Measurement of the W Boson Pair Production in pp Collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

GK Seminar

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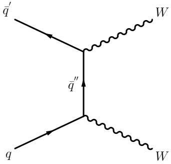
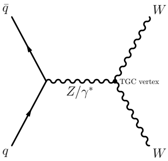
Results public under:
ATLAS-CONF-2014-033

$pp \to WW$ production at the LHC

Leading order processes:

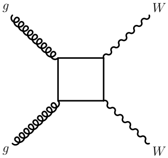
t- and s-channel scattering of $q\bar{q}$ initial states

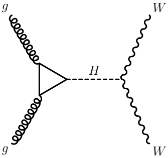




Higher order processes:

via gluon fusion,
SM Higgs contributes $\sim 7\%$ to total cross-section





Motivation:

- important test of EW theory
- TGC vertex in s-channel
- sensitivity to Higgs physics

$\rightarrow$ irreducible background to Higgs property measurements in $h \to WW$

Measurement:

- signature:
  two leptons (e or μ) and $E_{\mathrm{T}}^{\mathrm{miss}}$
- first measurement at $\sqrt{s} = 8$ TeV in ATLAS
- first measurement including the Higgs

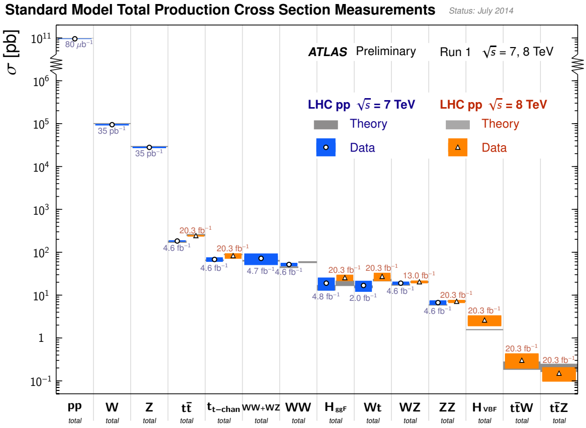
Past measurements at Tevatron and the LHC

		cross-section (meas.) [pb]	cross-section (theo.) [pb]	
CDF@1.96 TeV	3.6 fb^{-1}	$\sigma_{p\bar{p}\to WW} = 12.1 \pm 0.9(\text{stat})^{+1.6}_{-1.4}(\text{syst})$	$\sigma_{p\bar{p}\to WW} = 11.7 \pm 0.7$	link
DØ@1.96 TeV	9.7 fb^{-1}	$\sigma_{p\bar{p}\to WW} = 11.6 \pm 0.4(\text{stat}) \pm 0.6(\text{syst})$	$\sigma_{p\bar{p}\to WW} = 11.3 \pm 0.7$	link
CMS@7 TeV	4.9 fb^{-1}	$\sigma_{pp\to WW} = 52.4 \pm 2.0(\text{stat}) \pm 4.5(\text{syst}) \pm 1.2(\text{lumi})$	$\sigma_{pp\to WW} = 47.0 \pm 2.0$	link
ATLAS@7 TeV	4.6 fb^{-1}	$\sigma_{pp\to WW} = 51.9 \pm 2.0(\text{stat}) \pm 3.9(\text{syst}) \pm 2.0(\text{lumi})$	$\sigma_{pp\to WW} = 44.7 \pm 2.8$	link
CMS@8 TeV	3.5 fb^{-1}	$\sigma_{pp\to WW} = 69.9 \pm 2.8(\text{stat}) \pm 5.6(\text{syst}) \pm 3.1(\text{lumi})$	$\sigma_{pp\to WW} = 57.3^{+2.4}_{-1.6}$	link

The theory prediction for 8 TeV is $58.7^{+3.0}_{-2.7}$ pb, it's the sum of:

Process	Cross section [pb]	Scale [pb]	PDF+α_s [pb]	Branching fraction [pb]	Calculation	Total [pb]
$q\bar{q} \to WW$	53.2	$^{+2.3}_{-1.9}$	$^{+1.0}_{-1.1}$	-	NLO MCFM [1]	$^{+2.5}_{-2.2}$
$gg \to WW$	1.4	$^{+0.3}_{-0.2}$	$^{+0.1}_{-0.1}$	-	LO MCFM [1]	$^{+0.3}_{-0.2}$
$gg \to H \to WW$	4.1	$\pm$ 0.3	$\pm$0.3	$\pm$0.2	NNLO+NNLL QCD, NLO EW [3]	$\pm$0.5

Background Processes

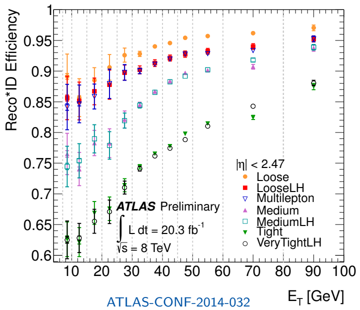


- need to reject processes with cross-sections many orders of magnitude higher
- some of them have very similar signatures to the fully leptonic *WW*
- crucial is the effective rejection of fake leptons and (*b*-)jets
- and the performance of missing transverse energy

Lepton Selection

- fake leptons are difficult to model and estimate
- strategy is to reduce as much of it as possible, here explained for electrons

- requirements of opposite-sign leptons with $p_T > 25/20$ GeV for leading and sub-leading lepton
- very strict criteria on lepton identification (ID)



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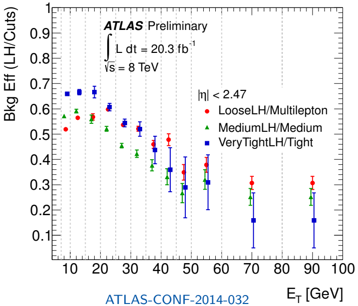

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- choose strictest criterion and use brandnew MVA based (LH) ID menu
- on top of that a strict selection on impact parameters, calorimeter and track isolation (efficiency $\sim 95\%$) are applied

Data-Set and Backgrounds

- full 2012 dataset of $L = 20.3 \pm 0.6\,\text{fb}^{-1}$ at 8 TeV
- exactly two isolated, opposite charge leptons with $p_T > 25/20$ GeV

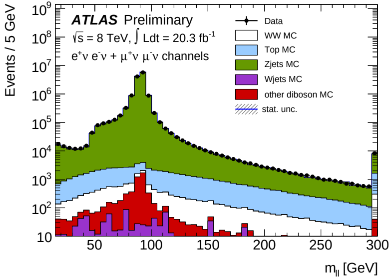
- large background from Z+jets in same-flavour channels
- background from $Z/\gamma^* \to \tau\tau$ in $e\mu$ channel

→ rejected by selection on Z mass window (in same-flavour channels only) and E_T^{miss}

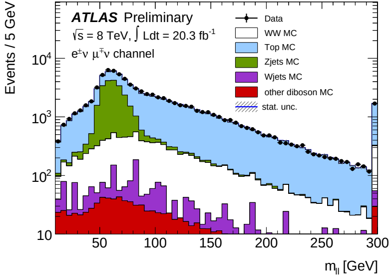
- background from top with W from top decay

→ rejected by vetoing events with one or more jets

- variety of diboson background, $W\gamma$, $W\gamma^*$, WZ and ZZ



$Z/\gamma^* \to ee, \mu\mu$, $M_{\ell\ell} > 15$ GeV, $|M_{\ell\ell} - m_Z| < 15$ GeV



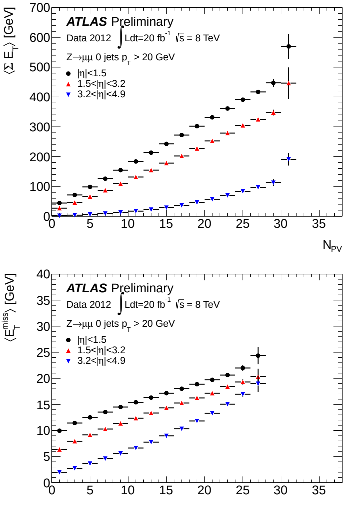
$Z/\gamma^* \to \tau\tau$, $M_{\ell\ell} > 10$ GeV

Event Selection on $E_{\mathrm{T}}^{\mathrm{miss}}$

- the only handle to reject Z+jets background is missing transverse energy $E_{\mathrm{T}}^{\mathrm{miss}}$
- limited $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution in 2012 run-conditions necessitates harder selection

- using $E_{\mathrm{T,\,Rel}}^{\mathrm{miss}}$, i.e. the projection of $E_{\mathrm{T}}^{\mathrm{miss}}$ on close-by ($\Delta\phi < \pi/2$) leptons or jets
- additional selection on $p_{\mathrm{T}}^{\mathrm{miss}}$, based on tracks in inner detector (using spectrometer and calorimeter information for muons and electrons respectively)
- selection on azimuth separation between the two

- $E_{\mathrm{T,\,Rel}}^{\mathrm{miss}} > 15/45$ GeV in $e\mu$ and $ee/\mu\mu$
- $p_{\mathrm{T}}^{\mathrm{miss}} > 20/45$ GeV in $e\mu$ and $ee/\mu\mu$
- $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\mathrm{miss}}) < 0.6/0.3$ in $e\mu$ and $ee/\mu\mu$



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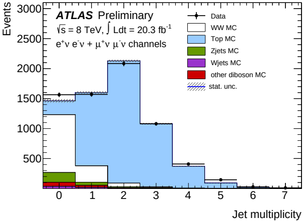
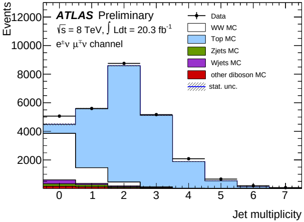
- $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\mathrm{miss}})$ is crucial for background estimation as Z+jets backgrounds are uncorrelated in this variable

Event Selection on Jet Veto

- top background has very similar signature to the *WW* signal, but additional jets
- rejected by requiring 0 jets in the event
- large source of experimental and theoretical uncertainties





- jet veto correction to $q\bar{q} \to WW$ events derived from $q\bar{q} \to Z$ events

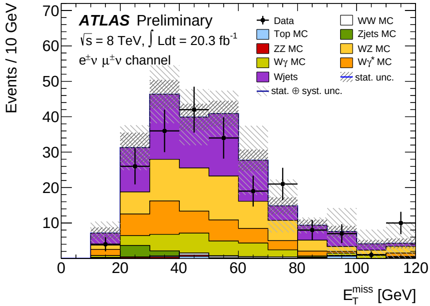
$$\epsilon_{WW}^{\text{data}} = \epsilon_{WW}^{\text{MC}} \times f_Z \quad \text{with} \quad f_Z = \frac{\epsilon_Z^{\text{data}}}{\epsilon_Z^{\text{MC}}}$$

- Z events provide an effective calibration of jet energy scale and resolution
- $f_Z = 0.990 \pm 0.029(\text{exp.}) \pm 0.032(\text{theo.})$

- theo. uncertainties determined by varying independently factorisation and renormalisation scales, variation of PDF, parton shower, generator
- benefit of cancelling experimental uncertainties is partially offset by theory-induced uncertainties

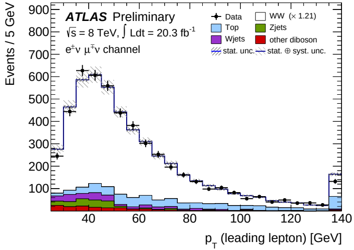
Background Estimation

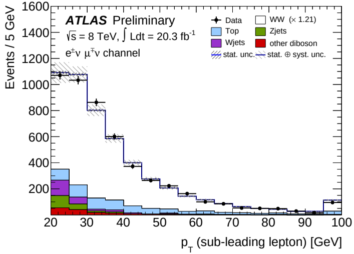
- data-driven background estimation using JVSP (top), matrix-method (W+jets) and shape-fit (Z+jets)
- diboson background determined from MC simulation



- validation of W+jets and diboson estimate in $e\mu$ same-sign region
- nominal selection, but same-sign instead of opposite-sign requirement
- data agrees with estimated yield within uncertainties

Signal and Background Yield





- highest signal yield with lowest background contamination in $e\mu$ channel
- same-flavour channels suffer from hard E_T^{miss} selection
- muons have the higher selection efficiency and acceptance

Channel	$e^{\pm}\mu^{\mp}$	$e^{+}e^{-}$	$\mu^{+}\mu^{-}$
Observed Events	5067	594	975
Total expected events	$4376 \pm 26 \pm 280$	$536 \pm 10 \pm 42$	$873 \pm 12 \pm 63$
MC *WW* signal	$3224 \pm 10 \pm 248$	$346 \pm 3 \pm 32$	$610 \pm 5 \pm 56$
Top(data-driven)	$609 \pm 18 \pm 52$	$92 \pm 7 \pm 8$	$127 \pm 9 \pm 11$
W+jets(data-driven)	$220 \pm 15 \pm 112$	$14 \pm 5 \pm 9$	$3 \pm 5 \pm 6$
Z+jets (data-driven)	$166 \pm 3 \pm 26$	$55 \pm 1 \pm 23$	$96 \pm 2 \pm 27$
Other dibosons (MC)	$157 \pm 4 \pm 31$	$30 \pm 2 \pm 5$	$39 \pm 1 \pm 5$
Total background	$1152 \pm 24 \pm 130$	$190 \pm 9 \pm 26$	$264 \pm 11 \pm 30$

Acceptance Correction Factors

To extrapolate the signal yield to a cross-section the correction factors C_{WW} and A_{WW} are defined as

$$A_{WW\to\ell\nu\ell\nu} = \frac{N^{\text{gen in fiducial region}}_{WW\to\ell\nu\ell\nu}}{N^{\text{all gen}}_{WW\to\ell\nu\ell\nu}} \text{ and } C_{WW\to\ell\nu\ell\nu} = \frac{N^{\text{reco in fiducial region}}_{WW\to\ell'\nu\ell'\nu}}{N^{\text{gen in fiducial region}}_{WW\to\ell\nu\ell\nu}}$$

with $\ell = e \text{ or } \mu$ and $\ell' = e, \mu \text{ or } \tau(\to e, \mu)$.

For a given channel $WW \to \ell\nu\ell\nu$ with $\ell = e \text{ or } \mu$ the fiducial cross section is defined

$$\sigma^{\text{fid}}_{WW\to\ell\nu\ell\nu} = \frac{N^{\text{obs}}_{\ell\nu\ell'\nu} - N^{\text{bkg}}_{\ell\nu\ell'\nu}}{\mathcal{L} \times C_{WW\to\ell\nu\ell\nu}}$$

The fiducial cross-sections include only prompt electrons and muons from W bosons.

The total cross-section in the total phase space volume in each channel is calculated with

$$\sigma^{\text{tot}}_{WW} = \frac{\sigma^{\text{fid}}_{WW\to\ell\nu\ell\nu}}{A_{WW\to\ell\nu\ell\nu} \times \text{BR}\,(WW \to \ell\nu\ell\nu)}$$

The total cross-section includes all decay modes of the W bosons.

Channels	C_{WW}	$A_{WW} \times C_{WW}$
$e\nu\mu\nu$	0.511 ± 0.025	0.116 ± 0.007
$e\nu e\nu$	0.291 ± 0.021	0.025 ± 0.002
$\mu\nu\mu\nu$	0.471 ± 0.033	0.044 ± 0.004

Systematic Uncertainties

- overall systematic uncertainty of 5.4% in $e\mu$ channel
- largest theoretical uncertainty originating from jet veto
- experimental uncertainties mainly from pileup modelling, E_T^{miss}, JER and jet veto
- strict criteria on E_T^{miss} in same-flavour channels cause a higher uncertainty
- di-lepton triggers give large uncertainties
- A_{WW} and C_{WW} uncertainties partially cancel when calculating the product

Sources	$e^\pm\mu^\mp$	e^+e^-	$\mu^+\mu^-$
C_{WW} **experimental uncertainties**			
Pileup	1.3%	1.9%	2.0%
e trigger efficiency	0.3%	2.5%	–
μ trigger efficiency	0.3%	–	2.8%
Muon MS resolution	0.0%	–	0.1%
Muon ID resolution	0.5%	–	1.5%
Muon scale	0.1%	–	0.4%
Muon efficiency	0.4%	–	0.8%
Muon isolation/IP	0.6%	–	1.1%
Electron resolution	0.0%	0.2%	–
Electron energy scale	0.4%	1.4%	–
Electron efficiency	0.9%	2.0%	–
Electron isolation/IP	0.2%	0.4%	–
Jet vertex fraction	0.2%	0.2%	0.2%
Jet energy scale	2.6%	2.6%	2.6%
Jet energy resolution	2.3%	2.2%	2.9%
E_T^{miss} soft term resolution	0.3%	0.3%	0.5%
E_T^{miss} soft term scale	2.3%	4.2%	3.8%
p_T^{miss} soft term resolution	0.1%	0.0%	0.2%
p_T^{miss} soft term scale	0.3%	0.6%	0.5%
Total experimental uncertainties	3.7%	6.3%	6.3%
C_{WW} **theoretical uncertainties**			
Jet-veto requirement (theory)	3.2%	3.2%	3.2%
PDF	0.4%	0.6%	0.1%
Scale	0.6%	1.7%	0.7%
Total theoretical uncertainties	3.3%	3.7%	3.3%
Total (exp.+theo.)	5.0%	7.3%	7.1%
$A_{WW} \times C_{WW}$ **theoretical uncertainties**			
Jet-veto requirement (theory)	3.3%	3.3%	3.3%
PDF	1.3%	1.6%	0.8%
Scale	1.5%	2.0%	1.8%
Total theoretical uncertainties	3.9%	4.2%	3.8%
Total (exp.+theo.)	5.4%	7.6%	7.4%

Fiducial and Total Cross-Sections

Resulting fiducial cross-sections in the individual channels are

Channel	$\sigma_{WW}^{\text{fiducial}}$ [fb]
$e\mu$	$377.8^{+6.9}_{-6.8}$ (stat) $^{+25.1}_{-22.2}$ (syst) $^{+11.4}_{-10.7}$ (lumi)
ee	$68.5^{+4.2}_{-4.1}$ (stat) $^{+7.7}_{-6.6}$ (syst) $^{+2.1}_{-2.0}$ (lumi)
$\mu\mu$	$74.4^{+3.3}_{-3.2}$ (stat) $^{+7.0}_{-6.0}$ (syst) $^{+2.3}_{-2.1}$ (lumi)

The corresponding theoretical fiducial cross-sections $\sigma_{\text{theo}}^{\text{tot}} \times A_{WW}$ are $\sigma_{WW\to\ell\nu\ell\nu}^{\text{fid}} = 58.7$ (ee), 63.8 ($\mu\mu$) and 311.2 fb($e\mu$)

Fiducial and Total Cross-Sections

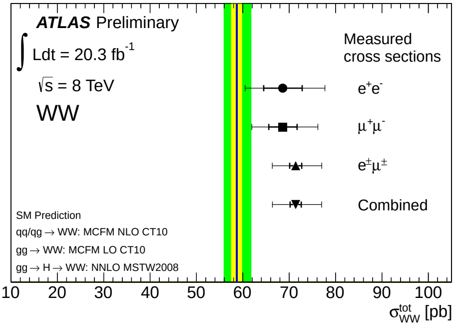
The total cross-sections measured in the individual channels are:

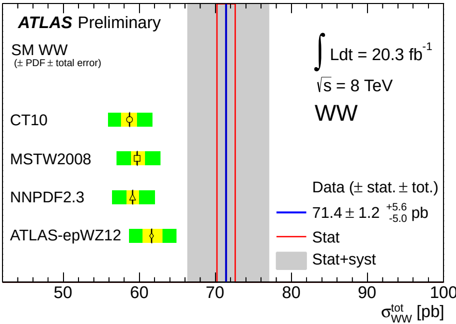
Channel	$\sigma_{WW}^{\text{total}}$ [pb]
$e\mu$	$71.4^{+1.3}_{-1.3}$ (stat) $^{+5.0}_{-4.4}$ (syst) $^{+2.1}_{-2.0}$ (lumi)
ee	$68.6^{+4.2}_{-4.1}$ (stat) $^{+7.8}_{-6.7}$ (syst) $^{+2.1}_{-2.0}$ (lumi)
$\mu\mu$	$68.6^{+3.1}_{-3.0}$ (stat) $^{+6.6}_{-5.6}$ (syst) $^{+2.1}_{-2.0}$ (lumi)
Combined	$71.4^{+1.2}_{-1.2}$ (stat) $^{+5.0}_{-4.4}$ (syst) $^{+2.2}_{-2.1}$ (lumi)

The three channels yield consistent results, they are all higher than the Standard-Model prediction of 58.7 pb.

Observed an excess of $\sim 20\%$ or 2.1σ.

Total Cross-Sections





- compatibility of the three channels in graphical visualisation and combined result (left)
- combined in comparison with theoretical cross-section calculated for different PDFs (right)

Summary

- presented the WW cross-section measurement with 20 fb^{-1} of data
- observed 6636 events, where $\sim$ 5865 are expected (S+B)
- measurement has been performed in three different channels, all yielding consistent results
- combined cross section was measured to:

$$\sigma_{WW}^{\text{tot}} = 71.4^{+1.2}_{-1.2}(\text{stat})^{+5.0}_{-4.4}(\text{syst})^{+2.2}_{-2.1}(\text{lumi})\text{pb}$$

- this is $\sim$ 20% and 2.1σ higher than the MCFM calculation @ NLO with CT10

- analysis has been documented in a ATLAS-CONF-2014-033

Backup

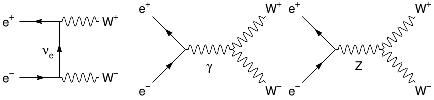
Neglected $pp \to WW$ contributions and PDFs

Total prediction for WW production		
Process	cross section [pb]	Calculation
Total WW	$58.7^{+3.0}_{-2.7}$	see Table 1
Neglected estimated contributions to WW production		
Process	Estimated change in total cross section [pb]	Calculation
$gg \to WW$	up to +2.8	see Ref. [4]
WW	-0.5	see Ref. [5]
$\gamma\gamma$-induced WW	+0.5	see Ref. [5,6]
Vector boson scattering topology	<+0.5	see Ref. [7]
Double parton interaction	+0.04	see Ref. [11]

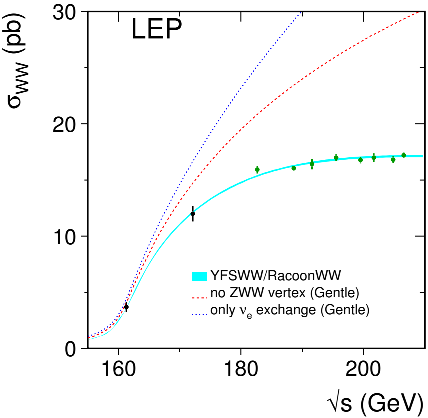
	CT10	NNPDF2.3	MSTW2008	ATLAS-epWZ12
$pp \to WW$ [pb]	$54.6^{+1.0}_{-1.1}$	$55.0^{+0.9}_{-0.9}$	$55.6^{+1.0}_{-0.8}$	$57.5^{+1.4}_{-1.2}$
non-resonant gg contribution [pb]	1.4	1.5	1.5	1.3

W Pairs at LEP

- W^+W^- production at in e^+e^- collisions:



- process has been used at LEP to prove non-abelian structure of the electroweak interaction
- used to measure the W mass from turn-on vs. $\sqrt{s}$
- experimental results on the right plot show that all three feynman diagrams must exist



- agreement with MC prediction as a function of $\sqrt{s}$
- documented in Phys.Rep. 532, 119-244 (2013)

Electron ID efficiency for background processes

- fake electron efficiency wrt. reco + track-quality for different fake categories
- the efficiency for reco + track-quality is $8.89 \pm 0.16(\text{stat.})$ %

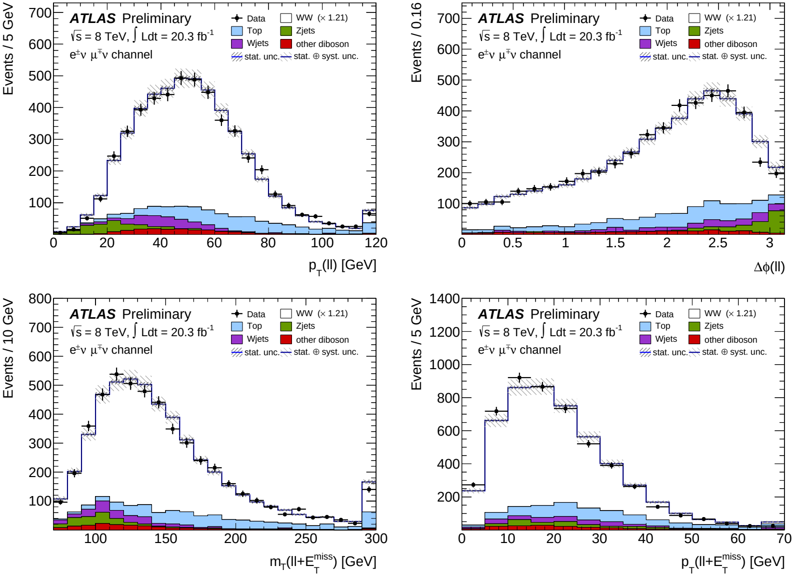
$20 < E_T < 50$ GeV								
Selection	Data efficiency $Z \to ee$ signal	MC efficiency Background (prompt e excluded)	Background composition (%)			MC efficiency (%) for background categories		
			non-iso e	bkg e	hadron	non-iso e	bkg e	hadron
Track Quality	100.0	100.00	1.1	16.1	82.8	100.0	100.00	100.000
loose cuts	95.7 ± 0.2	4.76 ± 0.04	7.4	48.4	44.2	32.5±0.8	14.3±0.2	2.54±0.03
multilepton cuts	92.9 ± 0.2	1.64 ± 0.02	22.5	34.5	43.0	34.2±0.8	3.51±0.08	0.85±0.02
medium cuts	88.1 ± 0.2	1.11 ± 0.02	25.8	50.5	23.7	26.5±0.8	3.46±0.08	0.32±0.01
tight cuts	77.5 ± 0.2	0.46 ± 0.01	54.5	29.9	15.6	23.0±0.7	0.85±0.04	0.086±0.006
LOOSE LH	92.8 ± 0.2	0.94 ± 0.02	40.2	42.0	17.9	34.8±0.8	2.44±0.07	0.20±0.01
MEDIUM LH	87.8 ± 0.3	0.51 ± 0.01	48.8	40.6	10.7	23.1±0.7	1.29±0.05	0.066±0.005
VERY TIGHT LH	77.0 ± 0.3	0.29 ± 0.01	63.7	28.9	7.4	16.9±0.7	0.51±0.03	0.026±0.003

- documented in ATLAS-CONF-2014-032

Fiducial Cut-flow

Selections	$e\mu$ Channel		ee Channel		$\mu\mu$ Channel	
	$e\nu\mu\nu$	$\tau\nu\ell'\nu$	$e\nu e\nu$	$\tau\nu\ell'\nu$	$\mu\nu\mu\nu$	$\tau\nu\ell'\nu$
Total	27821	10655	13911	5327	13911	5327
Trigger, Lepton ID and lepton p_{T}	7977	872	3052	353	5020	507
$m_{ll} > 10/15$ GeV	7971	872	3030	351	4978	503
$\lvert m_{ll} - m_Z \rvert < 15$ GeV	7971	872	2345	261	3840	376
$E_{\mathrm{T,\ Rel}}^{\mathrm{miss}} > 15/45$ GeV	6180	639	892	77	1531	118
$p_{\mathrm{T}}^{\mathrm{miss}} > 20/45$ GeV	5522	574	698	54	1196	81
$\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, p_{\mathrm{T}}^{\mathrm{miss}}) < 0.6/0.3$	4313	440	453	35	786	53
Jet-veto requirement	2941	284	325	21	574	36
Efficiency	10.6%	2.7%	2.3%	0.4%	4.1%	0.7%

Kinematic Distributions in $e\mu$ channel



Cross-Section Extraction

The cross-section is extracted by minimizing the negative log-likelihood function:

$$-\ln L(\sigma, \{x_k\}) = \sum_{i=1}^{3} -\ln\left(\frac{e^{-(N_s^i(\sigma,\{x_k\})+N_b^i(\{x_k\}))} \times (N_s^i(\sigma, \{x_k\}) + N_b^i(\{x_k\}))^{N_{\text{obs}}^i}}{(N_{\text{obs}}^i)!}\right) + \sum_{k=1}^{n} \frac{x_k^2}{2}$$

with the number of expected signal, background and observed data events $N_S^i, N_b^i, N_{\text{obs}}^i$ for channels $i = ee, \mu\mu, e\mu$ and systematic uncertainties k. This is essentially the Poisson probability that $N_S^i + N_b^i$ events will produce N_{obs}^i events.

References

9 Summary

The WW production cross section in pp collisions at $\sqrt{s} = 8$ TeV is measured using 20.3 fb^{-1} of data collected by the ATLAS detector during 2012. The measurement is conducted using three final states with $e^{\pm}\mu^{\mp}$, $e^{+}e^{-}$and $\mu^{+}\mu^{-}$, all accompanied by $E_{\mathrm{T}}^{\mathrm{miss}}$. The measurement of the fiducial and the total production cross sections are reported. The measured WW production cross section in the total phase space is $71.4^{+1.2}_{-1.2}$ (stat) $^{+5.0}_{-4.4}$ (syst) $^{+2.2}_{-2.1}$ (lumi) pb.

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