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Strange particle correlations - coalescence at RHIC and LHC

Jana Bielcikova[*]
Yale University
E-mail: jana.bielcikova@yale.edu

I give an overview of results on strange particle production in p+p, d+Au and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at RHIC. In particular, I discuss the ratios of particle yields and two-particle correlations at intermediate-p_T (p_T = 2-6 GeV/c) for singly-strange (K^0_S, Λ) and multiply-strange (Ξ, Ω) particles in order to investigate the anomalous baryon production and properties of long range pseudo-rapidity correlations ('the ridge'). The results are compared to theoretical predictions with an emphasis on recombination/coalescence models. The paper concludes with predictions from the recombination/coalescence models at the LHC.

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[*]Speaker.

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1. Introduction

Studies of particle production in heavy-ion collisions at RHIC revealed a strong suppression of inclusive transverse momentum (p_T) spectra in central Au+Au collisions with respect to p+p collisions. Further investigation of the nuclear modification factors for light flavor (u, d, s) particle species have shown that in the intermediate-p_T range (p_T = 2-6 GeV/c) baryons are less suppressed than mesons. This observation together with enhanced baryon/meson particle ratios proves that jet fragmentation is not a dominant source of particle production even out to p_T = 6 GeV/c [1, 2, 3, 4].

A theoretical approach which proved to be successful in describing the findings at RHIC is based on parton recombination and coalescence. This idea was first formulated thirty years ago in [5] and many papers have been published after the first results at RHIC became available (e.g. [6, 7, 8, 9]). While in p+p collisions, it is the parton fragmentation which leads to production of hadrons, in heavy-ion collisions, the phase space is expected to be densely populated by partons which can also recombine and form hadrons. In this case by adding up the momenta of valence partons, a meson of a given p_T can be produced by coalescing two partons each carrying roughly 1/2 of the meson transverse momentum. Similarly, a baryon can be produced by coalescing three partons carrying roughly 1/3 of the baryon momentum. As can be easily seen recombination naturally favors baryon over meson production which is qualitatively in line with the data at RHIC. It can be shown, that for an exponential parton spectrum the recombination is always a more efficient particle production mechanism than fragmentation, but fragmentation will eventually dominate at high p_T where the parton spectrum has a power law form.

As more data became available, the studies at RHIC have moved from inclusive measurements, such as particle spectra and their ratios, towards azimuthal correlations among produced particles. One of the striking features of the measured di-hadron correlations was the observation of an additional long-range pseudo-rapidity correlation on the near-side (*ridge*) which is absent in p+p and d+Au collisions [10, 11]. Studies involving identified two-particle correlations are expected to provide additional information on the origin of long range pseudo-rapidity correlations, the baryon-meson anomaly and particle production mechanisms in general.

In the first part of the paper, I give an overview of results on strange particle production in p+p, d+Au and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV at RHIC. In particular, I discuss the ratios of particle yields and two-particle correlations at intermediate-p_T (p_T = 2-6 GeV/c) for singly-strange (K^0_S, Λ) and multiply-strange (Ξ, Ω) particles in order to investigate the anomalous baryon production and properties of long range pseudo-rapidity correlations ('the ridge'). The results will be compared to recent theoretical predictions with an emphasis on recombination/coalescence models. The second part of the paper is devoted to an overview of theoretical predictions from the recombination/coalescence models for the LHC.

2. Correlations with K^0_S and Λ particles

The STAR experiment has studied in detail properties of near-side di-hadron correlations of neutral strange baryons (Λ) and mesons (K^0_S) at intermediate p_T in d+Au and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV [12]. The acceptance corrected correlation functions were normalized to the number of trigger particles and corrected for the reconstruction efficiency of associated particles

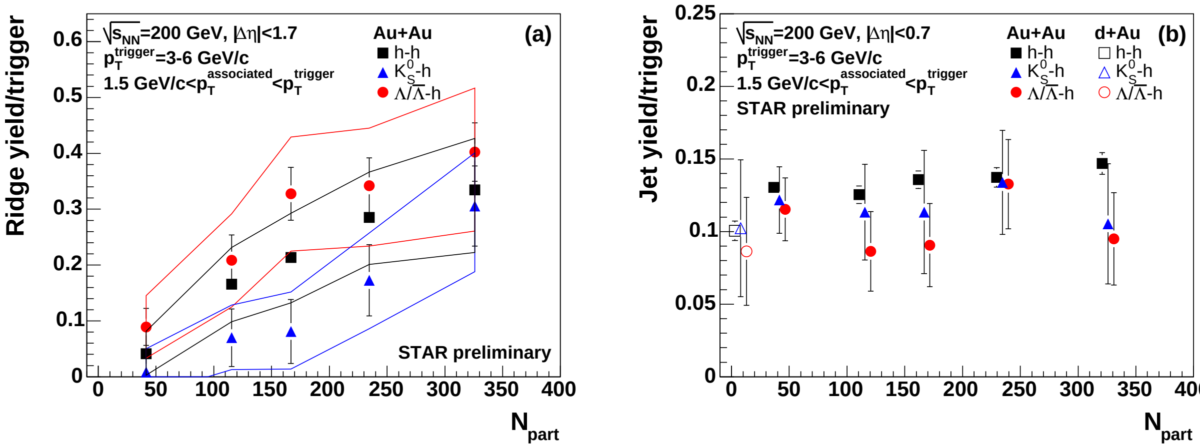

Figure 1: Centrality dependence of the ridge yield (a) and jet yield (b) of associated charged particles for various trigger species in d+Au and Au+Au collisions as indicated by the legend. The error bands represent systematic errors on the ridge yield due to the subtraction of elliptic flow (v_2). The figure is taken from [12].

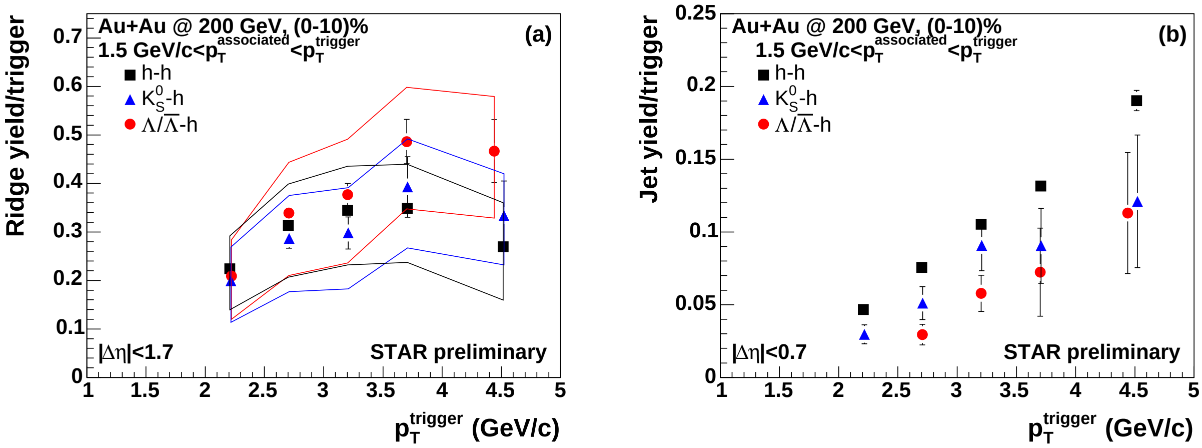

Figure 2: Dependence of the ridge yield (a) and jet yield (b) on $p_T^{trigger}$ for various trigger species in central (0-10%) Au+Au collisions as indicated by the legend. The bands represent systematic errors on the ridge yield due to the subtraction of elliptic flow (v_2). The figure is taken from [12].

and for the elliptic flow (v_2) contribution. In order to separate jet-like correlations from the ridge, the distributions were analyzed in two different $\Delta\eta$ windows: $|\Delta\eta| < 0.7$ (containing both jet and ridge contributions) and $|\Delta\eta| > 0.7$ (containing only the ridge contributions, assuming the jet is collimated around the trigger particle and thus its contribution at large $\Delta\eta$ is negligible). Assuming uniformity of v_2 with η at mid-rapidity, the jet yield is therefore free of systematic uncertainties due to the v_2 subtraction. For the ridge yield, these systematic errors were estimated by subtracting the v_2 measured by the event plane method (the lower bound) and by the 4-particle cumulant method (the upper bound).

Figure 1 shows the centrality dependence of ridge and jet yields on the near side in Au+Au collisions. While the jet yield is, within errors, independent of centrality and consistent with that in d+Au collisions, the yield of particles associated with the ridge shows a strong increase by a factor of 3-4 going from d+Au to central Au+Au collisions. No significant baryon/meson or particle/anti-particle trigger differences have been observed.

Next, I discuss the dependence of the near-side yield on the transverse momentum of the trigger particle, $p_T^{trigger}$, which is shown in Figure 2. While the ridge yield increases with $p_T^{trigger}$ and possibly flattens off for $p_T^{trigger} > 3.0$ GeV/c, the yield of particles associated with the jet increases steeply with $p_T^{trigger}$, as expected for jet production. The jet yield for Λ triggers is systematically below that of charged hadron and K_S^0 triggers. Two effects could possibly explain this difference: (1) the heavier Λ baryon takes away more energy than the lighter K_S^0 meson and thus leaves less energy available for the associated particle production, (2) an artificial track merging/crossing in the STAR Time Projection Chamber (TPC) causes a loss of particle pairs at small angular separation. These effects are currently under investigation.

The large increase in the yield of associated particles in Au+Au collisions with respect to d+Au collisions can be understood in the framework of the recombination model [13]. This calculation shows that in Au+Au collisions, a thermal-shower recombination plays a dominant role while it is much less important in the d+Au system. Although the calculation has been done for charged pions while the presented data are for identified-strange trigger hadrons associated with unidentified-charged particles, the qualitative features observed in the data agree with the recombination picture.

The validity of the recombination picture in the description of the origin in the ridge-like correlations can be further tested by analyzing distributions of the particles associated with the ridge. The recombination model predicts that the inverse slope of the p_T spectra of particles in the ridge should be only slightly higher, by about 15 MeV, than those of particles produced in the bulk. The studies performed on two-particle correlations with unidentified charged particles [11] in

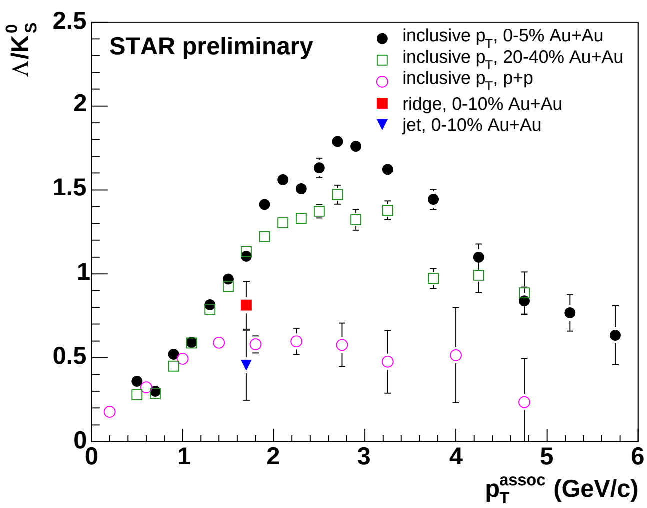

Figure 3: Λ/K_S^0 ratio measured in inclusive p_T distributions and near-side jet and ridge-like correlation peaks in Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV together with this ratio obtained from inclusive p_T spectra in p+p collisions. The figure is taken from [14].

a wide range of $p_T^{trigger}$ = 3-12 GeV/c and $p_T^{associated} > 2$ GeV/c have shown that the inverse slope of particles associated with the ridge is approximately independent of $p_T^{trigger}$ and reaches value of $\approx$ 400 MeV. This is higher than the inverse slope of particles produced in the bulk by $\approx$ 50 MeV (if an exponential fit is performed for $p_T > 2$ GeV/c). Contrary to the ridge, the inverse slope of particles associated with the jet was found to be steeply increasing with increasing transverse momentum of the trigger particle as expected for hard processes. Studies with strange trigger particles (Λ, K_S^0) revealed similar behavior to that observed for the unidentified particles [12].

It is also important to investigate particle composition in the ridge and look for enhanced baryon/meson ratios which are expected from coalescence models. A preliminary study [14] has been carried out for two-particle correlations using charged trigger particles with $p_T^{trigger}$ = 2-3 GeV/c which were associated with identified Λ and K_S^0 particles with 1.5 GeV/$c < p_T^{associated} < p_T^{trigger}$. The extracted Λ/K_S^0 ratio in the ridge and in the jet is shown in Figure 3 together with the same ratio measured from the inclusive p_T spectra. The Λ/K_S^0 ratio calculated for the jet is 0.46$\pm$0.21 and consistent with that measured in p+p. The same ratio in the ridge is 0.81$\pm$0.14, higher than in the jet. More data are needed to draw a definite conclusion on the baryon/meson ratios of particles associated with the ridge.

I remark here that there are also other theoretical approaches which attempt to explain the physics origin of the ridge. The interaction of high-p_T partons with a dense medium under the presence of strong longitudinal collective flow is predicted to lead to a characteristic breaking of the rotational symmetry of the average jet energy and multiplicity distribution in the $\eta \times \phi$ plane [15]. This will in turn cause a medium-induced broadening of gluon radiation in pseudo-rapidity and form a ridge in $\Delta\eta$. The mechanism suggested in [16], relates the origin of the spontaneous formation of extended color fields in a longitudinally expanding medium due to the presence of plasma instabilities. The momentum range of the partons contained in the ridge is in the recombination regime and therefore it should reflect itself in the baryon/meson ratio of associated hadrons. The effects of momentum broadening in an anisotropic plasma have also been studied [17]. It was shown that the momentum broadening, induced by energy loss is more pronounced along the longitudinal direction that in the reaction plane. A completely different mechanism for the ridge origin is based on jet quenching and strong radial flow [18]. The radial expansion of the system is predicted to create strong position-momentum correlations that lead to characteristic rapidity, azimuthal and p_T correlations among produced particles. First quantitative predictions based on this mechanism have appeared after the conference [19].

3. Recombination and multiply-strange particles

Based on recent calculations using parton recombination at RHIC [20], production of the ϕ meson and Ω baryon in heavy-ion collisions is expected to be very different from that of light flavor hadrons and other strange particles. As both ϕ ($s\bar{s}$) and Ω (sss) are particles created exclusively from strange quarks, the contribution from shower s quarks should be negligible for p_T up to 8 GeV/c. This has two observable consequences: (1) The Ω/ϕ ratio should rise at intermediate p_T linearly with transverse momentum, and (2) there should be no near-side associated particles for ϕ- and Ω-triggered correlations with $p_T > 3$ GeV/c because they are not produced from jet fragmentation.

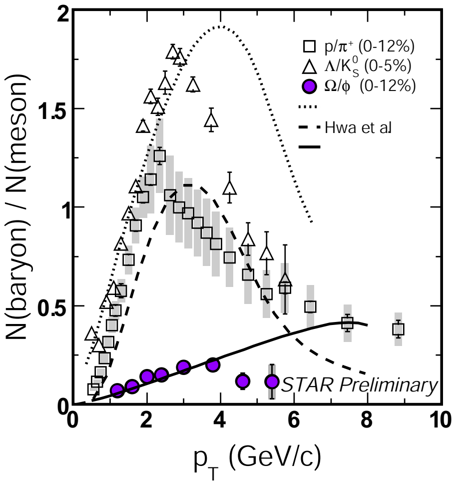

Figure 4: Baryon/meson ratios for Λ/K^0_S (triangles), p/π (squares), and Ω/ϕ (circles) compared to recombination model expectations: p/π (dotted line), Λ/K^0_S (dashed line), and Ω/ϕ (solid line) [20]. The figure is taken from [21].

These predictions have been tested by the STAR experiment and are discussed in further detail below.

Figure 4 shows the Ω/ϕ ratio measured in central Au+Au collisions together with p/π and Λ/K^0_S [21]. The measured baryon/meson ratios are compared to recombination model expectations from [20, 22]. We can see that the Ω/ϕ ratio behaves similarly to that of the other two baryon/meson ratios: its value first increases, has a turning point at intermediate p_T and finally decreases. The data agree well with the linear increase expected from the recombination up to p_T = 4 GeV/c, but the model overpredicts the measured data above this p_T. If we look closely at the data we can notice that the recombination model always predicts the turning points at higher p_T values than observed in the data. With increasing the strangeness content, this discrepancy becomes more prominent and may imply different production mechanisms for strangeness than for the lighter u and d flavors.

First results have also become available for two-particle correlations using Ω trigger particles [23]. Figure 5 shows a compilation of measured azimuthal correlation functions after elliptic flow modulated background subtraction for strange trigger baryons with increasing strangeness

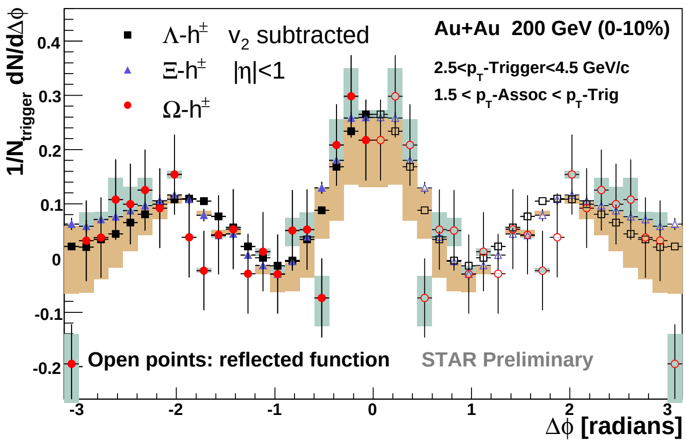

Figure 5: Azimuthal correlations of Λ, Ξ and Ω trigger particles with $p_T^{trigger}$=2.5-4.5 GeV/c associated with charged particles in 0-10% central Au+Au collisions measured by the STAR experiment. The bands indicate uncertainities due to the elliptic flow subtraction. The figure is taken from [23].

content: Λ (*uds*), Ξ (*uss*) and Ω (*sss*). Due to limited statistics for Ω, the trigger particles have now been selected with $p_T^{trigger}$ = 2.5 - 4.5 GeV/*c*. Clearly, a remaining near-side peak above the elliptic flow contribution is present for all discussed strange trigger species. The strength of the near-side correlations was found to be, within errors, independent of strangeness content in the trigger particle. More data are needed to separate jet and ridge-like contributions for the Ω-triggered correlations before a definite statement can be made on the validity of the recombination model prediction [20]. It might possibly be that all observed particles associated with the Ω trigger on the near-side originate from the ridge and not directly from the jet.

4. Recombination and coalescence at the LHC

As the parton recombination and coalescence approach proved to be successful at RHIC energies, it will be very interesting to test its validity at the LHC. Jet quenching at the LHC top energy is expected to be larger than at RHIC due to a higher energy density in the produced medium. For pions with p_T =10 GeV/*c*, the models predict suppression factors of 10-30 depending on produced particle multiplicity in Pb+Pb collisions. Consequently, the 'soft' thermal recombination is expected to push its limits to higher p_T. Calculations including thermal recombination, fragmentation and energy loss in the medium [24] predict that the crossover between the two domains, recombination and pQCD, will be shifted to p_T = 6 GeV/*c* (from 4 GeV/*c* at RHIC) for pions and to p_T = 8 GeV/*c* (from 6 GeV/*c*) for protons. The p/π^0 ratio calculated from this model will remain essentially the same as at RHIC, only the position of its peak value will be shifted towards larger p_T as demonstrated in Figure 6.

At even larger transverse momenta, 10 GeV/*c* < p_T < 20 GeV/*c*, the density of jets in Pb+Pb collisions is expected to be so large that the recombination of shower partons from neighboring jets

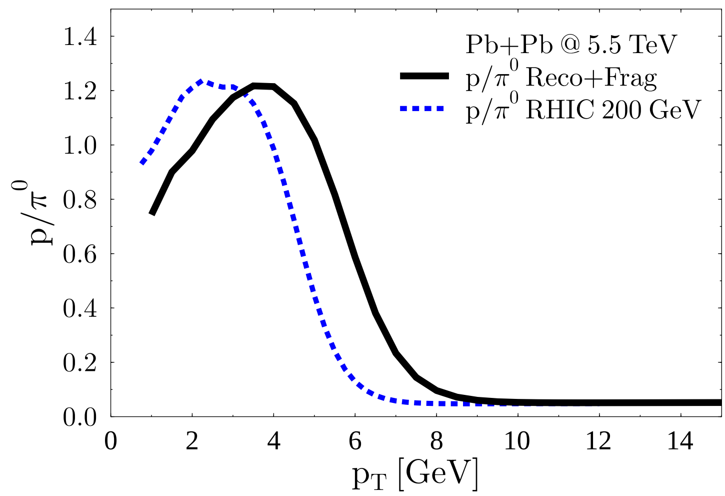

Figure 6: The p/π^0 ratio in Pb+Pb collisions at the LHC (solid line) and Au+Au collisions at RHIC (dashed line). Temperature of the thermalized parton phase T = 175 MeV and transverse radial flow velocity 0.75*c* were assumed. The figure is taken from [24].

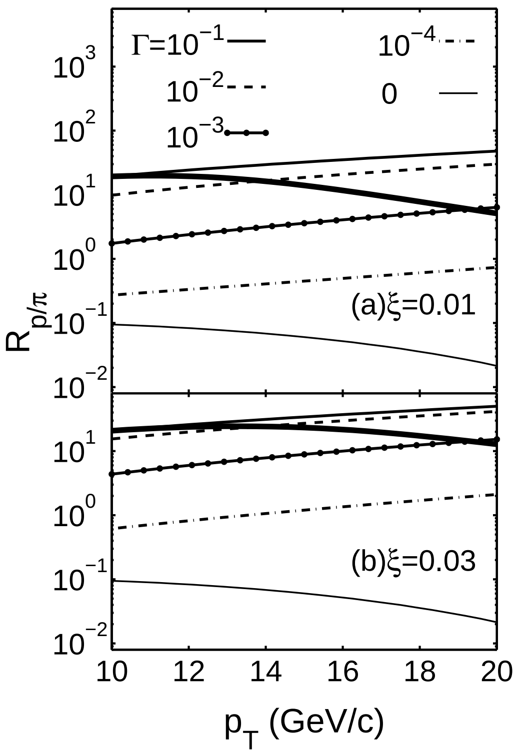

Figure 7: Expected transverse momentum dependence of the p/π ratio in Pb+Pb collisions at the LHC from [25]. The ratio was calculated for two suppression factors ξ (ξ = 0.01 (a) and ξ = 0.03 (b)) and several values of the probability Γ of overlap of neighboring jets. The thick solid line represents the p_T distribution of the p/π ratio when $\Gamma(p_T)$ is taken to decrease in accordance to a power law as p_T^{-7}. The thin solid line represents the ratio when only a single jet contribution is taken into account. The figure is taken from [25].

could significantly contribute to particle production [25]. The authors of this model consider in their calculation only $p_T > 10$ GeV/c in order to minimize systematic uncertaintites originating from the contribution of thermal partons which would require a fit to the p_T spectra of soft particles. Starting with a jet overlap probability Γ = 0.1 at p_T = 10 GeV/c and decreasing its value in accordance with a power law, $\Gamma(p_T) \sim p_T^{-7}$, large values of the p/π ratio are predicted. In the above mentioned p_T range, the ratio is predicted to decrease from 20 to 5 as shown by the thick solid line in Figure 7. The calculation based purely on thermal recombination and thus similar to that of [24] which I have discussed earlier in this section would lead to significantly smaller p/π ratio values as indicated by the thin solid line in Figure 7.

Besides the surprisingly large values of p/π ratios, the authors of the model in [25] predict that the large density of jets will lead to another striking phenomenon. If jet production is copious in every event, jets will be a part of the background. In addition, hadrons in 10 GeV/$c < p_T <$ 20 GeV/c range will be produced by recombination as discussed above and thus selecting them as trigger particles will not select any special sample of events, contrary to the situation at RHIC where jets are rare but triggering on a high-p_T particle helps to unravel them from the large underlying background. Thus the model predicts no associated particles beyond uncorrelated bacgkround if the trigger particle is selected in 10 GeV/$c < p_T <$ 20 GeV/c range.

5. Summary

The recombination and coalescence models have proven to be successful in describing many qualitative features of nuclear modification factors, particle ratios and elliptic flow at RHIC energy.

These models are currently being challenged by two-particle correlations using identified particles. As I have discussed above, recent studies with multiply-strange particles (Ω and ϕ) as well as the study of particle composition in the long range pseudo-rapidity correlations play a key role.

At the LHC, it is expected that pure thermal recombination will be pushed $\approx$ 2 GeV/c higher in p_T than at RHIC to 6 GeV/c for pions and 8 GeV/c for protons, respectively. In the p_T range of 10-20 GeV/c, it is expected that shower recombination in the high jet density environment will contribute significantly to particle production. This will in turn lead to a surprisingly large p/π ratio of 5-20 and absence of any peaks in di-hadron azimuthal correlations. These model predictions can be tested by the ALICE experiment which is designed to have sufficient particle identification capabilities out to large p_T. However, it is important to keep in mind, that the jet quenching will populate the recombination region at the LHC and thus complicate the interpretation of the measured data.

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