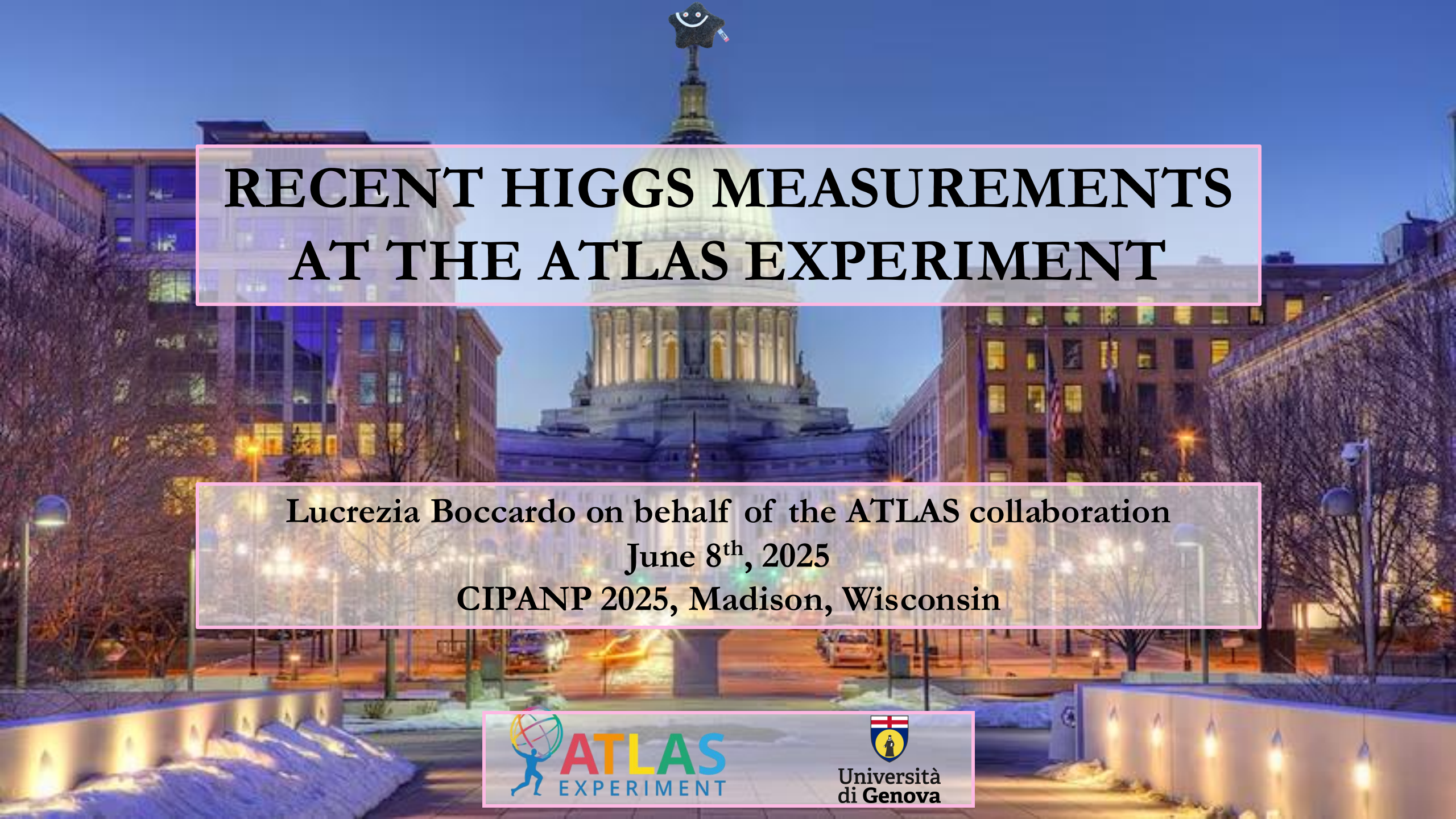


RECENT HIGGS MEASUREMENTS AT THE ATLAS EXPERIMENT

Lucrezia Boccardo on behalf of the ATLAS collaboration

June 8th, 2025

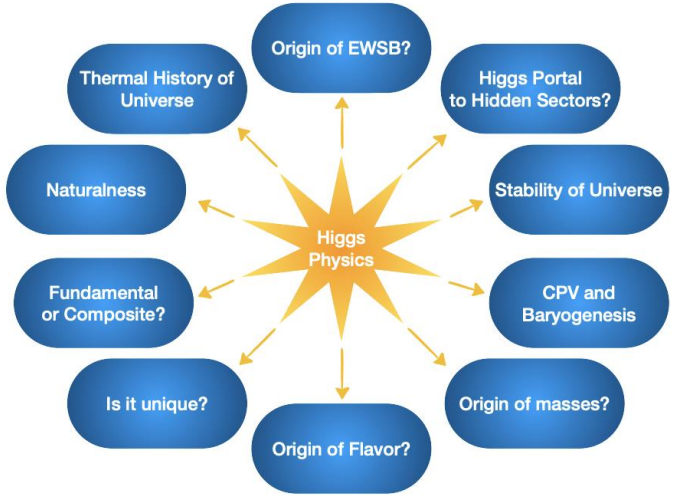
CIPANP 2025, Madison, Wisconsin

ATLAS EXPERIMENT

Università di Genova

The Higgs boson

- Since its discovery in 2012, the Higgs boson has always been one of the focuses of research in ATLAS, and we have now entered a precision measurement era.
- A simple equation: increasing statistics (Run 2 and Run 3) + innovative analysis techniques = ever-improving measurements.
- Featured in today's talk: production cross-section measurements, coupling measurements, width measurements: **all in good agreement with the Standard Model!**
- All measurements in the Higgs sector are intertwined with all the unresolved questions in today's physics!

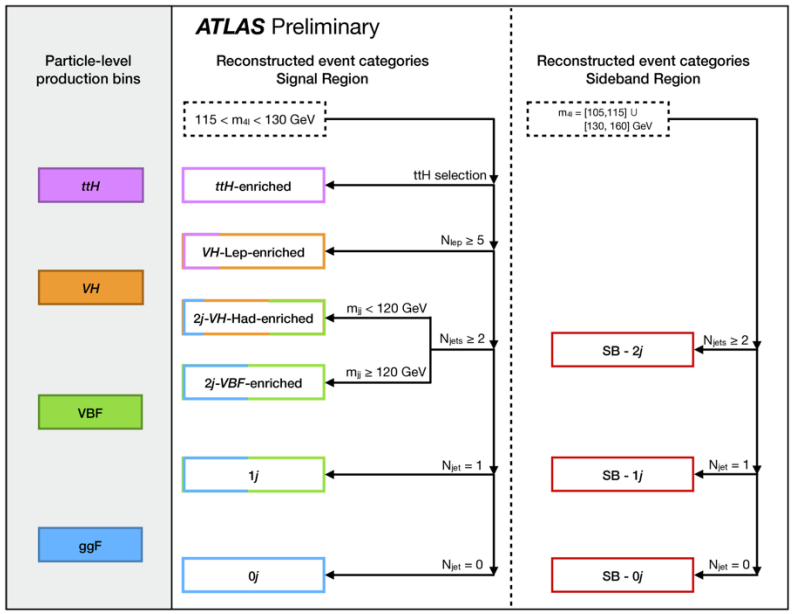


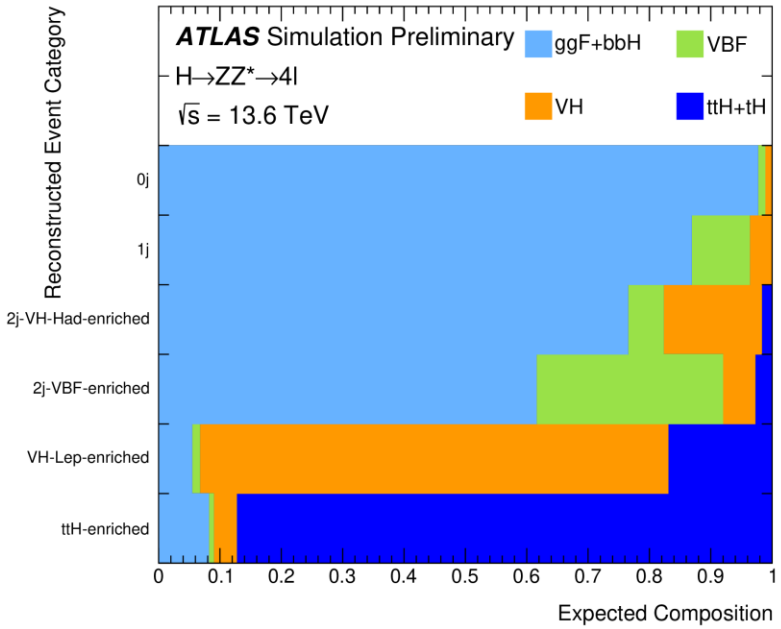
from the 2022 Snowmass Report

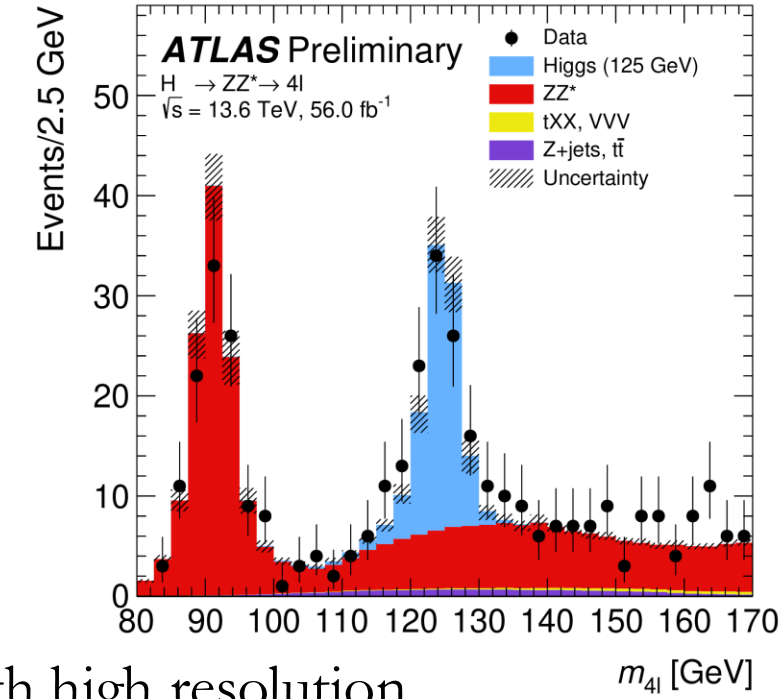
In today's talk

1. Precision measurements of **production cross-sections** for different modes:
   - $H \to ZZ^* \to 4\ell$ ATLAS-CONF-2025-002
   - $VH, H \to WW^*$ HIGG-2023-09
   - $(ggF + VBF)H \to WW^*$ HIGP-2024-07
2. **Width** measurements:
   - $H^* \to WW \to \ell\nu\ell\nu$ HIGP-2024-05
3. Higgs boson **pair production**
   - $HH \to b\bar{b}\gamma\gamma$ ATLAS-CONF-2025-005

$H \to ZZ^* \to 4\ell$ partial Run 3 differential measurement



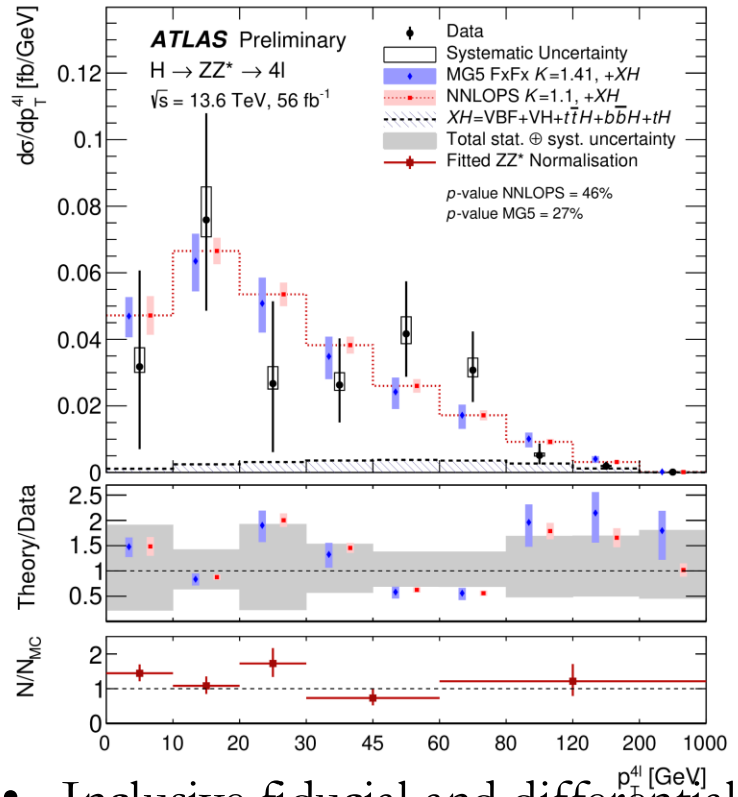


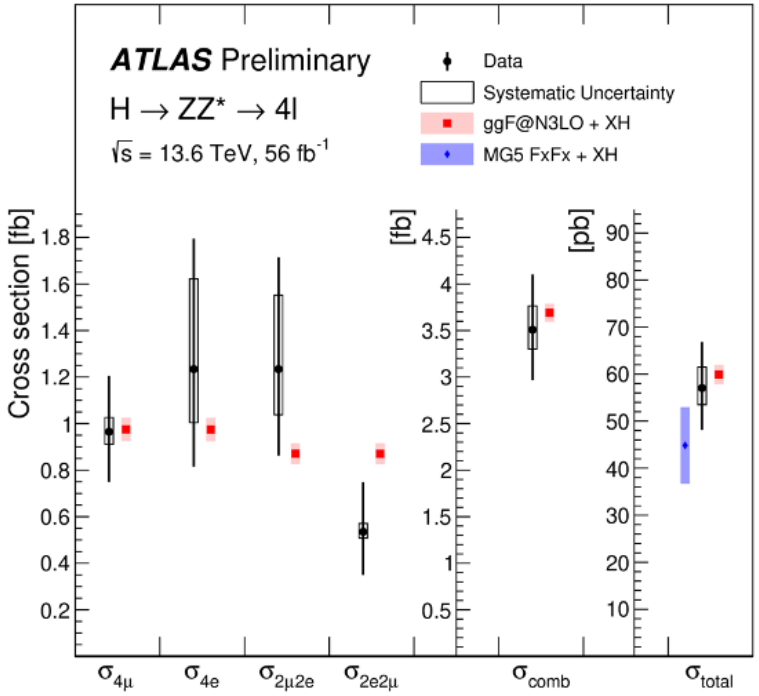


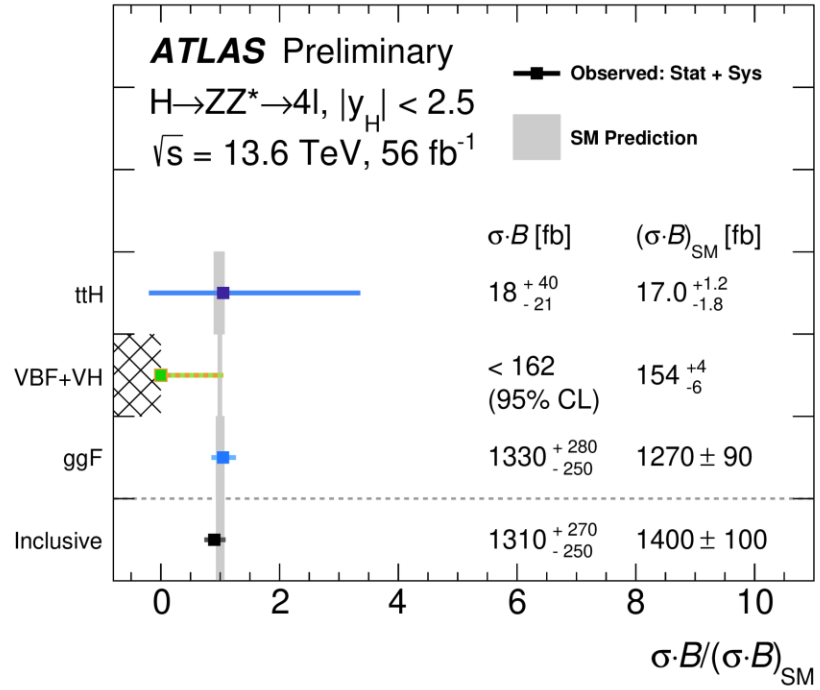
- Four lepton decays have a small BR but can be **fully resolved** with high resolution.
- Inclusive and differential measurements and the first **13.6 TeV** production mode cross-section measurements.
- Production mode discrimination based on **jet multiplicity** and **dijet invariant mass.**
- The colors of the reconstructed categories highlight the relative contribution from the particle level bin.

ATLAS-CONF-2025-002

$H \to ZZ^* \to 4\ell$ partial Run 3 differential measurement







$\sigma_{|yH|<2.5} \cdot \mathcal{B}(H \to ZZ^*) = 1.3^{+0.3}_{-0.2}\text{pb}$

- Inclusive fiducial and differential cross-sections generally in agreement with SM predictions⟶ sensitivity driven by $4\mu/2e2\mu$ channels.
- Neural network-based discrimination for **Higgs production modes** STXS measurement.
- VBF and VH probed together assuming SM values.
- Dominant uncertainty comes from limited data statistics.

$\sigma_{\text{fid}} \equiv \sigma \cdot \mathcal{B}(H \to ZZ^* \to 4\ell) = 3.5^{+0.6}_{-0.5}$ fb

$\sigma_{\text{total}} = 57^{+10}_{-9}$ pb

ATLAS-CONF-2025-002

$H \to WW^*$ Run 2 measurements: an overview

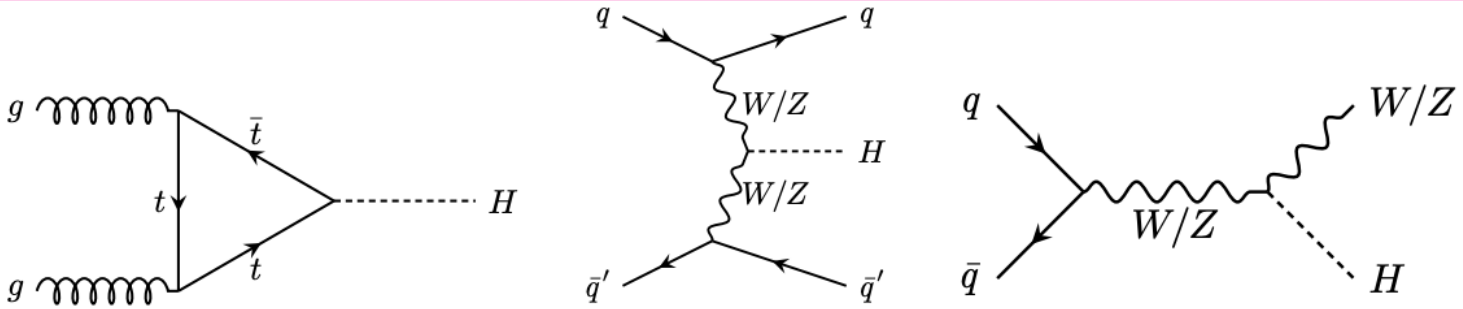
VH

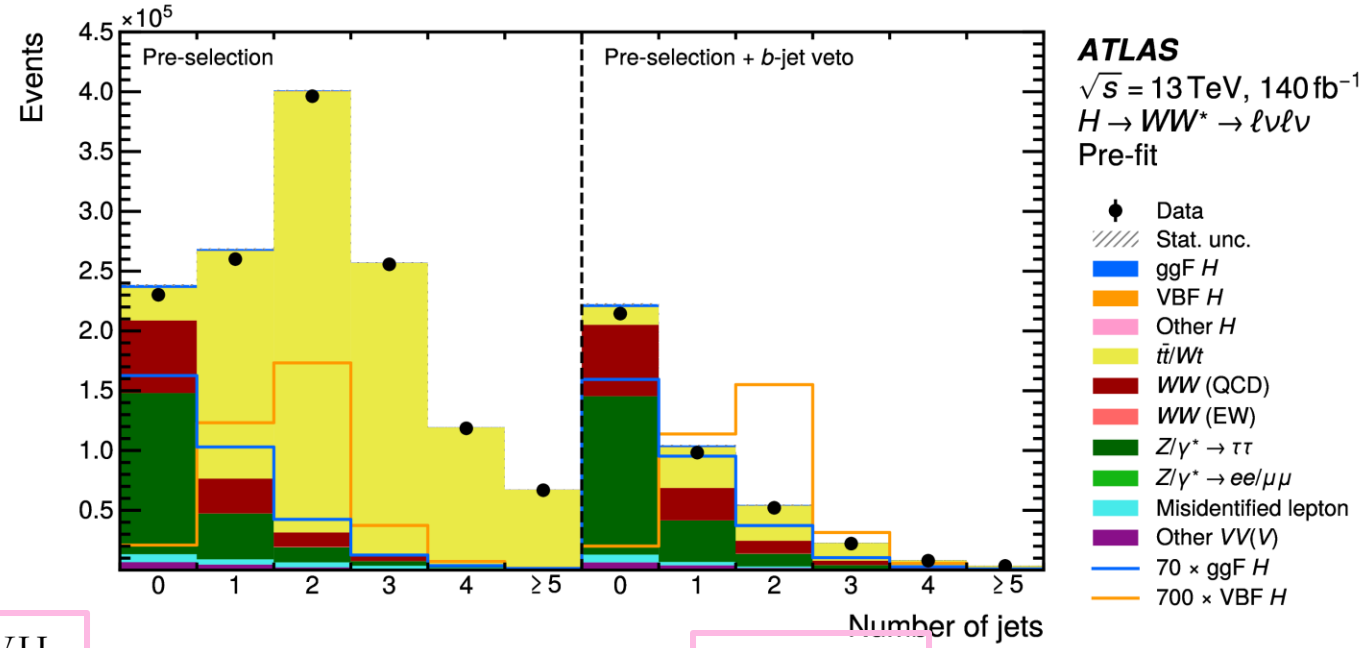
- Both fully-leptonic and semi-leptonic final states
- Use of BDTs, ANNs, and RNNs for signal-background discrimination
- SR definition based on n. of leptons
- Stage 1.2 STXS measurements

ggF + VBF

- Only fully-leptonic final-states
- NNs based signal-background discrimination
- SR definition based on jet multiplicity
- Finer granulation for STXS

Channel	SR	SR discriminant	Relevant CR(s)
Opposite-sign 2ℓ	–	ANN_{DFOS} (2(a))	Top, Z+jets, WW
Same-sign 2ℓ	SS2μ SS2e SSDF	RNN output (3(a)) RNN output (3(b)) RNN output (3(c))	–
3ℓ	Z-dominated Z-depleted	ANN_{Zdom} (4(a)) $\text{ANN}^{\Delta}_{\text{Zdep}}$ (4(b))	WZ 0-jet, WZ ≥1-jets
4ℓ	1-SFOS 2-SFOS	1-SFOS BDT output (5(a)) 2-SFOS BDT output (5(b))	ZZ





VH

ggF + VBF

HIGP-2024-07 (ggF+VBF)
HIGG-2023-09 (VH)

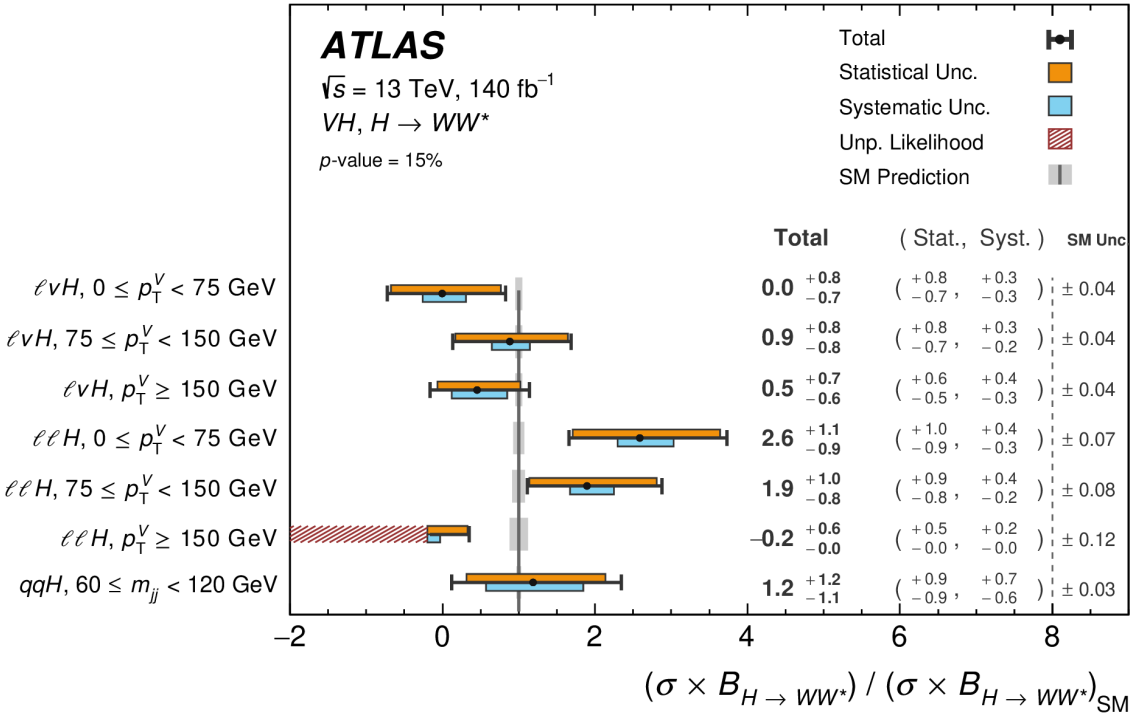
$H \to WW^*$ Run 2 measurements: an overview

VH

$\mu_{VH} = 0.92^{+0.21}_{-0.20}(\text{stat.})^{+0.13}_{-0.12}(\text{syst.})$

$\sigma_{WH} \times \mathcal{B}_{H\to WW^*} = 0.14^{+0.08}_{-0.07}\ (\text{stat.}) \pm 0.05\ (\text{syst.})\ \text{pb}$

$\sigma_{ZH} \times \mathcal{B}_{H\to WW^*} = 0.31^{+0.09}_{-0.08}\ (\text{stat.}) \pm 0.03\ (\text{syst.})\ \text{pb}$

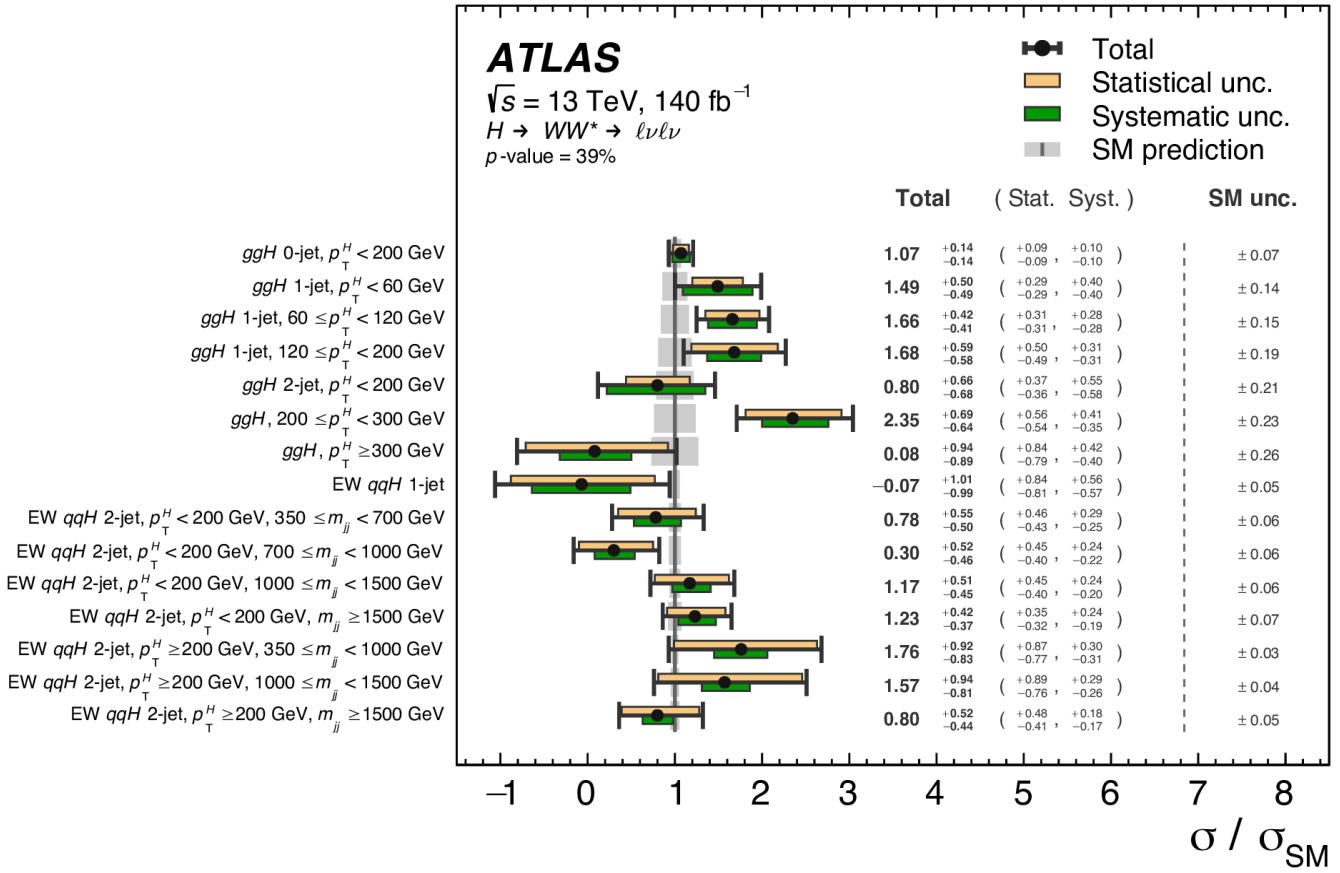


HIGG-2023-09 (VH)

ggF + VBF

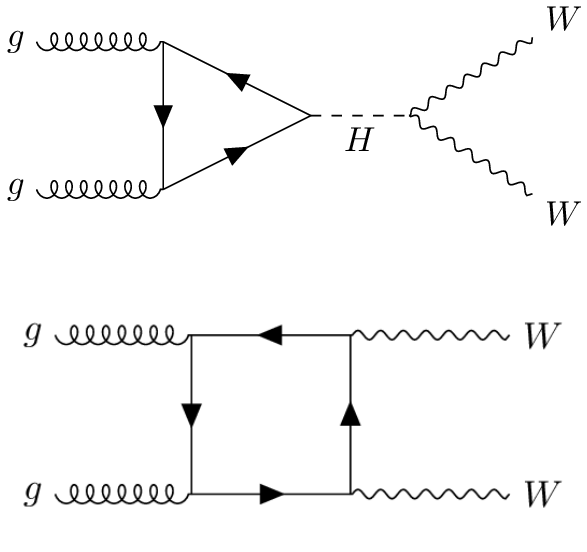
$\sigma_{ggF} \times \mathcal{B}_{H\to WW^*} = 12.4^{+1.3}_{-1.2}\ \text{pb}$

$\sigma_{VBF} \times \mathcal{B}_{H\to WW^*} = 0.79^{+0.18}_{-0.16}\ \text{pb}$

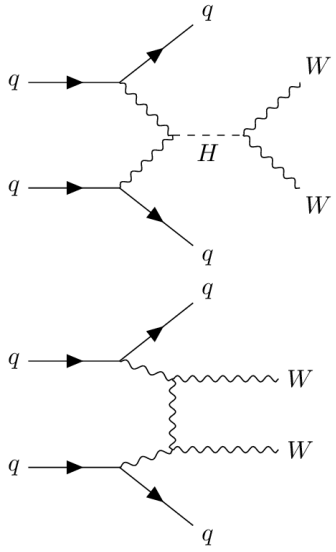


HIGP-2024-07 (ggF+VBF)

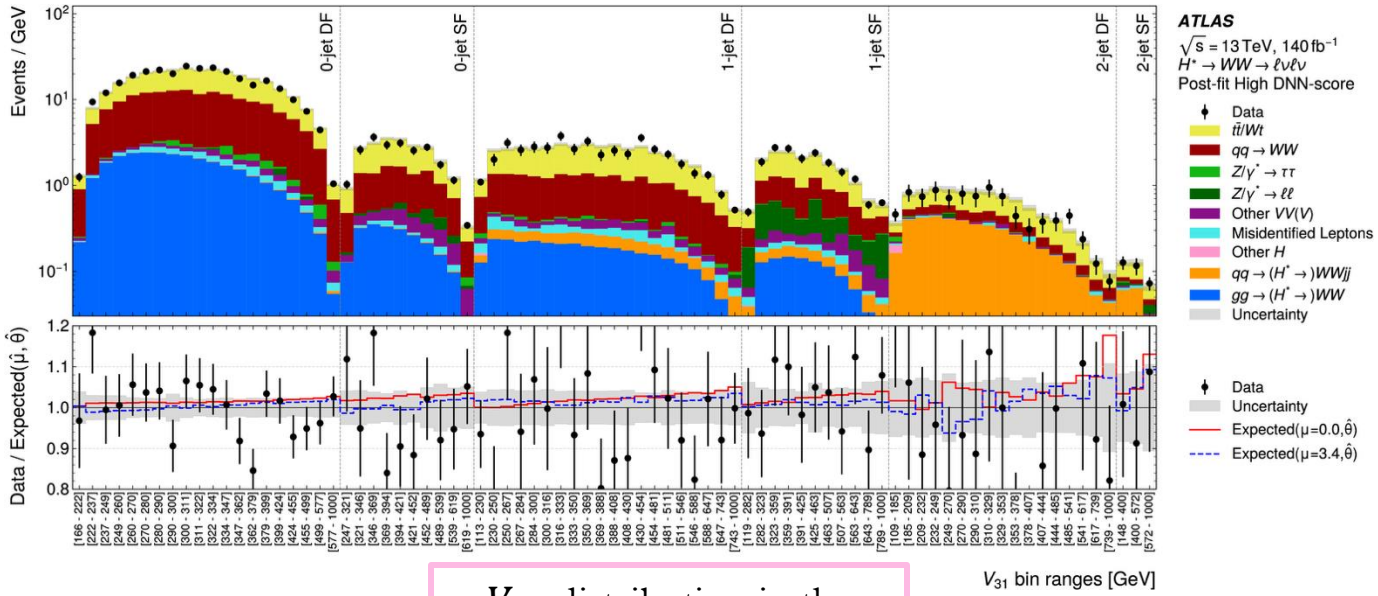
$H^* \rightarrow WW \rightarrow \ell\nu\ell\nu$ Run 2 off-shell production measurement



ggF



EW



V_{31} distribution in the SRs

- Precision measurements of Γ_H are essential for BSM studies, but limited resolution at the ATLAS detector makes on-shell measurements challenging;
- → **off-shell production** is enhanced at **invariant masses above $2m_V$.**
- This analysis includes both same flavour and different flavours decays of the W boson, including the intermediate τ decay;
- **6 analysis signal regions**, each with a **DNN** to classify in three categories: signal, full process (SBI) and non-interfering background.
- The V_{31} variable is used as a discriminant as a proxy for m_{WW}: a combination of dilepton invariant mass and the transverse mass of the dilepton+missing energy system;
- CRs are used **to constrain non-interfering background normalization.**

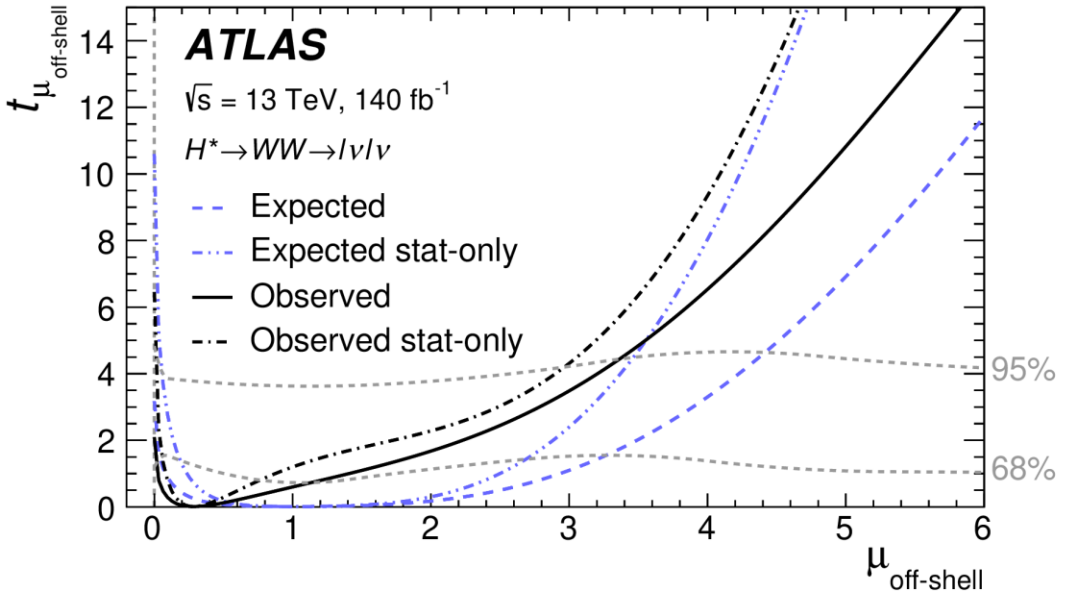
HIGP-2024-05

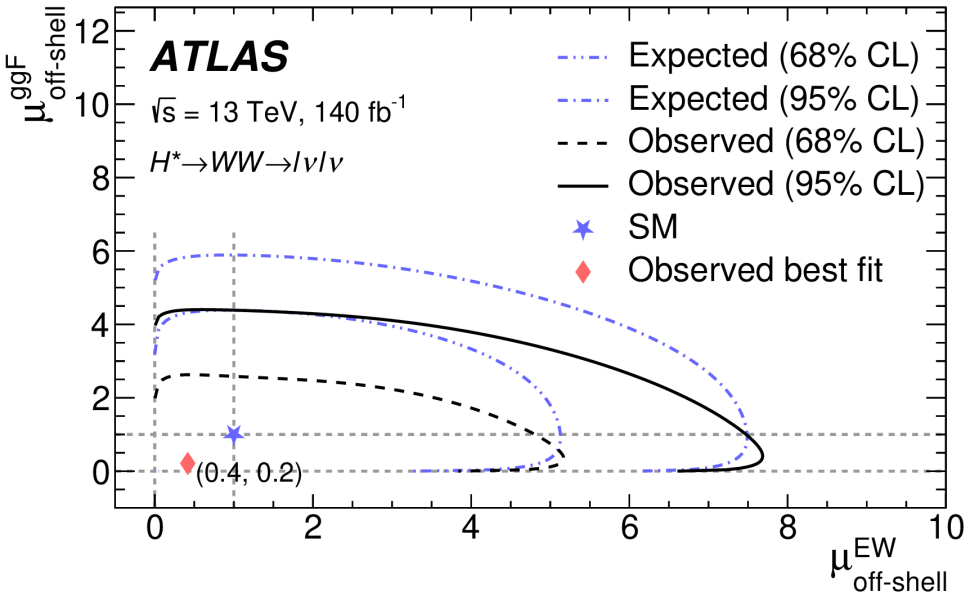
$H^* \to WW \to \ell\nu\ell\nu$ Run 2 off-shell production measurement

$$\sigma^{\text{on-shell}}_{i\to H^*\to f} \sim \frac{g_i^2 g_f^2}{m_H \Gamma_H} \qquad \sigma^{\text{off-shell}}_{i\to H^*\to f} \sim \frac{g_i^2 g_f^2}{m_f} \qquad \mu_{i\to H^*\to f} = \frac{\sigma_{i\to H^*\to f}}{(\sigma_{i\to H^*\to f})_{\text{SM}}} \qquad \frac{\Gamma_H}{\Gamma_H^{\text{SM}}} = \frac{\mu_{\text{off-shell}}}{\mu_{\text{on-shell}}}$$

- **Profile likelihood ratio fit** with both a single $\mu_{\text{off-shell}}$ and splitting the two production modes.
- Combination with on-shell analysis to extract Γ_H thanks to the ratio of on-shell and off-shell productions.

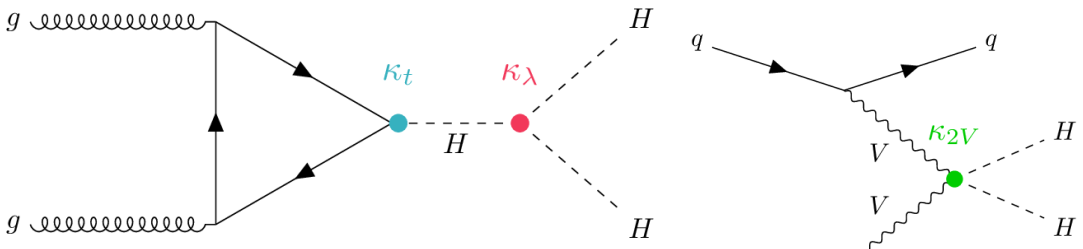
$$\mu_{\text{off-shell}} = 0.3^{+0.9}_{-0.3}\,(1.0^{+2.3}_{-1.0})$$
$$\mu^{\text{ggF}}_{\text{off-shell}} = 0.2^{+1.3}_{-0.2}\,(1.0^{+2.5}_{-1.0}) \qquad \mu^{\text{EW}}_{\text{off-shell}} = 0.4^{+3.4}_{-0.4}\,(1.0^{+2.9}_{-1.0})$$
$$\Gamma_H = 0.9^{+3.4}_{-0.9}\,(4.1^{+8.3}_{-3.9})\ \text{MeV}$$





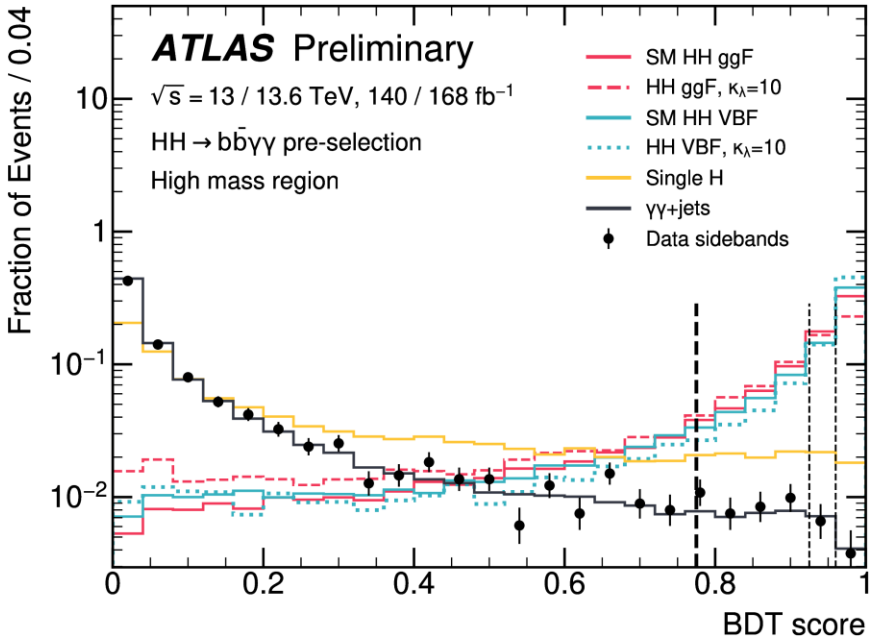
HIGP-2024-05

$HH \rightarrow b\bar{b}\gamma\gamma$ Run 2 + partial Run3 measurement

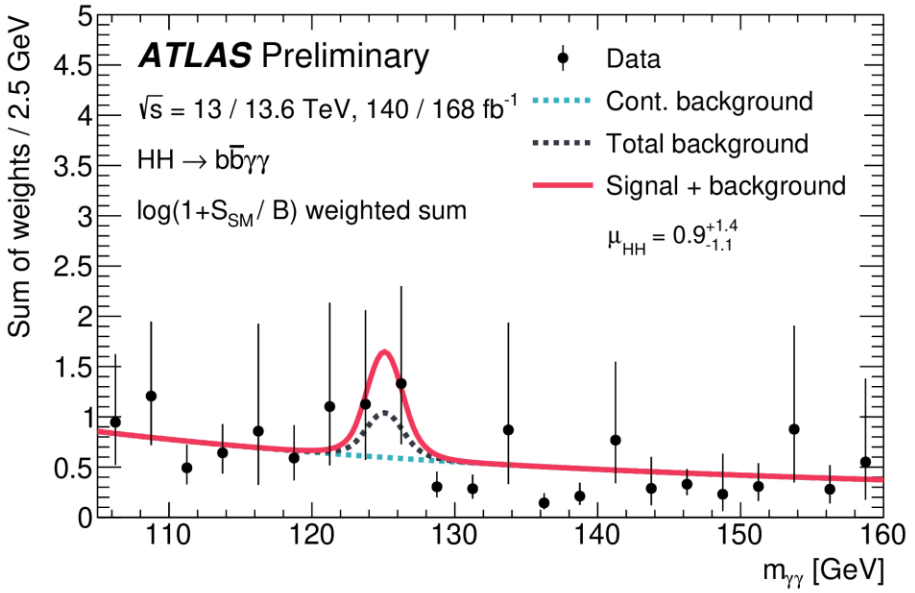


$$V(H) = \frac{1}{2}m_H^2 H^2 + \lambda_3 v H^3 + \lambda_4 H^4$$

- Despite the reduced BR (0.26%) this is a **golden channel for HH** due to **photon resolution** (~2/3 GeV).
- First ATLAS analysis with >300 fb^{-1} (140 fb^{-1} at 13 TeV, Run 2 + 168 fb^{-1} at 13.6 TeV, Run 3).
- New state-of-the-art transformer-based flavour tagging algorithm (GN2)+ kinematic fit.
- Selecting events with at least 2 b-jets and exactly 2 photons close to the Higgs mass.

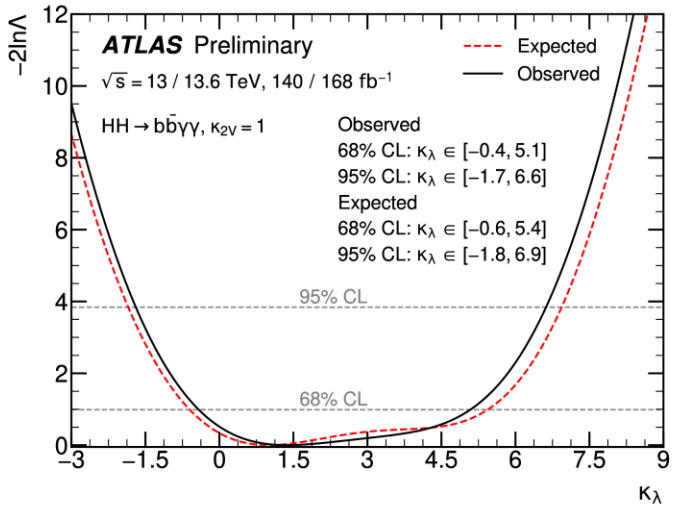


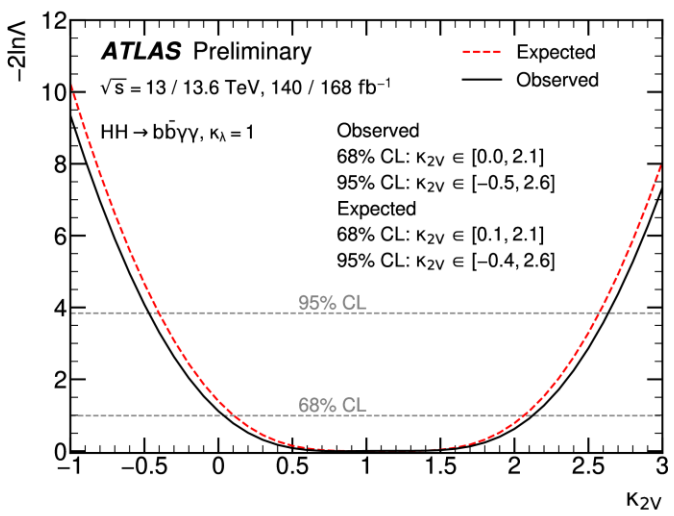
- Events are classified in two regions, **high-mass** and **low-mass**, based on the **improved four-body** invariant mass $m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - (m_{b\bar{b}} - 125\ \text{GeV}) - (m_{\gamma\gamma} - 125\ \text{GeV})$.
- Fitting the data in the sidebands.
- Simultaneous profile likelihood fit.
- Modelling signal with a **double-sided Crystal Ball** function and the background with an **exponential.**



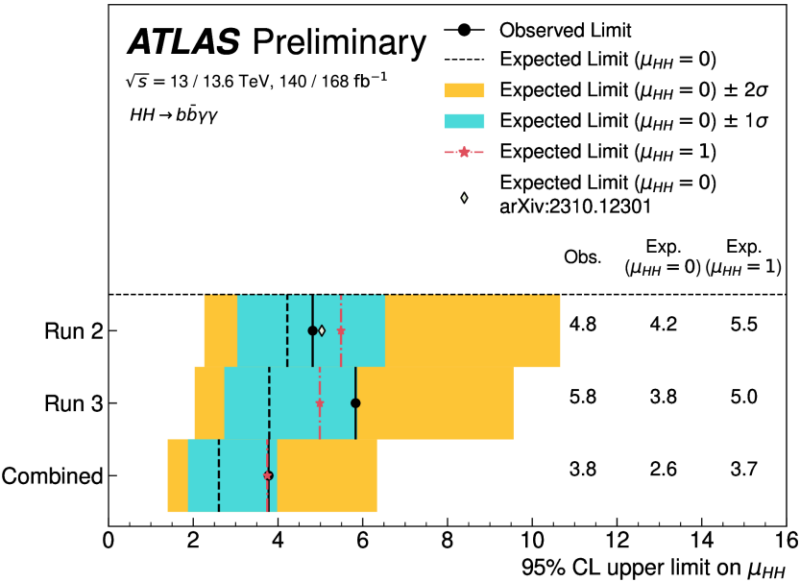
ATLAS-CONF-2025-005

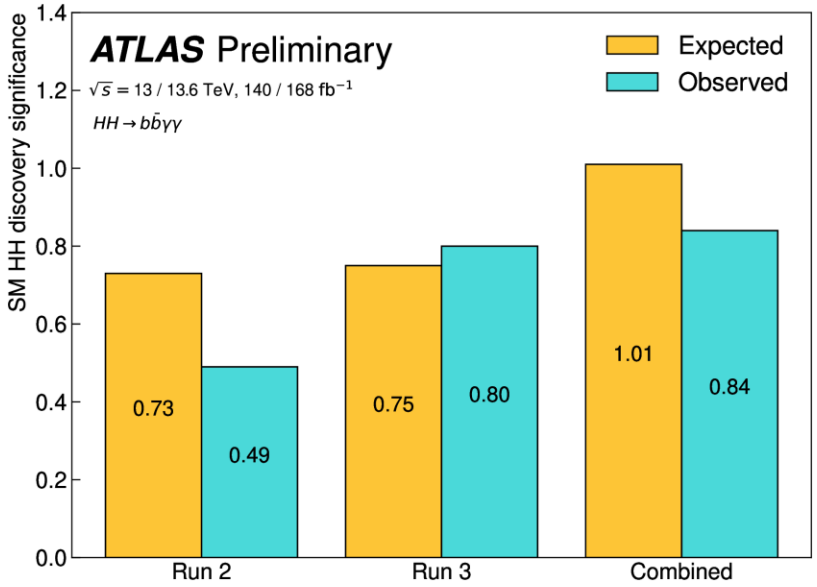
$HH \to b\bar{b}\gamma\gamma$ Run 2 + partial Run3 measurement





- Significance improvement:
  - 50% increased statistics;
  - 20% new flavour tagging;
  - 10% improved background modellings;
  - 5% kinematic fit;
- Improved previous Run 2 result by 100%.





$$\mu_{HH} = 0.9^{+1.3}_{-1.0}\,(\text{stat.})^{+0.6}_{-0.5}\,(\text{syst.})\;(1.3^{1.0}_{-1.3})$$

$$\mu_{HH} < 3.8\;(3.7)$$

$$-1.7 < \kappa_\lambda < 6.6\;(-1.8 < \kappa_\lambda < 6.9)$$

$$-0.5 < \kappa_{2V} < 2.6\;(-0.4 < \kappa_\lambda < 2.6)$$

ATLAS-CONF-2025-005

Conclusions

- The Higgs community in ATLAS is active and rich in innovative ideas.
- The increased statistics from Run 3 will lead to new and even more precise measurements.
- For an outlook on the future of Higgs measurements at the HL-LHC, take a look at the joint ATLAS+CMS input to the European Strategy for Particle Physics! ATL-PHYS-PUB-2025-018

THANK YOU!

Backup

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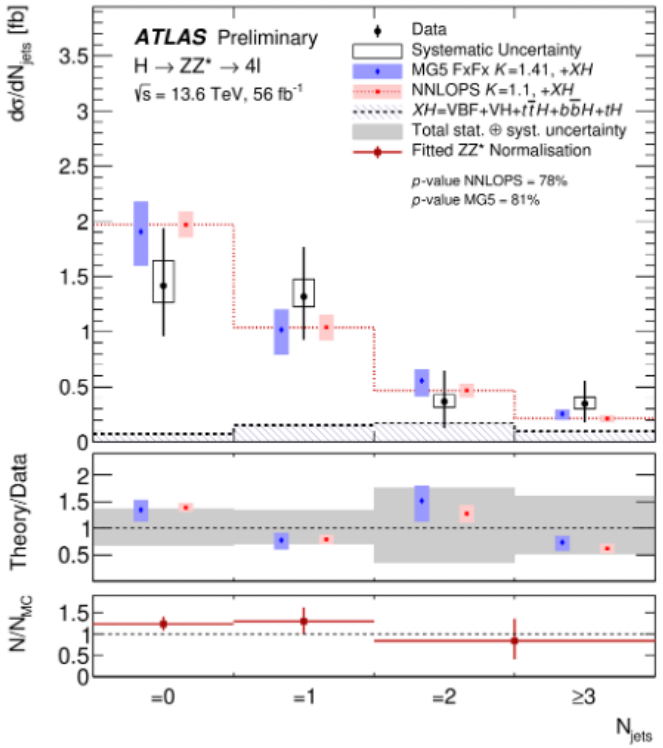
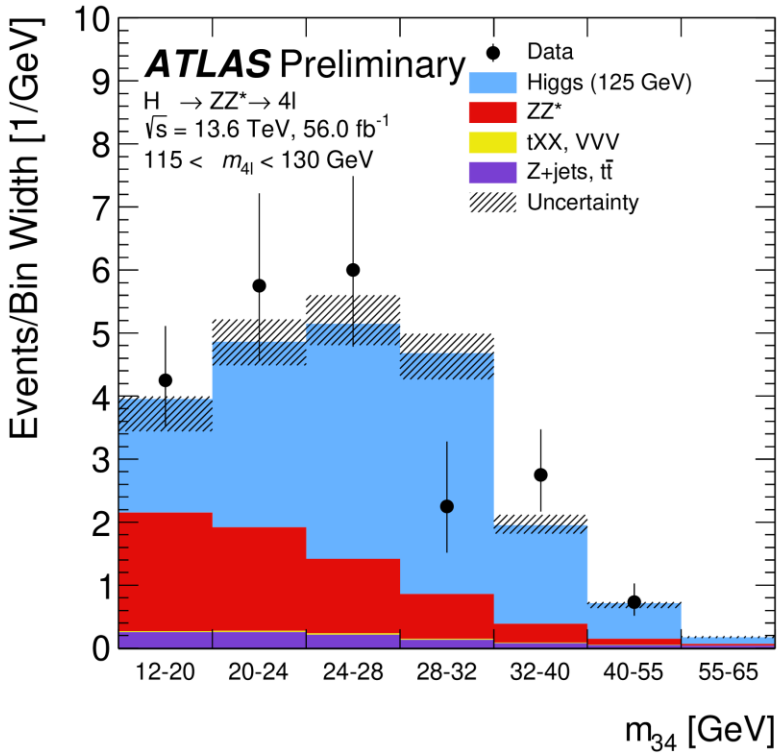
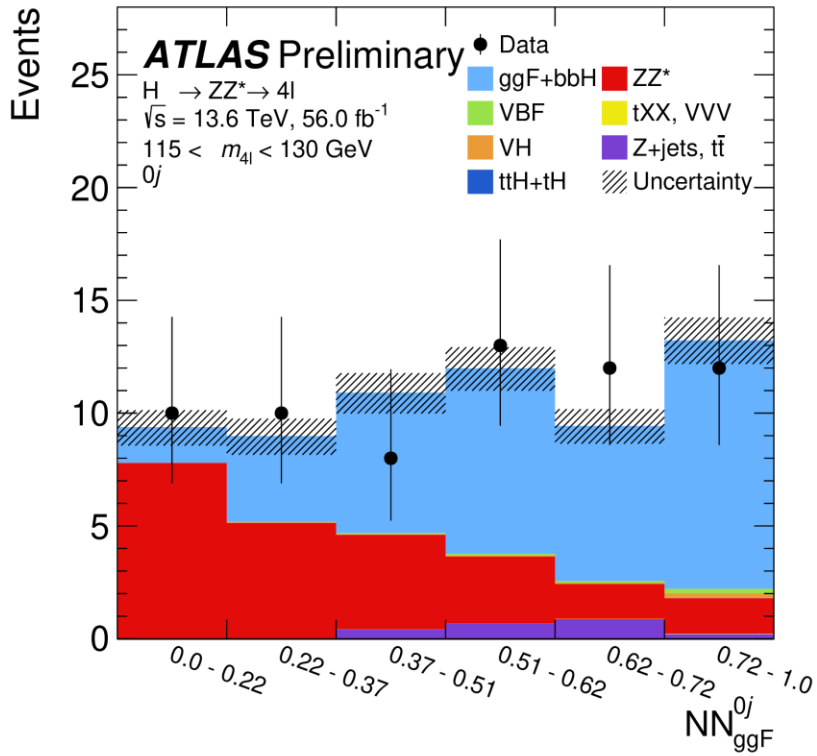
$H \to ZZ^* \to 4\ell$ partial Run 3 differential measurement







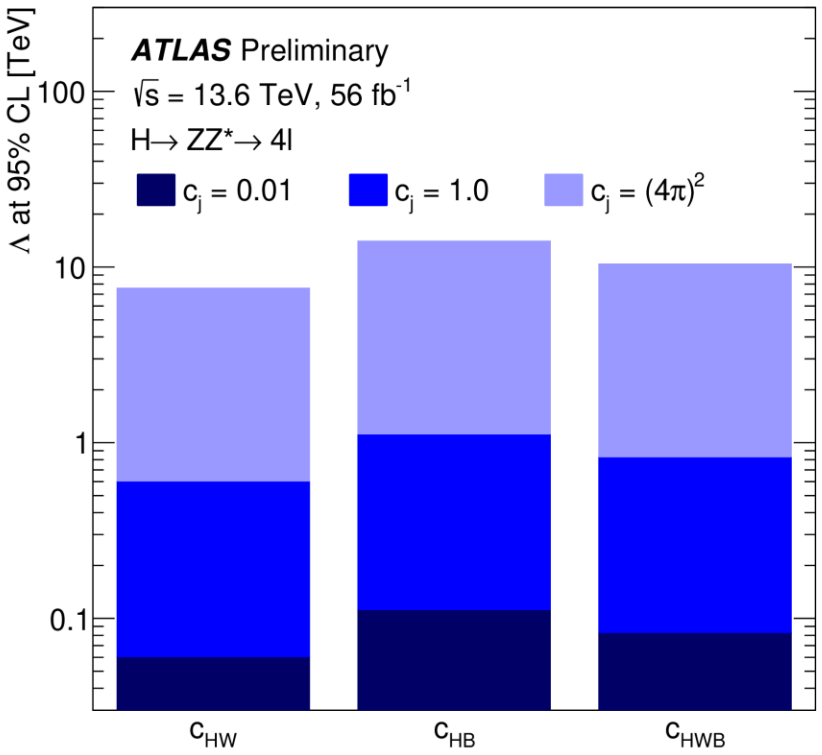
- Cross-sections for jet multiplicity
- Pre-fit m_{34} distributions
- Example of neural network output in ggF 0-jets region

ATLAS-CONF-2025-002

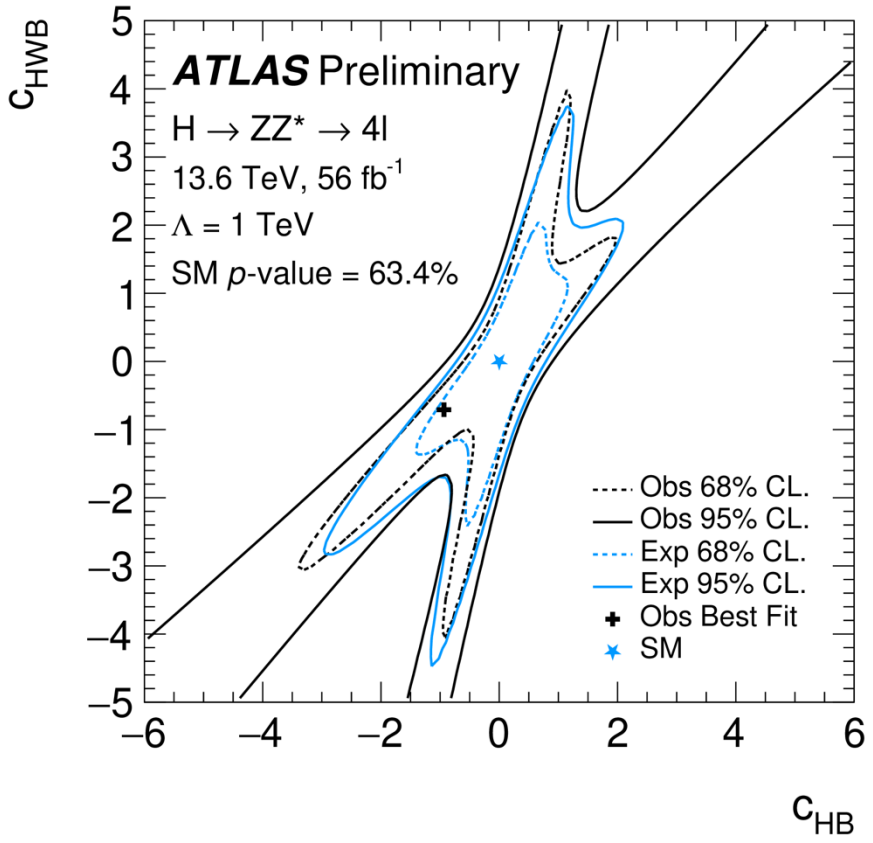
$H \to ZZ^* \to 4\ell$ partial Run 3 differential measurement

CP-even			CP-odd			Impact on	
Operator	Structure	Coeff.	Operator	Structure	Coeff.	production	decay
O_{HW}	$HH^\dagger W^I_{\mu\nu} W^{\mu\nu I}$	c_{HW}	$O_{H\widetilde{W}}$	$HH^\dagger \widetilde{W}^I_{\mu\nu} W^{\mu\nu I}$	$c_{H\widetilde{W}}$	VBF, VH	HZZ
O_{HB}	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$	c_{HB}	$O_{H\widetilde{B}}$	$HH^\dagger \widetilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\widetilde{B}}$	VBF, VH	HZZ
O_{HWB}	$HH^\dagger \tau^I W^I_{\mu\nu} B^{\mu\nu}$	c_{HWB}	$O_{H\widetilde{W}B}$	$HH^\dagger \tau^I \widetilde{W}^I_{\mu\nu} B^{\mu\nu}$	$c_{H\widetilde{W}B}$	VBF, VH	HZZ

$$\mathcal{L}_{EFT} = \mathcal{L}_S + \sum_i \frac{C_i^{(d)}}{\Lambda^{(d-4)}} \mathcal{O}_i^{(d)} \text{ for } d > 4$$

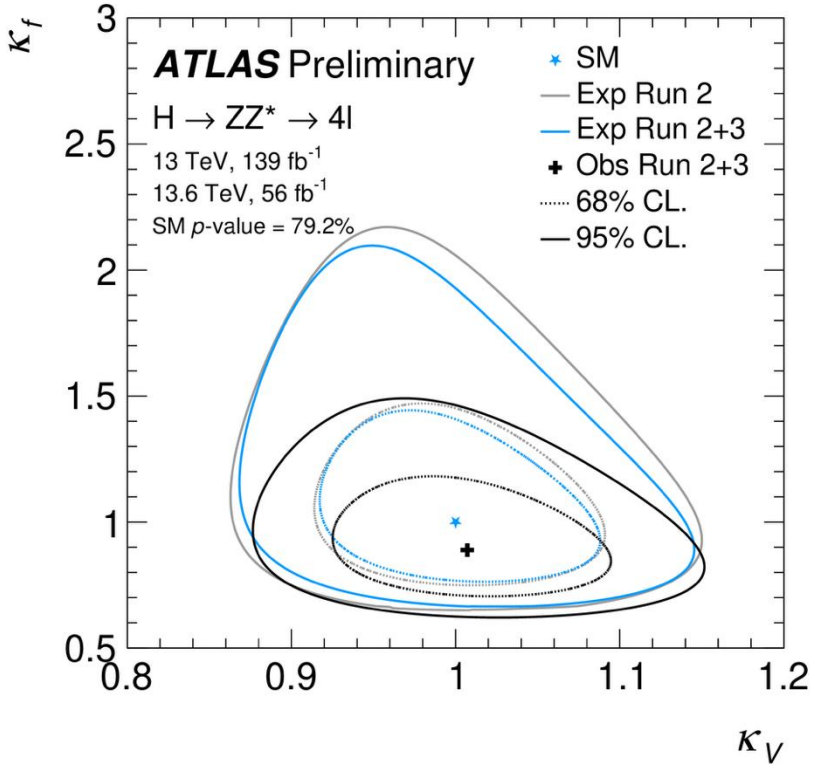


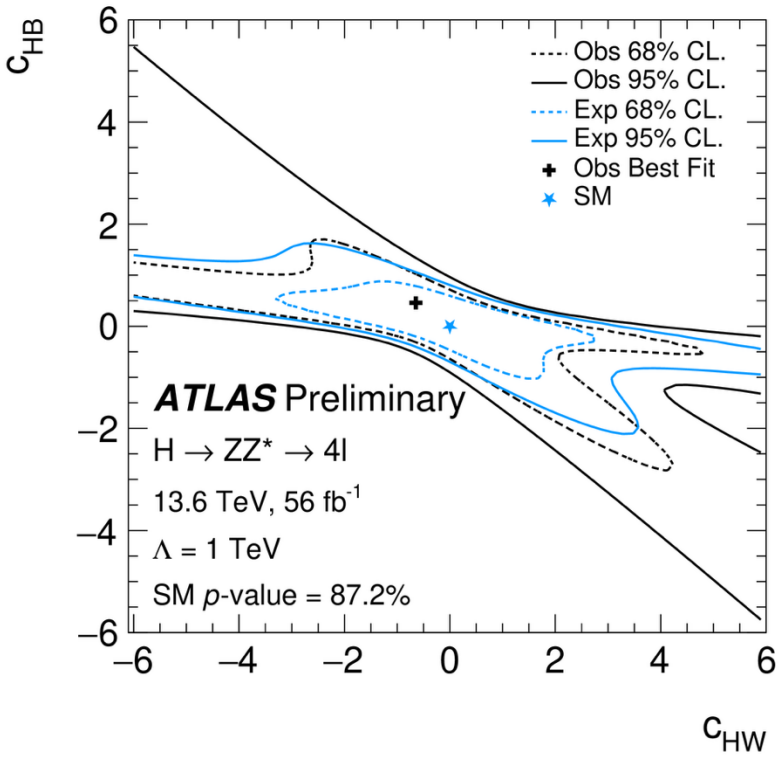
- Additional SMEFT interpretation: constraints on the Wilson coefficients associated to vector-boson interactions in the Warsaw basis
- **95% CL observed lower limits** on the scale of new physics Λ for three Wilson coefficient values (all other coefficients are assumed zero)
- Constraints are obtained comparing the measured signal cross-section in the **unfolded m_{34}** differential distribution

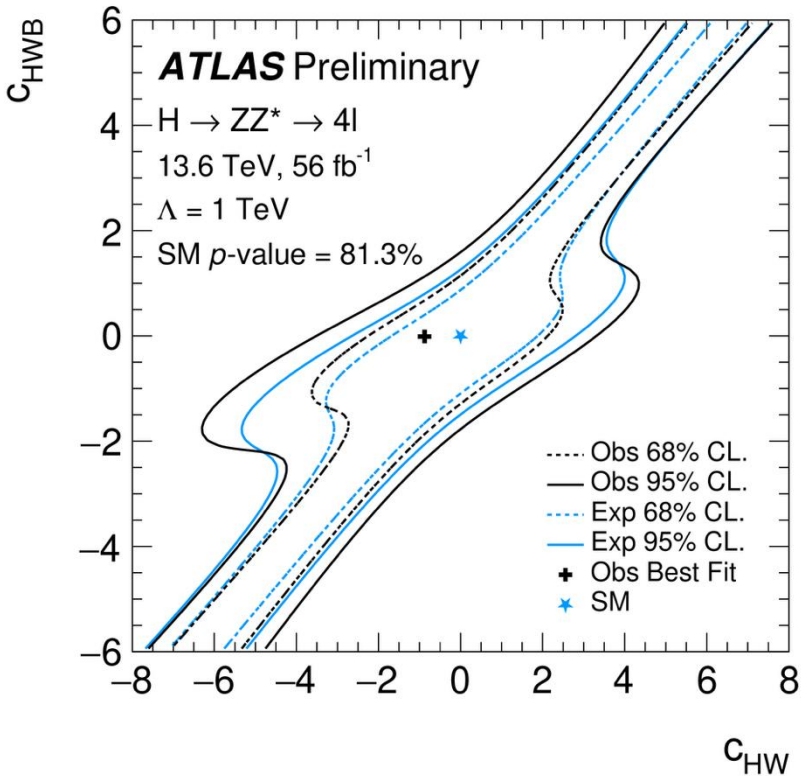


ATLAS-CONF-2025-002

$H \to ZZ^* \to 4\ell$ partial Run 3 differential measurement



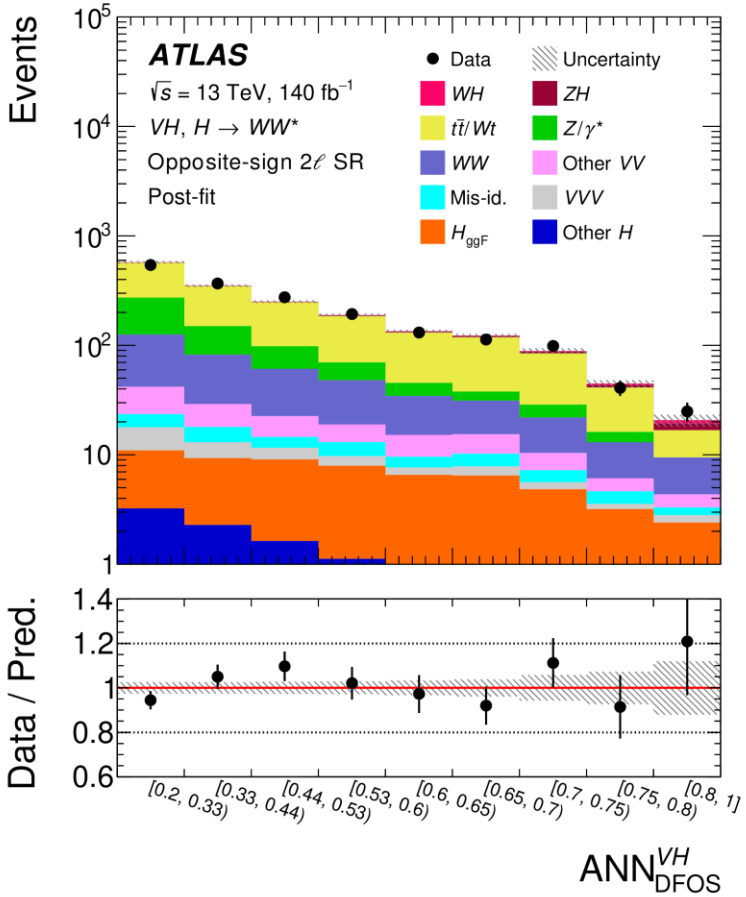




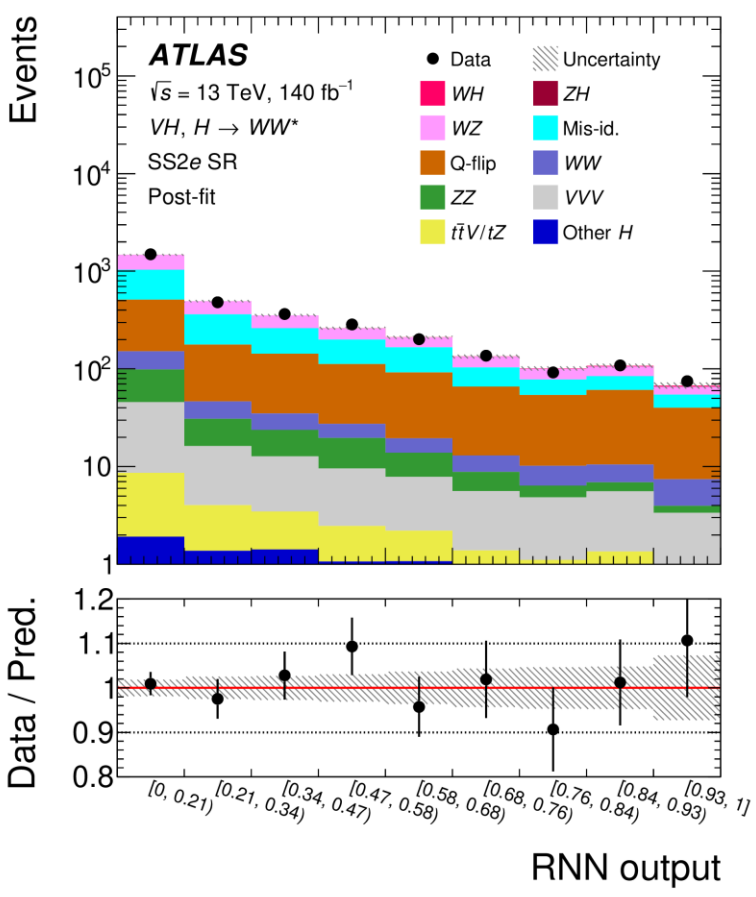
- Likelihood contours in the (κ_f, κ_V) plane
- 2D exclusion contours for (C_{HB},C_{HW}) and (C_{HWB},C_{HW})

ATLAS-CONF-2025-002

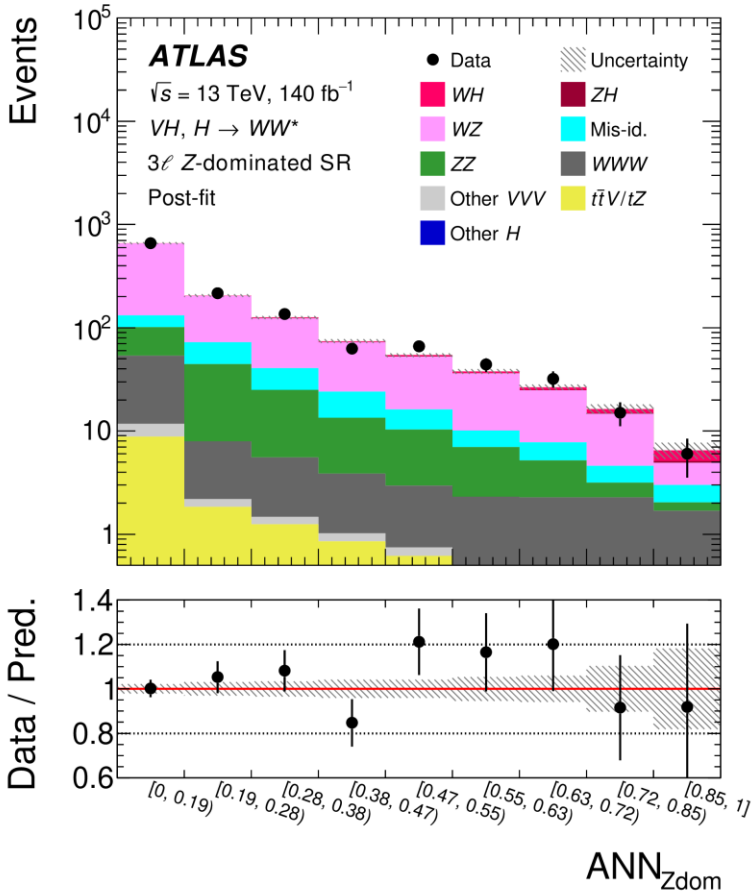
$H \to WW^*$ Run 2 measurements: an overview



VH, 2L OS



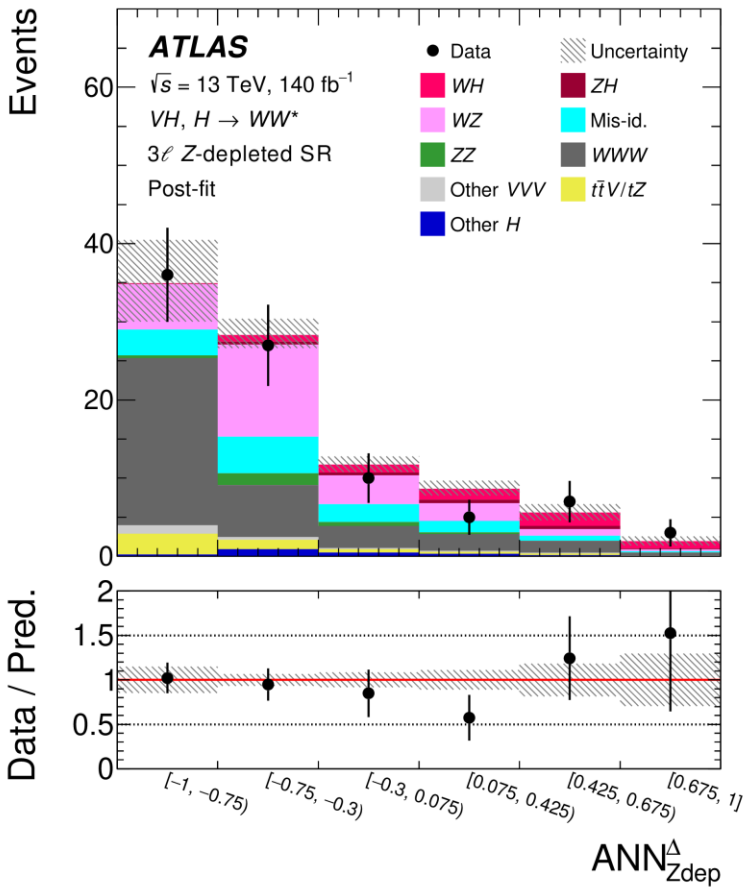
VH, 2L SS, 2μ



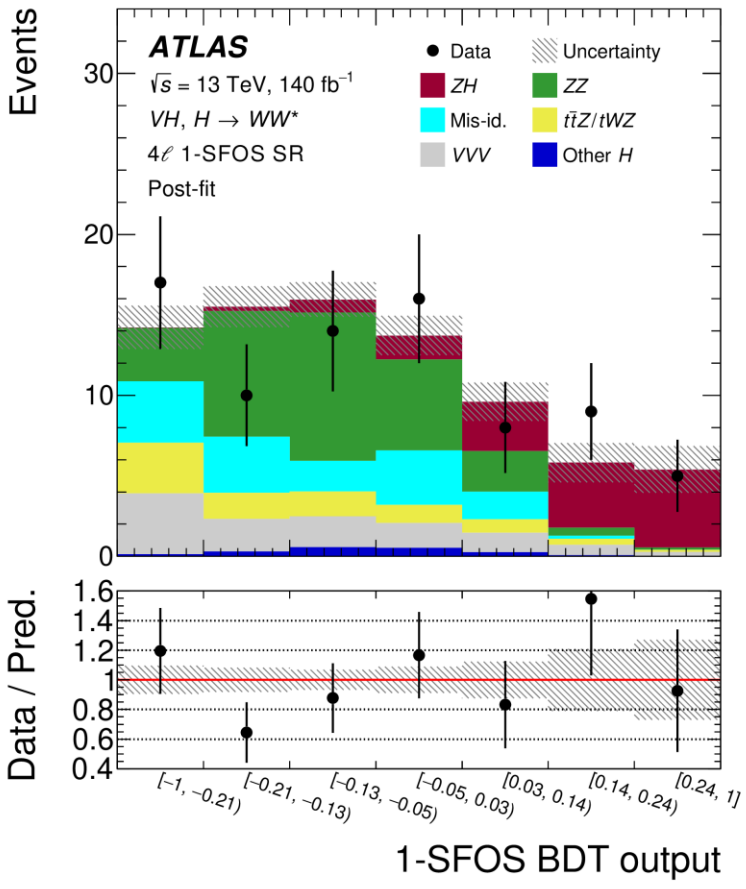
VH, 3L, Z dom

HIGG-2023-09 (VH)

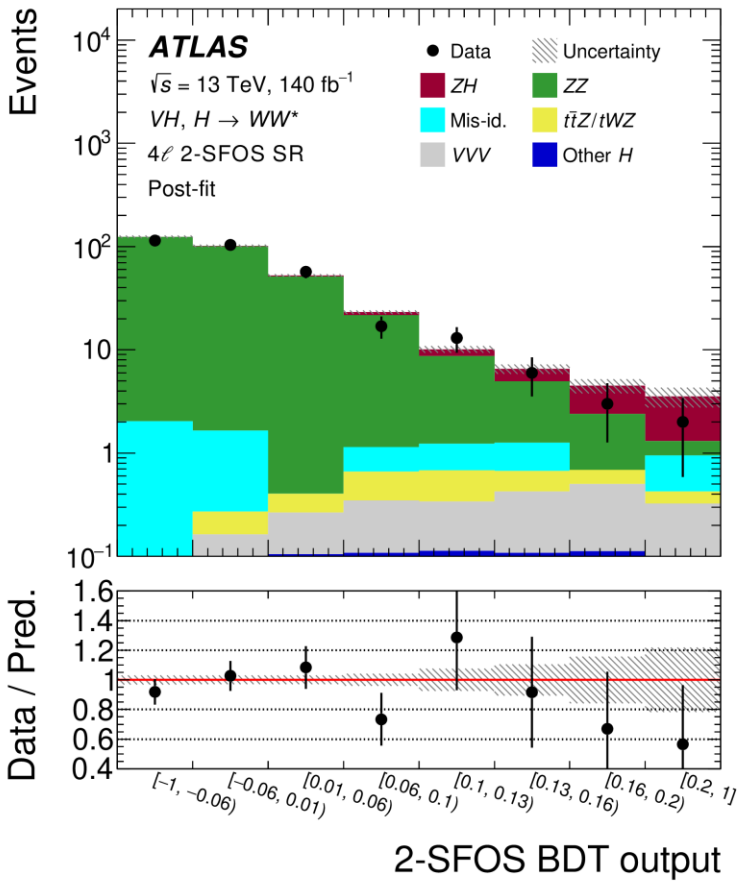
$H \to WW^*$ Run 2 measurements: an overview



VH, 3L, Z depl.



VH, 4L, 1-SFOS



VH, 4L, 2-SFOS

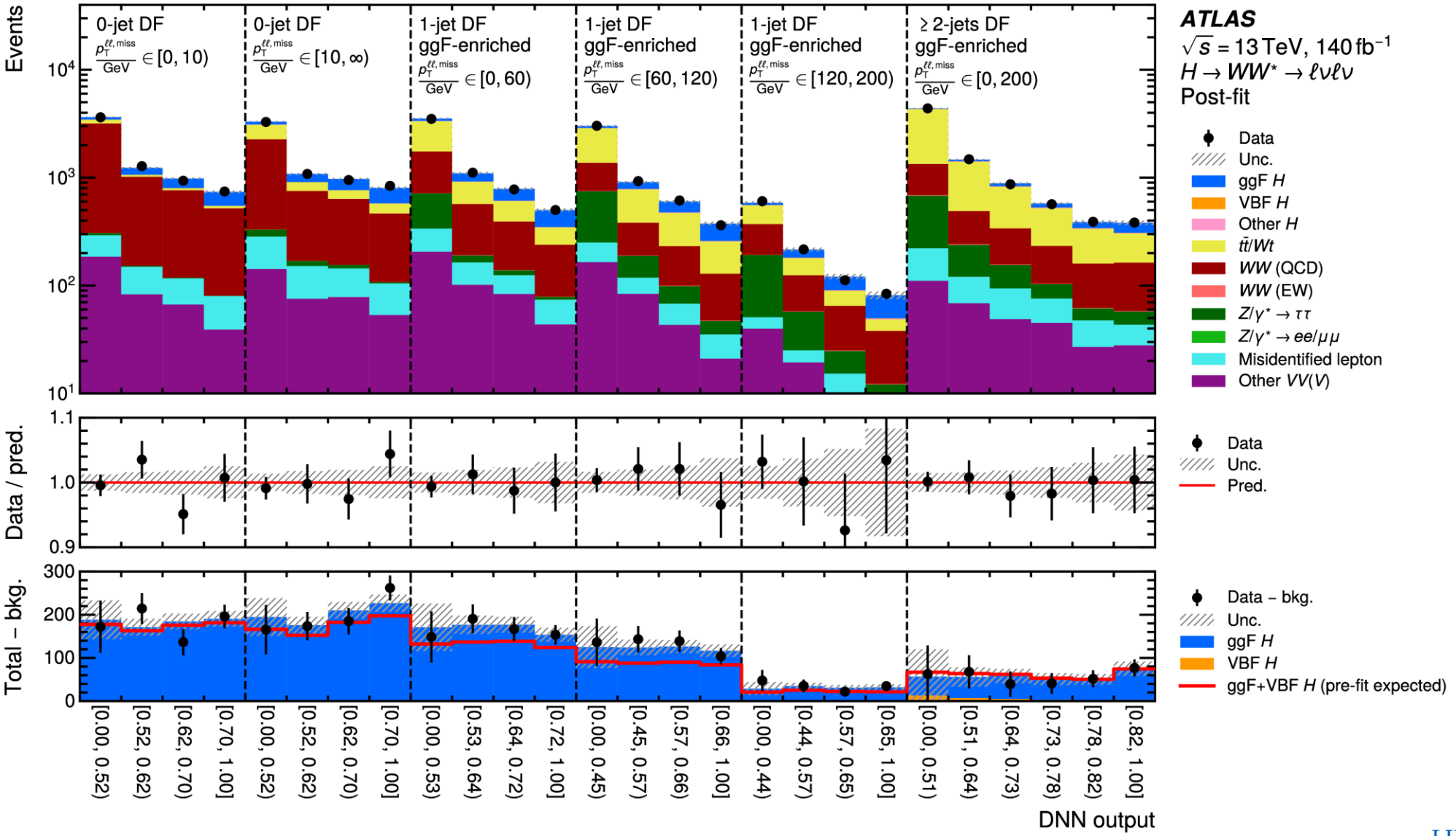
HIGG-2023-09 (VH)

$H \to WW^*$ Run 2 measurements: an overview

Purpose	Event class			
	$N_{\text{jets}} = 0$	$N_{\text{jets}} = 1$	$N_{\text{jets}} \geq 2$ ggF-enriched	$N_{\text{jets}} \geq 2$ VBF-enriched
Preselection	Two isolated, different-flavour (same-flavour) leptons with opposite charge $p_{\text{T}}^{\ell_0} > 22\,\text{GeV}$ and $p_{\text{T}}^{\ell_1} > 15\,\text{GeV}$ $m_{\ell\ell} > 10\,\text{GeV}$ (12 GeV) Different-flavour leptons		($\mathcal{S}_{\text{miss}} > 4$ and $p_{\text{T}}^{\ell\ell} > 40\,\text{GeV}$) Different- or same-flavour leptons	
Background suppression	$N_{b\text{-jets}}\,[p_{\text{T}} > 20\,\text{GeV}] = 0$ $E_{\text{T}}^{\text{miss}} > 20\,\text{GeV}$ $\Delta\phi_{\ell\ell} < 2.0\,\text{rad}$ $m_{\ell\ell} < 55\,\text{GeV}$ $\Delta R_{\ell\ell} > 0.6$		$m_{\tau\tau} < m_Z - 25\,\text{GeV}$ $\Delta\phi_{\ell\ell} < 1.8\,\text{rad}$ $m_{\ell\ell} < 55\,\text{GeV}$	– $m_{\ell\ell} < 70\,\text{GeV}$
Signal topology	$\Delta\phi_{\ell\ell,\text{miss}} > 1.57\,\text{rad}$	–	VH orthogonality Fail CJV or Fail OLV	$m_{jj} > 350\,\text{GeV}$ Pass CJV and Pass OLV

HIGP-2024-07 (ggF+VBF)

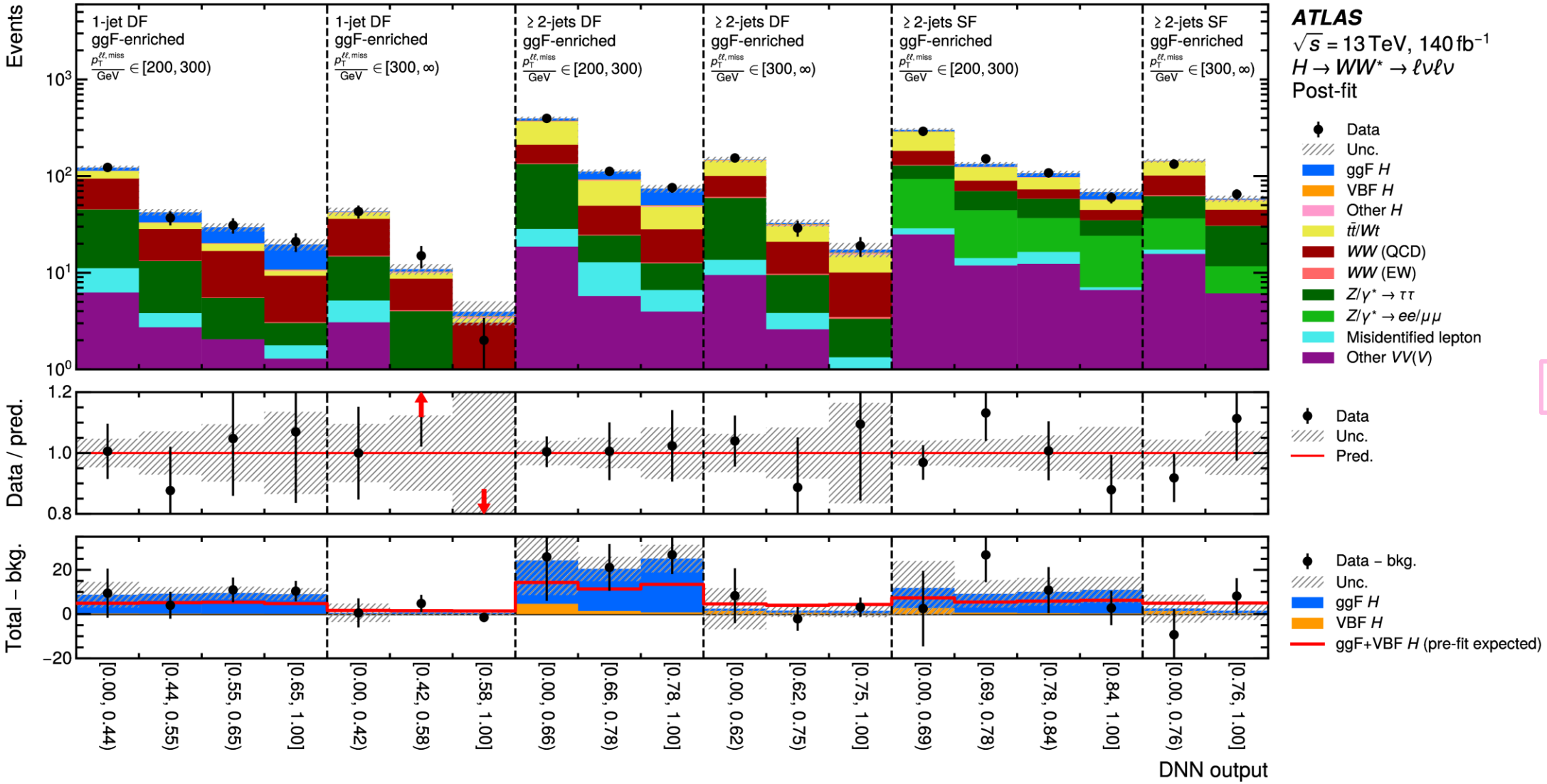
$H \to WW^*$ Run 2 measurements: an overview



ggF, 0/1/2+-jet SR

HIGP-2024-07 (ggF+VBF)

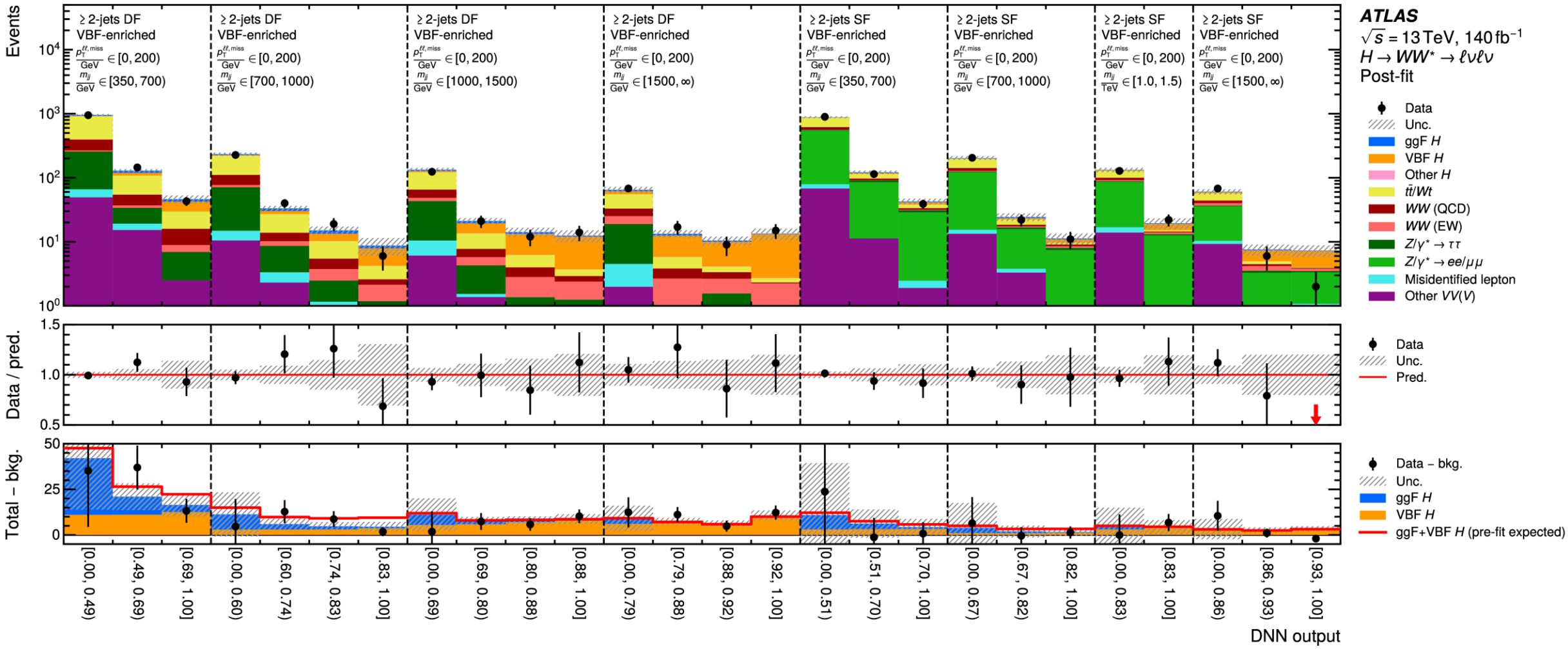
$H \to WW^*$ Run 2 measurements: an overview



ggF, 1/2+-jet SR

HIGP-2024-07 (ggF+VBF)

$H \to WW^*$ Run 2 measurements: an overview

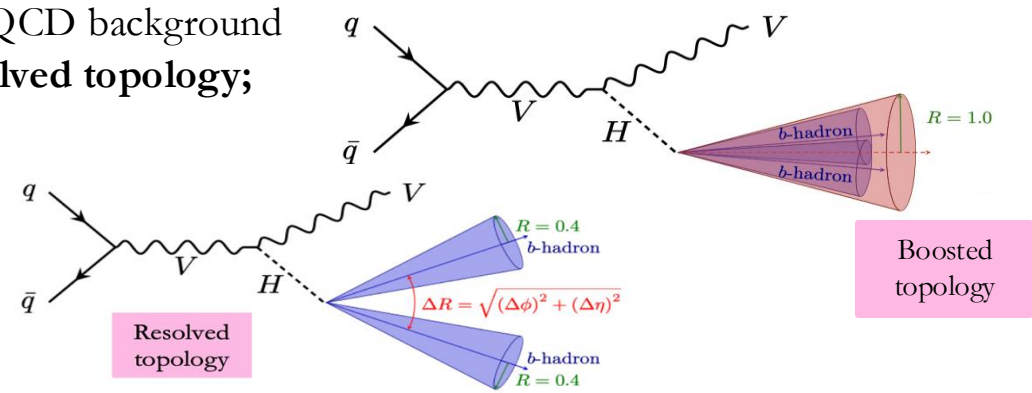


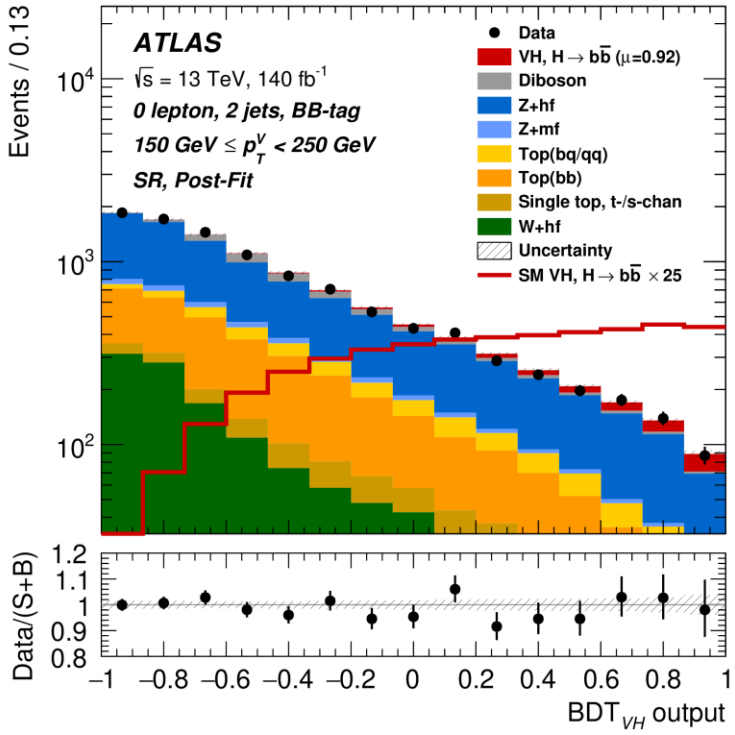
VBF, 2+-jet SR

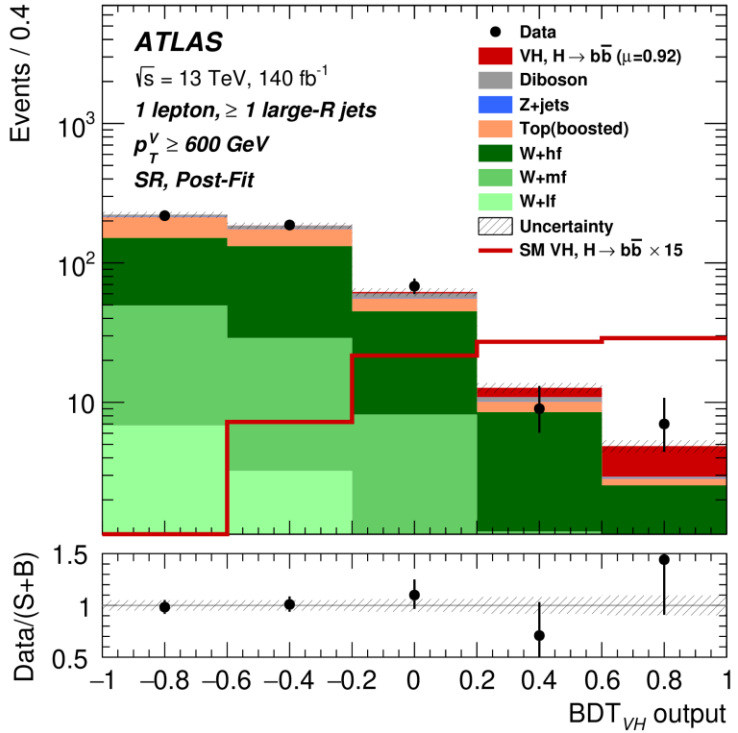
HIGP-2024-07 (ggF+VBF)

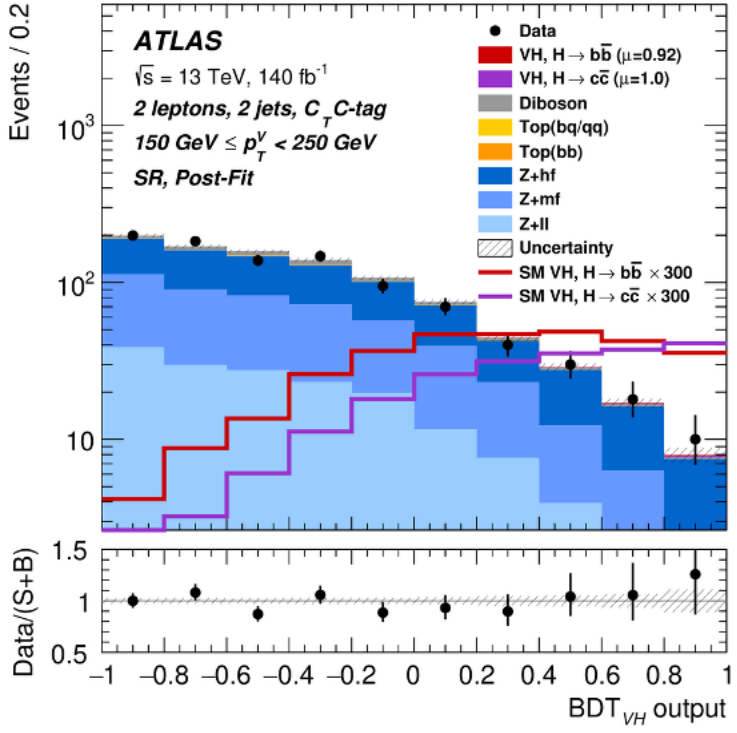
VH, H → $b\bar{b}/c\bar{c}$ Run 2 coupling measurement

- The **VH production method** with leptonic decay of the vector boson reduces QCD background
- Combined VH, H → $b\bar{b}$ **resolved and boosted** topologies and VH, H → $c\bar{c}$ **resolved topology;**
- 3 decay channels for the lepton boson
  - 0-lepton: $Z \to \nu\nu$
  - 1-lepton: $W \to \ell\nu$
  - 2-lepton: $Z \to \ell\ell$
- Simultaneous **profile likelihood fit** of 59 signal regions and 97 control regions.
- Signal versus background discrimination with Boosted Decision Trees.









HIGG-2020-20

VH, H → $b\bar{b}/c\bar{c}$ Run 2 coupling measurement

- **First observation of $WH, H \to b\bar{b}$.**
- **Strongest observed limit of $VH, H \to c\bar{c}$.**
- Cross section measurements in both the reduced and extended **STXS scheme.**
- Coupling to charm quarks measured to be **weaker** than to bottom quarks.

$VH, H \to b\bar{b}$: 7.4σ (8.0σ) $\quad 0.65 < |\kappa_b| < 1.37$ $(0.72 < |\kappa_b| < 1.62)$

$WH, H \to b\bar{b}$: 5.3σ (5.5σ) $\quad ZH, H \to b\bar{b}$: 4.9σ (5.6σ)

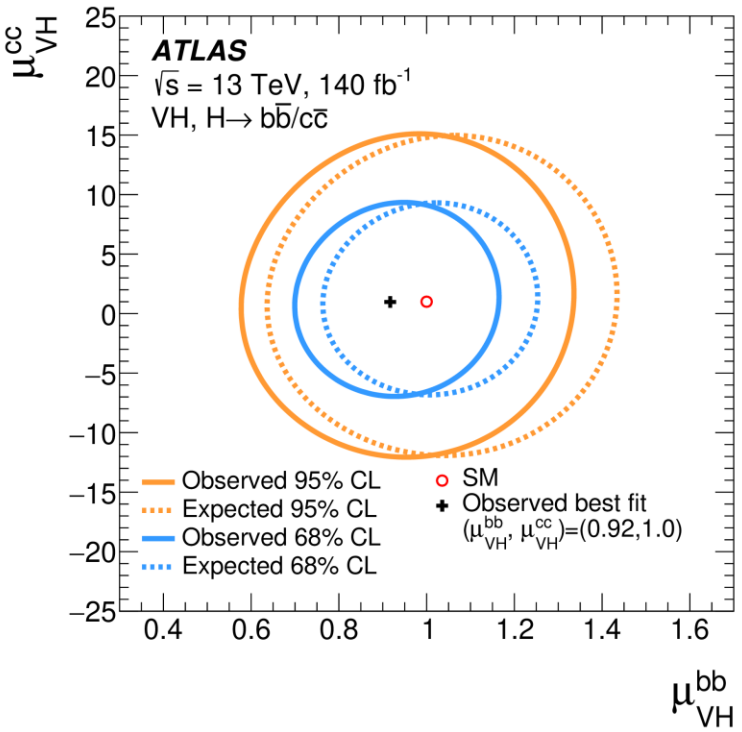
$VH, H \to c\bar{c}$ limit at 95% CL: 11.5(10.6)

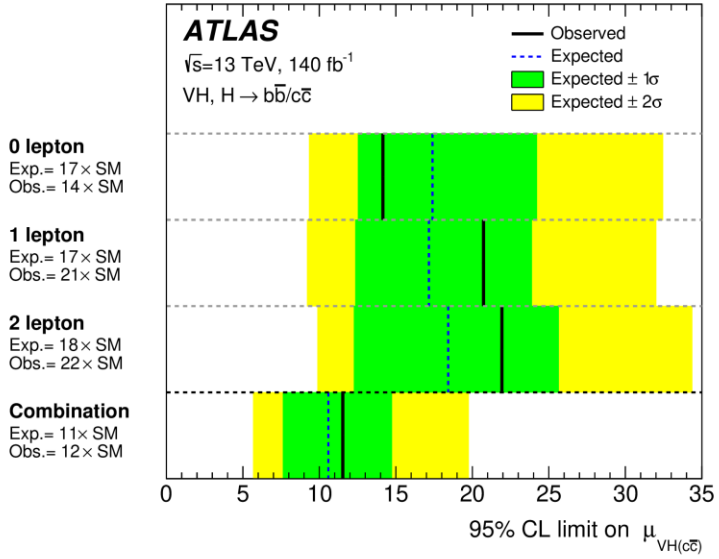
$|\kappa_c/\kappa_b|$ upper limit at 95% CL: 3.6(3.5)

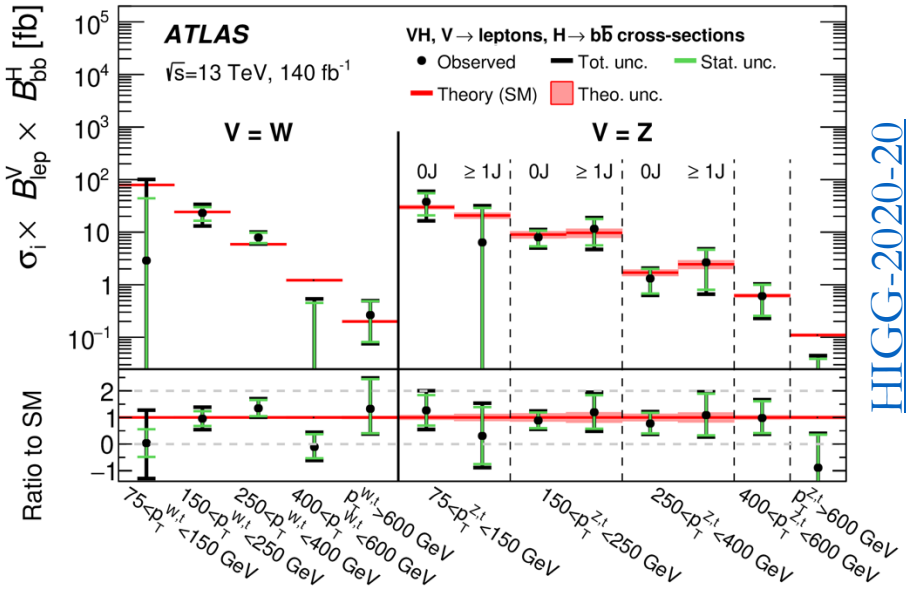
$|\kappa_c| < 4.2$ (4.1)

$\mu_{VH}^{bb} = 0.91^{+0.16}_{-0.15}$

$\mu_{VH}^{cc} = 1.0^{+5.4}_{-5.2}$

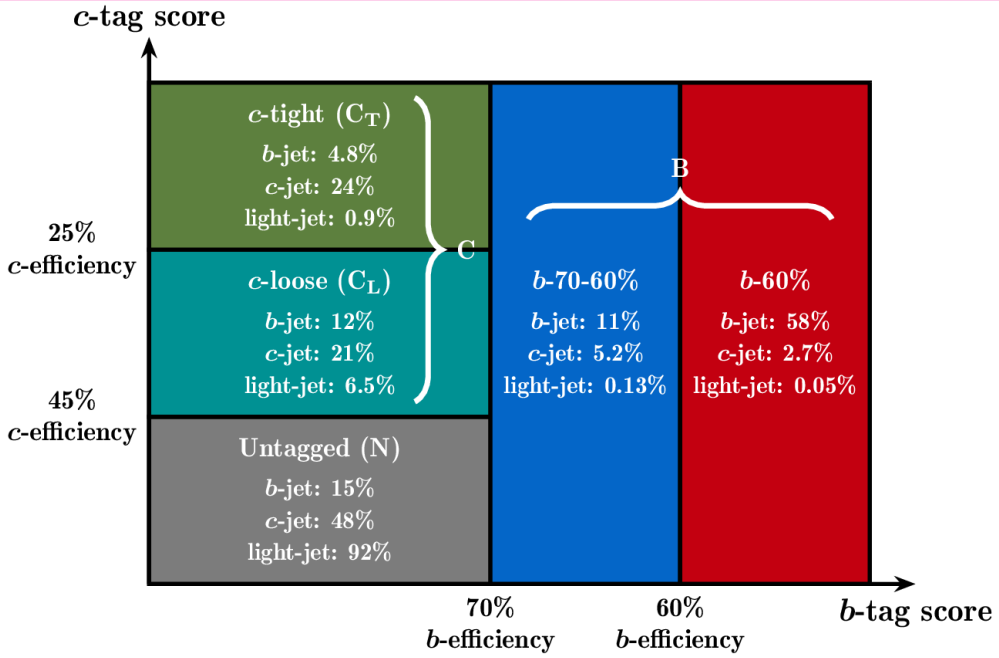


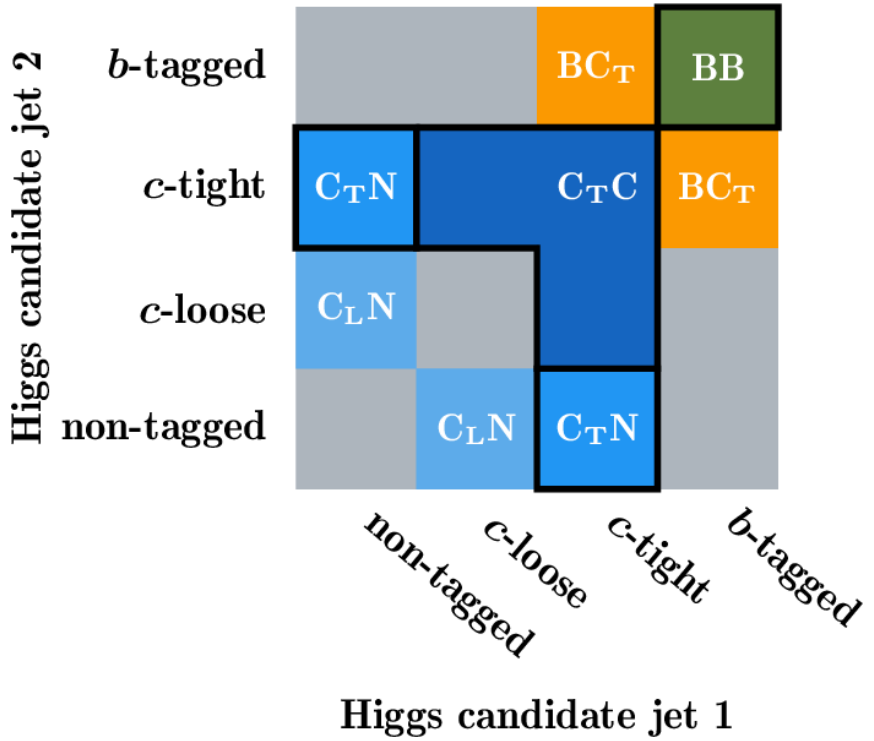




HIGG-2020-20

VH, H → $b\bar{b}/c\bar{c}$ Run 2 coupling measurement

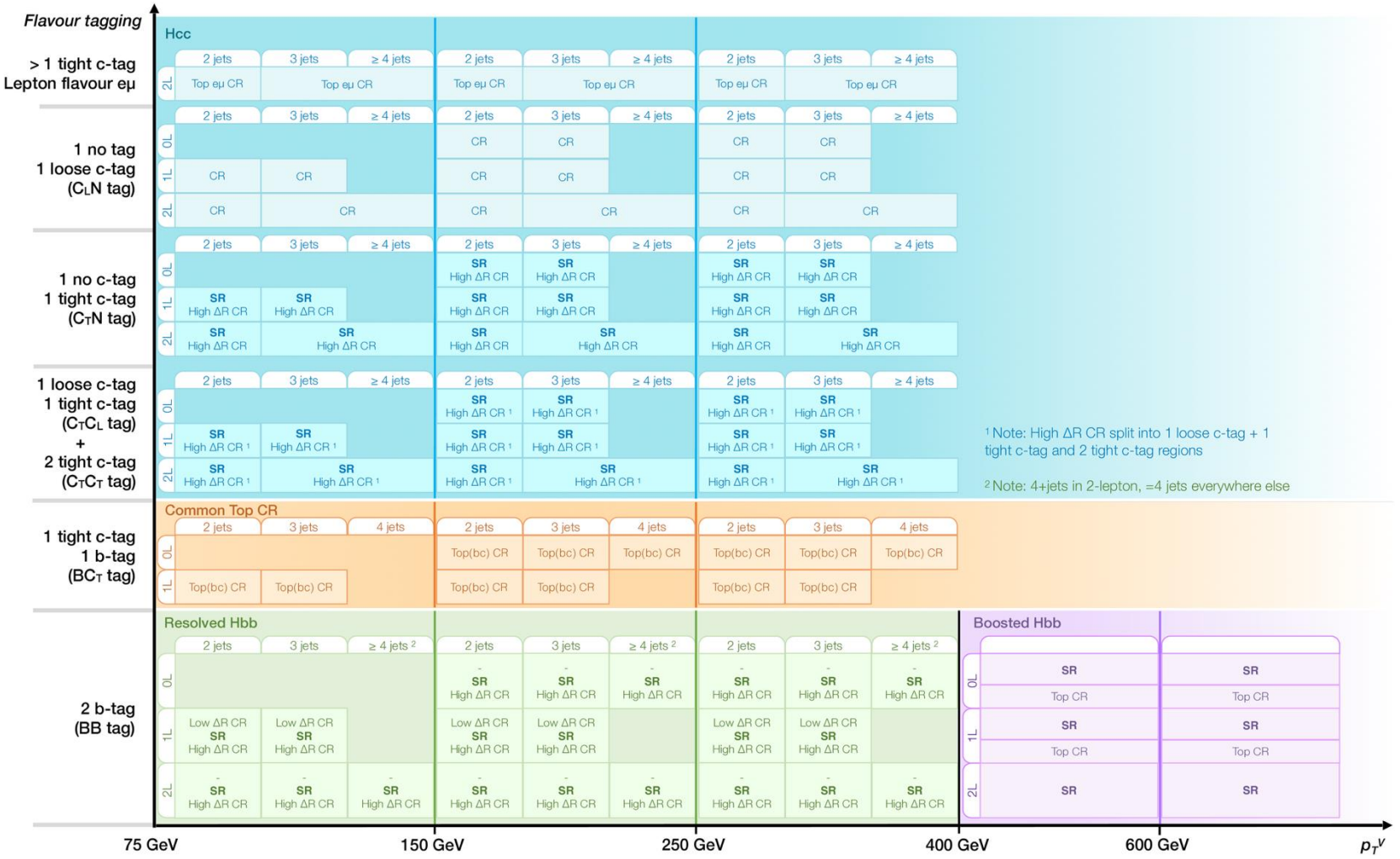




- Tagging regions definitions based on flavour tagging working points
- (next slide) overview of all signal and control regions of the analysis

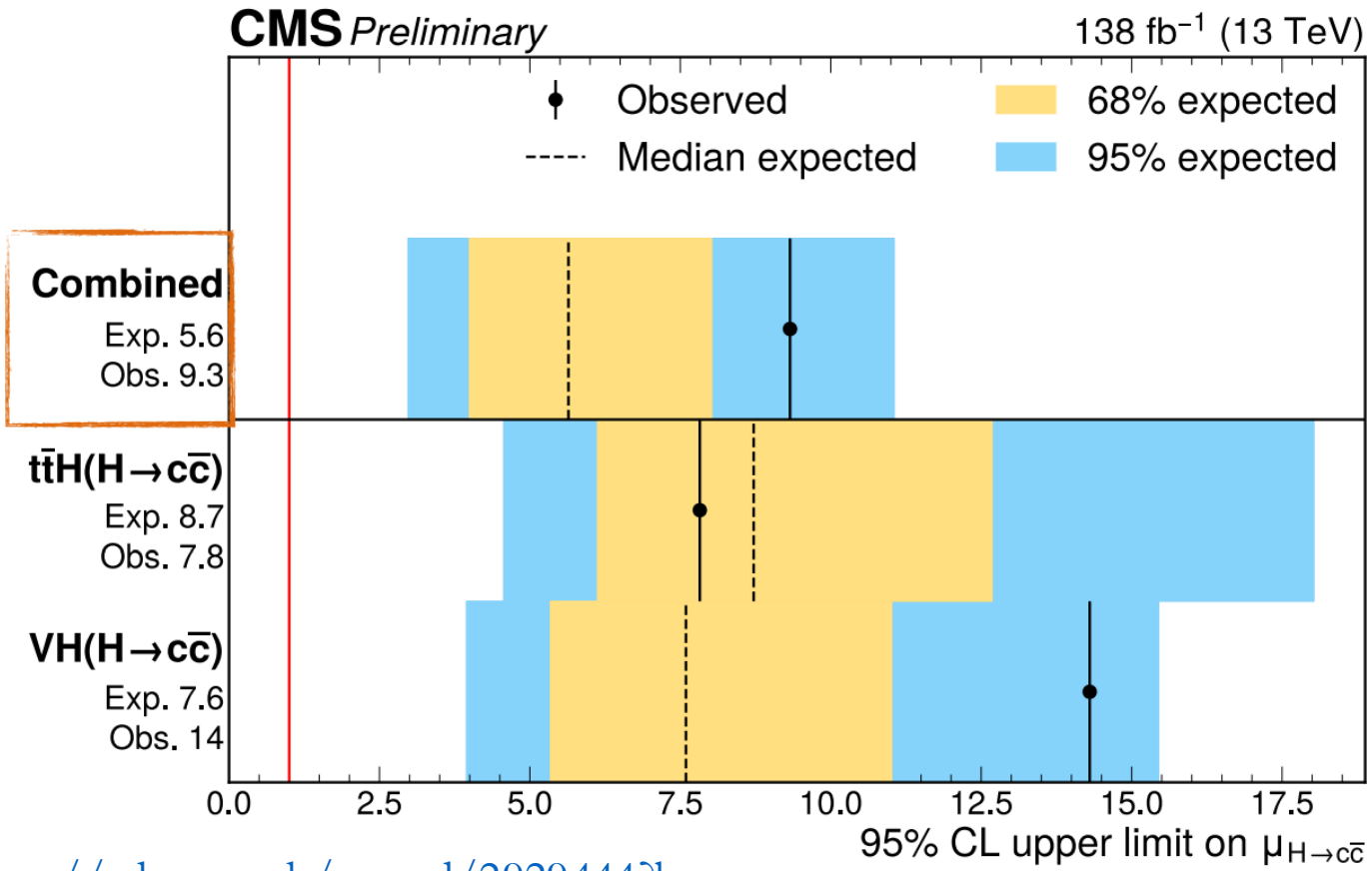
HIGG-2020-20

VH, H → $b\bar{b}/c\bar{c}$ Run 2 coupling measurement



HIGG-2020-20

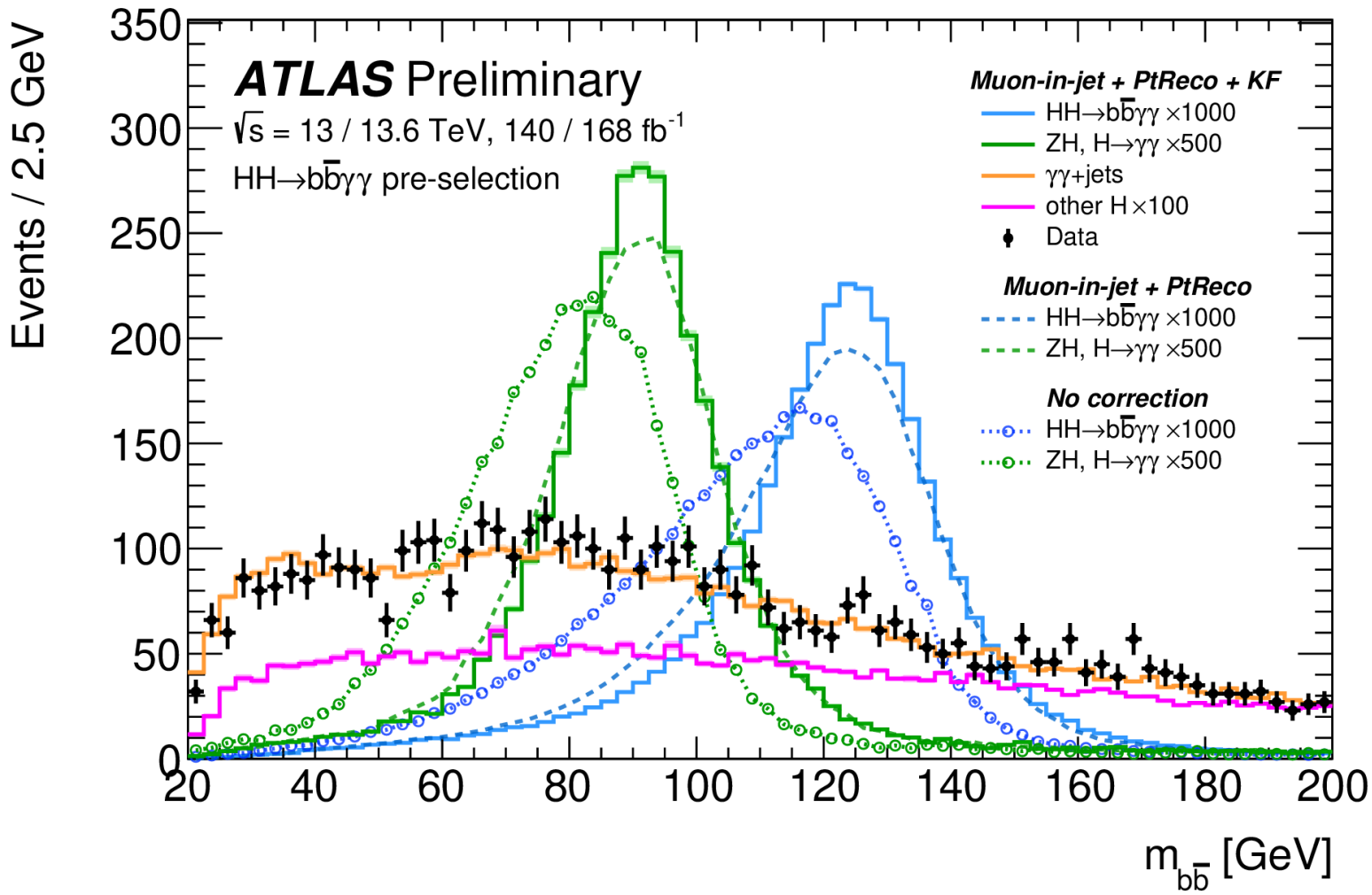
VH, H → $b\bar{b}/c\bar{c}$ Run 2 coupling measurement



https://cds.cern.ch/record/2929444?ln=en

- Comparison to most recent CMS results

$HH \to b\bar{b}\gamma\gamma$ Run 2 + partial Run3 measurement



- Dijet invariant mass distributions
  - after pre-selection
  - after corrections

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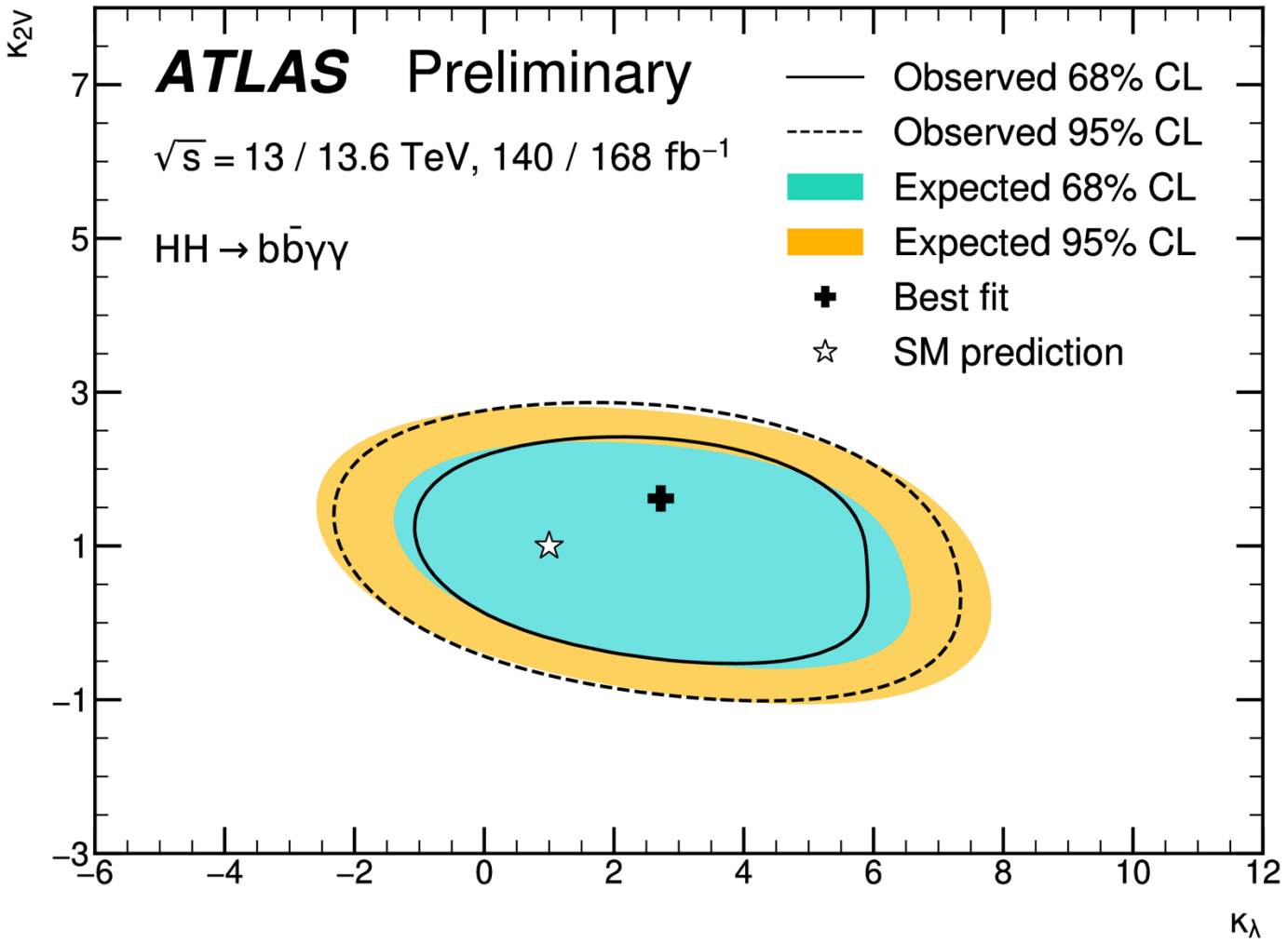
$HH \to b\bar{b}\gamma\gamma$ Run 2 + partial Run3 measurement



- Likelihood contours for the two coupling constants

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