Measurement of the $W^+W^- \rightarrow l\nu l\nu$ Production Cross Section at 8 TeV and 13 TeV and Limits on Anomalous Triple Gauge Couplings with the ATLAS Detector

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ICHEP 2016 Chicago

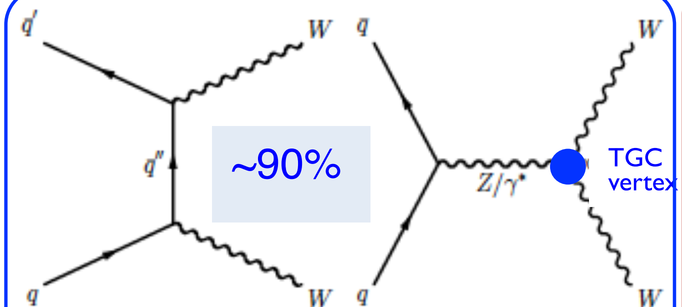
August 5th, 2016

Introduction: W^+W^- Diboson Physics

- WW production provides a test of the Standard Model (SM) at the TeV scale
  - precise measurement of the fiducial, total and differential cross sections
- Test NLO Electroweak Weak (EW) corrections and of QCD calculations (NNLO)
- Irreducible background to Higgs and beyond SM-searches
- Probe triple gauge-boson self-coupling (aTGC) to test the EW theory and to search for New Physics beyond the SM
- This talk will cover:
  1. WW production at 8 TeV and aTGCs
  2. WW+1 jet production at 8 TeV
  3. WW production at 13 TeV

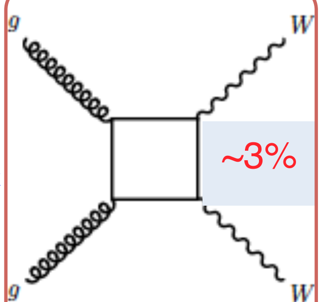
W^+W^- Signal @ 8 TeV

arXiv:1603.01702 submitted to JHEP



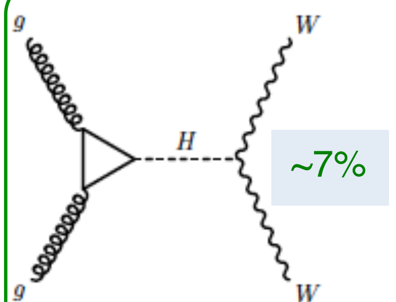
NNLO $O(\alpha_s^2)$

Contains Triple Gauge Coupling



LO $O(\alpha_s^2)$

large NLO corrections



NNLO+NNLL $O(\alpha_s^4)$ → pp→WW =63pb

Higgs XS WS, arXIv:1307.1347

- Measure **$W^+W^- \to l\nu l\nu$ (l=e, μ) + jet veto** in fiducial phase space and extrapolate to the total phase space

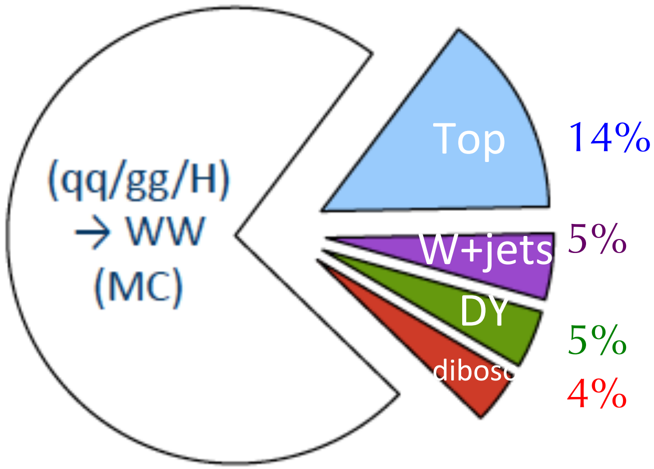
- Excess in early cross section measurements from both ATLAS and CMS has triggered a lot of theory papers about the NNLO calculations and further investigation on resummation effects at large logs
(arXiv:1407.4481, arXiv:1407.4537, arXiv:1410.4745, arXiv:1509.07118, arXiv:1507.02565, arXiv:1606.07062, arXiv:1606.01034, arXiv: 1408.5243, arXiv: 1511.08617, arXiv: 1605.02716, arXiv: 1506.04801)

Background (I)

Event Selection

- Reduce Top (ttbar+Wt) background
  - require events to have 0-jets
- Suppress Drell-Yan background:
  - Remove Z peak in ee,μμ

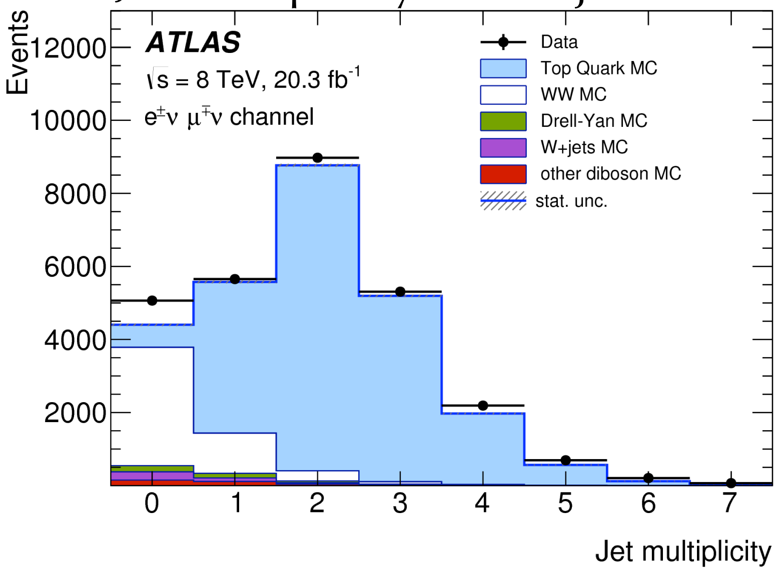
  + require large Etmiss



Background Estimates

- **Top: data-driven:** (Δ~10%)
  - Data(inclusive jets) x Jet-Veto efficiency (corrected using data)
- **W+jets**: data-driven (Δ~>40%)
  - Matrix Method
- **Drell-Yan**: data-driven (Δ~10-50%)
  - A simultaneous fit using control and signal regions
- **Other dibosons**: Monte Carlo based (Δ~20%)

Jet Multiplicity before jet veto

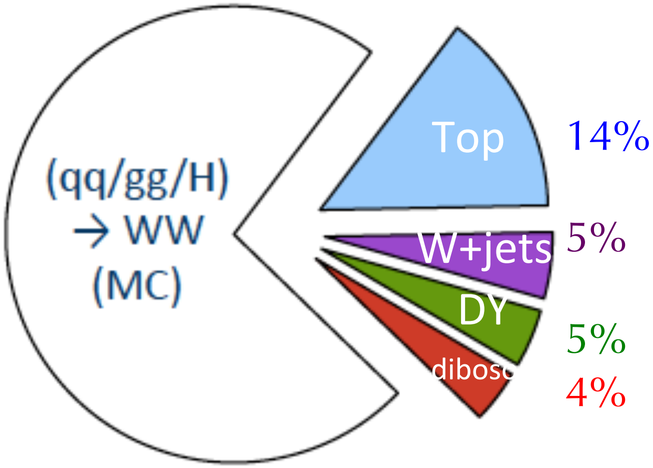


Background (II)

Event Selection

- Reduce Top (ttbar+Wt) background
  - require events to have 0-jets
- Suppress Drell-Yan background:
  - Remove Z peak in ee,μμ

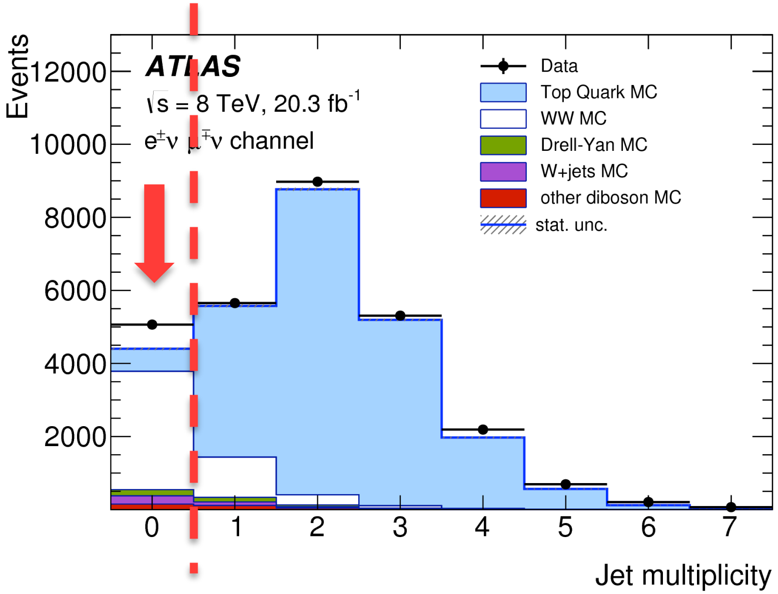
  \+ require large Etmiss



- **The 0-jet final state** suffers from large logarithmic terms in the prediction of fiducial cross sections and in the extrapolation to the total phase space

$$\frac{d\sigma}{dp_T^{\mathrm{veto}}} \sim \alpha_s^n \log^m \left(\frac{(m_{WW})^2}{(p_T^{\mathrm{veto}})^2} \right)$$

  - introduction of a new energy scale (jet veto scale)→Large logs which spoil perturbation theory → resummation



Cross section definitions

Fiducial selection

close to analysis selection

	$e\mu$	$ee/\mu\mu$
p_T^{ℓ} (leading/sub-leading)	> 25 / 20 GeV	
$\lvert\eta^{\ell}\rvert$	$\lvert\eta^{\mu}\rvert < 2.4$ and $\lvert\eta^{e}\rvert < 2.47$, excluding $1.37 < \lvert\eta^{e}\rvert < 1.52$	
$m_{\ell\ell}$	> 10 GeV	> 15 GeV
$\lvert m_Z - m_{\ell\ell}\rvert$	—	> 15 GeV
Number of jets with $p_T > 25$ GeV, $\lvert\eta\rvert < 4.5$	0	0
$\lvert\Sigma \mathbf{p}_T^{\nu_i}\rvert$ if $\Delta\phi_\ell > \pi/2$ $\lvert\Sigma \mathbf{p}_T^{\nu_i}\rvert \times \sin(\Delta\phi_\ell)$ if $\Delta\phi_\ell < \pi/2$ ($E_{T,\,Rel}^{miss}$)	> 15 GeV	> 45 GeV
Transverse magnitude of the vectorial sum of all neutrinos, $\lvert\Sigma \mathbf{p}_T^{\nu_i}\rvert$ (p_T^{miss})	> 20 GeV	> 45 GeV

$$\sigma_{fid} = \frac{N_{obs} - N_{bkgd}}{C \times \int \mathcal{L}dt} \qquad \sigma_{tot} = \frac{\sigma_{fid}}{A \times BR}$$

Efficiency Corrections

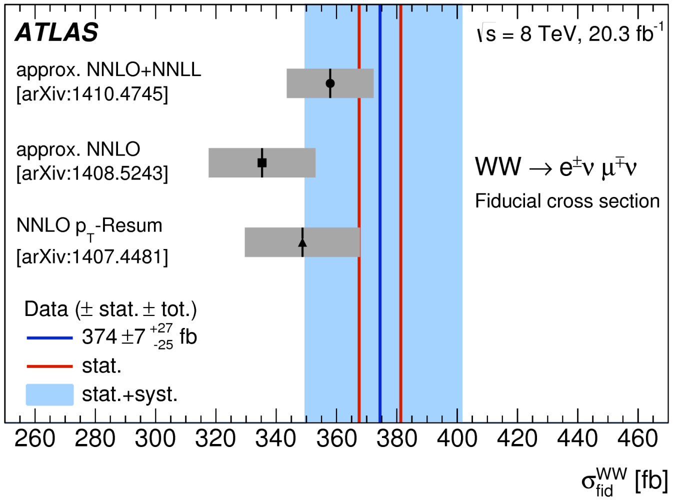
Acceptance

- Measurements are corrected to consistently defined "truth level" to allow proper theory comparisons
- Measure **fiducial cross section** (with minimal phase space extrapolations) and **total cross section** (Acceptance could suffer from uncertainty modelling)

Fiducial Cross Section Measurement

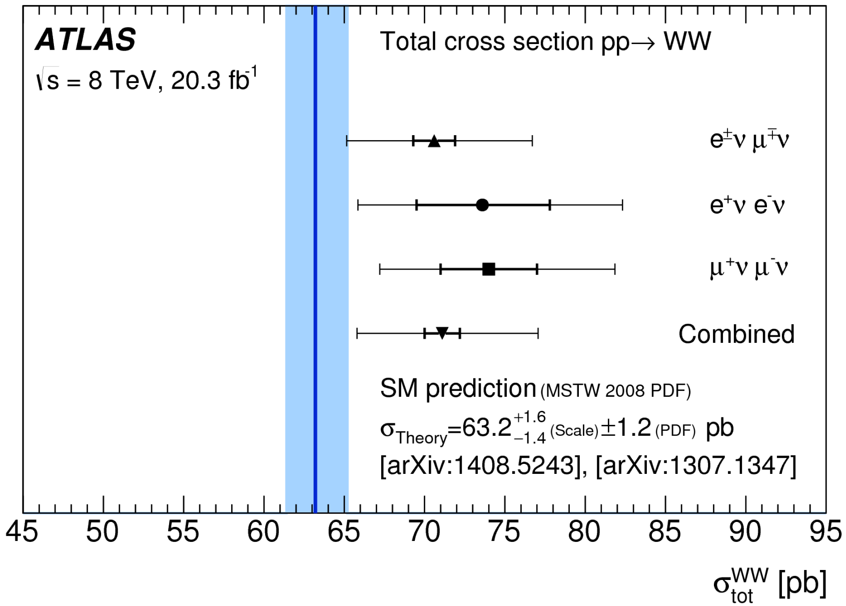
Prediction		Fiducial cross section $pp \to WW \to \ell\ell\nu\nu$ [fb]
Measured $\sigma^{e\mu}_{\rm fid}(WW)$		$374 \pm 7(\rm stat)\ ^{+25}_{-23}(\rm syst)\ ^{+8}_{-7}(\rm lumi)$
$\sigma(\rm nNLO_{fid,e\mu})$	PowHeg+Pythia8~NLO+NLL	311 ± 15
$\sigma(\rm approx.\ NNLO_{fid,e\mu})$	NNLO	335 ± 18
$\sigma(\rm approx.\ (NNLO + NNLL)_{fid,e\mu})$	Quoted from arXiv:1410.4745	358 ± 14
$\sigma(\rm NNLO\ p_T\text{-}Resum_{fid,e\mu})$	MC reweighted to NNLL resummed $p_T(WW)$	349 ± 19

- nNLO = NLO qq→WW + NNLO gg→H→WW + LO gg→WW
  NNLO= **NNLO** qq→WW + NNLO gg→H→WW + LO gg→WW
- The measurement is compared to various predictions:
  - 2σ larger than nNLO (NLO +PS)
  - 1σ against prediction with NNLO qq + resummation
- Fiducial cross section measurement uncertainty in eμ ~7%
  → dominant uncertainties:
  - Experimental: Jet Energy Scale (~4%), W+jets background (~3%), luminosity (~2%)
  - Theory : <1% minimal modelling uncertainty



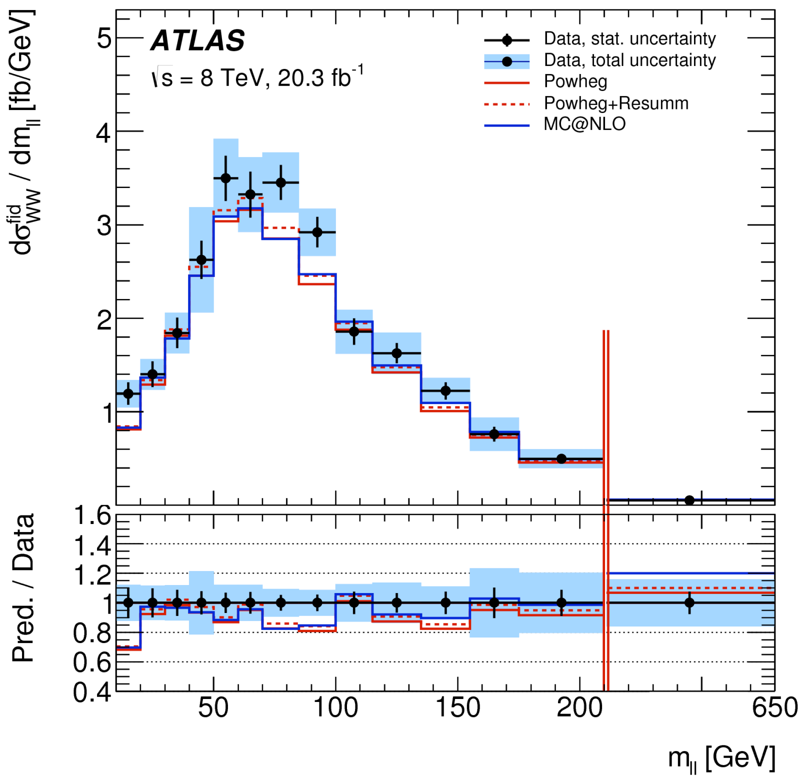
Total Cross Section Measurement

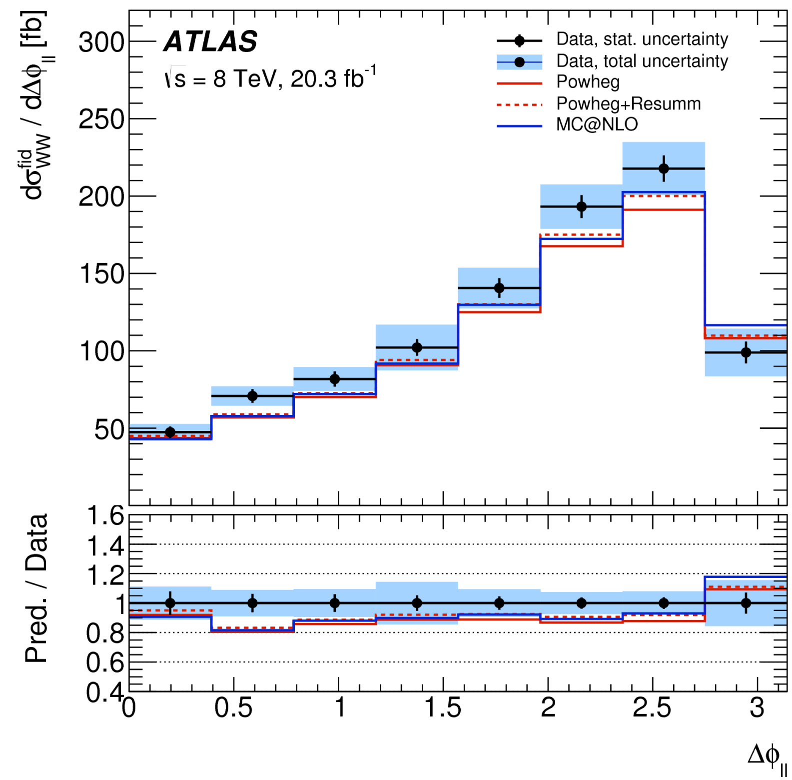
Final state	Total cross section $pp \to WW$ [pb]
$e\mu$	$70.6 \pm 1.3(\text{stat})\ ^{+5.8}_{-5.1}(\text{syst}) \pm 1.4(\text{lumi})$
ee	$73.6^{+4.2}_{-4.1}(\text{stat})\ ^{+7.5}_{-6.4}(\text{syst}) \pm 1.5(\text{lumi})$
$\mu\mu$	$74.0 \pm 3.0(\text{stat})\ ^{+7.1}_{-5.9}(\text{syst}) \pm 1.5(\text{lumi})$
Combined	$71.1 \pm 1.1(\text{stat})\ ^{+5.7}_{-5.0}(\text{syst}) \pm 1.4(\text{lumi})$
$\sigma(\text{NNLO}_{\text{tot}})$ theory	$63.2^{+1.6}_{-1.4}(\text{scale}) \pm 1.2(\text{PDF})$



- Cross section measurement uncertainty is ~8.5 %
- Dominant theory uncertainty in eμ comes from jet veto (3.4%), parton shower, hadronisation and underlying-event uncertainties (2.5%)
- The combined total cross section is compatible with NNLO within 1.4σ

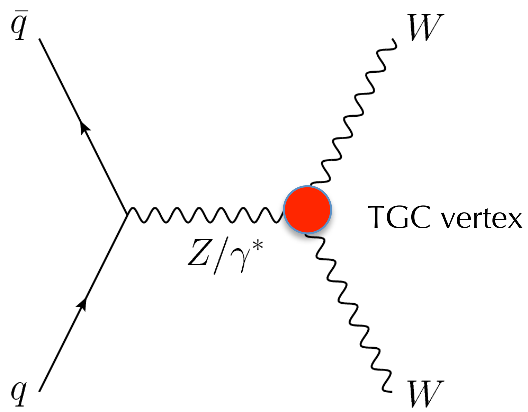
Differential Measurements@8TeV

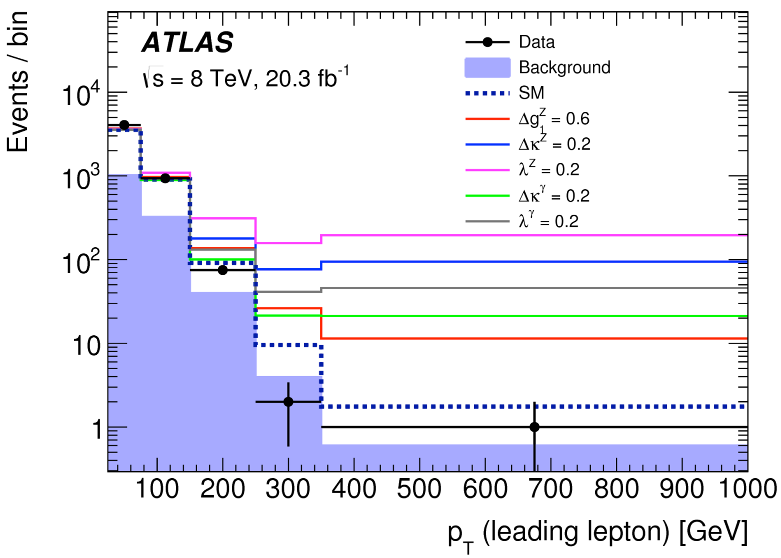




- Shapes of the measured unfolded differential distributions agree with the predictions at the level of 15%
- Overall normalisation offset between data and MC at NLO
- Measurement dominated by systematic uncertainties O(10%-30%)

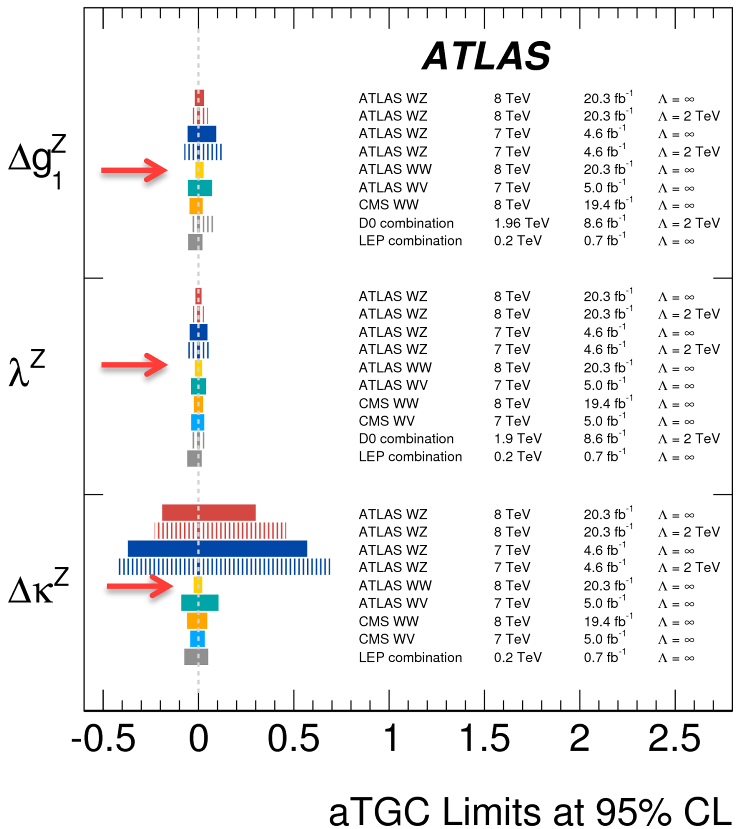
Constraints on anomalous Triple Gauge Couplings



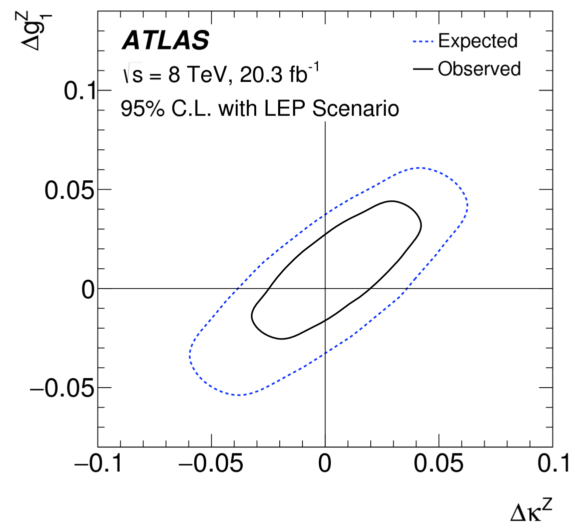


- Effects of aTGCs are modelled using an **Effective Lagrangian** which depends on few parameters (λ_Z, $\Delta\kappa_Z$, $\Delta g^Z{}_1$) or an **Effective Field Theory** (C_{www}/Λ^2, C_w/Λ^2, C_B/Λ^2) [arXiv:1205.4231]
- Manifest as an increase of cross section at high invariant mass and high transverse momentum
- Fit leading lepton $p^{lead}{}_T$ distribution to extract limits
  - NLO Electroweak correction is large in high $p^{lead}{}_T$
  - Major uncertainty of 20% comes from $p^{lead}{}_T$ shape comparison between PowHeg and MC@NLO

aTGCs Limits



- 1D Limits and 2D contours for different scenarios provided (No constrains, LEP, HISZ, equal couplings and EFT)
- **Results are more stringent than for 7 TeV and competitive with LEP**

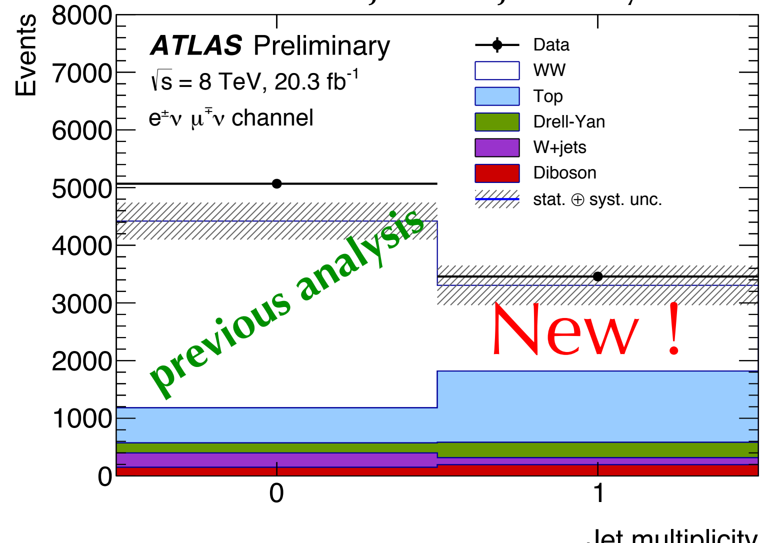


Scenario	Parameter	Expected [TeV^{-2}]	Observed [TeV^{-2}]
	C_{WWW}/Λ^2	[-7.62,7.38]	[-4.61,4.60]
EFT	C_B/Λ^2	[-35.8,38.4]	[-20.9,26.3]
	C_W/Λ^2	[-12.58,14.32]	[-5.87,10.54]

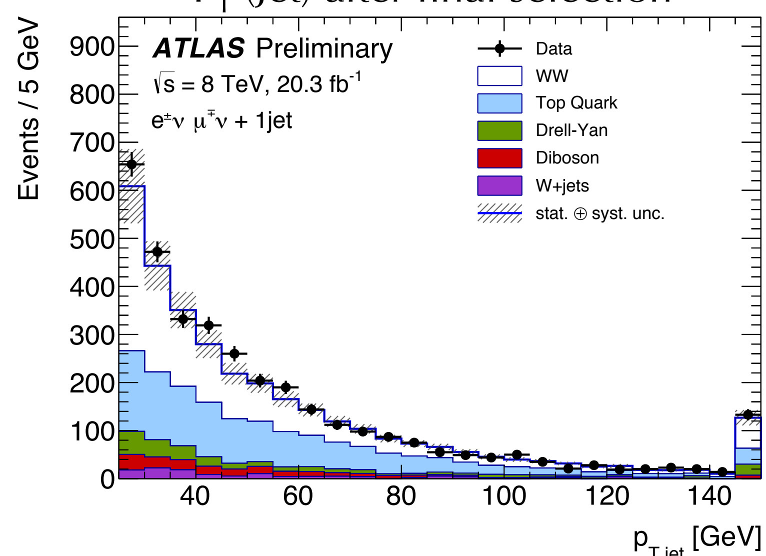
W^+W^- +1jet @8TeV : Signal and Background New !

- **Extend the previous measurement to 1-jet final states**
- In combination with previous result provide a **WW+≤ 1 jet fiducial cross section** with reduced logarithmic dependence
- Analysis is based on the previous 0-jet analysis, but using only eμ channel
  - kinematic selection criteria similar to 0-jet
  - largest background contribution from Top
  - Reject Top with strict b-jet veto
  - Background estimates are largely based on the previous analysis except for Top
  - Top yield is determined with a precision of 5.3%
- The largest contribution to data is signal, with similar amount of top background

Events in 0-jet & 1-jet analyses



P_T (Jet) after final selection



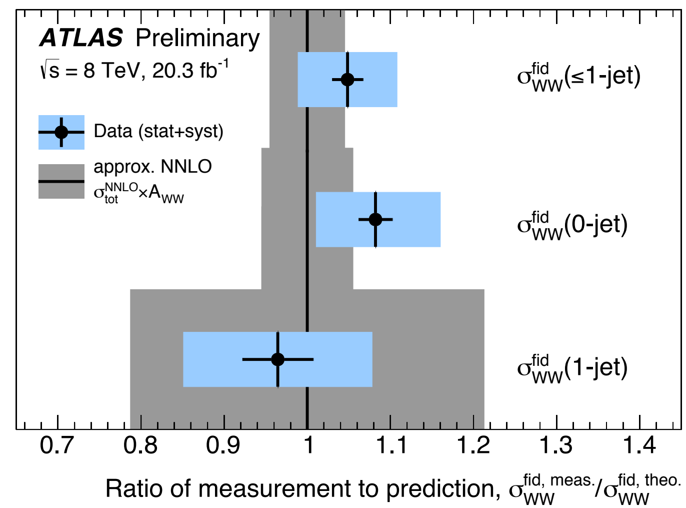
W^+W^- +1jet @8TeV: Cross Section New !

- ~20% of the expected signal yield is due to migrations from WW+0-jet events

- Take into account bin migration :

$$\begin{pmatrix}\sigma_{0j,fid}\\ \sigma_{1j,fid}\end{pmatrix} = \begin{bmatrix}R_{00} & R_{10}\\ R_{01} & R_{11}\end{bmatrix} \times \begin{pmatrix}N^{data-bkg}_{0j,reco}/\mathcal{L}\\ N^{data-bkg}_{1j,reco}/\mathcal{L}\end{pmatrix}$$

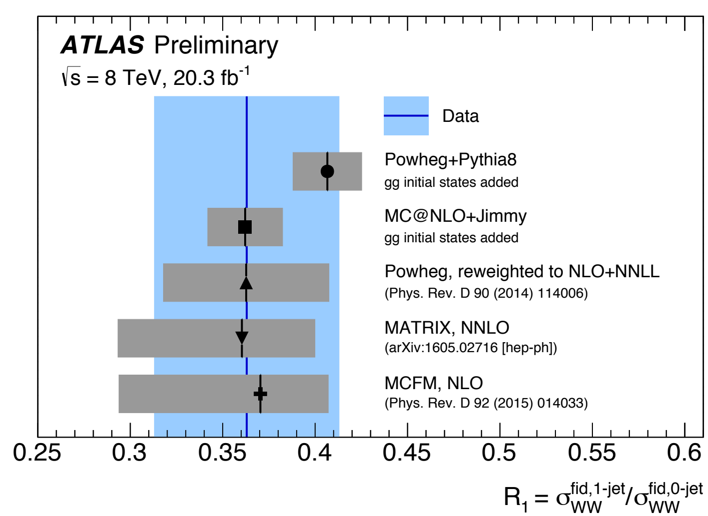
$$\sigma_{WW} = \frac{\sigma_{0j,fid} + \sigma_{1j,fid}}{A^{0+1j}_{WW} \times \mathcal{B}^2}$$



- Uncertainties in 0-jet and 1-jet bin are similar, except for JES, JER and b-tag

Ratio = $\sigma_{WW}^{fid,1\text{-}jet}/\sigma_{WW}^{fid,0\text{-}jet}$

- Cancellation of uncertainties between 0-jet and 1-jet bin results in smaller uncertainties on WW+≤ 1 jet and on the extrapolation



- The results in the fiducial region are in agreement with the theory predictions

- The result on total cross section is 12% more precise than the previous ATLAS measurement based on WW+0jet

W^+W^- @ 13 TeV (I)

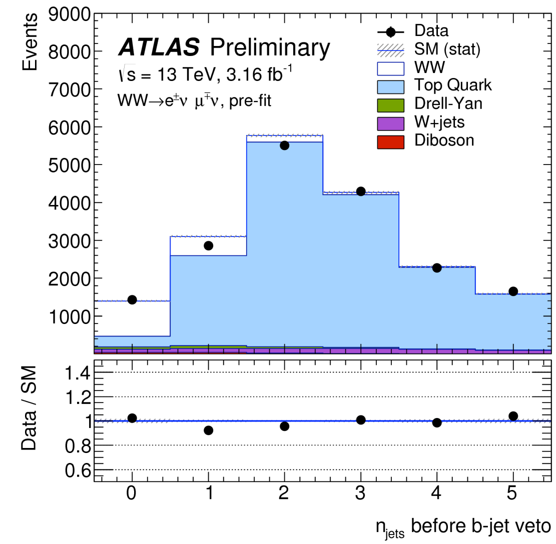
ATLAS-CONF-2016-090

New !

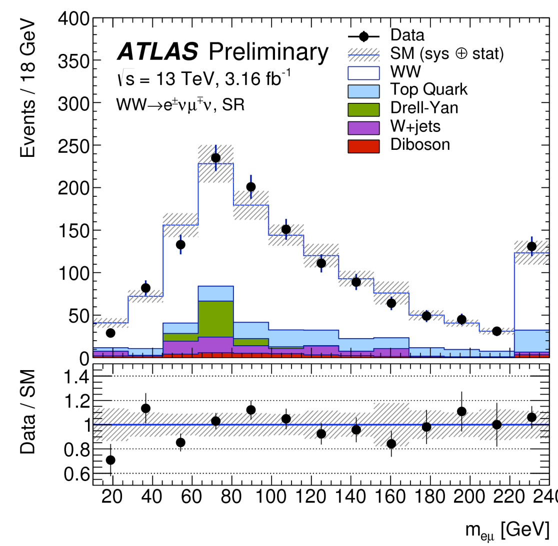
- **Main Changes compared to 8 TeV analysis**
  - Use eμ channel
  - Lepton p_T cut moved to 25/25 GeV instead of 25/20 GeV
  - Apply b-tag veto to reduce Top background
  - Top and Drell-Yan are estimated using Transfer Factor method
  - Fiducial cross section is extracted using a simultaneous fit of Signal Region and Top and Drell-Yan Control Regions →take into account systematic uncertainties and their correlations
  - Signal: ~71%, Top: ~ 16%, Drell-Yan: ~5%, W+jets+QCD: ~6%, Others: ~1-2%
- **Significant progress in theoretical calculations**
  - qq→WW (NNLO) $O(\alpha_s^2)$
  - gg→WW (NLO) $O(\alpha_s^3)$
  - gg→H→WW (N^3LO) $O(\alpha_s^5)$

  → Total : pp→WW = 128.4 pb

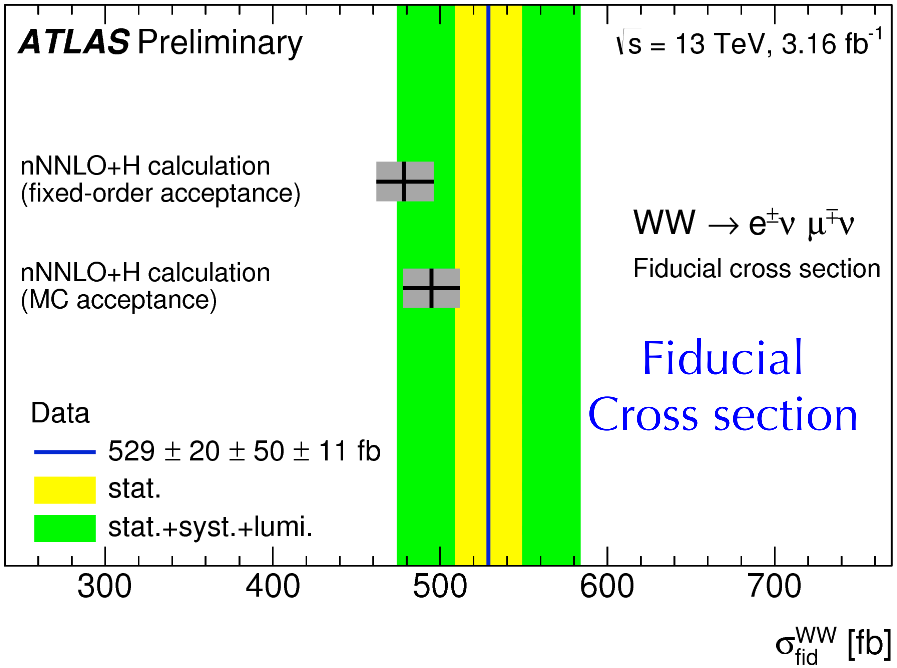
Jet Multiplicity before jet veto

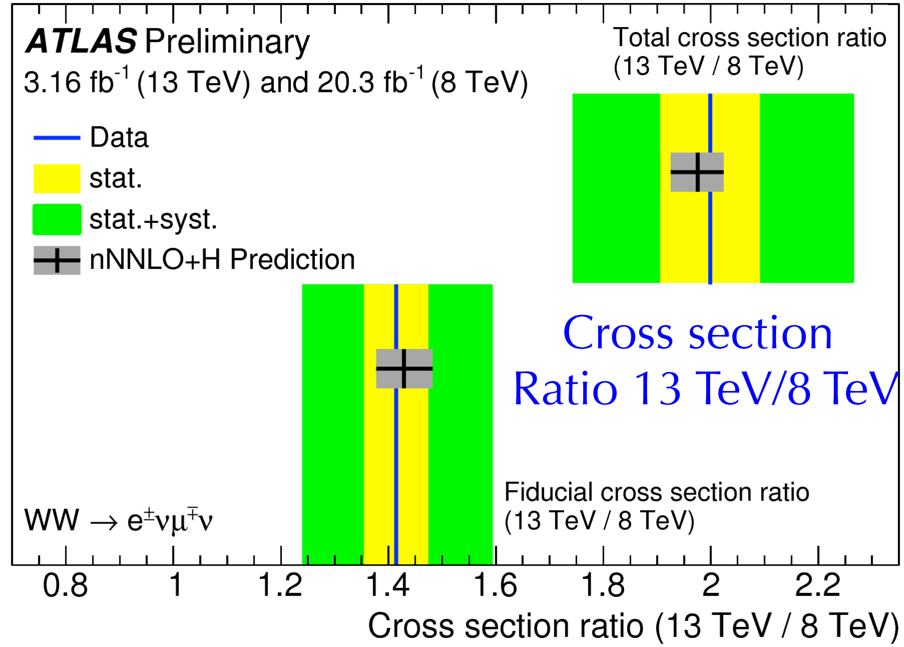


Dilepton Inv. Mass after fit



W+W- @ 13 TeV (II) New !



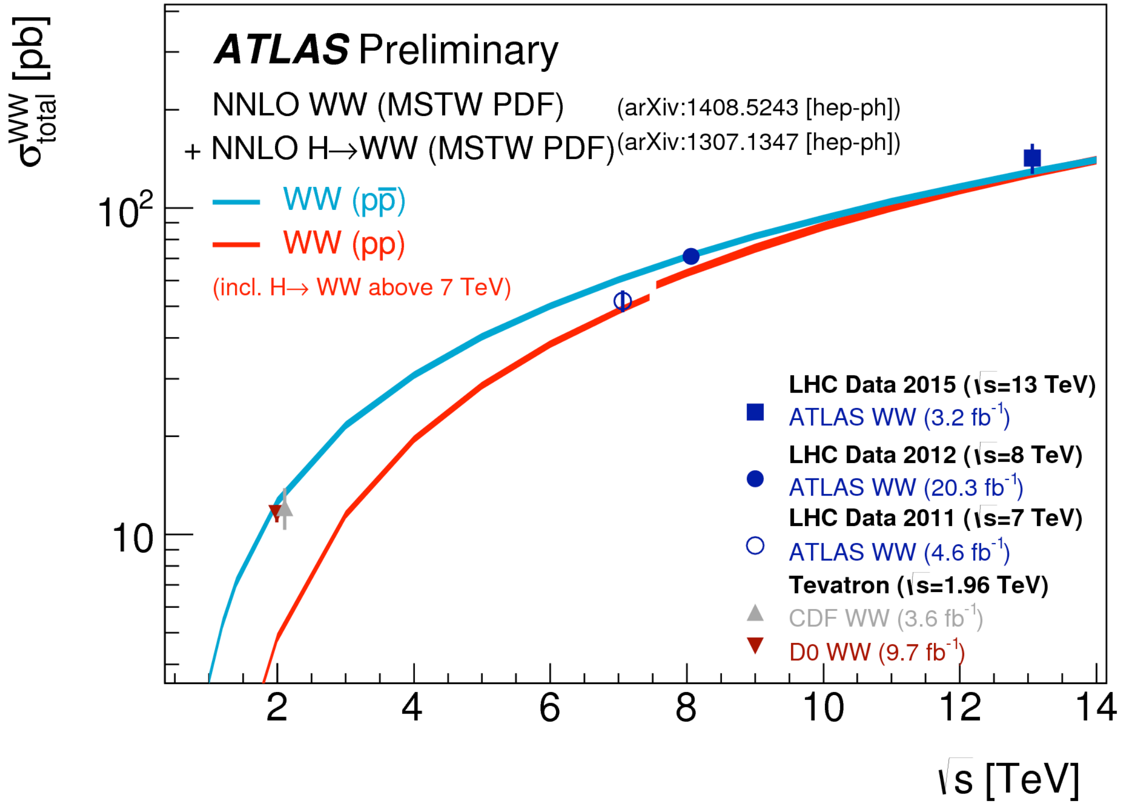


σ_{WW}^{tot}= 142 ±5 (stat) ±13 (syst)±3.0 (lumi) pb

$\sigma_{WW}^{theory}=128.4\ ^{+3.5}_{-3.8}$ pb

- High-order QCD calculations describe the data well

Summary



- WW di-boson production measured with precision O(8%) at 8 TeV
- Good agreement between measurements and recent NNLO predictions at 8/13 TeV
- No deviations from SM observed in the search for Anomalous Triple Gauge Couplings, limits start to surpass LEP results
- And still a lot of data at 13 TeV to be analysed…

Backup

Systematic Uncertainties WW@8TeV

Sources of uncertainty	$e\mu$	ee	$\mu\mu$	Combined
Experimental uncertainties in fiducial and total cross sections [%]				
Integrated luminosity	±2.0	±2.0	±2.0	±2.0
Pile-up	±1.35	±2.00	±2.03	±1.48
Trigger	±0.43	±2.8	±3.0	±0.75
Electron energy scale	±0.42	±1.45	—	±0.43
Electron energy resolution	±0.04	±0.23	—	±0.05
Electron identification and reconstruction	±0.99	±2.19	—	±0.91
Electron isolation	±0.22	±0.47	—	±0.21
Muon momentum scale	±0.10	—	±0.39	±0.14
Muon momentum resolution (ID)	±0.56	—	±1.67	±0.67
Muon momentum resolution (MS)	±0.09	—	±0.21	±0.11
Muon identification and reconstruction	±0.41	—	±0.82	±0.43
Muon isolation	±0.59	—	±1.20	±0.62
Jet vertex fraction (JVF)	±0.22	±0.26	±0.24	±0.23
Jet energy scale	±4.1	±3.9	±4.4	±4.1
Jet energy resolution	±1.35	±1.30	±1.47	±1.35
E_T^{miss} scale soft terms	±1.12	±2.07	±1.85	±1.28
E_T^{miss} resolultion soft terms	±0.31	±0.38	±0.53	±0.35
p_T^{miss} scale soft terms	±0.23	±0.38	±0.35	±0.25
p_T^{miss} resolution soft terms	±0.13	±0.19	±0.14	±0.13
Background uncertainties in fiducial and total cross sections [%]				
Top-quark background	±1.35	±1.82	±1.42	±1.39
W+jets & multijet background	±3.6	±3.1	±2.0	±2.8
Drell–Yan background	±0.46	±3.00	±2.26	±0.86
MC statistics (top-quark, W+jets, Drell–Yan)	±0.61	±2.03	±1.39	±0.53
Other diboson cross sections	±0.70	±1.01	±0.55	±0.69
MC statistics (other diboson)	±0.10	±0.32	±0.18	±0.09

	$\sigma(C_{WW})$ [%]			$\sigma(A_{WW})$ [%]		
	$e\mu$	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$
PDF	0.10	0.34	0.13	0.81	0.94	0.93
EWK corrections (SF_{EW})	0.01	0.06	0.04	0.46	0.41	0.43
Jet veto	—	—	—	3.4	3.4	3.4
Scale	0.62	0.62	0.62	0.22	0.22	0.22
Soft QCD	0.35	0.92	0.80	2.5	2.6	2.7
Total	0.70	1.2	1.0	4.3	4.4	4.5

	C_{WW} [%]			A_{WW} [%]		
	$e\mu$	ee	$\mu\mu$	$e\mu$	ee	$\mu\mu$
Total	51.2	29.1	47.4	22.8	8.6	9.3
$q\bar{q} \to W^+W^-$	51.4	29.2	47.7	23.5	8.7	9.5
$gg \to W^+W^-$ (non-resonant)	53.6	33.4	48.2	30.6	14.7	16.3
$gg \to H \to W^+W^-$	43.5	21.8	39.3	10.4	4.1	4.6

Systematic Uncertainties WW@13TeV

Sources of uncertainty	Relative uncertainty for $\sigma^{\text{fid}}_{WW\to e\mu}$
Jet selection and energy scale & resolution	7.3%
b-tagging	1.3%
$E_{\text{T}}^{\text{miss}}$ and $p_{\text{T}}^{\text{miss}}$	1.7%
Electron	1.0%
Muon	0.4%
Pile-up	0.9%
Luminosity	2.1%
Top-quark background theory	2.4%
Drell–Yan background theory	1.5%
W+jet and multijet background	3.8%
Other dibosons background	1.1%
Parton-shower	3.1 %
PDF	0.2 %
QCD scale	0.2%
MC statistics	1.2 %
Data statistics	3.7%
Total uncertainty	11%

WW@13TeV

$pp \to WW$ sub-process	order of $\mathcal{O}(\alpha_s)$	σ^{tot}_{WW} [pb]	A [%]	$\sigma^{\text{fid}}_{WW\to e\mu}$ [fb]
$q\bar{q}$ [10, 14]	$\mathcal{O}(\alpha_s^2)$	111.1 ± 2.8	16.20±0.13	422^{+12}_{-11}
gg (non-resonant) [34]	$\mathcal{O}(\alpha_s^3)$	$6.82^{+0.42}_{-0.55}$	$28.1^{+2.7}_{-2.3}$	44.9±7.2
$gg \to H \to WW$ [66][31]	$\mathcal{O}(\alpha_s^5)$ tot. / $\mathcal{O}(\alpha_s^3)$ fid.	$10.45^{+0.61}_{-0.79}$	4.5±0.80	11.0±2.1
$q\bar{q} + gg$ (non-resonant) + $gg \to H$	nNNLO+H	$128.4^{+3.5}_{-3.8}$	$15.87^{+0.17}_{-0.14}$	478±17

Table 5: Theoretical predictions for the WW cross section sub-processes and their associated uncertainties in the full phase space (σ^{tot}_{WW}) calculated up to the given order in $\mathcal{O}(\alpha_s)$ together with the respective acceptance corrections (A) for the fiducial phase space and the fiducial cross sections ($\sigma^{\text{fid}}_{WW\to e\mu}$). The resonant $gg \to H \to WW$ is calculated up to $\mathcal{O}(\alpha_s^5)$ for σ^{tot}_{WW} and to $\mathcal{O}(\alpha_s^3)$ for $\sigma^{\text{fid}}_{WW\to e\mu}$ and A. A correction is applied to $\sigma^{\text{fid}}_{WW\to e\mu}$ and A to account for non-perturbative effects. The quoted uncertainties include scale variations and PDF uncertainties, with the latter being evaluated at NLO. The scale uncertainties are treated as correlated, whereas PDF uncertainties are treated as uncorrelated between the $q\bar{q}$ and the gg-induced processes. A branching ratio of leptonic W-boson decays of $\mathcal{B} = 0.1083$ [58] is used.