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Can ϕ mesons give an answer to the baryon puzzle at RHIC?

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Abstract. The PHENIX experiment at RHIC has observed a large enhancement of baryon and anti-baryon production at $p_{\mathrm{T}} \approx$ 2–5 GeV/c, compared to expectations from jet fragmentation. While a number of theoretical interpretations of the data are available, there is not yet a definitive answer to the "baryon puzzle". We investigate the centrality dependence of ϕ-meson production at mid-rapidity in Au+Au collisions with $\sqrt{s_{NN}} = 200$ GeV. Comparison with the proton and anti-proton spectra reveal similar shapes, as expected for soft production described by hydrodynamics. However, the absolute yields show a different centrality dependence. The nuclear modification factors for ϕ are similar to those of pions, rather than (anti)protons that have similar mass. At intermediate p_{T}, baryon/meson effects seem to be more important than the mass effects, in support of recombination models.

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1 Introduction

A most unexpected result from the high-p_{T} measurements at RHIC is the large enhancement in the production of baryons and anti-baryons at $p_{\mathrm{T}} \approx$ 2–5 GeV/c [1,2], compared to expectations from jet fragmentation. In central Au+Au collisions the ratio $\overline{p}/\pi$ is of the order 1 — a factor of 3 above the ratio measured in peripheral reactions or in pp collisions. This large baryon fraction may indicate that the fragmentation functions, generally considered universal, are modified inside the hot and dense medium. Another possibility is that, due to collective effects, the soft processes play an important role up to high-p_{T} ($>$ 2 GeV/c). It was also observed [2] that, at intermediate p_{T}, the (anti)proton yields in Au+Au collisions of different centralities scale with their respective number of nucleon-nucleon collisions (N_{coll}), which is much faster than the expected scaling for soft processes. In contrast, strong suppression with respect to N_{coll}-scaling was discovered in pion production [3]. Unlike the scaling of yields, jet correlations obtained with baryon or meson trigger show a very similar behavior [4] indicating the presence of a strong hard component independent of the hadron's mass or quark content. Particle dependent suppression patterns are also present in the strange particle sector [5]. Recently, the "baryon puzzle" at RHIC was addressed by quark recombination models [6–8]. In this description, baryons are boosted to higher p_{T} by the addition of 3 quark momenta. In most cases, the recombination is dominated by soft quarks and special care needs to be taken to reproduce the measured jet correlations. This paper presents a study of ϕ-meson production in $\sqrt{s_{NN}}$= 200 GeV Au+Au collisions, as a function of centrality, measured in the K^+K^- decay channel by the PHENIX detector. Since the ϕ-meson mass is similar to that of the proton, these measurements can distinguish mass effects from the effects associated with the number of constituent quarks forming the hadrons and possibly help to resolve the "baryon puzzle".

2 Hydrodynamics description of identified hadron spectra

A common conjecture invoked to explain the large $\overline{p}/\pi$ ratios observed by PHENIX [2] is the strong radial flow [9] that boosts the momentum spectra of heavier particles to high p_T. In this scenario, the soft processes dominate the production of (anti)protons at 2–4.5 GeV/c, while the pions are primarily produced by fragmentation of hard-scattered partons. A study involving both light (π, K) and heavy $(\overline{p}, \phi)$ hadrons can test the range of applicability of the hydrodynamics description of the spectra. We concentrate on the comparison between protons, anti-protons and ϕ-mesons. Since ϕ-mesons may freeze-out earlier than protons, due to their smaller interaction cross-section, we first try to establish if a common hydrodynamics description is applicable to both.

The PHENIX experiment has measured the invariant yields of ϕ-mesons produced in Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV in 3 exclusive centrality classes: 0–10%, 10–40% and 40–92% [10]. The choice of centrality bins is governed by the limited statistics available from Run2 of RHIC. The $\pi^{\pm}, \pi^0, K^{\pm}$, p, and $\overline{p}$ spectra have been published [11,3] with much finer centrality binning, but to facilitate the comparison with the ϕ-meson data we present the results for the above classes of events.

In Fig. 1 we compare the central and peripheral spectra of $\pi^{\pm}$, $K^{\pm}$, p and $\overline{p}$ to a hydrodynamics-inspired param-

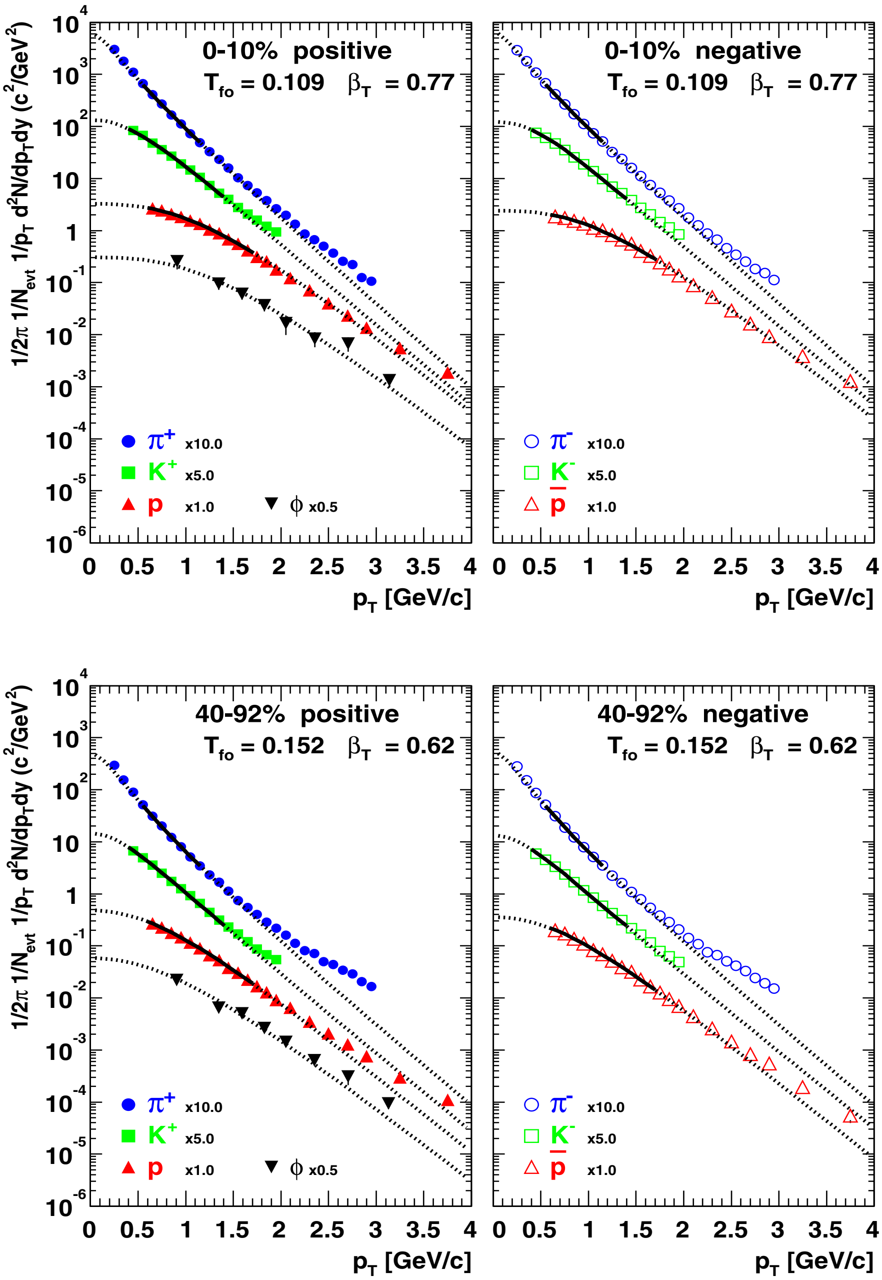

Fig. 1. $\pi^{\pm}$, $K^{\pm}$, p and $\overline{p}$ transverse momenta distributions, for central (top) and peripheral (bottom) Au+Au collisions at $\sqrt{s_{NN}}$= 200 GeV, fitted with a parameterization inspired by hydrodynamics (in the transverse momentum ranges indicated by the solid lines). The corresponding prediction for the ϕ transverse momentum spectrum is also shown

eterization [12] that has been fitted to the data. The free parameters in the model are the kinetic freeze-out temperature T_{fo}, the transverse flow velocity β_{T}, the absolute normalization and the choice of velocity profile (kept linear in all fits discussed here). We have checked that the parameters and the spectral shapes obtained with this simple parameterization are consistent with a full model calculation [13]. The extracted parameters are shown in the figure. The line drawn through the ϕ-meson spectrum is the model's prediction obtained after fitting all other particle species. We see that: 1) in central collisions, hydrodynamics gives a good description of the p and $\overline{p}$ spectral shapes up to ≈ 3 GeV/c; 2) the ϕ-meson spectrum can be described by the same parameters as the protons; 3) for lighter particles and for peripheral collisions the deviation from hydrodynamics happens at lower p_{T}. A fit including the ϕ was also performed [10] with practically no change in the model parameters. We note that our ϕ measurement does not extend to low-p_{T} (< 0.8 GeV/c) and, hence, it cannot constrain the flow velocity by itself. Nevertheless, the spectral shapes are consistent with the (anti)proton spectra (see also Fig. 3). If hydrodynamics flow is responsible for the enhanced (anti)proton production at $p_{\mathrm{T}} =$ 2–4.5 GeV/c, we may expect a similar enhancement in ϕ production. However, one also needs to take into account that the absolute normalization is a free parameter in the hydrodynamics fits and the shape comparison may not be enough to draw conclusions about production mechanisms of different particle species.

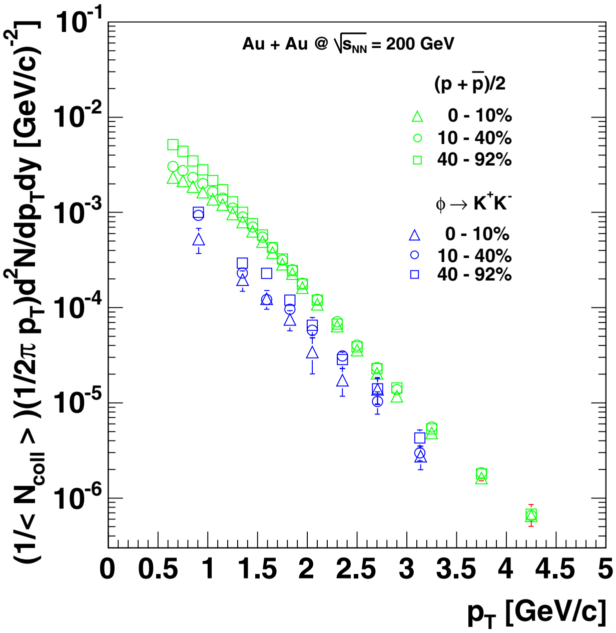

Fig. 2. p_{T} spectra of protons and ϕ mesons at different centralities, scaled down by N_{coll}

3 Scaling of yields and nuclear modification factors

We now examine the scaling of the yields as a function of centrality. The expectation is that for soft production the yields will scale as the number of nucleons participating in the collision (N_{part}), while for hard processes the scaling is with N_{coll}. In Fig. 2 the p_{T} distributions for (anti)protons and ϕ mesons are scaled down by their respective N_{coll}. The (anti)proton spectra show two pronounced features. Below $p_{\mathrm{T}} = 1.5$ GeV$/c$, the spectral shapes are strongly influenced by the radial flow and thus the more central data have a harder slope. Above $p_{\mathrm{T}} = 1.5$ GeV$/c$, the effect of radial flow is negligible. The spectra converge to the same line. Moreover, they scale with N_{coll} for all centrality classes, as expected for hard-scattering un-affected by the nuclear medium. The ϕ spectra have a quite different behavior. There is no visible curvature at lower p_{T}. This could be due to the fact that the ϕ spectra have only two (rather wide) bins below $p_{\mathrm{T}} = 1.5$ GeV$/c$ — the region where the curvature in the proton spectra is most pronounced. A curved functional form can be fit to the spectra with acceptable χ^2, as already discussed above. To further illustrate this point, a comparison of the central ϕ and $p+\bar{p}$ spectra is shown in Fig. 3. Returning to the N_{coll}-scaled yields, we observe that at higher p_{T} the ϕ spectra run parallel to the (anti)proton spectra, but do not obey N_{coll} scaling.

To examine this feature on a linear scale, we plot the ratio between the central and peripheral data, i.e. the ratio R_{CP} (Fig. 4). The 19% systematic error arising from the determination of N_{coll} , which is common to all particle species, is represented by a bar around $R_{CP} = 1$. Since we are interested in the *comparison* between the R_{CP} values for the protons and the ϕ, the important systematic errors to consider are those that can move the ϕ points with respect to the proton points. When determining a ratio of spectra measured at different centralities, most systematic errors cancel. After removing the N_{coll} error, the sources of error that remain for the ϕ come from the multiplicity dependent corrections and the effect of the choice of the mass window used for extraction of the ϕ yields. The relative error between the ϕ and the proton measurements is evaluated at 7% and is represented by the extended solid bar just below $R_{CP} = 1$. Clearly, the ϕ behaves in a way more similar to the pions than to the protons. Thus we

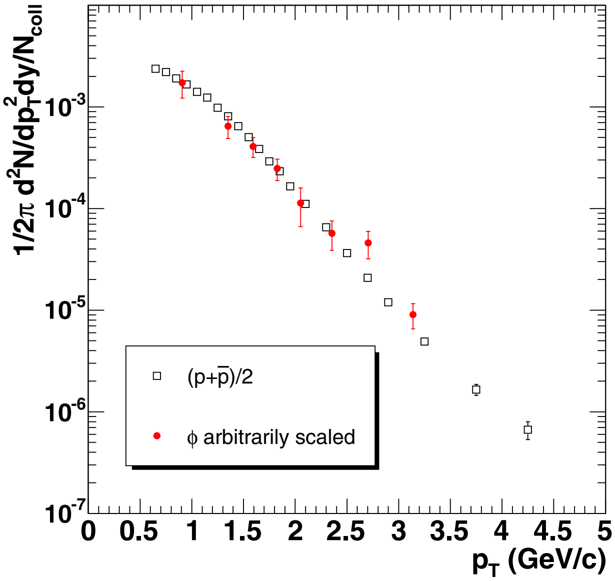

Fig. 3. Shape comparison between $(p+\bar{p})/2$ and ϕ p_{T} distributions obtained in the 10% most central Au+Au collisions

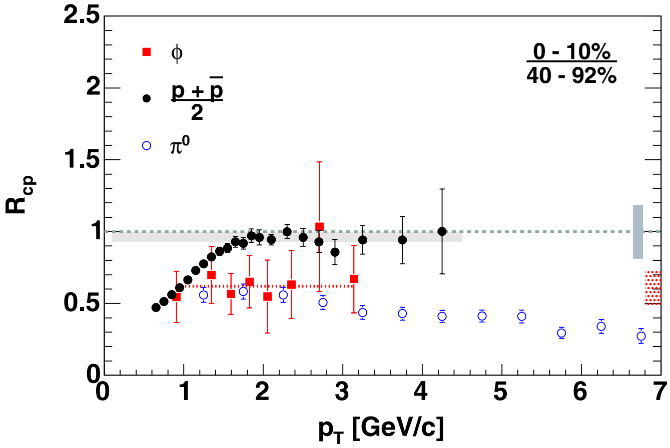

Fig. 4. N_{coll}-scaled central to peripheral ratio, R_{CP}, for $(p+\bar{p})/2$, π^0, and ϕ. The vertical bar on the right represents the error on $N_{\mathrm{coll}}^{0-10\%}/N_{\mathrm{coll}}^{40-92\%}$. The shaded solid bar around $R_{CP} = 1$ represents a 7% systematic error within which the proton and ϕ points can move with respect to each other. The dotted horizontal line at $R_{CP} = 0.62$ is a straight line fit to the ϕ data

conclude that the ϕ meson exhibits a suppression effect at intermediate p_{T} similar to that of the pions. Although we cannot determine whether ϕ production at this intermediate p_{T} is dominated by soft or hard processes, this observation provides support for models which depend on the number of constituent quarks in the hadron as opposed to models which depend upon just the mass of the particle in order to explain the anomalous proton yields.

4 Conclusions

The PHENIX experiment has obtained data on ϕ production, at mid-rapidity, in Au+Au collisions with $\sqrt{s_{NN}} =$ 200 GeV at RHIC. The spectral shapes and the centraily dependence of the yields have been studied and compared to the results from protons and anti-protons. The goal is to examine the behavior for particles with similar mass but different quark content in order to distinguish between hydrodynamics and recombination models, and possibly resolve the "baryon puzzle" at RHIC. Our study reveals that the spectral shapes for protons and ϕ mesons are very similar and can be fitted with satisfactory χ^2 using the same freeze-out temperatures and flow velocities. This finding is in accord with the hydrodynamics description. However, when the absolute yields are considered, the ϕ and the protons do not exhibit the same behavior as a function of centrality. In the nuclear modification factors, R_{CP}, we observe a split according to the quark content, as expected in recombination models: ϕ mesons show a suppression similar to that of pions, while the protons remain un-suppressed. This finding does not yet give a definitive answer if the intermediate p_{T} region for ϕ is dominated by soft or hard processes. Jet correlation measurements involving ϕ mesons would be needed in order to prove that the $R_{CP} < 1$ is due to jet suppression. This measurement will be possible with the high statistics data sample obtained in Run4 of RHIC, which is currently being analyzed.

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