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G. Pancheri:

ARE WE WITNESSING QUARK-MATTER FORMATION AT THE CERN $S\bar{p}pS$ COLLIDER?

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ARE WE WITNESSING QUARK-MATTER FORMATION AT THE CERN S$\bar{p}$pS COLLIDER?

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Abstract

We examine the experimental evidence, coming from the Cern $S\bar{p}pS$ collider, relevant to a possible phase transition from the hadron gas to the quark gluon plasma. Some current interpretations of the anomalous behaviour observed in the multiplicity and transverse momentum spectra are discussed. The conclusion is that there are experimental facts which favour an explanation in terms of abundance of jets in the high multiplicity region.

1. INTRODUCTION

The formation of a quark gluon plasma is expected from QCD when the energy density and/or the temperature, measured over an extended region, are so high that the quarks are no longer confined to the typical hadronic matter dimensions of 1 fm, but freely move within the larger region. The expectation is that for sufficiently high energy density, there should be a phase transition from the hadron gas to a quark gluon plasma [1]. Such a transition has been studied and observed in lattice gauge theories [2,3]. This transition can also be studied in high energy collisions if one relates typical high energy observables like particle density and transverse spectra to thermodynamical quantities like entropy and temperature. In particular, the number of particles measures the entropy [4] and, since the typical longitudinal extent of the system is measured by the spread in rapidity [5], the particle density $\frac{\Delta n}{\Delta y}$ appears proportional to the entropy density of the blob of hot hadronic matter produced during the collision. Moreover, correlations between the transverse momentum spectra of the secondaries produced in the central region and particle multiplicity may give information on a possible phase transition. Indeed, because of the limiting behaviour

$$e^{-\frac{p_t}{<p_t>}}$$

observed at lower energies, $< p_t >$ is a measure of the temperature of the system [6].

In sect.2 we discuss two anomalous effects observed at the collider to see whether they can be interpreted as signals for a phase transition. In sects.3 and 4, various phenomenological and theoretical interpretations are discussed. We present some additional experimental facts and conclusions in sects.5 and 6.

2. EXPERIMENTAL FACTS FROM UA1 AND UA5 COLLABORATIONS

Two anomalous effects have been observed during the last year by the UA1 [7] and UA5 [8,9] Collaborations. The UA1 effect, first reported at the 1982 Paris Conference, shows a strong multiplicity dependence of the transverse momentum distribution of charged particles produced in proton- antiproton collisions at $\sqrt{s} = 540 GeV$. The effect is shown in Fig.1. This figure shows that

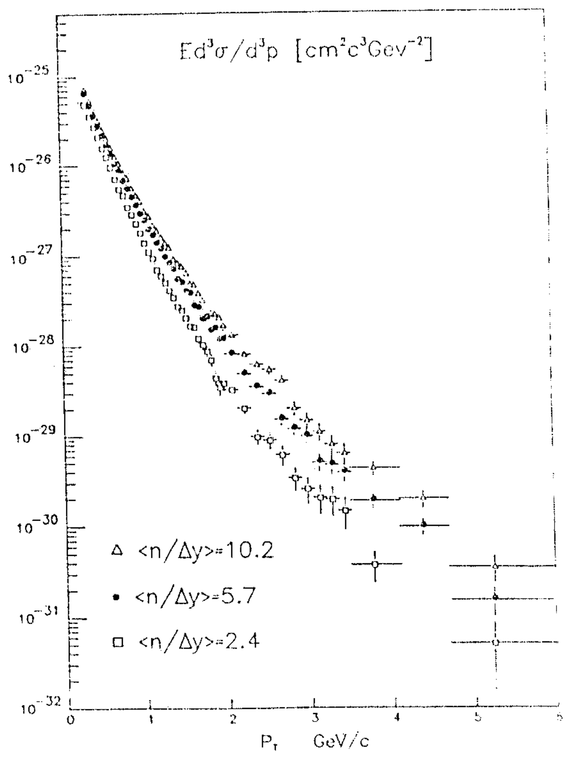

FIG. 1 - Inclusive p_t spectrum for different multiplicity densities. UA1 Collaboration, (Ref. 7).

inclusive single particle spectra, when analysed in different multiplicity regions, exhibit a flattening of the cross-section with increasing multiplicity. This effect was not completely unexpected. In fact, a correlation between transverse spectra and multiplicity had been observed in cosmic ray experiments[10]. The observation of cosmic rays jets in emulsion chambers, in the region of primary energy $10 \div 1000 TeV$, shows that jets are characterized by 3 distinct types of multiple pion production. In Fig.2 we reproduce the observed γ-rays transverse momentum spectra for the three different type of jets in which one can divide the entire sample [10]. In the figure we have also indicated the characteristic number of γ per unit rapidity interval. The broadening of the p_t-distribution with increasing multiplicity is very evident, larger in fact than the effect observed at the collider. In Table I, we reproduce, from ref.[10], the main characteristics of these events. For a comparison with

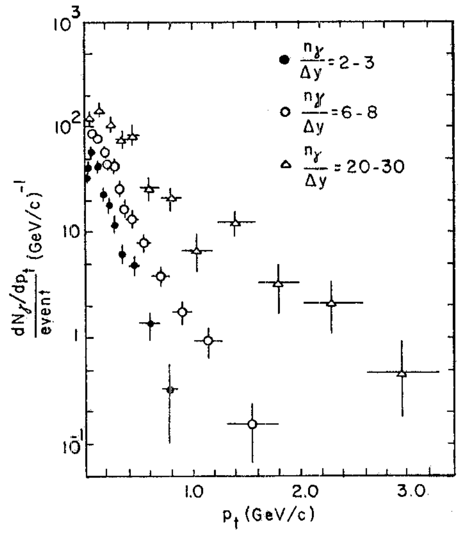

FIG. 2 - Transverse momentum distribution of γ-rays observed in cosmic ray events, for three types of jets; ●:Mirim jets; o: açu jets; △: guaçu jets. (Ref. 10).

TABLE I

type of jet	characteristics of produced gamma-produced rays		composition of particles
	$<p_t>$	n_γ per unit rapidity interval	
Mirim-jet	140 MeV/c	2-3	Mainly pions
Açu-jet	220	6-8	non-negligible
Guaçu-jet	400-500	20-30	yield of X-particles

Remark: Mirim, Açu and Guaçu mean small, large and very large in BrazilianIndian language.

collider data, we recall that $n_\gamma = 2n_{\pi^0} = n_{ch}$ and $< p_t >_\gamma = \frac{1}{2} < p_t >_{\pi^0}$. The difference between events in various multiplicity intervals has been studied using the fire-ball hypothesis. To date, it is not understood how much of the effect can be attributed to interaction of complex nuclei and how much is a genuine new phenomenon. One cannot but stress however the correlation between multiplicity and transverse spread of the produced pions: higher multiplicity events are characterized by flatter p_t distributions or, at high multiplicity, pions are produced at larger angles. It is the same effect, albeit not as large, which has been observed at the collider.

After the observation of the above correlations by the UA1 Collaboration, the effect has been searched for at lower energies by other groups.

No effect was found by NA5 at $\sqrt{s} = 20GeV$[11]. The effect has also been searched at ISR by the ABCDHW Collaboration[12]. While no multiplicity dependence was detected at $\sqrt{s} = 30Gev$, a significant effect was observed at $\sqrt{s} = 63GeV$. In Figs.3a and 3b, we reproduce their results.

Although significant, the effect is however not as dramatic as at the collider, as one can see from Fig.4, where the collider data are directly compared with ISR data at $\sqrt{s} = 63GeV$. From

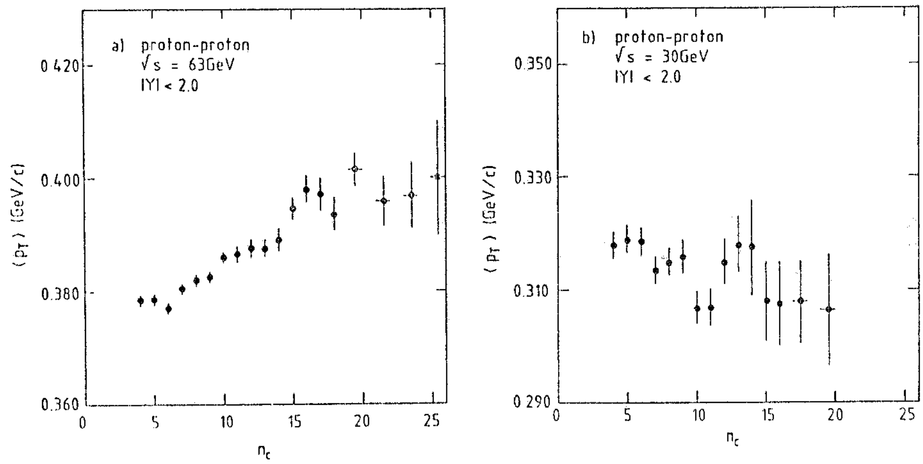

FIG. 3 - Mean charged momentum for charged particles produced in the central region of rapidity, $|y| < 2$, versus charged multiplicities at c.m. energies $\sqrt{s}$=30 GeV and $\sqrt{s}$=63 GeV. (Ref. 12).

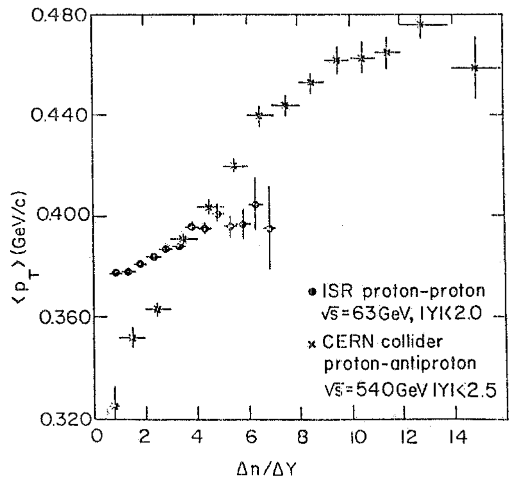

FIG. 4 - Mean transverse momentum as a function of charged particle density in the central rapidity region, at ISR and $\bar{p}p$ Collider. (Ref. 12).

the accelerator data, we can thus conclude that some sort of threshold seems to occur in the middle of the ISR range. As the energy increases, pions in the high multiplicity region are found to be emitted, on the average, at larger angles.

The second anomalous observation at the collider concerns the high multiplicity tail of the KNO function. The UA5 Collaboration has reported [8,9,11] an apparent excess of events in the multiplicity distribution for $n > 3 < n >$. The apparent excess refers to the asymptotic KNO curve as obtained from low energy data. We recall here very briefly the main facts relative to the well known scaling property of the multiplicity distribution, known as KNO scaling. In 1972, Koba, Nielsen and Olesen[13] argued, on the basis of Feynman scaling and the definition of topological cross-sections,that the function

$$\Psi(n,s) =< n(s) > \frac{\sigma_n(s)}{\sigma_{inel}(s)}$$

is independent of s and is only a function of the KNO variable $z = \frac{n}{<n>}$. This scaling property has been found to be approximately true from very low energies, $\sqrt{s} = 1.5GeV$, up to ISR energies,$\sqrt{s} = 63GeV$[14]. In Fig.5 we show a recent compilation of low energy data [9] together with an approximate fit, drawn to guide the eye and to illustrate the scaling behaviour. When this approximate curve is compared with the UA5 data as in Fig.6, one immediately sees the appearance of possible scaling violations. To pin point the discrepancy, one can study the fraction of events above a given multiplicity threshold at different energies. This was done by the UA5 Group [9] and we show it in Fig.7 for n> 2<n>. We see that while, at lower energies, only 2% of the events are in this region, at the collider this fraction has increased by a factor 3. Clearly the source of the effect is a phenomenon which is not dominant in the overall cross-section but which may become quite important at large multiplicities. In the following section, some of the current interpretations of the effects discussed here will be examined.

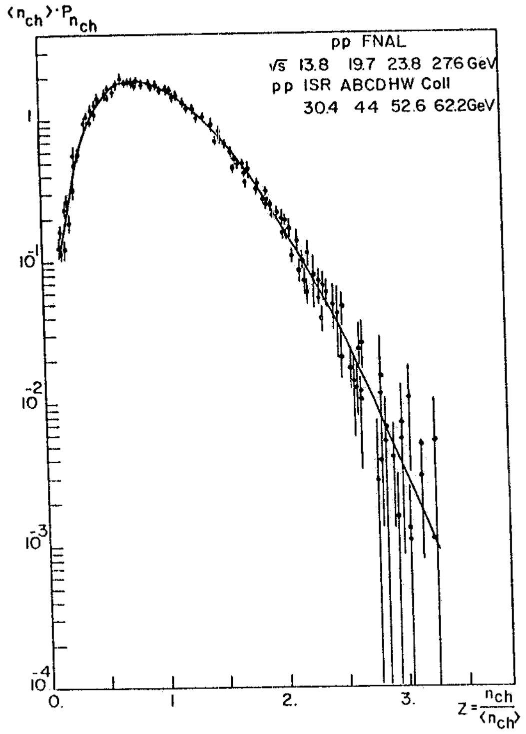

FIG. 5 - Non single diffractive multiplicity distribution from $\sqrt{s}$=13.8 GeV to $\sqrt{s}$=62.2 GeV. (Ref. 9).

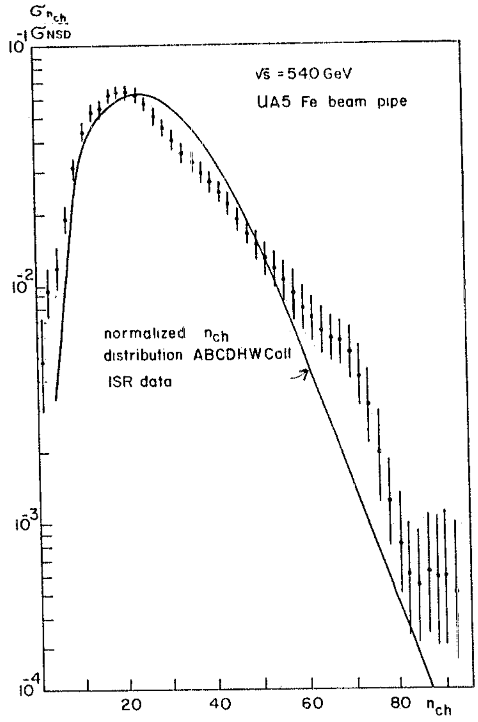

FIG. 6 - Non single diffractive multiplicity distribution at $\sqrt{s}$=540 GeV. UA5 Collaboration (Ref. 9).

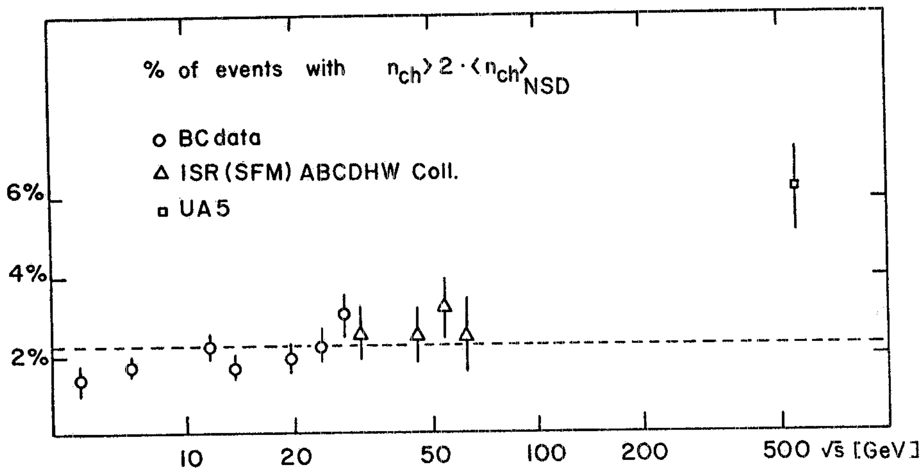

FIG. 7 - Fraction of events with charged multiplicity larger than twice the mean vales. (Ref. 9).

3. THEORETICAL INTERPRETATIONS OF THE KNO FUNCTION.

The apparent validity of KNO scaling and the shape of the multiplicity distribution have been the subject of a large number of theoretical and phenomenological interpretations. The shape has been obtained through geometrical-dynamical models [15,16,17], QCD clusters[18,19], dual parton model [20], QCD jet calculus [21,22,23,24], generalized Bose-Einstein distributions [25], soft QCD radiation [26]. In the following we shall try to discuss in detail some of these approaches to evidentiate if and how they can incorporate scaling violations of the type observed by UA5.

In the geometrical-dynamical models, the multiplicity distribution is related to the impact parameter representation of the scattering process. These models are based on the physical idea that central collisions ($b \approx 0$) contribute to large multiplicity, while large values of the impact parameter characterize small multiplicity events. Scaling is then understood as a reflection of geometric scaling. In ref.[17], Barshay introduces the idea of a normalized multiplicity distribution for each value of the impact parameter. The hadronic distribution is given by :

$$P_n(s) = \frac{\int P_n(b,s)\sigma_{inel}(b,s)db^2}{\int \sigma_{inel}(b,s)db^2}$$

Upon using geometric scaling for the eikonal $\Omega(b,s)$, the inelastic cross-section is parametrized as

$$\sigma_{inel}(s) = \int (1 - e^{-2\Omega})db^2 \approx \int e^{-\lambda b^2} db^2$$

Scaling in the variable $z = \frac{n}{<n>}$ is obtained since the function $P_n(b,s)$ depends upon b and s only through the variable

$$z = \frac{n}{< n(b,s) >}$$

with

$$< n(b,s) > = N(s)\sqrt{\Omega(b,s)}$$

The functional dependence of $P_n(b,s)$ on the variable z is taken to be the same as that of the corresponding function for e^+e^-[17]. Barshay fits well the KNO function from lower energies up to ISR values. To accomodate scaling violations, Barshay invokes a two component mechanism[27], by adding to the main term a very narrow distribution which,at high energy,is more sensitive to small values of b (and hence to large n) : the physical idea is that $<n(s)>$ will slowly change its functional form as the new addition, a function of s, becomes more important.

Barshay asks two interesting questions :

(i) Does the distribution for e^+e^- have a tendency to narrow or to broaden as the energy increases?

(ii) since <n(b,s)> for small b increases more strongly with energy than at large impact parameters, is the system at small b approaching the quark-gluon plasma phase?

KNO scaling is also obtained by summing QCD jets . Using the jet calculus technique[21,22], it has been possible to derive an expression which describes the growth of the mean multiplicity from low energy up to $\sqrt{s} = 540GeV$. This expression, which is given by[23,24,28]

$$< n(s) >= Ae^{\sqrt{Blns}}$$

may provide a better fit to the data than the lower energy parametrization[14] :

$$< n(s) >= a + blns + c(lns)^2$$

Chain fragmentation and dual parton models[20] obtain the shape of the KNO function by summing Poisson distributions with a weight given by the rapidity spectra. Kaidalov proposes an expression which shows a broadening at large multiplicity with increasing energy. Thus, in this calculation, scaling violations of the type observed by UA5, are expected.

Approximate scaling is obtained in the cluster type approach of Sterman and Hayot[19]. This approach gives results similar to those obtained by exponentiating the lowest order QCD diagrams in the Leading Logarithm Approximation (LLA). This QCD calculation predicts very slow scaling violations of the type $lnln\frac{s}{\Lambda^2}$. Their effect is to produce a narrower distribution as the energy increases.

Recently Carruthers and Shih[25] have obtained the shape of the KNO function from very general statistical laws. They propose an expression obtained from a generalized Bose-Einstein distribution :

$$P_n(k) = \frac{(n+k-1)!}{n!(k-1)!}\left(\frac{\frac{\bar{n}}{k}}{1+\frac{\bar{n}}{k}}\right)^n \frac{1}{(1+\frac{\bar{n}}{k})^k}$$

with k, the number of cells, which regulates the shape of the function. By altering how many cells participate to the process, the shape can be changed. To incorporate scaling violations of the type observed by UA5, one then needs to decrease the number of cells as the energy increases. This model has the attractive feature of describing KNO scaling in a very general statistical framework.

That the shape of the KNO function can be thought in very general terms, also follows from the interpretation put forward in ref.[26]. There, the shape of the distribution appears as a special (QCD) case of the expression one obtains when summing massless quanta emitted by independent semiclassical sources, with a constraint due to overall energy conservation. In the energy variable, this summation leads to the distribution

$$dP(K_0) = \frac{dK_0}{2\pi} \int dt e^{iK_0 t} exp\Big(- \int d^3\bar{n}(k)(1 - e^{-ikt})\Big)$$

where $d^3\bar{n}(k)$ is the spectrum of single quanta emitted by a semiclassical source. This summation procedure, when applied to QED, produces the typical soft photon spectrum $k^{-1+\epsilon}$. The same spectrum averaged over the condensed matter coordinates, like in electrical circuits, reproduces the well known $\frac{1}{f}$ noise [29]. The same summation technique can also be used for soft graviton emission[30]. What discriminates among different physical processes is the energy spectrum of the single quantum which is exponentiated by the summation i.e. the nature of the point like-current which generates the massless fiels. For the hadronic case, the distribution is averaged over the hadronic matter coordinates. The KNO function is then obtained by making use of the following two hypotheses :

$$\sum_{1}^{npions} \omega_i = K_0$$

with ω_i the energy of each pion, and

$$P_n = \frac{\sigma_n}{\sigma_{inel}} = < Resummed\, Soft\, Gluon\, Distribution >_{Hadronic\, matter}$$

We obtain the following expression for the KNO function:

$$\Psi(\frac{n}{< n >}) = < n > P(n, s) =$$

$$= \beta(s) \int \frac{dt}{2\pi} e^{i\beta \frac{n}{<n>} t - \beta \int_0^1 \frac{dk}{k}(1 - e^{-ikt})} \qquad (1)$$

with $\beta(s) \approx lnlns$. The value $\beta(s) = 1.82$ gives a good fit to the UA1 data for $|\eta| < 3.5$. The spectrum β is proportional to the kinematical cuts, thus for $|\eta| < 1.5$ the relative data should be fitted by a smaller β. The two fits are shown in Figs.8a and 8b.

So far this model does not show scaling violation of the kind presently discussed. In fact, in this model, as the energy increases, the KNO curve will go to zero more rapidly at large z. This behaviour can easily be detected if we use the approximation :

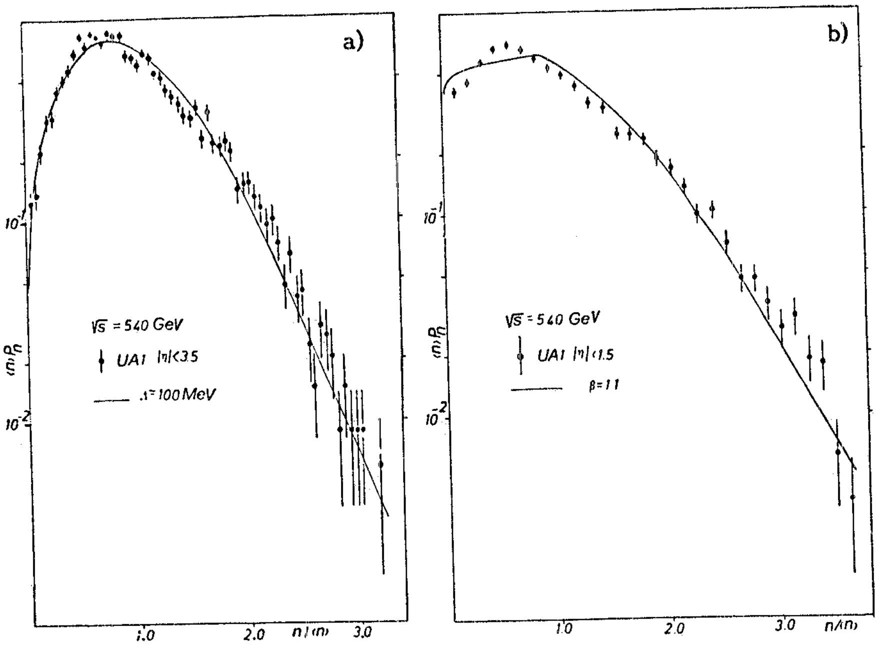

FIG. 8 - UA1 multiplicity distribution at $\sqrt{s}$=540 GeV. Data are from Ref. (35). The solid line is the soft gluon formula from Eq. (1) of the text.

$$\Psi(z) \approx \beta \frac{(\beta z)^{\beta z - 1}}{\Gamma(\beta)} e^{-\beta z},$$

Thus this bremsstrahling model shows that, by summing Poisson distributions with an energy conservation constraint, one obtains scaling violations, but opposite to the type observed. However. one should not expect such a simple soft gluon model to correctly predict what happens at really large z, which, in this context, corresponds to really large energy being emitted by the colliding partons. For, at very large energy, for instance, rescattering may become important. Besides rescattering and contributions from hard scattering between the constituents, there might also be spectator interactions, which would also increase the multiplicity.

4. PHENOMENOLOGICAL AND THEORETICAL INTERPRETATIONS OF THE UA1 EFFECT

The most interesting discussion of the UA1 effect is due to L.Van Hove [30] who has discussed it as a possible signal of a phase transition from the hadron gas to the quark-gluon plasma. Following the hydrodynamical model. he notices that while the particle density $\frac{dn}{dy}$reflects the entropy, the transverse momentum of the inclusively produced particles receives contributions from both the temperature and the transverse expansion of the system. The latter consists originally of a blob of hot hadronic matter formed in the collision between very high energy hadrons.

Thus, at the beginning, the entropy increases as the temperature, and hence $< p_t >$, increases. If there is a phase transition, however, the temperature will remain constant while the entropy increases through the transition. After the quark-gluon plasma has formed, the temperature should start increasing again for growing n, but this will not reflect in a similar $< p_t >$ increase since the outcoming pions have been produced when the quarks and gluons freezed into hadrons,at a lower temperature. This mechanism thus explains the apparent saturation of the p_t spectra at very large n. The growth of $< p_t >$ with multiplicity appears because both the tewmperature and the entropy of the system are increasing towards the transition point, while the saturation is understood because the pions will always appear at the temperature at which they have been produced, around the critical temperature. In Fig.(9) we reproduce the expected $< p_t >$ vs. $\frac{dn}{dy}$ dependence. This

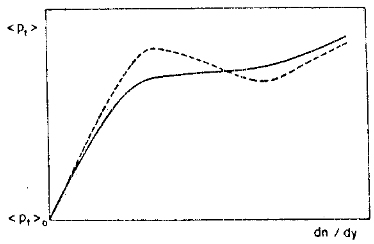

FIG. 9 - Expected structure in the $<p_t>$ versus dn/dy correlation resulting from a possible phase transition. Reproduced from Ref. (31).

qualitative behaviour is very similar to the one observed in the UA1 effect.

On the phenomenological level, there exists a more standard interpretation by S.Barshay [32]. As mentioned in relation to the UA5 effect, Barshay introduces a normalized multiplicity distribution in the impact parameter space. With this distribution, more particles are produced at small values of the impact parameter than otherwise. Thus n is larger for central collisions. Barshay calculates the average value of the squared impact parameter for each multiplicity value, $< b^2(n,s) >$ and relates it to the transverse spectra through a functional relationship of the type

$$< p_t(n,s) > \approx < b^2(n,s) >^{-\gamma}$$

where γ is different at different energies. The choice of γ is, at present, phenomenological. It should be noticed that, in Barshay's model, the mean transverse momentum as a function of n does not show complete saturation, but only a slowing down of the rate at which it grows.

An interpretation which differs from both of the above, but which may lead to understand both the UA1 and the UA5 effect, has been put forward by M.Jacob[33]. Jacob suggests that the collider energy is high enough for a new type of reaction mechanism to occur. Just like it was the case for açu events in cosmic rays observations, it is possible that, from ISR to the collider, an energy threshold has been crossed such that many low-x partons have now enough energy to undergo hard scattering and produce several mini-jets, of a few GeV each, which fragment independently from one another. This produces both an increase in the particle density as well as an increase in the average $< p_t >$, since the jet mechanism allows for large angle scattering. The threshold effect would then be due to the same mechanism which is responsible for the emergency of jets from lower energy configurations.

5. SUGGESTIONS FROM RECENT EXPERIMENTAL OBSERVATIONS

It is by now apparent that we are witnessing two anomalous behaviours, relative to lower energy data, which both involve large multiplicity effects. Are there other anomalies in the multiplicity behaviour at the collider? A study of UA1 data, as presented at the recent Brighton Conference[34], shows the following :

(i) Events with jets show a remarkable increase of particle multiplicity away from the trigger jet. This can be seen from Fig.(10) where the mean charged multiplicity in a given rapidity and azimuthal interval , in the presence of a jet, is plotted for different pseudo-rapidity intervals, centered around the jet axis. Away from the jet, one notices a rather constant "jet floor", which can be called the jet associated multiplicity. This jet associated multiplicity appears to be more than twice the multiplicity of the minimum bias events. This constant, higher multiplicity background can be explained as due to the presence of additional small jets.

(ii) Mini-jets or low energy jets can easily go undetected since present detection thresholds for jet algorithms are high. We could of course argue that mini-jets need not have the same associated high multiplicity as regular jets. A study of associated multiplicities as a function of the trigger jet energy threshold, as in Fig.(11), shows them to be rather constant even for low E_T values. We can therefore expect these high multiplicities to persist also for those undetected jets.

It may very well be that, selecting events at high multiplicity, lead to contamination from broad undetectable jets and thus to an increase of the observed $< p_t >$. At the same time, the jet and mini-jet mechanism can also be responsible for the increase at large multiplicities observed in the

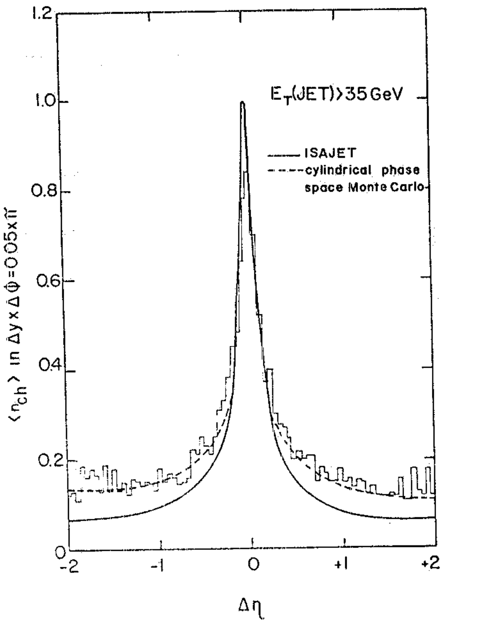

FIG. 10 - Mean charged multiplicity (in $\Delta y \Delta\phi = 0.05\pi$) for jet events, as a function of the pseudo-rapidity interval around the jet axis. UA1 Collaboration, Ref. (34).

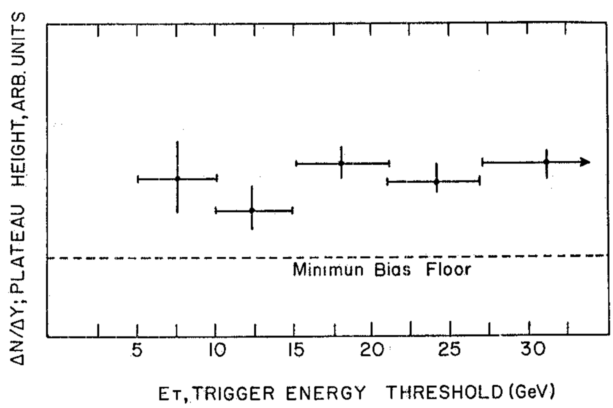

FIG. 11 - Particle density $\Delta n/\Delta y$ off the jet for different energies of the trigger jet. Preliminary data from the UA1 Collaboration.

KNO function, since this is a mechanism which was not present al lower energies and which is becoming increasingly important at high energy. This might explain the observed KNO scaling violations.

6. CONCLUSIONS

Present data from the CERN Collider of interest to quark-matter formation have been discussed. It appears that the anomalous high multiplicity tail observed by the UA5 Collaboration and the multiplicity dependence of inclusive p_t spectra reported by UA1 can probably be explained by invoking the persistent high multiplicity associated with low energy (few GeV) jet evets. These events are certainly present and their effects are sufficiently important at collider energy as to mask possible quark-matter formation a la Van Hove.

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