

# Effective Field Theory interpretation of the VBF HWW differential analysis with the ATLAS detector

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July 12, 2021  
DPF21



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## 1 Standard Model measurement

## 2 EFT prediction

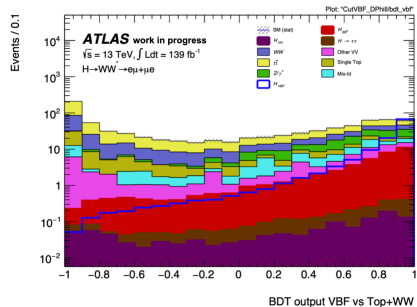
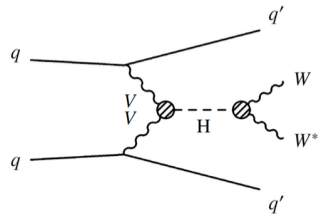
## 3 EFT parametrization

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# Overview of VBF HWW differential analysis

- Anysis will perform on Run-2 data of  $139 \text{ fb}^{-1}$  of integrated luminosity by ATLAS in 2015-2018
- Analysis targets Higgs production via Vector Boson Fusion (VBF) and decay channel  $H \rightarrow W + W \rightarrow e\nu + \mu\nu$
- Kinematics cuts, boosted decision tree technique and background dominated control regions used to extract signal from large background: ggF, top, SM WW, Drell-Yan, etc. (more details in [parallel session](#) by Sagar)
- Background subtracted data in signal region unfolded to particle-level
  - to be compared with various Monte Carlo simulations
  - to be re-interpreted with Effective Field Theory (EFT) formalism



# Fiducial phase space

- Fiducial cuts designed to ensure large signal over background ratio and BSM sensitivity

Category	Fiducial Requirement	Cut Value
Leptons ( $e + \mu, \mu + e$ )	$ \eta(\ell) $	$< 2.5$
	$p_T^{\text{lead}}$	$> 22 \text{ GeV}$
	$p_T^{\text{sublead}}$	$> 15 \text{ GeV}$
	$N_{\text{leptons}}$	$\geq 2$
	OS and OF pair	Yes
	$\Delta R(\ell, \ell)$	$> 0.1$
	$m_{\ell\ell}$	$> 10 \text{ GeV}$
	$m_{\tau\tau}$	$< m_Z - 25 \text{ GeV}$
Jets (anti- $k_t$ R=0.4)	$p_T(\text{jet})$	$> 30 \text{ GeV}$
	$ \eta(\text{jet}) $	$< 4.5$
	$N_{\text{jets}}$	$\geq 2$
	$N_{\text{b-jet}}$	$< 1$
	$M_{jj}$	$> 450 \text{ GeV}$
lepton-jet separation	$\Delta y_{jj}$	$> 2.1$
	$\Delta R(\ell, \text{jet})$	$> 0.4$
VBF	outside lepton veto	Yes
	central jet veto	$< 20 \text{ GeV}$

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# SMEFT: from Lagrangian to observable

- $\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{O}_i$ 
  - $\mathcal{O}_i$ : EFT operator
  - $c_i$ : Wilson coefficient
  - $\Lambda$ : cutoff energy scale
- $\mathcal{M}_{\text{SMEFT}} = \mathcal{M}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} \mathcal{M}_i$
- $|\mathcal{M}_{\text{SMEFT}}|^2 = |\mathcal{M}_{\text{SM}}|^2 + 2 \sum_i \frac{c_i}{\Lambda^2} \text{Re}(\mathcal{M}_{\text{SM}}^* \mathcal{M}_i) + \sum_i \frac{c_i^2}{\Lambda^4} |\mathcal{M}_i|^2$
- $\sigma \propto |\mathcal{M}_{\text{SMEFT}}|^2$

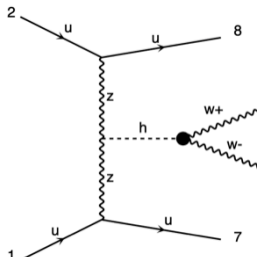
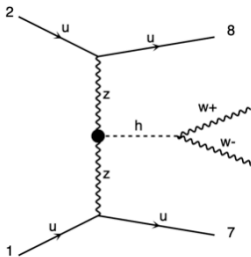
# EFT operators

- EFT operators constructed by SM gauge and Higgs fields in Warsaw basis.
- Analysis sensitive to the following CP-even operators (plus 3 CP-odd:  $\tilde{c}_{HW}$ ,  $\tilde{c}_{HWB}$ ,  $\tilde{c}_{HB}$ ).

Wilson coefficient	Operator definition
$C_{HW}$	$\Phi^\dagger \Phi W_{\mu\nu}^I W^{I\mu\nu}$
$C_{HB}$	$\Phi^\dagger \Phi B_{\mu\nu} B^{\mu\nu}$
$C_{HWB}$	$\Phi^\dagger \Phi W_{\mu\nu}^I B^{I\mu\nu}$
$C_{Hq1}$	$(i\Phi^\dagger \overleftrightarrow{D}_\mu \Phi)(\bar{q}\gamma^\mu q)$
$C_{Hq3}$	$(i\Phi^\dagger \overleftrightarrow{D}_\mu^I \Phi)(\bar{q}\sigma^I \gamma^\mu q)$
$C_{Hu}$	$(i\Phi^\dagger \overleftrightarrow{D}_\mu^I \Phi)(\bar{u}\gamma^\mu u)$
$C_{Hd}$	$(i\Phi^\dagger \overleftrightarrow{D}_\mu^I \Phi)(\bar{d}\gamma^\mu d)$

# Motivation: EFT in VBF HWW differential analysis

- The VBF HWW process has two HVV vertices which can be very sensitive to anomalous coupling
- Example anomalous coupling diagrams of  $O_{HW} = \Phi^\dagger \Phi W_{\mu\nu}^I W^{I\mu\nu}$ :



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# Differential parametrization in the fiducial region

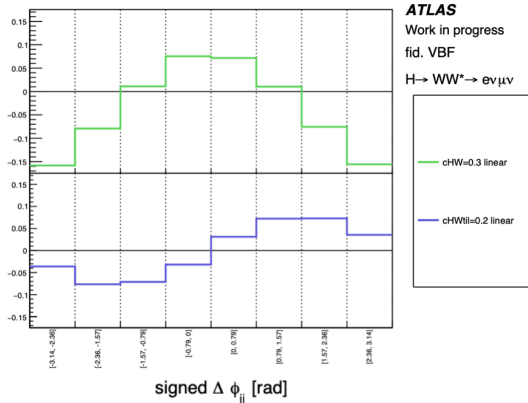
- Dedicated EFT samples generated with MadGraph5+Pythia8 and SMEFTsim package
- Goal: find BSM differential cross section parametrization for n-th bin as functions of  $c_i$ :

$$\sigma_n^{\text{BSM, fid.}}(c_i) = \sigma_n^{\text{SM, fid.}}(A_{n,i}c_i + B_{n,i}c_i^2)$$

- Quadratic term suppressed by  $1/\Lambda^4$
- In general, comparison of limits set by using linear only and full (linear+quadratic) parametrization can suggest quadratic term impact

EFT impact CP-even vs. CP-odd (linear only):  $c_{HW}$ ,  $\tilde{c}_{HW}$ 

EFT parametrization ratio to SM

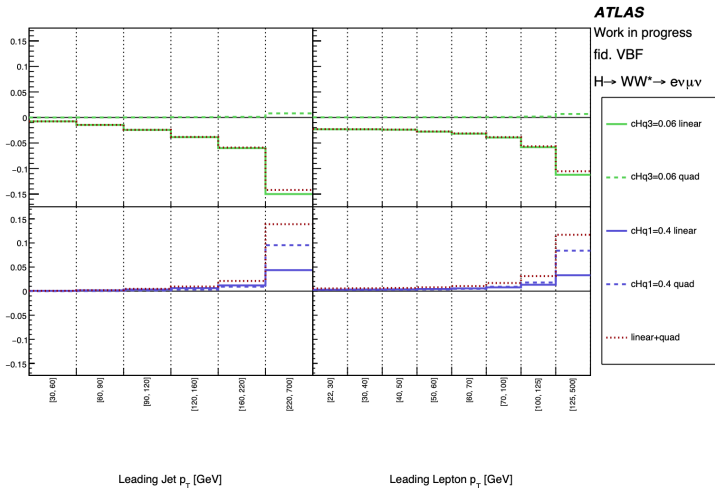


- x-axis:  
 $\Delta \phi_{jj} = \phi_j^{\text{forward}} - \phi_j^{\text{central}}$
- y-axis:
  - $\sigma^{\text{BSM}}(c_{HW} = 0.3) / \sigma^{\text{SM}}$
  - $\sigma^{\text{BSM}}(\tilde{c}_{HW} = 0.2) / \sigma^{\text{SM}}$
- CP-even operator impact symmetric
- CP-odd operator impact asymmetric

# EFT impact linear vs. full parametrization: $C_{Hq3}$ , $C_{Hq1}$

- Example shows  $C_{Hq1}$  quadratic impact is significant

EFT parametrization ratio to SM



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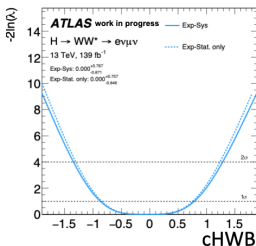
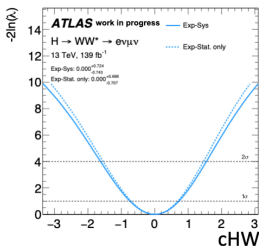
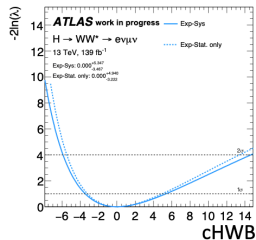
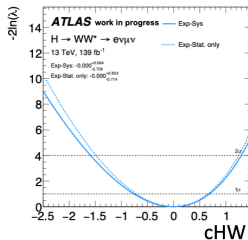
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# Profile likelihood scan with SM pseudo data

- Linear only (1st row) and full (2nd row) parametrization
- Limits dominated by statistical uncertainty



# Preliminary EFT fit result

- Limits set at 95% C.L.
- Some full parametrizations are work in progress
- $\tilde{c}_{HW}$  and  $c_{Hq3}$  are constrained within  $\pm 1$  with linear only parametrization
- $c_{HB}$  and  $c_{Hq3}$  are constrained within  $\pm 1$  with the full parametrization
- $c_{HWB}$ ,  $c_{HB}$ ,  $c_{Hq1}$ ,  $c_{Hu}$  and  $c_{Hd}$  quadratic term have non-negligible impact in the limit

Model Parameter	Observable	Best-fit value	Linear only	full
$c_{HW}$	signed $\Delta\phi_{jj}$	0.00	[-1.59, 1.30]	[-1.62, 1.55]
$\tilde{c}_{HW}$	signed $\Delta\phi_{jj}$	0.00	[-0.11, 0.12]	—
$c_{HWB}$	signed $\Delta\phi_{jj}$	0.00	[-5.89, 14.63]	[-1.35, 1.29]
$\tilde{c}_{HWB}$	signed $\Delta\phi_{jj}$	0.00	[-5.16, 5.29]	—
$c_{HB}$	signed $\Delta\phi_{jj}$	0.00	[-7.43, 3.88]	[-0.70, 0.74]
$\tilde{c}_{HB}$	signed $\Delta\phi_{jj}$	0.00	[-8.92, 9.17]	—
$c_{Hq1}$	leading jet $p_T$	0.00	[-9.93, 13.47]	[-1.76, 1.56]
$c_{Hq3}$	leading jet $p_T$	0.00	[-0.48, 0.39]	[-0.39, 0.67]
$c_{Hu}$	leading jet $p_T$	0.00	[-7.25, 5.74]	[-1.91, 2.46]
$c_{Hd}$	leading jet $p_T$	0.00	[-17.28, 21.66]	[-2.89, 2.58]

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# Summary and outlook

- VBF HWW differential analysis is expected to be sensitive to anomalous couplings
- Optimal observables are chosen to constrain different Wilson coefficients
- Preliminary EFT fit using SM-like pseudo data shows possibility to set stringent limits on some Wilson coefficients
- Quadratic effects of some EFT operators are not negligible

## 6 Additional Material

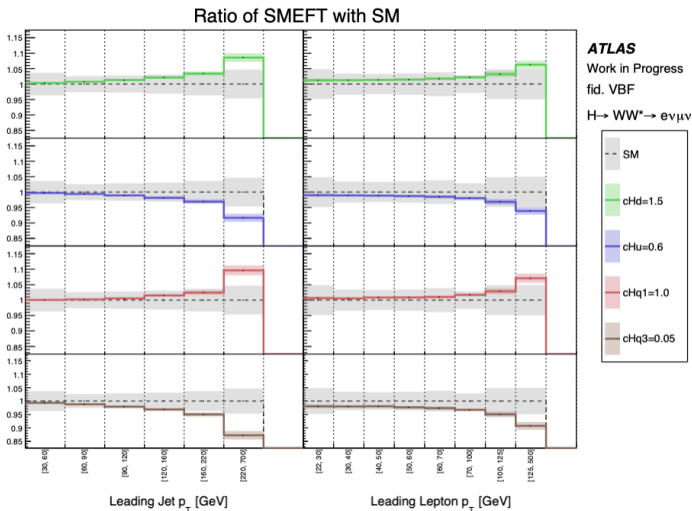
# Differential cross section fitting strategy

- Multidimensional and simultaneous fit over three macro signal region and control regions (CRs): VBF signal region, Drell-Yan CR and ggF CR
- Signal region further splitted into various observable bins to be unfolded
- Likelihood function

$$\mathcal{L}(\mu_i, \mu_b) = \prod_i P(N|\mu_i s_i + \mu_b b_{\text{SR},i}^{\text{exp}}) \times P(M|\mu_b b_{\text{CR}}^{\text{exp}})$$

$$\mu_i s_i = \sum_j^{N_{\text{fid. bins}}} \mathcal{L} \cdot M_{i,j} \cdot \sigma^{\text{fid},j} + f_i \cdot \mathcal{L} \cdot \sigma^{\text{fid}}$$

- $\mathcal{L}$ : luminosity
- $M_{i,j}$ : unfolding migration matrix
- $f_i \cdot \mathcal{L} \cdot \sigma^{\text{fid}}$ : fiducial fakes
- $\sigma^{\text{fid},j}$ : fiducial cross section in the j-th bin
  - to be replaced with EFT parametrization function

SMEFT vs SM (leading jet and lepton  $p_T$ ):  $C_{Hd}$ ,  $C_{Hu}$ ,  $C_{Hq1}$ ,  $C_{Hq3}$ 

# EFT sensitivity in SMWW and HWW

Constraining one Wilson coefficient at a time in combined EFT interpretation of SMWW and HWW [ATL-PHYS-PUB-2021-010](#)

