Strangeness and onset of deconfinement

F. Becattini[1, *]

[1]*Dipartimento di Fisica dell' Università di Firenze and INFN, Florence, Italy*

In this talk I will review the current status of global strangeness production in relativistic heavy ion collisions with particular emphasis on recent results from core-corona model. I will discuss its relevance for the detection of the onset of deconfinement.

1. INTRODUCTION

The enhancement of relative (to u, d quarks) strange quark production in high energy heavy ion collisions with respect to elementary collisions has been predicted long time ago to be a signature of the Quark Gluon Plasma (QGP) formation [1]. The idea was that chiral symmetry restoration favours strange quark production because of the reduced mass compared to its zero temperature constituent value. This abundant strangeness production could be observed provided that it survives hadronization, i.e. if the early produced strange quarks coalesce into hadrons without reannihilating. A specific prediction of such a mechanism is the enhancement of multiply strange particles, especially hyperons.

These phenomena have been indeed observed: the ratio of newly produced strange to u,d quarks (the so-called Wroblewski ratio $\lambda_S = \langle s\bar{s}\rangle/2(\langle u\bar{u}\rangle + \langle d\bar{d}\rangle)$ shows about a factor 2 increase going from elementary to heavy ion collisions, (see Fig. 4) as first observed in Ref. [2], and the hyperons shows a clear hierarchical enhancement in central PbPb collisions with respect to peripheral PbPb and pPb collisions at top SPS energy ($\sqrt{s_{NN}} = 17.2$ GeV), as observed by the WA97–NA57 collaboration [3]. Also, it seems that this ratio increases quickly in heavy ion collisions as a function of centre-of-mass energy going from 1 to few GeVs and stay constant thereafter.

The issue here is the origin of this observed strangeness enhancement. Is the original prediction of generation in the plasma and subsequent coalescence still viable? Or,

* Electronic address: becattini@fi.infn.it

rather, are the excess strange quarks produced essentially at hadronization? Or, finally, is strangeness produced during an intense hadronic re-scattering stage, according to transport models *ansatz*? Before trying to answer these questions, it is necessary to address a preliminary very important issue, i.e. whether we have produced a completely equilibrated hadron gas or not. If we have a completely equilibrated hadron gas, strangeness content is completely determined and gives information on freeze-out state, but it is not a probe of earlier stage of the process. Solving this problem may have a considerable impact on our understanding of strangeness production in relativistic heavy ion collisions.

2. STATISTICAL MODEL AND CANONICAL SUPPRESSION

The main tool to probe the formation of an equilibrated hadron gas are the fits of the measured particle multiplicities or ratios to the statistical model, that is the ideal hadron-resonance gas. Many authors have performed such analyses trying to pinpoint the thermodynamical parameters of the hadron emitting source at the chemical freeze-out. A recent overview of the subject can be found in Ref. [4].

Much emphasis has been given, in most studies, to the issue of chemical equilibrium of strangeness at a hadronic level. It is by now established that a strangeness undersaturation parameter $\gamma_S < 1$ is needed to reproduce particle multiplicities in relativistic heavy ion collisions. For central collisions, this parameter shows an increasing trend from AGS to RHIC, where it attains its maximal value 1 (see Fig. 2). Moroever, a $\gamma_S < 1$ is needed in peripheral collisions at RHIC, where the analysis include midrapidity densities, as shown in Fig. 2 and also observed by many others [5].

It has been argued [6] that this observed strangeness undersaturation (i.e. $\gamma_S < 1$) is owing to the so-called canonical suppression effect. Namely, strange particles are further suppressed with respect to their expected yield in a grand-canonical ensemble (or thermodynamic limit) because strangeness is exactly vanishing within a small volume, called strangeness correlation volume (SCV), not necessarily coinciding with the global volume. Therefore, going from *pp* collisions to central heavy ion collisions through peripheral ones, one expects to observe a relative enhancement of strange particles due to approaching the thermodynamic limit, which is hierarchical: Ω yield increases faster than Ξ which increases faster than Λ's or kaons. Yet, although this hierarchy of enhancements is observed (see Fig. 4), neither SPS nor RHIC have observed the saturation which should be there if the SCV attains a sufficiently large value. In fact, this means that the SCV only reaches its saturation value (the one sufficient for the system to be essentially grand-canonical) at RHIC precisely in central collisions, where $\gamma_S \simeq 1$. This would be quite a striking coincidence. Therefore, the canonical suppression is quite an unnatural explanation of the data, as already pointed out, e.g. in Ref. [7].

The best probe to investigate the phenomenon of strangeness undersaturation is indeed the ϕ meson. This is not an open strange particle, thus it is not canonically suppressed, yet, being a $s\bar{s}$ state, it must be γ_S^2 suppressed. Furthermore, ϕ meson has almost no feeding from heavier light-flavoured species and its production is entirely direct.

It was pointed out quite early [8] that a statistical model with canonical suppression mechanism, i.e. with SCV as additional parameter, would have not been able to explain the deviation of the ϕ meson yield from its grand-canonical value and this has been demonstrated in fits to NA49 multiplicities [9]. The STAR collaboration has measured the midrapidity densities of ϕ meson very accurately [10] and the observed pattern as a function of centrality clearly shows (see Fig. 4) that these do not scale linearly with the number of participants, rather the ratio to pp value increases rapidly at very peripheral collisions slowly saturating thereafter. This non-linear increase cannot be attributed to a variation of the chemical freeze-out temperature because this is astonishingly constant as a function of N_{P} [5, 19] and proves that a genuine extra suppression related to the strange quark is needed, as also reflected in the γ_S fitted value (see Fig. 2).

3. CORE-CORONA MODEL

Can we explain γ_S in relativistic heavy ion collisions in more fundamantal terms? Some years ago R. Stock [9] proposed that $\gamma_S < 1$ in global fits could be the effect of superposing a completely equilibrated hadron gas ($\gamma_S = 1$) originated from the core of the nuclear collision (i.e. the hadronization of the plasma) to a corona of single NN collisions, where particle readily escape the interaction region. Since strangeness is largely suppressed in NN collisions with respect to the grand-canonical value while the temperature is almost the same as we know from pp statistical model analysis [11, 12], if the number of such single NN collisions accounts for a significant fraction of total particle production, a global fit to one hadron-resonance gas would actually find γ_S significantly less than 1. Indeed, this idea proved to be able to satisfactorily reproduce particle multiplicities in central CC, SiSi, and PbPb collisions at top SPS energy.

This core-corona superposition mechanism has been invoked by several authors in the past few years [13, 14]. A sharp superposition of a completely equilibrated hadron gas with NN collisions is indeed a zero-order approximation as the actual process is certainly more complex with those two extremes continuously linked through intermediate steps and indeed in Ref. [14] a more general concept of corona has been used, defined as a “dilute" peripheral region distinguished from the “dense" region in the core. Yet, this simple superposition scheme has proved to be very useful to understand the physics of particle production and also very effective to describe the centrality dependence of many observables [15–18]. According to this model, the rapidity density at midrapidity of any particle species is given by a simple superposition [16]:

$$\begin{aligned} \left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle &= \frac{N_{\mathrm{PC}}}{2} \left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{NN} + \left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{\mathrm{core}} \\ &\simeq \frac{N_{\mathrm{PC}}}{2} \left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{pp} + \left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{\mathrm{core}}, \end{aligned} \tag{1}$$

where $N_{\mathrm{PC}} = N_{\mathrm{S}}^A + N_{\mathrm{S}}^B$ is the mean number of participants in the low density corona, which undergo single nucleon-nucleon collisions; the second term on the right hand side is the particle density per unit rapidity coming from the core, assumed to be a completely equilibrated hadron gas, with $\gamma_S = 1$. After simple manipulations [16], we obtain from Eq. (1) the expression:

$$R_A = \frac{2 \left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{\mathrm{AA}}}{N_{\mathrm{P}} \left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{pp}} = \frac{2 f \rho_0}{2 n_0} \frac{\left\langle \frac{\mathrm{d}n_i}{\mathrm{d}y} \right\rangle_{\mathrm{core}}}{\left\langle \frac{\mathrm{d}N_i}{\mathrm{d}y} \right\rangle_{pp}} \left(1 - \frac{N_{\mathrm{PC}}}{N_{\mathrm{P}}}\right) + \frac{N_{\mathrm{PC}}}{N_{\mathrm{P}}} = \frac{N_{\mathrm{PC}}}{N_{\mathrm{P}}} + A \left(1 - \frac{N_{\mathrm{PC}}}{N_{\mathrm{P}}}\right), \tag{2}$$

where N_{P} is the number of participants and A is an unknown constant. Except for this constant, all other quantities can be easily determined with a Monte-Carlo Glauber calculation (see Fig. 4). Remarkably, for the ϕ meson, the constant A is independent of N_{P} because T is in fact independent of centrality [5, 19] and ϕ does not suffer possible canonical suppression. This parameter can be determined by matching the model to the measured value in the most central bin and then the centrality evolution is completely determined. The obtained curve is in impressive agreement with the data, as shown in Fig. 4; the formula matches the experimental points to a high degree of accuracy. This is a clear evidence that the envisaged core-corona superposition is able to account for the strangeness undersaturation phenomenon.

The same exercise can be repeated for open strange particles, the result being shown in Fig. 4. It can be seen that the curves match the data in the most central bins, while they overestimate the measured points in most peripheral bins: this is likely due to the canonical suppression effect in the core which makes the parameter A dependent on centrality at very peripheral collisions.

Similar studies conducted by other groups come to a similar conclusions [18].

4. DISCUSSION AND OUTLOOK

The success of the core-corona model shows that the centrality dependence of strange particle production (the so-called strangeness enhancement) in relativistic heavy ion collisions is mainly a geometrical effect. Canonical suppression plays a role only in the most peripheral collisions. Moreover, the ϕ data supports evidence for a completely equilibrated hadron gas in the core throughout all centralities at RHIC, whose temperature is constant and equal to 165 MeV [19].

The same conclusion is likely to apply to SPS too. The fact that there $\gamma_S \simeq 0.85$ in central collisions [12], significantly lower than at RHIC, is related to the lower weight of the core compared to the corona. Indeed, as energy decreases, so does the freeze-out volume of the core and the multiplicity of particles stemming from it, while the the number of single NN collisions decreases only slightly, the NN cross section being slowly varying. This would nicely explain the mild increase of γ_S as a function of center-of-mass energy (see Fig. 2), nevertheless a complete reanalysis of the data is compelling. As has been mentioned, early analysis of central collisions at top SPS energy based on this picture were fairly successful [9], but a systematic analysis of peripheral collisions are indispensable to confirm this idea.

If the very existence of a core as a fully chemically equilibrated hadron gas signals the formation of a region of deconfined matter, the next obvious step would be the search of the energy at which a proper core sets in. For this purpose, a systematic collection and analysis of heavy ion collisions data as a function of energy, in the $\sqrt{s_{\rm NN}}$ region between few and few tens of GeV, and of system size is necessary. The forthcoming SPS and JINR programs are very promising in this respect.

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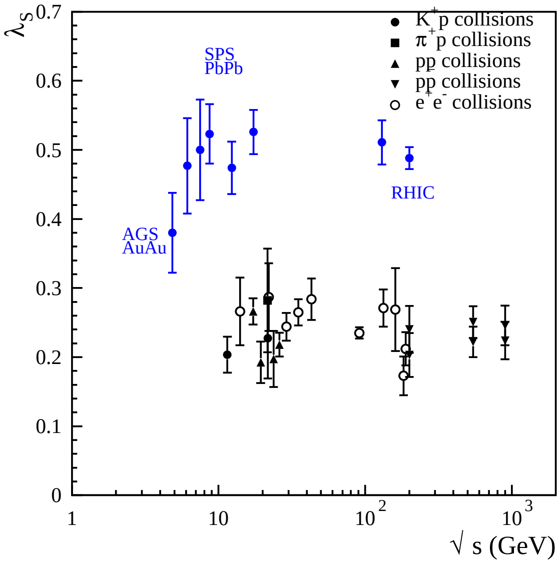

Figure 1. Wroblewski ratio in elementary and heavy ion collisions as estimated from statistical model fits [15].

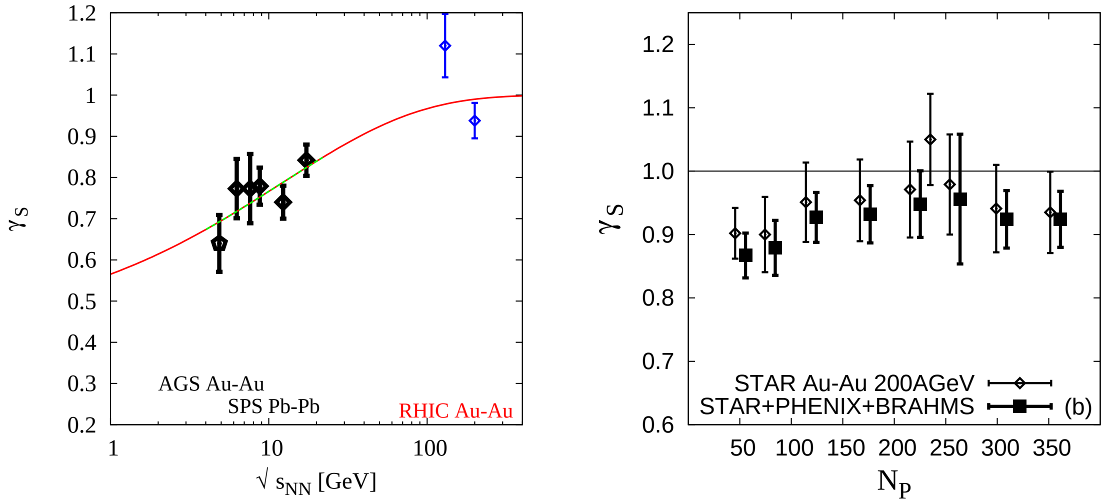

Figure 2. (a) γ_S as a function of centre-of-mass energy in central heavy ion collisions. (b) γ_S as a function of centrality in AuAu collisions at $\sqrt{s}_{\rm NN} = 200$ GeV [19].

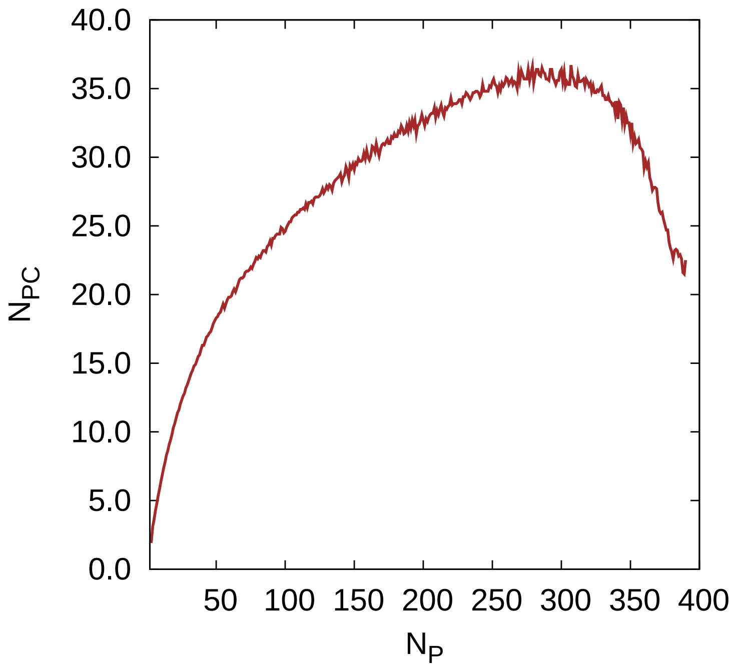

Figure 3. Number of participants in the corona as a function of number of participants in AuAu collisions at $\sqrt{s_{\rm NN}} = 200$ GeV according to Glauber Monte-Carlo model [16].

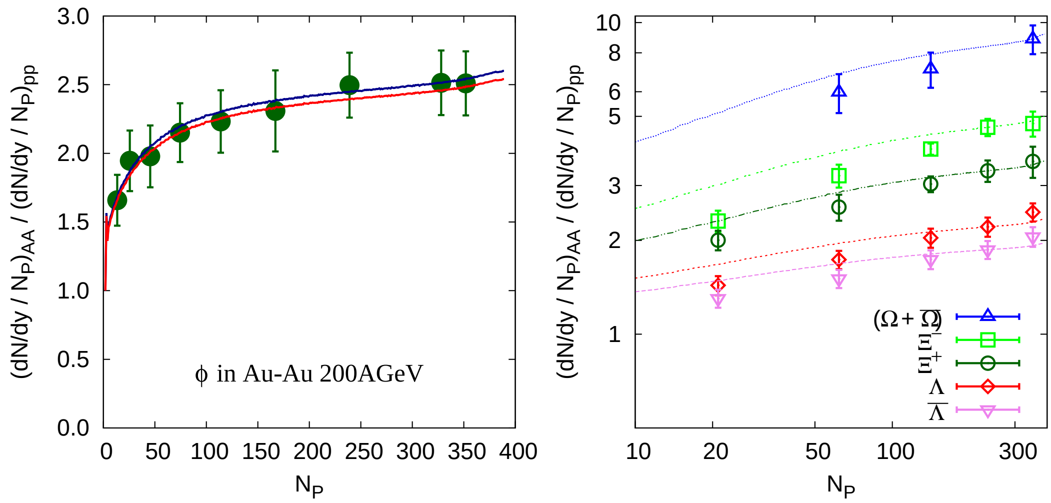

Figure 4. ϕ (a) and hyperons (b) rapidity density per wounded nucleon as a function of participants normalized to pp collisions. Data points from STAR [10, 20]; solid lines are the predictions from core-corona superposition [16].

FIGURE CAPTIONS

Fig.1: Wroblewski ratio in elementary and heavy ion collisions as estimated from statistical model fits [15].

Fig.2: (a) γ_S as a function of center-of-mass energy in central heavy ion collisions. (b) γ_S as a function of centrality in AuAu collisions at $\sqrt{s}_{\mathrm{NN}} = 200$ GeV [19].

Fig.3: Number of participants in the corona as a function of number of participants in AuAu collisions at $\sqrt{s}_{\mathrm{NN}} = 200$ GeV according to Glauber Monte-Carlo model [16].

Fig.4: ϕ (a) and hyperons (b) rapidity density per wounded nucleon as a function of participants normalized to *pp* collisions. Data points from STAR [10, 20]; solid lines are the predictions from core-corona superposition [16].