Measurement of ZZ production with the ATLAS detector and constraints on associated triple gauge couplings

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Overview

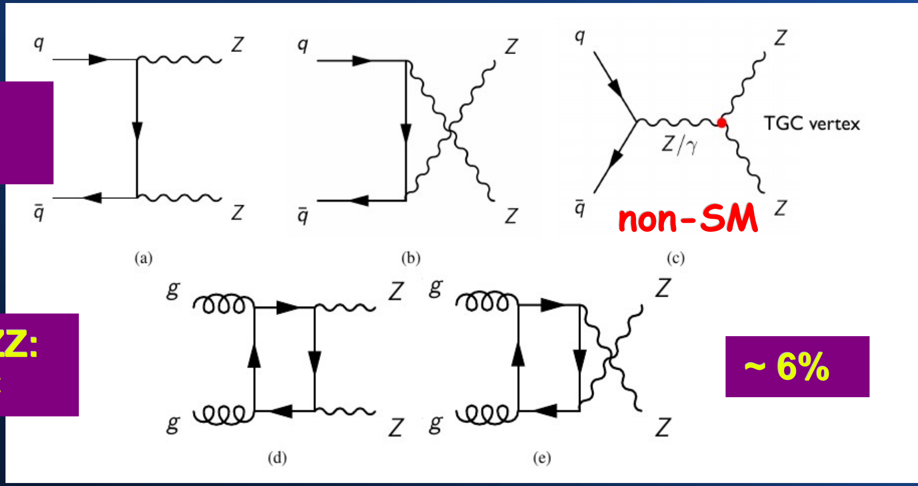
- Motivation
- Event Selection
- Event Yield and Background
- Fiducial and Total Cross Section Results
- Differential Cross Section Measurements
- Neutral Anomalous Triple Gauge Coupling Limit (nATGC)
- Conclusions

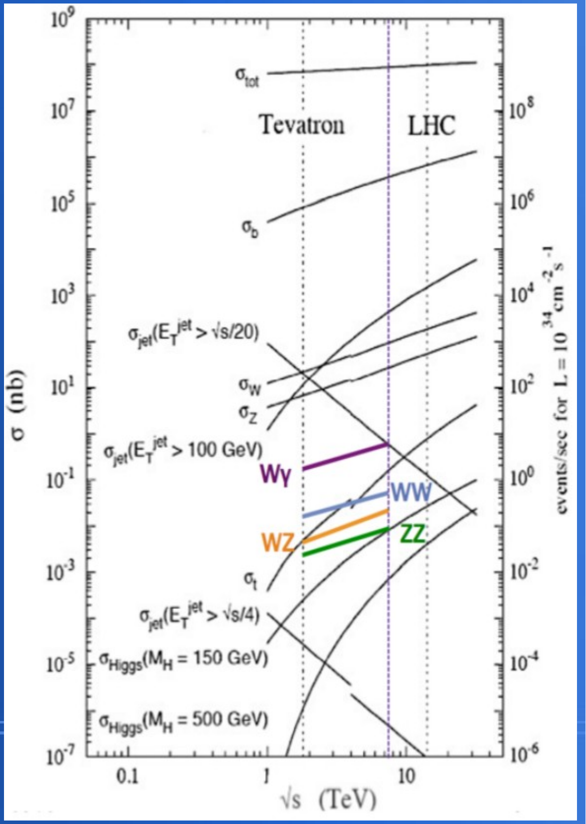
Physics Motivations and Measurements

- Provide a test of the predictions of the electroweak sector of the SM at TeV scale, in particular predictions on the nTGC (absent in SM)
- Probe for new physics by searching deviation from SM
  - Anomalous triple gauge couplings, heavy resonances in Z boson pairs, ...

NLO qq →ZZ: PowHeg

NNLO gg → ZZ: GG2ZZ MC





- Fiducial and total cross section measurements for:
  - $ZZ \rightarrow 4l$, $ZZ^* \rightarrow 4l$, $ZZ \rightarrow 2l2\nu$ [l=e,μ]
- Differential cross section and aTGC limits

Cross Section Measurement Fiducial vs. Total

Fiducial Cross Section (A_{ZZ}= 1):

$$\sigma_{ZZ}^{fid} = \frac{N_{obs} - N_{bkg}}{L \cdot C_{ZZ}}$$

C_{ZZ}: Experimental signal selection acceptance from MC corrected for data-driven measurements of MC mismodeling of detector effects

A_{ZZ}: acceptance correction for the phase space region not probed experimentally (MC based)

Total Cross Section:

(ZZ production with $66<M_Z<116$ GeV)

$$\sigma_{ZZ}^{\mathrm{total}} = \frac{N_{\mathrm{obs}} - N_{\mathrm{bkg}}}{A_{ZZ} \times C_{ZZ} \times \mathcal{L} \times \mathrm{BF}}$$

ZZ production in the experimental phase-space region:

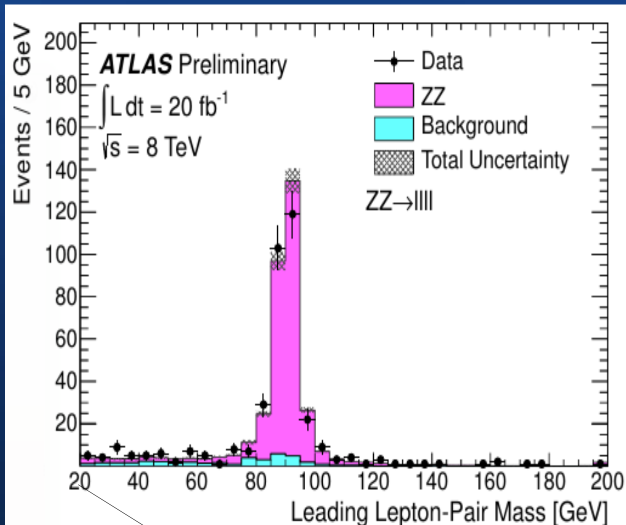
- Defined by lepton p_T, $|\eta|$, ΔR, Et^{miss} coverage

Measurements Overview

Final 7 TeV (2011) results published in: **JHEP 03 (2013) 128,** Preliminary 8 TeV (2012) results published in: **ATLAS-CONF-2013-020**	2011 ($4.6\ fb^{-1}$)	2012 ($20\ fb^{-1}$)
$ZZ \rightarrow 4l$	✓	✓
$ZZ^* \rightarrow 4l$	✓	
$ZZ \rightarrow l\nu l\nu$	✓	
Use electrons in the barrel/endcap calorimeter cracks ($1.37<\lvert\eta\rvert<1.52$)	✓	✓
Use electrons with brem-recovery reconstruction (~2% higher reconstruction efficiency for high E_T , 6-8% for $E_T<20$ GeV)		✓
Use electrons in the Forward Region ($2.5<\lvert\eta\rvert<3.2$) (No tracking coverage, $E_T>20$ GeV, 6% gain in event yield)	✓	
Use forward muons ($2.5<\lvert\eta\rvert<2.7$, $P_T>10$ GeV) (Outside nominal acceptance of Inner Detector, $p_T>10$ GeV, 6% gain in event yield)	✓	✓
Use calorimeter-tagged muons ($\lvert\eta\rvert<0.1$, $P_T>20$ GeV) (Limited geometric coverage of muon spectrometer, $p_T>10$ GeV, 4% gain in event yield)	✓	✓
Differential cross section for p_T^Z, m^{ZZ}, $\Delta\Phi(l^+,l^-)$	✓	
Anomalous neutral triple gauge coupling limit	✓	

Event Selection

ZZ(*) → 4l



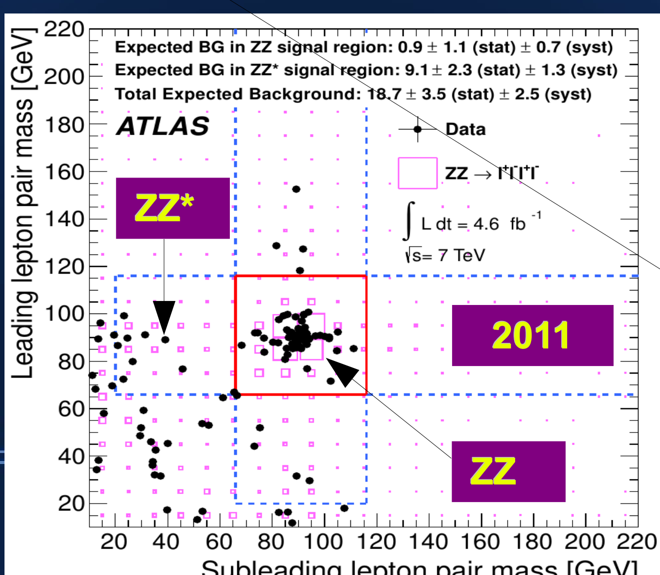
P_T > 7 GeV, isolated

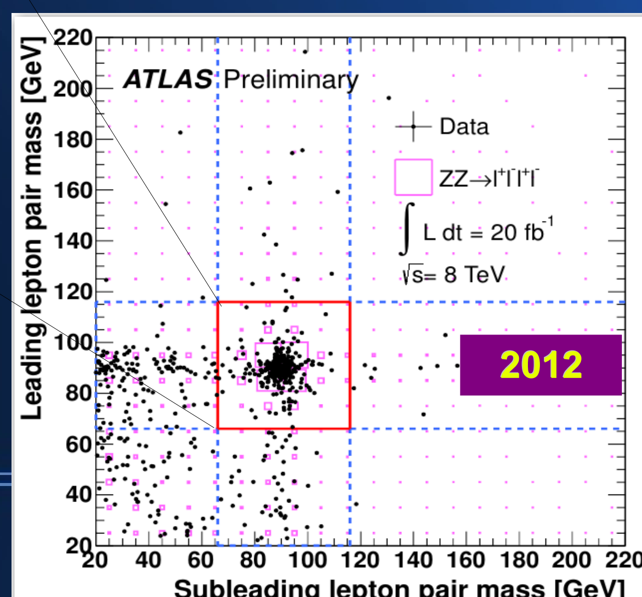
DR(l_1,l_2) > 0.2

66 < m_{12} < 116 GeV

66 < m_{34} < 116 GeV [ZZ]

m_{34} > 20 GeV [ZZ*]





ZZ → 2l2ν

PT> 20 GeV, isolated

66 < m12 < 116 GeV

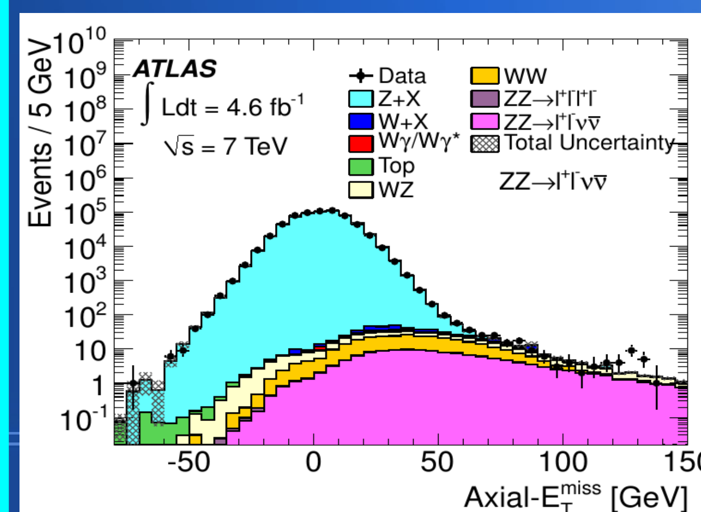
DR(l1,l2) > 0.2

DR(l,jet) > 0.3

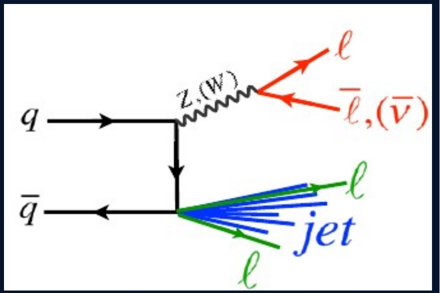
Jet veto (P_T>25 GeV)

0.6 < E_t^{miss}/ P_T < 1.4

Axial-E_T^{miss} > 75 GeV



Background



- Define lepton-like jets (J):
  - Invert isolation, d_0 (μ), or PID (e)
- Use jets in events with one Z to calculate the efficiency ratio $f(E_T,\eta)$:
  - $f(E_T,\eta) \sim (\text{jet} \rightarrow l) / (\text{jet} \rightarrow J)$
- Estimate the number of "fake" N_{4l} as:

$$N_{4\ell}^{\text{fake}} = N(\ell\ell\ell j) \times f - N(\ell\ell jj) \times f^2 - N_{ZZ}^{Correction}$$

Data Driven Method

$ZZ \rightarrow 4l$ Channel

$Z + j/\gamma + j$

($jj \rightarrow ll$ or $\gamma \rightarrow e$, $j \rightarrow e$)

Top, diboson, etc.. (small)

- WW/Wt/tt/$\tau\tau$ extrapolated from a e- control sample, weighted for BR and ratio of efficiencies ε_{ee} and $\varepsilon_{e\mu}$
- WZ background if MC estimated validated with a 3 lepton control region
- Z+jets background estimated with γ+jets data (reweighted by kinematic)

$ZZ \rightarrow 2l2\nu$ Channel

WW/Wt/Top/$Z \rightarrow \tau\tau$ (~41%)

Z+jet (fake E_T^{miss}) (~44%)

W+jets ($j \rightarrow l$) (~3%)

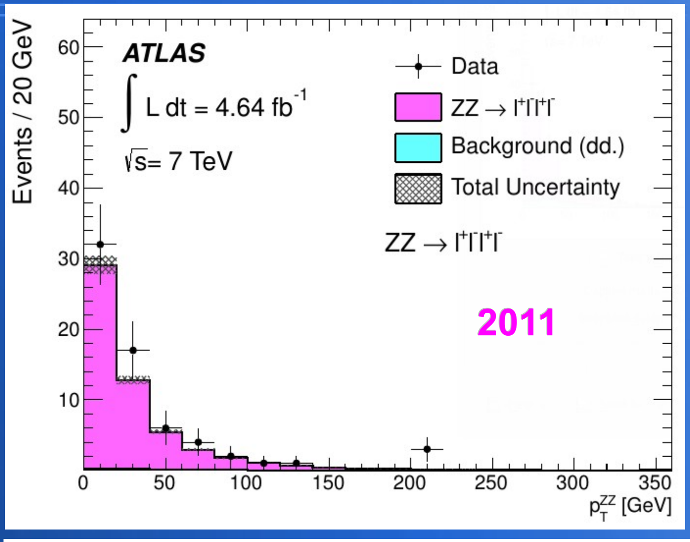
WZ (~11%)

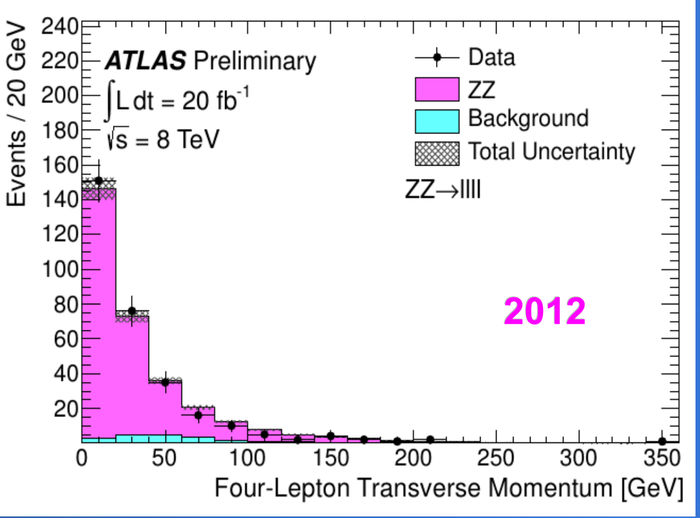
Event Yield

$ZZ^{(*)} \to \ell^+\ell^-\ell'^+\ell'^-$		$e^+e^-e^+e^-$	$\mu^+\mu^-\mu^+\mu^-$	$e^+e^-\mu^+\mu^-$	$\ell^+\ell^-\ell'^+\ell'^-$
Observed ZZ	2011	16	23	27	66
Observed ZZ^*	2011	21	30	33	84
Expected ZZ signal	2011	$10.3 \pm 0.1 \pm 1.0$	$16.5 \pm 0.2 \pm 0.9$	$26.7 \pm 0.2 \pm 1.7$	$53.4 \pm 0.3 \pm 3.2$
Expected ZZ^* signal	2011	$12.3 \pm 0.2 \pm 1.2$	$20.5 \pm 0.2 \pm 1.1$	$31.6 \pm 0.3 \pm 2.0$	$64.4 \pm 0.4 \pm 4.0$
Expected ZZ background	2011	$0.5 \pm 0.6 \pm 0.3$	< 0.6	$0.7 \pm 0.7 \pm 0.6$	$0.9 \pm 1.1 \pm 0.7$
Expected ZZ^* background	2011	$4.3 \pm 1.4 \pm 0.6$	< 0.9	$5.8 \pm 1.6 \pm 0.9$	$9.1 \pm 2.3 \pm 1.3$
Observed ZZ	2012	62	85	158	305
Expected ZZ signal	2012	59.5±4.0	90.2±2.7	142.7±5.6	292.5±10.6
Expected ZZ bkg.	2012	10.0±1.8±1.4	1.1±1.4±0.5	9.3±2.1±3.1	20.4±2.9±5.0

$ZZ \to \ell^+\ell^-\nu\bar{\nu}$		$e^+e^-E_T^{miss}$	$\mu^+\mu^-E_T^{miss}$	$\ell^+\ell^-E_T^{miss}$
Observed ZZ	2011	35	52	87
Expected ZZ signal		$17.8 \pm 0.3 \pm 1.7$	$21.6 \pm 0.3 \pm 2.0$	$39.3 \pm 0.4 \pm 3.7$
Expected ZZ background		$20.8 \pm 2.3 \pm 1.2$	$26.1 \pm 2.8 \pm 1.4$	$46.9 \pm 4.8 \pm 1.9$

P_T^{ZZ} Distributions





Signal Efficiency and Acceptance

C_{ZZ}: experimental acceptance in fiducial region

$$C_{ZZ} = \frac{N^{\text{MC Pass All Cuts}}_{\text{Reconstructed } ZZ} \times \text{SF}}{N^{\text{MC Fiducial Volume}}_{\text{Generated } ZZ}} \quad \text{with} \quad SF = \frac{\epsilon^{data}_{trig}}{\epsilon^{MC}_{trig}} \cdot \frac{\epsilon^{data}_{reco}}{\epsilon^{MC}_{reco}}$$

Selection	**2011, 2012** C_{ZZ}
$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	$0.552 \pm 0.002 \pm 0.021$
$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	**0.68 ± 0.02**
$ZZ^* \to \ell^+\ell^-\ell'^+\ell'^-$	$0.542 \pm 0.002 \pm 0.022$
$ZZ \to \ell^+\ell^-\nu\bar{\nu}$	$0.679 \pm 0.004 \pm 0.014$

A_{ZZ}: fiducial → total region

Selection	**2011, 2012** A_{ZZ}
$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	$0.804 \pm 0.001 \pm 0.010$
$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	**0.64 ± 0.01**
$ZZ \to \ell^+\ell^-\nu\bar{\nu}$	$0.081 \pm 0.001 \pm 0.004$

Systematic Uncertainties on C_{ZZ} and A_{ZZ}

Source	$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ (2011)	$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ (2012)	$ZZ^* \to \ell^+\ell^-\ell'^+\ell'^-$	$ZZ \to \ell^+\ell^-\nu\bar{\nu}$
C_{ZZ}				
Lepton efficiency	3.0%	**2.8%**	3.1%	1.3%
Lepton energy/momentum	0.2%	**0.1%**	0.3%	1.1%
Lepton isolation and impact parameter	1.9%	**1.6%**	2.0%	0.6%
Jet+E_T^{miss} modelling	—		—	0.8%
Jet veto	—		—	0.9%
Trigger efficiency	0.2%	**0.1%**	0.2%	0.4%
PDF and scale	1.6%	**1.5%**	1.5%	0.4%
A_{ZZ}				
Jet veto	—		—	2.3%
PDF and scale	0.6%	**1.0%**	—	1.9%
Generator modelling and parton shower	1.1%	**0.8%**	—	4.6%

Cross Section Measurements and Comparison with Theory

Total Cross Sections:

$$\sigma_{ZZ}^{tot}(8\ \mathrm{TeV}) = 7.1^{+0.5}_{-0.4}(\mathrm{stat.}) \pm 0.3(\mathrm{syst.}) \pm 0.2(\mathrm{lumi})\ \mathrm{pb}\quad [\mathrm{SM:}\ 7.2^{+0.3}_{-0.2}]$$

$$\sigma_{ZZ}^{tot}(7\ \mathrm{TeV}) = 6.7 \pm 0.7(\mathrm{stat.})^{+0.4}_{-0.3}(\mathrm{syst.}) \pm 0.3(\mathrm{lumi})\ \mathrm{pb}\quad [\mathrm{SM:}\ 5.89^{+0.22}_{-0.18}]$$

Fiducial Cross Sections:

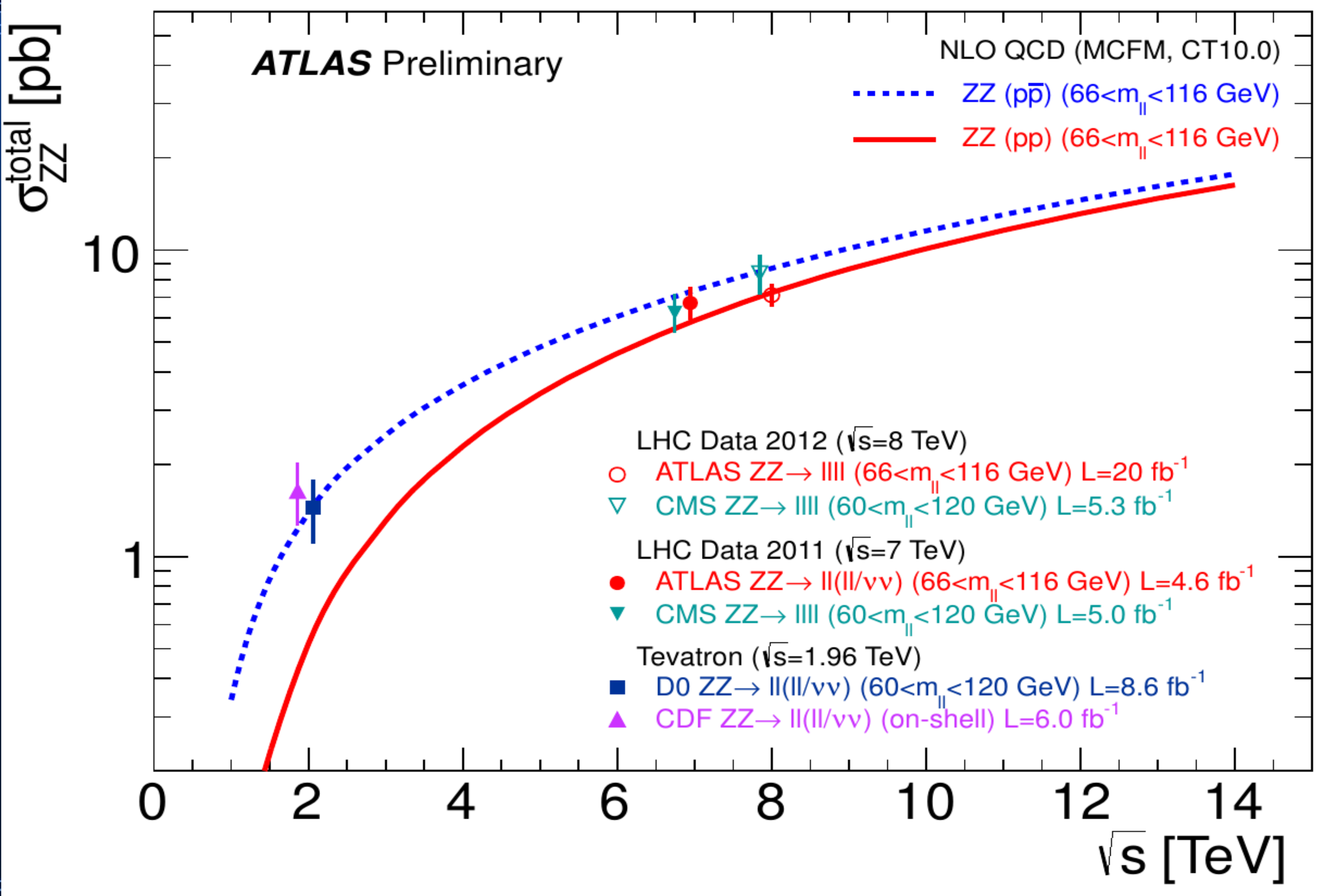
8 TeV

Channel	Measured σ_{fid} [fb]	Theoretical σ_{fid} [fb]
$ZZ \rightarrow e^+e^-e^+e^-$	$4.6^{+0.8}_{-0.7}(\mathrm{stat.})^{+0.4}_{-0.4}(\mathrm{syst.})^{+0.1}_{-0.1}(\mathrm{lumi.})$	$5.3^{+0.2}_{-0.2}$
$ZZ \rightarrow \mu^+\mu^-\mu^+\mu^-$	$5.0^{+0.6}_{-0.5}(\mathrm{stat.})^{+0.2}_{-0.2}(\mathrm{syst.})^{+0.2}_{-0.2}(\mathrm{lumi.})$	$5.3^{+0.2}_{-0.2}$
$ZZ \rightarrow e^+e^-\mu^+\mu^-$	$11.1^{+1.0}_{-0.9}(\mathrm{stat.})^{+0.5}_{-0.5}(\mathrm{syst.})^{+0.3}_{-0.3}(\mathrm{lumi.})$	$10.5^{+0.4}_{-0.4}$
$ZZ \rightarrow \ell^+\ell^-\ell'^+\ell'^-$	$20.7^{+1.3}_{-1.2}(\mathrm{stat.}) \pm 0.8(\mathrm{syst.}) \pm 0.6(\mathrm{lumi.})$	$21.1^{+0.9}_{-0.7}$

7 TeV

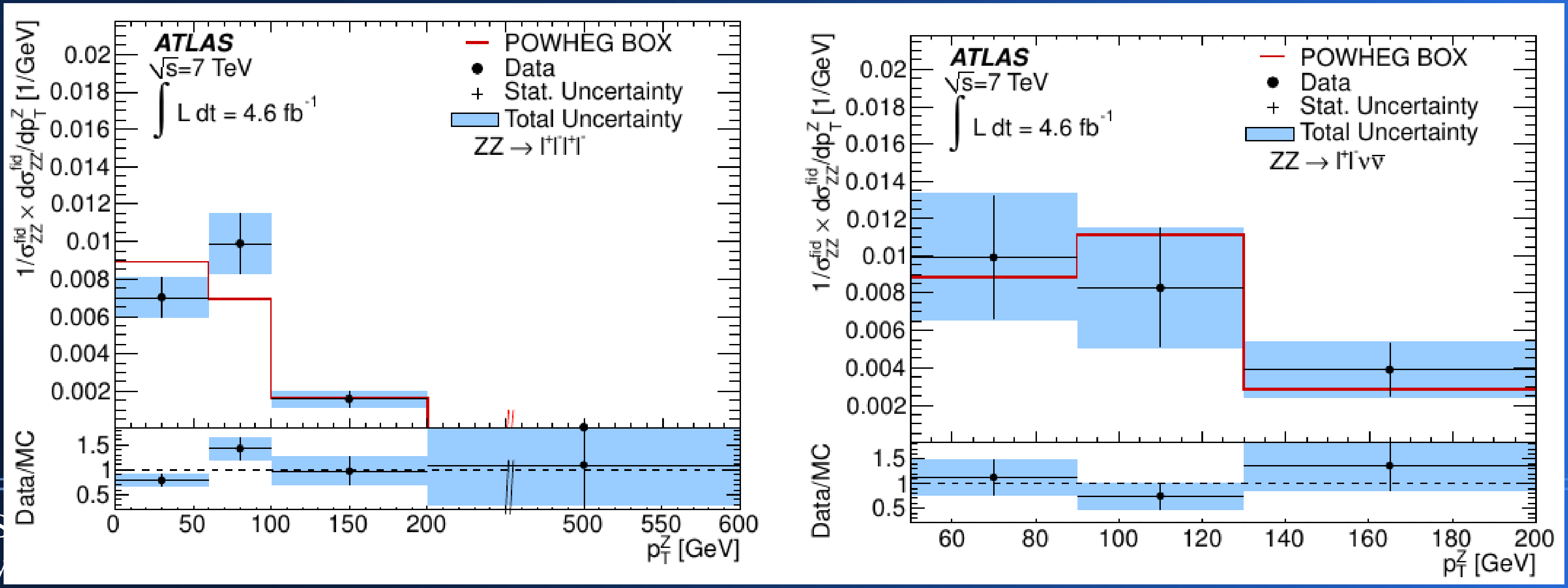
Measured σ_{fid} [fb]	Theoretical σ_{fid} [fb]
$\sigma^{\mathrm{fid}}_{ZZ\rightarrow\ell^+\ell^-\ell'^+\ell'^-} = 25.4^{+3.3}_{-3.0}\ (\mathrm{stat.})\ ^{+1.2}_{-1.0}\ (\mathrm{syst.}) \pm 1.0\ (\mathrm{lumi.})$	$20.9 \pm 0.1\ (\mathrm{stat.})\ ^{+1.1}_{-0.9}\ (\mathrm{theory})$
$\sigma^{\mathrm{fid}}_{ZZ^*\rightarrow\ell^+\ell^-\ell'^+\ell'^-} = 29.8^{+3.8}_{-3.5}\ (\mathrm{stat.})\ ^{+1.7}_{-1.5}\ (\mathrm{syst.}) \pm 1.2\ (\mathrm{lumi.})$	$25.6 \pm 0.1\ (\mathrm{stat.})\ ^{+1.3}_{-1.1}\ (\mathrm{theory})$
$\sigma^{\mathrm{fid}}_{ZZ\rightarrow\ell^+\ell^-\nu\bar{\nu}} = 12.7^{+3.1}_{-2.9}\ (\mathrm{stat.})\ ^{+1.7}_{-1.7}\ (\mathrm{syst.}) \pm 0.5\ (\mathrm{lumi.})$	$12.5 \pm 0.1\ (\mathrm{stat.})\ ^{+1.0}_{-1.1}\ (\mathrm{theory})$

Cross Section Measurements and Comparison with Theory



Differential Cross Sections

- Differential cross sections provide detailed comparison with theory, and comparison of kinematic distributions to new theories
- Variables more sensitive to new phenomena: p_T^Z, m^{ZZ}, $\Delta\Phi(l^+,l^-)$
- Distributions are unfolded to hadron level, accounting for effects of detector resolution, efficiency and acceptance
  - Use response matrix: MC truth (x) & MC reconstruction (y)



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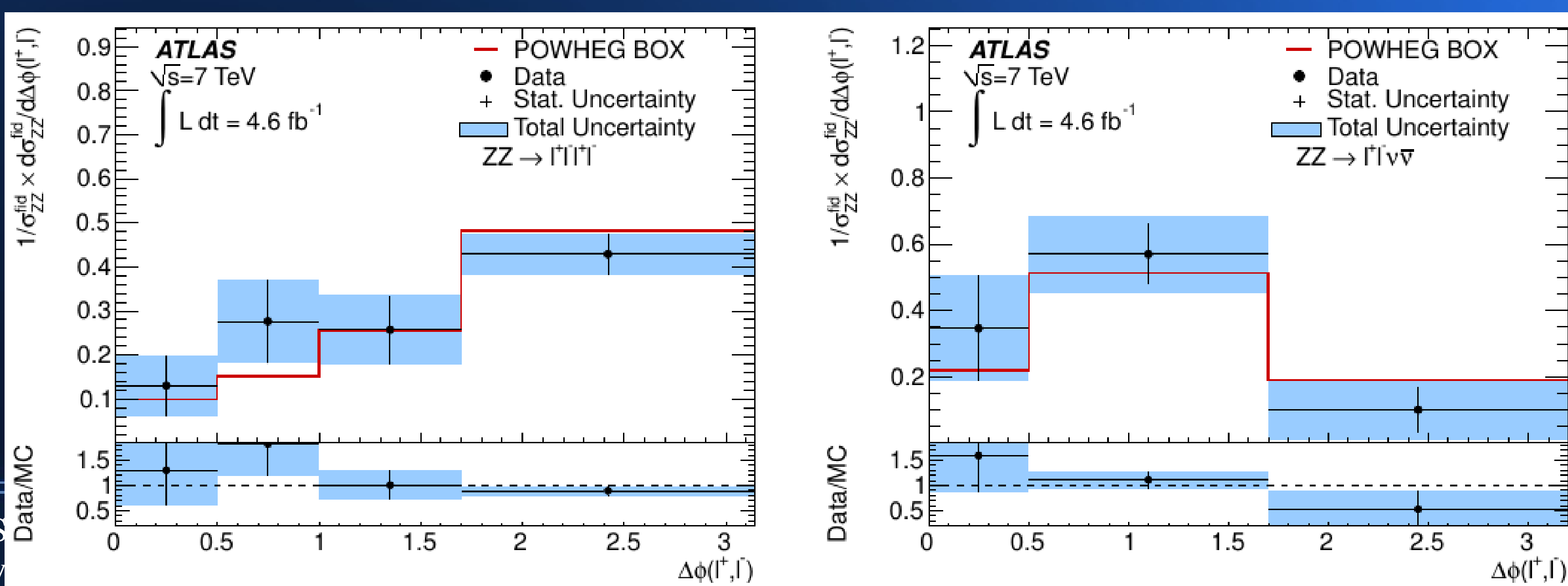

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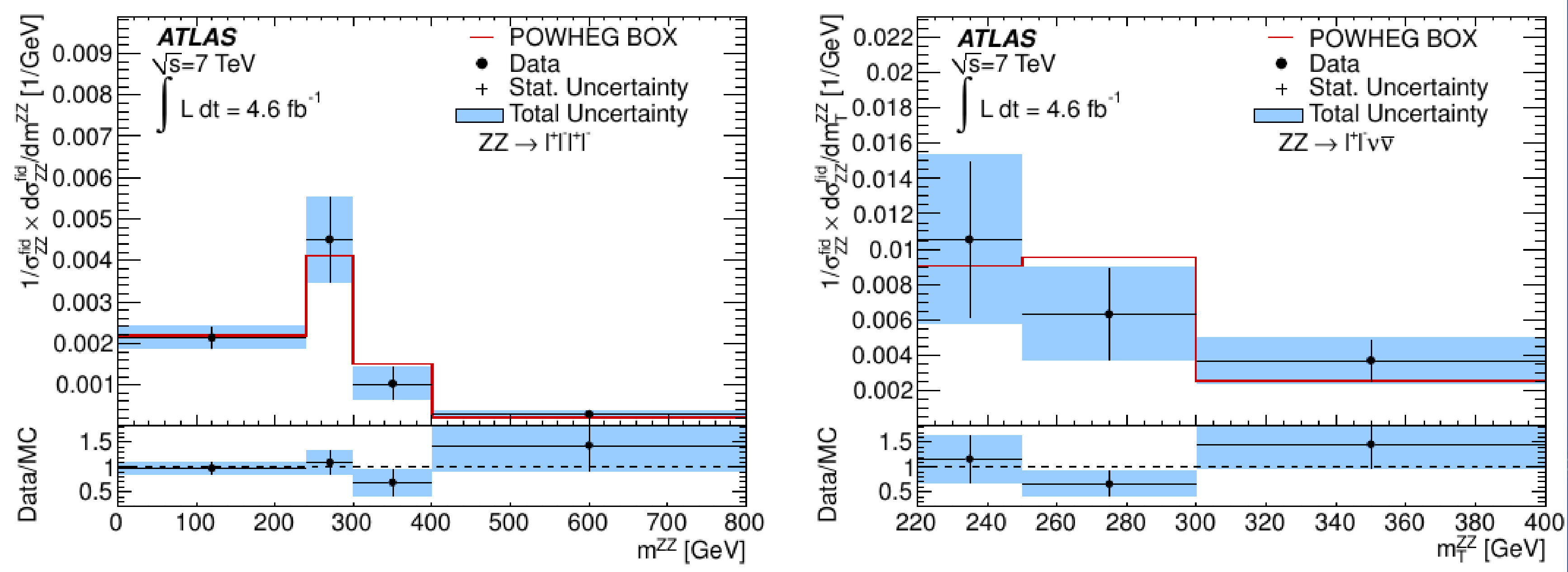


Anomalous TGC Limit

- Effective Lagrangian for neutral Triple Gauge Coupling (ZZZ, ZγZ)

$$L = -\frac{e}{M_Z^2}[f_4^V(\partial_\mu V^{\mu\beta})Z_a(\partial^a Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta]$$

- Contribution parametrized by (V=Z,γ):
  - Two CP-violating parameters: f^Z_4, f^γ_4
  - Two CP-conserving parameters: f^Z_5, f^γ_5
  - Form-factor parametrization with cut-off scale Λ (scale for new physics)

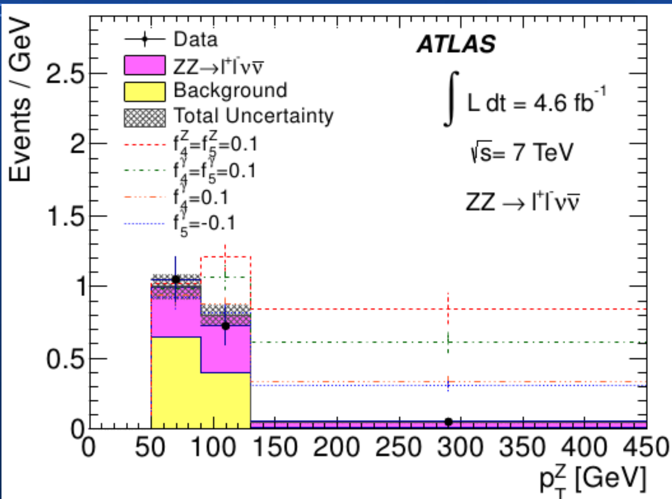
$$f_i^V = \frac{f_{i0}^V}{(1+\hat{s}/\Lambda^2)^2}$$

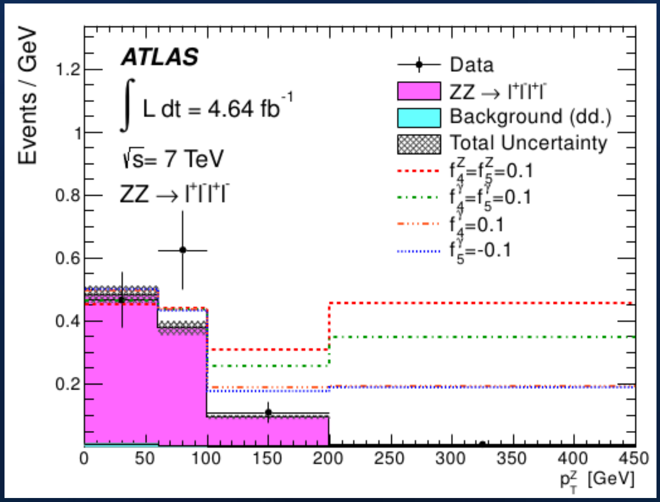
- Anomalous Couplings enhance cross section at high boson transverse momentum (p_T) or mass scale (M_{ZZ})
- Limit on nATGC determined by number of events binned in p^Z_T

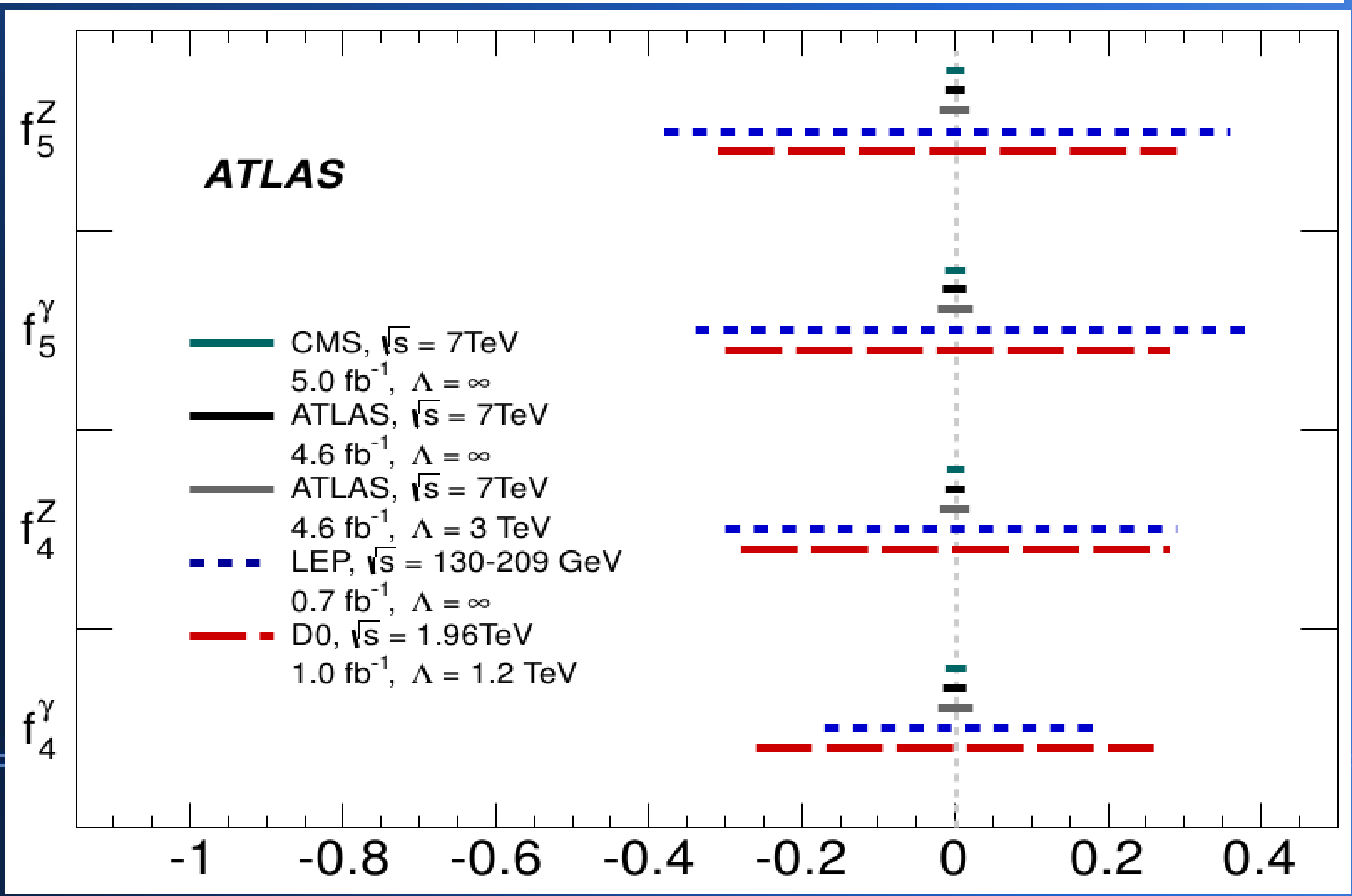
Anomalous TGC Limit

Anomalous nATGC 95% confidence intervals

Λ	f_{40}^{γ}	f_{40}^{Z}	f_{50}^{γ}	f_{50}^{Z}
3 TeV	$[-0.022, 0.023]$	$[-0.019, 0.019]$	$[-0.023, 0.023]$	$[-0.020, 0.019]$
∞	$[-0.015, 0.015]$	$[-0.013, 0.013]$	$[-0.016, 0.015]$	$[-0.013, 0.013]$







Conclusions

- ZZ production cross section measured in ATLAS both at 7 TeV (final results) and at 8 TeV (preliminary results) and compared with SM NLO predictions
- Both fiducial and total cross section measured
- Analyses used full power of the ATLAS detector lepton identification
- Uncertainties on the cross section measurements limited by statistics, even for the full 20 fb^{-1} 8 TeV preliminary results
- For final 7 TeV results included also ZZ* and $2l2\nu$ channels, unfolded differential cross sections and limit on nATGC
- Analysis ongoing with full 2012 statistics to measure the differential cross sections at 8 TeV and set new nATGC limit