Higgs measurements in the di-boson final state

Rencontres de Moriond
Electroweak Interactions and Unified Theories
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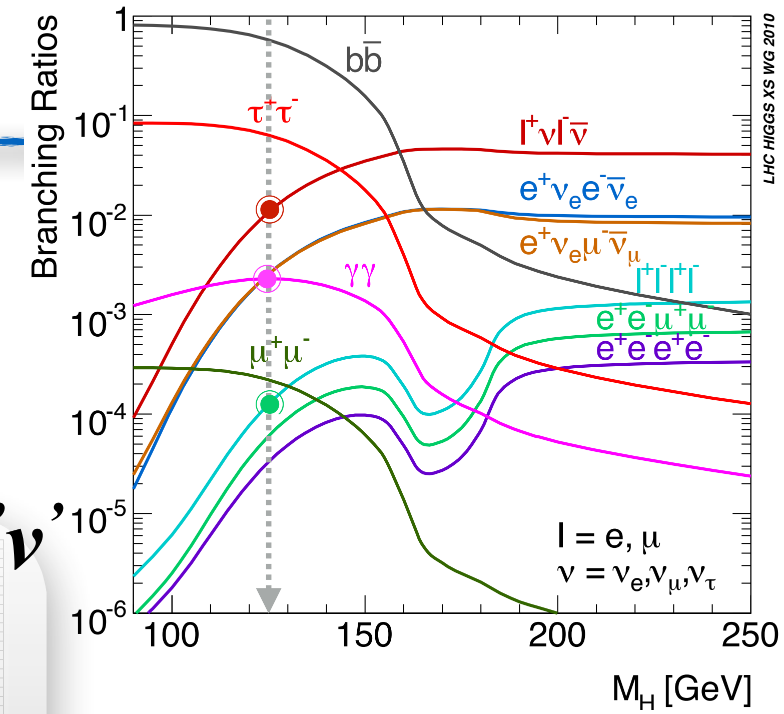
La Thuile

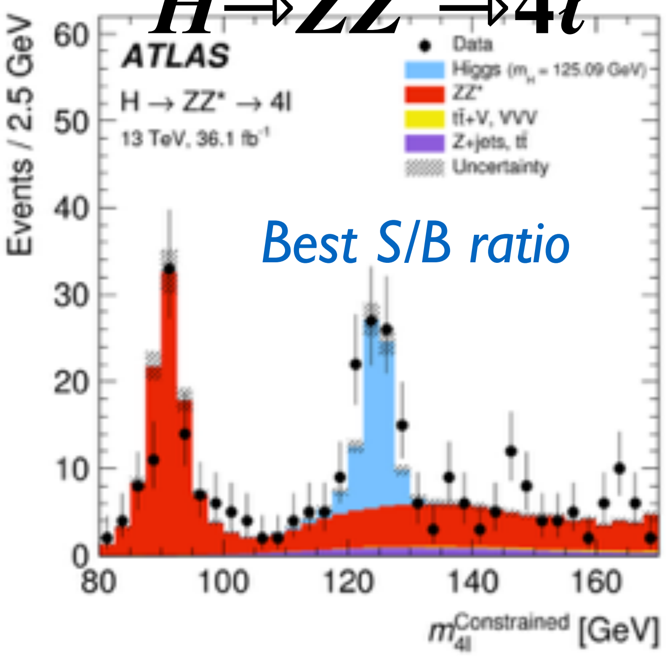
Ioannis Nomidis
on behalf of the ATLAS collaboration

Measurements in diboson final states



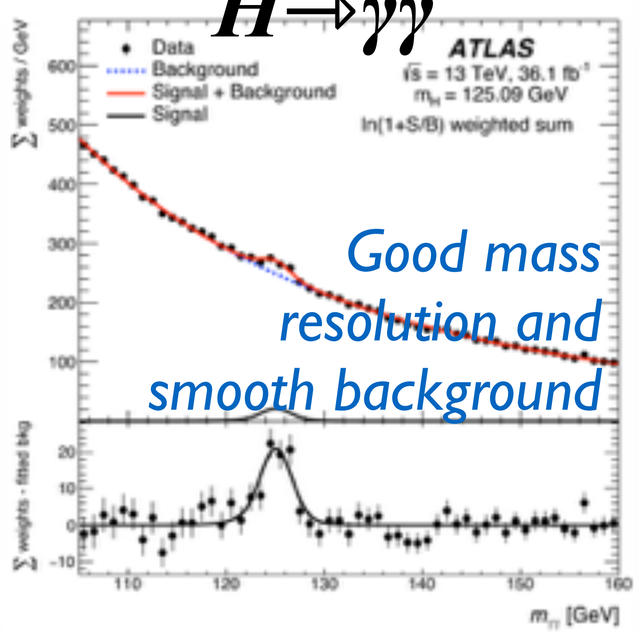
- Not favoured in terms of branching ratio but have other advantages
  - *Clean signal peak, fully reconstructed, extracted from well understood backgrounds, also in multi-jet environments*

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



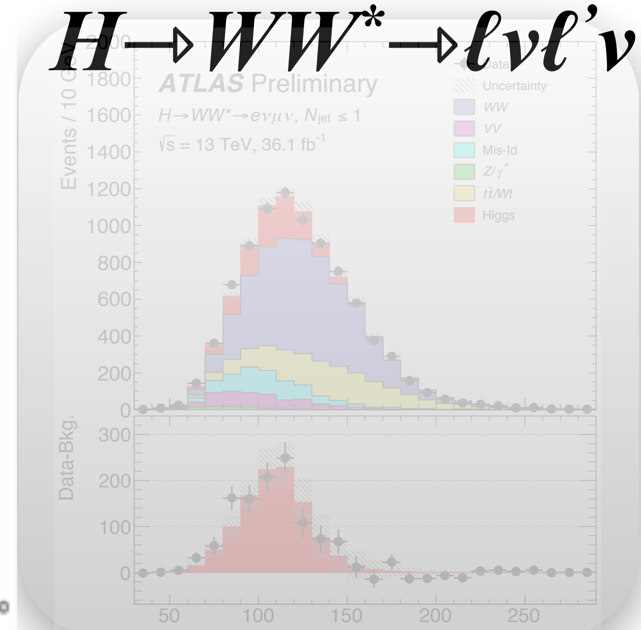
Best S/B ratio

$H \to \gamma\gamma$

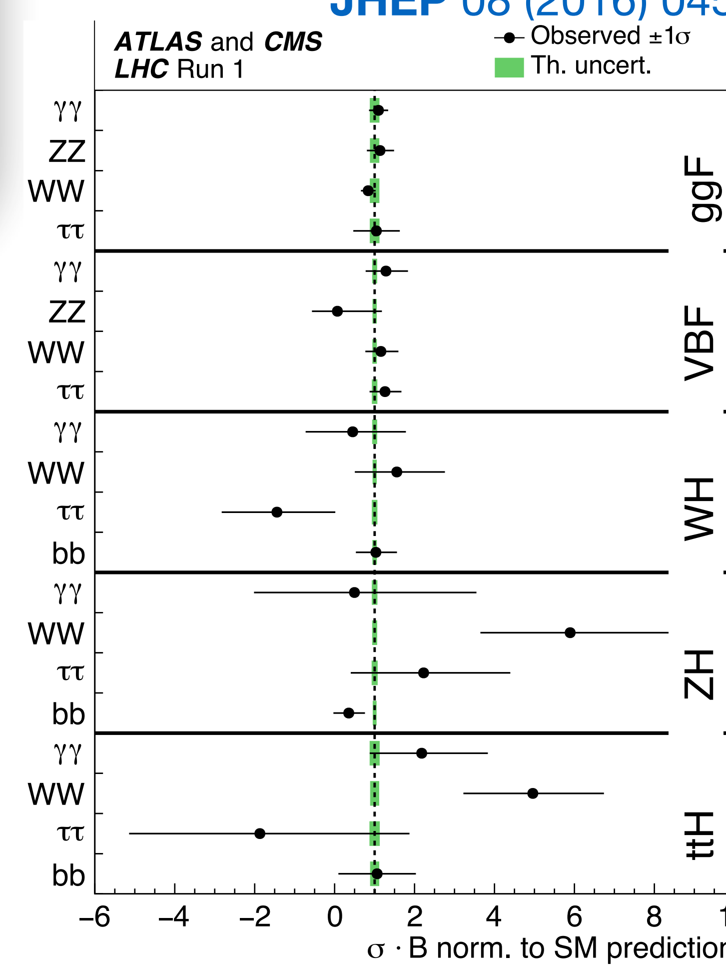


Good mass resolution and smooth background

$H \to WW^* \to \ell\nu\ell'\nu'$



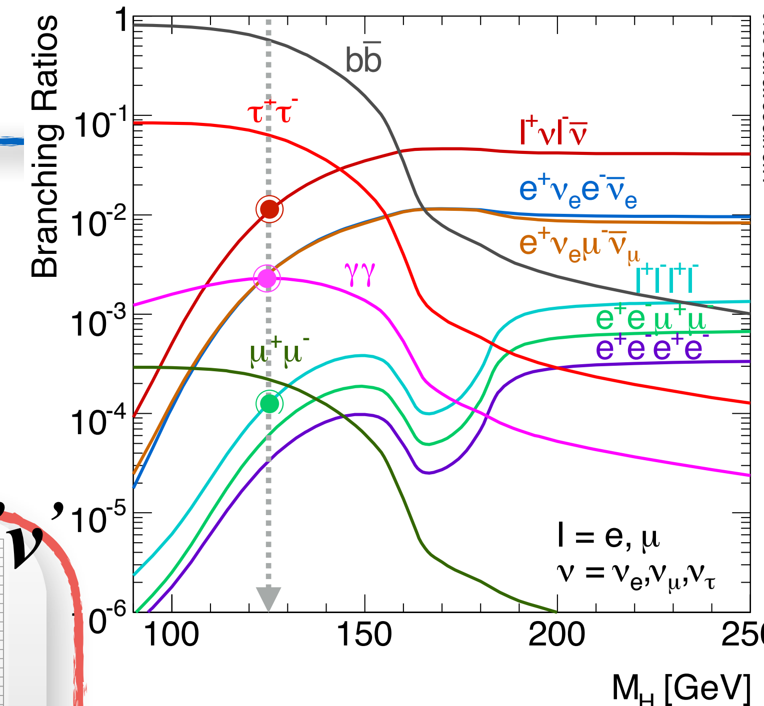
JHEP 08 (2016) 045



  - *Can probe all major production modes (ggF, VBF, VH, ttH)*
  - *Can measure the mass (4ℓ, γγ), an important parameter*
- Measurements in diboson final states contributed significantly to the understanding of the Higgs properties in Run-1
  - *Run-2: ATLAS analyzed 36.1 fb^{-1} so far (2015+2016) and measured fiducial & differential cross-sections, couplings, mass*

See talks by D. Sperka, S. Menary

Measurements in diboson final states



- Not favoured in terms of branching ratio but have other advantages
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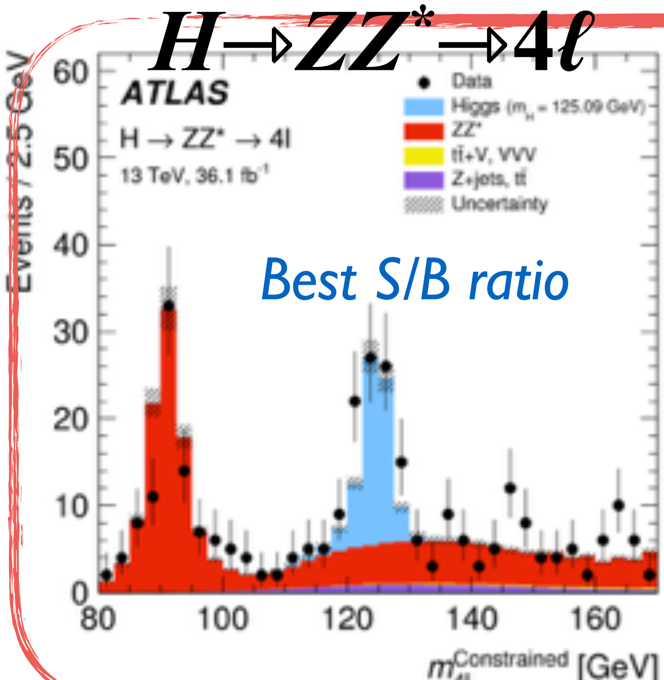
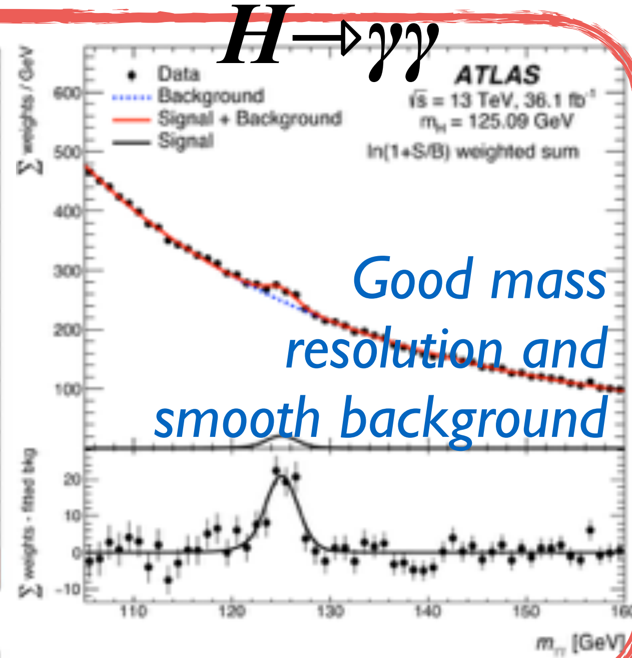
$H \to ZZ^* \to 4\ell$ $H \to \gamma\gamma$ $H \to WW^* \to \ell\nu\ell'\nu'$



Best S/B ratio

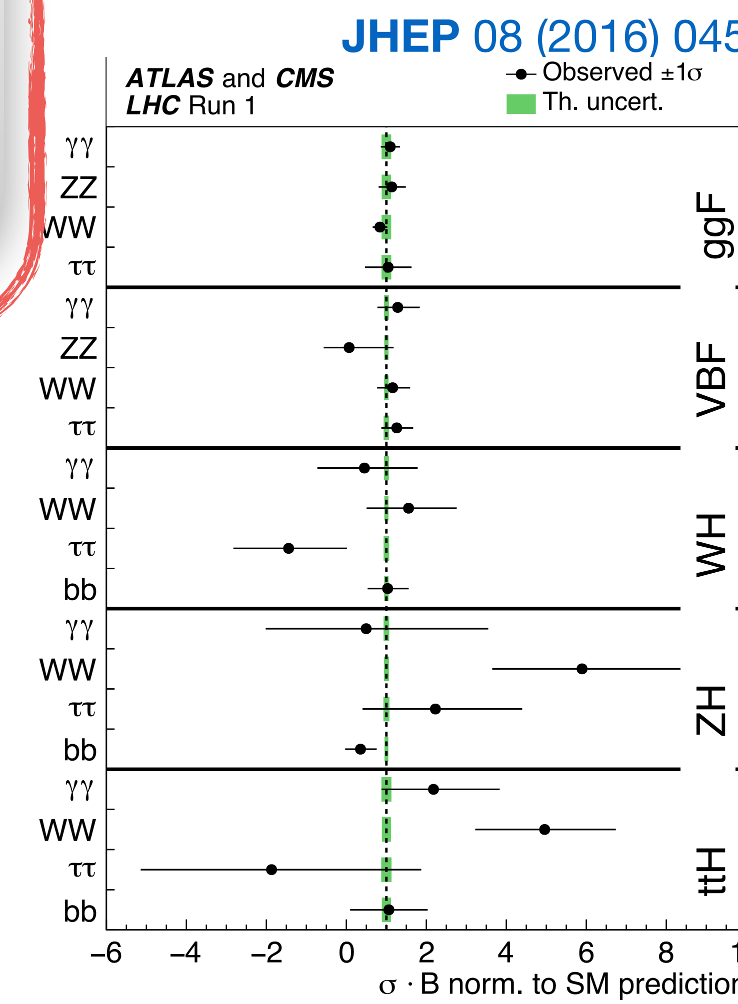


Good mass resolution and smooth background

New Run-2 measurements

Combination of cross-sections

- *Can probe all major production modes (ggF, VBF, VH, ttH)*
- *Can measure the mass (4ℓ, γγ), an important parameter*



- Measurements in diboson final states contributed significantly to the understanding of the Higgs properties in Run-1
  - *Run-2: ATLAS analyzed 36.1 fb^{-1} so far (2015+2016) and measured fiducial & differential cross-sections, couplings, mass*

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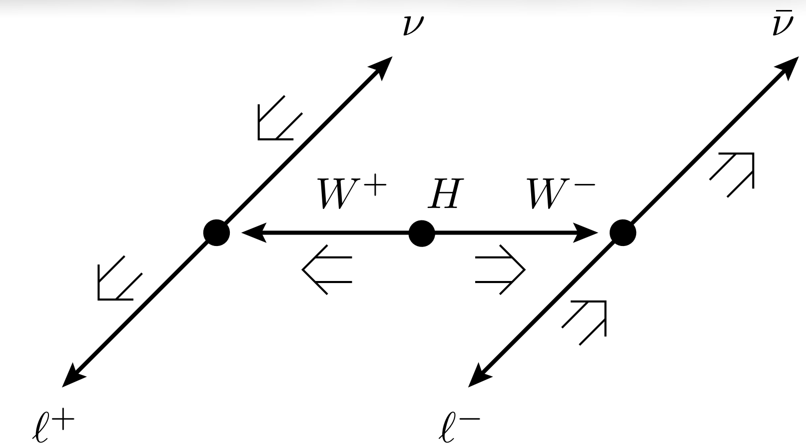
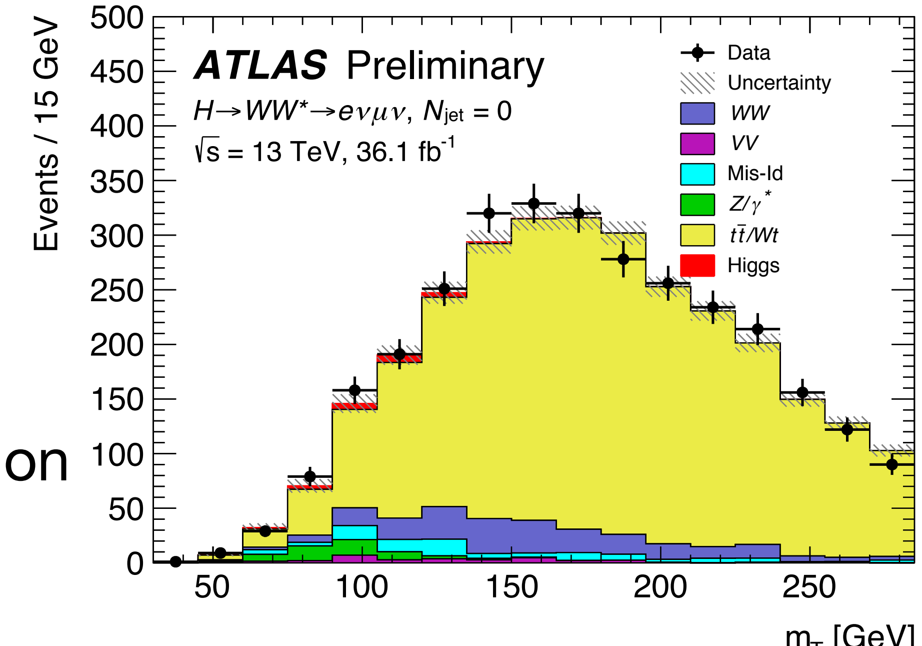
H→WW* production measurements

ATLAS-CONF-2018-004



Signal consists of two prompt isolated leptons produced with a small opening angle and missing transverse energy

- Goal is to probe the Higgs production modes
  - Study **ggF** and **VBF** production
  - Events with 0,1 and ≥2 jets studied separately (0,1j for ggF, ≥2j for VBF, p_T^{jet}>30 GeV)
- Suppressing the background and constraining its normalization are key elements
- Differences with the Run-1 analysis
  - 0j: *b-jet veto* (20<p_T^{jet}<30 GeV) for suppression of top background (large increase in Run-2 due to larger √s) and additional control region to constrain its normalization
  - $e^+e^-/\mu^+\mu^-$ not included; small significance because of larger DY background

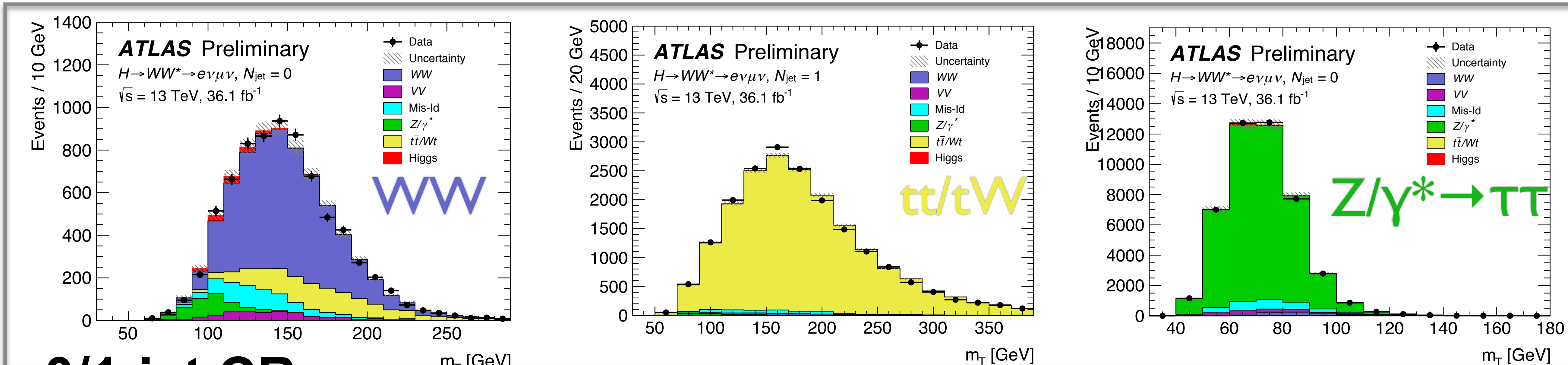


0-jet top CR

H→WW*: backgrounds

- *Dominant processes*: WW, tt/tW, Z/γ*→ττ

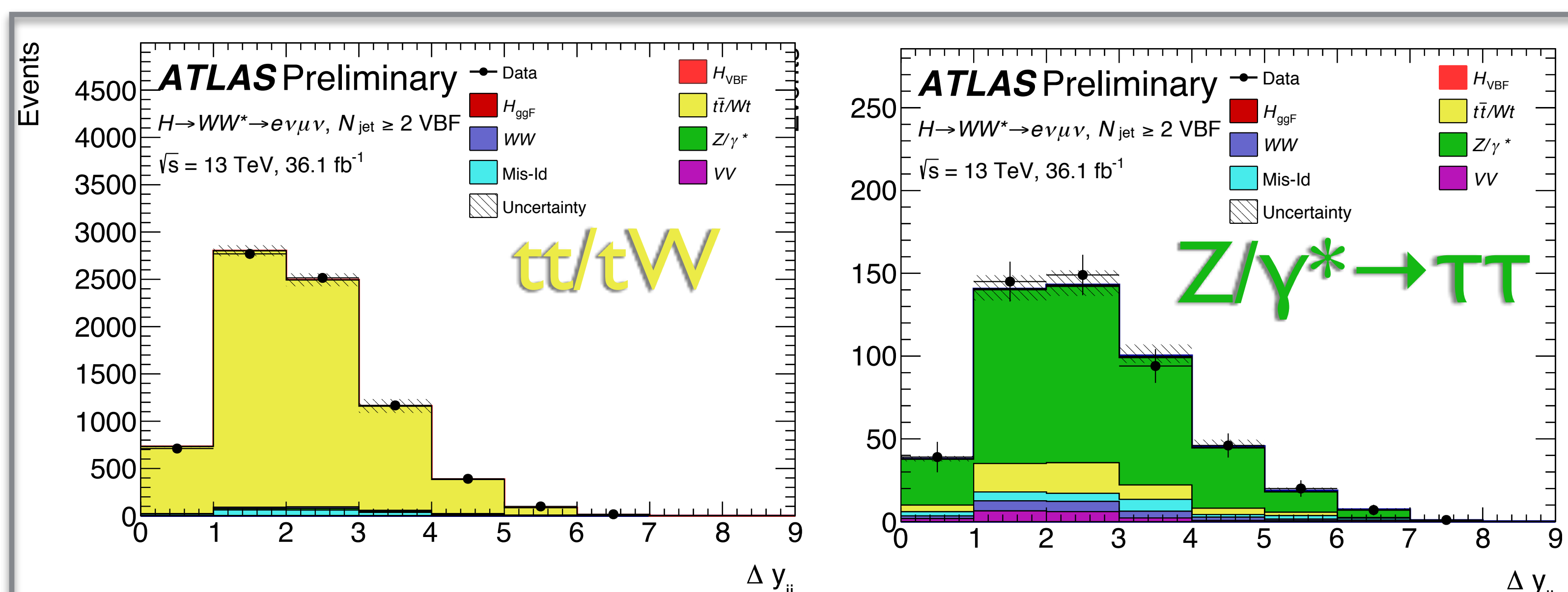
➪ *Normalization constrained from data in dedicated control regions (CRs)*



0/1-jet CRs

- Mis-identified leptons / *W*+jets

➪ *Evaluated with data using a fake-factor (FF) method; FFs determined from Z+jets data and corrected for expected differences with W+jets (i.e. jet flavour)*



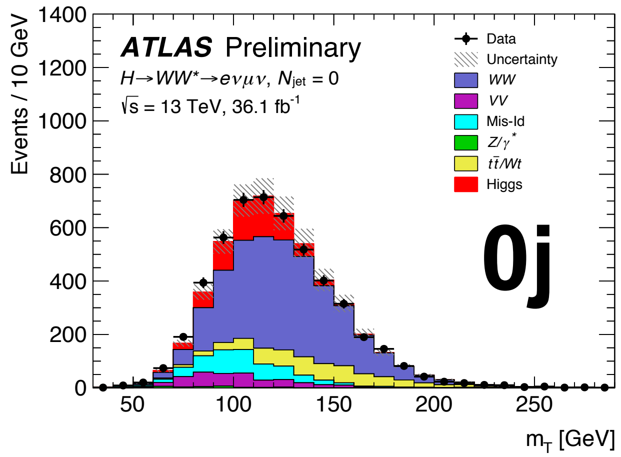
VBF-like CRs

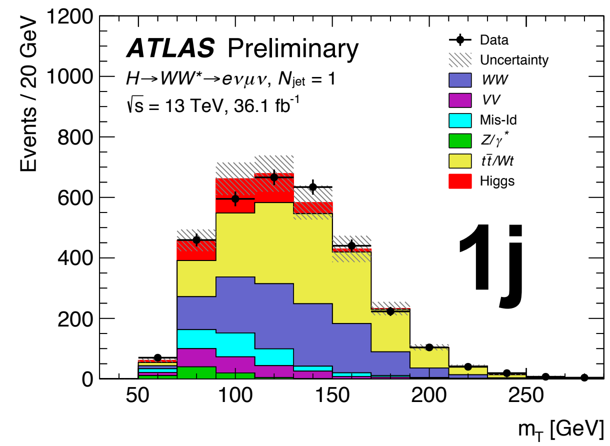
- *Other dibosons (WZ, ZZ, Wγ)*

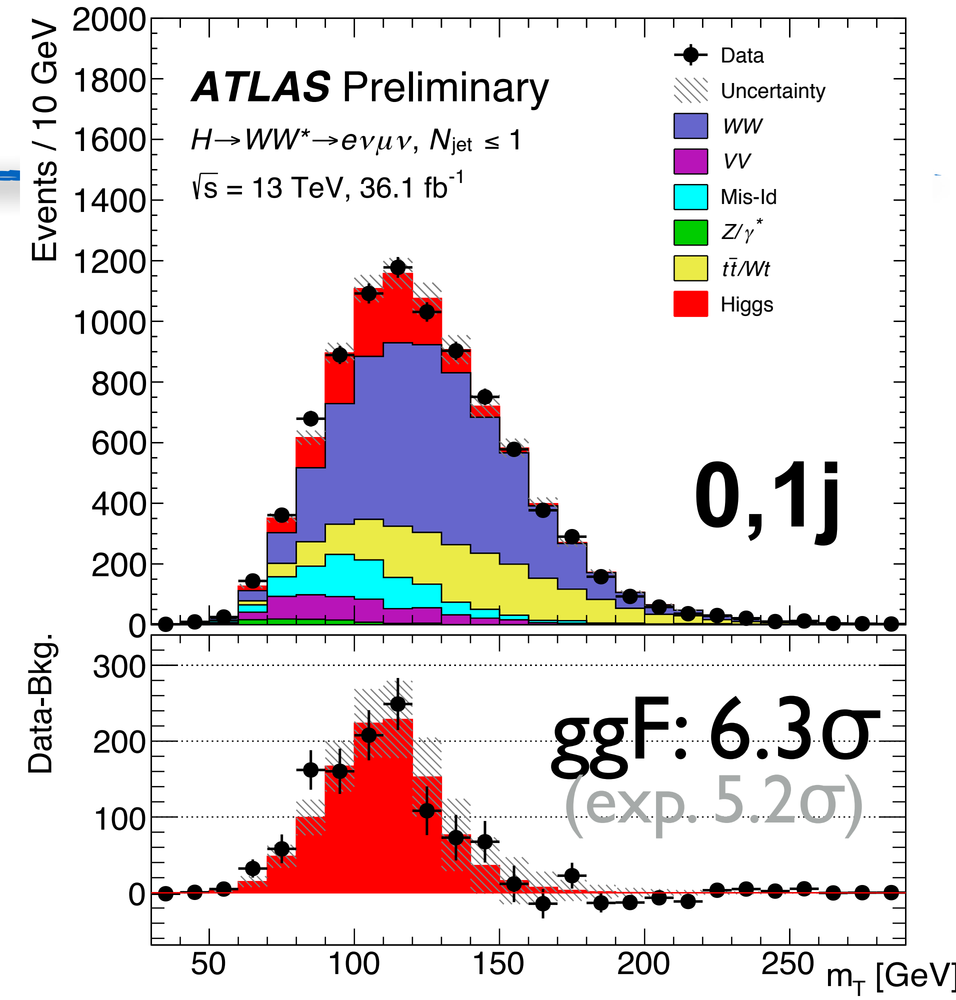
➪ *Evaluated with MC simulation normalized to best prediction*

H→WW*: signal regions

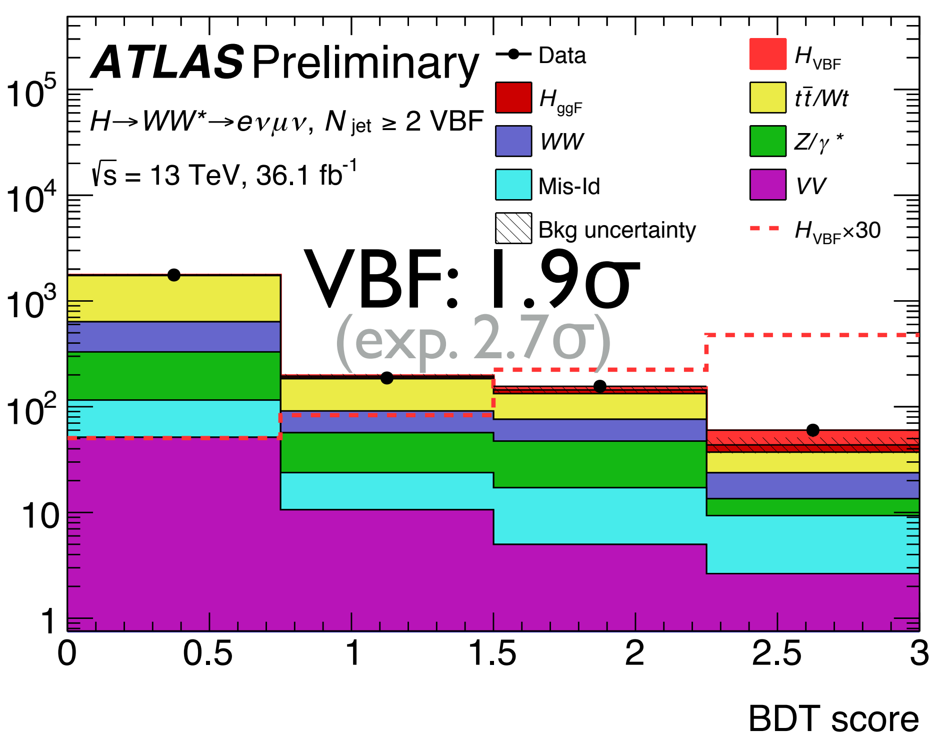
- **ggF** measurement combines 16 categories
  (2 in $m_{\ell\ell}$) × (2 in $p_T^{\ell 2}$) × (eμ/μe) × (0/1 jet)
  - Discriminant: $m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - |\mathbf{p}_T^{ll} + \mathbf{E}_T^{\rm miss}|^2}$







- **VBF** production measurement with BDT discriminant
  - BDT built from: jet/ℓ kinematics, m_{jj}, $m_{\ell\ell}$, Δy_{jj} , $\Delta\phi_{\ell\ell}$



⇨ *Experimental uncertainties under control (<10%)*

⇨ *Sizeable theoretical uncertainties mainly from modelling (parton showers, missing higher orders)*

Source	$\frac{\Delta\sigma_{\rm ggF}}{\sigma_{\rm ggF}}$ [%]	$\frac{\Delta\sigma_{\rm VBF}}{\sigma_{\rm VBF}}$ [%]
Data statistics	±8	±46
CR statistics	±8	±9
MC statistics	±5	±23
Theoretical uncertainties	±8	±21
ggF signal	±5	±15
VBF signal	<1	±15
WW	±5	±12
Top-quark	±4	±4
Experimental uncertainties	±9	±8
b-tagging	±5	±6
Pile-up	±5	±2
Jet	±3	±4
Electron	±3	<1
Misidentified leptons	±5	±9
Luminosity	±2	±3
TOTAL	±17	±59

H→WW*: results **New!**

Best H→WW* measurements

	Run-1 ATLAS+CMS	Run-2 15 fb^{-1} CMS
	$0.84^{+0.17}_{-0.17}$	
	$1.2^{+0.4}_{-0.4}$	$1.4^{+0.8}_{-0.8}$

- Signal strength:

$$\mu_{\rm ggF} = 1.21^{+0.12}_{-0.11}({\rm stat.})^{+0.18}_{-0.17}({\rm sys.}) = 1.21^{+0.22}_{-0.21}$$
$$\mu_{\rm VBF} = 0.62^{+0.30}_{-0.28}({\rm stat.}) \pm 0.22({\rm sys.}) = 0.62^{+0.37}_{-0.36}$$

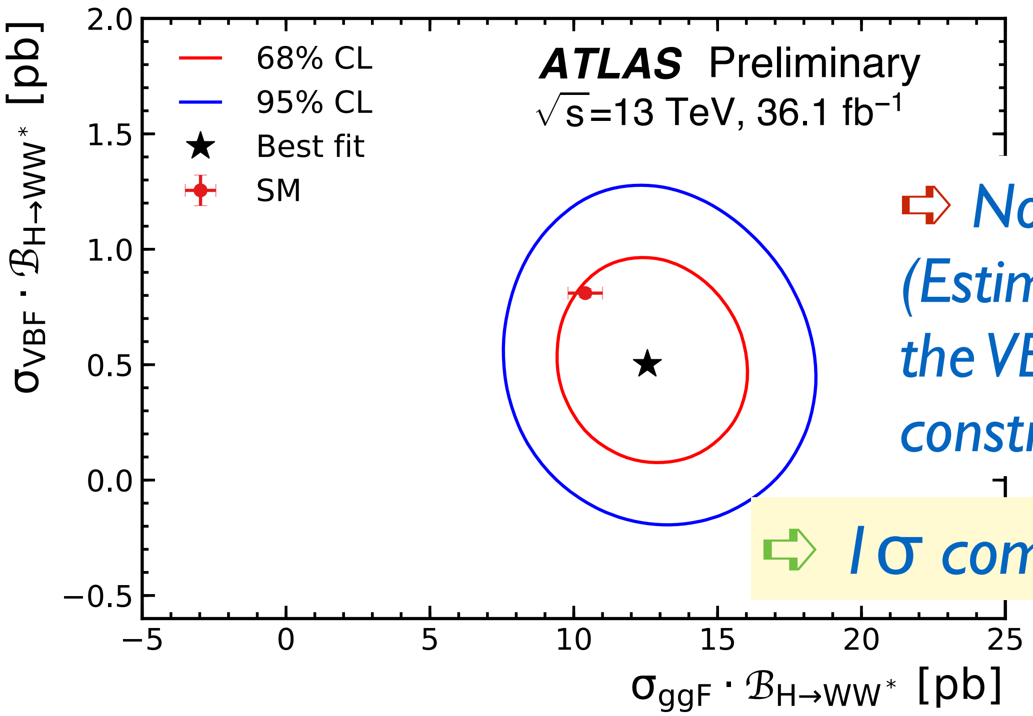
⇨ *Uncertainties in good agreement with expectations*

$$\mu^{exp}_{ggF} = 1.00 \pm 0.10(stat.) \pm 0.18(sys) = 1.00^{+0.21}_{-0.21}$$
$$\mu^{exp}_{VBF} = 1.00^{+0.33}_{-0.31}(stat.) \pm 0.25(sys) = 1.00^{+0.42}_{-0.40}$$

⇨ *Precision as good or better than the Run-1 combination*

- Cross-section times branching ratio:

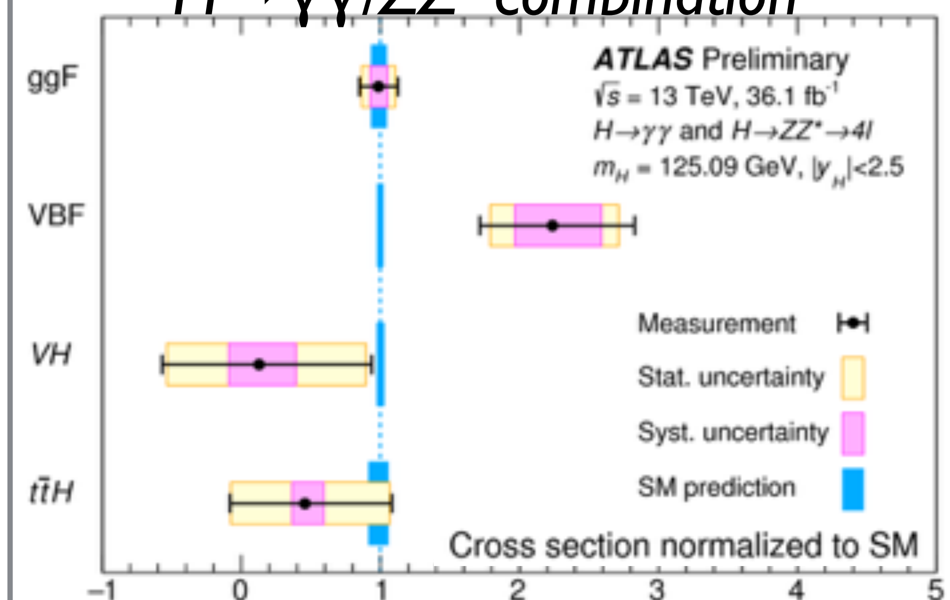
$$\sigma_{\rm ggF} \cdot \mathcal{B}_{H\to WW^*} = 12.6^{+1.3}_{-1.2}({\rm stat.})^{+1.9}_{-1.8}({\rm sys.})\ {\rm pb} = 12.6^{+2.3}_{-2.1}\ {\rm pb}$$
$$\sigma_{\rm VBF} \cdot \mathcal{B}_{H\to WW^*} = 0.50^{+0.24}_{-0.23}({\rm stat.}) \pm 0.18({\rm sys.})\ {\rm pb} = 0.50^{+0.30}_{-0.29}\ {\rm pb}$$

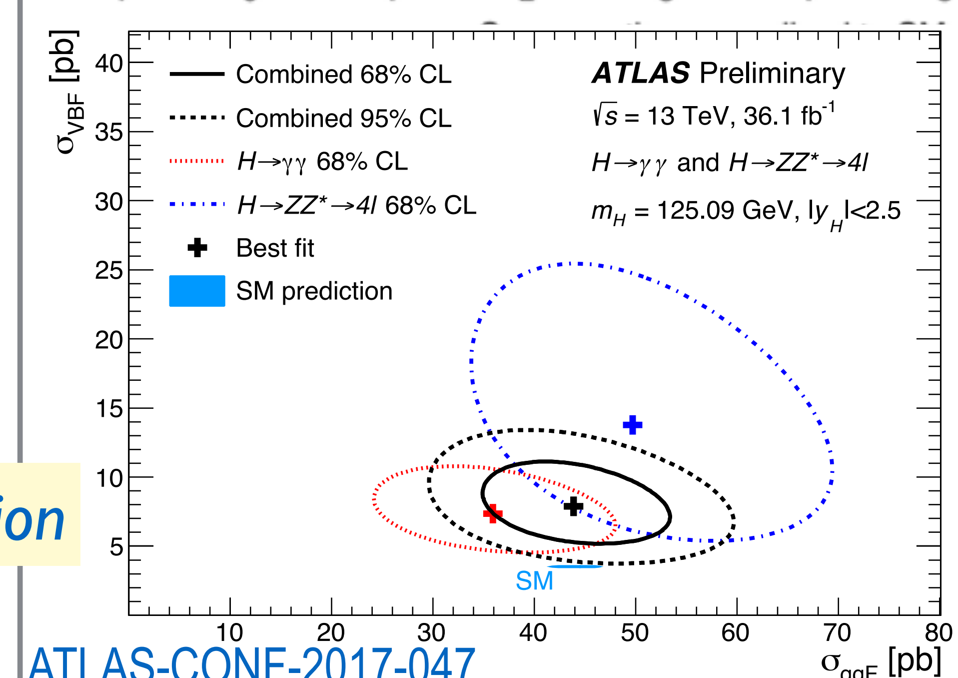


⇨ *No strong correlation (Estimate of ggF leakage into the VBF signal region is well-constrained by the 0,1j data)*

⇨ *1σ compatibility with SM prediction*

H→γγ/ZZ* combination





ATLAS-CONF-2017-047

H→γγ/ZZ* x-sections inclusive in production

γγ: arXiv:1802.04146
4ℓ: JHEP 10 (2017) 132

Fiducial measurements

- Inclusive: $(\sigma\cdot BR)_{(pp\to H\to f)} = N_{signal} / (\mathcal{L}\cdot\varepsilon)$

➪ *Compare with best available predictions in the phase space directly accessible by our detectors*

- Differential: $d(\sigma\cdot BR)/dx$,
  x: p_T^H, y^H, n_{jets}, $p_T^{j1,2}$, p_T^{Hjj}, $\cos\theta^*$, m_{jj}, $\Delta\phi_{jj}$, H_T, …

➪ *Observables sensitive to new physics and interesting for tests of the QCD calculations*

- Doubly-differential: $d^2(\sigma\cdot BR)/(dp_T^H\cdot dn_{jets})$

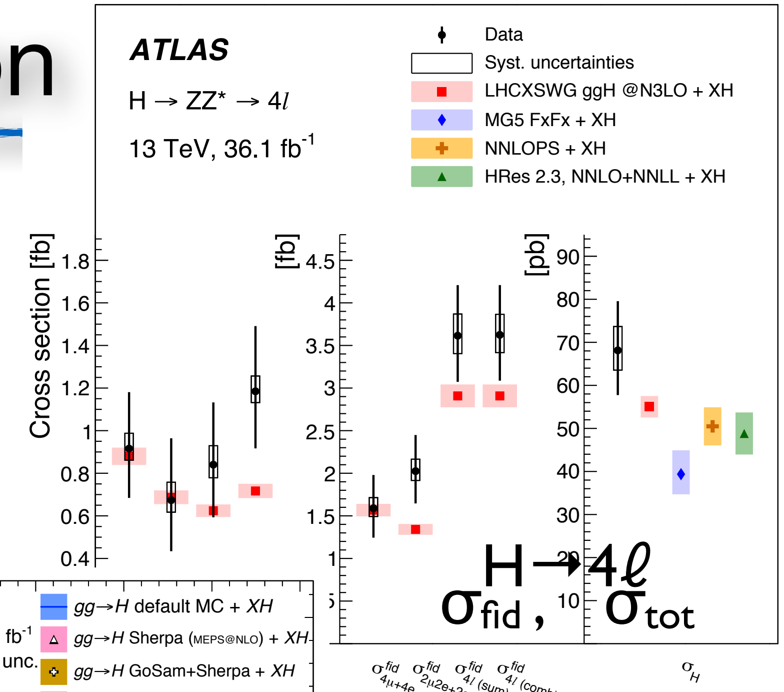
➪ *To disentangle the large correlations between N_{jets} and p_T^H*

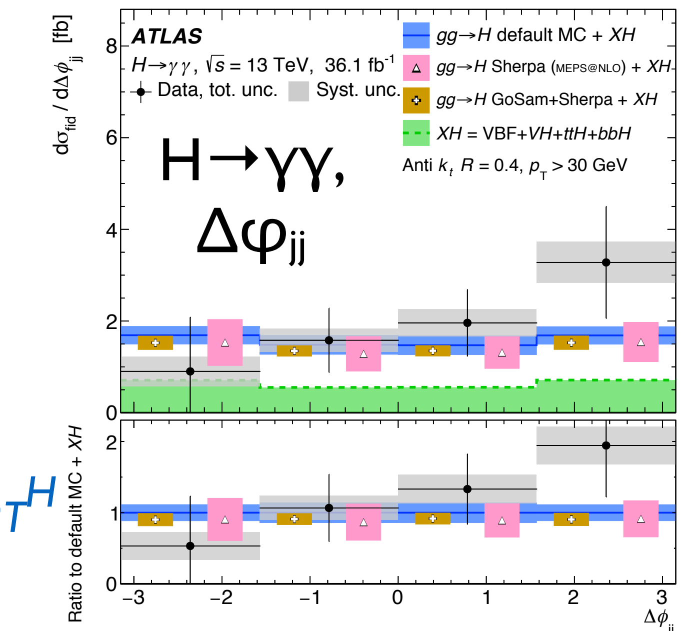
Largely model-independent measurements; potential modelling bias on the corrections/unfolding procedure is evaluated and is insignificant in most of the bins considered

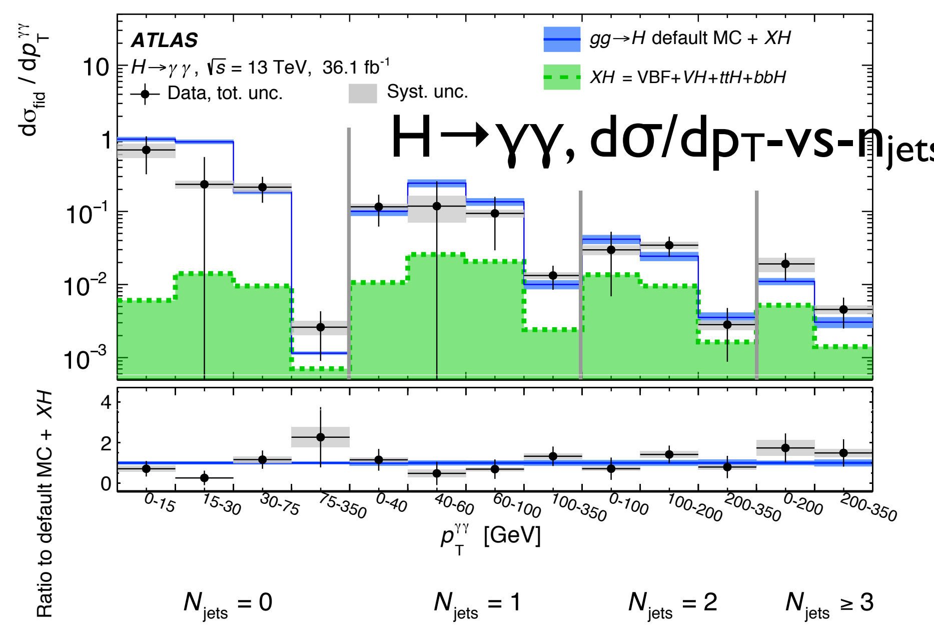
➪ *Good agreement overall with the SM predictions*

➪ *Theory calculations still more precise than current experimental measurements*

➪ *Comparisons will become more interesting with more data*







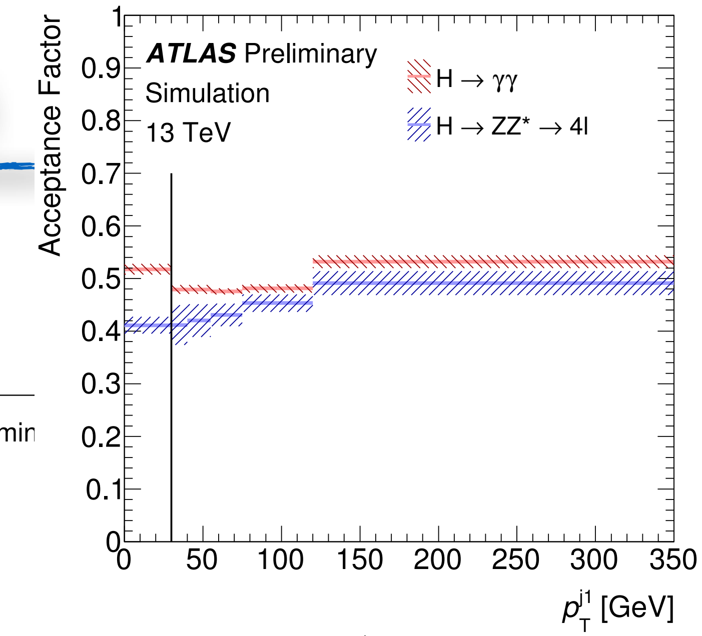
H→γγ/ZZ* x-sections inclusive in production

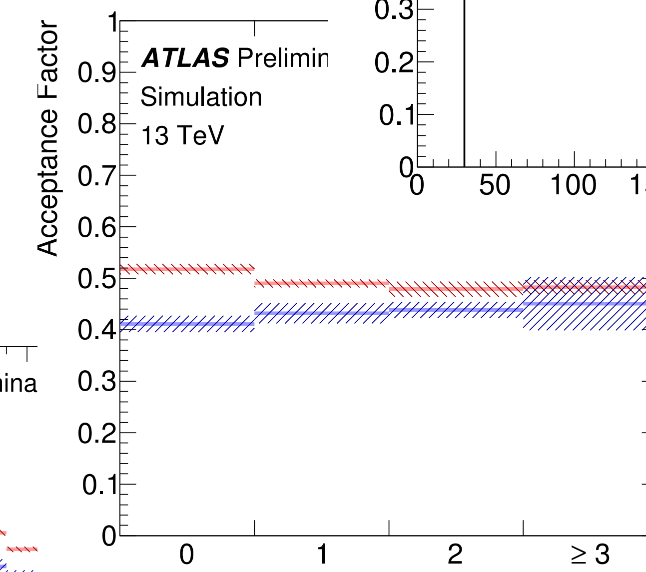
Combination of the diphoton and four-lepton measurements:

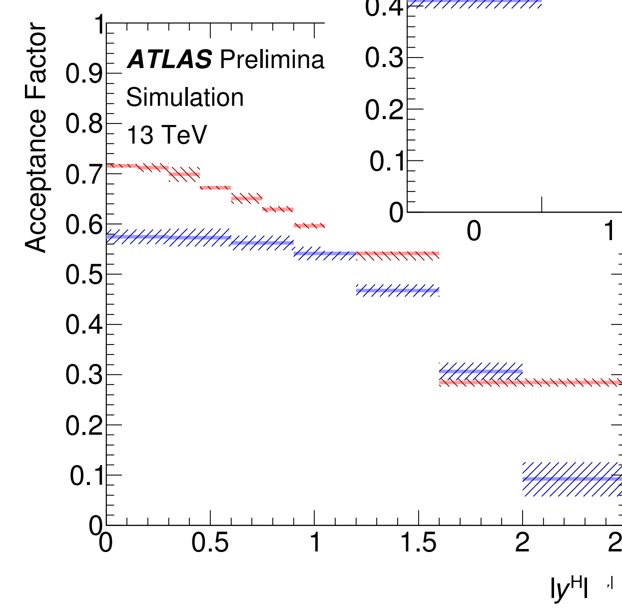
ATLAS-CONF-2018-002

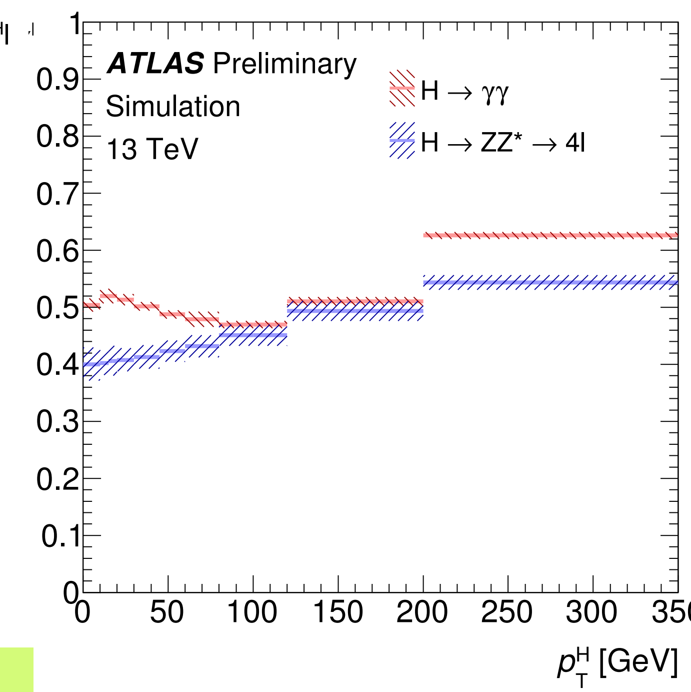
$$\sigma_{(pp\to H)} = N_{signal} / (\mathcal{L}\cdot\varepsilon\cdot \mathbf{A}\cdot \mathbf{BR}_{H\to f})$$

- Assume the SM branching ratios @ m_H=125.09 GeV
  - BR(H→γγ)~0.227% , BR(H→4ℓ)~0.0125%
- Acceptance correction (fiducial → full phase space) calculated with MC simulated events generated with (N)NLO precision
  - A(H→γγ)~50%, A(H→4ℓ)~42%
  - fairly stable with p_T and n_{jets}









$\sigma_{(pp\to H)}$: 57.0 $^{+6.0}_{-5.9}$ (stat.) $^{+4.0}_{-3.3}$ (syst.) pb

theory: 55.0 ± 2.5 pb [LHC HXS WG, arXiv:1610.07922]

➪ *13 TeV measurement in perfect agreement with theory*

- Results in bins of p_T^H, y^H, n_{jets}, p_T^{j1} (anti-kt jets of p_T>30 GeV)

H→γγ/ZZ* x-sections inclusive in production

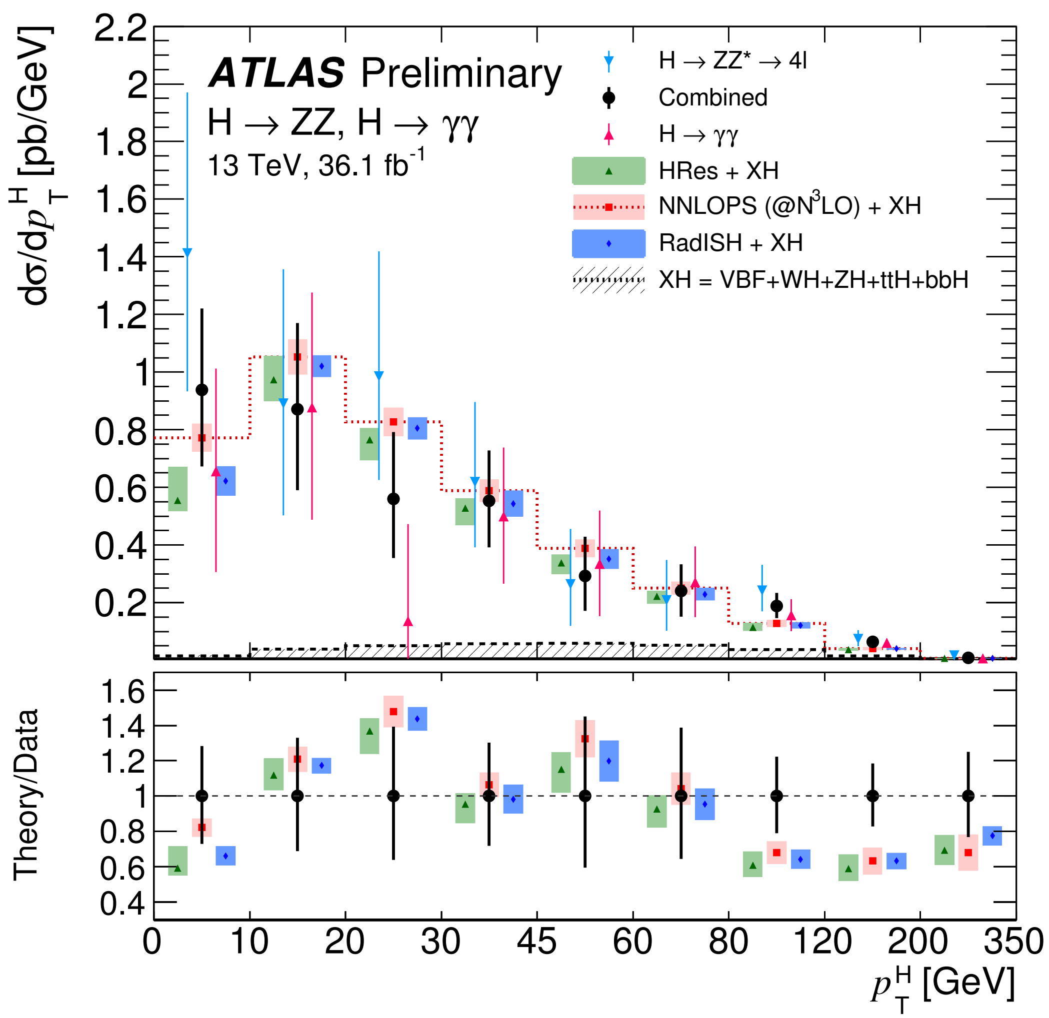
Combination of the diphoton and four-lepton measurements:

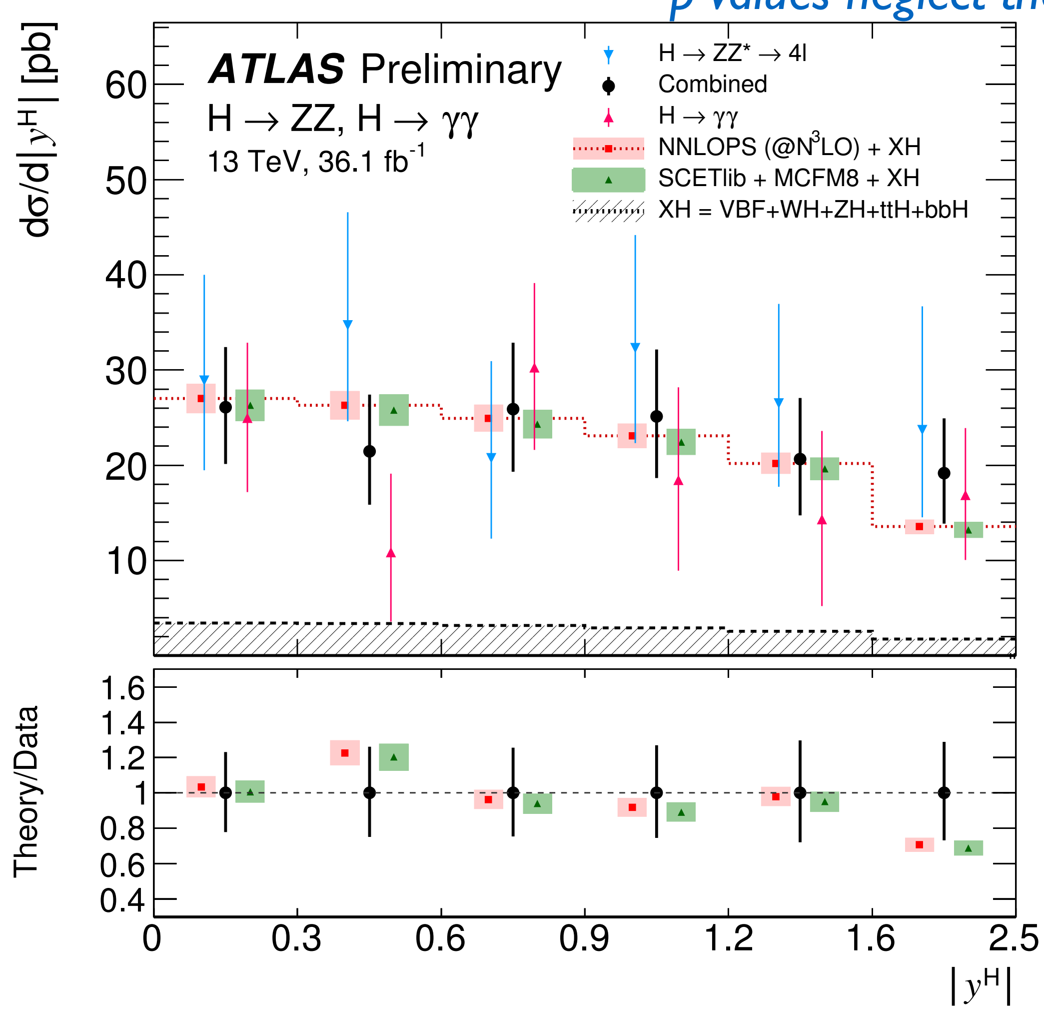
- Statistical uncertainties ~20-30%
- Systematics from luminosity (4%), background estimation (γγ, 2-6%), jet reconstruction experimental uncertainties (3-6%, >10% for n_{jets}>2)

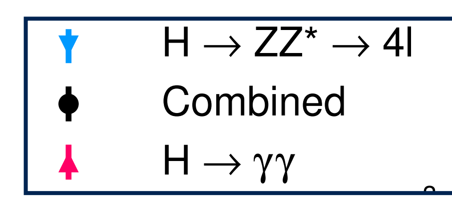
➪ *Excellent compatibility of 4ℓ/γγ measurements (>40% for all observables)*

p-values [%]	p_T^H	$\lvert y^H \rvert$	N_{jets}	p_T^{j1}
NNLOPS (@N3LO)	29	92	45	5
HRes (NNLO+NNLL)	5	–	–	–
RaDISH + NNLOJET	29	–	–	–
SCETlib	–	91	–	21
MadGraph5_aMC@NLO (@N3LO)	–	–	57	–

p-values neglect theoretical uncertainties







New!

H→γγ/ZZ* x-sections inclusive in production

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- Statistical uncertainties ~20-30%
- Systematics from luminosity (4%), background estimation (γγ, 2-6%), jet reconstruction experimental uncertainties (3-6%, >10% for n_{jets}>2)

Mild excess at the high p_T^H / p_T^{j1} / n_{jets} seen in both channels

p-values [%]	p_T^H	$\lvert y^H \rvert$	N_{jets}	p_T^{j1}
NNLOPS (@N3LO)	29	92	45	5
HRES (NNLO+NNLL)	5	–	–	–
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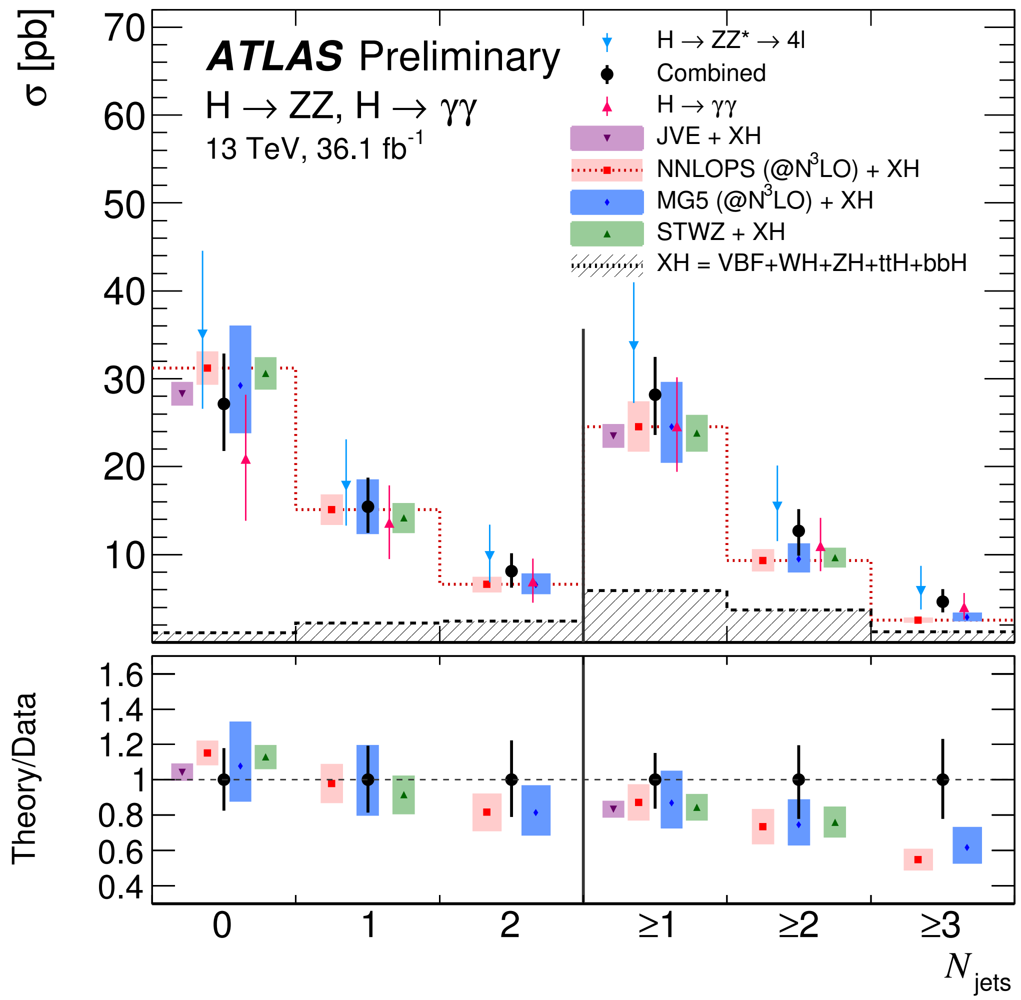
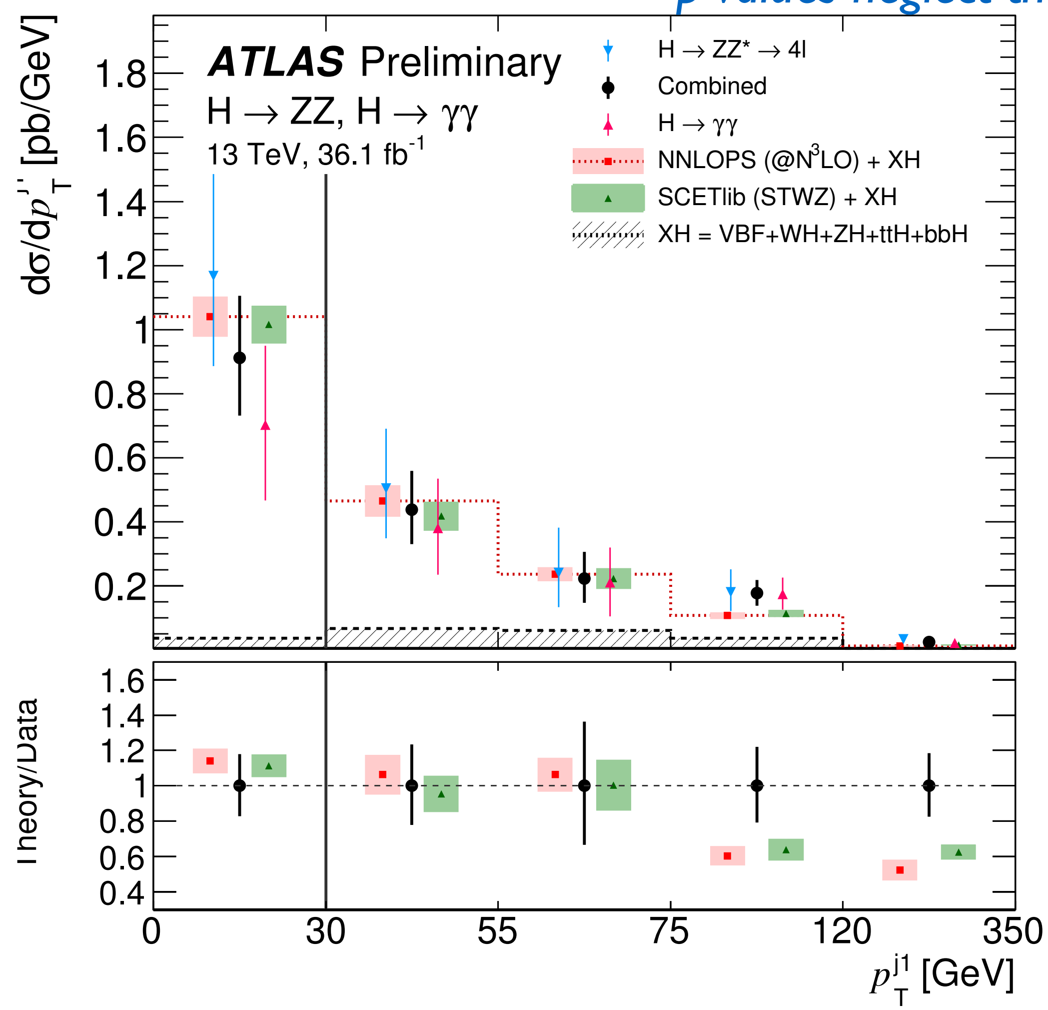
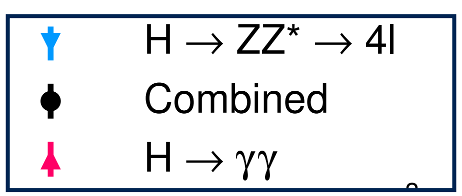
SCETLIB	–	91	–	21
MADGRAPH5_AMC@NLO (@N3LO)	–	–	57	–

p-values neglect theoretical uncertainties







New!

Summary

- With Run-2 data, we are entering the precision era; analysis of the diboson final states is allowing measurements with precision better than Run-1
- Analysis of the 2015+2016 dataset (36 fb^{-1}) is a milestone in preparation for the Run-2 legacy physics results
    - Methodology is established - high quality results already improve on the Run-1 measurements

New ATLAS measurements

- Analysis of ggF and VBF production in the $H \rightarrow WW^*$ channel yields most sensitive single-channel measurements so far in Run-2
    - Cross-section in agreement with the SM predictions
- Inclusive production in the 4ℓ and $\gamma\gamma$ channels: independent measurements with minimal theory assumptions
    - Now combined to obtain differential measurements ($d\sigma/dx$, x: p_T^H, y^H, n_{jets}, p_T^{j1}) :
        - No significant deviations from the SM seen
        - More data will allow interesting tests of QCD calculations

Additional material

H→WW* event selection

<table>
<tr><th>Category</th><th>$N_{\text{jet}} = 0$</th><th>$N_{\text{jet}} = 1$</th><th>$N_{\text{jet}} \geq 2$, VBF</th></tr>
<tr><td rowspan="2">Preselection</td><td colspan="3">Two isolated, different-flavour, leptons ($\ell = e, \mu$) with opposite charge
$p_{\text{T}}^{\text{lead}} > 22$ GeV , $p_{\text{T}}^{\text{sublead}} > 15$ GeV
$m_{\ell\ell} > 10$ GeV</td></tr>
<tr><td colspan="2">$E_{\text{T}}^{\text{miss, track}} > 20$ GeV</td><td></td></tr>
<tr><td rowspan="3">Background rejection</td><td colspan="3">$N_{b\text{-jet},(p_{\text{T}}>20\text{ GeV})} = 0$</td></tr>
<tr><td rowspan="2">$\Delta\phi(\ell\ell, E_{\text{T}}^{\text{miss}}) > \pi/2$
$p_{\text{T}}^{\ell\ell} > 30$ GeV</td><td>$\max\left(m_{\text{T}}^{\ell}\right) > 50$ GeV</td><td></td></tr>
<tr><td colspan="2">$m_{\tau\tau} < m_Z - 25$ GeV</td></tr>
<tr><td>$H \to WW^* \to e\nu\mu\nu$
topology</td><td colspan="2">$m_{\ell\ell} < 55$ GeV
$\Delta\phi_{\ell\ell} < 1.8$</td><td>Central Jet Veto
Outside Lepton Veto</td></tr>
<tr><td>Discriminant Variable
BDT input variables</td><td colspan="2">m_{T}</td><td>BDT
m_{jj}, Δy_{jj}, $m_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, m_{T}, $\sum C_{\ell}$, $\sum_{\ell,j} m_{\ell j}$, $p_{\text{T}}^{\text{tot}}$</td></tr>
</table>

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<tr><th>CR</th><th>$N_{\text{jet}} = 0$</th><th>$N_{\text{jet}} = 1$</th><th>$N_{\text{jet}} \geq 2$, VBF</th></tr>
<tr><td rowspan="3">WW</td><td>$55 < m_{\ell\ell} < 110$ GeV
$\Delta\phi_{\ell\ell} < 2.6$</td><td>$m_{\ell\ell} > 80$ GeV
$|m_{\tau\tau} - m_Z| > 25$ GeV</td><td rowspan="3"></td></tr>
<tr><td colspan="2">b-jet veto</td></tr>
<tr><td></td><td>$m_{\text{T}}^{\ell} > 50$ GeV</td></tr>
<tr><td rowspan="3">Top-quark</td><td rowspan="3">$N_{b\text{-jet},(20\text{ GeV}<p_{\text{T}}<30\text{ GeV})} > 0$
$\Delta\phi(\ell\ell, E_{\text{T}}^{\text{miss}}) > \pi/2$
$p_{\text{T}}^{\ell\ell} > 30$ GeV
$\Delta\phi_{\ell\ell} < 2.8$</td><td>$N_{b\text{-jet},(p_{\text{T}}>30\text{ GeV})} = 1$
$N_{b\text{-jet},(20\text{ GeV}<p_{\text{T}}<30\text{ GeV})} = 0$
$\max\left(m_{\text{T}}^{\ell}\right) > 50$ GeV</td><td>$N_{b\text{-jet},(p_{\text{T}}>20\text{ GeV})} = 1$
Central Jet Veto</td></tr>
<tr><td colspan="2">$m_{\tau\tau} < m_Z - 25$ GeV</td></tr>
<tr><td></td><td>Outside Lepton Veto</td></tr>
<tr><td rowspan="2">$Z \to \tau\tau$</td><td colspan="2">no $E_{\text{T}}^{\text{miss, track}}$ requirement
$m_{\ell\ell} < 80$ GeV</td><td>Outside Lepton Veto
Central Jet Veto</td></tr>
<tr><td>$\Delta\phi_{\ell\ell} > 2.8$</td><td colspan="2">$m_{\tau\tau} > m_Z - 25$ GeV
$N_{b\text{-jet},(p_{\text{T}}>20\text{ GeV})} = 0$</td></tr>
</table>

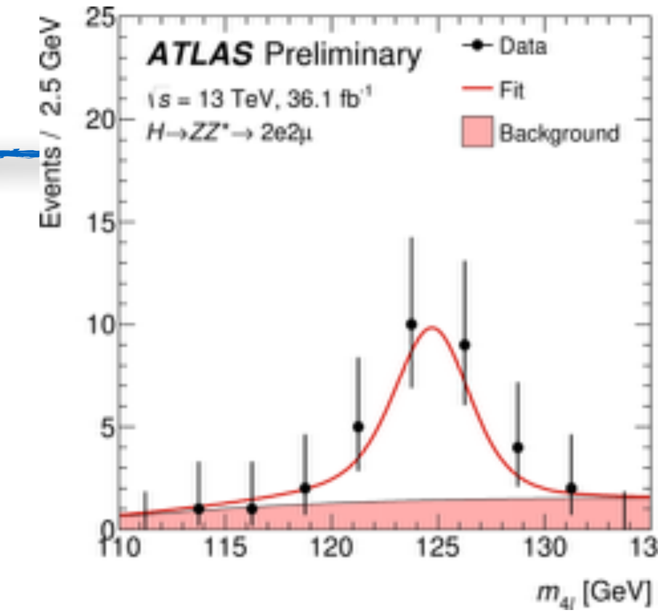
H→WW* MC simulation

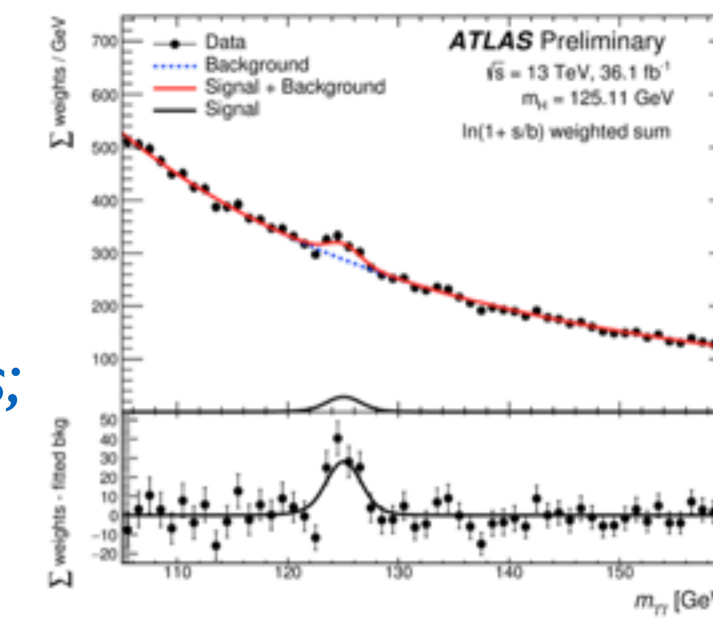
Process	Matrix Element (Alternative)	PDF	PS (Alternative)	Precision σ
ggF	POWHEG-BOX v2 NNLOPS [4–6] (MG5_aMC@NLO [22, 23])	PDF4LHC15 NNLO [7]	PYTHIA 8 [8] (HERWIG 7 [24])	N^3LO QCD + NLO EW [10–14]
VBF	POWHEG-BOX v2 (MG5_aMC@NLO)	PDF4LHC15 NLO	PYTHIA 8 (HERWIG 7)	NNLO QCD + NLO EW [10, 15–17]
VH	POWHEG-BOX v2 [25]	PDF4LHC15 NLO	PYTHIA 8	NNLO QCD + NLO EW[26–28]
$qq \to WW$	SHERPA 2.2.2 [29, 30] (POWHEG-BOX v2, MG5_aMC@NLO)	NNPDF3.0NNLO [31]	SHERPA 2.2.2 [32, 33] (HERWIG++ [24])	NLO [34]
$gg \to WW$	SHERPA 2.1.1 [34]	CT10 [35]	SHERPA 2.1	NLO [36]
WZ/Vγ^*/ZZ	SHERPA 2.1	CT10	SHERPA 2.1	NLO [34]
Vγ	SHERPA 2.2.2 (MG5_aMC@NLO)	NNPDF3.0NNLO	SHERPA 2.2.2 (CSS variation [32, 37])	NLO [34]
$t\bar{t}$	POWHEG-BOX v2 [38] SHERPA 2.2.1	NNPDF3.0NLO	PYTHIA 8 [39] (HERWIG 7)	NNLO+NNLL [40]
Wt	POWHEG-BOX v1 [41] (MG5_aMC@NLO)	CT10 [35]	PYTHIA 6.428 [42] (HERWIG++)	NLO [41]
Z+jets	SHERPA 2.2.1	NNPDF3.0NNLO	SHERPA 2.2.1	NLO [43]

Higgs mass measurement

Measuring the only free parameter of the Higgs sector of the SM:

- Combined 4ℓ+γγ fit, modelling correlated systematics
  - 4ℓ measurement drives the overall performance, combination with γγ improves significantly the precision
  - Excellent agreement with the combined ATLAS+CMS Run-1 measurement





4l limited by statistics

γγ limited by photon energy scale systematics

➪ *Preliminary result with inflated photon systematics; improvements underway!*