Centrality dependence of strangeness enhancement in ultrarelativistic heavy ion collisions: A core-corona effect

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In ultrarelativistic heavy ion collisions, the multiplicity of multistrange baryons per participating nucleon increases with centrality in a different fashion for different systems and energies. At RHIC, for copper+copper (CuCu) collisions the increase is much steeper than for gold-gold (AuAu) collisions. We show that this system size dependence is due to a core-corona effect: the relative importance of the corona as compared to the core (thermalized matter) contribution varies and the contribution of a corona nucleon to the multiplicity differs from that of a core nucleon. ϕ mesons follow—as all hadrons—the same trend, but the difference between core and corona multiplicity is relatively small, and therefore the CuCu and AuAu results are quite similar. This simple geometrical explanation makes also a strong case in favor of the validity of Glauber geometry in the peripheral regions of ultrarelativistic heavy ion collisions, which is crucial for understanding the early evolution of the system.

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Even before the first relativistic heavy ion beam has been delivered, the enhancement of the production of strange particles has been considered as a possible signal for the existence of a plasma composed of quarks and gluons (QGP) [1]. This enhancement may occur if due to compression the chemical potential of the up and down quarks becomes so large that the system creates preferably strange quarks and antiquarks which materialize finally into strange hadrons. Since then strangeness enhancement is one of the hot topics in the analysis ultrarelativistic heavy ion collisions.

In the meantime heavy ion experiments have revealed that the multiplicity per participating nucleon of (multi)strange baryons is up to 20 times larger than that observed in pp collisions per participating proton at the same energy and that this enhancement is strongly centrality dependent [2]. The observed multiplicities in central collisions of heavy systems at RHIC and SPS energies can be well described assuming that the hadrons are in statistical equilibrium at a temperature close to the critical temperature predicted by lattice gauge calculations [3–6]. The chemical potential which is obtained by a fit to the data is small and therefore the relation to the originally predicted enhancement [1] is not evident.

Despite of many efforts, the centrality dependence of this experimentally observed enhancement has not yet found a generally accepted explanation. In (grand) canonical statistical models the enhancement for symmetric systems is not dependent on the centrality. It has been advocated that the increase with centrality may be due to finite size effects (canonical suppression), but this gives only a sizable effect for very small volumes [7]. To agree with data one needs to assume that the effective volume depends on the number of participants as $N_{\text{part}}^{1/3}$, which is in contradiction to the observation at lower beam energies and which has not found a physical explanation yet. It has also been shown that the centrality dependence can by parameterized as a sum of two terms, one proportional to the number of participants, N_{part}, the other proportional to the number of binary collision, N_{bin}, [8], however no physical interpretation of this dependence has been given.

Picking up an older idea [9] recently it has been proposed that the dependence of the multiplicity on the centrality has a geometrical origin [10]: In this model one distinguishes between a dense volume area, referred to as *core*, and a low density peripheral region, referred to as *corona*. Only the core participates in a collective expansion and produces particles in a statistical manner, whereas the corona region consists mainly of hadrons produced in nucleon-nucleon collisions. Employing this idea in the framework of one of the most advanced models for the simulation of heavy ion reaction, EPOS 1.9, it has been shown that the difference in the centrality dependence between AuAu at RHIC and PbPb at the SPS can be explained in a natural way with this core-corona hypothesis. Later the authors of Ref. [3] advanced a similar idea.

The parameters for this model have been determined to describe the AuAu data. Therefore, in order to validate this approach, data for other systems are necessary. The recent analysis of the RHIC CuCu data at the same beam energy provides such a data set: in the core-corona approach the particle multiplicities for different systems are determined by the relative size of the core and the corona. This is given by geometry. Therefore, the centrality dependence of the particle multiplicities for CuCu can be predicted without any new parameter.

The purpose of this article is twofold: (a) to demonstrate that these CuCu data are reproduced by EPOS 1.9 and (b) to show that the physics of the centrality dependence of the different (multi)strange hadrons in different systems can be understood in a simple model based on the geometrically determined relative size of corona and core.

Without any calculation some basic features of the CuCu data find their natural explanation in this core-corona approach. The observed identical enhancement (as compared to pp collisions) for central CuCu and AuAu collisions is due to

the fact that central collisions are to almost 100% core (and the cores in CuCu and AuAu behave identically at the same beam energy). Consequently, the slope of the enhancement as a function of N_{part} is larger in CuCu. With decreasing centrality the corona contributes more and more, up to $N_{\text{part}} = 2$ which is pure corona ($= pp$). In pp collisions the suppression (as compared to high energy e^+e^- strings) of strange baryons increases with the number of strange quarks which it contains [11]. Therefore the production of multistrange baryons is much more important in the core (thermal production) as compared to the corona (string decay). Dividing the central yield in heavy ion reactions by the yield in pp collisions the enhancement factor increases with the number of strange quarks contained in the baryon. This experimental observation has baptized strangeness enhancement although, physically speaking, it is due to a strangeness suppression in pp.

This picture also explains naturally why strangeness enhancement is more pronounced at SPS as compared to RHIC. There are two reasons: First, at lower energies the corona contribution relative to the core contribution is larger over the whole range of N_{part}. Second, as has already been discussed quite a while ago [11], the average string mass in pp collisions is rather small and even at $\sqrt{s} = 200A$ GeV more than 30% of the strings have an energy smaller than the threshold for Ω production. Therefore the multi(strange) baryon/pion ratio is suppressed as compared to a very energetic e^+e^- string, and this suppression increases with decreasing proton energy.

In order to understand the physics of the centrality dependence of the multiplicities we develop first a toy model, which reproduces nevertheless *quantitatively* the experimental results. Later will we employ the sophisticated three-dimensional implementation of the core-corona concept in the

EPOS model, which confirms the conclusion of this simple model.

In our toy model, we separate the wounded (or participating) nucleons, N_{part}, into two classes. Those which have only scattered once are considered as "corona participants," which hadronize as a string in pp collisions. The others form the fireball and the particle multiplicity is given by phase space. Defining $f(N_{\text{core}})$ to be the ratio of participating "core nucleons" to all participants, and assuming that the multiplicity per wounded core nucleon, M_{core}, and the one per wounded corona nucleon, M_{corona}, does neither depend on N_{part} nor on the system size, the centrality dependence of hadron multiplicities is given as

$$M^i(N_{\text{part}})$$
$$= N_{\text{part}} \left[f(N_{\text{core}}) \cdot M^i_{\text{core}} + (1 - f(N_{\text{core}})) \cdot M^i_{\text{corona}} \right], \quad (1)$$

where i refers to the hadron species. It is important to notice that for a given total number of wounded nucleons, f depends on the size of the interacting system. For RHIC experiments at $\sqrt{s} = 200$ and $62\,A$ GeV, $f(N_{\text{core}})$ has recently been published [12]. However, there the calculations are done for the center of the centrality bins, whereas here we use a Glauber model calculation which averages $f(N_{\text{core}})$ over the centrality bins. This gives different results in more peripheral reactions. M_{core} can either by taken from statistical model fits or can be directly determined from experiment. For our calculation, we fix M_{core} by applying Eq. (1) to the most central AuAu or PbPb data point, by replacing the left hand side of Eq. (1) by the experimental value. M_{corona} is given as half of the multiplicity measured in pp collisions. Once these parameters are fixed, the centrality dependence of M^i is determined

TABLE I. Corona, M_{corona}, and bulk, M_{core}, multiplicity per wounded nucleon as well as statistical model predictions [6] for M_{core}.

c.m. energy		M_{corona}	M_{core}	$M^{\text{stat}}_{\text{core}}$
200	Λ	0.0193 ± 0.0018	0.05	0.043
	$\bar{\Lambda}$	0.018 ± 0.0017	0.038	0.037
	Ξ	0.0013 ± 0.0005	0.0067	0.0052
	$\bar{\Xi}$	0.00145 ± 0.0005	0.0056	0.0046
	$\Omega + \bar{\Omega}$	0.00017 ± 0.0001	0.0016	0.0016
	ϕ	0.009 ± 0.0015	0.024	0.019
62	Λ	0.0112	0.047	0.04
	$\bar{\Lambda}$	0.00816	0.022	0.022
	Ξ	0.00088	0.0055	0.0044
	$\bar{\Xi}$	0.00074	0.0036	0.0030
	$\Omega + \bar{\Omega}$	0.0001	0.0012	0.00123
	ϕ	0.0065	0.024	0.014
NA49	Λ	as	0.033	
17.2	$\bar{\Lambda}$	for	0.00514	
	Ξ	NA 57	0.005	
NA57	Λ	0.0137 ± 0.0002	0.057	0.043
17.2	$\bar{\Lambda}$	0.0044 ± 0.00008	0.0073	0.0060
	Ξ	0.0006 ± 0.00004	0.00648	0.0036
	$\bar{\Xi}$	0.00027 ± 0.00004	0.00158	0.0010
	$\Omega + \bar{\Omega}$	0.000064 ± 0.000024	0.00125	0.00065

by Eq. (1). The centrality dependence of the lighter CuCu system especially follows then without any further input.

The values of M_{core} and M_{corona} as well as the thermal predictions [6] of M_{core}^{stat} are summarized in Table I. All multiplicities in this paper refer to $dn/dy|_{y=0}$. To determine M_{corona} we use the data of [13] for $\sqrt{s} = 200A$ GeV and EPOS 1.9 results for $\sqrt{s} = 62A$ GeV. M_{corona} is determined from pBe for the NA57 and the NA49 data. The experimental results can be found in [13–17] and are partially still preliminary. We include in our analysis the centrality dependence of the ϕ meson because in the past it has been argued that it reflects the increased production of s-quarks in a dense medium [18].

The results of our calculation Eq. (1) are displayed in Fig. 1 for reactions at $\sqrt{s} = 200A$ GeV, $\sqrt{s} = 62A$ GeV, and $\sqrt{s} = 17.2A$ GeV, respectively. We plot the so-called nuclear enhancement, i.e., the ratio of the multiplicity per participant to half the multiplicity in proton-proton scattering, as a function of N_{wound} [2] for different hadrons and different systems. It is evident that the simple toy model, i.e., Eq. (1), describes the experimentally observed centrality dependence for all three energies, for the strange baryons as well as for the ϕ. Of course the assumptions of an abrupt transition between string fragmentation and fireball formation is rather crude but the large experimental error-bars make it impossible to refine this model. At SPS energies data sets from two experiments, NA49 and NA57, are available. They do not agree. It is therefore useful to display calculations for both data sets. Our calculation reproduces the NA49 data but is for peripheral reactions less steep than the NA57 data set.

It is interesting to display the core corona effect in a different way. In Fig. 2 we display the multiplicity per participating nucleon of all observed hadrons in peripheral reactions normalized to the same multiplicity in the most central collisions as a function of $M_{corona}^i / M_{core}^i$. We see that all, nonstrange as well as strange, particles fall on the same curve. More precisely, both theory and experiment show exactly the same linear increase. This means that the enhancement of the multiplicity in central heavy ion collisions as compared to peripheral reactions is for all particles strongly correlated with the multiplicity difference in pp collisions as compared to what is expected in a purely thermal environment.

Let us now turn to a somewhat more sophisticated implementation of the core-corona picture in the framework of the EPOS approach [10]. EPOS is a parton model, so in case of a nucleus-nucleus collision, there are many binary interactions, each one represented by a parton ladder [19,20]. Such a ladder may be considered as a longitudinal color field, conveniently treated as a relativistic string. In case of proton-proton scattering, the strings decay via the production of quark-antiquark pairs, creating in this way string fragments—which are usually identified with hadrons. When it comes to heavy ion collisions, the procedure is modified: one considers the situation at an early proper time τ_0, long before the hadrons are formed: one distinguishes between string segments in dense areas (more than some critical density ρ_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. Compared to our toy model, here we perform a real three-dimensional core/corona separation: the core contribution will be more
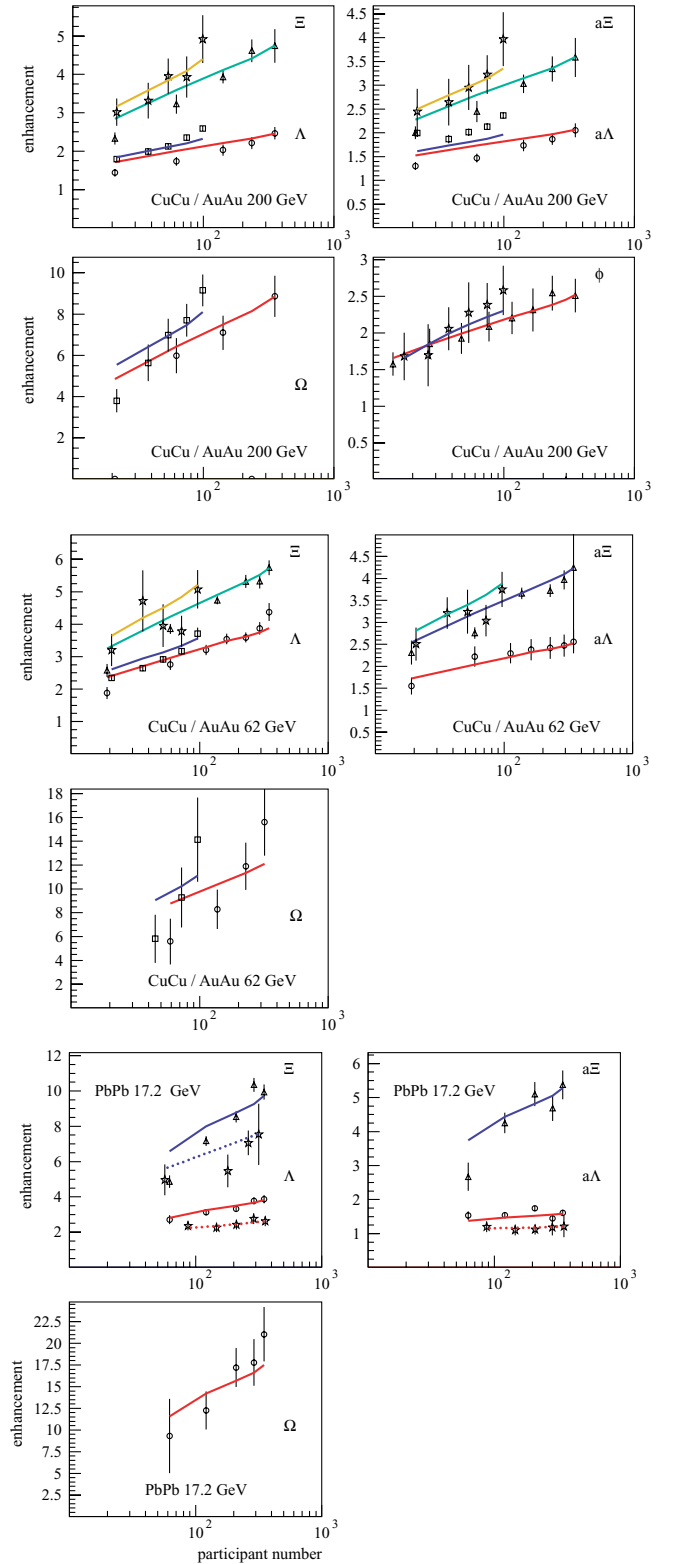

FIG. 1. (Color online) Enhancement of nuclear strange particle production for different energies/systems. We compare toy model predictions [lines (dashed lines for the NA49 results)] and data (points).

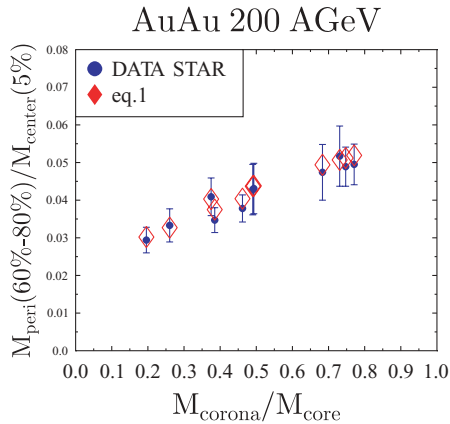important at central rapidities as compared to projectile and target rapidities.

FIG. 2. (Color online) Ratio of the peripheral and central multiplicity of all particles observed in 200A GeV AuAu reactions as a function of the ratio of the corona and the core multiplicity.

Whereas corona particle production is as in proton-proton scattering, the core part is assumed to be collectively expanding: Bjorken-like in longitudinal direction with in addition some transverse expansion. We assume particles to freeze-out at some given energy density ε_{FO}, having acquired at that moment a collective radial flow. The latter one is characterized by a linear radial rapidity profile from inside to outside with maximal radial rapidity y_{rad} (model parameter). Hadronization then occurs according to covariant microcanonical phase space. So the core definition and its hadronization are parametrized in terms of few global parameters, for details see [10].

In Fig. 3, we plot the nuclear enhancement obtained from EPOS 1.9. We observe, as already in the simple toy model, a steeper increase of multiplicities with centrality in case of CuCu compared to AuAu, due to a different N_{part} dependence of the relative core/corona weight in the two systems.

In conclusion, we have shown that the centrality dependence of strange hadron production can be well explained as a purely geometrical effect: the total volume is composed of a low density part—the corona, and a high density part—the core. Particle production in the corona is essentially string breaking as in pp collisions, whereas the core represents a fireball from which hadrons are produced according to phase space as in statistical models. This approach explains in a natural way the striking difference in the centrality dependence in CuCu compared to AuAu, being simply due to a different relative core/corona weight at a given N_{part} for the two systems.

The ϕ mesons fit perfectly into this picture, the difference with respect to other hadrons like Ω or Ξ is quantitative. The ratio of core to corona multiplicity is considerably bigger for the latter ones, therefore the enhancement increases faster with N_{part} than in case of ϕ. As a consequence, the ϕ enhancement for CuCu is close to the AuAu result.

We have demonstrated that a very simple core/corona toy model already explains the main features seen in the data. More sophisticated EPOS simulations confirm these finding.[1]

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[1]In this framework, adding a final state hadronic cascade, we find that the corona part actually survives the space time evolution.
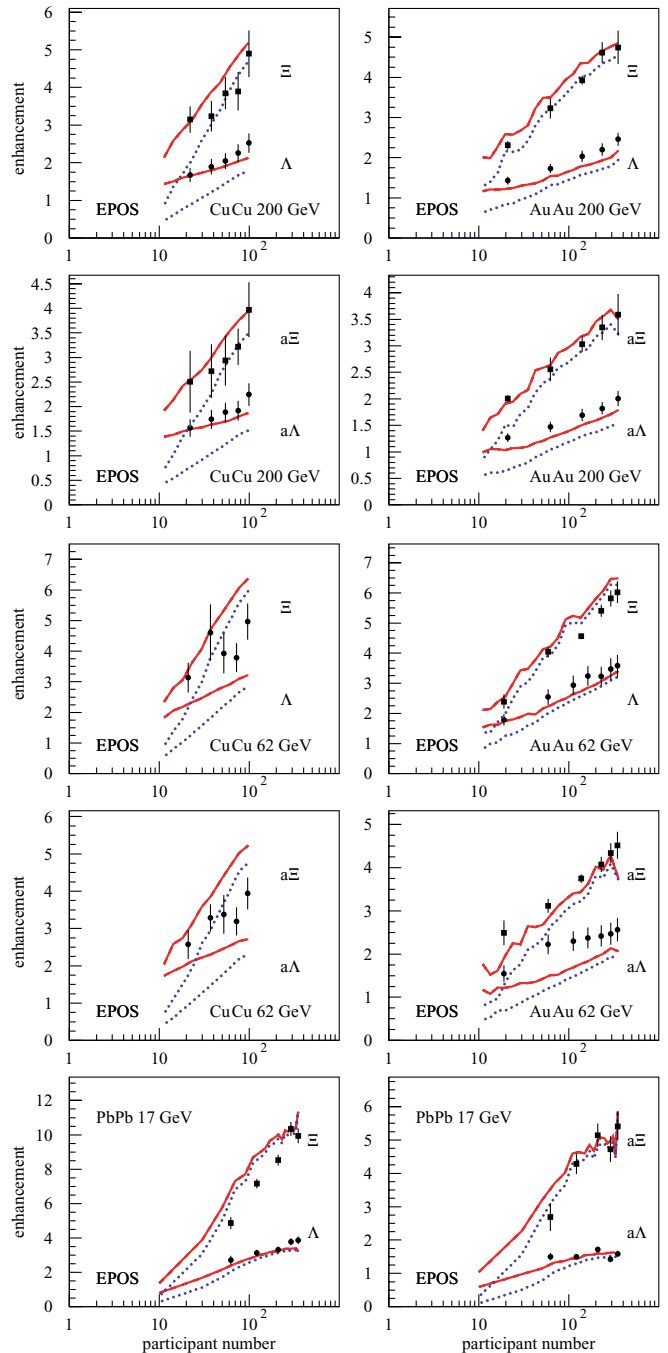

FIG. 3. (Color online) Enhancement of nuclear strange baryon production for different energies/systems. We show the full EPOS 1.9 results as well as the core contribution (dotted). Data are displayed as points.

It is a consequence of this observation that the production of strange baryons—as that of all other hadrons—follows very simple rules: after subtracting the corona part (whose importance depends on centrality/system size), all particles are created from some bulk matter whose properties are independent of the size of the system. It is actually remarkable that the core part is strictly determined by geometry and becomes therefore very small for the very peripheral reactions.

This continuity implies that the expected new state of matter would exists also in very small systems. Another important consequence of this observation is that the hadron yield of hadrons containing u, d, and s quarks only, is sensitive to the freeze-out of the matter. If one wants to have information on earlier stages other probes have to be used.

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