Z production in p-Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV with ALICE

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Overview

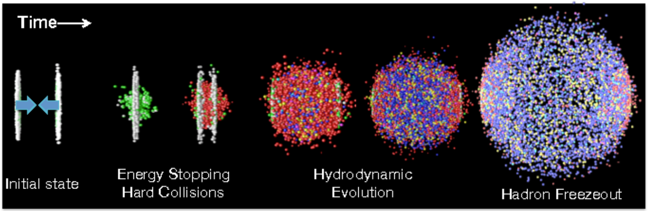
Topic: evaluate the production cross-section of the Z boson in heavy-ion collisions (p–Pb and Pb–p) $\sqrt{s_{\mathrm{NN}}} = 8.16\,\mathrm{TeV}$.

Goal: study the nuclear effects and constrain the nuclear partonic distribution functions.

Content :

- theory and experimental context,
- kinematics of the Z in HIC,
- data processing and signal extraction,
- efficiency factor,
- results, discussion and perspectives.

Heavy-ion collisions



initial state effects → QGP effects → final state effects

Experimental study of nuclear effects at colliders:

- p–p,
- p–A,
- A–A.

Nuclear effects:

- hot (QGP induced),
- cold (the others).

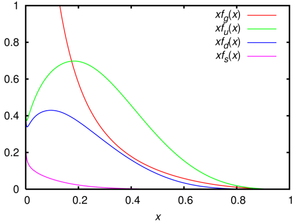
Need to disentangle hot and cold for QGP study.

Nuclear partonic distribution function

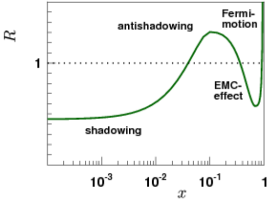
Partonic distribution function (PDF): probability of finding a parton carrying a fraction x of the total momentum at an energy Q^2.

Expect a difference between the PDF of a bound nucleon and the PDF of a free one (proton):

$$R(x, Q^2) = \frac{f_{nuclear}(x, Q^2)}{f_{proton}(x, Q^2)}$$



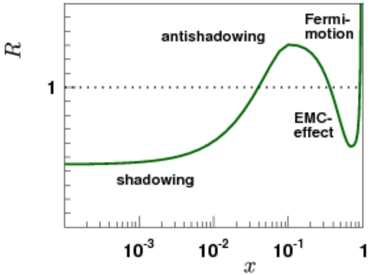
Nadolsky, PR, D78 (2008)



Paukkunen et Salgado, JHEP, 3 (2011)

Nuclear effects

Fermi motion: dynamics of the nucleons in the nucleus.
EMC effets: not yet fully understood, believed to come from the modification of the characteristics of the nucleon (radius and mass) when it is bound in a nucleus, as well as multi-nucleons effects.
Shadowing and **anti-shadowing**: constructive or destructive interferences of amplitudes due to multiple scatterings between partons in the nucleus.



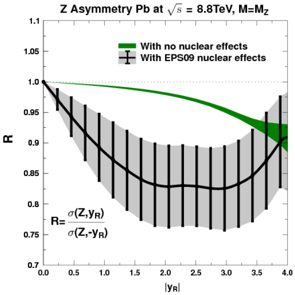
Paukkunen et Salgado, JHEP, 3 (2011)

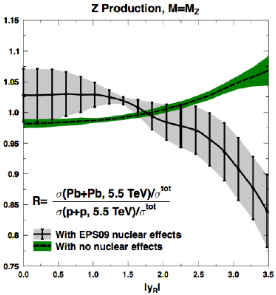
Nuclear modification factor

Key measurement in HIC: nuclear modification factor R_{AA}, ratio between the production cross-section in HIC to the one in proton–proton:

$$R_{AA} = \frac{1}{N_{bin}} \cdot \frac{\sigma_{AA}}{\sigma_{NN}}$$

$R_{AA} \neq 1$ points to nuclear modifications.





Paukkunen and Salgado, JHEP, 3 (2011)

Z in heavy-ion collisions I

Z known to a high degree of precision.

Mass M_Z (GeV)	Width Γ_Z (GeV)	Leptonic decay (%)
91.1876 ± 0.0021	2.4952 ± 0.0023	3.3658 ± 0.0023

In HIC : LO Drell-Yan process:

$$q\bar{q} \to Z/\gamma^* \to \mu^+\mu^-$$

Cross-section:

$$\sigma_{AB} = \sum_q \frac{4\pi e_q^2 \alpha^2}{9\hat{s}} f_q(x_1, Q^2) f_{\bar{q}}(x_2, Q^2)$$

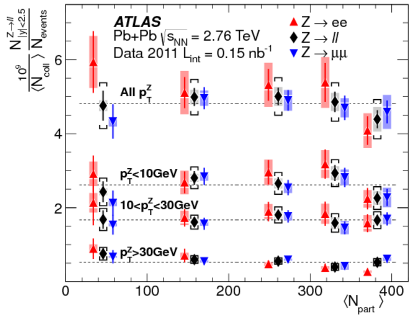
Z and muons:

- insensitive to strong interaction,
- EM interactions negligible (Conesa, EPJ C 61(4), 2009),
- insensitive to final state effects.

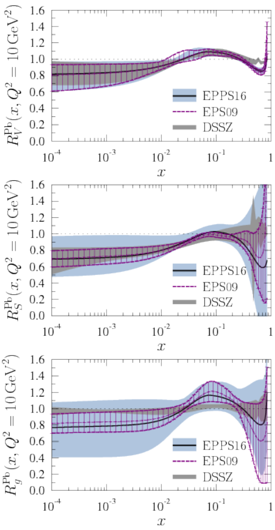
$\Rightarrow$ probe of the initial state, comparison between p–p, p–Pb and Pb–Pb

Z in heavy-ion collisions II

- probe of the PDF modifications,
- calibration of muons and electrons detectors,
- estimator of the collision centrality.



ATLAS, PRL, 110 (2013)

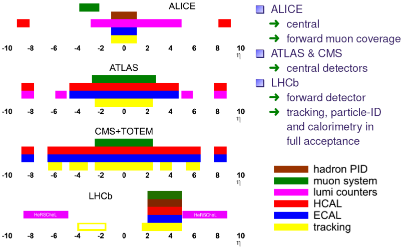


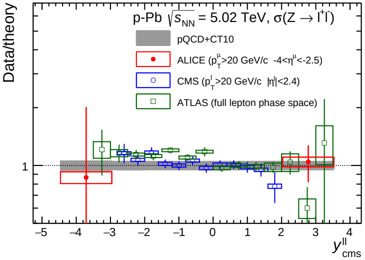
Eskola et al, EPJ, C77 (2017)

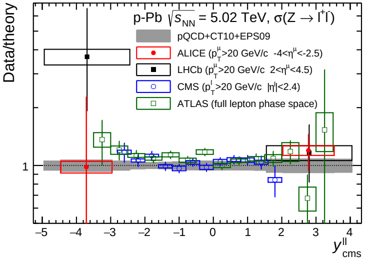
Z analysis at $\sqrt{s_{\rm NN}} = 5.02$ TeV

Z production measured by the four main LHC experiments, at various geometrical coverages.

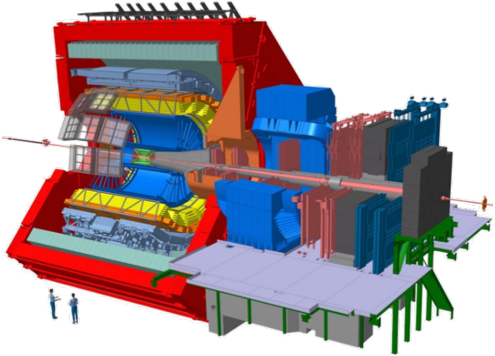
At $\sqrt{s_{\rm NN}} = 5.02$ TeV, unable to disentangle between CT10 (PDF) and CT10+EPS09 (nPDF).





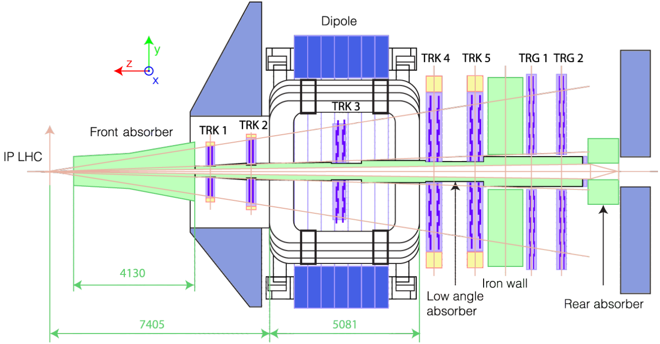


ALICE: generalities



Set of detectors around the collision point: vertex position, centrality, multiplicity, collision time...
Central barrel: hadrons, electrons and photons detection.
Muon spectrometer: weak bosons ($W^{\pm}$, Z), quarkonia (J/Ψ, Υ), low mass mesons (ρ, ϕ, ω), heavy flavour hadrons (charm and beauty).

ALICE: muon spectrometer



Trigger: 18 resistive plate chambers in two stations.
Tracking: 10 multi-wire proportional chambers, two-by-two in five stations.
Dipolar magnet: integrated field of 3 T m for charge and momentum measurements.
Absorbing system: background rejection.

FAST simulation

p–Pb and Pb–p collisions at à $\sqrt{s_{\mathrm{NN}}} = 8.1624\,\mathrm{TeV}$. 100,000 events for each configuration. Process: $q\bar{q} \rightarrow Z/\gamma^{*} \rightarrow \mu^{+}\mu^{-}$ at leading order (PYTHIA-6). No constrain on the emission.

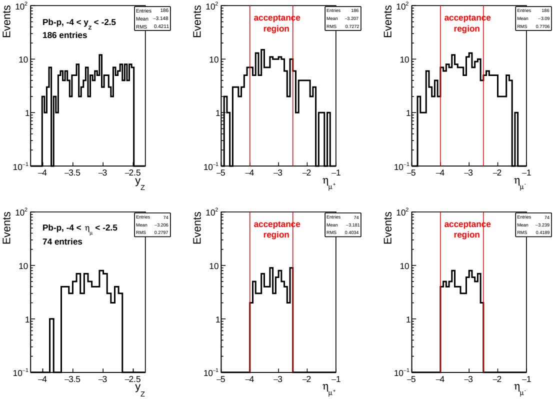
Goal: study the Z production kinematics, acceptance and background considerations.

Cuts:

- pseudo-rapidity: $-4 < \eta < -2.5$ to stay within the spectrometer acceptance,
- transverse momentum: $p_{\mathrm{T}} > 20\,\mathrm{GeV\,c^{-1}}$ to reject various background sources.

Acceptance

Spectrometer acceptance: $-4 < \eta < -2.5$, $\rightarrow$ cut on the muons pseudo-rapidity.

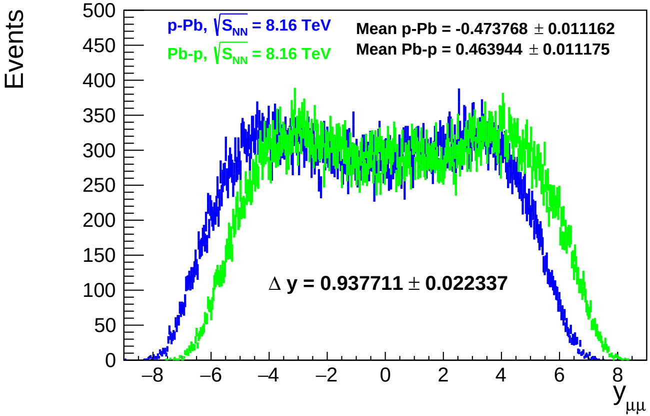


Decrease of the population: from 341 to 128 events in p–Pb, 186 to 74 events in Pb–p ($\simeq$ factor 2).

Rapidity shift

Proton–lead: asymetrical collisions, $y_{cm/lab} \neq 0$. Predicted shift:

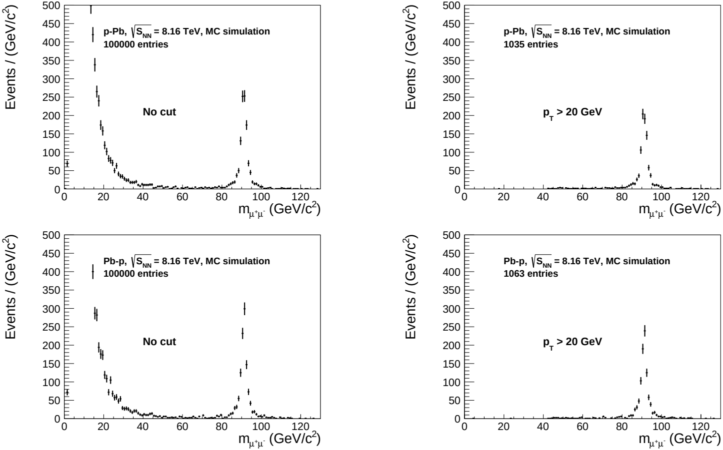
$$y = \pm 0.4654$$



p_{T} cut and γ^* contribution

Want to get rid of $q\bar{q} \to \gamma^* \to \mu^+\mu^-$. Solution: cut on the transverse momentum, suppress γ^*.

$\Rightarrow \gamma^*$ negligible (first approximation).



Framework

- Z production cross-section in heavy-ion collisions

Z in the muon channel, with individual muon tracks within the spectrometer acceptance. Fiducial region:

$$\begin{cases} -4.0 < \eta_\mu < -2.5, \\ p_{\mathrm{T}\mu} > 20\mathrm{GeV\,c^{-1}}, \\ 60 < m_{\mu\mu} < 120\mathrm{GeV\,c^{-2}}. \end{cases}$$

Cross-section in p–Pb:

$$\sigma_{Z\rightarrow\mu\mu}(2.03 < y_{CM} < 3.53)$$

Cross-section in Pb–p:

$$\sigma_{Z\rightarrow\mu\mu}(-4.46 < y_{CM} < -2.96)$$

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Outlook

- The analysis
  - Data samples and muon track selection
  - Signal extraction
  - Background contribution
  - MC full simulation and detector efficiency

- Results
  - Two methods performed at Subatech Nantes and LPC Clermont
  - Comparison between methods
  - Comparison with theory

- Conclusion and perspectives

Data samples

- 2 data taking periods in 2016 : p-Pb collisions at $\sqrt{s_{NN}} = 8.16$ TeV

Trigger class : Events with two unlike sign muons with $p_T^{\mu} > 0.5$ GeV/c

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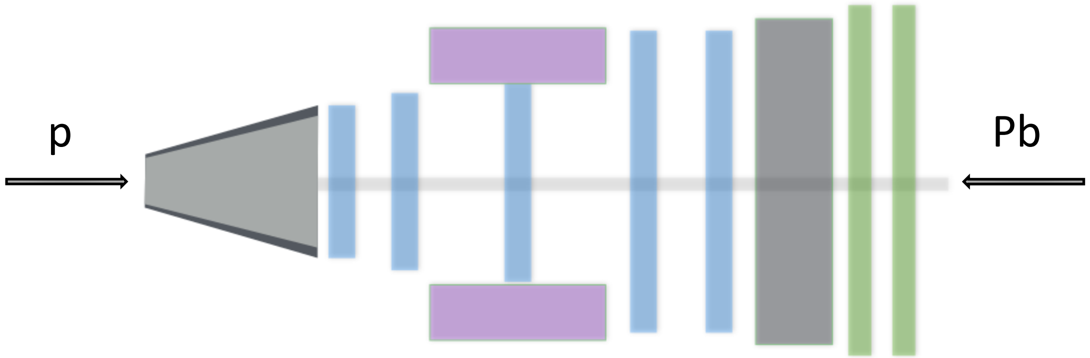


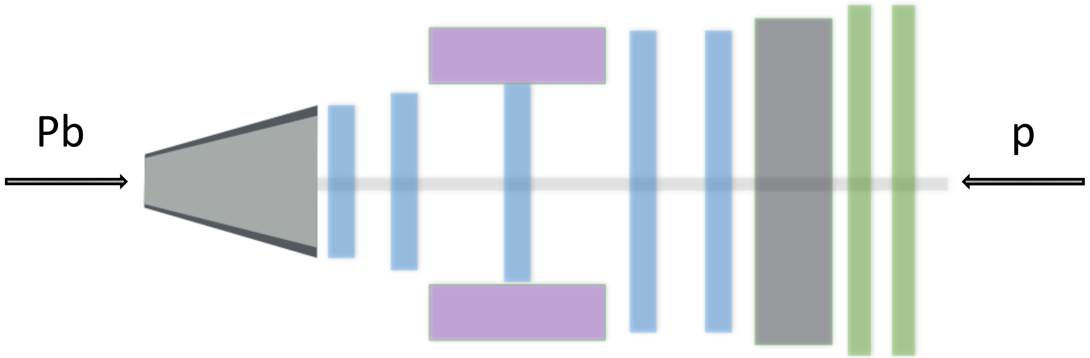
p-Pb configuration

57 validated runs

$$2.03 < y_{CM} < 3.53$$

$$L_{int} = 8.46 \pm 0.17\, nb^{-1}$$

$N_{events} = 26 \cdot 10^6$ after physics selection



Pb-p configuration

80 validated runs

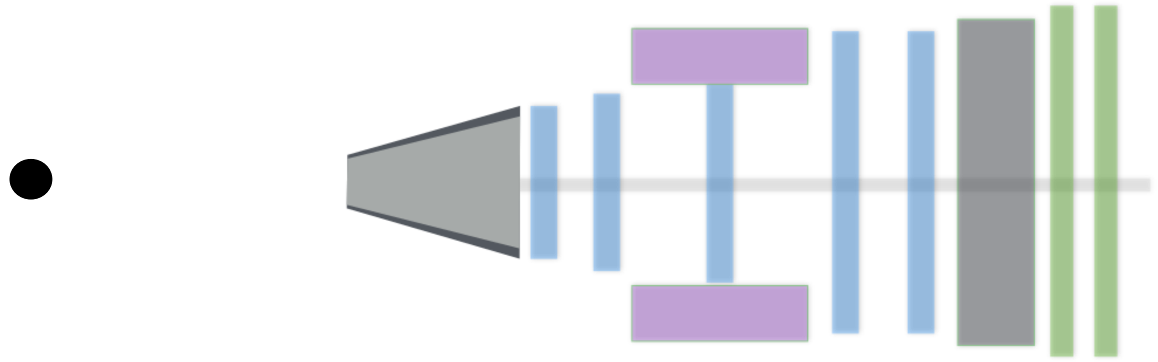
$$-4.46 < y_{CM} < -2.96$$

$$L_{int} = 12.79 \pm 0.24\, nb^{-1}$$

$N_{events} = 72 \cdot 10^6$ after physics selection

Muon track selection

- Z candidats obtained by combining pairs of opposite sign tracks :



Muon track selection

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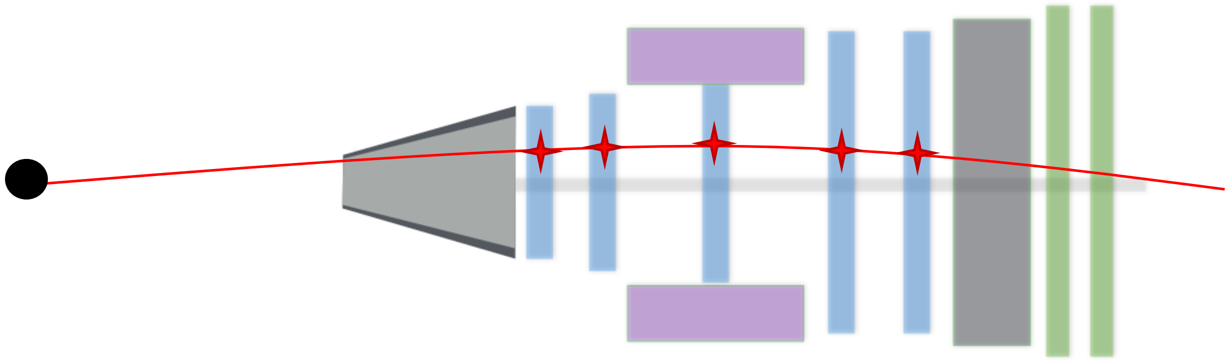

- Single muon cuts :
  - ✓ Matched tracks

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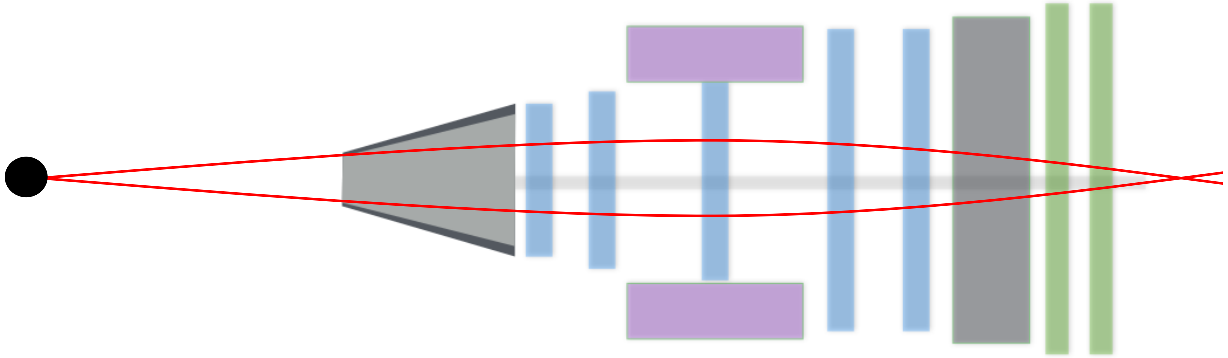

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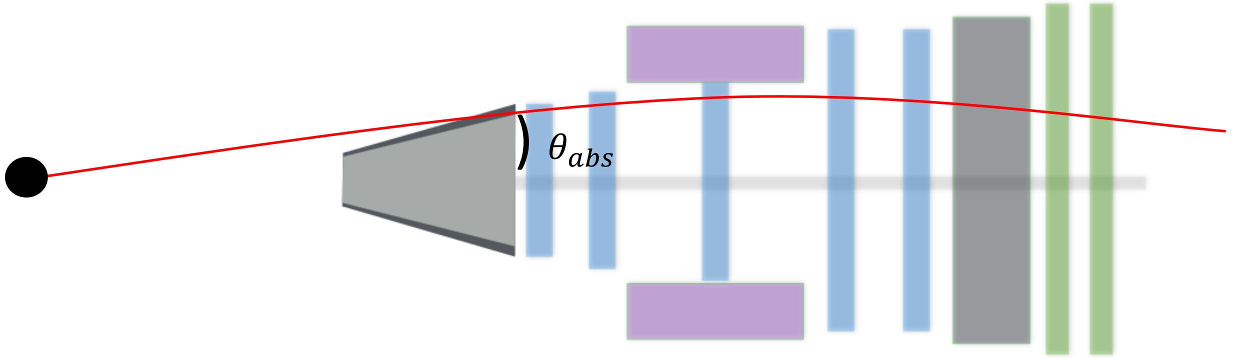

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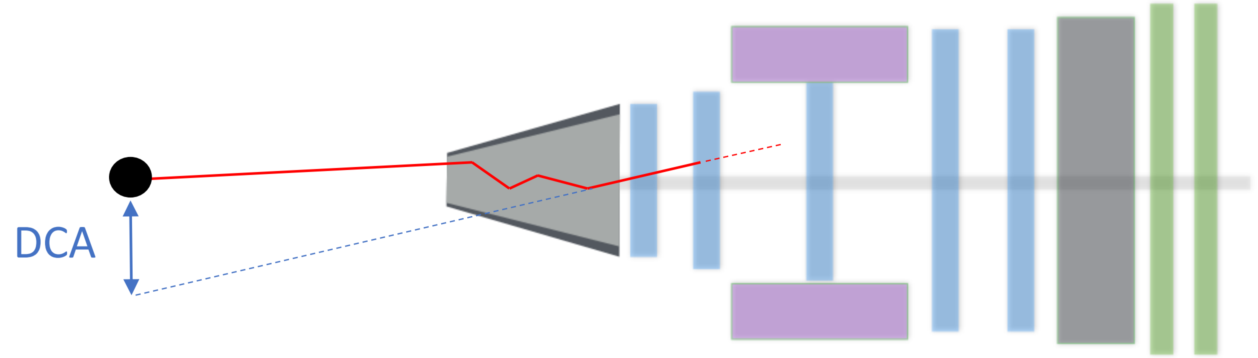

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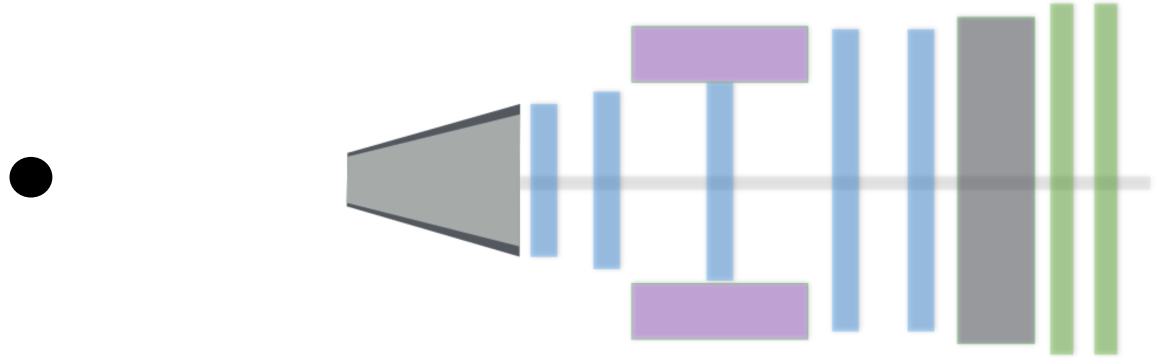

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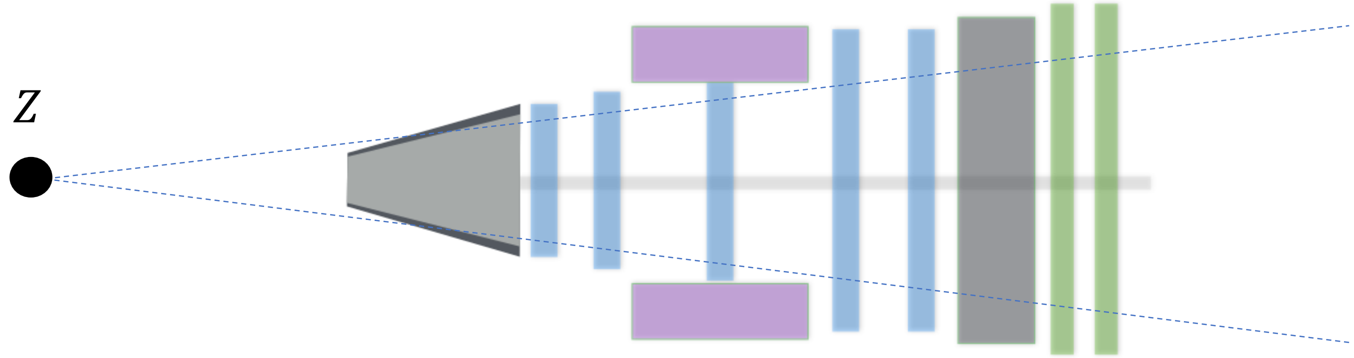

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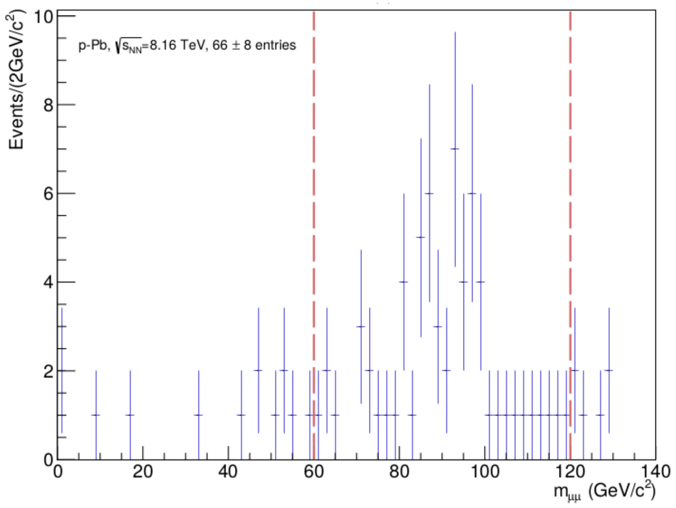
- Reconstructed dimuon cuts :
  - ✓ Rapidity : $-4.0 < y_{lab} < -2.5$ → spectrometer acceptance

Signal extraction

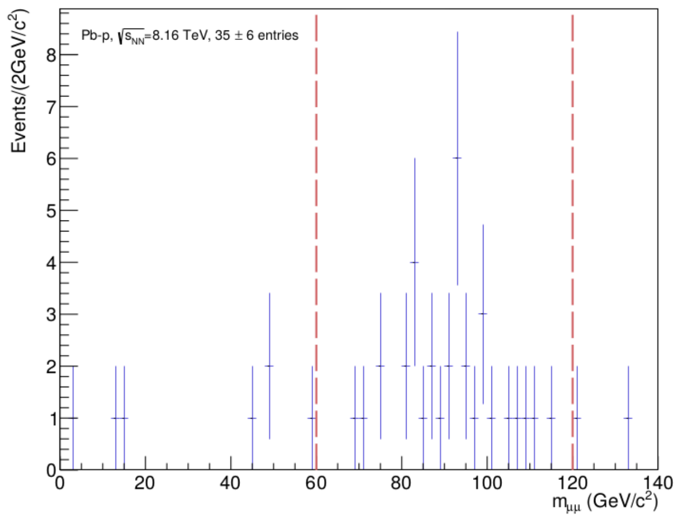
- Z^0 study in the dimuon decay channel :

$$m_{\mu^+\mu^-} = \sqrt{m_1^2 + m_2^2 + 2(E_1 \cdot E_2 - \vec{p}_1 \cdot \vec{p}_2 \cdot cos\theta_{12})}$$

- Signal extracted in the invariant mass range : $60 < m_{\mu\mu} < 120$ GeV/c^2



$N_Z(2.03 < y_{CM} < 3.53) = 66 \pm 8$ (stat)



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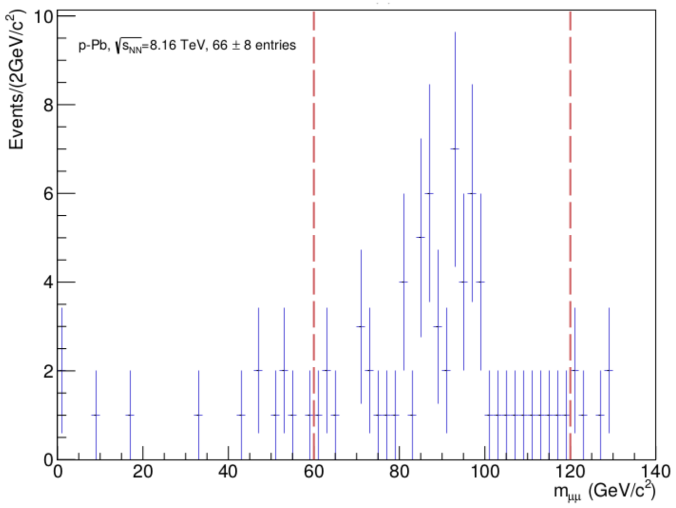

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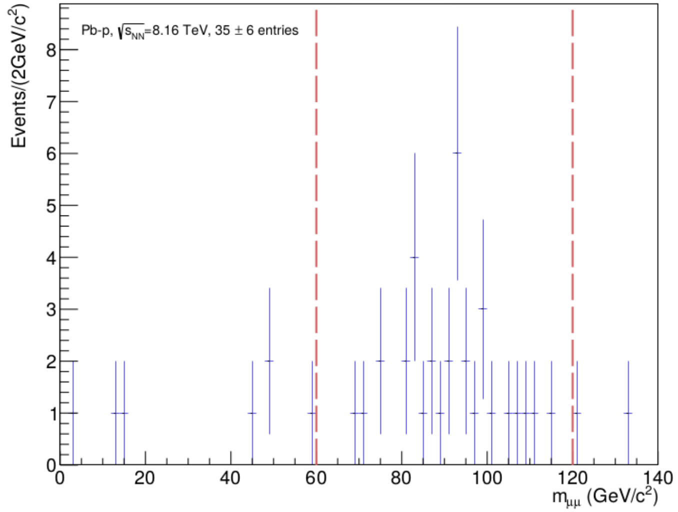

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- Lower kinematic acceptance of the Z cross section at backward rapidity.

Background

p_T cut on single muons tracks should make the background contribution very small.

- Possible sources:
  - Semi-leptonic decays from $b\bar{b}$ and $c\bar{c}$
  - Process $t\bar{t} \rightarrow \mu\mu$
  - Process $Z \rightarrow \tau\bar{\tau} \rightarrow \mu\mu$

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↳ Z boson production analysis in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV showed these contributions are negligible in the signal region.

Full Monte-Carlo simulation

- p-Pb and Pb-p collisions at $\sqrt{s_{NN}} = 8.16$ TeV

POWHEG : Generator for the process $q\bar{q} \rightarrow Z/\gamma^{*} \rightarrow \mu^{+}\mu^{-}$

- ✓ With NLO contributions
- ✓ EPS09 : nPDF set used for nuclear effects

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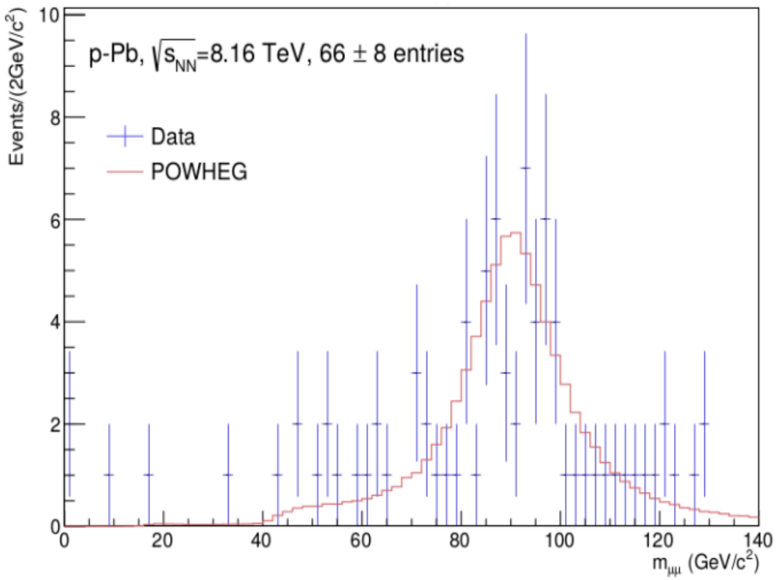
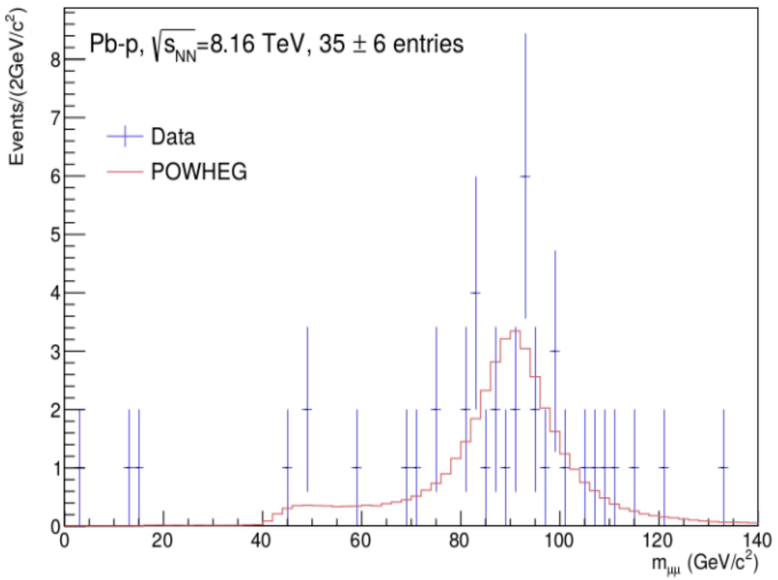
- Set up
  - ✓ Generation in the fiducial region of the muon spectrometer : $-4.0 < y_{lab} < -2.5$
  - ✓ p_T cut on the single muons : $p_T(\mu) > 10$ GeV/c → reduce the γ^* contribution

Comparison data / simulation

- Z reconstructed from the simulation
  - ✓ With the muon track selection
  - ✓ With the resolution of the tracking system

- Number of generated events normalized to data





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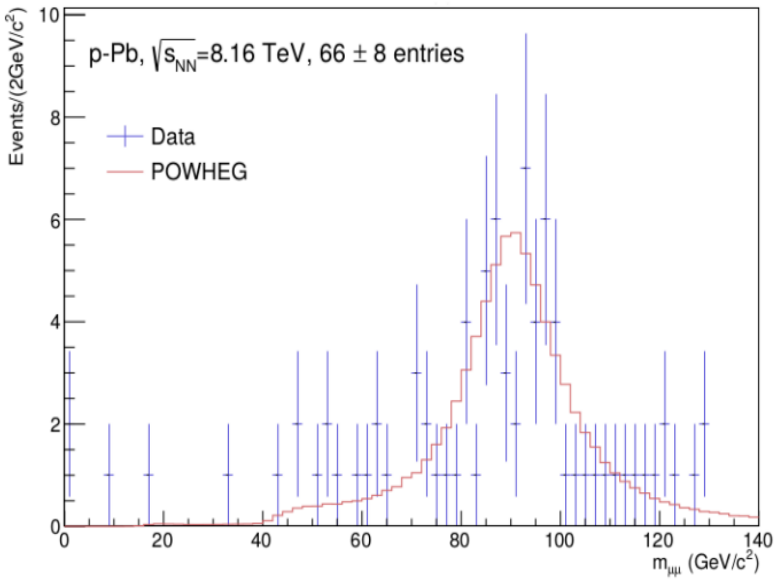

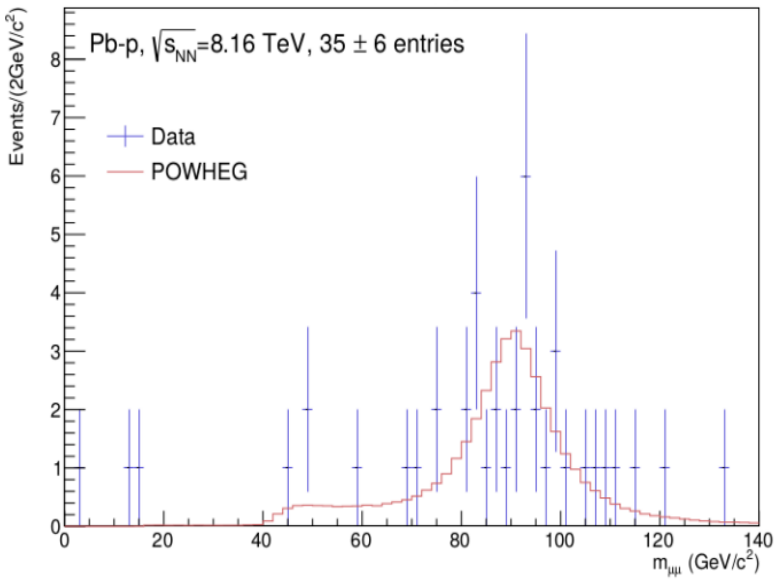

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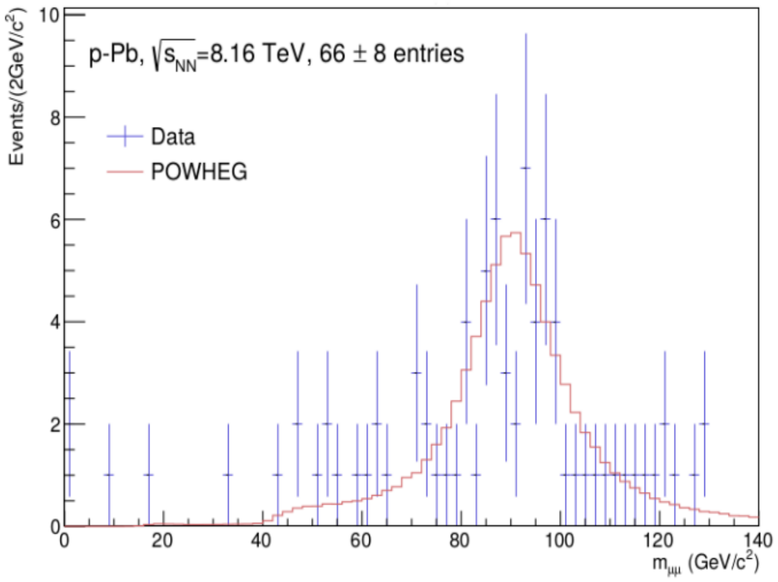

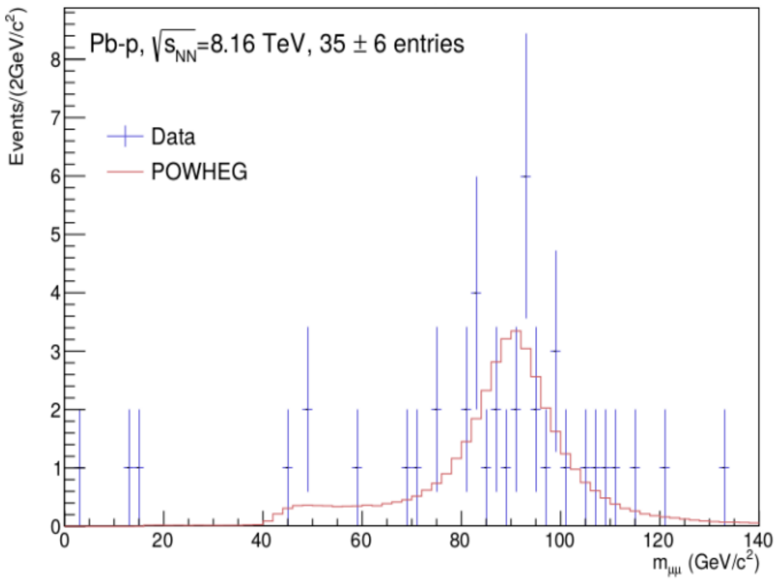

→ Monte-Carlo distribution discribes well the data

→ Drell-Yan process seems to be the only contribution $40 < m_{\mu\mu} < 60$ GeV/c^2
⇒ Background negligible in Z mass range

Detector efficiency

- Efficiency computed run by run from the simulation : $\epsilon = \frac{N_{rec}}{N_{gen}}$

Reconstruction :

- ✓ With the muon track selection
- ✓ With and without cluster resolution → systematic on the efficiency

Generated Z :

- ✓ With two muons in the acceptance $-4 < \eta_{\mu} < -2.5$

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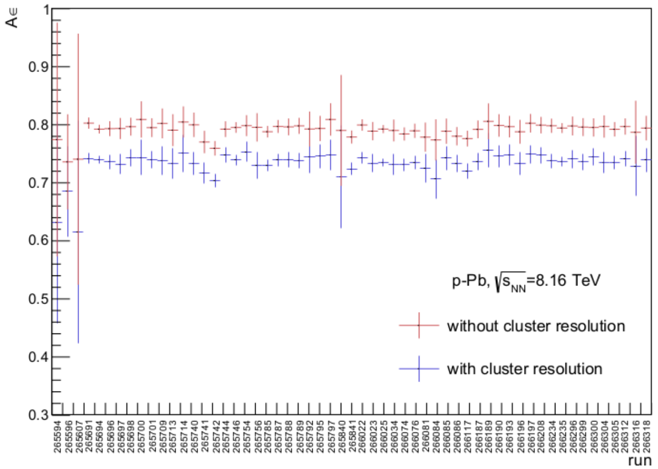
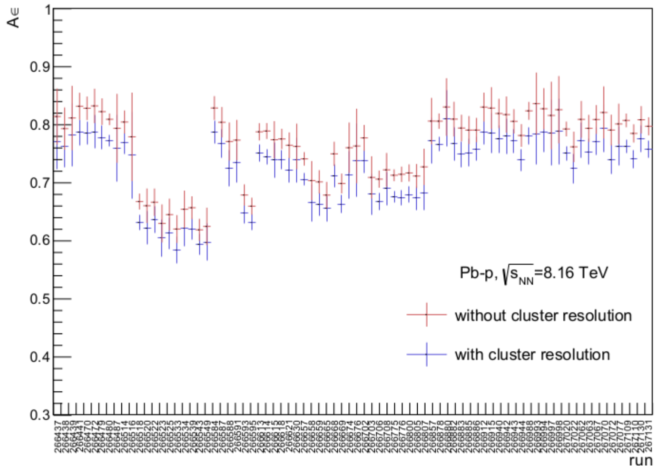
- Efficiency extracted in the invariant mass range $60 < m_{\mu\mu} < 120$ GeV/c^2





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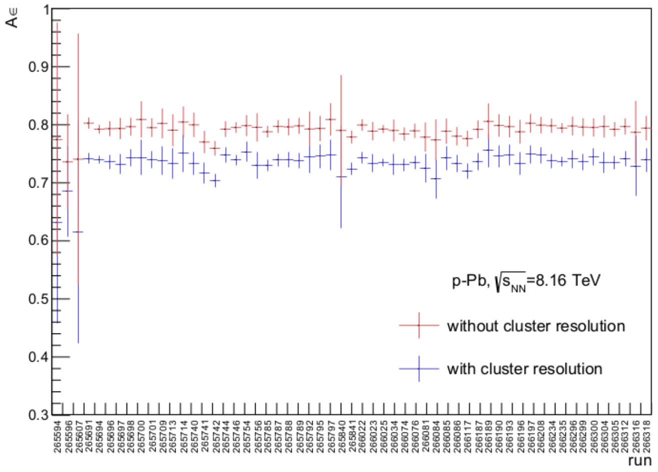
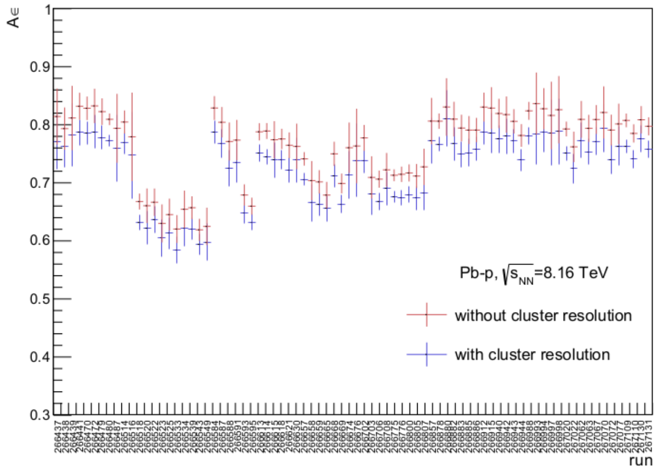
- Efficiency extracted in the invariant mass range $60 < m_{\mu\mu} < 120$ GeV/c^2





Efficiency over the full period as the average weighted by the number of unlike sign dimuon events by run

$$\varepsilon(2.03 < y_{CM} < 3.53) = 0.76 \pm 0.04 \text{ (syst)}$$

$$\varepsilon(-4.46 < y_{CM} < -2.96) = 0.74 \pm 0.03 \text{ (syst)}$$

Results on the cross section : first method at Subatech

$$\sigma_{Z\rightarrow\mu\mu} = \frac{N_Z}{L_{int} \cdot \epsilon}$$

- Cross section given in the fiducial region

$$\begin{cases} -4 < \eta_\mu < -2.5 \\ p_T(\mu) > 20 \text{ GeV}/c \\ 60 < m_{\mu\mu} < 120 \text{ GeV}/c^2 \end{cases}$$

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$$\sigma_{Z\to\mu\mu}(2.03 < y_{CM} < 3.53) = 10.26 \pm 1.25\ \text{(stat)} \pm 0.62\ \text{(syst) nb}$$
$$\sigma_{Z\to\mu\mu}(-4.46 < y_{CM} < -2.96) = 3.71 \pm 0.63\ \text{(stat)} \pm 0.18\ \text{(syst) nb}$$

- Statistical error from the number of Z candidates
- Systematic error is the quadratic sum of the different sources : luminosity, cluster resolution, efficiency of the tracking, trigger and matching

Results on the cross section : second method at LPC

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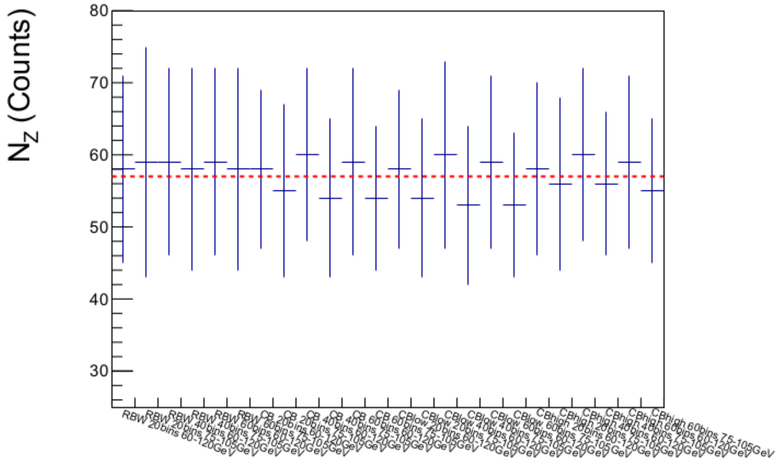

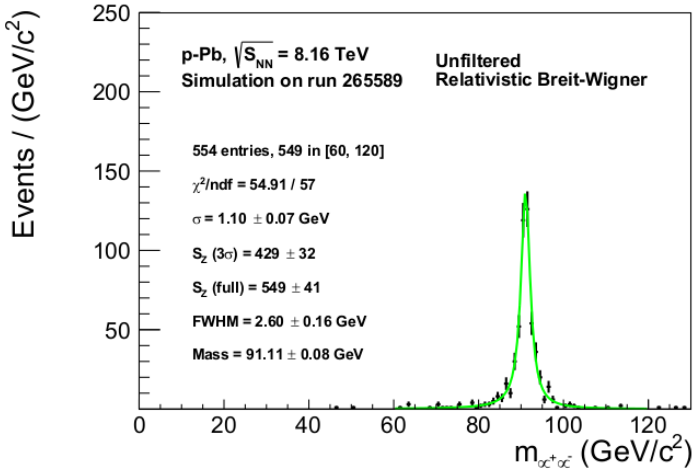

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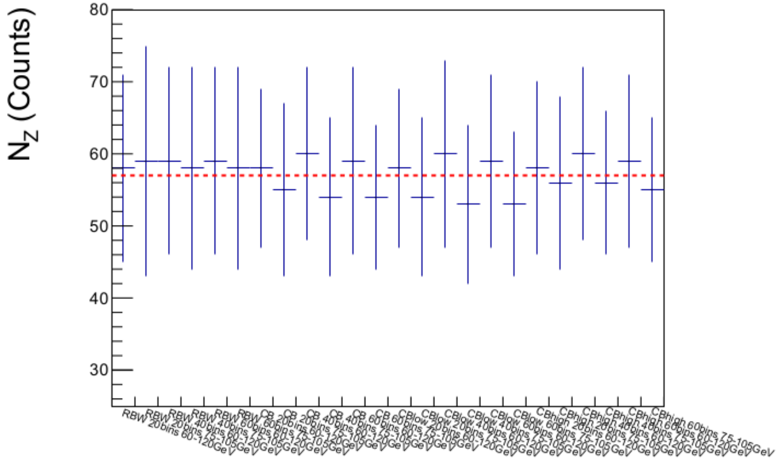
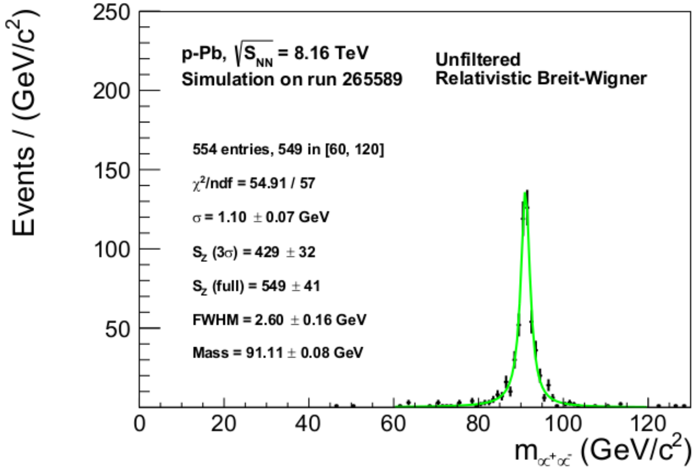


- Full simulation : for the first and last run of each period

  pythia6 : shower MC program and generator for the process $q\bar{q} \rightarrow Z \rightarrow \mu^+\mu^-$

  - ✓ With LO contributions
  - ✓ CTEQ5L : nPDF set used for nuclear effects



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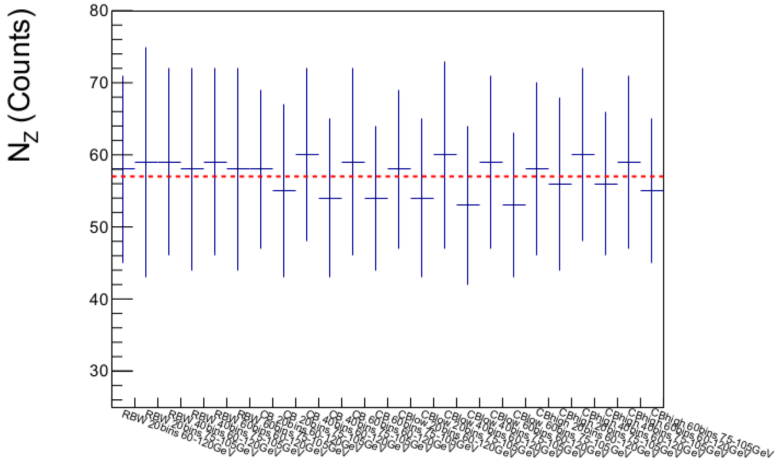

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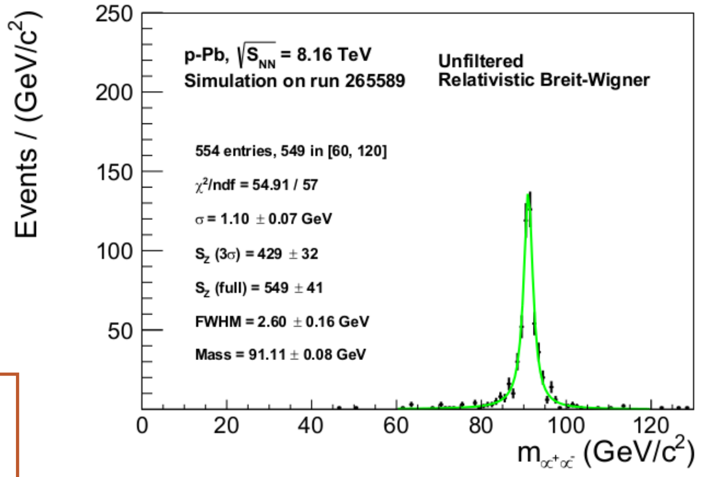
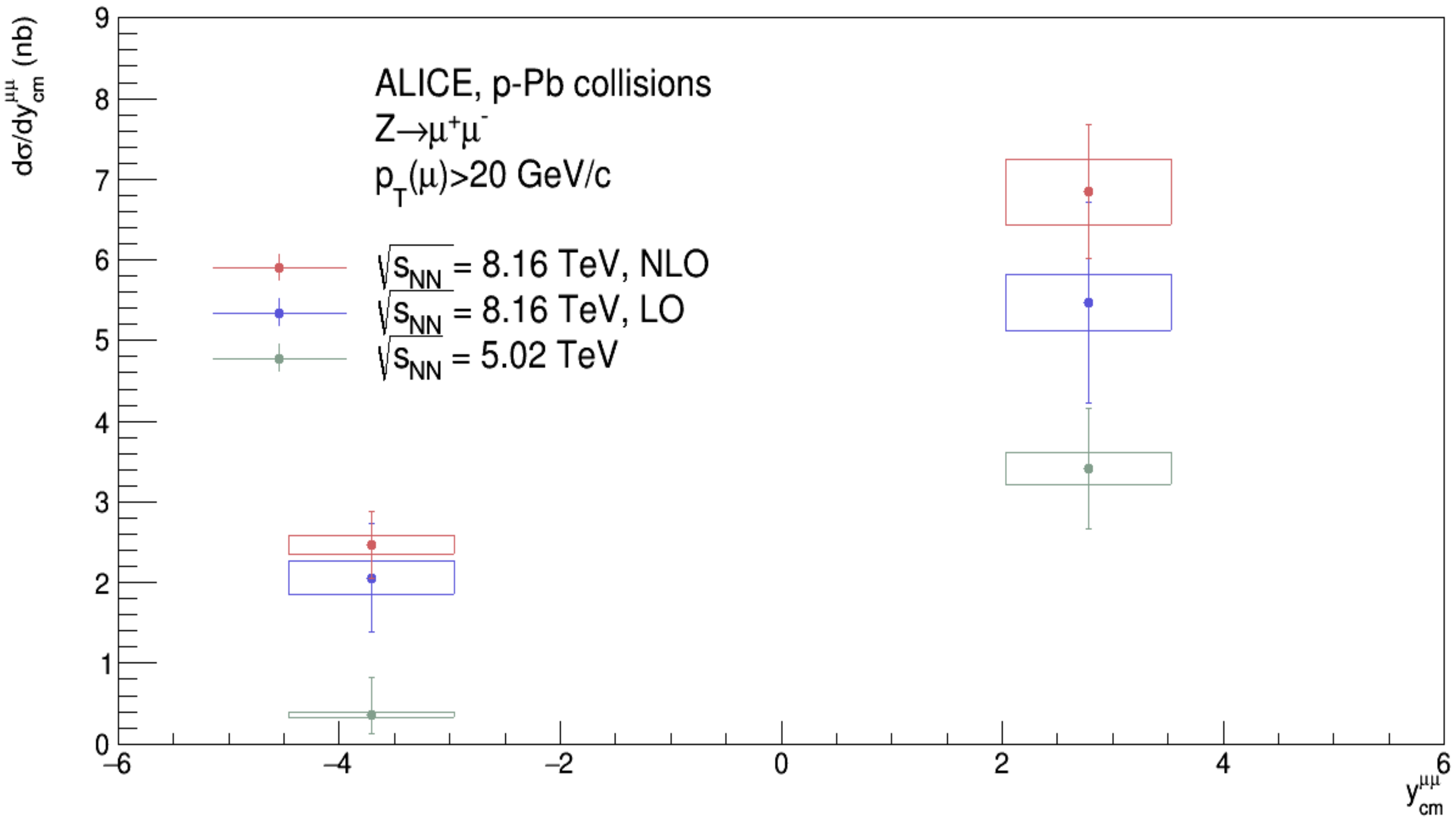


- Results

$$\sigma_{Z\rightarrow\mu\mu}(2.03 < y_{CM} < 3.53) = 8.21 \pm 1.95 \text{ (stat) } \pm 0.53 \text{ (syst) nb}$$
$$\sigma_{Z\rightarrow\mu\mu}(-4.46 < y_{CM} < -2.96) = 3.09 \pm 1.02 \text{ (stat) } \pm 0.30 \text{ (syst) nb}$$

Results comparison

- Between the two methods
  - ✓ Agreement within statistical errors



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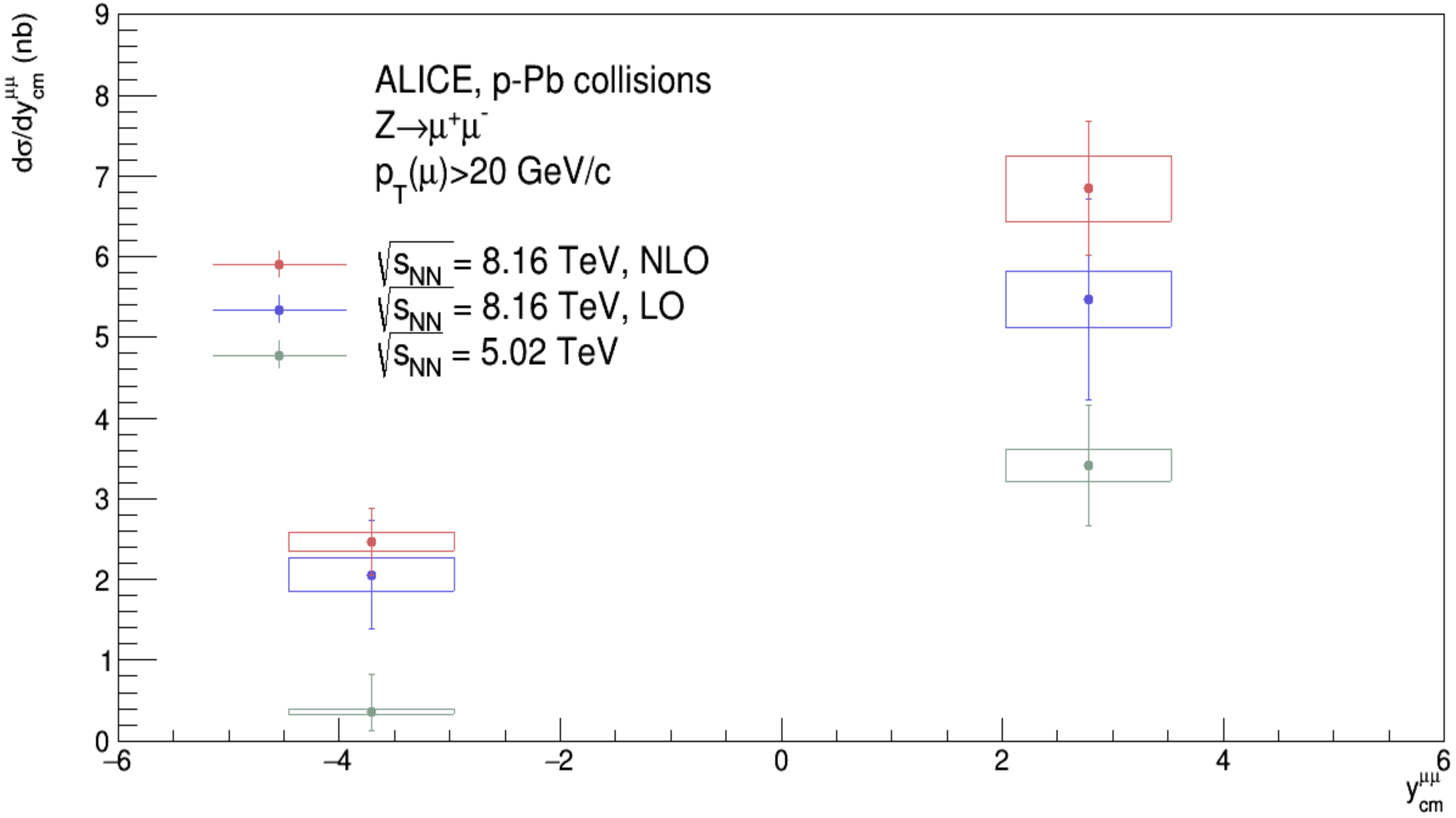
- With data from p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV
  - ✓ Increase of the cross section with energy at forward and backward rapidities
  - ✓ Higher precision



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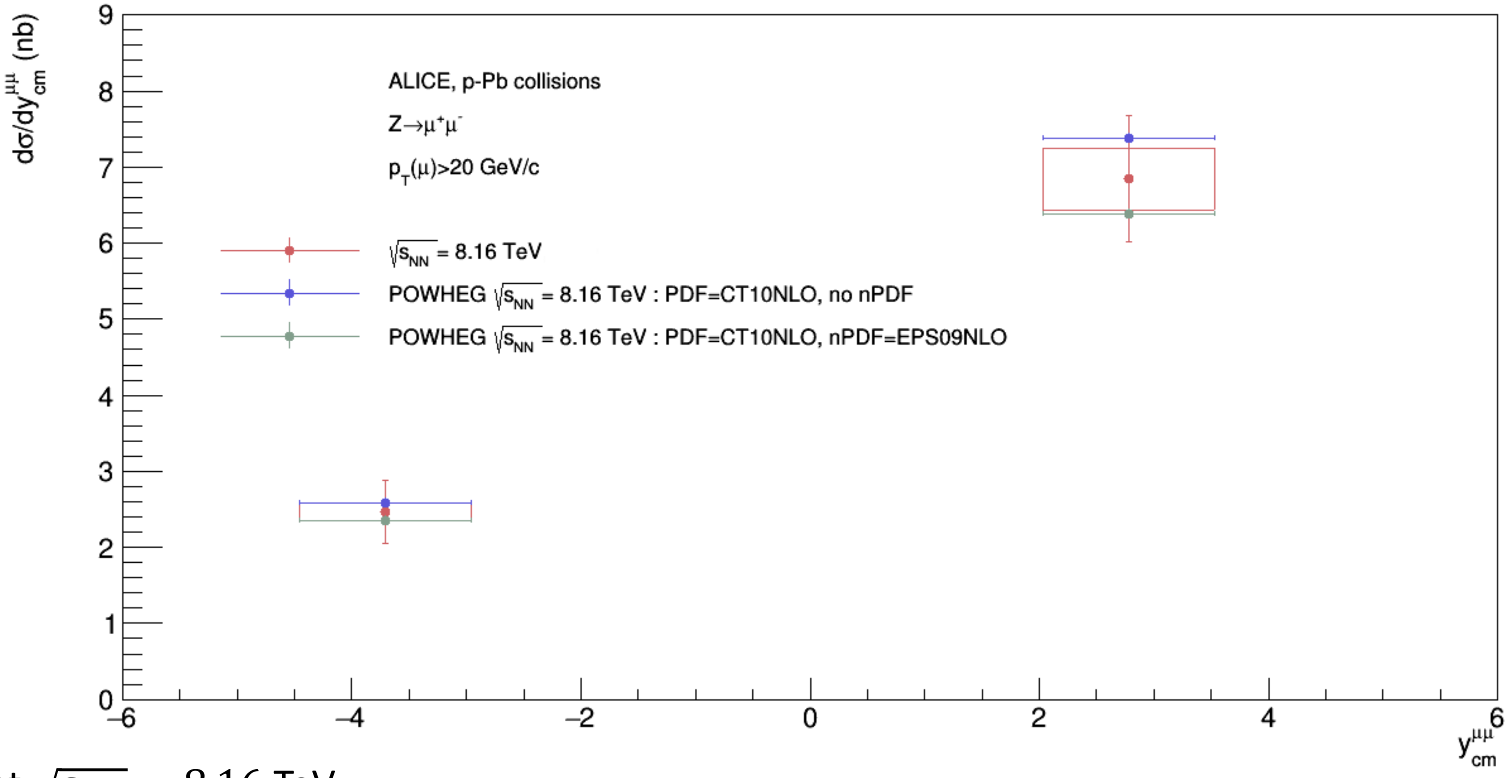

- With theory
  - Simulation p-Pb at $\sqrt{s_{NN}} = 8.16$ TeV
  - with nuclear isospin effects
  - with PDF set CT10 at NLO
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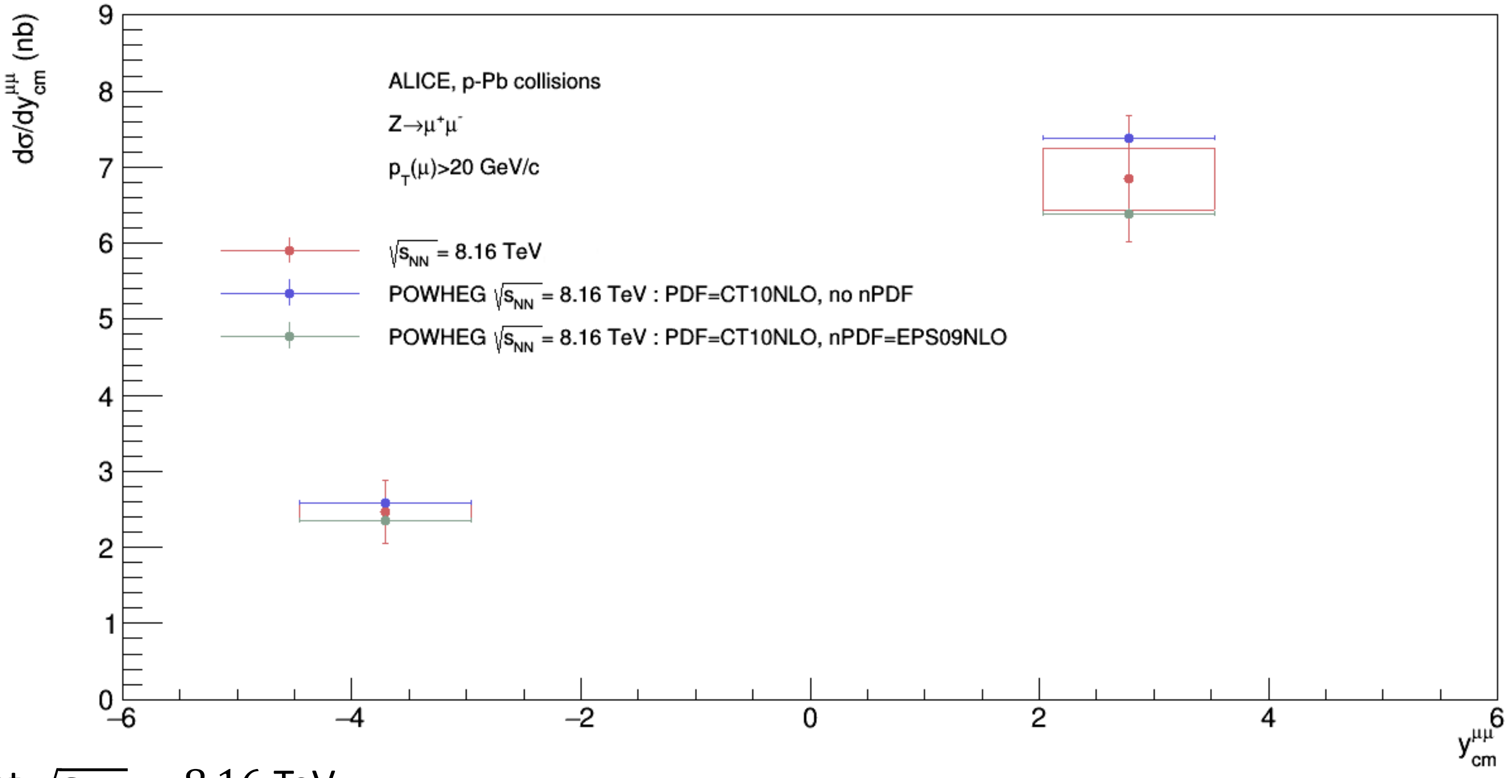

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- Study of the Drell-Yan continium → possible for the run3 with the future Muon Forward Tracker (MFT)

Thank you for listening

Luminosity

- Integrated luminosity corresponding to unlike sign dimuon events

$$L_{int} = \frac{N_{MB}}{\sigma_{MB}}$$

- Minimum bias cross section σ_{MB} estimated by a Van-der-Meer scan

- Number of minimum bias events N_{MB} associated to the number of unlike sign dimuon events

$$N_{MB} = F_{Norm} \cdot N_{CMUL}$$

	N_{CMUL}	N_{MB}	σ_{MB} (b)	L_{int} (nb^{-1})
$2.03 < y_{CM} < 3.53$	$25.87 \cdot 10^6$	$17.67 \cdot 10^9$	$2.09 \pm 0{,}04$ (syst)	$8.46 \pm 0{,}17$ (syst)
$-4.46 < y_{CM} < -2.96$	$72.17 \cdot 10^6$	$26.87 \cdot 10^9$	$2.10 \pm 0{,}04$ (syst)	$12.79 \pm 0{,}24$ (syst)

Statistic error neglected over the sytematic error

Systematic error

As a percentage of the cross section

	Cluster resolution	Tracking efficiency	Trigger efficiency	Matching efficiency	Luminosity
$2.03 < y_{CM} < 3.53$	5.3 %	1 %	1 %	1 %	2 %
$-4.46 < y_{CM} < -2.96$	4.1 %	2 %	1 %	1 %	1.9 %

The tracking, trigger and matching efficiencies are taken from the Υ analysis at $\sqrt{s_{NN}} = 8.16$ TeV