Jet Physics with Identified Particles at RHIC and LHC

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Abstract. I will present the latest results on particle identified spectra and two particle correlations at high transverse momentum measured with the STAR detector at RHIC. I will compare those measurements with the projected capabilities for the LHC using the ALICE detector. The effects of string fragmentation and quark recombination in the intermediate momentum range will be discussed in the context of hadron formation in proton-proton and Au-Au collisions, as well as energy loss mechanisms in the dense partonic phase. The necessity for gamma-jet and heavy quark jet measurements will be detailed based on the ambiguity of existing particle identified results.

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1. Introduction

The measurement of particle identified high momentum spectra and two-particle correlations can be considered the next step in the characterization of the dense partonic phase created in relativistic heavy ion collisions at RHIC. Much emphasis is presently given to the similarities in the light and heavy quark behavior in the plasma, but these measurements are detailed in other contributions to this workshop [1, 2]. Here I will mostly focus on the flavor dependence in light hadron production, i.e. hadrons consisting of u,d,s quarks. I will address in particular the question of baryon versus meson production through fragmentation and recombination as competing mechanisms. In order to determine the baryon production mechanism in AA collisions we need to understand the production in pp first. The main question is whether there is a difference between the light baryon production in the medium and in the vacuum. In the following section I will briefly review the latest particle identified pp results from STAR and then move on to results from AuAu collisions. The ambiguity in the production mechanism as deduced from single particle properties such as the suppression at high pt and elliptic flow v2 can be partially resolved by analyzing two particle correlations. I will show that early
results of intermediate $p_T$ associated particle production are surprisingly featureless regarding flavor dependencies that were expected from perturbative QCD calculations in vacuum. In contrast, the single particle spectra suppression at high $p_T$ in $AA$ seems very much affected by flavor suppression in the proton-proton system, in particular for strange particles. I will try to argue that this effect should be unique to the strange quark, only if the strange quark generation is gluon dominated and the heavy quark production is quark dominated. Many of the studies at RHIC lack the statistics to map out the transition from medium effects to pure vacuum fragmentation. I will show that these measurements are readily accessible at the LHC, in particular with the ALICE detector.

2. Why is pp so important?

The latest strange and non-strange hadron production results obtained in proton-proton collisions by STAR, were presented at this workshop [3, 4]. They show that simple leading order fragmentation codes are not sufficient to describe the baryon production at RHIC energies. Next to leading order calculations do well as soon as quark separated fragmentation functions are used [5], in other words there are contributions in the baryon spectra from non-valence quark fragmentation. In a leading order calculation this fact can apparently be approximated by increasing the K-factor and the multiple parton scattering contribution to the underlying event [6]. These effects are expected to be significantly less pronounced at higher incident energies [7]. In other words, next to leading order contributions are more important at RHIC energies than at LHC energies.

One important new pp result is the break-down of the so called $m_T$-scaling [8, 9] at sufficiently high transverse mass at RHIC. Fig.1a shows the measured spectra of all particle identified species obtained by STAR. After appropriate scaling of each spectrum the $m_T$-scaling plot (Fig.1b) can be devised. Clearly the $m_T$-scaling at lower $m_T$, which had previously been established through measurements at lower energies [10, 11], can be confirmed. The noticeable deviation from simple scaling at sufficiently high $m_T$ ($m_T > 3$ GeV/c) is a new feature, though. The spectra seem to group into common baryon and meson curves at these momenta. This is a surprising effect in elementary pp collisions which is nevertheless described quantitatively in PYTHIA, as shown in Fig.2.

Figs.2a and 2b break down the effect, as modeled in PYTHIA, for gluon and quark jets. The combined spectrum (Fig.2c) is dominated by the gluon jets. According to PYTHIA the ratio of gluon to quark jets is about 2:1 at RHIC energies.

One very interesting feature in the parton separated spectra (Figs.2a and 2b) is that apparently the gluon jet fragmentation leads to a baryon/meson difference at high $m_T$, whereas the quark jets show a mass ordering of the high $m_T$ spectra. Gluon fragmentation dominates at RHIC (and even more at LHC) energies, and based on PYTHIA the baryon/meson splitting effect in the kinematic spectra is due to the di-quark formation process which is a pre-requisite for baryon formation in LUND
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Fig. 1. (a) Identified transverse mass spectra as measured by STAR in pp collisions. (b) Same spectra as in Fig.1a but scaled via multiplicative factors to the measured pion spectrum.

Fig. 2. PYTHIA simulation of the scaled identified mt spectra in Fig.1b from (a) gluon jet fragmentation (g-g or q-g) only, (b) quark jet fragmentation (q-q) only, and (c) sum of all parton fragmentation processes based on the relative ratio of quark to gluon jets at 200 GeV according to PYTHIA.
Fig. 3. Measured Anti-\( \Lambda \) over \( \Lambda \) ratio compared to PYTHIA ratio from gluon and quark jets.

type string fragmentation [12]. The initial di-quark formation leads to a lowering of the \( <p_T> \) for the baryons (the so called di-quark suppression factor), whereas for mesons the simple quark-antiquark hadronization does not affect the \( <p_T> \).

This feature in the fragmentation of elementary gluon jets could be considered the seed of the baryon meson differences in AA collisions. The effect by itself is not big enough, though, to quantitatively describe the strong peak in the baryon/meson ratio at intermediate \( p_T \) in AA, but the overall feature (a bump at intermediate \( p_T \)) can already be seen in pp collisions and might be simply enhanced by additional effects in AA. In AA one needs the combined effects of radial flow and quenching to 'pile-up' the baryons over mesons in the intermediate \( p_T \) range. Still it is important to note that the baryon/meson differences already have their origin in the basic fragmentation process in pp collisions. This measurement also hints at the validity of the fragmentation process as modeled by PYTHIA. It is my opinion that in its nature the diquark-quark formation process is similar to a three quark coalescence process and thus exhibits equivalent features.

Another conclusion from the pp modeling is that, although early pQCD calculations predicted a stronger drop in the anti-baryon over baryon ratio, our results are in accordance with PYTHIA calculations if one takes into account the strong gluon dominance at RHIC energies as shown in Fig.3.

In order to unambiguously determine the predicted drop, which is due to the difference between quark and gluon distribution functions and the relative contribution of these partons to the baryon and anti-baryon production, one needs measurements at higher \( p_T \). The momentum range of the spectra will be greatly enhanced at the LHC. Fig.4 shows a projection of \( p_T \)-ranges for identified spectra
based on a scaled LHC pQCD calculation. Generally the light quark spectra will reach out to at least 20 GeV/c in the first year of running, which allows for a more unambiguous study of the flavor effects at high \( p_T \).

One interesting feature in the gluon dominated regime at RHIC and the LHC is that the \( \gamma \)-jet process is dominated by Compton scattering, which leads to a \( \gamma \)-quark-jet combination in the outgoing channel. This means not only is the tagged \( \gamma \) the ‘standard candle’ for the jet energy measurements, but it is also a good trigger for quark-jet events in the gluon dominated regime. The rate, based on early simulations using the ALICE calorimeter, is significantly limited compared to di-jet events, but one can still expect on the order 10,000 events with a \( \gamma \) energy above 50 GeV. A similar quark-jet selection can be achieved by triggering on heavy mesons as leading particles. Projected rates for all jet measurements with the proposed ALICE EMCal are shown in Fig.5.

3. Flavor dependencies in identified high pt AA spectra

One of the most surprising results of the past year was the apparent difference between \( R_{AA} \) and \( R_{CP} \) measurements, in particular for strange baryons. Figs.6 and 7 show a direct comparison of strange and non-strange baryons and mesons.
Fig. 6. Nuclear suppression factor ($R_{AA}$) as measured by STAR.

Fig. 7. Nuclear suppression factor ($R_{CP}$) as measured by STAR.

The strong jet quenching effect at high $p_T$ and the slight baryon/meson splitting due to recombination at moderate $p_T$ as shown on the $R_{CP}$ plot is not visible in the $R_{AA}$ plot. The $R_{CP}$ suppression has been established for all particle species from pions to charmed mesons, and besides the already mentioned baryon/meson difference at intermediate $p_T$ the suppression is surprisingly flavor independent. The $R_{AA}$ pattern though exhibits a very strong flavor dependence, in particular for baryons. An enhancement of the high $p_T$ yield, rather than a suppression compared to the pp spectrum, actually increases as a function of the strangeness content in baryons. A similar enhancement pattern was previously measured for integrated particle yields, and is generally attributed to canonical suppression of strange quarks in small systems [13], but it is unexpected that apparently this effect of a small correlation volume in an equilibrated system should also affect the high $p_T$ particle production. Not only does it lead to an enhancement of the intermediate $p_T$ yield from pp to AA but there is also no evidence of quenching in the strange baryon $R_{AA}$ plot at high $p_T$. This effect is actually not seen in preliminary results of charmed meson suppression, so it could indeed be unique to the strange quarks. A measurement of a charmed baryon ($\Lambda_c$) is needed to unambiguously determine the difference between the quark flavors. Because of the difference between $R_{CP}$ and $R_{AA}$ the strange quark flavor effects need to have their origin in the particle production in the pp system. This is a good indicator that even intermediate $p_T$ strange baryons are predominantly produced through coalescence from a thermalized partonic system. In other words the initial gluon dominated scattering processes leads to thermalized strange quarks which coalesce into strange baryons. The effect of the correlation volume during hadronization is still dominant even at rather large (up to 3 GeV/c) transverse momentum. Beyond the intermediate $p_T$ range the spectrum gets quenched, but it is still enhanced in AA collisions compared to the pp system. The question is whether this strange
particle production mechanism drives the pp to AA comparison even in the pure fragmentation regime above 7 GeV/c. The RHIC experiments do not have a big enough reach to establish an answer. Fig.4 shows that these measurements can be achieved at the LHC, though. We know from $e^+e^-$ experiments that the strangeness suppression factor in the quark condensate is about 0.4 [14], but this is just the relative quark production probability in the hadronization sea, which should also exist in the medium. In addition, the strangeness saturation factor increases from pp to AA by a factor two at RHIC energies based on measurements of integrated strange particle yields [15]. The factor in AA can be described quantitatively in lattice QCD [16].

The difference between baryons and mesons in $R_{CP}$ (Fig.7), which is generally attributed to either recombination or an interplay between radial flow and jet quenching [17], can also be described by the so-called Corona effect, which was shown elsewhere at this conference [18, 19]. The principle here is that the formed medium consists of a dense core, which follows hydrodynamics and a corona of pp interactions dominated by multiple scattering. The main reason for such a distinction and the strong contribution from the corona is the relative diffuseness of the nuclear surface, which is not well described by hard spheres. The pp interactions can be modeled by codes such as EPOS which take into account the increased parton cascade activity in the low momentum sector. In these models effects such as baryon/meson splitting in $v_2$ occur because the corona, which carries very little $v_2$, has a much stronger contribution to the light particle spectrum than the heavy particle spectrum, so it pulls down the hydro $v_2$ for mesons to lower values than for baryons.

Finally one can measure identified two particle correlations at intermediate $p_T$ in order to detect flavor dependencies that are expected from simple fragmentation arguments. The correlations shown in Fig.8 show surprisingly little trigger particle flavor dependence. Again it seems that non-fragmentation processes, such as recombination, dominate in this $p_T$ range. There is evidence for long-range correlations in $\Delta \eta$ which could be due production mechanisms that do not exhibit the flavor dependencies of simple fragmentation. These correlations lead to a significant enhancement of the associated yield for any trigger species over the associated yields measured in pp, which are in agreement with the PYTHIA simulations shown in Fig.8b.

4. Summary

The interpretation of our pp collision results reveal that the baryon production yields require either multiple scattering through a soft particle production model such as EPOS or NLO corrections in pQCD models such as PYTHIA. It is interesting to note that the basic string fragmentation differences in baryon and meson production lead to a breakdown of the universal $m_T$-scaling of identified particle spectra. Apparently this breakdown is driven by the baryon production mechanism
Fig. 8. High \( p_T \) two particle correlations using identified trigger particles and charged hadron as associated particles. a.) measurements in 0-5% centrality Au-Au collisions in STAR, b.) PYTHIA simulations of the same correlations in pp collisions.

in gluon jets and manifests itself as a slope difference at high \( m_T \) when comparing baryon to meson spectra. This basic effect in pp is not sufficient though to describe the large baryon over meson yield enhancement at intermediate \( p_T \) in AA collisions.

Besides the baryon/meson difference there is a surprising absence of strong flavor effects in the particle to anti-particle ratios in AA, the identified two particle correlations in AA, and even the jet quenching in the medium. Thus, it is still an open question whether the partonic energy loss in AA shows the expected Casimir factor when comparing hadrons from a fragmenting gluon jet to a quark jet, i.e. is the energy loss really non-Abelian?

The only strong flavor effect is in the strangeness sector. High \( p_T \) strange baryon production in AA is enhanced instead of suppressed compared to pp. This could be due to simple canonical suppression in pp. This thermodynamic effect, which is due to a limited strangeness phase space occupancy, has been measured for the first time as a function of transverse momentum, and it is obvious that the effect is not limited to low momentum or simply bulk properties. Surprisingly the intermediate \( p_T \) part scales well with the canonical suppression factors, which indicates that the hadronization mechanism of strange baryons, even at higher \( p_T \), is driven by a correlation volume, which is distinctly different from charmed meson production.
The D-meson yield and high $p_T$ suppression factors in AA are consistent with scaled hard scattering cross section, i.e. production from string fragmentation.

In identified two particle correlations in AA collisions we see a strongly enhanced associated particle yield compared to pp, independent of the trigger particle species. Long range $\Delta \eta$ correlations might account for that and they might be due to recombination [20]. A small baryon/meson trend can be found in those correlations but the effect is not very significant. Larger predicted effects for $\phi$ and $\Omega$ triggered correlations [21] are under investigation.

In summary, I believe that studies of the hadronization mechanism at RHIC and LHC energies in vacuum and in medium hold the key to the puzzle of baryonic matter formation in the universe. We need to first understand the basic baryon production mechanism(s) in pp (string fragmentation vs. recombination, di-quark formation (?). Then we need to determine whether the baryon production mechanism in AA collisions is modified from the vacuum production. For a more detailed study the high pt reach and the particle identification properties of the LHC detectors are crucial.

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