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FOR CENTRAL ULTRA-RELATIVISTIC HEAVY-ION INTERACTIONS

WA80 - collaboration

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**Global and Local Fluctuations in Multiplicity and Transverse Energy
for Central Ultra-Relativistic Heavy-Ion Interactions**

WA80 - collaboration

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Abstract

We present results from a comparison between experimental data and model calculations, in this case represented by the Fritiof model, regarding global and local fluctuations in the distributions of transverse energy and charged particle multiplicity. The results indicate that the observed fluctuations originate predominantly from the distribution of sources, i.e. either the number of participating nucleons or the number of binary collisions. The apparently larger widths of the distributions observed in restricted regions of phase space, are explained to be of purely statistical nature. As a result of the analysis the cross section for events with energy densities much larger than the typical value for a central collision is limited. The results of the analysis are essentially independent of whether intermittence is of importance in the reactions or not. The very small scales, normally associated with studies of intermittent behaviour, are not within the scope of this paper.

Recent experimental results from the oxygen and sulphur runs at the CERN SPS have suggested that central collisions have multiplicity, n_{ch} , and transverse energy, E_T , distributions of Gaussian shape¹⁻³. The widths of the distributions are believed to contain information about the reaction mechanism as well as the nuclear geometry⁴. Baym et al³ discuss the widths of E_T -distributions and find that the widths are larger than can be accounted for by a superposition of independent binary collisions, i.e. they have to introduce coherence in order to explain the experimental widths.

When new phenomena, like the creation of a quark-gluon plasma are considered, it is extremely important to understand the behaviour of the tails of the distributions, since these can be strongly influenced by the existence of the plasma. This paper is an effort to clarify how the features of the distributions can be understood, exemplified within the framework of one specific model. We have here concentrated on the second moments of the distributions and studied how different contributions add up to the observed widths.

In ref 3, the total variance of the distribution of any observable has been shown to be a sum of four terms. The formula can be written

$$V(X) = \langle X^2 \rangle - \langle X \rangle^2 = \sum_{n=1}^{n_{\max}} P(n) \cdot \left\{ \sum_{i=1}^n (\langle X_i^2 \rangle - \langle X_i \rangle^2) + (n^2 - \langle n \rangle^2) \cdot x_0^2 + \right. \\ \left. + \left(\sum_{i=1}^n (\langle X_i \rangle - x_0) \right)^2 + 2 \cdot x_0 \cdot (n - \langle n \rangle) \cdot \sum_{i=1}^n (\langle X_i \rangle - x_0) \right\}, \quad (1)$$

where X is n_{ch} or E_T . X_i is the contribution to X from the i^{th} source. With $x_i \equiv \langle X_i \rangle$, one can express $x_0 = \langle X \rangle / \langle n \rangle$ as

$$x_0 = \langle n \rangle^{-1} \cdot \sum_{n=1}^{n_{\max}} P(n) \cdot \sum_{i=1}^n x_i. \quad (2)$$

$P(n)$ is the probability of having n sources.

The sources can be taken as the binary collisions between nucleons from the two nuclei, as in ref 3, but could equally well be taken as the wounded or participating nucleons.

Each of the terms in eq (1) can be given a physical interpretation in a picture where a nucleus-nucleus interaction is thought of as a sum of the contributions from many sources created in an early stage of the interaction.

Term 1) The fluctuations in each of the sources.

If all sources are numbered in the order they are created, the contribution from the n^{th} source in an interaction will fluctuate around the average obtained for the n^{th} source in all the observed interactions.

Term 2) The fluctuation in the number of sources.

If interactions at different impact parameters are studied the number of sources can have large fluctuations. Even if the impact parameter window is narrowed, density variations within the nuclei will still make this term non-zero.

Term 3) The fluctuations emerging from differences in the sources due to e g energy degradation, i e differences between $\langle X_i \rangle$ and $\langle X_j \rangle$, $i \neq j$.

Generally if there are many sources in an interaction their importance will gradually decrease as a function of their creation number (see term 1).

Term 4) A damping due to an anticorrelation between term 2 and term 3.

If an interaction has a large number of sources the importance of each source will generally decrease, and vice versa.

In the derivation of the formula it is assumed that the different sources are independent of each other, i e $\langle X_i X_j \rangle = \langle X_i \rangle \cdot \langle X_j \rangle$, $i \neq j$. Generally there will be an anticorrelation between different sources. If the contribution from an early source is exceptionally large the contributions from the following sources will tend to be smaller since the amount of available energy is less than the average.

In this paper we will investigate the multiplicity and transverse energy distributions for central oxygen-gold interactions, obtained with the WA80 setup⁵. The centrality is determined event-by-event from the forward energy flux measured by the Zero Degree Calorimeter, ZDC. Utilizing the Monte-Carlo code

Fritiof (version 1.7)⁶, the terms in eq (1) are estimated in order to trace the origin of the fluctuations.

It is important to have a good trigger criterion for central events, which does not directly influence the distribution under investigation. Thus triggers like a high- E_T trigger or a high multiplicity trigger are not suitable for the purpose. The E_{ZDC} -trigger in the WA80-experiment is, however, ideal for the task.

In fig 1 we show, for different cuts in E_{ZDC} , the n_{ch} and E_T distributions for oxygen induced interactions at 200 A GeV^{7,8}. The local pseudo-rapidity interval $2.5 < \eta < 3.5$ has been chosen, i.e. a region where both multiplicity and energy measurements have good resolution. The region is furthermore symmetric around the nucleon-nucleon center of mass. The curves in the figure show Gaussian fits for the different cases. The average values and the widths of the distributions are rather insensitive to the centrality for $E_{ZDC} \lesssim 500$ GeV.

In order to investigate the importance of the chosen η -range the normalized variance $\Omega(X) = V(X)/\langle X \rangle^2$ is studied as a function of η and $\Delta\eta$ for the case $X = n_{ch}$. A purely statistical consideration, assuming that a particle produced by a given source has a fixed probability to fall inside the observed region (see Appendix I), leads to

$$\Omega(\eta, \Delta\eta) = (\Delta\eta \cdot \langle \rho(\eta) \rangle)^{-1} = \text{const.} \quad (3)$$

where $\Delta\eta$ is a region around η with $\langle \rho \rangle = dX/d\eta$.

In fig 2a we show Ω , for the n_{ch} distribution, as a function of $\Delta\eta$ for bins centered around $\eta = 3.0$. The data have been compared to the calculations from eq (3), normalized to the data at $\Delta\eta = 1$. In these calculations the detector inefficiency was taken into account. The data and the calculation agree well except for the smallest values of $\Delta\eta$. A similar trend is seen in fig 2b where the same is exhibited for Fritiof. The excess for small $\Delta\eta$ -bins is mainly due to two-particle correlations and a possible intermittent behaviour. Several methods⁹ are devised to deal with these non-statistical effects. The Fritiof model does neither include all final state interactions nor any non-statistical effects, which might explain the larger deviation in fig 2a for small rapidity windows. In fig 3a we show Ω as a function of η for a fixed $\Delta\eta$ -value of 0.1. Eq (3) is normalized at $\eta = 3.05$. Here the calculation agrees well with the data over the whole region studied. The same is shown for Fritiof in fig 3b.

The success of eq (3) indicates that the observed local fluctuations to a large extent are determined by the underlying global ones. The results obtained for the chosen η -range will be possible to generalize to any other choice of range, provided that the fragmentation regions are excluded, where the fluctuations may be of a different origin.

In order to estimate the relative contributions from the different terms in eq (1) Fritiof is used. The E_{zDC} -spectrum from Fritiof has been shown to agree well with the experimental one⁷ and the trigger can thus be simulated. After the trigger cut has been applied, the source distribution is calculated, as well as x_0 , x_i and $V(X_i) = \langle X_i^2 \rangle - \langle X_i \rangle^2$. Both participants and binary collisions are separately considered as sources. The findings are summarized in Table 1. The first column gives the total scaled variance, $\omega = \Omega \cdot \langle n \rangle$, of the distributions and the next five columns give the corresponding contributions from the four terms in formula 1 and their sum. The last two columns give the average number of sources and the average contribution per source, respectively.

First, it is observed that by using the number of participants or the number of binary collisions, essentially the same trend is obtained, if the larger number of binary collisions as compared to participants in a given interaction is taken into account. Furthermore it is observed that the total scaled variance is identical to the sum of the four terms and that term 3 is rather small compared to the other terms. It is thus possible to conclude that the variations of the sources as a function of their creation number is of minor importance for the shape of the final distributions. This is actually a consequence of the long formation time in the model which makes effects of energy degradation small. Other models assuming a long formation time should give similar results.

Due to the basic assumptions of Fritiof, it is observed that the effects of energy degradation are more pronounced for the binary collision scenario than for the participant scenario. We are thus left with the important terms 1, 2 and 4. Of these three terms the first one is of special interest. If we keep the discussion concerning eq (3) in mind it was found that the width of a distribution is strongly dependent on the size of the region of observation. The only term which can be influenced by this is term 1, since this is the only term containing the second moments of X_i . This can be checked by applying the same kind of analysis on Fritiof data but using the global n_{ch} and E_{T} distributions. The results of this analysis are also given in Table 1. The scaled variances

have decreased. All terms are essentially the same as before except for term 1, which has decreased drastically. The sum of the terms and the total scaled variance are still equal.

We can thus conclude that the final shape is basically governed by the shape of the source distribution, although influenced by the damping of term 4. The apparent importance of the fluctuations from each of the sources, in the case when a limited region of phase space is observed, is a consequence of the stochastic nature of the sources, where a random process determines if a given particle will fall inside the studied region or not.

As mentioned earlier the authors of ref 3 deduced that a certain amount of coherence had to be included in order to explain the large widths observed experimentally. Our conclusion is that the limited range under observation gives an apparent broadening of the spectra which has to be considered if this kind of analysis is to be pursued. If we compare the experimental Ω -value, in the limited range, for the n_{ch} distribution with the corresponding one from the Fritiof calculation there is a nice agreement; 2.64×10^{-2} from the data and 2.40×10^{-2} from the model. For the E_T -case the model distribution is even broader than the experimental one.

As a last comment to Table 1, it is worth pointing out that for the local region the E_T distribution is the widest, whereas for the global case the n_{ch} distribution is the widest. One interpretation is that globally E_T is constrained due to energy conservation but locally the constraint is negligible. In a local region the measured E_T will be subject to the same fluctuations as the number of particles and in addition the E_T of each particle can vary. At some chosen range the widths of the two distributions thus coincide but the exact choice of this range may be very model dependent.

It has since long been established that experimentally obtained n_{ch} and E_T distributions, where so called minimum bias triggers are used, are almost exclusively influenced by the source distributions, normally referred to as geometrical effects¹⁰. For comparison the above analysis is extended also to a minimum bias sample generated from the Fritiof model.

The results of the analysis are given in Table 2. The general trends are the same as for the central sample in Table 1. There are, however, a few notable differences. In all the cases the sum of the four terms is somewhat larger than the total scaled variance given in column one, indicating that there is indeed an anticorrelation between the different sources. This difference is however

small compared to the total width and can thus be neglected. For central interactions no such anticorrelation was observed presumably due to the large number of sources in each event. In events with only a few active sources the correlations between any two of the sources will be stronger. Term 2 is, as expected, always the dominant one. For participants term 4 is positive (except in one case where the value is close to zero), i.e. we have a positive correlation between the contribution from each source and the number of sources. This can be understood since a minimum bias sample is mainly focusing on interactions with a limited number of participants. In these cases the introduction of a new participant will also mean that an old participant, with which it collides will be further excited. The contribution from the new participant will thus be the sum of the effect on the two nucleons involved. Only when the number of participants is large this effect starts to drop since the energy available in the subcollision is not enough to further excite the nucleons. In the case of binary collisions, however, the probability, that a new binary collision will include two new unexcited nucleons is monotonically decreasing and thus term 4 will always be negative. The exact behaviour of term 4 will probably be very model dependent and the observed behaviour is mainly due to the emphasis that Fritiof places on the participants as compared to the binary collisions.

It is also worth noting that the x_0 -values and the values of terms 1 and 3, do not change drastically when changing from the central sample to the minimum bias sample, again indicating only a minor importance of the energy degradation.

It should be mentioned that the values in Tables 1 and 2 are quite sensitive to the exact definitions of the trigger cuts applied, the conclusions however are not.

In fig 4a both tails of the experimental n_{ch} and E_T distributions are plotted as a function of $(X - \langle X \rangle)^2 / \langle X \rangle^2$ for central ^{160}Au interactions with $E_{ZDC} < 400$ GeV, corresponding to about 10% of the minimum bias sample. In this representation a Gaussian distribution will be a straight line, with both tails overlapping. The slope is given by $(-2 \cdot \Omega(X))^{-1}$. In fig 4b the corresponding results from the Fritiof model are shown and in fig 4c the distributions of participants and binary collisions are indicated.

In all the cases there is a difference between the behaviour of the tail extending to large values and the tail extending to small values. For both the participant and binary collision distributions this effect is rather small, and

those distributions are well described by Gaussians. One of the most dominant features is that the experimental multiplicity distribution is wider than the E_T distribution, whereas in the model the situation is the opposite. As discussed above this might depend on the chosen region and we do not comment on it further. Also the experimental resolutions, for E_T and n_{ch} , are somewhat different and will give a small contribution to the observed width. In the case of the multiplicity the experimental resolution will contribute with approximately 8% of the total width. For the E_T measurements the value is believed to be similar but the exact number is not easily determined. The broadening due to uncertainties in the E_{ZDC} -measurements are small and can be neglected.

When we compare the final distributions with the source distributions, we find that the widths have increased. This is, as discussed above, mainly due to the stochastic part of term 1. That there is a difference between the tails on the low and high sides can, furthermore, be understood due to the presence of term 4. The reason why the low side is steeper than the high side is not easy to understand and has to be investigated further. It is, however, clear that the splitting is larger in Fritiof than in the data.

The Gaussian shape of the experimental E_T -distributions also has the following consequence; the distribution of the energy density $\varepsilon \sim E_T$ will also be of Gaussian shape, i.e. $P(\varepsilon) \sim \exp(-(\varepsilon/\varepsilon_0 - 1)^2/(2 \cdot \Omega))$. This almost certainly prevents us from finding events with largely differing energy densities ($\gg \varepsilon_0$), i.e. if no new mechanism is revealed. The situation will, furthermore, not be improved notably by the introduction of harder triggers.

Based on the above discussion we draw the following conclusions:

- i) The n_{ch} and E_T distributions are mainly determined by the source distributions, also when a hard trigger is applied.
- ii) When limited regions are considered the stochastic nature of the sources will broaden the distributions in accordance with eq (3). The observed local fluctuations are to a large extent determined by the global ones. An intermittent behaviour, if experimentally established, will only marginally change this conclusion.

- iii) The shape of the distributions is strongly influenced by the correlations between the number of sources and the gradual decrease in their strength, i.e. term 4 in eq (1).
- iv) Either the number of participants or the number of binary collisions can be used to determine the distributions. For a specific model one of the descriptions might be more relevant than the other.
- v) Gaussian tails of E_T -distributions limit the possibility of finding events with energy densities much larger than the typical energy density, ε_0 , in a central event sample.

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Appendix I

Let x_i , $i = 1, 2, \dots, m$, be m uncorrelated observations of a random variable distributed according to some known function $g(x)$, where $\rho(x) = m \cdot g(x)$ is the corresponding density distribution. The probability, p , that a given observation, x_j , will fall in the small interval Δx , is then given by

$$p = \frac{\langle \rho \rangle \cdot \Delta x}{m},$$

where $\langle \rho \rangle$ is the average density in the interval Δx . Furthermore, the number of observations in the interval Δx , follows binomial statistics with the mean given by $m \cdot p$.

We now turn to the case where several sets of observations with different multiplicities, m , are considered, all distributed according to the same $g(x)$. Furthermore the multiplicity distribution $P(m)$ is assumed to be known, at least the two first moments of the distribution.

The variance in the number of observations, k , in a given interval Δx , is

$$\begin{aligned} V(k) = \langle k^2 \rangle - \langle k \rangle^2 &= \sum_m P(m) \cdot \left\{ \sum_{k=0}^m k^2 \cdot \binom{m}{k} \cdot p^k \cdot (1-p)^{m-k} \right\} - \langle k \rangle^2 = \\ &= p^2 \cdot (\langle m^2 \rangle - \langle m \rangle) + p \cdot \langle m \rangle - \langle k \rangle^2. \end{aligned}$$

This leads to the expression for the normalized variance, $\Omega(k)$,

$$\Omega(k) \equiv \frac{V(k)}{\langle k \rangle^2} = \frac{p^2}{\langle k \rangle^2} \cdot (\langle m^2 \rangle - \langle m \rangle) + \frac{p \cdot \langle m \rangle}{\langle k \rangle^2} - 1.$$

Using the expressions for $\langle k \rangle$ and p , i.e. $\langle k \rangle = p \cdot \langle m \rangle$ and $p = \langle \rho \rangle \cdot \Delta x / \langle m \rangle$, respectively, we finally obtain

$$\Omega(k) = \frac{\langle m^2 \rangle - \langle m \rangle^2}{\langle m \rangle^2} - \frac{1}{\langle m \rangle} + \frac{1}{\langle \rho \rangle \cdot \Delta x}$$

from which equation 3 follows. Note that this result can be symmetrically expressed as

$$\Omega(k) - \langle k \rangle^{-1} = \Omega(m) - \langle m \rangle^{-1}.$$

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Figure Captions

- Fig 1. a) n_{ch} - and b) E_T -distributions for central $^{16}O+Au$ interactions at 200 A GeV. The curves are Gaussian fits to the distributions from the different event selections.
- Fig 2. The normalized variance Ω as a function of $\Delta\eta$ for central $^{16}O+Au$ interactions at 200 A GeV for a) experimental data and b) for the Fritiof sample. The histograms correspond to the calculations from eq (3), normalized at $\Delta\eta = 1.0$.
- Fig 3. The normalized variance Ω as a function of η for central $^{16}O+Au$ interactions at 200 A GeV for a) experimental data and b) for the Fritiof sample. The histograms correspond to the calculations from eq (3), normalized at $\eta = 3.05$.
- Fig 4. Gaussian representations of a) experimental n_{ch} - and E_T -distributions, b) n_{ch} - and E_T -distributions from the Fritiof sample and c) the source distributions (participants and binary collisions). The best line fits to the points are indicated in a) for the region $(X - \langle X \rangle)^2 / \langle X \rangle^2 < 0.4$ for both tails, and in c) for the region $(X - \langle X \rangle)^2 / \langle X \rangle^2 < 0.16$ but only for the tail extending to higher values. Filled symbols always indicate the tails reaching higher values, whereas the open symbols represent the low value tails.

T A B L E 1

Disentangling of the total widths of E_T and n_{ch} distributions into components as given by the Fritiof model.

Central Interactions

	$\omega = \Omega \cdot \langle n \rangle$	Term 1	Term 2	Term 3	Term 4	Σ terms	$\langle n \rangle$	x_0
2.5 < η < 3.5								
Participants								
n_{ch}	1.52	1.02	1.06	0.12	-0.69	1.51	63.39	1.21
E_T	2.07	1.73	1.06	0.22	-0.95	2.07	63.39	0.70
Binary Collisions								
n_{ch}	2.17	1.62	1.77	0.39	-1.63	2.16	90.35	0.85
E_T	2.94	2.56	1.77	0.55	-1.95	2.94	90.35	0.49
Global								
Participants								
n_{ch}	0.75	0.22	1.06	0.09	-0.62	0.75	63.39	4.69
E_T	0.58	0.21	1.06	0.19	-0.89	0.58	63.39	2.43
Binary Collisions								
n_{ch}	1.07	0.56	1.77	0.41	-1.67	1.07	90.35	3.29
E_T	0.83	0.45	1.77	0.55	-1.95	0.83	90.35	1.71

Typical errors are for ω 0.01, for the sum of the terms 0.03, and for $\langle n \rangle$ and x_0 , 0.04 and 0.01, respectively. x_0 is given in GeV for E_T .

T A B L E 2

Disentangling of the total widths of E_T and n_{ch} distributions into components as given by the Fritiof model.

Minimum Bias

$\omega=\Omega \cdot \langle n \rangle$	Term 1	Term 2	Term 3	Term 4	Σ terms	$\langle n \rangle$	x_0	
2.5 < η < 3.5								
Participants								
n_{ch}	11.93	1.18	9.89	0.09	0.88	12.04	36.22	1.16
E_T	12.31	1.96	9.89	0.12	0.51	12.46	36.22	0.68
Binary Collisions								
n_{ch}	14.92	1.49	19.20	0.76	-6.40	15.04	45.31	0.93
E_T	15.40	2.37	19.20	0.92	-6.92	15.56	45.31	0.54
Global								
Participants								
n_{ch}	10.34	0.29	9.89	0.04	0.22	10.43	36.22	4.63
E_T	10.02	0.35	9.89	0.06	-0.12	10.17	36.22	2.40
Binary Collisions								
n_{ch}	12.94	0.49	19.20	0.93	-7.57	13.05	45.31	3.70
E_T	12.54	0.46	19.20	1.06	-8.00	12.71	45.31	1.92

Typical errors are for ω 0.06, for the sum of the terms 0.09, and for $\langle n \rangle$ and x_0 , 0.13 and 0.01, respectively. x_0 is given in GeV for E_T .

Fig 1

Fig 2

Fig 3

Fig 4