Probing the initial state of heavy-ion collisions with electroweak bosons in ATLAS

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Outline

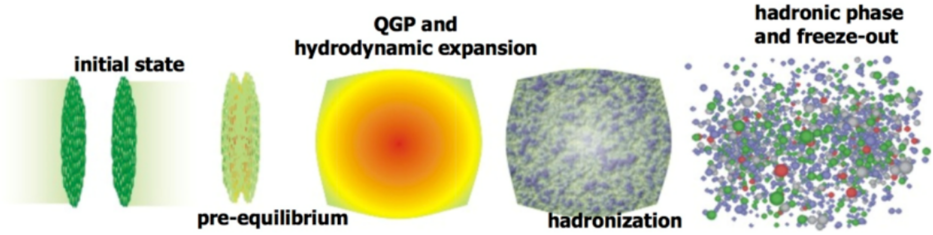
- Connection between electroweak boson measurements and studies of the initial state of heavy-ion collisions:
  - Collision centrality and geometry
  - Cold nuclear matter effects
- Measurement of prompt photon production in p+Pb collisions:
  - Results
  - Comparison to theory

  Phys. Lett. B 796 (2019) 230
- Measurements of W and Z boson production in Pb+Pb collisions:
  - Corrections for detector effects
  - Results
  - Comparison to theory

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

  arXiv:1910.13396
- Summary and outlook

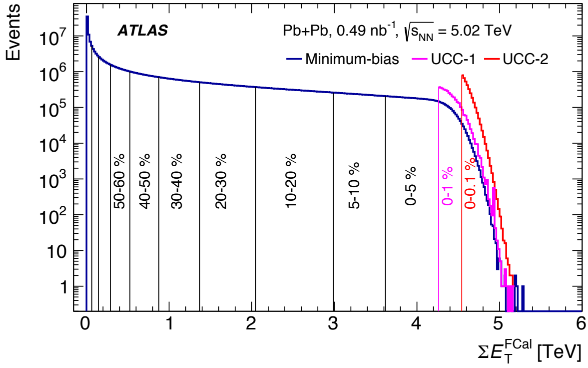
Centrality and geometry of heavy-ion collisions



- Relativistic heavy-ion collisions produce a **hot and dense medium (quark-gluon plasma, QGP)**, in which particles with colour charge lose energy.
- In an experiment, the centrality and geometry of a collision, which impacts the amount of energy loss, is not known for each collision.
- Instead events are categorised in centrality classes based on the Glauber model.
- Electroweak (γ, W, Z) bosons or their leptonic decay products ($\ell = e, \mu$) are not affected significantly by the QGP $\rightarrow$ useful tools for **cross-checks and calibration** of experimental **centrality determination**.

Experimental determination of centrality and geometry

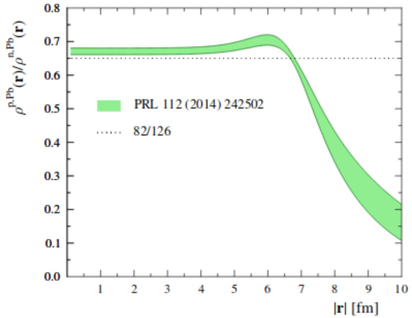
- The determination of collision centrality in an experiment requires a detector-level observable, which is highly correlated with centrality.
- Predictions based on Monte Carlo Glauber model are fitted to the data.
- Events are categorised in centrality classes based on this fit.
- The Glauber model allows to extract geometric parameters such as N_{part} or N_{coll} for each class.

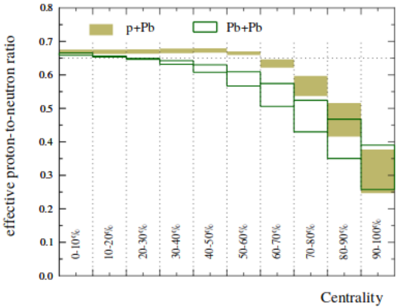


Isospin and neutron skin effects

- Isospin effect refers to the different proportions of *u* and *d* quarks in a nucleus compared to the proton (due to the presence of neutrons).
- Neutrons in a nucleus have a wider radial distribution than protons → ”neutron skin”.
- Neutron skin impacts the proton-to-neutron ratio in different centrality classes.
- In particluar *W* boson production sensitive to isospin and neutron skin effects:

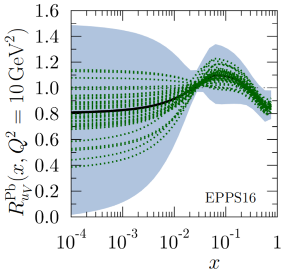
$$u\bar{d} \rightarrow W^{+},\ d\bar{u} \rightarrow W^{-}$$

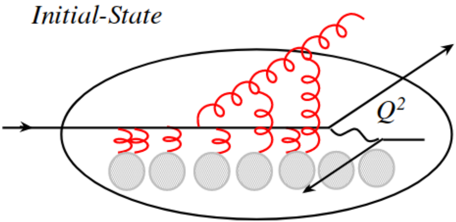




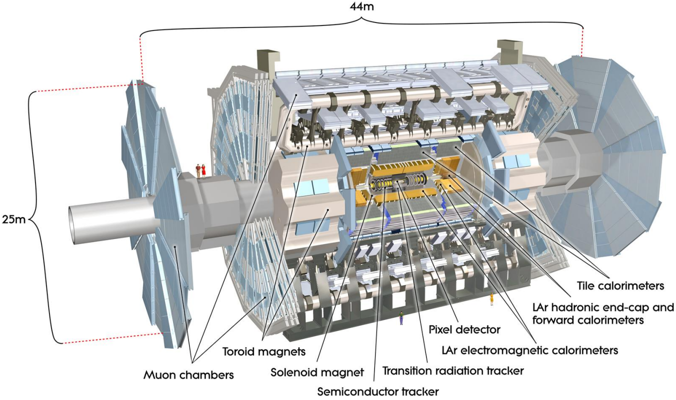
Cold nuclear matter effects

- The structure of nucleons bound in a nucleus differs from the structure of free nucleons, in particular the parton distribution functions (PDFs) are modified.
- **Nuclear modifications to parton distribution functions (nPDFs)** are based on global fits to data, similar to standard PDF fits.
- **Initial-state partons can lose energy** through soft interactions with partons in the target nucleus **before a hard scattering** occurs.
- **Cold nuclear matter effects** are present in nucleus-nucleus collisions, but can be better studied in **proton-nucleus collisions**.





- Measurements of prompt photons and of W/Z bosons in **leptonic decay channels** make use of all major components of ATLAS:
    - **Charged particle tracking** in $|\eta| < 2.5 \rightarrow$ electrons, muons, MET
    - **Calorimeter system** in $|\eta| < 4.9 \rightarrow$ electrons, photons, centrality, ZDC
    - **Muon reconstruction** in $|\eta| < 2.4$ (muon spectrometer + inner detector)



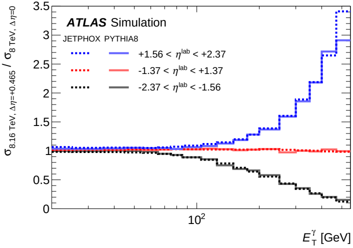
Datasets:

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

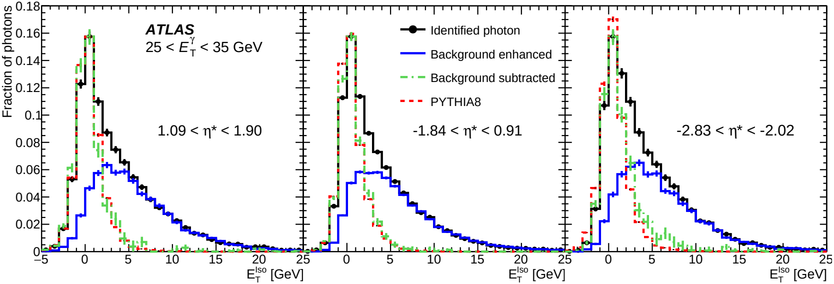
Prompt photons in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV

Prompt photons in p+Pb: Measurement strategy

Phys. Lett. B 796 (2019) 230



- Events collected with **single-photon triggers** (p_T^γ thresholds between 15 GeV and 35 GeV).
- Photons required to pass reconstruction quality and isolation selections.
- Kinematic selections: $p_T^\gamma > 20$ GeV, $|\eta_\gamma| < 1.37$ or $1.56 < |\eta_\gamma| < 2.37$
- **Background estimation using sidebands** in isolation and identification (purity between 45% and 99%).
- No direct reference measurement in *pp* collisions, **existing results at 8 TeV extrapolated to 8.16 TeV** using NLO calculations.



Prompt photons in p+Pb: Nuclear modification factor

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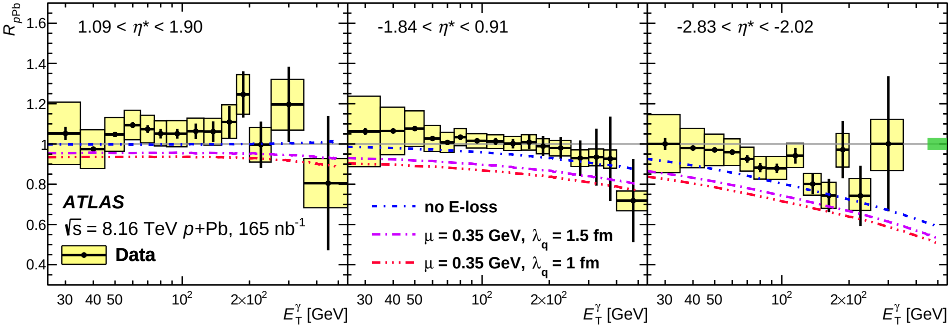
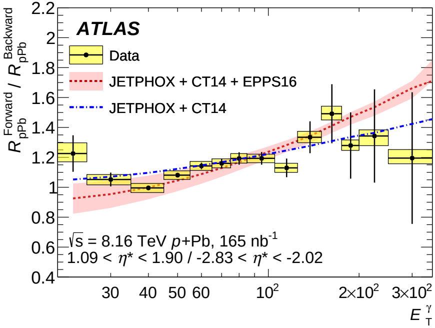
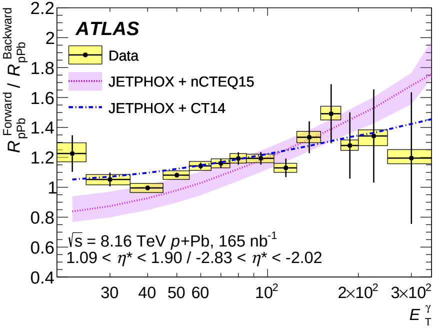


- **Nuclear modification factor** $R_{pPb} = \frac{d\sigma^{p+Pb\to\gamma+X}/dE_T^\gamma}{A\cdot d\sigma^{pp\to\gamma+X}/dE_T^\gamma}$ ($A = 208$ is the Pb mass number)
- At **forward and central rapidities**, nuclear effects are small resulting in R_{pPb} values **consistent with unity**.
- For **backward 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**.

Prompt photons in p+Pb: Forward-backward R_{pPb} ratios

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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV

W/Z bosons in Pb+Pb: Measurement procedure

- W/Z boson **production yields** are measured in **fiducial phase-space volumes**:
  - $p_{\mathrm{T}}^{\ell} > 25$ GeV, $|\eta_\ell| < 2.5$, $p_{\mathrm{T}}^{\nu} > 25$ GeV, $m_{\mathrm{T}} > 40$ GeV ($W^\pm \to \ell^\pm \nu$)
  - $p_{\mathrm{T}}^{\ell} > 20$ GeV, $|\eta_\ell| < 2.5$, $66 < m_{\ell\ell} < 116$ GeV ($Z \to \ell^+ \ell^-$)
- Normalised production yields are calculated as: $N_{W[Z]} = \frac{S_{W[Z]} - B_{W[Z]}}{C_{W[Z]} \cdot N_{\mathrm{evt}} \cdot \langle T_{\mathrm{AA}} \rangle}$
  - $S_{W[Z]}$ and $B_{W[Z]}$ are the number of selected events in data and the expected number of background events, respectively.
  - $C_{W[Z]}$ are correction factors evaluated from simulation which account mainly for detector-related inefficiencies.
  - N_{evt} is the total number of minimum-bias events.
  - $\langle T_{\mathrm{AA}} \rangle$ is the mean nuclear thickness function.
- **Nuclear modification factor** defined using pp cross-sections:

$$R_{\mathrm{AA}} = N_{W[Z]} / \sigma_{W[Z]}^{pp}$$

- **Lepton charge asymmetry** defined using differential W boson yields:

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

W bosons in Pb+Pb: Measurement strategy

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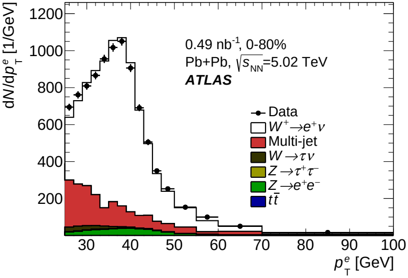
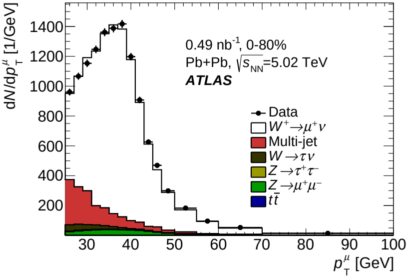
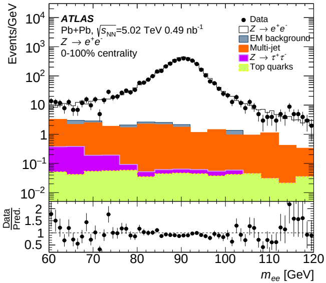


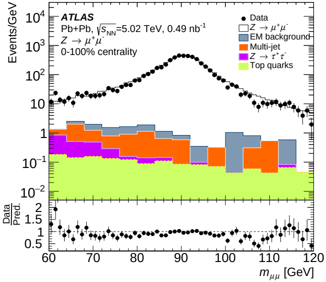


- Events collected with **single-lepton triggers** (thresholds at $p_T = 15/8$ GeV for e/μ).
- Leptons required to pass reconstruction quality and isolation selections + match trigger.
- Kinematic selection: $p_T^\ell > 25$ GeV, $|\eta_{e(\mu)}| < 2.47(2.4)$
- Selection on **missing transverse momentum reconstructed from charged-particle tracks**: $p_T^{miss} > 25$ GeV, $m_T > 40$ GeV
- Additional **veto on Z boson candidate** events.
- Between **18000** and **27000** $W^\pm \to \ell^\pm\nu$ **candidate events** selected per charge and decay channel.
- **Background levels**: **5-6% EW and $t\bar{t}$** estimated from simulation, **6-20% multi-jet** estimated with data-driven method.
- **ZDC** used to reject **photonuclear/EM background** in peripheral collisions, as well as **pile-up** events.

Z bosons in Pb+Pb: Measurement strategy

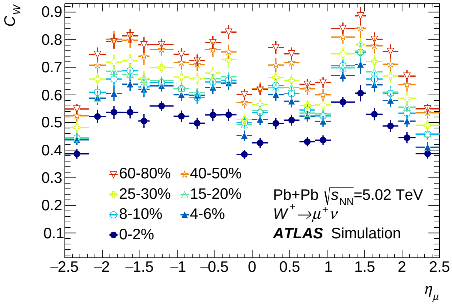
arXiv:1910.13396

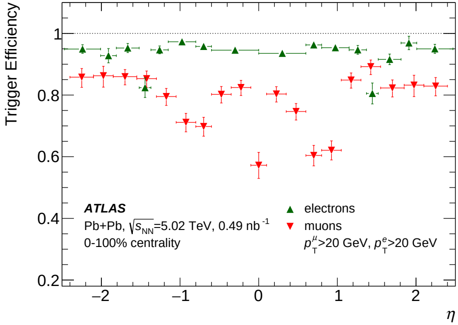




- Events collected with **single-lepton triggers** (thresholds at $p_{\mathrm{T}} = 15/8$ GeV for e/μ).
- Leptons required to pass reconstruction quality selections + match trigger for at least one lepton.
- Kinematic selection: $p_{\mathrm{T}}^{\ell} > 20$ GeV, $|\eta_{e(\mu)}| < 2.47(2.4)$
- Selection of ***Z* boson candidate** events from **opposite-charge lepton pairs** with invariant mass $66 < m_{\ell\ell} < 116$ GeV.
- About **4000 (5000) $Z \rightarrow \ell^+\ell^-$ candidate events** selected in the electron (muon) channel.
- **Background levels**: **<0.5% EW and $t\bar{t}$** estimated from simulation, **0.5-2% multi-jet** and **EM** estimated with data-driven methods.
- Suppression of **photonuclear/EM background** in peripheral collisions by using **ZDC** and requiring **no rapidity gaps**.

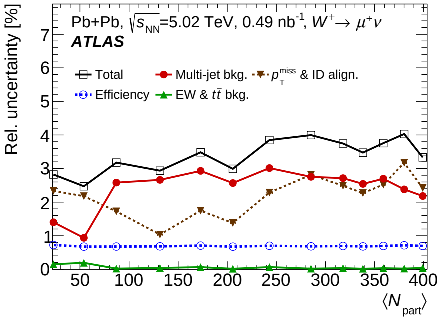
W/Z bosons in Pb+Pb: Detector corrections

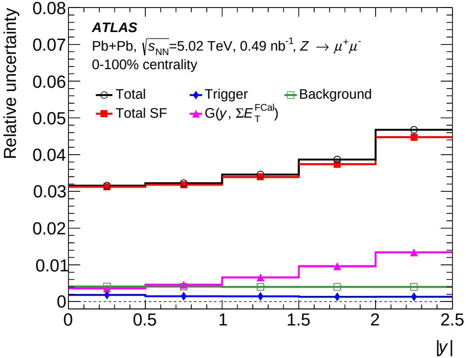




- **Many dedicated performance studies** were carried out for these measurements, since any detector inefficiencies or mis-calibrations need to be corrected for.
- Lepton efficiencies measured with the **tag-and-probe method in $Z \to \ell^+\ell^-$ events**.
- Correction factors $C_{W[Z]}$ account not only for lepton efficiencies, but also for lepton momentum calibrations, the reconstruction of missing transverse momentum (W), and small acceptance corrections.

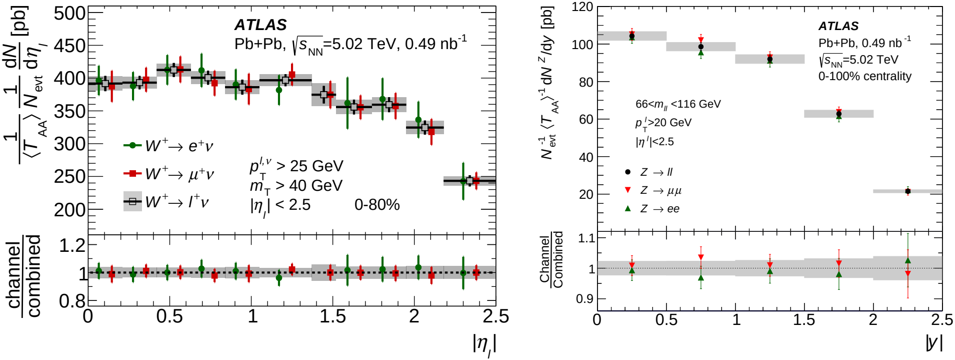
W/Z bosons in Pb+Pb: Systematic uncertainties





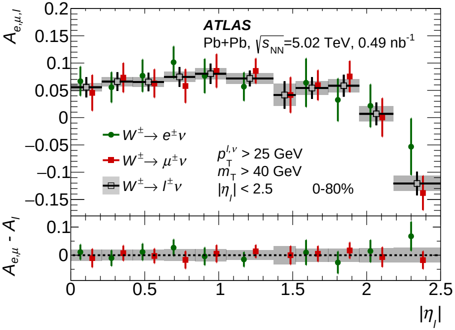
- Lepton- and p_T^{miss}-related uncertainties are propagated through their impact on correction factors $C_{W[Z]}$.
- **Largest systematic uncertainties**:
  - $W^\pm \to \ell^\pm \nu$: multi-jet background, p_T^{miss} reconstruction
  - $Z \to \ell^+\ell^-$: lepton efficiencies
- **Significant uncertainty** in peripheral collisions from $\langle T_{AA} \rangle$ uncertainty (not shown).

W/Z bosons in Pb+Pb: Channel comparison



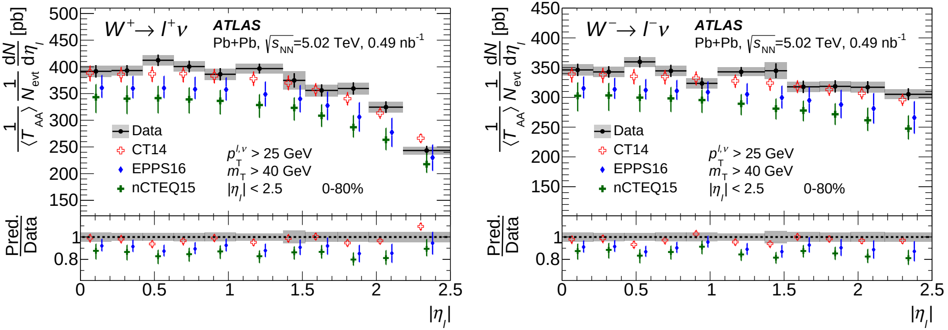
- For W bosons, there is a good agreement between yields measured in the two decay channels.
- Yields of Z bosons measured in the muon channel are systematically slightly larger than in the electron channel.
- Results from electron and muon channels are **combined, accounting for uncertainty correlations** across channels and measurement bins.

W bosons in Pb+Pb: Channel comparison



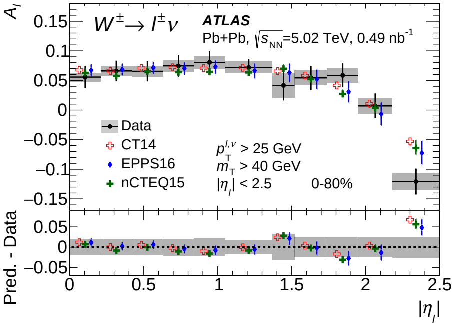
- **Lepton charge asymmetry** is calculated from differential W boson yields, separately for the electron/muon channels and for the combined results.
- Uncertainties are dominated by the statistical components, but systematic uncertainties also play a role.
- In general, a relatively **good agreement between the channels** is observed.

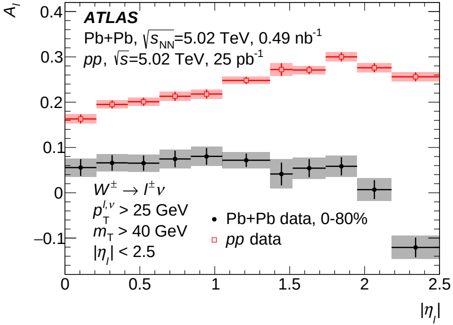
W bosons in Pb+Pb: $|\eta_\ell|$-differential yields



- **Lepton pseudorapidity differential yields** measured in **fiducial** phase-space volume.
- Data are compared to theoretical predictions calculated at NLO in QCD with MCFM using CT14 free-nucleon PDFs and EPPS16 or nCTEQ15 nPDFs.
- Predictions using CT14 PDFs describe data best, while predictions using nPDFs underestimate data by 10-20%.

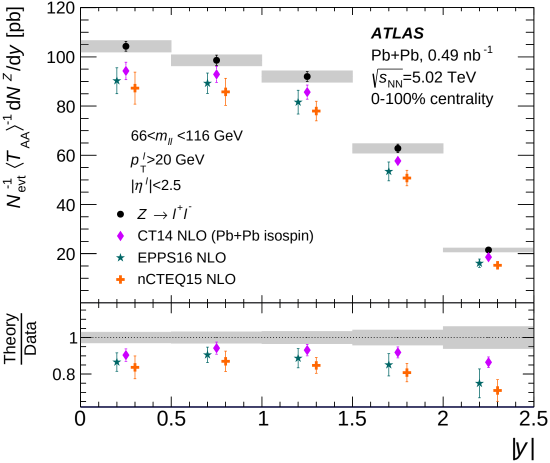
W bosons in Pb+Pb: Lepton charge asymmetry





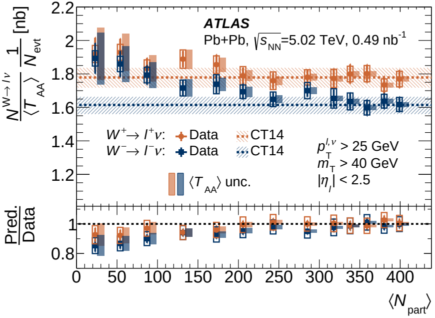
- **Systematic uncertainties**, which are partially correlated between W^+ and W^- boson measurements, are **reduced**.
- **Good agreement of predictions** from all considered **(n)PDF** sets with measured asymmetry.
- Much smaller asymmetry and different shape than in *pp* collisions are a consequence of the **isospin effect**.

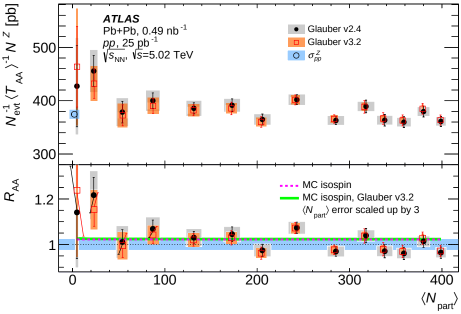
Z bosons in Pb+Pb: $|y_{\ell\ell}|$-differential yields



- **Rapidity differential yields** measured in **fiducial** phase-space volume.
- Predictions using free-nucleon CT14 PDFs are closest to data, but underestimate them slightly.
- Predictions using nPDFs deviate from measurements by $1-3\sigma$.

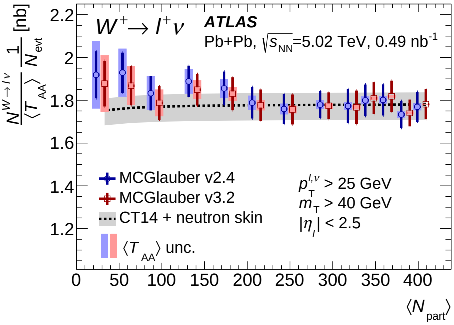
W/Z bosons in Pb+Pb: Yields vs. $\langle N_{\text{part}} \rangle$

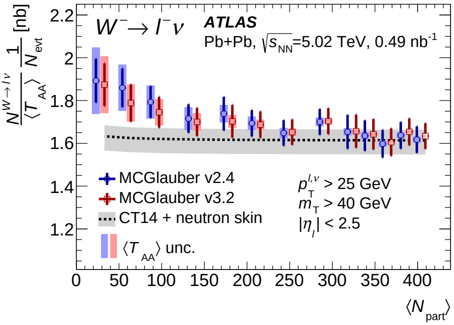




- Yields are approximately constant with centrality (represented by $\langle N_{\text{part}} \rangle$).
- For W bosons, there is a hint of increase in the most peripheral collisions, but deviations from a constant are not larger than 1.7σ.
- Measurements in peripheral collisions limited by normalisation ($\langle N_{\text{part}} \rangle$) uncertainty.
- Data are in good agreement with predictions using free-nucleon CT14 PDFs and accounting for isospin effect.

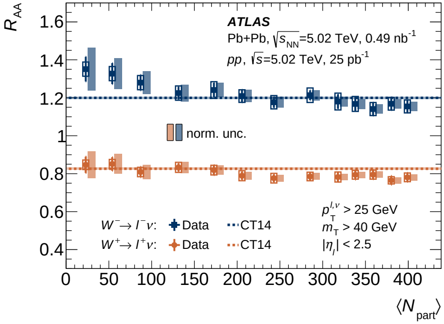
W bosons in Pb+Pb: Yields vs. $\langle N_{\text{part}} \rangle$





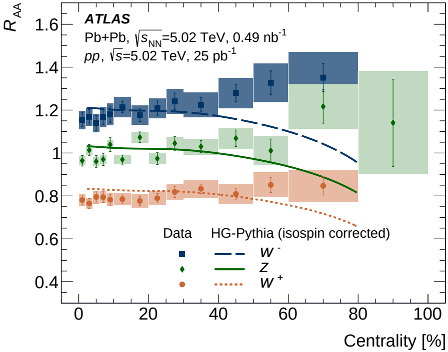
- Comparison of yields extracted using geometric parameters from two versions of MCGlauber code.
- Effect on measured yields is smaller than measurement uncertainties.
- By using MCGlauber v3.2, neutron skin effect can be incorporated into predictions, since it provides different radial profiles for protons and neutrons.
- Experimental sensitivity to neutron skin effect is limited.

W bosons in Pb+Pb: Nuclear modification factor



- Nuclear modification factor calculated using *pp* cross-sections (EPJC 79 (2019) 128).
- Trends similar as for normalised production yields.
- Deviations from unity are expected from isospin effect.
- Deviations from free-nucleon CT14 PDF predictions do not exceed 1.8σ.

W/Z bosons in Pb+Pb: Centrality bias



- Comparison of measured nuclear modification factors with predictions incorporating centrality bias from HG-PYTHIA model.
- Recent ALICE measurement of charged-hadron suppression is in agreement with HG-PYTHIA.
- Trends for W/Z bosons do not follow the HG-PYTHIA prediction, but details of soft-particle production are different.

Summary and outlook

Summary

- Prompt photons in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV:
  - model with **no significant initial-state energy loss** preferred
  - **best description of data using free-nucleon PDFs**, but nPDF predictions also consistent with data
- W and Z bosons in Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV:
  - **data best described using free-nucleon PDFs**, while nPDF predictions tend to underestimate data
  - normalised **yields and R_{AA}** approximately **constant with N_{part}/centrality**, with hint of increase in peripheral collisions
  - limited experimental sensitivity to **neutron skin effect**
  - trends with centrality do not follow **centrality bias** predictions

Outlook

- Larger dataset from Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV (increase in luminosity by factor of 3.5!) was collected in 2018.
- Measurement of W boson production in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV ongoing.

Additional slides