Production of W bosons in p-Pb collisions measured with ALICE at the LHC

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Outline

- Physics motivation
- W-boson measurements in p-Pb collisions with ALICE
- ALICE detector setup
- Data sample
- Analysis method
- Cross-section results
- Yields of $\mu^{\pm} \leftarrow W^{\pm}$ scaled to $\langle N_{\mathrm{coll}} \rangle$
- Summary

Physics Motivation

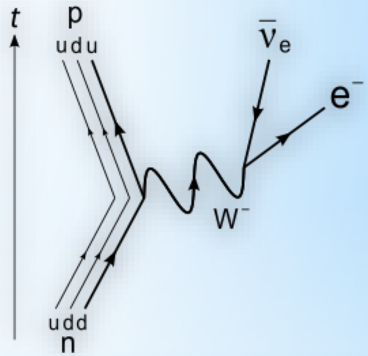
Electroweak W boson: Mass: 80.385 ± 0.015 GeV/c^2 and life time ≈ 0.1 fm/c

(J. Beringer et al.(Particle Data Group), PR D86 , 010001 (2012))

- Discovered at CERN SPS in 1983

  1984 Nobel Prize in Physics: Rubbia and van der Meer

- Produced in initial hard processes before formation of QGP
  - Dominant process LO approximation: $\mathbf{q} + \overline{\mathbf{q}}' \rightarrow \mathbf{W}^{\pm}$
  - Colorless probes → not affected by the strong interaction
  - Sensitive to (valence) quark and (sea) antiquark content of the nucleus



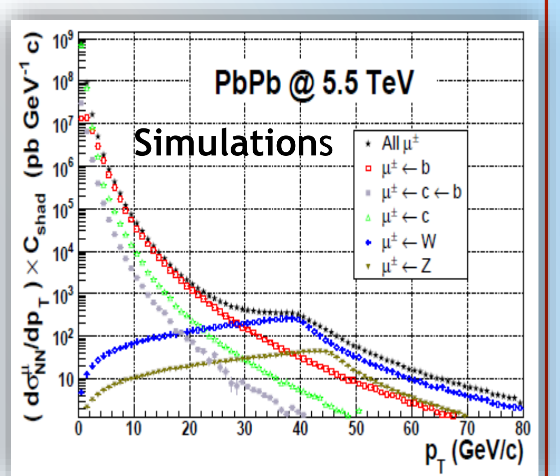
- W-boson production in p-Pb collisions
  - Investigate cold nuclear matter effects and constrain nuclear PDFs JHEP 1103 (2011) 071
  - Measurements serve as an important baseline for the understanding and the interpretation of the Pb-Pb data

W-boson measurements in p-Pb collisions

- Measurement in the semi-muonic decay channel → no modification by strongly-interacting matter.

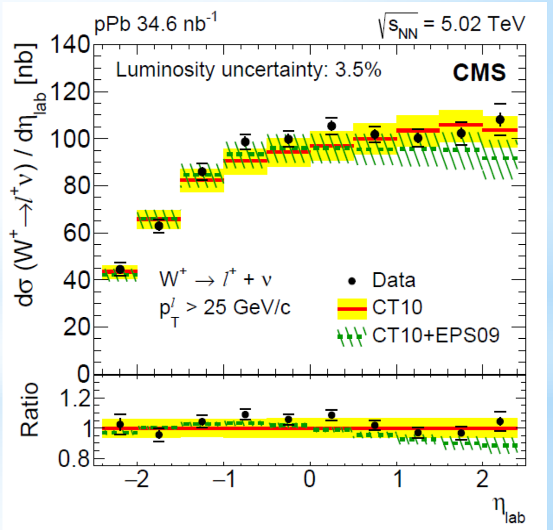
$$W^+ \xrightarrow{10.57\pm0.15\%} \mu^+ + \nu_\mu \,,\quad W^- \xrightarrow{10.57\pm0.15\%} \mu^- + \overline{\nu_\mu}$$

- p_T distribution peaks at $p_T \approx M_W/2 \approx 40$ GeV/c
- Dominant at $p_T > 30$ GeV/c in the single muon p_T distribution



ALICE-INT-2006-021 & Eur. J. C49 (2007) 149

- Previous measurements in p-Pb collisions
- CMS collaboration: W→μν and W→eν, $|\eta_{lab}| < 2.4$, $p_T > 25$ GeV/c arXiv:1503.05825



Example of cross section for $W^+ \rightarrow l^+\nu$
CMS collaboration: arXiv:1503.05825

- In this study we use the **ALICE Forward Muon Spectrometer**

$2.03 < y^{\mu}_{cms} < 3.53$ and **$-4.46 < y^{\mu}_{cms} < -2.96$**, **$p^{\mu}_T > 10$ GeV/c**

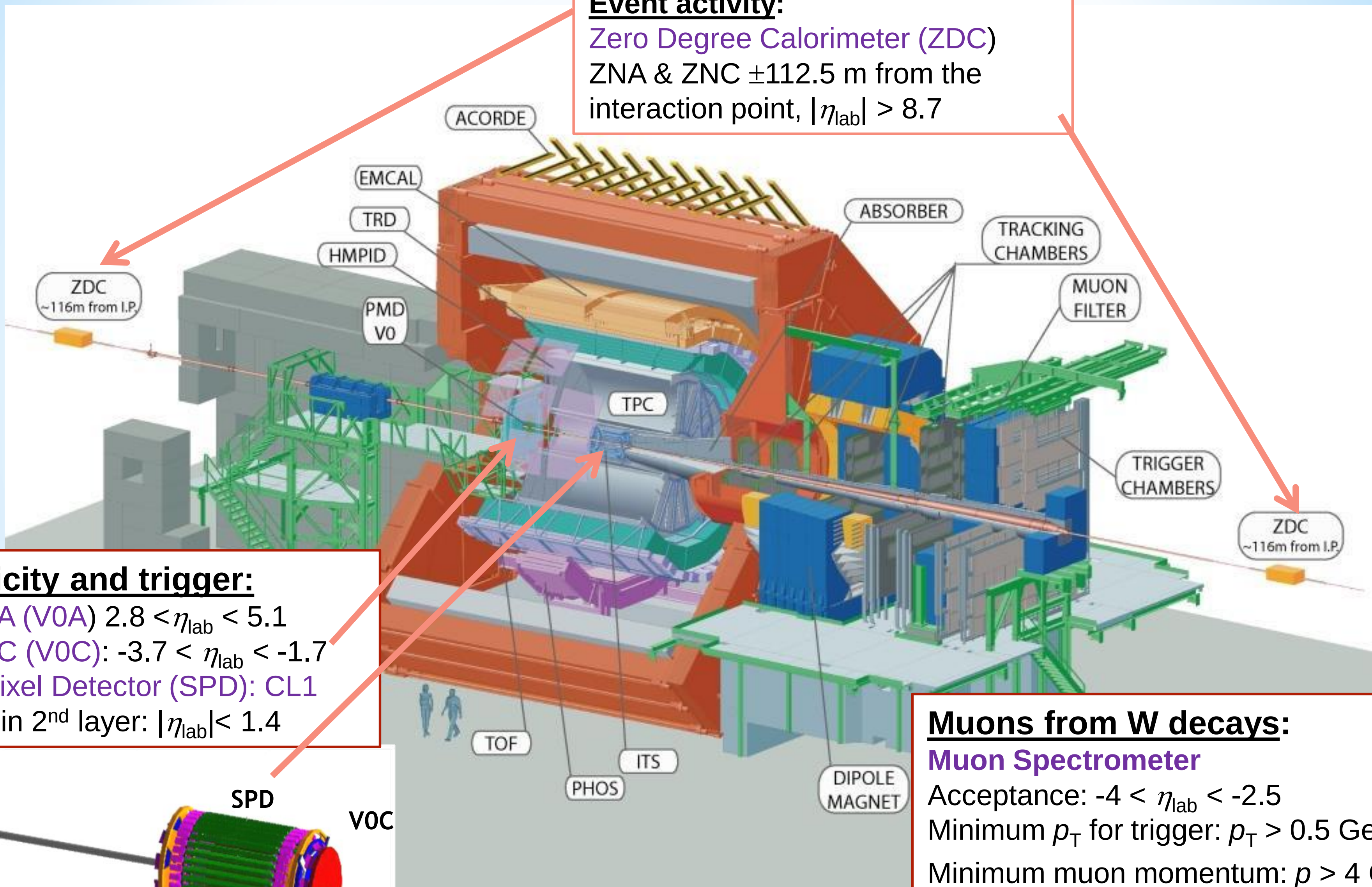
→ Rapidity coverage complementary to that of CMS

→ Probe Bjorken-x region ~10^{-4} - 10^{-1}

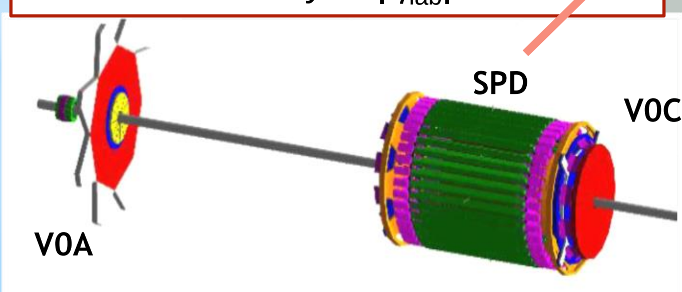
ALICE detector setup

Detectors used in the measurements

Event activity:
Zero Degree Calorimeter (ZDC)
ZNA & ZNC ±112.5 m from the interaction point, $|\eta_{lab}| > 8.7$



Multiplicity and trigger:
VZERO-A (V0A) $2.8 < \eta_{lab} < 5.1$
VZERO-C (V0C): $-3.7 < \eta_{lab} < -1.7$
Silicon Pixel Detector (SPD): CL1
Clusters in 2nd layer: $|\eta_{lab}| < 1.4$



Muons from W decays:
Muon Spectrometer
Acceptance: $-4 < \eta_{lab} < -2.5$
Minimum p_T for trigger: $p_T > 0.5$ GeV/c
Minimum muon momentum: $p > 4$ GeV/c

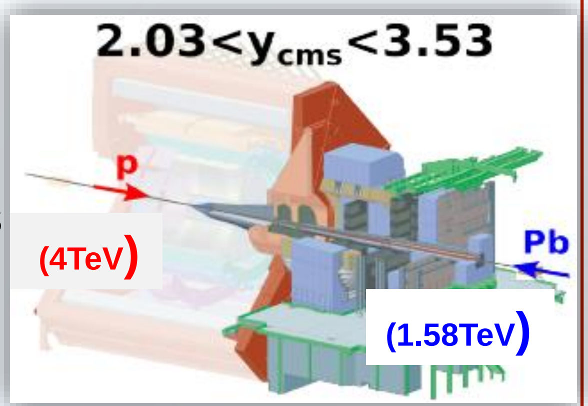
Data Sample

p-Pb and Pb-p collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

Forward rapidity:

p-beam direction

(proton moving towards the muon arm)

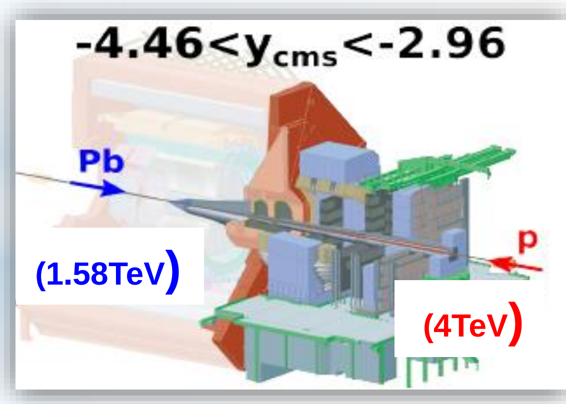


Δy_{cms} = 0.465 in the p-beam direction

Backward rapidity:

Pb-beam direction

(Pb nucleus moving towards the muon arm)



- Trigger condition:
  High-p_T muon triggered events: minimum-bias (MB) events (coincidence of V0A ∩ V0C) and muon with $p_T \geq$ 4 GeV/c

- Integrated luminosity:
  Forward: 4.9 nb^{-1} Backward: 5.8 nb^{-1}

- Muon track selection:
  - Geometrical acceptance

    $-4 < \eta^{\mu}_{lab} < -2.4$, $170° < \theta^{\mu}_{lab} < 178°$
  - Matching between tracking and trigger tracks

    → reject punch-through hadrons
  - pxDCA - correlation of momentum (p) and the Distance of Closest Approach (DCA) to the interaction vertex

    → remove tracks from beam-gas interactions as well as particles produced in the absorber.

Analysis Method

- $W^{\pm} \rightarrow \mu^{\pm}$ main contributor in the single-muon p_T distribution at $p_T > 30$ GeV/c
- Main background sources:
  - Heavy-flavour decay muons: $8 < p_T < 40$ GeV/c
  - Z^0 / γ^*: $p_T > 50$ GeV/c
- Signal extraction - number of $\mu^{\pm} \leftarrow W^{\pm}$ ($N_{\mu^{\pm} \leftarrow W^{\pm}}$) estimated through suitable fits of the p_T distribution

$$f(p_T) = N_{bkg} \cdot f_{bkg}(p_T) + N_{\mu \leftarrow W} \cdot f_{\mu \leftarrow W}(p_T) + N_{\mu \leftarrow Z/\gamma^*} \cdot f_{\mu \leftarrow Z/\gamma^*}(p_T),$$

$f_{bkg}(p_T)$ → Fixed Order Next-to-Leading-Log (FONLL) based template JHEP 1210 (2012) 137

$f_{\mu \leftarrow W}(p_T)$ and $f_{\mu \leftarrow Z/\gamma^*}(p_T)$ → Monte Carlo templates (POWHEG)

N_{bkg} and $N_{\mu \leftarrow W}$ → free normalization parameters

$N_{\mu \leftarrow Z/\gamma^*}$ → fixed to $N_{\mu \leftarrow W}$

- Correct signal ($N_{\mu^{\pm} \leftarrow W^{\pm}}$) for acceptance x efficiency (A x ε)
- Normalize the yield of $\mu^{\pm} \leftarrow W^{\pm}$ ($Y_{\mu^{\pm} \leftarrow W^{\pm}}$) to MB cross section
- Compare cross-section results with pQCD at NLO calculations JHEP 1103 (2011) 071
- Measure the yield of $\mu^{\pm} \leftarrow W^{\pm}$ ($Y_{\mu^{\pm} \leftarrow W^{\pm}}$) scaled to $\langle N_{coll} \rangle$

Signal Extraction

- W and Z^0/γ^* templates from realistic Monte Carlo (MC) simulations are used for signal extraction
  - $N_{\mu\pm\leftarrow W\pm}$ and N_{Z^0/γ^*} generated with POWHEG[1] using CTEQ6m[2] PDF set in pp and pn collisions
  - Forced to decay to $\mu^\pm$
  - Shadowing effects evaluated using PYTHIA 6.4[3]
  - Systematics determination

[1] (JHEP 0807 (2008) 060)

[2] (JHEP 0207 (2002) 012)

[3] (JHEP 0904 (2009) 065)

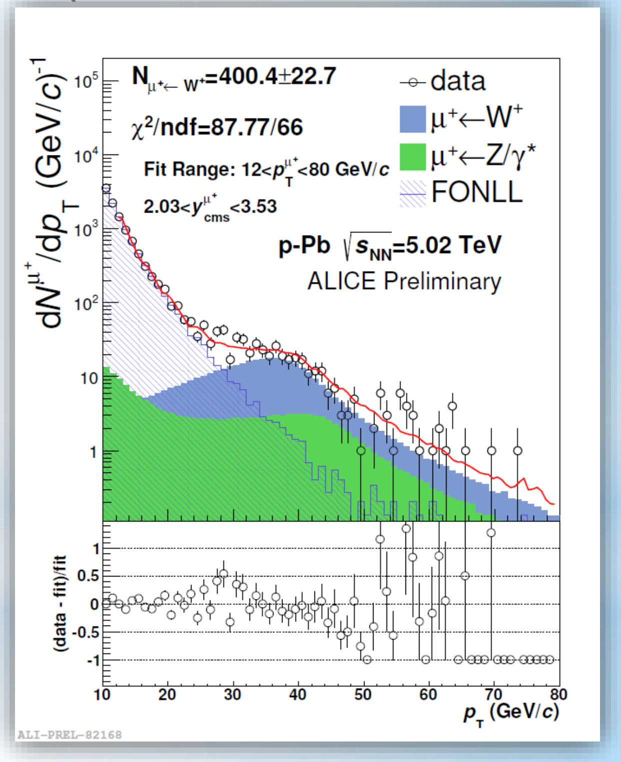
- Simulation: pp and pn collisions are considered.

  Templates obtained by combining results using:

$$\frac{1}{N_{pPb}} \cdot \frac{dN_{pPb}}{dp_{\mathrm{T}}} = \frac{Z}{A} \cdot \frac{dN_{pp}}{dp_{\mathrm{T}}} + \frac{A-Z}{Z} \cdot \frac{dN_{pn}}{dp_{\mathrm{T}}} ,$$

A = 208 (mass number of Pb nucleus),

Z = 82 (atomic number of Pb nucleus)



- Background consists of muons from heavy-flavour decays
  - Small shadowing effects expected at high p_T → FONLL based template JHEP 1210 (2012) 137

- $\mu^\pm\leftarrow W^\pm$ yields ($Y_{\mu\pm\leftarrow W\pm}$) obtained by correcting $N_{\mu\pm\leftarrow W\pm}$ for acceptance x efficiency (Axε)

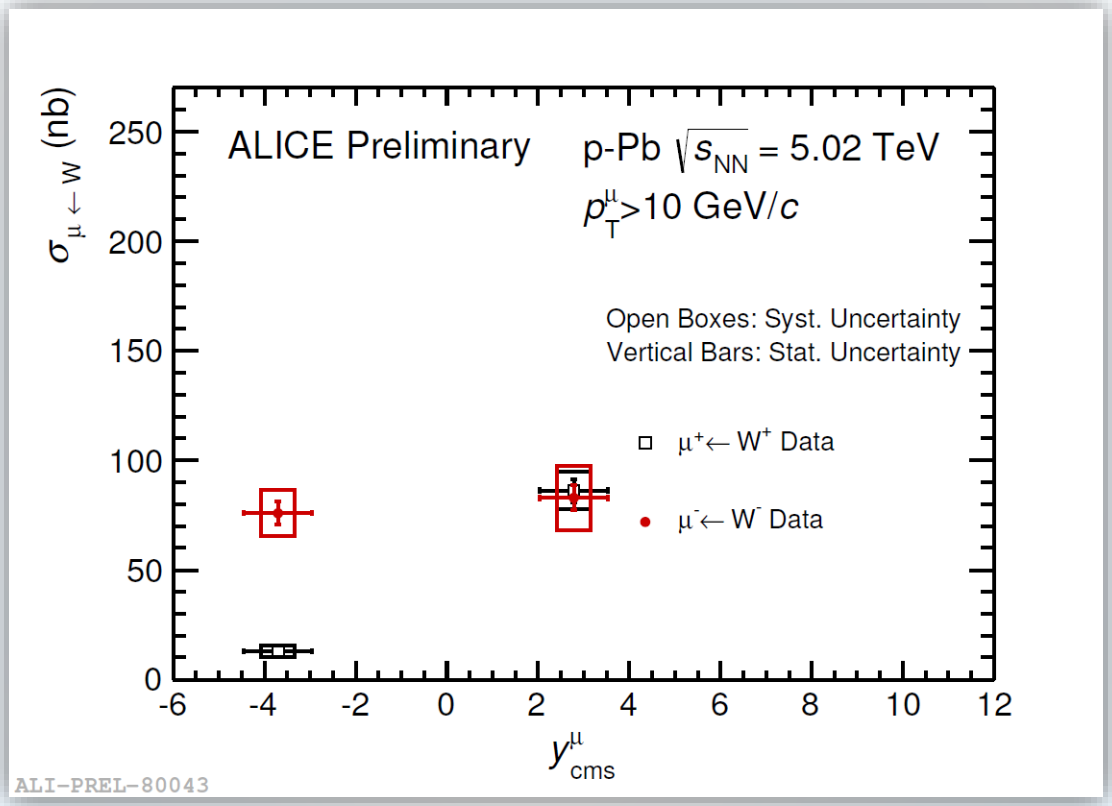
Systematic uncertainties

- Number of $\mu^{\pm} \leftarrow W^{\pm}$ is a weighted average over a number of fit trials obtained by varying
  - p_T range of the fit
  - QCD background description
  - Fraction of Z^0/γ^* to W decay muons obtained from PYTHIA and POWHEG
  - Alignment effects – varying the position of detector elements

- Systematic uncertainties considered are

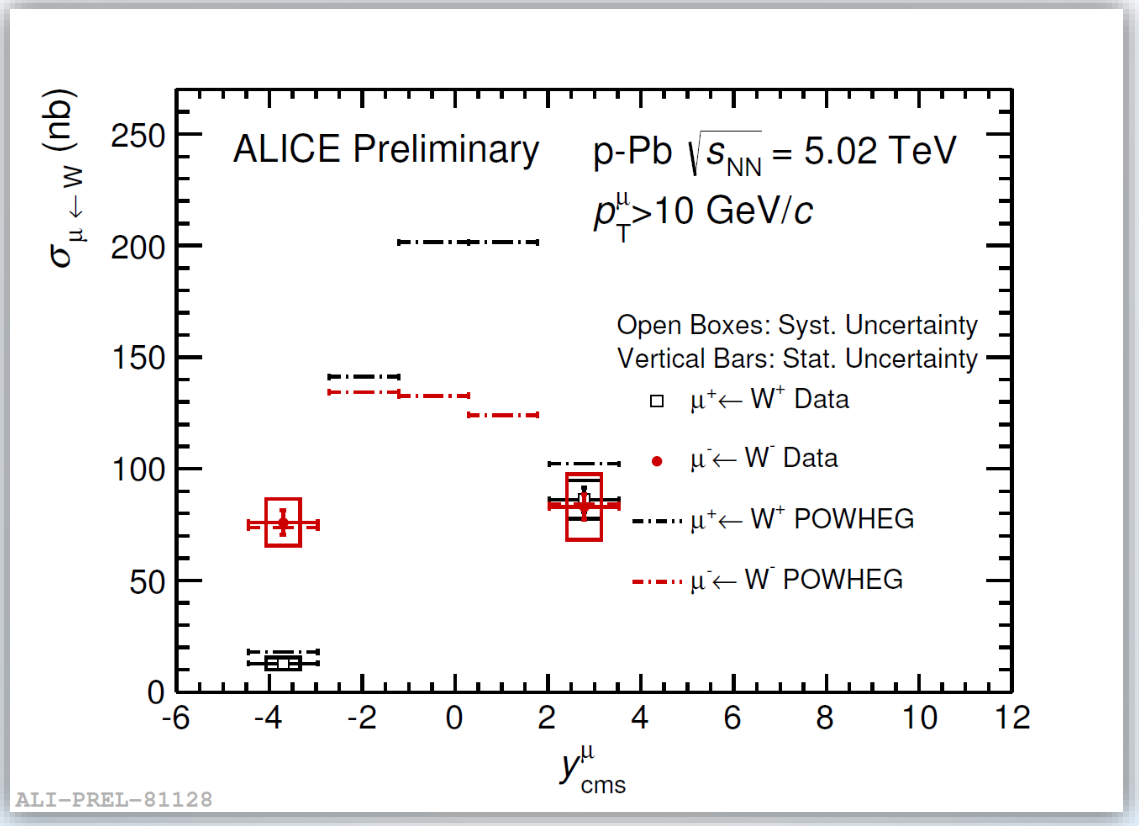
Summary of systematic uncertainties	
Signal extraction	~ 6-10%
Acceptance x efficiency - Tracking / trigger efficiency - Alignment	 2.5% 1%
Normalization to MB - F_{norm} - σ_{MB} - Pile up	 1% 3.2% (forward) and 3% (backward) 0 - 7.5%

Measured cross sections at forward and backward rapidity



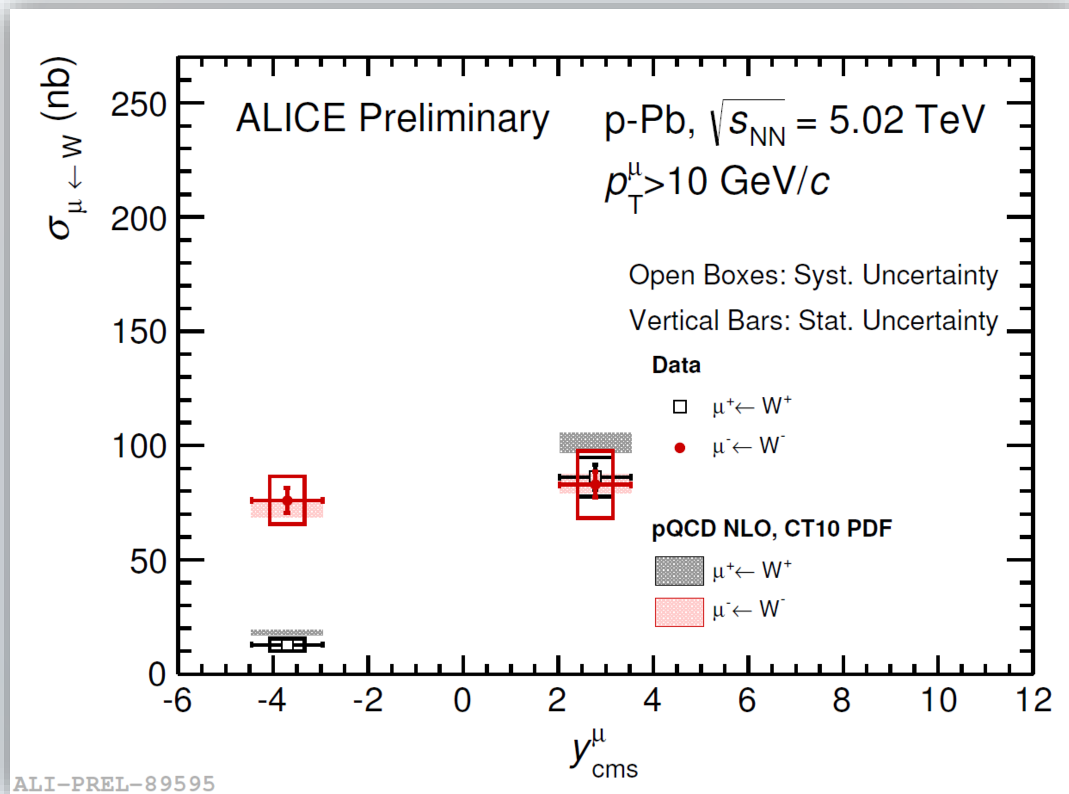
- $\sigma_{\mu\pm \leftarrow W\pm}$ measured in rapidity intervals: $2.03 < y^{\mu}_{cms} < 3.53$ and $-4.46 < y^{\mu}_{cms} < -2.96$
- Isospin effects are visible at backward rapidity: more d quarks than u quarks in Pb compared to proton
  - → $\sigma_{W-} \sim \sigma_{W+}$ at forward rapidity and $\sigma_{W-} > \sigma_{W+}$ at backward rapidity

Measured cross sections vs POWHEG predictions



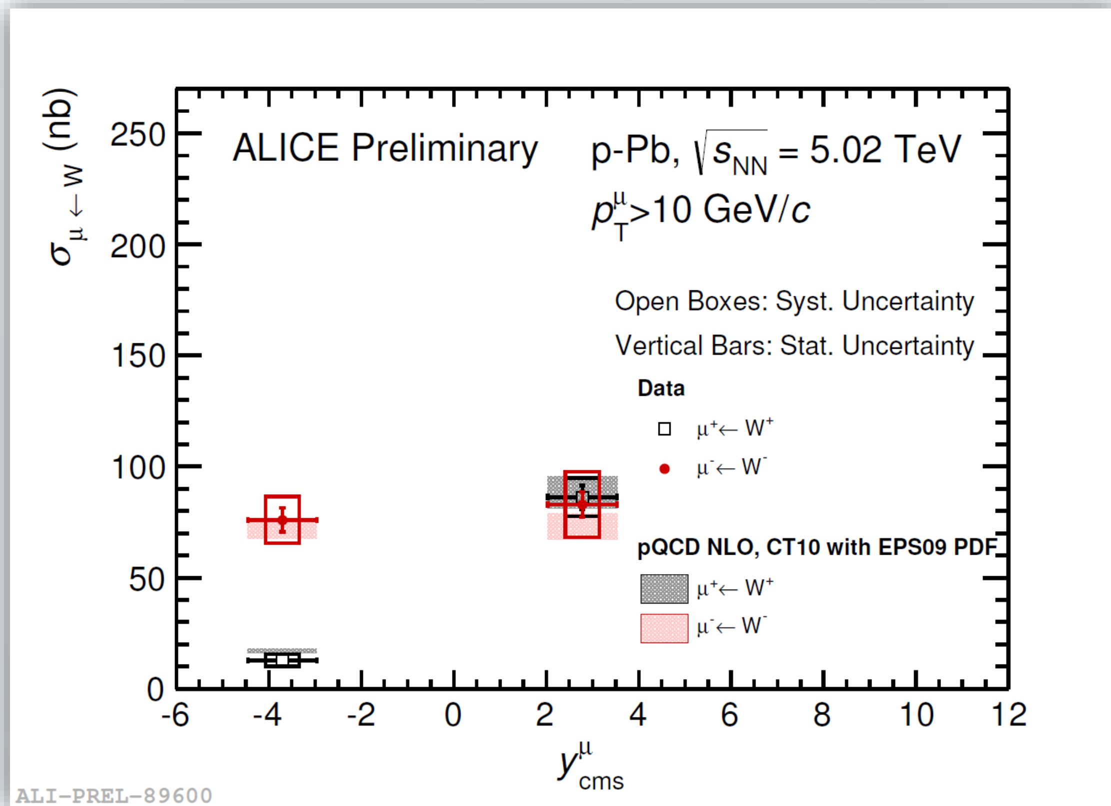
- $\sigma_{\mu\pm \leftarrow W\pm}$ measured in rapidity intervals: 2.03 < y^{μ}_{cms} < 3.53 and -4.46 < y^{μ}_{cms} < - 2.96
- POWHEG predictions do not include nuclear shadowing effects
- Agreement between measurement and POWHEG predictions is within 1.5σ

Measured cross sections vs pQCD NLO predictions



- $\sigma_{\mu\pm \leftarrow W\pm}$ measured in rapidity intervals: $2.03 < y^{\mu}_{cms} < 3.53$ and $-4.46 < y^{\mu}_{cms} < -2.96$
- pQCD NLO with CT10 (PDFs) predictions by Paukkunen *et al.** are in agreement with the measurements within uncertainties *Hannu Paukkunen and Carlos A Salgado, JHEP 1103 (2011) 071
- Consistent with observations by CMS collaboration arXiv:1503.05825

Measured cross sections vs pQCD at NLO predictions with nuclear PDFs



- $\sigma_{\mu\pm \leftarrow W\pm}$ measured in rapidity intervals: $2.03 < y^{\mu}_{cms} < 3.53$ and $-4.46 < y^{\mu}_{cms} < -2.96$
- pQCD NLO with CT10 (PDFs) and EPS09 (nPDFs) predictions by Paukkunen *et al.** are compared with measurements *Hannu Paukkunen and Carlos A Salgado, JHEP 1103 (2011) 071
- At forward rapidity measured $\sigma_{\mu^+ \leftarrow W^+}$ and $\sigma_{\mu^- \leftarrow W^-}$ are in better agreement with predictions including nPDFs
- Consistent with observations by CMS collaboration arXiv:1503.05825

Yields of $\mu^{\pm} \leftarrow W^{\pm}$ scaled to $\langle N_{\text{coll}} \rangle$

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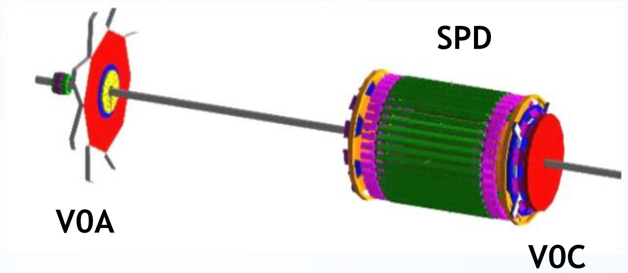
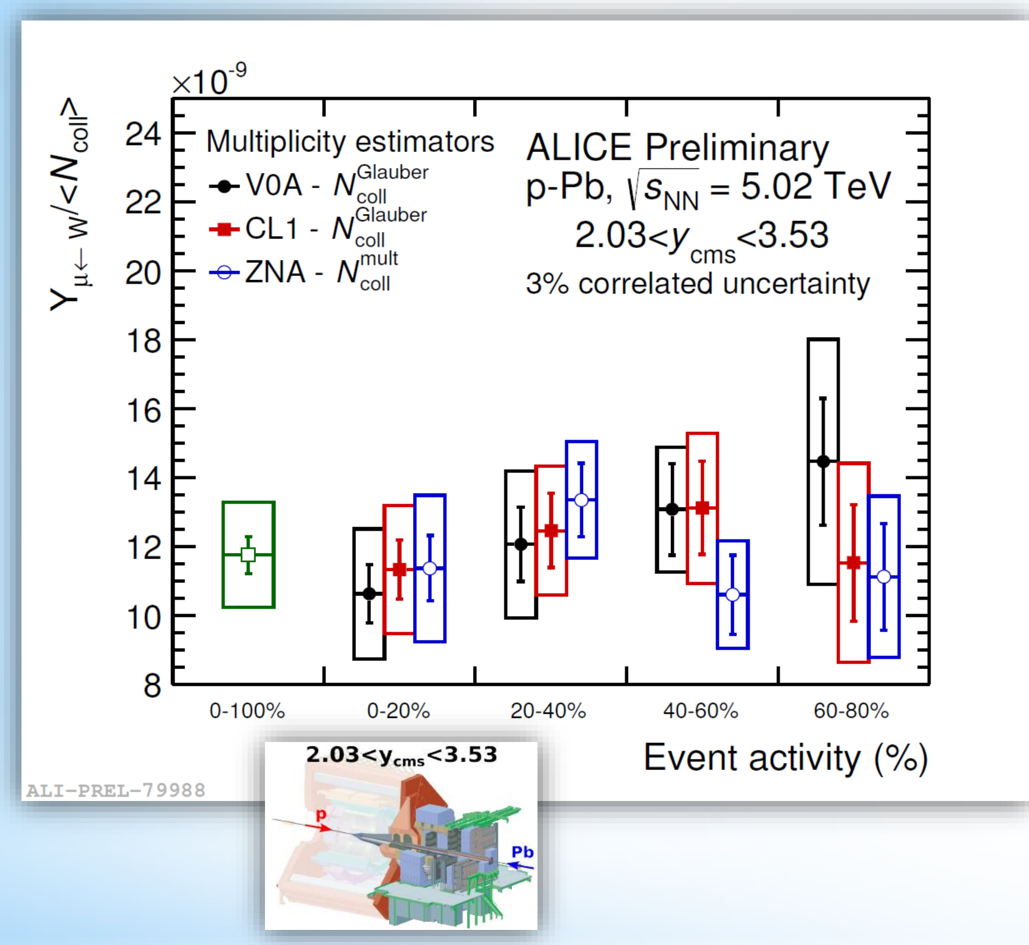
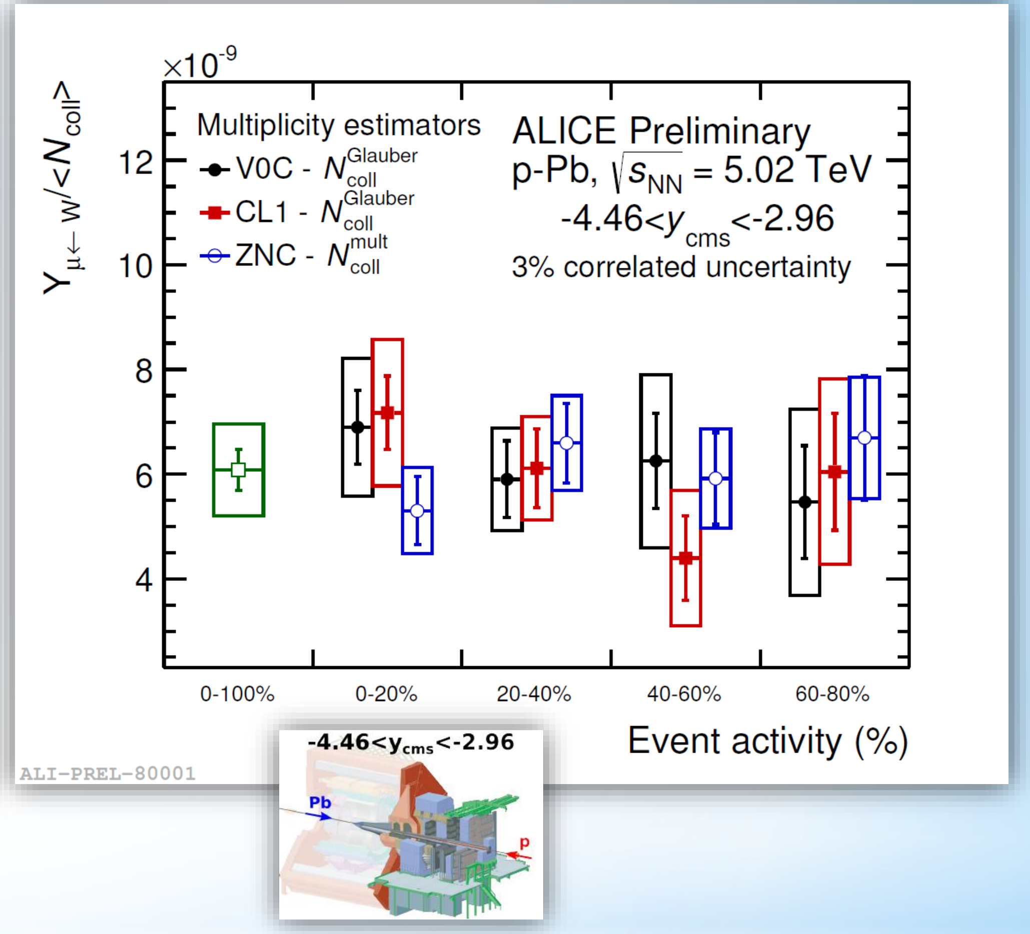
- $W^{\pm}$ production is a hard process thus it is expected to scale with the number of binary nucleon-nucleon collisions, N_{coll}
- $\langle N_{\text{coll}} \rangle$ expected to correlate with the event activity
- Use different estimators with different approaches to extract $\langle N_{\text{coll}} \rangle$
  - Glauber fit + Negative Binomial Distribution fit to V0A, V0C



  - Hybrid Method
    $\langle N_{\text{coll}}^{\text{Mult}} \rangle$ is calculated by scaling $\langle N_{\text{coll}} \rangle$ in minimum-bias collisions by the ratio between the average multiplicity density measured at mid-rapidity for a given ZDC energy event class and the one measured in minimum bias collisions
- Systematic uncertainty on the normalization to $\langle N_{\text{coll}} \rangle$: 8 - 21% depending on a multiplicity bin

Yields of $\mu^{\pm} \leftarrow W^{\pm}$ normalized to $\langle N_{coll} \rangle$





- The yield of $\mu^{\pm} \leftarrow W^{\pm}$ is normalized to $\langle N_{coll} \rangle$ to test binary scaling
- To increase statistics, results of $\mu^{+} \leftarrow W^{-}$ and $\mu^{-} \leftarrow W^{-}$ are added together
- Within uncertainties, the yield of $\mu^{\pm} \leftarrow W^{\pm}$ per binary collision is independent of the event activity
- Results from different estimators are compatible within uncertainties

Summary

- $\mu^{\pm} \leftarrow W^{\pm}$ are measured in two rapidity intervals in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

- Cross-section results

- Isospin effects are visible at backward rapidity: more d quarks than u quarks in Pb compared to proton
  - → $\sigma_{W-} \sim \sigma_{W+}$ at forward rapidity and $\sigma_{W-} > \sigma_{W+}$ at backward rapidity
- Measured cross sections agree with POWHEG predictions within 1.5σ
- Agreement between measured cross sections with predictions by pQCD NLO without shadowing (CT10 PDFs) is within uncertainties
- A pQCD calculation including nuclear shadowing (nPDFs) agrees better with the measured cross sections
- Results are consistent with observations by CMS collaboration arXiv:1503.05825

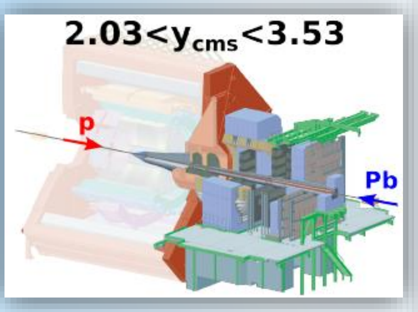
- Yields scaled to $\langle N_{coll} \rangle$ is estimated using different estimators
- Results from different estimators are compatible within uncertainties
- $Y_{\mu^{\pm} \leftarrow W^{\pm}} / \langle N_{coll} \rangle$ is independent of the event activity within systematic uncertainties

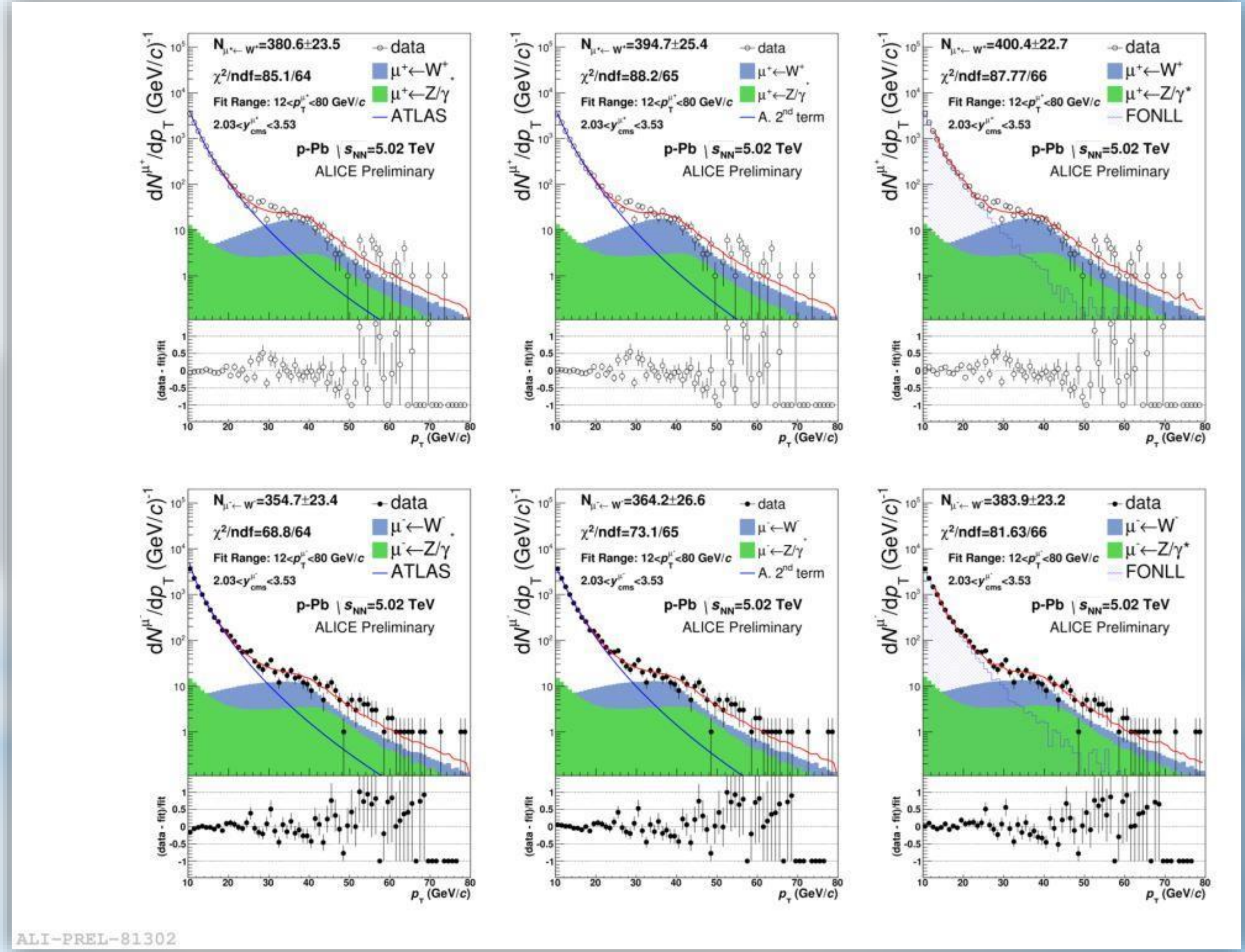
THANK YOU

Back up slides implement

Fit examples: Signal extraction for W-boson in p-Pb collisions

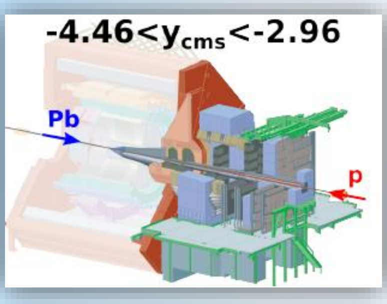
proton-going direction

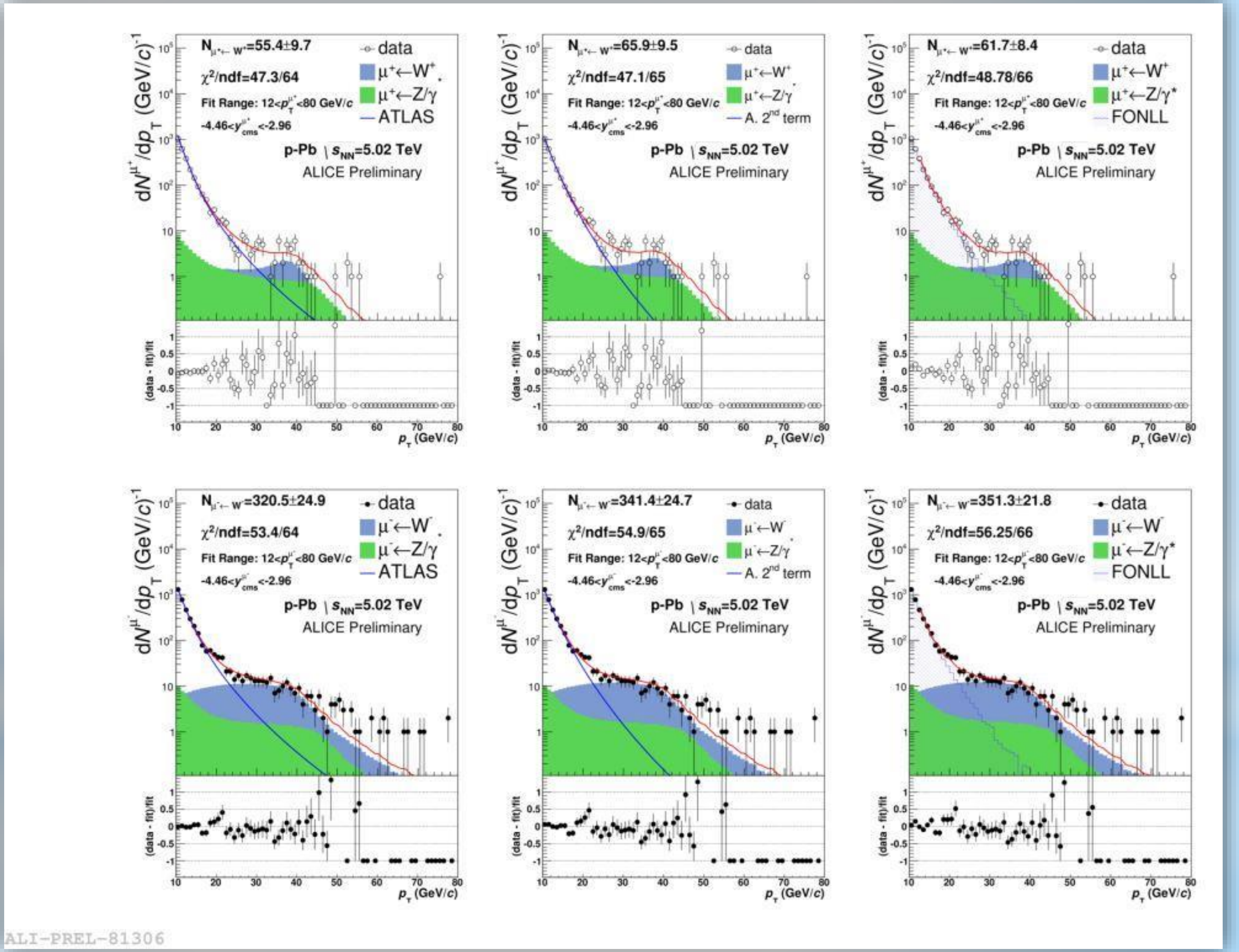




Fit examples: Signal extraction for W-boson in p-Pb collisions

Pb-going direction



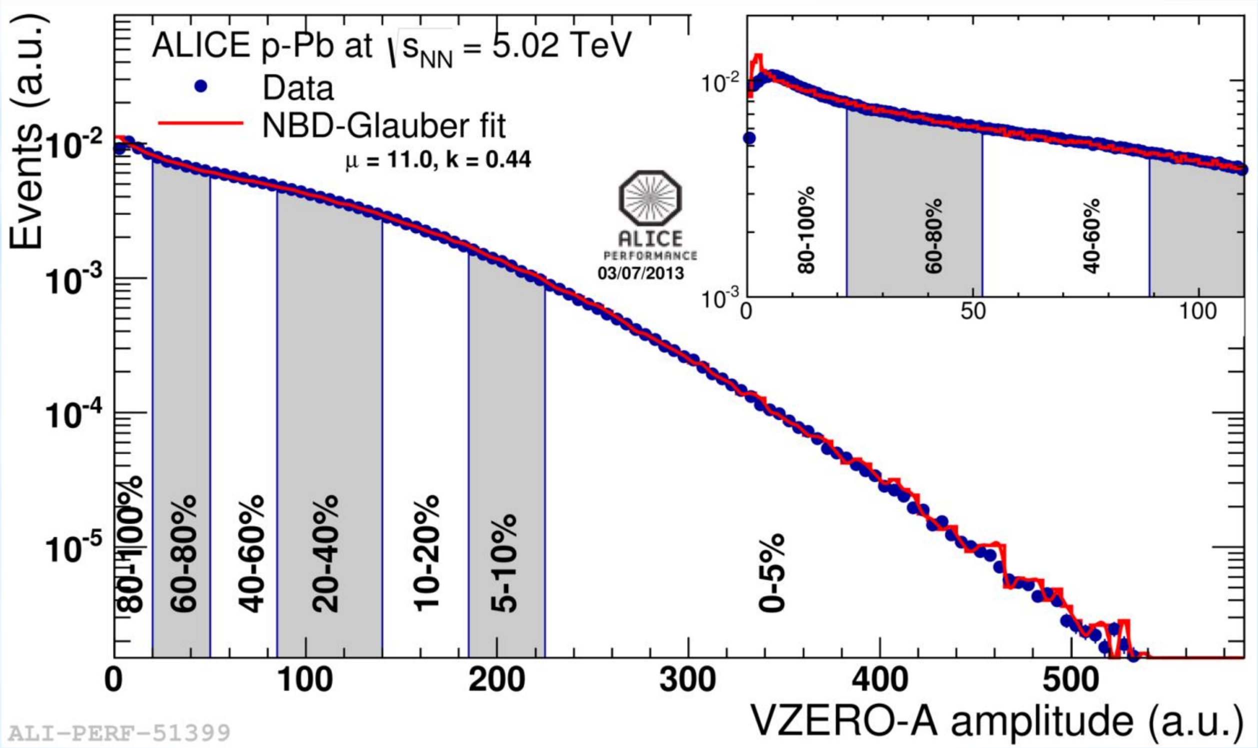


Glauber fit + NBD

ALICE, Phys. Rev. C 88, 044909 (2013)

Same procedure as for Pb-Pb

- Glauber MC to obtain $P(N_{part})$ assuming N_{part} = number of particle sources (ancestors)
- multiplicity distribution per ancestor from Negative Binomial Distribution (NBD)
- minimization procedure to find NBD parameter values
- centrality classes defined slicing measured multiplicity distributions in percentiles of cross section
- $\langle N_{part}\rangle$, $\langle N_{coll}\rangle$, $\langle T_{pA}\rangle$ for each centrality class from Glauber



Glauber fit + SNM

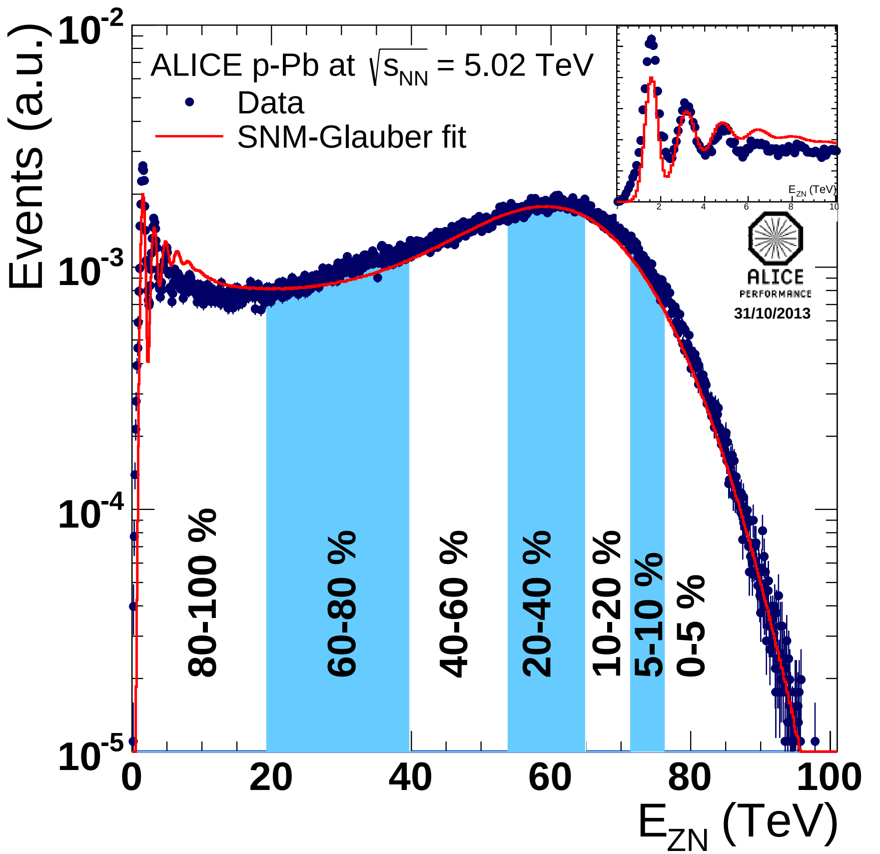
Similar procedure but coupled with a model for slow nucleon emission (SNM)
No model is currently available for LHC energies!

F. Sikler, arXiv: 0304.065

Features of emitted nucleons weakly dependent on projectile energy from 1 GeV to 1 TeV
→ "Phenomenological" model based on experimental results at lower energies

- number of protons and neutrons as a function of N_{coll}
- kinematical properties of emitted slow nucleons

→ able to reproduce essential features of the spectrum, still ongoing work!



W-bosons in Heavy-Ion: Nuclear PDFs

*Hannu Paukkunen and Carlos A Salgado, JHEP 1103 (2011) 071

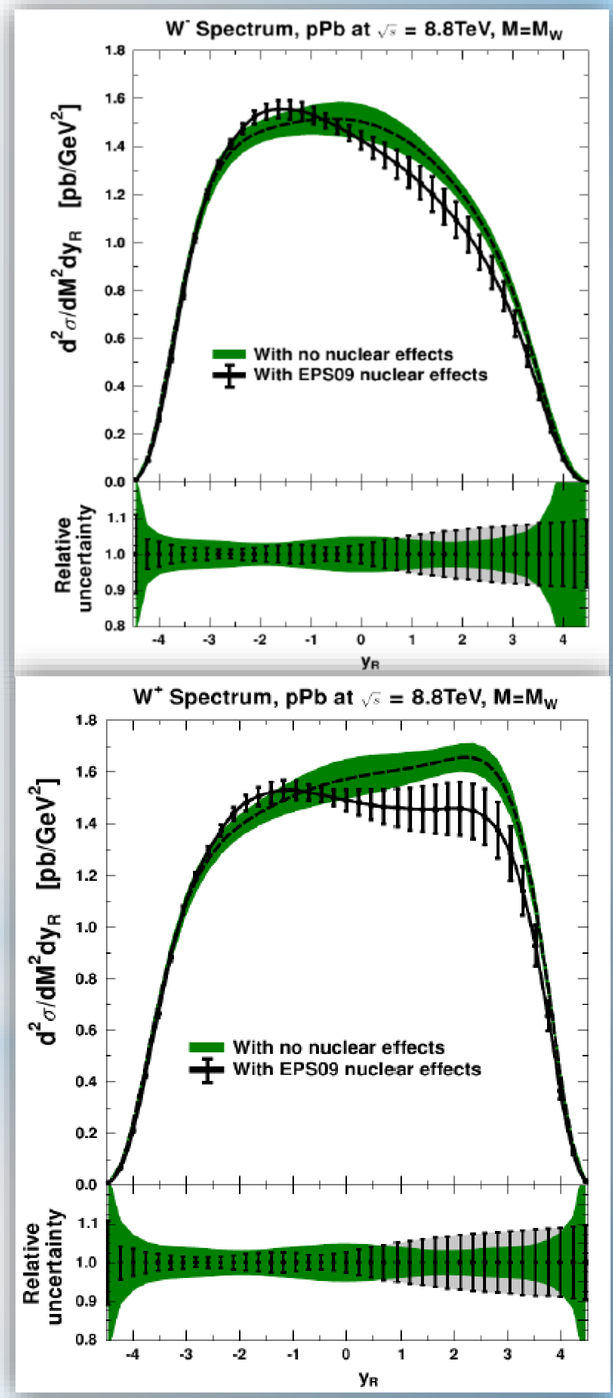
<u>Nuclear effects</u>:

- Difference between cross sections in collisions involving heavy-ion and those in free nucleons (EPS09)

$$x_a = \frac{M_W}{\sqrt{s}} exp(y_W),\ x_b = \frac{M_W}{\sqrt{s}} exp(-y_W)$$

- W-boson are sensitive to nuclear effects: Fermi motion
  EMC effects
  anti-shadowing
  shadowing

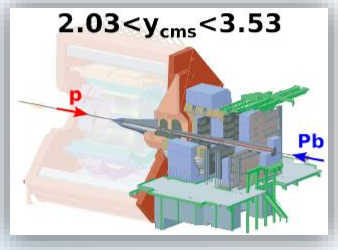
- Isospin effects remain sizable

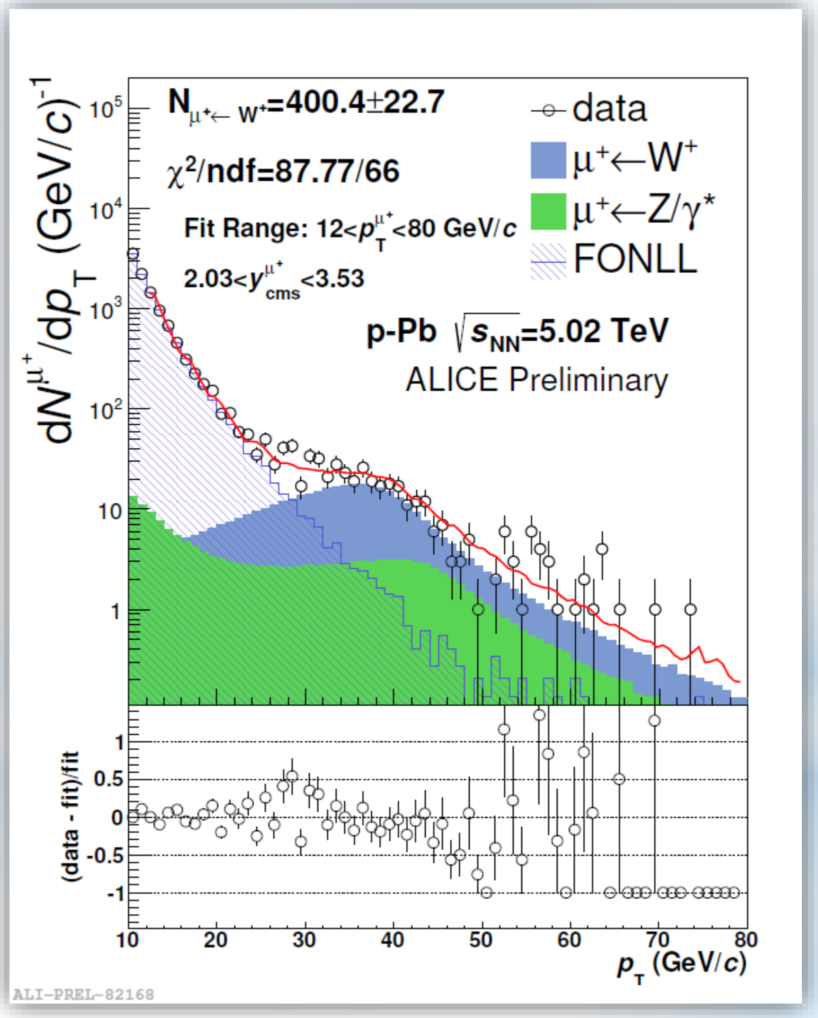


Signal extraction: example of global fit

- Fit range: $12 < p_T < 80$ GeV/c
- Raw $N_{\mu+\leftarrow W+}$ and $N_{\mu-\leftarrow W-}$ extracted by integrating $\mu^{\pm}\leftarrow W^{\pm}$ at $10 < p_T^{\mu} < 80$ GeV/c

proton-going direction





Normalization of yields to MB cross section

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- To obtain the cross section $\sigma_{\mu\leftarrow W}$ the yield of $\mu^{\pm} \leftarrow W^{\pm}$ is normalized to the MB cross section by considering

$$\boldsymbol{\sigma_{\mu\leftarrow W} = \frac{N_{\mu\leftarrow W}}{A \times \varepsilon} \times \frac{\sigma_{MB}}{N_{MSH} \times F_{norm}}},$$

where

- $A \times \varepsilon$ - factor for the acceptance and efficiency
- N_{MSH} - number of high-p_T muon triggered (MSH) events
- σ_{MB} - the MB cross section is 2.09±0.07 barn for p-Pb collisions and 2.12±0.06 barn for Pb-p JINST 9 (2014) 11, P11003
- F_{norm} - fraction of MSH events in MB-triggered data computed using 2 methods:
  - Method 1: uses offline information from trigger inputs
  - Method 2: uses online information from trigger counters

  → Systematic difference between methods is ~ 1%

Systematic uncertainties

- Number of $\mu^{\pm} \leftarrow W^{\pm}$ is a weighted average over a number of fit trials obtained by varying
  - p_T range of the fit
  - QCD background description
  - Fraction of Z^0/γ^* to W decay muons obtained from PYTHIA and POWHEG
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Summary of systematic uncertainties	
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Acceptance x efficiency - Tracking / trigger efficiency - Alignment	 2.5% 1%
Normalization to MB - F_{norm} - σ_{MB} - Pile up	 1% 3.2% (LHC13de) and 3% (LHC13f) 0 - 7.5%