Heavy electroweak boson production in Pb+Pb and *pp* collisions with ATLAS

Jakub Kremer for the ATLAS Collaboration

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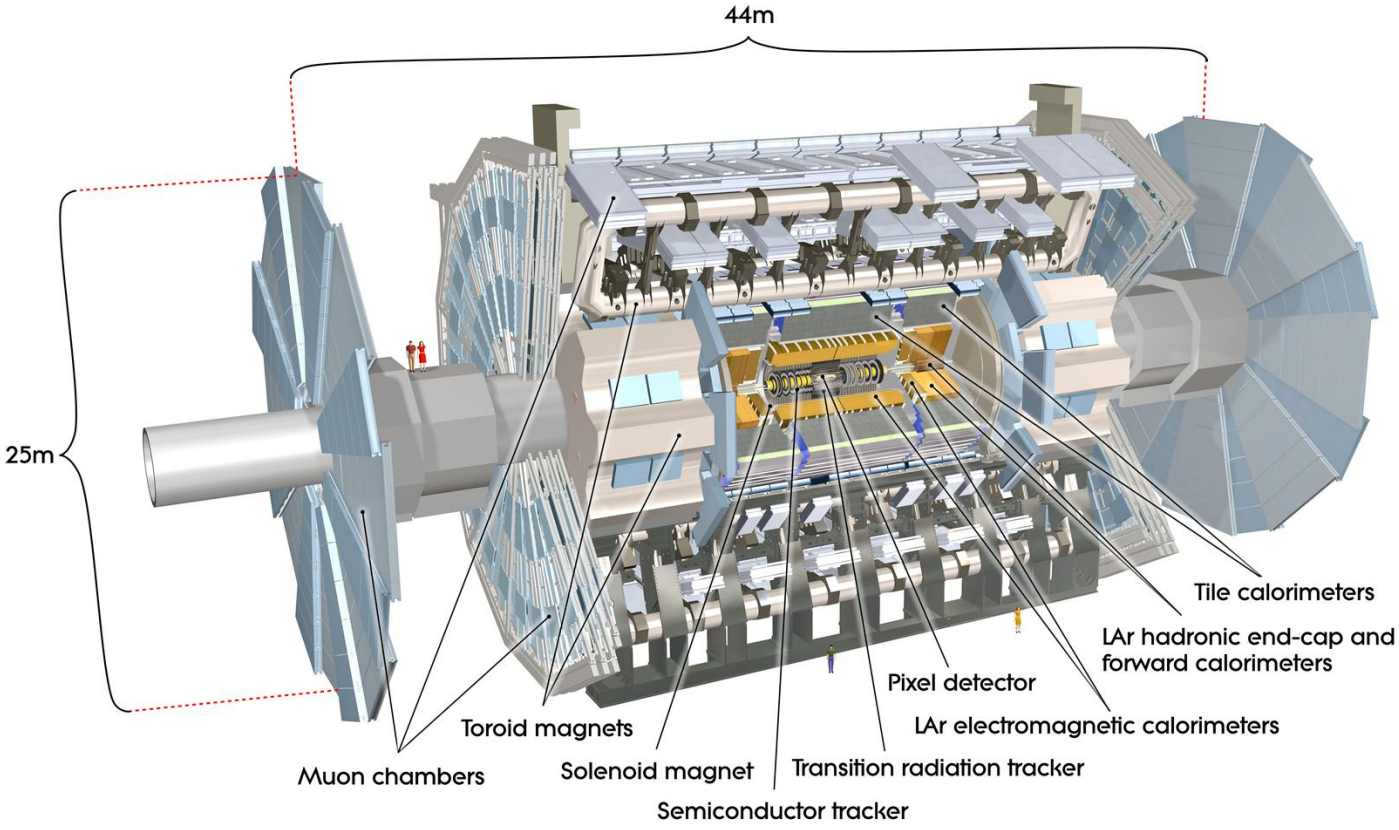
AGH University of Science and Technology, Kraków, Poland

Introduction

- Heavy electroweak bosons are not expected to be affected by a strongly interacting **quark-gluon plasma** as created in nucleus-nucleus collisions at LHC energies.
- They give insight into **collision centrality and geometry** through T_{AA} scaling.
- EW boson production in nucleus-nucleus collisions is affected by **nuclear modifications of PDFs (nPDFs)**.
- Measurements in proton-proton collisions are used as **reference**, but also provide constraints on **free proton PDFs**.
- Presentation of results from:
  - W/Z production in pp at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV (2015 dataset): ATLAS-HION-2018-02 NEW!
  - W production in Pb+Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV: ATLAS-CONF-2017-067
  - Z production in Pb+Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV: ATLAS-CONF-2017-010
- Focus on leptonic final states ($W^{\pm} \to \ell^{\pm}\nu$, $Z \to \ell^{+}\ell^{-}$, where $\ell = e,\ \mu$):
  - high-p_{T} leptons from EW boson decays do not interact significantly with QGP
  - excellent lepton reconstruction capabilities of ATLAS

ATLAS detector / Datasets

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

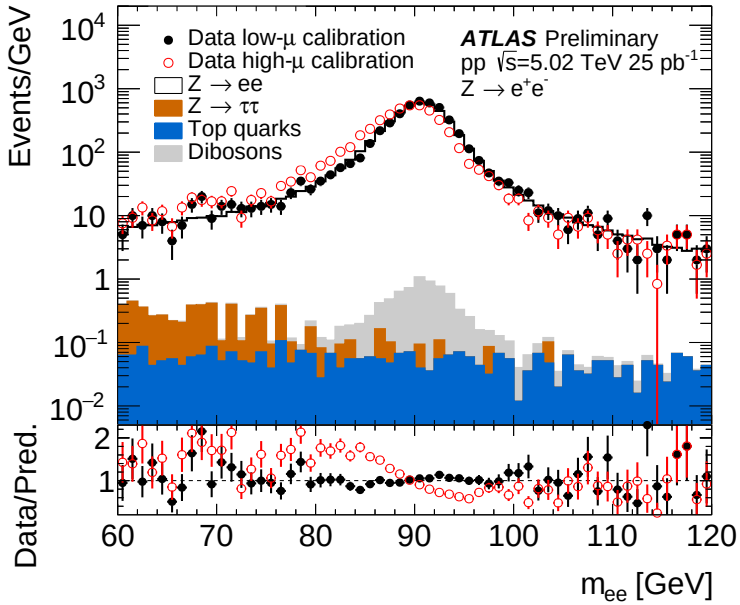


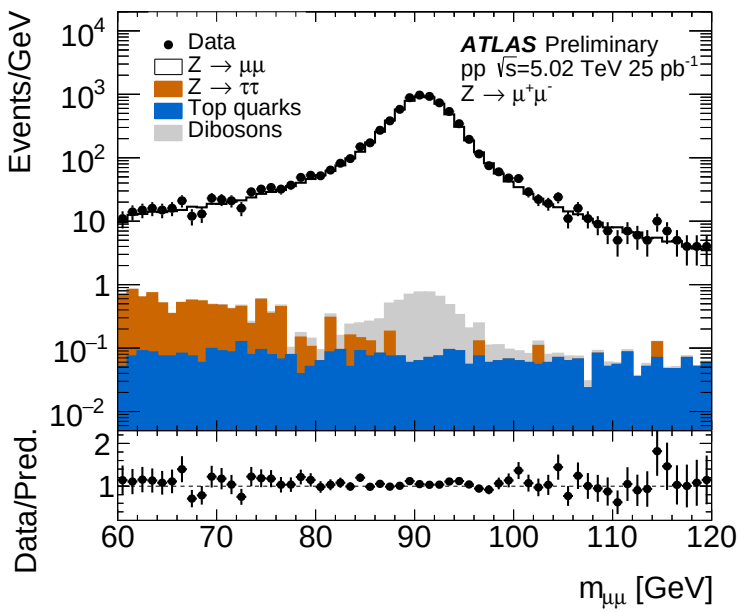
Datasets:

- Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV: 0.49 nb^{-1} (2015)
- *pp* collisions at $\sqrt{s} = 5.02$ TeV: 25 pb^{-1} (2015)
- **Luminosity uncertainty of 1.9%** for *pp* dataset.

Z bosons in pp: Measurement strategy

ATLAS-HION-2018-02

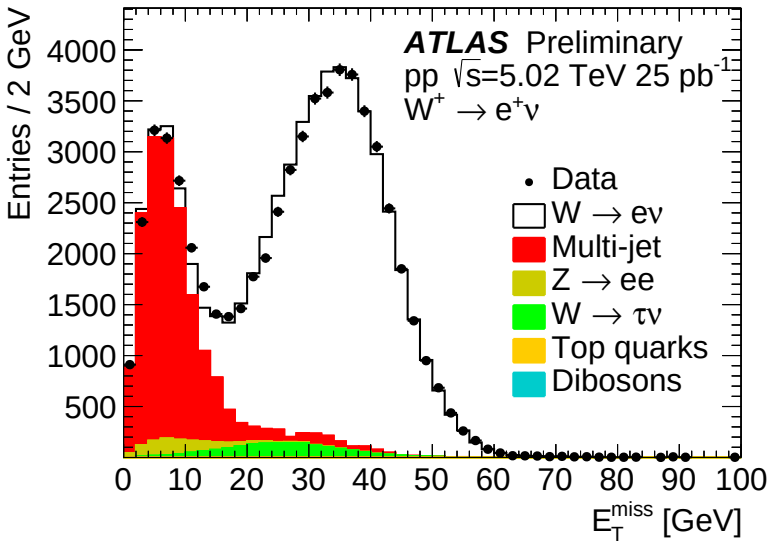


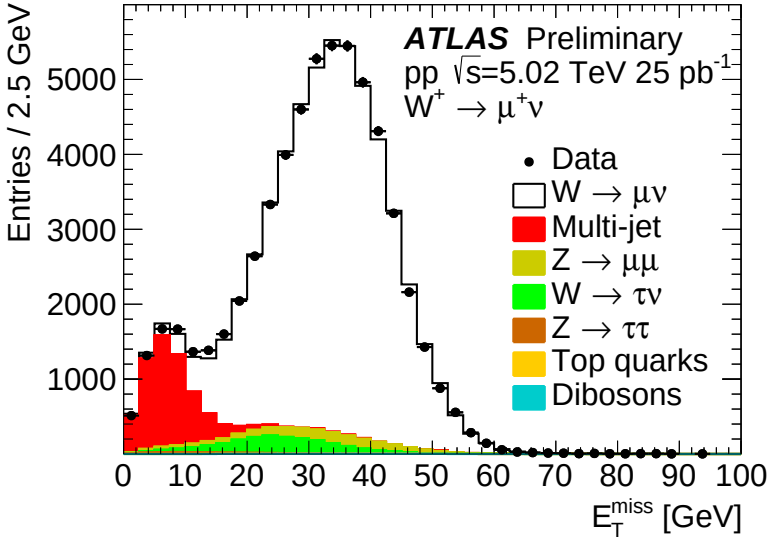


- Events collected with **single-lepton triggers** ($p_{\mathrm{T}}^{e} = 15$ GeV and $p_{\mathrm{T}}^{\mu} = 14$ GeV thresholds).
- Leptons required to pass reconstruction quality and isolation selections.
- Kinematic selections: $p_{\mathrm{T}}^{e(\mu)} > 20$ GeV, $|\eta_e| < 1.37$ or $1.52 < |\eta_e| < 2.47$, $|\eta_\mu| < 2.4$
- Opposite-charge dilepton pairs in mass range: $66 < m_{\mu\mu} < 116$ GeV
- One of the leptons required to match trigger.
- Roughly **4800 (7400)** events with $Z \to ee$ ($Z \to \mu\mu$) **candidates** found.
- Dedicated **low-pileup electron energy calibration** helps.
- **Subtracted backgrounds** ($Z \to \tau\tau$, $t\bar{t}$ and dibosons from MC, multi-jet from data) **at the level of 0.3%**.
- Corrections applied for trigger, reconstruction and isolation efficiencies.

W bosons in pp: Measurement strategy

ATLAS-HION-2018-02

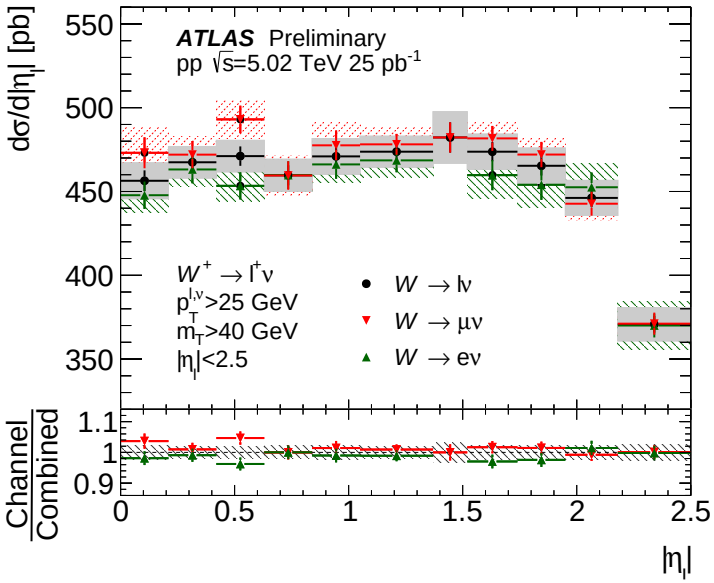


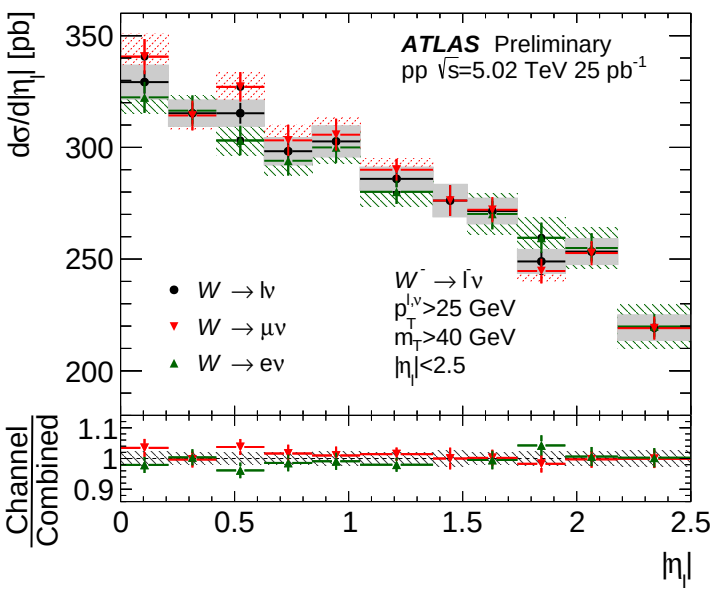


- Events collected with **single-lepton triggers** ($p_{\mathrm{T}}^{e} = 15$ GeV and $p_{\mathrm{T}}^{\mu} = 14$ GeV thresholds).
- Leptons required to pass reconstruction quality and isolation selections + match trigger (allow exactly one per event - **veto on Z boson candidates**).
- Kinematic selections: $p_{\mathrm{T}}^{e(\mu)} > 25$ GeV, $|\eta_e| < 1.37$ or $1.52 < |\eta_e| < 2.47$, $|\eta_\mu| < 2.4$
- Selection on **missing transverse momentum** calculated using **hadronic recoil reconstructed from particle flow**: $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV, $m_{\mathrm{T}} > 40$ GeV
- **$\sim$38000 (44000) $W^+ \to e^+\nu$ ($W^+ \to \mu^+\nu$) candidates**
- **$\sim$24000 (27000) $W^- \to e^-\nu$ ($W^- \to \mu^-\nu$) candidates**
- **Subtracted backgrounds**: **2-6% EW, top-quark and diboson** estimated from MC, **0.1-1.4% multi-jet** estimated with data-driven method
- Corrections applied for trigger, reconstruction and isolation efficiencies, as well as **hadronic recoil calibration**.

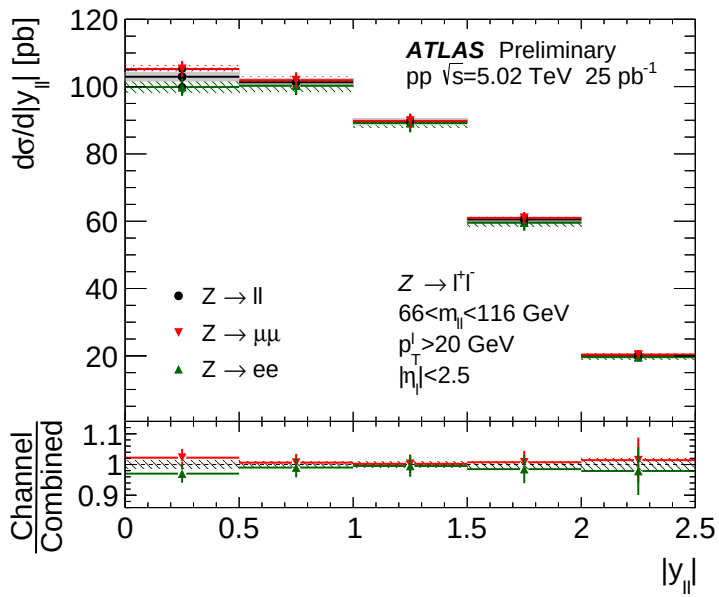
W/Z bosons in pp: Fiducial cross-sections

ATLAS-HION-2018-02





- W/Z boson **production cross-sections** 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 bosons)
  - $p_{\mathrm{T}}^{\ell} > 20$ GeV, $|\eta_{\ell}| < 2.5$, $66 < m_{\ell\ell} < 116$ GeV (Z bosons)
- Results from electron and muon channels are **combined** using the BLUE method, **accounting for uncertainty correlations** across channels and measurement bins.



Z bosons in pp: Differential cross-sections

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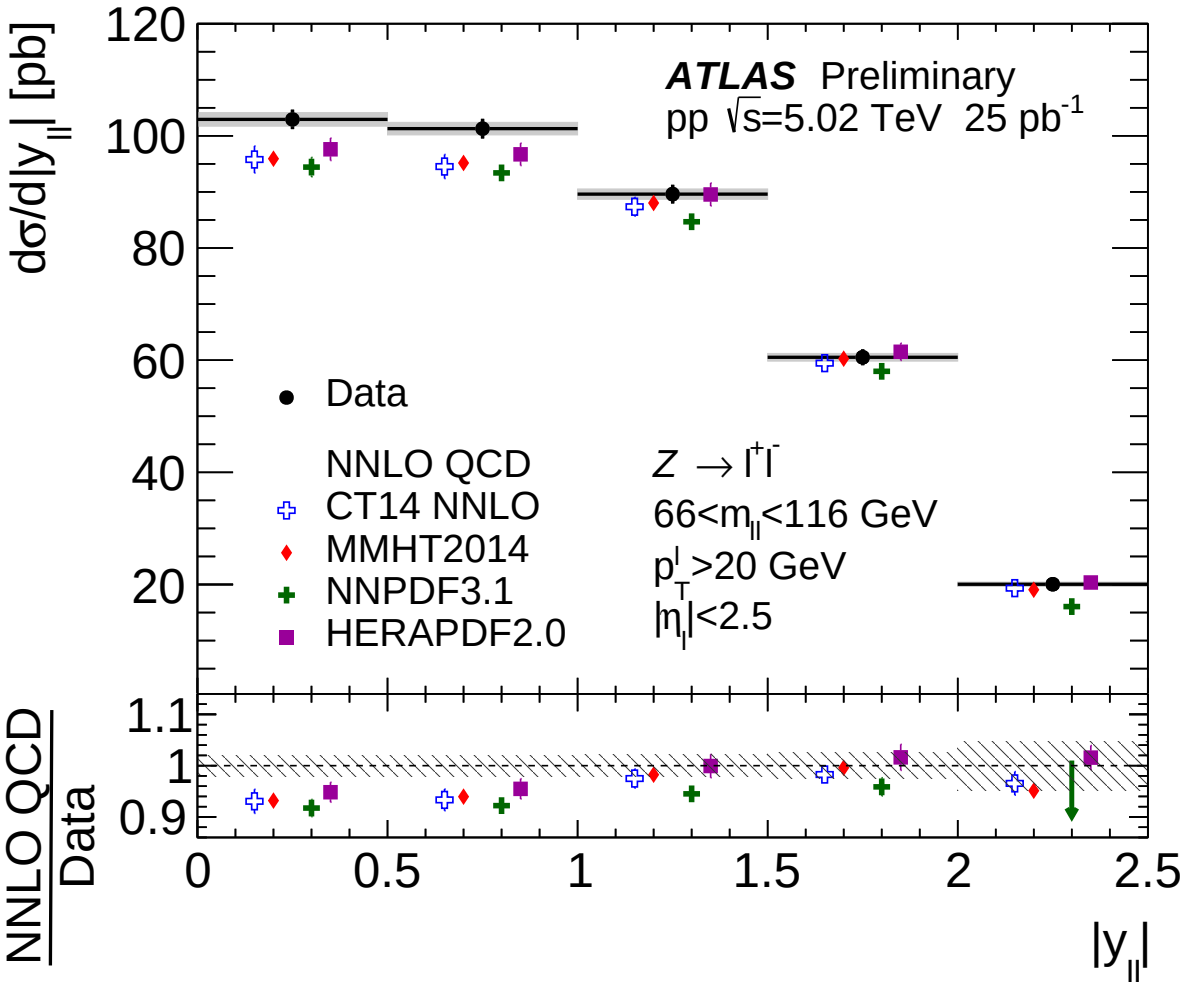
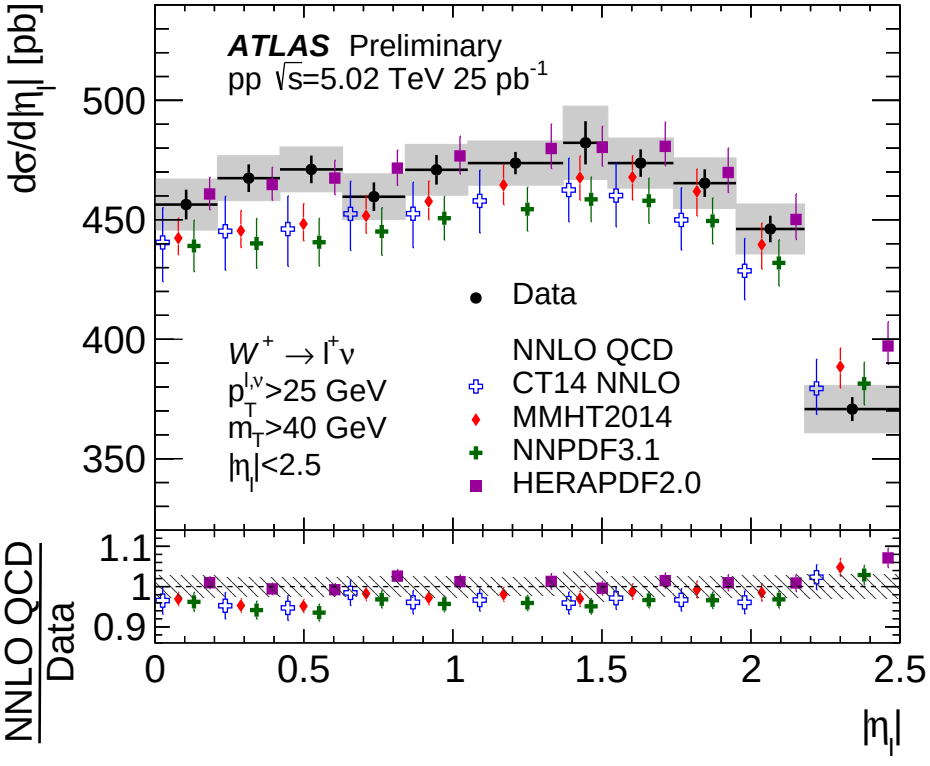
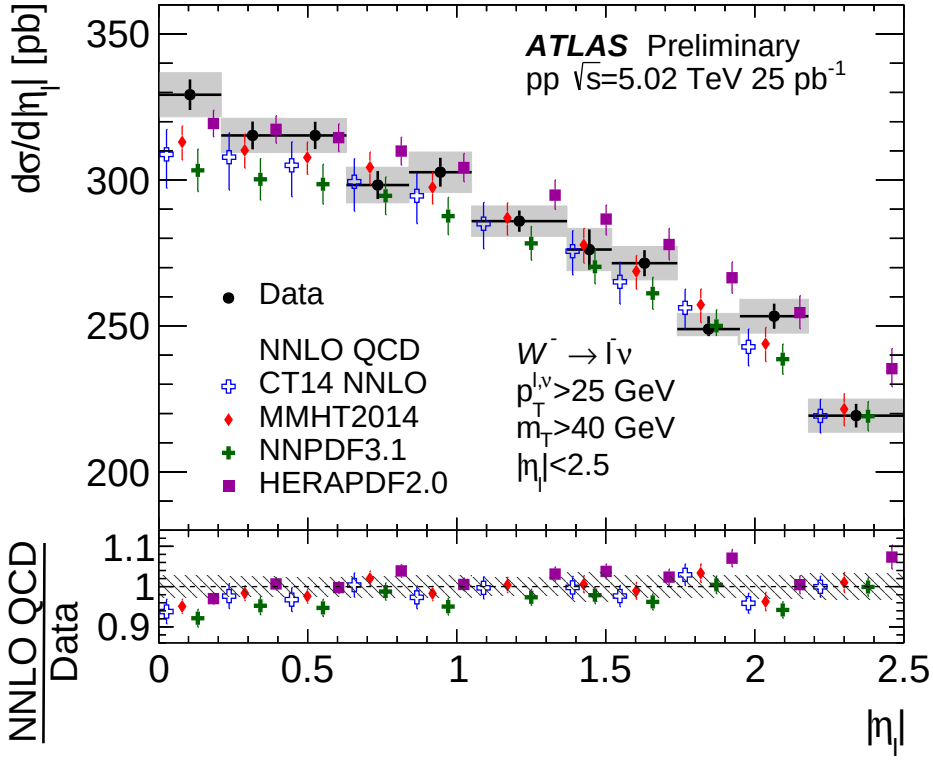


- **Rapidity differential cross-sections** measured in **fiducial** phase-space volume.
- **Combined results** are compared with several **theory predictions (different PDF sets)** calculated at **NNLO** using an optimised version of DYNNLO 1.5.
- At **central rapidities** ($|y_{\ell\ell}| < 1$) all predictions tend to **underestimate measured cross-sections**.
- At **larger rapidities good agreement** with most considered PDF sets.

W bosons in *pp*: Differential cross-sections

ATLAS-HION-2018-02

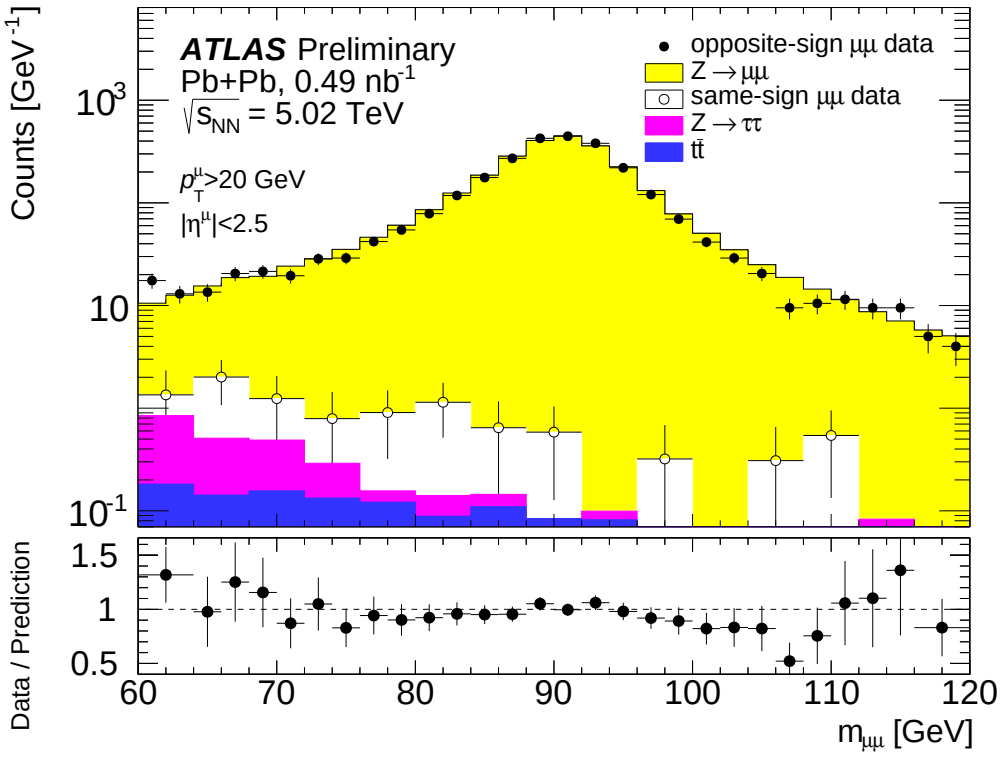




- **Lepton pseudorapidity differential cross-sections** measured in **fiducial** phase-space volume.
- **Predictions (except using HERAPDF 2.0)** systematically tend to **underestimate measured cross-sections**, but deviations are at the level of 1-2σ.
- Similar observations made in previous ATLAS measurements at 7 and 13 TeV.

Z bosons in Pb+Pb: Measurement strategy

ATLAS-CONF-2017-010

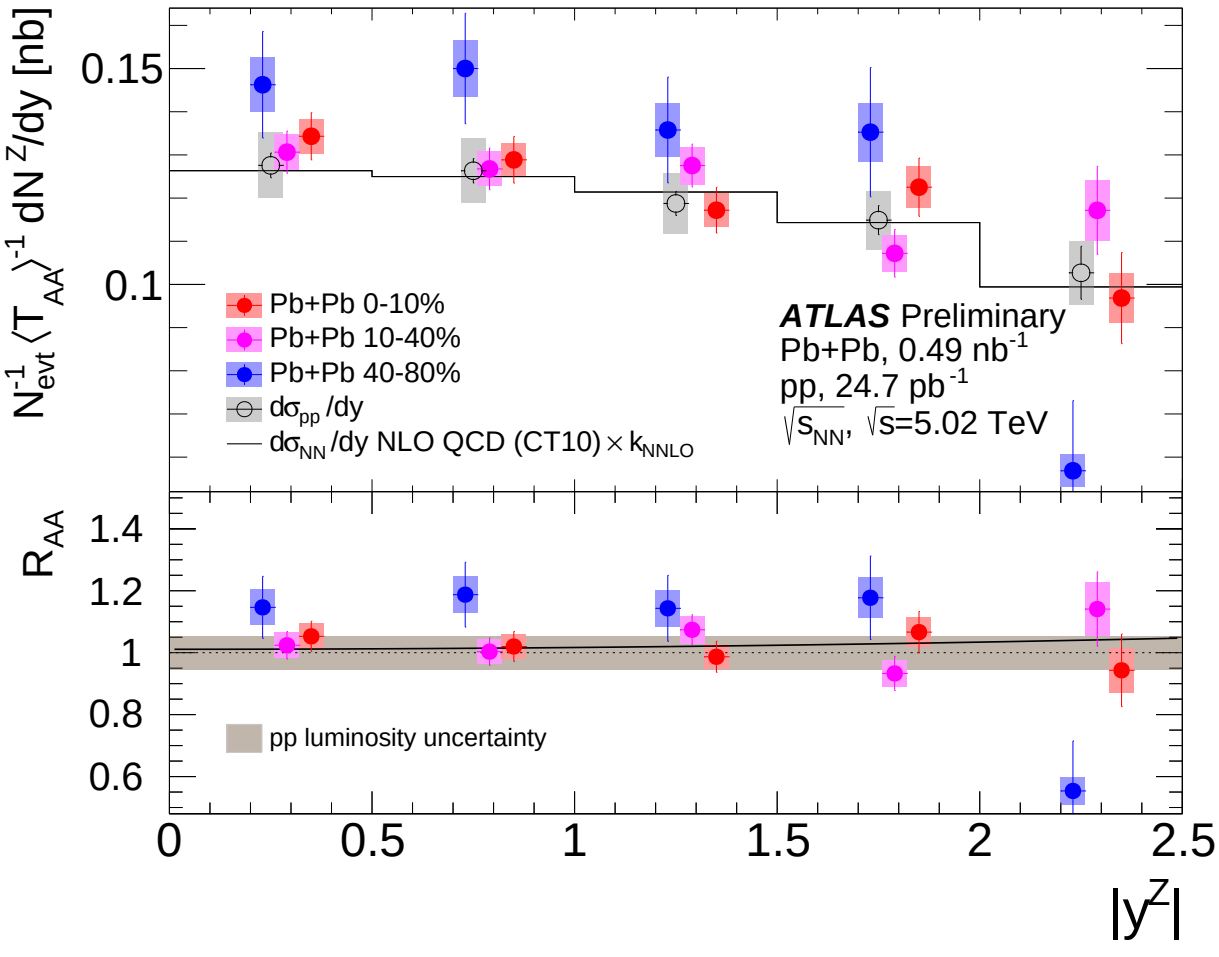


- Events collected with **single-muon trigger** ($p_{\mathrm{T}} = 8$ GeV threshold).
- Muons required to pass reconstruction quality selection.
- Kinematic selections: $p_{\mathrm{T}}^{\mu} > 20$ GeV, $|\eta_{\mu}| < 2.5$
- Opposite-charge dimuon pairs in mass range: $66 < m_{\mu\mu} < 116$ GeV
- One of the muons required to match trigger.

- Roughly **5500** events with ***Z* boson candidates** found.
- **Subtracted backgrounds** ($Z \to \tau\tau$ and $t\bar{t}$ estimated from MC, multi-jet from data) **at the level of 0.5%**.
- Dimuon candidates are corrected for reconstruction efficiency, trigger efficiency and muon p_{T} selection.

Z bosons in Pb+Pb: Yields vs. rapidity

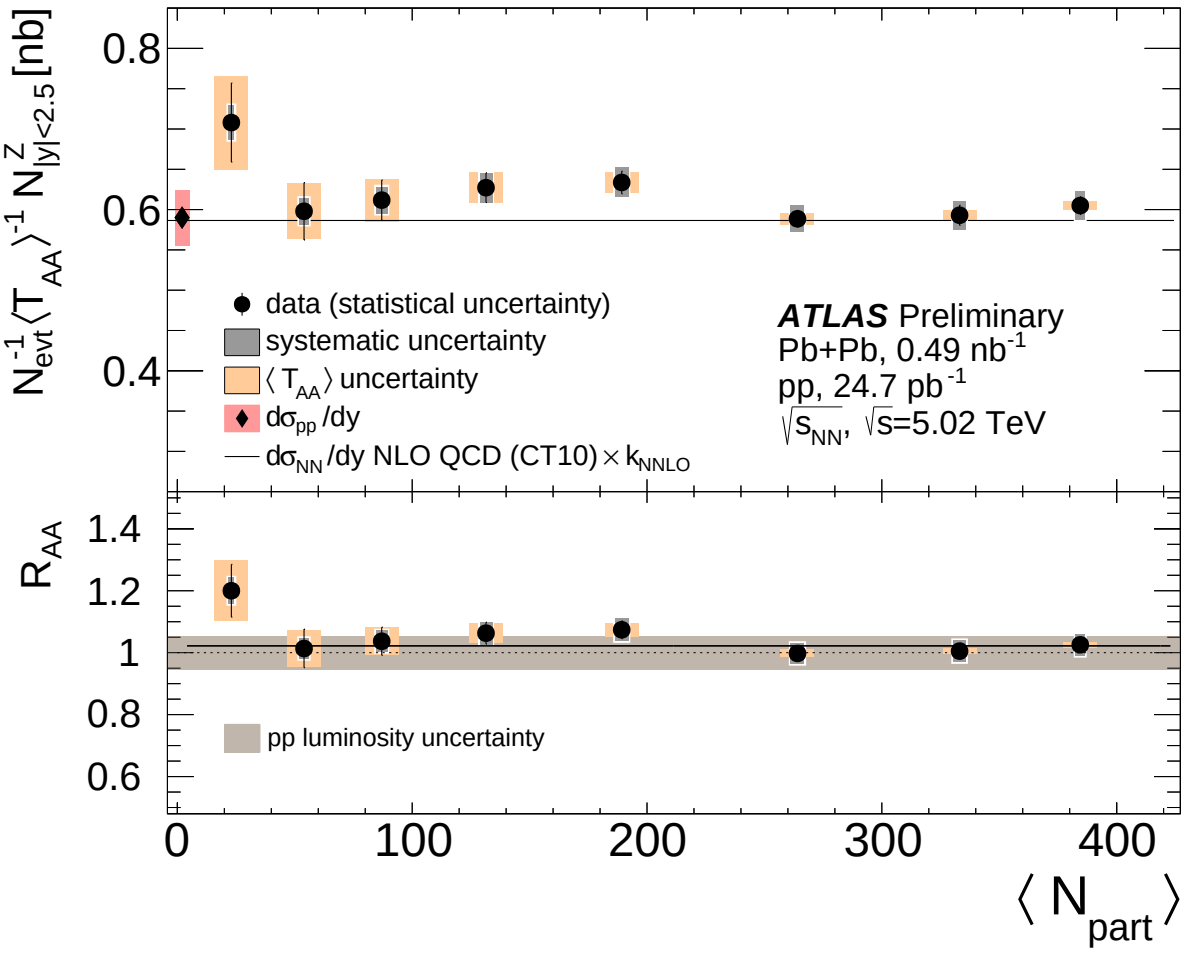
ATLAS-CONF-2017-010



- **Rapidity differential yields** per minimum-bias event **divided by** $\langle T_{AA}\rangle$ to compare with *pp* cross-sections.
- Mostly consistent with $\langle T_{AA}\rangle$ **scaling** - only **peripheral bin** is somewhat high ($\sim 1.5\sigma$).
- **Nuclear modification factor** $R_{AA} = \frac{N_{AA}^Z / N_{evt}}{\langle T_{AA}\rangle \times \sigma_{pp}^Z}$ expected to be ≈ 1.02 because of **isospin effect**.
- Caveat: preliminary results on *pp* cross-sections used to construct R_{AA}.

Z bosons in Pb+Pb: Yields vs. centrality

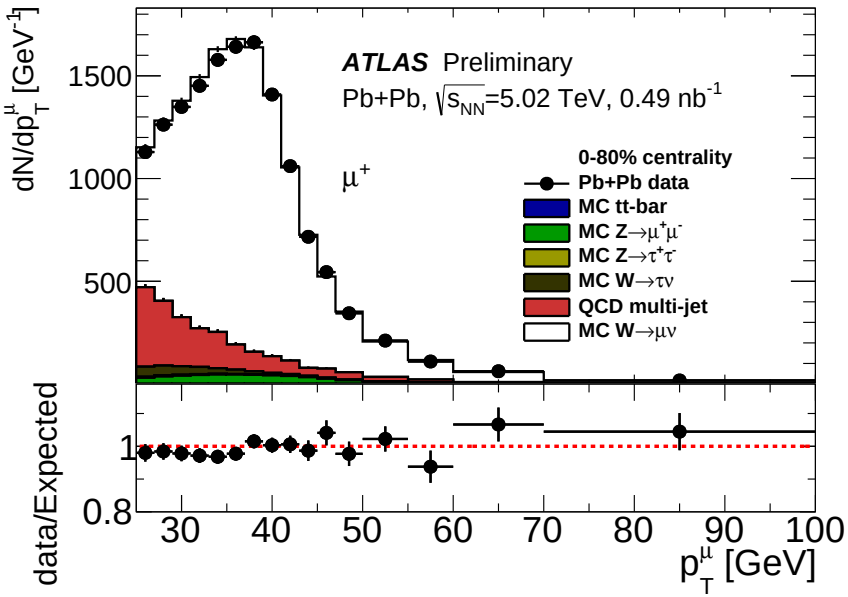
ATLAS-CONF-2017-010

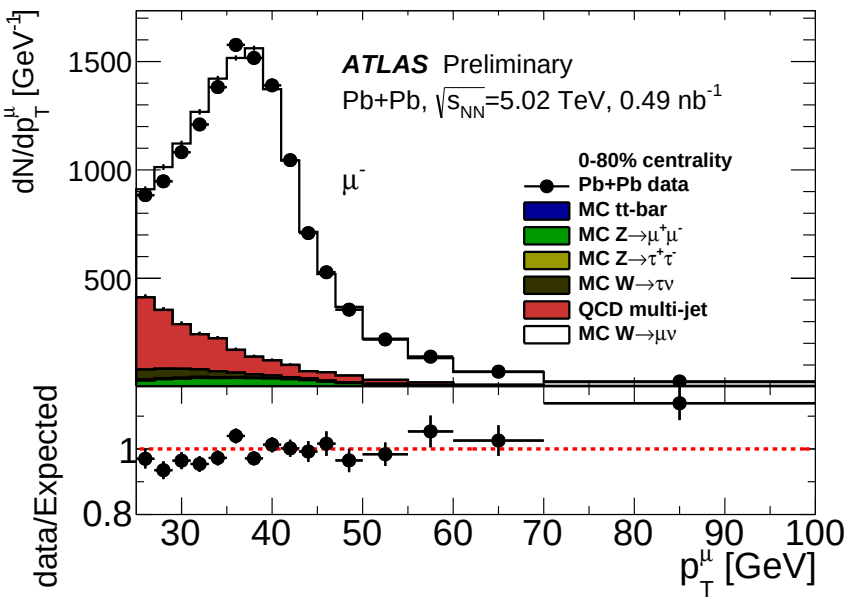


- **Yields** per minimum-bias event divided by $\langle T_{AA}\rangle$ (**integrated** in $|y_Z| < 2.5$).
- **High-precision measurement**: uncertainties related to EW bosons smaller than normalisation uncertainties.
- Most **peripheral bin** shows a hint of excess, otherwise **no significant dependence** of scaled yields or R_{AA} **on centrality** observed.
- Replace R_{AA} for other hard probes with $Z_{AA} = \frac{N^X_{AA} \cdot \sigma^Z_{pp}}{\sigma^X_{pp} \cdot N^Z_{AA}}$?

W bosons in Pb+Pb: Measurement strategy

ATLAS-CONF-2017-067

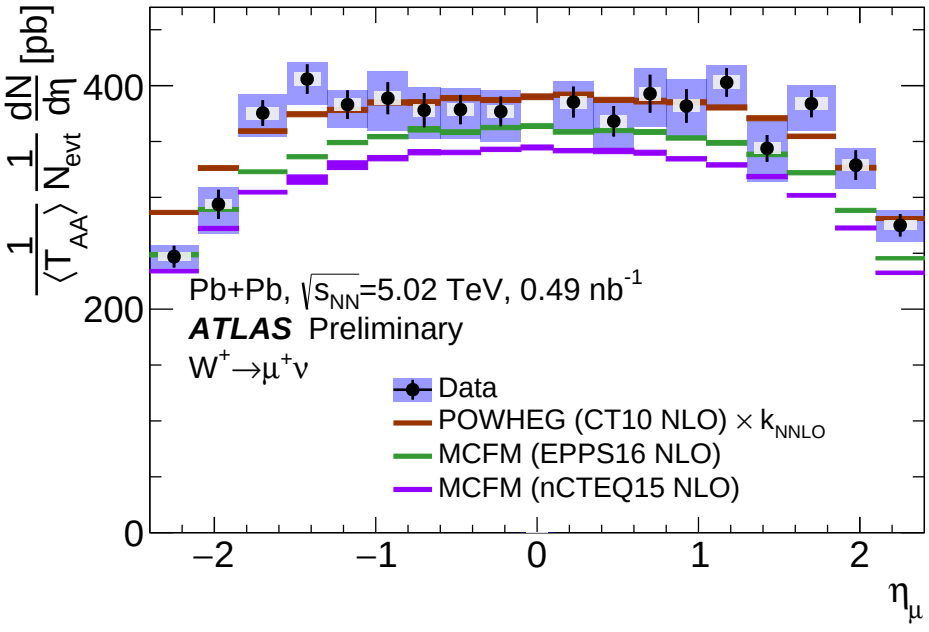


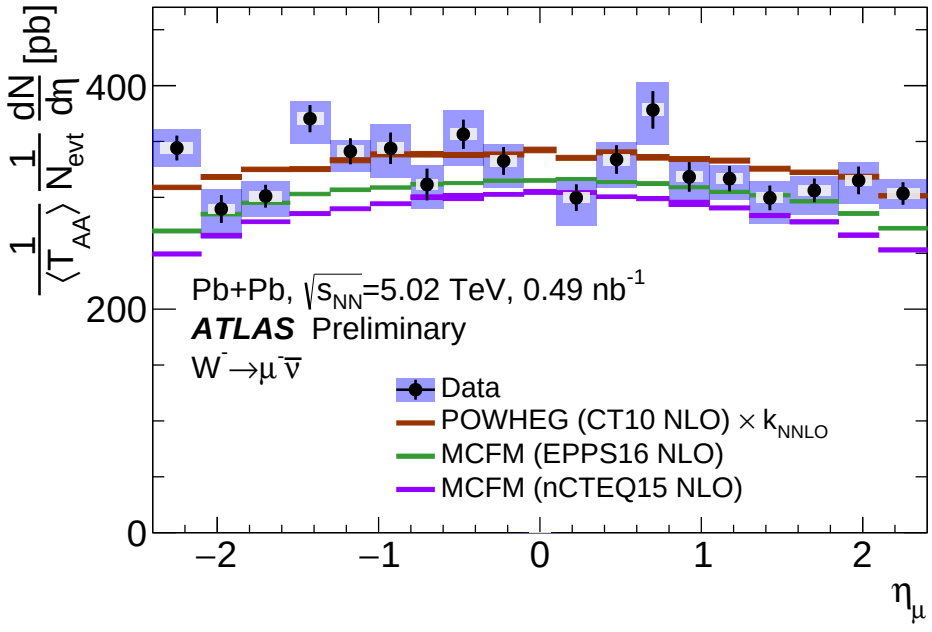


- Events collected with **single-muon trigger** ($p_{\mathrm{T}} = 15$ GeV threshold).
- Muons required to pass reconstruction quality and isolation selections + match trigger.
- Kinematic selection: $p_{\mathrm{T}}^{\mu} > 25$ GeV, $0.1 < |\eta_{\mu}| < 2.4$
- Selection on **missing transverse momentum reconstructed from charged-particle tracks**: $p_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV, $m_{\mathrm{T}} > 40$ GeV
- Additional **veto on Z boson candidate** events.
- Roughly **25000 (23000)** events with W^+ (W^-) **boson candidates** found.
- **Subtracted backgrounds**: **2-3% EW and $t\bar{t}$** estimated from MC, **6-12% multi-jet** estimated with data-driven method
- Corrections applied for trigger, reconstruction and isolation efficiencies, as well as **MET resolution** effects.

W bosons in Pb+Pb: Yields vs. rapidity

ATLAS-CONF-2017-067

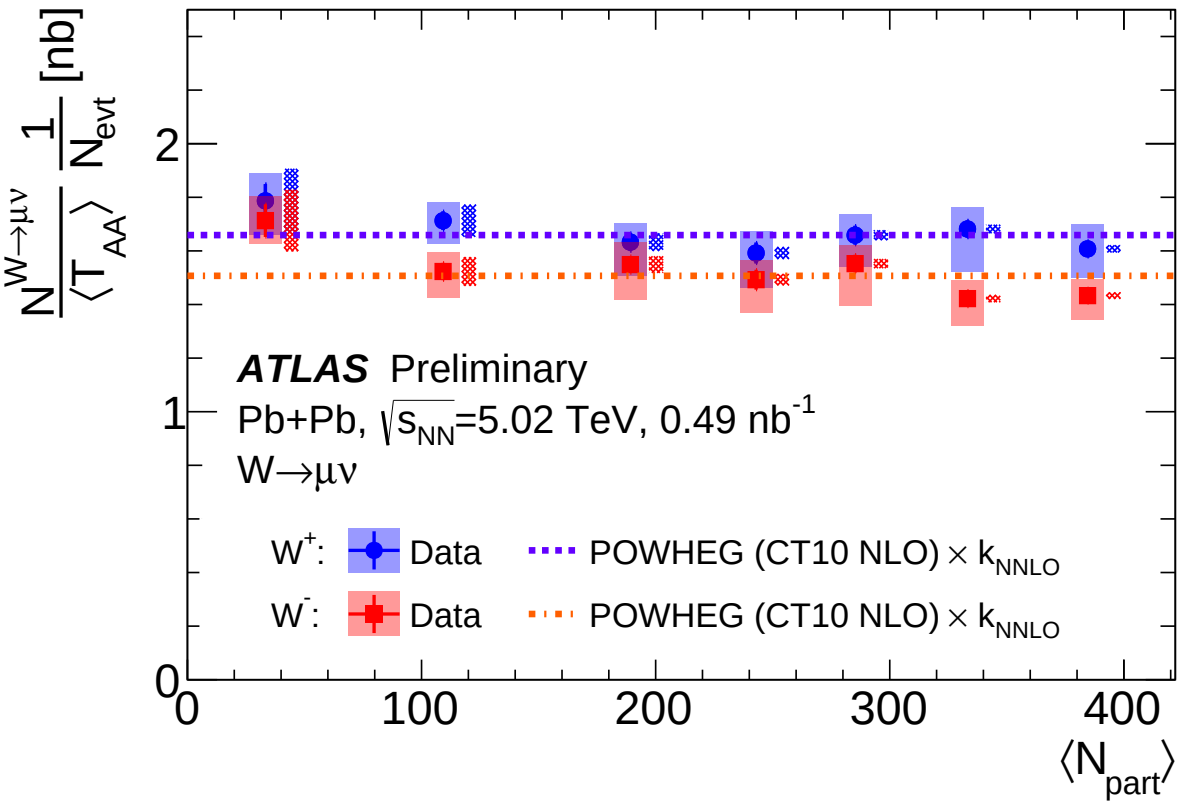




- **Lepton pseudorapidity differential yields** per minimum-bias event **divided by** $\langle T_{AA}\rangle$ for **fiducial** phase-space volume: $p_T^\mu > 25$ GeV, $p_T^{miss} > 25$ GeV, $m_T > 40$ GeV.
- Comparisons with several **theory predictions**:
  - CT10 **free-nucleon PDFs** (Powheg+Pythia8, NLO scaled to NNLO)
  - EPPS16 and nCTEQ15 **nPDFs** (both MCFM, NLO)
- **Best agreement** with NLO calculation obtained with free-nucleon PDFs scaled to **NNLO results**, while NLO calculations with nPDFs are somewhat below data.

W bosons in Pb+Pb: Yields vs. centrality

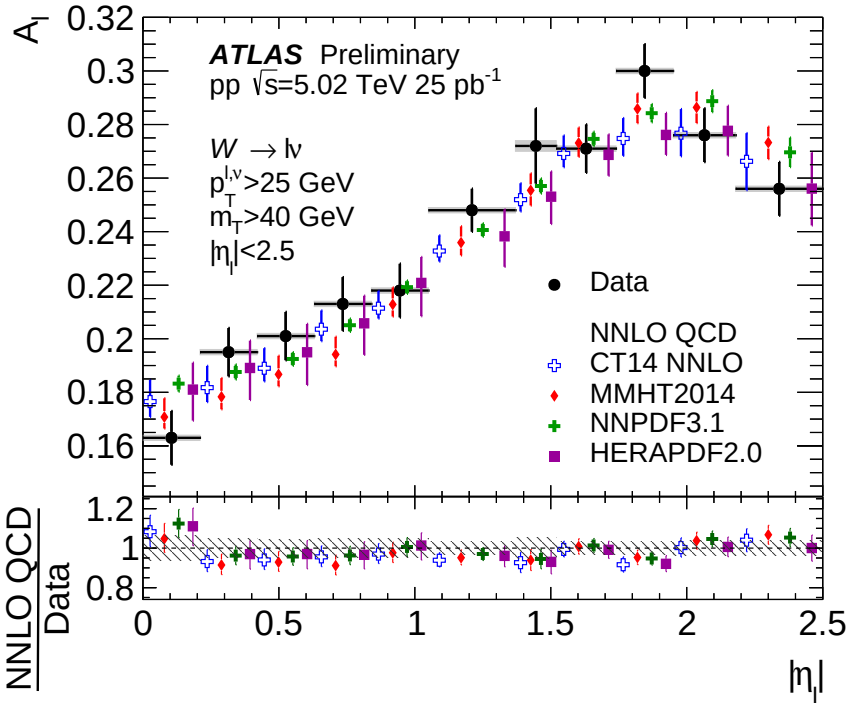
ATLAS-CONF-2017-067

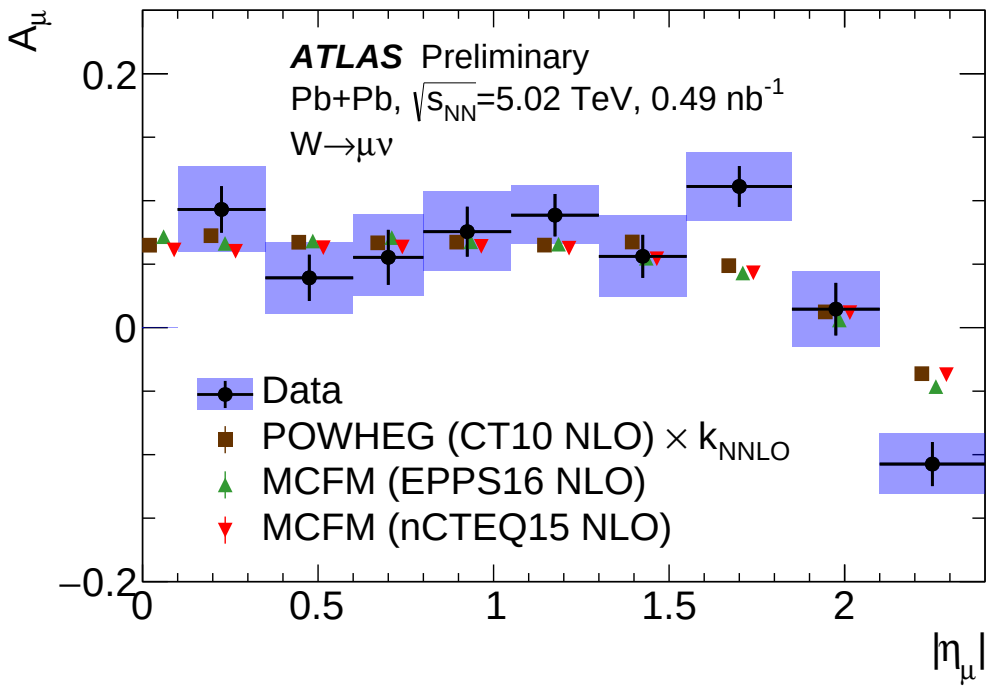


- **Fiducial yields** per minimum-bias event **divided by** $\langle T_{AA}\rangle$ **(integrated** in $0.1 < |\eta_\mu| < 2.4$).
- Similarly to Z bosons, most **peripheral bin** shows a hint of excess.
- Otherwise **no significant dependence** of scaled yields **on centrality** observed.
- **Predictions** from Powheg+Pythia8 including **isospin effect** and **scaled to NNLO** agree with data.

W bosons in *pp*/Pb+Pb: Lepton charge asymmetry

ATLAS-HION-2018-02, ATLAS-CONF-2017-067





- **Lepton charge asymmetry** defined using differential cross-sections (or yields for Pb+Pb):

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

- **Systematic uncertainties**, which are partially correlated between W^+ and W^- boson measurements, are **reduced** to a large extent.
- *pp*: **good agreement of predictions** from all considered **PDF** sets with measured asymmetry.
- Pb+Pb: **no preference** observed for **nPDF** sets (little sensitivity with present uncertainties).

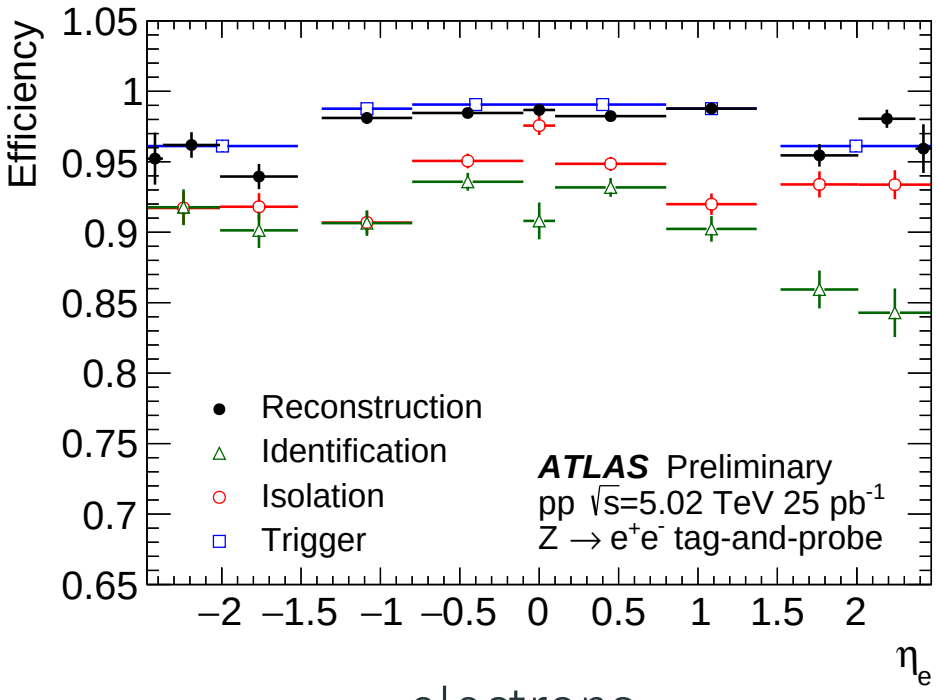
Summary

- Presented ATLAS measurements of heavy electroweak boson production in Pb+Pb and *pp* collsions at 5.02 TeV.
- *pp* collisions:
  - **New measurement** will serve as **high-precision baseline** for Pb+Pb results.
  - Expect **improved R_{AA} measurements**.
  - **Theory predictions** calculated with different PDF sets at NNLO tend to systematically **understimate measured cross-sections** - similar behaviour observed in ATLAS measurements at 7 and 13 TeV.
- Pb+Pb collisions:
  - Measurements consistent with expectations from T_{AA} **scaling**, no significant dependence of yields on centrality (except **most peripheral collisions**).
  - With current uncertainties there is **little** experimental **sensitivity to nPDFs**.
- **Updated Pb+Pb results** including electron channels and comparisons with most recent *pp* reference measurements **in preparation**.
- **More Pb+Pb data to be collected next month!**

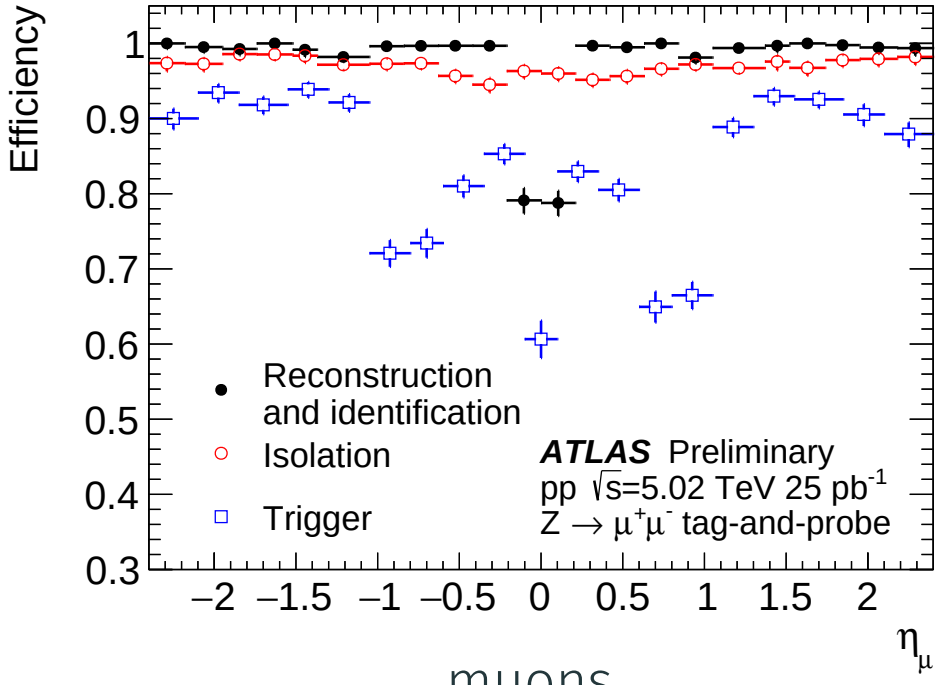
Additional slides

W/Z bosons in pp: Lepton efficiencies

ATLAS-HION-2018-02



electrons



muons

W/Z bosons in pp: Rapidity distributions

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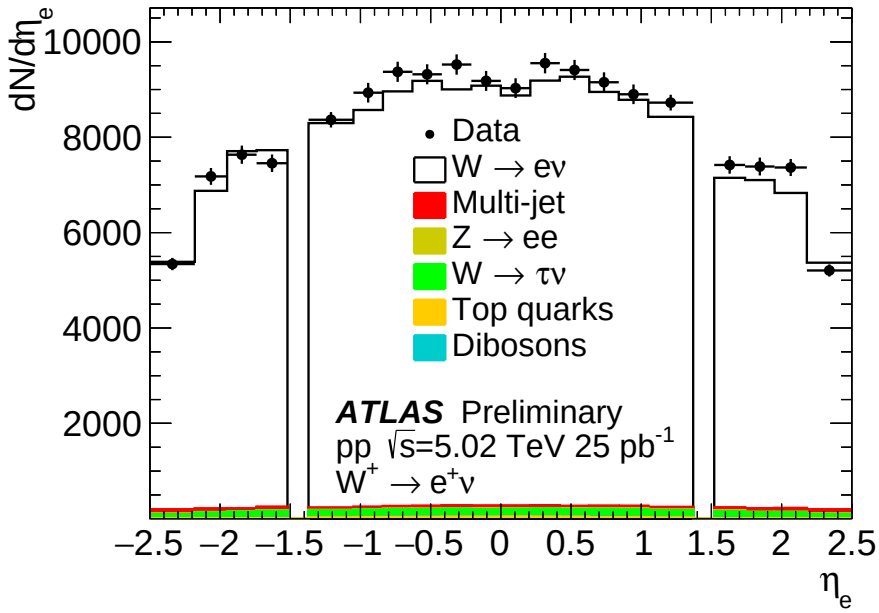

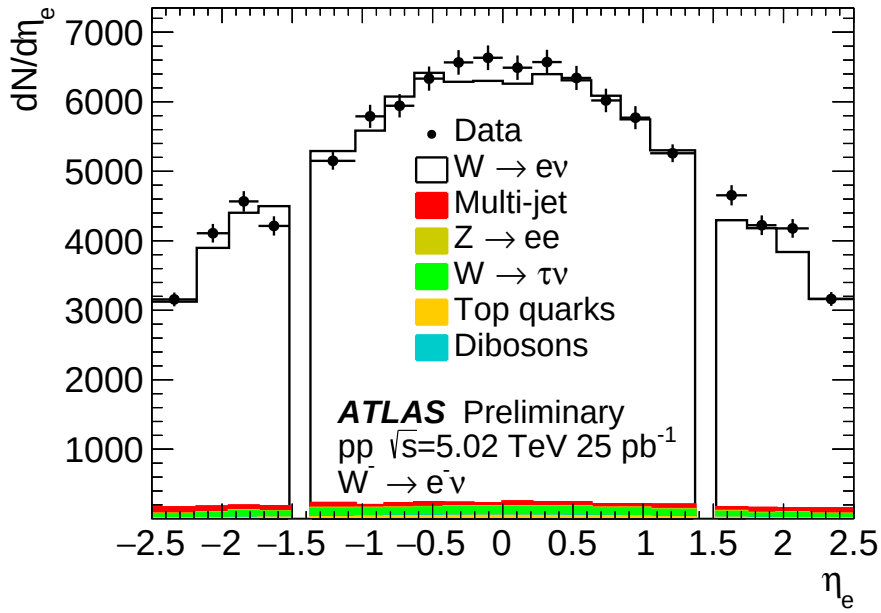

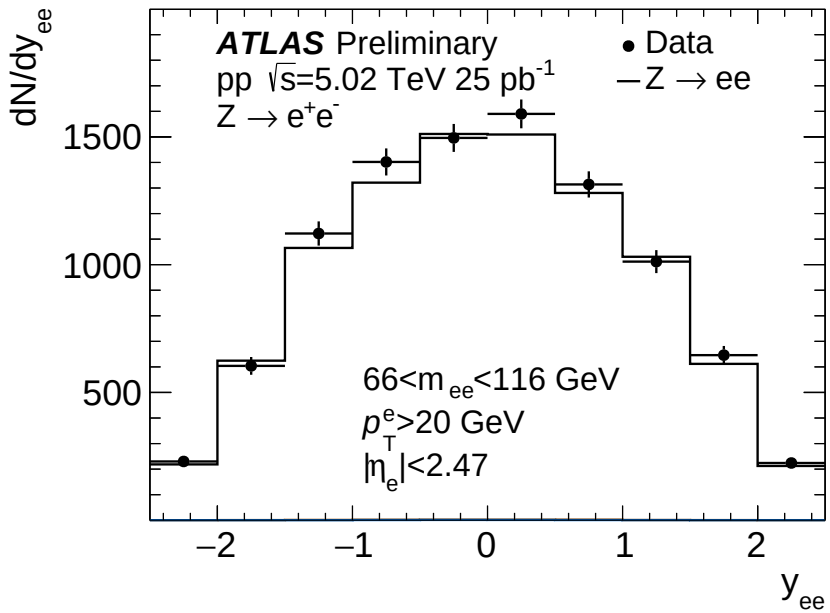

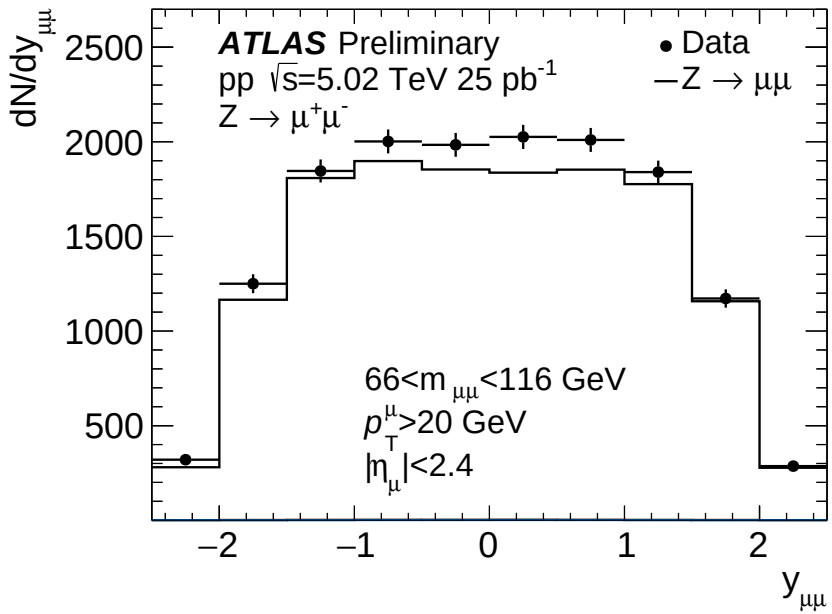

W bosons in *pp*: Lepton charge asymmetry combination

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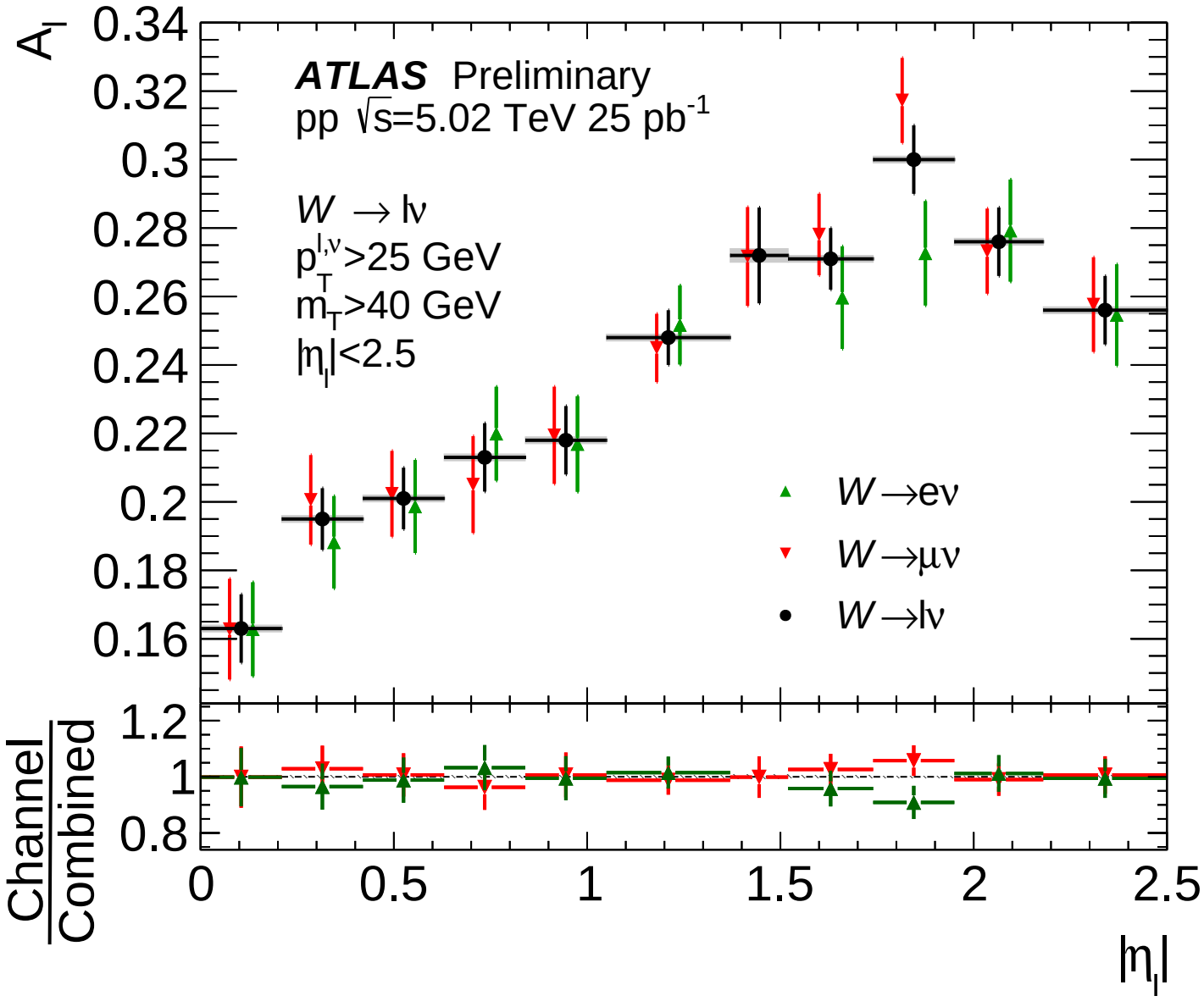
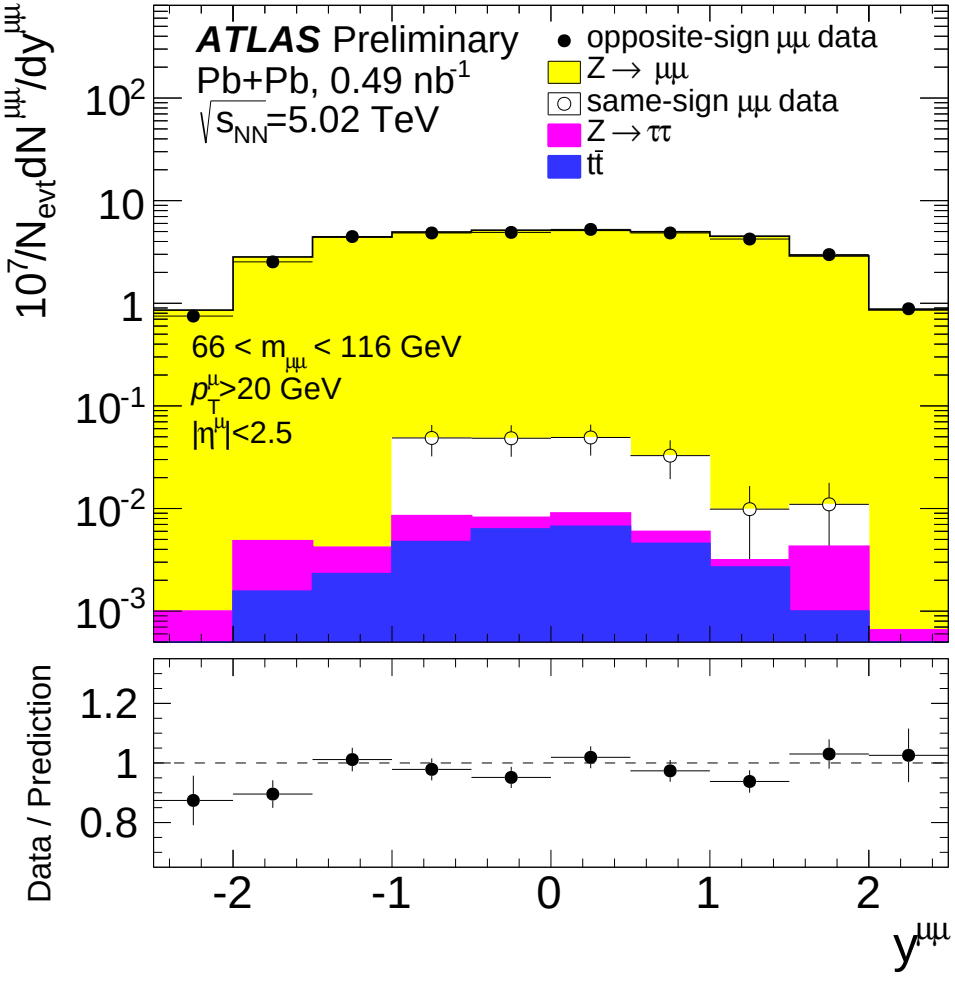
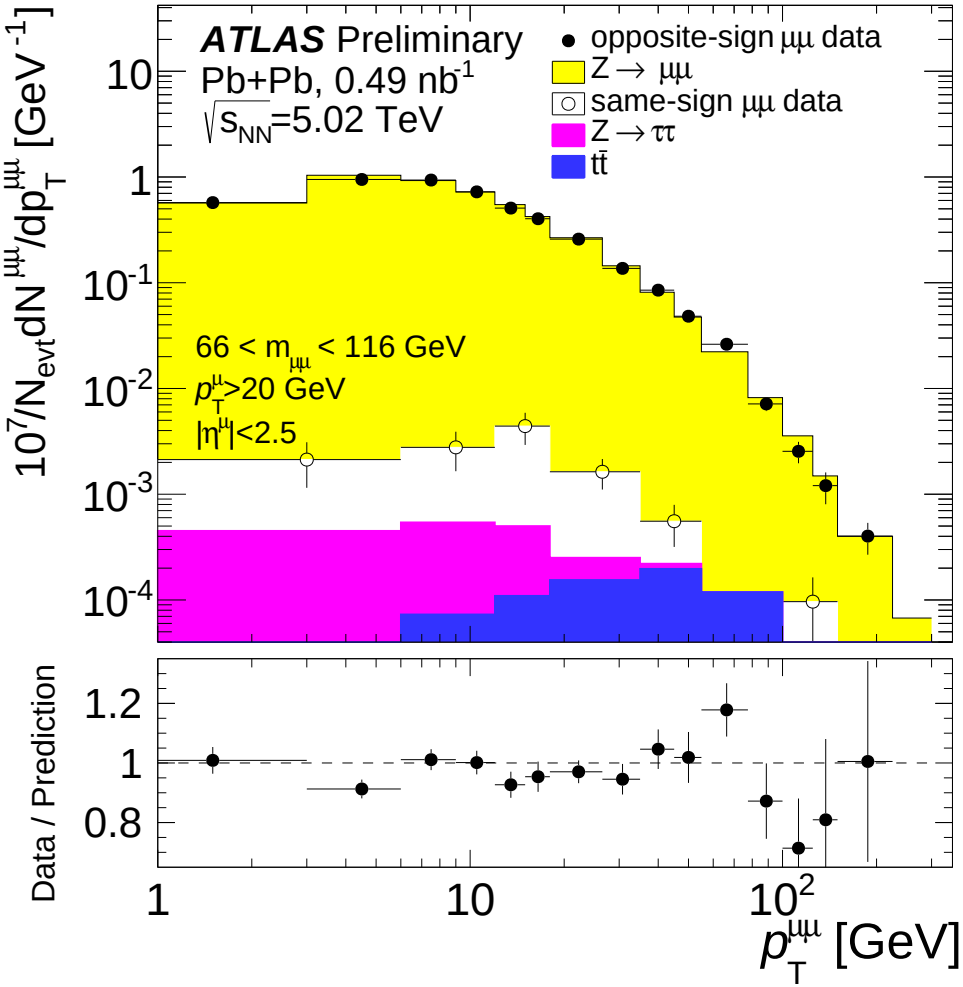


Z bosons in Pb+Pb: Kinematic distributions

ATLAS-CONF-2017-010





W bosons in Pb+Pb: Trigger efficiency

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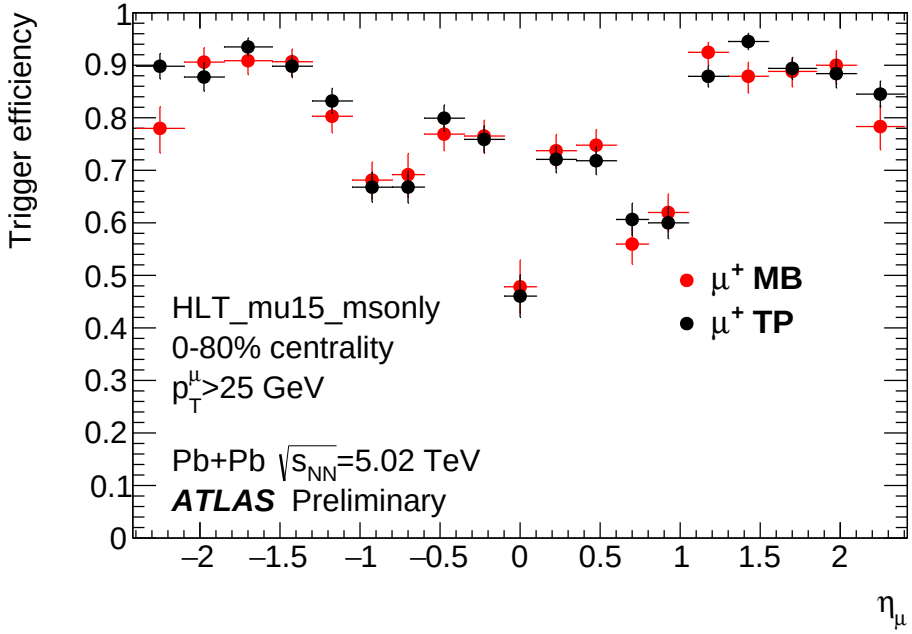
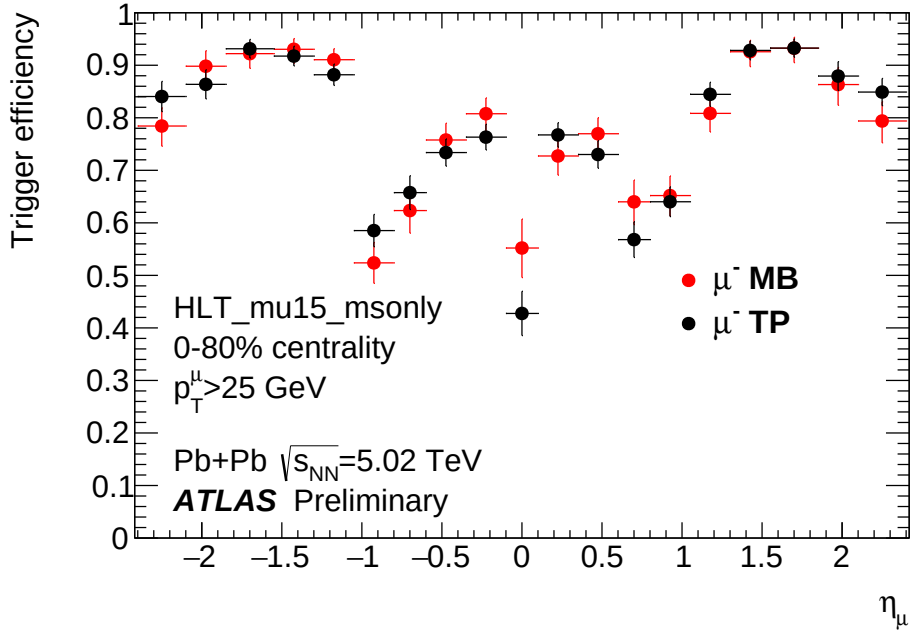
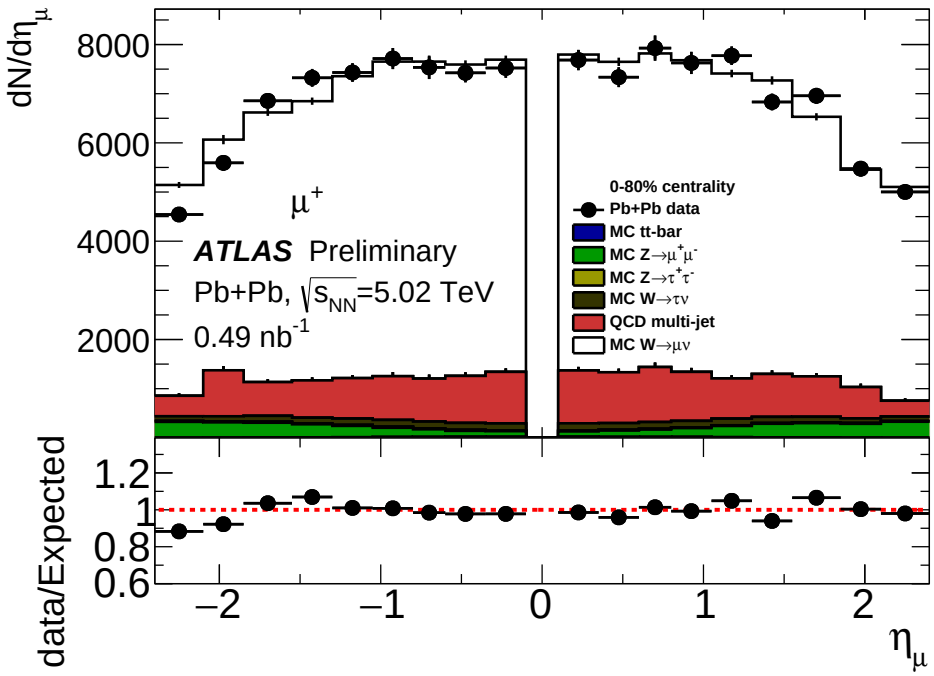
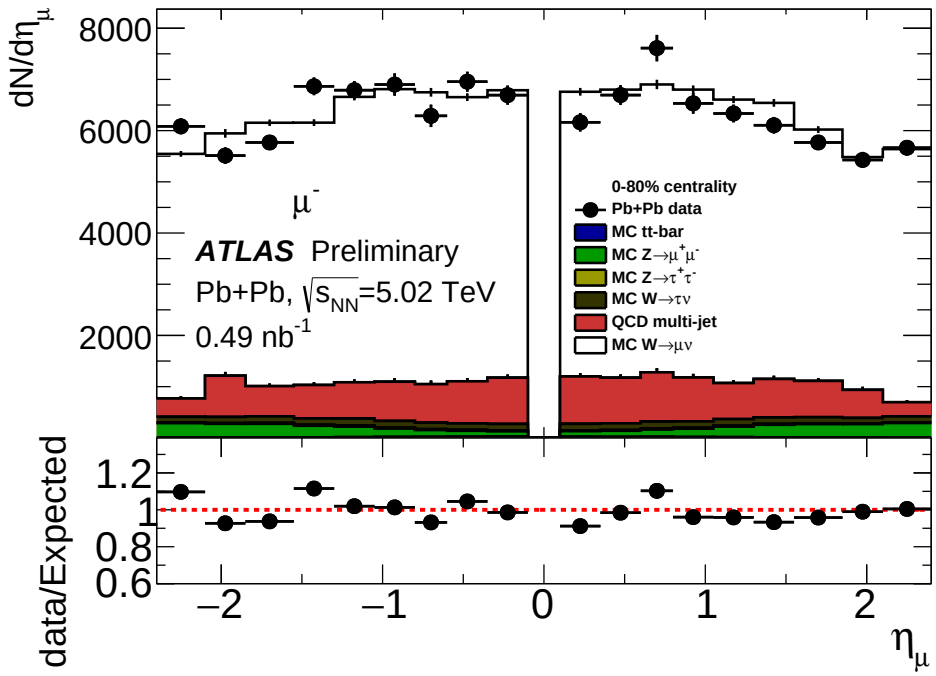




W bosons in Pb+Pb: Rapidity distributions

ATLAS-CONF-2017-067





W bosons in Pb+Pb: Rapidity differential yields

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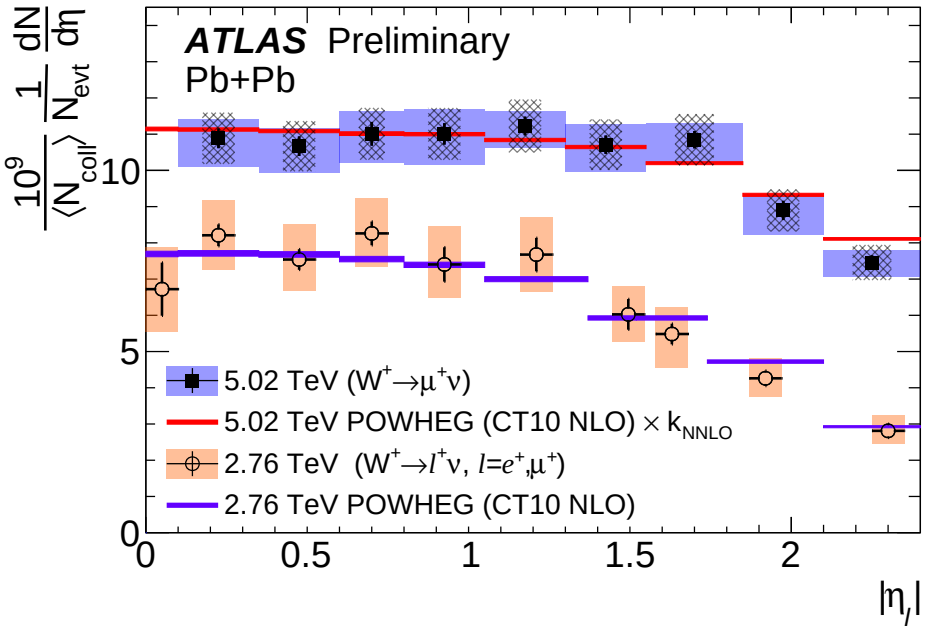

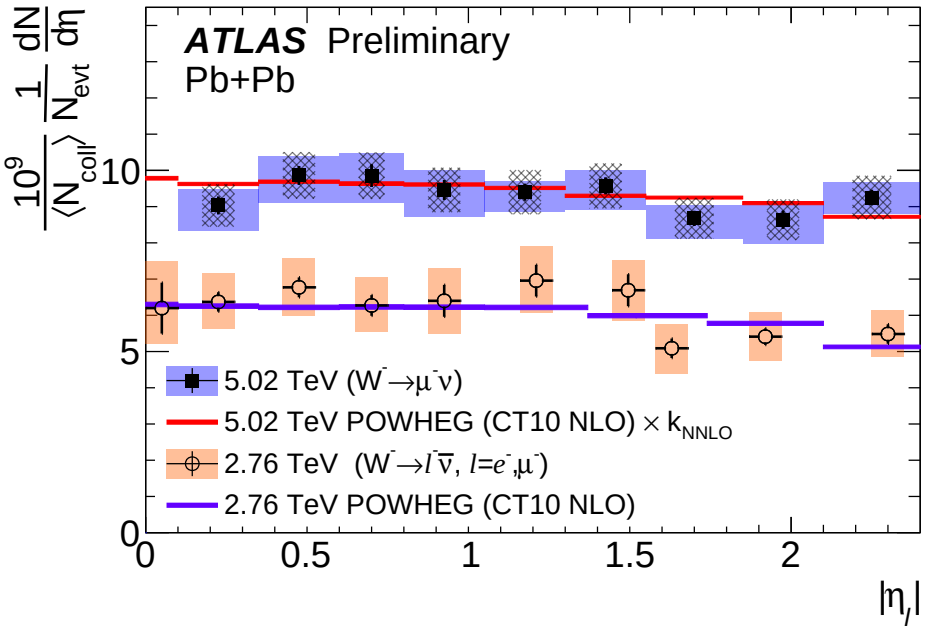

- Comparison of W boson yields measured at $\sqrt{s_{NN}} = 2.76$ TeV (combined electron and muon channels) and $\sqrt{s_{NN}} = 5.02$ TeV (muon channel only).
- Yields scale as the cross-section goes up with energy.
- Shapes similar between the two energies.
- Statistical precision of 5.02 TeV result is 2× better than of 2.76 TeV result.