Experimental results on differential Higgs boson cross sections from ATLAS and CMS

QCD@LHC 2016

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Introduction

- The time of precision measurements in the Higgs sector has started!
- Differential distributions of a variety of observables allow to test the SM theoretical predictions and to (in)directly search for BSM physics.
- Many differential measurements performed using Run 1 (and Run 2!!) LHC data in different channels:
  - Still limited by the size of statistical uncertainties
  - But useful to pave the way for future analyses
- Experimental results reported in the form of fiducial (differential) cross sections
  - Measurements are more model-independent
  - Reduced uncertainties on the extrapolation to phase space not covered by the detector

How these measurements are performed

1. **Fiducial region**: defined at particle level to match the reconstruction selection as closely as possible.

2. **Observables**: choose the interesting differential distributions for studying several aspects and define a binning.
   - Binning optimized according to resolution, statistical uncertainties or signal significance.
   - (Just a small selection of observables will be shown in this talk)

3. **Signal extraction**: extract the reconstructed signal yields in each bin of the distribution

4. **Unfolding**: correct the reconstructed spectra for detector effects
   - Different choices for ATLAS and CMS.

5. **Theory comparison**: compare the unfolded results with SM (and BSM) theoretical predictions.

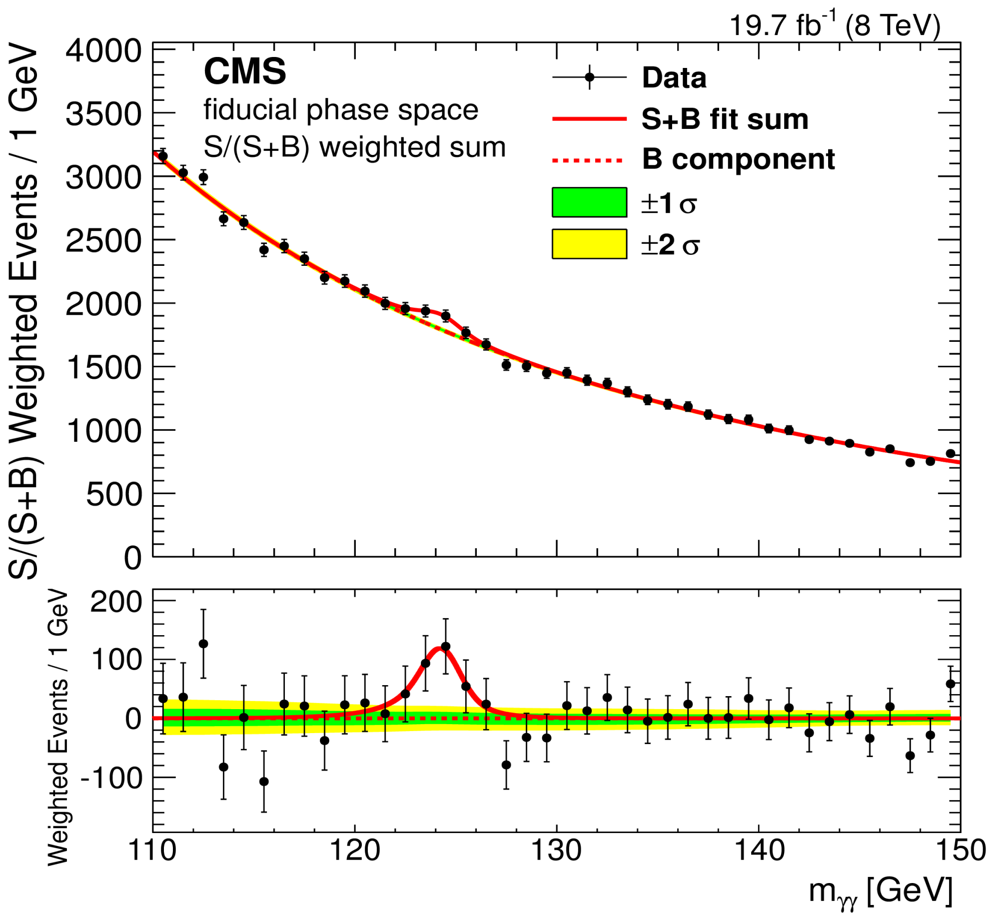
$H \rightarrow \gamma\gamma$

ATLAS: JHEP 09 (2014) 112, ATLAS-CONF-2016-067

CMS: EPJC 76 (2016) 13, CMS-PAS-HIG-16-020

H→γγ

- Clean final-state topology and precise reconstruction of the diphoton invariant mass.
- Small branching ratio but high selection efficiency
- Powerful channel for precision measurements
- Backgrounds: γγ, γ+jets, dijet
- Similar signal extraction strategies in ATLAS and CMS.
  - For a given distribution, the signal is extracted from a simultaneous fit of the diphoton mass spectrum in each bin.
  - **CMS**: events categorization based on diphoton mass resolution estimator



H→γγ fiducial phase space and unfolding

- Very similar fiducial phase space for ATLAS and CMS

Photon isolation
i runs over all the generator-level particles in a cone ΔR<0.4 around the photon direction

Variable	ATLAS	CMS
$\lvert\eta_\gamma\rvert$	< 2.37	< 2.5
$p_{\mathrm{T}}^{\gamma 1}/m_{\gamma\gamma}$	> 0.35	> 0.33
$p_{\mathrm{T}}^{\gamma 2}/m_{\gamma\gamma}$	> 0.25	> 0.25
$\sum_i E_{\mathrm{Ti}}$	$< 14\,\mathrm{GeV}$	$< 10\,\mathrm{GeV}$

- Different unfolding techniques:
  - **ATLAS**: bin-by-bin corrections

$$\sigma_i = \frac{\nu_i^{\mathrm{sig}}}{c_i \int L\mathrm{d}t} \qquad c_i = \frac{N_i^{\mathrm{reco}}}{N_i^{\mathrm{gen}}}$$

Correction factor derived from simulation

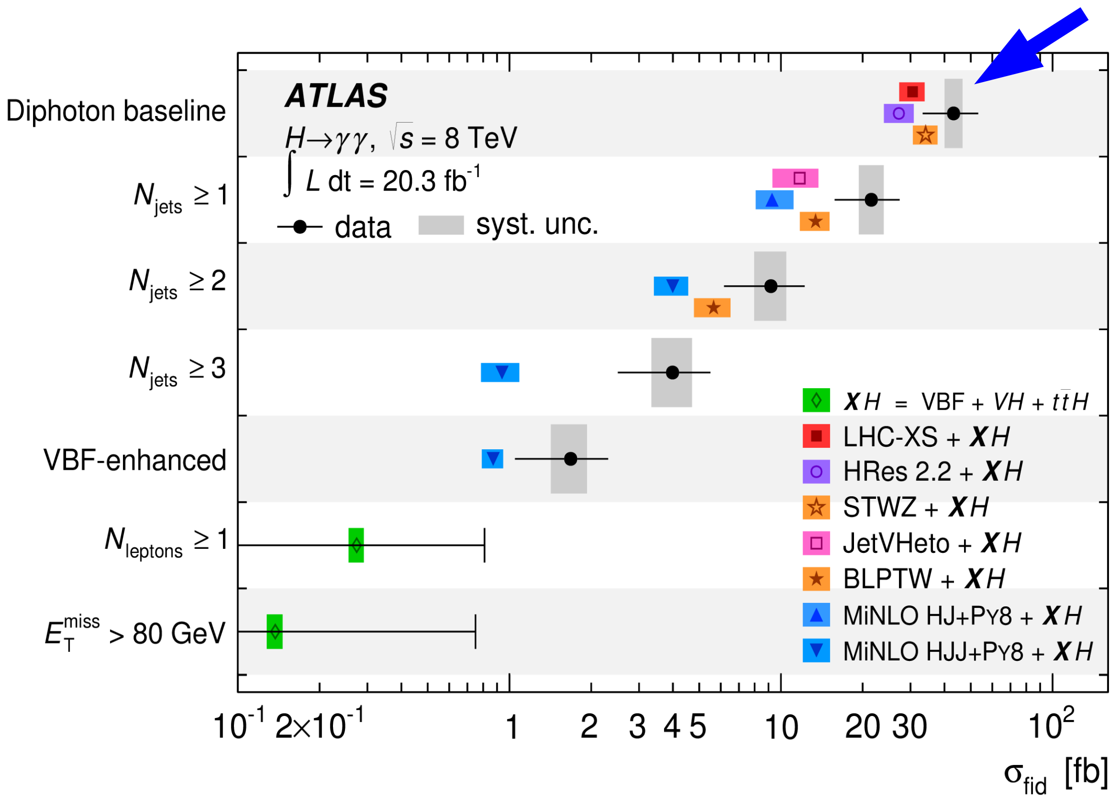
  - **CMS**: response matrix inversion embedded in the likelihood function
    - Cross section extracted directly from the fit in each fiducial bin.

- Model dependence estimated assuming different Higgs production models
  - e.g. varying the relative fractions of ggH, VBF, VH, ttH

H→γγ fiducial cross sections at 8 TeV

- **ATLAS**: fiducial cross section measured in several categories

$$\sigma_{\mathrm{fid}}(pp \to H \to \gamma\gamma) = 43.2 \pm 9.4(\mathrm{stat.})^{+3.2}_{-2.9}(\mathrm{syst.}) \pm 1.2(\mathrm{lumi})\mathrm{fb}$$



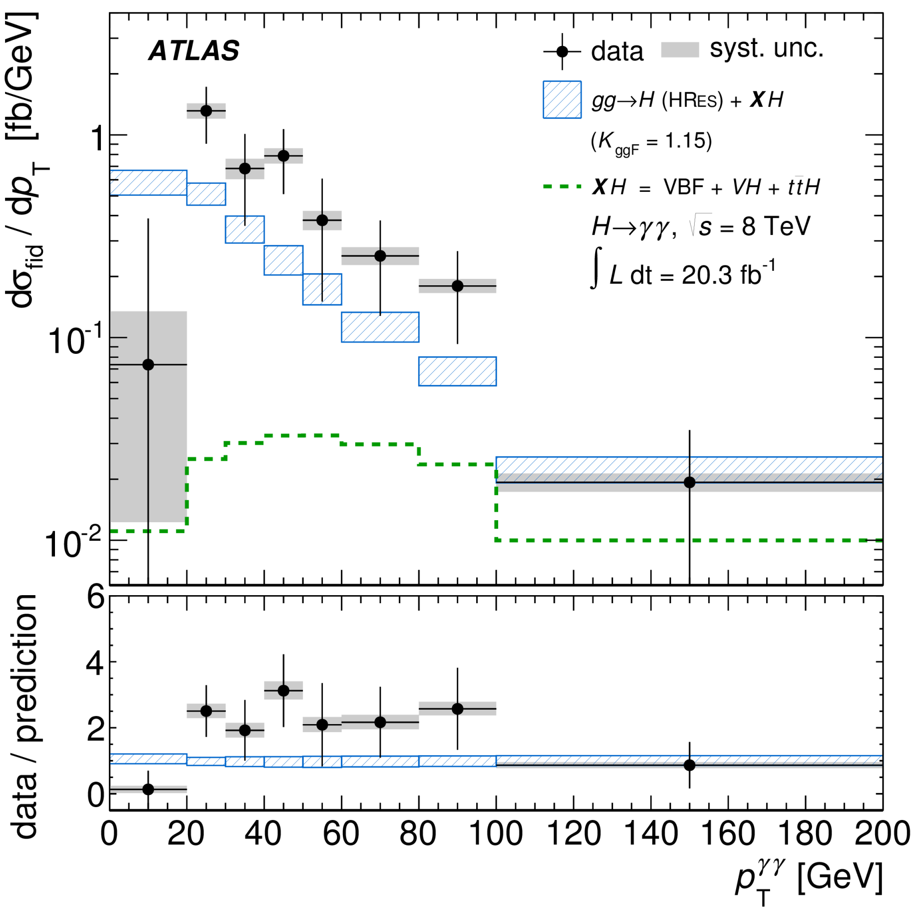
- Slight excess in all categories
- 2.1σ excess wrt SM predictions for $N_{jets} \geq 3$
- Upper limits set where no events are observed

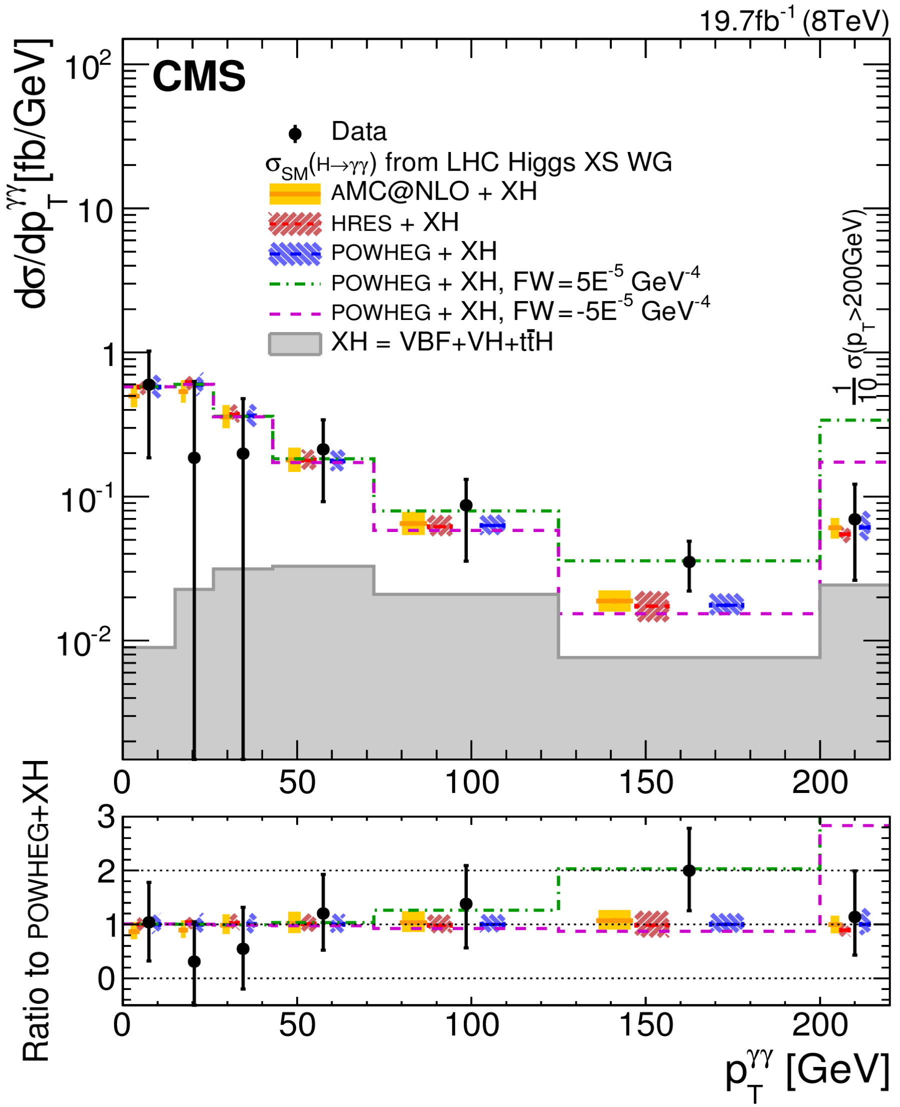
- **CMS**: fiducial cross section inclusive in the number of jets:

$$\sigma_{\mathrm{obs}} = 32^{+10}_{-10}(\mathrm{stat})^{+3}_{-3}(\mathrm{syst})\ \mathrm{fb}$$

In agreement with the HRES prediction of

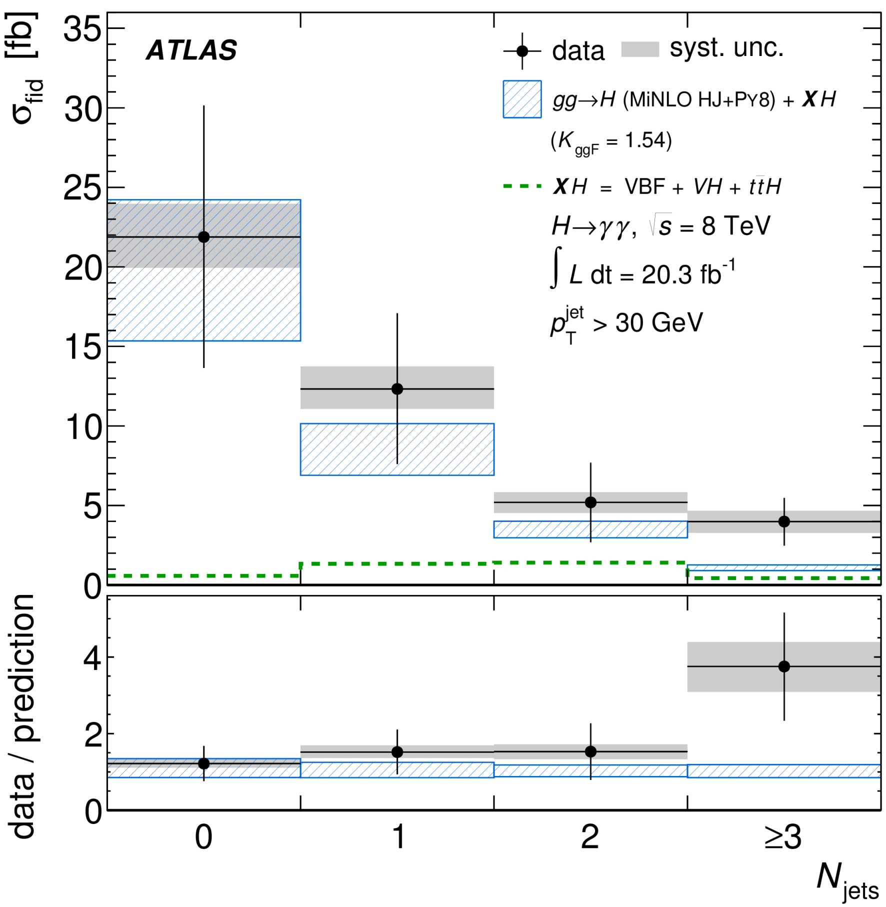
$$\sigma_{\mathrm{HRES+XH}} = 31^{+4}_{-3}\ \mathrm{fb}$$

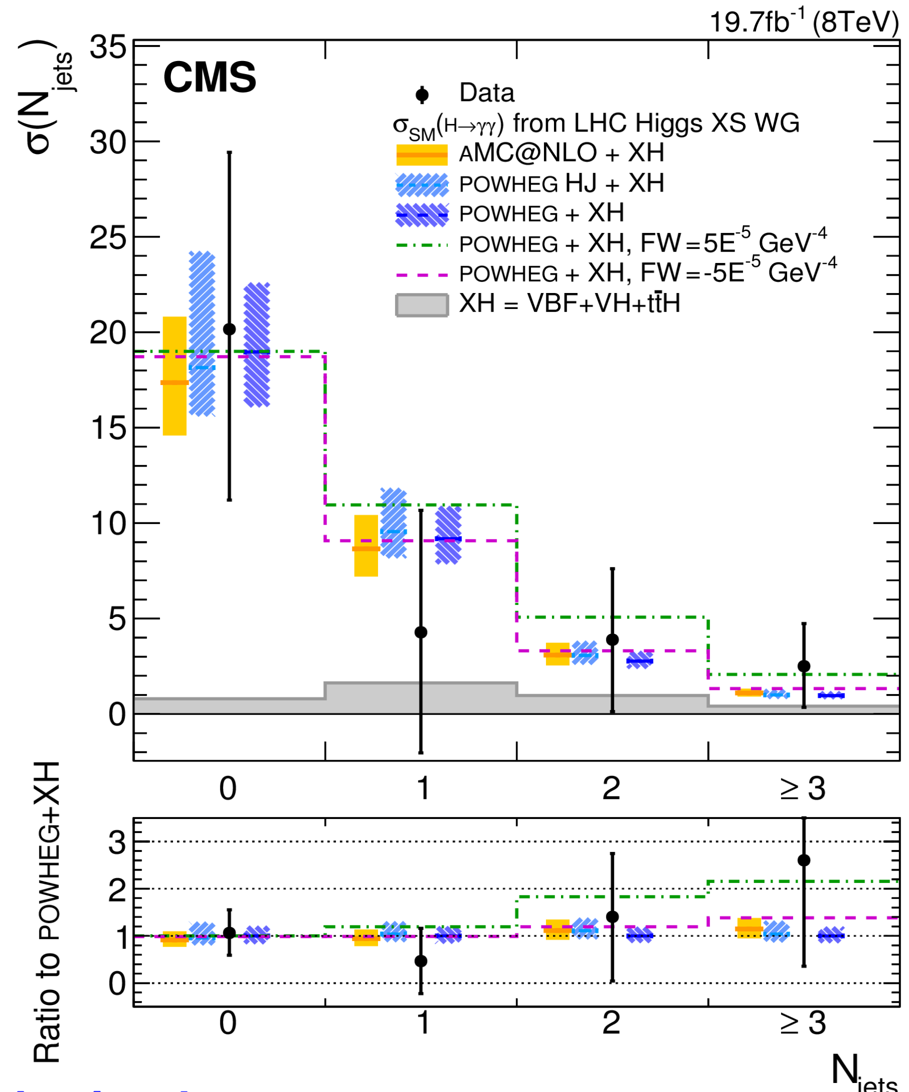




- ATLAS spectrum harder wrt SM expectations
- CMS spectrum in agreement with SM

$H\to\gamma\gamma$ differential cross sections at 8 TeV - N_{jets}





More plots in the backup

- Spectra in agreement with SM expectations

H→γγ at 13 TeV

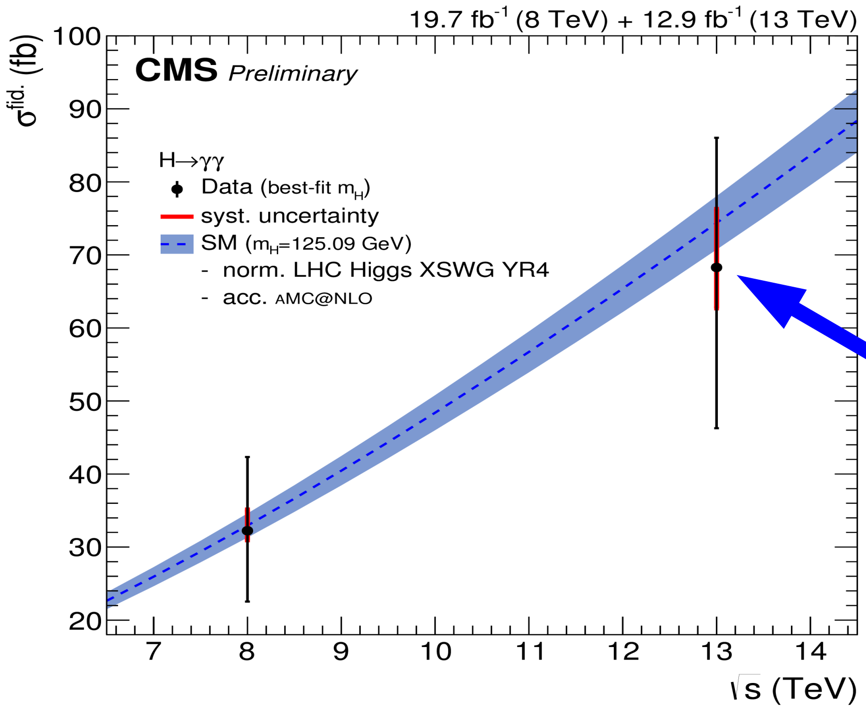
ATLAS-CONF-2016-067
CMS-PAS-HIG-16-020

NEW

- New preliminary results from ATLAS and CMS using 13 TeV data!
- Same strategy as 8 TeV is used
- Same fiducial phase space definition and unfolding

ATLAS

Fiducial region	Measured cross section (fb)	SM prediction (fb)	
Baseline	$43.2 \pm 14.9\,(\text{stat.}) \pm 4.9\,(\text{syst.})$	$62.8^{+3.4}_{-4.4}$	[N^{3}LO + XH]
VBF-enhanced	$4.0 \pm 1.4\,(\text{stat.}) \pm 0.7\,(\text{syst.})$	2.04 ± 0.13	[NNLOPS + XH]
single lepton	$1.5 \pm 0.8\,(\text{stat.}) \pm 0.2\,(\text{syst.})$	0.56 ± 0.03	[NNLOPS + XH]



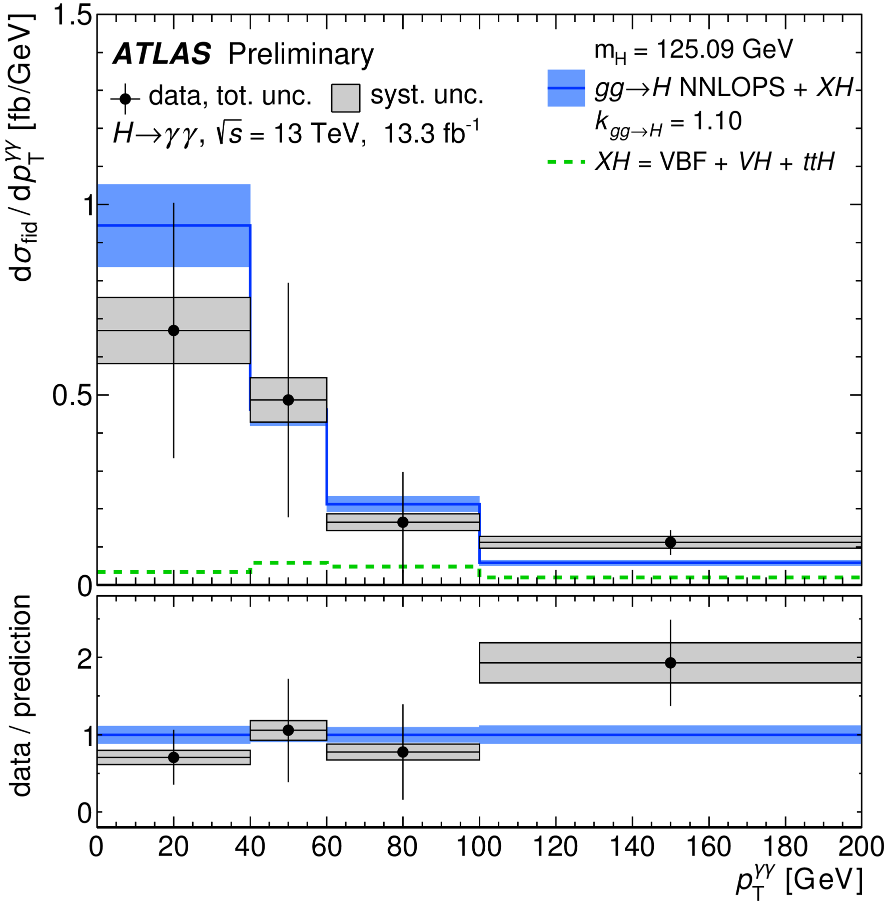
- Deficit observed in the “baseline” fiducial region.
- Agreement in the other categories.

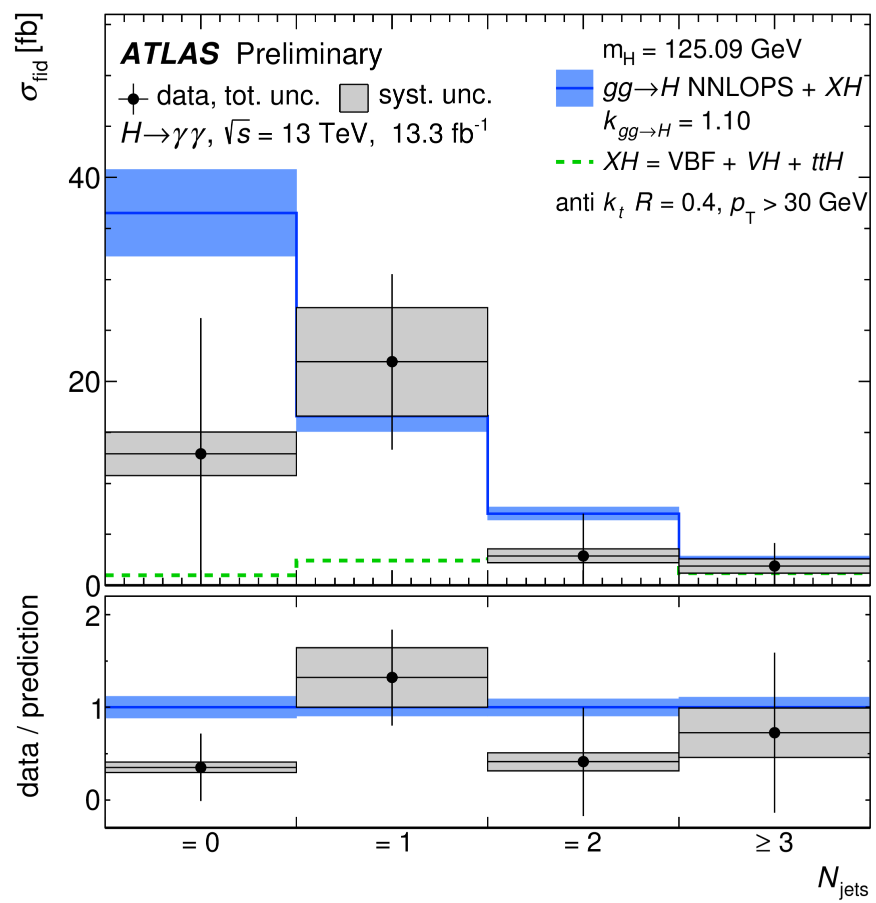
CMS

$$\sigma^{\text{fid}}_{\text{tot}} = 69^{+16}_{-22}(\text{stat.})^{+8}_{-6}(\text{syst})\ \text{fb}$$

H→γγ at 13 TeV (ATLAS only)

NEW





More plots in the backup

- Slightly harder p_T^H spectrum in agreement with 8 TeV ATLAS result.
- Deficit observed in the N_{jets}=0 category, agreement for the other N_{jets} bins.

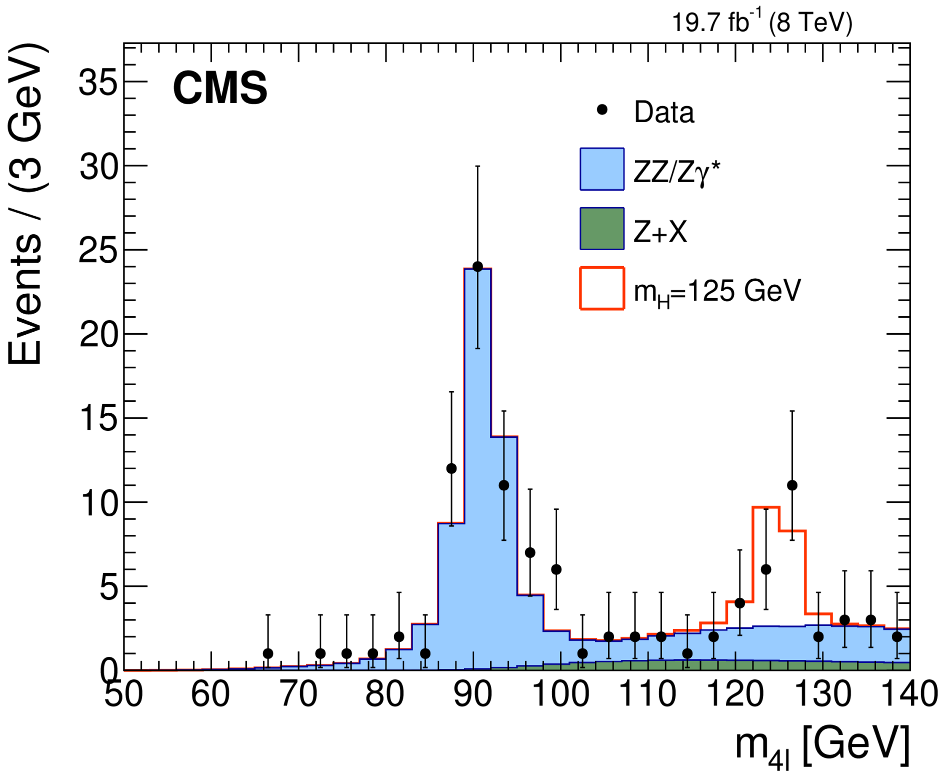
$H \to ZZ \to 4\ell$

ATLAS: PLB 738 (2014) 234, ATLAS-CONF-2016-079

CMS: JHEP 04 (2016) 005 , CMS-PAS-HIG-16-033

$H \to ZZ \to 4\ell$

- Very clean final state
  - Low signal yield but very low background yield
- Backgrounds:
  - Irreducible: quark- and gluon-induced ZZ production (estimated from simulation)
  - Reducible: Z+X with jets misidentified as leptons (estimated from data)



- Signal extraction:
  - **ATLAS**: counting events after background subtraction in m_{4l} window
  - **CMS**: maximum likelihood fit of signal and background to m_{4l}
  - For the inclusive fiducial measurement ATLAS uses a likelihood fit as well

H→ZZ→4ℓ fiducial cross sections at 8 TeV

- **ATLAS and CMS**: fiducial phase space defined at particle level using Born-level leptons (before the emission of FSR)
- **CMS**: lepton isolation requirement at particle level to minimize model dependence
- **ATLAS** fiducial cross section

$$\sigma_{\mathrm{tot}}^{\mathrm{fid}} = 2.11^{+0.53}_{-0.47}(\mathrm{stat.}) \pm 0.08(\mathrm{syst.})\ \mathrm{fb}$$

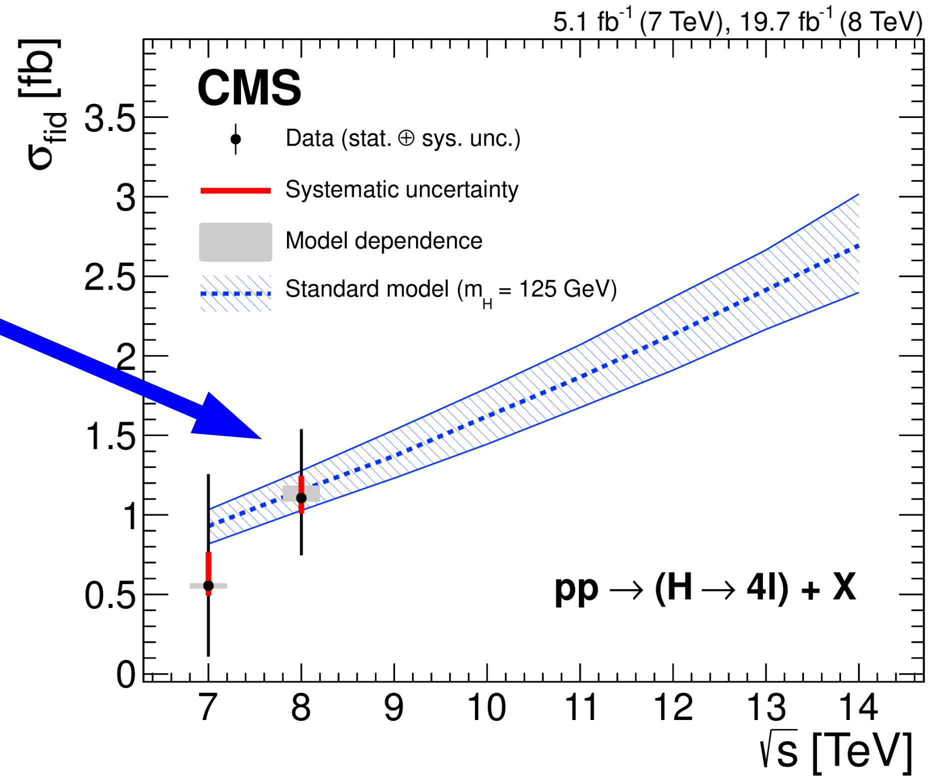
  - No significant deviation wrt the theoretical prediction of 1.30 ± 0.13 fb

- **CMS** fiducial cross sections at 7 and 8 TeV

$$\sigma_{\mathrm{tot}}^{\mathrm{fid}} = 1.11^{+0.41}_{-0.35}(\mathrm{stat})^{+0.14}_{-0.10}(\mathrm{syst})\ \mathrm{fb}$$

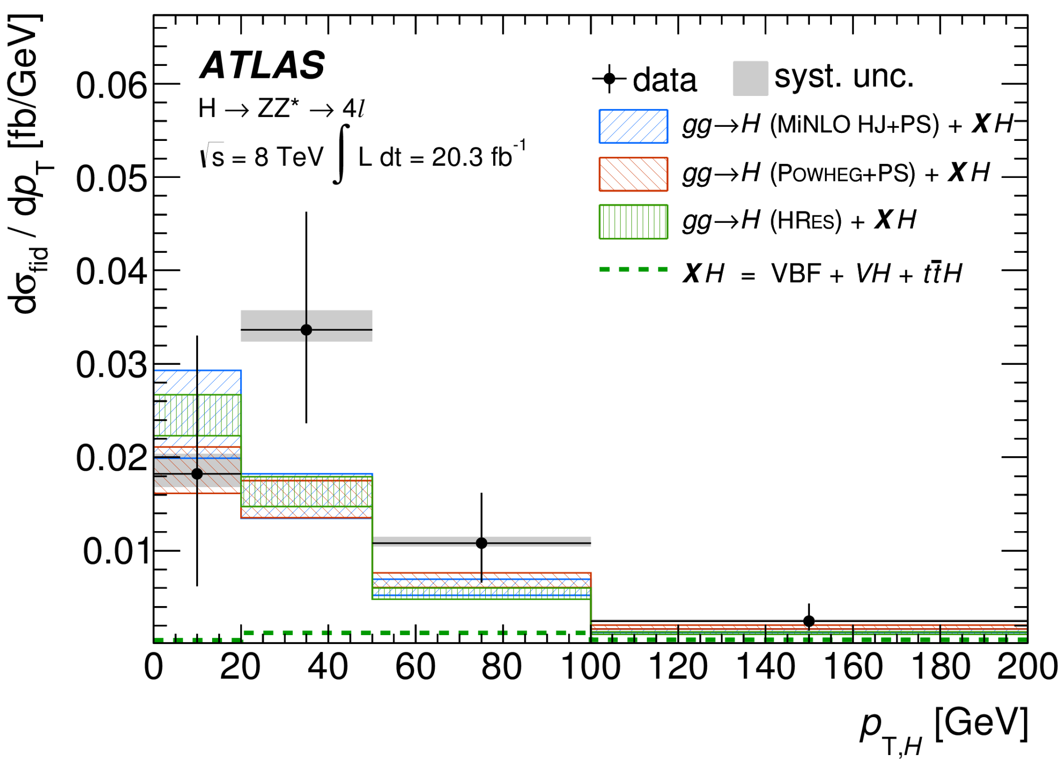
To be compared with the SM prediction of HRES

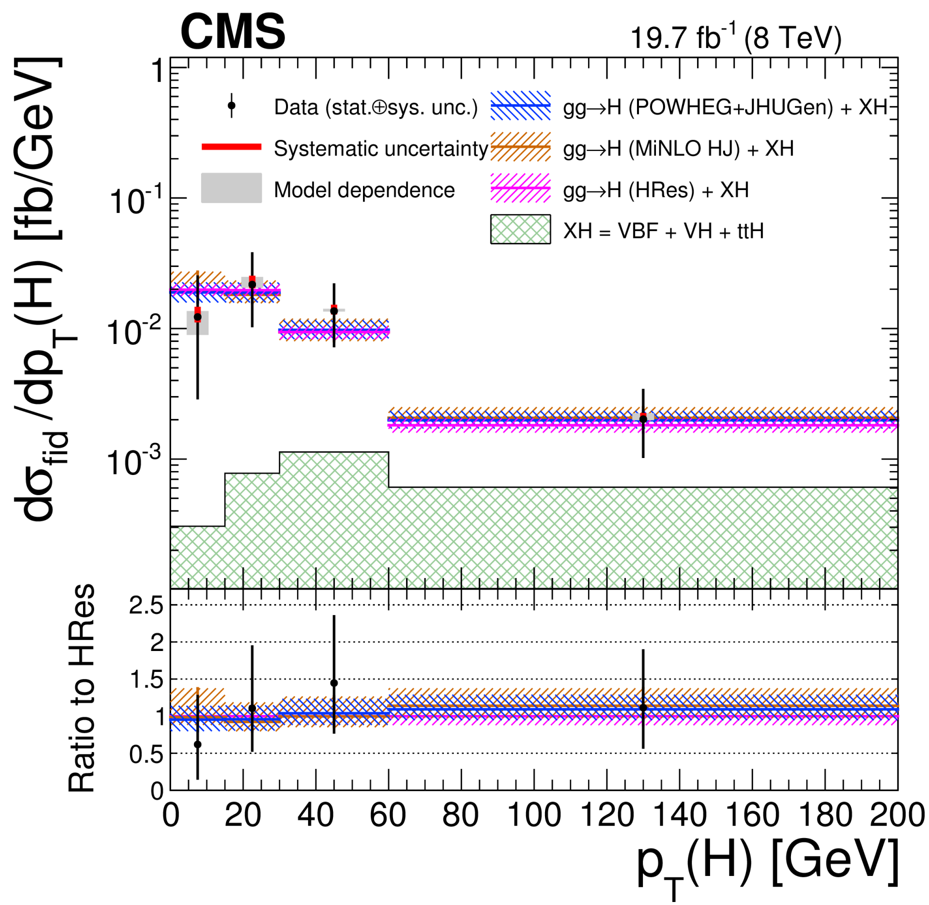
$$\sigma_{\mathrm{HRES+XH}} = 1.15^{+0.12}_{-0.13}\ \mathrm{fb}$$



$H \to ZZ \to 4\ell$ differential cross sections at 8 TeV - p_T^H

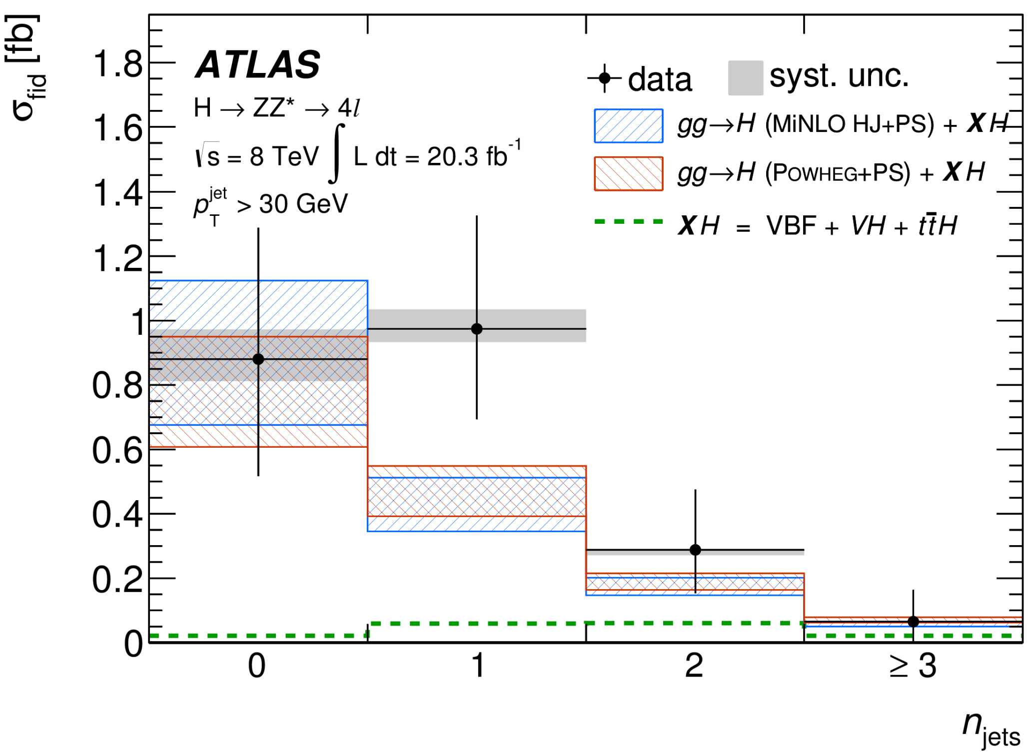
- ATLAS and CMS unfolding: same as $H \to \gamma\gamma$

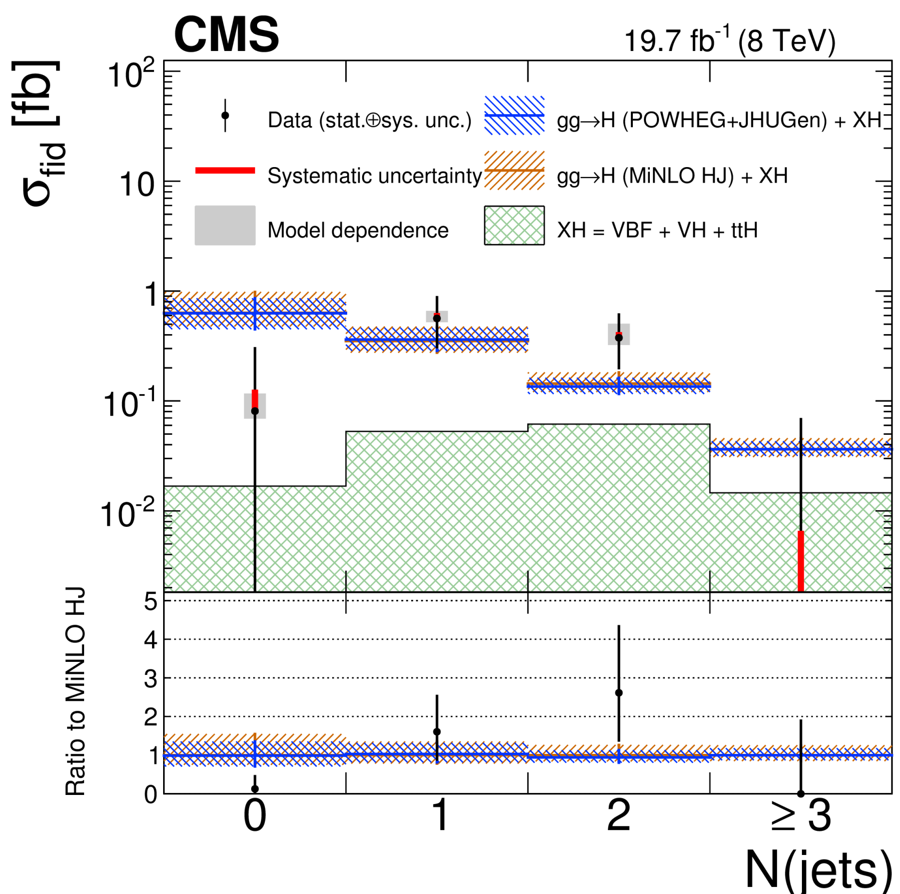




- ATLAS shape looks harder wrt SM prediction but in agreement within uncertainties
- Model dependence estimated assuming different Higgs production models

H→ZZ→4ℓ differential cross sections at 8 TeV - N_{jets}





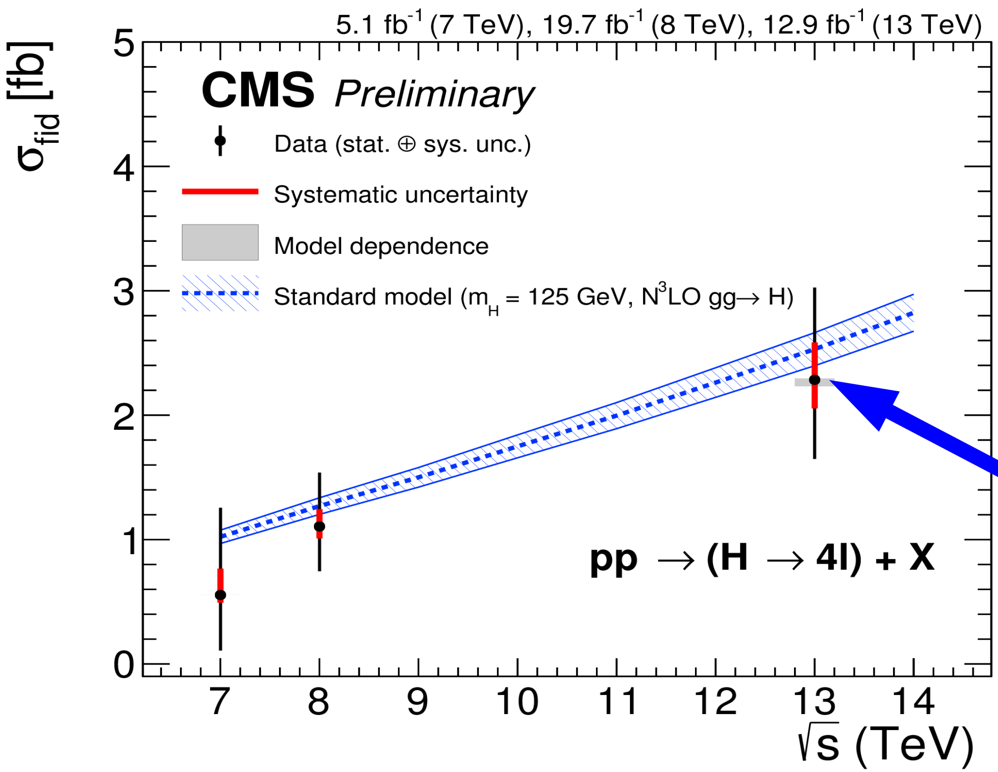
More plots in the backup

- Data show a slightly higher jet multiplicity but no significant deviation from SM predictions

H→ZZ→4ℓ at 13 TeV

- New preliminary results from ATLAS and CMS using 13 TeV data!
- Essentially the same signal extraction strategy is used.
- Very similar fiducial phase space definition
  - **CMS**: "dressed" leptons are used → 4-momenta of photons in a cone of radius ΔR<0.4 are summed to the bare lepton momentum
  - **ATLAS**: optimized mass window for fiducial cross section measurement

NEW



ATLAS

$$\sigma^{4\ell}_{\rm fid} = 4.54^{+1.02}_{-0.90}\ {\rm fb}$$

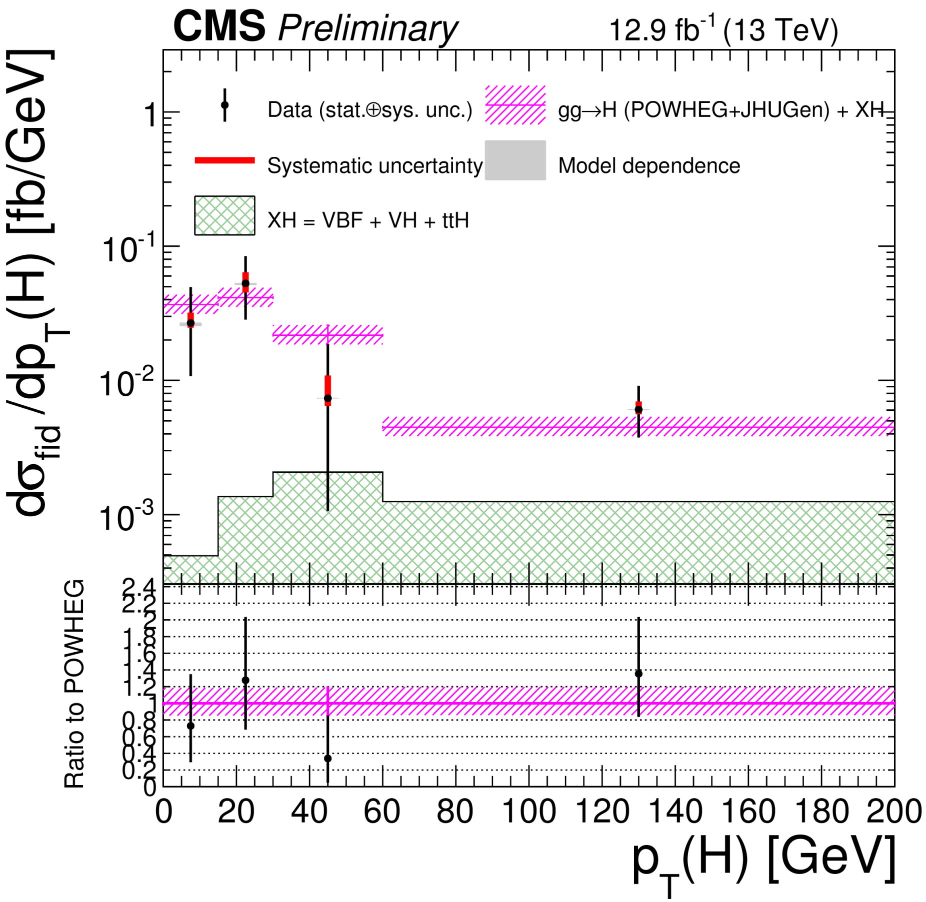
$$\sigma^{4\ell}_{\rm fid,SM} = 3.07^{+0.21}_{-0.25}\ {\rm fb}$$

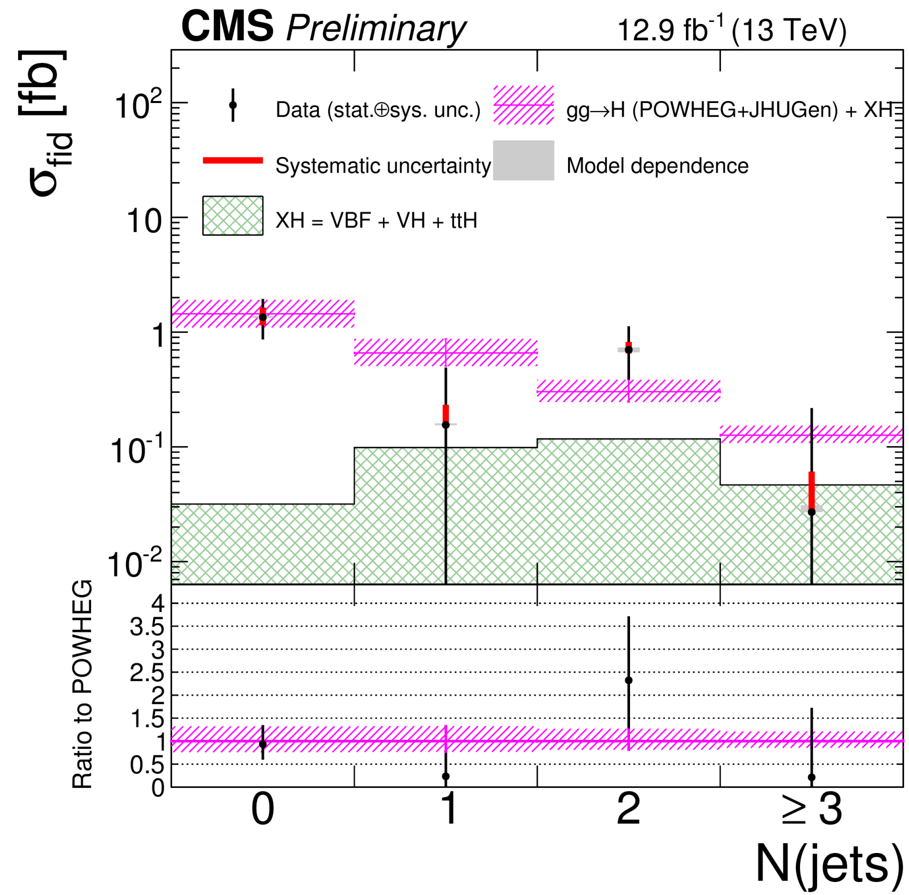
CMS

$$\sigma^{\rm fid}_{\rm tot} = 2.29^{+0.74}_{-0.64}({\rm stat.})^{+0.30}_{-0.23}({\rm syst})\ {\rm fb}$$

H→ZZ→4ℓ at 13 TeV (CMS only)

NEW





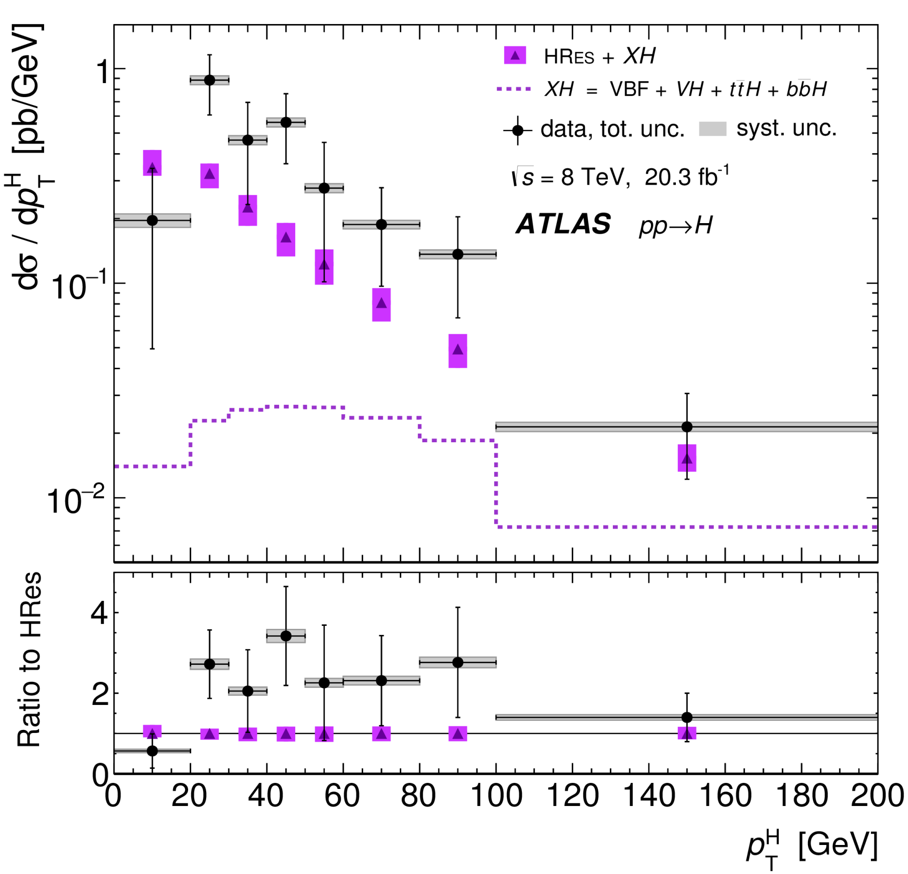
- Spectra are in good agreement with the SM POWHEG (w/o MINLO) prediction
- Uncertainties still dominated by statistical component
- Precision comparable to Run1 results

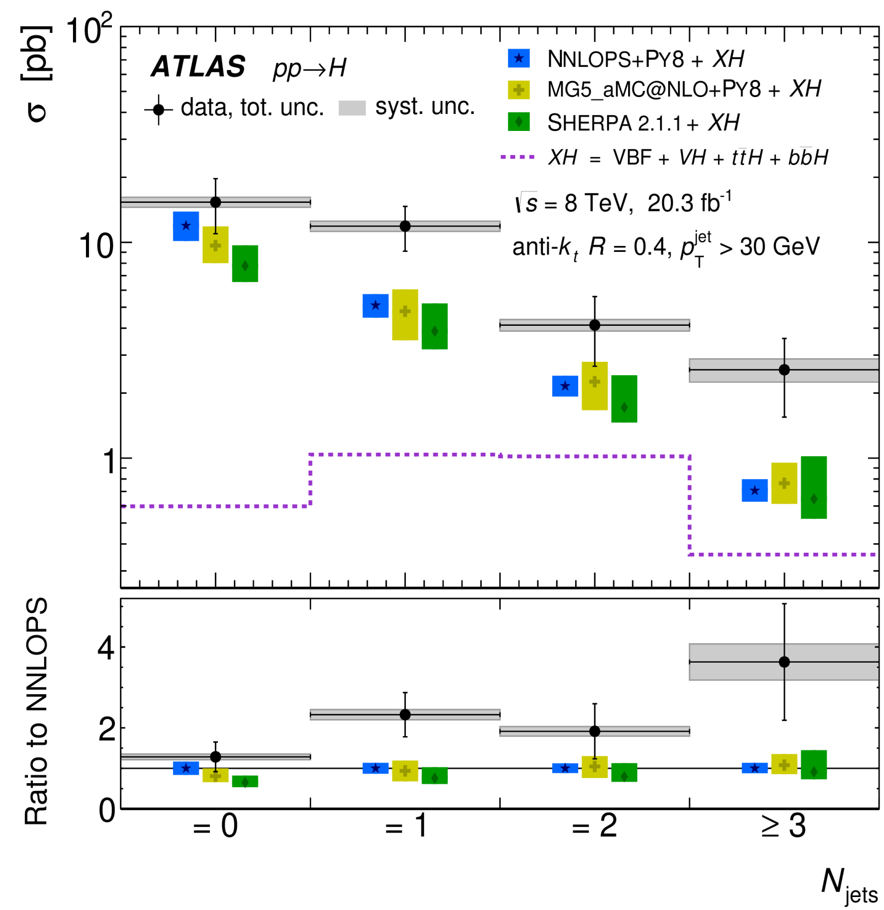
H→γγ and H→ZZ→4ℓ ATLAS combination

PRL 115 (2015) 091801

H→γγ and H→ZZ→4ℓ ATLAS combination at 8 TeV

- Cross sections combined after the extrapolation to the full phase space assuming the SM branching ratios.
- Reduction of the total uncertainty up to 40% (25-30% on average).





- No strong evidence that the excess is localized in a given p_T^H region and/or jet multiplicity bin

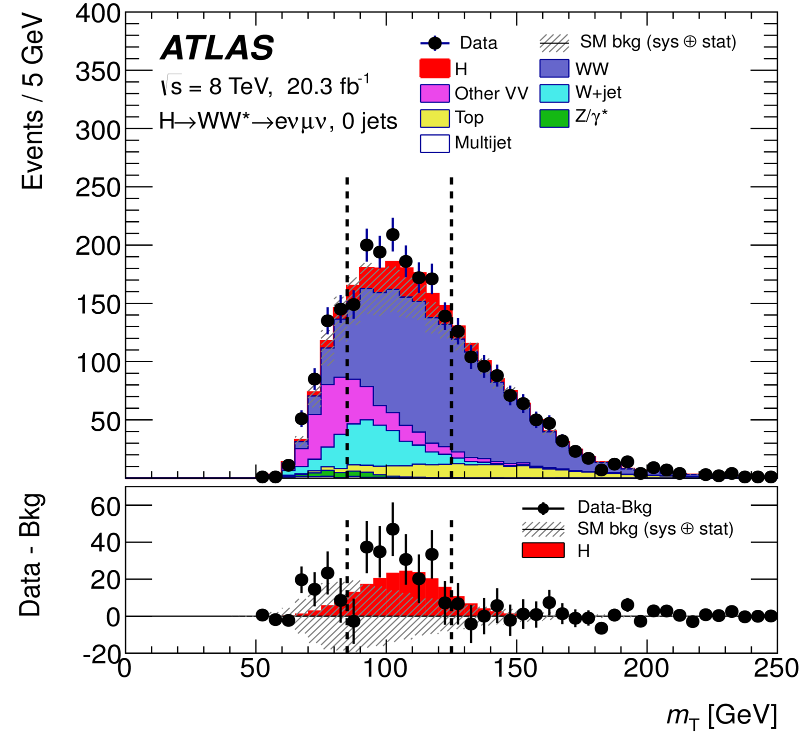
$H \to WW \to 2\ell 2\nu$

ATLAS: arXiv:1604.02997 - submitted to JHEP

CMS: arXiv:1606.01522 - submitted to JHEP

H→WW→2ℓ2ν

- Very large branching ratio compared to the other channels
- Good signal sensitivity despite large background
- Low resolution due to neutrinos in the final state
- Only different flavor leptons (eμ)
- Main backgrounds: WW and $t\bar{t}$
  - Estimated from control regions in data



- **ATLAS**: measurement of p_T^H, N_{jets}, $|\Delta y_{ll}|$, p_T^{j1}
  - 3 signal regions: N_{jets} = 0, = 1, ≥2
  - Signal (ggH only) extracted counting events inside an m_T window

p_T^H reconstructed using transverse observables

$$\vec{p}_T^{\,H} = \vec{p}_T^{\,\ell\ell} + \vec{p}_T^{\,miss}$$

- **CMS**: focused on the measurement of p_T^H
  - Inclusive in jet multiplicity
  - Signal (ggH+XH) extracted in each p_T^H bin from a 2D template fit of m_{ll} vs m_T

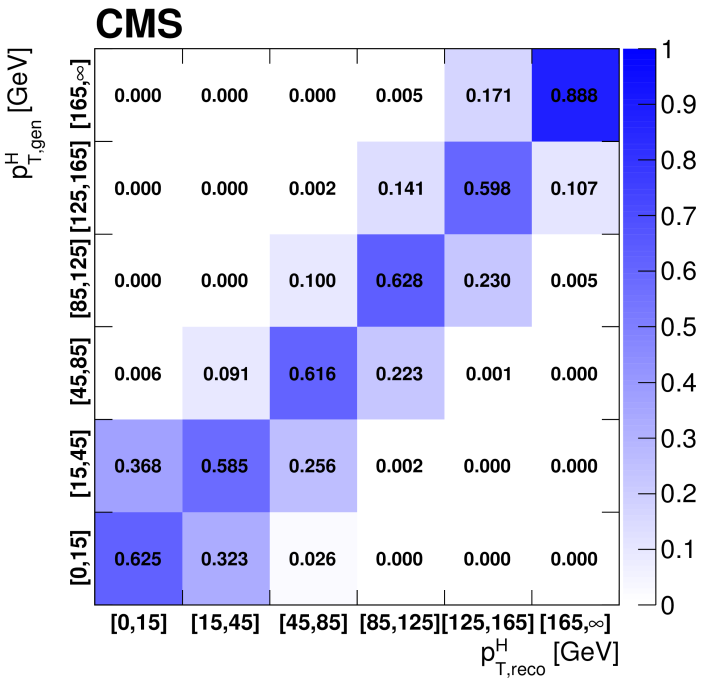
H→WW→2ℓ2ν fiducial phase space and unf.

- **ATLAS**: "dressed" leptons adding photons within a cone of radius ΔR<0.1
- **CMS**: Born-level leptons (effect of using "dressed" leptons is negligible)

Fiducial phase space main selections

Variable	ATLAS	CMS
Leptons p_T	$> 22, 15\,\mathrm{GeV}$	$> 20, 10\,\mathrm{GeV}$
$m_{\ell\ell}$	$10 < m_{\ell\ell} < 55\,\mathrm{GeV}$	$> 12\,\mathrm{GeV}$
$p_\mathrm{T}^\mathrm{miss}$	$> 20\,\mathrm{GeV}$	$> 0\,\mathrm{GeV}$
$\Delta\phi_{\ell\ell}$	< 1.8	None
$p_\mathrm{T}^{\ell\ell}$	None	$> 30\,\mathrm{GeV}$
$\mathrm{m_T}$	None	$> 50\,\mathrm{GeV}$

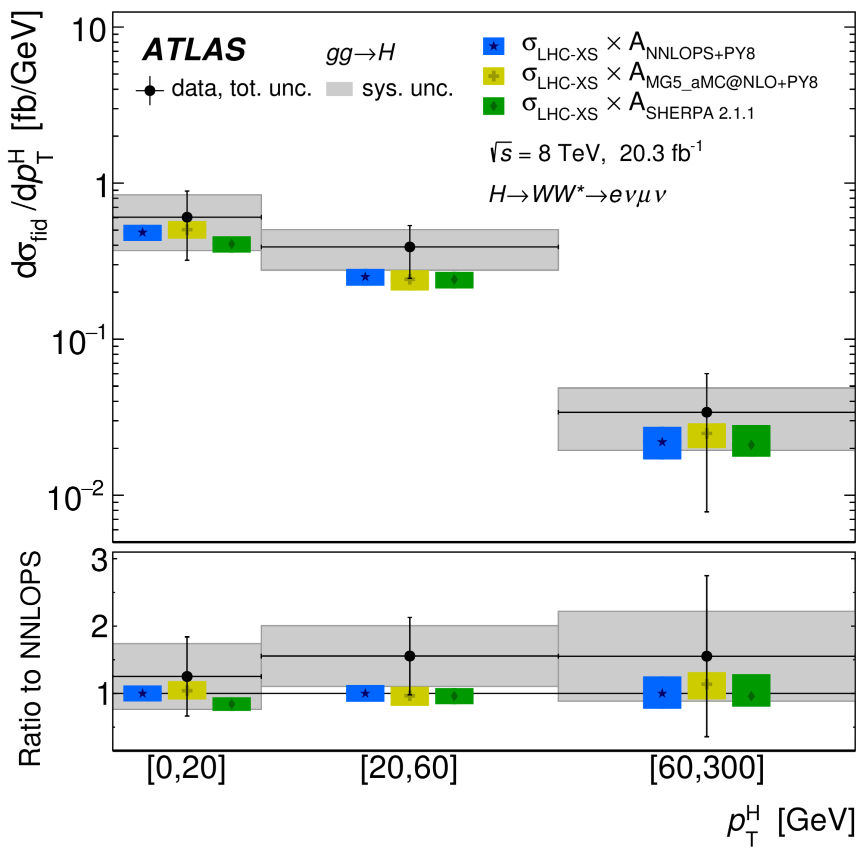
- Low resolution variables cause large bin migrations.
- Both use regularized unfolding techniques
  - **ATLAS**: D'Agostini iterative method with 2 iterations
  - **CMS**: singular value decomposition with Tikhonov regularization



H→WW→2ℓ2ν differential cross sec. at 8 TeV - p_T^H

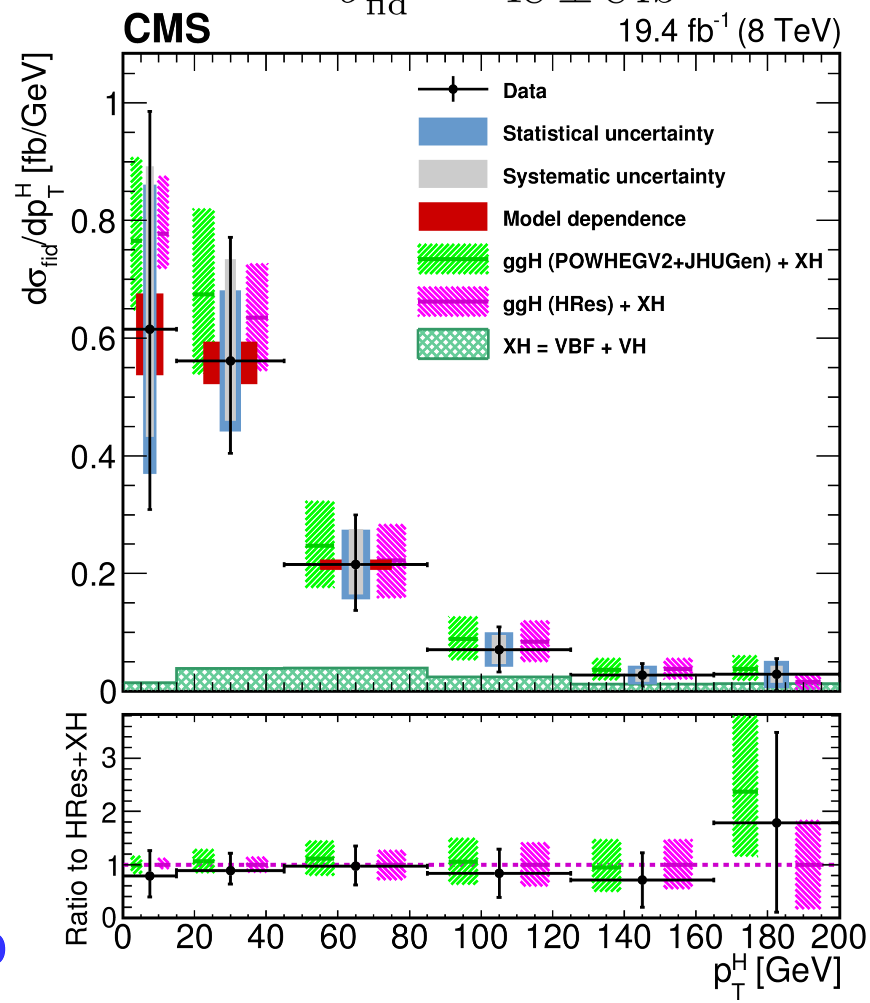
$$\sigma^{\mathrm{fid}}_{\mathrm{ggF}} = 36.0 \pm 7.2(\mathrm{stat}) \pm 6.4(\mathrm{syst}) \pm 1.0(\mathrm{lumi})\ \mathrm{fb}$$

$$\sigma^{\mathrm{fid}}_{\mathrm{ggF,SM}} = 25.1 \pm 2.6\ \mathrm{fb}$$



$$\sigma_{\mathrm{fid}} = 39 \pm 8(\mathrm{stat}) \pm 9(\mathrm{syst})\ \mathrm{fb}$$

$$\sigma^{SM}_{\mathrm{fid}} = 48 \pm 8\ \mathrm{fb}$$



More plots in the backup

- Adjacent bins are highly correlated.
- Statistical and systematic components are comparable.

Conclusions

- Higgs fiducial (differential) cross sections are important measurements
  - Test SM predictions
  - Indirect searches of BSM physics
  - Allow comparison of LHC data with future predictions

- Many results provided by ATLAS and CMS using Run 1 LHC data
  - Only bosonic channels so far
  - Measurement generally limited by statistics
  - No significant discrepancy wrt SM predictions

- Analyses using Run 2 data can provide a great improvement of the current results!

- New $H \to \gamma\gamma$ and $H \to ZZ \to 4\ell$ preliminary results using Run 2 data have been shown.

BACKUP

Observables

Higgs production

$p_{\mathrm{T}}^{\mathrm{H}} \quad |y^{\mathrm{H}}|$

- Probe the pQCD modelling of the Higgs production mechanism and PDF.
- Sensitive to BSM effects.

Higgs decay

$\Delta\Phi^{\gamma\gamma} \quad cos\theta^{*}$

- Sensitive to the properties of the decay products
- Probe the spin-CP properties

Jet activity

$p_{\mathrm{T}}^{\mathrm{j1}} \quad N_{\mathrm{jets}}$

- Relative contribution of different Higgs production mechanisms
- Probe pQCD radiation effects

VBF-sensitive

$m_{\mathrm{jj}} \quad \Delta\Phi_{\mathrm{jj}} \quad \Delta\eta_{\mathrm{jj}}$

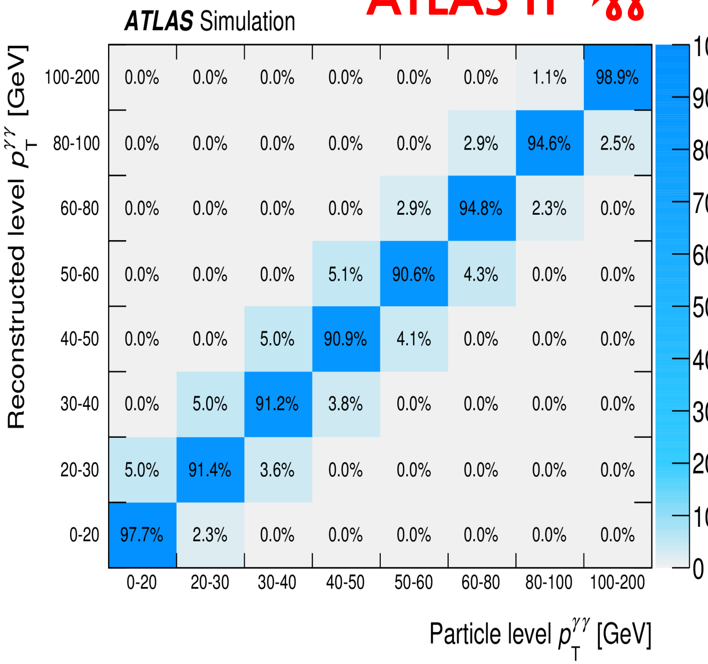
- Sensitive to the VBF production mechanism and to additional jet radiation

- Also other observables have been measured
- Just a small selection of these will be discussed (more plots in the backup).

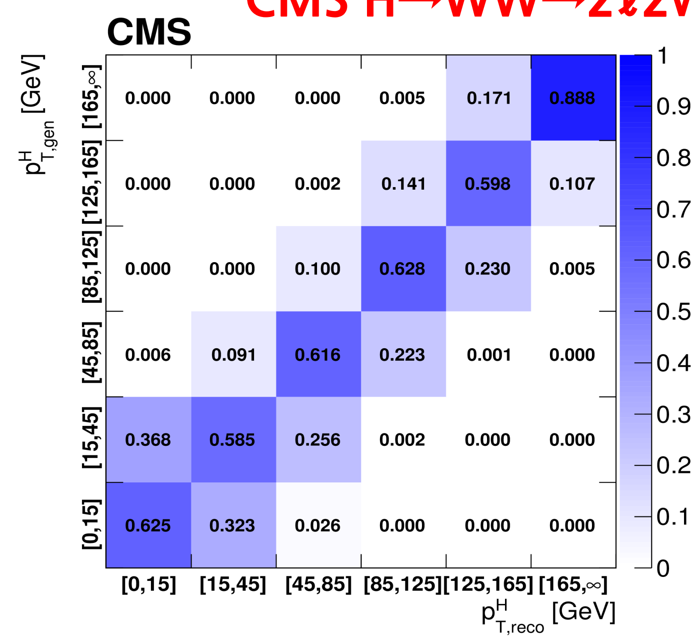
Unfolding

- Needed to correct for detector efficiency and resolution effects.
- Different choices made by different analyses
  - Bin-by-bin corrections
  - Response matrix inversion embedded in the likelihood function
  - D'Agostini iterative method
  - Singular value decomposition approach
- Response matrices are ~diagonal for high resolution observable (photon or leptons)
- When low resolution observables are involved (jets, MET), bin migrations become important.

ATLAS H→γγ



CMS H→WW→2ℓ2ν



H→ZZ→4ℓ fiducial phase space and unfolding

- **ATLAS and CMS**: fiducial phase space defined at particle level using Born-level leptons (before the emission of FSR)
- **CMS**: lepton isolation requirement at particle level to minimize model dependence

ATLAS

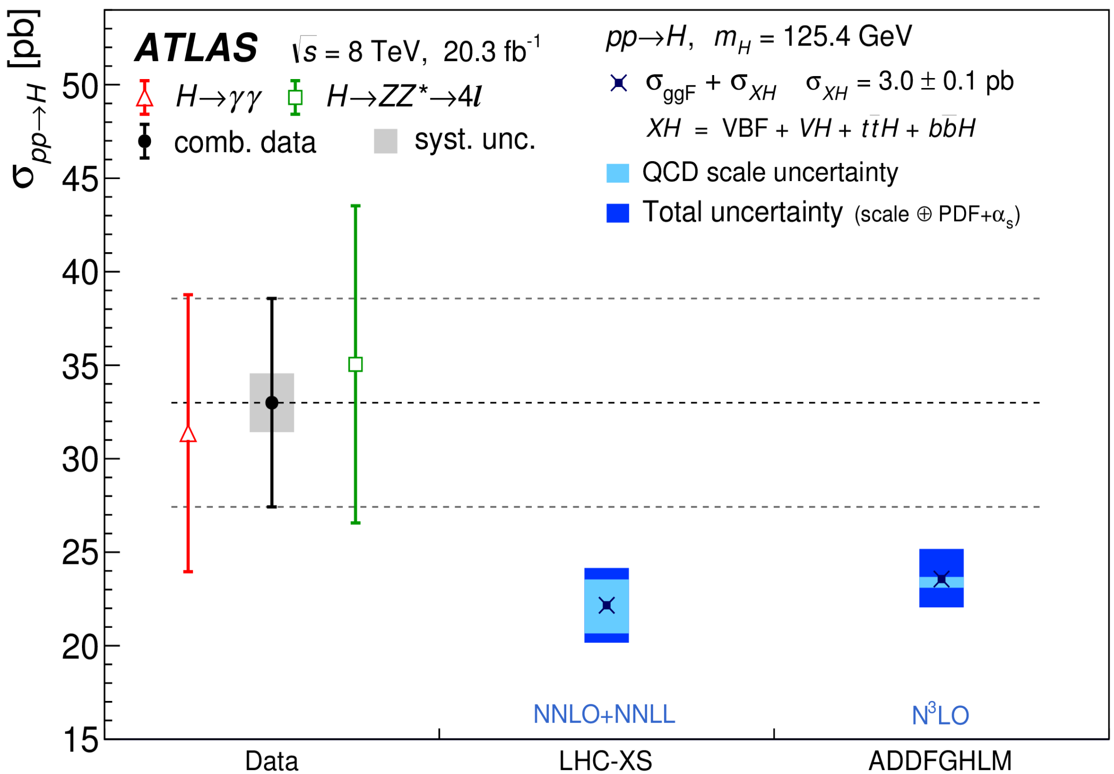
Lepton selection	
Muons:	$p_T > 6$ GeV, $|\eta| < 2.7$
Electrons:	$p_T > 7$ GeV, $|\eta| < 2.47$
Lepton pairing	
Leading pair:	SFOS lepton pair with smallest $|m_Z - m_{\ell\ell}|$
Subleading pair:	Remaining SFOS lepton pair with smallest $|m_Z - m_{\ell\ell}|$
Event selection	
Lepton kinematics:	$p_T > 20, 15, 10$ 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

CMS

Requirements for the $H \to 4\ell$ fiducial phase space	
Lepton kinematics and isolation	
Leading lepton p_T	$p_T > 20$ GeV
Sub-leading lepton p_T	$p_T > 10$ GeV
Additional electrons (muons) p_T	$p_T > 7$ (5) GeV
Pseudorapidity of electrons (muons)	$|\eta| < 2.5$ (2.4)
Sum of scalar p_T of all stable particles within $\Delta R < 0.4$ from lepton	$< 0.4 p_T$
Event topology	
Existence of at least two SFOS lepton pairs, where leptons satisfy criteria above	
Inv. mass of the Z_1 candidate	$40 < m(Z_1) < 120$ GeV
Inv. mass of the Z_2 candidate	$12 < m(Z_2) < 120$ GeV
Distance between selected four leptons	$\Delta R(\ell_i \ell_j) > 0.02$
Inv. mass of any opposite-sign lepton pair	$m(\ell_i^+ \ell_j^-) > 4$ GeV
Inv. mass of the selected four leptons	$105 < m_{4\ell} < 140$ GeV

H→γγ and H→ZZ→4ℓ ATLAS combination

- ATLAS performed a combination of the previous channels using 8 TeV data.
- Reduction of the total uncertainty up to 40% (25-30% on average).
- Cross sections combined after the extrapolation to the full phase space
- Statistical uncertainties still dominant



Combined cross section for the inclusive pp→H production

$$\sigma_{\mathrm{pp}\to\mathrm{H}} = 33.0 \pm 5.3(\mathrm{stat.}) \pm 1.6(\mathrm{syst})\ \mathrm{fb}$$

- Larger signal yield observed in data
- Data/theory p-value:
  - 5.5% for LHC-XS
  - 9% for ADDFGHLM

H→WW→2ℓ2ν fiducial phase space and unf.

- **ATLAS**: "dressed" leptons adding photons within a cone of radius $\Delta R<0.1$
- **CMS**: Born-level leptons (effect of using "dressed" leptons is negligible)

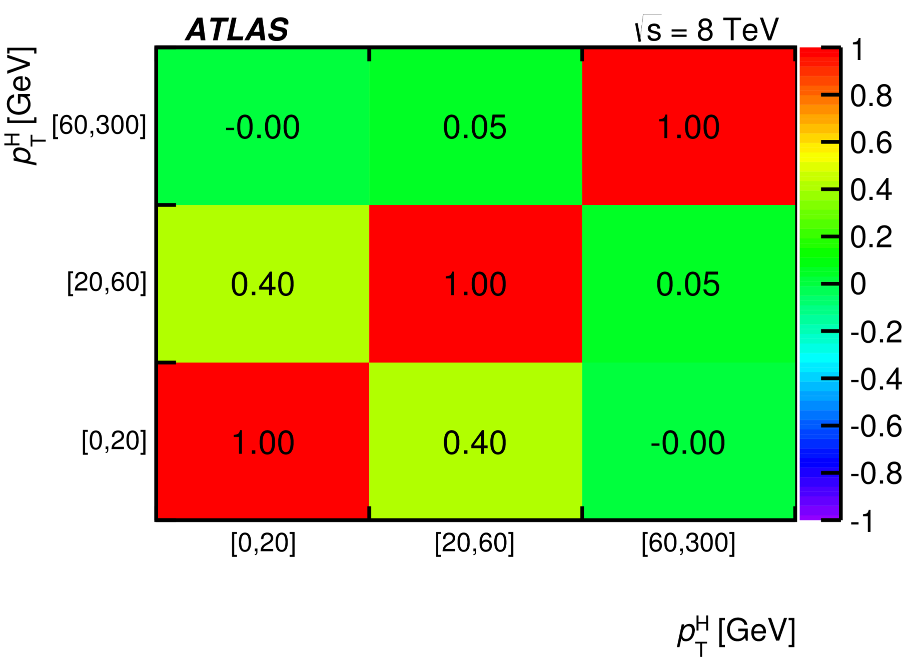
ATLAS

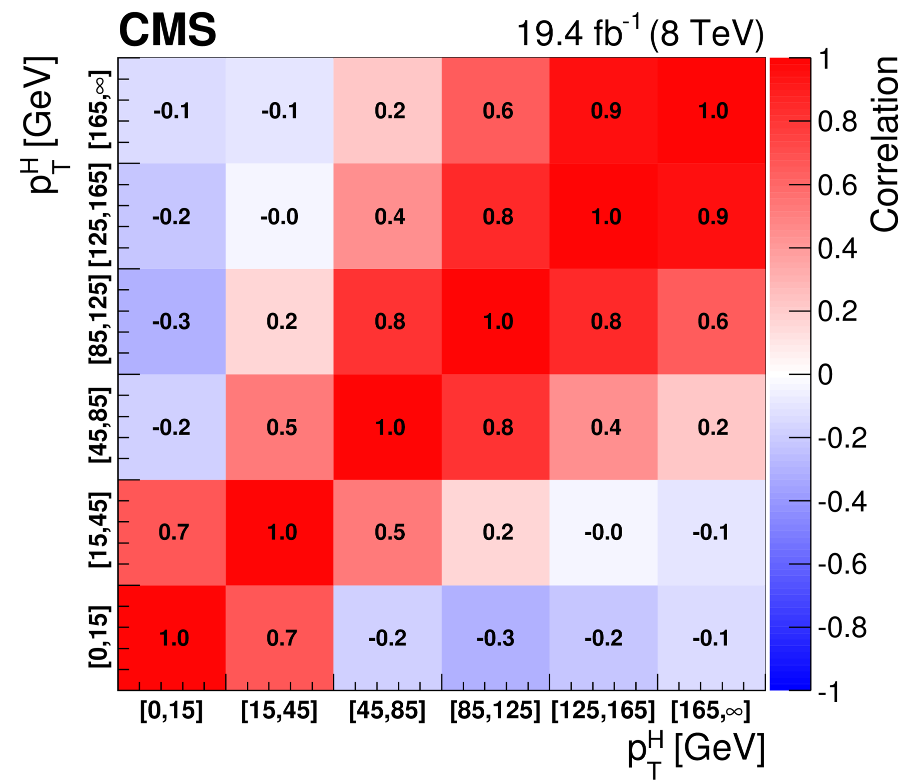
Object selection	
Electrons	$p_{\mathrm{T}} > 15 GeV$, $\|\eta\| < 1.37$ or $1.52 < \|\eta\| < 2.47$
Muons	$p_{\mathrm{T}} > 15 GeV$, $\|\eta\| < 2.5$
Jets	$p_{\mathrm{T}} > 25 GeV$ if $\|\eta\| < 2.4$, $p_{\mathrm{T}} > 30 GeV$ if $2.4 \leq \|\eta\| < 4.5$
Event selection	
Preselection	$p_{\mathrm{T}}^{\mathrm{lead}}(\ell) > 22 GeV$
	$m_{\ell\ell} > 10 GeV$
	$p_{\mathrm{T}}^{\mathrm{miss}} > 20 GeV$
Topology	$\Delta\phi_{\ell\ell} < 1.8$
	$m_{\ell\ell} < 55 GeV$

CMS

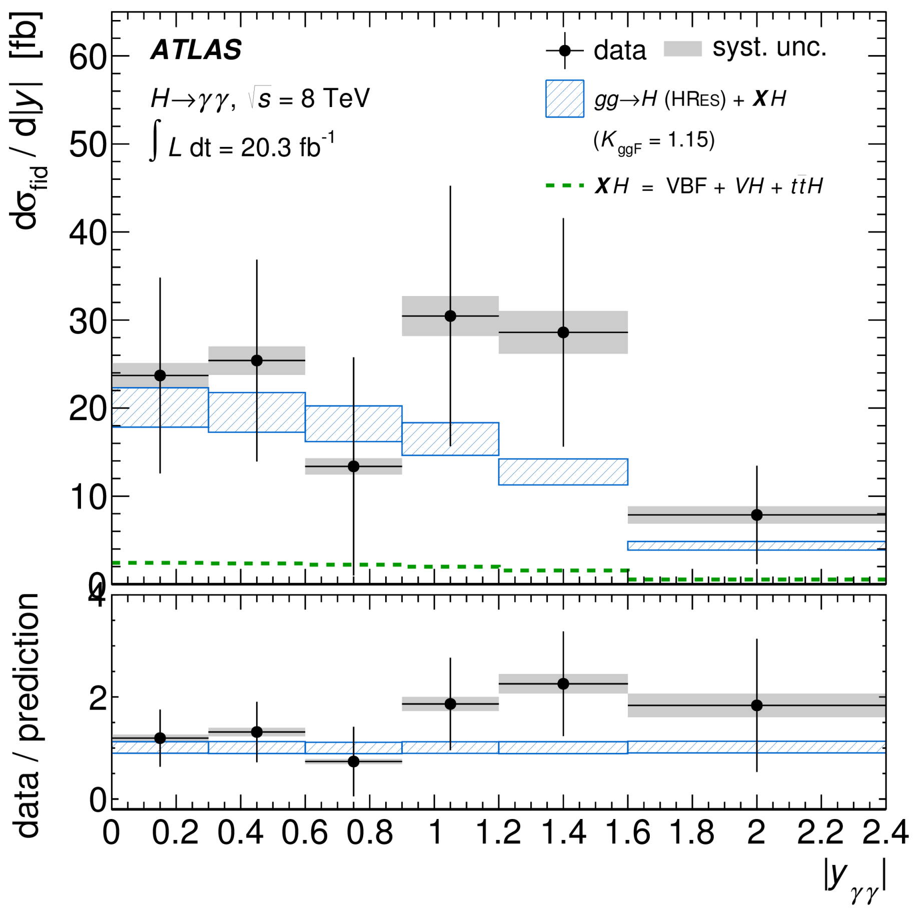
Physics quantity	Requirement
Leading lepton p_{T}	$p_{\mathrm{T}} > 20\,\mathrm{GeV}$
Subleading lepton p_{T}	$p_{\mathrm{T}} > 10\,\mathrm{GeV}$
Pseudorapidity of electrons and muons	$\|\eta\| < 2.5$
Invariant mass of the two charged leptons	$m_{\ell\ell} > 12\,\mathrm{GeV}$
Charged lepton pair p_{T}	$p_{\mathrm{T}}^{\ell\ell} > 30\,\mathrm{GeV}$
Invariant mass of the leptonic system in the transverse plane	$m_{\mathrm{T}}^{\ell\ell\nu\nu} > 50\,\mathrm{GeV}$
$E_{\mathrm{T}}^{\mathrm{miss}}$	$E_{\mathrm{T}}^{\mathrm{miss}} > 0$

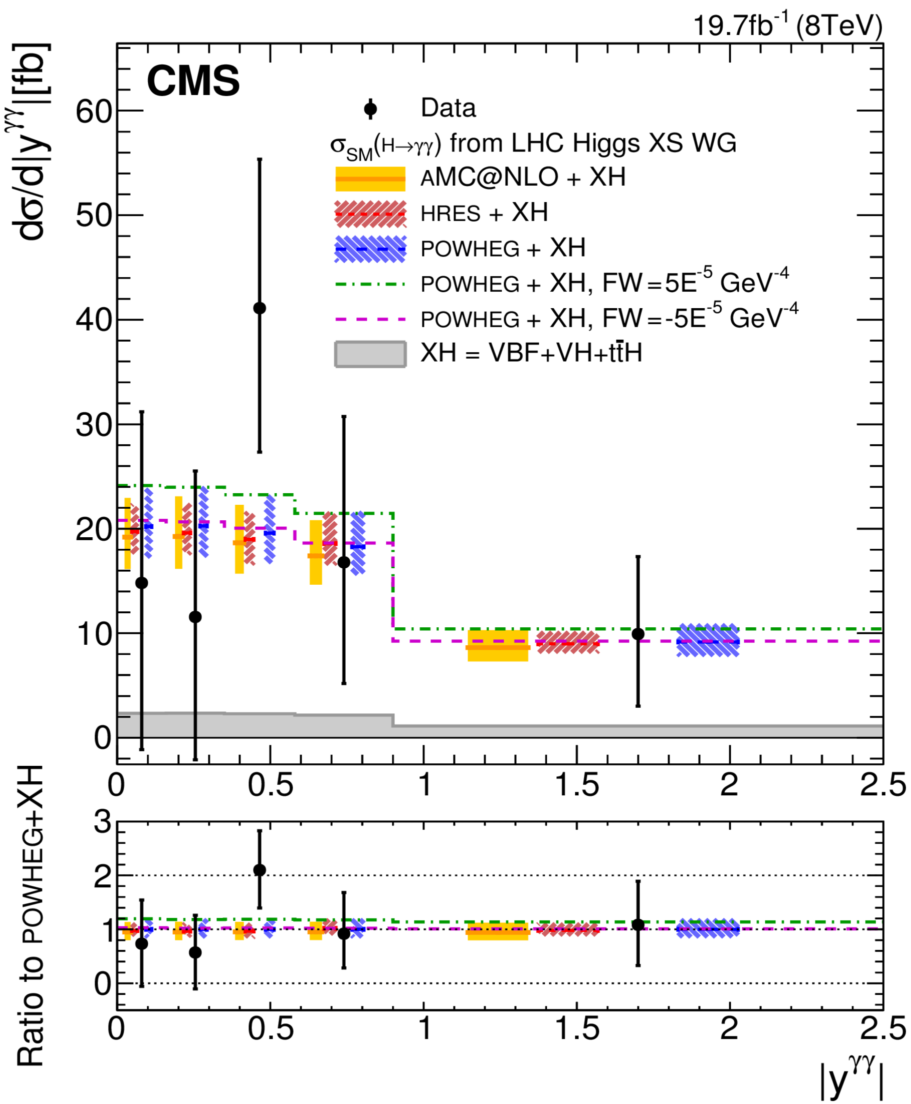
$H \to WW \to 2\ell 2\nu$ p_T^H correlation matrix



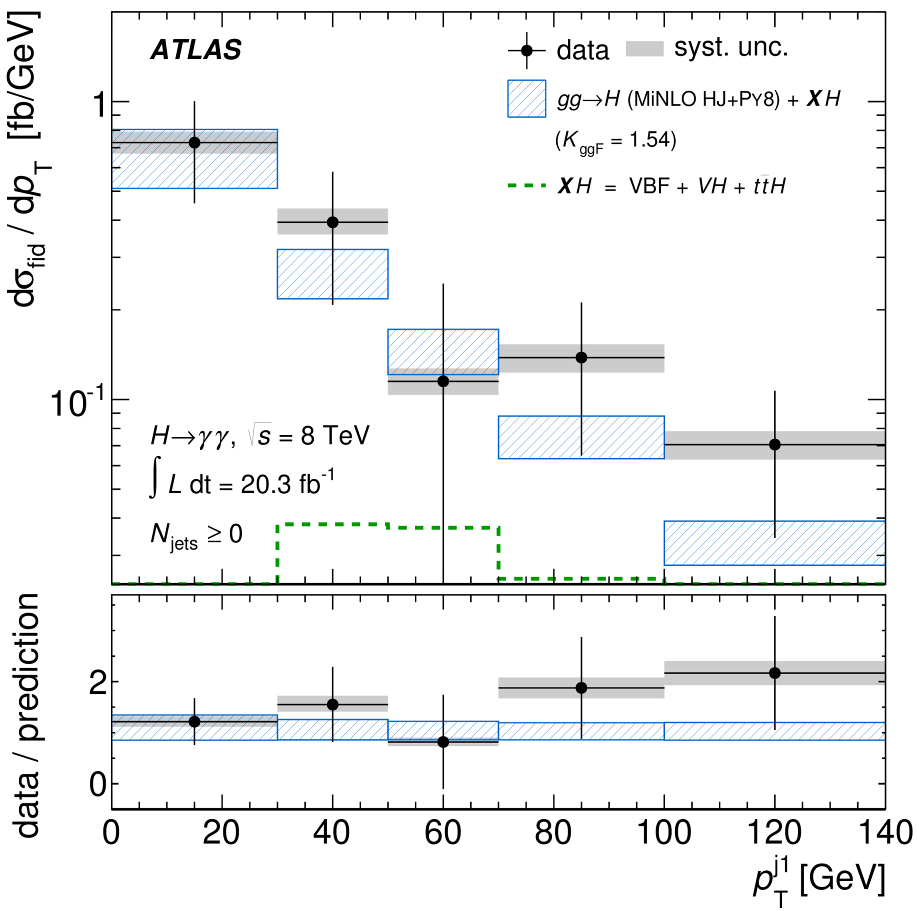


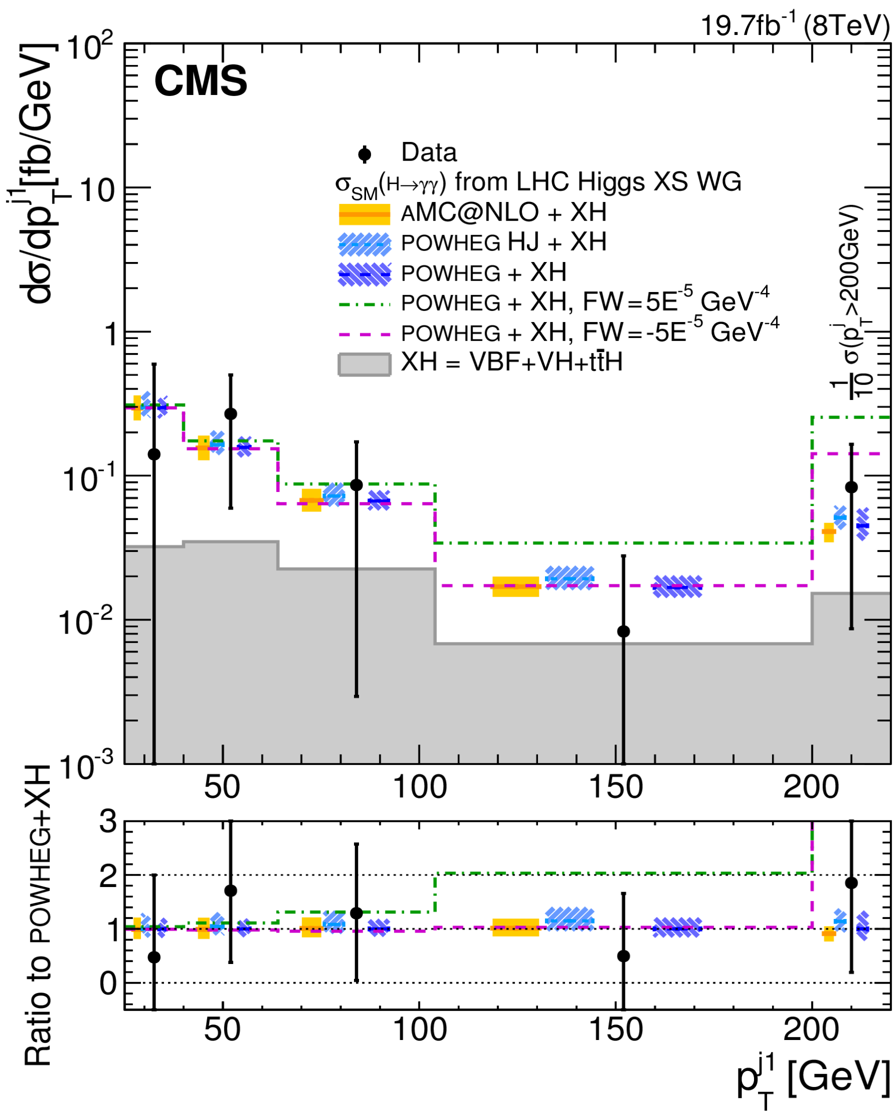
H→γγ differential cross sections - |y^H|



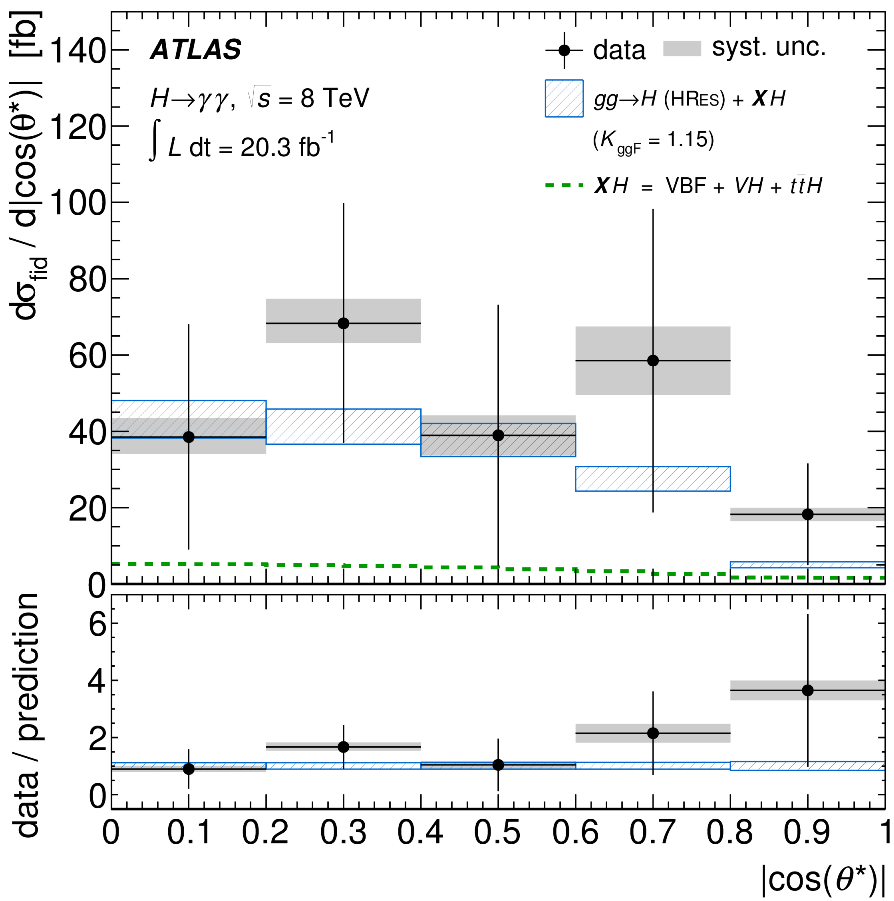


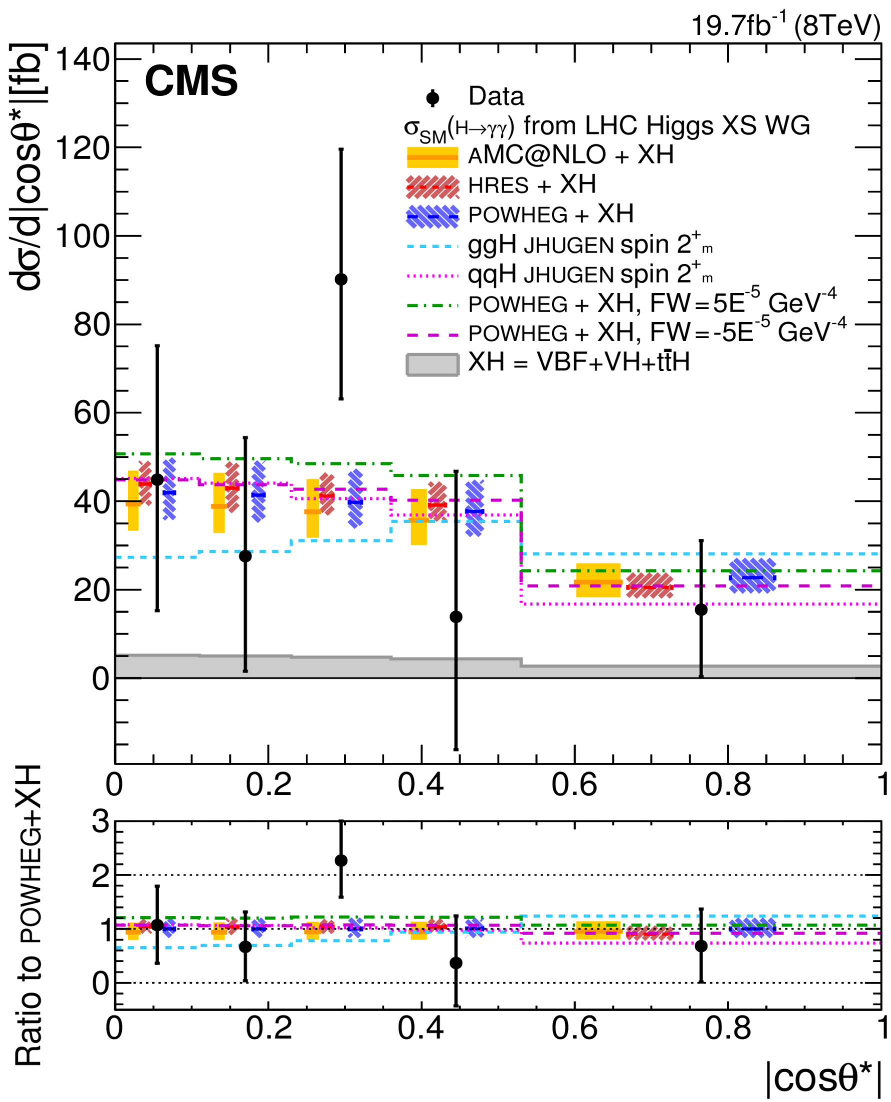
H→γγ differential cross sections - p_T^{j1}



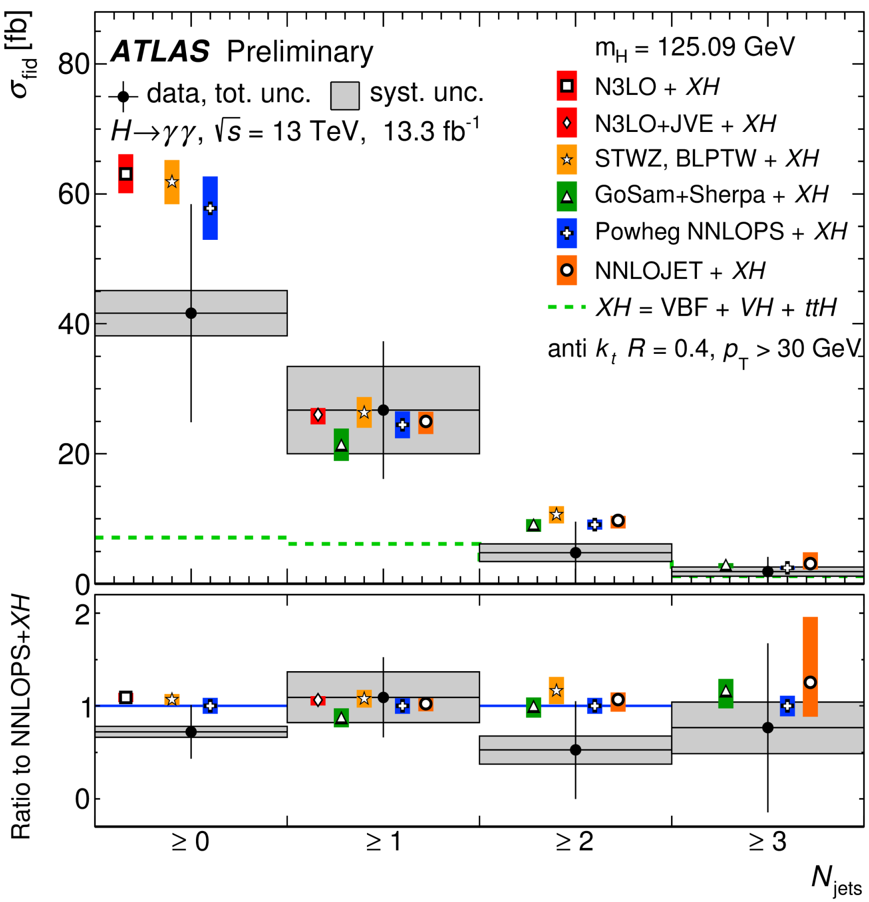


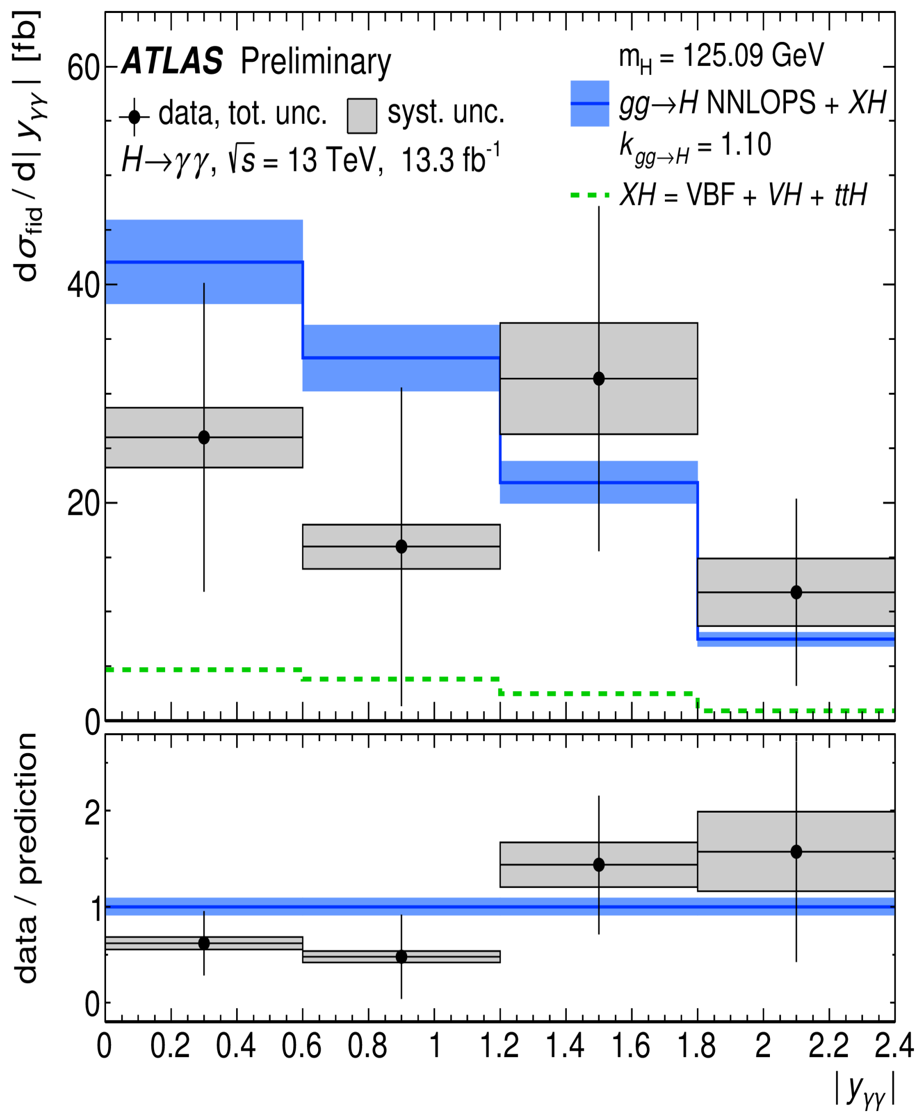
H→γγ differential cross sections - cosθ*



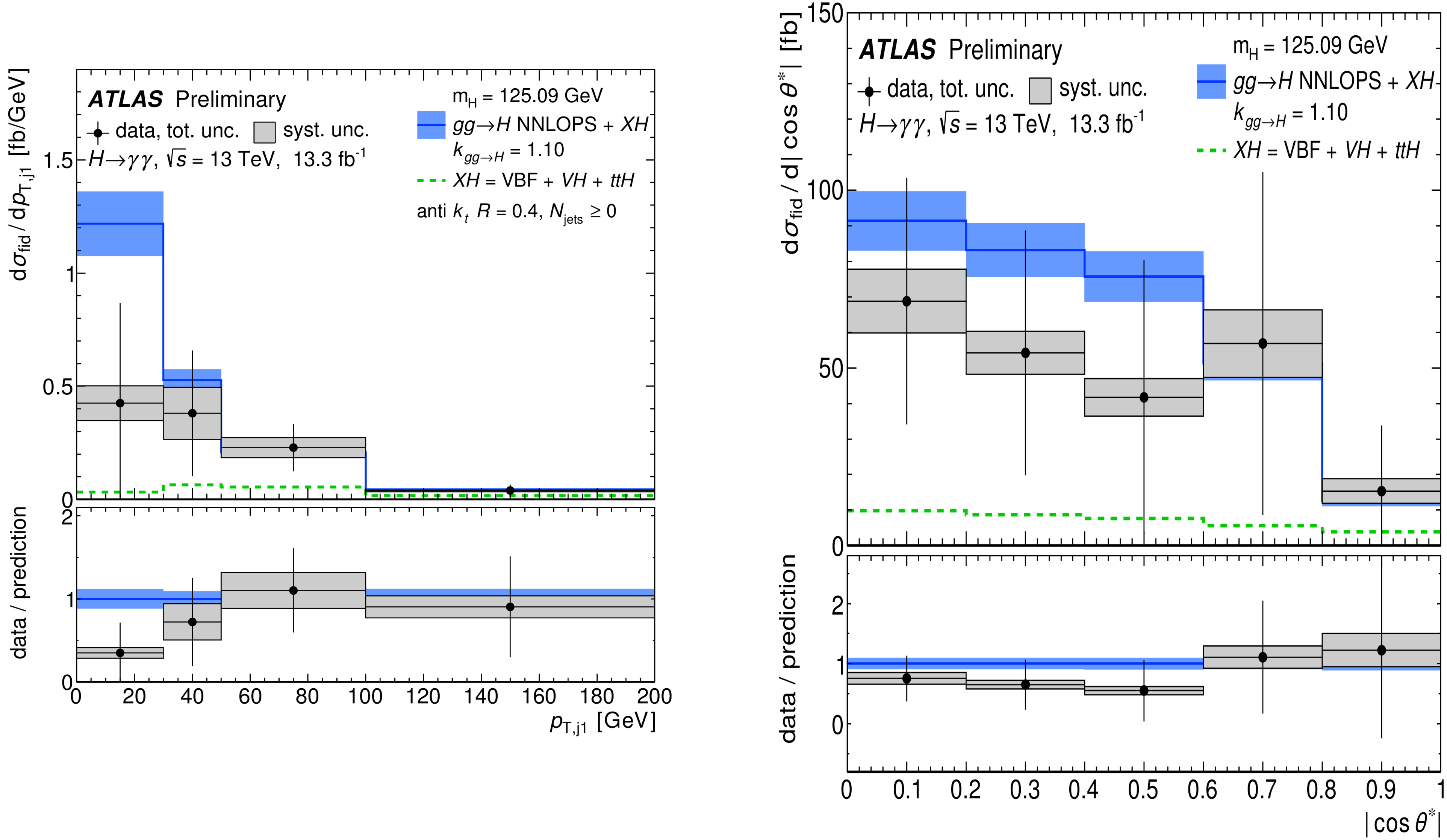


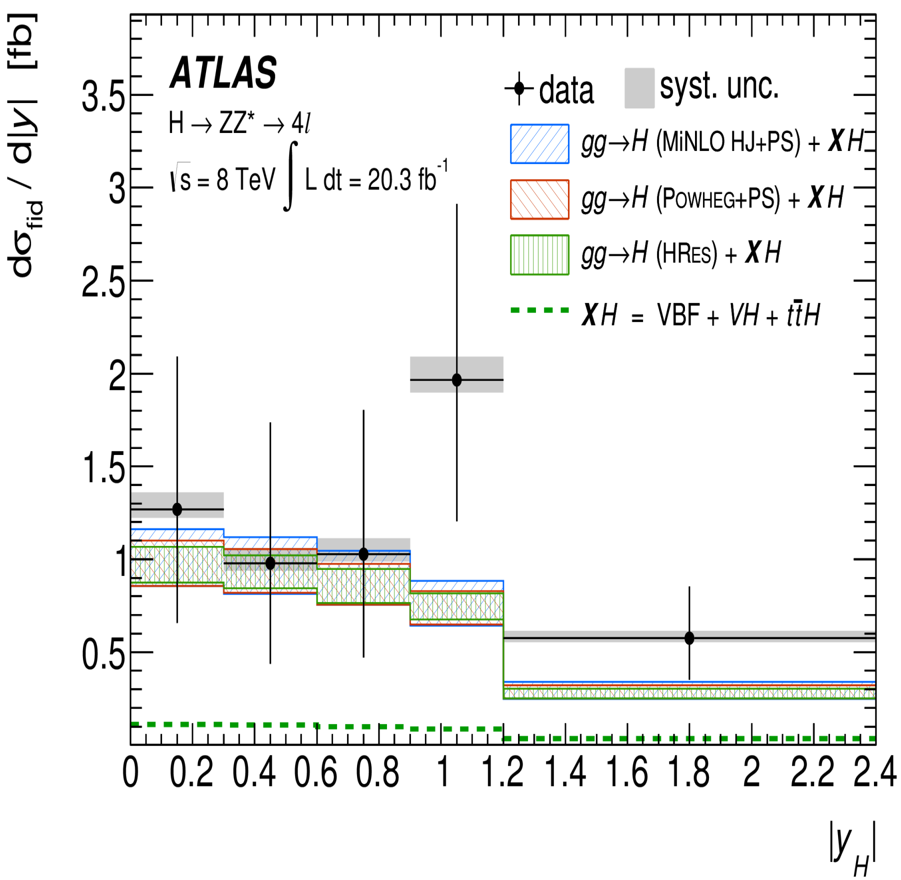
H→γγ 13 TeV differential cross sections (ATLAS)



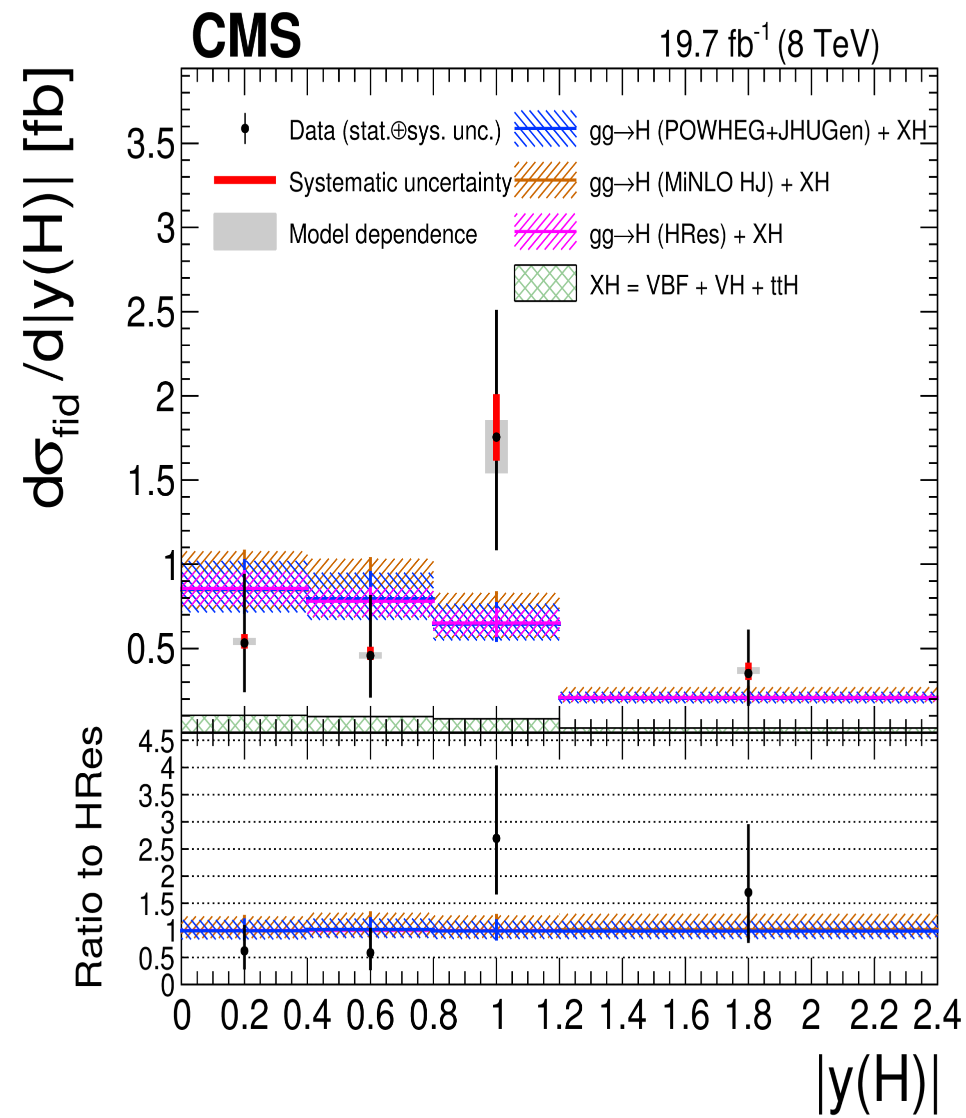


H→γγ 13 TeV differential cross sections (ATLAS)



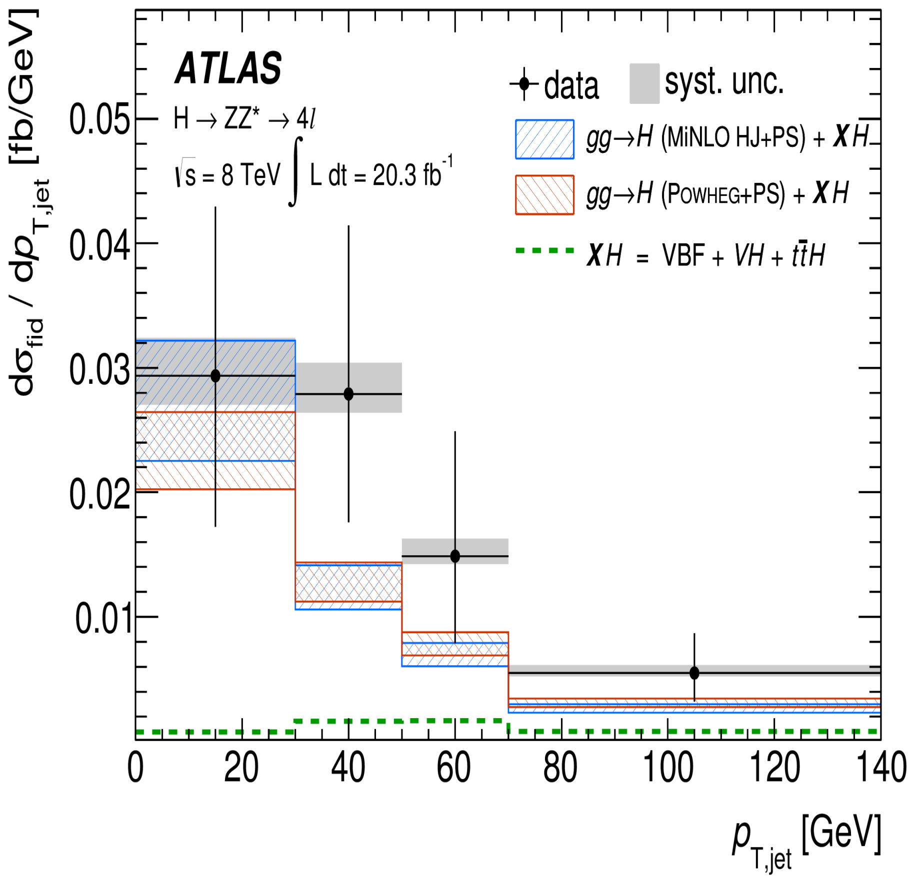


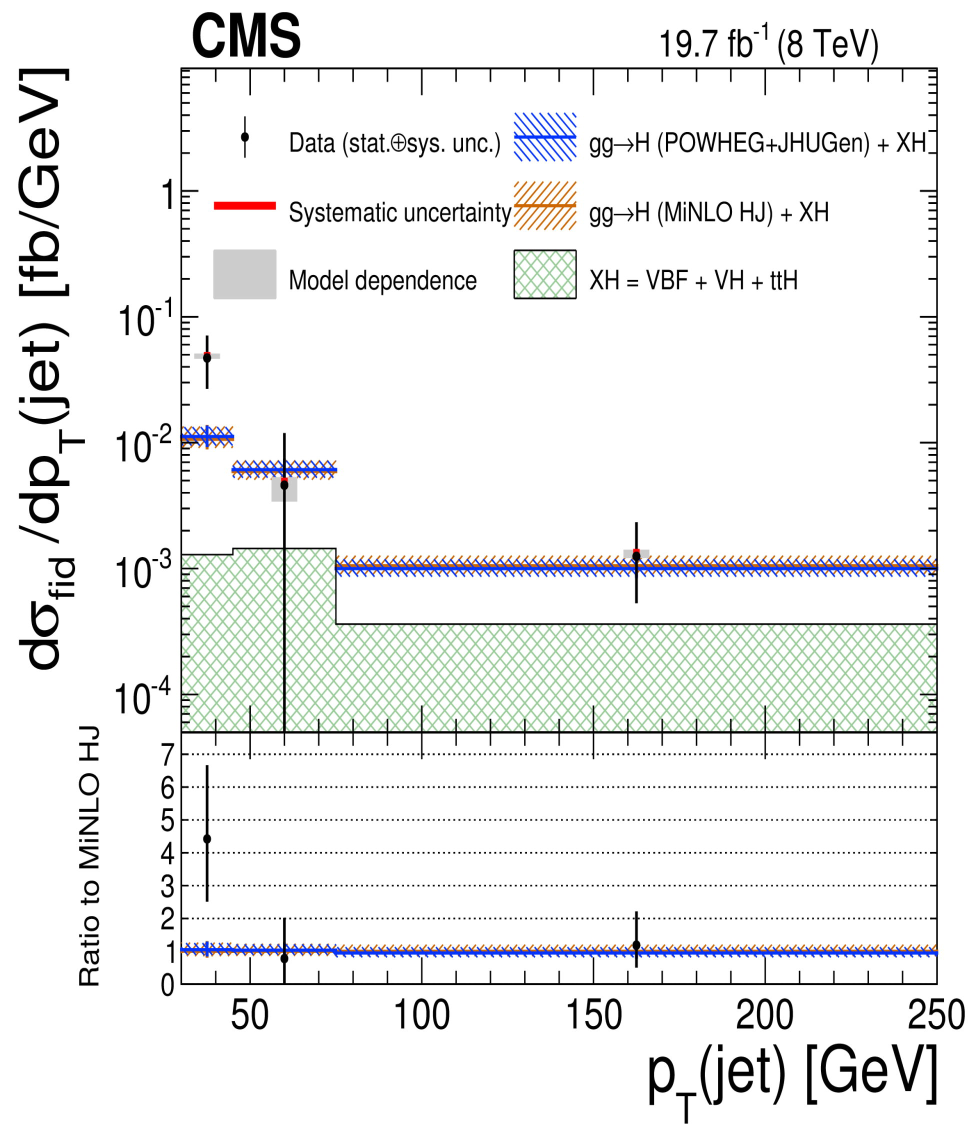
ATLAS
H → ZZ* → 4l
√s = 8 TeV ∫ L dt = 20.3 fb-1
data
syst. unc.
gg→H (MiNLO HJ+PS) + XH
gg→H (POWHEG+PS) + XH
gg→H (HRES) + XH
XH = VBF + VH + ttH
dσfid / d|y| [fb]
|yH|



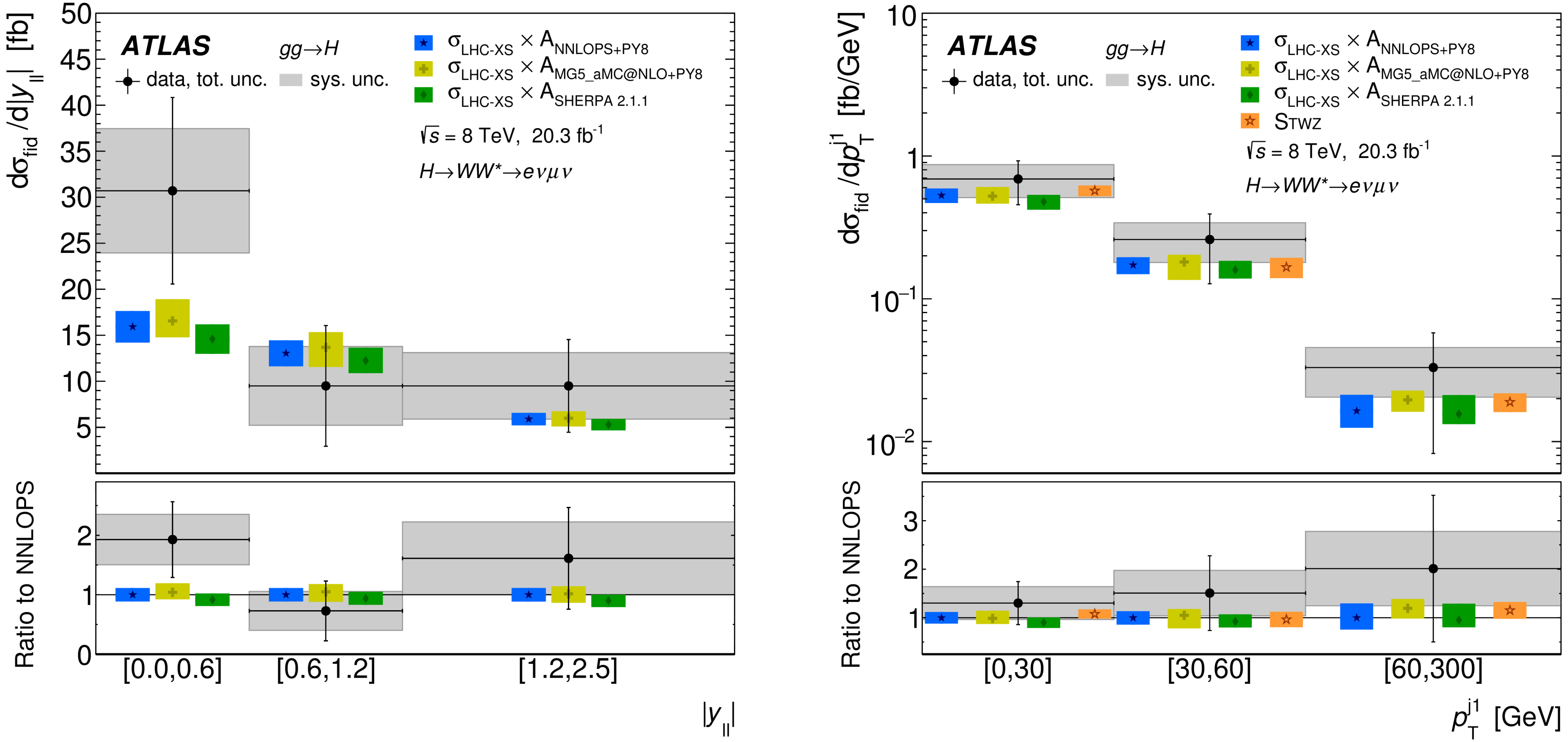
CMS
19.7 fb-1 (8 TeV)
Data (stat.⊕sys. unc.)
Systematic uncertainty
Model dependence
gg→H (POWHEG+JHUGen) + XH
gg→H (MiNLO HJ) + XH
gg→H (HRes) + XH
XH = VBF + VH + ttH
dσfid /d|y(H)| [fb]
Ratio to HRes
|y(H)|

H→ZZ→4ℓ differential cross sections - p_T^{j1}





H→WW→2ℓ2ν differential cross sections

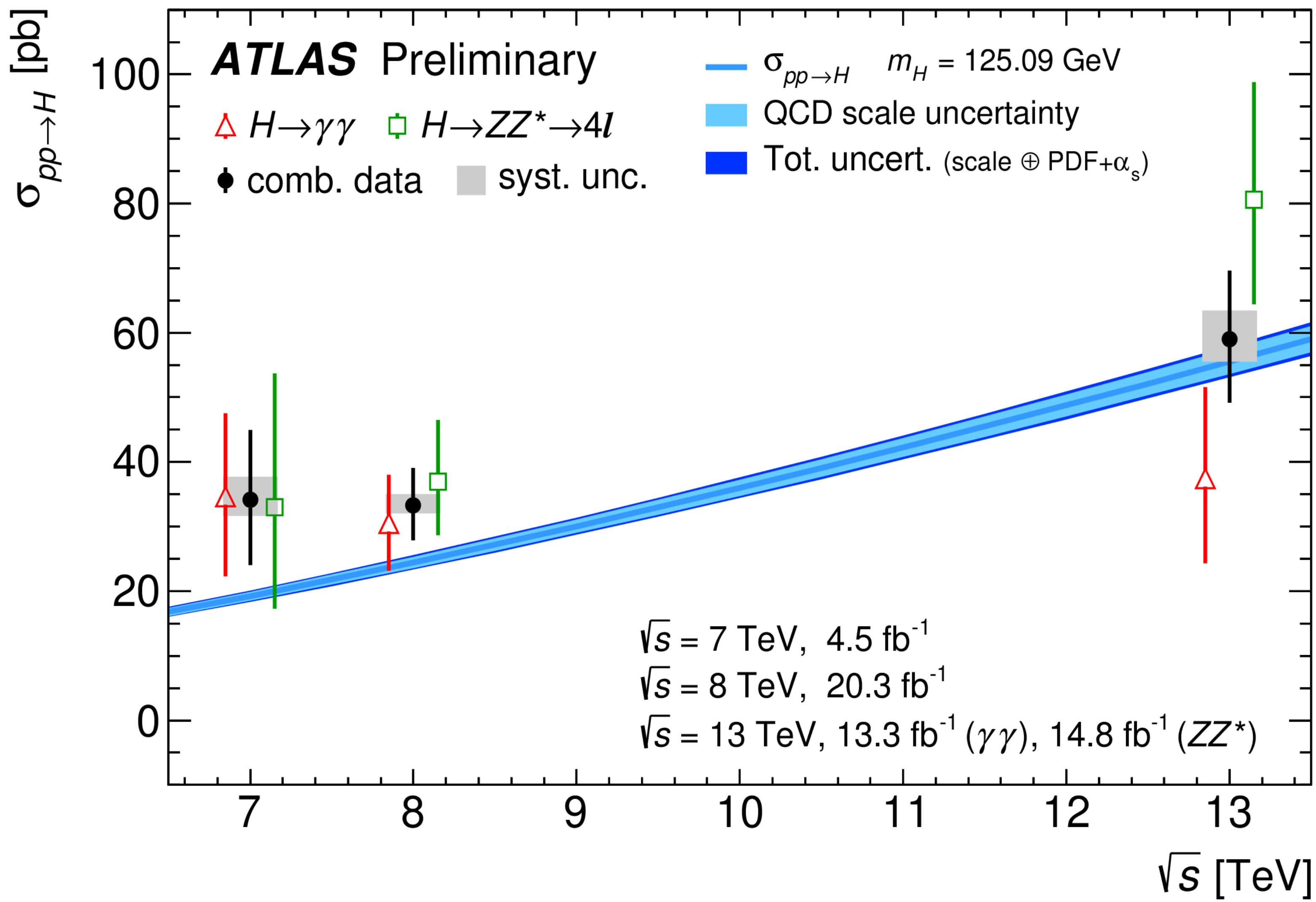


Model dependence estimation

- Uncertainties due to the theoretical modelling are included in all the measurements using similar prescriptions.
- Let's take the ATLAS $H \rightarrow \gamma\gamma$ analysis as an example.
- The uncertainty in the correction factors are estimated in 3 ways, each time recalculating the correction factors:
  - Replacing the default POWHEG+PYTHIA samples with alternative MC simulations: POWHEG+PYTHIA w/o MPI, POWHEG+HERWIG, MINLO HJ, MINLO HJJ, SHERPA;
  - Increasing/decreasing the VBF and VH relative contributions changing the cross sections by 0.5 and 2.0. The ttH cross section is also changed by a factor of 5 or removing it completely;
  - Reweighting the p_T^H and y^H simulations to the distributions observed in the data.
- All the uncertainties are summed in quadrature.
- The total uncertainty is ~1-3% for the baseline selection and up to ~6% for events containing jets.

$H\to\gamma\gamma$ and $H\to ZZ\to 4\ell$ ATLAS combination at 13 TeV

NEW



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- Constraints on BSM Higgs interactions using differential $H \to \gamma\gamma$ distributions
- The measured distributions are fitted simultaneously taking into account correlations
- Limits set on Wilson coefficients using EFT approach (CP-even/CP-odd interactions)