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

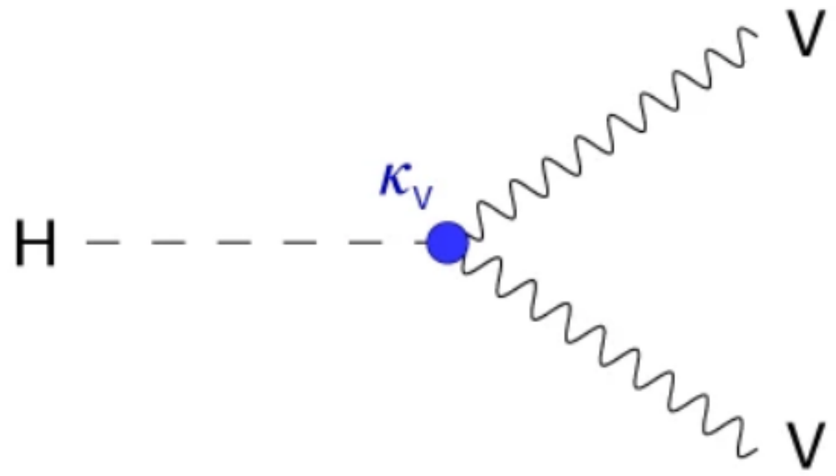
Rabia Shaheen on the behalf of the ATLAS collaboration
KTH Royal Institute Of Technology

43rd International Symposium on Physics in Collision, 2024

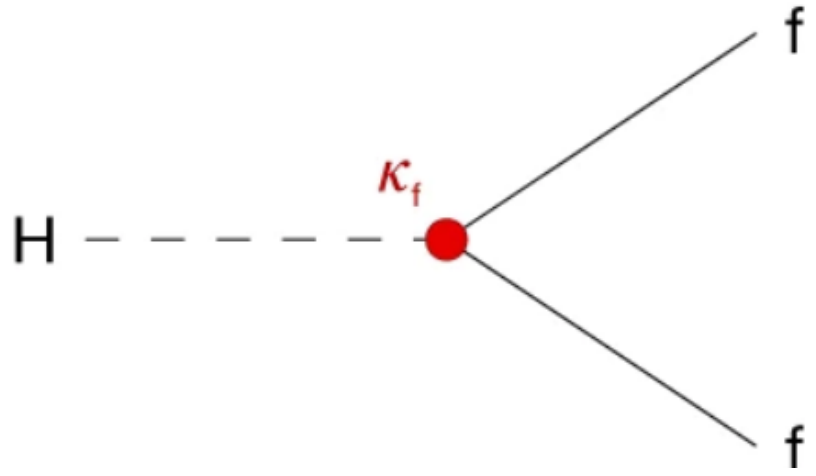
23/10/2024

Introduction

- Since discovery of Higgs boson, experiments focus on measuring its **properties**
- Higgs Boson couplings to massive particles fall into these main categories:
  - **Gauge Couplings to vector boson**

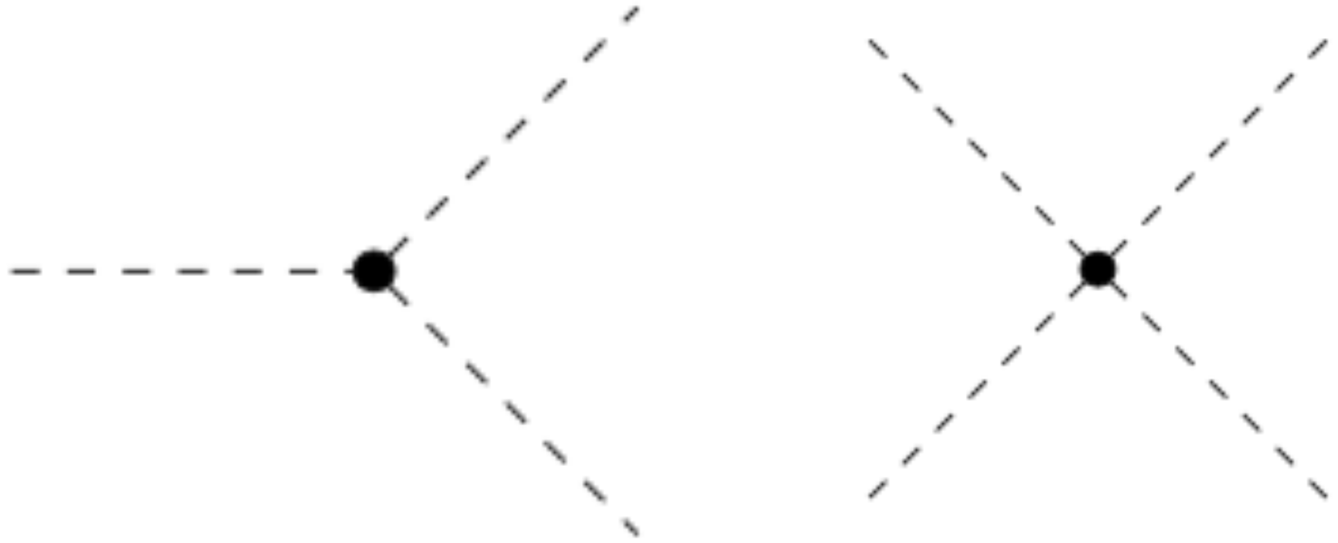


  - **Yukawa couplings to fermions**



  - **Self-coupling of the Higgs field**

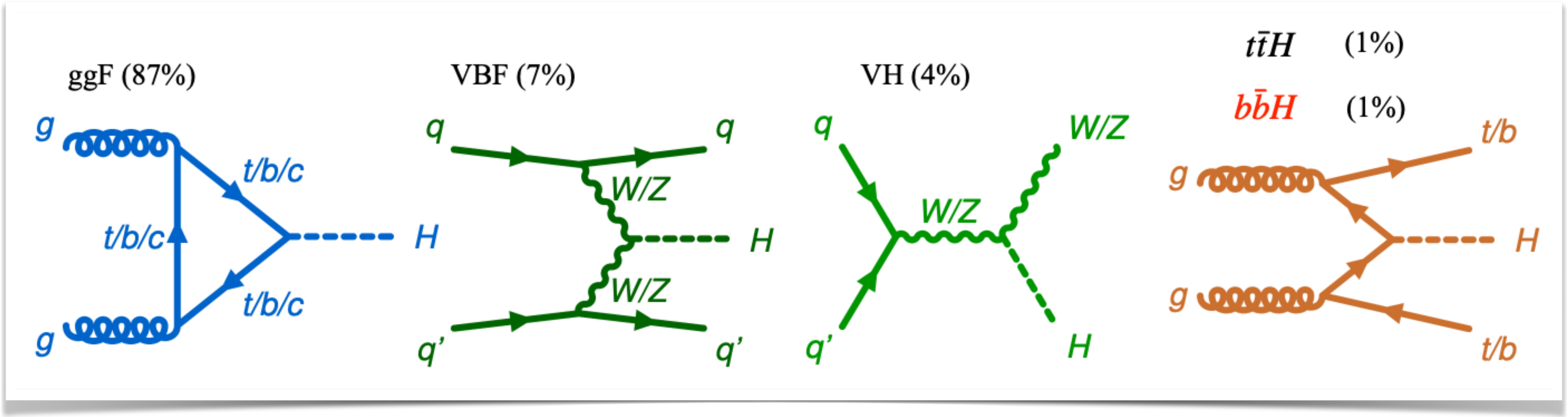
    (Not part of this presentation) talk by Ang Li

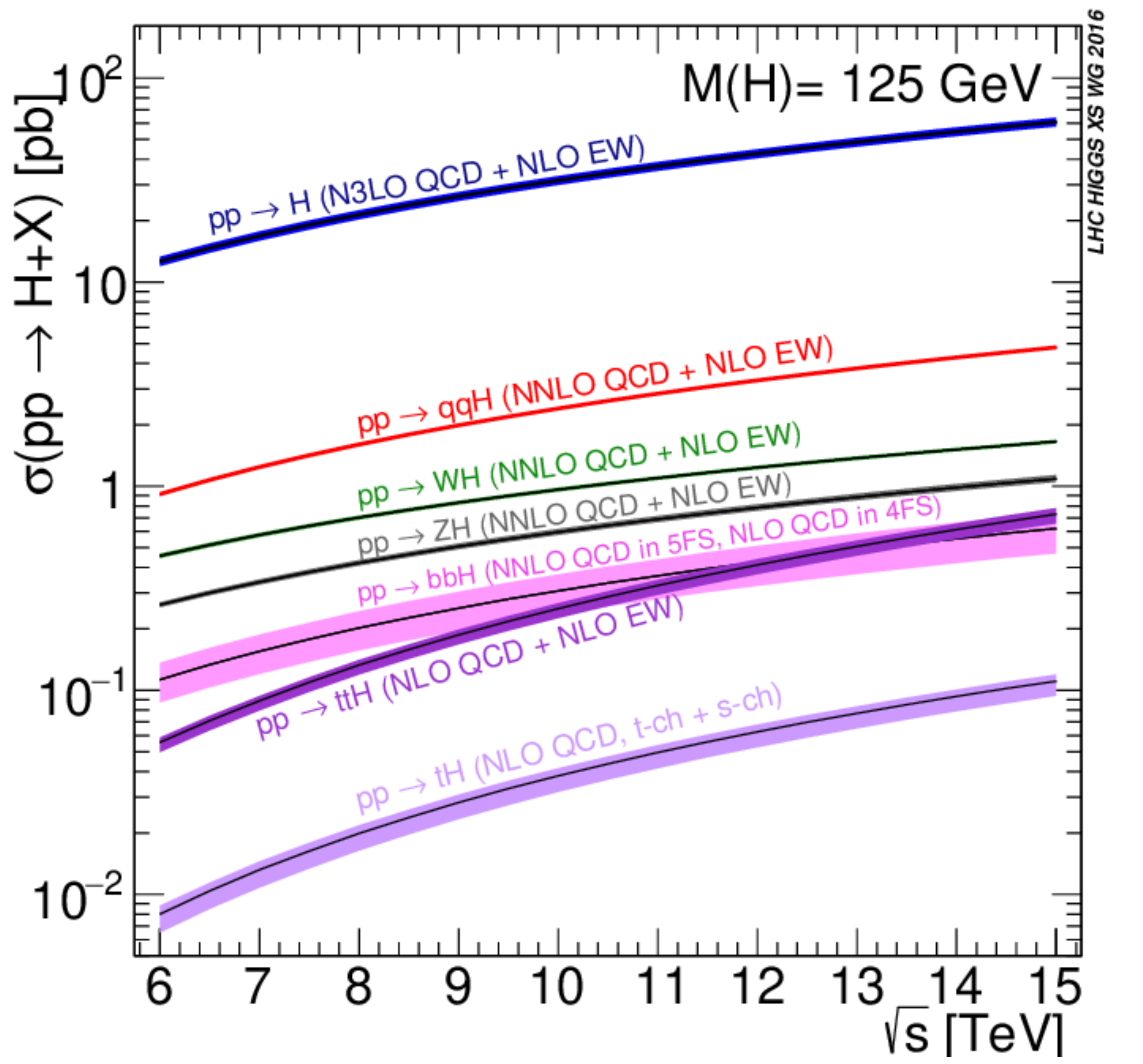


- Precise measurements of these couplings are a crucial test of **Standard Model (SM)** and **Beyond Standard Model (BSM)**

Higgs Boson Production and Decay Modes

- Various production and decays channels for the Higgs boson, Abraham talk
  - 4 main production channel
  - 5 Key decay channels:
    - $H \to b\bar{b}$, $H \to \tau\tau$ and $H \to WW^*$, high BR but low resolution
    - $H \to \gamma\gamma$ and $H \to ZZ^*$, low BR but high resolution
- Run 2, ATLAS recorded **~140 fb^{-1}** from *pp* collisions data
- **~9 million** Higgs bosons were produced
- Only **0.3%** are experimentally accessible
- Cross section measurements are essential for understanding processes



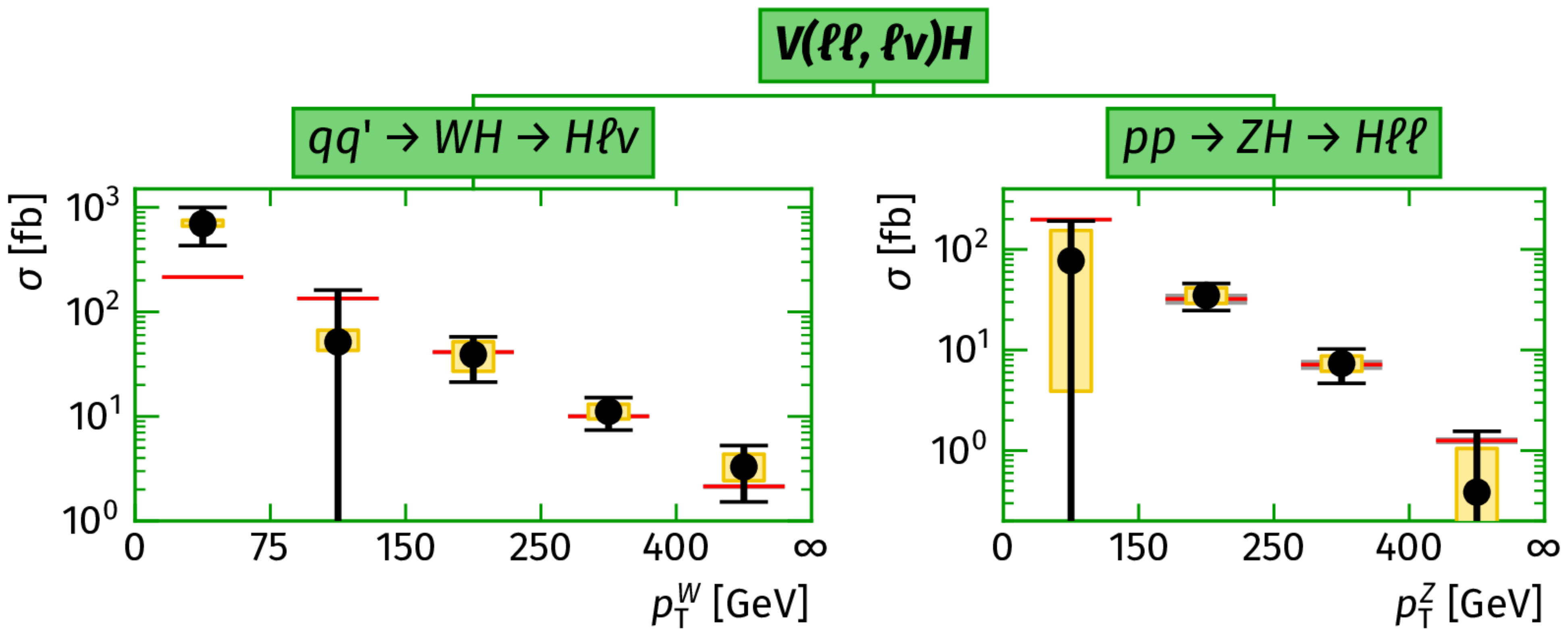


Run 1 Run 2 Run 3

Cross section Measurements

Simplified Template Cross-section (STXS):

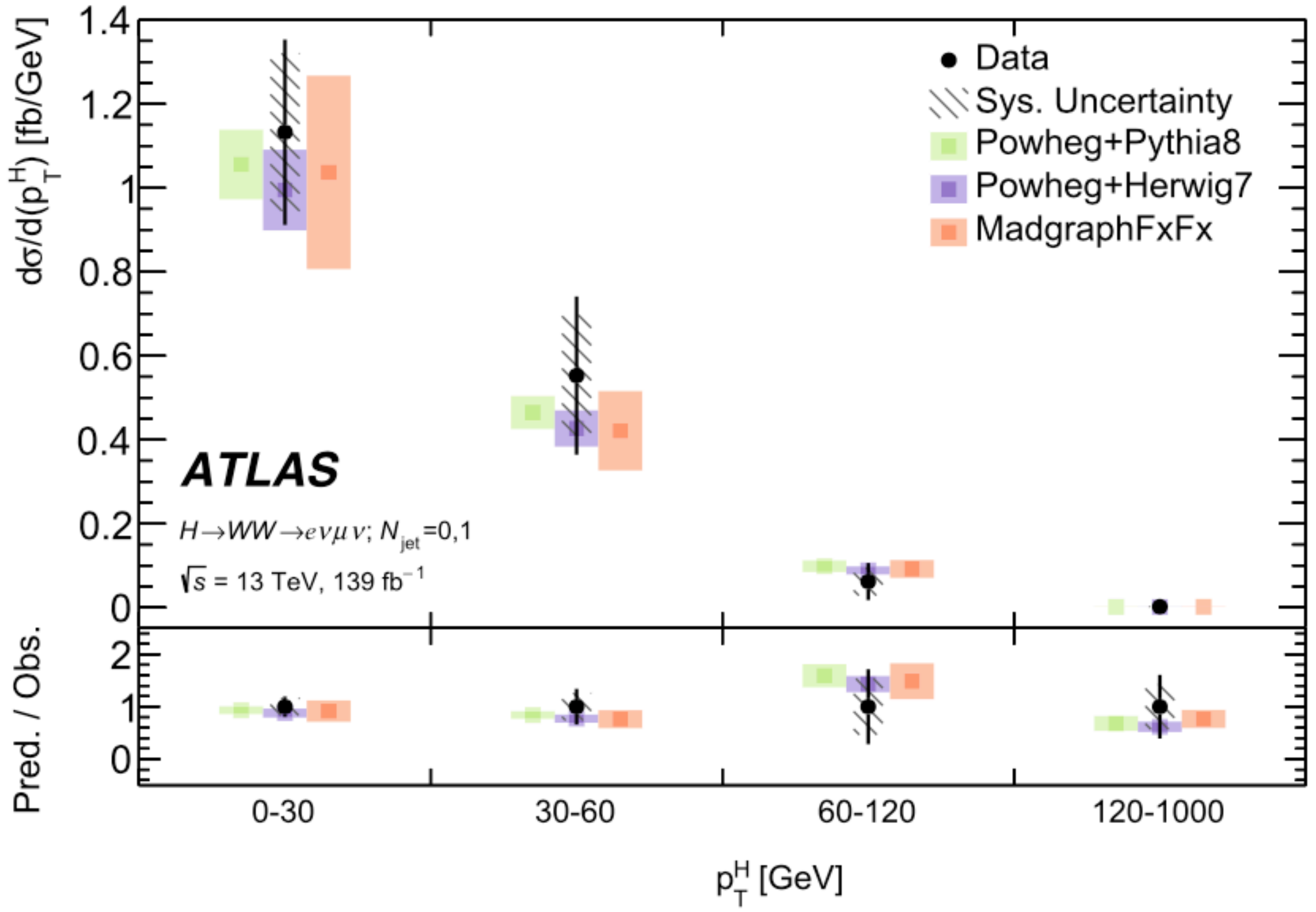
- Done for each production mode
- Split regions by the specific kinematic properties of the Higgs boson and associated jets, W or Z
- Template for deviations from the SM predictions



Nature 607 (2022) 52-59

Fiducial and differential measurements:

- Phase spaces with specific selections
- σ in bins of sensitive observables, i.e: p_T^H
- Shape of $d(\sigma)/d(p_T^H)$ for further interpretations



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

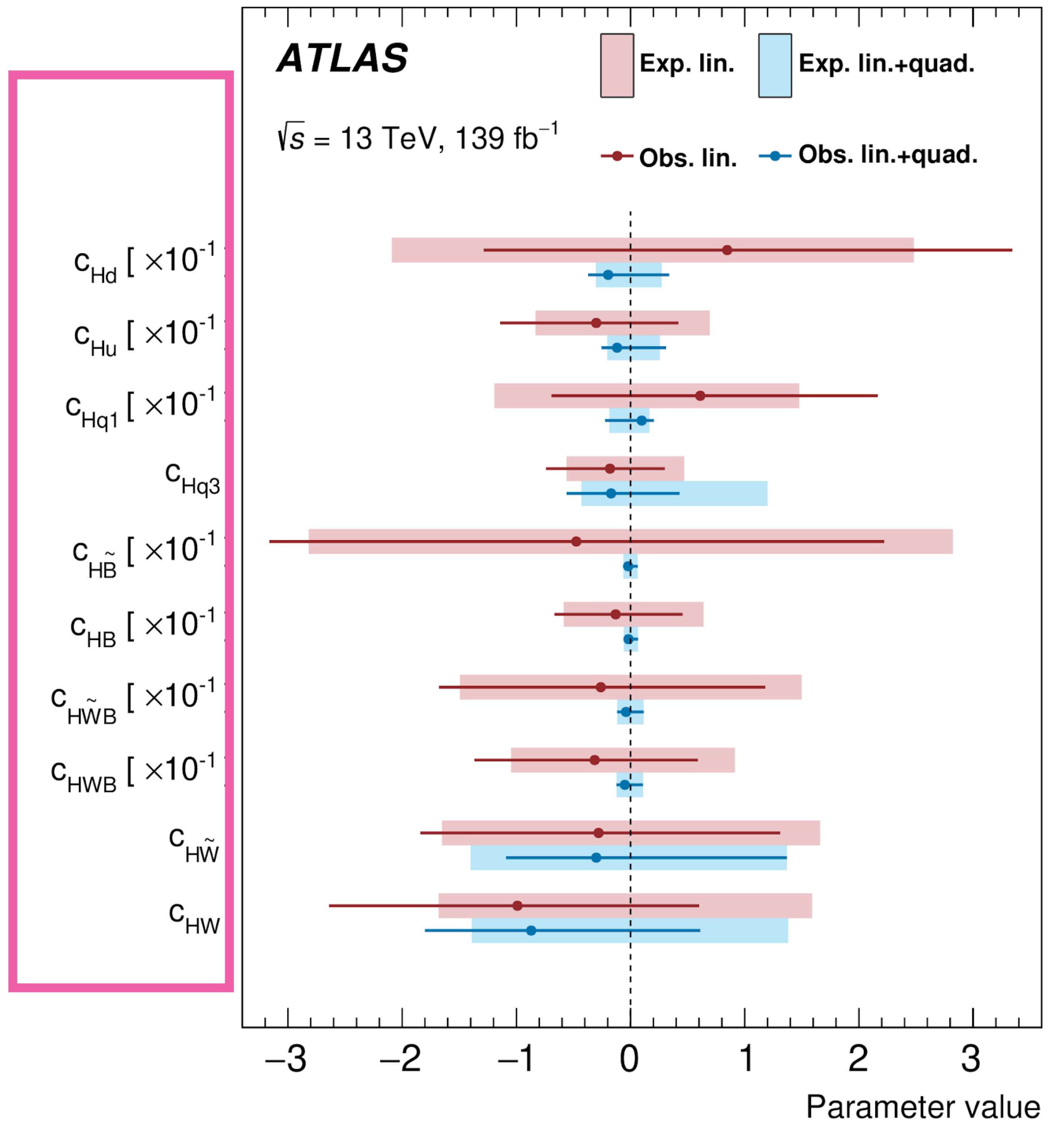
Interpretation based on SMEFT

- Model-Independent approach to study SM deviation
- SMEFT langrangian in terms of SM:

$$\mathscr{L}_{\mathrm{SMEFT}} = \mathscr{L}_{\mathrm{SM}} + \sum_i^6 c_i/\lambda^2 \mathcal{O}_i^6 + \sum_j^8 b_j/\lambda^4 \mathcal{O}_j^8$$

- Cross section relative to SM expectation:

$$\sigma_{EFT}/\sigma_{SM} = 1 + \sum A_i c_i + \sum B_{ij} c_i c_j$$



Phys. Rev. D 108 (2023) 072003

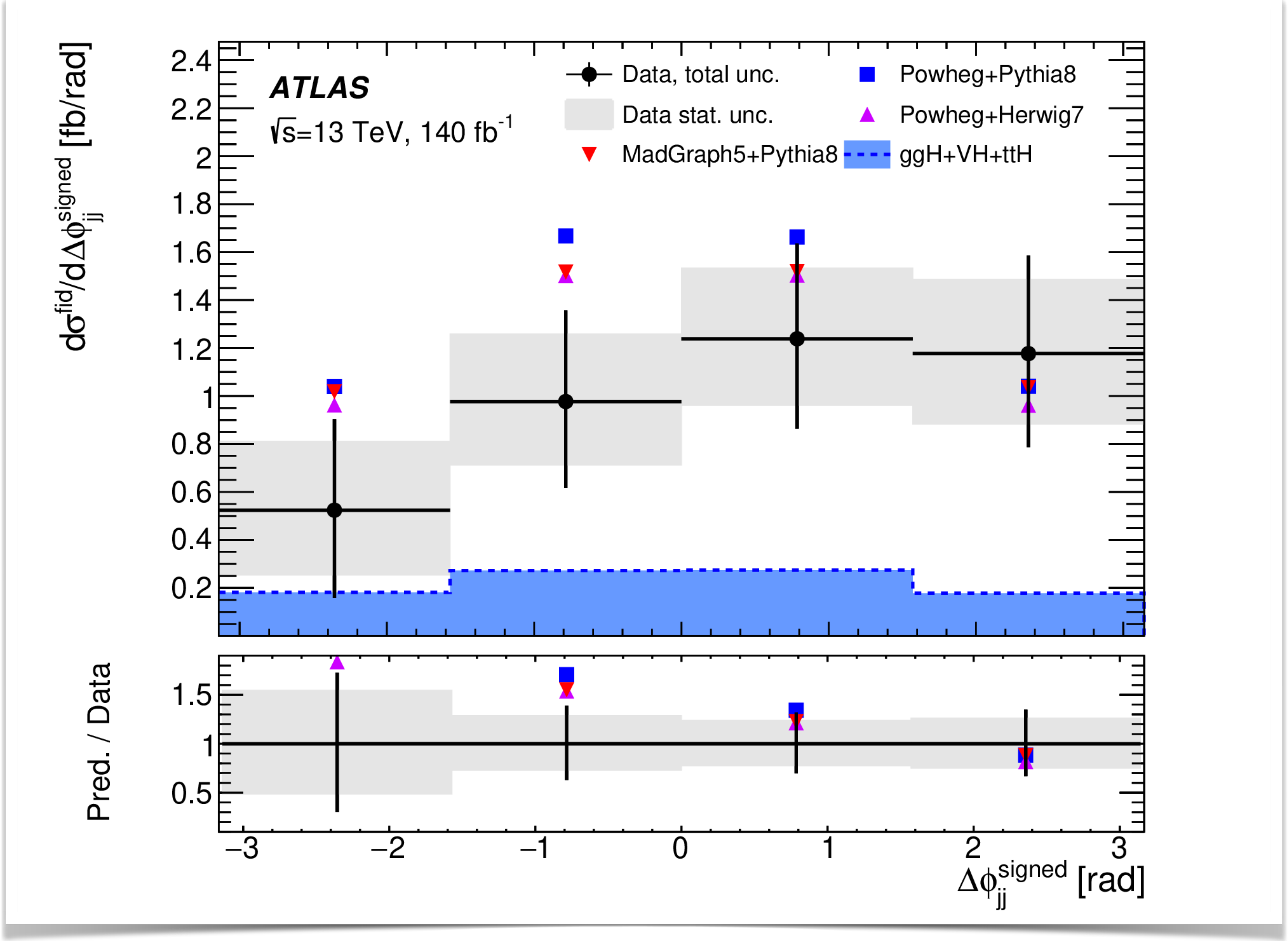
Recent ATLAS Higgs coupling results

- Differential cross-section **H** $\rightarrow \tau\tau$ **decay** channel HIGG-2022-07
- Relative sign of the Higgs boson couplings to W and Z bosons using **WH production via vector-boson fusion** arXiv:2402.00426
- Direct constraint on the **Higgs-charm coupling** from a search for $H \rightarrow c\bar{c}$ arXiv:2201.11428
- Study of High-Transverse-Momentum Higgs Boson Production in Association with a Vector Boson in the ***qqbb*** Final State arXiv:2312.07605
- Higgs boson production by **ggF** and **VBF** using $H \rightarrow WW^*$ decays Phys. Rev. D 108 (2023) 032005
- **Higgs Combination Results** : Nature 607 (2022) 52-59

H → $\tau\tau$ Analysis (1/2)

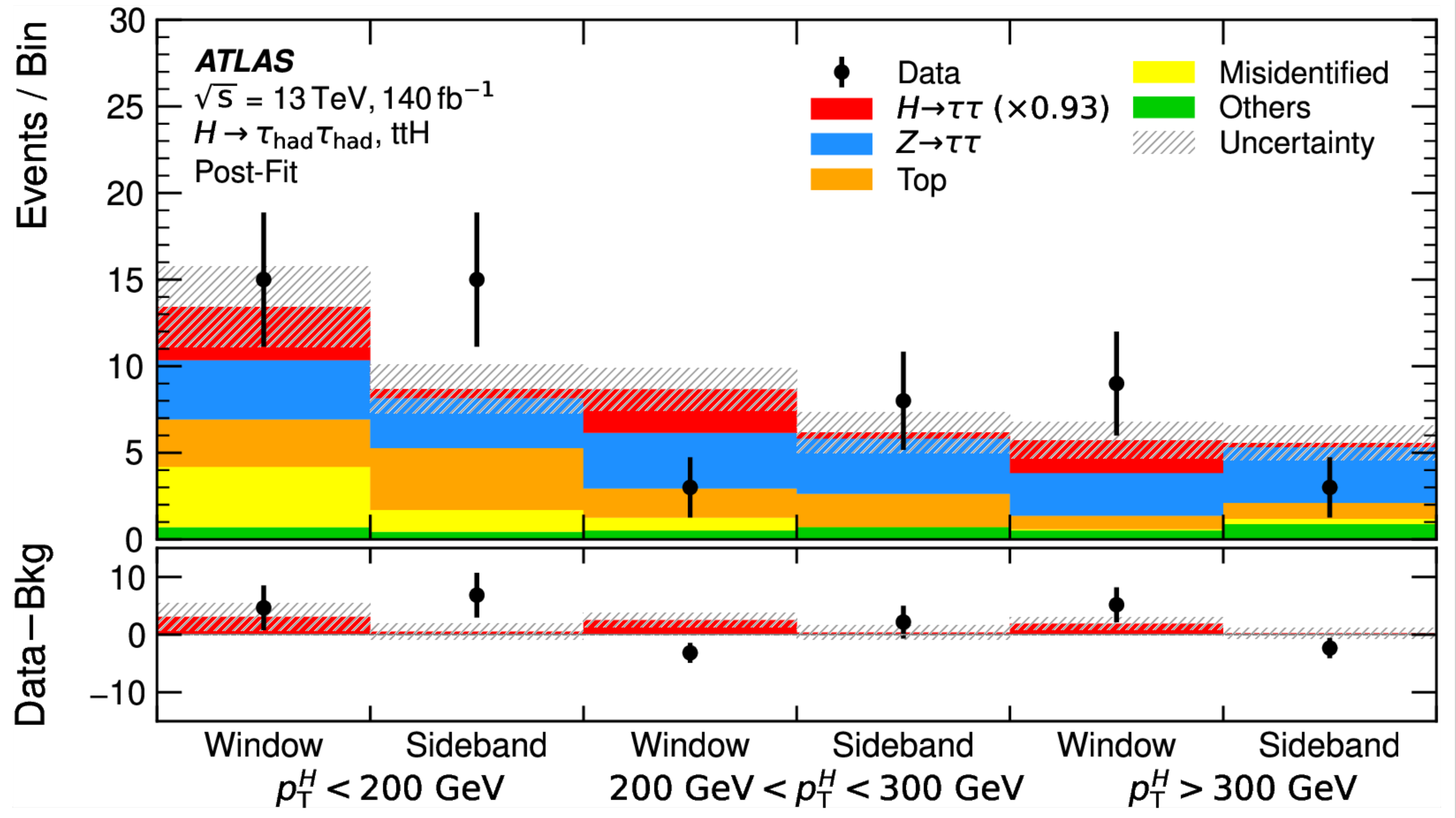
- ggF, VBF, VH and $t\bar{t}H$ production modes, H → $\tau\tau$
- **Largest branching ratio** to leptons enables study of **Yukawa couplings** and of a broad range of production modes
- $t\bar{t}H$: Categorisation based on $m_{\tau\tau}$ and p_T(H)
- Differential cross section and STXS measurement for :$\Delta\phi_{jj}$, $p_T^{j_0}$, p_T^H, $\Delta\phi_{jj}$ Vs p_T^H

Differential Measurements



Improvement of 30%–50%

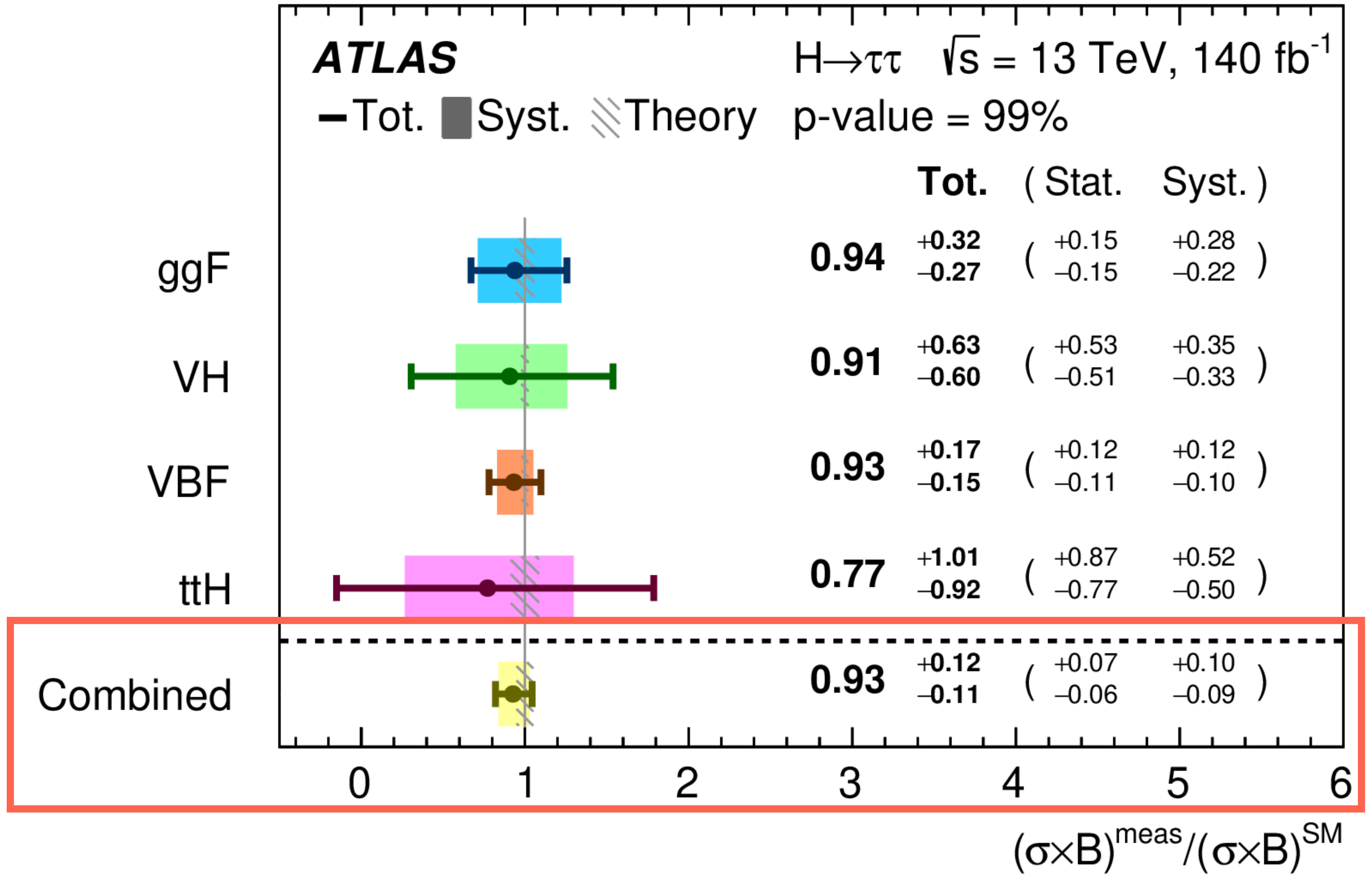
HIGG-2022-07



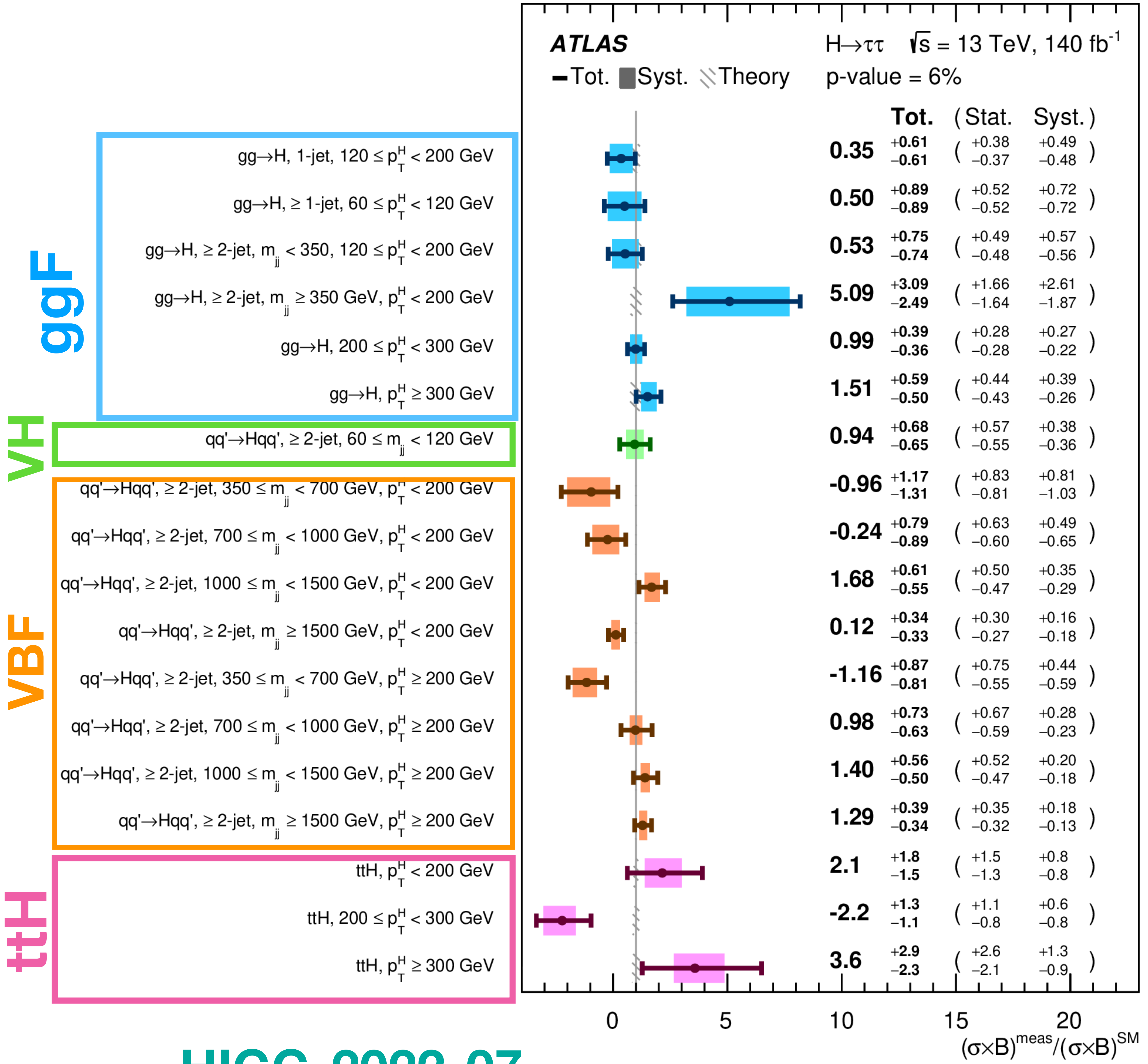
$H \rightarrow \tau\tau$ Analysis (2/2)

- **8%** improvement in the combined fit, ~**25%** (**$t\bar{t}H$**) improvement in the signal strength (statistically limited) compared to previous analysis
- $(\sigma \times B)/(\sigma \times B)_{SM}$ = 0.93 ± 0.07 (stat) ± 0.10 (sys) → consistent with SM

Inclusive Cross Section



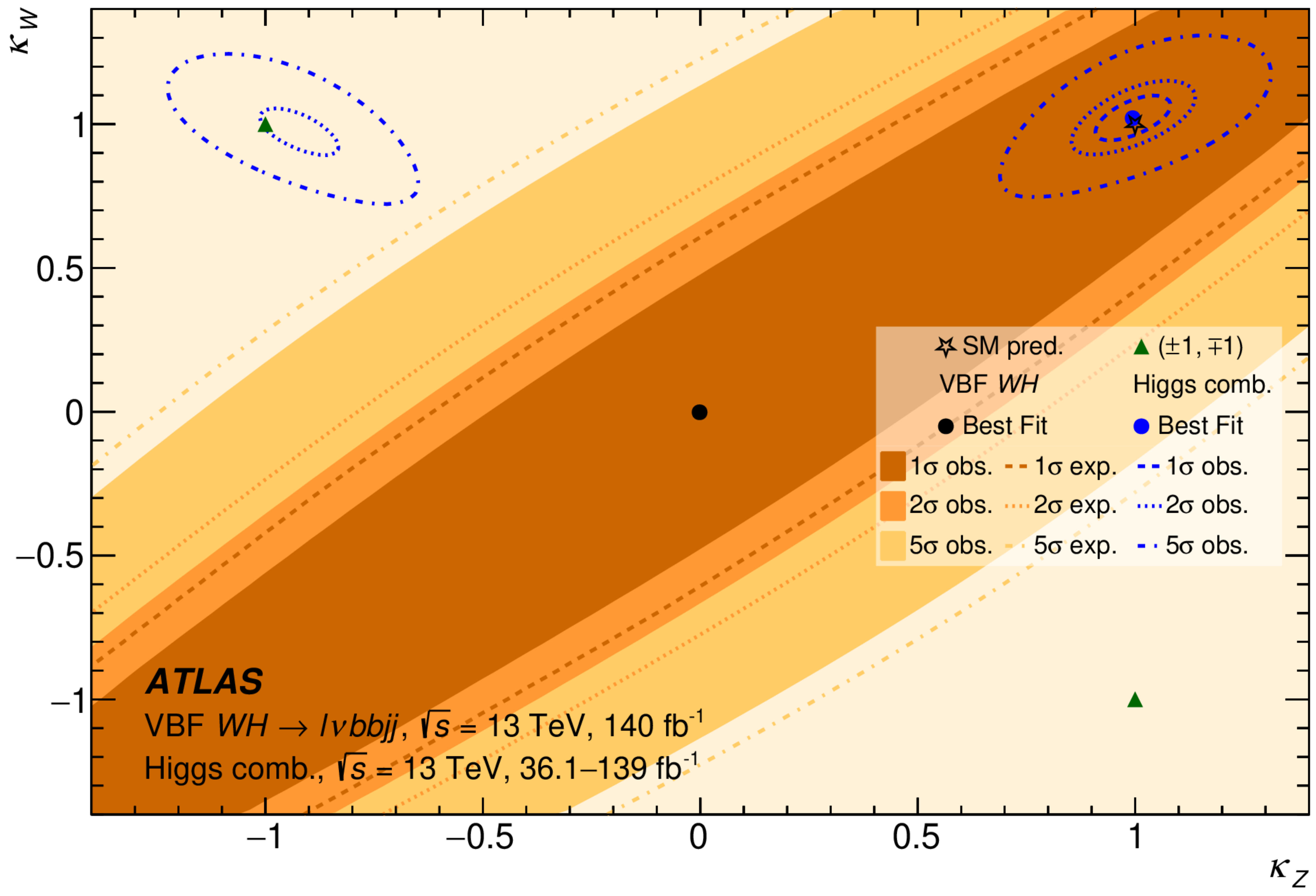
STXS categorisation



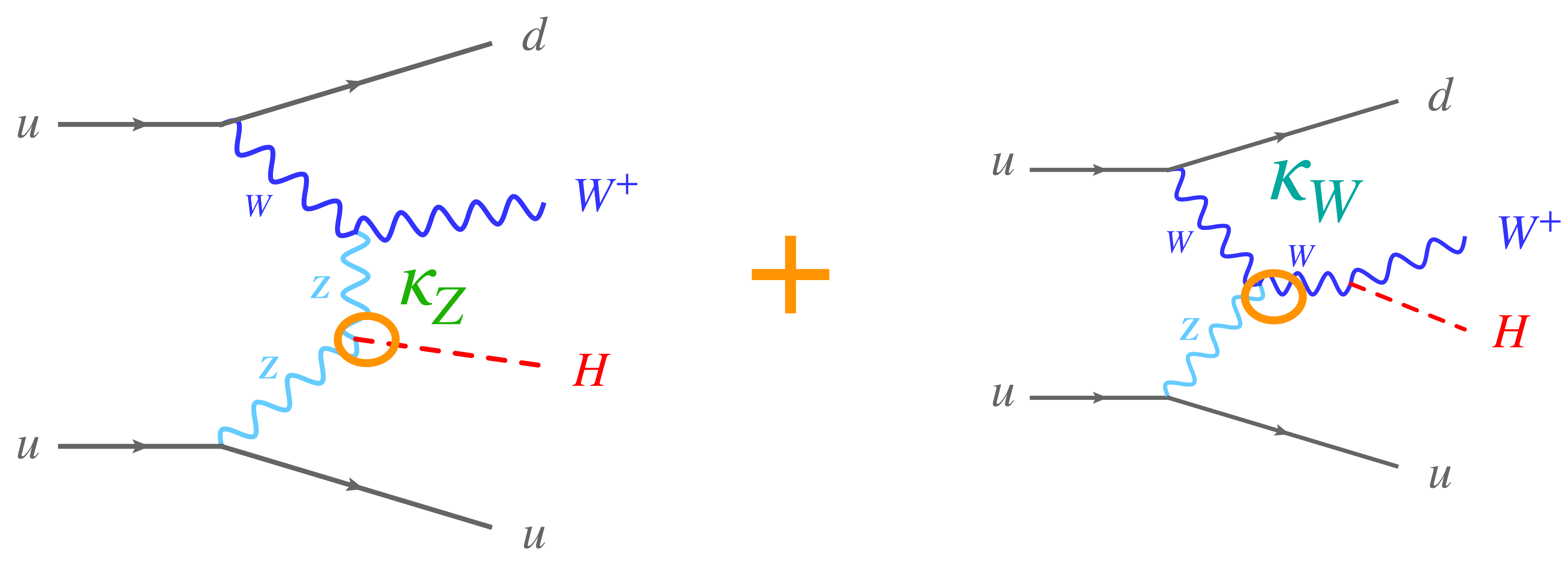
HIGG-2022-07

Relative sign of the Higgs boson couplings to W and Z bosons using WH production via VBF

- Search for **WH** production via **VBF** with $H \to b\bar{b}$ decay (arXiv:2402.00426)
- Coupling of higgs boson with W and Z bosons expressed with κ_W and κ_Z
- Analysis probes the **sign** of $\lambda_{WZ} = \dfrac{\kappa_W}{\kappa_Z}$ and **test SM prediction** ($\lambda_{WZ} = 1$)
- The values of κ_W and κ_Z are determined to have the **same sign**
- **Opposite-sign hypothesis** excluded with **significance** $>5\sigma$



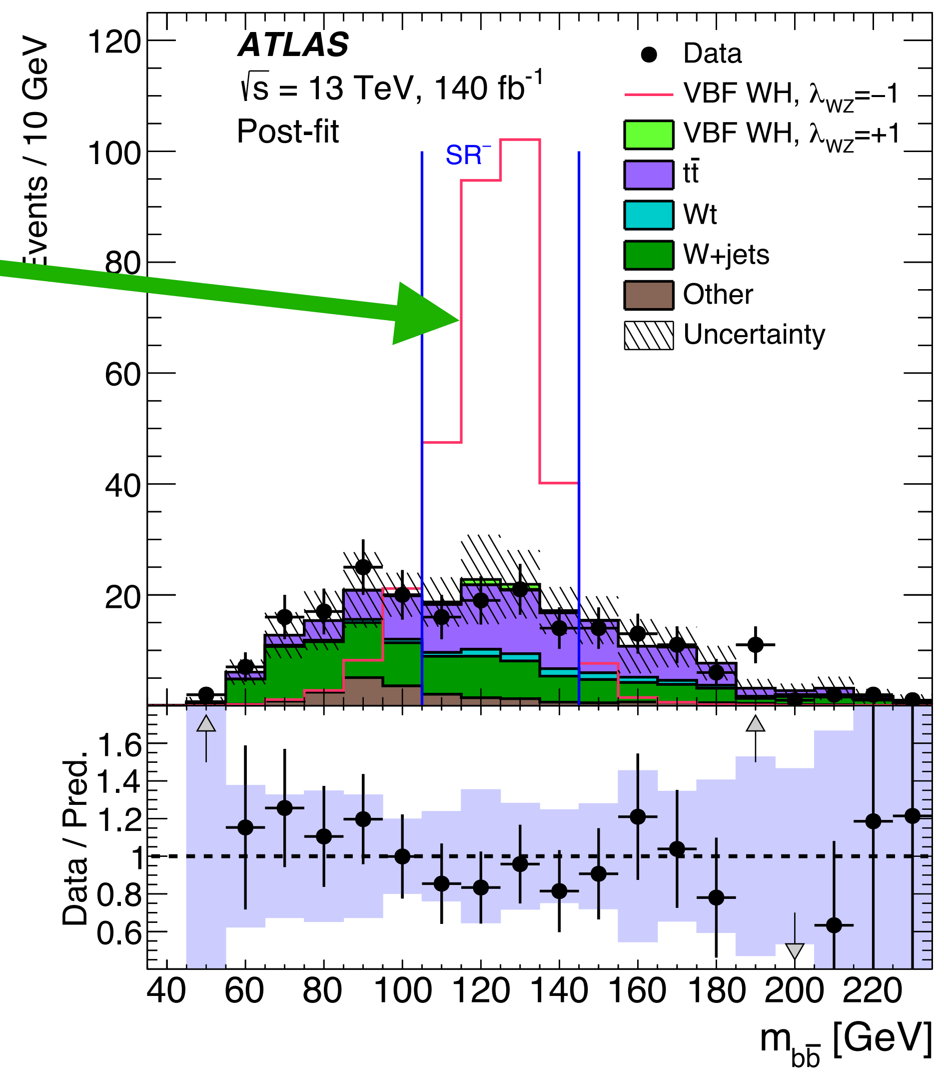
VBF WH production



$\sim \kappa_Z^2$ Interference $\sim \kappa_W \kappa_Z$ $\sim \kappa_W^2$

$$\sigma_{\mathrm{VBF},WH} \propto \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\,\kappa_Z \kappa_W \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$
$$= \kappa_Z^2 |\mathcal{M}_Z|^2 + \kappa_W^2 |\mathcal{M}_W|^2 - 2\,\kappa_Z^2 \lambda_{WZ} \Re[\mathcal{M}_Z^\dagger \mathcal{M}_W]$$

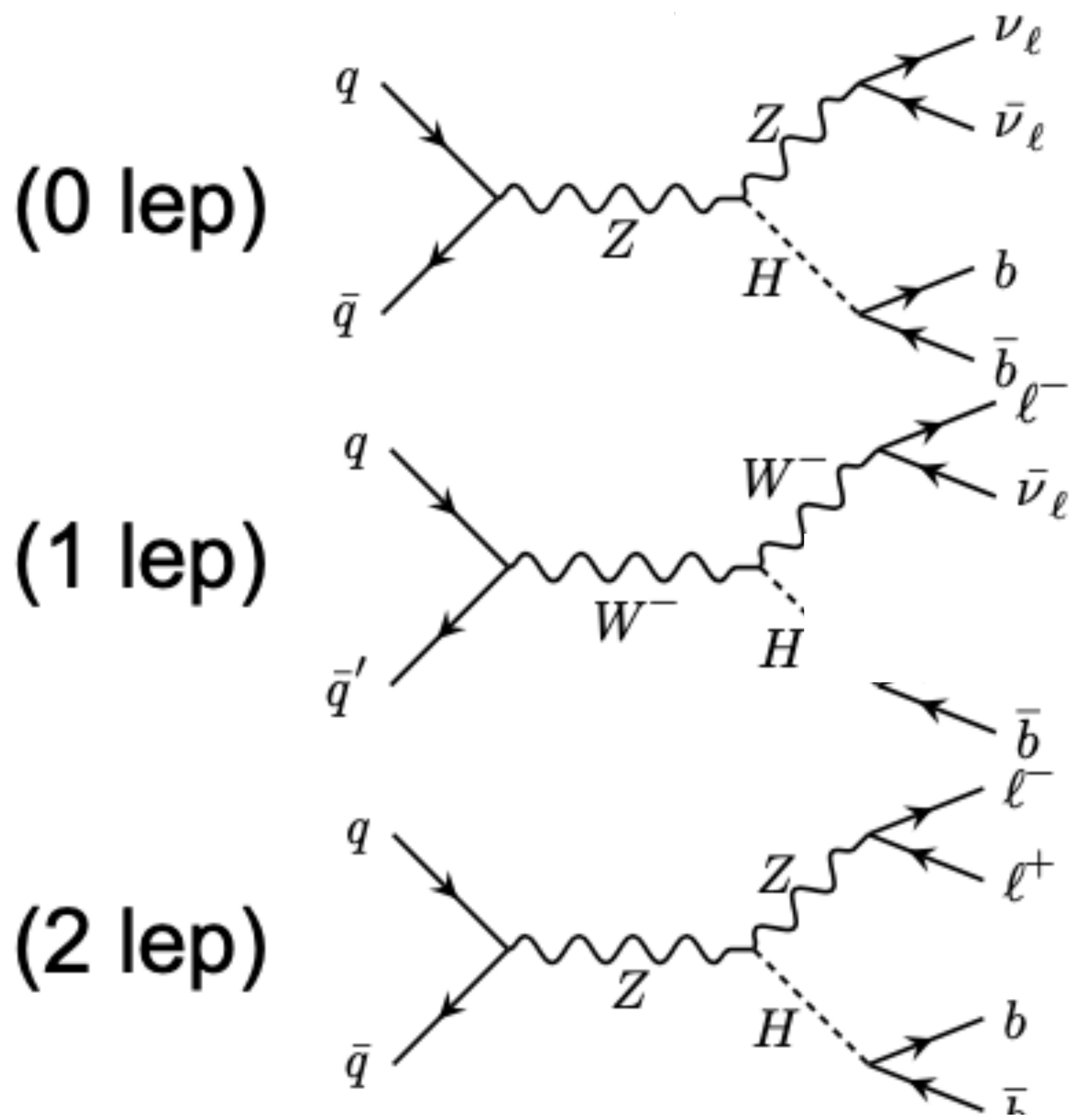
No signal

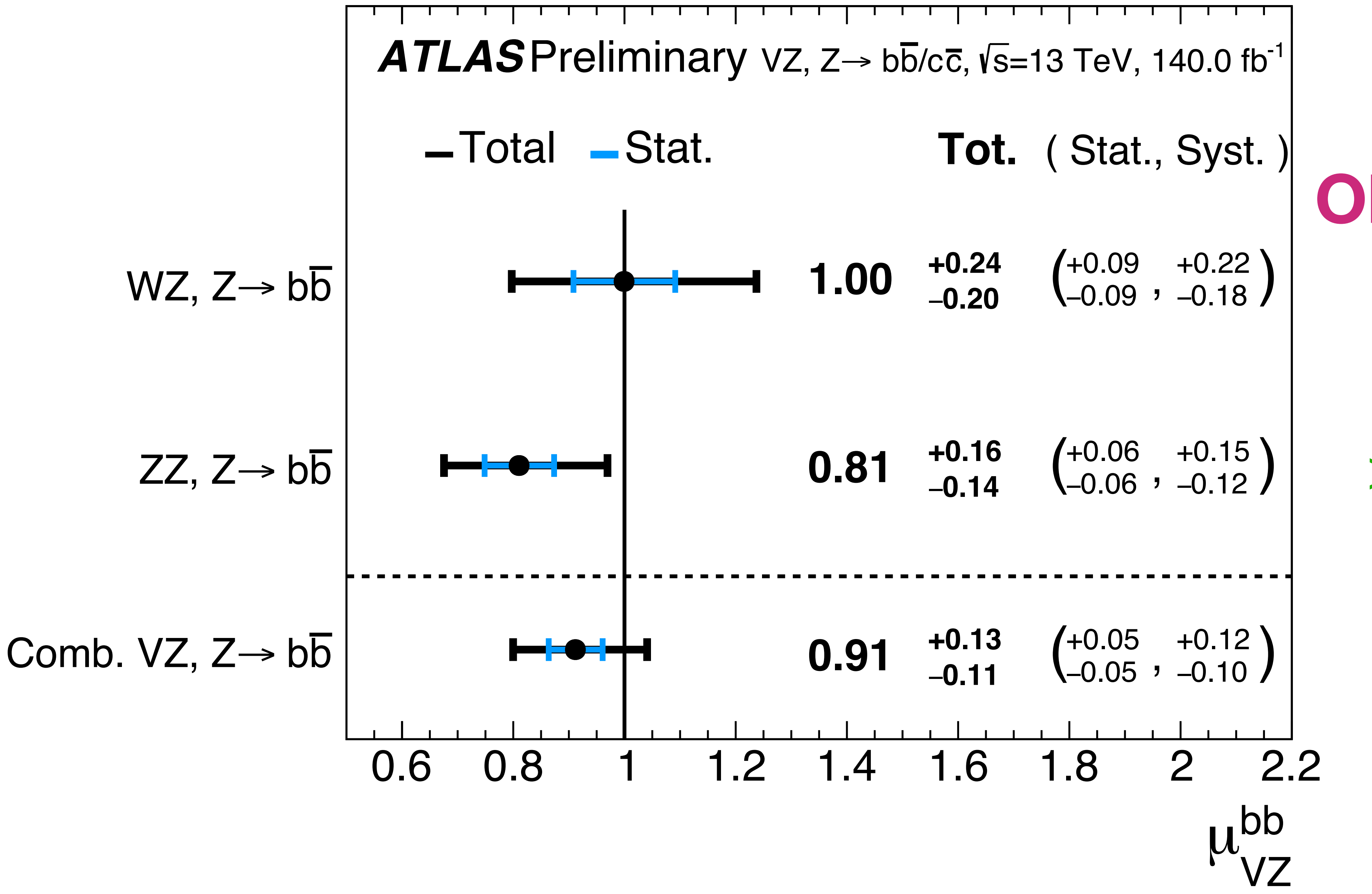


arXiv:2402.00426

Legacy V($\rightarrow$ lepton)H($\rightarrow b\bar{b}/c\bar{c}$) 1/2

- Analysis selects $H \rightarrow b\bar{b}/c\bar{c}$ events associated with a W or Z boson → **rarest higgs production modes**
- Better object **reconstruction/calibrations/ Improved** analysis strategy as compared to previous analysis
- Analysis strategy **validated** searching diboson *WZ* and *ZZ* signal



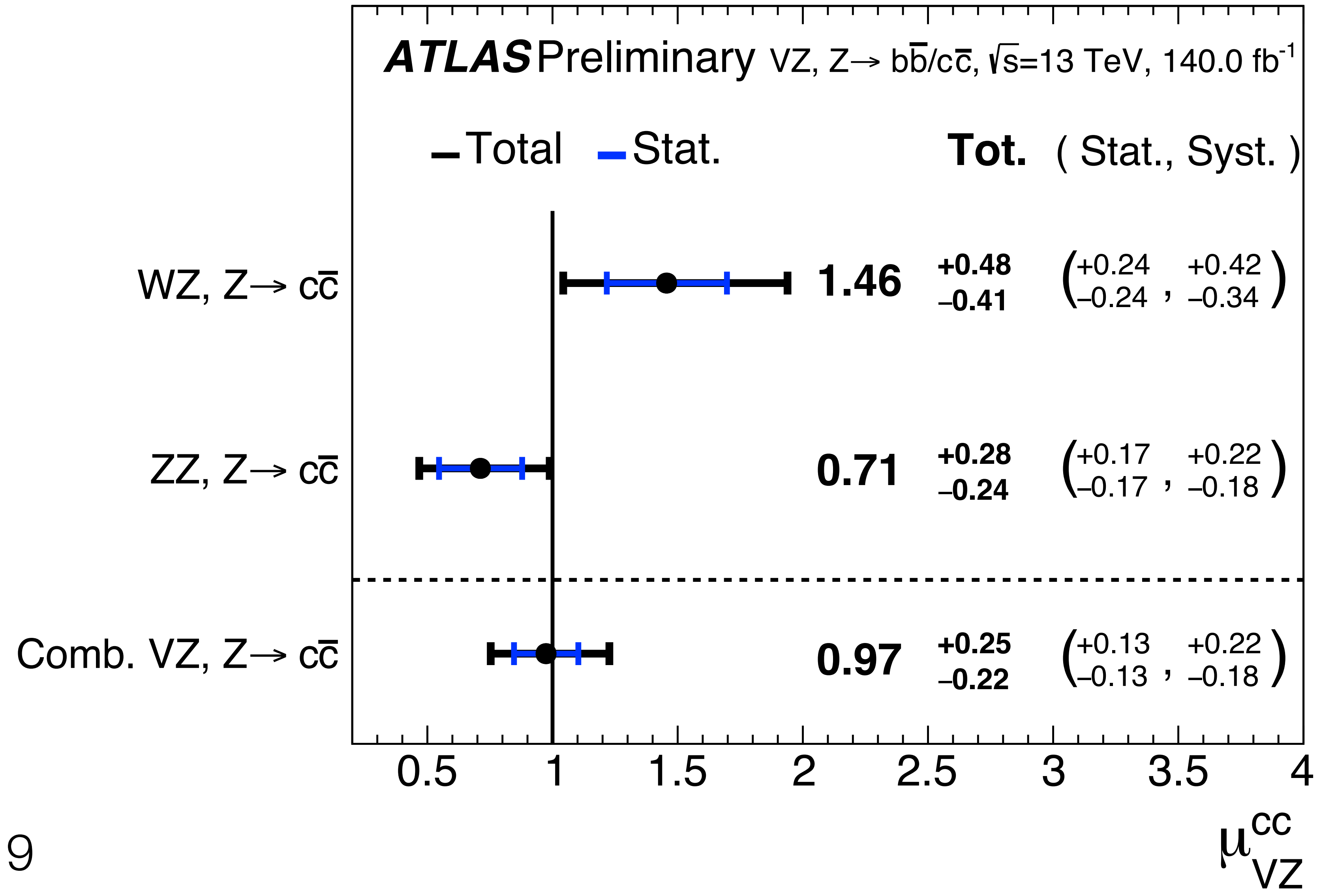


Obs.sig

6.4σ

$>10\sigma$

Improvement



Obs.sig

3.9σ

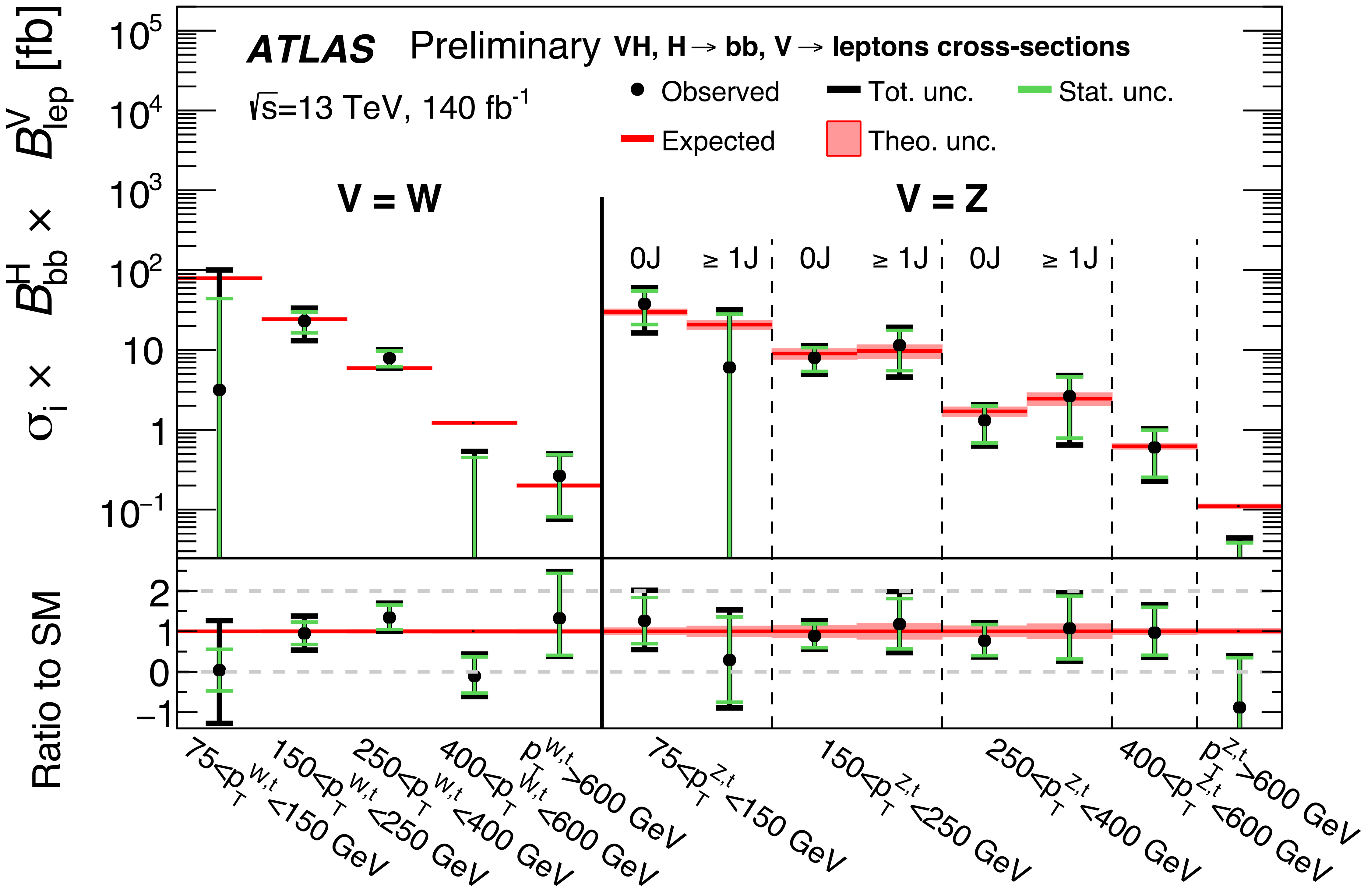
3.1σ

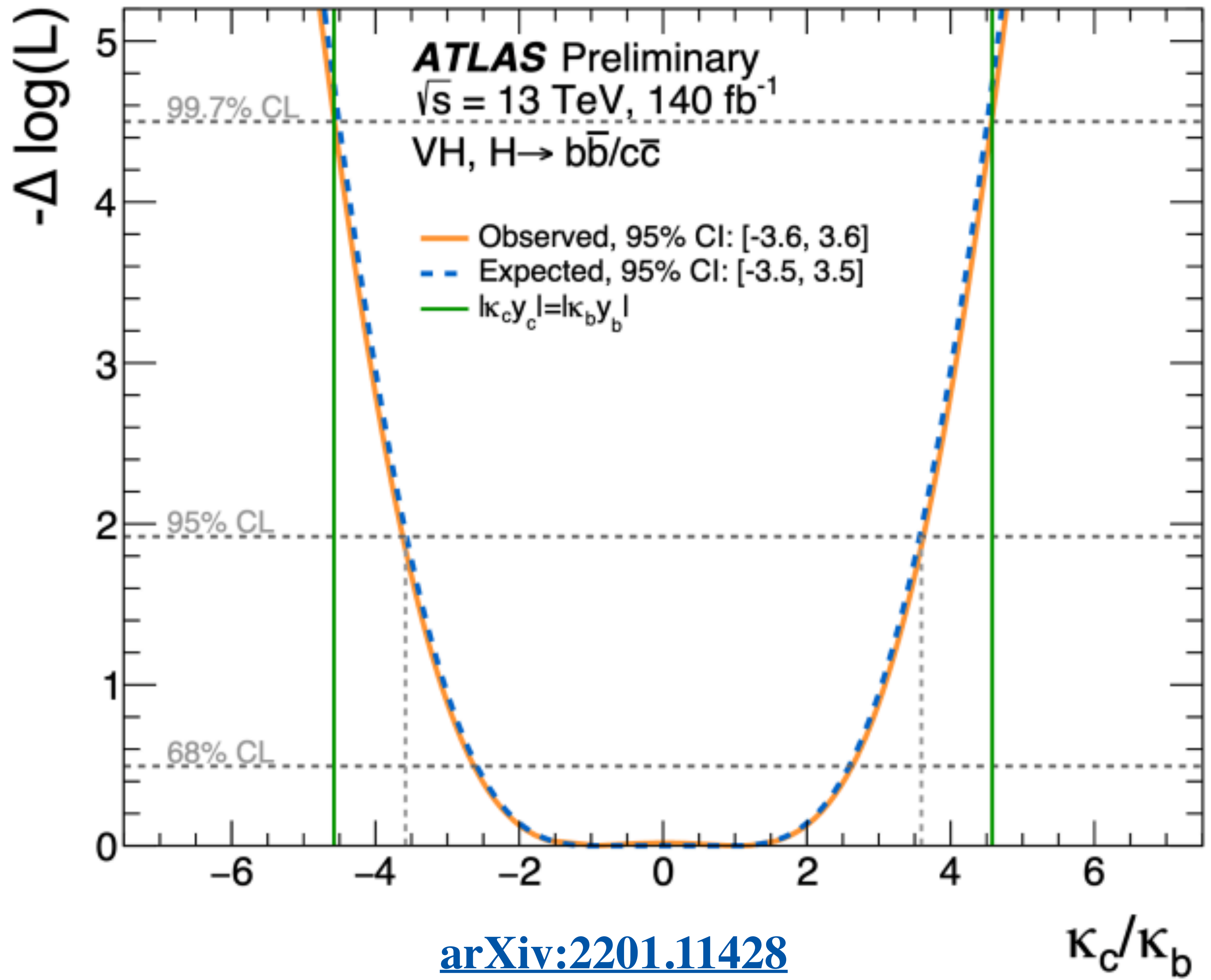
$>5\sigma$

arXiv:2201.11428

Legacy VH($\to b\bar{b}/c\bar{c}$) 2/2

- Extended (n_{jets} splitting) and reduced STXS categorisation for **V (→ leptons) H($\to b\bar{b}$)**
- Constraints on a charm Yukawa coupling modifier $|\kappa_c|$ **< 4.2 at 95 % CL**
- Ratio of $|\kappa_c|$ **and** $|\kappa_b|$ **is less than 4.5**
  - **Excludes the hypothesis that the Higgs-charm interaction is stronger than or equal Higgs-bottom coupling at 95% CL**

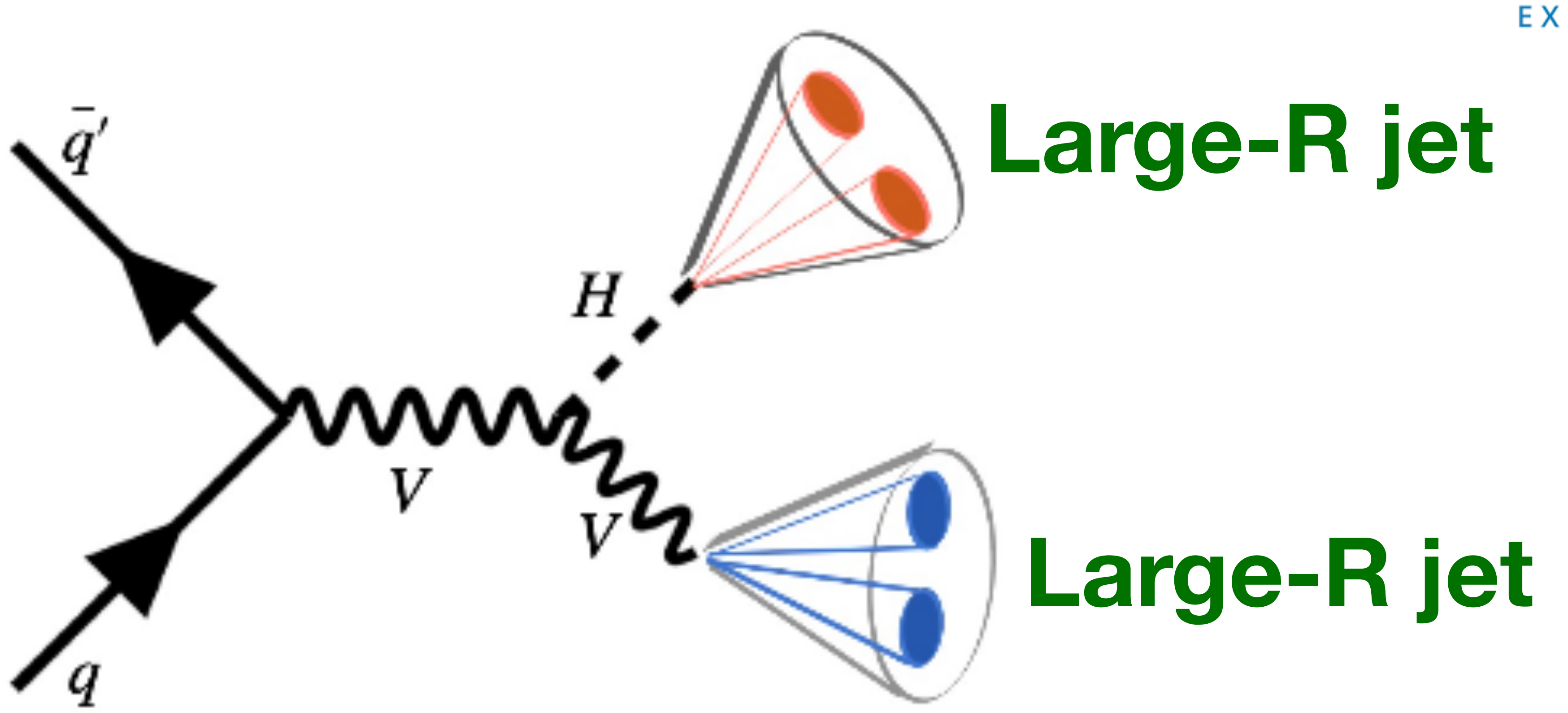




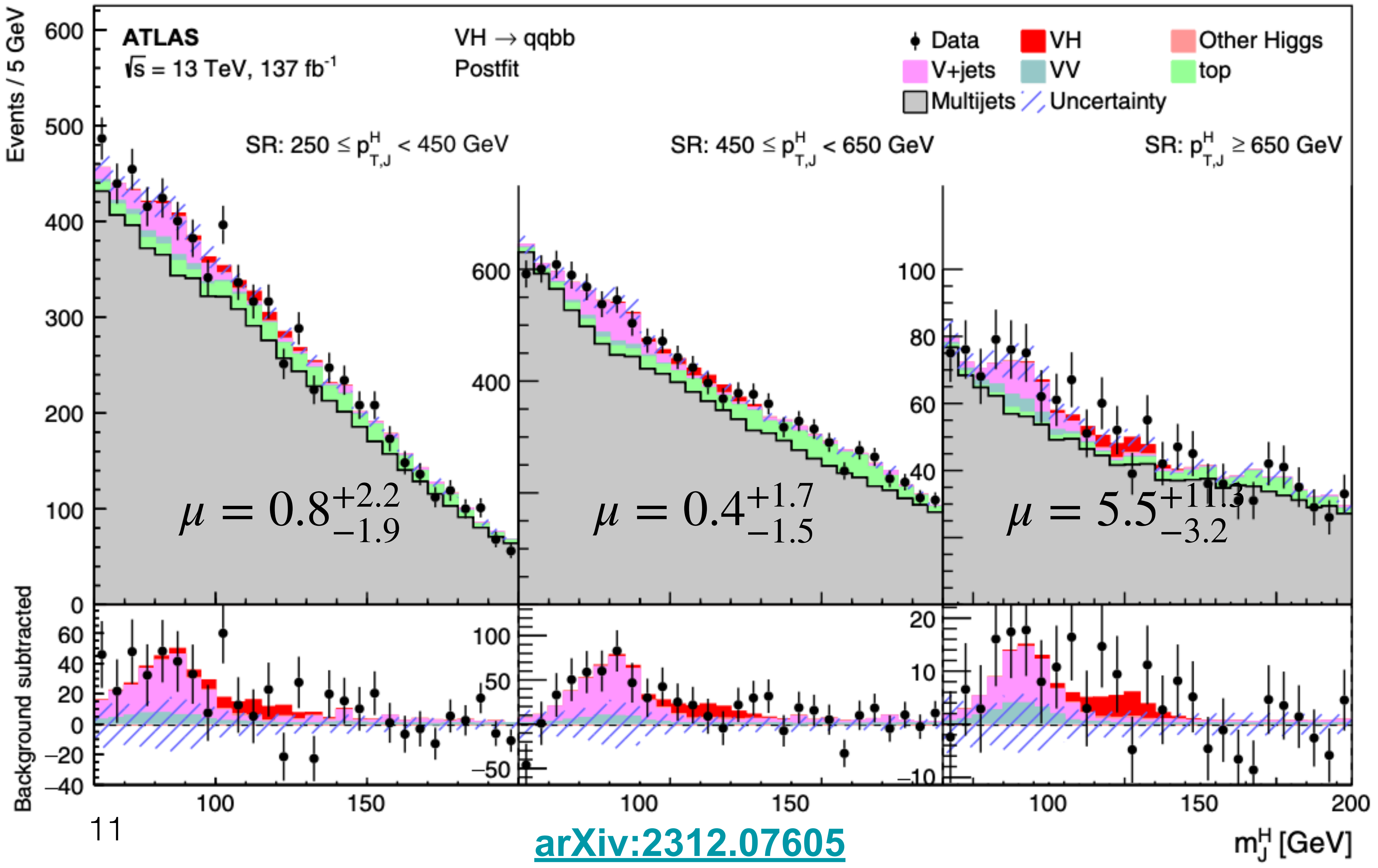
arXiv:2201.11428

Boosted VH analysis in fully hadronic final state

- V($\to qq'$) H($\to b\bar{b}$) are highly boosted → Two-large radius jets
- Neural network technique to tag boosted H $\to b\bar{b}$
- Full hadronic decay BR is larger compared to leptonic
  - Potential of probing high-p_T^H higgs boson
- Multijet backgrounds are estimated through data
- Signal strength $\mu = 1.4^{+1.0}_{-0.9}$ in agreement with SM
- Differential cross section in several ranges of p_T^H



Differential Measurement

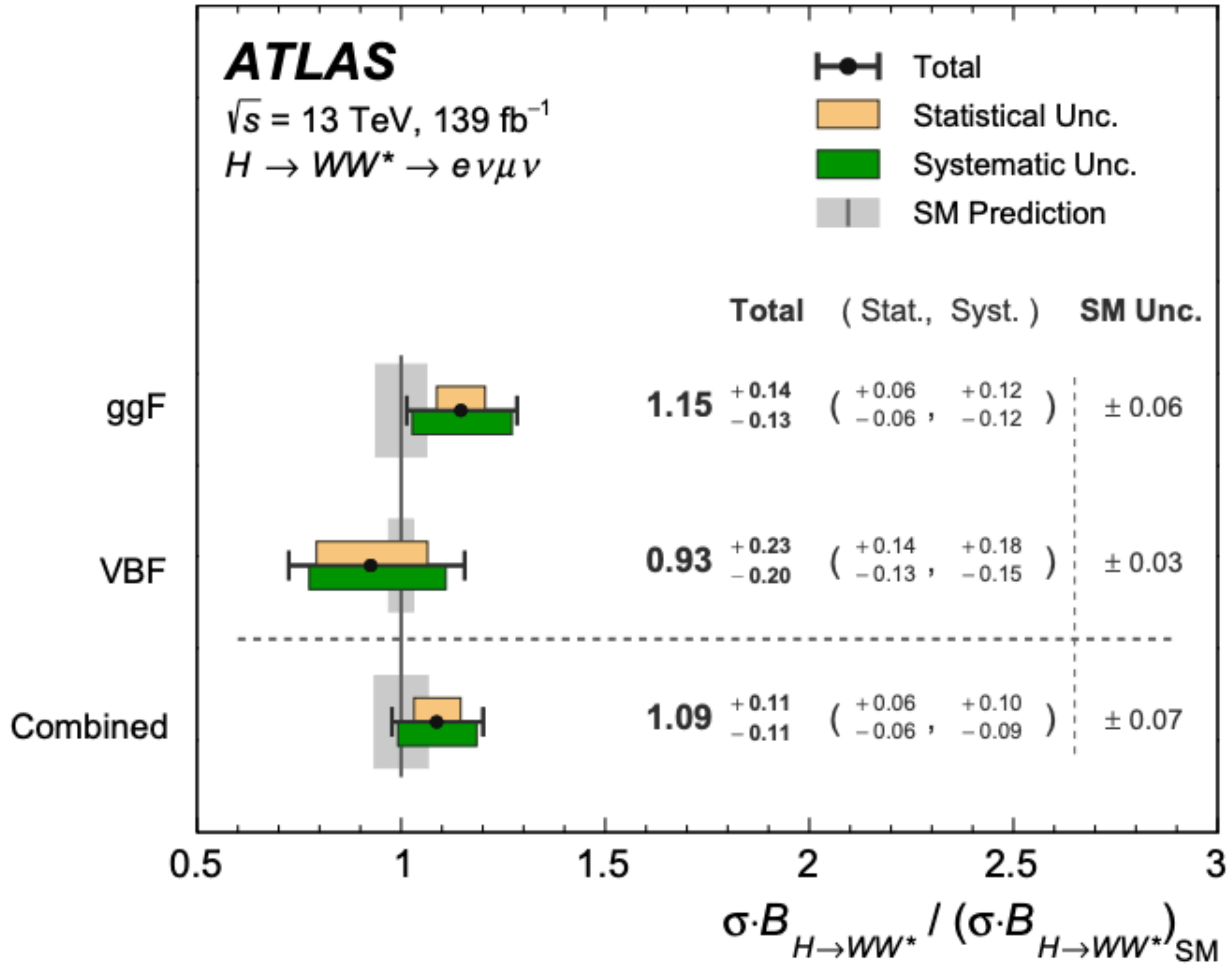


arXiv:2312.07605

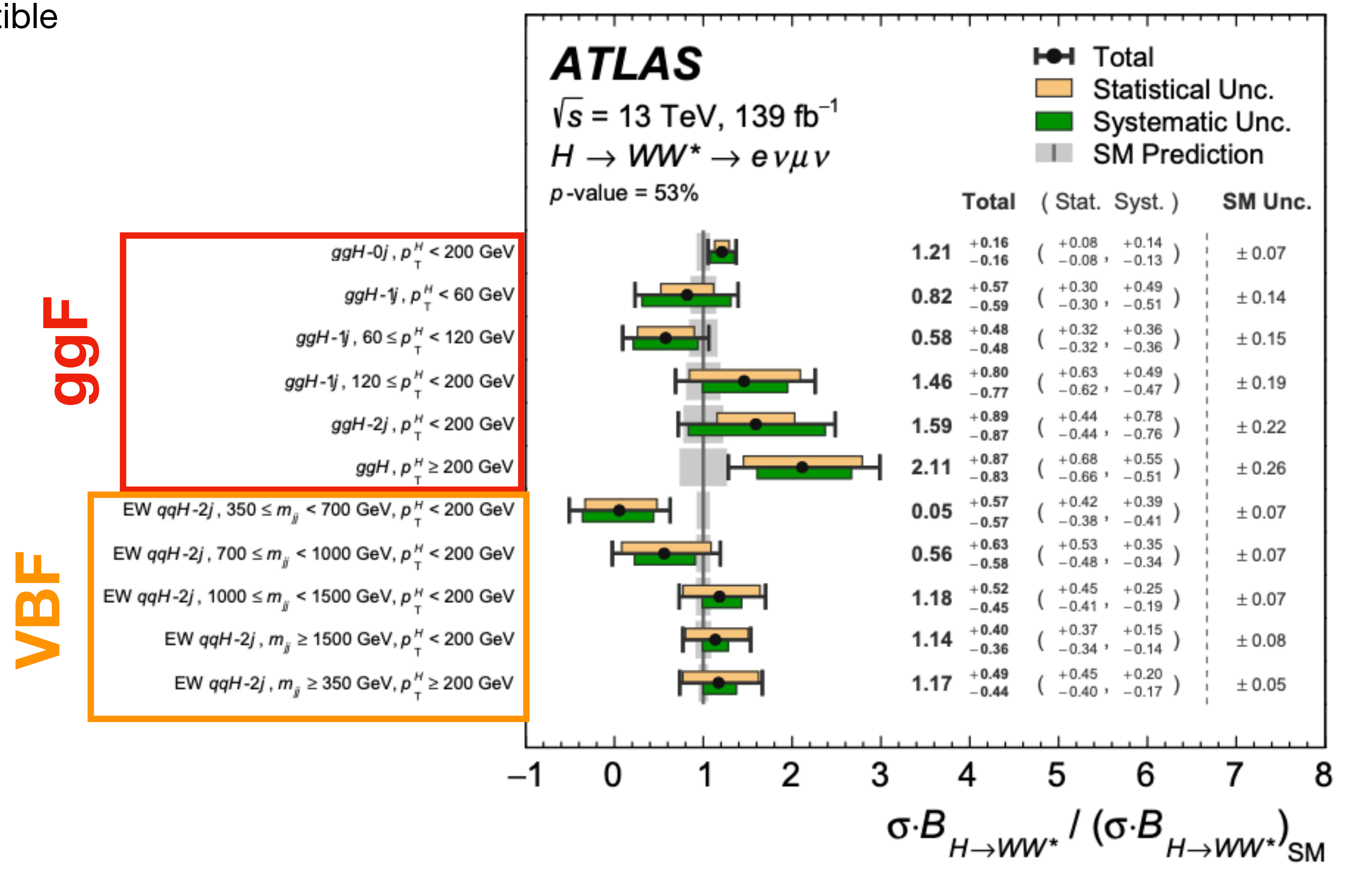
$H \to WW^*$ analysis

- $H \to WW^*$ production using ggF and VBF production channels
- n_{jets} for channel categorisation, m_T^H as a discriminant in the ggF channel and **DNN** in the VBF channel
- Inclusive and STXS cross section measurements are compatible with the SM

Inclusive Cross Section



STXS categorisation



HIGG-2020-24

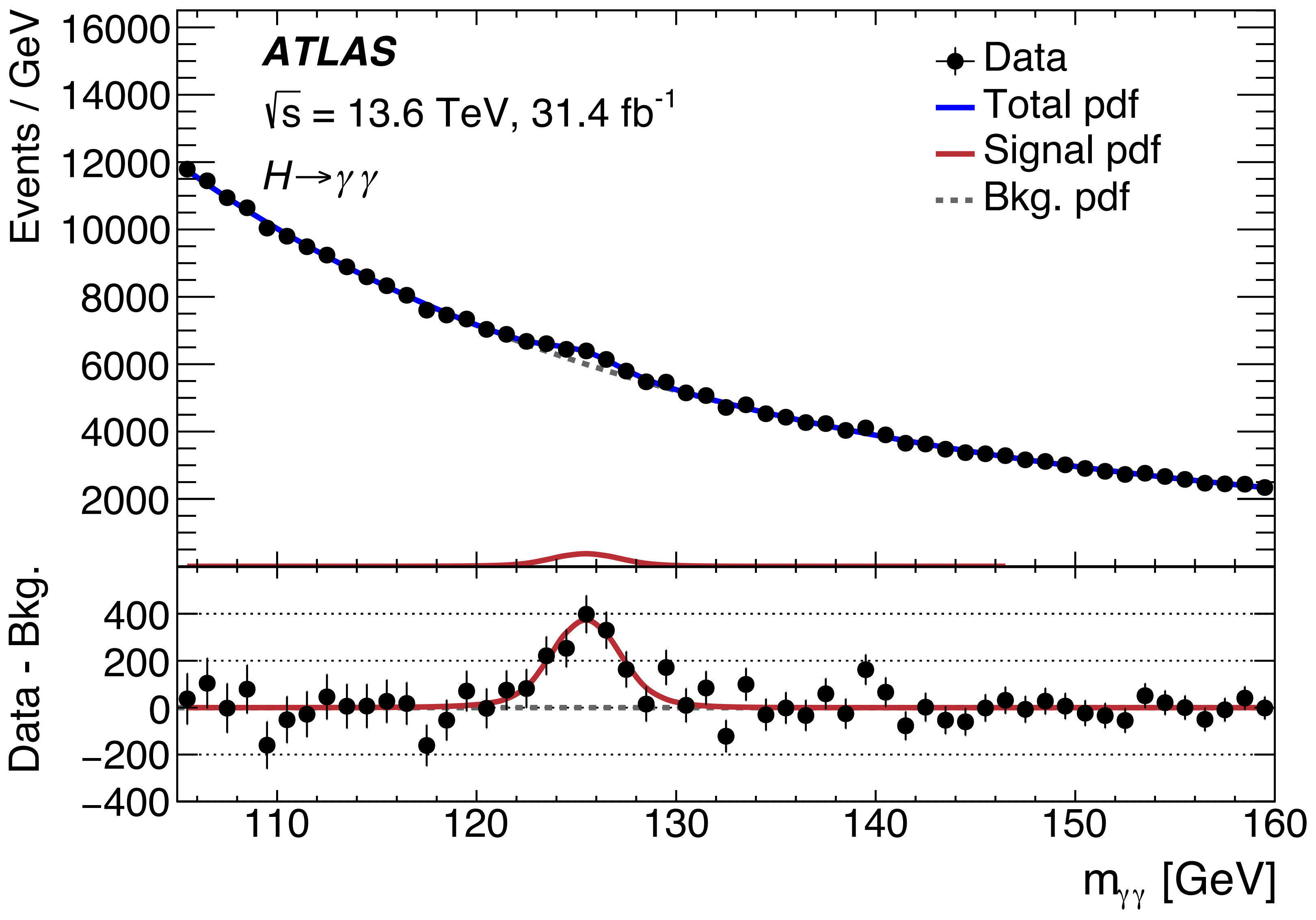
First Look at $\sqrt{s}$=13.6 TeV: $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^*$ cross section

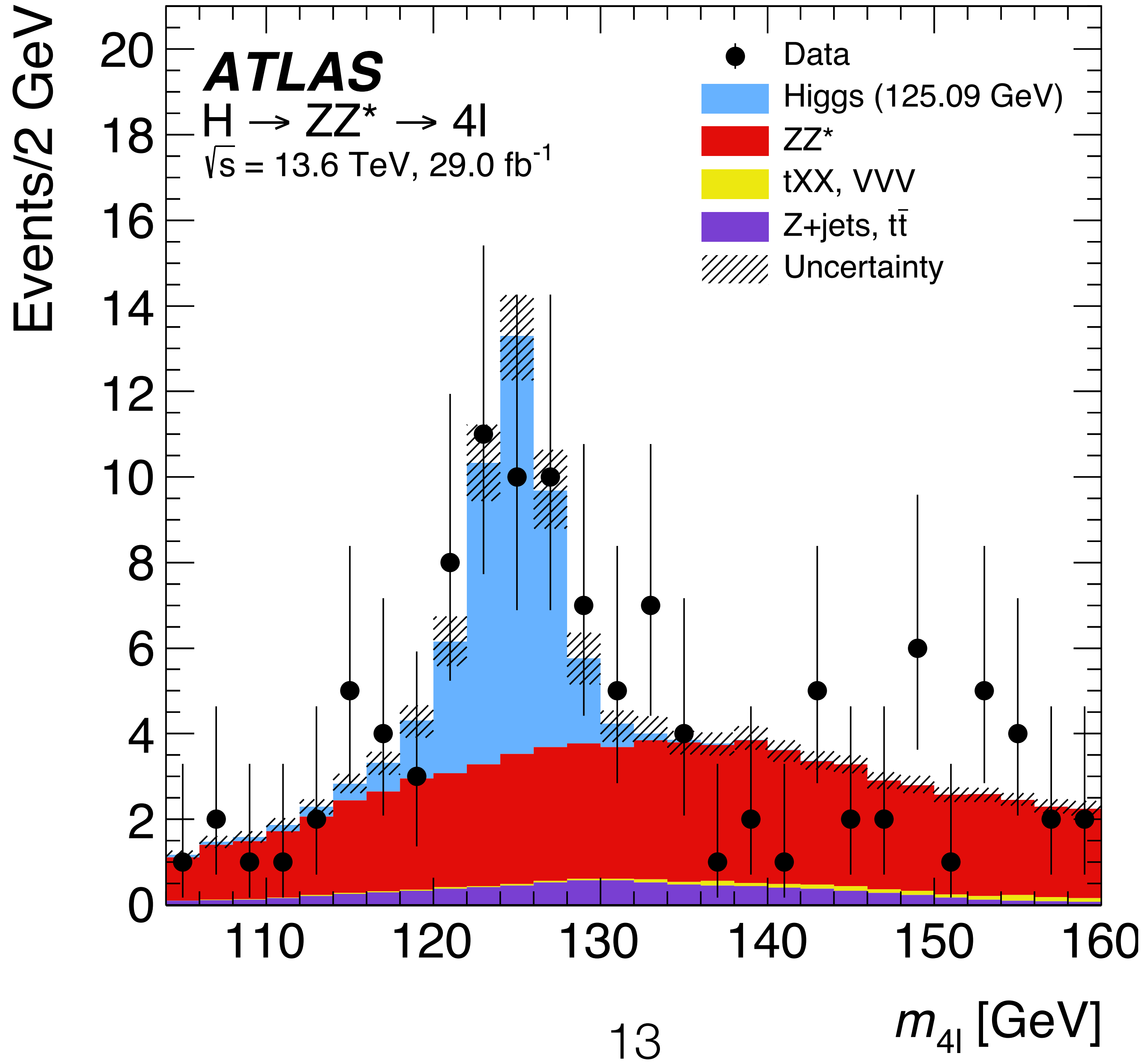
- Inclusive and fiducial cross section measurements in the di-photon and $ZZ^* \rightarrow 4l$ decay channels using 31.4 and 29.0 fb^{-1} pp collision data at a $\sqrt{s}$ = 13.6 TeV → **both are in agreement with SM**

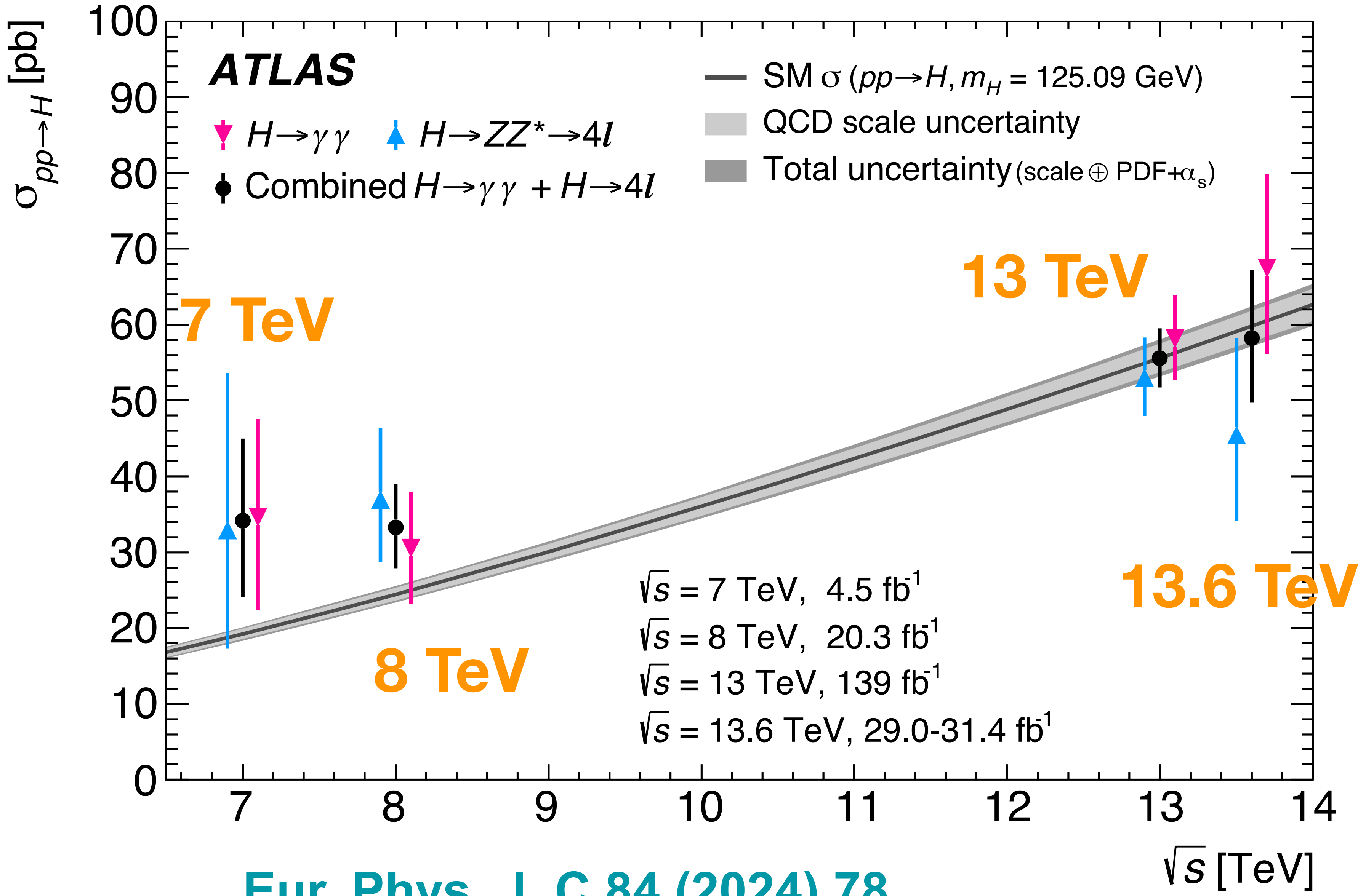
- Di-photon invariant mass within the fiducial region in the window of $105 \leq m_{\gamma\gamma} \leq 160$ GeV

- Di-lepton invariant mass in the window of $105 \leq m_{\gamma\gamma} \leq 160$ GeV

- Values of cross section measurements as a function of $\sqrt{s}$
  - SM predicted values are shown with shaded band
  - Combination of di-photon and di-lepton channels is shown with black color
  - Overall ~15 % relative uncertainty on combine cross section with 13.6 TeV data







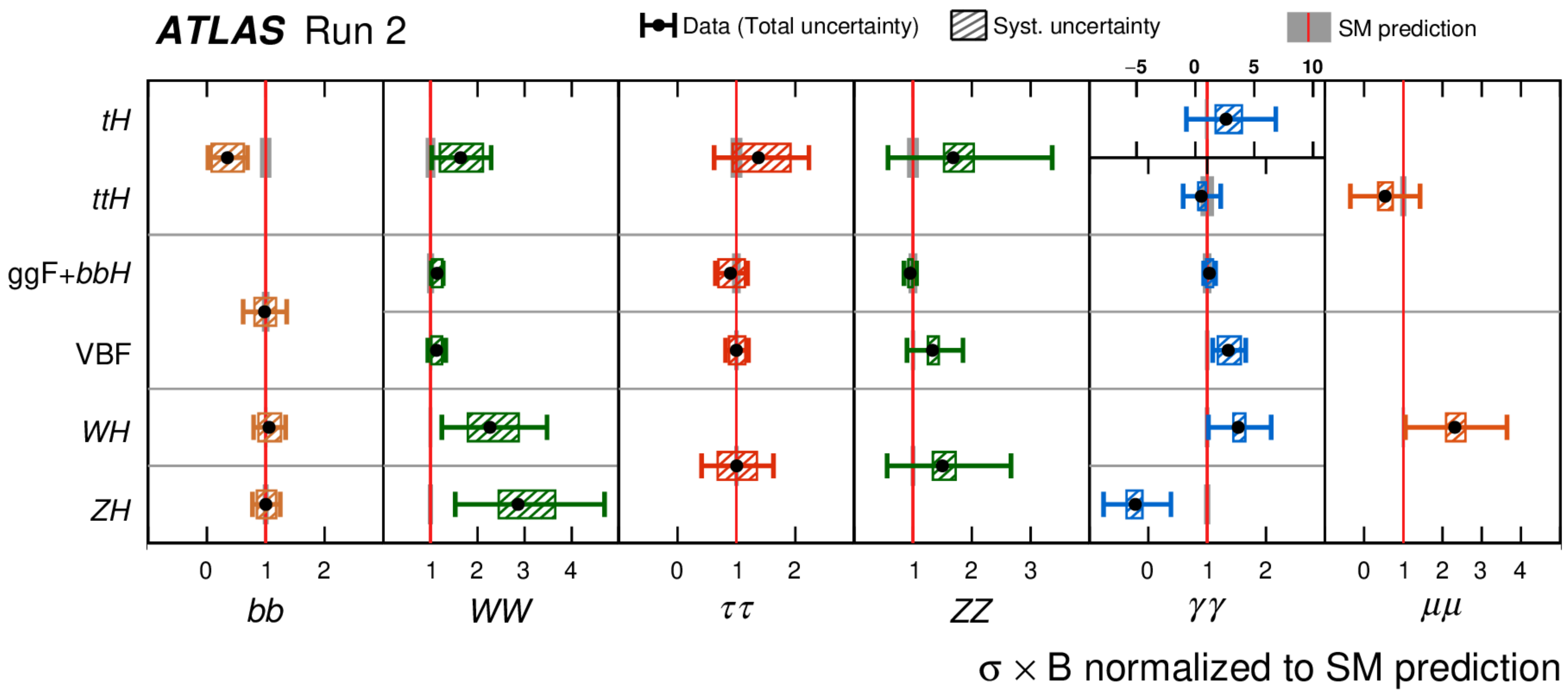
[Eur. Phys. J. C 84 (2024) 78]

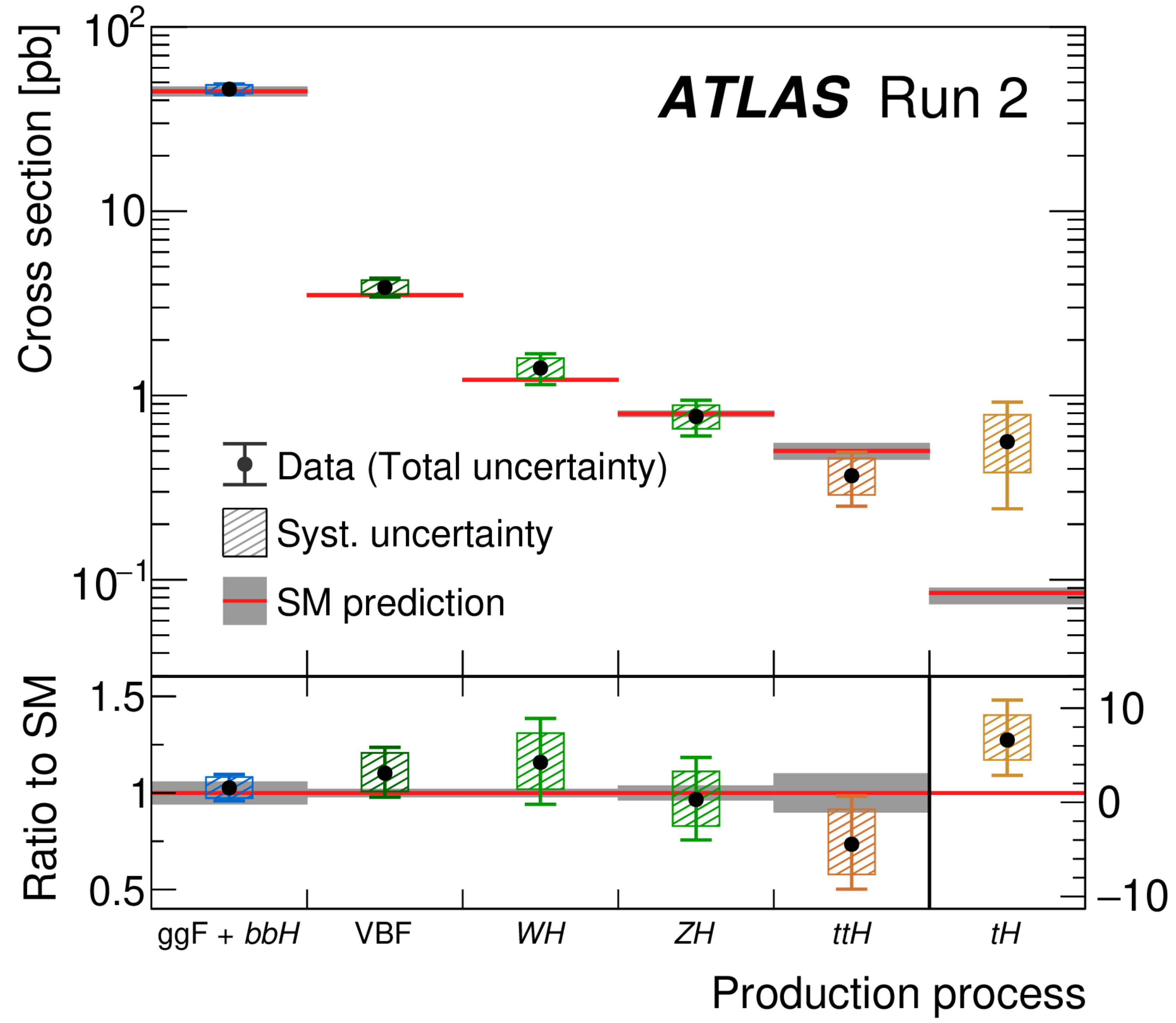
Inclusive Cross section measurements in Run 2

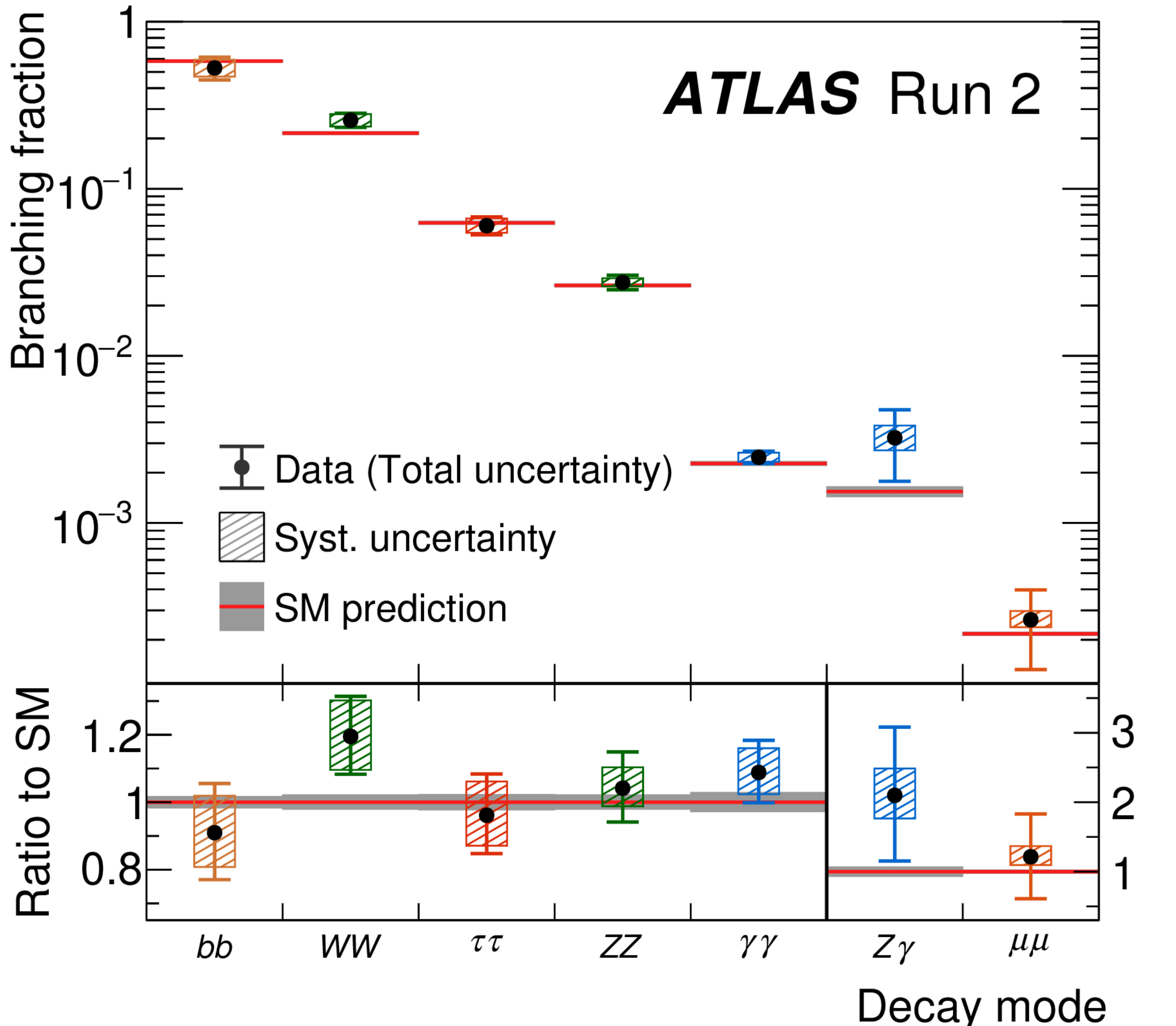
- 2022: ATLAS combination of all available production and decay modes is performed to measure the signal strength

$$\mu = \frac{(\sigma \times B)_{obs}}{(\sigma \times B)_{SM}} = 1.05 \pm 0.06$$

- **All agrees with the SM prediction**



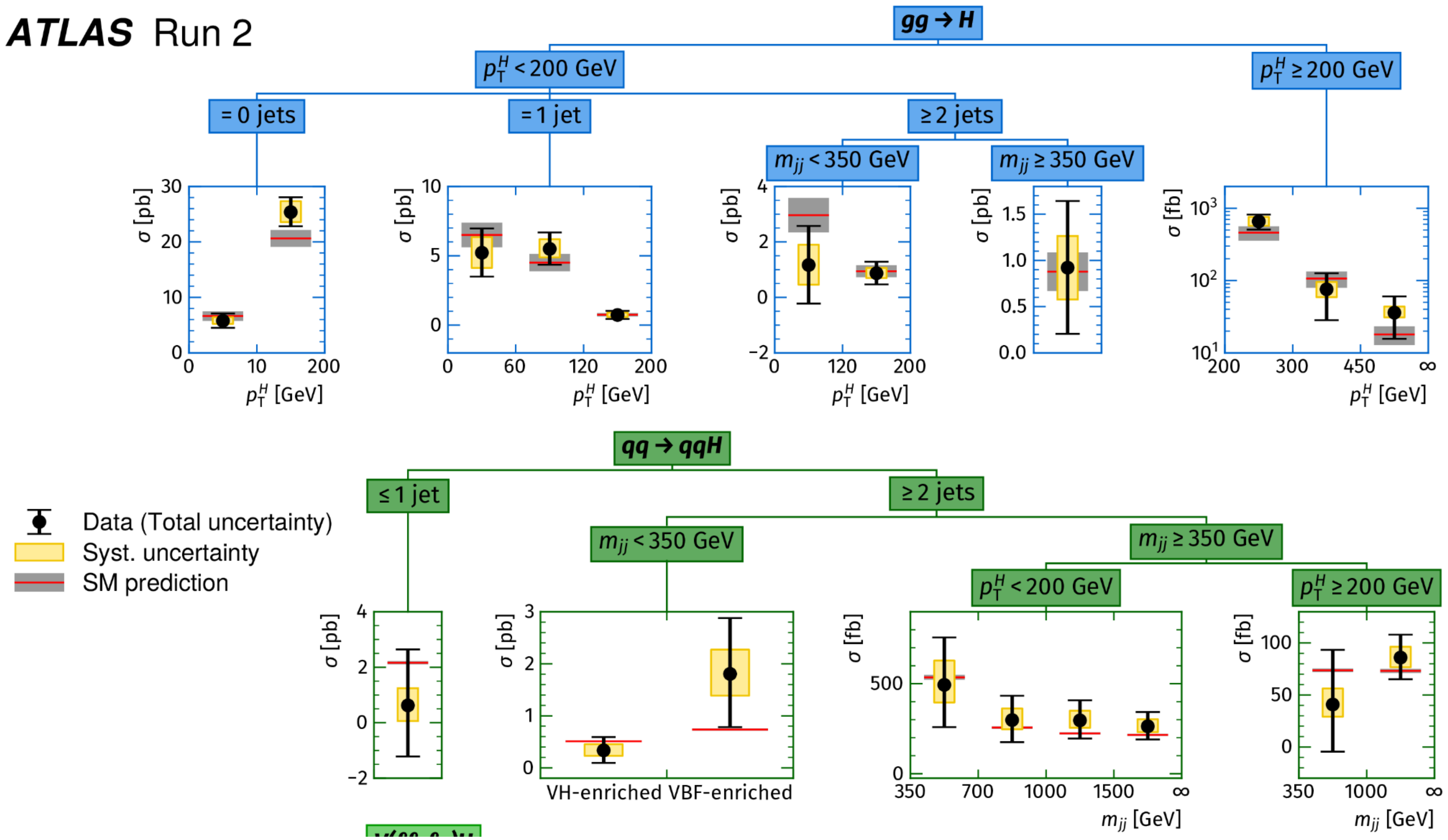


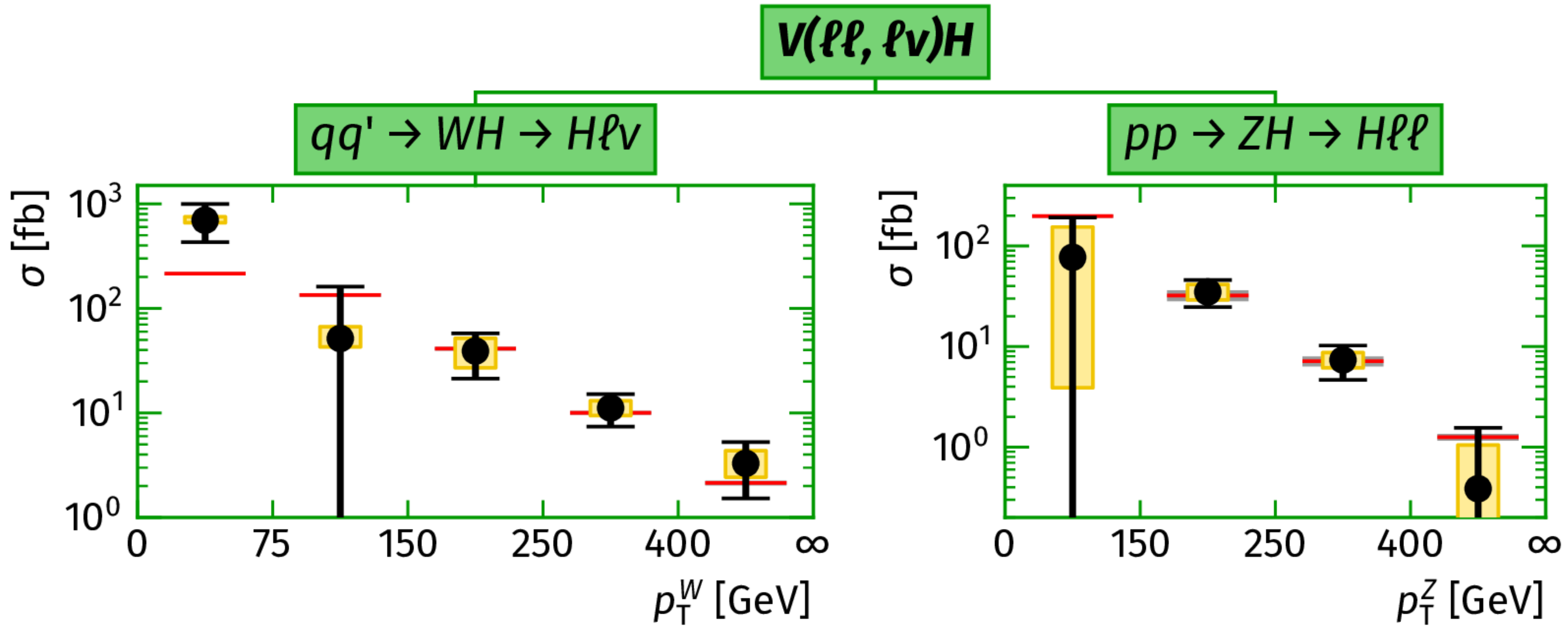


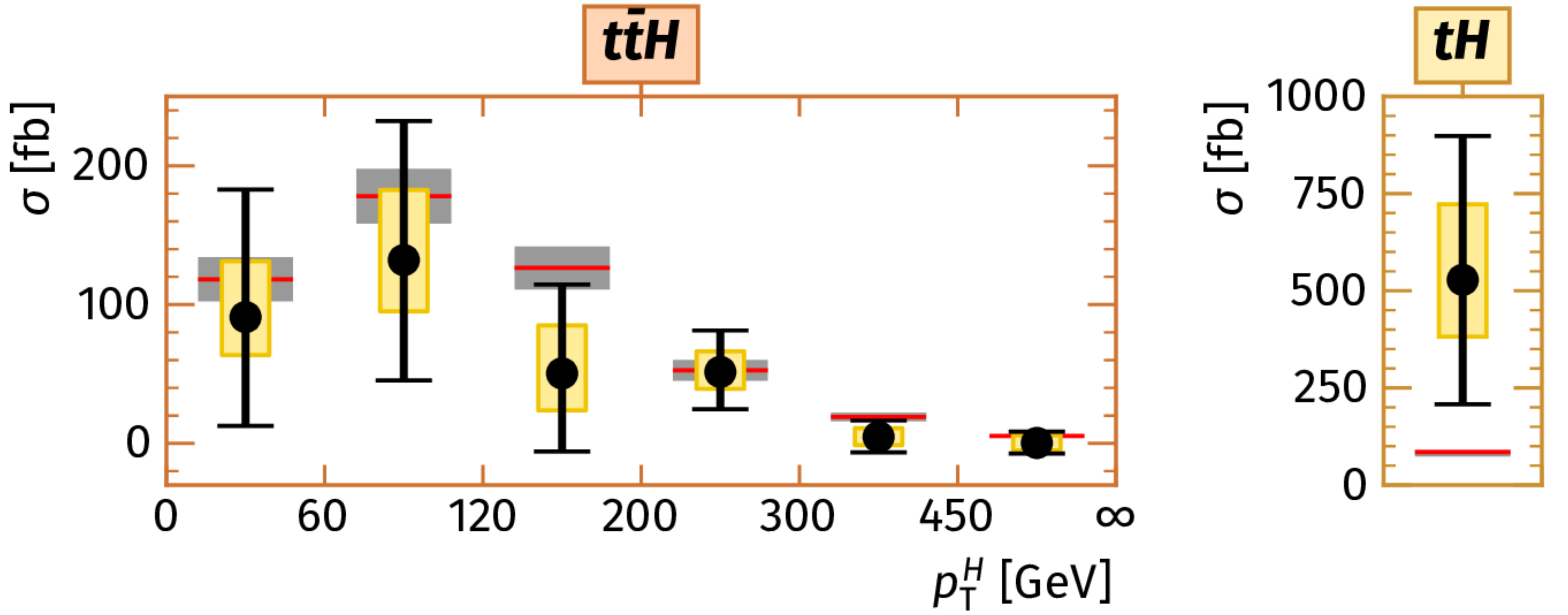
[Nature 607 (2022) 52-59](#)

STXS categorisation

- 2022 : ATLAS combination, mostly based on Run 2 data
- Split phase space of Higgs production processes into 36 kinematic regions







Nature 607 (2022) 52-59

All measurements are consistent with the SM predictions

Summary

- Precision measurements are crucial for constraining Higgs-boson couplings, so far measurements are consistent with the SM
- We are entering a precision era with uncertainties below 10% for some measurements, though some channels still face statistical uncertainties
- Extend coupling measurements to second-generation fermions
- New advanced techniques and increased statistics are enabling the exploration of more channels while enhancing existing measurements
- STXS interpretations are used to rigorously test the validity of the SM across different phase space regions
- Look forward to Run3 results with improved statistics and analysis methods

$H \to WW^*$ analysis

- sizable branching ratio, rich phenomenology in 2-stage decay
- no full reconstruction, complex and diverse backgrounds

ggF and VBF: fiducial/differential, in-likelihood
unfolding to particle level for **various observables**

Cross section Measurements

Simplified Template Cross-section (STXS):

- Done for each production mode
- Split regions by the sensitive kinematic properties of the Higgs boson and associated jets, W or Z
- A template to study deviations from the SM predictions

Fiducial and differential Measurements:

- Specific phase spaces with selected criteria
- Determine cross section in bins of **some sensitive** observables, i.e: p_T^H
- The **shape of differential σ distribution** use for range of further interpretations

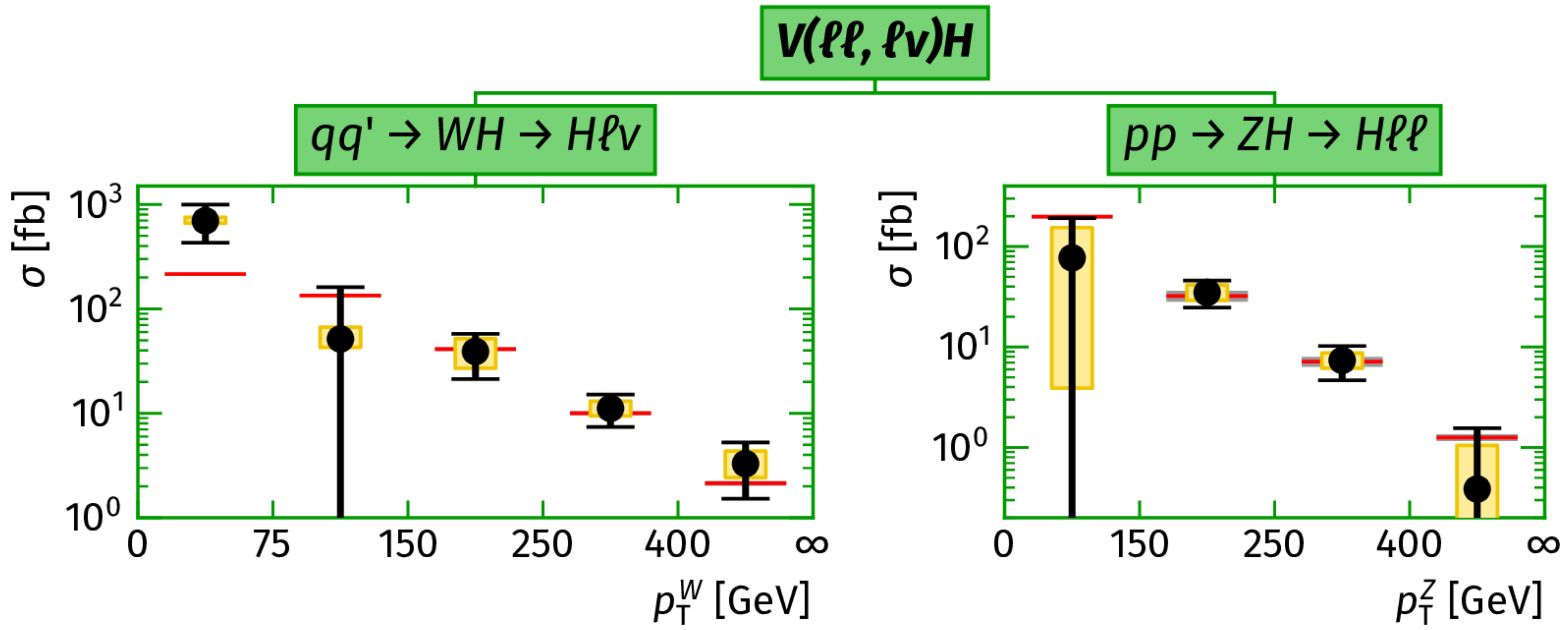
Interpretation based on SMEFT

- SMEFT langrangian in terms of SM:

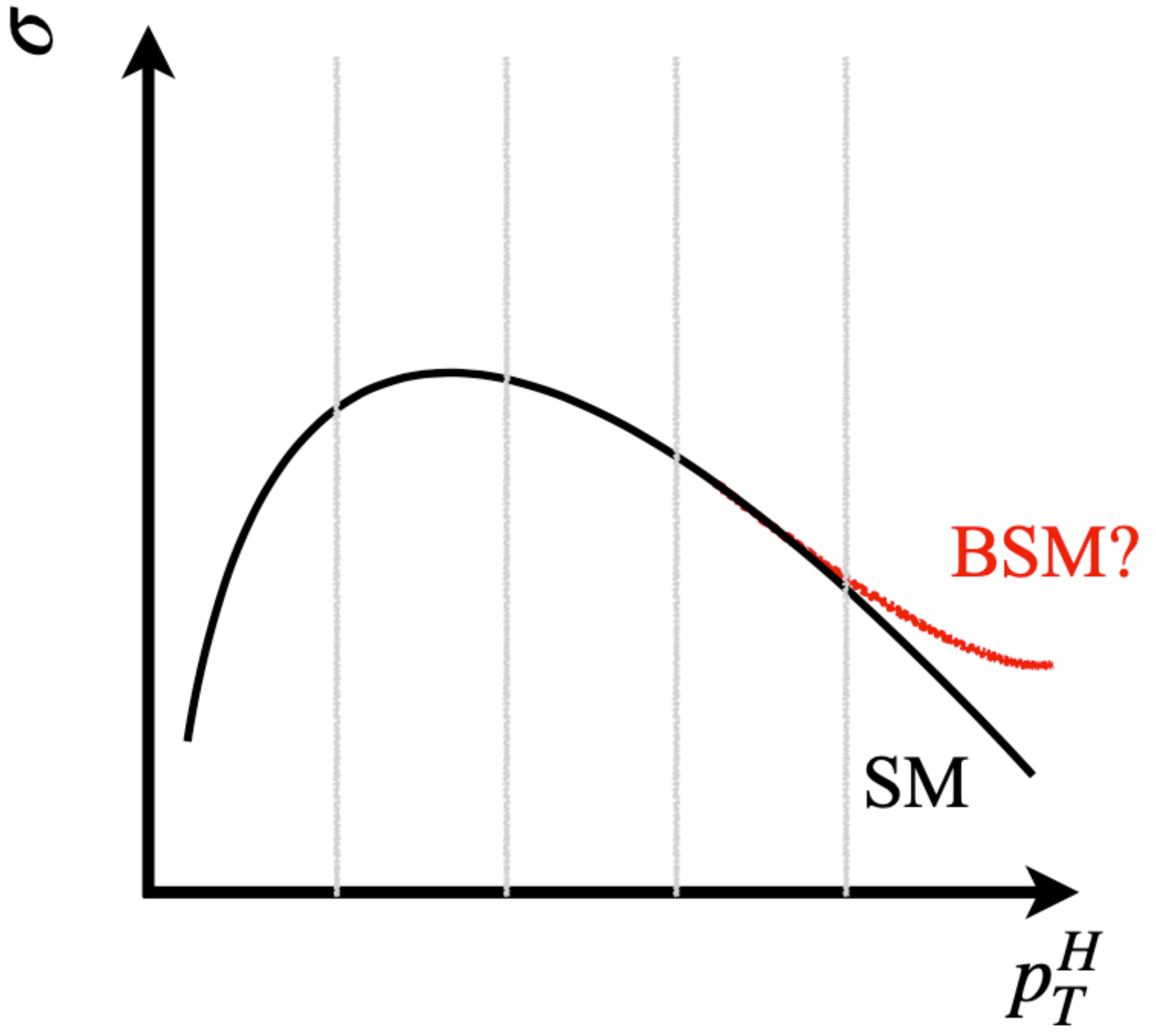
$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i^6 c_i/\lambda^2 \mathcal{O}_i^6 + \sum_j^8 b_j/\lambda^4 \mathcal{O}_j^8$$

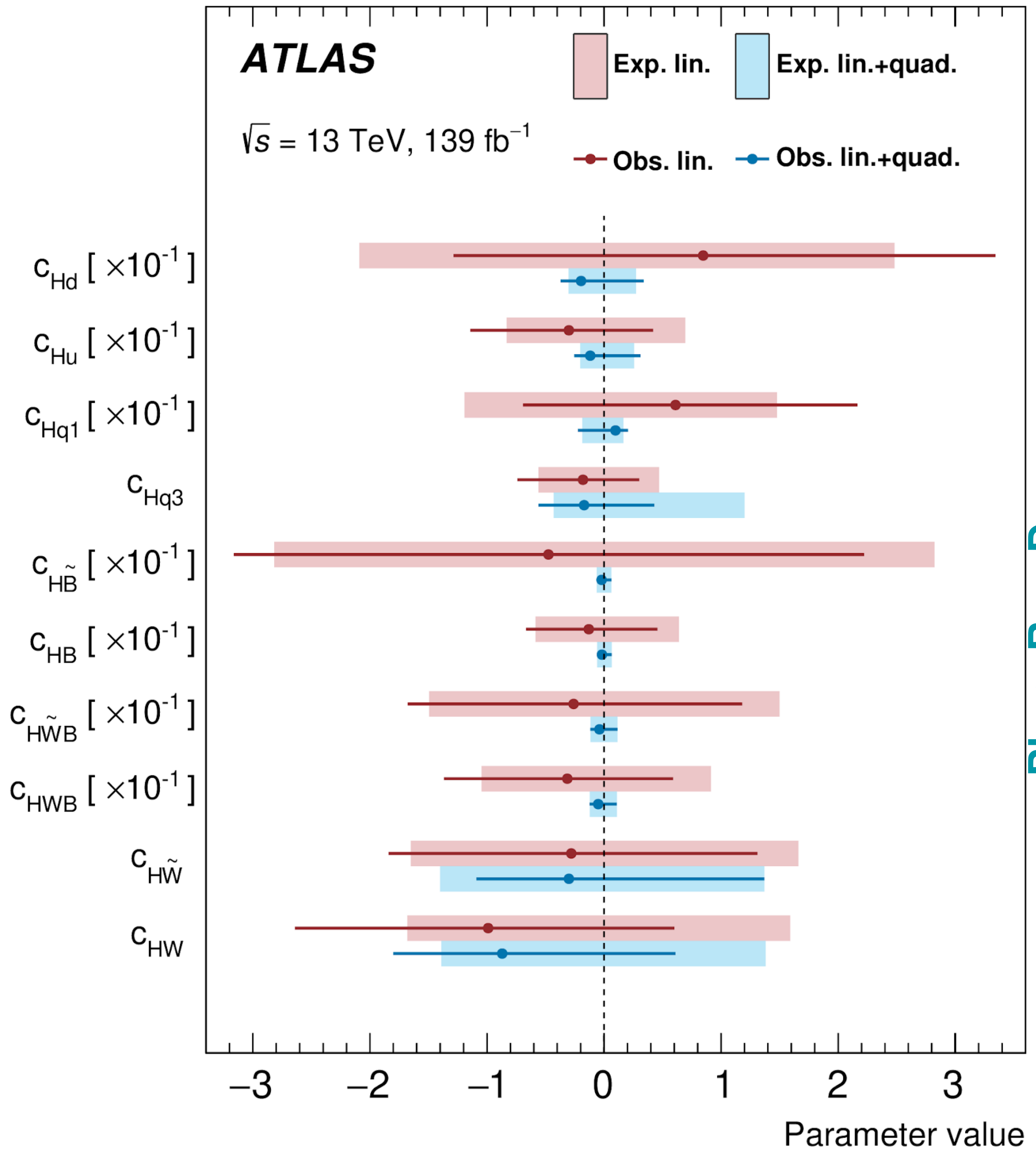
- Cross section relative to SM expectation:

$$\sigma_{EFT}/\sigma_{SM} = 1 + \sum_i A_i c_i + \sum_{ij} B_{ij} c_i c_j$$



Nature 607 (2022) 52-59



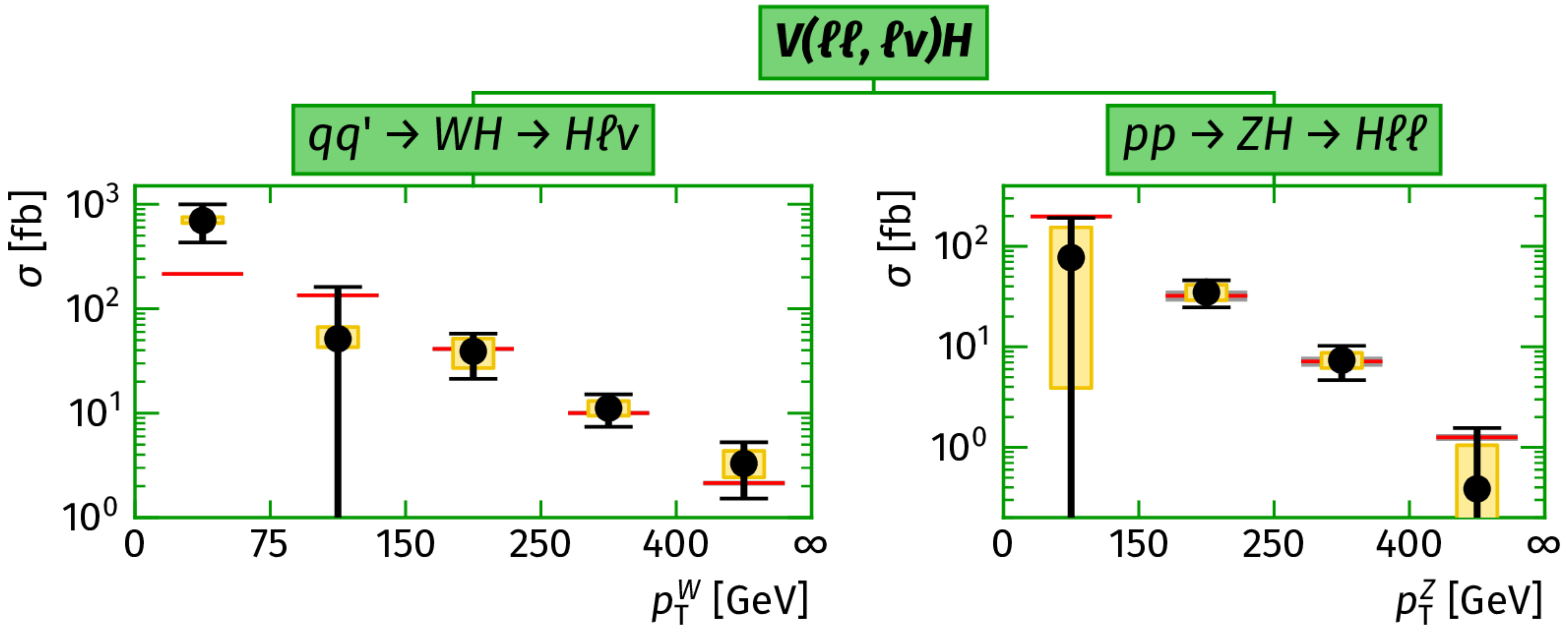


Phys. Rev. D 108 (2023) 072003

Cross section Measurements

Simplified Template Cross-section (STXS):

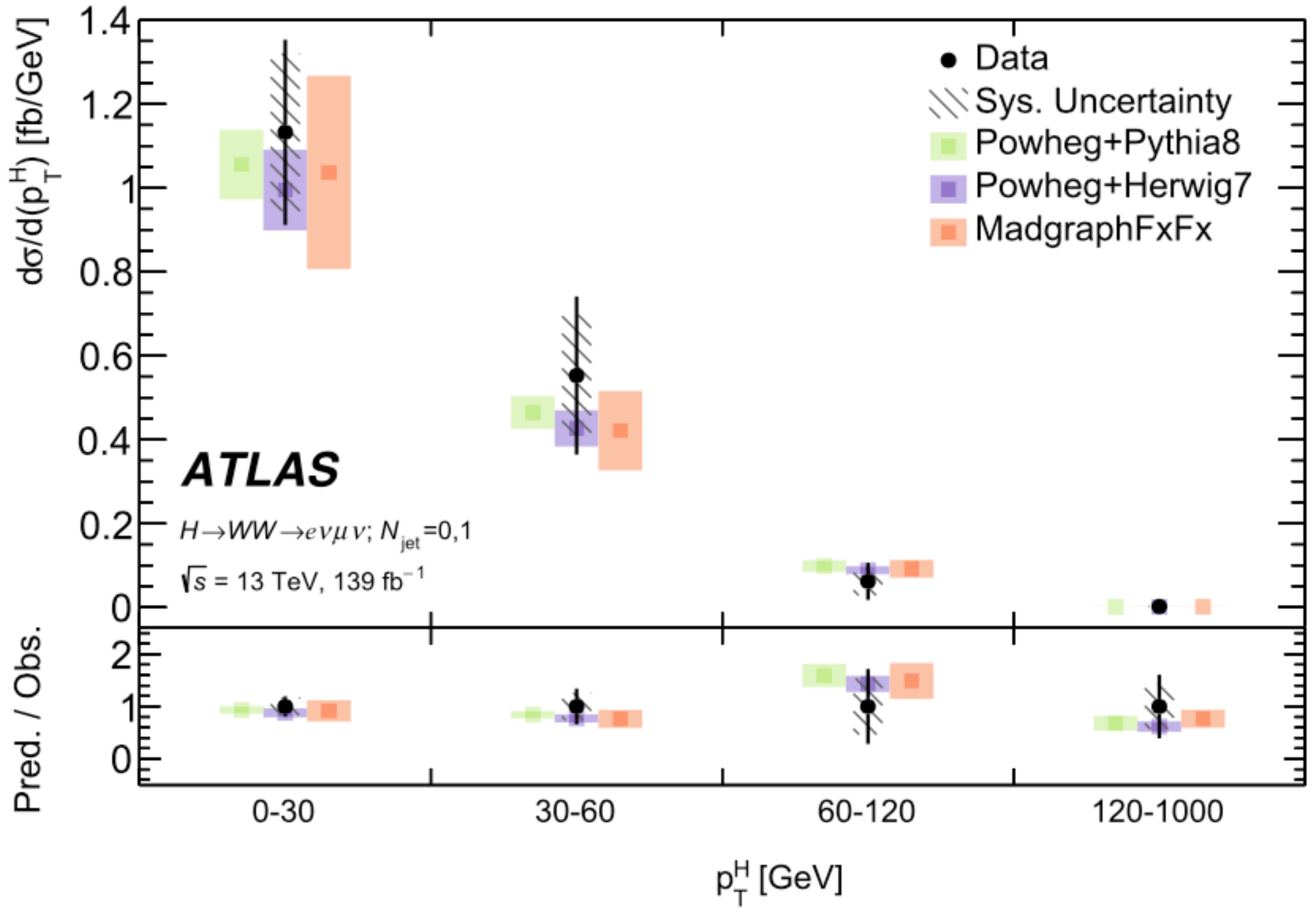
- Done for each production mode
- Regions designed based on Higgs boson and particle properties
- A template to study deviations from the SM predictions



Nature 607 (2022) 52-59

Fiducial and differential Meaurements:

- Specific phase spaces with selected criteria
- Determine cross section in bins of some sensitive observables, i.e: p_T^H
- The shape of differential cross section use for interpretations



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

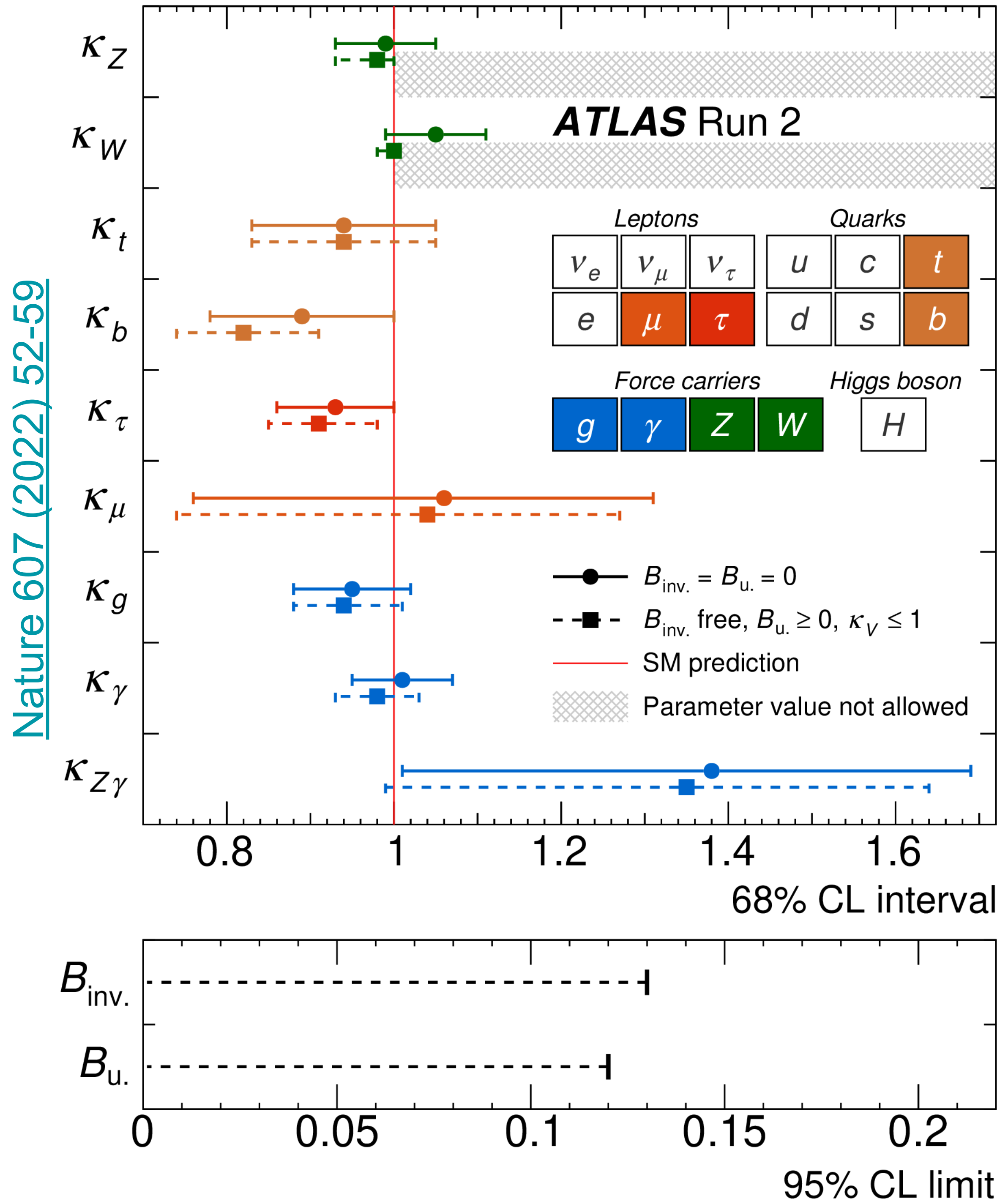
κ-framework:

Use coupling modifiers (κ) to show deviations from SM predictions and probe new physics

$$\sigma(i \to H \to f) = \sigma_i \, . B_f = \frac{\sigma_i^{SM} \, . \Gamma_f^{SM}}{\Gamma_H^{SM}} \, . \frac{\kappa_i^2 \, . \kappa_f^2}{\kappa_H^2}$$

, where $\kappa_i^2 = \frac{\sigma_i}{\sigma_i^{SM}}$, $\kappa_f^2 = \frac{\Gamma_f}{\Gamma_i^{SM}}$,

$SM \to \kappa = 1,$ κ_H is the total width of Higgs boson

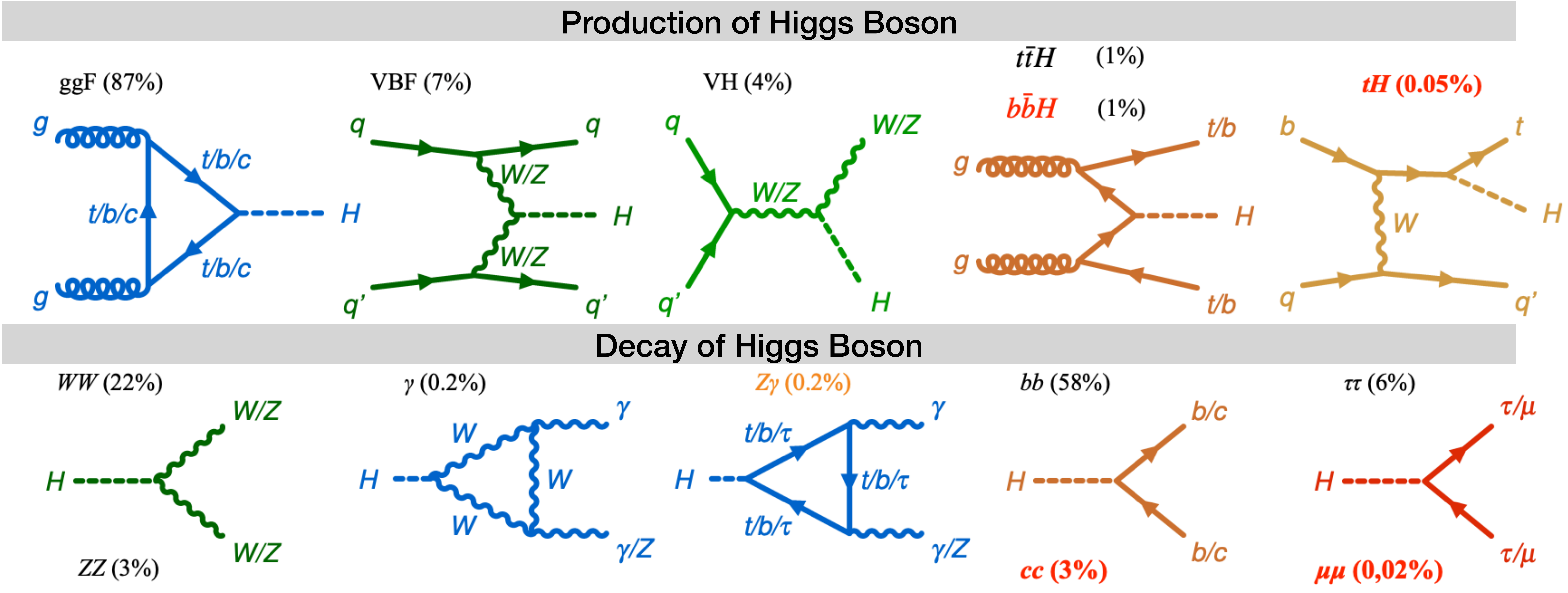


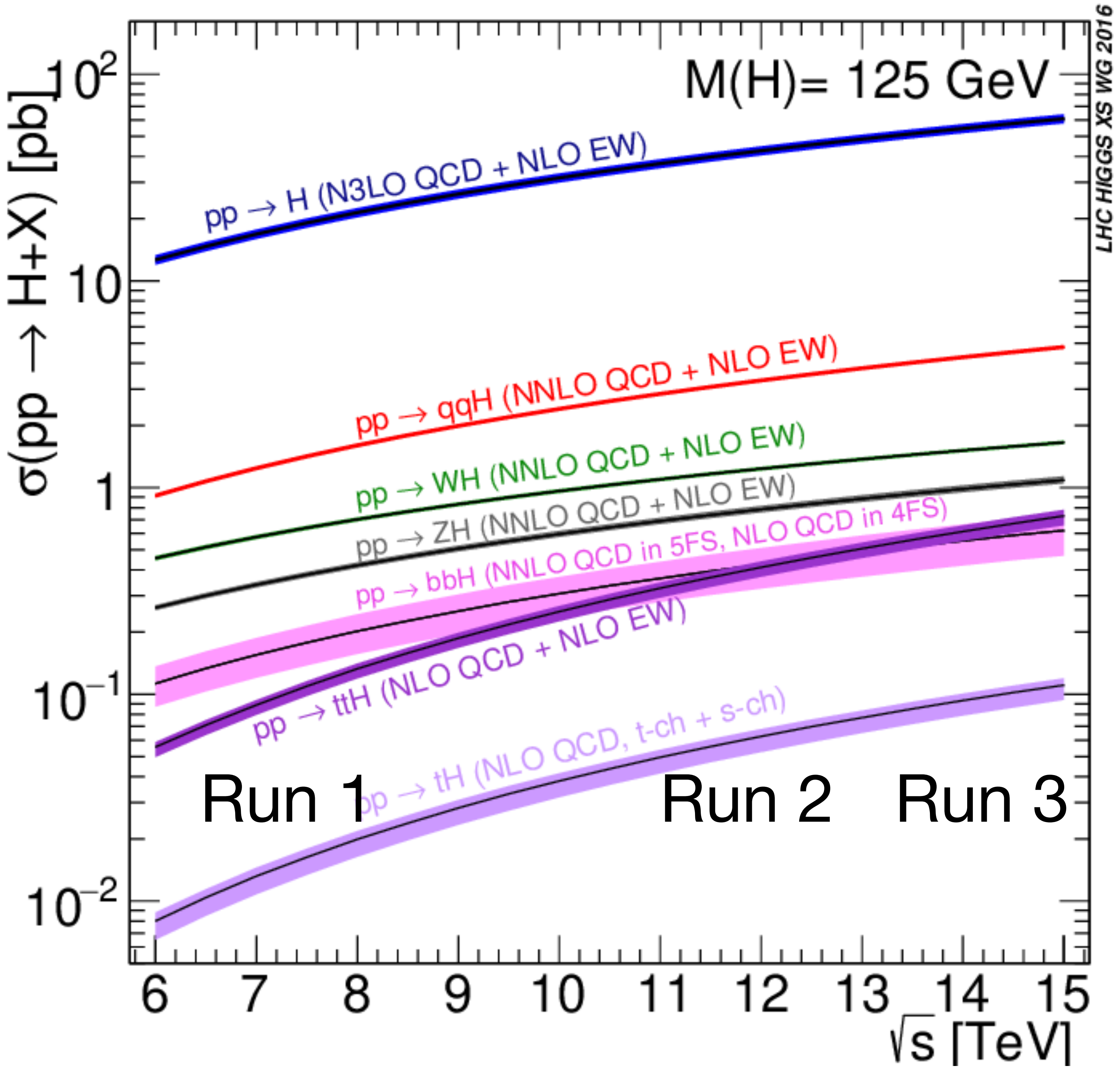
Higgs Boson Production and Decay Modes

- During Run 2, ATLAS recorded around 140 fb^{-1} of integrated luminosity in proton-proton collisions

- Nearly 9 million Higgs bosons were produced, consistent with Standard Model (SM) predictions, though only 0.3% were experimentally accessible

- Several Higgs boson production and decay modes were studied





- Gluon-gluon fusion (ggF) was the dominant production mode at the LHC, offering an indirect measurement of the top-quark coupling through virtual loops (first observed in Run 1)

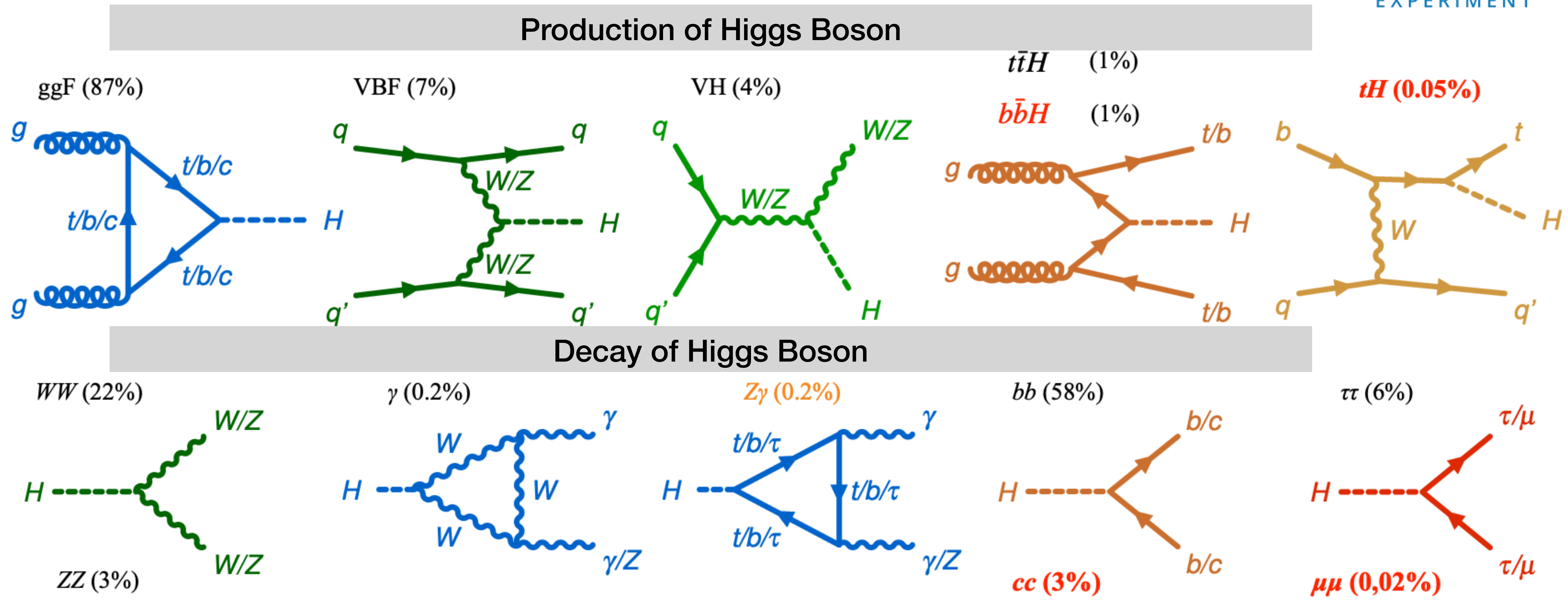
- The ttH process provides a direct measurement of the Higgs Yukawa coupling to the top quark, though it occurs at a much lower rate

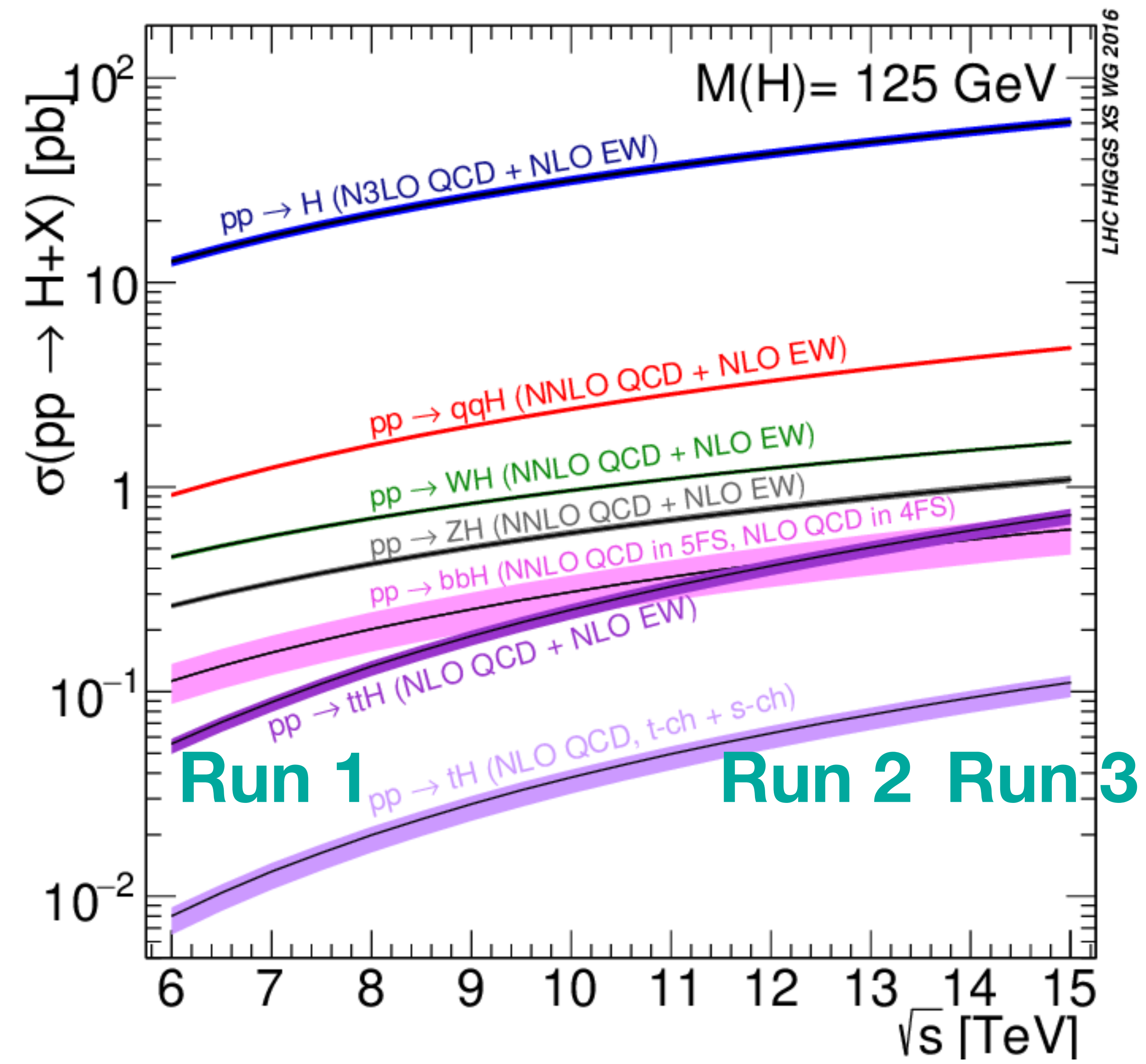
- The ttH, VH, and ZH production modes were observed during Run 2 of the LHC

Channel	Branching ratio	Mass resolution
$H \to bb$	High	Low
$H \to \tau\tau$	High	Low
$H \to WW$	High	Very Low
$H \to ZZ^*$ ($\to 4l$)	Low	High
$H \to \gamma\gamma$	Low	High

Higgs Boson Production and Decay Modes

- Various Production and decays channels for the Higgs boson
  - **Gluon-gluon fusion (ggF)** is the dominant production mode (87%)
    - Indirect top-quark coupling via loops (first seen in Run 1)
  - **Vector Bososn Fusion (VBF)** is the second dominant production channel (7%)
  - **Top-anti top quark pair** (ttH) directly measures the Higgs-top Yukawa coupling but occurs at a lower rate
  - **Radiation of vector bosons** (W/Z) leads to rare channels **VH** or **tH** (Run 2)
  - $H \to b\bar{b}$, $H \to \tau\tau$ and $H \to WW^*$, high BR but low resolution
  - $H \to \gamma\gamma$ and $H \to ZZ^*$ low BR but high resolution
- In Run 2, ATLAS recorded ~140 fb^{-1} from proton-proton collisions
- About 9 million Higgs bosons were produced, but only 0.3% are accessible
  - Precise production rate measurements is essential for understanding processes





- sizable branching ratio, rich phenomenology in 2-stage decay
- no full reconstruction, complex and diverse backgrounds

ggF and VBF: fiducial/differential, in-likelihood
unfolding to particle level for **various observables**