Measurements of the Higgs boson fiducial and differential cross sections in bosonic final states at the ATLAS experiment

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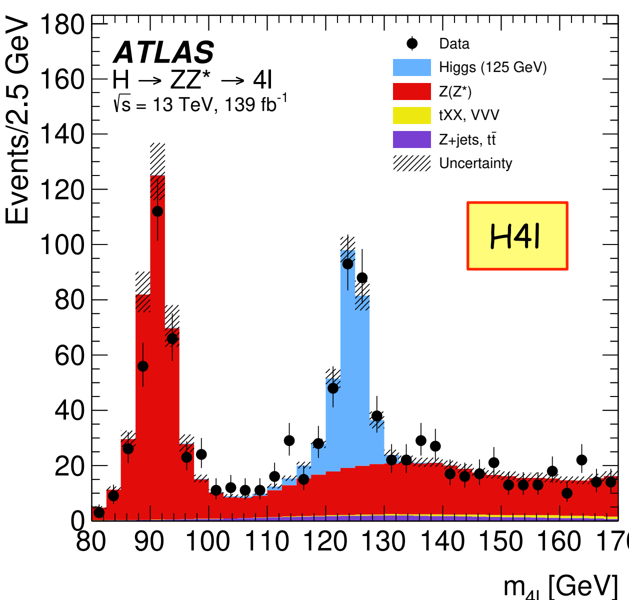
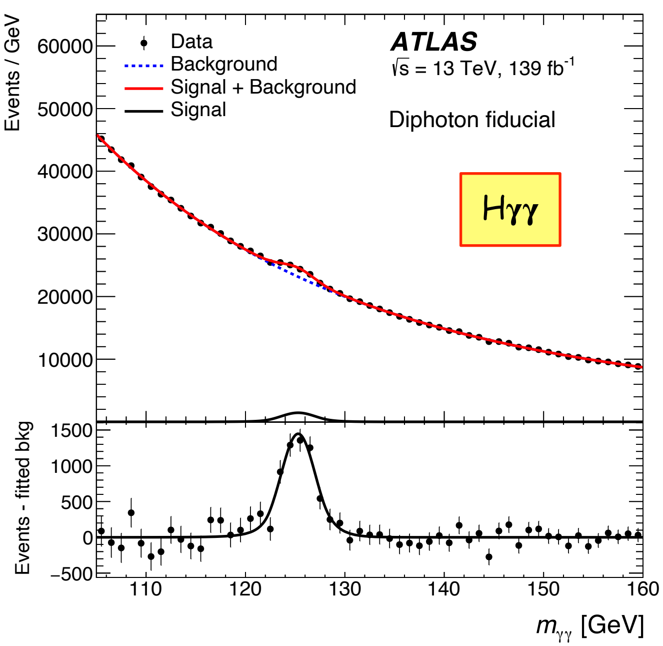
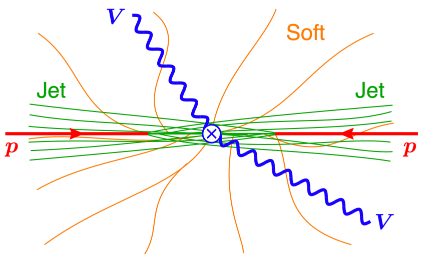
H→ZZ*→4l (H4l) and H→γγ (Hγγ) channels

- Report today on final Run 2 results the individual fiducial measurements:
  - H → 4l Eur. Phys. J. C 80 (2020) 942   Nov 2020
  - H → γγ Submitted to JHEP   Feb 2022
- and their combination:
  - CERN-EP-2022-143 *NEW*
- H4l and Hγγ are fully-resolved high-resolution Higgs decay channels
  - See refs for details of each channel



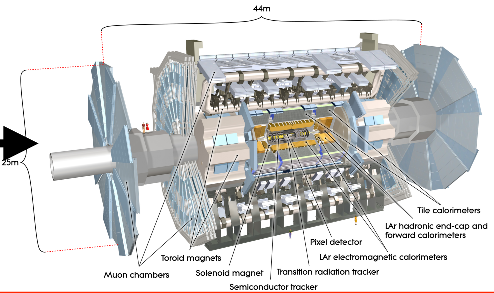


Inclusive and differential fiducial measurements



Higgs production in full phase space:
hard scatter + parton shower

fiducial region:
particle-level selection
close to final selection



selected events at reconstructed level

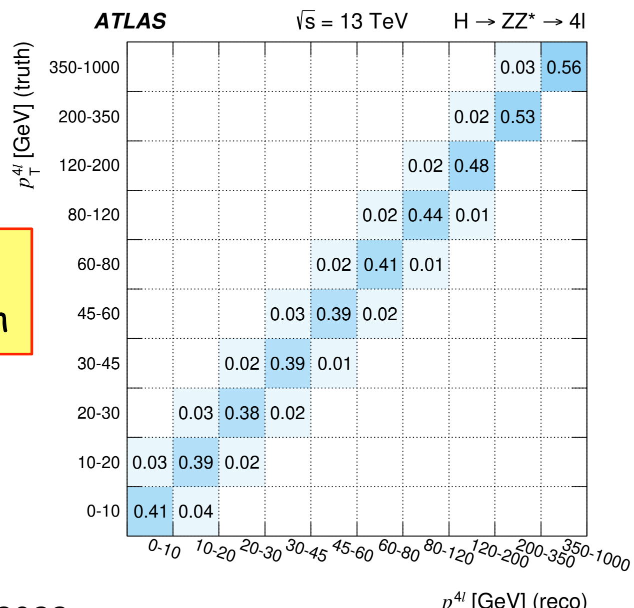
- Cross sections and kinematic distributions are measured in space defined by the detector acceptance (fiducial region)
  - Includes minimum physics assumptions
  - Allows for easy comparison of physics models today and in the future
    - Tradeoff some precision relative to reco-level measurements for “longevity” of data
- Measurements are corrected for detector response (unfolding)
  - Response matrix unfolding is included in the likelihood fit
    - past measurements used bin-by-bin
- To combine two decay channels, e.g. $H \rightarrow 4l$ and $H \rightarrow \gamma\gamma$, one must “correct”/“unfold” to the full phase space since fiducial regions are different (acceptance + BR)
  - Requires assumption on acceptance correction from fiducial to full phase space (acc ~50%)
  - But of course, combining the two results improves statistical precision

A word on "unfolding"

- To "extract" distributions in fiducial volume, one uses a response matrix R_{truth_reco} to map reco to truth accounting for bin migrations
- An important point is to adjust the "bin sizes" to limit bin migration in truth <-> reco
  - This limits the "inflation" of the statistical uncertainty in transformation of reco to truth
    - little migration for Higgs variables (p_T, decay, masses),
    - larger for jet-related due to resolution

p_T^{4l} response matrix: few % migration

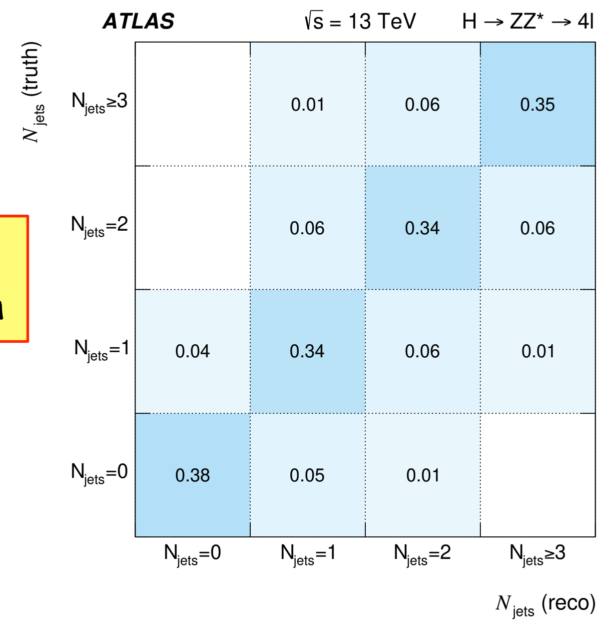
p_T^{4l} truth



p_T^{4l} reco

N_{jet} response matrix: ~20 % migration

N_{jets} truth



N_{jets} reco

Cross sections, distributions and interpretations

- Most measurements are "inclusive" of production mode => dominated by ggF
- Total cross sections:
  - in fiducial phase space for H4l and $H\gamma\gamma$, total phase space for combined
- Common distributions H4l and $H\gamma\gamma$:
  - Higgs: p_T, $|y|$, p_T vs $|y|$, Jets: N_{jets}, $N_{b\text{-}jets}$, p_T^{j1}, VBF: m_{jj}, $|\Delta\eta_{jj}|$, $\Delta\varphi_{jj}$
- Distributions specific to H4l:
  - Z masses: m_{12}, m_{34}, decay angles (masses most sensitive to BSM)
- Distributions specific to $H\gamma\gamma$:
  - $p_T^{\gamma 1}/m_{\gamma\gamma}$, $p_T^{\gamma 2}/m_{\gamma\gamma}$, additional 1-jet and 2-jet variables
  - Has fiducial phase spaces for VBF, VH and ttH
- Interpretations:
  - H4l: anomalous couplings to H and Z (Pseudo Observables Framework)
  - $H\gamma\gamma$: EFT constraints on Warsaw-basis couplings with $p_T^{\gamma\gamma}$, N_{jets}, p_T^{j1}, m_{jj}, $\Delta\varphi_{jj}$ distributions
  - Combined: constraints on c- and b-quark Yukawa couplings

Inclusive and differential fiducial measurements

- **Predictions for comparison:** (see HIGG-2019-13 for details)
  - ggF: (~90% of x-sec)
    - NNLOPS - normalized to N3LO (default)
    - MG5 FxFx - normalized to N3LO
    - HRes 2.3 - normalized to N3LO
    - RadISH + NNLOJet, MATRIX+RadISH
    - SCETlib + MCFM8
    - Sherpa + MCFM + OpenLoops
  - Others production modes use state-of-the-art generators, and normalized to NNLO for VBF,VH and NLO for ttH,bbH
    - labelled: XH = VBF+WH+ZH+ttH+bbH (~10% of x-sec)
  - Normalizations all include EW corrections

Total cross sections

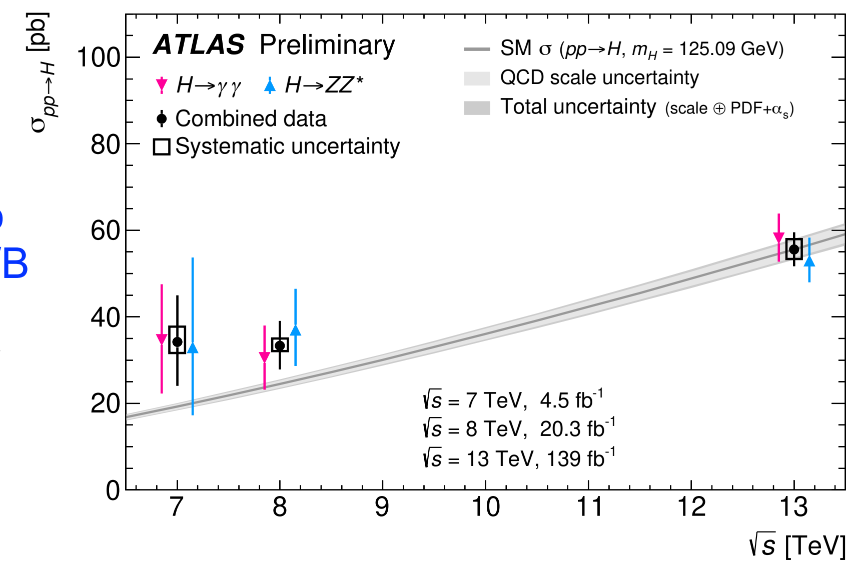
- Total x-sec for H4l and Hγγ in fiducial phase space, and
- Total combined x-sec is full phase space

13 TeV x-sec	Obs	uncert	SM	uncert	Obs/SM
H4l fid (fb)	3.28 ± 0.32	10 %	3.41 ± 0.18	5 %	0.96 ± 0.11
Hγγ fid (fb)	67 ± 6	9 %	64 ± 4	6 %	1.05 ± 0.11
Comb tot (pb)	$55.5^{+4.0}_{-3.8}$	7 %	55.6 ± 2.8	5 %	1.00 ± 0.09

Note: $BR_{\gamma\gamma}$ ~ 18 BR_{4l}

Similar precision due to different background S/B

Error bars - full uncertainty
boxes - stat-only



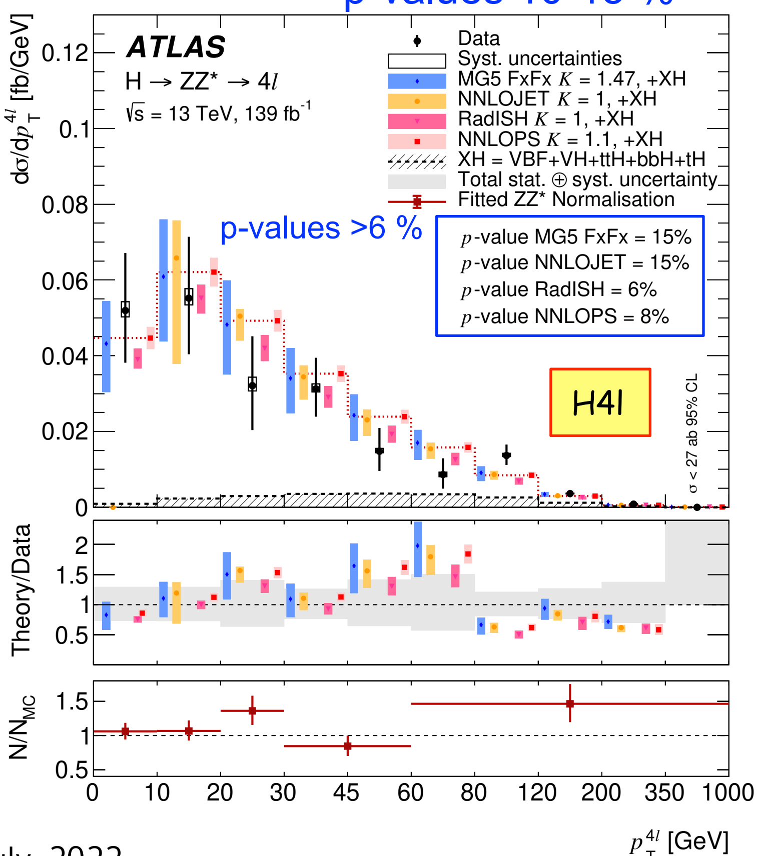
Total cross section vs √s

13 TeV x-sec full uncertainties:
55.5 ± 3.2 (stat) $^{+2.4}_{-2.2}$ (sys)
statistics dominated

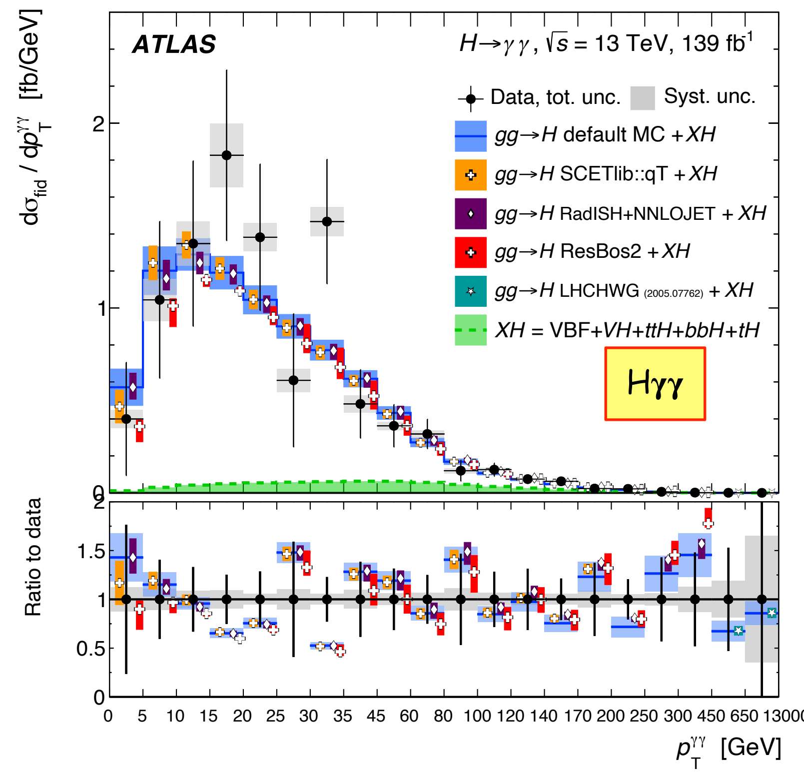
Higgs p_T - H4l and H$\gamma\gamma$ separately

- Higgs p_T probes the QCD modeling of the ggF production mechanism:
  - low p_T: soft/collinear QCD emission (resummation)
  - high p_T: H + ≥1 jet (Fixed order calc) can expect BSM effects at high p_T
  - => jet diff distributions can help constrain calculations for Higgs p_T (see backup p_T^{j1} vs p_T^{j2})

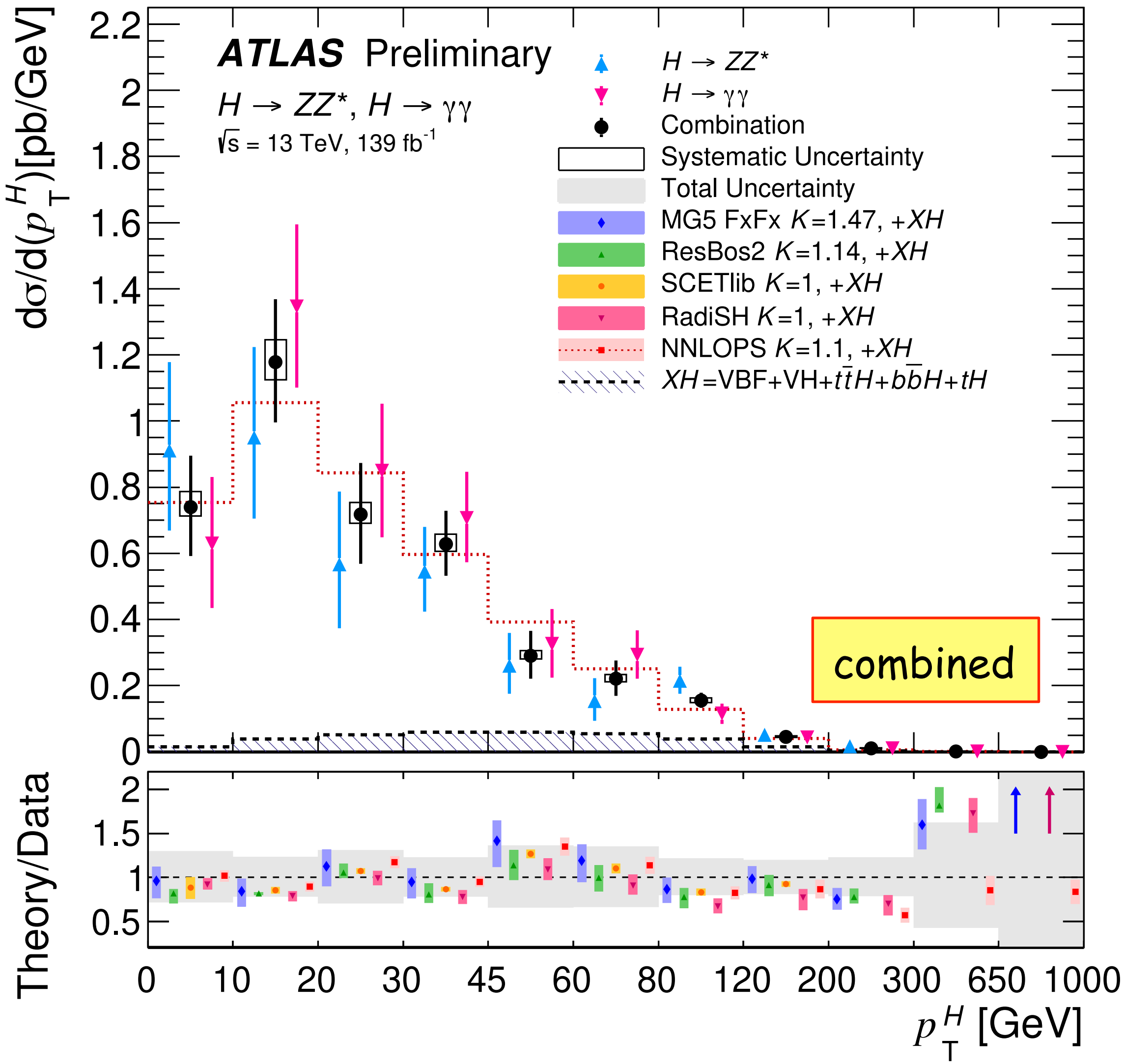
p-values 10-15 %



p-values >50 %



Higgs p_T - combined



p-values:

H4l/Hγγ: 20 %

MG5 FxFx: 73%

NNLOPS: 91%

include theory uncert

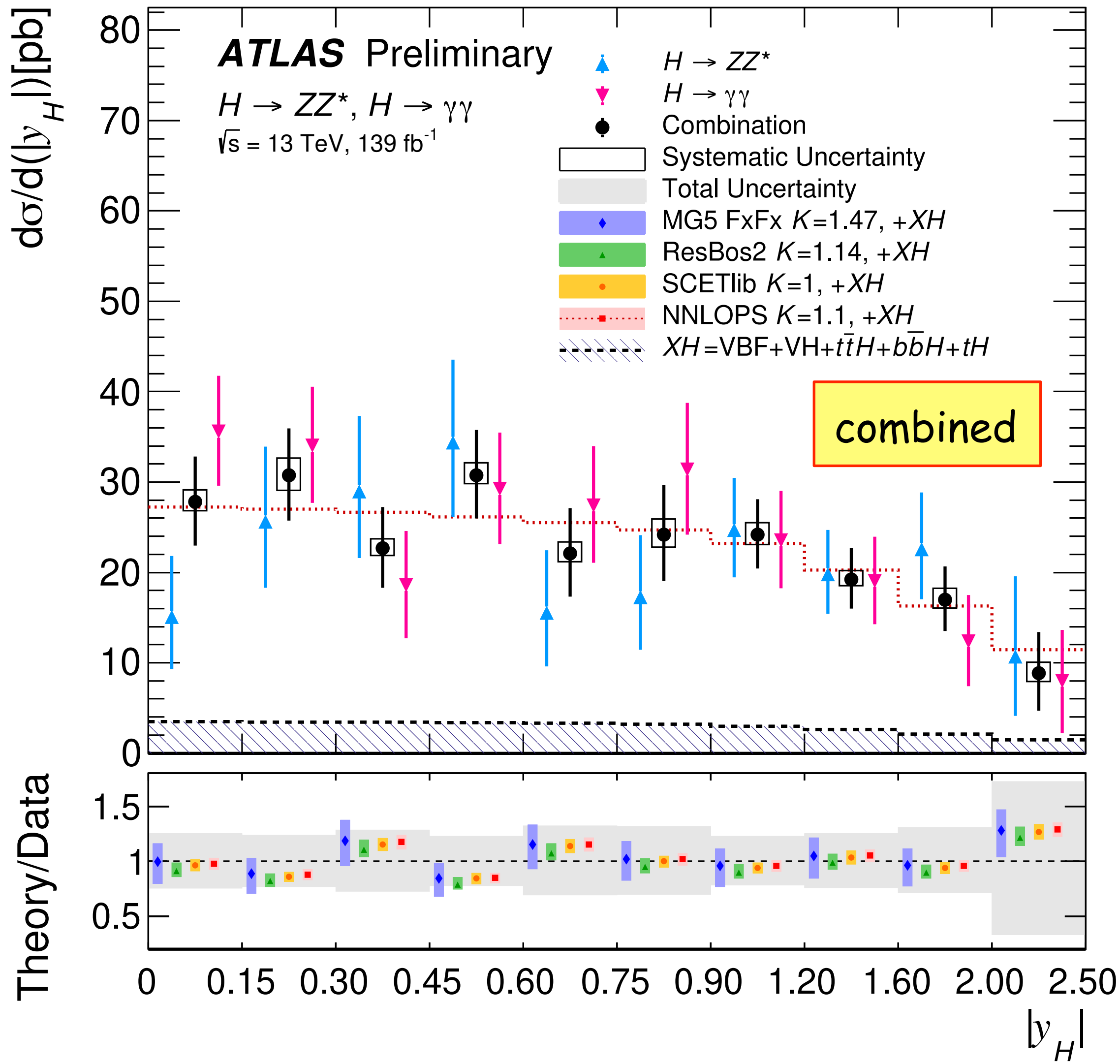
p_T^H precision:

20-30% up to 300 GeV

~60% 300-650 GeV

>100% 650-1200 GeV

y_H (rapidity)



p-values:

H4l/Hγγ: 23%

MG5 FxFx: 98%
NNLOPS: 98%
include theory uncert

y_H precision:

20-30% up to 2.0

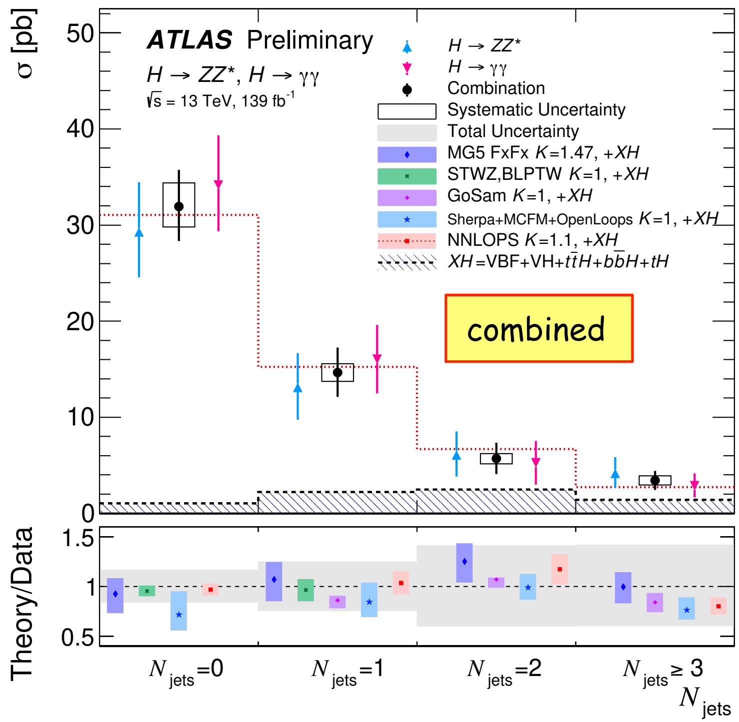
Probes PDFs and perturbative QCD modeling of the ggF production mechanism

N_{jet} and $p_T^{leading\ jet}$

p-values:
H4l/Hγγ: 80%

MG5 FxFx: 86%
NNLOPS: 95%

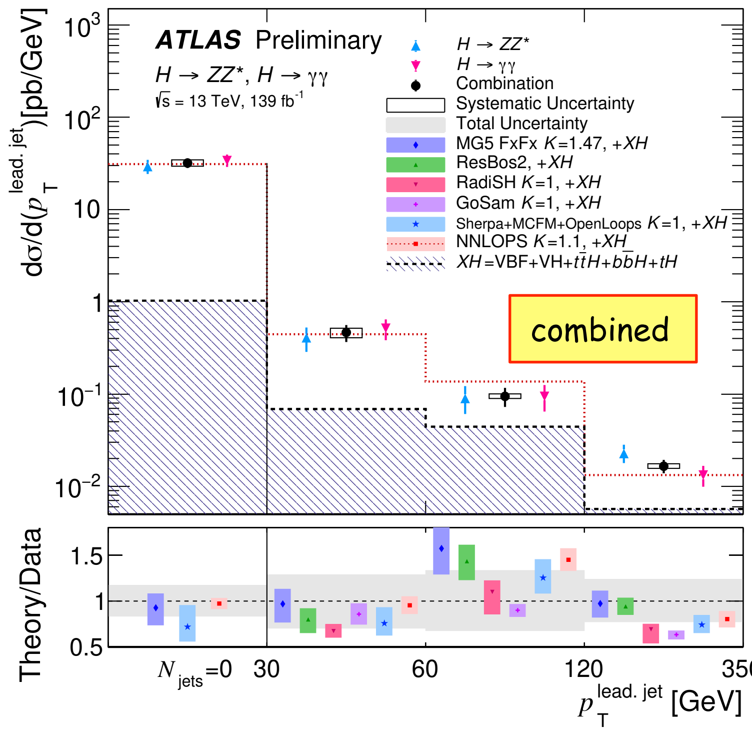
N_{jets}



p-values:
H4l/Hγγ: 37%

MG5 FxFx: 23%
NNLOPS: 34%

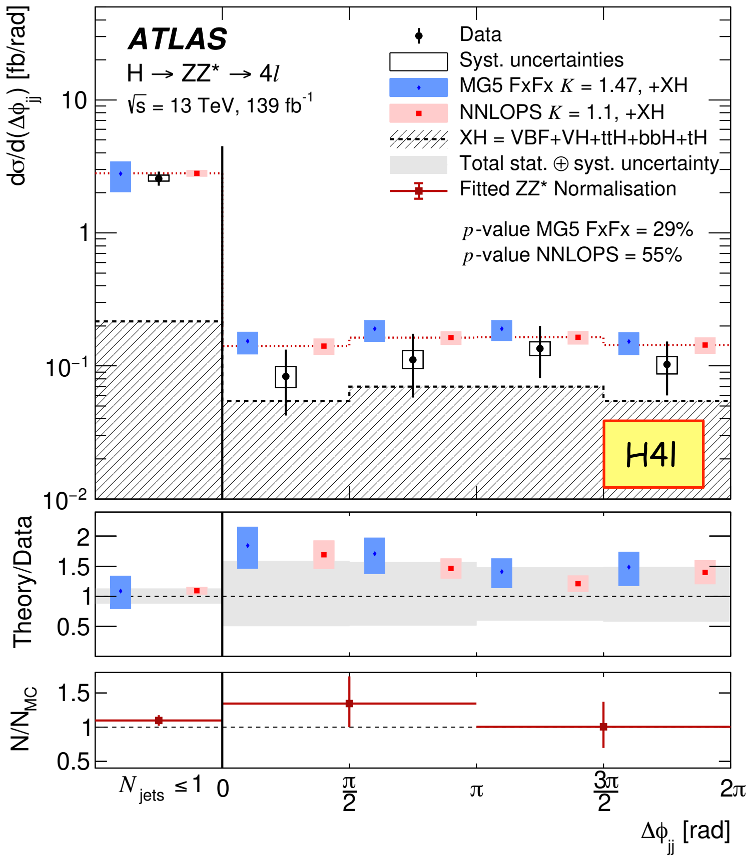
$p_T^{leading\ jet}$

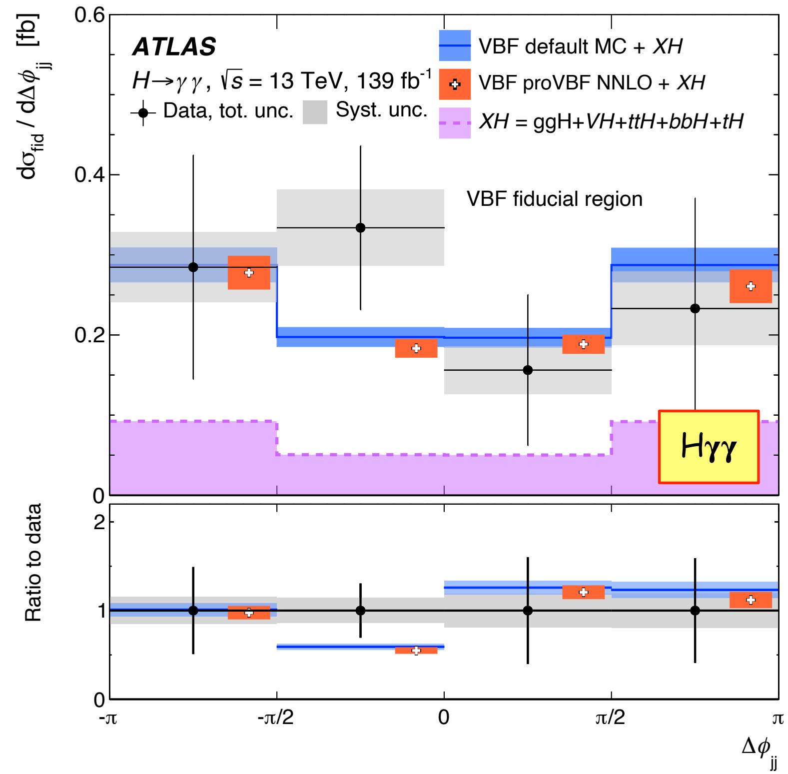


N_{jet} and $p_T^{pleading\ jet}$ precision: 20-30%

Jet distributions to test perturbative QCD modeling of the ggF production mechanism, and contributions of other production modes

Δφjj - asymmetry indicates CP-odd coupling

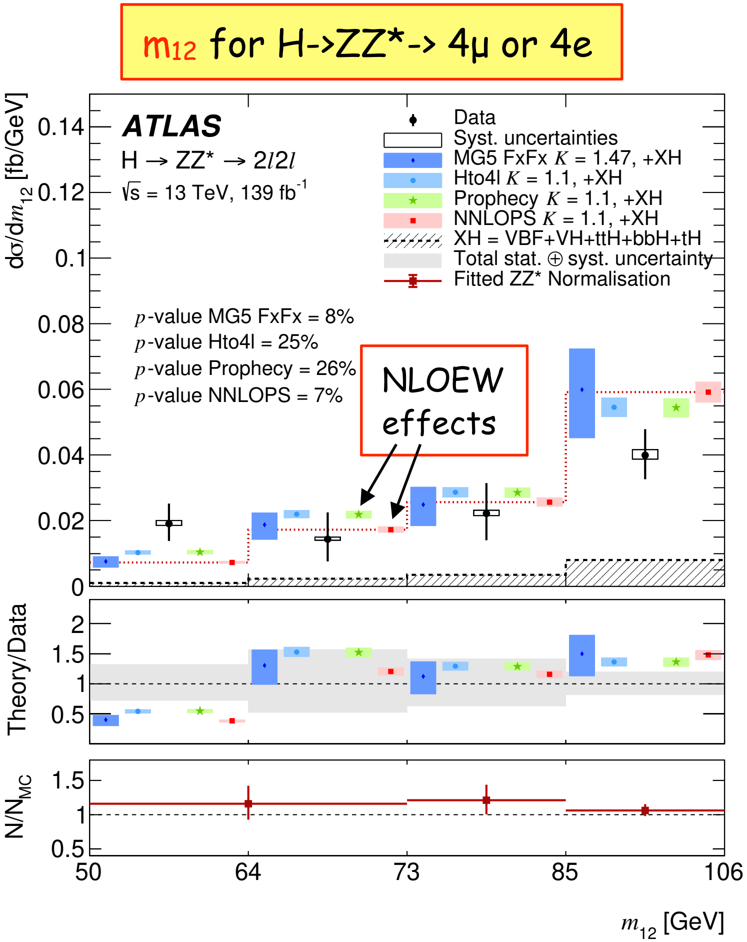


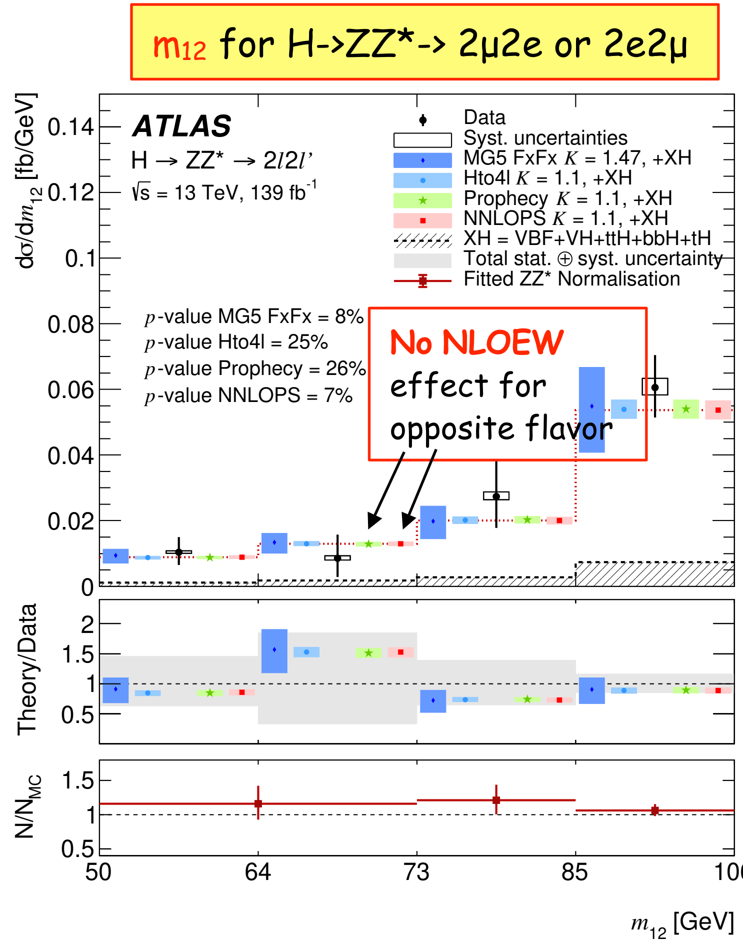


H4l - in inclusive fiducial phase space

Hγγ - in VBF-specific fiducial phase space (m_{jj} > 600 GeV, $|\Delta y_{jj}|$ > 3.5)

NLOEW contributions to H4l decay





Leading lepton pair mass, m_{12}, is sensitive to NLOEW effects in decay (final state interactions)

Affects 4μ or 4e decays (same flavor), but not 2μ2e or 2e2μ (opposite flavor)

Expectations with Prophecy4F or Hto4l for decay (blue/green) compared to std (pink NNLOPS)

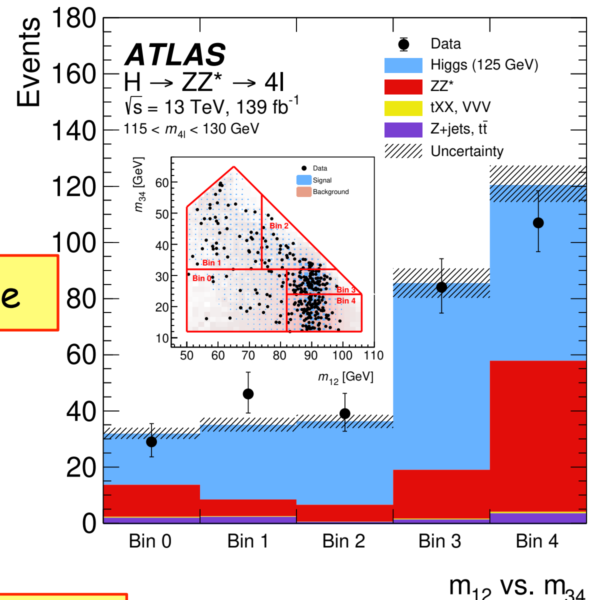
Small preference in p-values for Prophecy4f/Hto4l

BSM limits: m_{12} vs m_{34} Pseudo Observables

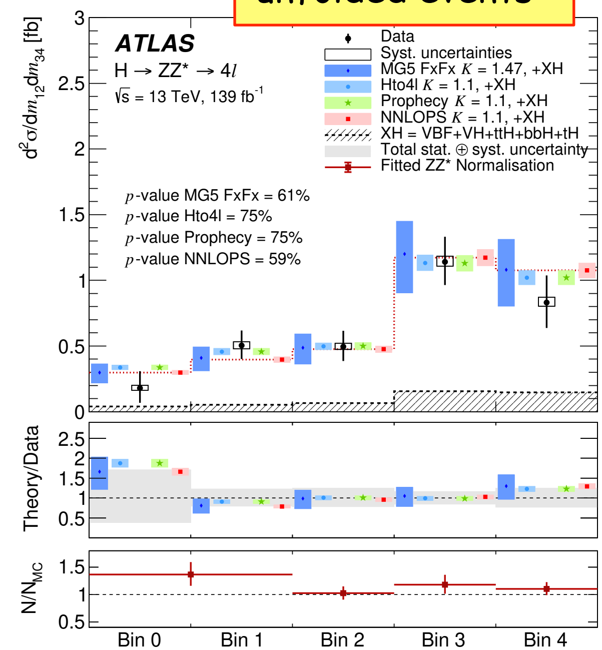
H4l

5 regions of m_{12} vs m_{34} plane

reconstructed events



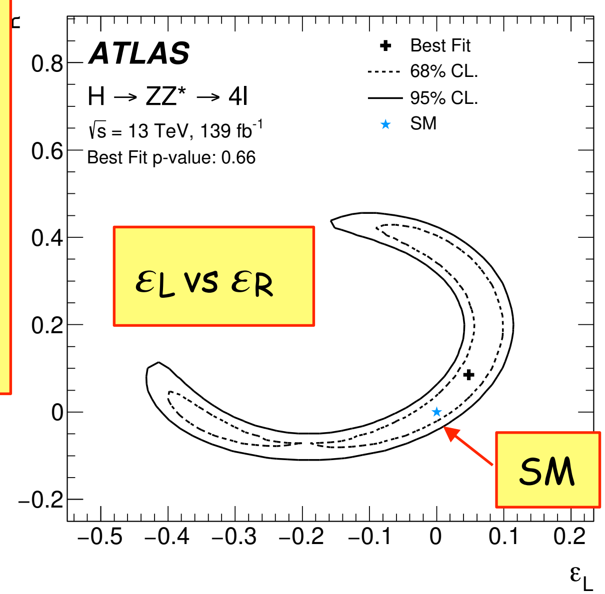
unfolded events

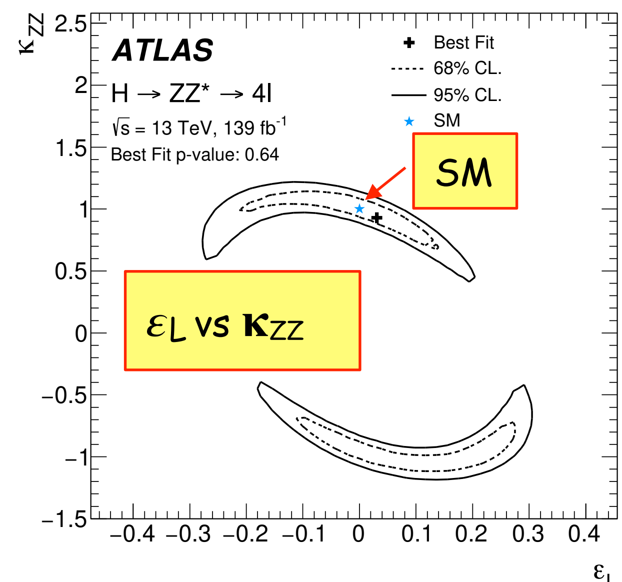


pseudo-observables (arXiv:1504.04018):

ε_L, ε_R : contact interaction couplings for left- and right-handed leptons to Higgs boson

κ_{ZZ} modifies the H to Z coupling





Constraints on b- and c-quark Yukawa couplings via p_T^H

Heavy quark production can be enhanced at low p_T^H due to interference between ggF and quark-initiated production (1606.09253)

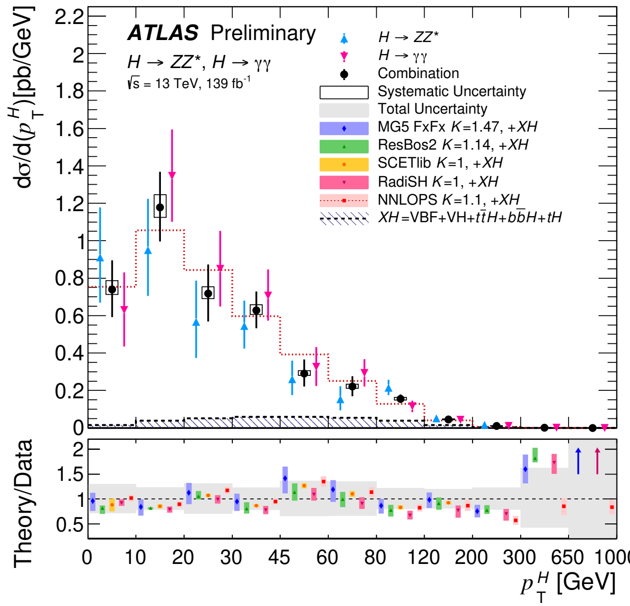
Constrain Higgs couplings modifiers κ_c and κ_b with shape of the p_T^H distribution

(SM rate for c-quark is ~x400 smaller than for b-quarks)

Limit extraction relies on accuracy of QCD radiation estimates

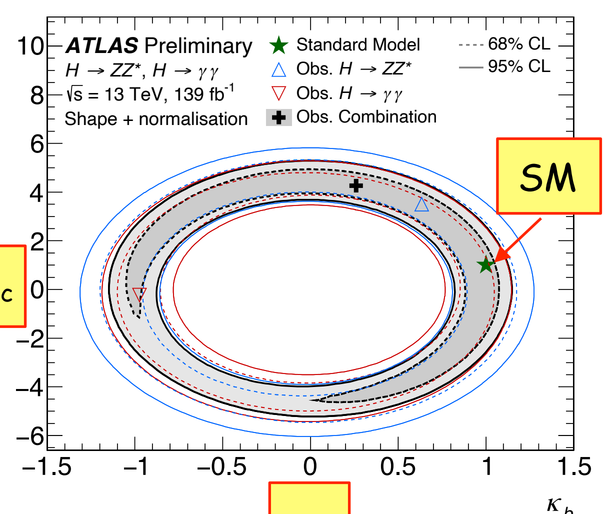
Other tree-level couplings assumed to be SM

Can combine with VH(-> bb, cc) measurements - right plot



Combined p_T^H

p_T^H : shape+normalisation κ_c vs κ_b

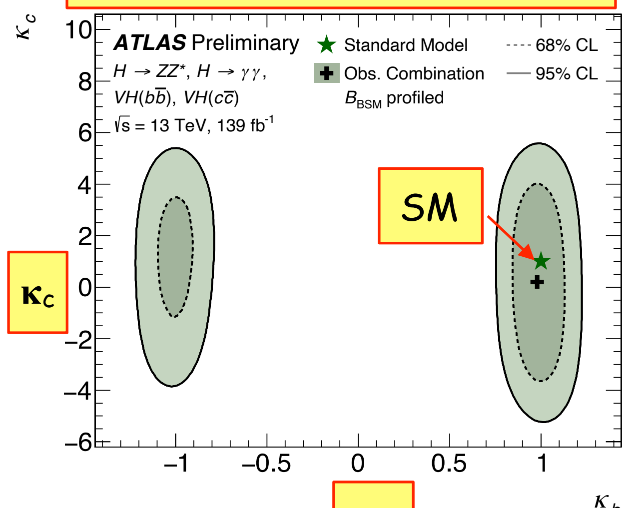


SM

κ_c

κ_b

p_T^H + VH(-> bb, cc) floating B_{BSM}: κ_c vs κ_b



SM

κ_c

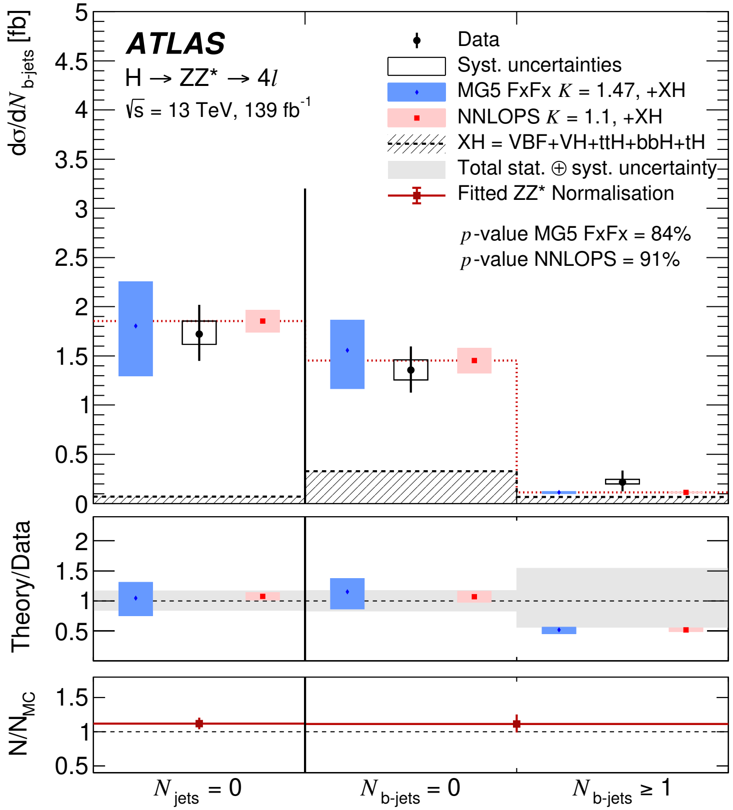
κ_b

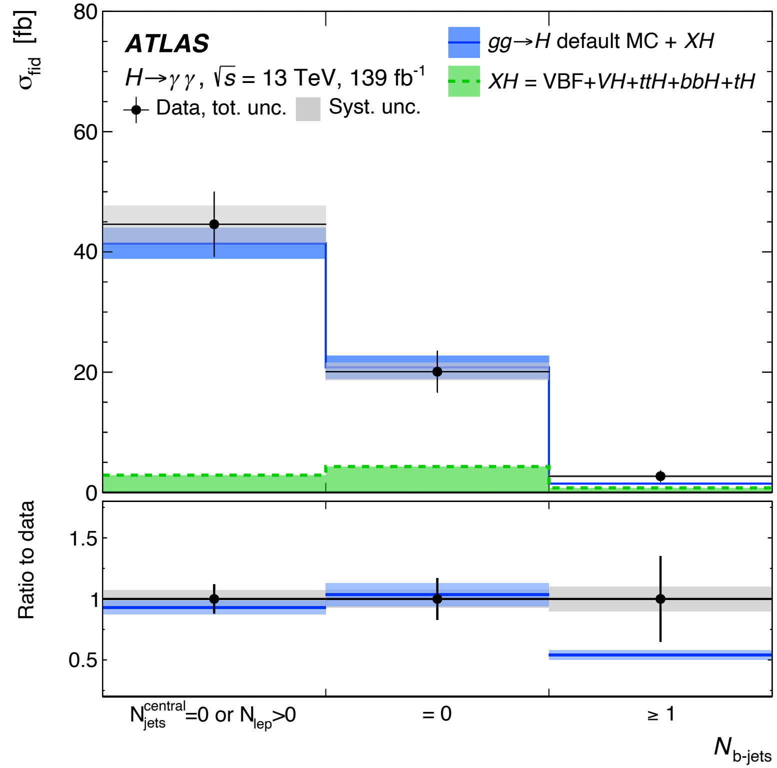
Summary

- Final Run 2 results for fiducial cross sections and distributions are now available for H->ZZ*->4l and H->$\gamma\gamma$ decay channels, as well as their combination
  - allowing tests of the SM Higgs production and QCD modeling
- The combine Higgs production cross section is measured to be: 55.5 ± 3.2 (stat) $^{+2.4}_{-2.2}$ (sys) pb (SM: 55.6 ± 2.8 pb)
- Example interpretations for Pseudo-observables (H4l) and c- and b-quark couplings (combined) have been shown
- All measurements are statistics limited, indicating that precision will continue to improve with more data
- All measurements are compatible with the SM

BACKUP

Number of b-jets





H4l: fraction of events with b-jet: 6.8 ± 3.2 %

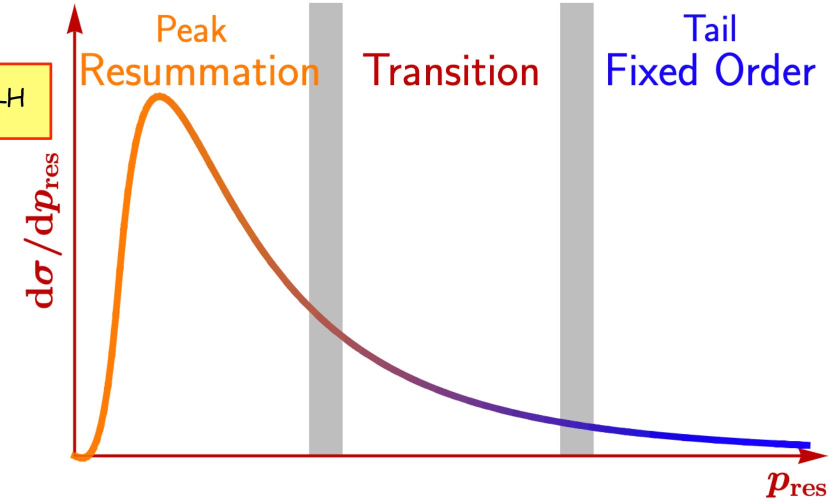
Hγγ: fraction of events with b-jet: 4.0 ± 1.0 %

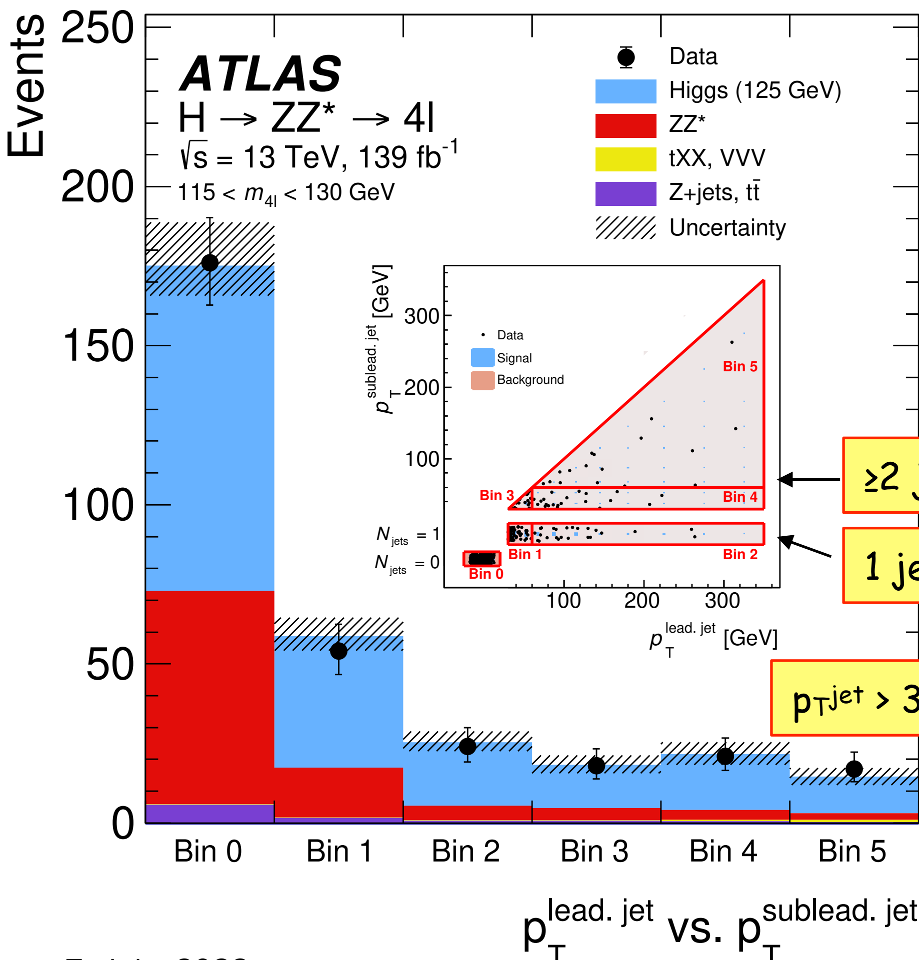
Theory: fraction of events with b-jet: 3.5 ± 0.2 %

$p_T^{\text{leading jet}}$ vs $p_T^{\text{subleading jet}}$

Differential distribution leading and subleading jet p_T can help test calculations to understand QCD recoil for Higgs p_T

p_T^H

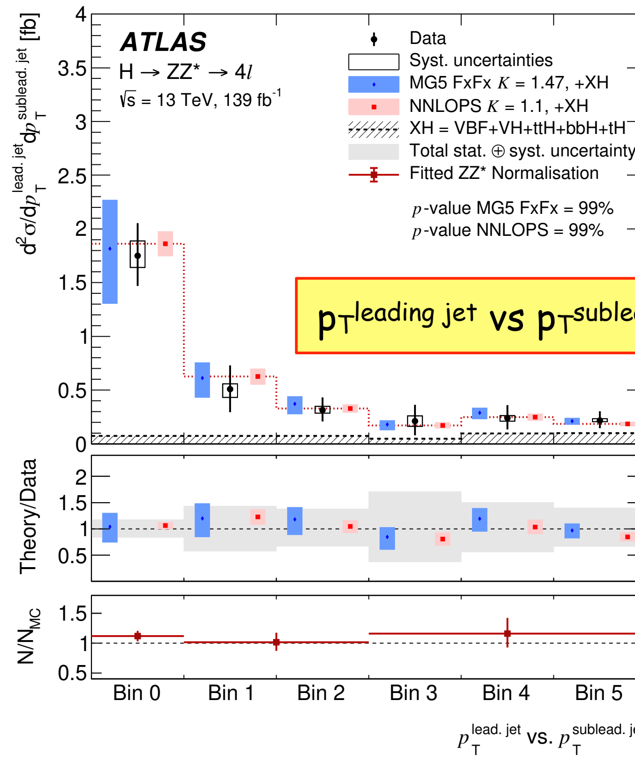




≥2 jets

1 jet

p_T^{jet} > 30 GeV



$p_T^{\text{leading jet}}$ vs $p_T^{\text{subleading jet}}$

EFT constraints with Hγγ differential distributions

Constraints on Wilson coefficients in Warsaw basis (SMEFT)

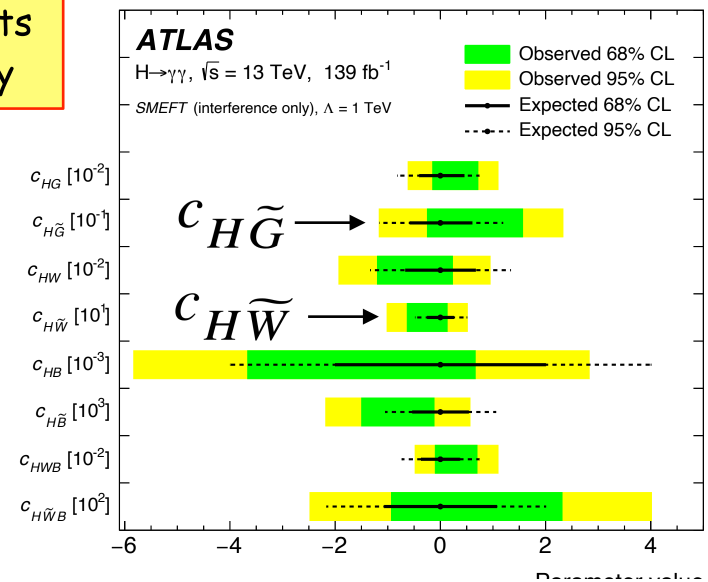
Using distributions: $p_T^{\gamma\gamma}$, N_{jets}, p_T^{j1}, m_{jj}, $\Delta\varphi_{jj}$

x-sec contain:
- linear interference terms constraining CP-odd couplings
- quadratic terms constraining CP-even couplings

c_{HG}, c_{HGtil} affect ggF x-sec
c_{HW}, c_{HB}, c_{HWB} affect VBF/VH x-sec but more importantly the $B\gamma\gamma$

$\Delta\varphi_{jj}$ is the sensitive distribution for CP-odd constraints

Constraints linear-only



Constraints linear + quadratic