THE UNIVERSITY of EDINBURGH
School of Physics
and Astronomy

ATLAS EXPERIMENT

Higgs highlights at ATLAS

Liza Mijović on behalf of the ATLAS Collaboration

MoriondQCD 2022, 20 March

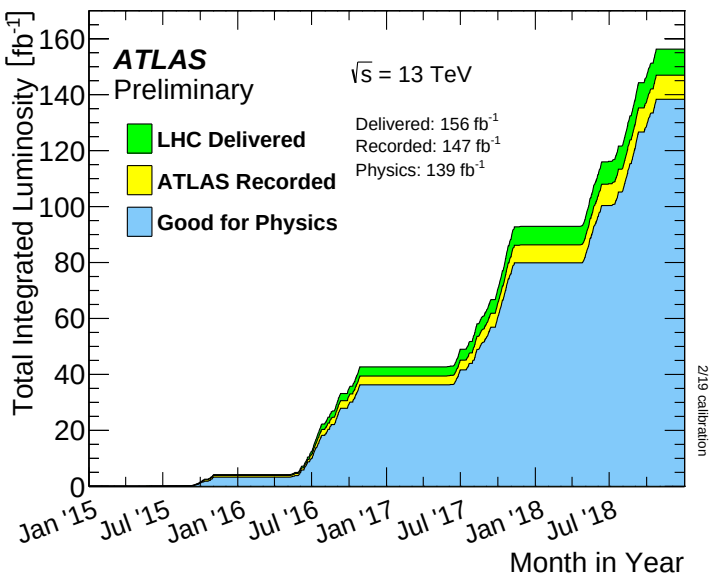
ATLAS Higgs highlights

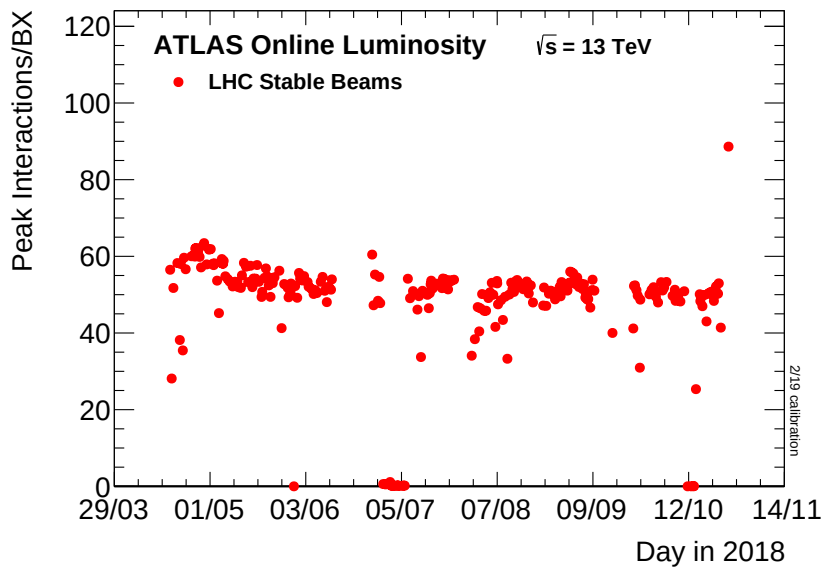
- **Combined total and differential cross-sections in $H\to\gamma\gamma$ and $H\to ZZ^*\to 4\ell$:** ATLAS-CONF-2022-002.
- **Higgs coupling & production cross-section combination**, ATLAS-CONF-2021-053.
- **Direct constraint on Higgs-charm coupling from VH,H$\to c\bar{c}$ production**, arXiv:2201.11428.
- **HH production:** combination ATLAS-CONF-2021-052 and HL-LHC projection, ATL-PHYS-PUB-2022-005.
- **New results for Moriond 2022:**
  - HH searches: HEFT interpretation ← Guillermo's talk
  - CP of top Yukawa interaction in $t\bar{t}H$ and tH, $H\to b\bar{b}$, ATLAS-CONF-2022-016.
  - Fiducial cross-section of VH, $H\to b\bar{b}$ + 0 leptons, ATLAS-CONF-2022-015.

More on cross-section & properties in Adinda's talk,
more on exotic Higgs decays in Guillermo's talk.

ATLAS: data-taking

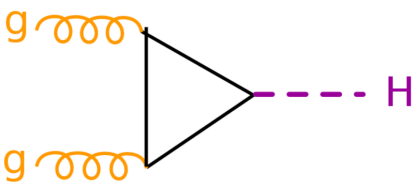
- Preparing for Run3: 2022-2025.
- Results today: **Run2** pp collision data-set, $\sqrt{s} = 13\ \mathrm{TeV}$.
- About x2 LHC design instantaneous luminosity & pile-up.
- Data-taking efficiency: 94%, data quality fraction: 95%
  $\Rightarrow$ **139 fb^{-1} of data**.



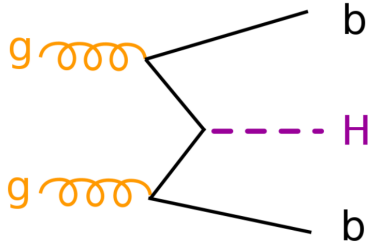


Higgs Production and Decay

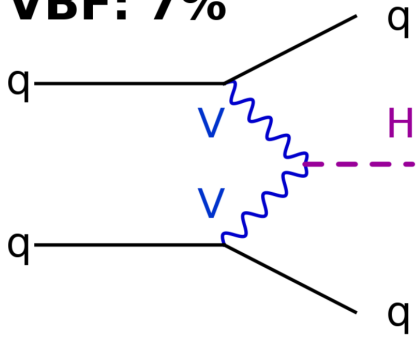
ggF: 87%



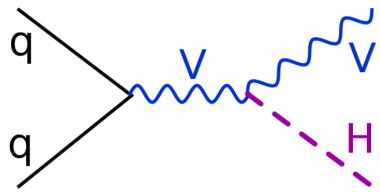
bbH: 1%



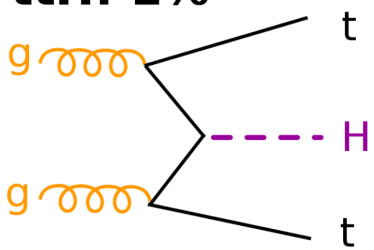
VBF: 7%



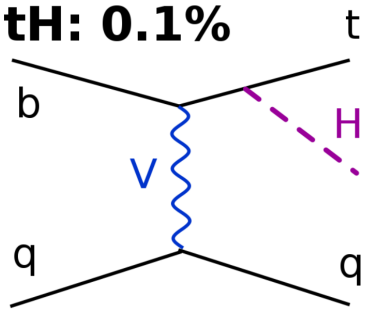
VH: 4%

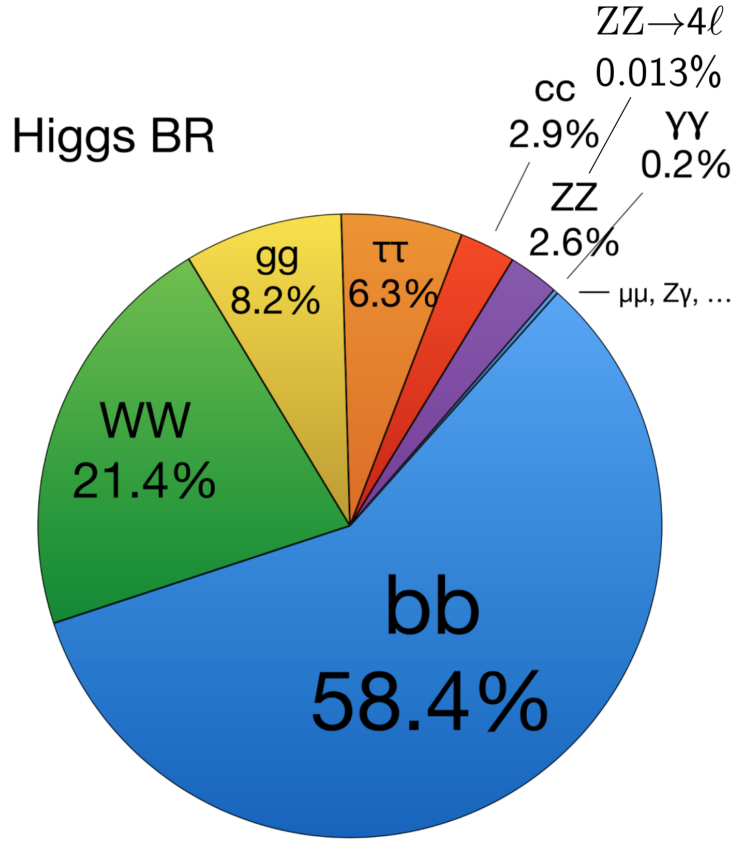


ttH: 1%



tH: 0.1%

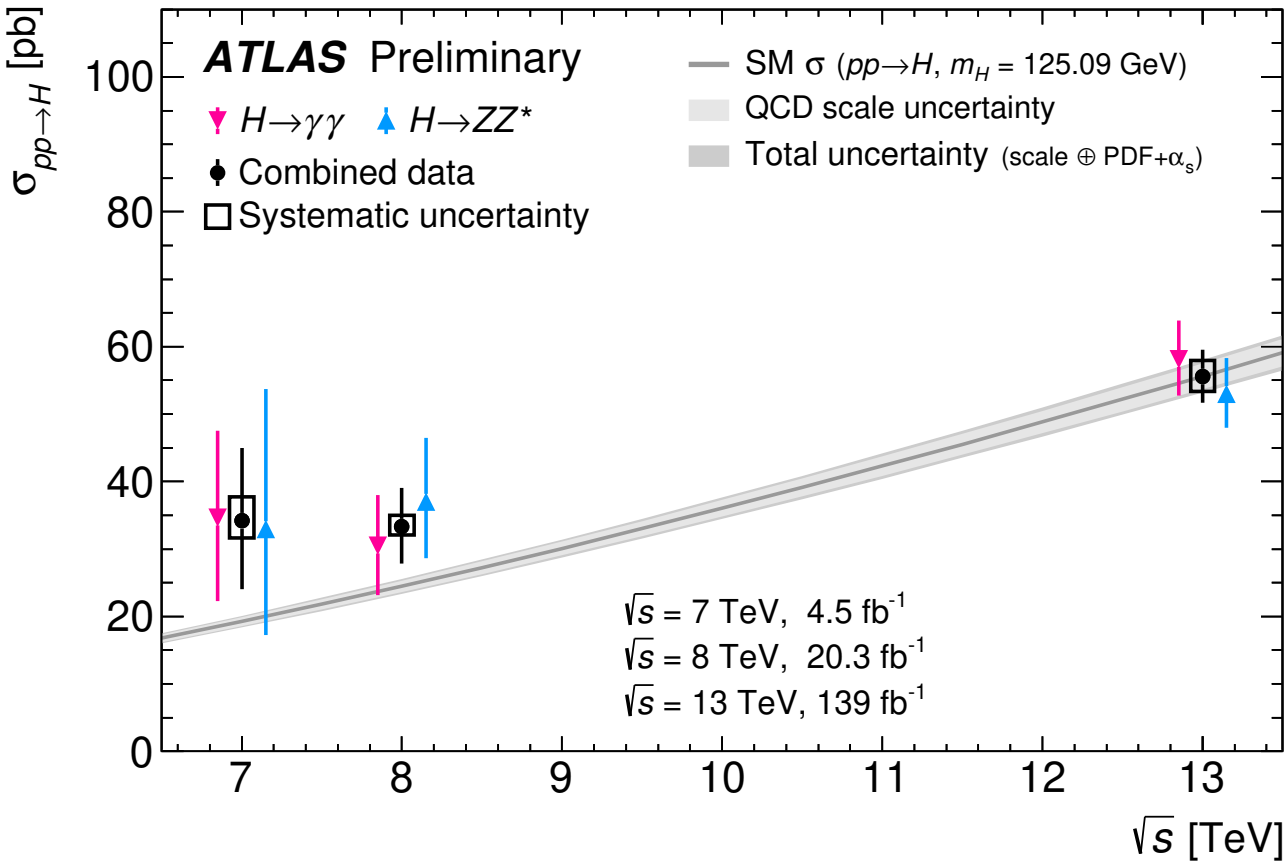




Combined $H\to\gamma\gamma$ & $H\to ZZ^*\to 4\ell$ x-sections

$$\text{Comb.}: \sigma(pp\to H, \sqrt{s} = 13\ \text{TeV}) = 55.5^{+4.0}_{-3.8}\ \text{pb}\,(\pm 3.2(\text{stat.})\ ^{+2.4}_{-2.2}(\text{sys.}))$$

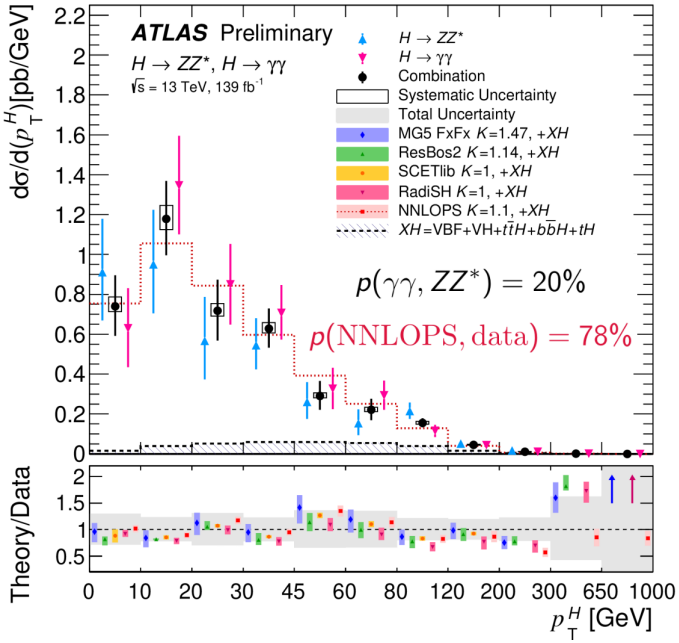
$$\text{SM}: \sigma(pp\to H, \sqrt{s} = 13\ \text{TeV}) = 55.6\ \pm\ 2.5\ \text{pb}$$

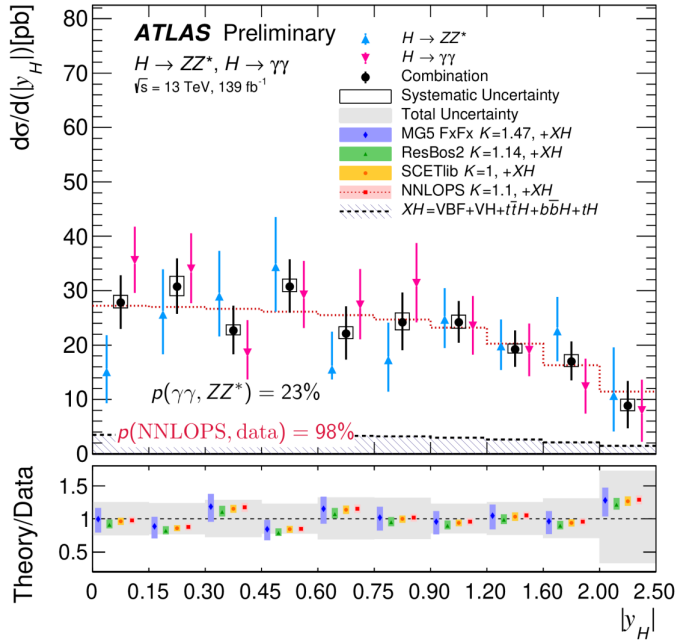


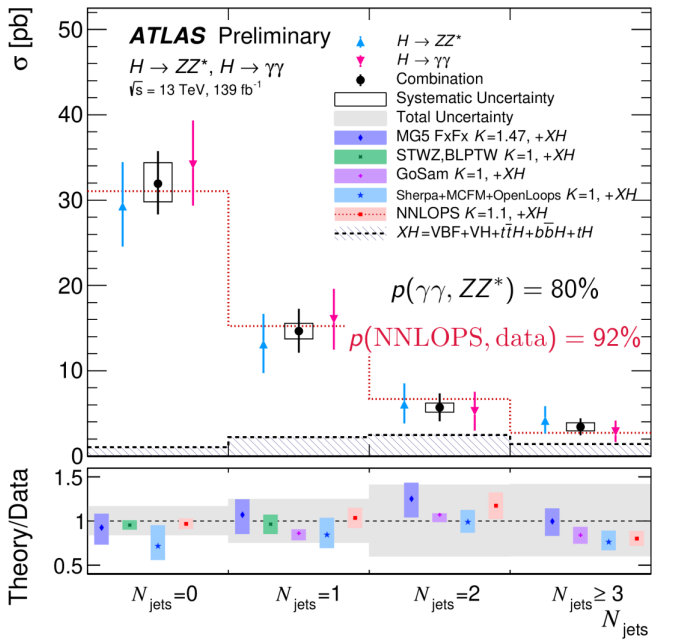
$$\text{H}\to\gamma\gamma:\ \sigma = 58.1^{+5.7}_{-5.4}\ \text{pb}\,(\pm 4.2(\text{stat.})\ ^{+3.9}_{-3.5}(\text{sys.}))$$

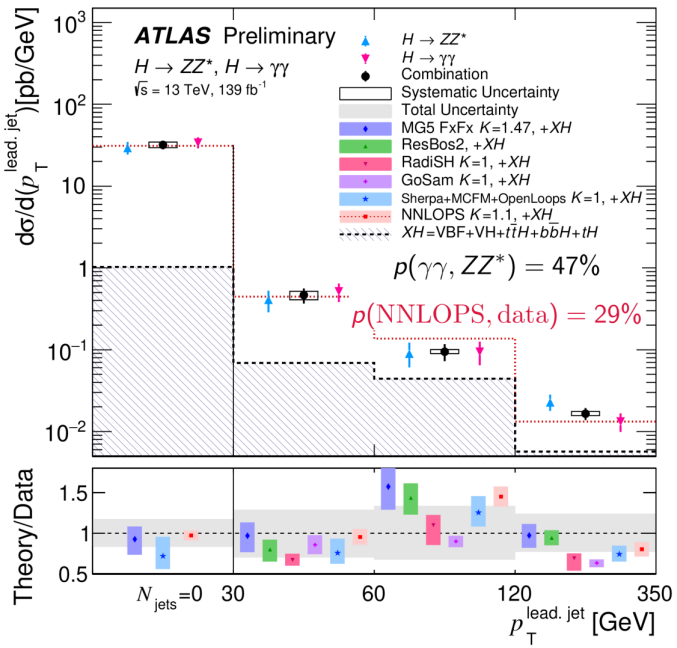
$$H\to ZZ^*\to 4\ell:\ \sigma = 53.0^{+5.3}_{-5.1}\ \text{pb}\,(^{+4.9}_{-4.8}(\text{stat.})\ ^{+2.0}_{-1.7}(\text{sys.}))$$

Combined $H\to\gamma\gamma$ & $H\to ZZ^*\to 4\ell$ x-sections









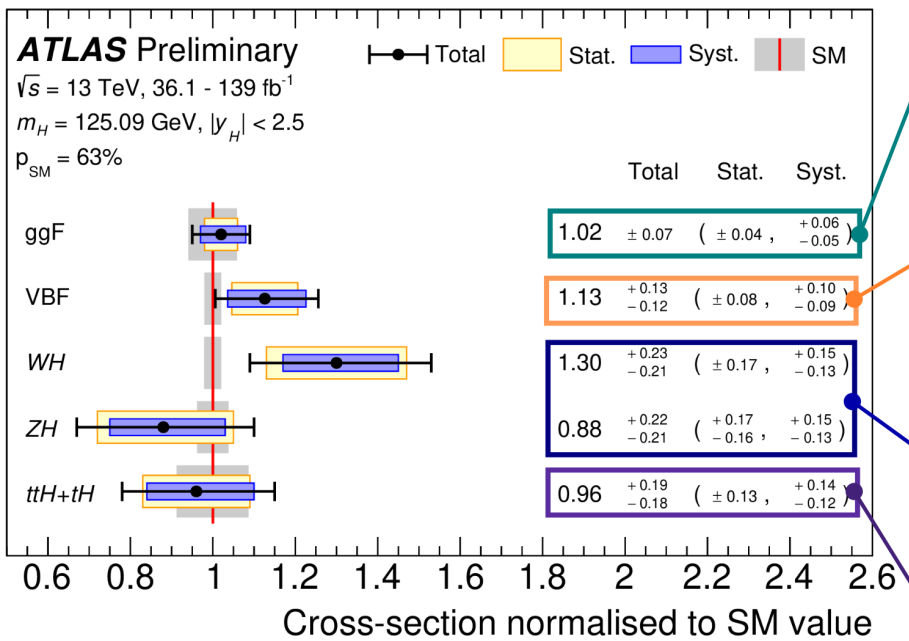
Higgs couplings combination

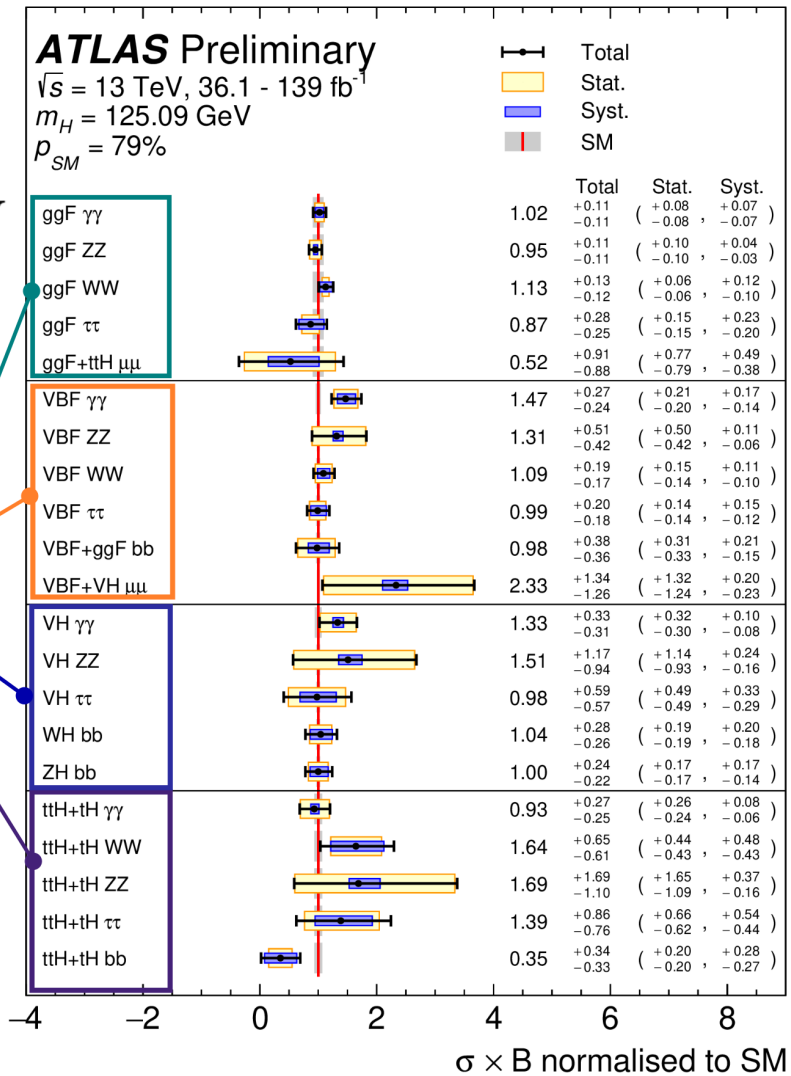
Combination of cross-section measurements in prod./decay modes.

Total signal strength:

$\mu = 1.06 \pm 0.06$;

0.03 stat. $\oplus$ 0.03 exp. $\oplus$ 0.04 theory



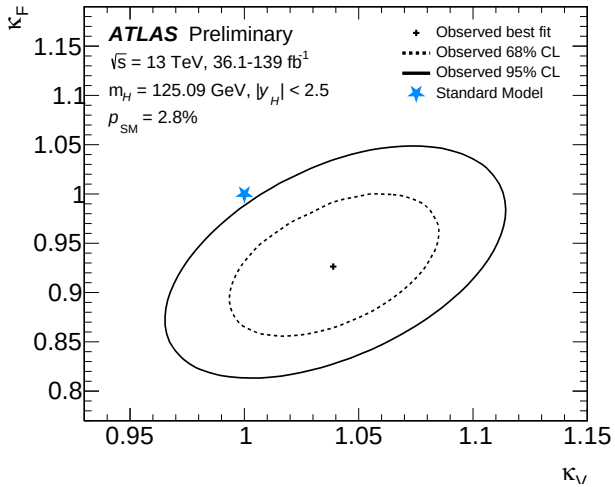


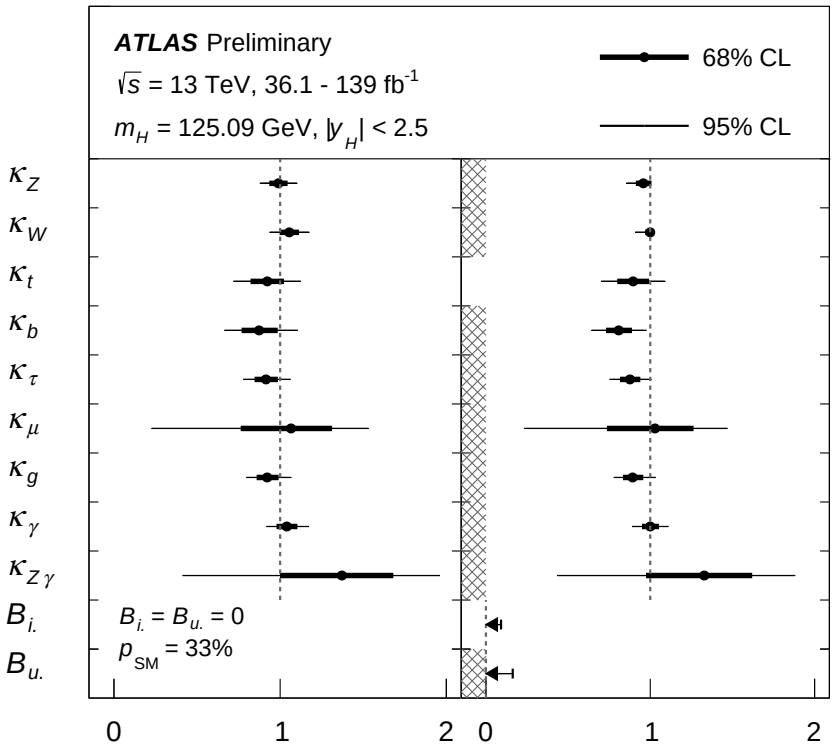
Higgs couplings interpretation

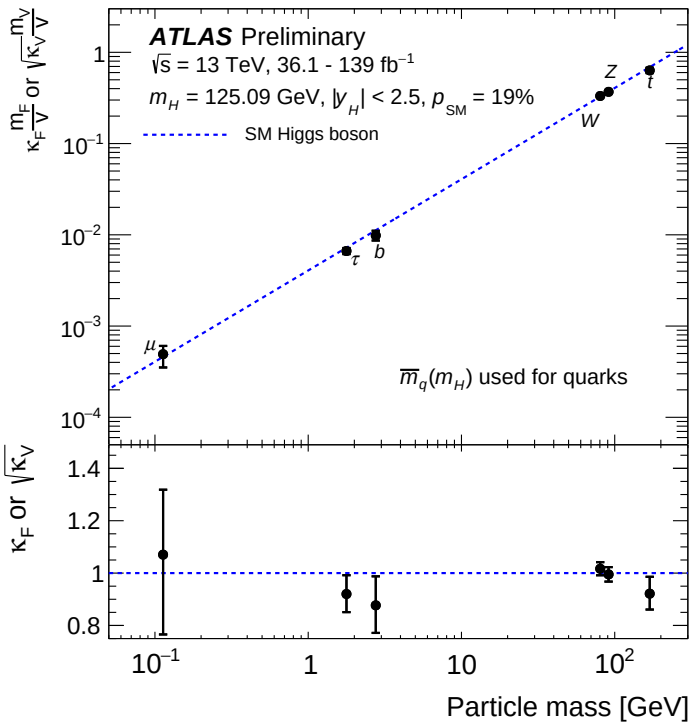
SMEFT, 2HDM & **κ-framework:**

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

$$\kappa_{\mathrm{H}}^2(\kappa, B_{\mathrm{i.}}, B_{\mathrm{u.}}) = \frac{\sum_j B_j^{\mathrm{SM}} \kappa_j^2}{1 - B_{\mathrm{i.}} - B_{\mathrm{u.}}}$$

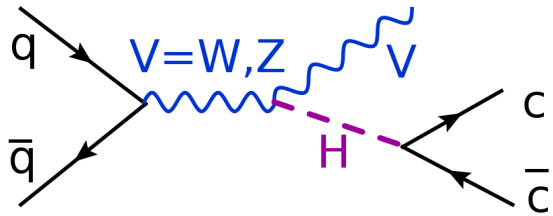






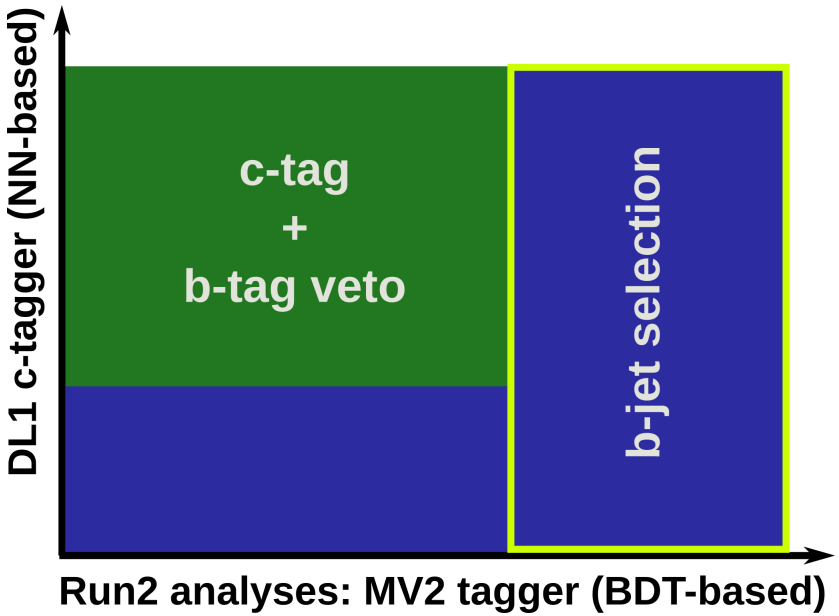
Higgs-charm coupling from VH, H→ $c\bar{c}$

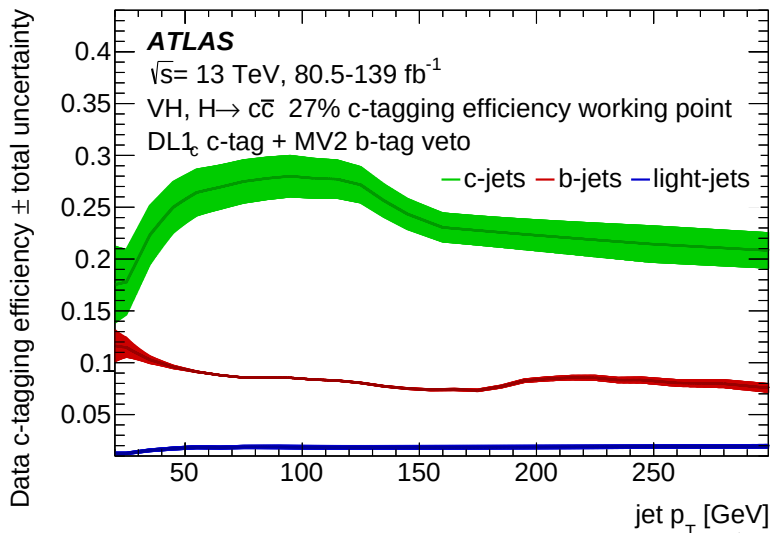
- Analysis uses VH production: golden channel for $VH, H \to b\bar{b}$ measurements.
- Direct probe of Higgs-charm coupling.



Challenges of VH, $H \to c\bar{c}$ in addition to $VH, H \to b\bar{b}$ ones:

- BR($H \to c\bar{c}$)=2.9% << BR($H \to b\bar{b}$)
- Tagging charm jets:
  - Based on 2 algorithms: c-tagging DL1 and b-tagging MV2.
  - MV2 vetoes b-jets, ensures orthogonality with $VH, H \to b\bar{b}$.
  - Efficiency(tag+veto): c-jet:27%, b-jet:8%, light: 1.6%



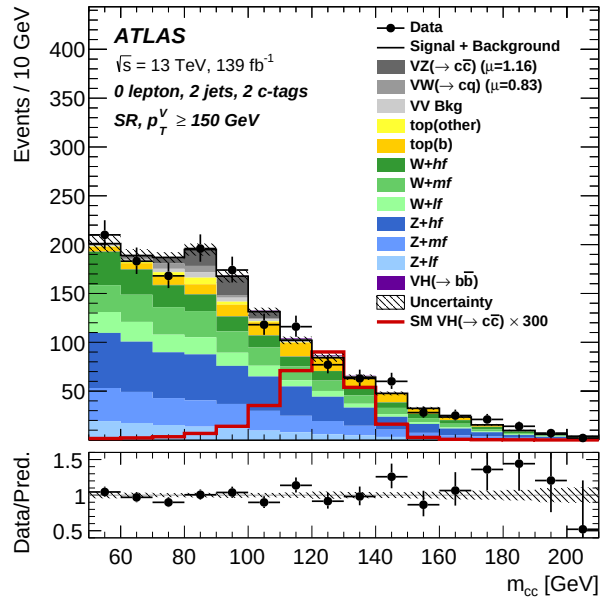


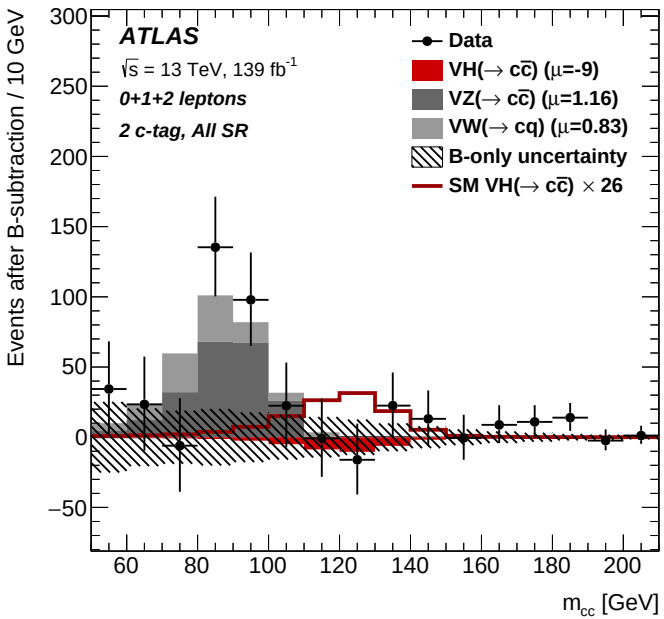
Higgs-charm coupling from VH, H$\to c\bar{c}$

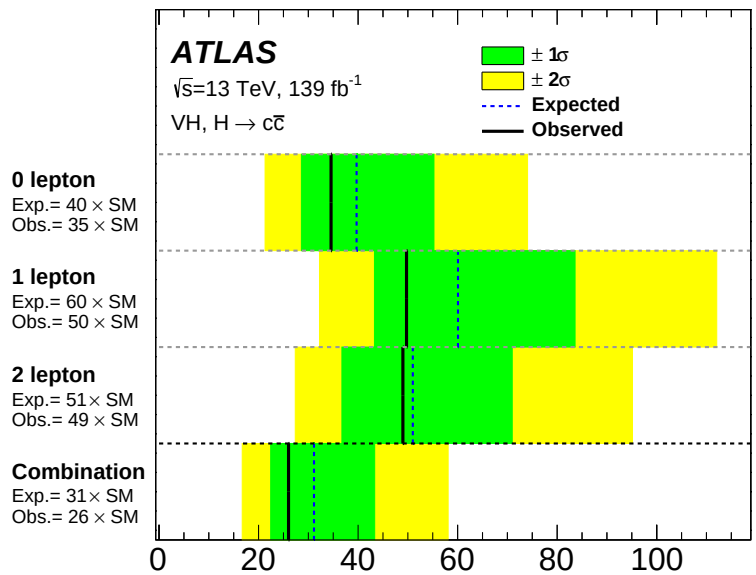
Aim: extract signal & background from a combined fit to 44 regions:

- 16 SR-s: N(ℓ), N(c-tags), N(jets),$\mathrm{p_T}$(V).
- 16 CR-s: large $\Delta R(\mathrm{jet1}, \mathrm{jet2})$.
- Further CRs: 0-tag and top.

Best-fit value $\mu(VH, H\to c\bar{c}) = -9$.





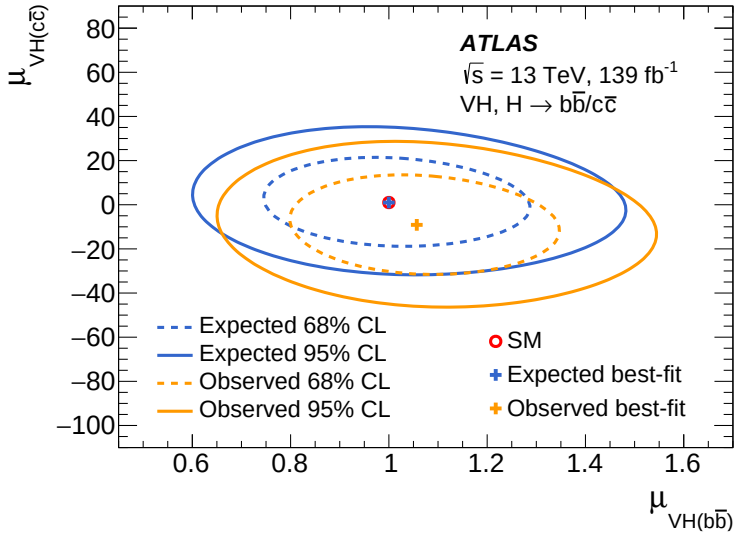


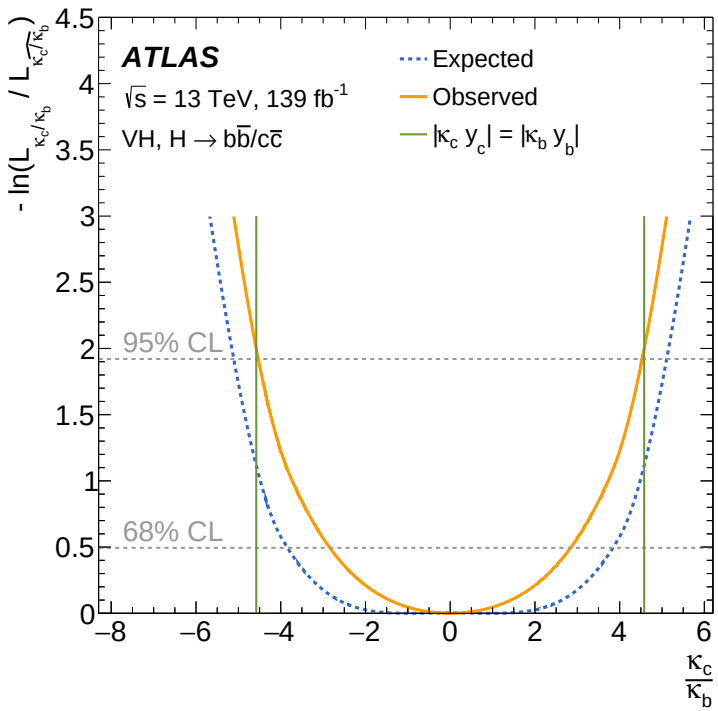
VH, H$\to c\bar{c}$: interpretation

κ_c affects coupling strength & the Higgs width;
under assumptions on Γ_H:
$|\kappa_c| < 8.5$ @ 95% CL.

$|\kappa_c/\kappa_b|$ is extracted from combination with $VH, H\to b\bar{b}$:

- Key: b-jet veto in $VH, H \to c\bar{c}$; ensures orthogonality.
- No assumptions on Γ_H.
- $m_b/m_c = 4.578 \pm 0.008$
- $|\kappa_c/\kappa_b| < 4.5$ @ 95% CL.
- Higgs-charm coupling < Higgs-bottom coupling.



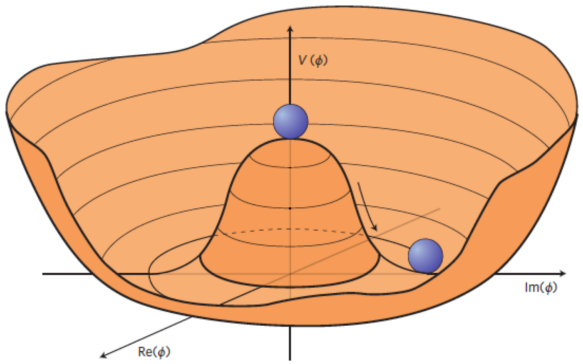


Searches for HH production

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

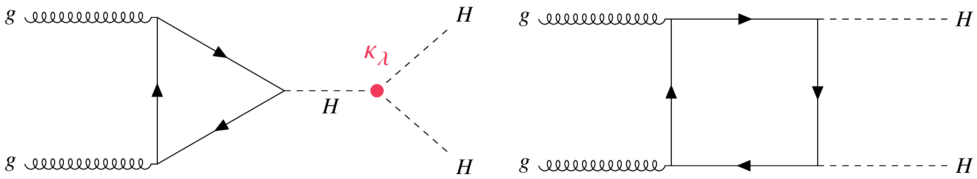
$$\mathrm{SM} : \lambda_3 = \lambda_4 = \lambda^{\mathrm{SM}} = m_H^2/(2v^2)$$

$$\text{Define} : \kappa_\lambda = \lambda_3/\lambda_3^{\mathrm{SM}}$$

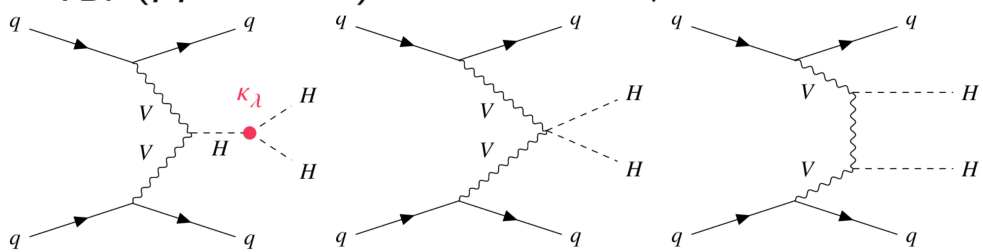


HH production cross-sections and event shapes sensitive to κ_λ.

$\sigma_{ggF}(pp \to HH) = 31.05$ fb @ $\sqrt{s} = 13$ TeV



$\sigma_{VBF}(pp \to HH) = 1.73$ fb @ $\sqrt{s} = 13$ TeV



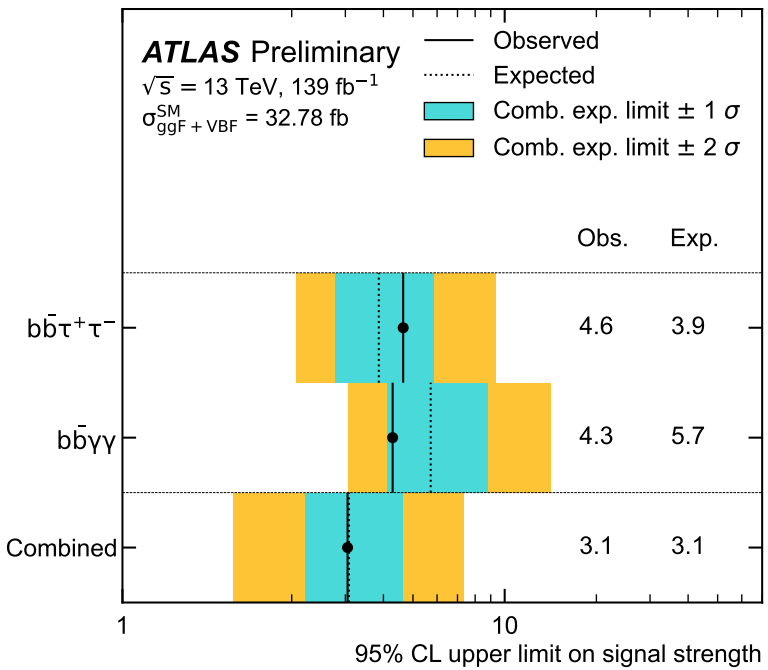
HH branching ratios:

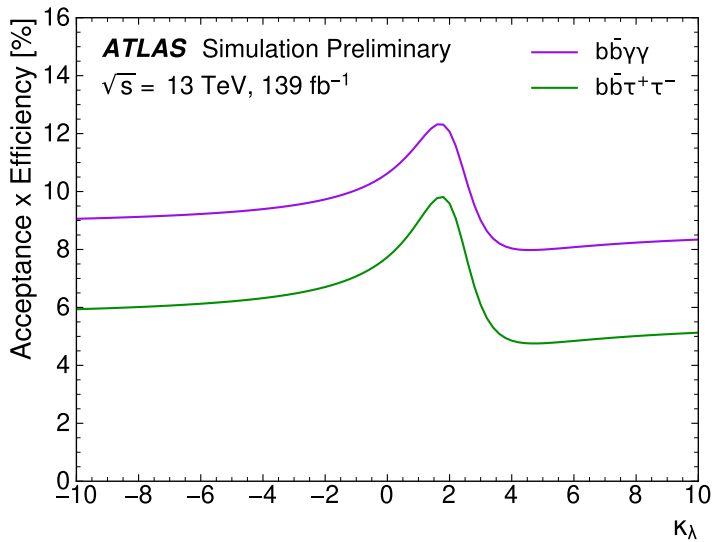
	bb	WW	ττ	ZZ	γγ
bb	34%				
WW	25%	4.6%			
ττ	7.3%	2.7%	0.39%		
ZZ	3.1%	1.1%	0.33%	0.069%	
γγ	0.26%	0.10%	0.028%	0.012%	0.0005%

HH: combination results

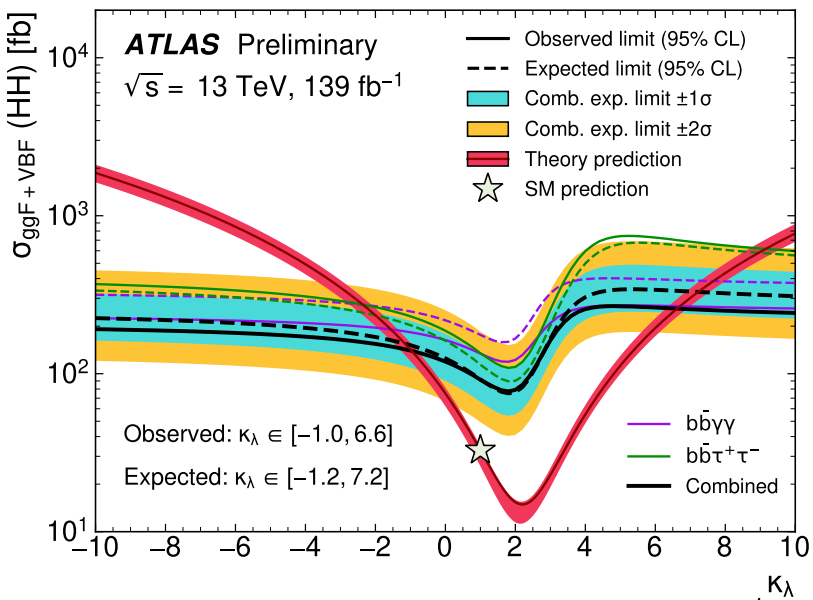
Signal strength:

$\sigma(pp \to HH)/\sigma(pp \to HH)^{\mathrm{SM}}$





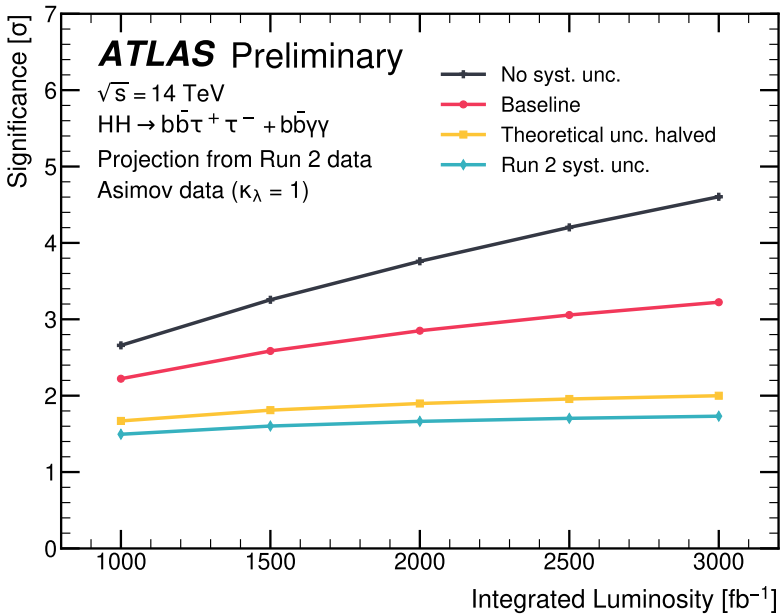
Interpreted in terms of κ_λ, accounting for cross-section, shape & acceptance $\times$ efficiency effects.

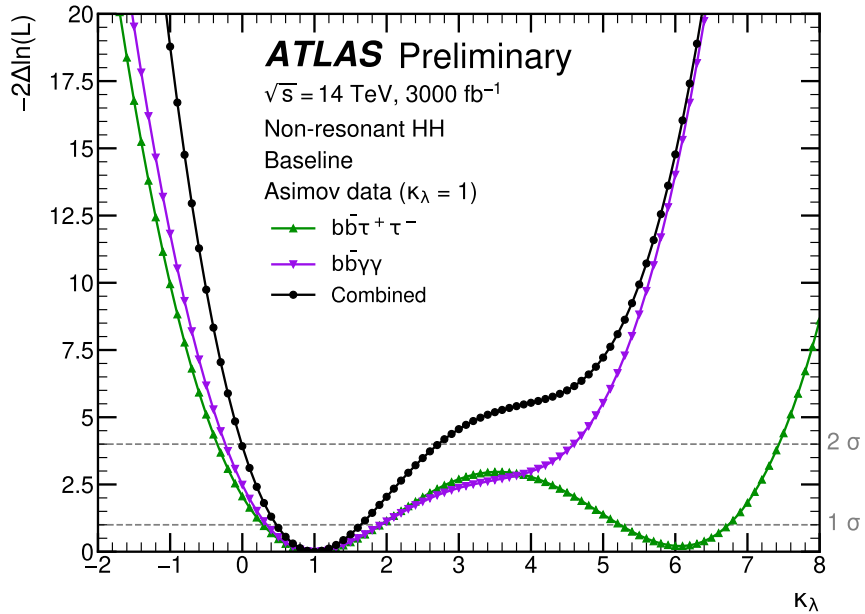


HH: HL-LHC projection

Projection of $HH \to b\bar{b}\gamma\gamma$ and $HH \to b\bar{b}\tau\tau$.

- Assume 3000 fb^{-1} of HL-LHC data at $\sqrt{s} = 14$ TeV.
- Various scenarios for evolution of the uncertainty; baseline scenario: halved theory, scaled Run2 syst. uncertainty
- HH signal strength: 23% stat. and $^{34\%}_{-31\%}$ stat. $\oplus$ syst.
- κ_λ 1-σ interval: [0.6,1.5] stat. and [0.5,1.6] stat. $\oplus$ syst.

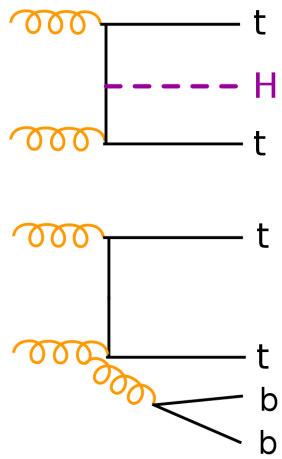




Top Yukawa CP: $t\bar{t}H$ and tH, $H \to b\bar{b}$

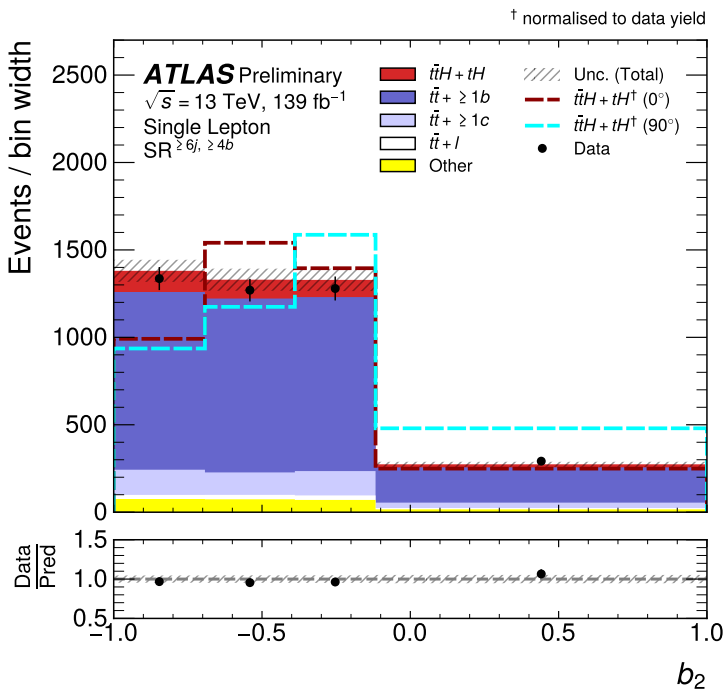
New measurement probing:

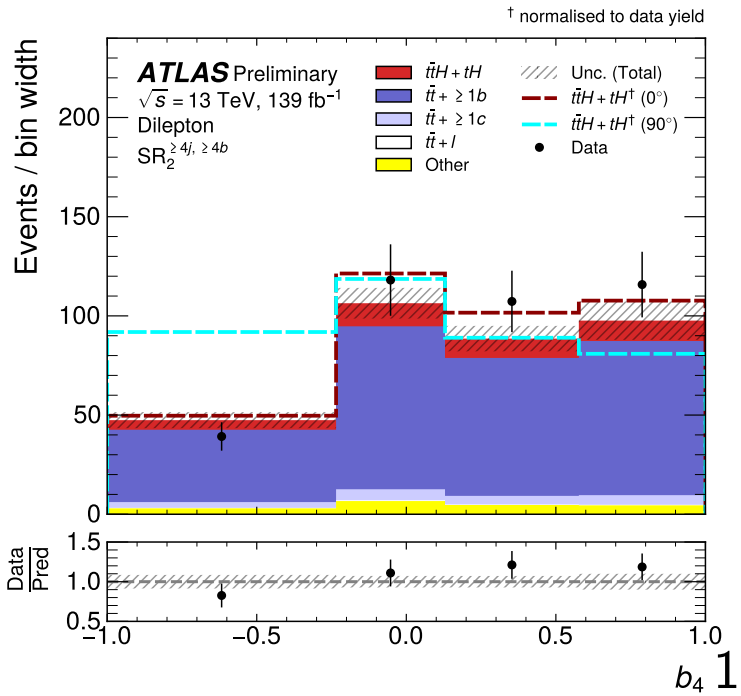
$$\mathcal{L} = -\frac{m_t}{v}\overline{\Psi}_\top \kappa'_\top (\cos(\alpha) + i\sin(\alpha)\gamma^5)\Psi_\top H$$



- Background dominated by $t\bar{t}+b\bar{b}$. Shape from MC prediction, normalisation from data.
- Fit to CP sensitive variables in analysis regions:

$$b2 = \frac{(\vec{p}_{\mathrm{t}} \times \hat{n}) \cdot (\vec{p}_{\bar{\mathrm{t}}} \times \hat{n})}{|\vec{p}_{\mathrm{t}}||\vec{p}_{\bar{\mathrm{t}}}|} \qquad b4 = \frac{p^z_{\mathrm{t}} p^z_{\bar{\mathrm{t}}}}{|\vec{p}_{\mathrm{t}}||\vec{p}_{\bar{\mathrm{t}}}|}$$





Top Yukawa CP: $t\bar{t}H$ and tH

$$\mathcal{L} = -\frac{m_t}{v}\overline{\Psi}_\top \kappa'_\top (\cos(\alpha) + i\sin(\alpha)\gamma^5)\Psi_\top H$$

New $H\to b\bar{b}$ result:

Best fit: $\alpha^{\mathrm{CP}} = 11^\circ {}^{+56^\circ}_{-77^\circ}$;

Systematic uncertainty: ${}^{+43^\circ}_{-58^\circ}$

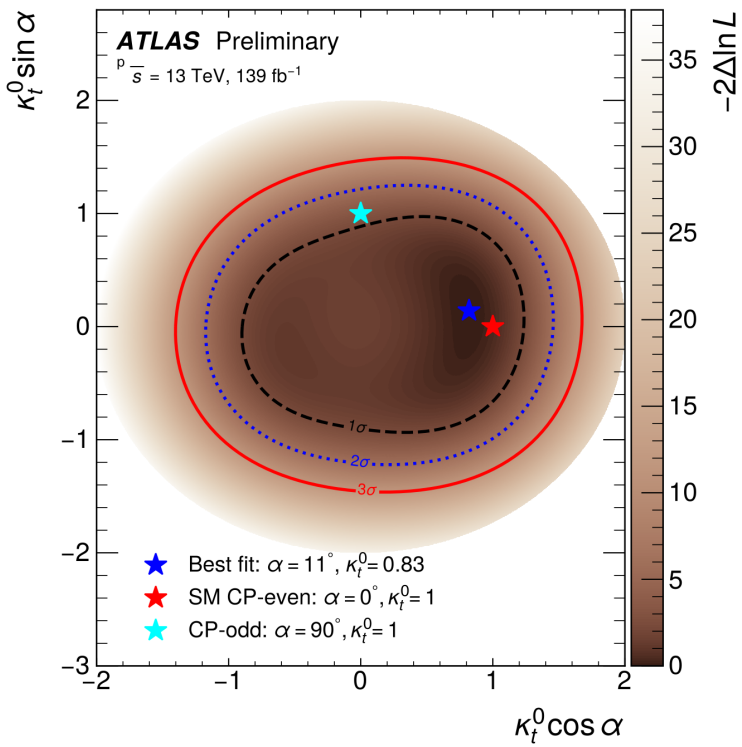
Disfavours pure CP odd: 1.2σ

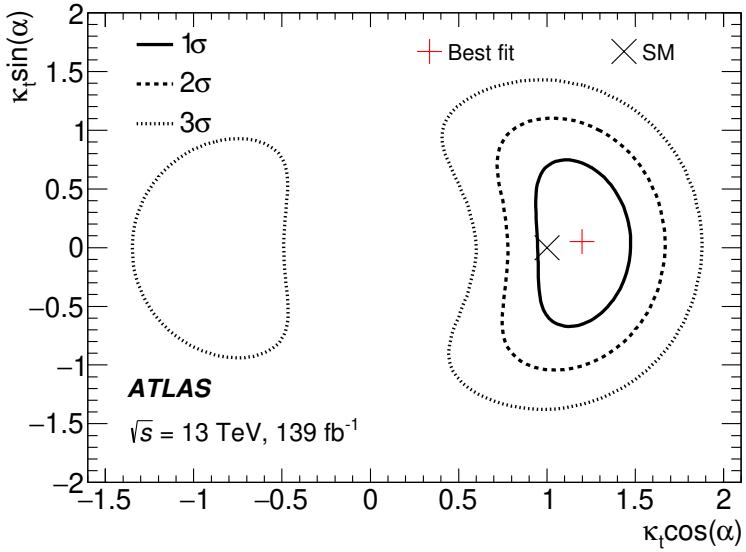
$H\to\gamma\gamma$ result (2020):

$|\alpha^{\mathrm{CP}}| < 43^\circ$ @ 95CL

Stat. uncertainty $\ll$ syst..

Excludes pure CP odd: 3.9σ

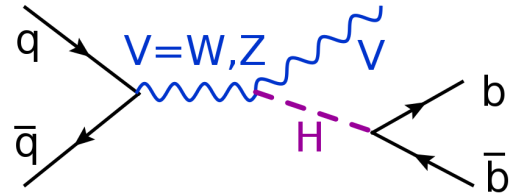


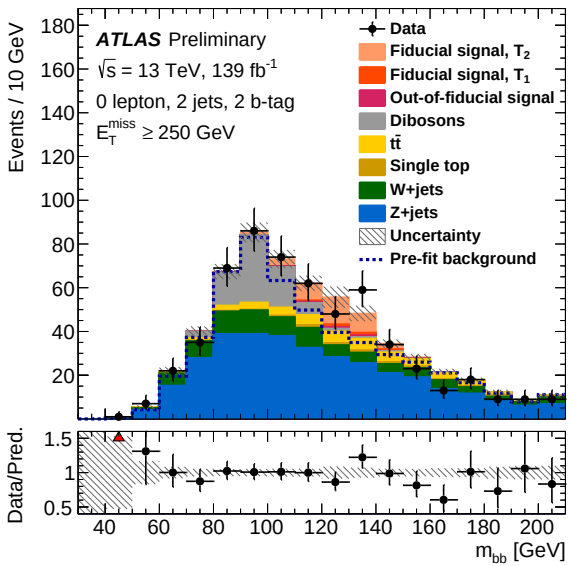


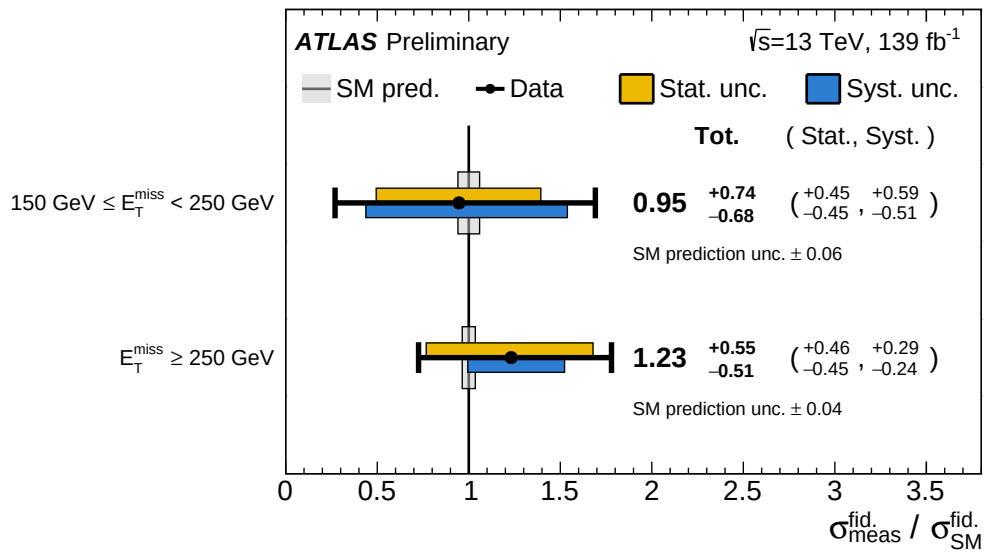
VH, $H \to b\bar{b}$ + 0 leptons

New fiducial cross-section measurement:

- Particle-level selection criteria as close as possible to detector-level. Unfolded measurement can be interpreted with particle-level predictions & BSM models.
- μ_{T1} : 150 GeV$<E_T^{\mathrm{miss}}<$250 GeV, μ_{T2} : $E_T^{\mathrm{miss}}>$250 GeV.







Complementary to VH, $H \to b\bar{b}$ STXS measurement, which: uses 0, 1 & 2 lepton channels, WH sensitivity: 4.0σ, ZH sensitivity: 5.3 σ.

Summary

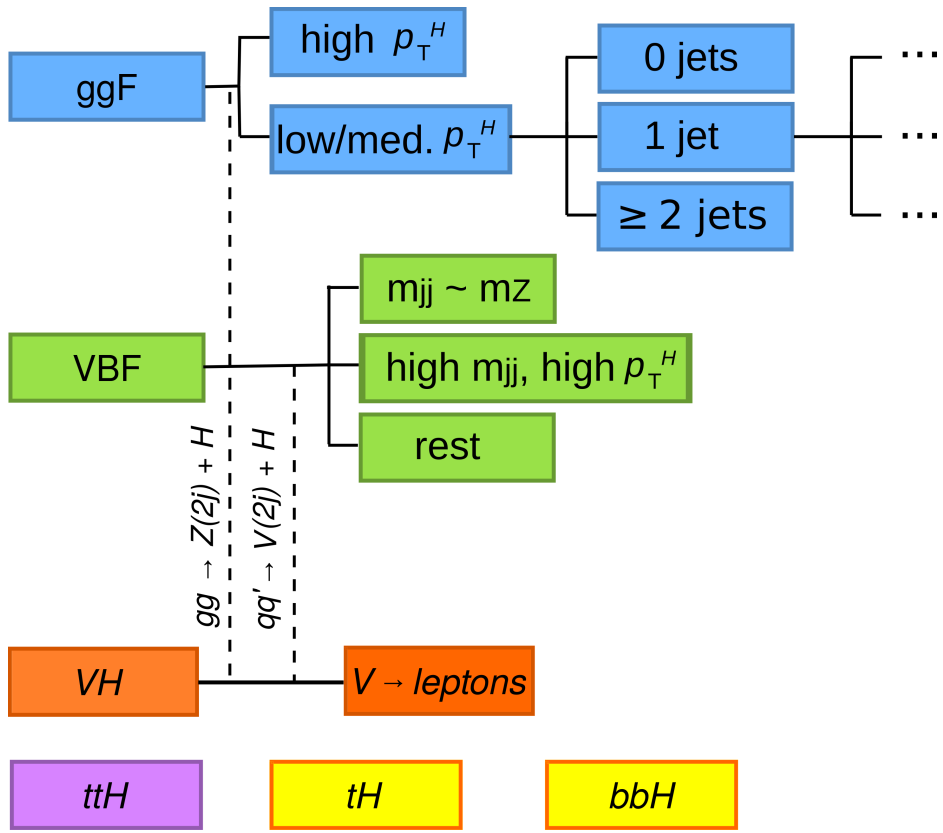
- **Combined cross-sections in $H\to\gamma\gamma$ and $H\to ZZ^*\to 4\ell$ and couplings&production cross-section combination**: <10% probe of Higgs mechanism, consistent with the SM.
- **Direct constraint on Higgs-charm coupling from $VH,H\to c\bar{c}$ production**:
  Higgs-charm coupling < Higgs-bottom coupling (95% CL).
- ***HH* production:**
  - Current Run2 combination: $\kappa_\lambda \subset$ [-1.0, 6.6] (95% CL).
  - HL-LHC projection: $\kappa_\lambda \subset$ [0.5, 1.6] (1-σ).
- **New results for Moriond 2022:**
  - Probe CP of top Yukawa interaction in $t\bar{t}H$ and tH, $H\to b\bar{b}$: $\alpha^{\mathrm{CP}} = 11^{\circ}{}^{+56^{\circ}}_{-77^{\circ}}$
  - Fiducial cross-section measurement of $VH,H\to b\bar{b}$ + 0 leptons: complementary to $VH,H\to b\bar{b}$ STXS results.
  - *HH* searches: HEFT interpretation will be discussed by Guillermo.

For many ATLAS Higgs results I did not cover, please see ATLAS Higgs results page and Adinda's & Guillermo's talks today.

Extra

Simplified Template X-Sections

STXS targets phase space regions within production modes, using Standard Model kinematics as a template.



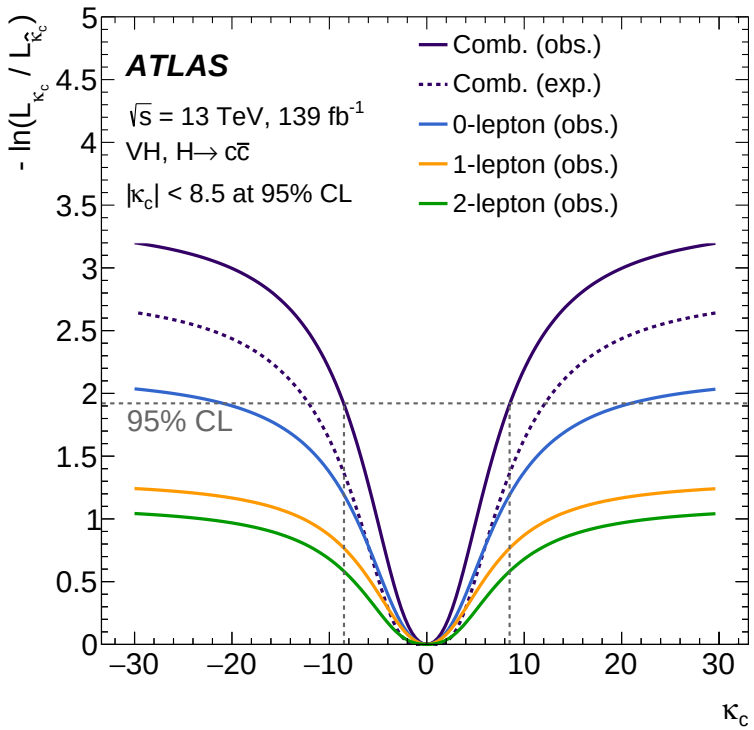
Compromise: maximise experimental sensitivity vs minimise dependence on theory assumptions.

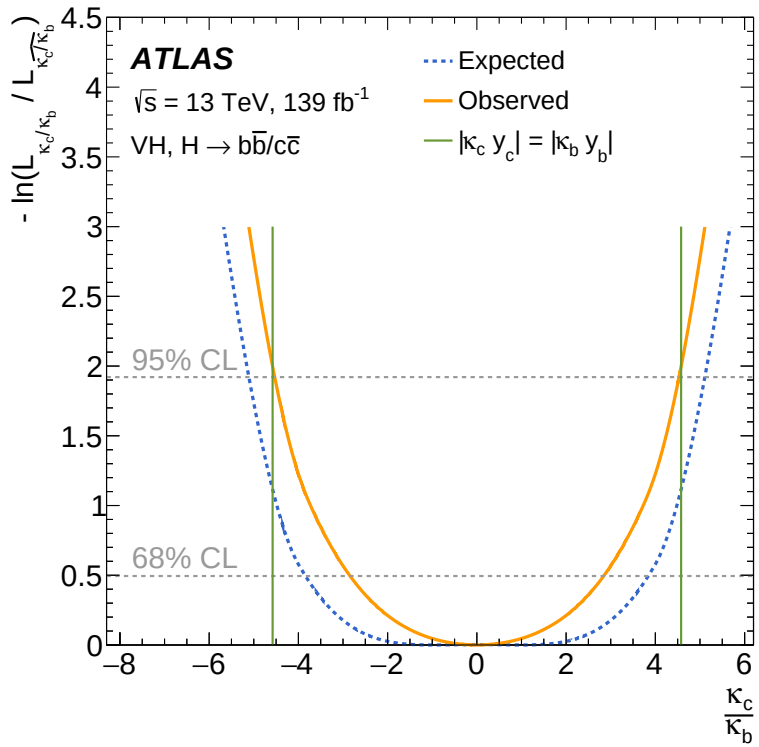
VH, H$\to c\bar{c}$: κ_c interpretation

- κ_c affects coupling strength & the Higgs width.
- Negative best-fit value pushes κ_c toward 0.
- $|\kappa_c| < 8.5(12.4)$ @ 95% CL.

Combination with VH,$H\to b\bar{b}$:

- $m_b/m_c = 4.578 \pm 0.008$
- $|\kappa_b/\kappa_c| < 4.5$ @ 95% CL.
- Higgs-charm coupling < Higgs-bottom coupling.





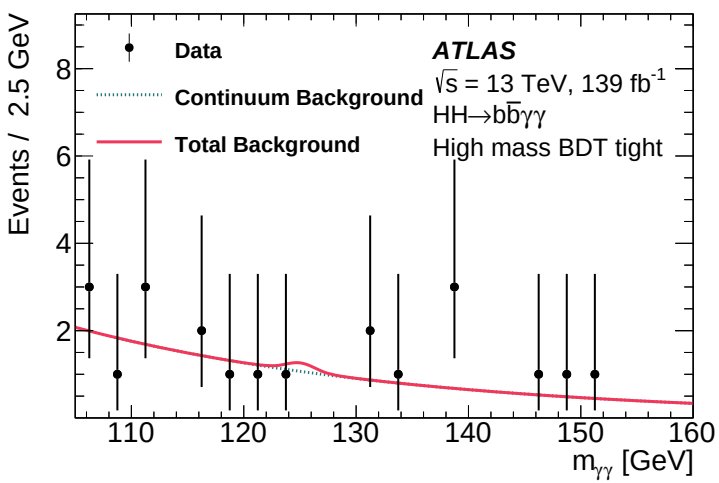
HH: combination

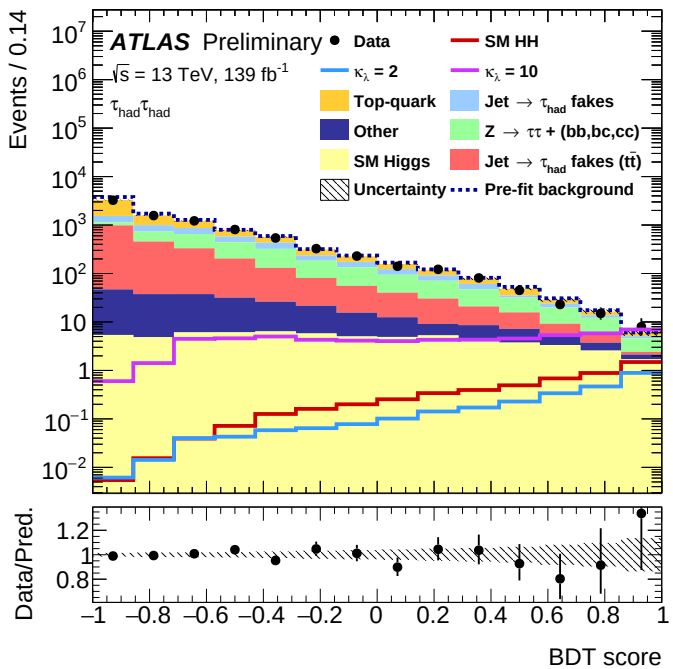
H→$b\bar{b}\gamma\gamma$ analysis:

- BDT for background rejection: yy+jets, single-H production.
- 4 categories: m_{HH}, BDT
- Signal from $m_{\gamma\gamma}$ fit.
- Limited by statistical uncertainty.

H→ $b\bar{b}\tau\tau$ analysis:

- Non-resonant background norm. & shape from data.
- 3 categories: trigger & $\{\tau_{\mathrm{had}}\tau_{\mathrm{had}}, \tau_{\mathrm{had}}\tau_{\mathrm{lep}}\}$
- Fit to MVA output.
- Limited by stat. uncertainty.

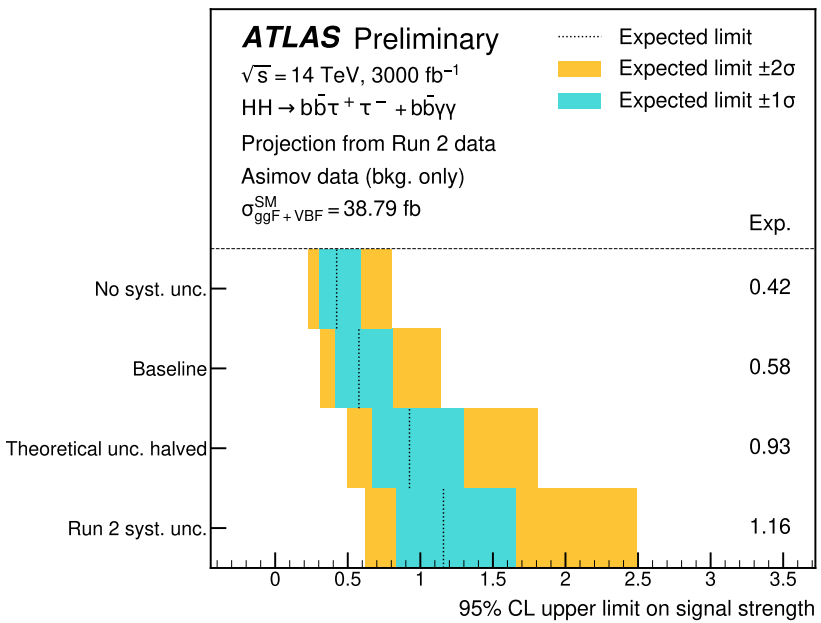


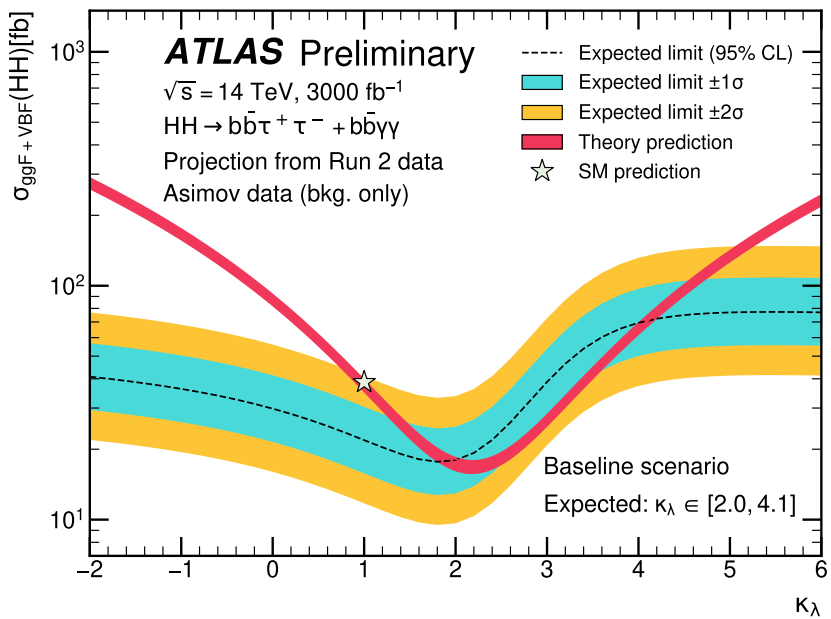


HH: HL-LHC projection

Combination of $HH \to b\bar{b}\gamma\gamma$ and $HH \to b\bar{b}\tau\tau$ analyses.

- Assume 3000 fb^{-1} of HL-LHC data at $\sqrt{s} = 14$ TeV.
- Various scenarios for evolution of the uncertainty.
- HH signal strength: 23% stat. ($^{34\%}_{-31\%}$ stat. + syst.)
- κ_λ 1-σ interval: [0.6,1.5] stat. ([0.5,1.6] stat.+syst.)

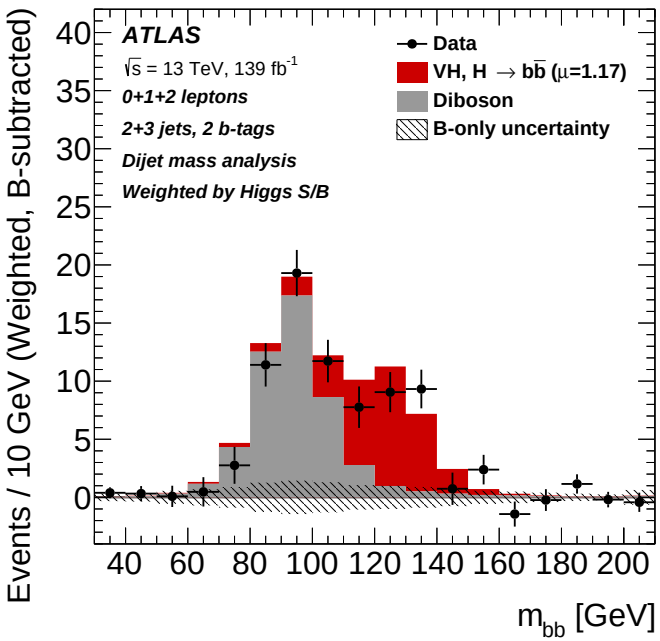


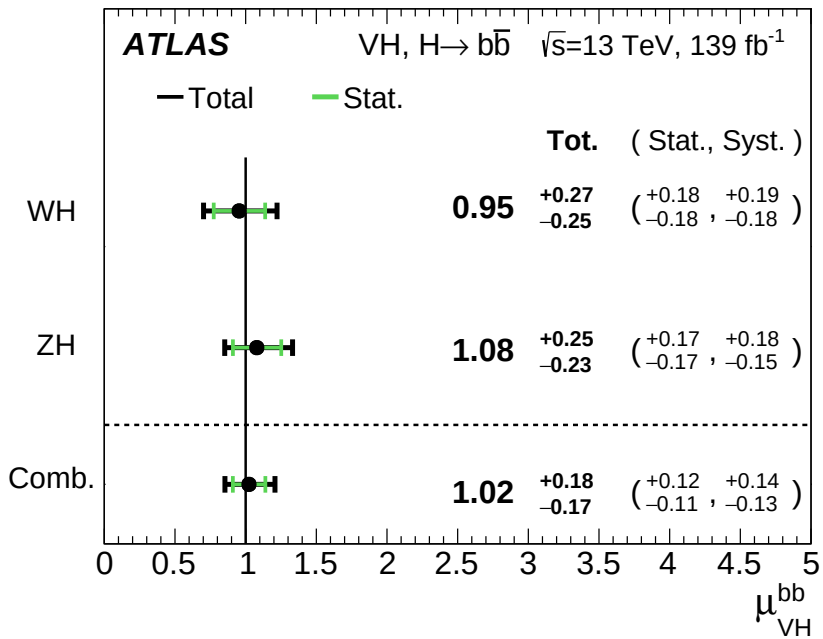


VH, $H \to b\bar{b}$

New VH, $H \to b\bar{b}$+0 leptons fiducial cross-section measurement is complementary to VH, $H \to b\bar{b}$ STXS measurement (2021), which:

- Uses 0, 1 & 2 lepton channels.
- Fit to MVA discriminant; fit to $m_{b\bar{b}}$ used as control analysis.
- WH sensitivity: 4.0 (4.1) σ expected (observed).
- ZH sensitivity: 5.3 (5.1) σ expected (observed).





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