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**The nonstatistical fluctuations and low p_T phenomena caused by
Bose-Einstein correlations**

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Abstract

For a study of the influence of known quantum mechanical effects on the intermittency patterns observed in nucleus-nucleus collisions, the Fritiof Monte Carlo program has been modified. Bose-Einstein (BE) correlations were introduced as a final state interaction between two particles. For a realistic strength of the BE effect as measured in heavy ion collisions, a good description of the bin size dependence of the normalized factorial moments in the distributions of secondary particles in OAu NA35 data is observed. The p_t dependence of the normalized factorial moments, and the low p_t enhancement in the single particle p_t spectra, caused by BE correlation are discussed.

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In the past few years there was much interest in the study of particle density fluctuations in small phase space bins in high energy collisions. By analysing the normalized factorial moments F_i ($i = 2, 3, \dots$), as proposed by Bialas and Peschanski (1), it is possible to separate statistical from dynamical fluctuations in the distributions of the secondary particles, produced in high energy interactions. It was shown that self-similar fluctuations of many different phase space bins lead to a characteristic power law dependence of the factorial moments on the bin size : $F_i = a_i \cdot M^{\phi_i}$. Such a dependence, called intermittency, is now claimed in all studied types of interactions, such as e^+e^- , $h-h$, $h-A$, and $A-A$ interactions (for recent reviews see (2)). Though recent investigations (3) of charged particle multiplicity distributions in e^+e^- annihilation show that the bin size dependence of their moments is well described by standard Monte Carlo models, the theoretical and experimental situation in all other reaction types is less clear (2). This suggests further experimental and theoretical investigations, to answer the question whether we face new physics (e.g. quark gluon plasma?), or some known effects have not yet been implemented in the presently used models. Apart from the unexplained size of the intermittency exponents ϕ_i we mention their p_t dependence observed by the EHS/NA22 collaboration (4) (we will discuss this later), and the strong dependence of ϕ_i on dN/dy in the UA1 data (5). The latter effect was explained by the assumption that events with high multiplicity are simply a superposition of several independent particle sources (6). Thereby a decrease of the intermittency strength with increasing multiplicity is expected. $(\phi_i (dN/dy) \sim (dN/dy)^{-1}$. Contrary to the UA1 data which follow such a law quite closely, the nucleus-nucleus data strongly deviate from this rule (2). For example the ϕ_2 and ϕ_3 values observed by KLM and EMU-01 (7) are about ten times higher than the values expected from an extrapolation of $h-h$ data a feature that may be interpreted as an indication for collective effects in particle production from collisions of heavy nuclei. At the same time the intermittency exponents ϕ_2 and ϕ_3 determined from the KLM and EMU01 data decrease with increasing multiplicity when target and projectile are fixed. In the explanation of the experimentally observed results for $A-A$ collisions some collective effects seem to be required and Bose-Einstein (BE) correlations are an obvious candidate (8-10).

In this letter we present a modification of the Fritiof 1.6 code (11) for nucleus-nucleus collisions, and discuss the effects of the inclusion of the BE correlation in the model. The BE correlations have been introduced into the Fritiof Monte Carlo program in a similar manner as in Jetset 7.2 (12). The particle production in the basic

event takes place without any regard to the BE effect, and only afterwards nearby identical particles are shifted towards smaller Q -invariant by final state interactions, in such a way as to reproduce the parametrized two-particle enhancement of the four momentum difference of the pairs. (The two particle correlation function was parametrized by the Gaussian form $C_2(Q) = 1 + \lambda \cdot \exp(-Q^2 \cdot R^2)$, where λ and R are the parameters). In the calculation it is assumed that for the $Q \leq Q_C = 300$ (MeV/c) the number of pairs N_p , in the absence of the final state interaction, is proportional to the phase space volume. Under this assumption the distribution dN_p/dQ is approximated by $f(Q) = Q/(Q^2 + 4m^2)^{1/2}$ (Note that $Q = 2p^*$ in the center of mass of two particles (equal masses) m with momenta p^*). To conserve the number of the particles, for a given Q^{old} of the pair, the new value Q^{new} is calculated solving the equation :

$$\int_0^{Q^{\text{old}}} f(Q) dQ = \int_0^{Q^{\text{new}}} f(Q) C_2(Q) dQ \quad (1)$$

from $\delta(Q) = Q^{\text{old}} - Q^{\text{new}}$ we calculate the new momentum, i. e. the corresponding momentum shift $\delta \vec{p}_{ij}$ of particle i due to presence of particle j . For the region where the BE effect is negligible ($Q > Q_C$) the four momentum shift $\delta(Q)$ is calculated from the values $\delta(Q_C)$ using the formula $\delta(Q) \cdot f(Q) = \delta(Q_C) f(Q_C)$. The calculation was done for all the possible pairs, meaning that for an event with N like-sign particles, the final momentum of particle i will be

$$\vec{p}_i^{\text{new}} = \vec{p}_i^{\text{old}} + \sum_{i \neq j=1}^N \delta \vec{p}_{ij} \quad (i = 1, N). \quad (2)$$

It should be emphasized that the parametrization by $C_2(Q)$ gives only the relative enhancement of the pairs in the region of small Q , while their absolute number is controlled by the original phase space density.

Figure 1 shows the correlation functions $C_2(Q)$ of negative pions for central OAu collision events at 200 GeV/n from the Fritiof model without BE effect (dots), and with BE effect (open circles) in the phase space region defined by $0 < \phi < 2\pi$, $0 < p_t < 2.0$ (GeV/c), $1 < y < 3$. The enhancement at low values of Q is simulated not by weighting factors, but as explained above by shifting nearby identical particles towards smaller Q . This fact allows us to calculate normalized factorial moments F_i

for the Fritiof +BE model by the same method as for the experimental data. In fig.2 we present normalized factorial moments $F_i(M)$ ($i = 2, 3, 4, 5$), versus the number M of the three dimensional phase space subdivisions in central OAu collisions at 200 GeV/n from the Fritiof + BE model (dashed curves), together with NA35 experimental results (13). The model calculations are performed in the same acceptance region and for the same number of events as in experimental data, since it was observed that the slope of the normalized factorial moments depends somewhat on the number of events used in analysis. The model results of the third to fifth moment are normalized to the NA35 experimental data at $M = 1$. (The normalization constants are $C_2 = 1.$, $C_3 = 1.04$, $C_4 = 1.08$, $C_5 = 1.13$ for the second (F_2) to the fifth (F_5) moment respectively). Knowing that the Fritiof model without BE effect does not give any rise of the normalized factorial moments F_i as a function of M (13), the results presented in fig.2 confirm the earlier conclusions (8-10) that BE interference naturally leads to enhanced fluctuations of the multiplicity in narrow regions of momentum space. As it can be seen from fig.2 the model describes relatively well the experimental results. It should be stressed that such an agreement is achieved by putting in the model BE correlations with a strength as shown in fig.1. The largest deviation from the experimental data is for the last two points in F_2 , where the model significantly underestimates the experimental results. It should be emphasized that the rise of the moments in the region of very small phase space cells is mainly determined by pairs with a very small Q (≤ 10 MeV/c). If such a "peak" is present in the NA35 data this could explain this deviation, and at the same time it would be an indication of the presence of other sources responsible for such an excess (particles from resonance decay, which are not handled in a proper way, because the complete space-time correlation is not treated in the model), or it may be of experimental nature (for example double measurements). Another possible explanation is that the Fritiof model simply underestimates the two particle phase space density, which controls the absolute number of pairs in this region. We would like to stress here, that the rise of the factorial moments as a function of M is generally, in the whole region of interest, correlated to the excess of pairs e.g. to the strength of the BE effect, under the assumption that the original phase space density (in the absence of any state interaction) is the same for different $C_2(Q)$. Indeed calculations done for a broader $C_2(Q)$ distribution, with approximately the same lambda λ , (which is usually interpreted as a smaller source "radius") show a stronger effect in F_i . This, at least qualitatively, can explain the decrease of the intermittency exponents ϕ_i with increased centrality of the ion reactions (2), since with increasing

centrality we expect a larger source "radius", e.g. a narrower distribution in $C_2(Q)$. As it can be seen from fig.2 the data and model predictions for the F-moments are not consistent with a power law behaviour. Figure 3 shows the second factorial cumulant moment $K_2(M)$, which filters out two particle correlations (14), for the NA35 OAu data (full dots, ref. 13) and the model (open dots). For both, the data and the model the K_2 moments are more consistent with a power law behaviour than the F_2 moments.

The model also has consequences for the p_t dependence of the factorial moments. As an example, the model predictions for the second and third moments for different p_t cuts are shown in fig.4. It is clearly seen that for particles with $p_t < 0.3(\text{GeV}/c)$ an increase of the factorial moments is observed relative to the full sample ($0 < p_t < 2.(\text{GeV}/c)$), while a decrease is observed for the particles with $p_t > 0.3(\text{GeV}/c)$. This behaviour follows naturally from our model. Namely for low p_t particles the probability to be member of a low Q pair is larger than for high p_t particles. Indeed the single particle p_t spectrum from the pairs with $Q < 100(\text{MeV}/c)$ is narrower and has a smaller mean p_t than the single particle p_t spectrum for the full Q phase space. Hence, restricting the analysis to low p_t particles, we are in the kinematical region where the bulk of the pairs carrying the BE correlations is located. As already mentioned, a p_t dependence of the factorial moments has been observed by the EHS/NA22 collaboration analysing charged particles from π^+p and K^+p collisions at $250(\text{GeV}/c)$ (4). They concluded that intermittency observed in their data is due to low transverse momentum particles, rather than to semi-hard effects.

From the above arguments one also expects that an enhancement in the p_t spectra at low p_t values should be observed for the Monte Carlo events where BE correlations are included compared to those without BE correlations. Figure 5a show for OAu collisions the negative pion spectra $1/p_t \cdot dN/dp_t$ from the Fritiof model with (solid line) and without (dashed line) BE correlations. In fig. 5b the ratio $R(p_t)$ of the p_t distributions of negative pions for those two models is given. A low p_t enhancement in the spectrum including the BE effect becomes apparent. In experimental analyses of high multiplicity pp, p-nucleus and nucleus-nucleus reactions such low- p_t enhancements have been observed (for a recent review see (15)). Clearly BE correlations should therefore be included in models used to describe those data.

In summary, dynamical fluctuations in the distributions of secondary particles, produced in heavy-ion collision at CERN energies, have been discussed. The BE

correlations have been simulated in the Fritiof Monte Carlo program by modifying the momenta of the final state particles. It was shown that for a given strength of the BE effect (see fig.1) we can relatively well describe the bin size dependence of the normalized factorial moments observed by the NA35 collaboration in OAu reactions. This is a strong indication that BE correlations are, in the case of heavy-ion collisions, an important source of short range nonstatistical fluctuations in the distributions of secondary particles. It was also shown that the inclusion of BE correlations predicts a p_t dependence of the normalized factorial moments, as already observed in h-h data (EHS/NA22 collaboration). The low p_t enhancement in the single particle p_t spectra caused by BE correlations is discussed in a qualitative way. We believe that the BE effect as a source of experimentally observed nonstatistical fluctuations in distributions of secondary particles is present in all reaction types from e^+e^- to A-A. It was pointed out (3) that in the case of e^+e^- other mechanisms are dominant (gluon radiation is the most important). Since in h-h collisions we expect some kind of superposition of such or similar effects (for example the effects in connection with hadronization schemes), a weakening of the "intermittency" effect with increasing number of "sources" is predicted (6). An experimental confirmation was given by the UA1 collaboration (5) for $p\bar{p}$ collisions. Because of the large number of colliding nucleons such effect will play an even smaller role in A-A collisions. Therefore the "collective" effects, as a source of nonstatistical fluctuations, will be much more pronounced.

In order to improve the quantitative predictions of the model Coulomb final state interactions will be included and the parametrisation of the BE correlations may need modification according to a more detailed comparison with experimental data.

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Figure captions :

- Fig. 1. The correlation functions $C_2(Q)$ of negative pions for central OAu collision events at 200 GeV/n from the Fritiof models without Bose-Einstein (BE) effect (dots), and with BE effect (open circles).
- Fig. 2 The three dimensional normalized factorial moments $F_i(M)$ ($i = 1, 5$) as a function of the number of phase space subdivisions M ($M = M_y \cdot M_{p_t} \cdot M_\phi = \Delta y/\delta y \cdot \Delta p_t/\delta p_t \cdot \Delta \phi/\delta \phi$) in central OAu collisions at 200 GeV/n for NA35 data (13) ($i = 2$ ($\circ$), $i = 3$ ($\bullet$), $i = 4$ (Δ), $i = 5$ ($\blacktriangle$)) together with the predictions of the Fritiof model with BE correlations (dashed curves).
- Fig. 3 The NA35 data (13) on the second cumulant moment $K_2(M)$ (points), and the model predictions (open circles).
- Fig. 4 The model predictions for the second and third factorial moment for different p_t cuts. ($0 < p_t < 0.3$ (GeV/c) (Δ), $0.3 < p_t < 2$ (GeV/c) ($\circ$), $0 < p_t < 2$ (GeV/c) ($\bullet$)).
- Fig. 5 a) The negative pion p_t spectra from the Fritiof model without (dashed curve), and with (full line) BE correlations.
b) The ratio $R(p_t)$ of the single particle p_t spectra for those two models.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5