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

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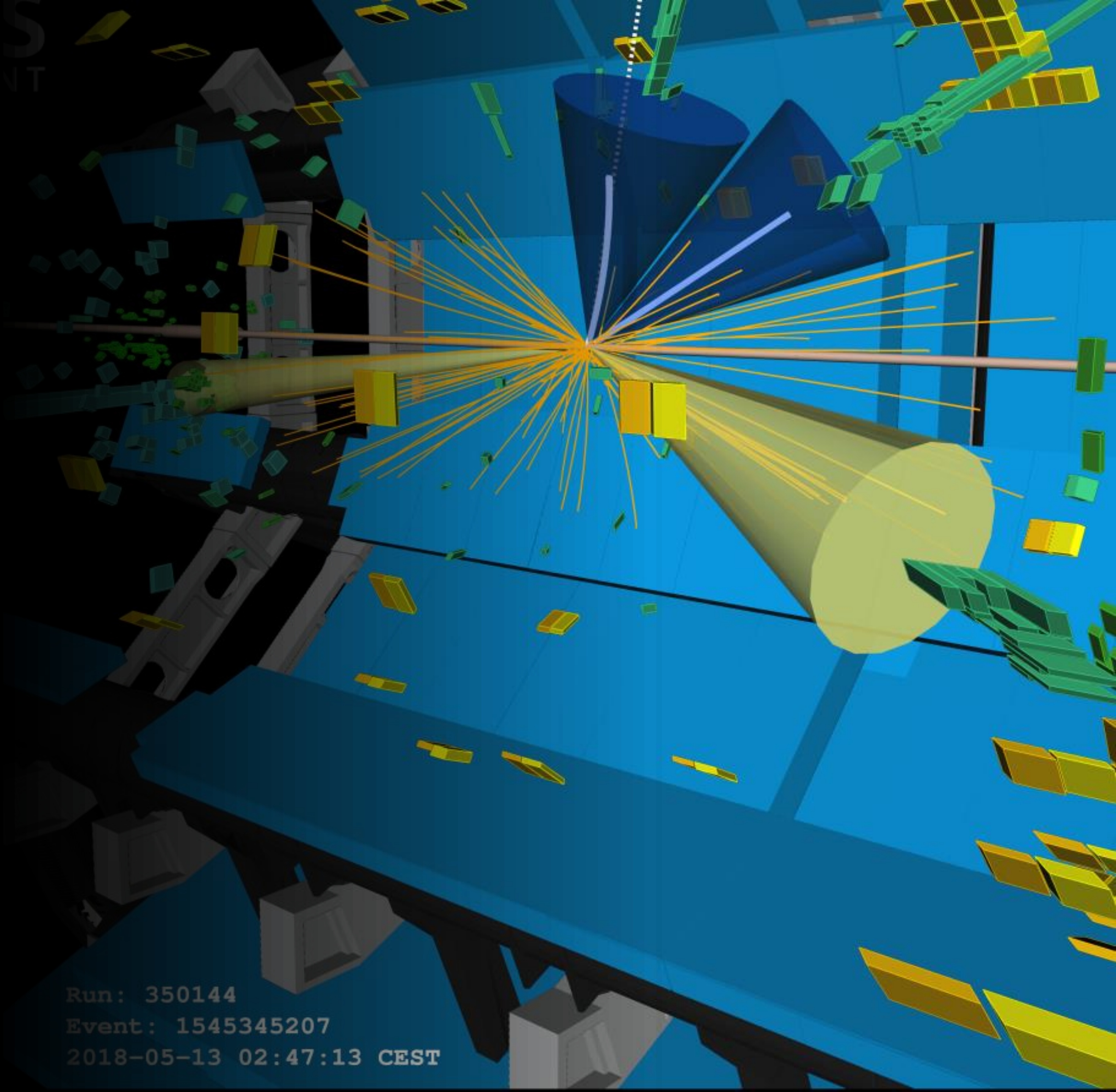
On behalf of the ATLAS collaboration

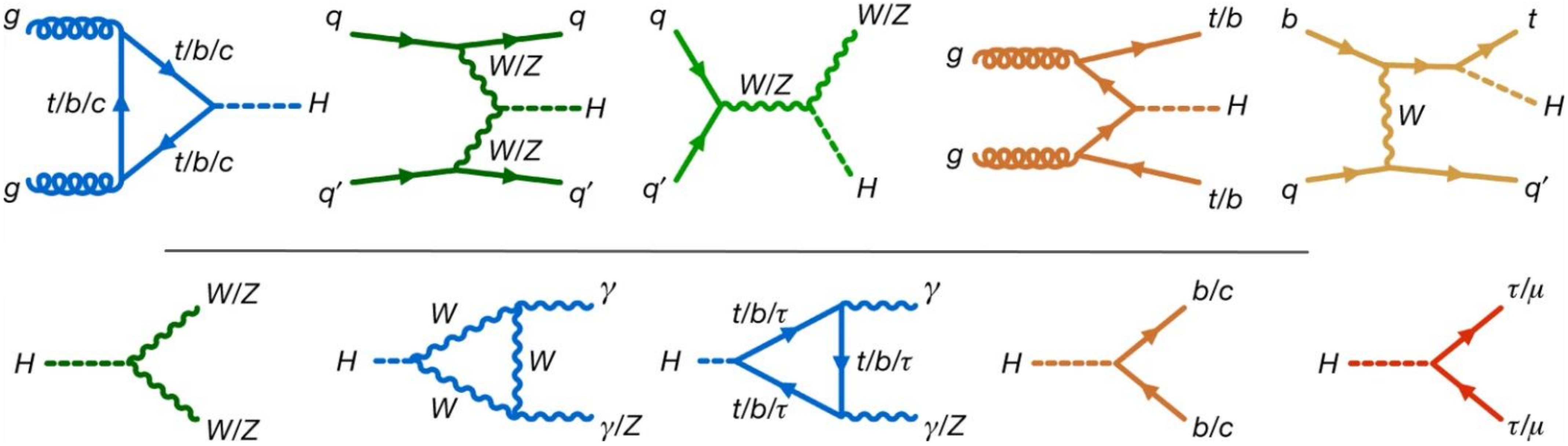
ICNFP 2024



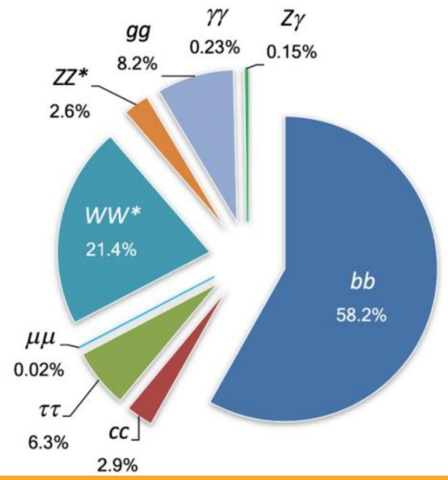
Event Display: **ATLAS-PHOTO-2022-033**

Overview of Higgs Production and Decay

ggF 87% | VBF 7% | VH 4% | ttH/bbH 2% | tH 0.2%



- Couplings are probed both in production and decay
- Loop contributions also in many cases sensitive to (potential) BSM effects
- ttH offers direct measurement of top–Higgs coupling
- High improvement in flavor tagging: BDT -> DNN -> NN
  => Major driver of sensitivity increases

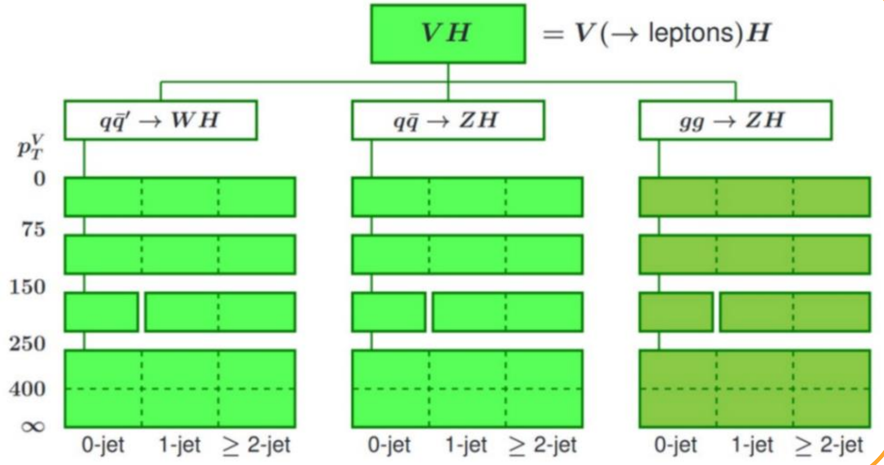


Cross sections

Simplified Template Cross Sections (STXS)

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

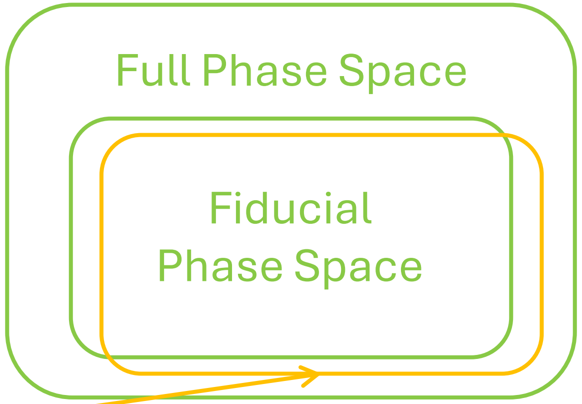
- Reduce theorical uncertainties
- Common framework for combination of orthogonal decay channels
- Defined in stages with increasing granularity
- Large p_T bins are sensitive for BSM physics search



Fiducial Cross Section

Cross sections measured in a phase space closely matching detector acceptance

- Avoids extrapolation of results into phase space out of acceptance
- More model-independent
- 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 are used to parametrize possible BSM physics:

Kappa framework

Coupling of Higgs to *p* is modified by coupling modifier κ_p

$$\kappa_p^2 = \sigma_p / \sigma_p^{SM} \text{ for production}$$

$$\kappa_p^2 = \Gamma_p / \Gamma_p^{SM} \text{ for decay}$$

$$\kappa_p = 1 \Rightarrow SM$$

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)

$$\mathcal{L}_{SMEFT} = \mathcal{L}_{SM} + \sum \frac{c_i^{(5)}}{\Lambda} O_i^{(5)} + \sum \frac{c_i^{(6)}}{\Lambda^2} O_i^{(6)} + \cdots$$

Wilson coefficients

New physics mass scale

Operators obeying symmetries

d=5,7 operators = 0 as they introduce lepton/baryon number violation

=> Focus on d= 6 operators

Allows any coupling that doesn't violate symmetries

List of papers

Run 2

- VH, H → WW* → $\ell\nu\ell\nu$ + $\ell\nu jj$ (**ATLAS-CONF-2022-067**) → See Back Up
- VBF, $H \rightarrow WW^* \rightarrow e\nu\mu\nu$ (**Phys. Rev. D 108 (2023) 072003**)
- ggF, H → WW* → $e\nu\mu\nu$ (**Eur. Phys. J. C 83 (2023) 774**) → See Back Up
- H → $\gamma\gamma$ + c (**arXiv:2407.15550 (hep-ex)**)
- H → Zγ combination measurement ATLAS + CMS (**Phys. Rev. Lett. 132 (2024) 021803**)
- STXS + Fiducial, H → ττ (**arXiv:2407.16320**)
- VH, H → ττ (**Phys. Lett. B 855 (2024) 138817**)
- VBF VH, H → bb (**arXiv:2402.00426**)
- ttH, H → bb (**arXiv:2407.10904**) → See Stephano Passaggio's talk
- VH, H → bb + H → cc (**ATLAS-CONF-2024-010**) → See Stephano Passaggio's talk

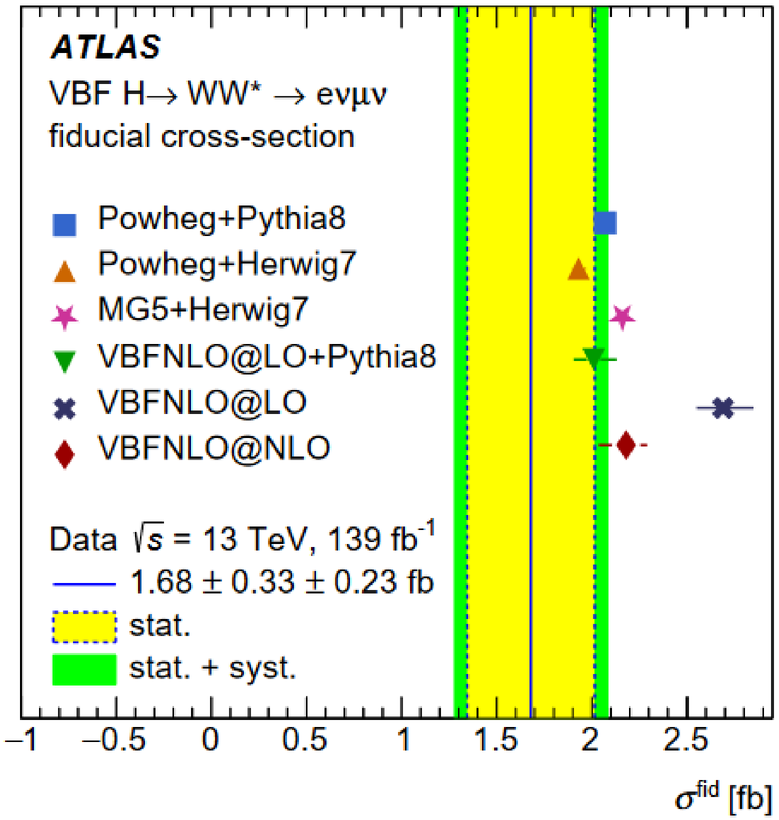
Run 3

- H→ $\gamma\gamma$ (**ATLAS-CONF-2023-03**)
- H → ZZ → 4l combined with H→ $\gamma\gamma$ (**Eur. Phys. J. C 84 (2024) 78**)

Overview of Recent Results using Run 2 data

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

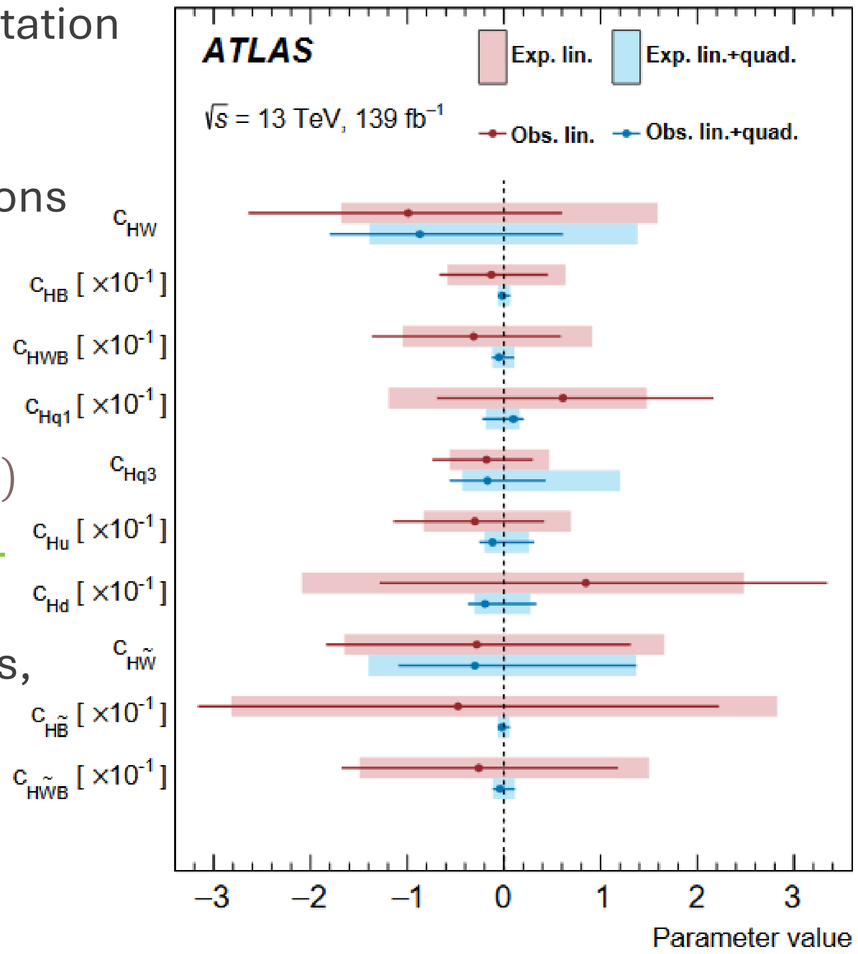
- Data: 139 fb^{-1}, full ATLAS Run 2
- Measurements: Fiducial single + inclusive cross sections, SMEFT interpretation
- Final states with >= 2 jets are considered
- VBF production – direct probe of Higgs coupling to W/Z bosons
- Simultaneous binned likelihood fit of MVA discriminants in kinematic regions



$$\sigma \propto |M_{EFT}|^2 = \left| M_{SM} + \sum_i \frac{c_i}{\Lambda^2} M_i \right|^2$$

$$= |M_{SM}|^2 + 2\sum_i \frac{c_i}{\Lambda^2} \mathrm{Re}(M_{SM}^* M_i) + \sum_{i,j} \frac{c_i c_j}{\Lambda^4} \mathrm{Re}(M_i^* M_j)$$

CP-sensitive through rate modifications, theory-dependent

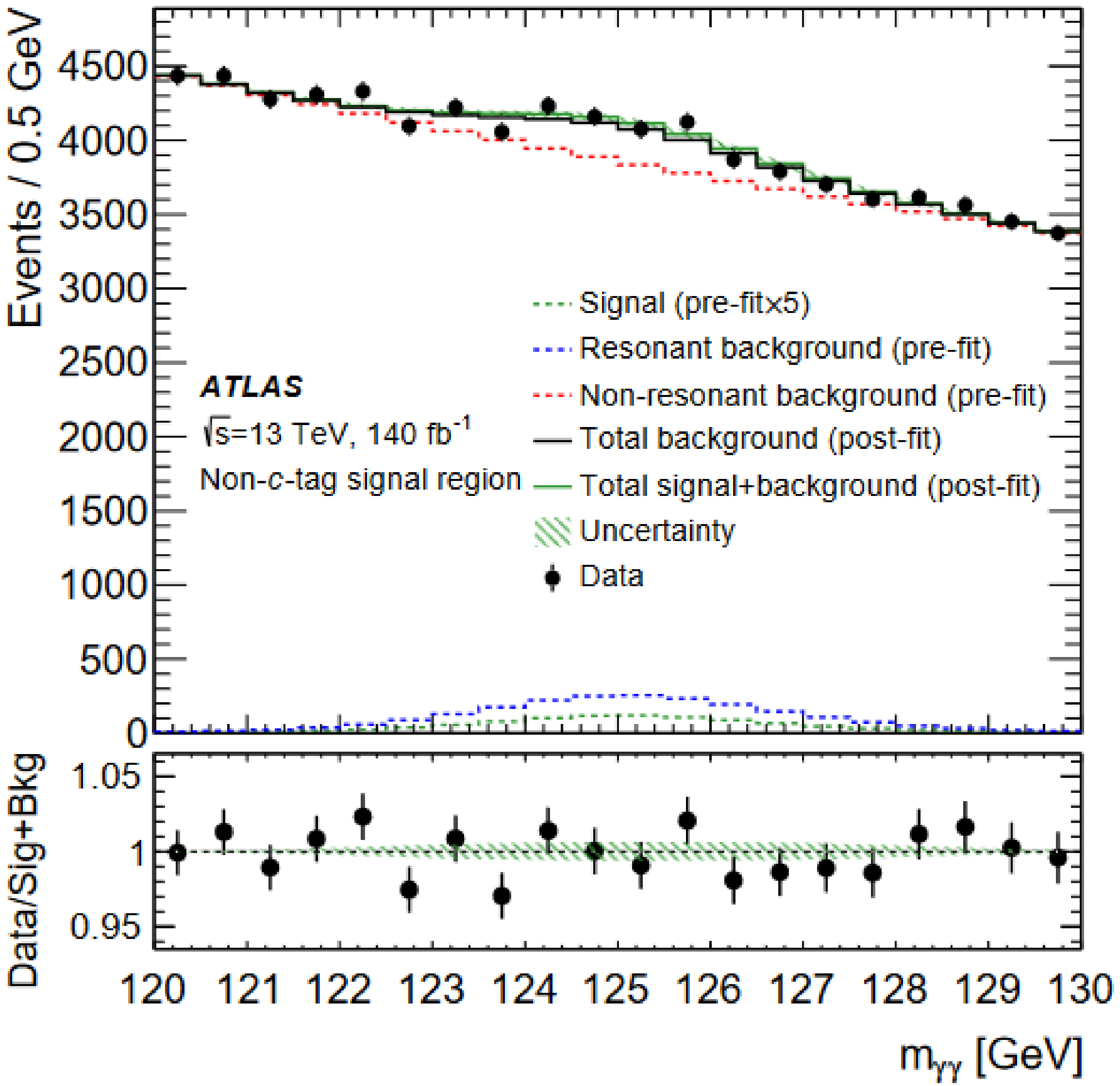


Measurements are consistent with the SM

H→ γγ + c

arXiv:2407.15550 (hep-ex)

- Data: 139 fb^{-1}, full ATLAS Run 2
- Measurement: σ in full phase space
- Only accessible second-generation quark Yukawa coupling but difficult to probe:
  - This process has low yield in SM
  - It has an important hadronic background
    => use of the clean diphoton decay mode
- Fit: Approach based on Gaussian process regression to model the non-resonant diphoton background



First direct constraint on the **inclusive** *H* + *c* cross-section:

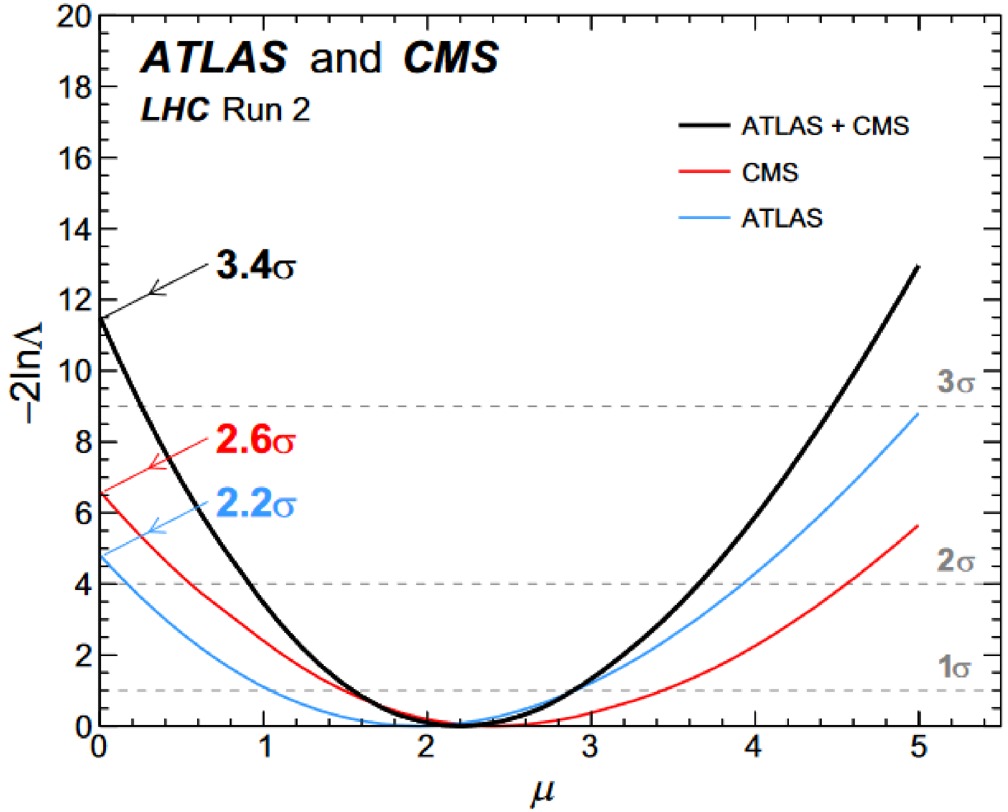
$$\boldsymbol{\sigma_{H+c} = 5.2 \pm 3.0\ pb}$$

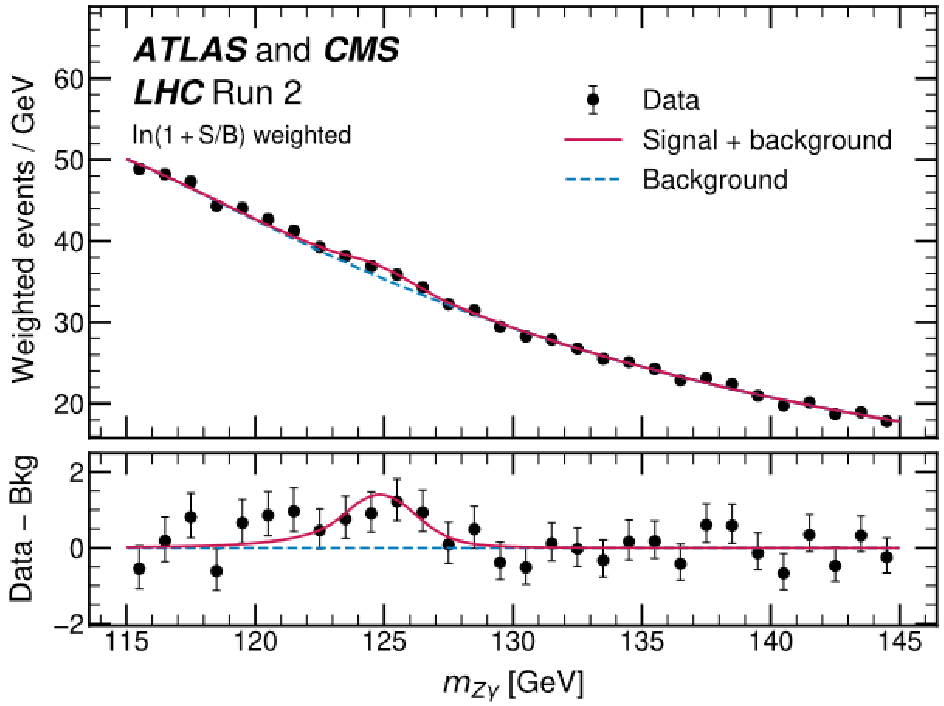
$$(\sigma_{SM} = 2.9\ pb)$$

H→Zγ combination measurement ATLAS + CMS

Phys. Rev. Lett. 132 (2024) 021803

- Data: 140 fb^{-1} for each experiment, full ATLAS + CMS Run 2
- Measurement: Combined analysis of the searches performed by ATLAS and CMS, σ in full phase space
- Decay occurs via loop diagram => sensitive to several BSM scenarios that would lead to an increase of the BR
- Final state: Z decays into electron or muon pairs





BR(H→Zγ) = (3.4 ± 1.1) x 10^{-3}

BR$(H\to Z\gamma)_{SM}$ = (1.5 ± 0.1) x 10^{-3}

In agreement with SM predictions within 1.9σ

First evidence of H→Zγ!

STXS + Fiducial, H→ττ

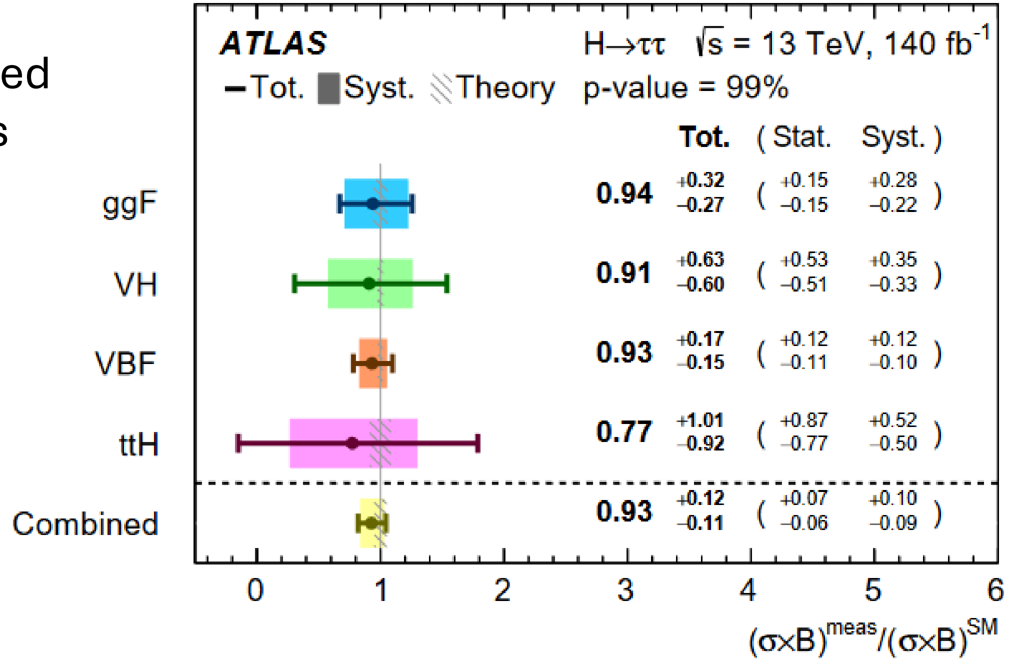
arXiv:2407.16320

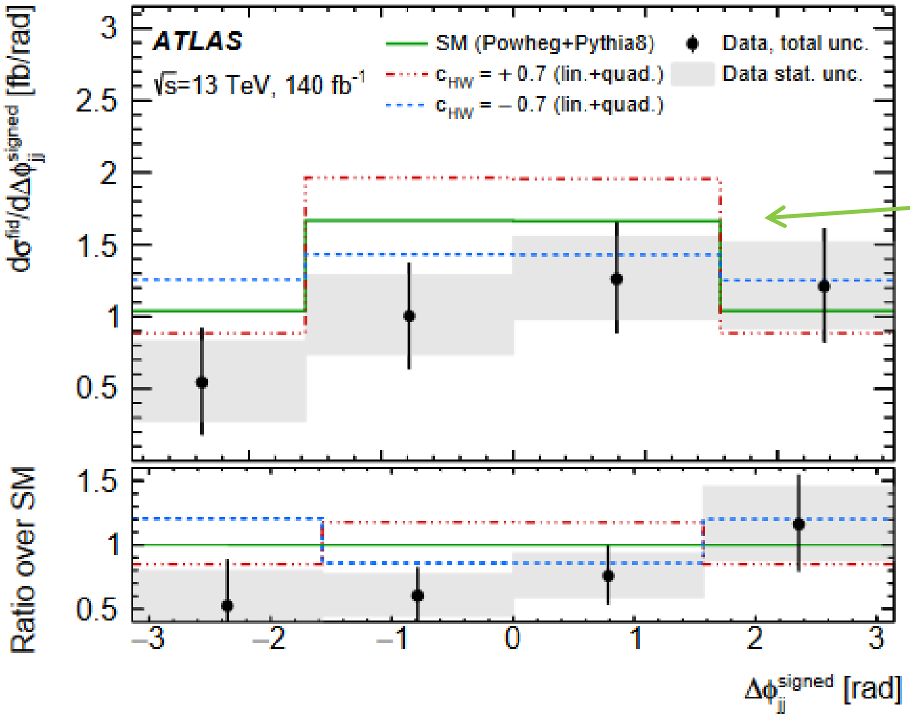
- Data: 140 fb^{-1}, Full ATLAS Run 2
- Measurements: σ in full phase space in STXS framework, unfolded fiducial differential σ in VBF phase space, SMEFT interpretations
- STXS: Categorized in p_T^H, n_{Jets}, m_{jj} regions

$$\mu_{VBF} = 0.93^{+0.17}_{-0.15}$$

=> Good agreement with SM

Most precise single measurement of VBF





CP-odd effective coupling

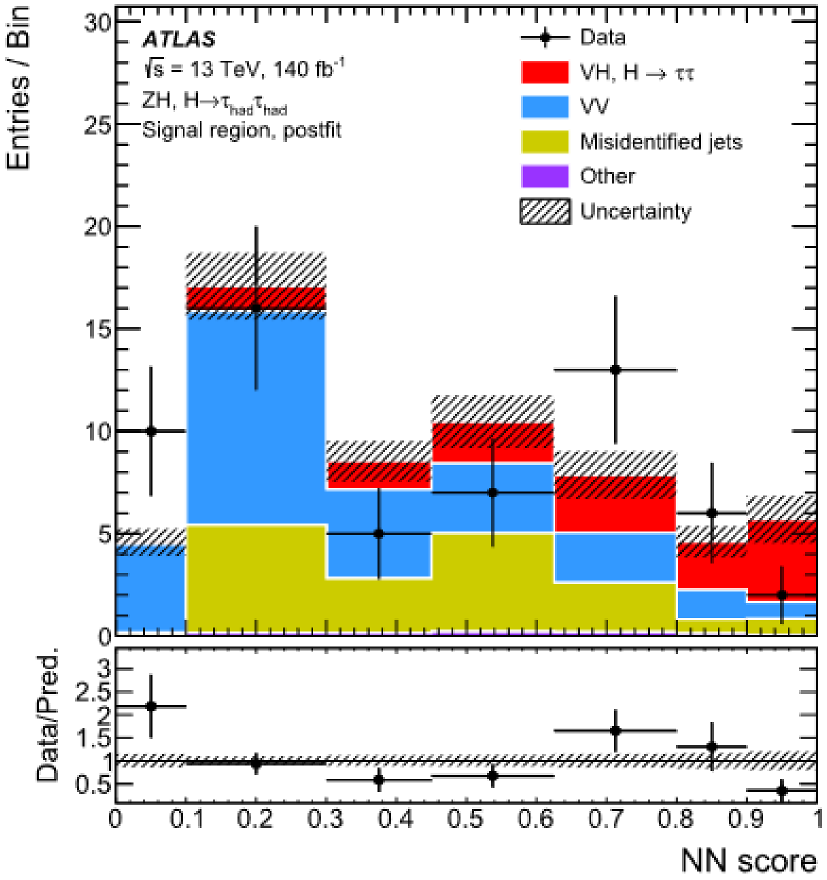
- Fiducial: Binned as function of observables sensitive to SMEFT effects e.g. $\Delta\phi_{jj}^{signed}$
- σ measurement is in good agreement with the SM
- Variables used to unfolded the mass distribution are sensible to Wilson coefficients

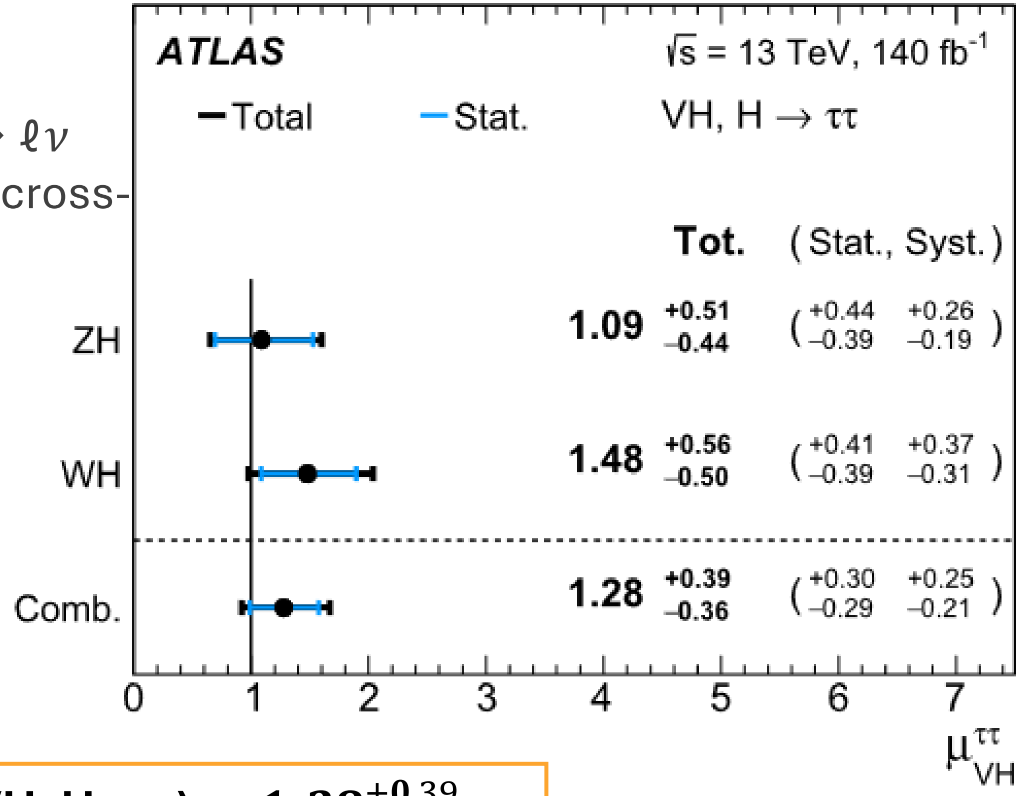
-0.31 < $c_{H\widetilde{W}}$ < 0.88 at 95% CL => Best constraint so far!

VH, H→ττ

Phys. Lett. B 855 (2024) 138817

- Data: 140 fb^{-1}, full ATLAS Run 2
- Measurements: σ in full phase space
- Channel: At least 1 τ-lepton decaying hadronically + Z→ $\ell\ell$ and W → $\ell\nu$
- Fit to a NN classifiers score distribution + mass-based analysis for cross-checking





$$\mu(\text{VH, H→ττ}) = 1.28^{+0.39}_{-0.36}$$

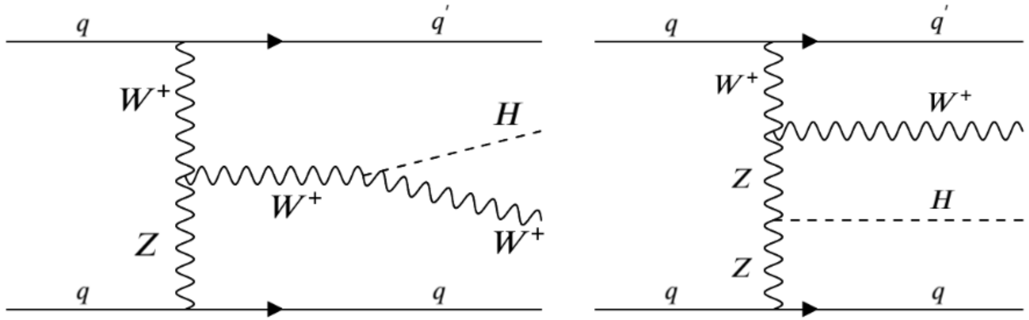
Measurement consistent with SM

=> Limitation by the data sample size

=>Improvement to see with Run 3

VBF VH, H→bb

arXiv:2402.00426



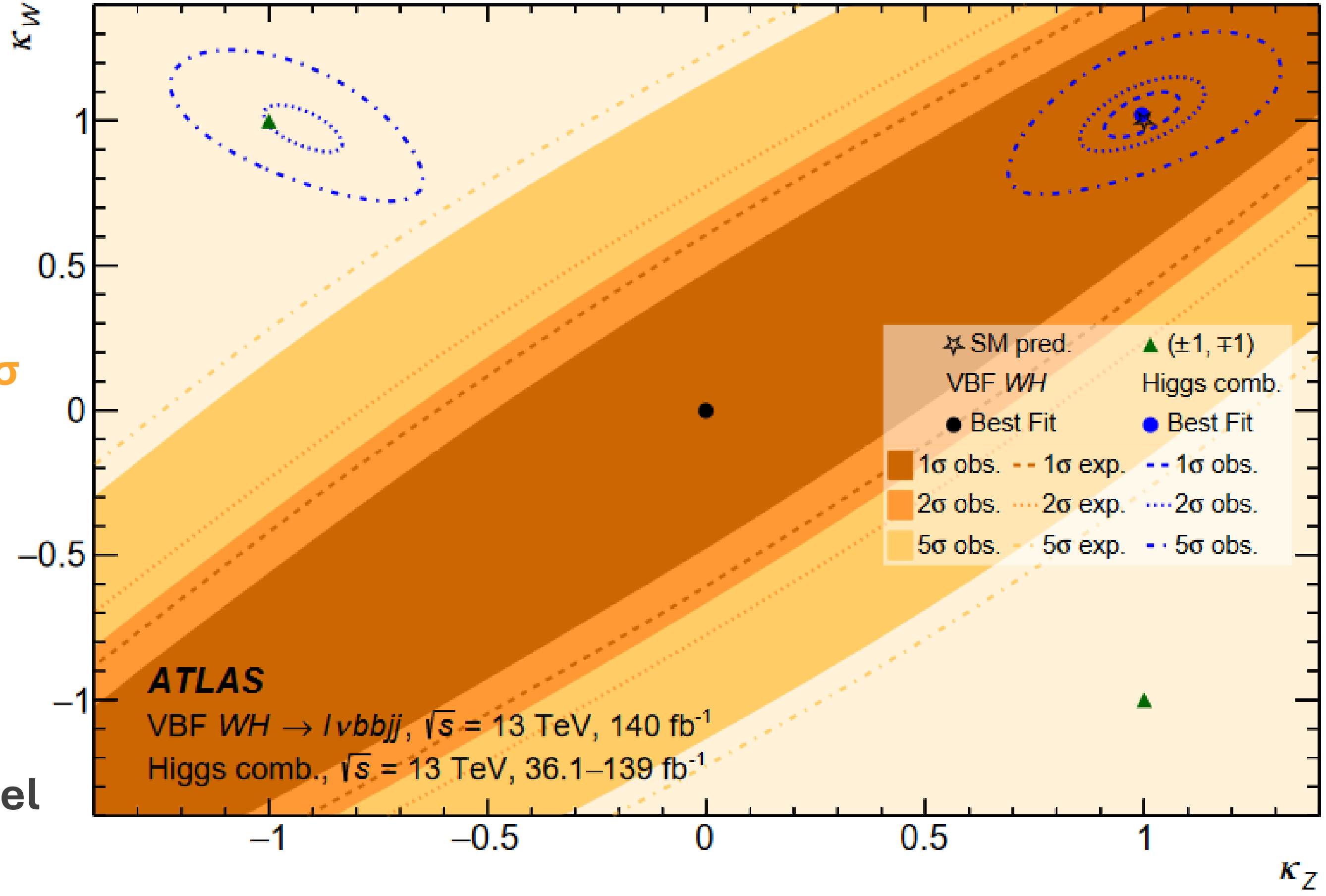
- Data: 140 fb^{-1}, full ATLAS Run 2
- Measurements: σ in full phase space, kappa framework
- Goal: Measure the relative sign of H couplings to W and Z : $\lambda_{wz} = \kappa_W/\kappa_z$
  - $\lambda_{wz} \neq 1$ -> BSM
- Final states: H→bb and Z → $\ell\ell$ and W → $\ell\nu$
- Two separate analyses:
  - Negative λ_{wz}: works with BSM scenarii

Opposite sign excluded with significance > 5σ

  - Positive λ_{wz}: works with SM-like scenario

Observed (expected) upper limit on σ is 9.0 (8.7) times the SM value

Measurements consistent with the Standard Model

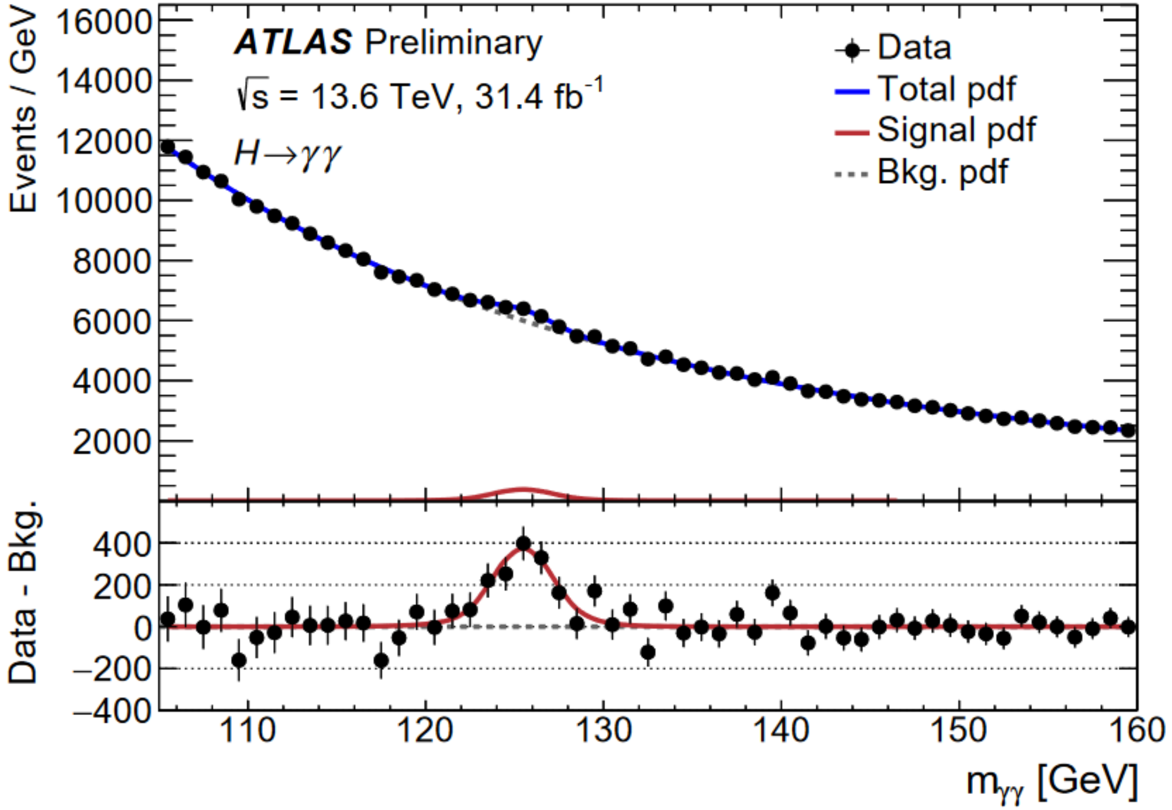


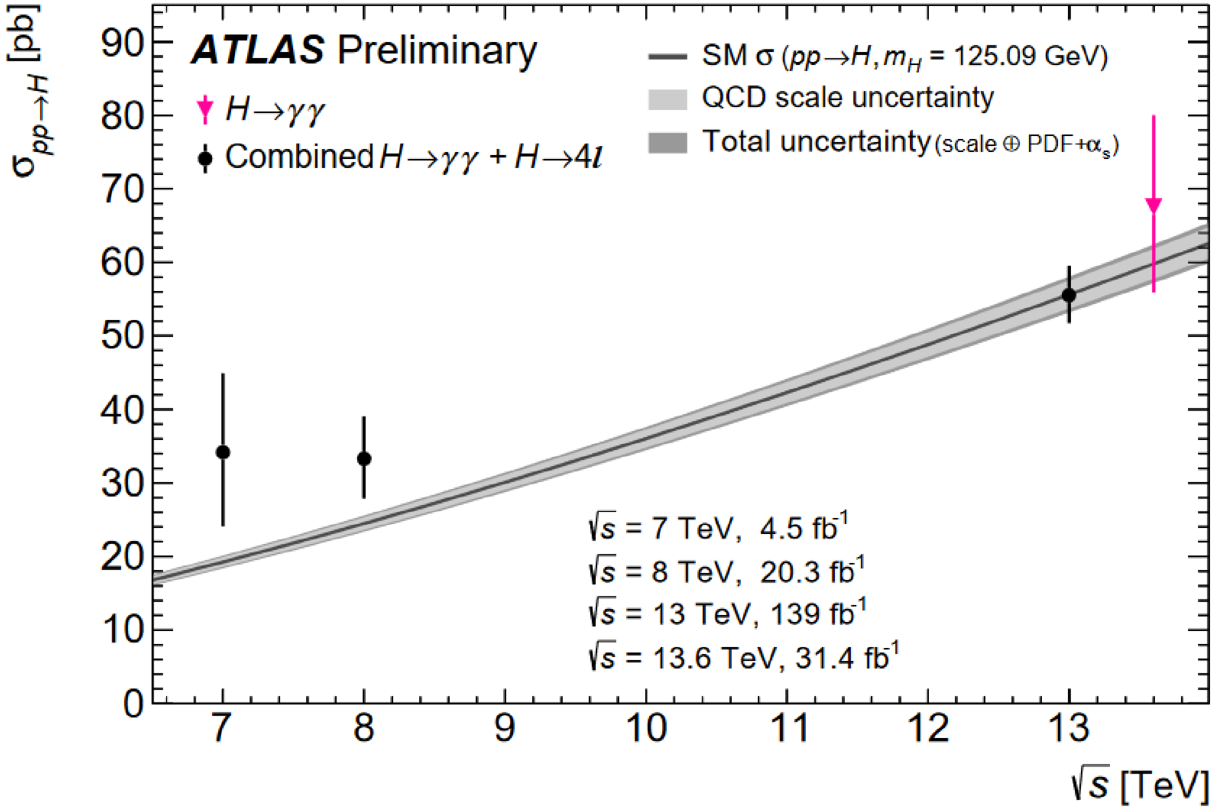
Overview of Recent Results using Run 3 data

H→γγ

ATLAS-CONF-2023-03

- Data: 31.4 fb^{-1} @13.6 TeV (H→γγ)
- Measurement: Fiducial σ, shape analysis using $m_{\gamma\gamma}$ distribution
- Measurement in fiducial phase space and extrapolation to full phase space yielding



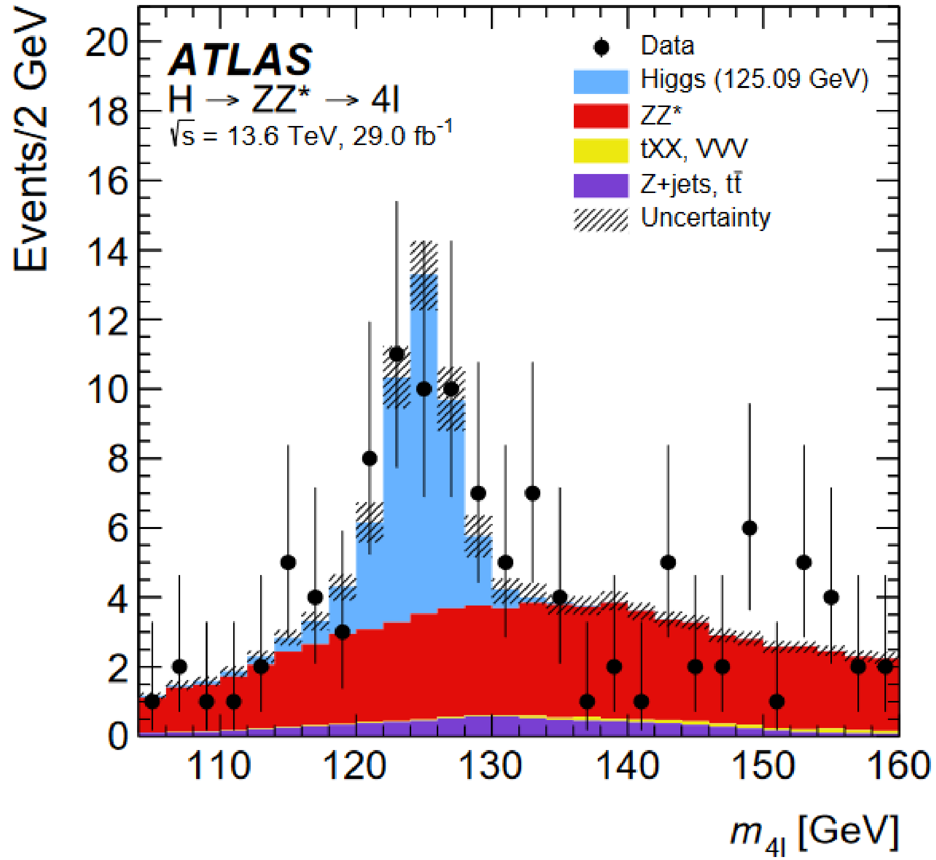


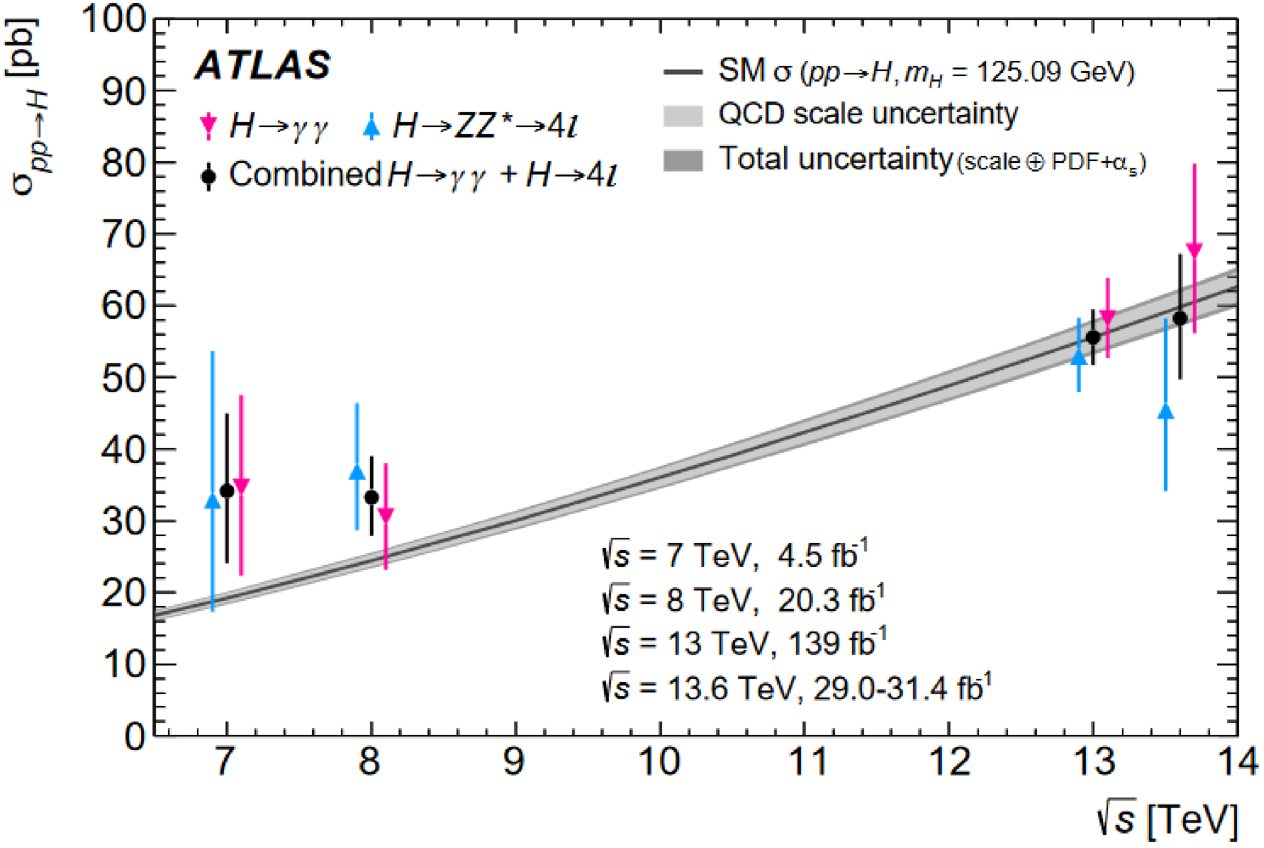
Good agreement with the SM

H→ZZ→4l combined with H→γγ

Eur. Phys. J. C 84 (2024) 78

- Data: 31.4 fb^{-1} @13.6 TeV (H→γγ) & 29.0 fb^{-1} @13.6 TeV (H→ZZ→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 the SM at unprecedent 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
- Many more to come in the next years!

- All results are consistent with the Standard Model
- Dataset of LHC is expected to increase by a factor of 20 by 2040

Thank you!

Back Up

ggF, H→WW* →$e\nu\mu\nu$

Eur. Phys. J. C 83 (2023) 774

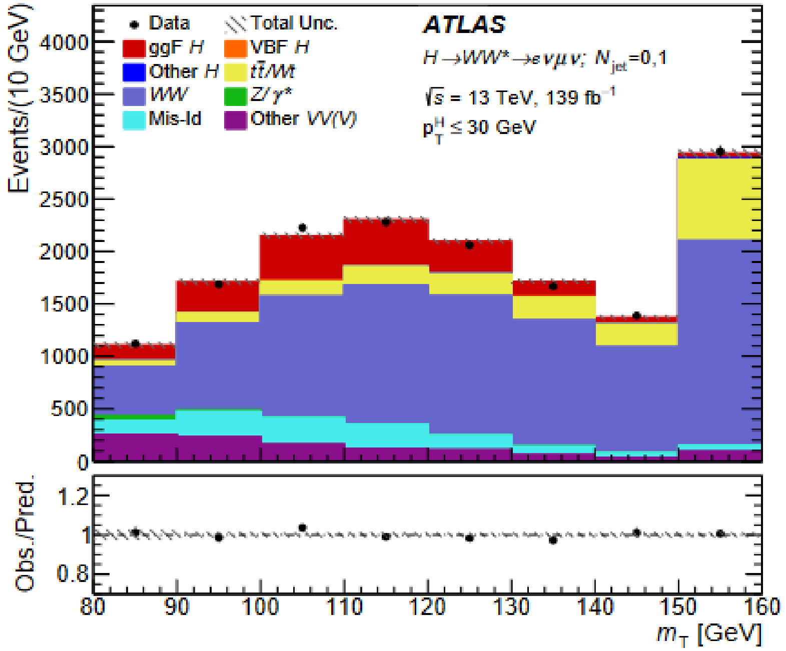
- Data: 139 fb^{-1}, full ATLAS Run 2
- Measurements: Fiducial single + double differential σ
- Final states with ≤ 1 jets are considered
- Fit is performed to m_T in each bin of each observable which sensitive to higher-order corrections (e.g. nJets), PDF (e.g. y_H), Higgs couplings in production (e.g. p_T^H) and decay (e.g. m_{ll})

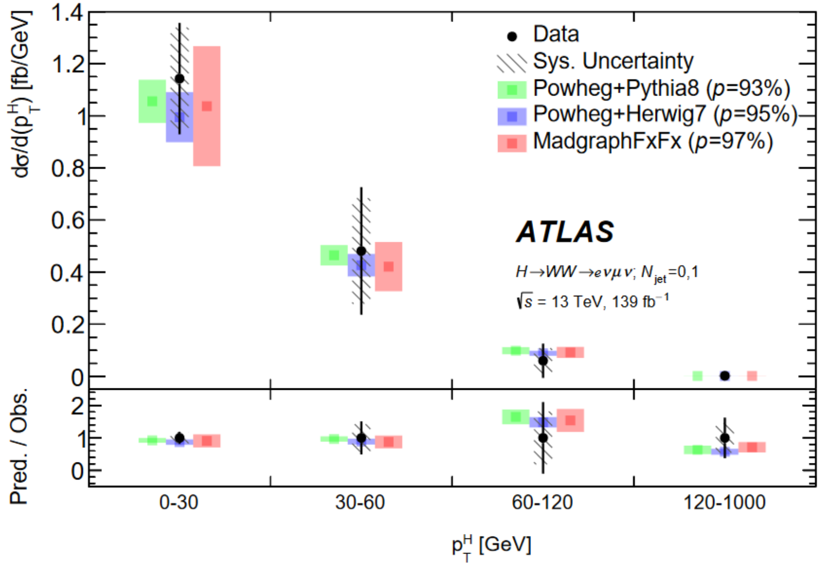
$$m_T = \sqrt{\left(E_T^{ll} + E_T^{miss}\right)^2 - \left|\boldsymbol{p}_T^{ll} + \boldsymbol{E}_T^{miss}\right|^2}$$

Dominant sources of uncertainty:

- Jet, muon reconstruction
- t, WW backgrounds
- Difficulty in modelling Z/γ

Measurements are consistent with the SM





ggF, H→WW* →$e\nu\mu\nu$

Eur. Phys. J. C 83 (2023) 774

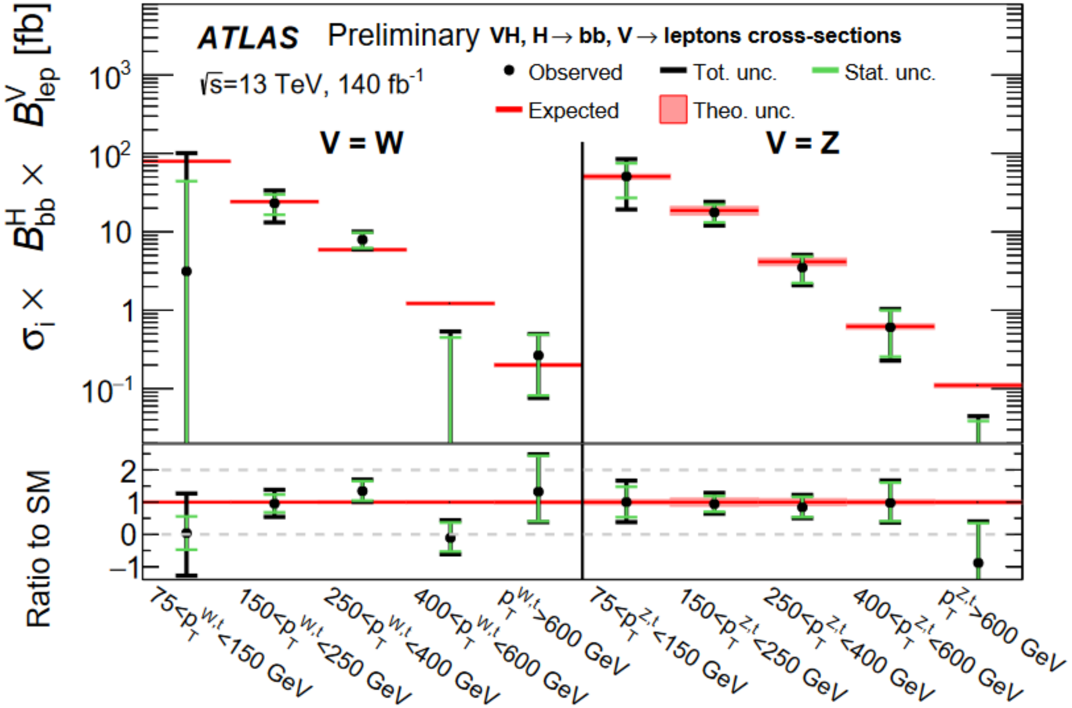
Variable	Data Statistical [%]	MC Statistical [%]	Experimental [%]	Theory [%]
$y_{\ell\ell}$	14–22	5.3–10	6.9–15	5.9–15
$p_T^{\ell\ell}$	15–29	6.4–14	8.2–31	6.8–27
$p_T^{\ell 0}$	13–28	6.3–13	9.3–28	14–34
$\Delta\phi_{\ell\ell}$	11–39	6.1–18	7.8–22	13–27
y_{j0}	23–51	12–26	21–54	26–58
$\cos\theta^*$	11–15	5.8–7.6	8.5–11	8.9–14
p_T^H	8.5–72	6.2–18	10–58	12–27
$m_{\ell\ell}$	12–25	5.6–11	7.5–15	7.3–20
$y_{\ell\ell}$ vs N_{jet}	9.0–62	3.9–25	8.0–20	5.0–53
$p_T^{\ell\ell}$ vs N_{jet}	9.8–36	4.7–20	12–41	9.9–50
$p_T^{\ell 0}$ vs N_{jet}	9.6–50	5.8–20	10–35	9.4–74
$\Delta\phi_{\ell\ell}$ vs N_{jet}	9.6–65	5.6–18	6.8–31	14–74
$\cos\theta^*$ vs N_{jet}	13–50	6.8–25	7.7–39	8.9–58
$m_{\ell\ell}$ vs N_{jet}	12–152	5.7–44	8.9–58	7.2–82

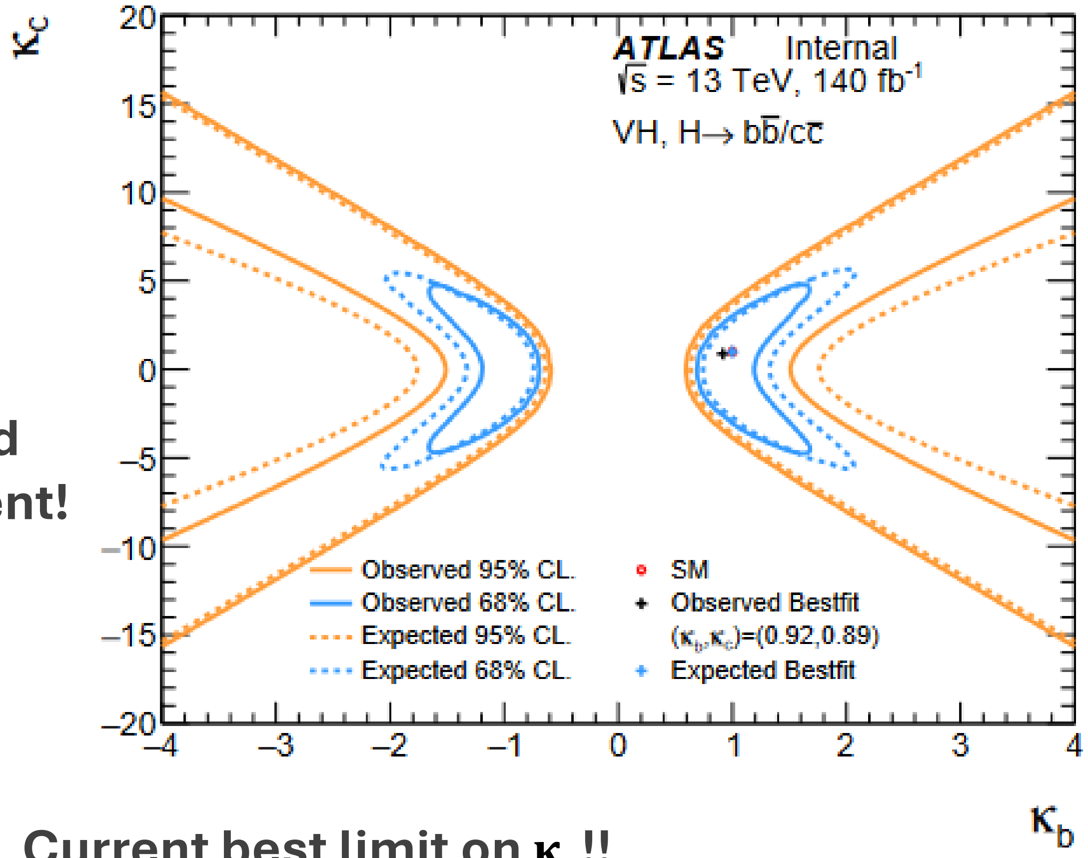
VH, H→bb + H→cc

- Data: 140 fb^{-1}, full ATLAS Run 2
- Measurements: Differential σ with STXS framework, kappa interpretation
- Validation with VZ, Z→bb or cc
- Final state: Z → $\ell\ell$ and W → $\ell\nu$

σ consistent with SM expectations at 90%

$\mu(VH, H\to cc) = \mathbf{1.0^{+5.4}_{-5.2}}$ ← **Best world measurement!**





Current best limit on κ_c!!

↓

$|\kappa_c| < 4.2\ (|\kappa_c|_{expected} < 4.2)$

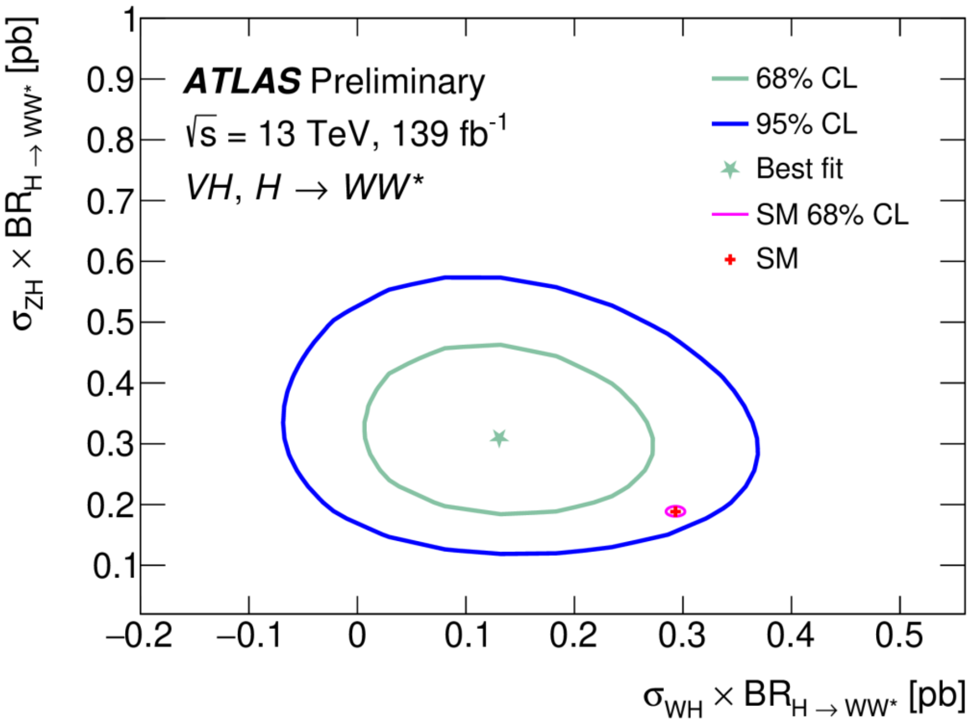
$0.67 < |\kappa_b| < 1.38\ (0.72 < |\kappa_b|_{expected} < 1.56)$

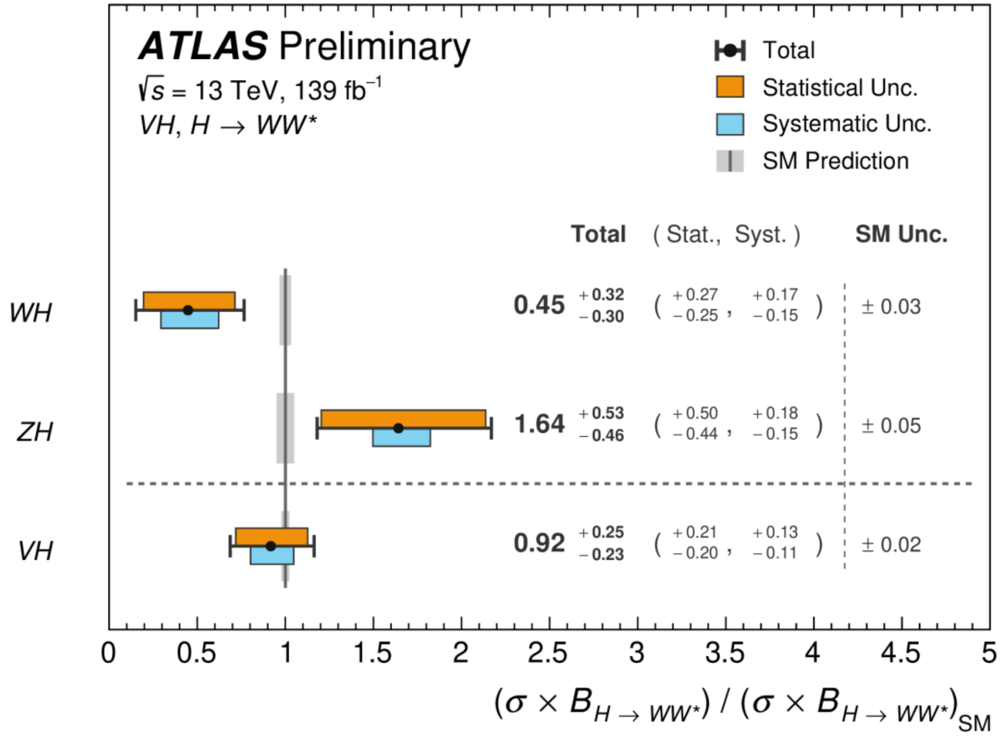
VH, H→WW* → $\ell\nu\ell\nu + \ell\nu jj$

- Data: 139 fb^{-1}, full ATLAS Run 2
- Performed in 4 channels
- Different MVA discriminants adapted to background composition are used
- Used input variables based on reconstructed objects kinematics

  e.g. $E_T^{miss}, m_T^W, p_T^{l_0}$
- Measurements are stats dominated

Measurements consistent with SM

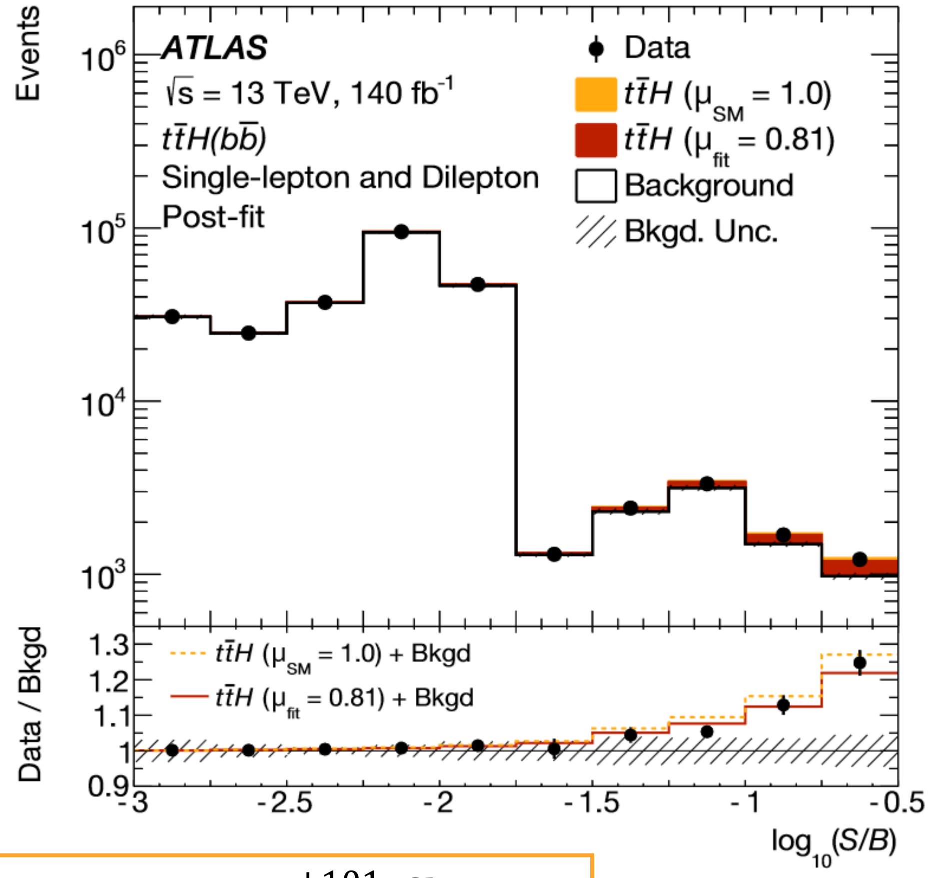


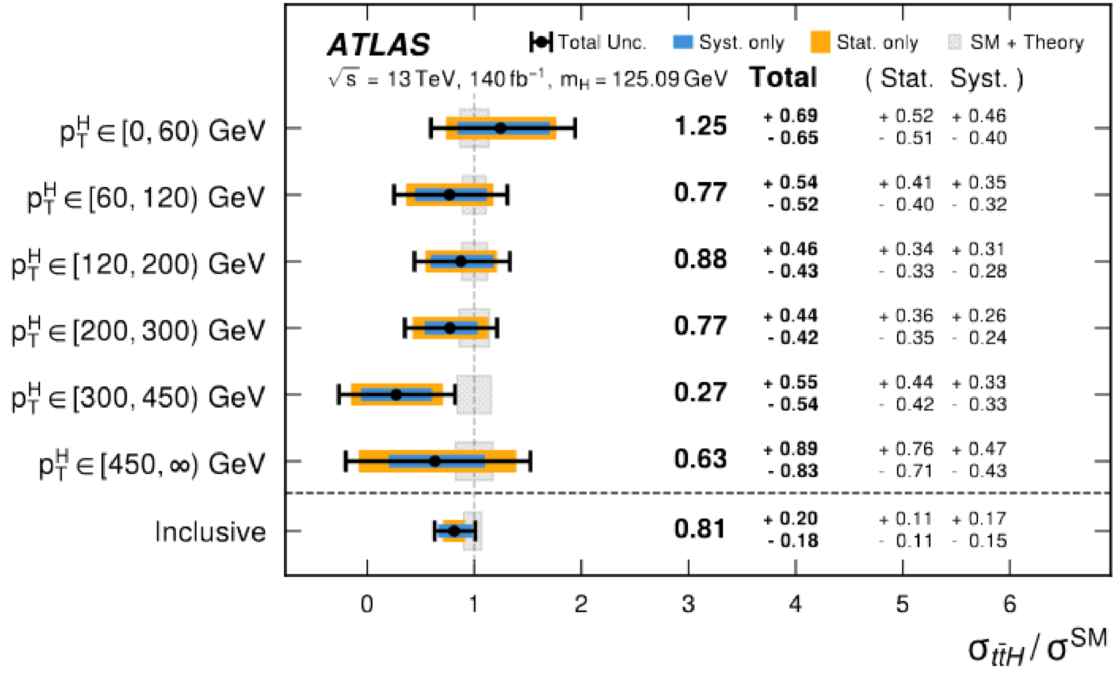


ttH, H→bb

arXiv:2407.10904

- Data: 140 fb^{-1}, full ATLAS Run 2
- Measurement: Inclusive σ in full phase space, STXS
- Final state: single + dilepton channels
- Fit: Classification in p_T^H bins by a multiclass NN; reconstruction of p_T^H and separation signal to background by a MVA





$\sigma(\text{ttH}) = 411^{+101}_{-92}\ fb$

$\sigma(\text{ttH})_{SM} = 507^{+35}_{-50}\ fb$

Consistent with SM => Test SM in extreme phase-space