Experimental Potential for *CP* sensitivity from STXS splitting

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VBF workshop, Geneva, 20 October 2022

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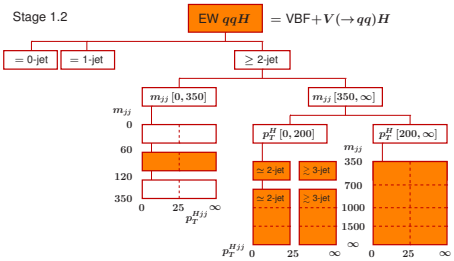
Bundesministerium
für Bildung
und Forschung

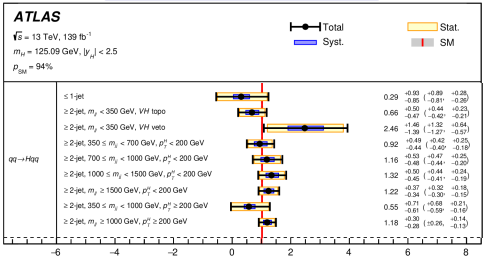
Introduction

- 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:
  - illustrate role of VBF STXS categories for EFT interpretation
  - discuss how to make STXS sensitive to *CP* violation with EFT as example
  - STXS is designed to study Higgs production. Will focus on VBF for this workshop
  - 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

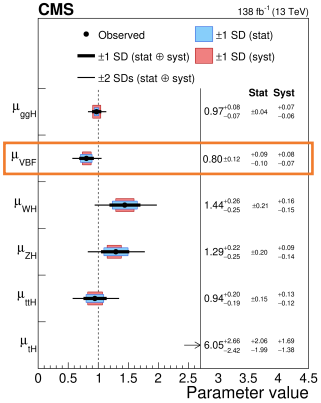
STXS Measurements for VBF



ATLAS combination, Nature 607 (2022) 52



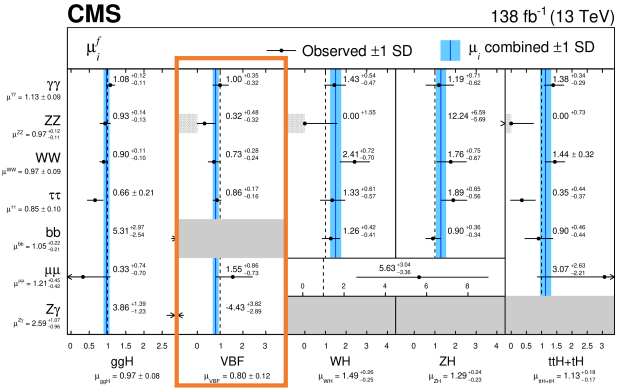
CMS combination, Nature 607 (2022) 60



- 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

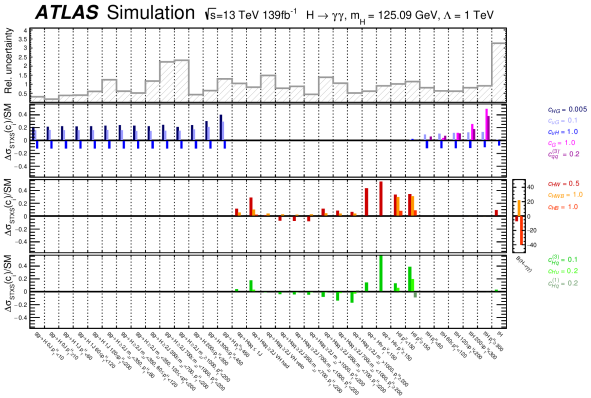
Contributions per Decay Channel

▸ CMS combination, Nature 607 (2022) 60



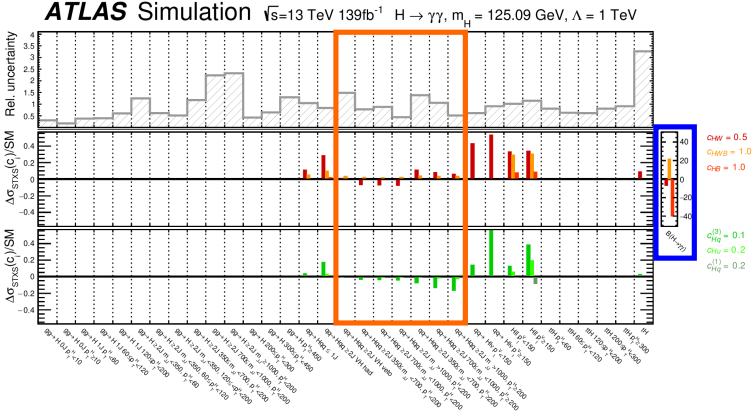
- Currently driven by $\tau\tau$ and WW, which will remain dominant for high m_{jj} and $p_T^H > 200\,\text{GeV}$. ($H \to bb$ may contribute/dominate for extreme phase space)
- $\gamma\gamma$ and ZZ catching up for inclusive and for low m_{jj} with $p_T^H < 200\,\text{GeV}$

EFT Interpretation of STXS Measurement



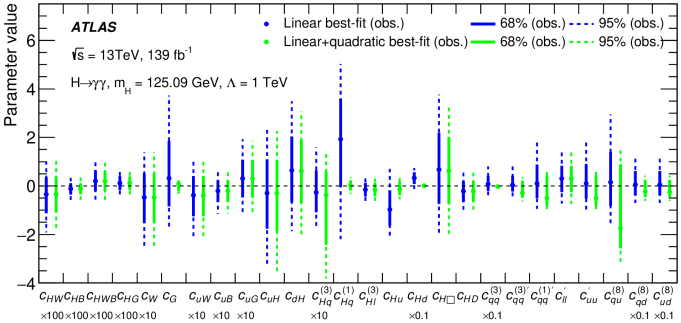
- STXS provides sensitivity to Wilson coefficients (Wilsons) that change overall normalization or relative yields of catergories. Use SMEFT parametrisation
- EFT interpretations of ATLAS and CMS combinations are yet to be performed
- Take ▸ ATLAS $H \to \gamma\gamma$ STXS measurement with EFT interpretation for illustration

EFT Interpretation of STXS Measurement



- The $H \to \gamma\gamma$ VBF categories are sensitive to c_{HW}, c_{HWB}, c_{HB}, $c_{Hq}^{(3)}$, and c_{Hu}
- The $H \to \gamma\gamma$ branching ratio is extremely sensitive to c_{HW}, c_{HWB} and c_{HB}
- Current STXS: Effect of CP-odd Wilsons similar to CP-even counterparts. Can only measure CP-odd Wilsons if CP-even ones fixed.

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

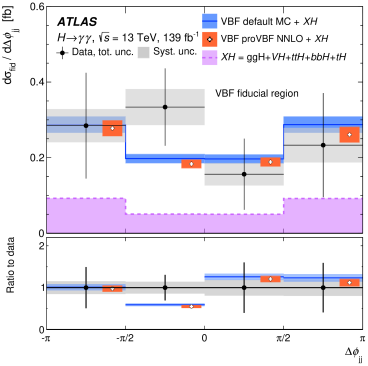
Can already measure multiple Wilsons at once with $H \to \gamma\gamma$. Will do better when combining with other channels, ATLAS+CMS and Run 2+3

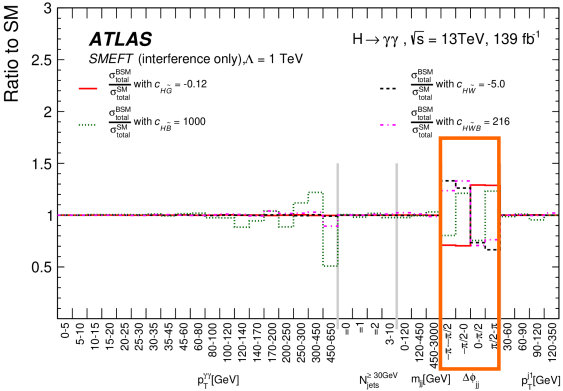
Linear SMEFT parameterization, linear+quadratic in paper

Model parameter	Observed			Expected	
	Value	Uncertainty		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	±0.006	$^{+0.012}_{-0.010}$	$^{+0.006}_{-0.005}$	$^{+0.011}_{-0.010}$
EV3	0.04	±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	$^{+1.2}_{-1.3}$	±0.6	$^{+1.1}_{-1.3}$
EV6	0.2	±0.8	$^{+1.7}_{-1.6}$	$^{+0.8}_{-0.7}$	±1.5
EV7	−1.7	±1.0	$^{+2.0}_{\mathbf{-1.3}}$	$^{+1.1}_{-1.0}$	$^{+2.2}_{-2.1}$
EV8	−0.7	$^{+3.5}_{-3.2}$	$^{+7}_{-6}$	$^{+3.9}_{-3.4}$	$^{+8}_{-7}$
EV9	7.5	$^{\mathbf{+2.5}}_{-5.2}$	$^{\mathbf{+2.5}}_{-11}$	$^{+5}_{-5}$	$^{+10}_{-11}$
EV10	0	$^{+7}_{-9}$	$^{\mathbf{+8}}_{-19}$	$^{+5}_{-7}$	$^{+9}_{-16}$
EV11	−6	$^{+9}_{-10}$	$^{+18}_{-19}$	±10	±19
EV12	3	$^{\mathbf{+12}}_{-13}$	$^{\mathbf{+12}}_{-25}$	±12	±24

How to Make STXS Sensitive to *CP*

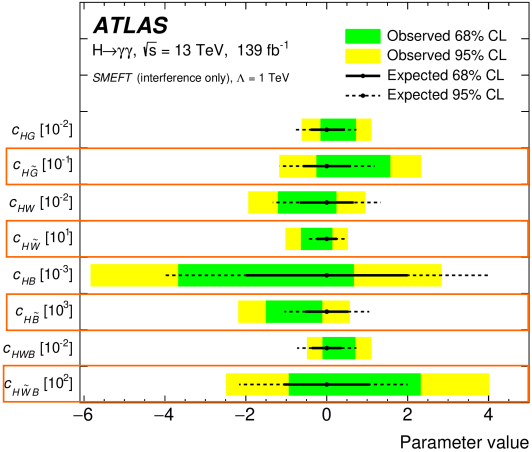
$\Delta\phi_{jj}$ for VBF fiducial region ▸ ATLAS $H \to \gamma\gamma$ differential





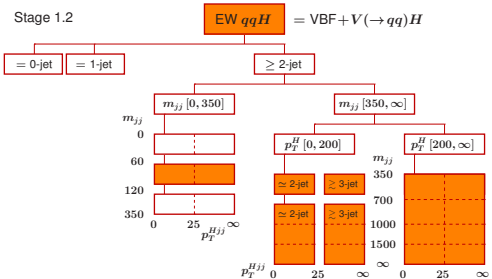
- Dedicated *CP* measurements utilize complex observables constructed from the matrix elements, see examples ▸ CMS $H \to \tau\tau$ ▸ CMS $H \to ZZ^*$ ▸ ATLAS $H \to \gamma\gamma$ ▸ ATLAS $H \to \tau\tau$
- The $\Delta\phi_{jj}$ observable is more suitable for STXS and provides good sensitivity to *CP*
- Bin correlations $\leq 7\%$ for $H \to \gamma\gamma$. Can reconstruct $\Delta\phi_{jj}$ well for all decay modes

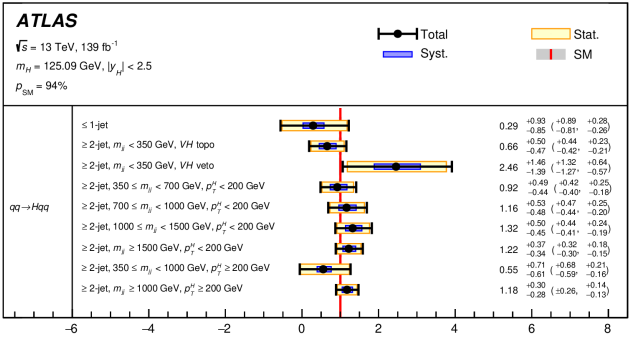
How to Make STXS Sensitive to *CP*



- *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 is most sensitive for large m_{jj}

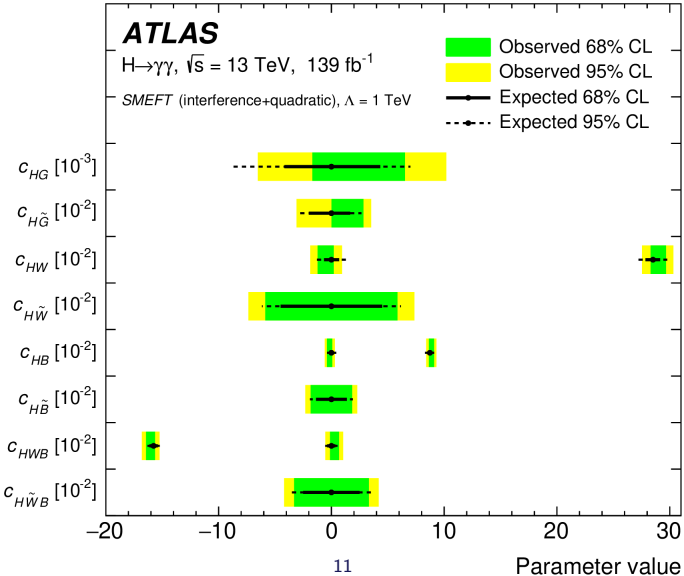
For Discussion: Options for Run 2+3





- Try to measure more stage 1.2 bins
  - Already measure all for $p_T^H < 200$ except p_T^{Hjj}
  - For key $H \to \tau\tau$ and $H \to WW^*$ channels the E_T^{miss} resolution makes it hard to bin in p_T^{Hjj}
- 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 $\Delta\phi_{jj}$ bins for CP sensitivity

Backup: Results from ▸ ATLAS $H \to \gamma\gamma$ differential with linear+quadratic terms



Backup: EFT eigenvectors

for ATLAS $H \to \gamma\gamma$ STXS

ATLAS $\sqrt{s}$=13 TeV 139fb^{-1}; H→γγ

	c_{HG}	c_{uG}	c_{uH}	c_{HW}	c_{HB}	c_{HWB}	c_{W}	c_{uW}	c_{uB}	$c_{Hl}^{(3)}$	c'_{ll}	c_{HDD}	c_{Hbox}	$c_{Hq}^{(3)}$	c_{Hu}	c_{Hd}	$c_{Hq}^{(1)}$	c_{He}	$c_{Hl}^{(1)}$	c_{G}	$c_{qq}^{(1)}$	$c_{qq}^{(1)'}$	$c_{qq}^{(3)}$	$c_{qq}^{(3)'}$	c_{uu}	c'_{uu}	$c_{ud}^{(8)}$	$c_{qu}^{(1)}$	$c_{qu}^{(8)}$	$c_{qd}^{(8)}$	$c_{ud}^{(1)}$	c_{eH}	c_{dH}	
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	λ =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	λ =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	λ =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	λ =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	λ =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	λ =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

Backup: Summary Signal Strengths

▸ ATLAS combination, Nature 607 (2022) 52