Fluctuations of the azimuthal particle distribution in NA49 at the CERN SPS

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Abstract. Event-by-event fluctuations and correlations in azimuthal angle are currently widely investigated in various experiments. In this paper the Φ measure (earlier used in experiments to evaluate fluctuations in $p_T$) is now applied to azimuthal angle $φ$. Properties of this $Φ_φ$ function are investigated through fast generators and with complex models. Preliminary results of NA49 on $Φ_φ$ are also presented.

1. $Φ_φ$ measure

1.1. Motivation

The reasons to perform event-by-event azimuthal angle fluctuations were to investigate plasma instabilities [1], search for the Critical Point and Onset of Deconfinement, and measure fluctuations of elliptic flow [2, 3]. In this work the $Φ$ measure [4] is chosen as it is a strongly intensive measure of fluctuations (does not depend on volume and on volume fluctuations). The $Φ$ measure was already successfully used by NA49 to study average $p_T$ fluctuations [5, 6] and charge fluctuations [7]. There are several other effects that influence the values of this measure, such as resonance decays, momentum conservation, flow, and quantum statistics. The $Φ$ measure is not well suited to the analysis of these effects which represent a background for the present study.

1.2. $Φ_φ$ definition

Let $φ$ be a particle’s azimuthal production angle. One can define a single-particle variable $z_φ ≡ φ − 〈φ〉$, where $〈φ〉$ is an average over the single-particle inclusive azimuthal angle distribution. Let us also define an event variable $Z_φ ≡ \sum_{i=1}^{N_s}(φ_i − 〈φ〉)$, where the summation runs over particles in a given event. Then the $Φ_φ$ measure is defined as: $Φ_φ ≡ \sqrt{\langle Z_φ^2 \rangle/N_s} − \sqrt{z_φ^2}$, where $\langle \ldots \rangle$ represents averaging over events. When particles are emitted by a number ($N_s$) of identical sources, which are independent of each other and $P(N_s)$ is the distribution of this number, then $Φ_φ(N_s)$ is independent of ($N_s$) (an intensive measure) and its distribution $P(N_s)$ (a strongly intensive measure). Additionally, if particles are produced independently (no inter-particle correlations), $Φ_φ$ equals zero.

1 for complete NA49 author list see http://na49info.web.cern.ch/na49info/na49/Collaboration/authors.html
2. Model studies

General properties of the $\Phi_\phi$ measure were already studied using analytical calculations [8]. Fluctuations due to elliptic flow, quantum statistics and resonance decays in the hadron gas were evaluated. In this paper we present model studies that were conducted to investigate in detail the behavior of $\Phi_\phi$. Several toy models were employed to test separately the influence of various physics effects. Full event generators such as UrQMD [9], Pythia [10], and Hijing [11] were used as a direct reference to experimental results².

2.1. Toy models of elliptic flow and momentum conservation

To simulate elliptic flow events were generated with azimuthal angle distribution of particles following $\rho(\phi) = 1 + 2v_2 \cos(2(\phi - \phi_R))$. For each event the reaction plane angle $\phi_R$ was generated from a flat distribution in azimuthal angle, and the multiplicity $N$ of particles in an event was taken from a Negative Binomial distribution with given $\langle N \rangle$ and dispersion $D_N \approx 0.5 \cdot \langle N \rangle$.

The value of $v_2$ was a simulation parameter, constant for each simulation series (Fig. 1) or varying from event to event according to a Gaussian distribution with $\sigma_{v_2}$ (Fig. 2). The elliptic flow effect results in positive $\Phi_\phi$ values which are increasing with increasing $v_2$. Moreover, event-by-event fluctuations in $v_2$ cause an additional increase of $\Phi_\phi$ values.

![Figure 1. $\Phi_\phi$ as a function of $v_2$ for elliptic flow simulation with constant $v_2$. Lines correspond to analytical formulas from [8].](image1)

![Figure 2. Difference between $\Phi_\phi$ values for constant and fluctuating $v_2$ as a function of relative size of $v_2$ fluctuations.](image2)

To simulate global momentum conservation, each particle had its transverse momentum $p_T$ drawn from the distribution $P(p_T) \sim p_T e^{-p_T/T}$, where $T = 200$ MeV, and its azimuthal angle from a flat distribution. Afterwards, for every particle $p_x$ and $p_y$ was modified: $p'_x = p_x - \frac{\sum_{N_i=1}^{N} p_{x_i}}{N}$, and $p'_y = p_y - \frac{\sum_{N_i=1}^{N} p_{y_i}}{N}$ to obey momentum conservation in the whole event ($N$ is the event multiplicity generated from a Negative Binomial distribution). The simulation results in negative $\Phi_\phi$ values (anti-correlation) which weakly depend on multiplicity (increase from about -370 miliradians for $\langle N \rangle = 10$ to around -300 miliradians for $\langle N \rangle = 1000$).

2.2. UrQMD – a full event generator

A simulation using UrQMD 3.3 was performed for p+p collisions in a wide energy range (SPS, RHIC, LHC) (Fig. 3). Default parameters of the generator were used, which for this version means simulation of hard processes (for energies $\sqrt{s} > 10$ GeV), but no hydrodynamics stage.

² see conference slides (http://hq2010.bnl.gov) for Pythia and Hijing results
For all energies and charge combinations $\Phi$ values are negative (domination of anti-correlations). Their magnitude increases for negatives and decreases for positives and all charged. At LHC energies the values become charge independent.

3. NA49 experiment
The NA49 experiment [12] at the CERN SPS registered data on p+p, C+C, Si+Si, and Pb+Pb interactions at a center of mass energy of 6.3 - 17.3 GeV per N+N pair. This fixed target hadron spectrometer (four TPCs, two of them, VTPC-1 and VTPC-2, inside a magnetic field) allowed for a precise determination of the collision centrality by measuring energy of projectile spectators (VCAL).

3.1. Detector
The NA49 detector has a limited azimuthal angle acceptance; the acceptance losses are concentrated mainly around the up-down regions. Due to the magnetic field in VTPC-1/2 particles of opposite charge are almost completely separated in the MTPCs (Fig. 4); the MTPCs cover mainly the forward rapidity region. As the detector is left-right symmetric, acceptance for positively and negatively charged particles is the same, provided the azimuthal angle for one charge is reflected. To allow a quantitative comparison of $\Phi$ for positively and negatively charged particles we rotate particles of one charge (Fig. 5).

Figure 4. Tracks registered in NA49; four TPCs with marked regions where particles of given charge are dominant. VCAL (see the text) was located behind MTPCs.

Figure 5. Examples of $\phi$ distributions at forward rapidity for positively and negatively charged particles before (upper plots) and after (lower plots) the shift.

3.2. Preliminary results
Figure 6 shows the energy dependence of $\Phi$ for the 7.2% most central Pb+Pb interactions. There is no significant energy dependence, however negatively charged particles show positive $\Phi$ values. The results from UrQMD, obtained with the same kinematic restrictions, show values consistent with zero. In the simulation the limited NA49 acceptance causes a major reduction in the absolute values of the $\Phi$ measure (for details see conference slides and Fig. 3, showing UrQMD results for p+p data, where the complete rapidity and azimuthal angle range was used). The main effect is due to the rapidity cut. For the SPS energy range, $\Phi$ values
for a complete rapidity range are around -150 miliradians for positively charged and around -80 miliradians for negatively charged. The rapidity cut brings them to around -20 miliradians and -10 miliradians, respectively. The additional azimuthal angle restriction results in a $\Phi$ value consistent with zero. Figure 7 presents the system size dependence of $\Phi$ at 158A GeV (top SPS energy). Significant positive values of $\Phi$ are observed with a maximum for peripheral Pb+Pb interactions. This result is qualitatively similar to the results of multiplicity [13] and average $p_T$ [5] fluctuations in NA49. Further studies are planned to understand these intriguing effects.

4. Summary
Event-by-event azimuthal fluctuations were analyzed using the $\Phi$ measure, for models and for NA49 data. The properties of $\Phi$ were studied using toy models and UrQMD. Elliptic flow results in positive values of $\Phi$ which increase with the magnitude of flow and are sensitive to its fluctuations. Contrary to flow, momentum conservation produces negative $\Phi$ values. The UrQMD model shows negative $\Phi$ values with a weak energy dependence. The NA49 measurements for central Pb+Pb collisions showed weak energy dependence and positive $\Phi$ values for negatively charged particles. On the other hand, a significant system size dependence is observed at the highest SPS energy. This result is qualitatively similar to the behavior found for multiplicity [13] and transverse momentum [5] fluctuations.

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