Measurement of the ZZ production cross section at 13 TeV with the ATLAS detector

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Stefan Richter (UCL, CERN)
Jonatan Rosten (Cambridge)

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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

"Z" = Z/γ^* with mass between 66–116 GeV (CMS uses 60–120 GeV)

ℓ = e, μ

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

Paper: Phys. Rev. Lett. 116, 101801 (2016)

Introduction

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Motivations:

- Good test of the electroweak sector of the Standard Model at unprecedented energy
- Important background to searches for rare multilepton final states (like H⟶ZZ)
- First step towards differential cross sections, aTGCS, etc.

Introduction

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Two examples of important Feynman diagrams

Three leptonic channels: 4e, 2e2μ, 4μ
Clean channel, small backgrounds
Small cross section: statistically limited

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

$|\eta| < 2.7$

Lepton selection

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

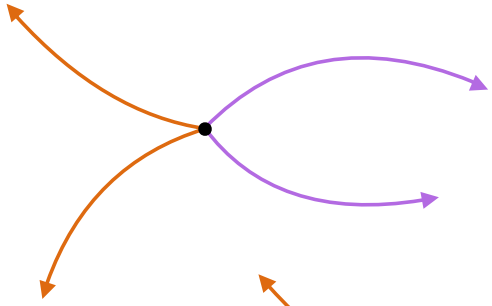
Transverse impact parameter significance $|d_0 / \sigma(d_0)| < 5$ (electrons) or 3 (muons)
Longitudinal impact parameter w.r.t. primary vertex $|z_0 \sin\theta| < 0.5$ mm

Isolated from other tracks/energy deposits

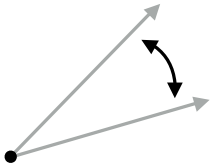
Event selection

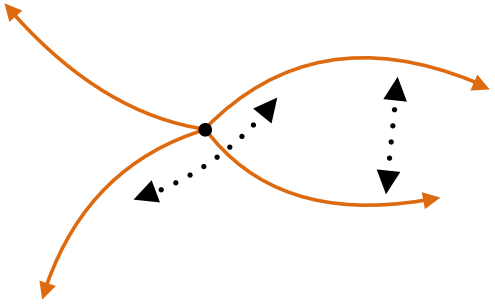
Same for fiducial and reconstructed
except for some reconstruction quality requirements

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*)

Candidate event (dilepton masses 95 and 88 GeV)

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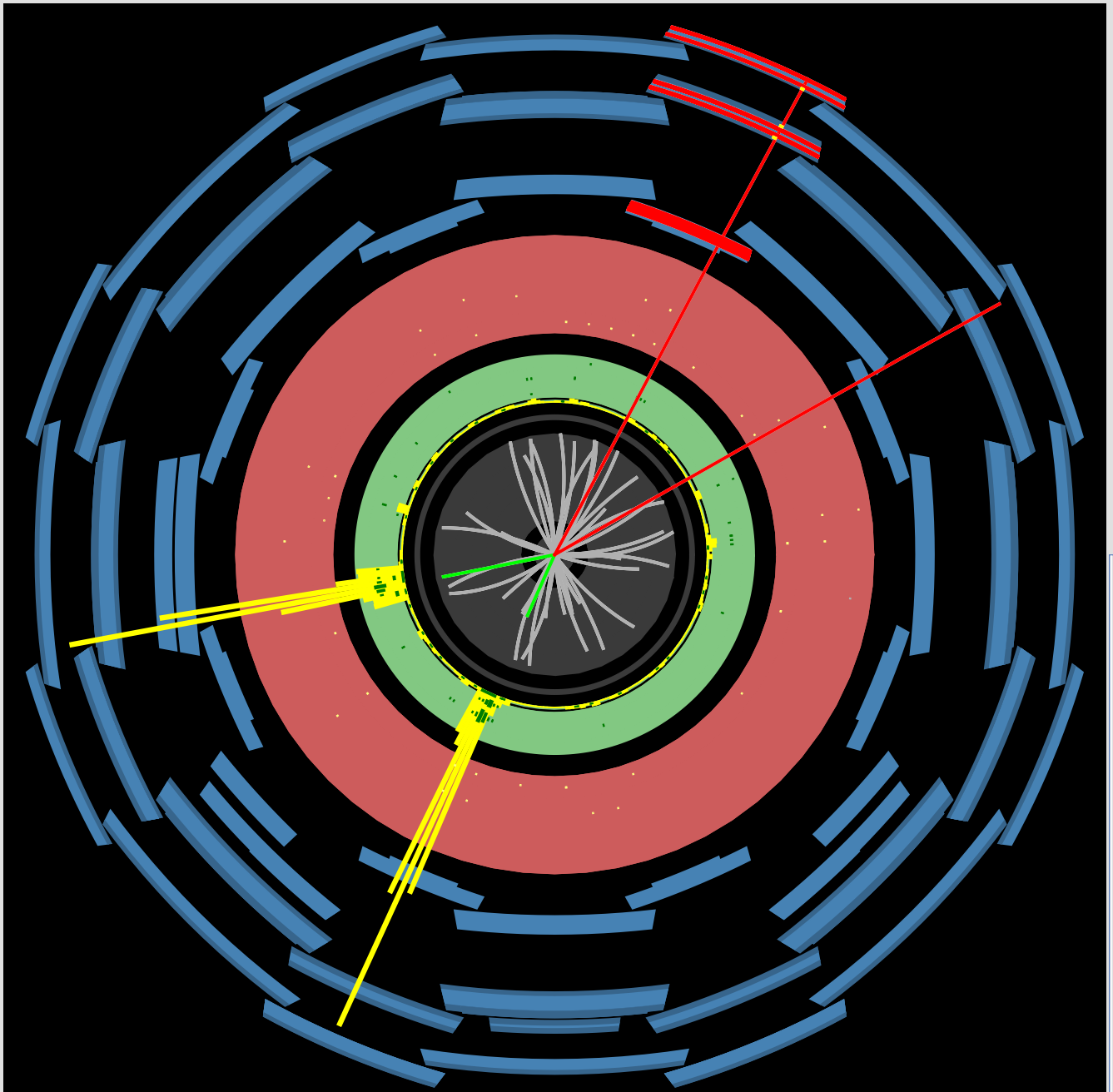
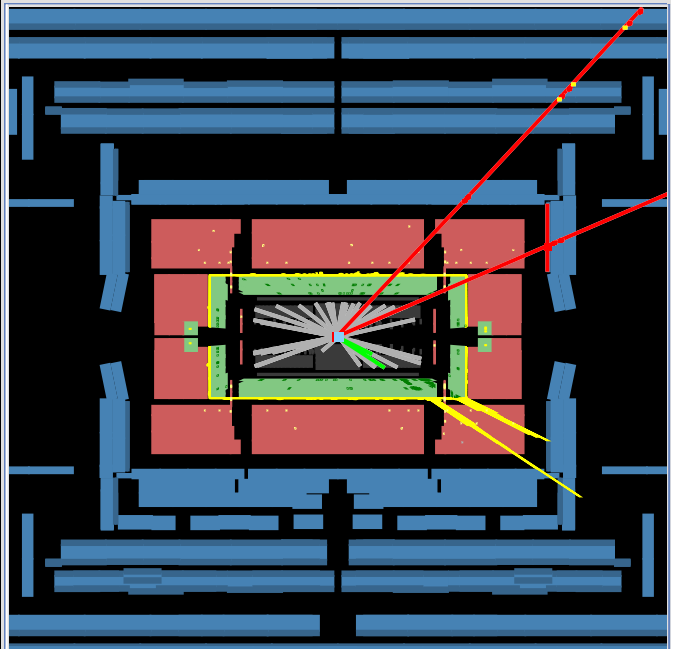


ATLAS EXPERIMENT

Run Number: 284285, Event Number: 4210157909

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



Backgrounds

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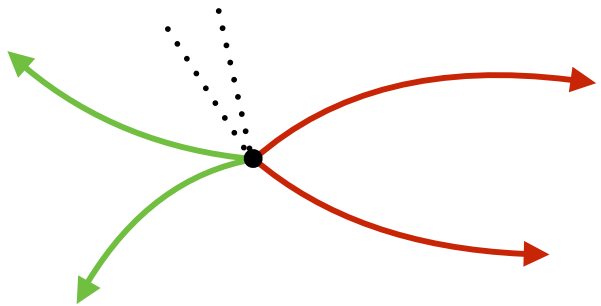
Two types of backgrounds, Irreducible and Fake leptons

Irreducible backgrounds have four genuine leptons



Triboson processes (ZZZ, WZZ, etc)
$ZZ \rightarrow [4\tau, 2\tau 2l]$
$t\bar{t}Z$

Well modelled in MC

Fake lepton backgrounds

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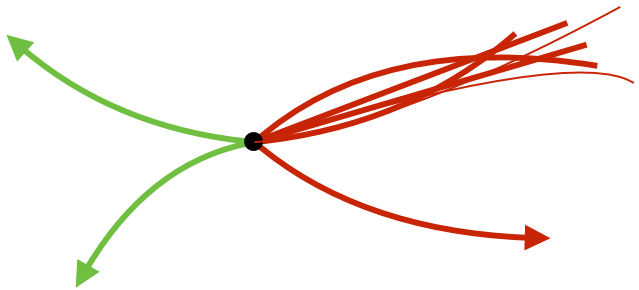
Fake lepton backgrounds: jets can be misidentified as leptons



One or two identified leptons might be jets

- Not modelled well in MC, use data driven "fake factor" method
- Equivalent to the matrix method, except no leptons faking jets

Fake factor

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Control region of leptons with inverted definition cuts

	Lepton-like	Jet-like
Electrons	Pass ID and ISO cut	Fail ID xor ISO cut
Muons	Pass d0 and ISO cut	Fail d0 or ISO cut

Assumption: Three lepton events are from Z+fake leptons (except ZZ, WZ)

Go through data, find Z+lepton events, save info on jet-like and lepton-like leptons

Data driven background

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$$F_{\text{mis-ID}} = \frac{L}{J}$$

$$N_{\text{bkg}}^{\text{misid. leptons}} = \left(N^{\ell\ell\ell j} - N_{ZZ}^{\ell\ell\ell j}\right) \times F_{\text{mis-ID}} - \left(N^{\ell\ell jj} - N_{ZZ}^{\ell\ell jj}\right) \times F_{\text{mis-ID}}^{2}$$

Assume fake rate is the same for second fake

Done in p_T and η bins, for each channel

Background yields

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$\sqrt{s}$ = 13 TeV, 3.2 fb^{-1}

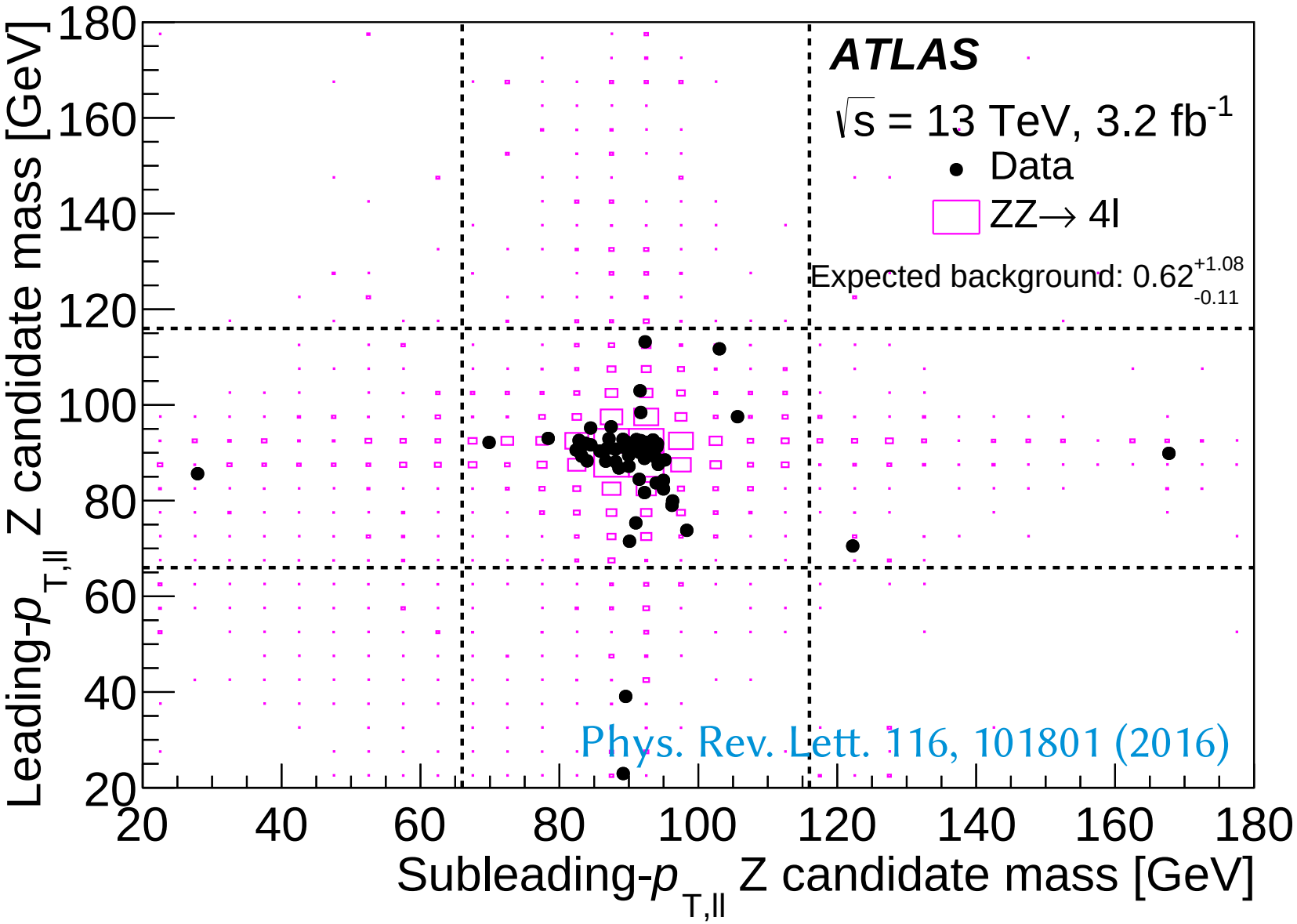
Channel	Total 4ℓ
$ZZ \to 2\ell 2\tau$, 4τ	0.07 ± 0.02
ZZZ, WZZ, WWZ	0.17 ± 0.05
$t\bar{t}Z$	0.30 ± 0.09
Data driven	$0.09^{+1.08}_{-0.04}$
Total	$0.62^{+1.08}_{-0.11}$

Yields

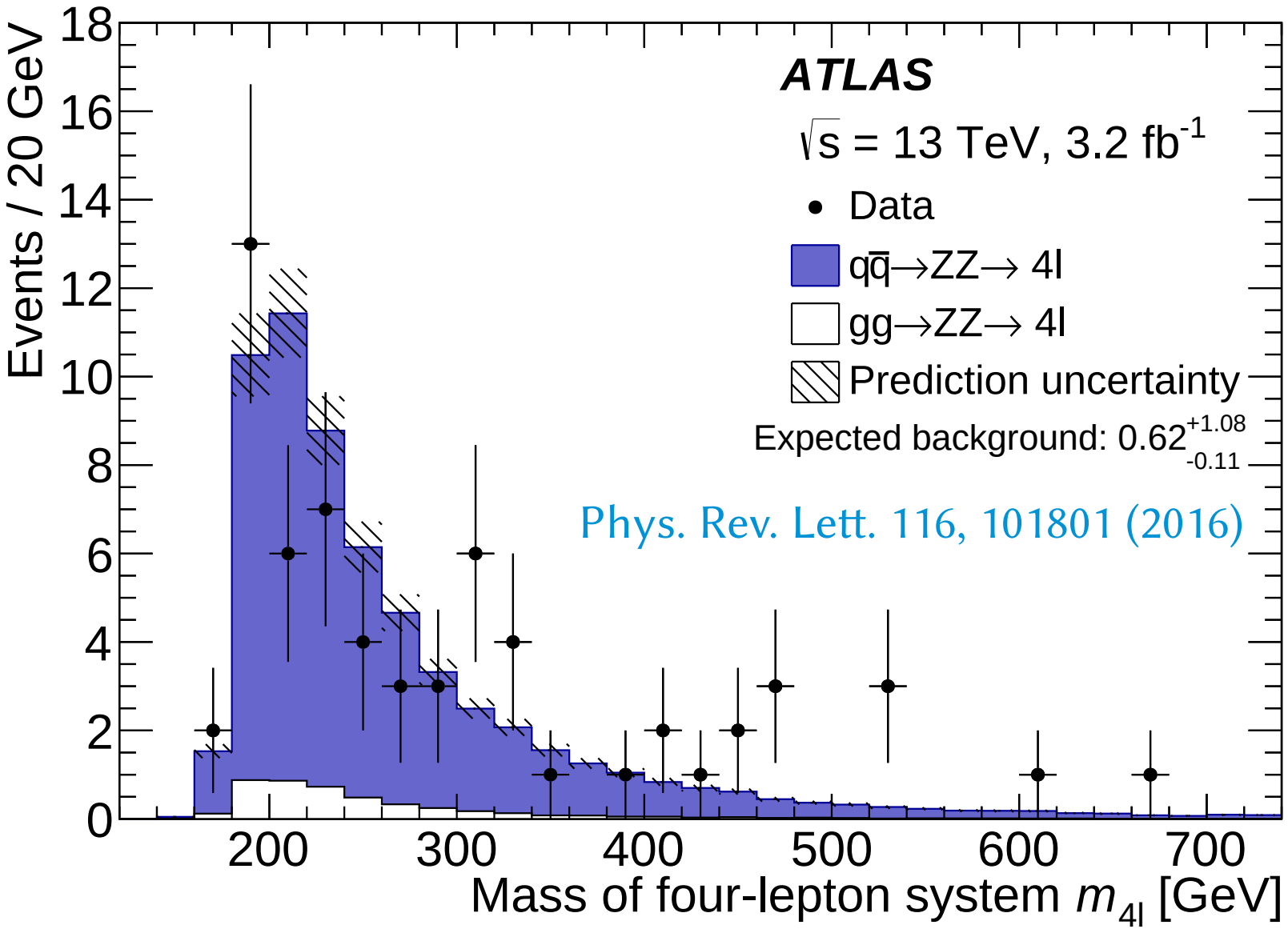
In 2015, LHC delivered 3.2 ± 0.2 fb^{-1} of useful $\sqrt{s}$ = 13 TeV, 25 ns data

Channel	$4e$	$2e2\mu$	4μ	Total 4ℓ
Observed	15	29	18	62
Expected background	0.20 ± 0.05	$0.25^{+0.40}_{-0.05}$	$0.17^{+1.00}_{-0.04}$	$0.62^{+1.08}_{-0.11}$

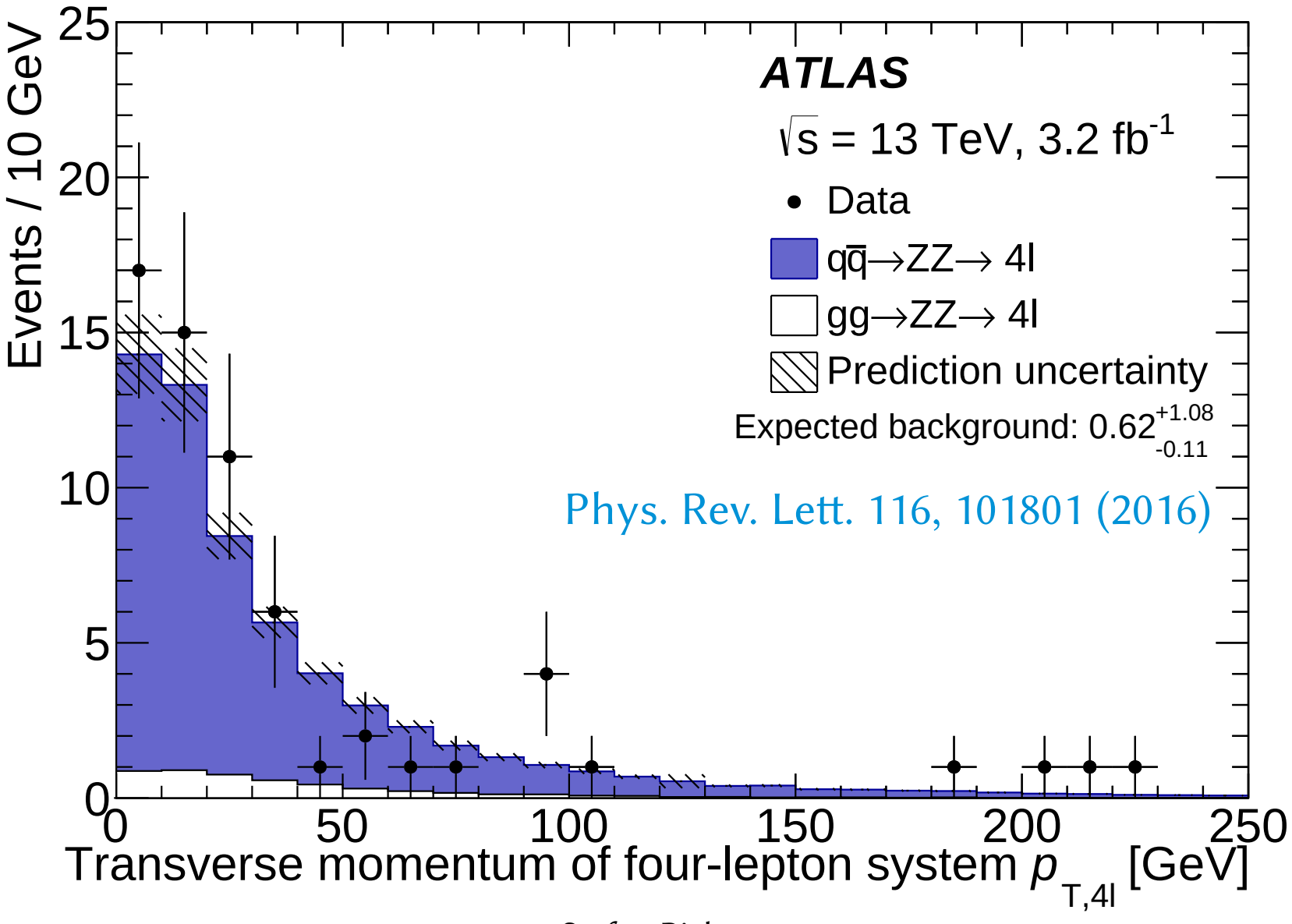
Dilepton masses (before on-shell requirement)



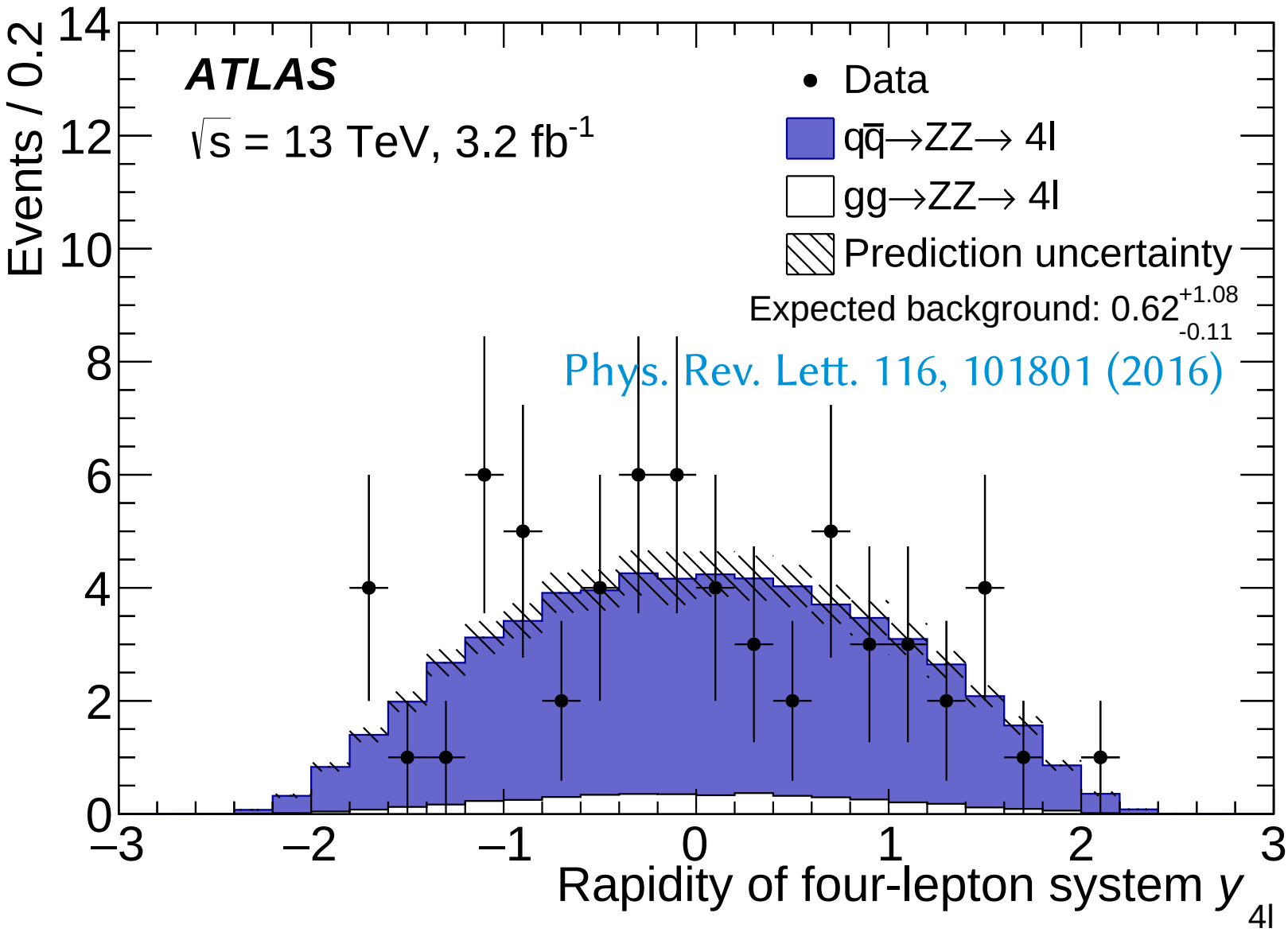
Four-lepton mass



Four-lepton $p_\perp$



Four-lepton rapidity



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
Theory (generator, PDFs)	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

$$A_{ZZ} \equiv \frac{\text{fiducial events}}{\text{on-shell events}} = 0.39 \pm 0.02$$

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

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$$N_{exp}^{chan} = \sigma_{\text{chan}}^{\text{fid}} \mathcal{L} C_{ZZ}^{chan} + N_{DD}^{chan} + N_{Irr}^{chan}$$

$$N_{exp}^{chan} = \sigma_{ZZ}^{\text{tot}} \mathcal{L} C_{ZZ}^{chan} A_{ZZ}^{chan} BR^{chan} + N_{DD}^{chan} + N_{Irr}^{chan}$$

Likelihood model,
poisson distributions model for statistical part

$$L_{stat} = \prod_{chan} Pois(N_{obs}^{chan}, N_{exp}^{chan})$$

Multiplied by Gaussians for systematic uncertainties

Cross section results

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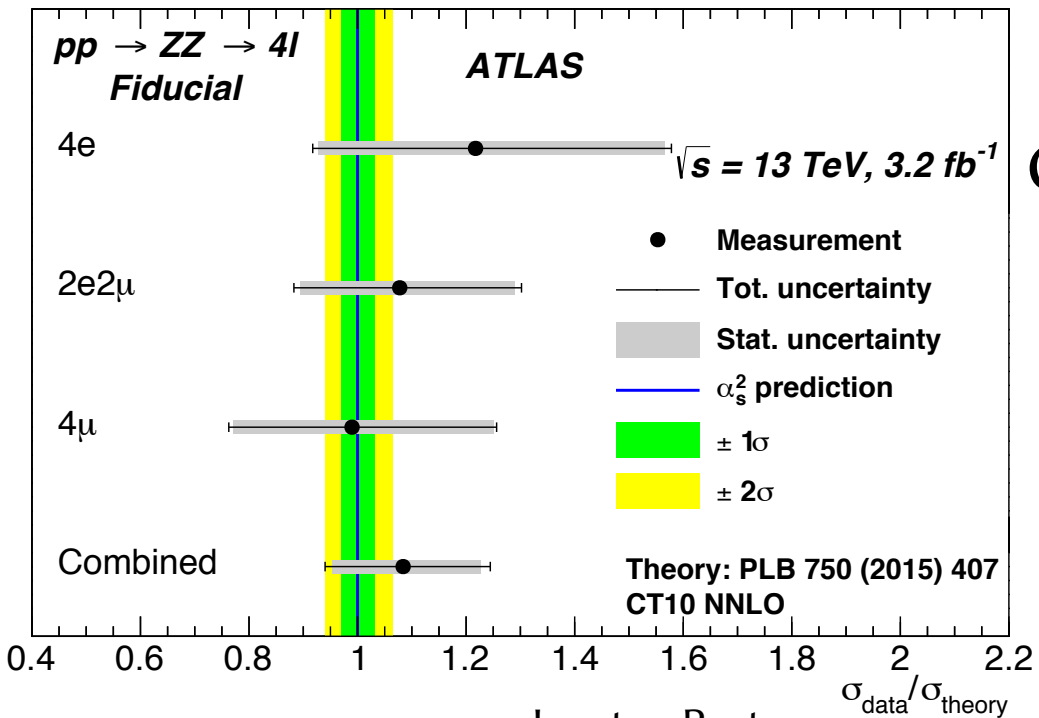
	Measurement	$O(\alpha_s^2)$ prediction
$\sigma^{\text{fid}}_{ZZ\to e^+e^-e^+e^-}$	$8.4\ ^{+2.4}_{-2.0}(\text{stat.})\ ^{+0.4}_{-0.2}(\text{syst.})\ ^{+0.5}_{-0.3}(\text{lumi.})$ fb	$6.9^{+0.2}_{-0.2}$ fb
$\sigma^{\text{fid}}_{ZZ\to e^+e^-\mu^+\mu^-}$	$14.7\ ^{+2.9}_{-2.5}(\text{stat.})\ ^{+0.6}_{-0.4}(\text{syst.})\ ^{+0.9}_{-0.6}(\text{lumi.})$ 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



Comparison with NNLO

Cross section results

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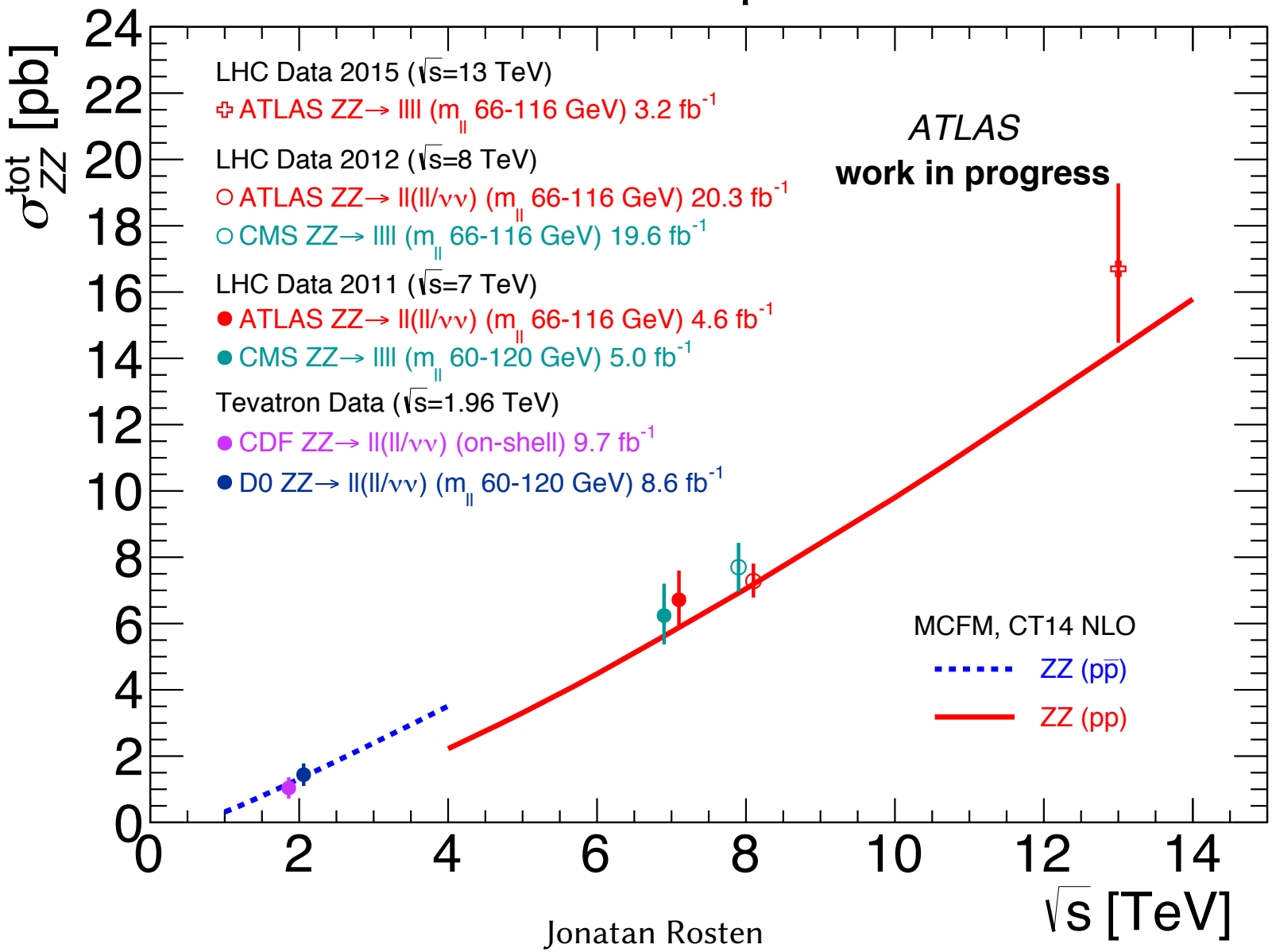
Total cross section, comparison with NLO



Theory considerations

NNLO prediction: [arXiv:1507.06257]

Correction for final-state photon radiation:
decrease fiducial cross section by ~4%

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

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

NLO-α electroweak corrections
could *decrease* prediction by ~7–8% [arXiv:1601.07787], [arXiv:1305.5402]

Conclusions

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

Total uncertainty ca. 15%, statistically dominated

Agreement with NNLO Standard Model prediction

Measurement uncertainty of similar size as gg-initiated loop-induced production → *start to be sensitive!*

Future goals with more data:

- differential cross sections
- search for anomalous gauge couplings
- double parton scattering contribution
- also $2\ell 2\nu$ and $2\ell 2q$ channels
- …

Thank you! Questions?

8 TeV analysis

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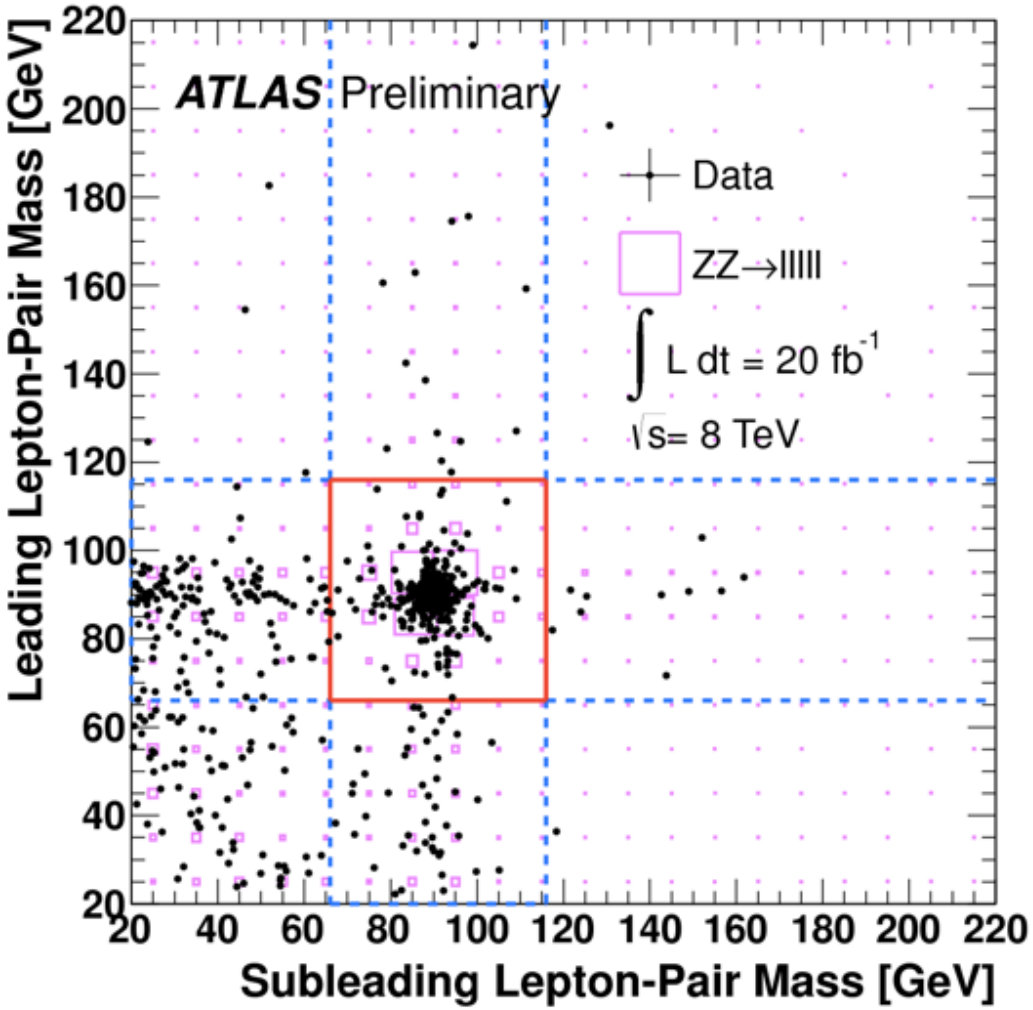
$\sqrt{s}$ = 8 TeV

Total of 321 events in 20.3fb^{-1} of 8 TeV data



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