

PHENO 2021



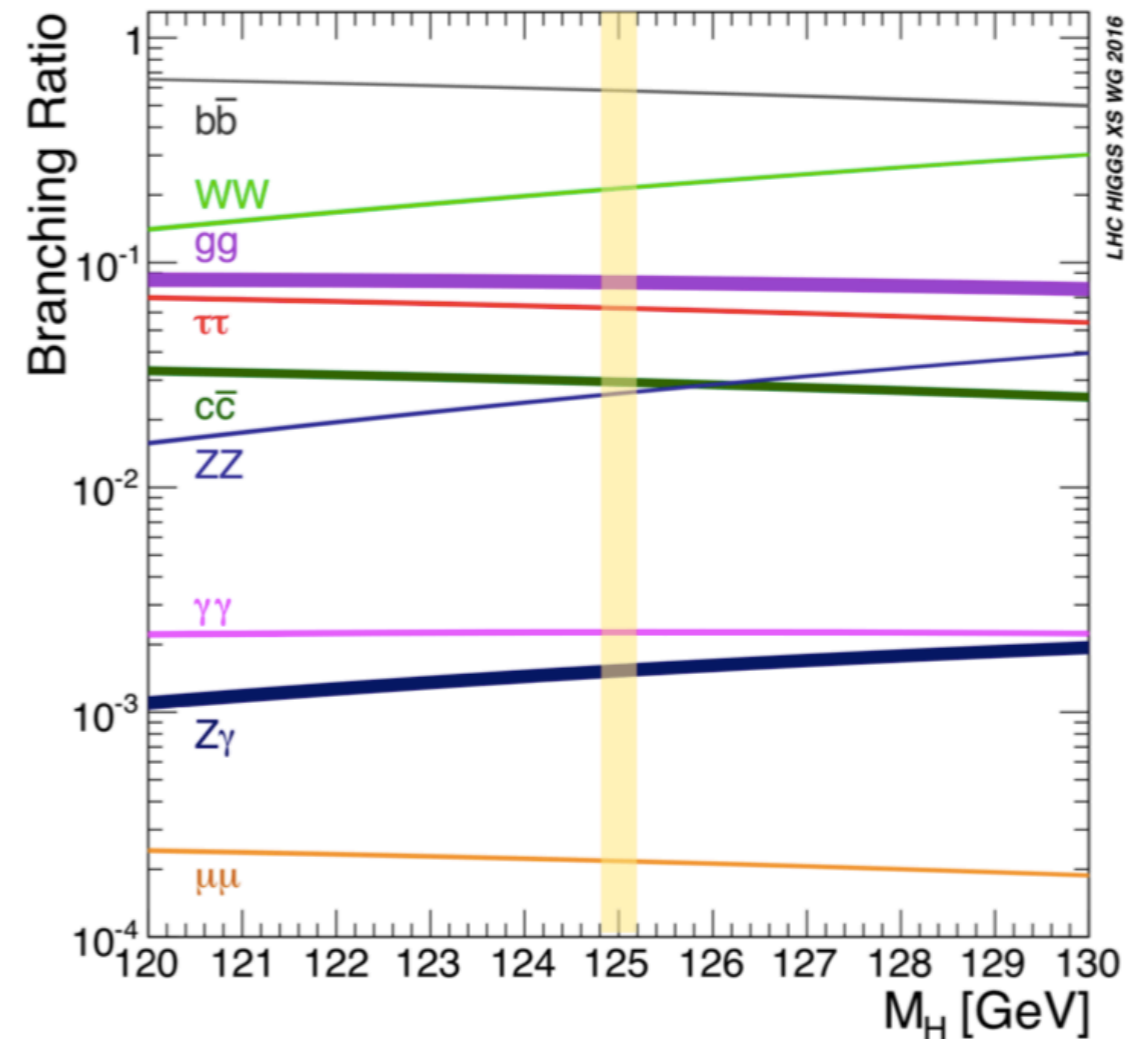
Determination
of
Higgs boson properties
in
decays to bosons
at
the ATLAS experiment

26.05.2021

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Outline

- Introduction
- $H \rightarrow \gamma\gamma$
- $H \rightarrow ZZ^*$
- $H \rightarrow WW^*$
- $H \rightarrow ll\gamma$
- $H \rightarrow Z\gamma$
- EFT Interpretations



Introduction

- ◉ Experimental characterization of the Higgs boson :
 - Critical for elucidating the **mechanism of the electroweak symmetry breaking**.
 - **Provide constraints** on physics beyond the Standard Model (SM).
- ◉ **Phenomenology**
 - Higgs couples directly to all massive particles
 - Variety of production/decay modes within reach at the LHC
- ◉ **Different paths taken** to further scrutinise the Higgs
 - Mass measurement (latest measurement $m_H = 124.97 \pm 0.24$ GeV) doi.org/10.1016/j.physletb.2018.07.050
 - Couplings measurement
 - Simplified template cross sections
 - Differential cross sections
 - CP measurement
 - EFT interpretations

Introduction

- Experimental characterization of the Higgs boson :

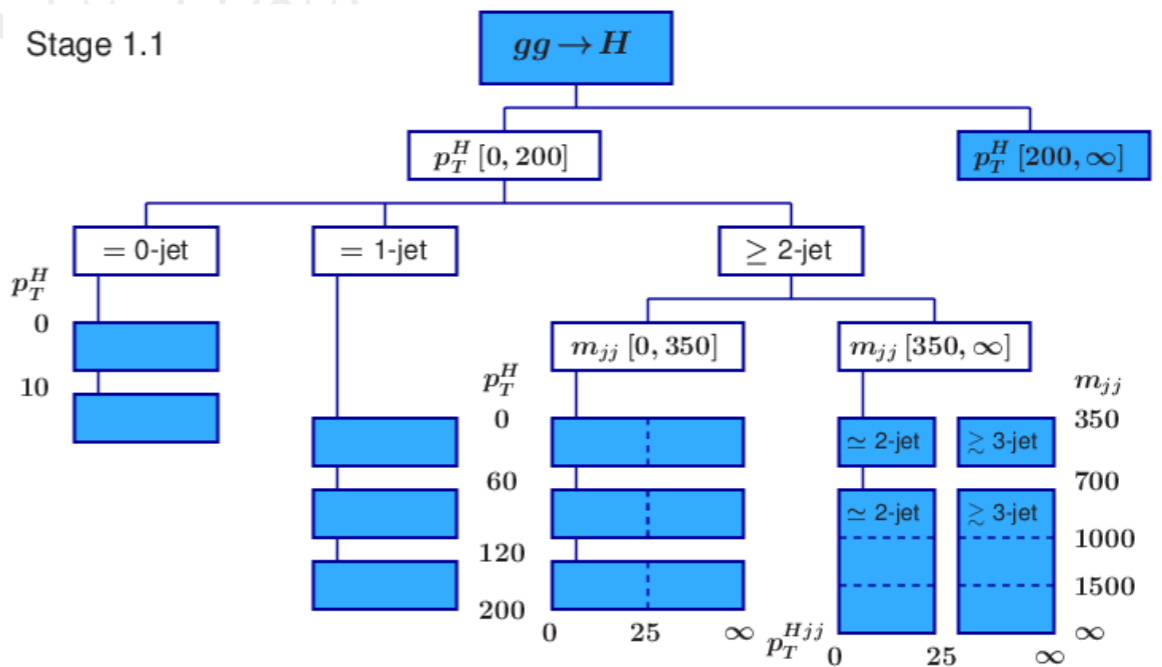
- Critical for elucidating the mechanism of the electroweak symmetry breaking.
- Provide constraints on physics beyond the Standard Model

- Phenomenology

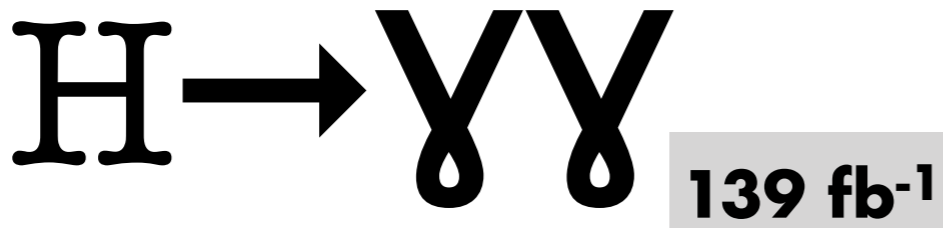
- Higgs couples directly to all massive particles
- Variety of production/decay modes within reach

- Different paths taken to further scrutinise the Higgs

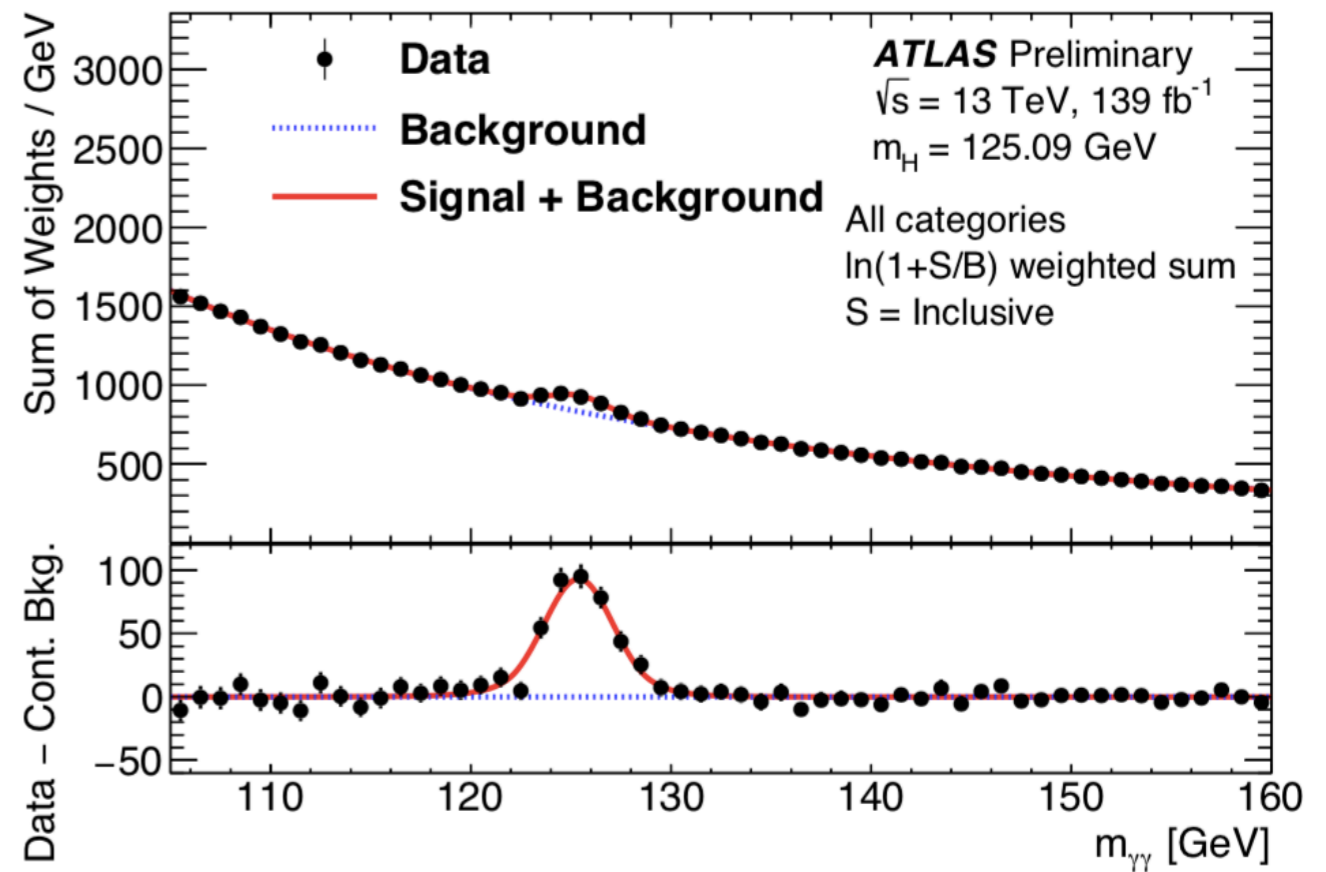
- Mass measurement
- Couplings measurement
- **Simplified template cross sections** →
- Differential cross sections
- CP measurement
- EFT interpretations



- ★ STXS have been adopted by the LHC experiments as a common framework for Higgs measurements.
- ★ Allow for combination of the measurements between different decay channels as well as between experiments.
- ★ Reduce the theoretical uncertainties as much as possible



- Signature: a **narrow resonance** with a width consistent with detector resolution rising above a smooth background in the diphoton invariant mass ($m_{\gamma\gamma}$) distribution.
- Despite a small branching ratio of about 0.227%, **precise measurements** of Higgs boson properties yielded.
 - Excellence performance of photon reconstruction and identification with the ATLAS detector.



Higgs boson production cross section times $H \rightarrow \gamma\gamma$ branching ratio

$$(\sigma \times B_{\gamma\gamma})_{\text{obs}} = 127 \pm 10 \text{ fb} = 127 \pm 7 \text{ (stat.)} \pm 7 \text{ (syst.) fb}$$

$$(\sigma \times B_{\gamma\gamma})_{\text{exp}} = 116 \pm 5 \text{ fb}$$

H → γγ

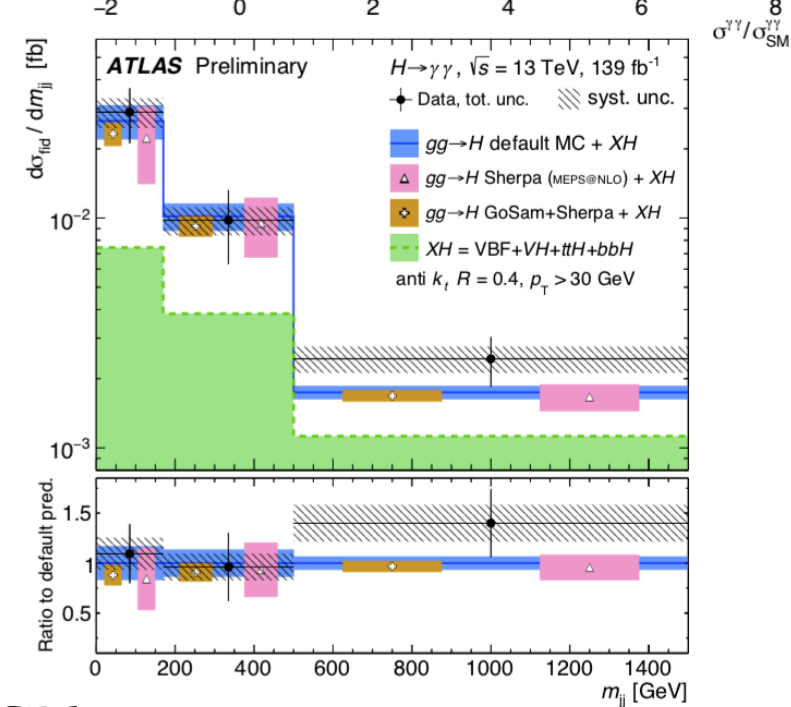
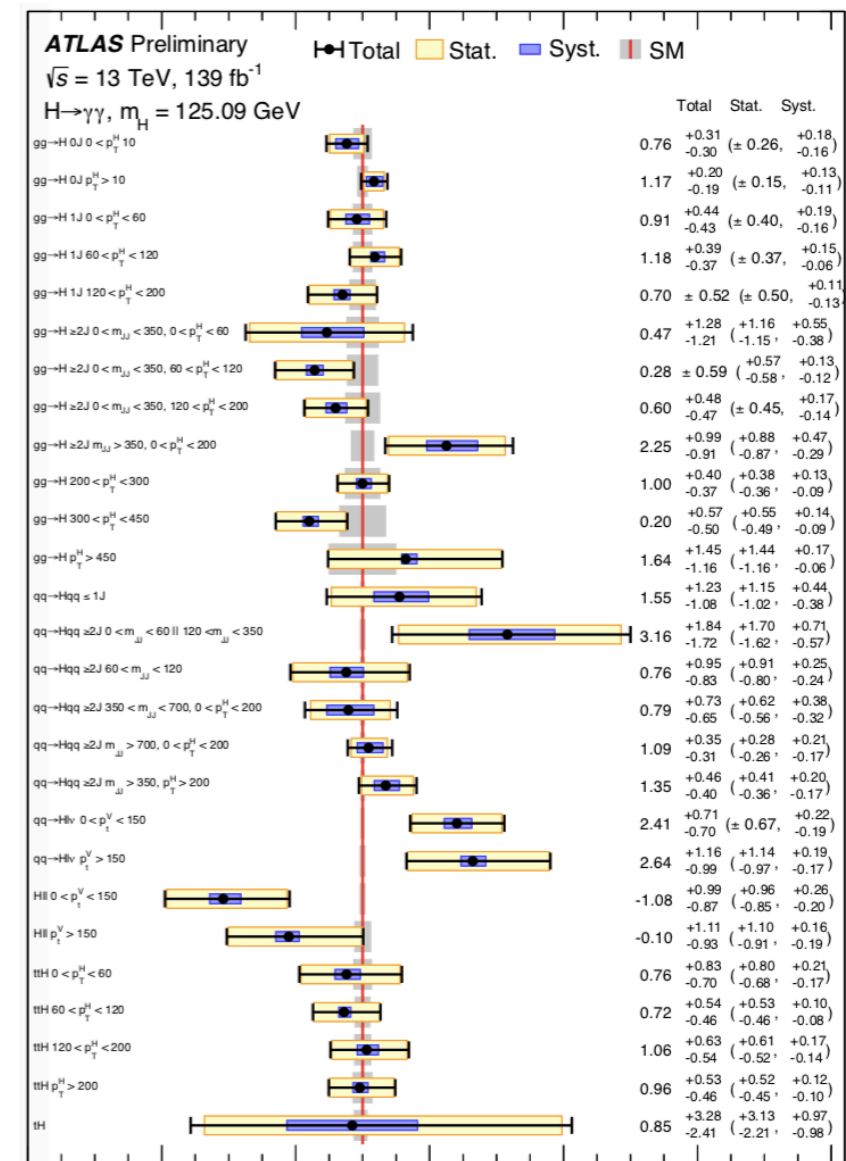
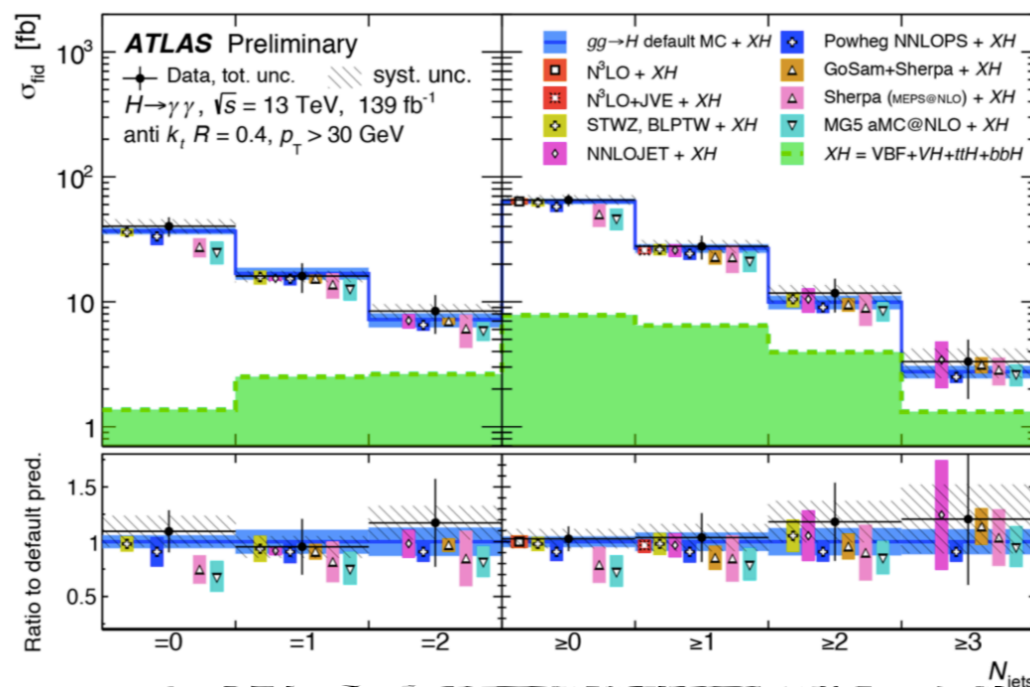
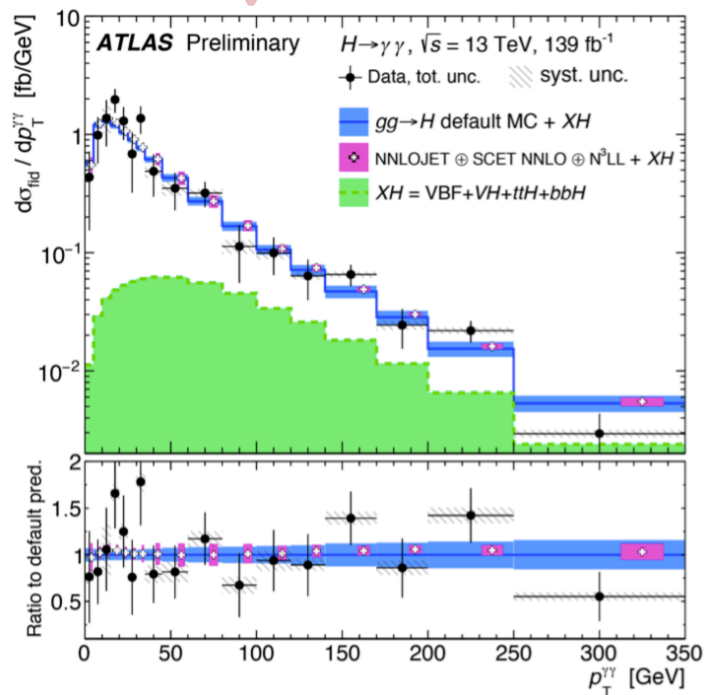
139 fb⁻¹

STXS:

- ✓ Cross-sections are presented in **27 regions** of Higgs boson production phase.
- ✓ level of compatibility between the measured STXS cross-sections and their Standard Model predictions is 60%.

Differential:

- ✓ N_{jets} sensitive to production modes and **higher order QCD effects**.
- ✓ di-jet kinematics **sensitive to anomalous operators** including CP-odd.





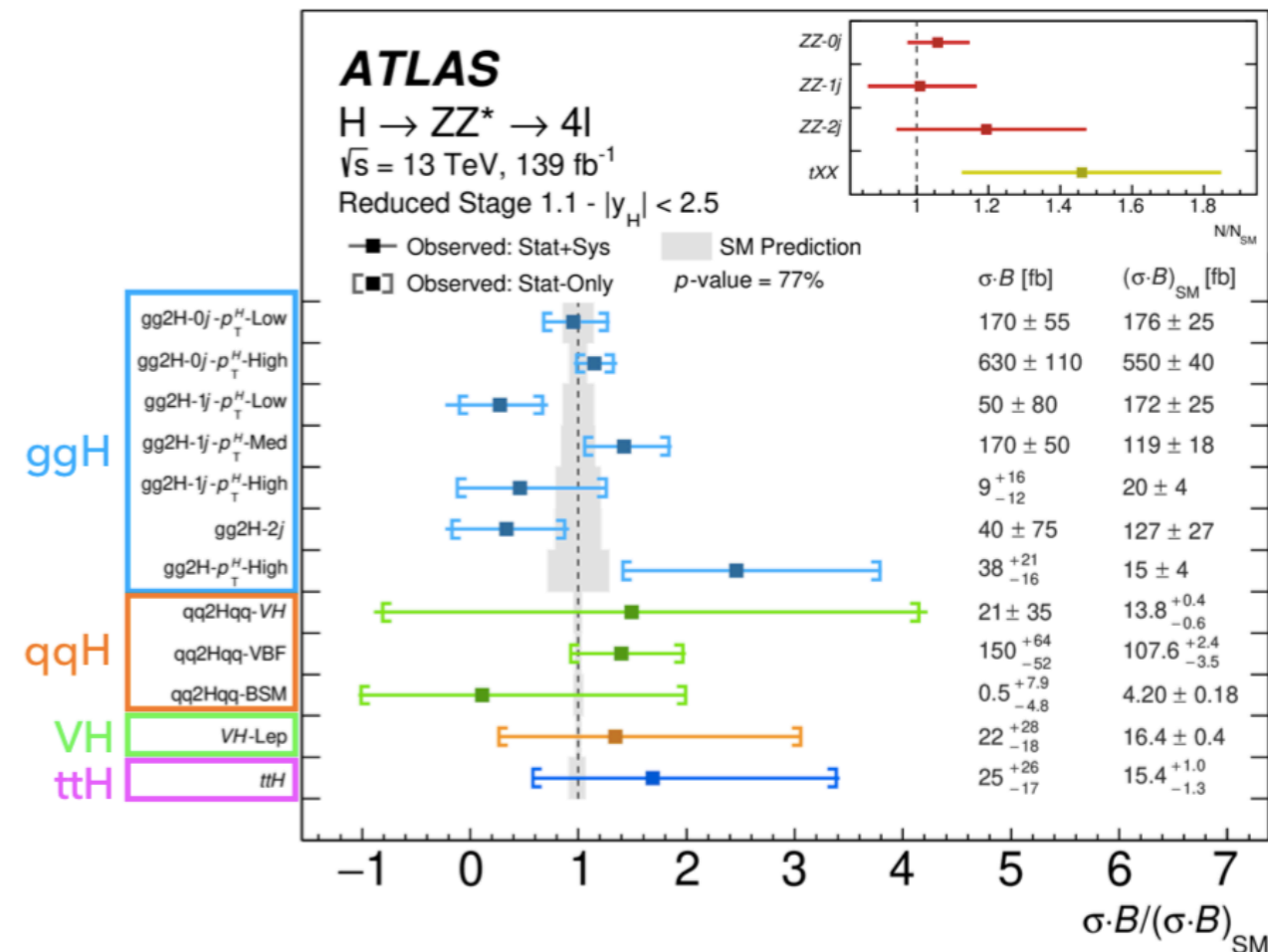
139 fb⁻¹

Improvements brought to the final Run-2 measurement:

- Improved lepton isolation to mitigate the impact of pile-up
- Improved jet reconstruction using a particle flow algorithm
- Additional event categories for the classification of Higgs boson candidates
- New discriminants to enhance the sensitivity to distinguish the various production modes of the SM Higgs boson
- Use of data sidebands to constrain the dominant ZZ* background process

STXS

- High S/B and clean signature with fully reconstructed final state.
- Several bins measured for ggH and qqH, despite few statistics (low BR).
- On top of kinematic categories matching the STXS categorisation, analysis utilises NN-based categorisation to define the observable for fit.
 - Kinematic categories minimise the model extrapolation.
 - NN discriminants maximise the sensitivity.
- Good agreement with SM predictions (within large stat. uncertainty).



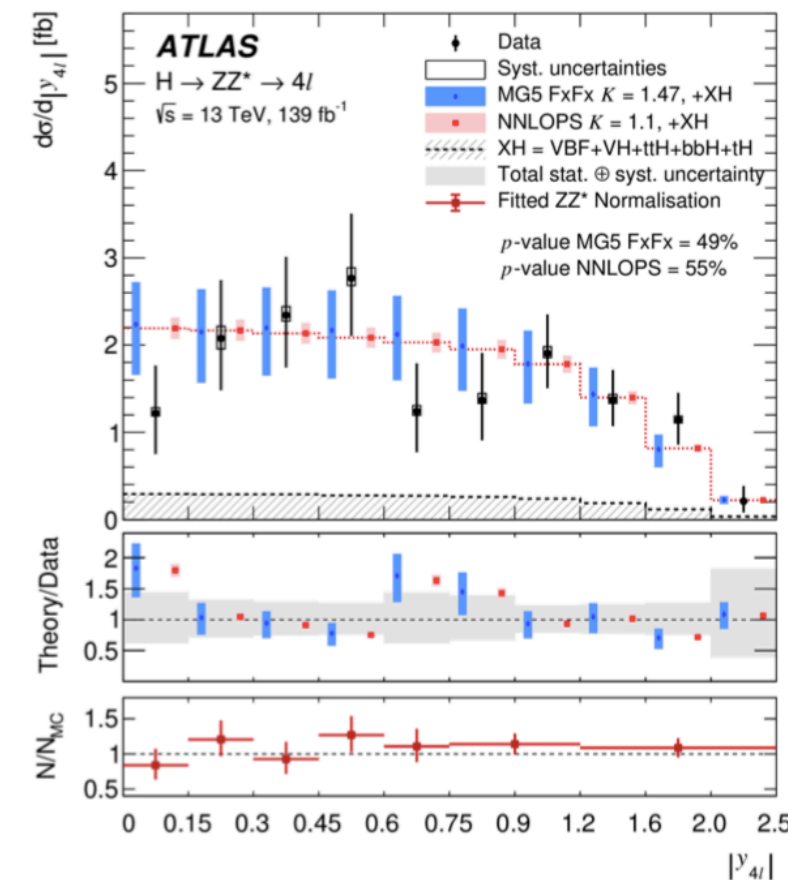
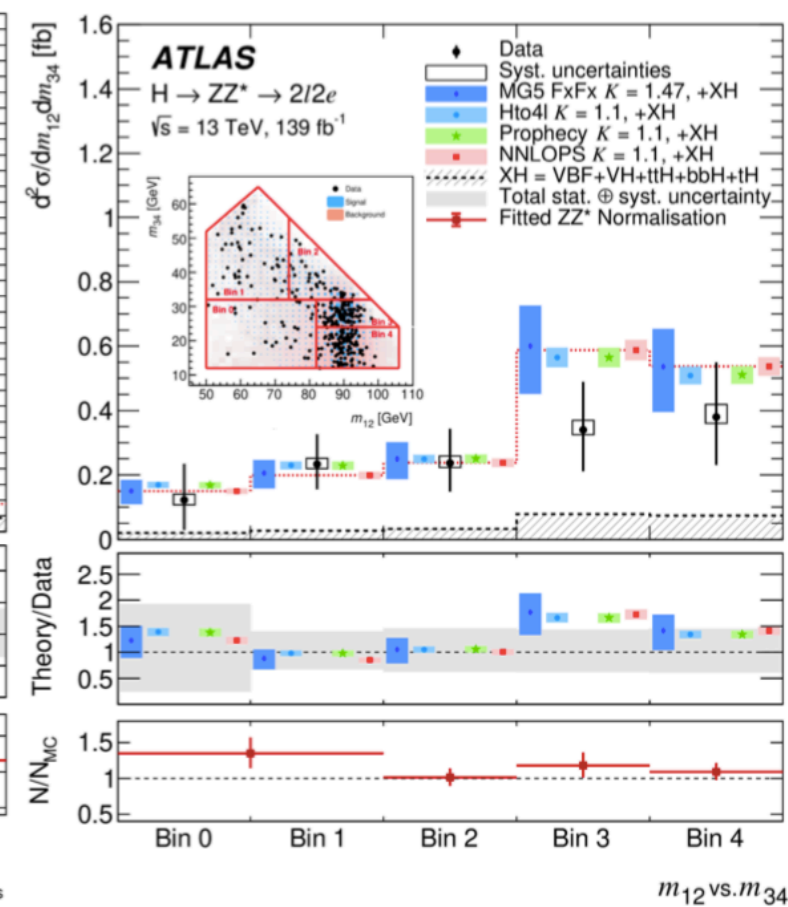
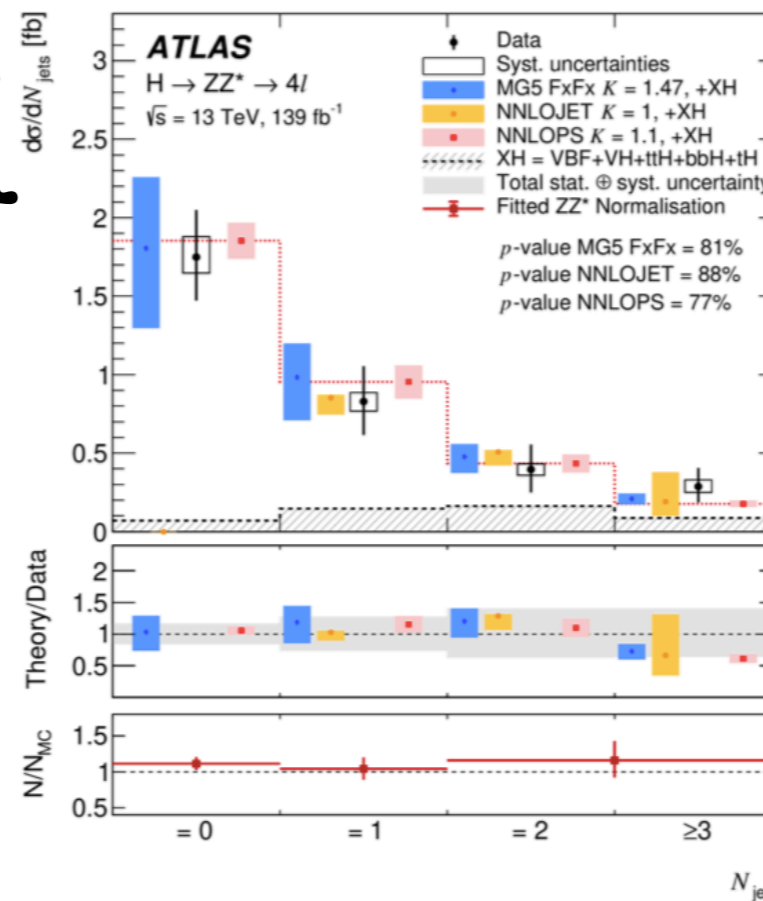
[arXiv:2004.03447](https://arxiv.org/abs/2004.03447)

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

139 fb⁻¹

DIFFERENTIAL

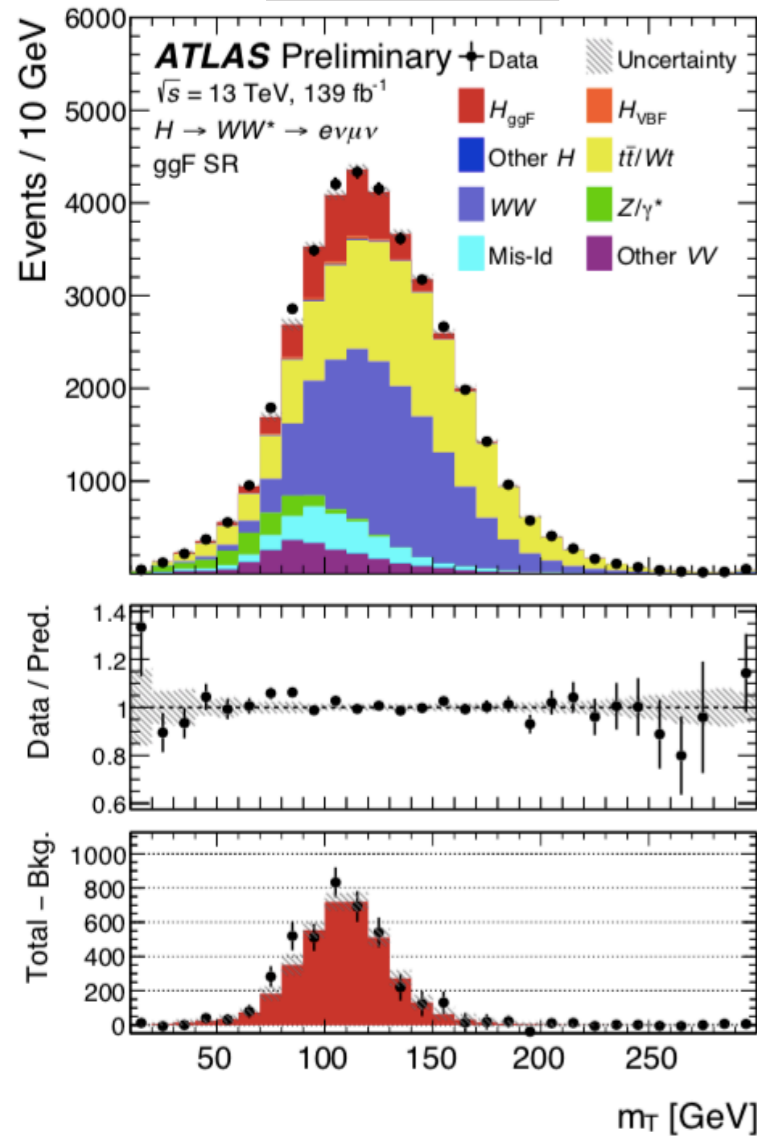
- Many distributions measured, including:
 - Higgs kinematics, including angular variables.
 - Jet activities.
 - m_{12} vs. m_{34} - specific to $ZZ^* \rightarrow 4l$ decays and offers good sensitivity to BSM physics.
 - p_T^{4l} constrains the Yukawa couplings of the Higgs boson with the b - and c -quarks.
 - Double differential distributions
- Limited by statistical uncertainties.
- Matrix-based likelihood unfolding.
- Probing transition region effects in p_{TH} (vs jets)
 - compared to state of the art calculations (RADISH, NNLOJET)



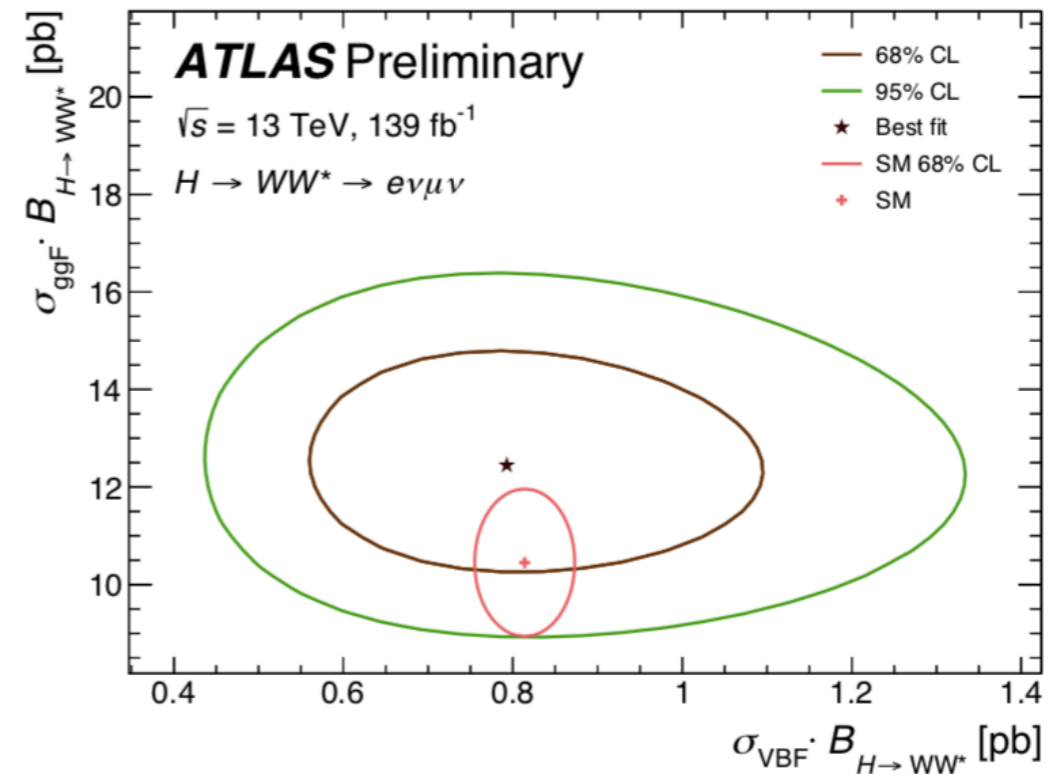
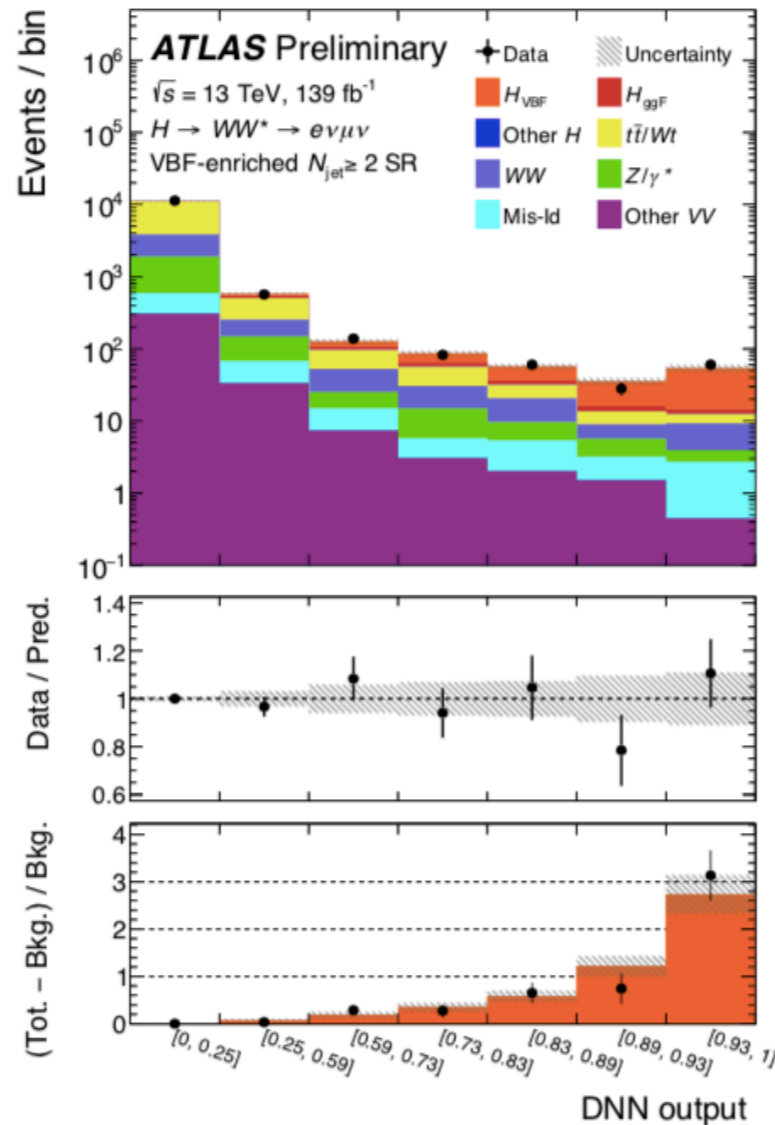
[arXiv:2004.03969](https://arxiv.org/abs/2004.03969)

$H \rightarrow WW^*$ 139 fb^{-1}

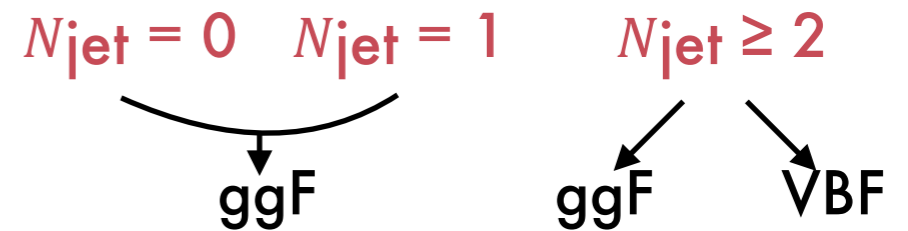
ggF mode



VBF mode



Analysis is performed separately w.r.t. jet multiplicity:



For ggF, m_T distribution is used as the final discriminant

For the VBF-enriched $N_{\text{jet}} \geq 2$ category, the DNN output is used as the discriminating variable \rightarrow enhance the low s/b.



139 fb⁻¹

$$\begin{aligned} \mu_{ggF} &= 1.20^{+0.16}_{-0.15} \\ &= 1.20 \pm 0.05 \text{ (stat.) }^{+0.09}_{-0.08} \text{ (exp syst.) }^{+0.10}_{-0.08} \text{ (sig theo.) }^{+0.12}_{-0.11} \text{ (bkg theo.)} \\ \mu_{VBF} &= 0.99^{+0.24}_{-0.20} \\ &= 0.99^{+0.13}_{-0.12} \text{ (stat.) }^{+0.07}_{-0.06} \text{ (exp syst.) }^{+0.17}_{-0.12} \text{ (sig theo.) }^{+0.10}_{-0.08} \text{ (bkg theo.)} \end{aligned}$$

$$\begin{aligned} \sigma_{ggF} \cdot \mathcal{B}_{H \rightarrow WW^*} &= 12.4 \pm 1.5 \text{ pb} \\ &= 12.4 \pm 0.6 \text{ (stat.) } \pm 0.9 \text{ (exp syst.) }^{+0.7}_{-0.6} \text{ (sig theo.) } \pm 1.0 \text{ (bkg theo.) pb} \\ \sigma_{VBF} \cdot \mathcal{B}_{H \rightarrow WW^*} &= 0.79^{+0.19}_{-0.16} \text{ pb} \\ &= 0.79^{+0.11}_{-0.10} \text{ (stat.) }^{+0.06}_{-0.05} \text{ (exp syst.) }^{+0.13}_{-0.09} \text{ (sig theo.) }^{+0.08}_{-0.06} \text{ (bkg theo.) pb,} \end{aligned}$$

Measurements are dominated by systematic uncertainties.

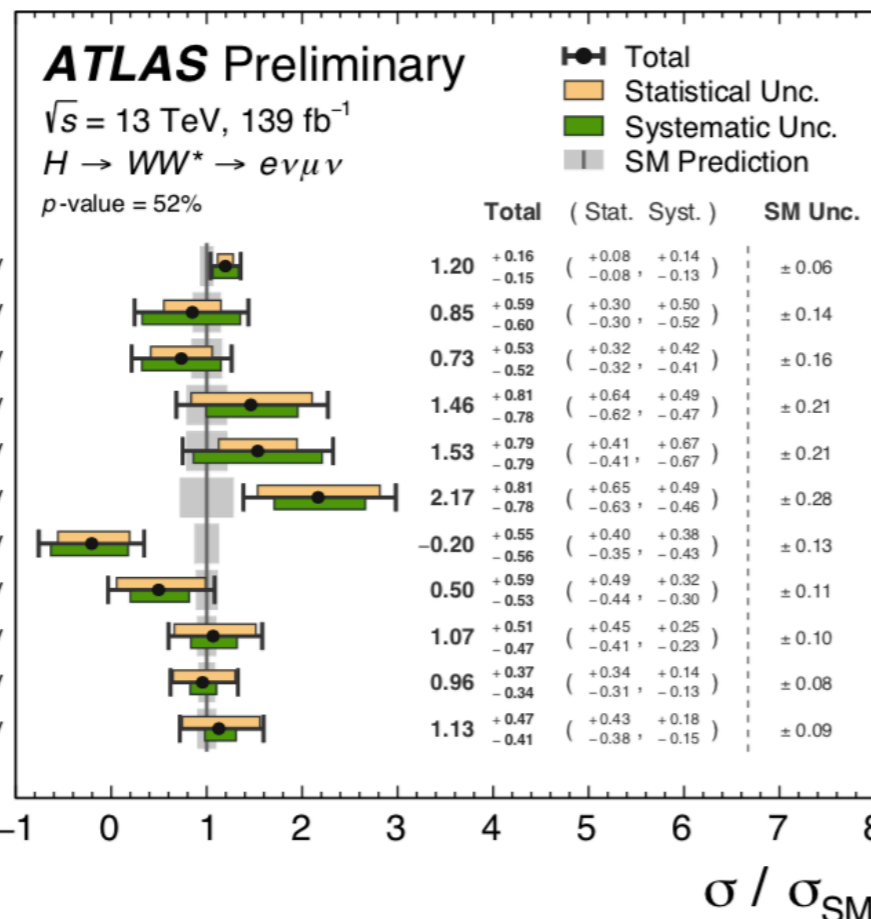
ggF → uncertainties from both experimental and theoretical sources are comparable.

VBF → signal theory uncertainties make up the largest contribution.

STXS

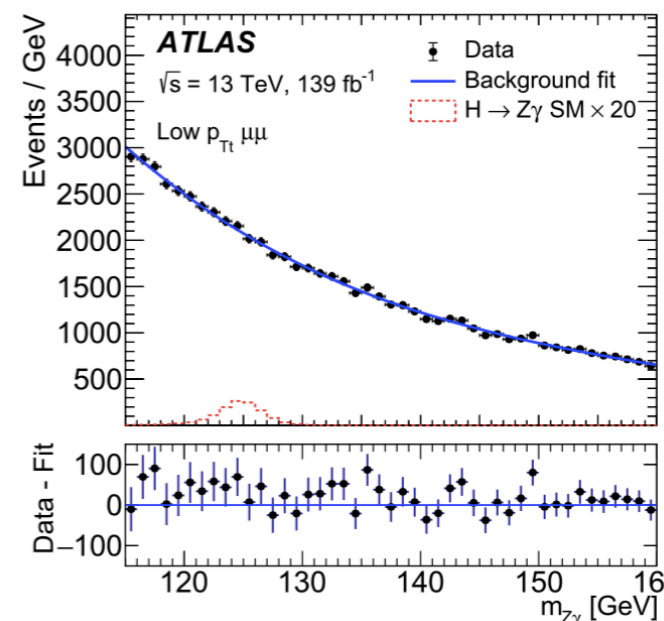
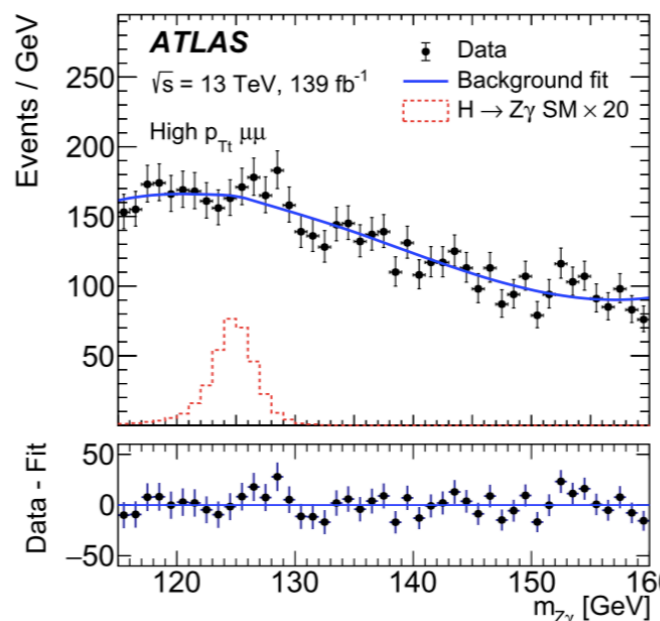
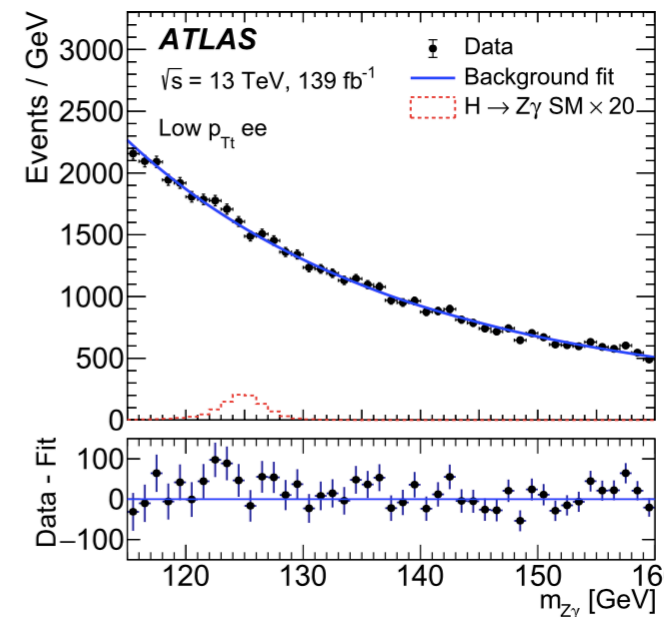
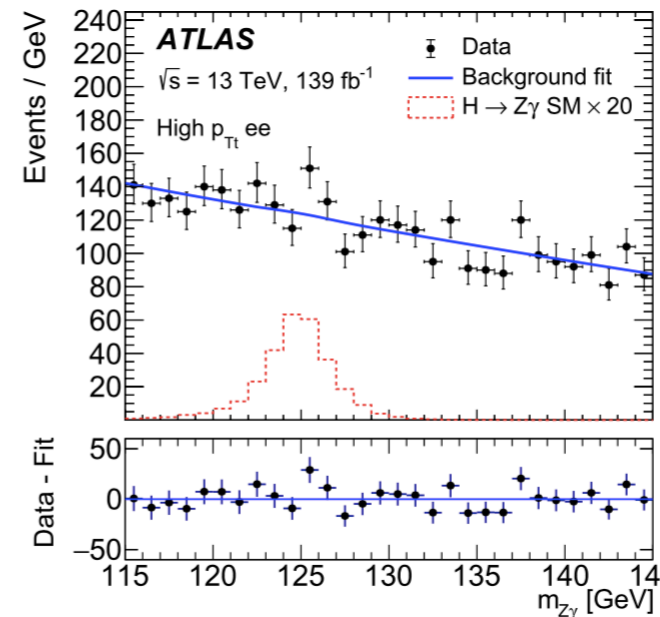
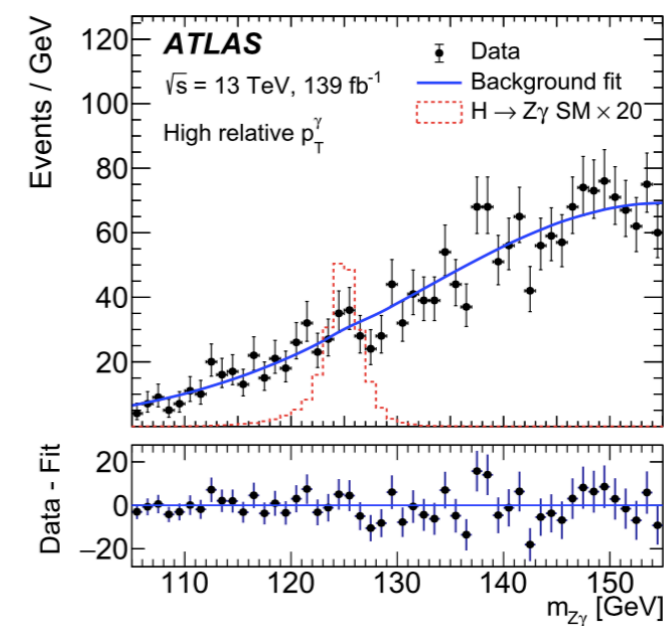
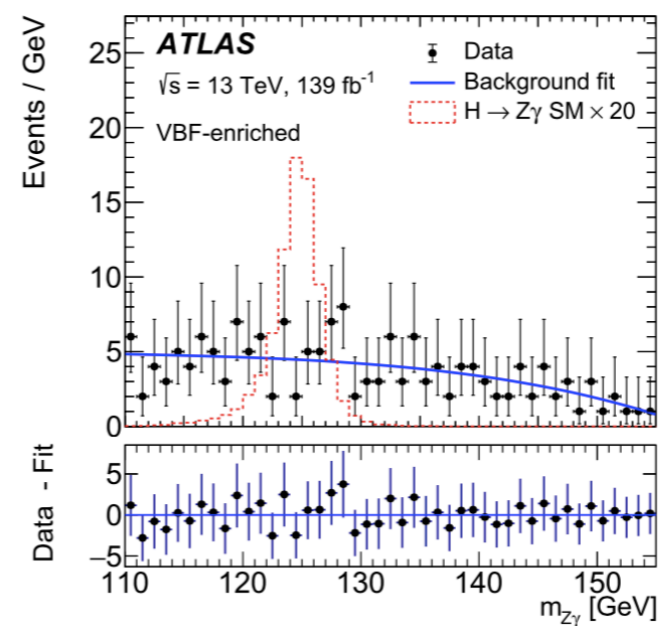
Higgs boson production is further characterised through measurements of STXSs in a total of 11 categories.

Results are compatible with the Standard Model predictions with a p-value of 52%.



$H \rightarrow Z\gamma$ 139 fb⁻¹

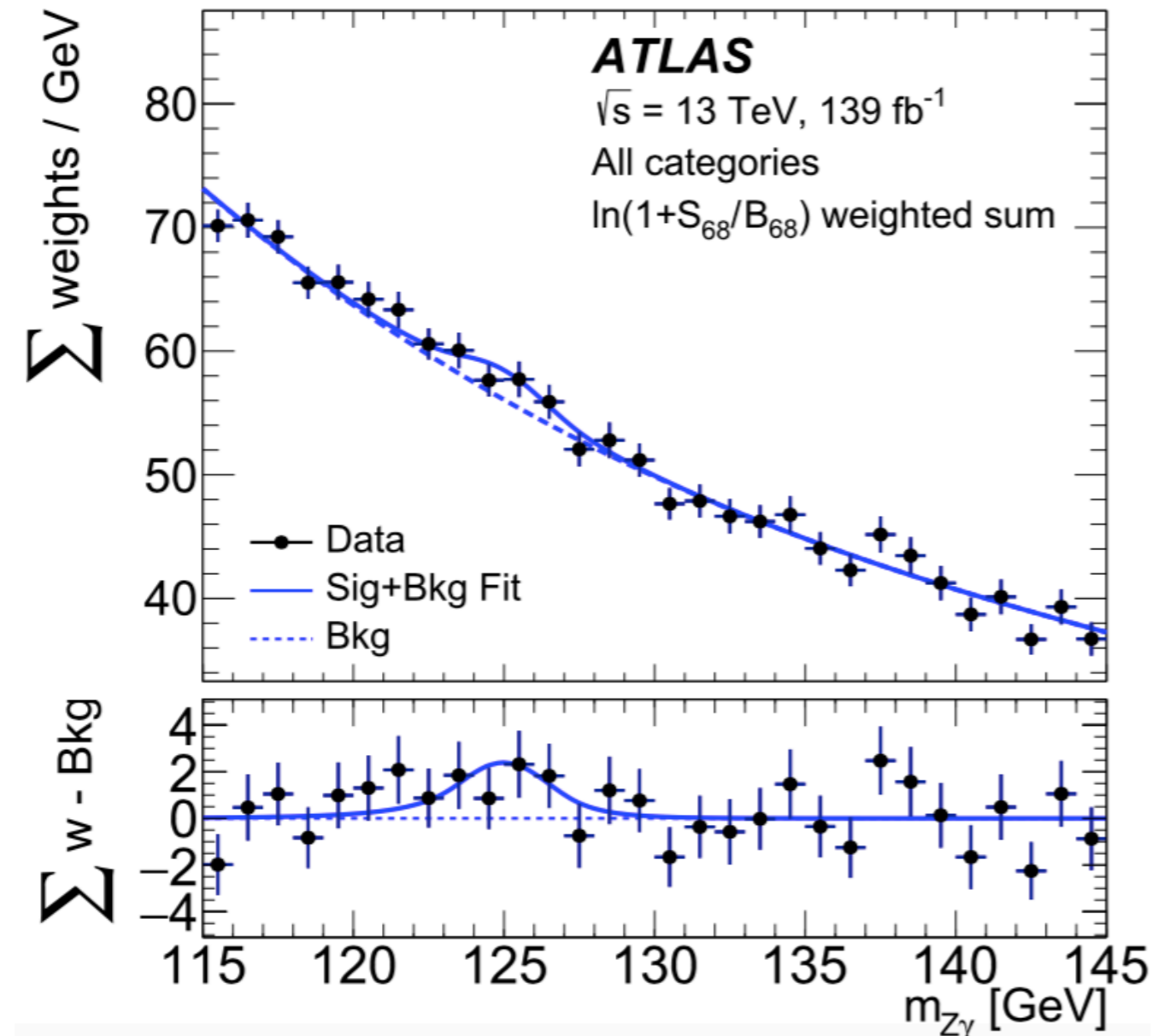
- This decay mode **probes several scenarios beyond the SM**, for example, if the Higgs boson were a neutral scalar of different origin or a composite state.
- **Improvements** w.r.t. previous iterations:
 - ✓ Increase in the size of the data set
 - ✓ An improved event categorisation
 - ✓ Optimised lepton and photon identification criteria.
- **Dominant background:** Irreducible non-resonant production of Z bosons together with photons.
- **Six Categories** in the fit:
 - VBF-enriched
 - High relative p_T^Y
 - High $p_{Tf} ee$
 - Low $p_{Tf} ee$
 - High $p_{Tf} \mu\mu$
 - Low $p_{Tf} \mu\mu$.
- Signal and background yields are extracted from a fit to the $m_{Z\gamma}$ distribution observed in data



[arXiv:2005.05382](https://arxiv.org/abs/2005.05382)

H → Zγ 139 fb⁻¹

Weighted H → Zγ selections in data



- Observed data are consistent with the expected background.
- Expected and Observed p -value are 12.3% and 1.3% respectively.
- Expected and Observed significance of 1.2 and 2.2 standard deviations, respectively.
- Observed 95% CL upper limit on the $\sigma(pp \rightarrow H) \cdot B(H \rightarrow Z\gamma)$ is 3.6 times the SM prediction for a Higgs boson mass of 125.09 GeV.
- Best-fit value for the signal yield normalised to the SM prediction is $2.0 +1.0 - 0.9$ where the **statistical component of the uncertainty is dominant**.
- The results represents an **improvement of about a factor of 2.4 in expected sensitivity** compared with the previous ATLAS publication.

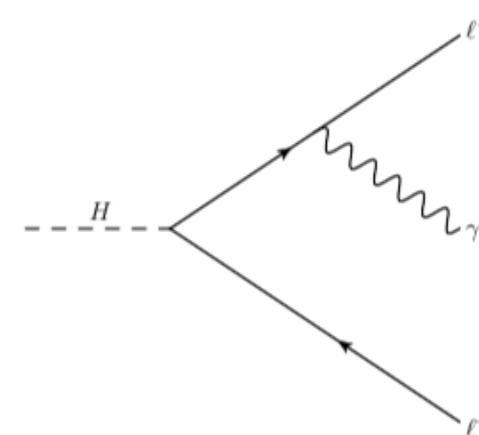
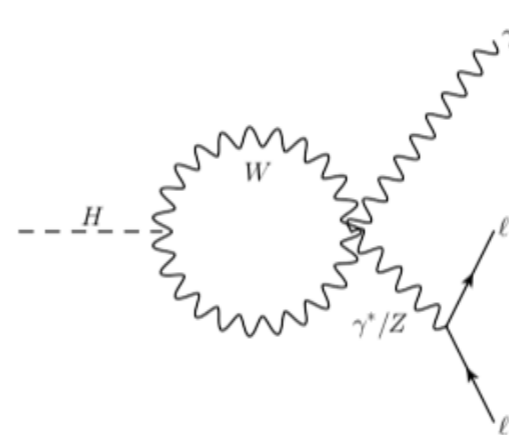
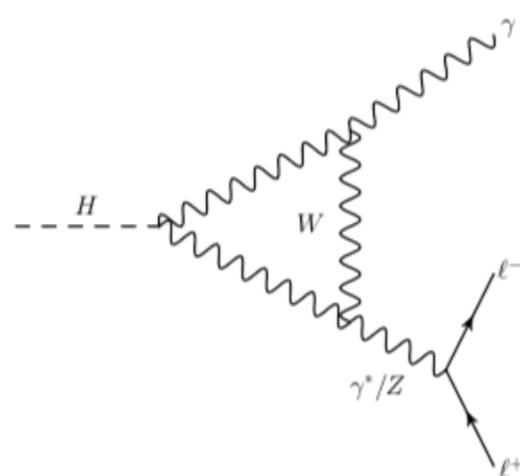
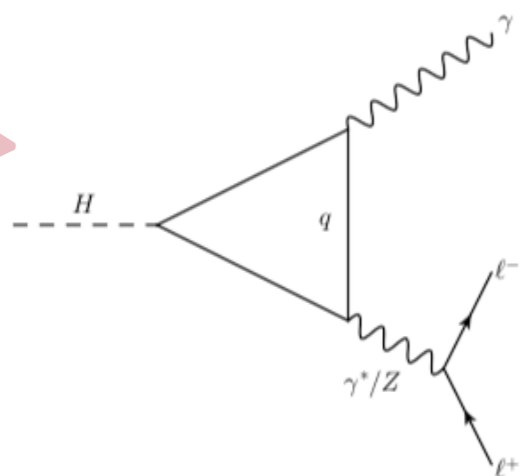
$H \rightarrow \ell\ell\gamma$

139 fb⁻¹

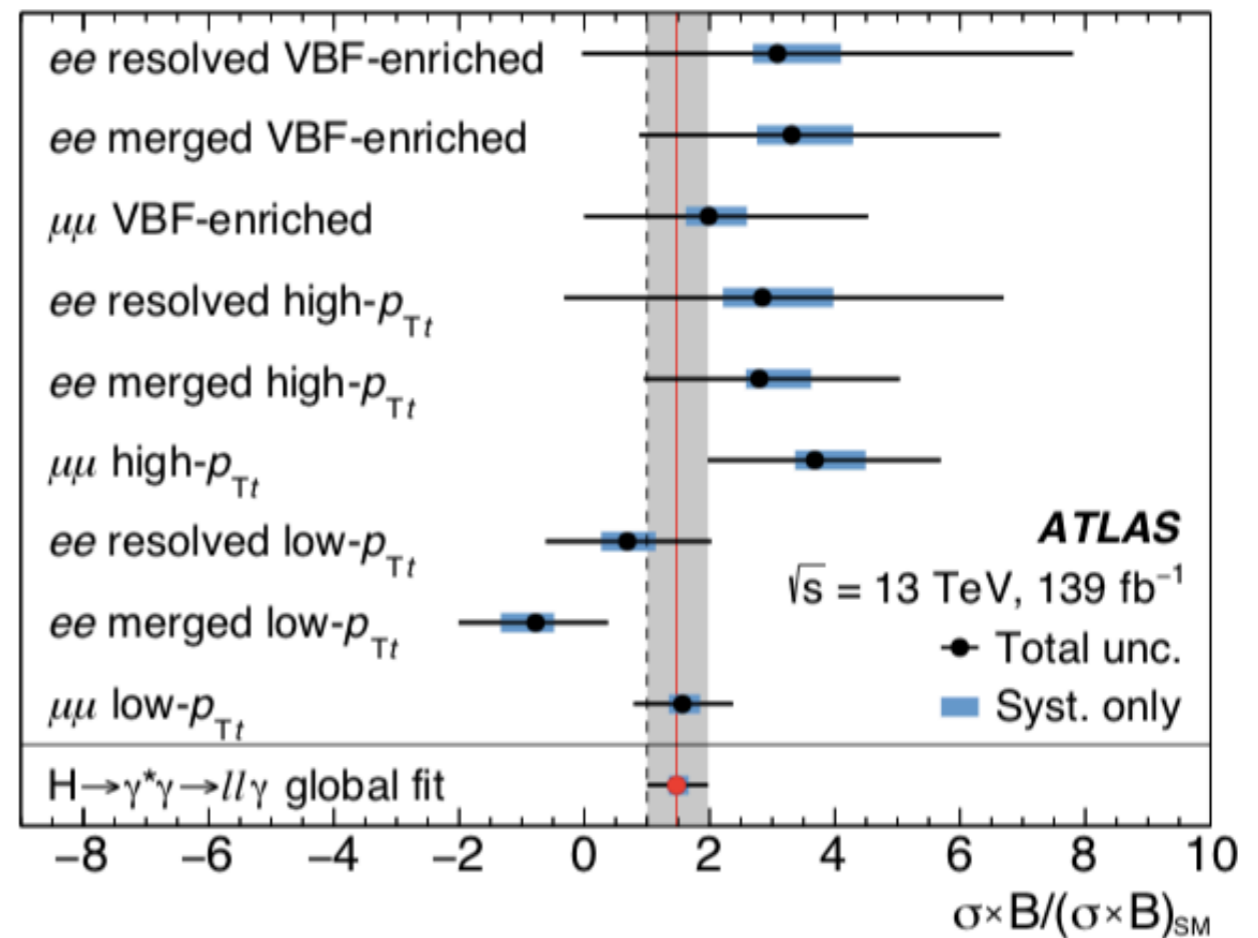
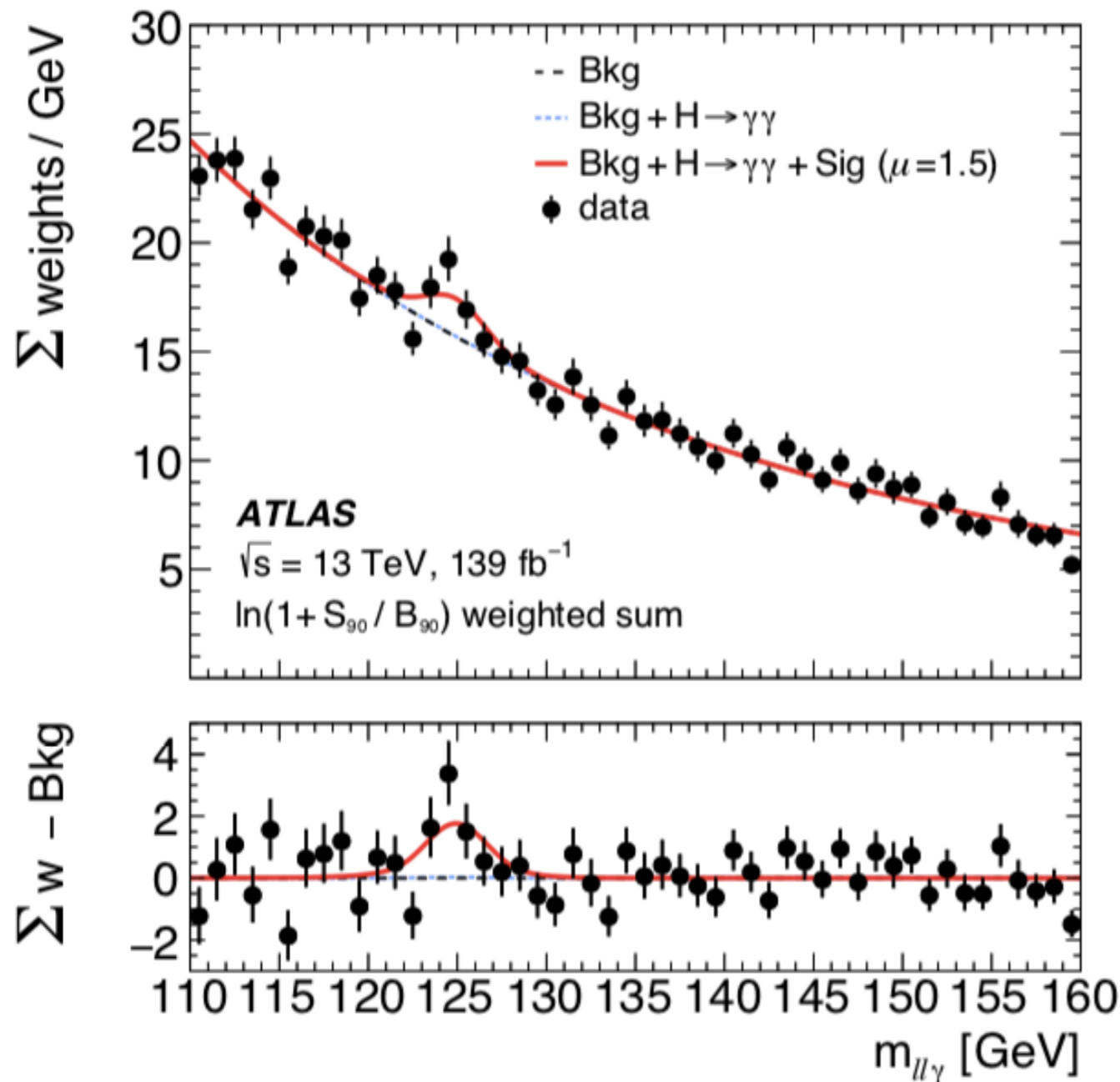
- Search for the Higgs boson decaying into a photon and a pair of electrons or muons with an invariant mass $m_{\ell\ell} < 30$ GeV.
 - Probe coupling modifications introduced by possible extensions to the SM.
 - Three-body Higgs boson decays can be used to probe *CP*-violation.
- Multiple processes contribute:
 - Dalitz decays involving a *Z* boson or a virtual photon.
 - Decay of the Higgs boson to two leptons and a photon from final-state radiation (FSR)
- To enhance sensitivity, selected events are divided into mutually exclusive categories, according to the event topology and lepton flavour.
- Dominant background: irreducible non-resonant production of $\ell\ell\gamma$.

Category

ee resolved VBF-enriched
 ee merged VBF-enriched
 $\mu\mu$ VBF-enriched
 ee resolved high- p_{Tt}
 ee merged high- p_{Tt}
 $\mu\mu$ high- p_{Tt}
 ee resolved low- p_{Tt}
 ee merged low- p_{Tt}
 $\mu\mu$ low- p_{Tt}




$H \rightarrow ll\gamma$ 139 fb⁻¹

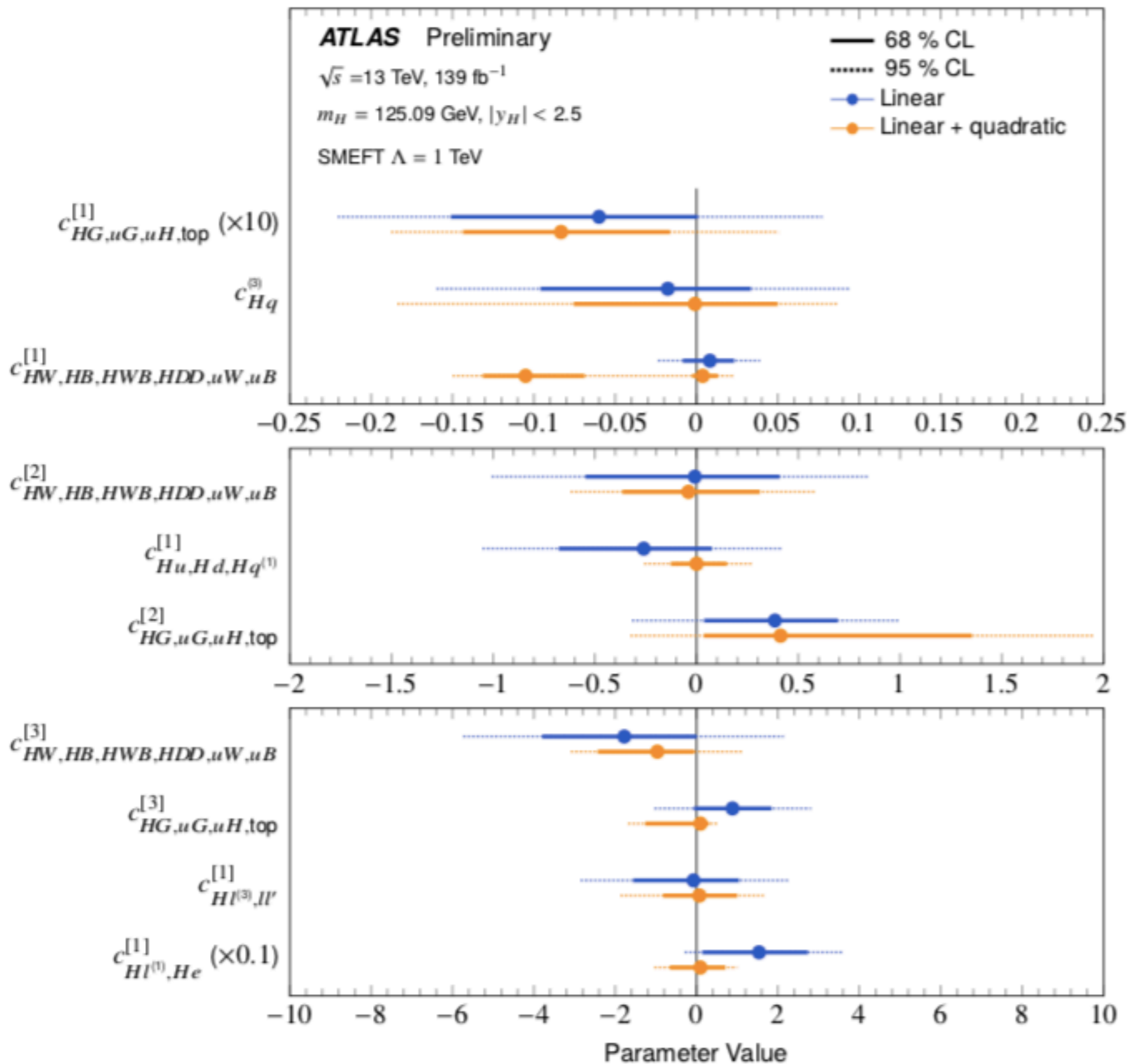


- **Evidence** for the $H \rightarrow ll\gamma$ process is found with a **significance of 3.2** over the background-only hypothesis.
- The Higgs boson production cross-section times the $H \rightarrow ll\gamma$ branching ratio for $m_{ll} < 30 \text{ GeV}$ is determined to be $8.7^{+2.8}_{-2.7} \text{ fb}$.

EFT Interpretations

- Novel interpretations of the combined Higgs boson measurements have been performed.
- Decay channels, targeted production modes and integrated luminosities of the datasets used in this combination. 
- Combination takes advantage of the eigen vector decomposition of the Wilson coefficients, to enhance sensitivity.
- Constraints on linear combinations of Wilson coefficients** corresponding to SMEFT operators.
- Constraints set on parameters m_A , $\tan \beta$ of the MSSM, in context of six **benchmark scenarios proposed by the BSM subgroup** of the LHC Higgs Cross-Section WG.

Analysis	Integrated lumi (fb^{-1})
$H \rightarrow \gamma\gamma$ (all production modes)	139
$H \rightarrow ZZ^* \rightarrow 4\ell$ (all production modes)	139
$H \rightarrow b\bar{b}$ (VH)	139
$H \rightarrow WW^*$ (ggH, VBF)	36.1
$H \rightarrow \tau\tau$ (ggH, VBF)	36.1
$H \rightarrow b\bar{b}$ (VBF)	24.5 – 30.6
$H \rightarrow b\bar{b}$ ($t\bar{t}H$)	36.1
$H \rightarrow \text{multilepton}$ ($t\bar{t}H$)	36.1
$H \rightarrow \mu\mu$ (all production modes)	139



- Comparison of results interpreted with a **linearized SMEFT** model and a model that also includes **quadratic terms** shows sizeable sensitivity to operators suppressed by Λ^4 in all of the measured parameters.
- In this model-independent parametrization of new physics effects, **no significant deviations from the SM** have been observed.
- Results are complementary to limits from direct searches for additional Higgs bosons.

Summary of observed measurements of the parameters c_i'

Conclusion

- **Many new results** across multiple Higgs production and decay modes for Run-2 ATLAS.
- With more stats and improvements in the analysis strategies, **more granularity in results**.
- **Advanced the knowledge of the Higgs properties** measuring cross sections (total, STXS and differential), CP, mass and width.
- Measurements continue to be **consistent with the Standard Model**, placing further constraints on new physics.
- **More results to come from Run-2, stay tuned!**

Thank you!