ATLAS H→γγ cross-section measurements and interpretations with the full Run-2 data

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Measurements of Higgs boson properties

- Various approaches:

More direct test of the SM ↑

Couplings: $\mu_{ggF}, \mu_{VBF}, \ldots \;\kappa_g, \kappa_V, \ldots$

STXS: $\sigma_{ggF} \times BR(H \to \gamma\gamma)$ *Production mode separation*

Fiducial xs: $\sigma_{incl} \times BR(H \to \gamma\gamma)$ *Inclusive in production mode*

↓ *Less assumptions*

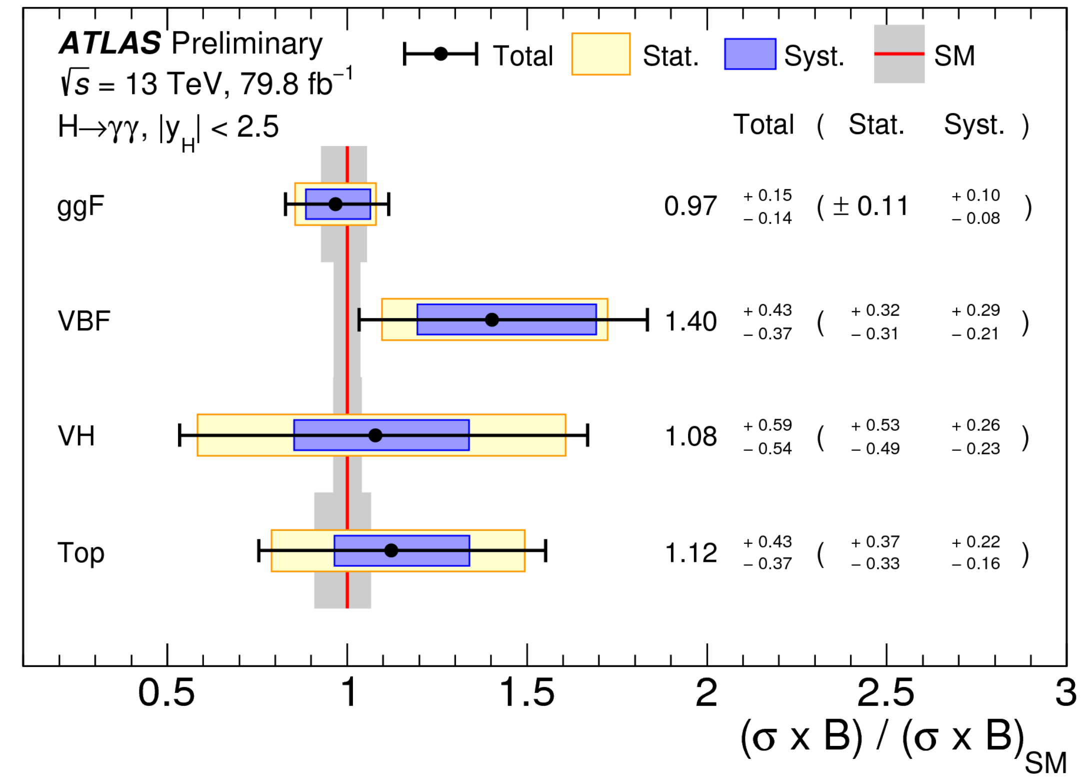
H→γγ cross sections

Latest STXS results with 80 fb⁻¹

ATLAS-CONF-2018-028

- Simplified Template X-Sections at two stages
  - Stage-0: *truth-level splitting of Higgs production processes*
  - Stage-1 (reduced): *Additional splitting based on Higgs kinematics and associated particles*

Minimal model dependence in these measurements; ideal setup for combinations of all channels and with CMS measurements

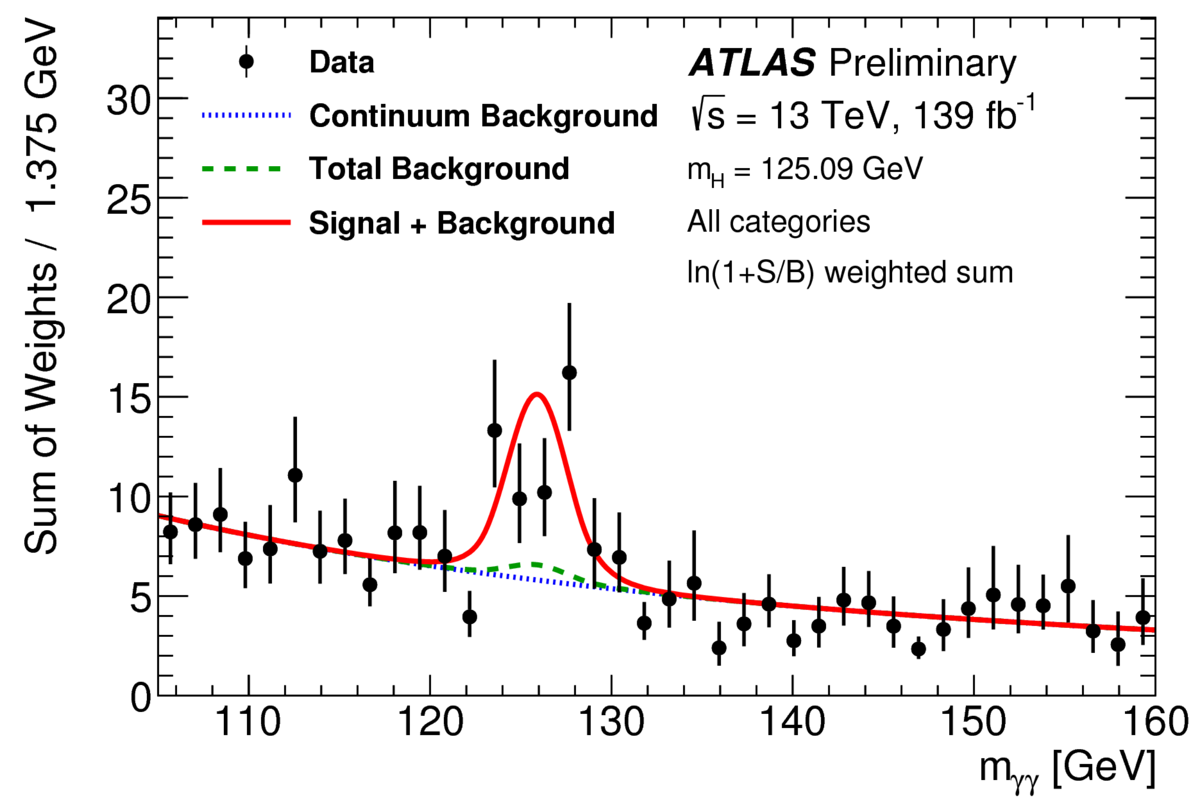


ttH measurement with 139 fb⁻¹

ATLAS-CONF-2019-004

$$\mu_{t\bar{t}H} = 1.38 \,^{+0.41}_{-0.36}$$

- 4.9σ observation



$H\rightarrow\gamma\gamma$ cross sections

New results with the full Run-2 data from the LHC, 139 fb^{-1}

ATLAS-CONF-2019-029

- Measurement of ***fiducial*** cross sections

  No separation of production modes, model-independent measurements allowing comparison with predictions in the phase space directly accessible by our detector

  - integrated:

    $$(\sigma\cdot\mathrm{BR})_{(pp\rightarrow H\rightarrow\gamma\gamma)} = \mathrm{N}_{\mathrm{signal}} / (\mathcal{L}\cdot\varepsilon)$$

  - differential:

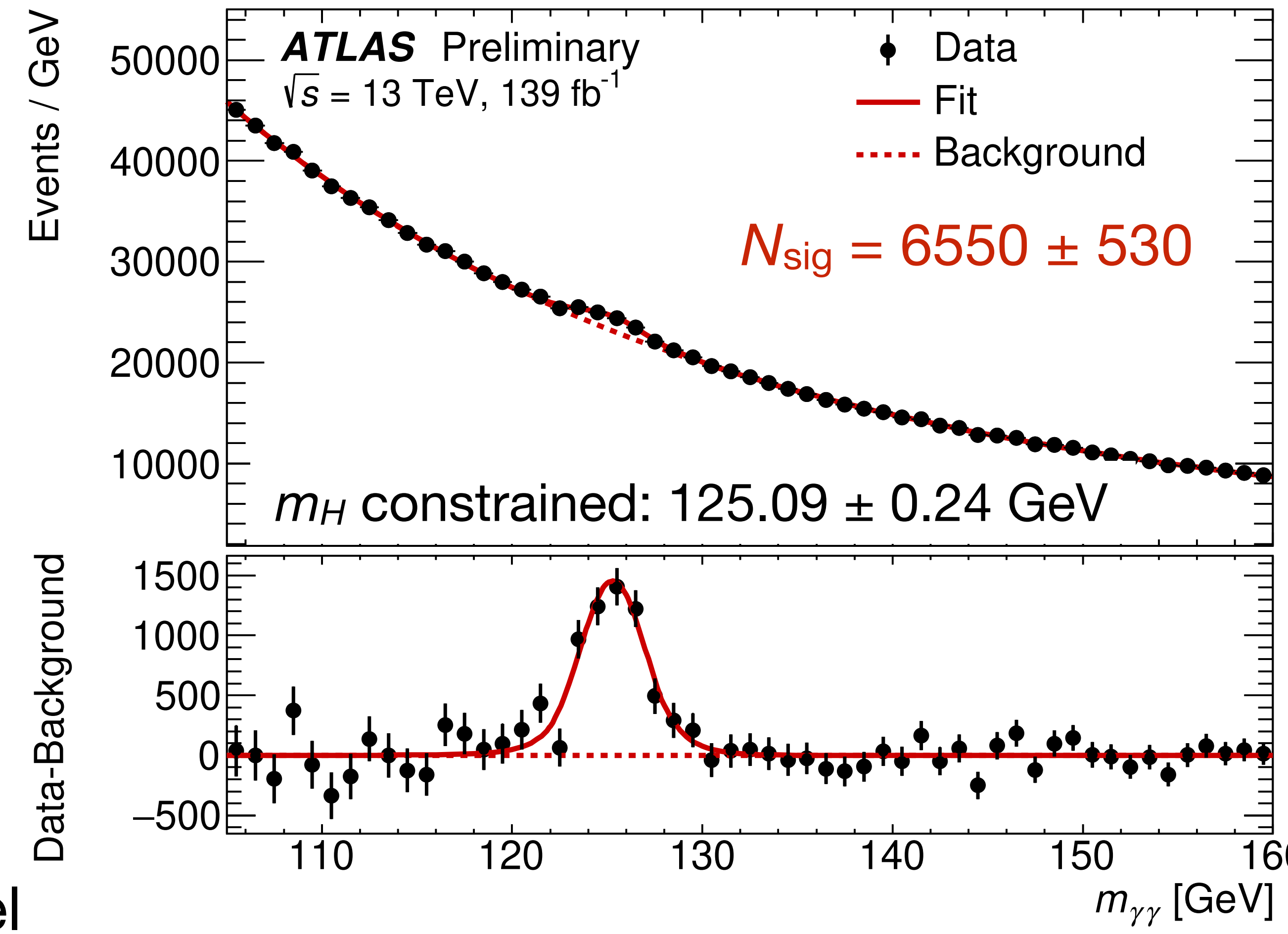
    $$d(\sigma\cdot\mathrm{BR})/dx\ ,\quad x:\ p_{\mathrm{T}}^{\gamma\gamma},\ y^{\gamma\gamma},\ \mathrm{N}_{\mathrm{jets}},\ p_{\mathrm{T}}^{\mathrm{j1}},\ m_{\mathrm{jj}},\ \Delta\phi_{\mathrm{jj}}$$

  Observables sensitive to new physics, CP-properties but also QCD calculations in the SM

- Interpretations of the differential measurements
  - Effective Lagrangian (SILH, Warsaw) with additional CP-odd and CP-even interactions
  - setting limits on charm-Yukawa coupling from shape of $p_{\mathrm{T}}^{\gamma\gamma}$

The analysis in a nutshell

- $H \to \gamma\gamma$ signal extracted from the continuous background with a mass fit
  - Background estimation directly from data using analytical functions
  - Background modelling uncertainty ('spurious signal') from fits to high-statistics MC-based background templates

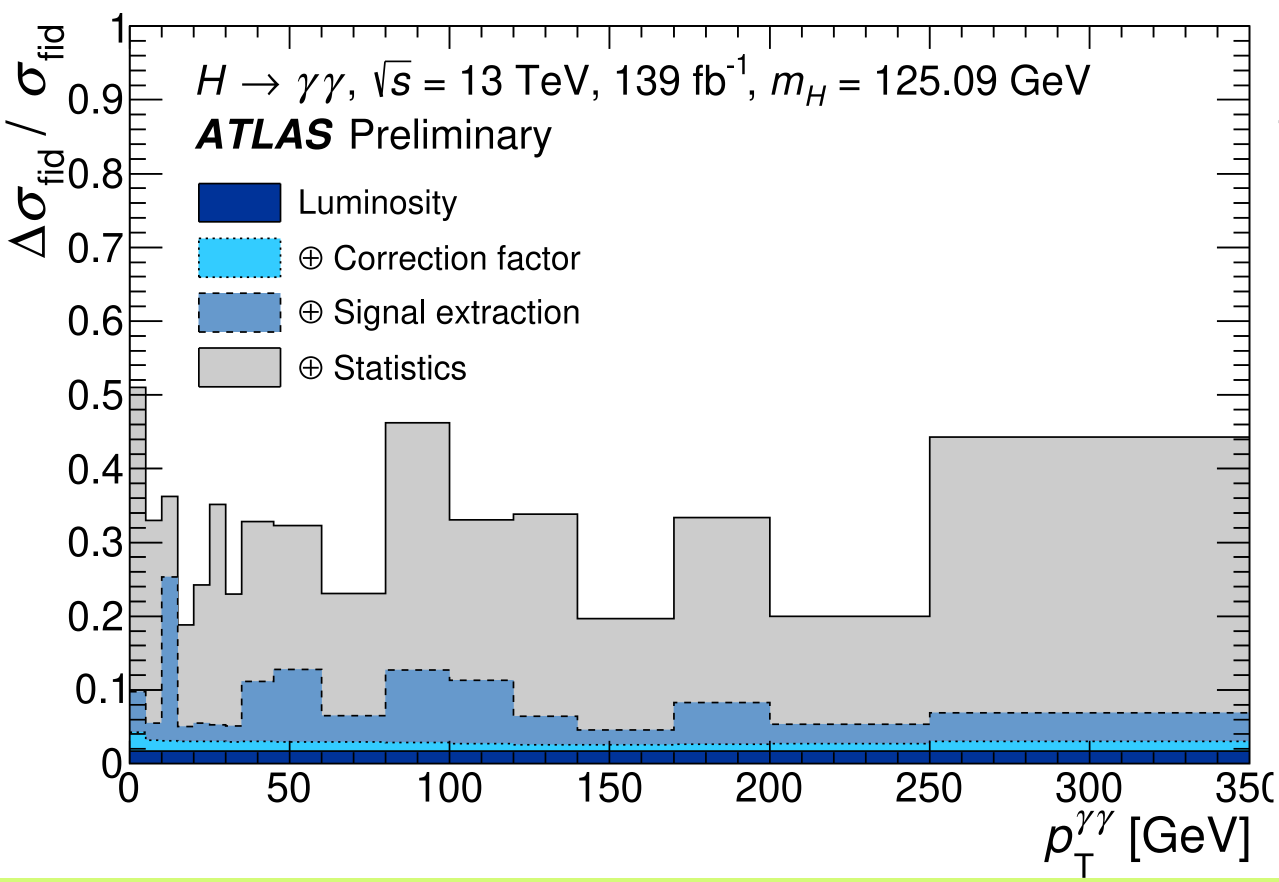


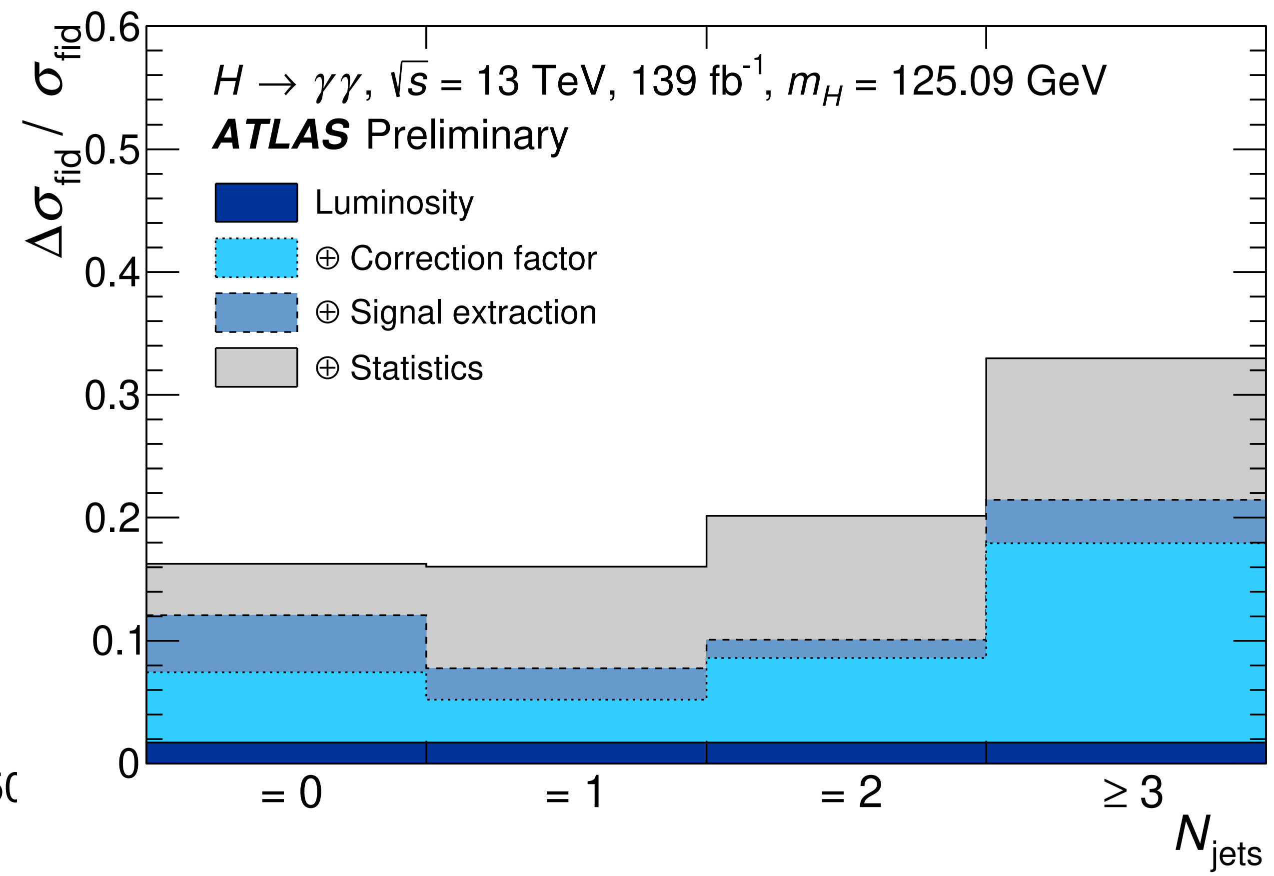
- Yields unfolded to a fiducial volume matching the experimental acceptance
- Kinematic selections:
  - $E_{T1} > 0.35 m_{\gamma\gamma}$, $E_{T2} > 0.25 m_{\gamma\gamma}$
  - $|\eta^{\gamma}| < 1.37$ or $1.52 < |\eta^{\gamma}| < 2.37$
  - Jets: $p_T > 30$ GeV, $|y| < 4.4$ (*jet-related observables*)
  - ✦ Photon isolation at recon. & particle level
- Unfolding technique:
  - Bin-by-bin correction factor from simulation, $c_{fid} = N_{sig}/N_{fid}$
  - Matrix-based unfolding as a check

$$\sigma_{fid} = \frac{N^{sig}}{c_{fid}\,\mathcal{L}_{int}}$$

Improvements with respect to previous measurements

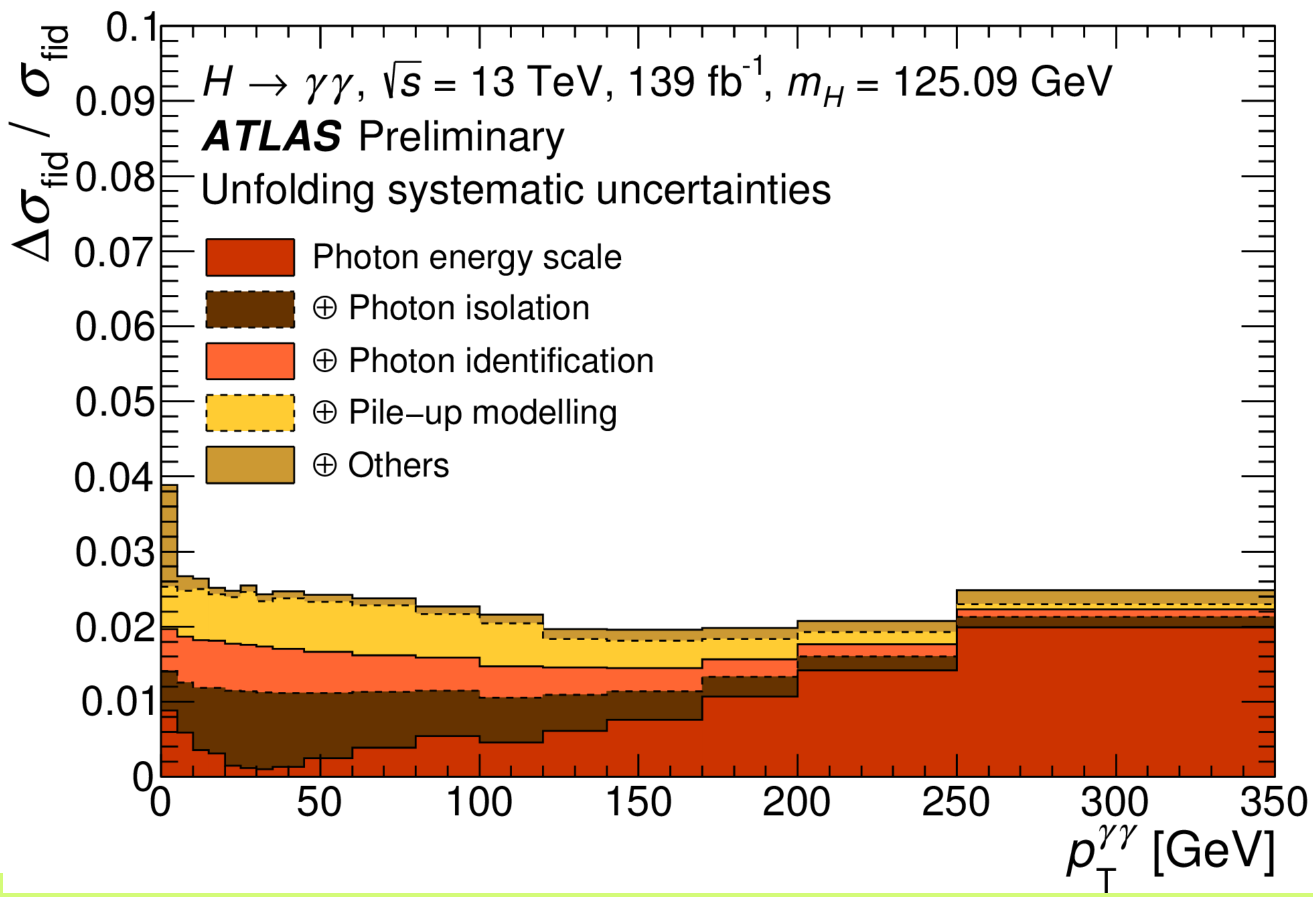
- Reduced statistical uncertainties
- Improved signal efficiency/background rejection for diphotons
  - new $p_T{}^{\gamma}$-dependent identification
- Reduced systematic uncertainties thanks to:
  - improved isolation efficiency measurements
  - improved jet calibration, optimized for Run-2 conditions
  - new technique in the estimation of the background modelling uncertainty, Gaussian Processes (arXiv: 1709.05681), used to smooth the MC-based templates

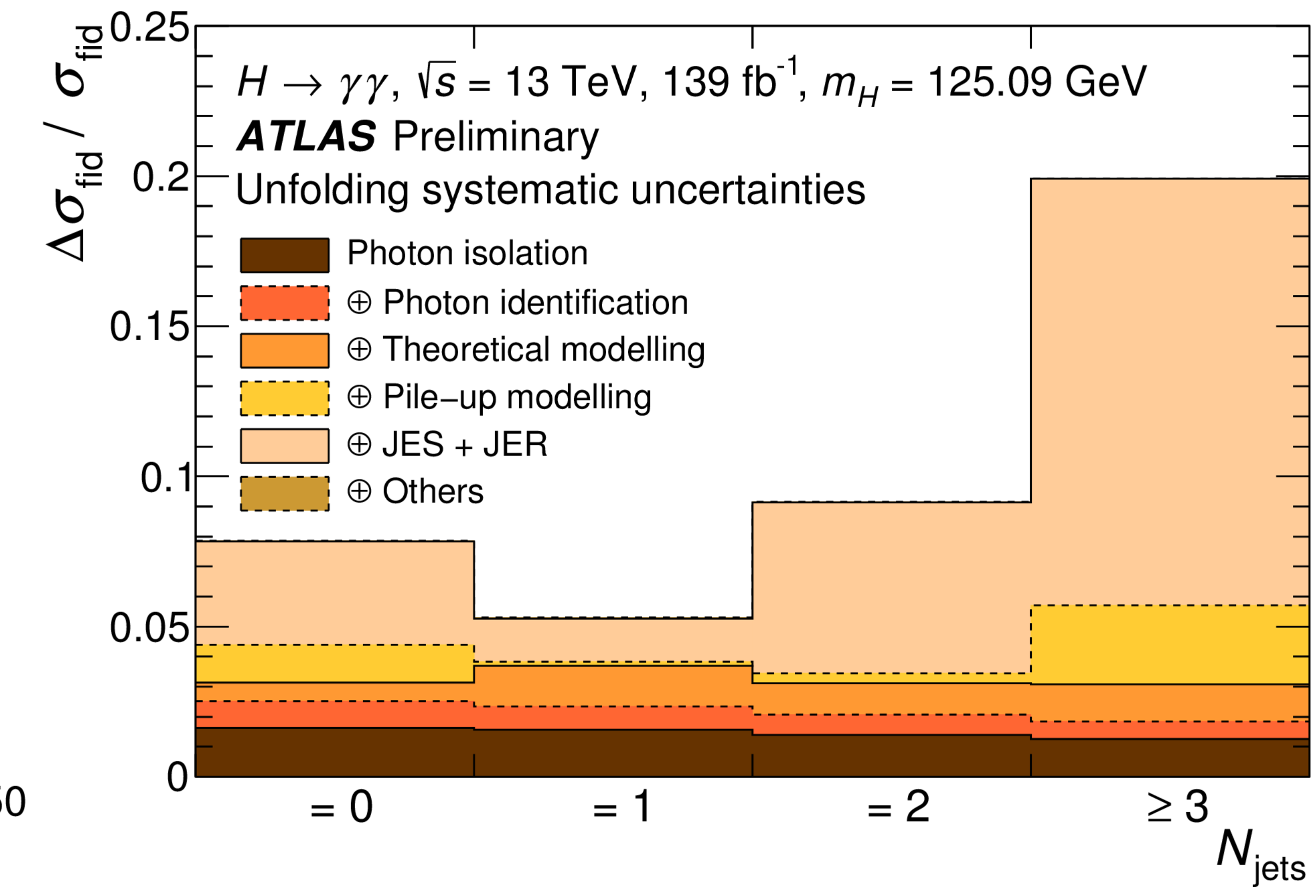




Unfolding uncertainties

- Experimental, from efficiencies and jet-energy scale/resolution => **dominant**
  - Photon identification and isolation efficiency accurate at the 1% level
  - JES/JER is dominant for jet-based observables
- Theoretical, from dependence on the SM assumptions => **subdominant**
  - Parton showering
  - Higgs kinematics / production mode
  - Dalitz contributions





Integrated cross-section

- Fiducial xsection times $H \to \gamma\gamma$ branching ratio:

$$\sigma_{\text{fid}} = 65.2 \pm 4.5\,(\text{stat.}) \pm 5.6\,(\text{syst.}) \pm 0.3\,(\text{theo.})\,\text{fb}$$

SM prediction: **63.6 ± 3.3** fb , arXiv: 1610.07922 [hep-ph]

- SM prediction based on calculations accurate to:
  - N^3LO for ggF
  - NNLO (approx.) VBF
  - (N)NLO for *VH*, *ttH* and *bbH*
- Experimental uncertainties dominate:
  - photon energy resolution
  - background modelling

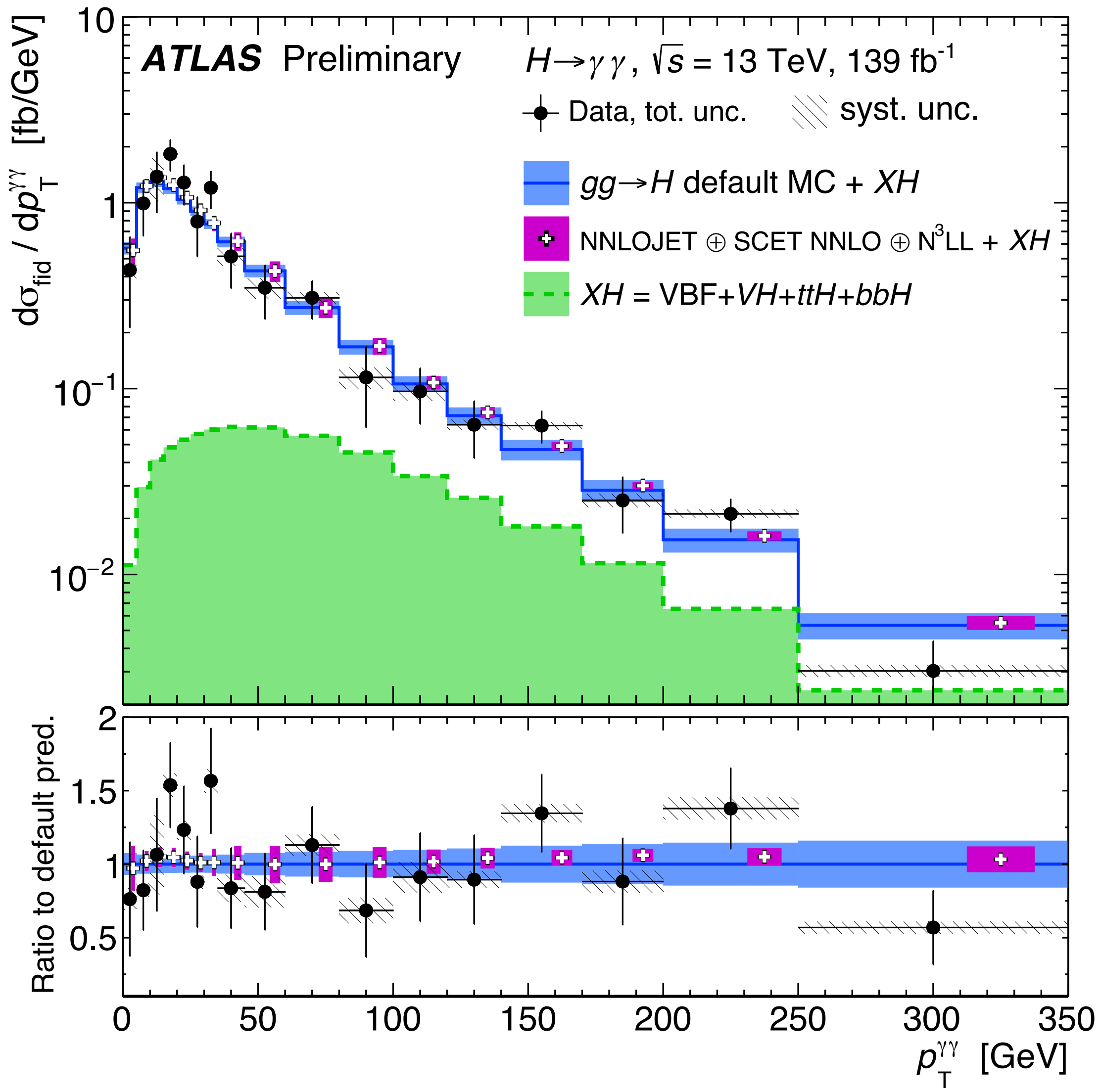
Source	Uncertainty (%)
Statistics	6.9
Signal extraction syst.	7.9
Photon energy scale & resolution	4.6
Background modelling (spurious signal)	6.4
Correction factor	2.6
Pile-up modelling	2.0
Photon identification efficiency	1.2
Photon isolation efficiency	1.1
Trigger efficiency	0.5
Theoretical modelling	0.5
Photon energy scale & resolution	0.1
Luminosity	1.7
Total	11.0

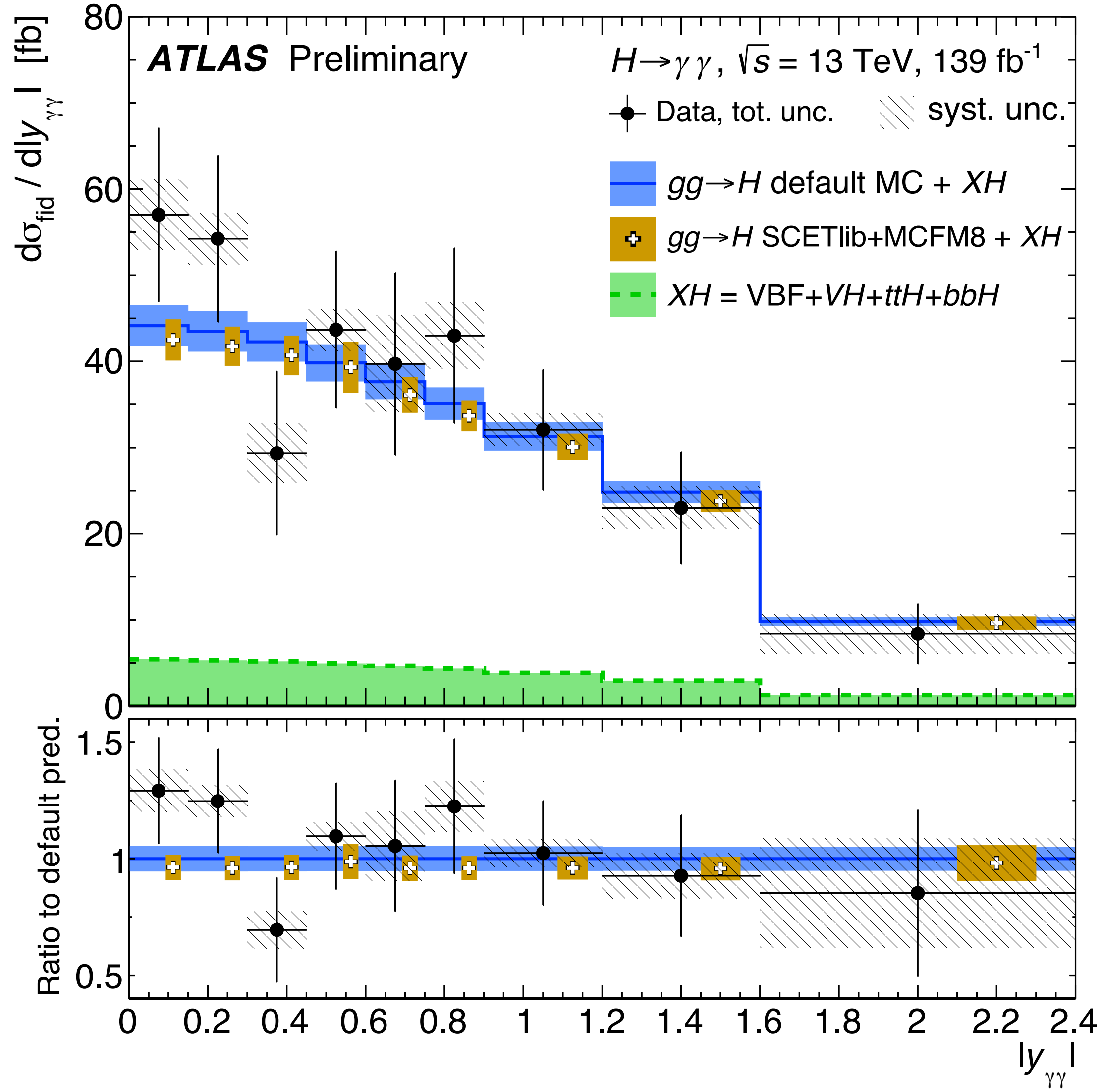
Differential cross-section vs $p_T^{\gamma\gamma}$ and $|y^{\gamma\gamma}|$

- High $p_T^{\gamma\gamma}$: sensitive to top-quark mass effects and new physics contributions
- Low-$p_T^{\gamma\gamma}$: sensitive to resummation effects; fine binning used to probe the Higgs-boson Yukawa coupling to the charm quark
- Rapidity is sensitive to the gluon distribution in the proton

Good agreement observed between data and the predictions

(Default ggF MC: Powheg NNLOPS scaled to N³LO)

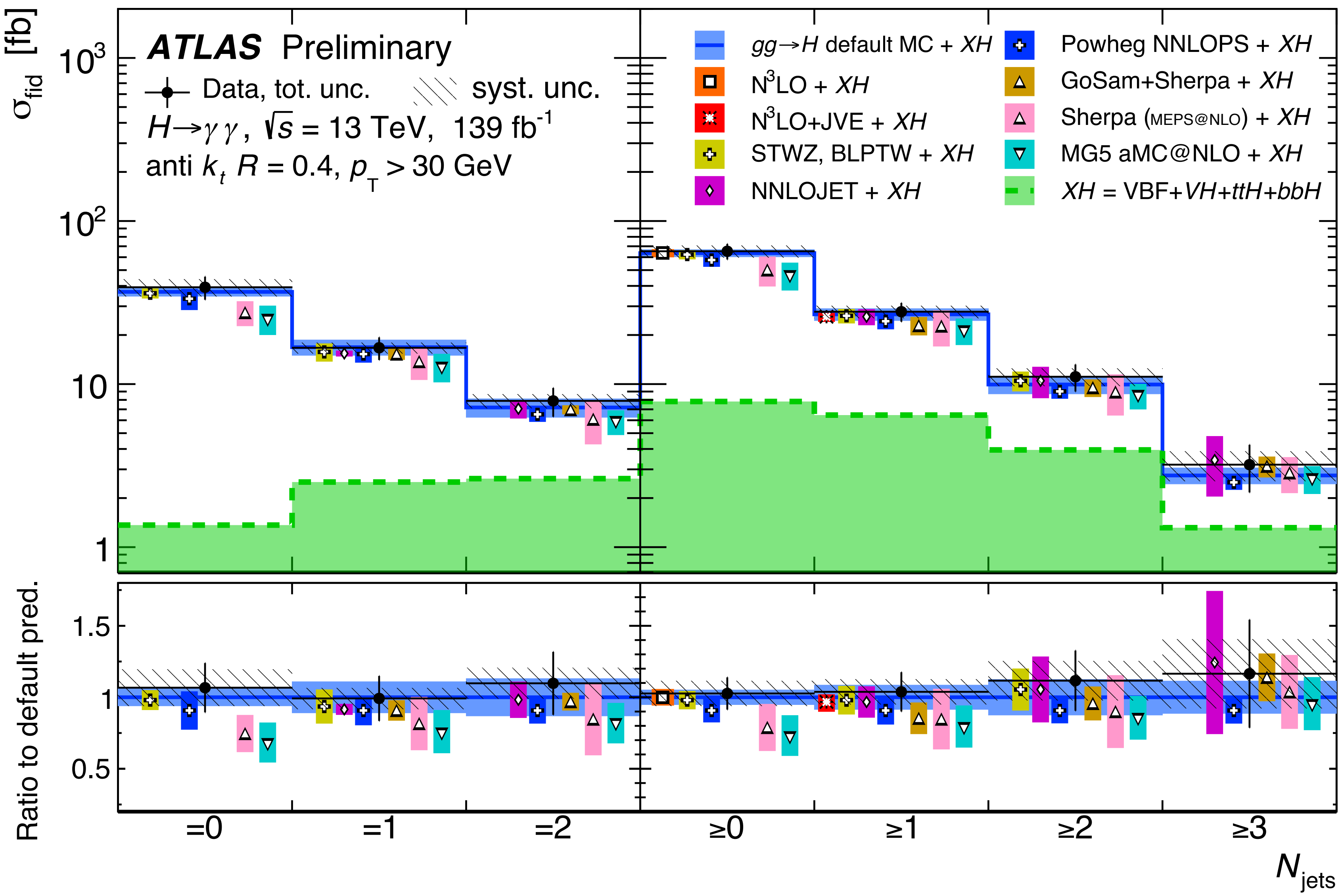




Cross-section vs N_{jets}

- Large systematic uncertainties from jet-energy scale and resolution, 6%-25%
- Comparison for multiple ggF predictions added to the same *XH* component
- Comparison in bins of exclusive and inclusive jet multiplicity

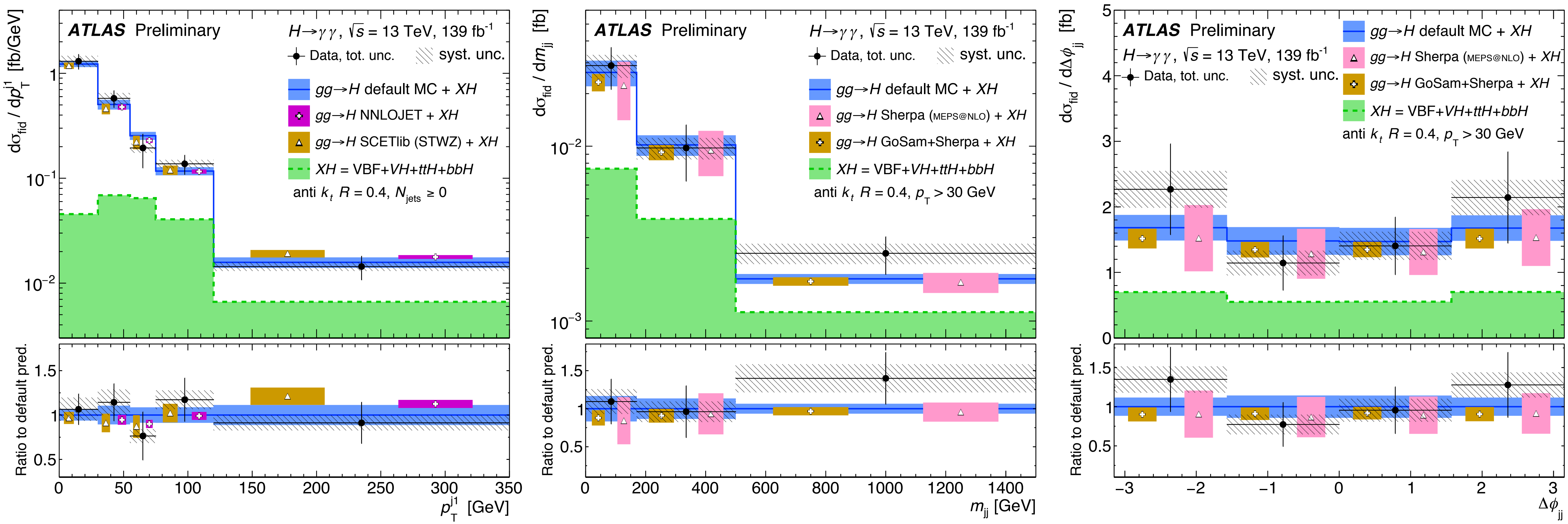
Good agreement seen with the predictions; N³LO normalization improves agreement



Differential cross-section vs p_T^{j1}, m_{jj}, $\Delta\phi_{jj}$

- Observables with sensitivity to new physics
    - p_T^{j1}: jet leading in p_T
    - m_{jj} (*for the two leading-p_T jets*): sensitivity to VBF in the high mass bin
    - $\Delta\phi_{jj}=\phi^{j1}-\phi^{j2}$, $\eta^{j1}>\eta^{j2}$ (*for the two leading-p_T jets*): sensitivity to CP properties of the Higgs boson

Good agreement observed; no significant excess that would indicate non-SM behaviour



EFT interpretation using the differential cross-sections

- Dim-6 extension of the SM Lagrangian in the SILH (*Higgs Effective Lagrangian*) and Warsaw (*SMEFT*) bases

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{SM}} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)}$$

  - *Wilson* coefficients c_i quantify the strength of the new interactions (CP-even/odd)

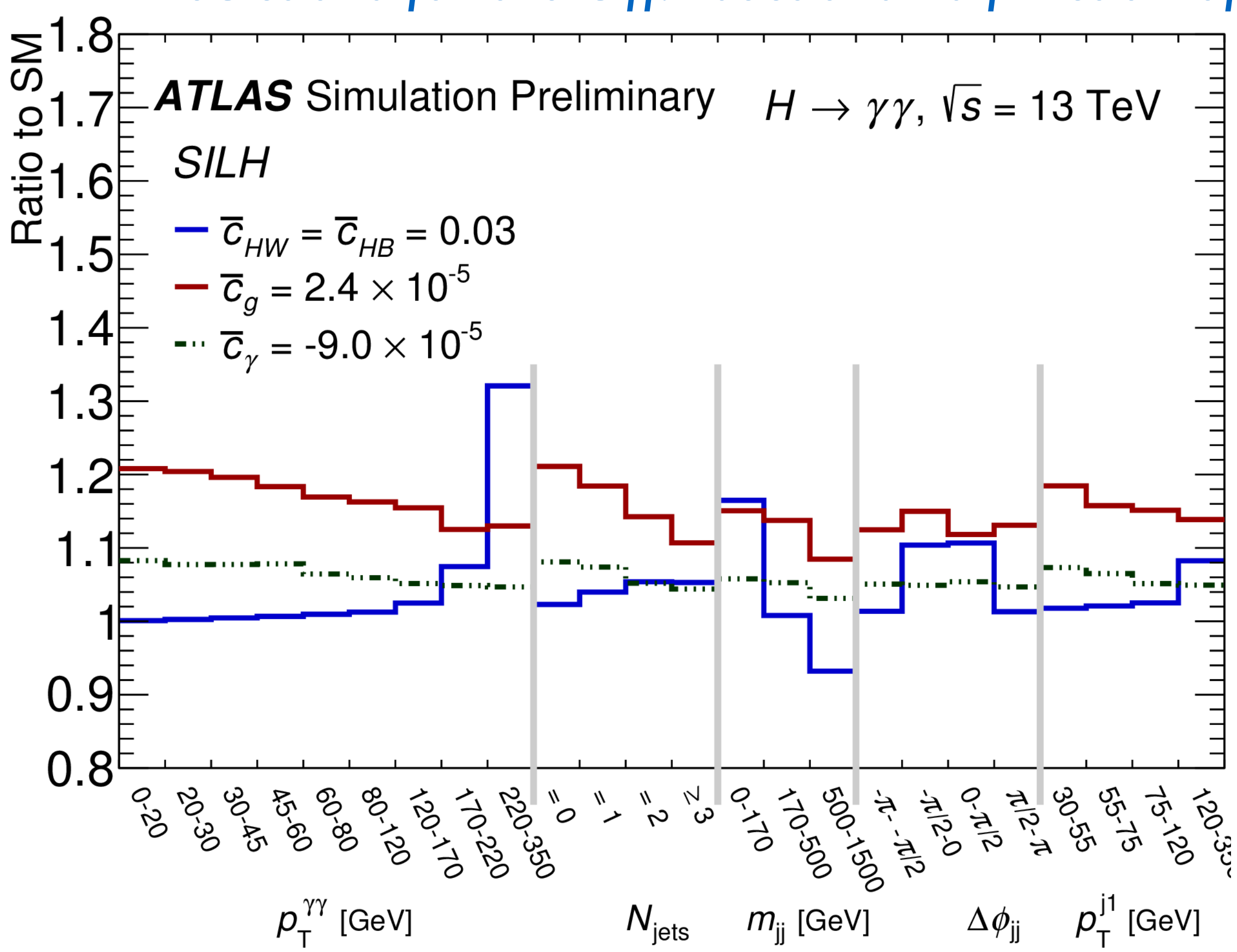
$$\mathcal{L}_{\text{eff}}^{\text{SILH}} \supset \bar{c}_g O_g + \bar{c}_\gamma O_\gamma + \bar{c}_{HW} O_{HW} + \bar{c}_{HB} O_{HB} + \tilde{c}_g \widetilde{O}_g + \tilde{c}_\gamma \widetilde{O}_\gamma + \tilde{c}_{HW} \widetilde{O}_{HW} + \tilde{c}_{HB} \widetilde{O}_{HB}$$

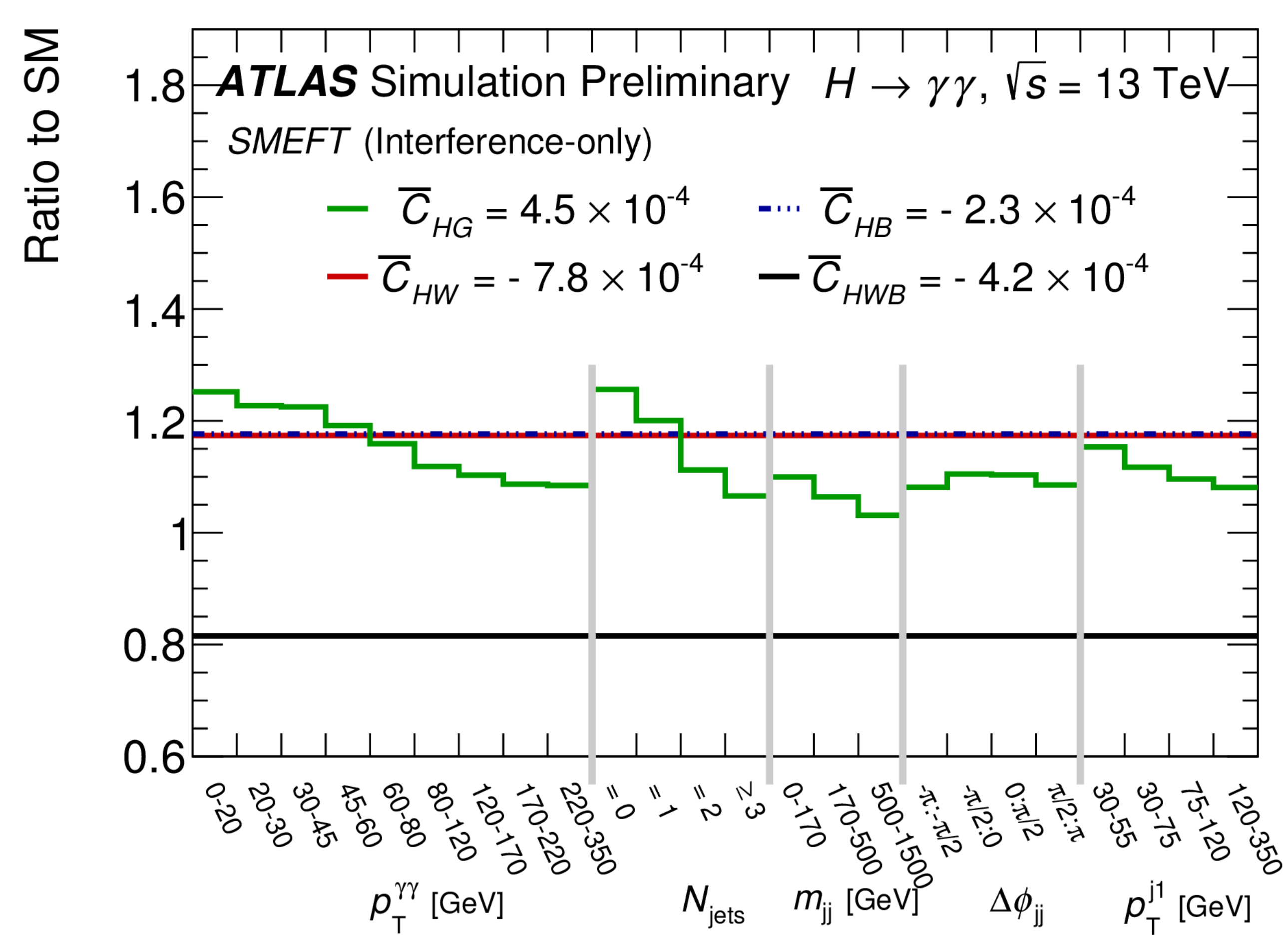
$$\mathcal{L}_{\text{eff}}^{\text{SMEFT}} \supset \bar{C}_{HG} O'_g + \bar{C}_{HW} O'_{HW} + \bar{C}_{HB} O'_{HB} + \bar{C}_{HWB} O'_{HWB} + \widetilde{C}_{HG} \widetilde{O}'_g + \widetilde{C}_{HW} \widetilde{O}'_{HW} + \widetilde{C}_{HB} \widetilde{O}'_{HB} + \widetilde{C}_{HWB} \widetilde{O}'_{HWB}$$

$$\bar{C}_i \equiv C_i v^2/\Lambda^2$$

- Fiducial measurements can probe the strength of new interactions

Predictions for the diff. xsections as function of c_i, from MadGraph (SILH) and SMEFTsim (Warsaw)





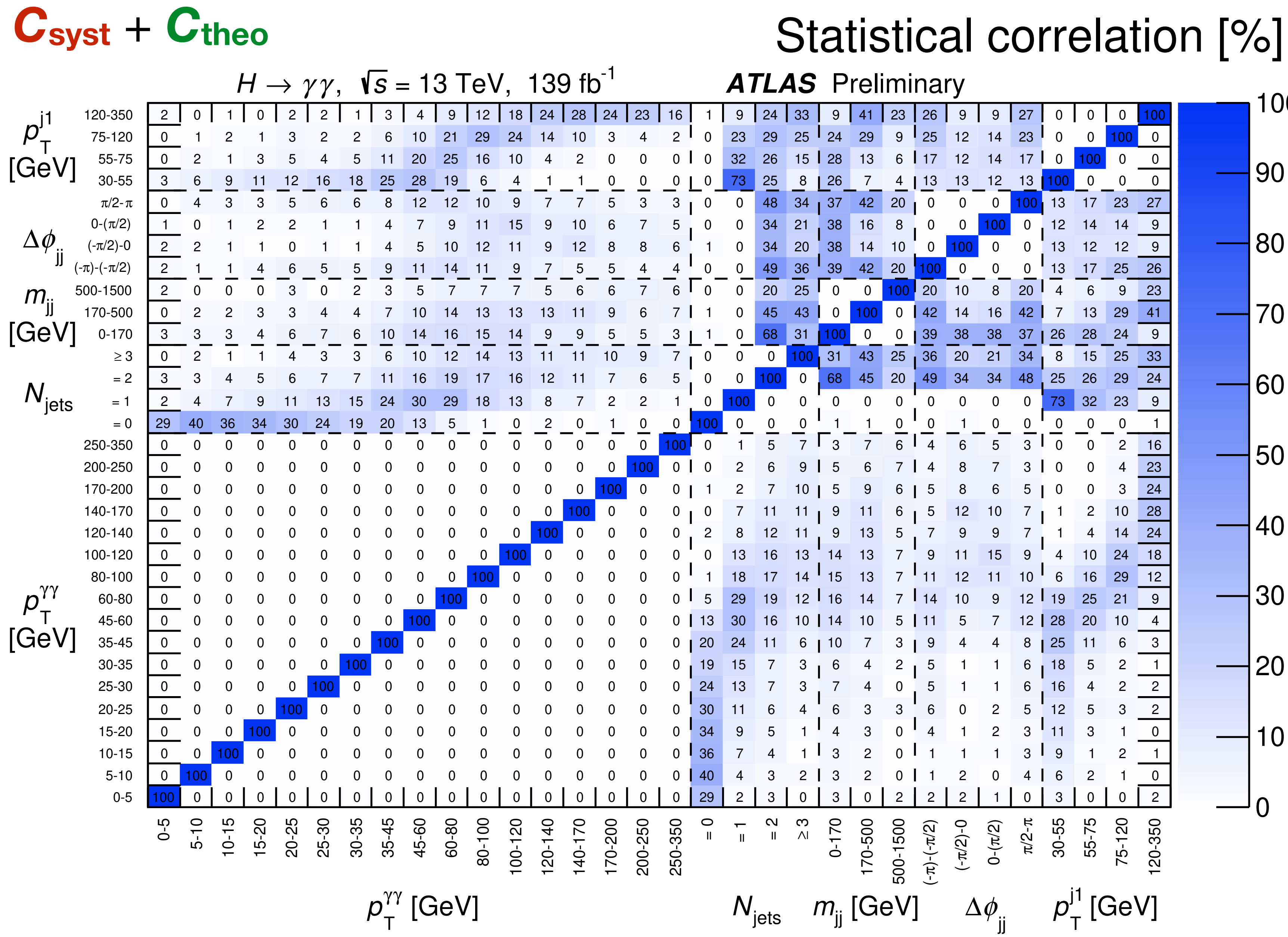
EFT interpretation using the differential cross-sections

- Procedure to set limits on the Wilson coefficients:

$$\mathcal{L} = \frac{1}{\sqrt{(2\pi)^k\,|C|}} \exp\left(-\frac{1}{2}\left(\vec{\sigma}_{\mathrm{data}} - \vec{\sigma}_{\mathrm{pred}}\right)^T C^{-1} \left(\vec{\sigma}_{\mathrm{data}} - \vec{\sigma}_{\mathrm{pred}}\right)\right)$$

- C: covariance matrix: C_{stat} + C_{syst} + C_{theo}

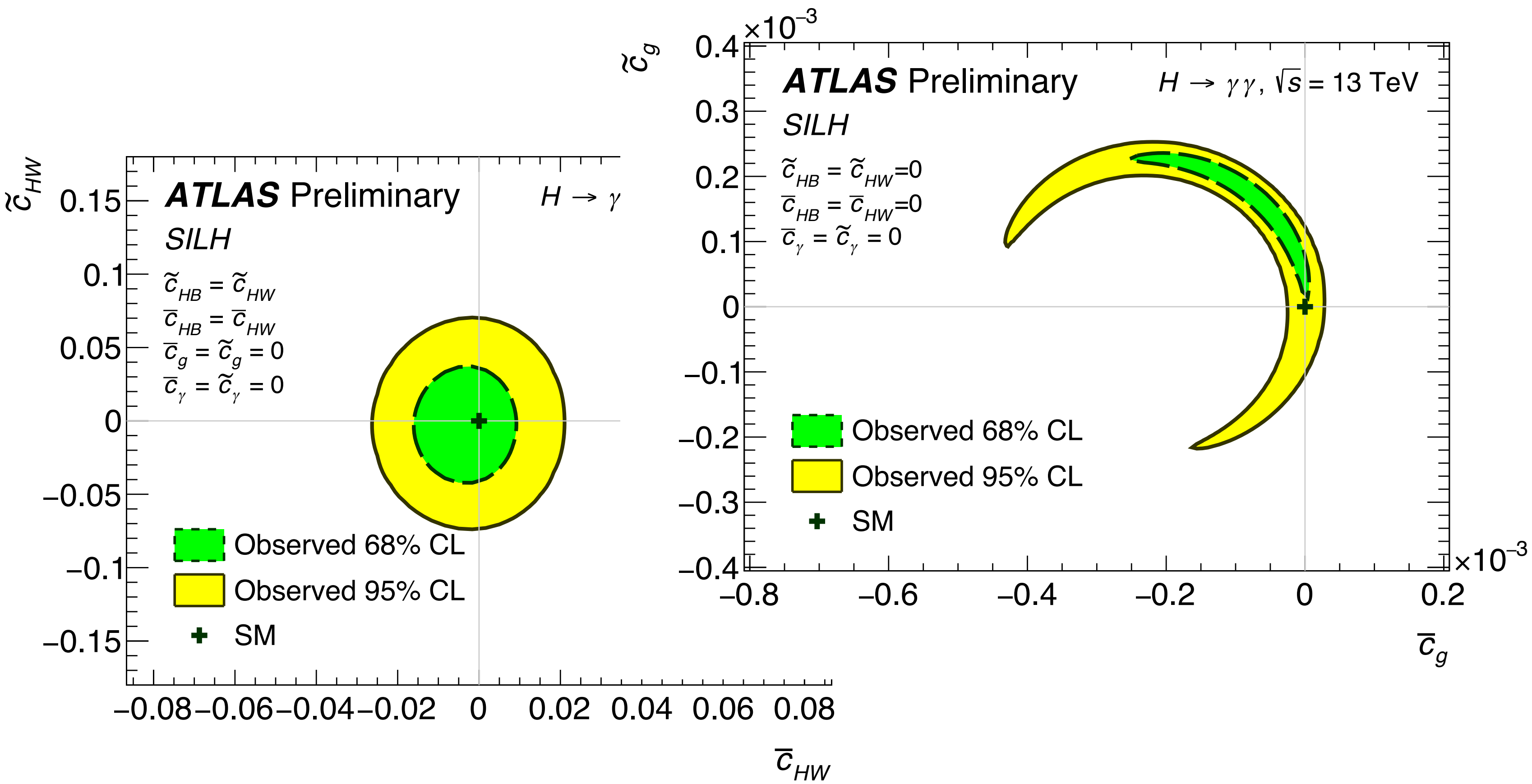
- C_{stat} built from statistical correlations between bins
- C_{syst} built from experimental uncertainties of the measured xsections
- C_{theo} built from theoretical uncertainties on the predicted xsections



EFT interpretation using the differential cross-sections

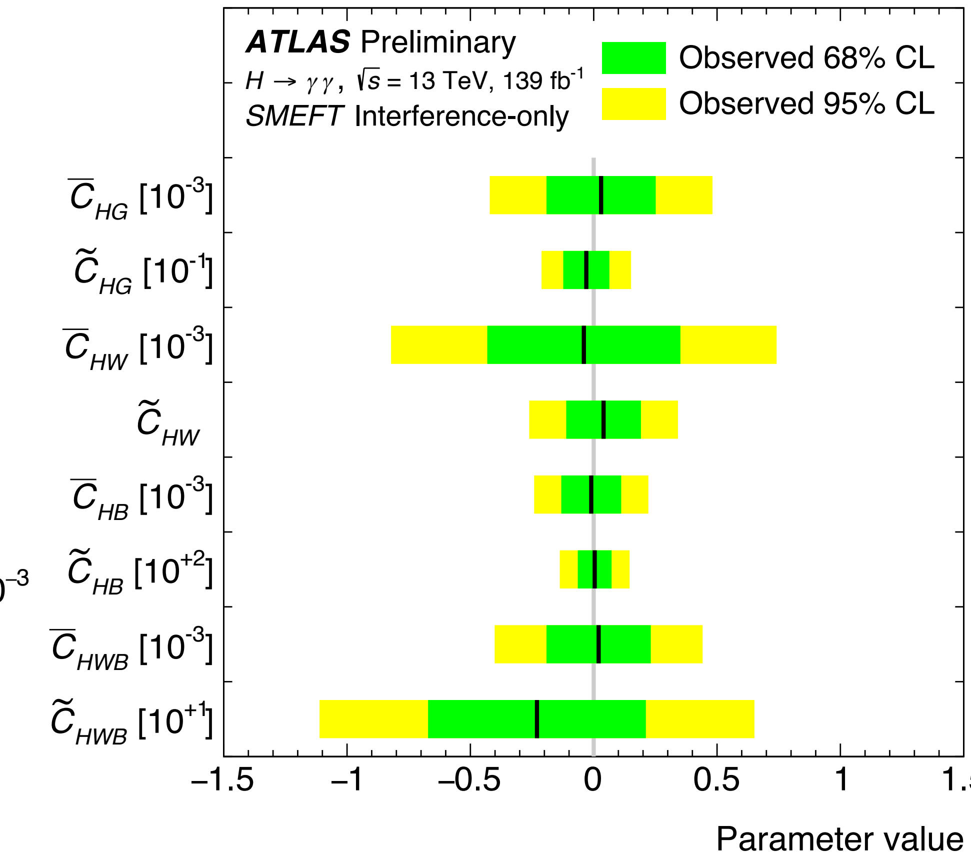
- 1d and 2d limits on SILH coefficients

Fitting one (or two) coeff., with others fixed to zero



- 1d limits on SMEFT coefficients

Interference of dim.6-SM operators studied separately



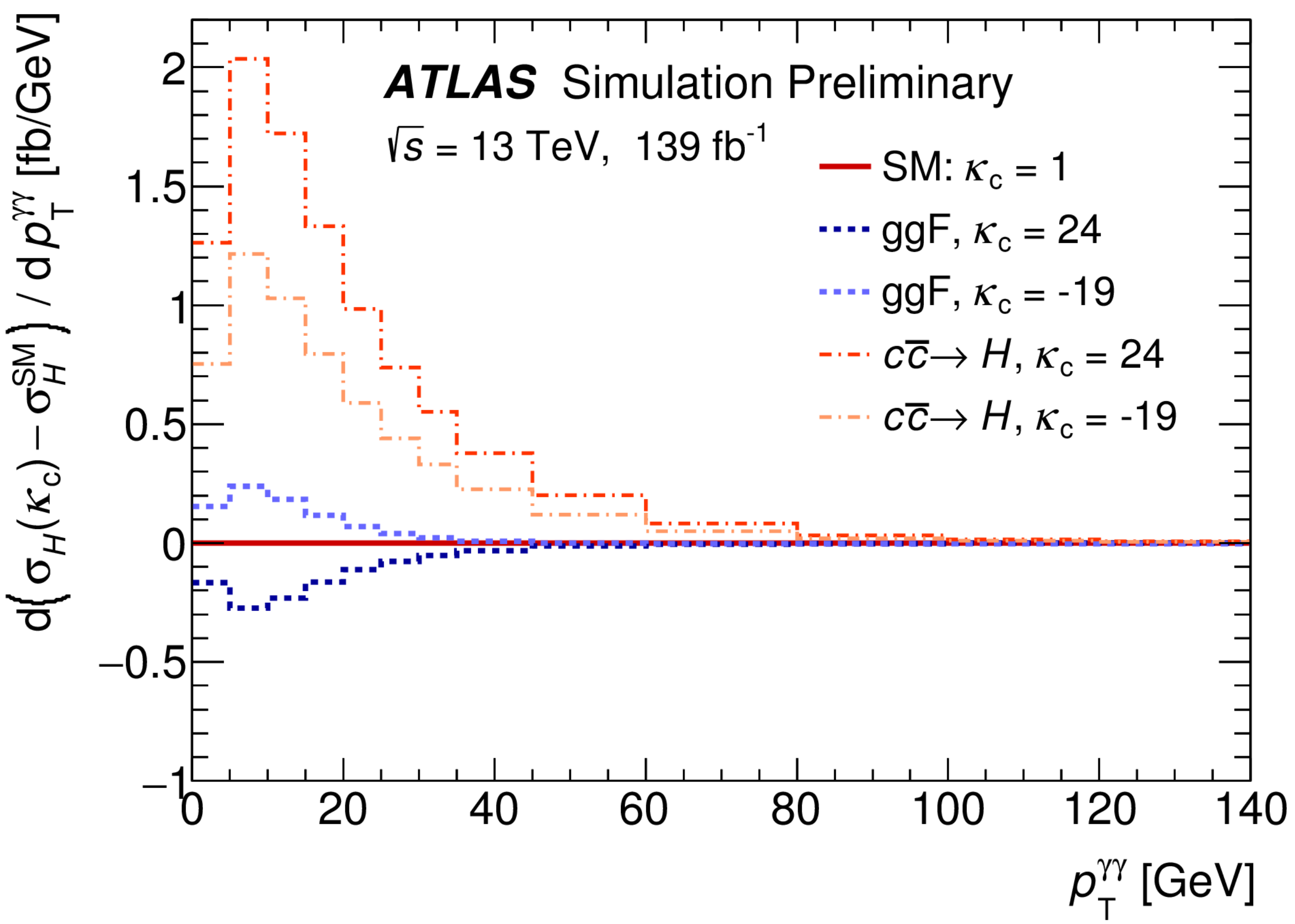
Given high-level of compatibility of cross-section measurements with the SM, setting narrow limits around the SM expectation (c_i=0)

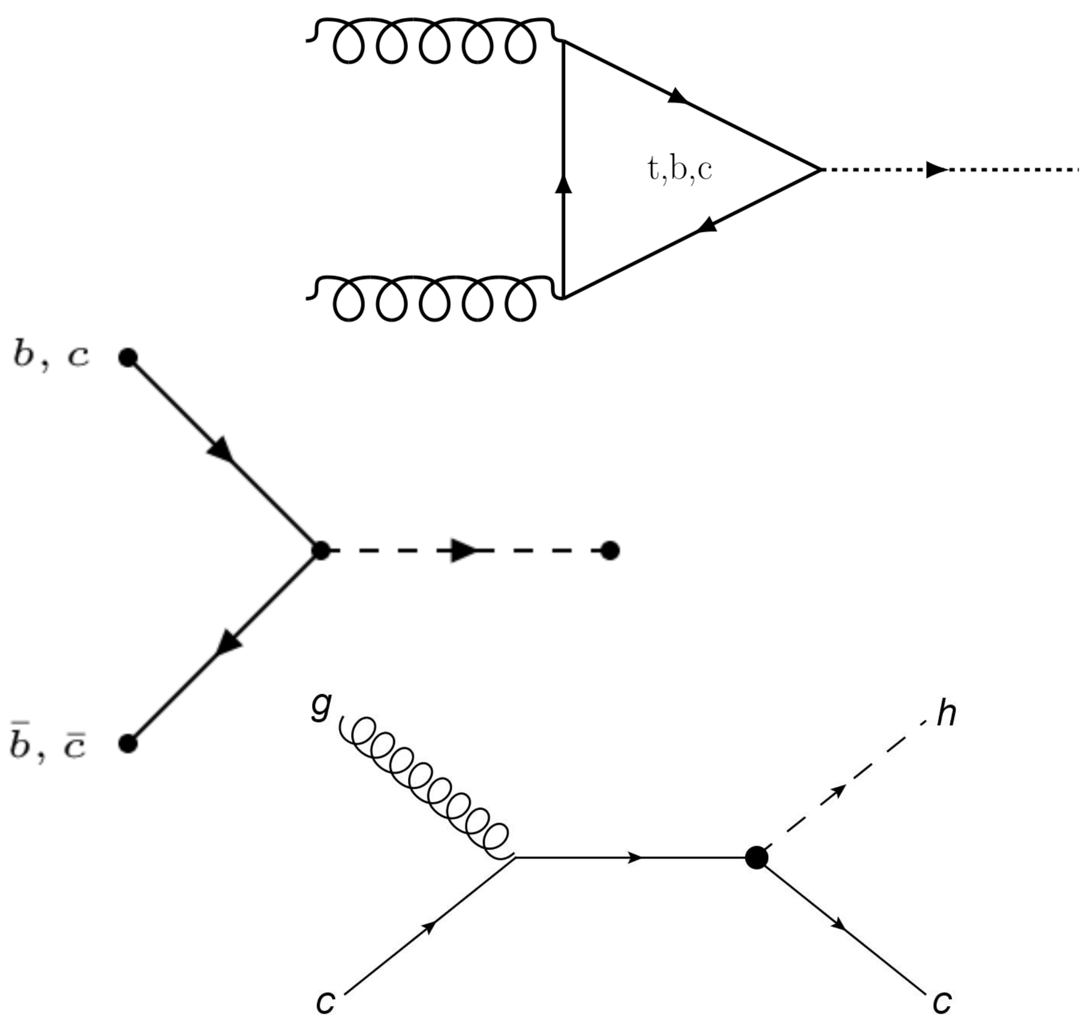
- SILH: ×2 improvement compared to last ATLAS results with 36 fb^{-1}

- SMEFT/Warsaw: First ATLAS results

charm-Yukawa interpretation of $p_T^{\gamma\gamma}$

- Limit on the $\kappa_c = Y_c/Y_c^{SM}$ modification of the charm coupling with an indirect approach
- Modelling the effect of κ_c on the **shape of the $p_T^{\gamma\gamma}$ distribution**, assuming:
  - Modification on gg→H (from *c* in the loop) cross section — from RadISH (NNLL+NLO)
  - Modification on cc/cg→H cross section — from MadGraph (NLO)

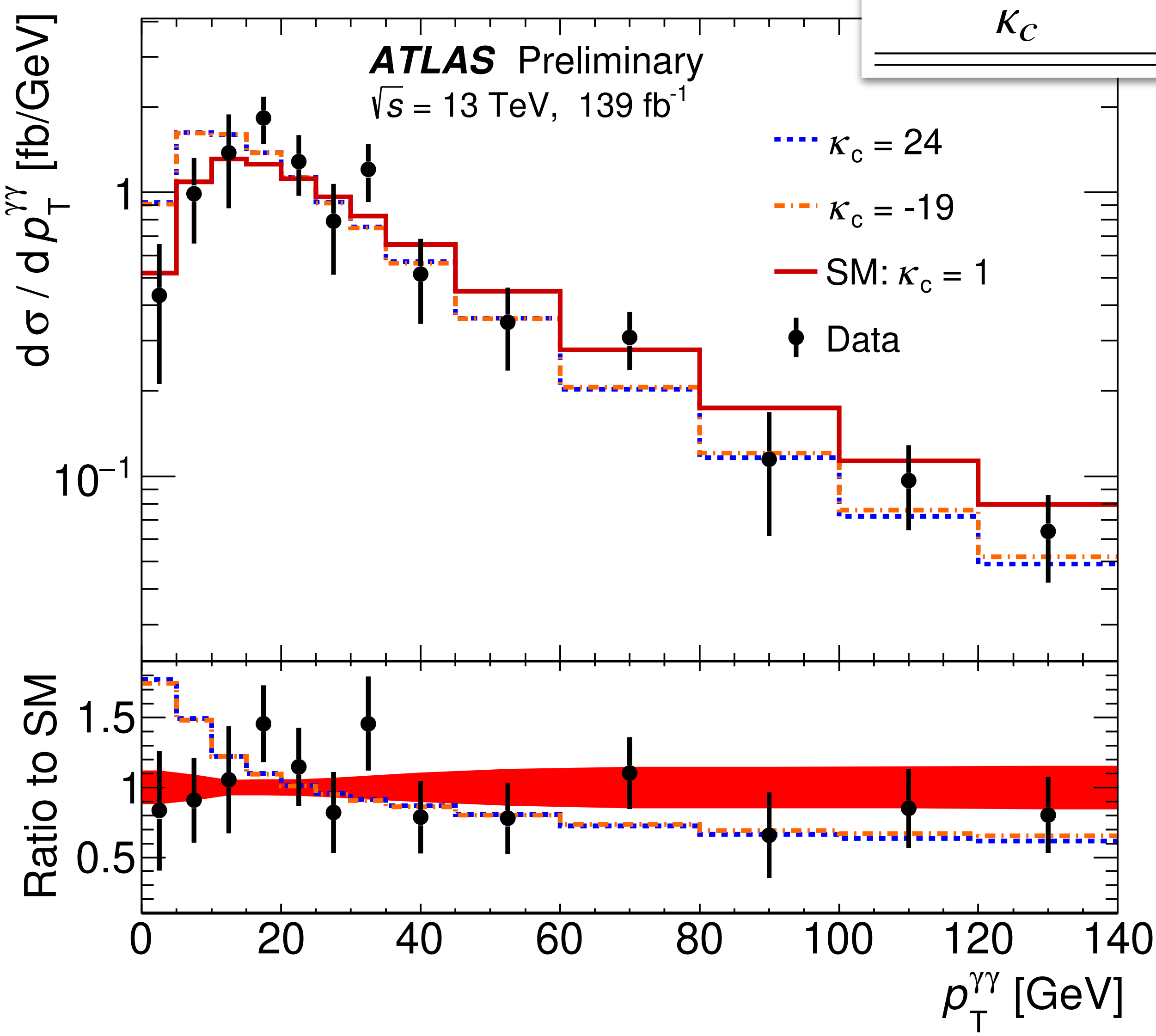




charm-Yukawa interpretation of $p_T^{\gamma\gamma}$

- Indirect approach using the shape of $p_T^{\gamma\gamma}$ (normalization is profiled)
  - Limited by statistical uncertainty
  - Big loss of sensitivity by not modelling the effect of κ_c on the branching ratio, at the benefit of a simpler model with fewer assumptions

Coefficient	Observed 95% CL limit	Expected 95% CL limit
κ_c	$[-19, 24]$	$[-15, 19]$



Less stringent than direct H→cc searches but still complementary.

Source	$\delta\kappa_c$ ($^{+\text{up}}_{-\text{down}}$)
Stat.	$^{+10.2}_{-8.2}$
Exp. syst.	$^{+3.0}_{-2.8}$
QCD scale (ggF)	$^{+5.5}_{-5.4}$
QCD scale ($c\bar{c} \to H$)	$^{+0.8}_{-0.2}$
PDF (ggF)	$^{+0.5}_{-0.5}$
PDF ($c\bar{c} \to H$ & $b\bar{b} \to H$)	$^{+0.3}_{-0.1}$
Parton shower ($c\bar{c} \to H$)	$^{+1.5}_{-0.7}$
Total	$^{+12.2}_{-10.3}$

Summary and conclusions

- Preliminary measurements and interpretations with the full Run-2 dataset
- Integrated fiducial cross section becomes systematically limited; in agreement with the SM prediction
- Model-independent differential fiducial cross-section measurements still statistically limited
    - Useful comparisons with higher-order QCD calculations
- Interpretations in the context on an effective Lagrangian
    - Now exploiting CP-sensitive variables, i.e. $\Delta\phi_{jj}$
    - Improved limits with SILH basis compared to previous analyses thanks to the larger dataset
    - First ATLAS limits on the SMEFT/Warsaw basis
- Limits on charm Yukawa coupling of the Higgs boson, exploiting only shape information for minimal model dependence

Backup

SMEFT - Warsaw basis

- Terms contributing to the cross section in the dim.6 EFT expansion:

$$\sigma \propto |\mathcal{M}_{\mathrm{EFT}}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + |\mathcal{M}_{\mathrm{d6}}|^2 + 2Re(\mathcal{M}^*_{\mathrm{SM}}\mathcal{M}_{\mathrm{d6}})$$

$$\frac{c_i^2}{\Lambda^4} \qquad \frac{c_i}{\Lambda^2}$$

For small values of c_i, the interference term dominates => σ has linear dependence on c_i

- Useful feature for interpolating between different values of c_i
- Interference term disappears for CP-odd operators; tiny modification of all observables except $\Delta\phi_{jj}$
- Results are provided considering both the linear and the quadratic terms
    - Useful for considerations of the EFT validity regarding its dim.6 truncation