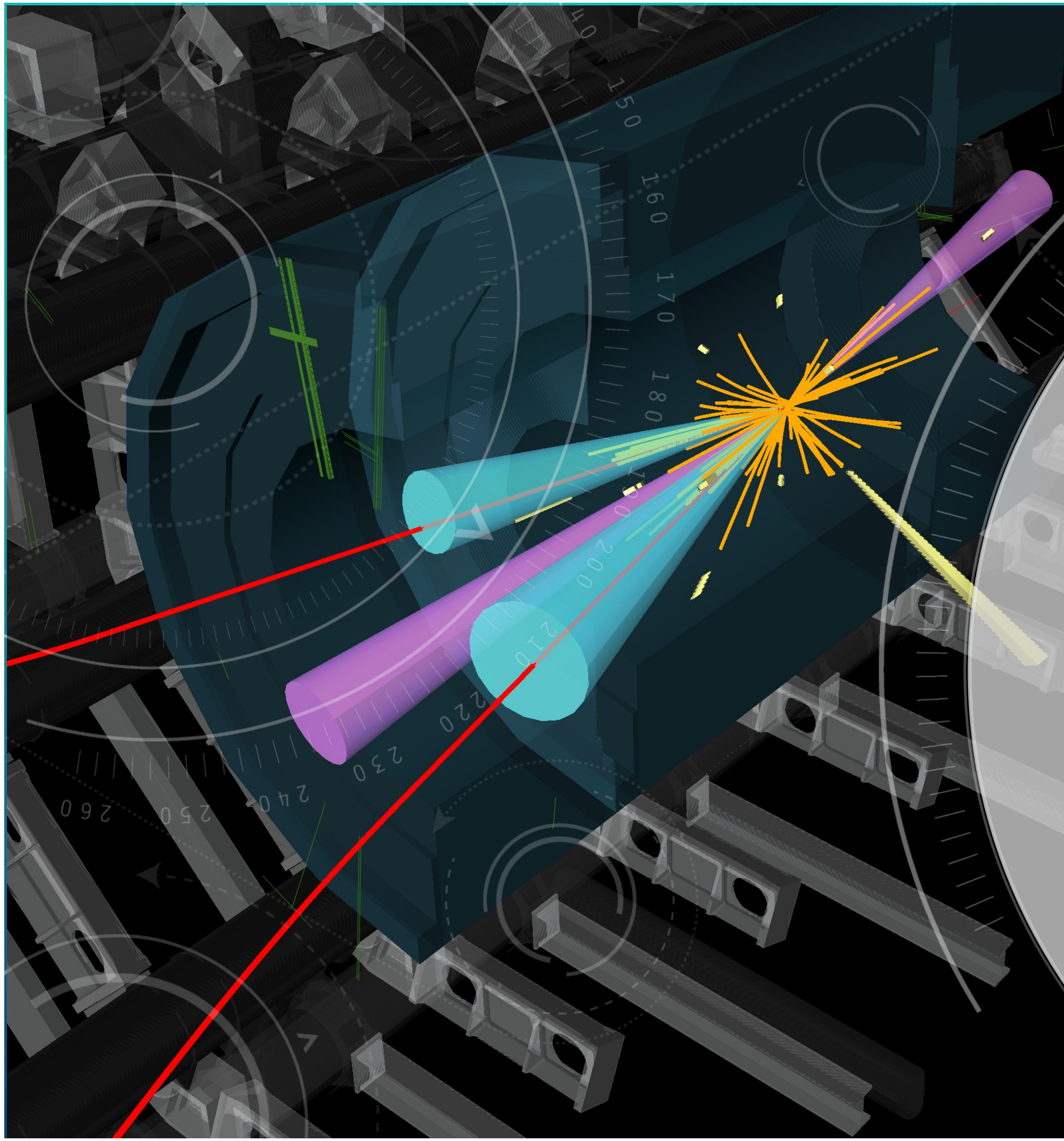

# MEASUREMENTS OF THE HIGGS BOSON PROPERTIES AND THEIR INTERPRETATIONS WITH THE ATLAS EXPERIMENT

CAROLYN GEE

PHENO 2022

MAY 9-11

# THE HIGGS BOSON

- Higgs discovery ~10 years ago
- Now: Higgs precision era
  - Contact trace all the Higgs' interactions:
    - Production modes *ggF, VBF, WH, ZH,* $t\bar{t}H$ + *tH* all observed
    - Decay modes *H*→*γγ, ZZ*, WW*, ττ,* $b\bar{b}$, Zγ all observed, closing in on μμ & $c\bar{c}$

| Decay channel | Target Production Modes | $\mathcal{L}$ [fb$^{-1}$] |
|---|---|---|
| $H \to \gamma\gamma$ | ggF, VBF, $WH, ZH, t\bar{t}H, tH$ | 139 |
| $H \to ZZ^*$ | ggF, VBF, $WH, ZH, t\bar{t}H(4\ell)$ | 139 |
| | $t\bar{t}H$ | 36.1 |
| $H \to WW^*$ | ggF, VBF | 139 |
| | $t\bar{t}H$ | 36.1 |
| $H \to \tau\tau$ | ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{had}\tau_{had})$ | 139 |
| | $t\bar{t}H$ | 36.1 |
| $H \to b\bar{b}$ | $WH, ZH$ | 139 |
| | VBF | 126 |
| | $t\bar{t}H$ | 139 |
| $H \to \mu\mu$ | ggF, VBF, $VH, t\bar{t}H$ | 139 |
| $H \to Z\gamma$ | ggF, VBF, $VH, t\bar{t}H$ | 139 |
| $H \to inv$ | VBF | 139 |

ATLAS-CONF-2021-53


# THE HIGGS BOSON

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- Now: Higgs precision era
  - Contact trace all the Higgs' interactions:
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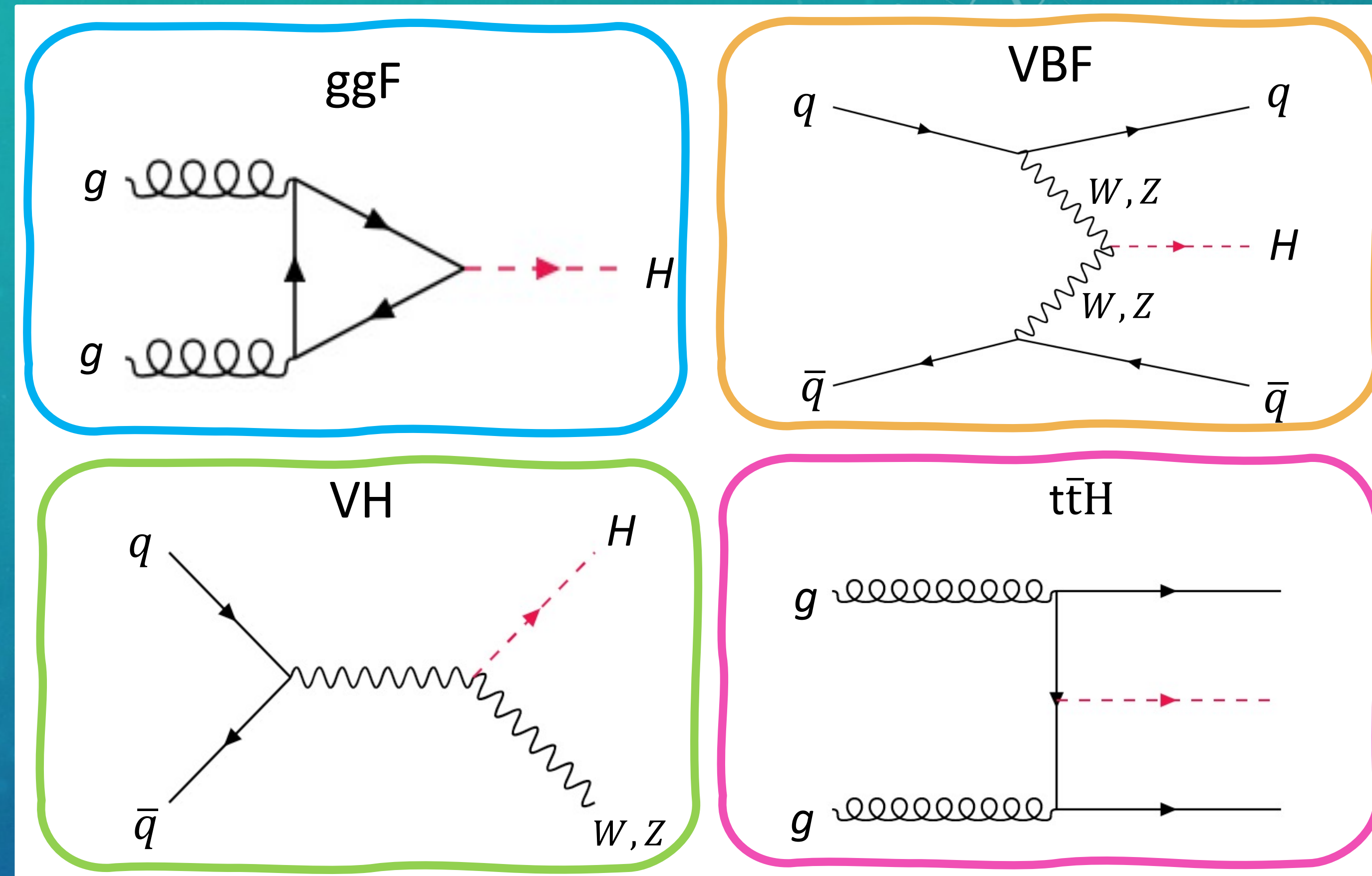


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| | $t\bar{t}H$ | 36.1 |
| $H \to WW^*$ | ggF, VBF | 139 |
| | $t\bar{t}H$ | 36.1 |
| $H \to \tau\tau$ | ggF, VBF, $WH, ZH, t\bar{t}H(\tau_{\text{had}}\tau_{\text{had}})$ | 139 |
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| $H \to Z\gamma$ | ggF, VBF, $VH, t\bar{t}H$ | 139 |
| $H \to inv$ | VBF | 139 |

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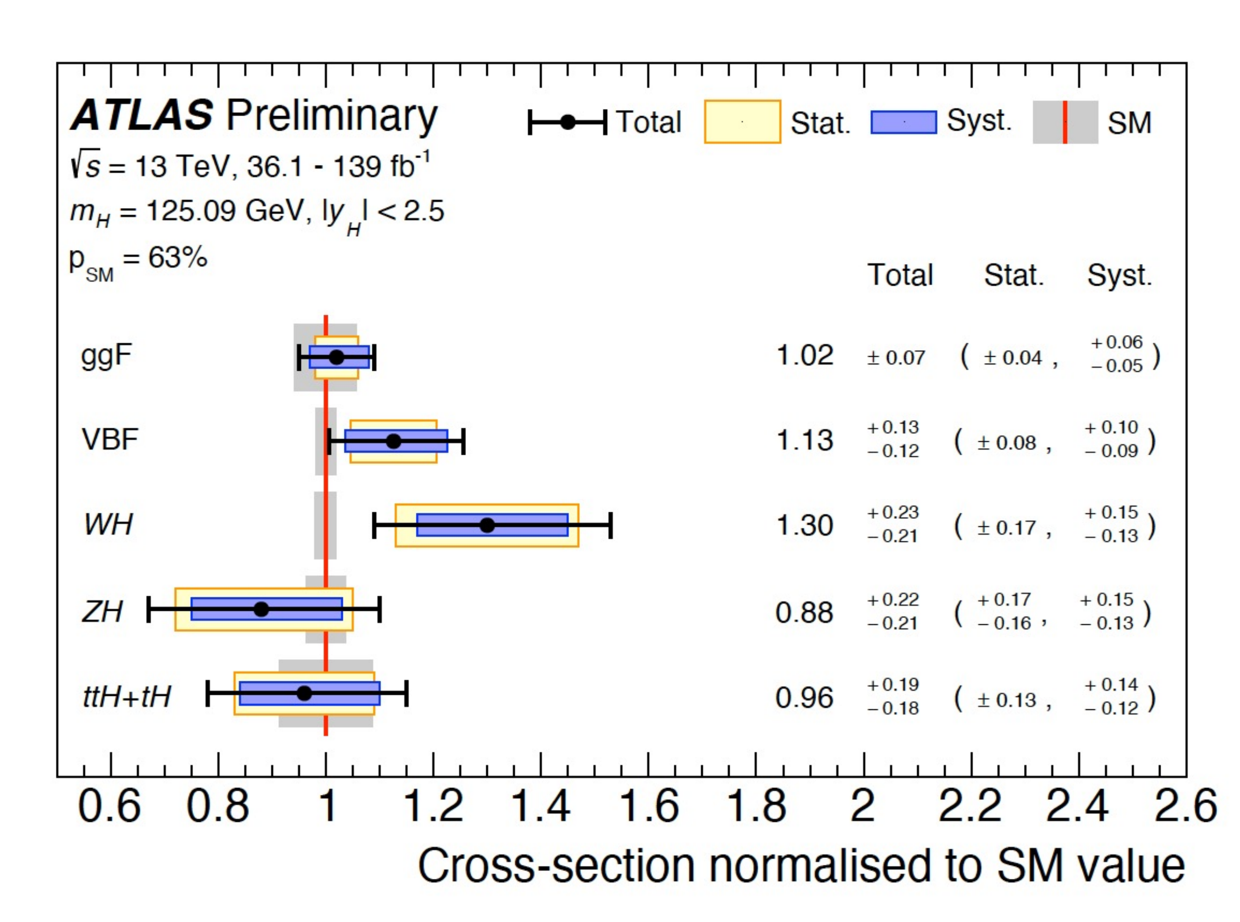
# MULTITUDES OF RESULTS

- **Signal strength, μ:** Measured result compared to SM prediction
- **Production cross sections, σ:** Describes Higgs production modes, assumes SM branching ratios
- **Cross section x branching fraction, (σ x B)**: Describes combination of Higgs production and decay mechanisms, fewer assumptions
- **Simplified Template X-Sections (STXS)**

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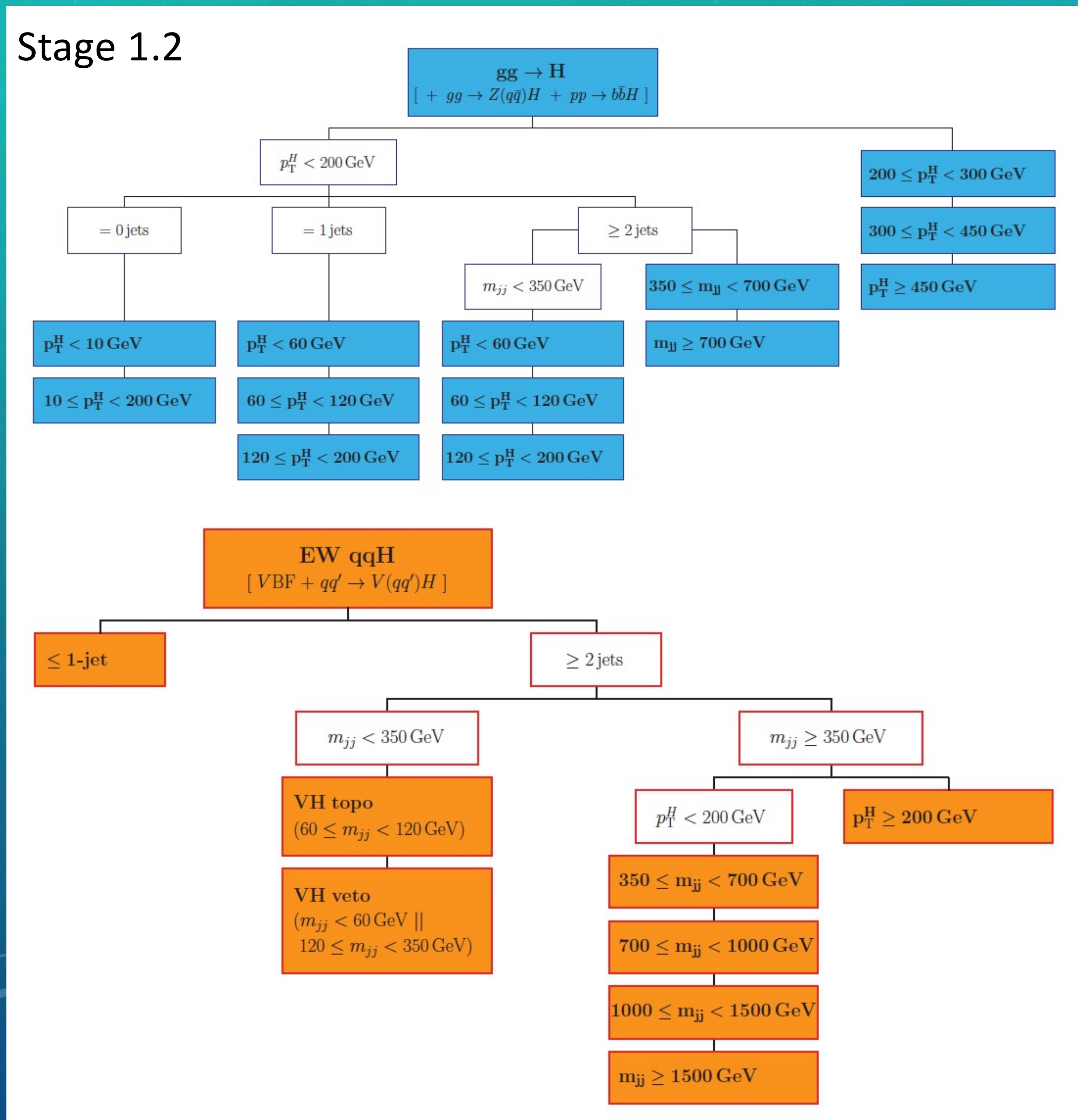
*For ATLAS Higgs Differential and Fiducial Cross section results, see Benedict Winter's Talk

*For ATLAS CP Higgs Coupling Results, see Christian Grefe's Talk

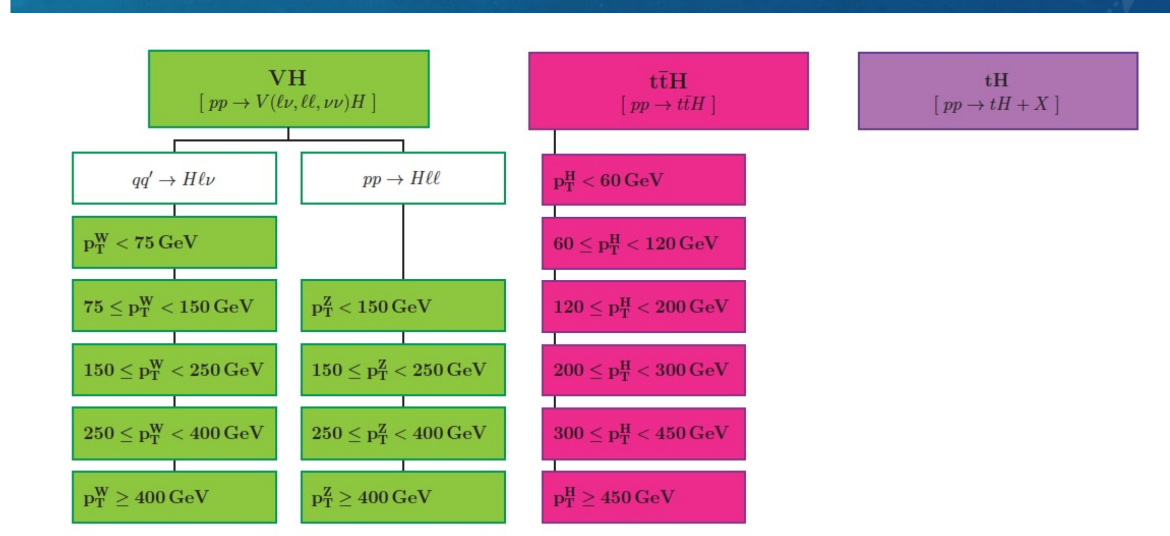
# SIMPLIFIED TEMPLATE X-SECTIONS (STXS)




**Problem:** Measurements have SM theory dependencies

**Solution:** Separate measurement and interpretation steps. Divide Higgs phase spaces into regions based on Higgs production mode properties

- Useful for re-interpretating, deriving x-sec upper limits, & constraining anomalous couplings in SMEFT

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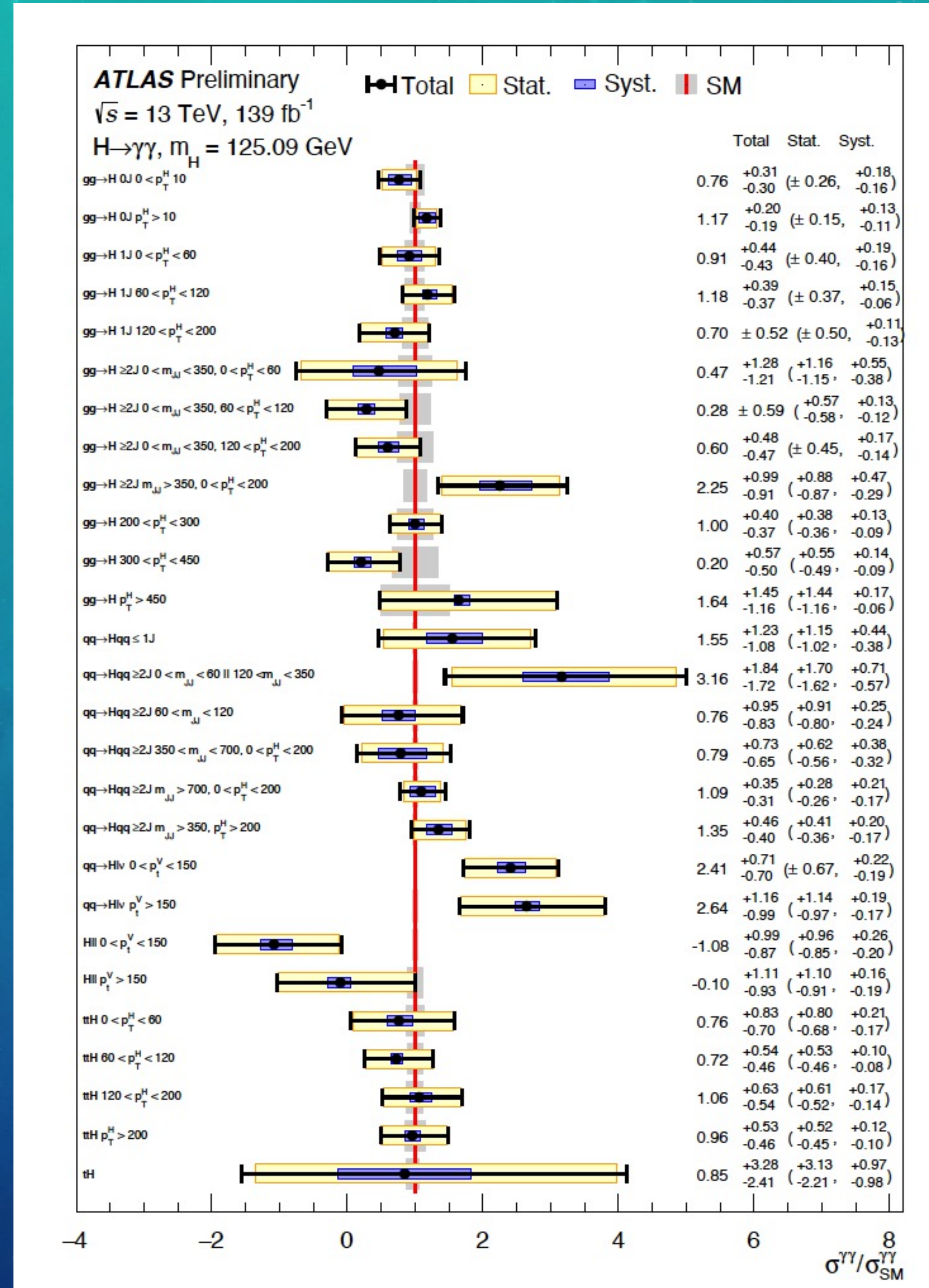
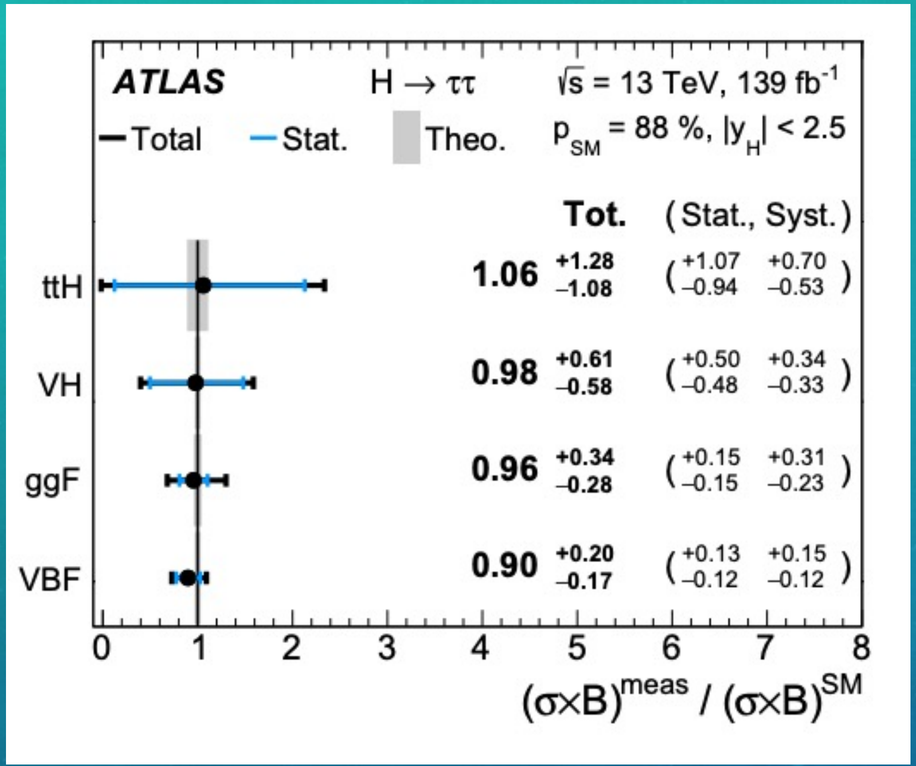
**H→γγ:** [ATLAS-CONF-2020-026]

- Inclusive Higgs production in 27 STXS regions
- Small $\mathcal{B}$, clean γ measurement
- $(\sigma \times \mathcal{B})/(\sigma \times \mathcal{B})_{SM} = 1.09^{+0.09}_{-0.08}$

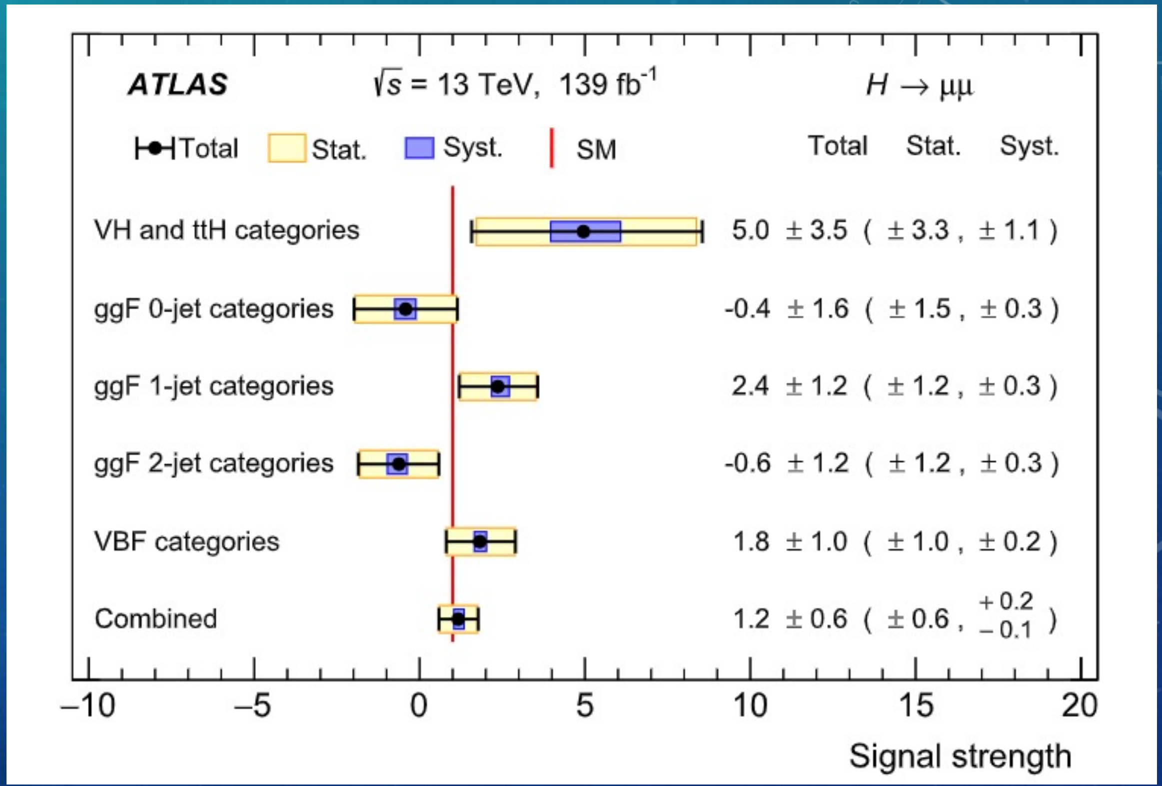


# HIGGS DECAYING TO LEPTONS




## H→μμ: HIGG-2019-14

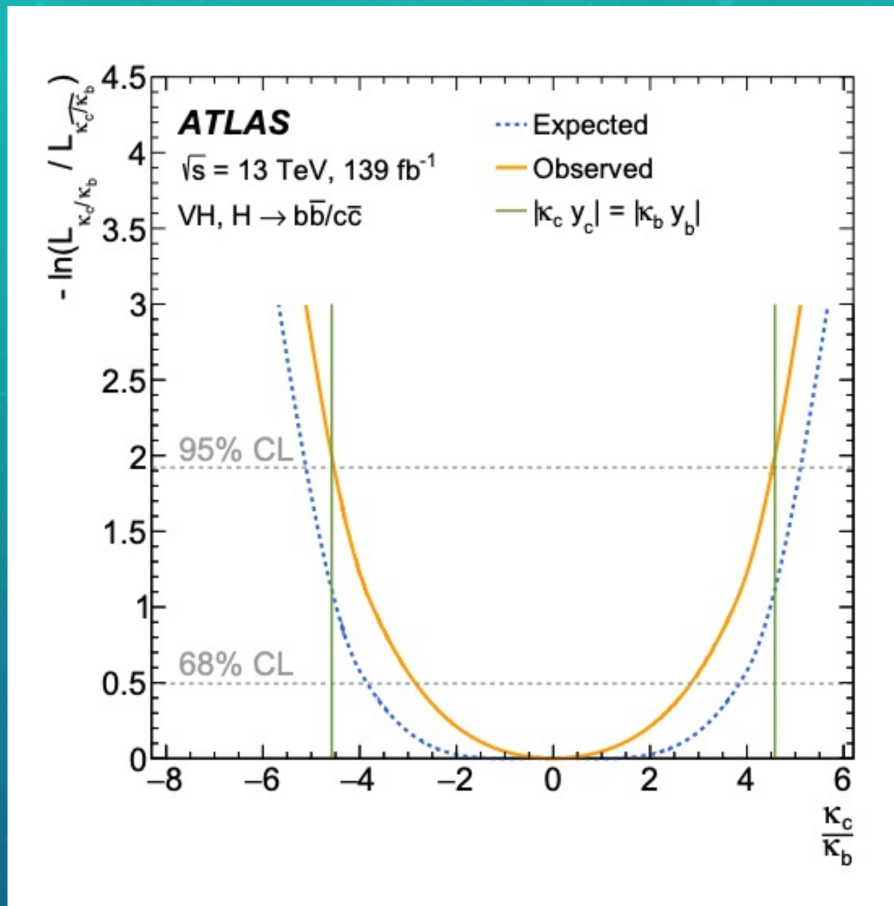
- Measures production modes $t\bar{t}H$, VH, ggF, and VBF
- Best opportunity to measure Higgs interactions with second-generation fermions
- **Significance: 2.0σ (1.7σ) obs. (exp.); μ = 1.2 ± 0.6**




## $H \rightarrow \tau^+\tau^-$ : HIGG-2019-09

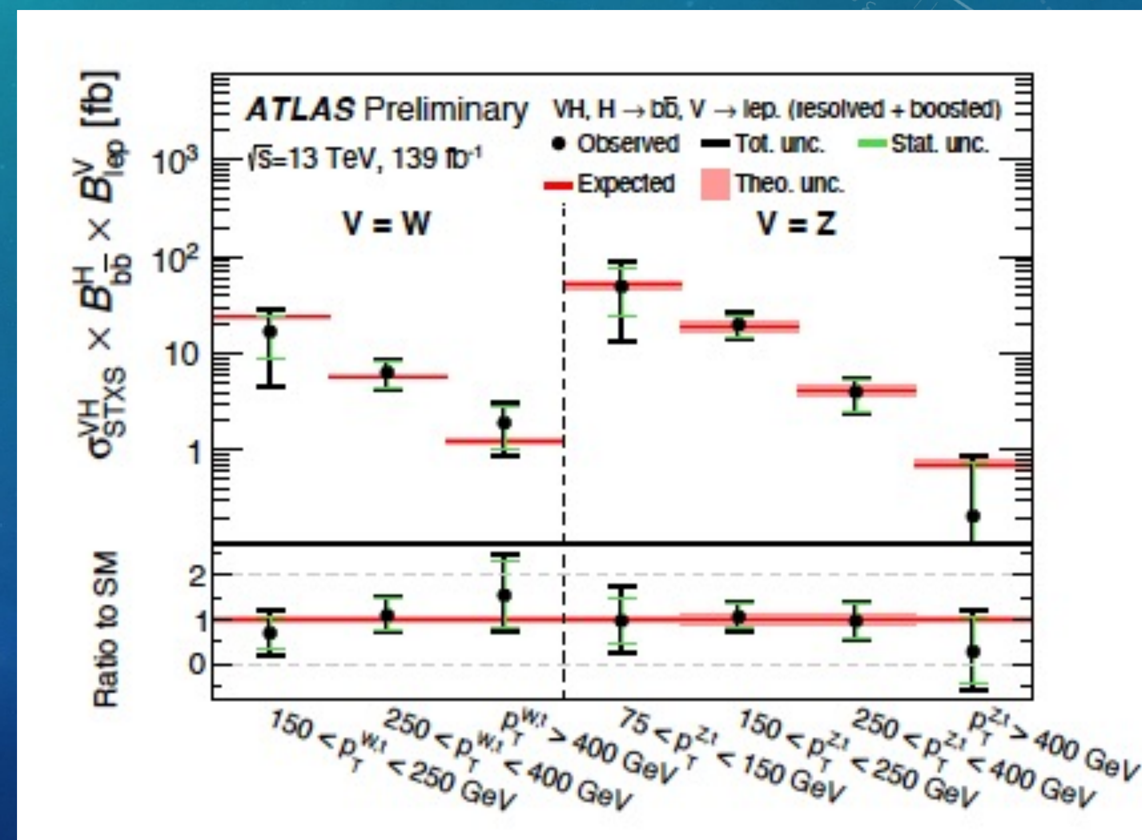
- Includes leptonic ($\tau \rightarrow l\nu_l\nu_\tau$) and hadronic ($\tau \rightarrow$ hadrons $\nu_\tau$) decays
- Largest $\mathcal{B}$ of Higgs bosons → leptons, provides opportunity to study Yukawa mechanism
- **$\sigma = 2.94 \pm 0.21\,(\text{stat})^{+0.37}_{-0.32}(\text{syst})$ pb**
- **VBF H→ττ: 5.3(6.2)σ & ggF H→ττ 3.9(4.6)σ**

# HIGGS DECAYING TO QUARKS




## VH($b\bar{b}$): ATLAS-CONF-2021-051

- Resolved + boosted combination targeting W/Z bosons plus a Higgs decaying to b-quarks
- Best inclusive sensitivity of H→ $b\bar{b}$ so far, due to large Higgs boson $\mathcal{B}$ and clean measurement of lepton decays
- $\mu = 1.00^{+0.18}_{-0.17}$

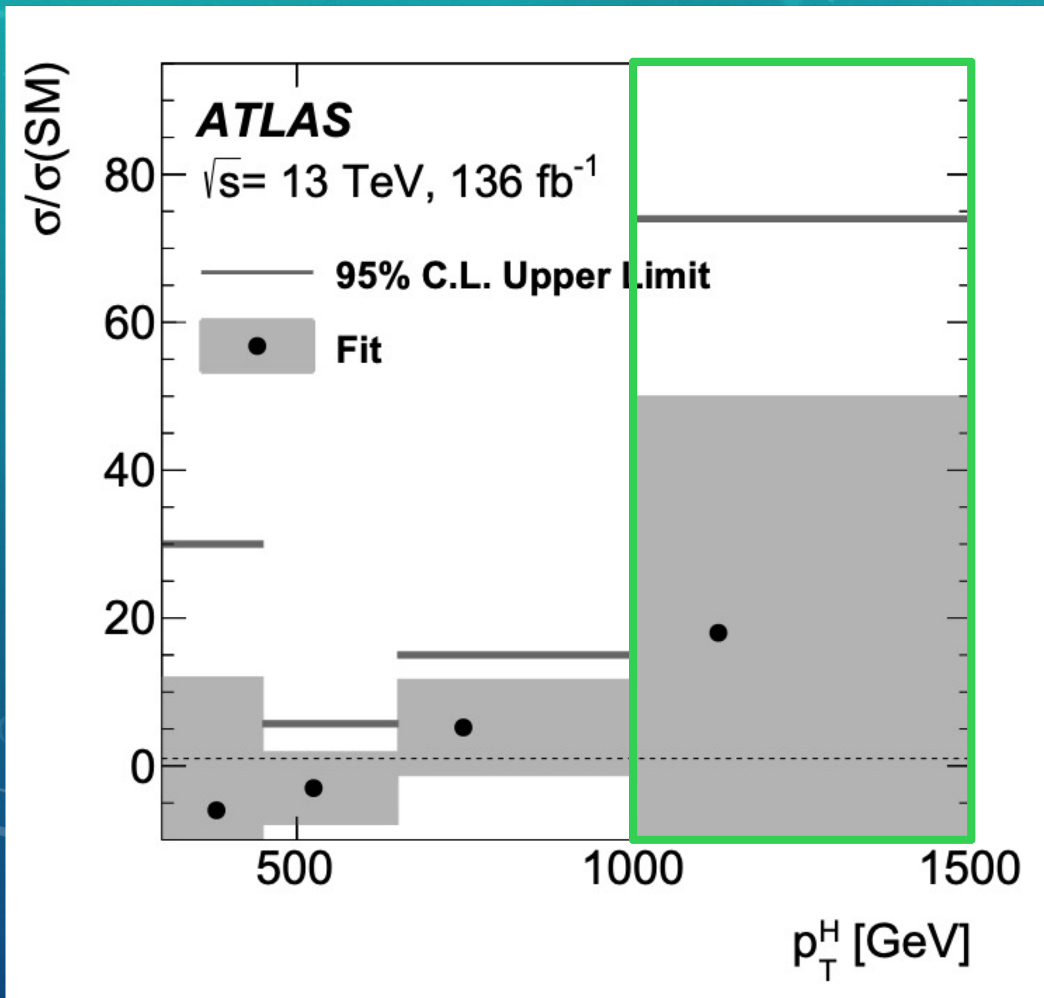



## VH($c\bar{c}$): HIGG-2021-12

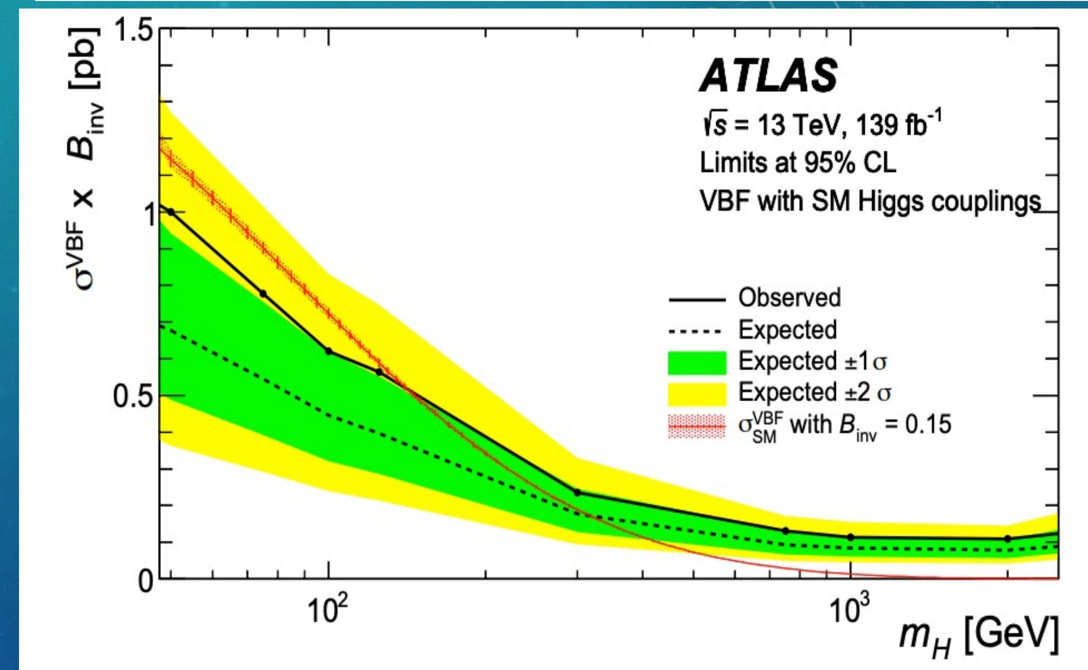
- Targets $ZH \rightarrow \nu\nu c\bar{c}$, $WH \rightarrow \ell\nu c\bar{c}$ and $ZH \rightarrow \ell\ell c\bar{c}$
- Combination with VH($b\bar{b}$) constrained $|K_c/K_b| < 4.5$, c-coupling to Higgs weaker than b-coupling

## All-hadronic Boosted $H(b\bar{b})$: HIGG-2021-08

- First ATLAS analysis of Higgs bosons produced with $p_T^H > 1$ TeV
- $\sigma_{ggF} \approx \sigma_{VH}$; $\sigma_{VBF} \sim 0.6\sigma_{ggF}$ & $\sigma_{ttH} \sim 0.3\sigma_{ggF}$ at high $p_T$
- Improved S/B ratio & potential BSM effects enhanced at high $p_T^H$



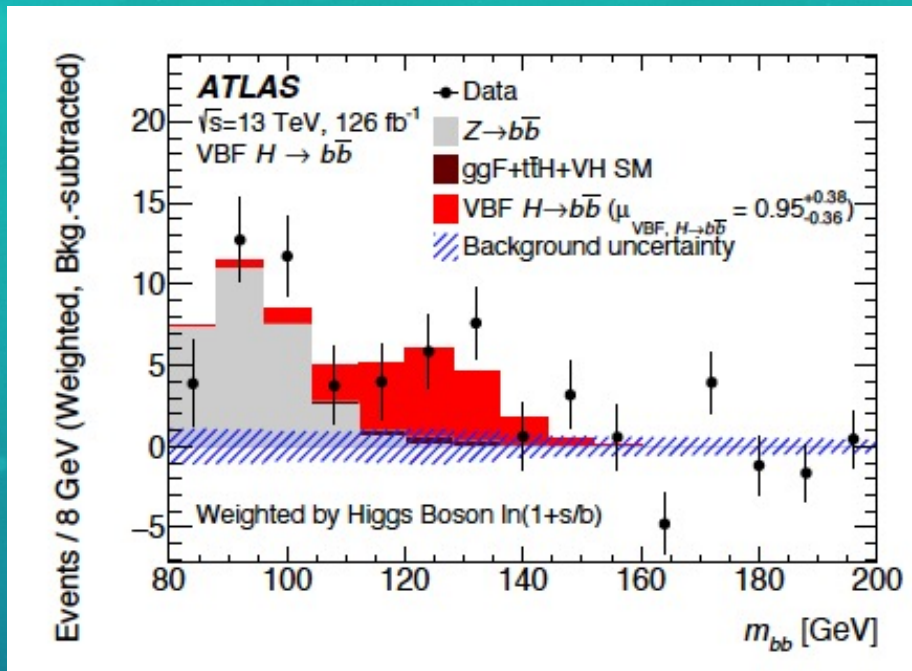

| Analysis | $\sqrt{s}$ [TeV] | Int. luminosity [fb$^{-1}$] | Best fit $\mathcal{B}_{H\to\text{inv}}$ | Observed upper limit | Expected upper limit |
|---|---|---|---|---|---|
| Run 2 VBF | 13 | 139 | $0.00^{+0.07}_{-0.07}$ | 0.13 | $0.13^{+0.05}_{-0.04}$ |
| Run 2 $t\bar{t}H$ | 13 | 139 | $0.04^{+0.20}_{-0.20}$ | 0.40 | $0.36^{+0.15}_{-0.10}$ |
| Run 2 Comb. | 13 | 139 | $0.00^{+0.06}_{-0.07}$ | 0.13 | $0.12^{+0.05}_{-0.04}$ |
| Run 1 Comb. | 7, 8 | 4.7, 20.3 | $-0.02^{+0.14}_{-0.13}$ | 0.25 | $0.27^{+0.10}_{-0.08}$ |
| Run 1+2 Comb. | 7, 8, 13 | 4.7, 20.3, 139 | $0.00^{+0.06}_{-0.06}$ | 0.11 | $0.11^{+0.04}_{-0.03}$ |




### H→inv: ATLAS-CONF-2020-052 & EXOT-2020-11

- Direct search for decay of SM Higgs boson to dark matter particles, using MET triggers
- Comb. of VBF+MET & $t\bar{t}H$+MET from Runs 1 & 2
- **New:** VBF+MET upper lim. set on σ x B (0.1 pb-1.0 pb)

# *VBF H (+ γ)*



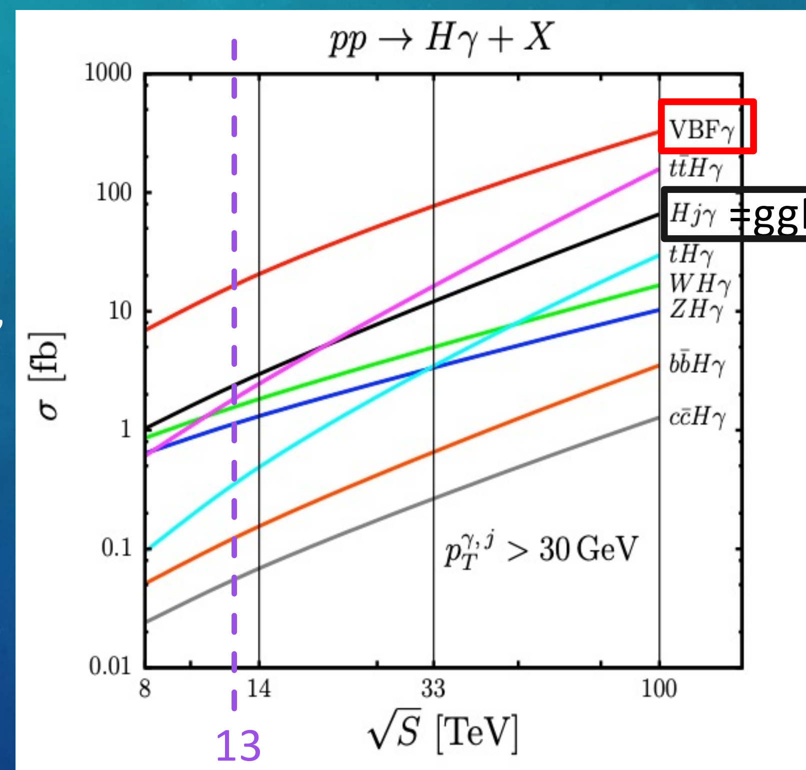

## VBF H($b\bar{b}$)+γ: HIGG-2020-14

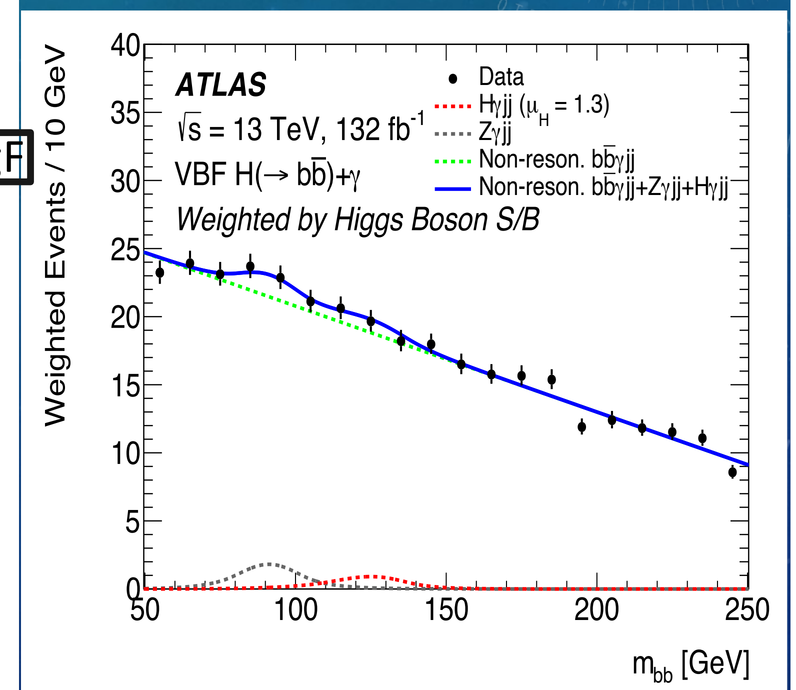
- Photon requirement reduces non-resonant QCD bkg through destructive interference
- VBF is dominant production mode for H + γ
- Clean signature from triggering on high-energy photon
- Suppressed ZZ fusion, leaving a clean WW fusion measurement

## VBF H($b\bar{b}$): HIGG-2019-04

- Second most dominant production mode, but is challenging because of QCD background

| $\mu^H$ | Obs. Sig. | Exp. Sig. |
|---|---|---|
| VBF: $0.95^{+0.38}_{-0.36}$ | 2.6σ | 2.8σ |
| VBF+γ: 1.3±1.0 | 1.3σ | 1.0σ |
| Comb: $0.95^{+0.37}_{-0.35}$ | 2.7σ | 2.9σ |

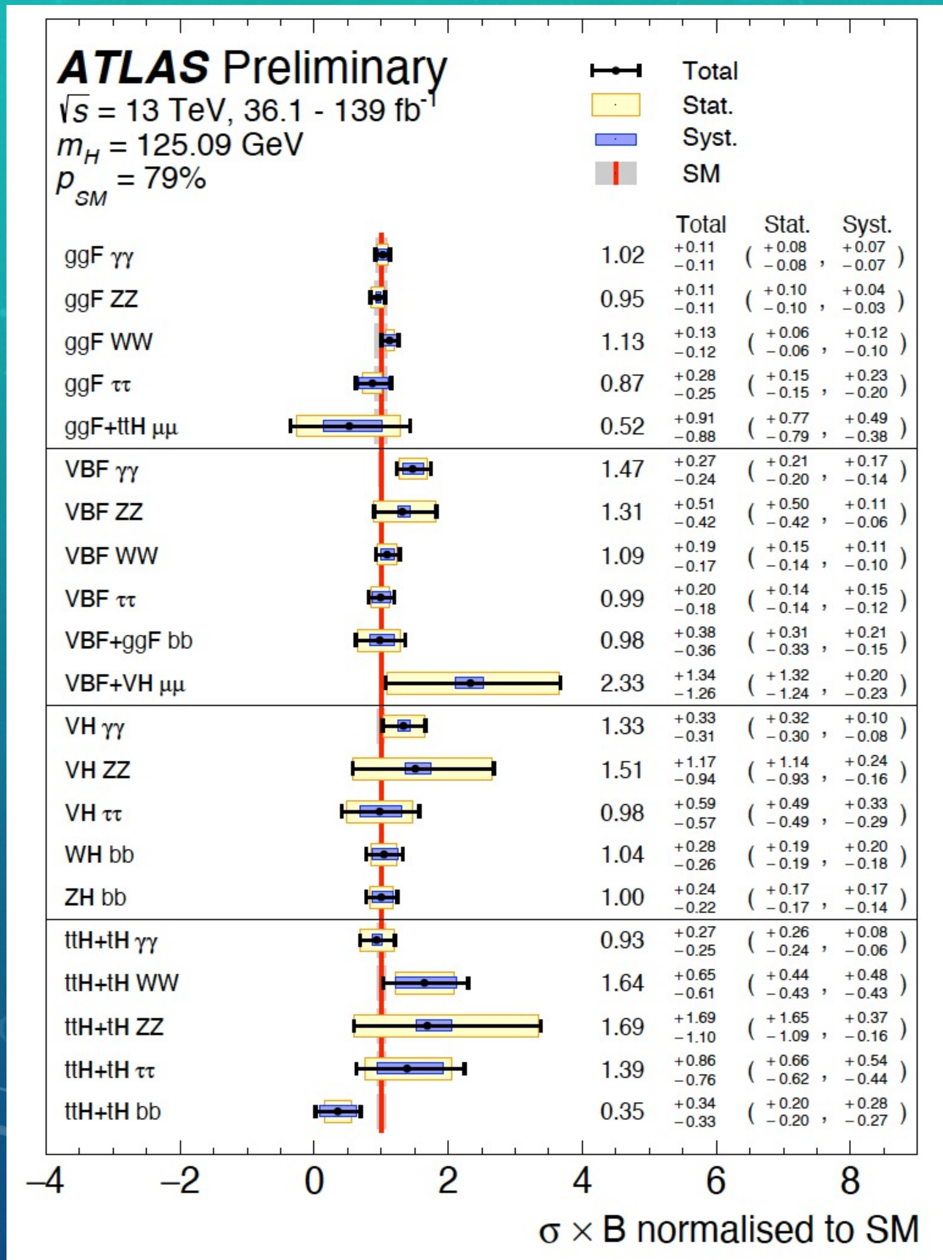



E. Gabrielli et. al

# HIGGS COMBINATION X-SEC & BRANCHING FRACTIONS

21 bins

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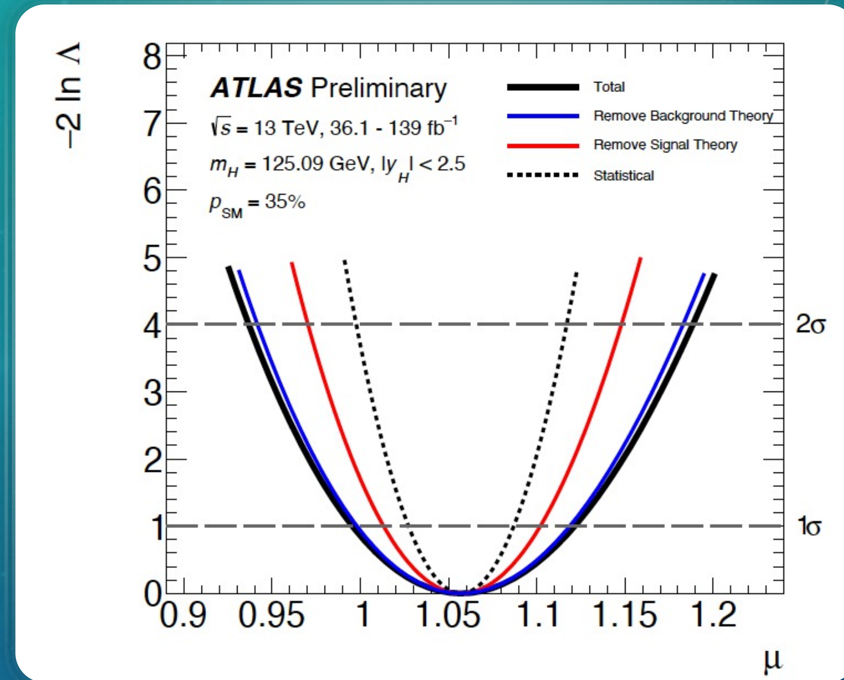



$\mu_{comb.} = 1.06 \pm 0.06$

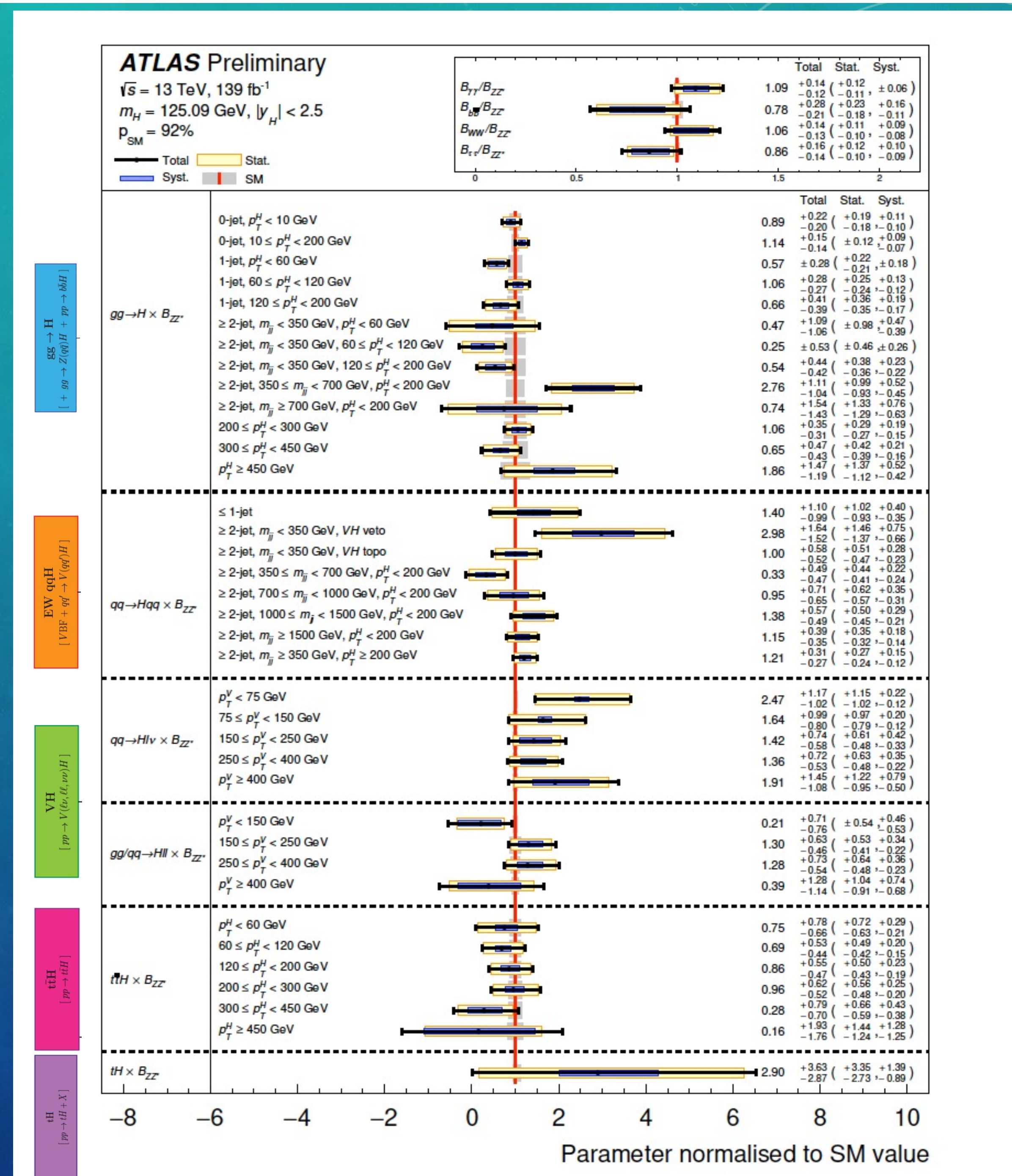
- Probe Higgs with unprecedented levels of precision
- Largest correlations due to cross contamination between processes in analyses

# STXS COMBINATION RESULTS

$$(\sigma \times B)_{if} = (\sigma \times B)_{i,ZZ} \cdot \left(\frac{B_f}{B_{ZZ}}\right)$$

In terms of B(gg→H→ZZ*): precisely measured & has small systematic uncertainties

- Jet bins merged in comb. to account for:
  - Limited sensitivity to σ in bins where there are few events
  - Strongly correlated measurements where sensitivity is for a combination of bins
- Some model-dependence due to kinematics assumptions, can address with finer phase space definitions
- In agreement with SM predictions: $p_{SM}$ = 92%




ATLAS-CONF-2021-53

# HIGGS BOSON COUPLING STRENGTHS: BSM K FRAMEWORK

- Modifications of the Higgs boson BSM couplings are studied with coupling strength modifiers κ
  - For given decay mode *j*:

$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{SM}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{SM}}$$

$K_j = 1$ for SM

- No significant deviations from SM

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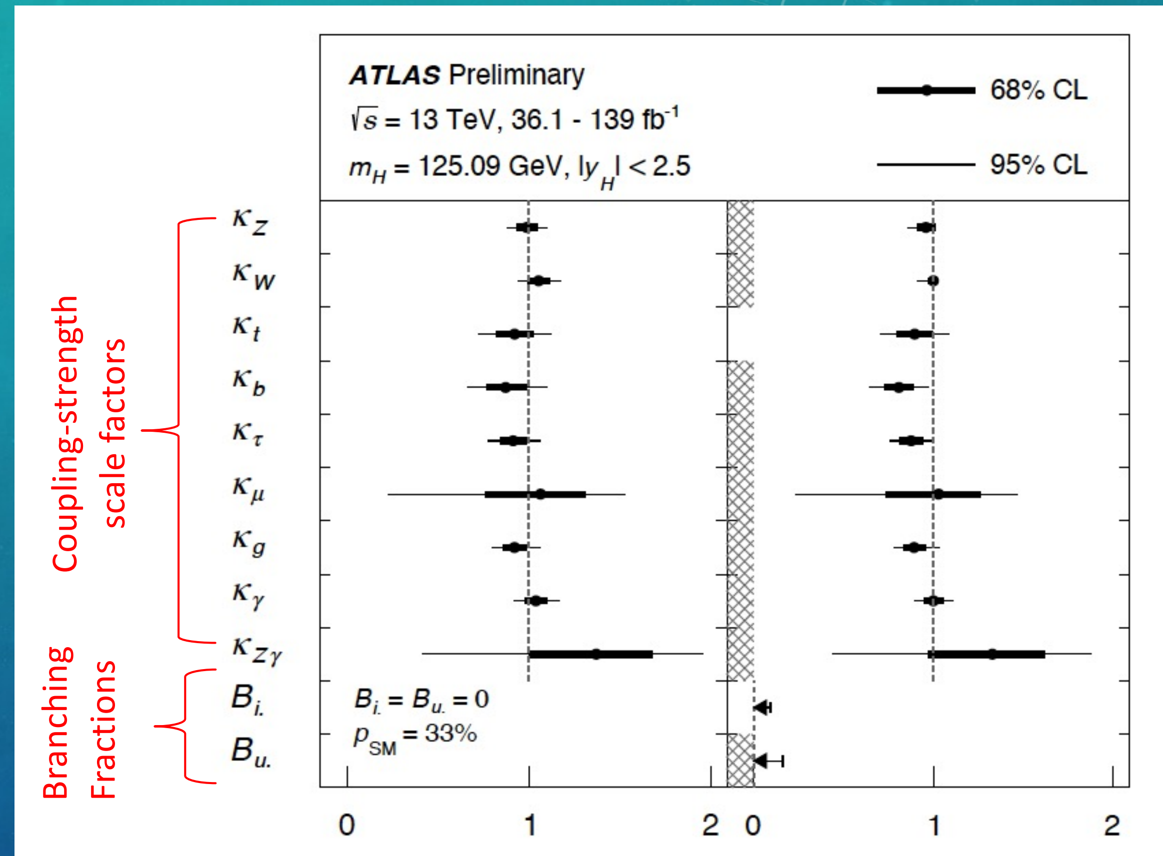



$B_i$ = BSM contribution of Higgs to invisible BR

$B_u$ = BSM contribution of Higgs to undetected processes BR

$B_i = B_u = 0$, Assumes no invisible or undetected Higgs

$B_i$ & $B_u$ free parameters, Possibility of invisible or undetected Higgs

S M E F T

(STANDARD MODEL EFFECTIVE FIELD THEORY)

# INTERPRETATIONS

- Model-independent approach to parametrize effects of candidate BSM theories that reduce to SM at low energies

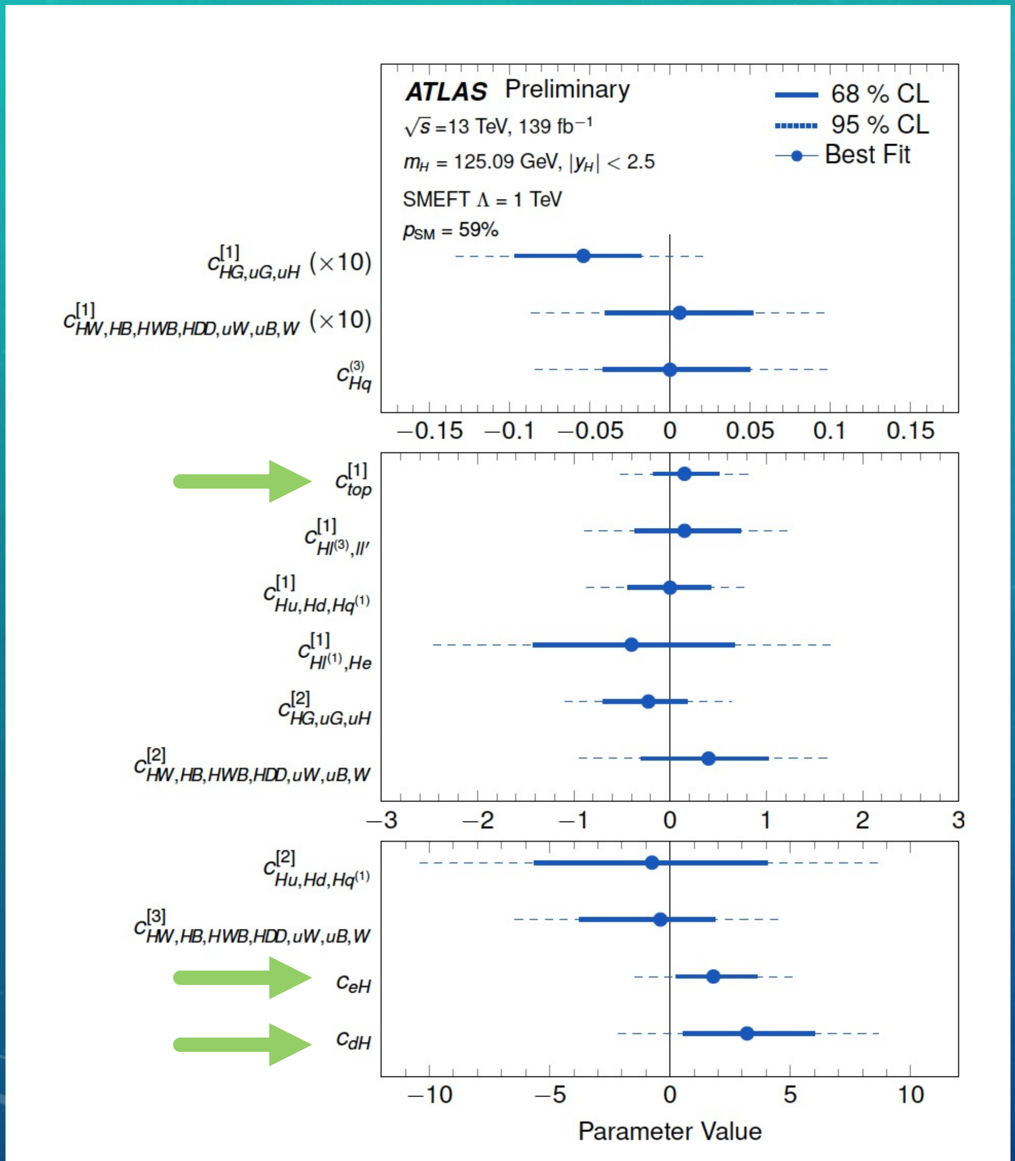
Wilson coefficients

$$\mathcal{L}_{\mathrm{SMEFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{i}^{N_{d6}} \frac{c_i}{\Lambda^2} O_i^{(6)} + \sum_{j}^{N_{d8}} \frac{b_i}{\Lambda^4} O_i^{(8)} + \ldots$$

Energy Scale Operators of mass dimension

- When Λ is large compared to Higgs vacuum expectation value, effects of BSM physics can be parameterized at low energies
  - Can constrain Wilson coefficients associated with each SMEFT operator using STXS measurements in various Higgs boson decay processes in order to constrain new physics at a given scale Λ

# SMEFT IN HIGGS COMBINATION

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Observed measurements of Wilson coefficients $c_i$'

- Fit basis is a linear combination of Warsaw-basis operators
- Consistent with SM expectation within uncertainties
- First time $c_{eH}$, $c_{dH}$, and coefficients affecting $t\bar{t}H$ ($c^{[1]}_{top}$) parameters have been measured independently of other fit parameters
- Improved sensitivity as a result of including H→WW*, H→ ττ, VBF, ttH, and VH at high $p_T$

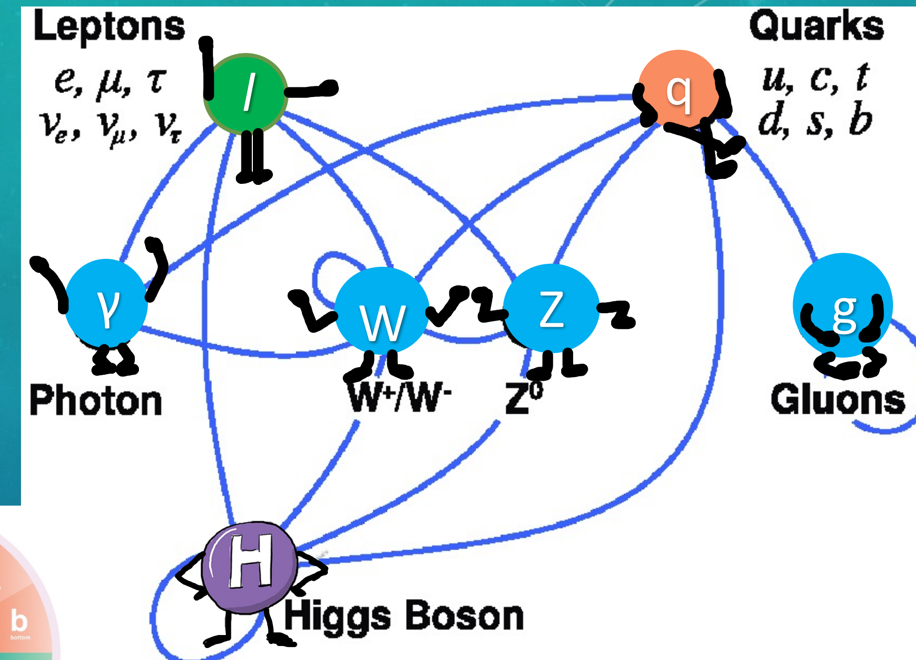
# SUMMARY AND FUTURE WORK

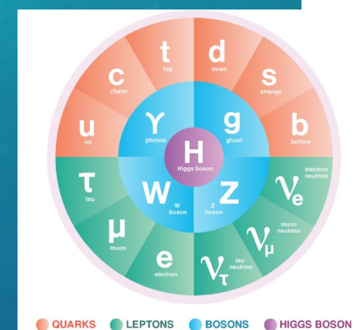
**Summary:**

- A lot learned about the Higgs production and decay mechanisms over the last 10 years; All main production modes observed
- STXS measurements have helped reduce model-dependence
- SMEFT parameters measured to search for BSM physics
- Results agree with SM predictions

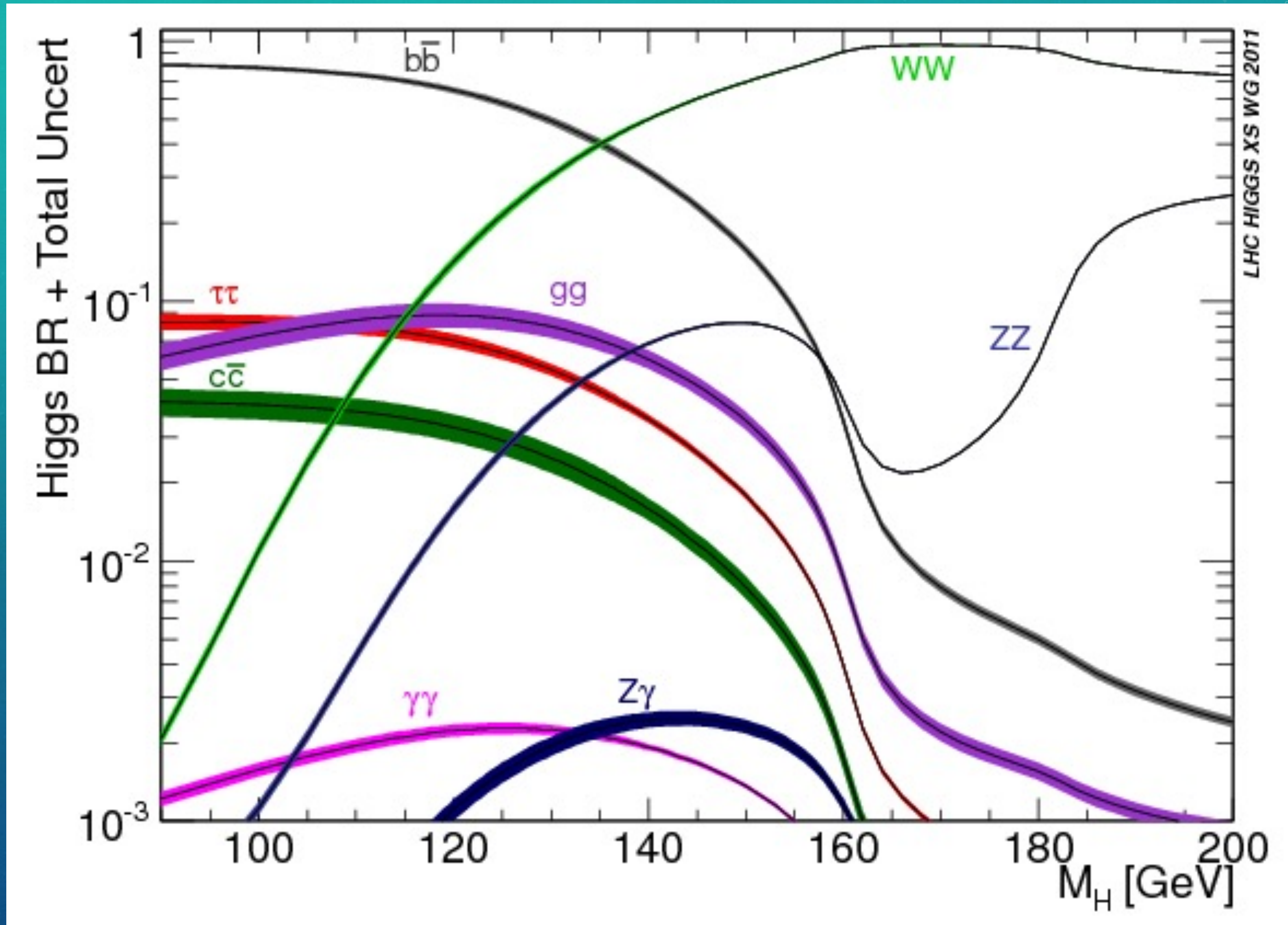
**Future work:**

- Room to improve measurements of channels not included in this Higgs combination in Legacy analyses and during Run 3
- Aiming to add finer STXS bins:
  - Help further reduce model-dependence
  - Benefit analyses that cannot use current STXS binning: i.e. VBF H+γ analysis

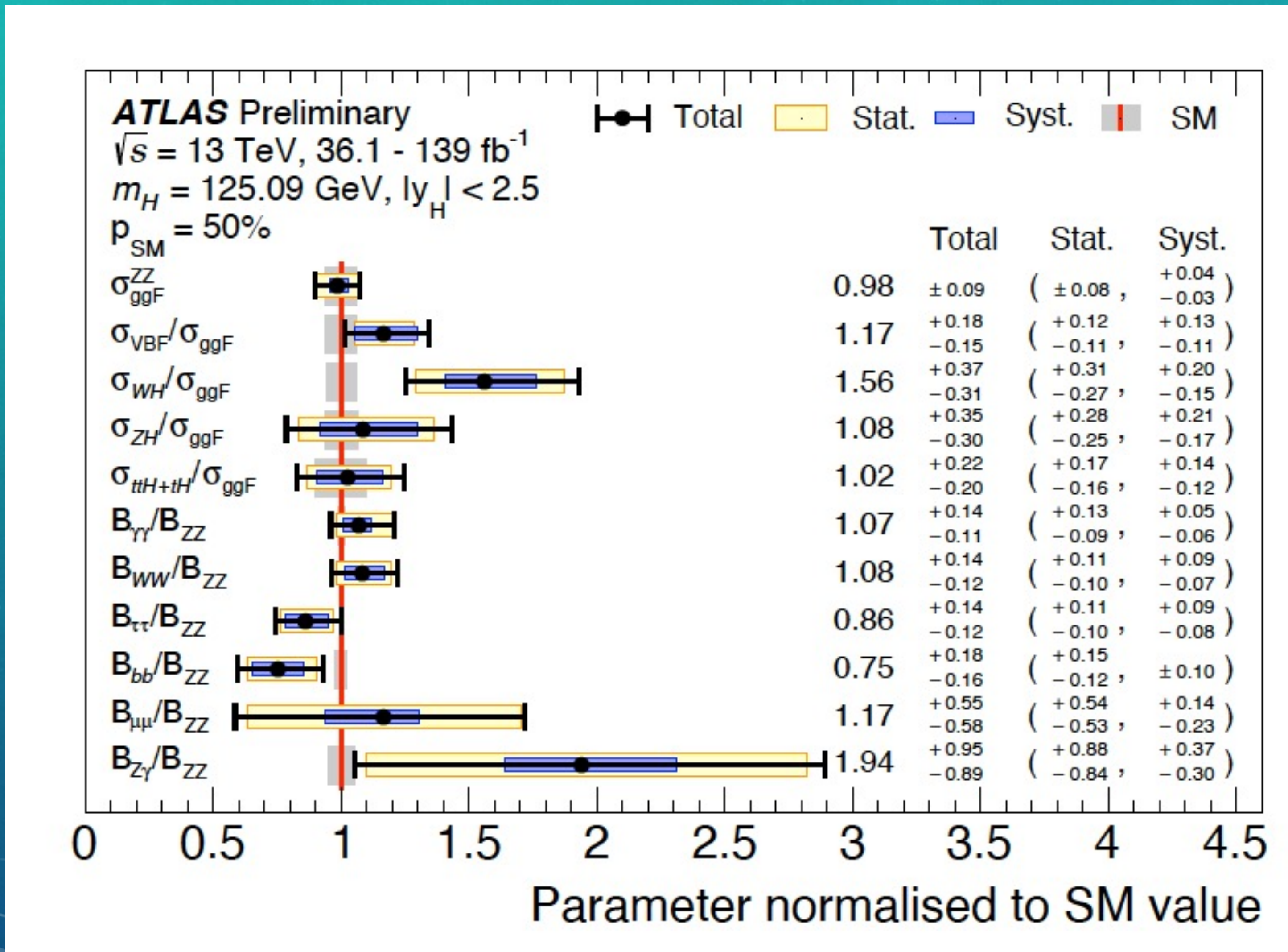



# BACKUP


Higgs BR + Total Uncert
1
10$^{-1}$
10$^{-2}$
10$^{-3}$
b$\bar{b}$
WW
ττ
gg
c$\bar{c}$
ZZ
γγ
Zγ
100
120
140
160
180
200
$M_H$ [GeV]
LHC HIGGS XS WG 2011

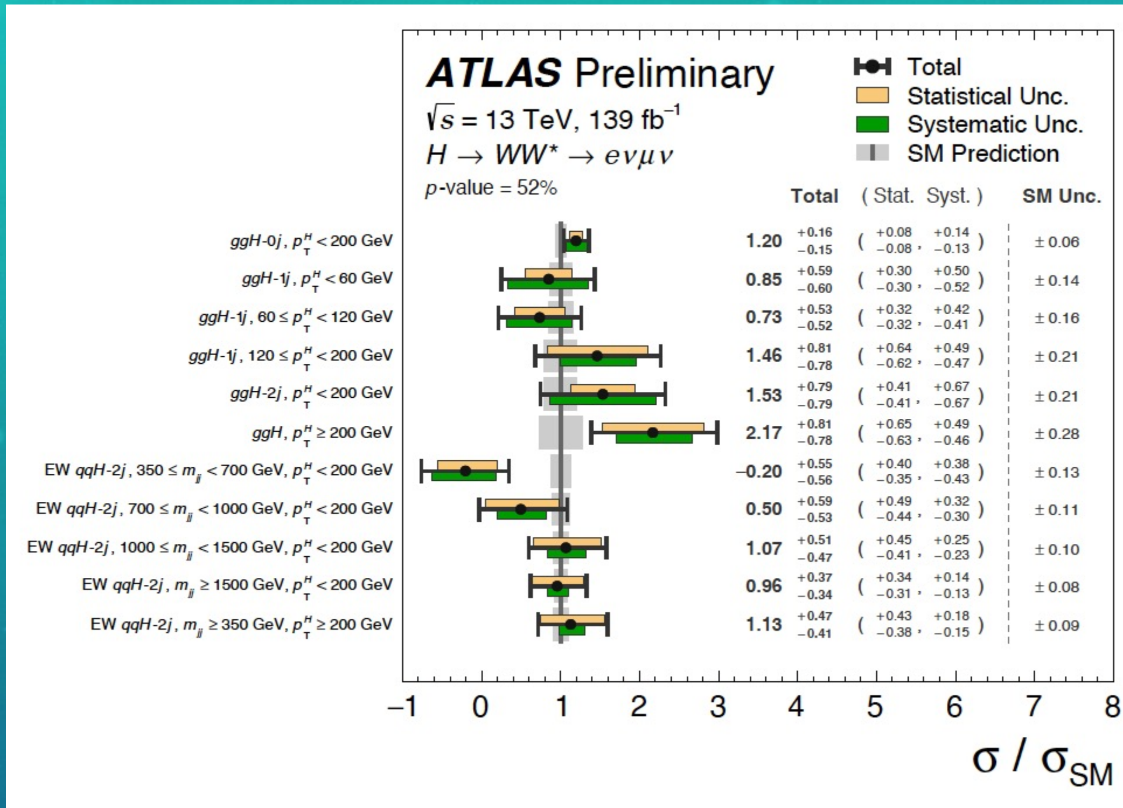
# RATIOS OF CROSS SECTIONS AND BRANCHING FRACTIONS




$$(\sigma \times B)_{if} = \sigma_{\mathrm{ggF}}^{ZZ} \cdot \left(\frac{\sigma_i}{\sigma_{\mathrm{ggF}}}\right) \cdot \left(\frac{B_f}{B_{ZZ}}\right)$$

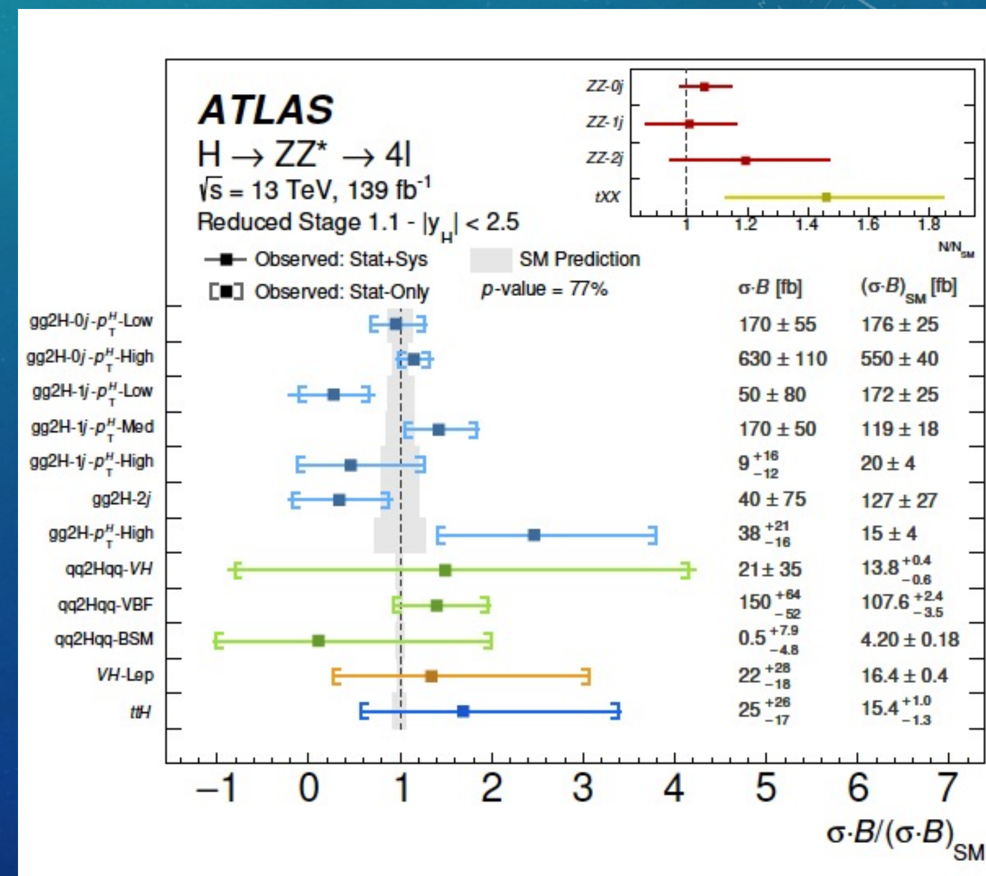
- Differences in overall results because cross section ratios and branching fraction ratios are closely related
- 11 degrees of freedom

# HIGGS DECAYING TO BOSONS



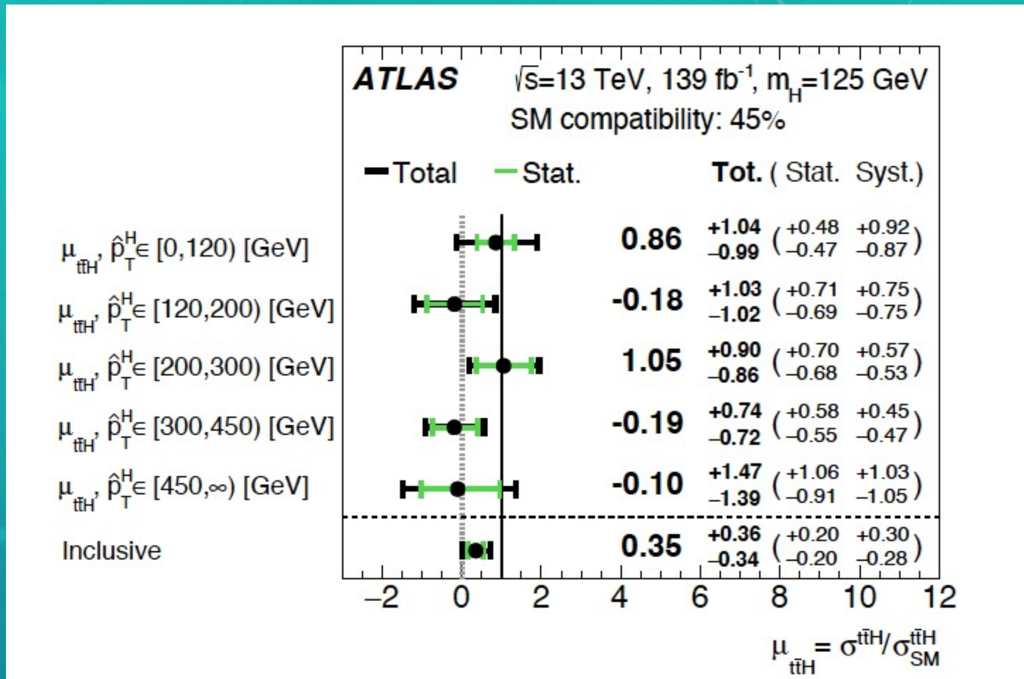

## H→ZZ*→4*l* : HIGG-2018-28

- Inclusive Higgs production + STXS measurement in 12 regions
- Smaller $\mathcal{B}$, but leptons allow clean final state measurement & high S/B
- **($\sigma$ x $\mathcal{B}$) = 1.34 ± 0.12 pb**



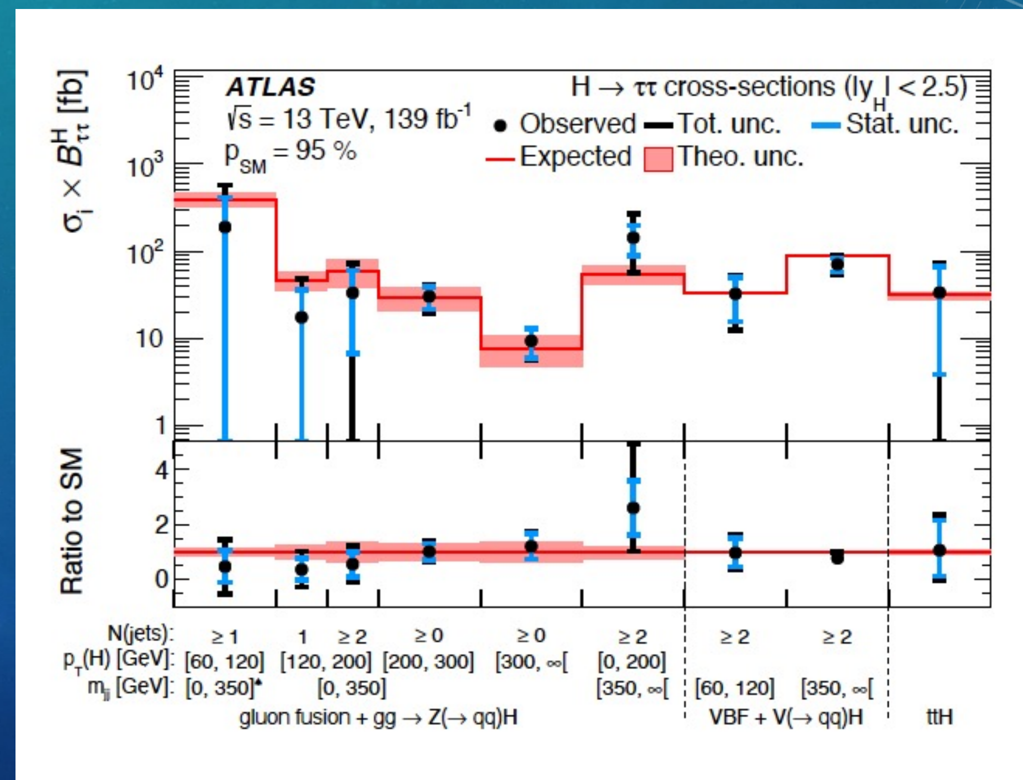

## H→WW*→*eνμν*: ATLAS-CONF-2021-014

- ggF & VBF coupling + STXS measurement in 11 regions
- Large $\mathcal{B}$ but resolution limited by neutrinos
- **$\sigma_{ggF}$ x $\mathcal{B}_{H\rightarrow WW^*}$ = 12.4 ± 1.5 pb**
- **$\sigma_{VBF}$ x $\mathcal{B}_{H\rightarrow WW^*}$ = $0.79^{+0.19}_{-0.16}$ pb**



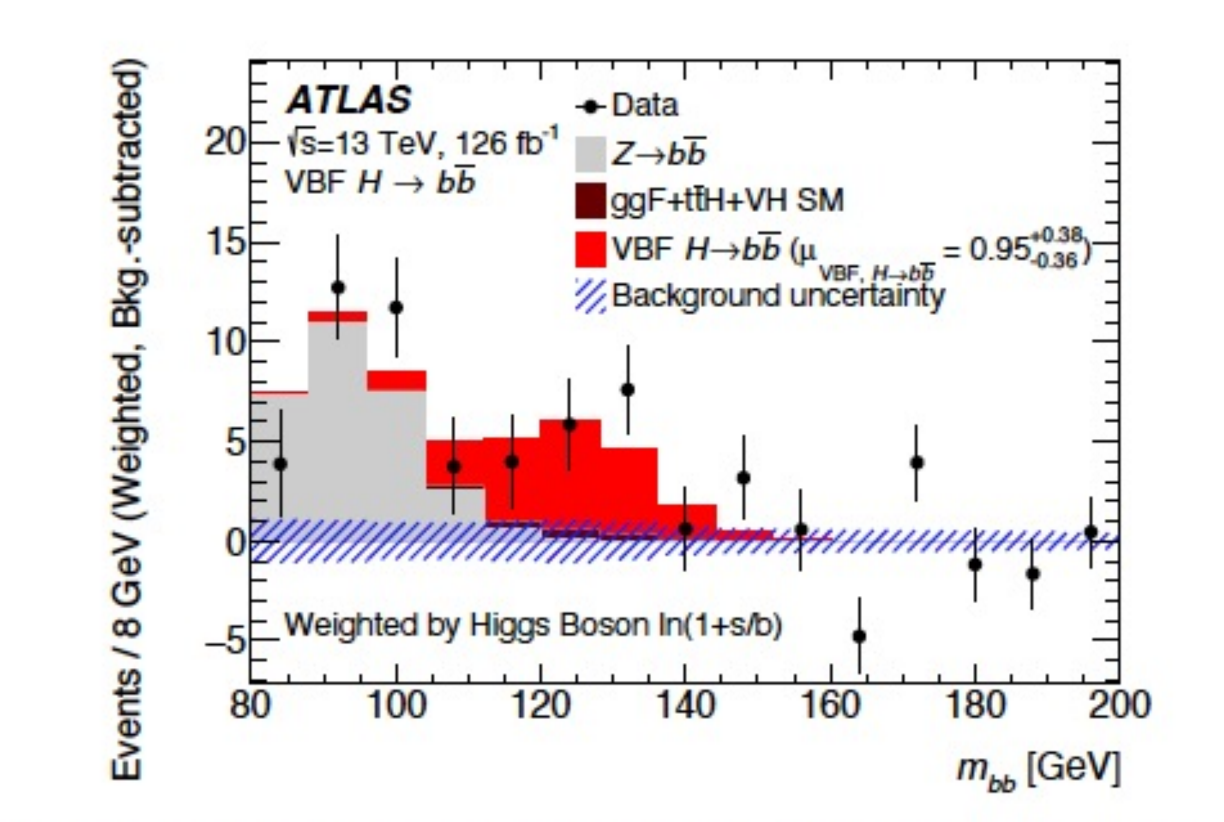

## H→ $\tau^+\tau^-$ : HIGG-2019-09

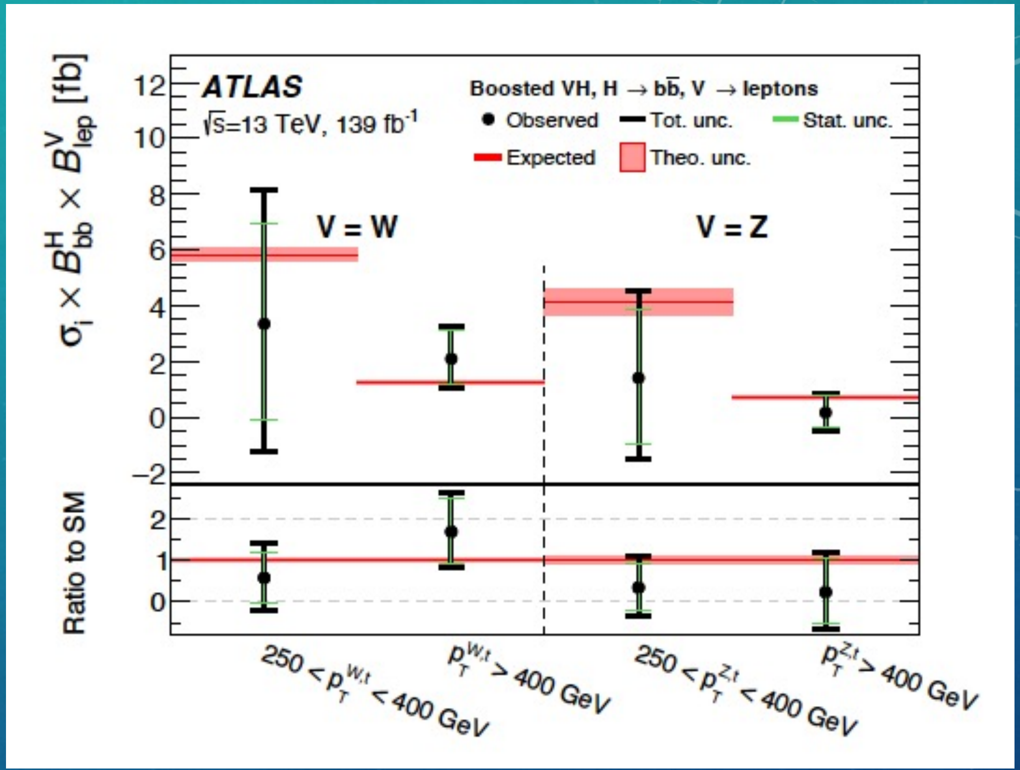
- Measures production modes ggF, VBF, V(had)H, & $t\bar{t}H$ + 9 STXS regions
- σ mostly from ggF contributions, as well as VBF which is the most precise—best combo of high signal yields and purity




## $t\bar{t}H(b\bar{b})$: HIGG-2020-23

- Measured in events with 1 or 2 electrons or muons + 5 STXS bins
- $t\bar{t}H$ is best chance to extract direct information on t-quark Yukawa coupling without potential BSM physics assumptions
- Large reduction in systematic uncertainties
- μ = $0.35^{+0.36}_{-0.34}$



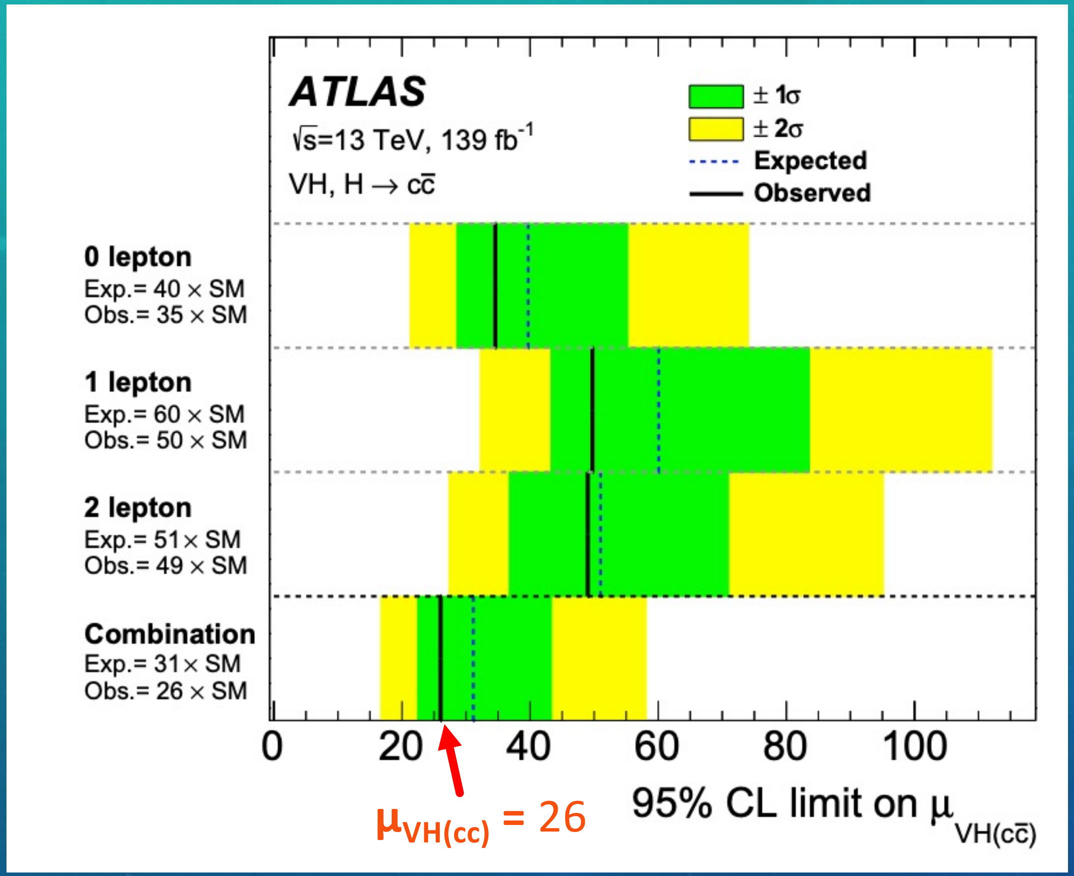

VBF: HIGG-2019-04

- Second most dominant production mode, but is most poorly measured major Higgs channel because of QCD background
- $\mu = 0.95^{+0.32}_{-0.32}(\text{stat})^{+0.20}_{-0.17}(\text{syst})$

**VH($b\bar{b}$):** HIGG-2018-52

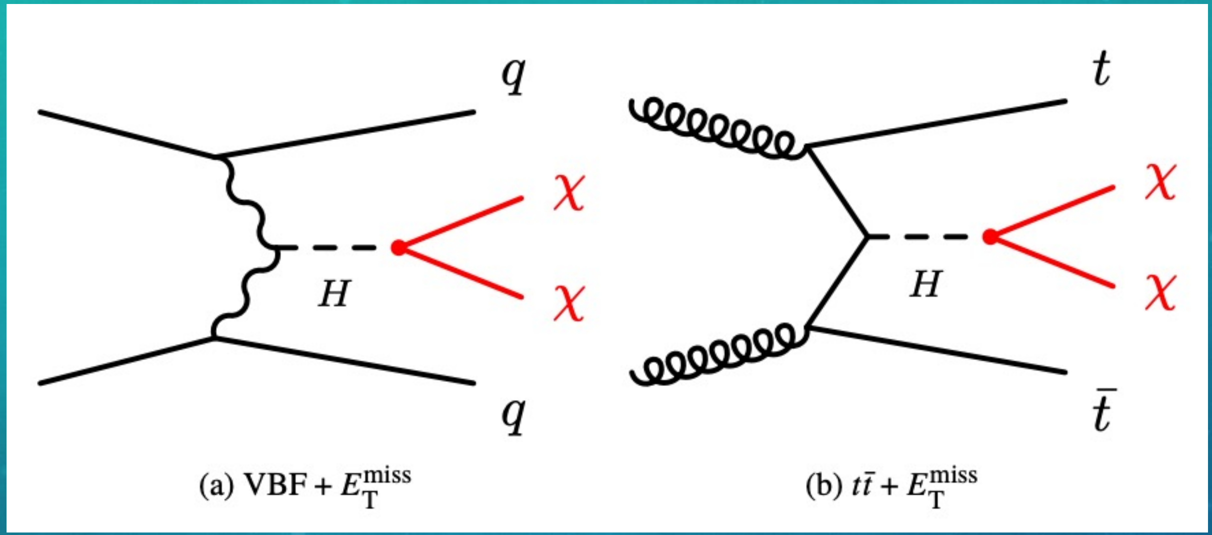
- $p_T^H > 250$ GeV, this range is sensitive to BSM physics
- Measured separately for ZH and WH, in 2 $p_T$ bins each
- $\mu = 0.72^{+0.39}_{-0.36}$

# VH(CC): HIGG-2021-12




- To enhance the signal sensitivity, events are categorised according to the $p$T of the reconstructed vector boson, the number of jets and the number of $c$-tagged jets. The $m_{cc}$ observable is used as the main discriminant in the likelihood fit to extract the signal.
- c-coupling weaker because |Kc/Kb| is less than the ratio of b to c quark masses

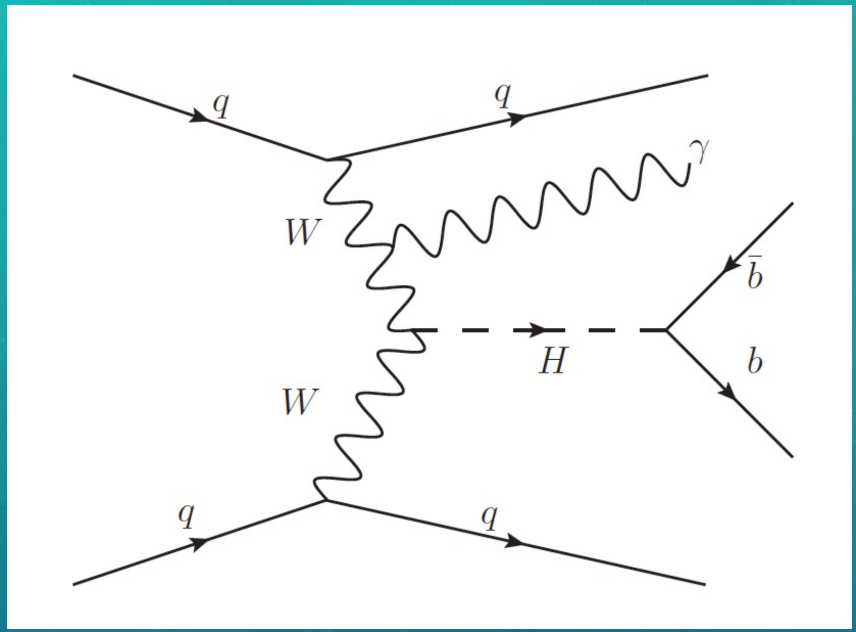
# HIGGS to Invisible: VBF and ttH + MET

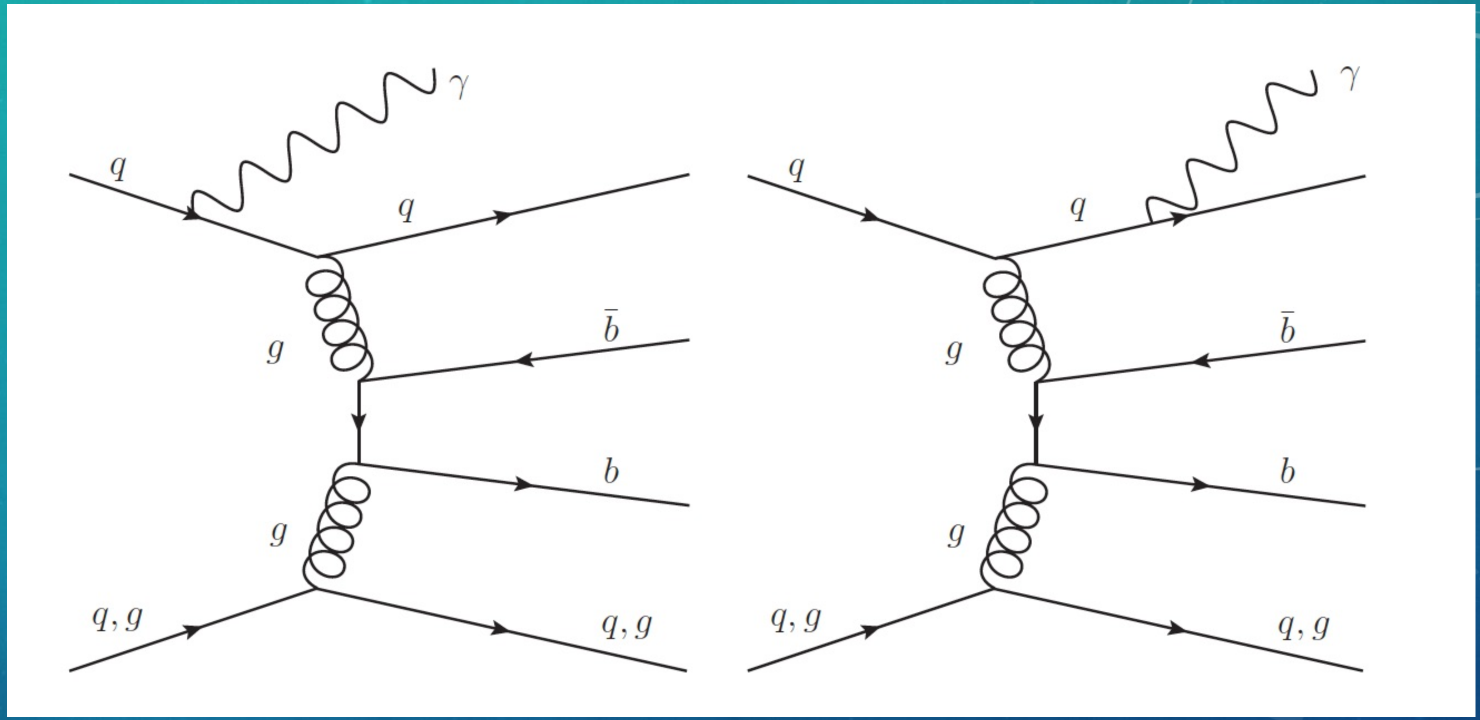



H→inv: ATLAS-CONF-2020-052 & EXOT-2020-11

- Observed and expected upper limits on B_H→inv at 95% CL from direct searches for invisible decays
- VBF $E_T^{miss}$ > 200 GeV to suppress multijet background, and $t\bar{t}H$ $E_T^{miss}$ > 250 GeV to optimize lepton trigger efficiency
- Main sensitivity from VBF+MET
- No overlap between VBF+MET & $t\bar{t}H$+MET as a result of b-tagging requirements

# VBF H + $\gamma$:



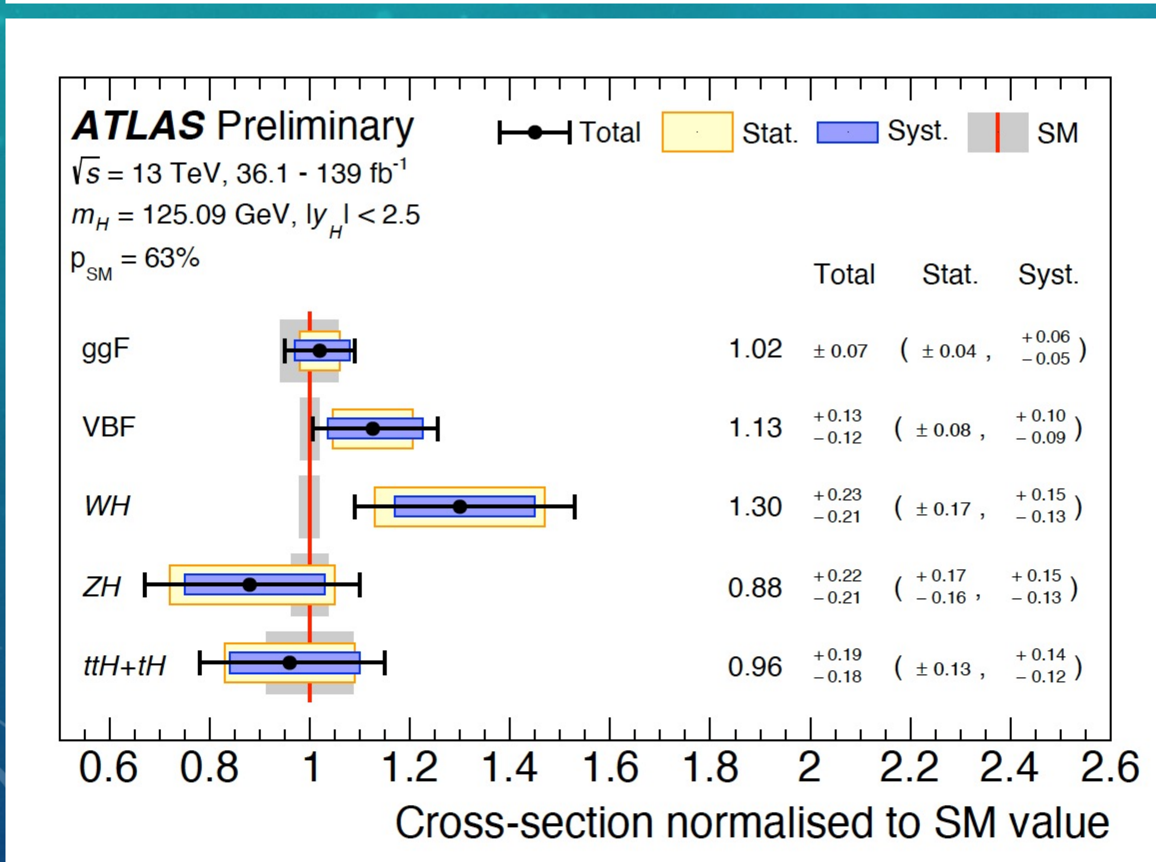



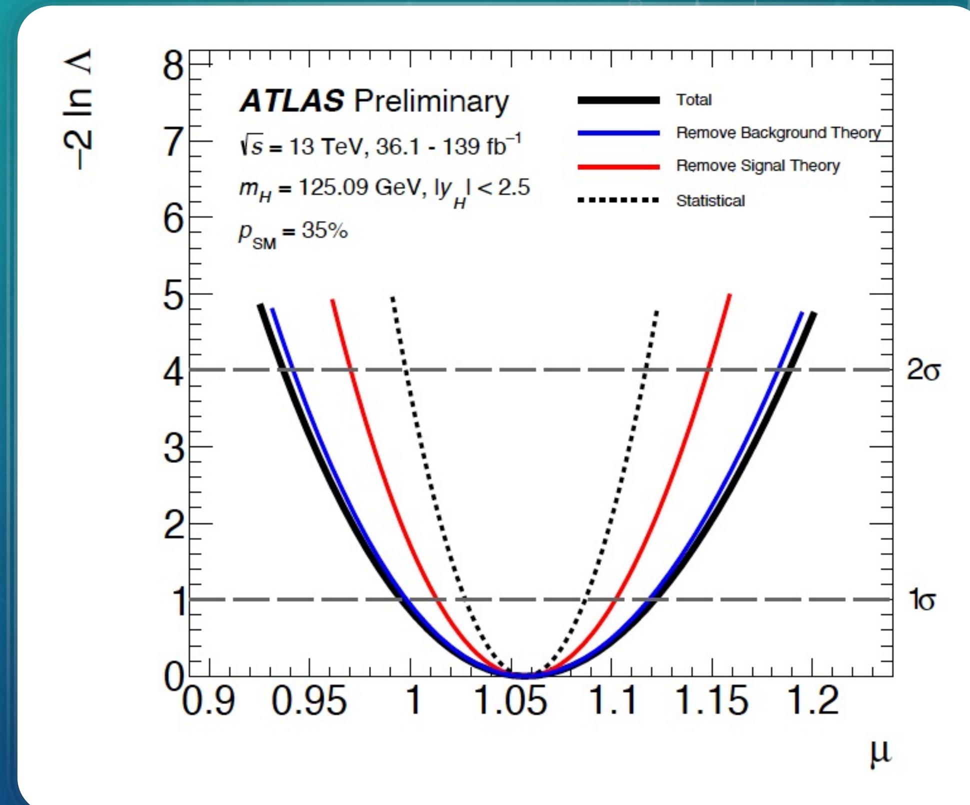

Background $b\bar{b}\gamma jj$

- Photon requirement reduces non-resonant QCD, the dominant background, through destructive interference (https://arxiv.org/pdf/1601.03635.pdf)

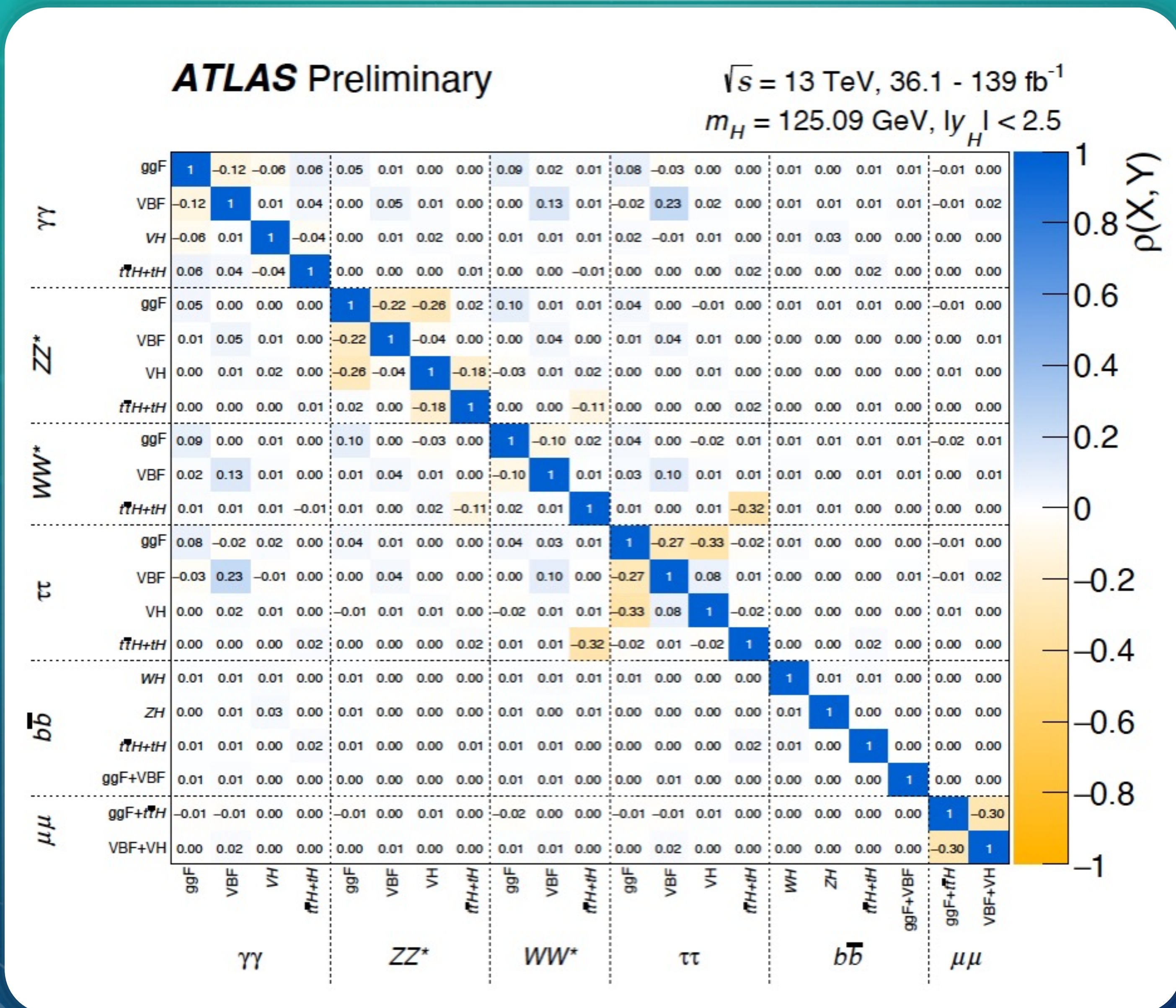
# HIGGS COMBINATION GLOBAL SIGNAL STRENGTH

| Process ($\|y_H\| < 2.5$) | Observed [pb] | Uncertainty [pb] Total | Stat. | Syst. | SM prediction [pb] |
|---|---|---|---|---|---|
| $\sigma_{ggF}$ | 45.7 | $^{+3.0}_{-3.2}$ | $^{+1.7}_{-1.8}$ | $^{+2.2}_{-2.7}$ | 44.8 ± 2.6 |
| $\sigma_{VBF}$ | 4.0 | ± 0.4 | ± 0.3 | $^{+0.3}_{-0.4}$ | 3.51 ± 0.07 |
| $\sigma_{WH}$ | 1.56 | $^{+0.26}_{-0.27}$ | $^{+0.20}_{-0.21}$ | $^{+0.16}_{-0.18}$ | 1.203 ± 0.024 |
| $\sigma_{ZH}$ | 0.70 | $^{+0.16}_{-0.18}$ | ± 0.13 | $^{+0.10}_{-0.12}$ | 0.795 ± 0.030 |
| $\sigma_{ttH+tH}$ | 0.56 | $^{+0.10}_{-0.11}$ | ± 0.08 | $^{+0.07}_{-0.08}$ | 0.58 ± 0.05 |




- $\mu = 1.06 \pm 0.06$




- Largest correlations due to cross contamination between processes in analyses

# STXS

STXS binning criteria:

- Sensitive to deviations from SM expectation
- Reduce theory uncertainties in corresponding SM predictions
- Minimize model-dependent extrapolations

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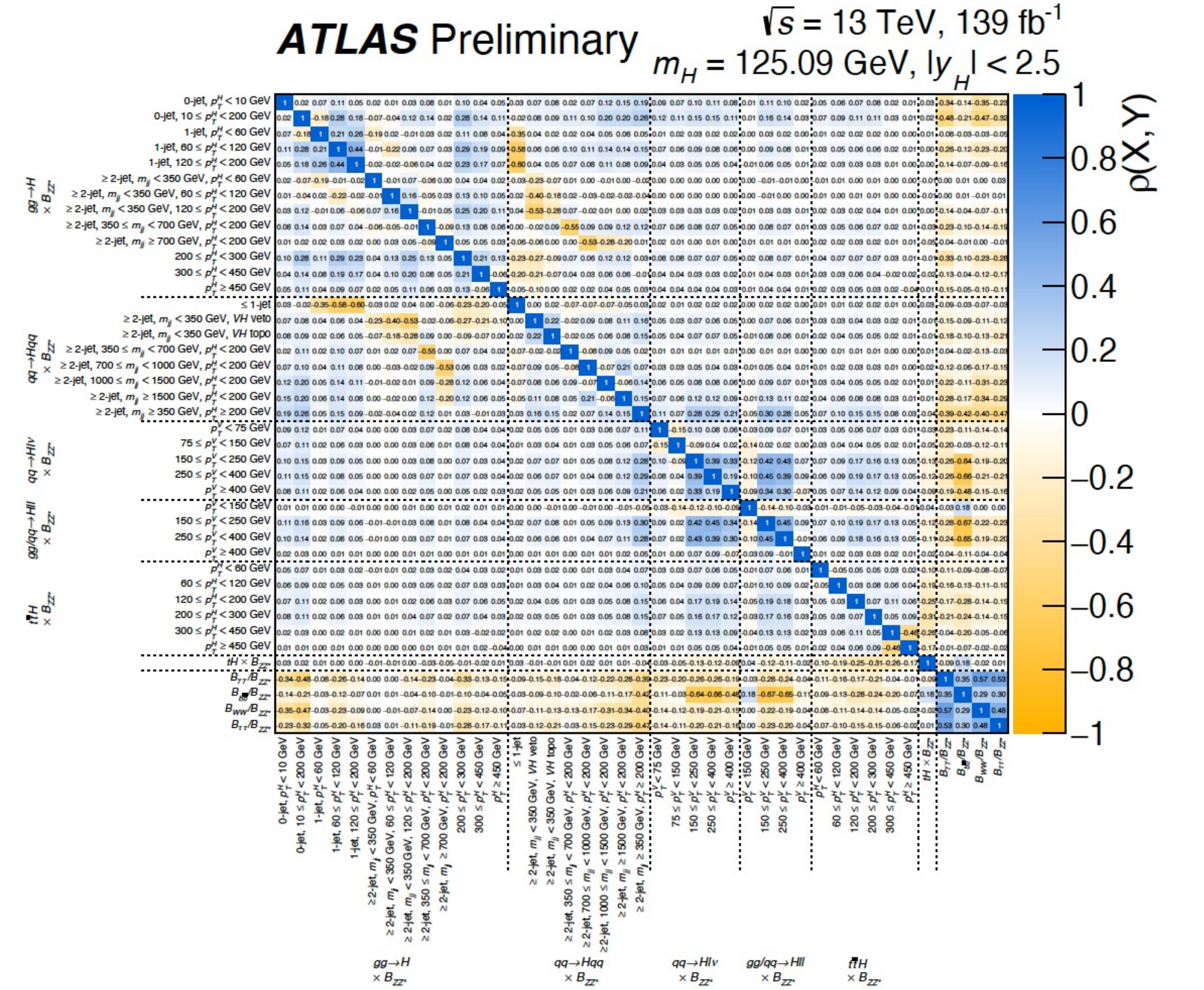


Figure 9: Correlation matrix for the measured values of the simplified template cross sections and ratios of branching fractions. The fit parameters are the products $(\sigma_i \times B_{ZZ})$ and the ratios $B_f / B_{ZZ}$. The linear correlation coefficient $\rho(X,Y)$ between pairs of observables is indicated in color and given numerically.

# K FRAMEWORK

$$\sigma_i \times B_f = \frac{\sigma_i(\kappa) \times \Gamma_f(\kappa)}{\Gamma_H}$$

$\Gamma_H$ is total width of Higgs boson, $\Gamma_f$ is the partial width for Higgs boson decay into final state *f*

- $B_i$ = Contribution to branching ratio for a SM produced Higgs decaying to invisible BSM, mostly from H→ZZ*→4 neutrinos (predicted to be 0.1% in SM)
- $B_u$ = BSM Contribution to undetected branching fraction, such as decays to light quarks or undetected BSM particles without sizable MET in final state, or other decays to which none of analyses in combination are sensitive (i.e. decays to gluon pairs)

# SMEFT

- Simulated with MadGraph, calculations performed at LO accuracy in QCD with SMEFTsim or SMEFTatNLO
- **dim-6**: operators have an energy dimension of up to E^6
- **Warsaw basis:** a complete basis of gauge invariant operators up to dim-6

Linear combination:

- As degrees of freedom left unconstrained by the data do not necessarily correspond to individual coefficients $c_i$, but may also be linear combinations $\Sigma_i a_i c_i$, a modified basis of Wilson coefficients is estimated. First, the eigenvalue decomposition procedure is performed based on the SM expected covariance matrix

| Wilson coefficient | Operator | Wilson coefficient | Operator |
|---|---|---|---|
| $c_{H\Box}$ | $(H^\dagger H)\Box(H^\dagger H)$ | $c_{uG}$ | $(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\tilde{H}\,G^A_{\mu\nu}$ |
| $c_{HDD}$ | $(H^\dagger D^\mu H)^*(H^\dagger D_\mu H)$ | $c_{uW}$ | $(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\tilde{H}\,W^I_{\mu\nu}$ |
| $c_{HG}$ | $H^\dagger H\,G^A_{\mu\nu}G^{A\mu\nu}$ | $c_{uB}$ | $(\bar{q}_p\sigma^{\mu\nu}u_r)\tilde{H}\,B_{\mu\nu}$ |
| $c_{HB}$ | $H^\dagger H\,B_{\mu\nu}B^{\mu\nu}$ | $c'_{ll}$ | $(\bar{l}_p\gamma_\mu l_t)(\bar{l}_r\gamma^\mu l_s)$ |
| $c_{HW}$ | $H^\dagger H\,W^I_{\mu\nu}W^{I\mu\nu}$ | $c^{(1)}_{qq}$ | $(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$ |
| $c_{HWB}$ | $H^\dagger\tau^I H\,W^I_{\mu\nu}B^{\mu\nu}$ | $c^{(3)}_{qq}$ | $(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$ |
| $c_{eH}$ | $(H^\dagger H)(\bar{l}_p e_r H)$ | $c_{qq}$ | $(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$ |
| $c_{uH}$ | $(H^\dagger H)(\bar{q}_p u_r\tilde{H})$ | $c^{(31)}_{qq}$ | $(\bar{q}_p\gamma_\mu\tau^I q_t)(\bar{q}_r\gamma^\mu\tau^I q_s)$ |
| $c_{dH}$ | $(H^\dagger H)(\bar{q}_p d_r\tilde{H})$ | $c_{uu}$ | $(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$ |
| $c^{(1)}_{Hl}$ | $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$ | $c^{(1)}_{uu}$ | $(\bar{u}_p\gamma_\mu u_t)(\bar{u}_r\gamma^\mu u_s)$ |
| $c^{(3)}_{Hl}$ | $(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$ | $c^{(1)}_{qu}$ | $(\bar{q}_p\gamma_\mu q_t)(\bar{u}_r\gamma^\mu u_s)$ |
| $c_{He}$ | $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$ | $c^{(8)}_{ud}$ | $(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$ |
| $c^{(1)}_{Hq}$ | $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$ | $c^{(8)}_{qu}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$ |
| $c^{(3)}_{Hq}$ | $(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$ | $c^{(8)}_{qd}$ | $(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$ |
| $c_{Hu}$ | $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$ | $c_W$ | $\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$ |
| $c_{Hd}$ | $(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$ | $c_G$ | $f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$ |

Wilson coefficients $c_i$ and corresponding dim-6 SMEFT operators $O_i^{(6)}$ used in this analysis

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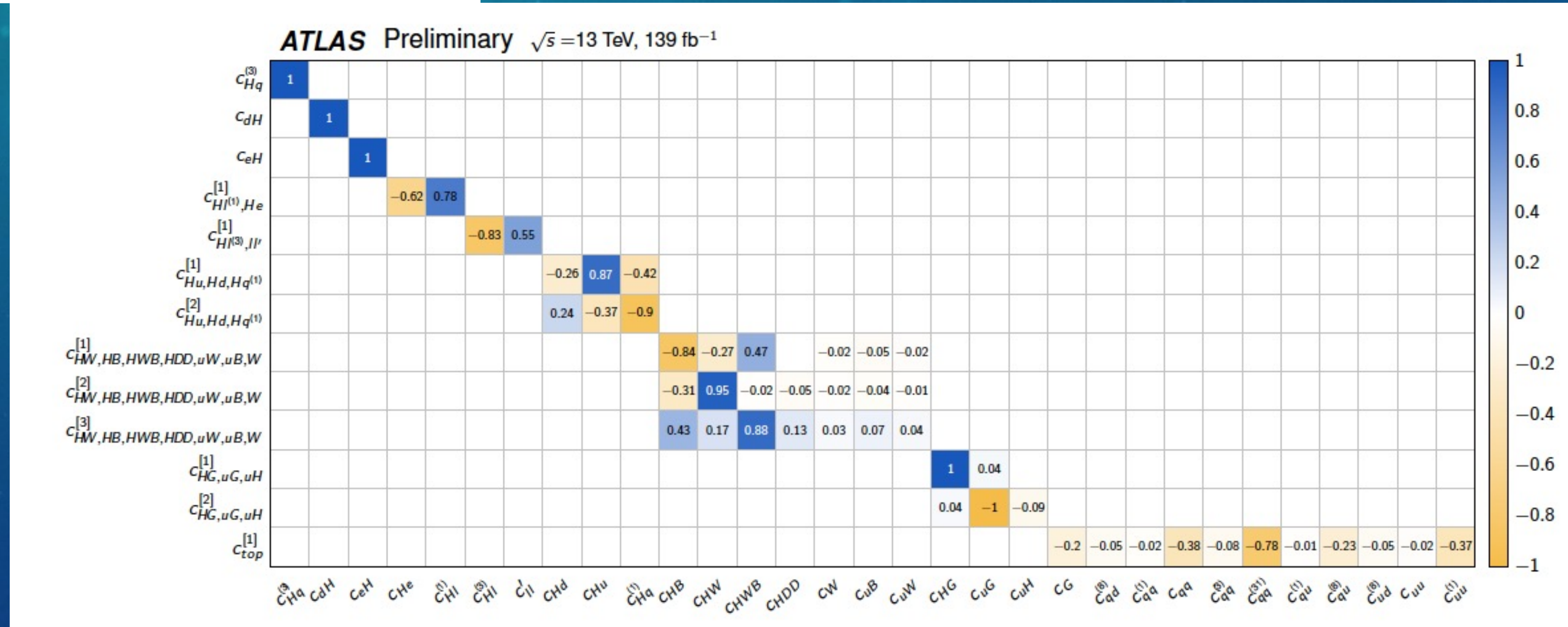
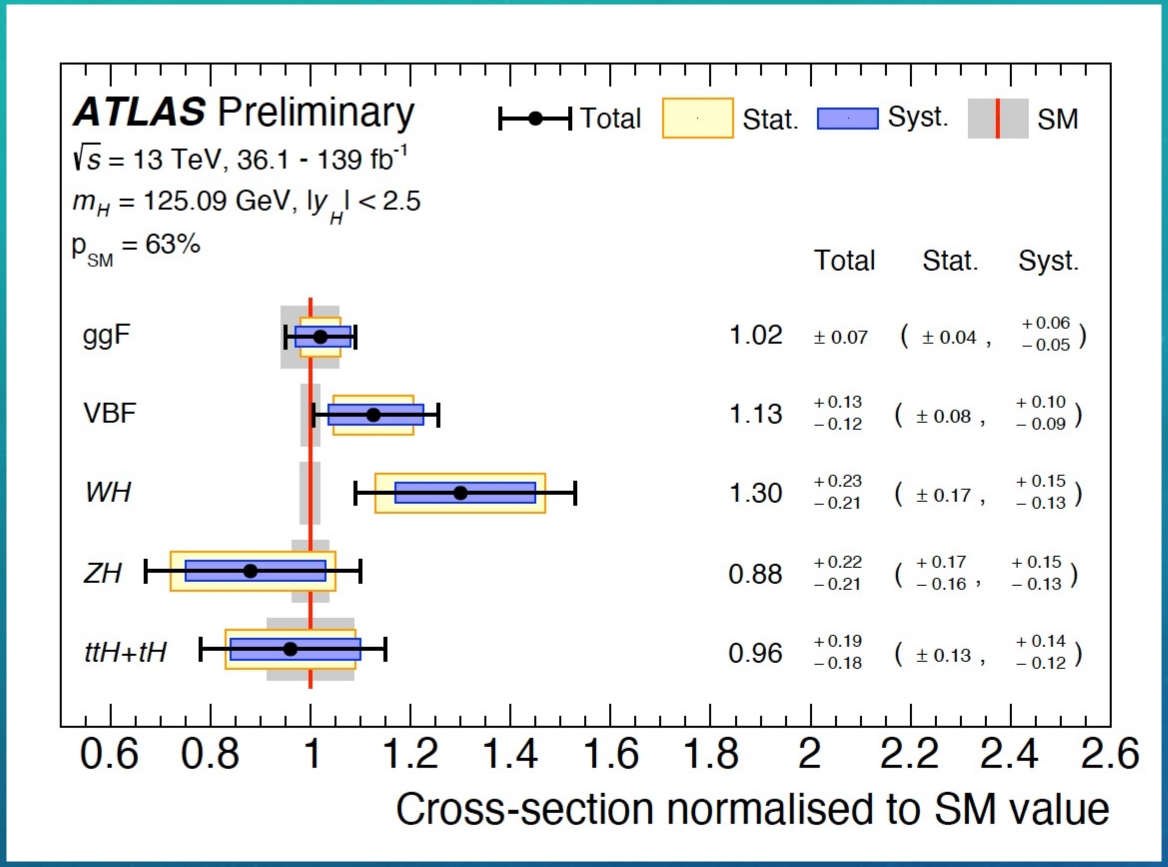
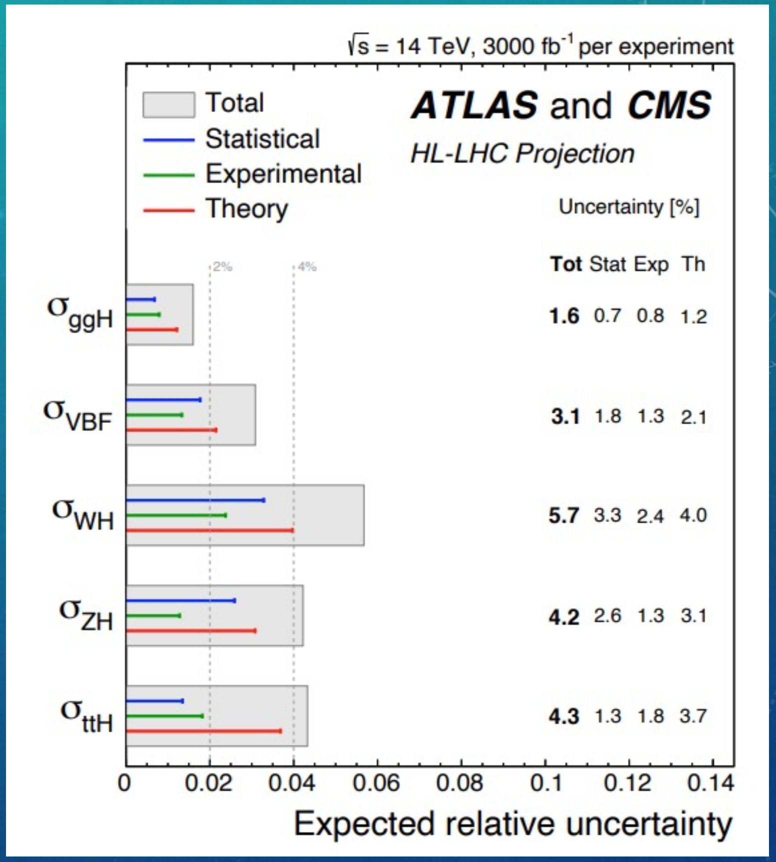
Projection matrix from Warsaw basis (x-axis) to fit basis (y-axis)



# RUN 3 PROJECTIONS

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Greatly reduced uncertainty projected compared to Run 2 uncertainties