Production of strange particles at intermediate p_T at RHIC

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Abstract

The recombination model is applied to the production of K, ϕ, Λ and Ω at all p_T in central Au+Au collisions. The thermal-shower component of the recombination is found to be important for K and Λ, but not for ϕ and Ω in the intermediate to high p_T region. The normalization and inverse slope of the thermal partons in the strange sector are determined by fitting the low-p_T data. The peak in the Λ/K ratio is shown to rise to nearly 2. The yields for ϕ and Ω are suppressed and the corresponding inverse slope for thermal s quark is higher. The contribution from shower s quarks is found to be unimportant for p_T of ϕ and Ω up to 8 GeV/c. We give reasons on the basis of the p_T dependence that ϕ cannot be formed by means of K^+K^- coalescence. Our result leads us to predict a rather spectacular feature in events where ϕ or Ω are used as trigger with $p_T > 3$ GeV/c: there are no assoiciated particles at any azimuthal angle, none that can be distinguished from background.

1 Introduction

The production of strange particles has always been a subject of great interest in heavy-ion collisions because of their relevance to possible signatures of deconfinement and flavor equilibration [1, 2]. Strangeness enhancement that has been observed at various colliding energies is a phenomenon associated with soft particles in the bulk matter [3, 4]. At high transverse momentum (p_T), on the other hand, the production of jets does not favor strange particles, whose fragmentation functions are suppressed compared to those for non-strange particles. At intermediate p_T range between the two extremes the p_T distribution depends sensitively on both the strangeness content and the production mechanism. It has been shown that in that p_T range the spectra of π and p can be well described by parton recombination [5]. In this paper we study the production of the openly strange particles K, Λ and Ω, as well as the hidden strange hadron ϕ. The aim is to get a broad view of strangeness production at intermediate and high p_T in a unified framework.

The four particles emphasize four different aspects of hadronization: K and Λ involve non-strange quarks, whereas ϕ and Ω do not; K and ϕ are mesons, whereas Λ and Ω are baryons, although ϕ and Λ are comparable in masses. To get all four spectra correctly at all p_T would require a high degree of coordination in the theoretical description. We have already a fairly good description of the production of hadrons in the non-strange sector [5]; however, for the strange sector we must deal with a new set of problems. Gluon conversion feeds the s quarks in the thermal medium and leads to strangeness enhancement [6]. On the other hand, the production of s quarks at high p_T in jets is suppressed. The interplay between the enhanced thermal s partons and the suppressed shower s partons results in very unusual outcome. Furthermore, how the supply of s quarks is partitioned into various channels of hadrons containing open and hidden strangeness is an aspect of the recombination process that was not encountered in the non-strange sector, but was studied algebraically by quark counting in Refs. [7, 8] without gluon conversion. Our consideration here treats the problem in a much wider scope where the p_T distributions of all four strange particles are investigated. The nature of the problem can be illustrated by the following question: if an s quark is in the environment of u, d and their antiquarks, how would the medium affect its rate of recombination with an $\bar{s}$ quark in comparison to $s\bar{s}$ recombination in vacuum? The question becomes even more acute for the recombination of three s quarks.

We shall use the basic recombination formula to compute the p_T distributions of all four particles. The thermal s quark distribution is determined by fitting the low-p_T data of K production. The shower parton distributions (SPD) are known [9]. Thus one can proceed to the calculation of the Λ spectrum essentially without adjustable parameters. In the cases of ϕ and Ω the competition for multiple strange quarks to form such high mass states would lead to suppression. Moreover, since the s quarks from the showers are suppressed compared to non-strange shower partons, ϕ and Ω produced at large p_T do not benefit from hard scattering as much as K and Λ do, for which light shower partons can contribute. These issues will be examined quantitatively in this paper.

At the lower p_T range where thermal-thermal recombination is dominant, it is possible to see that the exponential behavior of the p_T distribution of ϕ can only arise from $s\bar{s}$ recombination, but not from K^+K^- coalescence, simply by comparing the inverse slopes of the two exponential behaviors.

2 Formulation of the Problem

We shall assume that all hadrons produced in heavy-ion collisions are formed by recombination of quarks and/or antiquarks, the original formulation of which is given in [10, 11] for pp collisions. In recent years the recombination model has been extensively studied by many groups [12, 13, 14, 5] with great success in reproducing the p_T spectra in the intermediate p_T region of Au+Au collisions. In our 1D description of the recombination process the invariant inclusive distribution of a produced meson with momentum p is

$$p^0 \frac{dN_M}{dp} = \int \frac{dp_1}{p_1} \frac{dp_2}{p_2} F_{q\bar{q}'}(p_1, p_2) R_M(p_1, p_2, p), \tag{1}$$

and for a produced baryon

$$p^0 \frac{dN_B}{dp} = \int \frac{dp_1}{p_1} \frac{dp_2}{p_2} \frac{dp_3}{p_3} F_{qq'q''}(p_1, p_2, p_3)\, R_B(p_1, p_2, p_3, p). \tag{2}$$

The properties of the medium created by the collisions are imbedded in the joint quark distributions $F_{q\bar{q}'}$ and $F_{qq'q''}$. The RFs R_M and R_B depend on the hadron structure of the particle produced, but for a high mass hadron the normalization can in addition be influenced by the competition among possible channels. In the valon model description of hadron structure [11, 15], the RFs are

$$R_M(p_1, p_2, p) = g_M\, y_1 y_2\, G_M(y_1, y_2), \tag{3}$$

$$R_B(p_1, p_2, p_3, p) = g_B\, y_1 y_2 y_3\, G_B(y_1, y_2, y_3), \tag{4}$$

where $y_i = p_i/p$, and g_M and g_B are statistical factors. G_M and G_B are the non-invariant probability densities of finding the valons with momentum fractions y_i in a meson and a baryon, respectively. Equations (1) and (2) apply for the produced hadron having any momentum $\vec{p}$. We consider $\vec{p}$ only in the transverse plane, and write p_T as p so that $dN/p_T dp_T$ becomes $(pp^0)^{-1}$ times the right-hand sides of Eqs. (1) and (2).

The wave function $G(y_i)$ in terms of the momentum fractions of the valons cannot be probed for K, ϕ, Λ, and Ω, as one can for proton. However, we can make reasonable estimates. For the hidden strange particles ϕ and Ω, it is relatively simple, since only one type of valon is involved. Since the masses of those two particles are nearly at the threshold of the sum of the constituent quark masses, loose binding means narrow wave function in the momentum space. Thus we approximate G_ϕ and G_Ω by δ-functions:

$$G_\phi(y_1, y_2) = \delta(y_1 - 1/2)\,\delta(y_2 - 1/2), \tag{5}$$

$$G_\Omega(y_1, y_2, y_3) = \delta(y_1 - 1/3)\,\delta(y_2 - 1/3)\,\delta(y_3 - 1/3). \tag{6}$$

For the openly strange particles K and Λ, there is a mixture of strange and non-strange constituents with different masses, so the corresponding momentum fractions are different. The wave function of K has been considered before [16]; it has the form

$$G_K(y_1, y_2) = \frac{1}{B(a+1, b+1)}\; y_1^a y_2^b\,\delta(y_1 + y_2 - 1). \tag{7}$$

The ratio of the average momentum fractions $\bar{y}_1$ and $\bar{y}_2$ of the u and s type valons, respectively, should be roughly the ratio of their masses $m_U/m_S \approx 2/3$. That puts a constraint on the parameters a and b, which is $b = (3a+1)/2$. Phenomenological analysis of the process $K^+ + p \to \pi^+ + X$ in the valon model then results in $a = 1$ and $b = 2$ [16]. Finally, for the hyperon Λ the wave function can be written in the form [6]

$$G_\Lambda(y_1, y_2, y_3) = \frac{1}{B(\alpha+1, \alpha+\beta+2)B(\alpha+1, \beta+1)}\; (y_1 y_2)^\alpha\, y_3^\beta\;\delta(y_1 + y_2 + y_3 - 1)\;, \tag{8}$$

where y_1 and y_2 refer to the non-strange valon, and y_3 to the strange valon. The ratio of the average momentum fractions $\bar{y}_1/\bar{y}_3$ is $(\alpha+1)/(\beta+1)$, which yields a similar constraint: $\beta = (3\alpha+1)/2$. We suppose that their values are roughly the same as for proton [15], so they shall be set at $\alpha = 1$ and $\beta = 2$.

To calculate the p_T distributions, we start with the production of K_s^0, for which we consider the $d\bar{s}$ and $s\bar{d}$ contributions to $F_{q\bar{q}'}$ and write

$$F_{d\bar{s},s\bar{d}} = \mathcal{T}\mathcal{T}_s + \mathcal{T}_s(\mathcal{S}_d + \mathcal{S}_{\bar{d}})/2 + \mathcal{T}\mathcal{S}_s + \{\mathcal{S}\mathcal{S}_s\} \ , \tag{9}$$

where a sum over all relevant quark species is implied when not indicated explicitly. The thermal and shower parton distributions of the light quarks are, respectively, [5]

$$\mathcal{T}(p_1) = p_1 \frac{dN_q^{\rm th}}{dp_1} = C\, p_1 \exp(-p_1/T) \ , \tag{10}$$

$$\mathcal{S}(p_2) = \xi \sum_i \int_{k_0}^{\infty} dk\, k\, f_i(k)\, S_i(p_2/k) \ . \tag{11}$$

The parameters C and T have been determined in [5]:

$$C = 23.2 \text{ GeV}^{-1} \ , \quad T = 0.317 \text{ GeV} \ . \tag{12}$$

S_i is the SPD for a light quark in a shower initiated by a hard parton i, $f_i(k)$ is the transverse-momentum (k) distribution of hard parton i at midrapidity in central Au+Au collisions, and ξ is the average fraction of hard partons that can emerge from the dense medium to hadronize. As in [5], $f_i(k)$ is taken from Ref. [17], k_0 is set at 3 GeV/c, and ξ is found to be 0.07. For the strange quarks the corresponding thermal and shower parton distributions are

$$\mathcal{T}_s(p_1) = p_1 \frac{dN_s^{\rm th}}{dp_1} = C_s\, p_1 \exp(-p_1/T_s), \tag{13}$$

$$\mathcal{S}_s(p_2) = \xi \sum_i \int_{k_0}^{\infty} dk\, k\, f_i(k)\, S_i^s(p_2/k), \tag{14}$$

where C_s and T_s are now new parameters. The SPDs S_i^s are known from [9] and cannot be altered. Indeed, S_i and S_i^s are so well determined from the meson fragmentation functions

(FFs) that we have recently been able to calculate the baryon FFs from them in agreement with data [18], thus solidifying the validity of our approach to fragmentation in the framework of recombination. The thermal s quark distribution in Eq. (13) is determined by fitting the low-p_T data on K_s^0 production. Since K^* decays totally into πK, we have $g_K = 1$.

The last term of Eq. (9) symbolizes

$$\{\mathcal{S}\mathcal{S}_s\} = \xi \sum_i \int_{k_0}^{\infty} dk\, k\, f_i(k) \left[\left\{ S_i^d\left(\frac{p_1}{k}\right), S_i^{\bar{s}}\left(\frac{p_2}{k-p_1}\right) \right\} + \left\{ S_i^{\bar{d}}\left(\frac{p_1}{k}\right), S_i^{s}\left(\frac{p_2}{k-p_1}\right) \right\} \right] /2, \quad (15)$$

where $\{\cdots,\cdots\}$ on the RHS represents symmetrization of p_1 and p_2. The two terms in the square brackets are not the same because of the valence quark contribution to the d-initiated jet. Despite the appearance of the product form on the LHS, there is only one integral over k because both shower partons belong to the same jet inititated by one hard parton i. Since we sum i over $u, d, s, \bar{u}, \bar{d}, \bar{s}$ and g, Eq. (15) contains 28 terms. However, when they are combined with the RF, they become the FF $D_i^{K_s^0}(p/k)$ [5].

For Λ production we need

$$F_{uds} = \mathcal{T}\mathcal{T}\mathcal{T}_s + \mathcal{T}\mathcal{T}_s\mathcal{S} + \mathcal{T}\mathcal{T}\mathcal{S}_s + \mathcal{T}_s\{\mathcal{S}\mathcal{S}\} + \mathcal{T}\{\mathcal{S}\mathcal{S}_s\} + \{\mathcal{S}\mathcal{S}\mathcal{S}_s\}\ , \quad (16)$$

where the last term involves the symmetrization of all three shower partons in the same jet. Clearly, there are now many more terms for F_{uds}. We shall find that up to $p_T \approx 4$ GeV/c, the relative importance of each of the six terms in Eq. (16) diminishes in the order they appear on the RHS. Nevertheless, they all have to be calculated in order to determine the emergence of certain terms, as p_T is increased. For the RF of Λ the statistical factor g_Λ is 1/4. With the parameter α in the Λ wave function expressed in Eq. (8) set at 1 to simulate the proton, there are no adjustable parameters in this Λ production problem.

For ϕ and Ω the p_T distributions can be written out explicitly because of the simplicity of their RFs. They are

$$\frac{dN_\phi}{pdp} = \frac{g_\phi}{pp_0} F_{s\bar{s}}(p/2, p/2), \tag{17}$$

$$\frac{dN_\Omega}{pdp} = \frac{g_\Omega}{pp_0} F_{sss}(p/3, p/3, p/3), \tag{18}$$

where

$$F_{s\bar{s}} = \mathcal{T}_s\mathcal{T}_s + \mathcal{T}_s\mathcal{S}_s + \{\mathcal{S}_s\mathcal{S}_s\}, \tag{19}$$

$$F_{sss} = \mathcal{T}_s\mathcal{T}_s\mathcal{T}_s + \mathcal{T}_s\mathcal{T}_s\mathcal{S}_s + \mathcal{T}_s\{\mathcal{S}_s\mathcal{S}_s\} + \{\mathcal{S}_s\mathcal{S}_s\mathcal{S}_s\} \ . \tag{20}$$

We allow the normalization factors g_ϕ and g_Ω to be adjustable in order to account for the medium effect on the recombination of $s\bar{s}$ and sss. Because of the limited supply of s quarks and the abundance of the light quarks in the vicinity, it is expected that the formation of the multi-strange particles at higher masses would be suppressed. Without a principle from outside the recombination model, there is no way to determine the suppression factors. In the following we vary g_ϕ and g_Ω as free parameters to fit the normalizations of the corresponding spectra.

Current data on the strange particles do not extend to very high p_T. For ϕ the data are available only up to $p_T \approx 3$ GeV/c [19, 20], while for K_s^0, Λ and Ω they reach almost 6 GeV/c [21, 22]. In the case of Ω the data are for $\sqrt{s} = 130$ GeV [22], while all others are at 200 GeV.

3 Results

We first show the result of our calculation for kaon production. In Fig. 1 is shown the contributions from the three components indicated in the figure. The thermal-shower component includes both the $\mathcal{T}_s\mathcal{S}$ and $\mathcal{T}\mathcal{S}_s$ subcomponents. However, $\mathcal{T}\mathcal{S}_s$ is negligible because the production of s quark in showers induced by u, d and g hard partons is suppressed, and a jet initiated by an s hard parton is negligible in heavy-ion collisions (HIC) even though the valence s shower parton is not negligible. The contribution from $\mathcal{T}_s\mathcal{S}$, on the other hand, is important because thermal s quarks are not negligible, as evidenced by the $\mathcal{T}\mathcal{T}_s$ component that is dominant for $p_T < 3$ GeV/c. The $\{\mathcal{S}\mathcal{S}_s\}$ component does not become important until $p_T > 8$ GeV/c.

In fitting the low-p_T region for $p_T < 2$ GeV/c we obtain

$$C_s = 15.5 \text{ GeV}^{-1} , \qquad T_s = 0.323 \text{ GeV} . \tag{21}$$

Note that it is because of the importance of the contribution of the thermal-shower recombination for $p_t > 3$ GeV/c that the p_T distribution is well reproduced over the whole range where data are available [21].

Having determined C_s and T_s, we can now proceed to the calculation of Λ production without adjusting any parameters. There are, however, two cases to consider that are related to the valence quarks in the showers. The question is whether the leading parton is likely to form a leading meson in a jet or a baryon with higher mass, remembering that there is only one valence quark in a quark-initiated shower. We calculate the p_T distributions of Λ for the two cases, where (a) only the sea quarks in the showers are used for the formation of Λ, and (b) all contributions including all valence quarks are included. The results are shown in

Fig. 2(a) and (b), respectively. There is a small but perceptible difference between the two cases for $p_T > 4$ GeV/c. The inclusion of valence quarks in (b) naturally has the effect of increasing the yield at high p_T.

In Fig. 2 we first note that the recombination of three thermal partons (TTT) is dominant up to about 4 GeV/c, where the TTS contribution becomes more important at higher p_T. The TSS component is unimportant below 6 GeV/c, and SSS is even less important. Fig. 2(a) gives a more satisfactory reproduction of the data [21] than Fig. 2(b). It implies that the valence quarks that have larger momentum fractions in a jet are mainly in the mode of formation of mesons instead of hyperons. Gluon jets make the dominant contribution to the shower partons that form the Λ.

With the calculated p_T distributions of K_s^0 and Λ at hand, we can take their ratio and compare it with the data on Λ/K_s^0 [21, 23]. Since the latter is shown in linear scale, it is far more sensitive to the details of the p_T distributions than the spectra themselves plotted in log scale. What is shown by the solid line in Fig. 3 is the result on the Λ/K_s^0 ratio using the p_T distributions shown in Figs. 1 and 2(a). Our calculated result in Fig. 3 does not reproduce the data for $p_T > 3$ GeV/c, although they agree well at lower p_T. The solid line has the right structure of a peak reaching almost as high as 2. The disagreement with data is an amplification of the small discrepancies between theory and experiment in Figs. 1 and 2(a), where our calculated distribution for K_s^0 in the region $4 < p_T < 6$ GeV/c is about 40% lower than the data, but for Λ it is about 30% higher than the data. That intermediate p_T region is where the shower contributions become important. Evidently, our model for the production of such strange particles is not good enough to yield better than 40% accuracy. We have changed α in Eq. (8) to 1.2 and found essentially no difference. Among other possibilities, it is likely that the recombination of s quarks in the thermal medium with shower partons for hadronization into different strange hadronic channels needs to take into account the partition problem in the strange sector.

For the production of ϕ and Ω the thermal components ($\mathcal{T}_s\mathcal{T}_s$ and $\mathcal{T}_s\mathcal{T}_s\mathcal{T}_s$) dominate over other components that involve shower contributions because of the suppression of shower s quarks. Figure 4 shows the p_T distributions of ϕ, in which the dashed line for the thermal components is mostly covered up by the solid line that represents the sum, for p_T up to 7 GeV/c. The $\mathcal{T}_s\mathcal{S}_s$ component represented by the dashed-dotted line is more than an order of magnitude lower. In Fig. 5 for Ω production all components involving $\mathcal{S}_s$ are even lower, so the solid line completely covers up the dashed line for $\mathcal{T}_s\mathcal{T}_s\mathcal{T}_s$. Thus if we ignore all but the first terms on the RHS of Eqs. (19) and (20), we obtain from (17), (18) and (13)

$$\frac{dN_\phi}{pdp} = g_\phi C_s^2 \frac{p}{4p_0} e^{-p/T_s} \ , \tag{22}$$

$$\frac{dN_\Omega}{pdp} = g_\Omega C_s^3 \frac{p^2}{27p_0} e^{-p/T_s} \ . \tag{23}$$

To get a good fit of the data on the ϕ spectrum [19, 20] we have used

$$T_s = 0.382 \text{ GeV} \ . \tag{24}$$

That is higher than the value of T_s in Eq. (21). To fit the normalizations of the distributions, the values of g_ϕ and g_Ω are found to be

$$g_\phi = 0.3 \ , \quad g_\Omega = 0.008 \ . \tag{25}$$

They represent the degree of suppression of the rate of recombination of an s quark with an $\bar{s}$ and two other s quarks in the environment of light quarks to form ϕ and Ω. The same T_s in Eq. (24) is used to obtain the p_T dependence of Ω forming out of three thermal s quarks.

Since our result reproduces the shape of the data [22] very well even up to $p_T = 5$ GeV/c, it further supports the implication that the shower partons have no effect. In the case of proton production the light-quark shower partons already make a significant contribution to the formation of proton at $p_T = 5$ GeV/c. Thus if the data points in Fig. 5 were above the solid line on the high end of p_T, then our model would be at a loss in finding a cause for that deviation, since the next component involving $\mathcal{S}_s$ is so far below to be able to come to the rescue. Implications of our results are discussed in the next section.

Within the framework of recombination it is possible for us to examine the reality of ϕ formation through K^+K^- coalescence, which is a mechanism that has been advocated in certain models. If $H_h(p_T)$ denotes the invariant inclusive p_T distribution, $p^0 dN_h/dp_T$, of hadron h at $y = 0$ in heavy-ion collisions, then the coalescence process of $K^+ + K^- \to \phi$ implies by use of Eq. (1) that

$$H_\phi^{[KK]}(p_T) \propto H_K^2(p_T/2) \tag{26}$$

apart from a multiplicative constant associated with the RF. On the other hand, if ϕ is produced by $s\bar{s}$ recombination as we have done here, then the same procedure yields

$$H_\phi^{[ss]}(p_T) \propto \mathcal{T}_s^2(p_T/2), \tag{27}$$

where the dominance of the thermal parton recombination is used. Thus it is a matter of comparing $H_K(p)$ with $\mathcal{T}_s(p)$, which are the invarant distributions of the entities that recombine. Since a kaon is formed by $\bar{s}q$ recombination, where q denotes either u or d, whose thermal distribution $\mathcal{T}(p)$ is characterized by C and T shown in Eq. (12), the exponential part of $H_K(p)$ has an inverse slope T' that is between T and T_s, given by Eq. (21), i.e., $e^{-p/T'}$ where $T' \approx 0.32$ GeV. That is to be compared to the exponential part of $\mathcal{T}_s^2(p/2) = \mathcal{T}_s(p)$ for

ϕ production, which is e^{-p/T_s} with $T_s = 0.382$ GeV given by Eq. (24). In view of our good fit of the ϕ data in Fig. 4, we conclude that an alternative fit using $H_K(p)$ characterized by T' would fail. It therefore follows from the consideration of the p_T dependence alone that ϕ cannot be formed by K^+K^- coalescence. This conclusion is consistent with that of [19] based on the centrality independence of the ϕ/K^- ratio.

4 Discussion

In the approach to the hadronization problem that we have adopted there are certain properties that we cannot change, while there are others that we can determine only by fitting the data. The former involve the hard partons and their shower parton distributions. The latter involve the soft thermal partons, for which several parameters have been used for non-strange and strange quarks. Since our aim has never been to model the soft component, it does not matter how many parameters have been used to reproduce the low p_T behavior. Our aim has been to understand strange particle production at intermediate and high p_T, and we have found some valuable information to provide significant insight into the strange sector. The recombination model has been effective in illuminating the physics involved.

From K_s^0 and Λ spectra we have seen how the deviation from the exponential form that describes the thermal components can be understood as being due to the emergence of the shower contribution arising from jets. It happens at around $p_T \approx 4$ GeV/c. Those are openly strange hadrons, and the strange quarks are not from the shower, but from the thermal source, because the production of s quarks in hard scattering or in showers is suppressed. What is learned there, when applied to ϕ and Ω that contain no light quarks, leads to the conclusion that the data observed so far on their production are all due to thermal s quarks. In our calculation we do not see any effect that can arise out of hard scattering even for p_T up to 8 GeV/c. That makes the $p_T < 8$ GeV/c region a very clean laboratory to study the properties of the s quarks in the thermal source, bearing in mind that the transverse momenta of the s quarks themselves would be < 4 GeV/c.

Since the distribution of thermal s quarks in that region is a simple extrapolation of the exponential behavior from below 2 GeV/c up to 4 GeV/c, we have no theoretical reason to trust its accuracy. Thus it is necessary to have data on ϕ and Ω distributions out to $p_T \approx 8$ GeV/c. A way to check whether the thermal components can dominate in that wide p_T region is to see whether Ω/ϕ ratio is linearly rising throughout. From Eqs. (22) and (23) we have

$$R_{\Omega/\phi}(p) = \frac{dN_\Omega/pdp}{dN_\phi/pdp} = \frac{4g_\Omega C_s}{27g_\phi}\ p\ . \tag{28}$$

Departure from linearity would imply that either (a) the simple exponential behavior of the thermal s quarks that is responsible for the spectra of ϕ and Ω is invalid, or (b) the shower components begin to contribute in that region. The Λ/K ratio, on the other hand, is known to bend over at $p_T \sim 3$ or 4 GeV/c. Although the location of the peak in our theoretical result is higher than that of the data, the decrease at higher p_T is a definitive attribute of the dominance of the thermal-shower recombination.

There is one definitive prediction that follows naturally from our result that the s quarks in the jets make negligible contribution to the formation of hadrons with hidden strangeness for p_T up to 8 GeV/c. The prediction is that in events where ϕ and Ω are produced in the 3-5 GeV/c p_T range, treated as trigger particles, (and at higher p_T if statistics justifies a wider range for consideration up to 8 GeV/c) there are no particles associated with the trigger at any azimuthal angle. It means that the $\Delta\phi$ spectrum in those events have no near-side or away-side peaks. This is in sharp contrast to the situation where the trigger particles are charged particles dominated by the non-strange species [24]. This prediction can be checked in the present data with appropriate event selection and even without background subtraction. Since thermal partons are uncorrelated, all particles associated with the trigger consisting of ϕ or Ω are in the background.

In fitting the low-p_T data we have found that T_s is nearly equal to T for K and Λ production, but T_s is about 20% higher than T for ϕ and Ω production. While this result is suggestive of hydrodynamical flow, we stress that the matter that flows is partonic, as opposed to hadronic, since our whole approach is based on the premise that hadronization by recombination takes place at the end of the expansion phase. The s quarks, being somewhat more massive than the u and d quarks, can have higher T_s. The production of ϕ and Ω may occur at an earlier time when the density of the s quarks is higher and their recombination among themselves is more likely. The production of K and Λ, on the other hand, may occur later when T_s is lower and when the density of the s quarks is low enough such that their recombination with light quarks becomes the only feasible channel for hadronization.

The presence of the light quarks does affect the yield of ϕ and Ω. The result on g_Ω suggests that to find three s quarks available for Ω formation in the midst of a sea of light quarks is highly suppressed. The formation of ϕ is also suppressed, but not as severely. These are aspects of the problem that are worth further investigation, especially in the framework of a more appropriate model for the thermal medium than what we have considered here.

The application of our approach to the present problem takes care of what is from hard scattering that is calculable and clarifies what is from soft interaction that remains to be elucidated. The most amazing lesson that we have learned is that hard scattering of partons is unimportant for the formation of ϕ and Ω even for p_T as high as 8 GeV/c. It opens up the question of the meaning of the thermal source of s quarks up to 4 GeV/c, a subject worthy of focused study in the future.

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Figure Captions

Fig. 1. Transverse momentum distribution of K_s^0 in central Au+Au collisions. Data are from [21]. The solid line is the sum of the three contributions: $\mathcal{TT}$ (dashed line), $\mathcal{TS}$ (dashed-dot line), $\mathcal{SS}$ (line with crosses).

Fig. 2. Transverse momentum distribution of Λ in central Au+Au collisions. Data are from [21]. The heavy solid line is the sum of the four contributions: $\mathcal{TTT}$ (dashed line), $\mathcal{TTS}$ (dashed-dot line), $\mathcal{TSS}$ (line with crosses), $\mathcal{SSS}$ (light solid line). (a) no valence quarks are included; (b) valence quarks are included.

Fig. 3. The ratio of Λ to K_s^0. Data are from [21, 23]. The solid line is from Fig. 1 and Fig. 2 (a).

Fig. 4. Transverse momentum distribution of ϕ in central Au+Au collisions. Data are from [19, 20]. The solid line is the sum of the three contributions: $\mathcal{TT}$ (dashed line), $\mathcal{TS}$ (dashed-dot line), $\mathcal{SS}$ (line with crosses). The dashed line is totally obscured by the solid line.

Fig. 5. Transverse momentum distribution of Ω in central Au+Au collisions. Data are from [22]. The heavy solid line is the sum of the four contributions: $\mathcal{TTT}$ (dashed line), $\mathcal{TTS}$ (dashed-dot line), $\mathcal{TSS}$ (line with crosses), $\mathcal{SSS}$ (light solid line). The dashed line is totally obscured by the solid line.