Diboson Cross Section Measurements and Limits on Anomalous TGCs with the ATLAS detector

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On behalf of the ATLAS Collaboration

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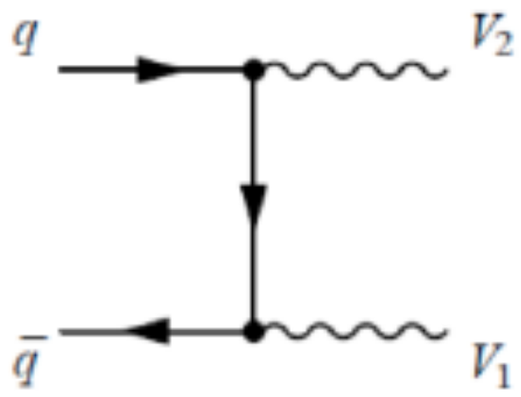
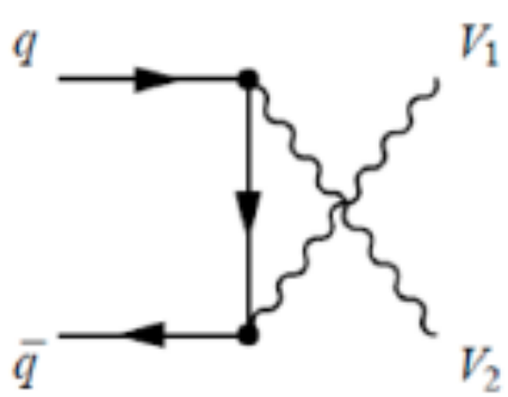
Introduction

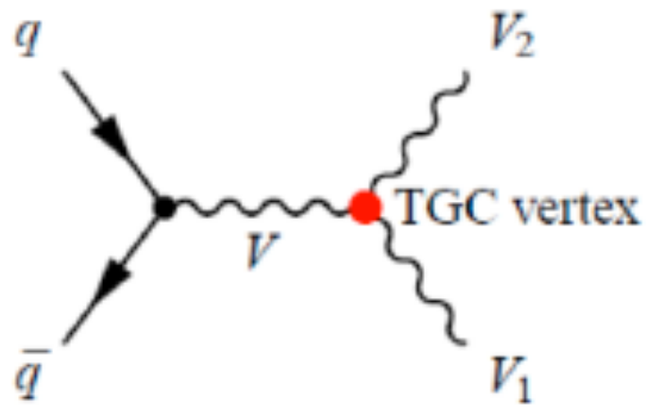
Motivation

- Test of the Electroweak Sector at the TeV energy regime
- Probe to new physics through deviations of Triple Gauge Couplings from SM predictions
- Sensitive to new phenomena beyond the SM
- Irreducible background in the studies of the Higgs boson ($H \rightarrow ZZ^{(*)}/WW^{(*)}$)

Production mechanisms @ LHC







Introduction

Diboson channels to be discussed

$$W\gamma \to \ell\nu\gamma$$

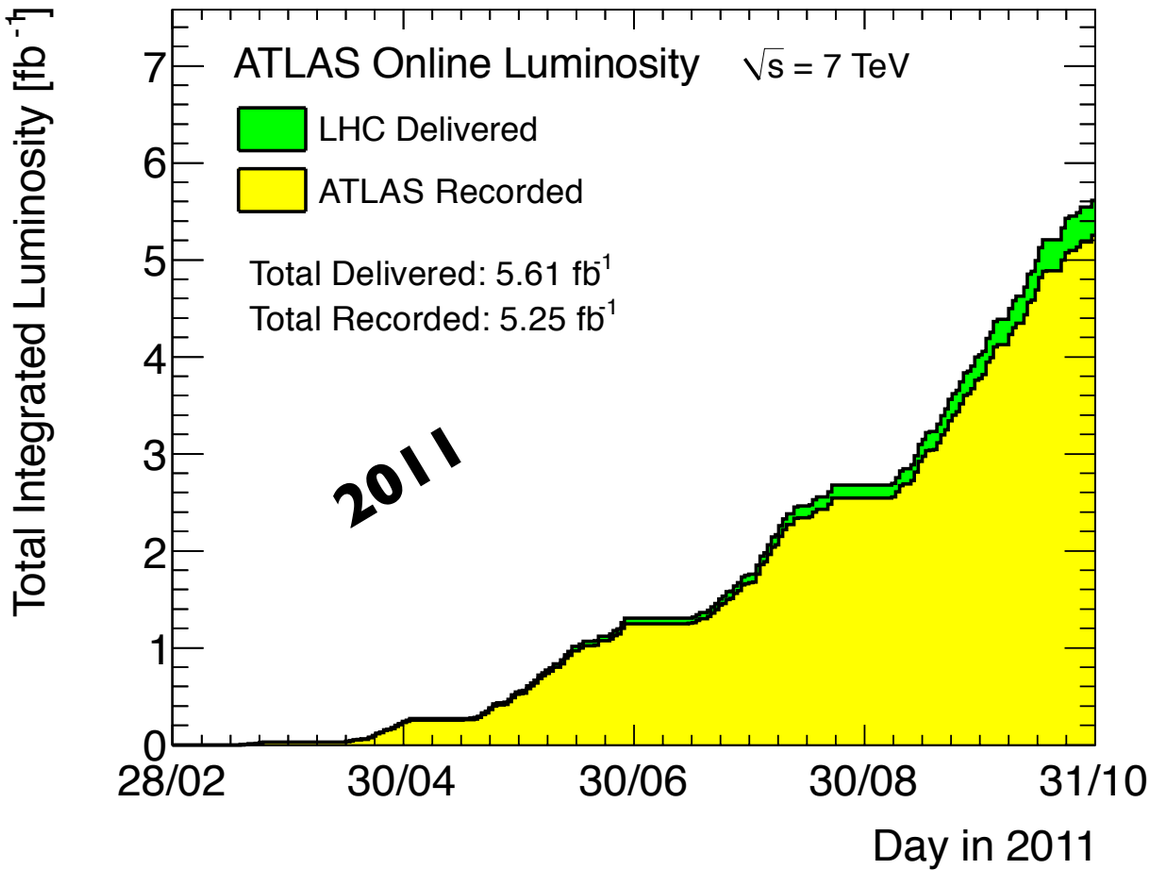
$$Z\gamma \to \ell\ell\gamma$$

$$WW \to \ell\nu\ell\nu$$

$$WZ \to \ell\nu\ell\ell$$

$$ZZ \to \ell\ell\nu\nu$$

$$ZZ \to \ell\ell\ell\ell$$



All the cross section measurements correspond to $\sqrt{s}$ = 7 TeV unless it is noted.

Diboson cross section measurement

Strategy

1. Select candidate events

2. Background estimation

3. Correct for selection efficiencies $C_{V_1V_2}$

4. Calculate fiducial cross section

$$\sigma(pp \to V_1V_2) \times BR = \frac{N_{data} - N_{bkg}}{C_{V_1V_2} \times L}$$

5. Correct for branching fraction (BR) for each of the decay modes

$$W\gamma \to \ell\nu\gamma, Z\gamma \to \ell\ell\gamma, WW \to \ell\nu\ell\nu, WZ \to \ell\nu\ell\ell, ZZ \to \ell\ell\nu\nu, ZZ \to \ell\ell\ell\ell \; (\ell = e, \mu)$$

6. Correct for the acceptance of the fiducial volume (kinematic and geometric cuts) $A_{V_1V_2}$

7. Measure total cross section

$$\sigma(pp \to V_1V_2) = \frac{N_{data} - N_{bkg}}{C_{V_1V_2} \times L \times BR \times A_{V_1V_2}}$$

$W\gamma \to \ell\nu\gamma$ / $Z\gamma \to \ell\ell\gamma$

arXiv:1205.2531

Background Contamination

- Z/W + jets (dominant)
- $t\bar{t}, W \to \tau\nu, WW$

Selection requirements

Photon (γ)

- E_T > 15 GeV, |η| < 2.4
- Calorimetric isolated
- $\Delta R(\ell,\gamma) > 0.7$ (suppress FSR)

Z boson

- $m_{\ell\ell}$ > 40 GeV

W boson

- m_T > 40 GeV

Exclusive Wγ and Zγ measurements

- Jet veto (p_T > 30 GeV)

$W\gamma \to \ell\nu\gamma$ / $Z\gamma \to \ell\ell\gamma$

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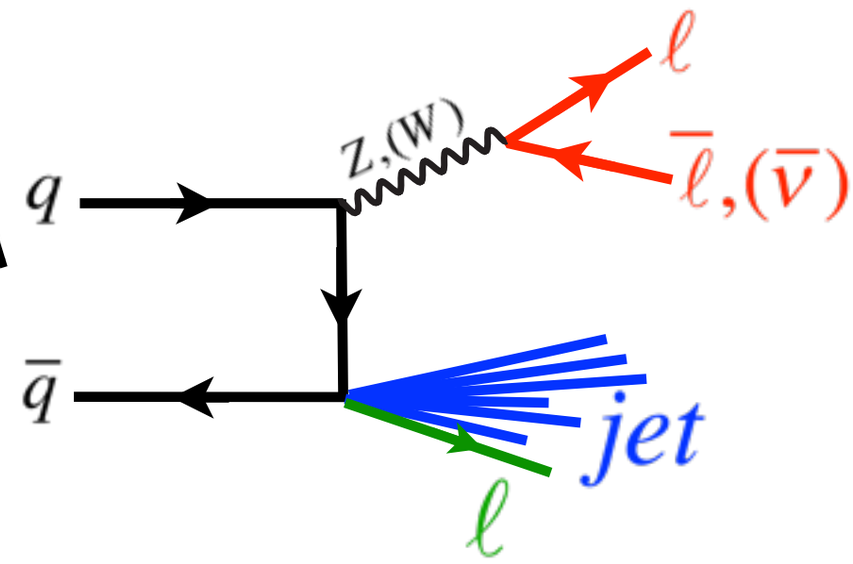

$W\gamma \to \ell\nu\gamma$ / $Z\gamma \to \ell\ell\gamma$

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- m_T > 40 GeV

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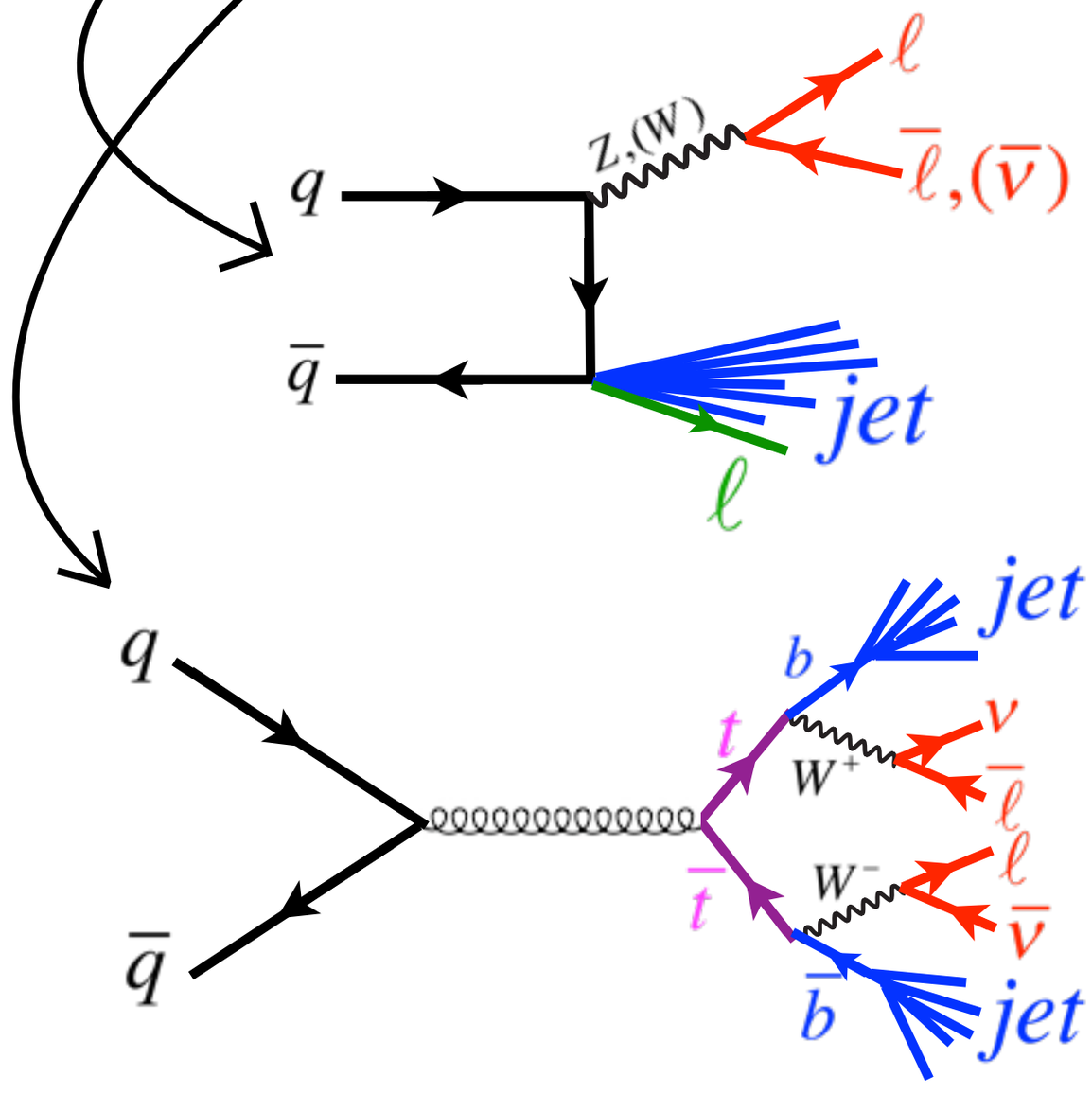
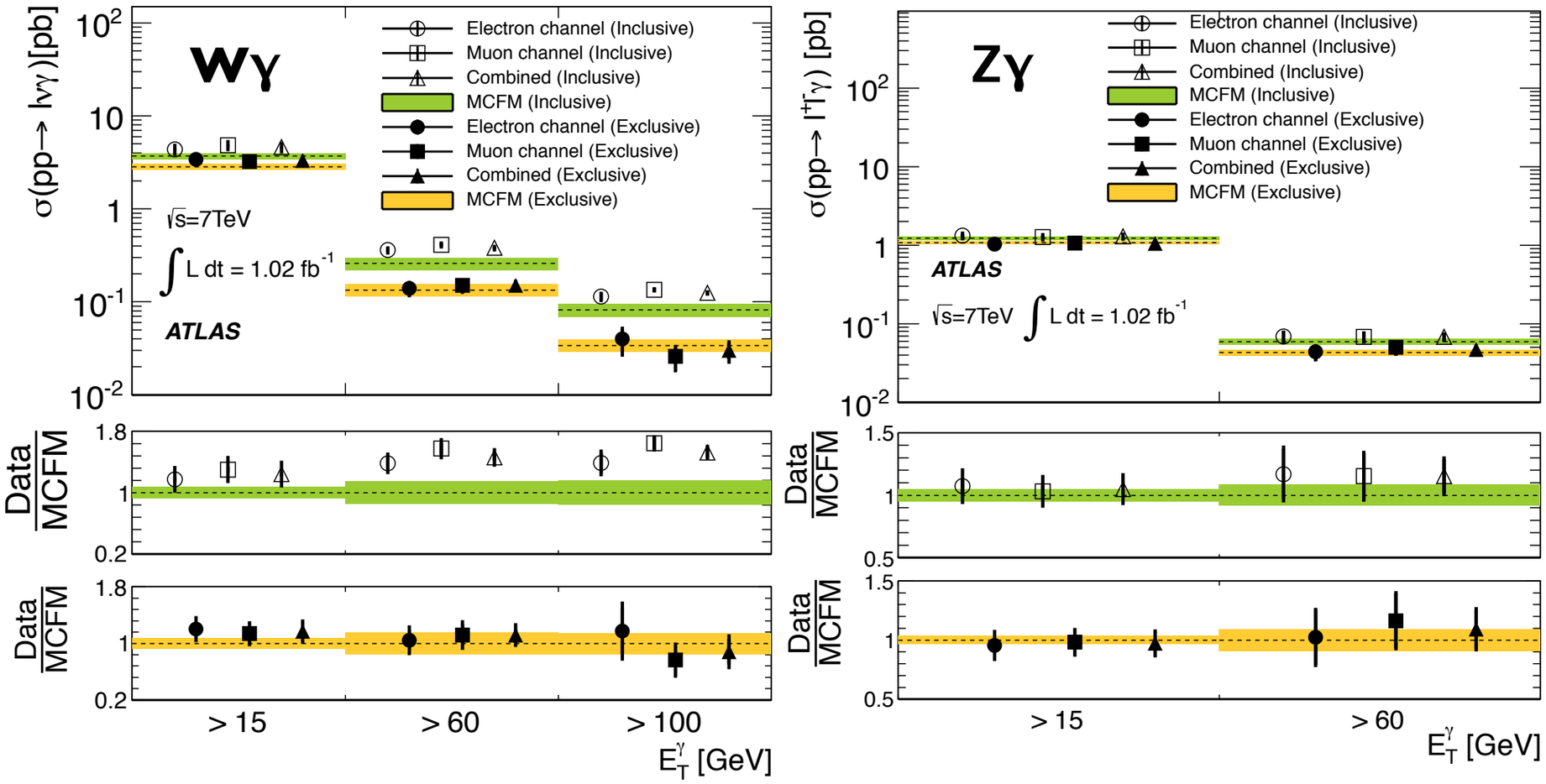
- $t\bar{t}, W \to \tau\nu, WW$



$W\gamma \to \ell\nu\gamma$ / $Z\gamma \to \ell\ell\gamma$

arXiv:1205.2531

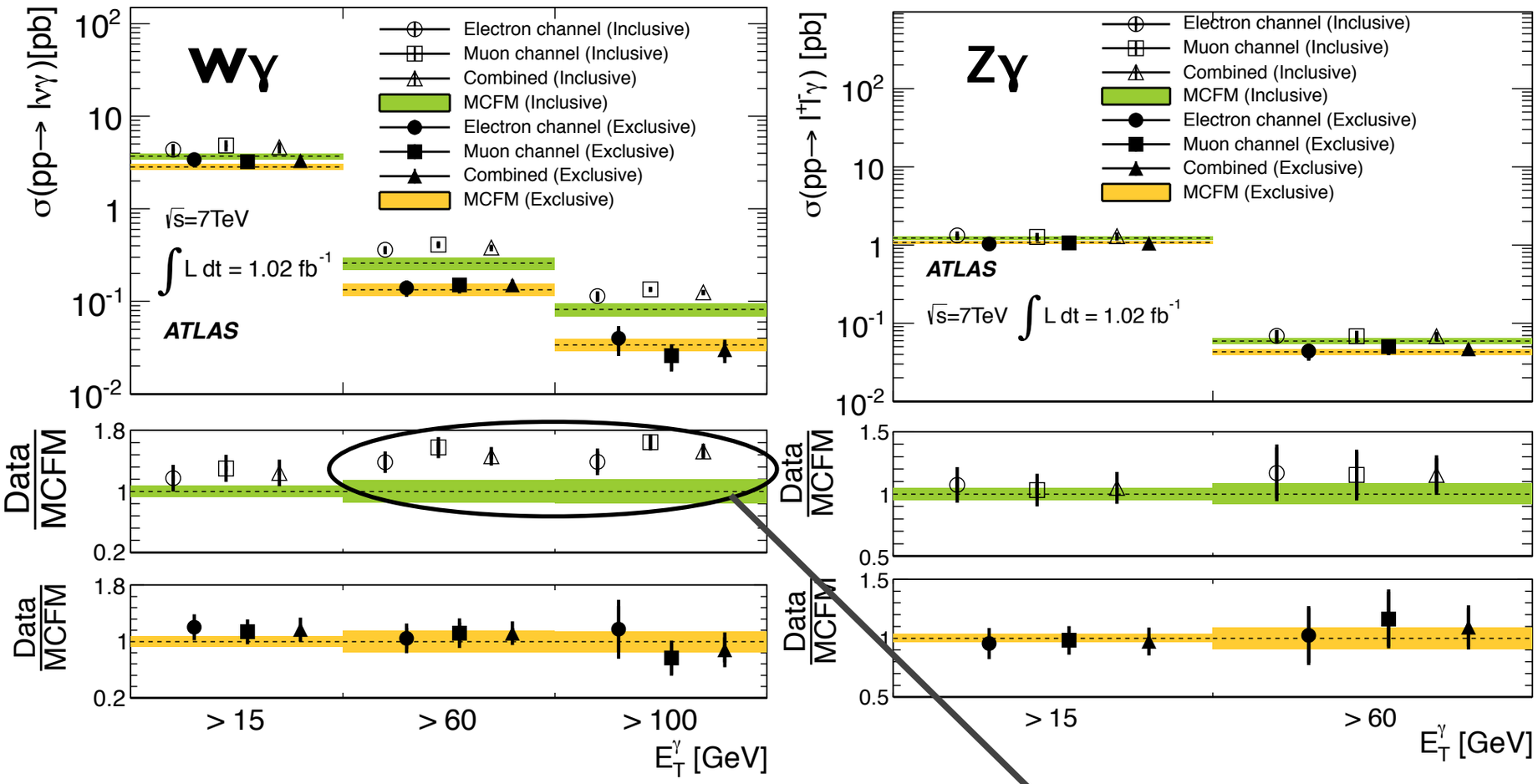


$$E_T^\gamma > 60 \text{ GeV}$$

	$W\gamma \to \ell\nu\gamma$	$Z\gamma \to \ell\ell\gamma$
Exclusive	$\sigma_{exc}^{W\gamma} = 0.15 \pm 0.01 \pm 0.02$ pb	$\sigma_{exc}^{Z\gamma} = 0.047 \pm 0.007 \pm 0.004$ pb
	$\sigma_{exc}^{NLO,W\gamma} = 0.134 \pm 0.021$ pb	$\sigma_{exc}^{NLO,Z\gamma} = 0.043 \pm 0.004$ pb
Inclusive	$\sigma_{inc}^{W\gamma} = 0.38 \pm 0.02 \pm 0.03$ pb	$\sigma_{inc}^{Z\gamma} = 0.068 \pm 0.008 \pm 0.005$ pb
	$\sigma_{inc}^{NLO,W\gamma} = 0.260 \pm 0.038$ pb	$\sigma_{inc}^{NLO,Z\gamma} = 0.059 \pm 0.005$ pb

$W\gamma \to \ell\nu\gamma$ / $Z\gamma \to \ell\ell\gamma$

arXiv:1205.2531



Disagreement

Good agreement
for the ***exclusive*** x-section measurements

Disagreement due to lack of higher order QCD contributions in MCFM (W/Zγ + 0,1,2,3,4... partons)

$$E_T^\gamma > 60 \text{ GeV}$$

	$W\gamma \to \ell\nu\gamma$	$Z\gamma \to \ell\ell\gamma$
Exclusive	$\sigma_{exc}^{W\gamma} = 0.15 \pm 0.01 \pm 0.02$ pb	$\sigma_{exc}^{Z\gamma} = 0.047 \pm 0.007 \pm 0.004$ pb
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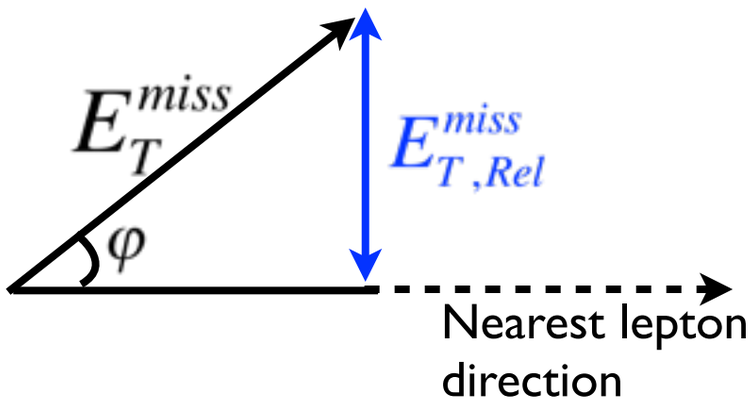
	$\sigma_{inc}^{NLO,W\gamma} = 0.260 \pm 0.038$ pb	$\sigma_{inc}^{NLO,Z\gamma} = 0.059 \pm 0.005$ pb

$WW \to \ell\nu\ell\nu$

ATLAS-CONF-2012-025

Selection requirements

- exactly 2 isolated leptons with p_T > 15 GeV
- $E_{T,Rel}^{miss}$ > 25, 50, 55 (eμ, ee, μμ)
- One OS-SF lepton pair
- Jet veto (p_T > 25 GeV)
- Z veto ($|m_{\ell\ell} - m_Z|$ < 15 GeV)



Background Contamination

- Drell-Yan (removed from Z veto and $E_{T,Rel}^{miss}$)
- $t\bar{t}, Wt$ (removed by jet veto)
- $W + jets$
- $WZ, ZZ, W\gamma^{(*)}$ (lepton veto if >3 leptons / event)

Fiducial cross section

$$\sigma_{WW\to\ell\nu\ell\nu}^{fid} = 374.5 \pm 14.9(stat) \pm 28.1(syst) \pm 14.6(lumi)\ \text{fb}$$

NLO Fiducial cross section

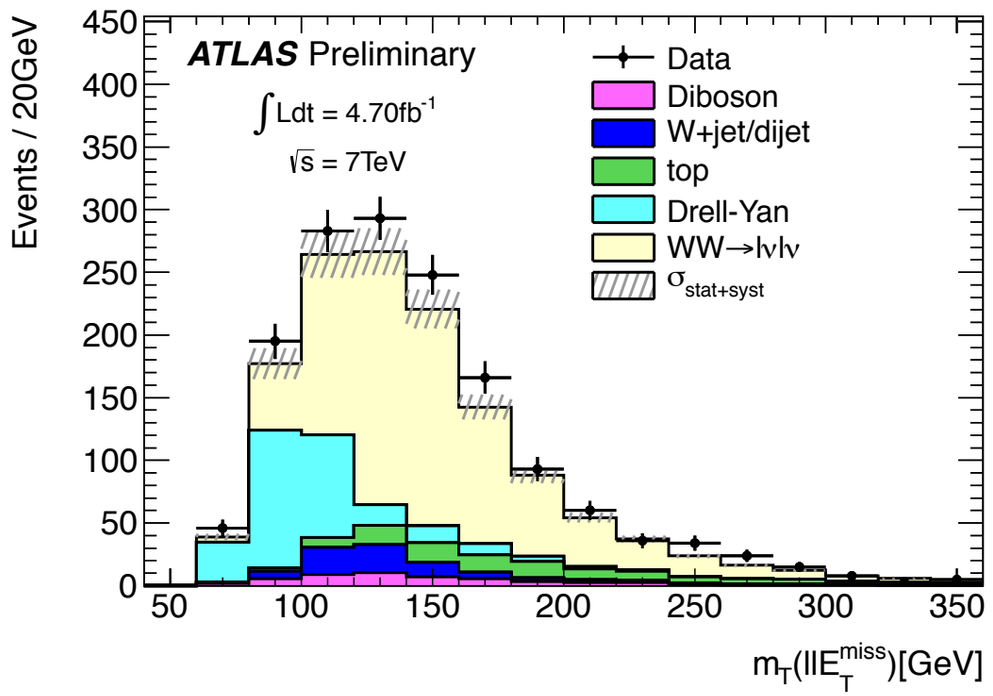
$$\sigma_{fid,NLO}^{SM} = 320.3 \pm 26.2\ \text{fb}$$

Total cross section

$$\sigma_{WW}^{tot} = 53.4 \pm 2.1(stat) \pm 4.5(syst) \pm 2.1(lumi)\ \text{pb}$$

NLO SM prediction (MC@NLO)

$$\sigma_{NLO}^{SM} = 45.1 \pm 2.8\ \text{pb}$$



$WW \to \ell\nu\ell\nu$

ATLAS-CONF-2012-025

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- exactly 2 isolated leptons with p_T > 15 GeV
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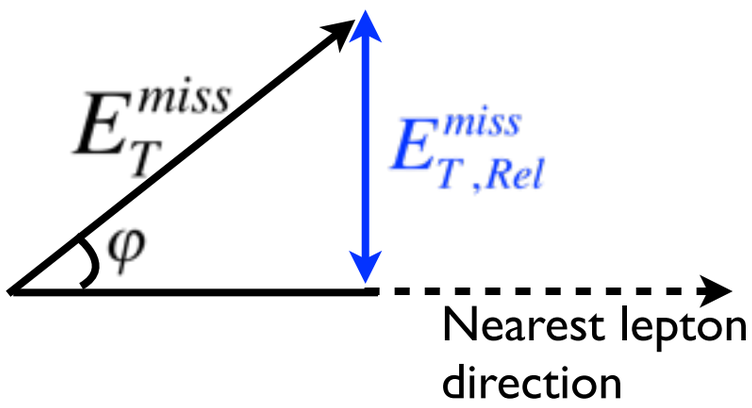

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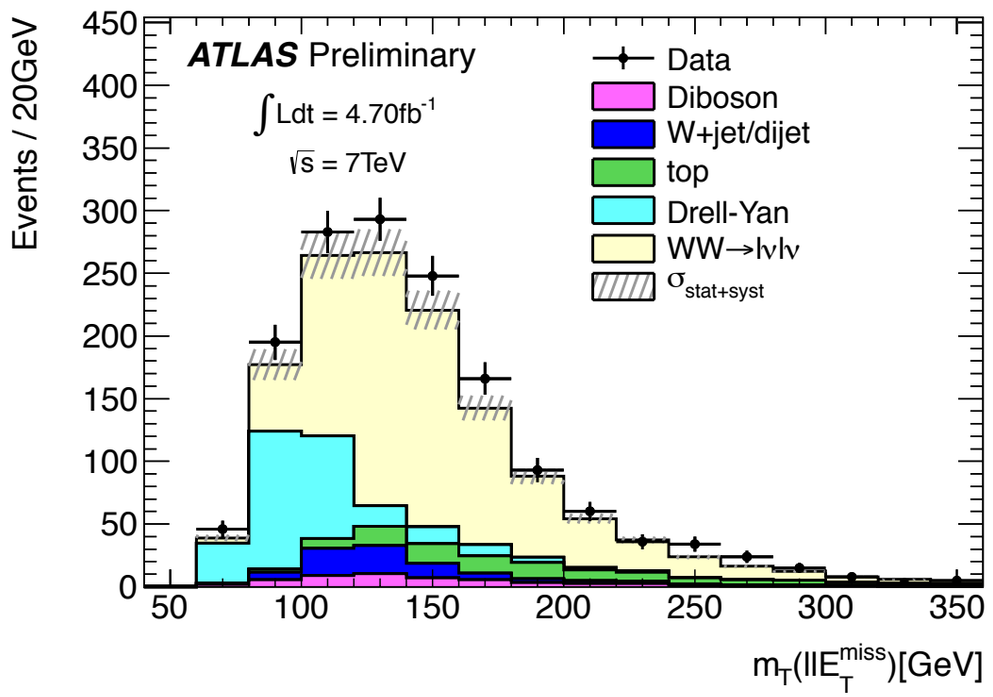
NLO SM prediction (MC@NLO)

$\sigma_{NLO}^{SM} = 45.1 \pm 2.8$ pb

Dominant uncertainty:

Systematic due to background estimation



$WZ \to \ell\nu\ell\ell$

arXiv:1208.1390

Selection requirements

- 3 isolated leptons with p_T > 15 GeV
- Jet Veto (p_T > 20 GeV)
- Z→ $|m_{\ell\ell} - m_Z| < 10$ GeV
- W→ M_T^W > 20 GeV

Background Contamination

- Drell-Yan
- $t\bar{t}$
- $ZZ, Z\gamma$

Fiducial cross section

$$\sigma^{fid}_{WZ\to\ell\nu\ell\ell} = 92^{+7}_{-6}(stat) \pm 4(syst) \pm 2(lumi)\ \text{fb}$$

NLO Fiducial cross section

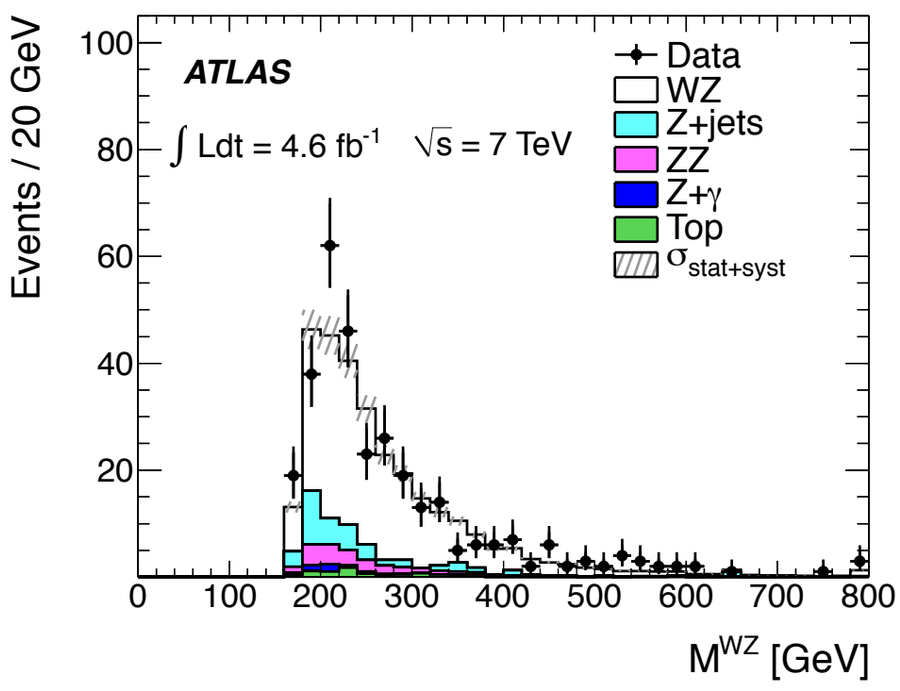
$$\sigma^{SM}_{fid,NLO} = 82.5^{+5.3}_{-4.8}\ \text{fb}$$

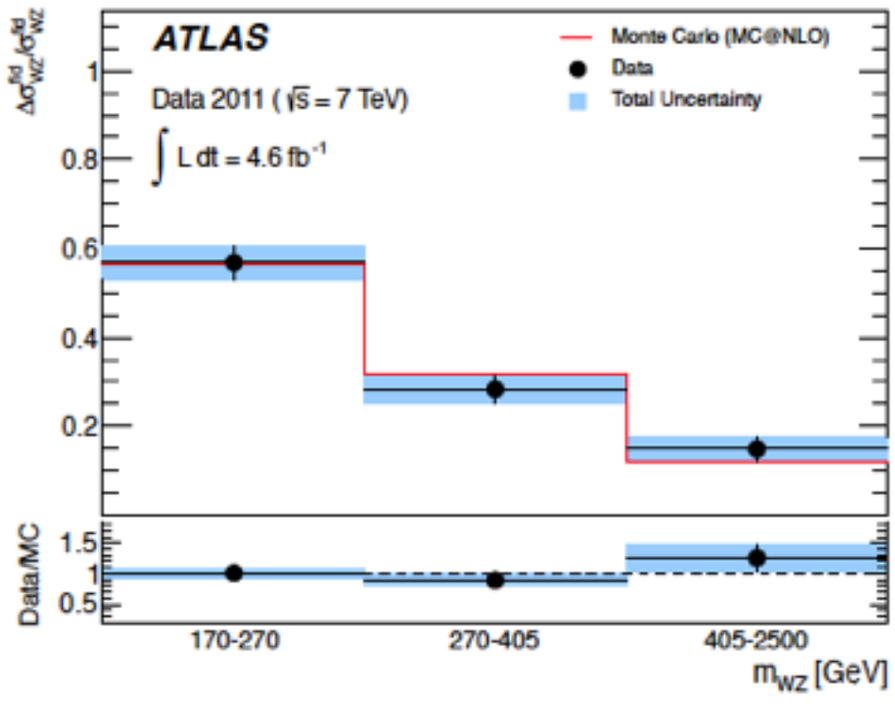
Total cross section

$$\sigma^{tot}_{WZ} = 19.0^{+1.4}_{-1.3}(stat) \pm 0.9(syst) \pm 0.4(lumi)\ \text{pb}$$

NLO SM prediction (MCFM)

$$\sigma^{SM}_{NLO} = 17.6^{+1.1}_{-1.0}\ \text{pb}$$





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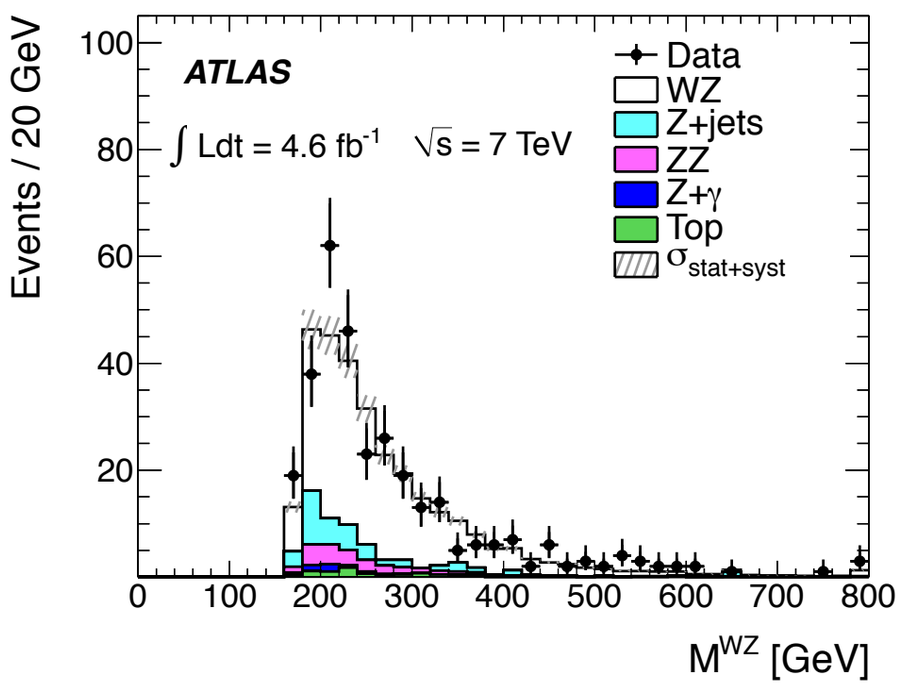
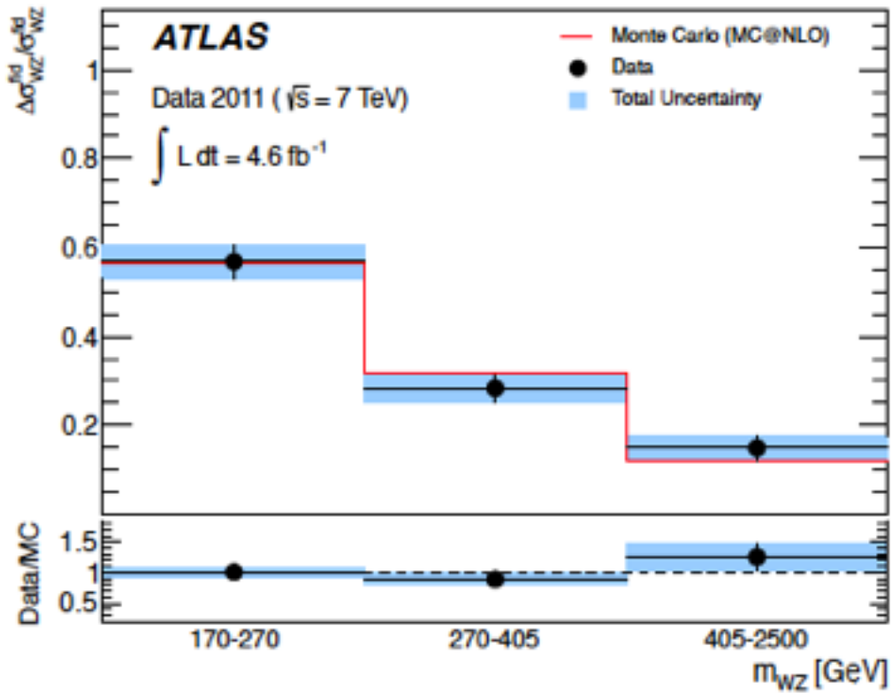
NLO SM prediction (MCFM)

$$\sigma^{SM}_{NLO} = 17.6^{+1.1}_{-1.0}\ \text{pb}$$

Dominant uncertainty:
Statistical



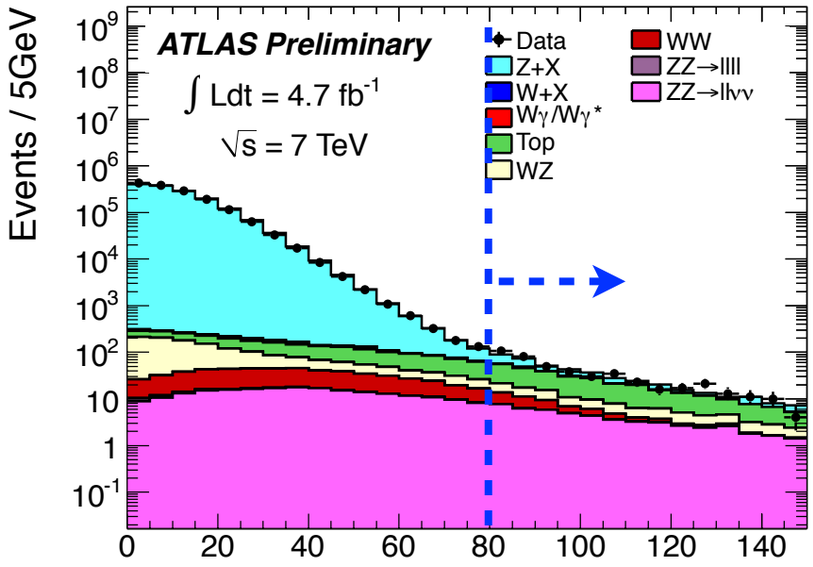


$ZZ \to \ell\ell\nu\nu$

ATLAS-CONF-2012-027

Selection requirements

- 2 isolated leptons with p_T > 20 GeV and $|\eta| < 2.5$
- One OS-SF lepton pair
- Axial E_T^{miss} > 80 GeV
- Jet veto if p_T > 25 GeV
- 3rd lepton veto (p_T > 10 GeV)
- $|m_{\ell\ell} - m_Z| < 15$ GeV



Background Contamination

- Drell-Yan (suppressed by the axial E_T^{miss} cut)
- $t\bar{t}$ (suppressed by the jet veto)
- WW, WZ (dominant), Wγ

Fiducial cross section

$$\sigma^{fid}_{ZZ\to\ell\ell\nu\nu} = 12.2^{+3.0}_{-2.8}(stat) \pm 1.9(syst) \pm 0.5(lumi)\ \text{fb}$$

NLO Fiducial cross section

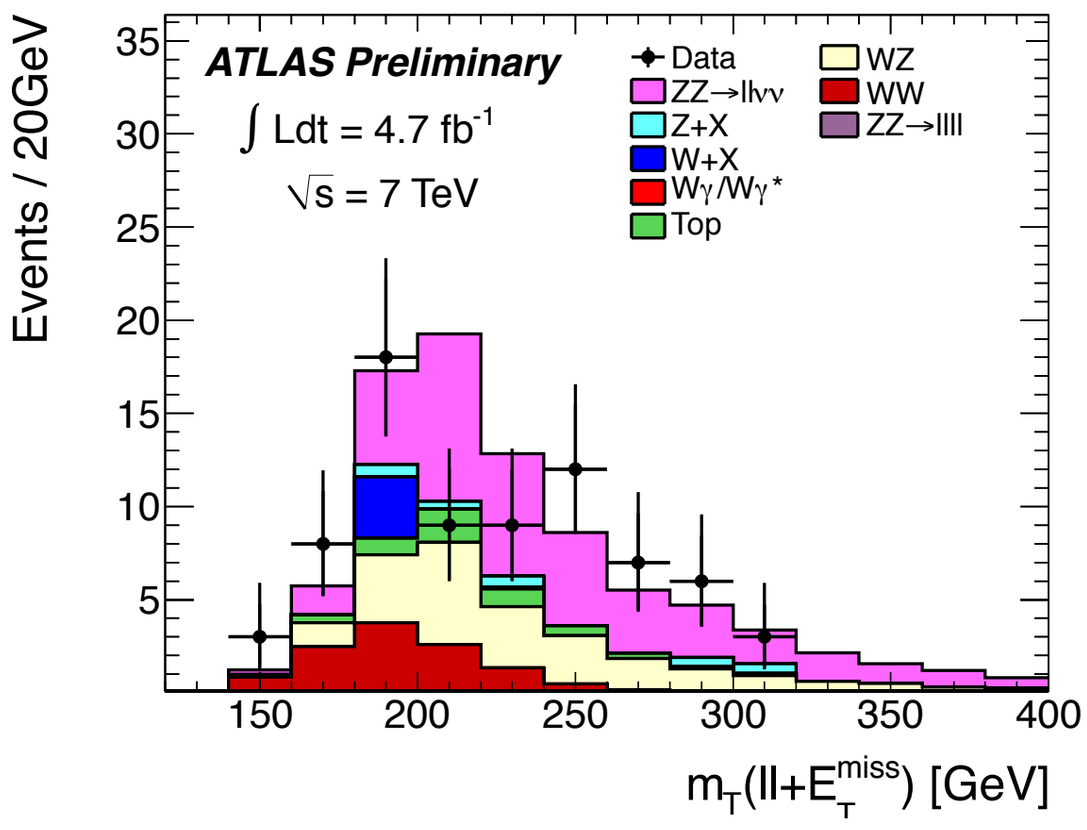
$$\sigma^{SM}_{NLO} = 14.7^{+2.4}_{-2.3}\ \text{fb}$$

Total cross section

$$\sigma^{tot}_{ZZ} = 5.4^{+1.3}_{-1.2}(stat)^{+1.4}_{-1.0}(syst) \pm 0.2(lumi)\ \text{pb}$$

NLO SM prediction (MCFM)

$$\sigma^{SM}_{NLO} = 6.5^{+0.3}_{-0.2}\ \text{pb}$$



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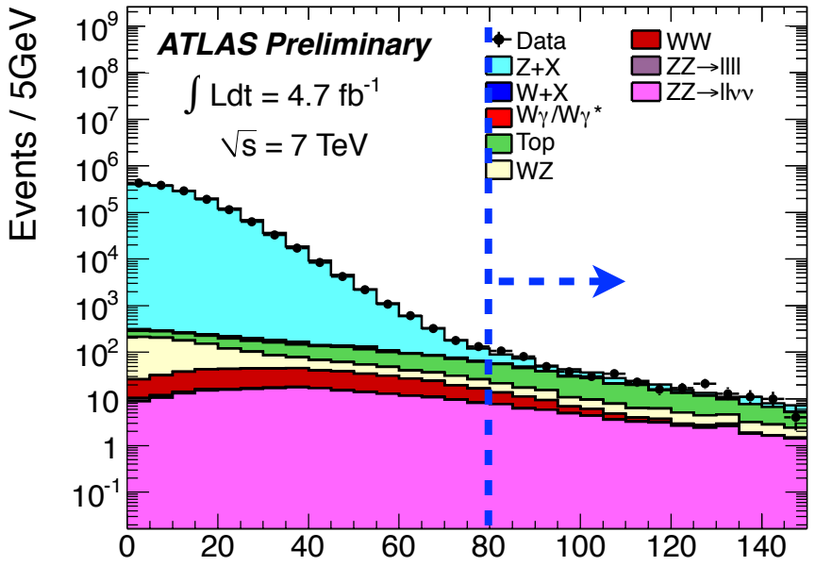

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NLO Fiducial cross section

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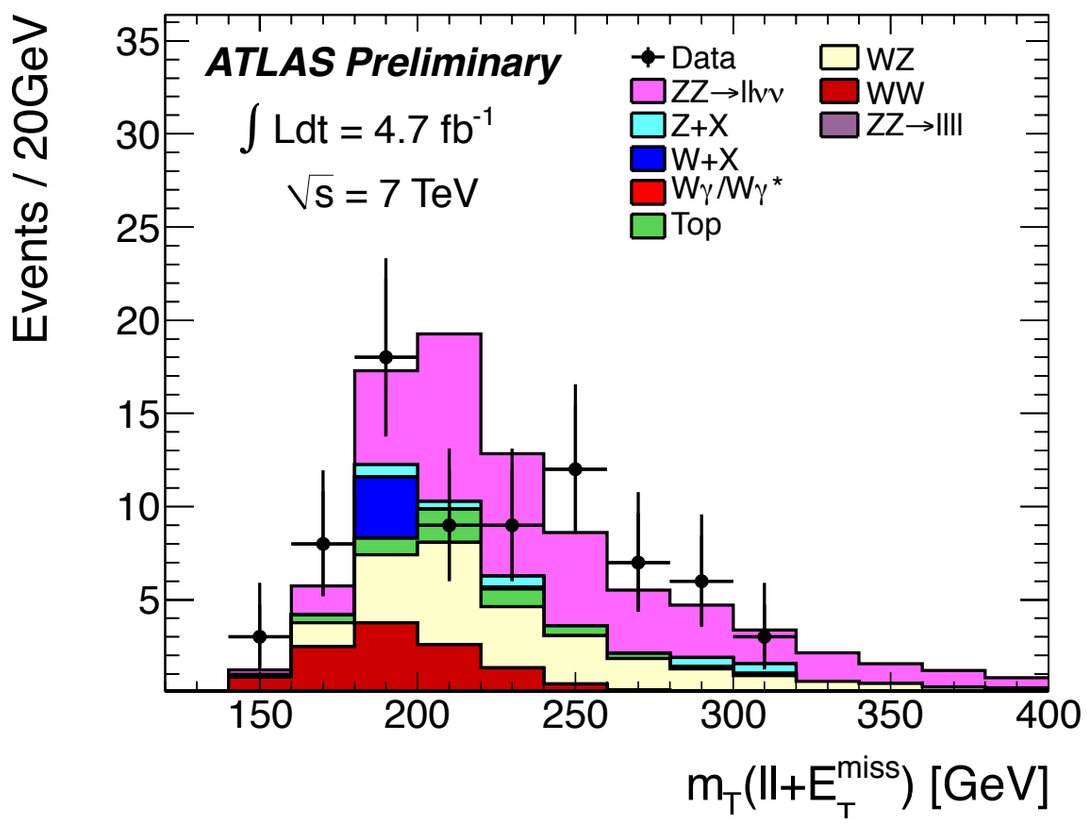
Comparable statistical and systematic uncertainties

Total cross section

$$\sigma^{tot}_{ZZ} = 5.4^{+1.3}_{-1.2}(stat)^{+1.4}_{-1.0}(syst) \pm 0.2(lumi)\ \text{pb}$$

NLO SM prediction (MCFM)

$$\sigma^{SM}_{NLO} = 6.5^{+0.3}_{-0.2}\ \text{pb}$$



$ZZ \to 4\ell$ @ $\sqrt{s}$ = 7 TeV

ATLAS-CONF-2012-026

Selection requirements

- $|\eta_\ell| < 2.7$
- 4 isolated leptons with p_T > 7 GeV
- leading lepton p_T > 20 (25) GeV (e,μ)
- Two SF-OS isolated lepton pairs
- $66 < m_{\ell\ell} < 116$ GeV

Background Contamination

- $Z + jets$ (dominant)
- Background contamination (< 2%)

Fiducial cross section

$\sigma^{fid}_{ZZ\to 4\ell} = 21.2^{+3.2}_{-2.7}(stat)^{+1.0}_{-0.9}(syst) \pm 0.8(lumi)$ fb

NLO Fiducial cross section

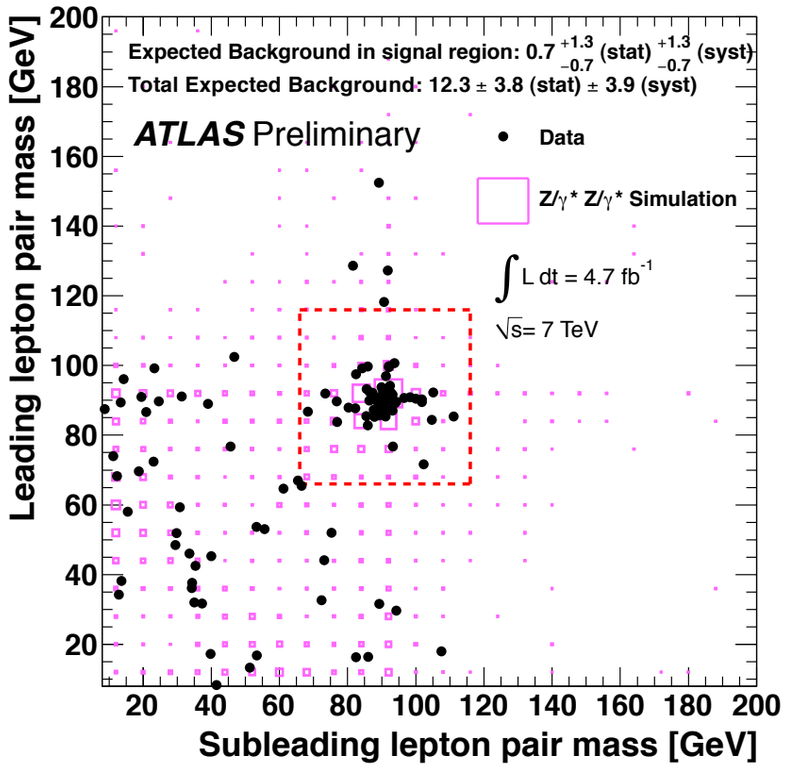
$\sigma^{SM}_{fid,NLO} = 19.0^{+0.9}_{-0.7}$ fb

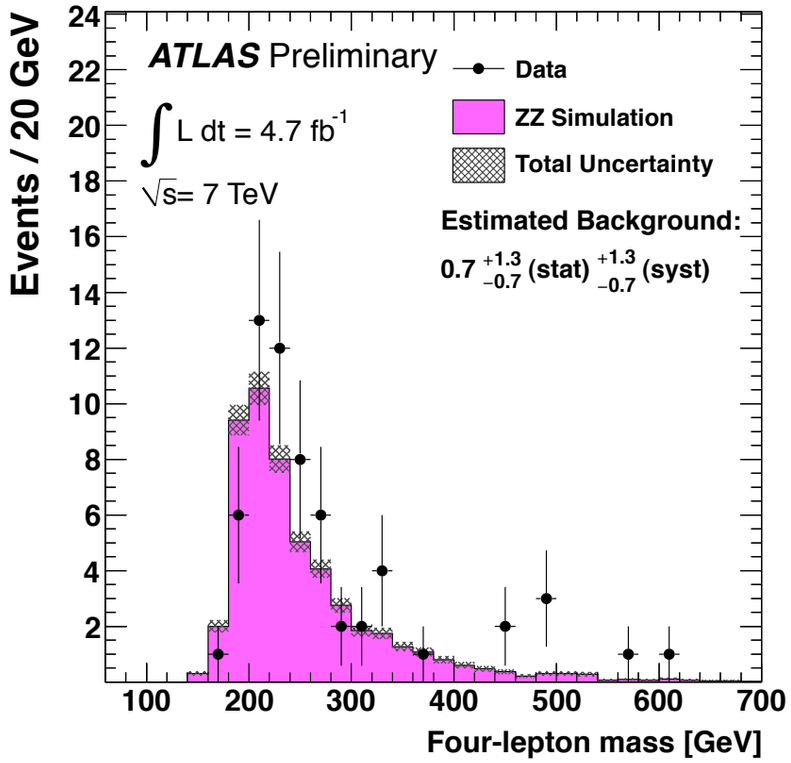
Total cross section

$\sigma^{tot}_{ZZ} = 7.2^{+1.1}_{-0.9}(stat)^{+0.4}_{-0.3}(syst) \pm 0.3(lumi)$ pb

NLO SM prediction (MCFM)

$\sigma^{SM}_{NLO} = 6.5^{+0.3}_{-0.2}$ pb





$ZZ \to 4\ell$ @ $\sqrt{s}$ = 7 TeV

ATLAS-CONF-2012-026

Selection requirements

- $|\eta_\ell| < 2.7$
- 4 isolated leptons with p_T > 7 GeV
- leading lepton p_T > 20 (25) GeV (e,μ)
- Two SF-OS isolated lepton pairs
- $66 < m_{\ell\ell} < 116$ GeV

Background Contamination

- $Z + jets$ (dominant)
- Background contamination (< 2%)

Fiducial cross section

$$\sigma^{fid}_{ZZ\to 4\ell} = 21.2^{+3.2}_{-2.7}(stat)^{+1.0}_{-0.9}(syst) \pm 0.8(lumi) \text{ fb}$$

NLO Fiducial cross section

$$\sigma^{SM}_{fid,NLO} = 19.0^{+0.9}_{-0.7} \text{ fb}$$

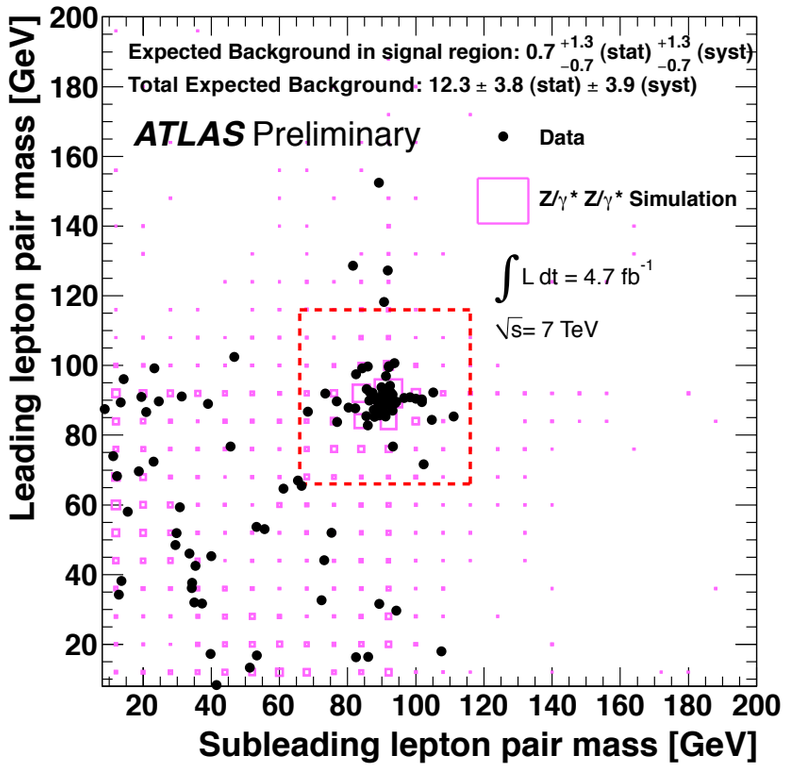
Dominant uncertainty: Statistical

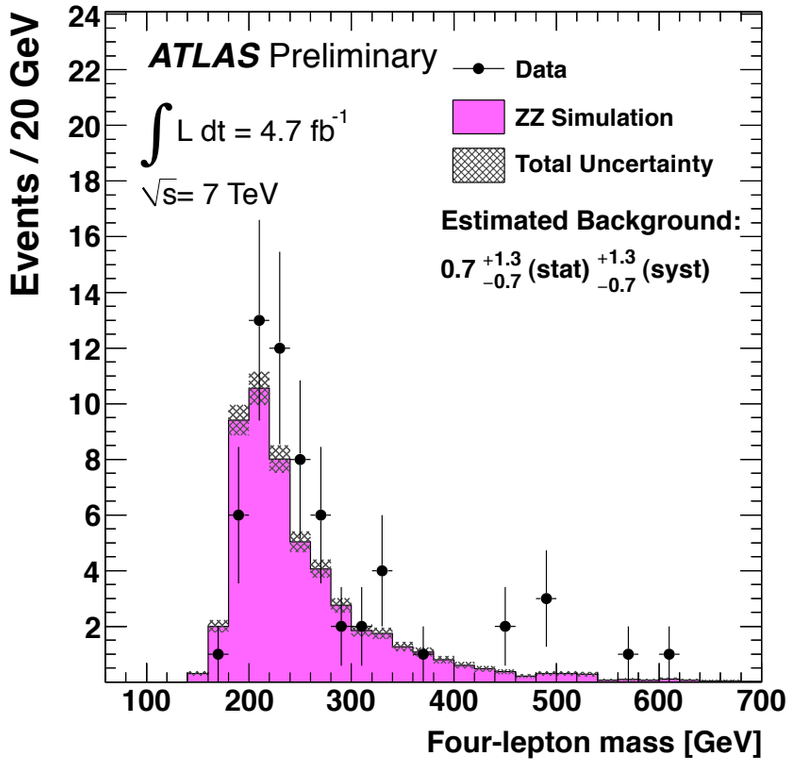
Total cross section

$$\sigma^{tot}_{ZZ} = 7.2^{+1.1}_{-0.9}(stat)^{+0.4}_{-0.3}(syst) \pm 0.3(lumi) \text{ pb}$$

NLO SM prediction (MCFM)

$$\sigma^{SM}_{NLO} = 6.5^{+0.3}_{-0.2} \text{ pb}$$





$ZZ \rightarrow 4\ell$ @ $\sqrt{s}$ = 8 TeV

ATLAS-CONF-2012-090

Selection requirements

- 4 isolated leptons with p_T > 15 GeV
- leading lepton p_T > 25 GeV
- Two SF-OS isolated lepton pairs
- Mass cut: 66 < M_{ll} < 116 GeV

Fiducial cross section

$$\sigma^{fid}_{ZZ\rightarrow 4\ell} = 21.0^{+2.4}_{-2.2}(stat)^{+0.6}_{-0.5}(syst) \pm 0.8(lumi) \text{ fb}$$

NLO Fiducial cross section

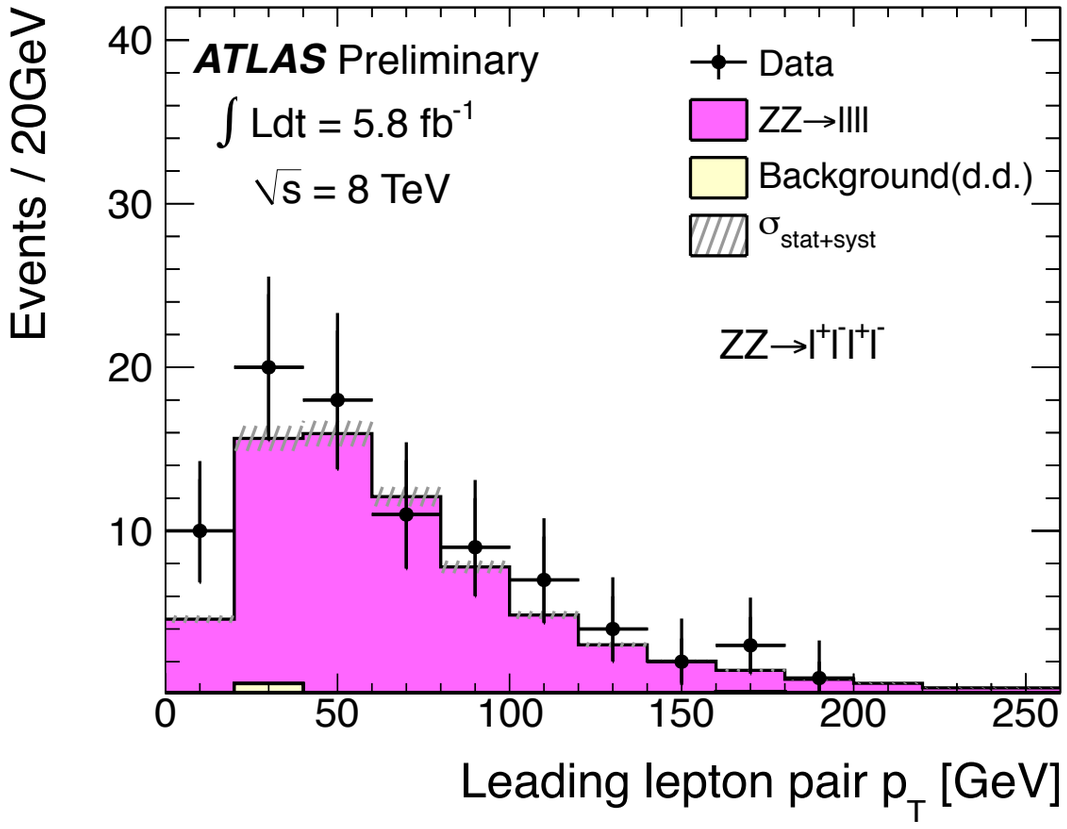
$$\sigma^{SM}_{fid,NLO} = 16.8^{+0.5}_{-0.3} \text{ fb}$$

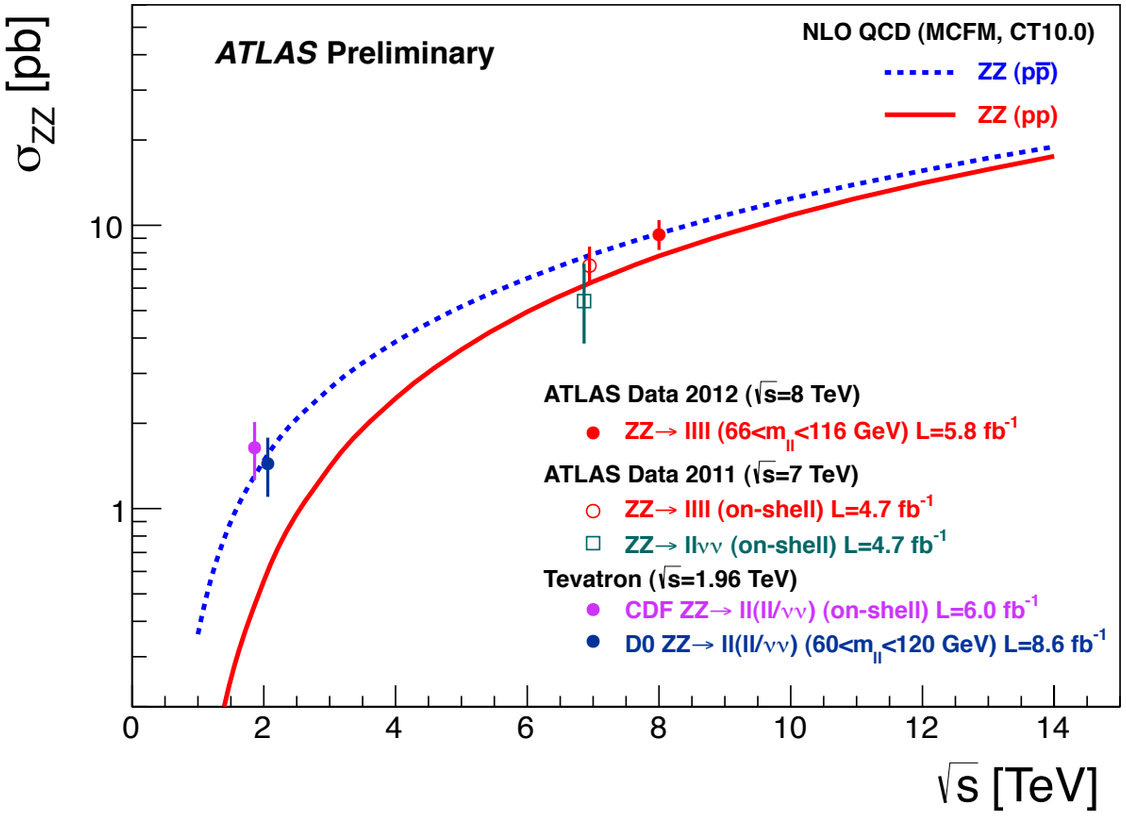
Total cross section

$$\sigma^{tot}_{ZZ} = 9.3^{+1.1}_{-1.0}(stat)^{+0.4}_{-0.3}(syst) \pm 0.3(lumi) \text{ pb}$$

NLO SM prediction (MCFM)

$$\sigma^{SM}_{NLO} = 7.4 \pm 0.4 \text{ pb}$$





$ZZ \rightarrow 4\ell$ @ $\sqrt{s}$ = 8 TeV

ATLAS-CONF-2012-090

Selection requirements

- 4 isolated leptons with p_T > 15 GeV
- leading lepton p_T > 25 GeV
- Two SF-OS isolated lepton pairs
- Mass cut: 66 < M_{ll} < 116 GeV

Fiducial cross section

$$\sigma^{fid}_{ZZ\rightarrow 4\ell} = 21.0^{+2.4}_{-2.2}(stat)^{+0.6}_{-0.5}(syst) \pm 0.8(lumi) \text{ fb}$$

NLO Fiducial cross section

$$\sigma^{SM}_{fid,NLO} = 16.8^{+0.5}_{-0.3} \text{ fb}$$

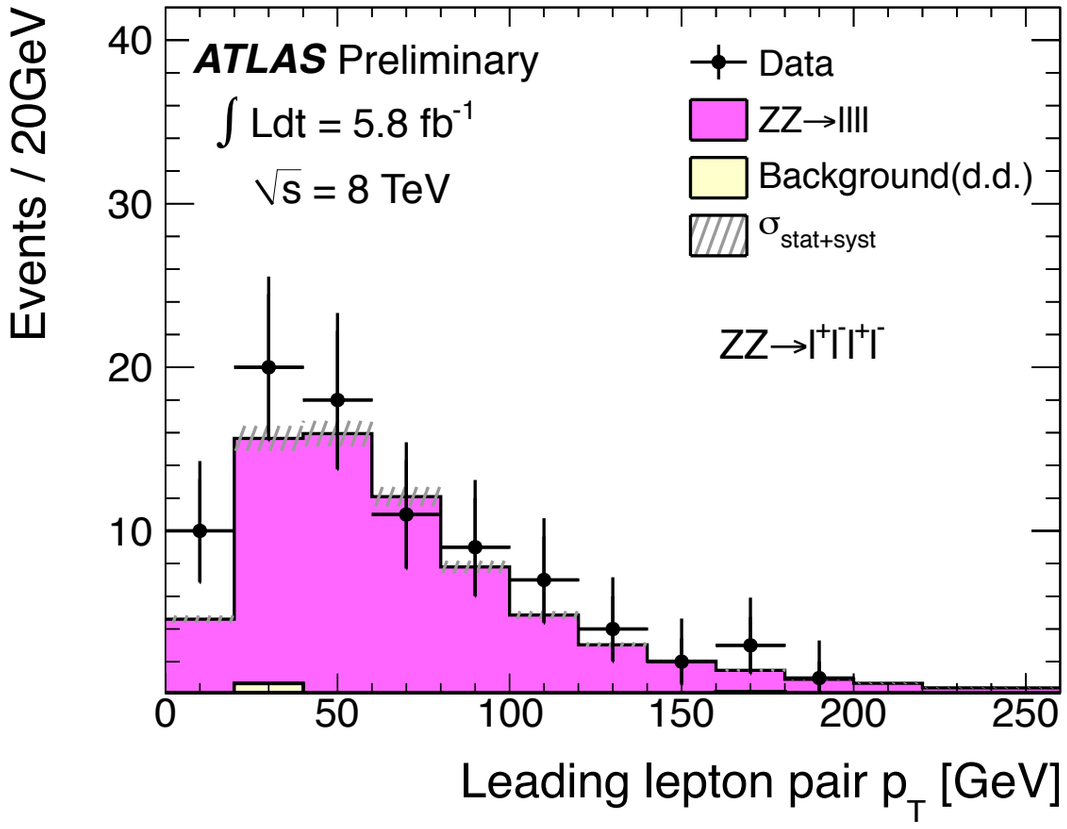
Dominant uncertainty:
Statistical

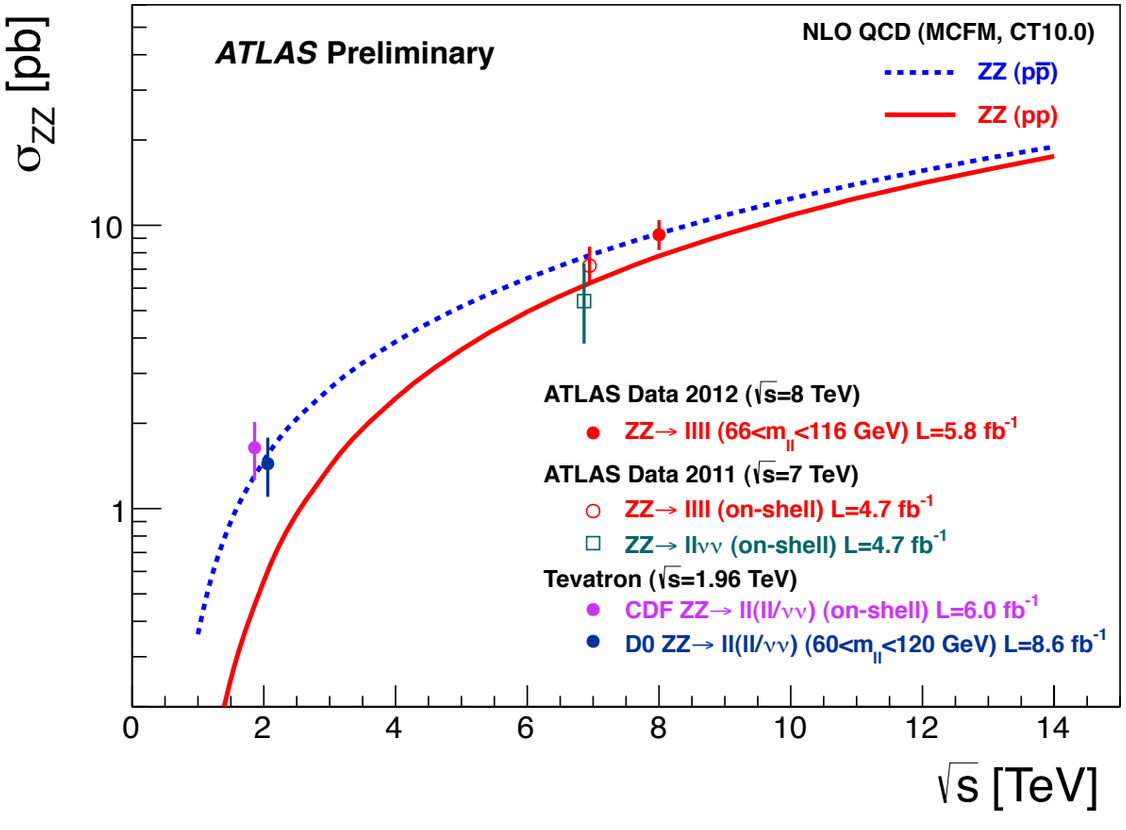
Total cross section

$$\sigma^{tot}_{ZZ} = 9.3^{+1.1}_{-1.0}(stat)^{+0.4}_{-0.3}(syst) \pm 0.3(lumi) \text{ pb}$$

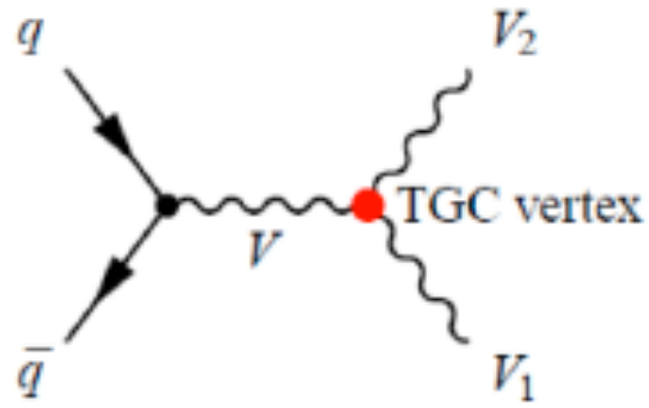
NLO SM prediction (MCFM)

$$\sigma^{SM}_{NLO} = 7.4 \pm 0.4 \text{ pb}$$





anomalous Triple Gauge Couplings



aTGC → increase of cross section at high invariant mass and high transverse momentum

Effective Lagrangian

$$WWV(V=Z,\gamma): \quad \frac{L_{WWV}}{g_{WWV}} = i\left(g_1^V\left(W_{\mu\nu}^{\dagger}W^{\mu}V^{\nu} - W_{\mu\nu}W^{\dagger\mu}V^{\nu}\right) + \kappa^V W_{\mu}^{\dagger}W_{\nu}V^{\mu\nu} + \frac{\lambda^V}{m_W^2}W_{\rho\mu}^{\dagger}W_{\nu}^{\mu}V^{\nu\rho}\right)$$

$$ZZV(V=Z,\gamma): \quad L = \frac{e}{m_Z^2}\left[f_4^V\left(\partial_{\mu}V^{\mu\beta}\right)Z_a\left(\partial^{\alpha}Z_{\beta}\right) + f_5^V\left(\partial^{\sigma}V_{\sigma\mu}\tilde{Z}^{\mu\beta}Z_{\beta}\right)\right]$$

Standard Model couplings:

$$g_1^V = \kappa_V = 1$$

$$\lambda_V = f_4^V = f_5^V = h_3^V = h_4^V = 0$$

→ Set limits on

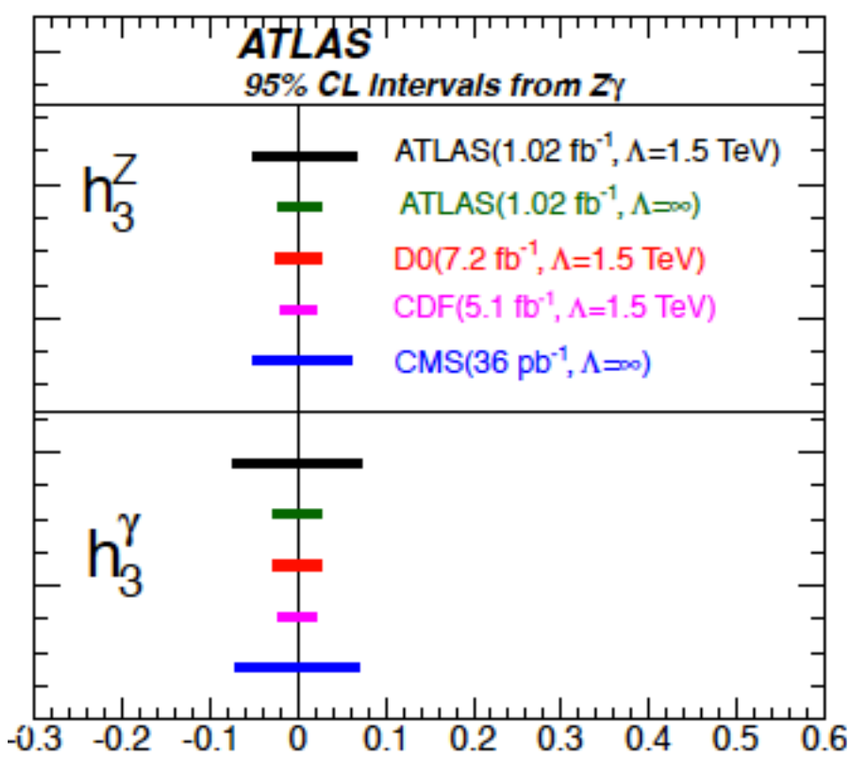
$$\Delta g_1^Z = g_1^Z - 1, \Delta\kappa_Z = \kappa_Z - 1, \lambda_Z, f_4^V, f_5^V, h_3^V, h_4^V$$

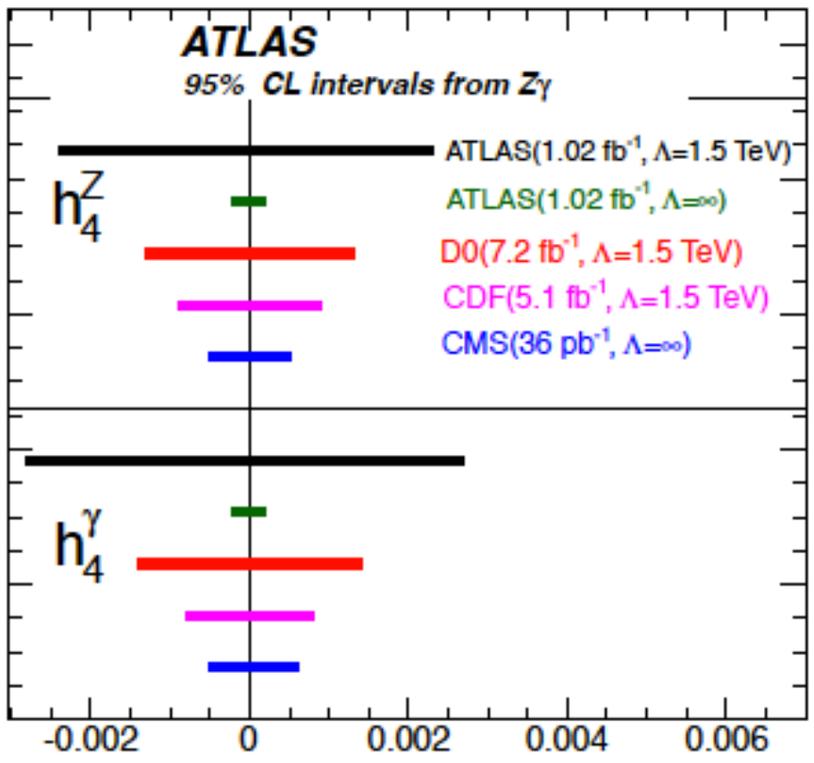
Introduce Form Factors to preserve unitarity at high $\sqrt{\hat{s}}$: $a(\hat{s}) = \dfrac{a_0}{\left(1+\hat{s}/\Lambda^2\right)^n}$

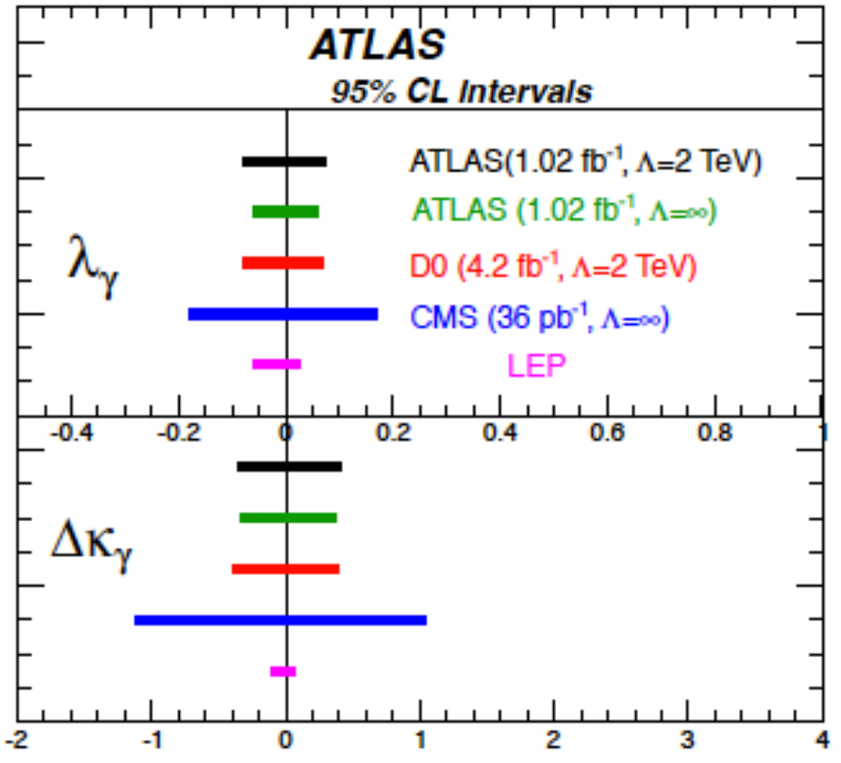
Anomalous couplings from Wγ/Zγ

arXiv:1205.2531

- Exclusive fiducial cross sections for Wγ production with E_T^γ > 100 GeV and Zγ production with E_T^γ > 60 GeV are used to extract limits on aTGC.
- WWγ vertex: $\lambda_\gamma, \Delta\kappa_\gamma = \kappa_\gamma - 1$
- ZVγ vertex: h_3^V, h_4^V (where V = Z, γ)
- Limits of aTGC parameters are extracted from Bayesian approach



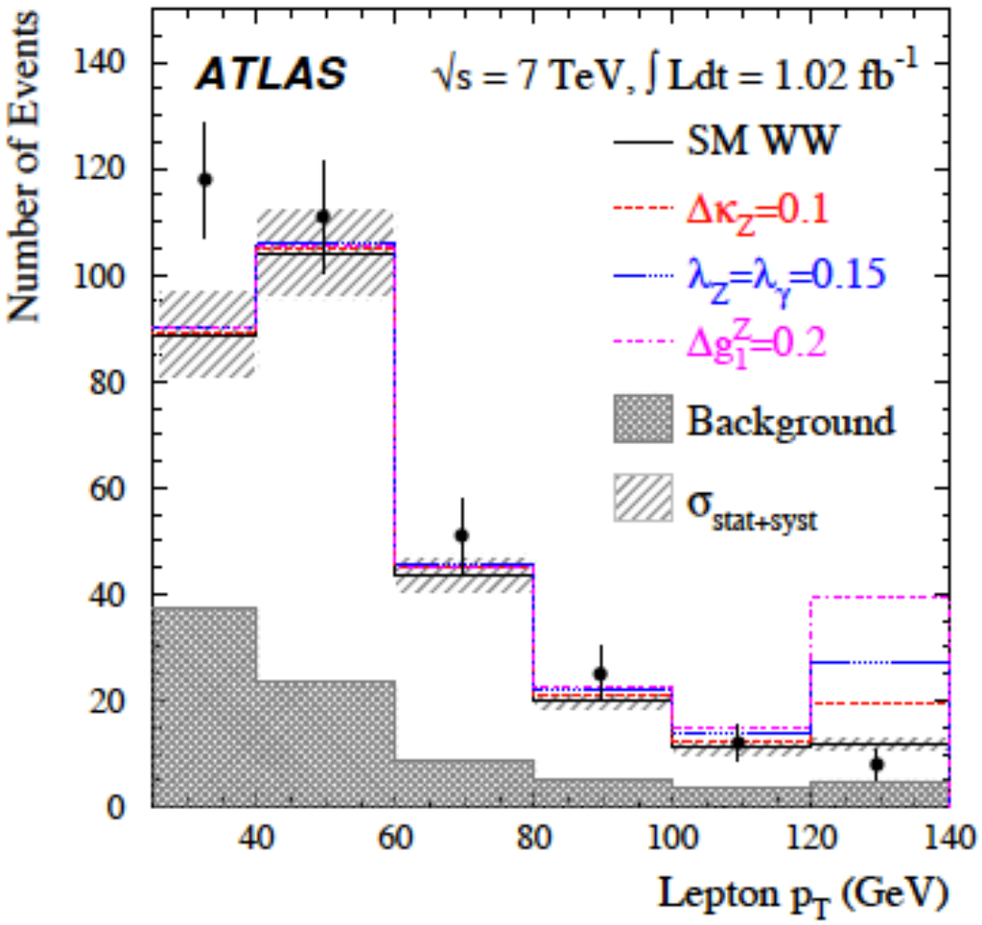


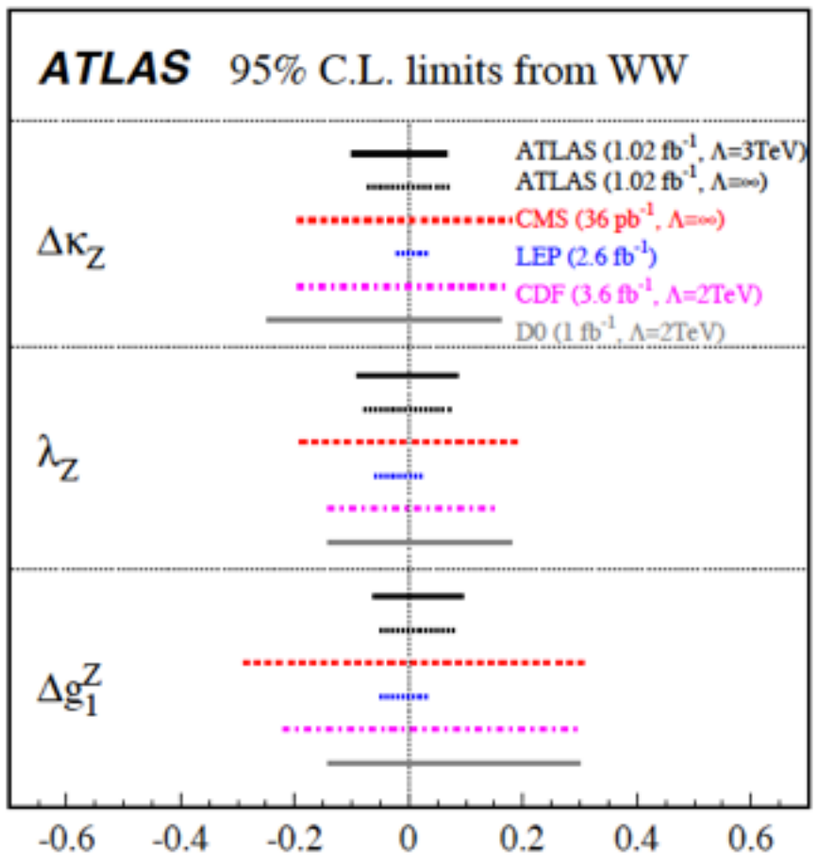


Anomalous couplings from WW

Phys.Rev.Lett. 107 (2011) 041802

- Leading lepton p_T distribution is used in a binned likelihood fit in order to extract aTGC limits



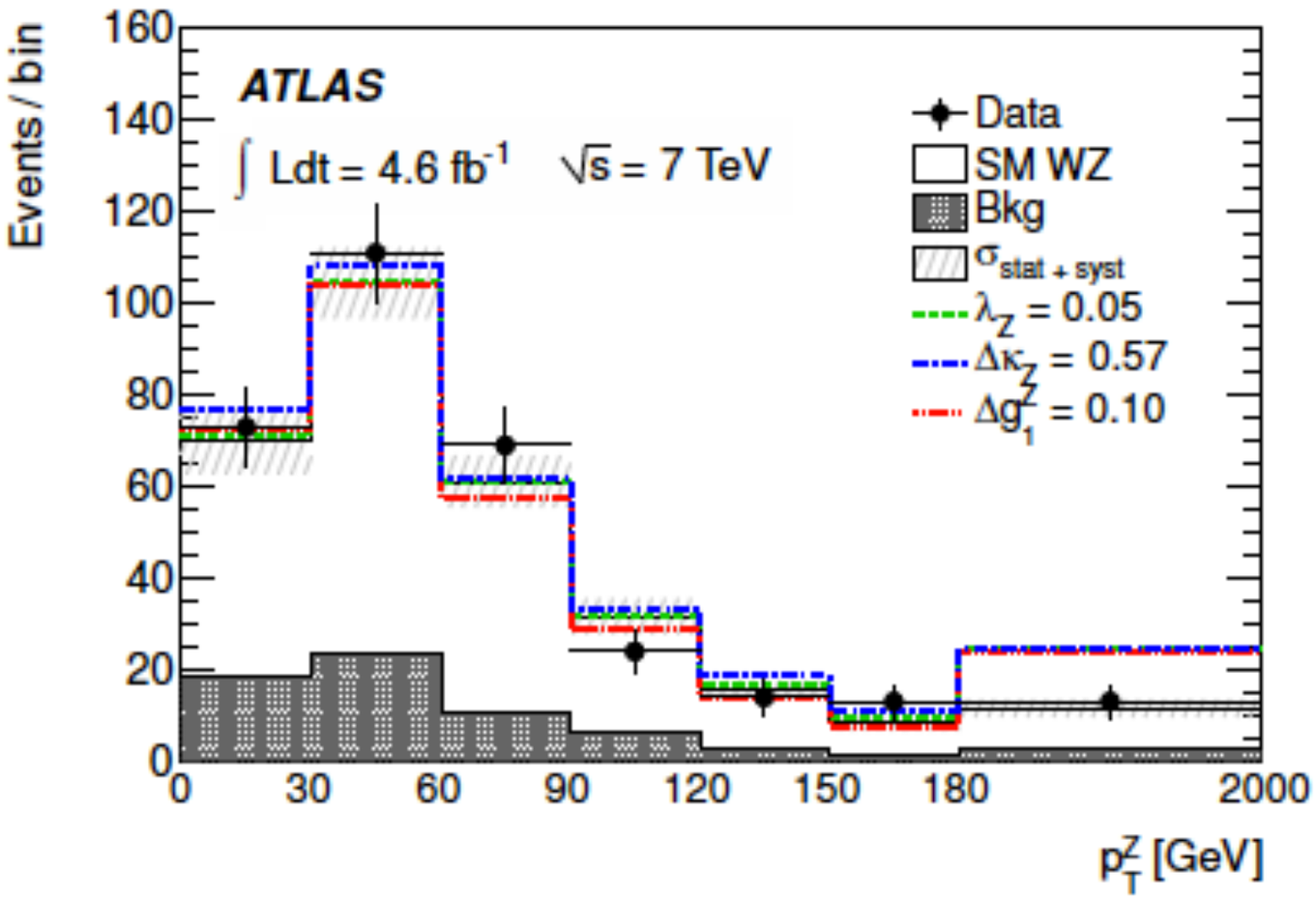


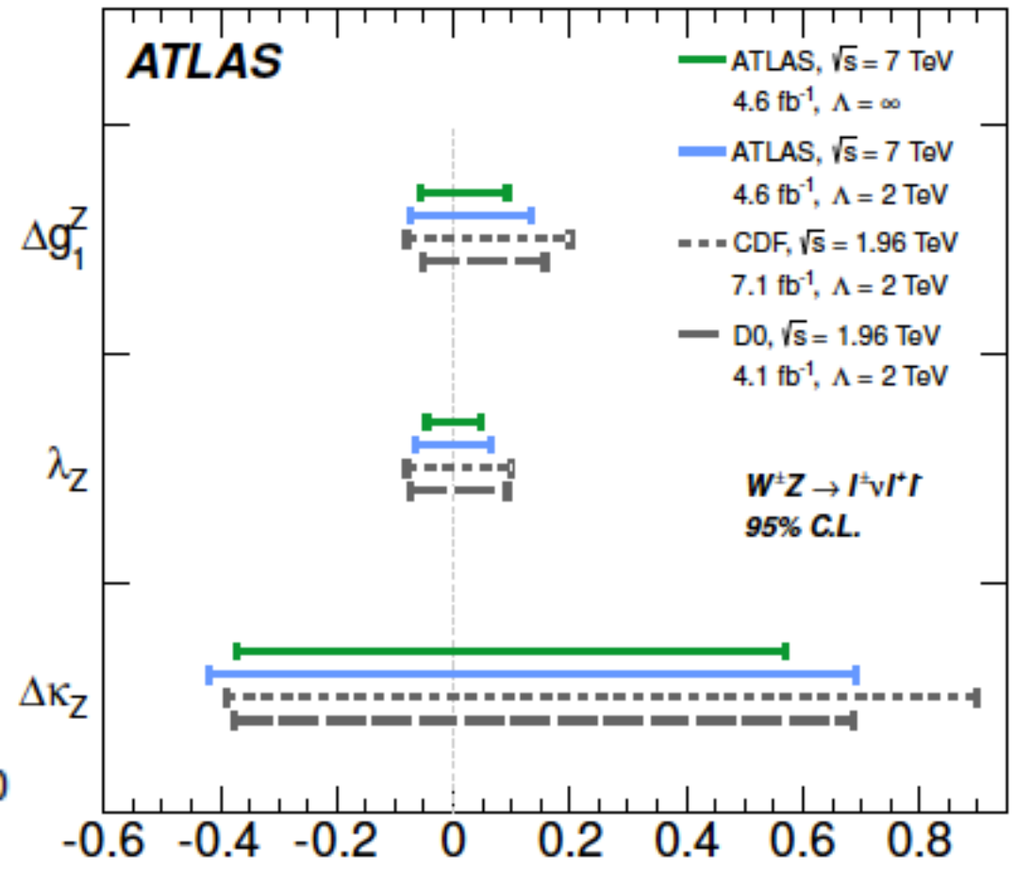
- More stringent limits compared to Tevatron limits because of the higher center of mass energy and higher WW production cross section.

Anomalous couplings from WZ

arXiv:1208.1390

- WWZ vertex: $\Delta g_1^Z = g_1^Z - 1, \Delta\kappa_Z = \kappa_Z - 1, \lambda_Z$
- 1- and 2- dimensional limits have been calculated by maximizing the profile likelihood method
- Limits determination on aTGCs by using the observed events binned in p_T^Z

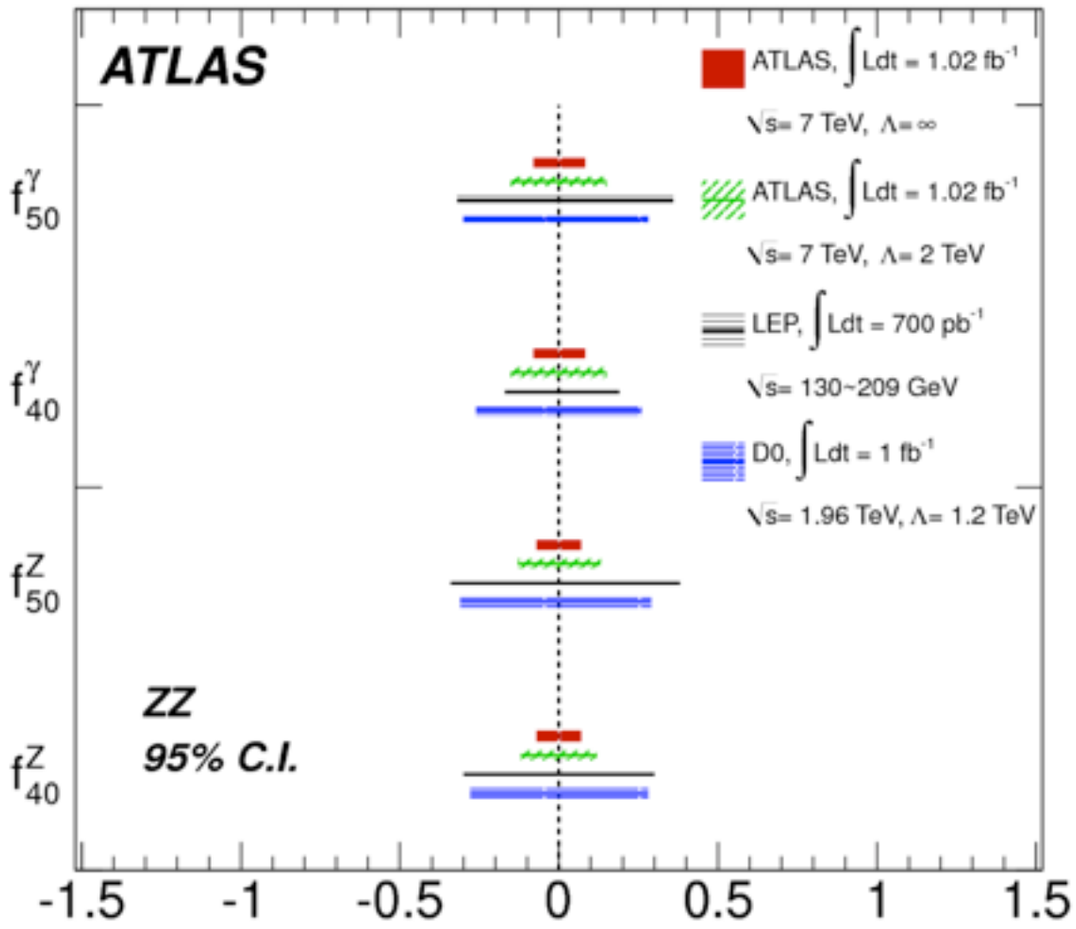




Anomalous Couplings From ZZ

Phys.Rev.Lett. 108 (2012) 041804

- ZZ→4l @ 1fb^{-1}
- Extraction of limits using total cross section
- Calculation of each coupling by setting all others to their SM values

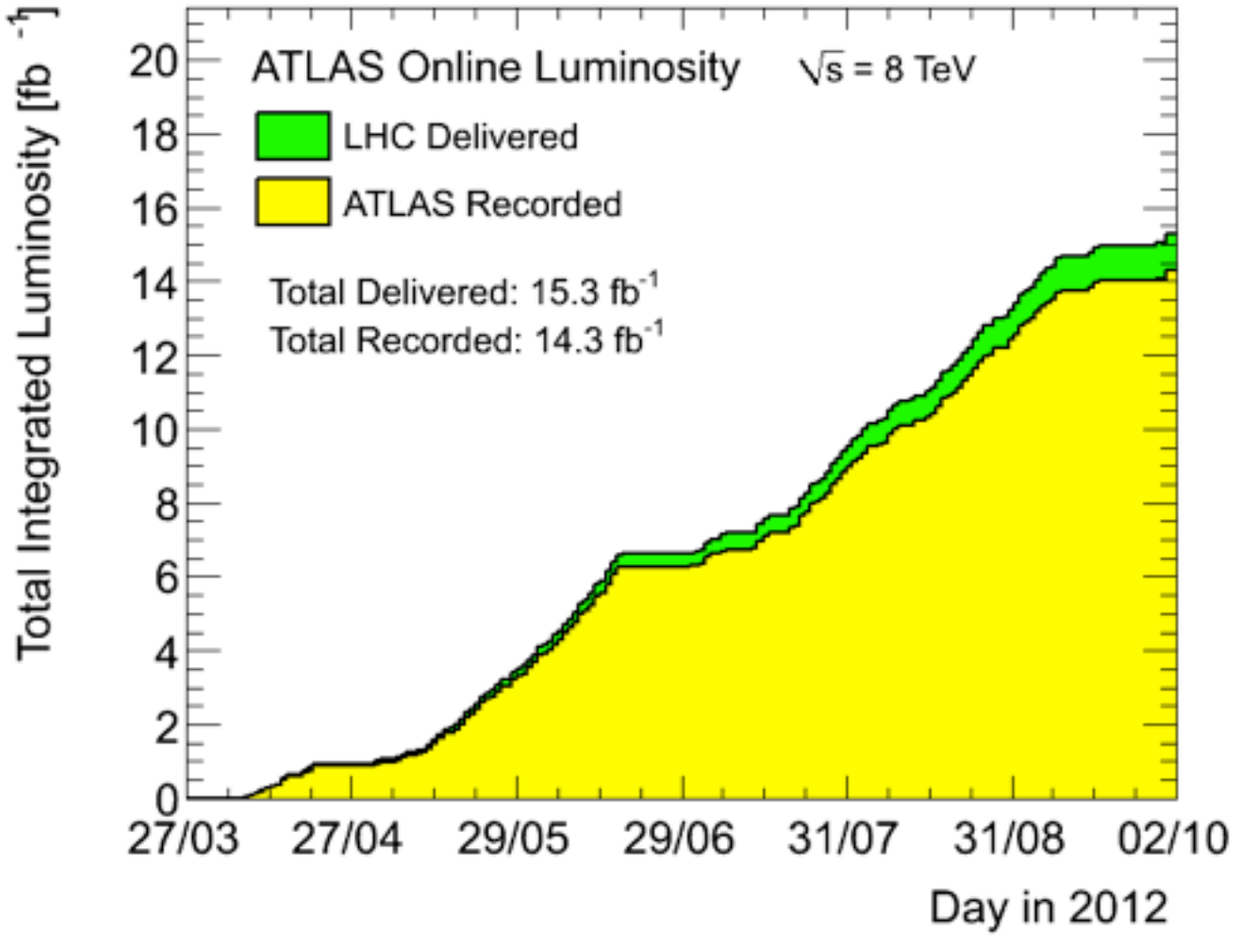


Conclusions

- Diboson production cross sections have been measured using full 2011 dataset (L ~ 5 fb^{-1})
  - Good agreement with the SM expectations

- aTGC limits have been set; most of them are at ~0.1

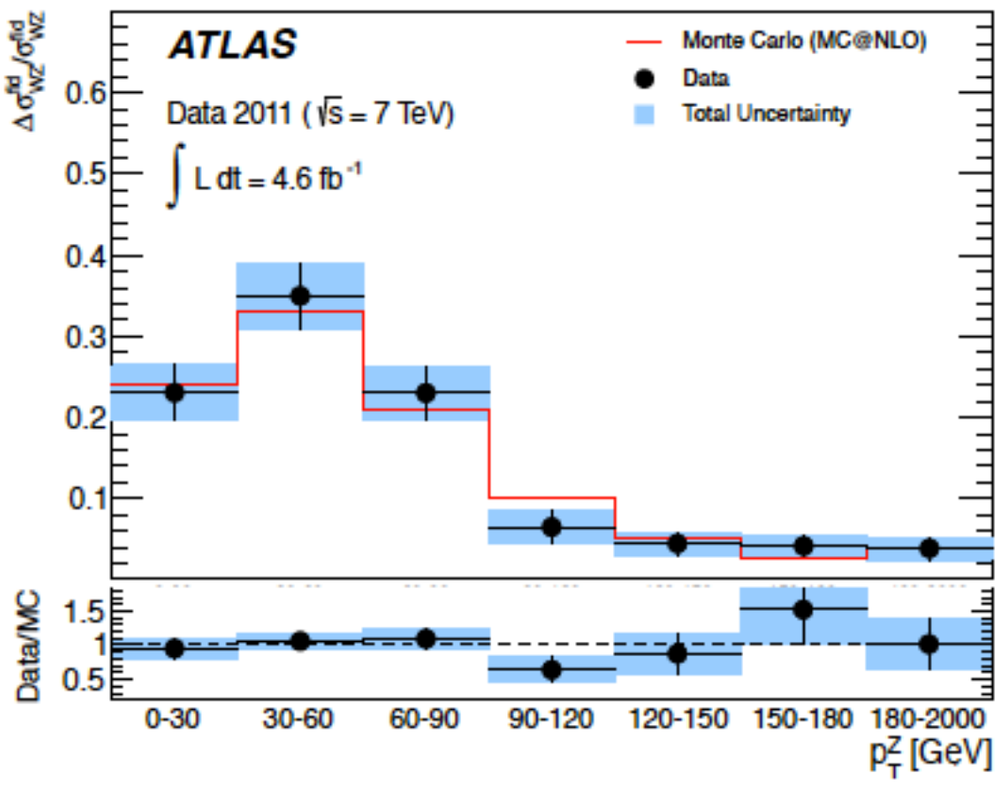
- LHC performs well... Aiming for 30 fb^{-1} by the end of this year
  - Higher center of mass energy $\sqrt{s}$ = 8 TeV
  - Cross section measurements and limits on aTGCs

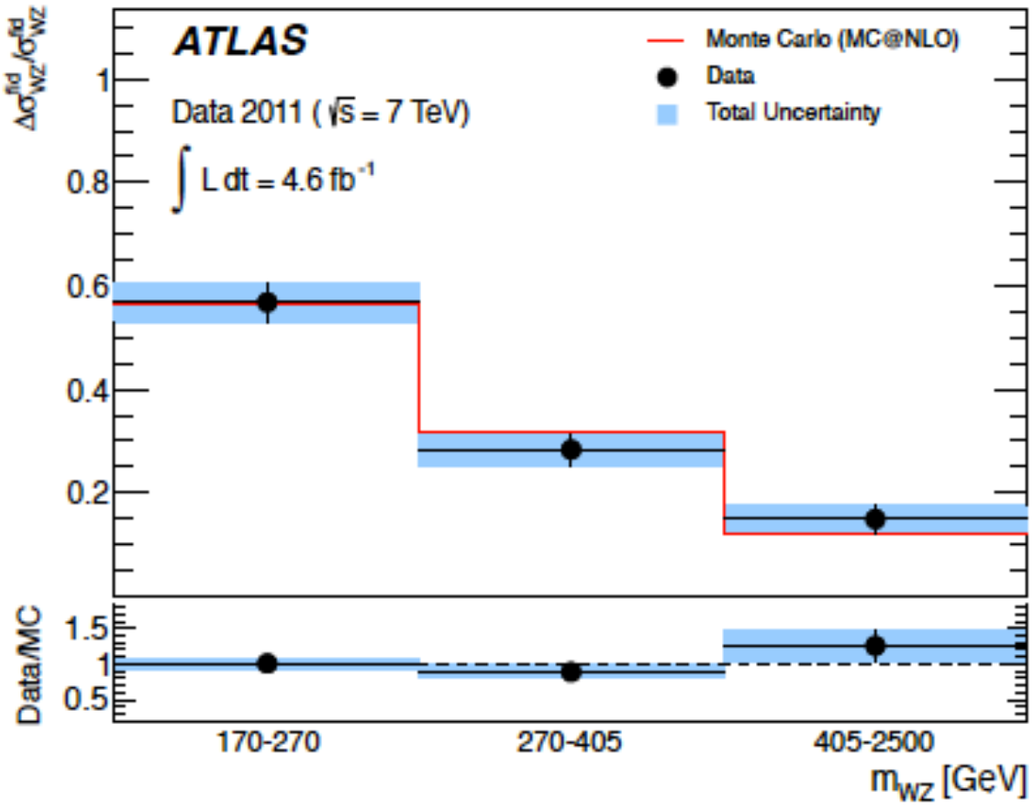


Back-up

$WZ \to \ell\nu\ell\ell$

arXiv:1208.1390

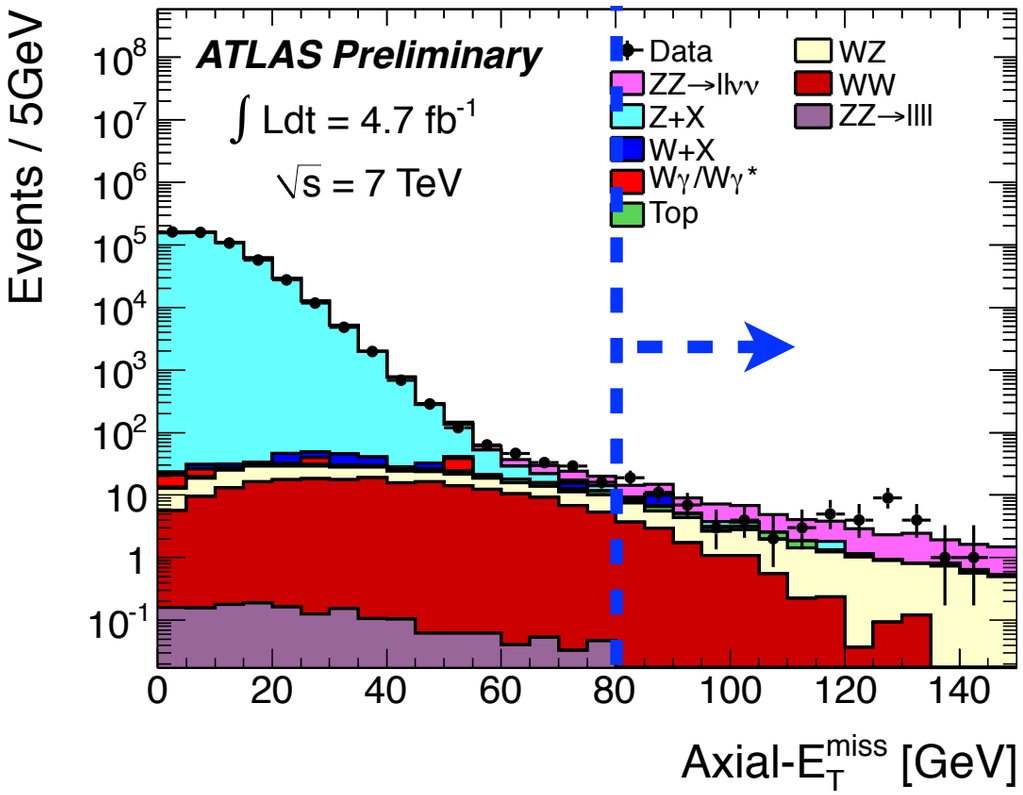


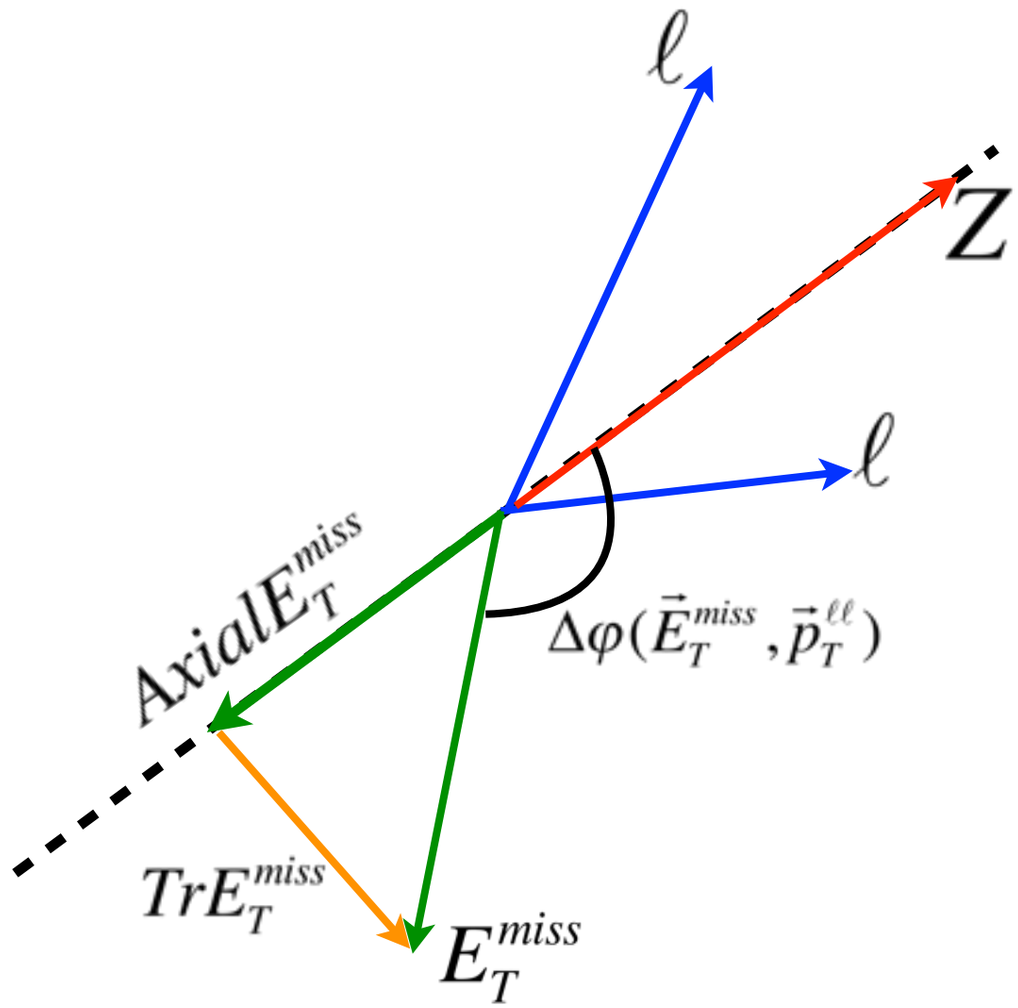


Axial E_T^{miss}

Axial E_T^{miss}: E_T^{miss} projection along the direction of Z

$$E_T^{miss} \cos\Delta\varphi(\vec{E}_T^{miss}, \vec{p}_T^{\ell\ell})$$





Important to remove Drell-Yan events

Selection of W and Z bosons

Lepton Selection

Single lepton (electron or muon) trigger
p_T > 7 - 15 GeV
|η| < 2.5
Track and Calorimetric based isolation
Impact parameter requirements

E_T^{miss} selection

Reconstruction based on calo clusters, leptons and jets

W selection

1 high p_T isolated lepton
E_T^{miss} > 25 - 50 GeV
M_T^W > 20 GeV

Z selection

1 SF-OS lepton pair
$|m_{\ell\ell} - m_Z|$ <10 - 25 GeV (WZ)