Production of WW($\rightarrow l\nu l\nu$) and WW/WZ($\rightarrow l\nu jj$) at ATLAS and Constraints on Triple Gauge Couplings

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On behalf of the ATLAS collaboration

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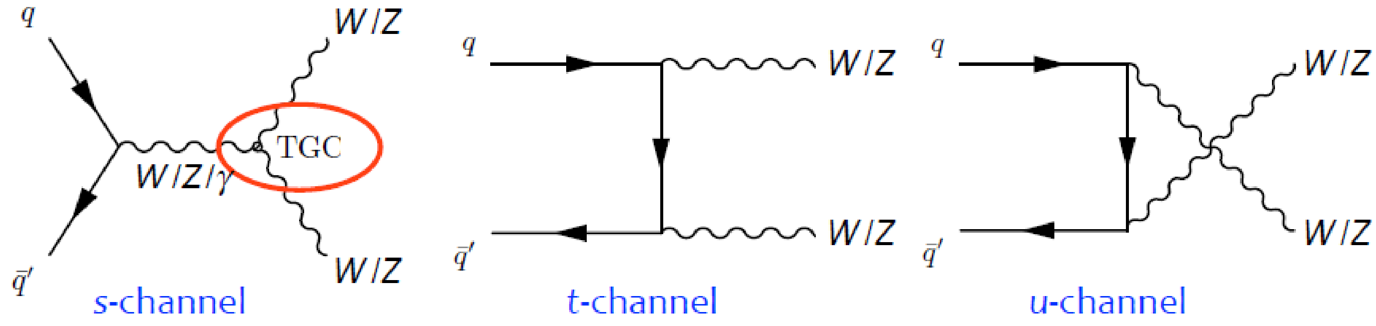
Introduction

- **WW and WZ production arises predominantly from $q\bar{q}$ initial states at LHC**

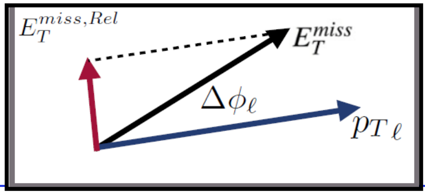


- **Motivation**
  – Test the electro-weak theory at the high energy frontier
  – Probe anomalous triple gauge couplings
  – Important backgrounds to Higgs analyses and searches beyond Standard Model (SM) with similar final states.
- **Signatures**
  – **WW→lνlν (leptonic final state)**
    - Two oppositely charged isolated high p_T leptons (ee, μμ or eμ including leptons from tau leptonic decays).
    - Large missing energy (E_T^{miss}) and no energetic jets
  – **WW/WZ→lνjj (semi-leptonic final state)**
    - One charged isolated high p_T leptons (e or μ)
    - Large E_T^{miss} and two energetic jets

Event Selections and Backgrounds

- **WW→lνlν** (~ 4.6 fb^{-1}@7 TeV)
  - **Selection**
    - Exactly an opposite-sign high p_T isolated di-lepton pair (ee, $\mu\mu$ and $e\mu$)
    - m_{ll}>15 GeV && $|m_{ll}-m_Z|$>10 GeV (ll = ee / $\mu\mu$), m_{ll} > 10 GeV (ll = $e\mu$)
    - **Modified E_T^{miss}**> 45 GeV in ee and $\mu\mu$, and > 25 GeV in $e\mu$
    - Jet veto: No jets with (p_T>25GeV, $|\eta|$<4.5)
    - $p_T(ll)$ > 30 GeV
  - **Main backgrounds**
    - W+jets, Drell-Yan, top($t\bar{t}$, single top), non-WW diboson (WZ/γ*, ZZ, W/Zγ)

Modified E_t^{miss} definition



$$E_{\mathrm{T,\ Rel}}^{\mathrm{miss}} = \begin{cases} E_{\mathrm{T}}^{\mathrm{miss}} \times \sin(\Delta\phi) & \text{if } \Delta\phi < \pi/2 \\ E_{\mathrm{T}}^{\mathrm{miss}} & \text{if } \Delta\phi \geq \pi/2 \end{cases}$$

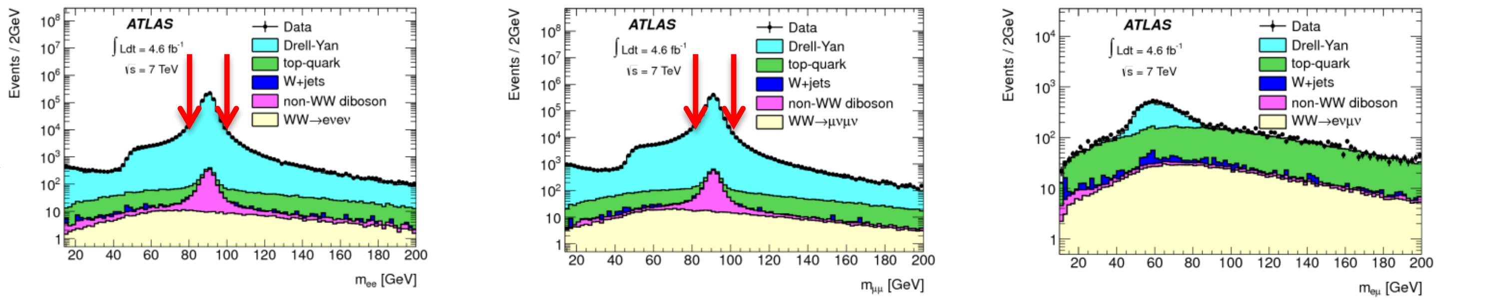
where $\Delta\phi$ is the difference in the azimuthal angle between the $\vec{E}_{\mathrm{T}}^{\mathrm{miss}}$ and the nearest lepton or jet.

- **WW/WZ→lνjj** (~ 4.6 fb^{-1}@7 TeV)
  - **Selection**
    - Exactly an high p_T isolated lepton (e or μ)
    - E_T^{miss} > 30 GeV
    - Transverse mass of the lepton and E_T^{miss} (m_T) > 40 GeV
    - Exactly two jets with (p_T>25 GeV, $|\eta|$<2) && leading jet p_T>30 GeV
    - $\Delta\phi(E_T^{miss}$, leading jet)>0.8 && ΔR(jet1, jet2)>0.7 && $\Delta\eta$(jet1, jet2)<1.5
  - **Main backgrounds**
    - W/Z+jets, QCD multi-jet, top($t\bar{t}$, single top)

Data and MC comparisons for WW→lνlν

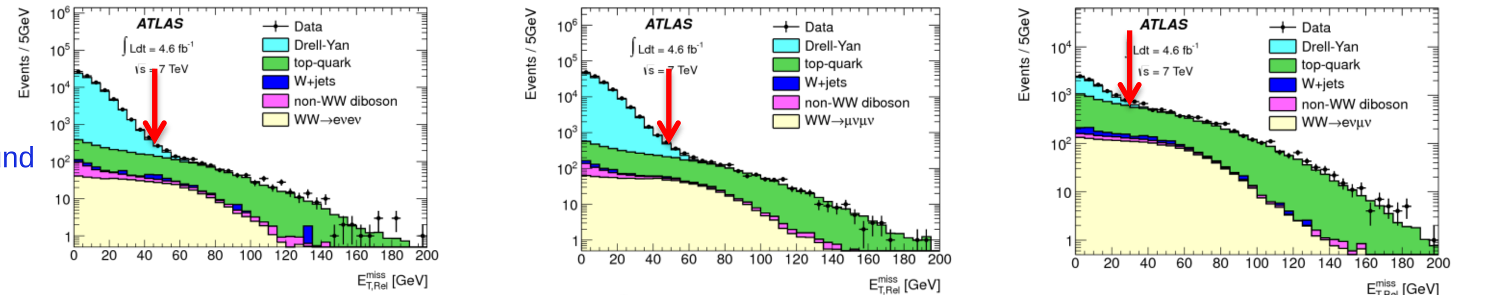
m_{ll} after di-lepton selection

Z mass veto removes the bulk of Drell-Yan background in ee and $\mu\mu$ channels



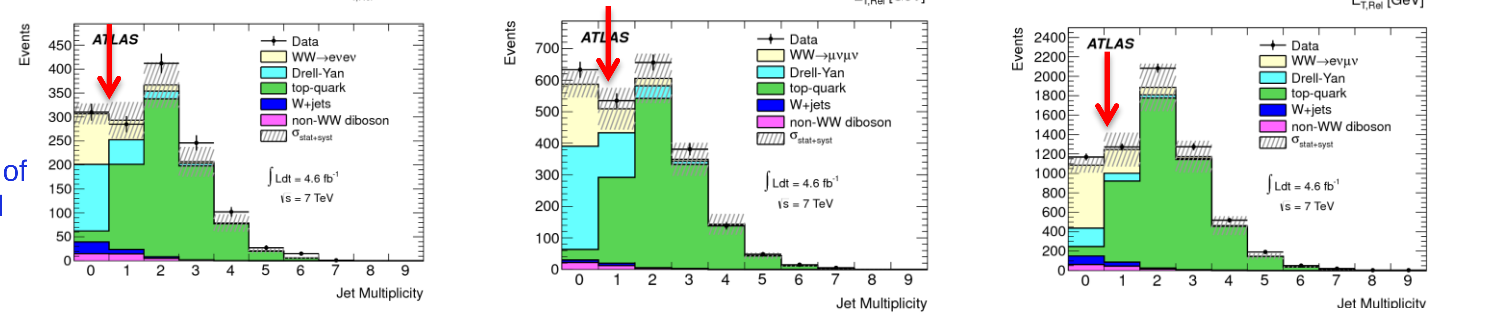
$E_{\mathrm{T,\ Rel}}^{\mathrm{miss}}$ after Z veto

Cutting on E_T^{miss} further removes Drell-Yan background in all 3 channels



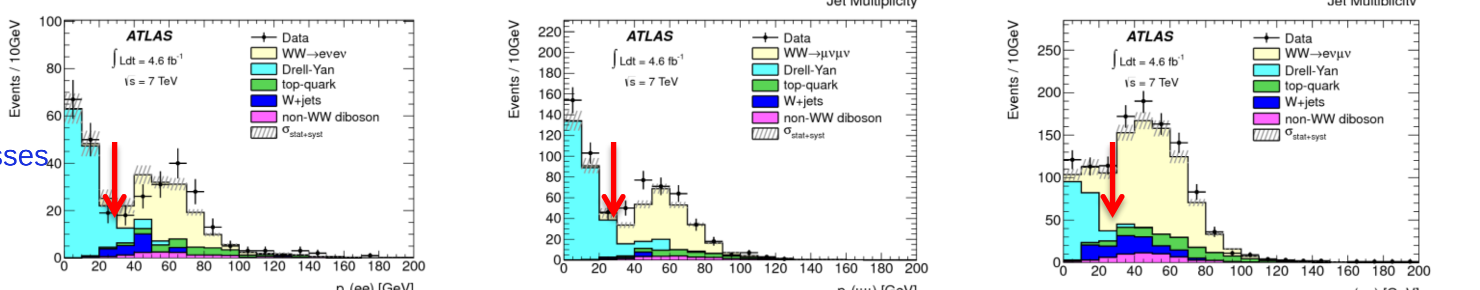
Jet multiplicity after Z veto

Restricting to 0 jet bin gets rid of the majority of top background



p_T(ll) after Jet veto

Cutting on p_T(ll) further suppresses Drell-Yan background



ee **μμ** **eμ**

Background Estimation for WW→lνlν

- **W+jets** (fake-factor method)
  - Construct a W+jets enriched control region by inverting some of the selection criteria on one lepton
  - Scale the control region by a fake factor (f_l) derived using a dijet data control sample

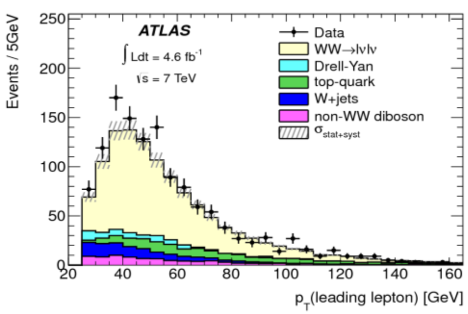
$$N_{\text{one id + one fake}} = f_l \times N_{\text{one id + one jet-rich}} \qquad f_l \equiv \frac{N_{\text{identified lepton}}}{N_{\text{jet-rich lepton}}}$$

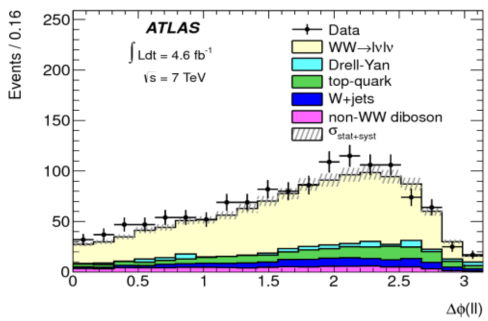
- **Drell-Yan** (normalized to data using a control region)
  - Define a Drell-Yan dominated control region by reverting the $p_T(ll)$ cut
  - Extrapolate the control region to the signal region using MC
- **Top** (utilizing jet multiplicity)
  - Construct a jet multiplicity distribution for top events using a top control sample from data by b-tagging a jet.
  - Subtract the non-top background from the jet multiplicity distribution using a partial data driven technique.
  - Extrapolate the background-subtracted jet multiplicity to signal region using MC.
- **Non-WW diboson** (using simulation)
  - Processes concerned : $WZ/\gamma*$, ZZ, $W/Z\gamma$
  - Estimated using simulation
  - Normalized by NLO cross section predictions

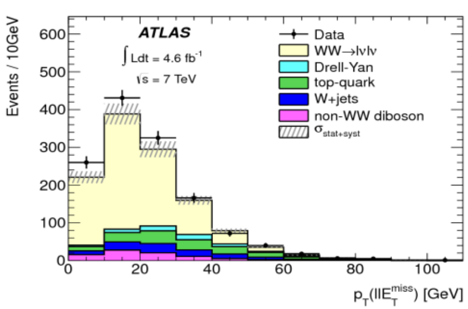
Observed vs. Expected for WW→lνlν

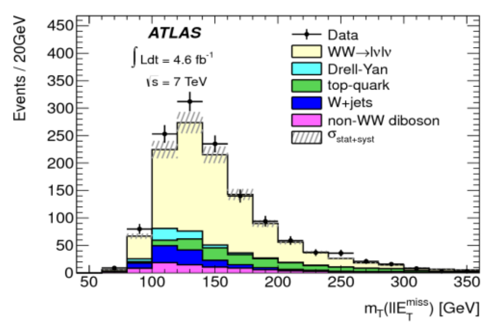
4.6 fb^{-1} @ 7 TeV

	ee	$\mu\mu$	$e\mu$	Combined
Data	174	330	821	1325
WW	100±2±9	186±2±15	538±3±45	824±4±69
Top	22±12±3	32±14±5	87±23±13	141±30±22
W+jets	21±1±11	7±1±3	70±2±31	98±2±43
Drell-Yan	12±3±3	34±6±10	5±2±1	51±7±12
Other dibosons	13±1±2	21±1±2	44±2±6	78±2±10
Total background	68±12±13	94±15±13	206±24±35	369±31±53
Total expected	169±12±16	280±16±20	744±24±57	1192±31±87









Good agreement between data and predictions within uncertainties

Cross Sections from WW→lνlν

- Total cross sections measured in individual channels and statistically combined
- Cross sections also measured in a fiducial phase space that is defined to mimic the analysis selection to minimize theoretical extrapolation errors.

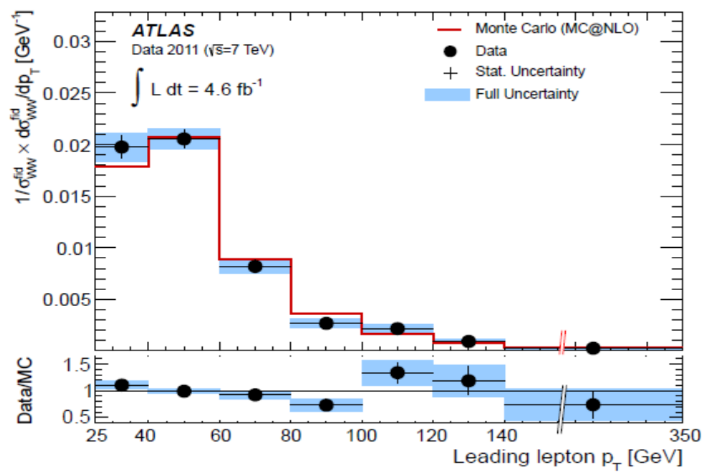
4.6 fb^{-1} @ 7 TeV

Total and fiducial WW production cross sections

	Measured $\sigma^{\rm fid}_{WW}$ (fb)	Predicted $\sigma^{\rm fid}_{WW}$ (fb)	Measured σ_{WW} (pb)	Predicted σ_{WW} (pb)
ee	$56.4 \pm 6.8 \pm 9.8 \pm 2.2$	54.6 ± 3.7	$46.9 \pm 5.7 \pm 8.2 \pm 1.8$	$44.7^{+2.1}_{-1.9}$
$\mu\mu$	$73.9 \pm 5.9 \pm 6.9 \pm 2.9$	58.9 ± 4.0	$56.7 \pm 4.5 \pm 5.5 \pm 2.2$	$44.7^{+2.1}_{-1.9}$
$e\mu$	$262.3 \pm 12.3 \pm 20.7 \pm 10.2$	231.4 ± 15.7	$51.1 \pm 2.4 \pm 4.2 \pm 2.0$	$44.7^{+2.1}_{-1.9}$
Combined	···	···	$51.9 \pm 2.0 \pm 3.9 \pm 2.0$	$44.7^{+2.1}_{-1.9}$

- NLO total WW production cross section:
  - Calculated using MCFM with CT10, gluon-gluon fusion contribution included, contribution from pp→H→WW (amounting to ~8%) wasn't considered.
  - Uncertainty due to scale variations: $^{+4.8\%}_{-4.2\%}$, and $^{+3.1\%}_{-3.4\%}$ due to PDF

Normalized differential WW fiducial cross section as a function of leading lepton P_T



Measured and predicted (NLO) are in agreement within uncertainties

WW production cross section measurement evolution at ATLAS →

7 TeV	34 pb^{-1}	$\sigma_{WW\to 2l2\nu} = 41.2 \pm 20(\text{stat}) \pm 5.0(\text{syst}) \pm 1.0(\text{lumi})$ pb
7 TeV	1.02 fb^{-1}	$\sigma_{WW\to 2l2\nu} = 54.4 \pm 4.0(\text{stat}) \pm 3.9(\text{syst}) \pm 2.0(\text{lumi})$ pb
7 TeV	4.6 fb^{-1}	$\sigma_{WW\to 2l2\nu} = 51.9 \pm 2.0(\text{stat}) \pm 3.9(\text{syst}) \pm 2.0(\text{lumi})$ pb

Triple Gauge Couplings (TGCs)

Lorentz invariant Lagrangian describing *WWV* (*V*=*Z*, *γ*) TGCs assuming electromagnetic gauge invariance and C and P conservations

$$\frac{\mathcal{L}_{WWV}}{g_{WWV}} = ig_1^V(W_{\mu\nu}^+ W^\mu V^\nu - W_\mu^+ V_\nu W^{\mu\nu}) + i\kappa_V W_\mu^+ W_\nu V^{\mu\nu} + \frac{i\lambda_V}{m_W^2} W_{\lambda\mu}^+ W_\nu^\mu V^{\nu\lambda}$$

- Both *WWZ* and $WW\gamma$ TGCs involved in WW production
- 5 parameters: $\Delta g_1^Z (\equiv g_1^Z - 1)$, $\Delta\kappa_Z (\equiv \kappa_Z - 1)$, $\Delta\kappa_\gamma (\equiv \kappa_\gamma - 1)$, λ_Z, λ_γ
- Parameters in red are zero in SM. Any deviations from zero are regarded as anomalous triple gauge couplings (aTGCs)
- Additional constraints commonly imposed to reduce number of free parameters

Equal coupling	$\Delta g_1^Z = 0$, $\Delta\kappa_Z = \Delta\kappa_\gamma$, and $\lambda_Z = \lambda_\gamma$
LEP scenario	$\Delta g_1^Z - \Delta\kappa_Z = \Delta\kappa_\gamma \tan^2\theta_W$ and $\lambda_Z = \lambda_\gamma$
HISZ scenario	$\Delta\kappa_Z = \Delta g_1^Z(\cos^2\theta_W - \sin^2\theta_W)$, $\Delta\kappa_\gamma = 2\Delta g_1^Z \cos^2\theta_W$ and $\lambda_Z = \lambda_\gamma$

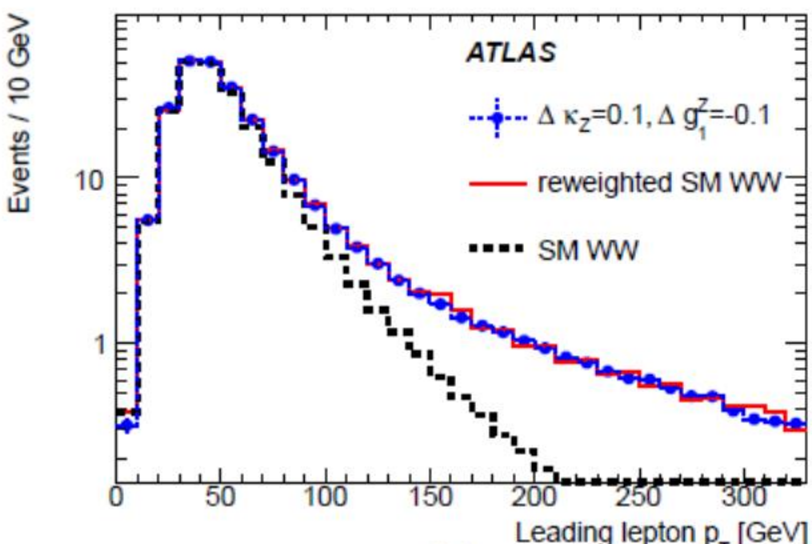
- Introduce a dipole form factor to each of the aTGCs to ensure unitarity:

$$\alpha = \frac{\alpha 0}{\left(1+\frac{\hat{s}}{\Lambda^2}\right)^2}$$

α^0 is the bare coupling, $\hat{s}$ is the square of the invariant mass of the WW pair, Λ is the unitarization energy scale.

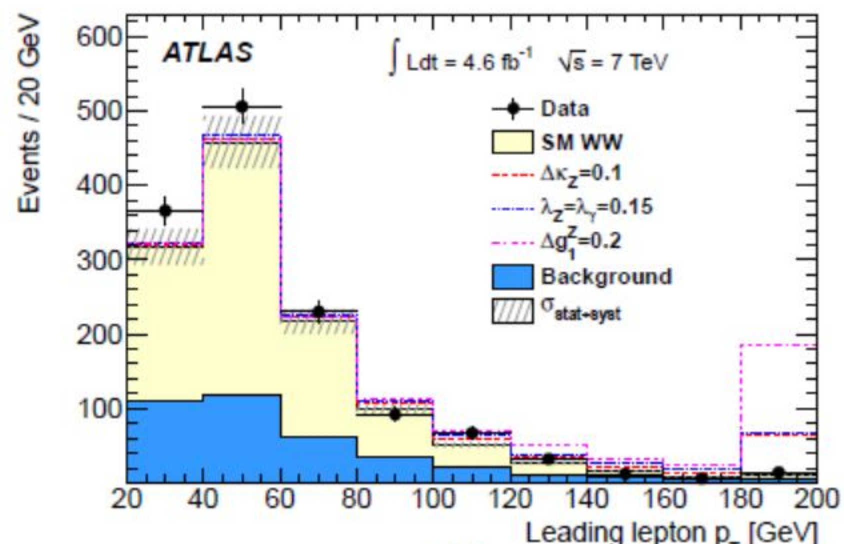
aTGC Extraction for WW→lνlν

- Access the whole aTGC parameter space using a kinematic reweighting technique
- No deviations from SM observed. Use leading lepton p_T as observable to derive aTGC limits.



(a)

SM leading lepton p_T reweighted with the kinematic reweighting procedure to an aTGC point vs. leading lepton p_T directly produced for the aTGC point.



(b)

Leading lepton p_T with various aTGC parameters values. Sensitivity to aTGCs lies in high p_T region.

aTGC 95% C.L. limits from WW→lνlν

4.6 fb^{-1} @ 7 TeV

Expected and observed aTGC limits

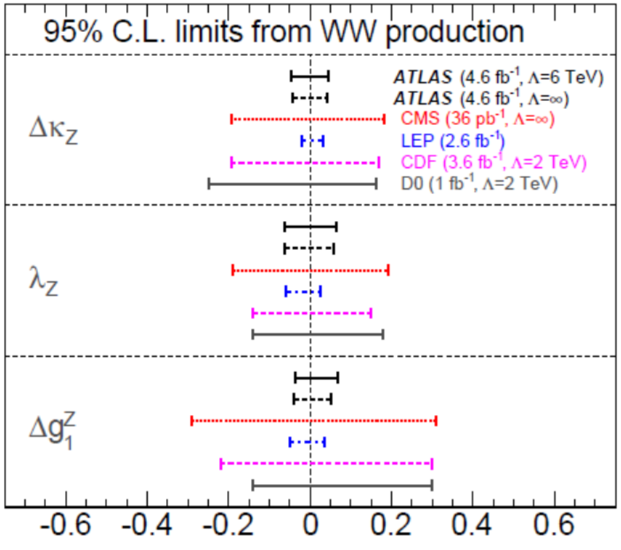
for various constraint scenarios and different aTGC unitarization energy scales

Scenario	Parameter	Expected ($\Lambda = 6$ TeV)	Observed ($\Lambda = 6$ TeV)	Expected ($\Lambda = \infty$)	Observed ($\Lambda = \infty$)
LEP	$\Delta\kappa_Z$	[−0.043, 0.040]	[−0.045, 0.044]	[−0.039, 0.039]	[−0.043, 0.043]
	$\lambda_Z = \lambda_\gamma$	[−0.060, 0.062]	[−0.062, 0.065]	[−0.060, 0.056]	[−0.062, 0.059]
	Δg_1^Z	[−0.034, 0.062]	[−0.036, 0.066]	[−0.038, 0.047]	[−0.039, 0.052]
HISZ	$\Delta\kappa_Z$	[−0.040, 0.054]	[−0.039, 0.057]	[−0.037, 0.054]	[−0.036, 0.057]
	$\lambda_Z = \lambda_\gamma$	[−0.064, 0.062]	[−0.066, 0.065]	[−0.061, 0.060]	[−0.063, 0.063]
Equal Couplings	$\Delta\kappa_Z$	[−0.058, 0.089]	[−0.061, 0.093]	[−0.057, 0.080]	[−0.061, 0.083]
	$\lambda_Z = \lambda_\gamma$	[−0.060, 0.062]	[−0.062, 0.065]	[−0.060, 0.056]	[−0.062, 0.059]

aTGC limits without constraints

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]

Comparison among experiments



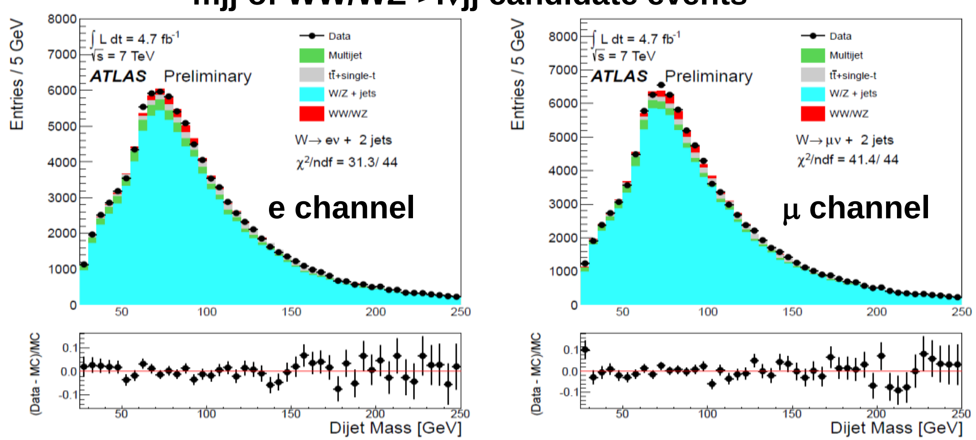
Due to higher energy and higher WW production cross section at the LHC, the limits from ATLAS are better than the Tevatron results and approach the precision of the combined limits from the LEP experiments. (Caveat: Tevatron limits are not the latest ones)

WW/WZ→lνjj

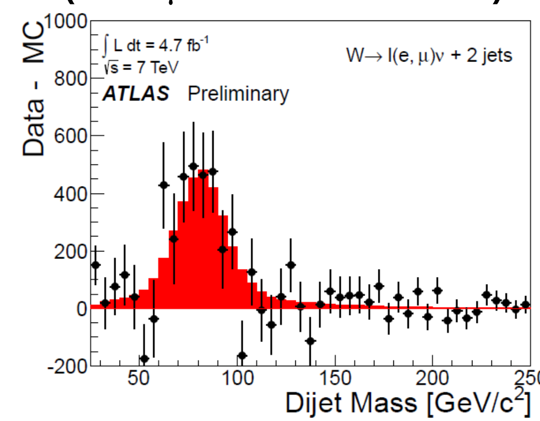
- Signal modeling
  - HERWIG for nominal samples, PYTHIA for systematic studies
  - Cross section calculated to NLO using MCFM with MSTW2008NLO
- Signal yield extraction
  - Fit di-jet invariant mass (m_{jj}) of reconstructed W/Z→jj candidate events with signal and background m_{jj} templates.
- Leading sources of systematic uncertainty
  - MC statistics , Jet energy scale, W/Z+jets normalization
- Background estimation
  - top: using MC for both shape and normalization
  - W/Z+jets: shape from MC, normalized to data
  - QCD multi-jet: data driven approach for both shape and normalization
  - MC statistics , Jet energy scale, W/Z+jets normalization

4.6 fb^{-1} @ 7 TeV

mjj of WW/WZ->lνjj candidate events



Background subtracted mjj (e and μ channels combined)



$$\sigma_{measured}(WW+WZ) = 72 \pm 9(stat.) \pm 15(syst.) \pm 13(MC\ stat.) pb$$

$\sigma_{SM@NLO}(WW+WZ) = 63.4 \pm 2.6$ pb

Measurement consistent with SM prediction

Summary

- ***WW*→lνlν with 4.6 fb^{-1} @ 7 TeV [Phys. Rev. D 87, 112001 (2013)]**
  - WW production cross section was measured. Result consistent with SM Prediction.

Measurement	SM NLO Prediction
$51.9 \pm 2.0\ (\mathrm{stat}) \pm 3.9\ (\mathrm{syst}) \pm 2.0\ (\mathrm{lumi})\ \mathrm{pb}$	$44.7^{+2.1}_{-1.9}\ \mathrm{pb}$

  - Anomalous *WWZ* and $WW\gamma$ couplings were probed using the leading lepton p_T spectrum for various aTGC constraint scenarios and different unitarization scales. The obtained aTGC limits approach the precision of the combined limits from the four LEP experiments.

95% C.L. limits on $\Delta\kappa_Z$ and λ_Z in equal couplings scenario

$\Delta\kappa_Z$	λ_Z
$[-0.061, 0.093]$	$[-0.062, 0.065]$

- ***WW/WZ*→lνjj with 4.6 fb^{-1} @ 7 TeV [ATLAS-CONF-2012-157]**
  - Combined WW/WZ production cross section was measured. Result consistent with SM prediction.

$$\sigma_{measured}(WW + WZ) = 72 \pm 9(stat.) \pm 15(syst.) \pm 13(MC\ stat.)pb$$

$$\sigma_{SM@NLO}(WW+WZ) = 63.4 \pm 2.6\ \mathrm{pb}$$

Backup

- Sources of background uncertainty for WW/WZ→lνjj analysis
  - Theoretical cross section uncertainties for W/Z+jets and top
  - Object modeling for W/Z+jets and top
    - Jet energy scale and jet energy resolution
    - Electron and muon identification
  - MC generation for W/Z+jets and top
    - W/Z+jets
      - Variation of renormalization and factorization scale (different scale schemes and different scale values)
      - Variations of strong coupling constant
      - Variation of minimum p_T and parton-jet matching cone size in the MLM matching scheme.
      - Difference between ALPGEN and SHERPA
    - top
      - Variation of ISR/FSR
  - PDF uncertainties for W/Z+jets and top
  - Comparison using different control regions for QCD multi-jet
    - Normalization obtained using an alternative data control region
    - Shape determined with an alternative data control region