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

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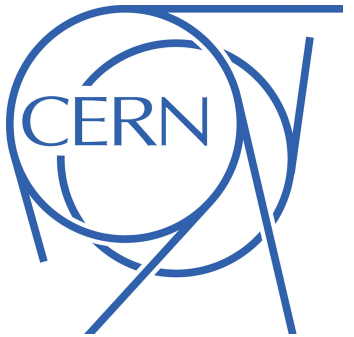
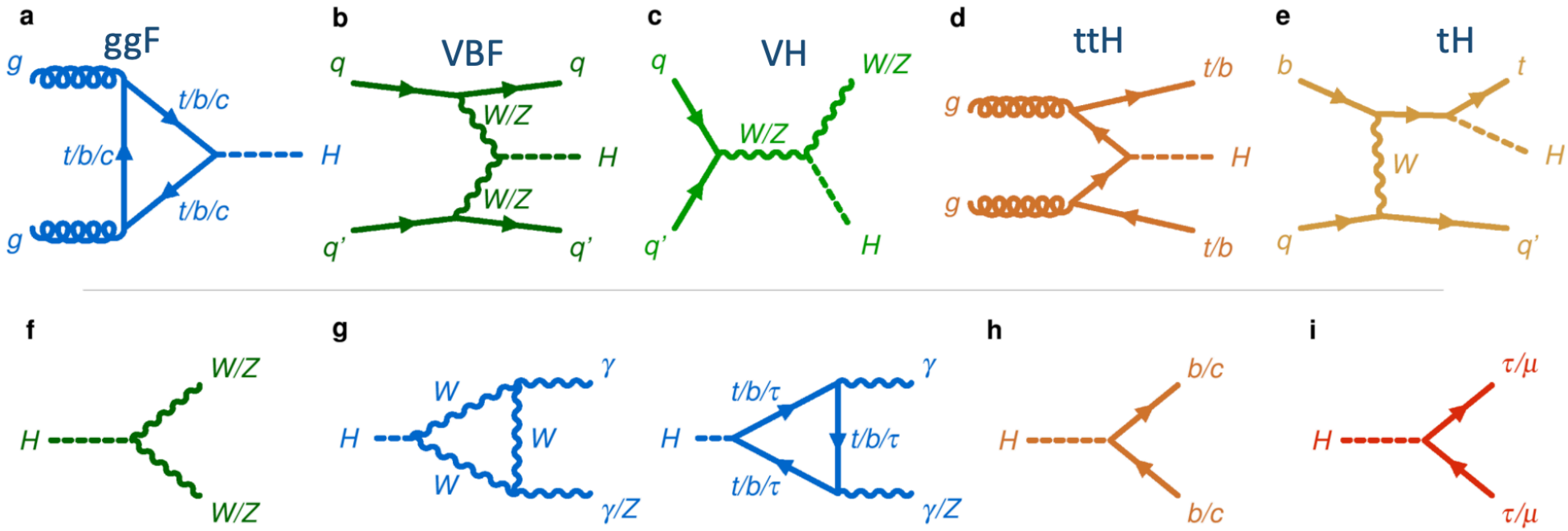
On behalf of the ATLAS collaboration

ICHEP, 2024, Prague

# Overview of Higgs Production and Decay




- Couplings are probed both in production and decay
- Loop contributions are in many cases more important for testing BSM theories
- Gluon-gluon fusion (ggF) the dominant production mode
- Vector boson fusion (VBF) subdominant
- ttH offers direct measurement of top –Higgs coupling

# Cross sections

Full Phase Space

Fiducial Phase Space

## 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**

**➔ Extrapolation to full phase space is required to combine analyses**

## Simplified Template Cross Sections (STXS)

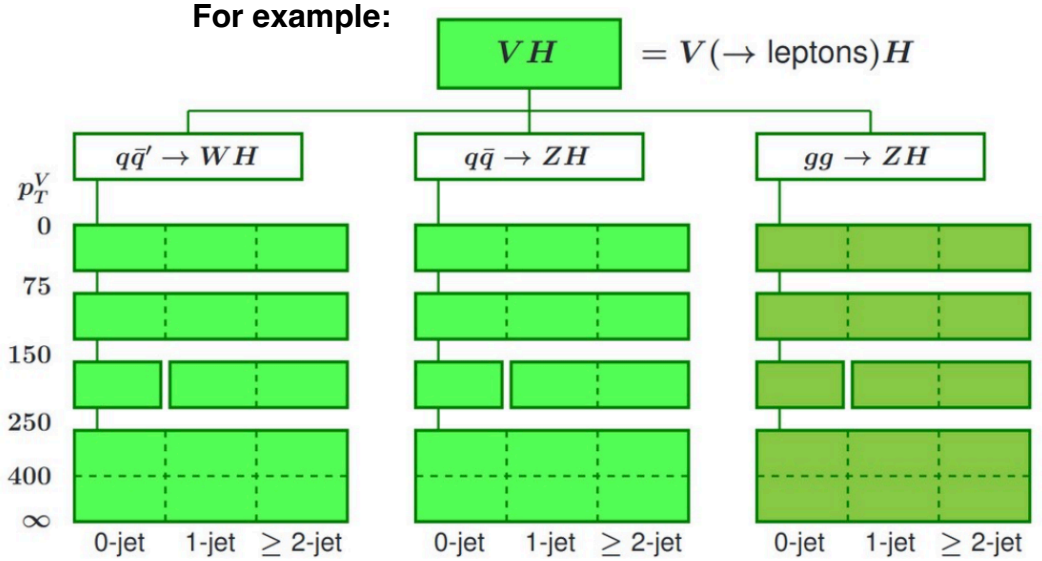
**Multiple non-overlapping phase space regions based on production mode of the Higgs boson, kinematics of the process**

**➔ Reduces theoretical uncertainties**

**➔ Common framework for combination of orthogonal decay channels**

**➔ Large pT bins are sensitive for BSM physics search**

**For example:**




**Defined in stages with increasing granularity**

# Interpretations

- **BSM physics modify the Higgs couplings**
- **Deformations are model dependent, but which model?**
- **Two frameworks** for “parametrising our ignorance”

**Kappa framework**

Coupling of Higgs to p is modified by $\kappa_p$

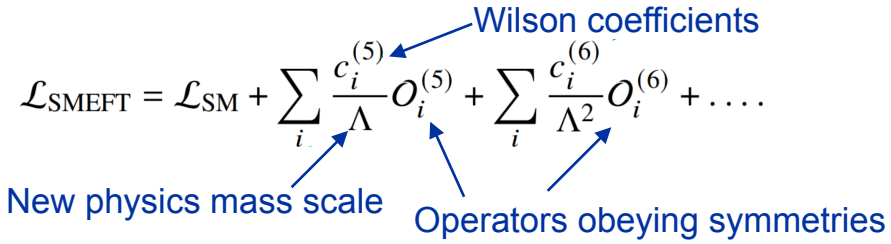
$$\kappa_p^2 = \sigma_p / \sigma_p^{SM_p} \text{ (for production)}$$
$$\kappa_p^2 = \Gamma_p / \Gamma_p^{SM_p} \text{ (for decay)}$$

$$\kappa_p = 1 \rightarrow \text{SM}$$

For loop induced processes sometimes use effective modifiers, eg: $\kappa_{Z/\gamma}$

**Usually assumes tree-level coupling structure of the SM**

**SM Effective Field Theory (SMEFT)**



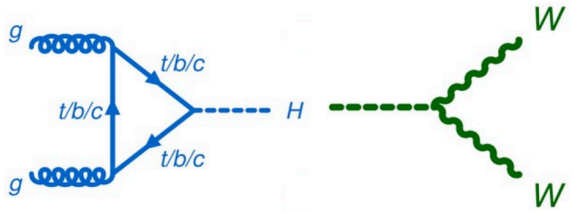

d=5,7 operators introduce lepton/baryon number violation

=> focus on d=6 operators

**Allows any coupling that doesn’t violate symmetries**

# Overview of Recent Results

# ggF H→WW* → evμv




**Data: 139 fb-1, full ATLAS Run 2**

**Measurements: Fiducial single + double $d\sigma$**

**Final states with <=1 j are considered**

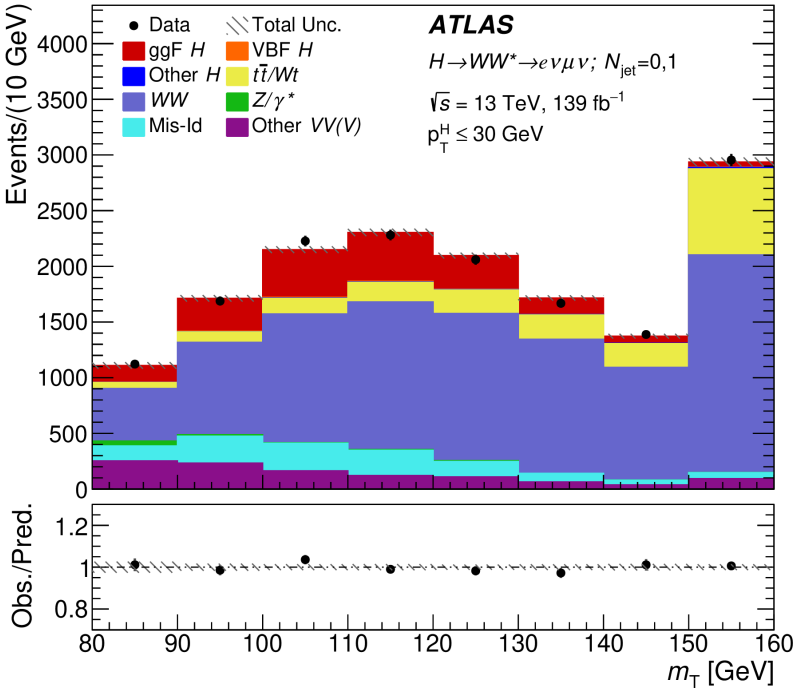
**Fit is performed to $m_T$ in each bin of observable which sensitive to higher-order corrections (eg. nJets), PDF (eg. yH), Higgs couplings in production (eg. pTH) and decay (eg. mll)**

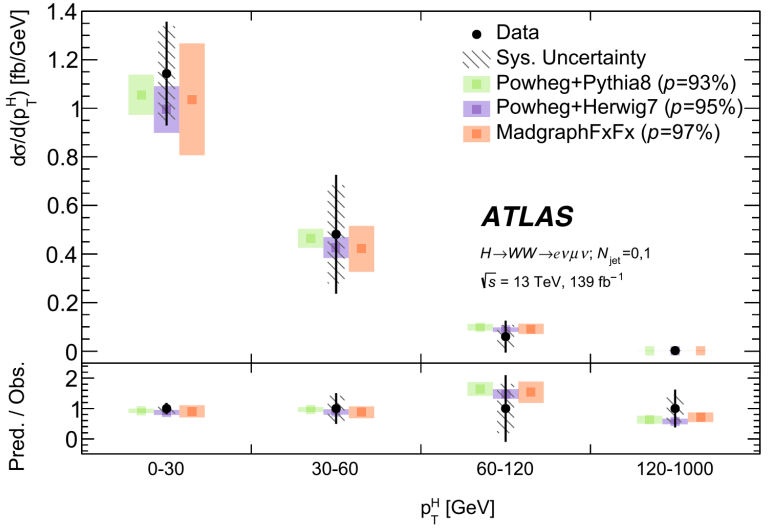
$$m_T = \sqrt{\left(E_T^{ll} + E_T^{\text{miss}}\right)^2 - \left|\mathbf{p}_T^{ll} + \mathbf{E}_T^{\text{miss}}\right|^2} \qquad E_T^{ll} = \sqrt{\left|\mathbf{p}_T^{ll}\right|^2 + m_{ll}^2}$$

**Dominant sources of uncertainty:**

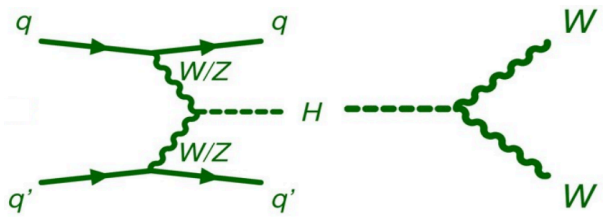
- **Jet, muon reconstruction**
- **t, WW backgrounds**
- **Difficulty in modelling Z/γ**

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



# VBF H→ WW* → evμv




Phys.Rev.D 108 (2023) 7, 072003

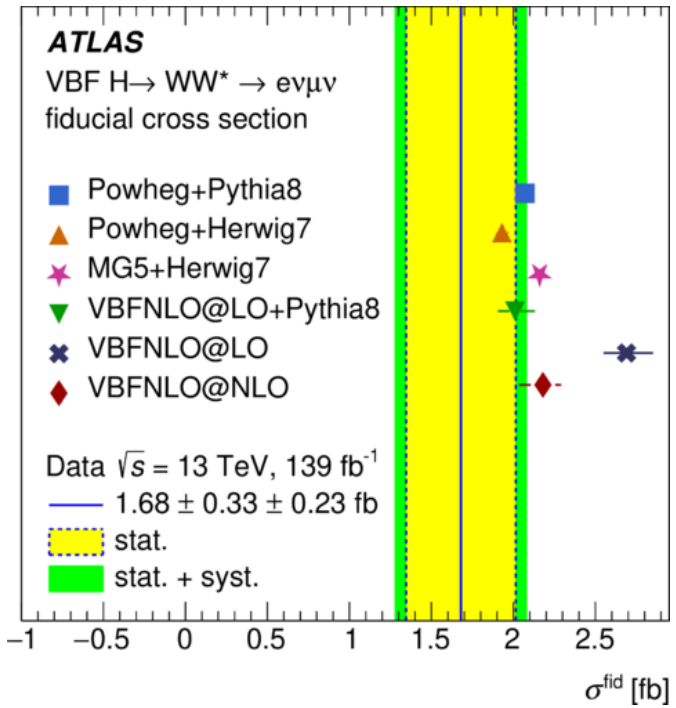
**Data: 139 fb-1, full ATLAS Run 2**

**Measurements: Fiducial single + inclusive cross sections, SMEFT interpretation**

**Final states with >= 2 j are considered**

**VBF - direct probe of Higgs coupling to W/Z bosons**

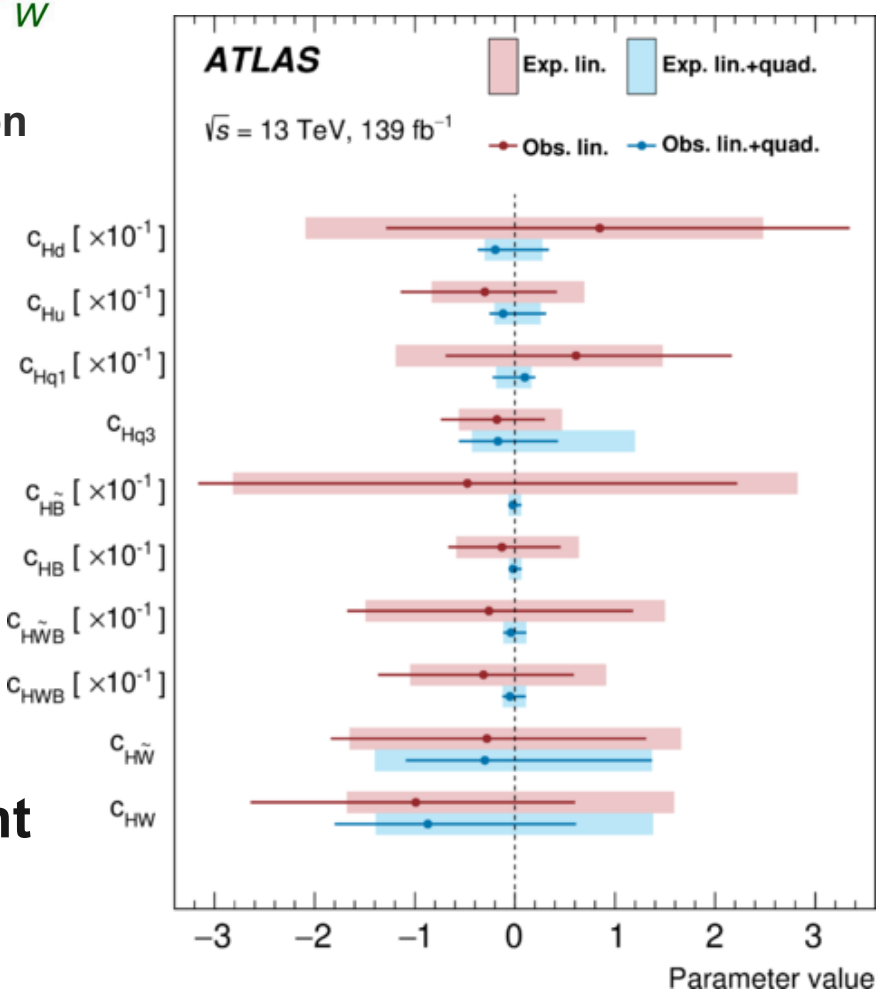
**Simultaneous binned likelihood fit of MVA discriminants in kinematic regions.**




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

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

**quad term:**
**CP-sensitive, theory-dependent**




**Measurements are consistent with the SM**

# H→WW* → eνμν

Phys. Rev. D 108 (2023) 032005

**Data: 139 fb-1, full ATLAS Run 2**

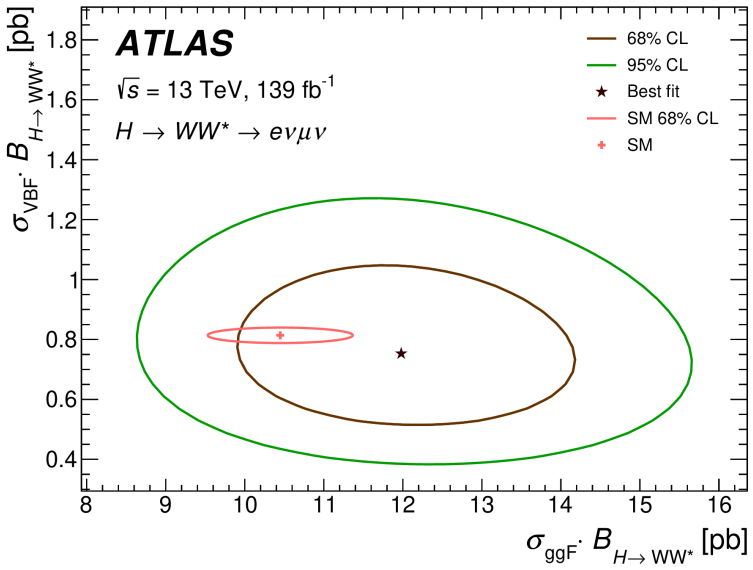
**Measurements: : σ in full phase space, STXS**

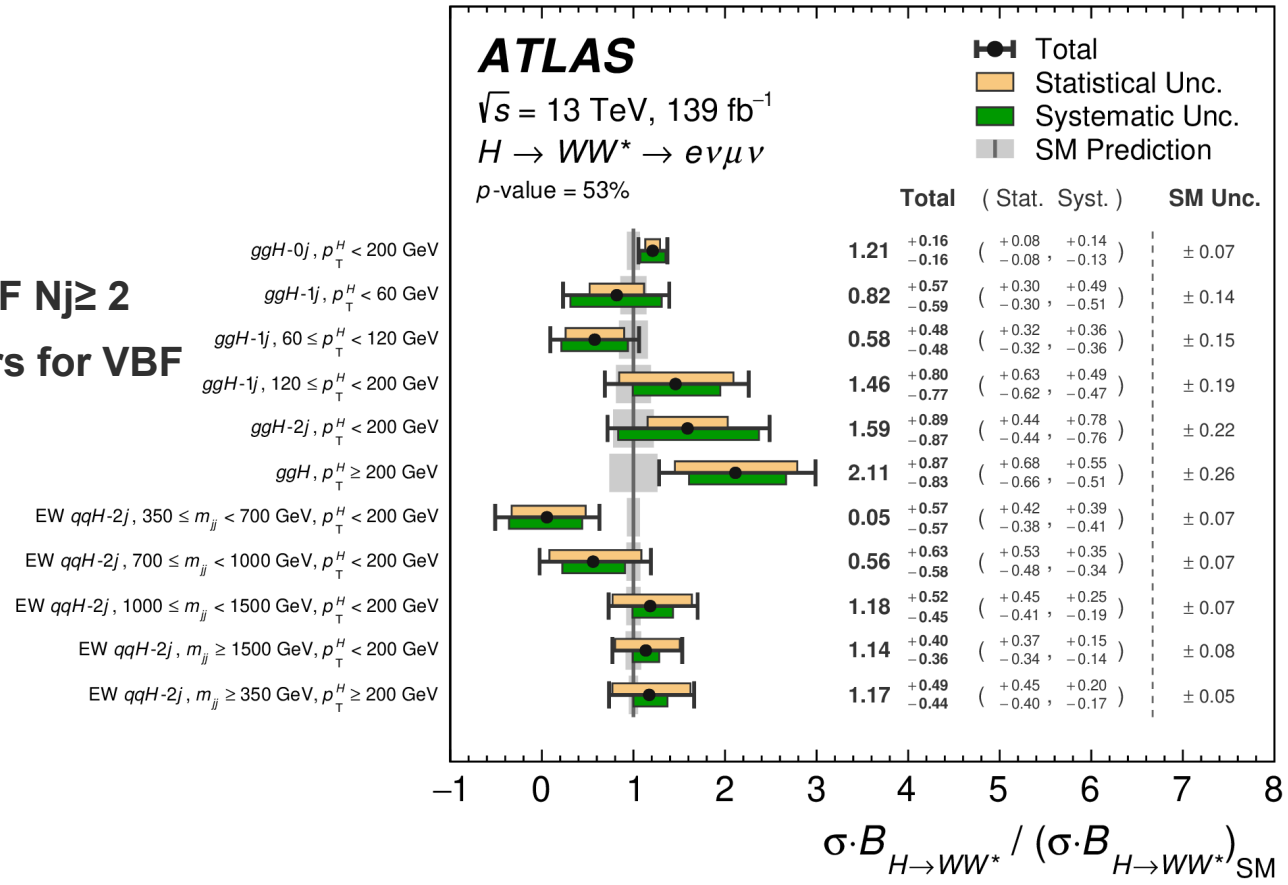
**New from last iteration: (arXiv:1808.09054, 36.1 fb$^{-1}$)**

- **Larger dataset**
- **ggF in ≥ 2 j final state – increase in statistics**
- **Cross section reported in 11 STXS bins**

**Analysis performed in 4 regions – for ggF Nj=0,1,≥2 , for VBF Nj≥ 2**

**Fit to mT in ggF regions, fit to DNN trained on VBF vs. others for VBF**

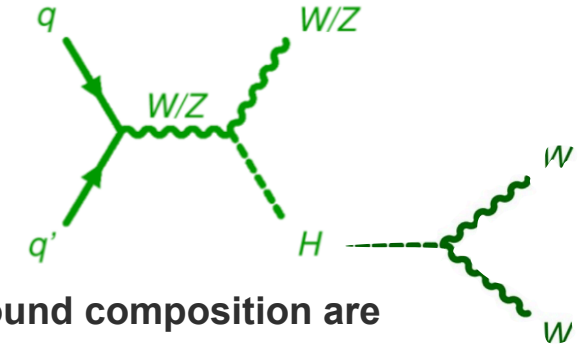



**Measurements are consistent with the SM**

# VH, H→ WW*

ATLAS-CONF-2022-067




**Data: 139 fb-1, full ATLAS Run 2**

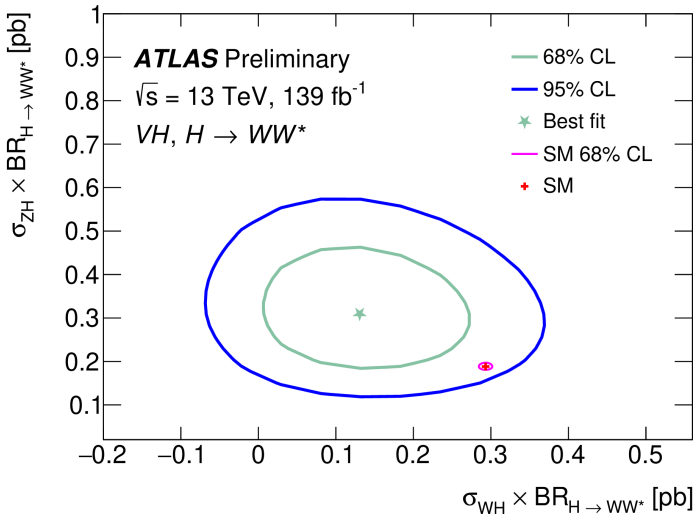
**Measurement: inclusive cross-section**

**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**

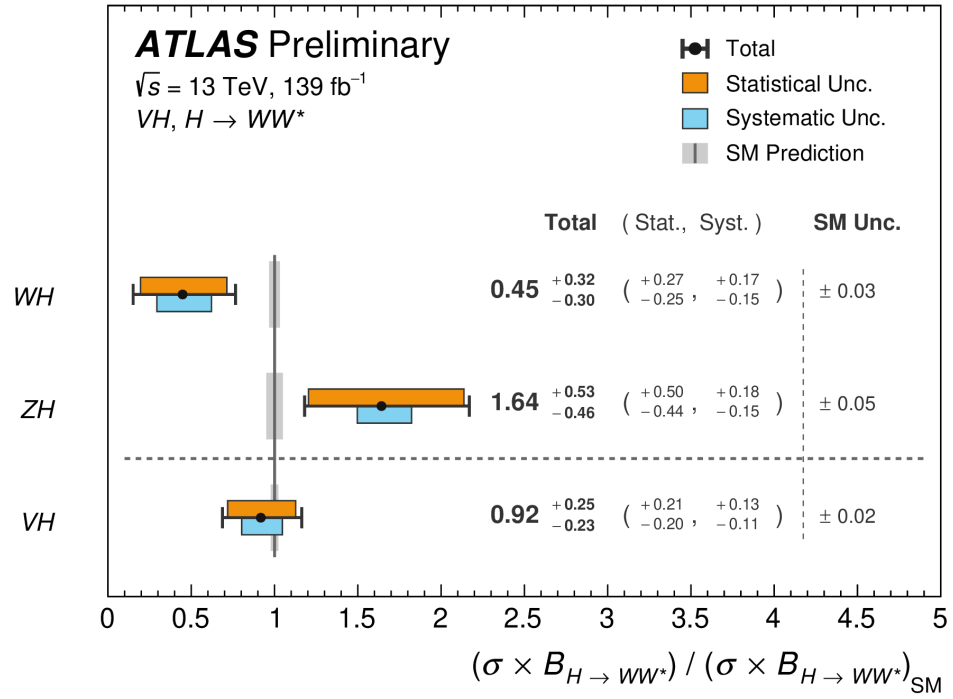
| Channel | Backgrounds |
|---|---|
| OS, 2l | tt, Wt |
| SS, 2l | W(Z/gamma), W+gamma,W+jets |
| 3l | W(Z/gamma), WWW |
| 4l | ZZ, WWZ |




**Measurements are consistent with the SM**

**Dominant systematic uncertainties in WH:**

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

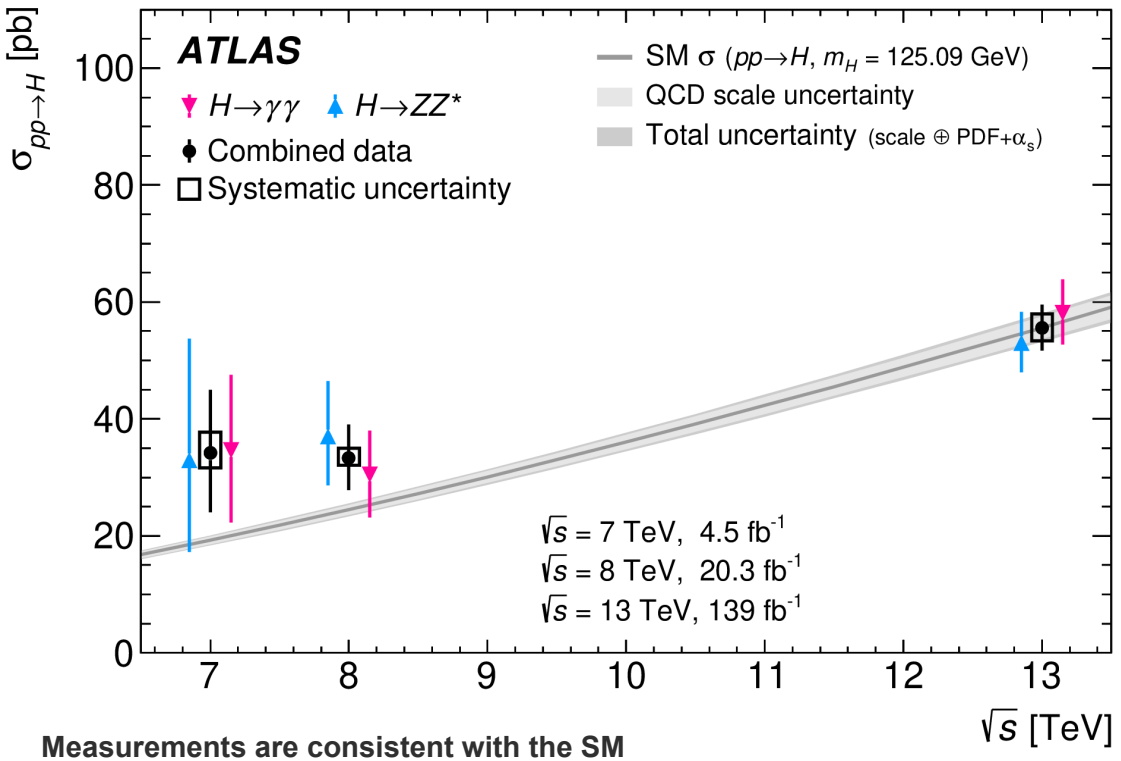


# Combination of differential cross section measurements in H→ZZ*→4l and H→γγ

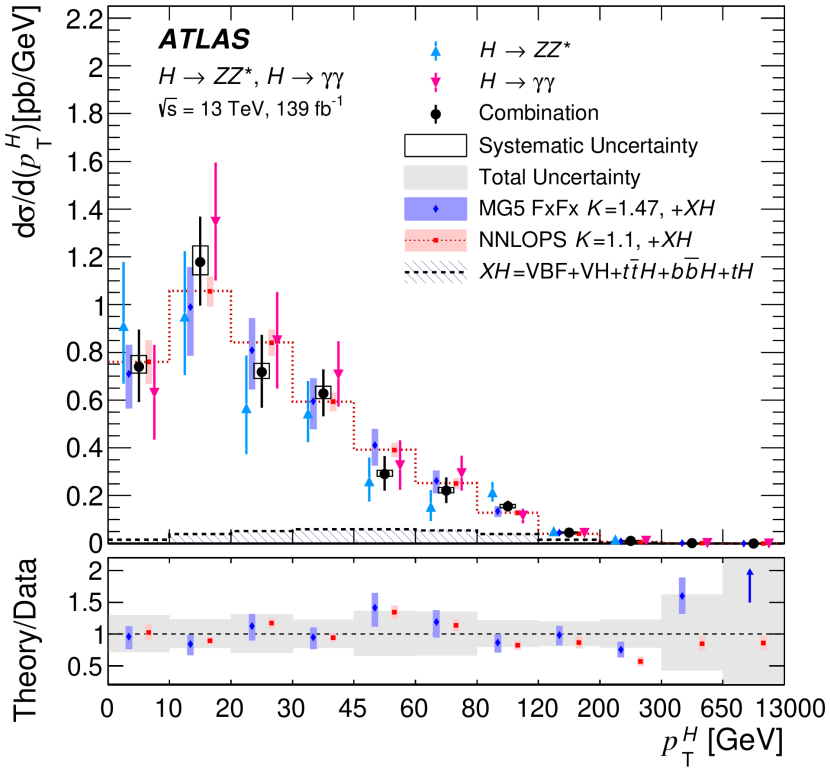
JHEP 05 (2023) 028

**Data: 139 fb-1, full ATLAS Run 2**

- **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 σ(pp→ H) measurement due to larger dataset and combination of channels**
- **Measurement of differential cross sections: $p_T^H$, $|y_H|$, $N_j$, $p_T^{lead.,jet}$ - each probing different aspect of Higgs production**



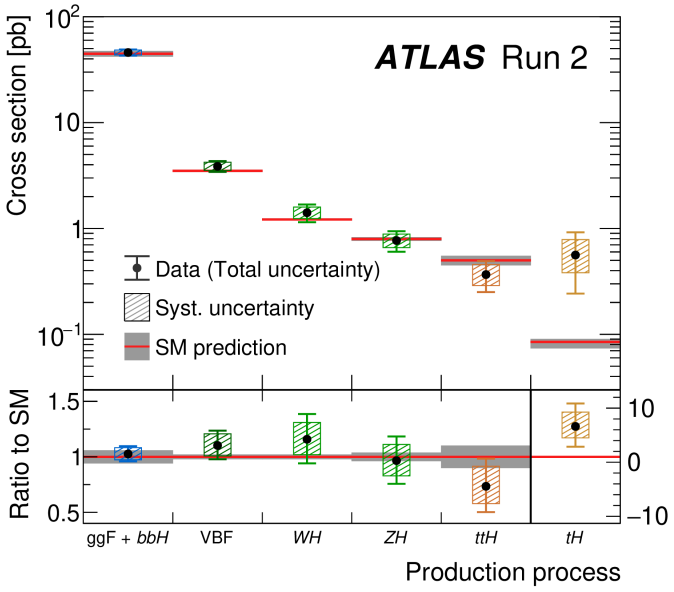

**Measurements are consistent with the SM**

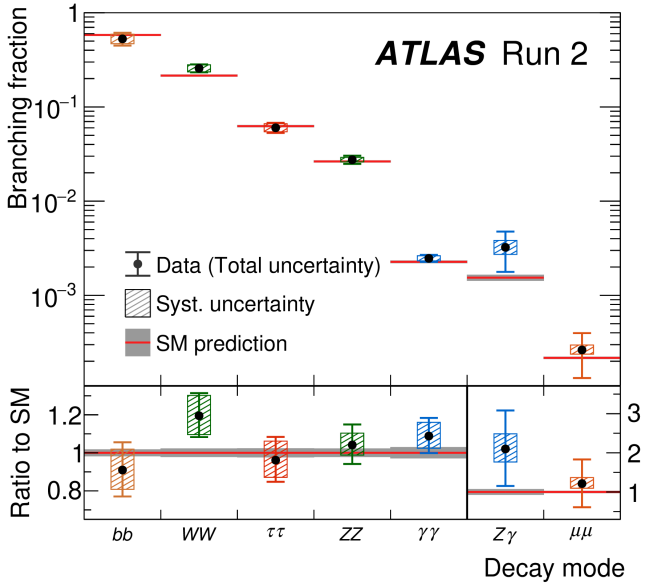


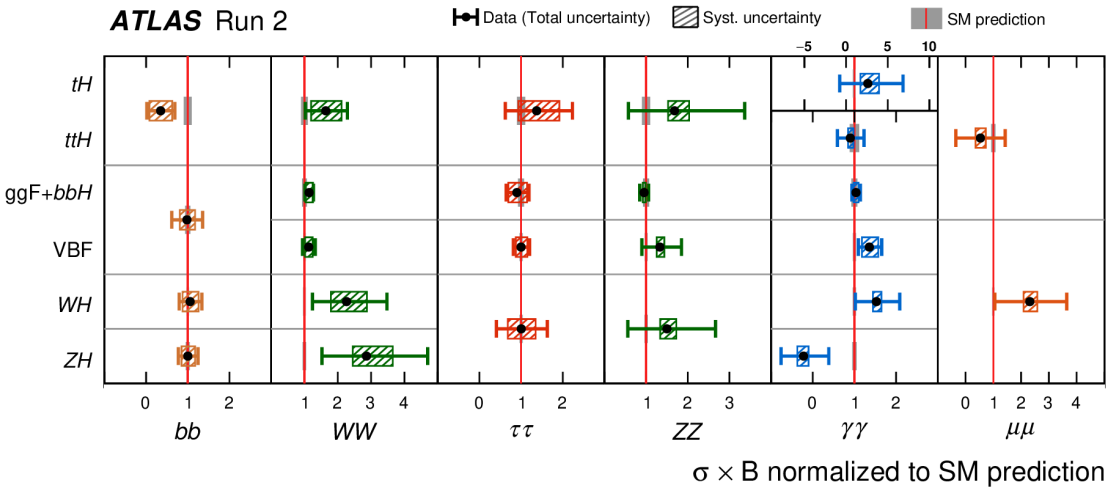
# Combined measurements

Nature 607, 52 (2022)

**Combination of multiple Higgs analyses in multiple decay channels and production processes was performed**



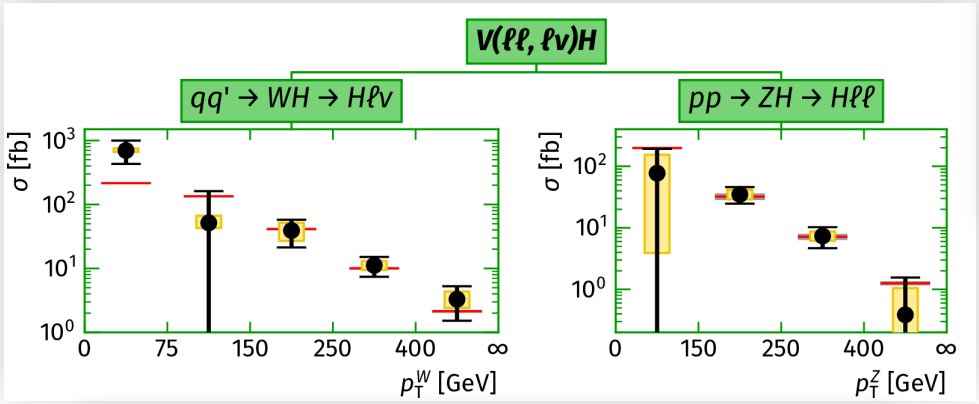



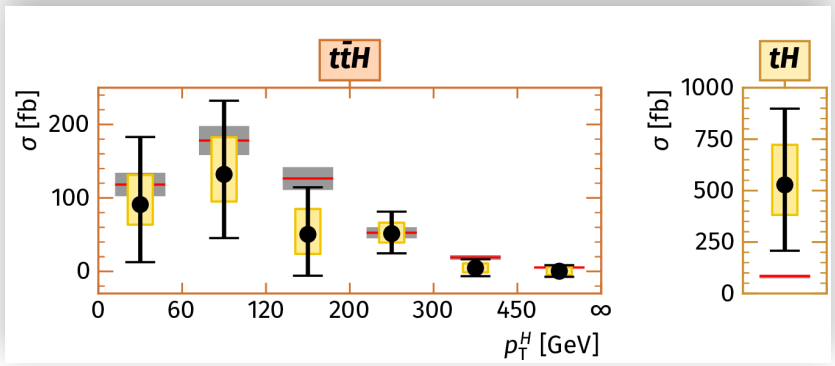

**Combined measurements are consistent with the SM**

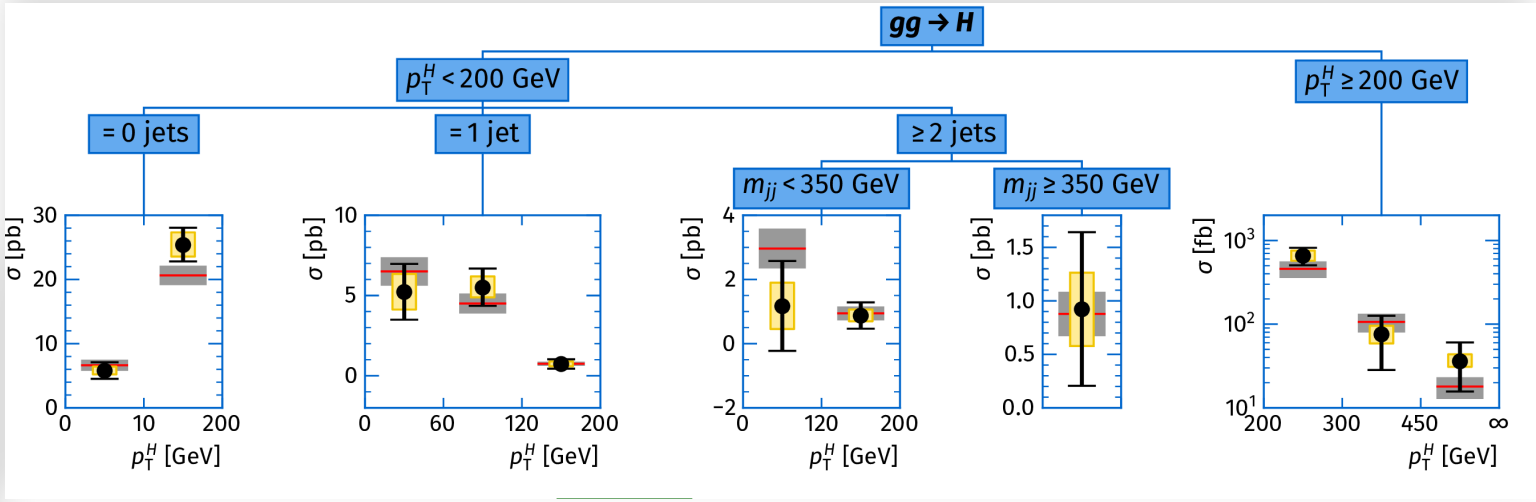
# Combination in STXS

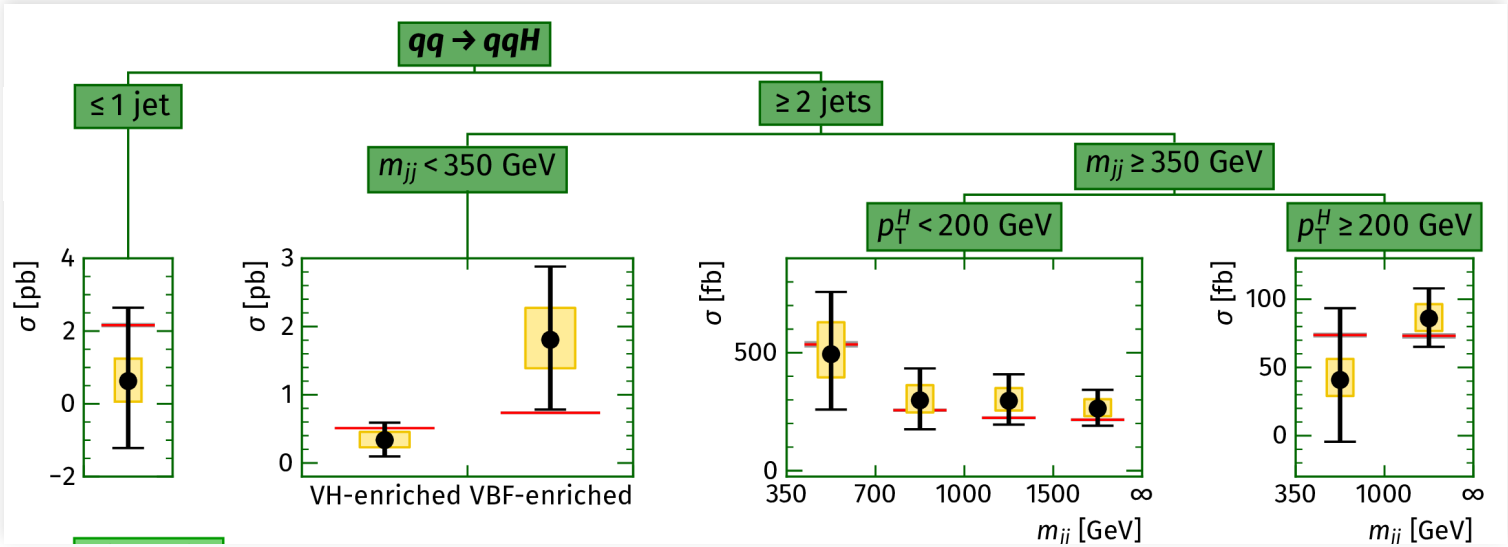
Nature 607, 52 (2022)

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



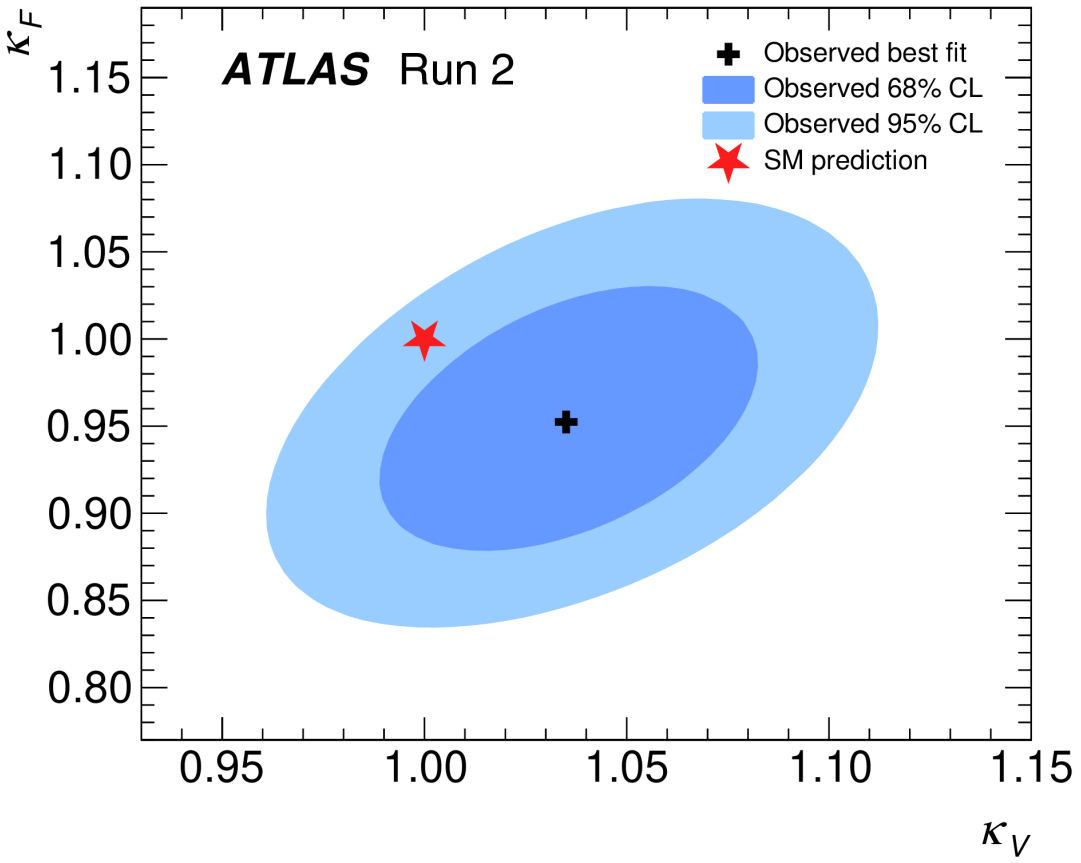




**Combined measurements are consistent with the SM**

# Combination in STXS

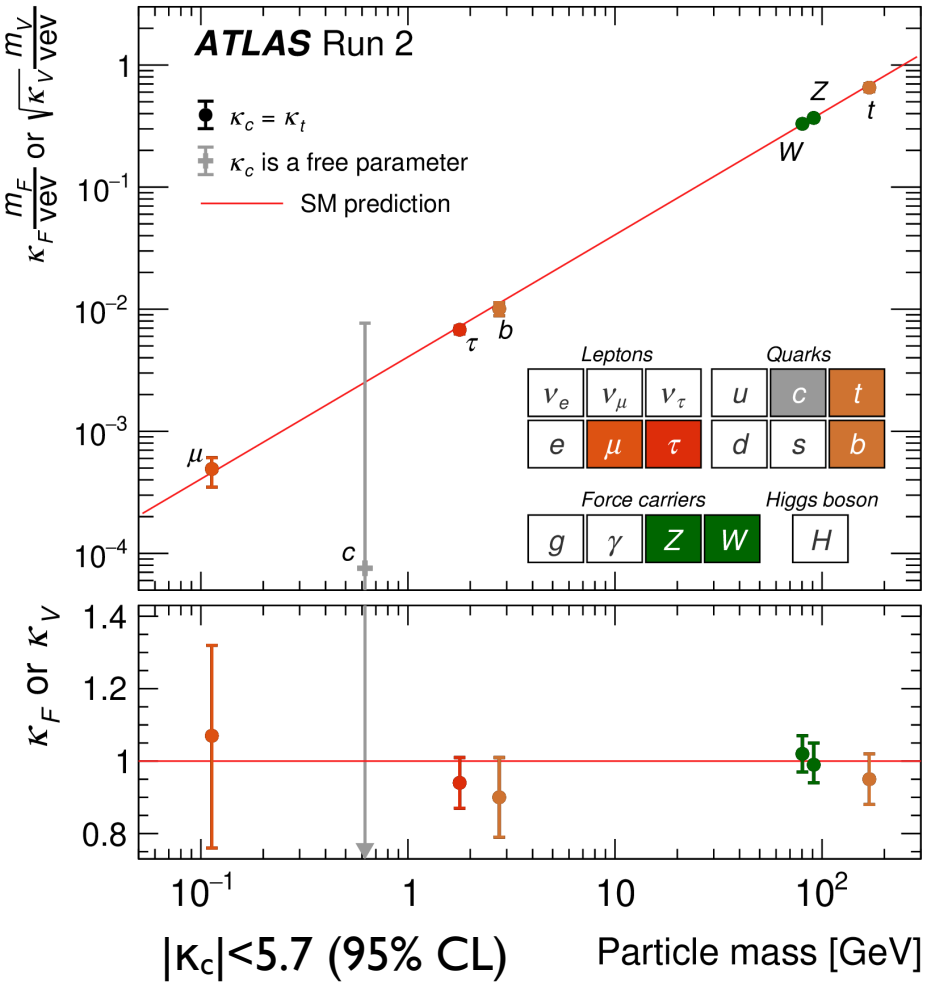
Nature 607, 52 (2022)

## Two modifiers - $\kappa_V$ (vector bosons), $\kappa_F$ (Fermions) Assuming no BSM contributions




**Combined measurements are consistent with the SM**

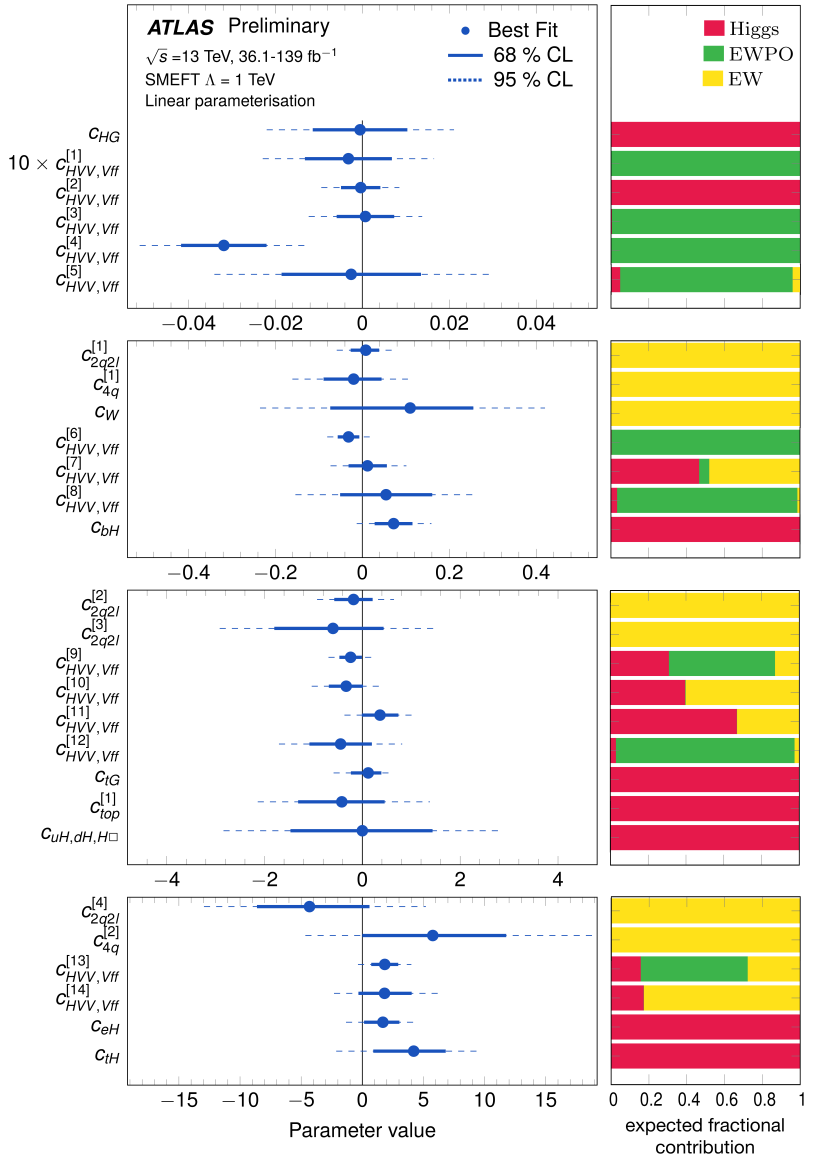
## No BSM contributions $\kappa_c$ free or $\kappa_c = \kappa_t$



# Combination EFT interpretation

ATL-PHYS-PUB-2022-037

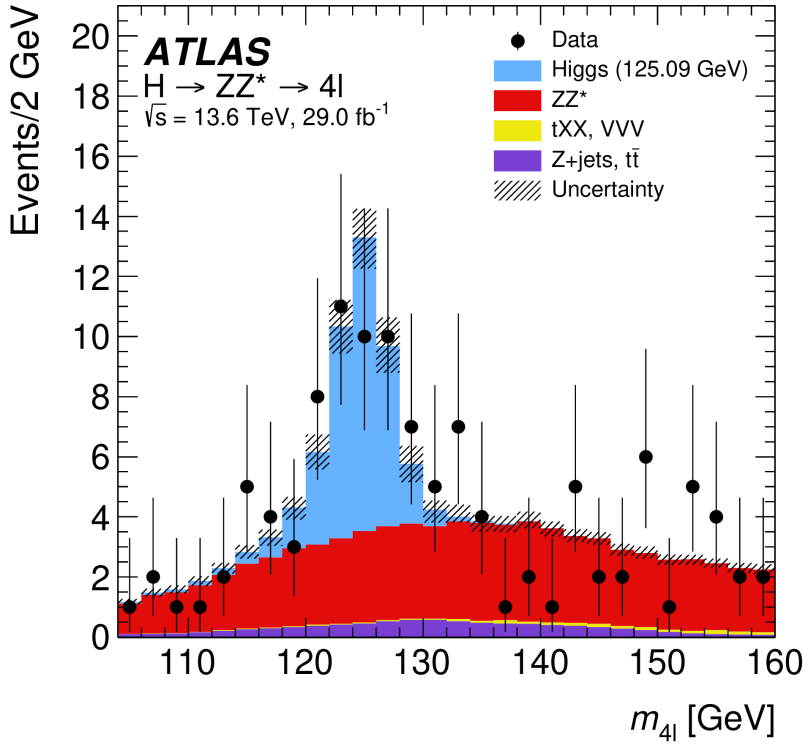
- First ATLAS global EFT fit
- Framework allows to include additional measurements to improve the combination
- Multiple combined measurements:
  - ATLAS Higgs boson data
  - ATLAS EW data
  - EW precision observables (EWPO) from LEP and SLC
- Cross sections and branching ratios reparametrized in terms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

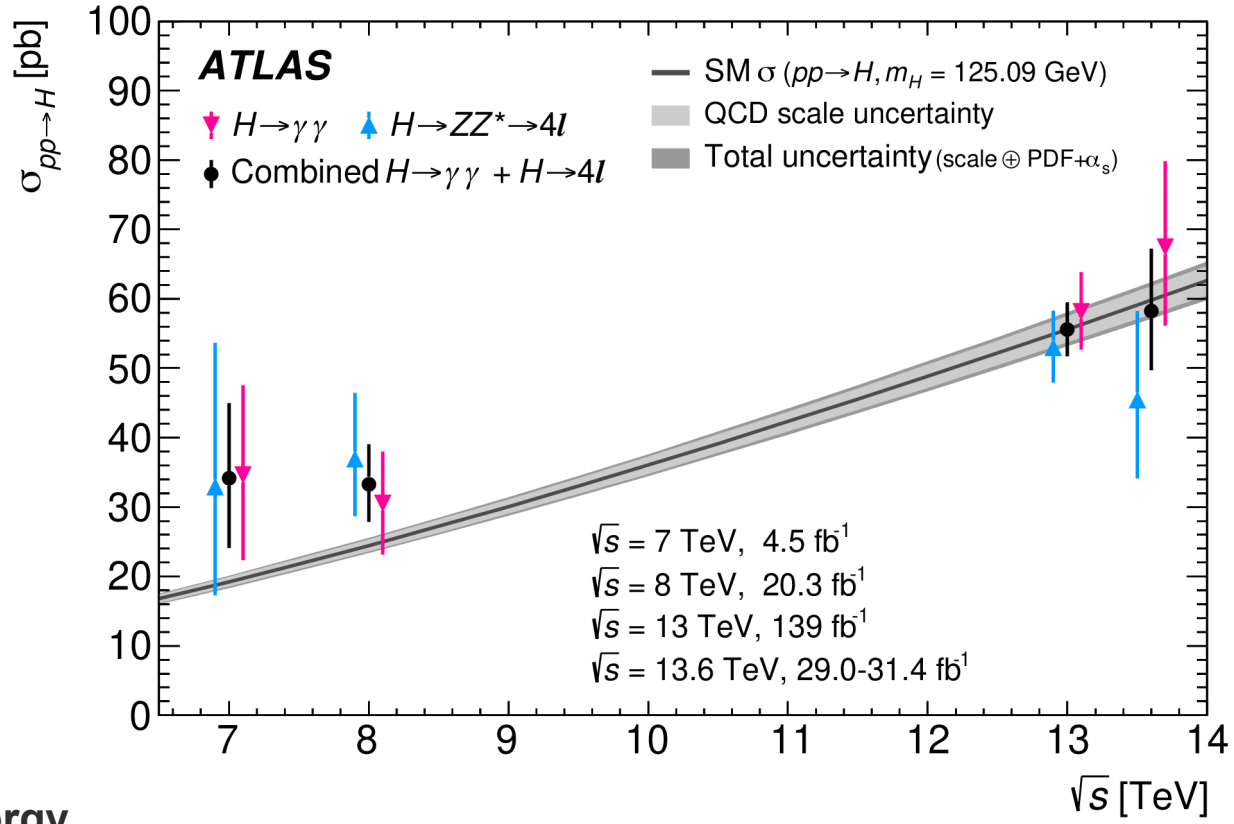


# Run 3 H→ ZZ*→4l + H→γγ

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



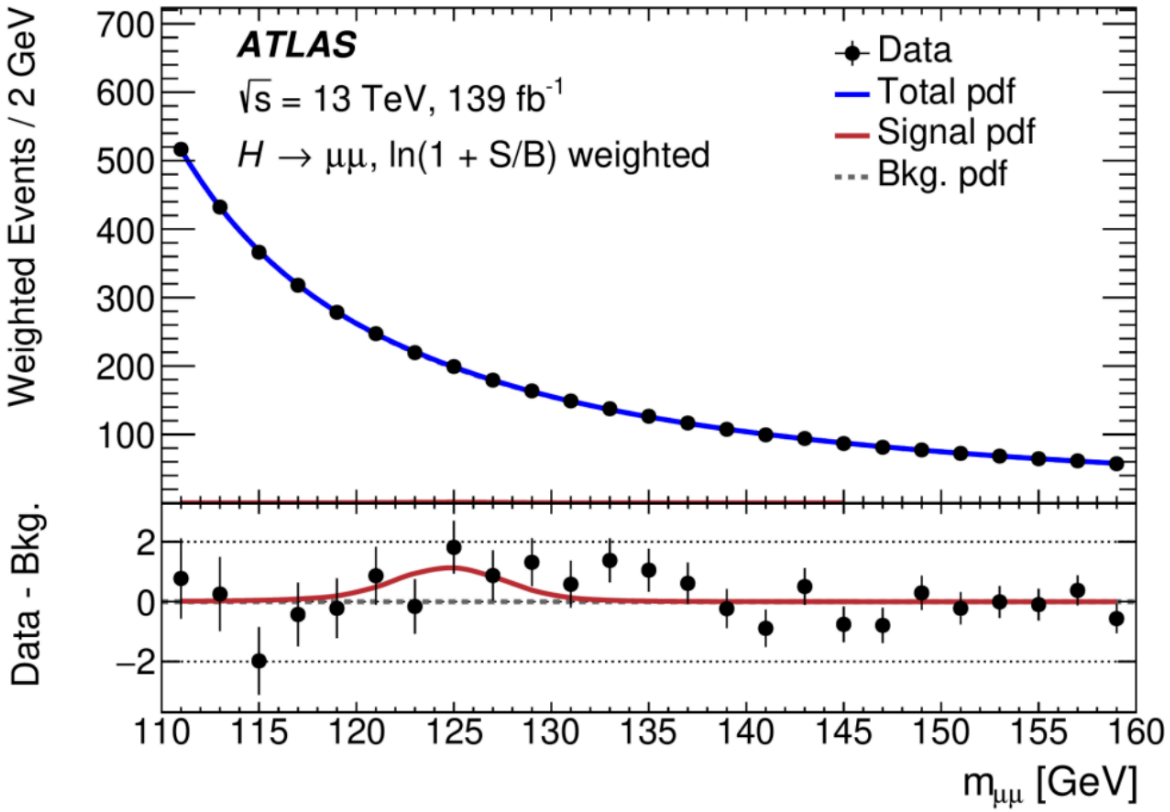




- **Good agreement with SM at unprecedented COM energy**

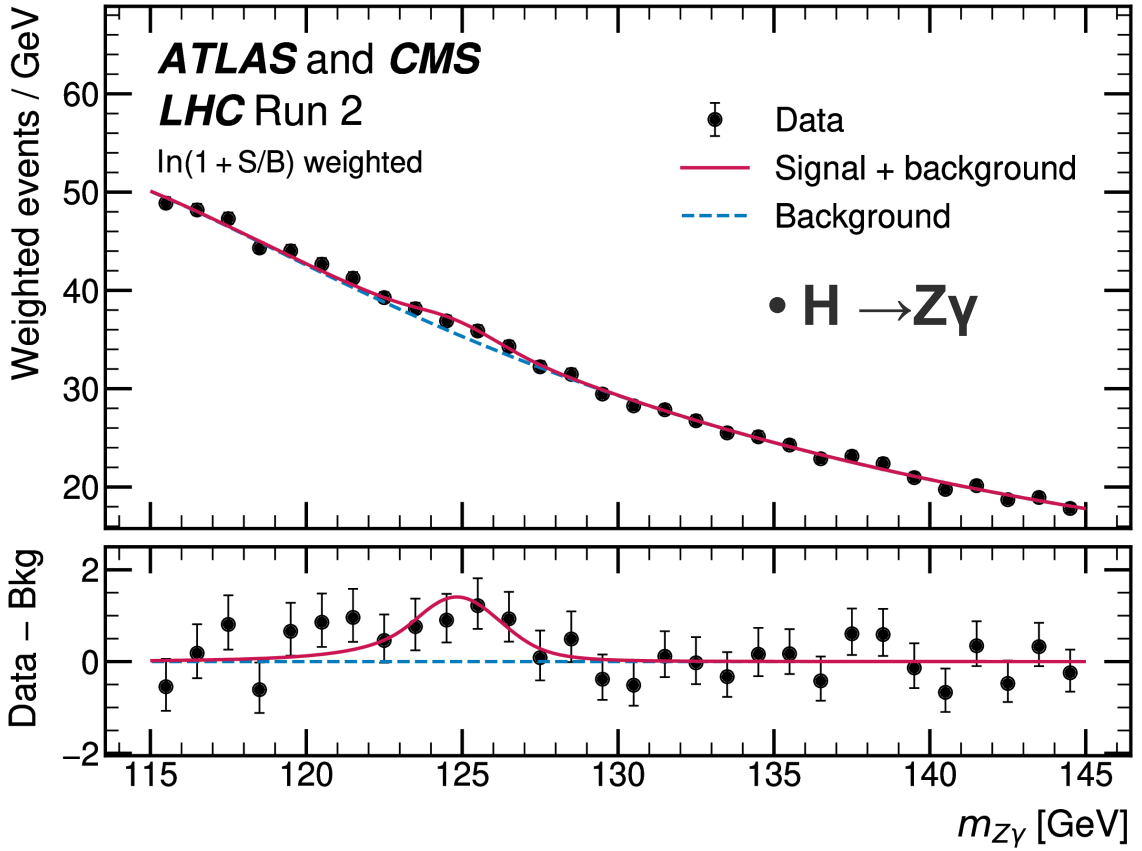
# Rare Higgs decays

Phys. Rev. Lett. 132 (2024) 021803
Phys. Lett. B 812 (2021) 135980

- **Data: 139 fb-1 @13 TeV (H→μμ, H→Zγ)**




- **H →μμ has BF of 2×10-4 ATLAS measures 2σ (CMS over 3σ)**




- **First evidence for H →Zγ with ATLAS and CMS combination**
  - **ATLAS 2.2 σ, CMS 2.8 σ, ATLAS+CMS 3.4σ**

# 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

**Thanks!**

# Backup

# Constraints on $\kappa_c$ , $\kappa_b$

Nature 607, 52 (2022)

**Higgs coupling to cc is very challenging - low BR, high jet background**

**Combining VHcc and VHbb**

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

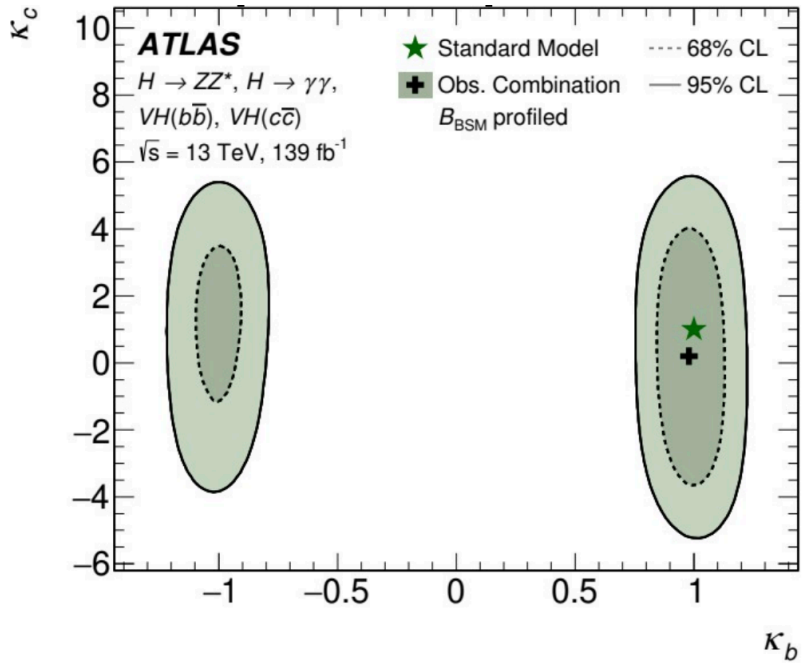
**In H→ ZZ*→4l + H→γγ,** $d\sigma/dp_T^H$ **is used to derive limits on** $\kappa_c$ , $\kappa_b$ .

**No BSM contributions $\kappa_c$ free or $\kappa_c = \kappa_t$**

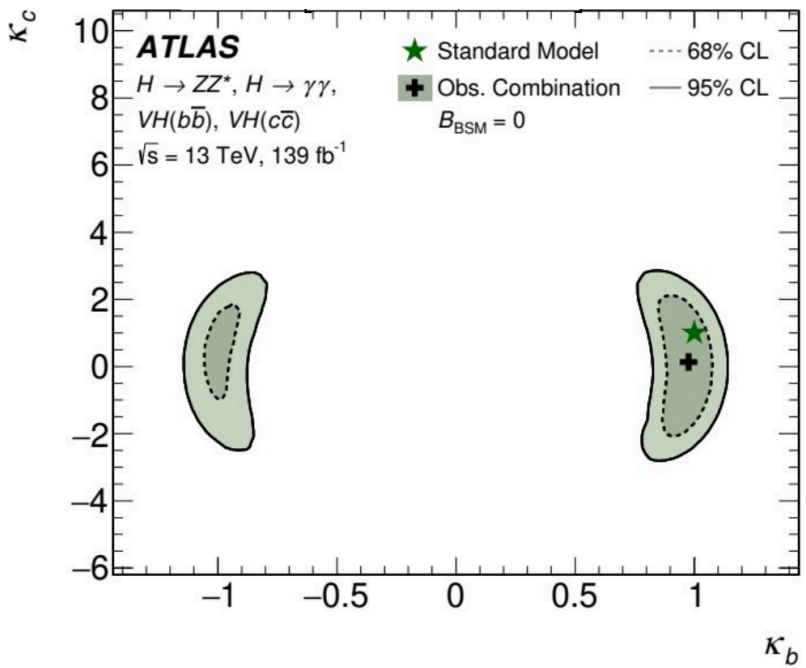
**Most stringent constraints on** $\kappa_c$ **in two scenarios – decays to BSM particles allowed/not allowed**

VHbb, VHcc, H→ ZZ*→4l + H→γγ

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



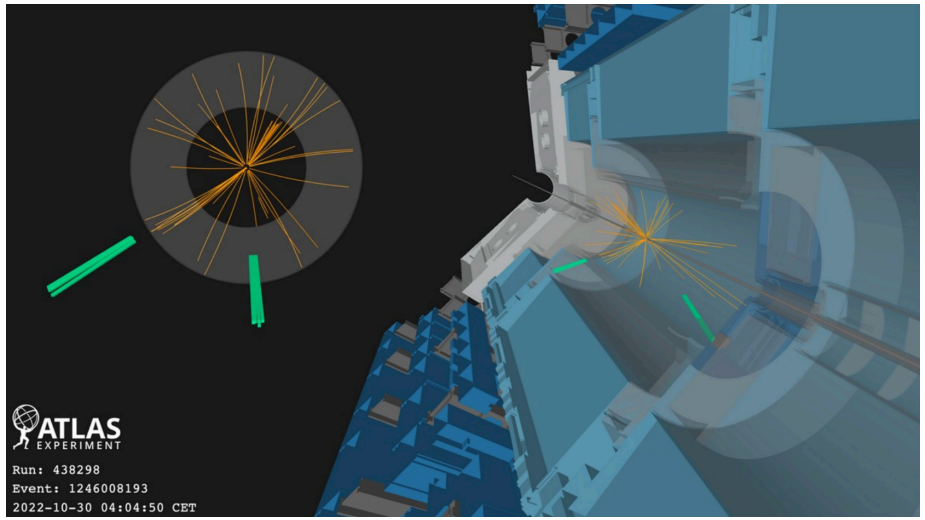

$\kappa_c \in [-2.47, 2.53]$



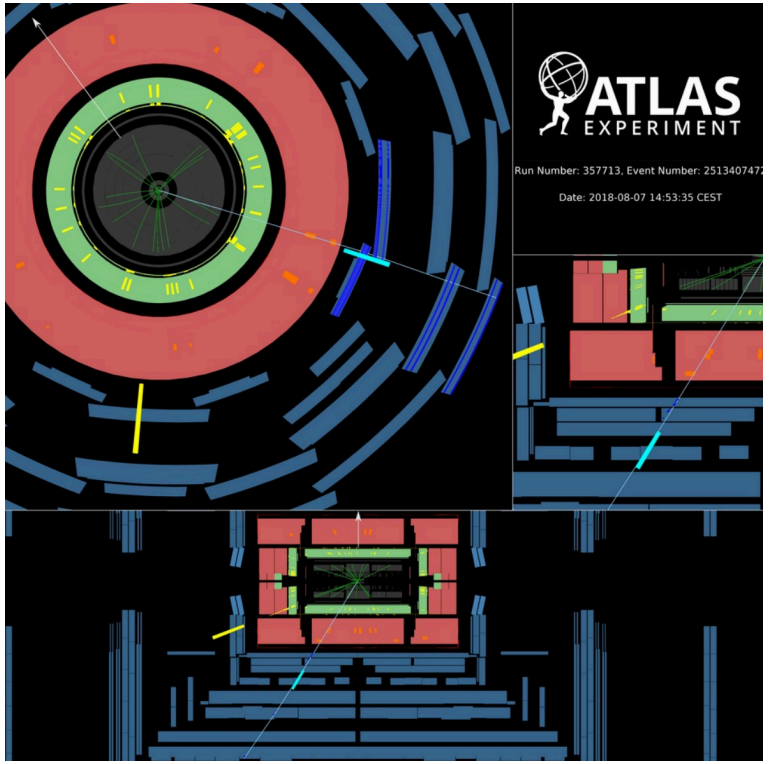

$|\kappa_c|<5.7$ (95% CL)

# Event display

H→γγ candidate




ggF H→ WW*→ eνμν Canidate (0 jets)




VBF H→ WW*→ eνμν canidate