WG2+ WG3 extended scalars: overview

Tania Robens

Rudjer Boskovic Institute

.

on behalf of **WG2 conveners**:

S. Heim, G. Ortona, K. Mimasu, D. Barducci

and **WG3 Extended Higgs Sector conveners**:

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

The 20th Workshop of the LHC Higgs Working Group
CERN

15. November '23

Factsheet

Conveners

- **WG2:** S. Heim (ATLAS); G. Ortona (CMS); K. Mimasu, D. Barducci (TH)
- **WG3, extended scalars:** L. Zivkovic, N. Rompotis (ATLAS); M. d'Alfonso, S. Laurila (CMS); T. Robens, R. Santos (TH)

Meetings

- 23.6.22, https://indico.cern.ch/event/1173518/
- 11.1.23, https://indico.cern.ch/event/1230456/
- 26.9.23, https://indico.cern.ch/event/1327545/

e-groups

lhc-higgs-properties, lhc-higgs-neutral-extended-scalars

[slide stolen from K. Mimasu, Summary of WG2 CPV activity, General assembly '22]

Joint WG2/WG3 activity

- CPV in Higgs interactions often means extended scalar sector
- Many interesting signatures of spontaneous/explicit CPV in extended Higgs sectors

Discovery of BSM Higgs in multiple decay channels ⇒ CPV

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

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

- Undoubtedly complementarity with h_{125} CP properties
- Establish some benchmark models & identify regions of parameter space where one or the other can provide complementary sensitivity

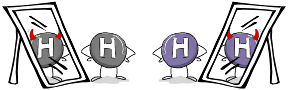
Joint activities with WG2: CP violation and Higgs Sector

three meetings over the last 2 years, $\sim$ 20 talks

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



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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 $\Rightarrow$ 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 $\Rightarrow$ CPV

Decay angular distributions etc.

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

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

Topics covered this year

- very open call ⇒ **CP violation in SM EFTs and BSM**

⇒ **large variety of topics**

Examples

- **Studies of specific CP violating couplings and prospects at LHC and beyond:**
  Sarmah, Bhardwaj, Barrue, Menen, Barman, Sahoo
- **general discussion and parameter ranges in specific models:**
  Osland, de Giorgi

time is limited

⇒ **will concentrate on a few examples in the following**

List of all talks this year [slide by R. Santos]

WG2+WG3 meetings

Thursday 23 Jun 2022

- Electroweak Baryogenesis and Dark Matter with an Inert Doublet, Sven Fabian.
- BSM Higgs Flavoured Correlations, Arturo de Giorgi.
- P-even, CP-violating Signals in Scalar Mediated Processes, Venus Keus.
- Direct and indirect probes of Higgs CP violation, Stefania Gori.
- CP-violation in ttPhi: asymmetries and interferences, Duarte Azevedo.
- Electroweak phase transition in a dark sector with CP-violation, Lisa Biermann.
- Di-Higgs-Production and Baryogenesis in the C2HDM, Milada Muhlleitner.

Wednesday 11 Jan 2023

- Study of anomalous gauge-Higgs couplings using Z boson polarization at LHC, Priyanka Sarmah.
- Constraining Higgs-Higgs-Z couplings in the 3HDM, Per Osland.
- Machine-enhanced CP-asymmetries in the Higgs sector, Akanksha Bhardwaj.
- Simulation-based inference in the search for CP violation in leptonic WH production Higgs, Ricardo Barrué.

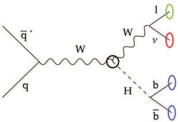
Tuesday 26 Sept 2023

- Flavour and Higgs physics in Z2-symmetric 2HD models near the decoupling limit, Arturo de Giorgi.
- Classifying the CP properties of the ggH coupling in H+2j production, Marco Menen.
- Non-linear top-Higgs CP violation, Akanksha Bhardwaj.
- Analysis of interference effects in the di-top final state for CP-mixed scalars in extended Higgs sectors, Romal Kumar.
- Returning CP-observables to the frames they belong, Rahool Kumar Barman.
- Probing CP violation in H -> tau+ tau- gamma, Dibyakrupa Sahoo.
- Search for an invisible scalar in tt final states at the LHC, Rodrigo Capucha.

Example: R. Barrue, *Simulation-based inference in the search for CP violation in leptonic WH production Higgs*

CP violation in HWW interaction

Goal: optimize search for CP violation in the HWW interaction via WH production



SMEFT, Warsaw basis, **1** dimension-6 CP-odd operator

$$O_{H\widetilde{W}} = \frac{c_{H\widetilde{W}}}{\Lambda^2} H^\dagger H \, \epsilon_{\mu\nu\rho\sigma} W^{I\mu\nu} W^{I\rho\sigma}$$

WG2+WG3 meeting - CPV in Higgs sector 11/1/23 3

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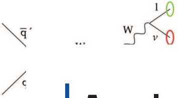


SMEFT, Warsaw basis, **1** dimensi

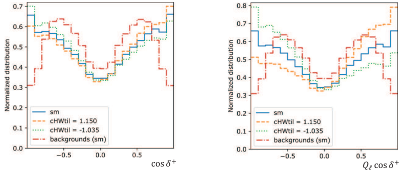
$O_{H\widetilde{W}}$

WG2+\

Angular observables

$$\cos\delta^{+} = \frac{\vec{p}_{\ell}^{(W)} \cdot (\vec{p}_H \times \vec{p}_W)}{|\vec{p}_{\ell}^{(W)}||\vec{p}_H \times \vec{p}_W|} \text{ [3]}$$

$\vec{p}_{\ell}^{(W)}$: momentum of lepton in W boson rest frame



- Symmetric for SM signal and backgrounds, asymmetric for $c_{H\widetilde{W}} \neq 0$
- Can extract sign of $c_{H\widetilde{W}}$, weighting by lepton charge increases asymmetry

[3]: R. Godbole et al, *"Jet substructure and probes of CP violation in Vh production"*, arXiv:1409.5449

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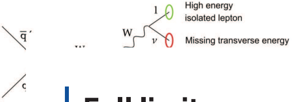

SMEFT, Warsaw basis, **1** dimensi

$O_{H\widetilde{W}}$

WG2+\

Full limits

Determined expected limits w/ full likelihood ratio **(shape-only)**

- Properly takes into account the effect of terms ∝ $c^2_{H\widetilde{W}}$ in the likelihood ratio

Observable	$c_{H\widetilde{W}}$ S+B 95% CL (L= 300 fb[-1])
1D: p_{T_W}	[-0.192, 0.216]
2D: $p_{T_W} \times m_{T_{\ell\nu b\bar{b}}}$	[-0.36, 0.384]
1D: $Q_\ell \cos\delta^+$	[-0.264, 0.216]
2D: $p_{T_W} \times Q_\ell \cos\delta^+$	[-0.096, 0.072]
MVA: SALLY, 48 input variables	[-0.144, 0.12]
MVA: SALLY, 48 input variables + p_{z_ν}, $Q_\ell \cos\delta^+$, $Q_\ell \cos\delta^-$, $\cos\theta^*$	[-0.168, 0.096]

2D combination of p_{T_W} and $Q_\ell \cos\delta^+$ yields the best limits

- SALLY no longer optimal when quadratic effects included

Example: M. Menen, *Classifying the CP properties of the ggH coupling in H+2j production* [arXiv:2309.03146]

BSM framework

Free parameters:

- Higgs characterisation model: Higgs H assumed to be mixed CP state
- Effective Higgs-gluon coupling:

Artoisenet et al. ´13

$$\mathcal{L}_{ggH} = -\frac{1}{4v}\left(-\frac{\alpha_s}{3\pi} c_g G^a_{\mu\nu} G^{\mu\nu,a} + \frac{\alpha_s}{2\pi} \tilde{c}_g G^a_{\mu\nu} \tilde{G}^{\mu\nu,a}\right) H$$

- Effective CP-even (c_g) and CP-odd ($\tilde{c}_g$) coupling modifiers
- SM obtained for $c_g = 1$, $\tilde{c}_g = 0$

- Higgs-gluon coupling corresponds to top-Yukawa in the heavy top limit and if there are no low-mass BSM particles in the ggF loop ⇒ $c_g = c_t$, $\tilde{c}_g = \tilde{c}_t$
- We impose a cut $p_T^H < 200\text{GeV}$ to remain in the heavy top limit

26.09.2023 Marco Menen, Leibniz University Hannover / PTB Braunschweig 4

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BSM framework

Free parameters:

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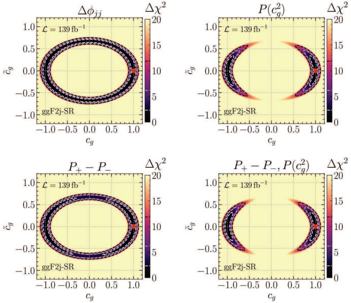
$$\mathcal{L}_{ggH} = -\frac{1}{4v}\left(-\frac{\alpha_s}{3\pi}\right.$$

- Effective CP-even (c_g) and CP-...
- SM obtained for $c_g = 1$, $\tilde{c}_g =$ ...
- Higgs-gluon coupling correspo... if there are no low-mass BSM ...
- We impose a cut $p_T^H < 200$Ge...

26.09.2023 Marco Menen

ggF2j signal region

- Ellipse from total rate
- $\Delta\phi_{jj}$ alone is not able to resolve the ellipse
- 2D-limits dominated by the $P(c_g^2)$ classifier (low interference contribution)
- $|\tilde{c}_g| \leq 0.32$ @ 1σ



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Example: R. Capucha, *Search for an invisible scalar in tt final states at the LHC* [arXiv:2308.00819]

DM Lagrangian and CP-observables

- Analysis performed within the context of **simplified models of DM production** at the LHC. The **DMsimp** model was used.

$$\mathcal{L}_{SM}^{Y_0} = \frac{y_{33}^t}{\sqrt{2}} \bar{t}(g_{u_{33}}^S + i g_{u_{33}}^P \gamma^5) t Y_0$$

Backovic et al. – 1508.05327

$$\mathcal{L}_{X_D}^{Y_0} = \bar{X}_D (g_{X_D}^S + i g_{X_D}^P \gamma_5) X_D Y_0$$

- **CP-even:** g_{u33}^S= 1, g_{u33}^P= 0. **CP-odd:** g_{u33}^S= 0, g_{u33}^P= 1. **CP-mixed:** $g_{u33}^{S/P} \neq 0$ (**CP-violating interaction**).
- $t\,(\bar{t}) \to W^+ b\,(W^- \bar{b})$ and $W^+(W^-) \to l^+ \upsilon_l (l^- \bar{\upsilon}_l)$: **dileptonic final state**, with $l = e, \mu$.
- **BR** $(\mathbf{Y_0 \to X_D \bar{X}_D}) \approx \mathbf{1}$. We focus only on the tops and mediator interaction.

- **Several observables** have been proposed to **probe the CP-nature of the Higgs** in the Higgs-top couplings. To illustrate our findings, we considered the **azimuthal angle difference of the charged leptons** from the tops decay, $\boldsymbol{\Delta\phi_{l+l-}}$, and the $\mathbf{b_4}$ **variable** in the laboratory frame (LAB)

$$b_4 = (p_t^z \cdot p_{\bar{t}}^z)/(|\vec{p}_t| \cdot |\vec{p}_{\bar{t}}|)$$

Gunion, He - hep-ph/9602226,
Buckley, Gonçalves - 1511.06451

- In order to evaluate this variable, the kinematic reconstruction of the $t\bar{t}$ system needs to be accomplished.

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$\mathcal{L}_S^Y$

$\mathcal{L}_X^Y$

➢ **CP-even:** g^S_{u33}= 1, g^P_{u33}= 0. **CP-odd:** g^S_{u33}= 0, g

➢ t ($\bar{t}$) → W^+b ($W^-\bar{b}$) and W^+(W^-) → $l^+\upsilon_l$(l^-

➢ **BR** ($\mathbf{Y_0 \rightarrow X_D\bar{X}_D}$) ≈ **1**. We focus only on the tc

- **Several observables** have been proposed to **pr** findings, we considered the **azimuthal angle d variable** in the laboratory frame (LAB)

- In order to evaluate this variable, the kinematic

Results – heavier masses

- Results extended to a **massive DM mediator**, with m_{Y_0}= 1, 10, 125 GeV. As expected, **exclusion limits worsen as masses increase** in both scenarios, since the $t\bar{t}Y_0$ production cross section decreases for heavier Y_0 masses.

- The observable choice can have some impact on the exclusion limits, even in scenario 1, for heavier masses, because of the cross section decrease.

Scenario 1

Exclusion Limits from $\Delta\phi_{l^+l^-}$		$L = 200$ fb^{-1} (68% CL)	$L = 200$ fb^{-1} (95% CL)	$L = 3000$ fb^{-1} (68% CL)	$L = 3000$ fb^{-1} (95% CL)
$m_{Y_0} = 1$ GeV	$g^S_{u33} \in$	[-0.073, +0.073]	[-0.142, +0.142]	[-0.038, +0.038]	[-0.068, +0.068]
	$g^P_{u33} \in$	[-0.89, +0.89]	[-1.65, +1.65]	[-0.43, +0.43]	[-0.83, +0.83]
$m_{Y_0} = 10$ GeV	$g^S_{u33} \in$	[-0.198, +0.198]	[-0.368, +0.372]	[-0.098, +0.098]	[-0.188, +0.188]
	$g^P_{u33} \in$	[-0.87, +0.87]	[-1.65, +1.65]	[-0.44, +0.44]	[-0.83, +0.83]
$m_{Y_0} = 125$ GeV	$g^S_{u33} \in$	[-0.328,+0.322]	[-0.608, +0.612]	[-0.162, +0.162]	[-0.308, +0.308]
	$g^P_{u33} \in$	[-1.48, +1.49]	[-2.77, +2.78]	[-0.75, +0.75]	[-1.41, +1.41]

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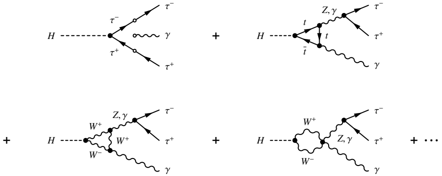
Example: D. Sahoo, *Probing CP violation in* $H \to \tau^+\tau^-\gamma$

The 3-body decay $H \to \tau^+\tau^-\gamma$ offers an alternative methodology.

Decay proceeds via both tree and loop diagrams



$\text{Br}(H \to \tau^+\tau^-\gamma)_{\text{SM}} \sim 3.24 \times 10^{-3}$ with $E_\gamma > 5$ GeV and angular separation $> 5°$ in rest frame of H

[See for example Phys. Rev. D **55**, 5647-5656 (1997); Phys. Rev. D **90**, no.11, 113006 (2014); Eur. Phys. J. C **74**, no.11, 3141 (2014); JHEP **12**, 111 (2016).]

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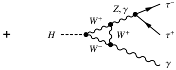
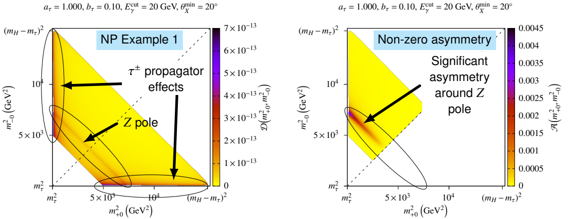


The forward-backward asymmetry can be easily observed in Lorentz invariant Dalitz plot distribution.

$\mathrm{Br}(H \to \tau^+\tau^-\gamma)_{\mathrm{SM}} \sim 3.24 \times 10^{-3}$ with E

[See for example Phys. Rev. D **55**, 5647-5656
74, no.11, 3141 (2014); JHEP **12**, 111 (2016).



Example: A. de Giorgi, *Flavour and Higgs physics in Z2-symmetric 2HD models near the decoupling limit* [Nucl.Phys.B 994 (2023) 116323]

Higgs-Fermion Couplings

$$-\mathcal{L}_Y^{\text{eff}} \supset M_f \bar{f} f + \frac{M_f}{v} h \left(\kappa_f \bar{f} f + \tilde{\kappa}_f \bar{f} i \gamma_5 f \right) + \dots ,$$

$$\kappa_u = \kappa_d = \kappa_e = 1 - \zeta_f \left| \tilde{\lambda}_6 \right| \cos(\rho) \frac{v^2}{\tilde{m}_2^2} ,$$

$$\tilde{\kappa}_u = \tilde{\kappa}_d = \tilde{\kappa}_e = -\zeta_f \left| \tilde{\lambda}_6 \right| \sin(\rho) \frac{v^2}{\tilde{m}_2^2} ,$$

$$\rho \equiv \arg \left[\tilde{\lambda}_6^* \, e^{-i\xi/2} \right]$$

Stronger than flavour symmetries!
(see last year presentation or **2109.07490**)

Universal deviation for each fermion-type
+
Correlations among different ones

	Type I	Type II	Type III (X)	Type IV (Y)
ζ_u	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
ζ_d	$\cot\beta$	$-\tan\beta$	$\cot\beta$	$-\tan\beta$
ζ_e	$\cot\beta$	$-\tan\beta$	$-\tan\beta$	$\cot\beta$

Arturo de Giorgi, arXiv: **2304.10560**

D. Egana-Ugrinovic and S. Thomas, Effective Theory of Higgs Sector Vacuum States, arXiv:1512.00144.

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Higgs-Fermion Couplings

$$-\mathscr{L}_Y^{\text{eff}} \supset M_f \bar{f} f + \frac{M_f}{v} h \left(\kappa_f \bar{f} f + \widetilde{\kappa}_f \bar{f} i\gamma_5 f\right) + \dots ,$$

$$\kappa_u = \kappa_d = \kappa_e = 1 - \zeta_f \left|\widetilde{\lambda}_6\right| \cos(\rho) \frac{v^2}{\widetilde{m}_2^2} ,$$

$$\widetilde{\kappa}_u = \widetilde{\kappa}_d \dots$$

Universal deviation for

Stronger than flavour symmetries!
(see last year presentation or **2109.07490**)

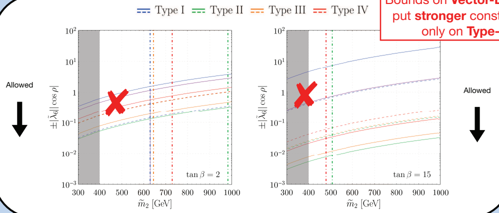
	Type I
ζ_u	$\cot\beta$
ζ_d	$\cot\beta$
ζ_e	$\cot\beta$

Arturo de Giorgi, arXiv: **2304.10560**

Bounds on the parameters

$$g_{hVV} = \frac{2m_V^2}{v^2}\left[1 - \frac{1}{2}\left|\widetilde{\lambda}_6\right|^2 \left(\frac{v^2}{\widetilde{m}_2^2}\right)^2\right] \equiv \frac{2m_V^2}{v^2}\kappa_V \qquad \left|\widetilde{\lambda}_6\right| \left(\frac{v^2}{\widetilde{m}_2^2}\right) \leq 0.17 .$$

Bounds on **Vector-Bosons** put **stronger** constraints only on **Type-I**



Arturo de Giorgi, arXiv: **2304.10560**

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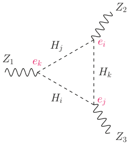
Example: P. Osland, *Constraining Higgs-Higgs-Z couplings in the 3HDM*

CP violation and alignment

In a CP-violating 2HDM, all pairs of neutral scalars couple to the Z, allowing the triangle diagram



The existence of these couplings induces a CP-violating amplitude,

Example: P. Osland, *Constraining Higgs-Higgs-Z couplings in the 3HDM*

CP violation and alignment

Also other diagrams, but importantly

f_4^Z is proportional to the invariant $\mathrm{Im}\, J_2 \propto e_1 e_2 e_3$

CP-violating

In the alignment limit, two of the e_i vanish, the ZZZ amplitude vanishes

$e_i \to v$ ➡ $e_j, e_k \to 0$ $\mathrm{Im}\, J_2 \to 0$

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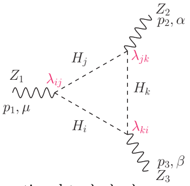
$e_i \to v$ ➡ $e_j, e_k \to 0$ $\quad \mathrm{Im}\, J_2 \to 0$

CP violation and alignment

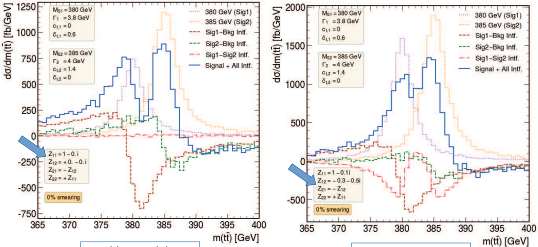
In a 3HDM



contributions proportional to $\lambda_{ij}\lambda_{jk}\lambda_{ki}$

This does not vanish in the alignment limit!

Example: R. Kumar, *Analysis of interference effects in the di-top final state for CP-mixed scalars in extended Higgs sectors*



Without mixing | With mixing

Zero signal-signal interference | Non-zero signal-signal interference

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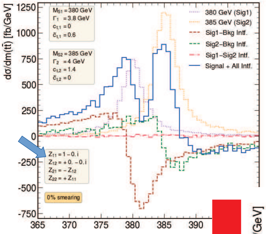
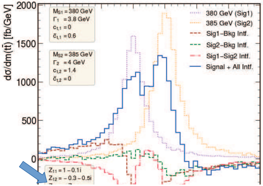
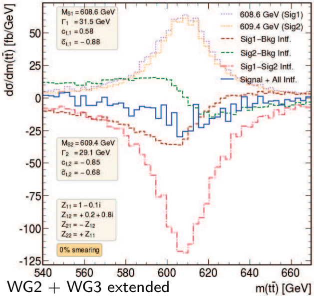


Without mixing

Zero signal-signal interfere





Experimental conclusion(s) can be tricky: complementarity is desired/required

Large destructive signal-signal interference

Further plans

- very open calls ⇒ **large variety of topics**
- **we will continue these open calls, hopefully several/ year**
- iff there is a YREP5, we will contribute w **summary of state of the art and maybe benchmarks**
- currently no other plans

Comments ? Suggestions ?

Example: R. Kumar, *Analysis of interference effects in the di-top final state for CP-mixed scalars in extended Higgs sectors*

Di-top final state

- Total amplitude:

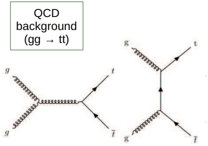
  $$\mathcal{A} = \mathcal{A}(gg \to t\bar{t}) + \mathcal{A}(gg \to \Phi \to t\bar{t})$$

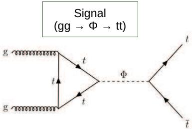
- Signal-background interference

  $$\propto \mathrm{Re}[\mathcal{A}(gg \to \Phi \to t\bar{t})\mathcal{A}^*(gg \to t\bar{t})]$$

  large destructive contribution

- Invariant mass distribution of the top quarks ($m_{t\bar{t}}$) significantly distorted → peak-dip structure



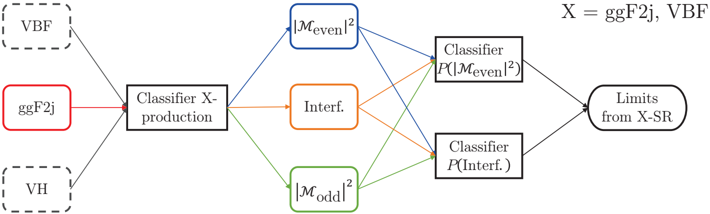


4

Example: M. Menen, *Classifying the CP properties of the ggH coupling in H+2j production* [arXiv:2309.03146]

Analysis strategy

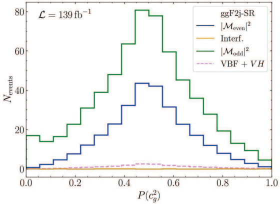
$$|\mathcal{M}_{\text{ggF2j}}|^2 = c_g^2 |\mathcal{M}_{\text{even}}|^2 + \underbrace{2 c_g \tilde{c}_g \text{Re}[\mathcal{M}_{\text{even}} \mathcal{M}_{\text{odd}}^*]}_{\text{Interference}} + \tilde{c}_g^2 |\mathcal{M}_{\text{odd}}|^2$$

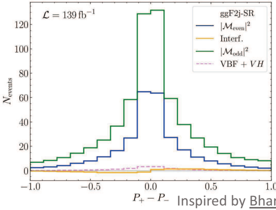


- Train a CP-even and a CP-odd classifier in a ggF2j-SR and a VBF-SR

Example: M. Menen, *Classifying the CP properties of the ggH coupling in H+2j production* [arXiv:2309.03146]

ggF2j signal region





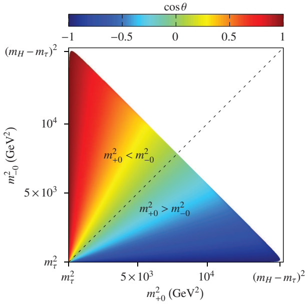
Inspired by Bhardwaj et al. `21

- $P(c_g^2)$ differentiates between $c_g^2|\mathcal{M}_{\mathrm{even}}|^2$ and $\tilde{c}_g^2|\mathcal{M}_{\mathrm{odd}}|^2$
- Kinematically very similar, but some separation in outer bins
- Interference term cancels out

- $P_+ - P_-$ differentiates between positive and negative interference
- Interference barely visible due to low cross section & looks more VBF-like
- CP-even terms are symmetric

26.09.2023 Marco Menen, Leibniz University Hannover / PTB Braunschweig 7

The amplitude square can be expressed using Lorentz invariant mass-squares.



- Only 3 Lorentz invariant mass-squares:

$$m_{+-}^2 \equiv (p_H - p_0)^2 = (p_+ + p_-)^2\,,$$
$$m_{+0}^2 \equiv (p_H - p_-)^2 = (p_+ + p_0)^2\,,$$
$$m_{-0}^2 \equiv (p_H - p_+)^2 = (p_- + p_0)^2\,,$$
$$m_{+-}^2 + m_{+0}^2 + m_{-0}^2 = m_H^2 + 2\,m_\tau^2\,.$$

∴ Only 2 *independent* mass-squares.

- In the GJ frame,

$$m_{+0}^2 = M^2 - M'^2\cos\theta,$$
$$m_{-0}^2 = M^2 + M'^2\cos\theta,$$
$$\text{where } M^2 = \frac{1}{2}\left(m_H^2 + 2\,m_\tau^2 - m_{+-}^2\right),$$
$$M'^2 = \frac{1}{2}\left(m_H^2 - m_{+-}^2\right)\left(1 - \frac{4\,m_\tau^2}{m_{+-}^2}\right)^{\frac{1}{2}}.$$