Measurement of the ZZ(*) and Zγ production cross sections at 8 TeV and 13 TeV and limits on anomalous triple gauge couplings with the ATLAS detector

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and Related Subjects

ATLAS EXPERIMENT

Motivation

- Test electroweak sector of Standard Model
- Important background in studies of Higgs boson
- Sensitive to triple neutral-gauge boson couplings
  - Not allowed in SM

Cross Section Measurement Method

Measure the cross section in the detector's fiducial region...

$$\sigma^{fid}(pp \to ZZ \to 4l) = \frac{N_{obs} - N_{bkg}}{L \cdot C}$$

efficiency correction for detector effects
obtained by Monte Carlo
corrected by measured efficiencies in data

$$C = \frac{reconstructed\ events}{generated\ fiducial\ events}$$

… and then extrapolate to the full phase space

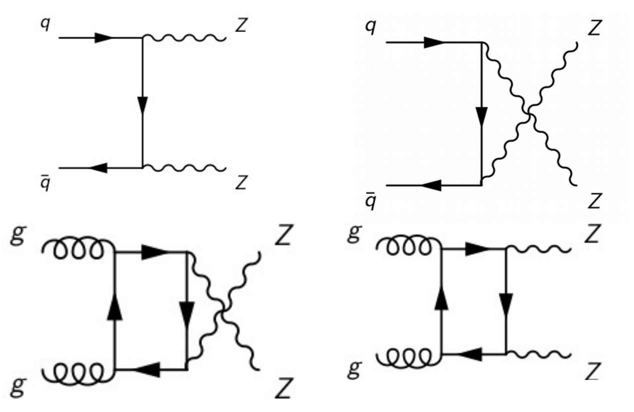
$$\sigma^{tot}(pp \to ZZ) = \frac{N_{obs} - N_{bkg}}{L \cdot BR \cdot C \cdot A}$$

branching ratio
correction

acceptance correction based on
kinematic and geometric selection
criteria

$$A = \frac{fiducial\ events}{total\ events}$$

ZZ@13TeV: Production & Event Selection



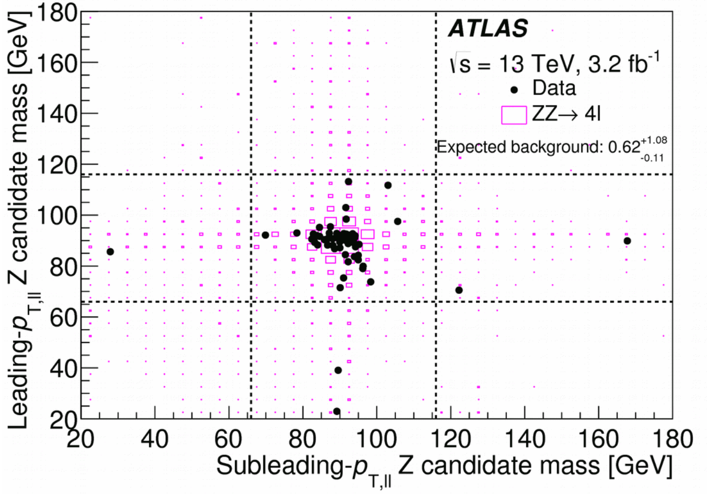
- Exactly four isolated ($\Delta R_{l,l} > 0.2$) prompt final state leptons (e,μ)
- All four leptons must have $p_T > 20$ GeV
- Electrons must satisfy $|\eta| < 2.47$
- At least one muon with $|\eta| < 2.4$, the remaining with $|\eta| < 2.7$
- 66 GeV < $|m_{ll}|$ < 116 GeV

$$\Delta R_{l,l} = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$$

For 4 leptons with the same flavor, select the pairs minimizing $|m_{1,2} - m_Z| + |m_{3,4} - m_Z|$

Observed events

Channel	Events
4e	15
2e2μ	30
4μ	18
Total	63



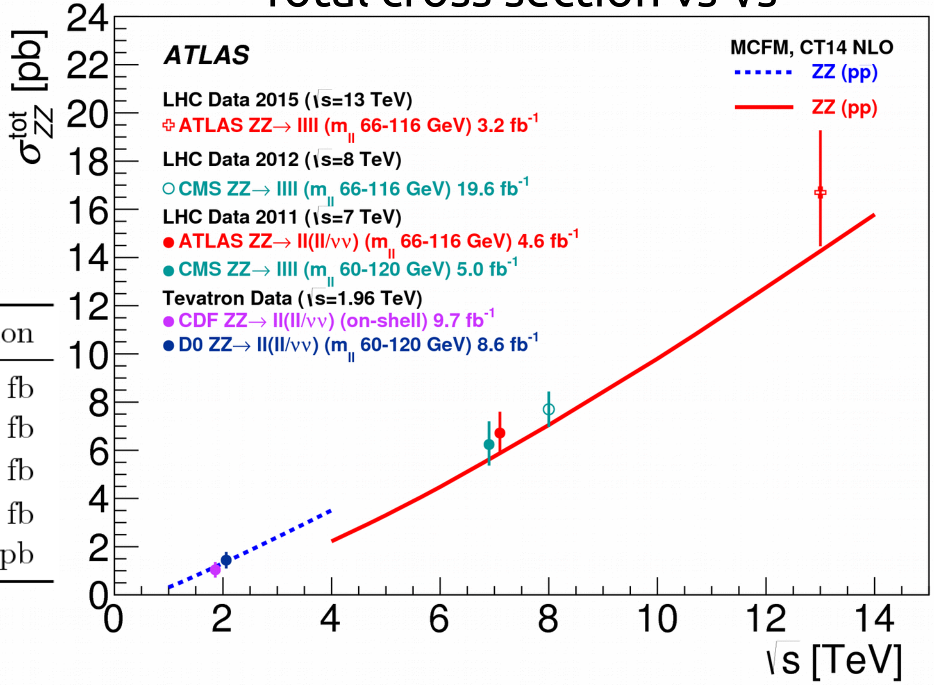
ZZ@13TeV: Cross Section

L = 3.2 fb^{-1}

- Maximum-likelihood fit.
- Signal and background yields treated as Poisson variables.
- Systematic uncertainties treated as Gaussian nuisance parameters.

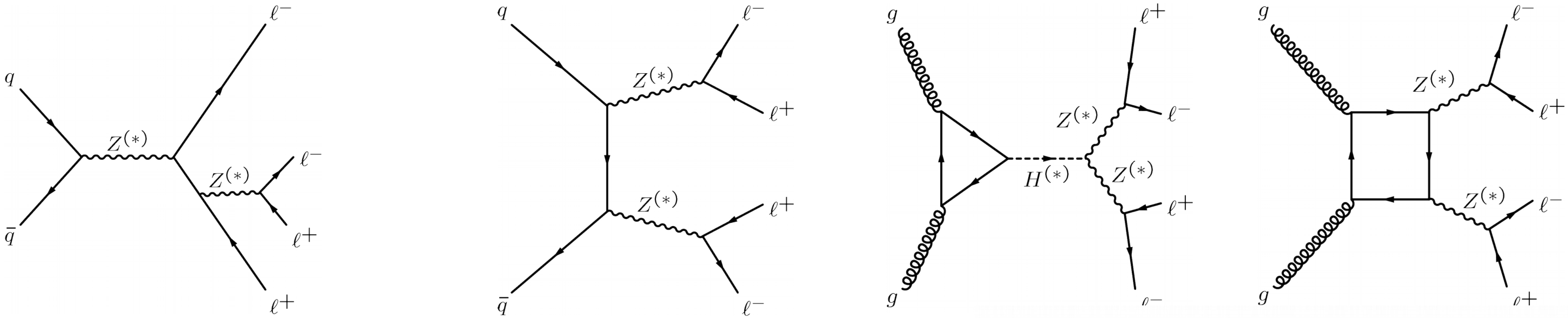
	Measurement	$\mathcal{O}(\alpha_s^2)$ prediction
$\sigma^{\text{fid}}_{ZZ\to e^+e^-e^+e^-}$	$8.4\ ^{+2.4}_{-2.0}(\text{stat.})\ ^{+0.4}_{-0.2}(\text{syst.})\ ^{+0.5}_{-0.3}(\text{lumi.})$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{\text{fid}}_{ZZ\to e^+e^-\mu^+\mu^-}$	$14.7\ ^{+2.9}_{-2.5}(\text{stat.})\ ^{+0.6}_{-0.4}(\text{syst.})\ ^{+0.9}_{-0.6}(\text{lumi.})$ fb	$13.6^{+0.4}_{-0.4}$ fb
$\sigma^{\text{fid}}_{ZZ\to \mu^+\mu^-\mu^+\mu^-}$	$6.8\ ^{+1.8}_{-1.5}(\text{stat.})\ ^{+0.3}_{-0.3}(\text{syst.})\ ^{+0.4}_{-0.3}(\text{lumi.})$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{\text{fid}}_{ZZ\to \ell^+\ell^-\ell'^+\ell'^-}$	$29.7\ ^{+3.9}_{-3.6}(\text{stat.})\ ^{+1.0}_{-0.8}(\text{syst.})\ ^{+1.7}_{-1.3}(\text{lumi.})$ fb	$27.4^{+0.9}_{-0.8}$ fb
σ^{tot}_{ZZ}	$16.7\ ^{+2.2}_{-2.0}(\text{stat.})\ ^{+0.9}_{-0.7}(\text{syst.})\ ^{+1.0}_{-0.7}(\text{lumi.})$ pb	$15.6^{+0.4}_{-0.4}$ pb

Total cross section vs √s

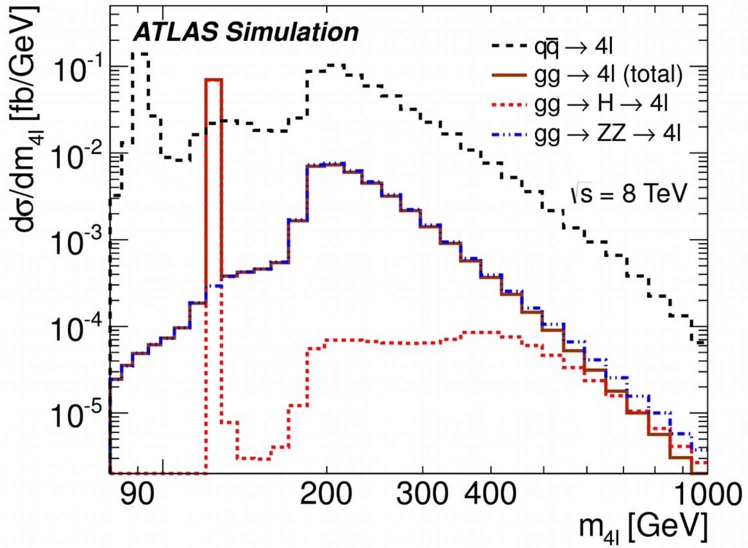


DOI: 10.1103/PhysRevLett.116.101801

4l@8TeV: Production & Event Selection



- Cross section measured in fiducial and extended phase space.
- Integrated luminosity for the analysis is 20.3 ifb.



4l@8TeV: Background composition & Yields

Background composition

Process	$4e$	4μ	$2e2\mu$
$t\bar{t}$	0.45 ± 0.24	0.68 ± 0.19	1.3 ± 0.5
$Z + \text{jets}$	0.6 ± 0.29	5.3 ± 1.5	6.3 ± 1.4
Diboson	1.25 ± 0.18	0.83 ± 0.18	2.84 ± 0.34
Triboson	0.67 ± 0.12	0.97 ± 0.14	1.46 ± 0.19
Z+top	0.62 ± 0.15	1.19 ± 0.32	1.7 ± 0.5

Derived from data-driven methods

Estimated from MC

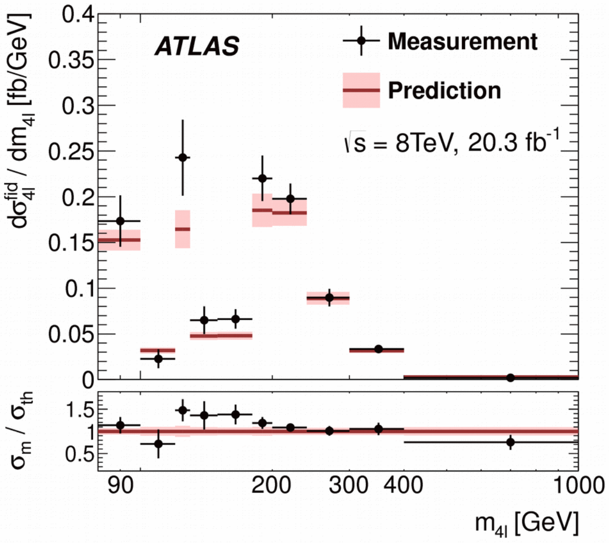
Yields

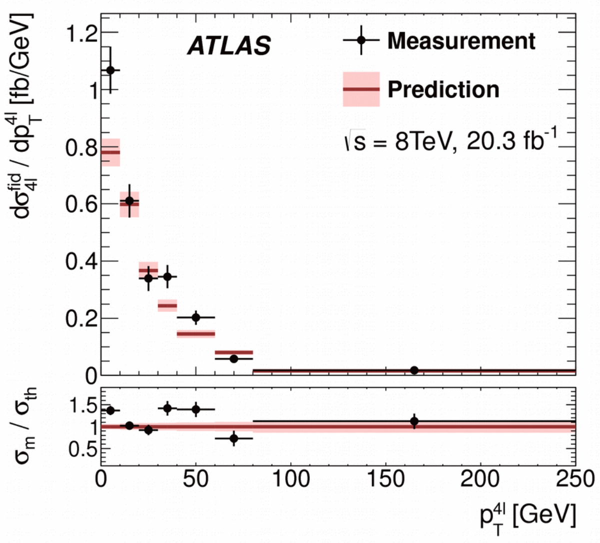
Channel	N^{Data}	$N^{\text{Total}}_{\text{expected}}$	$N^{\text{signal}}_{\text{non}-gg}$	N^{signal}_{gg}	N^{MC}_{τ}	N_{bkg}
$4e$	85	80 ± 4	68.4 ± 3.4	6.24 ± 0.31	1.28 ± 0.06	3.6 ± 0.5
4μ	156	150.2 ± 2.9	128.2 ± 2.5	11.00 ± 0.21	2.18 ± 0.09	9.0 ± 1.5
$2e2\mu$	235	205 ± 5	172 ± 5	16.0 ± 0.4	3.08 ± 0.13	13.6 ± 2.1
Total	476	435 ± 9	369 ± 9	33.3 ± 0.8	6.54 ± 0.14	26.2 ± 3.6

4l@8TeV: Cross Section

4ℓ	Measured $\sigma^{\rm fid}$ [fb]	SM $\sigma^{\rm fid}$ [fb]	Measured $\sigma^{\rm ext}$ [fb]	SM $\sigma^{\rm ext}$ [fb]
$4e$	$7.4^{+0.9}_{-0.8}$ (stat) $^{+0.4}_{-0.3}$ (syst) $^{+0.2}_{-0.2}$ (lumi)	6.9 ± 0.4	$17.8^{+2.1}_{-2.0}$ (stat) $^{+1.5}_{-1.1}$ (syst) $^{+0.5}_{-0.5}$ (lumi)	16.4 ± 1.0
4μ	$8.7^{+0.8}_{-0.7}$ (stat) $^{+0.2}_{-0.2}$ (syst) $^{+0.3}_{-0.2}$ (lumi)	8.3 ± 0.5	$17.3^{+1.5}_{-1.4}$ (stat) $^{+0.9}_{-0.7}$ (syst) $^{+0.5}_{-0.5}$ (lumi)	16.4 ± 1.0
$2e2\mu$	$15.9^{+1.1}_{-1.1}$ (stat) $^{+0.5}_{-0.4}$ (syst) $^{+0.5}_{-0.4}$ (lumi)	13.7 ± 0.9	$37.7^{+2.7}_{-2.6}$ (stat) $^{+2.5}_{-2.0}$ (syst) $^{+1.1}_{-1.1}$ (lumi)	32.1 ± 2.0
Total			73^{+4}_{-4} (stat) $^{+4}_{-4}$ (syst) $^{+2}_{-2}$ (lumi)	65 ± 4

Differential cross section performed in fiducial phase space.
Iterative Bayesian unfolding.





DOI: 10.1016/j.physletb.2015.12.048

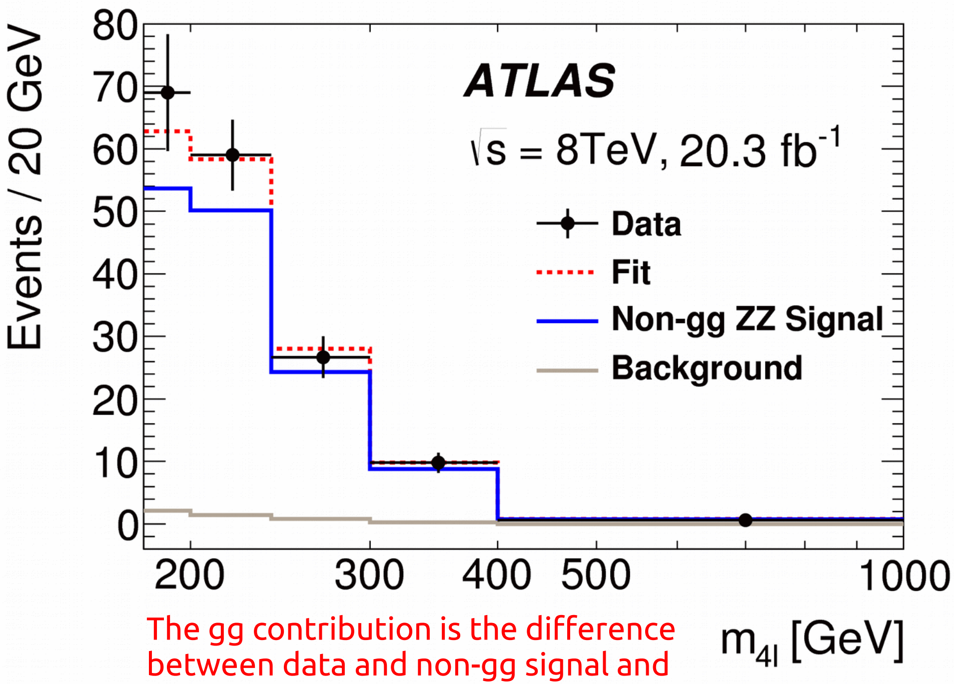
gg → 4l Signal Contribution in m_{4l} > 180 GeV region

- Above m_{4l} > 180 GeV, gg → 4l is dominated by the continuum gg → ZZ → 4l process.
- m_{4l} is used as thediscriminant w.r.t. LO prediction: $\mu_{gg} = \frac{\sigma(data)}{\sigma(LO)}$
- Extracted from likelihood fit using reconstructed m_{4l} distributions.
- Uncertainties treated as fully correlated between gg and qq processes.

Result:

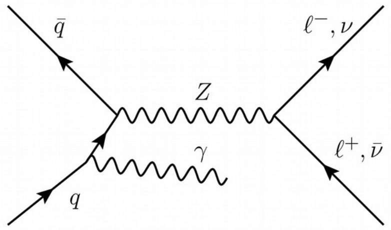
μ_{gg} = 2.4±1.0(stat.)±0.5(syst.)±0.8(theory)

Corresponds to gg-initiated cross section of 3.1fb.
Same relative uncertainties as μ_{gg} in fiducial volume including m_{4l} > 180 GeV.



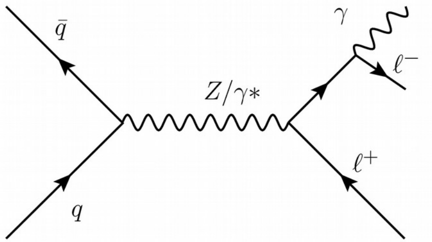
The gg contribution is the difference between data and non-gg signal and background

Zγ@8TeV: Production & Event Selection



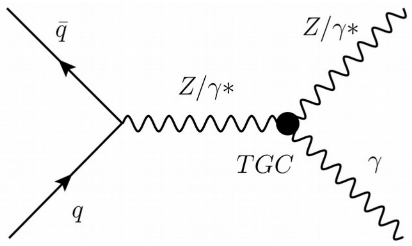
$l^+l^-\gamma$

- Same flavor, opposite-charge isolated leptons
- Isolated photon with $E_T^\gamma > 15$ GeV
- $m_{ll} > 40$ GeV
- Lepton-photon separation:
  - $\Delta R > 0.7$



$\nu\bar{\nu}\gamma$

- $E_T^{miss} > 100$ GeV
- $E_T^\gamma > 130$ GeV
- $|\Delta\phi(p_T^{miss}, \gamma)| > \pi/2$

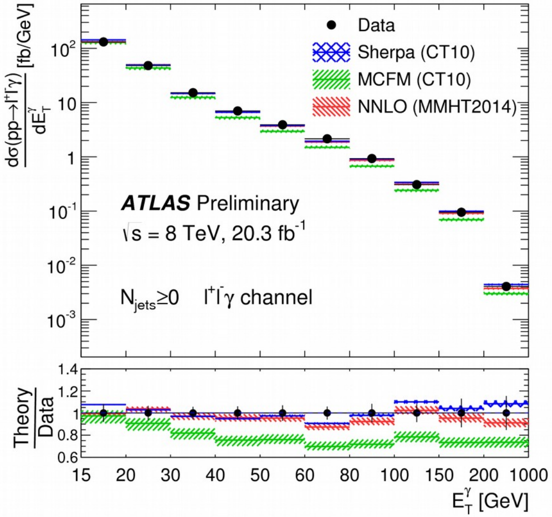


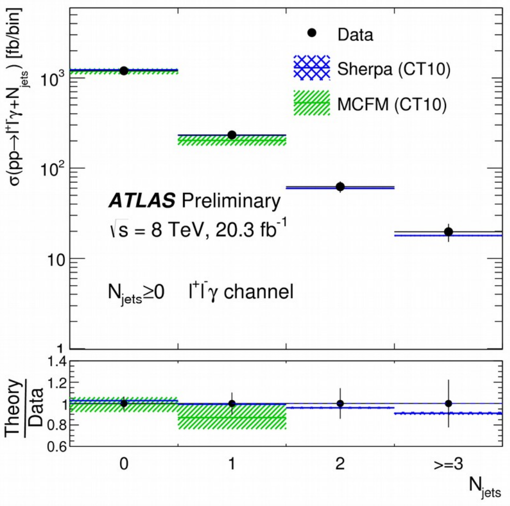
Inclusive events: No requirements on jets (Unconstrained hadronization)
Exclusive events: count jets with $E_T > 30$ GeV, $|\eta|<4.5$,
and classify events w.r.t Njets.

Zγ@8TeV: Background Composition

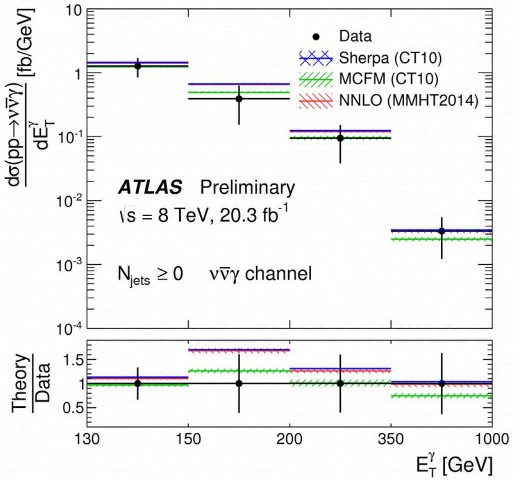
- $l^+l^-\gamma$ Background:
  - Dominated by hadronic jets misidentified as prompt photons.
    - Estimated using Data driven methods
  - Smaller backgrounds originate from ττγ, WZ, $t\bar{t}\gamma$
    - Estimated from simulation
- $\nu\bar{\nu}\gamma$ Background:
  - Mismeasured jet momenta
  - Wγ
  - Real E_T^{miss}, misidentified photons from jets

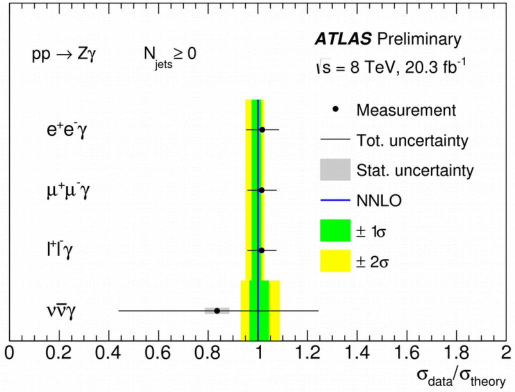
Zγ@8TeV: Cross Section Measurement

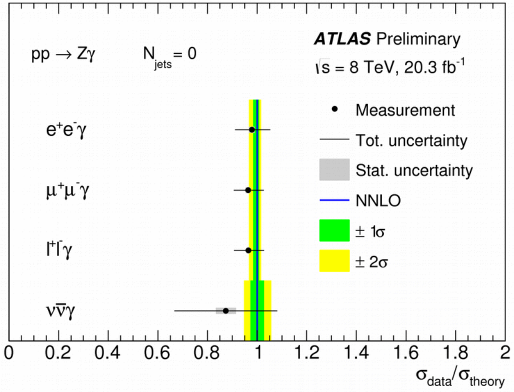




l+l-γ

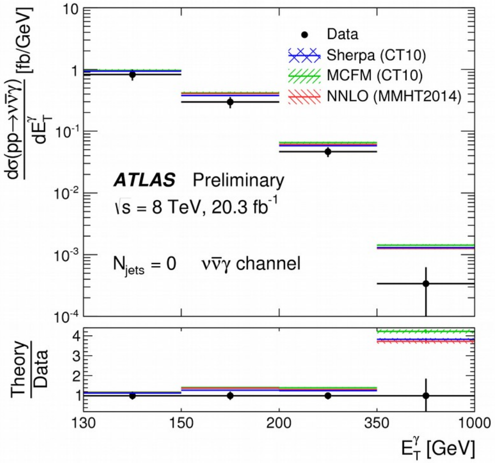




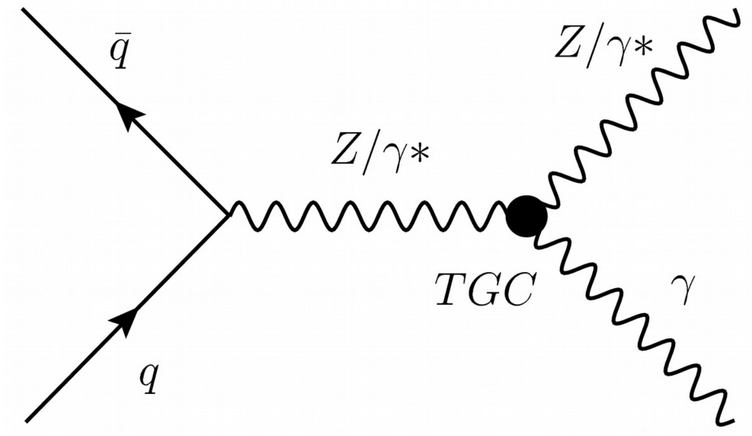


$\nu\bar{\nu}\gamma$

First ATLAS measurement for this channel



Anomalous Triple Gauge Couplings (aTGC)



- ATGCs for Zγ production can be parametrized by four CP-violating (h_1^V, h_2^V) and four CP-conserving (h_3^V, h_4^V) complex parameters where V = Z, γ.
- SM prediction for the parameters is 0.
- Limits from this study are expressed in terms of the CP-conserving h_3^γ, h_4^γ, h_3^Z, h_4^Z.
  - The aTGC contribution to the cross section is expressed as second order polynomial of these couplings.
- Limits set for Λ = ∞ and Λ = 4 TeV.

$$h_3^V = \frac{h_{30}^V}{\left(1+\frac{s}{\Lambda^2}\right)^n}$$

Λ is the scale at which contributions from new physics become observable

ZZ example:

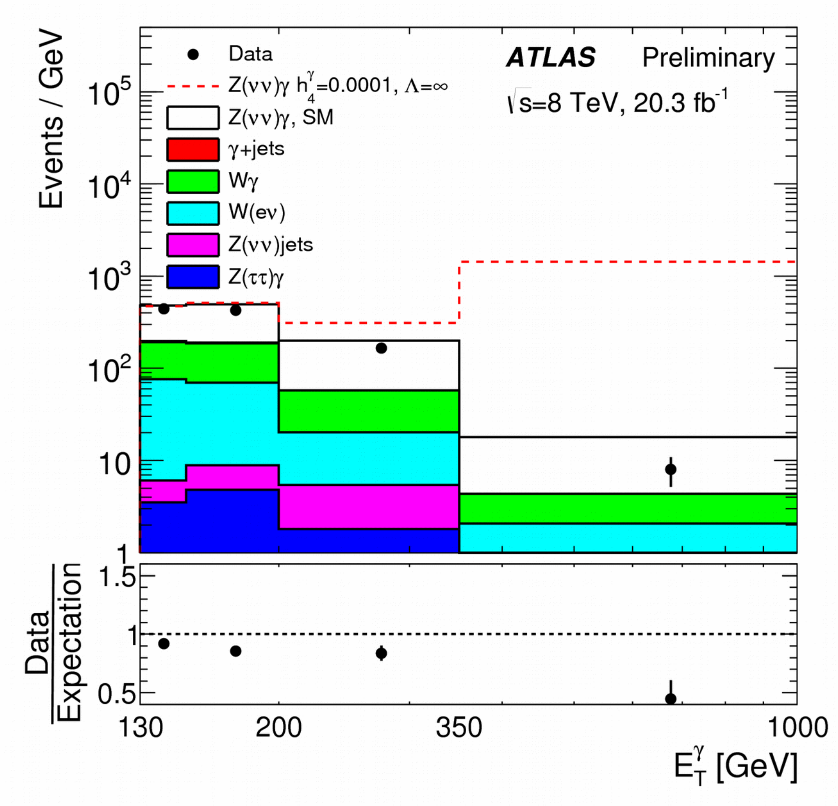
SM

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

- Exclusive, zero-jet selection used to set the limits.

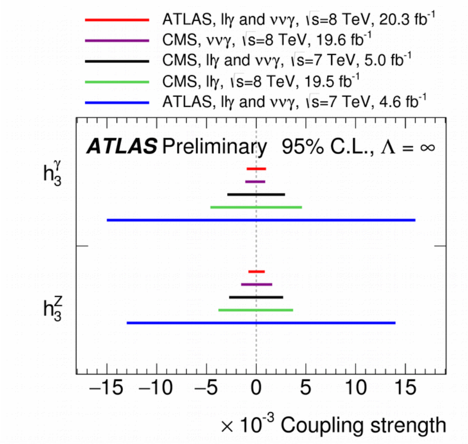
Zγ@8 TeV Comparison of SM with aTGC

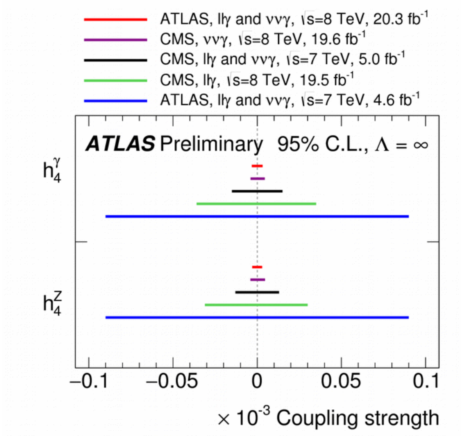
Photon transverse energy for exclusive $\nu\bar{\nu}\gamma$ events.



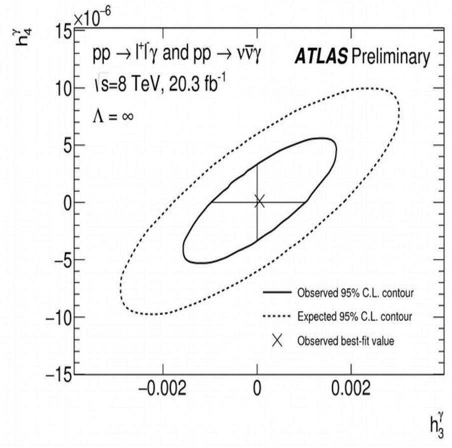
aTGC inclusion increases the yield in the high E_t^{γ} region.

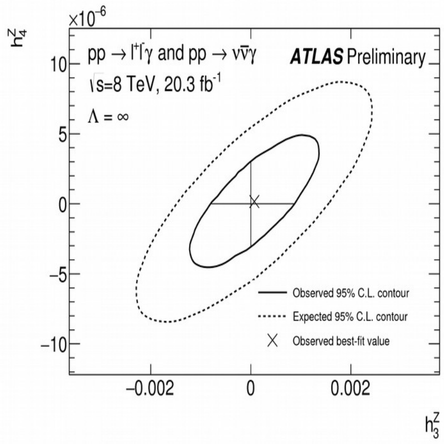
Limits on ZZγ (h_3^Z, h_4^Z) and Zγγ (h_3^γ, h_4^γ) aTGCs

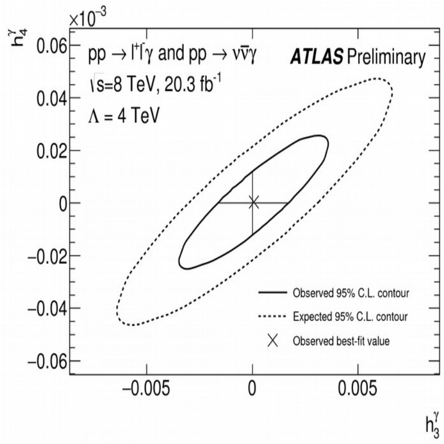


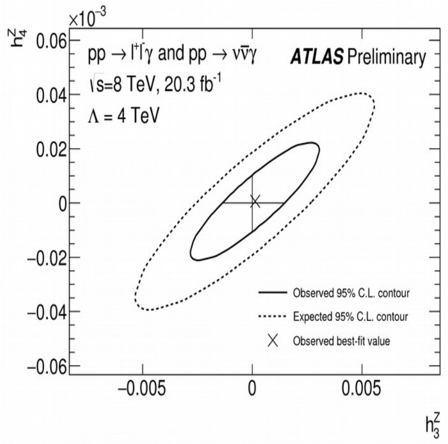


ATLAS Limits at 8TeV:
Best limits to date









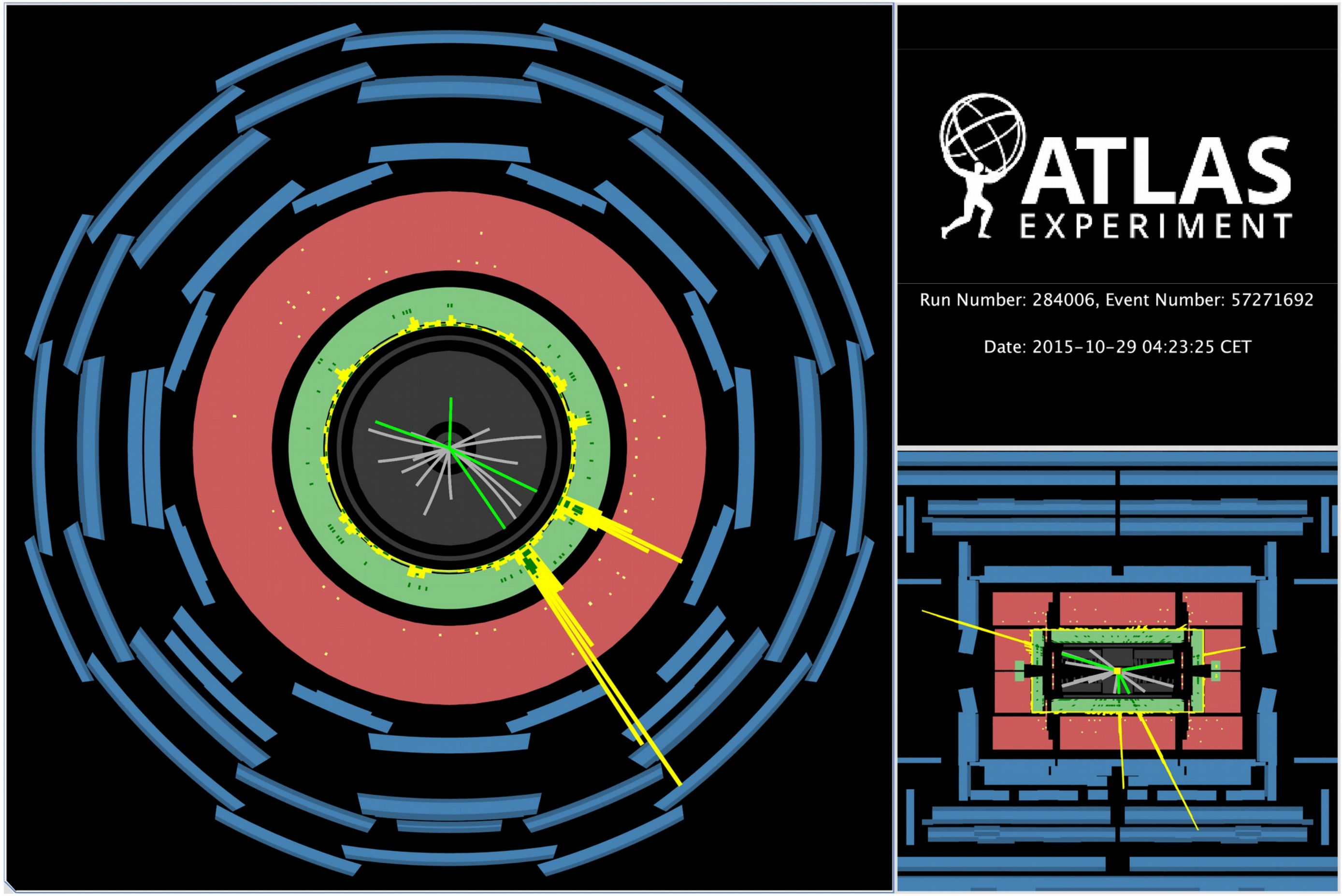
Conclusions

- ZZ production cross section measured at 13 TeV (3.2 fb^{-1}).
  - Total uncertainty ~15%, statistically dominated.
  - Agreement with NNLO SM prediction.
- 4l production cross section measured at 8 TeV (20.3 fb^{-1}).
  - $\sigma_{tot} = 73 \pm 4 \pm 4 \pm 2$ fb
  - Compatible with SM prediction of 65 ± 4 fb
- Zγ production cross section measured at 8 TeV (20.3 fb^{-1}).
  - Measurement compatible with the NNLO SM prediction.
- No deviation from SM predictions → aTGC limits on Zγ production.
  - Most stringent limits to date.

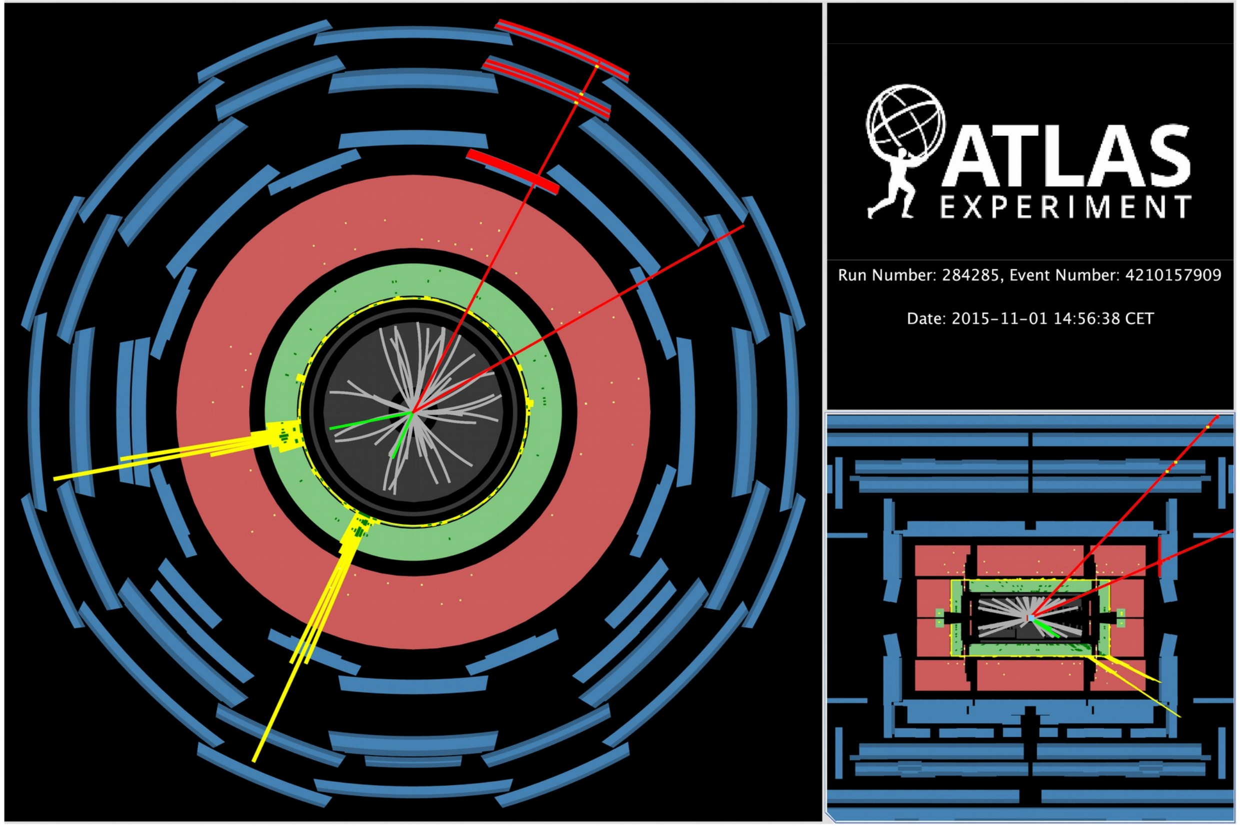
Measurement of the ZZ production cross section in pp collisions at sqrt(s)=13 TeV with the ATLASw detector	arXiv:1512.05314
Measurements of four-lepton production in pp collisions at √ s = 8 TeV with the ATLAS detector	arXiv:1509.07844

Backup Slides

ZZ → 4e candidate event



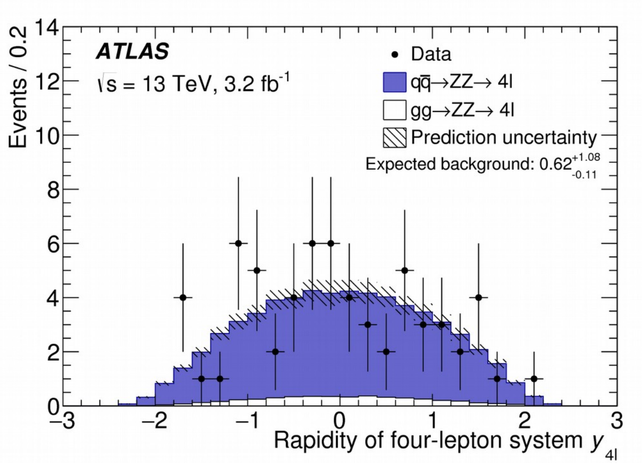
ZZ at 13 TeV Event Display & Background

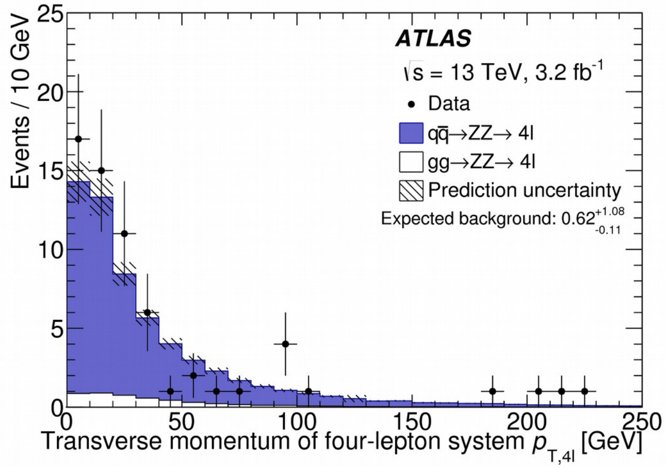


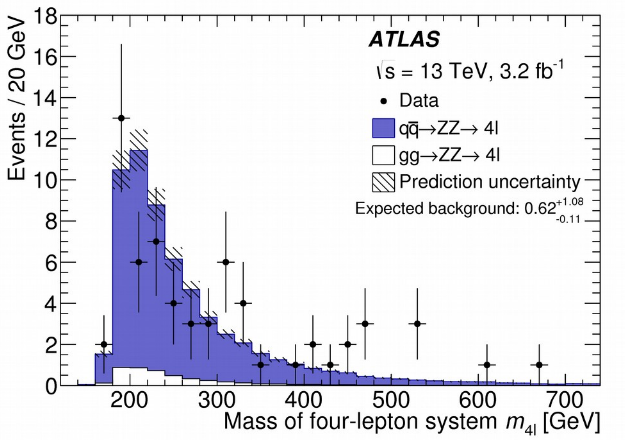
Main background sources:

- ZZ$\rightarrow$ 2l2τ, 4τ
- Nonhadronic triboson processes
- Lepton misidentification

ZZ at 13 TeV 4l Kinematics







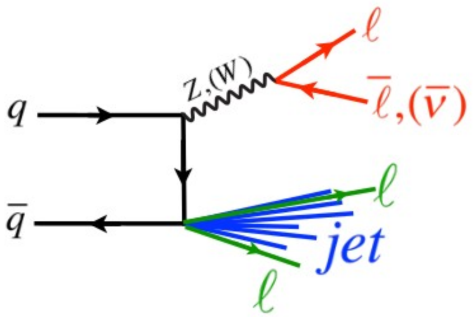
ZZ at 13 TeV Background Composition & Yields

Background process	Expected events
$ZZ \rightarrow 2\ell 2\tau, 4\tau$	0.07 ± 0.02
ZZZ, WZZ, WWZ	0.17 ± 0.05
$t\bar{t}Z$	0.30 ± 0.09
1–2 misidentified leptons*	$0.09^{+1.08}_{-0.04}$
Total	$0.62^{+1.08}_{-0.11}$

Estimated from MC

Derived from data-driven methods

Dominated by small number of events in control samples



Yields

Channel	4e	2e2μ	4μ	Total 4ℓ
Observed	15	30	18	63
Expected background	0.20 ± 0.05	$0.25^{+0.40}_{-0.05}$	$0.17^{+1.00}_{-0.04}$	$0.62^{+1.08}_{-0.11}$

ZZ at 13 TeV Efficiency & Acceptance

$$\sigma^{tot} = \frac{N_{obs} - N_{bkg}}{L \cdot BR \cdot C \cdot A}$$

C_{zz} corrects measured cross section for detector effects

	4e	2e2μ	4μ
C_{ZZ}	0.55 ± 0.02	0.63 ± 0.02	0.81 ± 0.03

C_{ZZ} Uncertainties

Source	4e	2e2μ	4μ
Statistical	0.7	0.5	0.5
Theoretical	2.5	2.5	2.5
Experimental efficiencies	2.3	2.2	2.0
Momentum scales and resolutions	0.4	0.2	0.1
Total	3.5	3.3	3.2

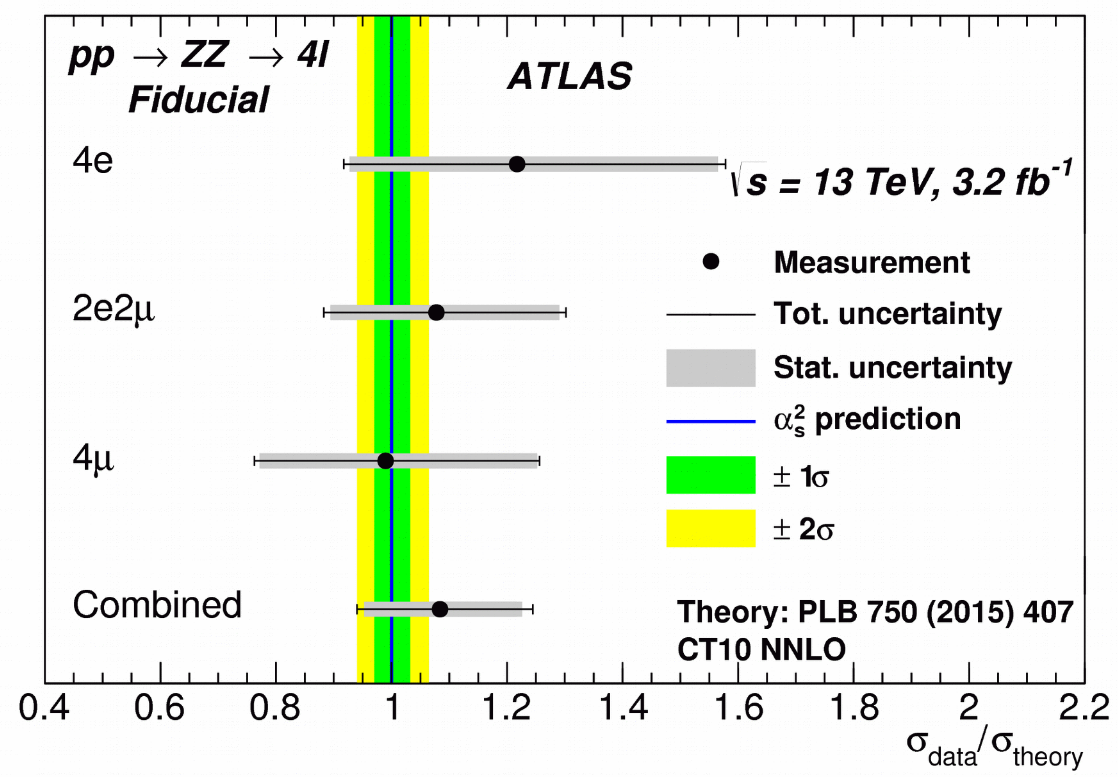
A_{zz} extrapolates fiducial cross section to total cross section

$A_{ZZ} = 0.39 \pm 0.02$
for all channels

A_{ZZ} Uncertainties

Source	Uncertainty
Statistical	0.9
Generator	3.4
Parton shower	0.8
PDFs	0.8
QCD scales	0.3
Total	3.7

ZZ at 13 TeV Fiducial Cross Section Results



4l at 8TeV Fiducial and Extended Phase Space

Fiducial Phase Space

Lepton selection	
Muons:	$p_T > 6$ GeV, $\|\eta\| < 2.7$
Electrons:	$p_T > 7$ GeV, $\|\eta\| < 2.5$
Lepton pairing	
Leading pair:	SFOS lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Sub-leading pair:	The remaining SFOS with the largest $m_{\ell\ell}$
For both pairs:	$p_T^{\ell^+\ell^-} > 2$ GeV
Event selection	
Lepton $p_T^{\ell_1,\ell_2,\ell_3}$:	$> 20, 15, 10 (8 \text{ if } \mu)$ GeV
Mass requirements:	$50 < m_{12} < 120$ GeV $12 < m_{34} < 120$ GeV
Lepton separation:	$\Delta R(\ell_i, \ell_j) > 0.1$ (0.2) for same- (different-) flavour leptons
J/ψ veto:	$m(\ell_i^+, \ell_j^-) > 5$ GeV
4ℓ mass range:	$80 < m_{4\ell} < 1\,000$ GeV

Extended phase space

- $80 < m_{4l} < 1000$GeV
- $m_{ll} > 4$ GeV
- $P_T^Z > 2$ GeV
- Four leptons with $p_T > 5$ GeV and $|\eta| < 2.8$

Common phase space where electrons and muons have the same geometric and kinematic acceptance

4l at 8 TeV Efficiency & Acceptance

$$\sigma^{ext} = \frac{N_{obs} - N_{bkg}}{L \cdot BR \cdot C \cdot A}$$

	4e	2e2μ	4μ
C_{4l}	53.3%	67.7%	82.2%

C_{ZZ} Uncertainties

Sources	$\Delta C_{4\ell}/C_{4\ell}$ 4e	4μ	$2e2\mu$
Experimental (e)	4.8%	-	2.3%
Experimental (μ)	-	1.8%	0.9%
Theoretical	0.1%	0.1%	0.2%
Extra gg corrections	0.6%	0.2%	0.3%
Combined uncertainty	4.9%	1.9%	2.5%

	4e	2e2μ	4μ
A_{4l}	41.6%	42.2%	50.3%

A_{ZZ} Uncertainties

Sources	$\Delta A_{4\ell}/A_{4\ell}$ 4e	4μ	$2e2\mu$
Theoretical	1.2%	1.0%	1.6%
Extra gg corrections	4.0%	3.0%	3.9%
	$\Delta(A_{4\ell} \times C_{4\ell})/(A_{4\ell} \times C_{4\ell})$		
Theoretical	1.4%	1.1%	1.7%
Extra gg corrections	4.6%	3.2%	4.2%

Particle reconstruction for ZZ

- Muons
  - Matching a track in the MS to a track in ID.
  - Momentum calculated by combining information on the two systems, correcting for energy deposition in the calorimeter.
  - For limited coverage regions, match calorimeter signal consistent with muons to ID tracks
- Electrons
  - Matching energy deposition in calorimeter with ID track.
  - Algorithm uses several identification criteria relying on shapes of EM showers.

ZZ(*) Signal Simulation

- POWHEG-BOX MC for qqbar, ggF and VBF
  - Includes perturbative QCD corrections at NLO
  - qg initial state and NLO contribution to qqbar process
- PYTHIA8 for VH and ttbarH
- MFCM (LO) for non-resonant ggF
- MADGRAPH (LO) for non-resonant VBF and VBS