ϕ-Meson Production at RHIC, Strong Color Fields and Intrinsic Transverse Momenta

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We investigate the effects of strong color fields and of the associated enhanced intrinsic transverse momenta on the ϕ-meson production in ultrarelativistic heavy ion collisions at RHIC. The observed consequences include a change of the spectral slopes, varying particle ratios, and also modified mean transverse momenta. In particular, the composition of the production processes of ϕ mesons, that is, direct production vs. coalescence-like production, depends strongly on the strength of the color fields and intrinsic transverse momenta and thus represents a sensitive probe for their measurement.

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Ultrarelativistic heavy ion collisions provide a unique tool to study elementary matter at energy densities so high that a phase transition from partonic deconfined matter to hadronic matter is predicted by QCD lattice calculations [1]. The properties of such a highly excited state depend strongly on the initial conditions such as the specific entropy density or the thermalization time. A very interesting feature of relativistically colliding heavy nuclei may be the production of strong color electric fields. Their existence implies a number of characteristic consequences that are of utmost importance for the interpretation of experimental data. Among them are, for example, the predicted strangeness enhancement [2] and a strong baryon transport [3, 4, 5].

Here, we focus on the production of the ϕ meson in Au+Au collisions at the BNL Relativistic Heavy Ion Collider ($\sqrt{s}_{NN} = 200\,\mathrm{GeV}$). The $\phi(s\bar{s})$ meson is expected to be a good messenger of the early stage of the evolution because its constituent quarks must have been produced during the collision (since they carry strangeness) and this must have occurred early on (since they are massive) [6, 7]. Moreover, ϕ's have a rather small hadronic cross section with nonstrange hadrons and thus may leave the hadronic phase relatively unperturbed [7]. We will demonstrate that the ϕ meson is particularly sensitive to the color field properties. Their abundance depends strongly on the field strength. The transverse momentum generation by the strong color fields may lead to a substantial hardening of the spectra. The interplay between the mass and transverse momentum generation strongly influences the composition of the spectra. Directly produced ϕ's are shown to compete with a substantial contribution of ϕ's produced in coalescence-like $K\bar{K}$ collisions. The relative contributions are directly correlated to the magnitude of the color field strength and the associated intrinsic transverse momenta.

Since the $\phi(s\bar{s})$ is analogous to the $J/\psi(c\bar{c})$ (they have the same quantum numbers: $I^G\,(J^{PC}) = 0^-\,(1^{--})$), an improved understanding of in-medium ϕ production and decay may also elucidate the features of the J/ψ dynamics. For example, J/ψ production by $D\bar{D}$ coalescence is probably an important production mechanism at RHIC [8] and corresponds to $K\bar{K} \to \phi$ coalescence.

The investigation is performed in the framework of a relativistic transport model (Ultrarelativistic Quantum Molecular Dynamics UrQMDv1.3) that is based on (di)quark, hadron (resonance), and string degrees of freedom [9]. It simulates multiple interactions of ingoing and newly produced particles, the creation and fragmentation of color strings, and the formation and decay of baryonic and mesonic resonances. At RHIC energies, subhadronic degrees of freedom are of major importance. They are treated via the introduction of formation times for hadrons that are produced in the fragmentation of strings [10]. Leading hadrons of the fragmenting strings contain the valence quarks of the original excited hadron. They interact even during their formation time, with a reduced cross section defined by the additive quark model, thus accounting for the original valence quarks contained in that hadron [9]. Newly produced (di)quarks are only allowed to interact after they have coalesced into hadrons. Their formation times are inversely proportional to the string tension κ via $t_f \sim 1/\kappa$. The larger the string tension the shorter and short-living are the strings with a certain total energy. Secondary scatterings are important, for example, for transporting baryon number from projectile and target rapidity closer to midrapidity. The collision spectra are largely dominated by (di)quark degrees of freedom [11]. Fully formed hadrons are involved only in the very first collisions and at the later stage. (For further details of the model, see Ref. [9, 12].)

Strong color electric fields, that is, an effectively increased string tension in a densely populated colored environment of highly excited matter leads to a modified particle production process in hadronic collisions. A background color electric field is formed between two receding hadrons which are color charged by the exchange of soft gluons while colliding. In nucleus-nucleus collisions the color charges may be considerably greater than in nucleon-nucleon collisions due to the almost simultaneous interaction of several participating nucleons [13]. This leads to the formation of strong color electric fields. With increasing collision energy, the number and density of strings grows so that they start overlapping, thus forming clusters that act as new effective sources for particle production [14, 15]. The multiplicities of, for example, strange baryons or antibaryons should be strongly enhanced [15, 16, 17, 18, 19] once the color field strength grows. The abundances of (multiply) strange (anti)baryons in central Pb+Pb collisions at CERN SPS [20], for example, can be understood within the framework of microscopic model calculations [18, 19] in terms of an enhancement of the elementary production probability of $s\overline{s}$ pairs, which is governed in the string models [10] by the Schwinger mechanism [21]. This corresponds either to a dramatic enhancement of the string tension κ (from the default $\sim 1\,\mathrm{GeV/fm}$ to $3\,\mathrm{GeV/fm}$) or to quark masses m_q that are reduced from their constituent quark values to current quark values as motivated by chiral symmetry restoration [18]. A variation of the string tension from $\kappa = 1\,\mathrm{GeV/fm}$ to $3\,\mathrm{GeV/fm}$ increases the pair production probability of strange quarks (compared to light quarks) from $\gamma_s = P(s\overline{s})/P(q\overline{q}) = 0.37$ to 0.72. Similarly, the diquark production probability is enhanced from $\gamma_{qq} = P(qq\overline{qq})/P(q\overline{q}) = 0.093$ to 0.45, leading to an effectively enhanced baryon-antibaryon pair production. In general, heavier flavors or diquarks (Q) are suppressed according to the Schwinger formula [21] by

$$\gamma_Q = \frac{P(Q\overline{Q})}{P(q\overline{q})} = \exp\left(-\frac{\pi(m_Q^2 - m_q^2)}{\kappa}\right) . \tag{1}$$

The string tension can also be expressed through its relation to the Regge slope α'. Based on a rotational string picture the string tension κ follows from the Regge slope α' as [22, 23]

$$\kappa = \frac{1}{2\pi\alpha'}. \tag{2}$$

The empirical value of the Regge slope for baryons is $\alpha' \approx 1\,\mathrm{GeV}^{-2}$ [24] which yields a string tension of approximately $1\,\mathrm{GeV/fm}$. However, the multi-gluon exchange processes dominated by Pomeron exchange in high-energetic nucleus-nucleus collisions are described by a Regge trajectoy with a smaller slope of $\alpha'_P \approx 0.4\,\mathrm{GeV}^{-2}$ [25, 26]. According to Eq. (2) this translates into a considerably larger (*effective*) string tension κ [5]. The magnitude of a typical field strength at RHIC energies has been suggested to be as large as $5 - 12\,\mathrm{GeV/fm}$ [4] (as a result of collective effects related to quark-gluon-plasma formation).

The transverse momentum generation in the string models is adjusted to describe elementary reactions. The newly produced particles from the decay of color strings obey a Gaussian distribution $f(p_t) \sim \exp(-p_t^2/\sigma^2)$ with a width $\sigma = 0.55\,\mathrm{GeV/c}\,(\approx \sqrt{(\kappa/\pi)})$. The Schwinger mechanism, the quantum tunneling of quark-antiquark and gluon pairs in the background color field, is governed by energy (and not only rest mass). Hence, the probability of producing a particle with mass m_i and transverse momentum p_t in a color field of strength ϵ follows from $P_i \sim \exp[-\pi(m_i^2 + p_t^2)/\epsilon]$. As a consequence, a stronger color field also leads to larger transverse momenta. In the present study we explore a general factorization *ansatz*,

$$P_i \sim \exp(-\pi m_i^2/\kappa) \cdot \exp(-p_t^2/\sigma^2) \ , \tag{3}$$

where the mass and transverse momentum scales, κ and σ, are independent. This allows us also to disentangle and better understand the effects of strong color fields on particle production via the parameter κ and on the transverse momentum generation via the intrinsic transverse momentum σ. An increased intrinsic transverse momentum has also been discussed, for example, in the context of the color glass condensate (CGC) model. The spectra of heavy ion data were shown to follow a simple scaling law in agreement with an intrinsic p_t broadening [27, 28]. In the framework of the CGC picture the transverse momentum distributions of hadrons in heavy ion collisions are basically determined through the initial momentum distributions of gluons which, in turn, are controlled by the saturation of the initial gluon density at high energies. As a consequence, the CGC picture predicts that the mean transverse momenta scale like the square root of the charged particle multiplicity per unit rapidity and unit transverse area ($\langle p_t\rangle \sim \sqrt{dN_{\mathrm{ch}}/(dy\,\pi R^2)}$). Also for the description of direct photon production a substantial p_t broadening effect is required [29]. Similarly, an increased intrinsic transverse momentum can be deduced from dilepton spectra (in the Drell-Yan region) [30].

Figure 1 shows the calculated transverse momentum distributions dN/dp_t of ϕ mesons. The distributions are calculated for different values of the color field strength κ (mass term) and the intrinsic transverse momentum σ. Moreover, the components of the spectra, i.e., ϕ's resulting from direct string decays and ϕ's produced via $K\bar{K}$ resonant scatterings are shown seperately. The relatively strong contributions from this coalescence-like production channel was already predicted for lower energies [19] and is also seen in other model calculations [31, 32, 33]. For the vacuum parameterization, i.e., $\kappa = 1\,\mathrm{GeV/fm}$ and $\sigma = 0.55\,\mathrm{GeV/c}$, these two components contribute about equally and the corresponding transverse momentum distributions exhibit the same slope. Increasing the intrinsic transverse momentum broadening parameter σ leads to a stronger dominance of the direct production for the ϕ-meson production. The slope of the total distribution is then largely dominated by the string channel, i.e., the coalescence mechanism contributes considerably less if the intrinsic transverse momentum is enhanced. In fact, the large values κ and σ describing the strong color fields lead to a power-law p_t distribution, most clearly seen in Fig. 1(h). On average, kaons have larger (relative) momenta (in the case of increased intrinsic transverse momenta) and, hence, they are less likely to produce a ϕ meson.

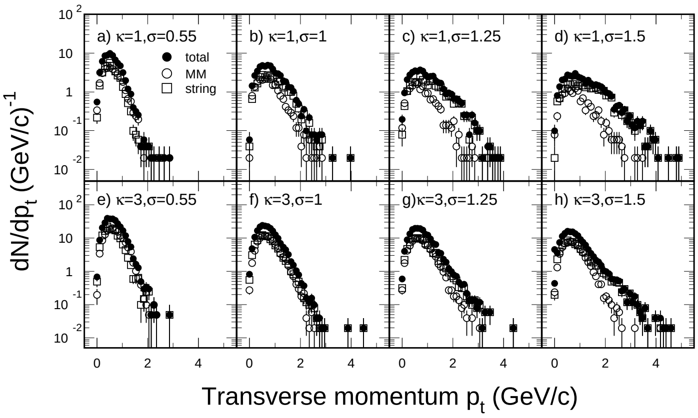

FIG. 1: Transverse momentum spectra of ϕ-mesons at midrapidity ($|y| < 1$) for central Au+Au collisions ($b < 2\,$fm) at RHIC ($\sqrt{s}_{NN} = 200\,$GeV). The different panels correspond to different values of the string tension κ and the intrinsic transverse momentum σ. The spectra of all ϕ's (full circles) are compared to those which result from meson meson coalescence (open circles) and to ϕ's that are produced directly from string decays (open squares).

The particle ratios ϕ/π, ϕ/K, K/π, and p/π are shown in Fig. 2 as a function of the intrinsic transverse momentum parameter σ and for the vacuum color field strength $\kappa = 1\,$GeV/c and for strong color fields $\kappa = 3\,$GeV/fm. Clearly, the strange particle ratios are strongly enhanced by increasing κ. The increased production probability of $s\overline{s}$ pairs enhances the yields of (multiply) strange particles relative to nonstrange particles. Increasing the intrinsic transverse momentum σ reduces the ϕ/π and ϕ/K ratios. This demonstrates again that ϕ production via $K\bar{K}$ coalescence becomes less important for larger intrinsic transverse momenta. The p/π ratio follows an opposite trend. It increases with σ. This is due to the hadronic final state interactions, i.e., absorption processes which strongly depend on the collision energy. The $p\overline{p}$ annihilation cross section increases strongly toward small relative momenta. In the $\kappa = 3\,$GeV/fm case, the p/π ratio increases also faster than in the $\kappa = 1\,$GeV/fm case. More $p\overline{p}$ pairs are initially produced in the system in the strong color field scenario but the corresponding increased phase space densities of protons and antiprotons and shorter formation times (more scatterings) also lead to more (re)absorption processes.

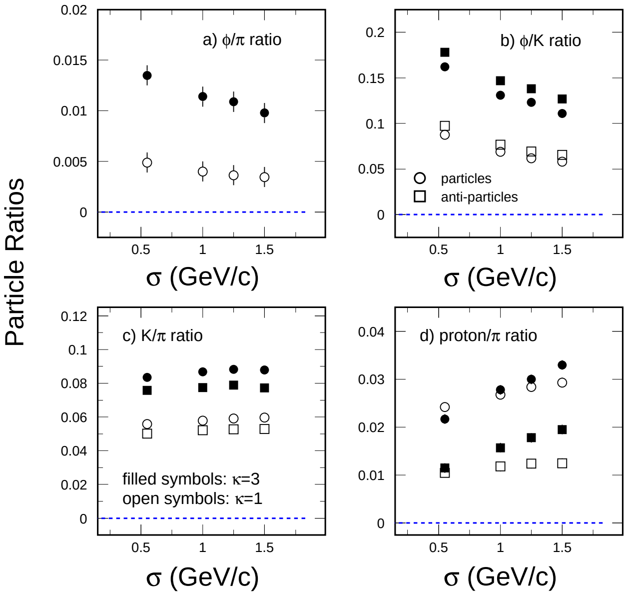

FIG. 2: Particle ratios (ϕ/π, ϕ/K, K/π, and p/π at midrapidity ($|y| < 1$) as a function of the intrinsic transverse momentum σ and for string tensions $\kappa = 1\,$GeV/fm (open symbols) and $\kappa = 3\,$GeV/fm (full symbols) for central Au+Au collisions ($b < 2\,$fm) at RHIC ($\sqrt{s}_{NN} = 200\,$GeV). Squares show the corresponding ratios for the antiparticles.

Figure 3 shows the calculated mean transverse momenta of pions, kaons, protons, and ϕ mesons in comparison to experimental data [34]. The mean transverse momenta naturally grow with the intrinsic transverse momentum σ. The vacuum parameters $\kappa = 1\,$GeV/fm and $\sigma = 0.55\,$GeV/c underpredict the mean transverse momenta. Better agreement is obtained with an increased broadening parameter σ. While the experimental values for protons and ϕ's are pretty close to each other the calculated values for ϕ's are smaller than those of protons. This can be attributed to the fact that the experimental ϕ yields shown here are determined by the reconstruction via the invariant mass of K^+K^- pairs. Since the decay products of ϕ's, i.e., the kaons, can suffer subsequent scatterings and thus get lost to this experimental identification criterion the apparent yields are considerably reduced. These rescatterings are more likely to happen at low momenta. As a consequence the experimentally observed (via K^+K^-) mean transverse momenta of ϕ's are larger than the ones of all ϕ's (accessible through the dielectron decay channel) including those whose decay products rescatter. The hadronic and leptonic decay channels thus neccessarily lead to *different* spectral slopes and yields. This appears to be supported by preliminary data from the PHENIX [35] and STAR [34] collaborations. Previously, data at the SPS ($E_{\rm lab} = 160\,A$GeV) from the NA49 [36] and NA50 [37] collaborations showed different results in the hadronic and dimuon decay channels, respectively. These differences, however, could only partially be attributed to the rescattering of the decay products [19, 38]. Moreover, calculations of a hadron gas at temperatures close to the phase boundary also yielded substantial rescattering for the ϕ mesons themselves [39]. The comparison of the two decay channels may help to probe the strength of the color fields because the overall spectrum and the losses in the hadronic channel are sensitive to the explicit values of the color field and to the intrinsic transverse momenta. In addition, the initial ϕ's (those that are possibly created through strong color fields) will be visible primarily in the dimuon channel [31].

In summary we have shown that the combined effects

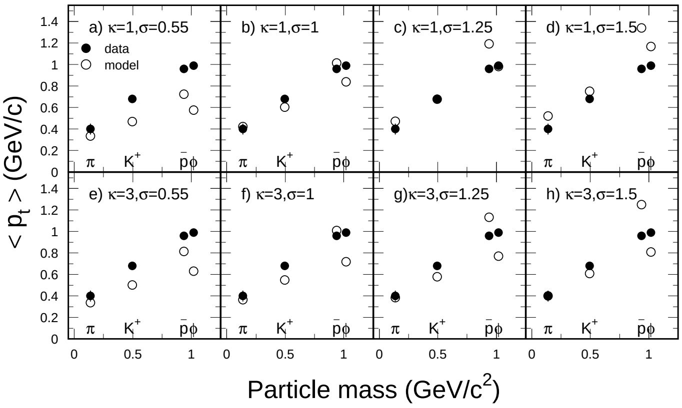

FIG. 3: Mean transverse momentum $\langle p_t \rangle$ as a function of particle mass at midrapidity in central Au+Au collisions ($b < 2\,\mathrm{fm}$) at RHIC ($\sqrt{s_{NN}} = 200\,\mathrm{GeV}$). The different panels correspond to different values of the string tension κ and the intrinsic transverse momentum σ. The calculations (open circles) are compared to experimental data (full circles).

of strong color fields as the enhanced production of heavier masses as well as increased intrinsic transverse momenta have a large impact on the hadronic observables, in particular for ϕ mesons. Their abundance depends strongly on the field strength. The spectra experience a substantial hardening due to the presence of strong color fields. Moreover, we have demonstrated that the interplay between the mass and transverse momentum generation strongly influences the composition of the spectra. Directly produced ϕ's have been shown to compete with a substantial contribution of ϕ's produced in coalescence-like $K\bar{K}$ collisions. The relative contributions are directly related to the magnitude of the color field strength and the associated intrinsic transverse momenta. The measurement of both the hadronic and the leptonic decay channels of ϕ mesons, and the analysis of the expected differences between them, should help to substantially improve our understanding of the production processes and the underlying dynamics which are both strongly influenced by the properties of the strong color fields.

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