Electroweak boson measurements in p+Pb and Pb+Pb collisions with ATLAS

Jakub Kremer for the ATLAS Collaboration

23 May 2019

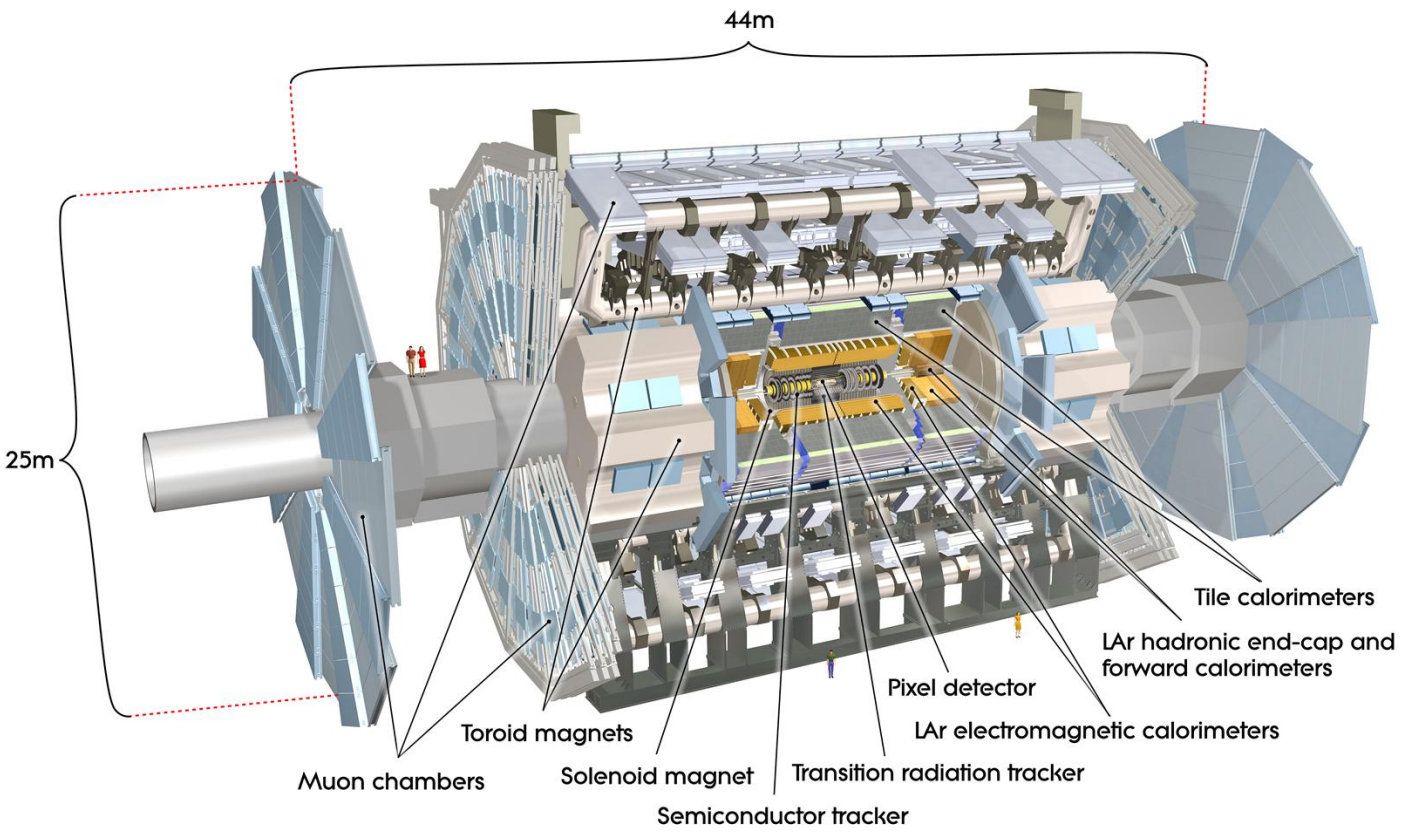
AGH University of Science and Technology, Kraków, Poland

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: arXiv:1903.02209 NEW!
  - W production in Pb+Pb at $\sqrt{s_{NN}} = 5.02$ TeV (2015 dataset): ATLAS-CONF-2017-067
  - Z production in Pb+Pb at $\sqrt{s_{NN}} = 5.02$ TeV (2015 dataset): ATLAS-CONF-2017-010

ATLAS detector / Datasets

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

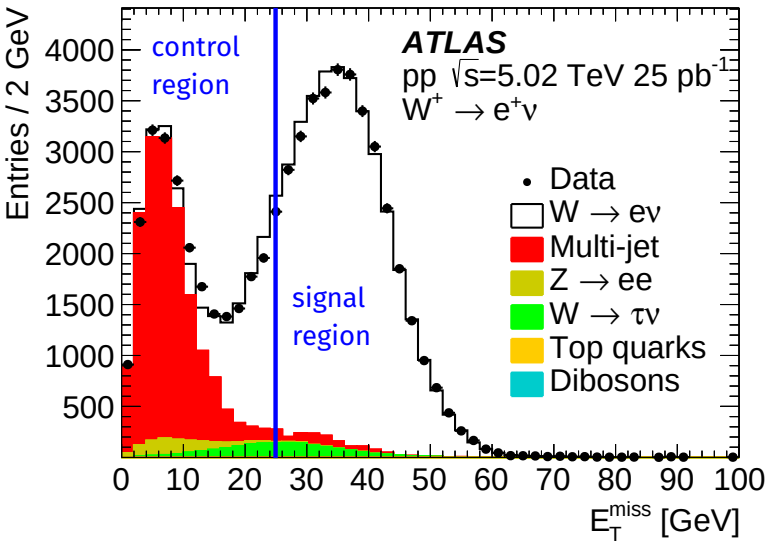


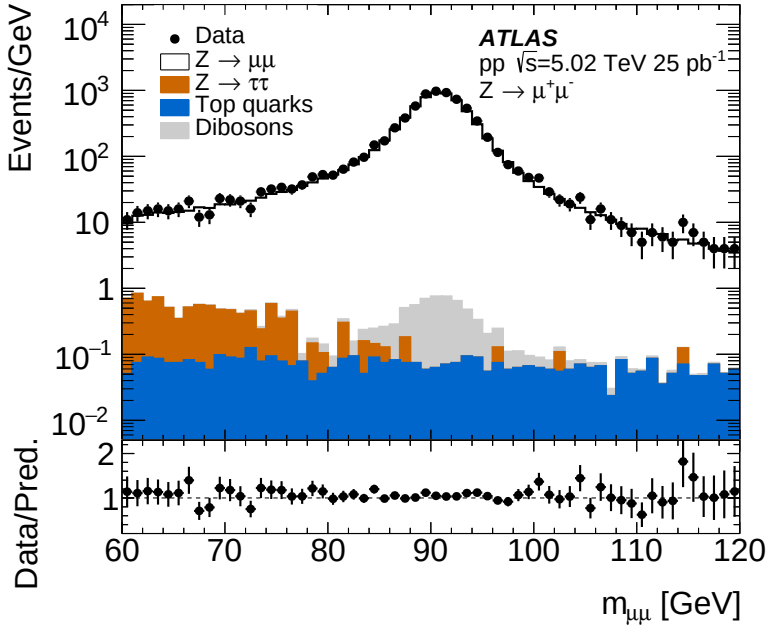
Datasets:

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

W/Z bosons in pp: Measurement strategy

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

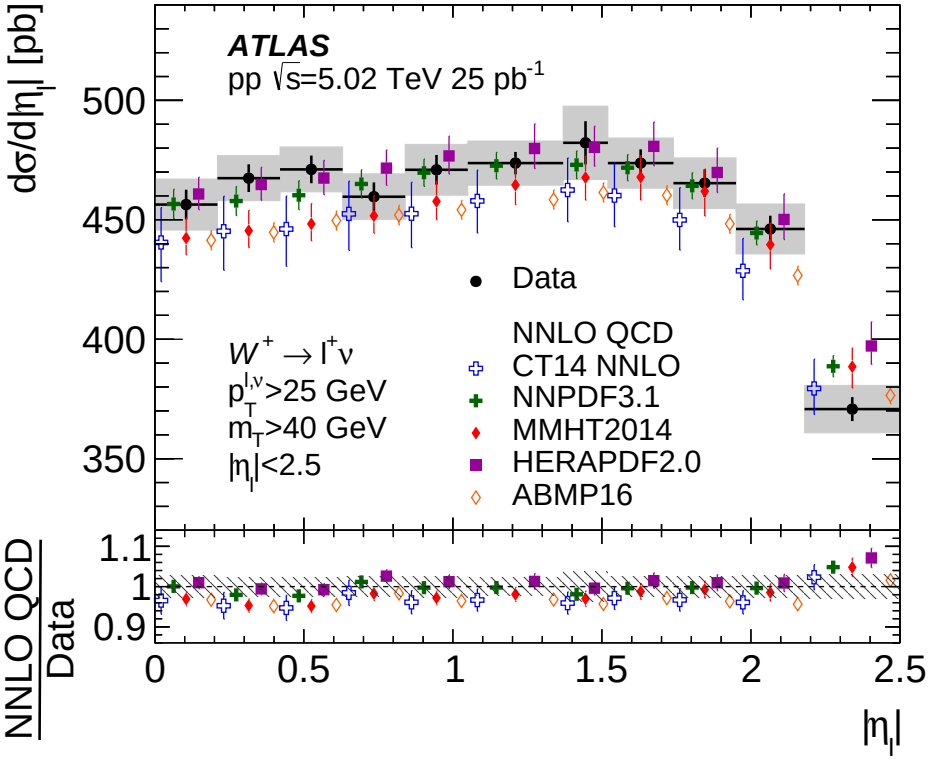


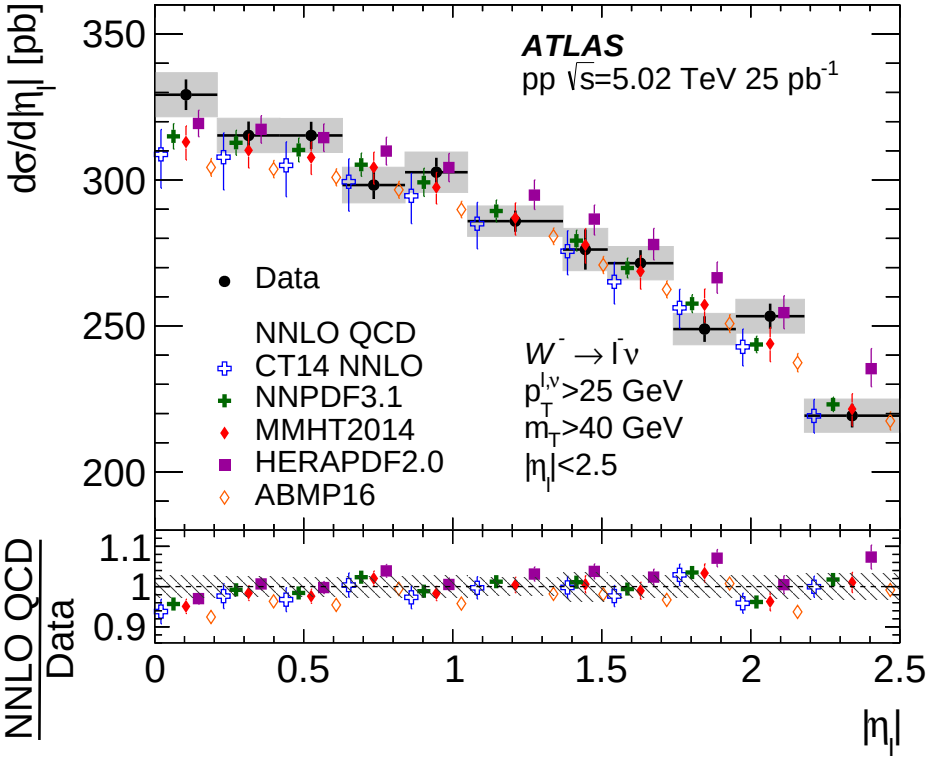


- Events collected with **single-lepton triggers** ($p_T^e = 15$ GeV and $p_T^\mu = 14$ GeV thresholds).
- Leptons required to pass reconstruction quality and isolation selections + match trigger.
- Kinematic selections for W (Z) boson selection: $p_T^{e/\mu} > 25$ (20) GeV, $|\eta_e| < 1.37$ or $1.52 < |\eta_e| < 2.47$, $|\eta_\mu| < 2.4$
- W boson selection:
  - **missing transverse energy** calculated using **hadronic recoil from particle flow**: $E_T^{miss} > 25$ GeV, $m_T > 40$ GeV
  - **veto Z boson candidates**
- Z boson selection:
  - **opposite-charge same-flavour lepton pairs** in mass range $66 < m_{\ell\ell} < 116$ GeV
- **Subtracted backgrounds** (EW bosons + dibosons and top quarks from MC, multi-jet from data): **3-4% ($W \to e\nu$), 5-6% ($W \to \mu\nu$), 0.3% ($Z \to \ell\ell$)**

W bosons in pp: Differential cross-sections

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

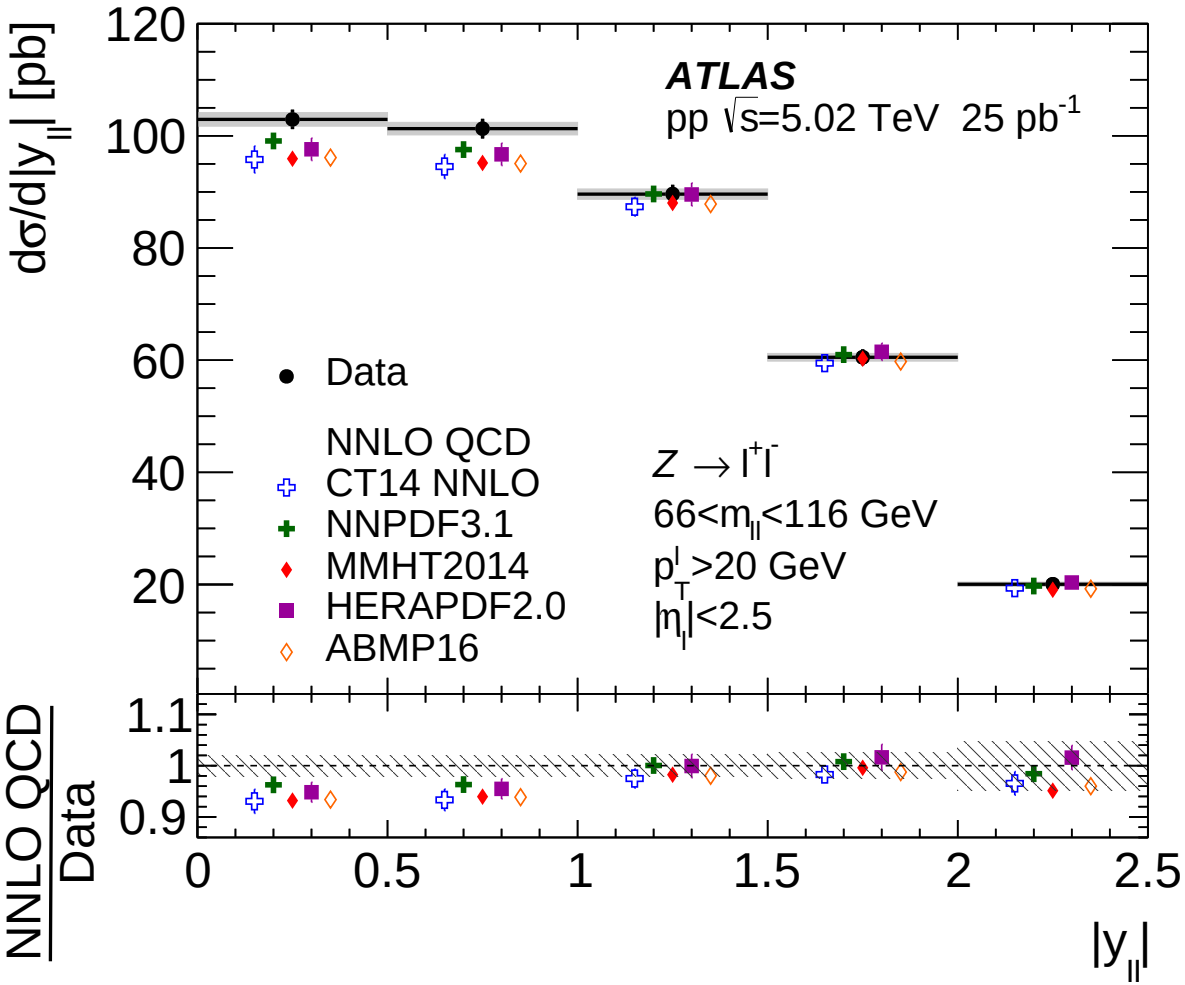




- **Lepton pseudorapidity differential cross-sections** measured in **fiducial** phase-space volume.
- **Combination** of decay channels using the BLUE method **accounting for uncertainty correlations**.
- Comparison to several **NNLO theory predictions (different PDF sets)** calculated with an optimised version of DYNNLO 1.5.
- **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.

Z bosons in pp: Differential cross-sections

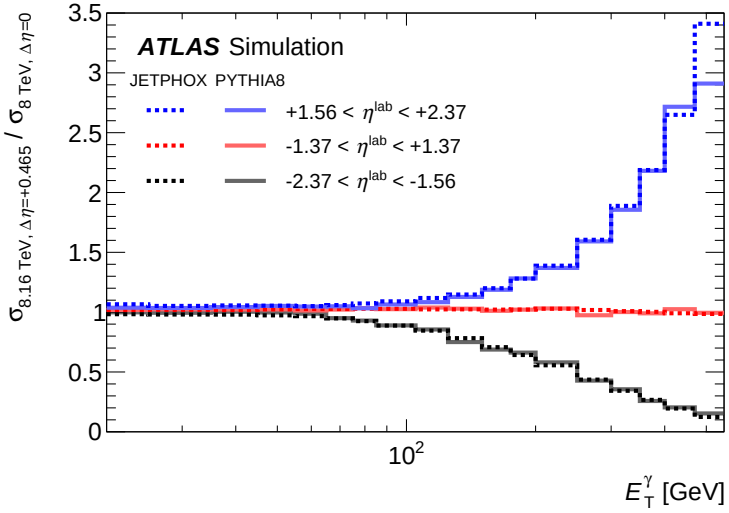
Eur. Phys. J. C 79 (2019) 128 and 79 (2019) 374



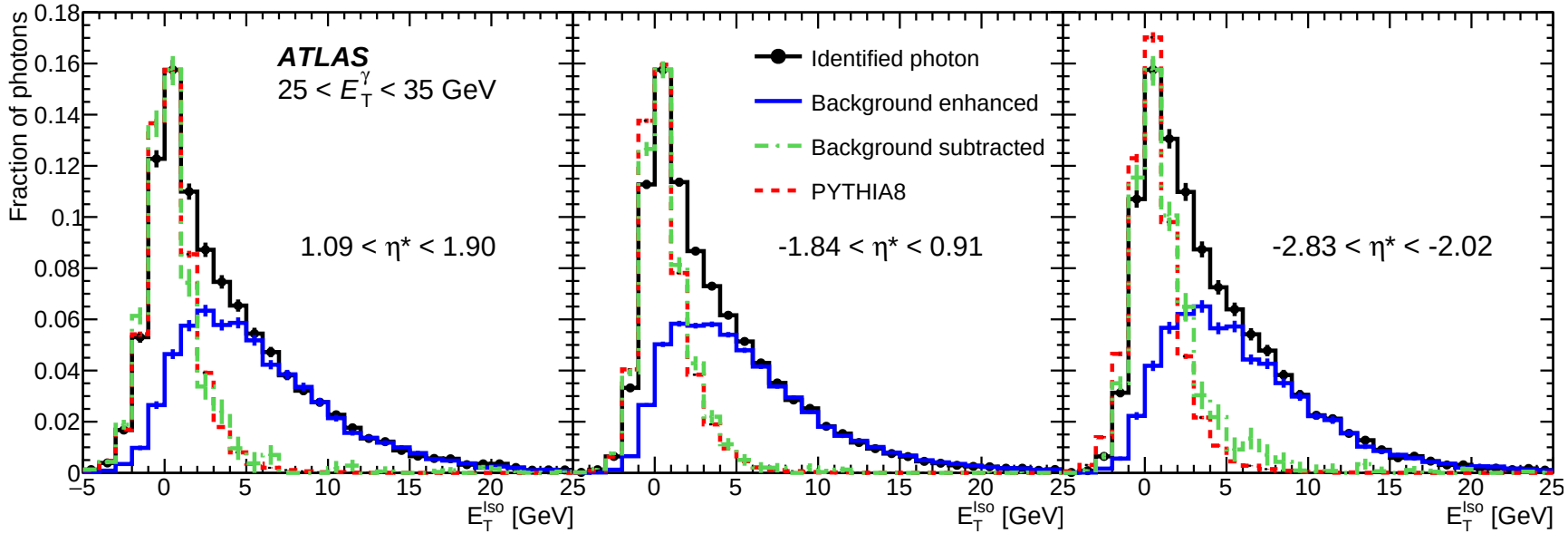
- **Rapidity differential cross-sections** measured in **fiducial** phase-space volume.
- Comparison to the same set of **theory predictions** as for W bosons.
- At **central rapidities** ($|y_{\ell\ell}| < 1$) all predictions tend to **underestimate measured cross-sections**.
- At **larger rapidities good agreement** with most considered PDF sets.
- Similar observations made in high-precision measurement at 7 TeV.

Prompt photons in p+Pb: Measurement strategy

arXiv:1903.02209

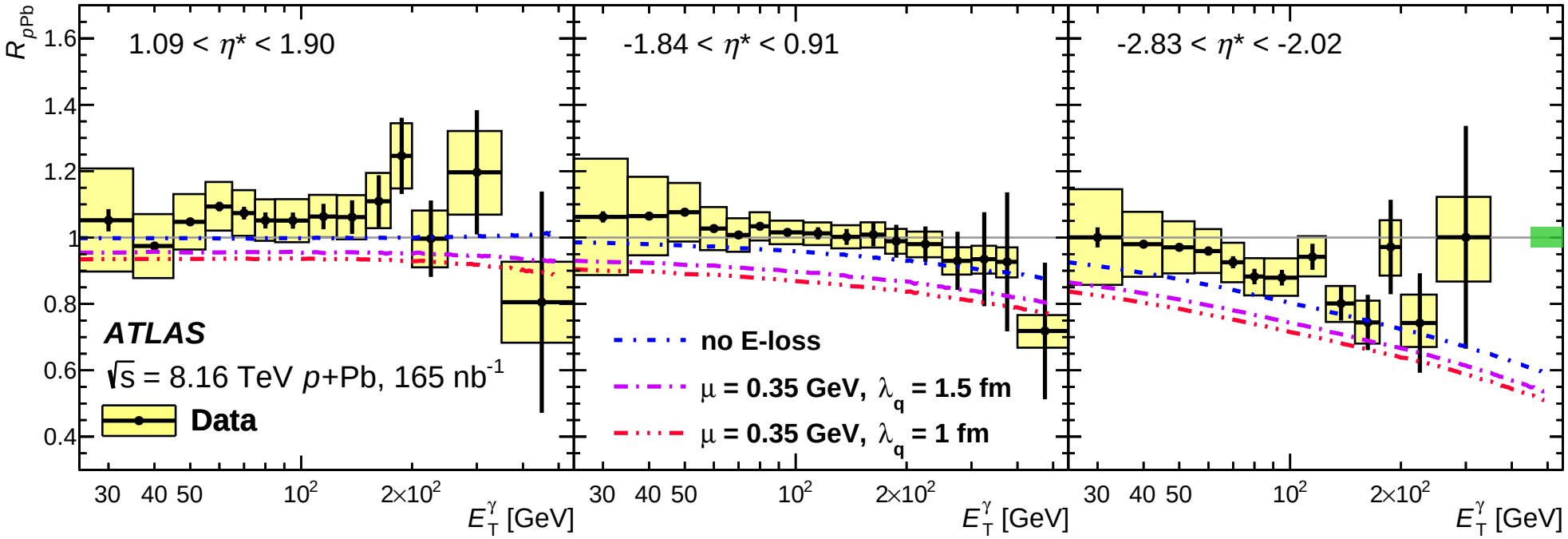


- Events collected with **single-photon triggers** (p_T^γ thresholds between 15 GeV and 35 GeV).
- Photons required to pass reconstruction quality and isolation selections.
- Kinematic selections: $p_T^\gamma > 20$ GeV, $|\eta_\gamma| < 1.37$ or $1.56 < |\eta_\gamma| < 2.37$
- **Background estimation 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

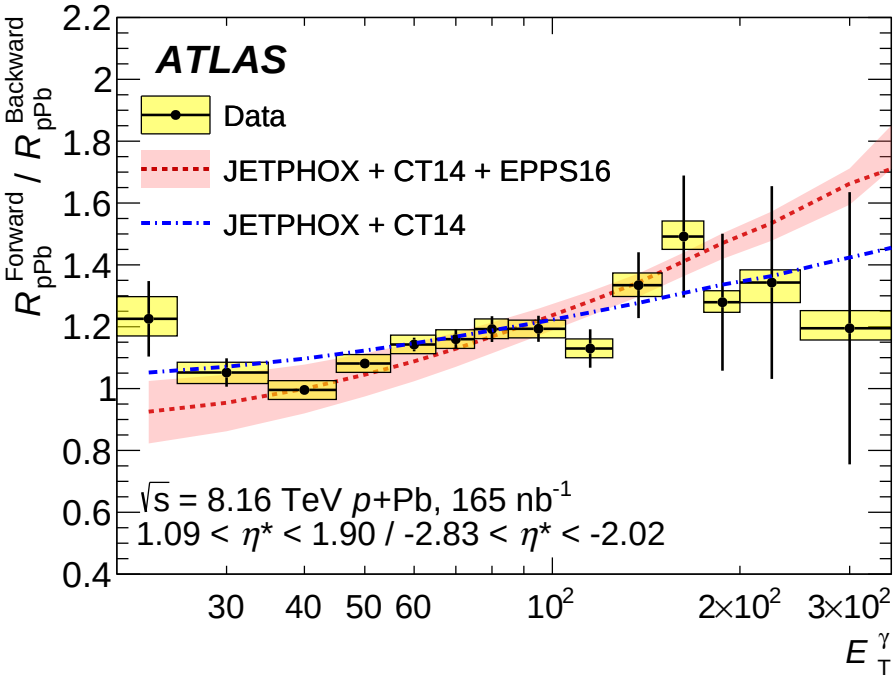
arXiv:1903.02209

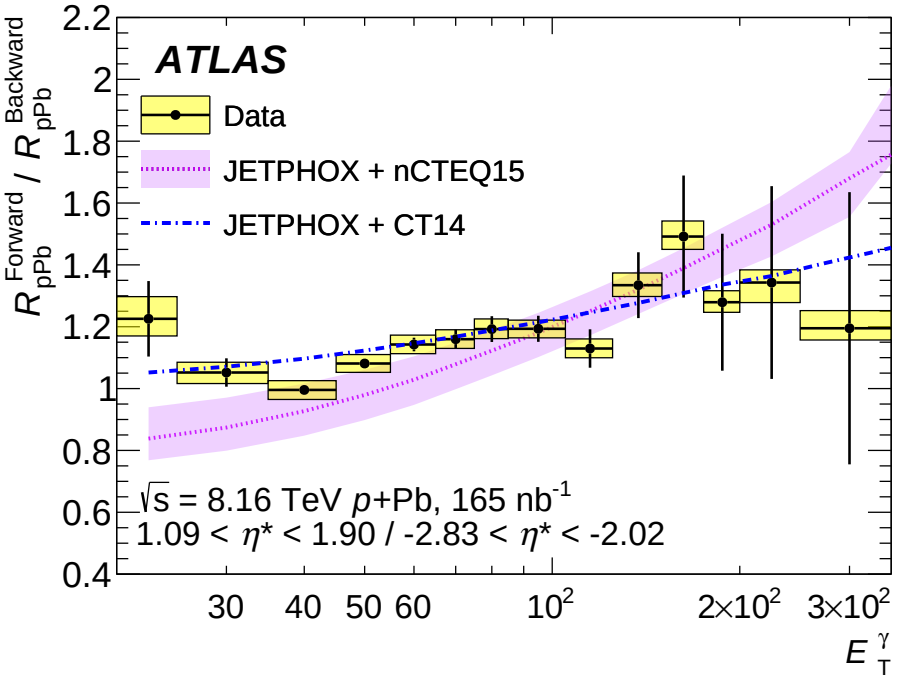


- **Nuclear modification factor** $R_{pPb} = \frac{d\sigma^{p+Pb\to\gamma+X}/dE_T^\gamma}{A\cdot d\sigma^{pp\to\gamma+X}/dE_T^\gamma}$ ($A = 208$ is the Pb mass number)
- At **forward and central rapidities**, nuclear effects are small resulting in R_{pPb} values **consistent with unity**.
- For **backward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

arXiv:1903.02209

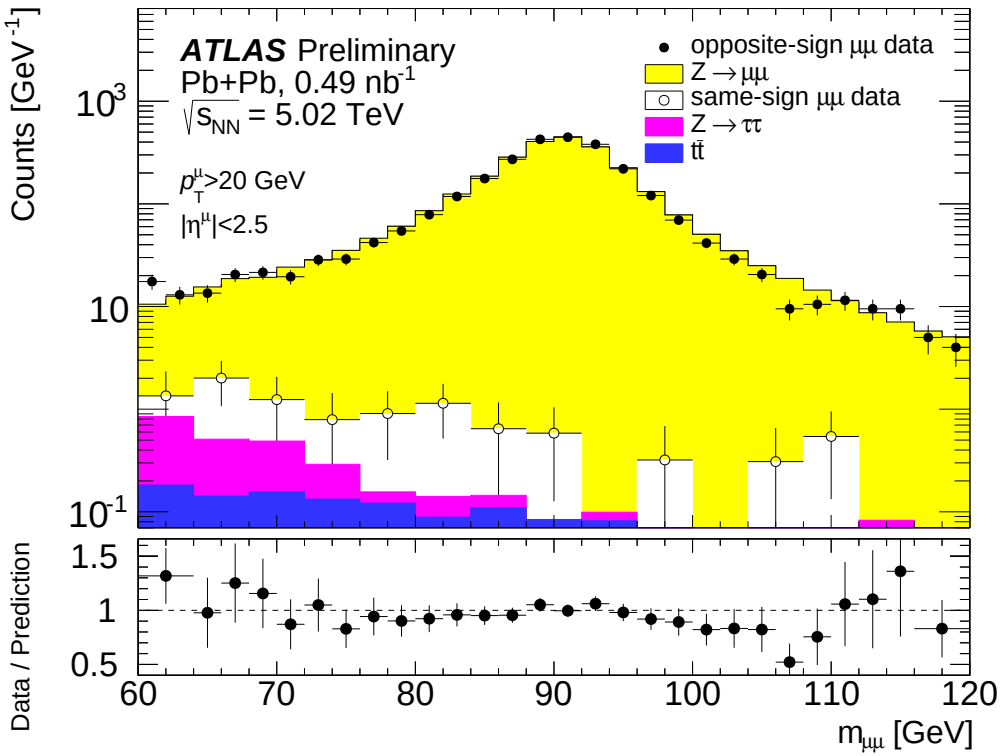




- **Reduction of systematic uncertainties** for ratios of forward and backward $R_{p\mathrm{Pb}}$.
- Comparison to **NLO calculations** from JETPHOX using **free-nucleon PDFs** (CT14) and **nPDFs** (EPPS16 and nCTEQ15).
- The **free-nucleon** prediction shows the **best agreement** with data.
- Data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

Z bosons in Pb+Pb: Measurement strategy

ATLAS-CONF-2017-010

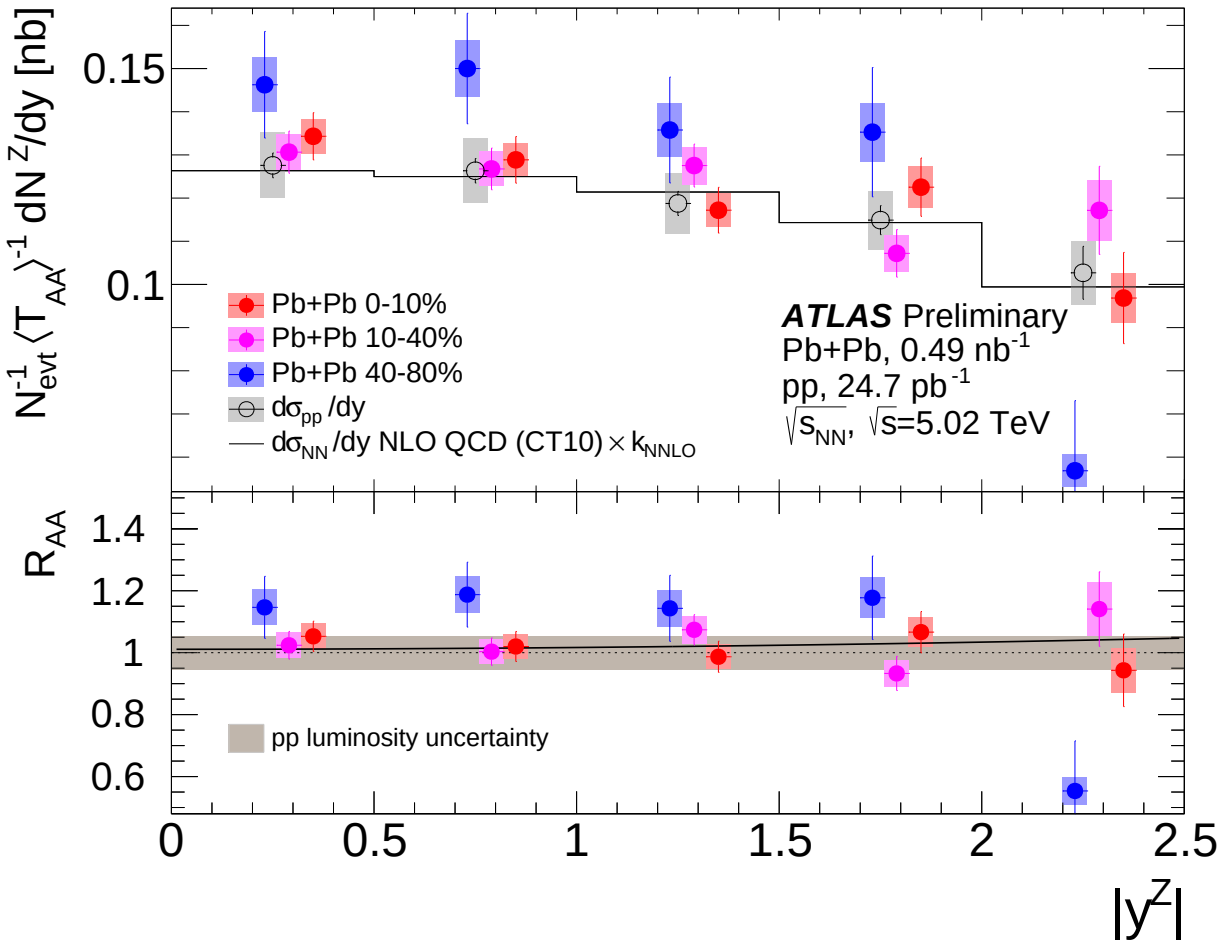


- Events collected with **single-muon trigger** ($p_T = 8$ GeV threshold).
- Muons required to pass reconstruction quality selection.
- Kinematic selections: $p_T^\mu > 20$ GeV, $|\eta_\mu| < 2.5$
- Opposite-charge muon pairs in mass range: $66 < m_{\mu\mu} < 116$ GeV
- One of the muons required to match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

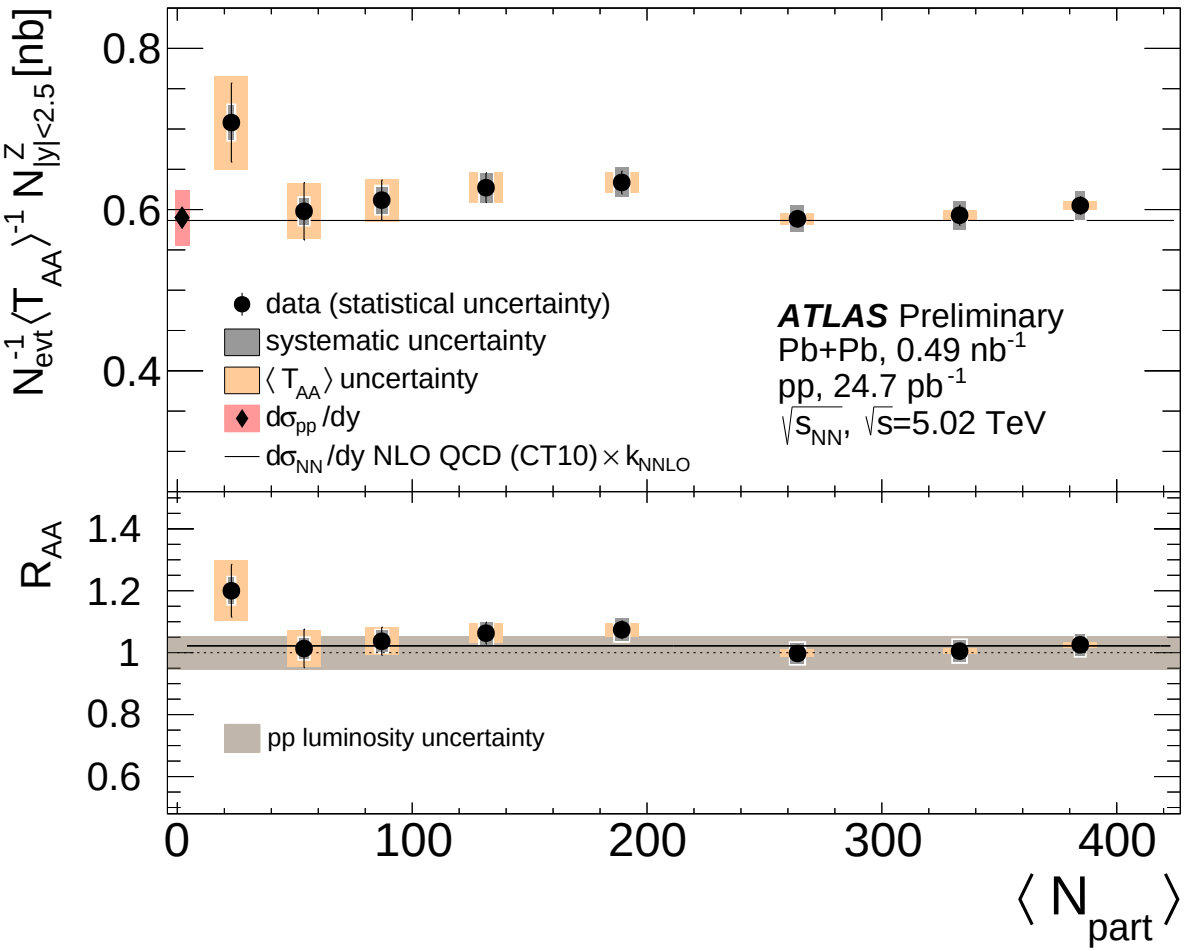
ATLAS-CONF-2017-010



- **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

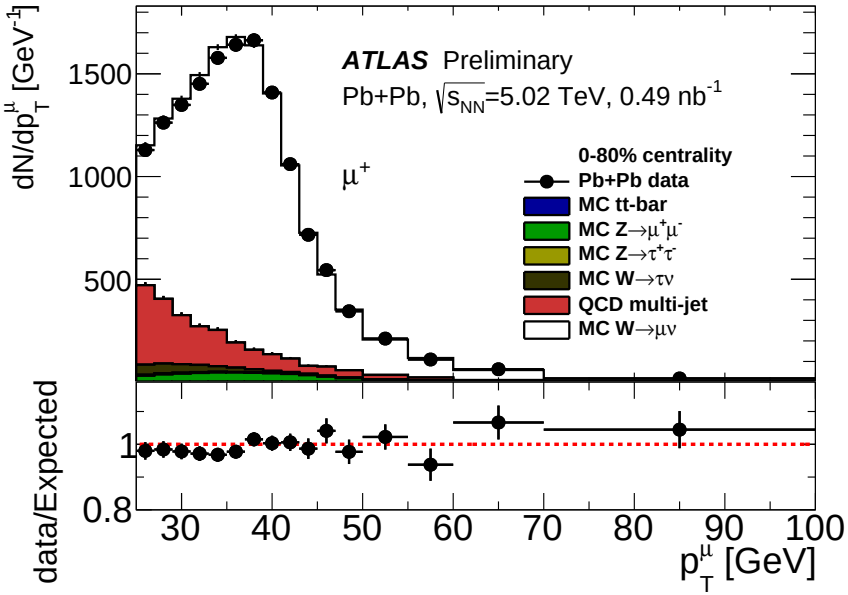
ATLAS-CONF-2017-010

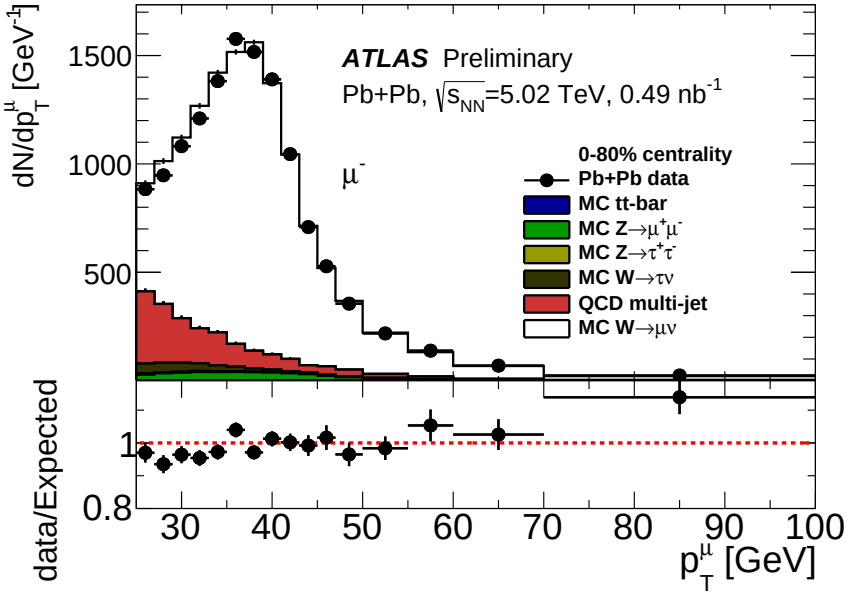


- **Yields** per minimum-bias event divided by $\langle T_{AA}\rangle$ (**integrated** in $|y_Z| < 2.5$).
- **High-precision measurement**: uncertainties related to EW bosons smaller than normalisation uncertainties.
- Most **peripheral bin** shows a hint of excess, otherwise **no significant dependence** 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

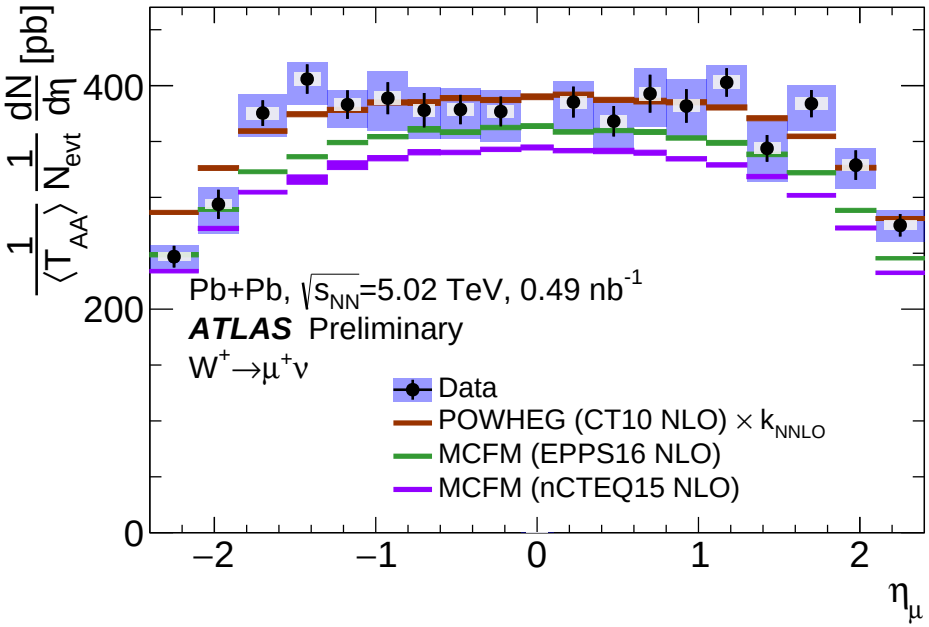


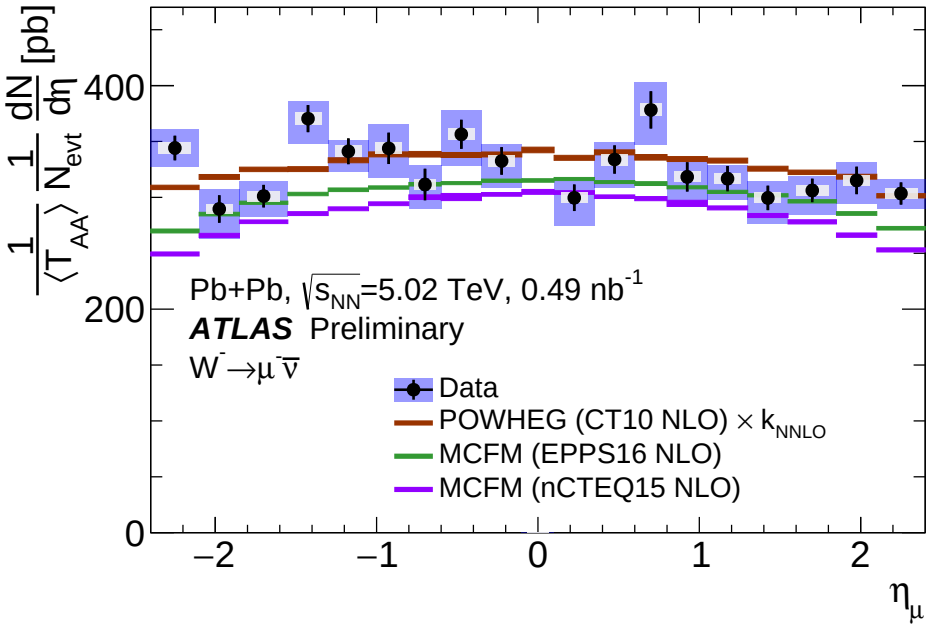


- Events collected with **single-muon trigger** ($p_T = 15$ GeV threshold).
- Muons required to pass reconstruction quality and isolation selections + match trigger.
- Kinematic selection: $p_T^\mu > 25$ GeV, $0.1 < |\eta_\mu| < 2.4$
- Selection on **missing transverse momentum reconstructed from charged-particle tracks**: $p_T^{miss} > 25$ GeV, $m_T > 40$ GeV
- Additional **veto on Z boson candidate** events.
- 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 effects related to p_T^{miss} **reconstruction**.

W bosons in Pb+Pb: Yields vs. rapidity

ATLAS-CONF-2017-067

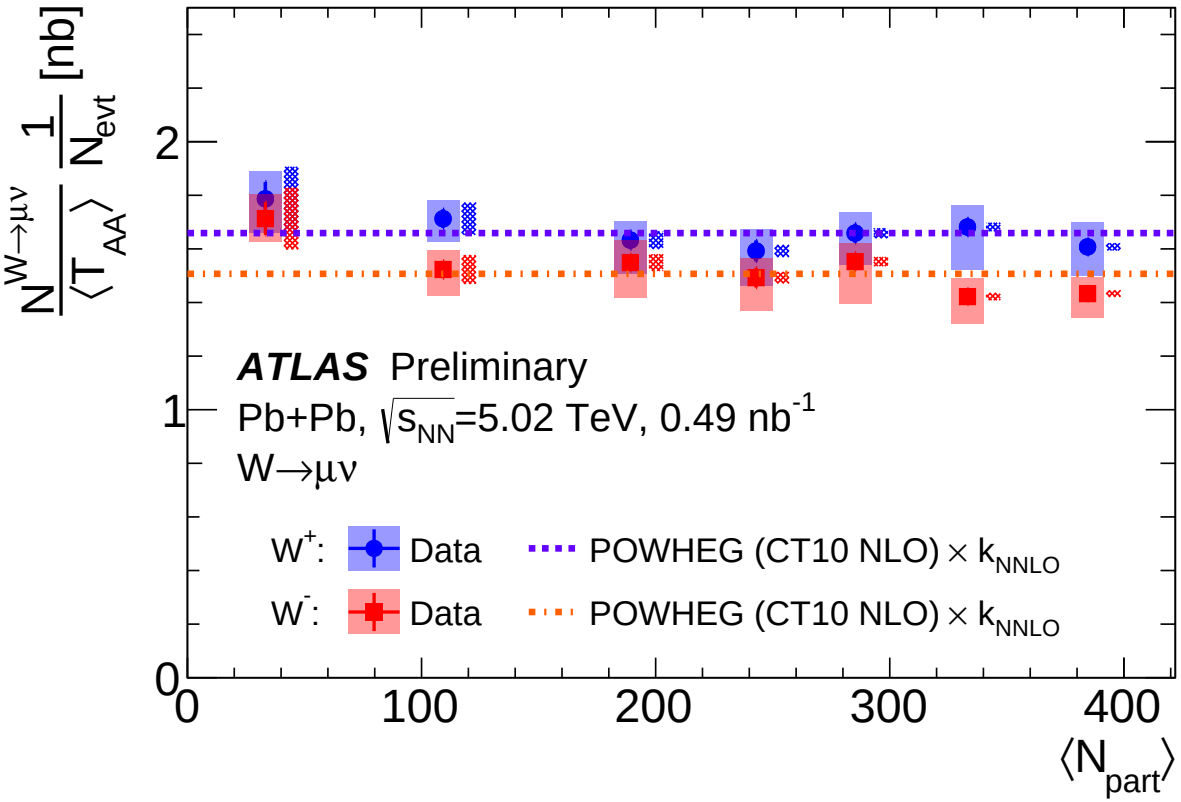




- **Lepton pseudorapidity differential yields** per minimum-bias event **divided by** $\langle T_{AA}\rangle$ for **fiducial** phase-space volume: $p_T^\mu > 25$ GeV, $p_T^{miss} > 25$ GeV, $m_T > 40$ GeV.
- Comparisons with several **theory predictions**:
  - CT10 **free-nucleon PDFs** (Powheg+Pythia8, 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

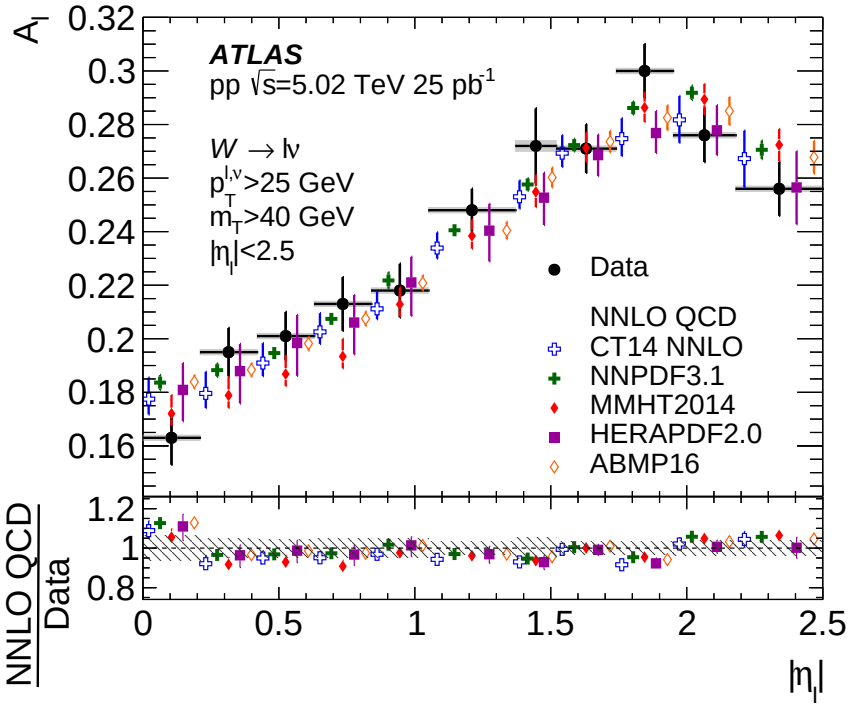
ATLAS-CONF-2017-067

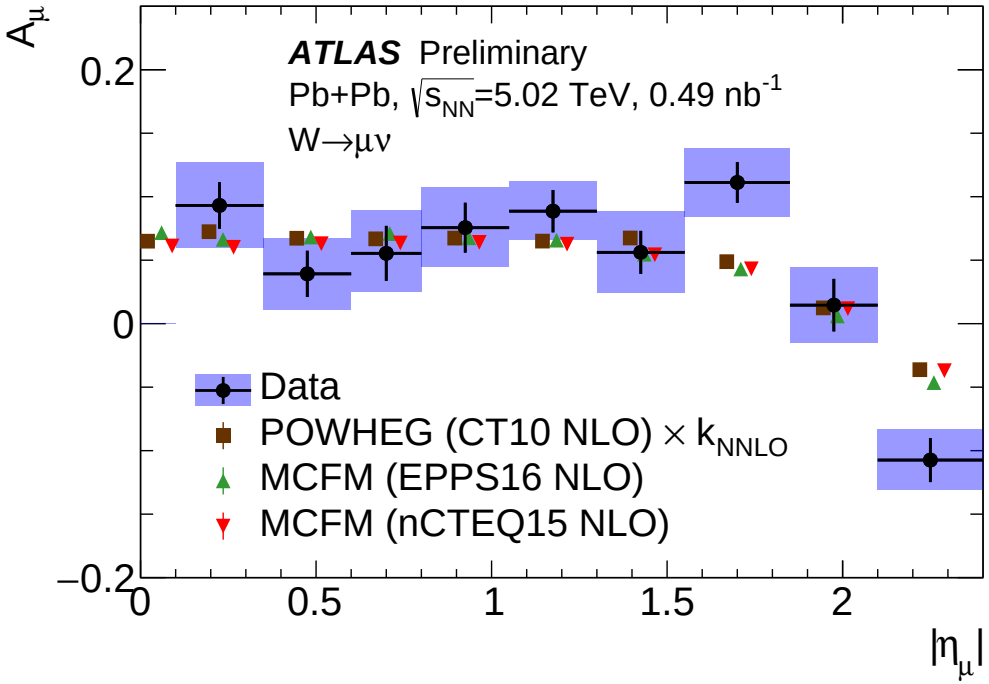


- **Fiducial yields** per minimum-bias event **divided by** $\langle T_{AA}\rangle$ **(integrated** in $0.1 < |\eta_\mu| < 2.4$).
- Similarly to Z bosons, most **peripheral bin** shows a hint of excess.
- Otherwise **no significant dependence** of scaled yields **on centrality** observed.
- **Predictions** 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):

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

- **Systematic uncertainties** are **reduced** to a large extent.
- **Different shapes** of asymmetry distributions in pp and Pb+Pb collisions due to **isospin effect**.
- 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).

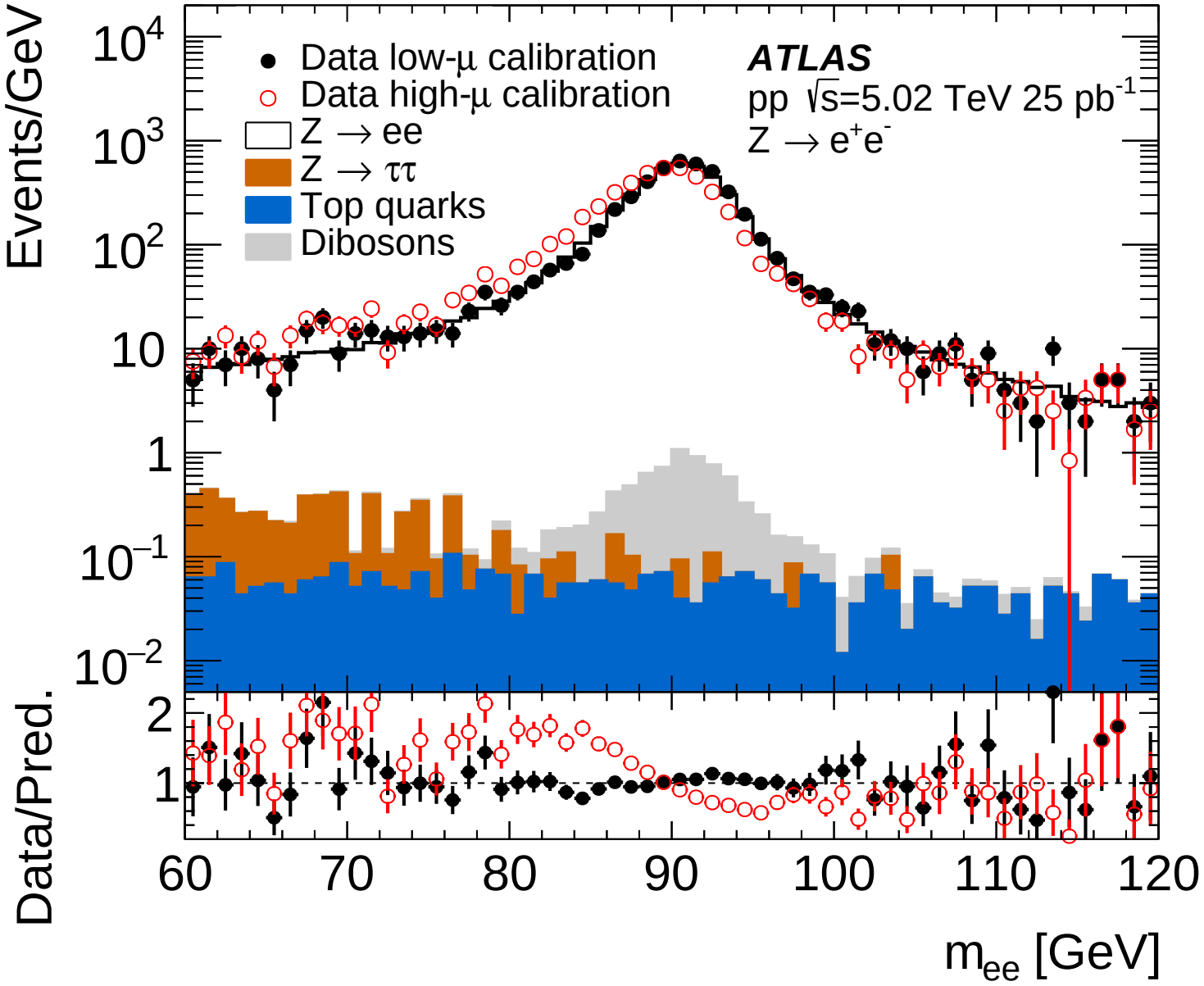
Summary

- Presented 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 baseline** for Pb+Pb results.
  - **Good agreement of NNLO theory predictions** calculated using NNPDF3.1 and HERAPDF2.0 PDFs with data.
- *p*+Pb collisions:
  - Measured nuclear modifications consistent with **nPDF predictions**, but disfavour large **initial-state parton energy loss**.
- 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 (electron channels, new *pp* reference) in preparation.
- 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

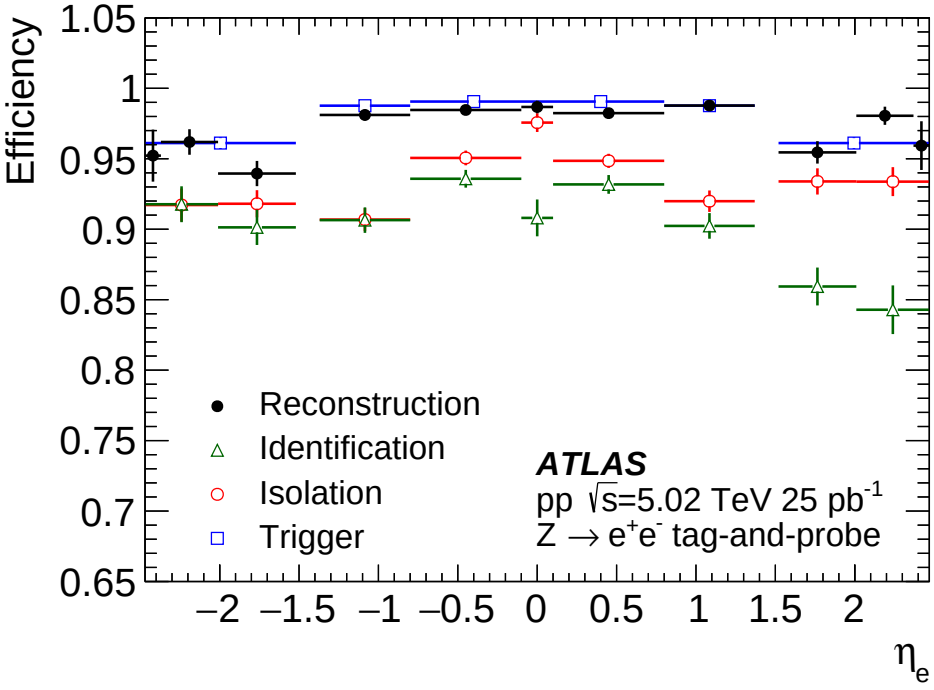
Eur. Phys. J. C 79 (2019) 128 and 79 (2019) 374



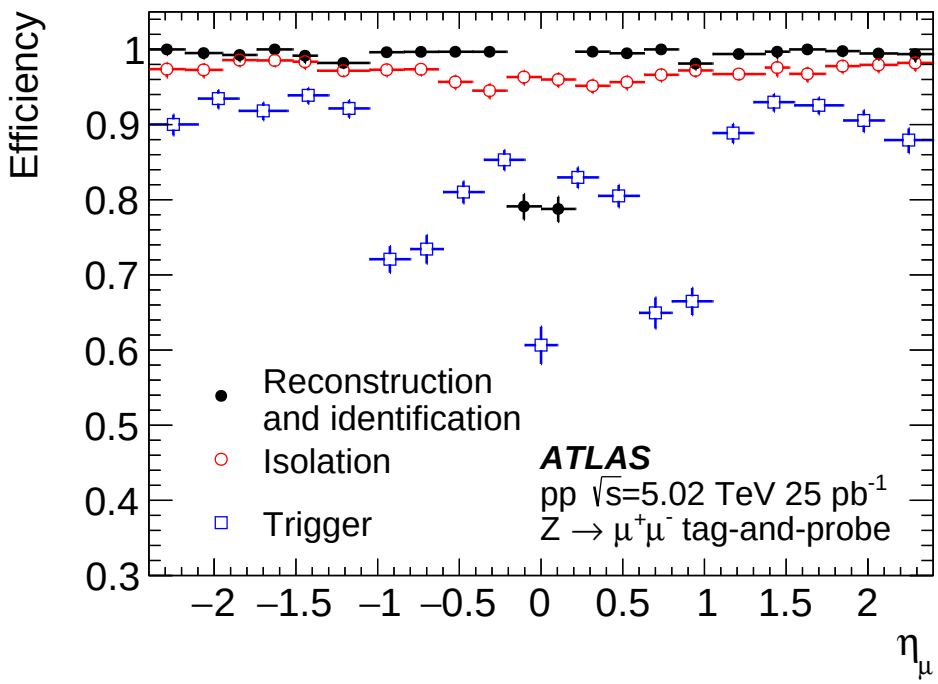
W/Z bosons in pp: Lepton efficiencies

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

electrons



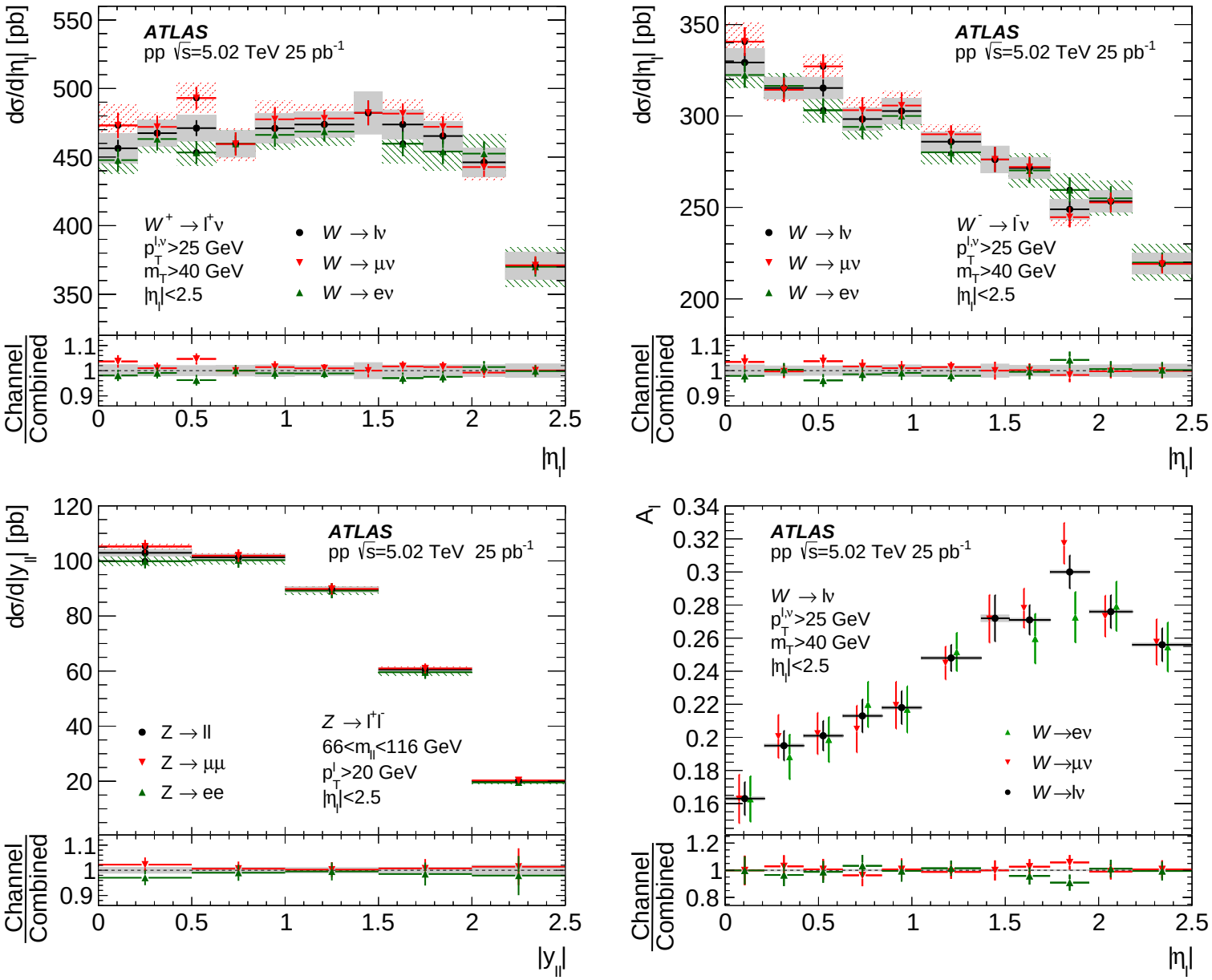
muons



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

W/Z bosons in pp: Channel combination

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



W/Z bosons in pp: Integrated cross-sections

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

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.) ± 29 (syst.) ± 43 (lumi) pb
- W^-: 1401 ± 7 (stat.) ± 18 (syst.) ± 27 (lumi) pb
- Z: 374.5 ± 3.4 (stat.) ± 3.6 (syst.) ± 7.0 (lumi) pb

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

W/Z bosons in pp: Systematic uncertainties

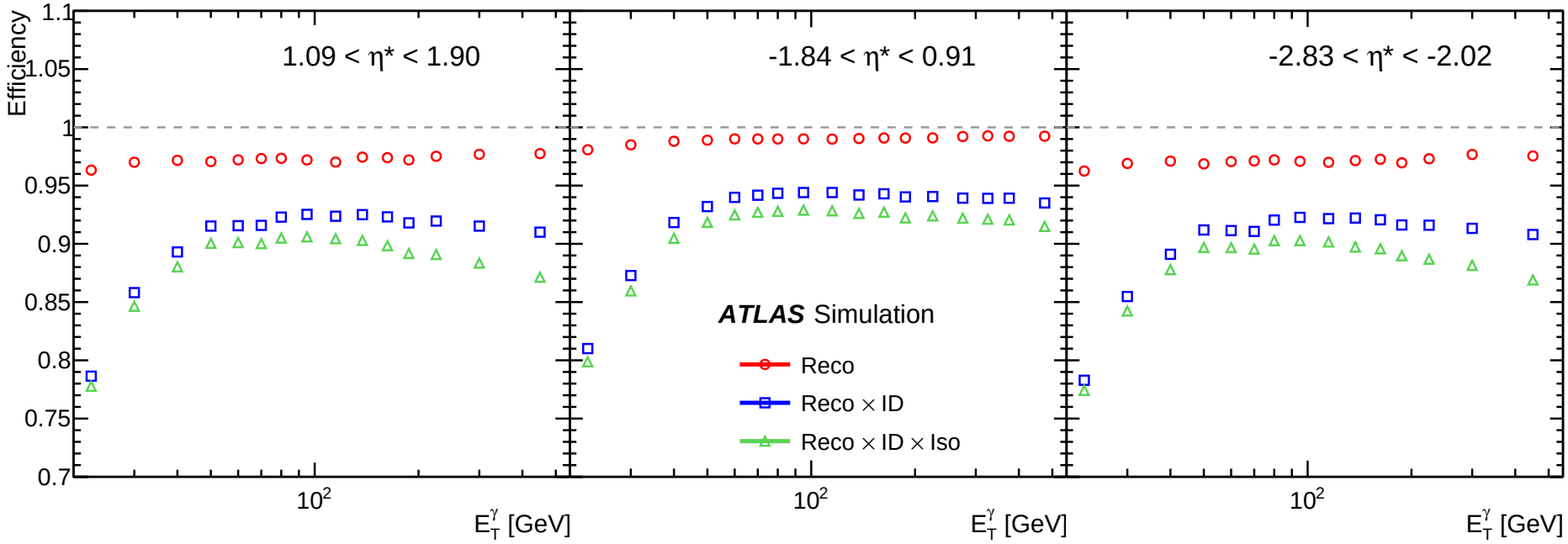
Eur. Phys. J. C 79 (2019) 128 and 79 (2019) 374

	$\delta\sigma_{W^+}$ [%]	$\delta\sigma_{W^-}$ [%]	$\delta\sigma_Z$ [%]
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

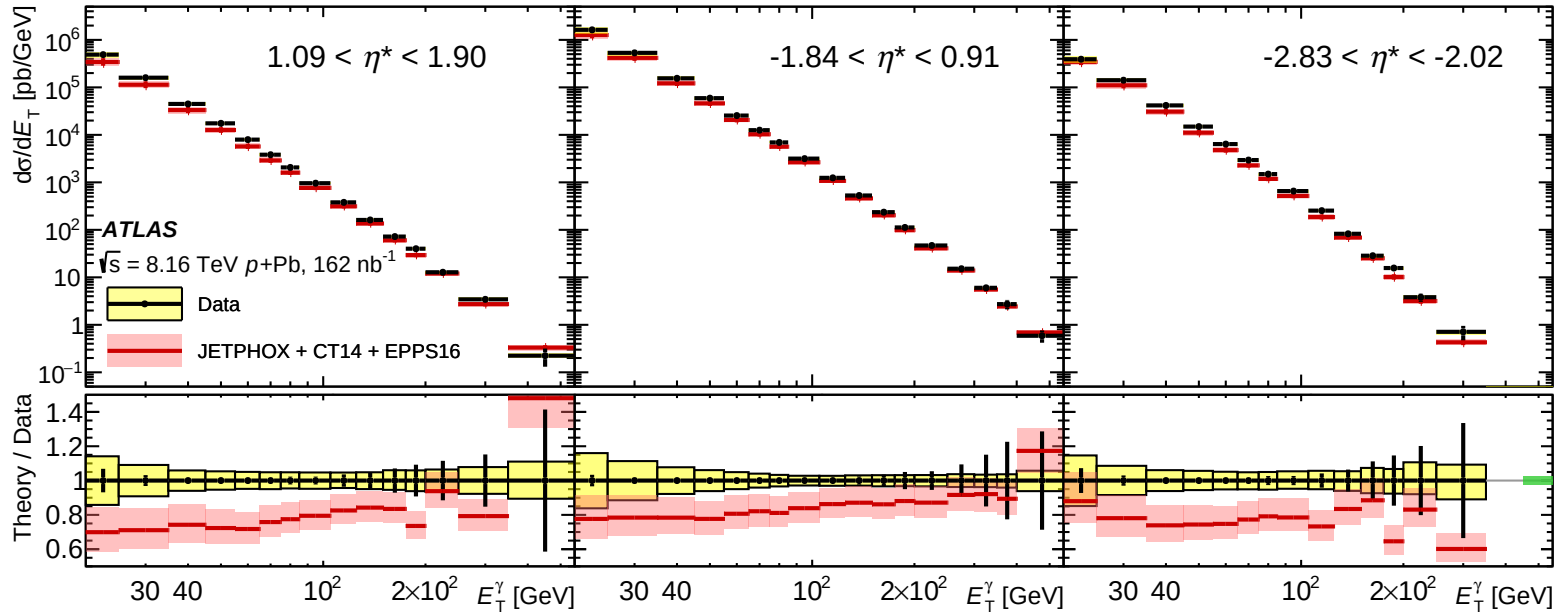
Prompt photons in p+Pb: Efficiencies

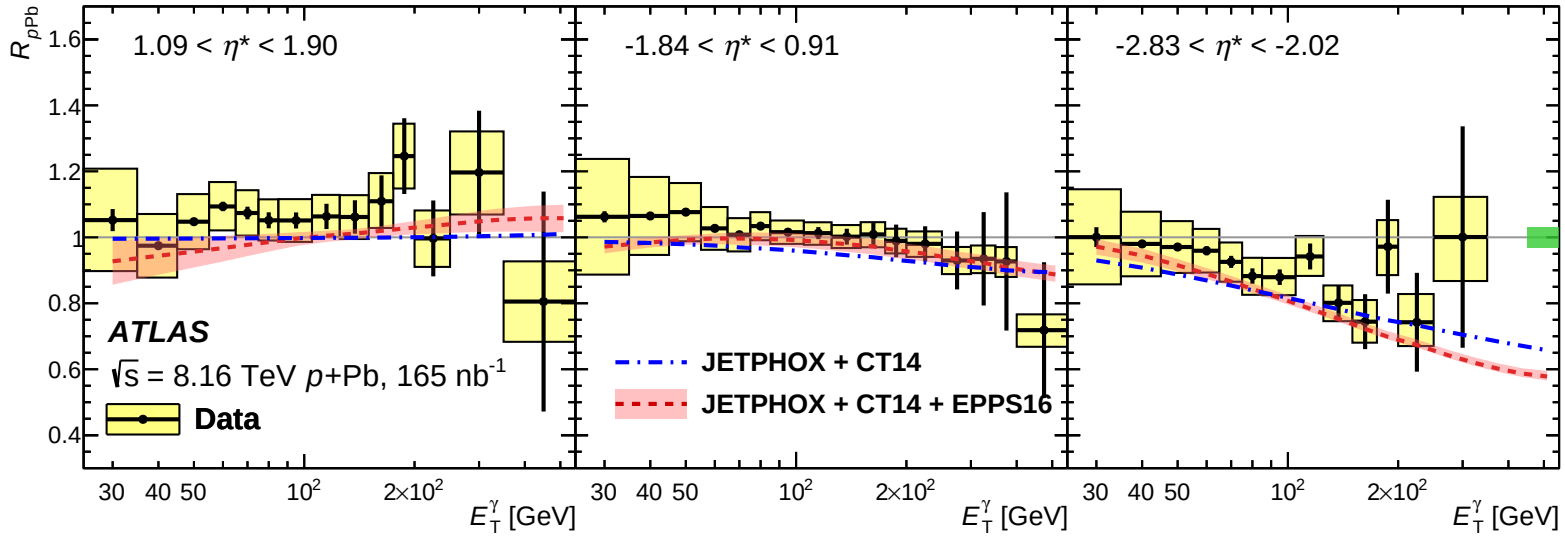
arXiv:1903.02209



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

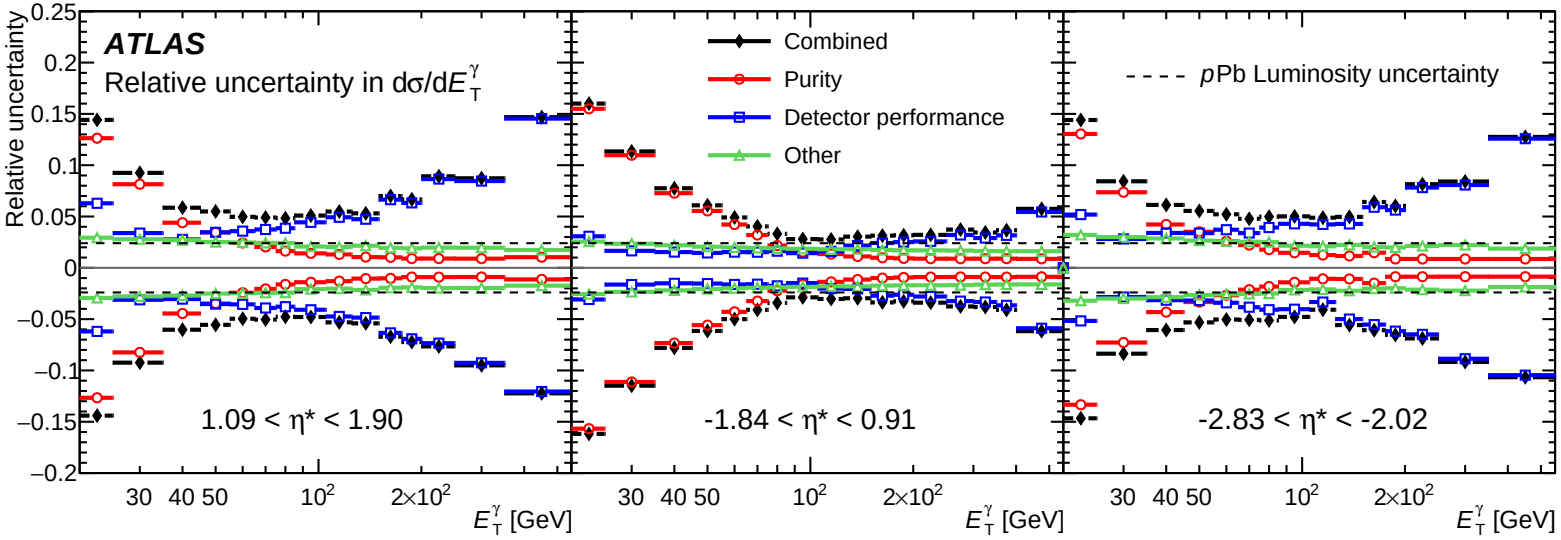
arXiv:1903.02209

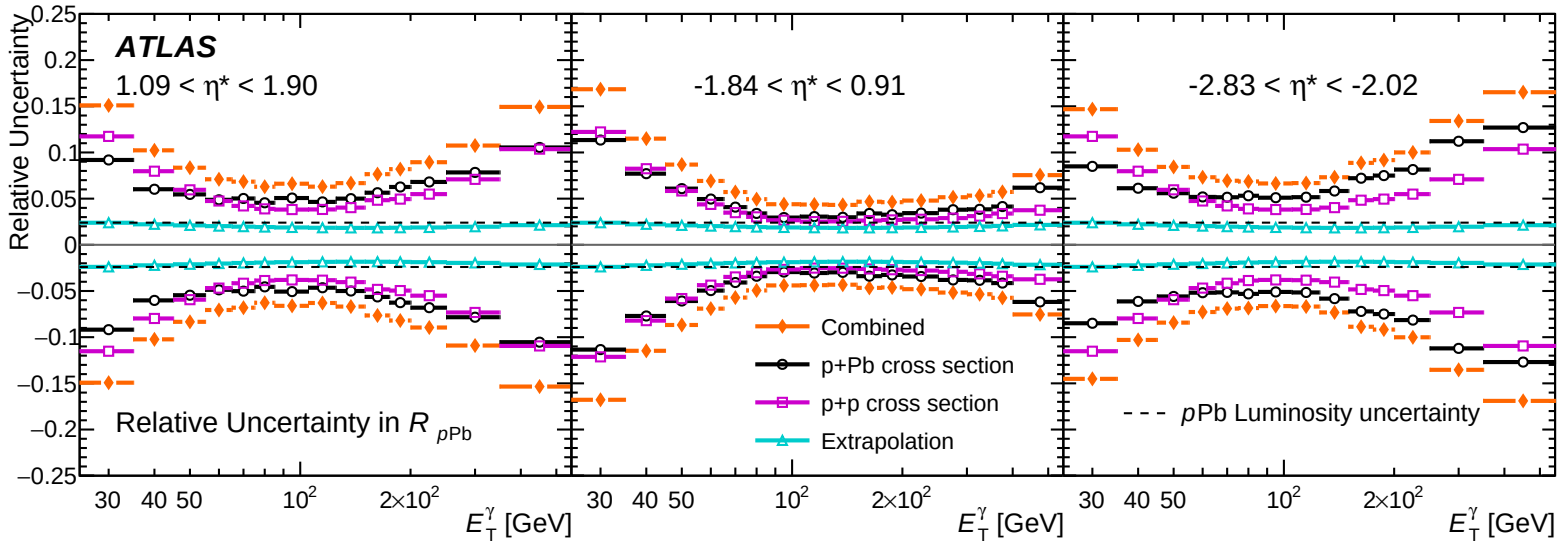




Prompt photons in p+Pb: Systematic uncertainties

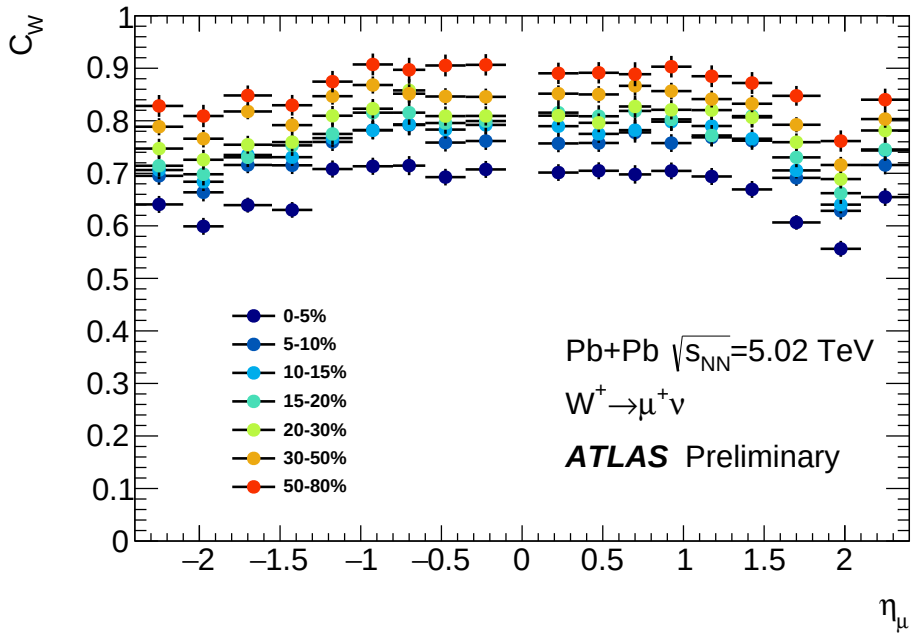
arXiv:1903.02209

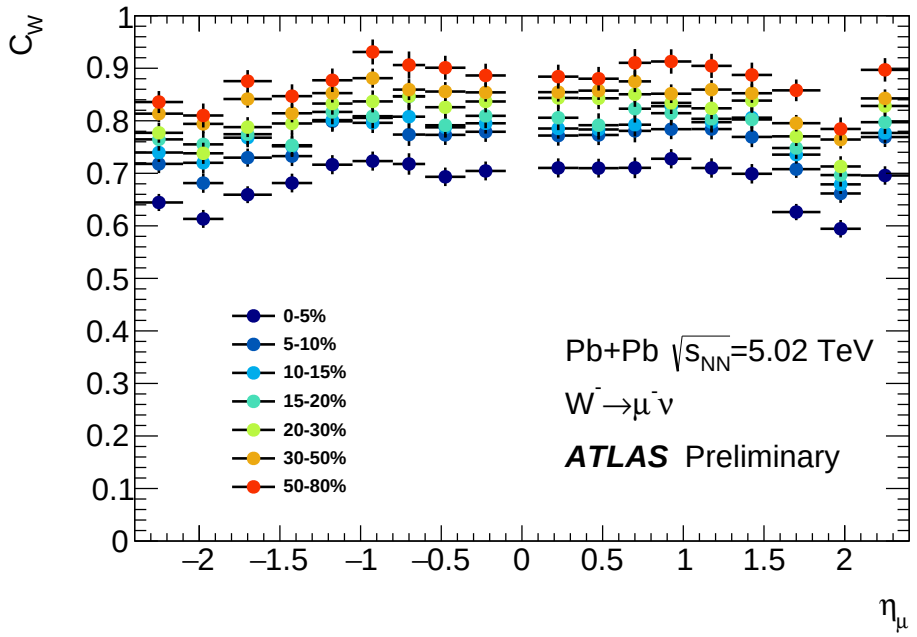




W bosons in Pb+Pb: Correction factors

ATLAS-CONF-2017-067





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