Higgs Boson Fiducial Cross Sections and Differential Distributions

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On behalf of the ATLAS and CMS collaborations

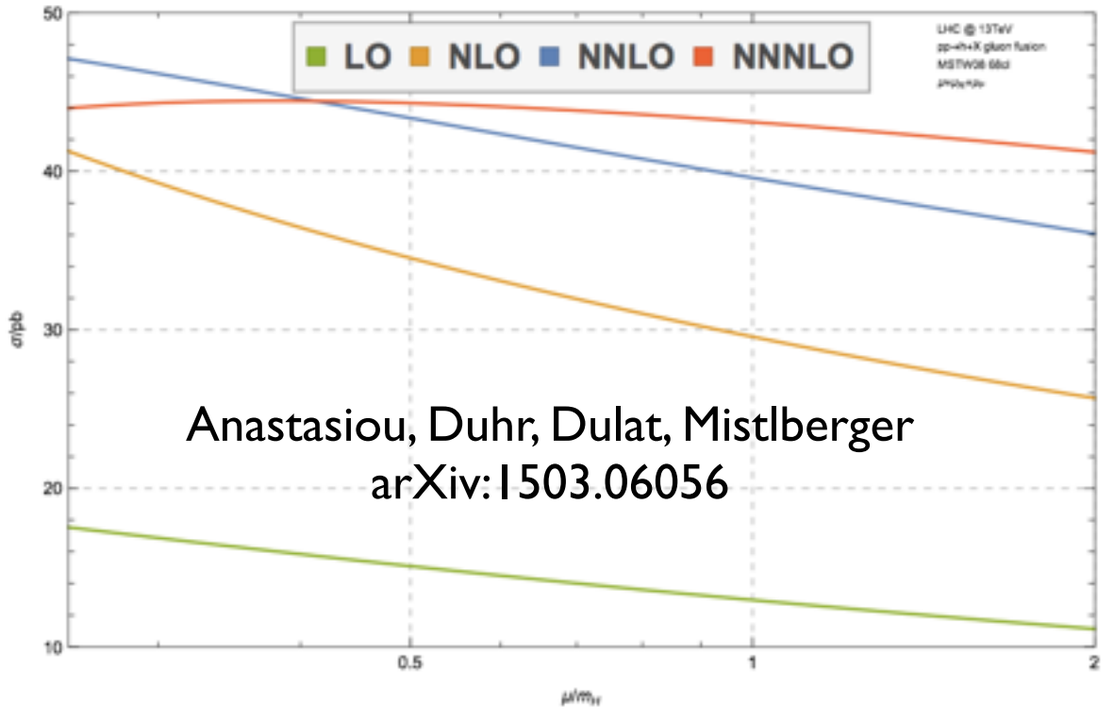
SM@LHC 2015 23 April 2015 GGI

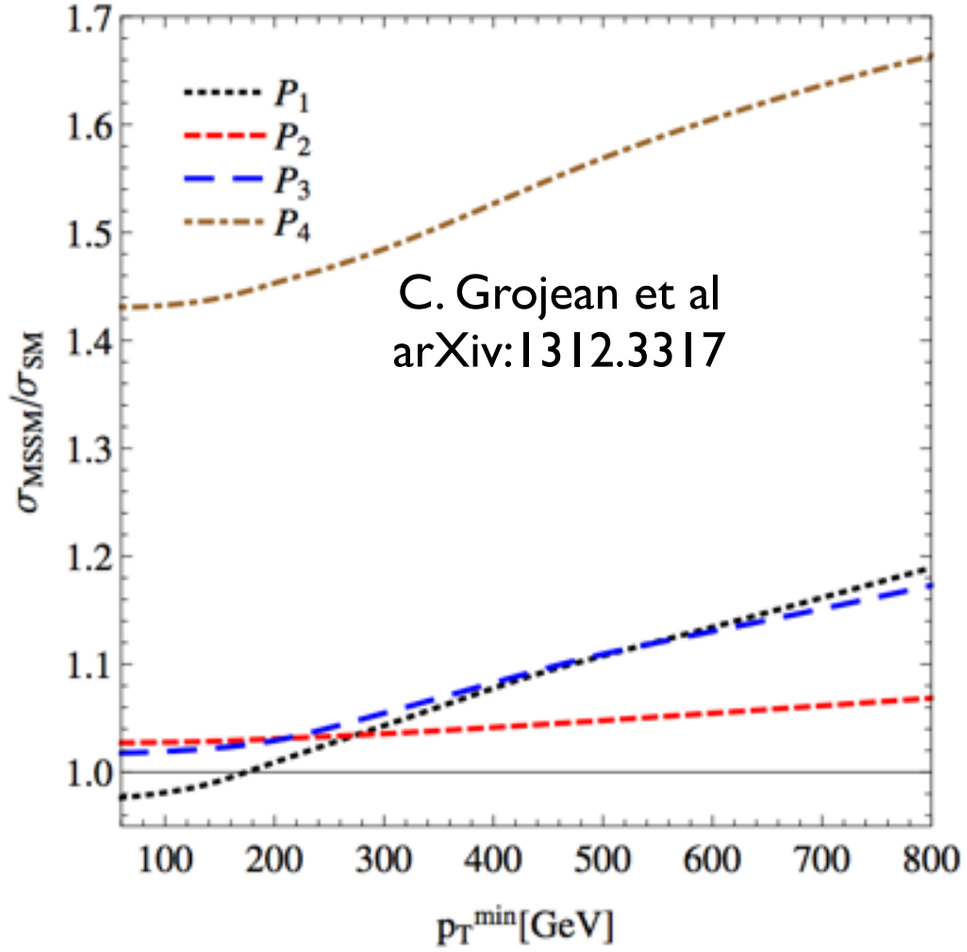
Outline

- Motivation for measuring fiducial cross-section and differential distributions
- Fiducial cross-section and differential distributions in
  - $H \to ZZ \to 4l$
  - $H \to \gamma\gamma$
- **Combined measurements from $ZZ \to 4l$ and $\gamma\gamma$**
  - Inclusive cross-section
  - Higgs pT, rapidity, jet multiplicity and leading jet pT
  - http://arxiv.org/abs/1504.05833 (Submitted to PRL today!)
- Summary

Motivation

- Inclusive/fiducial cross-section and differential distributions are key Higgs boson properties
  - **Less model-dependent and correction for detector effects**
    - **Compare with ggF N3LO total x-section**
  - Higgs pT
    - Probe perturbative QCD predictions
    - High pT region is sensitive to NP
  - Higgs rapidity
    - Probes the gg parton PDF
  - Jet multiplicities
    - Probes the different productions
  - Higgs decay
    - Sensitive to high dimensional operators





H→ZZ*→4l

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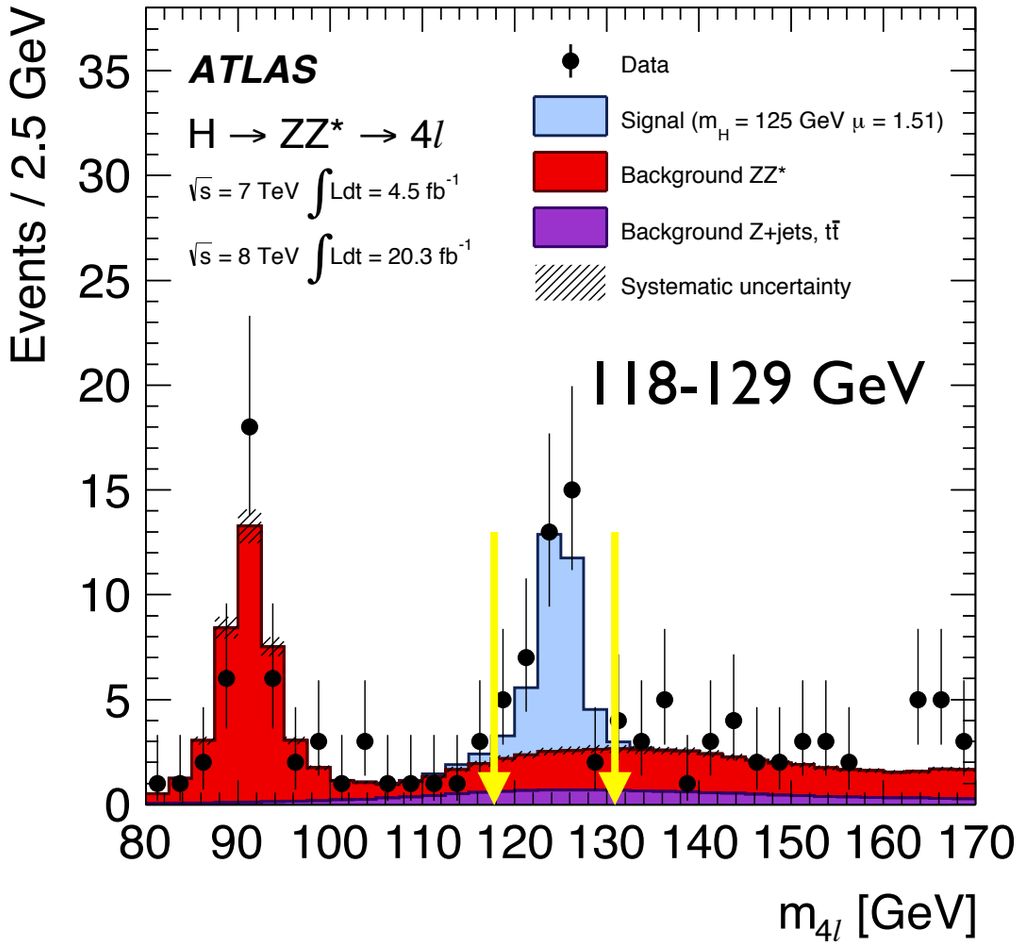


Analysis Overview

- Fiducial selections mimic the event-selections
  - Leptons selections: born-level
    - dressed-option is checked, yielding <0.5% difference in the acceptance
  - Jets are reconstructed from stable particles excluding e,μ,ν, using anti-Kt R=0.4
    - PT > 30 GeV, |y| < 4.4
    - Not from hardonic decays
    - Removed if within ΔR=0.2 from electron
- Differential distributions
  - Higgs boson kinematics
    - pT and rapidity of the Higgs
  - Jet activity
    - n_{Jets} and leading jet pT
  - Higgs decay kinematics:
    - m_{34} and production angle $|\cos\theta^*|$

Fiducial region Definition

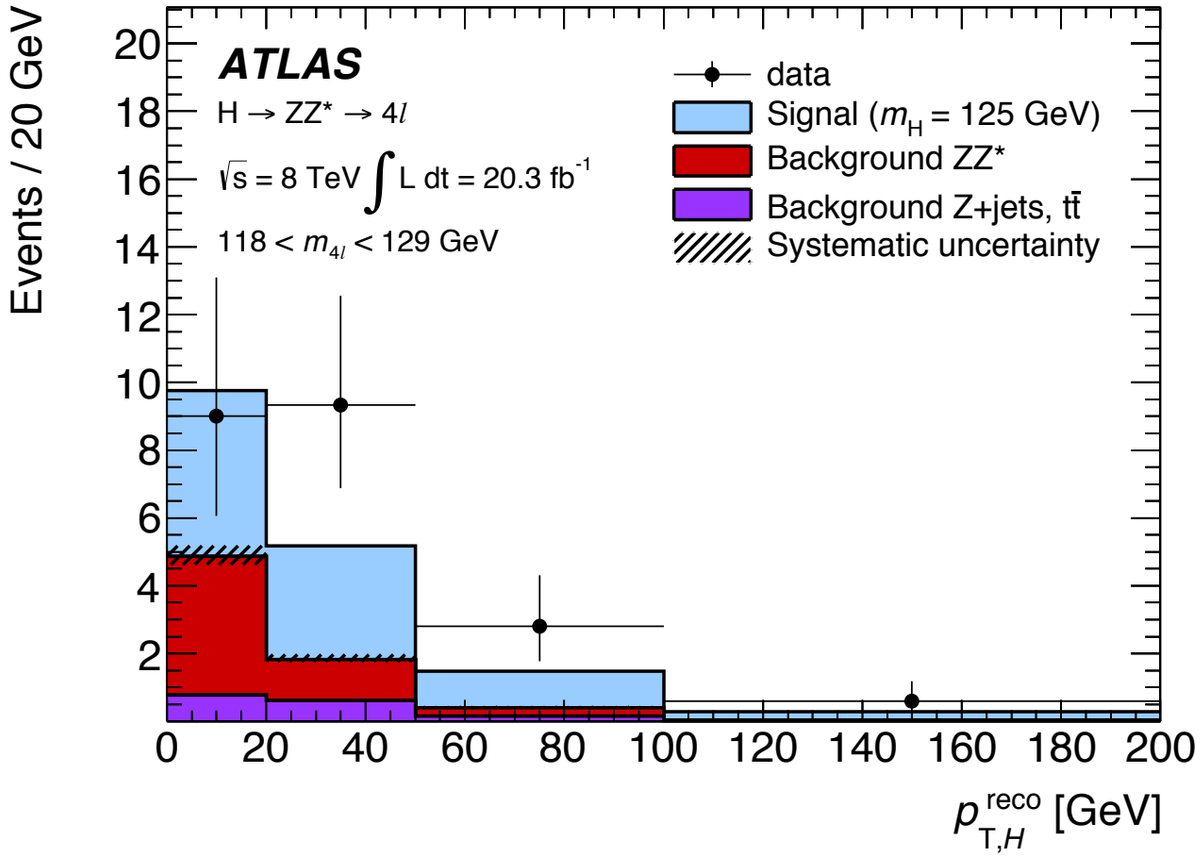
Lepton selection	
Muons:	$p_T > 6$ GeV, $\|\eta\| < 2.7$
Electrons:	$p_T > 7$ GeV, $\|\eta\| < 2.47$
Lepton pairing	
Leading pair:	SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair:	Remaining SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection	
Lepton kinematics:	$p_T > 20, 15, 10$ GeV
Mass requirements:	$50 < m_{12} < 106$ GeV $12 < m_{34} < 115$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1$ (0.2) for same- (different-) flavour leptons
J/ψ veto:	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window:	$118 < m_{4\ell} < 129$ GeV

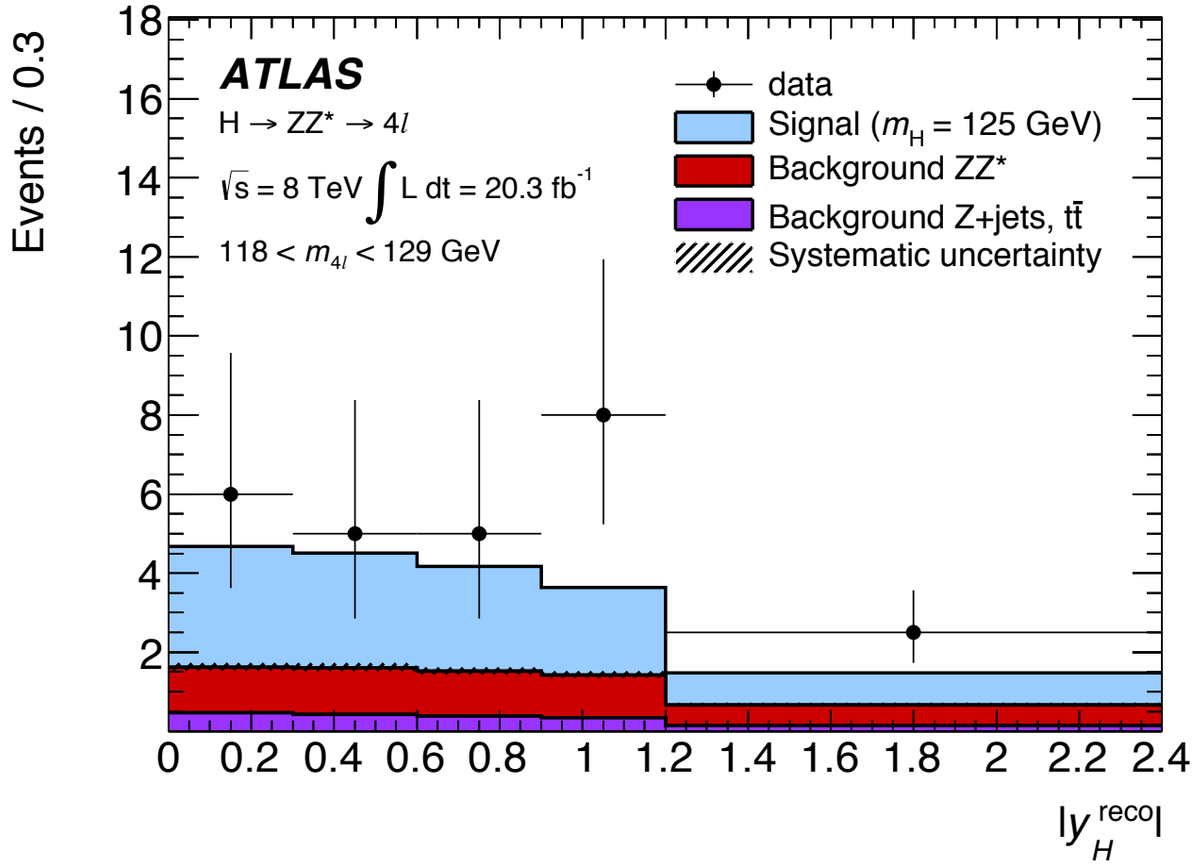
mH 125.4 GeV

Acceptance w.r.t full phase space 46%

Signal Extraction

- Fiducial cross-section
  - Perform a binned fit to m4l spectrum, fixing mH=125.4GeV
- Differential distribution
  - Given the low stat in each bin, signal is extracted by subtracting background within m4l [118-129] GeV
  - 6% difference in the inclusive signal yield to the fit method (due to fixed mH in the fit)



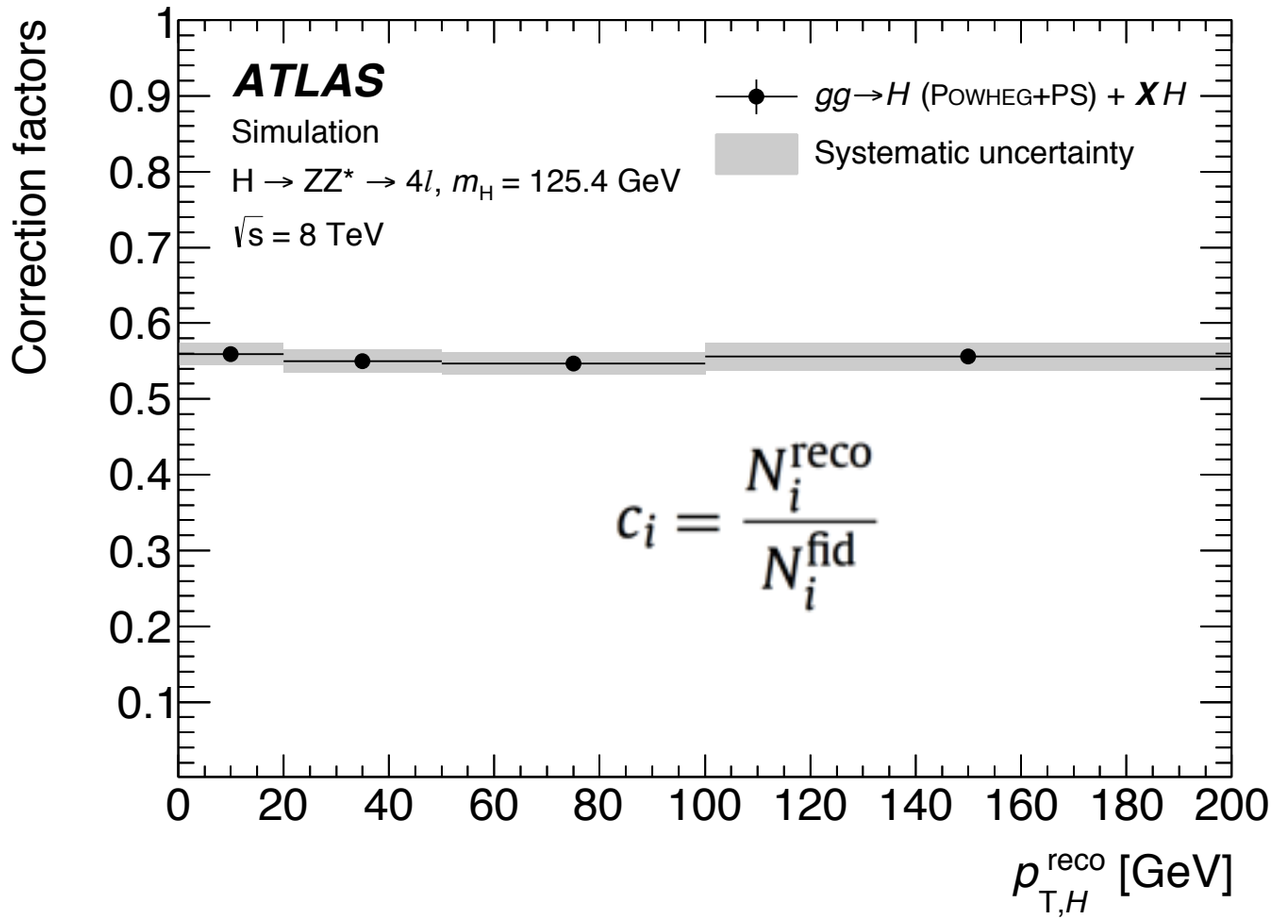


nSignal = $23.7^{+5.9}_{-5.3}(\text{stat.}) \pm 0.6(\text{syst})$

Fiducial Cross-section and Differential Cross-section

- Extracted signal events are corrected for detector efficiency and resolution for fiducial cross-section and differential distribution measurements
  - Bin-by-bin reco-to-fiducial correction factors ci are derived from signal MC
    - Reconstruction/ID efficiency and bin-by-bin migration

$$\frac{d\sigma_{\text{fid},i}}{dx_i} = \frac{n_i^{\text{sig}}}{c_i \cdot \mathcal{L}_{\text{int}} \cdot \Delta x_i}$$

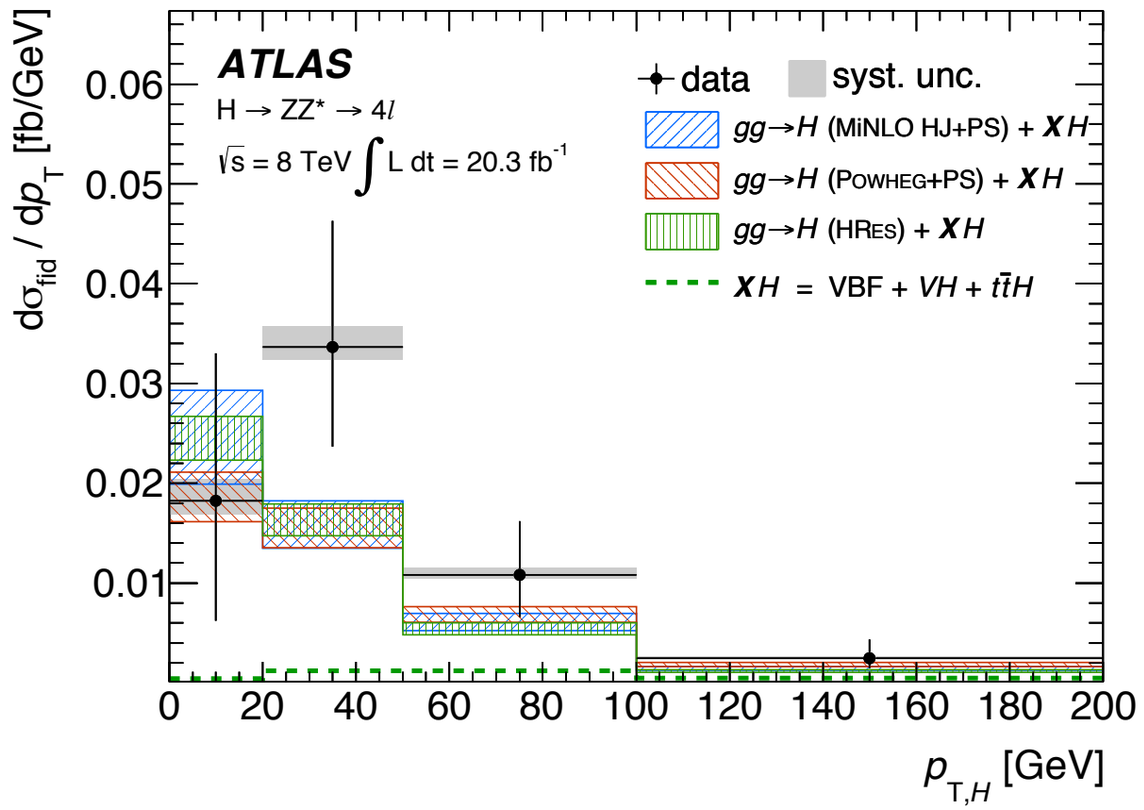


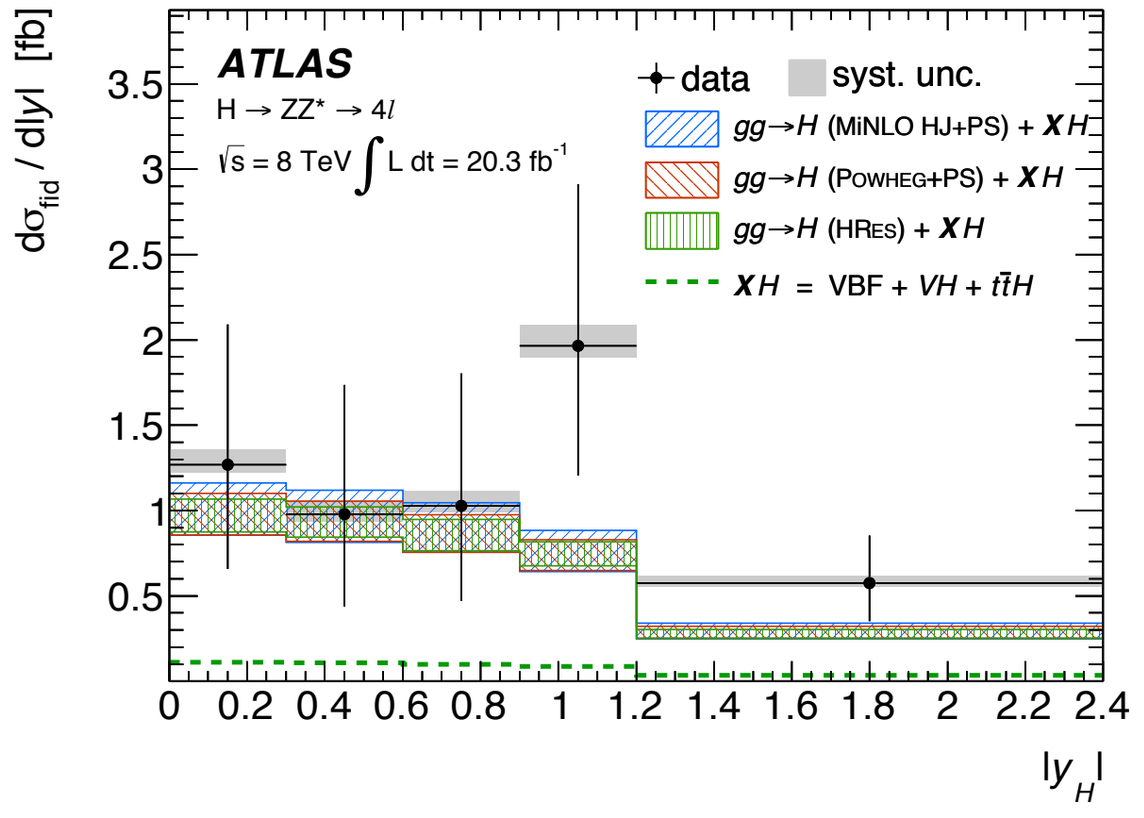
- Observed a mild excess (1-2 σ) in the fiducial cross-section
  - Compared to LHC-XS recommendation
  - More recent predictions using ggF N3LO will be shown later in the combination

Observed (fb)	Predicted (fb)
$2.11^{+0.53}_{-9.47}(\text{stat.}) \pm 0.08(\text{syst.})$	1.30 ± 0.13

Fiducial Cross-section Distributions

- Compare with 3 ggF predictions
  - POWHEG + PS
  - MINLO HJ + PS
  - Analytical HRES2 (v2.2)
    - fixed order σ up to NNLO
    - resummation at NNLL for small pT
    - t/b mass dependence NLO+NLL
    - QED final state radiation not included
  - More recent predictions using ggF N3LO will be shown later in the combination
- XH are added:VBF/VH/ttH/bbH
  - VBF: Powheg
  - VH/ttH/bbH: Pythia8
- Observed no significant discrepancy
  - **Slightly harder pT spectrum**





$H \to \gamma\gamma$

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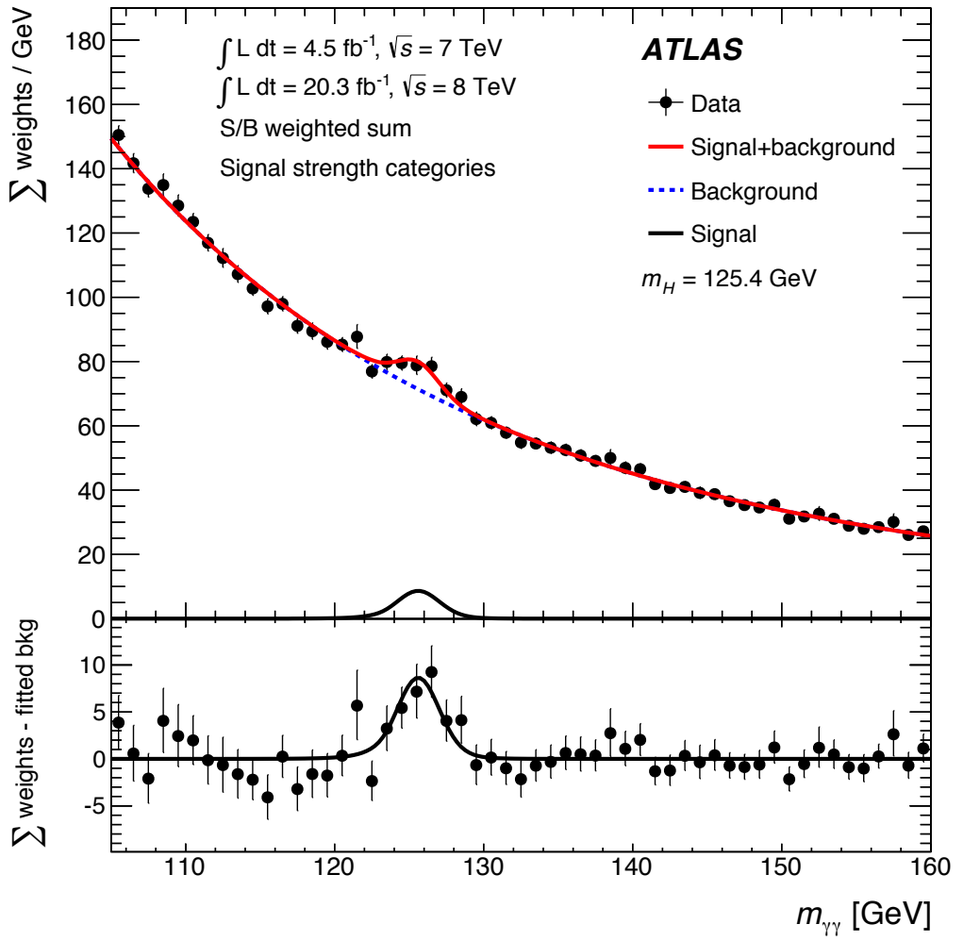
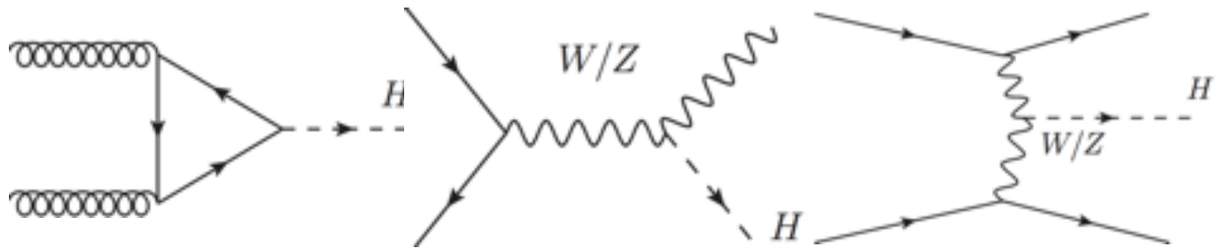


Analysis Overview

- Fiducial selections
  - Photons: require not from hardonic decays
  - Jets are reconstructed from stable particles excluding e,μ,ν, using anti-Kt R=0.4
    - pT > 30/50 GeV, |y| < 4.4
    - Not from hardonic decays
    - Removed if within ΔR=0.4 from leptons and photons
- Comprehensive differential distributions
  - Higgs boson kinematics
  - Jet activity
  - Spin-CP sensitive variables
  - VBF sensitive variables



7 Fiducial region definitions

1 Baseline
2 isolated photon $|\eta|<2.37$, $p_T/m_{\gamma\gamma}>0.35$ (0.25)

3 H+jets regions
nJets ≥1, 2, 3 pT(jet) > 30 GeV, $|y|<4.4$

1 Single Lepton region (WH)
electron/muon pT > 15 GeV, $|\eta| < 2.47$

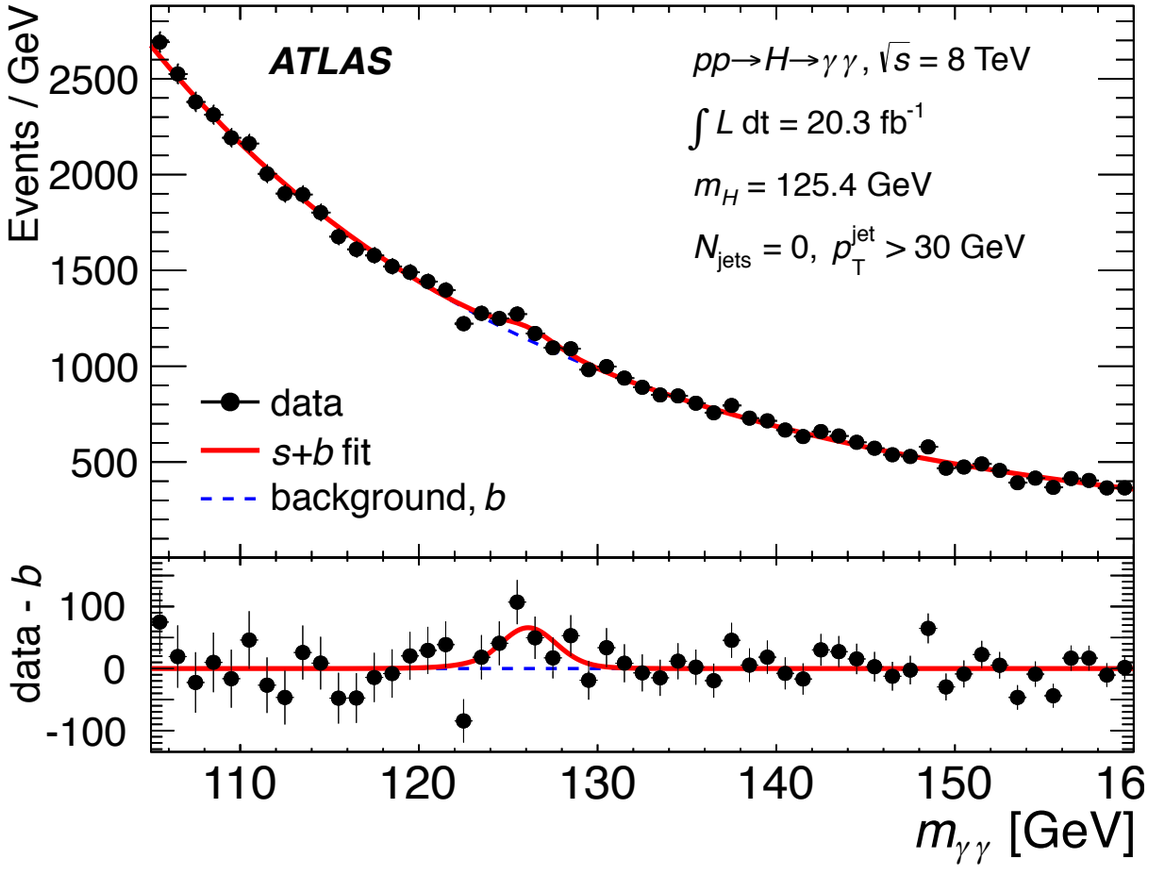
1 Large MET region (ZH)
MET > 80 GeV

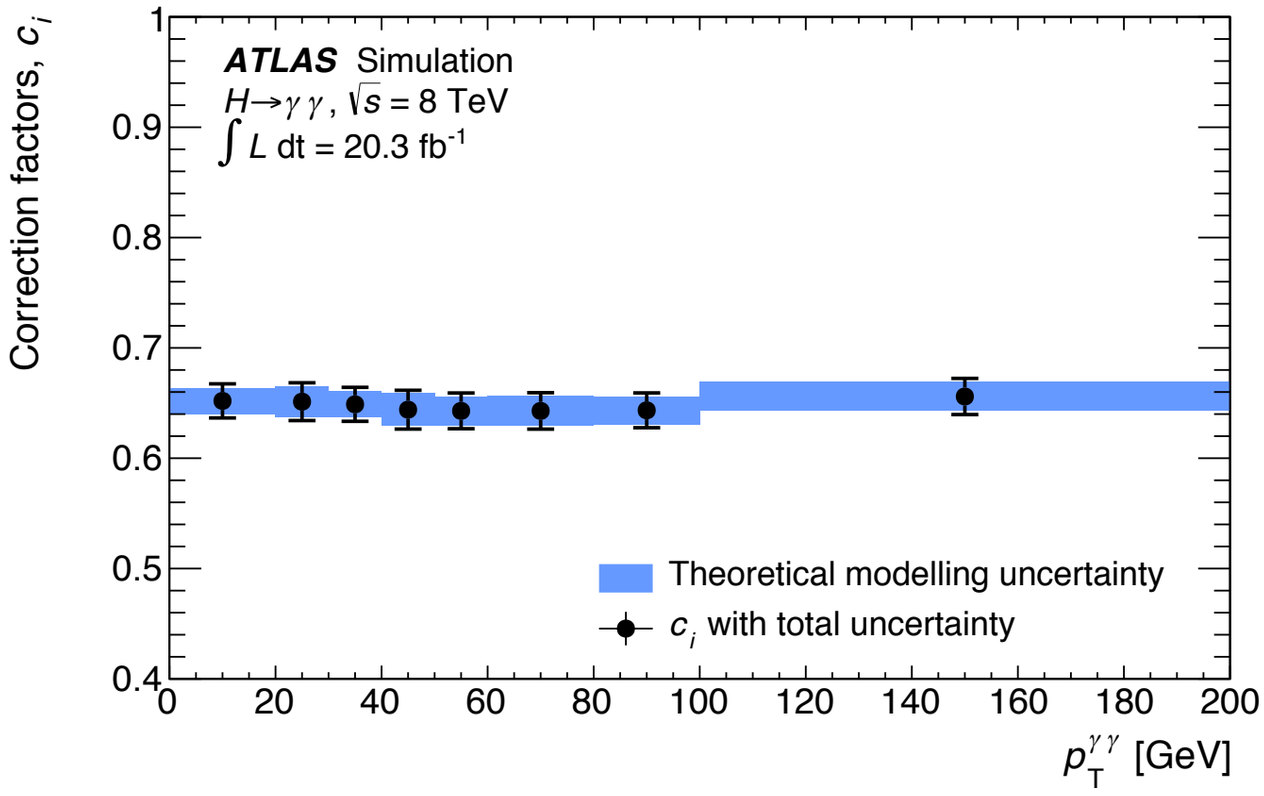
1 VBF region
$m_{jj}>400$ GeV, $|\Delta\phi_{\gamma\gamma,\,jj}| < 2.6$, $|\Delta y_{jj}|>2.8$

Signal Extraction and Fiducial Cross-section

- For a given fiducial region or bin of a differential cross-section, number of signal events is extracted by performing an unbinned ML fit to $m_{\gamma\gamma}$
  - Fitted yields ν^{sig} are higher than expected signal MC yield, but consistent within large errors
- The number of extracted signal events are then corrected to the particle level for fiducial cross-section and differential distribution measurements

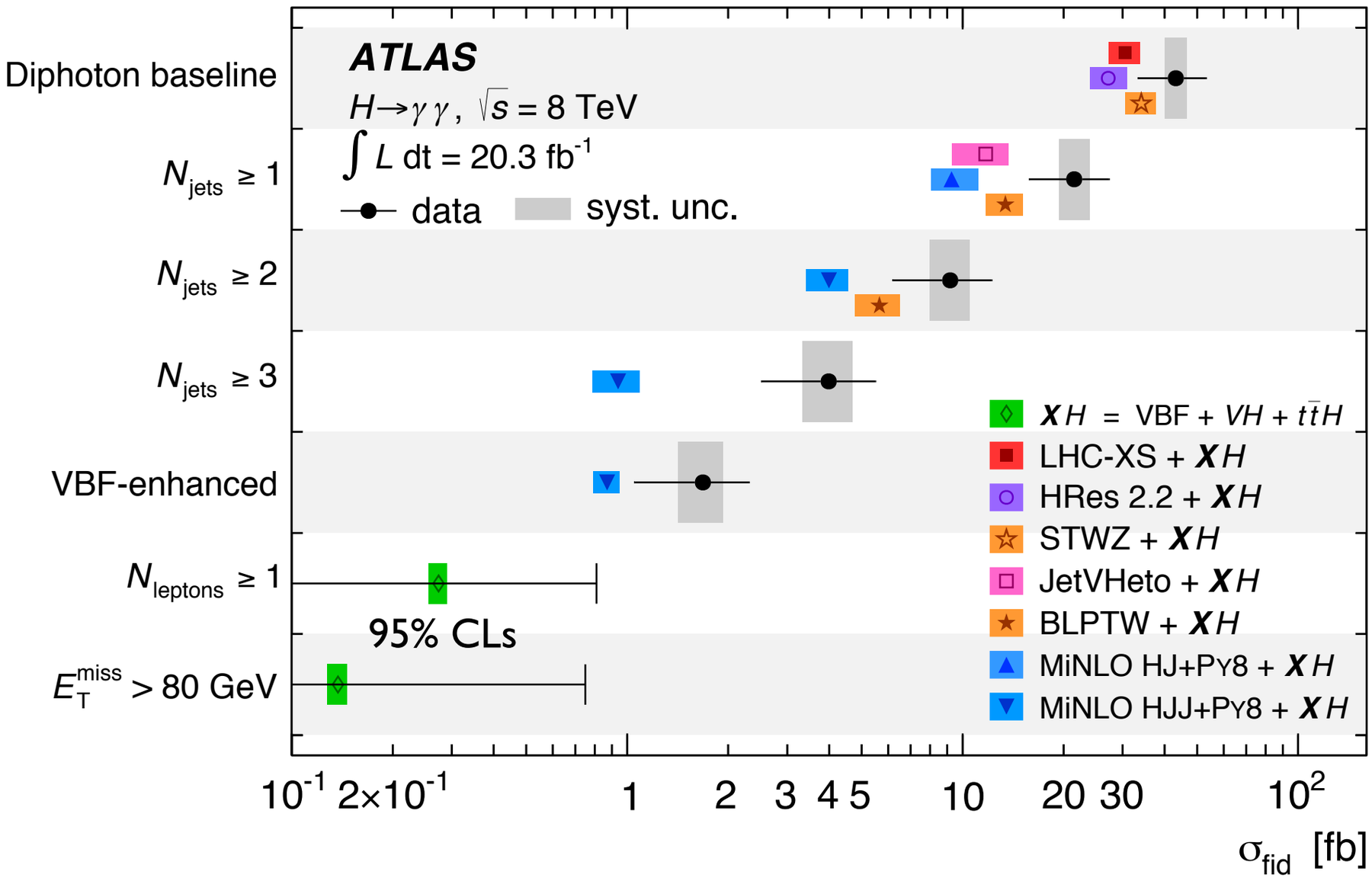
$$\sigma_i = \frac{\nu_i^{\mathrm{sig}}}{c_i \int L\,\mathrm{d}t}$$





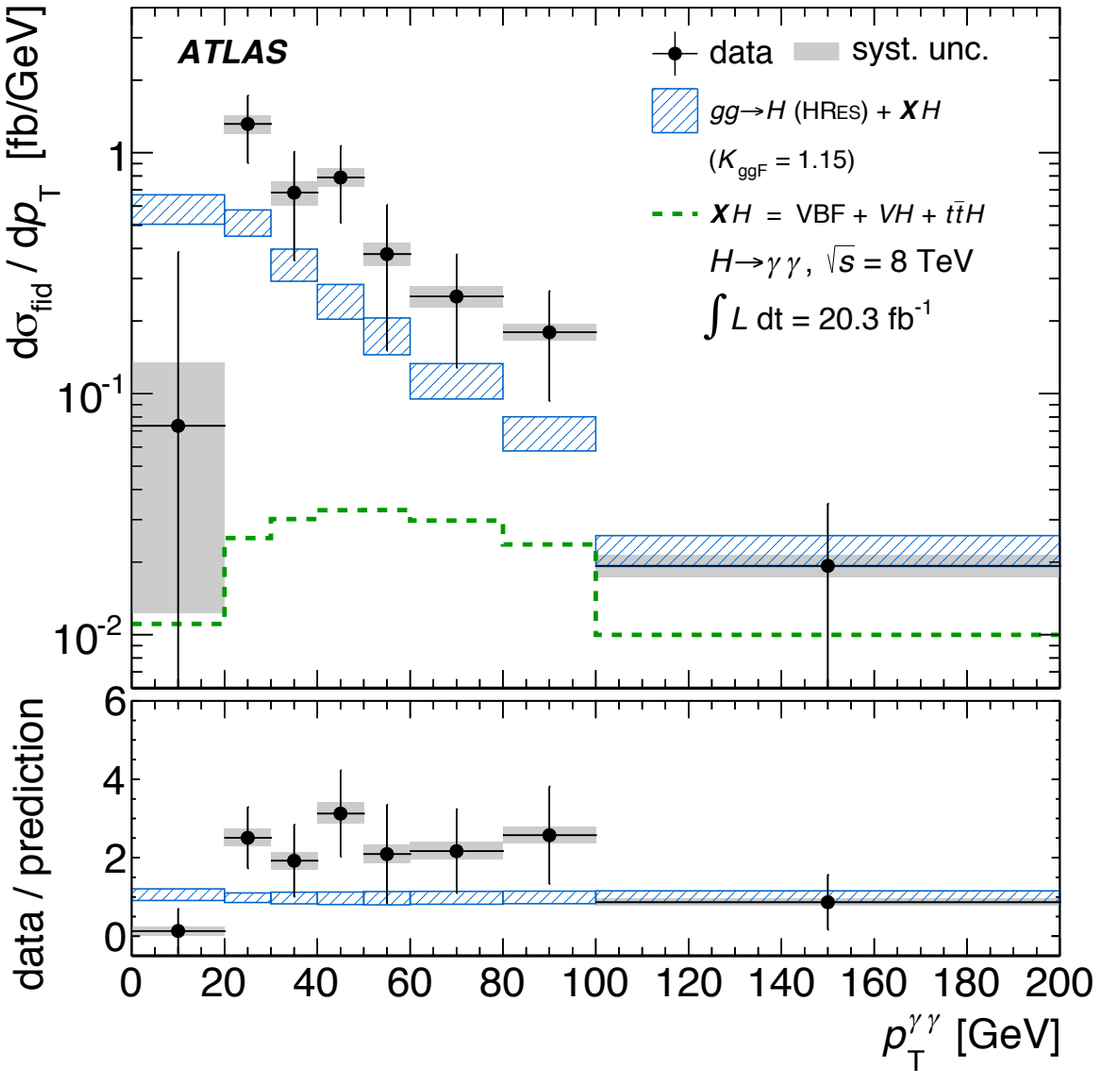
Results on Fiducial Cross-section

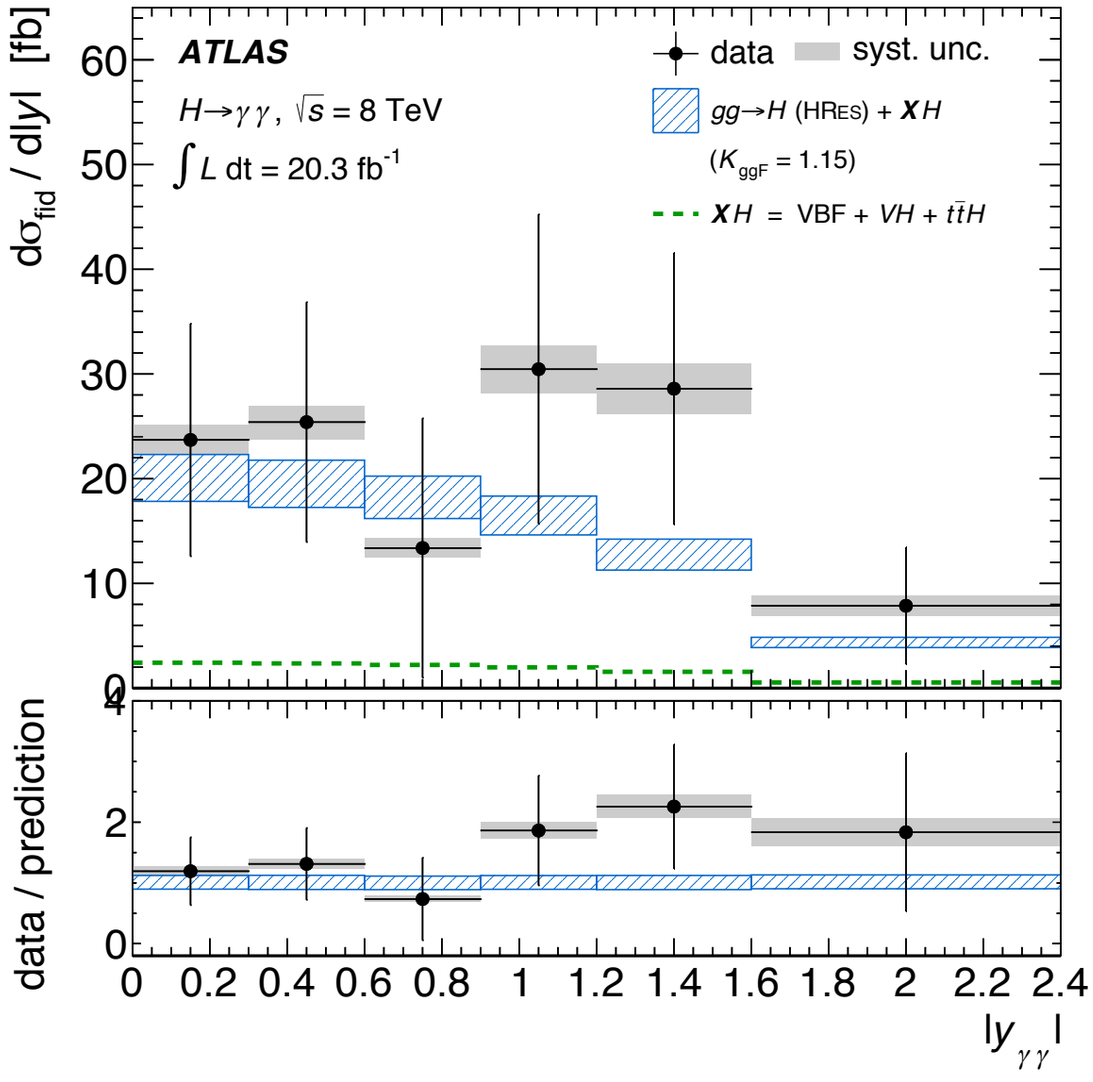
- Observed a mild excess as well in the fiducial cross-sections
  - Limited predictions for Njets >=3
  - More recent predictions using ggF N3LO will be shown later in the combination



Fiducial Cross-section Distributions ($P_T^{\gamma\gamma}$,$|y_{\gamma\gamma}|$)

- Observed a harder spectrum in pT(H), similar to 4l channel
  - Very good agreement in the Higgs rapidity
  - More recent predictions shown later in combination with γγ N3LO ggF prediction





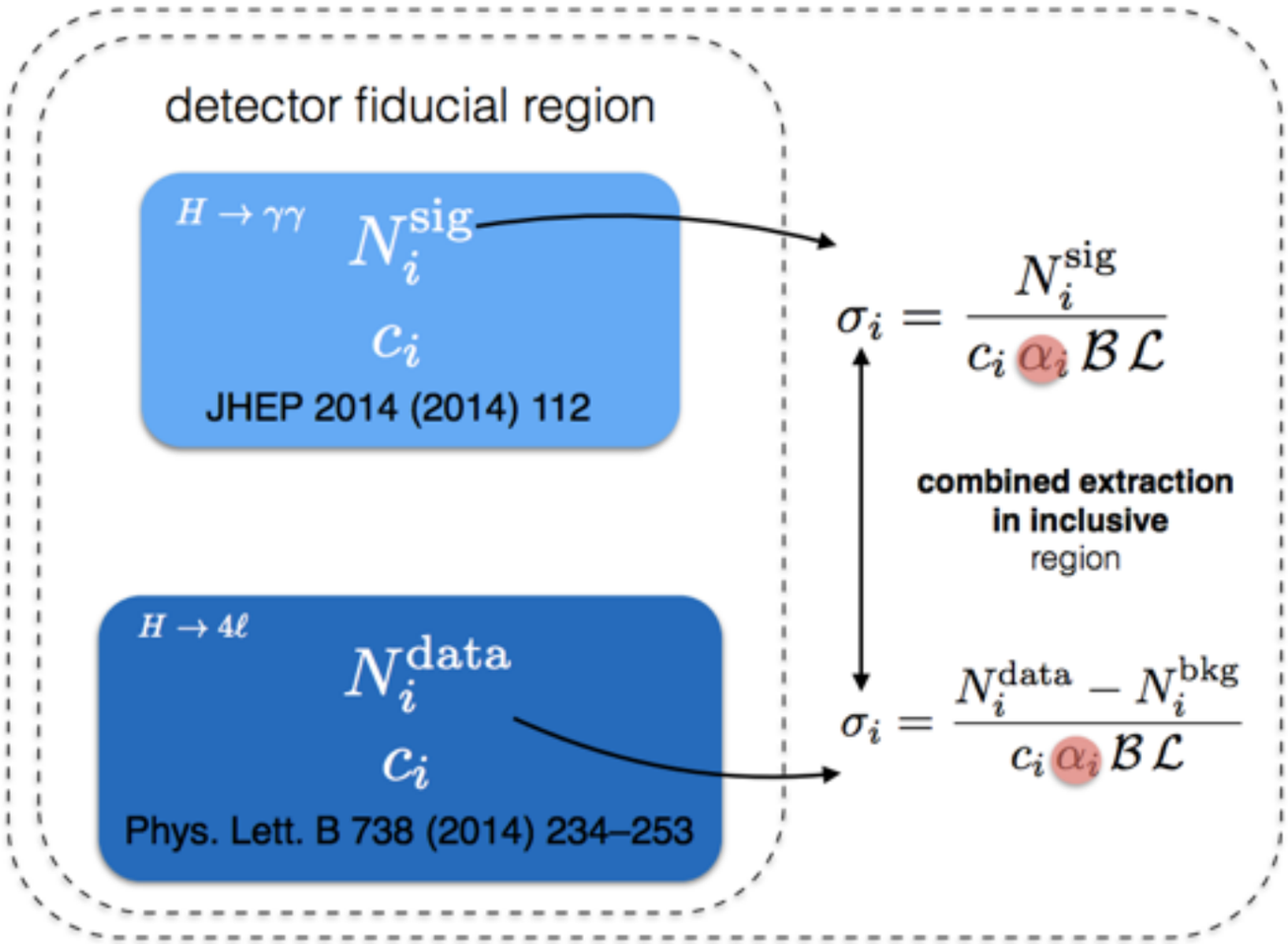
Combined Measurements

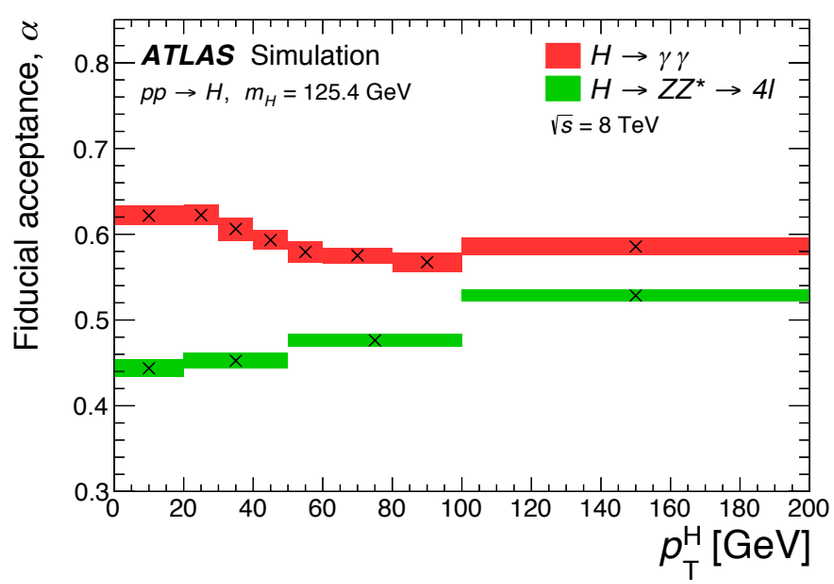
$ZZ^* \rightarrow 4l$ and $\gamma\gamma$

http://arxiv.org/abs/1504.05833

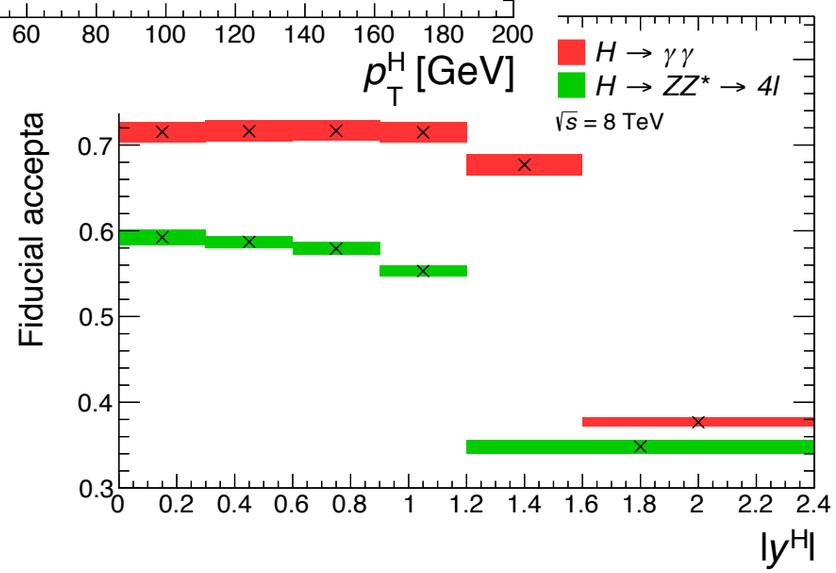
Combination Overview

- Measure inclusive H production cross-section, comparing with the latest N3LO ggF
  - Extrapolating to the full phase space by fiducial acceptance (α)
- Improve the statistical uncertainties by 20-40% for differential cross-section
  - Particularly interesting for the Higgs pT
- Perform simultaneous fit on the yields of the two channels to all bins
  - Proper correlated systematic uncertainties





$$\alpha_i = \frac{\sigma_{\mathrm{fid},i}}{\sigma_{\mathrm{incl},i}}$$



Theory Predictions

- In general we follow the LHC-XS recommendations and adopt the state-of-art predictions
- Total cross-section
  - ggF: ADDFGHLM N3LO
  - non-ggF: NNLO+NNLL
- Analytical differential distributions
  - HRES: NNLO+NNLL
  - Corrected for the PS and MPI using MC (Pythia and Hewig)
- Jet related distributions
  - POWHEG NNLO PS
  - ggF: multi-leg merged NLO MC

Total cross-section calculations	
LHC-XS	NNLO+NNLL [a,b,c]
ADDFGHLM	N^{3}LO [a,b,c]
Analytical differential cross-section predictions	
HRes 2.2	NNLO+NNLL [a,e,f]
STWZ, BLPTW	NNLO+NNLL [c,d,e,g,h]
JetVHeto 2.0	NNLO+NNLL [a,c,e]
Monte Carlo event generators	
SHERPA 2.1.1	$H+0,1,2$ jets @NLO [i,j]
MG5_aMC@NLO	$H+0,1,2$ jets @NLO [i,k,l]
Powheg Nnlops	NNLO$_{\geq 0j}$, NLO$^{\text{e,l,m}}_{\geq 1j}$

[a] Considers b- (and c-) quark masses in the $gg \to H$ loop
[b] Includes electroweak corrections
[c] Based on MSTW2008nnlo (α_s from PDF set)
[d] Uses π^2-resummed $gg \to H$ form factor
[e] NNLO refers to the total cross section
[f] Based on the CT10nnlo PDF set
[g] This corresponds to NNLL′
[h] Includes 1-jet resummation included at NLL′+NLO
[i] Based on the CT10nlo PDF set
[j] Uses MEPS@NLO method and CKKW merging scheme
[k] Software version 2.2.1, NLO merged using FxFx scheme
[l] Interfaced with Pythia8 for parton showering
[m] Uses Minlo method & y^{H} reweighting to HNNLO.

Truth Particle Definitions

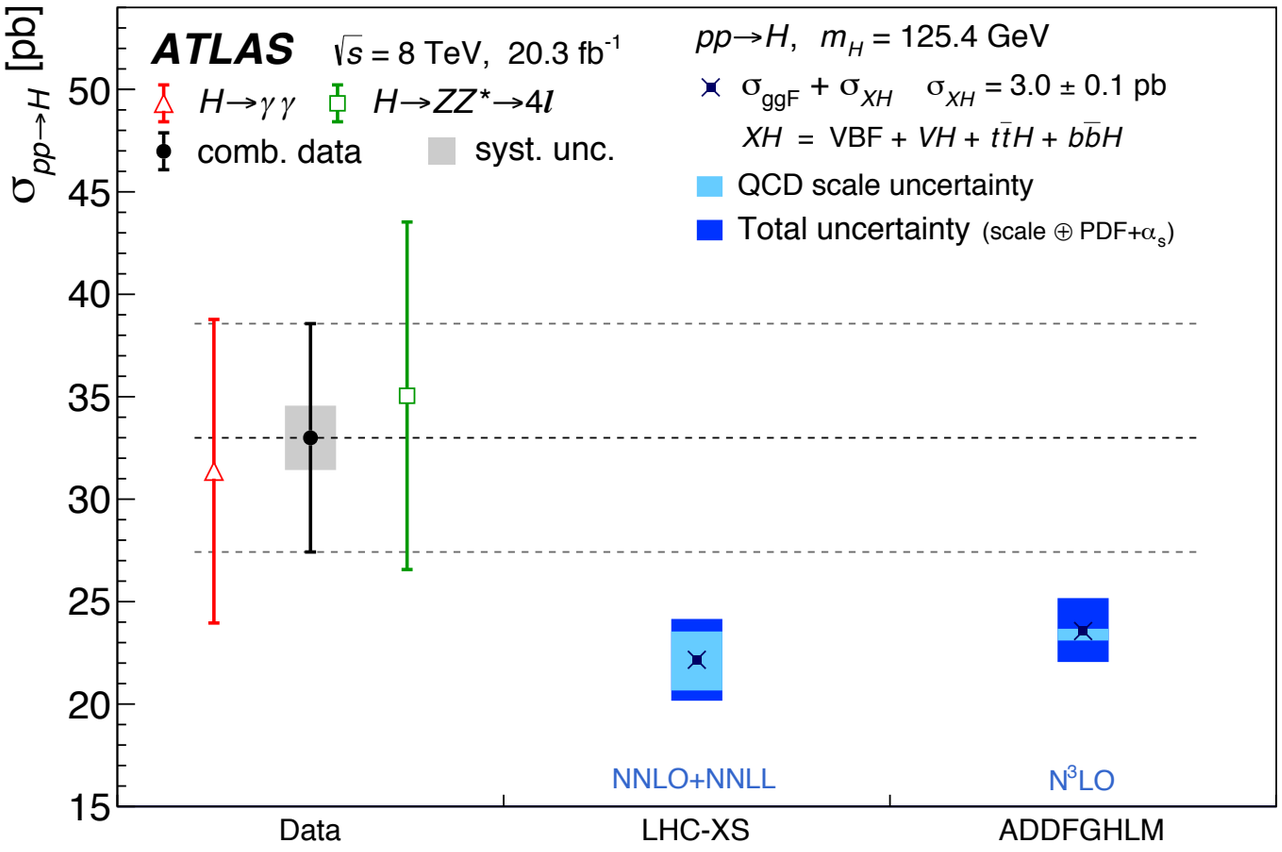
- Consistent definitions between the two channels
- Leptons
  - Required not to originate from hadrons, dressed with photons within $\Delta R<0.1$
- Photons
  - Required not to originate from hadrons
  - Photons close to leptons are added to leptons and removed from photon list
- Higgs
  - kept intact (stable!)
- Jets
  - Reconstructed from all particles with ct>10 mm, excluding the photons, leptons and Higgs as defined above, using the same jet algorithm as the reco quantities, anti-Kt with distance 0.4

Systematic Uncertainties

- Total systematic uncertainties on the combined differential cross-sections is 7-12%
  - Including experimental and theoretical systematic uncertainties affecting the signal yields, detector efficiencies, branching fractions and fiducial acceptance corrections
  - For Higgs pT and rapidity, leading sources are luminosity and background prediction
  - For jet multiplicity and leading jet pT, leading sources are jet energy scale and resolution
  - Theoretical uncertainties on fiducial acceptances 1-6%
    - Largest effect is from PDF variations
    - Missing higher order corrections (maximum of scale variations + pT reweighting)
    - Variation of mH by +/- 0.4 GeV
    - Production composition (vary VBF/VH by a factor of 0.5 and 2, ttH by a factor of 0-5)
    - Variation of hadronisation/UE modelling (Pythia8, Hewig)
- For the normalised shape uncertainties
  - The same as the differential distributions, excluding the normalisation systematic uncertainties (e.g. Luminosity, BF, efficiency)
- **Measurements are dominated by statistical uncertainties (23-75%)**

Results on the Inclusive Cross-section

- Observed a mild (~1-2σ) excess in the total cross-section
  - 33.0 ± 5.3 (stat) ± 1.6 (sys) pb, systematics dominated by luminosity and bkg estimations

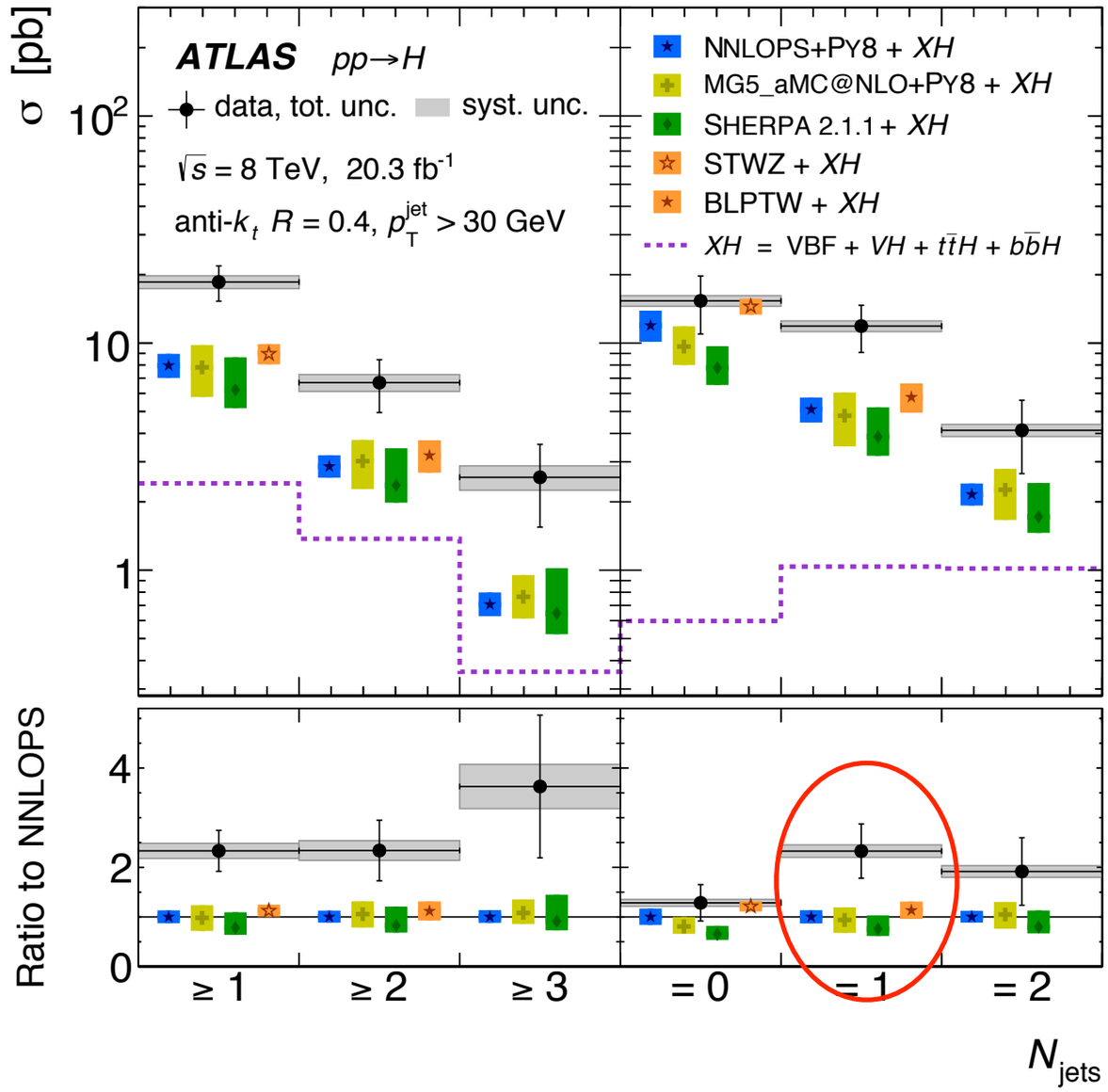


Data-prediction p-values:

LHC-XS : 5%
ADDFGHLM : 9%

Non-ggF cross section

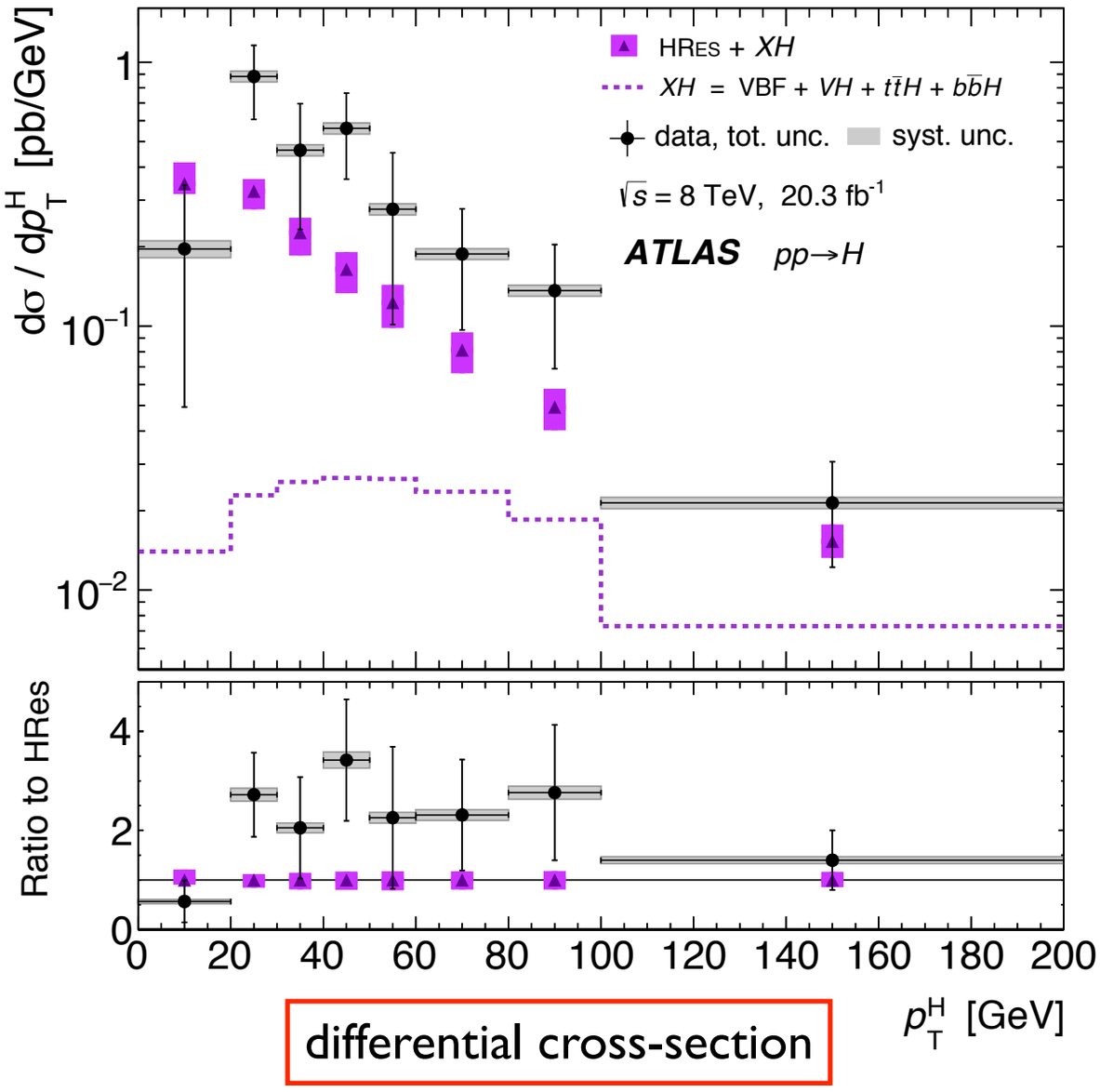
$\sigma_{XH} = 3.01^{+0.05}_{-0.06}\ (\text{scale}) \ \pm 0.09\ (\text{pdf})\ \text{pb}$



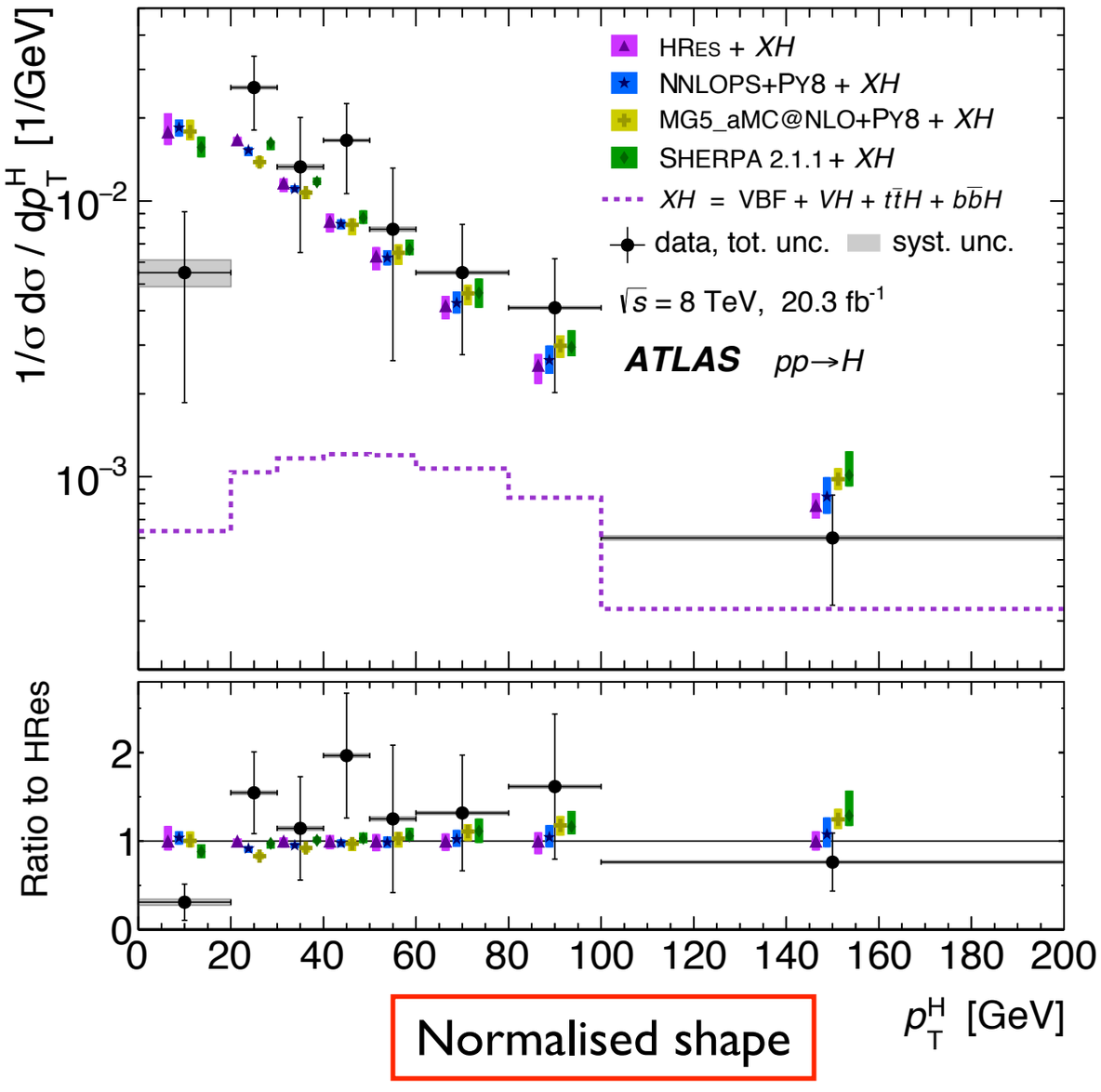
systematic dominated by jet energy scale and resolution

Higgs Boson pT

- Observed harder Higgs pT spectrum



differential cross-section



Normalised shape

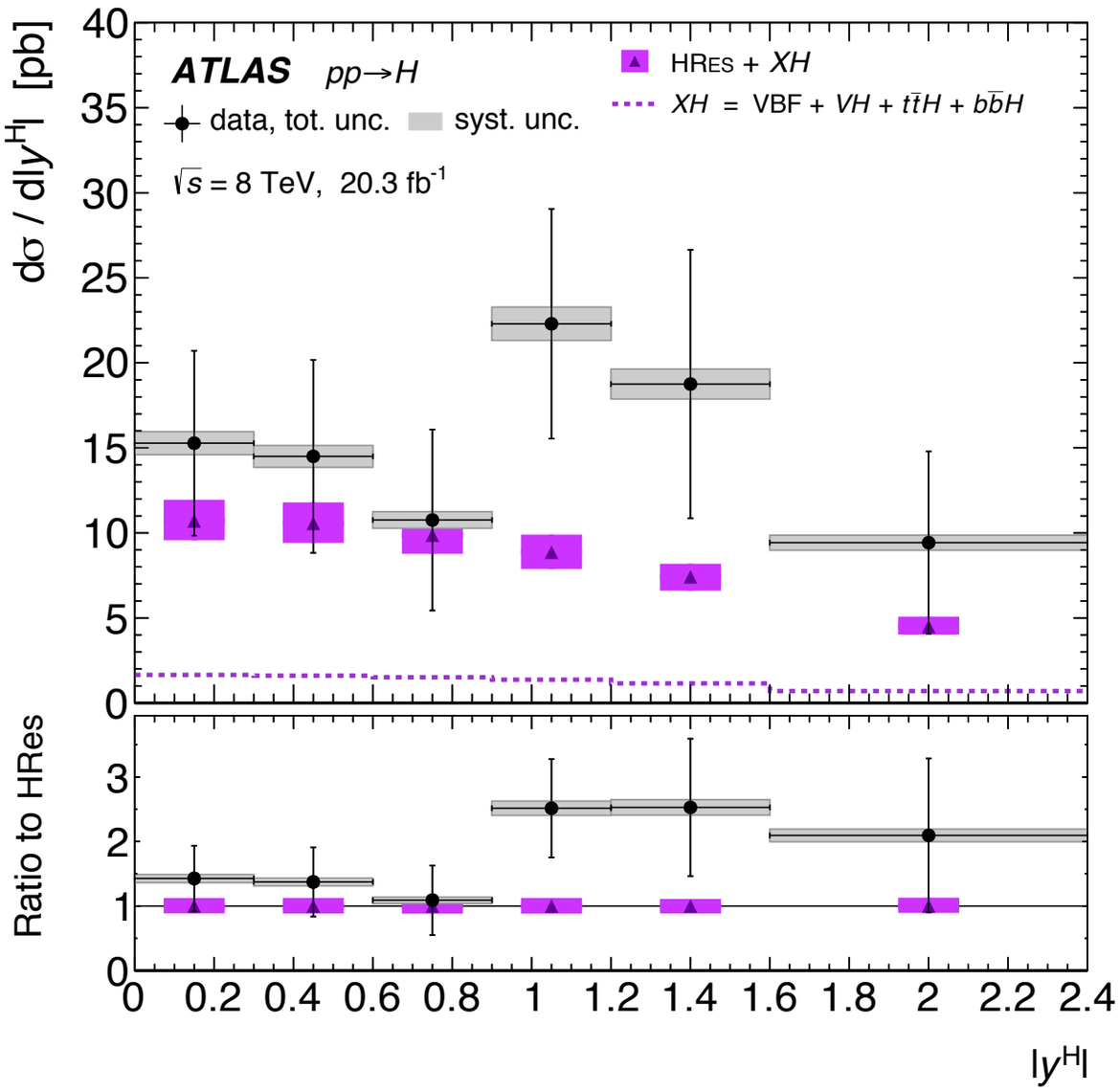
Use p-value to quantify the data-prediction compatibility

HRES: p-value: 2%

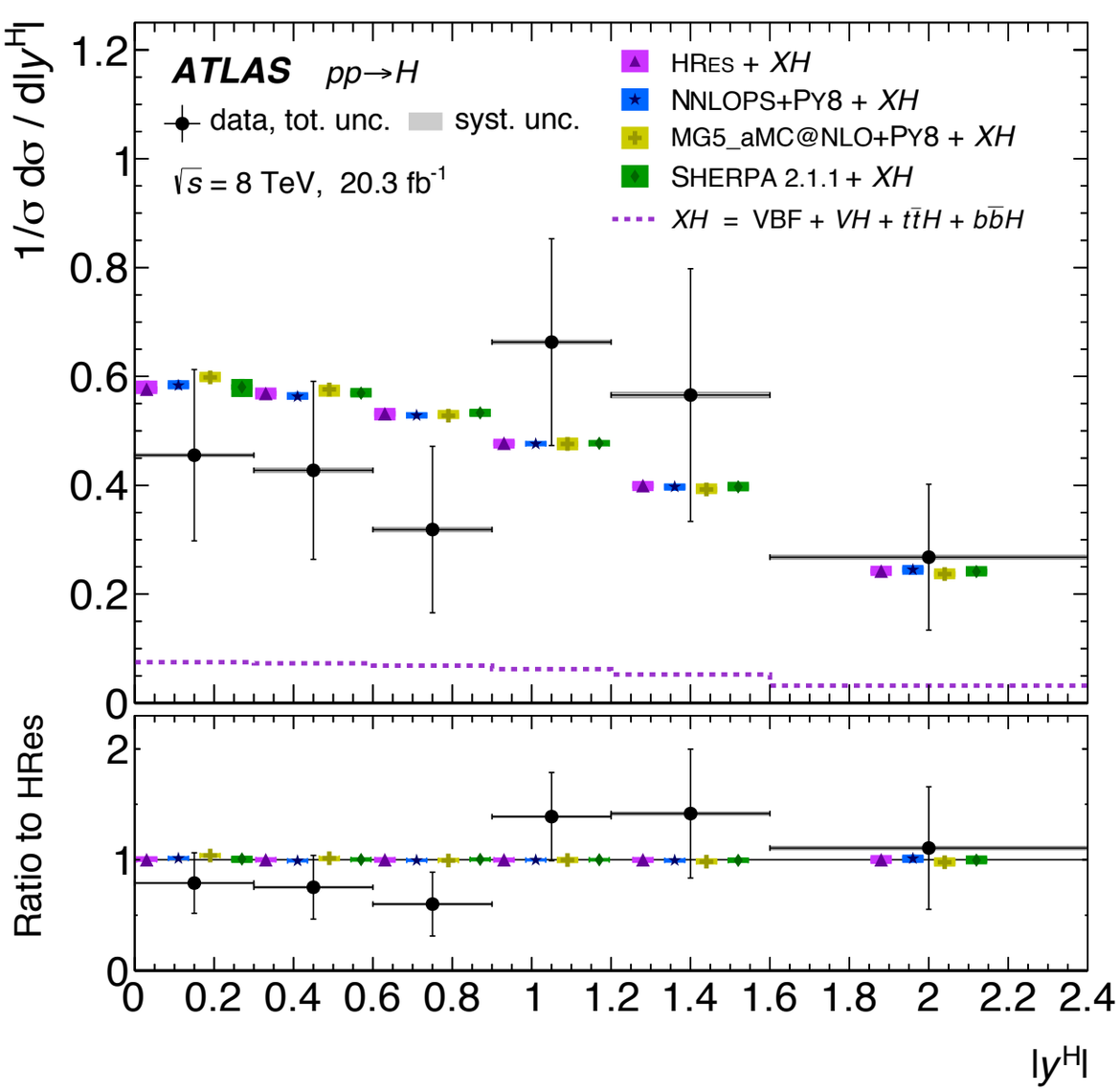
HRES	NNLOP	SHERPA 2.1.1	MG5 aMCNLO
15%	10%	22%	8%

Higgs Boson Rapidity

- Observed an overall mild excess in the differential cross-sections
  - Shapes are in good agreement with the SM predictions



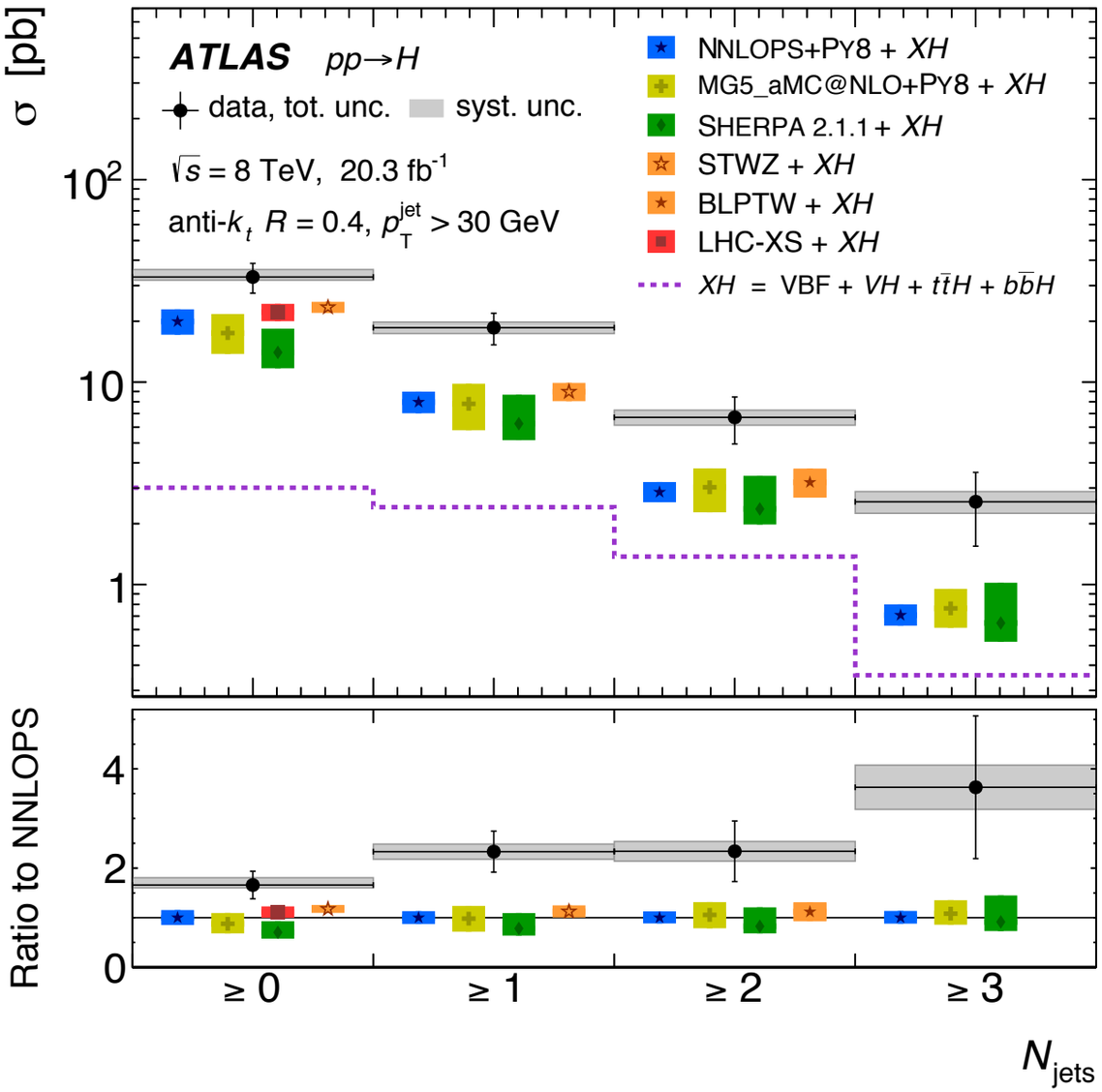
differential cross-section



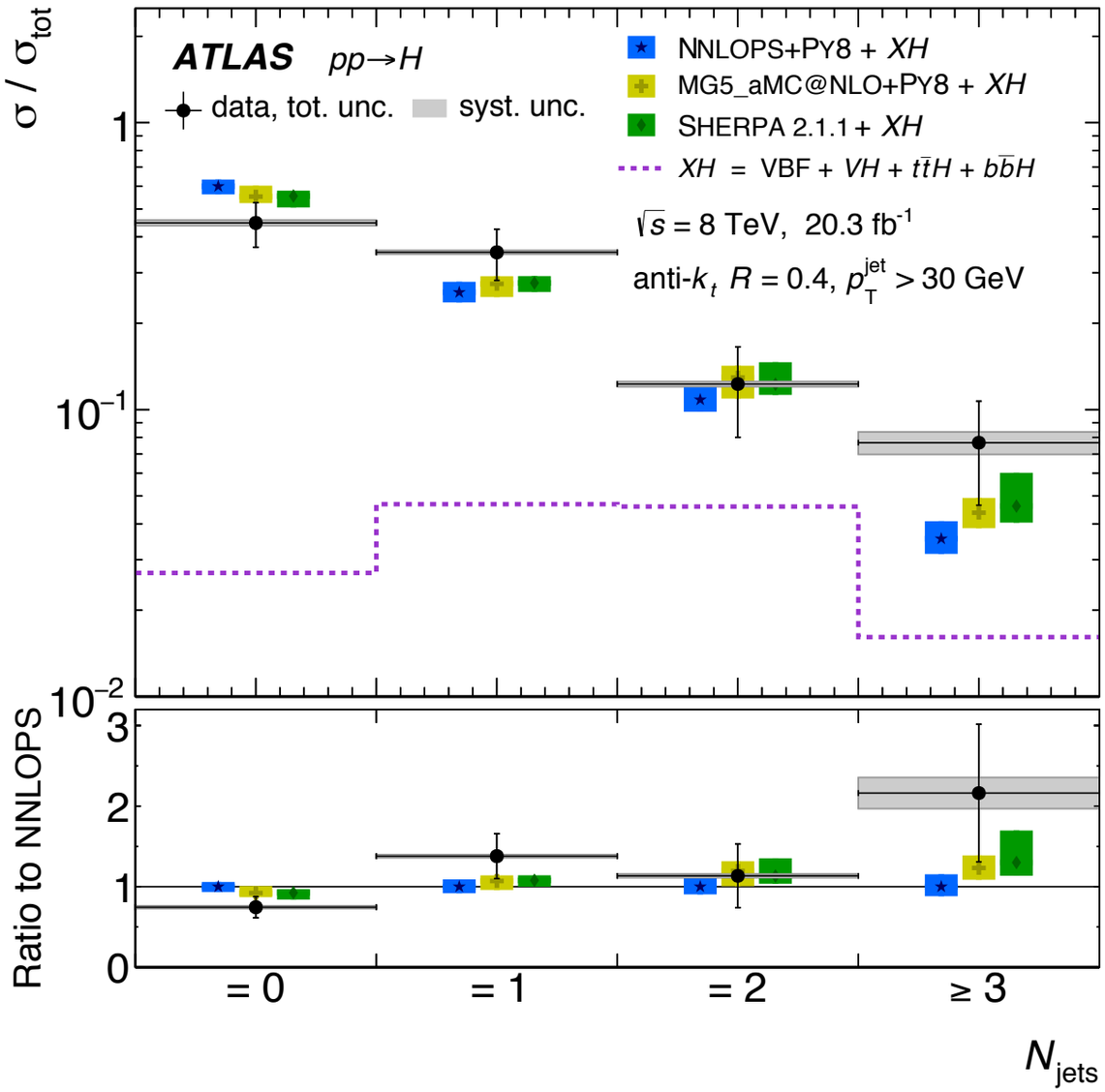
Normalised shape

Jet Multiplicities

- We observed mild excesses in the non-zero jet bins
  - Correlated with the observed harder Higgs pT spectrum in data



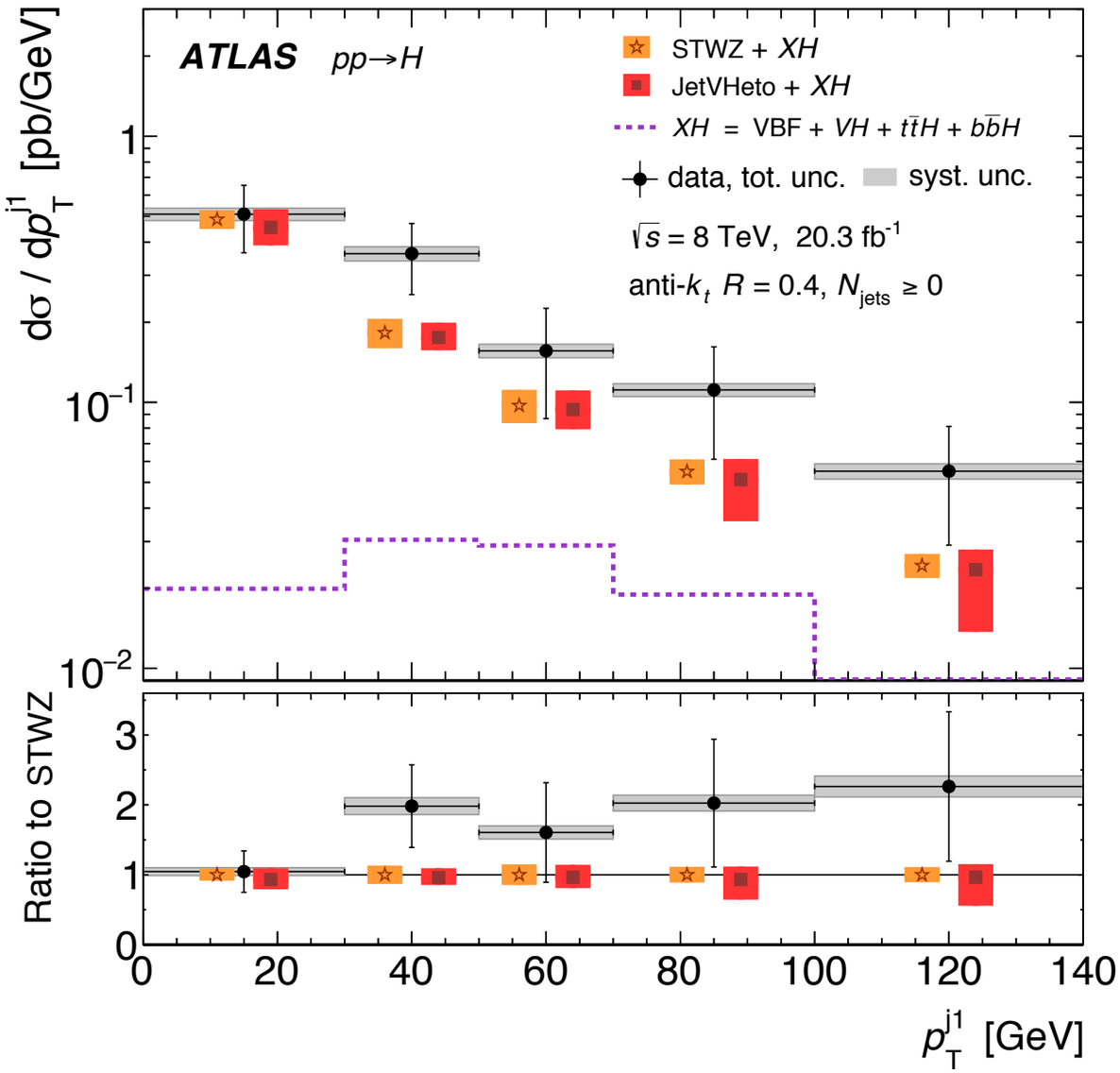
differential cross-section



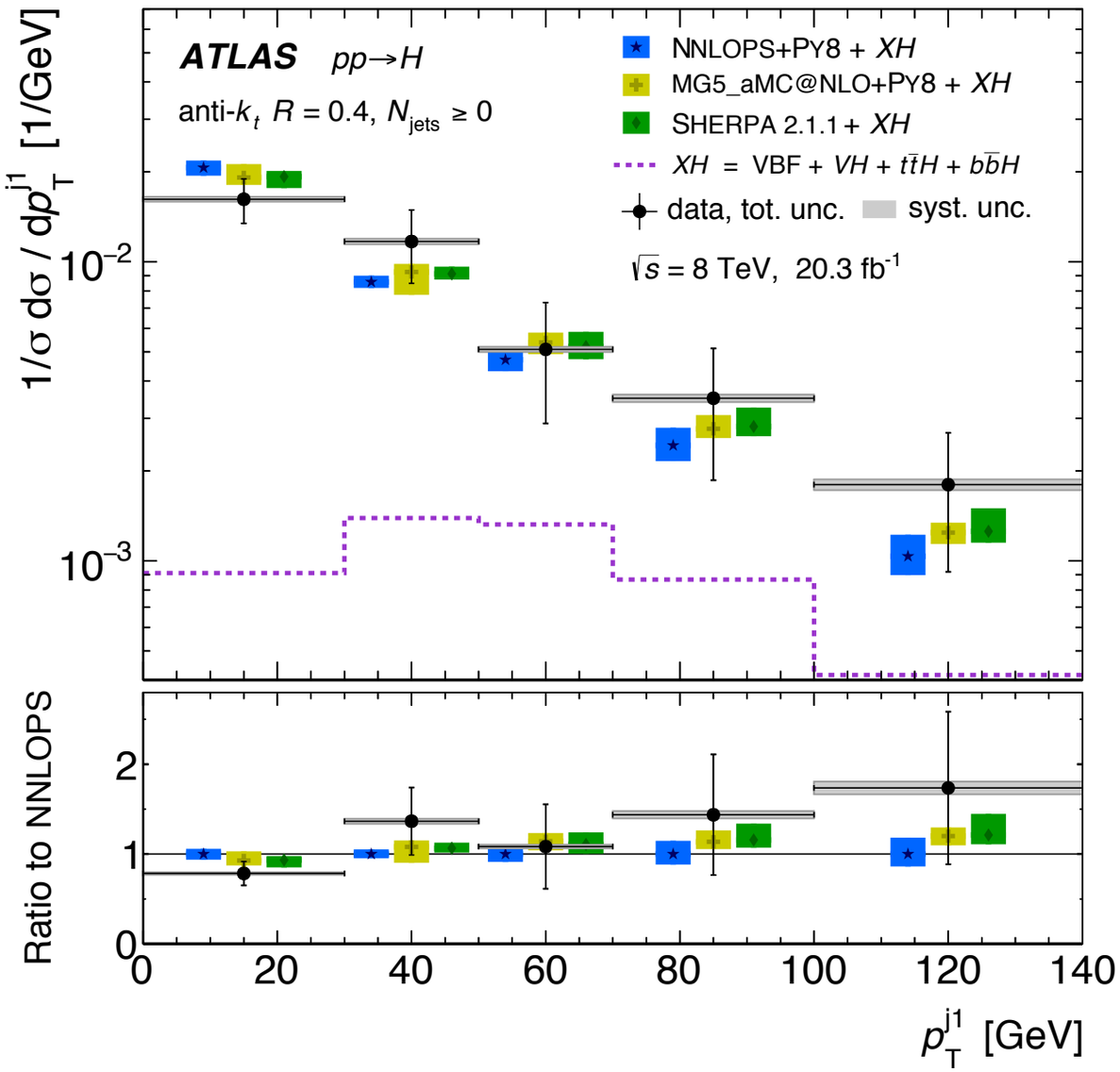
Normalised shape

Leading Jet pT

- We observed a mild excess in the high jet pT
  - Correlated with the excess in the higher Higgs pT and large nJets



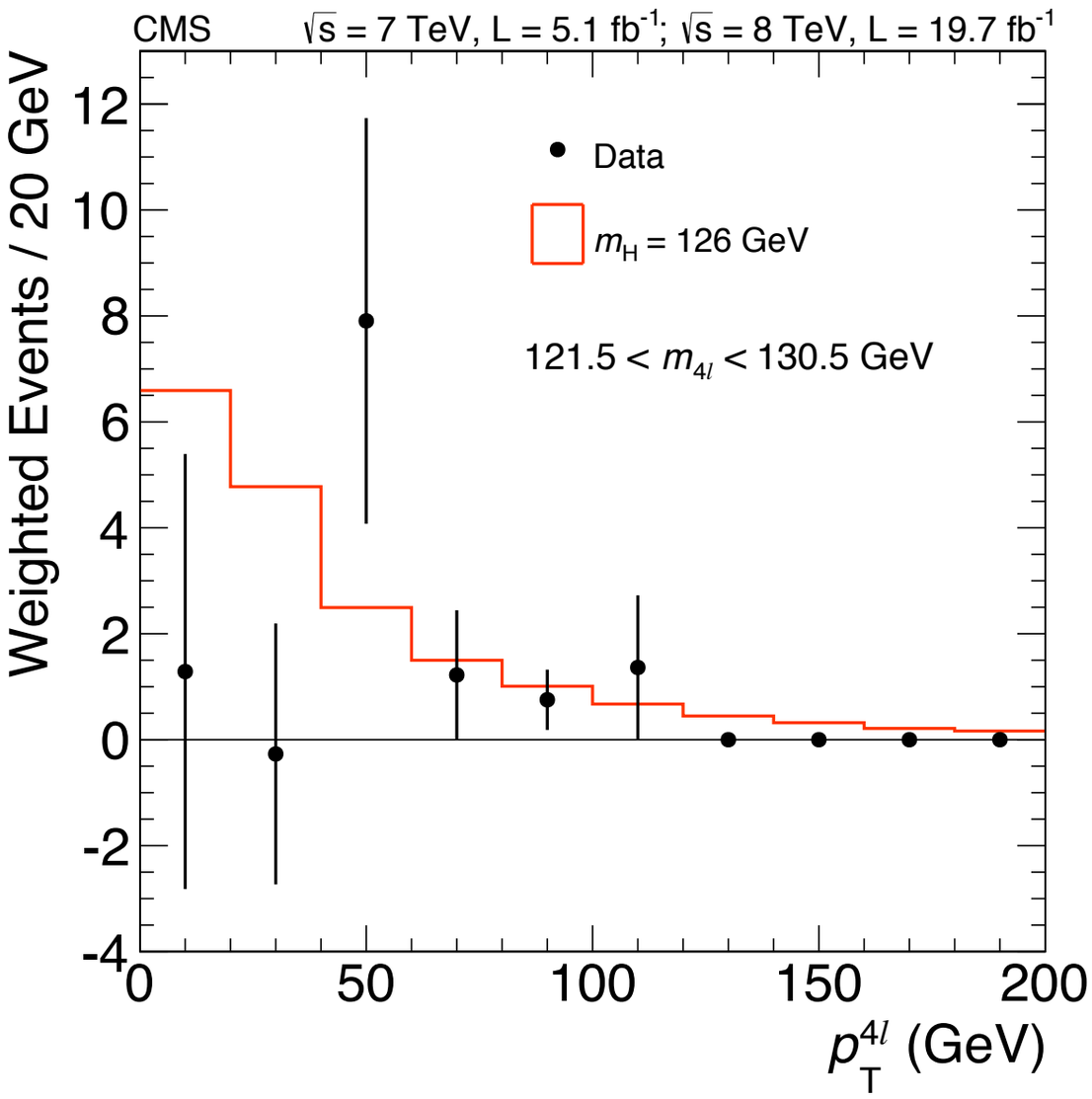
differential cross-section

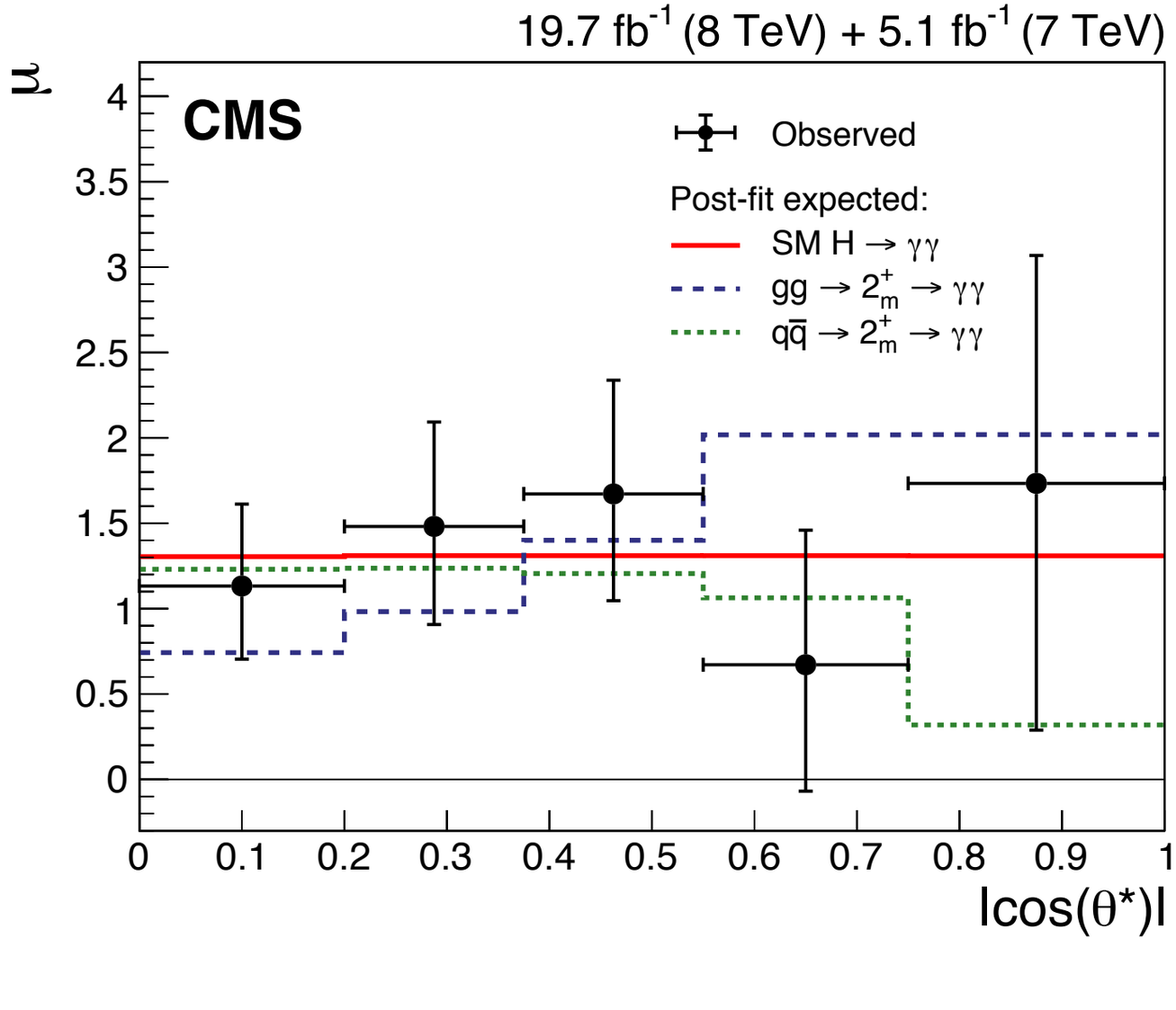


Normalised shape

Reco Level Differential Distributions (CMS)

- Most of the CMS analyses are in the pipe line
  - Generally good agreement in the observed compared to expectation within 2σ





Summary

- ATLAS performed comprehensive cross-section and differential distribution measurements of the Higgs boson (Run-1 legacy)
  - Combining ZZ→4l and γγ channels
- No significant discrepancies with the SM are found (mostly statistically limited)
  - **Observed a mild (1-2σ) excess in the total cross-section (includes the ggF N3LO)**

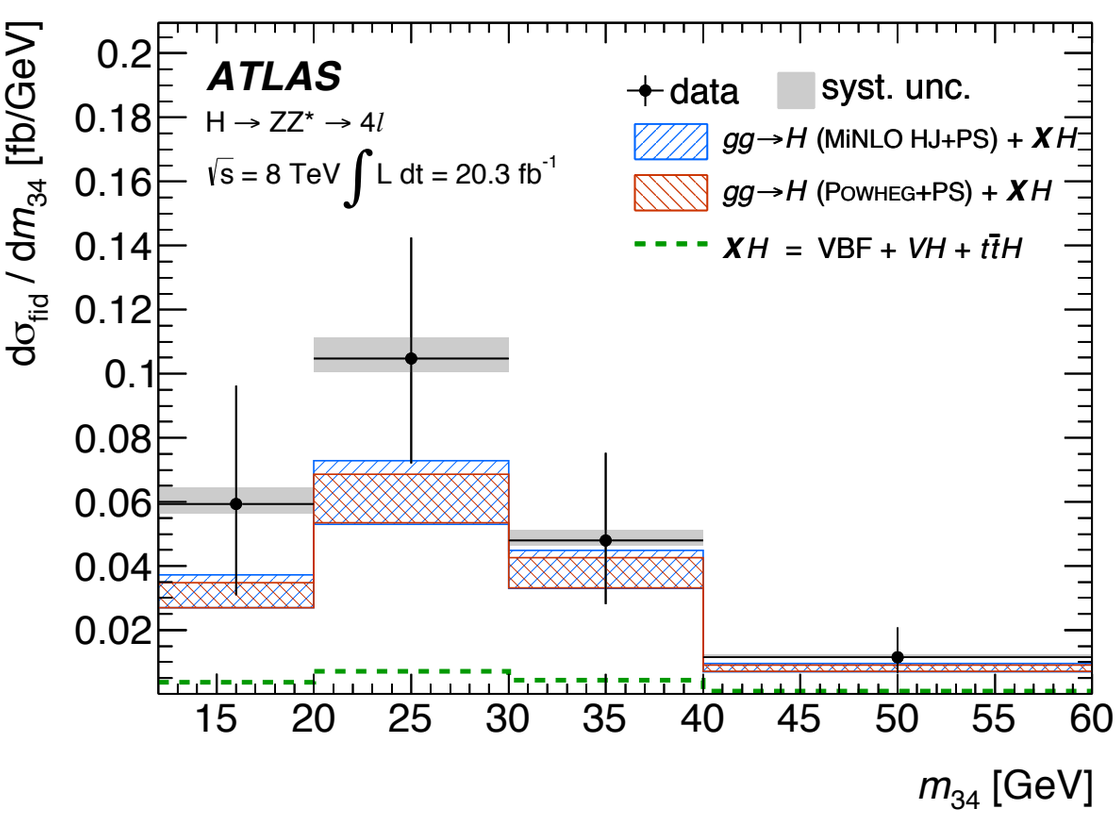
Name		$\sigma_{gg\to H}$ [pb]	
Data$-XH$	30.0	± 5.3 (stat)	± 1.6 (sys)
LHC-XS	19.15	$^{+1.38}_{-1.49}$ (scale)	$^{+1.44}_{-1.32}$ (pdf)
ADDFGHLM	20.55	$^{+0.04}_{-0.45}$ (scale)	$^{+1.60}_{-1.44}$ (pdf)

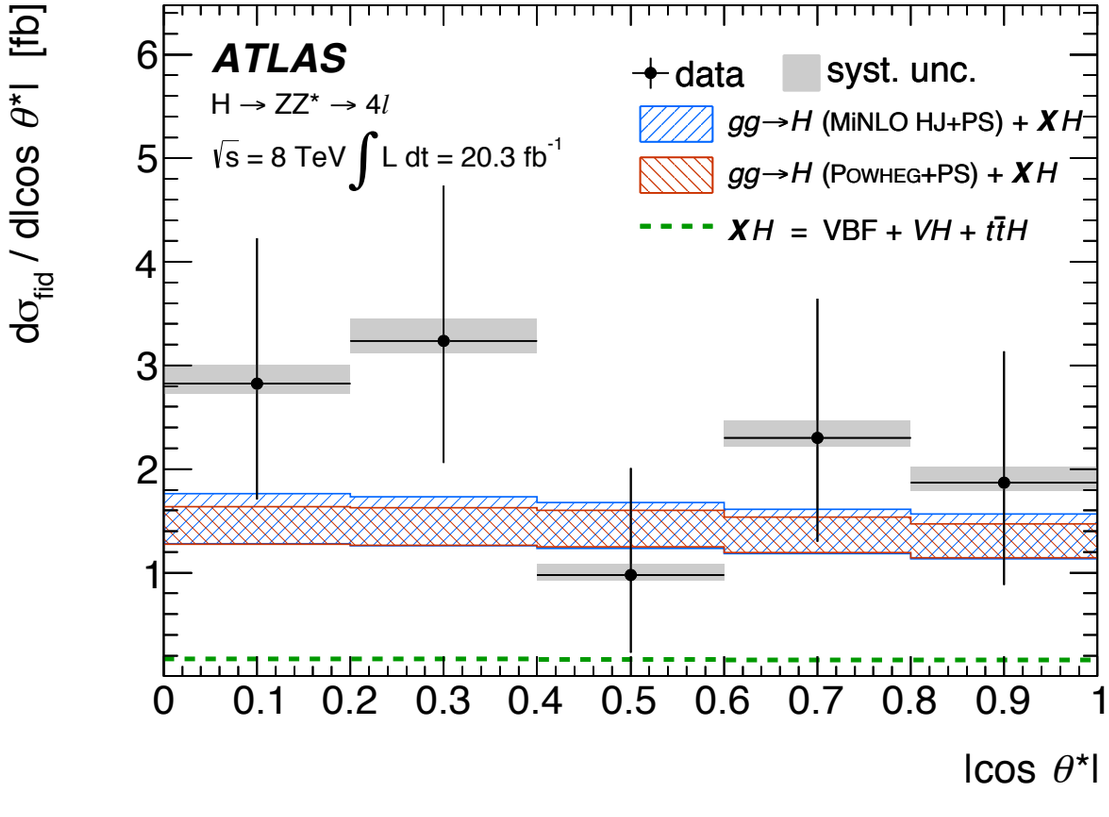
  - **Observed harder Higgs pT spectrum in data (2σ level w.r.t. SM predictions)**
- A lot to look forward to in the near future
  - CMS Run-1 results are in the pipeline
  - Promising results from other channels such as the large BR H→WW→lνlν
  - 13-14 TeV Run-2 data-taking is on the verge

Backup Slides

Fiducial Cross-section Distributions (m_{34}, $\cos\theta^*$)

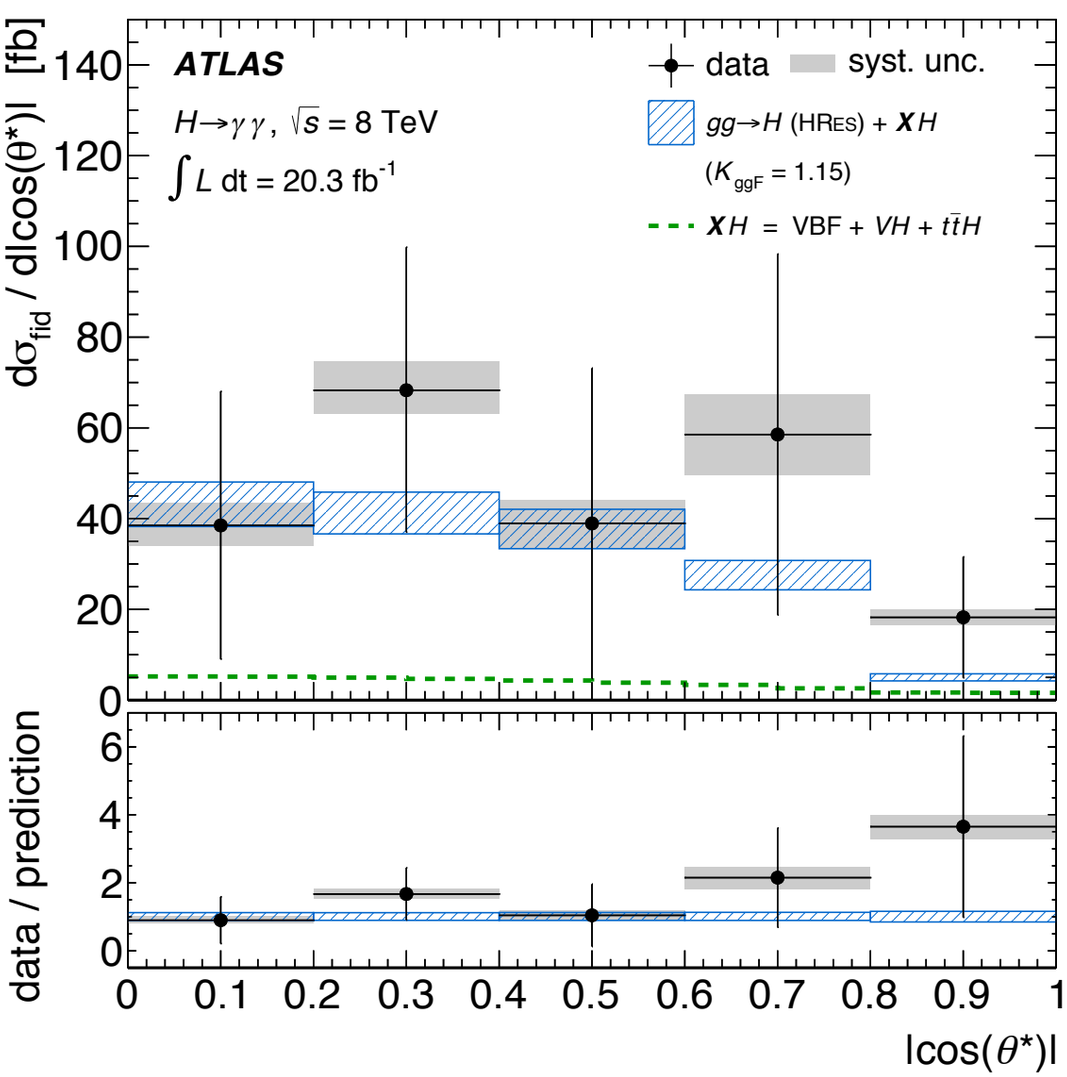
- No significant discrepancy is found

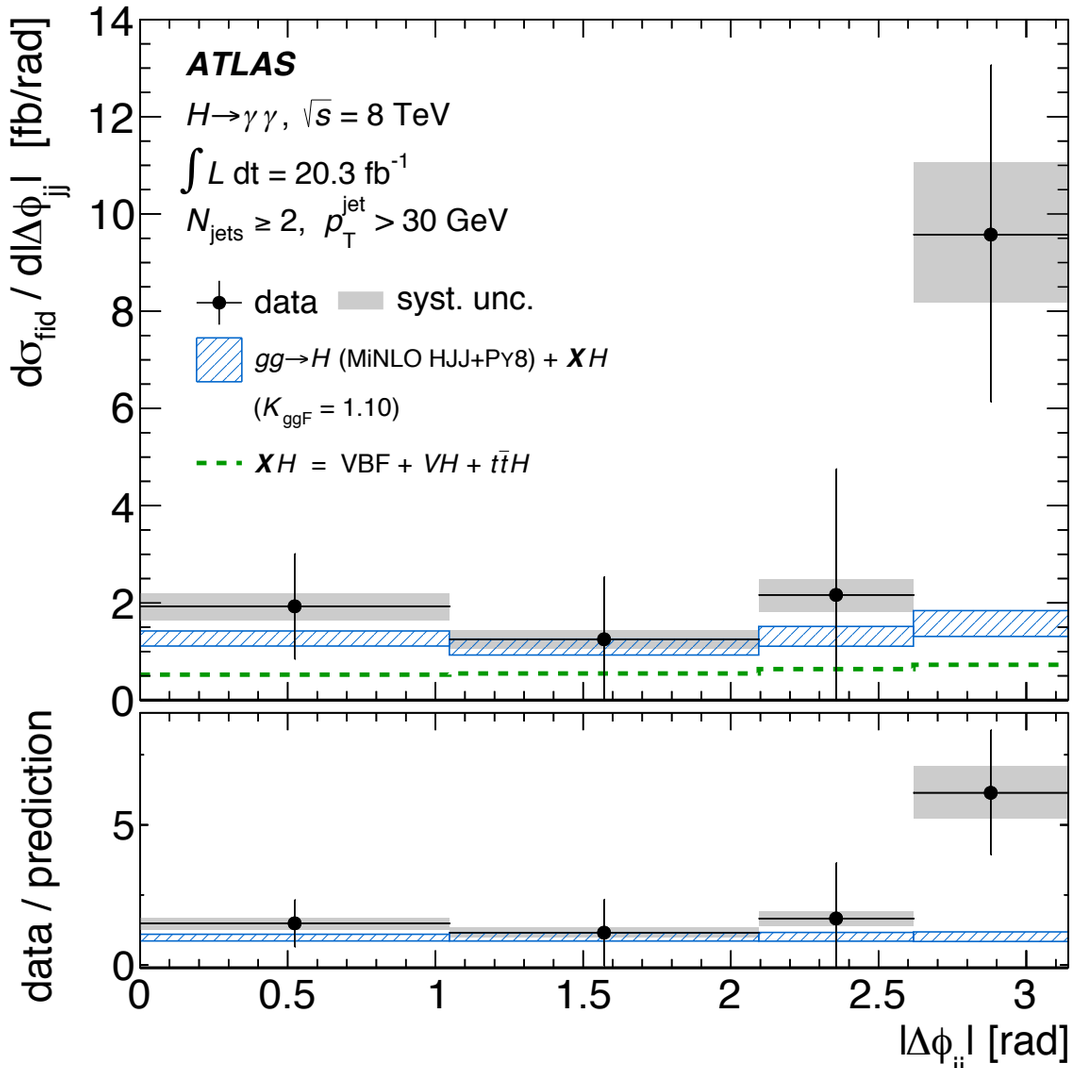




Fiducial Cross-section Distributions ($\cos\theta^*$, $\Delta\phi_{jj}$)

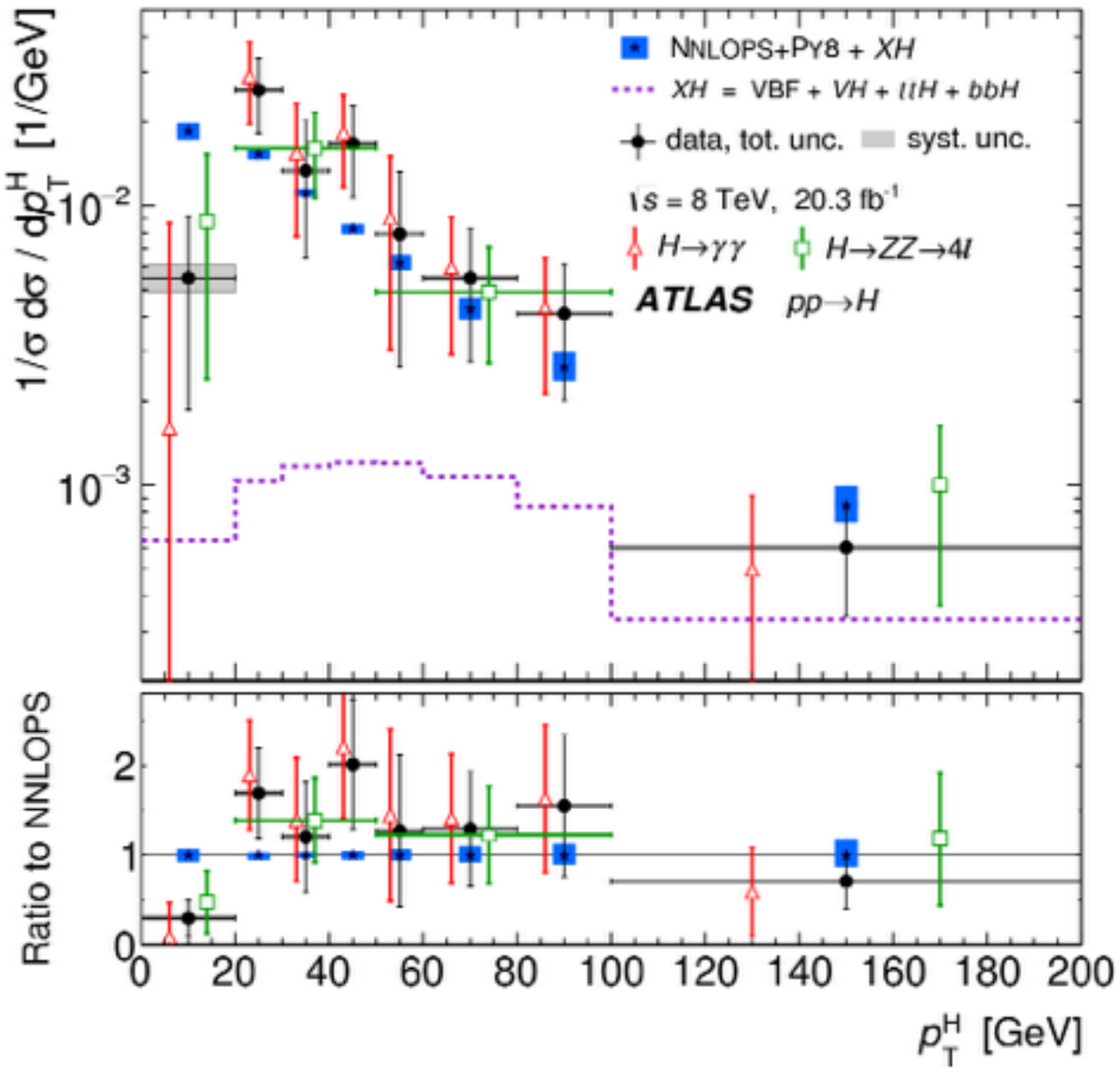
- Both are sensitive to the spin of the Higgs boson
  - Consistent with the SM prediction within 1-2 σ

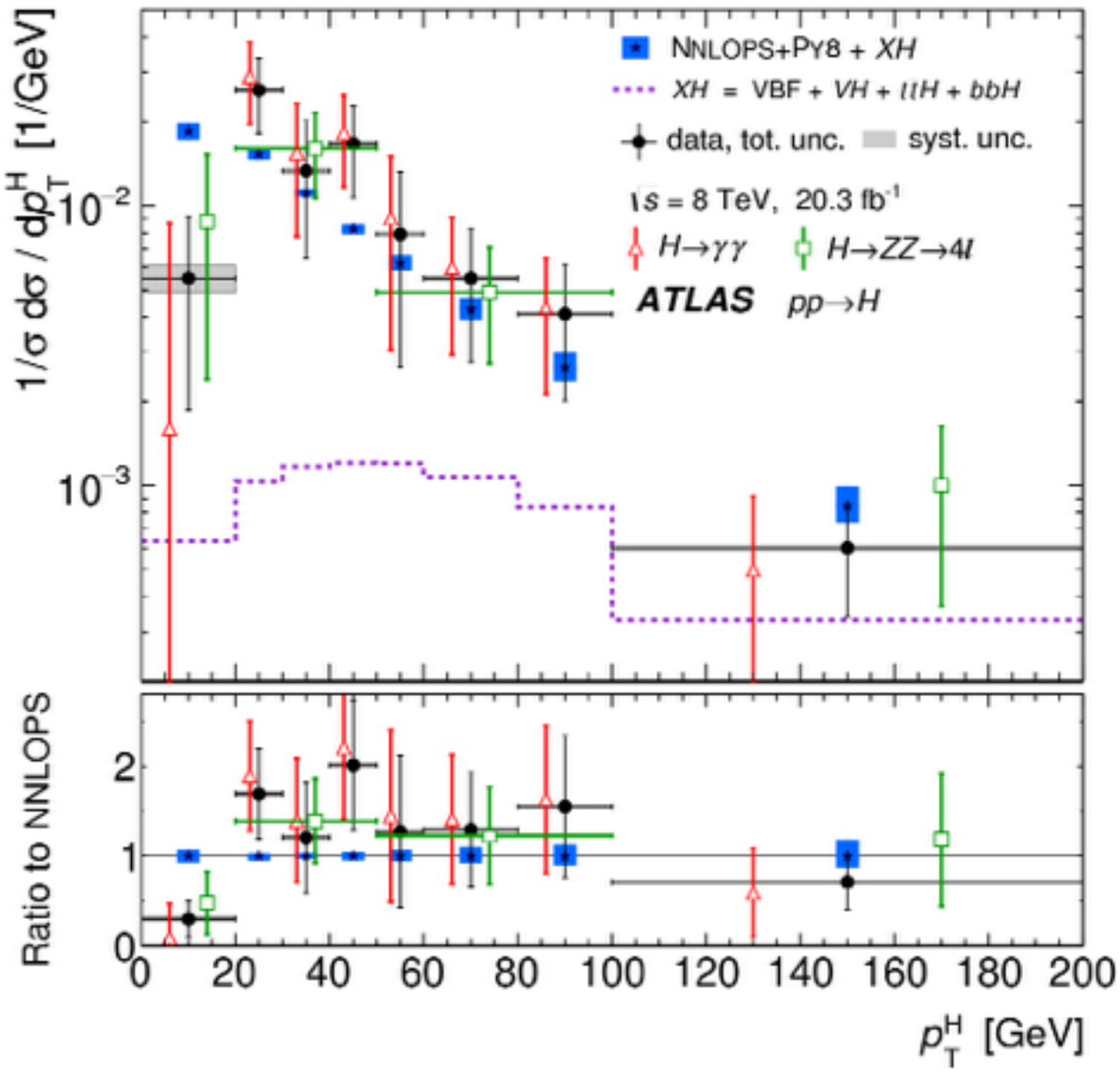




Combined Higgs pT Spectrum

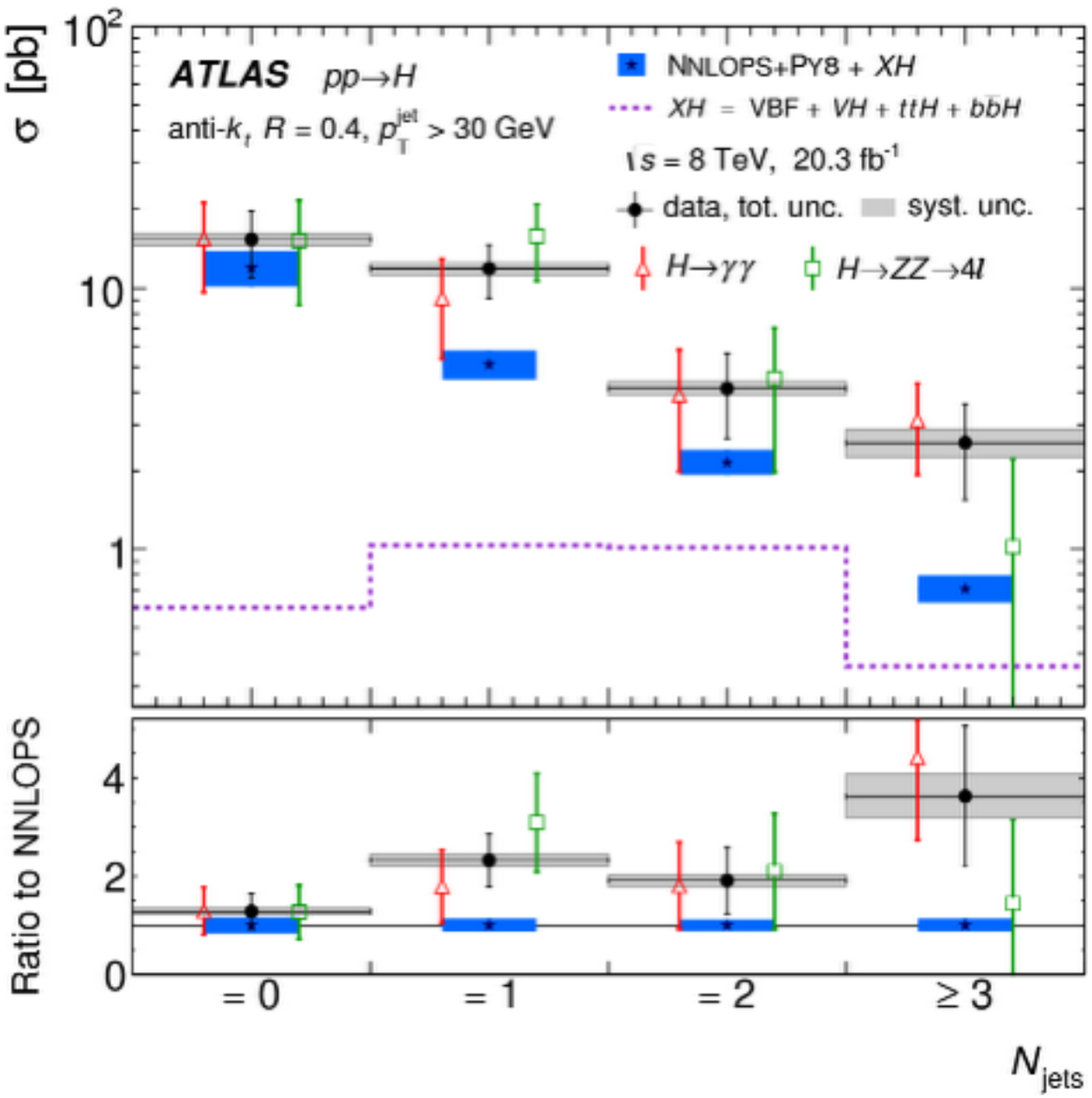
- Separately for each channel and combined

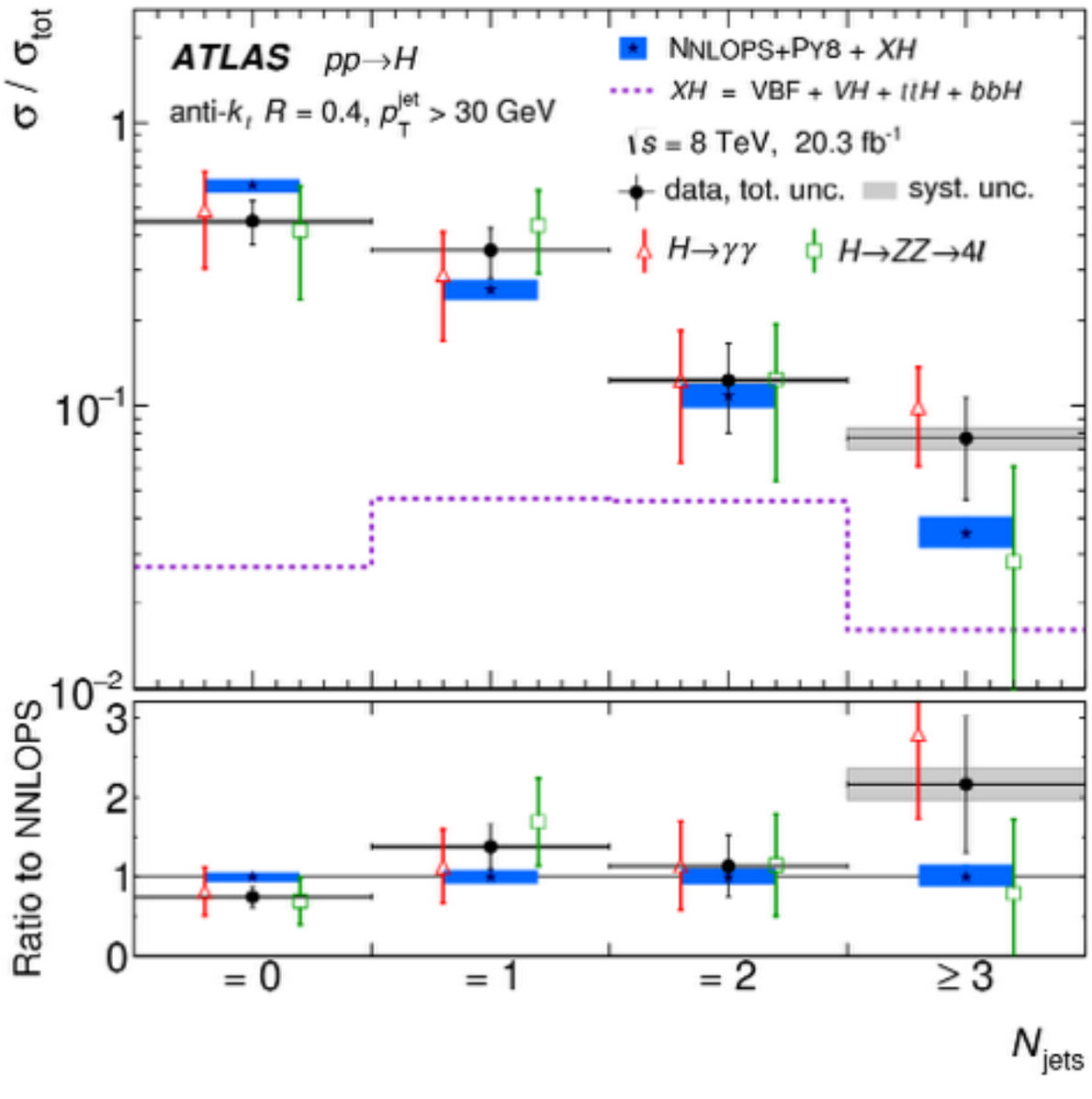




Combined Jet Multiplicities

- Comparable statistics between the 4l and yy





Lepton Selections in 4l Analysis

- Apply both track and calorimeter based isolations
  - Track isolation $\sum_{track} p_T(\Delta R = 0.2) < 0.15$
  - Electron calo-isolation $\sum_{calocells} E_T(\Delta R = 0.2) < 0.2$
    - Excludes cells within 0.125 × 0.175 (η×ϕ) around the photon
    - Pileup contribution is subtracted event-by-event
  - Muon calo-isolation $\sum_{calocells} E_T(\Delta R = 0.2) < 0.3$
    - Typical isolation efficiency is ~94-99% after the identification and impact parameter cuts
- FSR photons are added
  - Collinear (ΔR<0.15) photons is added to muon
  - Non-collinear (ΔR>=0.15) photons are added to both electron and muon
- Lepton overlap removal applied
  - $\Delta R(l_i, l_j) > 0.1(0.3)$ for SF/DF pairs

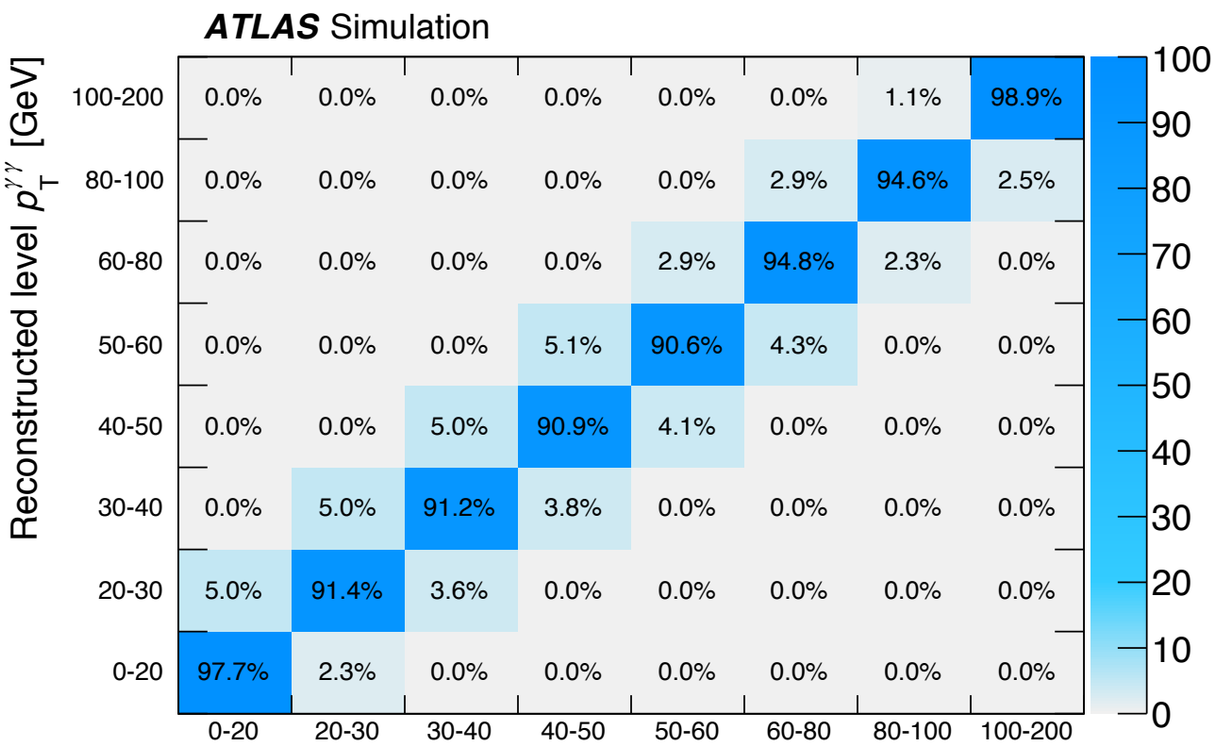
Photon and Lepton Selections in H→γγ

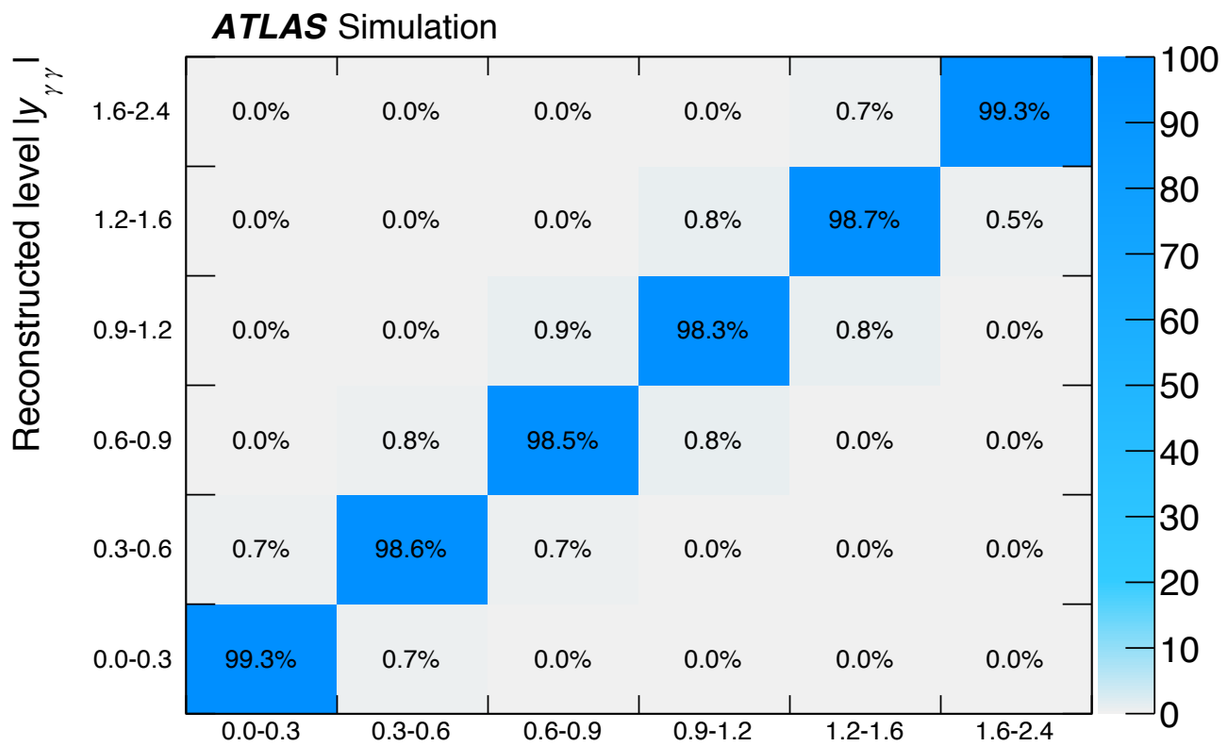
- Require isolation using both track and calorimeter information
  - Use only the tracks that are matched to the primary vertex
  - Calo-isolation excludes topo-clusters within 0.125 × 0.175 (η×ϕ) around the photon
- Photons
  - Absolution isolation $\sum_{track} p_T(\Delta R = 0.2) < 2.6 \text{ GeV}$ $\sum_{calocells} E_T(\Delta R = 0.4) < 6 \text{ GeV}$
    - ~95% efficiency
  - Photon overlap removal: remove electron within ΔR = 0.4 with the selected photon
- Lepton isolation
  - Relative isolation $\sum_{track} p_T(\Delta R = 0.2)/E_T < 0.2,\ \sum_{calocells} E_T(\Delta R = 0.4)/E_T < 0.2$
- Electron/photo overlap removal
  - Remove electron if it is within ΔR=0.4 from the selected photon

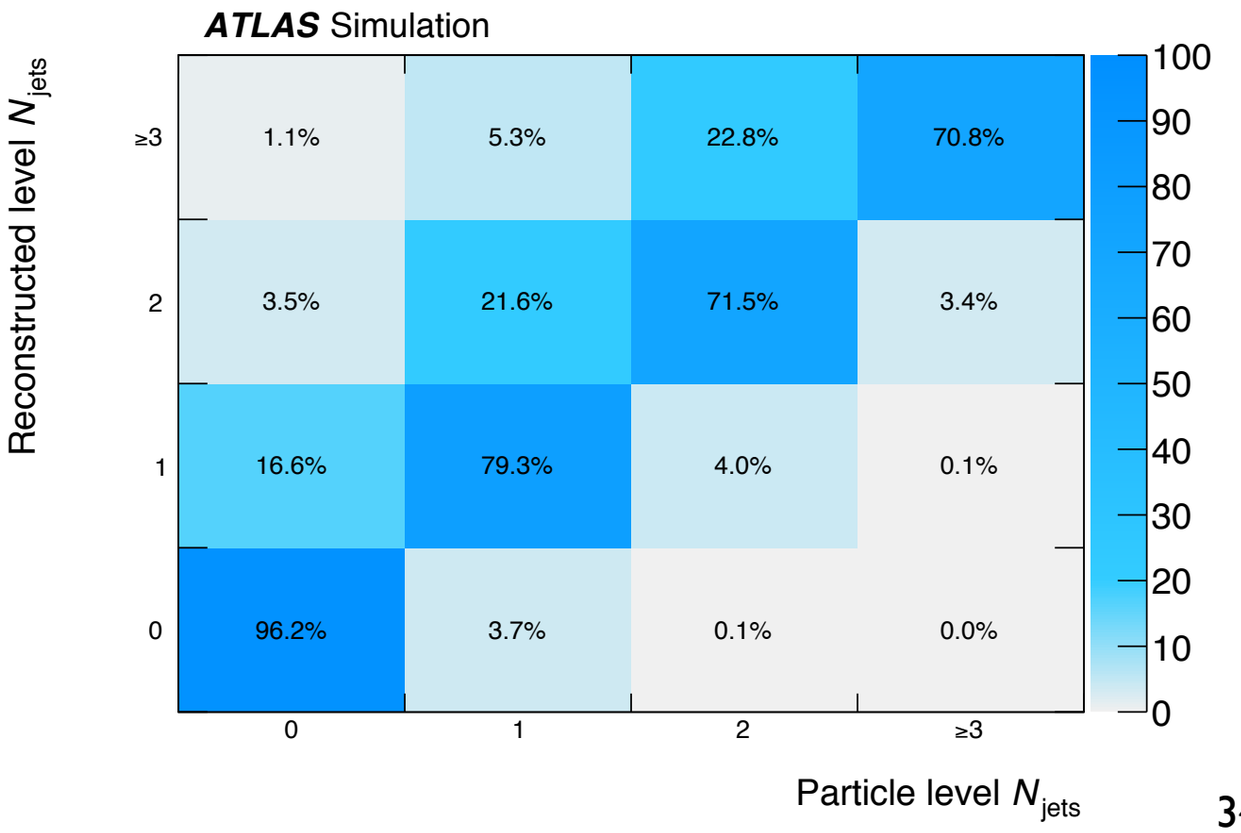
Jet Selections

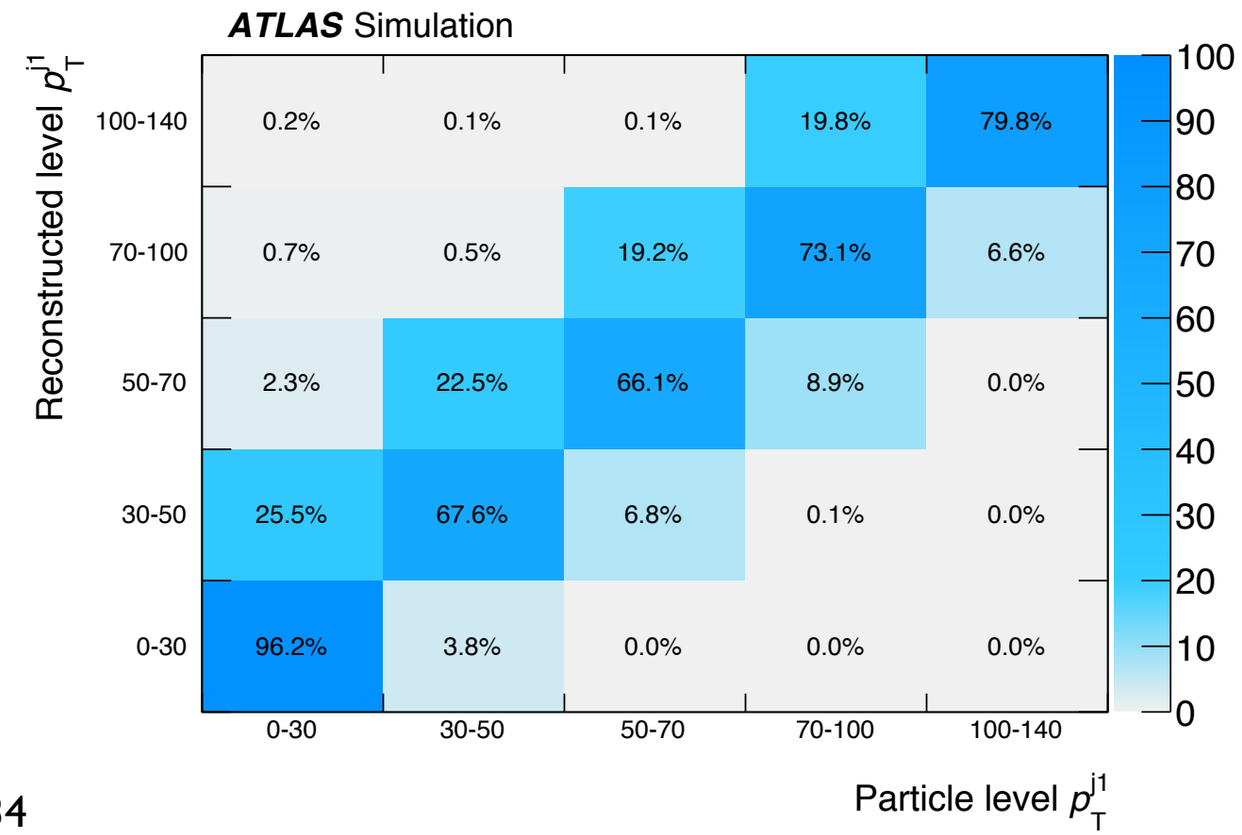
- Jets are reconstructed from topological clusters (calo cells)
  - anti-Kt jet algorithm with R=0.4
  - Pileup contribution is subtracted event-by-event
    - Using jet area and the median pT density ρ, NPV, inelastic pp interactions per Xing
    - ATLAS-CONF-2013-083
- Overlap removal is done with selected photon or leptons within ΔR=0.4

Migration Matrices H→γγ









Combined Likelihood Fit

- Construct likelihood from the product of PDFs of the individual measurements, using a Gaussian PDF for H→γγ (background already subtracted)

$$\mathcal{G}(N^i_{\rm sig}; \sigma^i \times \mathcal{L} \times \mathcal{B} \times \mathcal{A}_i/\mathcal{C}_i \prod_j (1+\theta_j\,\epsilon^i_j), \Delta N^i_{\rm sig})$$

- and Poisson PDF for H→ZZ (background included)

$$\mathcal{P}(N^i_{\rm data}; \sigma^i \times \mathcal{L} \times \mathcal{B} \times \mathcal{A}_i/\mathcal{C}_i \prod_j (1+\theta_j\ \epsilon^i_j) + N_{\rm bkg} \prod_k (1\ +\theta'_k\,\epsilon'^i_k))$$

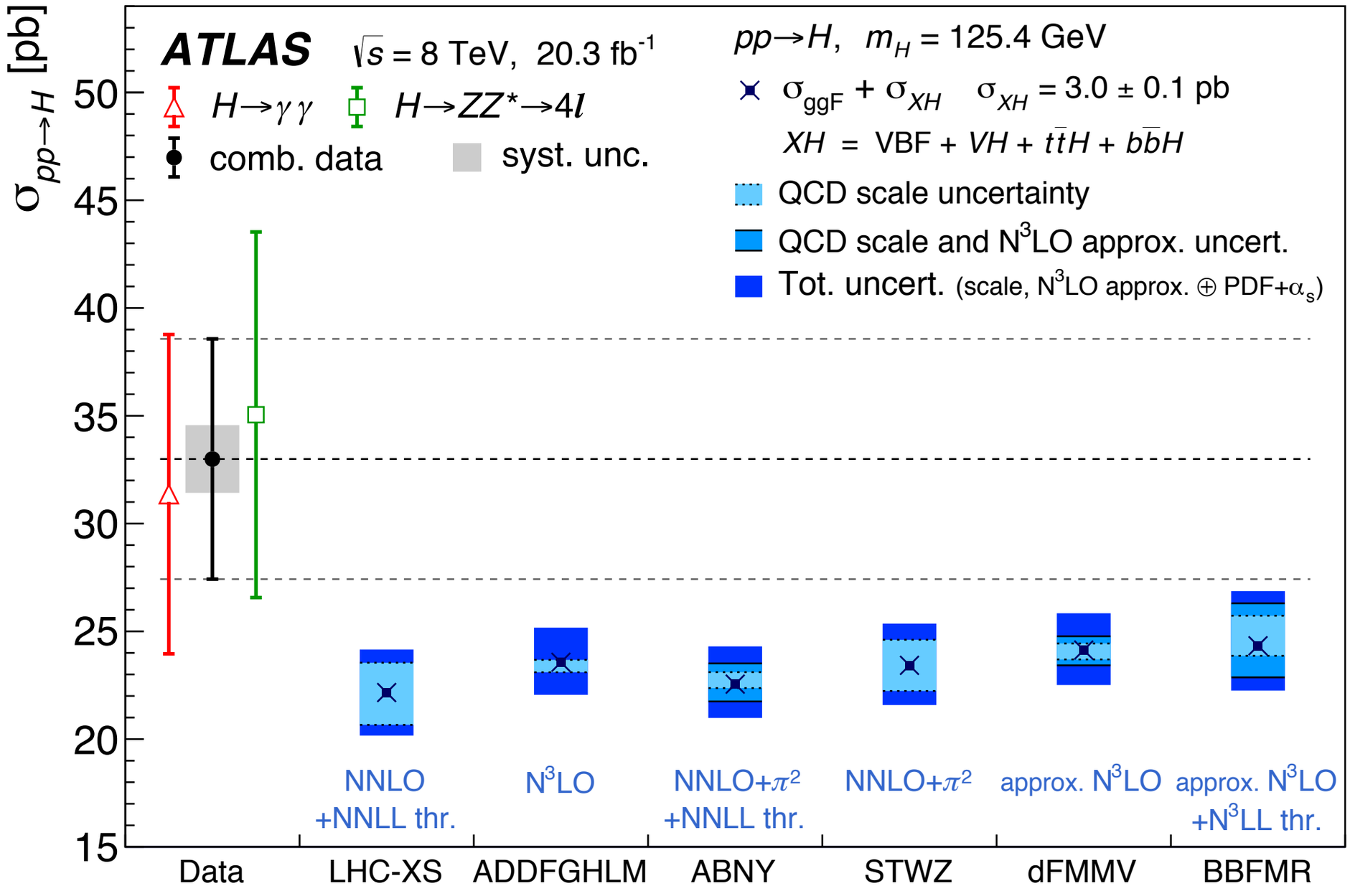
- The combined cross sections are those that maximise the total likelihood

$$\mathcal{L} = \prod_i \mathcal{P}_i \prod_j \mathcal{G}_j \times \prod_k \mathcal{G}_k(0;\theta_k,1)$$

- Different bin granularities can be incorporated into the likelihood by constructing PDFs from the sum of cross-sections

$$\mathcal{P}(N^i_{\rm data}; (\sigma_1+\sigma_2+\ldots) \times \mathcal{L} \times \mathcal{B} \times \mathcal{A}_i/\mathcal{C}_i \prod_j (1+\theta_j\ \epsilon^i_j) + N_{\rm bkg} \prod_k (1+\theta'_k\,\epsilon'^i_k))$$

Higgs Production Cross-section



Parton-to-Particle Non-Perturbative Correction

- Multiplicative non-perturbative correction factors and associated uncertainties that are applied to correct analytical parton-level predictions to particle level.
  - These corrections account for hadronisation and multiple parton interactions, and are derived based on a number of underlying event and showering tunes applied to the Higgs boson production MC samples used in the analysis
- Non-perturbative factors in percent with systematic uncertainties, accounting for the impact of hadronisation and underlying event.

Bin	1	2	3	4	5	6	7	8
$p_{\mathrm{T}}^{\mathrm{H}}$	99.5 ± 1.0	100.5 ± 1.3	99.9 ± 1.1	99.9 ± 1.4	100.2 ± 1.4	99.9 ± 1.1	100.4 ± 1.5	100.0 ± 1.0
$\lvert y^{\mathrm{H}} \rvert$	100.0 ± 0.8	100.1 ± 0.7	99.8 ± 0.7	100.1 ± 0.8	100.0 ± 0.7	99.8 ± 0.6		
N_{jets}, excl	100.6 ± 2.1	99.8 ± 2.9	99.3 ± 5.0	96.7 ± 6.7				
N_{jets}, incl	100.0 ± 0.0	99.2 ± 2.5	98.7 ± 5.3	96.8 ± 6.7				
$p_{\mathrm{T}}^{\mathrm{j1}}$	100.6 ± 2.1	99.6 ± 2.6	99.2 ± 2.9	99.1 ± 3.2	98.7 ± 3.6			