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**ϕ -meson production at forward rapidity in p-Pb collisions at
 $\sqrt{s_{NN}} = 5.02$ TeV and in pp collisions at $\sqrt{s} = 2.76$ TeV**

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Abstract

The first measurement of ϕ -meson production in p-Pb collisions at a nucleon-nucleon centre-of-mass energy $\sqrt{s_{NN}} = 5.02$ TeV has been performed with the ALICE apparatus at the LHC. The ϕ -mesons have been identified in the dimuon decay channel in the transverse momentum (p_T) range $1 < p_T < 7$ GeV/ c , both in the p-going ($2.03 < y < 3.53$) and the Pb-going ($-4.46 < y < -2.96$) directions, where y stands for the rapidity in the nucleon-nucleon centre-of-mass. Differential cross sections as a function of transverse momentum and rapidity are presented. The forward-backward asymmetry for ϕ meson production is measured for $2.96 < |y| < 3.53$, resulting in a factor ~ 0.5 with no significant p_T dependence within the uncertainties. The p_T dependence of the ϕ nuclear modification factor R_{pPb} exhibits an enhancement up to a factor 1.6 at $p_T = 3-4$ GeV/ c in the Pb-going direction. The p_T dependence of the ϕ -meson cross section in pp collisions at $\sqrt{s} = 2.76$ TeV, which is used to determine a reference for the p-Pb results, is also presented here for $1 < p_T < 5$ GeV/ c and $2.5 < y < 4$.

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*See Appendix A for the list of collaboration members

1 Introduction

Proton-nucleus (p-A) collisions are of special interest in the context of high-energy nuclear physics for two reasons. On one hand, a precise characterisation of particle production processes in p-A collisions is needed as a reference for nucleus-nucleus data. This allows in-medium effects — linked to the formation of a deconfined phase of the QCD matter, the quark-gluon plasma (QGP) [1–3] — to be disentangled from the effects already present in cold nuclear matter. Among them, a sizeable role is played by the transverse momentum broadening of initial-state partons due to multiple scattering inside the nucleus, responsible for the Cronin effect [4] which may lead to an enhancement of intermediate- p_T hadron spectra. In addition, p-A collisions at LHC energies provide a way to probe the parton distributions of the colliding nucleus at small values of Bjorken- x , in a regime where parton densities can reach saturation [5, 6]. In particular, the smallest x values contributing to the wave function of the colliding nucleus can be probed by looking at particle production at large rapidities, in the p-going direction. Such a measurement can thus extend towards lower x -values the results of the lower-energy measurements by the PHOBOS and BRAHMS experiments at the RHIC [7, 8]. Measurements of identified particle production may, in particular, provide useful constraints for forthcoming theoretical studies of the saturation mechanism at small x .

We have already reported results on charged particle production in p-Pb collisions at mid-rapidity. These results focused on the pseudorapidity density [9] and the p_T dependence of the nuclear modification factor [10, 11]; the latter was found to be consistent with unity for $p_T \gtrsim 2$ GeV/ c . The nuclear modification factor of charged hadrons was also studied by the BRAHMS and PHOBOS Collaborations in d-Au collisions at $\sqrt{s_{NN}} = 200$ GeV at the RHIC [12, 13], as a function of pseudorapidity, where values smaller than unity were found for $\eta \gtrsim 1$ corresponding to the d-going direction.

In this Letter we report the measurement of ϕ -meson production at forward rapidity in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the transverse momentum range $1 < p_T < 7$ GeV/ c , for the center-of-mass rapidity ranges $2.03 < y < 3.53$ (p-going direction) and $-4.46 < y < -2.96$ (Pb-going direction), in the dimuon decay channel with the ALICE detector. This measurement extends the investigation of soft particle production to forward rapidity. At the same time, it represents an essential baseline for the understanding of ϕ production in heavy-ion collisions, where an enhancement of strange particle yields relative to the ones measured in pp collisions has been proposed long ago as a signature of the formation of a QGP phase [14–16]. In particular, the p-Pb data presented here will provide an important reference for future measurements in Pb-Pb collisions in the LHC Run 2, which will be performed at a comparable energy.

The differential ϕ -meson cross section as a function of transverse momentum is also presented for pp collisions at $\sqrt{s} = 2.76$ TeV. This measurement complements the ALICE results on ϕ -meson production in pp collisions at $\sqrt{s} = 7$ TeV, already reported in [17] and, combined with the latter, is used to build the pp reference for the p-Pb measurements presented here.

2 Experimental setup

A full description of the ALICE detector can be found in [18, 19]. The results presented in this Letter have been obtained measuring the $\mu^+\mu^-$ decay channel with the muon spectrometer, covering the pseudorapidity region $-4 < \eta_{lab} < -2.5$. Here and in the following, the sign of η_{lab} is determined by the choice of the LHC reference system. The other detectors relevant for the analysis are the Silicon Pixel Detector (SPD) of the Inner Tracking System (ITS), the V0 detector and the Zero Degree Calorimeters (ZDC).

The elements of the muon spectrometer are a hadron absorber, followed by a set of tracking stations, a dipole magnet, an iron wall acting as muon filter and a trigger system. The hadron absorber is made of carbon, concrete and steel and is placed 0.9 m away from the interaction point. Its total material budget

corresponds to 10 hadronic interaction lengths. The dipole magnet provides an integrated magnetic field of $3 \text{ T} \cdot \text{m}$ in the vertical direction. The muon tracking is provided by five tracking stations, each one composed of two cathode pad chambers. The first two stations are located upstream of the dipole magnet, the third one in the middle of its gap and the last two ones downstream of it. A 1.2 m thick iron wall, corresponding to 7.2 hadronic interaction lengths, is placed between the tracking and trigger systems and absorbs the residual secondary hadrons emerging from the hadron absorber. The hadron absorber together with the iron wall stops muons with total momentum lower than $\sim 4 \text{ GeV}/c$. The muon trigger system consists of two detector stations, each one composed of two planes of resistive plate chambers, installed downstream of the muon filter.

The SPD consists of two silicon pixel layers, covering the pseudorapidity regions $|\eta_{\text{lab}}| < 2.0$ and $|\eta_{\text{lab}}| < 1.4$ for the inner and outer layer, respectively. It is used for the determination of the primary interaction vertex position. The V0 is composed of two scintillator hodoscopes covering the pseudo-rapidity regions $2.8 < \eta_{\text{lab}} < 5.1$ and $-3.7 < \eta_{\text{lab}} < -1.7$. It is used in the definition of the minimum bias trigger signal, and allows the offline rejection of beam-halo and beam-gas interactions to be performed. The ZDC detectors, positioned symmetrically at 112.5 m from the interaction point, are used to clean the event sample by removing beam-beam collisions not originating from nominal LHC bunches.

3 Data selection and signal extraction

The analysis presented in this paper is based on two data samples, collected by ALICE during the 2013 p-Pb and pp runs at $\sqrt{s_{NN}} = 5.02$ TeV and $\sqrt{s} = 2.76$ TeV, respectively. In this section we present the details of the data selection, as well as the procedure followed for the extraction of the ϕ -meson signal.

3.1 Data selection

The Minimum-Bias (MB) trigger for the considered data sample is given by the logical AND of the signals in the two V0 detectors [20]. Events containing a muon pair are selected by means of a specific dimuon trigger, based on the detection of two muon candidate tracks in the trigger system of the muon spectrometer, in coincidence with the MB condition. Due to the intrinsic momentum cut imposed by the detector, only muons with $p_T \gtrsim 0.5 \text{ GeV}/c$ manage to leave a signal in the trigger chambers.

Due to the different energy of the LHC proton and Pb beams ($E_p = 4 \text{ TeV}$, $E_{\text{Pb}} = 1.58 \text{ A} \cdot \text{TeV}$), in p-Pb collisions the nucleon-nucleon centre-of-mass moves in the laboratory with a rapidity $y_0 = 0.465$ in the direction of the proton beam. The directions of the proton and Pb beam orbits were inverted during the p-Pb data taking period: this allowed the ALICE muon spectrometer to access two different rapidity regions¹: the region $2.03 < y < 3.53$ where the proton beam is directed towards the muon spectrometer (p-going direction) and the region $-4.46 < y < -2.96$ where the Pb beam is directed towards the muon spectrometer (Pb-going direction). In the following, these two rapidity ranges are also referred to as “forward” and “backward”, respectively. For pp collisions at $\sqrt{s} = 2.76 \text{ TeV}$ the muon spectrometer covers the rapidity region $2.5 < y < 4$ ².

Background events not coming from beam-beam interactions are rejected by performing an offline selection, based on the requirement that the timing information from the V0 and ZDC detectors are compatible with a collision occurring in the fiducial interaction region $|z_{\text{vtx}}| \lesssim 10 \text{ cm}$.

The integrated luminosity for the p-Pb data samples was evaluated as $L_{\text{int}} = N_{\text{MB}}/\sigma_{\text{MB}}$, where N_{MB} is the equivalent number of MB events for the analysed triggered events, and σ_{MB} the MB trigger cross section. The value of N_{MB} was obtained by averaging the results of two different methods — one based on the ratio of trigger rates and the other based on the offline selection of dimuon events in the MB data

¹ The sign of y is defined by assuming the proton beam to have positive rapidity.

² In this case the sign of y is defined by assuming the proton beam entering the muon spectrometer to have positive rapidity.

sample [21] — while the MB trigger cross sections σ_{MB} was measured with a van der Meer scan and found to be 2.09 ± 0.07 b and 2.12 ± 0.07 b, respectively, for the beam configurations corresponding to the forward and backward rapidity coverage of the muon spectrometer [22]. For the pp data sample, the integrated luminosity is calculated with the method described in [23], using as reference the MB trigger cross section $\sigma_{MB} 47.7 \pm 0.9$ mb, measured in a van der Meer scan [24].

The resulting values of L_{int} for the analysed p-Pb data samples are 5.01 ± 0.19 nb $^{-1}$ and 5.81 ± 0.20 nb $^{-1}$ [21, 22] — corresponding to ~ 24000 and ~ 26000 reconstructed $\phi \rightarrow \mu\mu$ decays (see next section) — respectively for the forward and backward rapidity regions. For the pp data sample, the integrated luminosity amounts to 78 ± 3 nb $^{-1}$ for a total number of ~ 1400 reconstructed $\phi \rightarrow \mu\mu$ decays.

Track reconstruction in the muon spectrometer is based on a Kalman filter algorithm [17, 25, 26]. Muon identification is performed by requiring the candidate track to match a track segment in the trigger chambers (trigger tracklet). This request selects muons with $p_{T,\mu} \gtrsim 0.5$ GeV/ c and, as a consequence, significantly affects the collected statistics for dimuons with invariant mass $\lesssim 1$ GeV/ c^2 and $p_T \lesssim 1$ GeV/ c . It is also required that muon tracks lie in the pseudo-rapidity interval $-4 < \eta_\mu < -2.5$, where η_μ is defined in the laboratory frame, in order to remove the tracks close to the acceptance borders of the spectrometer, where the acceptance drops abruptly. Selected tracks are finally required to exit the hadron absorber at a radial distance from the beam axis, R_{abs} , in the range $17.6 < R_{abs} < 89.5$ cm: this cut, for all practical purposes equivalent to the one on η_μ , explicitly ensures the rejection of tracks crossing the region of the absorber with the highest density material, where multiple scattering and energy loss effects are large and can affect the mass resolution. Muon pairs are built combining two muon tracks that satisfy the above cuts.

3.2 Signal extraction

The Opposite-Sign (OS) muon pairs are composed of correlated and uncorrelated pairs. The former contain the signal of interest for the present analysis, while the latter — mainly coming from semi-muonic decays of pions and kaons — form a combinatorial background. The contribution of the combinatorial background to the OS mass spectrum was evaluated using an event mixing technique in which uncorrelated pairs are formed with muons taken from different events. A detailed description of the technique can be found in [17]. The ratio between correlated and uncorrelated OS dimuons at the ϕ -meson mass is ~ 0.65 (~ 0.40) in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at forward (backward) rapidity, and ~ 1.30 in pp collisions at $\sqrt{s} = 2.76$ TeV.

The invariant mass spectra in pp and p-Pb collisions, obtained after combinatorial background subtraction, are shown in Fig. 1 for the p_T -integrated samples. The signal is described in the low-mass region (from the threshold up to ~ 1.5 GeV/ c^2) by the superposition of a so-called hadronic cocktail and the open charm and open beauty processes. The processes included in the hadronic cocktail are the two-body and Dalitz decays of the light neutral mesons η , ρ , ω , η' and ϕ , which dominate dimuon production for invariant masses below ~ 1 GeV/ c^2 . The open charm and open beauty contributions arise from correlated semi-muonic decays of charm and beauty mesons and baryons.

The hadronic cocktail was simulated with a dedicated generator described in [17], tuned to the existing measurements whenever possible, otherwise based on the kinematic distributions extracted from PYTHIA [27]. In particular, the kinematic distributions of the ϕ have been tuned by means of an iterative procedure to the results presented in this Letter to ensure self-consistency for this analysis. The open charm and beauty generation is based on a parameterisation of the spectra generated with PYTHIA [25]. The detector response for all these processes is obtained with a simulation based on the GEANT3 [28] transport code. Simulated events are then subjected to the same reconstruction and selection procedure as the data.

When describing the signal with the superposition of the aforementioned contributions, four parameters

are adjusted in the fit procedure in each of the p_T or rapidity intervals considered in the analysis: the yield of the η , ω and ϕ mesons, and the open charm and beauty processes, with the relative beauty/charm contribution fixed (see later in this paragraph). In this way, each parameter is linked to a process dominating in at least one region of the considered mass spectrum. The remaining degrees of freedom are fixed either according to the relative branching ratios known from literature [29], or assuming specific hypotheses on the cross section ratios. In particular, the production cross section of the ρ meson is assumed to be the same as for the ω as suggested from both models and pp data [17], while the η' contribution was derived from the η cross section by applying the ratio of the corresponding cross sections $\sigma_{\eta'}/\sigma_{\eta} = 0.3$ taken from the PYTHIA tunes ATLAS-CSC and D6T which best describe the available low mass dimuon measurements at the LHC energies [17]. The open beauty normalisation is fixed to the open charm one via a fit of the p_T - and rapidity-integrated mass spectra in which the yields from both processes are free parameters; when performing differential studies, the beauty/charm ratio is scaled according to the differential distributions for the two processes, given by the Monte Carlo (MC) simulations.

For each p_T and rapidity interval, the raw number of ϕ mesons is determined via a fit procedure, shown in Fig. 1 for the p_T -integrated samples. Several tests have been performed to evaluate the robustness of the signal extraction and estimate an appropriate systematic uncertainty for it. They include in particular:

- Replacing the fit based on the full MC cocktail with a fit based on the superposition of various empirical functions. In this case the continuum is modelled either with exponential functions or variable-width Gaussians, while the $\rho+\omega$ and ϕ peaks are described by Crystal Ball functions [30] tuned on the MC.
- Varying the ratio between the yields of open beauty and open charm processes. It was verified that for perturbations as large as $\pm 50\%$ (resulting in a reasonably wide range of variation for the shape of the total continuum) no significant systematic effect is visible.
- Varying the ratios between the two-body and Dalitz branching ratios of the η and ω mesons, as well as the cross section ratios $\sigma_{\rho}/\sigma_{\omega}$ and $\sigma_{\eta'}/\sigma_{\eta}$, within the uncertainties coming either from the available measurements or from the differences between the PYTHIA tunes considered in the analysis of the pp data.
- Varying the considered fit range: in particular, the fit was performed both including and excluding the mass region from 0.4 to 0.65 GeV/ c^2 where the quality of the comparison between the data and the sum of the Monte Carlo sources turns out to be lower.

The total systematic uncertainty was taken as the quadratic sum of the above sources. The systematic uncertainty from the combinatorial background evaluation is added in quadrature, for each point of the mass spectrum of the signal, to the corresponding statistical uncertainty. In this way, this source of systematics is accounted for when evaluating the ϕ raw signal from the fit parameters. The uncertainty associated to the sum of the MC sources (red band in the plots of Fig. 1) is evaluated by combining the uncertainties on the normalisation of each considered process. For the processes whose normalisation is left free in the fit, this uncertainty is the statistical one resulting from the fit procedure itself; for the rest of the processes, we also propagate the systematic uncertainty on the parameters (branching ratios or cross section ratios) which fix their normalisations to those of the free processes.

4 Results

The results of the ϕ -meson analysis are presented as follows. We first present the measurement of the production cross sections, starting with its p_T -dependence in pp collisions at $\sqrt{s} = 2.76$ TeV, followed by p-Pb collision results as a function of p_T and rapidity. Then, we show the ratio of the

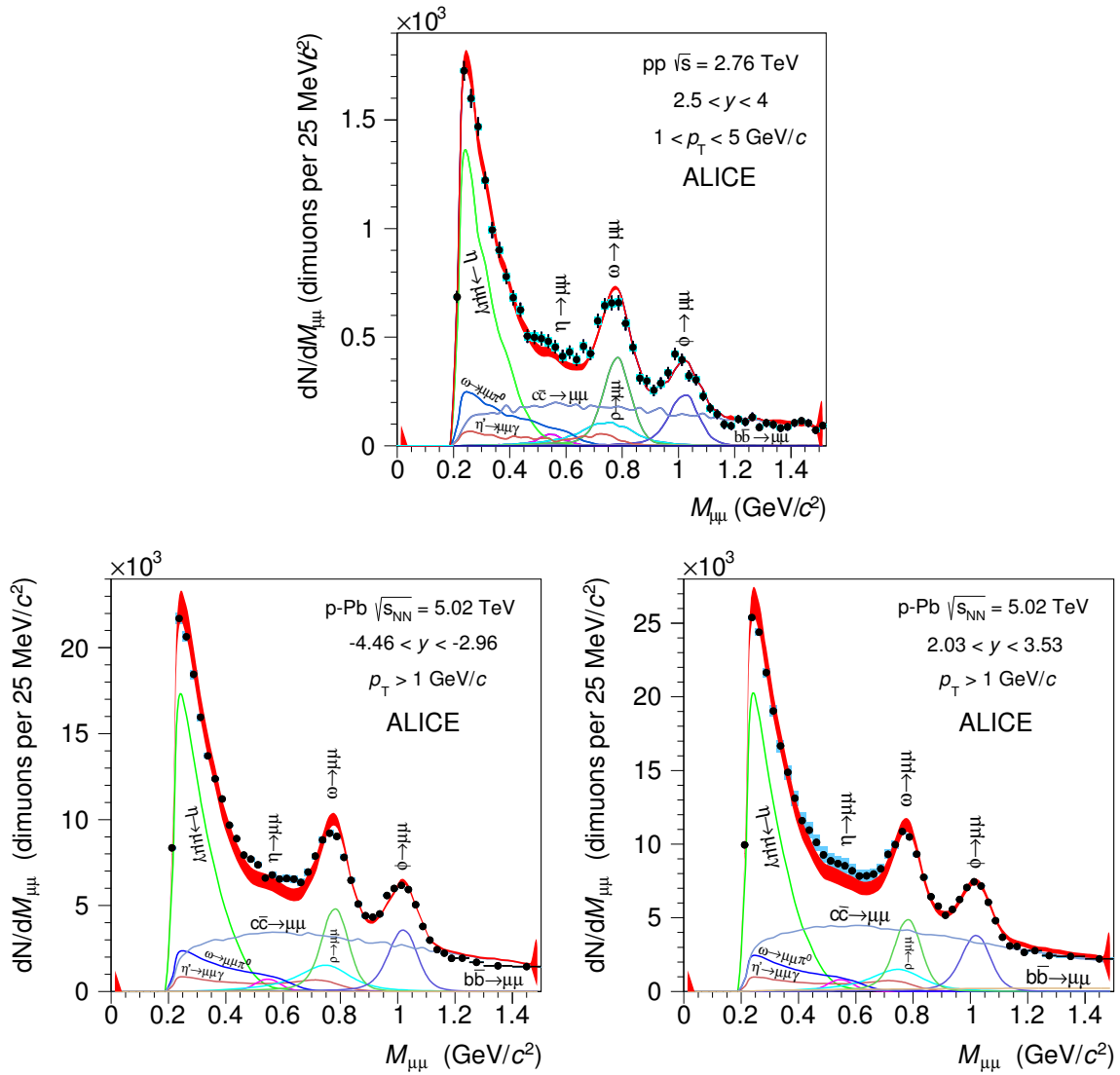


Fig. 1: Dimuon mass spectrum after combinatorial background subtraction: p_T -integrated pp sample (top panel) and p_T -integrated p-Pb sample in the backward (bottom left panel) and forward (bottom right panel) rapidity regions, compared to the result of the cocktail fit. Error boxes on data points (well visible only in some regions on the plots) represent systematic uncertainty due to the combinatorial background subtraction, while error bars account for the statistical uncertainty. The width of the cocktail fit result (red band) combines the statistical uncertainties of the free fit parameters with the systematic uncertainties on the fixed parameters (see text).

cross sections measured in the forward and backward regions, obtained in the common rapidity interval $2.96 < |y| < 3.53$. Finally, the measurement of the nuclear modification factor R_{pPb} as a function of p_T is presented, separately for the p-going and the Pb-going directions.

4.1 Production cross section in pp and p-Pb collisions

The cross section σ_ϕ was evaluated for each p_T and rapidity interval:

$$\sigma_\phi(x) = \frac{N_{\phi \rightarrow \mu\mu}^{\text{raw}}(x)}{[A \cdot \varepsilon](x) \cdot BR_{\phi \rightarrow \mu\mu} \cdot L_{\text{int}}},$$

where x stands for any specific p_T or rapidity interval considered. The total systematic uncertainty on $N_{\phi \rightarrow \mu\mu}^{\text{raw}}(x)$, after combining the different sources described above, ranges between 3% and 8% depend-

ing on the collision system and kinematic range. The branching ratio $BR_{\phi \rightarrow \mu\mu}$ was taken from [29] as the weighted average of the available measurements of $BR_{\phi \rightarrow \mu\mu}$ and $BR_{\phi \rightarrow ee}$, assuming lepton universality, resulting in a final uncertainty of approximately 1%. The product of the geometrical acceptance A and the reconstruction efficiency ε has been evaluated by means of Monte Carlo simulations, using the cocktail predictions for the differential input spectra. The values are obtained as the ratio between the number of dimuons at the output of the reconstruction chain — including the cuts and selections imposed on the data — and the number of dimuons injected as input. The uncertainty on $[A \cdot \varepsilon]$ mainly originates from the systematic uncertainty on the dimuon tracking and trigger efficiencies. In order to test possible systematic effects related to the hardware trigger p_T cut, imposing a non-sharp threshold at 0.5 GeV/c, the analysis was repeated with the additional offline sharp cuts $p_{T,\mu} > 0.5$ GeV/c and $p_{T,\mu} > 1$ GeV/c on single muons. For each of the two alternative scenarios, the corresponding measurement of the ϕ meson cross section was compared to the one coming from the reference analysis: the difference between the results was found to be smaller than the quadratic difference of the statistical uncertainties, showing that no significant bias related to the trigger threshold affects the results [31].

4.1.1 Production cross section in pp collisions

The inclusive, p_T -differential ϕ -meson cross section in pp collisions at $\sqrt{s} = 2.76$ TeV is shown in Fig. 2. The data points, also summarized in Table 1, are compared with the predictions from PHOJET [32] and PYTHIA [27], where for the latter the Perugia0, Perugia11 [33], ATLAS-CSC [34], and D6T [35] tunes are considered. An overall good agreement is found between predictions and data, with the exception of the Perugia0 and Perugia11 tunes of PYTHIA which underestimate the measured cross section by a factor of two, as already observed for the ϕ -meson measurements at $\sqrt{s} = 7$ TeV [17, 36]. It is worth to note that the D6T tune is not successful in describing the p_T evolution of the K/π ratio at mid-rapidity in pp collisions at $\sqrt{s} = 2.76$ TeV, as measured by the CMS Collaboration [37]: this suggests the idea that hidden strangeness is better reproduced than open strangeness in this specific PYTHIA tune. Data points were fitted with a Levy-Tsallis function [38]

$$\frac{1}{p_T} \frac{dN}{dp_T} \propto \left(1 + \frac{m_T - m_\phi}{nT} \right)^{-n}, \quad (1)$$

where $m_T = \sqrt{p_T^2 + m_\phi^2}$ stands for the transverse mass, obtaining the values $n = 10.2 \pm 4.8$ and $T = 284 \pm 72$ MeV for the fit parameters, where the errors reflect the statistical uncertainties only. The cross section integrated over the accessible p_T range $1 < p_T < 5$ GeV/c is $\sigma_\phi = 0.566 \pm 0.055$ (stat.) ± 0.044 (syst.) mb. The systematic uncertainties for this measurement are summarized in Table 2.

p_T (GeV/c)	$d^2\sigma_\phi/(dydp_T)$ (mb/(GeV/c))
[1.0, 1.5]	$0.423 \pm 0.067 \pm 0.043$
[1.5, 2.0]	$0.182 \pm 0.025 \pm 0.018$
[2.0, 2.5]	$0.089 \pm 0.011 \pm 0.007$
[2.5, 3.0]	$0.0340 \pm 0.0056 \pm 0.0020$
[3.0, 3.5]	$0.0139 \pm 0.0032 \pm 0.0011$
[3.5, 4.0]	$0.0087 \pm 0.0022 \pm 0.0006$
[4.0, 5.0]	$0.0028 \pm 0.0012 \pm 0.0002$

Table 1: p_T -differential production cross section for the ϕ meson in pp collisions at $\sqrt{s} = 2.76$ TeV, for $2.5 < y < 4$. The first uncertainty is statistical and the second is systematic.

4.1.2 Production cross section in p-Pb collisions

The ϕ cross section as a function of p_T in p-Pb collisions is shown in Fig. 3 for the forward and backward rapidity regions considered in the analysis. The results, also reported in Table 3, are fitted

Source	Syst. uncertainty on $\sigma_{pp}(\phi)$
Signal extraction	3-8 %
L_{int}	3.8 %
$BR(\phi \rightarrow \ell\ell)$	1 %
Tracking efficiency	4 %
Trigger efficiency	3 %

Table 2: Systematic uncertainties (in percent) contributing to the measurement of the ϕ cross section in pp collisions at $\sqrt{s} = 2.76$ TeV. When the uncertainty values depend on the p_T interval, their minimum and maximum values are quoted.

with the Levy-Tsallis distribution defined in Eq. (1), the resulting fit parameters being $\beta = 9.6 \pm 1.3$ and $T = 366 \pm 30$ MeV for the forward rapidity region and $\beta = 11.4 \pm 1.4$ and $T = 384 \pm 24$ MeV for the backward one, where the errors reflect the statistical uncertainties only. The predictions from HIJING 2.1 (with gluon shadowing) [39] and DPMJET [40] are also shown: these generators provided a good description of the ALICE $dN_{\text{ch}}/d\eta_{\text{lab}}$ results at mid-rapidity [9]. Averaging over the available p_T range, the discrepancy between the data and the predictions from HIJING and DPMJET amounts to $\sim 23\%$ and $\sim 57\%$, respectively, at backward rapidity (the Pb-going direction) and $\sim 20\%$ and $\sim 9.5\%$, respectively, at forward rapidity (the p-going direction). In all the cases, the generators underestimate the data points.

The ϕ cross section in p-Pb collisions, integrated over the accessible p_T range, $1 < p_T < 7$ GeV/c, is shown as a function of rapidity in Fig. 4. The data points, also summarized in Table 4, exhibit a significant asymmetry between the forward and backward rapidity regions. This observation complements the previous measurements of soft particle production (charged unidentified particles) reported in p-Pb by ALICE at the LHC at mid-rapidity [9], and in d-Au by PHOBOS at the RHIC ranging from mid to forward rapidity [13]. The comparison between the data and the predictions by HIJING and DPMJET,

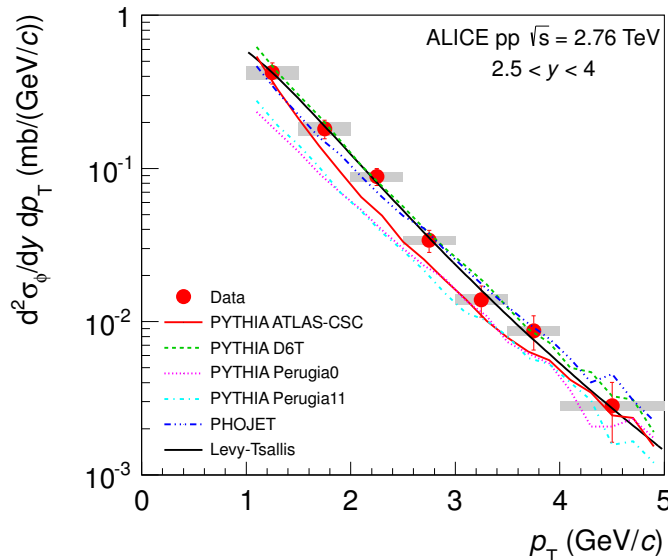


Fig. 2: ϕ -meson cross section as a function of p_T in pp collisions at $\sqrt{s} = 2.76$ TeV. Error bars and boxes represent statistical and systematic uncertainties, respectively. Predictions from PHOJET [32] and the PYTHIA tunes ATLAS-CSC [34], D6T [35], Perugia0 and Perugia11 [33] are also shown for comparison, as well as the result of a fit with the Levy-Tsallis function defined by Eq. (1).

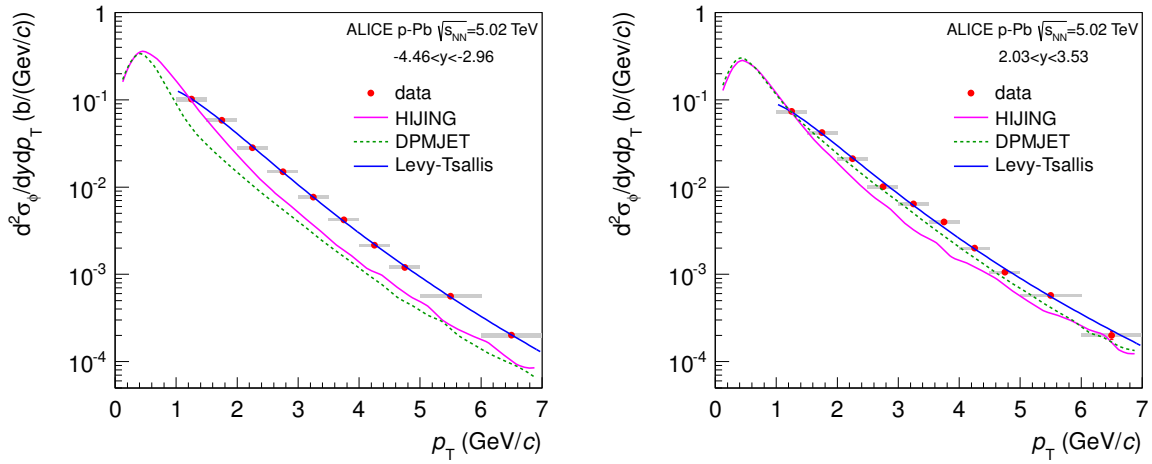


Fig. 3: ϕ -meson cross section in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of p_T in the backward (left) and forward (right) rapidity regions. Error bars (smaller than the markers) and boxes represent statistical and systematic uncertainties, respectively. Predictions by HIJING [39] and DPMJET [40] are also shown, together with the result of a fit with the Levy-Tsallis function (Eq. 1).

p_T (GeV/c)	$d^2\sigma_\phi / (dy dp_T)$ (mb/(GeV/c))	
	$-4.46 < y < -2.96$	$2.03 < y < 3.53$
[1.0, 1.5]	$102 \pm 8 \pm 12$	$73.3 \pm 5.6 \pm 8.0$
[1.5, 2.0]	$58.6 \pm 3.3 \pm 5.5$	$42.1 \pm 2.5 \pm 4.3$
[2.0, 2.5]	$28.3 \pm 1.4 \pm 2.9$	$21.0 \pm 1.2 \pm 2.0$
[2.5, 3.0]	$15.0 \pm 0.7 \pm 1.2$	$10.07 \pm 0.77 \pm 0.97$
[3.0, 3.5]	$7.66 \pm 0.40 \pm 0.70$	$6.38 \pm 0.41 \pm 0.61$
[3.5, 4.0]	$4.20 \pm 0.24 \pm 0.34$	$3.96 \pm 0.30 \pm 0.36$
[4.0, 4.5]	$2.15 \pm 0.17 \pm 0.16$	$1.99 \pm 0.20 \pm 0.15$
[4.5, 5.0]	$1.20 \pm 0.11 \pm 0.10$	$1.06 \pm 0.13 \pm 0.08$
[5.0, 6.0]	$0.560 \pm 0.052 \pm 0.054$	$0.570 \pm 0.088 \pm 0.043$
[6.0, 7.0]	$0.201 \pm 0.030 \pm 0.028$	$0.199 \pm 0.045 \pm 0.016$

Table 3: Production cross section for the ϕ meson in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, as a function of p_T , in the backward and forward rapidity regions. The first uncertainty is statistical and the second is systematic.

illustrated in Fig. 4, clearly shows how the models — which successfully described charged particle production at mid-rapidity in the same collision system [9] — fail to properly reproduce the shape and the normalisation of the observed rapidity dependence of the ϕ cross section. Still, HIJING prediction qualitatively reproduces the forward-backward asymmetry observed in the data, as well as — ignoring the normalisation — the shape of the y -dependence in the backward region. DPMJET, on the contrary, fails to reproduce even qualitatively the observed forward-backward asymmetry: it should be remarked that this behaviour seems to be related to the $p_T > 1$ GeV/c cut considered here, while at lower p_T the generator predicts a forward-backward asymmetry in favor of the Pb-going direction.

4.2 Forward-backward ratio in p-Pb collisions

To establish a more direct comparison of the cross section in the p-going and Pb-going directions, σ_ϕ was extracted as a function of p_T in the common $|y|$ range $2.96 < |y| < 3.53$. The p_T interval $1.0 < p_T < 1.5$ GeV/c was discarded in this measurement because of the poor statistics available in this limited rapidity range, resulting in an uncertainty larger than 50%.

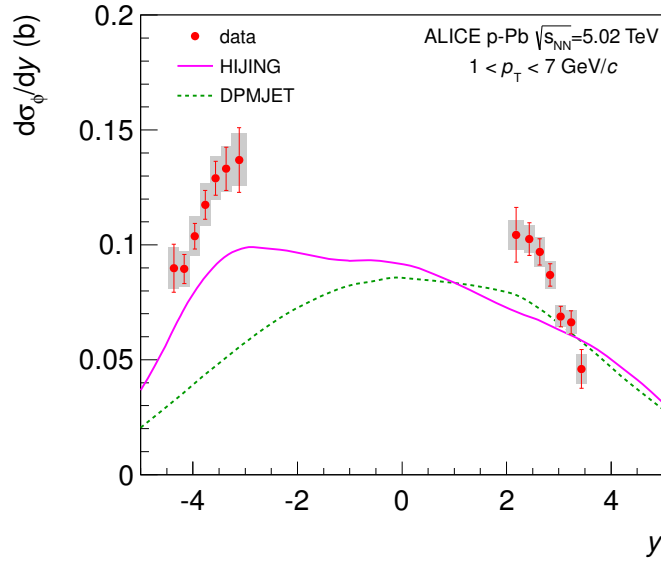


Fig. 4: ϕ cross section in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV as a function of rapidity, integrated over the range $1 < p_{\text{T}} < 7$ GeV/c. Error bars and boxes represent statistical and systematic uncertainties, respectively. Predictions by HIJING and DPMJET are also shown.

y	$d\sigma_{\phi}/dy$ (mb)	y	$d\sigma_{\phi}/dy$ (mb)
$[-4.46, -4.25]$	$136 \pm 14 \pm 11$	$[2.03, 2.35]$	$104 \pm 11 \pm 6$
$[-4.25, -4.05]$	$133 \pm 9 \pm 9$	$[2.35, 2.55]$	$102 \pm 7 \pm 5$
$[-4.05, -3.85]$	$128 \pm 7 \pm 9$	$[2.55, 2.75]$	$96 \pm 5 \pm 6$
$[-3.85, -3.65]$	$117 \pm 6 \pm 9$	$[2.75, 2.95]$	$86 \pm 4 \pm 5$
$[-3.65, -3.45]$	$103 \pm 5 \pm 8$	$[2.95, 3.15]$	$68 \pm 4 \pm 4$
$[-3.45, -3.25]$	$89 \pm 6 \pm 7$	$[3.15, 3.35]$	$66 \pm 5 \pm 5$
$[-3.25, -2.96]$	$89 \pm 10 \pm 9$	$[3.35, 3.53]$	$45 \pm 8 \pm 6$

Table 4: Production cross section for the ϕ meson in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV, as a function of rapidity, integrated over the range $1 < p_{\text{T}} < 7$ GeV/c. The first uncertainty is statistical and the second is systematic.

The ratio between the forward and backward cross section, R_{FB} , is shown as a function of p_{T} in Fig. 5. The data points exhibit no significant p_{T} dependence within the experimental uncertainties. Predictions by HIJING and DPMJET are also shown, with HIJING slightly overestimating the data points and DPMJET clearly failing to reproduce the observed values, staying above $R_{\text{FB}} = 1$ in the whole p_{T} range considered here. This observation is consistent with the observations in Fig. 4, where the forward-backward asymmetry of the ϕ yield was better reproduced by HIJING than it was by DPMJET.

4.3 Nuclear modification factor in p-Pb collisions

The ϕ meson nuclear modification factor R_{pPb} is defined as the ratio between the production cross section $\sigma_{\text{pPb}}(p_{\text{T}})$ in p-Pb collisions and the cross section $\sigma_{\text{pp}}(p_{\text{T}})$ in pp collisions — evaluated at $\sqrt{s} = 5.02$ TeV as described in the following — scaled by A_{Pb} :

$$R_{\text{pPb}}(p_{\text{T}}) = \frac{\sigma_{\phi}^{\text{pPb}}(p_{\text{T}})}{\sigma_{\phi}^{\text{pp}}(p_{\text{T}}) \cdot A_{\text{Pb}}}, \quad (2)$$

where A_{Pb} is the nuclear mass number for the Pb nucleus. Since for the pp cross section $\sigma_{\phi}^{\text{pp}}$ at $\sqrt{s} = 5.02$ TeV no direct measurement is currently available, it was evaluated by interpolating the measure-

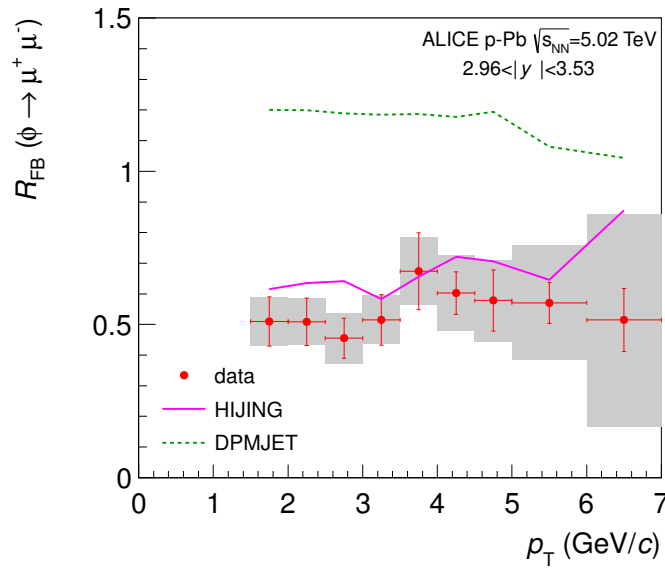


Fig. 5: Forward-backward ratio for the ϕ meson in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV as a function of p_T , in the rapidity range $2.96 < |y| < 3.53$ common to the two rapidity regions considered in the analysis. Error bars and boxes represent statistical and systematic uncertainties, respectively. Predictions from HIJING and DPMJET are also shown for comparison.

ments in the rapidity interval $2.5 < y < 4$ at $\sqrt{s} = 2.76$ (see Section 4.1.1) and 7 TeV [17]. For each p_T interval, the \sqrt{s} dependence of the differential cross section $d^2\sigma_\phi^{pp}/(dydp_T)$ was described with a power law $\sigma_{pp}(\sqrt{s}) = C \cdot (\sqrt{s})^\alpha$, where C and α are determined using the data at 2.76 and 7 TeV. Alternative parameterisations were also considered [41], namely a linear and an exponential function, and the mean of the results obtained with the three functions was taken. Since the pp measurements are limited to $1 < p_T < 5$ GeV/c, the cross section at $\sqrt{s_{NN}} = 5.02$ TeV was extrapolated towards higher p_T by means of a Levy-Tsallis function, which describes the calculated differential cross section in the p_T range covered by the measurements. The uncertainty on the interpolated cross sections arises from the choice of the function used for the interpolation, from the uncertainties in the measurements at 2.76 and 7 TeV, and — for $p_T > 5$ GeV/c — from the extrapolation based on the Levy-Tsallis fit. They range from about 7 % for $p_T = 1$ GeV/c to 20 % for $p_T = 5$ GeV/c, and exceed 30 % for $p_T > 5$ GeV/c, representing the major source of systematic uncertainty for the measurement of the nuclear modification factor. The interpolated cross section, which refers to the rapidity range $2.5 < y < 4$, was finally scaled to the forward and backward rapidity windows $2.03 < y < 3.53$ and $-4.46 < y < -2.96$, considered for the analysis of the p-Pb data. The relative scaling factors $f_{\text{fwd}} = 1.135 \pm 0.031$ and $f_{\text{bkw}} = 0.850 \pm 0.028$ were evaluated as an average from simulations with PHOJET and the Perugia0, Perugia11, ATLAS-CSC and D6T PYTHIA tunes. The uncertainties (amounting to about 3 %) correspond to the differences between the considered predictions. The numerical values are reported in Table 5.

The nuclear modification factor R_{pPb} as a function of p_T is shown in the two panels of Fig. 6 for the backward and forward rapidity regions considered in the analysis. The numerical values are also quoted in Table 6. For each p_T interval, the systematic uncertainty detailed in Table 7 results from the quadratic sum of the uncertainty on the ϕ cross section in p-Pb and the one of the pp reference. A rising trend of R_{pPb} when going from $p_T = 1$ GeV/c to $p_T \approx 3-4$ GeV/c can be observed both at backward and forward rapidity. The values of R_{pPb} in the two rapidity ranges, however, are significantly different. In particular, at backward rapidity we observe an enhancement of the ϕ cross section with respect to the scaled pp reference peaked around $p_T = 3-4$ GeV/c. This enhancement, absent in the forward rapidity region, reaches a factor of up to ~ 1.6 and could be associated either to an initial-state effect (including a possible

p_{T} (GeV/c)	$d^2\sigma_{\phi}/dydp_{\text{T}}$ (mb/(GeV/c))	
	$-4.46 < y < -2.96$	$2.03 < y < 3.53$
[1.0, 1.5]	0.491 ± 0.067	0.656 ± 0.090
[1.5, 2.0]	0.223 ± 0.015	0.297 ± 0.020
[2.0, 2.5]	0.0995 ± 0.0071	0.1328 ± 0.0095
[2.5, 3.0]	0.0467 ± 0.0032	0.0623 ± 0.0043
[3.0, 3.5]	0.0234 ± 0.0015	0.0312 ± 0.0020
[3.5, 4.0]	0.0125 ± 0.0011	0.0167 ± 0.0015
[4.0, 4.5]	0.00706 ± 0.00094	0.0094 ± 0.0012
[4.5, 5.0]	0.00419 ± 0.00082	0.0056 ± 0.0011
[5.0, 6.0]	0.00213 ± 0.00060	0.00284 ± 0.00081
[6.0, 7.0]	0.00093 ± 0.00039	0.00124 ± 0.00052

Table 5: Differential cross section for the ϕ meson in pp collisions at $\sqrt{s} = 5.02$ TeV in the backward and forward rapidity regions of interest for the analysis of the p-Pb data, as obtained interpolating the available measurements at $\sqrt{s} = 2.76$ and 7 TeV. Resulting uncertainties, combining statistical and systematic sources, are reported.

Cronin-like enhancement [4, 42]) or to a final state effect related to radial flow in p-Pb as proposed for recent ALICE measurements at mid-rapidity [43]. Discriminating between these two effects requires more detailed investigations, including differential analyses as a function of global event properties like collision centrality.

Concerning the behaviour at high p_{T} , we observe that the ϕ -meson R_{pPb} is compatible with unity for $p_{\text{T}} \gtrsim 4$ GeV/c in the p-going direction, similar to the observation for the measurement of the charged particle production at mid-rapidity [10]. The observations in the Pb-going direction do not allow a clear trend of the R_{pPb} factor at high p_{T} to be established. A possible saturation at $R_{\text{pPb}} \approx 1$ for $p_{\text{T}} \gtrsim 5$ GeV/c is, however, still compatible with the measurements.

p_{T} (GeV/c)	R_{pPb}	
	$-4.46 < y < -2.96$	$2.03 < y < 3.53$
[1.0, 1.5]	$1.00 \pm 0.08 \pm 0.18$	$0.537 \pm 0.041 \pm 0.094$
[1.5, 2.0]	$1.26 \pm 0.07 \pm 0.15$	$0.681 \pm 0.040 \pm 0.083$
[2.0, 2.5]	$1.37 \pm 0.07 \pm 0.17$	$0.760 \pm 0.043 \pm 0.091$
[2.5, 3.0]	$1.54 \pm 0.07 \pm 0.16$	$0.777 \pm 0.059 \pm 0.092$
[3.0, 3.5]	$1.57 \pm 0.08 \pm 0.18$	$0.98 \pm 0.06 \pm 0.11$
[3.5, 4.0]	$1.62 \pm 0.09 \pm 0.19$	$1.14 \pm 0.09 \pm 0.15$
[4.0, 4.5]	$1.46 \pm 0.12 \pm 0.22$	$1.02 \pm 0.10 \pm 0.15$
[4.5, 5.0]	$1.38 \pm 0.13 \pm 0.29$	$0.91 \pm 0.11 \pm 0.19$
[5.0, 6.0]	$1.26 \pm 0.12 \pm 0.38$	$0.97 \pm 0.15 \pm 0.29$
[6.0, 7.0]	$1.04 \pm 0.16 \pm 0.46$	$0.77 \pm 0.17 \pm 0.33$

Table 6: Nuclear modification factor R_{pPb} in p-Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV for the ϕ meson as a function of p_{T} in the backward and forward rapidity regions. The first uncertainty is statistical and the second is systematic.

Unfortunately, only few other existing measurements can be compared to our data. In particular, results on ϕ meson production in d-Au collisions at $\sqrt{s_{\text{NN}}} = 200$ GeV have been recently released by the PHENIX Collaboration [44]. The p_{T} -dependence of the R_{dAu} measured by PHENIX, as well as its evolution from backward to forward rapidity, is found to be similar to what observed in our results for the R_{pPb} . Mid-rapidity data on R_{dAu} , also presented by the PHENIX Collaboration for the ϕ meson, seem to sit between the forward- and backward-rapidity results. Forward-rapidity measurements in d-Au

Source	Syst. uncertainty on $\sigma_{p\text{-Pb}}(\phi)$ and $R_{p\text{Pb}}$	
	$-4.46 < y < -2.96$	$2.03 < y < 3.53$
Signal extraction	3-5 %	4-8 %
L_{int}	3.5 %	3.8 %
$BR(\phi \rightarrow \ell\ell)$	1 %	1 %
Tracking efficiency	6 %	4 %
Trigger efficiency	3.2 %	2.8 %
$\sigma_{pp}(\phi)$	7-30 %	7-30 %
$f_{\text{bkw}}, f_{\text{fwd}}$	3.3 %	2.7 %

Table 7: Systematic uncertainties (in percent) contributing to the measurement of the ϕ cross section and nuclear modification factor in the backward and forward rapidity regions in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. When the uncertainty values depend on the p_T interval, their minimum and maximum values are quoted.

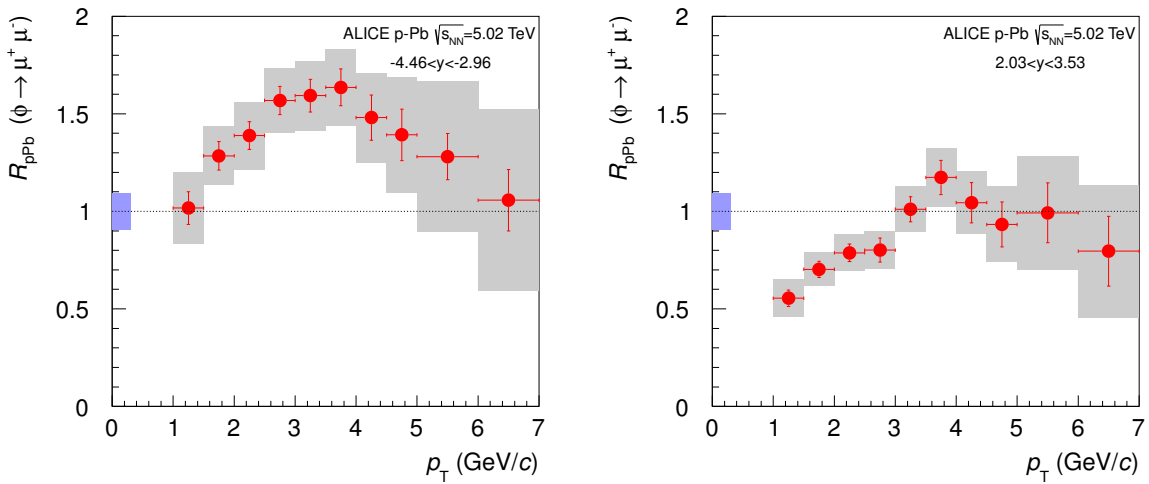


Fig. 6: Nuclear modification factor $R_{p\text{Pb}}$ in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for the ϕ meson as a function of p_T , in the backward (left) and forward (right) rapidity regions considered in the analysis. Error bars and boxes represent statistical and bin-to-bin uncorrelated systematic uncertainties, respectively. The blue box on the left represents the bin-to-bin correlated systematic uncertainty, see Table 7.

collisions at $\sqrt{s_{NN}} = 200$ GeV at the RHIC [12, 13] are also available for unidentified charged particles, although for the d-going direction only. These data exhibit, similar to our ϕ -meson results in the p-going direction, a rise of R_{dAu} from ~ 0.5 to ~ 1 between $p_T \sim 1$ GeV/c and $p_T \sim 4$ GeV/c. A similar rise of $R_{p\text{Pb}}$ is also observed in the measurement of unidentified charged particle production at mid-rapidity, performed by ALICE [10].

5 Conclusions

We have presented results on ϕ -meson production in the dimuon channel in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV obtained by the ALICE experiment at the LHC. Cross section and nuclear modification factor measurements were performed for $1 < p_T < 7$ GeV/c in the rapidity windows $2.03 < y < 3.53$ (p-going direction) and $-4.46 < y < -2.96$ (Pb-going direction). A corresponding cross section measurement in pp collisions at $\sqrt{s} = 2.76$ TeV has also been reported, extracting the production cross section for $1 < p_T < 5$ GeV/c in the region $2.5 < y < 4$. Predictions from HIJING and DPMJET are compared

to the p-Pb cross sections and are found to underestimate the data both at backward (by about 23 % and 57 % on average) and at forward rapidity (by about 20 % and 9.5 % on average). The forward-backward asymmetry in the ϕ meson cross section in p-Pb collisions was measured in the rapidity range $2.96 < |y| < 3.53$, and no significant p_T dependence was found within uncertainties. In this case, data points are significantly overestimated by the DPMJET model, while only a slight disagreement is observed with respect to the HIJING prediction.

In the p-going direction a rising trend of the nuclear modification factor R_{pPb} is observed from ~ 0.5 to ~ 1 , when going from $p_T = 1$ GeV/c to $p_T = 4$ GeV/c. This observation is compatible with the behaviour of charged particles at forward rapidity at RHIC energies, and at mid-rapidity at LHC energies. In the Pb-going direction, on the other hand, an enhancement is observed for R_{pPb} , reaching values as large as ~ 1.6 around $p_T = 3-4$ GeV/c. An interpretation of these results, either in terms of an initial-state (Cronin-like) effect or a final-state effect related to radial flow in p-Pb, is not possible yet, due to a general lack of theoretical predictions for soft particle production at forward rapidity in p-A collisions at the LHC energies.

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References

- [1] A. Bazavov, T. Bhattacharya, M. Cheng, C. DeTar, H. Ding, *et al.*, “The chiral and deconfinement aspects of the QCD transition,” *Phys.Rev.* **D85** (2012) 054503, arXiv:1111.1710 [hep-lat].
- [2] **Wuppertal-Budapest** Collaboration, S. Borsanyi *et al.*, “Is there still any T_c mystery in lattice QCD? Results with physical masses in the continuum limit III,” *JHEP* **1009** (2010) 073, arXiv:1005.3508 [hep-lat].
- [3] S. Borsanyi, G. Endrodi, Z. Fodor, A. Jakovac, S. D. Katz, *et al.*, “The QCD equation of state with dynamical quarks,” *JHEP* **1011** (2010) 077, arXiv:1007.2580 [hep-lat].
- [4] A. Accardi, “Cronin effect in proton nucleus collisions: A Survey of theoretical models,” arXiv:hep-ph/0212148 [hep-ph].
- [5] C. Salgado, J. Alvarez-Muniz, F. Arleo, N. Armesto, M. Botje, *et al.*, “Proton-Nucleus Collisions at the LHC: Scientific Opportunities and Requirements,” *J.Phys.* **G39** (2012) 015010, arXiv:1105.3919 [hep-ph].
- [6] M. Brandt, M. Klasen, and F. König, “Nuclear parton density modifications from low-mass lepton pair production at the LHC,” arXiv:hep-ph/14016817 [hep-ph].
- [7] **BRAHMS** Collaboration, I. Arsene *et al.*, “Quark gluon plasma and color glass condensate at RHIC? The Perspective from the BRAHMS experiment,” *Nucl.Phys.* **A757** (2005) 1–27, arXiv:nucl-ex/0410020 [nucl-ex].
- [8] B. Back, M. Baker, M. Ballintijn, D. Barton, B. Becker, *et al.*, “The PHOBOS perspective on discoveries at RHIC,” *Nucl.Phys.* **A757** (2005) 28–101, arXiv:nucl-ex/0410022 [nucl-ex].
- [9] **ALICE** Collaboration, B. Abelev *et al.*, “Pseudorapidity density of charged particles p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV,” *Phys.Rev.Lett.* **110** (2013) 032301, arXiv:1210.3615 [nucl-ex].
- [10] **ALICE** Collaboration, B. Abelev *et al.*, “Transverse Momentum Distribution and Nuclear Modification Factor of Charged Particles in p-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV,” *Phys.Rev.Lett.* **110** (2013) 082302, arXiv:1210.4520 [nucl-ex].
- [11] **ALICE** Collaboration, B. B. Abelev *et al.*, “Transverse momentum dependence of inclusive primary charged-particle production in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV,” *Eur.Phys.J.* **C74** no. 9, (2014) 3054, arXiv:1405.2737 [nucl-ex].
- [12] **BRAHMS** Collaboration, I. Arsene *et al.*, “On the evolution of the nuclear modification factors with rapidity and centrality in d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV,” *Phys.Rev.Lett.* **93** (2004) 242303, arXiv:nucl-ex/0403005 [nucl-ex].

- [13] **PHOBOS** Collaboration, B. Back *et al.*, “Pseudorapidity distribution of charged particles in d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV,” *Phys.Rev.Lett.* **93** (2004) 082301, arXiv:nuc1-ex/0311009 [nucl-ex].
- [14] J. Rafelski and B. Muller, “Strangeness Production in the Quark - Gluon Plasma,” *Phys.Rev.Lett.* **48** (1982) 1066.
- [15] A. Shor, “ ϕ -meson production as a probe of the Quark-Gluon Plasma,” *Phys.Rev.Lett.* **54** (1985) 1122–1125.
- [16] P. Koch, B. Muller, and J. Rafelski, “Strangeness in Relativistic Heavy Ion Collisions,” *Phys.Rept.* **142** (1986) 167–262.
- [17] **ALICE** Collaboration, B. Abelev *et al.*, “Light vector meson production in pp collisions at $\sqrt{s} = 7$ TeV,” *Phys.Lett.* **B710** (2012) 557–568, arXiv:1112.2222 [nucl-ex].
- [18] **ALICE** Collaboration, K. Aamodt *et al.*, “The ALICE experiment at the CERN LHC,” *JINST* **3** (2008) S08002.
- [19] **ALICE** Collaboration, B. B. Abelev *et al.*, “Performance of the ALICE Experiment at the CERN LHC,” *Int.J.Mod.Phys.* **A29** (2014) 1430044, arXiv:1402.4476 [nucl-ex].
- [20] **ALICE** Collaboration, M. Gagliardi, “Measurement of reference cross sections in pp and Pb-Pb collisions at the LHC in van der Meer scans with the ALICE detector,” *AIP Conf.Proc.* **1422** (2012) 110–116, arXiv:1109.5369 [hep-ex].
- [21] **ALICE** Collaboration, B. B. Abelev *et al.*, “ J/ψ production and nuclear effects in p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV,” *JHEP* **1402** (2014) 073, arXiv:1308.6726 [nucl-ex].
- [22] **ALICE** Collaboration, B. B. Abelev *et al.*, “Measurement of visible cross sections in proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV in van der Meer scans with the ALICE detector,” *JINST* **9** no. 11, (2014) P11003, arXiv:1405.1849 [nucl-ex].
- [23] **ALICE** Collaboration, B. B. Abelev *et al.*, “Measurement of quarkonium production at forward rapidity in pp collisions at $\sqrt{s} = 7$ TeV,” *Eur.Phys.J.* **C74** no. 8, (2014) 2974, arXiv:1403.3648 [nucl-ex].
- [24] **ALICE** Collaboration, B. Abelev *et al.*, “Measurement of inelastic, single- and double-diffraction cross sections in proton-proton collisions at the LHC with ALICE,” *Eur.Phys.J.* **C73** no. 6, (2013) 2456, arXiv:1208.4968 [hep-ex].
- [25] **ALICE** Collaboration, L. Aphecetche *et al.*, “Numerical Simulations and Offline Reconstruction of the Muon Spectrometer of ALICE,”
- [26] **ALICE** Collaboration, G. Chabratova *et al.*, “Development of the Kalman filter for tracking in the forward muon spectrometer of ALICE,”
- [27] T. Sjostrand, S. Mrenna, and P. Z. Skands, “PYTHIA 6.4 Physics and Manual,” *JHEP* **0605** (2006) 026, arXiv:hep-ph/0603175 [hep-ph].
- [28] R. Brun, F. Carminati, and S. Giani, “GEANT Detector Description and Simulation Tool,”
- [29] **Particle Data Group** Collaboration, J. Beringer *et al.*, “Review of Particle Physics (RPP),” *Phys.Rev.* **D86** (2012) 010001.
- [30] J. Gaiser, “Charmonium Spectroscopy From Radiative Decays of the J/ψ and ψ' ,” *PhD thesis* (1982).

- [31] R. Barlow, “Systematic errors: Facts and fictions,” arXiv:hep-ex/0207026 [hep-ex].
- [32] R. Engel and J. Ranft, “Hadronic photon-photon interactions at high-energies,” *Phys.Rev.* **D54** (1996) 4244–4262, arXiv:hep-ph/9509373 [hep-ph].
- [33] P. Z. Skands, “Tuning Monte Carlo Generators: The Perugia Tunes,” *Phys.Rev.* **D82** (2010) 074018, arXiv:1005.3457 [hep-ph].
- [34] C. Buttar, D. Clements, I. Dawson, and A. Moraes, “Simulations of minimum bias events and the underlying event, MC tuning and predictions for the LHC,” *Acta Phys.Polon.* **B35** (2004) 433–441.
- [35] R. Field, “Physics at the Tevatron,” *Acta Phys.Polon.* **B39** (2008) 2611–2672.
- [36] ALICE Collaboration, B. Abelev *et al.*, “Production of $K^*(892)^0$ and $\phi(1020)$ in pp collisions at $\sqrt{s} = 7$ TeV,” *Eur.Phys.J.* **C72** (2012) 2183, arXiv:1208.5717 [hep-ex].
- [37] CMS Collaboration, S. Chatrchyan *et al.*, “Study of the inclusive production of charged pions, kaons, and protons in pp collisions at $\sqrt{s} = 0.9, 2.76,$ and 7 TeV,” *Eur.Phys.J.* **C72** (2012) 2164, arXiv:1207.4724 [hep-ex].
- [38] C. Tsallis, “Possible Generalization of Boltzmann-Gibbs Statistics,” *J.Statist.Phys.* **52** (1988) 479–487.
- [39] X.-N. Wang and M. Gyulassy, “HIJING: A Monte Carlo model for multiple jet production in p p, p A and A A collisions,” *Phys.Rev.* **D44** (1991) 3501–3516.
- [40] S. Roesler, R. Engel, and J. Ranft, “The Monte Carlo event generator DPMJET-III,” arXiv:hep-ph/0012252 [hep-ph].
- [41] ALICE, LHCb Collaboration, “Reference pp cross-sections for J/ψ studies in proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV and comparisons between ALICE and LHCb results,” <http://cds.cern.ch/record/1639617>. CONF-2013-013.
- [42] HERA-B Collaboration, I. Abt *et al.*, “ K^0 and ϕ meson production in proton-nucleus interactions at $\sqrt{s} = 41.6$ GeV,” *Eur.Phys.J.* **C50** (2007) 315–328, arXiv:hep-ex/0606049 [hep-ex].
- [43] ALICE Collaboration, B. B. Abelev *et al.*, “Multiplicity Dependence of Pion, Kaon, Proton and Lambda Production in p-Pb Collisions at $\sqrt{s_{NN}} = 5.02$ TeV,” *Phys.Lett.* **B728** (2014) 25–38, arXiv:1307.6796 [nucl-ex].
- [44] PHENIX Collaboration, A. Adare *et al.*, “ ϕ meson production in $d+Au$ collisions at $\sqrt{s_{NN}} = 200$ GeV,” arXiv:1506.08181 [nucl-ex].

A The ALICE Collaboration

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