Measurement of *WW* and *ZZ* production with the ATLAS detector

Andy Nelson[1]
for the *WW* and *ZZ* analysis groups

[1] University of California, Irvine

October 10, 2012

Introduction

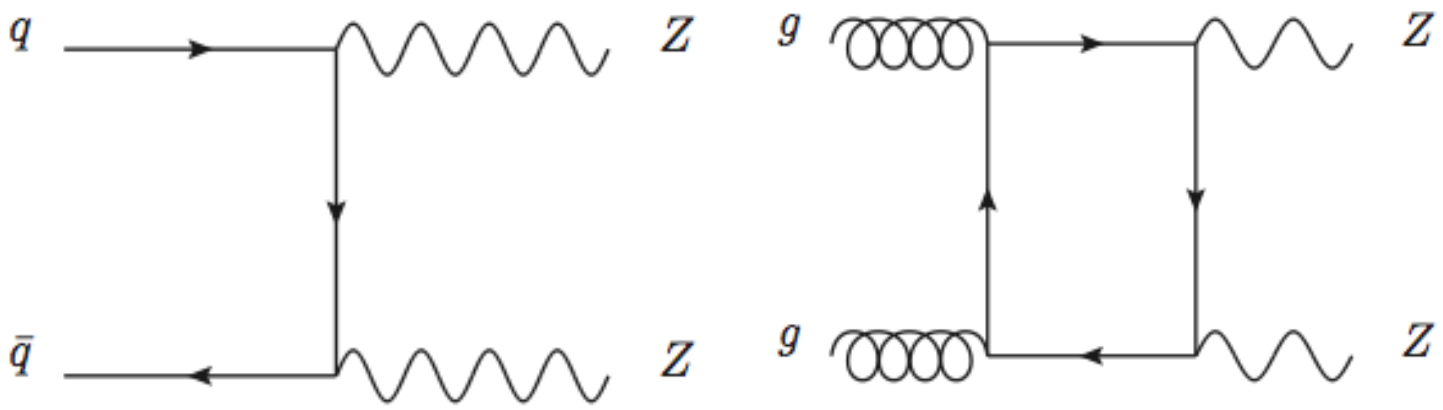
- Why is measuring *WW* and *ZZ* cross sections important?
  - Diboson processes provide a test of important properties of the Standard Model
  - Differences between measured and predicted SM cross sections can indicate new physics
  - Major backgrounds to Higgs and other new physics processes
- Measured cross sections both 7 TeV and 8 TeV
- Here we present measurements of the total cross section using reconstructed electrons and muons and $E_{\mathrm{T}}^{\mathrm{miss}}$
  - ℓ will refer to electrons or muons

Measurements

- $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ 4.7 fb^{-1} at $\sqrt{s} = 7$ TeV (ATLAS-CONF-2012-026)
- $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ 5.8 fb^{-1} at $\sqrt{s} = 8$ TeV (ATLAS-CONF-2012-090)
- $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ 4.7 fb^{-1} at $\sqrt{s} = 7$ TeV (ATLAS-CONF-2012-027)
- $WW \to \ell^+\nu\ell^-\bar{\nu}$ 4.7 fb^{-1} at $\sqrt{s} = 7$ TeV (ATLAS-STDM-2012-01, to be submitted to PRD)

ZZ and WW Cross Sections

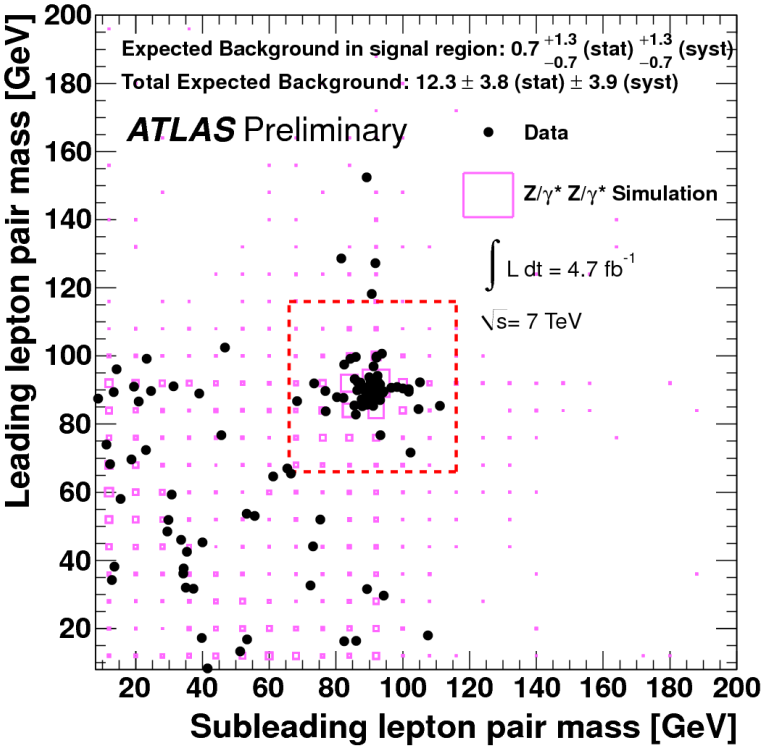
- Measure both fiducial and total cross sections
- ZZ is measured in the $\ell^+\ell^-\ell'^+\ell'^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states
- WW is measured in the $\ell^+\nu\ell^-\bar{\nu}$ final state
- ZZ and WW are produced from $q\bar{q}$ and gg in both t and u channels



$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ Fiducial Region

- Measurement at 7 TeV
  - Four and only four leptons (two positively and two negatively charged)
  - $p_{\mathrm{T}} >$ 7 GeV
  - $|\eta| <$ 2.7
  - Invariant mass of lepton pairs between 66 and 116 GeV
- Measurement at 8 TeV
  - Four and only four leptons (two positively and two negatively charged)
  - $p_{\mathrm{T}} >$ 15 GeV
  - $|\eta| <$ 2.5
  - Invariant mass of lepton pairs between 66 and 116 GeV
  - No pair of leptons with $\Delta R < 0.2$ ($\Delta R \equiv \sqrt{\Delta\phi^2 + \Delta\eta^2}$)

$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ Lepton Pair Mass



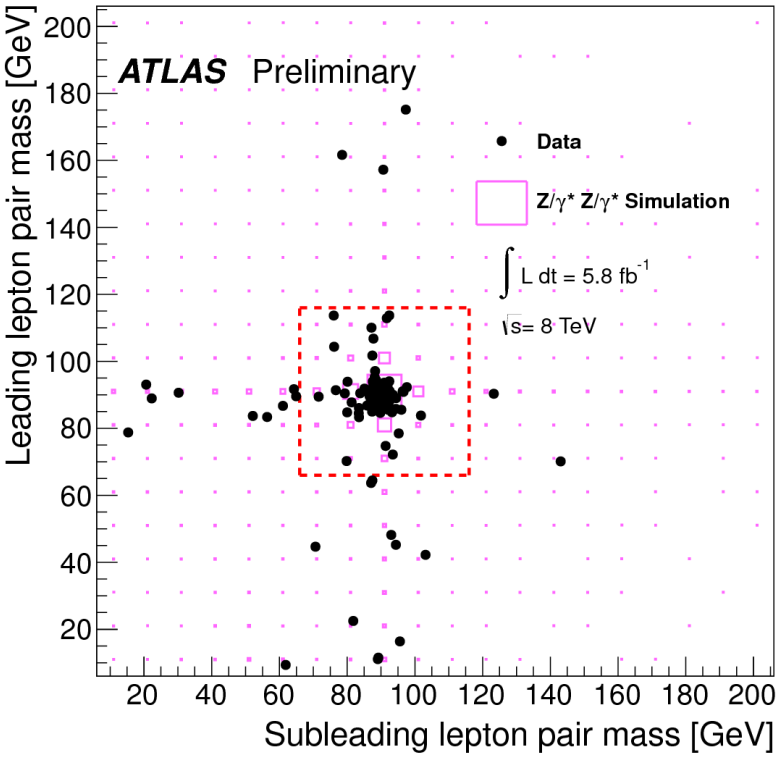


Figure: Invariant masses of the lepton pairs at 7 TeV (left) and 8 TeV (right)

$ZZ \to \ell^+\ell^-\nu\bar{\nu}$ Fiducial Region

- Two and only two oppositely charged leptons
- $p_{\mathrm{T}} >$ 20 GeV
- $|\eta| < 2.5$
- Component of vector sum p_{T} of neutrinos parallel to reconstructed $Z >$ 80 GeV (axial-$E_{\mathrm{T}}^{\mathrm{miss}}$)
- Relative difference of $E_{\mathrm{T}}^{\mathrm{miss}}$ and $p_{\mathrm{T}}^{Z} < 0.6$
- Reject events with a well-reconstructed jet of $p_{\mathrm{T}} >$ 25 GeV and $|\eta| < 4.5$

$ZZ \to \ell^+\ell^-\nu\bar{\nu}$ axial-E_T^{miss}

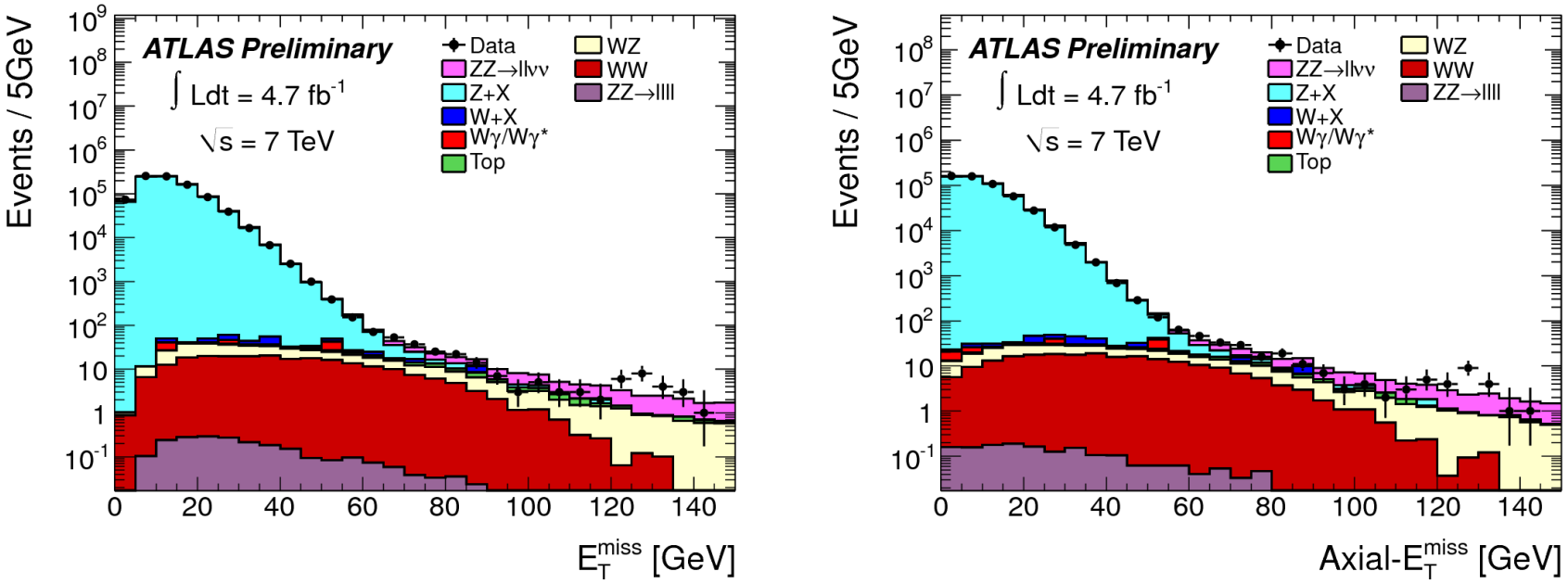


Figure: E_T^{miss} (left) and axial-E_T^{miss} (right)

$WW \to \ell^+\nu\ell^-\bar{\nu}$ Fiducial Region

- Two and only two oppositely charged leptons
- Leading lepton $p_{\mathrm{T}} >$ 25 GeV
- p_{T} of subleading leptons have $p_{\mathrm{T}} >$ 20 GeV
- $p_{\mathrm{T}}^{\ell\ell'} >$ 30 GeV
- Muons have $|\eta| < 2.4$; electrons have $|\eta| < 2.47$, excluding the transition region ($1.37 < |\eta| < 1.52$)
- Component of vector sum p_{T} of neutrinos perpendicular to the nearest lepton or jet (unless it is more than $\frac{\pi}{2}$ away) is called $E_{\mathrm{T}}^{\mathrm{miss}}$

Channel	ee	$\mu\mu$	$e\mu$
$E_{\mathrm{T,Rel}}^{\mathrm{miss}}$	$>$ 45 GeV	$>$ 45 GeV	$>$ 25 GeV

- Low mass cut and Z veto:

Channel	ee	$\mu\mu$	$e\mu$
$m_{\ell\ell'}$	$>$ 15 GeV	$>$ 15 GeV	$>$ 10 GeV
$\lvert m_{\ell\ell'} - m_Z \rvert$	$>$ 15 GeV	$>$ 15 GeV	$>$ 0 GeV

- Reject events with a well-reconstructed jet of $p_{\mathrm{T}} >$ 25 GeV and $|\eta| < 4.5$

$WW \to \ell^+\nu\ell^-\bar{\nu}$ $m_{\ell\ell'}$

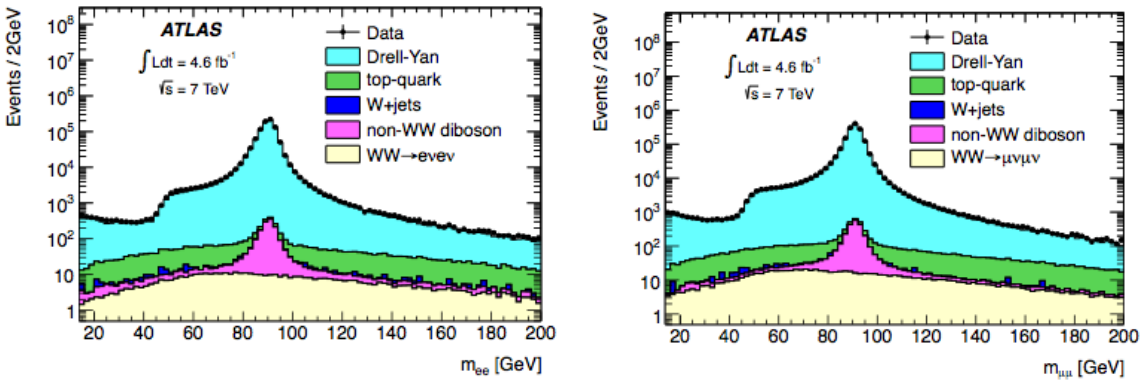


Figure: $m_{\ell\ell'}$ for the ee (left) and $\mu\mu$ (right) channels

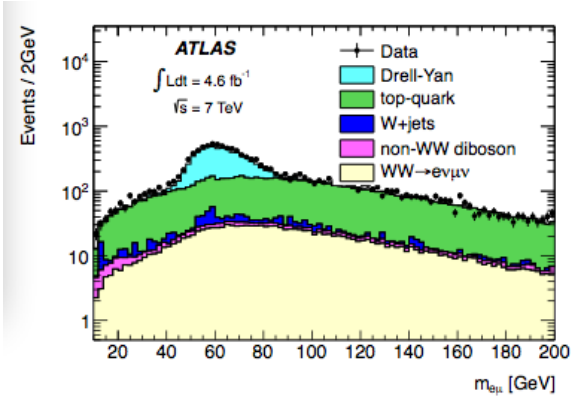


Figure: $m_{\ell\ell'}$ for the $e\mu$ channel

$WW \to \ell^+\nu\ell^-\bar{\nu}$ $E_{\mathrm{T,Rel}}^{\mathrm{miss}}$

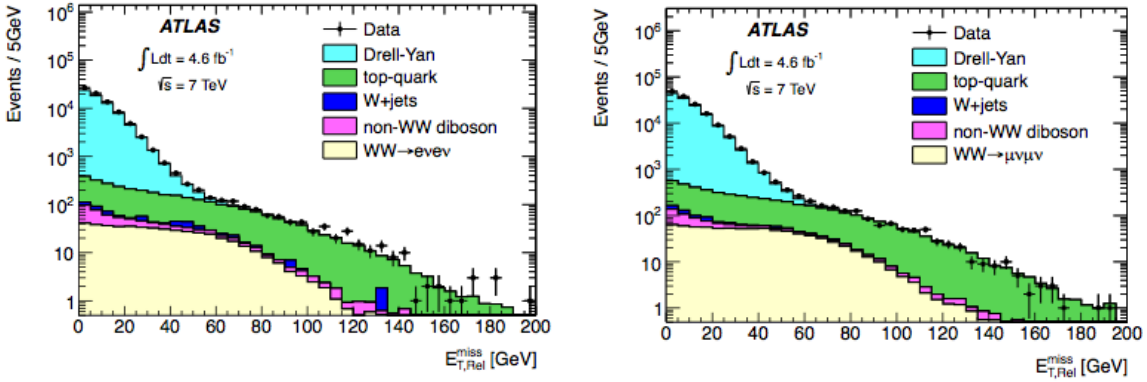


Figure: $E_{\mathrm{T,Rel}}^{\mathrm{miss}}$ for the ee (left) and $\mu\mu$ (right) channels

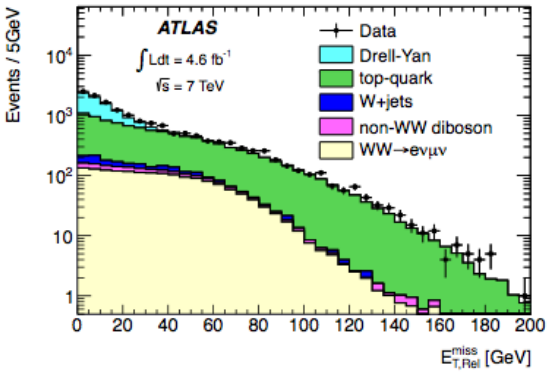


Figure: $E_{\mathrm{T,Rel}}^{\mathrm{miss}}$ for the $e\mu$ channel

Systematic Uncertainties

- Systematic uncertainty in the $ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$ channel is dominated by electron identification efficiency and muon reconstruction efficiencies
  - For electrons these uncertainties are

Channel	$e^+e^-e^+e^-$	$e^+e^-\mu^+\mu^-$
7 TeV	5.8%	2.8%
8 TeV	3.8%	1.9%

  - For muons these uncertainties are

Channel	$\mu^+\mu^-\mu^+\mu^-$	$e^+e^-\mu^+\mu^-$
7 TeV	1.3%	0.6%
8 TeV	1.0%	0.5%

- The dominant systematic uncertainty in the $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ and $WW \rightarrow \ell^+\nu\ell^-\bar{\nu}$ channels come from the jet veto efficiency, and are 5.3% and 3.6%, respectively

Cross Section Definition

- Measure fiducial cross section in phase space close to acceptance to reduce theory dependence:

$$\sigma_{\text{fiducial}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\mathcal{L} \times C_{VV}} \tag{1}$$

  - Where $\mathcal{L}$ is the integrated luminosity and C_{VV} is a correction factor $C_{VV} = \frac{N_{\text{reconstructed}}}{N_{\text{FiducialGenerated}}}$. $N_{\text{reconstructed}}$ is the number of reconstructed events after applying corrections to Monte Carlo.
- Total cross section is calculated by applying an acceptance factor to include the full space and the branching fraction

$$\sigma_{\text{total}} = \frac{N_{\text{obs}} - N_{\text{bkg}}}{\mathcal{L} \times C_{VV} \times \mathcal{BF} \times A_{VV}} \tag{2}$$

Cross Section Extraction

Cross sections are calculated using maximum likelihood fit.
Poisson functions are used to model the number of observed events.
Systematic uncertainties by either treating them as nuisance parameters in the maximum likelihood fit, or by error propagation.
For example, the likelihood equation for the *WW* channel is:

$$L(\sigma_{WW}^{\text{tot}}) = \ln \prod_{i=1}^{3} \frac{e^{(-N_{\text{s}}^{i}+N_{\text{b}}^{i})} \times (N_{\text{s}}^{i} + N_{\text{b}}^{i})^{N_{\text{obs}}^{i}}}{N_{\text{obs}}^{i}!} \tag{3}$$

Fiducial Cross Sections: $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$

Table: $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ Fiducial Cross Sections

Channel	Measured Cross Section (fb)	Predicted (fb)
7 TeV		
$\ell^+\ell^-\ell'^+\ell'^-$	$21.2^{+3.2}_{-2.7}$(stat.)$^{+1.0}_{-0.9}$(syst.)$\pm$0.8(lumi.)	$19.0^{+1.1}_{-1.0}$
8 TeV		
$\ell^+\ell^-\ell'^+\ell'^-$	$21.0^{+2.4}_{-2.2}$(stat.)$^{+0.6}_{-0.5}$(syst.)$\pm$0.8(lumi.)	16.8$\pm$1.0
$e^+e^-e^+e^-$	$6.3^{+1.5}_{-1.3}$(stat.)$^{+0.4}_{-0.3}$(syst.)$\pm$0.2(lumi.)	$4.2^{+0.2}_{-0.1}$
$e^+e^-\mu^+\mu^-$	$4.9^{+1.1}_{-1.0}$(stat.)$^{+0.1}_{-0.1}$(syst.)$\pm$0.2(lumi.)	$4.2^{+0.2}_{-0.1}$
$\mu^+\mu^-\mu^+\mu^-$	$9.9^{+1.7}_{-1.5}$(stat.)$^{+0.3}_{-0.3}$(syst.)$\pm$0.4(lumi.)	$8.4^{+0.4}_{-0.3}$

Good agreement between measurements and NLO predictions.

Fiducial Cross Sections: $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ and $WW \to \ell^+\nu\ell^-\bar{\nu}$

Table: $ZZ \to \ell^+\ell^-\nu\bar{\nu}$ and $WW \to \ell^+\nu\ell^-\bar{\nu}$ Fiducial Cross Sections

Channel	Measured Cross Section (fb)	Predicted (fb)
$ZZ \to \ell^+\ell^-\nu\bar{\nu}$		
$\ell^+\ell^-\nu\bar{\nu}$	$12.2^{+3.0}_{-2.8}$(stat.)$\pm$1.9(syst.)$\pm$0.5(lumi.)	-
$WW \to \ell^+\nu\ell^-\bar{\nu}$		
$e^+\nu e^-\bar{\nu}$	56.4$\pm$6.8(stat.)$\pm$9.8(syst.)$\pm$2.2(lumi.)	54.6$\pm$3.7
$\mu^+\nu\mu^-\bar{\nu}$	73.9$\pm$5.9(stat.)$\pm$6.9(syst.)$\pm$2.9(lumi.)	58.9$\pm$4.0
$e^+\nu\mu^-\bar{\nu}$	262.3$\pm$12.3(stat.)$\pm$20.7(syst.)$\pm$10.2(lumi.)	231.4$\pm$15.7

Good agreement between measurements and NLO predictions.

Unfolded differential distribution for $WW \to \ell^+\nu\ell^-\bar{\nu}$

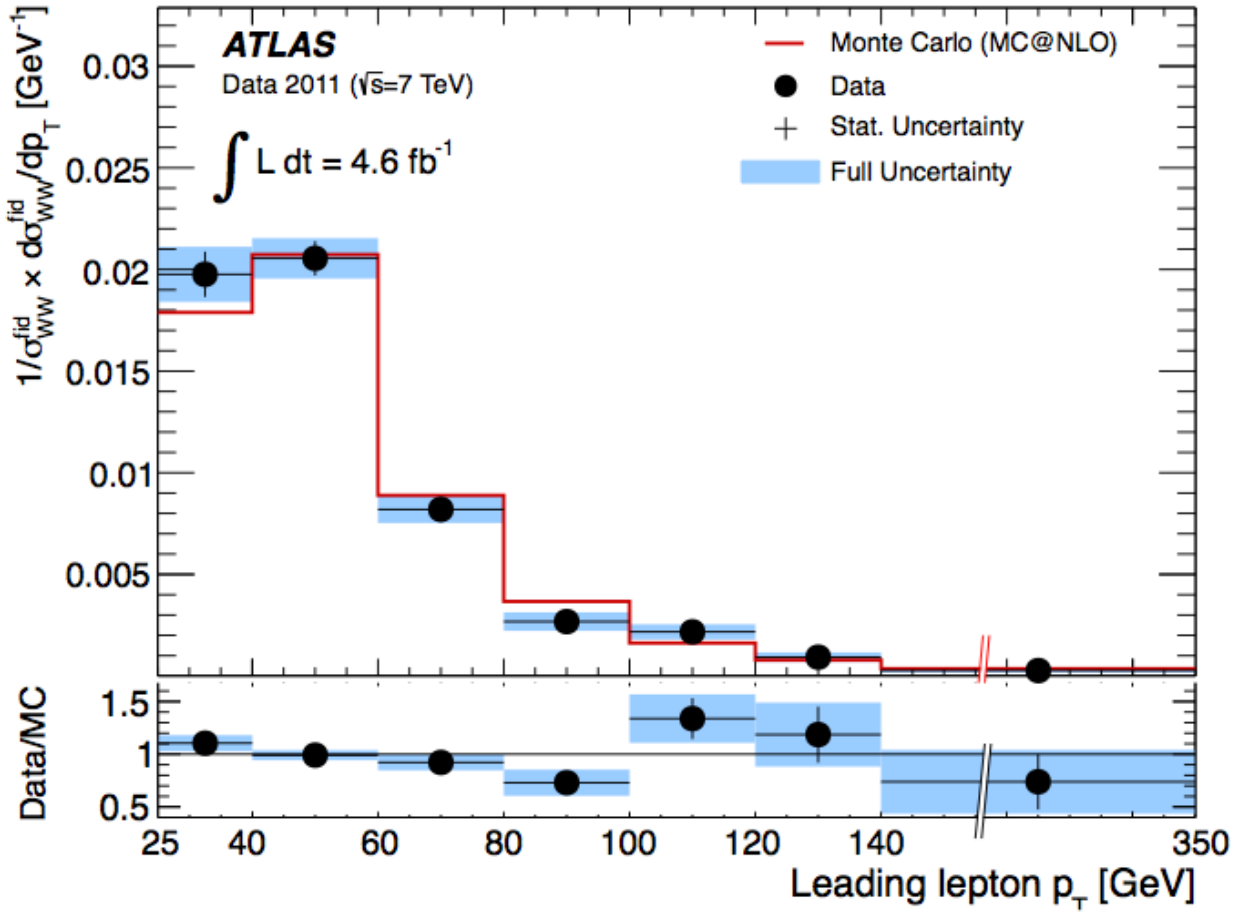


Figure: Normalized differential *WW* fiducial cross section as a function of leading lepton p_{T}.

Total Cross Sections

Channel	Measured Cross Section (pb)	Predicted (pb)
7 TeV		
$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	$7.2^{+1.1}_{-0.9}$(stat.)$^{+0.4}_{-0.3}$(syst.)$\pm$0.3(lumi.)	$6.5^{+0.3}_{-0.2}$
$ZZ \to \ell^+\ell^-\nu\bar{\nu}$	$5.4^{+1.3}_{-1.2}$(stat.)$^{+1.4}_{-1.0}$(syst.)$\pm$0.2(lumi.)	$6.5^{+0.3}_{-0.2}$
$WW \to \ell^+\nu\ell^-\bar{\nu}$	51.9$\pm$2.0(stat.)$\pm$3.9(syst.)$\pm$2.0(lumi.)	44.7$\pm$2.8
8 TeV		
$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	$9.3^{+1.1}_{-1.0}$(stat.)$^{+0.4}_{-0.3}$(syst.)$\pm$0.3(lumi.)	7.4$\pm$0.4

- All measurements agree with NLO Standard Model predictions.
- $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ used Monte Carlo with the zero-width approximation for 7 TeV, and moved to finite width at 8 TeV.

Total Cross Sections

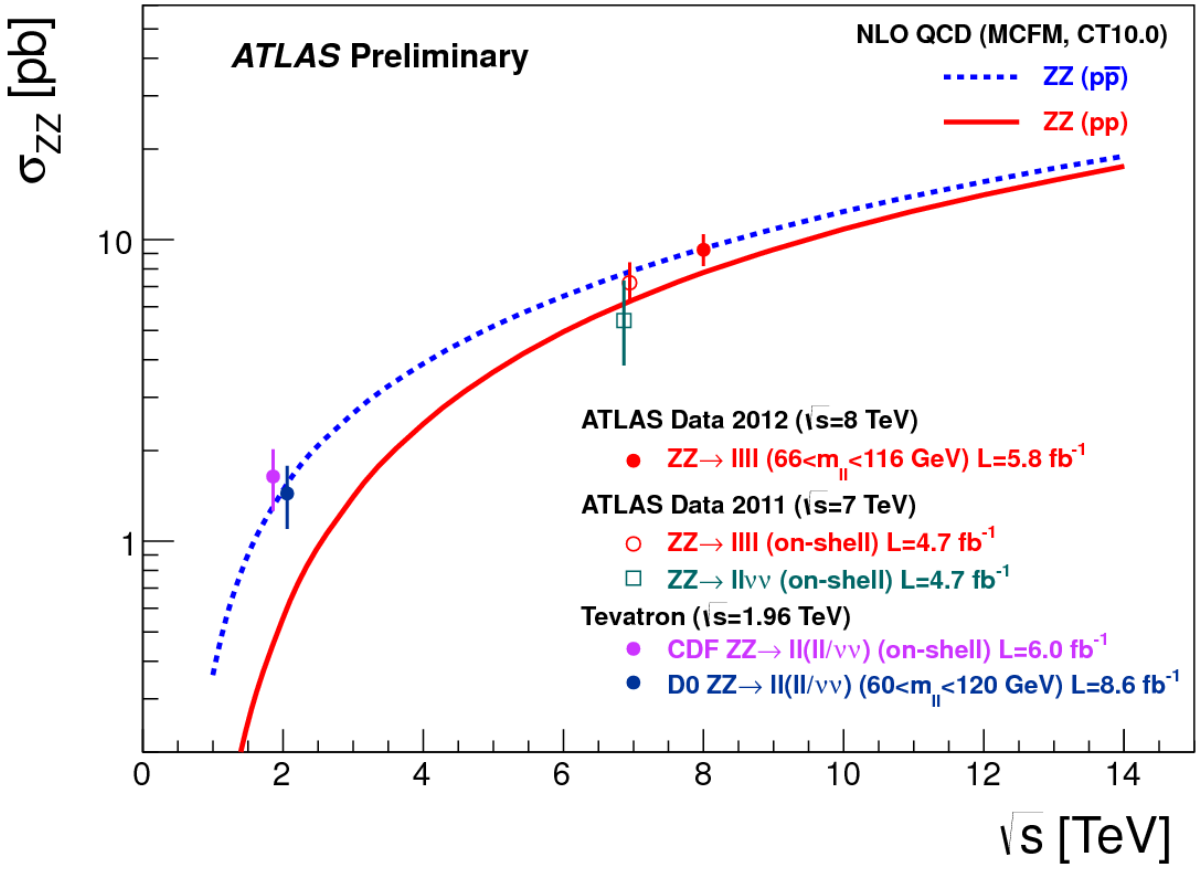


Figure: Total cross sections measured in the *ZZ* channel.

Summary and Next Steps

- Presented *ZZ* and *WW* fiducial and total cross section measurements
  - *ZZ* $\rightarrow \ell^+\ell^-\ell'^+\ell'^-$ at 7 and 8 TeV
  - *ZZ* $\rightarrow \ell^+\ell^-\nu\bar{\nu}$ and *WW* $\rightarrow \ell^+\nu\ell^-\bar{\nu}$ at 7 TeV
- Good agreement between measurements and NLO Standard Model predictions
- Full 7 TeV *ZZ* measurements with unfolded distributions and TGC limits coming soon...
- Extend cross section measurements to include VBS *WW* and *ZZ*