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

Tania Robens

Rudjer Boskovic Institute

The 18th Workshop of the LHC Higgs Working Group
2.12.21

Facts

- **conveners:** L. Zivkovic (Belgrade), N. Rompotis (Liverpool), ATLAS; M. d'Alfonso (MIT), S. Laurila (CERN), CMS; T. Robens (Zagreb), R. Santos (Lisbon), Theory
- **Twiki:** https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG3EX
- **Email (conveners/ all):** lhc-higgs-neutral-extended-scalars-convener_at_cern.ch/ lhc-higgs-neutral-extended-scalars_at_cern.ch
- **egroup:** lhc-higgs-neutral-extended-scalars

Recent activities

- reinstated regular meetings ($\sim 3/$ year), focus on

A) Overlooked signatures
B) Width and interference effects in BSM searches
C) Recasts

- **6./7.7.: https://indico.cern.ch/event/1050919/**
- **5.11.: https://indico.cern.ch/event/1091117/**
- around $\sim$ 30 talks over the 3 days

$\Longrightarrow$ next slides: personal selection ! $\Longleftarrow$

Y. Wang, "The analysis of $W + 4\gamma$ in the 2HDM type-I"

our BPs

$$pp \to H^\pm h \to W^{\pm(*)} hh \to \ell \nu_\ell + 4\gamma$$

soft γ from $h \to \gamma\gamma$

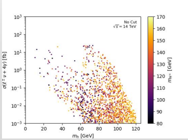
	M_h	M_A	$M_{H^\pm}$	$\sin(\beta-\alpha)$	$\tan\beta$	m_{12}^2	$\sigma_{13}(W+4\gamma)$ [fb]	$\sigma_{14}(W+4\gamma)$ [fb]
BP1	25.57	72.39	111.08	−0.074	13.58	11.97	101.40	112.55
BP2	35.12	111.24	151.44	−0.075	13.32	16.66	167.75	186.20
BP3	45.34	162.07	128.00	−0.136	7.57	80.96	10.76	11.93
BP4	53.59	126.09	91.49	−0.127	8.00	51.16	27.05	29.88
BP5	63.13	85.59	104.99	−0.056	18.09	190.24	179.31	198.61
BP6	65.43	111.43	142.15	−0.087	11.52	325.36	174.49	194.30
BP7	67.82	79.83	114.09	−0.111	8.94	326.32	177.72	197.23
BP8	69.64	195.73	97.43	−0.111	8.86	357.10	196.04	217.18
BP9	73.18	108.69	97.34	−0.122	8.06	594.64	193.56	214.57
BP10	84.18	115.26	148.09	−0.067	14.82	473.88	61.92	68.98
BP11	68.96	200.84	155.40	−0.112	8.64	531.46	62.02	69.14
BP12	71.99	91.30	160.10	−0.104	9.74	472.22	58.99	65.80
BP13	74.09	102.49	163.95	−0.092	10.56	503.74	55.58	62.04
BP14	81.53	225.76	168.69	−0.101	9.75	501.29	51.85	57.91

all BPs: m_H=125 GeV, $m_{H^\pm}<m_t$

on-shell W boson

off-shell W boson

$H^\pm \to W^{\pm(*)} h$



Y. Wang, "The analysis of $W + 4\gamma$ in the 2HDM type-I"

$\int \mathcal{L} = 300\ \mathrm{fb}^{-1}$

our BPs $pp \to H^{\pm}h \to W^{\pm(*)}hh \to \ell\nu_\ell + 4\gamma$

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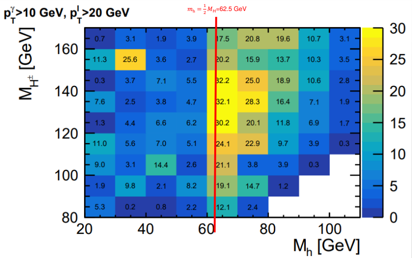
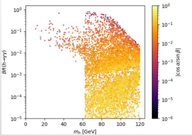
predicted significances for (Mh, MH±)

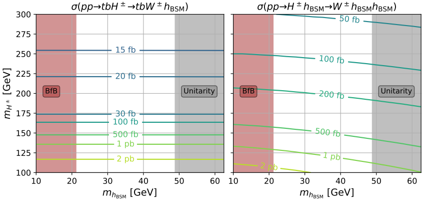




H. Bahl, "The forgotten channels: charged Higgs boson decays to a $W^\pm$ and a non-SM-like Higgs boson"

2HDM type I

$cH(Wh^{light}_{BSM})$ scenario — light h_{BSM}



- Requires fine-tuning of m_{12}^2 and $\tan\beta$ to suppress $h_{125} \to h_{BSM} h_{BSM}$ decays,
- $BR(h_{BSM} \to b\bar{b}) \sim 80\%$, $BR(h_{BSM} \to \gamma\gamma) \sim 10\%$,
- see also talk by Yan Wang.

H. Bahl, "The forgotten channels: charged Higgs boson decays to a $W^\pm$ and a non-SM-like Higgs boson"

cH($Wh_{\mathrm{BSM}}^{\mathrm{light}}$) scenario — light h_{BSM}

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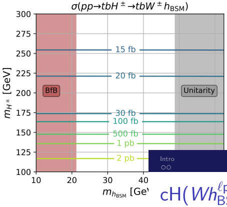
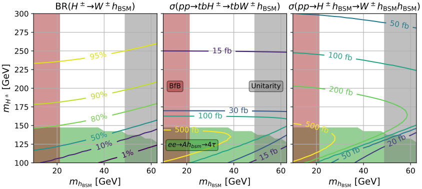


- Requires fine-tuning of m_{12}^2 and
- BR($h_{\mathrm{BSM}} \to b\bar{b}$) $\sim$ 80%, BR(h_{E}
- see also talk by Yan Wang.

cH($Wh_{\mathrm{BSM}}^{\ell\mathrm{phil}}$) scenario — light h_{BSM} in the LS 2HDM

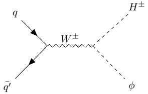


- Same as cH($Wh_{\mathrm{BSM}}^{\mathrm{light}}$) scenario but defined in the lepton-specific 2HDM $\to$ BR($h_{\mathrm{BSM}} \to \tau\tau$) $\sim$ 100%

P. Sanyal, "Prospects of same sign trilepton search in the Type I two Higgs doublet model at the LHC"

Same sign trilepton search at the LHC in Type I 2HDM

- For large $\tan\beta$ the cross section $pp \to W^{*\pm} \to H^{\pm}\phi$ dominates over the $pp \to H^{\pm}tb$ channel in Type I 2HDM.



- For close to the alignment limit $\phi \neq h_{SM}$.
- Signal:
  (A) $pp \to W^{*\pm} \to H^{\pm}H \to (W^{\pm}H)(W^{+}W^{-}) \to (W^{\pm}W^{+}W^{-})(W^{+}W^{-}) \to 3\ell^{\pm}\not{E}_T + X$
  (B) $pp \to W^{*\pm} \to H^{\pm}A \to (W^{\pm}H)(ZH) \to (W^{\pm}W^{+}W^{-})(ZW^{+}W^{-}) \to 3\ell^{\pm}\not{E}_T + X$
- SM backgrounds: $WZ+$ jets, $Z\ell^{+}\ell^{-}+$ jets and $t\bar{t}W+$ jets.
- Parameter Choice: $m_{H^\pm} - m_H = 85, 120$ GeV, $m_H \in [130 - 300]$GeV, $m_{H^\pm} \approx m_A$, $\tan\beta \in [1, 50]$, $\sin(\beta-\alpha) = 0.995$ and $m_{12}^2 \in [0, m_H^2 \sin\beta\cos\beta]$.

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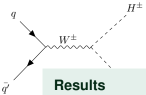
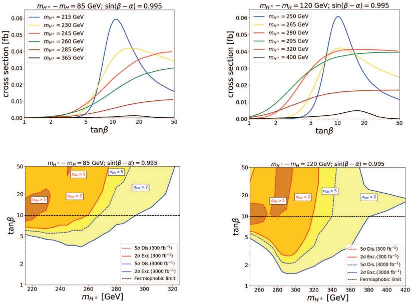


- For close to the alignment limit $\phi \neq$
- Signal:
  (A) $pp \to W^{*\pm} \to H^{\pm}H \to (W^{\pm}H)($
  (B) $pp \to W^{*\pm} \to H^{\pm}A \to (W^{\pm}H)($
- SM backgrounds: $WZ+$ jets, $Z\ell^{+}\ell^{-}$
- Parameter Choice: $m_{H^\pm} - m_H = 8$
  $m_{H^\pm} \approx m_A$, $\tan\beta \in [1, 50]$, $\sin(\beta -$

Results



T. Mondal and P. Sanyal, arXiv:2109.05682

T. Mondal, "Searches for a light pseudoscalar in L2HDM"

Leptophilic 2HDM

- 2HDM of type-X:

$$\mathcal{L}_Y = y_u \overline{q_L} \Phi_2^* u_R + y_d \overline{q_L} \Phi_2 d_R + y_l \overline{l_L} \Phi_1 e_R + h.c.$$

- 2HDM Higgs bosons: $h(125), H, H^{\pm}, A$
- In the alignment limit: $\sin(\beta-\alpha) \to 1;\ \cos(\beta-\alpha) \to 0$, or $2/t_\beta$ $\quad \begin{cases} \Phi_2 \to s_\beta(v+h) - c_\beta H - i c_\beta A \\ \Phi_1 \to c_\beta(v+h) + s_\beta H + i s_\beta A \end{cases}$

$$\mathcal{L}_Y = \kappa_f \frac{m_f}{v} \bar{f} h f + \frac{m_q}{v} \frac{1}{t_\beta} \bar{q}(H \pm i\gamma_5 A) q + \frac{m_l}{v} t_\beta \bar{l}(H + i\gamma_5 A) l \to$$ Leptophilic at large $\tan\beta$

- Muon g-2 favored (2σ): $m_H \approx m_{H^\pm} \gg m_A = (10-50)\text{GeV}, t_\beta = (35-70)$

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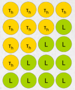
$$\mathcal{L}_Y = \kappa_f \frac{m_f}{v} \bar{f} h f + \frac{m_q}{v}\frac{1}{t_\beta} \bar{q}(H + i\gamma_5 A) q + \frac{m_l}{v} t_\beta \bar{l}(H + i\gamma_5 A) l \to \text{Leptophilic at large } \tan\beta$$

- Muon g-2 favored (2σ): m_H

LHC Search: $pp \to AH/AH^{\pm} \to A(\mu\mu)A(\tau\tau)Z/W^{\pm}$

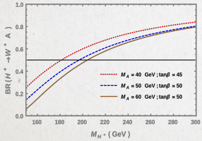
$$\Gamma(H^{\pm} \to W^{\pm} A) \sim \frac{m_{H^{\pm}}}{16\pi}\left(\frac{m_{H^{\pm}}}{v}\right)^2$$

$$\Gamma(H^{\pm} \to \tau^{+}\nu_\tau) \sim \frac{m_{H^{\pm}}}{16\pi}\left(\frac{\sqrt{2} m_\tau}{v}\tan\beta\right)^2$$



Possible Signatures

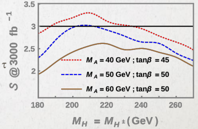
- $p\,p > H^{\pm} A > (W^{\pm} A)\, A > 1L + 4\tau$
- $p\,p > H\, A > (Z\, A)\, A > 2L + 4\tau$



Also : $Z/W > j\,j$ & $A > \mu\,\mu$

- $p\,p > H^{\pm} A > (W^{\pm} A)\, A > j\,j\ \mu\mu + 2\tau$
- $p\,p > H\, A > (Z\, A)\, A > j\,j\ \mu\mu + 2\tau$

$\text{IM}(j\,j\ \mu\mu) = m_{H\pm}$

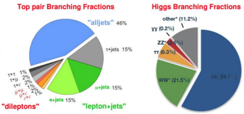


EJC, Dwivedi, TM, Mukhopadhyaya, Rai PRD 98 (2018) 7

10

R. Capucha, "Light Higgs searches in $t\bar{t}\Phi$ production at the LHC"

The model

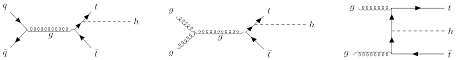


- **Goal:** study the possibility of probing the CP nature of the couplings of low mass Higgs bosons (ϕ) to top quarks in $\mathbf{t\bar{t}\phi}$.

- **SM + generic CP-violating Yukawa coupling to top-quark:**

$$\mathcal{L} = \kappa_t y_t \bar{t}(\cos\alpha + i\gamma_5 \sin\alpha)t\phi \; = y_t \bar{t}(\kappa + i\tilde{\kappa}\gamma_5)t\phi$$

- $\boldsymbol{y_t}$ - SM couplings. $\boldsymbol{\kappa_t}$ - coupling strength relative to SM. **CP-even** (α = 0, ϕ = H), **CP-odd** (α = π/2, ϕ = A).
- $\phi \rightarrow b\bar{b}$, $t\ (\bar{t}) \rightarrow\ W^+b\ (W^-\bar{b})$ and $W^+(W^-) \rightarrow\ l^+\upsilon_l(l^-\bar{\upsilon}_l)$ - **dileptonic state**, with $\mathbf{l} = \mathbf{e}, \boldsymbol{\mu}$.
- **Previous studies** covered **125** GeV, Phys. Rev. D 96 (2017) 013004, and **40-500** GeV, JHEP 06 (2020) 155. Here, $\boldsymbol{m_\phi}$**= 12 – 40 GeV.**



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- y_t - SM couplings. κ_t - coupling strength ı
- $\phi \to b\bar{b}$, $t\,(\bar{t}) \to W^+b\ (W^-\bar{b})$ and $W^+(W$
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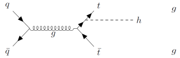
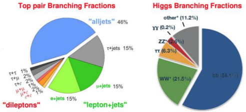
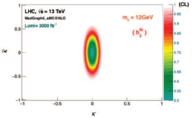
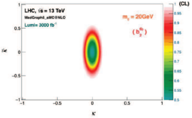
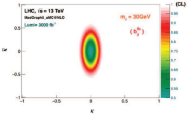


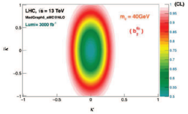


Results









$L = 3000\,\text{fb}^{-1}$		Exclusion Limits from $b_2^{t\bar{t}\phi}$ (68% CL)	(95% CL)	Exclusion Limits from $b_4^{t\bar{t}\phi}$ (68% CL)	(95% CL)
$m_\phi = 12\,\text{GeV}$	$\kappa \in$	[-0.05, +0.05]	[-0.11, +0.11]	[-0.05, +0.05]	[-0.11, +0.11]
	$\tilde{\kappa} \in$	[-0.26, +0.26]	[-0.50, +0.50]	[-0.26, +0.26]	[-0.50, +0.50]
$m_\phi = 20\,\text{GeV}$	$\kappa \in$	[-0.07, +0.07]	[-0.13, +0.13]	[-0.07, +0.07]	[-0.13, +0.13]
	$\tilde{\kappa} \in$	[-0.26, +0.26]	[-0.49, +0.49]	[-0.26, +0.26]	[-0.50, +0.50]
$m_\phi = 30\,\text{GeV}$	$\kappa \in$	[-0.07, +0.07]	[-0.14, +0.14]	[-0.07, +0.07]	[-0.14, +0.14]
	$\tilde{\kappa} \in$	[-0.26, +0.20]	[-0.50, +0.50]	[-0.26, +0.26]	[-0.50, +0.50]
$m_\phi = 40\,\text{GeV}$	$\kappa \in$	[-0.17, +0.17]	[-0.32, +0.32]	[-0.17, +0.17]	[-0.32, +0.32]
	$\tilde{\kappa} \in$	[-0.53, +0.53]	[-1.00, +1.00]	[-0.53, +0.53]	[-1.01, +1.01]

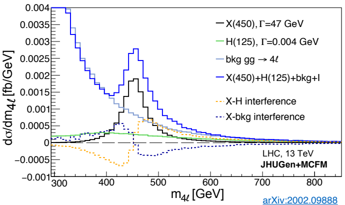
A. Gritsan, "Interference and finite width effects in di-boson resonance searches with the JHUGen framework"

E. Fuchs, "Interference effects in BSM searches"

Examples

- $gg \to (X/H^*) \to ZZ \to 4\ell$

  SM-like scalar couplings (tree-level)



arXiv:2002.09888

Andrei Gritsan, JHU 7 5 November 2021

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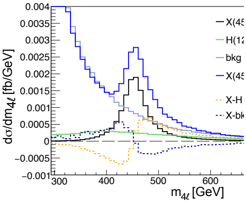
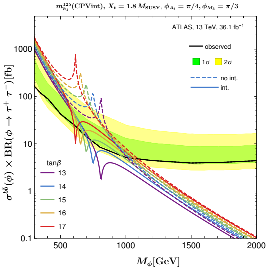


Andrei Gritsan, JHU 7

Comparison with experimental exclusion bounds

$\hat{Z}$-enhancement of cross sections, reduction by destructive interference



$m_{h_1}^{125}$(CPVint) A

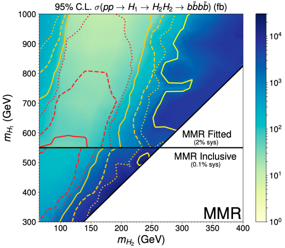
interference can suppress $\sigma_{\rm coh} < \sigma_{\rm exp}$ for some $(M_\phi, \tan\beta)$

Elina Fuchs (CERN) | BSM Interference Effects | 14

K. Mimasu, "Recasting $H \to h\,h \to 4\,b$ to search for Higgs-to-Higgs cascades"

S. Kraml, "Reinterpretation: considerations on what should be published"

Extended result: MMR



$\sigma(pp \to H_1 \to H_2 H_2 \to b\bar{b}b\bar{b})$
$= \hat{\sigma}(H_1) \times \kappa^2 \times \mathrm{BR}$

$\hat{\sigma}(H_1)$: SM-like $gg \to H_1$ production cross section

- $\kappa^2 \times$ BR = 0.02
- $\kappa^2 \times$ BR = 0.05
- $\kappa^2 \times$ BR = 0.1
- $\kappa^2 \times$ BR = 0.2
- $\kappa^2 \times$ BR = 0.5
- $\kappa^2 \times$ BR = 1
- $\kappa^2 \times$ BR = 3

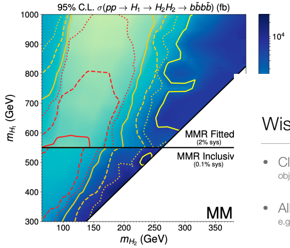
Systematics chosen to reproduce HL-LHC projections [CMS-PAS-FTR-16-002]

K. Mimasu - LHCHWG3 meeting - 05/11/2021 13 Recasting $H \to hh \to 4b$

K. Mimasu, "Recasting $H \to hh \to 4b$ to search for Higgs-to-Higgs cascades"

S. Kraml, "Reinterpretation: considerations on what should be published"

Extended result: MMR



$\sigma(pp \to H_1 \to H_2 H_2 \to b\bar{b}b\bar{b})$
$= \hat{\sigma}(H_1) \times \kappa^2 \times \text{BR}$

$\hat{\sigma}(H_1)$: SM-like $gg \to H_1$ production cross section

K. Mimasu - LHCHWG3 meeting - 05/11/2021

Wishlist for reinterpretation

- Clear, explicit and unambiguous analysis description
  object definitions, selection "cuts", etc., so that the analysis can be reproduced in a MC simulation
- All the relevant numbers regarding the results of the analysis
  e.g., expected and observed event counts in all kinematic regions, differential distributions, etc.
- Acceptance × efficiency values for specific signal hypotheses
  these allow fast reinterpretation w/o reproducing the full analysis; enable likelihood computation, etc
- The statistical model underlying the analysis

HEPData
!!!!!

Summary

Restarted regular meetings this summer

A) Overlooked signatures

B) Width and interference effects in BSM searches

C) Recasts

A) quite a few **suggestions for $p\,p \rightarrow H^{\pm}\,h_{\text{BSM}}$** into various final states $(W + 4\,\gamma\,/4\,\tau\,/\,4\,b\,/\,2\mu\,2\tau/...)$

B) many studies exist, but **impact for current searches not investigated in all detail** (personal opinion)

C) starts to be of interest, a lot of work has been done by **LHC BSM reinterpretation forum** [SciPost Phys. 9 (2020) 2, 022; arXiv:2109.04981]

Questions ? Suggestions ?

Appendix

Other Final States - Continued

NMSSM

$A_1A_1 - 4b$ $(H_1 = H^{SM})$ 367 fb

$A_1A_1 - 4t$ $(H_1 = H^{SM})$ 22.50 fb

$A_1H_2 \to A_1A_1A_1 \to b b A_1A_1$ 20.58 fb $(H_1 = H^{SM})$

$H_3H_3 \to A_1A_1A_1A_1$ $(H_1 = H^{SM})$ 62.32 fb Cool!

$H_3H_3 \to H_1H_1 t\bar{b}$ $(H_1 = H^{SM})$ 136.95 fb

$H_3H_3 \to H_1H_2H_1H_2$ $(H_1 = H^{SM})$ 98.25 fb Cool!

$H_3H_3 \to H_1H_2H^+W^-$ $(H_1 = H^{SM})$ 111.16 fb Cool!

$H_3H_3 \to H_1A_2 t\bar{t}$ $(H_1 = H^{SM})$ 233.57 fb

$H_3H_3 \to H_1H_2A_1Z$ $(H_1 = H^{SM})$ 118.52 fb

$H_3H_3 \to H^+W^-H^+W^-$ $(H_1 = H^{SM})$ 125.76 fb Cool!

$H_3H_3 \to H^+W^- t\bar{t}$ $(H_1 = H^{SM})$ 264.26 fb

$H_3H_3 \to ZA_1H^+W^-$ $(H_1 = H^{SM})$ 134.10 fb

$H_3H_3 \to t\bar{t}t\bar{t}$ $(H_1 = H^{SM})$ 7.8 pb !

$H_3H_3 \to t\bar{t}WW$ $(H_1 = H^{SM})$ 427.73 fb

$H_3H_3 \to ZA_1 t\bar{b}$ $(H_1 = H^{SM})$ 353.18 fb

$H_3H_3 \to WW \to H_1H_1$ $(H_1 = H^{SM})$ 14.57 fb

$H_3H_3 \to 4W$ $(H_1 = H^{SM})$ 45.52 fb

$H_3H_3 \to ZA_1WW$ $(H_1 = H^{SM})$ 11.12 fb

$H_3H_3 \to ZA_1ZA_1$ $(H_1 = H^{SM})$ 142.98 fb

Benchmark points/ planes [ASymmetric/ Symmetric]

AS **BP1:** $h_3 \to h_1 h_2$ $(h_3 = h_{125})$

SM-like decays for both scalars: $\sim$ 3 pb; h_1^3 final states: $\sim$ 3pb

AS **BP2:** $h_3 \to h_1 h_2$ $(h_2 = h_{125})$

SM-like decays for both scalars: $\sim$ 0.6 pb

AS **BP3:** $h_3 \to h_1 h_2$ $(h_1 = h_{125})$

(a) SM-like decays for both scalars $\sim$ 0.3 pb; **(b) h_1^3 final states:** $\sim$ 0.14 pb

S **BP4:** $h_2 \to h_1 h_1$ $(h_3 = h_{125})$

up to 60 pb

S **BP5:** $h_3 \to h_1 h_1$ $(h_2 = h_{125})$

up to 2.5 pb

S **BP6:** $h_3 \to h_2 h_2$ $(h_1 = h_{125})$

SM-like decays: up to 0.5 pb; h_1^4 **final states: around 14 fb**