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# Core - Corona Model describes the Centrality Dependence of $v_2/\epsilon$ .

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**Abstract.** Event by event EPOS calculations in which the expansion of the system is described by *ideal* hydrodynamics reproduce well the measured centrality dependence of  $v_2/\epsilon_{part}$ , although it has been claimed that only viscous hydrodynamics can reproduce these data. This is due to the core - corona effect which manifests itself in the initial condition of the hydrodynamical expansion. The centrality dependence of  $v_2/\epsilon_{part}$  can be understood in the recently advanced core-corona model, a simple parameter free EPOS inspired model to describe the centrality dependence of different observables from SPS to RHIC energies. This model has already been successfully applied to understand the centrality dependence of multiplicities and of the average transverse momentum of identified particles.

PACS numbers:

Ever since Drescher et al. [1] have claimed that the elliptic flow,  $\frac{v_2}{\epsilon}$ , observed in the RHIC experiments, is even for the most central collisions at least 25% below the ideal hydrodynamical limit, the centrality dependence of the elliptic flow is considered as one of the key variables for the understanding of ultrarelativistic heavy ion collisions. Before this finding one had concluded from other observables that the Quark Gluon Plasma, created in the energetic reaction, is a perfect liquid [2].

The analysis in [1] is based on the assumption that the centrality dependence of the elliptic flow can be described by a simple formula [3]:

$$\frac{v_2}{\epsilon} = \frac{v_2^{hydro}}{\epsilon} \frac{1}{1 + \frac{K}{K_0}}. \quad (1)$$

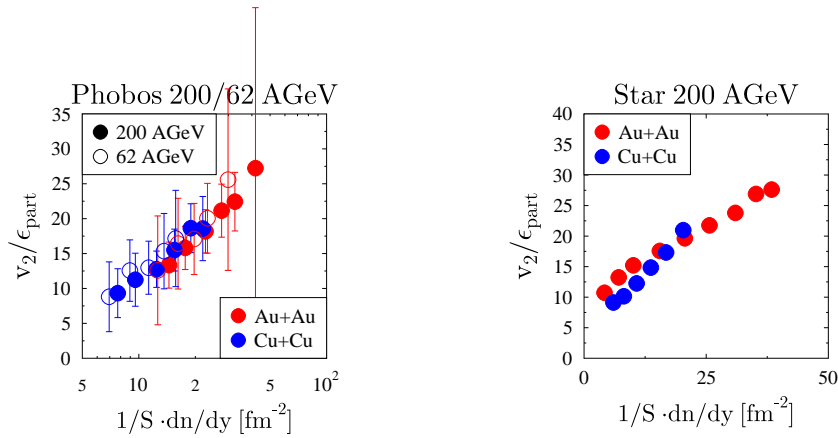
$K_0$  is a constant,  $v_2$  is the measured elliptic flow,  $v_2 = \langle \cos 2(\phi - \phi_R) \rangle$ , where  $\phi$  ( $\phi_R$ ) is the azimuthal angle of the emitted particle (reaction plane).  $v_2^{hydro}$  is the value of the elliptic flow expected in the hydrodynamical limit. The average is performed over many events which belong to the same centrality class of the reaction.  $\epsilon$  is the spatial participant eccentricity of the particles in an event at the beginning of the

hydrodynamical expansion, defined as  $\epsilon = \frac{\sqrt{(\sigma_y^2 - \sigma_x^2)^2 + 4\sigma_{xy}^2}}{\sigma_y^2 + \sigma_x^2}$  with  $\sigma_x^2 = \langle x^2 \rangle - \langle x \rangle^2$ ,  $\sigma_y^2 = \langle y^2 \rangle - \langle y \rangle^2$ ,  $\sigma_{xy} = \langle xy \rangle - \langle x \rangle \langle y \rangle$ . It has to be calculated in a theoretical model.  $K$  is the Knudsen number defined as

$$\frac{1}{K} = \frac{\sigma}{S} \frac{dN}{dy} c_s. \quad (2)$$

with  $\sigma$  being the partonic cross section,  $c_s$  being the sound velocity and  $S$  being the transverse area  $= 4\pi\sqrt{\sigma_x^2\sigma_y^2 - \sigma_{xy}^2}$ . Using a Glauber model to determine  $S$  and  $\epsilon$ , the measured [4] (phobos) or calculated values [5] (star) values of  $dn/d\eta$  as well as the experimentally observed  $v_2$  values of the Phobos [6], the Star [7, 8] and the Phenix collaboration [20, 21] one can calculate  $\frac{v_2}{\epsilon}$  as a function of  $dn/d\eta$ . The ratio between  $dn/d\eta$  and  $dn/dy$  depends on the particle species but is not far from 1. We assume here  $dn/d\eta = dn/dy$  because our conclusions do not depend on the precise value of this ratio. The result of this analysis is shown in fig. 1.

On the first view it seems that the data of different colliding systems at different energies fall in this representation on top of each other and therefore the Knudsen number depends indeed only on  $\frac{1}{S} \frac{dN}{dy}$ . However, if one regards the left figure in more detail one realizes that at a given centrality  $\frac{v_2}{\epsilon}$  is almost independent of the beam energy [6].  $dn/d\eta$  for 200 AGeV is about 1.4 times larger than that observed for 62 AGeV, almost independent of the centrality [4]. Thus the Knudsen number extracted from the 200 AGeV data is 40% smaller than that from the 62 AGeV data. This 40% change of the Knudsen number is hardly visible in the plot which means that this presentation is not very sensitive to the Knudsen number. That for the same value of  $dn/d\eta$  the value of  $\frac{v_2}{\epsilon}$  of the 62 AGeV data is systematically higher than that of the 200 AGeV data is unexpected in this model because it means that at the lower energy the system is closer to the hydrodynamical limit than at the higher energy. However, the error bars are too large to allow for firm conclusions. The scaling of  $\frac{v_2}{\epsilon}$  with  $dn/d\eta$



**Figure 1.** Dependence of  $v_2/\epsilon_{part}$  on  $\frac{1}{S} \frac{dn}{dy}$  in AuAu and CuCu collisions at 200 AGeV in comparison with the results of the STAR experiment [7, 8] and for 200 AGeV/62 AGeV in comparison with the Phobos data [6].

is questioned by the more recent Star data, displayed on the right hand side, where only statistical errors are shown. The Star collaboration has analyzed also peripheral AuAu events, in contradistinction to the Phobos collaboration. Therefore these data allow a more detailed comparison of both systems. We see for both systems an almost linear dependence of  $\frac{v_2}{\epsilon}$  with  $dn/d\eta$ . The slope for the CuCu system is, however, clearly different from that for AuAu, what one could have guessed already from the Phobos data [1].

By fitting the experimental results with the theoretical curve, eq. 2, one can determine  $K/(\sigma c_s)$  and finally the Knudsen number  $K$  of each centrality bin, assuming (centrality independent) values for  $\sigma$  and  $c_s$ . Even for the most central bins  $\frac{v_2}{\epsilon}$  depends on  $dn/d\eta$ . Thus the hydrodynamical limit  $K=0$  is not reached. From the extrapolation towards  $dn/d\eta \rightarrow \infty$ , corresponding to  $K \rightarrow 0$ , the authors concluded that the observed flow is at least 25 % below the limit for ideal hydrodynamics.

These findings triggered the development of codes using viscous hydrodynamics. Luzum et al.[9] showed in viscous hydrodynamical calculations that different viscosities yield a different centrality dependence of  $v_2/\epsilon_{part}$  and of  $\langle p_T \rangle$ . This dependence they used to identify that viscosity value which describes the 200 AGeV AuAu data. More recently, Song et al. [10] have extended the calculation to the CuCu system.

What has not been realized in this line of arguments is the importance of the initial configuration at the moment when the hydrodynamical expansion starts. The equations of ideal hydrodynamics predict how - for a given equation of state - this initial configuration develops in time under the assumption that the system is locally in equilibrium. Therefore it is expected that different initial conditions give different final distributions. The initial configuration at the beginning of the hydrodynamical expansion is unknown. It is difficult to asses because the time scale for equilibration in

the initial state is much faster than predicted by microscopical calculations.

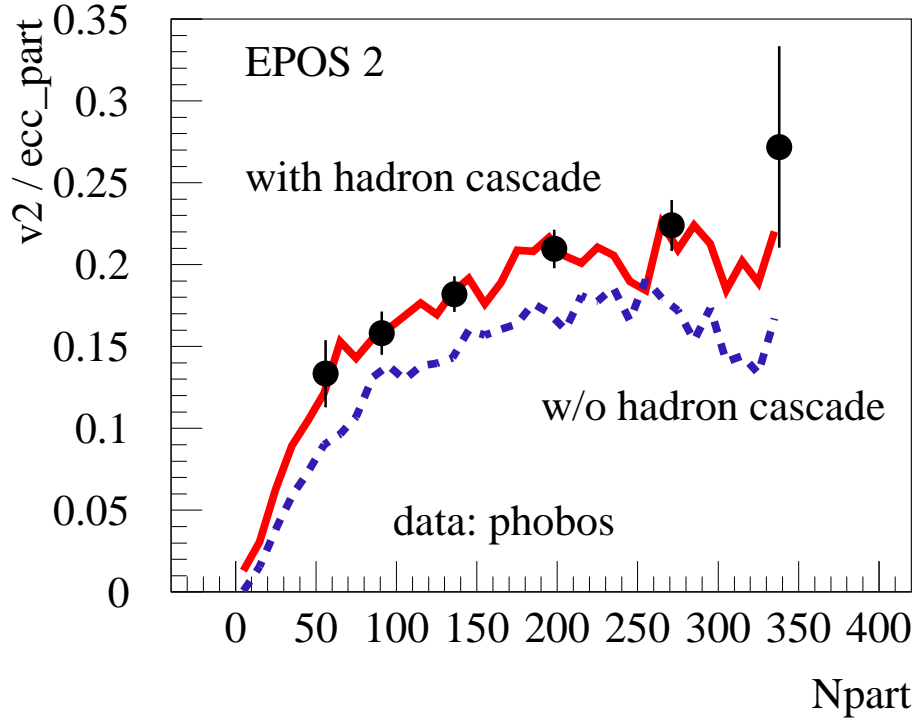
Recently one realized that event by event fluctuations of the initial conditions are not only much stronger than initially expected but also that they manifest themselves in the observables [11, 12]. Only the particles deep inside the interaction region, the core particles, collide sufficiently frequent to form a locally equilibrated source whereas those close to the surface, called corona particles, do not come to a local equilibrium and do therefore not take part in the hydrodynamical evolution of the system.

EPOS is a consistent quantum mechanical multiple scattering approach based on partons and strings [13], where cross sections and the particle production are calculated consistently, taking into account energy conservation in both cases (unlike other models where energy conservation is not considered for cross section calculations [14]). A special feature is the explicit treatment of projectile and target remnants, leading to a very good description of baryon and antibaryon production as measured in proton-proton collisions at 158 GeV at CERN [15]. Nuclear effects related to CRONIN transverse momentum broadening, parton saturation, and screening have been introduced into EPOS [16].

In heavy ion collisions (and more recently also in proton-proton collisions) collective behavior is taken into account [17], in the following fashion: the initial scatterings, as described above, lead to the formation of strings, which break into segments, usually identified with hadrons. When it comes to heavy ion collisions, the procedure is modified: one considers the situation at an early proper time  $\tau_0$ , long before the hadrons are formed: one distinguishes between string segments in dense areas (more than some critical density  $\rho_0$  segments per unit volume), from those in low density areas. The high density areas are referred to as core, the low density areas as corona [17]. It is important to note that initial conditions from EPOS are based on strings, providing a “flux-tube” like structure in case of individual events (a single flux tube in case of many overlayed events). Based on the four-momenta of the string segments which constitute the core, we compute the energy density  $\epsilon(\tau_0, \vec{x})$  and the flow velocity  $\vec{v}(\tau_0, \vec{x})$ .

Having fixed the initial conditions, the system evolves according to the equations of *ideal* hydrodynamics. Hadronization occurs finally based on the Cooper-Frye prescription. The centrality dependence of  $\frac{v_2}{\epsilon}$  of the EPOS calculation for AuAu at 200 AGeV is compared with the experimental results in fig. 2. We see an almost perfect agreement despite of the fact that EPOS uses ideal hydrodynamics. The centrality dependence is due to the core-corona effect in the initial configuration [17], which manifests itself also in other observables.

Recently we have developed a simple model [18, 19] to study the consequences of this core-corona effect and to interpret the very involved EPOS simulations. In this model we define corona particles as those nucleons which have only one initial collision whereas the others are considered as core particles.  $f_{core}$  is the fraction of core nucleons which depends on the centrality, the system size and (weakly) on the beam energy. This fraction is determined in the same Glauber model which is used to calculate the eccentricity  $\epsilon$  and the transverse area  $S$ . Core particles form a locally equilibrated source whereas corona nucleons are treated like elementary proton-proton collisions with no



**Figure 2.**  $v_2/\epsilon_{part}$  for AuAu collisions at  $\sqrt{s} = 200\text{GeV}$ , as predicted by EPOS, compared with data. The curves are the result of event - by event hydrodynamical calculations with a freeze out temperature of 166 MeV with (solid) and without (dashed) hadronic rescattering.

interactions with their environment. Of course this is a very crude model but it has the advantage that no free parameter is needed in this superposition of pp collisions and a thermalized source. The present experimental error bars do leave little room for an improvement as has been shown in [18, 19].

In this simple model we could show that, independent of the system size, the centrality dependence of the multiplicity  $M^i$  and of the  $\langle p_T^i \rangle$  of all identified hadrons from SPS to RHIC energies can quantitatively be described by

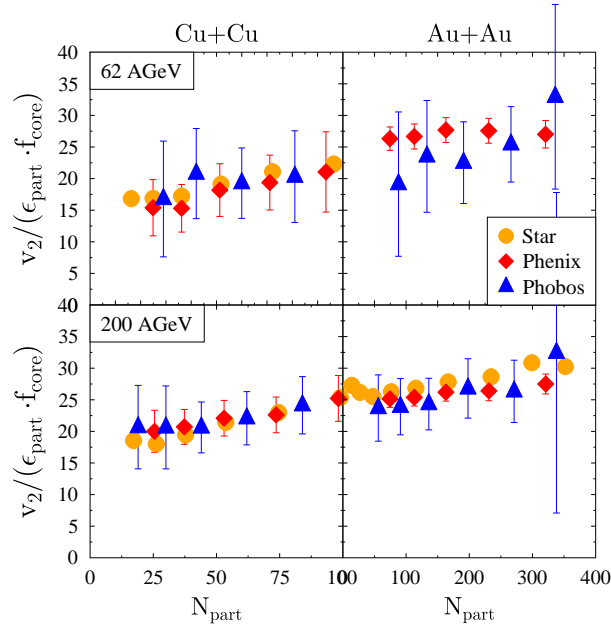
$$M^i(N_{part}) \quad (3)$$

$$= N_{part} [f_{core} \cdot M_{core}^i + (1 - f_{core}) \cdot M_{corona}^i]$$

$$\langle p_T^i \rangle (N_{part}) \quad (4)$$

$$= N_{part} [f_{core} \cdot \langle p_{T\ core}^i \rangle + (1 - f_{core}) \cdot \langle p_{T\ corona}^i \rangle].$$

For our calculation, we fix  $M_{core}$  ( $\langle p_{T\ core}^i \rangle$ ) by applying eq. 3 (4) to the most central AuAu or PbPb data point.  $M_{corona}$  and  $\langle p_{T\ corona}^i \rangle$  are given as half of the multiplicity and the  $\langle p_T^i \rangle$  measured in pp collisions. Once these parameters are fixed, the centrality dependence of  $M^i$  and  $\langle p_T^i \rangle$  is determined by eq. 3 and 4. Especially the centrality dependence of the observables for the lighter CuCu system follows then without any further input. Both, the core - corona model as well as the approach of Drescher et al. [1], assume that the system is not in the hydrodynamical limit, however



**Figure 3.**  $v_2/\epsilon_{part}(N_{part})/f_{core}(N_{part})$  as a function of  $N_{part}$  for the data at 62 (top) and 200 AGeV (bottom). The data are from refs. [7, 8] (Star), [6] (Phobos) and [20, 21] (Phenix).

the reason is different. In the approach of [1] it is assumed that all particles come to the same degree of thermalization independent of whether they are at the surface or in the interior of the interaction zone and that this thermalization is not complete. The degree of thermalization depends on the centrality. In the core - corona model the particles in the interior of the reaction zone have sufficient collisions to reach complete thermalization whereas those located at the surface do not come to equilibrium at all. They behave like being created in independent NN collisions. In this separation it follows the findings of the EPOS program. The centrality dependence is due to the centrality dependence of  $f_{core}$ .

In the core - corona model only the core particles feel the eccentricity of the overlap region. The particles produced by corona nucleons show an isotropic distribution in azimuthal direction. Therefore, in the core - corona model,  $v_2/\epsilon_{part}$  is expected to be  $\propto f_{core}$

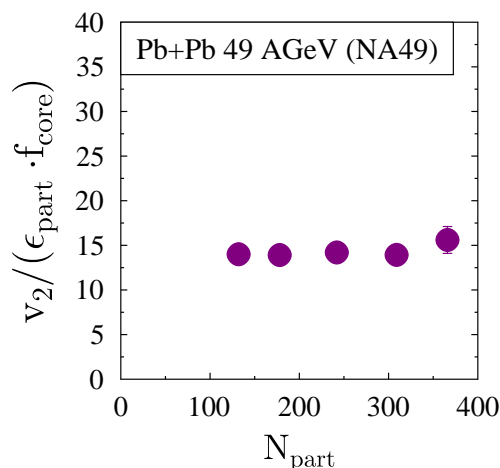
$$v_2/\epsilon_{part}(N_{part}) = f_{core}(N_{part}) \frac{v_2^{hydro}}{\epsilon}. \quad (5)$$

Because  $f_{core}(N_{part})$  and  $\epsilon_{part}$  is calculated in the Glauber model there is no free parameter. The core - corona model allows for some immediate predictions. Because  $f_{core}$  is similar in central CuCu and AuAu collisions (Fig. 3) we expect that central collisions of AuAu and CuCu show a similar  $v_2/\epsilon_{part}$  despite of the large difference of  $N_{part}$ . Therefore  $v_2/\epsilon_{part}$  plotted as a function of  $\frac{1}{S} \frac{dn}{dy}$  is in central CuCu data larger as

compared to AuAu data. In peripheral CuCu and AuAu collision  $v_2/\epsilon_{part}$  should be very similar for the same  $N_{part}$ . The easiest way to compare our results with experiments is to divide the experimental results by  $f_{core}(N_{part})$ . In this presentation we divided out the centrality dependence and therefore we expect that the data are horizontal straight lines.

In Fig. 3 all presently available experimental results are presented in that way. We see that in this presentation the 200 AGeV data of Phenix and Phobos, presented in the bottom part, follow a straight line. The Star data show a small slope. We should stress that for the peripheral CuCu data where the core contains about 15 nucleons we cannot expect that our assumptions are fully justified and one may doubt whether there the core forms really a fully thermalized source. Also the data at 62 AGeV, shown in the top panels, are compatible with our prediction that  $v_2^{hydro}/\epsilon_{part} = v_2/\epsilon_{part}(N_{part})/f_{core}$  is constant. However, whereas the Phobos data are compatible with the assumptions that  $v_2^{hydro}/\epsilon_{part}$  is the same for AuAu and CuCu, the Phenix data show a difference of 30% between CuCu and AuAu. This is not understood yet.

Our model can be extended to the lower SPS energies where  $v_2/\epsilon_{part}(N_{part})$  has been measured by the NA49 collaboration [22]. These results, show in fig. 4, are also compatible with a straight line.



**Figure 4.**  $v_2/\epsilon_{part}(N_{part})/f_{core}(N_{part})$  as a function of  $N_{part}$  for the NA49 data [22] at  $\sqrt{s} = 17.2 GeV$ .

In conclusions, we have shown that the experimentally observed centrality dependence of  $v_2/\epsilon_{part}(N_{part})$  is well described by the EPOS event generator using



*ideal* hydrodynamics. In contradistinction to other hydrodynamical calculations EPOS creates its initial condition which fluctuates from event by event. Only those regions of the interaction zone which have a density above a threshold density form a locally equilibrated source whereas the others are treated as independent NN collisions. The simple EPOS inspired core - corona model, which has successfully described the centrality dependence of the multiplicity and the average transverse momentum of identified particles, can also quantitatively explain the centrality dependence of  $v_2/\epsilon_{part}(N_{part})$ . Only core particles come to a local thermal equilibrium and develop a  $v_2$  whereas the corona particles decay isotropically. The fraction of both classes of particles depends on the centrality and the centrality dependence of the elliptic flow reflects directly this dependence. All parameters of this model are fixed either by other data or by geometry. This results questions the idea to use the centrality dependence to determine the viscosity of a quark gluon plasma.

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