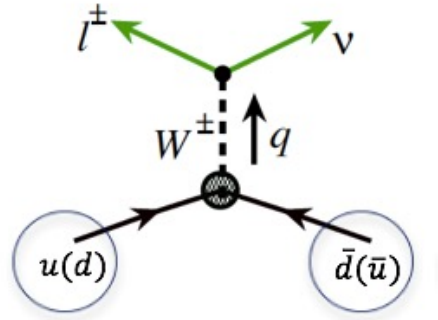
Electroweak-boson measurements from small to large collision systems with ALICE at the LHC

Shingo Sakai for the ALICE collaboration (Univ. of Tsukuba)

Motivation

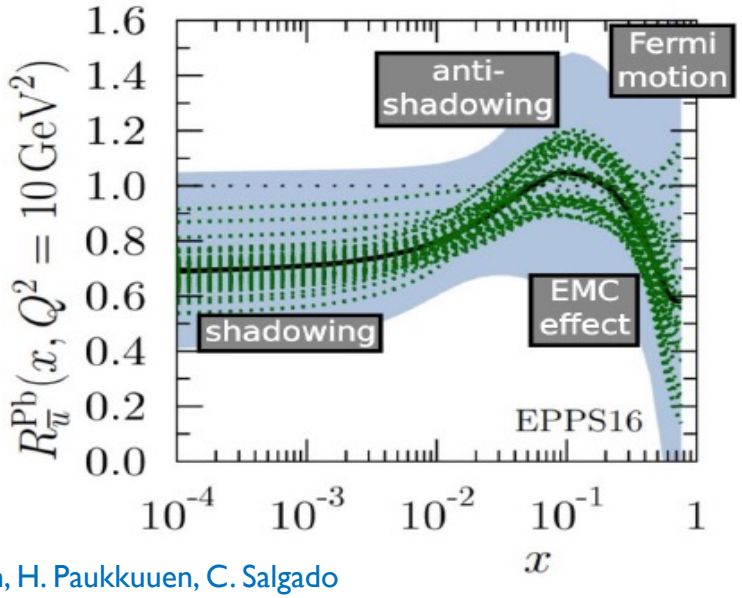
- W/Z boson
  - Produced predominantly via a quark – antiquark pair annihilation (Drell-Yan)
    - $u\bar{d} \rightarrow W^+, d\bar{u} \rightarrow W^-$, and $q\bar{q} \rightarrow Z$
    - Sensitive to isospin
  - Decay leptons insensitive to the strongly-interacting medium



The Universe 4 (2016) 3, 34-44
J. C. Peng and J. W. Qiu

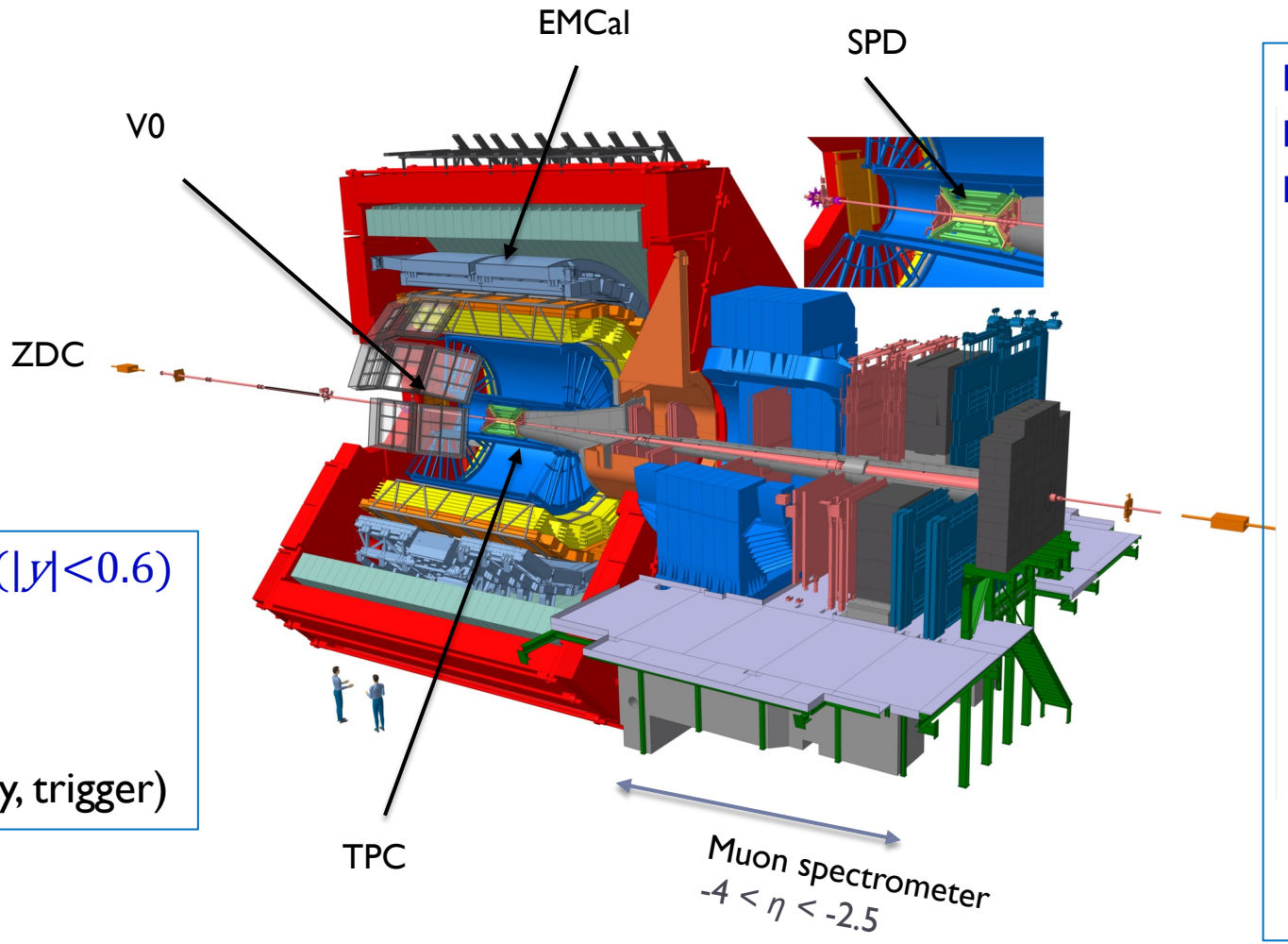
- pp collisions
  - Good test for pQCD and electroweak theory
  - Give insight into multiparton interactions (MPI) in high-multiplicity events and role of color-reconnection mechanism (CR)

- p–Pb and Pb–Pb collisions
  - Provide insights on the nuclear modification of the parton distribution functions (nPDF)
    - Important to understand the initial-state nuclear effects
  - A good test for binary scaling



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

ALICE detector



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

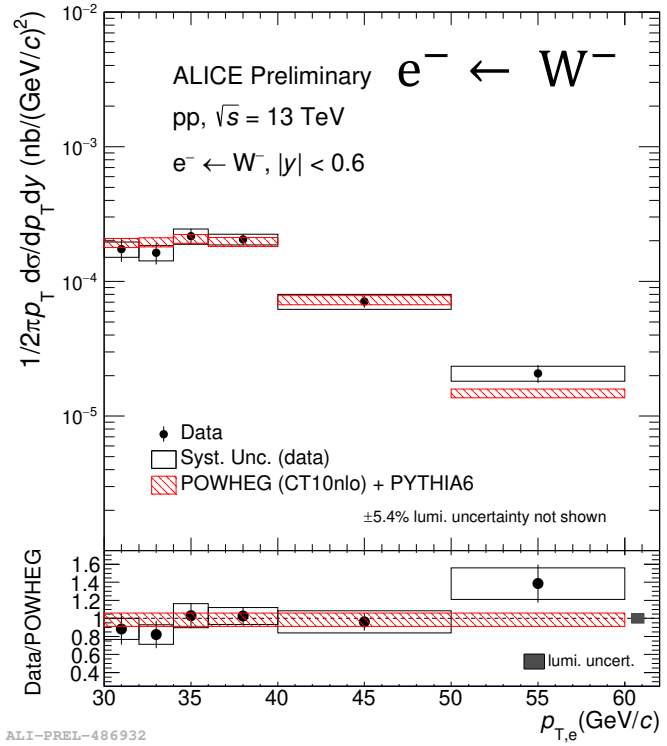
- Muon channel ($-4 < \eta < -2.5$)
- $\mu^{\pm} \leftarrow W^{\pm}$
- $Z \rightarrow \mu^{+}\mu^{-}$
  - Muon spectrometer
    - trigger
    - tracking
  - p–Pb, p-going
    - $2.03 < y_{cms} < 3.53$
  - p–Pb, Pb-going
    - $-4.46 < y_{cms} < -2.96$
  - Pb–Pb
    - $2.5 < y_{cms} < 4$

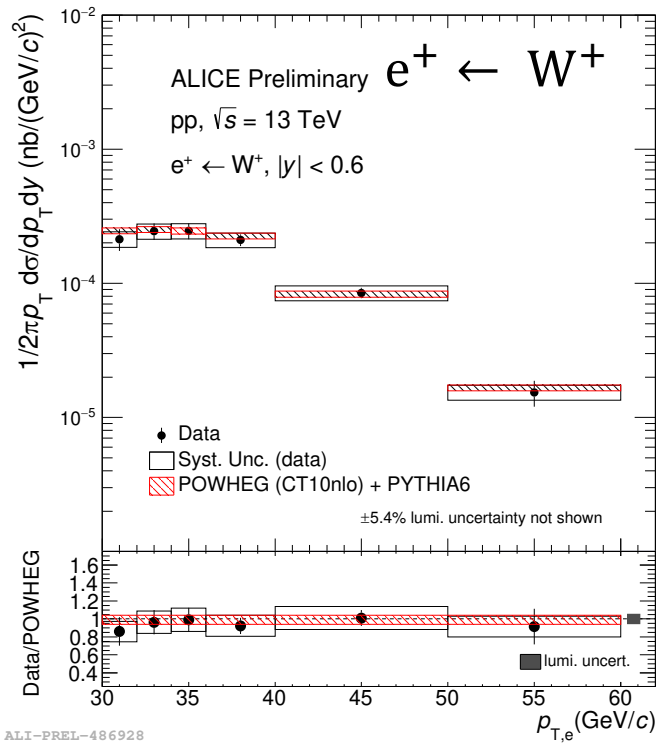
Weak-boson measurements with ALICE

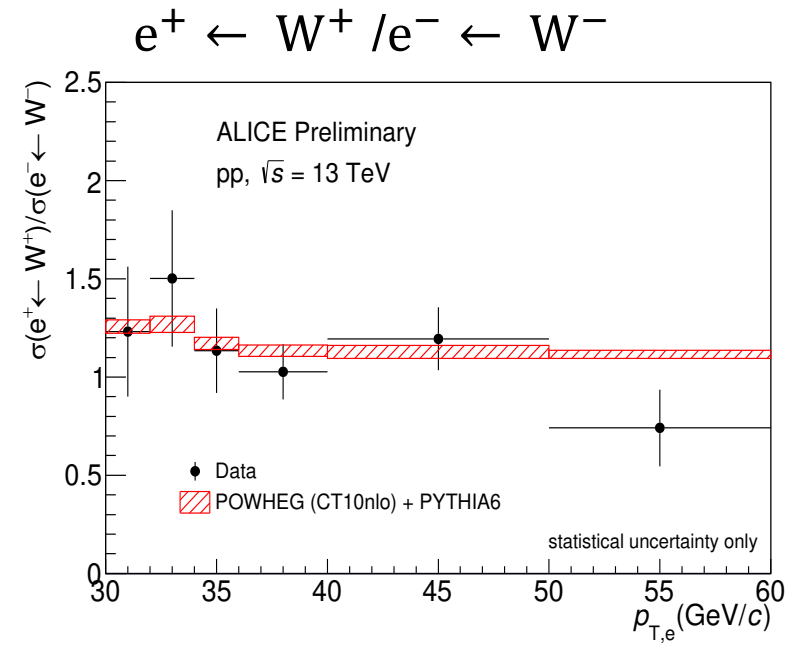
Collision system	Energy	Luminosity	Year	Analyses
pp	13 TeV	~6.6 pb^{-1}	2016 + 2017 + 2018	Z, W (e, midrapidity)
p–Pb Pb–p	5.02 TeV	5.03 ± 0.18 nb^{-1} 5.81 ± 0.20 nb^{-1}	2013	Z, W (μ, forward /backward)
p–Pb Pb–p	8.16 TeV	6.73 ± 0.16 nb^{-1} 10.0 ± 0.22 nb^{-1}	2016	Z, W (μ, forward /backward)
Pb–Pb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

- Recent weak boson measurements in ALICE
  - W-boson and Z-boson production at midrapidity in pp collisions at 13 TeV
  - W boson in p–Pb at 8.16 TeV and Pb–Pb at 5.02 TeV at forward rapidity (arXiv:2204.10640 [nucl-ex])

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



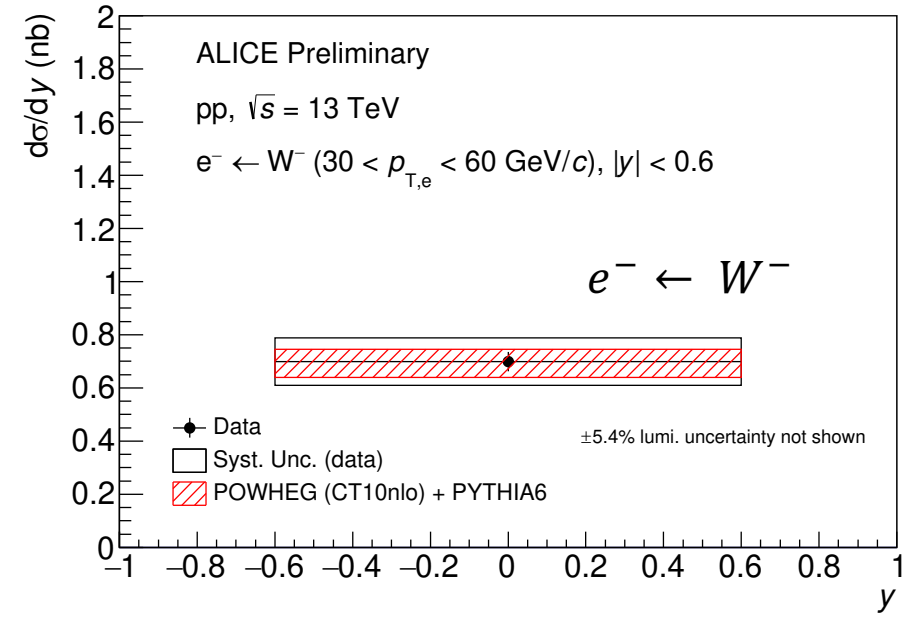




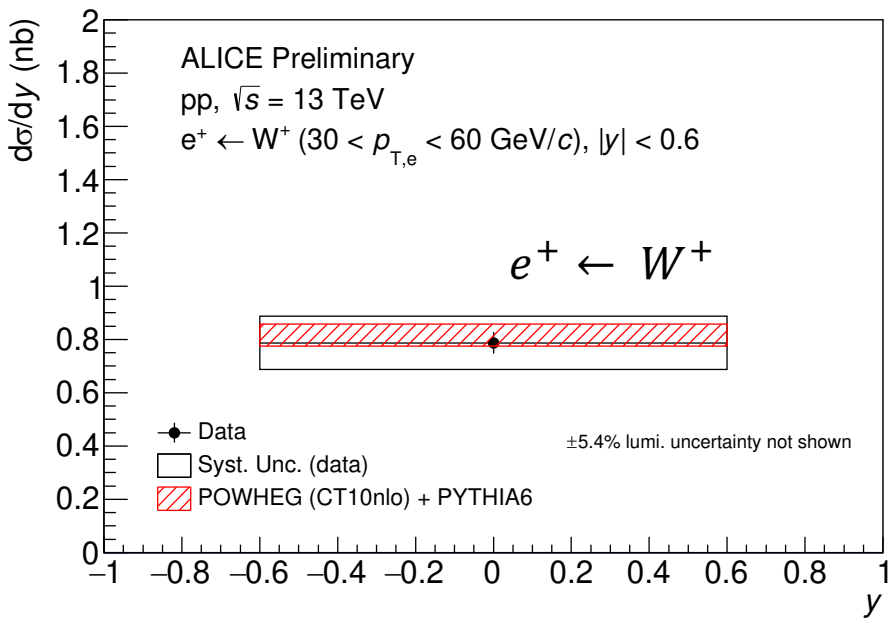
- p_T differential cross sections of $e^{\pm} \leftarrow W^{\pm}$ in $|y| < 0.6$, and ratio for $e^+ \leftarrow W^+$ and $e^- \leftarrow W^-$ as a function of p_T
- Compared to the predictions of pQCD NLO (POWHEG) + CT10NLO PDF
  - Measurements and model are consistent within the uncertainties
  - Larger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

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

$W^{\pm}$ in pp collisions at 13 TeV (2)



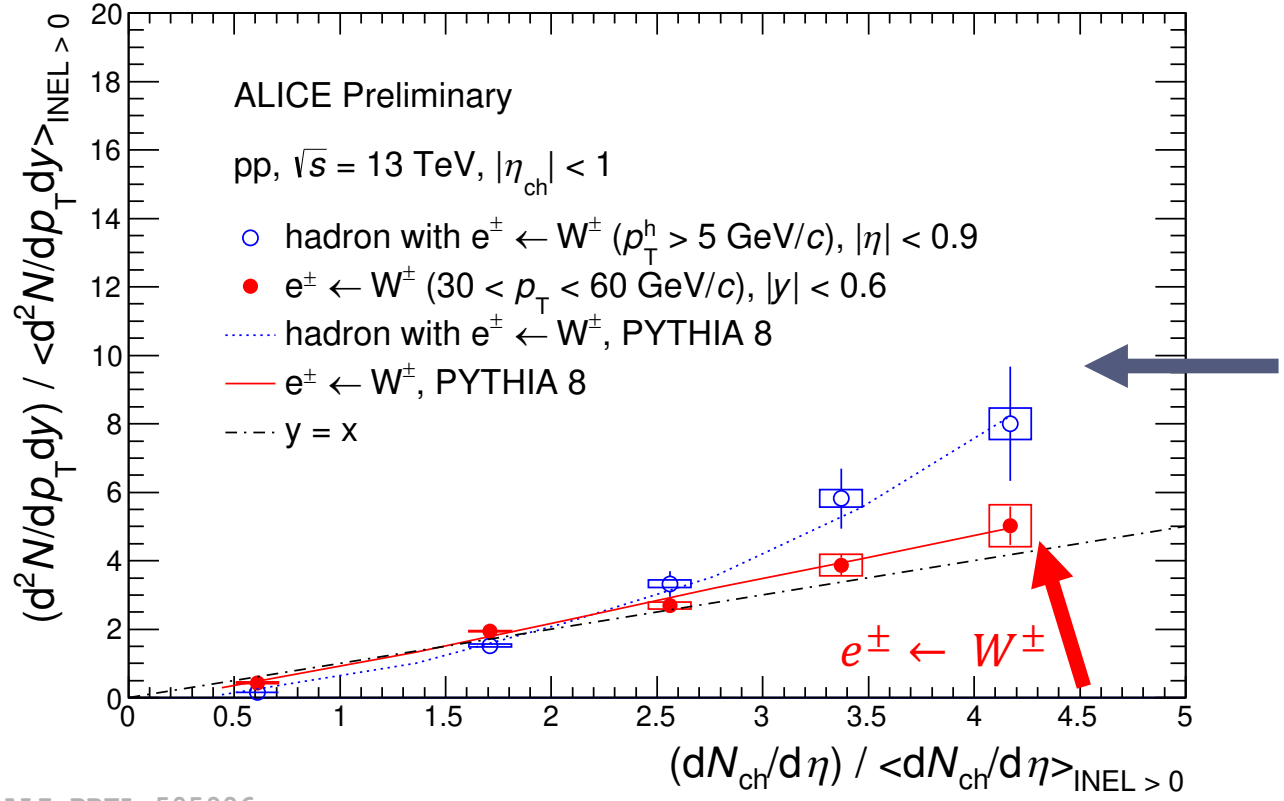
ALI-PREL-486940



ALI-PREL-486936

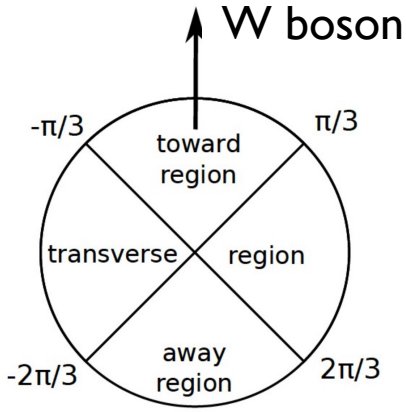
- Cross sections for $e^{\pm} \leftarrow W^{\pm}$ in |y| < 0.6
  - Electrons in 30 < p_T < 60 GeV/c
- Compared to a model including pQCD NLO (POWHEG) + CT10NLO
  - Consistent with data within uncertainties

Multiplicity dependence of W production



ALI-PREL-505996

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



A faster-than-linear trend was observed when requiring hadrons on the away side of the W boson:

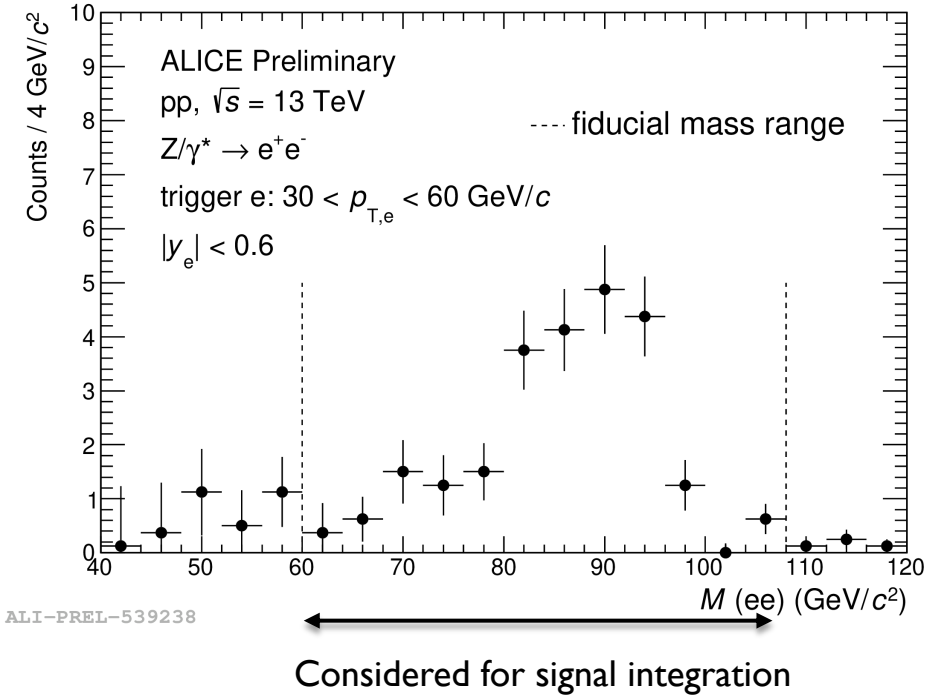
→ Non-linear dependence due to auto-correlation between hadrons and multiplicity in the absence of "strong" final-state interactions?

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

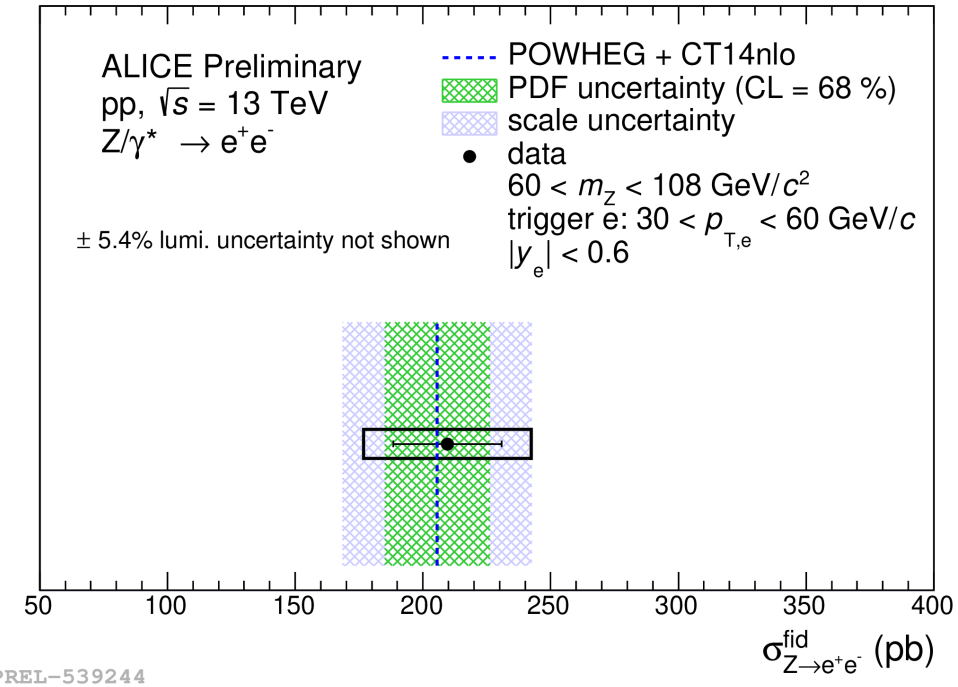
→ Insights into the observed non-linear dependence of heavy-flavor hadrons (D, J/ψ, …) vs multiplicity

Phys. Lett. B 712, 165-175 (2012), JHEP 09, 148 (2015)

Z production in pp at 13 TeV



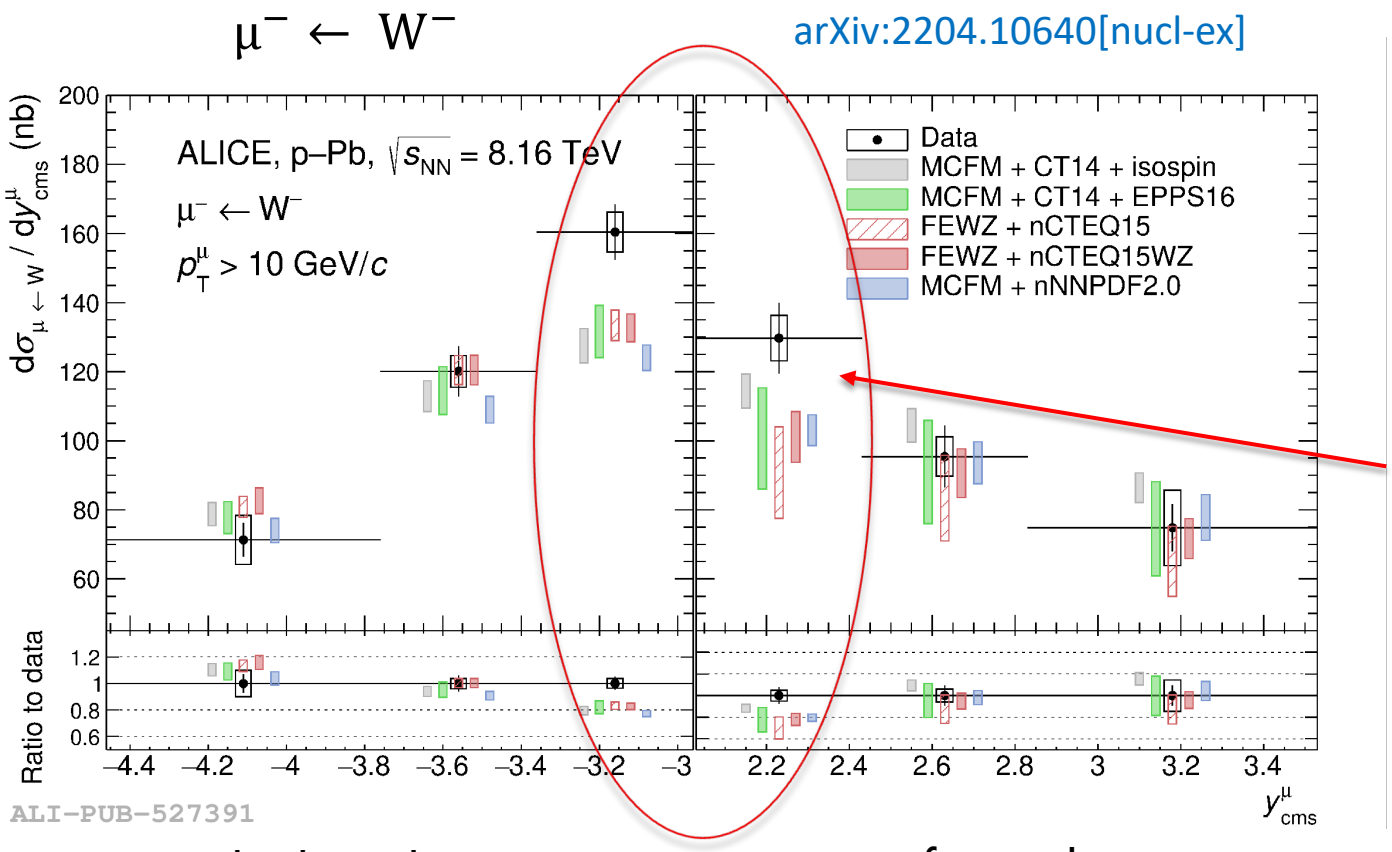
Considered for signal integration



New

- First ALICE measurement of the Z boson at midrapidity
- Z bosons are reconstructed by electron-positron pairs at midrapidity
  - One of electron (positron) has $p_{T,e}$>30 GeV/c & $|y_e|$<0.6
- Fiducial cross section of Z bosons (60 < M_Z < 108 GeV/c^2)
  - Consistent with POWHEG + CT14nlo PDF within uncertainties

$W^{\pm}$ in p–Pb at 8.16 TeV (1)



backward
$x \sim 10^{-1}$
Anti-shadowing

forward
$x \sim 10^{-4}$
Shadowing

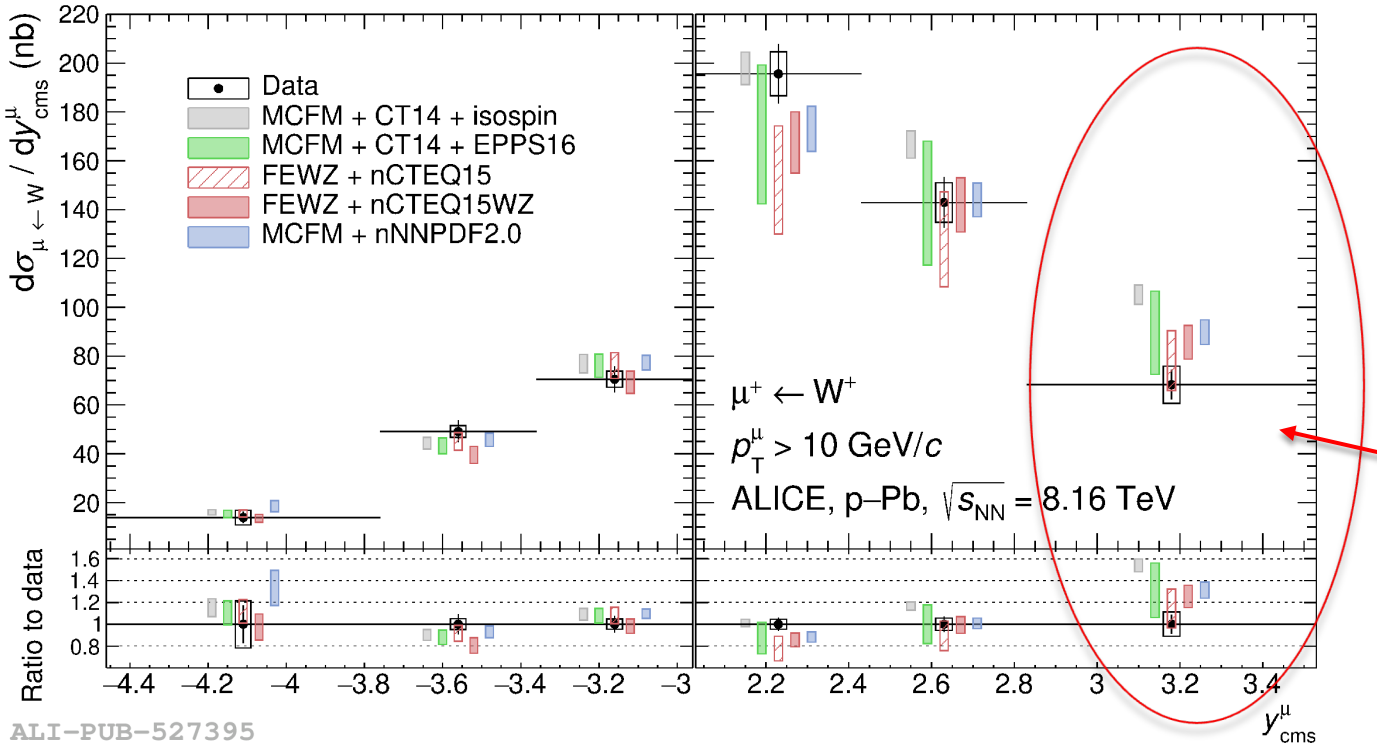
- W^{-} production cross section measured as a function of rapidity
- Model calculations
  - Based on pQCD predictions
  - including isospin effect with/without nPDF
- Calculations underestimate data for bins closest to midrapidity, both at forward and backward (1.4 and 2 σ from EPPS16 predictions)

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)

$\mu^+ \leftarrow W^+$

arXiv:2204.10640[nucl-ex]



backward
$x \sim 10^{-1}$
Anti-shadowing

forward
$x \sim 10^{-4}$
Shadowing

- W^+ production cross section measured as a function of rapidity
- Model calculations
  - Based on pQCD predictions
  - including isospin effect with/without nPDF
- 3.5σ deviation from free-PDF calculation (MCFM + CT14) for W^+ at forward rapidity for the bin at 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
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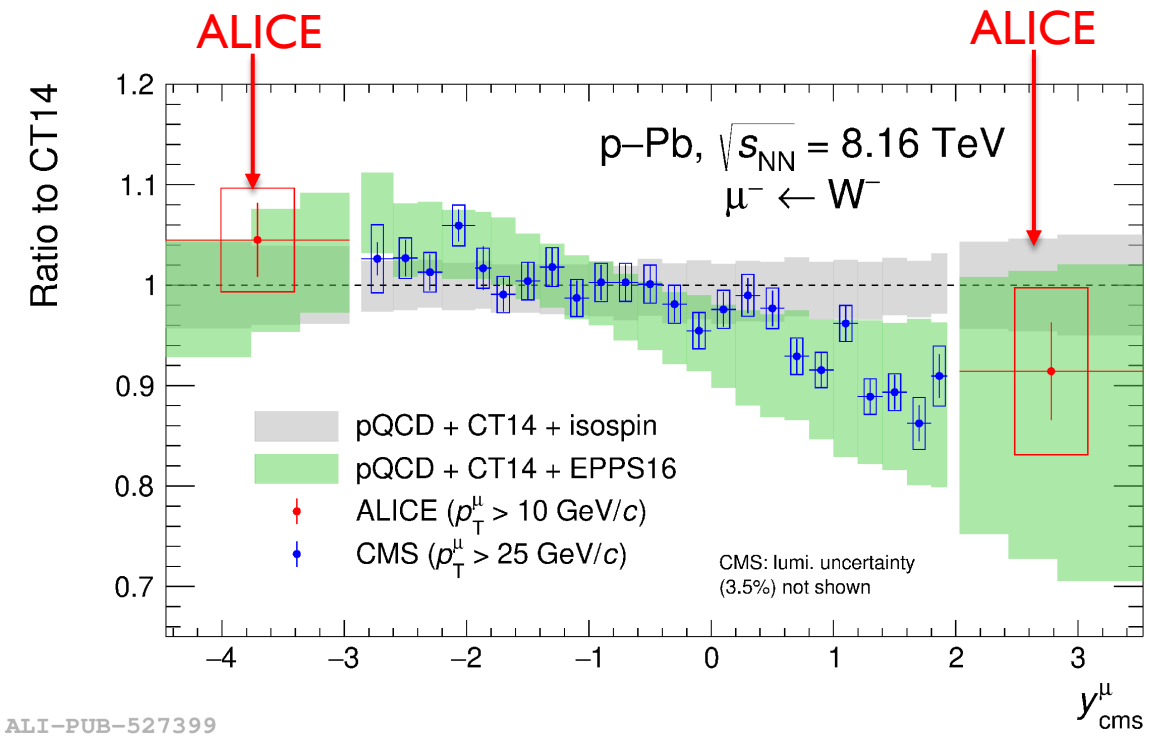
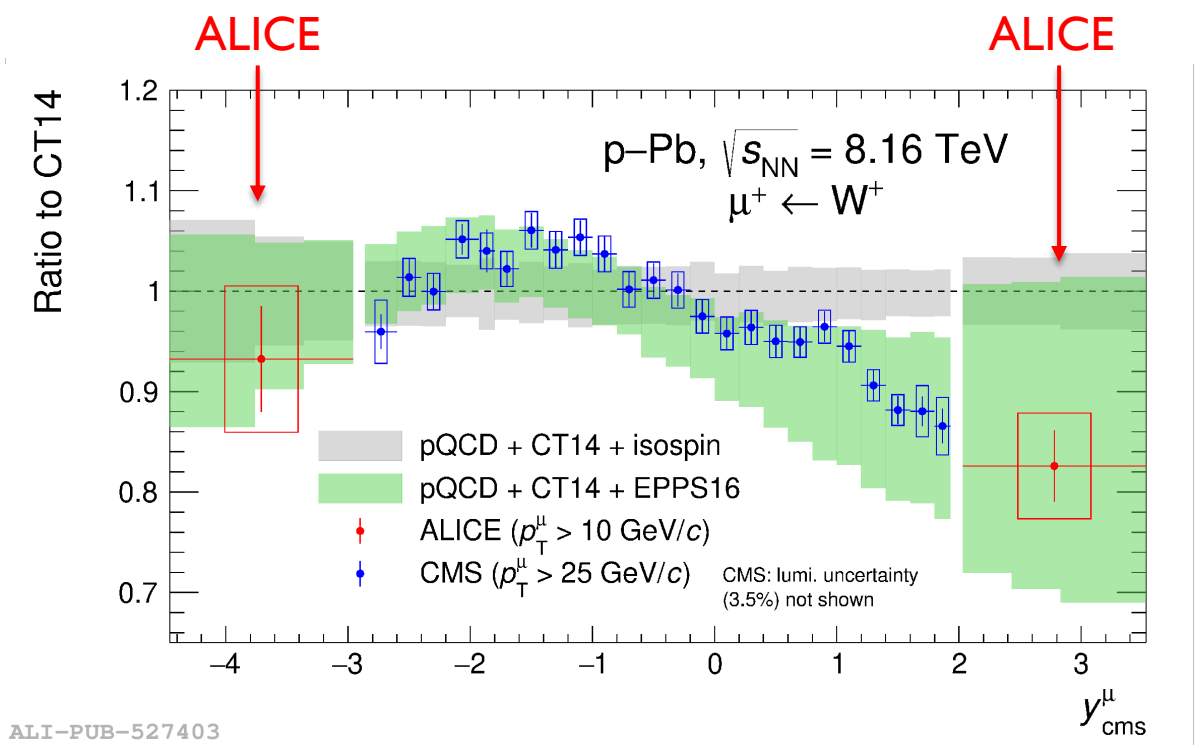
nNNPDF2.0 : JHEP 09 (2020) 183

$W^{\pm}$ in p–Pb at 8.16 TeV (3)



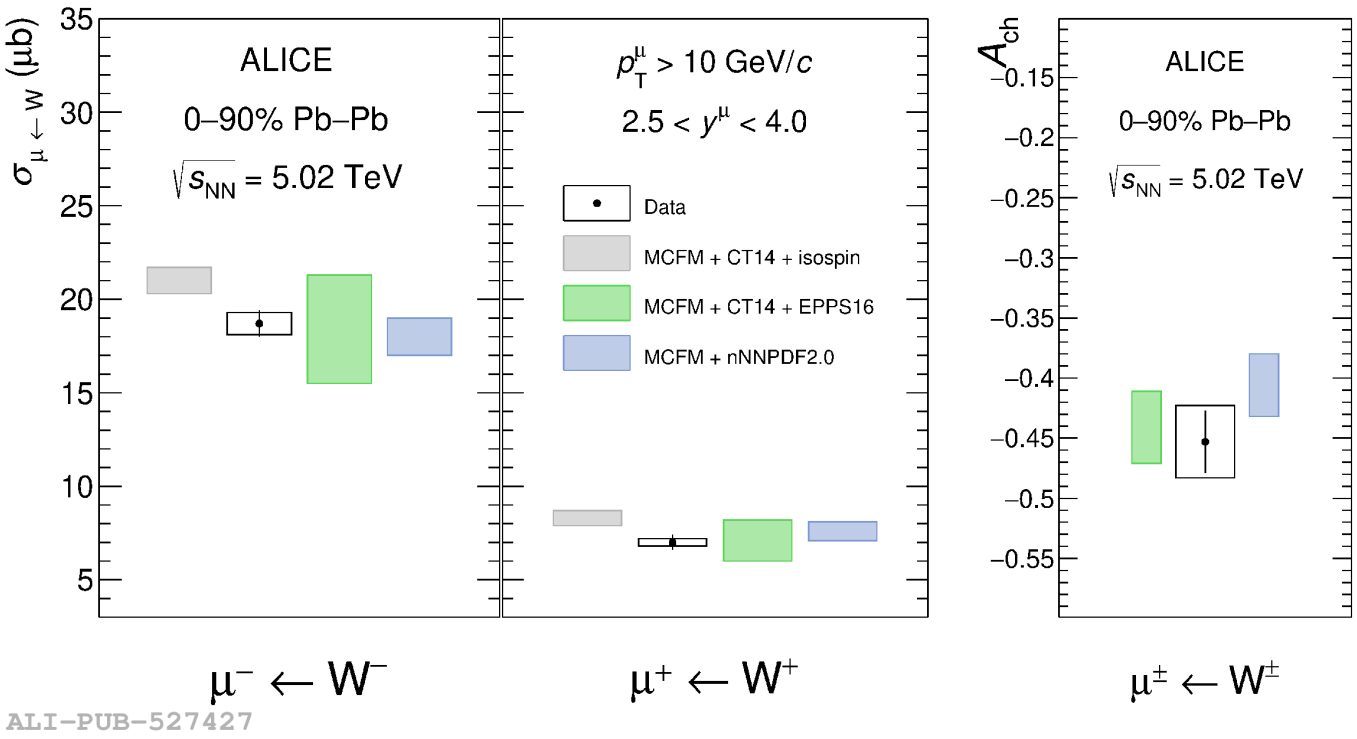


arXiv:2204.10640[nucl-ex]

- 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 at large rapidity

$W^{\pm}$ in Pb–Pb at 5.02 TeV (1)

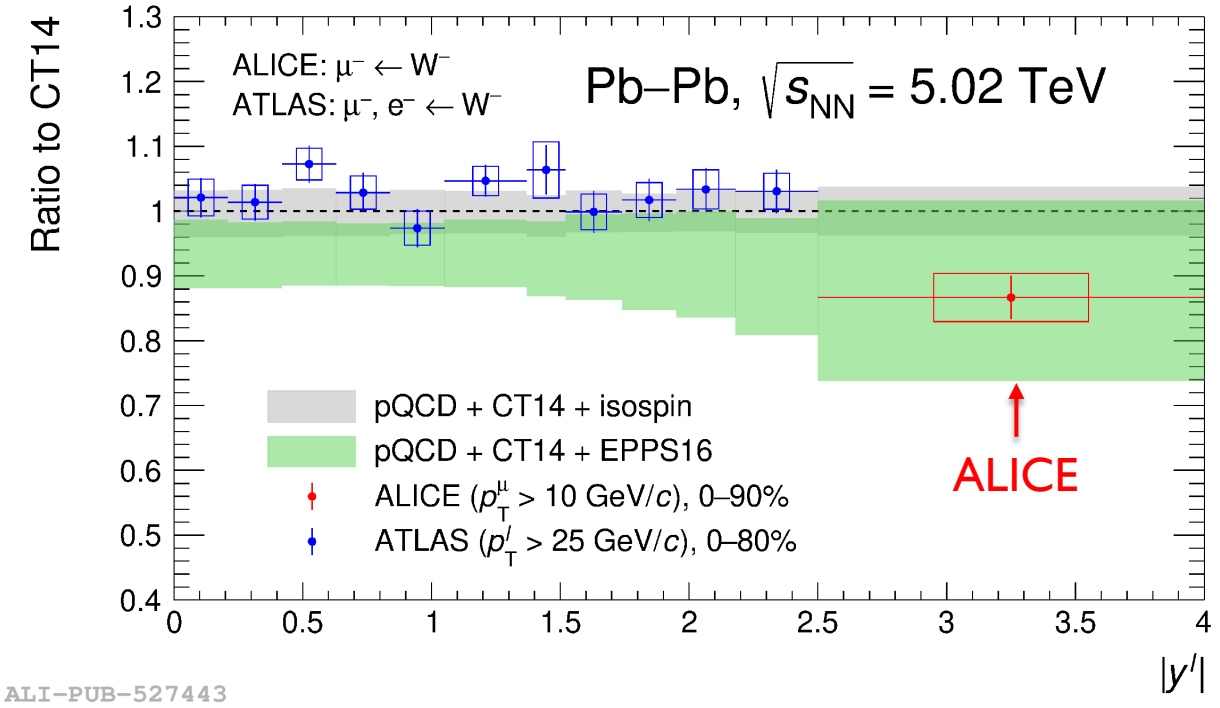
arXiv:2204.10640[nucl-ex]

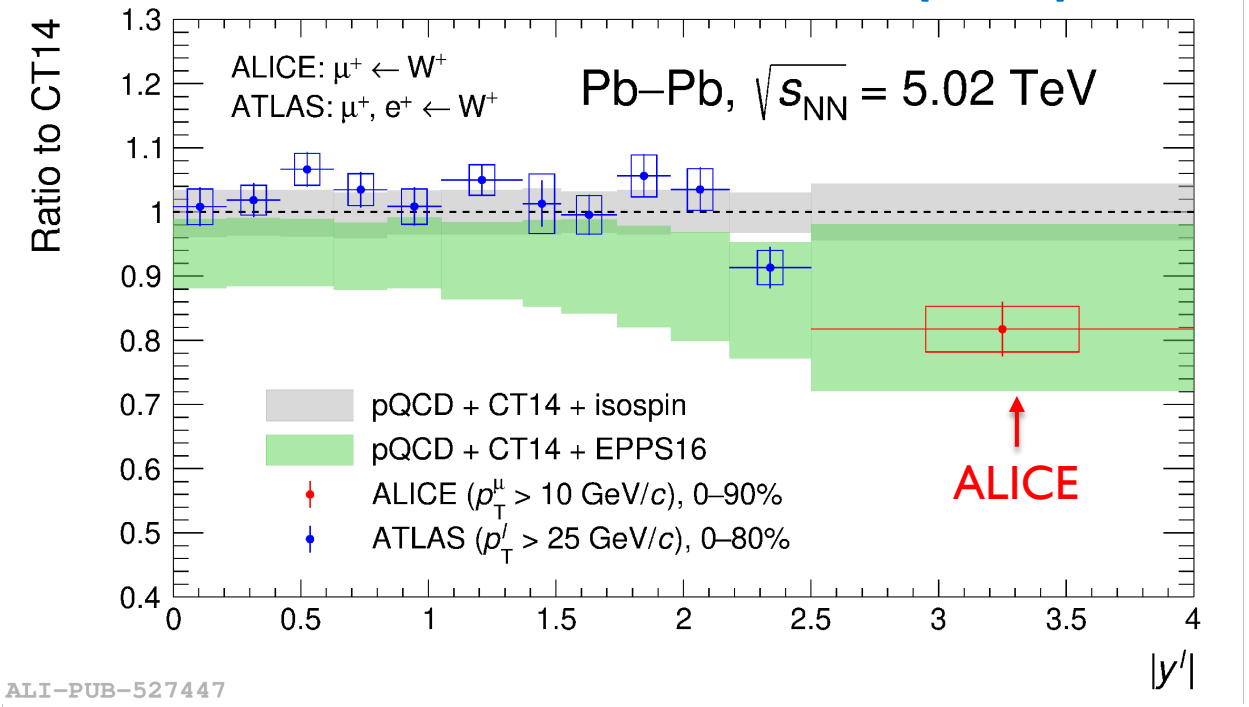


- larger cross section for $\mu^- \leftarrow W^-$ than for $\mu^+ \leftarrow W^+$
  - effect of isospin due to different content of u and d in Pb nucleus
- Model with CT14 for free nucleon (MCFU+CT14)
  - Overestimates the cross sections
  - Suggests a significant modification of the PDFs
  - Fair agreement with nPDF models

$W^{\pm}$ in Pb–Pb at 5.02 TeV (2)

arXiv:2204.10640[nucl-ex]

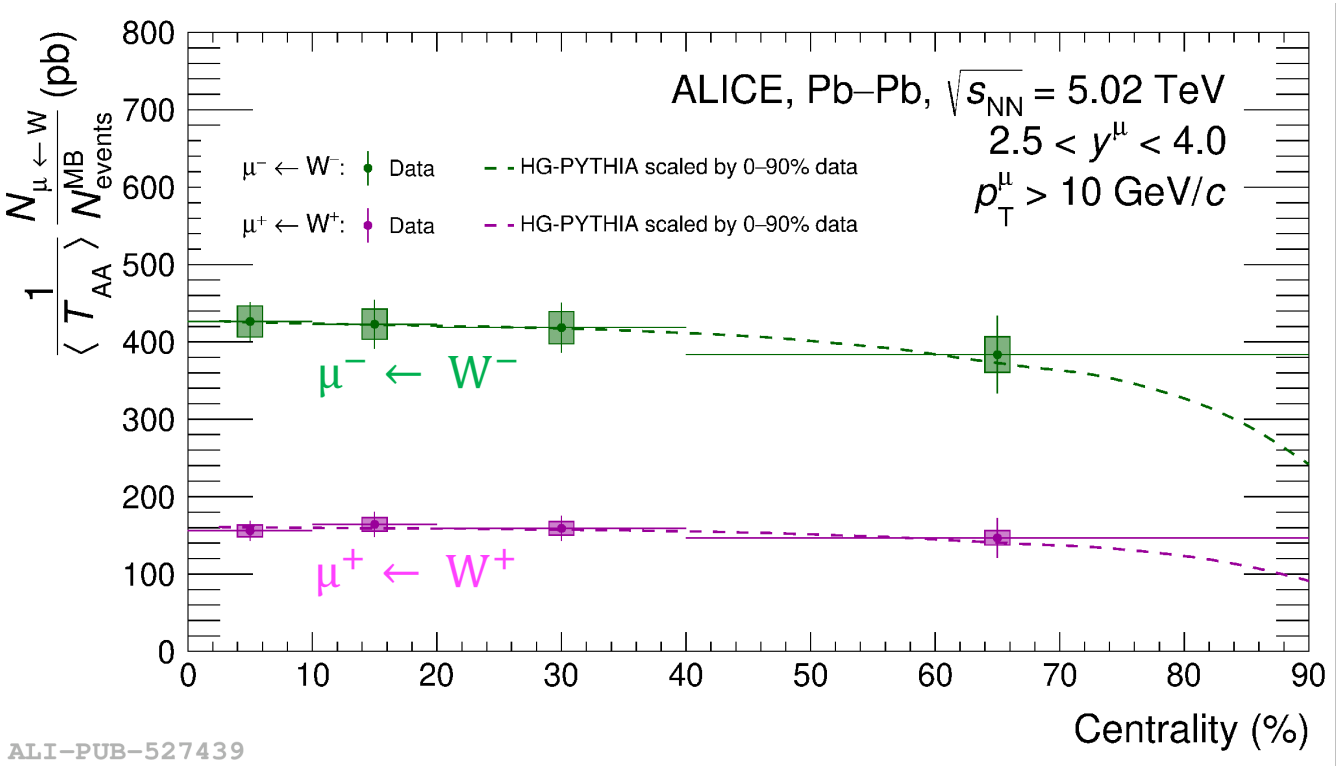




- Ratio to CT14 as a function of rapidity compared with ATLAS results (EPJC 79 (2019) 935)
  - ALICE results well described by EPPS16 calculations (2σ lower than CT14 without EPPS16)
  - EPPS16 underestimates ATLAS data
- Ratio to CT14 is smaller than unity at large rapidity
  - Suggests a significant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

$W^{\pm}$ in Pb–Pb at 5.02 TeV (3)

arXiv:2204.10640[nucl-ex]



- 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

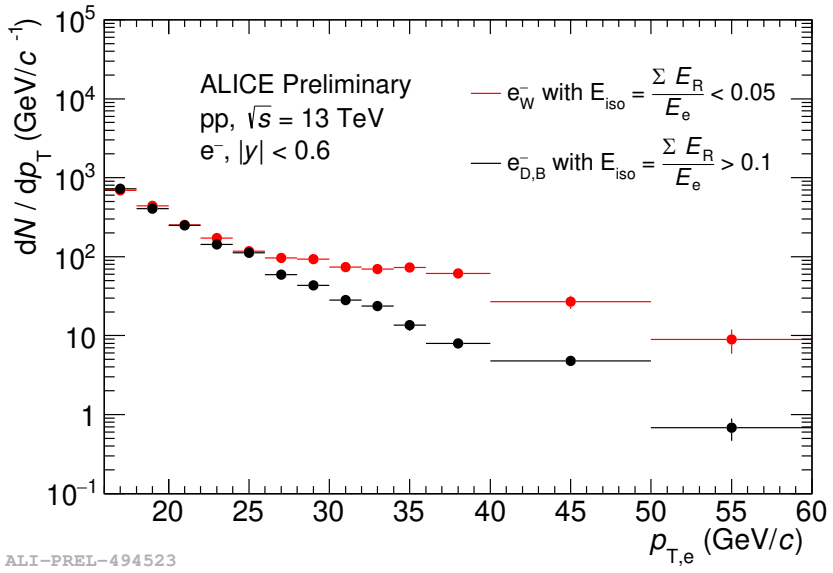
HG-PYTHIA
C. Loizides and A. Morsch, PLB 773 (2017) 408-411

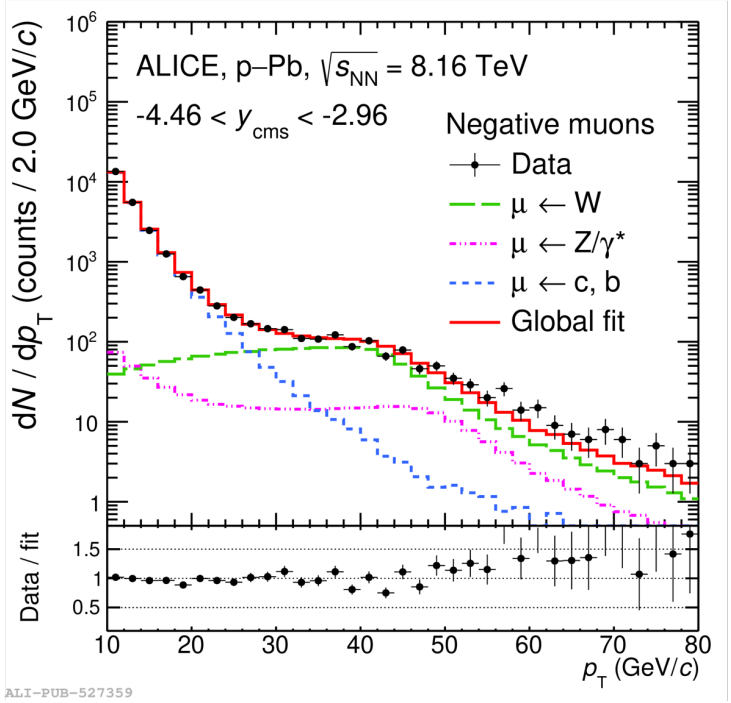
Summary

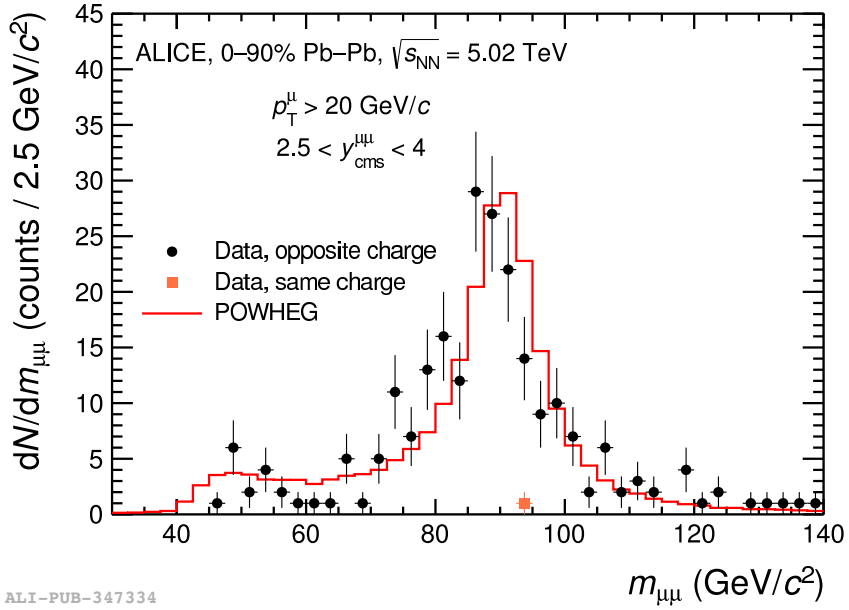
- Presented recent electroweak-boson production in ALICE from small to large collision systems with ALICE
  - pp collisions at 13 TeV
    - *(New)* Z boson production is consistent with NLO pQCD (POWHEG) + PDF (CT14NLO)
    - Linear dependence of W production on charged multiplicity
  - p-Pb collisions at 8.16 TeV and Pb-Pb collisions at 5.02 TeV
    - ALICE reaches the largest rapidity for W boson measurements
    - Suggests a significant modification of the nuclear PDFs
- Outlook at Run3
  - Significant increase of the luminosity (pp : 200/pb, Pb–Pb : 7/nb)
    - Detailed study of nPDFs
    - Differential study for electroweak-boson production (ex. W/Z + jet)

Back up

W/Z yields extraction in ALICE





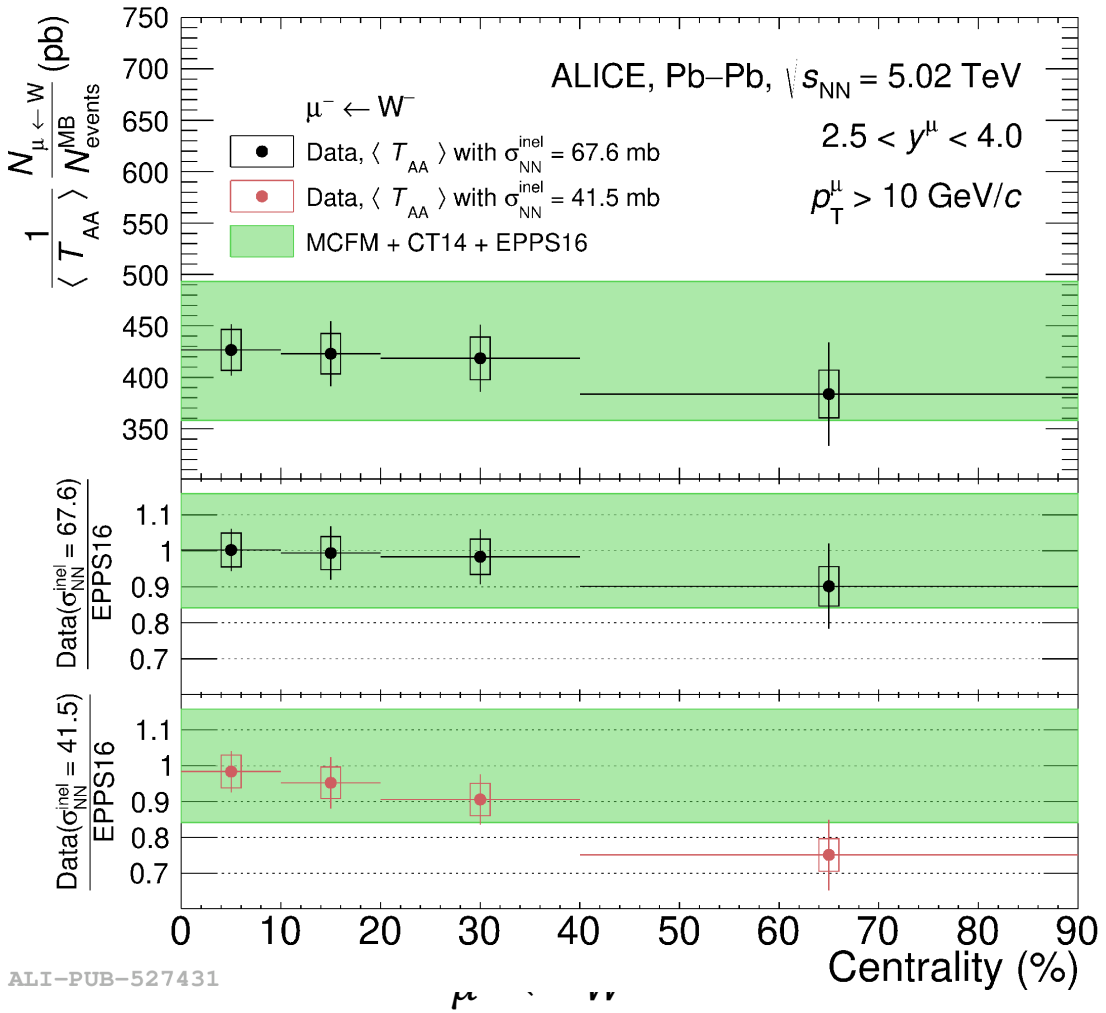


- $e^{\pm} \leftarrow W^{\pm}$ (|y| < 0.6); Based on isolation cuts on energy; $E_{iso} = \frac{\sum E_{R<0.3}}{E_e} < 0.05$
  - $e^{\pm} \leftarrow c, b$ are obtained by data driven subtraction (large isolation energy)
- $\mu^{\pm} \leftarrow W^{\pm}$ (-4< y_{lab} < -2.5); Fit of the single muons p_T distribution via MC templates
  - $\mu^{\pm} \leftarrow c, b$ by FONLL, $\mu^{\pm} \leftarrow W^{\pm}, Z$ by POWHEG
- $Z \rightarrow \mu^{\pm}$ (-4 < y_{lab} < -2.5); Invariant mass of opposite-sign muon pair

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

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

$W^{\pm}$ 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

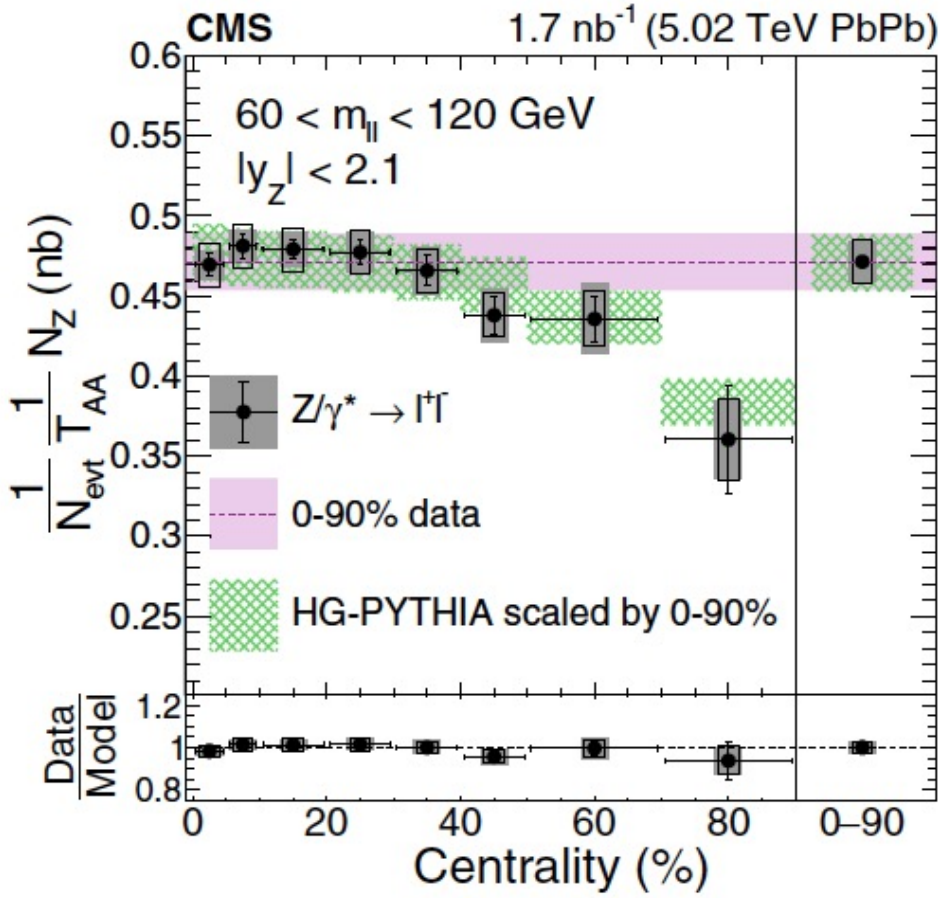
- Model calculation
  - CT14 PDFs with EPPS16
    - A good agreement with data

- 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

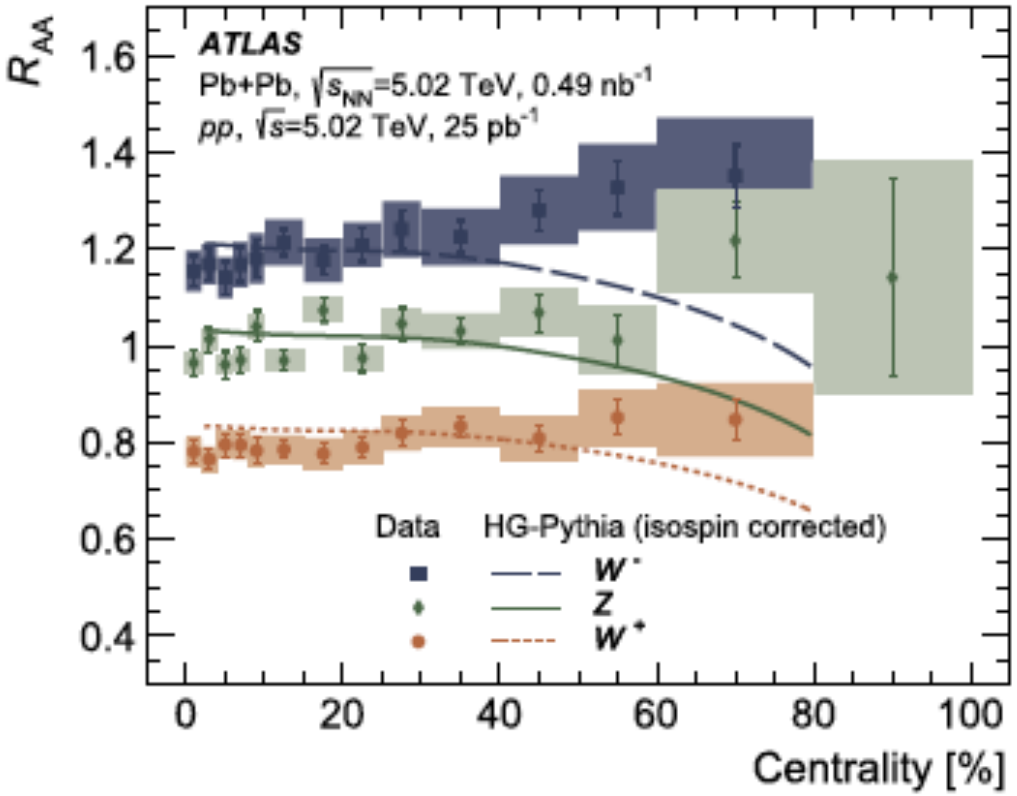
- $\langle T_{AA} \rangle$ re-evaluated, yields worse agreement between ALICE data and EPPS16

W/Z R_{AA} in CMS and ATLAS

PRL 127, 102002 (2021)



PLB 202 (2020) 135262



Modified cross section

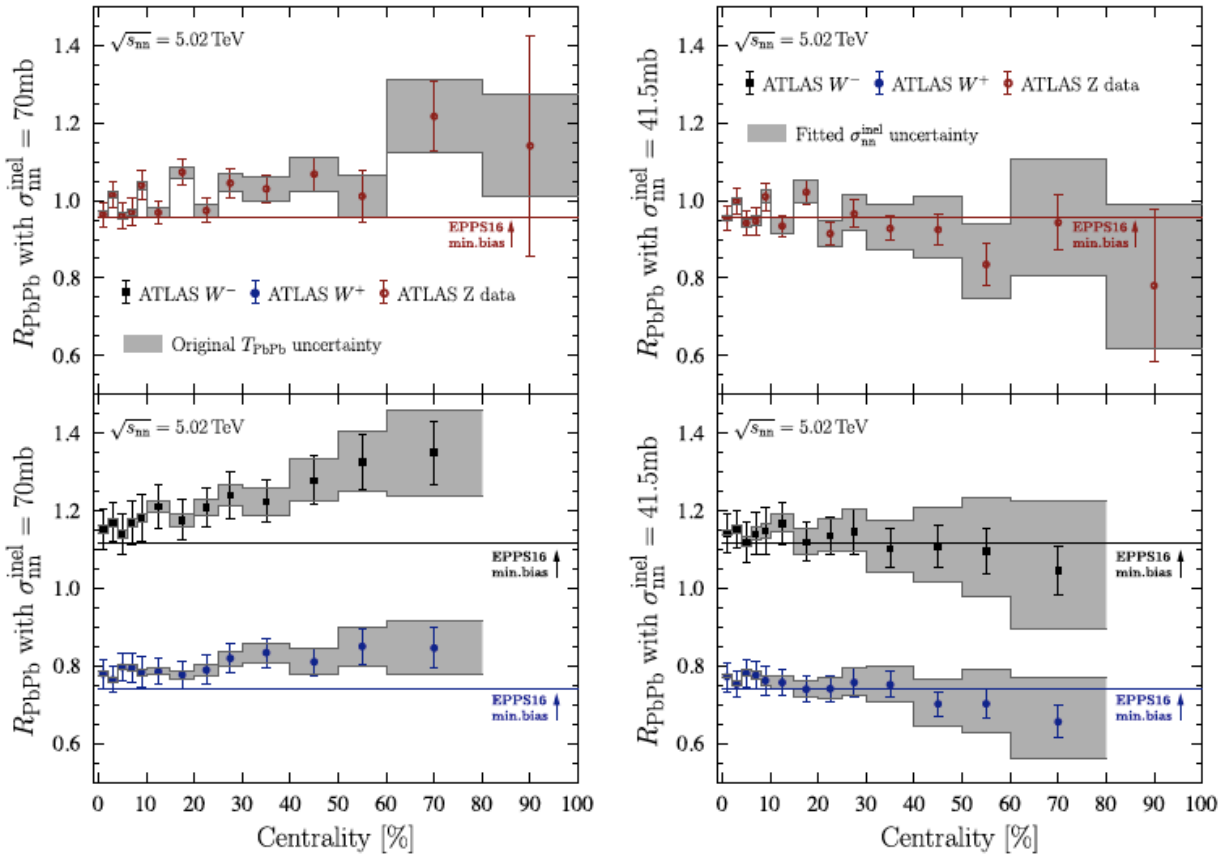
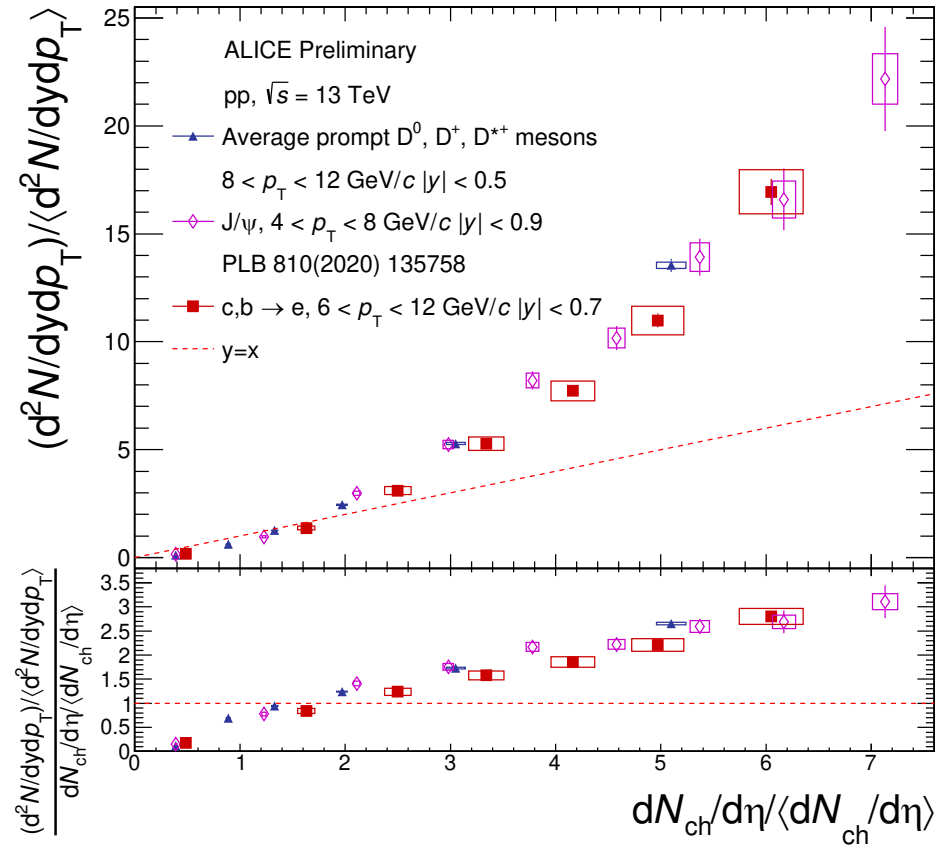


FIG. 3. The centrality-dependent nuclear modification ratios for $W^{\pm}$ and Z-boson production in Pb + Pb collisions from ATLAS [39,40] compared to NNLO pQCD calculation with EPPS16 nuclear modification with the nominal value of $\sigma_{\rm nn}^{\rm inel} = 70.0$ mb (left) and with the nuclear-suppressed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

Eskola et al. (PRL 125(2020)212301

Multiplicity dependence of W production (1)



- Heavy flavour production in pp collisions at 13 TeV
  - Observed productions is faster than linear w.r.t. charge particle multiplicity
- Not fully understood the trend
  - Q2 effect
  - Jet-bias effect
  - Color reconnection in multiparton interactions
- W boson
  - Very large Q2
  - One track in the final state
  - Colorless