Electroweak-boson production from small to large systems with ALICE at the LHC

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SQM 2022
13 - 17 June 2022
Busan, Republic of Korea

Physics motivations

W and Z bosons in hadronic collisions: produced in the hard processes, during the initial stages of the collisions. Production well described by perturbative QCD and electroweak theory.

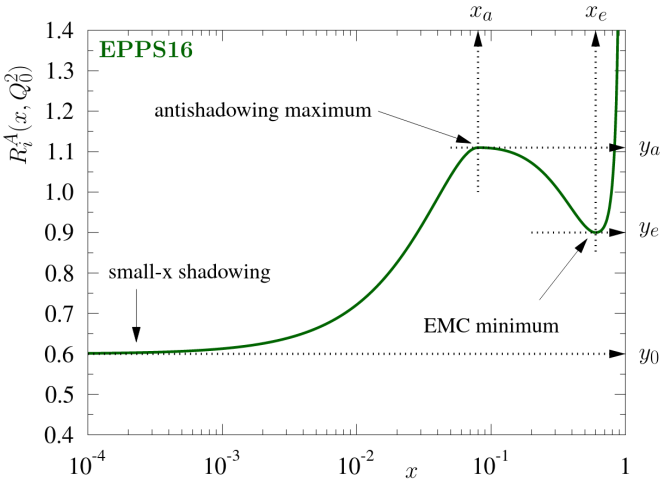
pp collisions:

- insights on multiparton interactions (MPI) in high-multiplicity events
- role of colour-reconnection (CR) mechanism

p–Pb and Pb–Pb collisions:

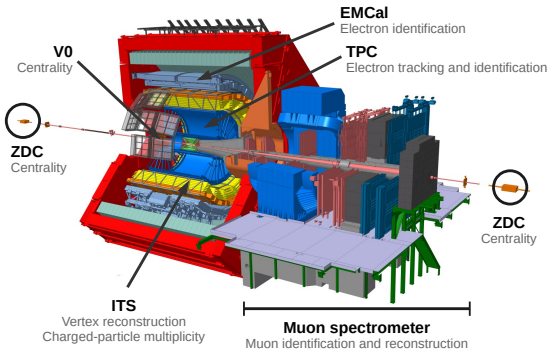
- decay leptons insensitive to the strongly-interacting medium
- probe of the initial state, especially the nuclear modifications of the nucleon PDF

EPJC (2017) 77:163



The ALICE detector

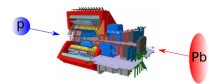
- Electrons reconstructed in the central barrel ($|y| < 0.6$), muons in the forward spectrometer ($-4 < y < -2.5$).



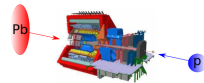
Proton-lead collisions:

$$\Delta y_{\mathrm{cms}} = 0.46$$

p–Pb, p-going:



p–Pb, Pb-going:



Triggers:
EG1: EMCAL, $p_{\mathrm{T}}^{e} > 10$ GeV/c, **MSH**: single $\mu^{\pm}$, $p_{\mathrm{T}}^{\mu} > 4.2$ GeV/c, **MUL**: $\mu^{+}\mu^{-}$, $p_{\mathrm{T}}^{\mu} > 0.5$ GeV/c.

W and Z measurements with ALICE

Collision system	Energy	Luminosity	Year	Analyses
pp	13 TeV	~ 6.6 pb^{-1}	2016 + 2017 + 2018	W NEW!
p–Pb Pb–p	5.02 TeV	5.03 ± 0.18 nb^{-1} 5.81 ± 0.20 nb^{-1}	2013	Z, W
p–Pb Pb–p	8.16 TeV	6.73 ± 0.16 nb^{-1} 10.0 ± 0.22 nb^{-1}	2016	Z, W NEW !
Pb–Pb Pb–Pb	5.02 TeV	~ 750 μb^{-1} 663 ± 15 μb^{-1}	2015 + 2018	Z, W NEW!

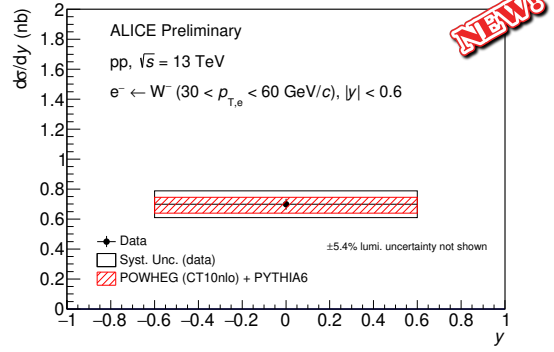
New results:

- pp collisions at $\sqrt{s} = 13$ TeV: multiplicity-dependence of the W-boson cross section at mid-rapidity, and production with associated hadrons
- W boson in p–Pb at $\sqrt{s_{\rm NN}} = 8.16$ TeV and Pb–Pb at $\sqrt{s_{\rm NN}} = 5.02$ TeV: final results, first measurements at large rapidities

New paper on ArXiv: `arXiv:2204.10640[nucl-ex]`: W in p–Pb and Pb–Pb collisions.

W in pp at 13 TeV: production cross section

$W^- \to e^-$



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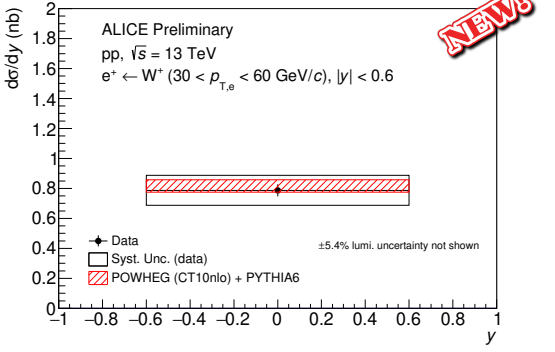
$W^+ \to e^+$



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$W^{\pm} \to e^{\pm}$, isolated electrons with:

$$\begin{cases} |y| < 0.6, \\ 30 < p_{\mathrm{T}} < 60 \text{ GeV}/c, \\ E_{\mathrm{iso}} = E_{R=0.3}/E_e < 0.05\mathrm{GeV}/c^2. \end{cases}$$

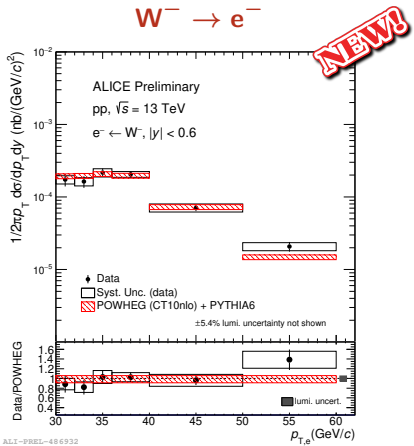
- W^+ cross section higher due to isospin effects
- Good agreement with pQCD calculations at NLO (POWHEG + CT10nlo)

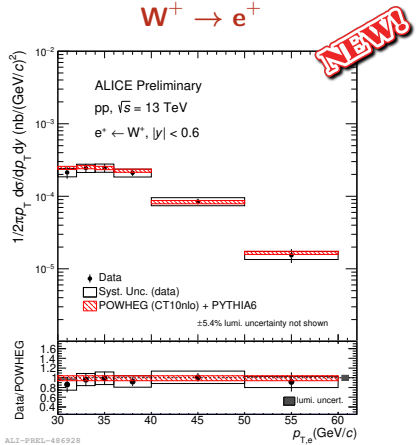
POWHEG: JHEP 06(2010)043, CT10: PRD 82(2010)074024

W in pp at 13 TeV: p_{T}-differential cross section

p_{T}-differential production cross section of $e^{\pm}$ from $W^{\pm}$ decays

- peak at about half the W-boson mass
- Comparison with pQCD (POWHEG + CT10nlo): good agreement between data and model

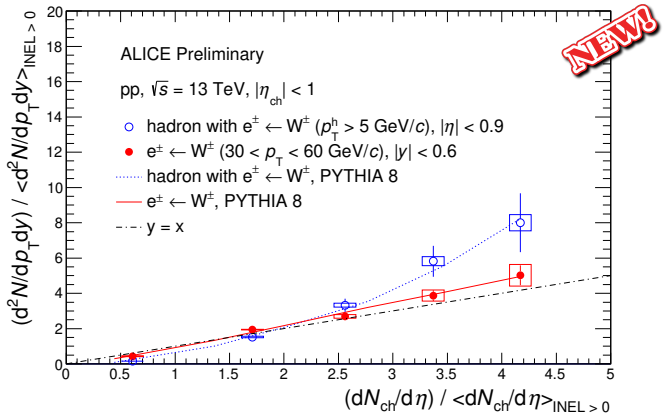




W in pp at 13 TeV: multiplicity dependence

$W^{\pm} \rightarrow e^{\pm}$ (charges combined) as a function of the charged-particle multiplicity

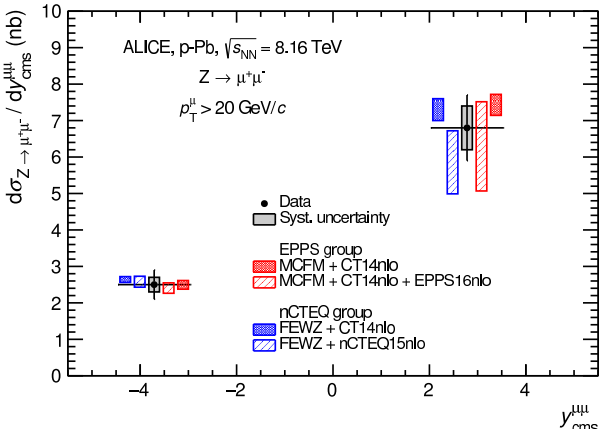
- $W^{\pm} \rightarrow e^{\pm}$
  linear with respect to multiplicity
  $\Rightarrow$ no strong autocorrelation for W boson
- $W^{\pm} \rightarrow e^{\pm}$ with associated hadron
  increase faster than linear w.r.t. multiplicity
  $\Rightarrow$ W less correlated with multiplicity than W + h



Both distributions reproduced by PYTHIA 8 with multiparton interactions and colour reconnection.

PYTHIA: arXiv:2203.1160

Z in p–Pb at 8.16 TeV: production cross section



ALI-PUB-347339

$Z \rightarrow \mu^+\mu^-$ measured at forward and backward rapidities, with:

$$\begin{cases} -4 < y^{\mu} < -2.5, \\ p_{\mathrm{T}}^{\mu} > 20 \text{ GeV}/c, \\ 60 < m_{\mu\mu} < 120 \text{ GeV}/c^2. \end{cases}$$

Compared with theory with (dashed) and without (full) nuclear modifications of the PDF with EPPS16 or nCTEQ15.

JHEP 2009(2020)076

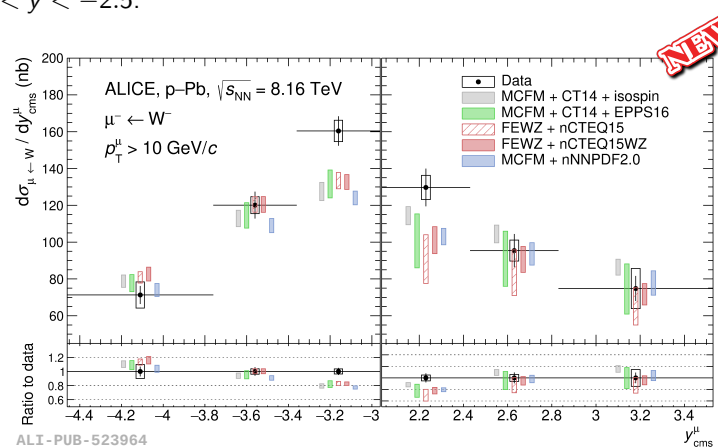
Comparison limited by theoretical and experimental precisions, prevents to draw firm conclusions on nuclear modifications.

CT14: PRD 93(2016)033006, EPPS16: EPJC 77(2017)163, nCTEQ15: PRD 93(2016)085037

W in p–Pb at 8.16 TeV: y-differential cross section

$W^- \to \mu^-$ cross section compared with theory, at backward and forward rapidities.
Muons with $p_T > 10$ GeV/c, $-4 < y < -2.5$.

- Models in fair agreement with each other
- nCTEQ15WZ (full bands) has better precision than original nCTEQ15 (dashed bands)
- Calculations underestimate data for bins closest to midrapidity, both at forward and backward (1.4 and 2σ from EPPS16 predictions)



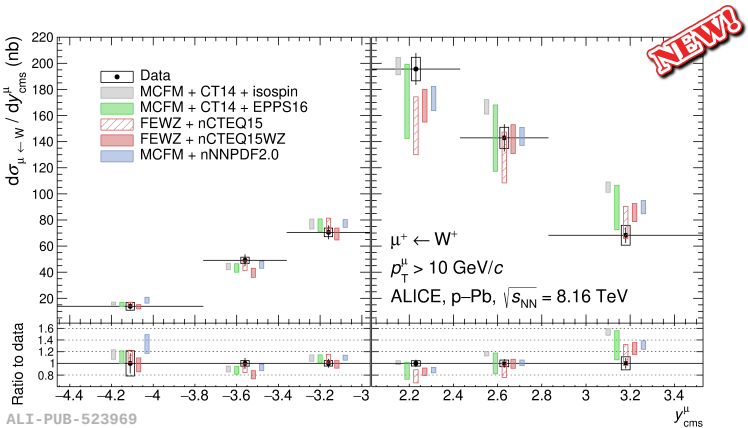
arXiv:2204.10640

$\Rightarrow$ ability to constrain the slope of the evolution of the nPDF vs. rapidity (i.e. vs. Bjorken-x).

W in p–Pb at 8.16 TeV: y-differential cross section

$W^+ \to \mu^+$ cross section compared to the same theory models as for W^-.

- Measurements are well reproduced by all nPDF models, no discrepancy in the bins closest to midrapidity
- Large deviation of 3.5 σ from free-PDF prediction at largest positive rapidities



nCTEQ15WZ: EPJC 80(2020)968

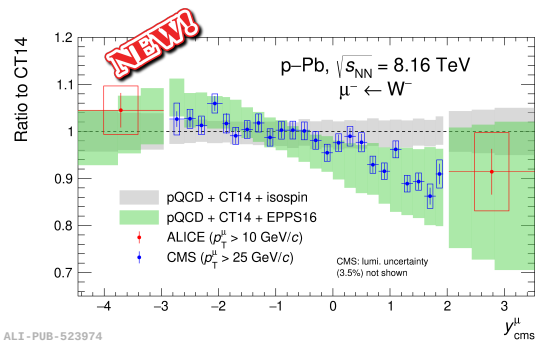
nNNPDF2.0: JHEP 09(2020)183

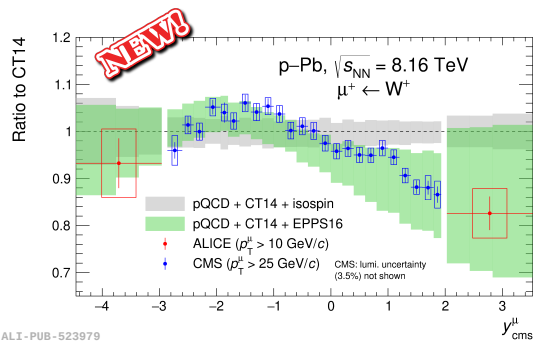
arXiv:2204.10640

$\Rightarrow$ ability to constrain nPDFs in the low-x region ($\sim 10^{-4}$) where constraints are scarce.

W in p–Pb at 8.16 TeV: comparison with mid-rapidity

Comparison with CMS results: measured in p–Pb at 8.16 TeV, at midrapidity, with integrated luminosity of 173.4 ± 6.1 nb^{-1} (PLB 800(2020)135048).



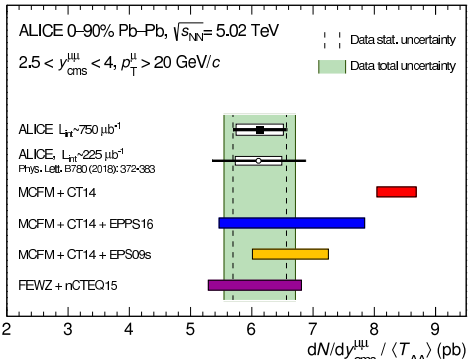


arXiv:2204.10640

ALICE results in agreement with the trend at the edges of the CMS acceptance. Shows the relevance of providing measurements at large rapidities for nPDF determination.

Z in Pb–Pb at 5.02 TeV: $\langle T_{AA} \rangle$-scaled yield

$Z \to \mu^+\mu^-$ yield scaled with average nuclear overlap $\langle T_{AA} \rangle$, same selection as in p–Pb.



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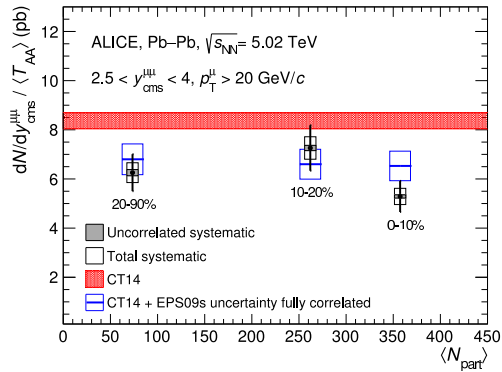

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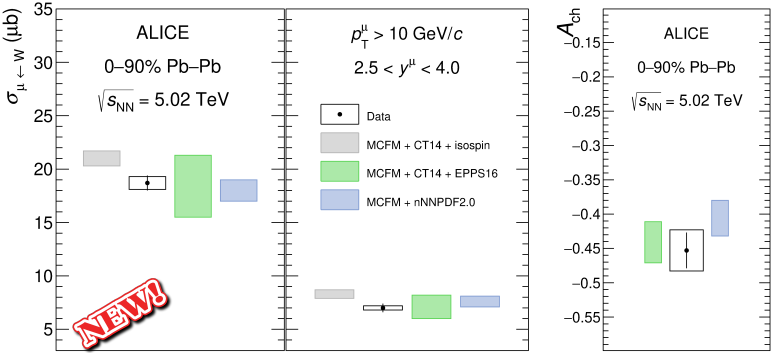
JHEP 09(2020)076

Measurement reproduced by models with nuclear modifications, 3.4 σ deviation from free-PDF prediction. Limited centrality dependence both in data and model. EPS09s: JHEP 07(2012)073

W in Pb–Pb at 5.02 TeV: cross section and A_{ch}

$\mathrm{W}^{\pm} \rightarrow \mu^{\pm}$, same selection as in p–Pb, 0–90% centrality.

$$A_{\mathrm{ch}} = \frac{N_{\mu^+ \leftarrow \mathrm{W}^+} - N_{\mu^- \leftarrow \mathrm{W}^-}}{N_{\mu^+ \leftarrow \mathrm{W}^+} + N_{\mu^- \leftarrow \mathrm{W}^-}}$$



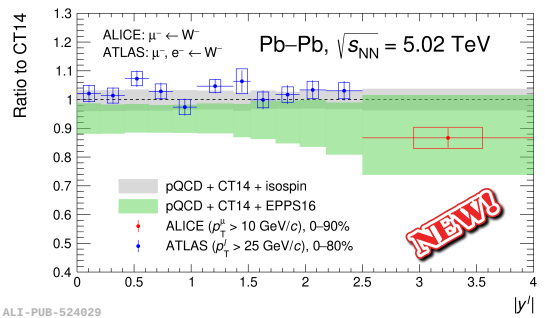
ALI-PUB-524009

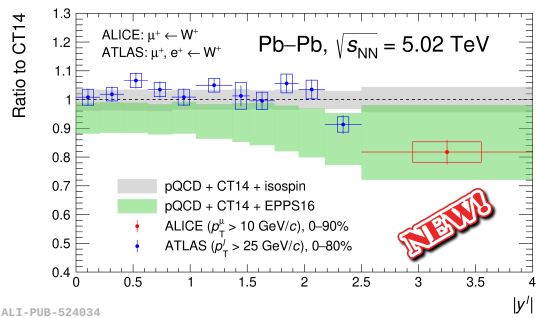
- Good agreement between nPDF models and the data
- CT14 predictions overestimate the measurements
- A_{ch} driven by isospin
- reduction in uncertainty, particularly visible for EPPS16

First W measurements in Pb–Pb collisions at forward rapidity, assessing the low-x region.

W in Pb–Pb at 5.02 TeV: comparison with mid-rapidity

Comparison with ATLAS results: measured in Pb–Pb at 5.02 TeV, at midrapidity, for 0–80% centrality (EPJC 79(2019)935). Integrated luminosity of 0.49 nb^{-1}.





ALICE results well described by EPPS16 calculations, which underestimates the ATLAS measurements more in favour of CT14 predictions.

arXiv:2204.10640

W in Pb–Pb at 5.02 TeV: centrality dependence

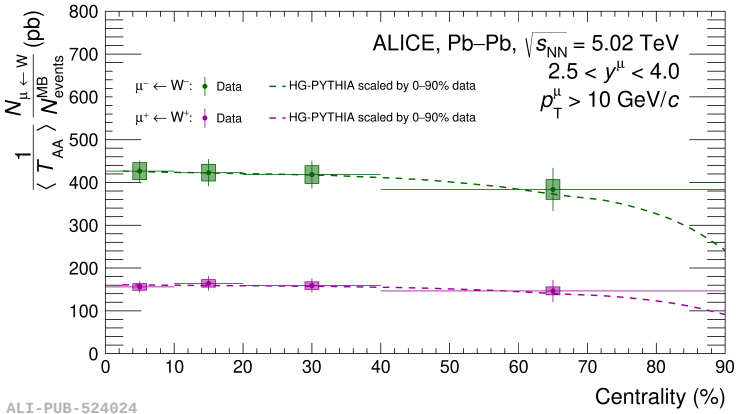
$\langle T_{AA} \rangle$-scaled yield measured in centrality intervals. arXiv:2204.10640

NEW

- Consistent with N_{coll} scaling expected if no significant centrality dependence of the shadowing

HG-PYTHIA: includes biases from event selection and geometry that cause suppression in peripheral collisions.

- Good agreement with data, can't conclude on peripheral events due to limited precision



ALI-PUB-524024

HG-PYTHIA: C. Loizides, A. Morsch, PLB 773(2017)408-411

Conclusion

Electroweak-boson measurements with ALICE **from small to large systems** at many different energies.

pp collisions:

- linear dependence on multiplicity of the W production
- measurement with associated hadron reproduced with PYTHIA 8 including MPI and CR

p–Pb collisions:

- tension with models (W^-), observation of nuclear modifications (W^+)
- consistency with CMS measurements, extending the reach in Bjorken-x down to $\sim 10^{-4}$

Pb–Pb collisions:

- measured yield in agreement with nPDF models
- important inputs for the study of the centrality dependence of nPDFs

Promising results in view of Run 3, with upgraded detector and extended statistics available.

Thank you!

Back-up

References: ALICE measurements

W (+ hadron) in pp collisions at 13 TeV:

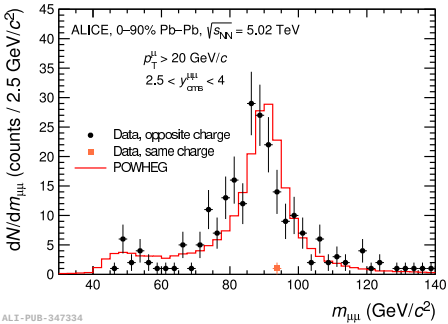
- preliminary figures: https://alice-figure.web.cern.ch/node/19628

Boson	System	Energy	Reference	ArXiv
W, Z	p–Pb	5.02 TeV	JHEP 02(2017)077	1611.03002
Z	p–Pb	8.16 TeV	JHEP 09(2020)076	2005.11126
	Pb–Pb	5.02 TeV		
W	p–Pb	8.16 TeV	submitted to JHEP	2204.10640
	Pb–Pb	5.02 TeV		

Z-boson yield extraction

Z candidates: opposite-sign muon pairs in the fiducial region:

$$\begin{cases} -4 < \eta_\mu < -2.5, \\ p_{\mathrm{T}}(\mu) > 20 \text{ GeV}/c, \\ 60 < m_{\mu^+\mu^-} < 120 \text{ GeV}/c^2. \end{cases}$$



FONLL: JHEP 10(2012)137

POWHEG: JHEP 07(2008)060

Background:

- $Z \to \tau\tau \to \mu\mu$, pairs from charm, bottom and top (FONLL, POWHEG), $\sim 1\%$ of the yield,
- combinatorial background (same-sign dimuon invariant mass distribution), negligible or subtracted from Z candidates.

Low background $\to$ signal extracted by counting the entries in the invariant mass distribution.
Raw yield corrected for the acceptance $\times$ efficiency of the detector (POWHEG+GEANT3), isospin accounted for by combining pp, pn and nn binary collisions.

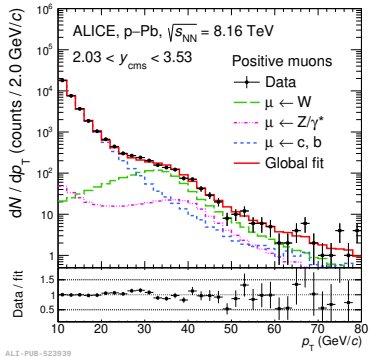
W-boson yield extraction

W extraction: challenging in ALICE, since the missing transverse energy or momentum can't be estimated contrary to ATLAS and CMS. Fit of the single muons p_{T} distribution:

$$f(p_{\mathrm{T}}) = N_{bkg} \cdot f_{bkg}(p_{\mathrm{T}}) + N_{\mu \leftarrow W} \cdot \left(f_{\mu \leftarrow W}(p_{\mathrm{T}}) + R \cdot f_{\mu \leftarrow Z}(p_{\mathrm{T}})\right)$$

- $f_X(p_{\mathrm{T}})$: MC templates (FONLL, POWHEG),
- N_X: free parameters,
- R: ratio of the Z to W cross sections from POWHEG.

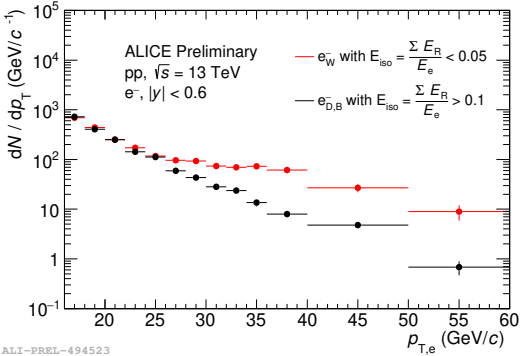
In the fiducial region: $\begin{cases} -4 < \eta_\mu < -2.5, \\ p_{\mathrm{T}}(\mu) > 10 \text{ GeV}/c. \end{cases}$

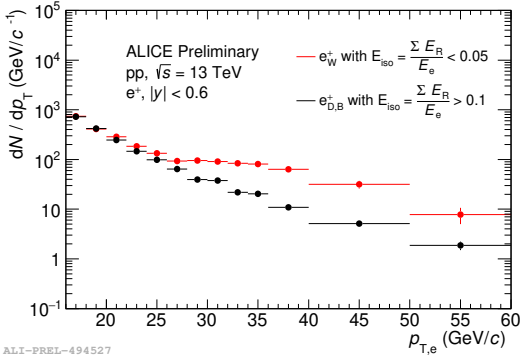


Same treatment of the isospin and acceptance × efficiency as for Z.

W-boson yield extraction in pp

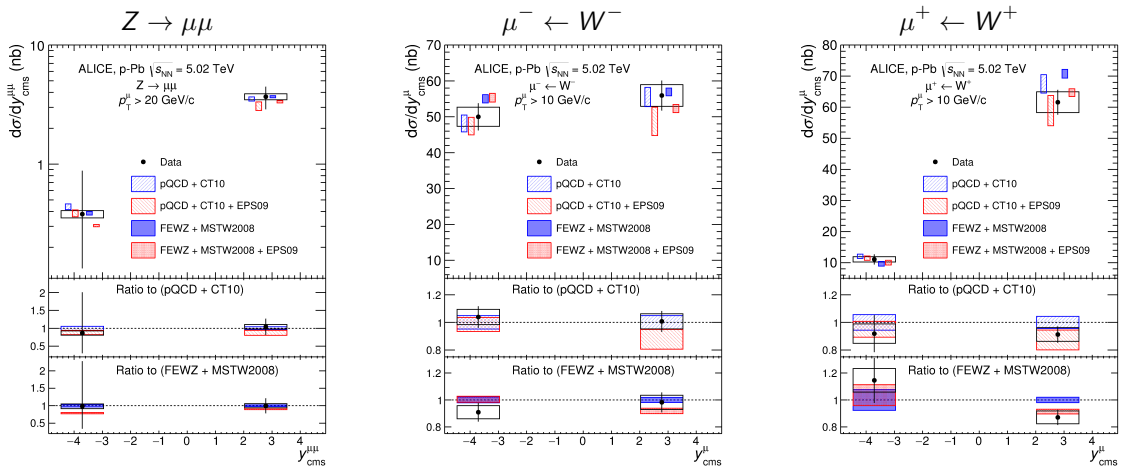
$e^{\pm} \leftarrow$ W candidates selected by looking for isolated electrons in EMCAL.





Background contamination evaluated from MC- and data-based methods and subtracted.
Associated hadron production via azimuthal correlation between electron and away-side hadron.

W and Z in p–Pb at 5.02 TeV



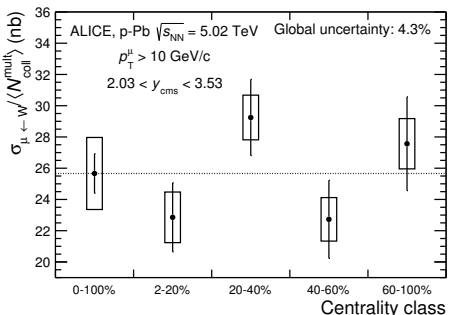
Cross-sections compared to pQCD and FEWZ: agreement with and without including nPDFs.

JHEP 1702 (2017) 077

W and Z in p–Pb at 5.02 TeV

Lepton charge asymmetry: partial cancellation of uncertainties, still compatible with and without including nPDFs.

Centrality dependence: compatible with constant (within uncertainties), scaling of the cross-section with the number of binary collisions.



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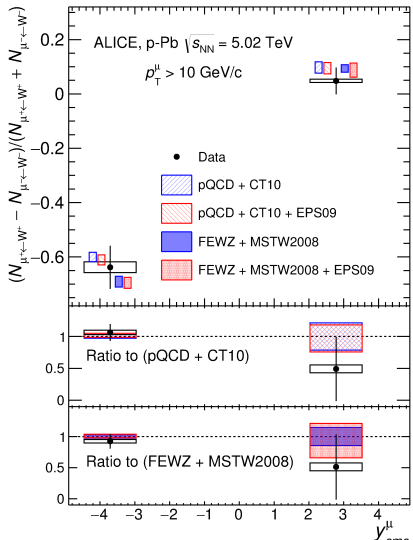

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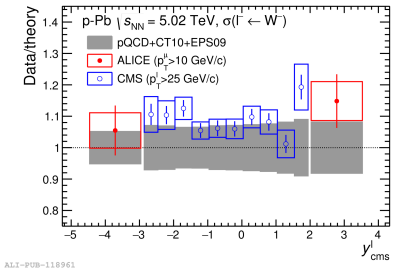
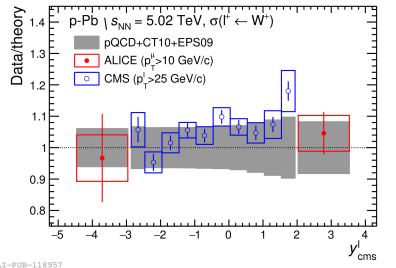
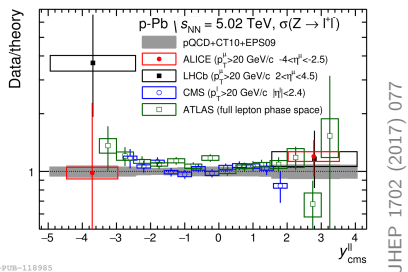
W and Z in p–Pb at 5.02 TeV







JHEP 1702 (2017) 077

nPDF models

nPDF set	EPS09	nCTEQ15	EPPS16	nNNPDF2.0
Order	NLO	NLO	NLO	NLO
Flavour separation	valence	valence	valence + sea	valence + sea
Proton baseline	CTEQ6.1	CTEQ6M-like	CT14NLO	NNPDF3.1
Free parameters	15	35	52	256 (NN)
Data points	929	708	1811	1467
Reference	JHEP 04(2009)065	PRD 93(2016)085037	EPJC 77(2017)163	JHEP 09(2020)183

- **New sets**: EPPS21 (EPJC 82(2022)413), nNNPDF3.0 (arXiv:2201.12363)
- **Extensions**: nCTEQ15HIX (PRD 103(2021)11), nCTEQ15WZ+SIH (arXiv:2105.09873), nCTEQ15HQ (arXiv:2204.09982)