Constraints on the initial state from heavy gauge boson and photon production in ALICE

Initial Stages, 10-15 Jan 2021

Sizar Aziz for the ALICE collaboration

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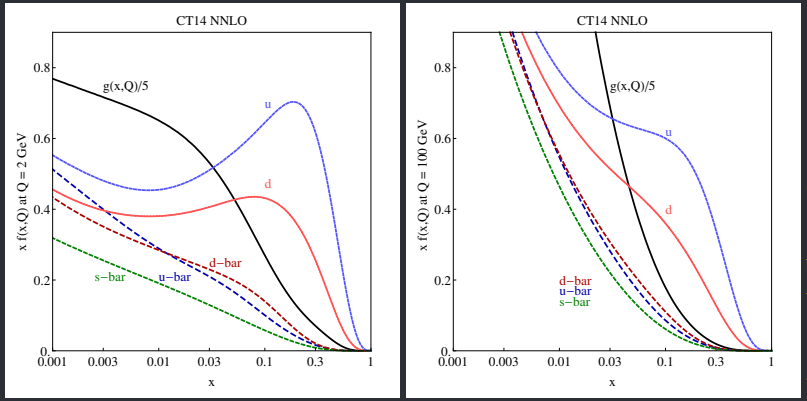
Introduction

- QCD hard scatterings involve partonic cross sections
- Sensitive to parton distribution functions PDFs $\rightarrow f_q(x, Q^2)$
- Nuclear environment modifies proton PDFs $\longrightarrow$ need for nuclear PDFs (nPDFs)



Phys.Rev.D 93 (2016) 3, 033006

Free proton PDFs at Q^2 = 2 (left) and 100 (right) GeV^2

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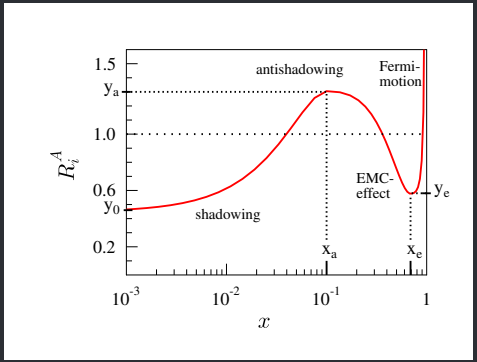

JHEP 04 (2009) 065

Ratio of proton-in-nucleus PDF to free proton PDF

Introduction

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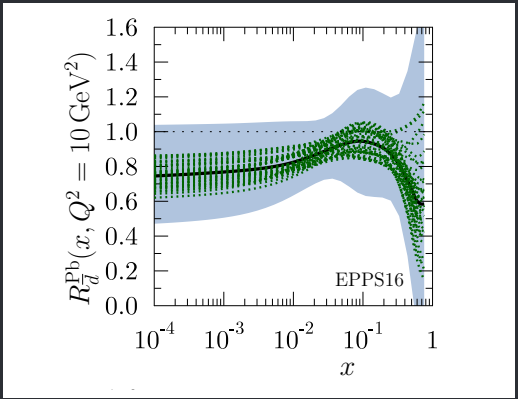
- Sensitive to parton distribution functions PDFs → $f_q(x, Q^2)$
- Nuclear environment modifies proton PDFs ⟶ need for nuclear PDFs (nPDFs)



Eur.Phys.J.C 77 (2017) 3, 163

(n)PDF shape and uncertainty depend on q, x and Q^2!

Introduction

Electroweak (EW) bosons

- Produced in early stages of collision
  - Cross sections calculated with perturbative QCD (NLO precision)
- Carry no color charge
  - In leptonic decay channels insensitive to QCD medium
- Sensitive to (nuclear) parton distribution functions
  - W and Z created in $q\bar{q}$ annihilation
  - **Prompt** photons created in quark-gluon Compton Scattering $qg \rightarrow \gamma q$ and $q\bar{q} \rightarrow \gamma g$ annihilation

(n)PDFs obtained from global fits to data

$\rightarrow$ measurements of EW boson production can help constrain them

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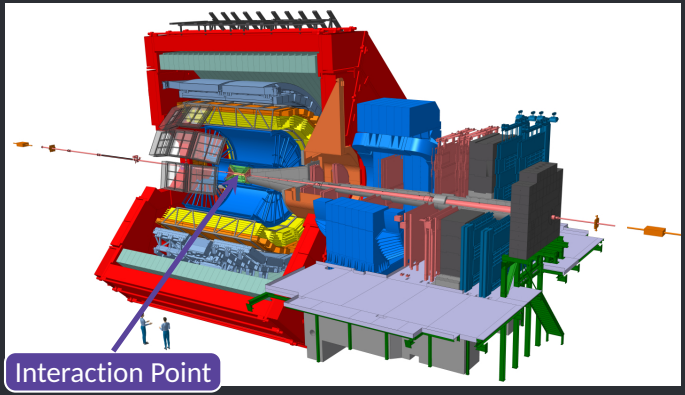
ALICE Detector



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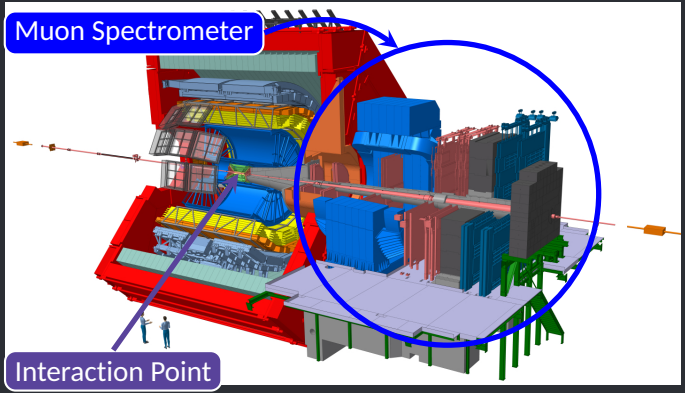
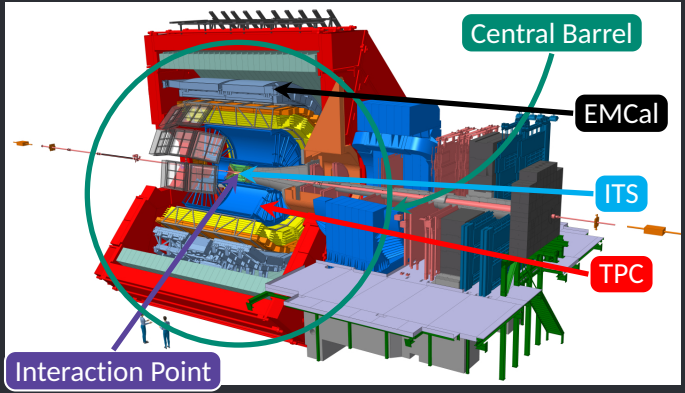


- Muon Spectrometer
  - Used for Z and W analyses
  - Identifies and reconstructs μ tracks, $-4 < \eta_\mu < -2.5$
  - Forward rapidity ⟶ both low and high Bjorken-x

ALICE Detector

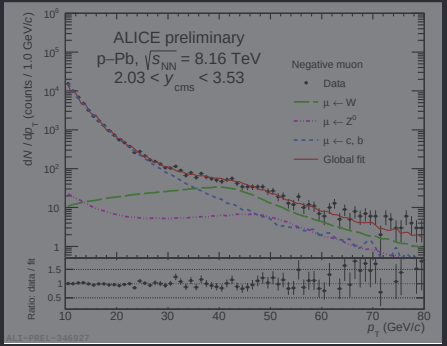


- Central Barrel
  - Used for isolated photon analysis
  - EMCal → photons, $|\eta| < 0.7$, $80° < \varphi < 187°$
  - ITS and TPC → charged particles, $|\eta| < 0.9$, full φ

Analysis method

W bosons

- Measured through $W \longrightarrow \mu\nu$ decay
- No possibility to reconstruct neutrino through missing transverse energy / momentum with ALICE detector
- W decay muon yield obtained through fits of p_{T} distributions using MC template functions
  - Corrected for detector acceptance and reconstruction efficiency ϵ



Fiducial region of measurement

- $-4 < \eta_{\mu} < -2.5$
- $p_{\mathrm{T}}^{\mu} > 10$ GeV/c

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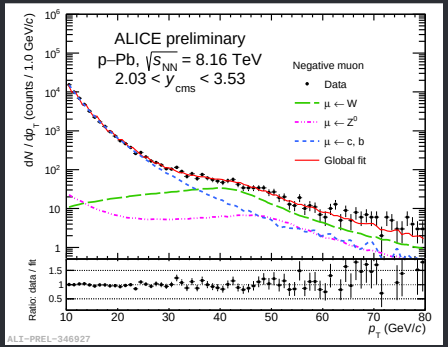

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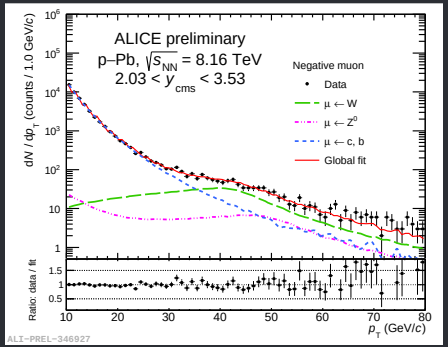

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- Measured through $Z \longrightarrow \mu\mu$ decay
- Invariant mass distribution of dimuons computed
- Raw yield obtained by histogram entry counts within 60-120 GeV/c^2
  - Up to 1% background in this interval
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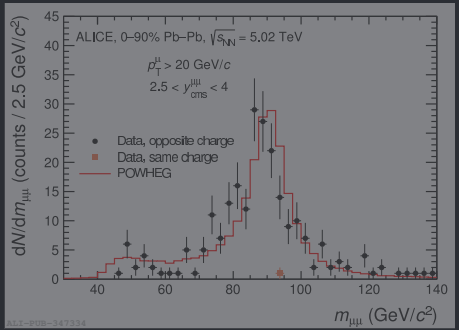

JHEP 09 (2020) 076

Fiducial region of measurement

- $-4 < \eta_{\mu} < -2.5$
- $p_{\mathrm{T}}^{\mu} > 20\ \mathrm{GeV}/c$
- $60 < m_{\mu\mu} < 120\ \mathrm{GeV}/c^2$
- $2.5 < y_{\mu\mu} < 4$

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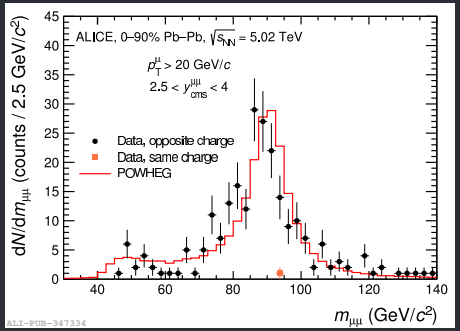

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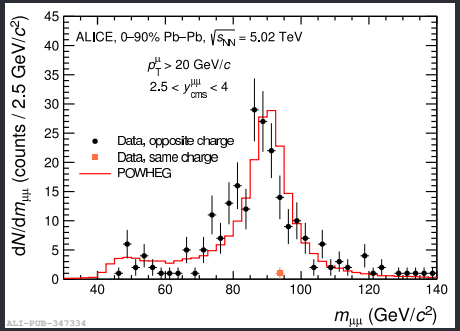

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Analysis method

Isolated photons

- Signal: isolated prompt photons
- Background: photons from neutral meson decays and fragmentation photons
- 3 step procedure to obtain signal

Analysis method

Isolated photons

- 1. Isolation selection
  - Define cone R around photon, with $R = \sqrt{(\Delta\eta)^2 + (\Delta\varphi)^2}$
  - $p_{\mathrm{T}}^{\mathrm{iso}} = \sum_{R<0.4} p_{\mathrm{T}}$ of neutral and charged particles
  - Isolation criterium: $p_{\mathrm{T}}^{\mathrm{iso}} < 2\ \mathrm{GeV}/c$
  - Removes photons from neutral meson decays as well as from jets (bremsstrahlung or fragmentation)
- 2. Cluster shower shape selection
- 3. Purity estimation

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Analysis method

Isolated photons

- 1. Isolation selection
- 2. Cluster shower shape selection
  - Geometrical variable σ^2_{long} computed
  - Isolated photons deposit most energy in a single cluster → circular cluster shape → low σ^2_{long}
  - In decays or jets, cluster can overlap with other decay photon or jet fragment cluster → elliptical cluster shape → high σ^2_{long}
  - Shower shape criterium: only photons with low σ^2_{long}
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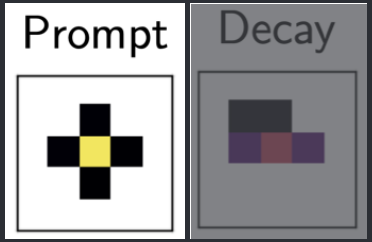

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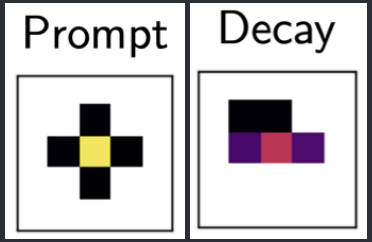

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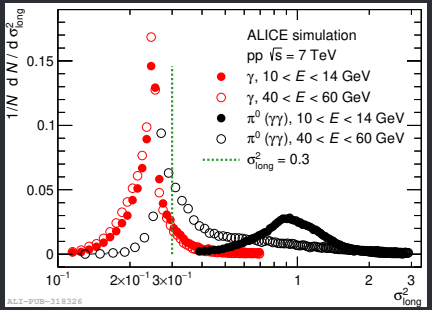

Eur.Phys.J.C 79 (2019) 11, 896

Analysis method

Isolated photons

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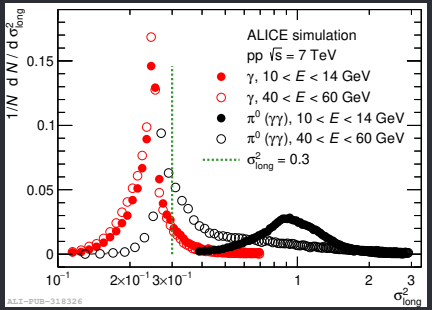
  - Photon decays from high-p_{T} mesons also have low σ^2_{long} !
  - Purity estimation done with ABCD method (backup)
    - » Used in ALICE (Eur.Phys.J.C 79 (2019) 11, 896) and ATLAS (Phys.Rev.D 89 (2014) 5, 052004) measurements



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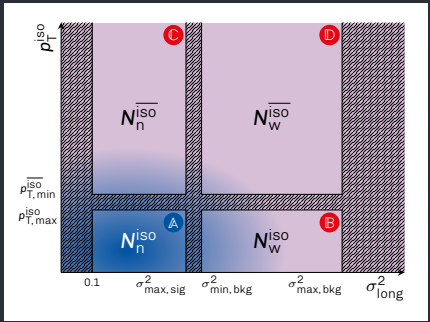

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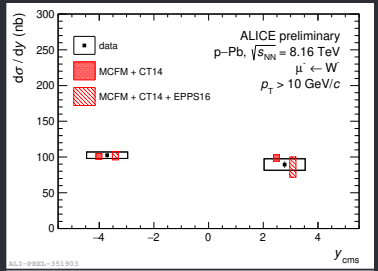
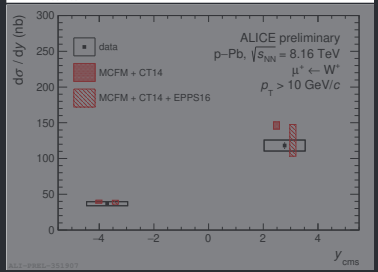
Results (preliminary)

W bosons in p–Pb at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$

- W^- cross section shows agreement with free-nucleon PDFs and nPDFs, at forward and backward rapidity
  - MFCM: Eur.Phys.J.C 77 (2017) + CT14 Phys.Rev.D 93 (2016)
  - EPPS16: Eur.Phys.J.C 77 (2017)

- W^+ cross section deviates from free-nucleon PDF prediction by 2.7σ at forward rapidity





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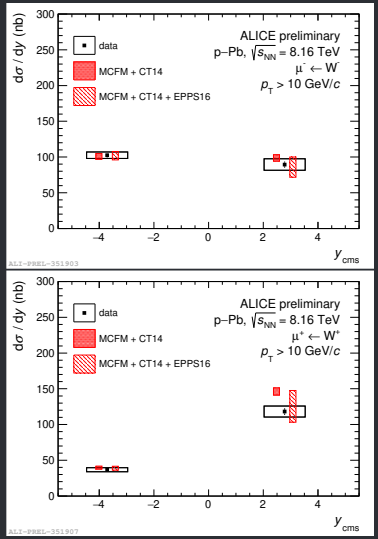

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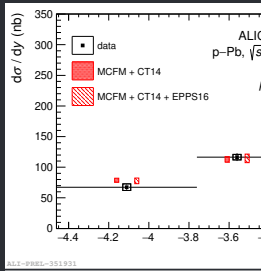
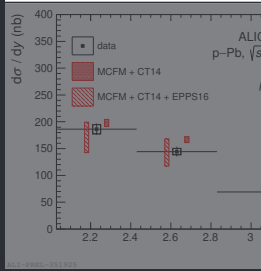
- W^+ forward *y*-**differential** cross section deviates from free-nucleon PDF prediction by 3.7σ in most forward bin





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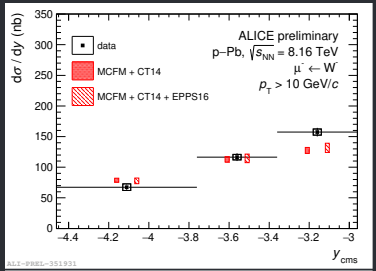
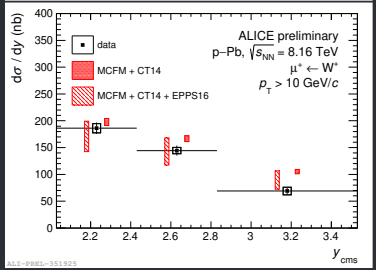
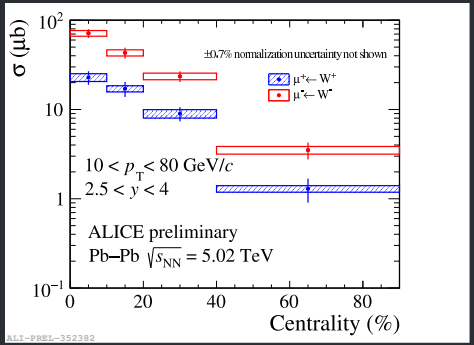
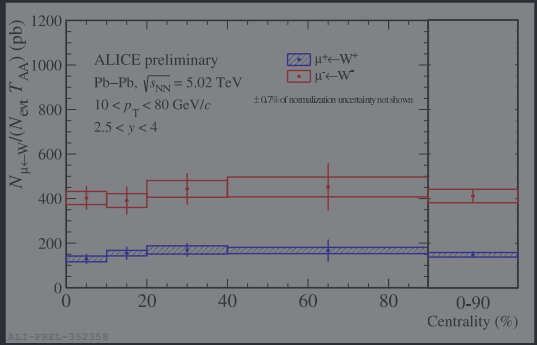




Results (preliminary)

W bosons in Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$





- Cross sections decrease towards peripheral events
  - Higher W^- yield reflects neutron down quark content
- Yield normalized by nuclear thickness function T_{AA} consistent with flat behaviour
  - Expected from NN collision scaling
- Preliminary results, obtained from ~30% of the $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ Pb–Pb data set

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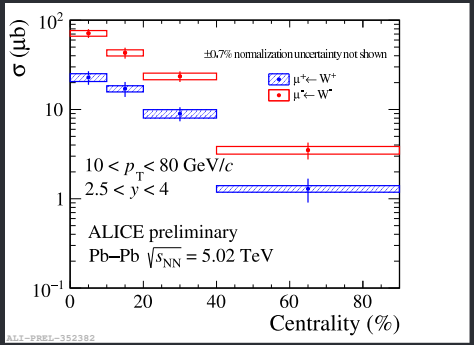

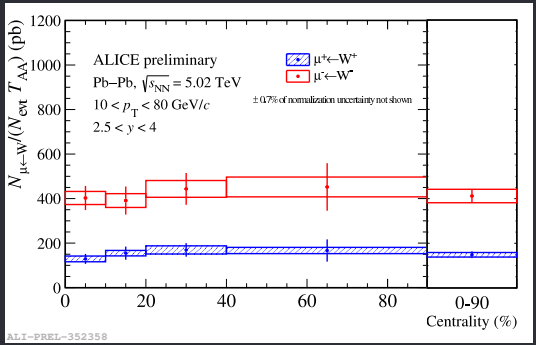

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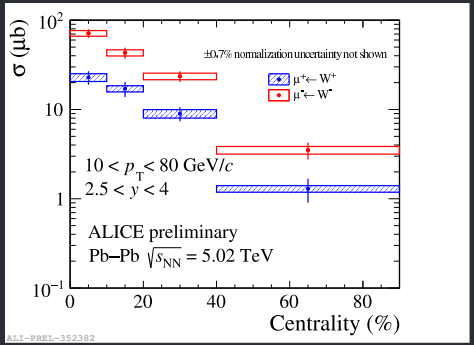

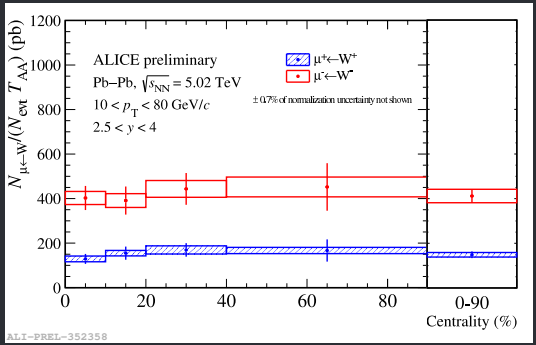

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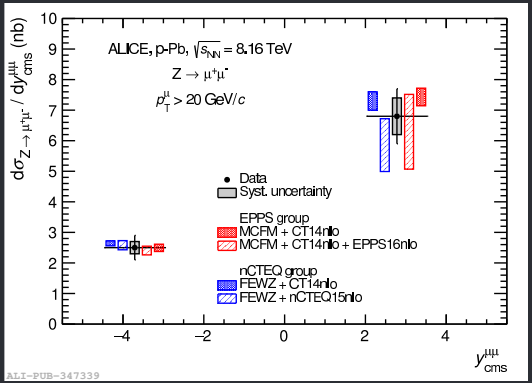


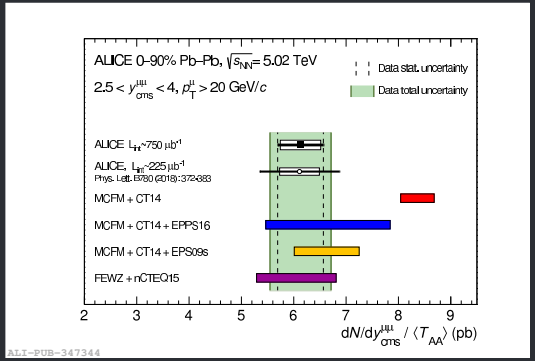
JHEP 09 (2020) 076

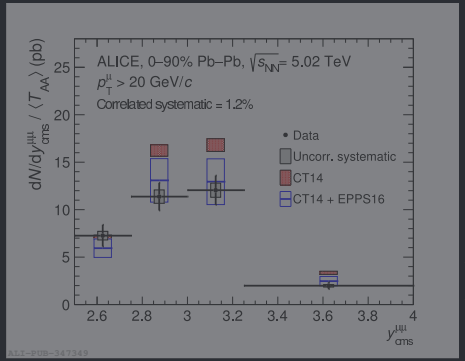
- Both free-nucleon PDFs and nPDFs agree with data
  - No strong conclusions due to experimental uncertainties and similarity of predictions
  - nPDFs: CT14 + EPPS16 and FEWZ (CPC 182(2011)) + nCTEQ15 (Phys.Rev.D93, 085037 (2016))

Results

Z bosons in Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$

- Integrated invariant yield (left) deviates from free PDF by 3.4σ, agrees with several nPDF predictions
  - Lower yield due to convolution of shadowing at low x and EMC-effect at high x





JHEP 09 (2020) 076
EPS09s: JHEP 07(2012)073

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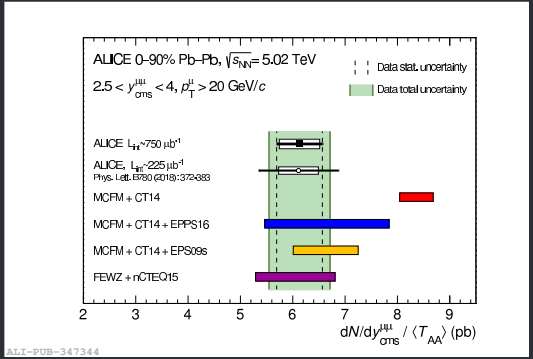

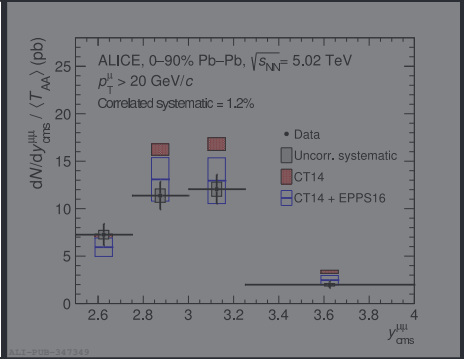

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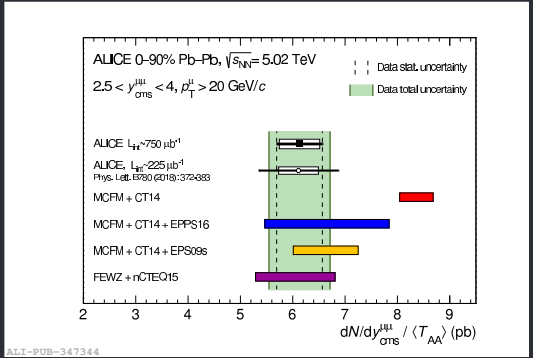

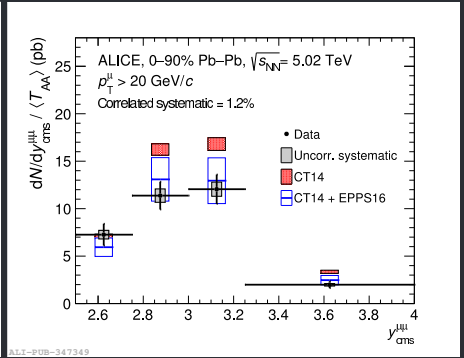

JHEP 09 (2020) 076
EPS09s: JHEP 07(2012)073

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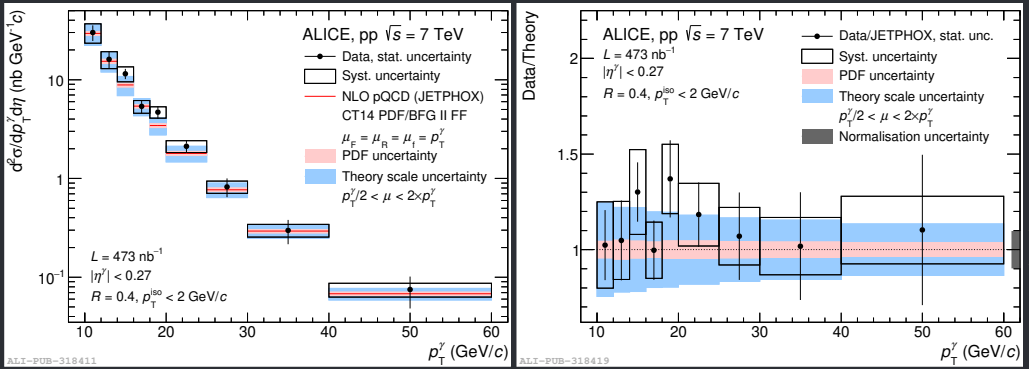
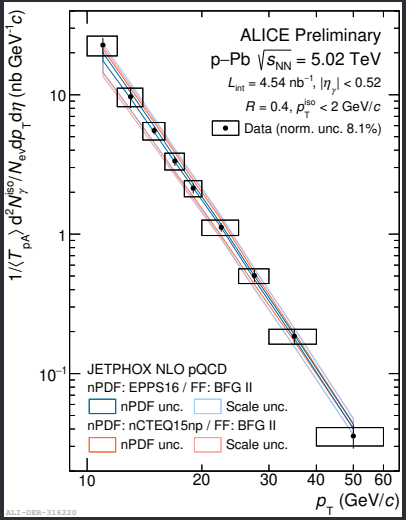
Isolated photons in pp at $\sqrt{s} = 7\,\mathrm{TeV}$

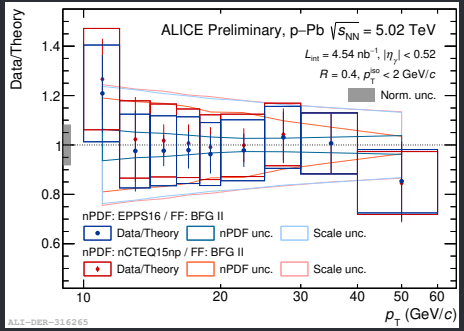


- Cross section versus p_{T} shows good agreement with JETPHOX (NLO pQCD) calculations (Phys.Rev. D73 (2006))
  - CT14 PDF set, BFG II for fragmentation (Eur.Phys.J.C 2 (1998))

Results (preliminary)

Isolated photons in p–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$





- Agreement between several JETPHOX calculations and data
  - Both EPPS16 as well as NCTEQ15np nPDFs describe data
  - BFG II used as fragmentation function

Conclusion

- W boson production cross section measured at forward rapidity in p–Pb at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ and Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$
  - Production described by nPDFs and in Pb–Pb binary scaling is observed
  - 2.7σ deviation from free PDF for W^+ in p–Pb
- Z production measured at forward rapidity in p–Pb at $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$ and Pb–Pb at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ (JHEP 09 (2020) 076)
  - p–Pb cross section described by free-nucleon PDF and nPDF
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- **Data can serve as constraints for future nPDF fits**

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Backup

W boson fitting template

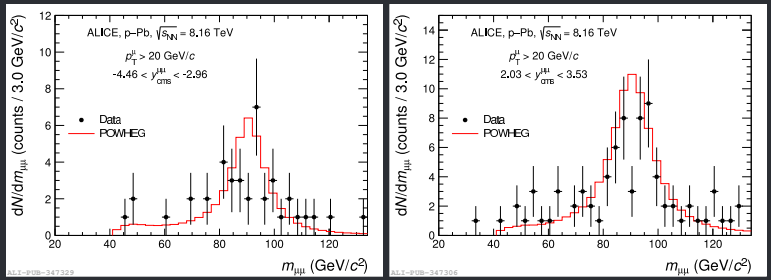
$$f(p_{\mathrm{T}}) = N_{\mu\leftarrow\mathrm{bkg}} \cdot f_{\mu\leftarrow\mathrm{bkg}}(p_{\mathrm{T}}) + N_{\mu\leftarrow W}(f_{\mu\leftarrow W} + R \cdot f_{\mu\leftarrow Z})$$

- Heavy flavor background from c and b decays
  - Generated using FONLL (JHEP 10(2012)137) calculations
- Signal from W and Z
  - Generated using POWHEG (HEP 07(2008)060) with EPS09 (JHEP 04(2009)065) nPDF
- $f_X(p_{\mathrm{T}})$ obtained from MC templates
- Free fit parameters $N_{\mu\leftarrow\mathrm{bkg}}$ and $N_{\mu\leftarrow W}$
  - No free $N_{\mu\leftarrow Z}$!
  - Instead, fixed to ratio R of cross section of Z/W

Isospin weighting

- In p–Pb collisions, quantity x (efficiency or yield)
  - $x_{\mathrm{p-Pb}} = \frac{Z}{A} x_{\mathrm{pp}} + \frac{A-Z}{A} x_{\mathrm{pn}}$
- in Pb–Pb collisions
  - $x_{\mathrm{Pb-Pb}} = \frac{Z^2}{A^2} x_{\mathrm{pp}} + \frac{(A-Z)^2}{A^2} x_{\mathrm{nn}} + \frac{Z(A-Z)}{A^2} (x_{\mathrm{pn}} + x_{\mathrm{np}})$

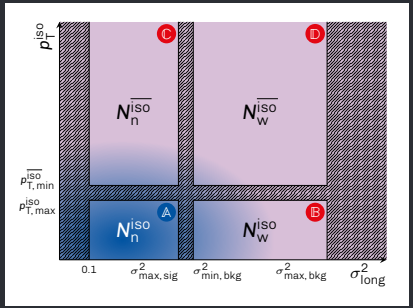
Z boson signal extraction in p–Pb



JHEP 09 (2020) 076

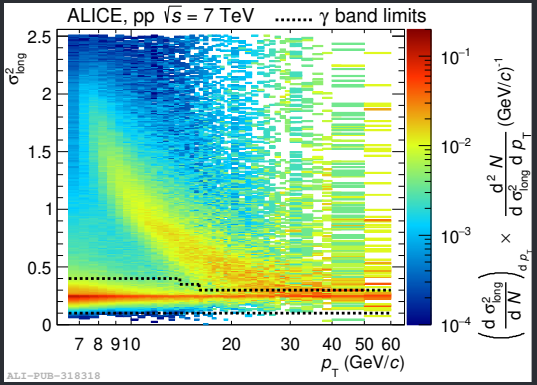
- Invariant mass distribution in Pb-going (left) and p-going (right) collisions

ABCD method for purity estimation



- Estimation based on 2 assumptions
  - 1. Ratio of non-isolated / isolated background same in narrow and wide σ^2_{long}, B / D = A / C
  - 2. No signal in B, C and D regions
- Assumptions are evaluated and corrected via MC simulations
  - Correlation between shower shape and isolation criteria taken into account

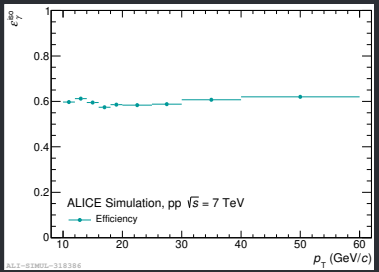
Shower shape distribution

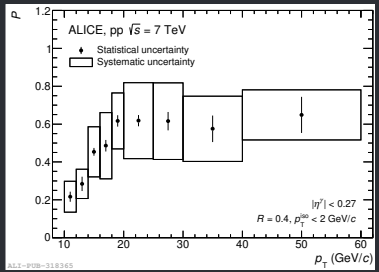


- Single dashed lines indicate shower shape selection region
- Most single photons reconstructed with $\sigma^2_{\mathrm{long}} \approx 0.25$

Isolated photon efficiency and purity versus p_{T}

pp at $\sqrt{s} = 7\,\mathrm{TeV}$



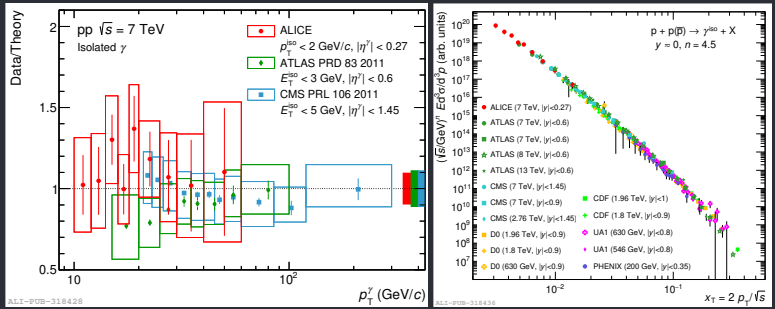


Eur.Phys.J.C 79 (2019) 11, 896

- Left: Isolated photon efficiency versus p_{T}
- Right: Isolated photon purity versus p_{T}

Comparison plots isolated photons

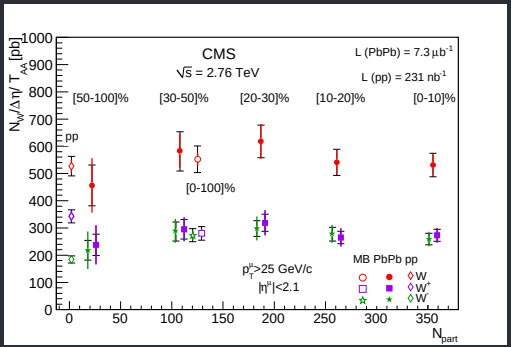
pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$



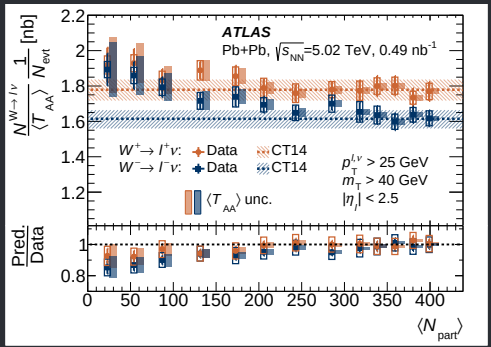
- Left: Comparison of data/theory for various LHC experiments
- Right: Cross section comparison as a function of $\sqrt{s}$

W boson production in other LHC experiments

- (left) Results from CMS in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76\,\mathrm{TeV}$
  - Consistent with expectation from binary scaling
- (right) Results from ATLAS in Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$
  - Slight tension in central events



Phys.Lett.B 715 (2012) 66-87



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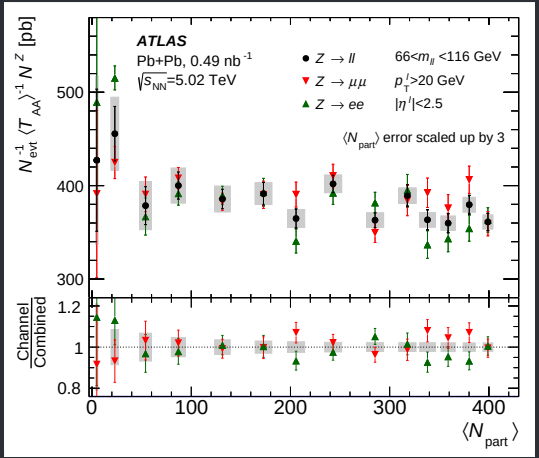
Z boson production in other LHC experiments



- No tension for Z boson production in ATLAS
  - Contrary to W boson production at same energy!