SMEFT Treatment for the Higgs Boson with the ATLAS Experiment Les Rencontres de Physique de la Vallée d'Aoste

he ATLAS Collaboration





Precision Program for the Higgs

- LHC Run-2 commences precision program of Higgs boson with ATLAS experiment **Differential Higgs cross-sections** measurements provide valuable kinematic information The **Standard Model Effective Field Theory** (SMEFT) provides a theoretically consistent framework to interpret these measurement in terms of new physical parameters
- <u>Today's talk based on ATLAS-CONF-2021-053</u>,
- Higgs kinematic properties with Simplified Template Cross Sections [STXS]
- Introduction to SMEFT framework
- Interpreting Higgs measurements in SMEFT framework



Inclusive Picture of Higgs Production

The five major SM Higgs production modes have been measured with O(10-20)% precision



Inclusive cross-section probe only changes to overall rate, no info. of underlying distributions With Run-2 dataset, for the first time, we can measure **differential information** across all

major Higgs production modes

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Kinematics with simplified template cross-sections

STXS framework - fiducial bins to measure kinematic properties across decay channels

Kinematic regions help isolate BSM effects (typically tails of distributions)





Full systematice modelling from experimental and theoretical sources used

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- SMEFT interpretation done at the level STXS, no detector-level SMEFT simulation required

Measurements of Higgs kinematics

Decay channel	Target Production Modes	$\mathcal{L} [\mathrm{fb}^{-1}]$
$H\to\gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139
$H \to ZZ^*$	ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$	139
$H \to WW^*$	ggF, VBF	139
$H \to \tau \tau$	ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{had}\tau_{had})$ $t\bar{t}H$	$139 \\ 36.1$
	WH, ZH	139
$H \rightarrow b \bar{b}$	VBF	126
	$t\bar{t}H$	139

→ New w.r.t to 2020 Higgs combination

Measure **37 kinematic bins** across 5 production modes using analyses of 5 major decay channels

Probe Higgs cross-sections ranging across 4 orders of magnitude !

Measurements are statistically limited



ATLAS	Preliminary			Total Stat. Syst.				
$\sqrt{s} = 13 \text{ TeV}. 139 \text{ fb}^{-1}$		B _{γγ} /B _{zz} .	1 .09	+0.14(+0.12) -0.12(-0.11, ±0.06)				
$m_{ij} = 125.09 \text{ GeV}, v < 2.5$		B _{bb} /B _{ZZ} ,	0.78	+0.28 (+0.23 +0.16) -0.21 (-0.18 -0.11)				
p = 92%	, o H.	B _{WW} /B _{ZZ*}	1.06	$+0.14 (+0.11 +0.09) \\ -0.13 (-0.10 , -0.08)$				
· SM	Stat	B _{rr} /B _{ZZ} .	0.86	$^{+0.16}_{-0.14}$ ($^{+0.12}_{-0.10}$, $^{+0.10}_{-0.09}$)	SM prediction			
Syst.	Stat.	0 0.5 1	1.5	2	[pb]			
				Total Stat. Syst.				
	0-jet, p_{τ}^{H} < 10 GeV		0.89	+0.22(+0.19+0.11)	6.6 ± 0.9			
	0-jet, $10 \le p_{\tau}^{H} < 200 \text{ GeV}$		1.14	$^{+0.15}_{-0.14}$ ($\pm 0.12^{+0.09}_{-0.07}$)	20.6 ± 1.6			
	1-jet, $p_{\tau}^{H} < 60$ GeV		0.57	$\pm 0.28 \left(\begin{array}{c} +0.22 \\ -0.21 \\ , \pm 0.18 \end{array} \right)$	6.5 ± 0.9			
	1-jet, $60 \le p_{\tau}^{H} < 120 \text{ GeV}$		1.06	$^{+0.28}_{-0.27} \left(\begin{array}{c} +0.25 \\ -0.24 \end{array} \right) + 0.13 \\ -0.24 \end{array} \right)$	4.5 ± 0.6			
	1-jet, $120 \le p_T^H < 200 \text{ GeV}$		0.66	$^{+0.41}_{-0.39}$ ($^{+0.36}_{-0.35}$, $^{+0.19}_{-0.17}$)	0.75 ± 0.13			
gg→n × B _{ZZ*}	\geq 2-jet, m_{jj} < 350 GeV, p_T^H < 60 GeV		0.47	$^{+1.09}_{-1.06}$ (± 0.98 $^{+0.47}_{-0.39}$)	1.17 ± 0.27			
	\ge 2-jet, m_{jj} < 350 GeV, 60 $\le p_T^H$ < 120 GeV		0.25	$\pm 0.53 (\pm 0.46 \pm 0.26)$	1.8 ± 0.4			
	\geq 2-jet, m_{jj} < 350 GeV, 120 $\leq p_{_T}^{_H}$ < 200 GeV		0.54	$^{+0.44}_{-0.42}$ ($^{+0.38}_{-0.36}$ $^{+0.23}_{-0.22}$)	0.94 ± 0.21			
	\geq 2-jet, 350 \leq m_{jj} < 700 GeV, p_{τ}^{H} < 200 GeV		2.76	$^{+1.11}_{-1.04} \left(\begin{array}{c} +0.99 \\ -0.93 \end{array} \right) + 0.52 \\ -0.45 \end{array} \right)$	0.61 ± 0.13			
	\geq 2-jet, $m_{jj} \geq$ 700 GeV, $p_T^H <$ 200 GeV		0.74	$^{+1.54}_{-1.43}$ ($^{+1.33}_{-1.29}$ $^{+0.76}_{-0.63}$)	0.27 ± 0.06			
	$200 \le p_T^H < 300 \text{ GeV}$		1.06	$^{+0.35}_{-0.31}($ $^{+0.29}_{-0.27},$ $^{+0.19}_{-0.15})$	0.46 ± 0.11			
	$300 \le p_{\tau}^H < 450 \text{ GeV}$		0.65	$^{+0.47}_{-0.43}($ $^{+0.42}_{-0.39},$ $^{+0.21}_{-0.16})$	0.106 ± 0.030			
	$p_{\tau}^{H} \ge 450 \text{ GeV}$		1.86	$^{+1.47}_{-1.19}($ $^{+1.37}_{-1.12},$ $^{+0.52}_{-0.42})$	0.018 ± 0.006			
				+110 + 102 + 040				
	\leq 1-jet		1.40	+1.10 (+1.02 +0.46) (-0.99 (-0.93) (-0.35) +1.64 (+1.46) +0.75)	2.10 ± 0.07			
	≥ 2 -jet, $m_{\parallel} < 350$ GeV, VH topo		2.98	-1.52(-1.37, -0.66) +0.58(+0.51+0.28)	0.728 ± 0.022			
	≥ 2 -jet, $m_{jj} < 350 \text{ GeV}$, VH topo		1.00	-0.52(-0.47, -0.23) +0.49(+0.44+0.22)	0.528 ± 0.019			
	≥ 2 -jet, $300 \leq m_{jj} < 700 \text{ GeV}, p_{\tau} < 200 \text{ GeV}$		0.33	-0.47 (-0.41, -0.24) +0.71 (+0.62 +0.35)	0.545 ± 0.016			
$qq \rightarrow Hqq \times B_{ZZ^*}$	≥ 2 -jet, $1000 \leq m_{ij} \leq 1000 \text{ GeV}, p_{\tau} \leq 200 \text{ GeV}$		0.95	-0.65(-0.57, -0.31) +0.57 (+0.50 +0.29)	0.266 ± 0.008			
	>2 -iet. $m_{\pi} > 1500$ GeV. $p^{H} < 200$ GeV		1.50	-0.49 -0.45 -0.21 $+0.39$ $+0.35$ $+0.18$	0.236 ± 0.007			
	\geq 2-jet, $m_{\mu} \geq$ 350 GeV, $p^{H} \geq$ 200 GeV	Ē	1.13	-0.35 (-0.32 - 0.14) +0.31 (+0.27 +0.15)	0.233 ± 0.008			
-0.27 (-0.24) - 0.12								
	$p_{\tau}^{V} < 75 \text{ GeV}$		2.47	$^{+1.17}_{-1.02}$ ($^{+1.15}_{-1.02}$ $^{+0.22}_{-0.12}$)	0.206 ± 0.008			
	$75 \le p_{\tau}^{V} < 150 \text{ GeV}$		1.64	+0.99 (+0.97 +0.20) -0.80 (-0.79 -0.12)	0.131 ± 0.006			
$qq \rightarrow HIv \times B_{ZZ^*}$	$150 \le p_{\tau}^{V} < 250 \text{ GeV}$		1.42	$^{+0.74}_{-0.58}$ $\begin{pmatrix} +0.61 & +0.42 \\ -0.48 & -0.33 \end{pmatrix}$	0.0416 + 0.0018 - 0.0019			
	$250 \le \rho_{\tau}^{V} < 400 \text{ GeV}$, and	1.36	$^{+0.72}_{-0.53}$ ($^{+0.63}_{-0.48}$, $^{+0.35}_{-0.22}$)	0.0108 ± 0.0005			
	$p_{\tau}^{V} \ge 400 \text{ GeV}$		1.91	$^{+1.45}_{-1.08} \left(\begin{array}{c} +1.22 \\ -0.95 \end{array} \right) $	0.00245 ± 0.00013			
	$p_T^V < 150 \text{ GeV}$		0.21	$^{+0.71}_{-0.76}$ (± 0.54 $^{+0.46}_{-0.53}$)	0.197 ± 0.008			
aa/aa→Hll × B ₇₇₄	$150 \le p_T^{\nu} < 250 \text{ GeV}$		1.30	+0.03 (+0.53 +0.34) -0.46 (-0.41, -0.22)	0.032 ± 0.004			
	$250 \le p_{\tau}^{\nu} < 400 \text{ GeV}$		1.28	$+0.73 (+0.64 +0.36) \\ -0.54 (-0.48 ,-0.23) \\ +1.28 +1.04 +0.74$	0.0073 ± 0.0008			
	$\rho_{\tau}^{\nu} \ge 400 \text{ GeV}$		0.39	-1.14(-0.91,-0.68)	0.00139 ± 0.00008			
	0 ^H < 60 GeV			+0.78 / +0.72 +0.29 \	0.118 ± 0.016			
	$\beta_T < 0.0 \text{ GeV}$ 60 < $\rho^H < 120 \text{ GeV}$		0.75	-0.66(-0.63, -0.21) +0.53 + 0.49 + 0.20	0.178 + 0.020			
	$120 \le p^{H} \le 200 \text{ GeV}$		0.09	-0.44 (-0.42 , -0.15) +0.55 (+0.50 +0.23)	0.178 ± 0.020			
$t\overline{t}H \times B_{ZZ^*}$	$200 \le p_{\perp}^H < 300 \text{ GeV}$		00.0 AQ Q	-0.47 (-0.43 - 0.19) + 0.62 (+0.56 + 0.25)	0.126 ± 0.016			
	$300 \le p_{\pi}^{T} < 450 \text{ GeV}$		0.00	-0.52 (-0.48, -0.20) +0.79 (+0.66, +0.43)	0.053 ± 0.008			
	$p_{\tau}^{H} \ge 450 \text{ GeV}$		0.16	-0.70(-0.59, -0.38) +1.93(+1.44 +1.28)	0.0190 ± 0.0031			
·				-1.76 \ -1.24 '-1.25 /	0.0054 ± 0.0009			
$tH \times B_{ZZ^*}$			1 2.90	$^{+3.63}_{-2.87} \left(\begin{array}{c} +3.35 \\ -2.73 \end{array} , \begin{array}{c} +1.39 \\ -0.89 \end{array} \right)$	0.085 + 0.011 - 0.005			
-8 -	6 –4 –2	0 2 4	6	8 10				
	Parameter normalised to SM value							

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Standard Model Effective Field Theory



 $\mathcal{L}^{(d)} = \sum c_i \mathcal{O}_i^{(d)}$ all possible local interactions allowed by symmetries $c_i \rightarrow Wilson coefficients$ - free parameters of model, using <u>Warsaw basis</u> here Operators act as a basis to systematically classify heavy new physics signatures

- 2499 operators at d=6 with $\Delta L = \Delta B = 0$, 60 CP-even operators with U(3)⁵ flavour symmetry



SMEFT dependence of observables

SMEFT dependence parameterised as polynomials in wilson coefficients,



Only linear is considered for current results Madgraph MC Predictions

- **<u>SMEFTsim</u>** to tree-level EFT contributions
- **<u>SMEFTatNLO</u>** for loop-induced QCD processes

Analytic Prediction

• NLO EW calculation for $H \rightarrow \gamma \gamma$ to resolve important loop contribution (1807.11504)

Analysis Acceptance

Effect of analysis selections for 4-body Higgs decay



Quadratic : $(d=6)^2$, missing SM x d=8 interference



SMEFT Impact on kinematics





SMEFT Impact on kinematics





$$G_F = G_F^{SM} + \sqrt{2}c_{Hl^{(3)}} - \frac{c_{ll}}{\sqrt{2}}$$

All operators at a glance,



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Many operators have similar impact affect inclusive observables appear as overall normalisation same shape across bins

Not enough information in measurements to constrain all EFT parameters !

Principal Component Analysis of Fisher information to identify sensitive directions

Fit basis definition

Operator grouping dictated by experimental sensitivity to physics



Fit basis defined with PCA in operator groups - fit only sensitive components, rest fixed to SM

Warsaw basis





Limits obtained from **simultaneously measuring** 3 linear combination of wilson coefficients

No strong tensions with the SM, 59% compatibility w.r.t SM

Different models of BSM physics lead to different patterns of deviations

Limits provide a proxy to the allowed scale of New **Physics** in the relevant processes

$$c_{Hq}^{(3)} < 0.1 \rightarrow \frac{\Lambda}{\sqrt{c_{Hq}^{(3)}}} > 3 \text{ TeV}$$



Differential measurements of Higgs production gives access to new kinematical information, improvement in statistics and kinematic splits with Run-3 and beyond

SMEFT becoming the standard interpretation method for Higgs STXS measurements, evolution of the κ framework

Lot of work ongoing both in terms of analysis design and theoretical considerations to uncover SMEFT effects in current data

SMEFT is global, provides an unifying framework to interpret measurements consistently across different sectors and experiments

Jhanks for your attention !



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