ($H_1 = H^{SM}$) 45.52 fb

$H_3 H_3 \to Z A_1 WW$ ($H_1 = H^{SM}$) 11.12 fb

$H_3 H_3 \to Z A_1 Z A_1$ ($H_1 = H^{SM}$) 142.98 fb

Summary

- Restarted regular meetings within Extended Higgs Sector subgroup this summer
- focus (among others) on **novel/ overlooked signatures**
- mainly presented: **2HDMs, 3HDMs and extensions**
- **discrete symmetries ⇒ DM candidates**

> **2 concrete models with missing energy signatures**
> [typical: $Z + \slashed{E}$]

- obviously (some) overlapp with DM working group

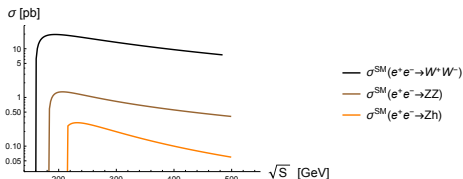# Appendix

Significance of the signal over the SM background

For all our BPs, the final state of the $e^+e^- \to Z^* \to S_iS_j$ process is $\not\!E_T f\bar{f}$,

$$e^+e^- \to Z^* \to S_1S_j \to S_1S_1Z^* \to S_1S_1f\bar{f},$$
$$e^+e^- \to Z^* \to S_iS_j \to S_1Z^*S_1Z^* \to S_1S_1f\bar{f}f\bar{f}, \qquad (i,j = 2,3,4)$$

The main SM background is through

$$e^+e^- \to ZZ \to f\bar{f}\nu\bar{\nu}, \qquad e^+e^- \to W^+W^- \to l^-\bar{\nu}\,l^+\nu, \qquad e^+e^- \to Zh \to f\bar{f}\not\!E_T$$

background decreases with increasing energy and is ≤ 1.8 pb

... in the NMSSM

$$W_{\text{NMSSM}} = \widehat{U}^C \mathbf{h}_u \widehat{Q} \widehat{H}_u + \widehat{D}^C \mathbf{h}_d \widehat{H}_d \widehat{Q} + \widehat{E}^C \mathbf{h}_e \widehat{H}_d \widehat{L} + \mu \widehat{H}_u \widehat{H}_d + \lambda \widehat{S} \widehat{H}_u \widehat{H}_d + \frac{\kappa}{3} \widehat{S}^3$$

$$\underbrace{\phantom{+\mu \widehat{H}_u \widehat{H}_d}}_{\boldsymbol{Z_3\text{-invariant}}}$$

$$H_d^0 = \begin{pmatrix} v_d + H_{dR} + iH_{dI} \\ H_d^- \end{pmatrix}, \quad H_u^0 = \begin{pmatrix} H_u^+ \\ v_u + H_{uR} + iH_{uI} \end{pmatrix}, \quad S = v_S + S_R + iS_I$$

A_0 (GeV)	$-5000 - 0$
μ_{eff} (GeV)	$100 - 1000$
$\tan\beta$	$1 - 40$
λ	$0.001 - 0.7$
κ	$0.001 - 0.7$
m_P (GeV)	$100 - 1000$
m_A (GeV)	$100 - 1000$

EWSB $\Rightarrow \mu_{\text{eff}} \equiv \lambda\langle\widehat{S}\rangle = \lambda v_s$

- *5 neutral Higgs bosons: h, h_s, H, a_s, A*

We scanned the NMSSM parameter space

for $m_H \approx m_{h_s}$ $\qquad M_{Q_{1,2,3}} = M_{U_{1,2,3}} = M_{D_{1,2,3}} = 3\,\text{TeV}$

Best points with $m_H \approx m_{h_s} \approx 410$ GeV ($m_h = 122$-128 GeV)
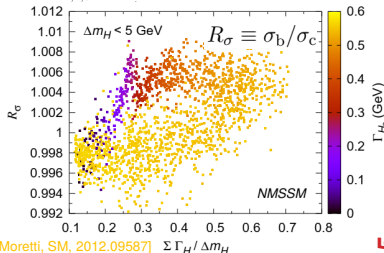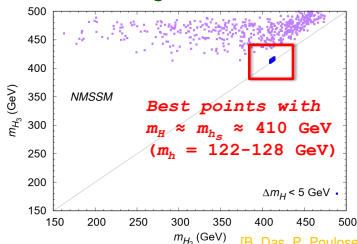
[B. Das, P. Poulose, S. Moretti, SM, 2012.09587]