MEASUREMENT OF THE ZZ PRODUCTION CROSS SECTION AND LIMITS ON ANOMALOUS NEUTRAL TRIPLE GAUGE COUPLINGS WITH ATLAS

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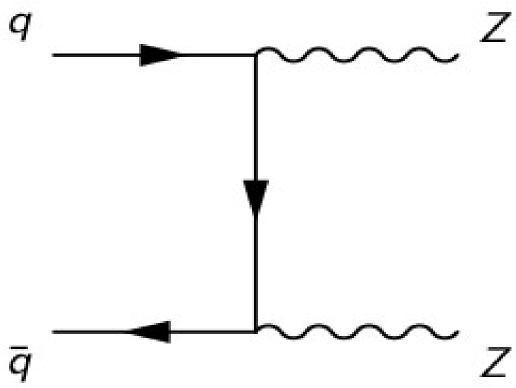
OUTLINE

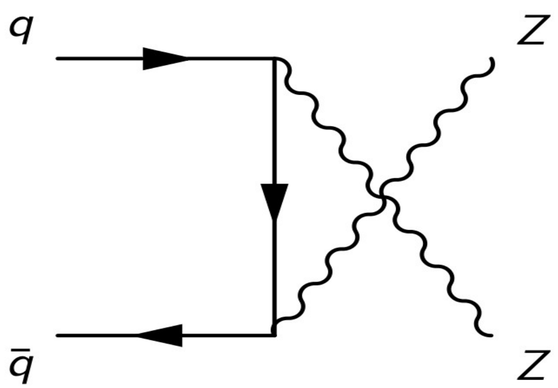
- Introduction to the measurement
- Analysis overview (Event selection, Background estimate, ZZ candidate distributions)
- **Measurements:**
  - **- pp--> ZZ cross section results @ $\sqrt{s}$ = 7 TeV**
  - **- Unfolded differential distributions**
  - **- Limits on nTGC**
- Conclusions

Introduction 1/2

- pp-->$ZZ^{(*)}$-->4l production is a rare process but with clear signature and low background

- Gluon-gloun fusion contribution is ~6 % of the cross section



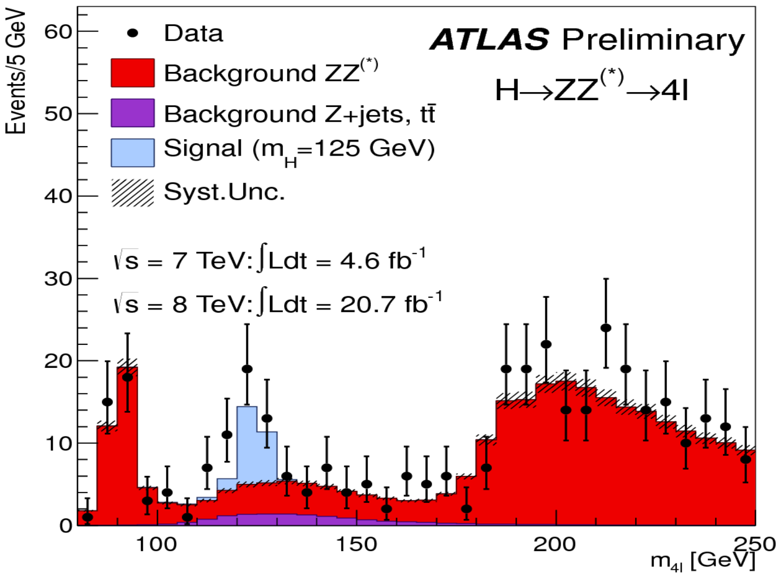


-Predicted SM ZZ total cross section at $\sqrt{s} = 7$ TeV value is **$5.89^{+0.22}_{-0.18}$ pb.**

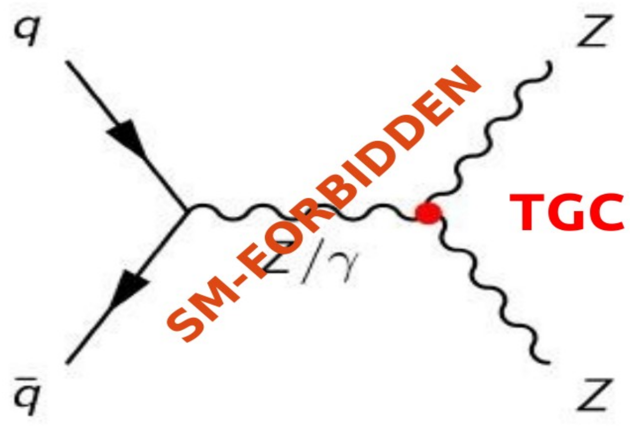
Introduction 2/2

Why study ZZ?

- Irriducibile background to the H-->ZZ-->4l channel

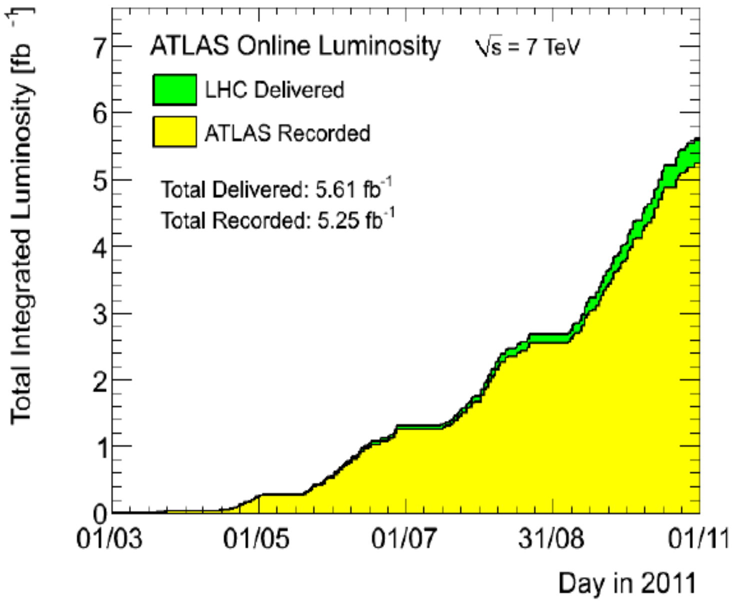


- Stringent SM test of the structure of the electroweak sector



-Enhancement of cross section could imply new physics such as nTGC

Luminosity of the Sample



- More than 5 fb^{-1} of total integrated Luminosity delivered by LHC in 2011

- ATLAS data taking efficiency of ~94%

ATLAS 2011 Z Counting Analysis

ATL-PHYS-INT-2012-049

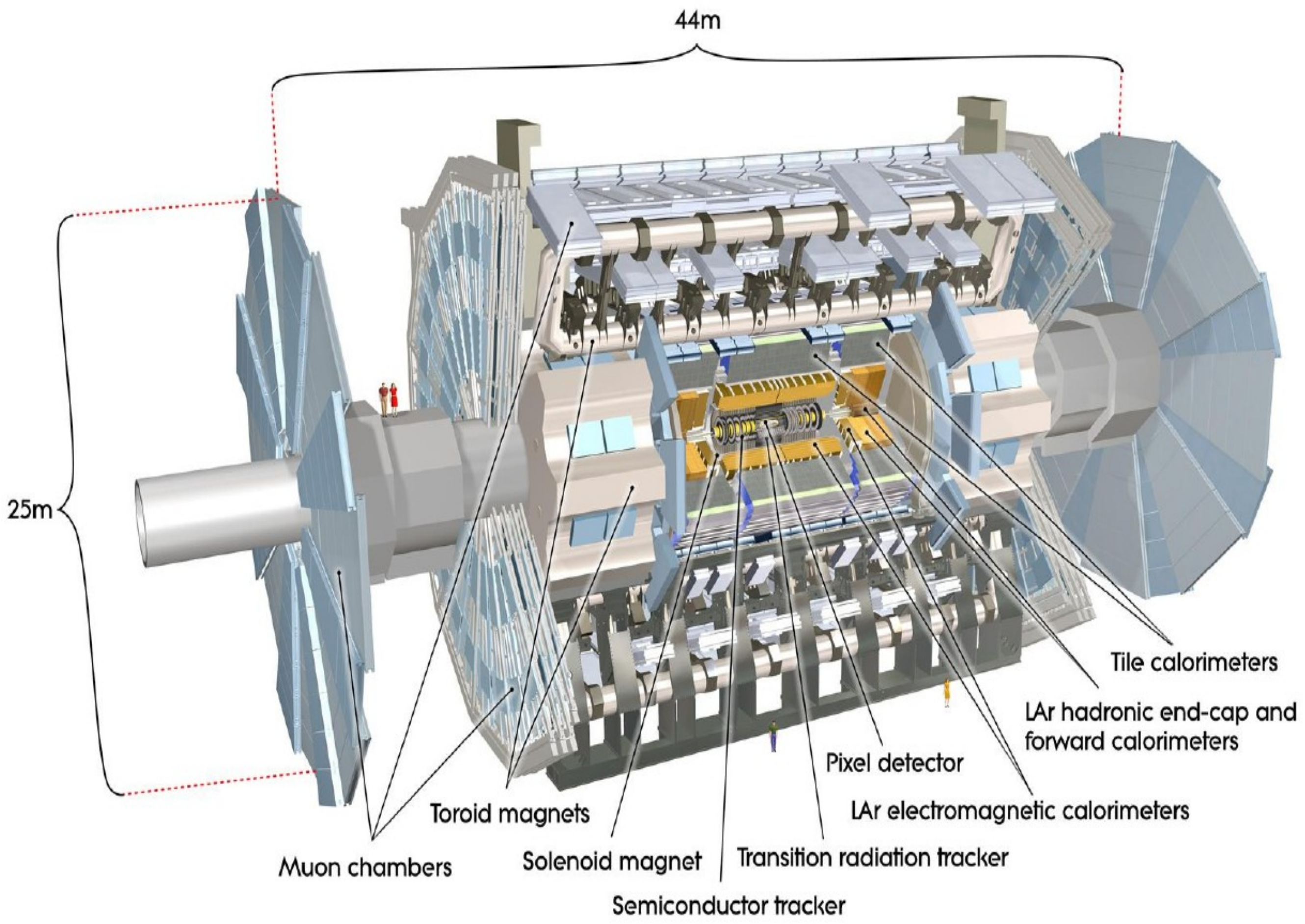
and luminosity uncertainty

Uncertainty Source	$\delta\mathscr{L}/\mathscr{L}$ [%]	
Data Year	2010	2011
Bunch Population Product	3.1	0.5
Other *vdM*		
Calibration Uncertainties	1.3	1.4
Afterglow Correction		0.2
BCM Stability		0.2
Long-Term Consistency	0.5	0.7
μ Dependence	0.5	0.5
Total	3.4	1.8

- An uncertainty estimation of 3.9% (preliminary) used in this analysis

- Further studies led to a lower uncertainty value on 2011 sample

The ATLAS Detector



General purpose experiment

- Inner Detector tracker
- EM calorimeter
- Hadronic calorimeter
- Muon detector

All main ATLAS subsystems are used to perform the measurement

Lepton Selection

- Events with only charged leptons in the final state are used

Muons

- Combine Muon Spectrometer tracks with Inner Detector tracks

- Kinematic cuts: $|\eta| < 2.7$, $p_T > 7$ GeV

Electrons

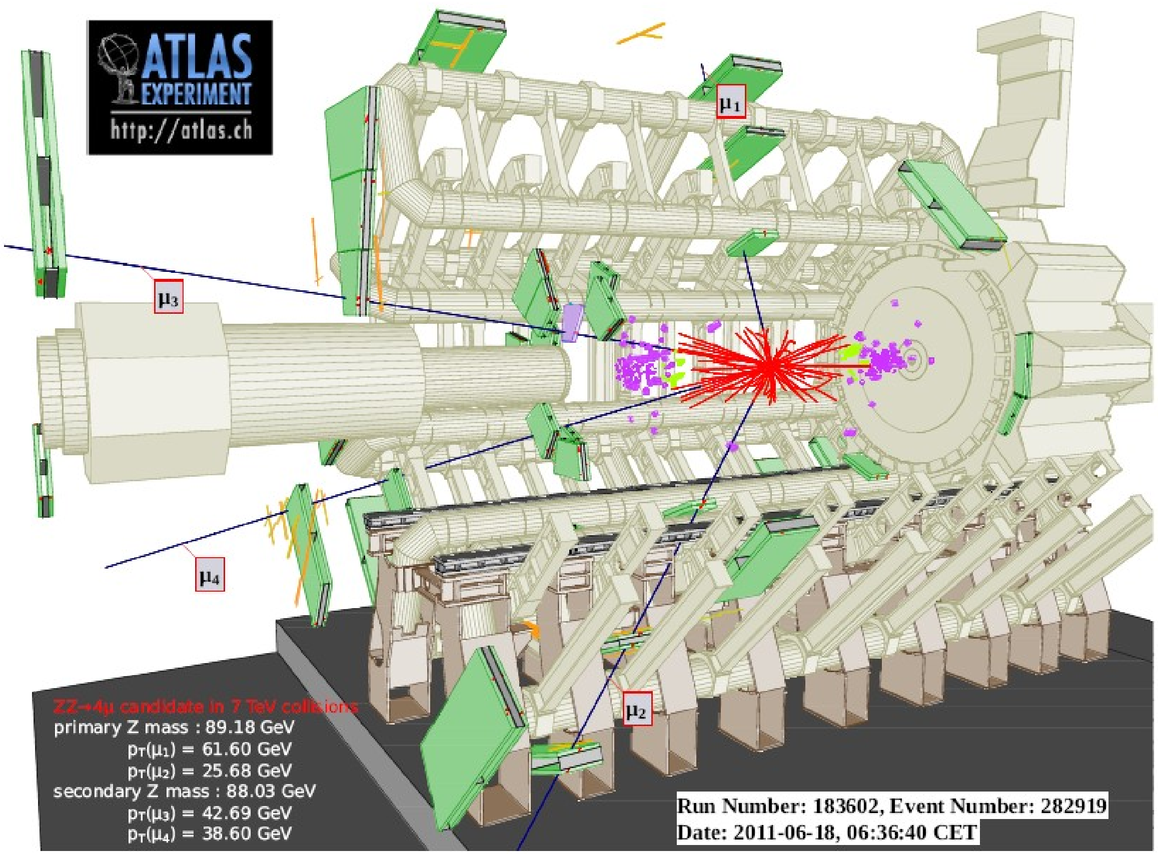
- Combine electromagnetic clusters with Inner Detector tracks

- Kinematic cuts: $|\eta| < 3.16$, $p_T > 7$ GeV

Apply requirements to leptons on ID track isolation, calorimeter isolation and longitudinal and transverse impact parameters to reject particle not coming from IP and fake leptons

Triggered lepton must have $p_T > 25$ (20) GeV for electrons (muons)

Event Selection



Display of a selected ZZ->$\mu^+\mu^+\mu^-\mu^-$event
with $m^{4\mu}$ = 239.7 GeV and $p_T^{4\mu}$ = 22.0 GeV

Events with exactly four leptons passing previous selection

Same-flavour opposite-sign pairs.
Minimizing $|m_{12}-m_Z|+|m_{34}-m_Z|$

ZZ selection

Both pairs required to be on-shell: 66 < m_Z < 116 GeV

ZZ* selection

Z_1 required to be on-shell:

66 < m_{Z1} < 116 GeV

while Z_2:

m_{Z2} > 20 GeV

Background Estimate

Main backgrounds are $Z \to l^+l^-$ with additional jets or photons, t- tbar, single-top and other diboson processes (WW, WZ). All involve one or more fake leptons

We can measure the number of selected leptons (L) and number of lepton-like jets that fail one or two of the lepton ID cuts (J)

The estimated background is:

$$N_{4\ell}^{\text{fake}} = (N_{LLLJ} - N_{LLLJ}^{ZZ}) \times FF - N_{LLJJ} \times FF^2$$

$$FF(p_\mathrm{T}, \eta) = \frac{FF(p_\mathrm{T}) \times FF(\eta)}{< FF(p_\mathrm{T}, \eta) >}$$

Fake Factors FF, the ratio of "selected" leptons to "leptonlike" jets in data, are measured using Z tag method

$ZZ \to l^+l^-l^+l^-$	ZZ selection	ZZ* selection
Expected D.D. bkg	**0.9 ± 1.1 ± 0.7**	**9.1 ± 2.3 ± 1.3**
Predicted MC bkg	**1.5 ± 0.4**	**8.3 ± 1.3**

Good agreement between Data Driven and MC background estimation

Observed Events

- **66 ZZ candidates**:
  16 eeee **23 μμμμ** **27 eeμμ**

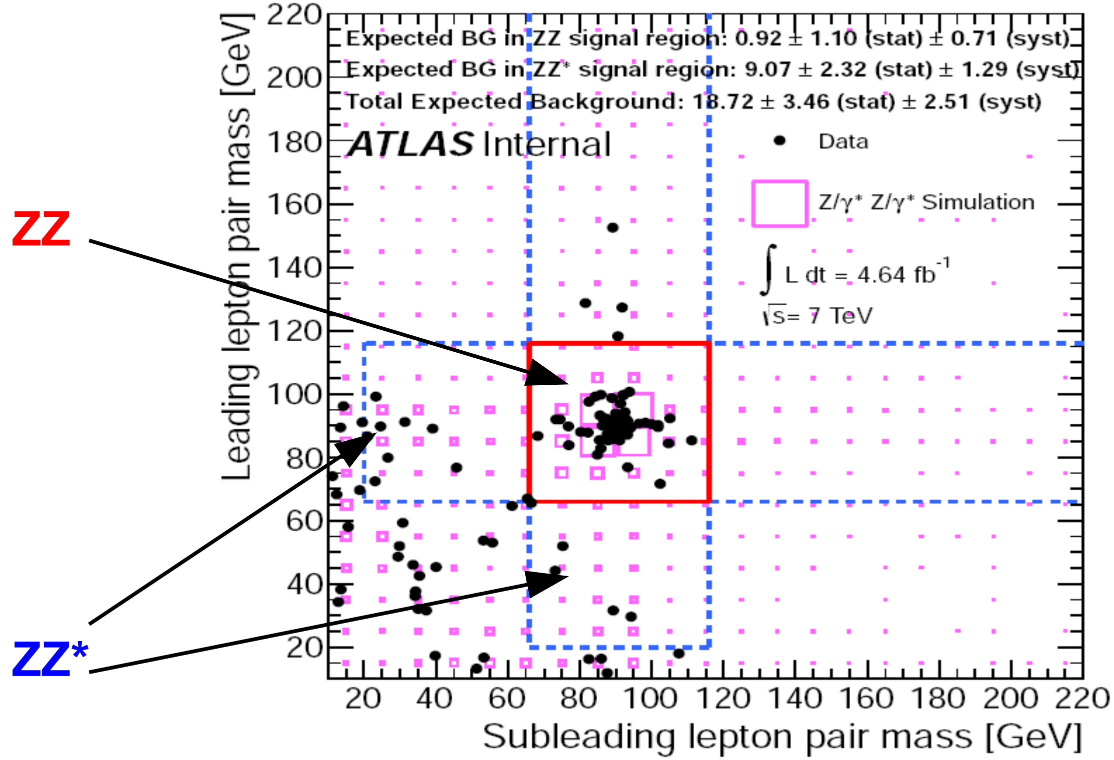
- Predicted background:
  0.9 ± 1.1 (stat) ± 0.7 (syst)

- Predicted signal (MC):
  53.4 ± 0.3 (stat) ± 3.2 (syst)

- **84 ZZ* candidates**:
  21 eeee **30 μμμμ** **33 eeμμ**

- Predicted background:
  9.1 ± 2.3 (stat) ± 1.3 (syst)

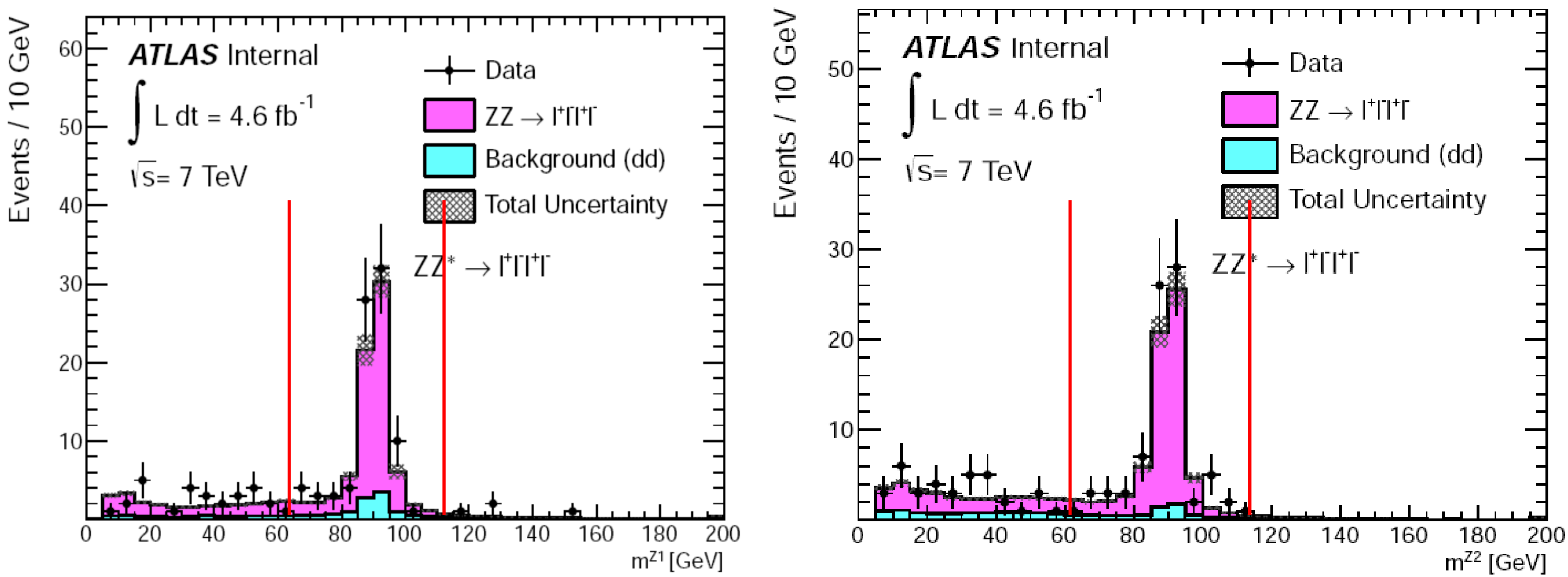
- Predicted signal (MC):
  64.4 ±0.4 (stat) ± 4.0 (syst)



Leading Z candidate: highest pT Z candidate

Signal prediction using PowhegBox (NLO) MC generator with CT10 PDF set.

Candidate Distributions

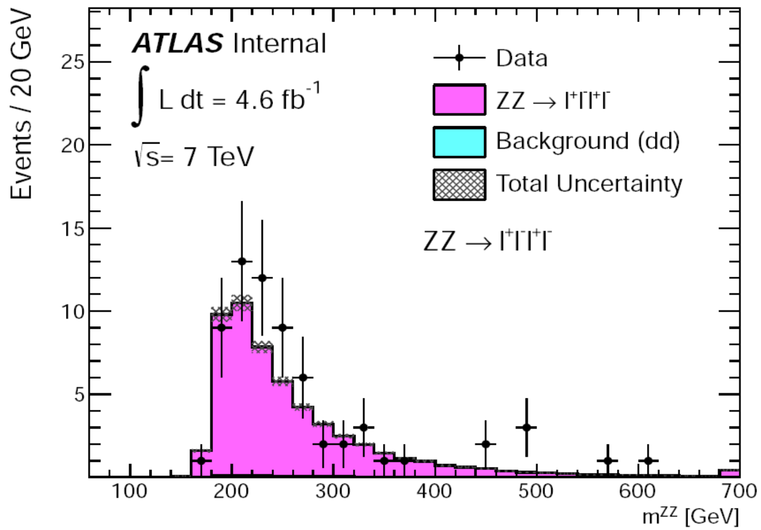


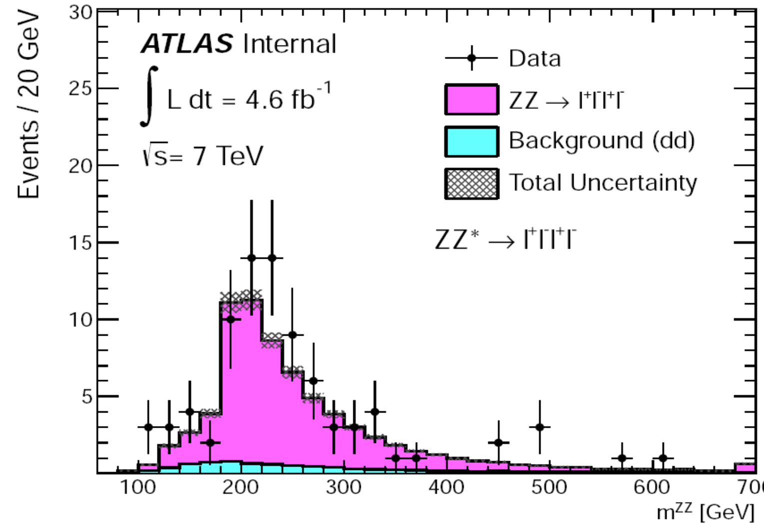
- Invariant mass distribution of the leading and subleading Z without the window mass cut
- Red line regions correspond to the mass window cut for the ZZ selection

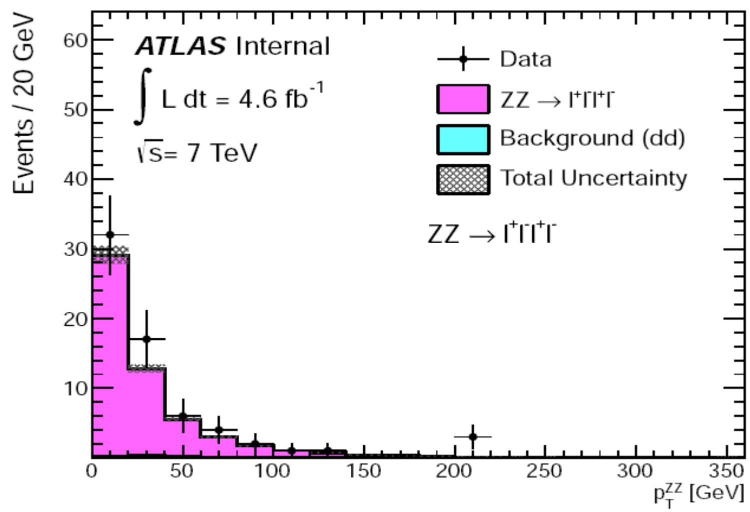
Candidate Distributions

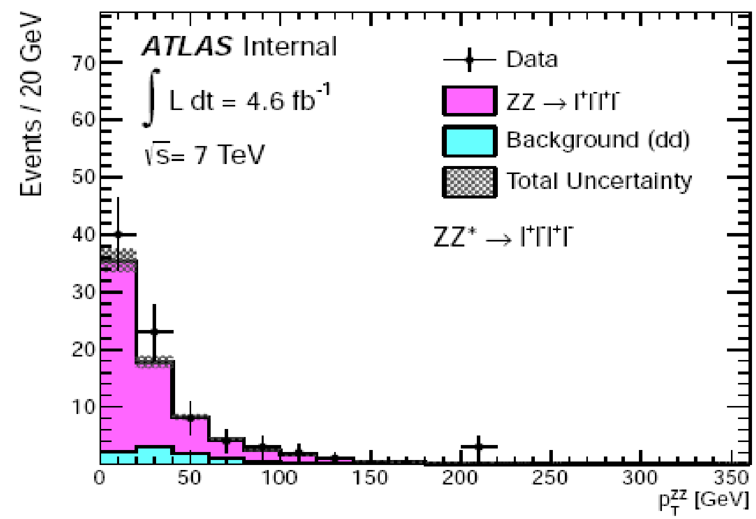
- Invariant mass (top) and transverse momentum (bottom) of the four lepton system
- Good agreement between data and Monte-Carlo

ZZ selection









ZZ^* selection

Fiducial & Total Cross Section Definition

$$\boxed{\sigma^{fid}_{ZZ\rightarrow 4l} = \frac{N_{obs} - N_{bkg}}{L \cdot C_{ZZ}}}$$

$$\sigma^{tot}_{ZZ} = \frac{N_{obs} - N_{bkg}}{L \cdot BR(ZZ \rightarrow 4l) \cdot A_{ZZ} \cdot C_{ZZ}}$$

First we measure cross section in a fiducial phase space close to experimental selection

Case ZZ (both on shell)

- $(Z/\gamma^*)(Z/\gamma^*) \rightarrow \ell^+\ell^-\ell^+\ell^-, \ell = e, \mu;$
- $66 < m_{12}(Z/\gamma^*) < 116$ GeV;
- $66 < m_{34}(Z/\gamma^*) < 116$ GeV;
- $p_T^\ell > 7$ GeV;
- $|\eta|<3.16$
- **ΔR>0.2 between any 2 leptons**

Case ZZ* (one Z can be off shell)

- **As above except: M_{34}>20 GeV**

Fiducial phase space

Then we extrapolate to the total cross-section by correcting for the acceptance (**A_{ZZ}**) of the fiducial cuts estimated using the MCFM NLO generator and the Z->ll branching ratios

Acceptances Definition

Reconstruction Acceptance Factor C_{ZZ}

- Extrapolates the number of reconstructed events to the true number of events in the fiducial phase space

$$C_{ZZ} = \frac{N^{MC\ Pass\ All\ Cuts}_{Reconstructed\ ZZ} \cdot SF}{N^{MC\ Fiducial\ Volume}_{Generated\ ZZ}}$$

Total Acceptance Factor A_{ZZ}

- Correction applied to extrapolate from the fiducial volume to the full phase space

$$A_{ZZ} = \frac{N^{MC\ Fiducial\ Volume}_{Generated\ ZZ}}{N^{MC\ All}_{Generated\ ZZ}}$$

$\ell^-\ell^+\ell^-\ell^+$ channel	A_{ZZ}	C_{ZZ}
ZZ^* Selection	$0.757 \pm 0.001 \pm \boxed{0.019}$	$0.542 \pm 0.002 \pm \boxed{0.022}$
ZZ Selection	$0.804 \pm 0.001 \pm \boxed{0.010}$	$0.552 \pm 0.002 \pm \boxed{0.021}$

Syst. unc. from measurement ---> Czz

Syst. unc. from theory ---> Azz

Systematic Uncertainties

Source %	$eeee$		$\mu\mu\mu\mu$		$ee\mu\mu$		$llll$	
Reconstruction Uncertainties	ZZ	ZZ^*	ZZ	ZZ^*	ZZ	ZZ^*	ZZ	ZZ^*
e energy resolution	< 0.1	< 0.1	-	-	< 0.1	< 0.1	< 0.1	< 0.1
e energy scale	0.5	0.6	-	-	0.1	0.1	0.1	0.2
e identification efficiency	5.5	6.0	-	-	2.7	2.8	2.4	2.5
e reconstruction	3.9	4.0	-	-	1.9	2.0	1.7	1.7
e isolation/z0/d0Sig	3.3	3.6	-	-	1.6	1.7	1.4	1.5
μ momentum resolution	-	-	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
μ momentum scale	-	-	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
μ reconstruction efficiency	-	-	1.2	1.2	0.6	0.6	0.7	0.7
μ isolation/z0/d0Sig	-	-	2.2	2.4	1.1	1.2	1.3	1.3
IP Resolution	< 0.1	< 0.1	0.4	0.4	0.3	0.3	0.3	0.3
Trigger	< 0.1	< 0.1	0.3	0.4	0.1	0.2	0.2	0.2
Total Reconstruction Uncertainty (C_{ZZ})	7.5	8.1	2.6	2.7	3.9	4.1	3.5	3.7
Theoretical Uncertainties	ZZ				ZZ^*			
MC Generator Difference (C_{ZZ})	1.6				1.5			
PDF & Scale (A_{ZZ})	0.6				2.5			
MC Generator Difference (A_{ZZ})	1.1				0.2			
Total (A_{ZZ})	1.3				2.5			
Total (C_{ZZ})	7.7	8.3	3.0	3.1	4.2	4.3	3.9	4.0
Luminosity	3.9							

Dominant uncertainties from electron and muon Reconstruction, Identification and Isolation

Evaluated using Sherpa MC

Evaluated using CT10 pdf error set changing factorization and renormalization scale by a factor 2

Cross Section Results

Fiducial cross sections

$$\sigma^{\mathrm{fid}}_{ZZ\to\ell^-\ell^+\ell^-\ell^+} = 25.4^{+3.3}_{-3.0}(\mathrm{stat.})^{+1.2}_{-1.0}(\mathrm{syst.}) \pm 1.0(\mathrm{lumi.})(\mathrm{fb})$$

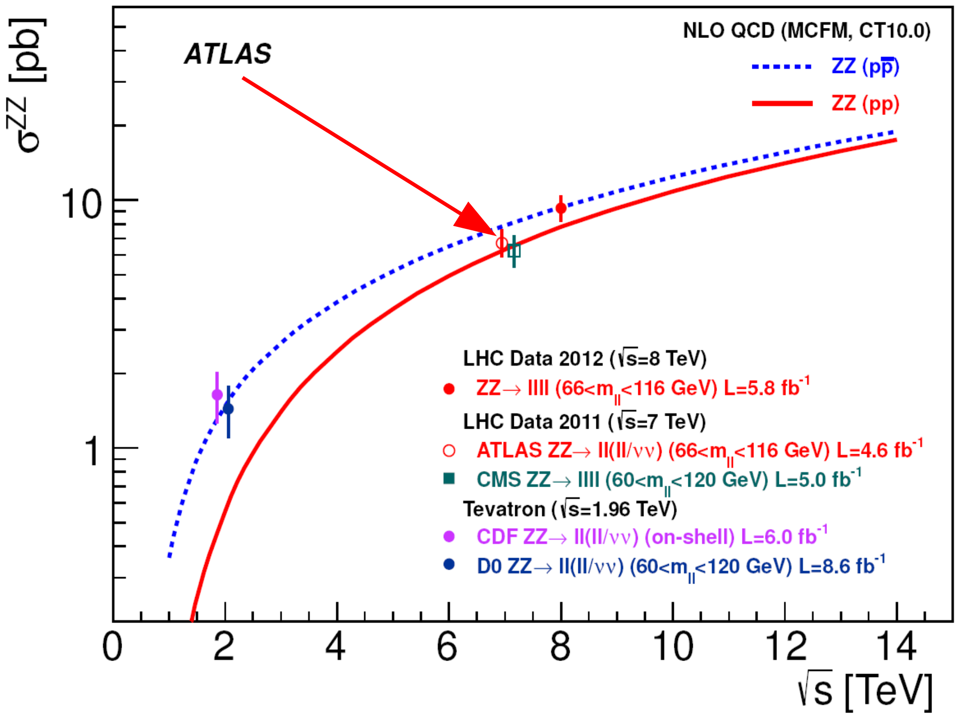
$$\sigma^{\mathrm{fid}}_{ZZ^*\to\ell^-\ell^+\ell^-\ell^+} = 29.8^{+3.8}_{-3.5}(\mathrm{stat.})^{+1.7}_{-1.5}(\mathrm{syst.}) \pm 1.2(\mathrm{lumi.})(\mathrm{fb})$$

Total cross section

With 1.8% lumi unc. **0.1**

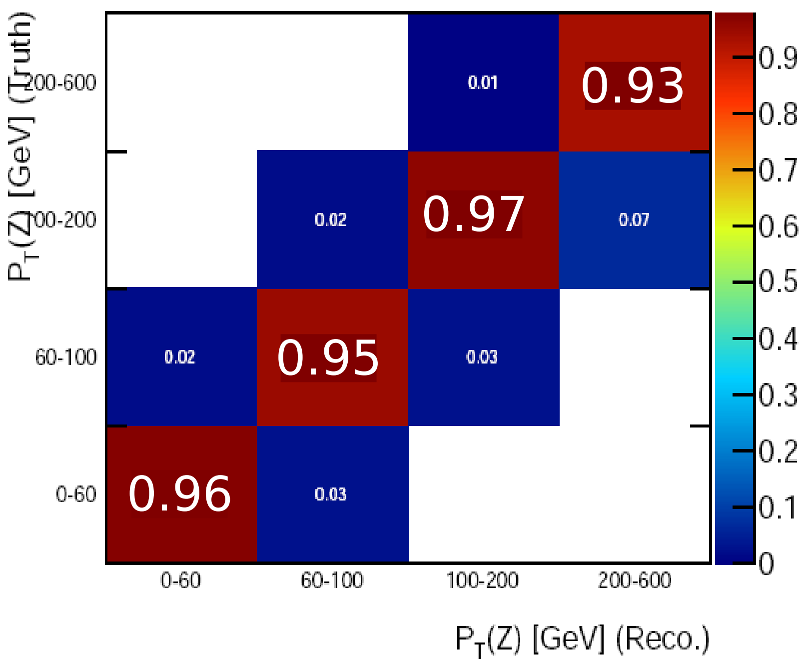
$$\boxed{\sigma^{\mathrm{tot}}_{\mathrm{ZZ}} = 7.0^{+0.9}_{-0.8}(\mathrm{stat.})^{+0.4}_{-0.3}(\mathrm{syst.}) \pm 0.3(\mathrm{lumi.})(\mathrm{pb})}$$

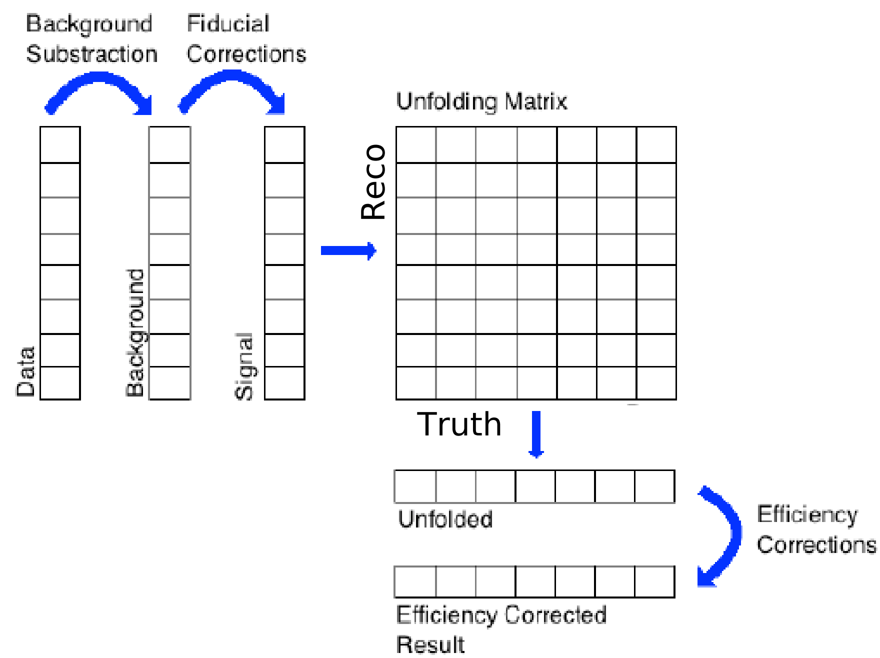
Observed total cross section is **consistent with the Standard Model** cross section, calculated with MCFM and PDF set CT10, of $\mathbf{5.89^{+0.22}_{-0.18}}$ pb.



Unfolded Differential Distributions

- Goal: Plot p_T^Z, m^{ZZ}, $\Delta\varphi(l,l)$
- Use MC truth (x) & MC reconstructed (y) to find the response matrix A used for unfolding
- Use A to unfold the distribution found in data



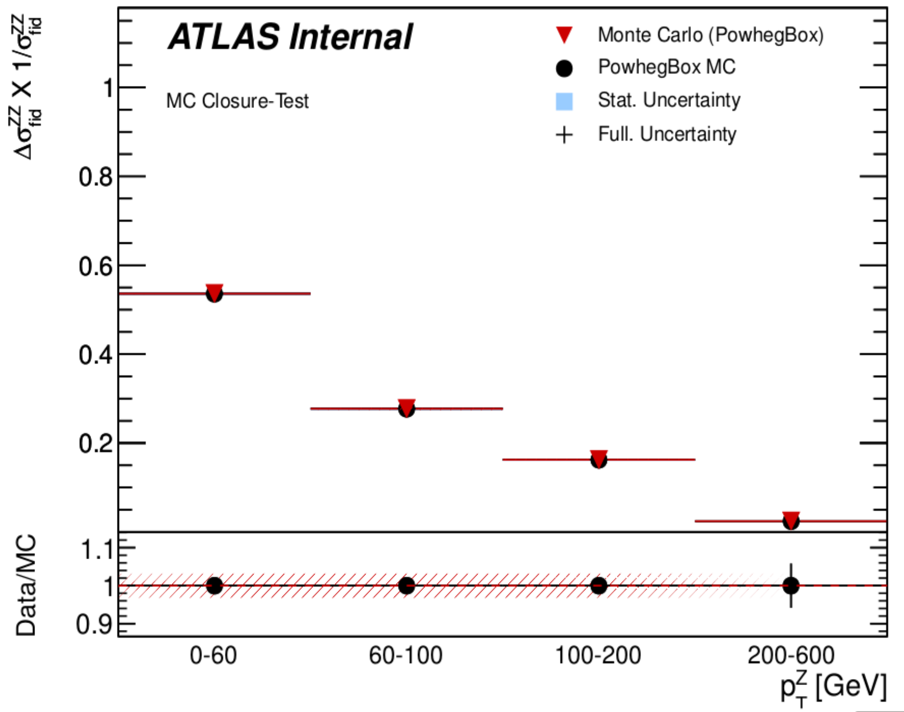


Bayesian iterative unfolding method used

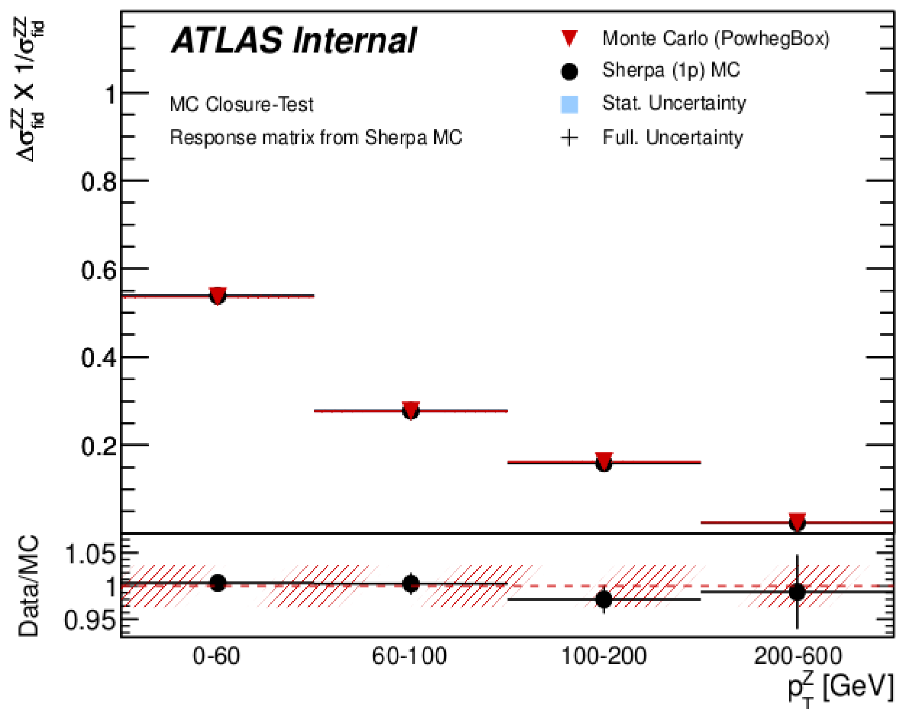
MC Closure Tests

Closure tests are performed to check the unfolding framework using MC distribution as pseudo-data

Using same MC (PowhegBox)
The unfolded and truth disributions are found to match exactly

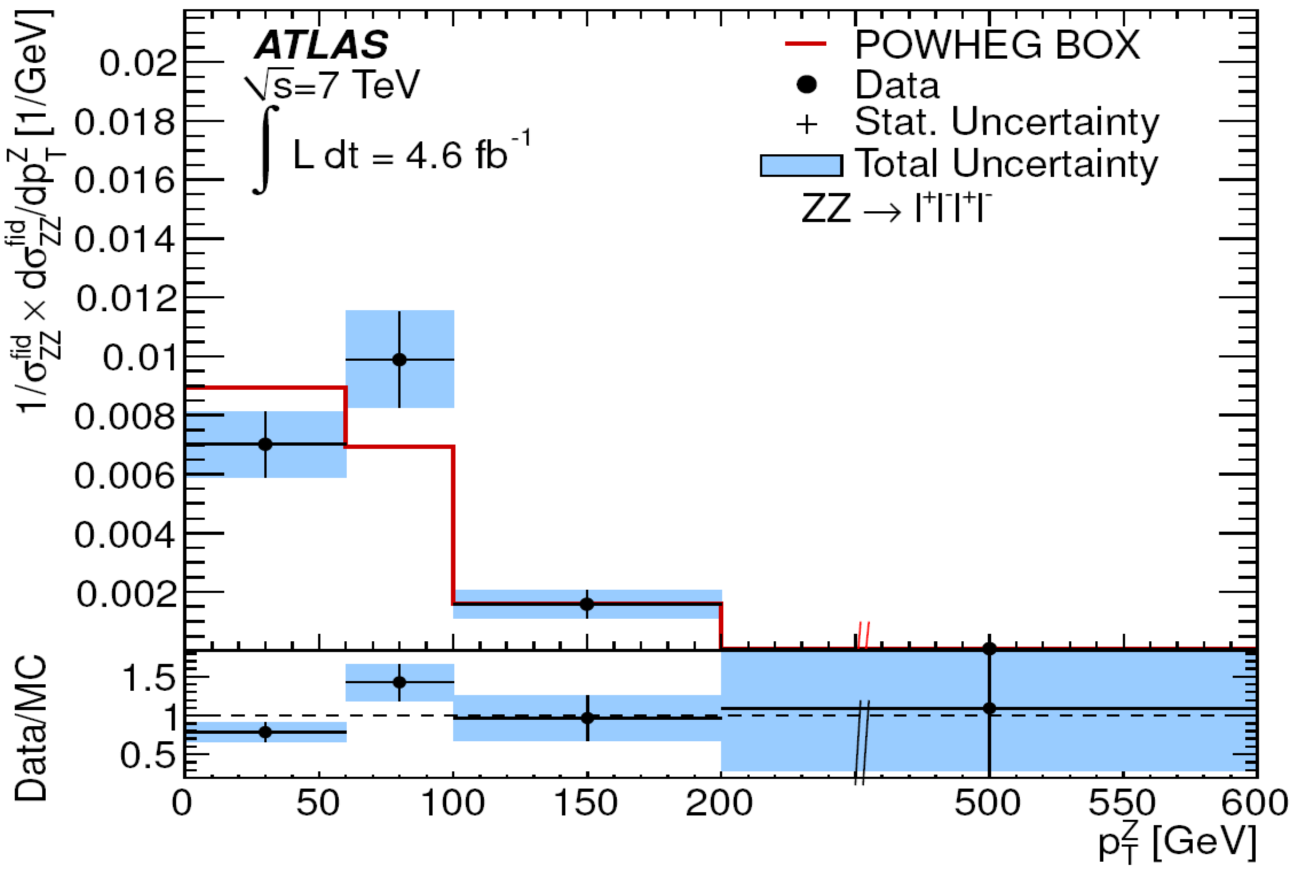


Additional systematics evaluated using the difference in using Response Matrix from Sherpa MC



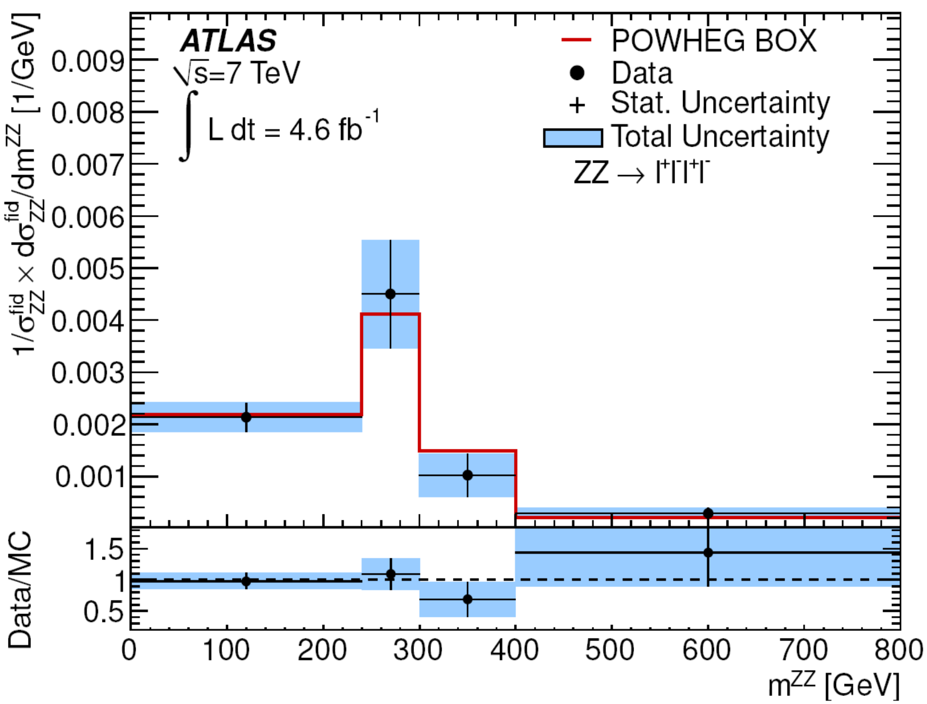
Unfolded Distributions: P_T^Z

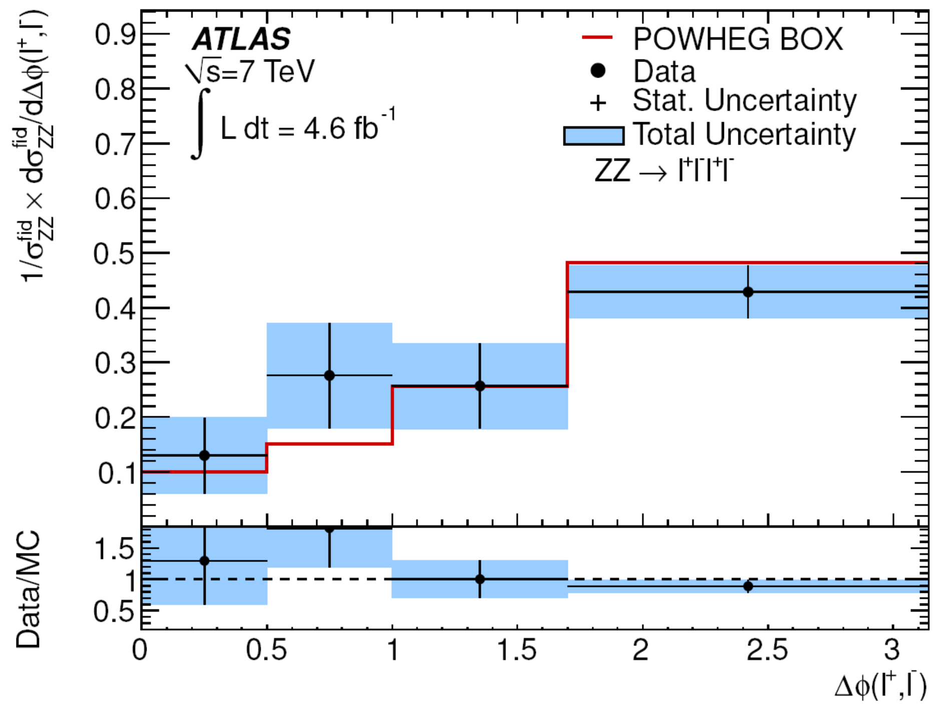
The distributions are normalised to the ZZ fiducial cross-section previously defined



Unfolded data distributions in agreement with SM prediction

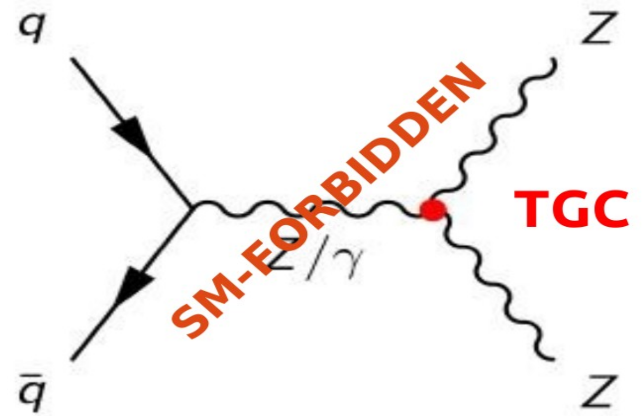
Unfolded Distributions: m^{ZZ}, $\Delta\phi(l,l)$





- The uncertainty on the unfolded distributions is dominated by the statistical uncertainty
- Consistency with the SM predicted distributions

Anomalous Triple Gauge Couplings



Lagrangian with general ZZV couplings parametrised using two CP-violating (f^V_4) and two CP-conserving (f^V_5) parameters

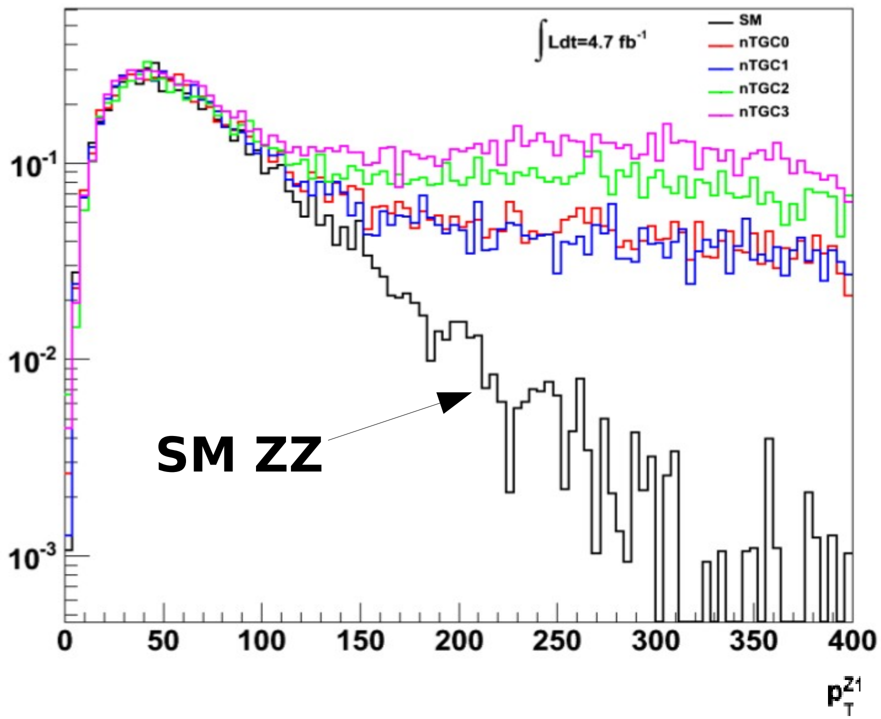
$$L = \frac{e}{M_Z^2}[f_4^V(\partial_\mu V^{\mu\beta})Z_\alpha(\partial^\alpha Z_\beta) + f_5^V(\partial^\sigma V_{\sigma\mu})\tilde{Z}^{\mu\beta}Z_\beta]$$

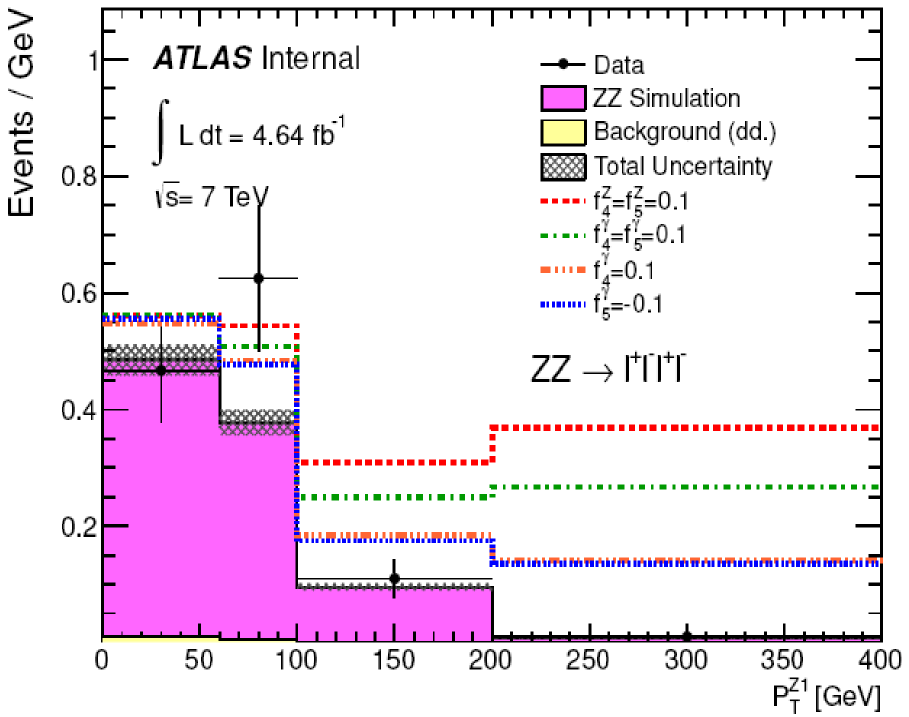
$$f_i^V(s) = \frac{f_{i0}^V}{(1+s/\Lambda_{FF}^2)^n}$$

Benchmark reference: Baur&Rainwater, PRD62 113011 (2000)

- n = 3
- Λ_{FF} is the scale for new physics
  - Λ_{FF}=2 TeV preserves unitarity, less general
  - No Form Factor violates unitarity at high energy, no model assumptions

Anomalous Triple Gauge Couplings





- Shape difference between SM and TGC distributions
- Enhanced yields at high p_T^Z predicted if any nTGC, not observed in data

Anomalous Triple Gauge Couplings

Reweighting procedure

Differential cross section has quadratic dependence on nTGC's

- Yield coefficients in each p_T bins are derived
- Sherpa MC generator sample with $f_4^{\gamma} = 0.0$; $f_5^{\gamma} = -0.1$; $f_4^{Z} = 0.0$; $f_5^{Z} = 0.0$ used

$$R(\vec{x}) = \frac{L_{prof}(\vec{x})}{\max[L_{prof}(\vec{x}')]}$$

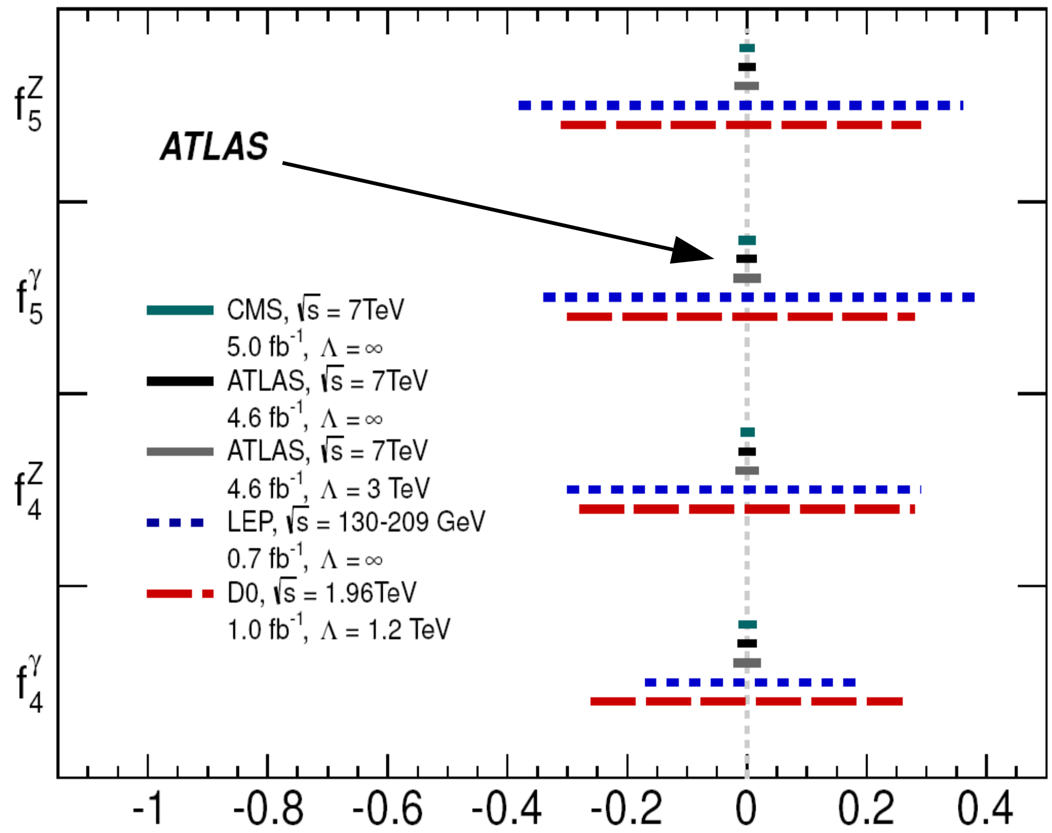
Limits are set using a maximum profile likelihood ratio

if 95% of pseudo experiments have larger profile likelihood ratio than actual experiment did, the nTGC value is rejected at 95% CL

Anomalous Triple Gauge Couplings

No deviation from the SM is observed.

LHC limits on the ZZ anomalous triple gauge couplings derived are the most stringent.



Couplings observed	f_4^γ	f_5^γ	f_4^Z	f_5^Z
	[-0.020,0.020]	[-0.017,0.017]	[-0.020,0.020]	[-0.017,0.017]

Conclusions

- pp-->ZZ total cross section measurement at $\sqrt{s}$= 7 TeV is consistent with SM prediction

- Measured unfolded differential distributions of **P_T^Z,m^{ZZ}** and **$\Delta\varphi^{(l,l)}$** are consistent with SM

- Limits on nTGC set using **P_T^Z** distribution measured with 4.64 fb^{-1} statistics show no deviation from SM prediction and are the most stringent so far

http://arxiv.org/abs/1211.6096

All the results will be published soon in JHEP

[hep-ex] 26 Nov 2012

CERN-PH-EP-2012-318

Submitted to: JHEP

Measurement of ZZ production in pp collisions at $\sqrt{s} = 7$ TeV and limits on anomalous ZZZ and $ZZ\gamma$ couplings with the ATLAS detector

BACKUP SLIDES

Cross section results

The profile likelihood function for the cross section is the product of a Poisson probability distribution (P) and Gaussian distribution function for each of the nuisance parameters (C_{ZZ} , A_{ZZ}, N^{bkg} , L) affected by a systematic uncertainty.

The Poisson function for the number of observed events N^{obs} is

$$P(\sigma, C_{ZZ}, N^{bkg}; N^{obs}) = \frac{e^{-(s(\sigma,C_{ZZ})+N^{bkg})} \cdot \left(s(\sigma, C_{ZZ}) + N^{bkg}\right)^{N^{obs}}}{N^{obs}!}$$

where the number of signal events is a function of the cross section, the background N^{bkg} and other quantities such as the integrated luminosity and correction factors.

For the total cross section

$$s(\sigma_{ZZ}^{\rm tot}, C_{ZZ}) = \sigma_{ZZ}^{\rm tot} \times C_{ZZ} \times A_{ZZ} \times \mathrm{BR_{comb}}(ZZ \to \ell^-\ell^+\ell^-\ell^+) \times \mathcal{L}$$

$BR_{comb} = 4 \times 0.033662^2 = 4.5 * 10^{-3}$

Anomalous Triple Gauge Couplings

Differential cross section has quadratic dependence on nTGC's

- **F_{00}: SM contribution**
- **F_{ij}: coefficients consisting of contributions from anomalous couplings (expected signal yield in each bin as a function of the nTGC parameter)**

$$
\begin{aligned}
d\sigma_{\mathrm{SM+TGC}} &= F_{00} + f_4^\gamma F_{01} + f_4^Z F_{02} + f_5^\gamma F_{03} + f_5^Z F_{04} \\
&+ (f_4^\gamma)^2 F_{11} + f_4^\gamma f_4^Z F_{12} + f_4^\gamma f_5^\gamma F_{13} + f_4^\gamma f_5^Z F_{14} \\
&+ \left(f_4^Z\right)^2 F_{22} + f_4^Z f_5^\gamma F_{23} + f_4^Z f_5^Z F_{24} \\
&+ (f_5^\gamma)^2 F_{33} + f_5^\gamma f_5^Z F_{34} \\
&+ \left(f_5^Z\right)^2 F_{44}
\end{aligned}
$$

- Yield coefficients in each pT bins are derived
- Sherpa MC generator sample with $f_4^\gamma = 0.0$, $f_5^\gamma = -0.1$ $f_4^Z = 0.0$ $f_5^Z = 0.0$ used to calculate the reweighted coefficients above

Anomalous Triple Gauge Couplings

Likelihood function: Poisson probability with Gaussian terms for nuisance parameters and N_{sig} expressed as functions of nTGC coefficients

$$L(\vec{x}, \vec{\beta}) = \prod_{i=1}^{m} P(N^i_{\mathrm{data}}, \mu^i(\vec{x}, \vec{\beta})) \times \frac{1}{(2\pi)^m} e^{-\frac{1}{2}\left(\vec{\beta}\cdot C^{-1}\cdot\vec{\beta}\right)},$$

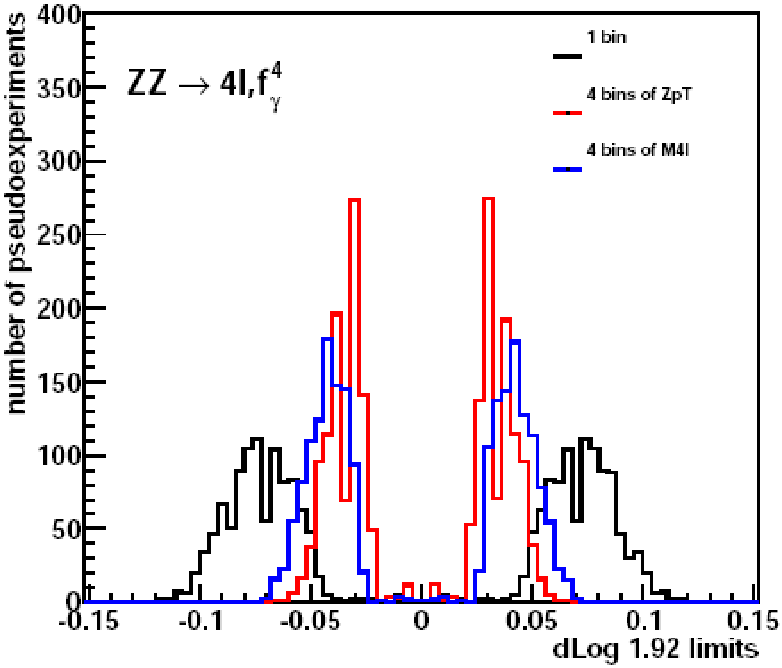
$$\mu^i(\vec{x}, \vec{\beta}) = N^i_{\mathrm{sig}}(\vec{x})(1 + \beta_i) + N^i_{\mathrm{bkg}}(1 + \beta_{i+m}).$$

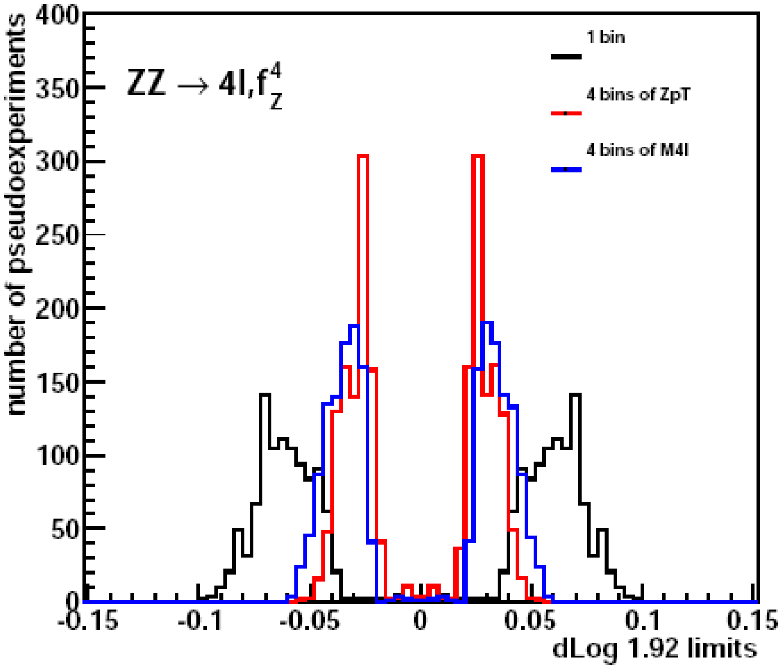
$$N_{\mathrm{sig}} = (Y_{\mathrm{SM}} + Y_{f_i^V} \cdot f_i^V + Y_{f_i^V f_i^V} \cdot (f_i^V)^2) \cdot \mathcal{L} \cdot C_{ZZ}.$$

Anomalous Triple Gauge Couplings

- Pseudo experiments are performed fluctuating the data around the oserved N_{events}

- Limits are calculated by setting deltaLog likelihood to 1.92





Anomalous Triple Gauge Couplings

	Couplings	f_4^γ	f_5^γ	f_4^Z	f_5^Z
No FF	expected	[-0.017,0.017]±0.0005	[-0.015,0.015]±0.0004	[-0.017,0.017]±0.0005	[-0.015,0.015]±0.0004
	observed	[-0.020,0.020]	[-0.017,0.017]	[-0.020,0.020]	[-0.017,0.017]
Λ_{FF}= 2 TeV	expected	[-0.038,0.038]±0.0010	[-0.031,0.032]±0.0008	[-0.039,0.038]±0.0010	[-0.032,0.032]±0.0008
	observed	[-0.044,0.044]	[-0.037,0.037]	[-0.045,0.045]	[-0.037,0.038]