Quark Gluon Plasma and Strangeness from SPS to RHIC and LHC

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Strangeness production provides many relevant observables to caracterise the hot and dense nuclear matter formed in high energy heavy ion collisions and to search for the Quark Gluon Plasma. The evolution of this research field is described, going from the the original idea of "strangeness enhancement" as a direct probe of deconfinement up to the the most recent and novel developments, thus demonstrating that strange hadrons are an essential tool for understanding the global chemical and kinetic freeze-out conditions caracterizing the collisions in order to extract information about the initial expected partonic medium and its expansion dynamics. A review of recent SPS and RHIC results, concerning the chemical composition (particle multiplicities and ratios) and the collective behaviour (transverse and elliptic flow) of the fireball, is presented and discussed, mainly on the basis of statistical approaches and hydrodynamical models. Particular emphasis is put also on the new era which has begun at RHIC with the onset of hard processes, opening the study of parton propagation in the medium (jet quenching effects). Finally, the new opportunity offered by the futur LHC is briefly examined.

1. Introduction

Heavy ion collisions at (ultra-)relativistic energies are expected to create sufficiently hot and dense matter to reach the phase diagram domain where Quantum Chromodynamics (QCD) predicts a transition from a state of hadronic constituents to a plasma of quarks and gluons (QGP) [1]. Over the large energy range going from SPS (Super Proton Synchrotron) up to RHIC (Relativistic Heavy Ion Collider) and the future LHC (Large Hadron Collider), strangeness production is considered as one of the most sensitive probes of this new state of matter.

Starting from the initial motivation: strangeness enhancement as a direct signature of deconfinement [2], we will then enlighten the essential role played by strange hadrons in the global caracterisation of the bulk of particles formed in these collisions. This bulk of soft hadrons ($m_T - m_0 < 2$ GeV) represents the dominant part ($> 99\%$) of the produced matter. The main interest for studying its properties, by measuring the final hadronic spectra, is that parameters caracterizing the freeze-out distributions constrain the dynamical evolution and thus yield indirect information about the early stages of the collision [1, 3, 4, 5].

The particle abundances which establish the chemical composition of the system, provide information on the temperature and the baryo-chemical potential at chemical freeze-out and may probe the degree of chemical equilibration. This is of particular interest, because the appearance of a QGP, that is a system at (or close to) local thermal equilibrium, and its subsequent hadronization should lead to chemical equilibrium in the resulting hadronic medium [3, 4, 5].

The study of transverse momentum spectra and anisotropies tell us about the expansion dynamics [6], probing the degree of kinetic equilibration and the degree of collectivity, hence indirectly the pressure built at the early time of the collision. Indeed, the measure of transverse and elliptic flow is of crucial interest to study, in particular, to which extent the system expansion is consistent with the hydrodynamical limit of infinitely fast (re-)scattering (implying instantaneous local thermalisation) which produces a high pressure and consequently a strong collective explosion superimposed to a local thermal motion. With this respect, strange particles represent an essential tool to solve the question whether this flow has originated in a partonic phase.

Besides the bulk of low p_T particles, if the collision energy is high enough, a non negligeable amount of high p_T hadrons are produced, resulting from very energetic parton-parton collisions at the early stage of the reaction. Hence, the last section of this review will be devoted to the new era which has opened up at RHIC with the onset of these hard processes, allowing for the study of new phenomena related, in particular, to parton propagation and energy loss in the medium (jet quenching effects)[7]. The novel opportunities offered by the LHC energies where the collision picture is expected to be dominated by the hard processes, will also be briefly discussed.

2. The original motivation

The relative enhancement of strange and multi-strange particle yields in nucleus-nucleus reactions with respect to hadronic interactions (proton-proton or proton-nucleus collisions) has been suggested early as one of the most sensitive signature for QGP formation [2].
In a purely hadronic scenario (at least in a hot and dense hadron gaz at equilibrium), the difficulty to form strange baryons increases with the strangeness content (or the mass) of the baryon. Direct production (one single reaction) is gradually suppressed, when going from Λ to Ξ and then to Ω particles, because of increasing energy thresholds. Whereas the production of multi-strange baryons, by means of a chain of rescattering processes, is caracterized by a long equilibrium time compared to the lifetime of the fireball. This equilibration time also increases with the strangeness content of the baryon ($\sim$ 100 fm/c for the Ω), hence the higher the strangeness content, the larger the suppression.
In contrast, in a QGP scenario, strange quark-antiquark pairs are easily created, predominantly in gluon-gluon interactions. These gluon fusion processes, associated with partial restauration of chiral symmetry which lowers the mass of the strange quark, lead to a fast (a few fm/c) chemical equilibration of strangeness. As a result, the production of all hyperons, even the heaviest, is favoured.

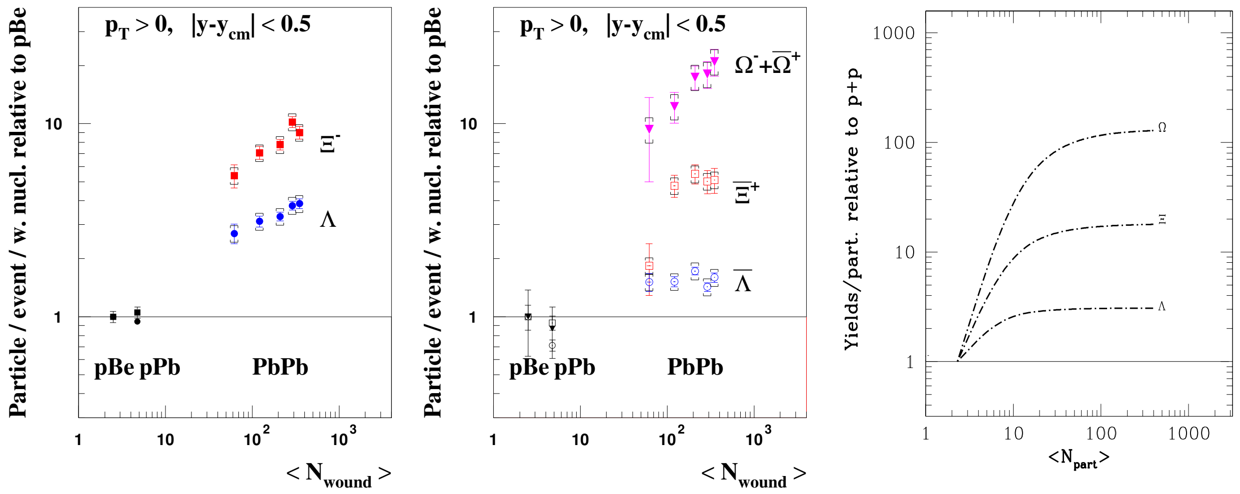

Figure 1: Left and middle pannels (from [9]): hyperon and anti-hyperon yields per number of wounded nucleons, expressed in units of corresponding yield per collision in p-Be reactions, measured at SPS ($\sqrt{s}$ = 17.3 GeV) by NA57. Right pannel: centrality dependence of relative enhancement of hyperon yield/participant, as predicted by statistical calculations in the Canonical Ensemble [11], at $\sqrt{s}$ = 8.73 GeV.

Hence, if a QGP is formed, a "hierarchical" enhancement of strangeness with respect to a hadronic scenario is expected to be seen, i.e. the relative hyperon and anti-hyperon yields, with respect to their values measured in hadronic references, should increase with the hyperon mass. Such an effect has indeed been observed by the WA97 [8] and NA57 [9] experiments at SPS (158 GeV/c). This is shown in figure 1 (left and middle) where the hyperon and anti-hyperon yields in Pb-Pb collisions are expressed per event and per wounded nucleon and normalized to their corresponding values in the hadronic reference p-Be. They are represented as a function of centrality, given by the mean number of "wounded" nucleons. This effect has been considered as a strong fooprint of the QGP. The magnitude of the observed enhancement (almost a factor 20 for Ω in the most central bin) was found to be in good agreement with the values expected in the case of QGP formation. However, some ambiguities remain in the interpretation of these data. If the QGP needs, as expected, a minimum sytem size to be created, a sudden discontinuity could appear in the yield evolution at a given centrality. But such a clear effect does not exist in the data, at least it is not visible in the measured centrality range (the substancial drop of the $\overline{\Xi}$ is no more present in the latest NA57 data obtained with larger statistics [10]). The rise of the yields with $< n_{wound} >$ is consistent with a smooth curve, without any discontinuity above 60. But below $< n_{wound} >= 60$, the question remains open, whether it could still be a brutal drop.

It has been shown recently [11] that the data trend can be qualitatively explained by Hadron Gaz statistical calculations performed in the frame of the Canonical ensemble which represents the "exact" treatment in case of rarely produced particles: this is the case for hyperons in pp and p-nucleus collisions as well as in very peripheral Pb-Pb collisions. Within this Canonical formulation, the exact conservation of quantum numbers, on an event by event basis, reduces severely the phase space available for particle production, when compared to the Grand Canonical approach. This might be the essence of the strangeness enhancement observed at SPS. Indeed, the Canonical curves shown in figure 1 (right pannel), exhibit, as the data, a strong dependence of the hyperon yields on the number of participant nucleons with a clear supression below $< Npart >\sim$ 10-15. Nevertheless, the onset of saturation when going to higher participant numbers seems to start much earlier in the model than in the data. The measured $\Omega+\ \overline{\Omega}$ behaviour exhibits even a continous increase without any sign of saturation at large $< N_{wound} >$.

The basic predictions of the canonical statistical model is that strangeness enhancement from p-p to A-A collisions decreases with increasing energy (by an order of magnitude for Ω from the lowest ($\sqrt{s}$ = 8.73 GeV) to the highest ($\sqrt{s}$ = 17.3 GeV) SPS energies [11]. It will be possible to check this prediction at the RHIC energy as soon as the pp and d-Au reference data will be fully analysed.

3. The statistical picture

Interpreting experimental particle abundancies within statistical models [13, 14, 15, 16] is considered as a very promising starting point for studying the bulk matter properties.

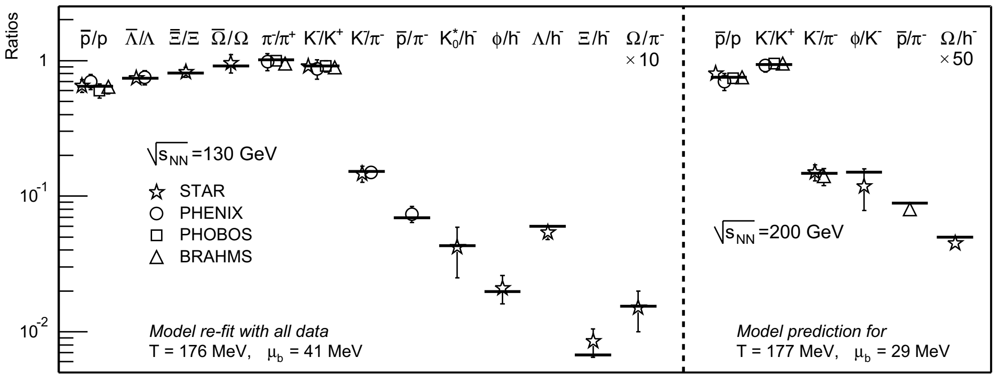

Figure 2: From [12]. Comparison between particle ratios measured at RHIC for $\sqrt{s}$ = 130 and 200 GeV and statistical model calculations [12, 14].

The basic goal of the statistical analysis is to find a unique set of independant thermal parameters, namely the temperature (T) and the baryochemical potential (μ_B), able to reproduce,

for a given system and a given energy, all the particle yields (or the multiplicity ratios) simultaneously. For large systems (central Pb+Pb or Au+Au collisions) at high energy (AGS, SPS and RHIC) the partition function of the Grand Canonical ensemble can be used while the Hamiltonian is usually described by the Hadron Resonance Gas.
The equilibrium statistical model has been applied with the same success to the SPS and the RHIC data shown in figure 2. At SPS, the data are consistent with a chemical freeze-out appearing at a temperature of about 165-170 MeV and a baryo-chemical potential around 270 MeV [13]. At RHIC, the particle ratios measured by STAR, PHENIX, PHOBOS and BRAHMS (see figure 2) for a c.m. energy of 130 GeV per nucleon pair, are well reproduced by a temperature of 175 MeV and a baryo-chemical potential of about 40 MeV [14]. At 200 GeV, the baryochemical potential drops down to 29 MeV while the temperature stays almost the same. The substantial decrease of the baryo-chemical potential when going from SPS to RHIC shows that we are approaching the baryon free region.
The main conclusion that may be drawn from this analysis is the following: the very good agreement between the statistical model and the data suggests that a high degree of chemical equilibration is reached. The appearance of the QGP in the initial state could be the driving force towards this equilibrium. However, another feeling is that the thermal picture works but that it is probably too simplistic. The statistical operator does certainly not provide a unique description of the data. Alternatively, the possible influence of in-medium effects on the chemical equilibrium description was studied [17] and a non-equilibration scenario of explosive hadronisation of a QGP fireball was also proposed [18], giving a reasonable agreement with the experimental yields. Besides, dynamical models aimed to describe the microscopic processes occuring during the various stages of the collision have also been helpful in the interpretation of heavy ion data, in particular on strangeness aspects [19]. An other important fact is that the statistical model works also remarkably well in describing the particle ratios in high energy pp or e^+e^- collisions. In this case, we are not dealing with a thermal system in the sense of Boltzmann, where a state of equilibrium is maintained by many particle collisions. Here, statistical may simply mean phase-space dominance [20]. In heavy ion collisions, the situation is different. There, we hope that the amount of rescattering is high enough to reach (or get close to) this equilibrated bulk of matter where we can give to the Lagrange-multipliers T and μ_B the physical meaning of temperature and chemical potential.
Hence, assuming that the reality is not too far from this situation, the statistical model may provide indirect information about the appearance of a QGP. First of all, it may tell us about a limiting temperature (as predicted by Hagedorn). Moreover, this limit appears to be close to the deconfinement temperature predicted by lattice QCD calculations [21]. This is shown on the phase diagram represented in figure 3 (left pannel). Already at SPS but especially at RHIC, the chemical freeze-out temperature gets remarkably close to the phase transition boundary. This suggests that, before chemical freeze-out, the system was at a temperature higher than this predicted limit and that the observed hadrons are originating from the deconfined medium [3, 4, 5], percolation of strangeness, for example, in the Grand Canonical ensemble, being most likely to occur in the QGP phase when the chemical freeze-out temperature is close to the critical one. Arguing that chemical equilibration after hadronisation is probably excluded by the time scale of the kinetics [22], one may reasonably believe that hadrons were born into chemical equilibrium. Surprisingly, the equilibration picture seems also to work rather well at much lower energies, where the necessary conditions for deconfinement are probably not satisfied. There, the reason for thermalisation is expected to be production and rescattering of hadronic constituents. The interpretation of heavy ion collision data with statistical models over the large energy domain going from SIS up to RHIC allows for building an unified picture (see figure 3 (left)). This picture is caracterized by an increase of T and a diminution of μ_B according to a constant average energy per hadron of about 1 GeV [16].
This phenomenological freeze-out curve provides the relation between temperature and chemi-

cal potential at all collision energies. This relation together with one particle ratio, the ratio of pion over participant particles, establishes the energy dependence of T and μ_B. Consequently, particle excitation functions can be predicted by the statistical model, in its canonical formulation. Figure 3 (right) shows that the predicted K/π ratio curves [23] agree rather well with the trend of the measured points from SIS to RHIC energies [24, 25].

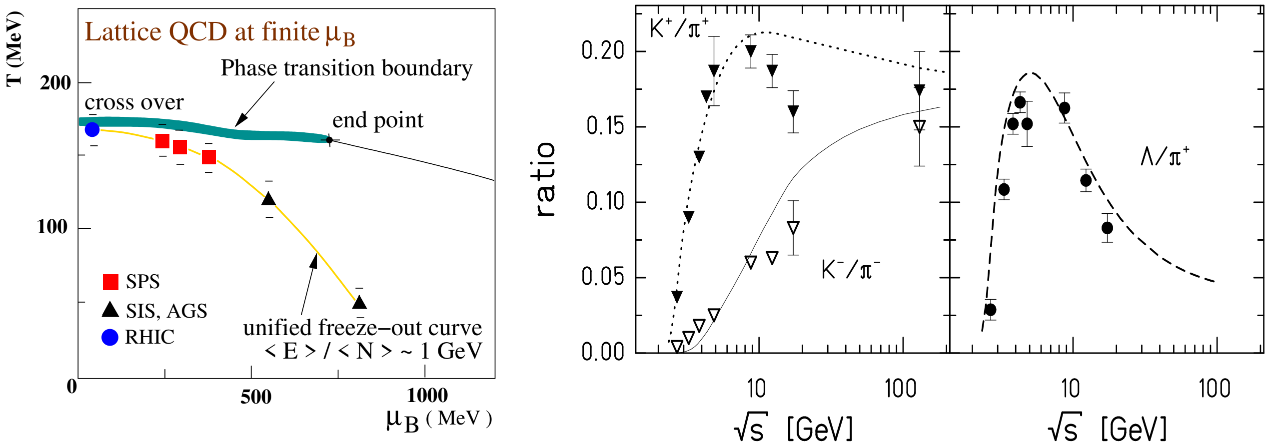

Figure 3: Left pannel: phase diagram of strongly interacting matter and chemical freeze-out conditions in H.I. collisions (from SIS to RHIC). Lattice QCD calculations at finite baryo-chemical potentiel (from [21]). Right pannel: experimental K/π and Λ/π^+ excitation functions from AGS to RHIC energies, compared to statistical model predictions [23].

The measured K^-/π^- ratio rises monotonically while the K^+/π^+ ratio shows a more complex behaviour. Its abrupt increase at low energy reflects the rise of T and the canonical suppression. At incident energies above AGS, the temperature is still increasing but the baryo-chemical potentiel starts dropping rapidly. This competition between T and μ_B results in a broad maximum around 30 A GeV laboratory energy. It creates a threshold at which the evolution of the ratio between newly created strange quarks and newly created light quarks is reversed. From SPS higher energy to RHIC energy, the increase of the temperature becomes negligible but μ_B keeps on decreasing, leading to a smooth drop of the K^+/π^+ ratio. The maximum effect is much clearly pronounced for Λ/π^+ ratios because baryons are more disadvantaged than mesons by the quick falling of the baryo-chemical potential. The thermal model reproduces well the measured Λ/π^+ ratio and the general trend of the K^+/π^+ ratio but fails to reproduce the magnitude of the K^+/π^+ drop when the SPS energy goes from 40 A GeV to 80 A GeV and then to 158 A Gev. Furthermore, a new point has been recently measured by NA49 at 30 A GeV SPS energy [25] and produces a surprisingly sharp maximum, neither reproduced by the statistical model nor by dynamical models like RQMD. This behaviour is of particular interest as it could be the signal of a new dynamics for strangeness production. It has even been conjectured that this property could indicate an energy threshold for QGP formation [26].

4. The expansion dynamics: transverse and elliptic flow

The first picture of the sytem expansion, in central collisions, may be obtained by measuring the transverse momentum or transverse mass spectra of the particles. The inverse slope of these m_T distributions are shown in figure 4 (left pannel) for various particles at SPS and RHIC [27]. This parameter can be interpreted as an "apparent" temperature, containing a contribution from the "true" temperature at kinetic freeze-out and a contribution from the flow effects. Indeed, it increases strongly with the rest mass of the particle, at least up to protons, which is

a typical behaviour expected from a system which undergoes transverse collective expansion, caracterized by the same average flow velocity for all particles. Transverse flow is not only seen at RHIC but also at SIS, AGS and SPS, its magnitude increasing with energy.
The trend of the m_T spectra suggests an "hydrodynamically motivated" fit, using the blast wave model [28], i.e. a model assuming a thermal source undergoing a collective expansion. The velocity profile of the particles is thus governed by the superposition of a local random motion and a collective cylindrical boost in the transverse direction, depending on their position: the larger their distance to the cylinder axis, the higher their flow velocity. The data can thus be fitted with only two parameters: T_{fo} (thermal freeze-out temperature) and $< \beta_T >$ (mean transverse flow velocity).

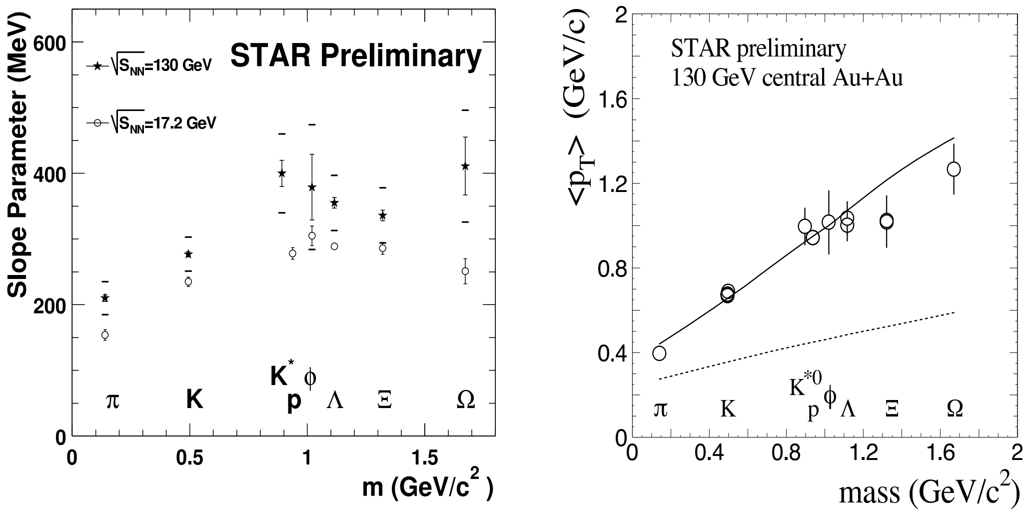

Figure 4: From [27]. Left pannel: inverse slope parameters as a function of particle mass for central collisions at SPS and RHIC (brackets represent systematic errors). Right pannel: mean transverse momenta of various particle species at RHIC along with blast wave model fit (upper curve: $T_{fo} \sim 100$ MeV, $< \beta_T > \sim 0.55$, lower curve (no flow): $\beta_T = 0$).

At RHIC energy, the blast wave model is able to reproduce the m_T distributions of π,K,p,Λ particles and their mean transverse momentum (see figure 4 (right pannel) [27] with a unique set of parameters: $T_{fo} \sim$ 100 - 110 MeV and $< \beta_T > \sim 0.55$. The Ξ and Ω particles seem to depart from this common thermal freeze-out behaviour [29, 30]. Their mean flow velocity is smaller: $< \beta > \sim 0.4$, while the associated temperature is found to be approximately the same as the chemical freeze-out temperature. This might indicate that these particles are decoupled earlier from the system due to their low rescattering cross section with surrounding medium. But in the mean time, the amount of flow is still substantial and this suggests that it could have developped at least partially in the early partonic stage. Part of the answer could be given by measuring their elliptic flow.
From the shape of the transverse momentum spectra, the main conclusion that may be drawn is that, apart from several deviations, the bulk of particles formed in high energy heavy ion collisions seems to behave according to hydrodynamics. This is clearly evidenced in figure 5 (left) where the relativistic hydrodynamical model developped by Heinz et al. [31] presents quite a nice overall agreement with pion and antiproton transverse momentum distributions measured in central collisions at RHIC.
This hydro-like behaviour is also corroborated by elliptic flow [33, 34, 35] measurements in non central collisions. There, the initial overlap zone between the two colliding nuclei is spatially deformed. This spatial anisotropy is almond shaped. However, the initial momentum distribution is locally isotropic. Only interactions between constituents generate a pressure gradient which

transforms the initial coordinate space anisotropy into a momentum space anisotropy. The momentum anisotropy manifests itself most strongly in the azimuthal distribution of transverse momenta (with respect to the reaction plane) [33] which can be quantified by the coefficients of an azimuthal Fourier decomposition of the distribution. The second harmonic coefficient v_2 is called elliptic flow. The spatial anisotropy is largest early in the collision, but as the elliptic flow develops, the matter begins to expand more rapidly in the initially short direction than in the long one. Therefore the spatial deformation disappears and the buildup of flow anisotropies from pressure gradients stops. That's why the magnitude of the elliptic flow should reflect the pressure, i.e. the extent of the rescattering, at relatively early time.

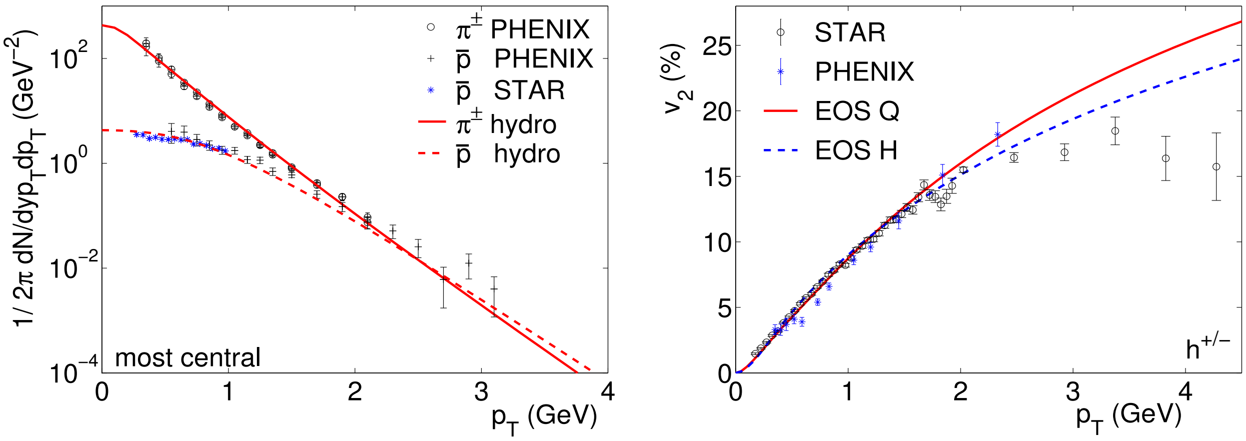

Figure 5: Left pannel: charged pion and antiproton spectra from central Au+Au collisions at $\sqrt{s} = 130$ GeV, compared to hydrodynamical calculations [31]. Right pannel: elliptic flow coefficient for all charged particles from 130 GeV minimum bias Au+Au collisions, compared to hydrodynamical calculations corresponding to equations of state with (Q) and without (H) phase transition [32].

The magnitude of elliptic flow has been found to increase substantially from AGS [36] to SPS [37] and RHIC [38] where it reaches the values predicted by hydrodynamical models [32], as shown in figure 5 (right), where the v_2 of charged hadrons (measured in PHENIX and STAR) is shown as a function of p_T. This suggests that very fast thermalization occurs [31, 32]. This conclusion is based on the intuitive argument that the hydrodynamic limit of infinitely fast rescattering, leading to instantaneous local thermal equilibrium produces the largest possible elliptic flow values [31] and that the data seem to saturate this limit. Data start to deviate from hydrodynamics only after p_T= 1.5 - 2 GeV/c, which might indicate the onset of the influence of hard processes (see next section).
The systematic study of strange particle elliptic flow is of great interest, especially for multi-strange baryons, because it may reveal directly the presence of partonic flow, according to the following argument [39]: in a possible partonic phase prior to the hadronic stage, the hadronic scattering cross sections for the final hadrons are not relevant. As such, if the elliptic flow of identified particles proves to be independent of their relative hadronic cross sections, it may be the evidence that v_2 is built during a partonic phase.

5. The onset of hard processes at RHIC

In heavy ion collisions at RHIC, hard parton-parton scattering at the very beginning of the nucleus-nucleus reaction starts to play a non negligeable role in our understanding of the produced system. These hard processes open the door to new observables of the early stage of the collision and new signatures of QGP. In hadronic collisions at high energies, partons distributed in the hadronic projectiles interact strongly in "hard" 2 to 2 processes. As they escape from each other, the energetic partons produced by the hard process radiate energy because of their color charges and finally hadronize into clusters of hadrons (jets). It has been shown that partons propagating in a QGP loose energy through gluon "bremsstrahlung" [7], or more precisely through gluon rescattering [40]. The magnitude of the energy loss is predicted to depend strongly on the gluon density of the medium. Measurement of partonic energy loss ("jet quenching") therefore provides a unique probe of the density of the medium and should allow for a distinction between a QGP and a hadronic system. Parton energy loss in the QGP should lead to a supression of high transverse momentum hadrons in the final state [7, 40, 41]. In order to search for evidence of such an effect, by comparing the spectra in nuclear collisions to a nucleon-nucleon reference, the so-called nuclear modification factor R_{AA} is introduced [42] (see definition in figure 6). $T_{AA} =< N_{bin} > /\sigma_{inel}^{NN}$ accounts for the collision geometry, averaged over the event centrality class, $< N_{bin} >$ being the mean number of binary NN collisions. This ratio is smaller than 1 at low p_T (in the soft physics regime, approximately below 2 GeV/c). In contrast, the yield at high p_T where hard processes are dominant should scale as $< N_{bin} >$ in the absence of nuclear medium effects ($R_{AA} = 1$). Hence, effects of the medium like parton energy loss may be measured at high p_T by the deviation of R_{AA} from unity. The problem is that, in addition to parton energy loss, R_{AA} may also be affected by initial-state nuclear effects: multiple scattering and shadowing of nuclear parton distributions [41] will modify the hadron production at high p_T.

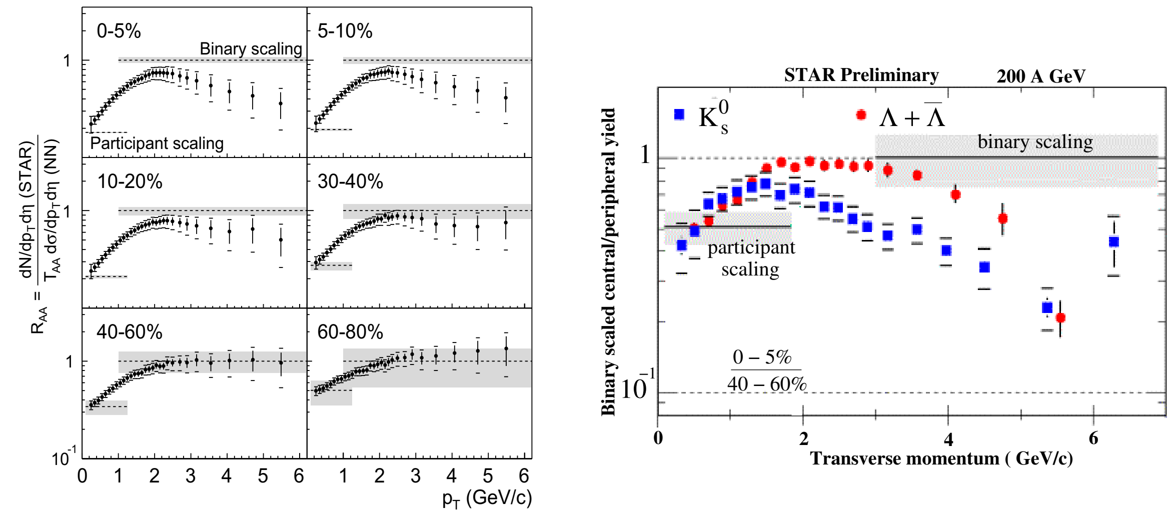

Figure 6: Left pannel (from [42]) : $R_{AA}(p_T)$ of charged hadrons, measured in STAR, for various centrality bins in Au + Au collisions at $\sqrt{s} = 130$ GeV. Right pannel (from [43]): nuclear modification ratios of $\Lambda + \bar{\Lambda}$ and K_s^0 yields for central over peripheral collisions, normalized to $< N_{bin} >$, in Au + Au collisions at 200 GeV.

The nuclear modification factor, measured by the STAR collaboration, for Au + Au collisions at $\sqrt{s}_{NN} = 130$ GeV, relative to reference data from nucleon-nucleon (NN) collisions is shown in figure 6 (left) [42]. The reference is provided by pp scaled cross sections from UA1 experiment and corrected for η acceptance. A clear supression of high p_T hadrons is observed in the most central collisions. Then the suppression diminishes when going to intermediate impact parameters and finally vanishes for peripheral collisions. The suppression is in qualitative agreement with predictions of partonic energy loss in a QGP. Furthermore, as shown recently [44], no suppression is observed in d-Au collisions. Arguing that the suppression should also be observed in d-Au if it is due to initial-state effects, one may conclude that the suppression phenomena seen in central Au + Au collisions are the result of final-state interactions in the dense matter.

Partonic energy loss could also explain the behaviour of elliptic flow observed at high p_T. As shown in figure 7 (left), the elliptic flow of K_s^0 and Λ starts saturating at high p_T [43], instead of growing continously with p_T as expected by nondissipative hydrodynamical calculations. This general form of $v_2(p_T)$ can be reproduced qualitatively by a model mixing hydrodynamics and jet quenching [45], as shown in figure 7 (right)). In this model, particle production is decomposed into phenomenological "soft" and pertubative QCD hard components. The non perturbative component incorporates hydrodynamic elliptic flow, whereas the pQCD part includes parton energy loss (jet-quenching). The fact that the deviation occurs earlier for mesons than for baryons is also predicted by the model.

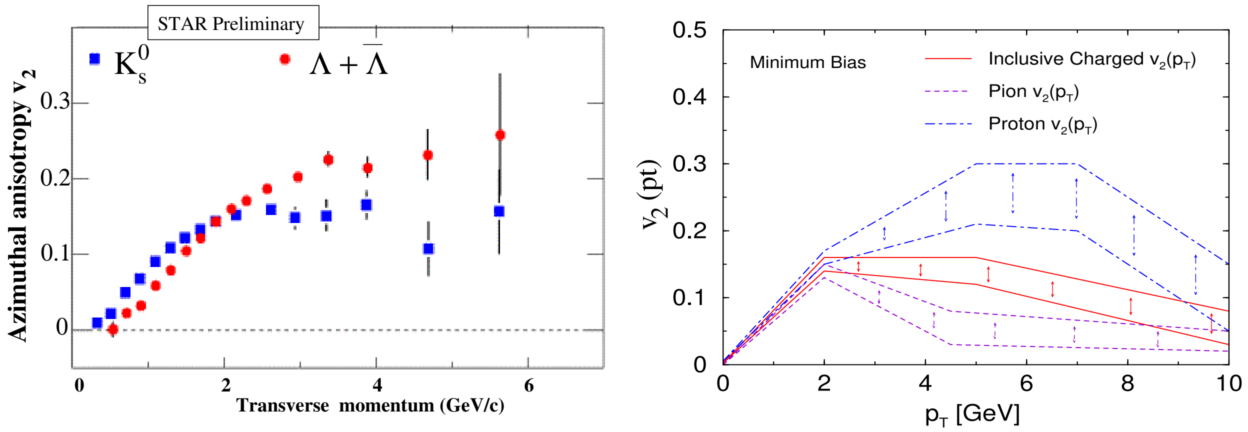

Figure 7: Left pannel: minimum bias $v_2(p_T)$ measurements for $\Lambda + \overline{\Lambda}$ and K^0_s in Au+Au collisions at 200 GeV [43, 46]. Right pannel (from [45]): elliptic flow for pions and protons predicted by a model combining hydrodynamics and jet quenching (see text).

Coming back to the nuclear modification factor, it is very interesting to see that baryons and mesons show also a different suppression pattern. As shown in figure 6 (right), Λ yields seems to scale with $< N_{bin} >$ for transverse momenta between 1.5 and 3 GeV/c, which is not the case for K^0_s yields. The suppression of baryons start only after $p_T = 3$ GeV/c, indicating that below this limit, their production dynamics is beyond the framework of fragmentation and parton energy loss. In contrast, meson suppression occurs before (between 1.5 and 2 GeV/c). Are those behaviours the result of a complex interplay between hard and soft process, between two competive hadronisation processes, namely quark coalescence at low p_T and parton fragmentation at high p_T ? [47, 48] To get answers, all pieces of the puzzle have to be put together, in particular the nuclear modification factor R_{AA} and the elliptic flow coefficient $v_2(pt)$ behaviours which are strongly correlated [43, 46] (see figures 6 and 7). For a given species, the saturation of v_2 and the fall off of R_{AA} occur at approximately the same p_T value: 2 GeV/c for K^0s and 3 GeV/c for Λ.

Summary and outlook

The systematic study of strangeness has entered a very sophisticated stage where the old observables combined to new ones allow for a much better understanding of the chemistry and the dynamics of heavy ion collisions and bring other pieces of the puzzle into play. As a result, many new footprints of the QGP but also related new questions have come up. The high level of thermalisation and collectivity suggested by the data as well as the unsusual behaviour in the high momentum probes seem to yield robust proofs of this new phase, on the basis of indirect evidence, but work is still necessary to get a deep understanding of this complex matter. In particular we need a detailed knowlwegde of hadronic references like d-Au, whose analysis has already started at RHIC, in order to draw solid conclusions about all the observed phenomena, both in the soft and the hard physics domains. Many other observables, unfortunately not presented in this non-exhaustive review, are also under study, in particular

those related to HBT and resonance measurements which yield essential information about the collision evolution. At the moment, they lead to quite puzzling timescales. The consistency of all observations and interpretations in the frame of stastistical, hydrodynamical and microscopic dynamical models has to be carefully checked. This will need important efforts. There are still analysis and interpretation work to perform with the SPS data and still years of data taking and analysis at RHIC. In order to really understand the matter formed in relativistic nucleus-nucleus collisions, the excitation functions of all observables must be studied in the largest possible energy domain. After RHIC, we will benefit of a huge jump in energy with the LHC program [49] as well as the possibility to explore another part of the phase diagram, i.e. the very high baryon density region with the futur GSI facility [50].
At LHC, the much higher expected energy density and particle multiplicity combined with the much larger influence of hard processes will offer novel kinds of observables and data analysis within the frame of the dedicated ALICE experiment. Due to the large number of newly produced particles, it will be possible for example, to extract the freeze-out conditions for single events. This will allow to caracterize selected event classes: high T and low T events, in order to disentangle different dynamic evolutions in the T-μ_B plane. By triggering on jet events "a chemical analysis" of the collisions will allow to extract the correlations between the initial and the freeze-out phases, between the soft and the hard processes. Concerning jet quenching effects, a part from high p_T hadrons suppression and its dependence on nuclear geometry, several other promising observables will be available for the study of parton energy loss, up to very high transverse momenta. For all these studies, hyperons play a major role because they are measured by their decay topology and can thus be identified up to very high momentum where traditional hadron identification (specific ionisation in gas detectors or time of flight measurements) fails. The futur of strangeness studies looks thus quite promising, both in the soft and the hard physics sectors. There is also an "exotic sector", that of hypothetical strange clusters (strangelets and MEMO's) [51], which could bring some surprises, may be at LHC but most probably in the compressed baryonic regime of SIS 100/200 [50].

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