Measurement of Higgs boson differential and fiducial cross sections with the ATLAS detector

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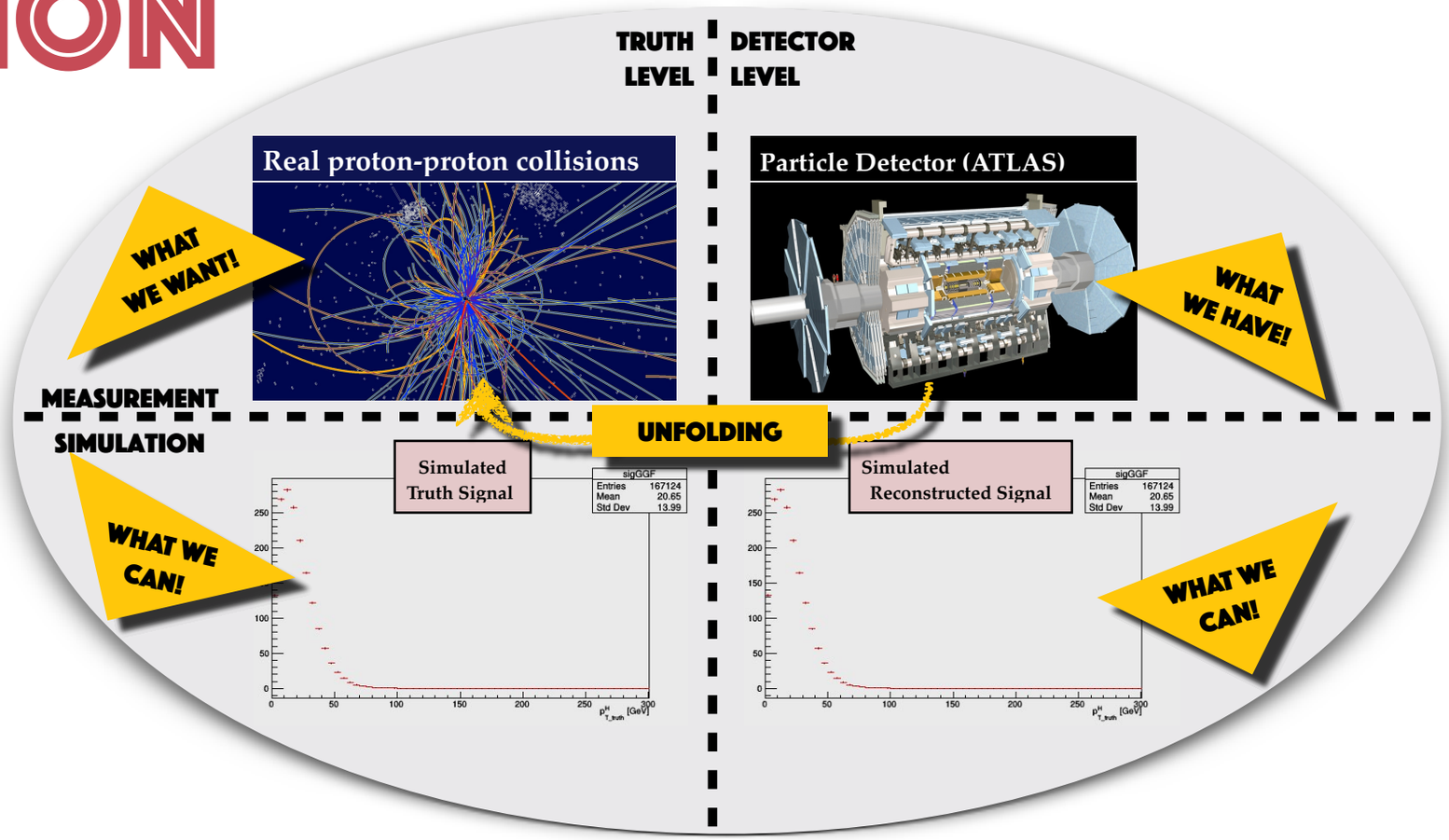
INTRODUCTION

The Higgs Boson has been discovered in 2012 by both ATLAS and CMS experiments at the LHC, CERN.

- **What after that?**
  - ✦ **precise measurements** of the properties of the Higgs Boson.
  - ✦ investigate new methods to probe SM predictions and to test for the presence of **new physics**.



Differential and fiducial cross sections of Higgs Bosons in different production and decay channels:

➡ Deviations of Higgs properties from SM.

➡ Enhance sensitivity to BSM (Beyond SM) effects.

➡ Effects of higher-order corrections in perturbative theory.

➡ Provide constraints on different couplings.

➡ Different Higgs properties probed via different variables.

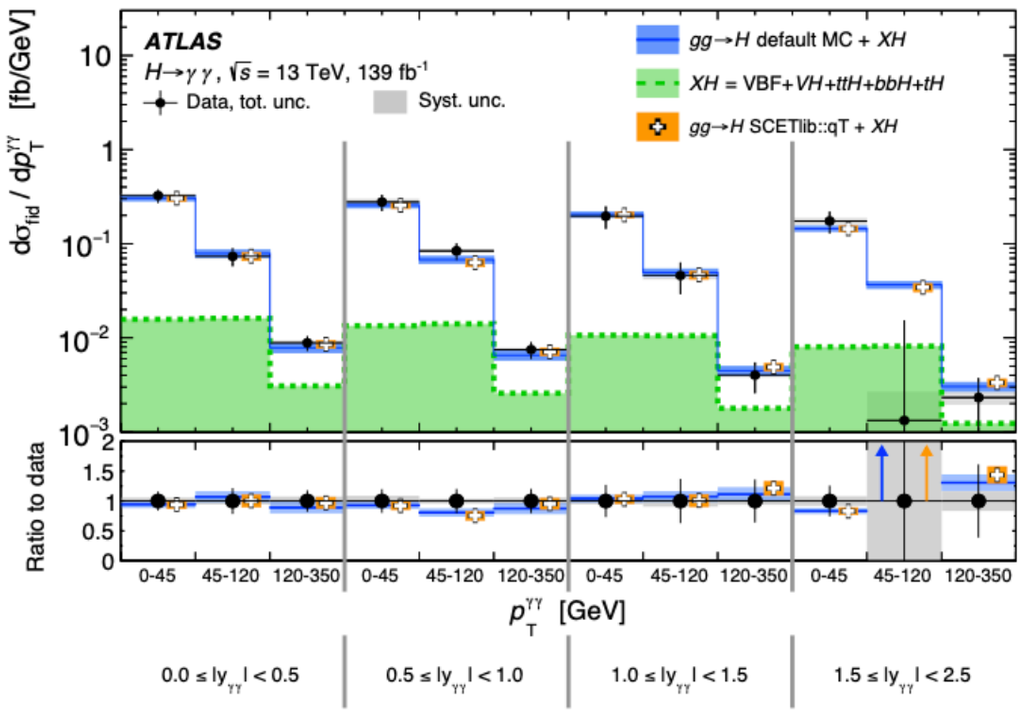
$H \rightarrow \gamma\gamma$

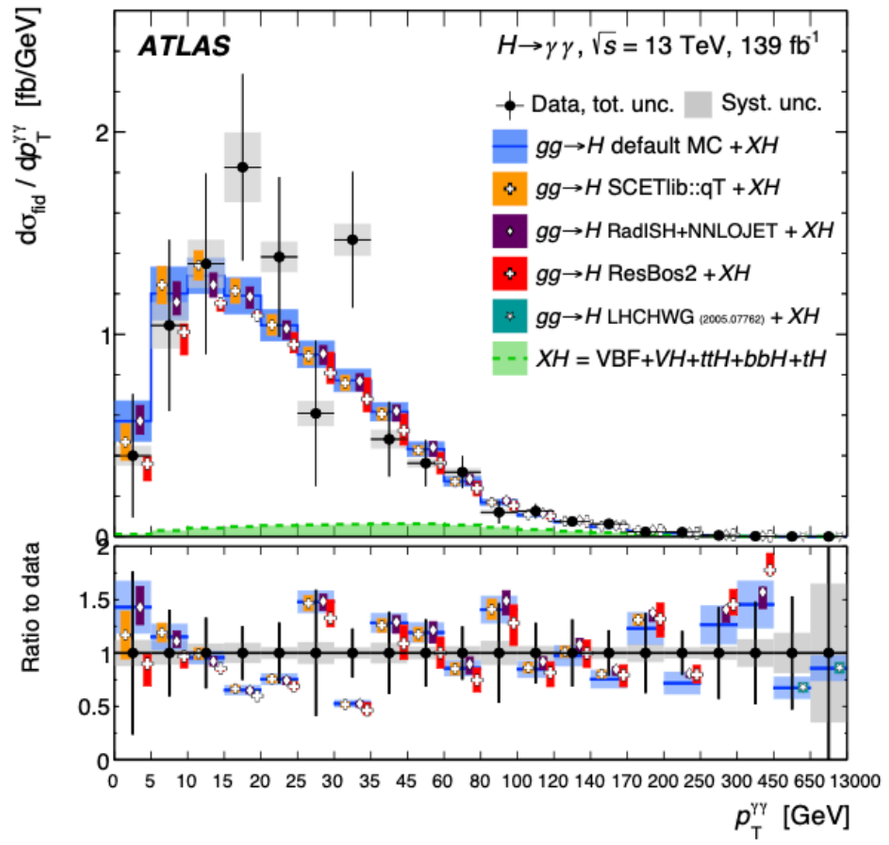
- Inclusive fiducial cross section: $\sigma_{\text{fid}} = 67 \pm 5\ (\text{stat.}) \pm 4\ (\text{sys.})\ \text{fb}$ $\quad \sigma_{\text{fid,SM}} = 64 \pm 4\,\text{fb}$
- Differential fiducial cross sections:
  - 20 differential cross-sections and 4 double-differential cross-sections in inclusive diphoton fiducial region.
  - 4 differential cross-sections and 1 double-differential cross-section in VBF-enhanced region.
  - Different variables sensitive to:
    - Higgs boson production kinematics,
    - jet kinematics,
    - spin, and CP quantum numbers of the Higgs Boson,
    - VBF kinematics and CP properties.
- New measurement of the cross-section in the high $p_T^{\gamma\gamma}$ region:
  - Strongest limits to date for the Higgs boson production cross-section above 450 GeV.
- All differential cross-sections compared with various SM predictions: No significant deviations found.

arxiv:2202.00487

Variable
$p_{\text{T}}^{\gamma\gamma}$
$\lvert y_{\gamma\gamma}\rvert$
$p_{\text{T}}^{\gamma 1}/m_{\gamma\gamma}$
$p_{\text{T}}^{\gamma 2}/m_{\gamma\gamma}$
N_{jets}
$N_{b\text{-jets}}$
$p_{\text{T}}^{j_1}$
H_{T}
$p_{\text{T}}^{\gamma\gamma j}$
$m_{\gamma\gamma j}$
$\tau_{C,j1}$
$\sum \tau_{C,j}$
$p_{\text{T}}^{\gamma\gamma}$, jet veto 30 GeV
$p_{\text{T}}^{\gamma\gamma}$, jet veto 40 GeV
$p_{\text{T}}^{\gamma\gamma}$, jet veto 50 GeV
$p_{\text{T}}^{\gamma\gamma}$, jet veto 60 GeV
m_{jj}
$\Delta\phi_{jj}$
$\pi - \lvert\Delta\phi_{\gamma\gamma,jj}\rvert$
$p_{\text{T},\gamma\gamma jj}$
VBF-enhanced: $p_{\text{T}}^{j_1}$
VBF-enhanced: $\Delta\phi_{jj}$
VBF-enhanced: $\lvert\eta^*\rvert$
VBF-enhanced: $p_{\text{T},\gamma\gamma jj}$
$p_{\text{T}}^{\gamma\gamma}$ vs $\lvert y_{\gamma\gamma}\rvert$
$(p_{\text{T}}^{\gamma 1} + p_{\text{T}}^{\gamma 2})/m_{\gamma\gamma}$ vs $(p_{\text{T}}^{\gamma 1} - p_{\text{T}}^{\gamma 2})/m_{\gamma\gamma}$
$p_{\text{T}}^{\gamma\gamma}$ vs $p_{\text{T}}^{\gamma\gamma j}$
$p_{\text{T}}^{\gamma\gamma}$ vs $\tau_{C,j1}$
VBF-enhanced: $p_{\text{T}}^{j_1}$ vs $\Delta\phi_{jj}$

$H \rightarrow \gamma\gamma$



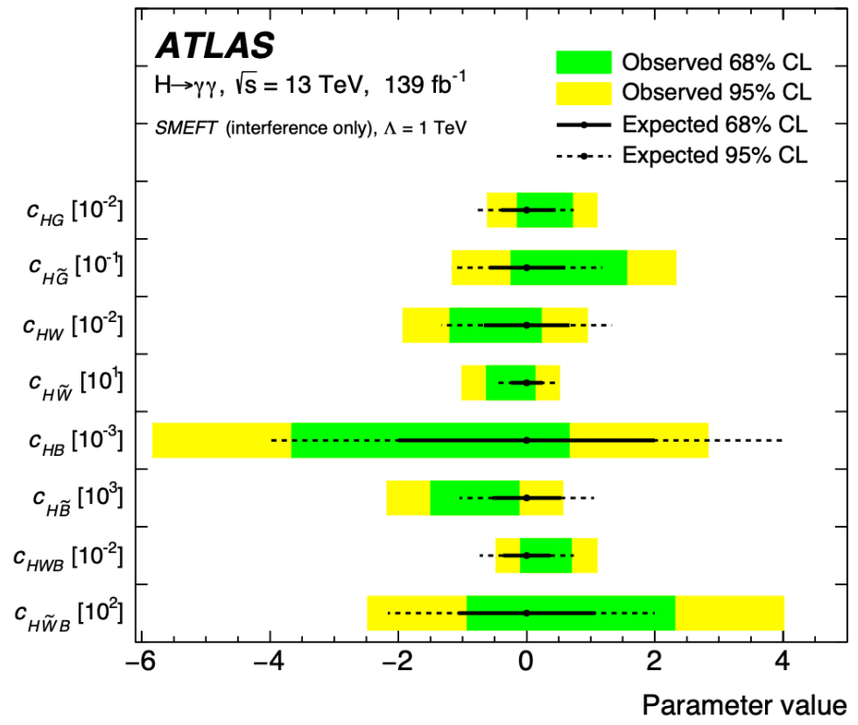


Limits on SMEFT Wilson coefficients using SM and dimension-6 operators interference-only terms

Interpretations:

1. Measured transverse momentum distribution of the Higgs boson is used as an indirect probe of the Yukawa coupling of the Higgs boson to the bottom and charm quarks.
   - 95% CL allowed range [−3.7, 10.4] for κ_b, and [−13.0, 18.9] for κ_c, using only the shape of transverse momentum distribution.

2. Strength and tensor structure of the Higgs boson interactions investigated using 5 variables in the effective field theory framework:
   $p_{\mathrm{T}}^{\gamma\gamma}$, N_{jets}, m_{jj}, $\Delta\phi_{jj}$ and $p_{\mathrm{T}}^{j_1}$
   - Constrain anomalous Higgs boson couplings to vector bosons in the Standard Model effective field theory framework.



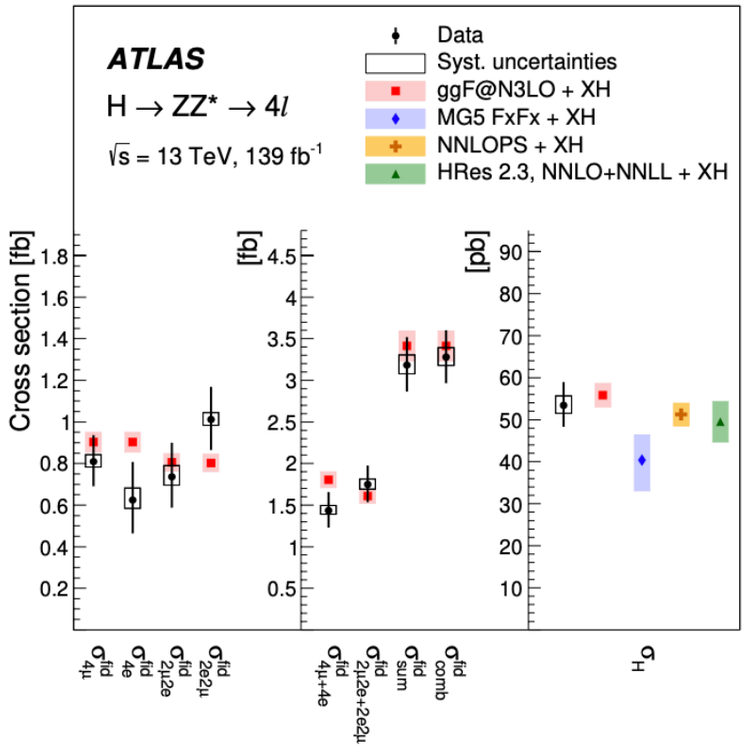
More Interpretations in combination with $H\rightarrow ZZ^*\rightarrow 4l$ on slide 8!

$H \rightarrow ZZ^* \rightarrow 4l$

VBF–enriched region	Signal for cross-section estimates	Purity of VBF signal	Expected cross-section [fb]	Observed cross-section [fb]
$N_{\text{jets}} \geq 2$, $m_{jj} \geq 400$ GeV	All production modes	59 %	$0.134^{+0.065\ +0.014}_{-0.053\ -0.012}$	$0.215^{+0.075\ +0.016}_{-0.063\ -0.013}$
$\lvert\Delta\eta_{jj}\rvert \geq 3.0$	VBF $+VH$ $+ttH$	95 %	$0.088^{+0.063\ +0.017}_{-0.053\ -0.020}$	$0.172^{+0.072\ +0.016}_{-0.062\ -0.018}$

- Same-flavour opposite-charge (SFOC) lepton pairs selected to form Higgs boson candidates.
- All major background processes estimated from data.
- Inclusive fiducial cross section: $\sigma_{\text{fid}} = 3.28 \pm 0.30\ (\text{stat.}) \pm 0.11\ (\text{syst.})$ fb

  $\sigma_{\text{fid,SM}} = 3.41 \pm 0.18$ fb
- Differential fiducial cross sections measured for a variety of observables sensitive to the production and decay of the Higgs boson.
- Signal events are corrected for detector measurement inefficiency and resolution by unfolding using the detector response matrix in the likelihood fit.
- Unfolding matrix used is well conditioned and no regularisation is required.
- An inclusive cross section in a VBF fiducial phase space is also measured.
- All measurements in agreement with the SM predictions.

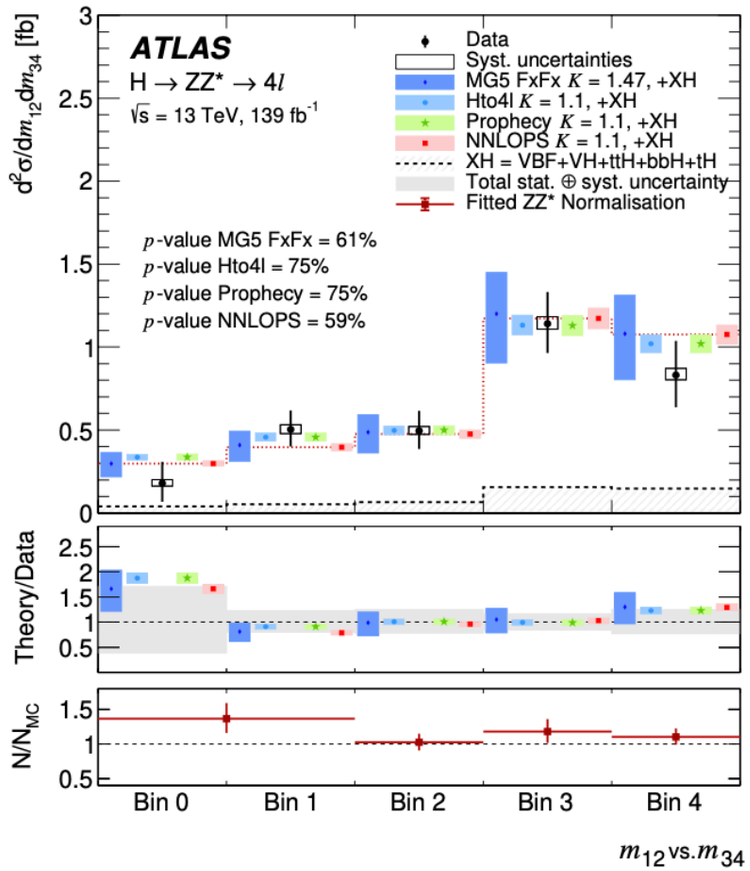


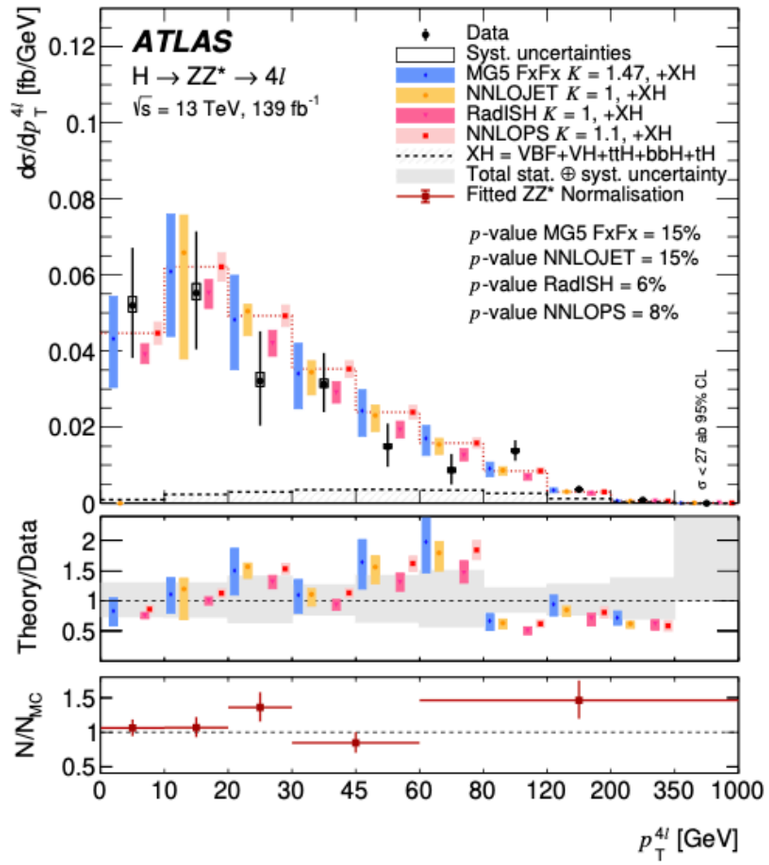
$p_{\text{T}}^{4\ell}$, $|y_{4\ell}|$
m_{12}, m_{34}
$|\cos\theta^*|$
$\cos\theta_1$, $\cos\theta_2$
ϕ, ϕ_1
$p_{\text{T}}^{4\ell\text{j}}$, $m_{4\ell j}$
$p_{\text{T}}^{4\ell\text{jj}}$, $m_{4\ell jj}$
N_{jets}, $N_{b\text{-jets}}$
$p_{\text{T}}^{\text{lead. jet}}$, $p_{\text{T}}^{\text{sublead. jet}}$
m_{jj}, $|\Delta\eta_{jj}|$, $\Delta\phi_{jj}$
m_{12} vs. m_{34}, $p_{\text{T}}^{4\ell}$ vs. $|y_{4\ell}|$
$p_{\text{T}}^{4\ell}$ vs. N_{jets}, $p_{\text{T}}^{4\ell}$ vs. $p_{\text{T}}^{4\ell\text{j}}$
$p_{\text{T}}^{\text{lead. jet}}$ vs. $p_{\text{T}}^{\text{sublead. jet}}$
$p_{\text{T}}^{4\ell\text{j}}$ vs. $m_{4\ell\text{j}}$
$p_{\text{T}}^{\text{lead. jet}}$ vs. $|y^{\text{lead. jet}}|$

arxiv:2004.03969

$H \rightarrow ZZ^* \rightarrow 4l$

Results used to constrain anomalous Higgs boson interactions with SM particles:

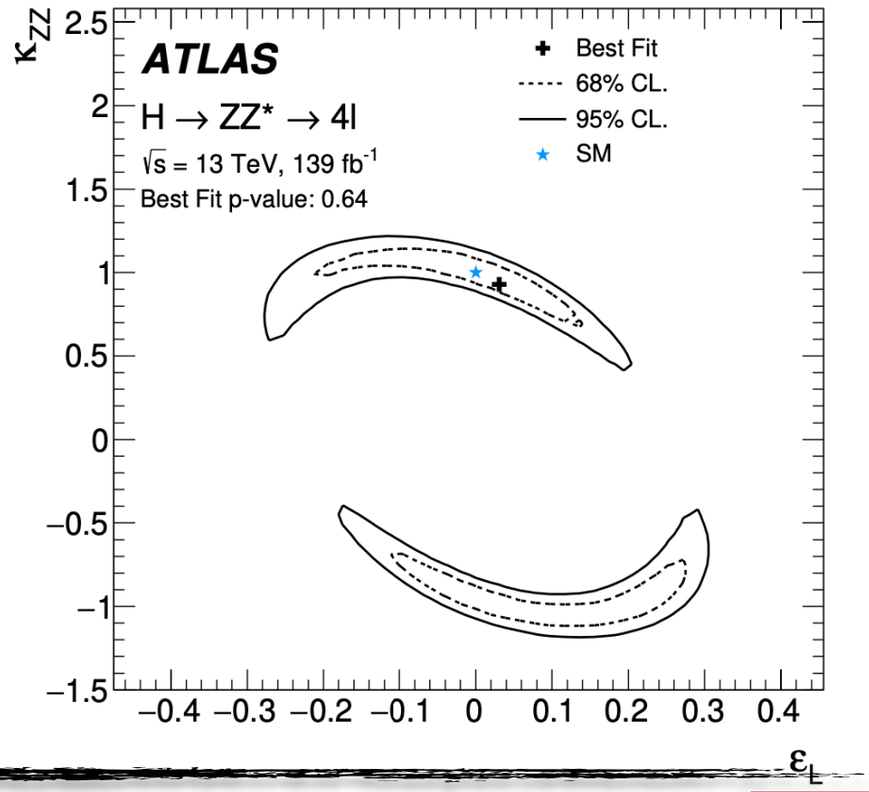




1. m_{12} vs. m_{34} double differential cross section used to probe several BSM scenarios within the framework of pseudo-observables
   - new and more stringent constraints on BSM scenarios where contact term interactions in the $H \rightarrow 4l$ amplitudes are set.

2. p^{4l} differential cross section used to constrain the Yukawa couplings of the Higgs boson with the *b*- and *c*-quarks
   - values of κ_c outside the range $\kappa_c \in [-12, +11]$ are excluded at 95% CL.

Observed limits on the modified Higgs boson decays within the linear EFT-inspired framework of the pseudo-observables



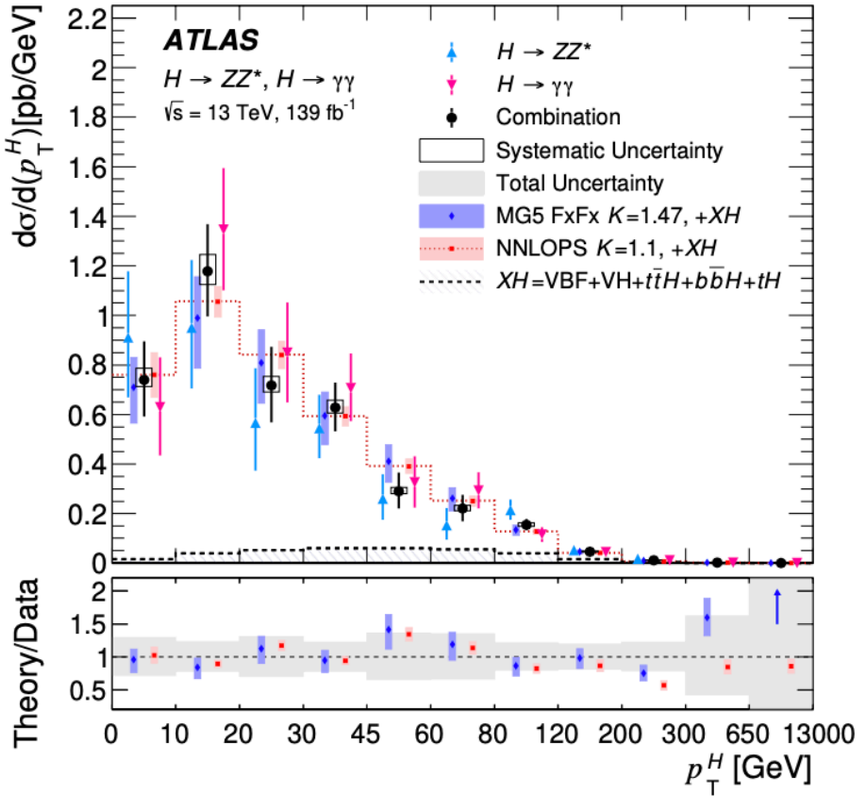
Combined $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$

- Measurements are extrapolated to the full phase space and the measured cross-sections are compared with SM predictions.
- Additional systematic uncertainties introduced by the extrapolation to the full phase space are counterbalanced by a significant reduction of the statistical uncertainty of the measurement (main limitation to the precision of the measurements in the individual decay channels).
- Total Higgs boson production cross-section: $55.5^{+4.0}_{-3.8}$ pb $(\pm 3.2(\text{stat.})\ ^{+2.4}_{-2.2}(\text{syst.}))$

$\sigma_{\text{fid,SM}} = 55.6 \pm 2.8$ pb

- Differential cross-sections:
  - $|y_H|$ sensitive to perturbative QCD calculations
  - p_{T}^{H} sensitive to the parton distribution functions (PDF)
  - N_{jets} and $p_{\text{T}}^{\text{lead. jet}}$ probe the theoretical modelling of high-pT QCD radiation in Higgs boson production

All results from the two decay channels are compatible with each other, and their combination agrees with the Standard Model predictions.



arxiv:2207.08615

Combined $H \to ZZ^* \to 4l$ and $H \to \gamma\gamma$

Constraints on the b- and c-quark Yukawa couplings

1. Constraints from the Higgs boson transverse momentum distributions

   - A joint interpretation, in terms of the b- and c-quark Yukawa coupling strengths to the Higgs boson, of the fiducial differential cross-sections measured as a function of p_T^H

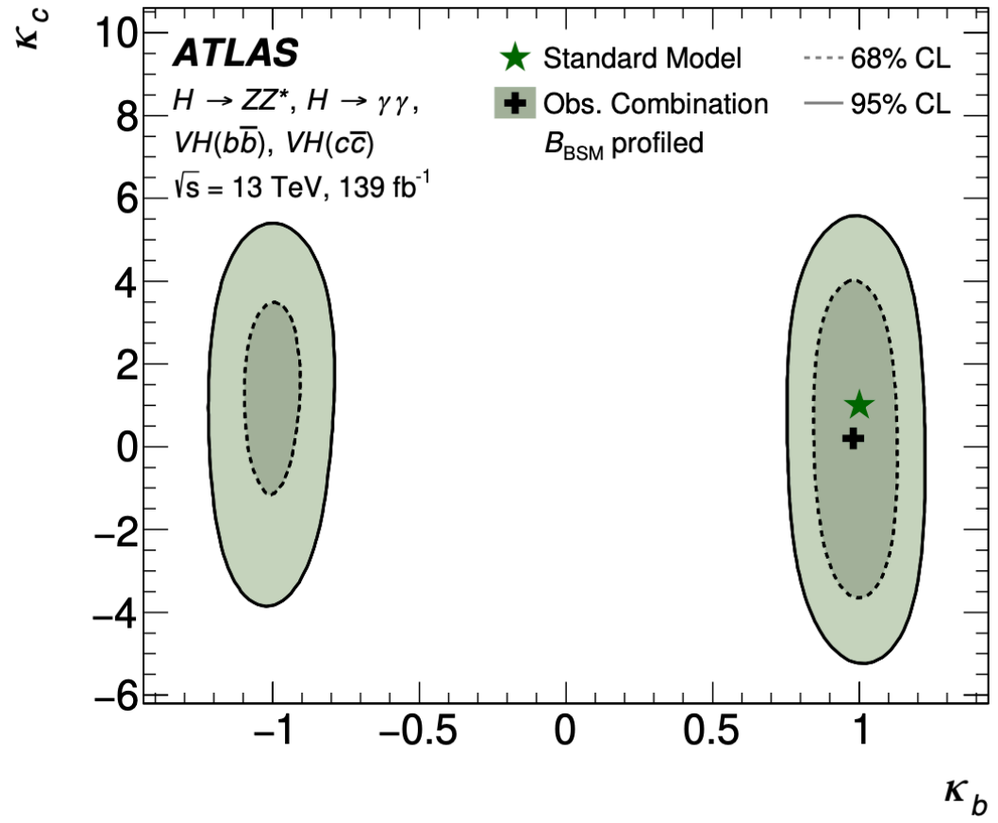
2. Combination with the constraints from $VH(b\bar{b})$ and $VH(c\bar{c})$ production

   - constraints set on the charm quark coupling modifier without any assumption on the bottom quark coupling.
   - Represent the most stringent constraints on κ_c to date in these scenarios.

Scenario	Observed 68% confidence interval	Observed 95% confidence interval
$B_{\text{BSM}} = 0$	$[-1.61, 1.70]$	$[-2.47, 2.53]$
No assumption on B_{BSM}	$[-2.63, 3.01]$	$[-4.46, 4.81]$

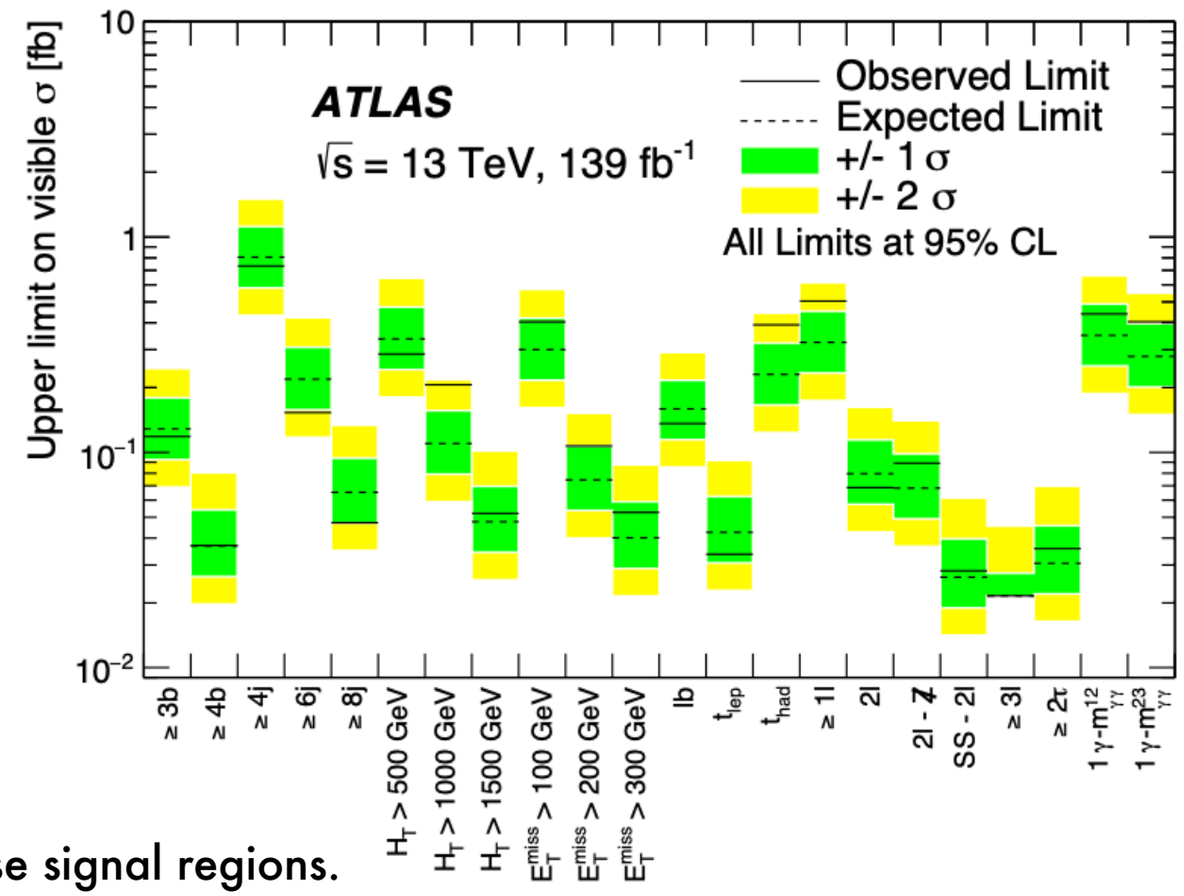
Assuming SM values of other couplings (κ)

	Parameter	Observed 95% confidence interval	Expected 95% confidence interval
p_T^H shape and normalisation	κ_b	$[-1.09, -0.86] \cup [0.81, 1.09]$	$[-1.14, -0.92] \cup [0.86, 1.15]$
	κ_c	$[-2.27, 2.27]$	$[-2.77, 2.75]$
p_T^H shape	κ_b	$[-2.0, 7.4]$	$[-2.0, 7.4]$
	κ_c	$[-8.6, 17.3]$	$[-8.5, 15.9]$



$H \rightarrow \gamma\gamma + X$

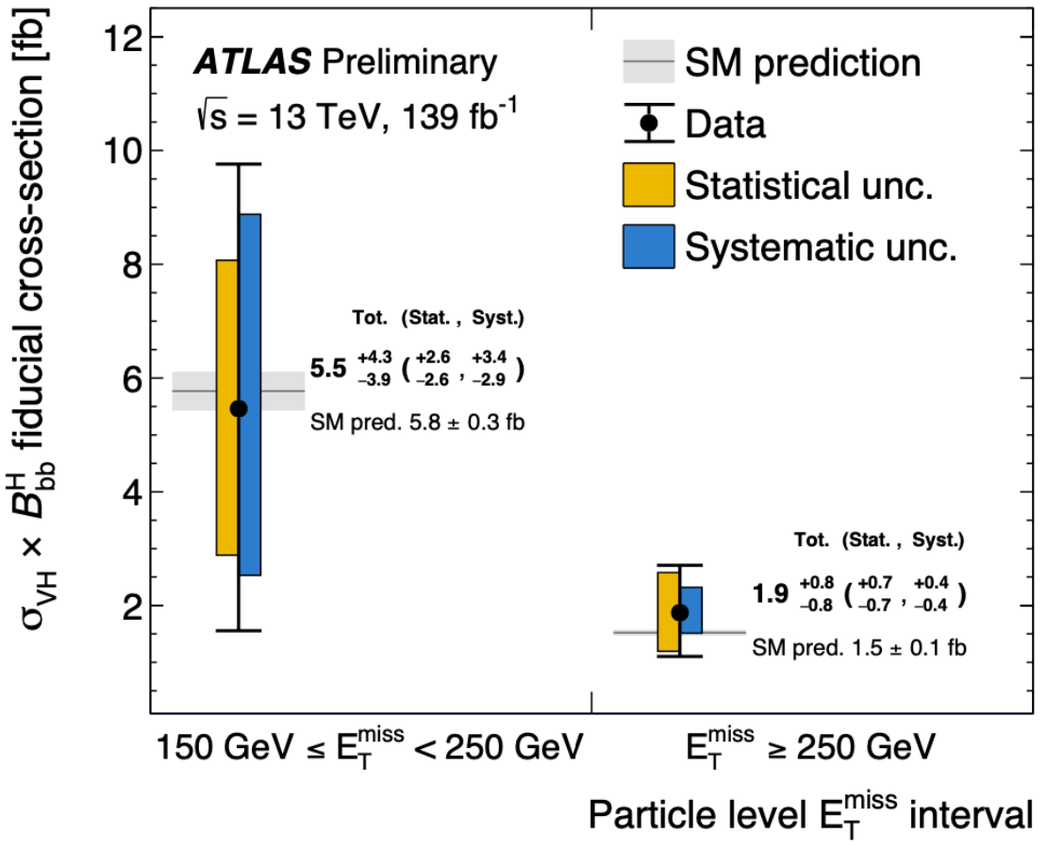
- Model-independent search for new physics leading to final states containing $H \rightarrow \gamma\gamma$ decays.
- Search examines 22 final states categorized by the objects that are produced in association with the Higgs boson.
- Objects include
  - isolated electrons or muons,
  - hadronically decaying τ-leptons,
  - additional photons,
  - missing transverse momentum,
  - hadronic jets, as well as jets that are tagged as containing a b-hadron.



- No significant excesses above Standard Model expectations are observed.
- Upper limits at 95% CL were set on the visible cross section of BSM Higgs boson production in each of these signal regions.
- Set of detector efficiency factors evaluated:
  - Enables interpretation of the results as a constraint on other models.

$H(\mathrm{bb}) + E_{\mathrm{T}}^{\mathrm{miss}}$

- First measurement of the fiducial cross-section of VH production (V=W,Z) in final states with missing transverse momentum where $H \rightarrow$ bb.
- Cross-sections are reported for two intervals of missing transverse momentum, $150 \leq E_T^{miss} < 250$ GeV and $E_T^{miss} \geq 250$ GeV.
- Results complement current cross-section measurements performed in the STXS framework, and provide a new way to probe $H \rightarrow b\bar{b}$ decays.
- Measured fiducial cross section are in agreement with the SM expectations.



$150 \leq E_T^{miss} < 250$ GeV bin: $5.5 \pm 2.6\,(\mathrm{stat.}) \pm 3.2\,(\mathrm{syst.})$ fb

$E_T^{miss} \geq 250$ GeV bin: $1.9 \pm 0.7\,(\mathrm{stat.}) \pm 0.4\,(\mathrm{syst.})$ fb

ATLAS-CONF-2022-015

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

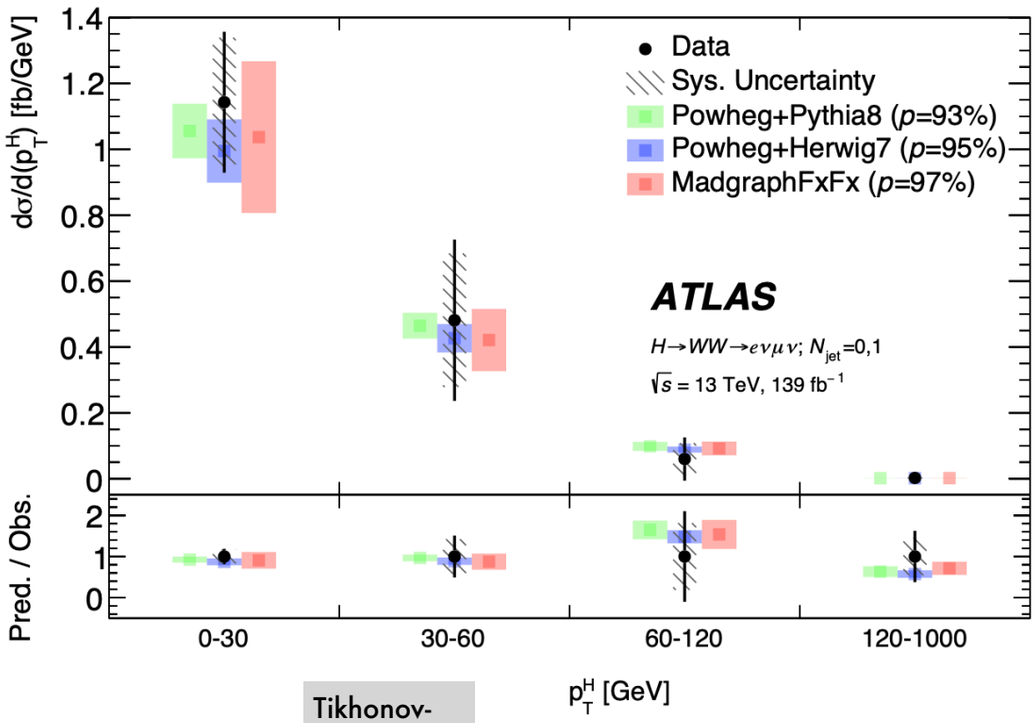
- Differential cross sections are measured in a fiducial phase space restricted to the production of at most one additional jet.
- Various observables in one and two-dimensions are measured which probe different properties of the Higgs Boson:
  - Higher-order QCD contributions to ggF production.
  - The spin structure and CP properties.
  - PDFs relevant for Higgs boson production.
  - Yukawa couplings of quarks and the Higgs boson.
- Signal region is defined using reconstructed objects and fiducial region is defined using particle-level objects.
- Fit is performed using the profile likelihood method.
- A signal region is defined for each bin of each observable, from which the number of signal events N_S is extracted from a fit to the data.
- A combined fit is performed in the m_T distribution in the range 80 to 160 GeV in bins of 10 GeV.

$p_{\mathrm{H}}^{\mathrm{T}}$
$M_{\ell\ell}$
$p_{\ell\ell}^{\mathrm{T}}$
$y_{\ell\ell}$
$\Delta\phi_{\ell\ell}$
$\cos\theta^*$
$p_{\ell 0}^{\mathrm{T}}$
y_{J0}
$M_{\ell\ell}$ versus N_{jet}
$p_{\ell\ell}^{\mathrm{T}}$ versus N_{jet}
$y_{\ell\ell}$ versus N_{jet}
$\Delta\phi_{\ell\ell}$ versus N_{jet}
$\cos\theta^*$ versus N_{jet}
$p_{\ell 0}^{\mathrm{T}}$ versus N_{jet}

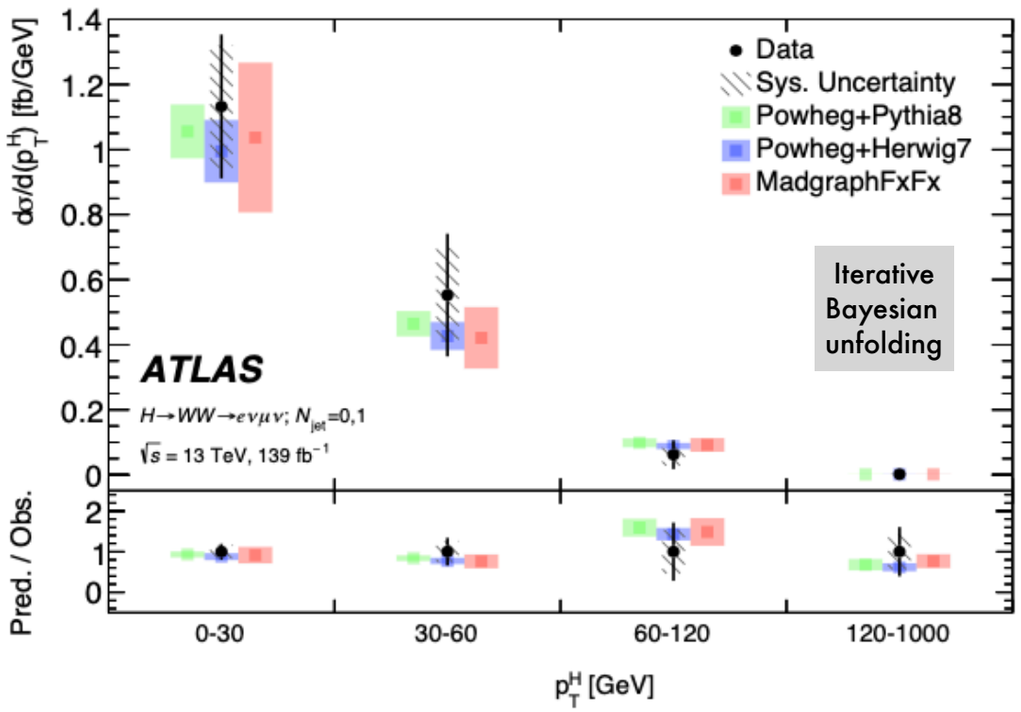
arxiv:2301.06822

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

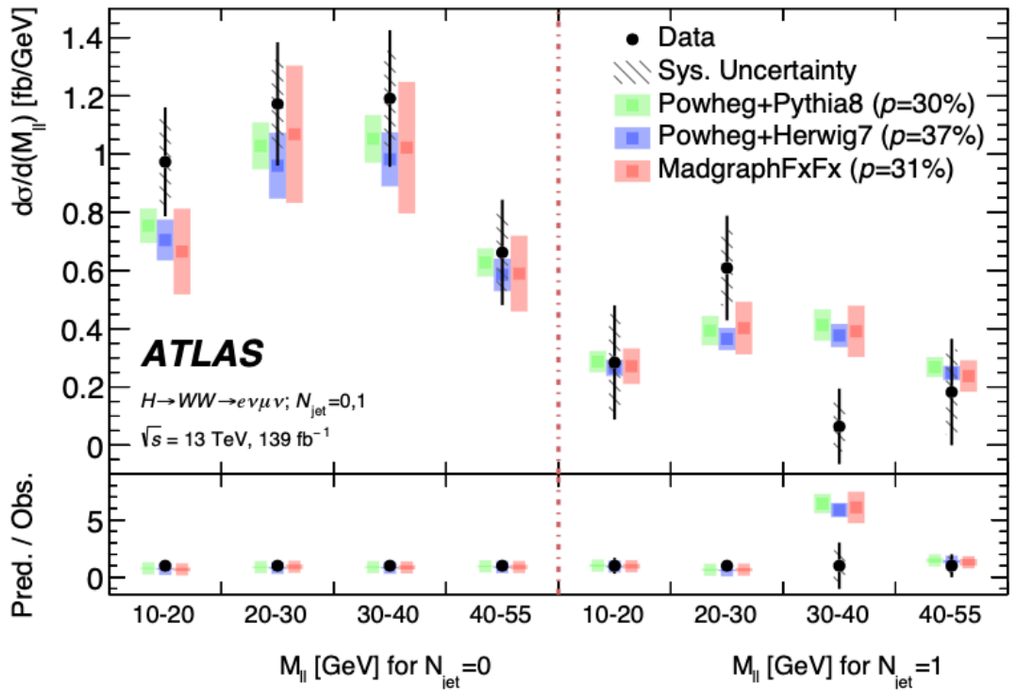
- Tikhonov-regularized in-likelihood unfolding (and Iterative Bayesian unfolding as a cross check) is used to obtain the differential distributions.
- The results are consistent with Standard Model expectations, derived using different Monte Carlo generators.



Tikhonov-regularized in-likelihood unfolding



Iterative Bayesian unfolding



VBF $H \to WW^* \to e\nu\mu\nu$

New Results!

- The cross sections are measured in a fiducial phase space.
  - Major processes extracted in data → minimisation of the background modelling uncertainties.
  - Multiple BDTs defined and trained to discriminate between signal and background processes, and BDT scores are used as templates in the fit to data.
  - Major backgrounds estimated in a simultaneous fit of the SR and CRs.

- Integrated fiducial cross section: $\sigma^{\text{fid}} = 1.68 \pm 0.40\ \text{fb} = 1.68 \pm 0.33\ (\text{stat}) \pm 0.23\ (\text{syst})\ \text{fb}$

- Differential measurements as a function of 13 variables which probe different properties of the Higgs boson:
  - Higgs boson spin, charge, parity – QCD effects – EW corrections – BSM contributions

- Fit & matrix-inversion Unfolding to particle-level performed in a single step of the Likelihood minimisation.

- The uncertainties in the differential cross-section measurements are driven by the data statistical uncertainty.

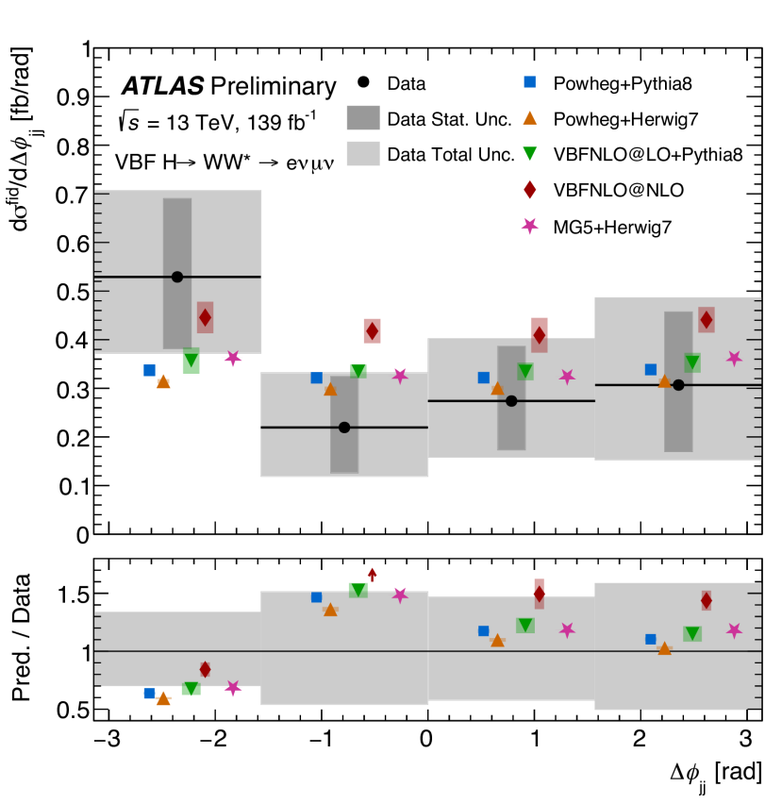
$$p_{\mathrm{T}}^{\mathrm{H}} \quad p_{\mathrm{T}}^{\ell\ell} \quad p_{\mathrm{T}}^{\ell_1} \quad p_{\mathrm{T}}^{\ell_2} \quad m_{\ell\ell} \quad |\Delta y_{\ell\ell}| \quad |\Delta\phi_{\ell\ell}| \quad \cos(\theta_{\eta}^{*})$$
$$p_{\mathrm{T}}^{\mathrm{j}_1} \quad p_{\mathrm{T}}^{\mathrm{j}_2} \quad m_{\mathrm{jj}} \quad |\Delta y_{\mathrm{jj}}| \quad \Delta\phi_{\mathrm{jj}}$$

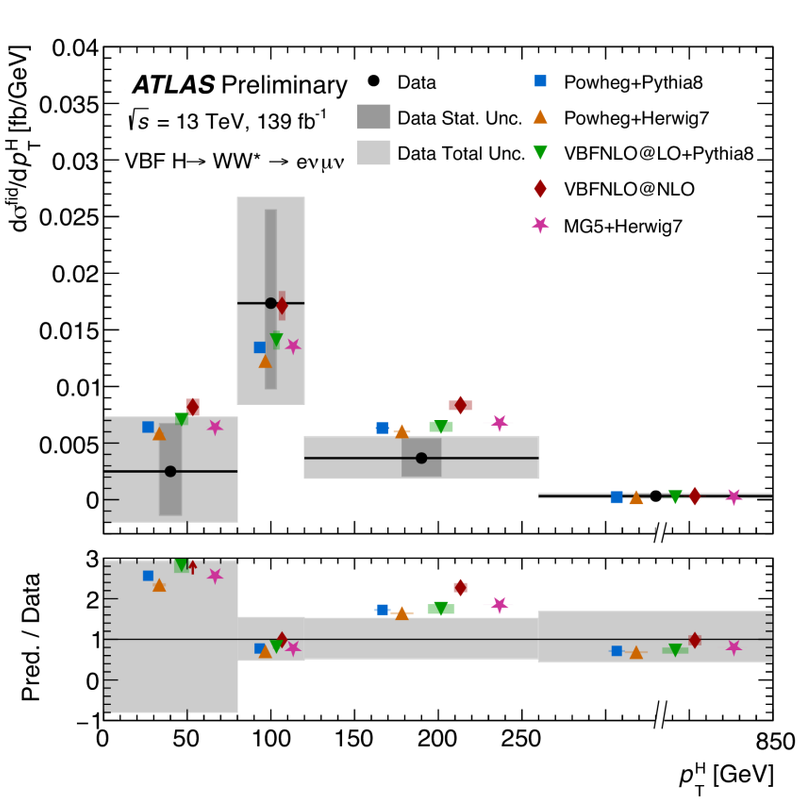
HIGG-2020-25

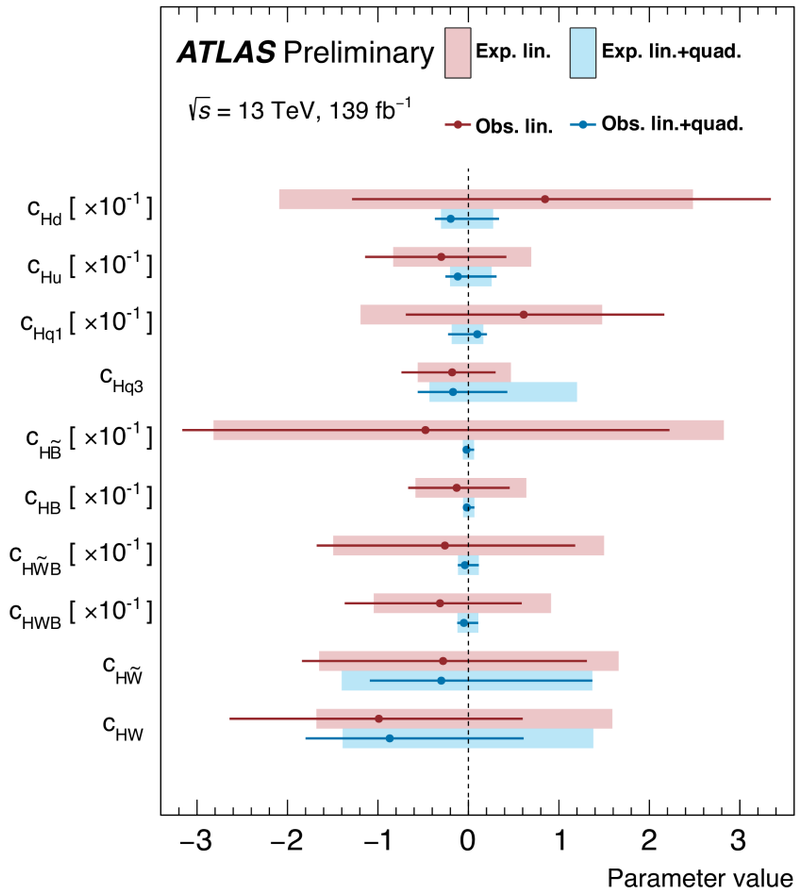
VBF $H \rightarrow WW^* \rightarrow e\nu\mu\nu$

New Results!

- Differential cross-sections are used to constrain anomalous interactions described by a dimension-six Effective Field Theory.
- Observed and expected values of SMEFT Wilson coefficients from CP-even and CP-odd operators.



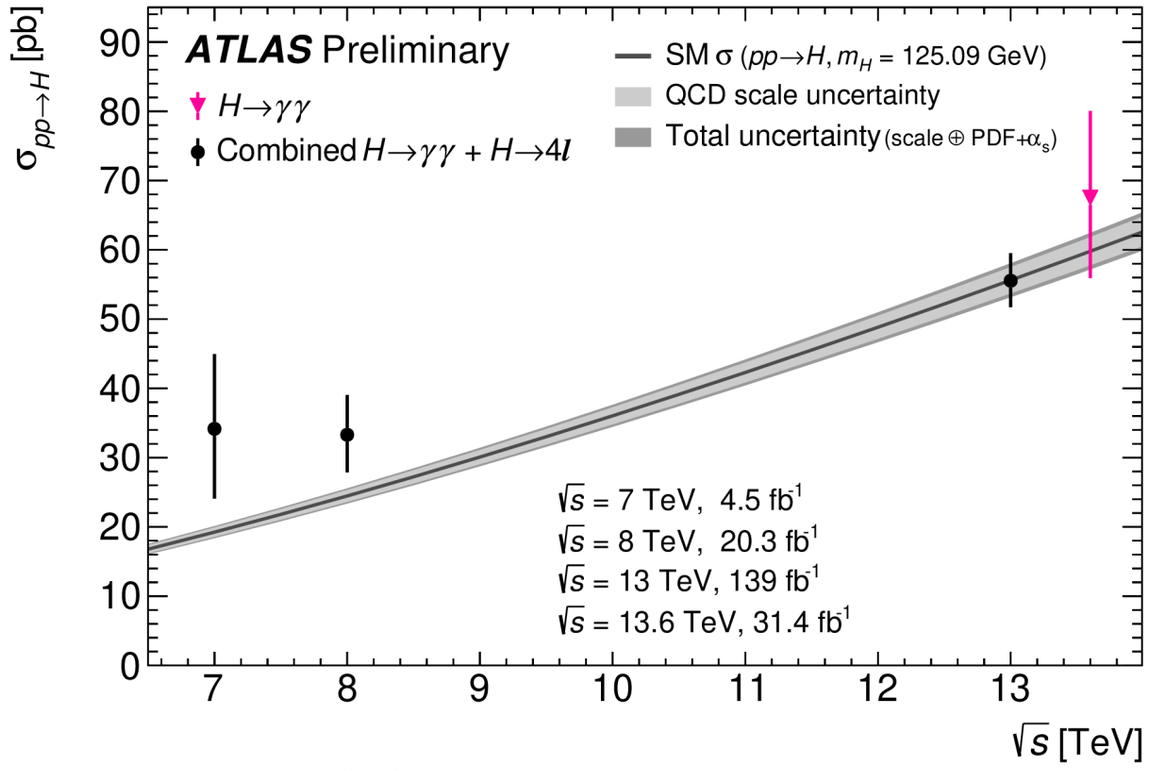




$H \rightarrow \gamma\gamma$

$\sqrt{s} = 13.6$ TeV

New Results!



- In 2022 the LHC has increased the centre-of-mass energy of the proton-proton (pp) collisions to the new world-record value of 13.6 TeV.
- About 31.4 fb^{-1} of pp collision data recorded with the ATLAS detector.
- First ATLAS measurement of the $H \rightarrow \gamma\gamma$ cross-section at this new energy.
- In order to reduce the model dependence, the measurement is restricted to a particle-level phase space matching closely the reconstruction-level photon kinematic selection, and it is corrected for detector effects:

$$\sigma_{\text{fid}}(pp \rightarrow H \rightarrow \gamma\gamma) = 76^{+14}_{-13} \text{ fb} \qquad \textbf{SM } \sigma_{\text{fid}}(pp \rightarrow H \rightarrow \gamma\gamma) = 67.5 \pm 3.4 \text{ fb}$$

- Fiducial measurement is extrapolated to the full phase space:

$$\sigma(pp \rightarrow H) = 67^{+13}_{-12} \text{ pb} \qquad \textbf{SM } \sigma(pp \rightarrow H) = 59.8 \pm 2.6 \text{ pb}$$

- These results do not show any significant deviation from the SM predictions.

ATLAS-CONF-2023-003

THANK YOU!