Measurement of W-boson production in p-Pb collisions with ALICE at the LHC

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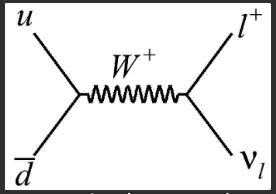
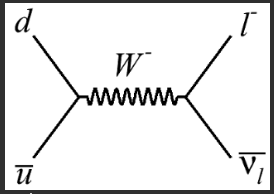
Outline

- Physics motivation
- Data sample
- Analysis strategy
- Results :
  - ✓ cross section vs. rapidity
  - ✓ yield/$\langle N_{coll} \rangle$ vs. event activity
- Conclusion

Physics motivation

- **Why ?**
  - Electroweak (EW) bosons are produced in initial hard partonic scattering processes
  - In p-p collisions :
    - ✓ W boson production is sensitive to Parton Distribution Functions (PDFs)
    - ✓ precise theoretical predictions
      - cross-check for luminosity and alignment effects
  - In p-Pb collisions :
    - ✓ investigate the cold nuclear matter effects
      - modification of PDFs in nuclei
  - In Pb-Pb collisions :
    - ✓ test binary scaling
    - ✓ reference for medium-induced effects
- **How ?**
  - Dominant production processes (LO)



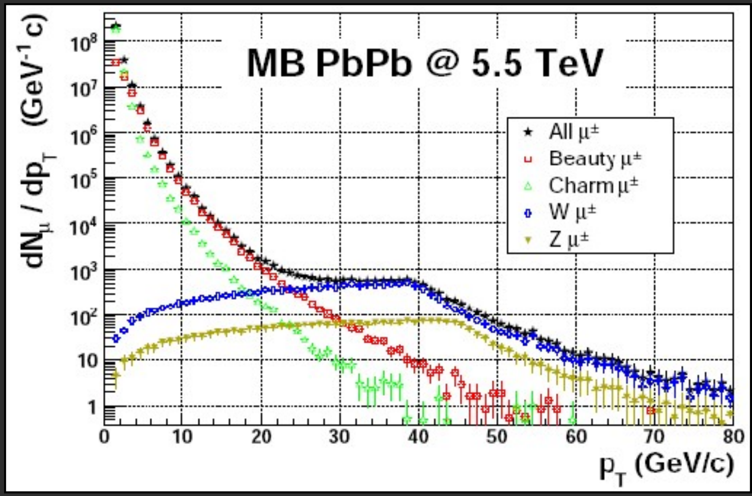


  - Detected through their muonic decay :

    $W^+ \rightarrow \mu^+ \nu_\mu \quad W^- \rightarrow \mu^- \bar{\nu}_\mu$

  - $\mu^\pm \leftarrow W^\pm$ production is maximum at ~ 40 GeV/c and dominates the high p_T range

statistics: 1 month ($L = 5.10^{26}$ cm^{-2} s^{-1}, $t = 10^6$ s)



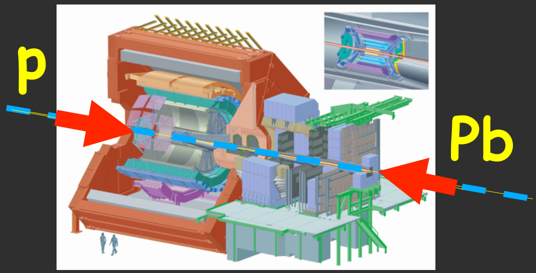
[Z. Conesa del Valle et al., ALICE-INT-2006-021 & Eur. Phys. J. C49 (2007) 149]

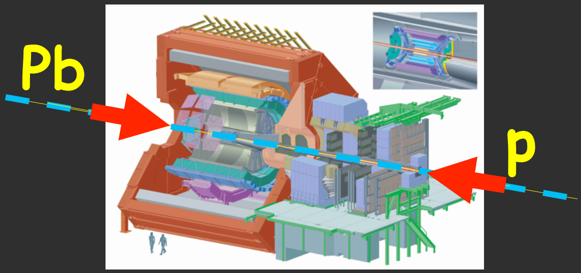
- **Where ?**
  - In the ALICE Muon Spectrometer, covering a rapidity range complementary to those of ATLAS and CMS

Data sample

❖ p-Pb collisions :

- **Beam energy** : $\sqrt{s_{NN}}$ = 5.02 TeV
  - Energy asymmetry of the LHC beams (E_p = 4 TeV, E_{Pb} = 1.58 A•TeV)
    → rapidity shift Δy = 0.465 in the proton direction
- **Beam configurations** :
  - Data collected with two beam configurations : p-Pb and Pb-p in the range $2.5 < y_{lab} < 4$
    → forward rapidity ($2.03 < y_{CMS} < 3.53$) backward rapidity ($-4.46 < y_{CMS} < -2.96$)





- **Trigger** : high p_T muon triggered events = MB events (coincidence of V0A & V0C) with a muon of p_T >~ 4.2 GeV/c in the spectrometer
- **Statistics** :

	Integrated luminosity
forward	4.9×10^3 ub^{-1}
backward	5.8×10^3 ub^{-1}

❖ Muon track selection :

- **acceptance and geometrical cuts**
- **muon trigger matching** : reject punch-through hadrons
- **pxDCA cut** : correlation between momentum and distance of closest approach (DCA) to the interaction vertex to remove beam-gas collisions and fake tracks

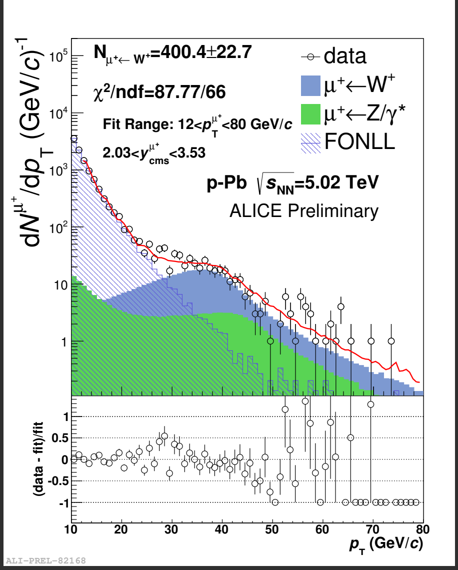
Analysis strategy

- W$^{\pm}$ decay muons are the main contributors in single muon momentum distribution at high p_T (p_T > 30 GeV/c)
- Heavy-flavor (b+c) decay muons are the dominant background at low p_T (8 < p_T < 40 GeV/c)
- For p_T > 50 GeV/c, Z^0/γ^* is the main source of background

- Extract W$^{\pm}$ signal from a fit of the transverse momentum distribution of single muons with

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

  - $f_{bkg}(p_T)$: phenomenological functions or FONLL-based MC template
  - $f_{\mu\leftarrow W}(p_T)$, $f_{\mu\leftarrow Z/\gamma^*}(p_T)$: Monte-Carlo templates
  - N_{bkg}, $N_{\mu\leftarrow W}$: free parameters
  - $N_{\mu\leftarrow Z/\gamma^*}$: fixed to $N_{\mu\leftarrow W}$



- Correct the extracted signal by Acceptance x Efficiency (Acc. x Eff)

- Normalize the corrected yield ($\mu^{\pm} \leftarrow W^{\pm}$) to the Minimum Bias cross-section

$W^{\pm}$ and Z^0/γ^* MC templates

Simulation configuration :

- $W^{\pm}$ and Z^0/γ^* generated with POWHEG in p-p & p-n collisions at 5.02 TeV
- $W^{\pm}$ and Z^0/γ^* forced to decay into muonic channels

Generators :

- **POWHEG :**
  [JHEP 0807(2008)060]
  - is interfaced with PYTHIA6.4 to apply showering, CTEQ6m PDF and no shadowing
- **PYTHIA6.4 :** (is used only for systematics, including effects of shadowing)
  [JHEP 05(2006)026]
  - shadowing : p or n considered in a Pb nucleus, parameterized with EPS09 [JHEP 0904(2009)065]
  - PDF set : CTEQ6l

Combine p-p & p-n to obtain p-Pb :

- A = 208, Z = 82

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

HF background: phenomenological functions

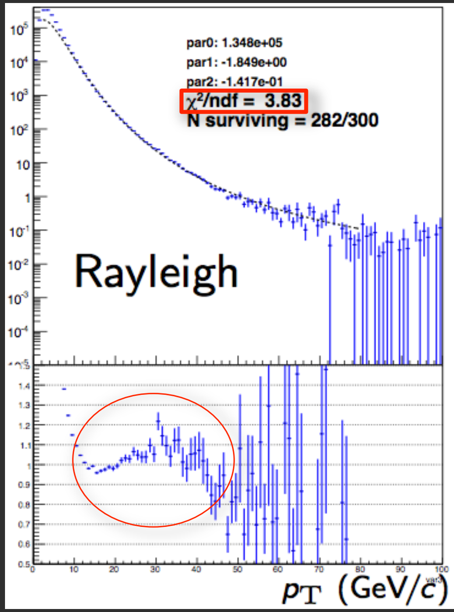
- The background mainly consists of muons from heavy-flavor decays
- Small shadowing effects expected at high p_T : use FONLL p_T shapes in the generation of D and B mesons
- Phenomenological functions used by CMS, ATLAS and LHCb collaboration for similar measurements at the LHC

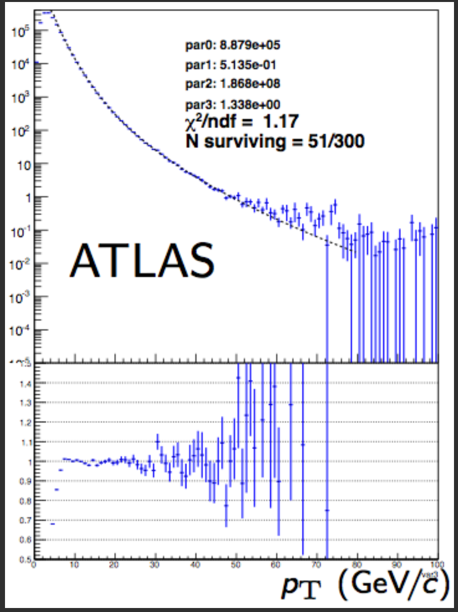
Rayleigh: $$f(p_T) = C \cdot p_T \cdot \exp\left(-\frac{p_T^2}{2(A+B\cdot p_T)^2}\right)$$ [Phys. Lett. B 715 (2012) 66]

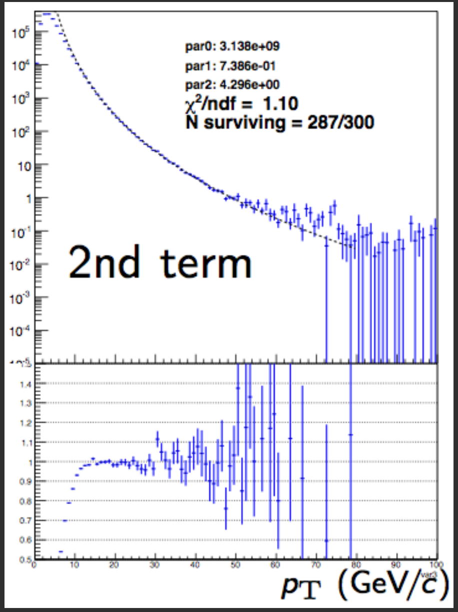
ATLAS: $$f(p_T) = A \cdot e^{-B\cdot p_T} + C \cdot \frac{e^{D\cdot\sqrt{p_T}}}{p_T^{2.5}}$$ [ATLAS-CONF-2011-078]

ATLAS 2nd term: $$f(p_T) = C \cdot \frac{e^{D\cdot\sqrt{p_T}}}{p_T^{E}}$$

- Test on FONLL-based MC template: reject Rayleigh



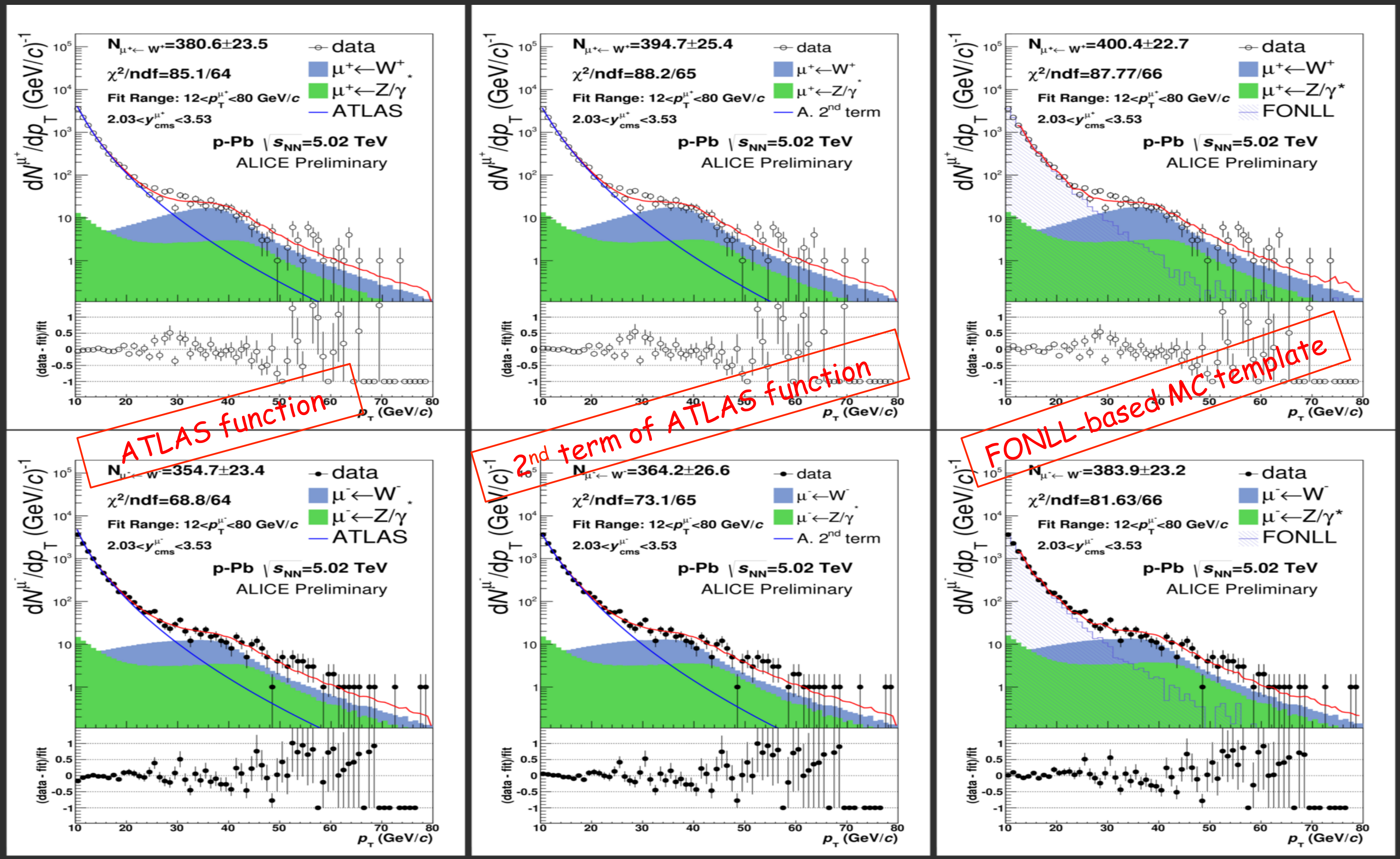




Example of W signal extraction (forward)

- The yield of $\mu^{\pm} \leftarrow W^{\pm}$ is defined as the integral W template for $p_T > 10$ GeV/c
- Fit range : $12 < p_T < 80$ GeV/c

Example of fit in forward rapidity:



- Three different shapes are used to provide a systematic uncertainty

Systematic on signal extraction

- Signal extraction : several fits performed on the muon p_T distribution (trials) by varying the fit configuration
  - heavy-flavor background description → change fit functions and p_T range of fit
  - fraction of muons from Z^0/γ^* decays → use difference between POWHEG and PYTHIA
  - alignment effects → vary the detector positions in simulations within uncertainties on alignment
- Shadowing effects : use PYTHIA (with EPS09) for W templates
- The yield of $\mu^{\pm} \leftarrow W^{\pm}$ is defined as the weighted average of the trials :
  - the results of (3 background descriptions) x (1 MC templates for signal) x (different p_T ranges) x (2 values of $N_{\mu \leftarrow Z/\gamma^*}/N_{\mu \leftarrow W}$) x (2 residual alignment files) are merged together to obtain the final value

$$\langle N_W \rangle = \frac{\sum_{i=1}^{n} w_i N_{\mu \leftarrow W,i}}{\sum_{i=1}^{n} w_i}$$

$$w_i = \frac{1}{\left(\frac{\sigma_{\mu \leftarrow W}}{\sqrt{N_{\mu \leftarrow W}}}\right)^2}$$

- The statistical error is given by propagating the error on each trial :

$$\sigma^{stat.}_{\langle N \mu \leftarrow W \rangle} = \frac{\sqrt{\sum_{i=1}^{n} (w_i \sigma_{\mu \leftarrow W,i})^2}}{\sum_{i=1}^{n} w_i} \cdot \sqrt{n}$$

- Assuming that the results from different trials come from a uniform distribution, one can finally estimate the systematic uncertainty as :

$$\sigma^{syst.}_{\langle N \mu \leftarrow W \rangle} = \frac{Max(N_{\mu \leftarrow W,i}) - Min(N_{\mu \leftarrow W,i})}{\sqrt{12}}$$

Acceptance x Efficiency: alignment effects

- The results should be corrected by Acc. x Eff.
- Acc. x Eff. is determined from the same simulations used to obtain the $\mu^{\pm} \leftarrow W^{\pm}$ templates

	forward		backward	
	μ^+	μ^-	μ^+	μ^-
Acc. x Eff.	0.889	0.887	0.773	0.754

Alignment effect :

- Systematics due to alignment are estimated by varying the alignment in the simulations and found to be < 1%

Tracking/trigger efficiency :

- Systematic uncertainties for muon tracks :
  - Tracking: 2%   Trigger: 1% (detector efficiency only at high p_T)   Matching: 0.5%
- Propagation to the number of muons from W decays
- A conservative uncertainty of 2.5% is considered for all multiplicity bins

Normalization

- MSL: muon single low p_T trigger (p_T >~ 0.5 GeV/c), MSH: muon single high p_T trigger (p_T >~ 4.2 GeV/c)
- MSH events must be normalized to equivalent minimum bias to obtain the cross-section
- Normalization factors estimated with two methods :
  - Offline method which uses trigger inputs :

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

    where $F_{pile-up} = \mu/(1-e^{-\mu})$ and μ is the mean value of Poisson distribution

  - Trigger scalers which use Level 0 (L0b) trigger counters :

$$F_{norm}^{MSH} = \frac{L0b_{MB} \times purity_{MB} \times F_{pile-up}}{L0b_{MSH} \times PS_{MSH}}$$

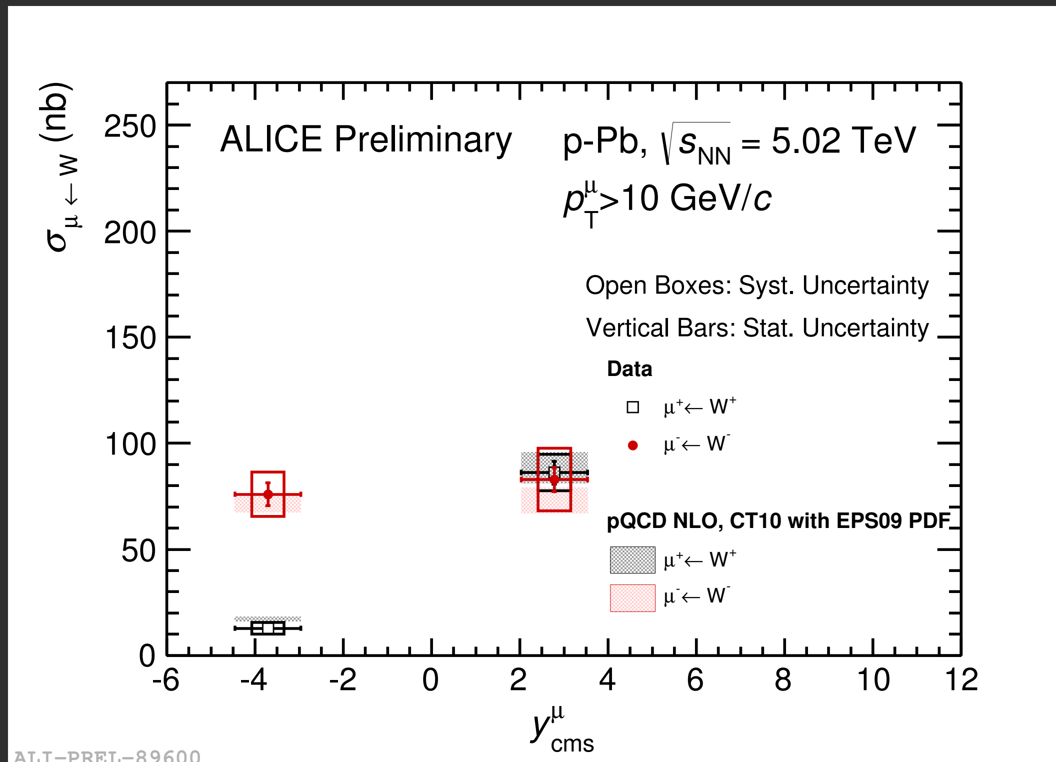
    PS_{MSH} fraction of accepted high p_T triggered events which pass the physics selection

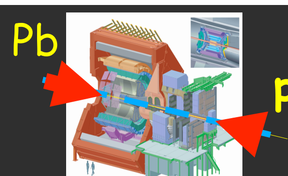
- The difference of the methods is used as systematic uncertainty (1%)
- MB cross sections :
  - p-Pb (forward) : 2.09 ± 0.07 b
  - p-Pb (backward) : 2.12 ± 0.06 b

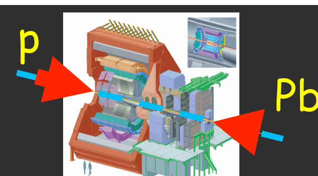
$$\sigma_{\mu \leftarrow W} = \frac{N_{\mu \leftarrow W}}{Acc. \times Eff.} \times \frac{\sigma_{MB}}{N_{MSH} \times F_{norm}}$$

Results: cross section vs. rapidity

- Cross section of muons from W decays with 2.03 < y_{CMS} < 3.53 (forward) and -4.46 < y_{CMS} < -2.96 (backward), p_T^{μ} > 10 GeV/c at $\sqrt{s_{NN}}$ = 5.02 TeV in p-Pb collisions



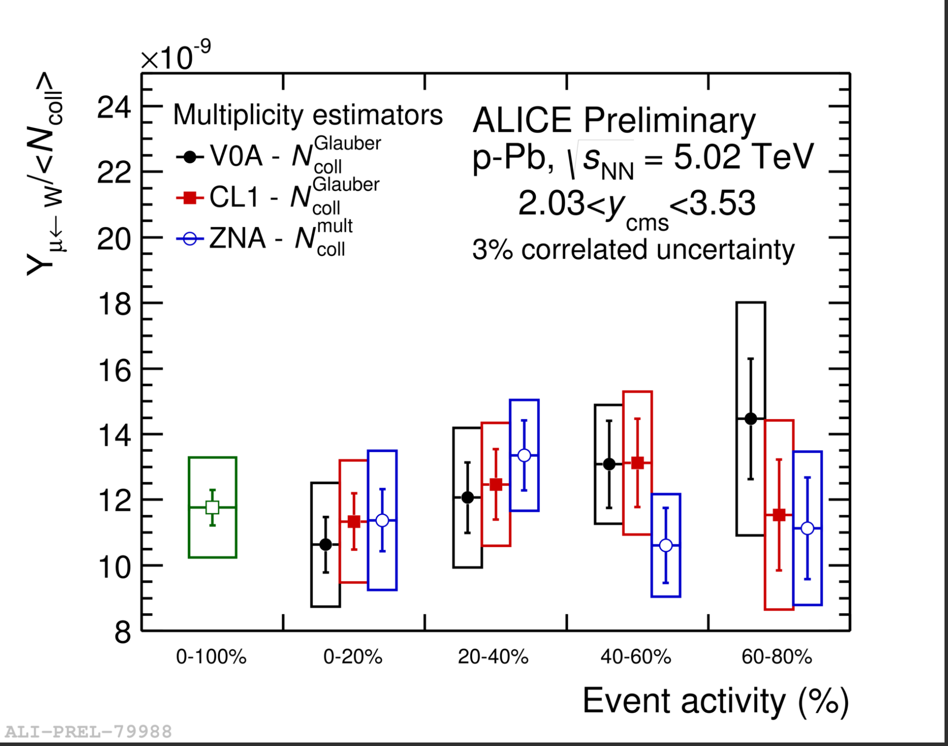




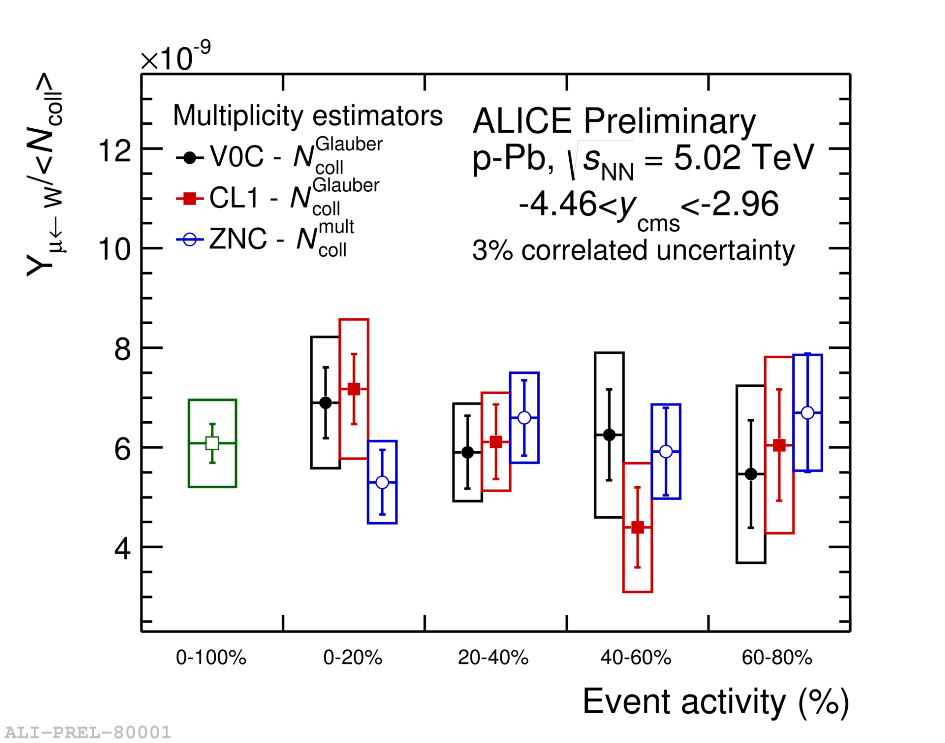
- ✓ Cross sections of muons from W decays are consistent with predictions including nPDFs
- ✓ More W^- than W^+ at backward rapidity

Results: Yield/$\langle N_{coll} \rangle$ vs. event activity

- In order to increase statistics, $\mu^+ \leftarrow W^+$ and $\mu^- \leftarrow W^-$ were added
- In case $\langle N_{coll} \rangle$ estimation is not biased, $Y/\langle N_{coll} \rangle$ is not expected to depend on event activity



forward



backward

- Behavior of different multiplicity estimators compatible within uncertainties

Conclusion

- The production of muons from W decays was measured in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV in the ranges 2.03 < y^{μ}_{CMS} < 3.53 and -4.46 < y^{μ}_{CMS} < -2.96, p_T^{μ} > 10 GeV/c

- Results:
  - ✓ cross section of muons with p_T^{μ} > 10 GeV/c as a function of y_{CMS}
  - ✓ yields/$\langle N_{coll} \rangle$ using different multiplicity estimators to determine $\langle N_{coll} \rangle$: yield in different event activity bins found to scale with $\langle N_{coll} \rangle$ within (large) uncertainties

- Cross sections are compared with predictions including nPDFs :
  - ✓ agreement within uncertainties

Outlook :

- Improve the determination of the systematic errors
  - drop LO generator (PYTHIA), include EPS09 in NLO generator (POWHEG)
  - use different set of PDFs and other NLO generator to re-weight POWHEG production
  - better estimation of alignment effects
  - cross-check in p-p collisions

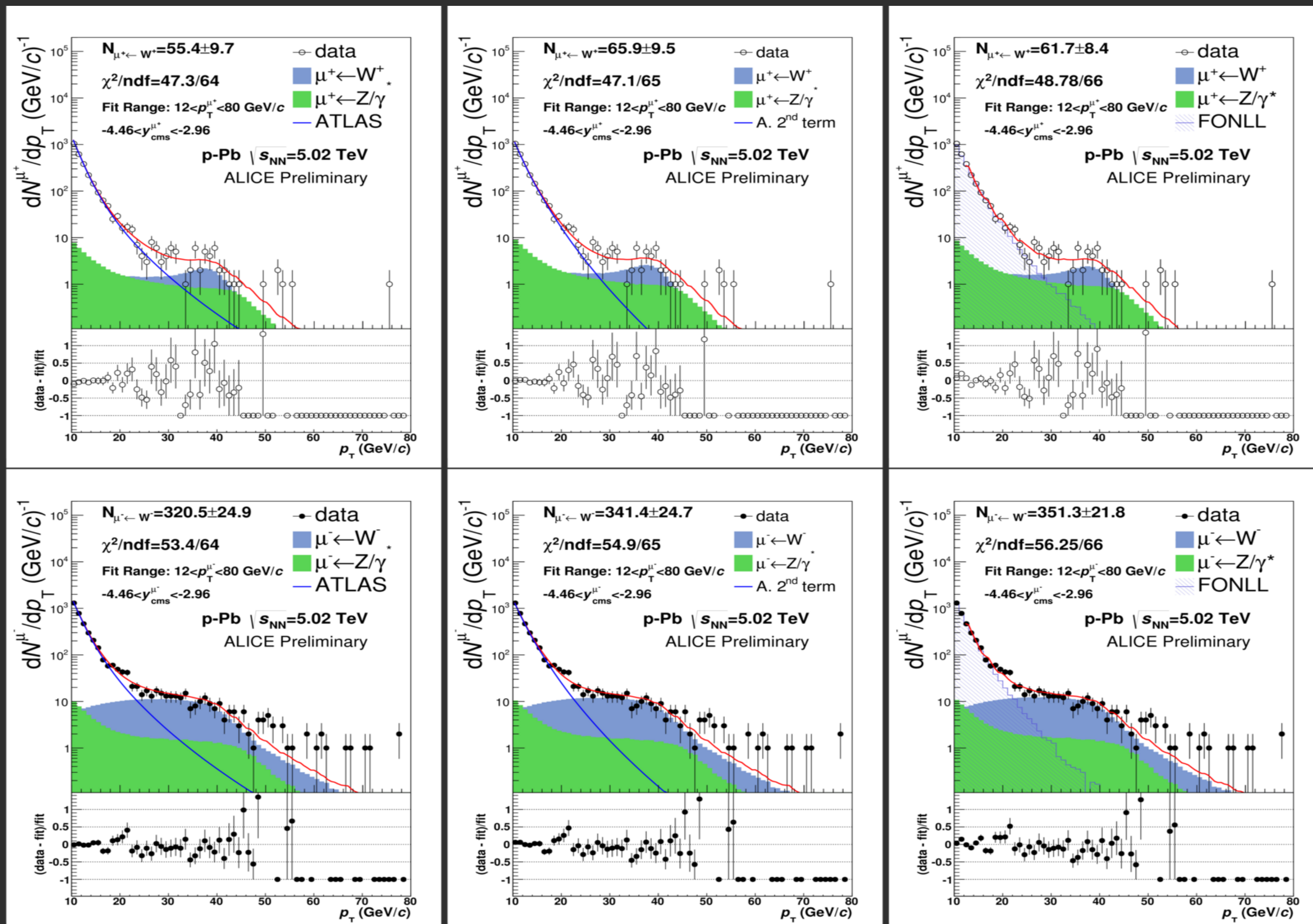
Backup

Example of combined fit (backward)

ATLAS function

2nd term of ATLAS function

FONLL-based MC template



Yileds of muons from W decays normalized to binary number of collisions

	V0A		CL1		V0C		Hybrid ZNA	
Multiplicity	$\langle N_{coll} \rangle$	syst.	$\langle N_{coll} \rangle$	syst.	$\langle N_{coll} \rangle$	syst.	$\langle N_{coll} \rangle$	syst.
0-20%	12.8	11%	13.4	11%	12.85	11%	11.5	9.3%
20-40%	9.36	10%	9.51	10%	9.39	10%	9.57	8.1%
40-60%	6.42	9%	6.29	9%	6.40	9%	7.01	9.9%
60-80%	3.81	21%	3.52	21%	3.74	21%	4.33	12.7%
0-100%	$\langle N_{coll} \rangle$: 6.8835 syst. : 8%							

- In order to increase the statistics, the results for $\mu^+ \leftarrow W^+$ and $\mu^- \leftarrow W^-$ are summed together
- The systematic uncertainties on signal extraction are considered as uncorrelated and summed in quadrature
- The uncertainties on the normalization factor and tracking & trigger uncertainties and efficiency are fully correlated among μ^+ and μ^- and also among the different multiplicity bins
- The uncertainties on Acc.xEff. are uncorrelated for μ^+ and μ^-, but correlated with multiplicity
- The uncertainties on pile-up and $\langle N_{coll} \rangle$ are correlated among μ^+ and μ^-, but uncorrelated in multiplicity

Summary of systematic uncertainties

- Systematic on the generator is based on : the NLO generator POWHEG and PYTHIA6.4 which is used to take into account systematics on nPDFs

- Other possible sources :
  - ✓ input PDFs
  - ✓ The ratio of Z^0/γ^*
  - ✓ All of above are < 1%

- The summary of systematics considered is shown below :

Signal extraction (includes alignment, fit stability/shape, etc.)	from ~ 6% to ~ 24%
Acc.xEff. - track./trig. Efficiencies - alignment	2.5% 1%
Normalization to MB - F_{norm} - σ_{MB} Pile-up	1% 3.2% (forward) 3% (backward) from 0 to 7.5%
Normalization to $\langle N_{coll} \rangle$	from 8% to 21% depending on bin