Extended Scalars

Tania Robens

Rudjer Boskovic Institute

.

on behalf of WG3 Extended Higgs Sector conveners:

M. d'Alfonso, S. Laurila, TR, N. Rompotis, R. Santos, L. Zivkovic

The 19th Workshop of the LHC Higgs Working Group
CERN
28. November '22

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, focus on

A) Overlooked signatures
B) Width and interference effects in BSM searches
C) Recasts
D) CPV
E) ...

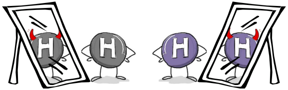
- **6./7.7.21: https://indico.cern.ch/event/1050919/**
- **5.11.21: https://indico.cern.ch/event/1091117/**
- **23.6.22: https://indico.cern.ch/event/1173518/**
- **16.11.22: https://indico.cern.ch/event/1217666/**
- around $\sim$ 50 talks over the 5 days

Joint activities with WG2: CP violation and Higgs Sector

one meeting in July this year; next: 11.1.2023

CPV in Higgs interactions:
WG2/WG3 (extended Higgs) joint meeting

WG3: Mariarosaria d'Alfonso, Santeri Laurila, Tania Robens, Nikos Rompotis, Rui Santos, Shufang Su & Lidija Zivkovic
WG2: Nicolas Berger, Mauro Donega, Ken Mimasu & Daniele Barducci



23rd June 2022

1

Joint WG2/WG3 activity

Todays meeting!

- Received several kick-off meeting contributions that overlapped with WG3 (extended Higgs sector) interests
- Many interesting signatures of spontaneous/explicit CPV in extended Higgs sectors
- From mixing of would-be CP-even/odd eigenstates

Discovery of BSM Higgs in multiple decay channels
⇒ CPV

Classes	C_1	C_2	C_3	C_4	C_5
Decays	$h_3 \to h_2 Z$	$h_2 \to h_1 Z$	$h_3 \to h_1 Z$	$h_3 \to h_2 Z$	$h_3 \to ZZ$
	$h_2 \to h_1 Z$	$h_1 \to ZZ$	$h_1 \to ZZ$	$h_2 \to ZZ$	$h_2 \to ZZ$
	$h_3 \to h_1 Z$	$h_2 \to ZZ$	$h_3 \to ZZ$	$h_3 \to ZZ$	$h_1 \to ZZ$

WG3 Proposal for CP violating benchmarks in the C2HDM ~ 2015
[Fontes et al.; PRD 92 (2015) 055014]

h_{125}-style CP properties study for BSM scalars
⇒ CPV

Decay angular distributions etc.

6

[Slides from K. Mimasu, https://indico.cern.ch/event/1173518/]

goal:
study CPV in models with extended Higgs sectors
will result in whitepaper/ report/ ...

K. Behr, Y. Cai, "Interference modeling for A/H→ttbar, ATLAS vs CMS"

s-channel resonance decaying to $t\,\bar{t}$

Summary of ATLAS/CMS differences

- Different LO UFO implementations
- Different approach to remove background component
  - ATLAS: (S+I+B) – B
  - CMS: 0.5 * [(S+I+B) - (S-I+B)]
- Different components being generated directly
  - ATLAS: S+I
  - CMS: I

Many thanks to Alexander Grohsjean and Afiq Anuar for providing the details about the CMS UFO and hacks!

K. Behr, Y. Cai, "Interference modeling for A/H→ttbar, ATLAS vs CMS"

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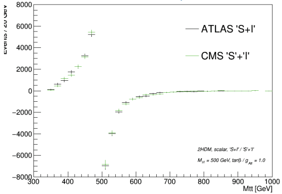
  - CMS: I

DESY.

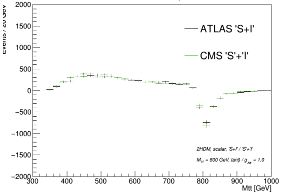
S+I shape comparison for H

- Final signal+interference shapes:
  - ATLAS: "S+I"
  - CMS: "S"+"I"

m_H = 500 GeV, tanβ = 1.0



m_H = 800 GeV, tanβ = 1.0



DESY.

Katharina Behr Page 16

D. Roy, " Signal interpretation in H→WW high mass analysis"

Signal samples

RWTH AACHEN UNIVERSITY KANSAS STATE UNIVERSITY

- Signals were produced with POWHEG, and the W boson decay simulated with JHUGen
- For mass ≤ 1 TeV, assumes a width of a SM-like Higgs boson of higher mass
  - Small width in O(100) GeV range, but becomes large approaching TeV range
  - 647 GeV width for 1 TeV signal
  - Also includes width effects from Complex Pole Scheme
- Above 1 TeV, a width of half the resonance mass is assumed

  → Very large and unphysical widths

  → Reweighting the signal distributions to follow scenarios of smaller widths

D. Roy, " Signal interpretation in H→WW high mass analysis"

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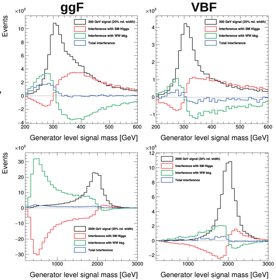
5 **Signal interpretation in H→WW high mass analysis**
Dennis Roy | Extended Higgs Sector meeting | 16.11.2022

Interference

- Interference for 20% rel. width signal
  - Top: 300 GeV
  - Bottom: 2000 GeV
- Contribution from interference much larger for larger widths



15 **Signal interpretation in H→WW high mass analysis**
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Dennis Roy | Extended Higgs Sector meeting | 16.11.2022

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  - Bottom: 2000 GeV
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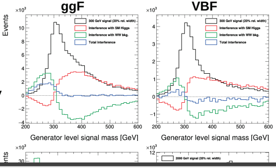


Compare with previous implementations ??
[inofficial discussion this evening...]

15 **Signal interpretation in H→WW high mass analysis**
Dennis Roy | Extended Higgs Sector meeting | 16.11.2022

S. Semlali, "A novel experimental search channel for very light Higgses in the Type-I 2HDM" / P. Sanyal, "Electroweak Multi-Higgs production: A smoking gun for the Type I 2HDM"

NEW SIGNATURE : $gg \to H_{sm} \to Z^*a \to Z^*Z^*h$

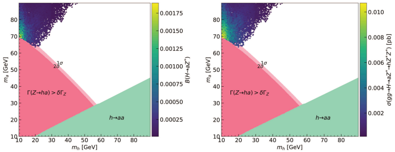


FIGURE – m_a and m_h vs. $\sigma(gg \to H_{sm} \to Z^*a)$ (left panel) and $\sigma(gg \to H_{sm} \to Z^*a \to Z^*Z^*h)$ (right panel) at 95% C.L in 2HDM Type-I

- 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!

S. Semlali, "A novel experimental search channel for very light Higgses in the Type-I 2HDM" / P. Sanyal, "Electroweak Multi-Higgs production: A smoking gun for the Type I 2HDM"

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

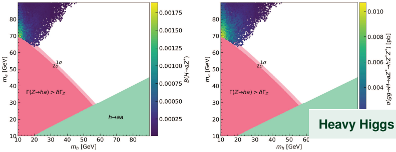


FIGURE – m_a and m_h vs. $\sigma(gg \to H_{sm} \to Z^* a)$ (left panel) and $\sigma(gg \to H_{sm} \to Z^* a -$
95% C.L in 2HDM Type-I

- The subsequent decay of a, when the decay chain $H \to aZ^*$ is open, co
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
- Watch this space for results!

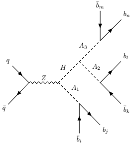
masses $\lesssim$ 100/200 GeV, $\sigma \sim 80 - 140$fb

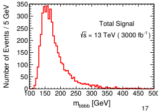
$m_H \sim 145$ GeV, $m_A \sim 70$ GeV for plot

Heavy Higgs mass reconstruction

H mass reconstruction is done based on the mode which contain $H \to AA \to 4b$ decay. AAA mode serves the purpose.

- In each event all possible combinations of three b-jet pairs are considered. The combination for which each b-jet pair satisfying the invariant mass condition of $m_A \pm 15$ GeV and the assymmetry cut is selected.
- Prompt pseudoscalar: A_1, non-prompt pseudoscalar: $A_{2,3}$
Then $p_T(A_1) > p_T(A_{2,3})$
- $b_i b_j$, $b_k b_l$ and $b_m b_n$ satisfy the invariant mass conditions and assymmetry cut. If $b_i b_j$ is from A_1, then
$(p_i + p_j)_T > (p_k + p_l)_T$ and $(p_i + p_j)_T > (p_m + p_n)_T$.
- $b_k b_l$ and $b_m b_n$ make the 4b-jet system. The invariant mass of the 4b-jet system reconstructs the mass of H.
- If more than one combination of 4b-jet system is possible. The correct combination gives the maximum separation of the reconstructed H and A_1 in the $\eta - \phi$ space.

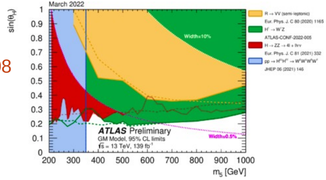




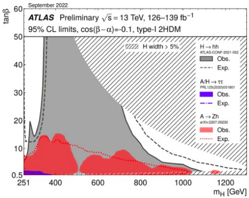
Recent ATLAS Extended Higgs results

- Overlay plots

ATL-PHYS-PUB-2022-008
(March 2022)
Georgi-Machacek



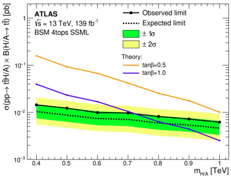
ATL-PHYS-PUB-2022-043
(Sept 2022) 2HDM

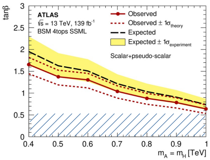


- ttA/H → tt

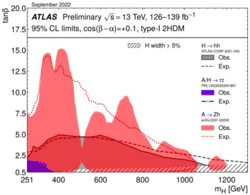
NEW

EXOT-2019-26





Type-II 2HDM



Nikolaos Rompotis (Liverpool)
Lidija Zivkovic (Belgrade)

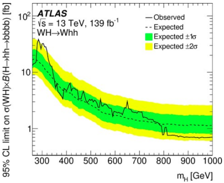
UNIVERSITY OF LIVERPOOL

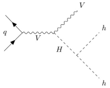
УНИВЕРЗИТЕТ У БЕОГРАДУ ИНСТИТУТ ЗА ФИЗИКУ | БЕОГРАД
ИНСТИТУТ ОД НАЦИОНАЛНОГ ЗНАЧАЈА ЗА РЕПУБЛИКУ СРБИЈУ

ATLAS EXPERIMENT

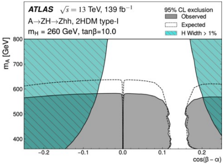
Recent ATLAS Extended Higgs results

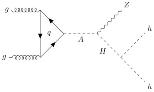
- ZH and WH production with H → hh





HDBS-2019-31 (October 2022)

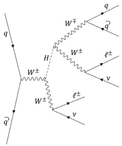


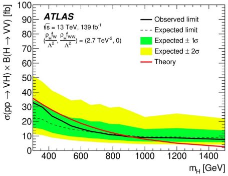


Nikolaos Rompotis (Liverpool)
Lidija Zivkovic (Belgrade)

- WH with H → WW **NEW**

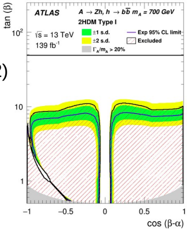
HDBS-2019-16





- A → Zh

HDBS-2020-19 (July 2022)



LHC Higgs workshop – December 2022

Recent CMS Extended Higgs Results

Santeri Laurila (CERN)
Mariarosaria D'Alfonso (MIT)

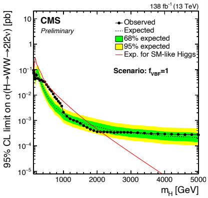
- **MSSM: ϕ(h/H/A) → ττ**
  - *Model independent limits for ggϕ and bbϕ (pseudo)scalars in 60-3500 GeV mass range*
  - *MSSM interpretations from a simultaneous fit of the 125 GeV plus another resonance*

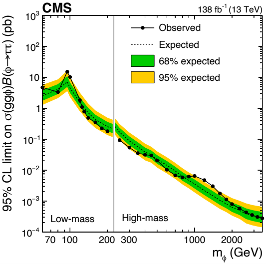
arXiv:2208.02717

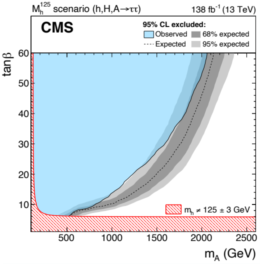
- **MSSM/2HDM: H → WW**

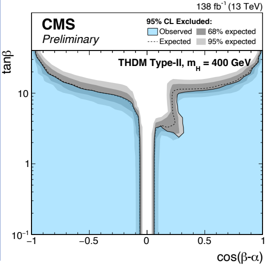
CMS-PAS-HIG-20-016

  - *ggH & VBF, 155-5000 GeV*
  - *Fully leptonic*









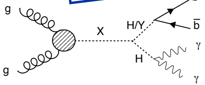
LHC Higgs Workshop – December 2022

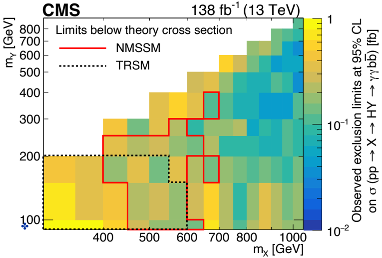
Recent CMS Extended Higgs Results

Santeri Laurila (CERN)
Mariarosaria D'Alfonso (MIT)

- **NMSSM, TRSM: X → YH → bbγγ**
  - *A new channel to complement the previous bbbb & bbττ results*

CMS-PAS-HIG-21-011

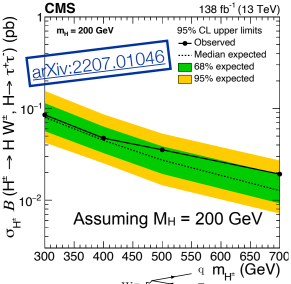


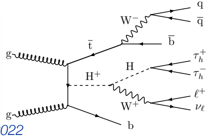


- TRSM benchmark values available here: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG3EX

- **2HDM: H^+ → H(ττ)W^+**
  - *First LHC limits on H^+→HW^+*

arXiv:2207.01046





LHC Higgs Workshop – December 2022

V. Keus, "P-even, CP-violating Signals in Scalar Mediated Processes" / D. Azevedo, "CP-violation in $t\bar{t}\phi$: asymmetries and interferences"

P-conserving, CP-violating processes in the 2HDM

We impose these requirements:

- all processes survive the Higgs alignment limit
- no quartic scalar couplings are involved (due to coupling and phase space suppressions)
- the dominant contribution to the CP-violating signal is P-even (C-even, CP-violating contributions due to scalar-fermion couplings are absent or suppressed)

Simultaneous observation of processes involving:

1. $h_2H^+H^-$, $h_3H^+H^-$, Zh_2h_3 ,
2. $h_2h_kh_k$, $h_3H^+H^-$, Zh_2h_3 , (for $k = 2$ or 3),
3. $h_3h_kh_k$, , $h_2H^+H^-$, Zh_2h_3 , (for $k = 2$ or 3),
4. $h_2h_kh_k$, $h_3h_\ell h_\ell$, Zh_2h_3 , (for $k, \ell = 2$ or 3).

would signal CP violation.

V. Keus, "P-even, CP-violating Signals in Scalar Mediated Processes" / D. Azevedo, "CP-violation in $t\bar{t}\phi$: asymmetries and interferences"

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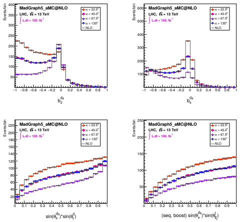
3. $h_3 h_k h_k$, , $h_2 H^+ H^-$, $Z h_2 h_3$, (for $k = 2$ or 3),
4. $h_2 h_k h_k$, $h_3 h_\ell h_\ell$, $Z h_2 h_3$, (for $k, \ell = 2$ or 3).

would signal CP violation.

Observables



- Shapes change smoothly with angle
- Non-normalized, number of total events will change

Additional topics meeting 16.11.22

- **triple Higgs couplings (K. Radchenko Serdula, J. Braathen)**
- **vector-like quarks (M. Boukidi, A. Arhib)**
- **singlet with $U(1)$ gauge group (Z. Peli)**
- **Axion-like ALPS (F. Arias Aragon)**

Appendix

Signal widths

- An event with gen-level mass $\mathbf{m_H}$ from a sample with mean resonance mass **M** following width **G** is described by Breit-Wigner:

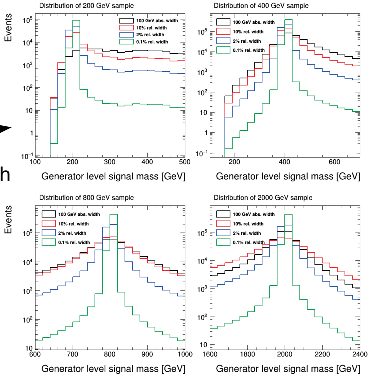
$$\frac{m_H \cdot G}{(M^2 - m_H^2)^2 + (m_H \cdot G)^2}$$

- The weight given per event is:
  - this function for "***G*** = *new width*"
  - over the same function with „***G*** = *CPS width*"
- Weights are normalized so integral over all events remains the same

Signal widths

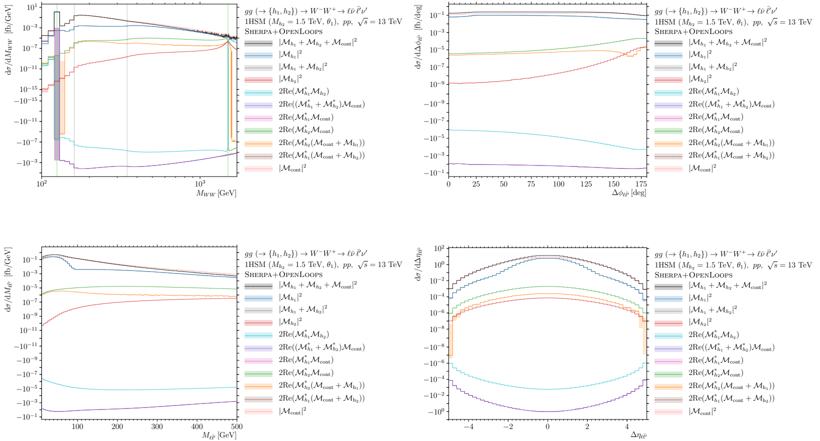
- Reweighting to different scenarios generally works fine, expect for low mass resonances
- Already produced with very low width

  → Problems with statistical precision when reweighting to follow larger width



Extra singlet, di-boson final states

[N. Kauer, A. Lind, P. Maierhoefer, W. Song, *JHEP 07 (2019) 108*]



$[\theta_2 \approx 0.14,\ \Gamma/M \approx 5\,\%]$

P. Sanyal, "Electroweak Multi-Higgs production: A smoking gun for the Type I 2HDM"

$4b + X$ via EW process

EW processes contributing to the $4b + X$ mode:

$$q\bar{q}' \begin{cases} 1.\ AAW^{\pm}:\ pp \to H^{\pm}A \to [AW^{\pm}][A] \to 4b + X, \\ 2.\ AAAW^{\pm}:\ pp \to H^{\pm}H \to [AW^{\pm}][AA] \to 4b + X \end{cases}$$

$$q\bar{q} \begin{cases} 3.\ AAA:\ pp \to HA \to [AA][A] \to 4b + X, \\ 4.\ AAW^{+}W^{-}:\ pp \to H^{+}H^{-} \to [AW^{+}][AW^{-}] \to 4b + X \end{cases}$$

Benchmark Points:

BP	m_A [GeV]	$m_{H^\pm}$ [GeV]	m_H [GeV]	$\tan\beta$	$\sin(\beta-\alpha)$	m_{12}^2 [GeV^2]
1	50	169.8	150.0	17.11	0.975	1275.0
2	70	169.7	144.7	7.47	0.988	2355.0
3	110	234.7	250.1	26.0	0.969	2324.7

Cross sections [fb] at 13 TeV:

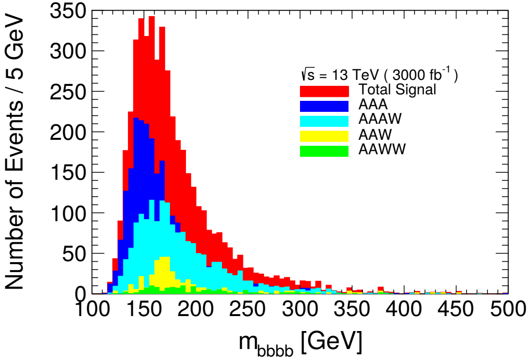
BP	$AAW^{\pm}$	$AAAW^{\pm}$	AAA	$AAW^{+}W^{-}$
1	228.21	33.829	87.93	34.77
2	165.70	68.61	141.45	31.60
3	35.21	3.16	5.0	6.85

Under preparation

Collaborators: Stefano Moretti, Shoaib Munir and Tanmoy Mondal

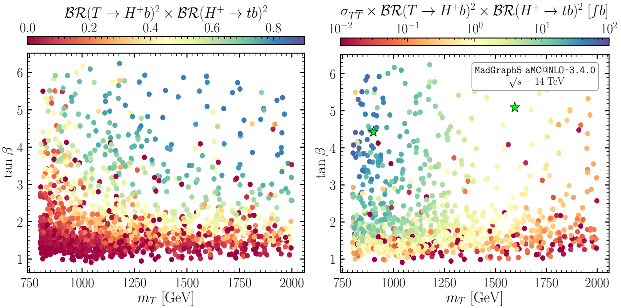
P. Sanyal, "Electroweak Multi-Higgs production: A smoking gun for the Type I 2HDM"

Backup



M. Boukidi, "Probing Light Charged Higgs Bosons in the 2HDM-II with Vector-Like Quarks"

2HDM-II+ (TB)



- The signal $ttbb + X$ could reach values up to 100 fb for medium $\tan\beta$ and for $m_T \leq 1000$ GeV.

M. Boukidi, "Probing Light Charged Higgs Bosons in the 2HDM-II with Vector-Like Quarks"

Benchmark Points

Parameters	2HDM-II+T BP$_1$	2HDM-II+T BP$_2$	2HDM-II+TB BP$_1$	2HDM-II+TB BP$_2$
m_h	125	125	125	125
m_H	208.74	451.66	593.30	582.40
m_A	186.93	565.47	582.15	574.28
$m_{H\pm}$	143.95	464.90	596.13	647.32
$\tan\beta$	1.42	0.95	4.43	5.09
m_T	942.33	1013.28	902.07	1595.80
m_B	–	–	913.55	1602.35
$\sin(\theta)^u_L$	-0.0272	0.0520	0.0141	-0.0037
$\sin(\theta)^d_L$	–	–	-0.0009	-0.0003
$\sin(\theta^u)_R$	–	–	0.0737	-0.0345
$\sin(\theta^d)_R$	–	–	-0.1735	-0.0966
y_T	-4.92	3.66	–	–
$\mathcal{BR}(H^\pm \to XY)$ in %				
$\mathcal{BR}(H^+ \to t\bar{b})$	0.21	98.34	98.01	96.12
$\mathcal{BR}(H^+ \to \tau\nu)$	83.97	0.88	1.79	3.03
$\mathcal{BR}(T \to XY)$ in %				
$\mathcal{BR}(T \to W^+b)$	36.86	29.33	13.59	5.21
$\mathcal{BR}(T \to Zt)$	16.62	13.39	1.09	0.32
$\mathcal{BR}(T \to ht)$	20.67	16.19	1.38	0.35
$\mathcal{BR}(T \to Ht)$	4.74	13.44	–	–
$\mathcal{BR}(T \to At)$	3.72	7.19	–	–
$\mathcal{BR}(T \to H^+b)$	17.39	20.45	83.94	94.12
Γ in GeV				
$\Gamma(T)$	0.55	3.15	53.43	238.85
σ [fb]				
$\sigma_{T\overline{T}} \times \mathcal{BR}(T \to H^+b)^2 \times \mathcal{BR}(H^+ \to \tau\nu)^2$	0.00	1.44	0.02	0.00
$\sigma_{T\overline{T}} \times \mathcal{BR}(T \to H^+b)^2 \times \mathcal{BR}(H^+ \to t\bar{b})^2$	1.23	0.00	51.18	1.08

D. Azevedo, "CP-violation in $t\bar{t}\phi$: asymmetries and interferences"

$t\bar{t}\phi$ and CP-observables

We can parameterize the general $t\bar{t}\phi$ interaction as

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

- CP-even: $\cos\alpha = 1, k_t = \kappa$
- CP-odd : $\sin\alpha = 1, k_t = \tilde{\kappa}$

Several proposed observables in the literature Bernreuther et al. (1994), Gunion et al. (1996), Ellis et al. (2014),..., we choose:

- Angular varibles: $a_1 = \sin\theta_{\phi}^{t\bar{t}\phi} * \sin\theta_{\bar{t}}^{t\bar{t}}, \qquad a_2 = \sin\theta_{\phi}^{t\bar{t}\phi} * \sin\theta_{b_{\bar{t}}}^{\bar{t}}$ (seq. boost)
- Gunion-He: $b_2 = (\vec{p}_t \times \hat{k}_z)\cdot(\vec{p}_{\bar{t}} \times \hat{k}_z)/(|\vec{p}_t||\vec{p}_{\bar{t}}|), \qquad b_4 = (p_t^z \cdot p_{\bar{t}}^z)/(|\vec{p}_t||\vec{p}_{\bar{t}}|)$

$\rightarrow$ Discriminate between signal/irreducible background Amor dos Santos et al. (2015)
$\rightarrow$ Sensitive to different scalar mass values $m_\phi \in [10, 500]$ GeV DA et al. (2021)
$\rightarrow$ Observables are CP-even $\rightarrow$ not sensitive to relative sign of the phase

Interesting Benchmark Point w.r.t test of CP violation

C2HDM Type I [Abouabid,Arhrib,Azevedo,ElFalaki,Ferreira,MM,Santos,'21]

input parameters

m_{H_1} [GeV]	m_{H_2} [GeV]	$m_{H^\pm}$ [GeV]	α_1	α_2	α_3	$\tan\beta$	$\mathrm{Re}(m_{12}^2)$ [GeV^2]
125.09	265	236	1.419	0.004	-0.731	5.474	9929

results

$\sigma^{\rm NLO}_{H_1H_1}$ [fb]	K-factor	$\Gamma^{\rm tot}_{H_1}$ [GeV]	$\Gamma^{\rm tot}_{H_2}$ [GeV]	$\Gamma^{\rm tot}_{H_3}$ [GeV]	$\Gamma^{\rm tot}_{H^\pm}$ [GeV]
387	2.06	4.106×10^{-3}	3.625×10^{-3}	4.880×10^{-3}	0.127

$\lambda_{3H_1}/\lambda_{3H}$	$y^e_{t,H_1}/y_{t,H}$	$\sigma^{\rm NNLO}_{H_1}$ [pb]	$\sigma^{\rm NNLO}_{H_2}$ [pb]	$\sigma^{\rm NNLO}_{H_3}$ [pb]	
0.995	1.005	49.75	0.76	0.84	

$$\sigma(H_2)\times \mathrm{BR}(H_2\to H_1H_1) = 191 \text{ fb}, \quad \sigma(H_2)\times \mathrm{BR}(H_2\to WW) = 254 \text{ fb},$$
$$\sigma(H_2)\times \mathrm{BR}(H_2\to ZZ) = 109 \text{ fb}, \quad \sigma(H_2)\times \mathrm{BR}(H_2\to ZH_1) = 122 \text{ fb},$$
$$\sigma(H_3)\times \mathrm{BR}(H_3\to H_1H_1) = 235 \text{ fb}, \quad \sigma(H_3)\times \mathrm{BR}(H_3\to WW) = 315 \text{ fb},$$
$$\sigma(H_3)\times \mathrm{BR}(H_3\to ZZ) = 136 \text{ fb}, \quad \sigma(H_3)\times \mathrm{BR}(H_3\to ZH_1) = 76 \text{ fb}.$$

Simultaneous measurements of 'CP-even decays' (H_1H_1,VV) and 'CP-odd decays' (VH_1)
=> CP violation