Measurement of the ZZ production cross section in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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XXII Epiphany Conference · Cracow, Poland · 7–9 January 2016

In short

Measure fiducial inclusive cross section for ZZ at $\sqrt{s} = 13$ TeV in the four-lepton channel, using 3.2 fb^{-1} of data

$\ell = e, \mu$

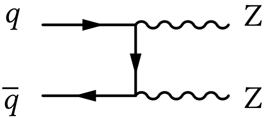
Also extrapolate to 'total' phase space and all Z boson decays

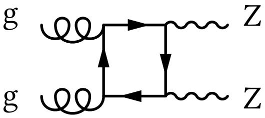
Leptonically decaying Z is not strictly separable from γ^*
$\rightarrow$ "Z" $\equiv Z/\gamma^*$ with mass between 66–116 GeV

(CMS uses 60–120 GeV)

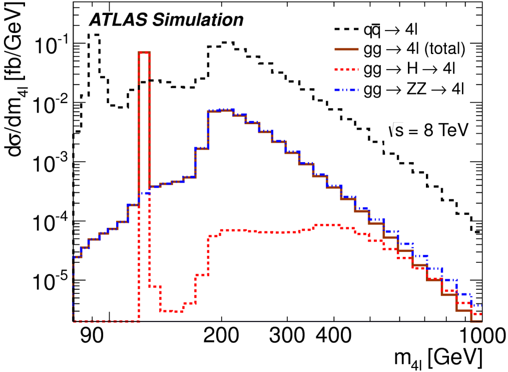
Paper: [1512.05314] (submitted to PRL)

ZZ production at the LHC





Predicted four-lepton mass spectrum at 8 TeV [1509.07844]:

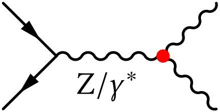


Why measure ZZ?

Standard Model test at 13 TeV

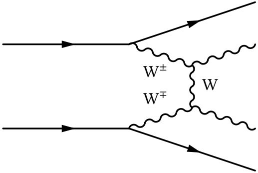
Appears in Higgs and new-physics analysis background and/or sidebands

Limits on anomalous gauge couplings:



red blob vertex forbidden in SM

Towards vector boson scattering:



ZZ $\rightarrow 4\ell$ channel

Advantage: extremely clean

tiny background

excellent Z mass resolution

Disadvantage: small cross section

$0.45\% \times 15.6$ pb (NNLO) $\approx$ 70 fb

$$\sigma_{pp\to ZZ} = \frac{N_{\mathrm{data}} - N_{\mathrm{background}}}{L\; BR_{ZZ\to 4\ell}\; A_{ZZ}\; C_{ZZ}}$$

Number of events passing signal selection

Predicted number of background events

Integrated luminosity

Leptonic branching ratio

Extrapolation from measurement to full phase space

Correction for detector effects

Fiducial lepton definition

Generator-level

Prompt final-state muons and electrons

'Dressing' to account for Bremsstrahlung: add four-momenta of prompt photons within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.1$

$p_\perp > 20$ GeV

$|\eta| < 2.7$

Reconstructed

Lepton identification

Electrons: electromagnetic calorimeter deposits + tracking info
Muons: tracking and/or muon spectrometer info, calorimeter signature consistent with muon

$p_\perp > 20$ GeV

$|\eta| < 2.47$ (electrons) or 2.7 (muons)

Associated with primary vertex

Transverse impact parameter significance $|d_0 / \sigma(d_0)| < 3$
Longitudinal impact parameter $|z_0 \sin\theta| < 0.5$ mm (z_0 w.r.t. primary vertex)

Isolated from other tracks/energy deposits

Event selection

Same for fiducial and reconstructed
except for some reconstruction quality requirements

Exactly 4 leptons in 2 same-flavour, opposite-charge pairs

$\Delta R_{\ell\ell} > 0.2$

If 4 same-flavour leptons, form pairs such that
$|m_{12} - m_Z| + |m_{34} - m_Z|$ is minimised

Z candidate selection: $66 \text{ GeV} < m_{12}, m_{34} < 116 \text{ GeV}$

In reconstructed: single-muon or dielectron trigger matched by selected leptons, hard-scattering vertex, and at most 1 muon without inner-detector or muon-system track (*standalone*, *calorimeter-tagged*)

Considered backgrounds

Four genuine prompt leptons

$ZZ \rightarrow [4\tau,\ 2\tau 2\ell] \rightarrow 4\ell$ + neutrinos
ZZZ, WZZ, WWZ
$t\bar{t}Z$
— from simulation

1–2 nonprompt or misidentified leptons

{Z, WZ, WW} + jets
$t\bar{t}$
…
— data-driven estimate

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	$0.62^{+1.08}_{-0.11}$

* Derived using data-driven method

Yields

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

Correction factor C_{ZZ}

Corrects measured cross section for detector effects

$$C_{ZZ} \equiv \frac{\text{selected reconstructed events}}{\text{fiducial events}}$$

Determined using simulated signal samples

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

Relative uncertainties in %:

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

Extrapolation factor A_{ZZ}

Extrapolates fiducial cross section to total phase space

$$A_{ZZ} \equiv \frac{\text{fiducial events}}{\text{on-shell events}} \approx 0.39 \pm 0.2$$

Determined using simulated signal samples

Relative uncertainties in %:

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

Cross section extraction

Maximum-likelihood fits:

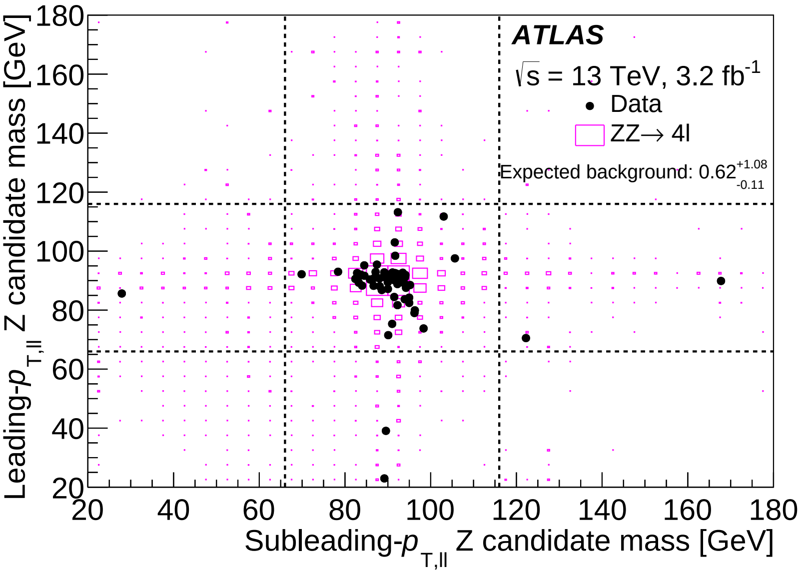
- Fiducial per-channel cross sections
- Fiducial combined cross section
- Total combined cross section

Signal and background yields treated as Poisson variables

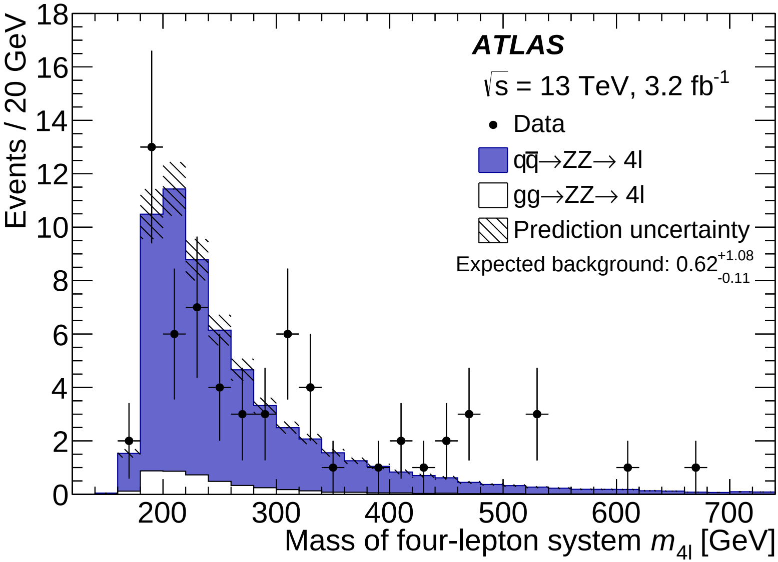
Systematic uncertainties treated as Gaussian nuissance parameters

Signal kinematics

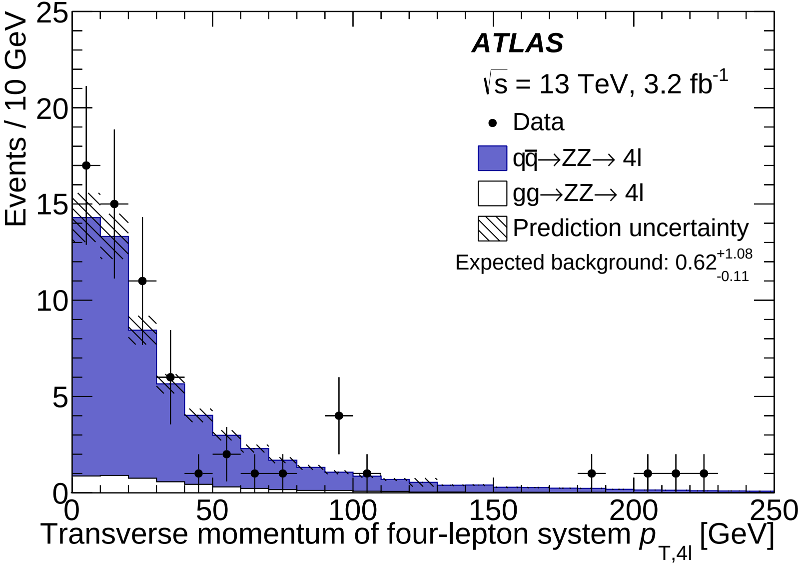
Dilepton masses (before on-shell requirement)



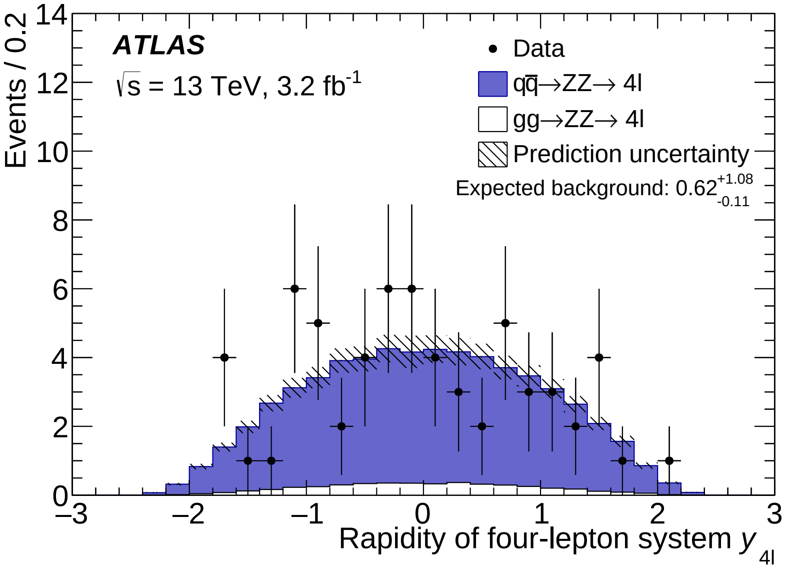
Four-lepton mass



Four-lepton $p_\perp$



Four-lepton rapidity



Results

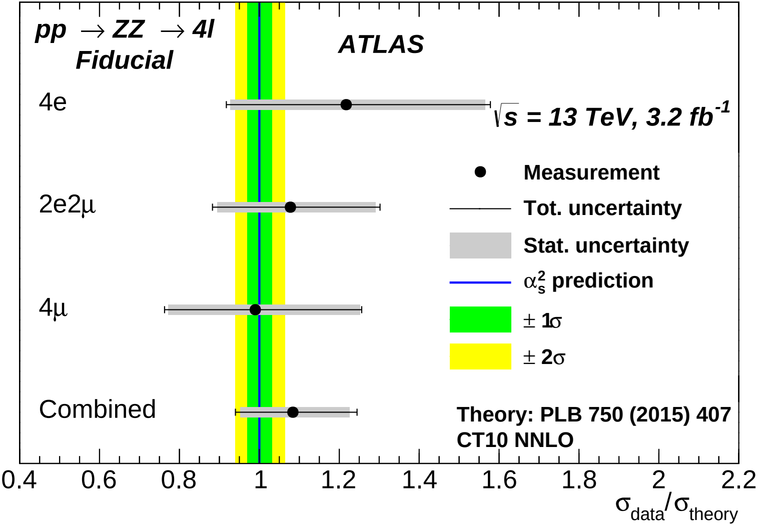
Fiducial and total cross sections

	Measurement	NNLO 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

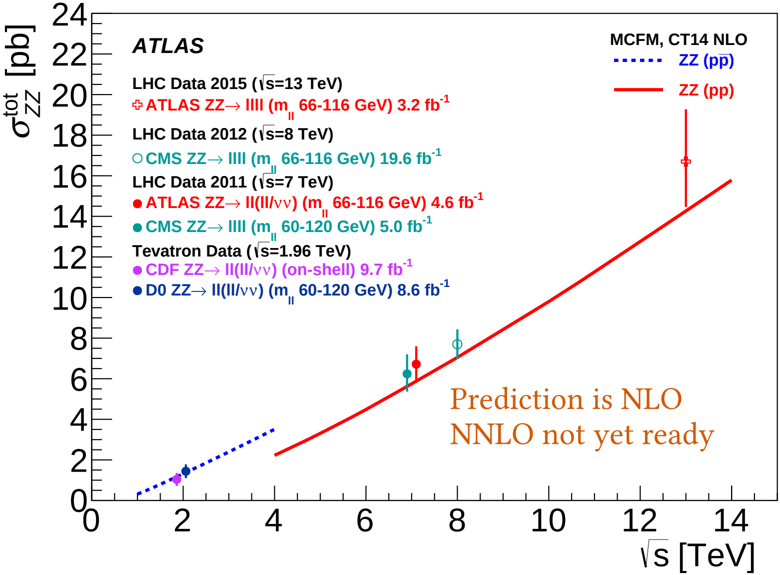
Theory prediction: [1507.06257]

Fiducial cross-section predictions include fiducial acceptance correction for final-state photon radiation (lowers by ~4%)

Theory comparison (fiducial)



Total cross section vs. $\sqrt{s}$



Conclusions

ZZ production cross section measured at $\sqrt{s} = 13$ TeV

Total uncertainty ca. 15%, statistically dominated

Agreement with NNLO Standard Model prediction

Starting to be sensitive to gg-initiated loop-induced production!

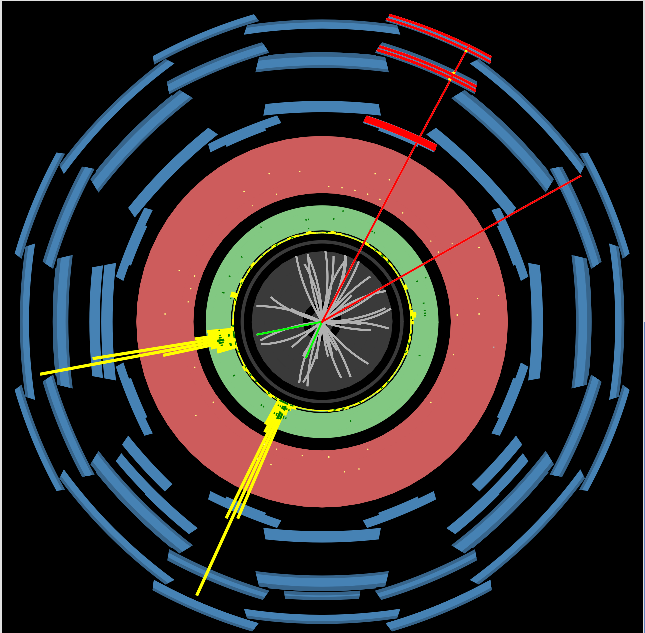
Future goals with more data:

- differential cross sections
- limits on anomalous gauge couplings
- …

Thank you! Questions?

Backup

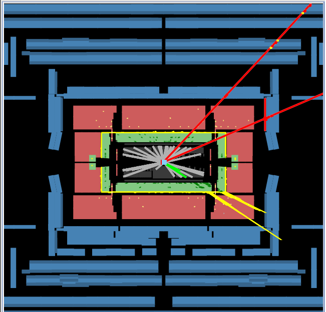
Candidate event (dilepton masses 95 and 88 GeV)



ATLAS EXPERIMENT

Run Number: 284285, Event Number: 4210157909

Date: 2015-11-01 14:56:38 CET



Theory considerations

Double parton scattering (~1%) included in measurement but not in prediction

NLO corrections to loop-induced process could *increase* prediction by ~4–5% [1509.06734]

NLO-α electroweak corrections could *decrease* prediction by ~7–8% [1305.5402], [Biedermann, Denner, Dittmaier, Hofer, Jäger; to be submitted]

Monte Carlo signal samples

Powheg + Pythia 8: ZZ + 0 jets @ NLO

Sherpa: ZZ + 0-1 jets @ NLO + 2-3 jets @ LO

Sherpa: gg $\rightarrow$ ZZ + 0-1 jets @ LO