State of the art review of current VBF Higgs results from ATLAS

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on the behalf of the ATLAS collaboration

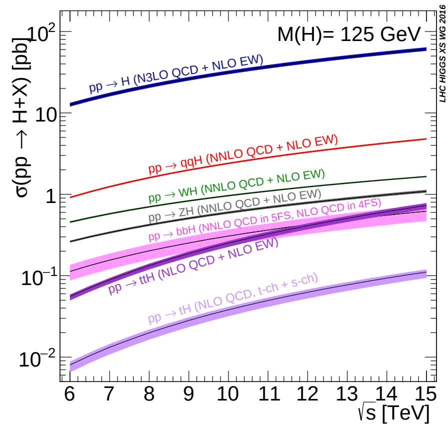
Past,Present and Future of VBF Workshop

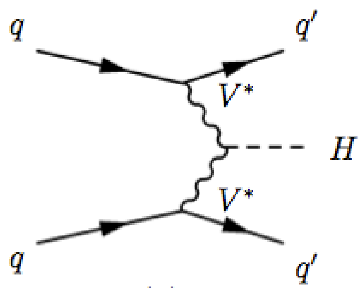
19/10/2022

Introduction to Vector Boson Fusion

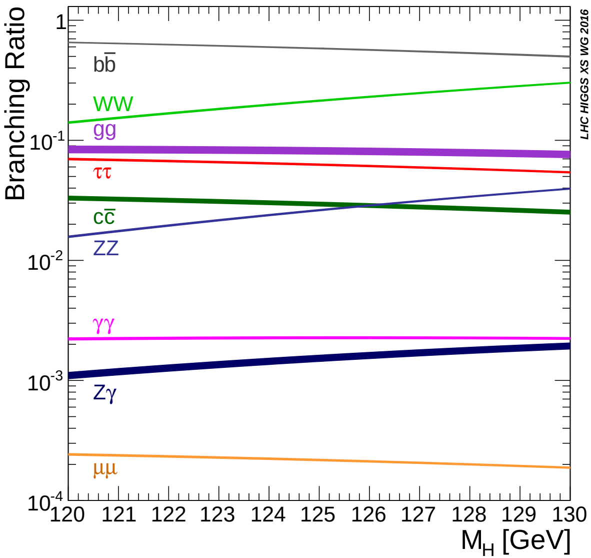
- 2nd main Higgs Boson production mode at LHC; cross section $\simeq$ 12 times less than gluon-gluon fusion, but cleaner experimental signature

- Suppressed color exchange between quark lines give rise to:
  - Little jet activity in central rapidity region
  - Scattered quarks $\rightarrow$ two forward tagging jets (energetic; large rapidity gap)
  - Higgs Boson decay products typically between tagging jets





Higgs boson decay branching ratios

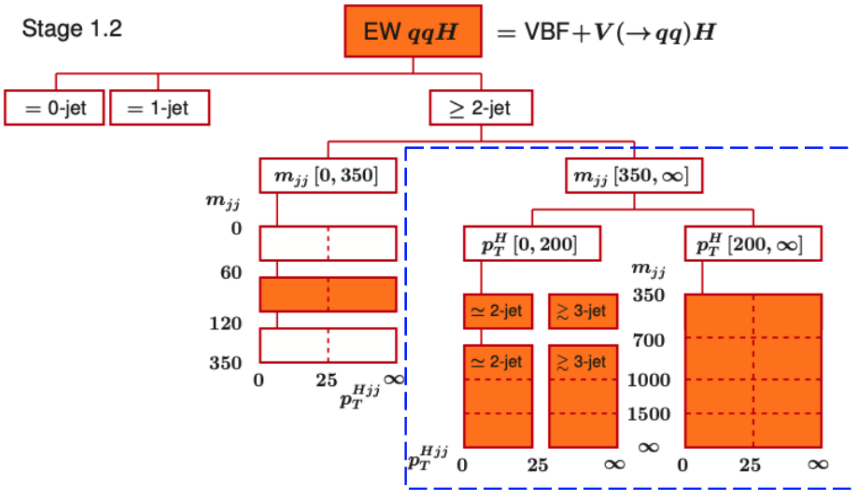


- Larger branching ratio (BR) for $H \to b\bar{b}$, $H \to WW^*$ and $H \to \tau\tau$, however poor mass resolution and large background contamination

- $H \to \gamma\gamma$ and $H \to ZZ^*(\to 4l/2l2\nu)$ have lower BR, but better mass resolution; can be used for precision measurements

VBF Measurements

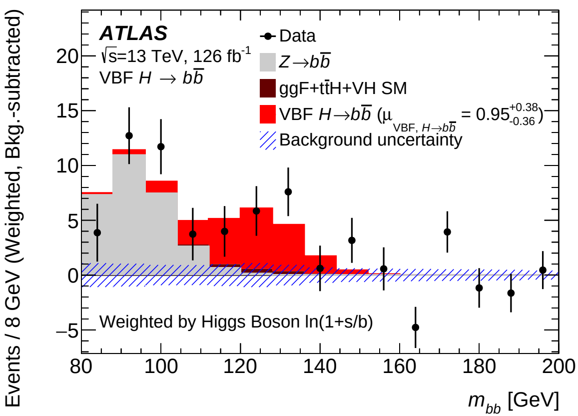
- Several type of measurements performed by ATLAS:
  - Inclusive/differential cross-section measurements
  - Measurement in the STXS framework arxiv-1906.02754
  - Charge-Parity (CP) measurements

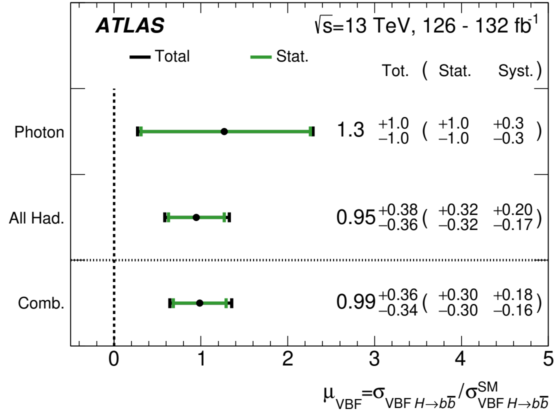


VBF H→ bb measurement arxiv-2011.08280

- Use ANN to discriminate signal vs non-resonant background and embedded $Z \to ll$ for resonant-background
- Result combined with less sensitive H→ $bb + \gamma$ analysis (arxiv-2010.13651)
- VBF measured with a significance of 3 σ

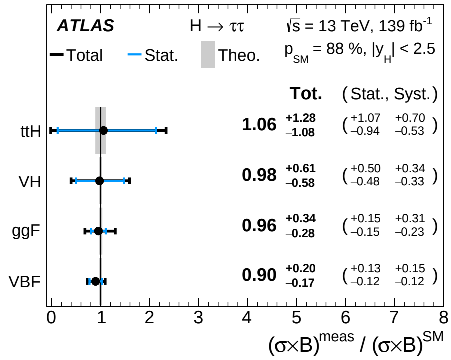
Results	VBF Production	Inclusive Production
Expected significance	2.9σ	3.0σ
Observed significance	2.9σ	3.0σ
Expected signal strength	$1.00^{+0.36}_{-0.34}$	$1.00^{+0.35}_{-0.34}$
Observed signal strength	$0.99^{+0.36}_{-0.34}$	$0.99^{+0.35}_{-0.33}$

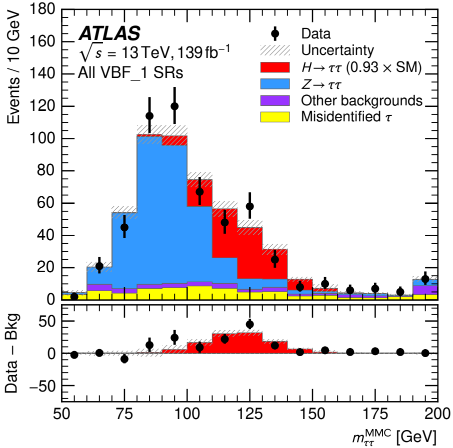


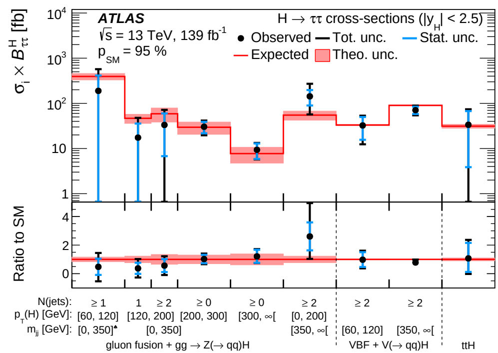


H$\rightarrow \tau\tau$ measurement arxiv-2201.08269

- VBF Higgs boson signal enhanced through BDT using dijet system variables
- VBF production established with 5.3 (6.2) σ obs. (exp)
- Only inclusive VBF measurement in STXS





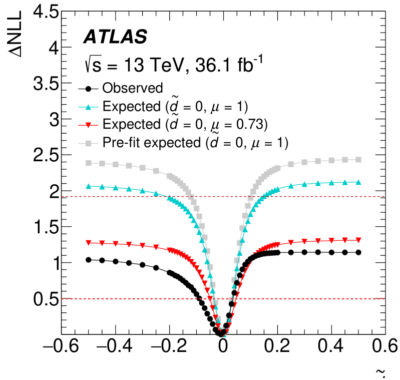


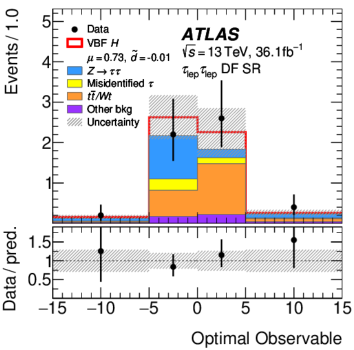
VBF H$\to \tau\tau$ CP measurement arxiv-2002.05315

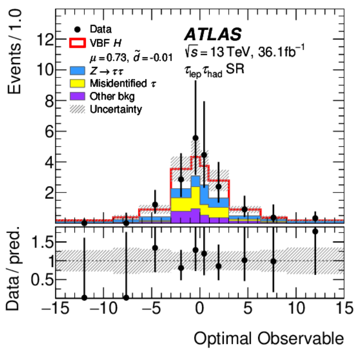
- Use *Optimal Observable* to measure CP-violating parameter $\tilde{d}$

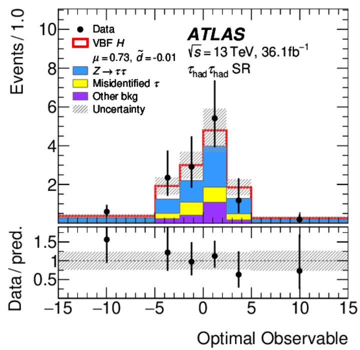
$$OO = \frac{2\ Re(M^{*}_{SM} M_{CP-Odd})}{|M_{SM}|^2}$$

- $< OO > \neq 0 \to$ CP violation neglecting re-scattering effects by new light particles in loops
- Expected (Observed) $\tilde{d} \epsilon$ [-0,035,0.033] ([-0.090,0.035]) at 68% confidence level (CL)



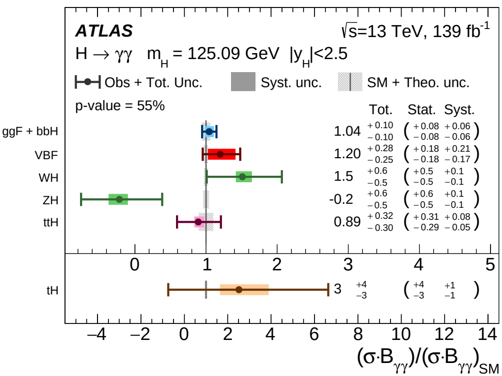




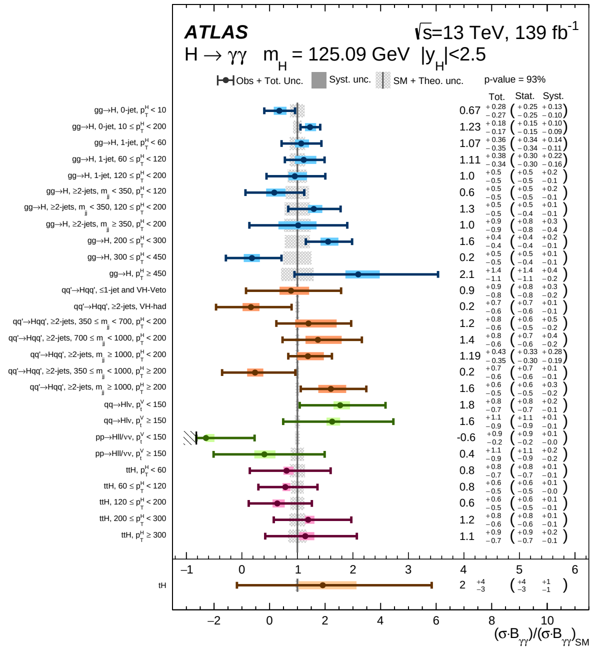


H→ $\gamma\gamma$ Incl. and STXS measurement

- Signal extracted from diphoton invariant mass in the range [105-160] GeV
  - Signal parameterised using Crystal Ball function
  - Background parameterised using an exponential of a second-order polynomial
- For STXS, most precise VBF measurement in the $M_{jj} > 1000$ GeV and $p_T^H < 200$ GeV bin

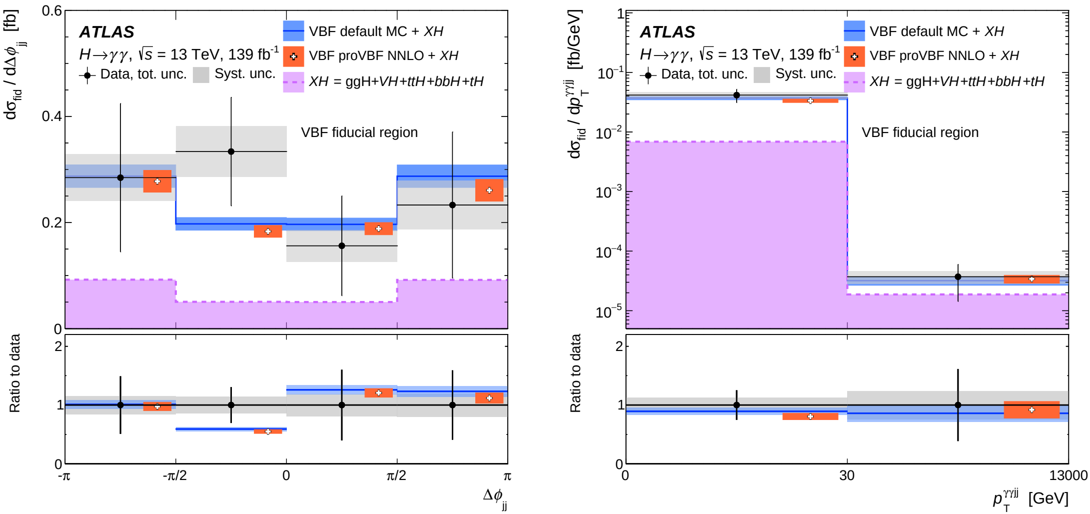


arxiv-2207.00348



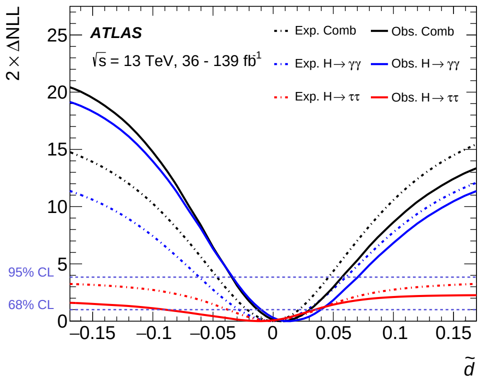
H→ $\gamma\gamma$ fiducial measurement arxiv-2202.00487

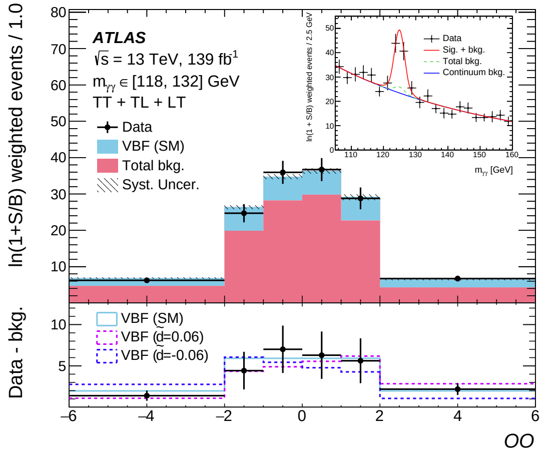
- Cross-section measured in the VBF-enhanced fiducial region (two jets with $M_{jj} > 600$ GeV and $|\Delta y_{jj}| < 3.5$) $\sigma_{meas} = 1.8 \pm 0.5$ (stat) $\pm\, 0.3$ (syst) fb in agreement with SM prediction $\sigma_{SM} = 1.53 \pm 0.10$ fb with a p-value of 64%
- Single/Double differential measurement performed for main VBF variables



H→ $\gamma\gamma$ CP measurement arxiv-2208.02338

- Use *Optimal Observable* to measure $\tilde{d}$
- Still no sign of CP violation (<OO> compatible with 0)
- Expected (Observed) $\tilde{d} \epsilon$ [-0,046,0.045] ([-0.034,0.057]) at 95% CL when combining with H→ $\tau\tau$

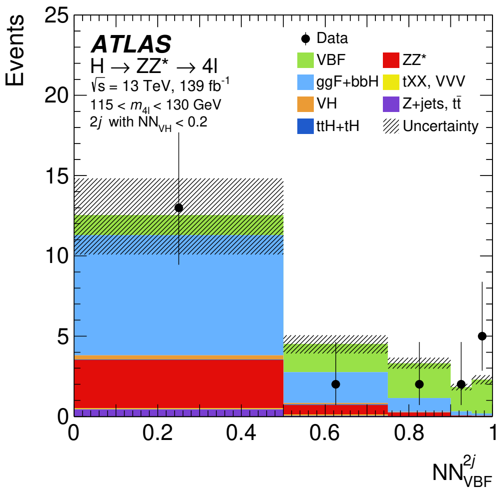




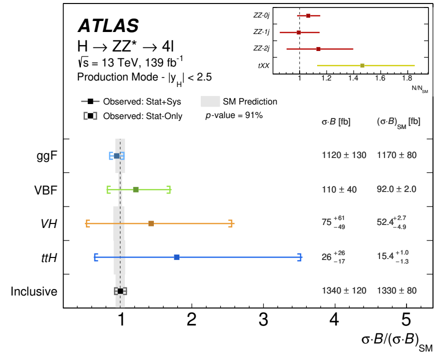
	68% (exp.)	95% (exp.)	68% (obs.)	95% (obs.)
$\tilde{d}$ (inter. only)	[−0.027, 0.027]	[−0.055, 0.055]	[−0.011, 0.036]	[−0.032, 0.059]
$\tilde{d}$ (inter.+quad.)	[−0.028, 0.028]	[−0.061, 0.060]	[−0.010, 0.040]	[−0.034, 0.071]
$\tilde{d}$ from $H \to \tau\tau$	[−0.038, 0.036]	–	[−0.090, 0.035]	-
Combined $\tilde{d}$	[−0.022, 0.021]	[−0.046, 0.045]	[−0.012, 0.030]	[−0.034, 0.057]
$c_{H\tilde{W}}$ (inter. only)	[−0.48, 0.48]	[−0.94, 0.94]	[−0.16, 0.64]	[−0.53, 1.02]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.48, 0.48]	[−0.95, 0.95]	[−0.15, 0.67]	[−0.55, 1.07]

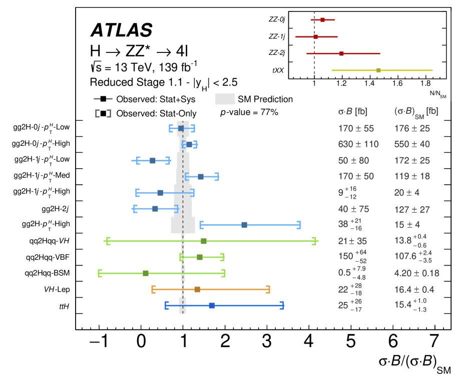
$H \to ZZ$ Incl. and STXS measurement

- Events classified using neural networks
- Final discriminant from 3 NNs : $4l$ system, jets and additional event info
- STXS results using Stage 1.1 binning; VBF results for $p_T^H < 200$ GeV bin



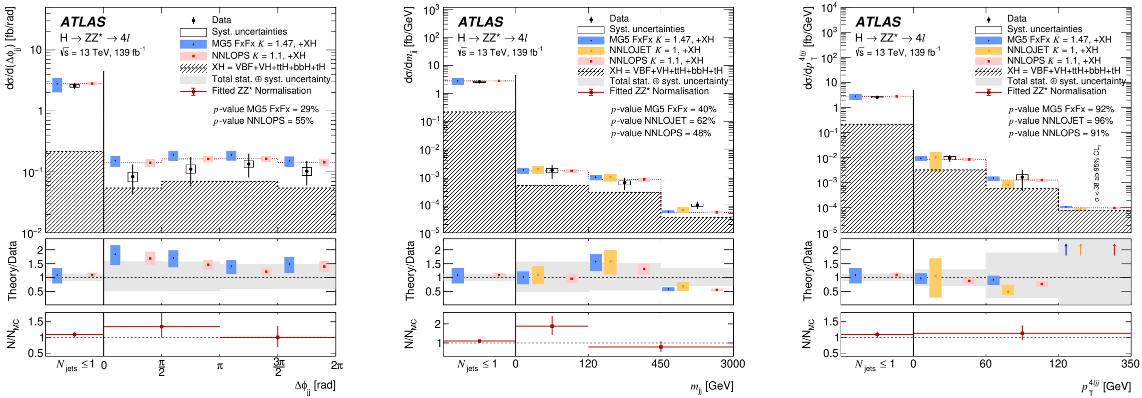
arxiv-2004.03447





H→ ZZ fiducial measurement arxiv-2004.03969

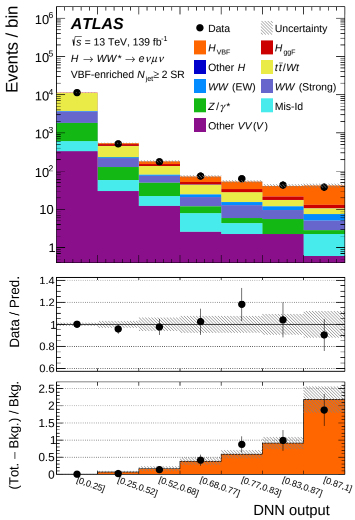
- No VBF-enhanced fiducial region like in H→ $\gamma\gamma$, but still measuring differential cross-sections in events with at least two jets
- Double-differential measurements for observables related to the Higgs and accompanying jets
- All measurements in agreement with SM prediction

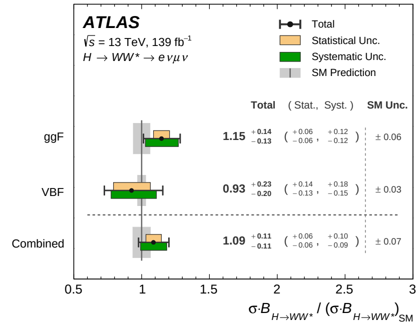


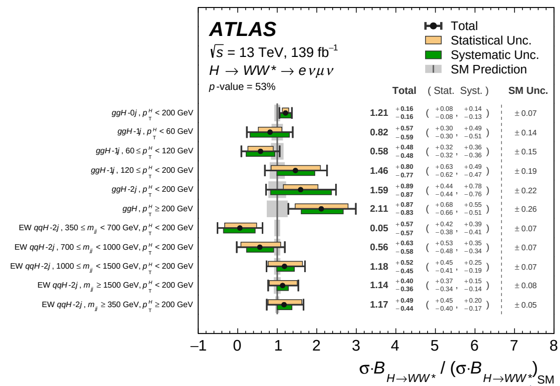
H→ WW Incl and STXS measurements

- Used DNN to enhance signal over background
- VBF production established with 5.8 (6.2) σ obs. (exp)
- For STXS, most precise VBF measurement in the $M_{jj} > 1500$ GeV and $p_T^H < 200$ GeV bin

arxiv-2207.00338

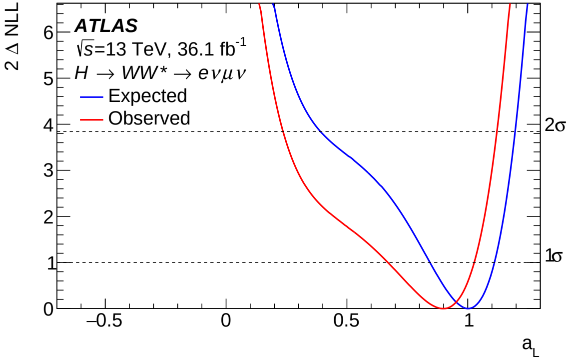


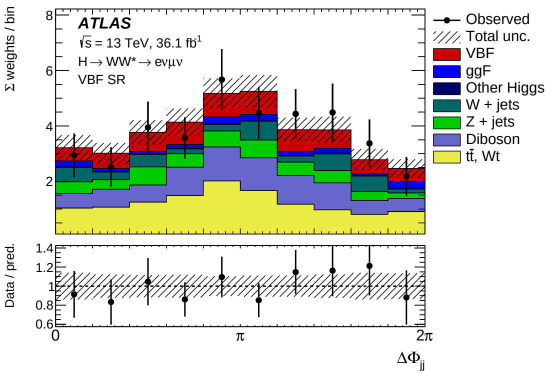




H→ WW CP measurement arxiv-2109.13808

- Use VBF to probe the Higgs boson couplings to longitudinally and transversely polarised W and Z bosons
- Measured polarisation-dependent coupling-strength with respect SM prediction :
  $a_L = 0.91^{+0.10}_{-0.18}(\text{stat.})^{+0.09}_{-0.17}(\text{sys})$
  $a_T = 1.2 \pm 0.4(\text{stat.})^{+0.2}_{-0.3}(\text{sys})$



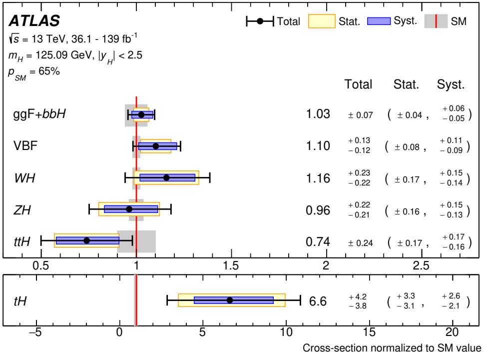


- Results in agreement with SM expectations

Type	Expected	Observed
a_T shape-only fit ($a_L = 1$)	$1.0 \pm 0.5(\text{stat.})^{+0.3}_{-0.4}(\text{syst.})$	$1.3^{+0.8}_{-0.4}(\text{stat.})^{+0.3}_{-0.2}(\text{syst.})$
a_L shape + rate fit ($a_T = 1$)	$1.00^{+0.08}_{-0.10}(\text{stat.})^{+0.07}_{-0.13}(\text{syst.})$	$0.90^{+0.09}_{-0.13}(\text{stat.})^{+0.08}_{-0.18}(\text{syst.})$
a_T shape + rate fit ($a_L = 1$)	$1.00^{+0.36}_{-0.49}(\text{stat.})^{+0.19}_{-0.27}(\text{syst.})$	$1.19^{+0.27}_{-0.32}(\text{stat.})^{+0.12}_{-0.14}(\text{syst.})$
a_L shape + rate fit (a_T profiled)	$1.00^{+0.08}_{-0.10}(\text{stat.})^{+0.08}_{-0.13}(\text{syst.})$	$0.91^{+0.10}_{-0.18}(\text{stat.})^{+0.09}_{-0.17}(\text{syst.})$
a_T shape + rate fit (a_L profiled)	$1.0^{+0.4}_{-0.5}(\text{stat.})^{+0.2}_{-0.4}(\text{syst.})$	$1.2 \pm 0.4(\text{stat.})^{+0.2}_{-0.3}(\text{syst.})$

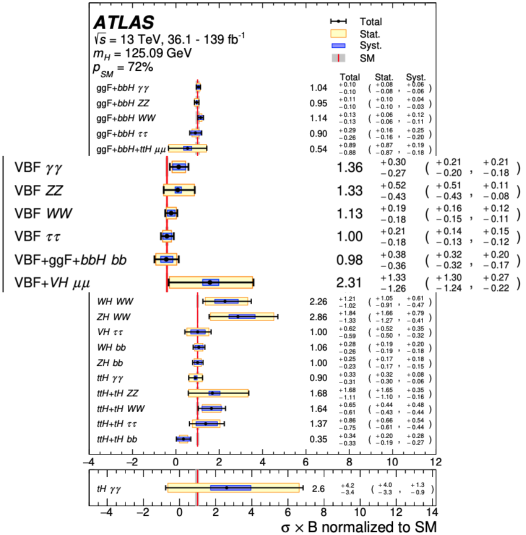
Higgs Comb. measurement arxiv-2207.00092

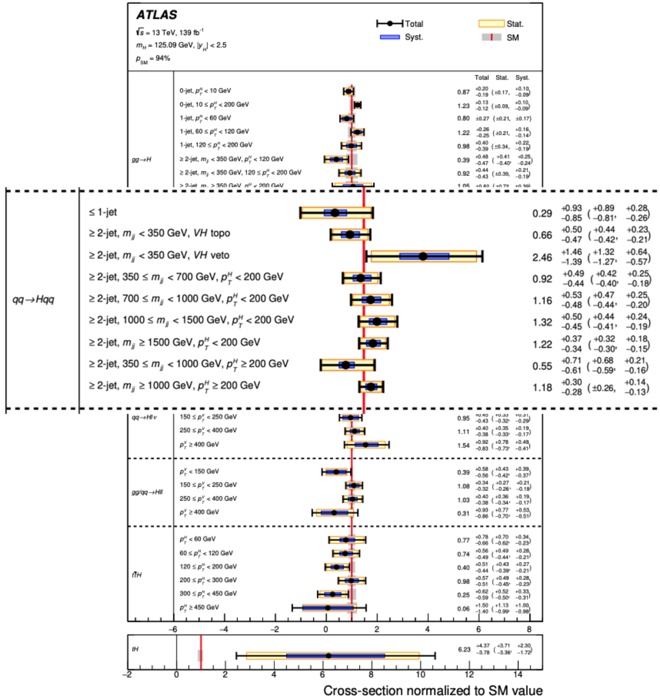
- Combine measurements from the different Higgs boson decays assuming SM Branching ratio
- VBF measured with a precision of $\simeq 10\%$ with almost same impact from stat and syst uncertainties
- Largest contribution from H$\rightarrow$ WW, H$\rightarrow$ $\tau\tau$ and H$\rightarrow$ $\gamma\gamma$



Decay mode	Targeted production processes	$\mathcal{L}$ [fb^{-1}]	Ref.	Fits deployed in
$H \rightarrow \gamma\gamma$	ggF, VBF, WH, ZH, $t\bar{t}H$, tH	139	[31]	All
$H \rightarrow ZZ$	ggF, VBF, WH ZH, $t\bar{t}H$ tH	139	[28]	All
	$t\bar{t}H$ tH (multilepton)	36.1	[39]	All but fit of kinematics
$H \rightarrow WW$	ggF, VBF	139	[29]	All
	WH, ZH	36.1	[30]	All but fit of kinematics
	$t\bar{t}H$ tH (multilepton)	36.1	[39]	All but fit of kinematics
$H \rightarrow Z\gamma$	inclusive	139	[32]	All but fit of kinematics
$H \rightarrow b\bar{b}$	WH, ZH	139	[33, 34]	All
	VBF	126	[35]	All
	$t\bar{t}H$ tH	139	[36]	All
	inclusive	139	[37]	Only for fit of kinematics
$H \rightarrow \tau\tau$	ggF, VBF, WH ZH, $t\bar{t}H$ tH	139	[38]	All
	$t\bar{t}H$ tH (multilepton)	36.1	[39]	All but fit of kinematics
$H \rightarrow \mu\mu$	ggF $t\bar{t}H$ tH, VBF WH ZH	139	[40]	All but fit of kinematics
$H \rightarrow c\bar{c}$	WH ZH	139	[41]	Only for free-floating κ_c
$H \rightarrow$ invisible	VBF	139	[42]	κ models with $B_{u.}$ & $B_{inv.}$
	ZH	139	[43]	κ models with $B_{u.}$ & $B_{inv.}$

Higgs Comb. measurement arxiv-2207.00092



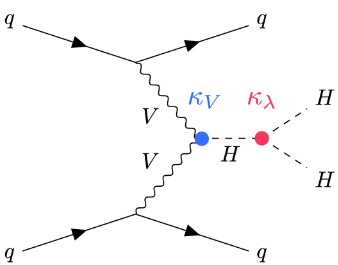


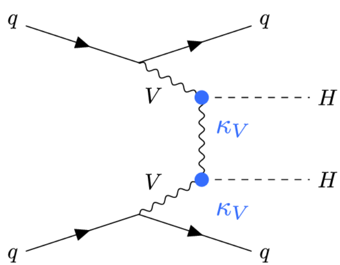
- Best precision in VBF bins with $M_{jj} > 1000$ GeV-$p_T^H > 200$ GeV bin and $M_{jj} > 1500$ GeV-$p_T^H < 200$ GeV (dominated by stat uncertainty)

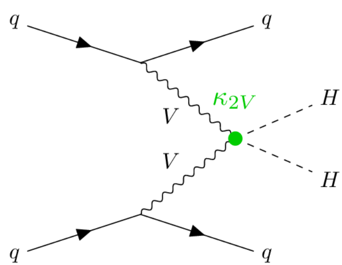
VBF Di-Higgs production

- Higgs potential influenced by Higgs boson trilinear self coupling term λ_{HHH}
- Direct way to measure the coupling modifiers is through Higgs boson pair production (HH)
  - VBF is unique way to probe VVHH vertex (k_{2V})
- Several HH decay final states have been explored but yet no observation

Higgs Decay	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.07%	
γγ	0.26%	0.10%	0.03%	0.01%	<0.001%

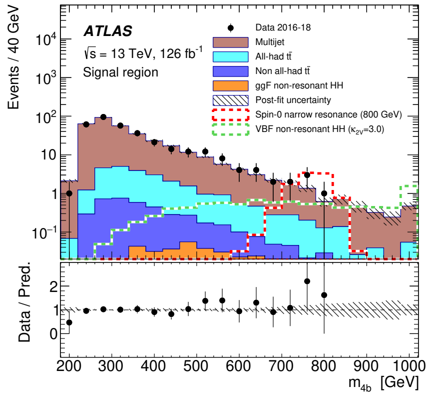


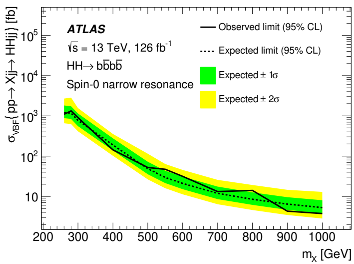


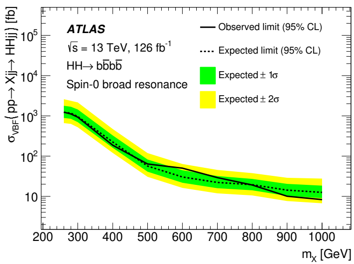


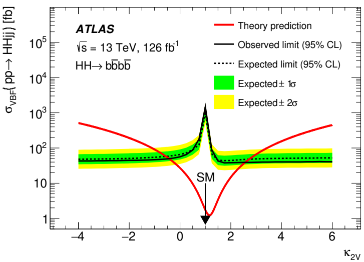
Search for VBF Di-Higgs 4b arxiv-2001.05178

- Search is sensitive to VBF production of additional heavy bosons decaying in Di-Higgs
- Non-resonant topology can constrain the quartic coupling between the Higgs bosons and vector bosons
- $k_{2V} < -0.43$ and $k_{2V} > 2.56$ excluded at 95% CL

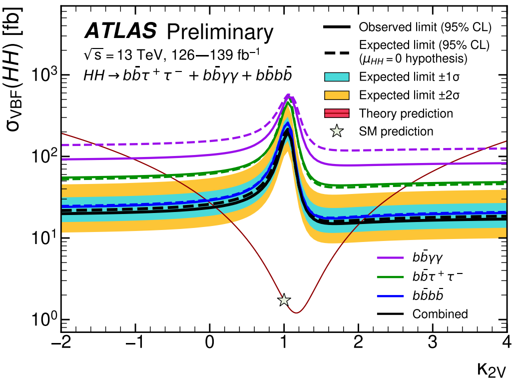


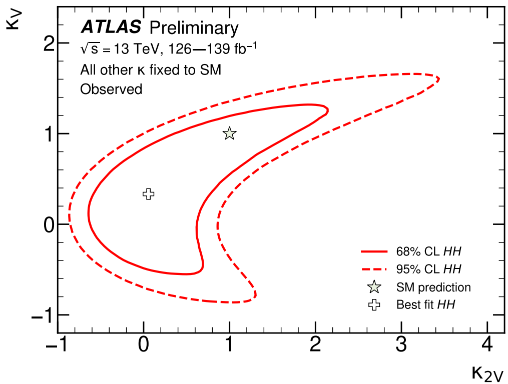






Di-Higgs Comb ATLAS-CONF-2022-050





- Results from combination of $HH \to bb\tau\tau$, $HH \to bb\gamma\gamma$ and $HH \to 4b$
- Observed (expected) 95% CL constraint on k_{2V}: 0.1 $< k_{2V} <$2.0 (0.0$< k_{2V} <$2.1)

Summary

- A review of the current VBF Higgs results from ATLAS has been presented
- Lots of results available for the inclusive and fiducial cross-section as well as cross section measurements within the STXS framework
- VBF also used to probe Higgs CP nature, but still no sign of physics beyond the standard Model
- Combination of single Higgs measurements lead ATLAS to measure VBF with a precision of $\simeq 10\%$, with most precision at high M_{jj} region
- VBF is unique way to probe VVHH vertex (k_{2V})
    - Combination measurement leads to observed 95% constraint $0.1 < k_{2V} < 2.0$

Thanks For Your Attention