Measurement of ZZ cross-sections in the four-lepton final state in pp collisions at $\sqrt{s} = 13.6$ TeV with the ATLAS experiment

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Introduction

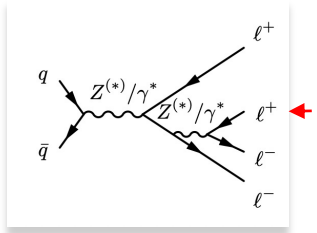
- This talk will be focusing on the recent 13.6 TeV Run-3 ZZ cross section measurement in the 4-lepton final state with the ATLAS detector.

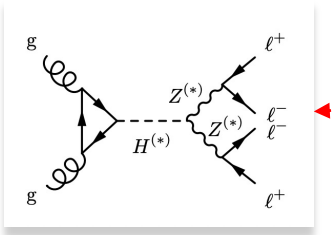
- Paper: Phys. Lett. B 855 (2024) 138764
- ATLAS briefing: ATLAS measures ZZ production using Run-3 data and a new slim data format

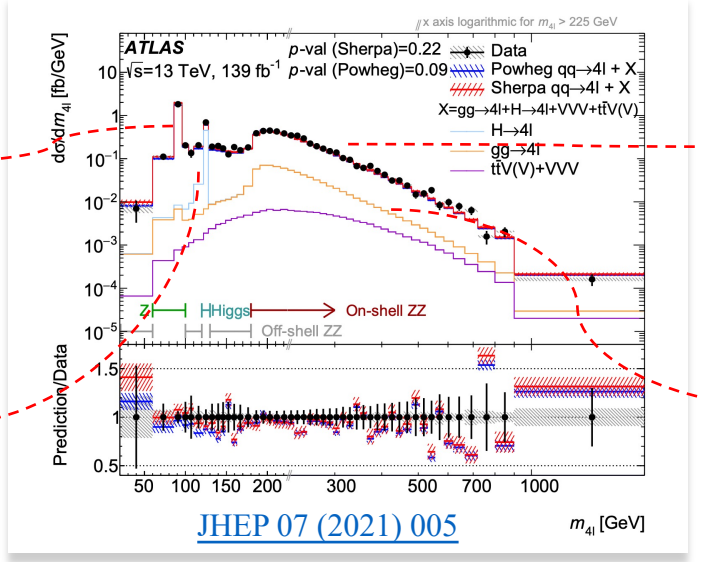
- The electroweak sector of the Standard Model has been tested at the highest available energies in a model-independent way!

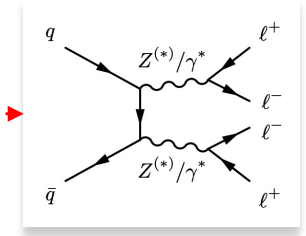
Introduction

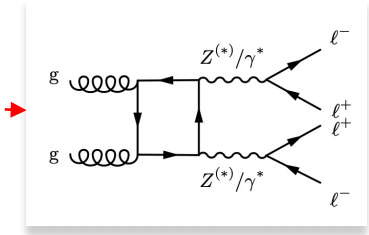
- Measurement of ZZ process
  - Low cross-section but clean background for the leptonic decay ($4l, l = e, \mu$).
  - Precision test of the Standard Model.
- Various measurements of ZZ production have been performed by ATLAS and CMS.
  - 4 lepton final state was measured in a wide range of m_{4l}.
    - Rich physics contents



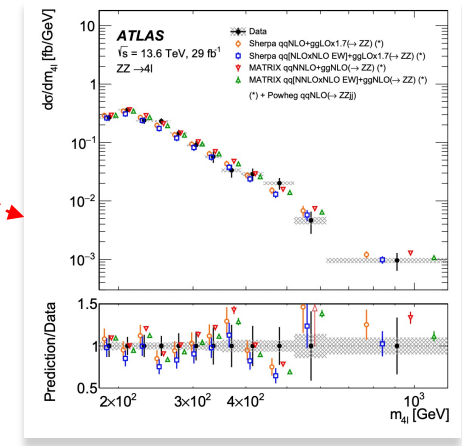








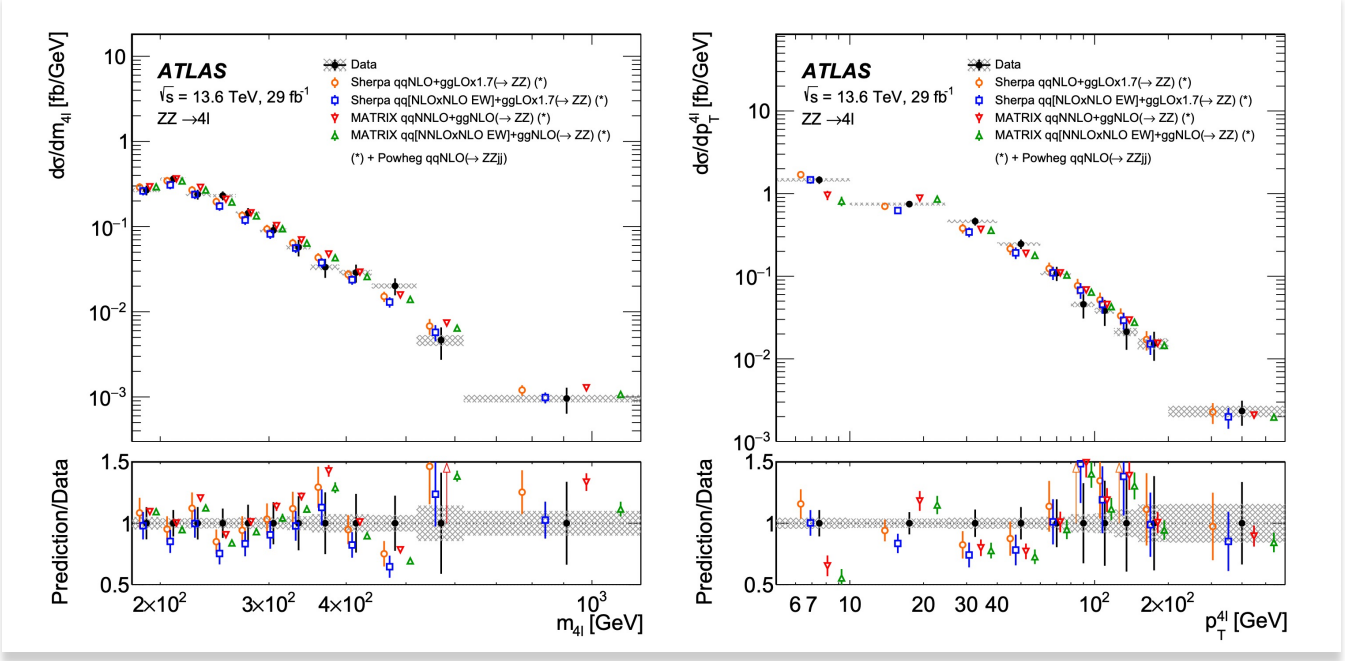
Partial Run-3 focus

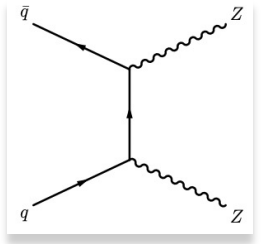


- Latest results using partial Run-3 data ($\mathrm{L} = 29\ \mathrm{fb}^{-1}$).
  - In the on-shell ZZ region using 4 lepton final state.
  - Total cross section and differential cross section measurements.

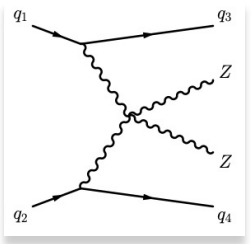
ZZ cross section measurement in Run-3

- The first look of di-boson process with LHC Run-3 data.

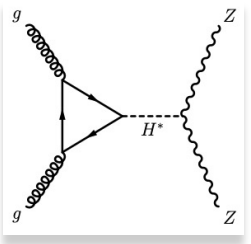


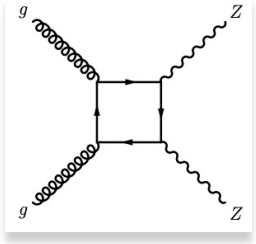


$q\bar{q} \rightarrow ZZ$



EW $q\bar{q} \rightarrow ZZ + 2j$





$gg \rightarrow ZZ$

	Measurement	MC prediction	MATRIX + EW $ZZjj$
Fiducial	$36.7 \pm 1.6(\text{stat}) \pm 1.5(\text{syst}) \pm 0.8(\text{lumi})$ fb	$36.8\ ^{+4.3}_{-3.5}$ fb	36.5 ± 0.7 fb
Total	$16.8 \pm 0.7(\text{stat}) \pm 0.7(\text{syst}) \pm 0.4(\text{lumi})$ pb	$17.0\ ^{+1.9}_{-1.4}$ pb	16.7 ± 0.5 pb

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Fiducial region and event selection

- Fiducial region
  - Designed to be as inclusive as possible.
  - Based on particle-level prompt leptons.
    - Particle level: after parton showering and QED FSR.
- Quadruplet (4-leptons)
  - Same flavor opposite charge (SFOC) lepton pair closest to Z mass is designated as the leading pair.
  - Remaining SFOC pair closest to Z mass is designated as sub-leading pair and completes the quadruplet.
  - One quadruplet defined in an event.
  - Three flavor categories: $4e$, $2e2\mu$, 4μ.
- Event selection
  - Leptons are first reconstructed and checked with object selection.
  - Tight criteria applied on leptons in quadruplet to mitigate misidentified or non-prompt leptons.
  - Z mass on-shell and ZZ on-shell cuts are finally applied to select ZZ events.

	Fiducial phase space
Muon selection	Bare, $p_{\mathrm{T}} > 5$ GeV , $\lvert\eta\rvert < 2.5$
Electron selection	Dressed, $p_{\mathrm{T}} > 7$ GeV , $\lvert\eta\rvert < 2.47$
Four-lepton signature	≥ 2 SFOC pairs
Lepton kinematics	$p_{\mathrm{T}} > 27/10$ GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.05$
Low-mass $\ell^+\ell^-$ veto	$m_{ij} > 5$ GeV
Z mass window	$66 < m_{\ell\ell,1}, m_{\ell\ell,2} < 116$ GeV
ZZ on-shell	$m_{4l} > 180$ GeV

Event selections in fiducial region

Total phase space

- To measure the ZZ inclusive total cross section.
- The phase space is formed with born-level leptons.
  - Born-level: after parton showering but before QED FSR.
- Focusing on the on-shell ZZ production.

Table 1: Definition of the fiducial and total lepton phase-space regions.

	Fiducial phase space	**Total lepton phase space**
Muon selection	Bare, $p_{\mathrm{T}} > 5$ GeV , $\lvert\eta\rvert < 2.5$	Born
Electron selection	Dressed, $p_{\mathrm{T}} > 7$ GeV , $\lvert\eta\rvert < 2.47$	Born
Four-lepton signature	≥ 2 SFOC pairs	≥ 2 SFOC pairs
Lepton kinematics	$p_{\mathrm{T}} > 27/10$ GeV	
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.05$	
Low-mass $\ell^+\ell^-$ veto	$m_{ij} > 5$ GeV	$m_{ij} > 5$ GeV
Z mass window	$66 < m_{\ell\ell,1}, m_{\ell\ell,2} < 116$ GeV	$66 < m_{\ell\ell,1}, m_{\ell\ell,2} < 116$ GeV
ZZ on-shell	$m_{4l} > 180$ GeV	

Define with born leptons

Remove lepton cut and ZZ on-shell cut

Compare with the fiducial phase space

SFOC: same flavor opposite charge.

Physics modelling

- MC samples are generated dedicatedly for each essential process.
- Signal (MC estimation)
  - $q\bar{q} \rightarrow ZZ$: Sherpa v2.2.12+MEPS@NLO w. 0,1j@NLO, 2,3 j@LO QCD
  - $gg \rightarrow ZZ$: Sherpa v2.2.12+MEPS@NLO w. 0,1j@LO
    - inclusive, $m_{4l} > 130$ GeV
    - 1.7 K-factor was applied to predicted cross section to account for higher order QCD corrections.
  - EW $q\bar{q} \rightarrow ZZ + 2j$: Powheg Box v2+Pythia 8.3 w. 2 add. jets(EW) @NLO
- Irreducible background (MC estimation, contribution ~1%)
  - VVV: Sherpa v2.2.12+MEPS@NLO w. 0j@NLO, 1,2 j@LO QCD
  - $t\bar{t}Z$: Sherpa v2.2.12+MEPS@NLO w. 0, 1j@NLO, 1j@LO QCD
- Fake background (data driven method, contribution ~4%)
  - $lll\nu$: Sherpa v2.2.12+MEPS@NLO w. 0,1j@NLO, 2,3 j@LO QCD
  - $t\bar{t}$: Powheg Box v2+Pythia 8.307 @NLO QCD
  - $Z + \text{jets}$: Sherpa v2.2.12+MEPS@NLO w. 0-2j@NLO, 3-5 j@LO QCD

Fake estimation

- Fake refers to events with one or more non-prompt/fake leptons entering quadruplet.
  - Large contributions from $Z + jets$ and $t\bar{t}$ processes.
  - Mainly originated from photon conversion and hadron decays.
  - Contributes about 4% or less in most measured bins.
- Fake background estimated with data-driven approach:
  - Fake Factor method
    - Estimate fake factor in Control Region and transfer it into Signal Region.
- Validation
  - A dedicated validation region is defined
    - The quadruplet should have one SFOC pair and one different-flavor opposite-charge pair.
    - Orthogonal to the SR.
  - Data/MC comparison was checked in validation region
    - In good agreement.

Uncertainties

- Multi-source of uncertainties are studied and estimated
  - Data statistics
    - Predominant uncertainty
  - Theoretical uncertainties
    - PDF + α_s, QCD scale variations and parton shower uncertainties.
    - Conservative variations on ZZjj ($\pm 20\%$), VVV ($\pm 10\%$) and $t\bar{t}Z$ ($\pm 15\%$) cross sections.
  - Experimental systematics
    - Lepton momentum resolution and energy scale.
    - Lepton identification, isolation, reconstruction and trigger efficiency.
    - Pileup reweighting.
    - Luminosity.
  - Fake background
    - Statistical uncertainty.
    - Fake factor systematic uncertainty.
    - MC systematic uncertainty.

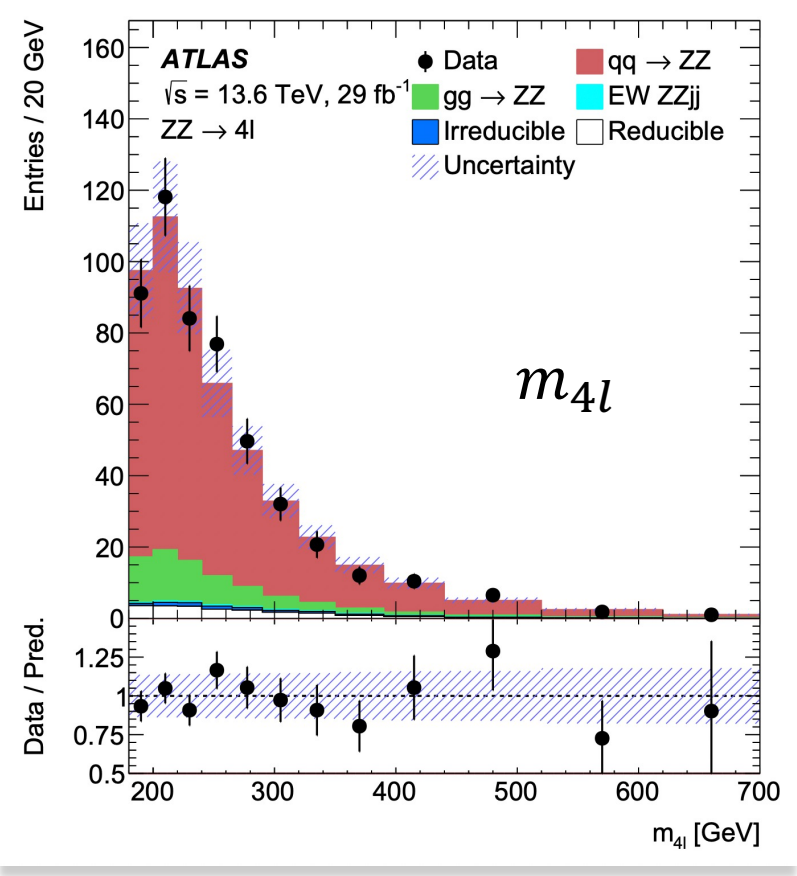
Largest contribution from electron ID.

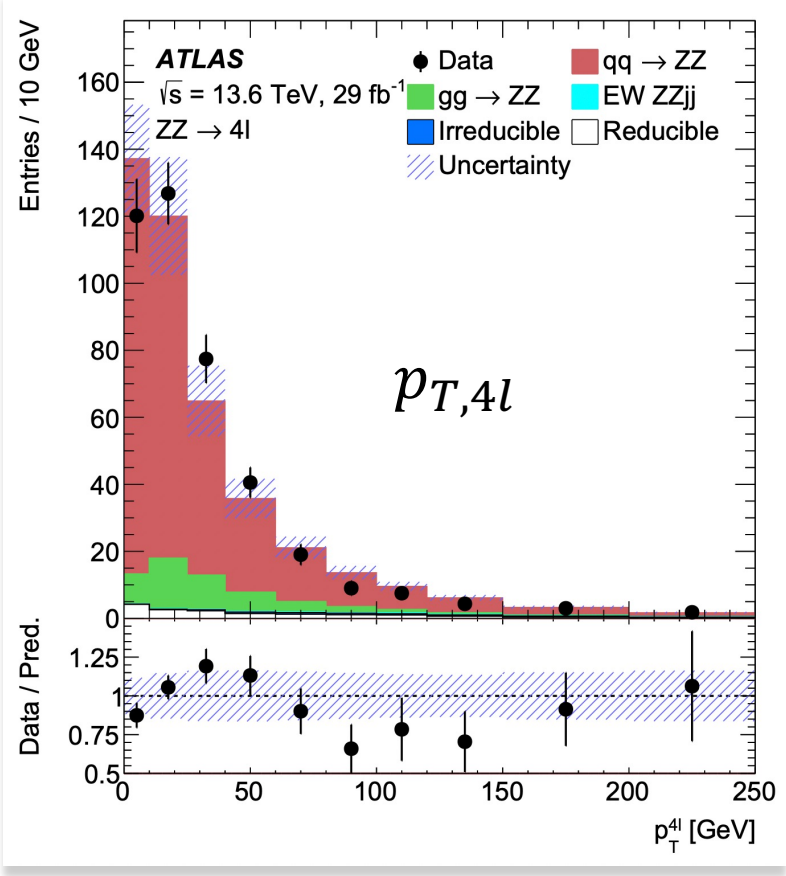
Source	Relative uncertainty(%)
Data statistical uncertainty	4.2
MC statistical uncertainty	0.3
Luminosity	2.2
Pile-up	0.3
Lepton momentum	0.2
Lepton efficiency	3.7
Background	1.6
Theoretical uncertainty	1.0
Total	6.3

Breakdown of relative uncertainty in the measured fiducial cross-section

Detector-level yields

- The $m_{4l}, p_{T,4l}$ spectrums are derived at reconstructed level.
- Generally in good agreement with limited statistics.



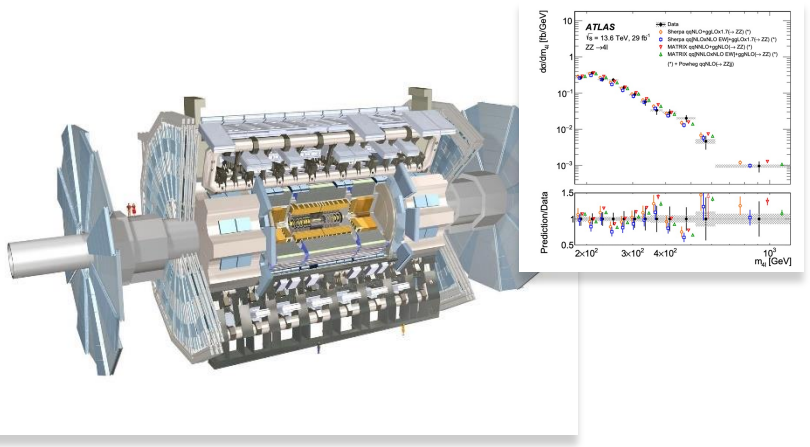


yields comparison

Process	Yield
$qqZZ$	515 ± 50
$ggZZ$	74 ± 44
$ZZjj$	4.7 ± 1.0
$ttll$	5.5 ± 0.8
triboson	2.1 ± 0.2
Fake	25.4 ± 8.1
Total	626 ± 88
Data 2022	625

Unfolding and detector correction

- Derive the $m_{4l}, p_{T,4l}$ spectrum corrected for detector effects at particle-level.
  - Remove the effect of the detector efficiency, resolution and acceptance.

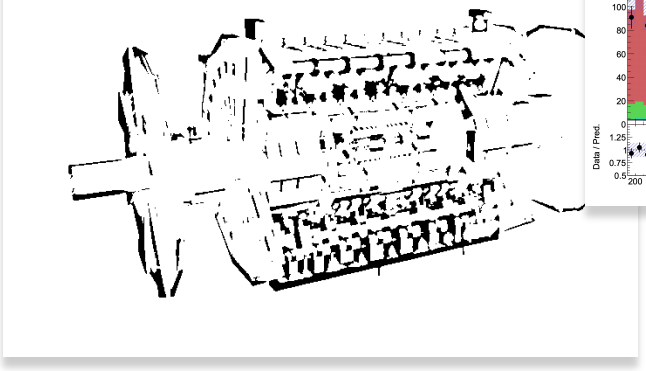


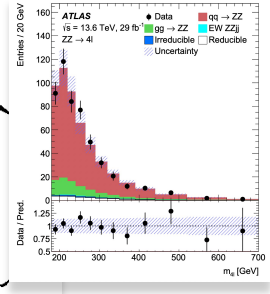
Truth distribution

Smearing/Folding

$Reco = M \cdot Truth$

Unfolding





Experimental distribution

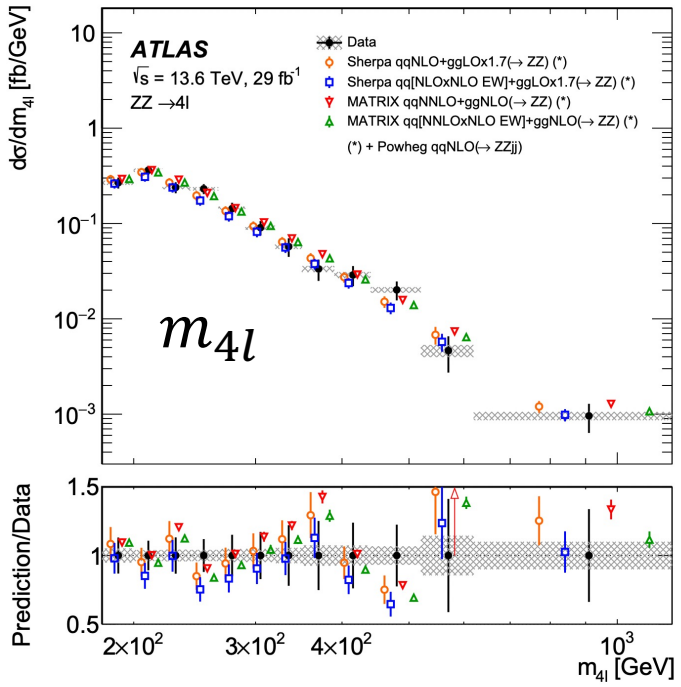
$$\begin{pmatrix} R_1 \\ \vdots \\ R_n \end{pmatrix} = \begin{pmatrix} F_{11} & \cdots & F_{1n} \\ \vdots & \ddots & \vdots \\ F_{n1} & \cdots & F_{nn} \end{pmatrix} \times \begin{pmatrix} T_1 \\ \vdots \\ T_n \end{pmatrix} \Longrightarrow \begin{pmatrix} T_1 \\ \vdots \\ T_n \end{pmatrix} = \begin{pmatrix} M_{11} & \cdots & M_{1n} \\ \vdots & \ddots & \vdots \\ M_{n1} & \cdots & M_{nn} \end{pmatrix} \times \begin{pmatrix} R_1 \\ \vdots \\ R_n \end{pmatrix}$$

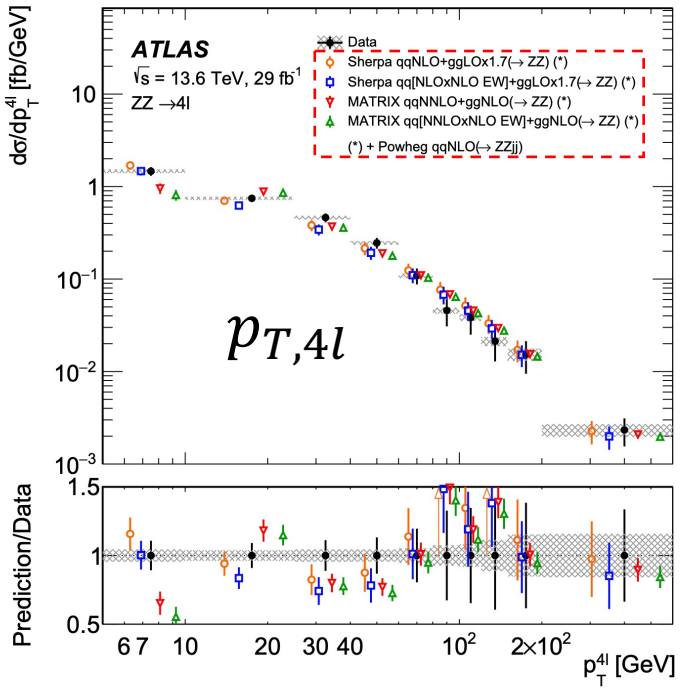
Detector-level distr. | Response Matrix | Particle-level distr. | Unfolding Matrix

- The unfolded distribution could be used to retrieve differential cross-section and compare with theoretical prediction directly

Differential cross sections

- Using unfolding method to correct the detector effects.
- Fiducial level data/MC comparison with 2 observables: m_{4l}, $p_{T,4l}$.
- Good agreement is shown at up to NNLO QCD + NLO EW order with limited statistics.
  - Different MC predictions at different accuracies are provided.

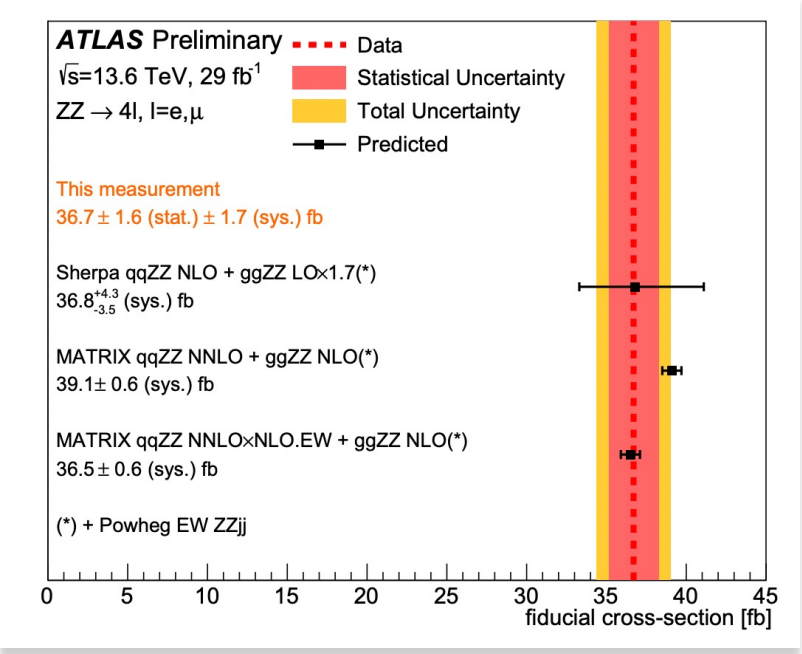




MC predictions provided with Sherpa/Powheg and MATRIX

Inclusive fiducial cross section

- Fiducial cross section: $\sigma_{\text{fid.}} = \frac{N_{obs} - N_{bkg}}{L \cdot C}$
- Correction factor: $C = \frac{N_{Reco}}{N_{Truth}}$
- $\sigma_{\text{fid.}} = 36.7 \pm 1.6\,(\text{stat.}) \pm 1.5(\text{sys.}) \pm 0.8\,(\text{lumi})\ \text{fb}$
- Agree with the theoretical predictions within uncertainties.



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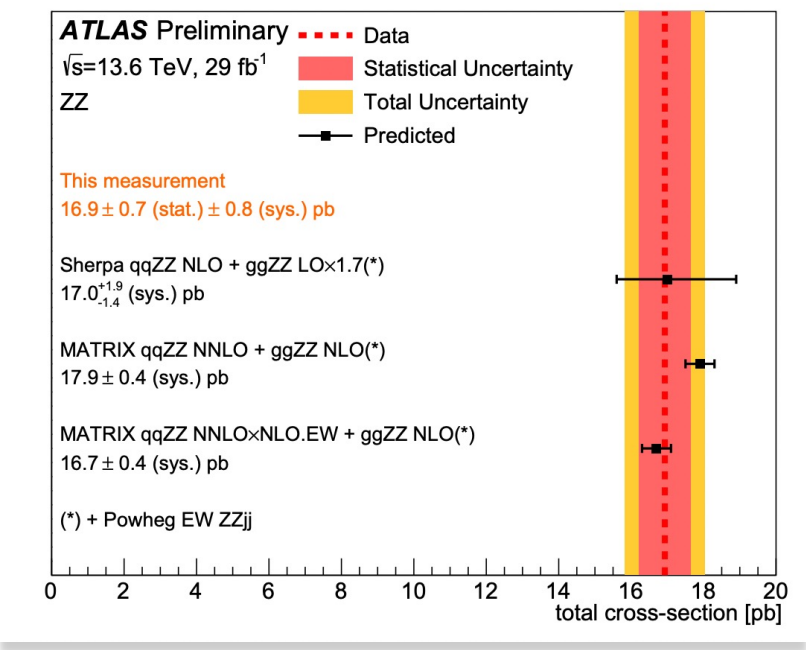
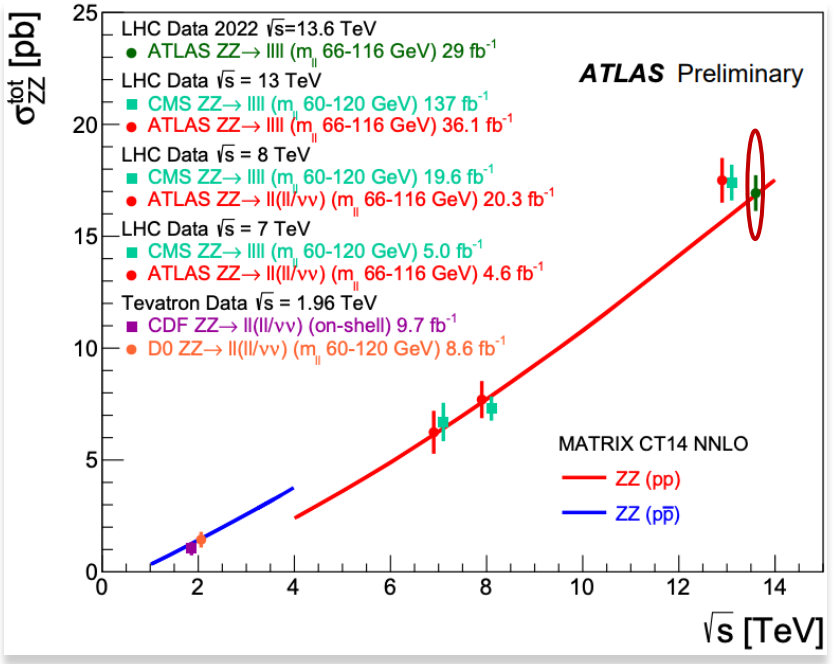
MC statistical uncertainty	0.3
Luminosity	2.2
Lepton momentum	0.2
Lepton efficiency	3.7
Background	1.6
Theoretical uncertainty	1.0
Total	6.3

Uncertainty breakdown on $\sigma_{\text{fid.}}$

Total cross section

- Total cross section: $\sigma_{total} = \frac{N_{data} - N_{bkg}}{L \cdot A \cdot C \cdot 4BR^2_{Z \to e^+e^-}}$
- Acceptance: $A = \frac{N_{truth}}{N_{total}}$
- $\sigma_{total} = 16.8 \pm 0.7\,(stat.) \pm 0.7(sys.) \pm 0.4\,(lumi)\ pb$





This analysis

Summary

- First Run-3 ZZ results are reported.
  - ZZ differential fiducial cross-sections as a function of m_{4l} and $p_{T,\,4l}$ are measured.
  - ZZ inclusive fiducial and total cross sections are measured.
  - Good agreement is shown with the limited statistics.

- The observed data agrees with the state-of-art MC simulation at up to NNLO QCD + NLO EW accuracy.

- The electroweak sector of the Standard Model has been tested at the highest available energies in a model-independent way!

Backup