MONTE CARLO ANALYSIS OF EVENT-BY-EVENT FLUCTUATIONS IN Au + Au COLLISIONS AT $\sqrt{s_{NN}} = 19$–200 GeV

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We present results on the event-by-event analysis of multiplicity and transverse momentum fluctuations for Au + Au collisions at RHIC energies. This analysis is based on Monte Carlo events obtained from HIJING and VENUS generators. The dependence of the results on centrality and energy of the collision as well as on the acceptance cuts is discussed. We found that the results obtained for the Monte Carlo generated events strongly depend on these parameters and disagree with a thermal model predictions. In a wide range of energies and centralities of the collisions the HIJING model predictions are different than those obtained from VENUS simulations.

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1. Introduction

Measurement of event-by-event fluctuations is an important experimental technique which can be used to detect critical fluctuations expected in the case of the phase transition between hadron matter and a Quark-Gluon Plasma (QGP). It is expected that fluctuations of suitably chosen observable in heavy ion collisions may reveal thermodynamic properties of the system at freeze-out [1–4]. The study of these correlations for different parameters characterizing the collision, such as energy, centrality and nuclear species, should provide information on the order of the phase transition between QGP plasma and hadron matter. Specifically, one would expect a non-monotonic behavior of fluctuations as a function of varying collision parameters in the vicinity of the tricritical point in the QCD phase diagram [5]. The present experimental results do not allow for the study of event-by-event fluctuations in a wide range of energies and for different centralities. Recently published NA49 results [6,7] on the fluctuations measured in central Pb + Pb collisions at $\sqrt{s_{NN}} = 18$ GeV show no evidence for the presence of critical phenomena in heavy ion collisions at the SPS energy.

Fortunately, with the advent of RHIC collider, a new range of parameters is now accessible for experimental studies. Various aspects of the multiparticle production will be investigated by the four RHIC experiments: BRAHMS, PHOBOS, PHOENIX, and STAR. While the experimental results on event-by-event analysis are not available at the moment, it is interesting to check what are the predictions of Monte Carlo models commonly used to describe heavy ion collisions beyond the SPS energy. Comparison of model predictions with the actually measured data may be used as a sensitive test of different dynamical mechanisms.

In this paper we present results obtained from the analysis of events generated by the HIJING [8] and VENUS [9] Monte Carlo models. Both models incorporate string-like mechanism to describe soft hadron production, although the charged particle multiplicities obtained from VENUS simulations are significantly larger (by about a factor of 2) than those predicted by the HIJING model. HIJING includes hard parton scatterings, described by the perturbative QCD, while these processes are not accounted for in the VENUS model. Thus, we may expect different predictions for multiparticle final states simulated by HIJING and VENUS Monte Carlo models. It is interesting to see whether these differences will show up in the analysis of event-by-event fluctuations. It should be pointed out that both MC models do not account for quantum-mechanical fluctuations, *e.g.* Bose–Einstein correlations.

In our simulations we used VENUS model with the rescattering switched off. For both models generated final hadron states include all stable hadrons, also those being the decay products of resonances. The only exception is Φ meson which we consider to be a stable particle. Weak decays are generally switched off, except for those of charmed particles. However the yields of both Φ and charmed mesons are so low that this special treatment of these particles should not affect the generality of conclusions from this fluctuation analysis.

Basing on samples of generated events we analyze the fluctuations in charged particle multiplicity and in the transverse momentum. The evolution of fluctuations with energy and centrality of the collision is investigated. In addition, the dependence on the acceptance cuts, that may be relevant for the data to be taken by RHIC experiments, is also studied. To our best knowledge, so far only the results on event-by-event fluctuations of transverse momenta obtained from the Quark–Gluon String Model were shown [10] for Pb+Pb collisions in a wide range of primary energies. Other Monte Carlo studies of event-by-event fluctuations [11, 12] do not include a systematic analysis of the dependence on the energy or other parameters characterizing the collision system.

2. Multiplicity fluctuations

The observable which measures event-by-event fluctuations of the multiplicity of produced charged particles is defined [5] as the ratio of the variance of the multiplicity distribution to its mean value:

$$\Omega(N_{\mathrm{ch}}) = \frac{\langle \Delta N_{\mathrm{ch}}^2 \rangle}{\langle N_{\mathrm{ch}} \rangle}, \tag{1}$$

where N_{ch} is the number of charged particles recorded in a collision. If the multiparticle production is a purely statistical process, governed by a Poisson distribution, the above ratio should equal 1. However, in reality, one expects various effects which in general should lead to $\Omega(N_{\mathrm{ch}})$ greater than unity. The obvious source of additional fluctuations is due to the fact that particles are not directly produced, but originate from resonance decays. Even, if the resonances themselves are produced independently, their decay products are not. Correlations coming from resonance decays were estimated on the basis of resonance gas model [5] giving the $\Omega(N_{\mathrm{ch}})$ value of ~ 1.5. In addition to the resonance production (*i.e.* interactions in the final state), the fluctuations of particle multiplicity are influenced by the initial state effects [13]. A trivial contribution is due to the geometry of the nucleus–nucleus collision. Expected sources of initial state effects include variation in the impact parameter of the collision and fluctuations in the number of elementary nucleon–nucleon (NN) interactions or in the number of participants. Some, small contributions, may be also due to the fluctuations in inelastic NN cross section, or to the deformed shape of the colliding nuclei. Analysis of the multiplicity fluctuations measured by the NA49 CERN experiment has shown that a resonance gas model and contributions from the initial state effects fully explain experimentally measured $\Omega(N_{\mathrm{ch}})$ value [14].

With increasing particle multiplicity at higher collision energies, the contribution of the initial state effects also increases. In Fig. 1(a) we present the dependence of the event-by-event charged pion multiplicity fluctuations on the collision energy, starting from just above the CERN SPS energy and up to the nominal RHIC energy of $\sqrt{s_{NN}} = 200$ GeV. Data points represent head-on Au + Au collisions simulated by HIJING and VENUS models. The same dependence for semi-central Au+Au interactions, selected as those with the number of participating nucleons, $N_{\mathrm{part}} \geq 300$, is also shown in Fig. 1(a). A strong increase of $\Omega(N_{\mathrm{ch}}^{\pi})$ with increasing $\sqrt{s_{NN}}$ is observed for both head-on and semi-central collisions. At the nominal RHIC energy the predicted $\Omega(N_{\mathrm{ch}}^{\pi})$ values are 10.25 ± 0.15 ($b = 0$ fm) and 42.48 ± 0.99 ($N_{\mathrm{part}} \geq 300$) for the HIJING MC model. The corresponding values of $\Omega(N_{\mathrm{ch}}^{\pi})$ for VENUS are: 9.83 ± 0.14 and 83.60 ± 2.00. At lower energies all calculated $\Omega(N_{\rm ch}^{\pi})$ values also largely exceed the prediction of the thermal resonance gas model, with the exception of the head-on HIJING collisions at the lowest energy of 19 GeV. As expected, the fluctuations observed in semi-central collisions are much stronger, indicating greater role of the initial state effects for more peripheral interactions. Comparing HIJING and VENUS predictions one can see that, for head-on collisions at high beam energies, VENUS predictions are not significantly different than those obtained from HIJING model. It is not the case for semi-central interactions for which fluctuations in VENUS events are much stronger than in HIJING events. Interestingly, after rescaling $\Omega(N_{\rm ch}^{\pi})$ values calculated for VENUS events by the ratio of average charged pion multiplicities: $\langle N_{\rm ch}^{\pi}\rangle_{\rm HIJING}/\langle N_{\rm ch}^{\pi}\rangle_{\rm VENUS}$ (see Fig. 1(b)) the differences observed for $N_{\rm part} \geq 300$ collisions in Fig. 1(a) are now significantly reduced. Later, we will show that the same rescaling procedure reduces the differences between VENUS and HIJING simulations for other selections of less central events. Apparently it does not work for head-on collisions. For these interactions the average charged pion multiplicity for VENUS events is larger by 2.3 times than for HIJING events at $\sqrt{s_{NN}} \geq 130$ GeV. Yet, the same $\Omega(N_{\rm ch}^{\pi})$ are obtained at 200 GeV, and at 130 GeV the difference amounts only to about 7 %.

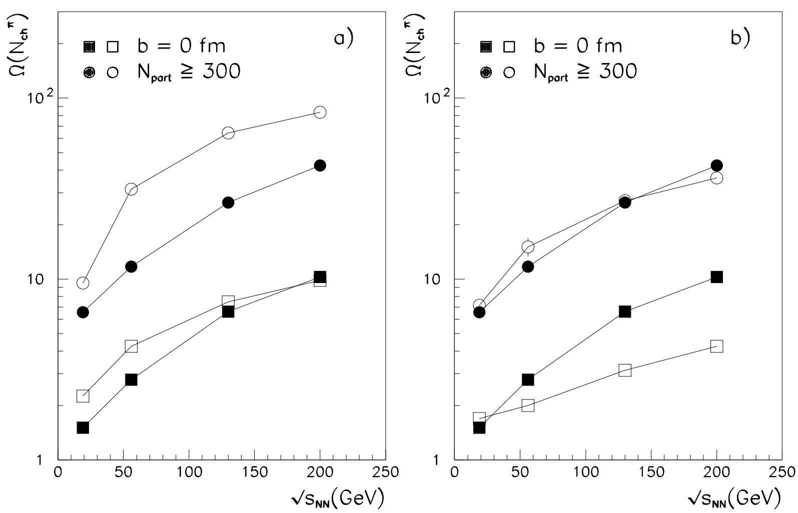

Fig. 1. (a) — Dependence of $\Omega(N_{\rm ch}^{\pi})$ on the collision energy. Filled symbols represent HIJING simulations, open symbols denote the results calculated for VENUS generated events. (b) — The same dependences as in (a) but with VENUS points rescaled by the ratio of the average charged pion multiplicities from HIJING and VENUS model.

To perform a systematic study of the dependence on the centrality of the collision we have divided the generated samples of minimum bias events at the two highest beam energies (each sample containing 50,000 events) into five independent sub-samples according to the number of participating nucleons: $N_{\rm part} < 40$, 40–99, 100–199, 200–299, ≥ 300. The dependence of $\Omega(N_{\rm ch}^{\pi})$ on the average number of participants is plotted in Fig. 2(a) for both HIJING and VENUS data sets. The points for the highest $\langle N_{\rm part}\rangle$ values correspond to $b = 0$ fm collisions. Calculated multiplicity fluctuations do not show a monotonic behavior as a function of the average number of participants. For peripheral collisions, covering large range in $\langle N_{\rm part}\rangle$, the $\Omega(N_{\rm ch}^{\pi})$ values scatter showing a weak dependence on the centrality of events. Only for most central collisions, a rapid decrease of the multiplicity fluctuations with increasing centrality is observed. The results are extremely sensitive to the selection of events. To illustrate this, we also show in Fig. 2(a) the $\Omega(N_{\rm ch}^{\pi})$ values calculated for HIJING events at $\sqrt{s_{NN}} = 200$ GeV for different choice of $N_{\rm part}$ groups (depicted by stars): $N_{\rm part} = 20$–39, 40–79, 80–119, 120–199. This non-monotonic behavior on centrality of the collision can be explained by the fluctuations in the number of participants, which are shown in Fig. 2(b) for HIJING and VENUS samples at 200 GeV.

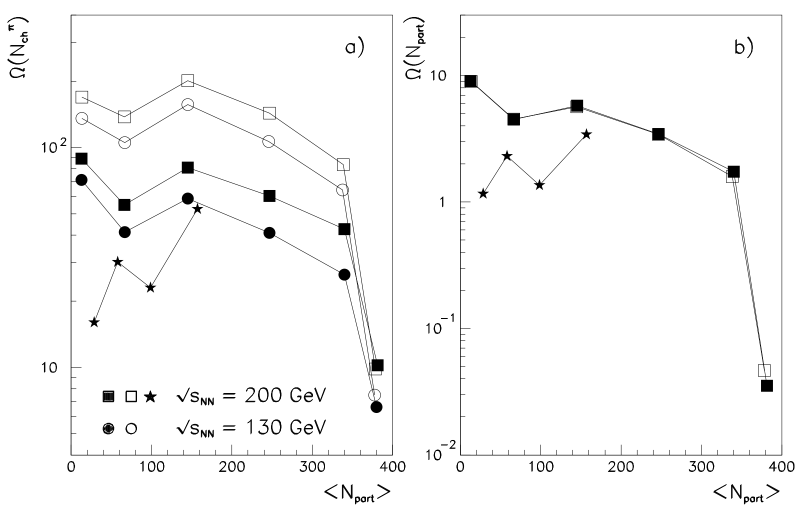

Fig. 2. (a) — Dependence of $\Omega(N_{\rm ch}^{\pi})$ on the centrality of the collision as measured by $\langle N_{\rm part}\rangle$ for the two beam energies. Filled symbols represent HIJING simulations, open symbols denote the results calculated for VENUS generated events. Stars denote the HIJING predictions for different selection of events (see text for more explanations). (b) — Dependence of $\Omega(N_{\rm part})$ on the centrality of the collision at 200 GeV. See part (a) for symbol description.

The fluctuations $\Omega(N_{\rm part})$ seem to follow a similar dependence on $\langle N_{\rm part}\rangle$ as those of $\Omega(N^{\pi}_{\rm ch})$. $\Omega(N_{\rm part})$ values are the same for both MC models and, as expected, are practically energy independent. The differences between VENUS and HIJING models shown in Fig. 2(a) can be explained if one assumes that multiplicity fluctuations scale with the average multiplicity. See Fig. 3(b) where VENUS fluctuations scaled by the ratio of average multiplicities of HIJING to VENUS events are compared to HIJING $\Omega(N^{\pi}_{\rm ch})$ values. This indicates that both models generate multiplicity distributions with approximately the same second normalized moment, $\langle N^2_{\rm ch}\rangle/\langle N_{\rm ch}\rangle^2$. Evidently this scaling of multiplicity fluctuations with the average multiplicity does not apply to most central ($b=0$ fm) collisions at high beam energies.

In Fig. 3(b) we show that the strength of multiplicity fluctuations is also sensitive to the criteria applied to select events with different centralities. In this figure the $\Omega(N^{\pi}_{\rm ch})$ values obtained for HIJING sub-samples of events selected according to $N_{\rm part}$ cuts are compared to $\Omega(N^{\pi}_{\rm ch})$ calculated for subsets of events selected by cuts in impact parameter. The impact parameter cuts are chosen to approximately match the fraction of events selected by $N_{\rm part}$ cuts. Larger fluctuations obtained when impact parameter cuts are applied, are due to larger fluctuations in $N_{\rm part}$ as compared to samples selected by $N_{\rm part}$ cuts.

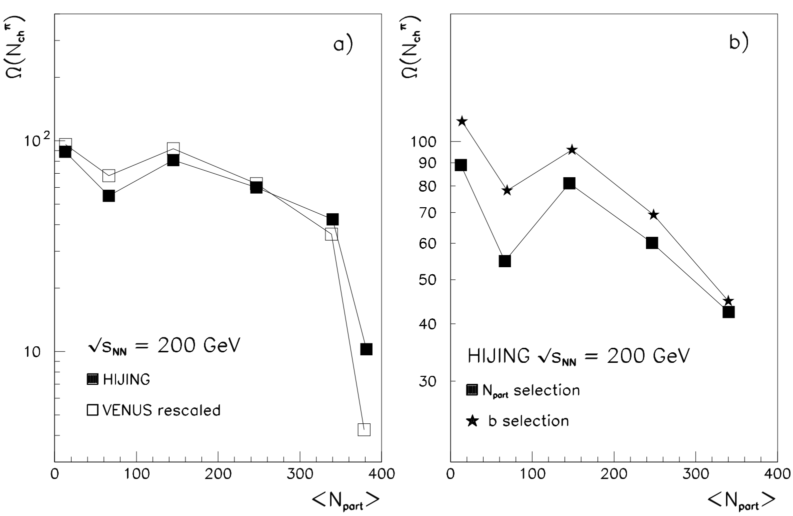

Fig. 3. (a) — Comparison of the HIJING predictions for multiplicity fluctuations with the rescaled VENUS results at 200 GeV as a function of centrality of the collision. (b) — Comparison of the HIJING predictions for multiplicity fluctuations as a function of centrality of the collision for subsamples of events selected by $N_{\rm part}$ cuts (squares) and by impact parameter cuts (stars).

The above analysis of the centrality dependence of multiplicity fluctuations clearly shows that any interpretation of measured fluctuations should require a precise knowledge of the centrality of analyzed events, which is not readily available in experimental analysis.

The other effect which should affect the strength of the measured fluctuations is a limited phase space acceptance which may lead to artificially reduced fluctuations. In order to test the influence of the acceptance cuts, we compare the results calculated for a full phase space (shown in Figs. 1–3) with those obtained with some acceptance cuts applied. Two acceptance cuts were used. One restricting the analyzed phase space to the pseudorapidity (η) interval from 0 to 2. The second restricts both particle pseudorapidities and azimuths (φ), *i.e.* only particles with pseudorapidities between 0 and 2 and azimuths $\mid \varphi \mid < 0.087$ rad are accepted. In the latter case $\sim 0.6\%$ of the full phase space is analyzed. This approximately matches the acceptance of a single arm of the spectrometer employed in the PHOBOS detector [15]. The results are shown in Table I for semi-central Au + Au collisions at different energies for both MC models. One can see a strong reduction of the multiplicity fluctuations in the case of the analysis of particles recorded in the limited phase space region. Both MC models predict weaker multi-

TABLE I

$\Omega(N^{\pi}_{\mathrm{ch}})$ for Au+Au semi-central collisions simulated from Monte Carlo models at different collision energies and for different acceptance cuts.

HIJING Au + Au collisions with $N_{\mathrm{part}} \geq 300$			
$\sqrt{s_{NN}}$	full phase space	$0 < \eta < 2$	$0 < \eta < 2$, $\mid \varphi \mid < 0.087$ rad
19 GeV	6.57 ± 0.16	3.45 ± 0.08	1.01 ± 0.03
56 GeV	11.70 ± 0.31	5.28 ± 0.14	1.15 ± 0.03
130 GeV	26.47 ± 0.62	11.55 ± 0.27	1.30 ± 0.04
200 GeV	42.48 ± 0.98	17.32 ± 0.40	1.47 ± 0.03
VENUS Au + Au collisions with $N_{\mathrm{part}} \geq 300$			
$\sqrt{s_{NN}}$	full phase space	$0 < \eta < 2$	$0 < \eta < 2$, $\mid \varphi \mid < 0.087$ rad
19 GeV	9.50 ± 0.54	4.82 ± 0.27	1.15 ± 0.07
56 GeV	31.38 ± 1.73	13.30 ± 0.73	1.28 ± 0.07
130 GeV	64.21 ± 1.55	25.11 ± 0.61	1.66 ± 0.04
200 GeV	83.60 ± 2.00	31.38 ± 0.75	1.92 ± 0.05

plicity fluctuations in the most restricted phase space than expected from the thermal model, irrespectively of the collision energy. In other words, a subset of particles, typically measured in experiments, looks more thermal than the complete set of produced stable hadrons. Therefore, the acceptance cuts should be thoroughly taken into account before concluding the onset of thermalization or other new effects in nucleus–nucleus collisions.

In the above analysis we have calculated fluctuations in event-by-event multiplicity of produced charged pions. Extending this analysis to all charged secondaries gives similar results with the size of fluctuations of charged particles larger up to about 15 % as compared to the fluctuations in charged pion multiplicities.

3. Transverse momentum fluctuations

Different quantities were considered as a measure of fluctuations of particle transverse momenta [5,16]. A quantity, $\Omega(p_{\mathrm{T}})$:

$$\Omega(p_{\mathrm{T}}) = \frac{\langle N_{\mathrm{ch}}\rangle^{1/2}\langle \Delta p_{\mathrm{T}}^2\rangle^{1/2}}{\langle p_{\mathrm{T}}\rangle}, \tag{2}$$

is used in this study. Particle transverse momentum is expected to be less sensitive to the initial state interactions, but it depends on the flow velocity of the transversal hydrodynamic expansion. The resonance thermal model prediction for $\Omega(p_{\mathrm{T}})$, modified for the flow effects, is ~ 0.68 [5]. The transverse momentum fluctuations were measured by the NA49 Collaboration for central Pb + Pb collisions at $\sqrt{s_{NN}} = 18$ GeV [6]. It was found that the measured strength of the fluctuations is compatible with the independent particle production if one takes into account the quantum statistics effects and final state interactions.

It is interesting to see how the fluctuations in the average transverse momentum of produced charged pions evolve with increasing collision energy. This is shown in Fig. 4(a) for head-on and semi-central Au + Au collisions simulated by the HIJING model. One can see, that similarly to the $\Omega(N_{\mathrm{ch}})$, the $\Omega(p_{\mathrm{T}}^{\pi})$ also increases with increasing $\sqrt{s_{NN}}$. This increase is, however, not so dramatic as that observed for multiplicity fluctuations and can be attributed to the increased importance of hard processes at higher collision energies. The final state particles originated from these hard processes (forming jets or mini jets) are strongly correlated in momentum space. In contrast, the VENUS model predictions are practically energy independent and even show some decrease of transverse momentum fluctuations with increasing energy at lowest energies (see Fig. 4(b)). The results obtained for the two collision centralities are not very different for both MC models. The two lower plots in Fig. 4 show energy dependence of the transverse momentum fluctuations calculated for all charged particles. Much stronger fluctuations, especially for VENUS events (Fig. 4(d)) are predicted when all charged particles are included in the analysis. We have checked that this increased strength of the transverse momentum fluctuations is mainly attributed to charged nucleons. Interestingly, VENUS predicts much stronger transverse momentum fluctuations for all charged particles than HIJING, the effect opposite to that seen in the analysis of charged pions only. It should be pointed out that all values of $\Omega(p_{\rm T})$, calculated for HIJING and VENUS simulations are significantly larger than the thermal model predictions (marked by dashed lines in Fig. 4).

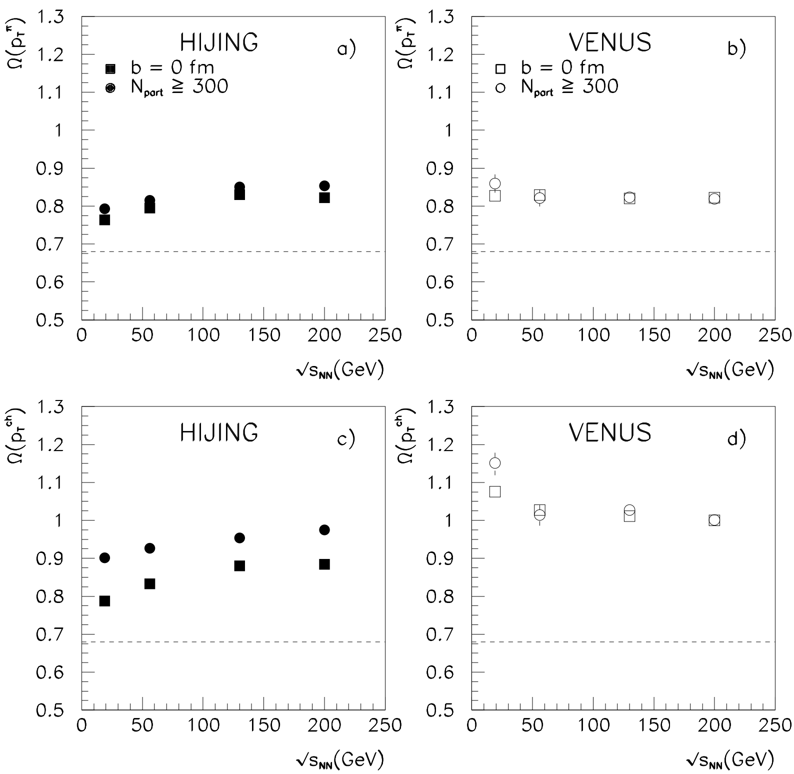

Fig. 4. Energy dependence of the fluctuations in transverse momenta of charged pions from HIJING (a) and VENUS (b) model. The two lower plots show the same dependences but for fluctuations in transverse momenta of all charged particles. Dashed lines show the prediction of the thermal model.

A systematic dependence on the centrality of the collision is depicted in Fig. 5 for the two highest collision energies for sub-samples selected according to $N_{\rm part}$ cuts. A sharp drop of $\Omega(p_{\rm T}^{\pi})$ is observed going from most peripheral collisions to events with slightly larger number of participants. This decrease can be related to the residual initial state effects. For more central collisions we see a weak decrease of $\Omega(p_{\rm T}^{\pi})$ for HIJING events, whereas the VENUS points level off. At both energies transverse momentum fluctuations predicted by HIJING are larger than those obtained from VENUS simulations, with the exception of most peripheral ($N_{\rm part} < 40$) and the most central ($b = 0$ fm) collisions. It is likely that hard scattering processes are responsible for this effect.

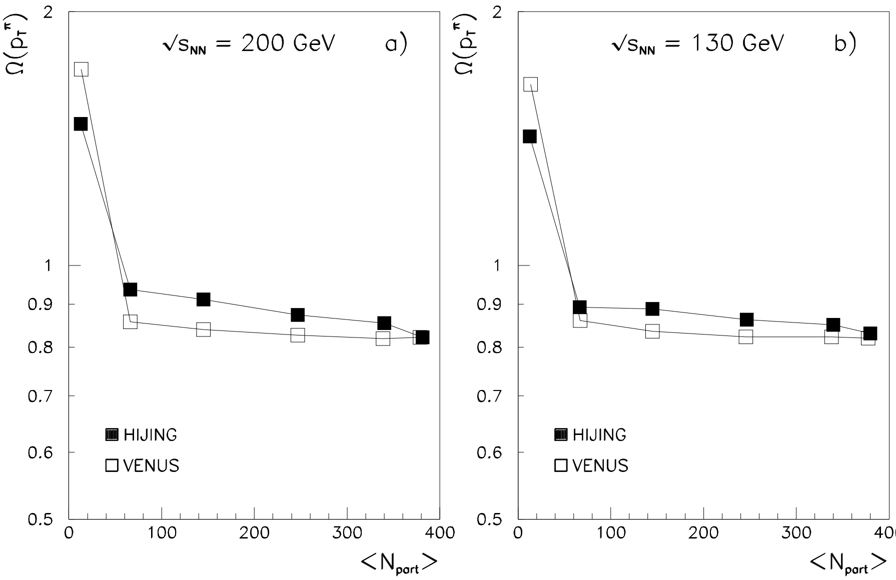

Fig. 5. Comparison of the HIJING and VENUS predictions for pion transverse momentum fluctuations as a function of centrality for Au + Au collisions at $\sqrt{s_{NN}}$ of 200 GeV (a) and 130 GeV (b).

The analysis of the data for different phase space cuts was also performed. The results are included in the Table II and show the decrease of the transverse momentum fluctuations for more restrictive phase space cuts. Therefore, similarly as in the case of event-by-event multiplicity fluctuations, the acceptance cuts have to be carefully accounted for in the experimental analysis of fluctuations in the particle transverse momenta.

TABLE II

$\Omega(p_{\mathrm{T}}^{\pi})$ for Au + Au semi-central collisions simulated from Monte Carlo models at different collision energies and for different acceptance cuts.

HIJING Au + Au collisions with $N_{\mathrm{part}} \geq 300$

$\sqrt{s_{NN}}$	full phase space	$0 < \eta < 2$	$0 < \eta < 2$ $\mid \varphi \mid < 0.087$ rad
19 GeV	0.793 ± 0.010	0.733 ± 0.009	0.738 ± 0.010
56 GeV	0.815 ± 0.011	0.729 ± 0.010	0.730 ± 0.010
130 GeV	0.851 ± 0.010	0.742 ± 0.009	0.722 ± 0.009
200 GeV	0.854 ± 0.010	0.767 ± 0.009	0.710 ± 0.008

VENUS Au + Au collisions with $N_{\mathrm{part}} \geq 300$

$\sqrt{s_{NN}}$	full phase space	$0 < \eta < 2$	$0 < \eta < 2$ $\mid \varphi \mid < 0.087$ rad
19 GeV	0.858 ± 0.024	0.720 ± 0.020	0.716 ± 0.021
56 GeV	0.821 ± 0.023	0.759 ± 0.021	0.704 ± 0.020
130 GeV	0.823 ± 0.010	0.733 ± 0.009	0.681 ± 0.008
200 GeV	0.819 ± 0.010	0.717 ± 0.009	0.697 ± 0.008

4. Summary

We have discussed HIJING and VENUS Monte Carlo predictions for event-by-event fluctuations in multiplicities and transverse momenta of particles produced in heavy ion collisions at high energies, up to the $\sqrt{s_{NN}} = 200$ GeV which will be available at the RHIC collider. These predictions are found to be significantly different from the thermal model expectations.

The important role of the initial state interactions (especially for the multiplicity fluctuations) at higher energies and for less central collisions is shown. As expected, the dependence on the collision energy does not show any evidence for the non monotonic behavior foreseen at the critical point of the hadron matter to a QGP transition. On the other hand some irregularities are observed in the dependence of multiplicity fluctuations on the centrality of the collision. They can be, however, attributed to a specific behavior of the fluctuations in the number of participating nucleons as a function of centrality. Differences in multiplicity fluctuations for HIJING and VENUS events are mainly due to the differences in charged particle multiplicities produced by each model. On the other hand, those observed in transverse momentum fluctuations for charged pions suggest that hard processes may contribute to particle correlations in the momentum space. For the most central, head-on collisions at the highest energy, both models predict the same strength of multiplicity and transverse momentum fluctuations. Apparently, for these collisions neither differences in charged particle multiplicities nor contributions from hard scatterings affect the magnitude of the predicted effect. It may suggest that effects due to these differences compensate each other in the most central interactions.

Furthermore, a strong sensitivity to the imposed acceptance cuts is observed, indicating that these detector effects should be thoroughly studied. The study of the fluctuations in particle transverse momenta requires also a good particle identification.

Summarizing, these Monte Carlo models predictions can be tested when data from the RHIC experiments become available and can be used to discriminate between different collision dynamics. However, an extreme care should be put to disentangle the effects due to the initial state fluctuations and final state interactions as well as to the acceptance cuts from those which can be attributed to the thermalization or the onset of new physics.

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