Measurements of W^+W^- production cross sections in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

(LHCEWWG-MB)

[ATLAS-CONF-2023-012]

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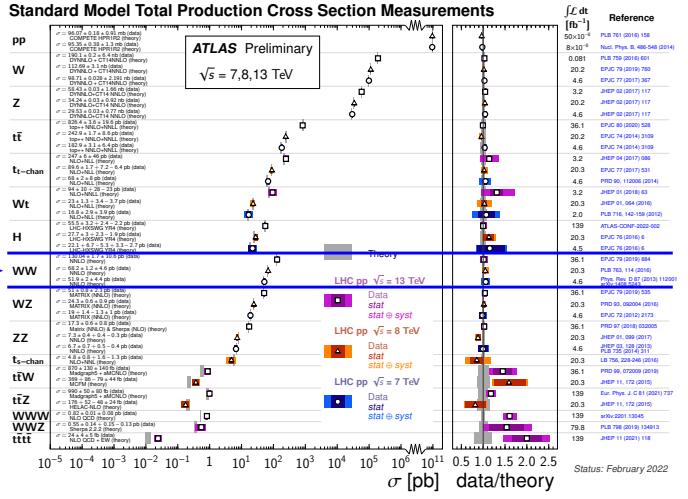
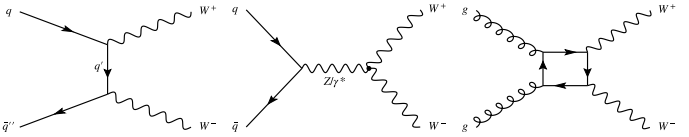
Motivation

- W-boson pair production key process to test self-couplings predicted by the SM
- Interesting test for perturbative QCD and EW corrections
- Important background in other SM (e.g. $H \to WW$) and BSM measurements
- Largest diboson production cross section with clean signature
  $\to$ High precision in full Run 2 dataset.

$\Rightarrow$

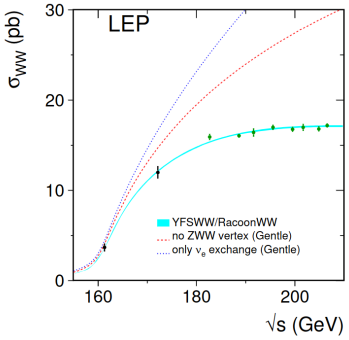




W^+W^- cross sections measurements: A quick walk-through

e^+e^- colliders

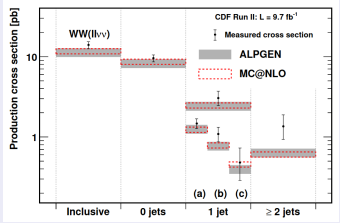
- ALEPH-L3-OPAL-DELPHI Combination: [Phys. Rept. 532 (2013) 119]



Hadron colliders

$p\bar{p}$ – Tevatron

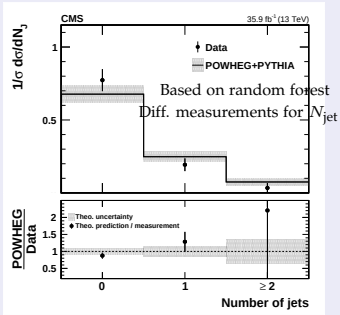
- First evidence CDF: [Phys.Rev.Lett. 78 (1997)]
- CDF: [Phys.Rev.Lett. 103 (2009)]
- D0: [Phys.Rev.Lett. 104 (2010)]



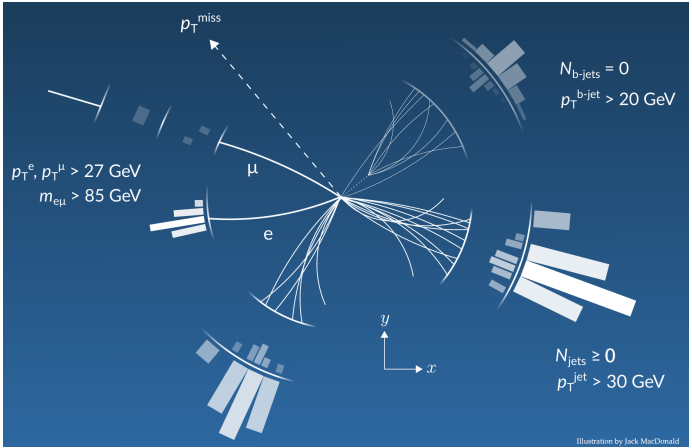
- Jet inclusive measurement of total production cross-section
- Differential distribution of p_T^{jet} in $N_{\text{jet}} == 1$ bin

pp – LHC

- ATLAS: [7 TeV] [8 TeV (0jet)] [8 TeV (1jet)] [13 TeV,3 fb^{-1}] [13 TeV,36 fb^{-1}] [13 TeV,139 fb^{-1},$\geq$ 1jets]
- CMS: [5 TeV] [7 TeV] [8 TeV] [13 TeV, 36fb^{-1}]



ATLAS jet-inclusive W^+W^- cross-sections using 140 fb^{-1}

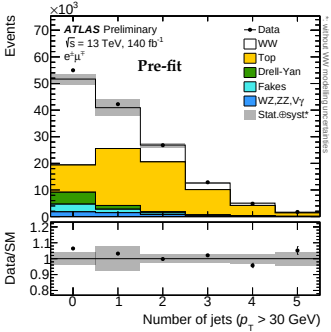


- Fully leptonic final states, different flavor and opposite charge, $WW \to e^{\pm}\mu^{\mp}\nu_e\nu_\mu$
- Suppress $Z \to \tau\tau$ and $H \to WW$ by $m_{e\mu} > 85$ GeV
- Reduce top-quark contributions using b-jet veto

First W^+W^- differential cross-section measurements in fully jet-inclusive phase space

Accurate top-quark and lepton misID background estimates using **data-driven techniques**

High precision in **jet-inclusive phase-space**



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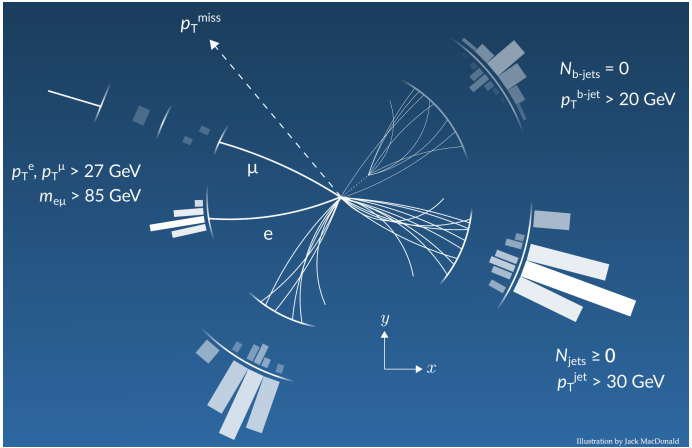

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Reported measurements

Total and fiducial integrated and differential cross-section across 12 observables related to lepton, jet and E_T^{miss} kinematics

- $p_T^{\text{lead lep}}$ and $p_T^{\text{sub-lead lep}}$,
- $p_{T,\ell\ell}$, $y_{\ell\ell}$, $m_{\ell\ell}$ and $\Delta\Phi_{\ell\ell}$,
- $\cos\theta^* = |\tanh(\Delta\eta_{\ell\ell}/2)|$,
- E_T^{miss},
- scalar sum of E_T^{miss} and lepton transverse momenta $H_T^{\text{lep+met}}$,
- transverse mass of the dilepton system and the missing transverse momentum, $m_{T,\ell\ell}$
- scalar sum of all jet and lepton transverse momenta, S_T, and
- jet multiplicity.

MC Samples

Process	Generator	Parton shower	Matrix element $\mathcal{O}(\alpha_S)$	Normalization
$q\bar{q} \to WW$	MiNNLO	Pythia8	NNLO	Generator
$gg \to WW$	Sherpa2.2.2	Sherpa	LO (0–1 jet)	NLO
$t\bar{t}$	Powheg Boxv2	Pythia8	NLO	NNLO+NNLL
Wt	Powheg Boxv2	Pythia8	NLO	NLO+NNLL
Z+jets	Sherpa2.2.1	Sherpa	NLO (0–2 jets), LO (3–4 jets)	NNLO
WZ, ZZ	Sherpa2.2.2	Sherpa	NLO (0–1 jet), LO (2–3 jets)	Generator†
$W\gamma, Z\gamma$	Sherpa2.2.8	Sherpa	NLO (0–1 jet), LO (2–3 jets)	Generator†

†: The cross-section calculated by Sherpa is found to be in good agreement with the NNLO result [35,36,37,38,39].

- $gg \to WW$ sample includes off-shell effects and Higgs contributions
- WW, Z+jets, diboson production: NNPDF3.0NNLO PDF sets
- $t\bar{t}$: NNPDF3.0NLO PDF sets

Data-driven Top background estimate: b-tag counting method

Method inspired by $t\bar{t}$ cross section measurements [arx:1910.08819]

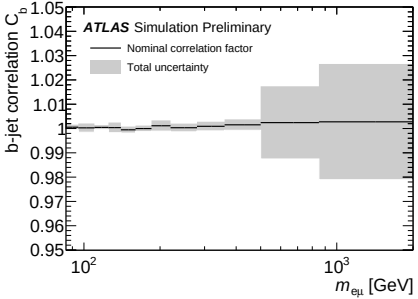
- Determine both number of $t\bar{t}$ events and probability ε_b of finding b-jets from event yields in one and two b-tag CRs
- Estimate yields in *each bin* of 0-b-jet region by extrapolation

$$N_{1b}^{t\bar{t}} = N_{\geq 0b}^{t\bar{t}} \cdot 2\varepsilon_b \left(1 - C_b \varepsilon_b\right) \ ,$$
$$N_{2b}^{t\bar{t}} = N_{\geq 0b}^{t\bar{t}} \cdot C_b \varepsilon_b^2 \ ,$$
$$N_{0b}^{t\bar{t}} = N_{\geq 0b}^{t\bar{t}} \cdot \left(1 - 2\varepsilon_b + C_b \varepsilon_b^2\right)$$

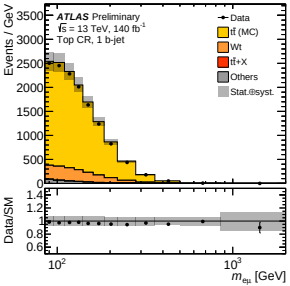
$$C_b = \frac{4 \cdot N_{\mathrm{MC}}^{t\bar{t}} N_{2b,\mathrm{MC}}^{t\bar{t}}}{\left(N_{1b,\mathrm{MC}}^{t\bar{t}} + 2 \cdot N_{2b,\mathrm{MC}}^{t\bar{t}}\right)^2}$$

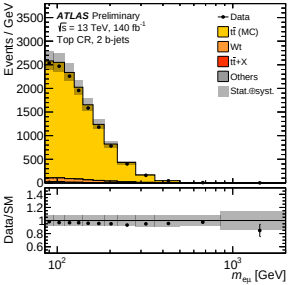
- Use *transfer factor method* where $N_{\mathrm{CR}2b} < 100$ events (≥ 1 b-jet CR)

$$N_{\mathrm{SR}}^{\mathrm{top}} = \frac{N_{\mathrm{SR}}^{\mathrm{top,MC}}}{N_{\mathrm{CR}}^{\mathrm{top,MC}}} \times \left(N_{\mathrm{CR}}^{\mathrm{data}} - N_{\mathrm{CR}}^{\mathrm{MC,others}}\right)$$



- Corrections C_b from MC are needed
  → Correlations finding 1st and 2nd b-jet
  → Modelling uncertainties on C_b,





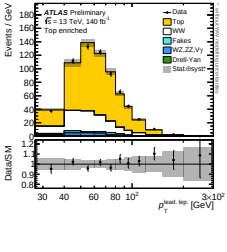
Other backgrounds and Validation

Data-driven lepton mis-ID estimate

- Extrapolation from CR (one loosened lepton fails ID selection) to SR
- Extrapolation factors computed in lepton misID-enriched region (dijet)
- Prompt contamination in CR (75%) subtracted using MC simulation.
- Dedicated calibration of loosened leptons
- Precision of 25% of background yields in SR

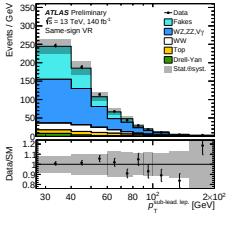
Top-enriched

$\geq$1 jet, m_{lj} <140 GeV,
$\Delta\phi(e,\mu) < \pi/2$



Same-sign VR

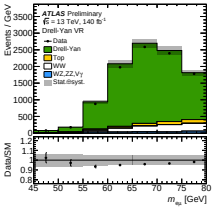
same-charge
dilepton system



Drell-Yan VR

(MC-based estimate)

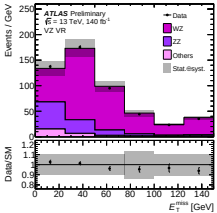
$45 < m_{e\mu} < 80$ GeV
$E_T^{\text{miss}} < 20$ GeV or
$p_{T,e\mu} < 30$ GeV



Diboson VR (WZ*,ZZ)

(MC-based estimate)

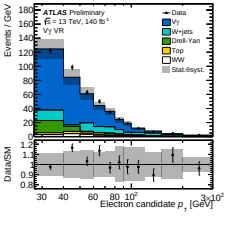
3ℓ, $m_{e\mu} > 45$ GeV
$80 < m_{\ell\ell,\text{SF}} < 100$ GeV



$V\gamma$ VR

(MC-based estimate)

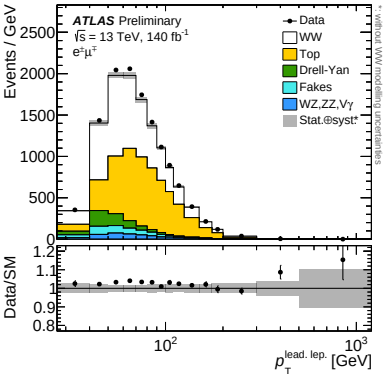
LooseLH electron ID
fail b-layer requirement

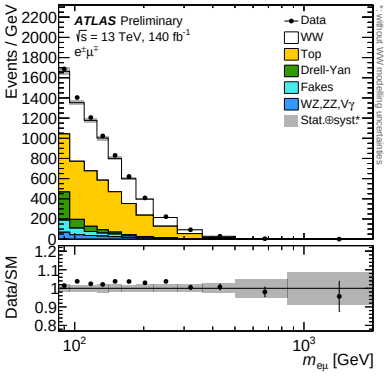


Good behavior of background estimates in VRs.

Selected W^+W^- events and differential observables

Category	Event yield	
Data	144221	
Total SM	139700 ± 2400	
WW	56900 ± 1100	41%
Total bkg.	82600 ± 2100	59%
Top	66500 ± 1900	48%
Drell-Yan	6500 ± 400	5%
Fakes	5000 ± 1300	4%
WZ,ZZ,$V\gamma$	4500 ± 600	3%





- Measurement dominated by background contributions
- Large top-quark background over signal, but estimated with better than 4% precision in most bins

Unfolding

- Differential cross-section measurements unfolded to particle level using iterative bayesian method (2 iterations)

Fit

Integrated fiducial cross-section determined using *profile log-likelihood fit*

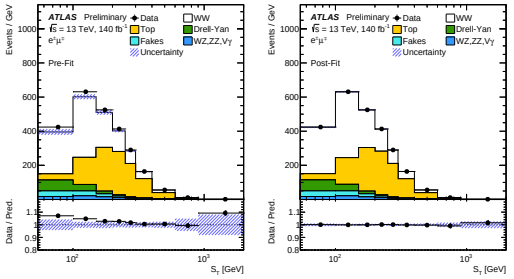
- Uncertainties better constrained by S_T distribution

Fiducial region

Object definition		
p_{T}^{ℓ}	$>$	27 GeV
$\lvert\eta^{\ell}\rvert$	$<$	2.5
$p_{\mathrm{T}}^{\ell,\ \mathrm{loose}}$	$>$	10 GeV
$\lvert\eta^{\ell,\ \mathrm{loose}}\rvert$	$<$	2.5
$p_{\mathrm{T}}^{b-\mathrm{jet}}$	$>$	20 GeV
$\lvert y^{b-\mathrm{jet}}\rvert$	$<$	2.5
$p_{\mathrm{T}}^{\mathrm{jet}}$	$>$	30 GeV
$\lvert y^{\mathrm{jet}}\rvert$	$<$	4.5

Fiducial selection requirements		
N_e	$=$	1
N_μ	$=$	1
$N_{\ell,\ \mathrm{loose}}$	$=$	2
$q_\mu \times q_e$	$=$	-1
$m_{e\mu}$	$>$	85 GeV
$N_{\text{b-jet}}$	$=$	0

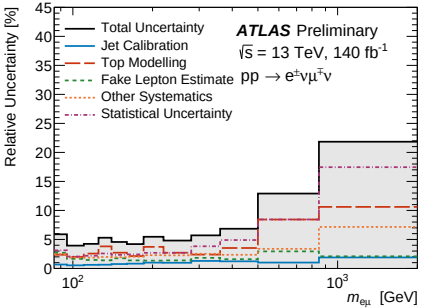
b-jet veto using ghost-association [arx:0707.1378]

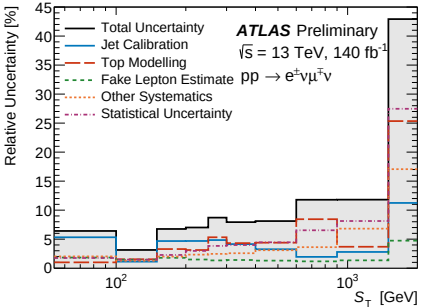


Uncertainties

- Dominated by systematic uncertainties from top-quark (MC modelling) and lepton mis-ID backgrounds
- Statistical uncertainties dominate in the high-energy tails

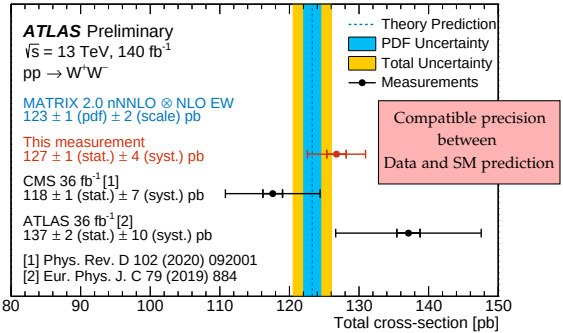
Uncertainty source	Effect
Total uncertainty	3.1%
Stat. uncertainty	1.1%
Top modelling	1.6%
Fake lepton background	1.5%
Flavour tagging	0.7%
Other background	0.9%
Signal modelling	1.0%
Jet calibration	0.6%
Luminosity	0.8%
Other systematic uncertainties	0.9%

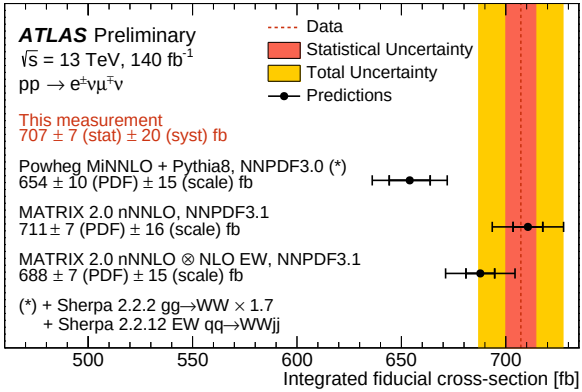




Total W^+W^- cross-section

- Profile log-likelihood fit of signal strength μ_{WW} in SR to determine integrated fiducial cross-section
- Extrapolate to full phase-space to obtain total cross-section
- Sizable differences between NNPDF3.0 and NNPDF3.1(+LUXQED) predictions
- Factor 2 improvement with respect to previous LHC measurements





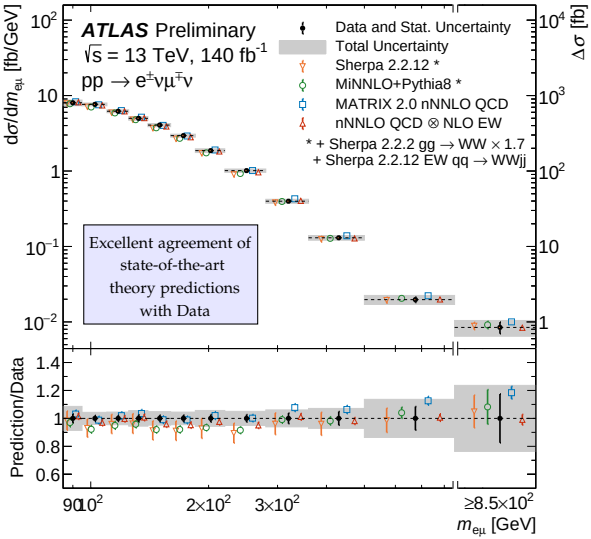
- **Precision of 3.1%**, dominated by top modelling and fake background estimate
- Excellent agreement with state-of-the-art theory prediction

Fiducial differential cross-section measurements

Theory predictions

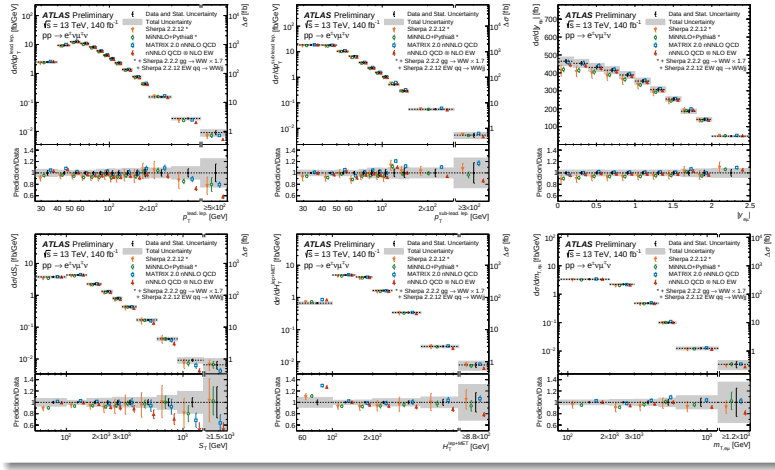
- **Sherpa 2.2.12**
  - $0,1j$@NLO-QCD, $2j$@LO. NNPDF3.0NNLO (*)
- **MiNNLO+Pythia8**
  - NNLO-QCD for inclusive distributions. NNPDF3.0NNLO (*)
- **Matrix 2.0 nNNLO QCD**
  - $qq \to WW$(NNLO-QCD)+$gg \to WW$(NLO-QCD)+$\gamma\gamma \to WW$. NNPDF3.1NNLO+LuxQED
- **Matrix 2.0 nNNLO QCD⊗NLO EW**
  - Also EW corrections

(*) Augmented with Sherpa 2.2.12 $VVjj$

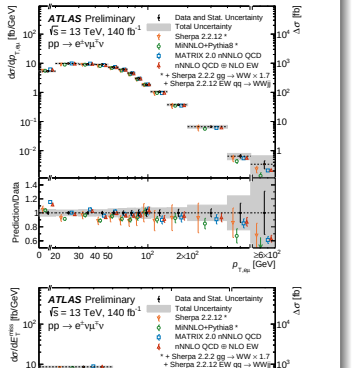


Fiducial differential cross-sections

QCD⊗EW corrections



QCD⊕EW corrections



Conclusions

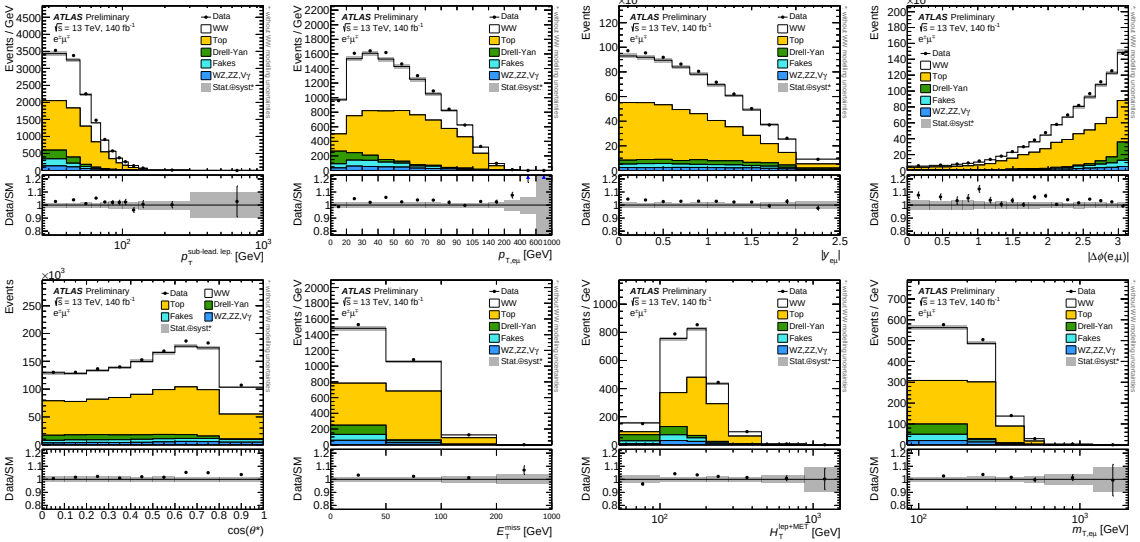
- Precision measurements of W^+W^- production are important tests of the Standard Model
- Fiducial (integrated and differential) cross-section measurements reported using full Run 2 dataset (140 fb^{-1}) recorded with the ATLAS experiment
  - $WW \to e^{\pm}\mu^{\mp}\nu\nu$ final states
  - b-jet veto to suppress top-quark background contributions
  - *No additional requirements on jet multiplicity*
- Top-quark and lepton misID background estimated using data-driven techniques with high accuracy.
- Fiducial cross-section with a precision of 3.1%, dominated by top-quark and lepton misID background estimates
  - Extrapolated to full phase space: $\sigma_{WW} = 127 \pm 4$ pb.
- Excellent agreement with state-of-the-art theory predictions

Backup slides

Selection criteria

Selection	Criteria
Lepton p_{T}	$> 27\,\mathrm{GeV}$
Lepton η	$\lvert\eta\rvert < 2.47$ and not $1.37 < \lvert\eta\rvert < 1.52$ (electron) $\lvert\eta\rvert < 2.5$ (muon)
Lepton identification	`TightLH` (electron), `Medium` (muon)
Lepton isolation	`Gradient` (electron), `Tight_FixedRad` (muon)
Lepton impact parameter	$\lvert d_0/\sigma_{d_0}\rvert < 5, 3$ (electron, muon) $\lvert z_0 \cdot \sin\theta\rvert < 0.5\,\mathrm{mm}$
b-jet selection	$p_{\mathrm{T}} > 20\,\mathrm{GeV}, \lvert\eta\rvert < 2.5$, DL1r (85% eff. WP)
Jet selection	$p_{\mathrm{T}} > 30\,\mathrm{GeV}$, $\lvert\eta\rvert < 4.5$
Lepton selection	1 electron and 1 muon of opposite charge, no additional lepton with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$, `Loose` isolation, and `LooseLH` (electron) / `Loose` (muon) identification
Number of b-jets	0
Dilepton invariant mass	$> 85\,\mathrm{GeV}$

Signal Region at reco level

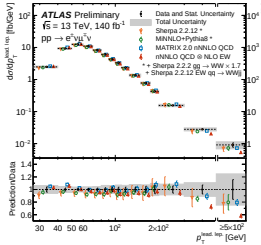


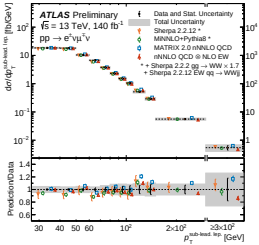
Theory Predictions

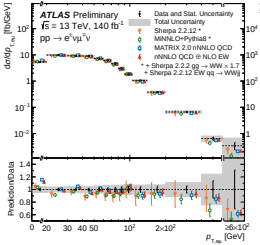
Process	Code	PDF	Perturbative order	Fid. cross-section	
$q\bar{q} \to WW$	MATRIX2.0.1	NNPDF3.1	NNLO QCD	674 fb	$\pm 1.8\,\%$
$q\bar{q} \to WW$	MiNNLO + Pythia8	NNPDF3.0	NNLO QCD + PS	624 fb	$\pm 1.1\,\%$
$q\bar{q} \to WW$	Sherpa2.2.12	NNPDF3.0	NLO QCD + PS †	630 fb	$\pm 7.2\,\%$
$gg \to WW$	MATRIX2.0.1	NNPDF3.1	NLO QCD	32 fb	$\pm 13\,\%$
$gg \to WW$	Sherpa2.2.2	NNPDF3.0	LO QCD + PS †	15 fb	$\pm 30\,\%$
$\gamma\gamma \to WW$	MATRIX 2.0.1	NNPDF3.1	LO	5 fb	$\pm 2.3\,\%$
$\gamma\gamma \to WW$	MATRIX 2.0.1	NNPDF3.1	NLO EW	11 fb	$\pm 2.3\,\%$
$q\bar{q} \to WWjj$ (EW)	Sherpa2.2.12	NNPDF3.0	LO + PS	4 fb	$\pm 7.0\,\%$
For calculation of NLO EW correction:					
$q\bar{q} \to WW$	MATRIX2.0.1	NNPDF3.1	LO	436 fb	$\pm 5.1\,\%$
$q\bar{q} \to WW$	MATRIX2.0.1	NNPDF3.1	NLO EW	418 fb	$\pm 5.1\,\%$

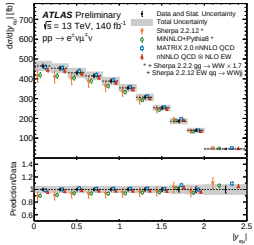
†: Includes matrix elements with additional parton emissions, matched and merged with the parton shower, which increases the accuracy of the simulation of high jet multiplicity events but also increases the nominal scale uncertainty.

Differential cross-section measurements









Differential cross-section measurements