Measurements of Higgs boson production and decay rates and their interpretation with the ATLAS experiment

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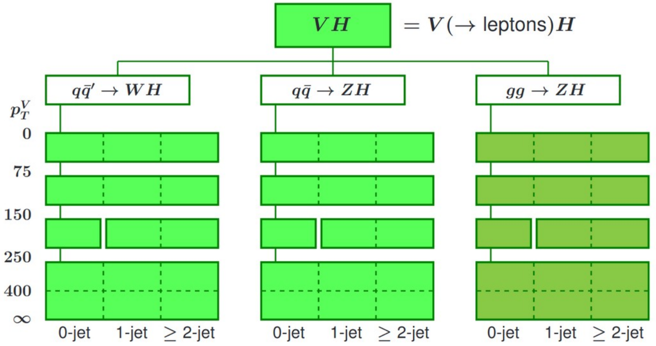
On behalf of the ATLAS collaboration
ICNFP 2023

Cross sections

Simplified Template Cross Sections (STXS)

Multiple non-overlapping phase space regions based on production mode of the Higgs boson, kinematics of the process

- Reduces theoretical uncertainties
- Common framework for combination of orthogonal decay channels

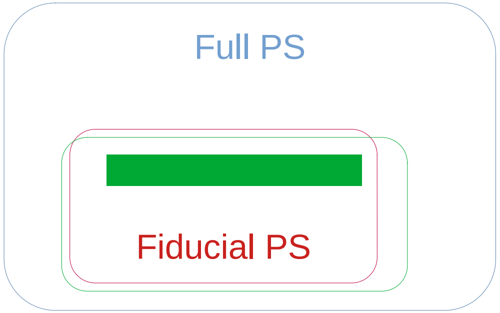


- Defined in stages with increasing granularity

Fiducial cross section

Cross sections measured in a phase space closely matching detector acceptance

- Avoids extrapolation of results into phase space out of acceptance
- Increases measurement precision



- Often extrapolation to full phase space is required to combine analyses

Interpretations

- BSM physics modify the Higgs couplings
- Deformations are model dependent, but which model?
- Two frameworks for "parametrizing our ignorance":

Kappa framework

Coupling of Higgs to p is modified by κ_p

$$\kappa_p^2 = \sigma_p / \sigma_p^{\text{SM}}$$
$$\kappa_p = 1 \Rightarrow \text{SM}$$

For loop induced processes sometimes use effective modifiers, e.g. $\kappa_{Z\gamma}$

Assumes tree-level coupling structure of the SM

SM Effective Field Theory (SMEFT)

Wilson coefficients

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots.$$

New physics mass scale

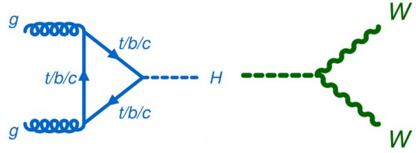
Operators obeying symmetries

d=5,7 operators introduce lepton/baryon number violation
=> Focus on d=6 operators

Allows any coupling that doesn't violate symmetries

ggF H$\rightarrow WW^{*} \rightarrow e\nu\mu\nu$

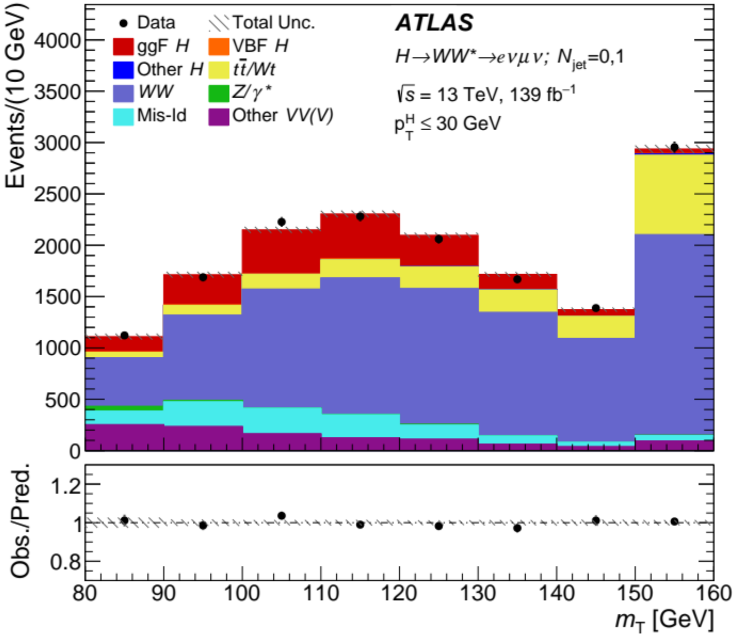
HIGG-2018-49

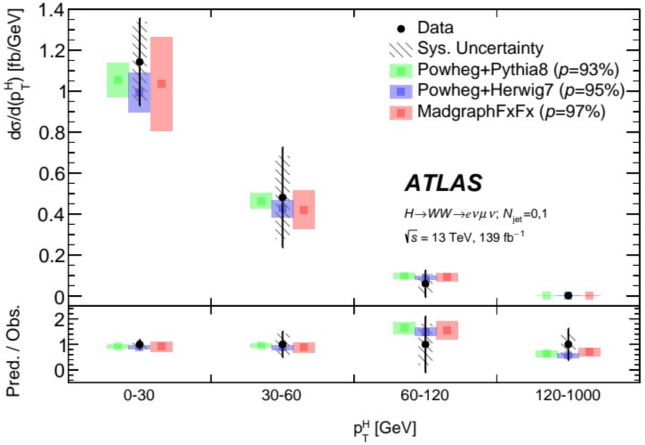


Data: 139 fb^{-1}, full ATLAS Run 2

- Measurements: Fiducial single + double $d\sigma$
- Final states with <=1 j are considered
- VBF, VH are fixed to SM and considered backgrounds
- Fit is performed to m_T in each bin of observable

$$m_T = \sqrt{\left(E_T^{ll} + E_T^{\text{miss}}\right)^2 - \left|\mathbf{p}_T^{ll} + \mathbf{E}_T^{\text{miss}}\right|^2} \qquad E_T^{ll} = \sqrt{\left|\mathbf{p}_T^{ll}\right|^2 + m_{ll}^2}$$

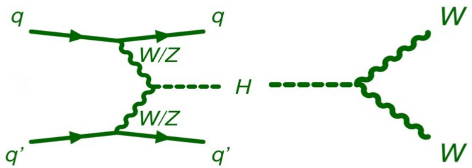




- **Dominant sources of uncertainty:**
  - Jet, muon reconstruction
  - t, WW backgrounds
  - Difficulty in modeling $Z\gamma$

Measurements are consistent with the SM

VBF H→ $WW^* \to e\nu\mu\nu$



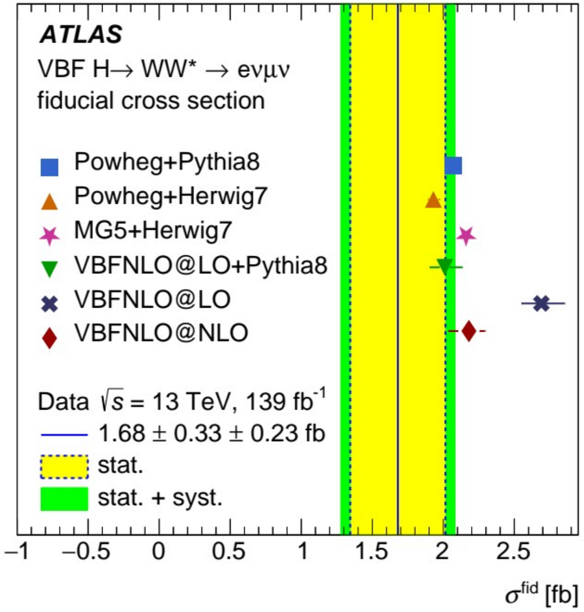
HIGG-2020-25

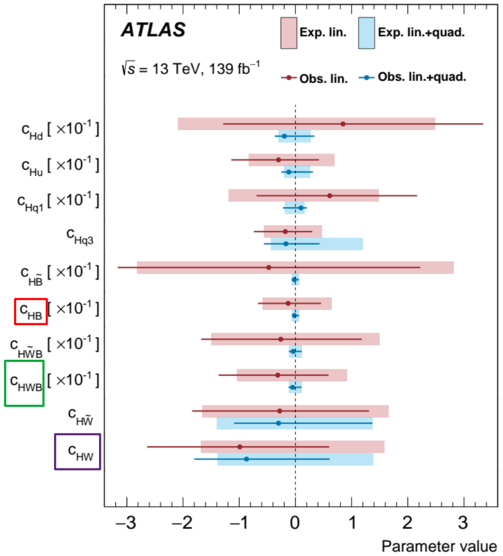
Data: 139 fb⁻¹, full ATLAS Run 2

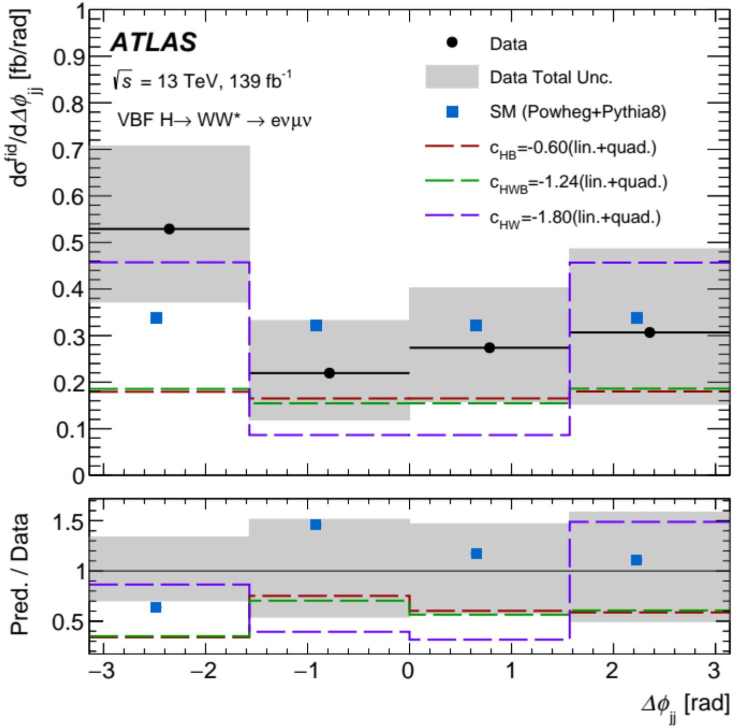
- **Measurements: Fiducial differential + inclusive cross sections, SMEFT interpretation**
- VBF - direct probe of Higgs coupling to W/Z bosons
- Simultaneous binned likelihood fit of MVA discriminants in several kinematic regions.
  - e.g. In the SR, two BDTs are trained to separate VBF from top+VV and top+VV from other backgrounds

$$\sigma \propto |\mathcal{M}_{\mathrm{EFT}}|^2 = |\mathcal{M}_{\mathrm{SM}} + \sum_i \frac{c_i}{\Lambda^2}\mathcal{M}_i|^2$$

$$= |\mathcal{M}_{\mathrm{SM}}|^2 + 2\sum_i \frac{c_i}{\Lambda^2} Re(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_i) + \sum_{i,j} \frac{c_i c_j}{\Lambda^4} Re(\mathcal{M}^*_i \mathcal{M}_j).$$







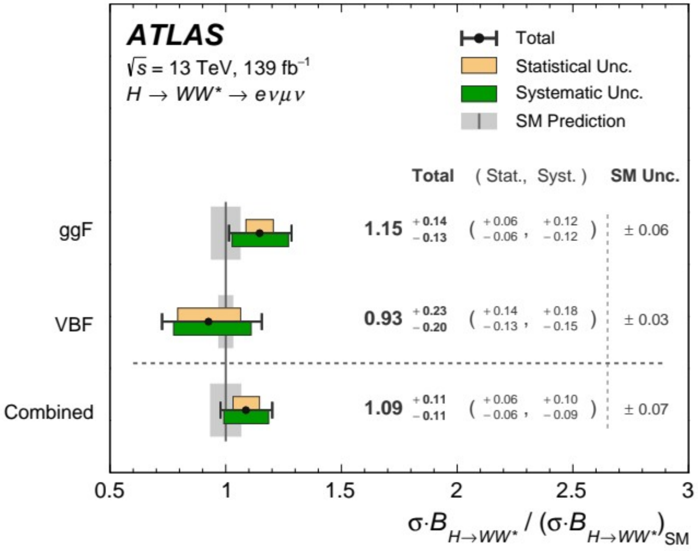
Measurements are consistent with the SM

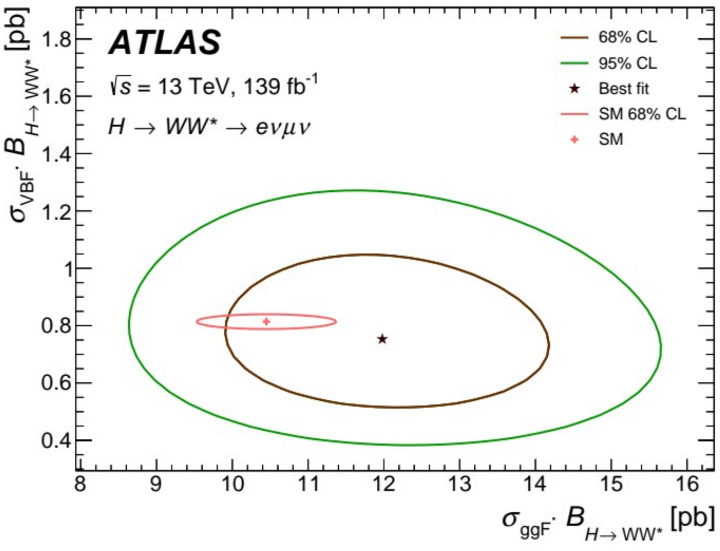
H→$WW^* \to e\nu\mu\nu$

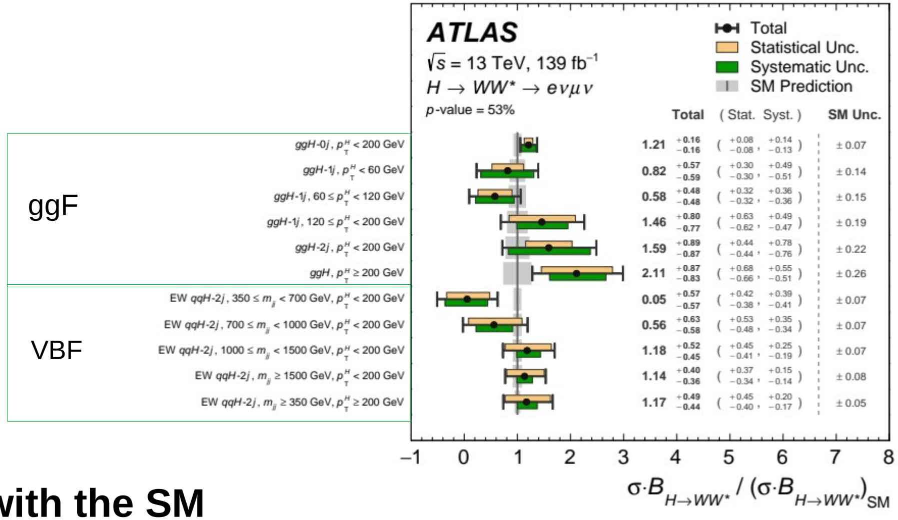
HIGG-2021-20

Data: 139 fb^{-1}, full ATLAS Run 2

- Measurements: σ in full phase space, STXS
- New from last iteration (arXiv:1808.09054, 36.1 fb^{-1})
  - Larger dataset
  - ggF in $\geq$ 2 j final state – increase in statistics
  - Cross section reported in 11 STXS bins
- Analysis performed in 4 regions – for ggF $N_j = 0, 1, \geq 2$, for VBF $N_j \geq 2$
- Fit to m_T in ggF regions, fit to DNN trained on VBF vs. others for VBF







Measurements are consistent with the SM

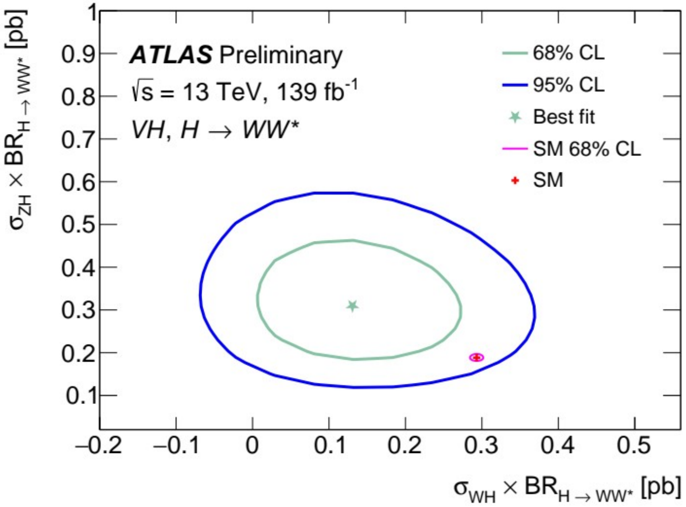
VH$\to WW^*\to l\nu l\nu + l\nu jj$

Data: 139 fb^{-1}, full ATLAS Run 2

ATLAS-CONF-2022-067

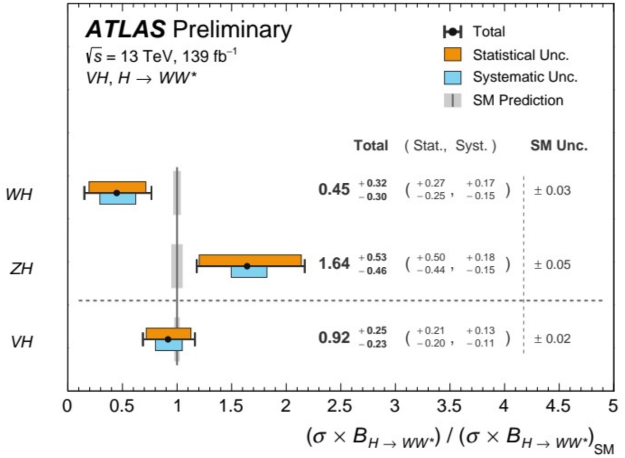
- Performed in 4 channels
- Different MVA discriminants adapted to background composition are used
  - ANN for multiclassification of signal + multiple backgrounds
  - RNN for S/B classification, events as arbitrarily long sequences of objects
  - BDT
- Used input variables based on reconstructed object kinematics
  e.g. $E_T^{\rm miss}, m_T^W, p_T^{l_0}$

Channel	Backgrounds
OS,2l	$t\bar{t}, Wt$
SS,2l	$W(Z/\gamma^*), W+\gamma, W+\text{jets}$
3l	$W(Z/\gamma^*), WWW$
4l	ZZ, WWZ



Dominant systematic uncertainties in WH:

- RNN shape due to RNN mismodelling
- $W(Z/\gamma^*), WWW$ background



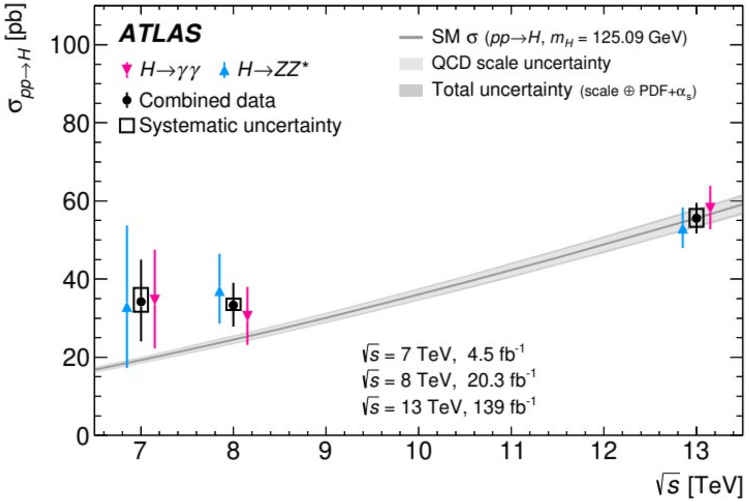
Measurements consistent with SM

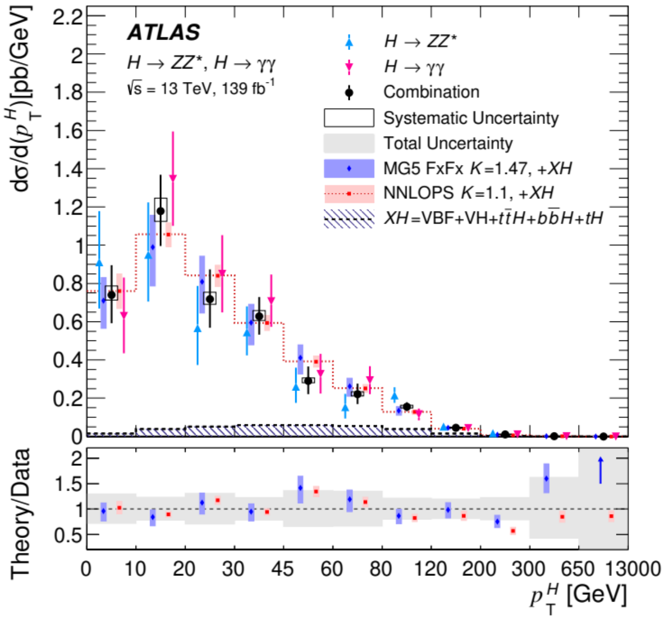
Combination of differential cross section measurements in $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$

Data: 139 fb^{-1}, full ATLAS Run 2

HIGG-2022-04

- Combination of arXiv:2004.03969 and arXiv:2202.00487
- Inclusive measurement for all H production modes
- Extrapolation to common phase space of both channels and combination
- Unprecedented 7% precision for $\sigma(pp \to H)$ measurement due to larger dataset and combination of channels
- Measurement of differential cross sections - $p_T^H, |y_H|, N_j, p_T^{\text{lead. jet}}$ each probing different aspect of Higgs production





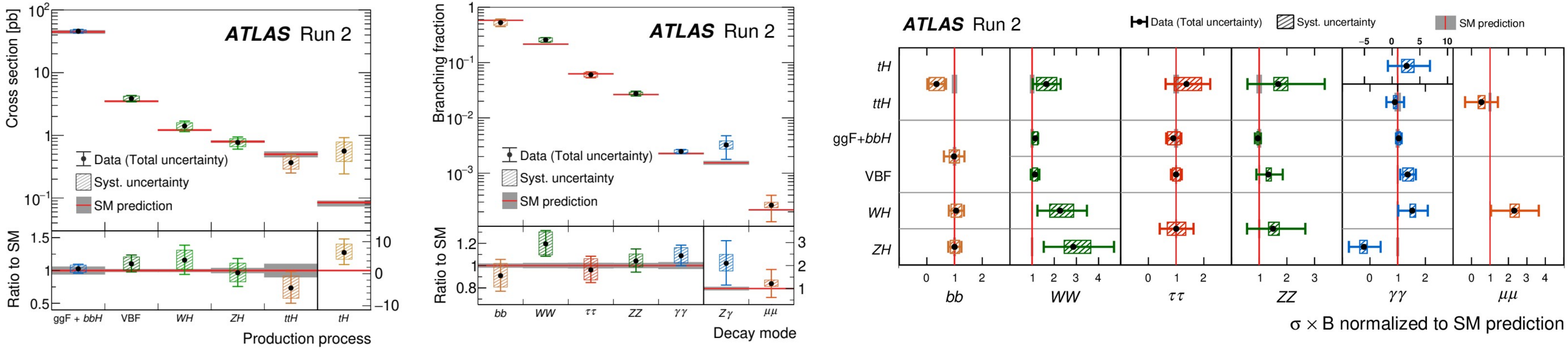
Sensitive to coupling to b/c quarks via ggF

Measurements are consistent with the SM

Combined measurements

HIGG-2021-23

Combination of multiple Higgs analyses in multiple decay channels and production processes was performed (Nature 607, 52-59 (2022))

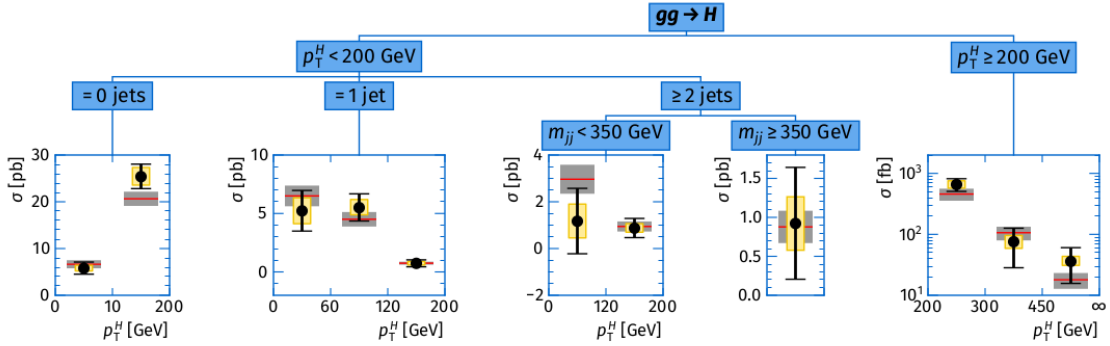


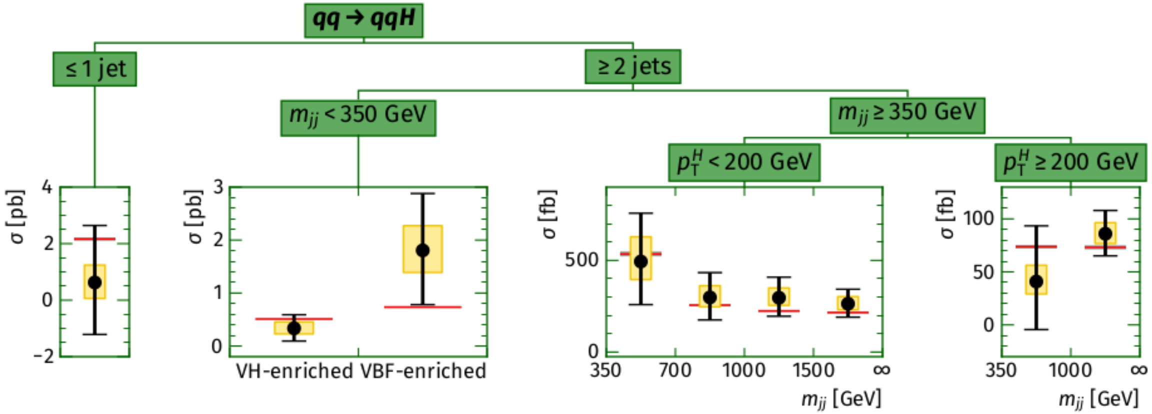
Combined measurements are consistent with the SM

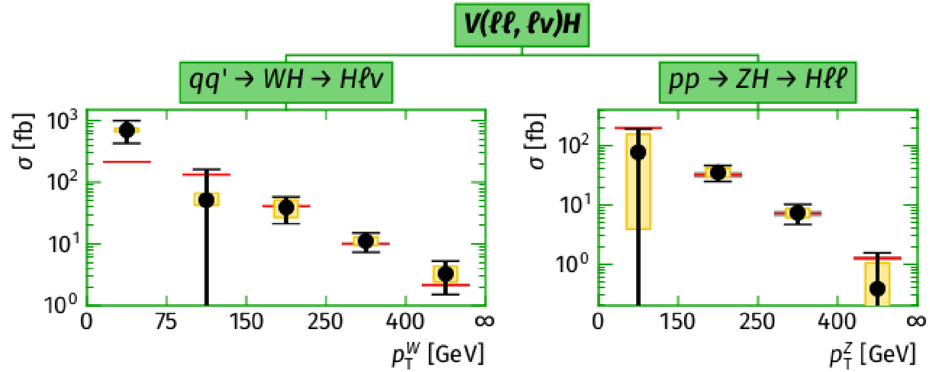
Combination in STXS

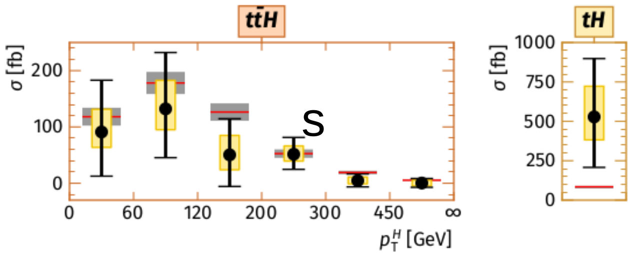
Nature 607, 52-59 (2022)

HIGG-2021-23









Measurements agree with the SM

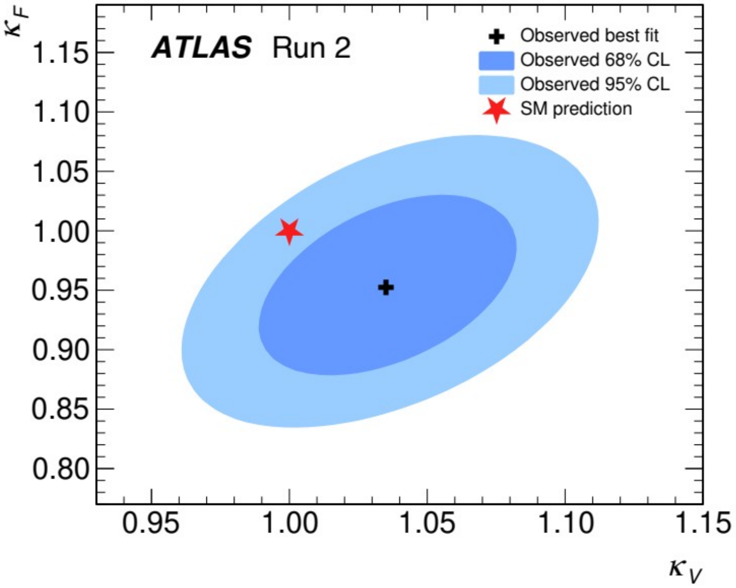
Combination – kappa interpretation

Nature 607, 52-59 (2022)

HIGG-2021-23

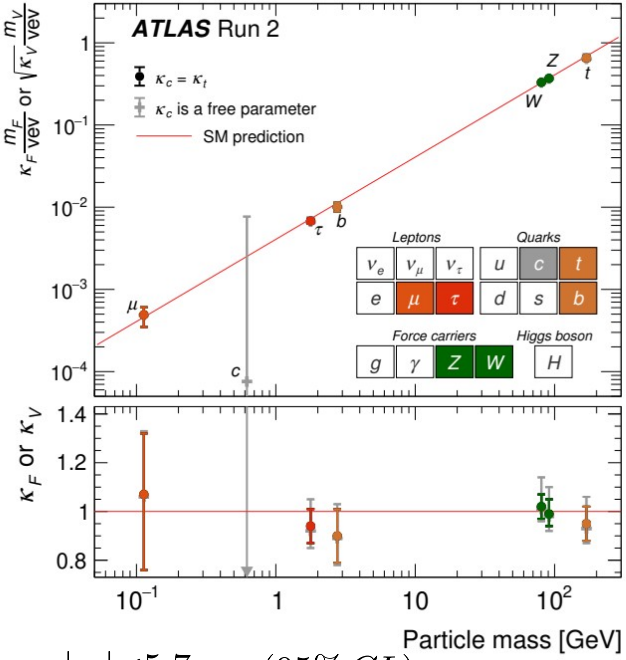
Two modifiers - κ_V (vector bosons), κ_F (Fermions)

Assuming no BSM contributions



No BSM contributions

κ_c free or $\kappa_c = \kappa_t$



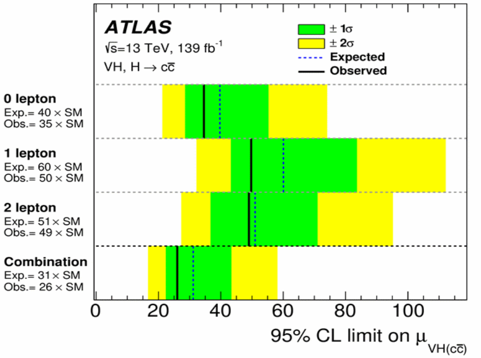
$|\kappa_c| < 5.7 \quad (95\% CL)$

Measurements agree with the SM

Constraints on κ_c, κ_b

- Higgs coupling to cc is very challenging - low BR, high jet background
- Combining VHcc and VHbb

  yields a 95%CL constraint $\left|\frac{\kappa_c}{\kappa_b}\right| < 4.5$ => Higgs coupling is weaker to c than to b at 95% CL

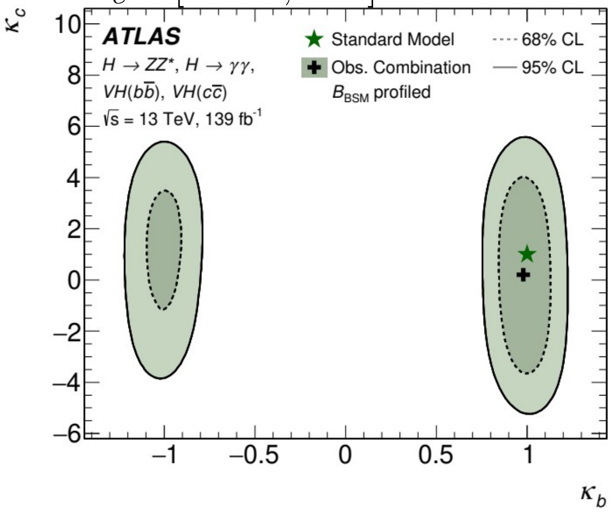


- In $H\rightarrow ZZ^{*}\rightarrow 4l + H\rightarrow\gamma\gamma$, $d\sigma/dp_T^H$ is used to derive limits on κ_c, κ_b.
  - Most stringent constraints on κ_c in two scenarios – decays to BSM particles allowed/not allowed

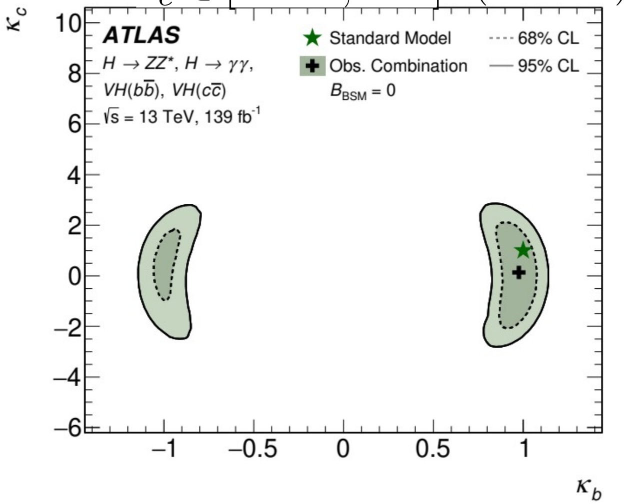
VHbb (arXiv:2007.02873)+ VHcc (arXiv:2201.11428)

+ $H\rightarrow ZZ^{*}\rightarrow 4l + H\rightarrow\gamma\gamma$ (arXiv:2207.08615)

$\kappa_c \in [-4.46, 4.81]$



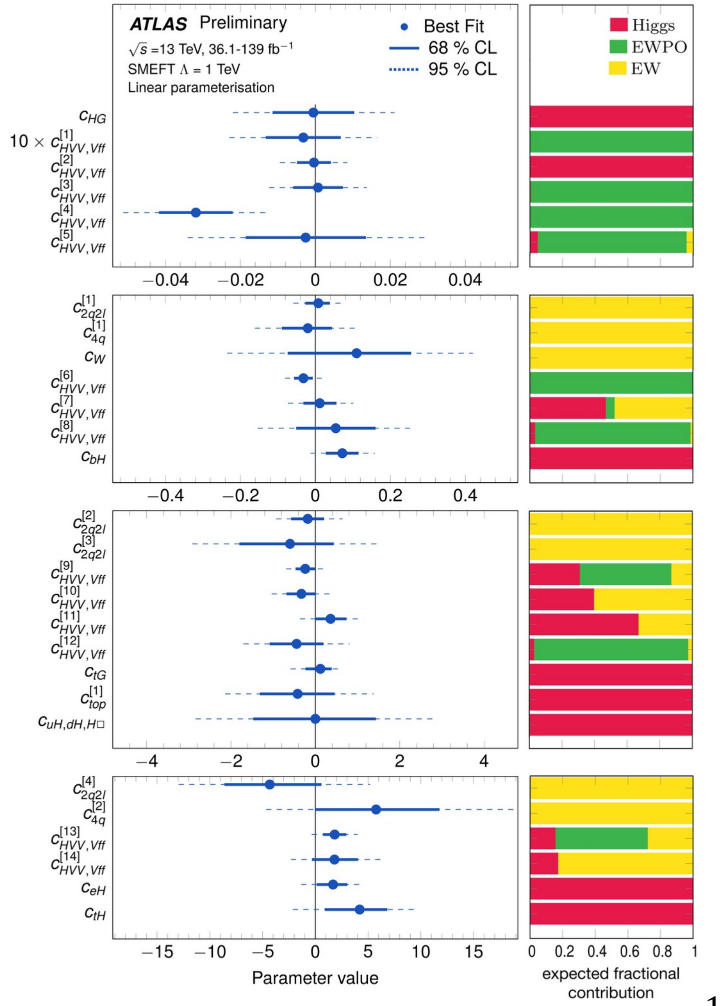
$\kappa_c \in [-2.47, 2.53]$ $(95\%\,CL)$



Combination EFT interpretation

ATL-PHYS-PUB-2022-037

- First ATLAS global EFT fit
- Framework allows to include additional measurements to improve the combination
- Multiple combined measurements:
  - ATLAS Higgs boson data
  - ATLAS EW data
  - EW precision observables (EWPO) from LEP and SLC
- Cross sections and branching ratios reparametrized in terms of wilson coefficients in STXS, constraints on 28 Wilson coefficients are determined



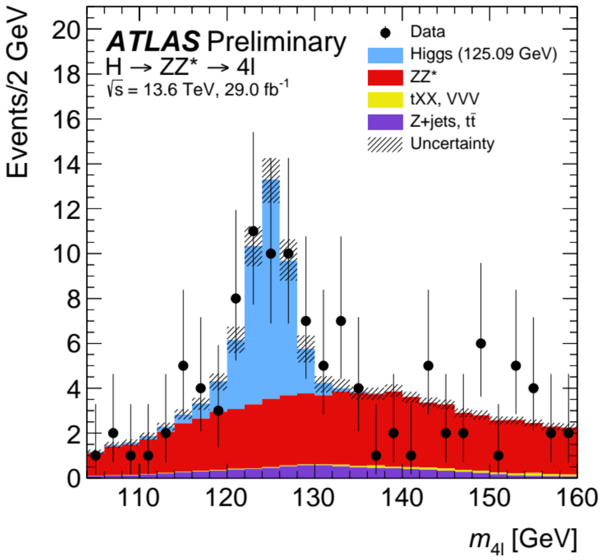
Run 3 $H \to ZZ^* \to 4l$ + $H \to \gamma\gamma$

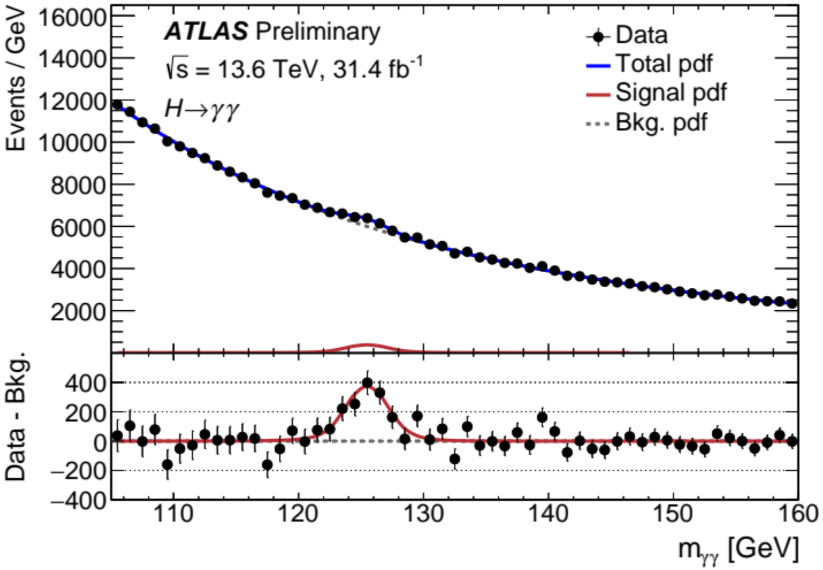
HIGG-2022-12

Data: 31.4 fb^{-1} @13.6 TeV ($H \to \gamma\gamma$)

29.0 fb^{-1} @13.6 TeV ($H \to ZZ^* \to 4l$)

- Measurement: Full phase space σ + fiducial & full phase space σ in each channel
- Each channel measured in fiducial phase space and extrapolated to full phase space for combination





Good agreement with SM at unprecedented COM energy

Conclusion

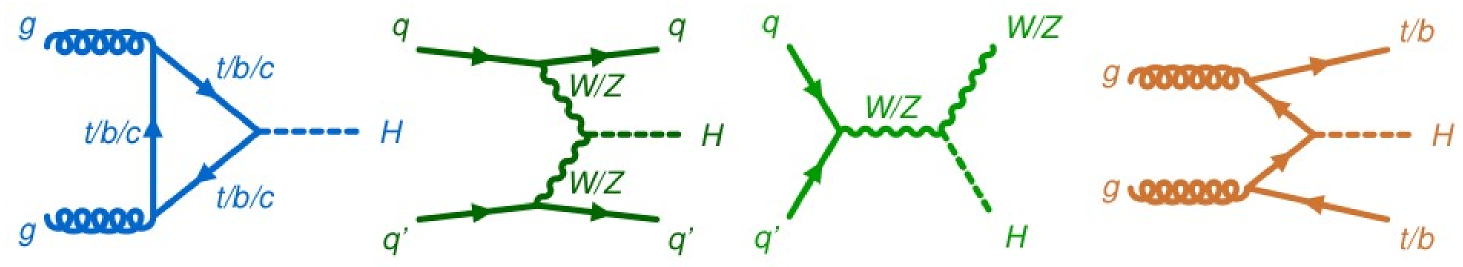
- **Run 2:**
  - Differential and inclusive cross sections from recent measurements are presented in the ATLAS experiment in STXS, full and fiducial phase spaces.
  - Combined measurements are interpreted in the SMEFT and kappa frameworks
  - Improved precision compared to Run-1 due to increased statistics and improved analysis methods, entering precision measurements era.
- **Run 3:**
  - First analyses at 13.6 TeV have been published
- All results are consistent with the SM
- Dataset of LHC is expected to increase by a factor of 20 by 2040

Thank you!

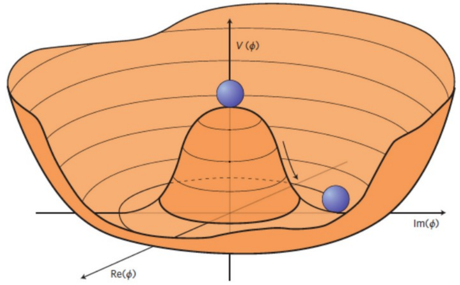
Backup

SM Higgs boson production and decay modes

Production modes – single Higgs



ggF 87% | VBF 7% | VH 4% | ttH,bbH 2%

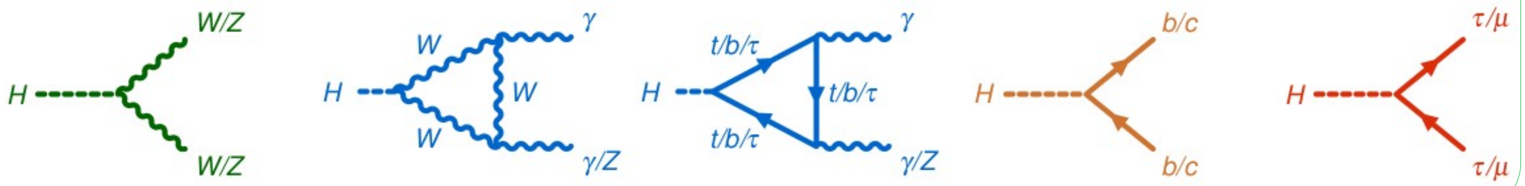


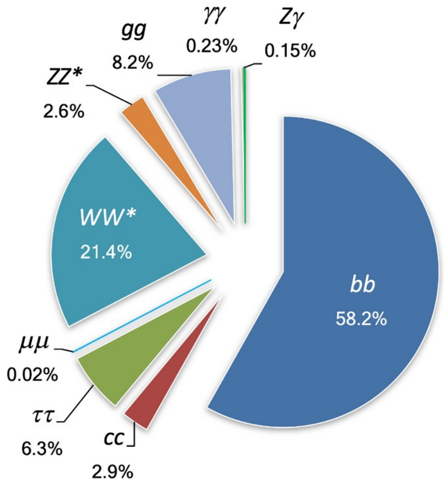
Coupling $\propto M_{Z/W}^2, \propto M_f$

M_H = 125 GeV

arXiv:1207.7214 (2012)

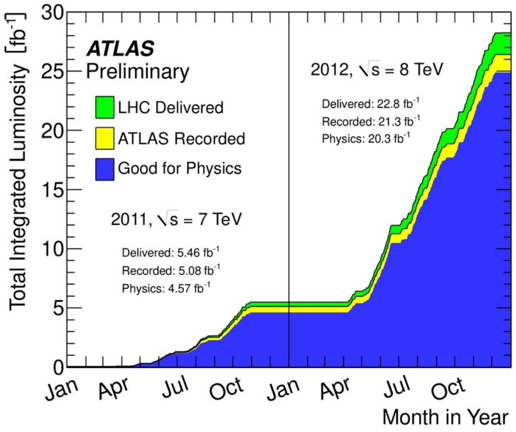
Decay modes



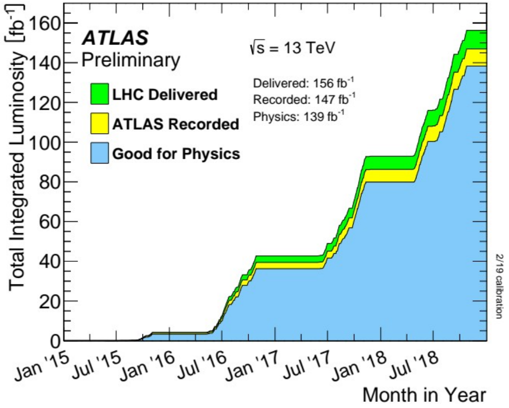


@ 13 TeV, $\sigma(pp \to H) = 57pb$ ~8M H produced during Run 2

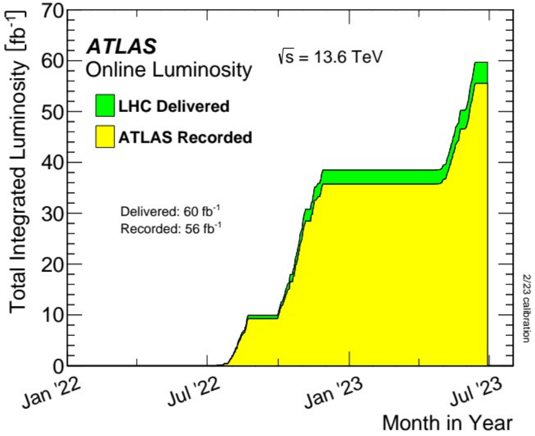
Data taking in ATLAS



Run 1, 2011-2012
- 7-8 TeV
- Higgs discovery



Run 2, 2015-2018
- 13 TeV
- Higgs couppling precision measurements in multiple channels
- Up to 50% better signal sensitivities than those expected from simple increase in data



Run 3, 2022-
- 13.6 TeV
- Data taking ongoing

Recent Higgs coupling measurements in ATLAS

$\sqrt{s}$= 13 TeV

ggF H$\rightarrow$WW*$\rightarrow e\nu\mu\nu$	Fiducial $d\sigma$	arXiv:2301.06822
VBF H$\rightarrow$WW*$\rightarrow e\nu\mu\nu$	Fid. $d\sigma, \sigma,$ SMEFT	arXiv:2304.03053
(VBF + ggF)$\rightarrow$WW*$\rightarrow e\nu\mu\nu$	Full σ, STXS	arXiv:2207.00338
VH H$\rightarrow$WW*$\rightarrow(l\nu l\nu+l\nu jj)$	Full σ	ATLAS-CONF-2022-067
HZZ* $\rightarrow 4l$ + H$\rightarrow\gamma\gamma$	Full $d\sigma, \sigma, \kappa$	arXiv:2207.08615
H$\rightarrow$cc	κ	arxiv:2201.11428v4

$\sqrt{s}$= 13.6 TeV

HZZ* $\rightarrow 4l$ + H$\rightarrow\gamma\gamma$	Fiducial & Full σ	arXiv:2306.11379

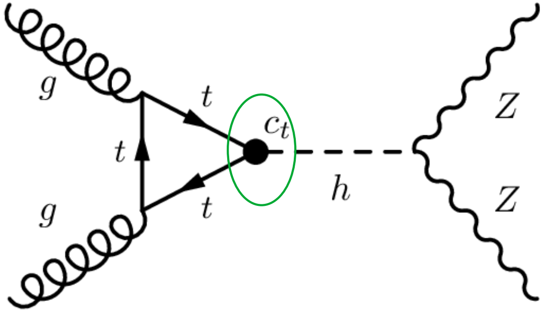
Combinations & interpretations	Combined SMEFT interpretation	ATL-PHYS-PUB-2022-037
	Combined measurement of Full $\sigma, STXS, \kappa$	Nature 607, 52-59 (2022)
	SMEFT constraints from H*$\rightarrow ZZ\rightarrow(4l+2l2\nu)$	ATL-PHYS-PUB-2023-012

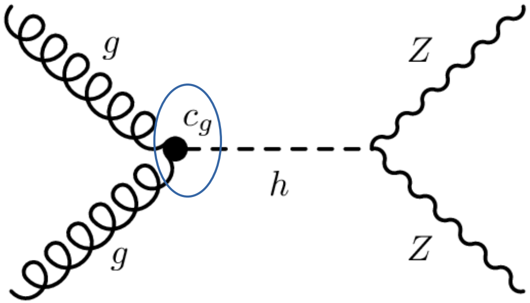
EFT interpretation
off-shell ggF $H \to ZZ \to (4l + 2l2\nu)$

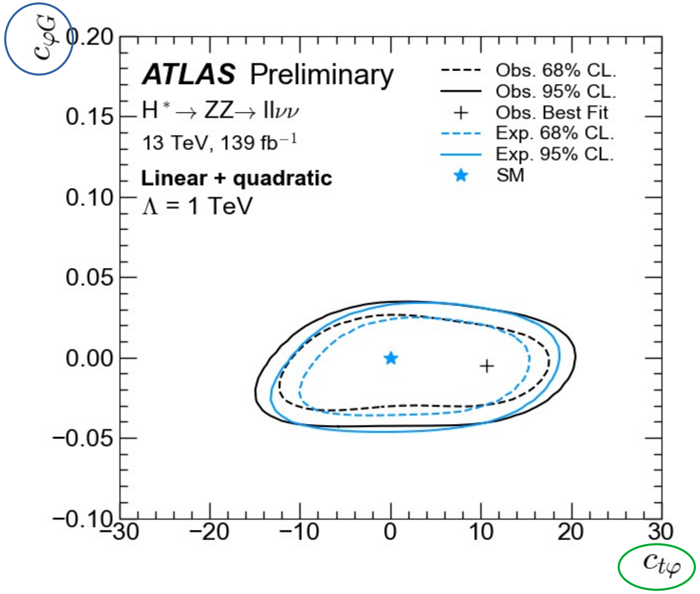
Off- shell Higgs removes c_g, c_t degeneracy:

ATL-PHYS-PUB-2023-012

$$\frac{\sigma^{\text{SMEFT}}(c_t, c_g)}{\sigma^{\text{SM}}} \simeq (c_t + c_g)^2 \left(1 - \frac{7}{15}\frac{c_g}{c_t + c_g}\frac{m_H^2}{4m_t^2}\right)$$







$c_{\varphi G}, c_{t\varphi}$ - coeffs. In Warsaw basis

Differential Cross Sections
Sensitivity of Some Observables

- p_T^H – at low values, sensitive to non-perturbative QCD effects, at high values sensitive to perturbative QCD calculations + BSM contributions
- $|y_H|$ - sensitive to PDFs
- $N_{\mathrm{jets}}, p_T^{j0}$ – probe theoretical modeling of high pT QCD radiation in higgs production, sensitive to H production process
- $|y_{j0}|$ - probes theoretical modeling of hard gluon and quark emission
- $cos\theta^*$ - sensitive to spin structure of produced diparticle pairs

Combination Details

Nature 607, 52-59 (2022)

Analyses used in combination

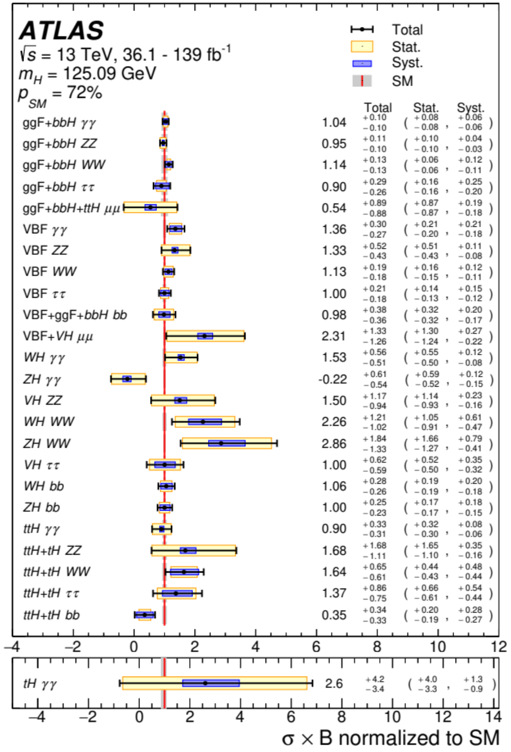
Decay mode	Targeted production processes	$\mathcal{L}$ [fb^{-1}]	Fits deployed in
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139	All
$H \to ZZ$	ggF, VBF, $WH+ZH, t\bar{t}H+tH$	139	All
	$t\bar{t}H+tH$ (multilepton)	36.1	All but fit of kinematics
$H \to WW$	ggF, VBF	139	All
	WH, ZH	36.1	All but fit of kinematics
	$t\bar{t}H+tH$ (multilepton)	36.1	All but fit of kinematics
$H \to Z\gamma$	inclusive	139	All but fit of kinematics
$H \to b\bar{b}$	WH, ZH	139	All
	VBF	126	All
	$t\bar{t}H+tH$	139	All
	inclusive	139	Only for fit of kinematics
$H \to \tau\tau$	ggF, VBF, $WH+ZH, t\bar{t}H+tH$	139	All
	$t\bar{t}H+tH$ (multilepton)	36.1	All but fit of kinematics
$H \to \mu\mu$	ggF $+ t\bar{t}H + tH$, VBF $+ WH + ZH$	139	All but fit of kinematics
$H \to c\bar{c}$	$WH+ZH$	139	Only for free-floating κ_c
$H \to$ invisible	VBF	139	κ models with $B_{\text{u.}}$ & $B_{\text{inv.}}$
	ZH	139	κ models with $B_{\text{u.}}$ & $B_{\text{inv.}}$

Likelihood

$$L(\boldsymbol{\alpha}, \boldsymbol{\theta}, \text{data}) = \prod_{k \in \text{cat}} \prod_{b \in \text{bins}} P(n_{k,b} | n^{\text{signal}}_{k,b}(\boldsymbol{\alpha}, \boldsymbol{\theta}) + n^{\text{bkg}}_{k,b}(\boldsymbol{\theta})) \prod_{\theta \in \boldsymbol{\theta}} G(\theta),$$

$$n^{\text{signal}}_{k} = \mathcal{L}_k \sum_i \sum_f (\sigma_i B_f)(A\epsilon)^k_{if},$$

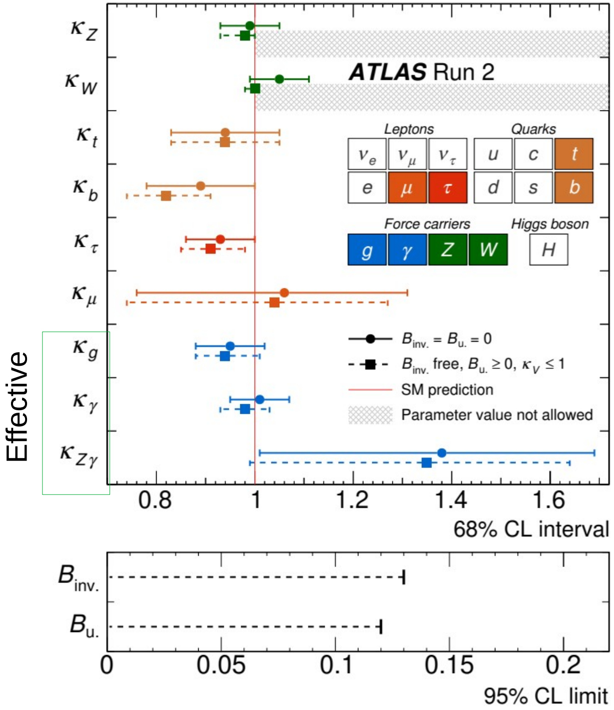
$\sigma \times B$ of each process after combination



Combination allowing BSM

Nature 607, 52-59 (2022)

HIGG-2021-23

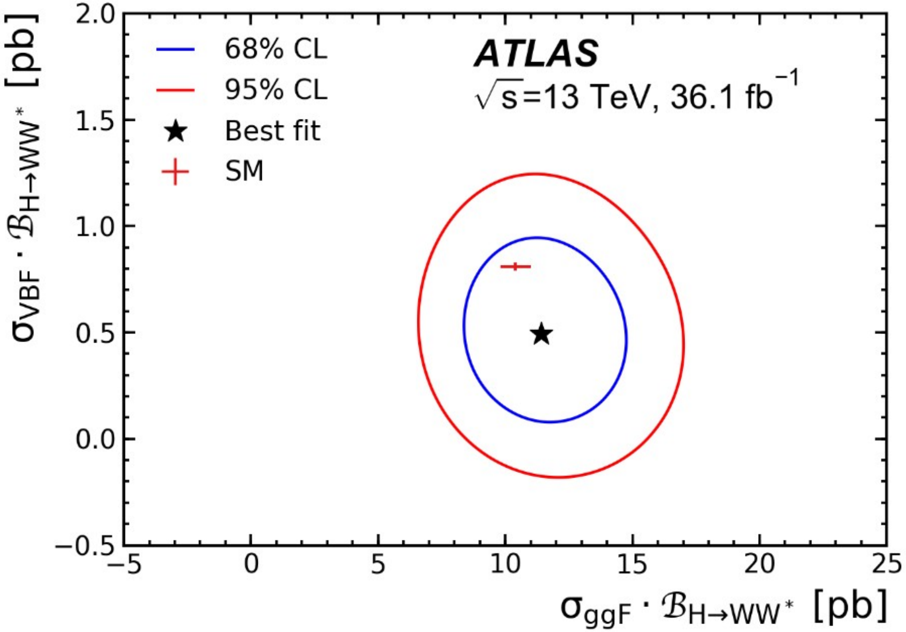


B_{inv} – Branching ratio to invisible BSM particles

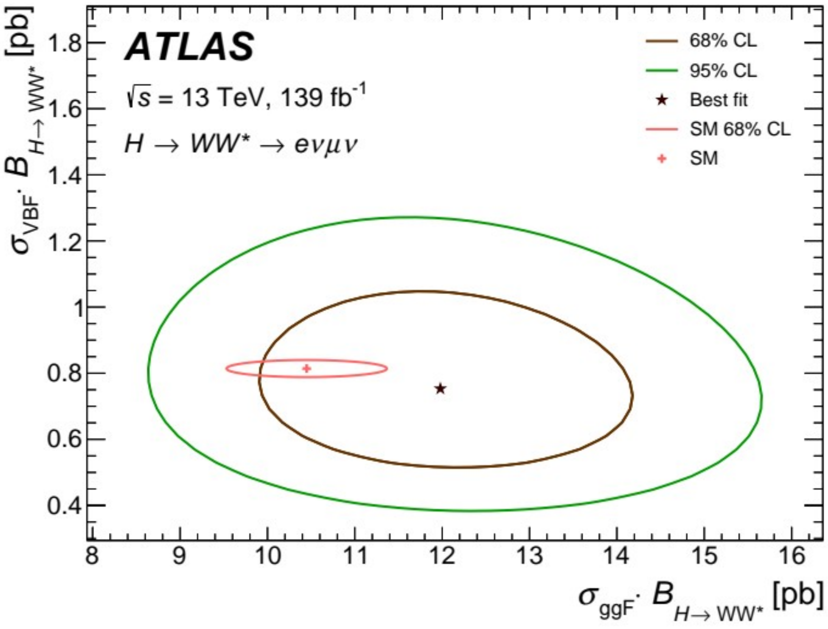
B_u – Branching ratio to BSM particles that cannot be detected due to large backgrounds

(ggF+VBF) H$\rightarrow WW^* \rightarrow e\nu\mu\nu$ improvement

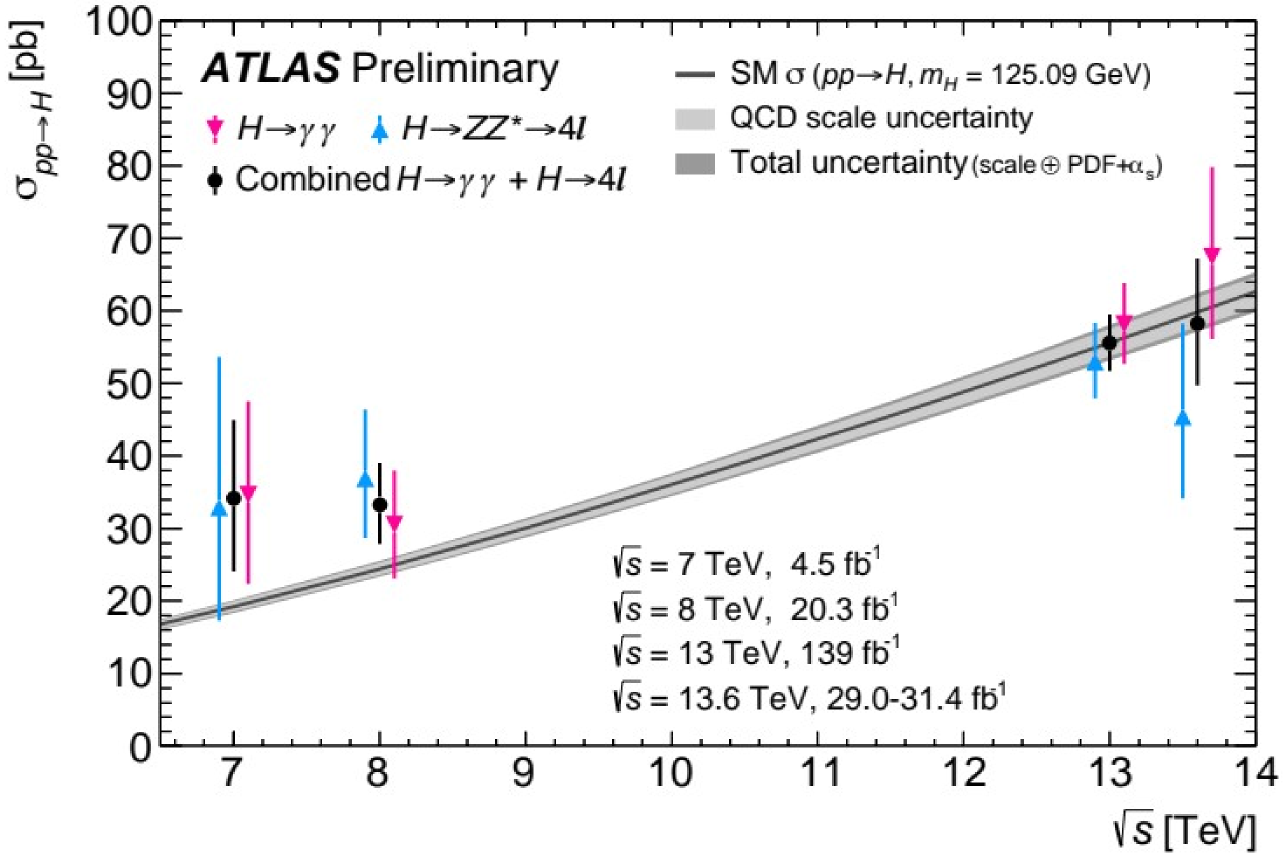
2018



2022

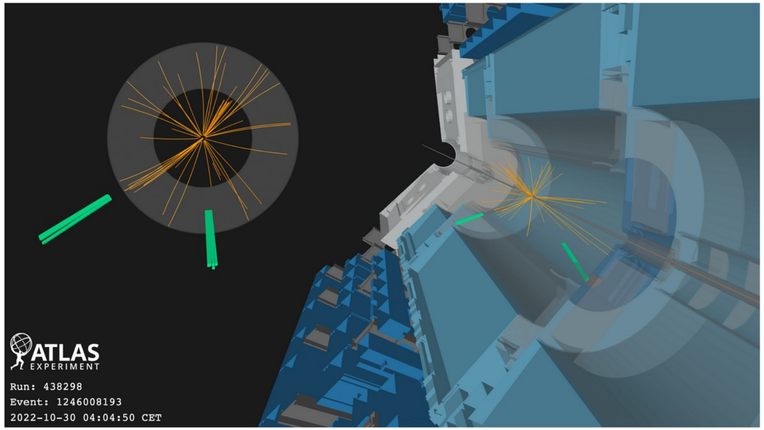


$H \to ZZ^* \to 4l + H \to \gamma\gamma$ including Run-3 result

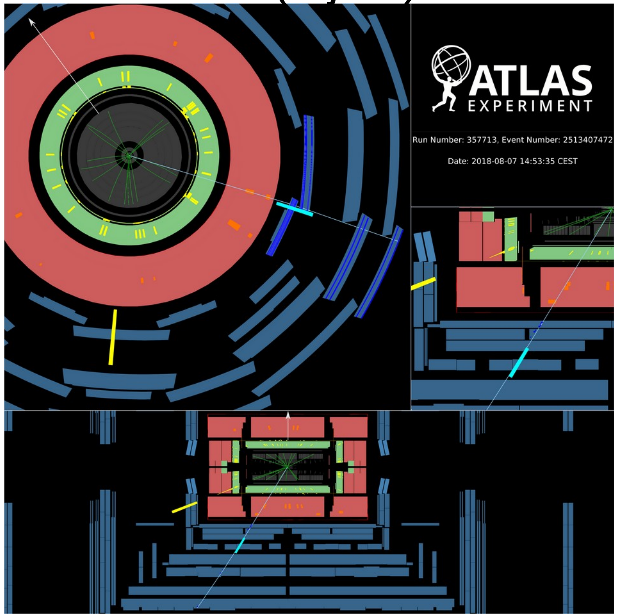


Event Displays

H$\to\gamma\gamma$ candidate



ggF H$\to WW^{*}\to e\nu\mu\nu$ Canidate (0 jets)



VBF H$\to WW^{*}\to e\nu\mu\nu$ canidate