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INTEGRATED AZIMUTHAL CORRELATIONS IN NUCLEUS–NUCLEUS COLLISIONS AT CERN SPS*

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Azimuthal correlations of particles produced in nucleus–nucleus collisions at CERN SPS are discussed. The correlations quantified by the integral measure Φ are shown to be dominated by effects of collective flow.

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1. Introduction

There are various sources of azimuthal correlations of particles produced in relativistic heavy-ion collisions. One mentions here jets and minijets resulting from (semi-)hard parton–parton scattering and collective flow due to the cylindrically asymmetric pressure gradients, see the review articles [1] and [2], respectively. More exotic sources of correlations are also possible. As argued in [3], the plasma instabilities, which occur at an early stage of collisions, can generate the azimuthal fluctuations. Except the dynamically interesting mechanisms, there are also rather trivial effects caused by decays of hadronic resonances or by energy-momentum conservation.

Several methods have been developed to study fluctuations on event-by-event basis. In particular, the so-called measure Φ proposed in [4] was used to measure the transverse momentum [5,6] and electric charge fluctuations [7].

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The measure proved to be very sensitive to dynamical correlations and it was suggested to apply it to study azimuthal ones [8]. Such an analysis is underway using experimental data accumulated by the NA49 and NA61 collaborations and some preliminary results are already published [9].

The fact that the measure Φ is sensitive to correlations of various origin is advantage and disadvantage at the same time. A signal of correlations can be rather easily observed but it is difficult to disentangle different contributions. For this reason we studied in [10] how various sources of azimuthal correlations contribute to the measure Φ. We make use of the study [10] to interpret the preliminary experimental results [9]. We show that the observed integrated correlations are mostly generated by the collective flow.

2. Measure Φ

Let us first introduce the correlation measure Φ. One defines the variable $z \stackrel{\rm def}{=} x - \overline{x}$, where x is a single particle's characteristics such as the particle transverse momentum, electric charge or azimuthal angle. The overline denotes averaging over a single particle inclusive distribution. In the subsequent sections, x will be identified with the particle azimuthal angle ϕ and the fluctuation measure will be denoted as Φ_ϕ. The event variable Z, which is a multiparticle analog of z, is defined as $Z \stackrel{\rm def}{=} \sum_{i=1}^{N}(x_i - \overline{x})$, where the summation runs over particles from a given event. By construction, $\langle Z \rangle = 0$, where $\langle \ldots \rangle$ represents averaging over events (collisions). The measure Φ is finally defined as

$$\Phi \stackrel{\rm def}{=} \sqrt{\frac{\langle Z^2 \rangle}{\langle N \rangle}} - \sqrt{\overline{z^2}}\,. \tag{1}$$

It is evident that $\Phi = 0$, when no inter-particle correlations are present. The measure also possesses a less trivial property — it is *independent* of the distribution of the number of particle sources if the sources are identical and independent from each other. Thus, the measure Φ is 'blind' to the impact parameter variation as long as the 'physics' does not change with the collision centrality. In particular, Φ is independent of the impact parameter if the nucleus–nucleus collision is a simple superposition of nucleon–nucleon interactions.

3. Experimental data

As already mentioned, the NA49 Collaboration undertook an effort to study Φ_ϕ in nucleus–nucleus collisions at CERN SPS and some preliminary results are already published [9]. In Fig. 1 we show Φ_ϕ as a function of the number of wounded nucleons for positively and negatively charged particles

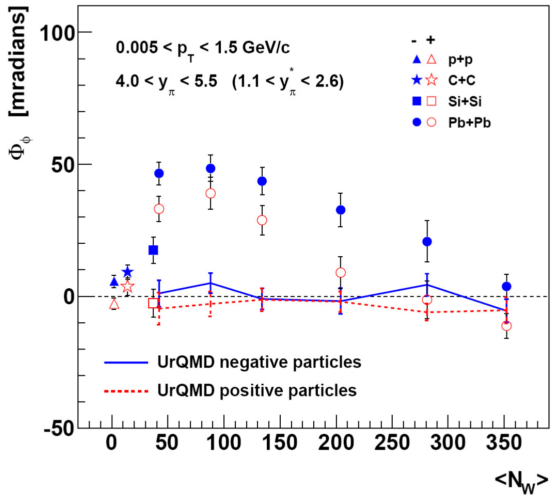

Fig. 1. Φ_ϕ as a function of the number of wounded nucleons for positively and negatively charged particles produced in various colliding systems: p+p, C+C, Si+Si and Pb+Pb at 158A GeV.

produced in various colliding systems (p+p, C+C, Si+Si and Pb+Pb) at 158 GeV per nucleon which is the top SPS energy. In the case of Pb+Pb collisions, a whole sample of events was split into six centrality classes. The measurement was performed in a rather limited domain of rapidity which in the laboratory frame is $4.0 \leq y_\pi \leq 5.5$. It corresponds to the center-of-mass rapidity interval $1.1 \leq y^*_\pi \leq 2.6$. To determine particle's rapidity the pion mass was assigned to all particles. The acceptance window in particle's transverse momentum was fairly broad ($0.005 \leq p_{\mathrm{T}} \leq 1.5$ GeV/c) but in azimuthal angle was incomplete, as in the NA49 measurement of transverse momentum fluctuations [5].

As seen in Fig. 1, significant positive values of Φ_ϕ are observed with a maximum at $\langle N_w \rangle \approx 50$ in Pb+Pb interactions. The correlations are very small for both the smallest and highest numbers of wounded nucleons. One also observes that Φ_ϕ is higher for negative particles than for positive ones.

Fig. 2 shows the energy dependence of Φ_ϕ for the 7.2% most central Pb+Pb interactions. The produced particles were registered in the fixed interval of center-of-mass rapidity $1.1 \leq y^*_\pi \leq 2.6$ and the acceptance was as in the NA49 measurement of collision energy dependence of transverse momentum fluctuations [6]. As seen, the values of Φ_ϕ for positive particles are consistent with zero but for negative particles Φ_ϕ is positive. No collision energy dependence of the correlations is observed.

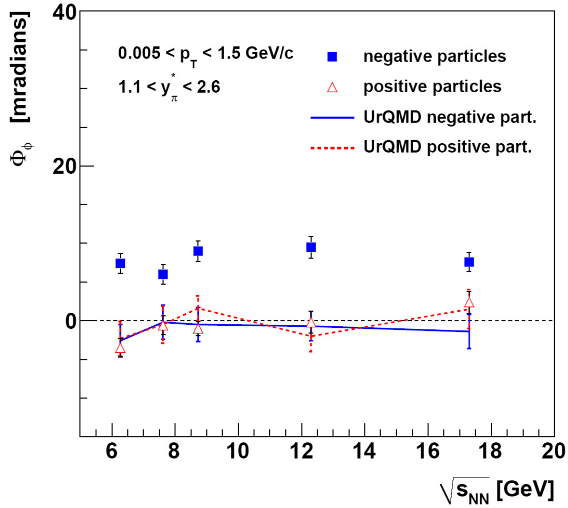

Fig. 2. Φ_ϕ as a function of the colliding center-of-mass energy of nucleon–nucleon system for positively and negatively charged particles produced in most central Pb+Pb collisions.

In Figs. 1 and 2 we also show predictions of the UrQMD model [11, 12]. Since an orientation of the reaction plane is fixed for all collisions in the model, it was randomly rotated to compare the model predictions with the experimental data. As seen in Figs. 1 and 2, the model provides vanishing values of Φ_ϕ within the experimental acceptance. Therefore, the mechanism responsible for the correlation signal is either missing or not strong enough in the UrQMD model.

4. Interpretation of experimental data

In our study [10] we considered separately the azimuthal correlations caused by the collective flow, resonance decays, jets and transverse momentum conservation. In contrast to all other mechanisms under study, which generate negative values of Φ_ϕ, the collective follow produces positive values. So, it is natural to expect that the correlations caused by the collective flow are responsible for the experimental signal seen in Figs. 1 and 2. The fact that Φ_ϕ almost vanishes for very central Pb+Pb collisions and p+p interactions suggests the same.

The collective flow quantified by the measure Φ_ϕ was studied in [8]. When the multiplicity distribution is Poissonian, which is true in narrow centrality classes, the measure was found to be

$$\Phi_\phi = \sqrt{\frac{\pi^2}{3} + \langle N \rangle S} - \frac{\pi}{\sqrt{3}}\,, \tag{2}$$

where

$$S \equiv 2 \left\langle \sum_{n=1}^{\infty} \left(\frac{v_n}{n}\right)^2 \right\rangle . \tag{3}$$

Thus, Φ_ϕ is fully determined by the average Fourier harmonics and average particle multiplicity.

Because of incomplete experimental acceptance in azimuthal angle, we used a simple Monte Carlo model instead of the formula (2) to check whether the collective flow is indeed responsible for the correlation signal seen in Fig. 1. Particle's number distribution was Poissonian with the average multiplicities of positively and negatively charged particles which were measured in a given acceptance window together with Φ_ϕ for every centrality. Negatively charged particles were all pions but among positively charged particles there was a 15% admixture of protons. The estimate was based on predictions of the UrQMD model within the NA49 acceptance. The azimuthal angle of each particle was generated from the distribution

$$P(\phi) \sim 1 + 2v_1\cos(\phi - \phi_{\mathrm{R}}) + 2v_2\cos\left(2(\phi - \phi_{\mathrm{R}})\right) , \tag{4}$$

where $0 \le \phi \le 2\pi$; the reaction plane angle ϕ_{R} of a given event was generated from the flat distribution. The Fourier harmonics v_1 and v_2 in the rapidity domain of interest in central, mid-central and peripheral Pb+Pb collisions at 158A GeV had been measured by the NA49 Collaboration [13].

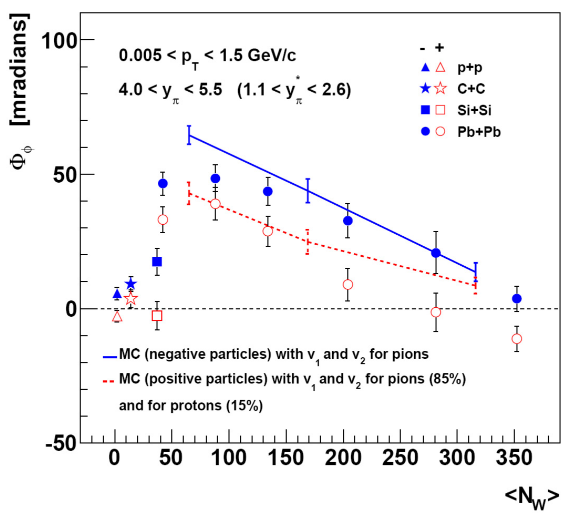

Fig. 3. Φ_ϕ as a function of the number of wounded nucleons for positively and negatively charged particles produced in various colliding systems: p+p, C+C, Si+Si and Pb+Pb at 158A GeV. The solid (dashed) line connects three points which represent the collective flow effect for negative (positive) particles.

The higher Fourier harmonics v_n with $n \geq 3$ were assumed to vanish. The predictions of our Monte Carlo model for central, mid-central and peripheral Pb+Pb collisions at 158A GeV are compared with the experimental data on Φ_ϕ in Fig. 3.

As seen, the model fairly well estimates the observed Φ_ϕ for both positively and negatively charged particles. The main contribution to Φ_ϕ comes from the directed flow represented by v_1. The difference of Φ_ϕ for positive and negative particles occurs because v_1 of protons is significantly smaller than that of pions [13].

5. Conclusions

The azimuthal correlations in nucleus–nucleus collisions at CERN SPS, which are quantified by the integral measure Φ_ϕ, are strongly dominated by the directed and elliptic flow generated in the collisions. In the forward rapidity window under study, the directed flow is more important than the elliptic one. The difference of Φ_ϕ for positive and for negative particles is caused by a 15% admixture of protons among positive particles.

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