Electroweak-boson production in p–Pb and Pb–Pb collisions at the LHC with ALICE

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Outline

1. Introduction and ALICE detector
2. W and Z with ALICE
3. Conclusions and perspectives

Physics motivation

Z and W bosons: sensitive probes of the nuclear modifications of the parton distribution functions (PDF):

- production well described by perturbative QCD and electroweak theory
- produced in the hard processes, during the initial stages of the collision
- if studied in their leptonic decay: insensitive to the strongly-interacting medium

Production in heavy-ion collisions modified compared to pp collisions following various nuclear effects.

Goal: help constraining the nuclear PDF (nPDF) in models by adding data for their global fits.

Production cross section: to be compared to the expression obtained with the QCD factorization theorem, expressed at leading order as:

$$\sigma_{AB} \propto \sum_q \frac{4\pi e_q^2 \alpha^2}{9\hat{s}} f_q(x_1, Q^2) f_{\bar{q}}(x_2, Q^2)$$

Nuclear modification factor: investigates the suppression or enhancement of the production due to nuclear effects with respect to pp collisions:

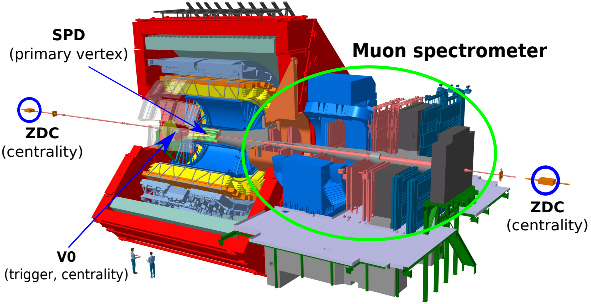
$$R_{\mathrm{AA}} = \frac{1}{\langle T_{\mathrm{AA}} \rangle} \cdot \frac{\mathrm{d}N_{\mathrm{AA}}/\mathrm{d}y}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}y}, \qquad R_{\mathrm{pA}} = \frac{1}{A} \cdot \frac{\mathrm{d}\sigma_{\mathrm{pA}}/\mathrm{d}y}{\mathrm{d}\sigma_{\mathrm{pp}}/\mathrm{d}y}$$

with T_{AA}: nuclear overlap function from Glauber model.

W charge asymmetry: sensitive to the down/up ratio and to quark densities in the nucleus:

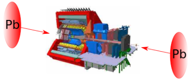
$$A = \frac{N_{\mu^+ \leftarrow W^+} - N_{\mu^- \leftarrow W^-}}{N_{\mu^+ \leftarrow W^+} + N_{\mu^- \leftarrow W^-}}.$$

The ALICE detector



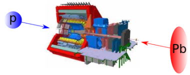
Large rapidities: probing of the low ($\sim 10^{-4}$ to $\sim 10^{-3}$) and high ($\sim 10^{-1}$ to almost unity) Bjorken-x regions

Pb–Pb:



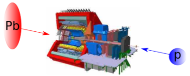
$2.5 < y_{\mathrm{cms}} < 4$

p–Pb, p-going:



$2.03 < y_{\mathrm{cms}} < 3.53$

p–Pb, Pb-going:



$-4.46 < y_{\mathrm{cms}} < -2.96$

W and Z with ALICE

Collision system	Energy	Luminosity	Year	Analyses
Pb–Pb	5.02 TeV	$663 \pm 15\ \mu b^{-1}$	2015 + 2018	W
Pb–Pb	5.02 TeV	$\sim 750\ \mu b^{-1}$	2015 + 2018	Z
p–Pb Pb–p	5.02 TeV	$5.03 \pm 0.18\ nb^{-1}$ $5.81 \pm 0.20\ nb^{-1}$	2013	Z, W
p–Pb Pb–p	8.16 TeV	$8.47 \pm 0.18\ nb^{-1}$ $12.77 \pm 0.25\ nb^{-1}$	2016	Z, W

- Z in Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV: measurement combining the data from the 2015 and 2018 periods.
- Z in p–Pb at $\sqrt{s_{NN}} = 8.16$ TeV: submitted along the Pb–Pb results
- W in p–Pb at $\sqrt{s_{NN}} = 8.16$ TeV and Pb–Pb at $\sqrt{s_{NN}} = 5.02$ TeV: preliminary results, first measurements at large rapidities

JHEP 2009 (2020) 076 (Z in p–Pb and Pb–Pb).

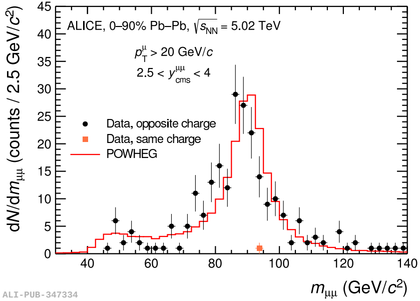
Z-boson yield extraction

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

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

FONLL: JHEP 10(2012)137

POWHEG: JHEP 07(2008)060



JHEP 2009 (2020) 076

Background:

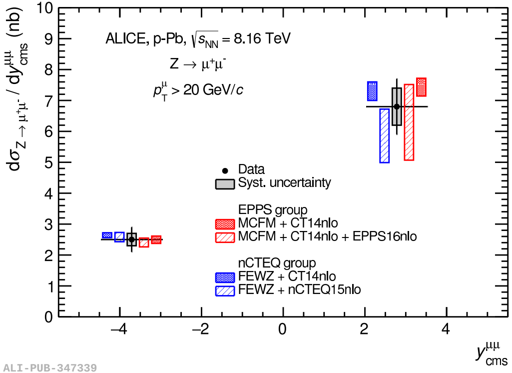
- Z→ $\tau\tau \to \mu\mu$, pairs from charm, bottom and top (FONLL, POWHEG), ($\sim 1\%$)
- combinatorial background (same-sign dimuon invariant mass distribution), negligible or subtracted from Z candidates

Low background → signal extracted by counting the entries in the invariant mass distribution.
Raw yield corrected for the acceptance × efficiency of the detector

Z in p–Pb at 8.16 TeV

Increased statistics with respect to p–Pb at 5.02 TeV:

- 3 times more Z boson identified at forward rapidity,
- 15 times more at backward rapidity.



ALI-PUB-347339

JHEP 2009 (2020) 076

Comparison with theory: using CT14 as baseline PDF and EPPS16 or nCTEQ15 for nuclear modifications.

Despite the better precision, unable to draw firm conclusions on PDF modifications.

CT14: Phys. Rev. D 93, 033006 (2016)

EPPS16: EPJC(2017) 77:163

nCTEQ15: Phys. Rev. D 93, 085037 (2016)

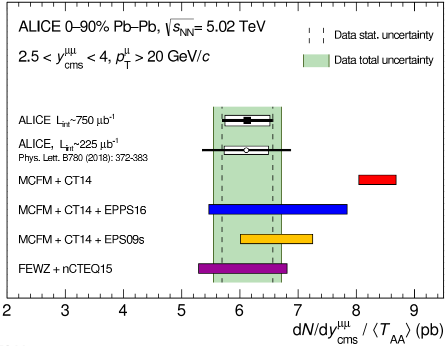
MCFM: EPJC 77(2017)7

FEWZ: Comp. Phys. Comm. 182(2011)2388-2403

Z in Pb–Pb at 5.02 TeV

Merging of the 2015 and 2018 data samples, luminosity increased from 225 to 750 μb^{-1}, 3 times more Z bosons. Improvement of the precision of the measurement.

JHEP 2009 (2020) 076



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- Compatible with calculations including nPDFs using three different models,
- 3.4σ deviation from free PDF prediction with CT14 (previous result: 2.3σ deviation).

EPS09: JHEP 04(2009)065

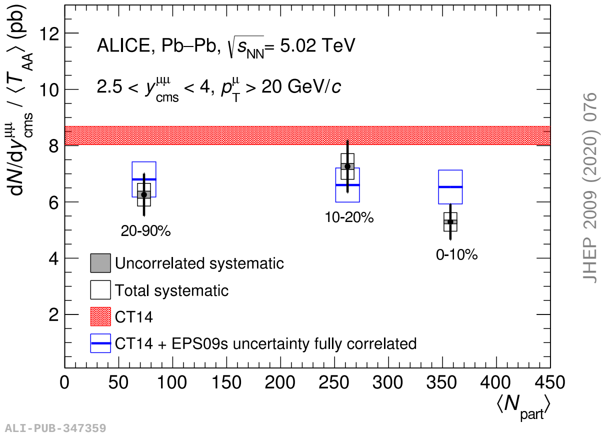
EPS09s: JHEP 07(2012)073

Strongest evidence of nuclear modifications with gauge bosons measured with ALICE.

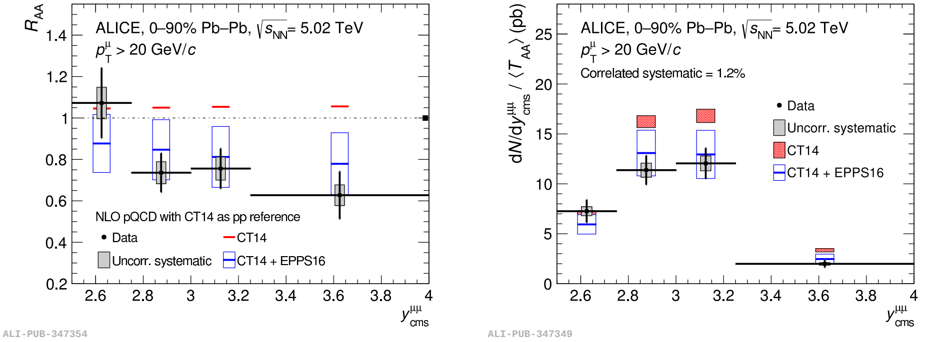
Z in Pb–Pb at 5.02 TeV

Differential studies with more bins than the previously published results:

- R_{AA} as a function of rapidity
- invariant yield as a function of centrality and rapidity
- Larger deviation for the most central events and the largest rapidities



Z in Pb–Pb at 5.02 TeV



JHEP 2009 (2020) 076

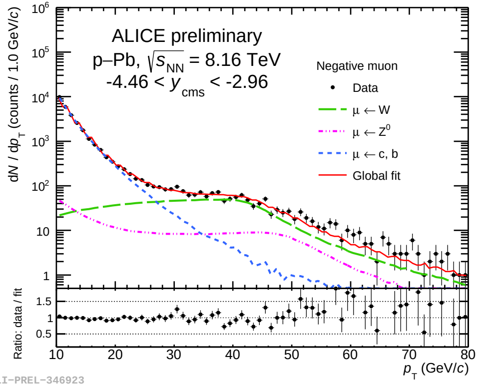
- Better agreement when including nuclear modifications

W-boson yield extraction

W extraction: Fit of the single muons p_{T} distribution:

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

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



In the fiducial region:

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

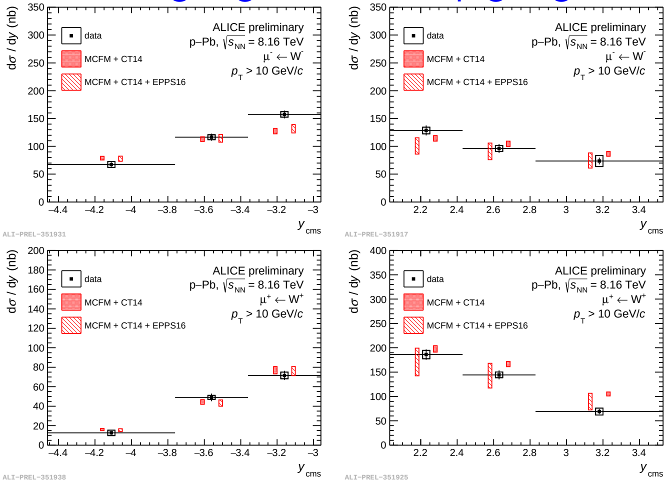
Same treatment of acceptance $\times$ efficiency as for Z.

$W^{\pm}$ in p–Pb at 8.16 TeV

Differential cross sections as a function of rapidity, compared to theoretical predictions.

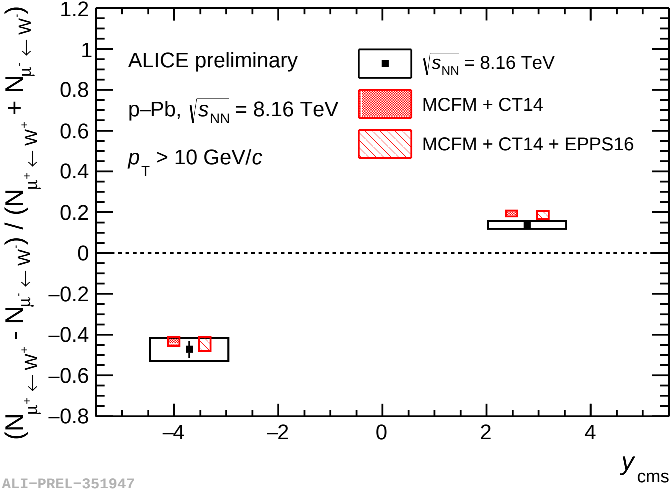
- Deviation from theory for W^{-} at backward rapidity in the most central bin

W^{-} Pb-going W^{-} p-going



W^{+} Pb-going W^{+} p-going

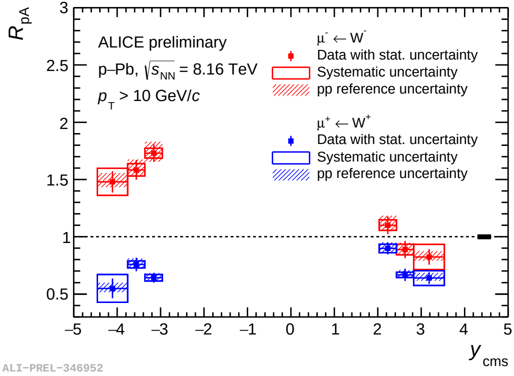
Lepton charge asymmetry compared with theoretical predictions.



$W^{\pm}$ in p–Pb at 8.16 TeV

Nuclear modification factor: measured as a function of rapidity.

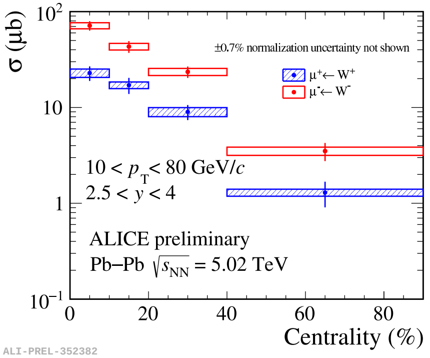
Reference cross section obtained from calculations with POWHEG and CT10nlo.



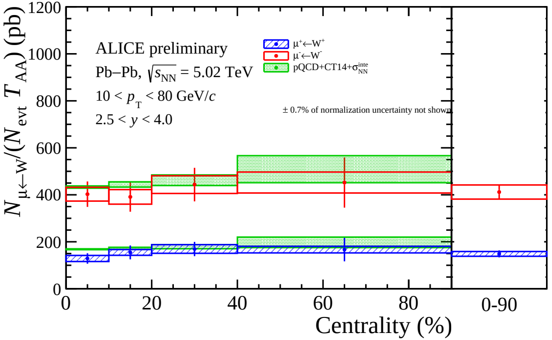
Deviation from 1 associated to isospin and nuclear effects.

First measurement of W in Pb–Pb at large rapidities.

Cross section as a function of centrality: decrease of the production for more peripheral events

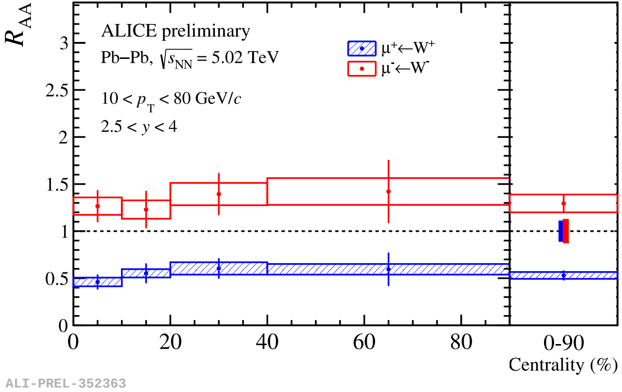


Normalized yield expected scaling of N_{W} with T_{AA}:



$W^{\pm}$ in Pb–Pb at 5.02 TeV

Nuclear modification factor: using reference cross section from POWHEG + CT10nlo.



Deviation from 1 associated to isospin and nuclear effects.

Conclusions and perspectives

In p–Pb:

- Z measurement results (JHEP 2009 (2020) 076), preliminary results for W
- Significant increase of statistics compared to analyses at 5.02 TeV, deviation of the measured W production from free-PDF calculation observed at large rapidities

In Pb–Pb:

- Z measurements combining 2015 and 2018 periods (JHEP 2009 (2020) 076), preliminary results for W
- More significant deviation from free-PDF prediction for Z
- Measurement of the W production at forward rapidity. The presented results includes the 2015 samples only, results with 2018 sample is approching.
- Statistic uncertainty dominates, can have improvement with Run3 and Run4 data

Large amount of measurements at large rapidities provide extra inputs for nPDFs global fits.

New paper of W in p–Pb and Pb–Pb is under collaboration review.

Back-up

PDG 2018:

$$m_Z = 91.1876 \pm 0.0021 \text{ GeV}/c^2$$
$$\Gamma_Z = 2.4952 \pm 0.0023 \text{ GeV}$$
$$BR_{Z\to\mu^+\mu^-} = 3.3662 \pm 0.0066 \text{ \%}$$

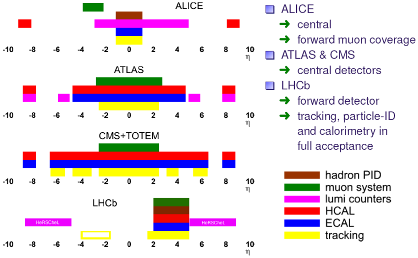
$$m_W = 80.379 \pm 0.012 \text{ GeV}/c^2$$
$$\Gamma_W = 2.085 \pm 0.042 \text{ GeV}$$
$$BR_{W\to\mu\nu} = 10.63 \pm 0.15 \text{ \%}$$

Higher order processes: include gluon and photon initial and final state radiations:

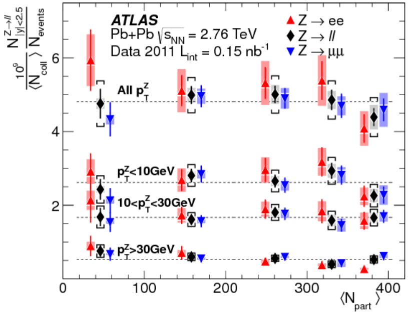
$$\begin{array}{ll} q+\bar{q}\to W+g & q+\bar{q}\to Z+g \\ q+\bar{q}\to W+\gamma & q+\bar{q}\to Z+\gamma \\ q+g\to W+q' & q+g\to Z+q' \\ q+\gamma\to W+q' & q+\gamma\to Z+q' \end{array}$$

Why measuring Z and W in HIC

- Probing the cold nuclear effects,
- reference for hot matter effects,
- calibration of muons and electrons detectors,
- estimator of the collision centrality.



Phys. Rev. Lett. 110, 022301 (2013)



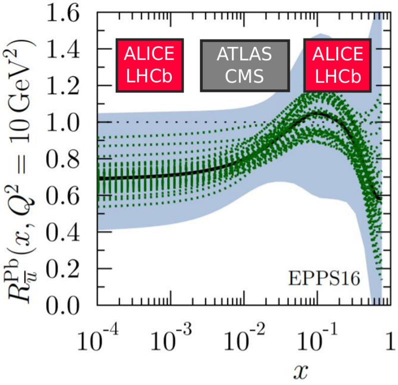
Complementarity of the coverages between the LHC experiments, allow to probe several Bjorken-x ranges.

Z and W at the LHC

Large rapidities: probing of the low ($\sim 10^{-4}$ to $\sim 10^{-3}$) and high ($\sim 10^{-1}$ to almost unity) Bjorken-x regions.

Complementary between the LHC experiments in term of Bjorken-x coverages:

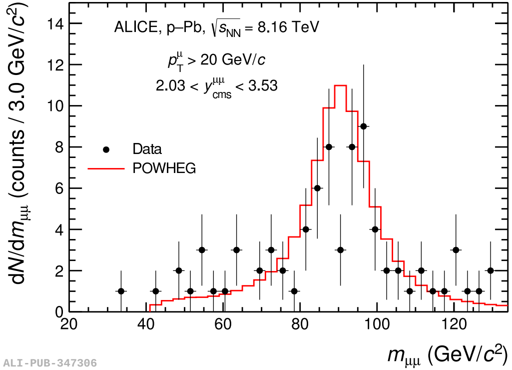
- ALICE and LHCb at high and low-x,
- ATLAS and CMS at mid-x.

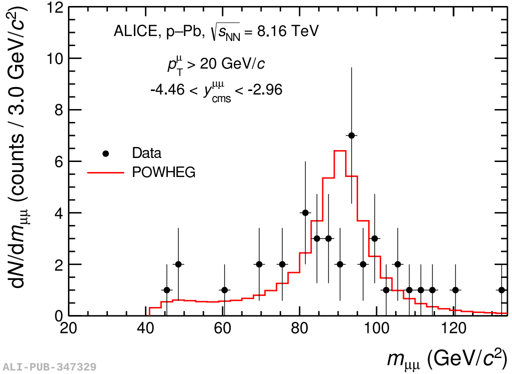


EPJC (2017) 77:163

Z signal extraction in p–Pb at 8.16 TeV

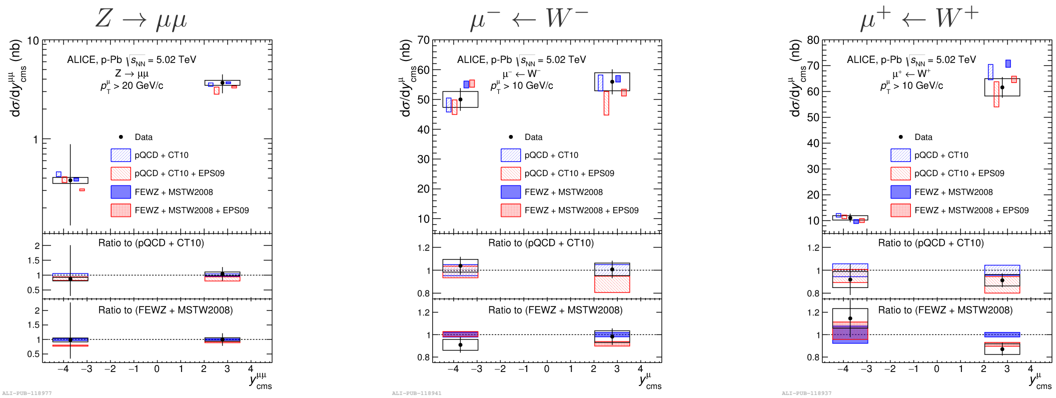
Dimuon invariant mass distribution after selection, compared with simulated distribution scaled to the number of events in the data.





arXiv:2005.11126

$W^{\pm}$ and Z p–Pb at 5.02 TeV



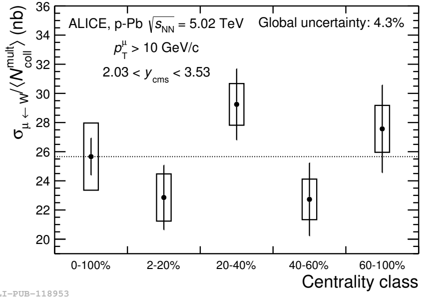
JHEP 1702 (2017) 077

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

$W^{\pm}$ and Z bosons results 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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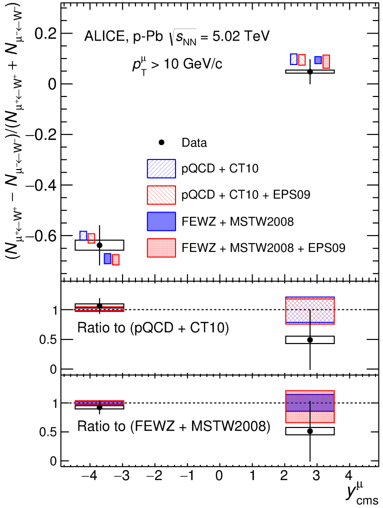

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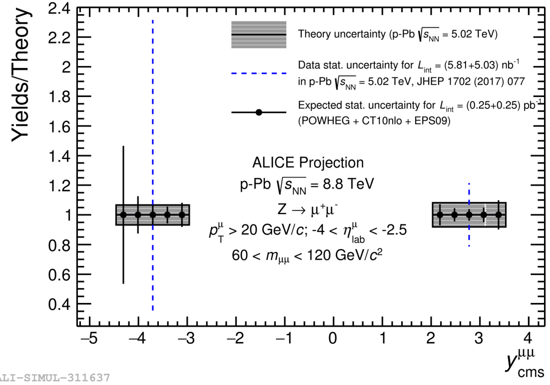
JHEP 1702 (2017) 077

Z uncertainty comparison between run 2 data and run 3 expectation

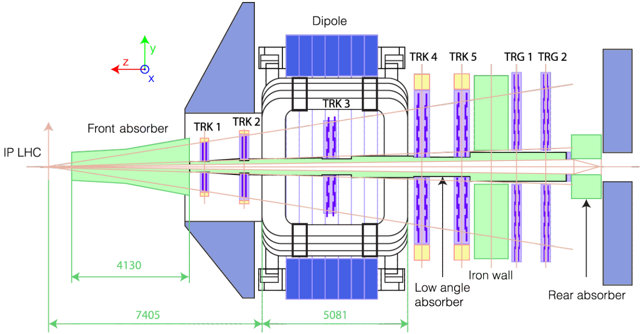
$\Rightarrow$ large reduction of the uncertainty, which becomes of the same order as the one on theoretical predictions.



ALICE-PUBLIC-2019-001

ALICE: muon spectrometer

ALICE Twiki



Trigger: 18 resistive plate chambers in two stations.

Tracking: 10 multi-wire proportional chambers, two-by-two in five stations.

Dipolar magnet: integrated field of 3 T m for charge and momentum measurements.

Absorbing system: background rejection.

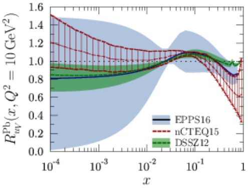
Nuclear effects

Shadowing and **anti-shadowing**: increase or decrease of the production following from constructive or destructive interferences of amplitudes arising from multiple scattering of partons in the nucleus.
EMC effect: not totally understood, believed to come from the modification of the nucleon radius and mass as well as multi-nucleons effects in the nucleus.
Fermi motion: dynamics of the nucleons in the nucleus.

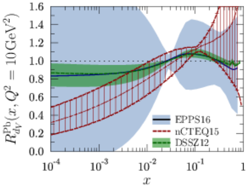
Color glass condensate: gluon density saturation reached in nucleus (from Lorentz contraction).
Cronin effect: broadening of the p_T spectra due to nucleon-nucleon interactions in the nucleus.
Nuclear absorption: breaking of a bound state passing through a nuclei.
Parton energy loss: elastic scattering from displacements inside the nucleus before hard scattering.
Comovers absorption: interaction between comovers as they move away from the interaction point.
Colour screening and sequential dissociation: dissociation of quarkonia bound states when the radius reaches the Debye screening radius.
Regeneration: new bound states created by initially produced quark and antiquarks.

nPDF models

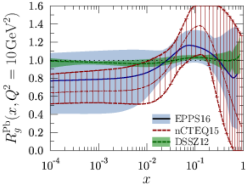
Up (valence):



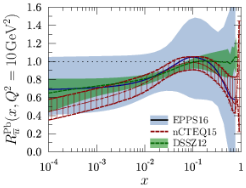
Down (valence):



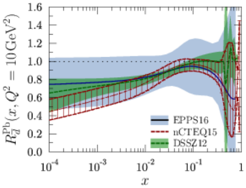
Gluon:



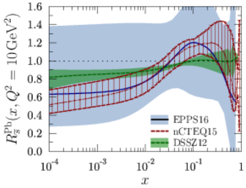
Anti-up:



Anti-down:



Anti-strange:



nPDF models

nPDF set	EPS09	nCTEQ15	EPPS16
Order	NLO	NLO	NLO
Flavour separation		valence quarks	valence + sea quarks
Proton baseline	CTEQ6.1	CTEQ6M-like	CT14NLO
Free parameters	15	35	52
Data points	929	708	1811
Included experimental data			
DIS in l^-+A	✓	✓	✓
Drell-Yan in p+A	✓	✓	✓
RHIC pions d+Au	✓	✓	✓
ν-nucleus DIS			✓
Drell-Yan in π+A			✓
LHC p–Pb dijets			✓
LHC p–Pb W and Z			✓

nPDF models

EPPS16 – nCTEQ15 comparison:

- **Valence quarks**: u and d independently parametrized, both models consistent with one another.
- **Sea quarks**: u, d and s independently parametrized in EPPS16, while not in nCTEQ15 $\Rightarrow$ more uncertainty but less bias (uncertainty mostly comes from strange quark).

Gluons: at large Bjorken-x, smaller uncertainty in EPPS16 due to constrains from LHC dijet data. At small Bjorken-x, smaller uncertainty in nCTEQ15 following from the form of the fit.

PoS (HardProbes2018) 014