W-boson production measurements with ALICE in p-Pb collisions at 5.02 TeV

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53rd International Winter Meeting on Nuclear Physics

BORMIO, Januray 26-30, 2015

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Why

- W is an electroweak probe produced in hard interactions
- Dominant production process: quark-antiquark annihilation

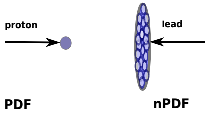
$$\mathbf{u\bar{d}} \rightarrow \mathrm{W}^{+} \qquad\qquad \mathbf{d\bar{u}} \rightarrow \mathrm{W}^{-}$$

In proton–proton (pp) collisions:

- Sensitive to parton distributions functions (PDFs)

In proton-lead (p-Pb) collisions:

- Sensitive to modification of parton distributions inside the nucleus
- Test binary scaling of hard processes
- Probes the (anti-)shadowing Bjorken-x region in the rapidity ranges $2.03 < y_{\mathrm{cms}} < 3.53$ and $-4.46 < y_{\mathrm{cms}} < -2.96$

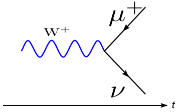


In lead-lead (Pb-Pb) collisions:

- Not sensitive to strong interaction $\Rightarrow$ reference for medium-induced effects
- Test binary scaling of hard processes

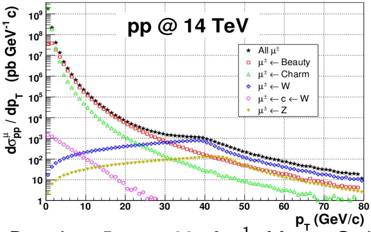
How

- Measured in single muon decay: no modification by the QCD medium



- p_T distribution is a Jacobean peak with maximum at $p_\mathrm{T} \sim M_\mathrm{W}/2$
- W boson dominates the single-muon p_T spectrum at $p_\mathrm{T} > 30$ GeV/c
- Single-muon decays of Z/γ^* and QCD (muons from heavy-flavour decays) are the main background sources

Eur. Phys. J.C(2007)149

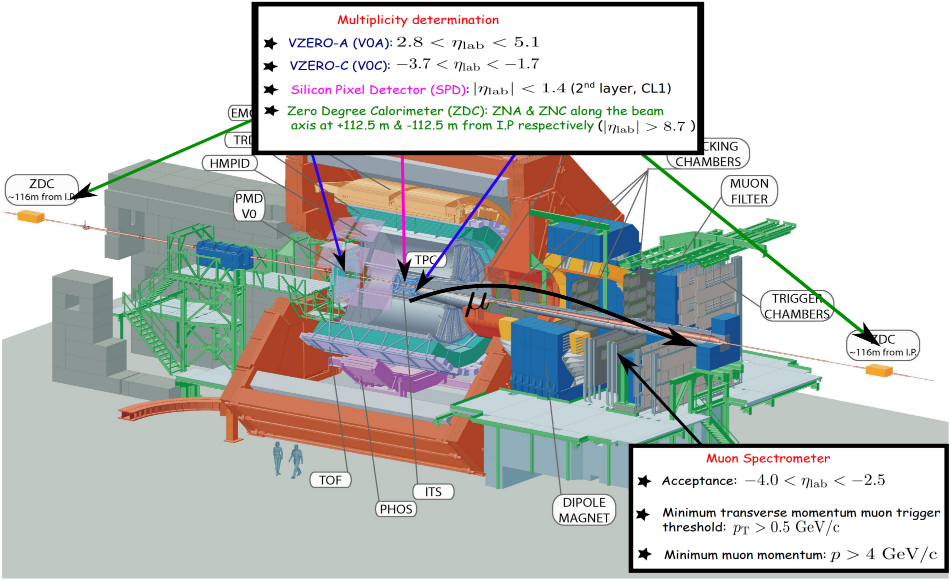


Based on $\mathrm{L_{int}} = 30\ \mathrm{pb}^{-1}$, Monte Carlo data

- W-boson signal is extracted by fits to the single-muon p_T distribution

ALICE setup

- ALICE setup indicating detectors used for multiplicity (event activity) determination and muon reconstruction



Multiplicity determination

- VZERO-A (V0A): $2.8 < \eta_{\mathrm{lab}} < 5.1$
- VZERO-C (V0C): $-3.7 < \eta_{\mathrm{lab}} < -1.7$
- Silicon Pixel Detector (SPD): $|\eta_{\mathrm{lab}}| < 1.4$ (2$^{\mathrm{nd}}$ layer, CL1)
- Zero Degree Calorimeter (ZDC): ZNA & ZNC along the beam axis at +112.5 m & -112.5 m from I.P respectively ($|\eta_{\mathrm{lab}}| > 8.7$)

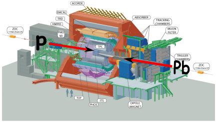
Muon Spectrometer

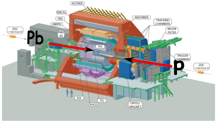
- Acceptance: $-4.0 < \eta_{\mathrm{lab}} < -2.5$
- Minimum transverse momentum muon trigger threshold: $p_{\mathrm{T}} > 0.5$ GeV/c
- Minimum muon momentum: $p > 4$ GeV/c

Data samples

- p-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV ($\rm E_p = 4$ TeV and $\rm E_{Pb}$ = 1.58 ATeV)
- Two beam configurations with a rapidity shift ($\triangle y = 0.465$) in the proton direction

Forward (p–Pb) | **Backward (Pb–p)**





$2.03 < y_{\rm cms} < 3.53$ | $-4.46 < y_{\rm cms} < -2.96$

$\Rightarrow y_{\rm cms}$ covered by the muon spectrometer

- Statistics
  - High $p_{\rm T}$ muon triggered events (V0A & V0C & muon with $p_{\rm T} \gtrsim 4$ GeV/c)

	Integrated Luminosity ($\rm nb^{-1}$)
Forward	**4.9**
Backward	**5.8**

- Muon track selection:
  - Geometrical acceptance cuts
  - Matching of the tracking and trigger tracks to reduce background from punch-through hadrons
  - Correlation of momentum (p) and **D**istance of **C**losest **A**pproach (**DCA**) to the interaction point to reduce tracks from beam-gas collisions and particles produced in the absorber

Analysis strategy

Background sources:

- $8 < p_{\mathrm{T}} < 40$ GeV/c : heavy-flavour decay muon background is dominant
- $p_{\mathrm{T}} > 50$ GeV/c : Z/γ^* is the main source of background

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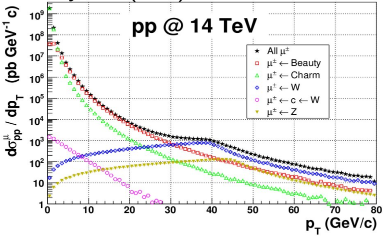

- $\mathrm{W}^{\pm}$ signal is extracted by fitting the single-muon p_{T} spectrum with:

$$f(p_{\mathrm{T}}) = N_{\mu\leftarrow\mathrm{QCD}} \cdot f_{\mu\leftarrow\mathrm{QCD}} + N_{\mu\leftarrow\mathrm{W}} \cdot f_{\mu\leftarrow\mathrm{W}} + N_{\mu\leftarrow\mathrm{Z}/\gamma^*} f_{\mu\leftarrow Z/\gamma^*}$$

where:

$f_{\mu\leftarrow\mathrm{QCD}}$ = functions or templates of muons from heavy-flavour decays
$f_{\mu\leftarrow\mathrm{W}}, f_{\mu\leftarrow\mathrm{Z}/\gamma^*}$ = POWHEG based Monte Carlo (MC) templates [**JHEP 0807(2008)060**]
$N_{\mu\leftarrow\mathrm{QCD}}, N_{\mu\leftarrow\mathrm{W}}$ = free normalization parameters
$N_{\mu\leftarrow\mathrm{Z}/\gamma^*}$ = fixed to $N_{\mu\leftarrow\mathrm{W}}$, using ratios of cross-sections from MC $\frac{\sigma_{\mu\leftarrow\mathrm{Z}/\gamma^*}}{\sigma_{\mu\leftarrow\mathrm{W}}}$

- Extracted signal is corrected for Acceptance×Efficiency $(\mathrm{A} \times \varepsilon)$ to obtain the yield

Signal (W) and Z/γ^* templates

Simulation configuration:

- W and Z/γ^* events generated using POWHEG[1] (default) with CTEQ6m[2] PDFs in pp and pn collisions
- Forced to decay to $\mu^{\pm}$

Generators and their roles:

◇ **POWHEG:**

- Generate hard events at Next to Leading order, no showering (no radiative corrections) and no shadowing

◇ **PYTHIA6.4[3]:**

- Used to include shadowing parameterized by EPS09[4] (p and n considered inside the Pb)
- Used only for systematic determination

Combine pp and pn with

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

to obtain the templates, where

$A = 208$ (mass number of the Pb nucleus)
$Z = 82$ (atomic number of the Pb nucleus)

[1] **JHEP 0807(2008)060**
[2] **JHEP 0207(2002)012**
[3] **JHEP 05(2006)026**
[4] **JHEP 0904(2009)065**

Heavy-flavour background

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◇ **Fixed Order Next-to-Leading-Log based template (FONLL) [JHEP 1210 (2012) 137]:**

- Muons from B and D mesons in pp collisions at $\sqrt{s} = 5.02$ TeV
  `http://www.lpthe.jussieu.fr/~cacciari/fonll/fonllform.html`
- CTEQ6.6 parton distribution functions is used
- Small effects of nuclear modification of the PDFs at high p_{T}
  Nucl. Phys. A931 (2014) 546-551

◇ **Phenomenological functions used by other LHC experiments:**

- ATLAS function [**ATLAS-COM-CONF-2011-088**]:

$$\boxed{f_{bkg}(p_{\mathrm{T}}) = a \cdot \exp\left(-b \cdot p_{\mathrm{T}}\right) + c \cdot \frac{\exp(-d \cdot \sqrt{p_{\mathrm{T}}})}{p_{\mathrm{T}}^{2.5}}}$$

- 2^{nd} term of the ATLAS function:

$$\boxed{f_{bkg}(p_{\mathrm{T}}) = c \cdot \frac{\exp(-d \cdot \sqrt{p_{\mathrm{T}}})}{p_{\mathrm{T}}^{2.5}}}$$

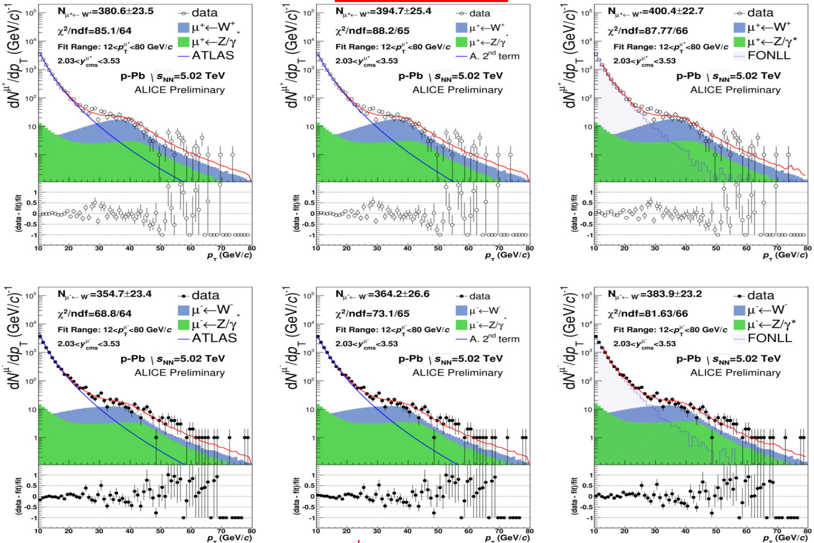
Signal extraction: global fits

- Fit range $12 < p_{\mathrm{T}} < 80$ GeV/c, $N_{\mu\leftarrow\mathrm{W}}$ extracted by integrating from $10 < p_{\mathrm{T}} < 80$ GeV/c

Forward rapidity

$\mu^+ \leftarrow W^+$

$\mu^- \leftarrow W^-$



ATLAS | 2^{nd} **ATLAS term** | **FONLL template**

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Systematics uncertainties

◇ $N_{\mu\leftarrow\mathrm{W}}$ is a weighted average over a large number of fit trials, varying:

- The p_{T} range where the fit is performed
- QCD or Heavy-flavour decay muons background description
- Fraction of Z/γ^{*} to W decay muons: $\Rightarrow$ obtained using PYTHIA and POWHEG
- Alignment effects $\Rightarrow$ vary the position of detector elements

◇ The statistical error is given by propagating the error on each trial

◇ Systematic error is estimated assuming $N_{\mu\leftarrow\mathrm{W}}$ is extracted from a uniform distribution

- **Signal extraction**
  $\Rightarrow$ vary between $\sim$ 6 % and $\sim$ 10 %

- **Acceptance×Efficiency:** $\mathrm{A}\times\varepsilon$
  $\Rightarrow$ estimated with two generators: about 1%

- **Alignment effects**
  $\Rightarrow$ systematics from detector configuration found to be $< 1\%$

- **Tracking/trigger efficiencies**
  $\Rightarrow$ tracking 2%, trigger 1% and track and trigger matching 0.5%
  $\Rightarrow$ propagate to $\mathrm{N}_{\mu\leftarrow\mathrm{W}}$ $\Rightarrow$ conservative uncertainty of 2.5% considered

◇ **These systematics hold for all event activity (multiplicity) bins**

Computing the cross section

- Cross-section is computed as:

$$\boxed{\sigma_{\mu\leftarrow \mathrm{W}} = \frac{N_{\mu\leftarrow \mathrm{W}}}{\mathrm{A}\times\varepsilon} \times \frac{1}{\mathrm{L_{int}}}}$$

where the integrated luminosity is:

$$\boxed{\mathrm{L_{int}} = \frac{N_{\mathrm{MB}}}{\sigma_{\mathrm{MB}}} = \frac{N_{\mathrm{MSH}} \times F_{\mathrm{norm}}}{\sigma_{\mathrm{MB}}}}$$

and $\mathrm{A}\times\varepsilon$ – acceptance and efficiency factor

- High p_{T} muon triggered (MSH) data sample
- Number of MSH events (N_{MSH}) must be normalized to the number of minimum-bias (MB) events N_{MB} to obtain the integrated luminosity:

◇ The normalization factor F_{norm} is the fraction of MSH events in the MB triggered data:

- Computed with two methods

  Method 1: uses offline information from trigger inputs

  Method 2: uses online information from trigger counters (scalers)

- Takes into account pile-up

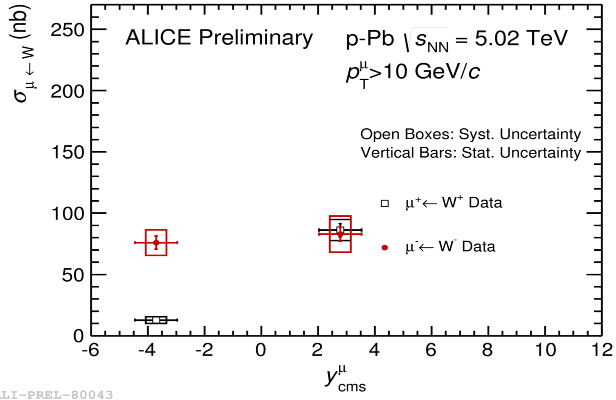
⇒ Systematic difference between these methods is $\sim 1\%$

◇ $\sigma_{\mathrm{MB}} = 2.09 \pm\ 0.07$ b and $\sigma_{\mathrm{MB}} = 2.12 \pm\ 0.06$ b for p–Pb and Pb–p, respectively
JINST 9 (2014) 11, P11003

Cross sections

- Cross section of $\mu \leftarrow \mathrm{W}$ is measured in two rapidity intervals, $2.03 < y^{\mu}_{\mathrm{cms}} < 3.53$ and $-4.46 < y^{\mu}_{\mathrm{cms}} < -2.96$
- Isospin effects are visible at backward rapidity

$\Rightarrow$ more *d*-quarks than *u*-quarks in Pb compared to p, thus $\sigma_{\mathrm{W}^-} \sim \sigma_{\mathrm{W}^+}$ at forward rapidity and $\sigma_{\mathrm{W}^-} > \sigma_{\mathrm{W}^+}$ at backward rapidity



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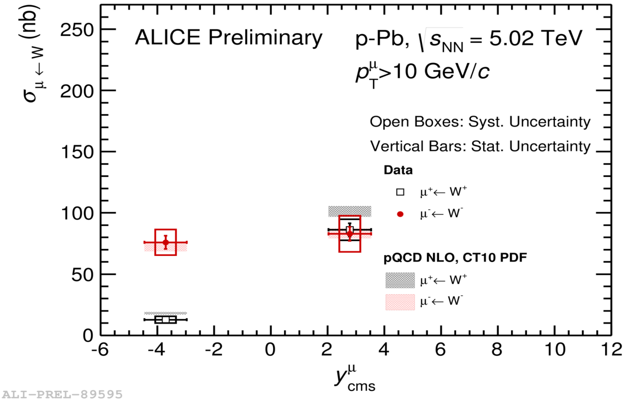
Cross sections vs pQCD at NLO calculations

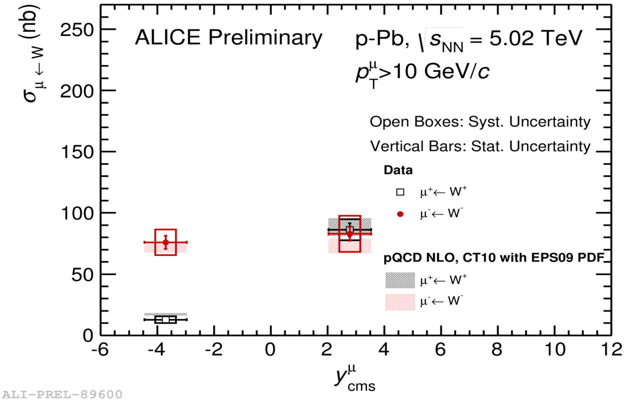
- Cross section of $\mu \leftarrow \mathrm{W}$ is measured in two rapidity intervals, $2.03 < y^{\mu}_{\mathrm{cms}} < 3.53$ and $-4.46 < y^{\mu}_{\mathrm{cms}} < -2.96$
- pQCD at NLO with CT10 (PDFs) predictions by H. Paukkunen et al[1] are in agreement with measurements within uncertainties



[1] JHEP 1103 (2011) 071

Cross sections vs pQCD at NLO calculations with nuclear PDF

- Cross section of $\mu \leftarrow \mathrm{W}$ is measured in two rapidity intervals, $2.03 < y^{\mu}_{\mathrm{cms}} < 3.53$ and $-4.46 < y^{\mu}_{\mathrm{cms}} < -2.96$
- pQCD at NLO with CT10 (PDFs) and EPS09 (nPDFs) predictions by H. Paukkunen et al[1] are compared with measurements
- With nPDFs the theory is in better agreement with the measured $\sigma_{\mu^+ \leftarrow \mathrm{W}^+}$ and $\sigma_{\mu^- \leftarrow \mathrm{W}^-}$ at forward rapidity within uncertainty



[1] JHEP 1103 (2011) 071

$\langle N_{\rm coll} \rangle$ scaling

- $N_{\rm coll}$ is the number of binary nucleon-nucleon collisions
- Since $\rm W$ production is a hard process it is expected to scale with $N_{\rm coll}$
- The average number of binary collisions $\langle N_{\rm coll} \rangle$ is expected to be correlated with event activity/multiplicity

◇ Different multiplicity estimators with different approaches were used to extract $\langle N_{\rm coll} \rangle$:

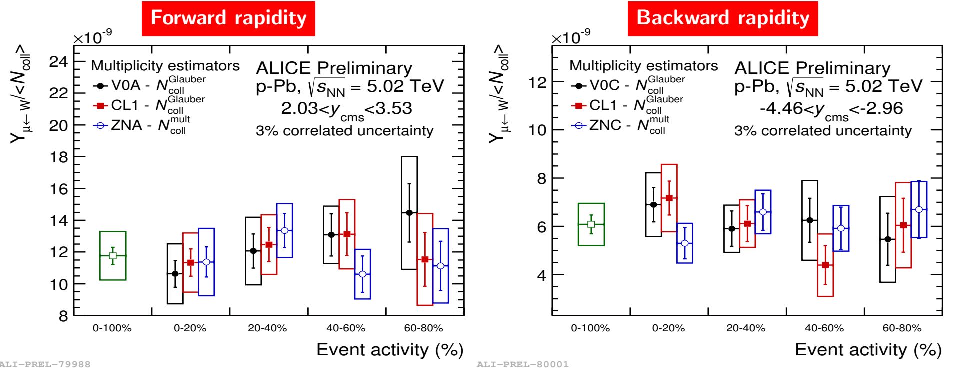
- Glauber Model+Negative Binomial Distribution fits to amplitude of
  $\Rightarrow$ the signal in the VZERO detectors on either side of the interaction point (V0A and V0C)
  $\Rightarrow$ the number of clusters in the first layer of the SPD detector (CL1)
- Hybrid method:
  $\Rightarrow$ Zero Degree Calorimeters on both sides of the interaction point (ZNA and ZDC): scaling $\langle N_{\rm part} \rangle$ in minimum-bias collisions by the ratio between the average multiplicity density measured at mid-rapidity in a given zero degree calorimeter energy event class and the one measured in minimum bias collisions

Systematic uncertainty on the normalisation to $\langle N_{\rm coll} \rangle$ range from 8% to 21% depending on a multiplicity bin

ALICE Collaboration, Particle production and centrality in p-Pb, arXiv:1412.6828 [nucl-ex]

Yield/$\langle N_{\rm coll} \rangle$

- Yield/$\langle N_{\rm coll} \rangle$: test the binary scaling of hard processes
- In order to increase statistics $\mu^+ \leftarrow W^+$ and $\mu^- \leftarrow W^-$ were combined
- $\mu \leftarrow W$ yield per binary collision is independent of event activity within systematics



Summary

- Production of $\mu^- \leftarrow \mathrm{W}^-$ and $\mu^+ \leftarrow \mathrm{W}^+$ was measured in two rapidity ranges in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$=5.02 TeV

Cross section:

- Theoretical predictions (pQCD NLO with CT10 PDFs) are in agreement with the measured cross sections with uncertainties
- Theoretical predictions including nPDFs provides a better agreement with the measured cross sections

Yield normalized to $\langle N_{\mathrm{coll}} \rangle$:

- Estimated with 3 multiplicity estimators
- Independent of the collision multiplicity within systematics

Backup

Determination of $\mathrm{F}_{\mathrm{norm}}$

Method 1:

$\Rightarrow$ offline method which uses trigger inputs

$$\boxed{F_{\mathrm{norm}}^{\mathrm{MSH}} = \frac{N_{\mathrm{MB}} \times F_{\mathrm{pile-up}}}{N_{(\mathrm{MB\&\&0MSL})}} \times \frac{N_{\mathrm{MSL}}}{N_{(\mathrm{MSL\&\&0MSH})}}}$$

where $F_{\mathrm{pile-up}} = \mu/(1 - e^{-\mu})$ and μ is the mean value of the Poisson distribution which describes the probability to have N collisions, MSL is muon single low ($p_{\mathrm{T}} \gtrsim 0.5$ GeV/c)

Method 2:

$\Rightarrow$ which uses L0b counters.

$$\boxed{F_{\mathrm{norm}}^{\mathrm{MSH}} = \frac{\mathrm{L0b}_{\mathrm{MB}} \times \mathrm{purity}_{\mathrm{MB}} \times F_{\mathrm{pile-up}}}{\mathrm{L0b}_{\mathrm{MSH}} \times PS_{\mathrm{MSH}}}}$$

where MB is minimum-bias and $\mathrm{PS}_{\mathrm{MSH}}$ is the fraction of MSH which passes physics selection.

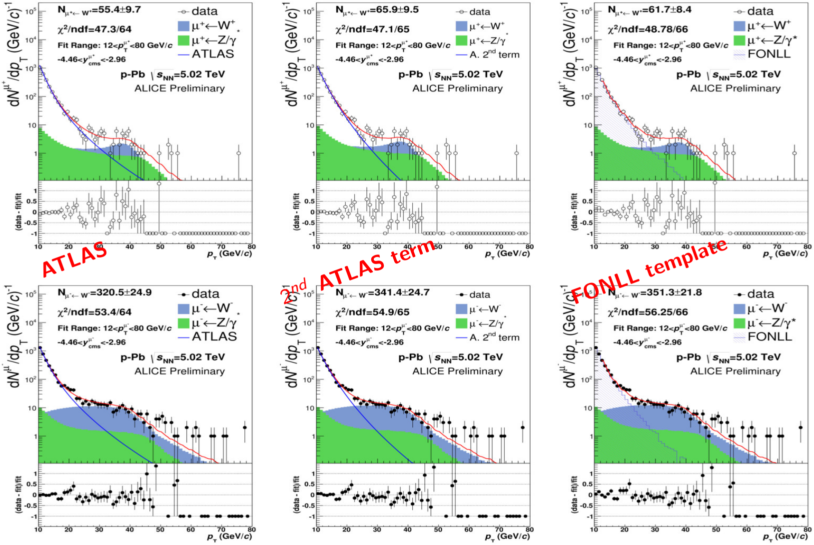
Signal extraction: Global fits

- Fit range $12 < p_{\mathrm{T}} < 80$ GeV/c, $\mathrm{N}_{\mu\leftarrow\mathrm{W}}$ extracted by integrating from $10 < p_{\mathrm{T}} < 80$ GeV/c

Backward rapidity

$\mu^+ \leftarrow W^+$

$\mu^- \leftarrow W^-$



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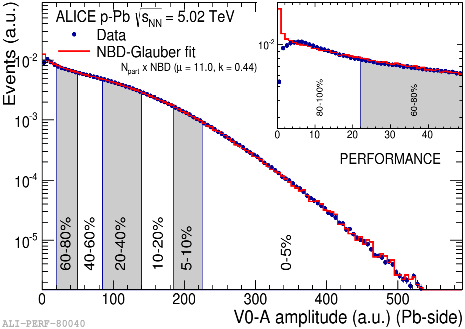
$\langle N_{coll} \rangle$

$$\langle N_{coll} \rangle = \langle N_{part} \rangle_{MB} \times \left(\frac{\langle dN/d\eta \rangle_i}{\langle dN/d\eta \rangle_{MB}} \right)_{-1<\eta<0} - 1$$



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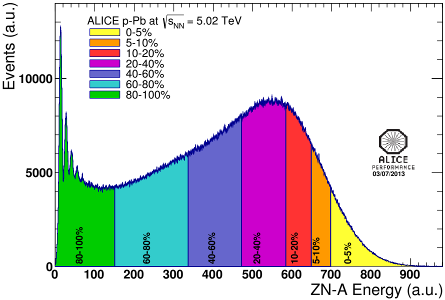

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Summary of the systematics

◇ Systematics on the generator based on POWHEG and PYTHIA

- PYTHIA also used to take into account shadowing effects

◇ Other systematics:

- variation of the input PDFs
- Z/γ^* to $\mathrm{W}^\pm$ fraction

both negligible

◇ Summary of the systematics:

Signal extraction *(includes alignment, fit stability/shape, etc.)*	from $\sim$ 6% to $\sim$ 10%
Acc.$\times$Eff.	
– track./trig. efficiencies	2.5%
– alignment	$<$ 1 %
Normalisation to MB	
– $\mathrm{F}_{\mathrm{norm}}$	1%
– σ_{MB}	3.2% (forward) 3% (backward)