Abstract: The fact that nuclei have diffuse surfaces (rather than being simple spheres) has dramatic consequences on the interpretation of the RHIC heavy-ion data. The effect is quite small (but not negligible) for central collisions, but gets increasingly important with decreasing centrality. One may actually divide the collision zone into a central part ("core"), with expected high energy densities, and a peripheral part ("corona"), with smaller energy densities, more like in pp or pA collisions. We will discuss that many complicated "features" observed at RHIC become almost trivial after subtracting the corona background. We are focussing on AuAu collisions at 200 GeV.

EPOS is a parton model, so in case of a AuAu collision there are many binary interactions, creating partons, which then hadronize employing a phenomenological procedure call string fragmentation. Here, we modify the procedure: we have a look at the situation at an early proper time $\tau_0$, long before the hadrons are formed: we distinguish between string segments in dense areas (more than $\rho_0$ segments per unit proper volume), from those in low density areas. In the following, we will use $\tau_0 = 1$ and $\rho_0 = 1 \text{ fm}^{-3}$. We refer to high density areas as core, and to low density areas as corona.

In figure. 1 we show two examples (randomly chosen) of semi-peripheral (40-50%) AuAu collisions at 200 GeV (cms), simulated with EPOS. We observe large fluctuations event by event, simply reflecting the randomness of the positions of binary nucleon-nucleon collisions. There is an important contribution from the low density area, contributing roughly 20% to the final particle production. But much more importantly, as discussed later, the importance of this contribution depends strongly on particle type and transverse momentum. For central collisions, the low density contribution is obviously less important, for more peripheral collisions this contribution will even dominate.

How do these low density contributions inter-
Figure 1: Two Monte Carlo realizations of semi-peripheral (40-50%) AuAu collisions at 200 GeV (cms). We show in red string segments in high density areas (core), and in green the string segments in low density environments (corona). The circles are put in just to guide the eye: they represent the two nuclei in hard sphere approximation. We consider a projection of segments within $z = \pm 0.8 \text{ fm}$ to the transverse plane (x,y).

act with the expanding core? Well, even a system of noninteracting particles expands, with the velocity of light (reflecting the outward moving particles). Inward moving particles may be absorbed by the core, on the other hand the core edges start to hadronize at the same time, with a good chance that early hadronization and absorption compensate each other. So we ignore any interaction for the moment. But even if part of the low density contribution will be absorbed, there will be a sizable effect.

In order to make a quantitative statement, we adopt the following strategy: the low density part will be treated using the usual EPOS particle production which has proven to be very successful in pp and dAu scattering (the peripheral interactions are essentially pp or pA scatterings). For the high density part, we simply try to parameterize particle production, in the simplest way possible (it is not at all our aim to provide a microscopic description of this part). Suppose we find such a simple parameterization of the core contribution, such that the total contribution reproduces all the relevant low and intermediate $p_t$ data, then our core parameterization represents in fact the data after “background subtraction”, and that is what we are really interested in!

In practice, we first divide the EPOS string segments into core and corona contribution, as discussed earlier (apart of the density, there is another condition: only segments with transverse momenta less than 4 GeV contribute to the core, the others escape freely, no jet quenching). We then consider the core contributions more closely, in longitudinal slices, characterized by some range in $\eta = 0.5 \ln(t + z)/(t - z)$. Since string segments show a Bjorken-fluid-like behavior, the particles in a segments around $\eta$ move with rapidities close to $\eta$. Connected core regions in a given segment are considered to be clusters, whose energy and flavor content are complete determined by the corresponding string segments. Clusters are then considered to be collectively expanding: Bjorken-like in longitudinal direction, with
in addition some transverse hadronization. We assume that the clusters transverse hadronize at some given energy density $\varepsilon_{\text{hadr}}$, having acquired at that moment a collective radial flow, with a linear radial rapidity profile from inside to outside, characterized by the maximal radial rapidity $y_{\text{rad}}$. In addition, we impose an azimuthal asymmetry, by multiplying the $x$ and $y$ component of the flow four-velocity with $1 + \epsilon f_{\text{ecc}}$ and $1 - \epsilon f_{\text{ecc}}$, where $\epsilon$ is the the initial spacial eccentricity, $\epsilon = \langle (y^2 - x^2)/y^2 + x^2 \rangle$, and $f_{\text{ecc}}$ a parameter. By imposing radial flow, we have to rescale the cluster mass as

$$M \to M \times 0.5 y_{\text{rad}}^2/(y_{\text{rad}} \sinh y_{\text{rad}} - \cosh y_{\text{rad}} + 1),$$

in order to conserve energy. Hadronization then occurs according to covariant phase space, which means that the probability $dP$ of a given final state of $n$ hadrons is given as

$$\prod_{\text{species } \alpha} \frac{1}{n_{\alpha}!} \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 2E_i} g_i s_i W \delta(E - \Sigma E_i) \delta(\Sigma \bar{p}_i) \delta_f \Sigma f_i,$$

with $p_i = (E_i, \vec{p}_i)$ being the four-momentum of the $i$-th hadron, $g_i$ its degeneracy, and $f_i$ its quark flavor content ($u - \bar{u}, d - \bar{d}...$). There is a factor $s_i = \gamma_s \pm 1$ for each strange particle (sign plus for a baryon, sign minus for a meson), with $\gamma_s$ being a parameter. The number $n_{\alpha}$ counts the number of hadrons of species $\alpha$. $E$ is the total energy of the cluster in its cms, $W$ is the cluster proper volume. The whole procedure perfectly conserves energy, momentum, and flavors (microcanonical procedure).

So the core definition and its hadronization are parameterized in terms of 6 global parameters:

| Parameter         | Value       | Description                        |
|-------------------|-------------|------------------------------------|
| $\tau_0$          | 1 fm       | core formation time                |
| $\rho_0$          | 1 fm$^{-3}$ | core formation density             |
| $\varepsilon_{\text{hadr}}$ | 0.22 fm$^{-3}$ | hadr. energy density           |
| $y_{\text{rad}}$  | 0.83        | max. radial flow rapidity            |
| $f_{\text{ecc}}$  | 0.5         | eccentricity coefficient            |
| $\gamma_s$        | 1.3         | hadronization factor                |

The final results are insensitive to variations of $\tau_0$, even changes as big as a factor of 2 do not affect the results at all. This is a nice feature, indicating that the very details of the initial state do not matter so much. We call these parameters “global”, since they account for all observables at all possible different centralities at RHIC. In the following, we are going to discuss results, all obtained with the above set of parameters.

All the discussion of RHIC data will be based on the interplay between core and corona contributions. To get some feeling, we first compare in fig. 2 the core contribution corresponding to a central (0-5%) AuAu collision (which means purely statistical hadronization, with flow) with pp scattering (which is qualitatively very similar to the corona contribution). We plot $m_t$ spectra of pions, kaons, protons, and lambda, the nuclear spectra are divided by the number of binary collisions (according to Glauber). We observe several remarkable features: the shapes of the different pp spectra are not so different among each each other, there is much more species dependence in the core spectra, since the heavier particles acquire large transverse momenta due to the flow effect. The second main observation concerns the yields, in particular at intermediate values of $m_t - m$: the yields for the different pp contributions are much wider spread than the core contributions; in particular, pion production is suppressed in the core hadronization compared to pp, whereas lambda production is favored. All this is quite trivial, but several “mysteries” discussed in the literature (and to be discussed later in this paper) are just due to this.

Let us now compare core and corona contributions for different centralities in AuAu collisions at 200 GeV. In fig. 3, we plot the relative contribution of the core (relative to the complete spectrum, core + corona) as a function of $m_t - m$, for different particle species. For central collisions, the core contribution dominates largely (around 90%), whereas for semi-central collisions (40-50%) and even more for peripheral collisions the core contribution de-
increases, giving more and more space for the corona part. Apart of these general statements, the precise $m_t$ dependence of the relative weight of core versus corona depends on the particle type, and can be easily understood by inspecting figure 2 since the corona contribution is up to a factor very close to pp.

We are now ready to investigate RHIC data. In fig. 4 we plot the centrality dependence of the particle yield per participant (per unit of rapidity), for $\pi^+, K^+$, and $p$, the data together with the full calculation, but also indicating the core contribution. The complete calculation follows quite closely the data. Whereas central collisions are clearly core dominated, the core contributes less and less with decreasing centrality. Similar results are obtained for $\pi^-, K^-$, and $\bar{p}$, and also lambdas and xis.

Next we consider particle ratios, as a function of centrality. In fig. 5 we show the ratios of different particles, with respect to pions. Whereas the complete contribution (as the data) show a strong centrality dependence, the rations are practically flat for the core contri-

Figure 2: Invariant yields $1/2m_t \, dn/dym_t$ of pions (red), kaons (blue), protons (green), and lambdas (yellow), for the core contribution corresponding to a central (0-5%) AuAu collision (full lines) and proton-proton scattering (dashed).

Figure 3: The relative contribution of the core (core/(core+corona)) as a function of the transverse mass for different centralities (0-5%: red, 40-50%: blue, 70-80%: green). Upper figure: pions (full) and kaons (dashed). Lower figure: protons (full) and lambdas (dashed).
Figure 4: Rapidity density $dN/dy$ per participant as a function of the number of participants, for $\pi^+$ (red), $K^+$ (blue), and $p$ (green). We show data (points) together with the full calculation (core + corona, full line) and just the core part (dashed).

Figure 5: Particle ratios as a function of centrality: $K^+/\pi^+$ (red), $K^-/\pi^-$ (green), $p/\pi^+$ (blue), $\bar{p}/\pi^-$ (cyan), $\Lambda/\pi^-$ (gray), $\Xi^-/\pi^-$. Complete calculation (full) and just ratio of the core contributions (dotted).

Figure 6: Nuclear modification factors in central AuAu collisions at 200 GeV. Lines are full calculations, symbols represent data. We show results for pions (red; circles), kaons (blue; squares), protons (green; triangles), and lambdas (yellow; inverted triangles).

So our first important conclusion: after subtracting the "corona background", the interesting part, the core contribution, shows an extremely simple behavior: there is no centrality dependence, the systems are simply changing in size (and the participant number is certainly not a good measure of the volume of the core part, this is why the overall multiplicities per participant decrease with decreasing centrality).

Let us come to $p_t$ or $m_t$ spectra. We checked all available low and intermediate $p_t$ data (pions, kaons, protons, lambdas, xis), and our combined approach (core + corona) describes well the data (better than the differences between STAR and PHENIX results). Lacking space, we just discuss a (typical) example: the nuclear modification factor (AA/pp/number of collisions), for pions, kaons, protons, and lambdas in central AuAu collisions at 200 GeV, see fig. 6. For understanding these curves, we simply have a look at fig. 2, where we compare the core contributions from AuAu (divided by the number of binary collisions) with pp. Since for very central collisions the core domi-
nates largely, the ratio of core to pp (the solid line divided by the dotted one, in fig. 2) corresponds to the nuclear modification factor. We discussed already earlier the very different behavior of the core spectra (phase space decay) compared to the pp spectra (string decay): pions are suppressed, whereas heavier particles are favored. Or better to say it the other way round: the production of baryons compared to mesons is much more suppressed in string decays than in statistical hadronization.

So what we observe here, is nothing but the very different behavior of statistical hadronization (plus flow) on one hand, and string fragmentation on the other hand. This completely statistical behavior indicates that the low $p_t$ partons do not suffer energy loss, they get completely absorbed in the core matter.

The $R_{cp}$ modification factors (central over peripheral) are much less extreme than $R_{AA}$, since peripheral AuAu collisions are a mixture of core and corona (the latter one being pp-like), so a big part of the effect seen in $R_{AA}$ is simply washed out.

Let us finally discuss elliptical flow, shown in fig. 7. We understand the results in the following way: the pion curve seems to saturate at high $p_t$, which is here simply due to the fact that with increasing $p_t$ the continuously increasing core curve is more and more “contaminated” by corona contributions. For the lambdas, the effect is much smaller, since the corona contributions are smaller, as seen from fig. 3. Eventually, the lambda curve will also saturate, but at larger $p_t$.

To summarize: we have discussed the influence of the corona contribution (occurring in the periphery of nuclear collisions) in AuAu collisions at RHIC. Our analysis is based on a model which works excellently for pp and pA, together with a very simple parameterization of the central (core) part. The fact that this simple treatment works, indicates that the part we are really interested in, the core, shows a very simple behavior. For example, contrary to the general believe, there seems to be no centrality dependence of particle production, just the volume changes.

We do not make any attempt here to explain these very interesting data, the only purpose here is to separate the interesting part (core) from the contamination (corona). We also did not make any efforts to optimize the fits, actually most parameters are essentially first guesses. To get more precision one need to enter into a more technical discussion about for example the feed-down correction procedures in the different experiments.

### References

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