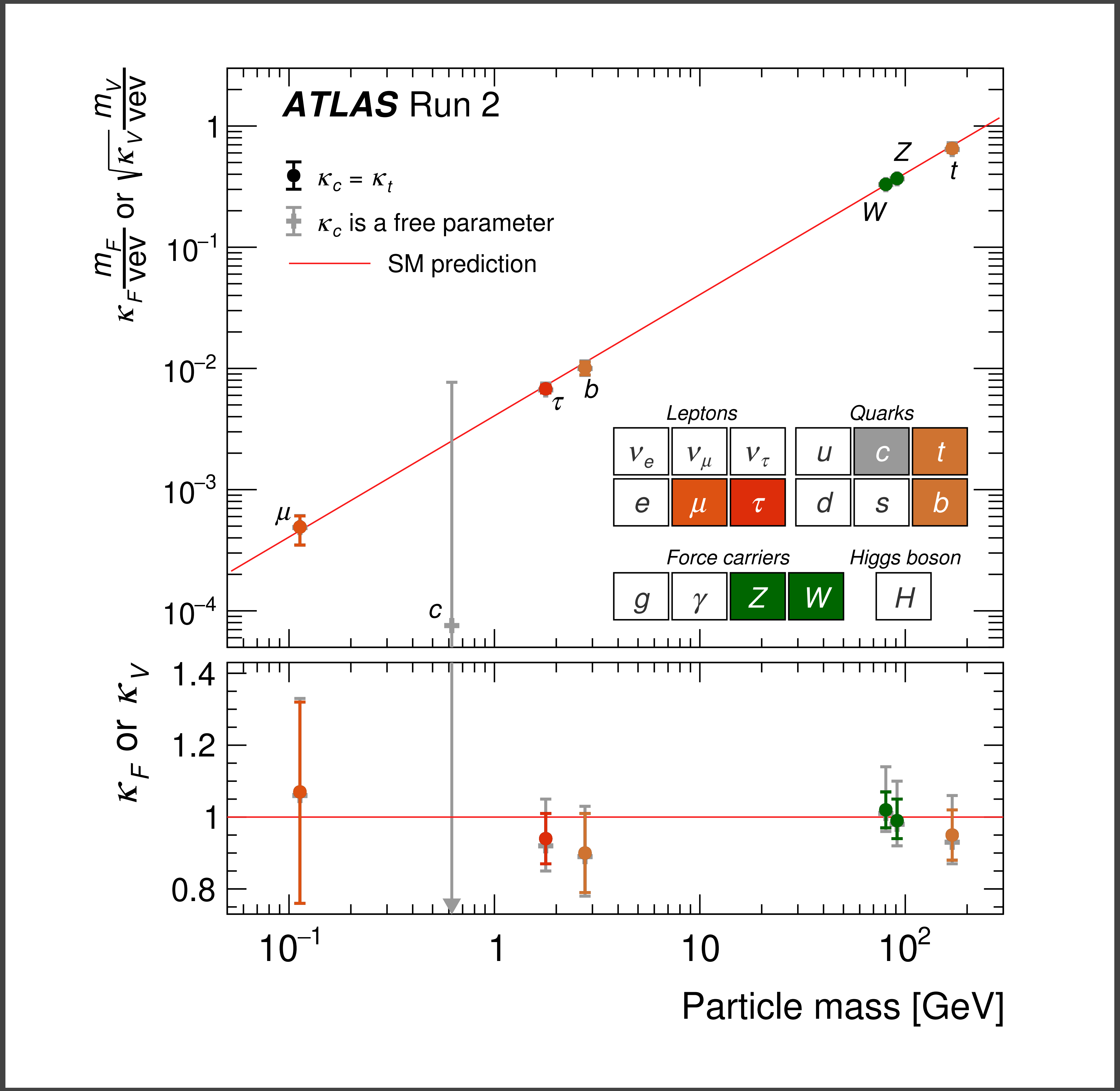
Measurements of the Higgs boson fiducial and differential cross sections at the ATLAS experiment

Yasuyuki Horii (Nagoya), on behalf of the ATLAS Collaboration

XI International Conference on New Frontiers of Physics, 6 Sep. 2022

Introduction

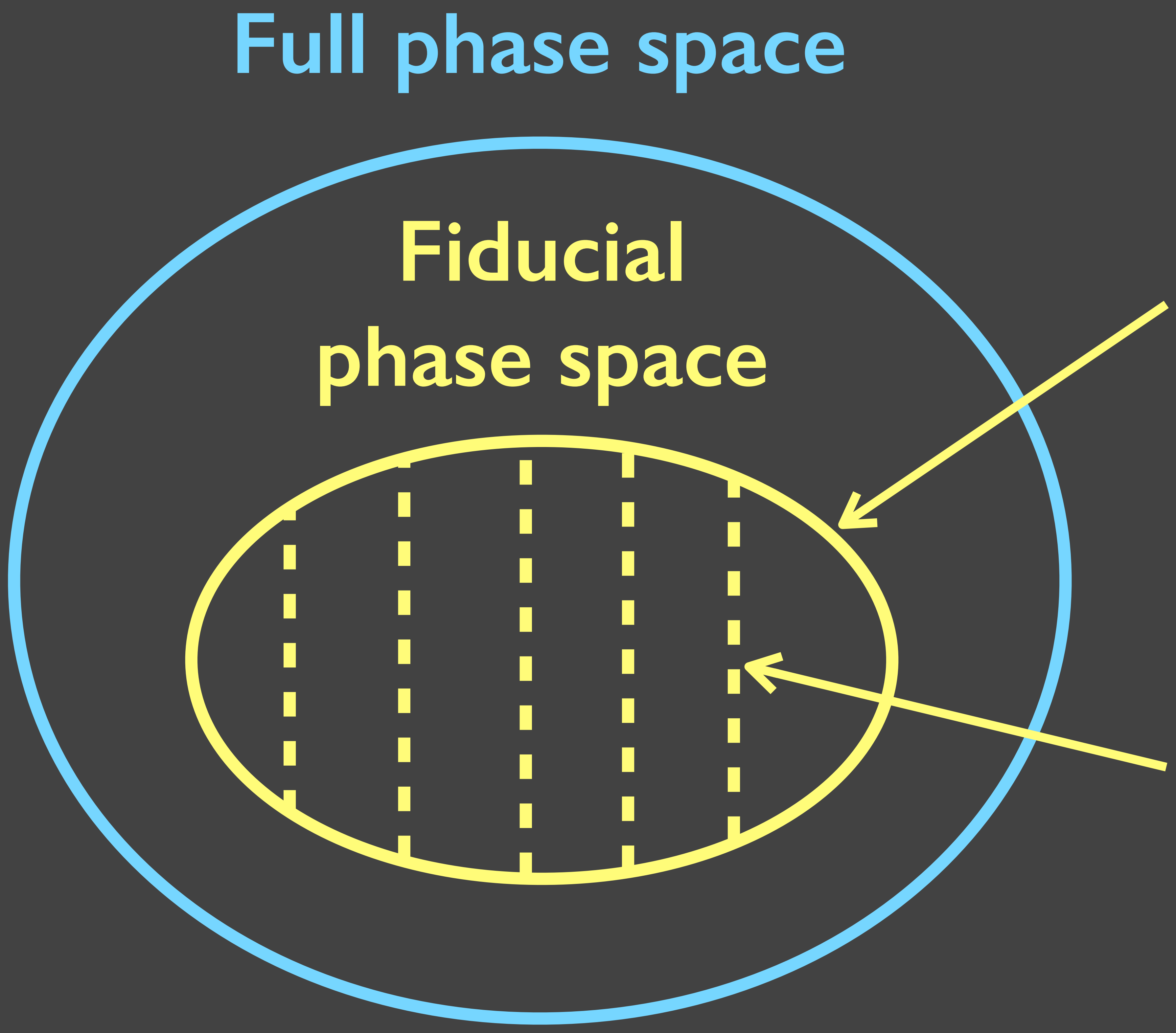
- Higgs boson plays a central role in the Standard Model (SM).
  - Electroweak symmetry breaking gives rise to massive W/Z bosons.
  - Yukawa couplings are introduced to provide massive fermions.
- Fiducial and differential cross section — test of the Higgs boson properties and probe for physics beyond the SM (BSM).



Nature 607, 52–59 (2022)

Fiducial Cross Sections

Fiducial phase space defined to closely match the analysis acceptance
Less model-dependent measurements — aim at minimising extrapolations and SM assumptions



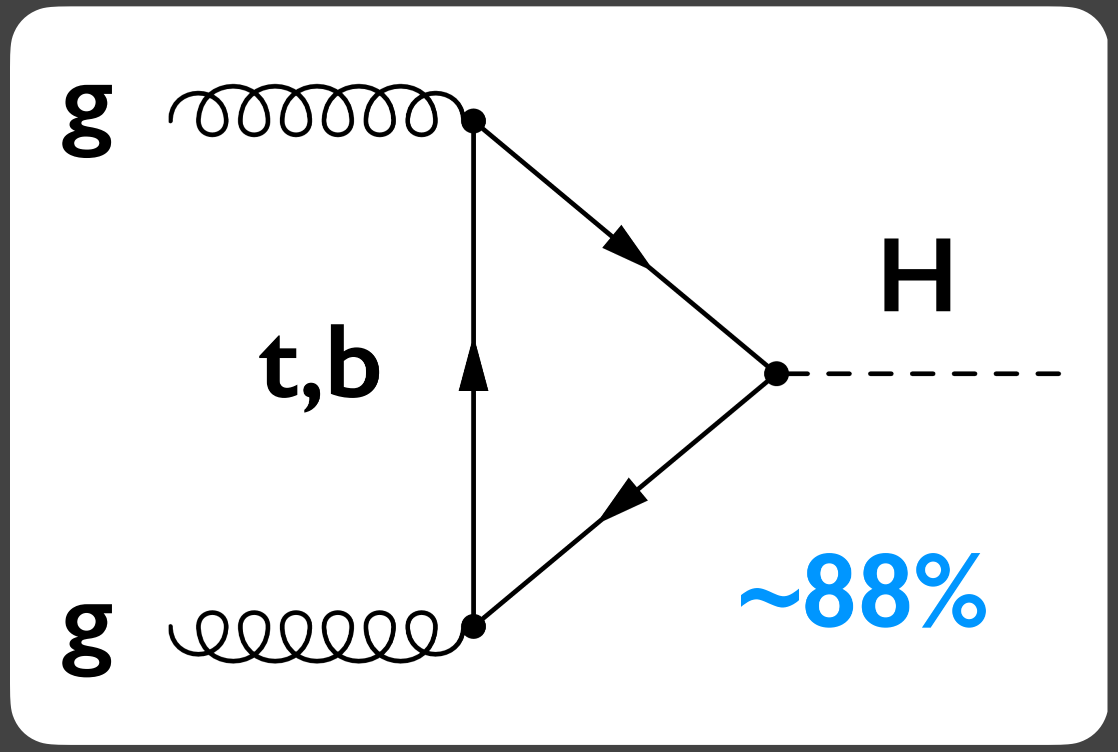
Inclusive fiducial cross section

Differential fiducial cross section
in bins of a variable (p_T^H, N_{jets}, …)
typically unfolded to particle-level quantities
— probe of pQCD, Yukawa coupling, BSM, …

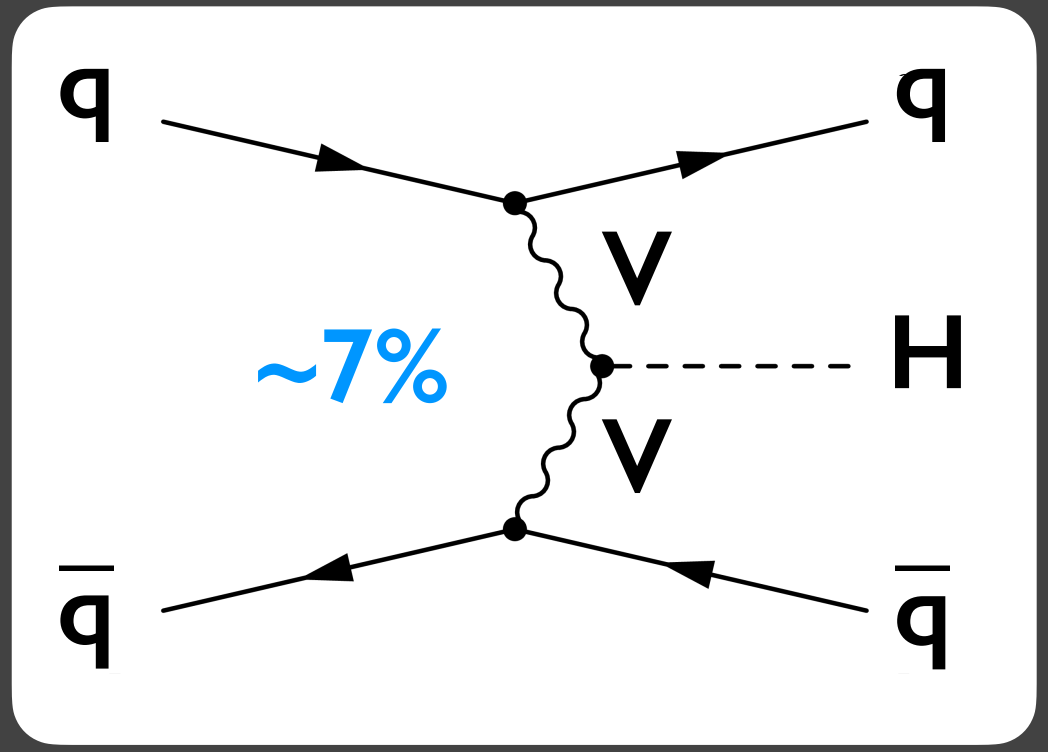
SM Higgs Production and Decay

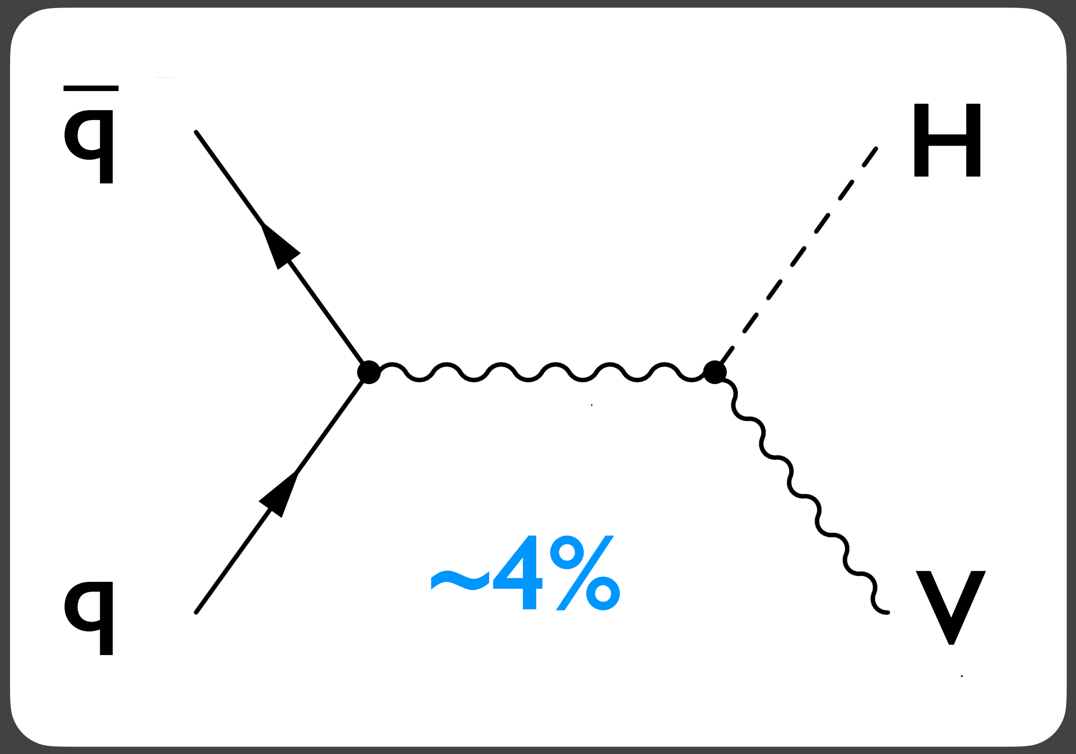
Various production and decay modes can be probed by fiducial/differential cross sections.

Gluon-gluon fusion (ggF)

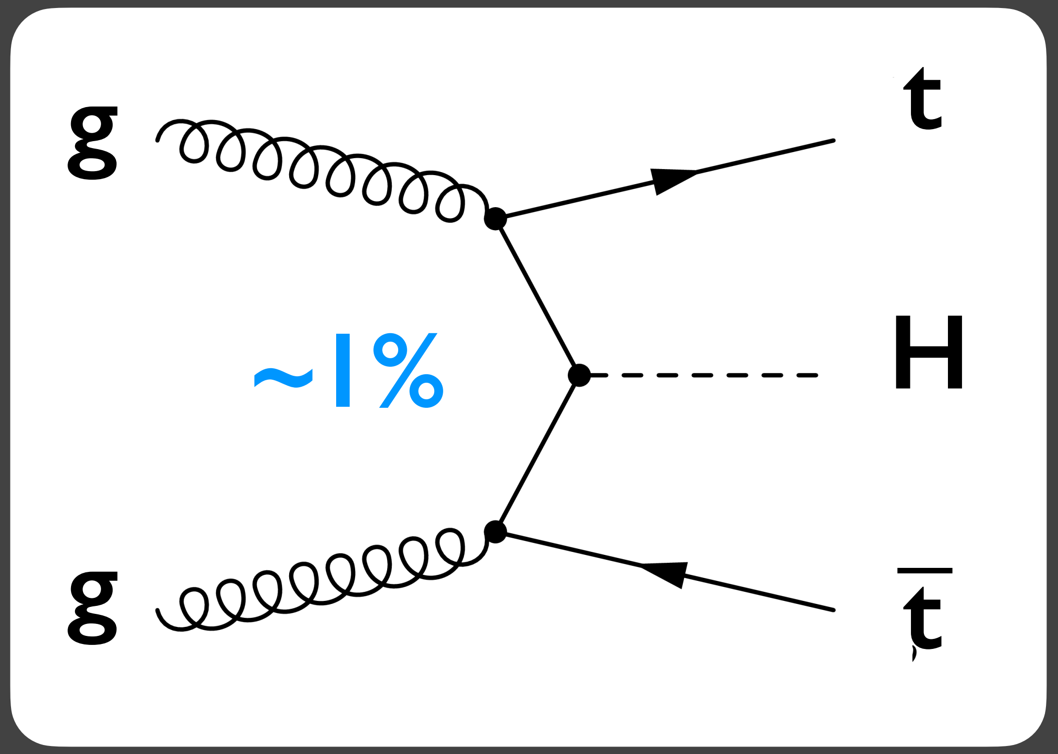


Vector-boson fusion (VBF)

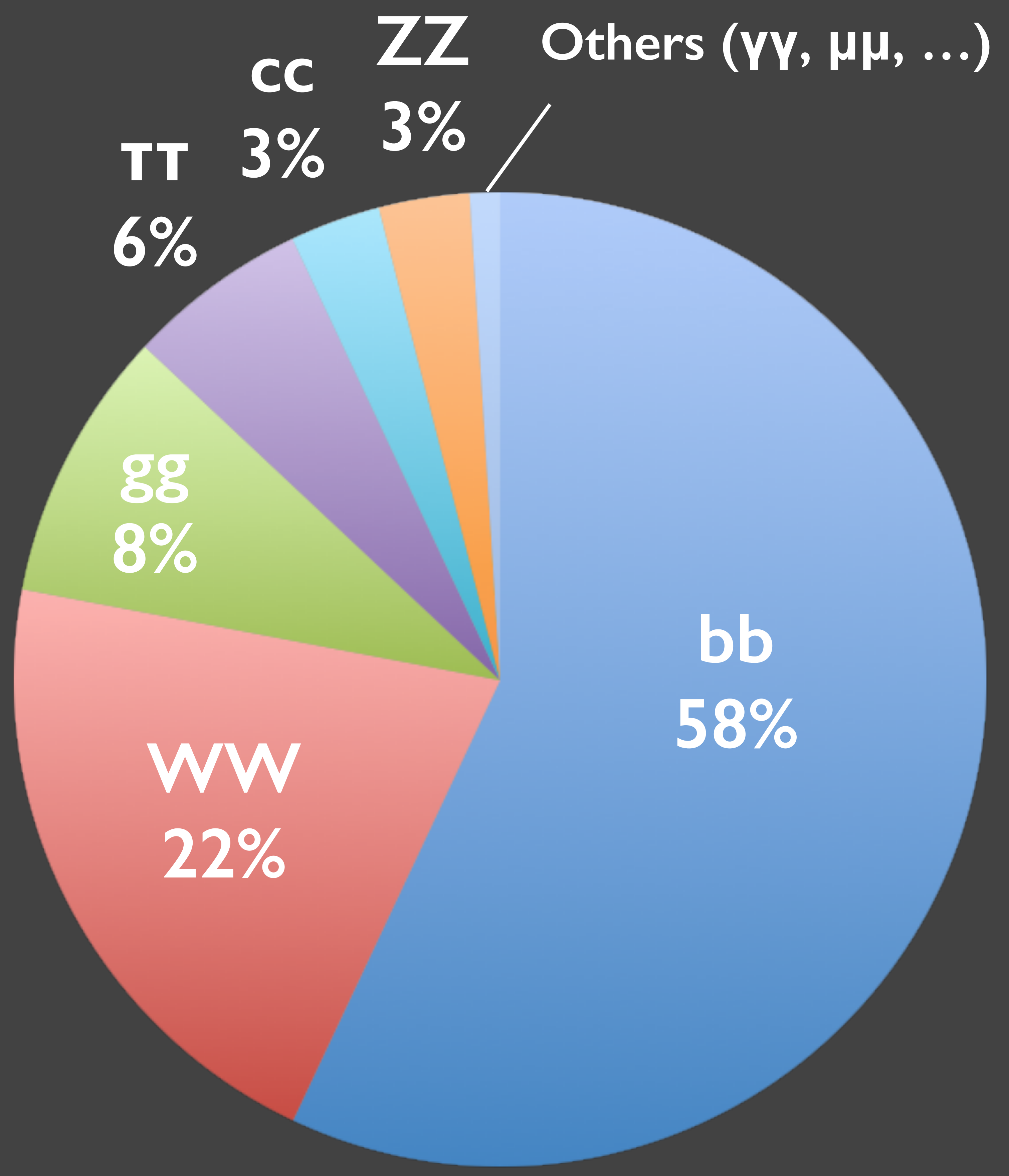




Associated production with vector boson (VH)



Associated production with top quark pair (ttH)

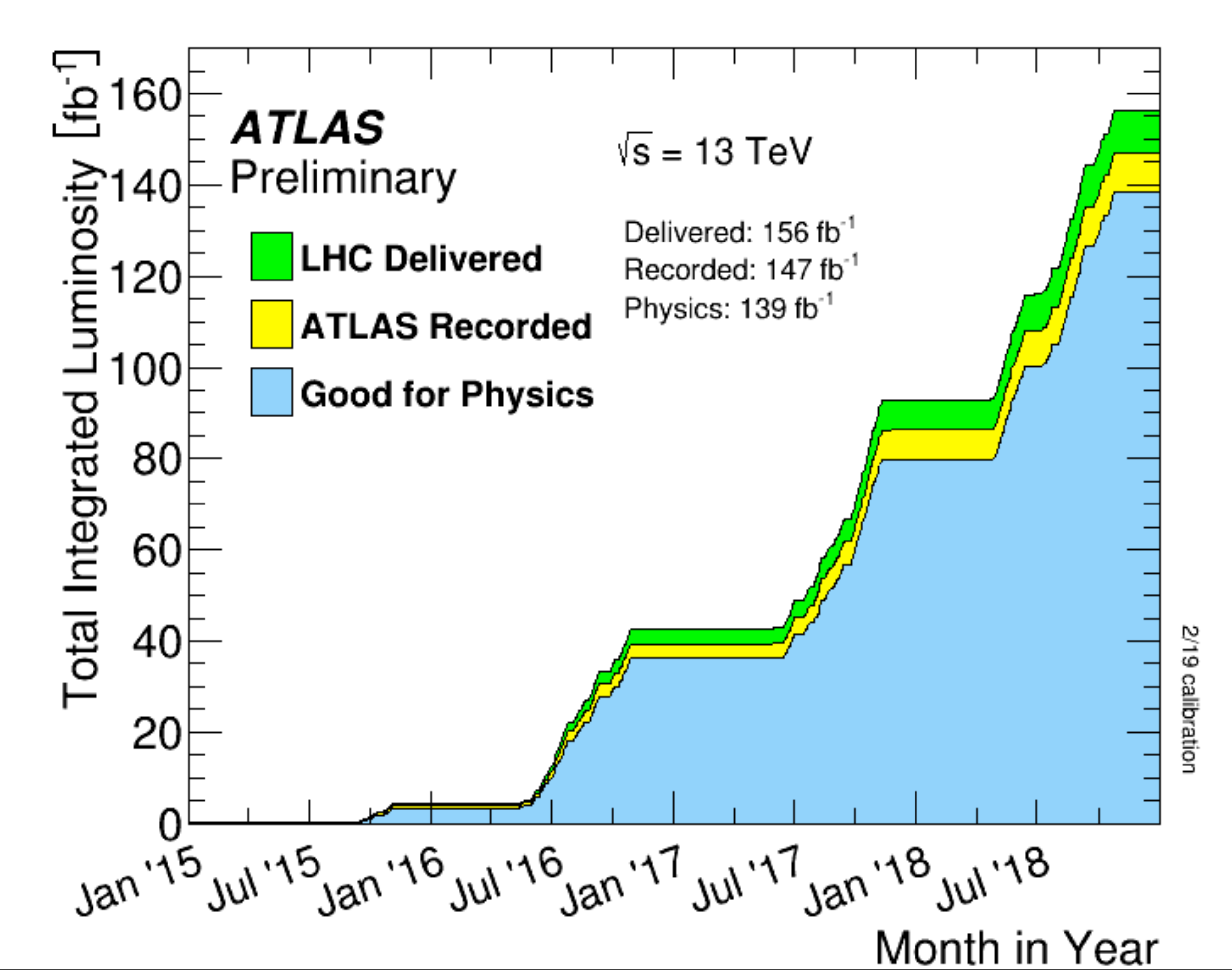


13 TeV, m_H = 125 GeV

Latest Results from ATLAS

Focus on the results obtained with the full Run 2 data sample

Higgs boson decay	Reference
H→ZZ	Eur. Phys. J. C 80, 942 (2020)
H→γγ	JHEP 08 (2022) 027
H→ZZ + H→γγ	arXiv:2207.08615
H→bb	Phys. Rev. D 105, 092003 ATLAS-CONF-2022-015



13 TeV, ~140 fb^{-1}

Example of Definitions (H→ZZ)

Fiducial phase space requirements

Leptons and jets	
Leptons	$p_\mathrm{T} > 5$ GeV, $\lvert\eta\rvert < 2.7$
Jets	$p_\mathrm{T} > 30$ GeV, $\lvert y\rvert < 4.4$
Lepton selection and pairing	
Lepton kinematics	$p_\mathrm{T} > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection (at most one quadruplet per event)	
Mass requirements	50 GeV$< m_{12} <$ 106 GeV and 12 GeV $< m_{34} <$ 115 GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
Lepton/Jet separation	$\Delta R(\ell_i, \mathrm{jet}) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Mass window	105 GeV $< m_{4\ell} <$ 160 GeV
If extra lepton with $p_\mathrm{T} > 12$ GeV	Quadruplet with largest matrix element value

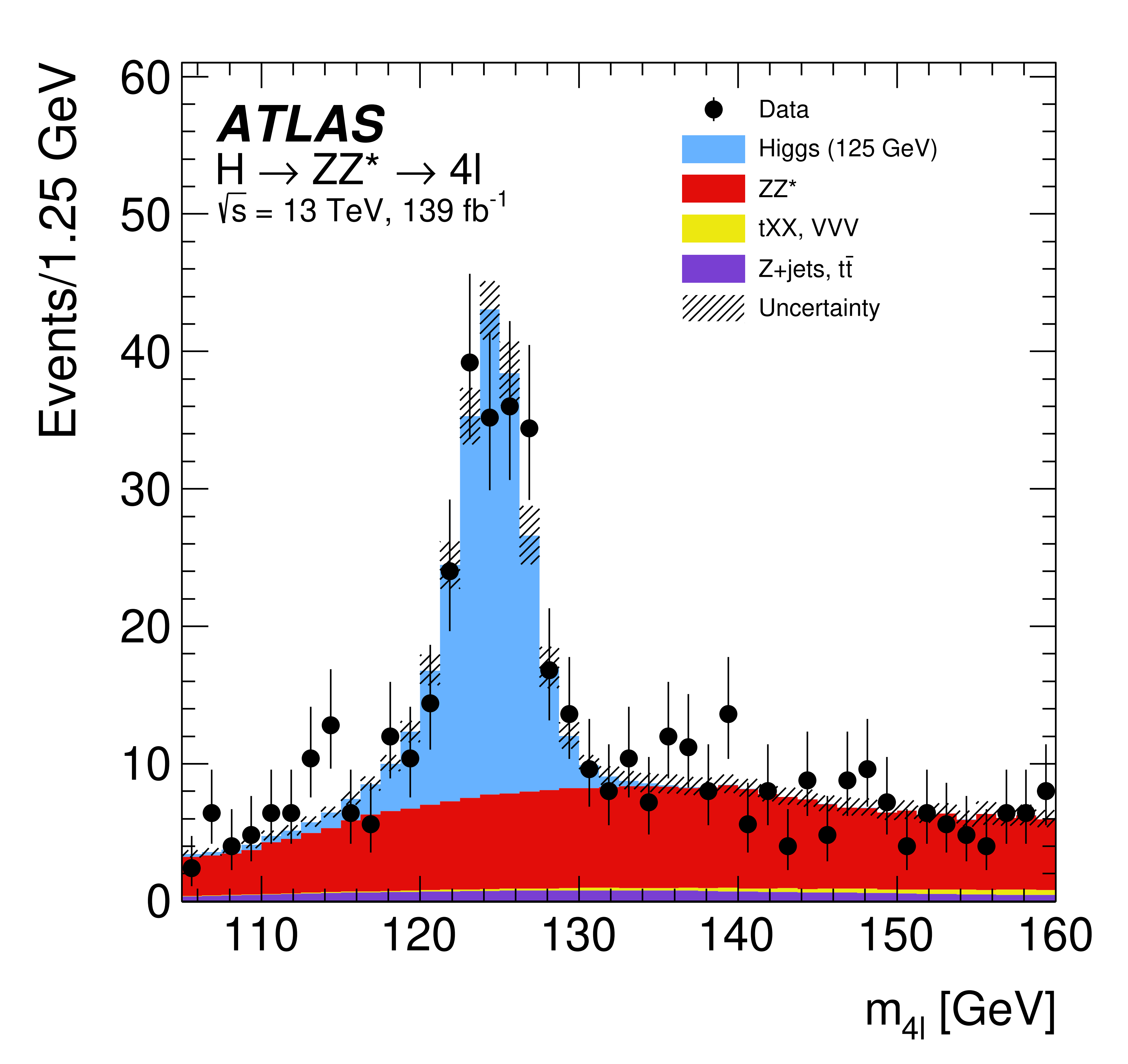
Analysis selection

Leptons and jets	
Muons	$p_\mathrm{T} > 5$ GeV, $\lvert\eta\rvert < 2.7$
Electrons	$E_\mathrm{T} > 7$ GeV, $\lvert\eta\rvert < 2.47$
Jets	$p_\mathrm{T} > 30$ GeV, $\lvert\eta\rvert < 4.5$
Lepton selection and pairing	
Lepton kinematics	$p_\mathrm{T} > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair (m_{34})	Remaining SFOC lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Event selection (at most one Higgs boson candidate per channel)	
Mass requirements	50 GeV$< m_{12} <$ 106 GeV and $m_\mathrm{threshold} < m_{34} <$ 115 GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1$
Lepton/Jet separation	$\Delta R(\mu_i(e_i), \mathrm{jet}) > 0.1 (0.2)$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Impact parameter	$\lvert d_0\rvert/\sigma(d_0) < 5$ (3) for electrons (muons)
Mass window	105 GeV $< m_{4\ell} <$ 160 GeV
Vertex selection:	$\chi^2/N_\mathrm{dof} < 6$ (9) for 4μ (other channels)
If extra lepton with $p_\mathrm{T} > 12$ GeV	Quadruplet with largest matrix element (ME) value

Similarity of the definition of the fiducial phase space to the analysis criteria

H→ZZ

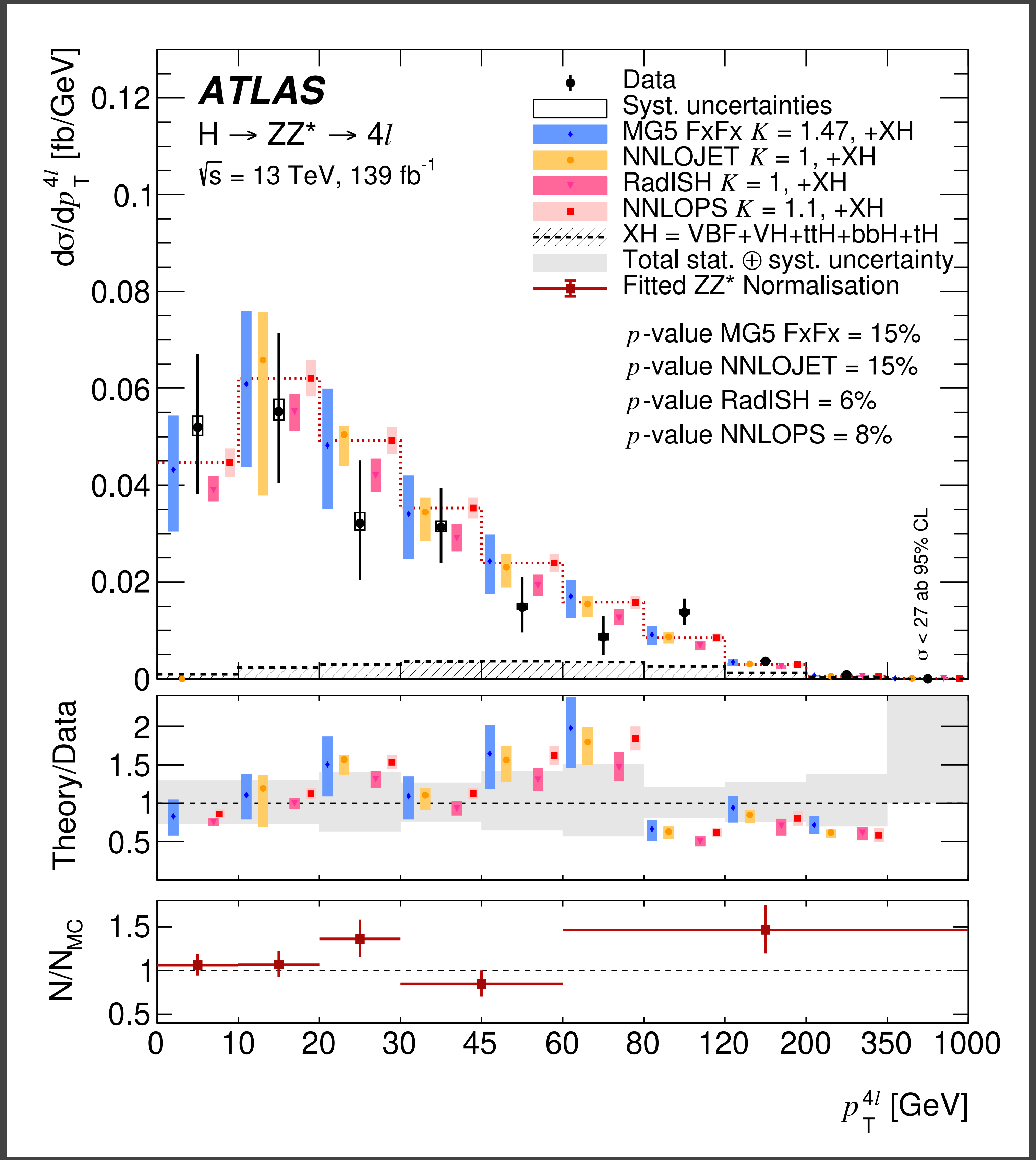
- Four low-p_T isolated leptons (e and μ) originating from the primary vertex
- Main background from ZZ continuum
- Fit to the distributions of m_{4l}
- Inclusive fiducial cross section for H→ZZ measured to be $\sigma_{\text{fid}} = 3.28 \pm 0.32$ fb, in agreement with the SM prediction of $\sigma_{\text{fid,SM}} = 3.41 \pm 0.18$ fb



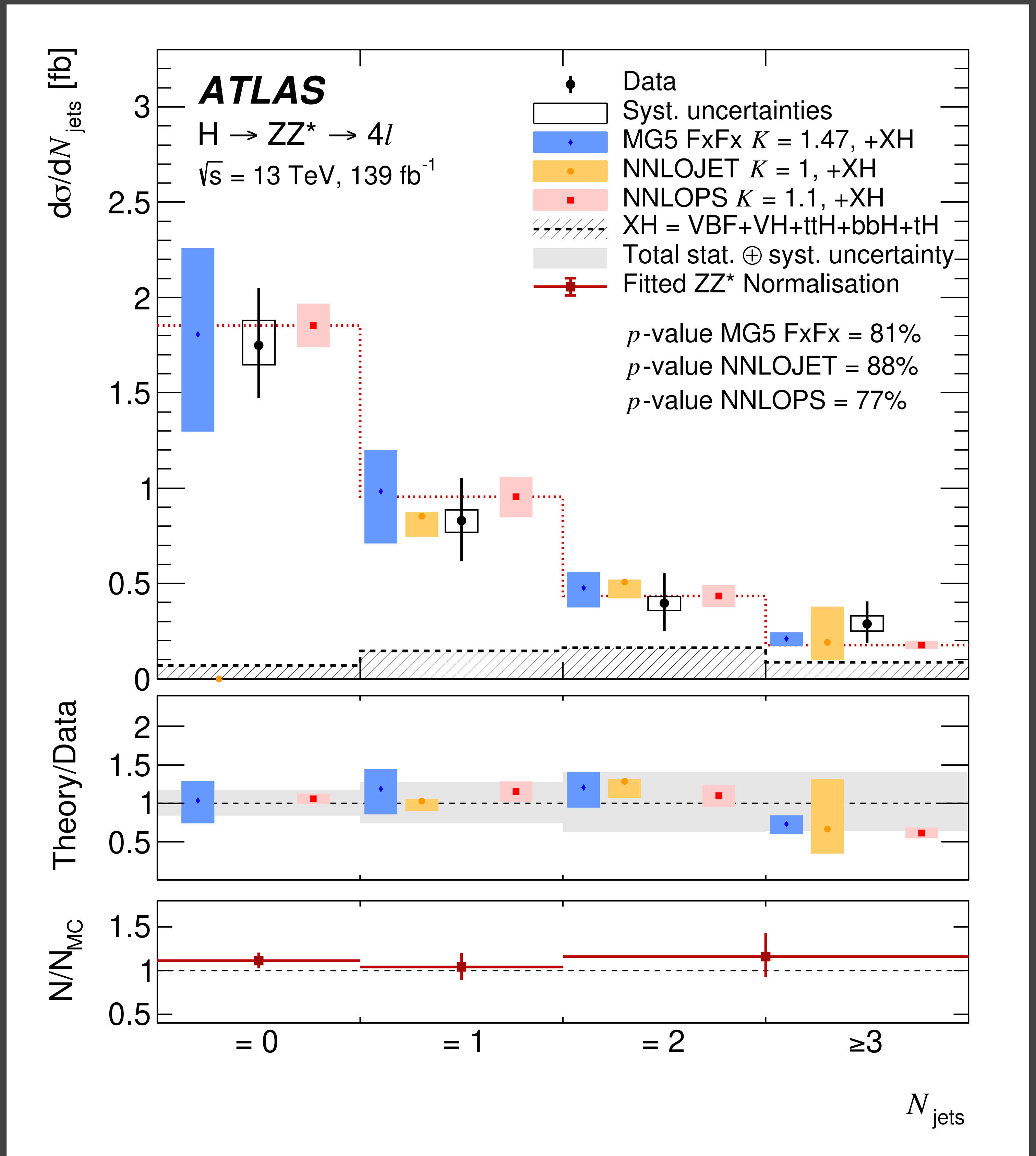
H→ZZ

[Eur. Phys. J. C 80, 942 (2020)](#)

- Differential fiducial cross sections measured.
- Example plots shown for p_T^{4l} and N_{jets}.
- The measurements are compared with different SM predictions. Good agreement is found.



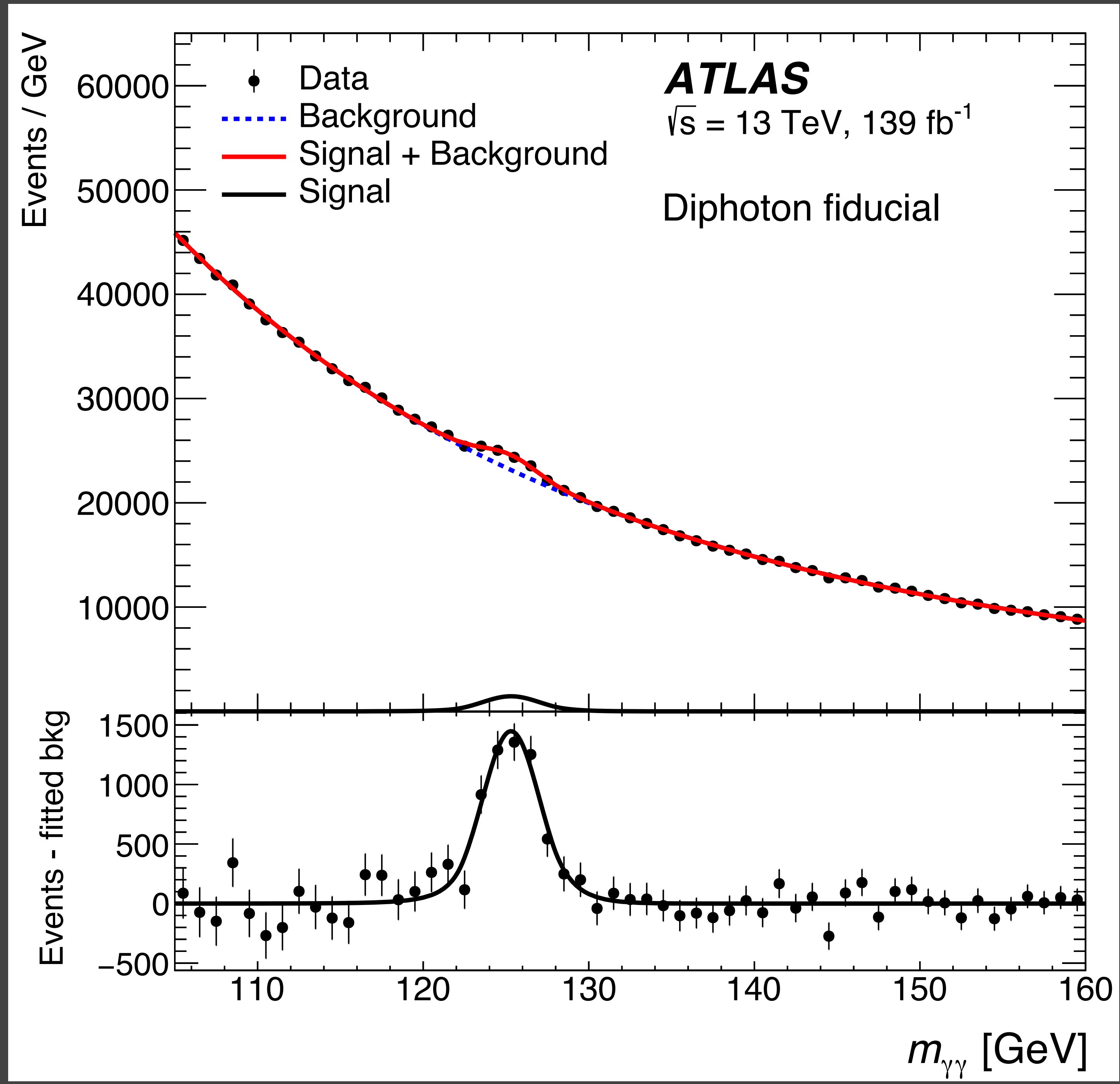
p-value for nominal prediction (NNLOPS): 8%

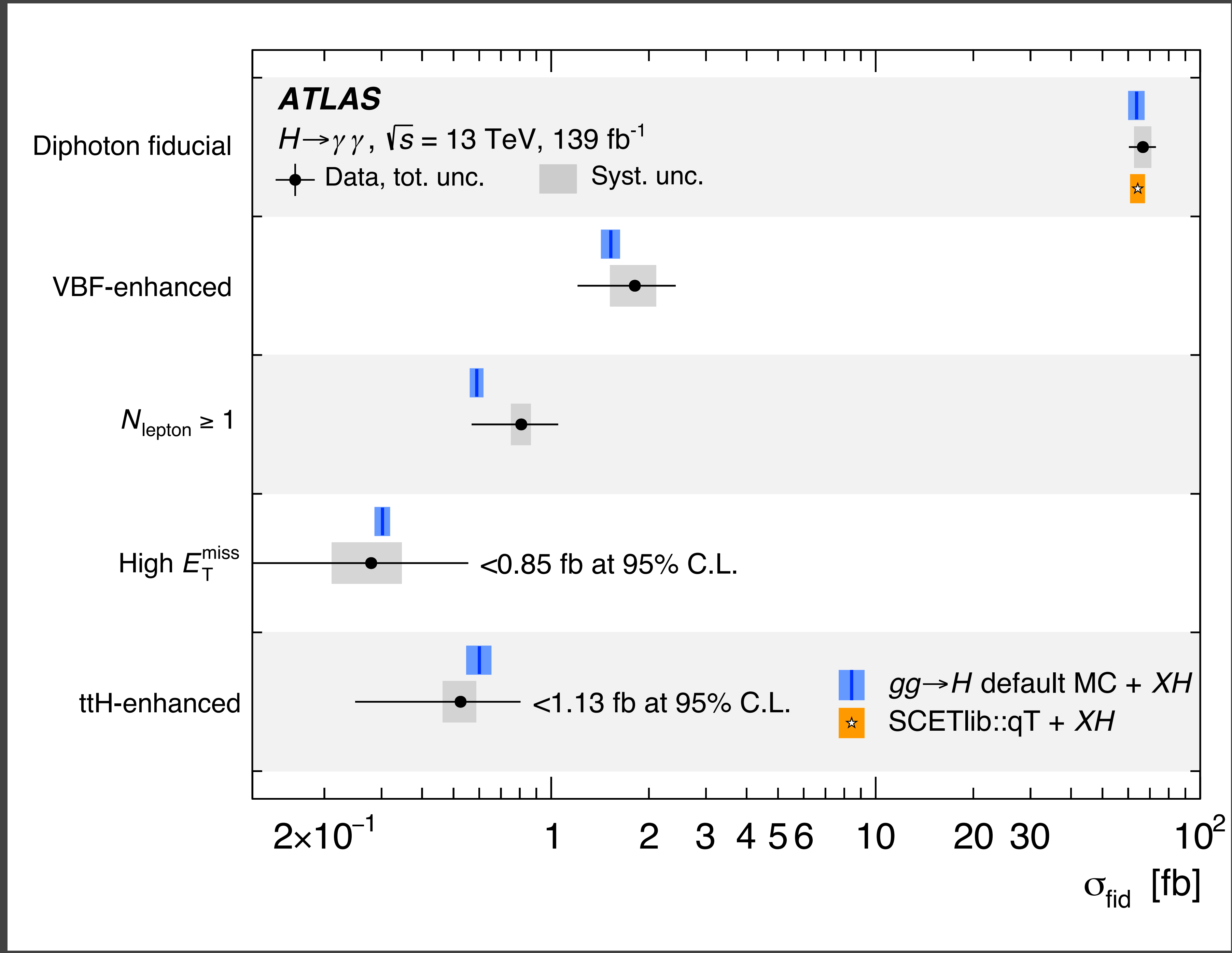


p-value for nominal prediction (NNLOPS): 77%

H→γγ

- Two isolated photons
- Main background from γγ continuum
- Fit to the $m_{\gamma\gamma}$ distributions

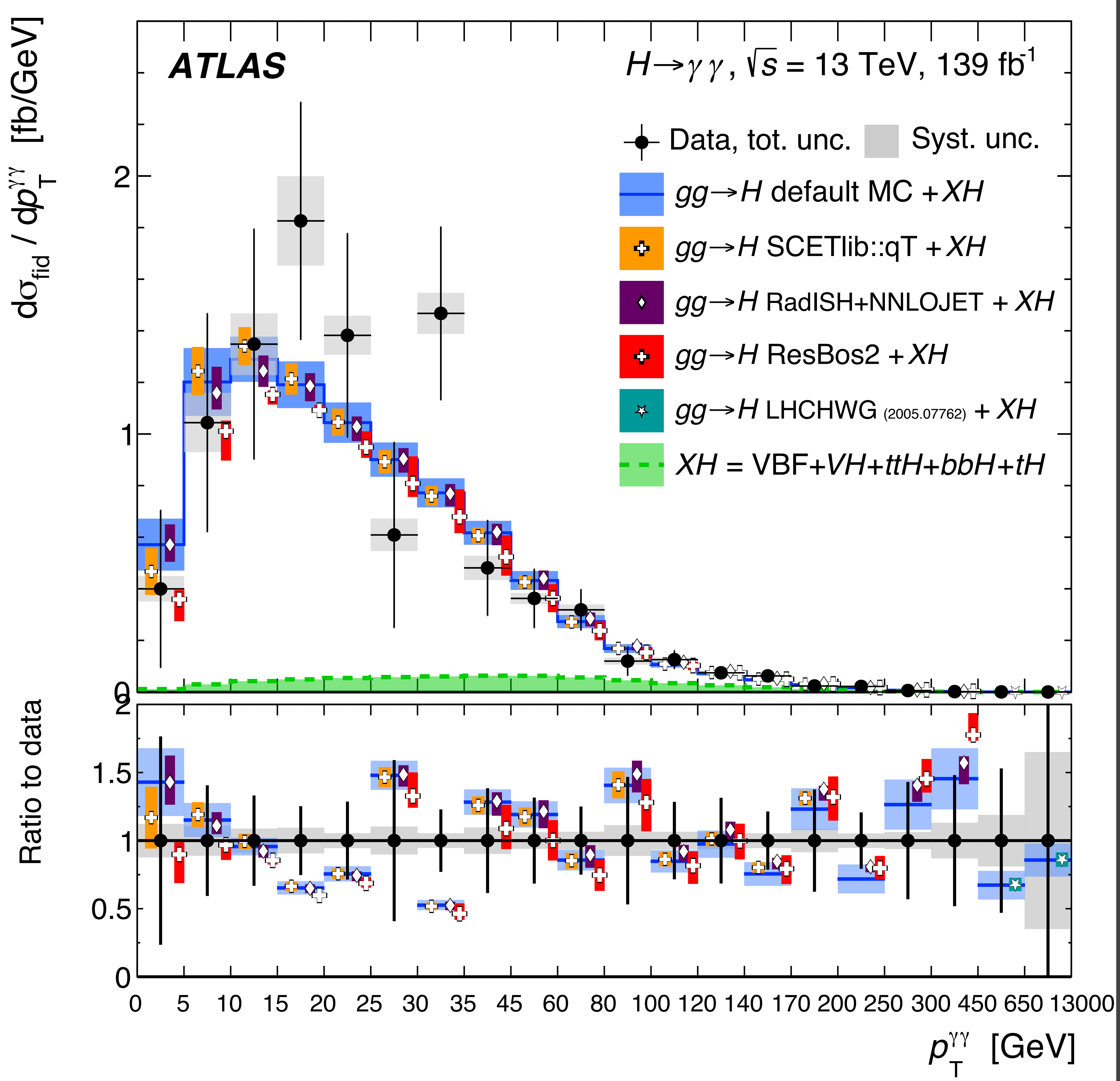


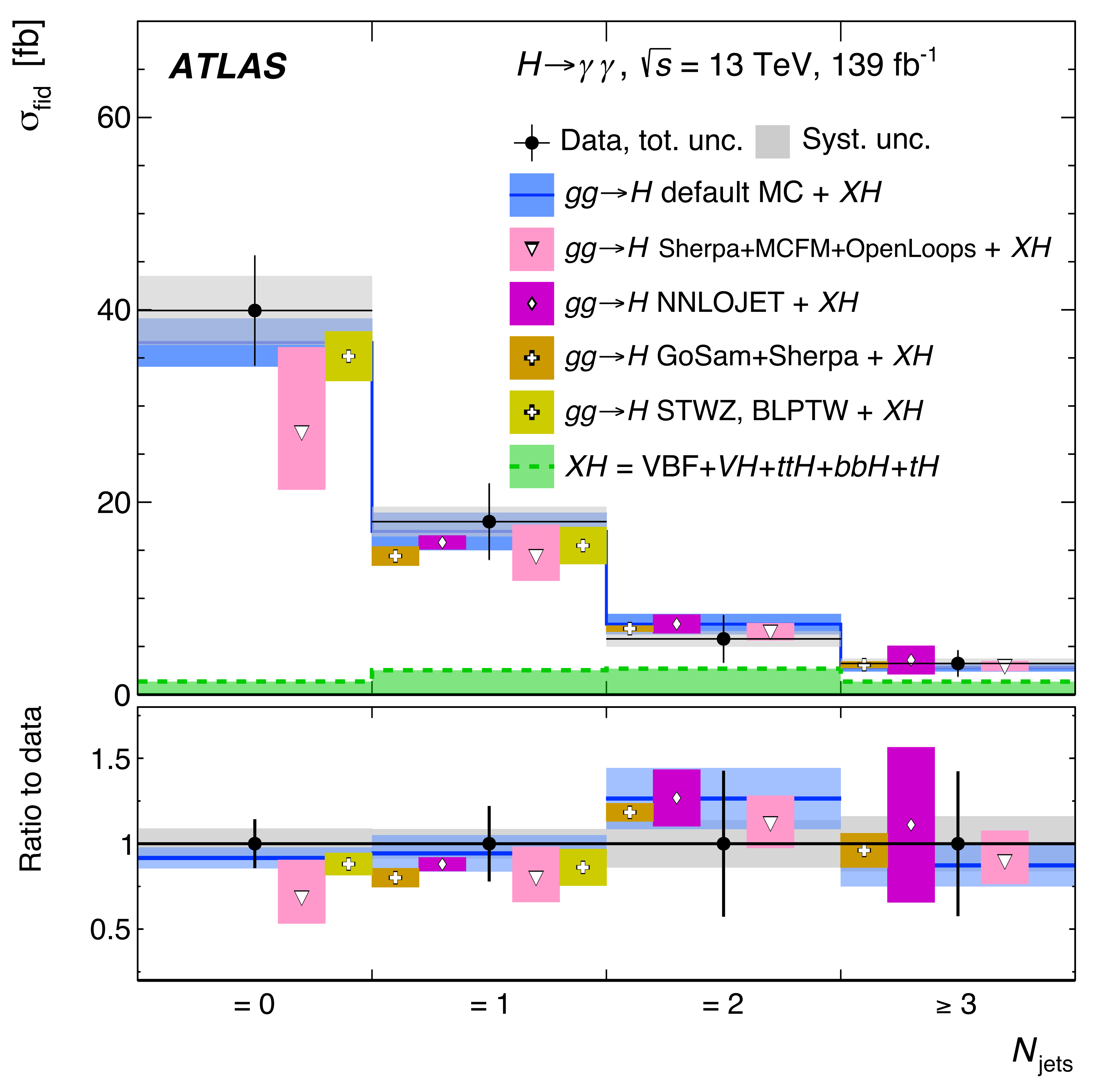


Inclusive fiducial cross section for H→γγ measured to be $\sigma_{\rm fid} = 67 \pm 6$ fb in agreement with the SM prediction of $\sigma_{\rm fid,SM} = 64 \pm 4$ fb

H→γγ

Differential fiducial cross section for H→γγ, example shown for $p_T^{\gamma\gamma}$ and N_{jets}

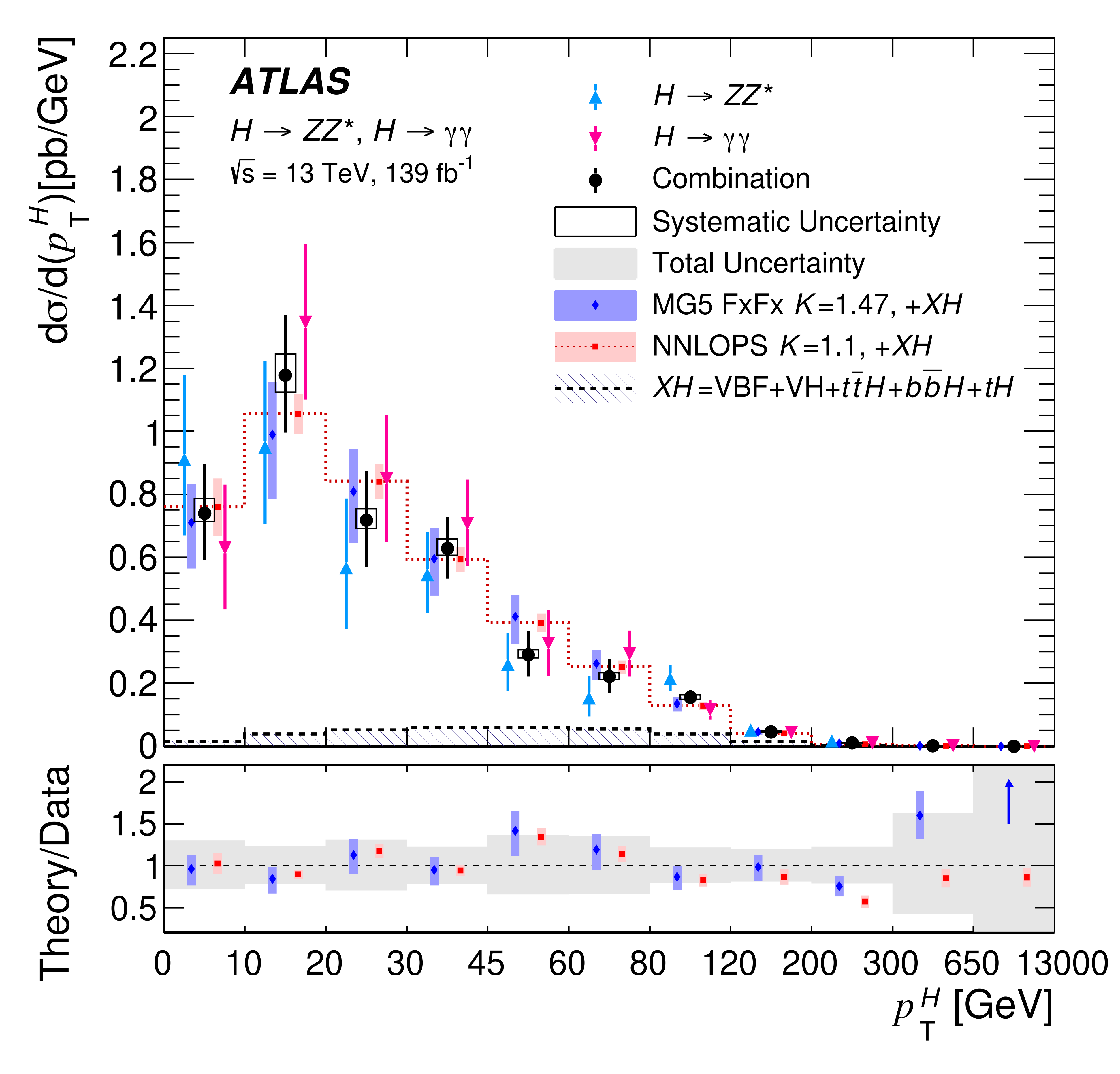




H→ZZ and H→γγ Combination

arXiv:2207.08615

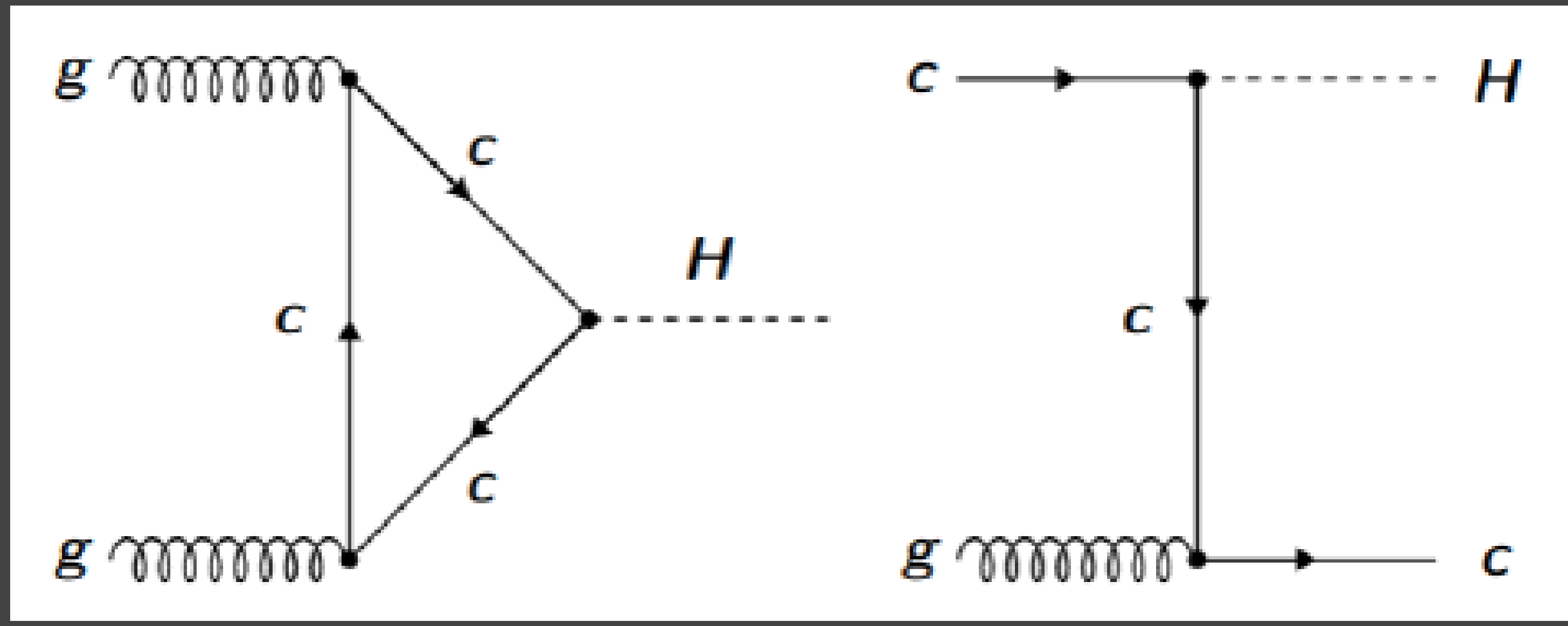
- Differential pp→H+X cross sections in the full phase space were measured by combining H→ZZ and H→γγ.
- Binning for the variables were harmonised and the results were extrapolated from the fiducial to the full phase space prior to the combination.
- Example plot is shown for p_T^H.

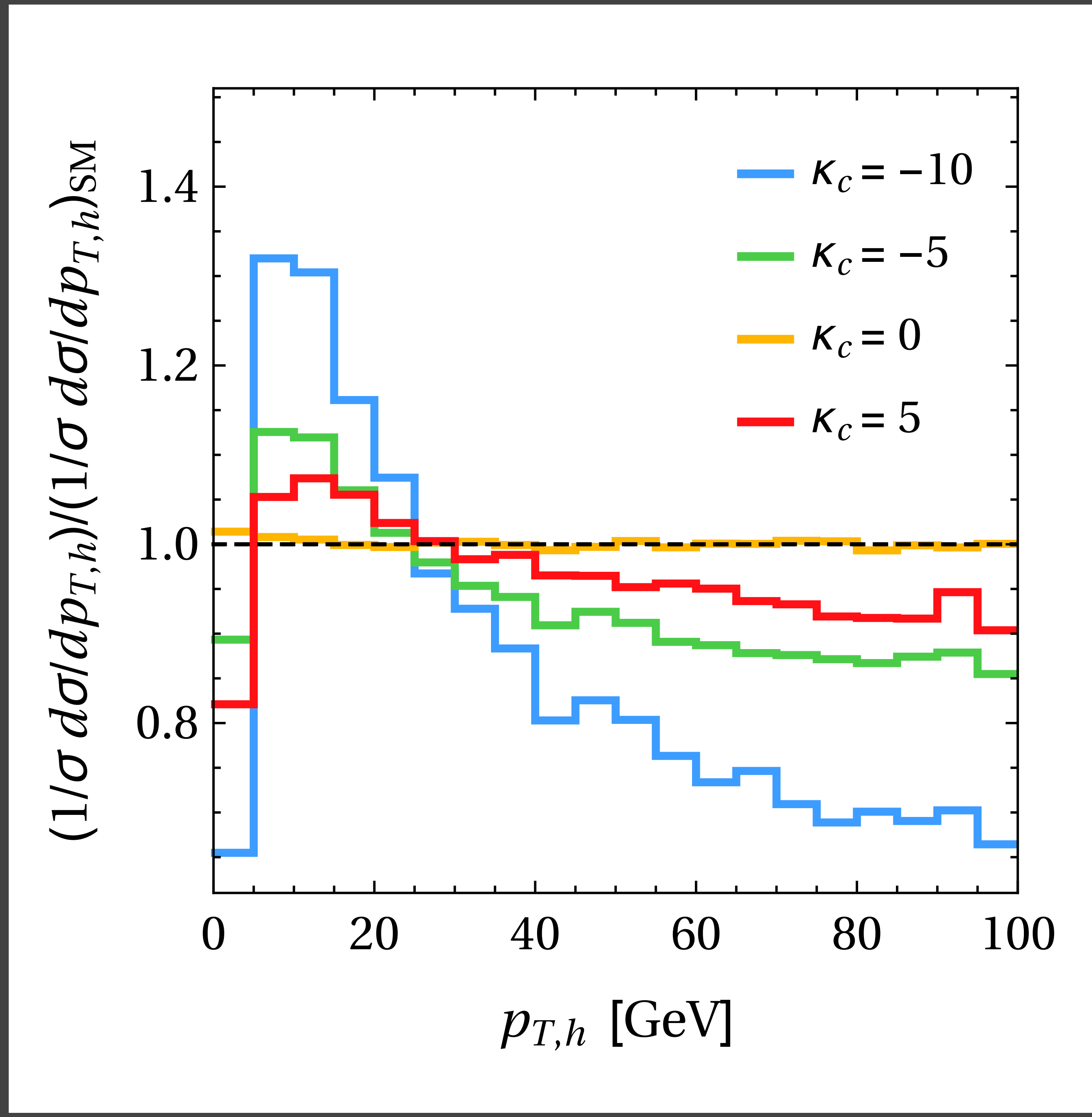


Total inclusive cross section: $55.5^{+4.0}_{-3.8}$ pb

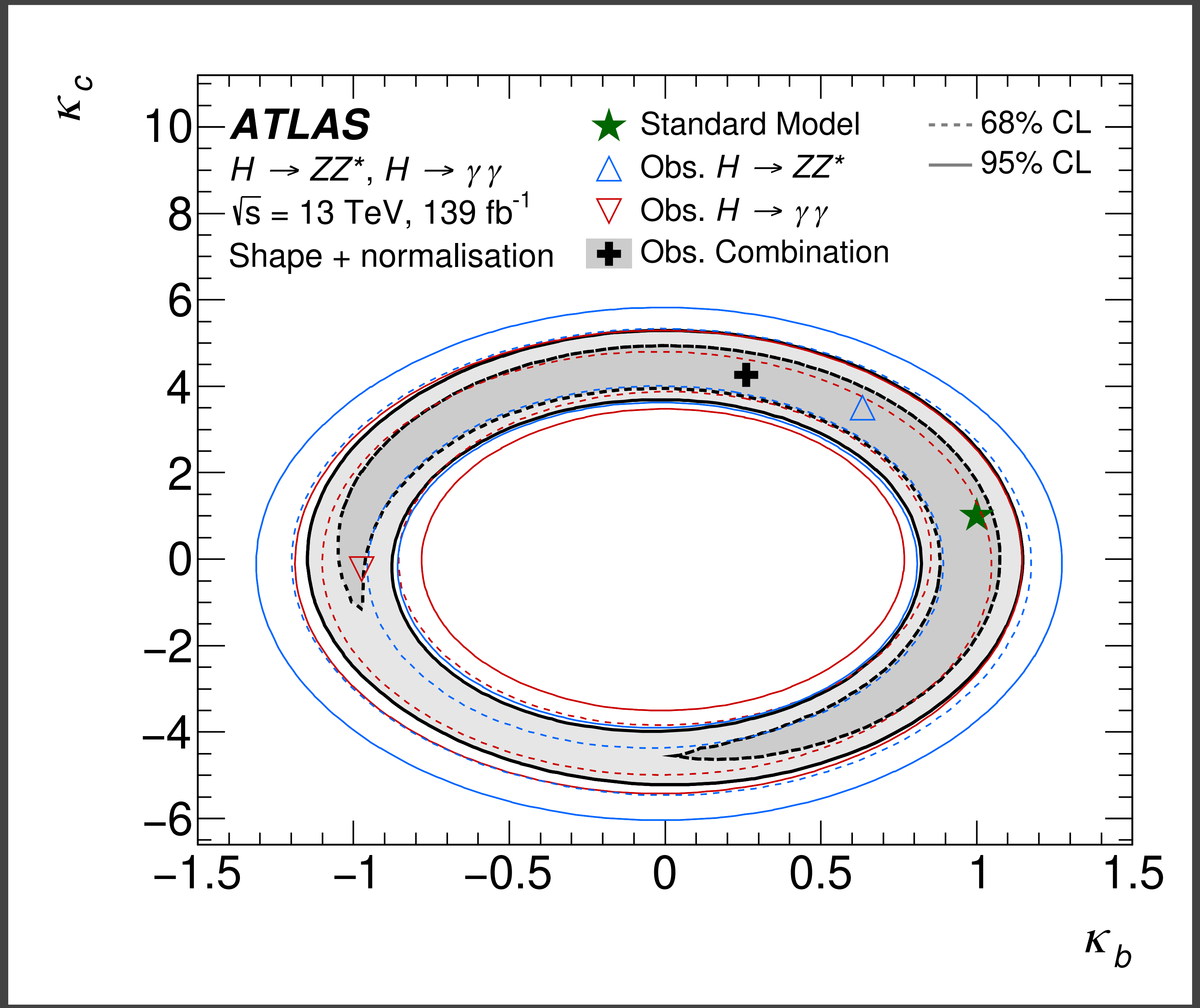
Indirect Constraints on κ_c and κ_b

Constraints on the Yukawa couplings between Higgs boson and c/b quarks relative to the SM predictions (κ_c and κ_b) derived from the p_T^H distributions in the $H \to ZZ$ and $H \to \gamma\gamma$ final states





PRL 118, 121801 (2017)

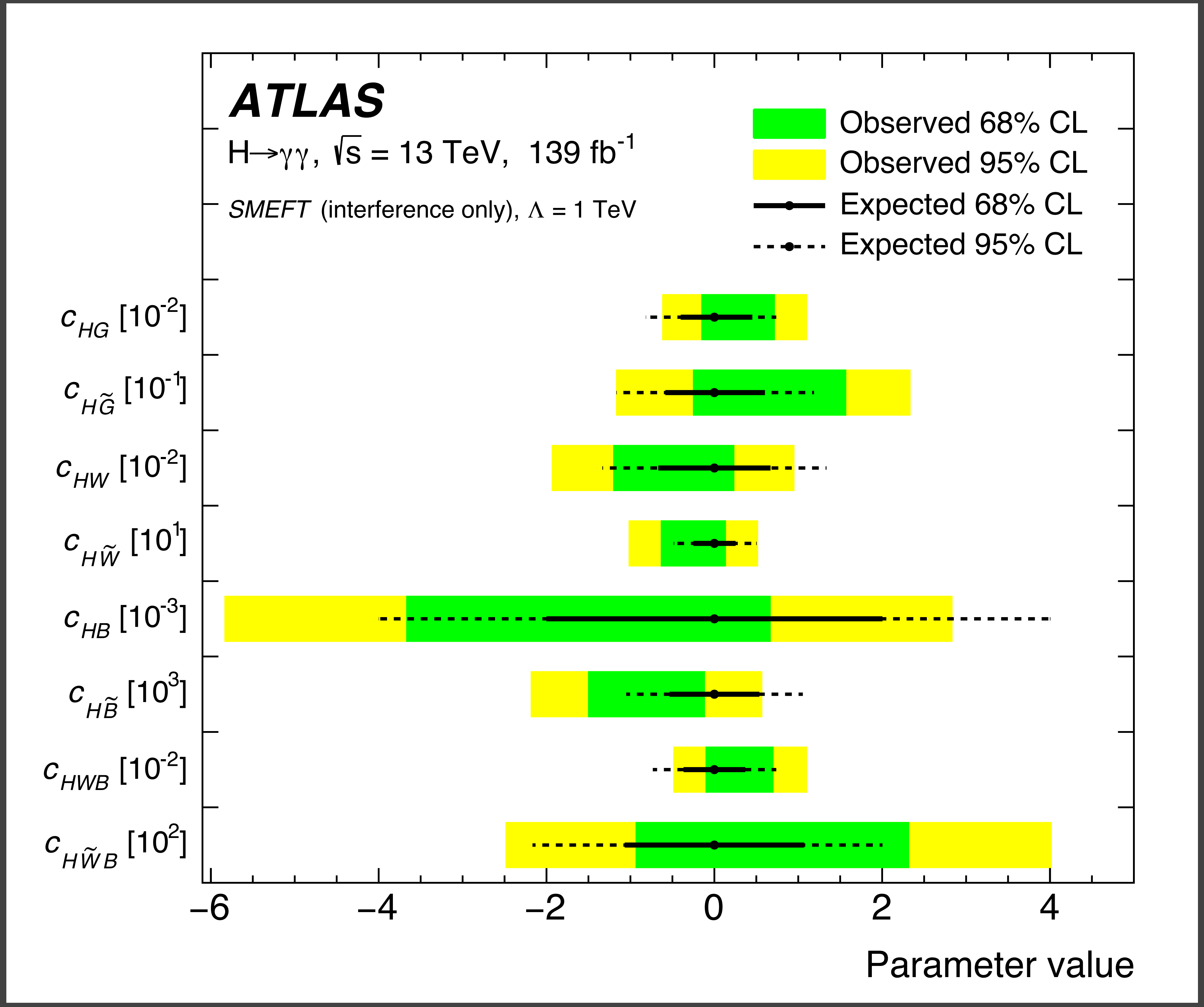


arXiv:2207.08615

Constraints on SMEFT

- The SM Effective Field Theory (SMEFT) [JHEP 10 (2010) 085, Phys. Rept. 793 (2019) 1] is a model-independent framework for characterising experimental deviations from the predictions of the SM.
- Limits on the coefficients (c_{HG}, etc.) obtained from fiducial differential cross sections on p_T^H, N_{jets}, m_{jj}, $\Delta\phi_{jj}$, and p_T^{j1} for $H\to\gamma\gamma$.

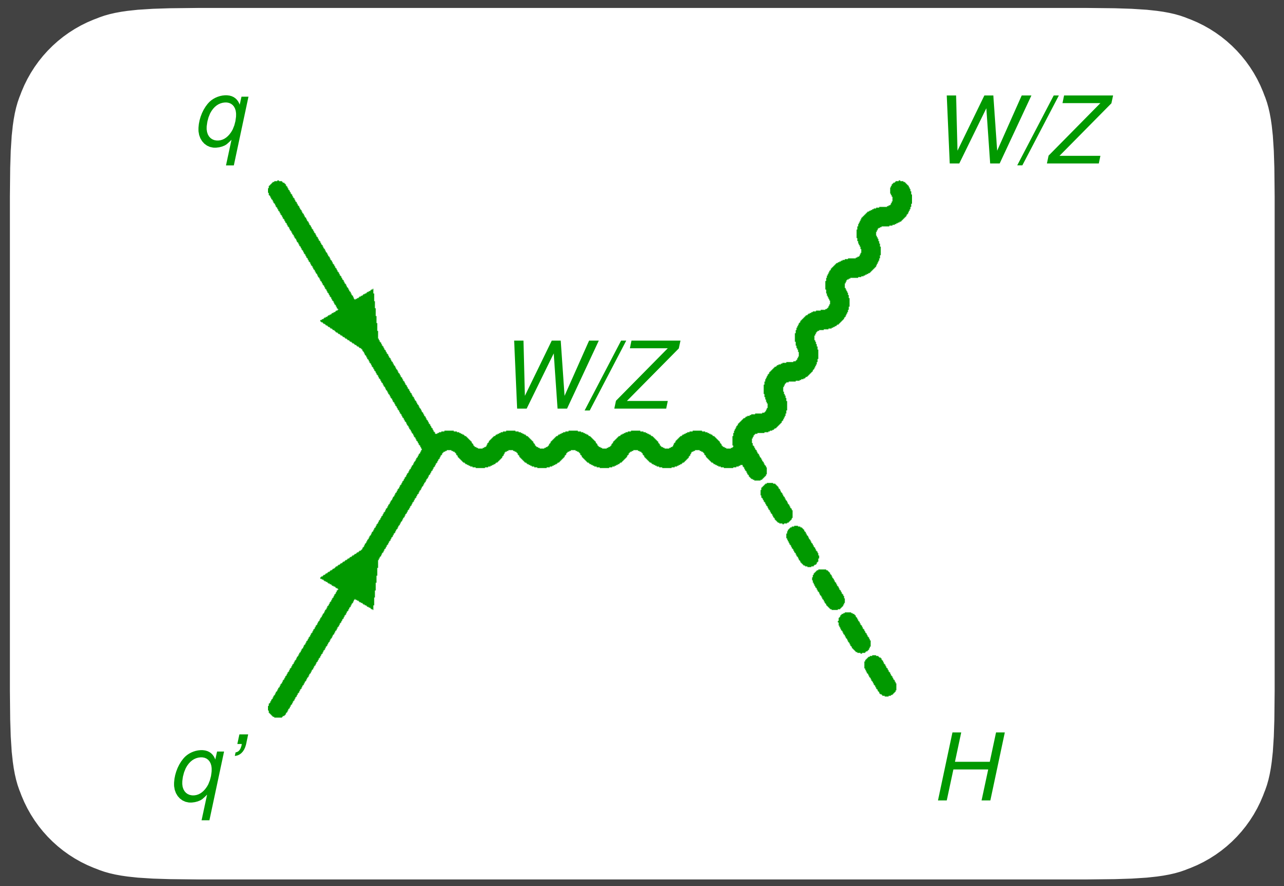
$$\mathcal{L}_{\text{eff}}^{\text{SMEFT}} \supset c_{HG}\mathcal{O}'_g + c_{HW}\mathcal{O}'_{HW} + c_{HB}\mathcal{O}'_{HB} + c_{HWB}\mathcal{O}'_{HWB} + c_{H\widetilde{G}}\widetilde{\mathcal{O}}'_g + c_{H\widetilde{W}}\widetilde{\mathcal{O}}'_{HW} + c_{H\widetilde{B}}\widetilde{\mathcal{O}}'_{HB} + c_{H\widetilde{W}B}\widetilde{\mathcal{O}}'_{HWB}$$

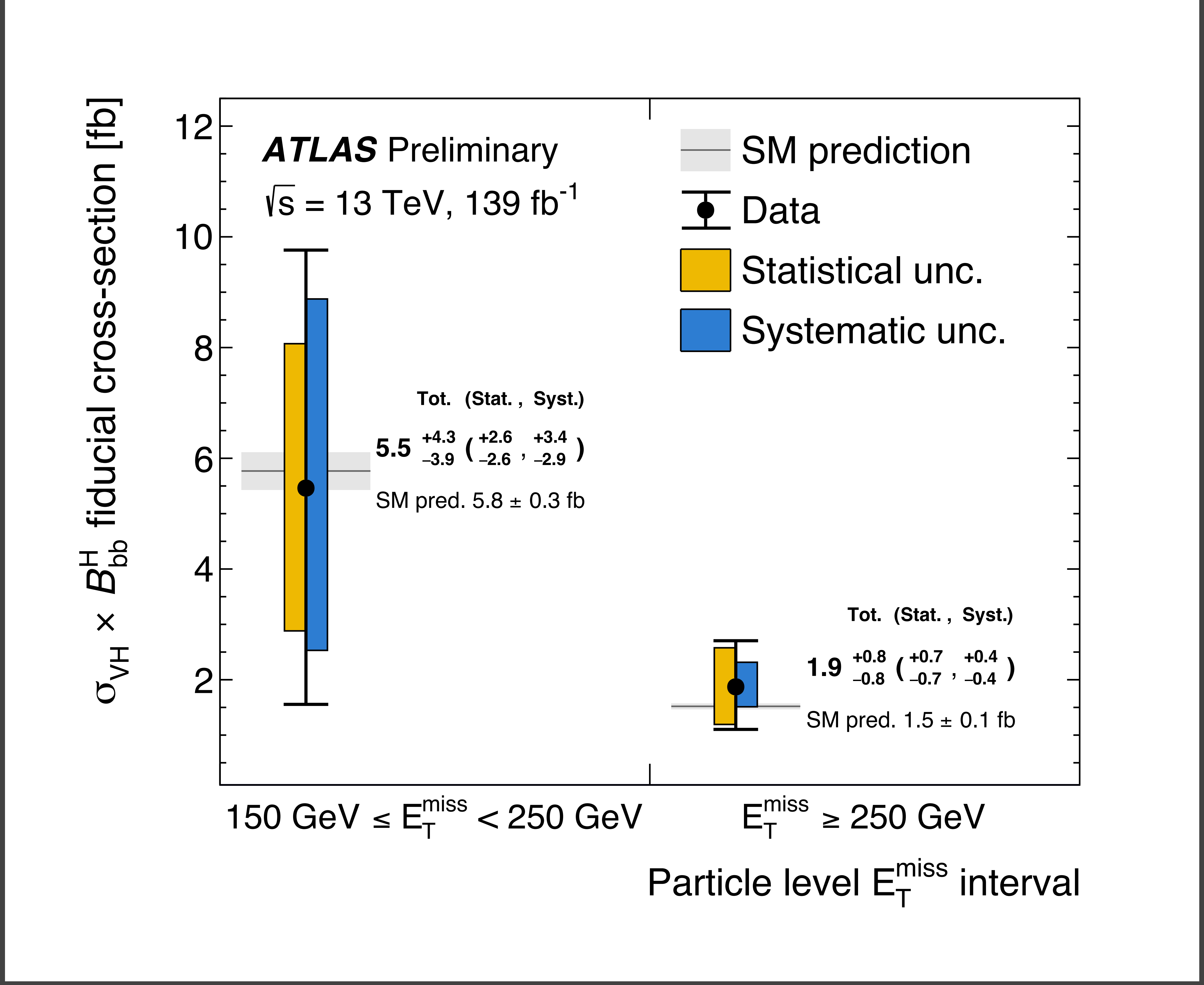


Fit one Wilson coefficient at a time

VH, H→bb, 0 Lepton

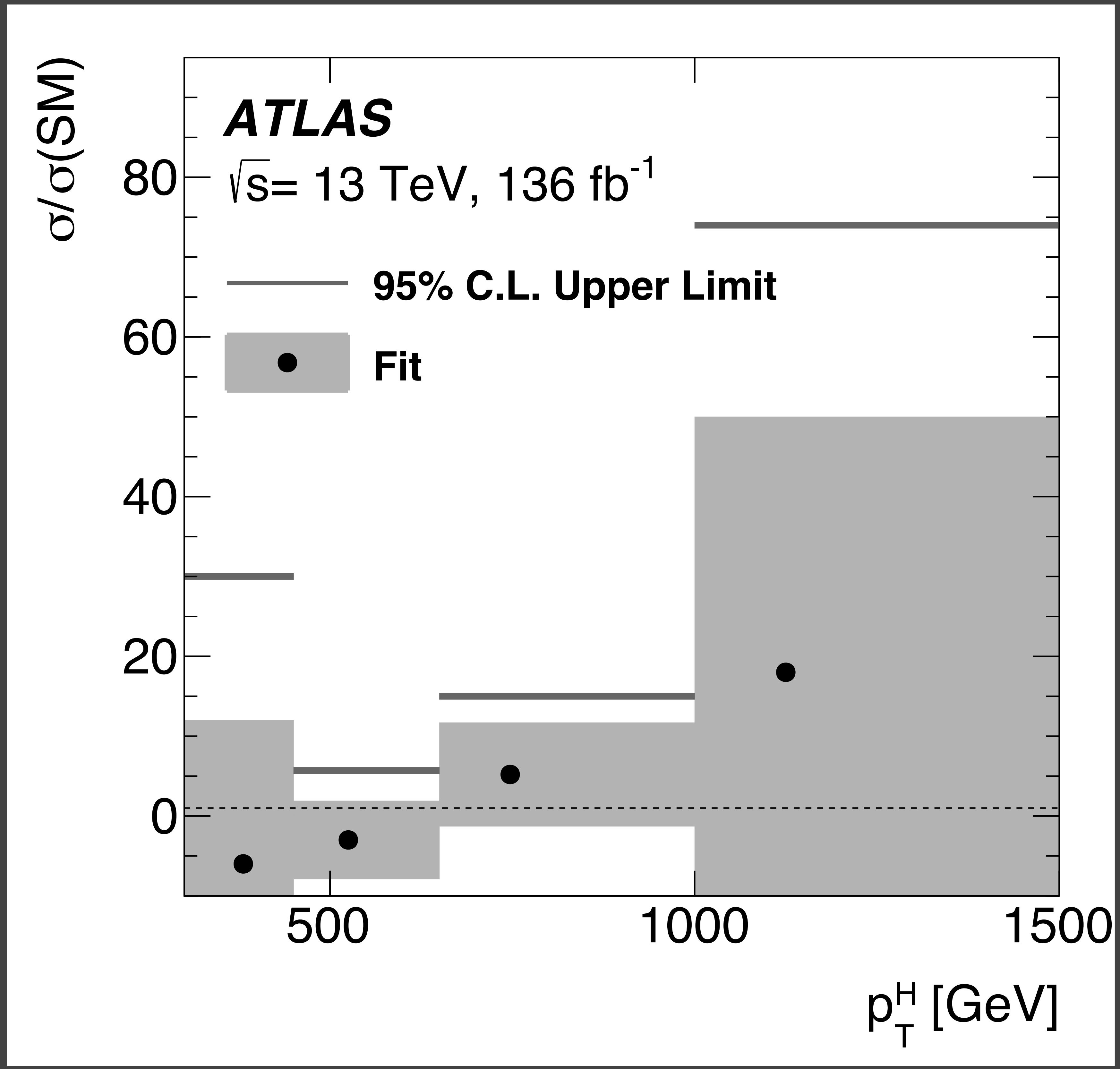
- Two b-tagged jets required.
- No electrons or muons required.
- The fiducial cross sections measured for the Higgs boson production in association with W or Z boson, VH (V = W or Z), followed by H→bb.

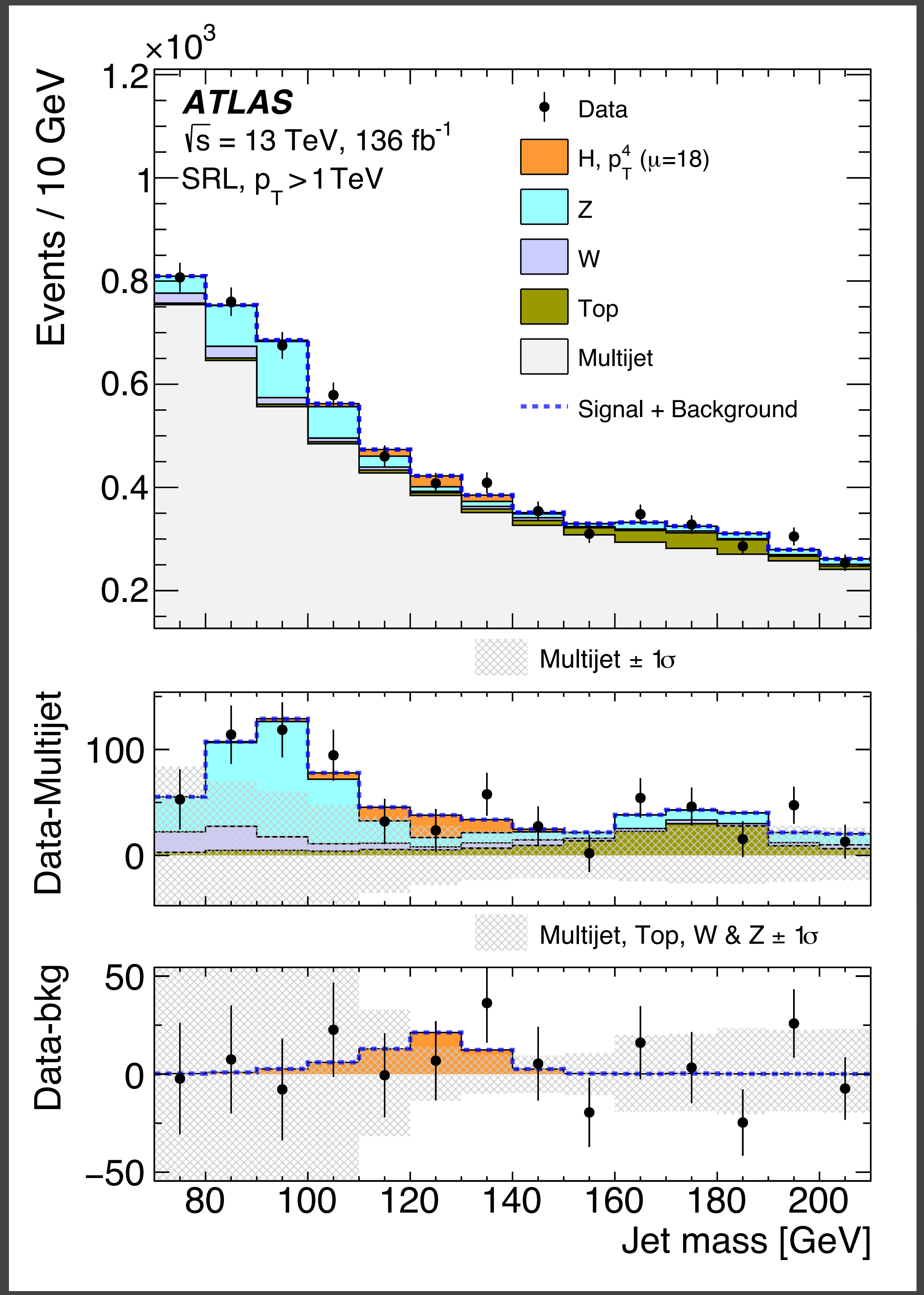




$H \to bb$, Boosted

- Higgs boson with large Lorentz boost reconstructed from single large-radius jet, allowing to explore high-p_T region (p_T^H > 1 TeV)
- At least two jets required (>450 GeV, >250 GeV)
- Main background from QCD multijet





The 95% confidence-level upper limit on the fiducial cross section for Higgs boson production with p_T^H > 450 GeV is 115 fb (18.4 fb expected from the SM).

Conclusion

- The Higgs physics entered the era of precision measurements.
- To be as model independent as possible, a lot of fiducial measurements have been performed both inclusively and differentially, which can easily be compared to theoretical models.
- Up to now, the measured values are consistent with the SM.
- Part of the inclusive and most of the differential measurements are dominated by statistical uncertainties. Stay tuned for Run 3 results!

Backup Slides

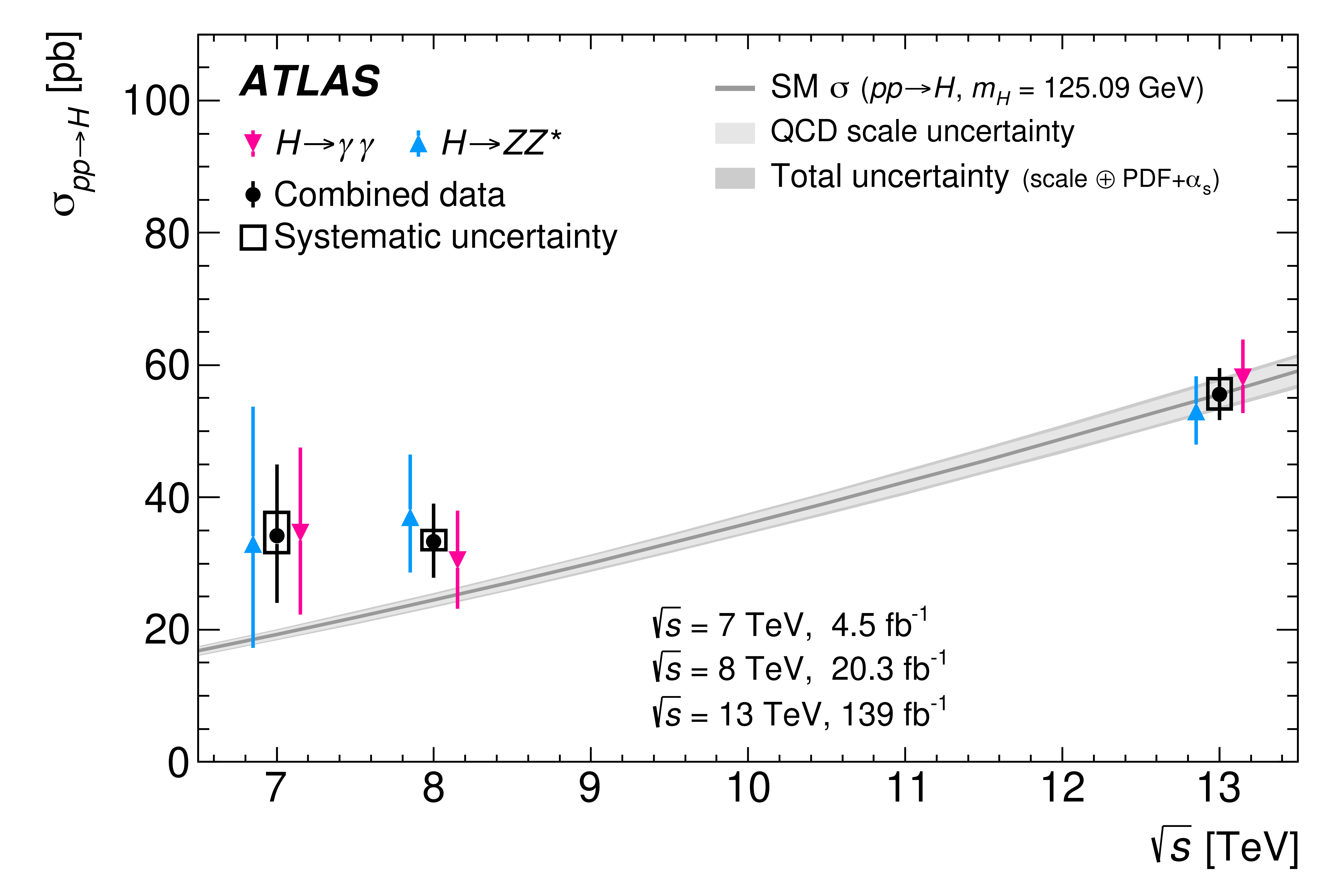
Fiducial region definitions

Region	definition
Diphoton	two selected photons
VBF-enhanced	at least two jets, $m_{jj} \geq 600\,\text{GeV}$, $\|\Delta y_{jj}\| \geq 3.5$
$N_{\text{lepton}} \geq 1$	electron or muon with $p_{\text{T}}^{\ell} > 15\,\text{GeV}$
High $E_{\text{T}}^{\text{miss}}$	$E_{\text{T}}^{\text{miss}} > 80\,\text{GeV}$, $p_{\text{T}}^{\gamma\gamma} > 80\,\text{GeV}$
$t\bar{t}H$-enhanced	at least one b-jet and $\left(N_{\ell} = 0 \text{ and } N_j \geq 4,\ \text{or} N_{\ell} \geq 1 \text{ AND } N_j \geq 3\right)$

H→ZZ and H→γγ Combination

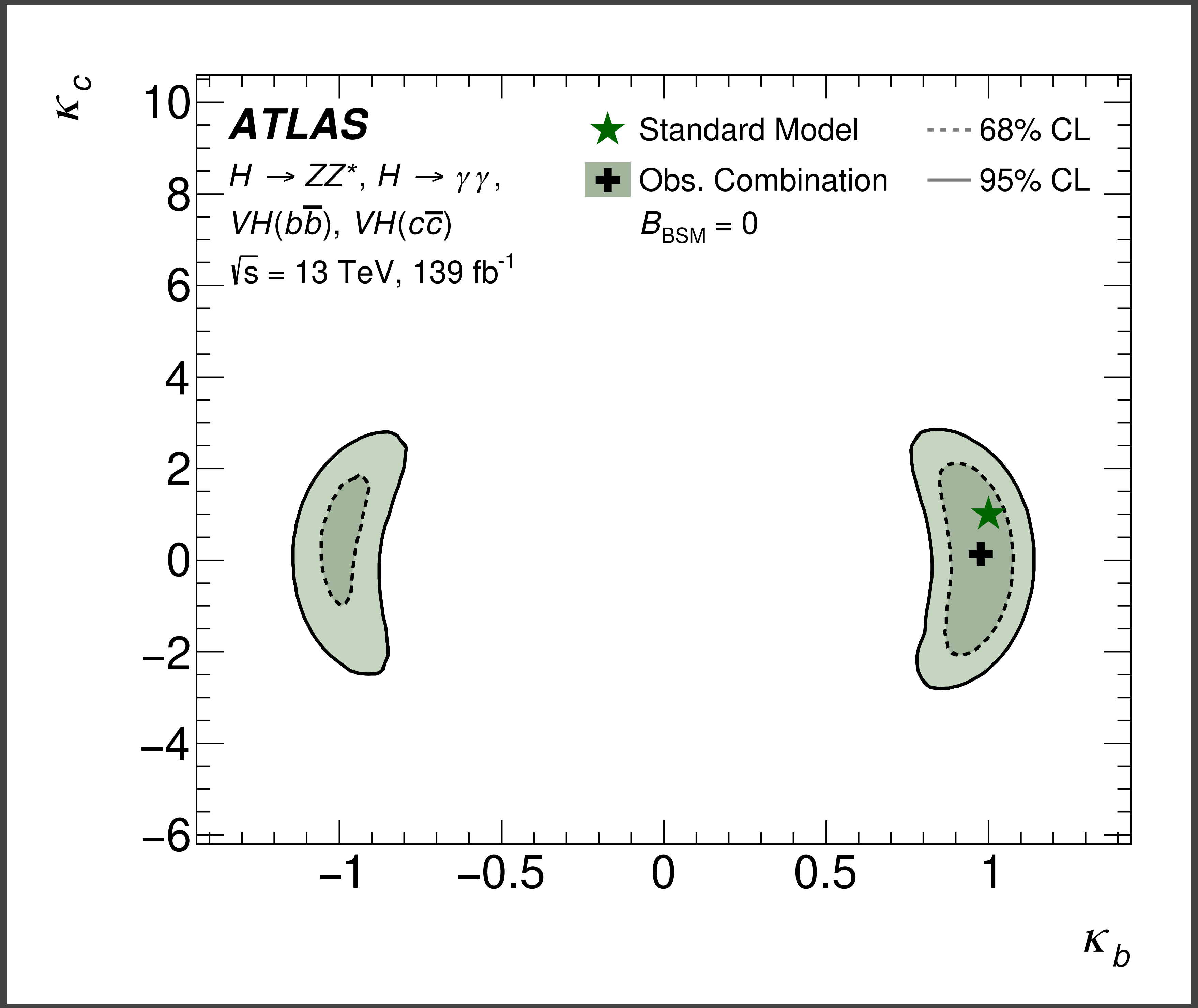
arXiv:2207.08615

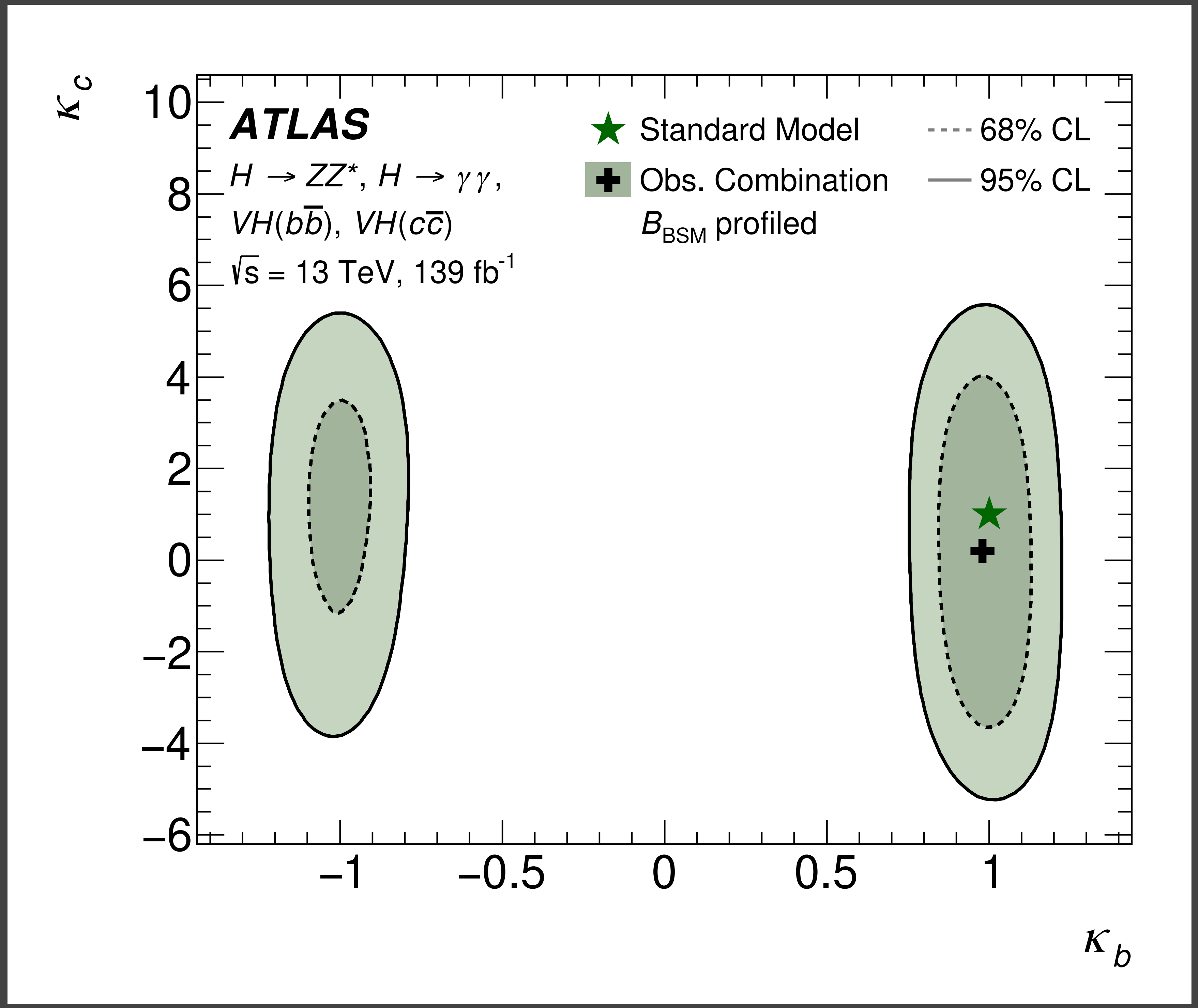
Total inclusive cross section for pp→H



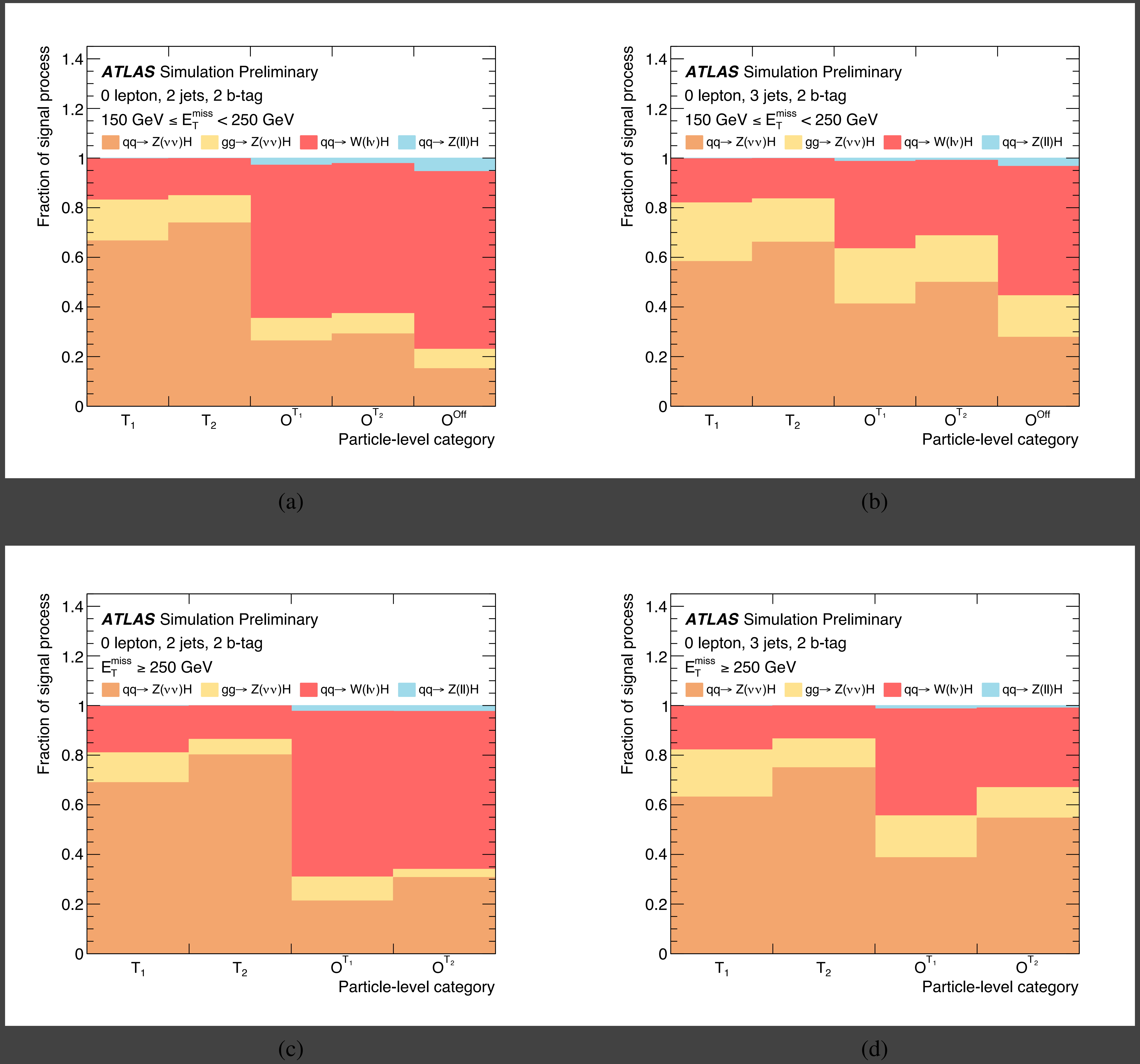
Constraints on κ_c and κ_b

Contours for κ_c and κ_b obtained from a simultaneous fit to the Higgs p_T fiducial cross sections in $H\to\gamma\gamma$ and $H\to ZZ$ and to multivariate discriminants used to identify VH events with $H\to bb$ and $H\to cc$.





VH, H→bb, 0 Lepton



Fraction of signal process

H→bb, Boosted

Signal acceptance times efficiency depending on the production processes

TABLE XII. Signal acceptance times efficiency for the STXS volumes in the differential measurement. Along with the p_T^H requirements shown, $|y_H| < 2$ is required. For events with $p_T^H < 300$ GeV, the acceptance times efficiency is less than 0.1×10^{-2}.

Process	$300 < p_T^H < 450$ GeV	$450 < p_T^H < 650$ GeV	$650 < p_T^H < 1000$ GeV	$p_T^H > 1$ TeV
All	1.3×10^{-2}	0.23	0.31	0.23
ggF	0.7×10^{-2}	0.25	0.35	0.28
VBF	0.4×10^{-2}	0.21	0.32	0.25
VH	1.7×10^{-2}	0.26	0.30	0.20
$t\bar{t}H$	4.7×10^{-2}	0.19	0.24	0.19