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

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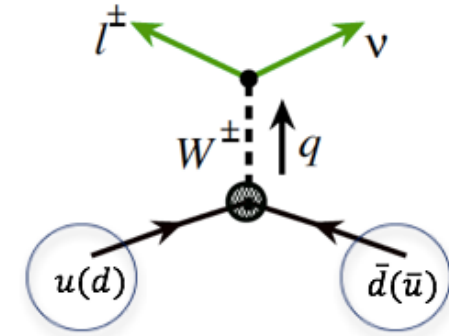
Motivation

- **W/Z boson**
  - Weakly interacting particles, and have large masses
  - Produced predominatly via a quark – antiquark pair annihilation (Drell-Yan)
    - $u\bar{d} \rightarrow W^+, d\bar{u} \rightarrow W^-$, and $q\bar{q} \rightarrow Z$
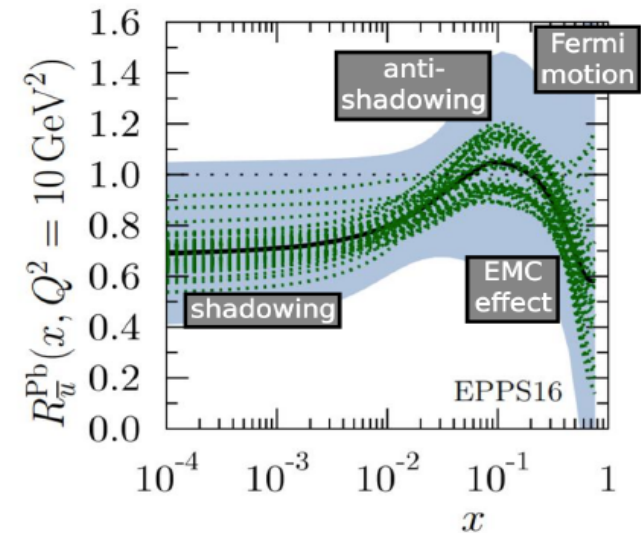   - Sensitive to isospin

- **pp collision**
  - 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)
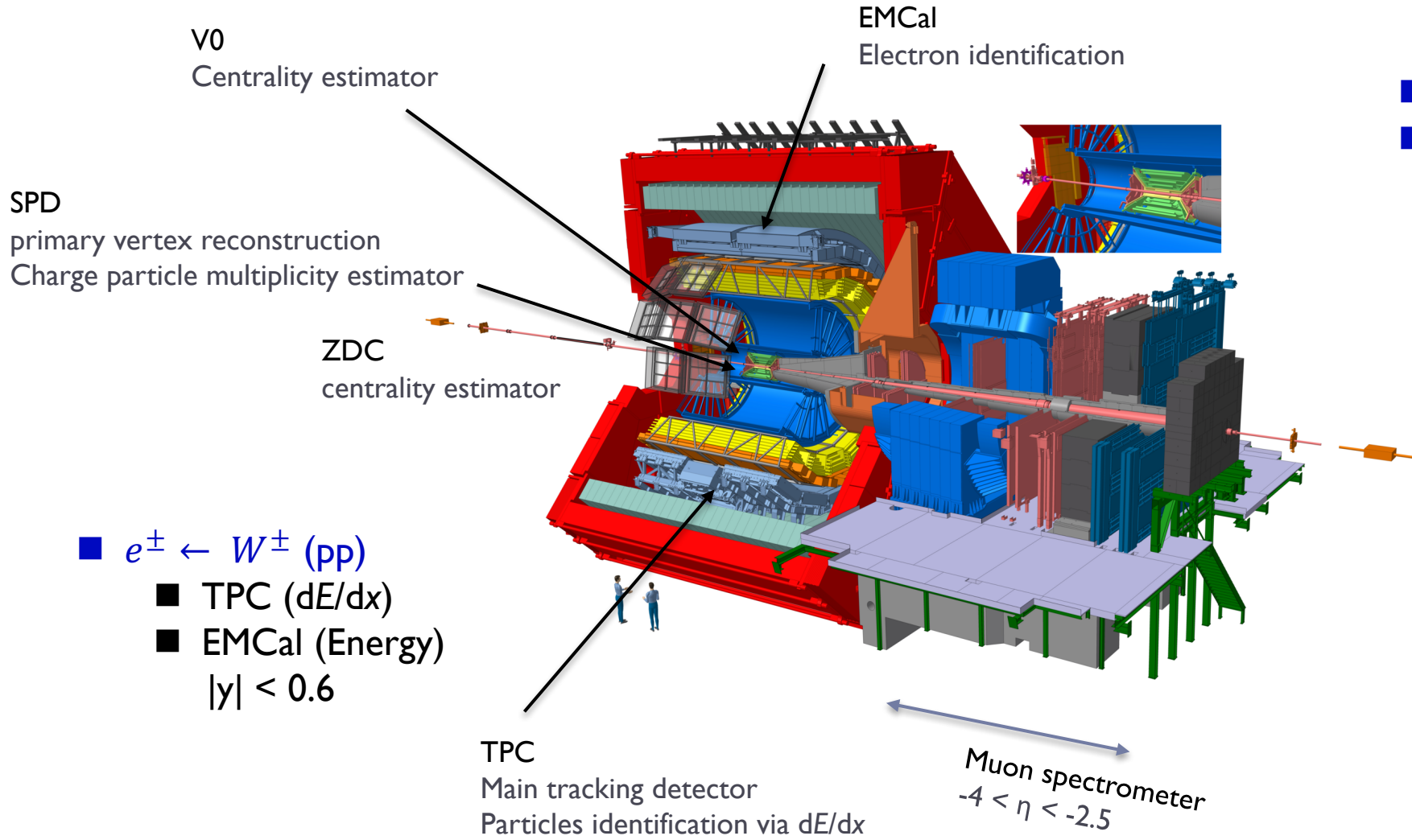 - Leptonic decay insensitive to the strongly-interacting medium

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

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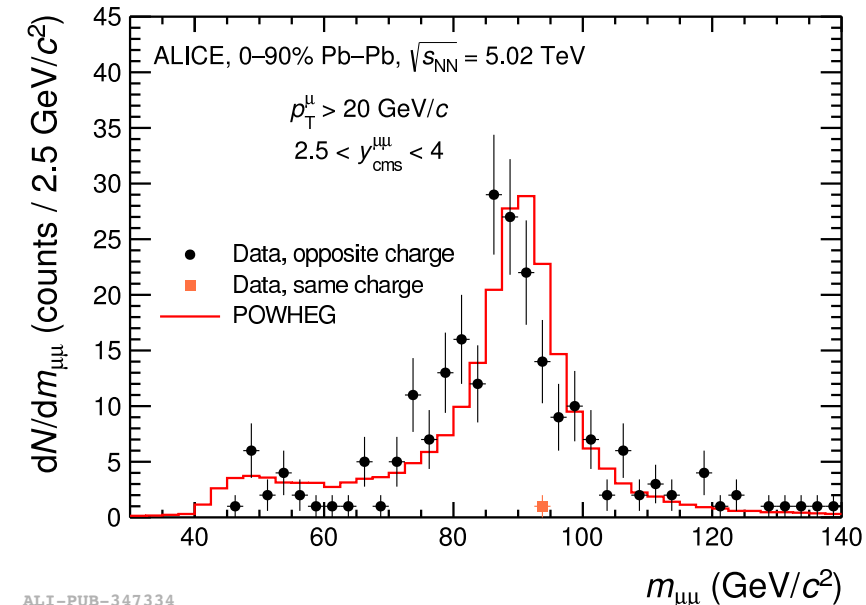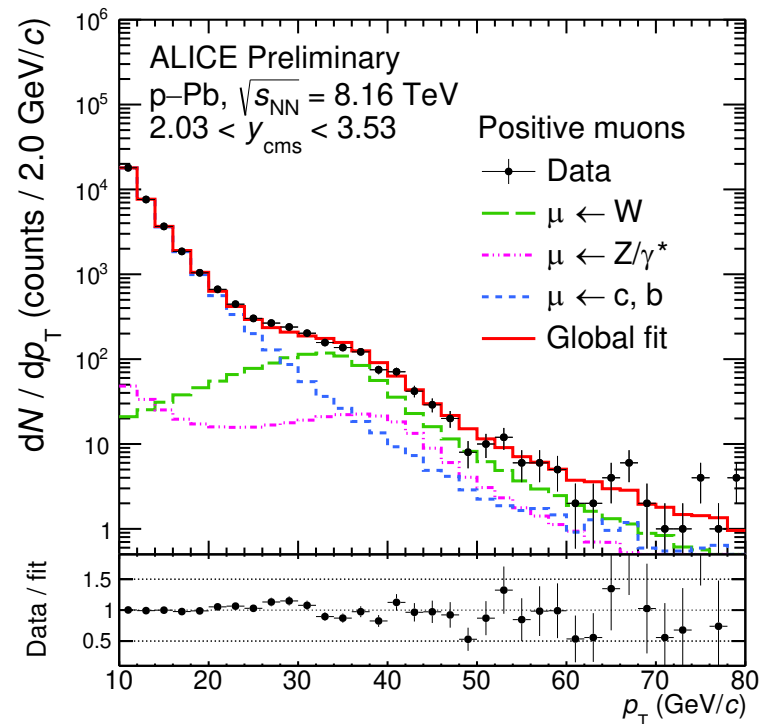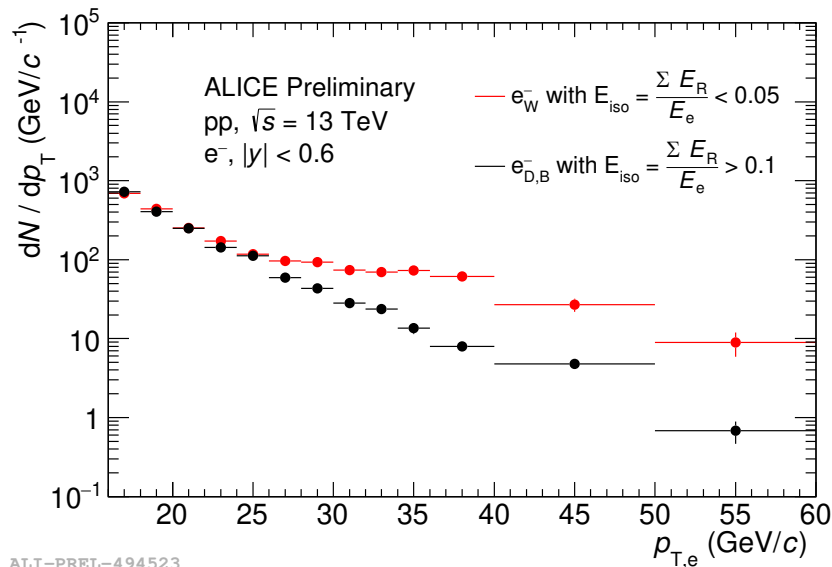K. Eskola, P. Paakkinen, H. Paukkuuen, C. Salgado

ALICE detector

V0
Centrality estimator

EMCal
Electron identification

SPD
primary vertex reconstruction
Charge particle multiplicity estimator

ZDC
centrality estimator

$e^{\pm} \leftarrow W^{\pm}$ (pp)
- TPC (dE/dx)
- EMCal (Energy)
  $|y| < 0.6$

TPC
Main tracking detector
Particles identification via dE/dx

Muon spectrometer
$-4 < \eta < -2.5$

- $\mu^{\pm} \leftarrow W^{\pm}$ (p-Pb, Pb-Pb)
- $Z \rightarrow \mu^{\pm}$ (p-Pb, Pb-Pb)
  - Muon spectrometer

  - p-Pb, p-going

    P $\longrightarrow$ $\longleftarrow$ Pb

    $2.03 < y_{cms} < 3.53$

  - p-Pb, Pb-going

    Pb $\longrightarrow$ $\longleftarrow$ P

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

  - Pb-Pb

    $2.5 < y_{cms} < 4$

W/Z yields extraction in ALICE

ALICE Preliminary
pp, $\sqrt{s}$ = 13 TeV
e^-, $|y|$ < 0.6

e^-_W with $E_{iso} = \frac{\Sigma E_R}{E_e} < 0.05$

$e^-_{D,B}$ with $E_{iso} = \frac{\Sigma E_R}{E_e} > 0.1$

ALI-PREL-494523

ALICE Preliminary
p–Pb, $\sqrt{s_{NN}}$ = 8.16 TeV
$2.03 < y_{cms} < 3.53$

Positive muons
- Data
- $\mu \leftarrow$ W
- $\mu \leftarrow Z/\gamma^*$
- $\mu \leftarrow$ c, b
- Global fit

ALI-PREL-516963

ALICE, 0–90% Pb–Pb, $\sqrt{s_{NN}}$ = 5.02 TeV
p_T^μ > 20 GeV/c
$2.5 < y_{cms}^{\mu\mu} < 4$

- Data, opposite charge
- Data, same charge
- POWHEG

ALI-PUB-347334

- $e^\pm \leftarrow W^\pm$ (|y| < 0.6); Based on isolation cuts on energy; $E_{iso} = \frac{\Sigma E_{R<0.3}}{E_e} < 0.05$
  - $e^\pm \leftarrow c, b$ 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
- $Z \to \mu^\pm$ (-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

New results for QM

▸ **pp collisions**

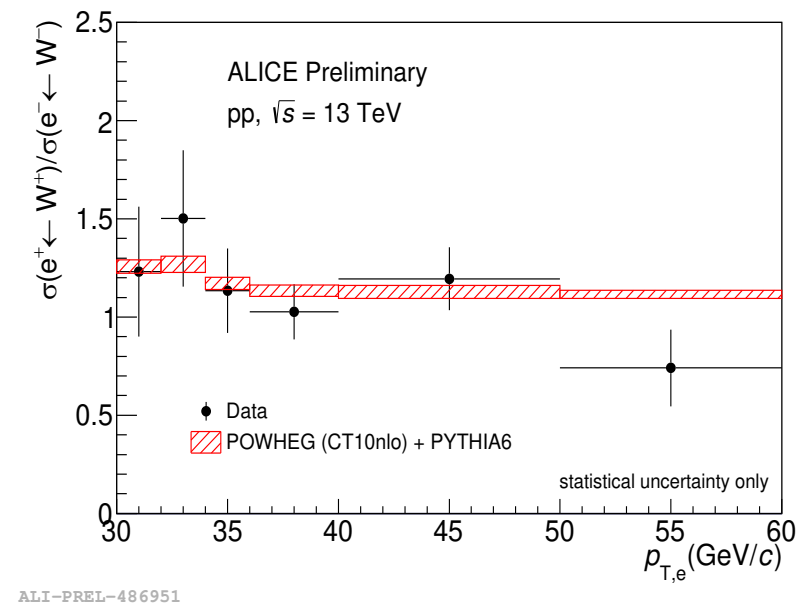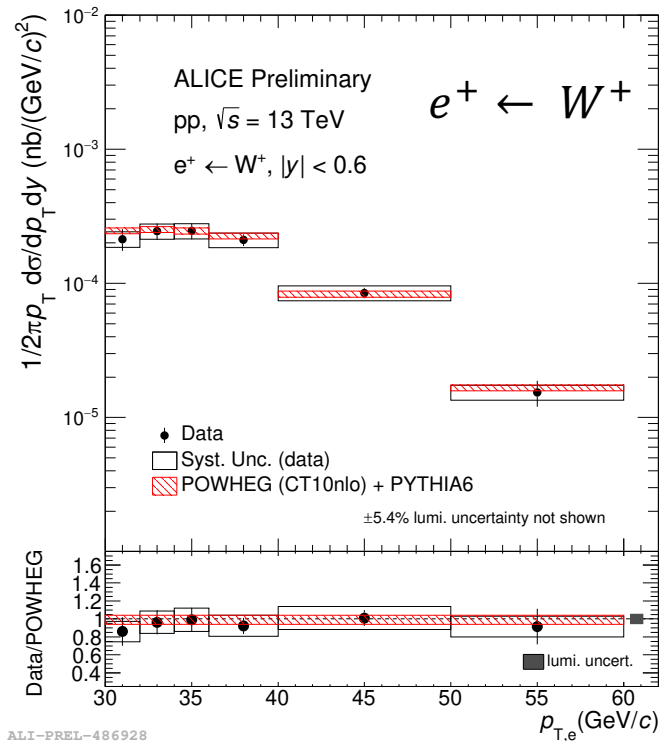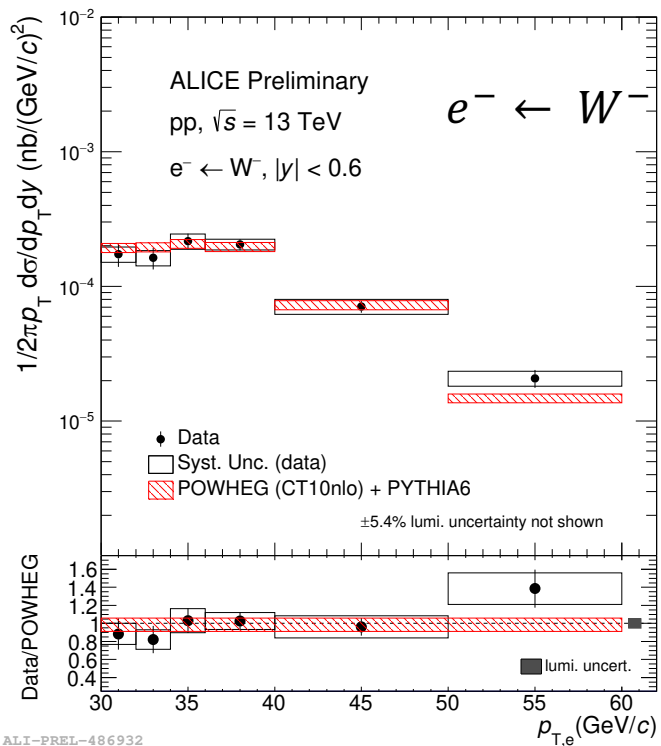　▸ Multiplicity dependence of W boson production in pp collisions

▸ **pPb collisions**

　▸ Cross section for $\mu^{\pm} \leftarrow W^{\pm}$ vs. rapidity in pPb

　▸ Charge asymmetry for $\mu^{\pm} \leftarrow W^{\pm}$ vs. rapidity in pPb

▸ **Pb-Pb collisions**

　▸ Cross section for $\mu^{\pm} \leftarrow W^{\pm}$ in Pb-Pb

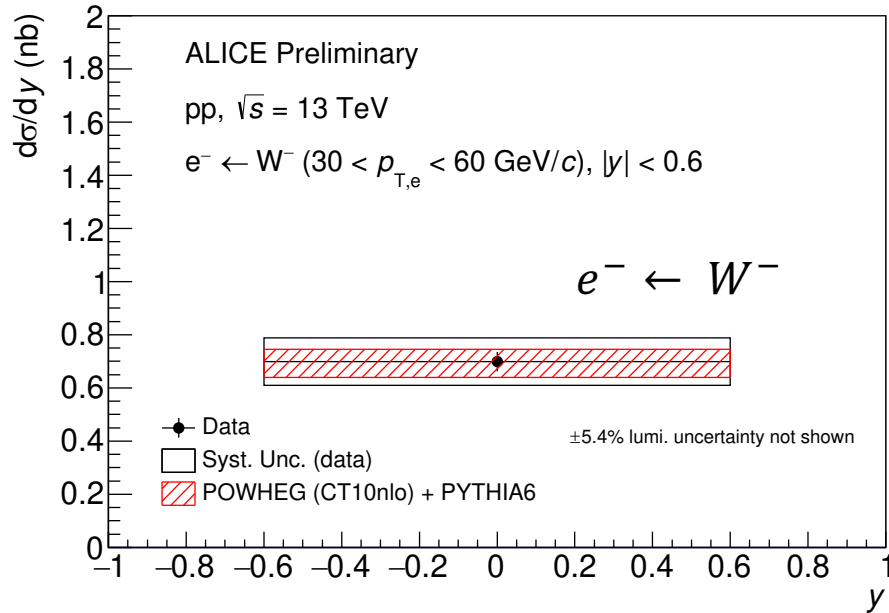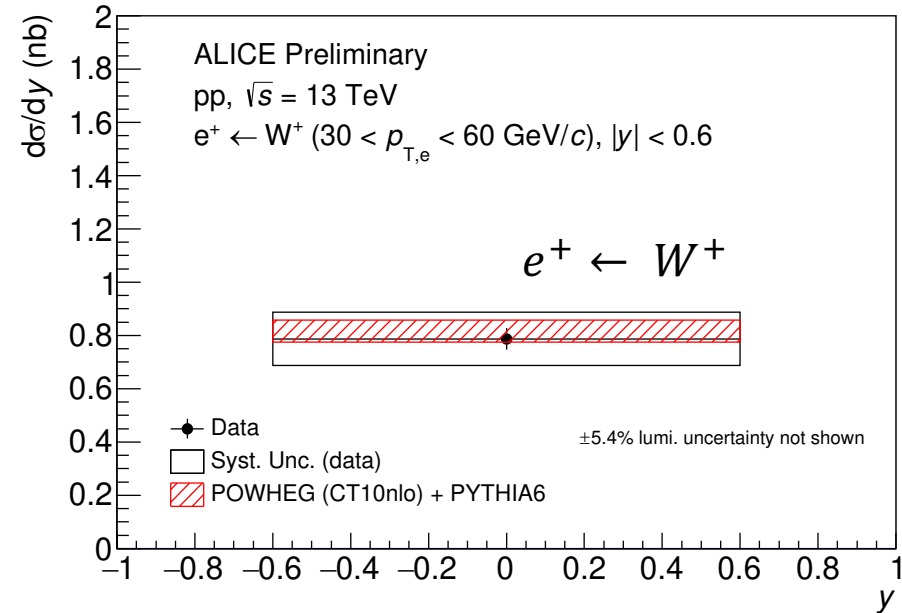　▸ Centrality dependence for $\mu^{\pm} \leftarrow W^{\pm}$ production

- p_T differential cross sections for $e^{\pm} \leftarrow W^{\pm}$ in $|y| < 0.6$, and ratio for $e^+ \leftarrow W^+$ and $e^- \leftarrow W^-$ as a function of p_T
- Compared to a model including pQCD NLO (POWHEG) + CT10nlo
  - Measurements and model are consistent within the uncertainties
  - Larger cross section for $e^+ \leftarrow W^+$ in data as expected from isospin effects

CT10nlo
H. L. Lai et. al.,
PRD 82 (2010), 074024
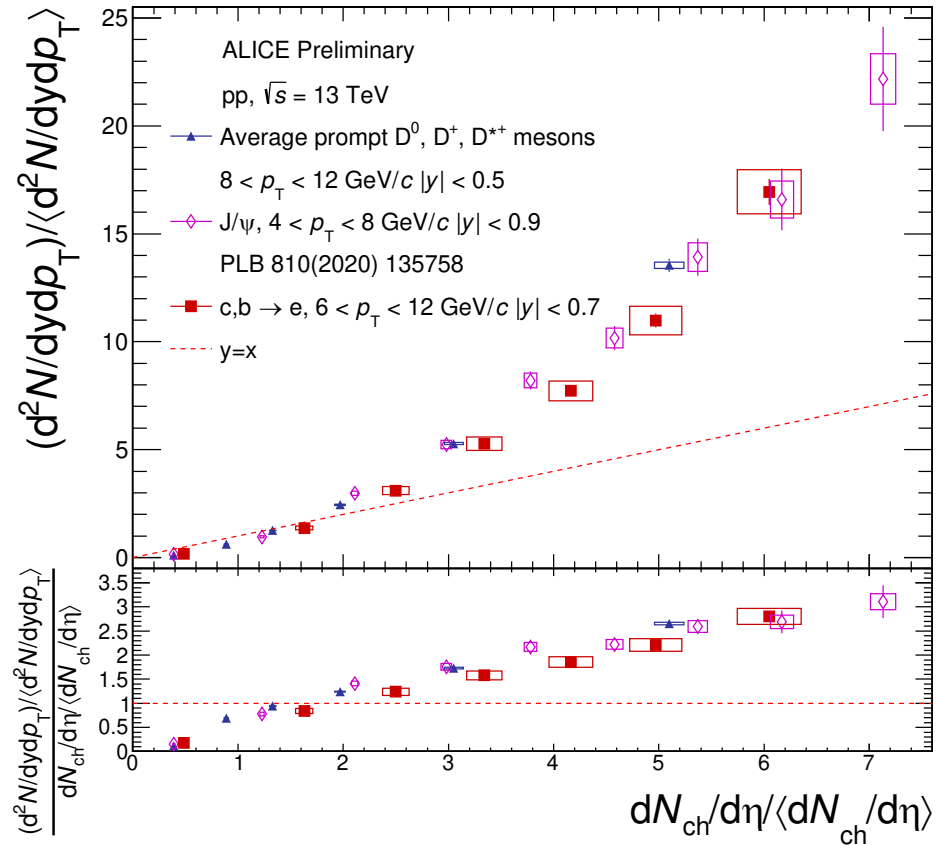
W$^\pm$ in pp collisions at 13 TeV (2)

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
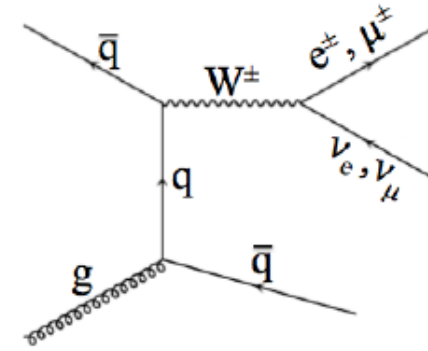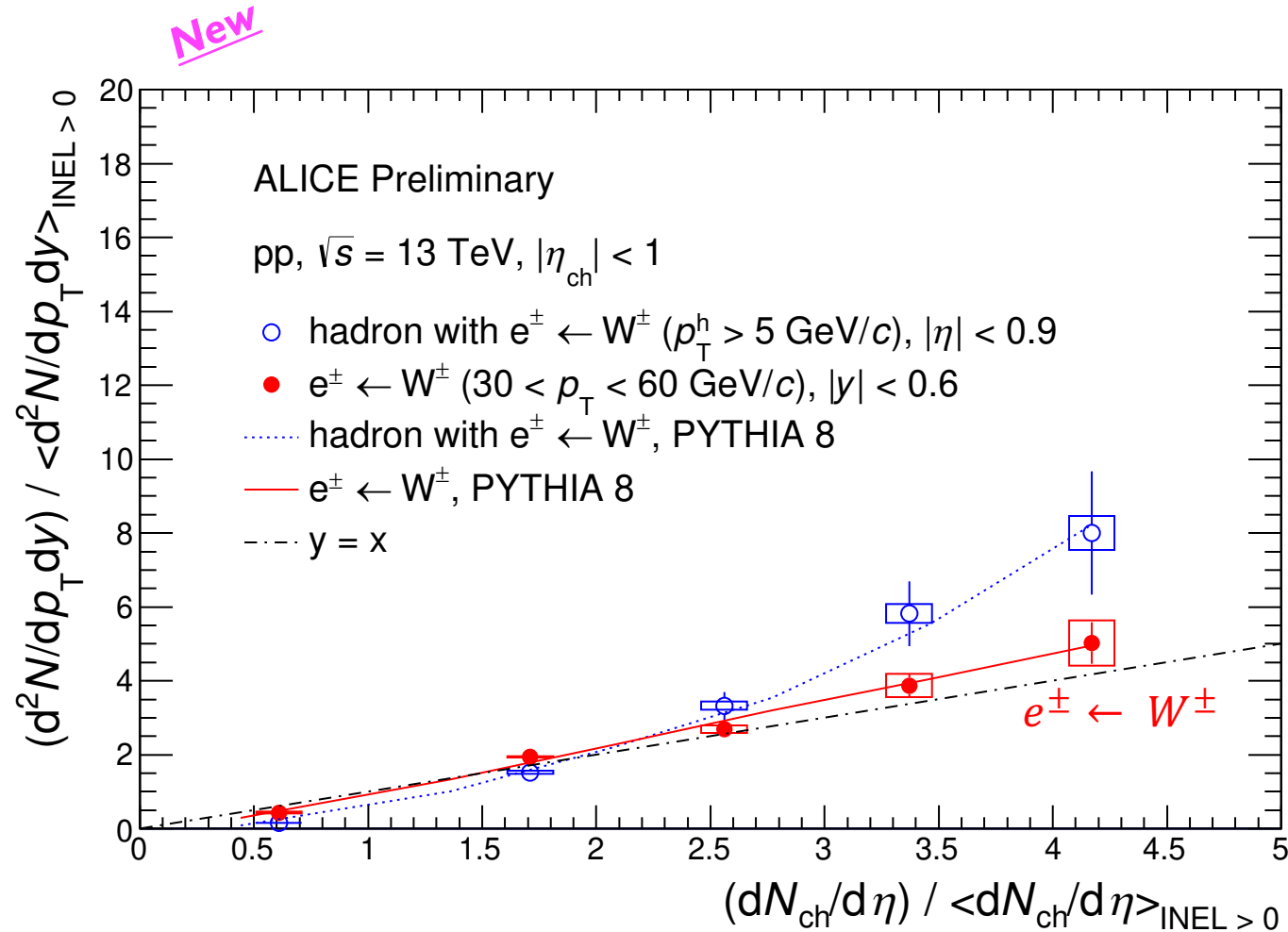 - Consistent with data within uncertainties

Multiplicity dependence of W production (1)

ALI-PREL-488924

- 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

Luigi Dello Stritto, talk on 7 Apr at 4 pm Parallel Session T14: Hadron prod. and col. dyn. I
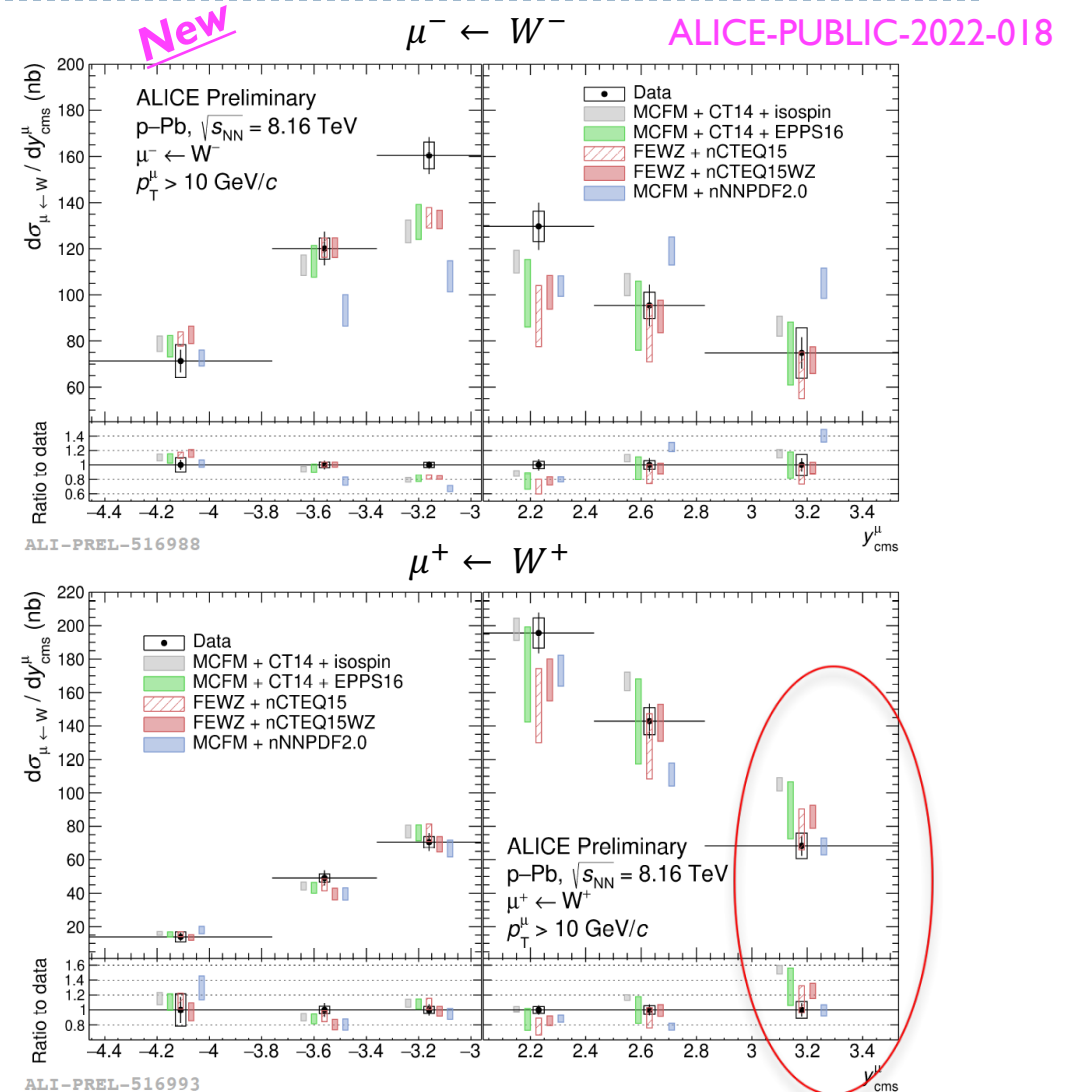
Multiplicity dependence of W production (2)

New

ALICE Preliminary

pp, $\sqrt{s}$ = 13 TeV, $|\eta_{ch}| < 1$

○ hadron with $e^{\pm} \leftarrow W^{\pm}$ ($p_T^h > 5$ GeV/c), $|\eta| < 0.9$

● $e^{\pm} \leftarrow W^{\pm}$ ($30 < p_T < 60$ GeV/c), $|y| < 0.6$

⋯⋯ hadron with $e^{\pm} \leftarrow W^{\pm}$, PYTHIA 8

— $e^{\pm} \leftarrow W^{\pm}$, PYTHIA 8

—·— y = x

$e^{\pm} \leftarrow W^{\pm}$

y-axis: $(d^2N/dp_T dy) / <d^2N/dp_T dy>_{INEL > 0}$

x-axis: $(dN_{ch}/d\eta) / <dN_{ch}/d\eta>_{INEL > 0}$

ALI-PREL-505996

■ **W-boson production is linear w.r.t. multiplicity**
  - ■ No strong autocorrelation* between W production and charged-particle multiplicity
- ■ Associated hadron production (W+ q -> h) is faster than linear w.r.t. multiplicity
  - ■ W boson is less correlated with multiplicity than associate hadron
- ■ Both multiplicity dependence is consistent with PYTHIA 8 with MPI + CR

*S. G. Weber, A. Dubla. A. Andronic, and A. Morsch
EPJC (2019) 79:36
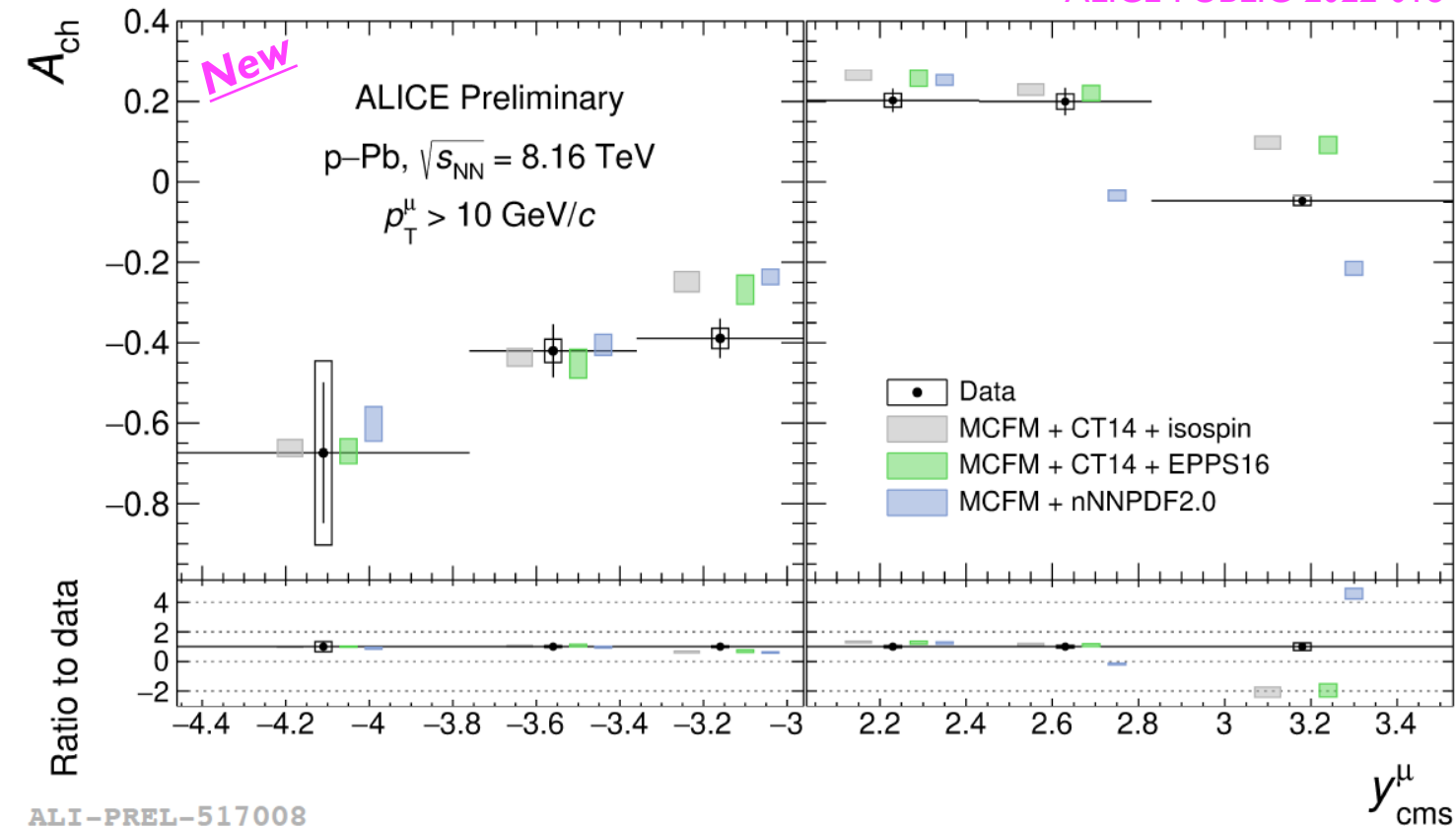
W$^{\pm}$ in p-Pb at 8.16 TeV (1)

■ W production cross section measured as a function of rapidity

■ Model calculations
- ■ Based on pQCD predictions
- ■ including isospin effect with/without nPDF

■ Within experimental and theoretical uncertainties,
pQCD + isospin with/without nPDF are consistent
with the measured cross section

- ■ 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
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

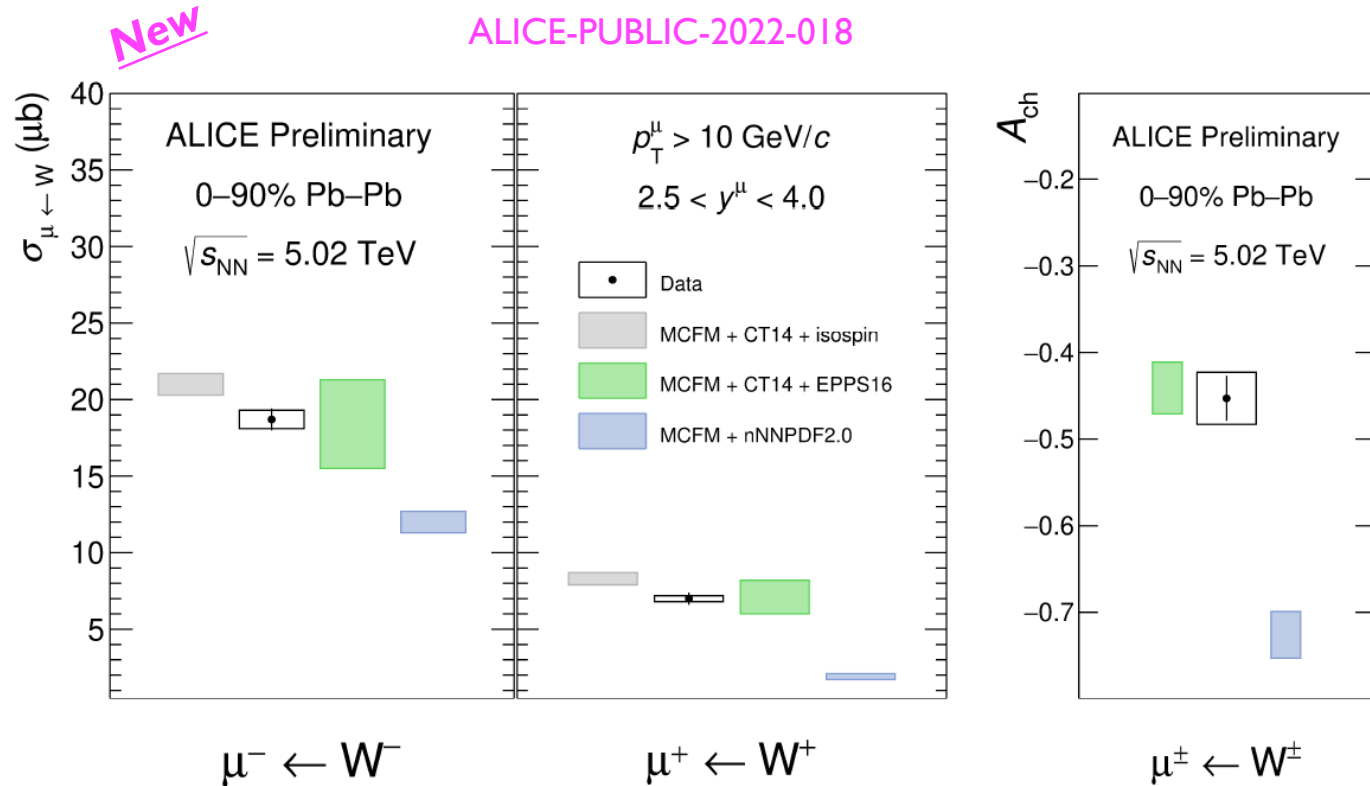# W$^{\pm}$ in p-Pb at 8.16 TeV (2)

ALICE-PUBLIC-2022-018

ALI-PREL-517008

- Charge asymmetry
  - A sensitive probe of the u and d nPDF
  - $-4.46 < y_{cms} < -2.96$; $d\bar{u} \to W^-$ dominant
  - $2.03 < y_{cms} < 3.53$; $u\bar{d} \to W^+$ dominant

- **Significant deviation between data and models at large forward rapidity region**

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

- $A_{ch} < 0$; W^- dominant
- $A_{ch} > 0$; W^+ dominant

W$^\pm$ in Pb-Pb at 5.02 TeV (1)

New

ALICE-PUBLIC-2022-018
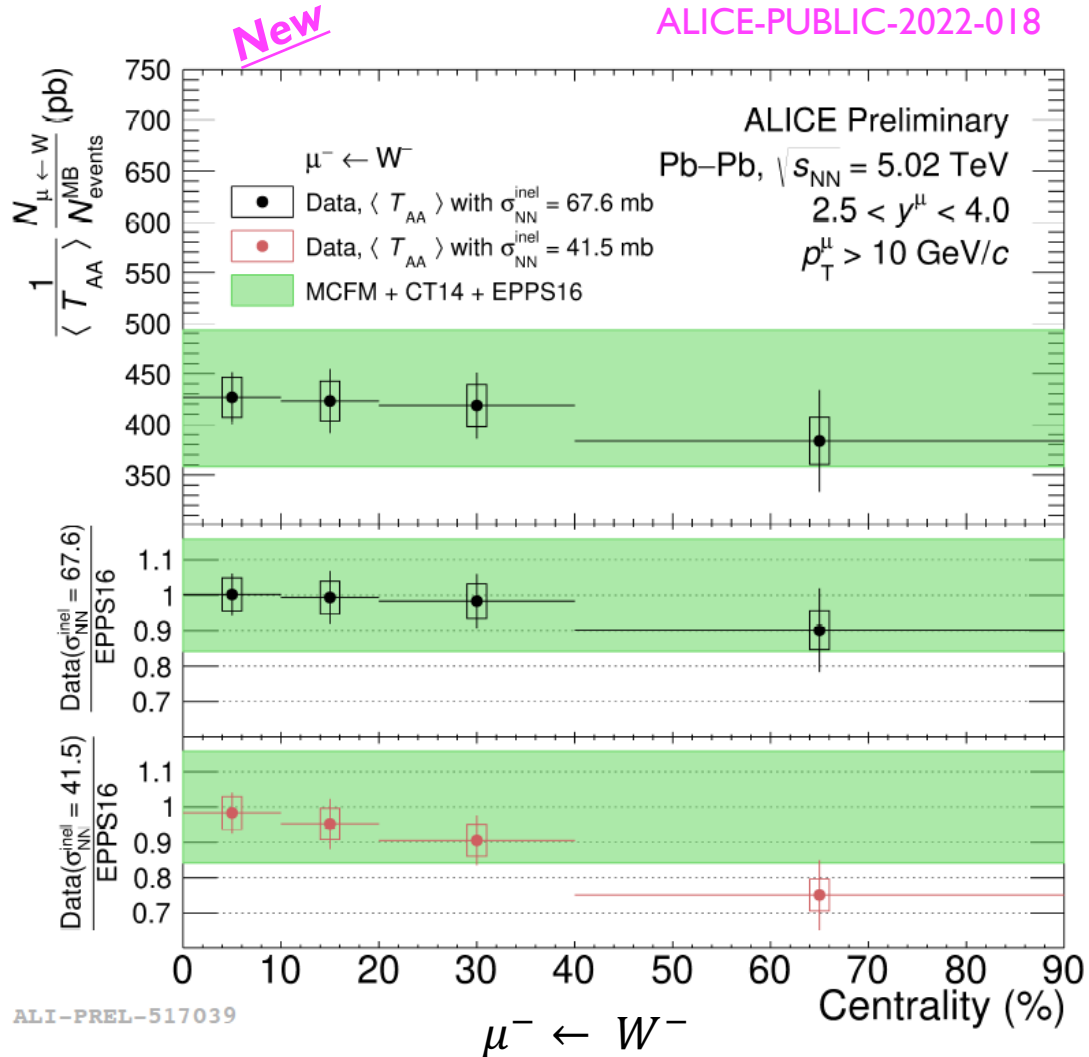

ALI-PREL-517034

- 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

- Model with CT14 for free nucleon (MCFU+CT14)
  - Overestimate the cross sections
  - Suggest a significant effect of modification of the PDFs

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

ALICE-PUBLIC-2022-018

New

ALI-PREL-517039

- **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 $<T_{AA}>$
    - $\sigma_{NN}^{inel} = 67.6 \pm 0.6$ mb
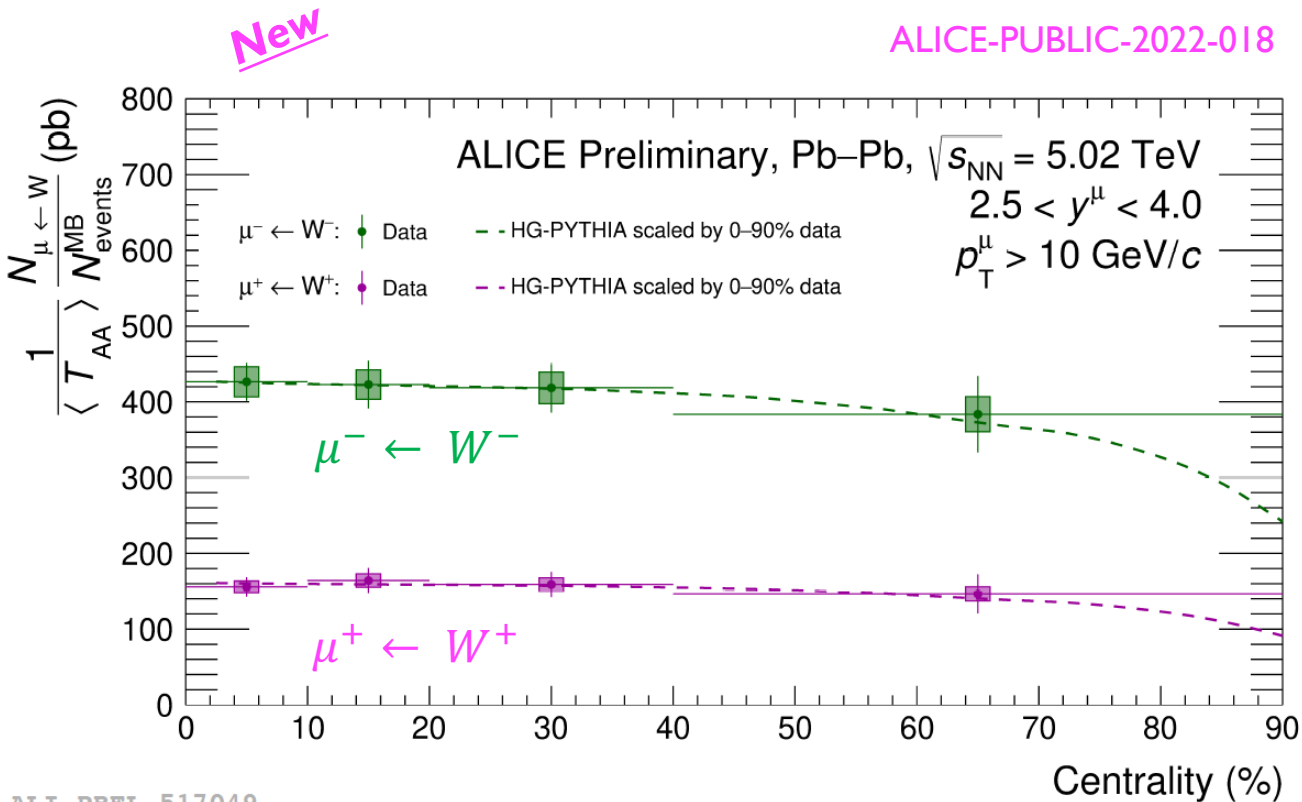 - Expected from a hard process

- **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))
  - $\sigma_{NN}^{inel} = 41.5_{-12.0}^{+16.2}$ mb

- **$<T_{AA}>$ re-evaluated, yields worse agreement between ALICE data and EPPS16**

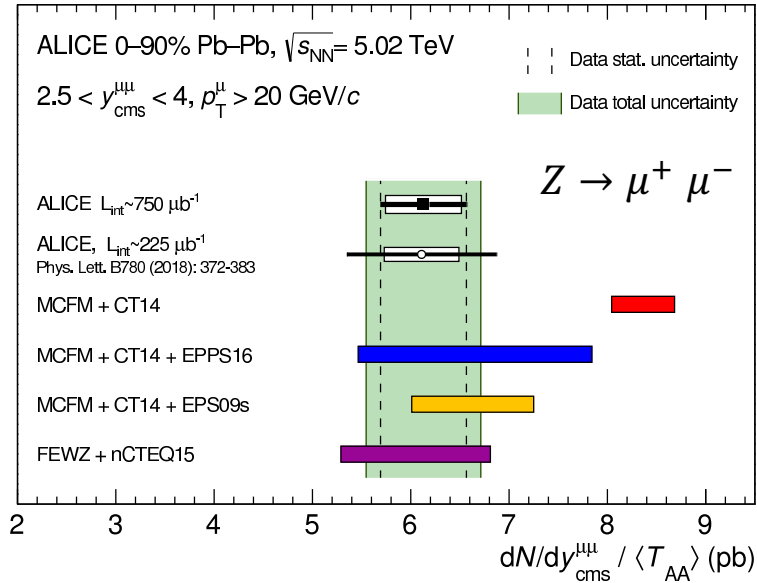# W$^\pm$ in Pb-Pb at 5.02 TeV (3)

ALI-PREL-517049

- Production of hard probes in peripheral collisions
  - Significantly affected by event selection and geometry biases
  - These bias cause a suppression in peripheral collisions

- Comparison with HG-PYTHIA
  - Including biases from event selection and geometry
  - Good agreement with data, but not allow to conclude the suppression due to limited statistics

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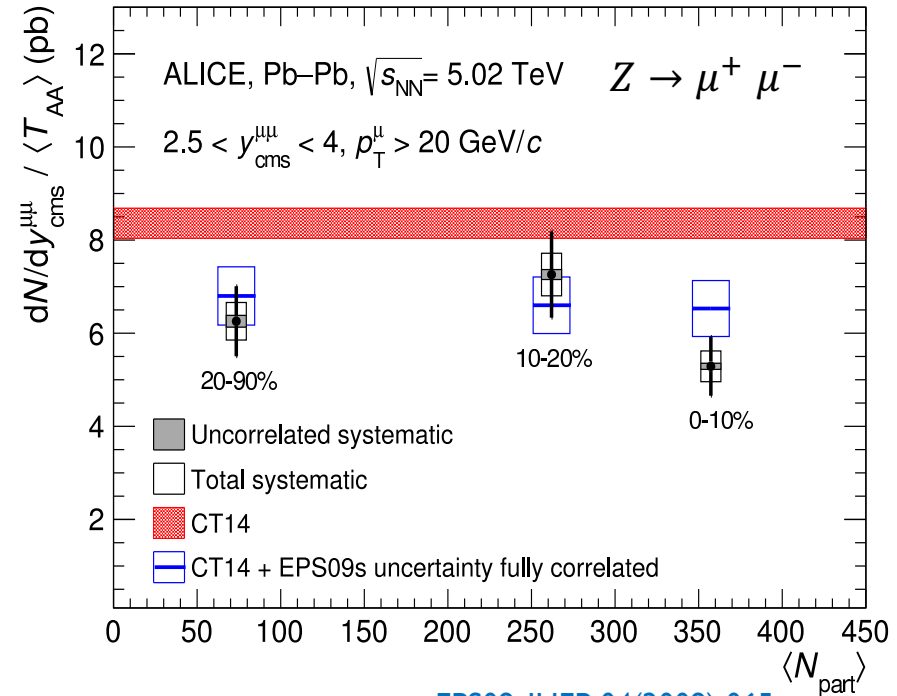C. Loizides and A. Morsch, PLB 773 (2017) 408-411

JHEP09(2020)076

ALI-PUB-347344

ALI-PUB-347359

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

- ■ Z Model with free PDF --- 3.4 σ deviation w.r.t. measured Z cross section
- ■ Models with nPDF --- well reproduced measured Z cross section
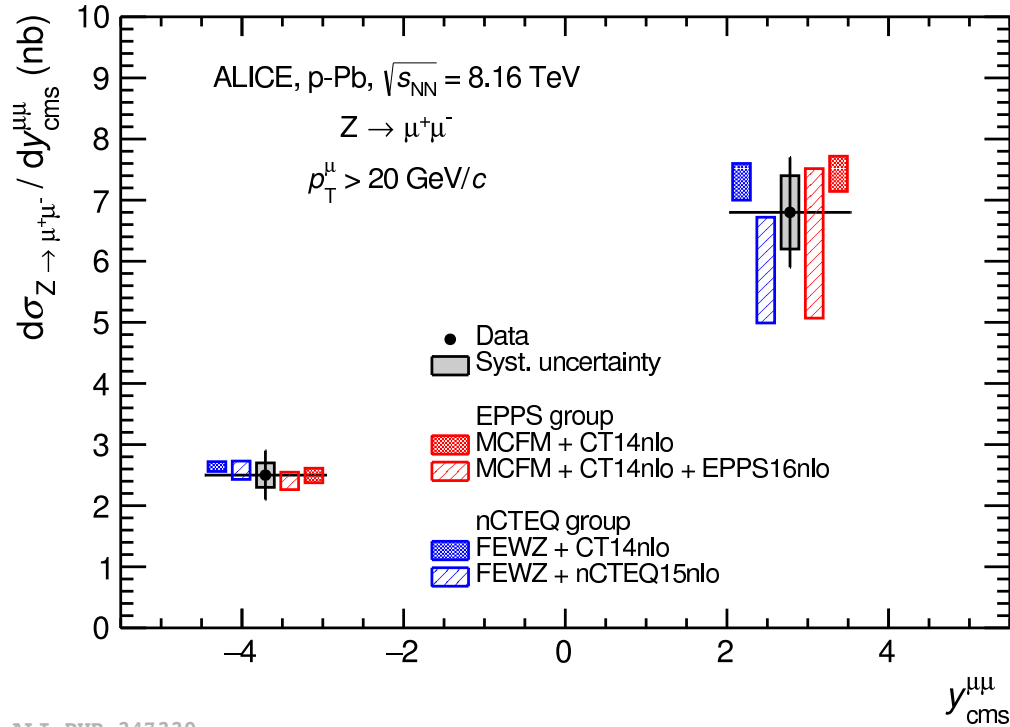- ■ **Strong evidence of modification of Z production in Pb-Pb collisions**

Summary

- **W production in pp collisions**
  - Consistent with POWHEG (NLO) + CT10nlo
  - Multiplicity dependence is linear, suggesting no autocorrelation and jet bias effect
    - PYTHIA included MPI + CR reproduced the dependence

- **W production in p-Pb**
  - Models + isospin with nPDF agree with the data
  - 3.5σ deviation from free-PDF calculation for W+ at forward rapidity for the bin at largest rapidity

- **W/Z production in Pb-Pb**
  - Model with CT14 PDF for free nucleons overestimate the production for W
    - Suggest nuclear modification of the PDF
  - Scaled by average nuclear overlap function $<T_{AA}>$
    - Trend with centrality disfavour explanations with reduced σ_{NN}

Back up

Z production in p-Pb @ 8.16 TeV

JHEP09(2020)076

ALICE, p-Pb, $\sqrt{s_{NN}}$ = 8.16 TeV

$Z \to \mu^+\mu^-$

p_T^μ > 20 GeV/c

- Data
- Syst. uncertainty

EPPS group
- MCFM + CT14nlo
- MCFM + CT14nlo + EPPS16nlo

nCTEQ group
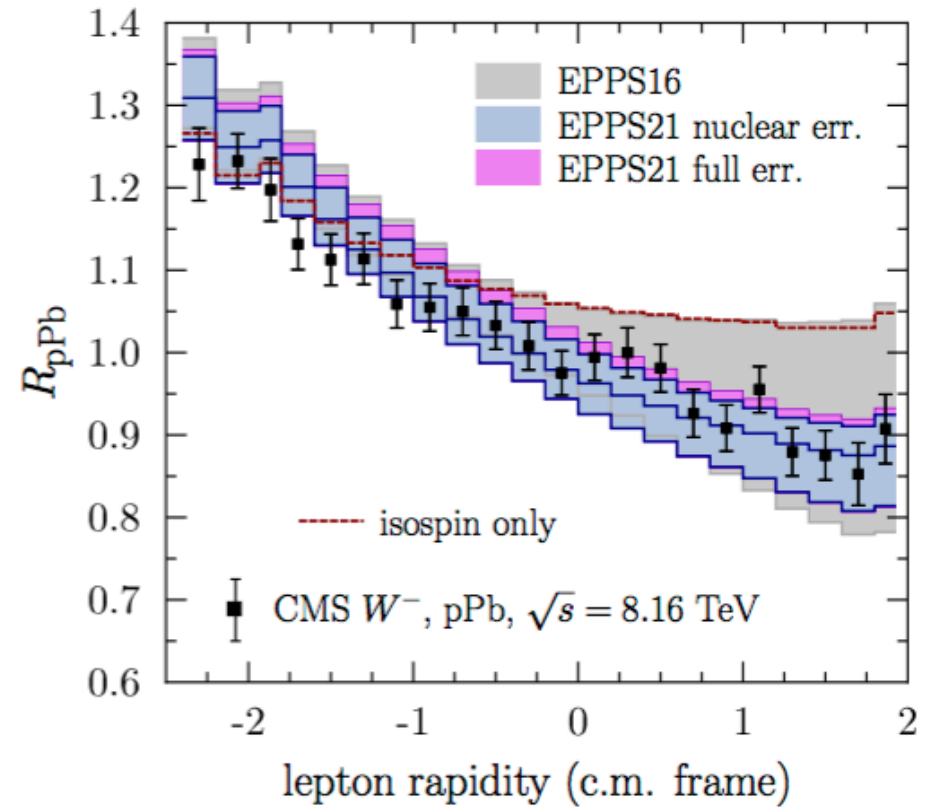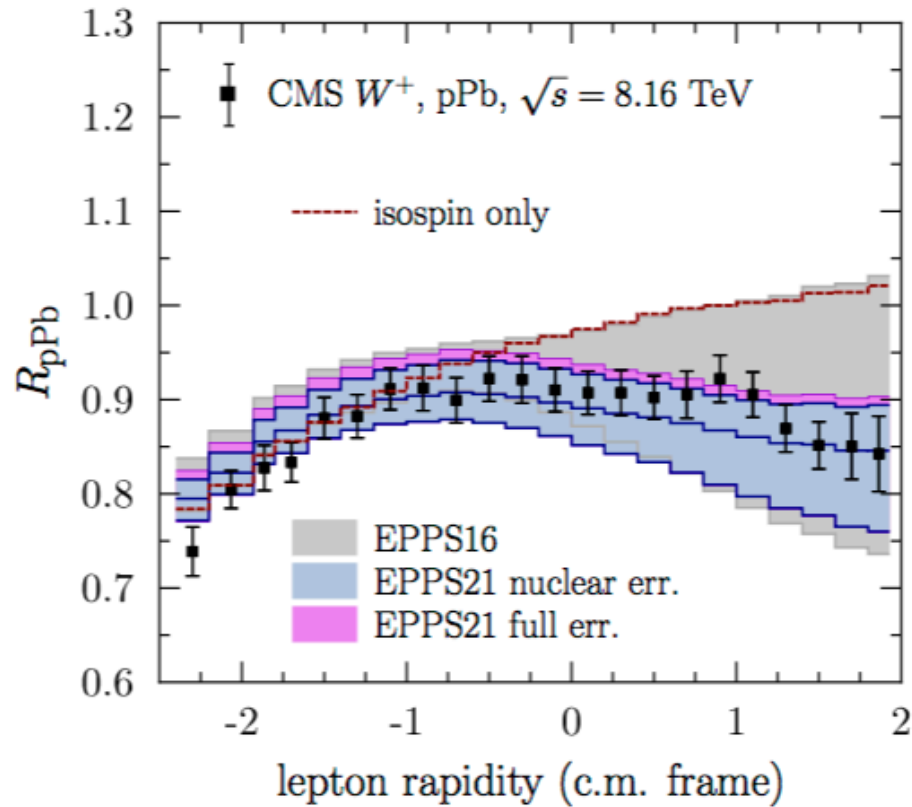- FEWZ + CT14nlo
- FEWZ + nCTEQ15nlo

ALI-PUB-347339

■ Different Z production cross section measured at forward and backward rapidity

■ Model calculations
   ■ Based on pQCD
   ■ including isospin effects
   ■ With/without nPDF

■ Within experimental and theoretical uncertainties, pQCD+isospin with/without nPDF are consistent with the measured cross section

EPPS16 vs. EPPS21

Kari J. Eskola, Petja Paakkinen, Hannu Paukkunen, Carlos A. Salgado
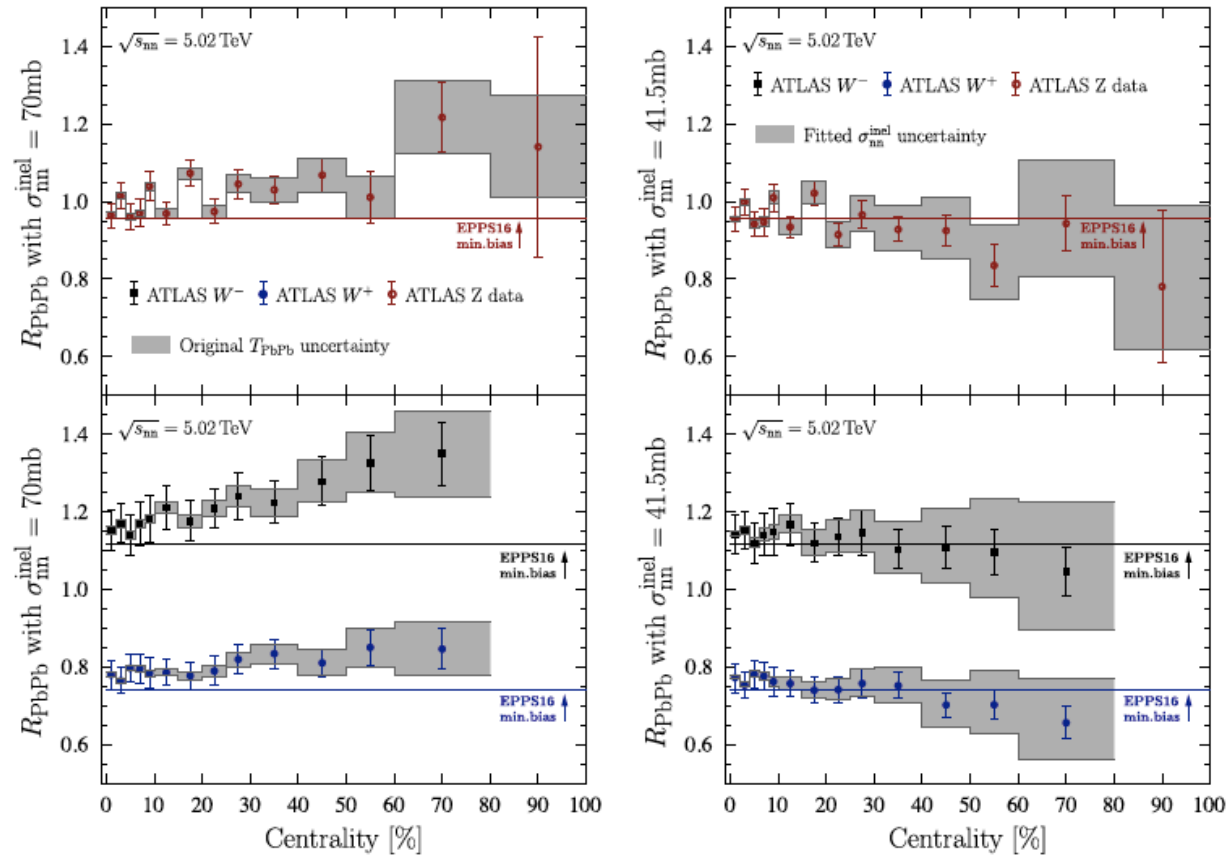ArXiv: 2112.12462

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 $\sigma_{nn}^{inel} = 70.0$ mb (left) and with the nuclear-suppressed value $\sigma_{nn}^{inel} = 41.5$ mb (right).

W/Z R_{AA} in CMS and ATLAS

PRL 127, 102002 (2021)

PLB 202 (2020) 135262