Measurement of W-boson production in p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV with ALICE

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Outline

- Physics motivation
- ALICE layout and data sample
- Analysis strategy :
  - measure muons from W decays at forward (p-side) and backward (Pb-side) rapidities
  - W signal extraction
  - Acc. x Eff. Correction
  - normalization
- Results :
  - cross-section vs. rapidity
  - Yield/$\langle N_{coll} \rangle$ vs. multiplicity
- Conclusion

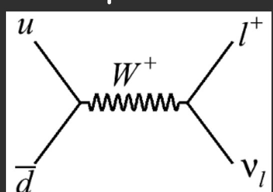
Physics motivation

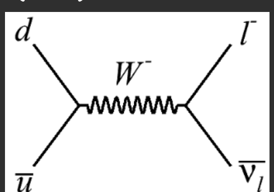
❖ Why ?

- Electroweak (EW) bosons are produced in initial hard partonic scattering processes
- In p-p collisions :
  - ✓ W boson production mechanism (e.g. via q-$\bar{q}$ annihilation) makes it sensitive to parton distribution functions (PDFs)
- In p-Pb collisions :
  - ✓ investigate the cold nuclear matter effects
  - ✓ modification of PDFs in nuclei
- In Pb-Pb collisions :
  - ✓ produced before QGP is formed
  - ✓ colorless probes which are supposed not to interact with QGP
- Luminosity and detector alignment cross-checks

❖ How ?

- Dominant production processes (LO)





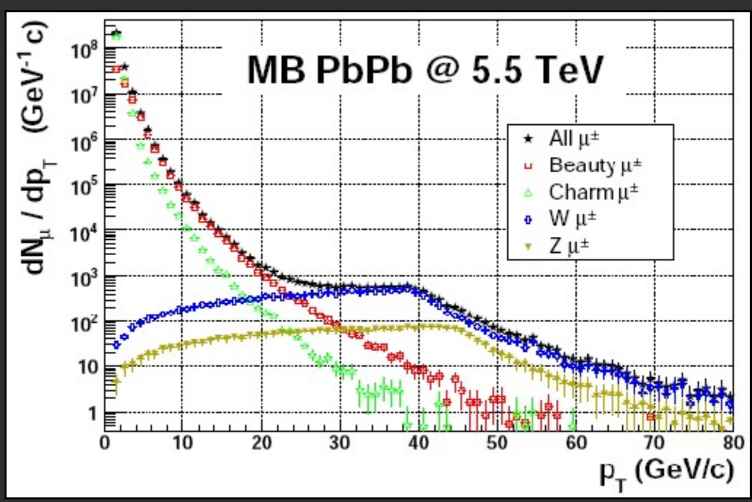
- Detected through their muonic decay :

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

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

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

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

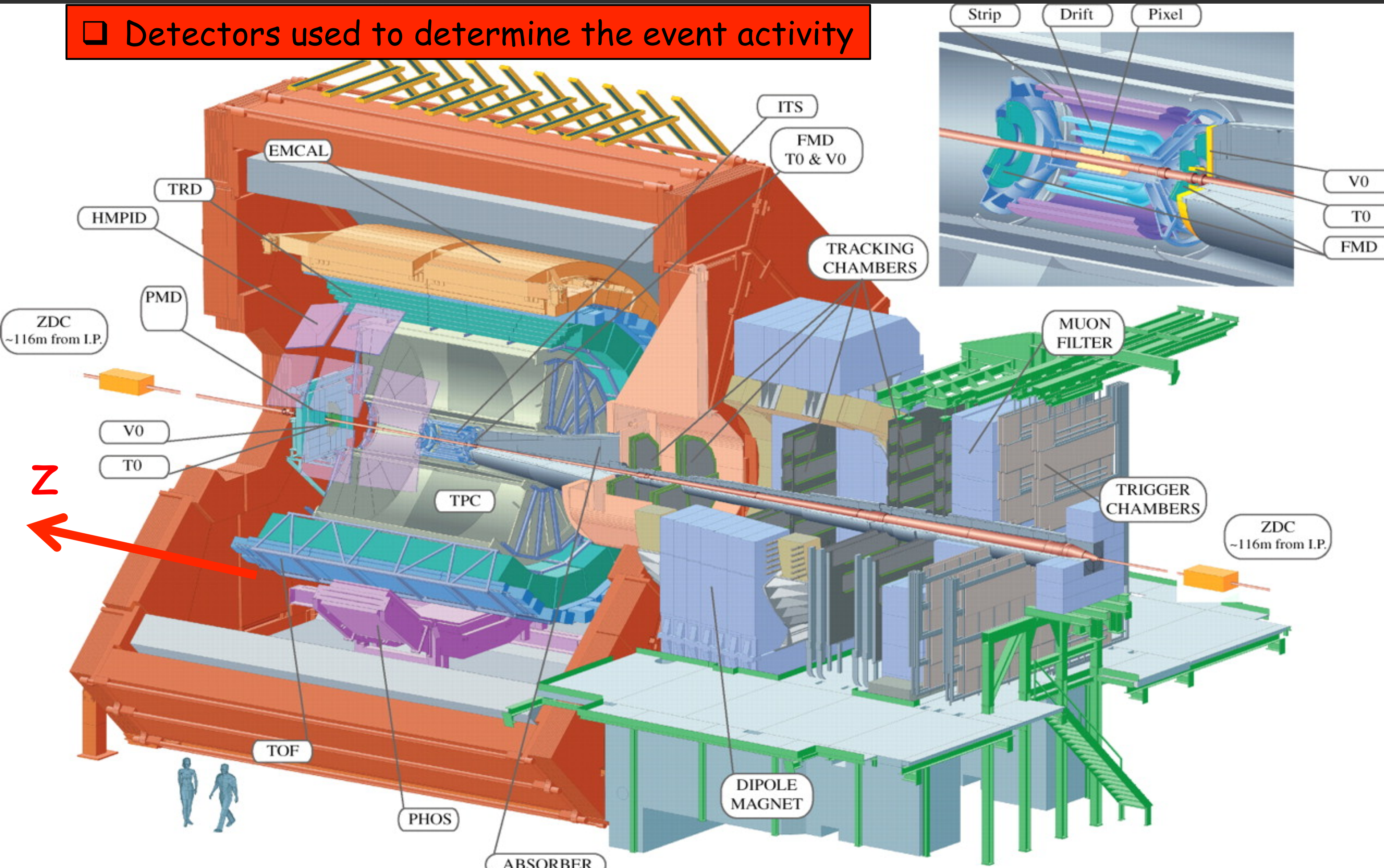


❖ Where ?

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

ALICE detector layout (I)

- Detectors used to determine the event activity



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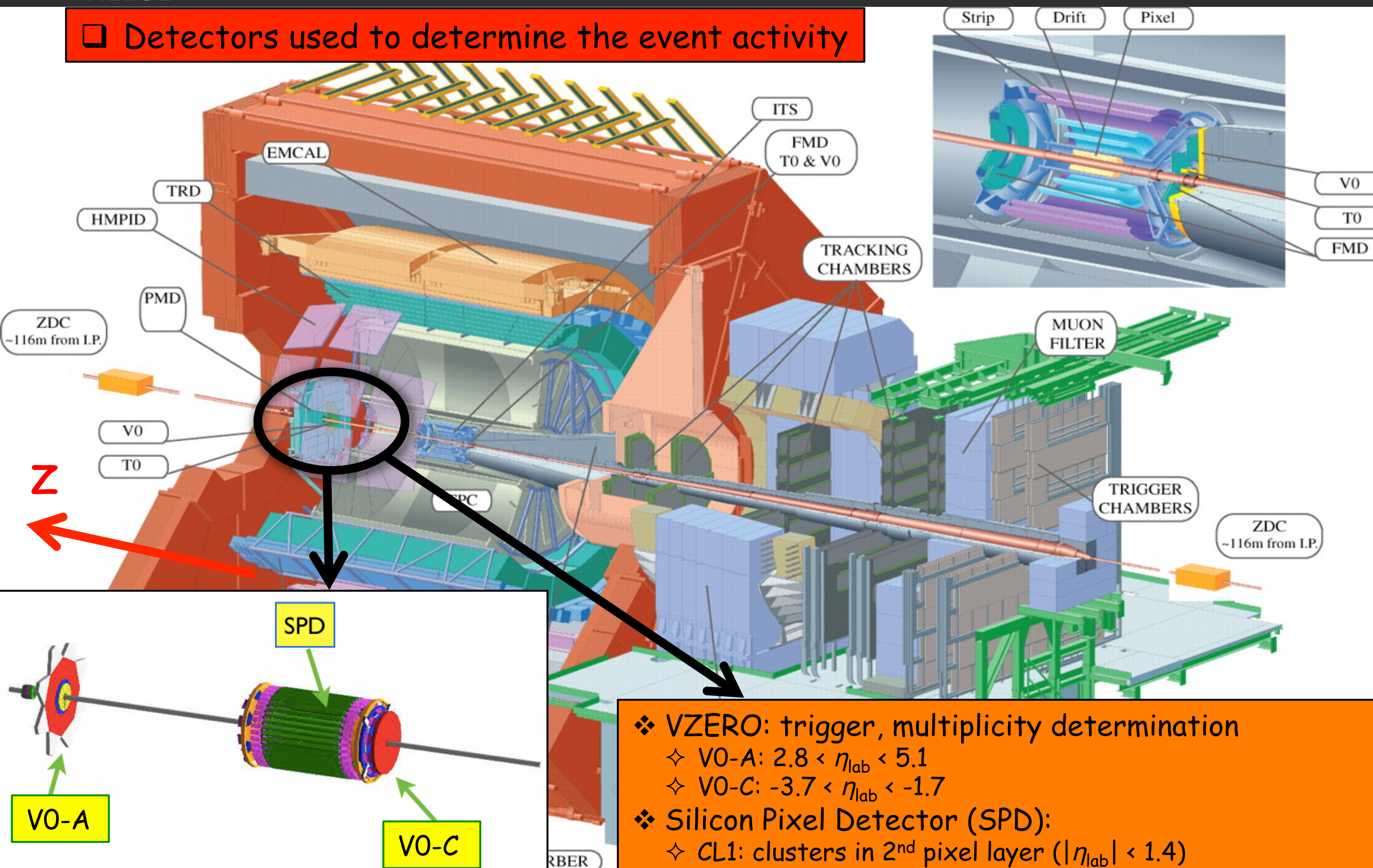
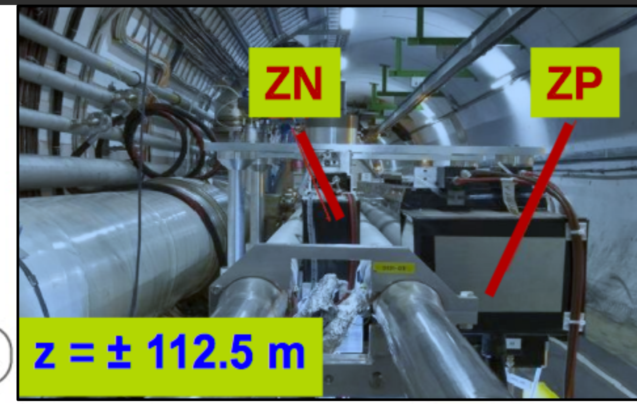


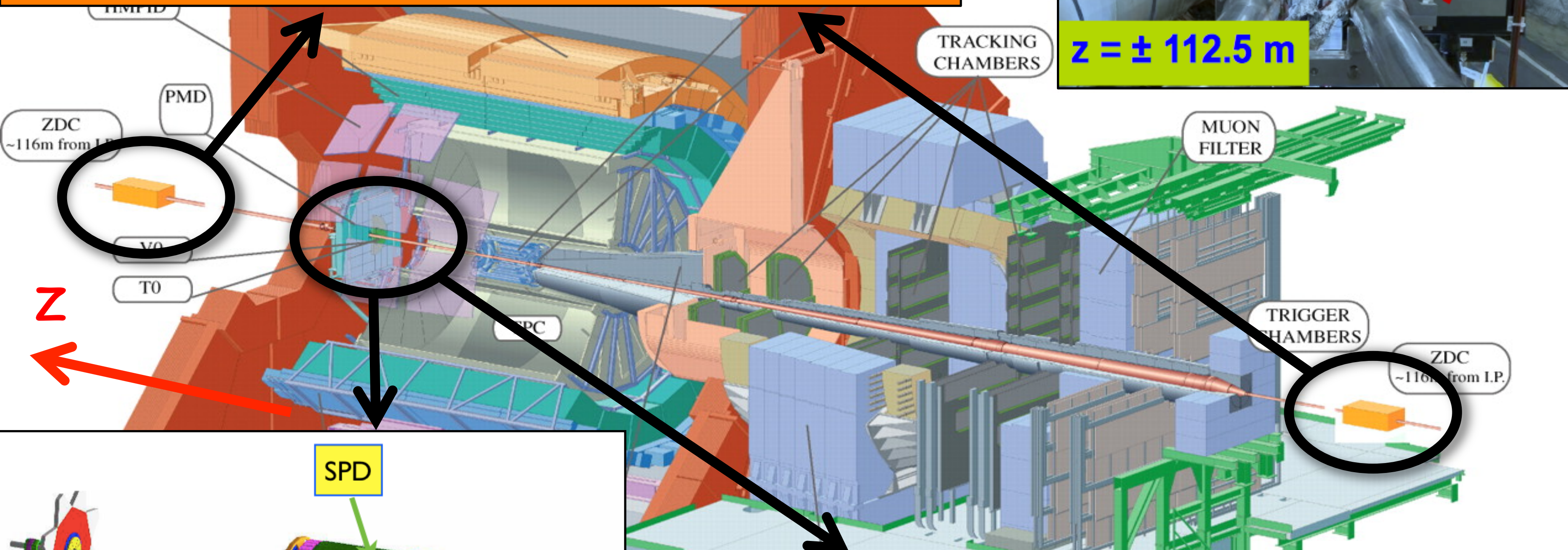
- VZERO: trigger, multiplicity determination
  - V0-A: $2.8 < \eta_{lab} < 5.1$
  - V0-C: $-3.7 < \eta_{lab} < -1.7$
- Silicon Pixel Detector (SPD):
  - CL1: clusters in 2[nd] pixel layer ($|\eta_{lab}| < 1.4$)

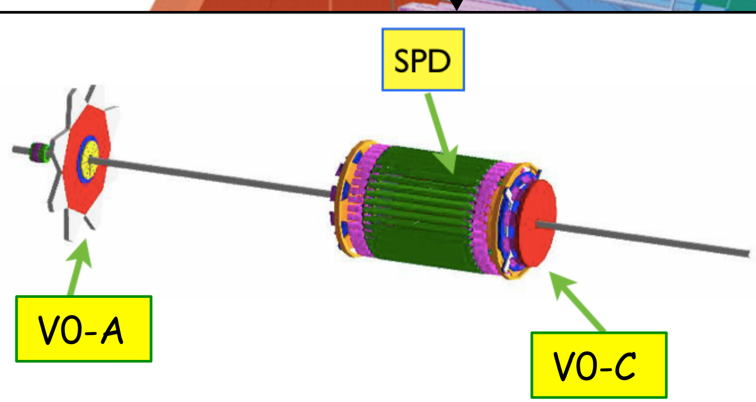
ALICE detector layout (I)

❑ Detectors used to determine the event activity

❖ Zero Degree Calorimeter (ZDC):
- ✧ ZNA (+112.5 m from I.P.), ZNC (-112.5 m from I.P.)
- ✧ each ZN is placed at zero degree with respect to the beam axis and is used to detect neutral particles at $|\eta_{lab}| > 8.7$







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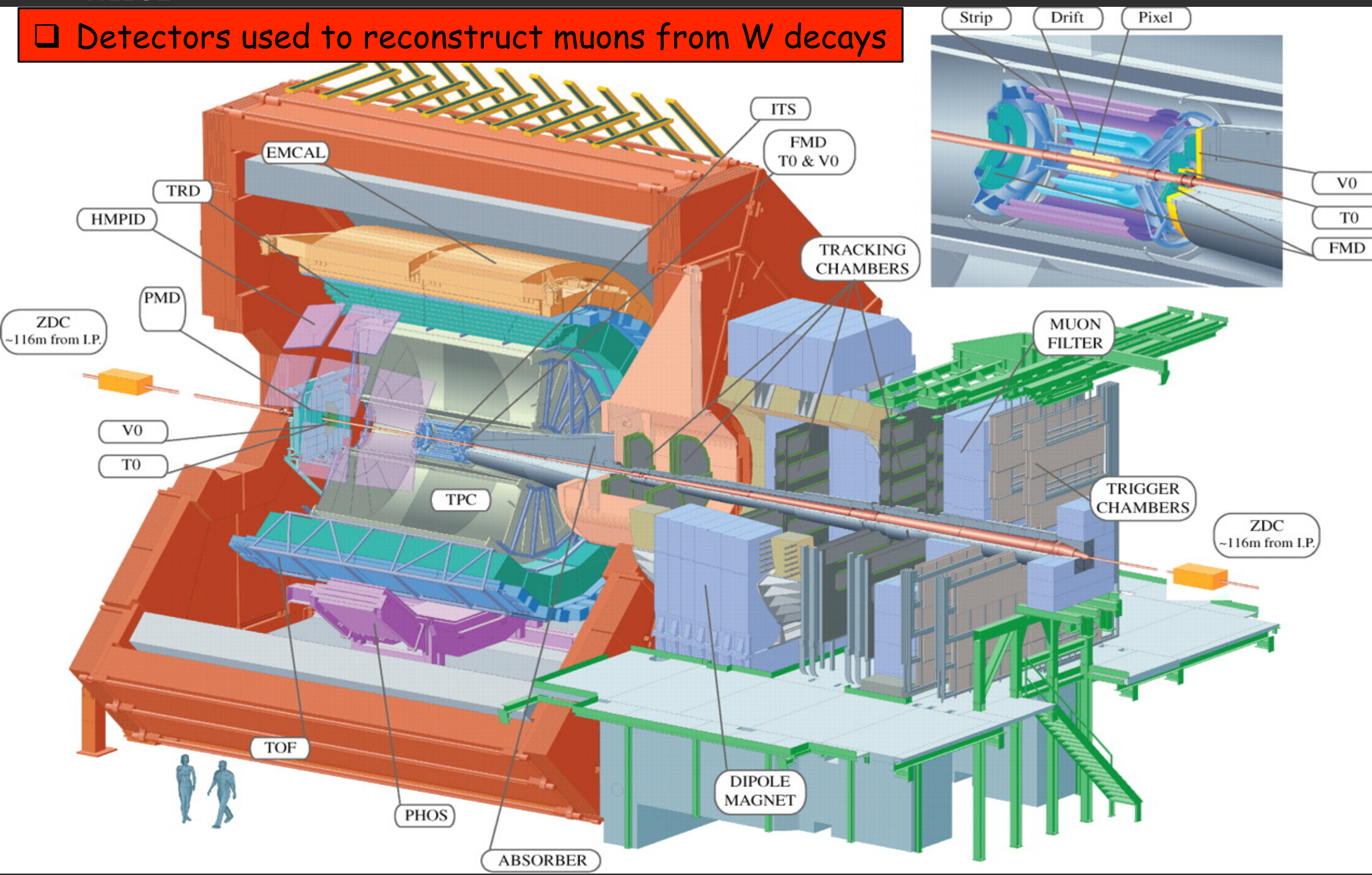
ALICE detector layout (II)

- Detectors used to reconstruct muons from W decays



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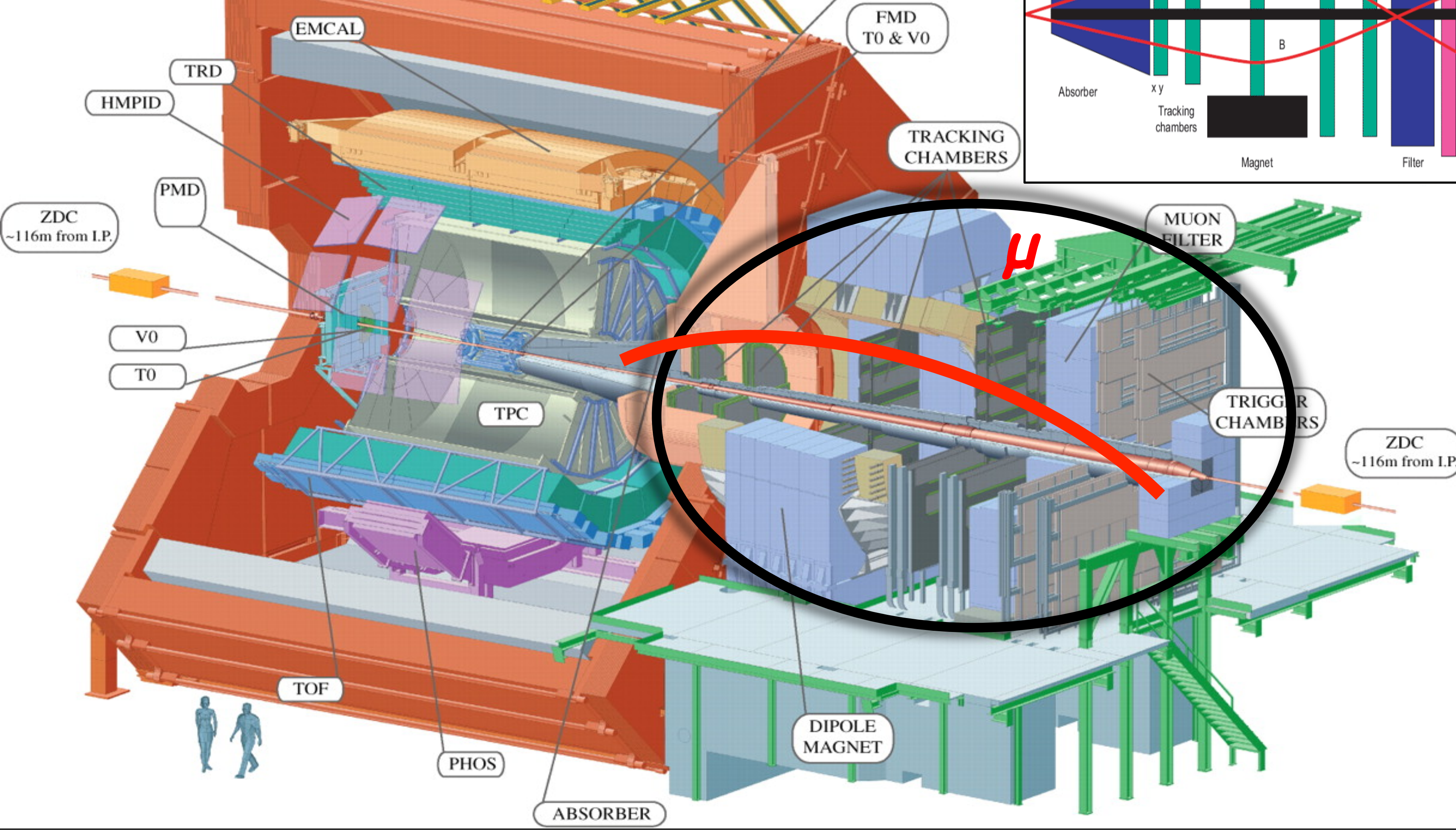

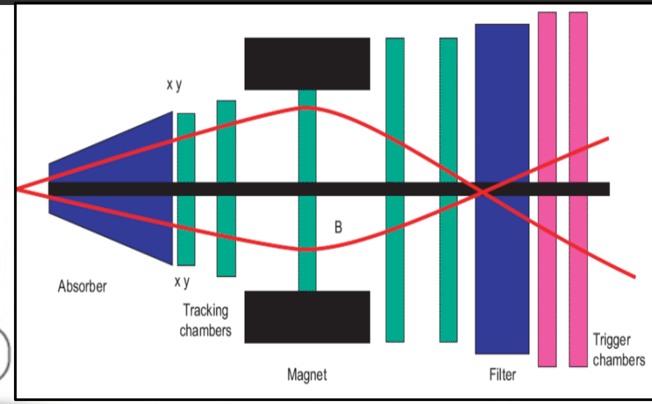

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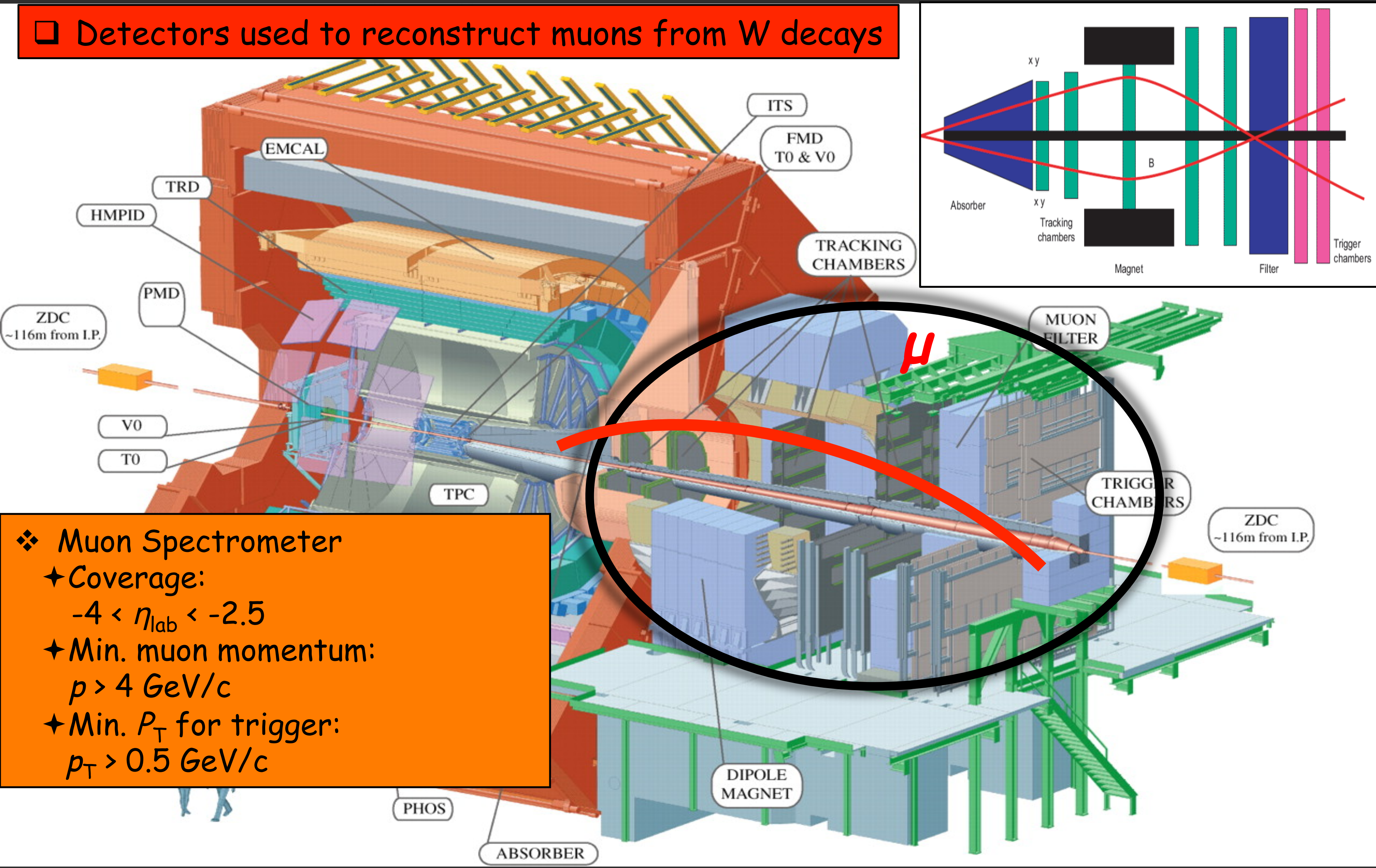
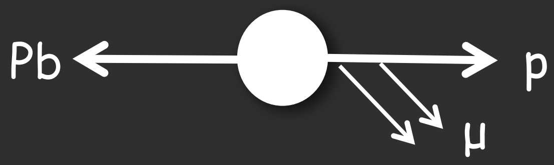


- Muon Spectrometer
  - Coverage: $-4 < \eta_{lab} < -2.5$
  - Min. muon momentum: $p > 4$ GeV/c
  - Min. P_T for trigger: $p_T > 0.5$ GeV/c

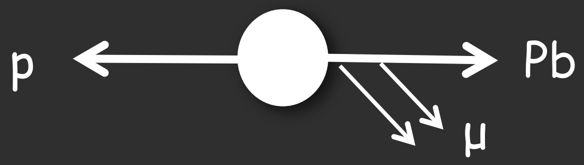
Data sample

❖ p-Pb collisions :

- Forward rapidity (p-going direction, $2.03 < y_{CMS} < 3.53$)



- Backward rapidity (Pb-going direction, $-4.46 < y_{CMS} < -2.96$)



- Center of mass energy: 5.02 TeV
- Trigger: Muon high p_T 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 (with high p_T) : reject punch-through hadrons
- pxDCA cut : correlation between momentum and distance of closest approach (DCA) which is to the interaction vertex to remove beam-gas tracks and fake tracks

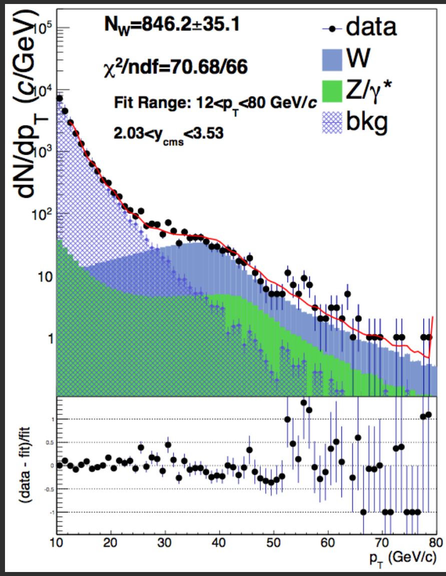
Analysis strategy

- $W^{\pm}$ is the main contributor in single muon momentum distribution at high p_T (p_T > 30 GeV/c)
- Heavy-flavor 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 (POWHEG)
  - 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
- Compare results with theory

$W^{\pm}$ 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
  - 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

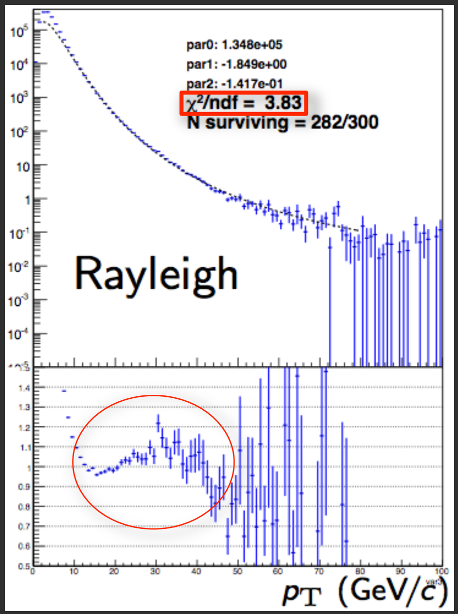
- The background mainly consists of muons from heavy-flavor (b+c) deacys
- Small shadowing effects expected at high p_T : use FONLL p_T shapes in the generation of D and B mesons
- Phenomenological functions used by CMS, ATLAS and LHCb collaboration for similar measurements at the LHC

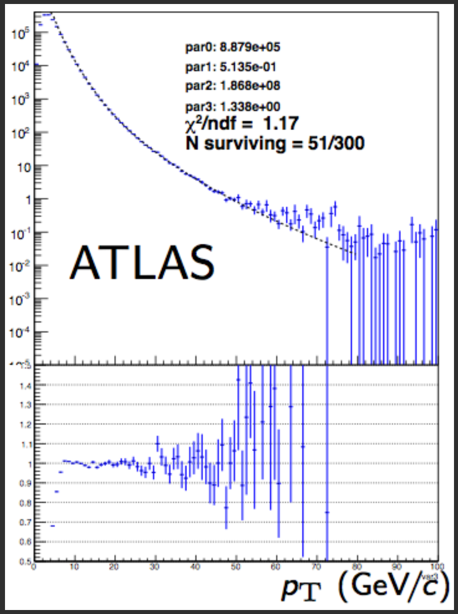
Rayleigh: $$f(p_T) = C \cdot p_T \cdot \exp\left(-\frac{p_T^2}{2(A + B \cdot p_T)^2}\right)$$ [Phys. Lett. B 715 (2012) 66]

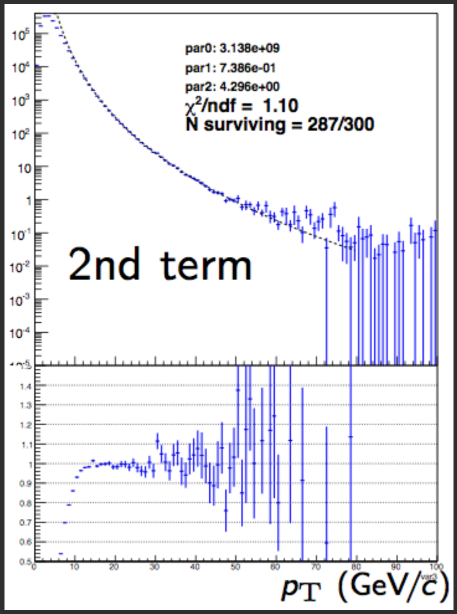
ATLAS: $$f(p_T) = A \cdot e^{-B \cdot p_T} + C \cdot \frac{e^{D \cdot \sqrt{p_T}}}{p_T^{2.5}}$$ [ATLAS-CONF-2011-078]

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



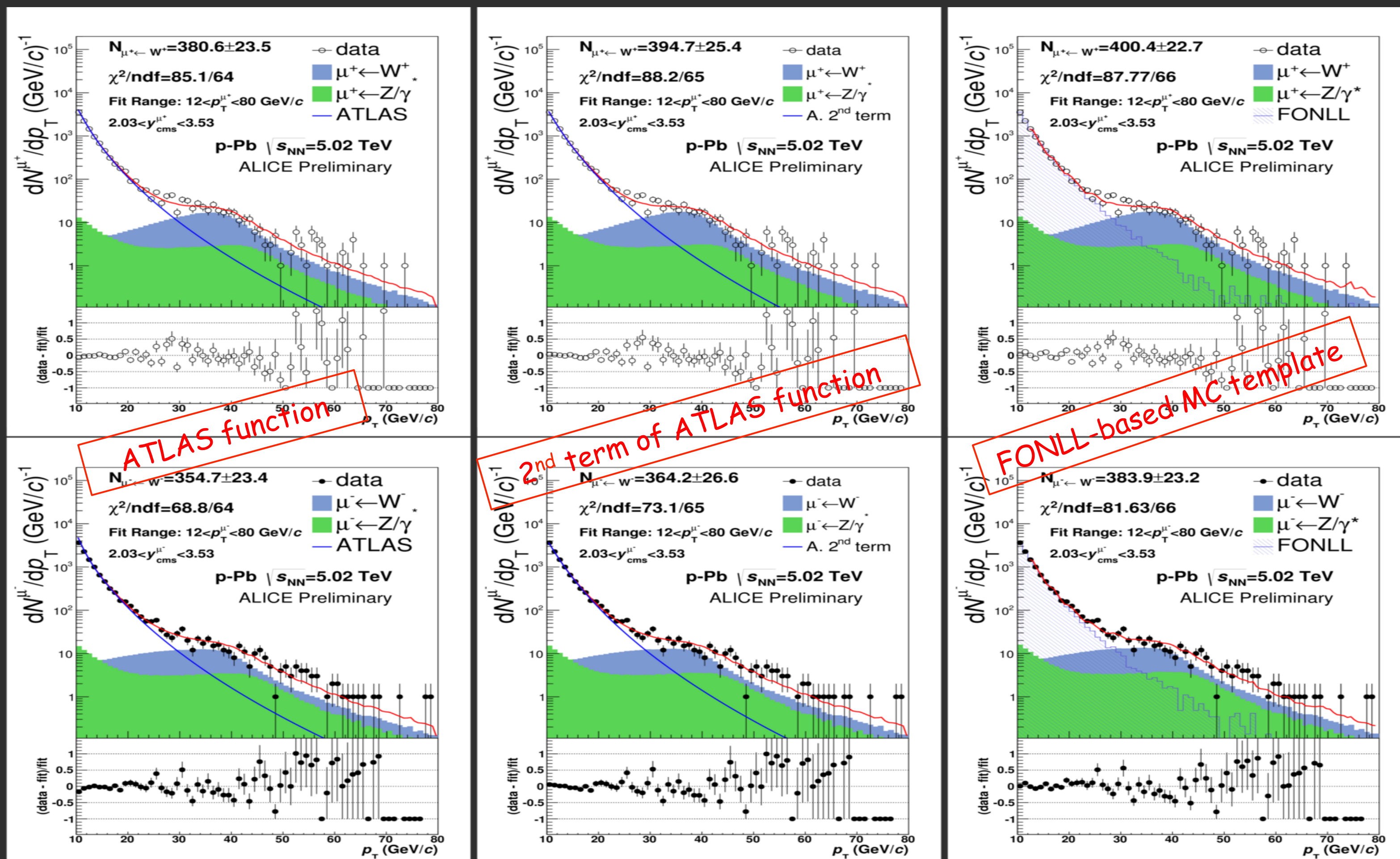




Example of W signal extraction (forward)

- 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:



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- Slight dependence of the W yield on the background description in the fit

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

- To take into account the systematic uncertainty of signal extraction, a weighted average over the trials is performed
  - the results of (3 background descriptions) x (1 MC templates for signal, POWHEG) 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

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

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

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

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

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

- **Shadowing effects :** use PYTHIA (with EPS09) for W templates

Acceptance x Efficiency: alignment effects

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- In order to get the real yield of W, 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.	0.888	0.887	0.775	0.760

Alignment effect :

- Systematics due to imperfect knowledge of the detector positions 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 :
  - assume above uncertainties are uncorrelated versus p_T →
  - assume full correlation
    - → the quadratic sum of the errors in the right table : 2.3%
- A conservative error of 2.5% is considered for all multiplicity bins

Multiplicity	$\sigma_{track/trigger}$
0-100%	2.65%
0-20%	-
20-40%	1.43%
40-60%	-
60-80%	1.77%

Normalization

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- 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 which describes the probability to have N collisions

  - 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, 2.03 < y_{CMS} < 3.53) : 2.09 ± 0.07 b
  - p-Pb (backward, -4.46 < y_{CMS} < -2.96) : 2.12 ± 0.06 b

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

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

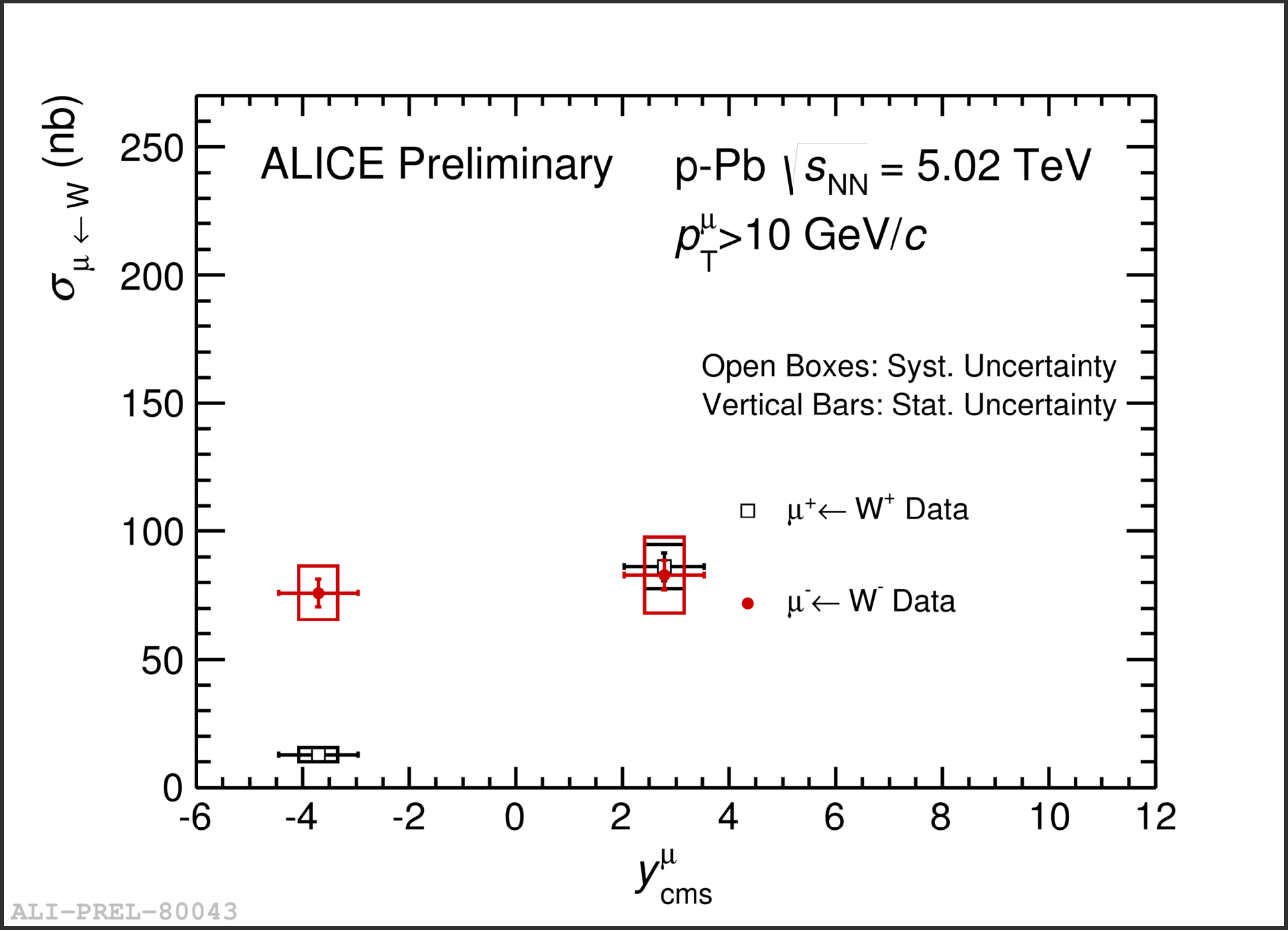
- Other possible sources :
  - ✓ input PDFs
  - ✓ The ratio of Z^0/Υ^*
  - ✓ All of above are < 1%

- 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% (LHC13de) 3% (LHC13f) from 0 to 7.5%
Normalization to $\langle N_{coll} \rangle$	from 8% to 21% depending on bin

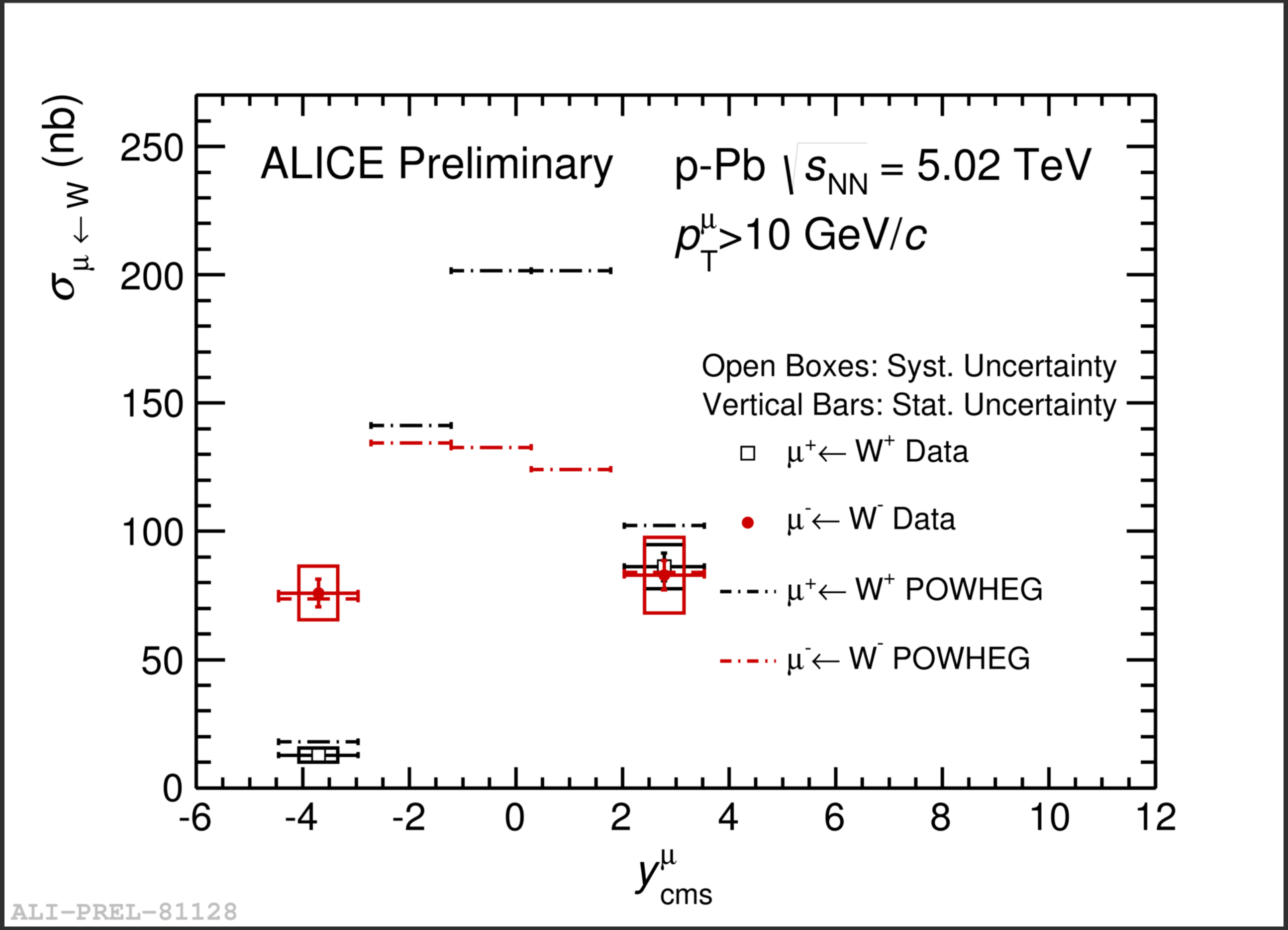
Results: cross-section vs. rapidity

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



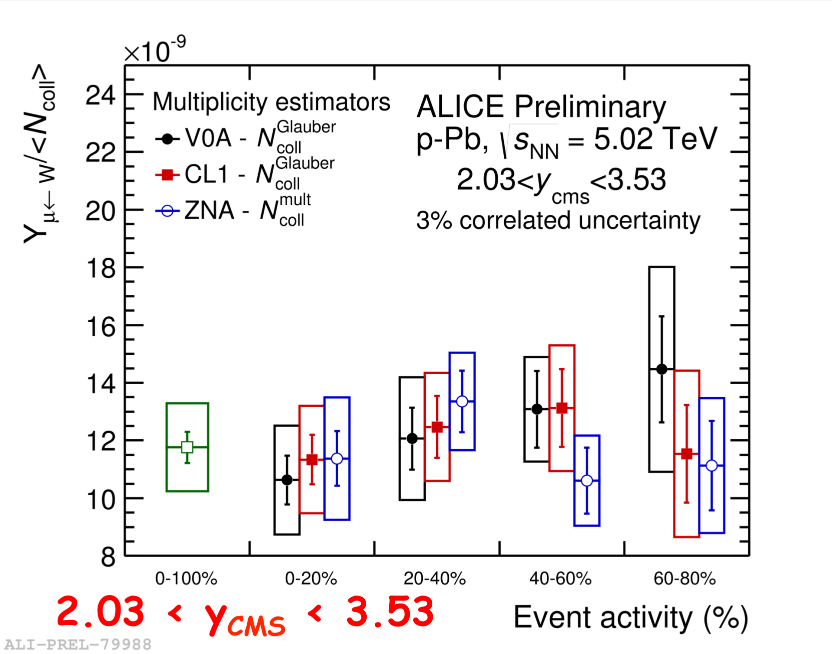
Results: cross-section vs. rapidity

- Cross section of muons from W decays with $2.03 < y_{CMS} < 3.53$ (forward) and $-4.46 < y_{CMS} < -2.96$ (backward), $p_T^{\mu} > 10$ GeV/*c* in p-Pb collisions
- Measurement is consistent with POWHEG cross-section within 1.5σ
- POWHEG here does not include nuclear PDF effects

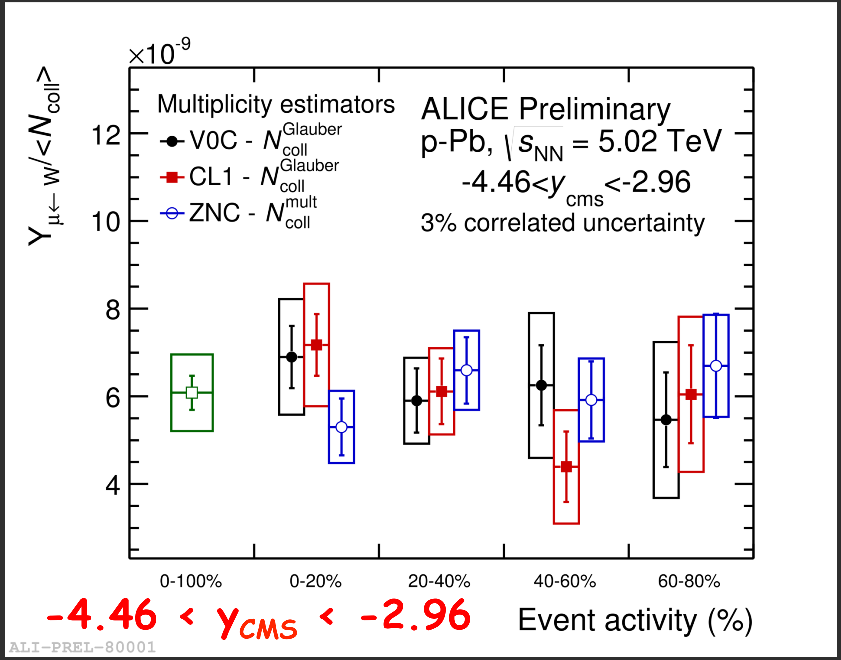


Results: yields vs. multiplicity normalized with $\langle N_{coll} \rangle$

- In order to increase statistics, $\mu^+ \leftarrow W^+$ and $\mu^- \leftarrow W^-$ were added
- Yields of muons from W decays normalized to $\langle N_{coll} \rangle$ as a function of multiplicity for CL1, V0A and ZNA (V0C and ZNC)
- Average number of collisions were estimated :
  - ✓ for V0A, V0C and CL1 : Glauber Model fits to multiplicity distribution
  - ✓ for ZNA and ZNC : scaling $\langle N_{part} \rangle$ in MB collisions by the ratio between the average multiplicity density measured at mid-rapidity given ZN energy event class and the one measured in MB collisions



2.03 < y_{CMS} < 3.53



-4.46 < y_{CMS} < -2.96

- 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 with 2.03 < y^{μ}_{CMS} < 3.53 and -4.46 < y^{μ}_{CMS} < -2.96, p_T^{μ} > 10 GeV/c

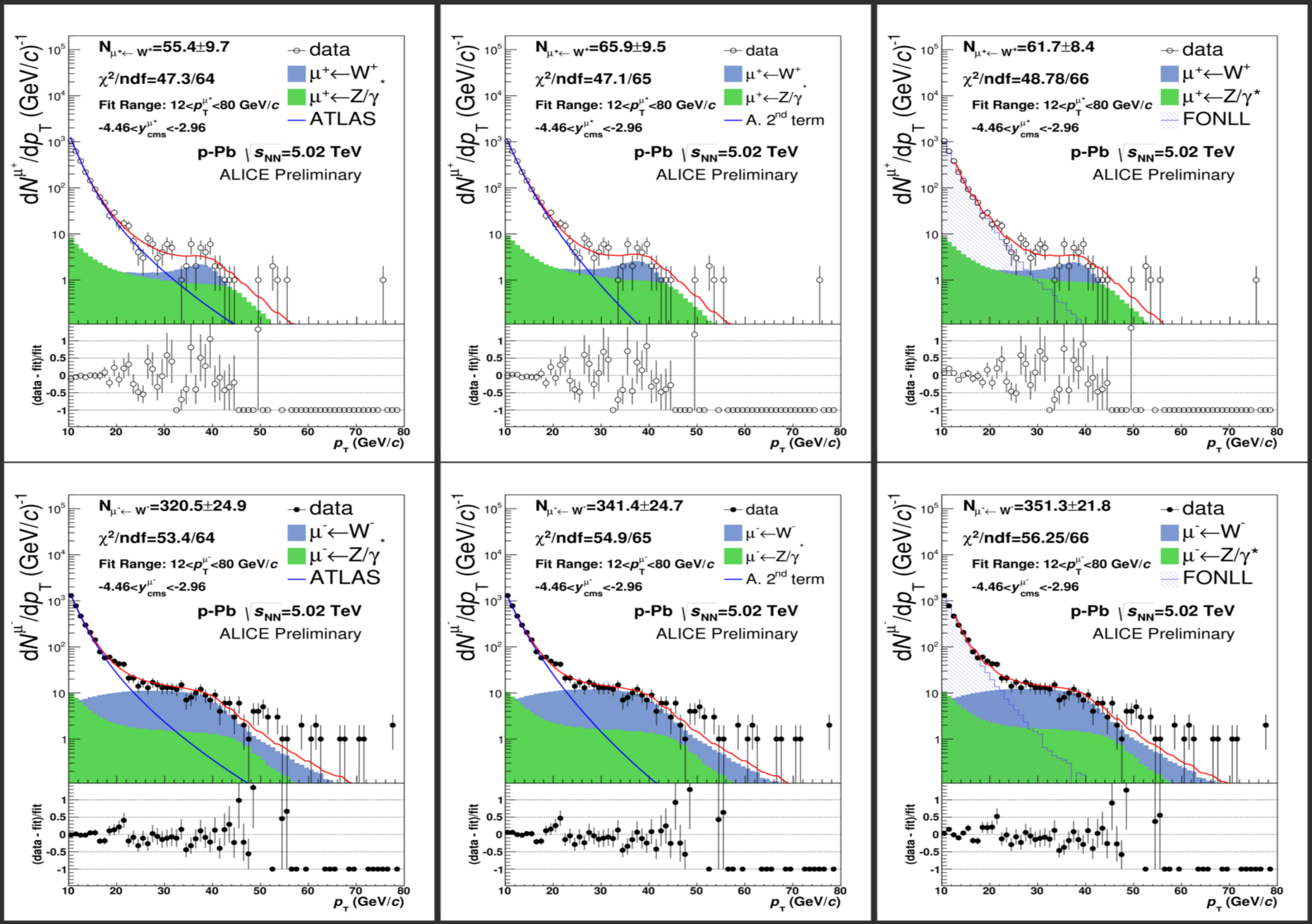
- Results:
  - Cross section of muons with p_T^{μ} > 10 GeV/c as a function of y_{CMS}
  - Yields/$\langle N_{coll} \rangle$ using different multiplicity estimators to determine $\langle N_{coll} \rangle$: yield in different event activity bins found to scale with N_{coll} within (large) uncertainties

- Cross section is compared with POWHEG: agreement within 1 (1.5) sigma for μ^- (μ^+)

Backup

Example of combined fit (backward)

ATLAS function | 2^{nd} term of ATLAS function | FONLL-based MC template



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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