Electroweak probes in heavy-ion collisions with ATLAS

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ATLAS EXPERIMENT

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VIRTUAL CONFERENCE

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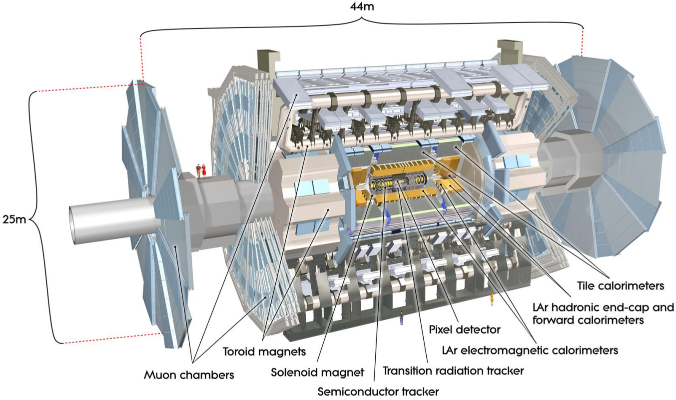
PRAGUE, CZECH REPUBLIC

Introduction

- Measurements of electroweak (γ, W, Z) bosons in **proton-proton** collisions provide **precise tests of Standard Model predictions** including both the EW theory and QCD.
- They are also important to set a **reference for heavy-ion analyses**.
- In **proton-nucleus** collisions, one can probe **cold nuclear matter effects** such as nuclear modifications of PDFs or energy loss of initial-state partons.
- **Nucleus-nucleus** collisions at LHC energies create a strongly interacting **quark-gluon plasma**, which however does not significantly affect EW bosons or their leptonic decay products.
- In addition to cold nuclear matter effects, the **collision centrality and geometry** can be studied through T_{AA} scaling of EW boson production.
- Presentation of results from:
  - W/Z production in pp at $\sqrt{s} = 5.02$ TeV (2015 dataset): Eur. Phys. J. C 79 (2019) 128, erratum: Eur. Phys. J. C 79 (2019) 374
  - γ production in p+Pb at $\sqrt{s_{NN}} = 8.16$ TeV: Phys. Lett. B 796 (2019) 230
  - W production in Pb+Pb at $\sqrt{s_{NN}} = 5.02$ TeV (2015 dataset): Eur. Phys. J. C 79 (2019) 935
  - Z production in Pb+Pb at $\sqrt{s_{NN}} = 5.02$ TeV (2015 dataset): Phys. Lett. B 802 (2020) 135262

- **Charged particle tracking** in $|\eta| < 2.5 \to$ electrons, muons, track MET
- **Calorimeter system** in $|\eta| < 4.9 \to$ electrons, photons, MET, centrality determination (forward calorimeters, $3.1 < |\eta| < 4.9$)
- **Muon reconstruction** in $|\eta| < 2.4$ (muon spectrometer + inner detector)



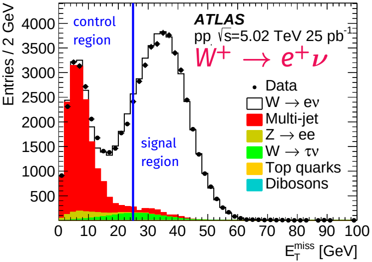
Datasets:

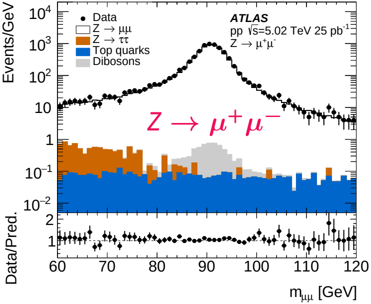
- Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV: $0.49\ \text{nb}^{-1}$ (2015)
- *p*+Pb collisions at $\sqrt{s_{\text{NN}}} = 8.16$ TeV: $165\ \text{nb}^{-1}$ (2016)
- *pp* collisions at $\sqrt{s} = 5.02$ TeV: $25\ \text{pb}^{-1}$ (2015)

W/Z bosons in pp collisions at $\sqrt{s} = 5.02$ TeV

W/Z bosons in pp: Measurement strategy

Eur. Phys. J. C 79 (2019) 128 and 79 (2019) 374

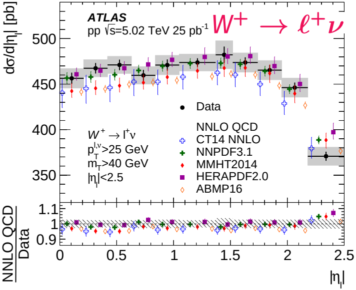


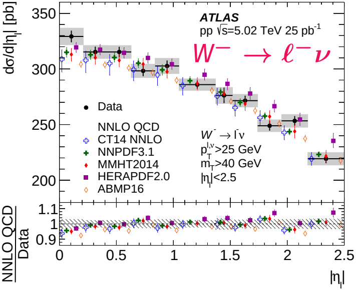


- Following **typical measurement strategy** for W/Z boson production at hadron colliders:
  - W: **single isolated lepton** with large p_T^ℓ (> **25 GeV**), events with large missing transverse energy (E_T^{miss} > **25 GeV**) and transverse mass (m_T > **40 GeV**)
  - Z: **isolated leptons** with large p_T^ℓ (> **20 GeV**), opposite-charge same-flavour **lepton pairs** in mass range **$66 < m_{\ell\ell} < 116$ GeV**
- **Separate measurements** of cross-sections in **electron** and **muon** decay channels.
- **Combination** of decay channels using the BLUE method **accounting for uncertainty correlations**.
- Summary of **uncertainties** for **integrated fiducial cross-sections**:
  - $\sim$ 1.3% (stat.+syst.)
  - 1.9% (lumi)

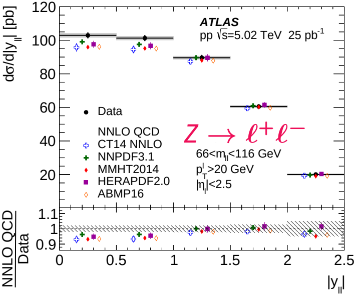
W/Z bosons in pp: Differential cross-sections

Eur. Phys. J. C 79 (2019) 128 and 79 (2019) 374





- Comparison to several **NNLO theory predictions (different PDF sets)** calculated with DYTURBO[1].
- **Good agreement** of predictions from **NNPDF3.1 and HERAPDF 2.0** PDFs with data, while other PDF sets systematically tend to underestimate measured cross-sections.
- **Well understood and precise reference** for measurements in Pb+Pb collisions.



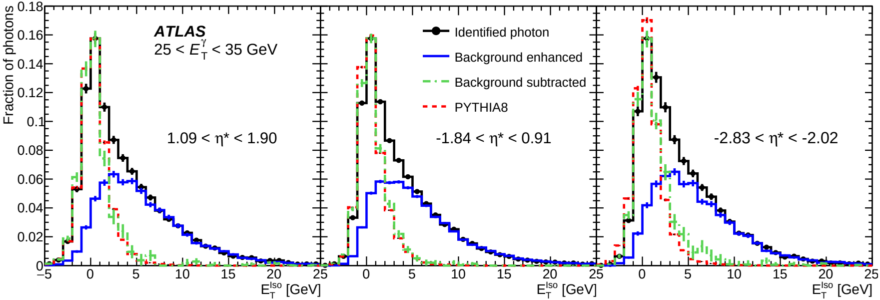
[1] S. Camarda et al., EPJC 80 (2020) 251

Prompt photons in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

Prompt photons in p+Pb: Measurement strategy

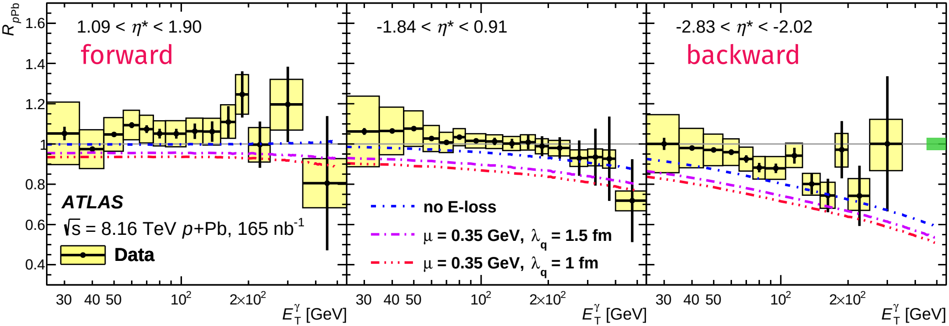
Phys. Lett. B 796 (2019) 230

- Events collected with **single-photon triggers** (E_{T}^{γ} thresholds from 15 to 35 GeV).
- Photons required to pass reconstruction quality and isolation selections.
- Kinematic selections: $E_{\mathrm{T}}^{\gamma} > 20$ GeV, $|\eta_{\gamma}^{\mathrm{lab}}| < 1.37$ or $1.56 < |\eta_{\gamma}^{\mathrm{lab}}| < 2.37$
- Due to asymmetric collision system, **pseudorapidity in center-of-mass frame is shifted** with respect to laboratory frame: $\eta^{*} = \eta^{\mathrm{lab}} - 0.465$
- **Background estimation using sidebands** in isolation and identification (purity between 45% and 99%).



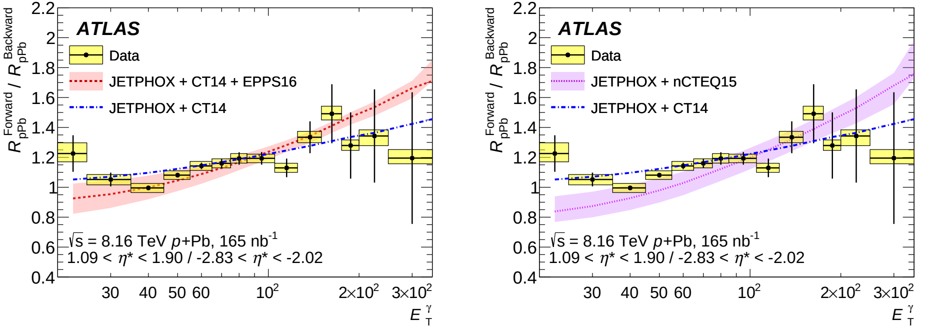
Prompt photons in p+Pb: Nuclear modification factor

Phys. Lett. B 796 (2019) 230



- **Nuclear modification factor** $R_{pPb} = \frac{d\sigma^{p+Pb\to\gamma+X}/dE_T^\gamma}{A\cdot d\sigma^{pp\to\gamma+X}/dE_T^\gamma}$ ($A = 208$ is the Pb mass number)
- No direct **reference** measurement in pp collisions, **existing results at 8 TeV extrapolated to 8.16 TeV** using NLO calculations from PYTHIA8 and JETPHOX.
- At **forward and central rapidities**, R_{pPb} values **consistent with unity**.
- For **backward rapidities**, the R_{pPb} seems to **decrease at high** E_T^γ which can be explained by **different fractions of** ***u*** **and** ***d*** **quarks** in the proton and the Pb nucleus.
- Comparison to model predictions suggests **no large initial-state parton energy loss**.

Phys. Lett. B 796 (2019) 230

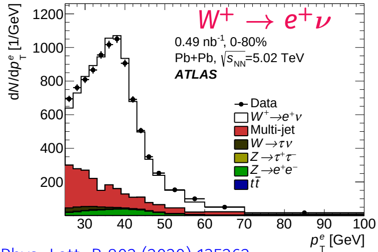


- **Reduction of systematic uncertainties** for ratios of forward and backward R_{pPb}.
- Comparison to **NLO calculations** from JETPHOX using **free-nucleon PDFs** (CT14) and **nPDFs** (EPPS16 and nCTEQ15).
- The **free-nucleon** prediction shows the **best agreement** with data.
- Data also **compatible with small nuclear modifications** represented by nPDFs in most of the considered E_T^{γ} range.

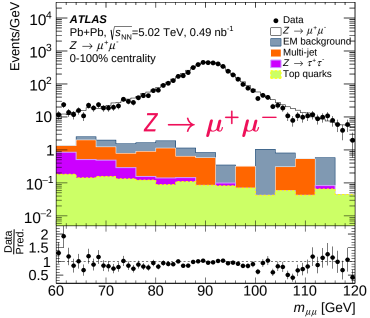
W/Z bosons in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

W/Z bosons in Pb+Pb: Measurement strategy

Eur. Phys. J. C 79 (2019) 935



Phys. Lett. B 802 (2020) 135262



- General measurement **strategy similar to *pp* analyses with some differences**:
  - **ZDC** used to reject **EM/photonuclear background** in peripheral collisions, as well as **pile-up** events
  - *W*: E_T^{miss} **reconstructed from charged-particle tracks** instead of particle-flow algorithm, **centrality dependent multi-jet** background
  - *Z*: suppression of **EM/photonuclear background** in peripheral collisions using **rapidity gaps**
- **Same fiducial phase-space volumes** as for the *pp* cross-sections.
- **Nuclear modification factor** defined as:

$$R_{AA} = \frac{1}{\langle T_{AA} \rangle} \frac{N_{W[Z]}/N_{evt}}{\sigma^{pp}_{W[Z]}}$$

  - $N_{W[Z]}/N_{evt}$ - yield per inelastic Pb+Pb collision
  - $\langle T_{AA} \rangle$ - mean nuclear thickness function
  - $\sigma^{pp}_{W[Z]}$ - cross-section measured in *pp* collisions
  - Note: $\langle T_{AA} \rangle$ and centrality classification are dependent on details of Glauber modelling

W/Z bosons in Pb+Pb: Yields differential in rapidity

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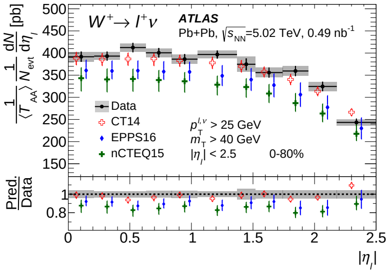
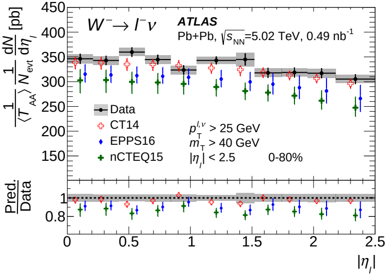
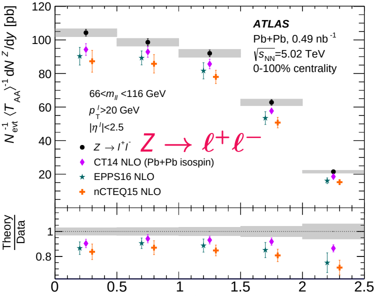




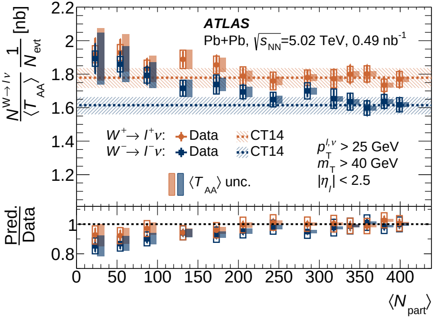
- Comparison to several **NLO theory predictions** calculated with MCFM using:
  - free-nucleon CT14 PDFs (with isospin effect)
  - EPPS16 nPDFs
  - nCTEQ15 nPDFs
- **Good agreement** of **free-nucleon** PDF predictions with ***W* boson** data, but some **underestimation** for ***Z* boson** data.
- Predictions from **nPDFs** are **10-20% below data**.



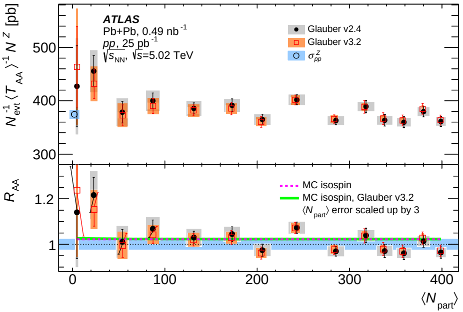
Phys. Lett. B 802 (2020) 135262

W/Z bosons in Pb+Pb: Yields differential in $\langle N_{\text{part}} \rangle$

Eur. Phys. J. C 79 (2019) 935 $W^{\pm} \rightarrow \ell^{\pm}\nu$



$Z \rightarrow \ell^{+}\ell^{-}$ Phys. Lett. B 802 (2020) 135262



- **Yields** are approximately **constant with centrality** (represented by $\langle N_{\text{part}} \rangle$).
- For ***W* bosons**, there is **hint of increase** in the most **peripheral collisions**, but deviations from a constant are not larger than 1.7σ.
- Data are in **good agreement** with predictions using **free-nucleon** CT14 PDFs and accounting for **isospin effect**.
- Measurements in peripheral collisions limited by $\langle T_{\text{AA}} \rangle$ uncertainty.
- Replace R_{AA} for other hard probes with $Z_{\text{AA}} = \dfrac{N^{X}_{\text{AA}} \cdot \sigma^{Z}_{pp}}{\sigma^{X}_{pp} \cdot N^{Z}_{\text{AA}}}$?

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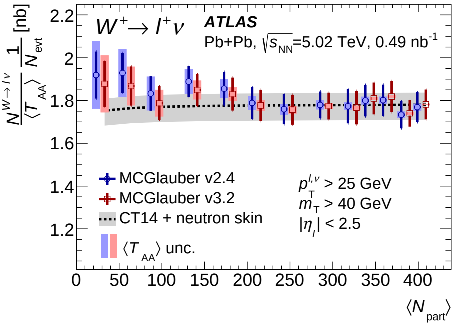

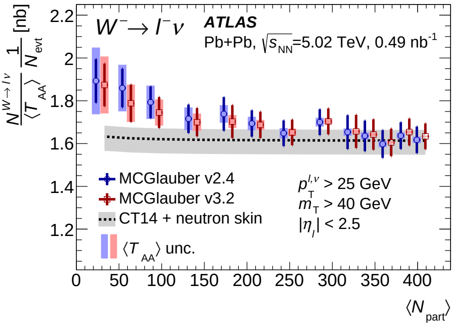

- Comparison of yields extracted using **geometric parameters from two versions of MCGlauber code**.
- MCGlauber v3.2 provides **separate radial profiles for protons and neutrons**.
- **Effect** on measured yields is **smaller than measurement uncertainties**.
- **Deviations** from a constant yield in **peripheral collisions** are **not fully explained by neutron skin effect** (a few % increase for W^- and decrease for W^+).

W/Z bosons in Pb+Pb: Nuclear modification factor

Eur. Phys. J. C 79 (2019) 935

$W^{\pm} \to \ell^{\pm}\nu$

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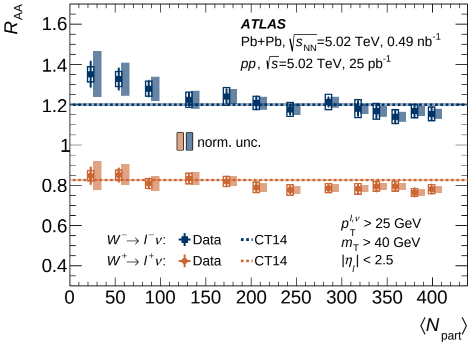
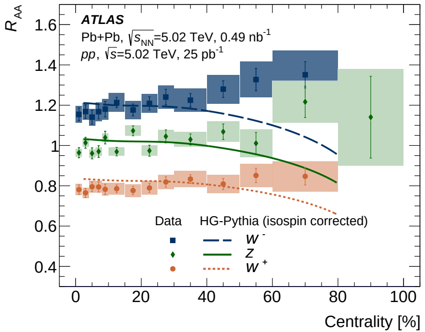
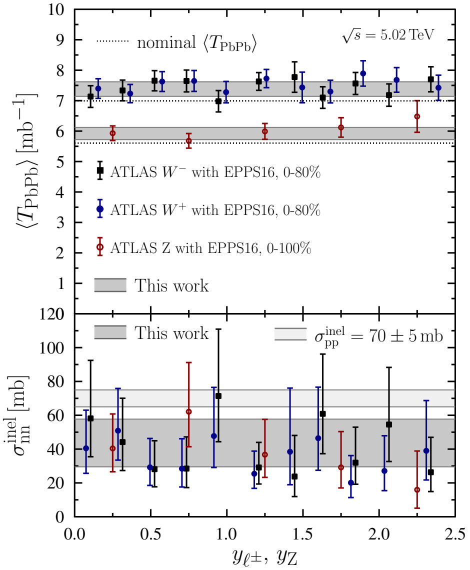




- For ***W* bosons**, deviations from unity are expected from **isospin effect**.
- Deviations from free-nucleon CT14 PDF predictions do not exceed 1.8σ.
- Comparison of **measured nuclear modification factors** with predictions incorporating **centrality bias from HG-PYTHIA model**.
- Trends for W/Z bosons do not follow the HG-PYTHIA prediction, but details of soft-particle production are different than for jet production.

W/Z bosons in Pb+Pb: Shadowing of σ_{nn}^{inel}?

K. Eskola et al., arXiv:2003.11856

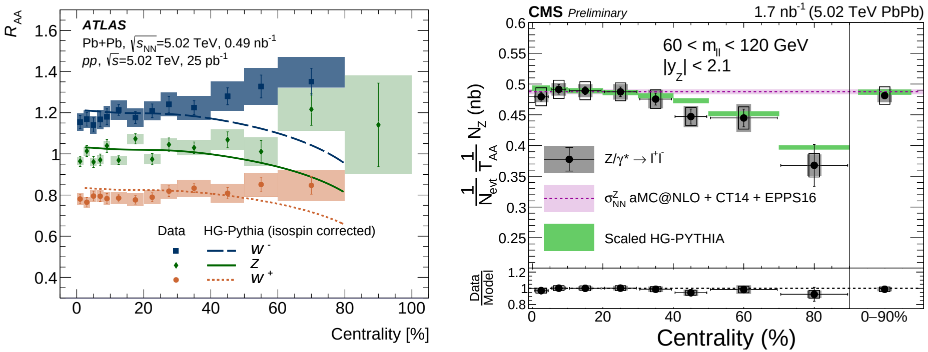


- How can these **measurements** be used to improve our **understanding of collision centrality and geometry**?
- ATLAS estimates **geometric parameters** of Pb+Pb collisions (e.g. $\langle T_{AA} \rangle$) using the **MCGlauber model**.
- This procedure assumes the **inelastic nucleon-nucleon cross-section** to be **unmodified** ($\sigma_{nn}^{inel} = \sigma_{pp}^{inel} = 70 \pm 5$ mb).
- **Recent theoretical study** uses the **ATLAS W/Z data** to show that $\boldsymbol{\sigma_{nn}^{inel}}$ could be **potentially suppressed** ($\sigma_{nn}^{inel} = 41.5^{+16.2}_{-12.0}$ mb).
- This is **equivalent to a modification of** $\langle T_{AA} \rangle$ with centrality such that the measured R_{AA} **would flatten**.

W/Z bosons in Pb+Pb: Interpretation?

Phys. Lett. B 802 (2020) 135262

CMS-PAS-HIN-19-003



- Recent **CMS measurement** of ***Z* boson** production shows significant **decrease of yields in peripheral collisions**.
- **Possible source of discrepancy**: details of **centrality determination** procedures, in particular in the treatment of peripheral collisions.
- Note: ATLAS results use MCGlauber v2.4, CMS measurement uses MCGlauber v3.2.
- **Needs to be followed up by centrality experts from both experiments**.

Summary

- Presented recent ATLAS measurements of electroweak boson production in *pp* and Pb+Pb collsions at 5.02 TeV, and in *p*+Pb collisions at 8.16 TeV.
- *pp* collisions:
  - *W*/*Z* boson measurements provide **high-precision reference** for Pb+Pb results.
- *p*+Pb collisions:
  - Measured nuclear modifications consistent with **nPDF predictions**, but disfavour large **initial-state parton energy loss**.
- Pb+Pb collisions:
  - **Data best described using free-nucleon PDFs**, while nPDF predictions tend to underestimate measurements.
  - Measurements consistent with expectations from T_{AA} **scaling**, no significant dependence of yields on centrality (slight increase in **peripheral collisions**).
  - Very **limited** experimental **sensitivity to neutron skin effect**.
- Before interpreting the data, need to resolve discrepancy with CMS results.
- Large Pb+Pb dataset collected in 2018 (3.5 times larger luminosity than in 2015) to be explored.

Additional slides

W/Z bosons in pp: Electron calibration

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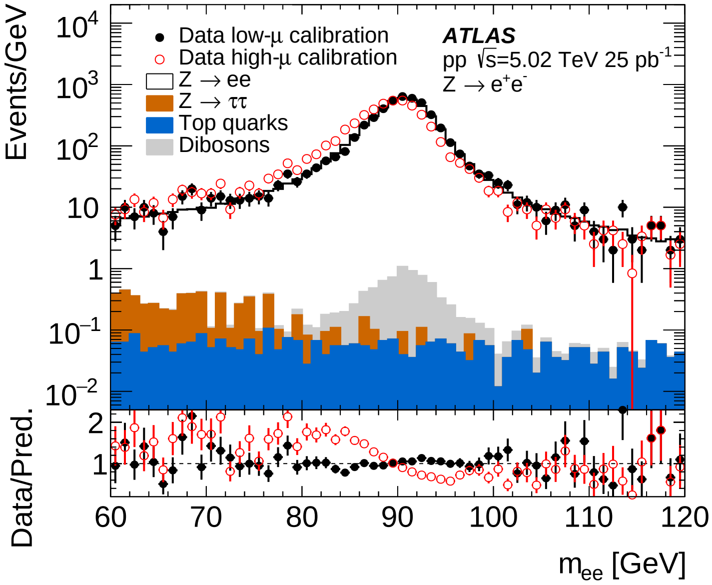

W/Z bosons in pp: Lepton efficiencies

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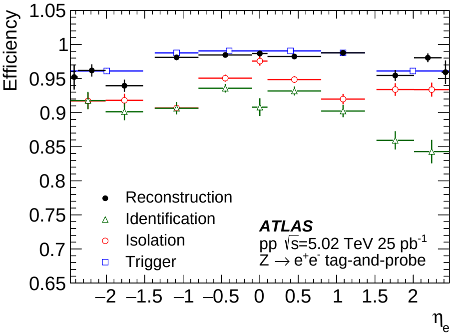
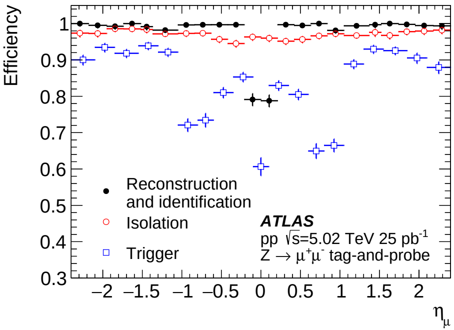
electrons



muons



- Efficiencies measured with the tag-and-probe method in $Z \rightarrow \ell\ell$ events in data.

W/Z bosons in pp: Channel combination

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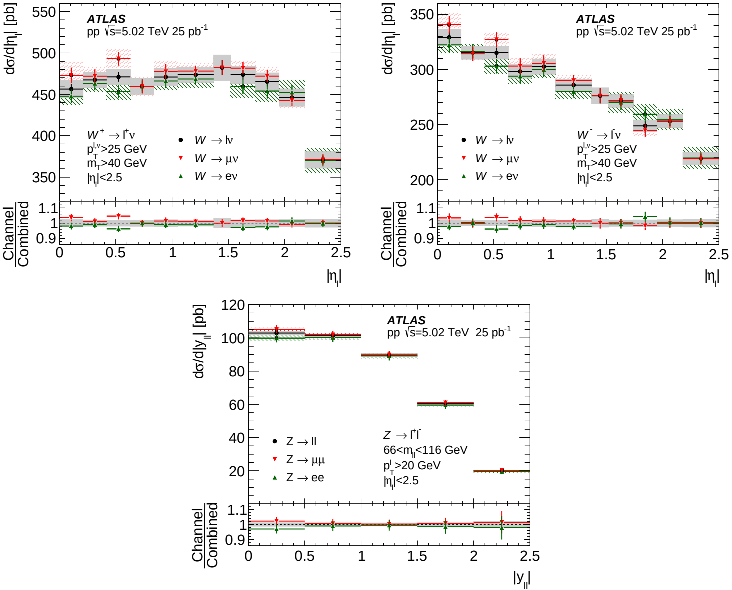

W/Z bosons in pp: Integrated cross-sections

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PDF set	$\sigma^{\text{fid}}_{W^+}$ [pb]	$\sigma^{\text{fid}}_{W^-}$ [pb]	σ^{fid}_{Z} [pb]	$\sigma^{\text{tot}}_{W^+}$ [pb]	$\sigma^{\text{tot}}_{W^-}$ [pb]	σ^{tot}_{Z} [pb]
CT14 NNLO	2203^{+62}_{-64}	1379^{+34}_{-42}	356^{+8}_{-10}	4299^{+112}_{-113}	2862^{+63}_{-77}	648^{+14}_{-16}
NNPDF3.1	2280 ± 27	1403 ± 17	371 ± 4	4393 ± 48	2926 ± 31	682 ± 7
MMHT2014	2244^{+40}_{-39}	1393^{+24}_{-28}	363^{+6}_{-5}	4357^{+75}_{-73}	2902^{+49}_{-57}	660^{+11}_{-10}
HERAPDF2.0	2291^{+92}_{-61}	1440^{+42}_{-27}	369^{+14}_{-7}	4459^{+180}_{-108}	3042^{+94}_{-56}	675^{+24}_{-13}
ABMP16	2205 ± 19	1363 ± 14	362 ± 3	4298 ± 37	2819 ± 32	654 ± 6
Additional uncertainties						
α_S	± 17	${}^{+13}_{-11}$	${}^{+3}_{-2}$	${}^{+31}_{-29}$	${}^{+27}_{-22}$	± 5
μ_R, μ_F scales	${}^{+18}_{-11}$	${}^{+11}_{-8}$	± 1	${}^{+25}_{-36}$	${}^{+13}_{-15}$	${}^{+3}_{-4}$
Data	2266 ± 53	1401 ± 33	374.5 ± 8.6	–	–	–

- W^+: 2266 ± 9 (stat.) $\pm$ 29 (syst.) $\pm$ 43 (lumi) pb
- W^-: 1401 ± 7 (stat.) $\pm$ 18 (syst.) $\pm$ 27 (lumi) pb
- Z: 374.5 ± 3.4 (stat.) $\pm$ 3.6 (syst.) $\pm$ 7.0 (lumi) pb

$R^{\text{fid}}_{W^+/W^-}$	1.617 ± 0.012 (stat) $\pm$ 0.003 (syst)
$R^{\text{fid}}_{W/Z}$	9.81 ± 0.13 (stat) $\pm$ 0.01 (syst)
$R^{\text{fid}}_{W^+/Z}$	6.06 ± 0.08 (stat) $\pm$ 0.01 (syst)
$R^{\text{fid}}_{W^-/Z}$	3.75 ± 0.05 (stat) $\pm$ 0.01 (syst)

W/Z bosons in pp: Systematic uncertainties

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	$\delta\sigma_{W^+}$ [%]	$\delta\sigma_{W^-}$ [%]	$\delta\sigma_{Z}$ [%]
Trigger efficiency	0.2	0.2	<0.1
Reconstruction efficiency	0.2	0.2	0.4
Identification efficiency	0.6	0.5	1.0
Isolation efficiency	0.4	0.4	0.6
Electron p_T resolution	<0.1	<0.1	0.1
Electron p_T scale	0.3	0.2	0.1
Hadronic recoil calibration	0.5	0.4	–
Multi-jet background	0.7	0.8	<0.1
Electroweak+top background	0.1	0.1	<0.1
Data statistical uncertainty	0.6	0.7	1.4

	$\delta\sigma_{W^+}$ [%]	$\delta\sigma_{W^-}$ [%]	$\delta\sigma_{Z}$ [%]
Trigger efficiency	1.4	1.4	0.4
Reconstruction efficiency	0.2	0.2	0.4
Isolation efficiency	0.4	0.4	0.7
Muon p_T resolution	0.1	<0.1	<0.1
Muon p_T scale	0.1	0.1	<0.1
Hadronic recoil calibration	0.5	0.5	–
Multi-jet background	0.1	0.2	<0.1
Electroweak+top background	0.1	0.2	<0.1
Data statistical uncertainty	0.5	0.6	1.2

W/Z bosons in pp: Lepton charge asymmetry

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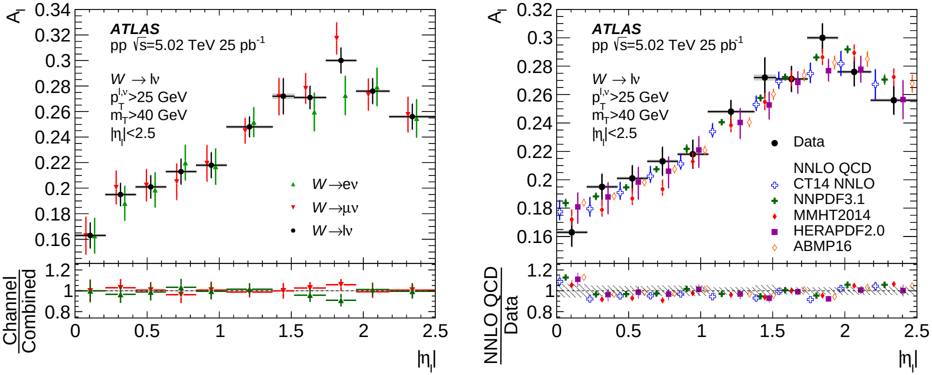
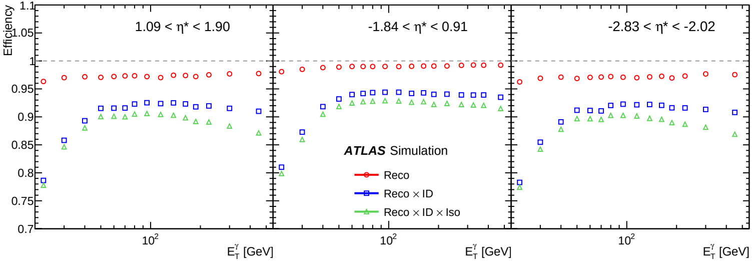
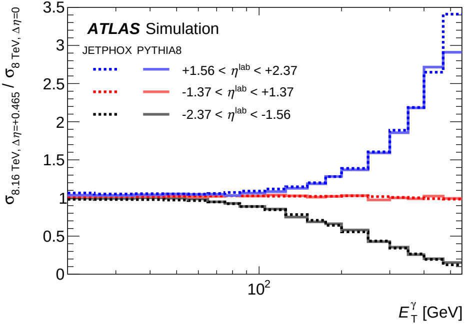


$$A_\ell(|\eta_\ell|) = \frac{d\sigma_{W^+}/d|\eta_\ell| - d\sigma_{W^-}/d|\eta_\ell|}{d\sigma_{W^+}/d|\eta_\ell| + d\sigma_{W^-}/d|\eta_\ell|}$$

Prompt photons in p+Pb: Efficiencies, extrapolation

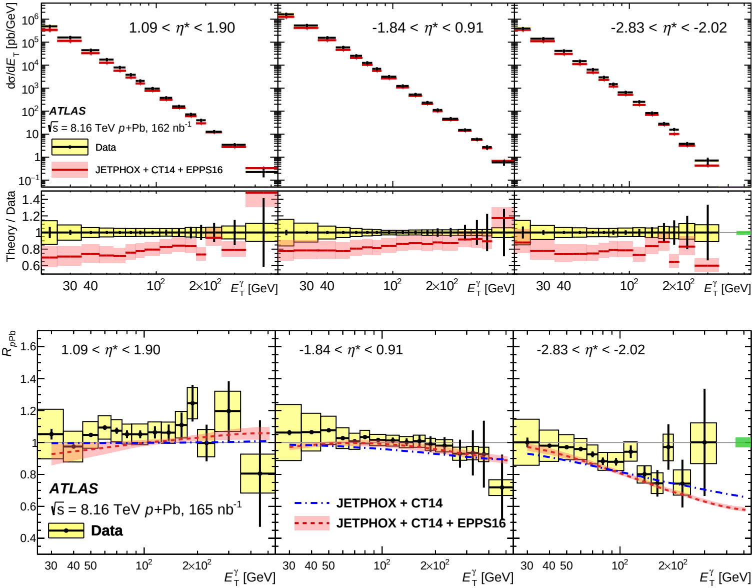
Phys. Lett. B 796 (2019) 230





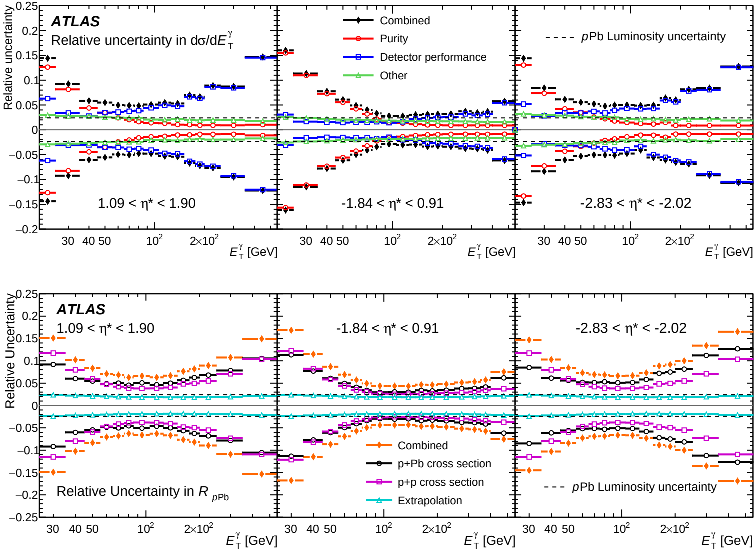
Prompt photons in p+Pb: Cross-sections, $R_{p\mathrm{Pb}}$

Phys. Lett. B 796 (2019) 230



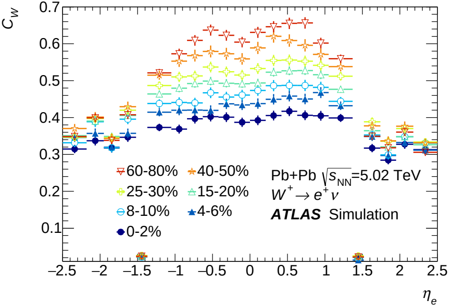
Prompt photons in p+Pb: Systematic uncertainties

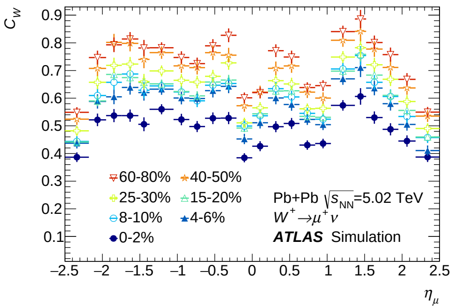
Phys. Lett. B 796 (2019) 230



W bosons in Pb+Pb: Correction factors

Eur. Phys. J. C 79 (2019) 935

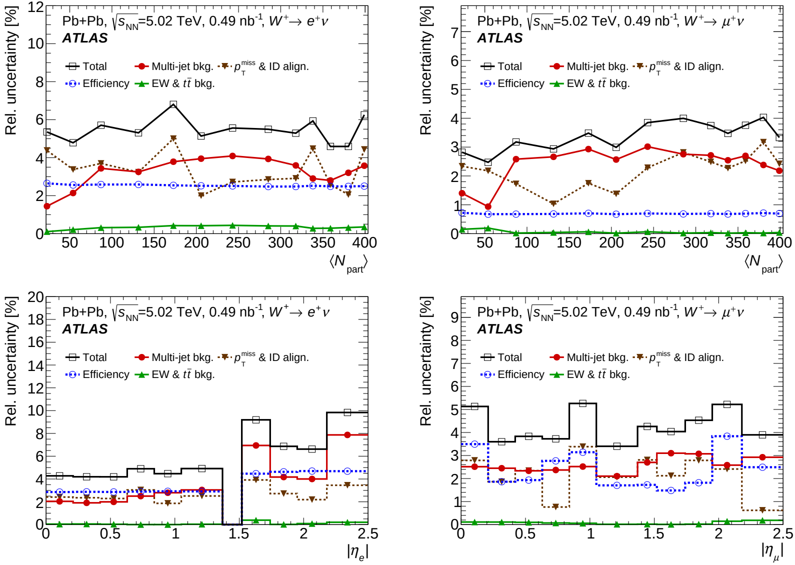




- C_W factors account mainly for detector effects, such as lepton calibration and efficiencies, and p_T^{miss} reconstruction.

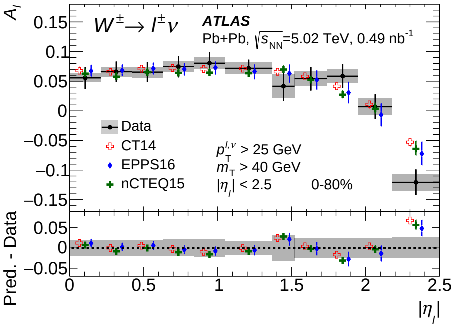
W bosons in Pb+Pb: Systematic uncertainties

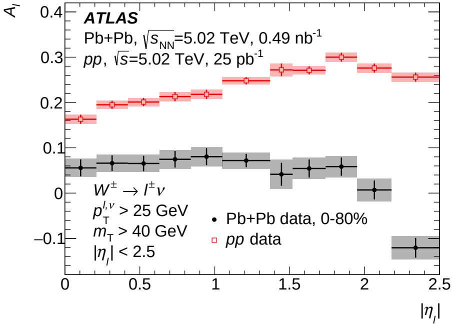
Eur. Phys. J. C 79 (2019) 935



W bosons in Pb+Pb: Lepton charge asymmetry

Eur. Phys. J. C 79 (2019) 935





$$A_\ell(|\eta_\ell|) = \frac{d\sigma_{W^+}/d|\eta_\ell| - d\sigma_{W^-}/d|\eta_\ell|}{d\sigma_{W^+}/d|\eta_\ell| + d\sigma_{W^-}/d|\eta_\ell|}$$

Z bosons in Pb+Pb: Lepton efficiencies

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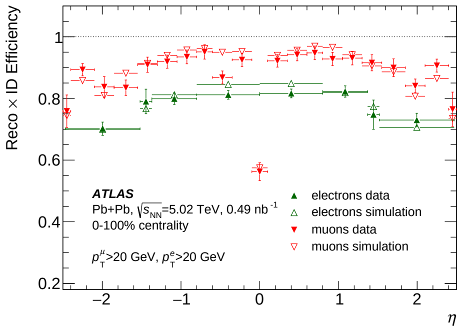
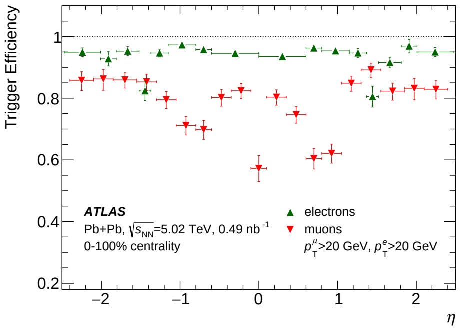
reco + ID



trigger



- Efficiencies measured with the tag-and-probe method in $Z \to \ell\ell$ events in data and simulation.

Z bosons in Pb+Pb: Systematic uncertainties

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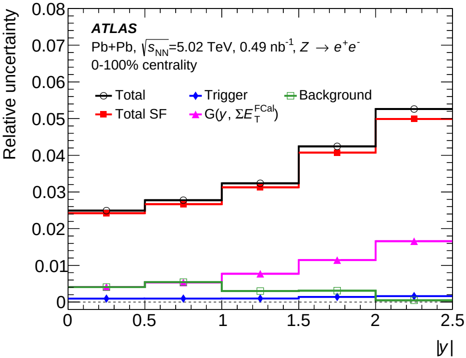
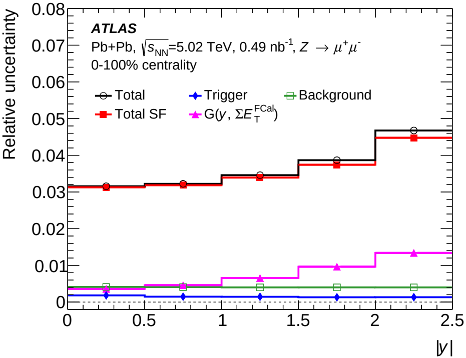
electrons



muons



W/Z bosons in Pb+Pb: Yield ratio

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