Measurement of multi-boson production and limits on anomalous gauge boson couplings

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On behalf of the ATLAS Collaboration

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2. W/Z γ Production
3. WW Production
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5. Semileptonic WW/WZ Decays
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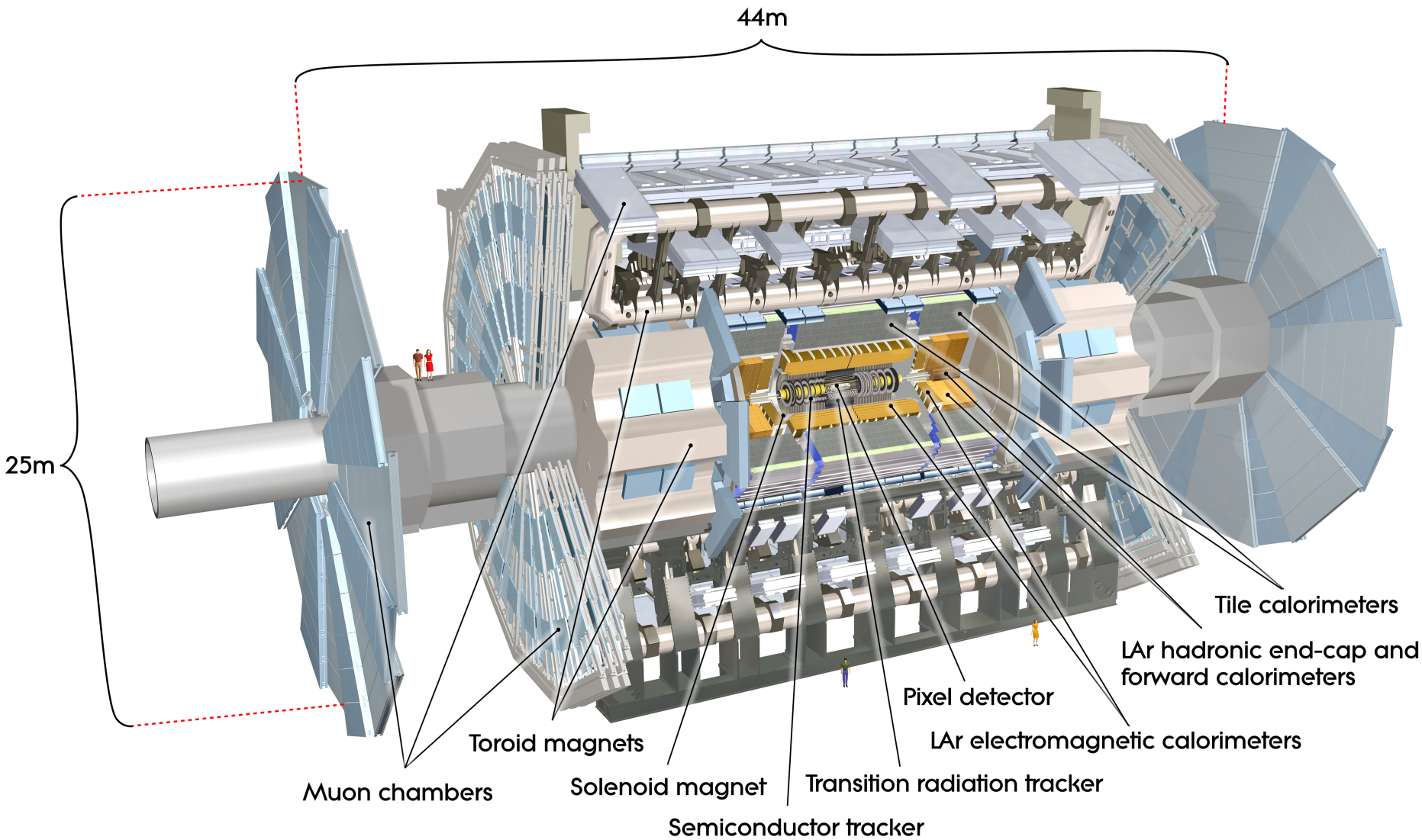
A Toroidal LHC ApparatuS



What We Measure: Cross Section

- Fiducial Cross Section
  - Define correction factor in selected region
  - $C_{VV} = \frac{N^{\text{MC Pass All Cuts}}_{\text{Reconstructed } VV} \times \text{SF}}{N^{\text{MC Fiducial Volume}}_{\text{Generated } VV}}$
  - $\sigma^{fid}_{VV} = \frac{N^{obs} - N^{bkg}}{\mathcal{L} \times C_{VV}}$
  - Smaller theoretical uncertainty
- Total Cross Section
  - Extrapolation to full cross section
  - $A_{VV} = \frac{N^{\text{MC Fiducial Volume}}_{\text{Generated } VV}}{N^{\text{MC All}}_{\text{Generated } VV}}$
  - $\sigma^{tot}_{VV} = \frac{N^{obs} - N^{bkg}}{\mathcal{L} \times BR\{VV\} \times A_{VV} \times C_{VV}}$
  - Pure theoretical uncertainty
- The cross sections are usually extracted using a negative log likelihood fit

$$-\ln L(\sigma, \vec{x}) = \sum_{i=1}^{n} -\ln \frac{e^{-[N^i_s(\sigma,\vec{x}) + N^i_b(\vec{x})]} [N^i_s(\sigma,\vec{x}) + N^i_b(\vec{x})]^{N^i_{obs}}}{N^i_{obs}!} + \frac{\vec{x} \cdot \vec{x}}{2}$$

What We Measure: Anomalous Triple Gauge Couplings (aTGC)

- Triple gauge couplings (TGC) occur in the s-channel diagrams
- Non-SM processes can be parameterized with an effective theory on the TGC
- Example: Charged aTGC Lagrangian WWV ($V = Z, \gamma$)

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = i\left[g_1^V(W^\dagger_{\mu\nu}W^\mu V^\nu - W_{\mu\nu}W^{\dagger\mu}V^\nu) + \kappa^V W^\dagger_\mu W_\nu V^{\mu\nu} + \frac{\lambda^V}{m_W^2}W^\dagger_{\rho\mu}W^\mu_\nu V^{\nu\rho}\right]$$

- In the Standard Model: $g_1^V = 1$, $\kappa^V = 1$ and λ^Z=0
- Usually parameterized as $\Delta g_1^Z = g_1^V - 1$ and $\Delta\kappa^Z = \kappa^V - 1$
- Neutral aTGC ZZV ($V = Z, \gamma$) are 0 at tree level in the SM
- The aTGCs must vanish as $\hat{s} \to \infty$ so a form factor is introduced

$$\alpha(\hat{s}) = \frac{\alpha_0}{(1+\hat{s}/\Lambda^2)^2}$$

- Results are presented with and without form factors

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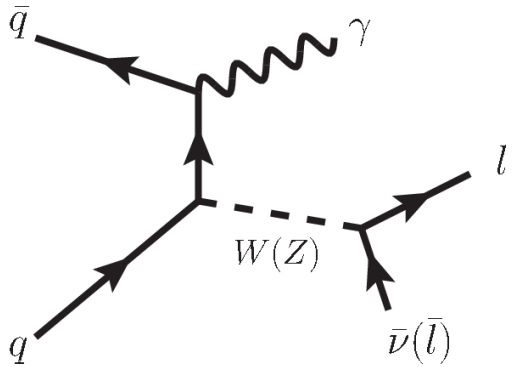
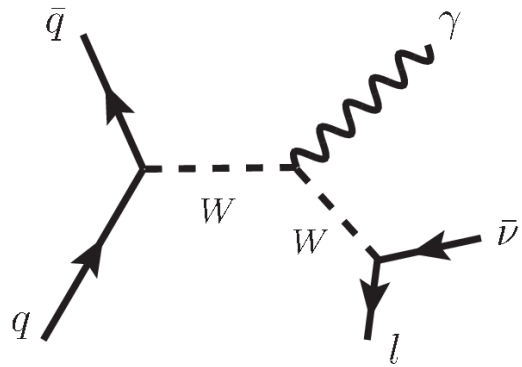
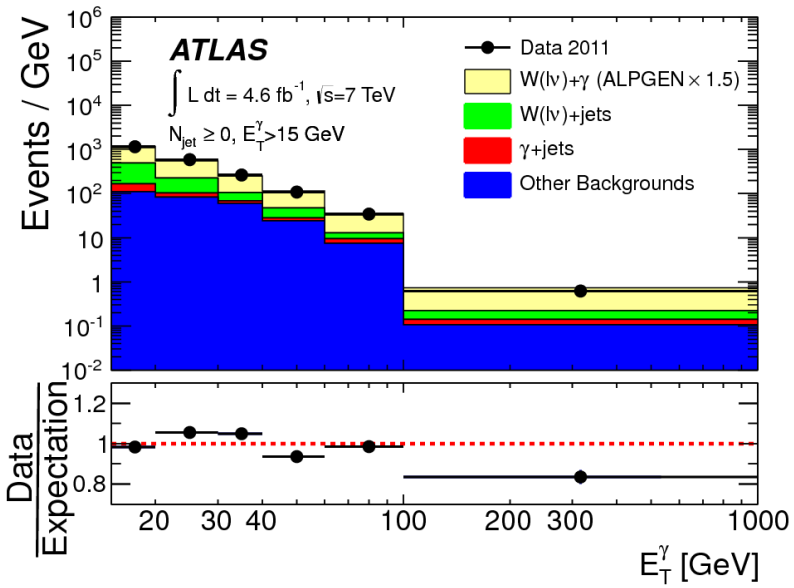
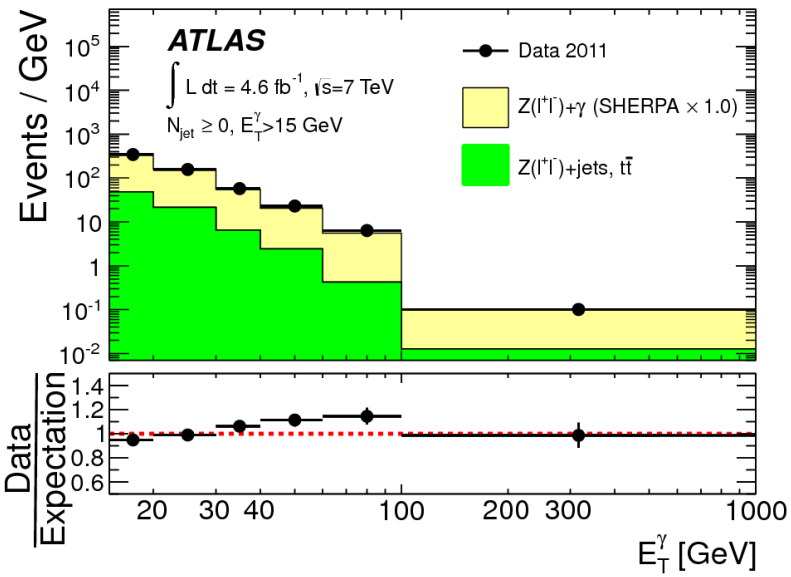
Event Selection

- $p_{\mathrm{T}}(\ell) > 25$ GeV, $E_T(\gamma) > 15$ GeV
- $W\gamma$: $m_T > 40$ GeV, $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV
- $Z\gamma$: $m_{\ell^+\ell^-} > 40$ GeV
- $W/Z + jet$ background estimated from data

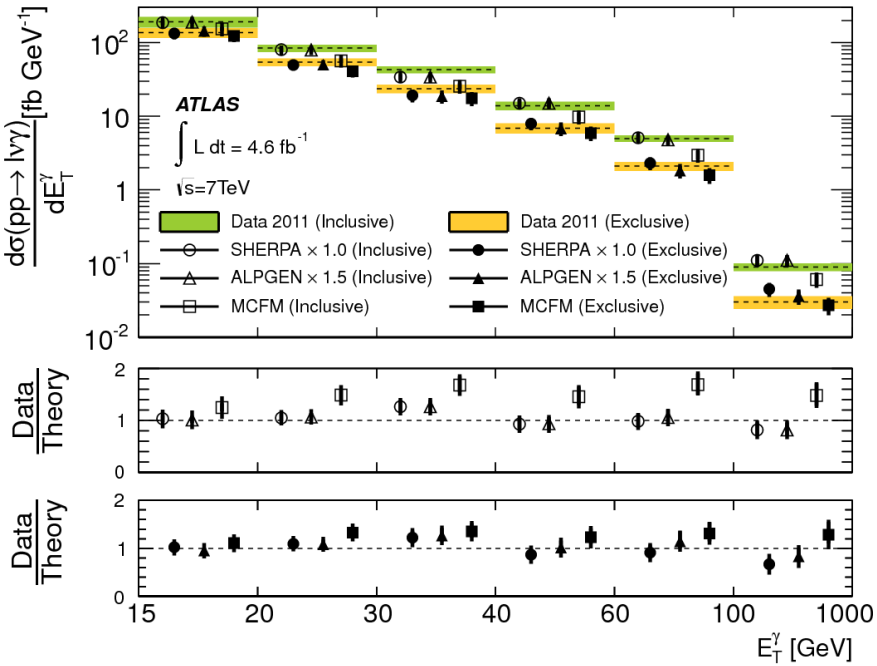


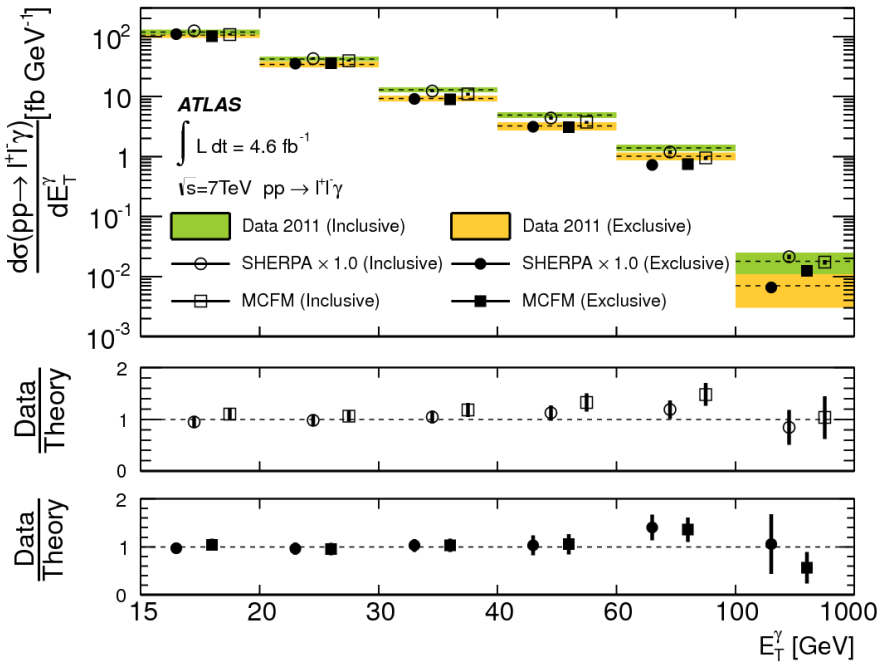






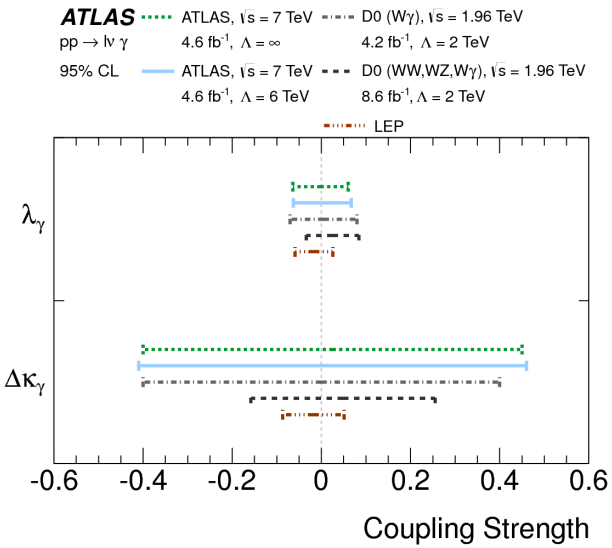
Cross Section

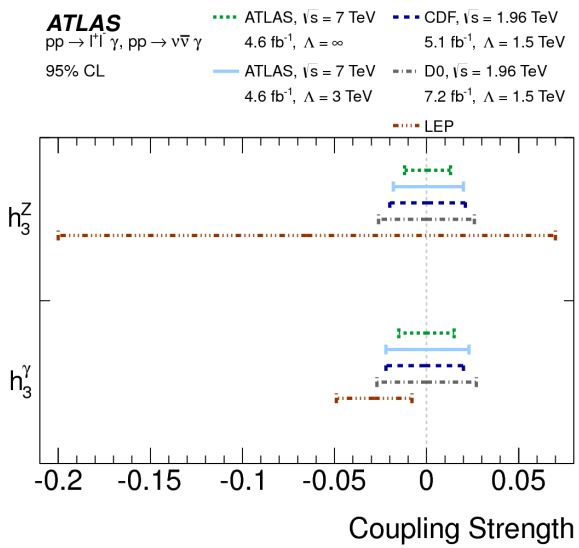


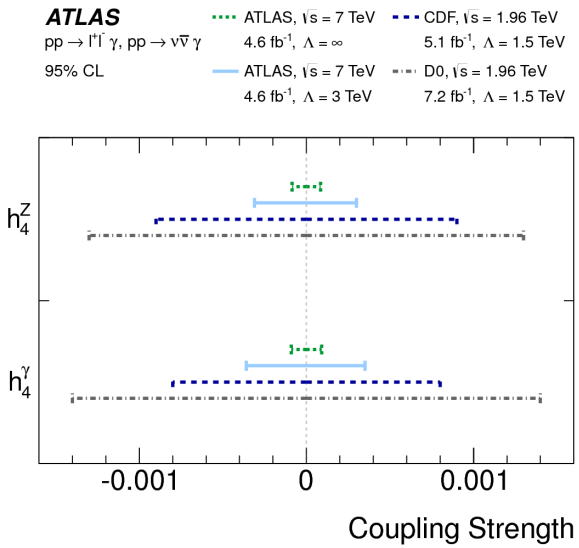


- Exclusive→no hard jets ($p_{\mathrm{T}} > 30$ GeV, $|\eta^{\mathrm{jet}}| < 4.4$) in the final state
- $\sigma_{W\gamma+X}^{\mathrm{ext-fid}} = 2.77 \pm 0.03(\mathrm{stat}) \pm 0.33(\mathrm{syst}) \pm 0.14(\mathrm{lumi})$ pb
- $\sigma_{W\gamma}^{\mathrm{ext-fid}} = 1.76 \pm 0.03(\mathrm{stat}) \pm 0.21(\mathrm{syst}) \pm 0.08(\mathrm{lumi})$ pb
- $\sigma_{Z\gamma+X}^{\mathrm{ext-fid}} = 1.31 \pm 0.02(\mathrm{stat}) \pm 0.11(\mathrm{syst}) \pm 0.05(\mathrm{lumi})$ pb
- $\sigma_{Z\gamma}^{\mathrm{ext-fid}} = 1.05 \pm 0.02(\mathrm{stat}) \pm 0.10(\mathrm{syst}) \pm 0.04(\mathrm{lumi})$ pb

aTGC limits







- Calculated in 4.6 fb^{-1} at 7 TeV
- The limits are extracted using the observed number of $V\gamma$ events with no jets and $E_T^\gamma > 100$ GeV
- 95% confidence intervals calculated using the maximum profile likelihood ratio
- The ratio was calculated for data and 10,000 pseudo experiments

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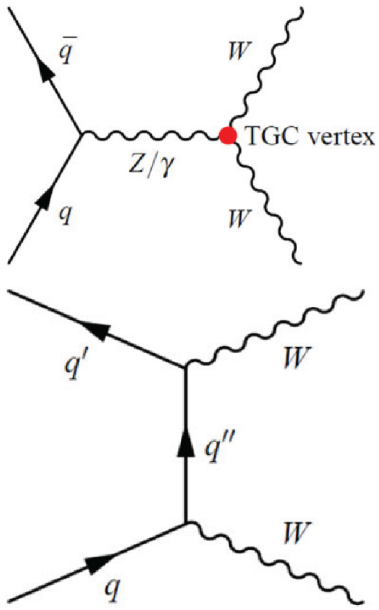
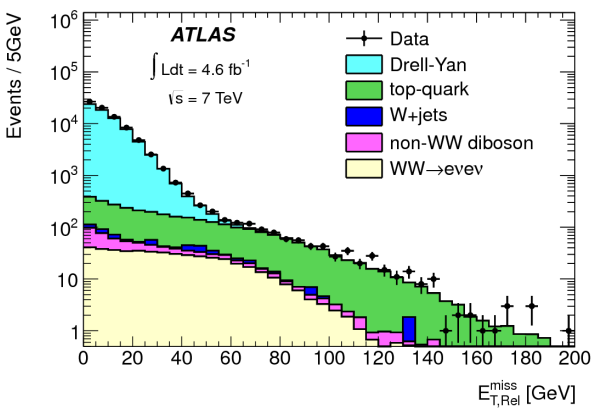
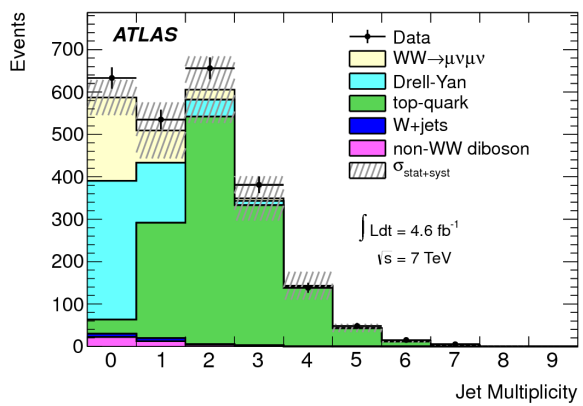
Event Selection

- $p_{\mathrm{T}}(\ell) > 20$ GeV, $p_{\mathrm{T}}(\ell\ell) > 30$ GeV
- At least one lepton with $p_{\mathrm{T}}(\ell) > 25$ GeV
- $m_{\ell'\ell} > 15$ (10) GeV for $ee/\mu\mu$ ($e\mu$)
- $|m_{\ell'\ell} - m_Z| > 15$ (0) GeV for $ee/\mu\mu$ ($e\mu$)
- $E_{\mathrm{T,rel}}^{\mathrm{miss}} > 45$ (25) GeV for $ee/\mu\mu$ ($e\mu$)
- Jet veto ($p_{\mathrm{T}} > 25$ GeV, $|\eta| < 4.5$)







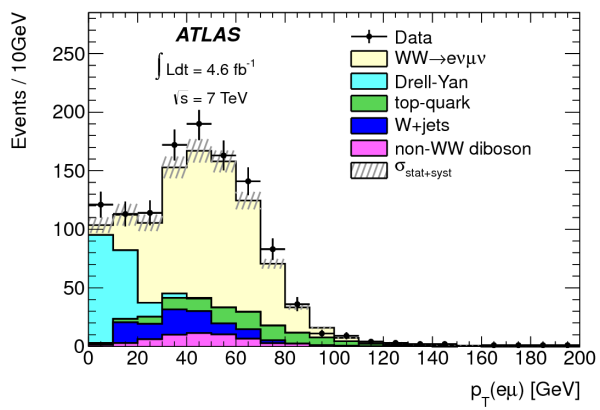


Figure: Left $e\nu e\nu$, Center $\mu\nu\mu\nu$, Right $e\nu\mu\nu$

Cross Section

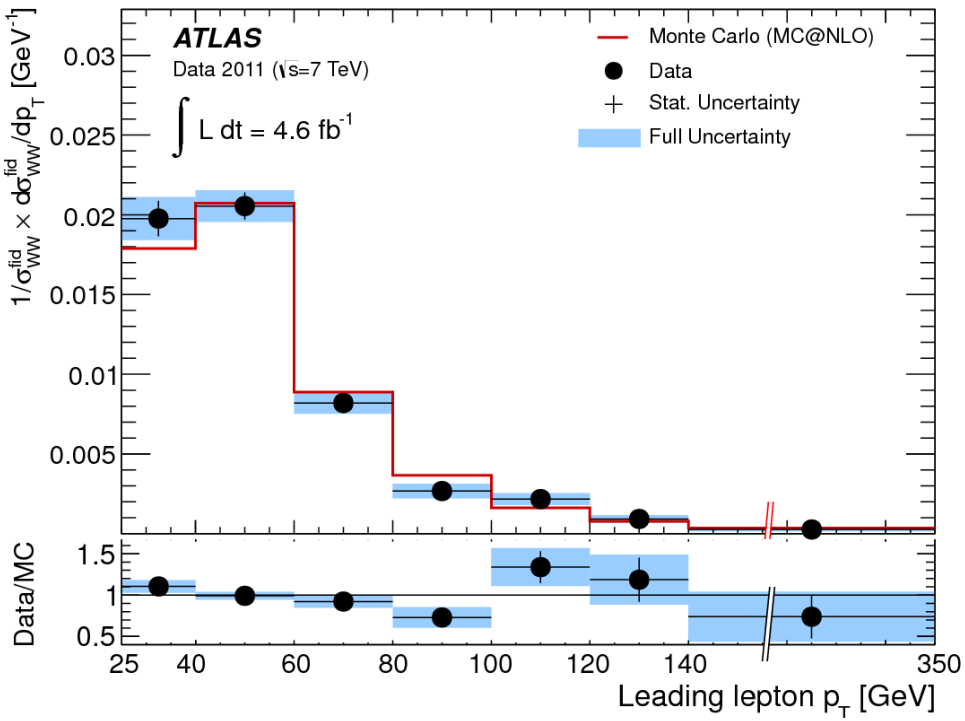
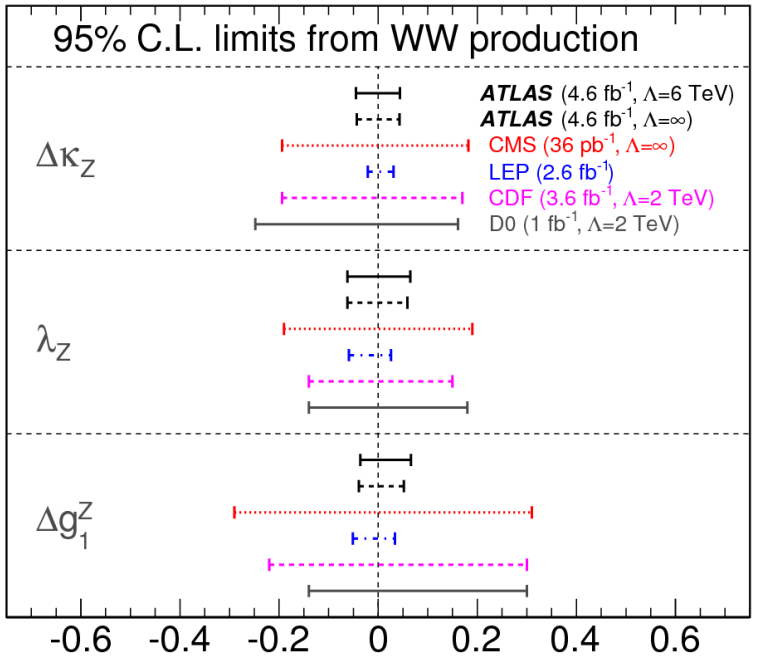


Figure: The normalized differential WW fiducial cross section as a function of the leading lepton p_{T} compared to the SM prediction

- Combined total cross section:
  $\sigma_{WW} = 51.9 \pm 2.0(\mathrm{stat}) \pm 3.9(\mathrm{syst}) \pm 2.0(\mathrm{lumi})$ pb
- SM expected total cross section: $\sigma_{WW} = 44.7^{+2.1}_{-1.9}$ pb

aTGC limits

- aTGC 95% confidence intervals were calculated by finding all the aTGC values for which the negative log-likelihood function increased by no more than 1.92 above the minimum
- The limits are extracted using the leading lepton p_{T} distribution



Parameter	Expected ($\Lambda = \infty$)	Observed ($\Lambda = \infty$)
$\Delta\kappa^Z$	[-0.077,0.086]	[-0.078,0.092]
λ^Z	[-0.071,0.069]	[-0.074,0.073]
λ^γ	[-0.144,0.135]	[-0.152,0.146]
Δg_1^Z	[-0.449,0.546]	[-0.373,0.562]
$\Delta\kappa^\gamma$	[-0.128,0.176]	[-0.135,0.190]

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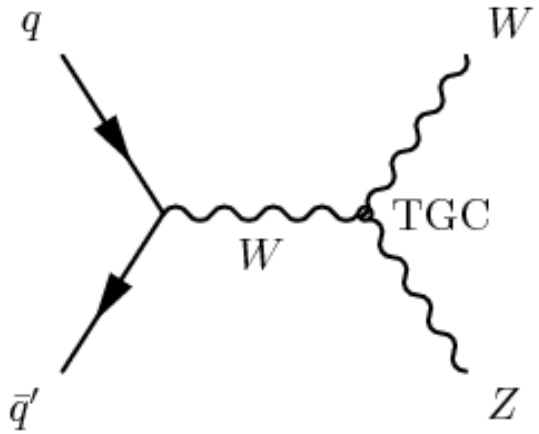
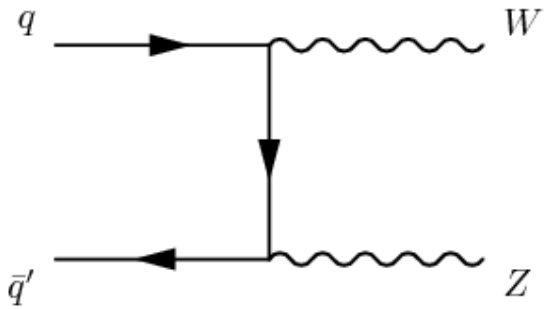
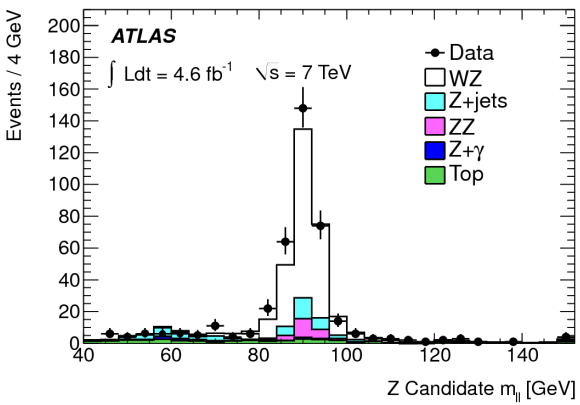
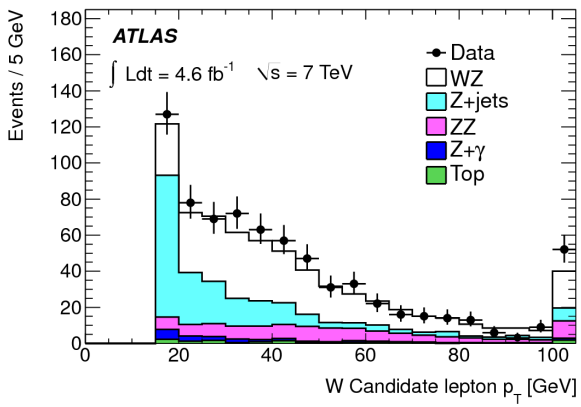
Event Selection

- Z: $p_{\mathrm{T}}(\ell) > 15$ GeV, $|m_{\ell\ell} - m_Z| < 10$ GeV
- W: $p_{\mathrm{T}}(\ell) > 20$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV
- $m_T(W) > 20$ GeV









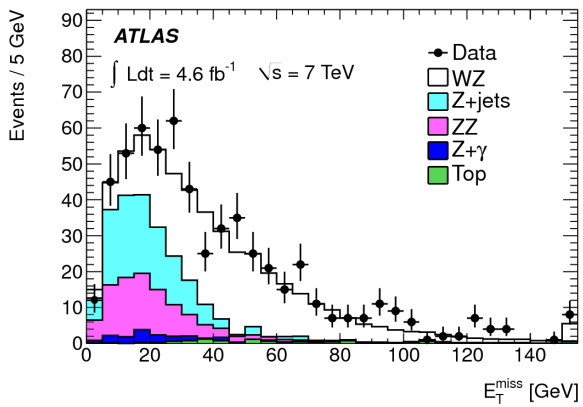
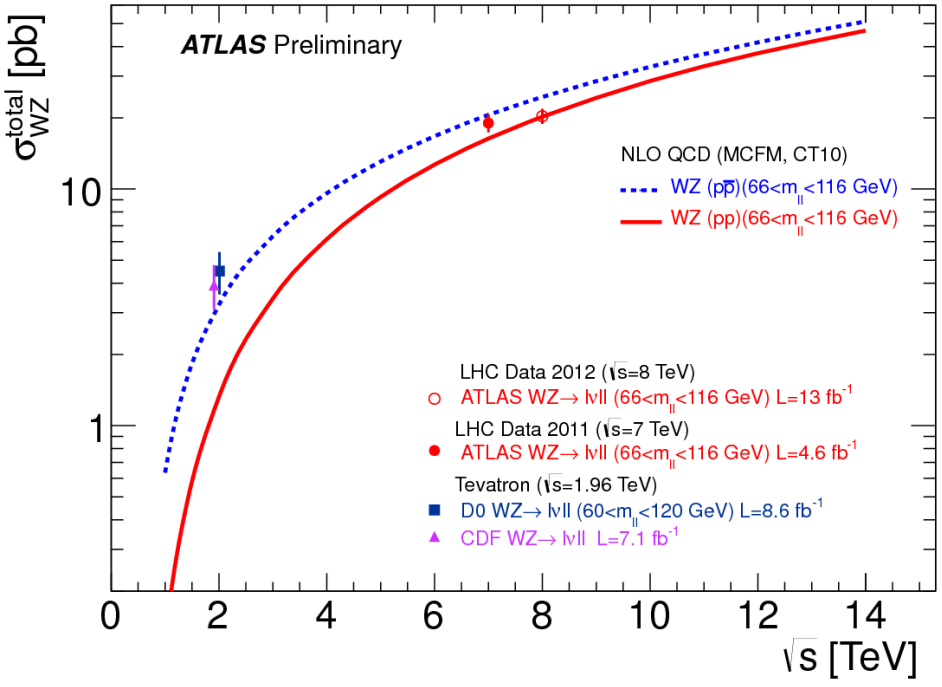
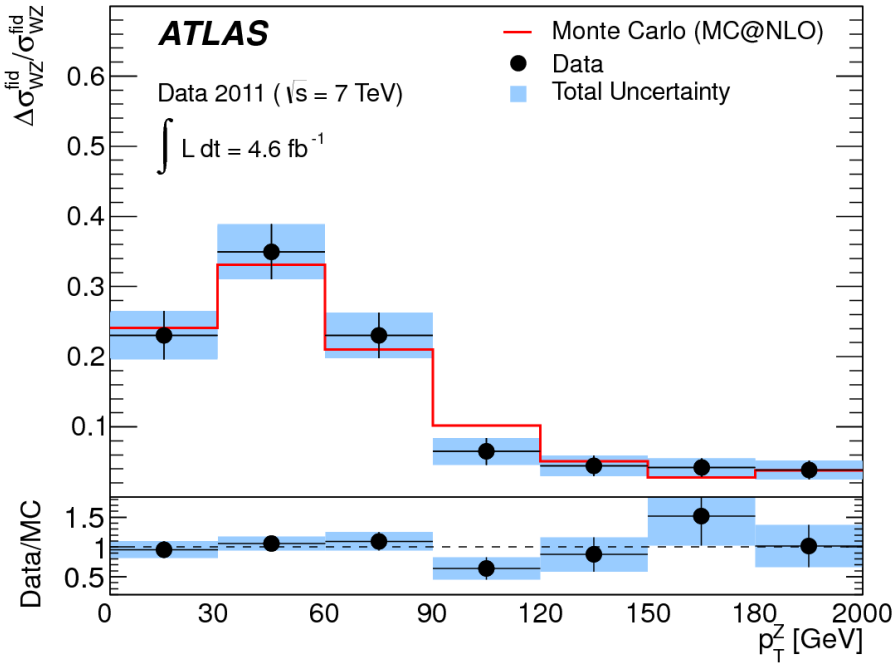


Figure: All cuts are applied in each plot except for the value on the x-axis

Cross Section

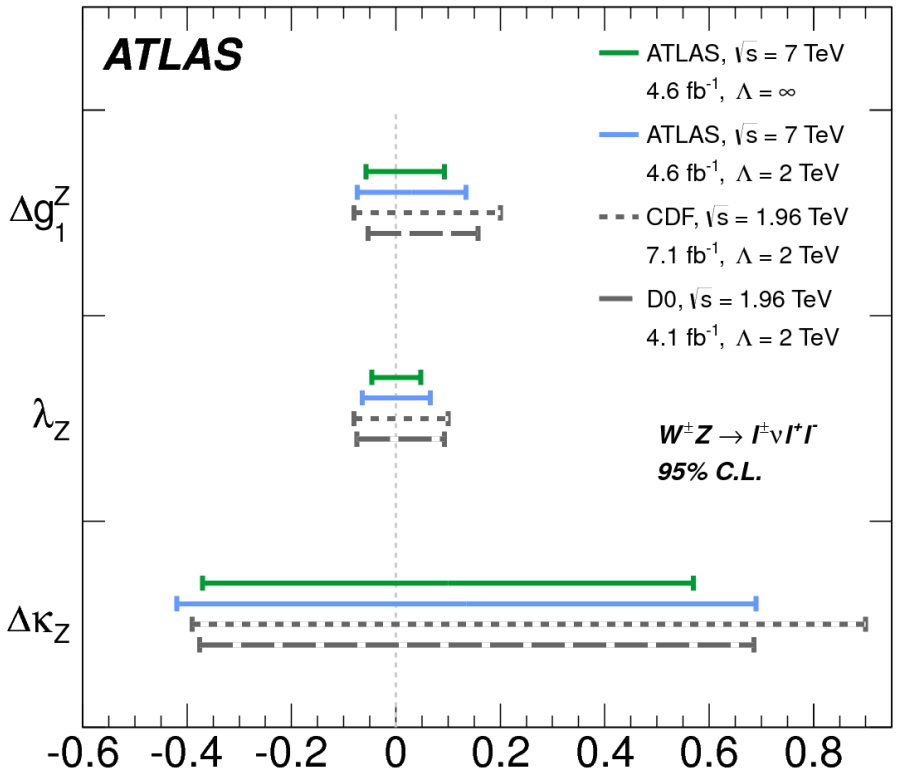




- Measured combined total cross section:
  - 7 TeV, 4.6fb^{-1}: $\sigma_{WZ} = 19.0^{+1.4}_{-1.3}(\text{stat}) \pm 0.9(\text{syst}) \pm 0.4(\text{lumi})$ pb
  - 8 TeV, 13fb^{-1}: $\sigma_{WZ} = 20.3^{+0.8}_{-0.7}(\text{stat})^{+1.2}_{-1.1}(\text{syst})^{+0.7}_{-0.6}(\text{lumi})$ pb
- Expected combined total cross section:
  - 7 TeV: $\sigma_{WZ} = 17.6^{+1.1}_{-1.0}$ pb
  - 8 TeV: $\sigma_{WZ} = 20.3 \pm 0.8$ pb

aTGC limits

- Calculated in 4.6 fb^{-1} at 7 TeV
- 95% confidence intervals calculated using the maximum profile likelihood ratio
- The ratio was calculated for data and 10,000 pseudo experiments
- the p_T^Z distribution in 7 bins was used to extract the limits



Parameter	Expected ($\Lambda = \infty$)	Observed ($\Lambda = \infty$)
Δg_1^Z	[-0.046,0.080]	[-0.074,0.093]
$\Delta\kappa^Z$	[-0.33,0.47]	[-0.37,0.57]
λ^Z	[-0.041,0.040]	[-0.046,0.047]

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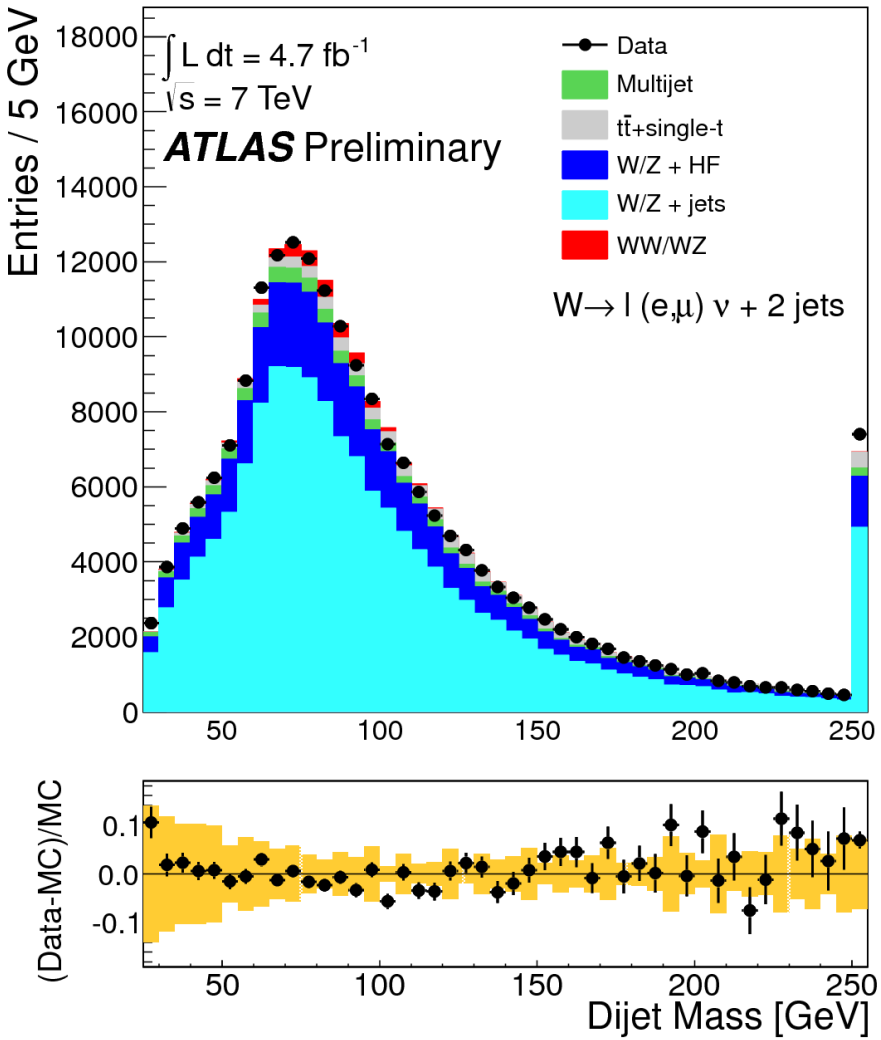
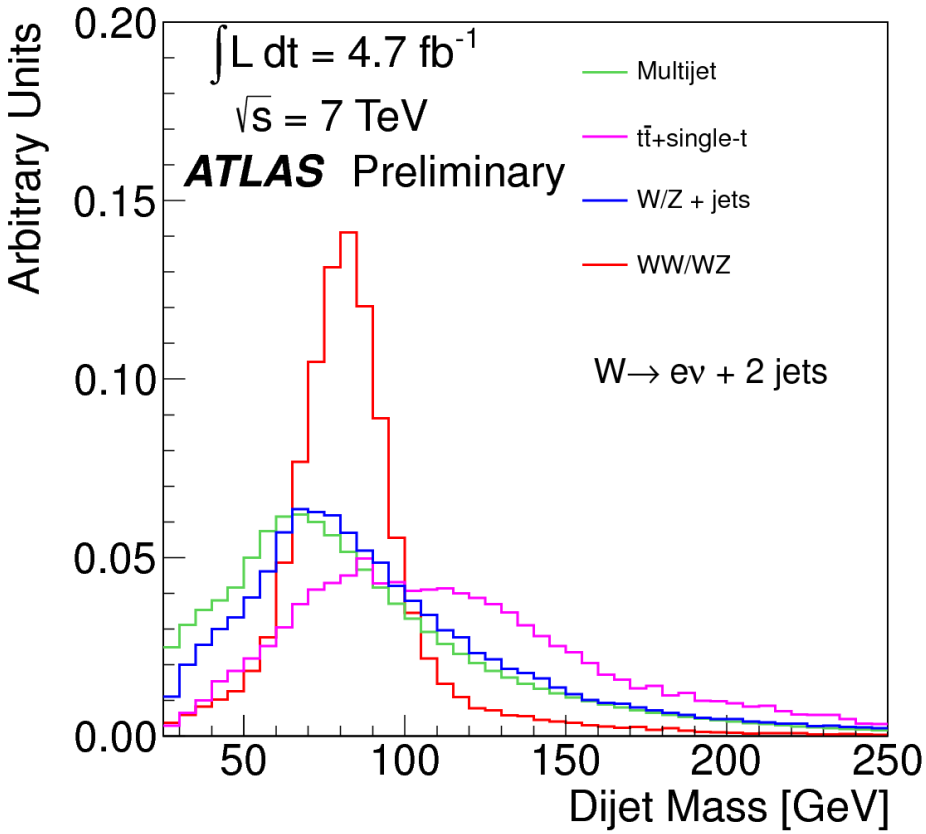
Event Selection

- Challenging analysis: S/B $< 1\%$
- Major background: W/Z+jet
- $p_{\mathrm{T}}(\ell) > 25$ GeV
- $E_{\mathrm{T}}^{\mathrm{miss}} > 30$ GeV
- $m_T > 40$ GeV
- Exactly two jets:
  - $p_{\mathrm{T}}(j) > 30$ & 25 GeV
  - $|\eta| < 2$
  - $\Delta R(j_1, j_2) > 0.7$
  - $|\Delta\eta(j_1, j_2)| < 1.5$
  - $\Delta\phi(E_{\mathrm{T}}^{\mathrm{miss}}, j_1) > 0.8$



Fitting Procedure

- Binned maximum-likelihood fit of observed di-jet mass distribution of $W/Z \to jj$ candidates
- Fit determines $\mu = \frac{\sigma_{obs}}{\sigma_{NLO}}$
- Contributions from signal and backgrounds are described by m_{jj} templates



Cross Section

- Top 3 systematics
  - MC Statistics $\pm 18\%$
  - Jet Energy Scale $\pm 12\%$
  - W/Z+jets normalization $\pm 11\%$
- Combined $\mu = 1.13 \pm 0.34$
- Combined total cross section: $\sigma_{WW+WZ} = 72 \pm 9(\text{stat}) \pm 15(\text{syst}) \pm 13(\text{MCstat})$ pb
- SM expected total cross section: $\sigma_{WW+WZ} = 63.4 \pm 2.6$ pb
- Expected significance: 3.0σ, Observed significance: 3.3σ

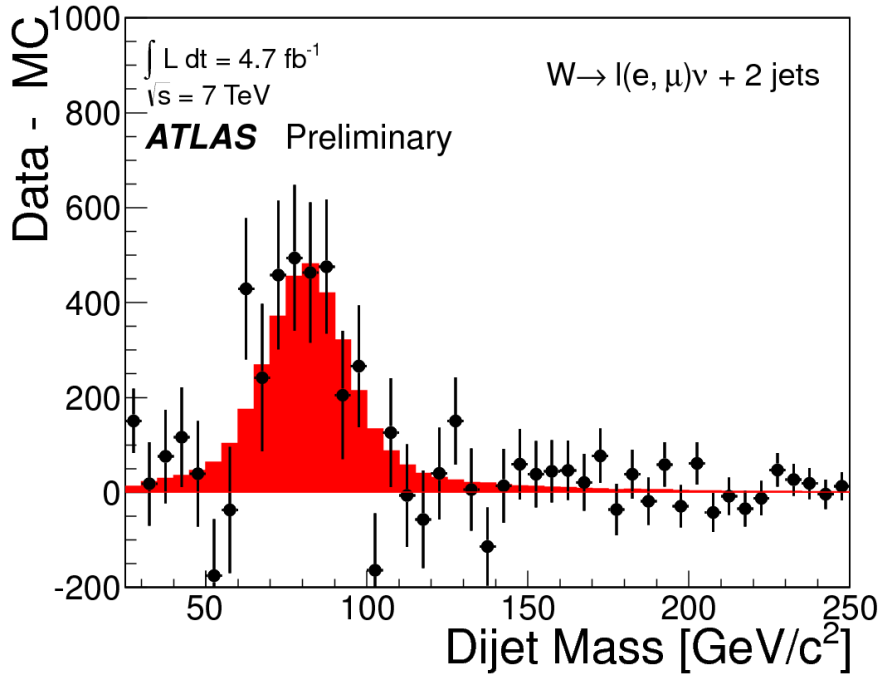


Figure: Background subtracted di-jet invariant mass distribution of reconstructed $W/Z \to jj$ candidates

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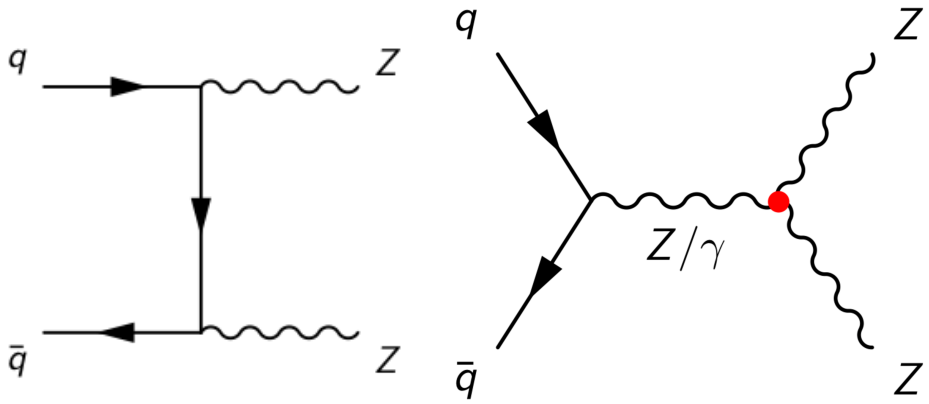
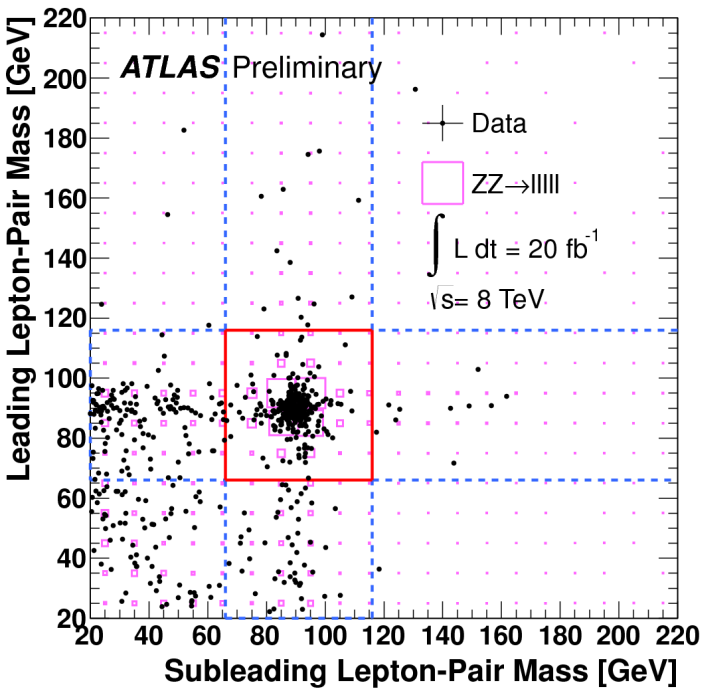
Event Selection: $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$

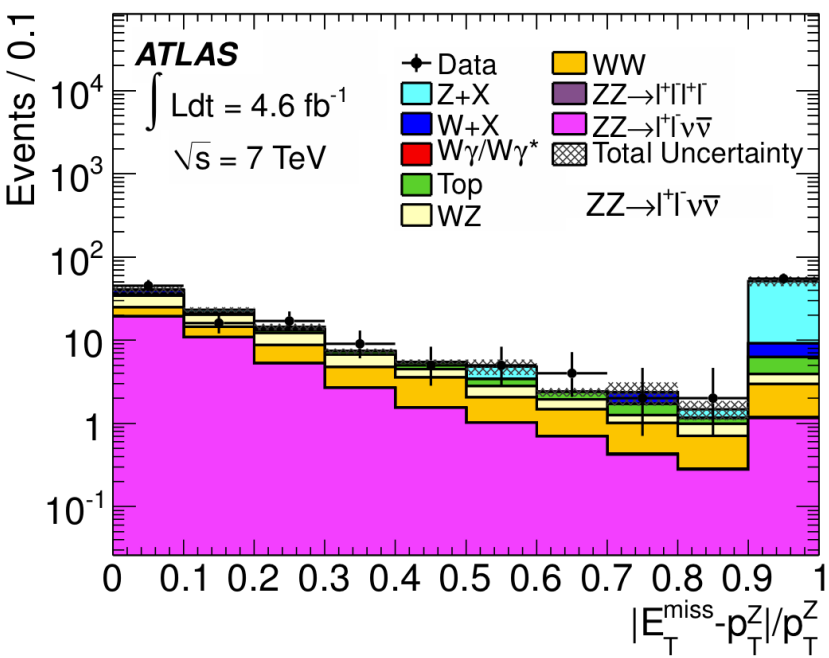


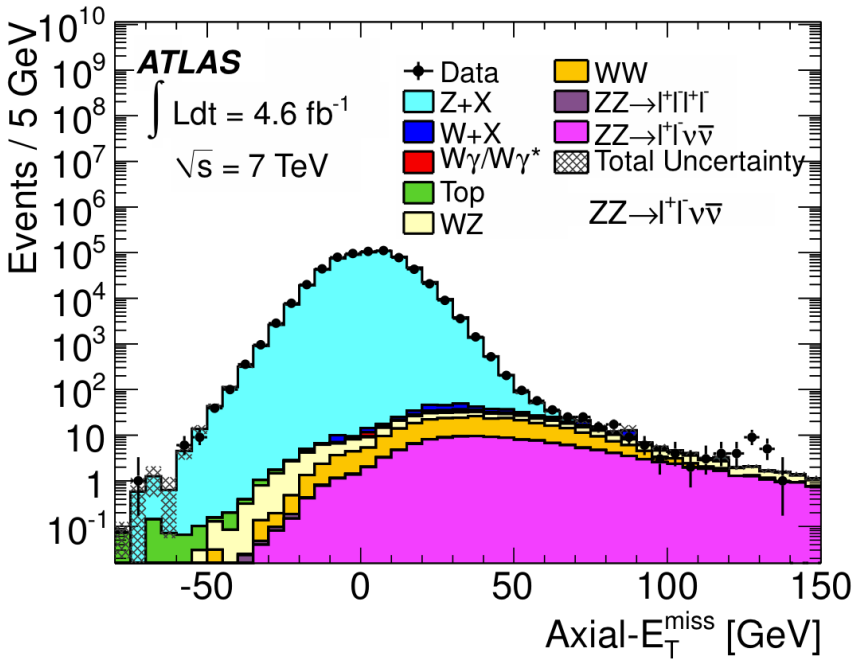
- $p_{\mathrm{T}}(\ell) > 7$ GeV
- One electron (muon) with $p_{\mathrm{T}}(\ell) > 25$ (20) GeV
- One pair with $66 < m_{\ell^+\ell^-} < 116$ GeV
- Second pair with $m_{\ell^+\ell^-} > 20$ GeV
- Changes for 8 TeV analysis:
  - One electron or muon with $p_{\mathrm{T}}(\ell) > 25$ GeV
  - Both Zs on shell ($66 < m_{\ell^+\ell^-} < 116$ GeV)



Event Selection: $ZZ \to \ell^+\ell^-\nu\bar{\nu}$

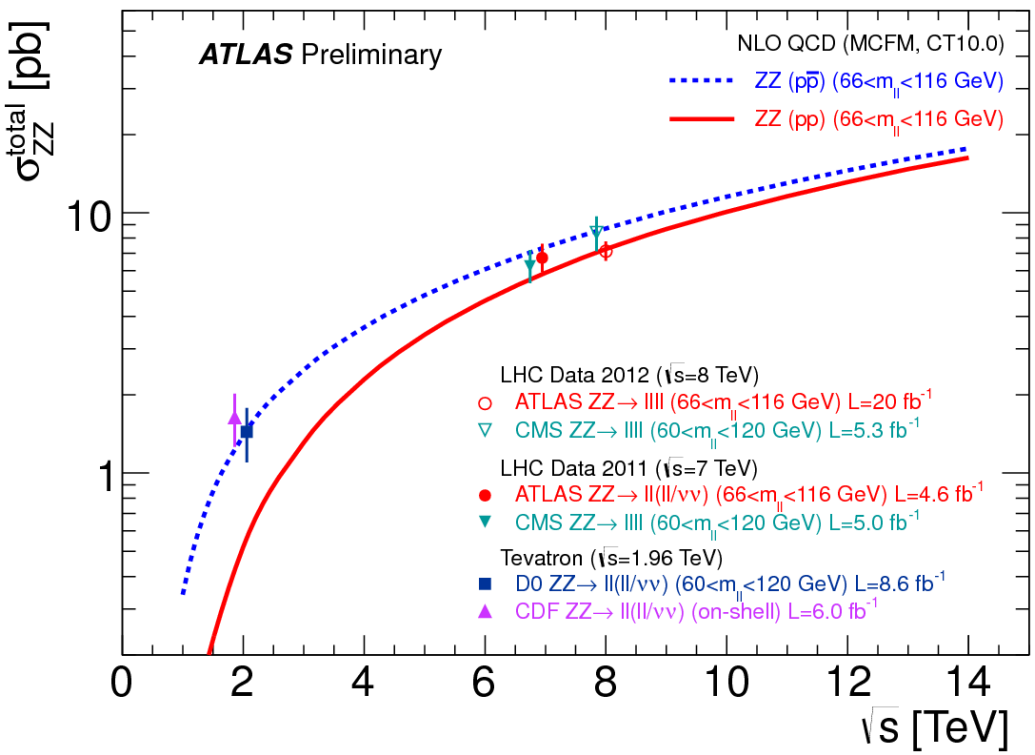
- $p_{\mathrm{T}}(\ell) > 20$ GeV
- $76 < m_{\ell^+\ell^-} < 106$ GeV
- axial-$E_{\mathrm{T}}^{\mathrm{miss}} = -\vec{E}_T^{\mathrm{miss}} \cdot \vec{p}_T^{Z}/p_{\mathrm{T}}^{Z} > 75$ GeV
- $|E_{\mathrm{T}}^{\mathrm{miss}} - p_{\mathrm{T}}^{Z}|/p_{\mathrm{T}}^{Z} < 0.4$
- Jet veto ($p_{\mathrm{T}} > 25$ GeV, $|\eta| < 4.5$)

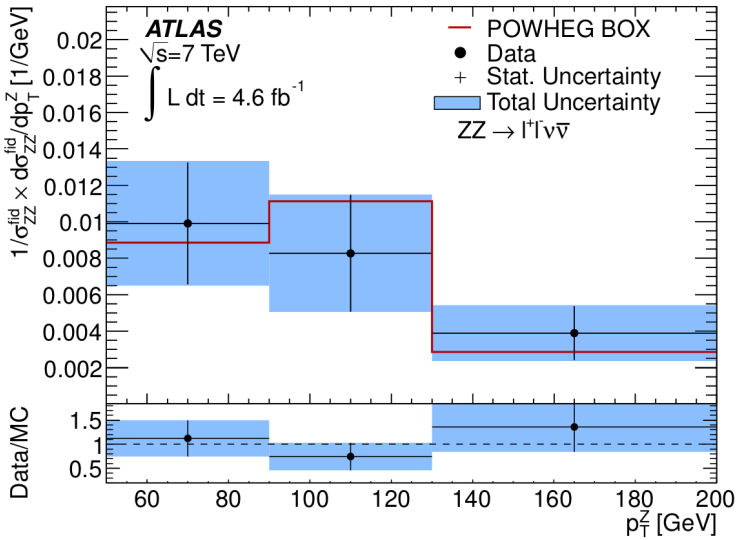


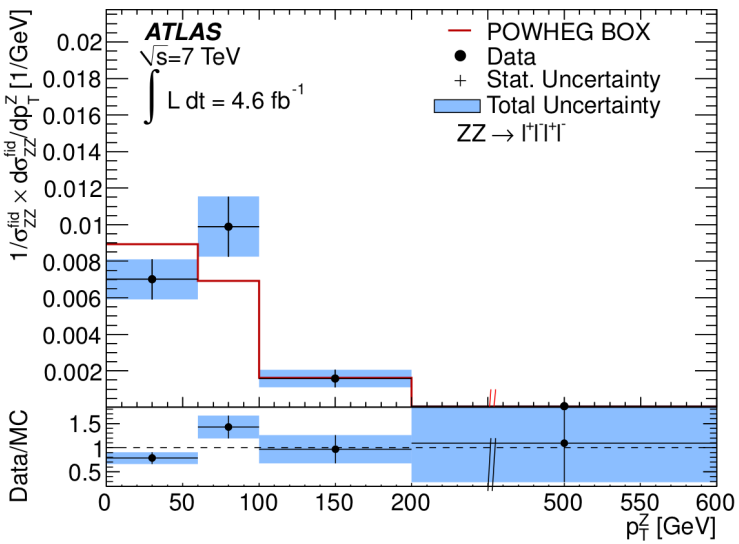


Cross Section

- Total cross section 4.6 fb^{-1} at 7 TeV:
  $\sigma_{ZZ} = 6.7 \pm 0.7(\text{stat})^{+0.4}_{-0.3}(\text{syst}) \pm 0.3(\text{lumi})$ pb
- Expected 7 TeV cross section: $5.89^{+0.22}_{-0.18}$ pb
- Total cross section 20 fb^{-1}at 8 TeV:
  $\sigma_{ZZ} = 7.1^{+0.5}_{-0.4}(\text{stat}) \pm 0.3(\text{syst}) \pm 0.2(\text{lumi})$ pb
- Expected 8 TeV cross section: $7.2^{+0.3}_{-0.2}$ pb

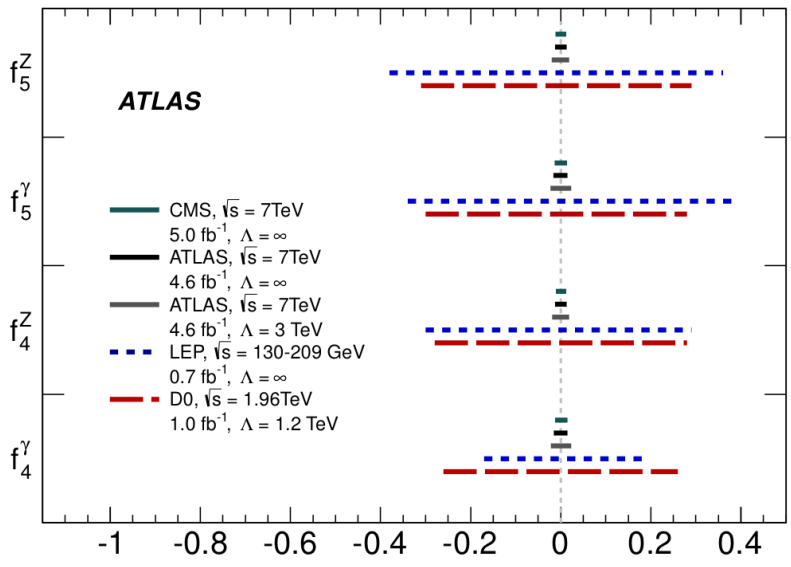






aTGC limits

- Calculated in 4.6 fb^{-1} at 7 TeV
- 95% confidence intervals calculated using the maximum profile likelihod ratio
- The ratio was calculated for data and 10,000 pseudo experiments
- The p_T^Z distribution of the leading Z is used for the extraction



Λ	f_4^γ	f_4^Z	f_5^γ	f_5^Z
3 TeV	[-0.022,0.023]	[-0.019,0.019]	[-0.023,0.023]	[-0.020,0.019]
∞	[-0.015,0.015]	[-0.013,0.013]	[-0.016,0.015]	[-0.013,0.013]

1 Introduction

2 W/Z γ Production

3 WW Production

4 WZ Production

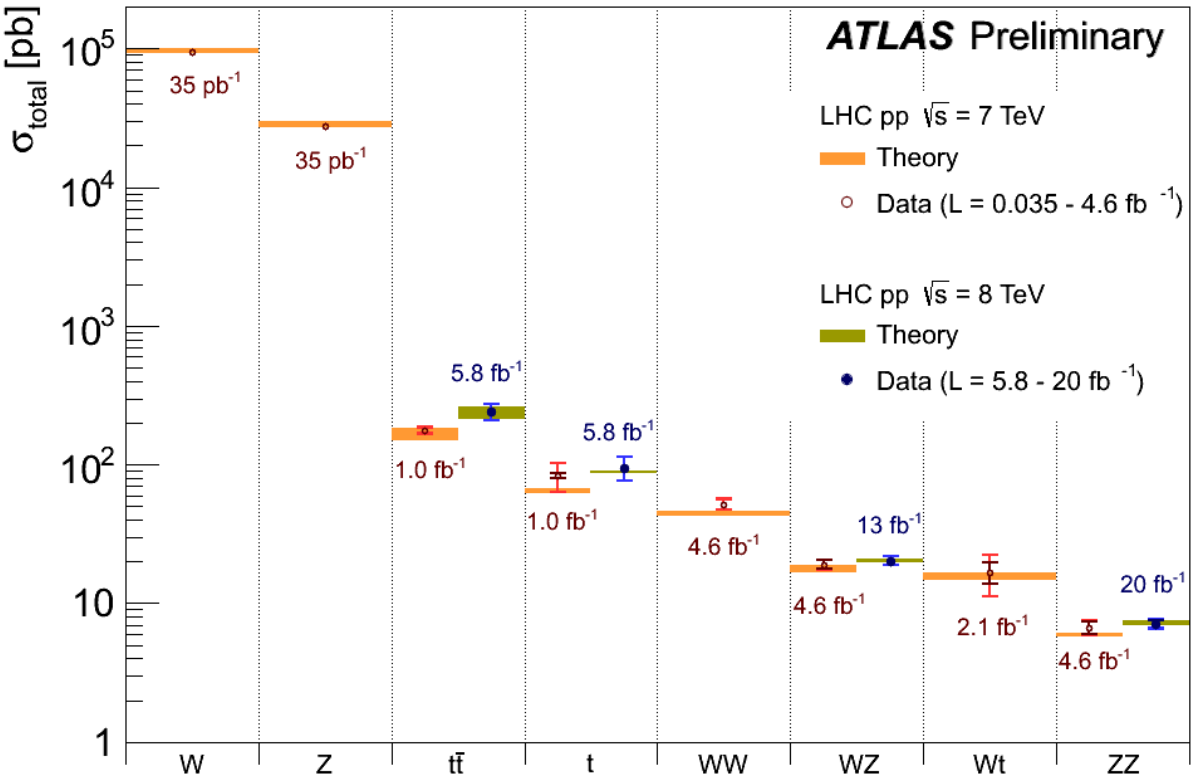
5 Semileptonic WW/WZ Decays

6 ZZ Production

7 Conclusion

8 Backup

Conclusion



- Cross sections have been measured in many diboson channels
- Measurements show agreement with NLO SM calculations
- Studies of 8 TeV data are still ongoing$\rightarrow$ further measurements of aTGC limits on 8 TeV

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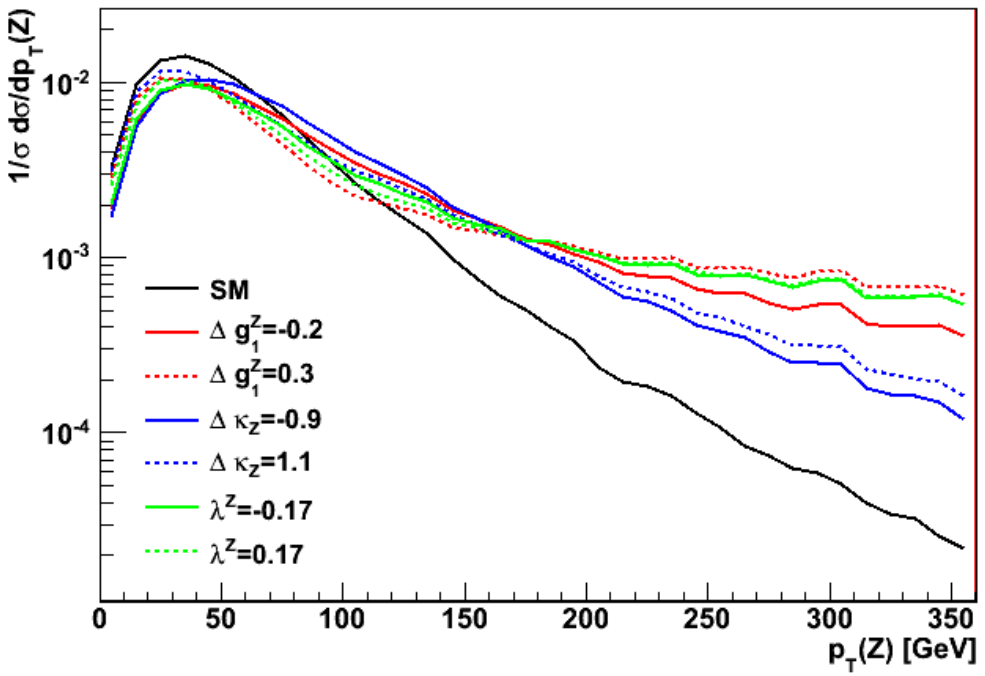
Effect of aTGC on WZ p_T^Z Distribution

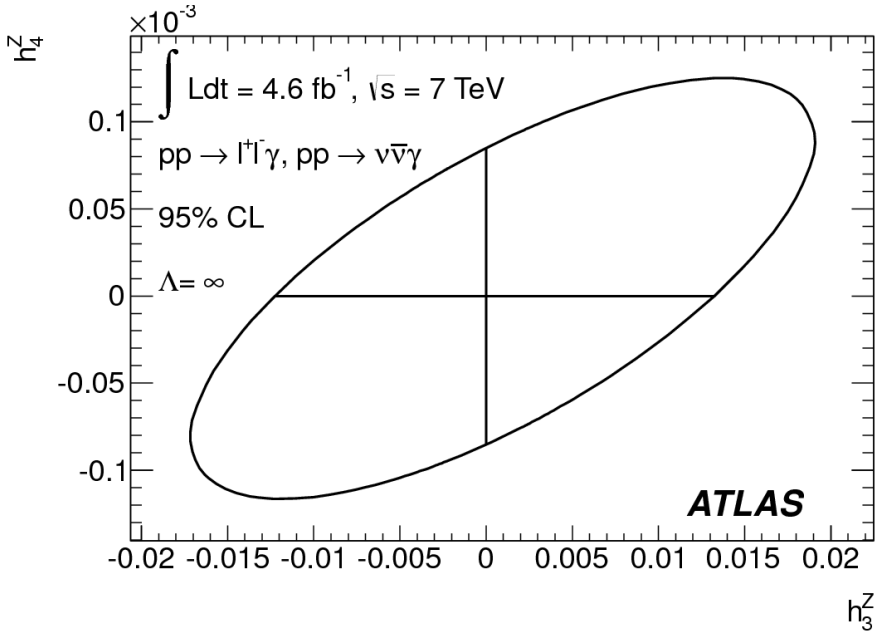


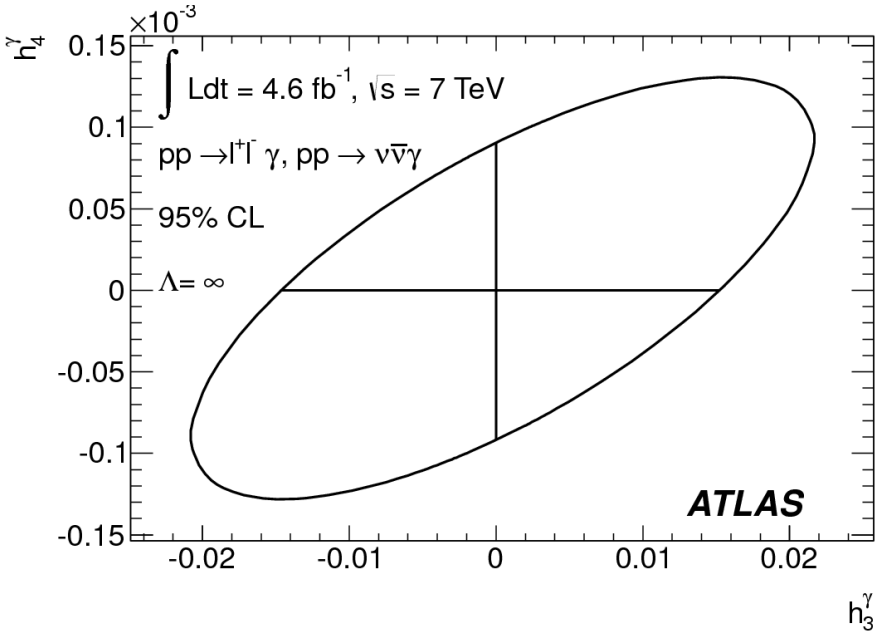
- Distribution of the Z boson p_{T}
- Non-zero aTGC values have a large affect on the shape of the tail

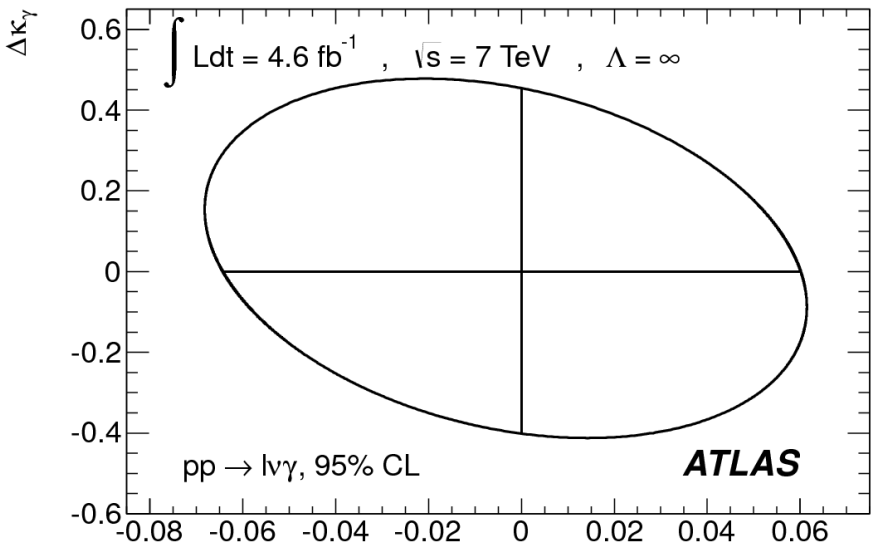
Charged aTGC Scenarios

- Assuming electromagnetic gauge invariance and *CP* conservation, the effective Lagrangian has five independent coupling parameters: g_1^Z, κ^Z, κ^γ, λ^Z, and λ_γ
- Different assumptions (scenarios) reduce these further
- "Equal Couplings Scenario"
  - Assume *WWZ* and *WW*γ couplings are the same
  - $\Delta\kappa^Z$=$\Delta\kappa^\gamma$, λ^Z=λ^γ, and Δg_1^Z=0
- "LEP Scenario"
  - Motivated by $SU(2) \times U(1)$ gauge invariance
  - $\lambda^Z = \lambda_\gamma$
  - $\Delta\kappa^\gamma = (\tan^2\theta_W)(\Delta g_1^Z - \Delta\kappa^Z)$
- "HISZ scenario"
  - $\lambda^Z = \lambda_\gamma$
  - $\Delta g_1^Z = \frac{\Delta\kappa^Z}{\cos^2\theta_W - \sin^2\theta_W}$
  - $\Delta\kappa^\gamma = \frac{2\Delta\kappa^Z \cos^2\theta_W}{\cos^2\theta_W - \sin^2\theta_W}$

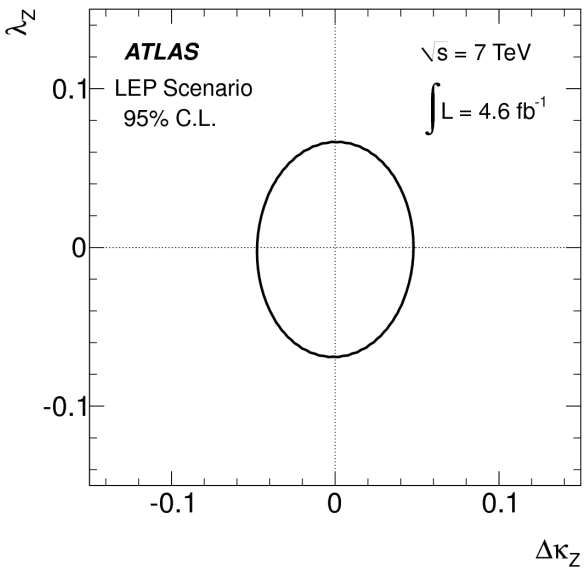
2D aTGC limits - $W/Z\gamma$

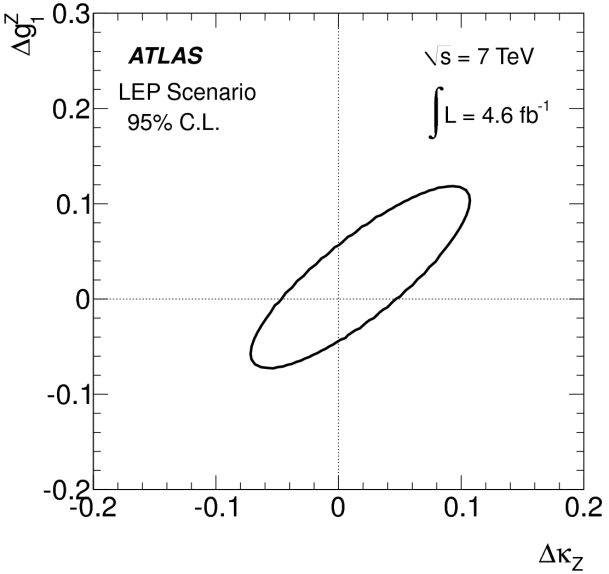


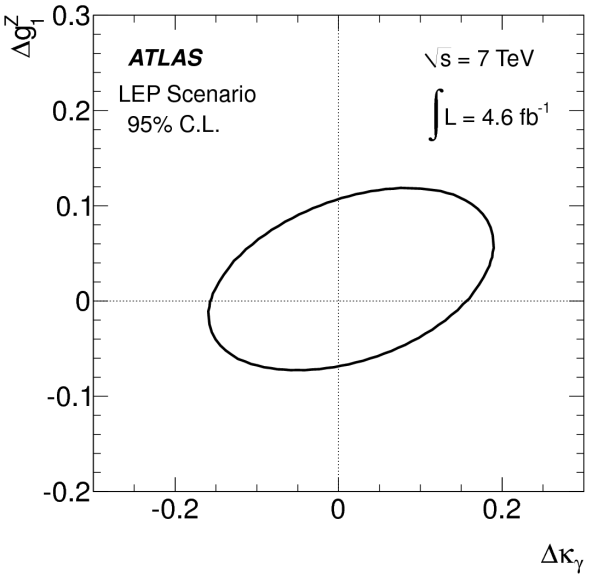


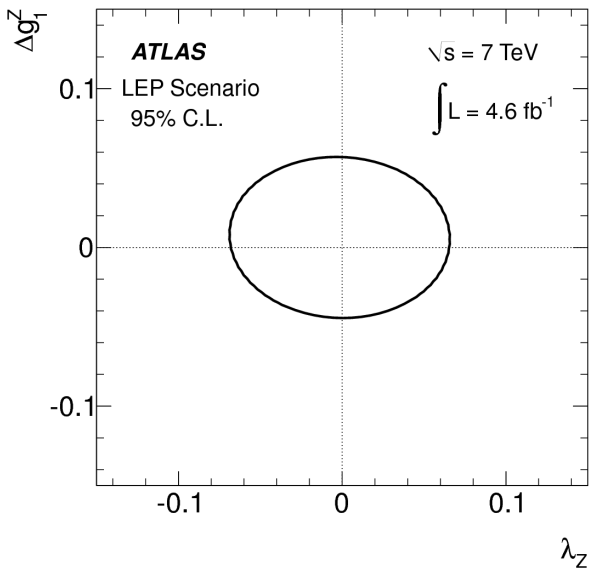


2D aTGC limits - WW

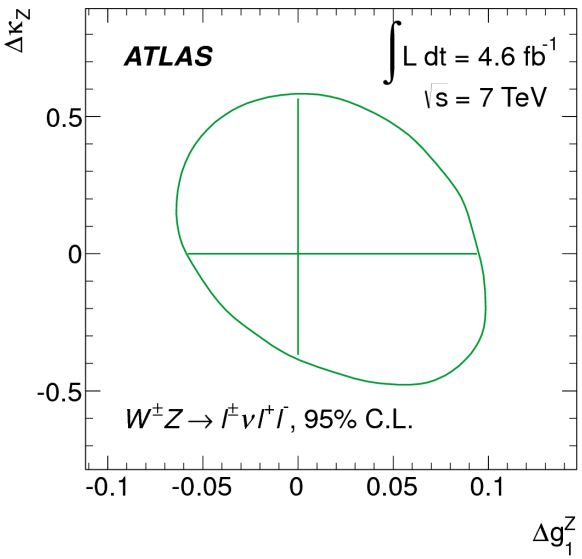


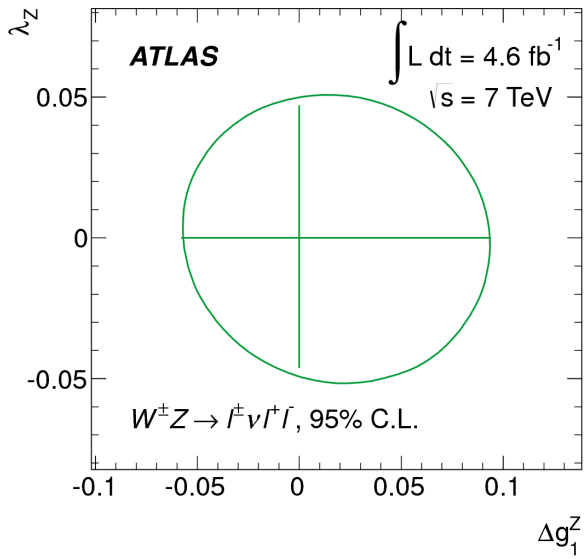


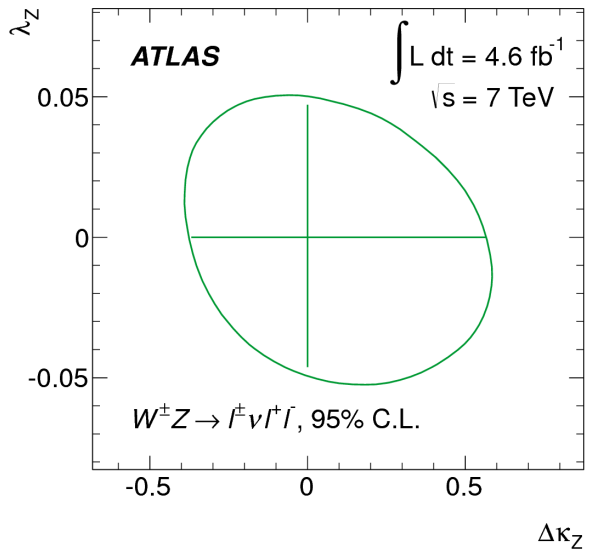
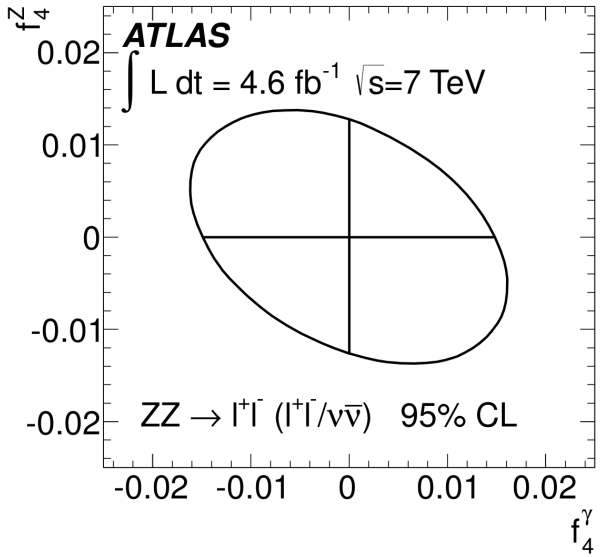
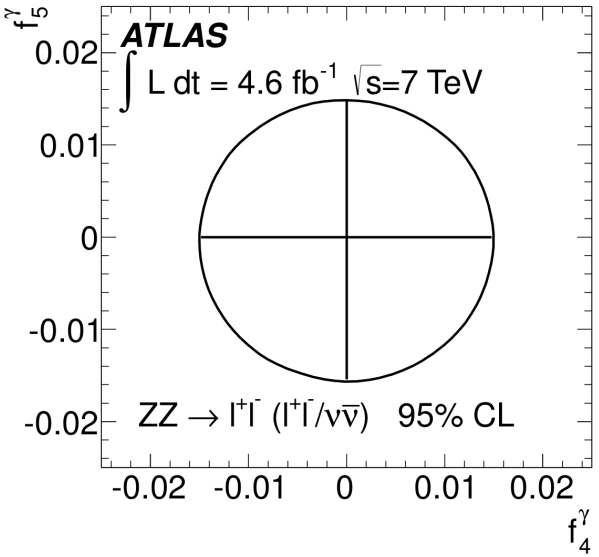
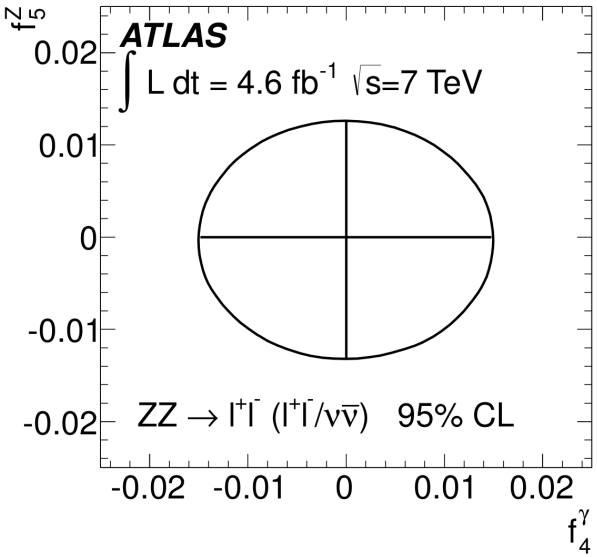
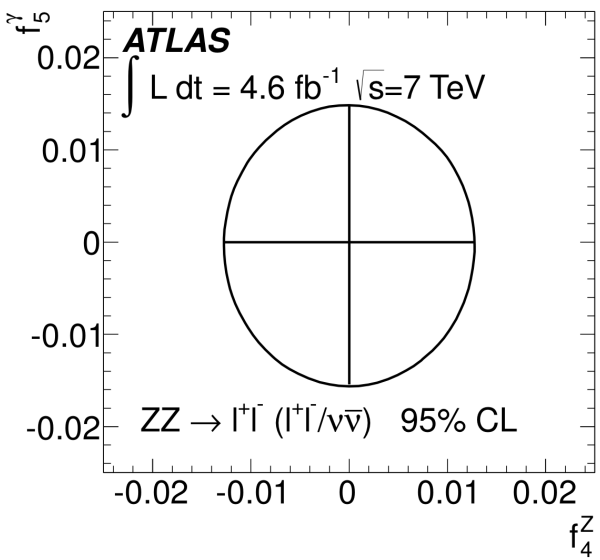
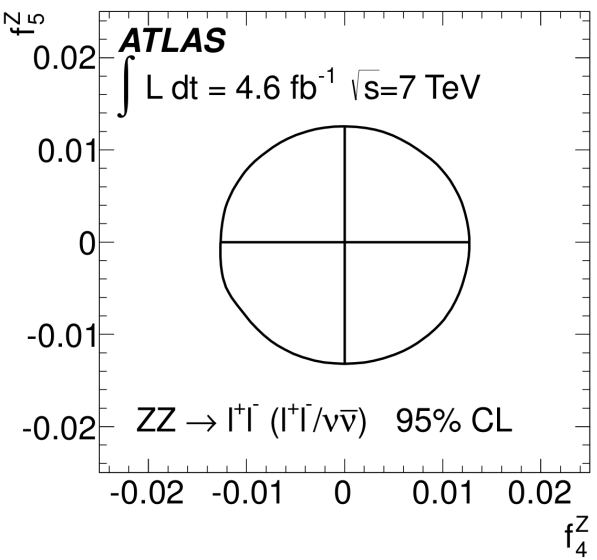
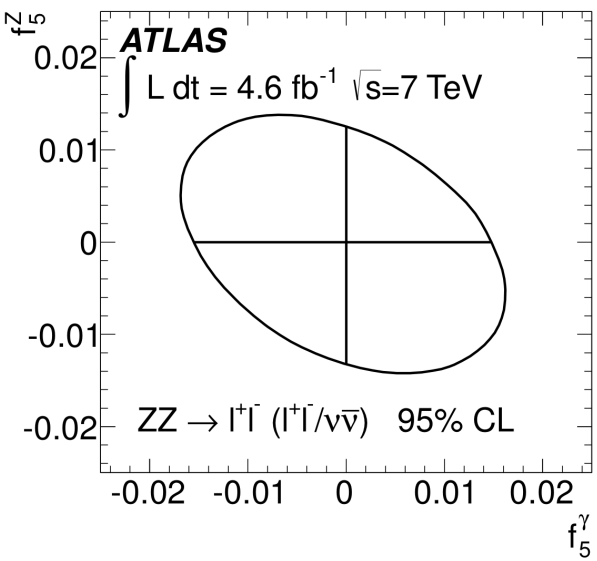




2D aTGC limits - WZ







2D aTGC limits - ZZ