Electroweak vector-boson production in hadronic collisions with ALICE at the LHC

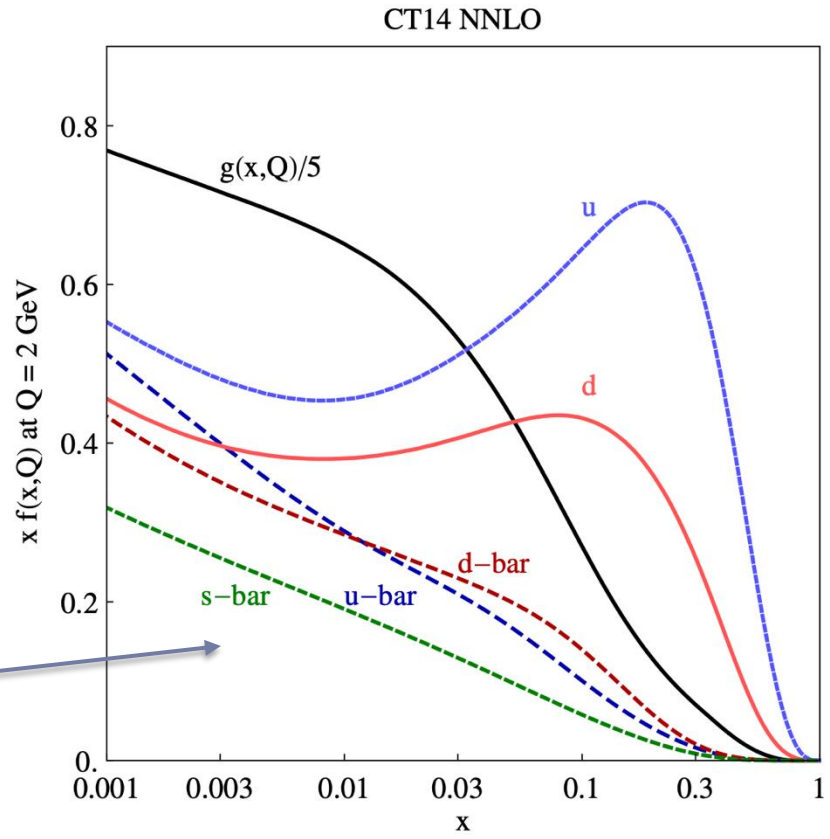
Shingo Sakai for the ALICE collaboration

(Tsukuba University of Technology)

Motivation (1)

- W/Z boson
  - Heavy mass
    - M_W = 80.377 ± 0.012 GeV/c^2
    - M_Z = 91.1876 ± 0.0021 GeV/c^2

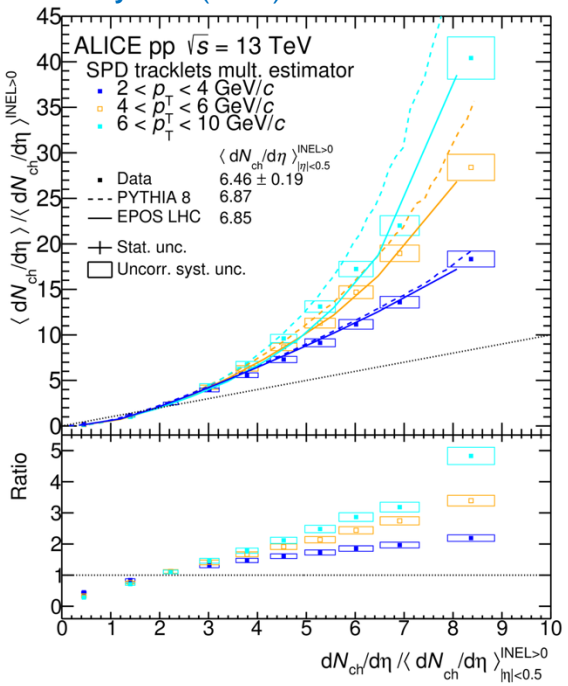
      Particle Data Group, PTEP 2022 (2022) 083C01
  - Weakly interacting particles
    - Decay leptons insensitive to the strongly-interacting medium
  - Produced predominantly via a quark – antiquark pair annihilation (Drell-Yan)
    - $u\bar{d} \rightarrow W^+, d\bar{u} \rightarrow W^-$, and $q\bar{q} \rightarrow Z$
    - Sensitive to parton distribution functions for up and down quarks



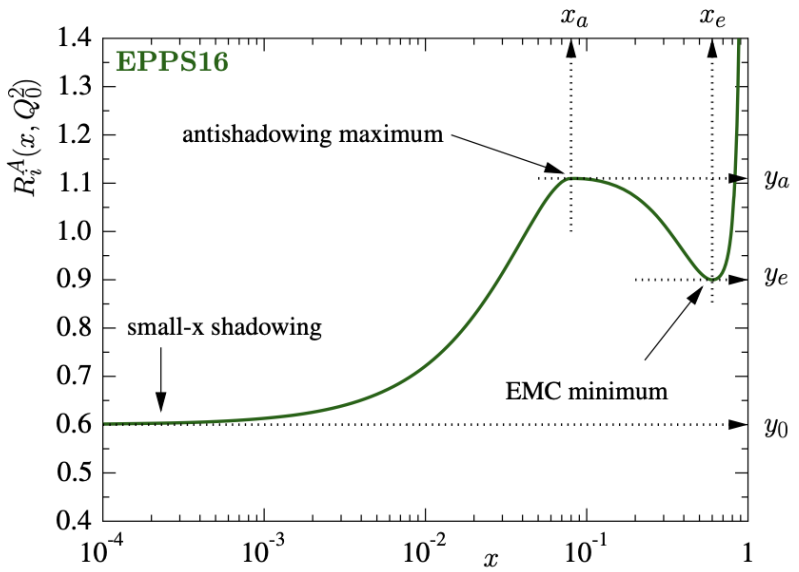
CT14nnlo : S. Dulat et al., PRD 93 (2016) 033006

Motivation (2)

EPJC 79 (2019) 857

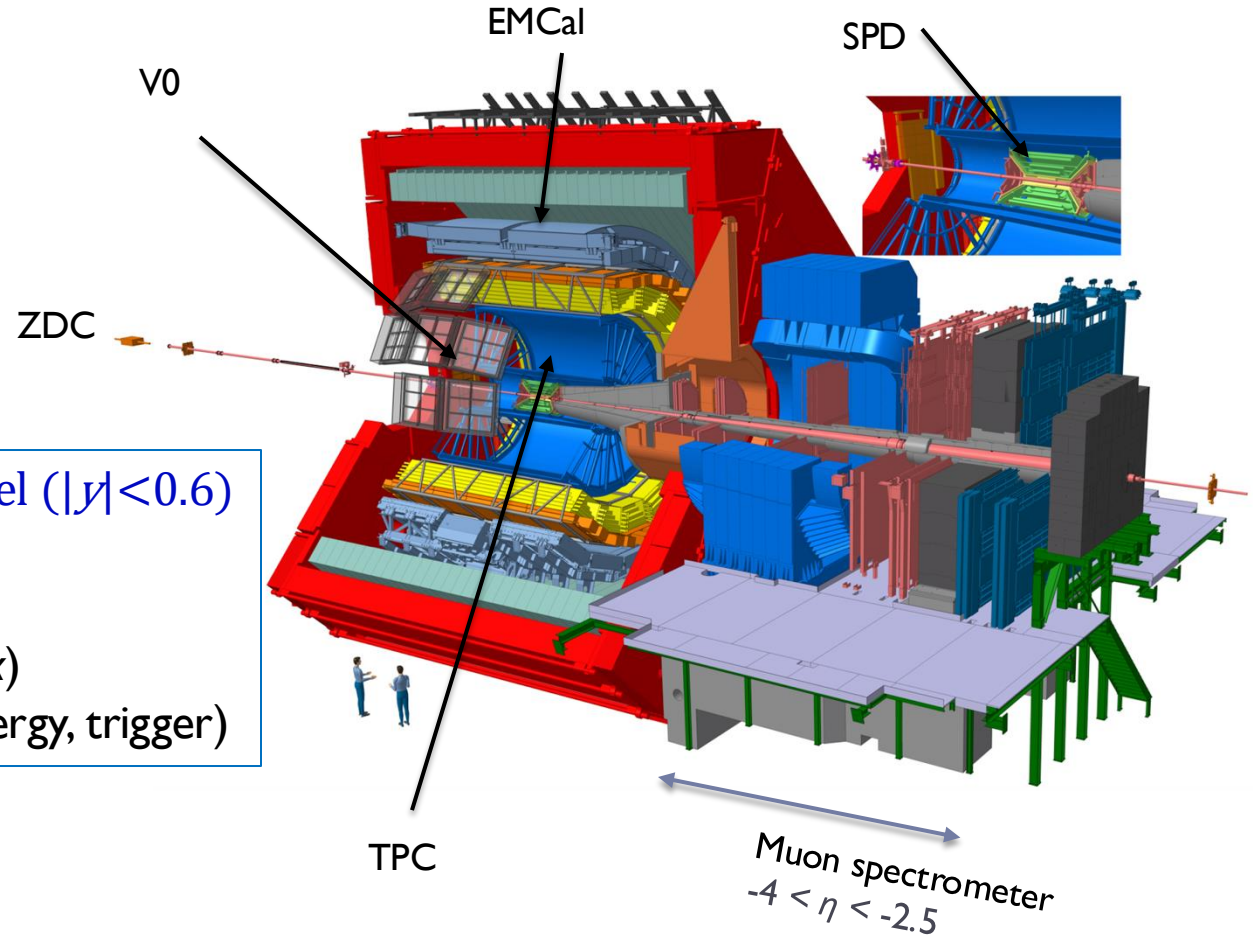


EPJC (2017)77:163K. Eskola, P. Paakkinen, H. Paukkuuen, C. Salgado



- pp collisions
  - Good test for pQCD and electroweak theory
  - Observed faster than linear production in high multiplicity pp events for charged-particle productions
  - W/Z bosons may different behavior due to their feature
    - Offering a unique perspective in the events
- p–Pb and Pb–Pb collisions
  - Provide insights on nuclear modification of parton distribution function (nPDF)
    - Important to understand the initial-state nuclear effects

ALICE detector in Run 2



- Electron channel ($|y|<0.6$)
- $e^{\pm} \leftarrow W^{\pm}$
- $Z \rightarrow e^{+}e^{-}$
  - TPC (dE/dx)
  - EMCal (Energy, trigger)

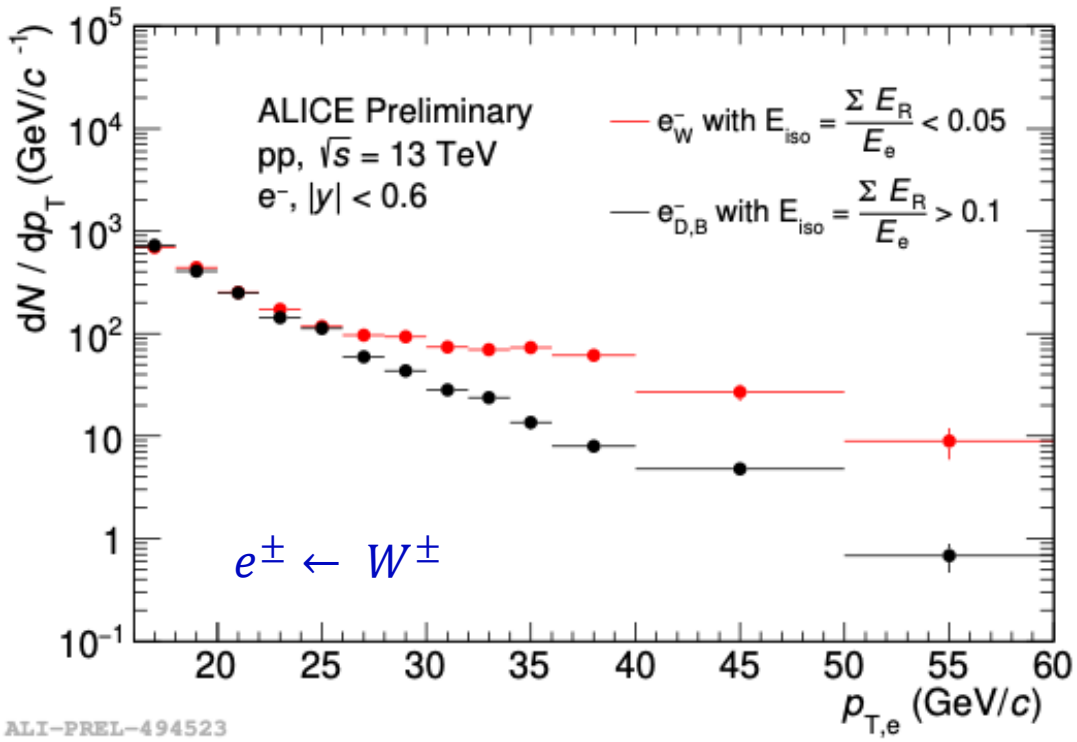
- Muon channel ($-4 < \eta < -2.5$)
- $\mu^{\pm} \leftarrow W^{\pm}$
- $Z \rightarrow \mu^{+}\mu^{-}$
  - Muon spectrometer
    - Trigger & tracking
  - p–Pb, p-going
    - $2.03 < y_{cms} < 3.53$
  - p–Pb, Pb-going
    - $-4.46 < y_{cms} < -2.96$
  - Pb–Pb
    - $2.5 < y_{cms} < 4$

- Probe different x regimes, from $x \sim 10^{-3} - 10^{-4}$ to $x \sim 10^{-1}$

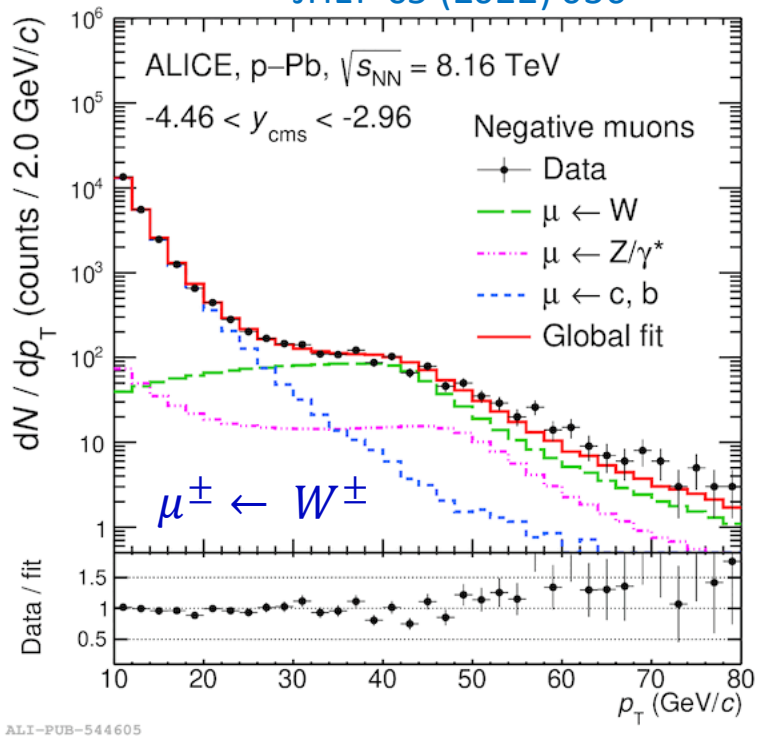
Weak-boson measurements with ALICE in Run 2

Collision system	Energy	Luminosity	Year	Analyses	publication
pp	13 TeV	~6.6 pb^{-1}	2016 + 2017 + 2018	Z,W (e, midrapidity)	
p–Pb Pb–p	5.02 TeV	5.03 ± 0.18 nb^{-1} 5.81 ± 0.20 nb^{-1}	2013	Z,W (μ, forward /backward)	Z,W : JHEP 02 (2017) 077
p–Pb Pb–p	8.16 TeV	6.73 ± 0.16 nb^{-1} 10.0 ± 0.22 nb^{-1}	2016	Z,W (μ, forward /backward)	W : JHEP 05 (2022) 036 Z : JHEP 09 (2020) 076
Pb–Pb	5.02 TeV	663 ± 15 μb^{-1}	2015 + 2018	Z,W (μ, forward)	W : JHEP 05 (2022) 036 Z : JHEP 09 (2020) 076

W yields extraction in ALICE



JHEP 05 (2022) 036



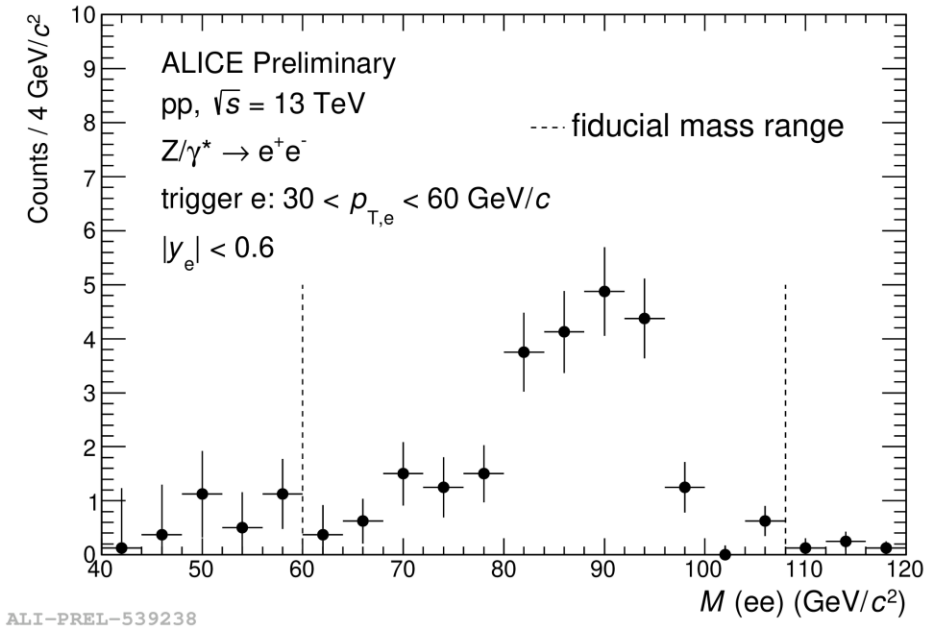
- $e^{\pm} \leftarrow W^{\pm}$ (|y| < 0.6); Based on isolation cuts on energy; $E_{\mathrm{iso}} = \frac{\sum E_{\mathrm{R<0.3}}}{E_{\mathrm{e}}} < 0.05$
  - Data-driven estimation and subtraction of $e^{\pm} \leftarrow c, b$ contribution
- $\mu^{\pm} \leftarrow W^{\pm}$ ($-4 < y_{\mathrm{lab}} < -2.5$); Fit of the single muons p_{T} distribution via MC templates
  - $\mu^{\pm} \leftarrow c, b$ by FONLL, $\mu^{\pm} \leftarrow W^{\pm}, Z$ by POWHEG

FONLL
M. Cacciari, M. Greco and P. Nason
JHEP 9805 (1998) 007

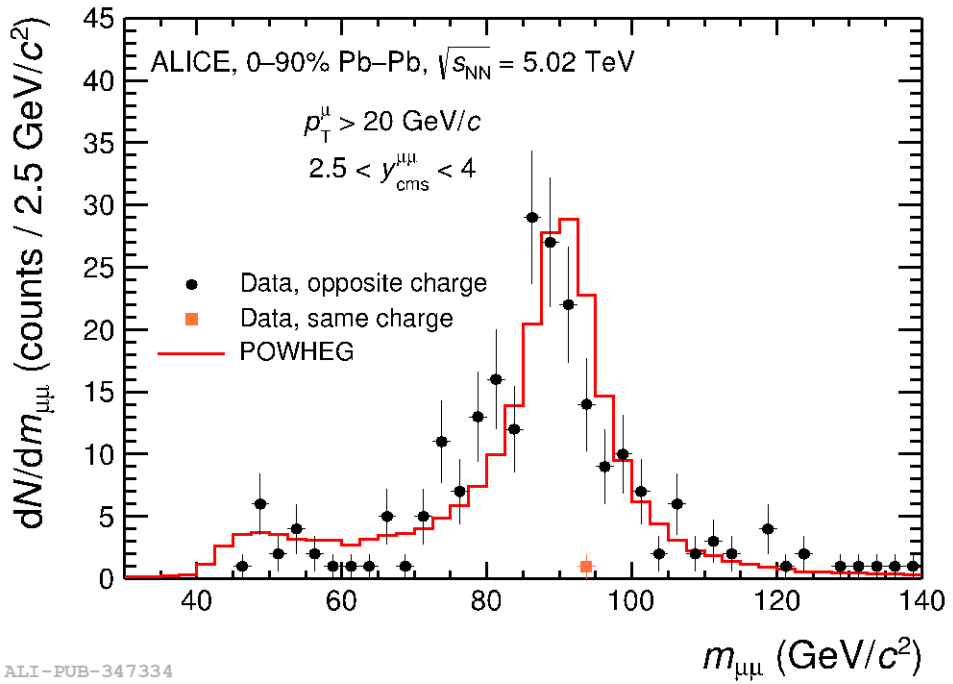
POWHEG
S. Aioli, P. Nason, C. Oleari and E. Re
HEP 07 (2008) 060

Z boson reconstruction in ALICE

$Z \rightarrow e^+e^-$ (midrapidity)



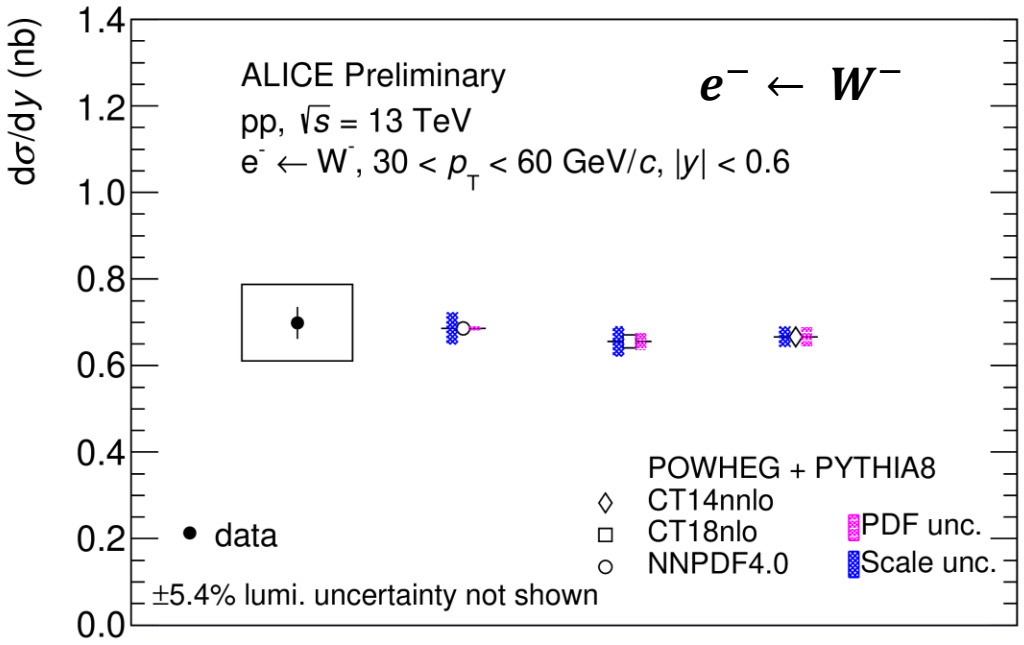
$Z \rightarrow \mu^+\mu^-$ (forward rapidity)



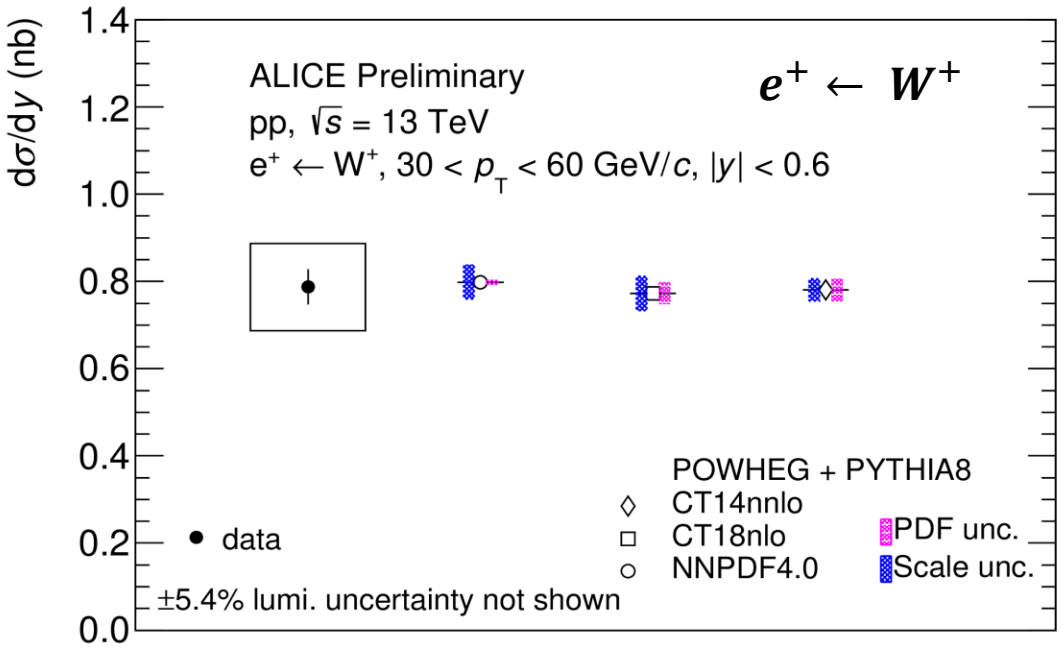
- Z bosons reconstruction at midrapidity : invariant mass of electron pairs
  - One of electron (positron) has $p_{T,e}$ > 30 GeV/c & $|y_e| < 0.6$
- Z boson reconstruction at forward rapidity : invariant mass of muon pairs
  - Both muons have $p_{T,\mu}$ > 20 GeV/c & 2.5 < y_μ < 4

JHEP09 (2020) 076

$W^{\pm}$ in pp collisions at 13 TeV



ALI-PREL-578448

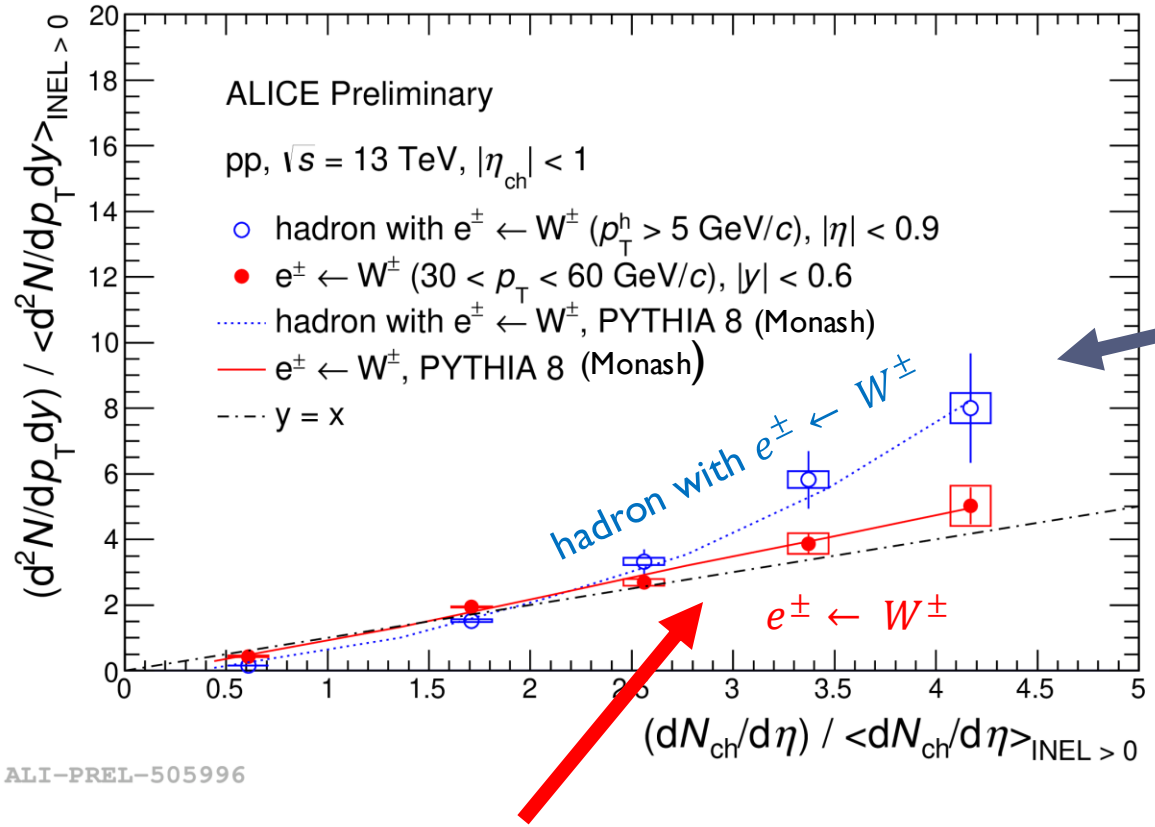


ALI-PREL-578455

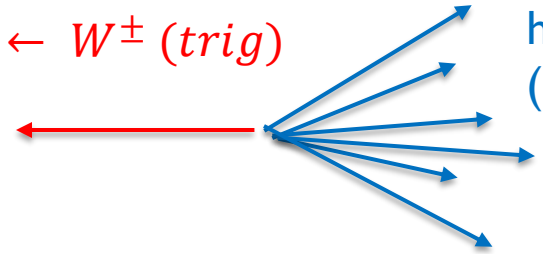
CT14nnlo : S. Dulat et al., PRD 93 (2016) 033006
CT18nlo : M. Yan et al., PRD 107 (2023) 116001
NNPDF4.0 : R. D. Ball et al., EPJ C82 (2022) 428

- Cross sections for $e^{\pm} \leftarrow W^{\pm}$ in $|y| < 0.6$
  - Electrons in $30 < p_T < 60$ GeV/c
- Compared to models including pQCD NLO (POWHEG) with PDFs (CT14nnlo, CT18nlo, NNPDF4.0)
  - Consistent with data within uncertainties

Multiplicity dependence of W production



W-boson production is linear as a function of the charged-particle multiplicity



A faster-than-linear trend for associated hadrons

→ Colour-reconnection
interaction with partons from other hard scattering via strong force

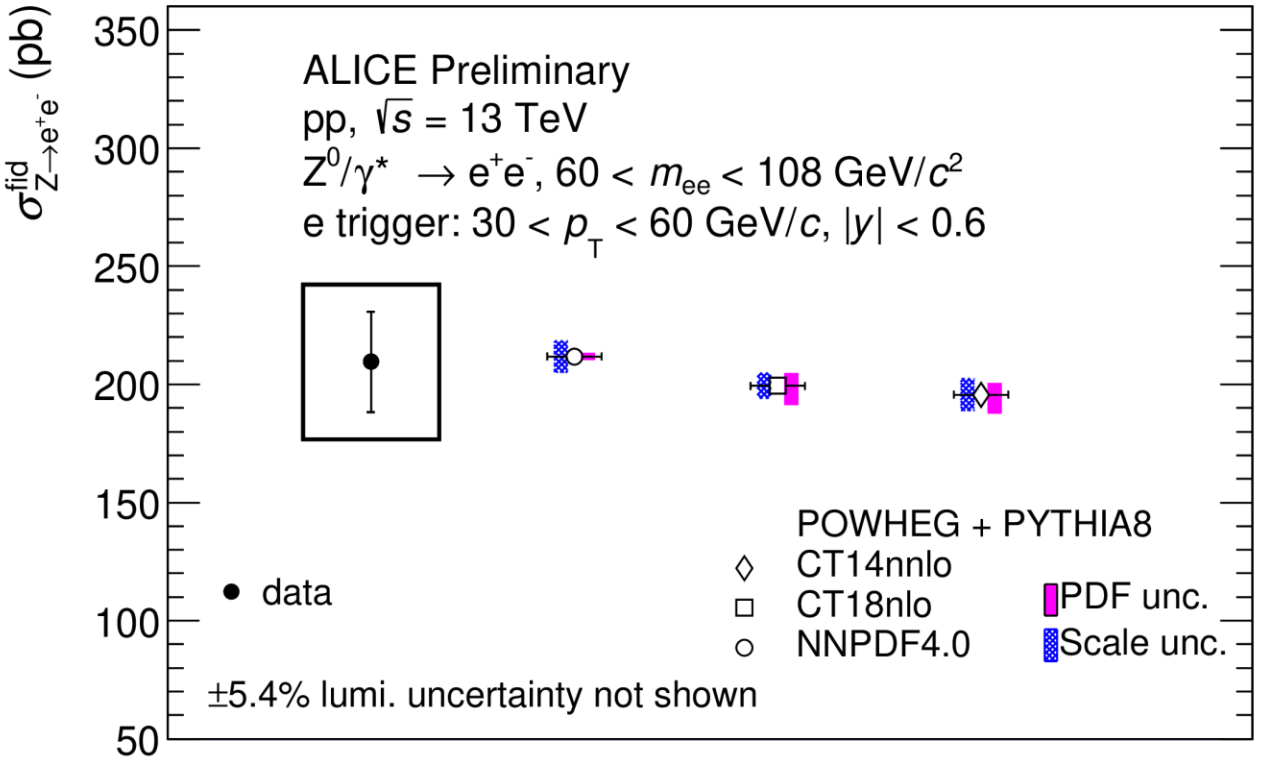
J. R. Christiansen and P. Z. Skands, JHEP 08 (2015) 003

→ Auto-correlation between jet-fragmentation products and hadron for multiplicity estimation

S. G. Weber, A. Dubla. A. Andronic, and A. Morsch EPJC (2019) 79:36

→ W-boson production is not affected by color-reconnection and autocorrelation

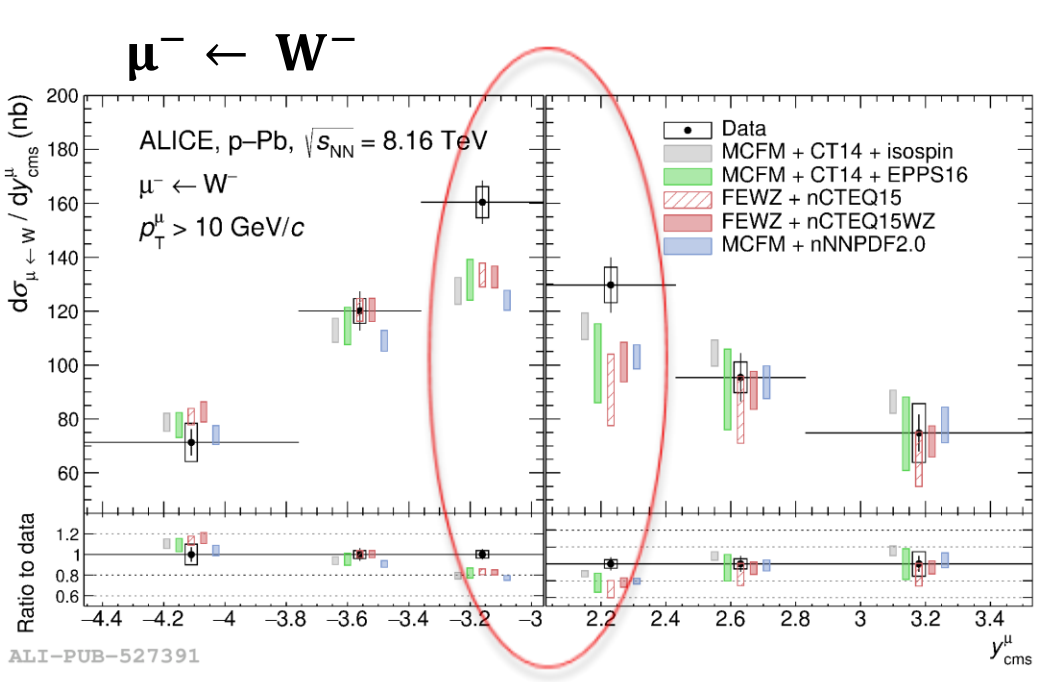
Z production in pp at 13 TeV

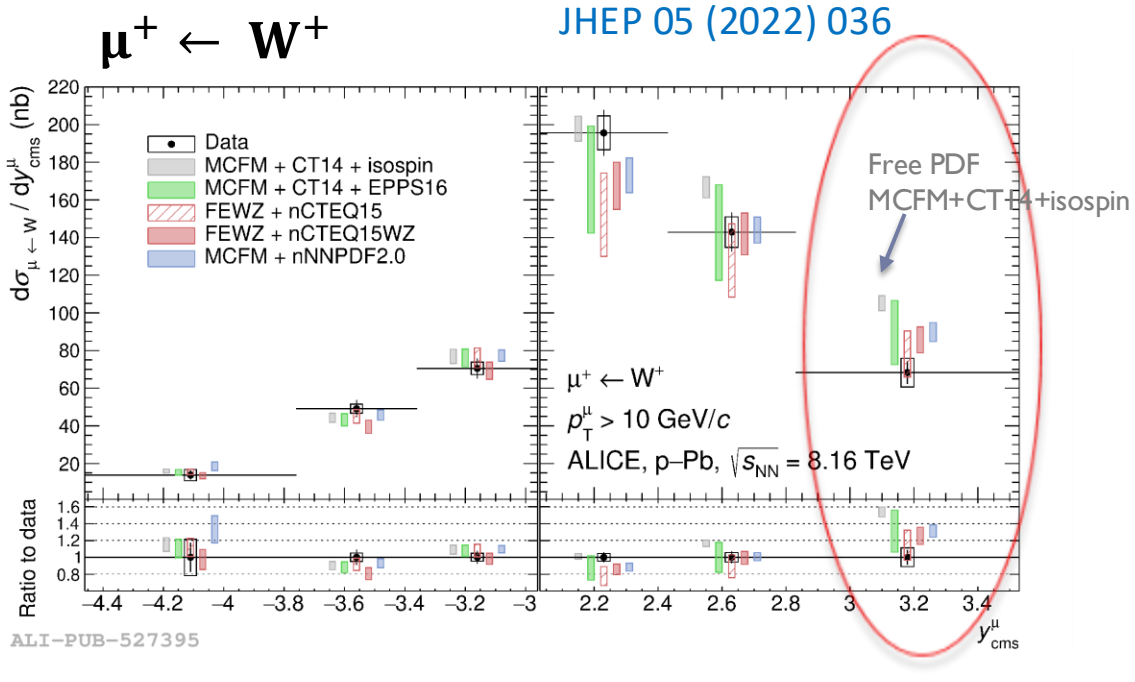


ALI-PREL-578440

- Fiducial cross section of Z bosons
  - One of electron (positron) has p_T > 30 GeV/c and |y| < 0.6
  - 60 < M_Z < 108 GeV/c^2
- Compared to models including pQCD NLO (POWHEG) with PDFs (CT14nnlo, CT18nlo, NNPDF4.0)
- Consistent with data within uncertainties
  - These models reproduce $e^{\pm} \leftarrow W^{\pm}$ at midrapidity

$W^{\pm}$ in p–Pb at 8.16 TeV (1)



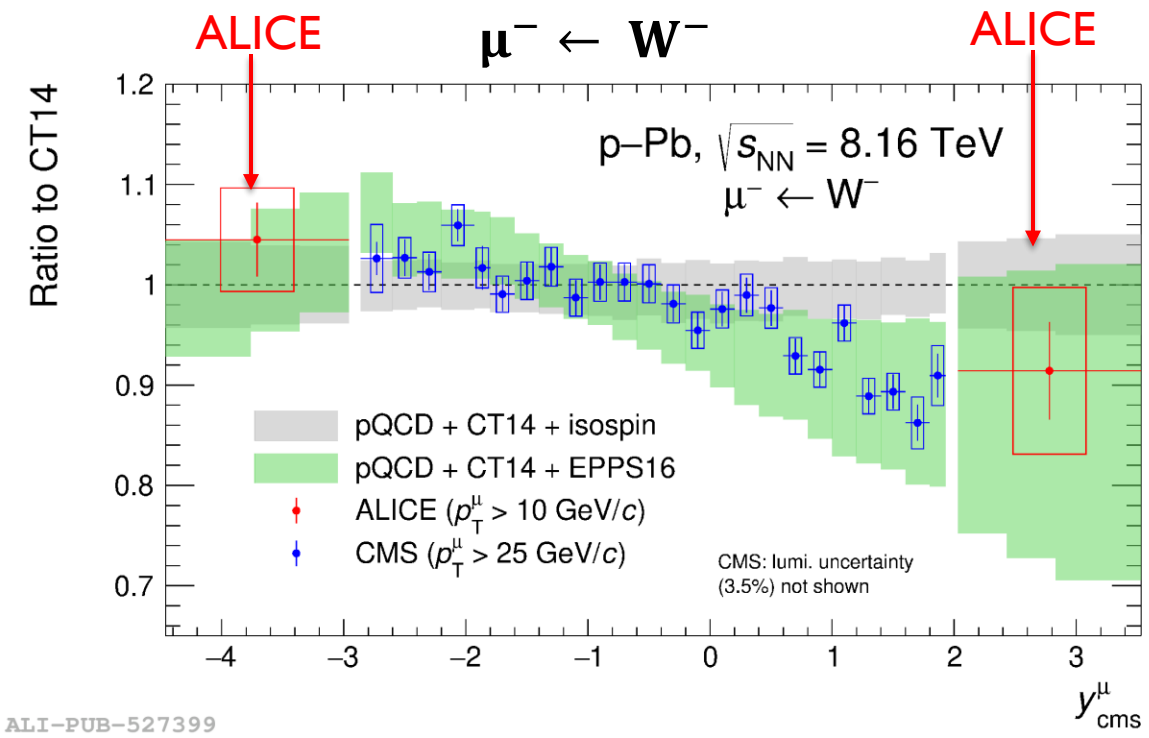


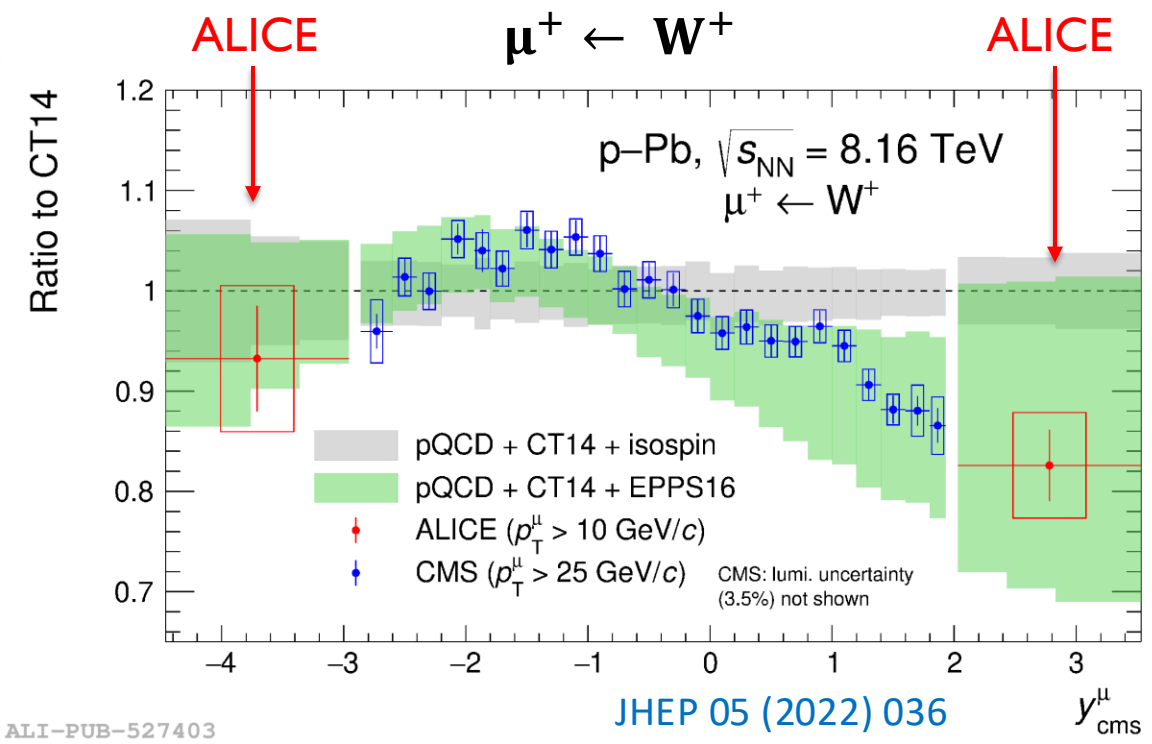
- Calculations underestimate data for intervals closest to midrapidity, both at forward and backward

- 3.5σ deviation from free-PDF calculation (MCFM + CT14) for W^+ at forward rapidity for the interval with the largest rapidity

MCFM : T. Campbell and T. Neumann, JHEP 12 (2019) 034 / **FEWZ** : R. Gavin, Y. Li. F. Petriello and S. Quackenbush, CPC 182 (2011) 2388-2403
CT14 : S. Dular et. al., PRD 93 (2016) 033006 / **CT14 + EPPS16** : K. J. Eskola et. al., EPJ C77 (2017) 163
nCTEQ15 : K. Kovarik et. al., PRD 93 (2016) 085037 / **nCTEQ15WZ**: A. Kusina et. al., EPJC 80 (2020) 968 /**nNNPDF2.0** : JHEP 09 (2020) 183

$W^{\pm}$ in p–Pb at 8.16 TeV (2)



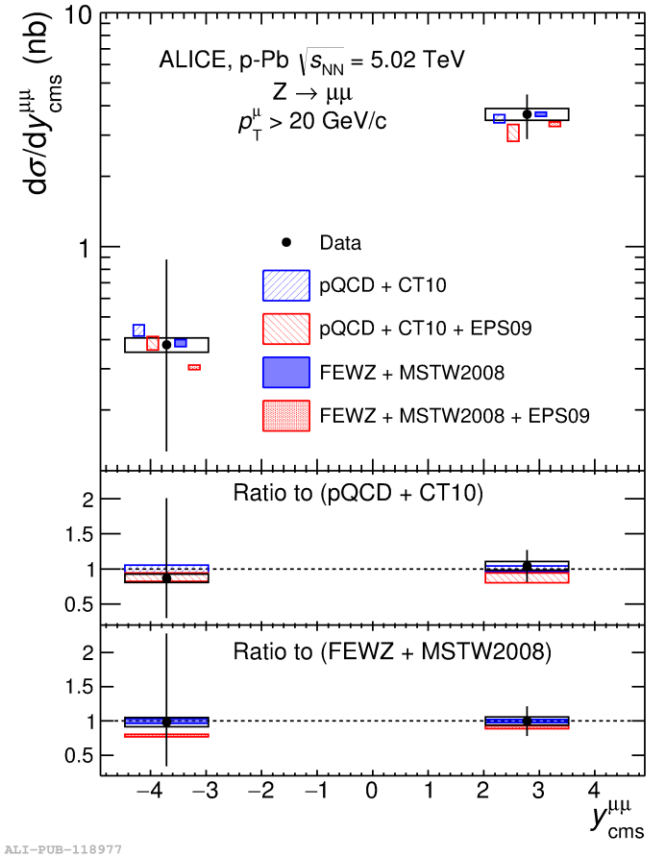


JHEP 05 (2022) 036

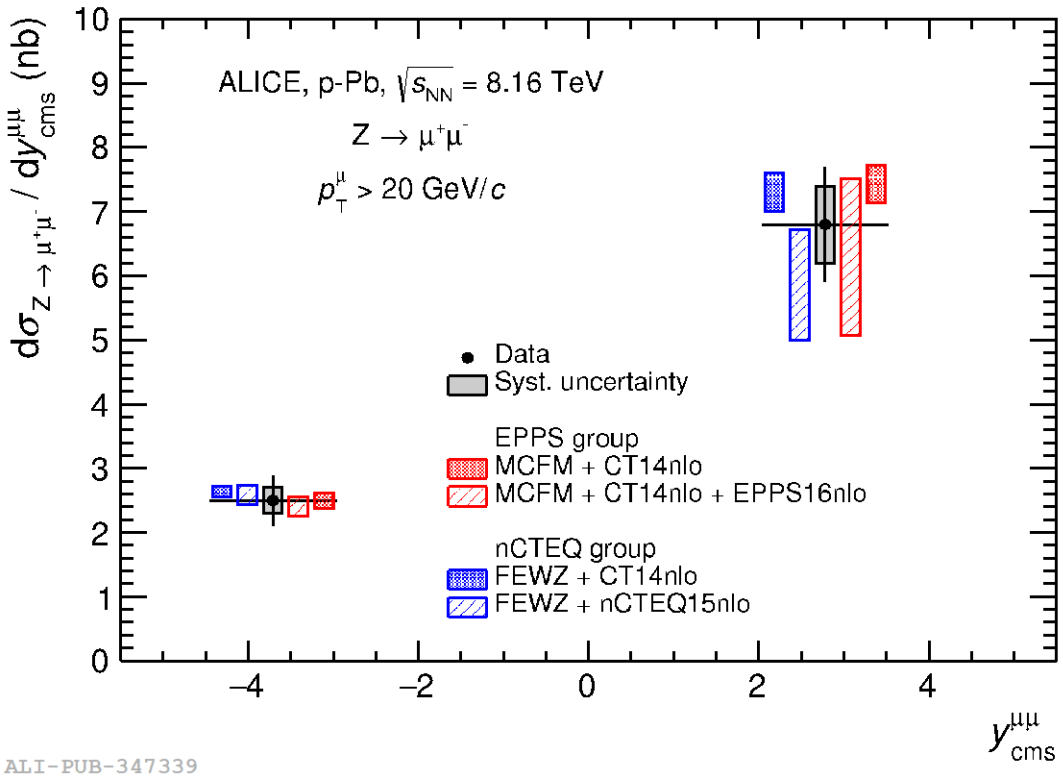
- Ratio to CT14 as a function of rapidity compared with CMS results (PLB 800 (2020) 135048)
  - ALICE reaches the largest |y| region (down to $x \sim 10^{-4}$ at forward region)
- ALICE results in agreement with the trend at the edges of the CMS acceptance
  - Suppression of W^+ boson production at large rapidity

Z production in p-Pb

p-Pb 5.02 TeV JHEP02 (2017) 077



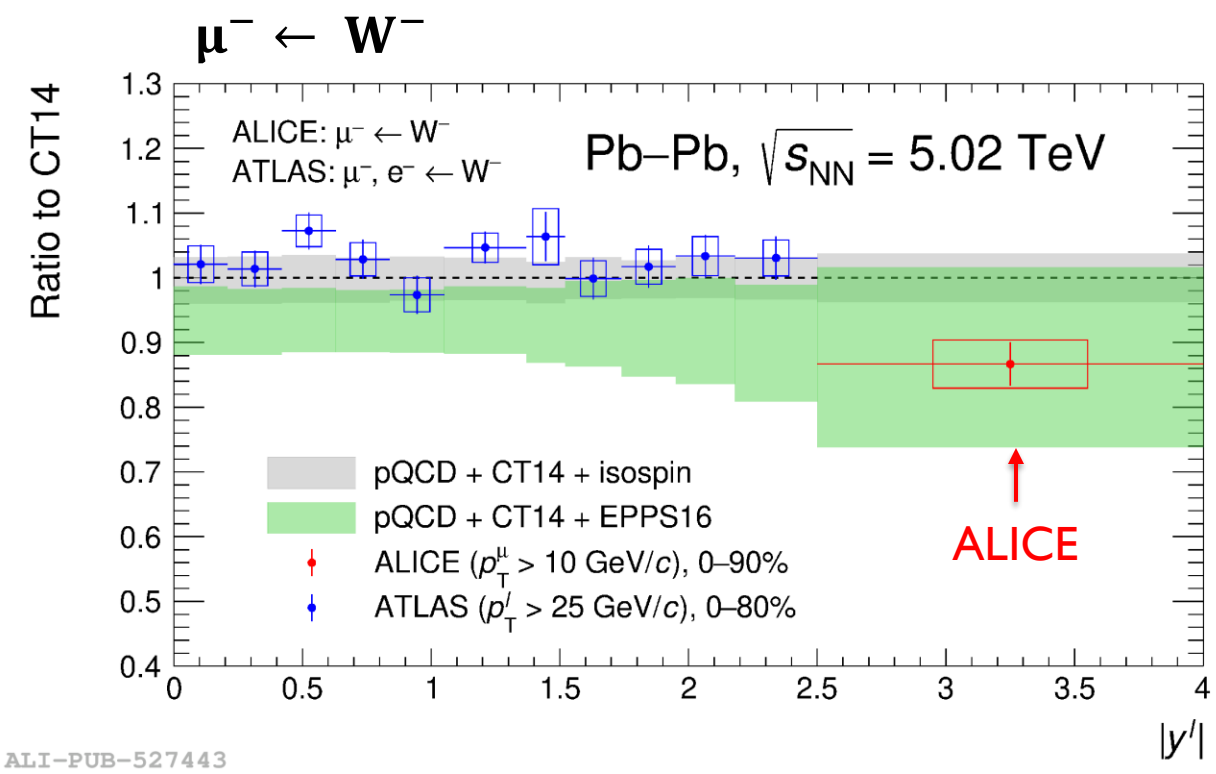
p-Pb 8.16 TeV JHEP09 (2020) 076

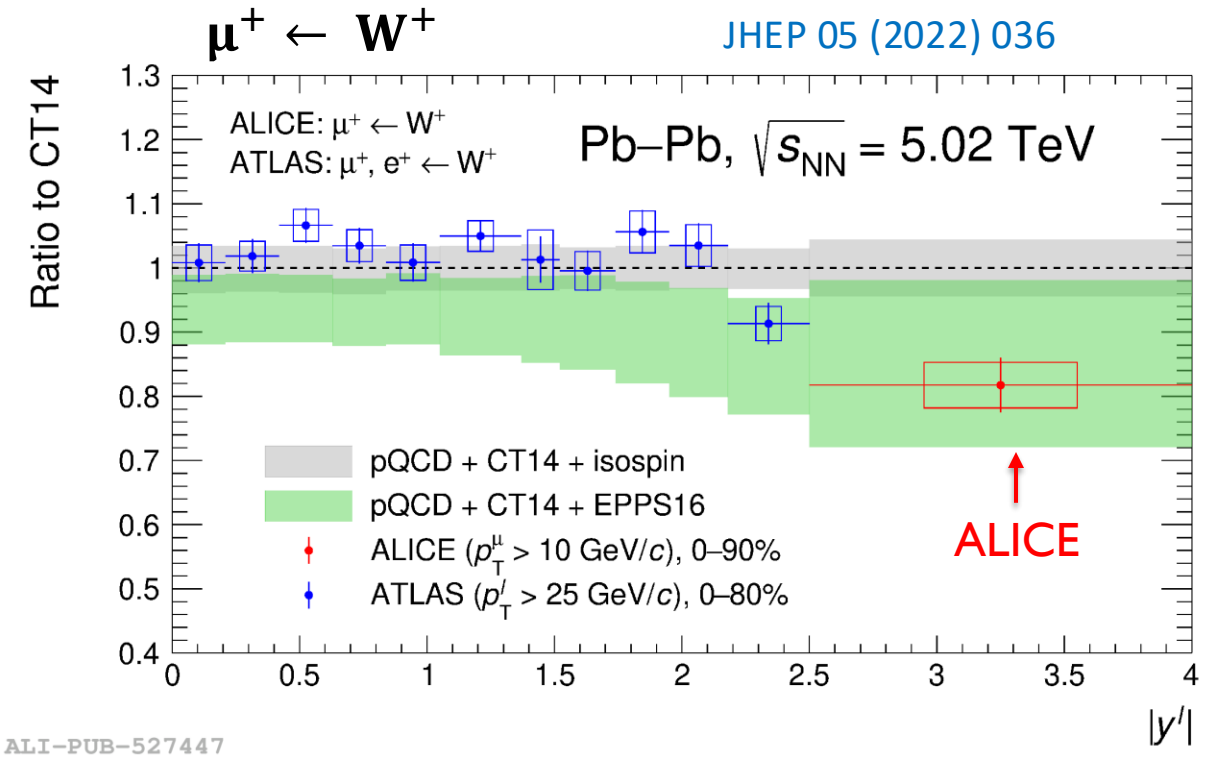


- Within experimental and theoretical uncertainties, pQCD+isospin with/without nPDF are consistent with the measured cross section at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV and $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV in p–Pb collisions

$W^{\pm}$ in Pb–Pb at 5.02 TeV

JHEP 05 (2022) 036

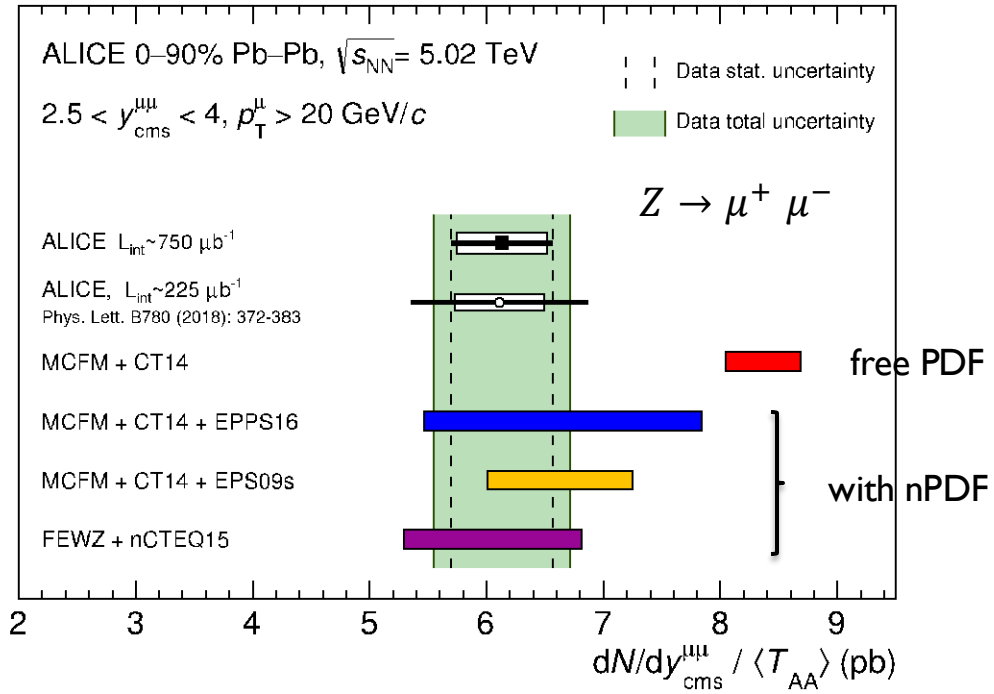




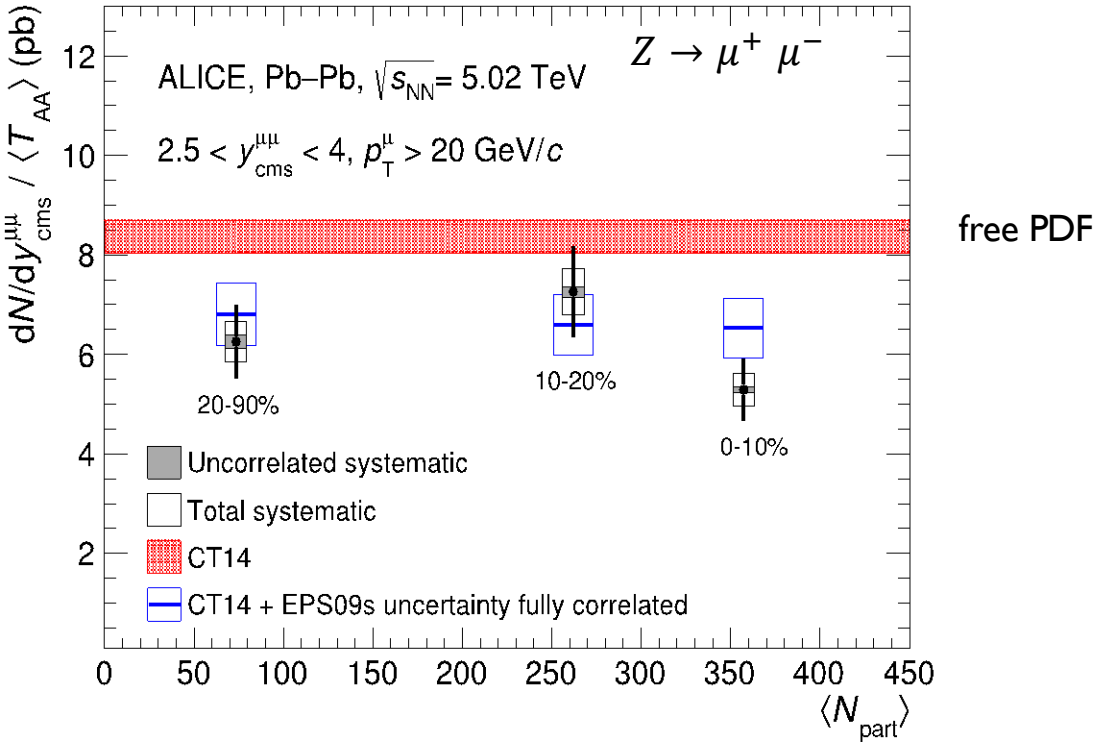
- Ratio to CT14 as a function of rapidity compared with ATLAS results (EPJC 79 (2019) 935)
  - ALICE results well described by EPPS16 calculations (2σ lower than CT14 without EPPS16)
  - EPPS16 underestimates ATLAS data
- Ratio to CT14 is smaller than unity at large rapidity
  - Suggests a significant modification of the PDFs

Z in Pb-Pb at 5.02 TeV

JHEP09 (2020) 076



ALI-PUB-347344



free PDF

ALI-PUB-347359

- Model with free PDF (MCFM+CT14) shows a 3.4σ deviation w.r.t. the measured Z cross section
- Models with nPDF (CT14+EPPS16, EPPS09s, nCTEQ15) show a well-reproduced measured Z cross section
- Strong evidence of modification of Z production in Pb–Pb collisions

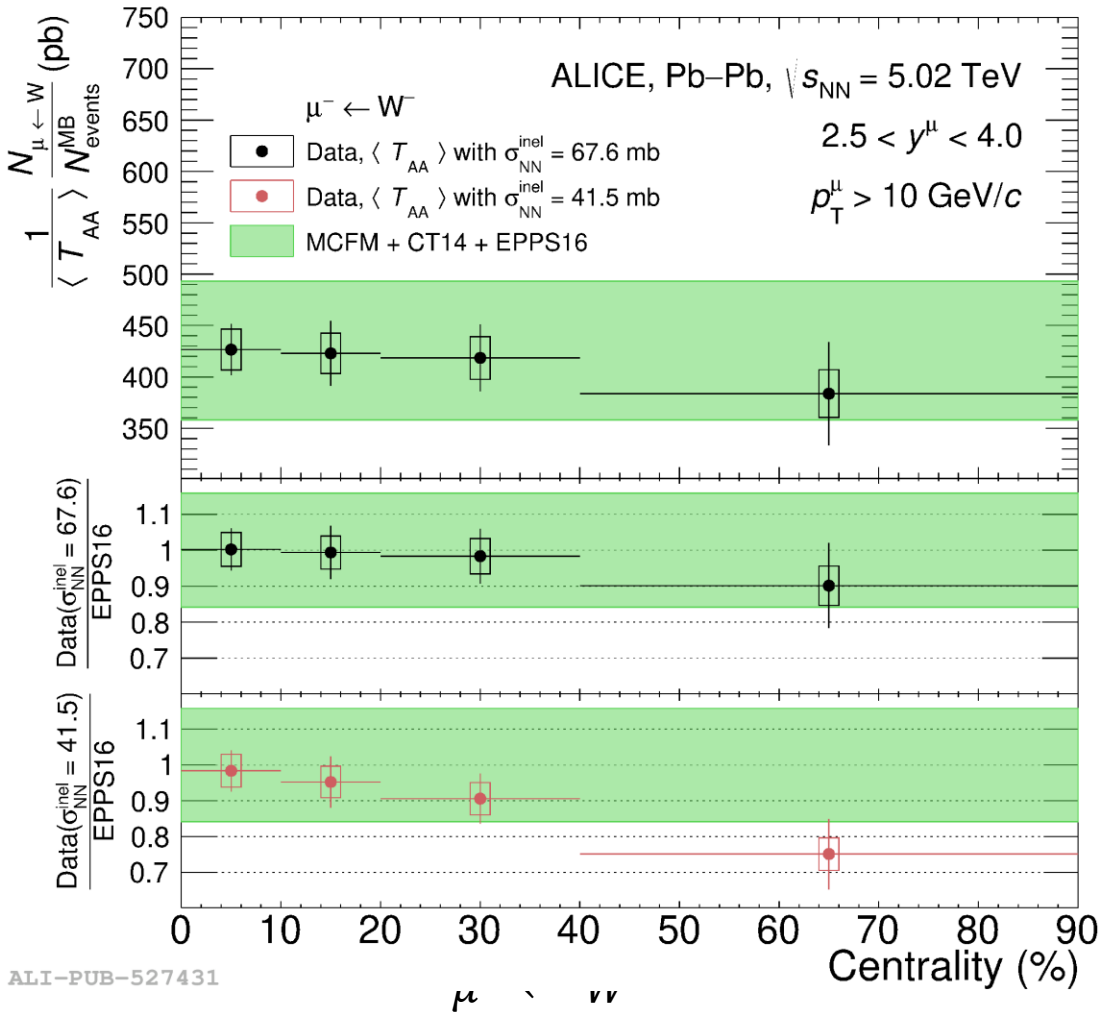
EPS09 : JHEP 04 (2009) 065
EPS09s : JHEP 07 (2012) 073

Summary

- Presented electroweak-boson production in ALICE from small to large collision systems with ALICE
  - pp collisions at $\sqrt{s_{\mathrm{NN}}}$ = 13 TeV
    - *W*/Z boson production is consistent with NLO pQCD (POWHEG) + PDF (CT14nnlo, CT18nlo and NNPDF4.0)
    - Linear dependence of W production on charged multiplicity
  - p–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ =5.02 and $\sqrt{s_{\mathrm{NN}}}$ = 8.16 TeV, and Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV
    - ALICE reaches the largest rapidity for W boson measurements
    - Suggests a significant modification of the nuclear PDFs
- Outlook at Run3
  - Detector upgrades : MFT, ITS and TPC
  - Significant increase in luminosity (up to 60 pb^{-1} in pp and 1.6 nb^{-1} in Pb-Pb)
    - Detailed study of nPDFs
    - Differential study for electroweak-boson production (ex. W/Z + jet)

Back up

$W^{\pm}$ in Pb-Pb at 5.02 TeV (2)



- Normalized yields as a function of centrality

$$\frac{1}{\langle T_{AA} \rangle} \times \frac{N_{\mu^{\pm} \leftarrow W^{\pm}}}{N_{events}^{MB}}$$

  - Scaled by average nuclear overlap function $\langle T_{AA} \rangle$
    - $\sigma_{NN}^{inel} = 67.6 \pm 0.6$ mb
  - Expected from a hard process

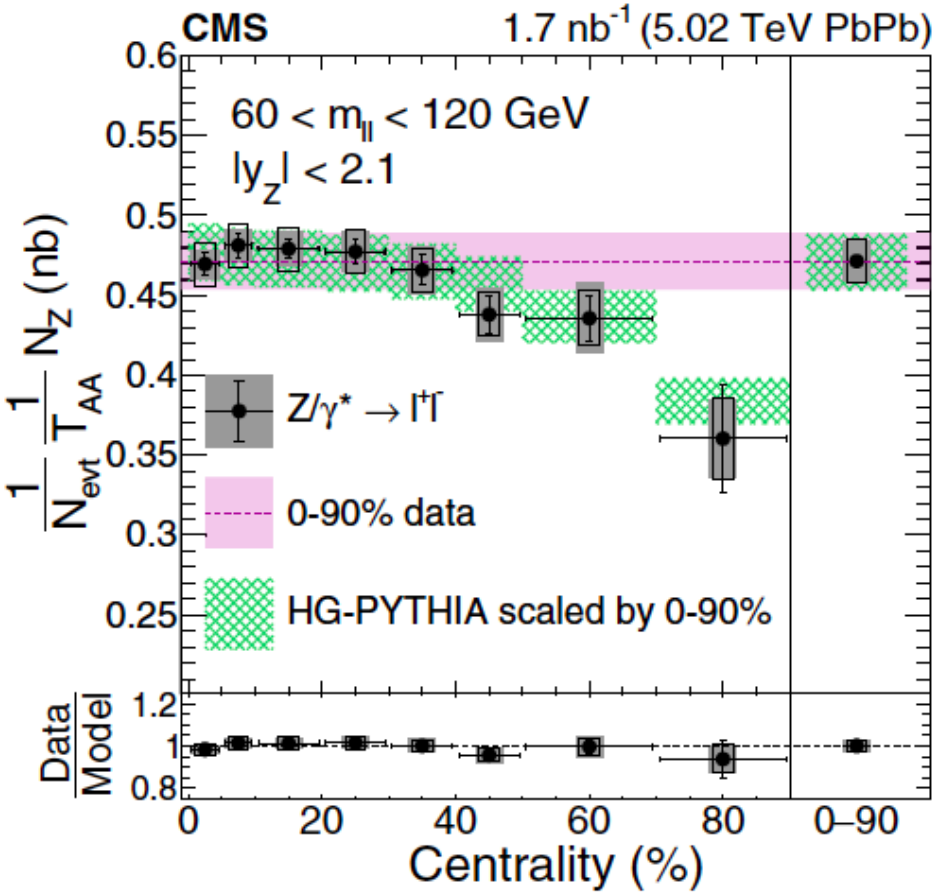
- Model calculation
  - CT14 PDFs with EPPS16
    - A good agreement with data

- Centrality-dependence through shadowed σ_{NN}^{inel}, obtained by forcing the agreement between EPPS16 and the W/Z ATLAS data (Eskola et al. (PRL 125(2020)212301))
  - $\sigma_{NN}^{inel} = 41.5^{+16.2}_{-12.0}$ mb

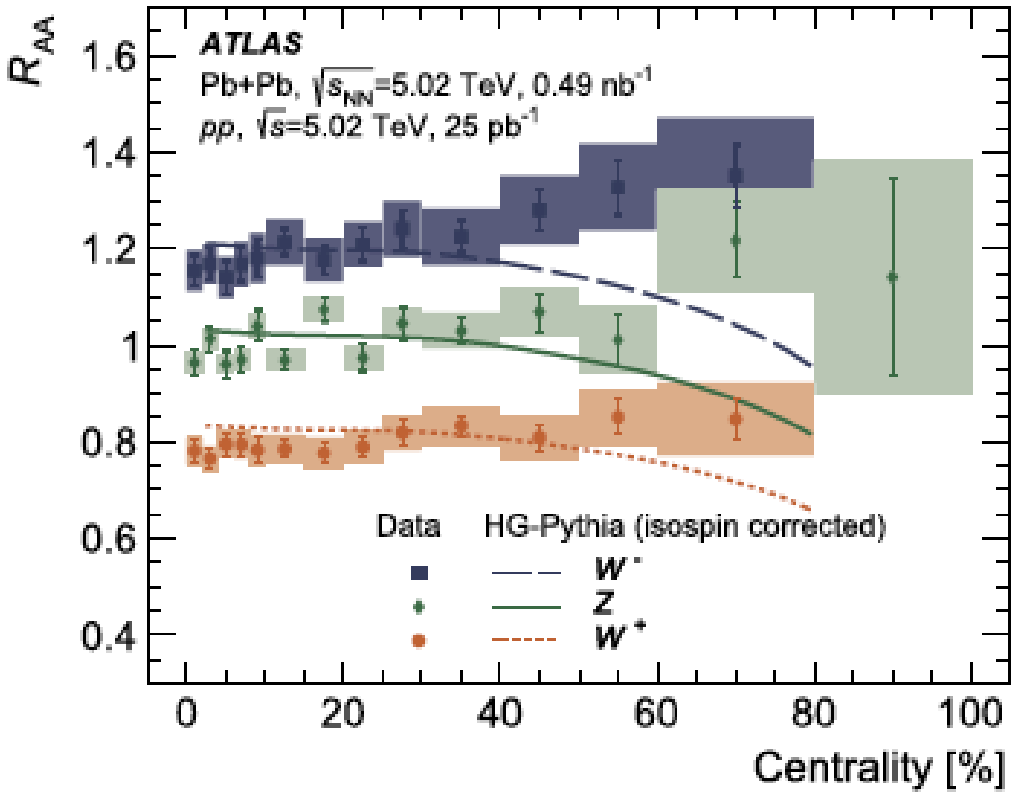
- $\langle T_{AA} \rangle$ re-evaluated, yields worse agreement between ALICE data and EPPS16

W/Z R_{AA} in CMS and ATLAS

PRL 127, 102002 (2021)



PLB 202 (2020) 135262



Modified cross section

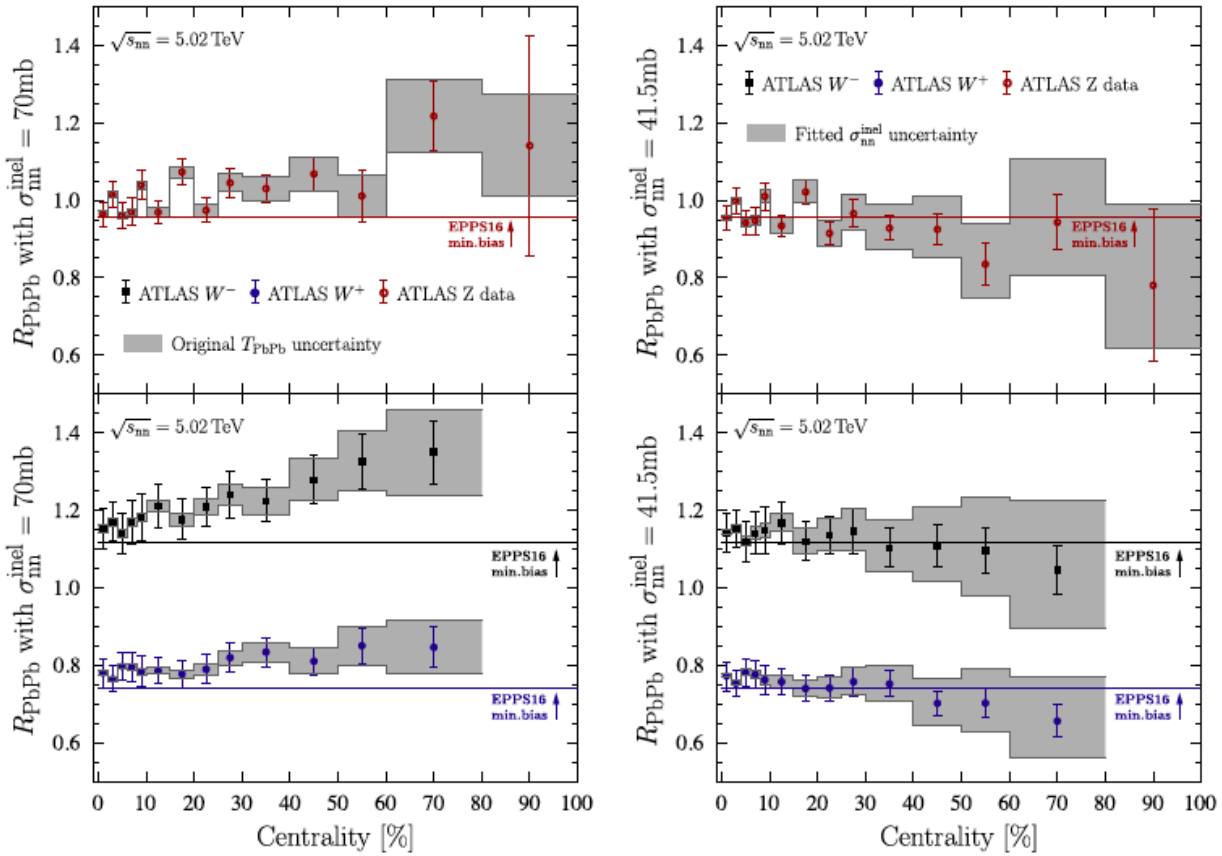
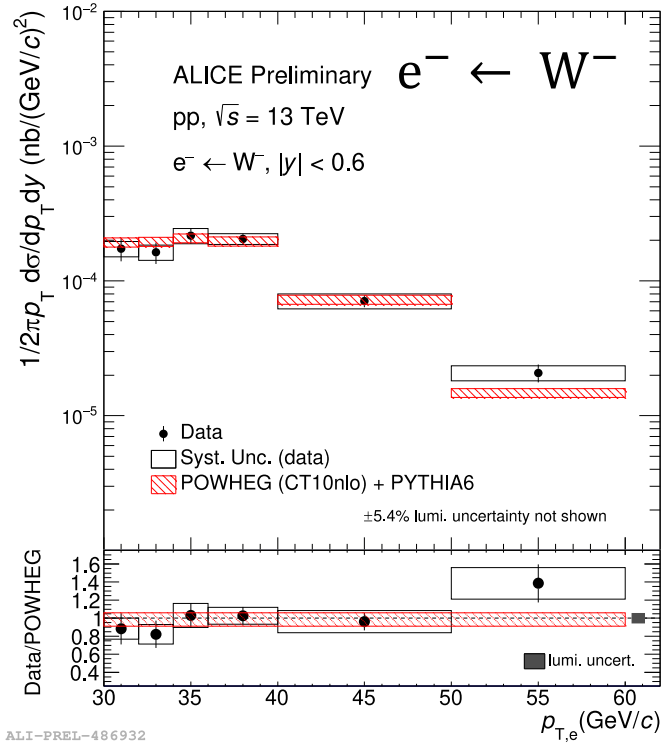
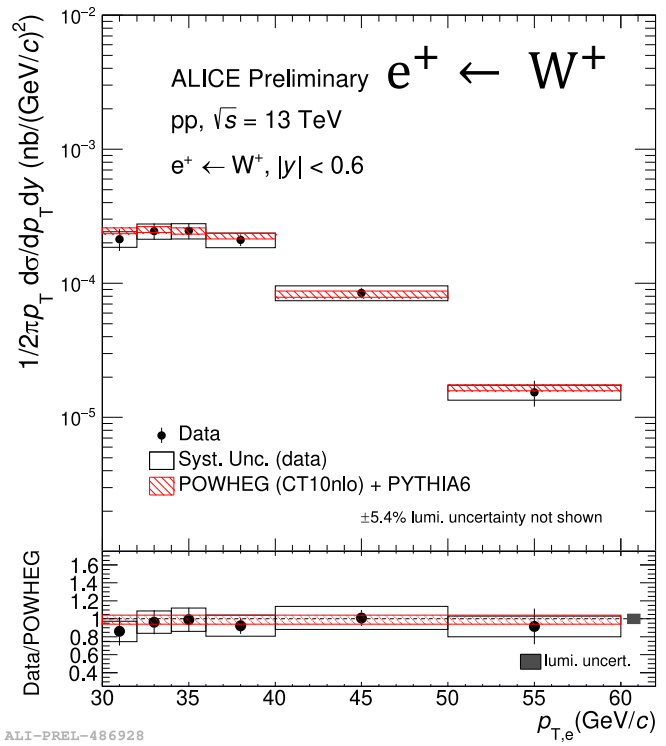


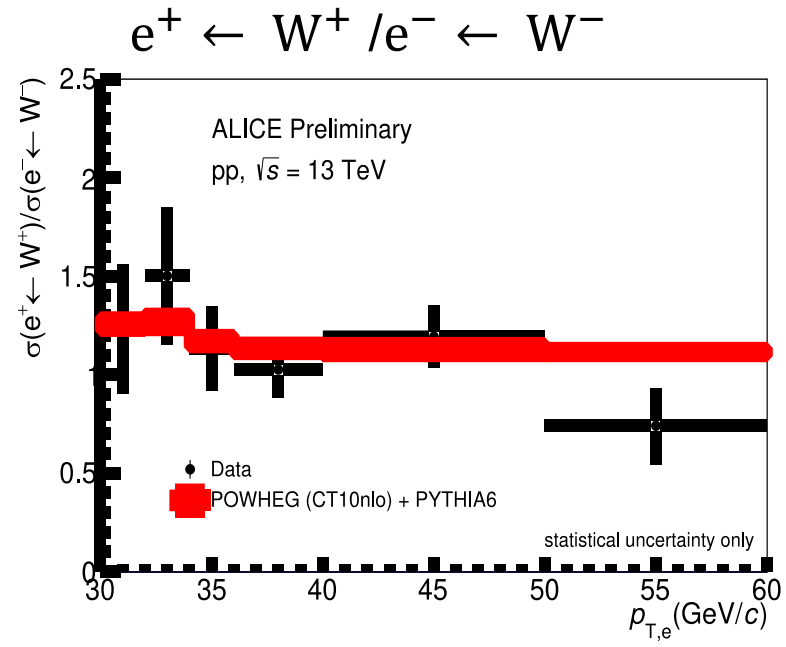
FIG. 3. The centrality-dependent nuclear modification ratios for $W^{\pm}$ and Z-boson production in Pb + Pb collisions from ATLAS [39,40] compared to NNLO pQCD calculation with EPPS16 nuclear modification with the nominal value of $\sigma_{\rm nn}^{\rm inel} = 70.0$ mb (left) and with the nuclear-suppressed value $\sigma_{\rm nn}^{\rm inel} = 41.5$ mb (right).

Eskola et al. (PRL 125(2020)212301

$W^{\pm}$ in pp collisions at 13 TeV (1)





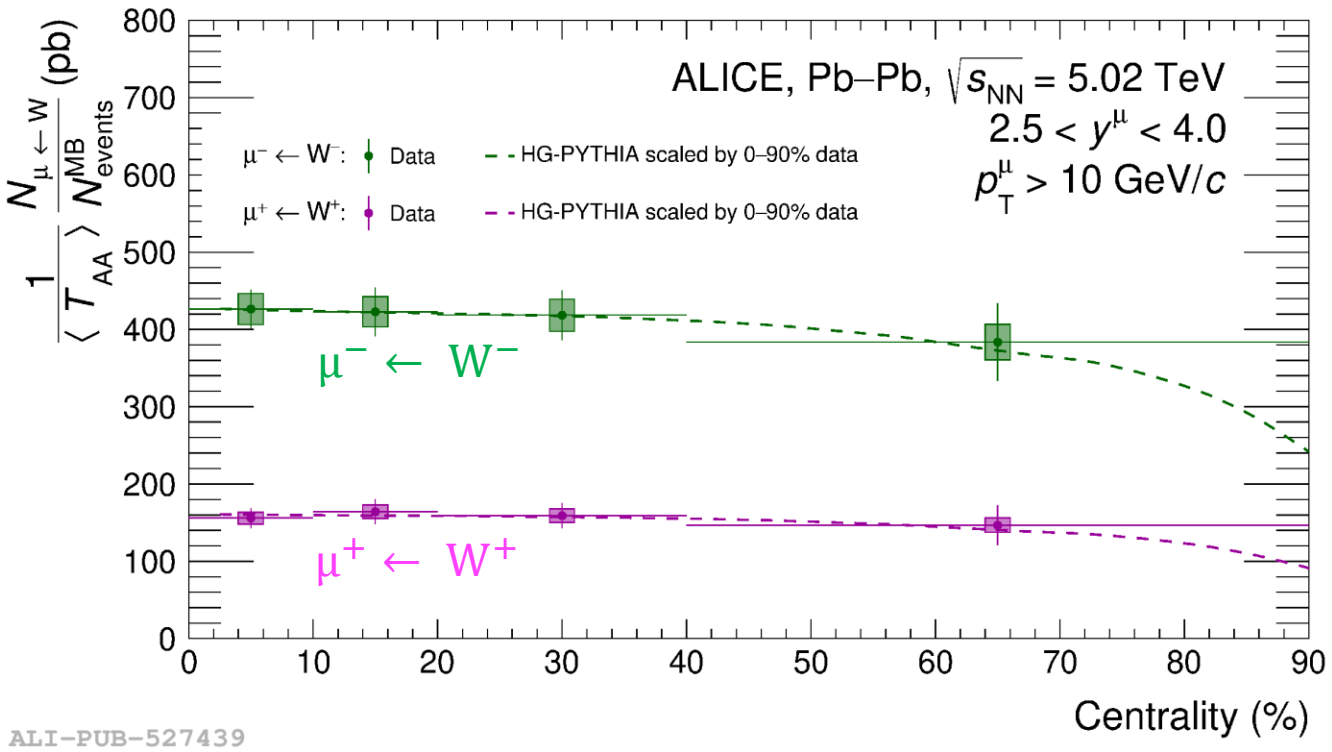


- p_T differential cross sections of $e^{\pm} \leftarrow W^{\pm}$ in $|y| < 0.6$, and ratio for $e^+ \leftarrow W^+$ and $e^- \leftarrow W^-$ as a function of p_T
- Compared to the predictions of pQCD NLO (POWHEG) + CT10NLO PDF
  - Measurements and model are consistent within the uncertainties
  - Larger cross section for $e^+ \leftarrow W^+$ due to isospin effects

CT10nlo
H. L. Lai et. al.,
PRD 82 (2010), 074024

$W^{\pm}$ in Pb–Pb at 5.02 TeV (2)

ALICE, JHEP 05 (2022) 036



- Production of hard probes in peripheral collisions
  - Significantly affected by event selection and geometry biases
  - These biases cause a "suppression" in peripheral collisions
- Comparison with HG-PYTHIA
  - Including biases from event selection and geometry

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