# Experimental Potential for CP sensitivity from STXS splitting

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University of Freiburg

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GEFÖRDERT VOM



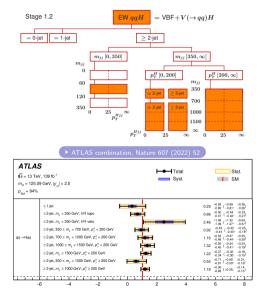
Bundesministerium für Bildung und Forschung

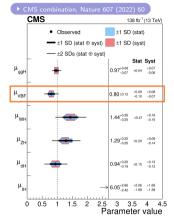
# Introduction

- The STXS framework is a powerful tool to combine Higgs measurements in various decay channels to constrain coupling parameters
- So far STXS does not provide sensitivity to CP violation
- This talk:
  - discuss how to make STXS sensitive to CP violation
  - STXS is designed to study Higgs production. Will discuss VBF and ggF
  - ignore *CP* violation in Higgs decays. STXS analyses are not affected since special effort must be made to observe it
  - ATLAS and CMS are expected to have similar sensitivity for measurements dicussed and this is the case where both have results already. Selected figures such that the talk is most clear

# STXS Measurements for VBF

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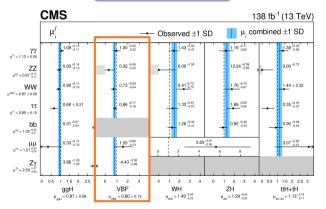




- Have measured VBF to  $\Delta \mu = 12\%$  inclusively and to 30 - 50% for several STXS bins
- STXS is stat. dominated. Run 3 will facilitate better precision and granularity

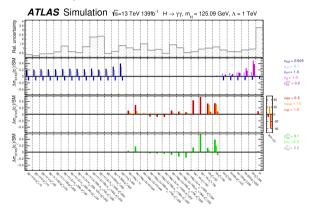
# Contributions per Decay Channel

CMS combination, Nature 607 (2022) 60



- Currently driven by  $\tau\tau$  and WW, which will remain dominant for high  $m_{jj}$  and  $p_{\rm T}^H > 200 \,{\rm GeV}$ . ( $H \to bb$  may contribute/dominate for extreme phase space)
- $\gamma\gamma$  and ZZ catching up for inclusive and for low  $m_{jj}$  with  $p_{\rm T}^H < 200 \,{\rm GeV}$

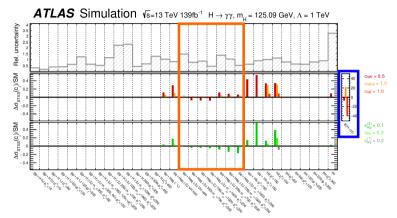
#### EFT Interpretation of STXS Measurement



- STXS provides sensitivity to Wilson coefficients (Wilsons) that change overall normalization or relative yields of catergories. Use SMEFT parametrisation
- EFT interpretations of ATLAS and CMS combinations are yet to be performed

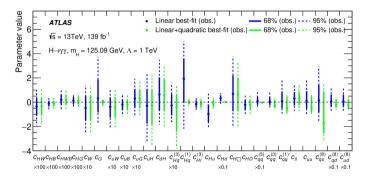
• Take • ATLAS  $H \rightarrow \gamma \gamma$  STXS measurement with EFT interpretation for illustration

#### EFT Interpretation of STXS Measurement



- The  $H \rightarrow \gamma \gamma$  VBF categories are sensitive to  $c_{HW}$ ,  $c_{HWB}$ ,  $c_{HB}$ ,  $c_{Ha}^{(3)}$ , and  $c_{Hu}$
- The  $H \rightarrow \gamma \gamma$  branching ratio is extremely sensitive to  $c_{HW}$ ,  $c_{HWB}$  and  $c_{HB}$
- Current STXS with *CP*-even observables only: linear terms from *CP*-odd Wilsons have no effect. Effect of quadratic terms similar to that of *CP*-even counterparts

#### EFT Interpretation of STXS Measurement



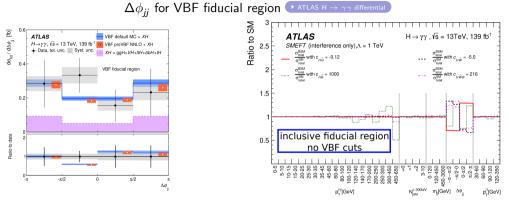
- Top: limits for single Wilsons if all others vanish
- Right: limits for 12 eigenvectors after PCA. Eigenvector composition in appendix

Can already measure multiple Wilsons at once with  $H \rightarrow \gamma \gamma$ . Will do better when combining with other channels, ATLAS+CMS and Run 2+3

#### Linear SMEFT parameterization, linear+quadratic in paper

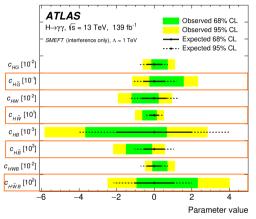
Model parameter		Observed	Expected								
	Value	Uncer	tainty	Uncertainty							
		68% CL	95% CL	68% CL	95% CL						
EV1	-0.0008	+0.0017 -0.0018	+0.0032 -0.0037	+0.0016 -0.0018	+0.0031 -0.0036						
EV2	0.000	$\pm 0.006$	+0.012 -0.010	+0.006	$^{+0.011}_{-0.010}$						
EV3	0.04	$\pm 0.10$	+0.18 -0.21	+0.09 -0.10	+0.18 -0.20						
EV4	-0.04	+0.25 -0.22	+0.5 -0.4	+0.24 -0.21	$^{+0.5}_{-0.4}$						
EV5	-0.2	±0.6	+1.2	±0.6	+1.1 -1.3						
EV6	0.2	$\pm 0.8$	+1.7	+0.8 -0.7	±1.5						
EV7	-1.7	$\pm 1.0$	+2.0	$^{+1.1}_{-1.0}$	+2.2 -2.1						
EV8	-0.7	+3.5	+7 -6	+3.9	+8 -7						
EV9	7.5	+2.5	+2.5	+5 -5	+10 -11						
EV10	0	+7 -9	+ <b>8</b> -19	+5	+9 -16						
EV11	-6	+9 -10	+18 -19	±10	±19						
EV12	3	+12 -13	+12 -25	±12	±24						

# How to Make STXS Sensitive to CP



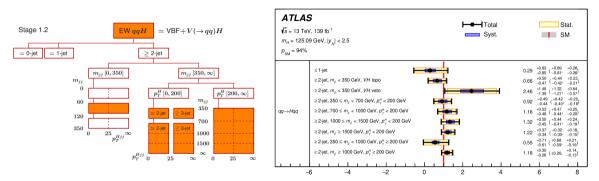
- Dedicated *CP* measurements utilize complex observables constructed from the matrix elements, see examples  $(MS H \rightarrow \tau\tau) (MS H \rightarrow ZZ^*) (ATLAS H \rightarrow \gamma\gamma) (ATLAS H \rightarrow \tau\tau)$
- The  $\Delta \phi_{jj}$  observable is more suitable for STXS and provides good sensitivity to *CP*. Sign is set via rapidity order of jets
- Bin correlations  $\leq 7\%$  for  $H \rightarrow \gamma\gamma$ . Can reconstruct  $\Delta\phi_{ii}$  well for all decay modes

### How to Make STXS Sensitive to CP



- CP odd operators measured from  $\Delta \phi_{jj}$  observable
- The binning from the previous slide (4 bins) would likely be a good choice
- The  $\Delta \phi_{jj}$  observable should be most sensitive for large  $m_{jj}$ . At least this was true in Run 1  $\rightarrow$  to be reviewed with new MC and for what we now call "large  $m_{jj}$ "

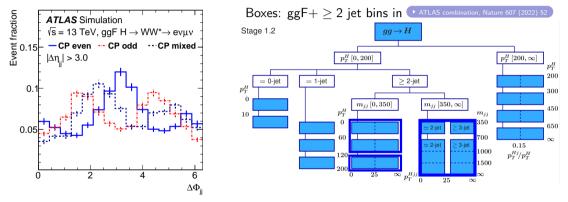
# For Discussion: Options for Run 2+3 for VBF



- Try to measure more stage 1.2 bins
  - Already measure all for  $p_{\rm T}^H < 200$  except  $p_{\rm T}^{H jj}$
  - For key  $H \rightarrow \tau \tau$  and  $H \rightarrow WW^*$  channels the  $E_T^{miss}$  resolution makes it hard to bin in  $p_T^{Hij}$
- Be more accurate for same/similar binning as now. Could be done, we are stat. limited
- Suggestion: split each current bin to e.g. four  $\Delta \phi_{ii}$  bins for CP sensitivity

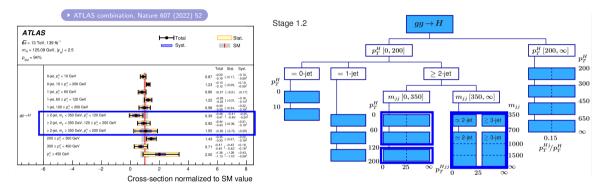
# CP Sensitivity in ggF

► ATLAS *HWW* properties



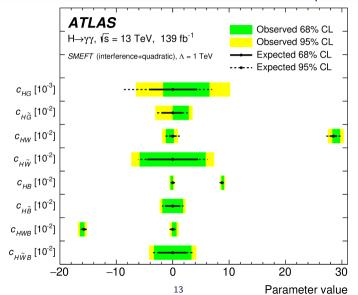
- $\Delta \phi_{ii}$  also provides sensitivity to *CP* for ggF with  $\geq 2$  jets
- Currently measure 3 bins for ggF with  $\geq$  2 jets in combinations
- No  $N_{jet}$  splitting for  $p_T^H > 200$  GeV. Splitting  $N_{jet}$  and  $\Delta \phi_{jj}$  likely not feasible for Run 2+3

# For Discussion: Options for Run 2+3 for ggF



- Try to measure more stage 1.2 bins. Splitting p<sup>Hjj</sup><sub>T</sub> is difficult for H → ττ and H → WW<sup>\*</sup>. But they are much less important than H → γγ other than for VBF
- Could consider splitting into  $\Delta \phi_{ii}$  instead of improving granularity for  $p_{\rm T}^{H}$  and  $p_{\rm T}^{Hij}$

Backup: Results from  $\frown$  ATLAS  $H \rightarrow \gamma\gamma$  differential with linear+quadratic terms



#### Backup: EFT eigenvectors • for ATLAS $H \rightarrow \gamma\gamma$ STXS

#### **ATLAS** √s=13 TeV 139fb<sup>-1</sup>; H→γγ

EV12	-0.00	-0.01	-0.15	0.01	-0.20	-0.36	-0.00	0.02	-0.01	-0.13	-0.16	-0.06	0.00	-0.00	0.37	-0.30	0.69	0.10	0.14	0.14	0.00	-0.02	-0.05	-0.01	0.00	-0.02	0.00	0.00	-0.01	-0.00	-0.00	0.00	0.00	$\lambda = 0.0067$
EV11	0.00	-0.01	0.04	0.01	-0.03	-0.05	-0.00	-0.02	0.00	-0.10	0.03	-0.00	0.00	0.00	0.06	-0.05	0.11	0.01	0.02	-0.95	-0.00	0.15	0.05	0.11	-0.01	0.13	-0.01	-0.01	0.09	-0.00	0.00	-0.00	0.00	$\lambda = 0.0108$
EV10	-0.00	-0.00	0.06	0.02	-0.09	-0.13	-0.00	0.37	-0.00	0.05	-0.02	-0.00	0.00	-0.00	0.01	0.02	-0.14	0.02	0.03	-0.05	0.00	0.04	-0.89	0.06	0.00	0.03	0.00	-0.00	0.02	0.00	0.00	0.00	0.00	λ =0.027
EV9	-0.00	0.01	0.03	0.09	-0.38	-0.65	-0.00	-0.08	-0.01	-0.17	0.03	-0.08	0.00	-0.02	0.13	0.04	-0.56	0.09	0.12	0.02	-0.00	-0.01	0.18	-0.02	-0.00	-0.01	-0.00	-0.00	-0.01	-0.00	-0.00	-0.00	0.00	λ =0.038
EV8	-0.00	0.27	0.38	0.02	0.06	0.10	0.00	0.02	0.00	-0.78	0.37	0.07	-0.00	0.01	-0.04	0.00	0.09	0.00	0.00	0.09	-0.00	-0.03	-0.06	-0.04	0.00	-0.03	0.00	0.00	-0.02	-0.00	-0.00	-0.00	-0.00	$\lambda = 0.075$
EV7	-0.00	0.03	0.03	0.09	0.15	0.32	0.00	0.00	0.00	0.02	0.01	0.05	0.00	-0.10	0.83	-0.25	-0.31	-0.04	-0.05	0.00	0.00	0.00	-0.01	0.00	0.00	0.00	-0.00	0.00	0.00	-0.00	-0.00	-0.00	0.00	$\lambda = 0.89$
EV6	0.01	-0.24	0.01	-0.90	0.21	-0.14	0.01	0.01	0.01	-0.11	0.01	0.01	-0.00	0.15	0.10	-0.03	-0.08	0.00	0.01	0.03	0.00	0.05	0.00	0.08	0.00	0.05	0.00	0.00	0.03	0.00	-0.00	-0.00	-0.00	$\lambda = 1.78$
EV5	-0.02	0.64	-0.09	-0.24	0.04	-0.06	0.00	0.00	0.00	0.15	-0.09	-0.01	-0.00	0.05	0.02	-0.01	-0.02	0.00	0.00	-0.19	-0.02	-0.28	-0.04	-0.52	-0.01	-0.27	-0.03	-0.01	-0.16	-0.03	0.00	-0.00	-0.00	λ =2.87
EV4	-0.01	0.68	-0.06	-0.08	0.01	-0.04	0.00	-0.01	-0.00	0.13	-0.07	-0.01	0.00	0.08	0.00	-0.00	-0.01	0.00	0.00	0.14	0.01	0.27	0.06	0.56	0.02	0.26	0.04	0.01	0.17	0.04	-0.00	-0.00	0.00	λ =20.2
EV3	-0.01	0.05	-0.01	-0.17	0.03	-0.04	0.00	0.00	0.00	-0.01	-0.01	0.00	-0.00	-0.98	-0.07	0.02	0.03	0.00	0.00	0.01	0.00	0.01	0.00	0.03	0.00	0.01	0.00	0.00	0.01	0.00	-0.00	0.00	-0.00	$\lambda = 106$
EV2	-0.85	-0.02	0.00	-0.14	-0.44	0.25	-0.01	-0.01	-0.02	-0.01	0.00	-0.00	0.00	0.01	0.00	-0.00	-0.00	-0.00	-0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	-0.00	0.00	0.00	λ =34473
EV1	-0.53	-0.02	0.00	0.23	0.71	-0.40	0.02	0.02	0.04	0.01	-0.00	0.00	-0.00	-0.00	-0.00	0.00	0.00	-0.00	-0.00	-0.00	0.00	-0.00	-0.00	-0.00	0.00	-0.00	-0.00	0.00	-0.00	-0.00	-0.00	-0.00	-0.00	λ =346827
	C <sub>HG</sub>	$\mathbf{C}_{\mathrm{uG}}$	C <sub>uH</sub>	с <sub>нw</sub>	C <sub>HB</sub>	C <sub>HWB</sub>	cw	C <sub>uW</sub>	$\mathbf{C}_{\mathrm{uB}}$	$c_{\rm HI}^{\rm (3)}$	C,	C <sup>HDD</sup>	C <sub>Hbox</sub>	$c_{\rm Hq}^{\rm (3)}$	C <sub>Hu</sub>	$\mathbf{C}_{Hd}$	$c_{\rm Hq}^{(1)}$	C <sub>He</sub>	$c_{\rm HI}^{\rm (1)}$	$c_{_{\mathrm{G}}}$	$c_{\rm qq}^{(1)}$	$C_{qq}^{(1)}$	$c_{\rm qq}^{\rm (3)}$	c <sup>(3).</sup>	c <sub>uu</sub>	C' <sub>uu</sub>	$c_{\rm ud}^{(8)}$	$c_{\rm qu}^{(1)}$	$c_{qu}^{(8)}$	$c_{\rm qd}^{(8)}$	$c_{\rm ud}^{(1)}$	C <sub>eH</sub>	C <sub>dH</sub>	

#### Backup: Summary Signal Strengths • ATLAS combination, Nature 607 (2022) 52

