Differential cross section measurements at ATLAS

Higgs Couplings 2019

Daniela Börner
on behalf of the ATLAS Collaboration
1 Oct 2019

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

erc European Research Council Established by the European Commission

ATLAS EXPERIMENT

DESY.

Motivation.

Fiducial and differential cross section measurements

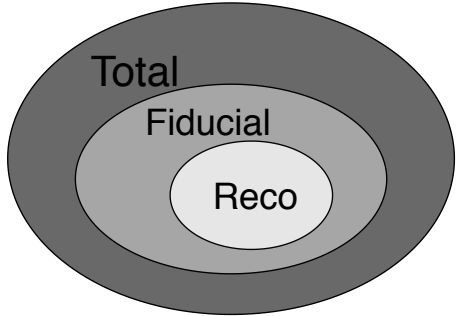
- Important test of the SM predictions (for observables sensitive to the order of the QCD calculations and also sensitive to new physics)
- Measurement inclusive in production mode
- Minimal model dependence $\rightarrow$ allows for interpretations
  - EFT $\Rightarrow$ Discussed in talk from Lianliang Ma [Thursday 10:00]
  - Coupling: low p_{T}^{H} sensitive to light Yukawa couplings

Discussed in this talk

- First full Run 2 measurements in $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^{*} \rightarrow 4\ell$ channel
  - Discovery channels: small branching ratio, but clean signal
- Combination of those results

Measurement Procedure.

$$\sigma = \frac{\nu_{\text{sig}}}{c_{\text{fid}} \cdot \mathcal{L}}$$

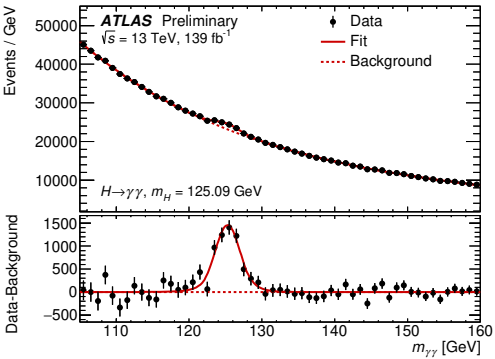


- Signal events ν_{sig} reconstructed in data
- Fiducial phase space defined to match the kinematic acceptance of the analysis and detector as closely as possible
- Correction factor c_{fid} to account for detector efficiency and resolution effects and out-of-fiducial migrations to ν_{sig}
  - Obtained from MC simulation
- Differential cross-section measurement
  - Binned in a variable of interest

$H \rightarrow \gamma\gamma$

[CONF-2019-029]

Fiducial cross section.



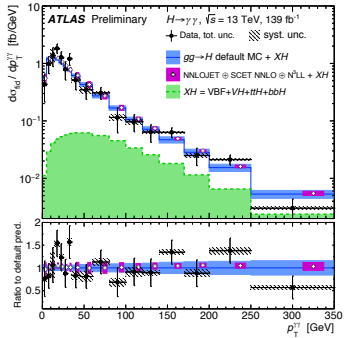
- Require two isolated, high quality photons
- Main backgrounds from SM $\gamma\gamma$ production and events with jet(s) faking photon(s)
- Background described by a smoothly falling function constrained from fit to data sidebands
- Signal modelled as double sided Crystal Ball, based on MC simulation
- Inclusive signal events: 6550 ± 530

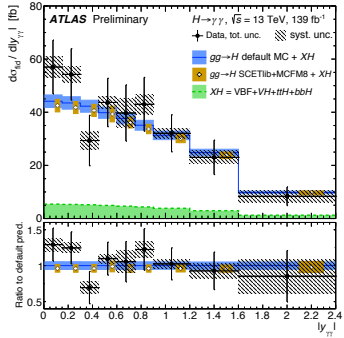
- Measured: 65.2 ± 4.5(stat.)± 5.6(syst.)± 0.3 (theo.) fb
  - Becomes systematically limited
  - Largest systematic uncertainty from background modelling
- SM: 63.6 ± 3.3 fb $\rightarrow$ consistent

Differential Cross Section.

$p(\chi^2) = 44\%$

Sensitive to top-quark mass effects, new physics contributions (e.g. Yukawa coupling modifications)





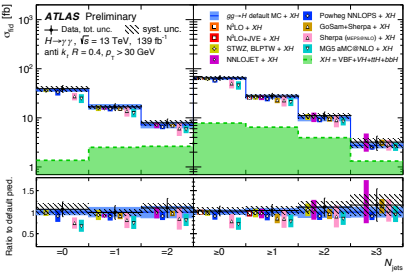
$p(\chi^2) = 68\%$

Sensitive to gluon distribution in the proton

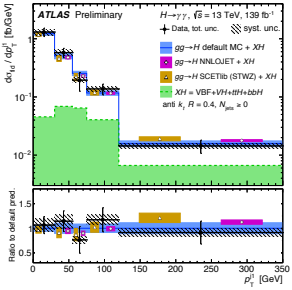
- Uncertainty is mainly statistical
- Good agreement with predictions

Differential Cross Section.

N_{jets}

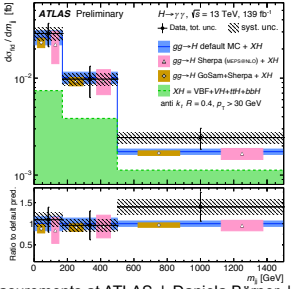


p_{T}^{j1}



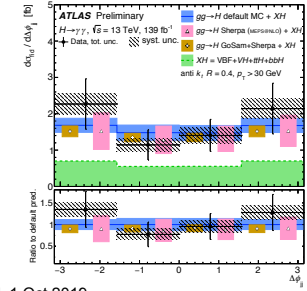
m_{jj}

Sensitive to VBF in high mass bin



$\Delta\phi_{jj}$

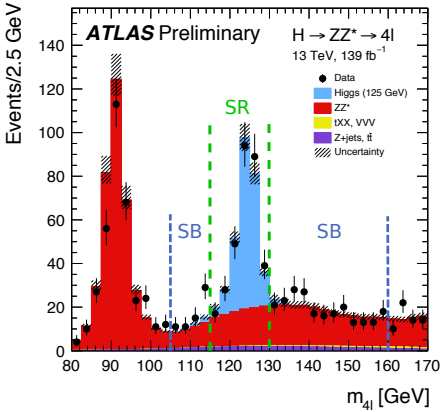
Sensitive to CP properties of the Higgs boson



$$H \rightarrow ZZ^* \rightarrow 4\ell$$

[CONF-2019-025]

Backgrounds.



- Main background: ZZ^* without Higgs
- Allowed to float, constrained in data sidebands (SB)

- VVV, ttV background taken from MC

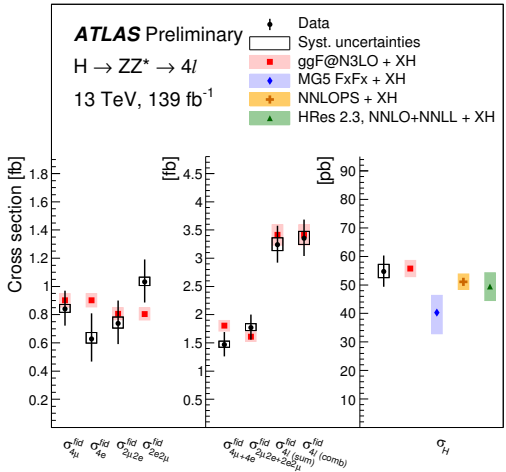
- Fake leptons mainly from Z+jets and $t\bar{t}$
- Data-driven method using control regions

- 4ℓ final state has very small background
- 316 events observed, 206 ± 13 signal and 97 ± 6 background expected

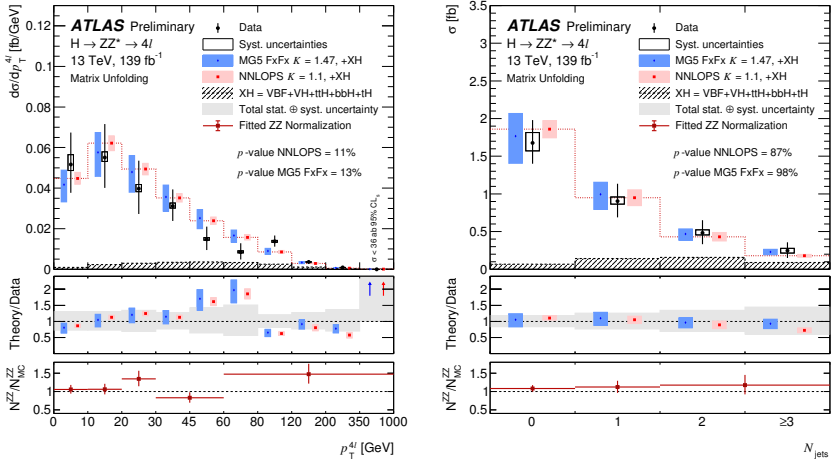
Fiducial cross section.

- Obtained from fit to $m_{4\ell}$ distribution for each final state and inclusively

- Measured:
  $3.35 \pm 0.30(\text{stat.}) \pm 0.12(\text{syst.})$ fb
  - Still statistically limited
- SM: 3.41 ± 0.18 fb $\rightarrow$ consistent p-value of 85%
- Total result (right panel) includes acceptance and BR values



Differential Cross Section.



> ZZ^* background normalisation compared to MC prediction

> Good agreement with SM predictions observed

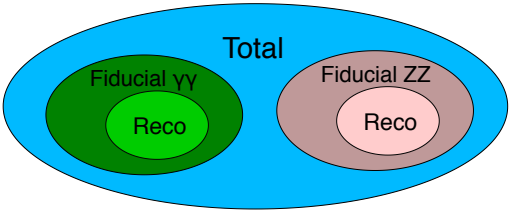
Combination of $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$

[CONF-2019-032]

Combination.

- Improve statistical power of differential results which are still statistically limited
- Profile-likelihood maximization
  - Likelihood includes correction-factor unfolding to particle level
  - Correlate experimental and theoretical uncertainties that affect both channels with common nuisance parameter

---

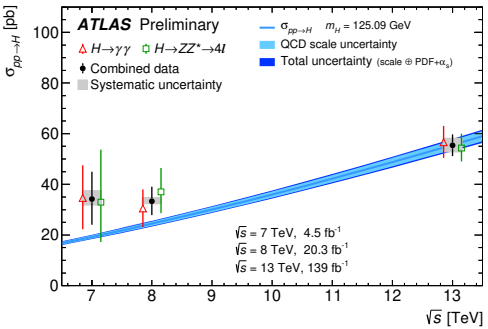


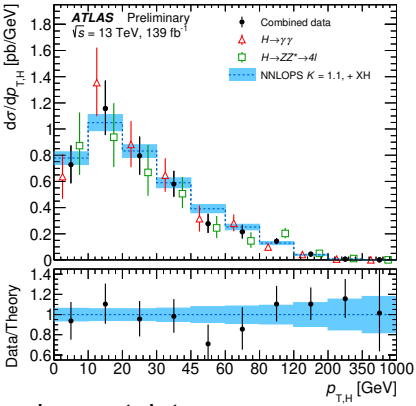
- Extrapolate both individual results to the total phase space by calculating the corresponding acceptance factors based on SM predictions
- Take branching fractions into account

→ More model dependence introduced

⇒ Improve the precision in the comparison with the SM predictions

Results.



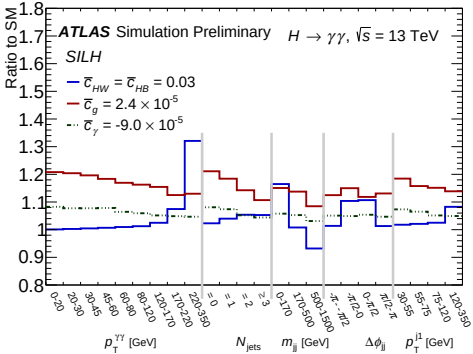


- All results are in agreement with the SM prediction
  - Total: p-value of 96%
  - p_{T}^{H}: p-value of 78%

- Reduced uncertainty:
  - Total: statistical and systematic uncertainty similar size
  - p_{T}^{H}: still statistically dominated
  - Largest systematic uncertainties: $\gamma\gamma$ background modelling, luminosity

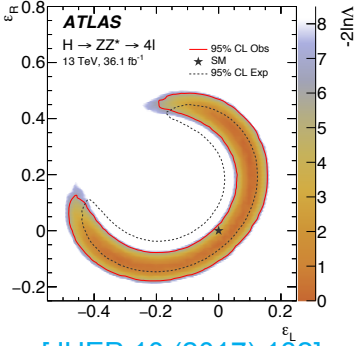
Interpretations Based on Differential Cross Section Measurements.

CP properties of the Higgs boson



→ EFT interpretation [Thursday 10:00]

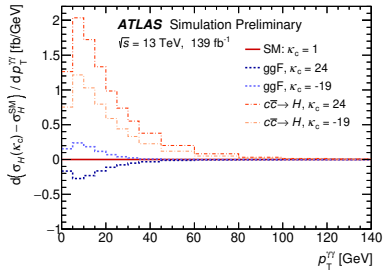
Contact terms between the Higgs boson and left- and right-handed leptons using m_{12} vs. m_{34}

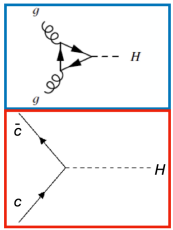


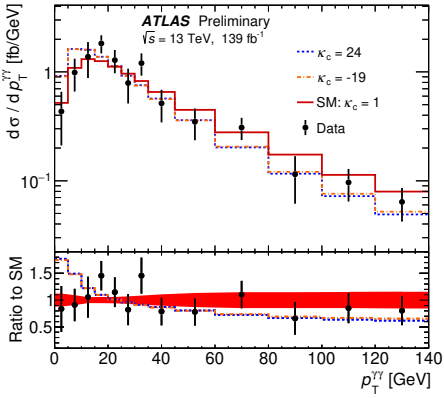
[JHEP 10 (2017) 132]

Charm Yukawa Coupling.

- $p_{\mathrm{T}}^{\gamma\gamma}$ sensitive to change in charm Yukawa coupling
  - → most sensitive region $p_{\mathrm{T}}^{\gamma\gamma} < 140\,\mathrm{GeV}$ considered
- Only shape information used, normalization profiled in fit







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

Differential cross section measurements at ATLAS

- First ATLAS results with full Run 2 dataset for $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ channel
- Inclusive cross-section and differential ones:
  - $p_{\mathrm{T}}^{4\ell}$, N_{jets} in 4ℓ channel
  - $p_{\mathrm{T}}^{\gamma\gamma}$, $|y_{\gamma\gamma}|$, N_{jets}, p_{T}^{j1}, m_{jj}, $\Delta\phi_{jj}$ in $\gamma\gamma$ channel
- Combination of both channels
  - Total cross section
  - p_{T}^{H} in extrapolated phase space
- Interpretations of differential results
  - Charm Yukawa coupling
  - EFT interpretations [Thursday 10:00]

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement no. 678215

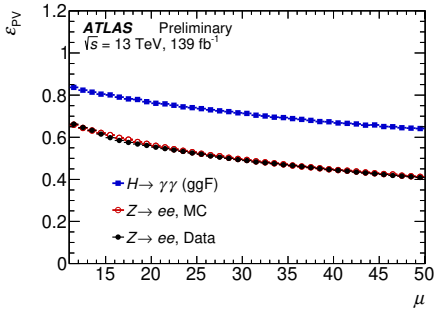
Contact

DESY. Deutsches Elektronen-Synchrotron
Daniela Börner
daniela.boerner@desy.de

www.desy.de

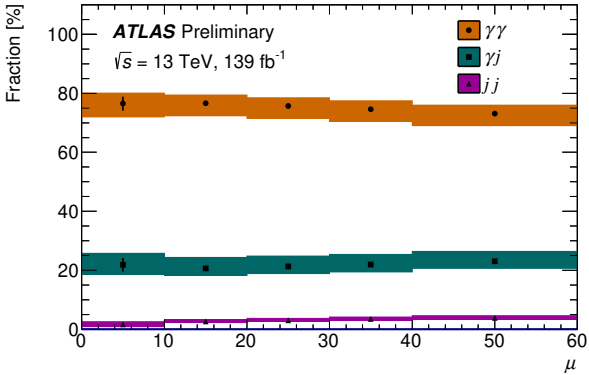
$H \to \gamma\gamma$ - Fiducial Selection.

Objects	Fiducial definition
Photons	$\lvert\eta\rvert < 2.37$ (excluding $1.37 < \lvert\eta\rvert < 1.52$), $\sum p_{\mathrm{T}}^{i}/p_{\mathrm{T}}^{\gamma} < 0.05$
Jets	anti-k_t, $R = 0.4$, $p_{\mathrm{T}} > 30$ GeV, $\lvert y\rvert < 4.4$
Diphoton	$N_\gamma \geq 2$, $105\,GeV < m_{\gamma\gamma} < 160\,GeV$, $p_{\mathrm{T}}^{\gamma_1}/m_{\gamma\gamma} > 0.35$, $p_{\mathrm{T}}^{\gamma_2}/m_{\gamma\gamma} > 0.25$



- Require isolated, high quality photons
- Diphoton vertex selected using dedicated NN

Background estimate.

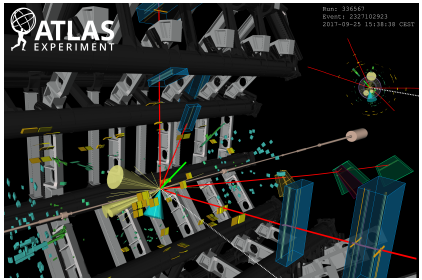


- Require two isolated, high-quality photons
- SM $\gamma\gamma$ production and events with jet(s) faking photon(s)

- Background described as smoothly falling distribution, from fit to data sidebands
  - Data-driven method to get the composition of the backgrounds
  - Background shapes from simulation ($\gamma\gamma$) or data control regions (γj, jj)
  - → Potential bias estimated in background only fit on background template

$H \to ZZ^* \to 4\ell$ - Fiducial Selection.

Leptons and jets	
Leptons	$p_{\mathrm{T}} > 5$ GeV, $\lvert\eta\rvert < 2.7$
Jets	$p_{\mathrm{T}} > 30$ GeV, $\lvert y\rvert < 4.4$
remove jets with	$\Delta R(\mathrm{jet}, \ell) < 0.1$
Lepton selection and pairing	
Lepton kinematics	$p_{\mathrm{T}} > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOS lepton pair with smallest $\lvert m_Z - m_{\ell\ell}\rvert$
Subleading pair (m_{34})	remaining SFOS 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	$\Delta R(\ell_i, \ell_j) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOS lepton pairs
Mass window	105 GeV $< m_{4\ell} <$ 160 GeV
If extra leptons with $p_{\mathrm{T}} > 12$ GeV	Quadruplet with the largest ME



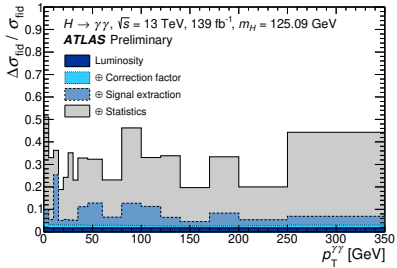
$H \to \gamma\gamma$ - p-Values.

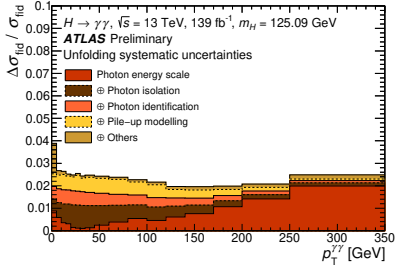
Distribution	$p(\chi^2)$ with Default MC Prediction
$p_{\mathrm{T}}^{\gamma\gamma}$	44%
$\lvert y_{\gamma\gamma}\rvert$	68%
$p_{\mathrm{T}}^{j_1}$	77%
N_{jets}	96%
$\Delta\phi_{jj}$	82%
m_{jj}	75%

- Calculation of $\Delta\phi(jj)$
- Azimuthal angle between more forward jet minus that of the more central one

$H \to \gamma\gamma$ - Systematic Uncertainties.

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



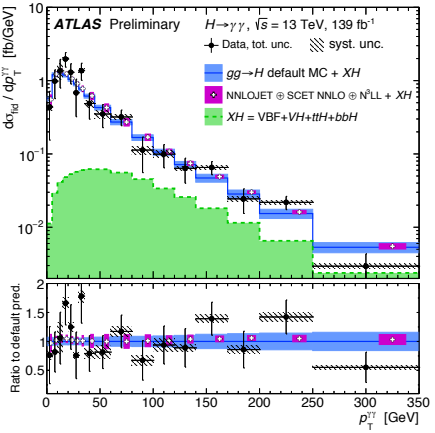


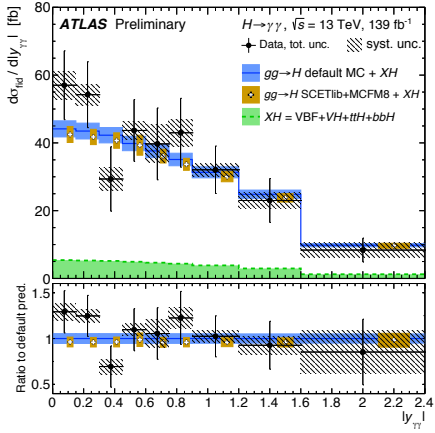
$H \to ZZ^* \to 4\ell$ - Systematic Uncertainties.

Measurement	Experimental uncertainties [%]				Theory uncertainties [%]					
	Lum.	e, μ, pile-up	Jets, flavour tagging	Reducible backgr.	ZZ^* backgr	tXX backgr.	PDF	QCD scale	Signal Parton Shower	Signal Composition
Fiducial cross section										
σ_{comb}	1.7	2.5	–	< 0.5	1	< 0.5	< 0.5	2	1	< 0.5
Per decay final state fiducial cross sections										
4μ	1.7	2.5	–	0.5	1	< 0.5	< 0.5	2	1	< 0.5
$4e$	1.7	7	–	0.5	1.5	< 0.5	< 0.5	2	0.5	< 0.5
$2\mu 2e$	1.7	5.5	–	0.5	1	< 0.5	< 0.5	2	1.5	< 0.5
$2e2\mu$	1.7	2.0	–	0.5	1	< 0.5	< 0.5	2	1	< 0.5
Stage-0 production bin cross sections										
ggF	1.7	1.5	1	0.5	1.5	< 0.5	0.5	1	2	–
VBF	1.7	1	4.5	0.5	2	0.5	1.5	8	6	–
VH	1.8	1.5	3.5	1	5	0.5	2	12	8	–
ttH	1.7	1	4.5	1	1	0.5	0.5	8	4	–

$H \to \gamma\gamma$ - Results.

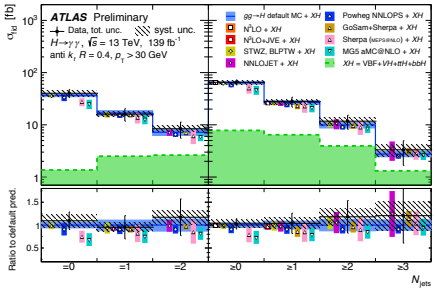
Using matrix inversion method instead of bin-by-bin unfolding

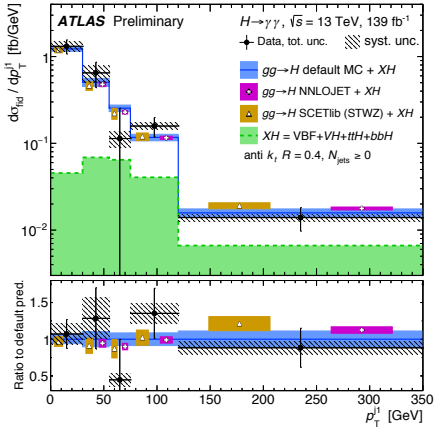




$H \to \gamma\gamma$ - Results.

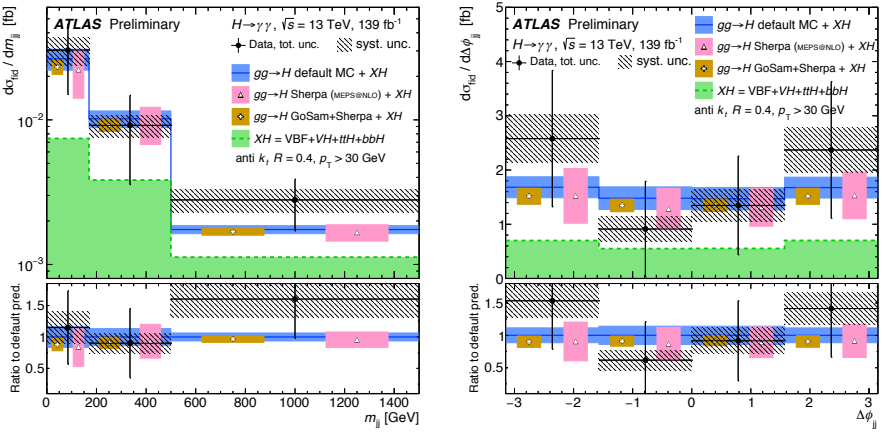
Using matrix inversion method instead of bin-by-bin unfolding



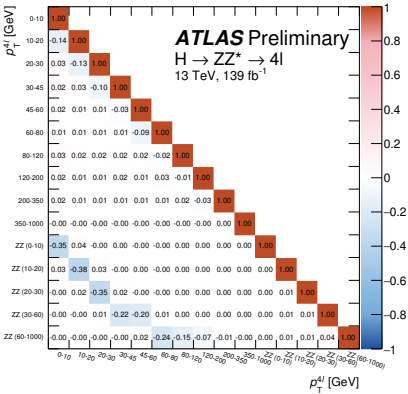


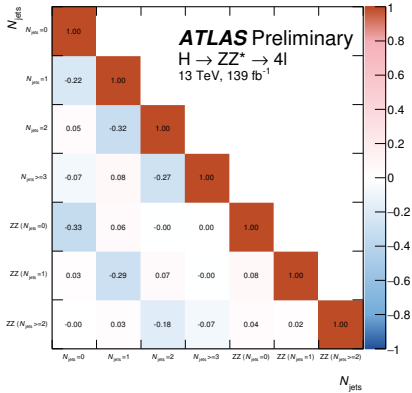
$H \to \gamma\gamma$ - Results.

Using matrix inversion method instead of bin-by-bin unfolding



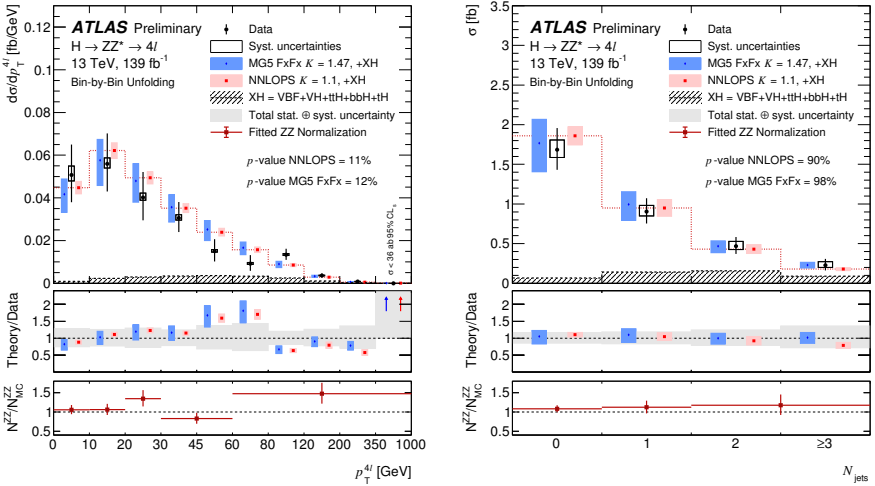
$H \to ZZ^* \to 4\ell$ - Correlation Matrices.





$H \to ZZ^* \to 4\ell$ - Results.

Using bin-by-bin unfolding instead of matrix inversion



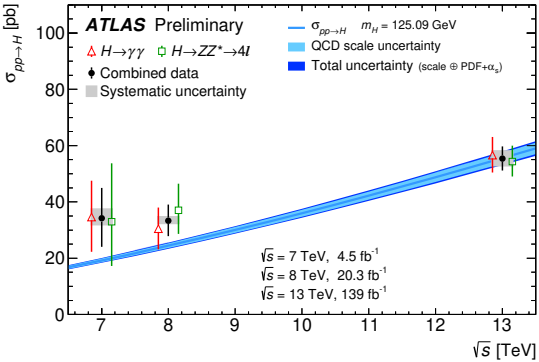
Acceptance factors.

ZZ^* 49% overall, 45% at low p_{T}^{H}, 65% at high p_{T}^{H}

$\gamma\gamma$ 50% overall, 50% at low p_{T}^{H}, 45% at intermediate values and about 75% at high p_{T}^{H}

Results.

Total cross-section



$H \to ZZ^* \to 4\ell$	$54.4^{+5.6}_{-5.4}$ pb
$H \to \gamma\gamma$	$56.7^{+6.4}_{-6.2}$ pb
Combination	$55.4^{+4.3}_{-4.2}$ pb
	$\pm 3.1(\text{stat.})^{+3.0}_{-2.8}(\text{sys.})$
SM	55.6 ± 2.5 pb