COLD QUARK–GLUON PLASMA AND MULTIPARTICLE PRODUCTION *)

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ABSTRACT

We propose a mechanism for several unexpected particle production phenomena observed recently in high energy collisions and characterized by very low transverse momenta or intermittency-type fluctuations in longitudinal rapidity. It is based on a QCD parton shower model extended to very soft partons, leading to the formation of globs of very cold, non-thermal quark-gluon plasma.

*) This paper is dedicated to Herman Feshbach in honour of his seventieth birthday, in recognition of his scientific contributions and as a token of friendship. It will be published in the "Herman Feshbach Festschrift", a special issue of Annals of Physics (New York).
1. INTRODUCTION

Recent high energy collision experiments have revealed several unexpected production phenomena characterized by very low transverse momenta \( p_T \lesssim 50 \text{ MeV}/c \) or very short range fluctuations in longitudinal rapidity \( \Delta y \lesssim 0.2 \). These ultrasoft effects are:

i) Sharp peak of \( d\sigma/dp_T^2 \) at \( p_T < 100 \text{ MeV}/c \) for charged hadrons (mostly pions) in high multiplicity hadronic and nuclear collisions [1,2,3,4].


iii) Fluctuations in the rapidity distribution (intermittent behaviour) of range \( \Delta y \lesssim 0.2 \) in hadronic and nuclear processes [9,10] and in \( e^+e^- \) annihilation [11,12]. Present indications are that intermittency may be slightly stronger in \( e^+e^- \) than in hadronic processes [10], and somewhat weaker again in nuclear processes [9].

The above ultrasoft effects have been observed in the central rapidity regions of the corresponding collisions.

We here propose that they are manifestations of the occurrence, early in the time development of at least some of the collisions, of an intermediate system with considerable lifetime and spatial extension (several fm/c and fm, respectively). Such an intermediate system should be produced not only in nuclear collisions, but also in elementary reactions (hadron-hadron, lepton-hadron and \( e^+e^- \)) despite the small initial size involved \( (\lesssim 1 \text{ fm}) \). Our proposed intermediate system is assumed to be composed of one or more globs of QCD partons (quarks, antiquarks and gluons), with predominantly small momenta \( P \) in the glob restframes (mean \( P \ll 350 \text{ MeV}/c \), the typical mean \( p_T \) in ordinary soft processes). The small \( p_T \)'s of the partons should account for the ultrasoft effects i and ii, while iii would be due to the small spread \( d\sigma/dp_T \) in longitudinal momenta of the partons in a glob.

Section 2 discusses a few general characteristics of our proposed Intermediate Parton System (IPS), arguing in particular that it is composed of a form of Cold Quark-Gluon Plasma (CQGP) far from thermal equilibrium. Section 3 proposes a formation mechanism for the IPS as a result of QCD parton processes discussed earlier by A. Giovannini and the present author [13,14]. Various consequences of the ultrasoft IPS model are mentioned in Section 4, and the last section gives concluding remarks.

2. GENERAL CHARACTERISTICS OF THE INTERMEDIATE PARTON SYSTEM

The characteristic restframe momenta of our IPS globs should be much smaller than the values \( \gtrsim 200 \text{ MeV}/c \) of mean parton momenta in a Thermalized Quark-Gluon Plasma (TQGP), because the temperature of the latter cannot be less than the deconfinement transition temperature \( T_c \sim 200 \text{ GeV}/c \) (this is the estimated value of \( T_c \) for small chemical potential, i.e., small net baryon number, as is relevant for \( e^+e^- \) annihilation as well as for hadron-hadron and lepton-hadron collisions at mid rapidity). On the other hand, our IPS should be disordered. The matter in the IPS is therefore expected to have in many respects the character of a very Cold Quark-Gluon Plasma (CQGP), with an average energy per parton much lower than in a TQGP.
It should be stressed that this QGP is necessarily in a state very far from equilibrium. For the same energy density, the equilibrium state would be a hadron gas with a temperature far below $T_c$, i.e., essentially a dilute pion gas. The parton wave functions in the latter are very different from those in a QGP; the partons in the gas are concentrated inside the pions with QCD vacuum in between, whereas the partons in the plasma, due to their very low momenta, have extended and widely overlapping wave functions without any QCD vacuum in between (see below for more details). Despite our ignorance of nonperturbative QCD we can therefore predict that any sizable glob of QGP needs much time to hadronize, simply because hadronization requires a very drastic rearrangement of partonic wave functions.

Also the space structure of a QGP can be discussed qualitatively in a model-independent way. The parton number density $n_p$ of a QGP can be as large as in a thermal QGP ($n_p \sim 3 \, \text{fm}^{-3}$ near $T_c$) or larger, but its energy density $\varepsilon$ is much lower than the 3-4 GeV fm$^{-3}$ characteristic of a thermal QGP near $T_c$. This implies that our QGP should not be obtainable by supercooling of a thermal QGP. In supercooling, we expect that $\varepsilon$ decreases only slightly faster than $d_p$ ($\varepsilon \propto T^4$ and $d_p \propto T^3$ in ideal massless gas approximation). In a QGP the low $\varepsilon$ is due to the low parton momenta and the small coherent field energy. To explain the experimental results listed in the introduction, we estimate that the interesting range for $\overline{\varepsilon}$, the mean parton momentum in the QGP restframe, is likely to be $\lesssim 50 \, \text{MeV}/c$, and we shall adopt $\overline{\varepsilon} \sim 30 \, \text{MeV}/c$ for our further considerations. The uncertainty principle then tells us that the wave packets of typical partons have a spatial extension of order $\overline{\varepsilon}^{-1} \sim 7 \, \text{fm}$. This implies that the time scale for the formation of the QGP is likely to be at least of order $7 \, \text{fs}/c$, and the hadronization time is probably much longer.

A useful characteristic of a QGP is its degree of overlap $D_{ov}$ between parton wave packets. We define it as

$$D_{ov} = \overline{\varepsilon}^{-3} d_p$$

It gives an estimate of the average number of partons whose wave packets overlap a given point of space at a given time. In a thermal QGP near $T_c$, the degree of overlap is of the order of $d_p$ expressed in fm$^{-3}$, i.e., $D_{ov} \sim 3$, since $\overline{\varepsilon}$ is of order $T_c \sim 1 \, \text{fm}^{-1}$. $D_{ov}$ remains of the same order at higher temperatures because $\overline{\varepsilon} \propto T$ and $d_p \propto T^3$ in rough approximation.

In contrast, $D_{ov}$ can be very much larger in a QGP. For example, $d_p \sim 3 \, \text{fm}^{-3}$ and $\overline{\varepsilon} \sim 30 \, \text{MeV}/c$ give $D_{ov} \sim 10^3$. At every spacetime point there can therefore be a strong compensation between the colour charges of the partons overlapping that point, and the coherent colour fields induced by them can be small. Hence we expect that the energy density $\varepsilon$ of the QGP will be composed of the parton energies with a rather small addition of coherent field energy density $\varepsilon_f$:

$$\varepsilon = \overline{\varepsilon}^{-3} d_p + \varepsilon_f$$

Here $\overline{\varepsilon}$ is the mean energy per parton, of order

$$\overline{\varepsilon}^{-3} d_p \sim (m_{\text{eff}}^2 + \overline{\varepsilon}^2)^{1/2}$$

with an effective mass which can be very small, perhaps as small as the $u$ and $d$ quark masses (5-10 MeV). For example, for $d_p \sim 3 \, \text{fm}^{-3}$ and $\overline{\varepsilon} \sim 30 \, \text{MeV}/c$, the parton term in (2) is of order

$$\overline{\varepsilon}^{-3} d_p \sim \overline{\varepsilon} d_p \sim 0.1 \, \text{GeV fm}^{-3}$$

The field term is expected to be of order of its value $\varepsilon \sim 0.1 \, \text{GeV fm}^{-3}$ in the bag model, or perhaps smaller because the vacuum condensates of QCD may not be melted completely by the very soft partons of the QGP. Eqs. (2) and (4) then give $\varepsilon \lesssim 0.2 \, \text{GeV fm}^{-3}$, to be compared
to the value of 3-4 GeV fm\(^{-3}\) near \(T_c\). In other words, for the same parton density, our example of CGGP contains a factor 15-20 less energy than the ThQGP near transition.

What can we say about the minimum parton number density of a CGGP? We want the degree of overlap to remain large, say

\[
\bar{d}_B - \bar{d}_p \gtrsim 10
\]

(5)

For \(\bar{F} \sim 30 \text{ MeV/c}\) this gives \(\bar{d}_p \gtrsim 0.03 \text{ fm}^{-3}\), a low value indeed. The parton term of the energy density (2) has then the lower bound

\[
\bar{d}_{\bar{p}} \bar{d}_p \gtrsim 10 \bar{F}^4
\]

(6)

which is of order 1 MeV fm\(^{-3}\) for \(\bar{F} \sim 30 \text{ MeV/c}\). For such low partonic energy density, one expects that the vacuum condensates will be affected very little, so that the field term of Eq.(2) should also be very small.

Our proposed IPS scheme can be regarded as a modification of the Soft Annihilation Model (SAM) developed a decade ago by the Bratise-lava theory group [16] and successfully applied to direct lepton production in the \(p_T\) range \(\sim 300 \text{ MeV/c}\). Our model differs from SAM by the very low value of \(\bar{F}\) and the large spatial extension of the ultra-soft globs of our IPS. Furthermore, our identification of the IPS with the final partons of a QCD shower (see next section) implies that it has an important gluon component not considered in SAM. This means that in our model direct photons and dileptons originate not only from \(q\bar{q}\) annihilation, but also from the Compton-like processes

\[
gq \rightarrow j'q \text{ and } j^* q, \ j^* \rightarrow e^+e^-
\]

(7)

3. INTERMEDIATE PARTON SYSTEM AND QCD PARTON SHOWER

In [13] A. Giovanni and the present author studied multiplicity distributions in \(e^+e^-\) annihilation by means of a QCD parton shower model which had been singled out in [17] by a best-fit procedure applied to a large class of experimental data. In this model, the shower development is stopped when the parton virtualities fall to \(Q_o \approx 1 \text{ GeV}\), a value above which perturbative formulae apply. The final partons are then assumed to hadronize through the Lund string fragmentation mechanism. For mid-rapidity intervals we found the approximate relation

\[
n_{ch} \approx \frac{2}{\bar{p}_T}\ n_p(1)
\]

(8)

between the mean multiplicities \(n_{ch}\) of charged hadrons (mostly pions) and \(n_p(1)\) of final partons in the shower (mostly gluons). The notation \(n_p(Q_o)\) refers to the virtuality \(Q_o\) expressed in GeV. In \(e^+e^-\) annihilation at c.m. energy \(s^{1/2} = 29 \text{ GeV}\), the HRS Collaboration found \(dn_{ch}/dy \approx 2.4\) at mid-rapidity, the longitudinal rapidity \(y\) being defined along the principal axis of the final state. We obtain from Eq.(8) the corresponding estimate

\[
e^+e^- : d_n_p(1)/dy \approx 1.2
\]

(9)

As we argued in [14], it is reasonable to assume that the picture which emerged in [13] and in particular Eq.(8) can be applied also to the other multihadron production processes. Using the experimental data quoted in [18] we then obtain at mid-rapidity the following estimates

\[
pp \text{ and } \pi^+p : d_n_p(1)/dy \approx 0.9
\]

(10)

\[
\mu^+p : \quad d_n_p(1)/dy \approx 0.8
\]

The \(pp\) and \(\pi^+p\) reactions are at \(s^{1/2} = 22 \text{ GeV}\), the deep inelastic
muon reaction creates a hadronic system of total effective mass selected in the interval 18-20 GeV. Experiments with a oxygen beam of 200 GeV/nucleon have shown that the mid-rapidity value of \( \frac{dN_{ch}}{dy} \) reaches \( \sim 120 \) for central collisions on the heaviest targets \([4]\), giving \( \frac{dN_{ch}}{dy} \sim 60 \).

From these values, one can estimate roughly the corresponding number densities \( d_{p}(1) \) of Q\(_{\nu} \sim 1 \) GeV partons in the mid-rapidity frame at an early proper time \( \tau_{a} \) (sufficiently early for the transverse expansion to be negligible). Let us use the reasoning which underlies Bjorken’s well-known estimate of the early energy density \([19]\)

\[
\varepsilon \approx \left( \frac{3 \pi^{2}}{2} \right) \frac{dN_{ch}}{dy} \left( \tau_{a} S_{a} \right)^{-1}
\]

(11)

with \( \bar{m}_{p} \) the mean transverse mass of mid-rapidity pions (the factor \( \frac{3}{2} \) taking care of the neutral ones), and \( S_{a} \) the early transverse area of the interaction region. The same reasoning gives us

\[
d_{p}(1) \approx \frac{dN_{ch}}{dy} \left( \tau_{a} S_{a} \right)^{-1}
\]

(12)

We take \( \tau_{a} \approx 1 \) fm/c and \( S_{a} \approx 1 \) fm\(^{2}\) for the elementary reactions (9,10) and find

\[
d_{p}(1) \approx \begin{cases} 1.2 \text{ fm}^{-3}, e^{+}e^{-} \\ 0.9 \text{ fm}^{-3}, pp \text{ and } \pi^{+}p \\ 0.8 \text{ fm}^{-3}, \mu^{+}p \end{cases}
\]

(13)

For the oxygen reaction we take \( S_{a} \approx 30 \) fm\(^{2}\) (corresponding to an oxygen radius of \( \sim 3 \) fm) and the corresponding estimate is \( d_{p}(1) \approx 2 \) fm\(^{-3}\).

Eqs.(8,11,12) give

\[
\varepsilon / d_{p}(1) \approx 3 \bar{m}_{p} \approx 1.0-1.2 \text{ GeV}
\]

(14)

since \( \bar{m}_{p} \approx 0.35-0.4 \) GeV. This is physically very reasonable; it means that the transverse mass of the partons is close to their virtual mass \( Q_{\nu} \), with little increase due to their \( p_{T} \), and that it is found back in the hadronic transverse masses at the same rapidity.

We now return to our proposed IPS. We assume it to be composed of the final partons of a QCD shower which differs from the model used in \([13,14]\) and from other such models by the property that the shower is allowed to continue to much lower virtualities and larger multiplicities by further parton splittings (with the possibility of some parton fusions). Due to our ignorance of non-perturbative QCD we are of course unable to calculate the soft parts of such a parton shower, but just as in the previous section a qualitative discussion is possible on general grounds. We note that the virtualities of the final partons have no reason to take a single value. We expect them to fluctuate, also among the partons produced in a single collision, the lower limits being zero for gluons and the current masses of order \( 5 - 10 \) MeV for quarks.

Let us consider the simplest case where one of the partons of virtuality \( Q_{\nu} \sim 1 \) GeV considered above (we shall call them the heavy partons) gives rise by further showering to one glob of the IPS. We characterize this glob by its multiplicity \( F \) (on the average, \( F \) will be the overall multiplication factor of the shower below \( Q_{\nu} \)). The mean energy \( \bar{E}_{p} \) per parton in the glob is then \( Q_{\nu}/F \). We write as in Eqs.(2,3) above

\[
\bar{E}_{p} = \left( \frac{m_{eff}^{2} + \bar{p}_{T}^{2}}{2} \right)^{1/2} - \frac{\varepsilon / d_{p}}{Q_{\nu}/F}
\]

(15)

Neglecting again the effective mass and the field energy, we obtain for the mean parton momentum in the glob restframe

\[
\bar{p} \sim Q_{\nu}/F \sim F^{-1} \text{ GeV}
\]

(16)
One expects of course also to have globs resulting from several heavy partons in case these have approximately equal rapidities. For then the estimate (16) holds with an average value of $F^{-1}$.

Eq. (16) shows that our desired range $\bar{P} \sim 30$ MeV/c corresponds to multiplication factors $F \sim 30$ for some fraction $f$ of the heavy partons of virtuality $Q_v \sim 1$ GeV. This ultrasonic fraction $f$ controls the ratio of the transverse energy contents of the ultrasonic versus the soft components of the final state. The data are compatible with small values of $f$ and the assumption that most final partons of the shower have virtualities $\sim 1$ GeV as in [13,14,17]. Under such conditions the ultrasonic effects modify only weakly the dominant soft effects.

We considered so far globs with $F \sim 30$ because they are the relevant ones for the observed ultrasonic effects mentioned in the introduction. What is expected in our model is not that $F$ is either $\ll 1$ or $\ll 1$, but that it has a smooth probability distribution $p(F)$ for $F > 1$, the ultrasonic fraction being of order

$$f = \int_{30}^{\infty} p(F) dF \ll 1$$

and most of the final state coming from smaller $F$. At this moment we have no proposal to make for the shape of $p(F)$. Such a proposal could only be related to hadronic data if we had a specific hadronization scheme for low virtuality partons, which is not yet the case. Our ignorance of non-perturbative QCD will probably require these open questions to be answered by trial and error, with the guidance of the experimental data which are rapidly becoming available. This opens a new direction of phenomenological work in soft QCD.

4. SOME CONSEQUENCES OF THE MODEL

4.1. Pion Interferometry

An obvious question raised by the ultrasonic features of our IPS model is how the large spacetime dimensions involved would manifest themselves in pion interferometry. On the basis of the discussion in the previous section the qualitative answer is that in the pion interferometry pattern of elementary collisions the ultrasonic component is likely to create a small and narrow central peak of size and width controlled by $p(F)$ for $F \gg 1$, on top of the broader structure mostly measured so far. For example, the range $F > 30$ would contribute at momentum differences $0 \leq \bar{P} \leq 30$ MeV/c. Indications for such a central peak have been seen at the ISR [20].

It is not easy to go beyond this simple observation. The conventional treatments linking the interferometry pattern to the spacetime dimensions of the pion source assume a point-like production of pions with phase incoherence between various points in the source. These assumptions are invalid for the ultrasonic globs of our IPS, because the parton wave functions which constitute the pion source are coherent over distances of order $\bar{P}^{-1} \gtrsim 7$ fm. Hence a new approach to pion interferometry will be needed. It should be compatible with the still unknown hadronization mechanism of very soft parton systems.

4.2. Multiplicity Dependence

In Section 3 we considered the simplest case of an ultrasonic glob originating from a single heavy quark ($Q_v \sim 1$ GeV) with a multiplicity factor $F \sim 30$. In the restframe of the heavy parton, the $\sim 30$ partons of the glob have $\bar{P} \sim 30$ MeV/c and a wave packet extension $\sim \bar{P}^{-1} \sim 7$ fm/c, which implies that the volume $V$ of the glob should
be larger than $p^{-3}$, say $V \sim 500$ fm$^3$. The resulting average parton number density is $n_p = F/V \sim 0.06$ fm$^{-3}$, a value only slightly above the lower limit of Eq.(5). Obviously, ultrasoft effects are more likely to be detected when they are due to denser blobs, as can originate by showering of several heavy partons of approximately equal rapidities. This should occur preferentially in events with large $d_{ch}/dy$, see Eq.(8). Note that the volume of such denser blobs would not be much larger than the value $V$ mentioned above, since the various heavy partons from which they originate are close together in space (distances of order 1 fm) and they have low relative velocities due to their heavy mass.

These considerations find support from the ISR experiment reported in [11] which shows an increase of the charged particle $p_T$ distribution at $p_T < 100$ MeV/c for large mid-rapidity multiplicities. We expect a similar enhancement with multiplicity of the electromagnetic ultrasoft effects listed under ii) in the Introduction.

4.3. Intermittency

Despite our ignorance of the hadronization mechanism, we can estimate the characteristic rapidity range $\delta y$ down to which our IPS model is expected to create fluctuations of intermittency type as reported in [9-11]. We assume that the fluctuations are induced by the ultrasoft globes of the IPS. The partons within a glob have a longitudinal momentum spread of order $\vec{P}$ in the glob restframe. The simplest hypothesis is that the same spread propagates to those final pions which are not decay products of resonances. The corresponding range in rapidity is of order

$$\delta y \sim \frac{\vec{P}}{m}$$  \hspace{1cm} (17)
4.4. Electromagnetic Effects

In most of our considerations we made no distinction between gluons and (anti)quarks in the IPS. For hadroproduction it is difficult to make a distinction without having a specific model for the hadronization of very soft partons. The situation is different for direct photon and dilepton production where the relative numbers of gluons and $q\bar{q}$ pairs control the relative weight of $q\bar{q}$ annihilation and the Compton-like process (7). While we do not undertake a calculation in the present paper, we note that the strong dominance of gluons over $q\bar{q}$'s found in the usual QCD shower models is related to the high virtuality cutoff $Q_0 = 1$ GeV. It is caused by the infrared increase of gluon emission over $g \to q\bar{q}$ in perturbative QCD. We see no reason that a strong gluon dominance would persist when the shower continues to develop in the non-perturbative regime, and we suggest that for given overall parton numbers the $q\bar{q}/g$ ratio in the IPS should be treated as a parameter which could perhaps be determined from the soft and ultrasmall electromagnetic production data.

As mentioned in the Introduction, at high energy the observed ultrasmall photons are far more abundant than can be produced by inner bremsstrahlung. This is not the case at lower energies, as found in [21] for $\sqrt{s} = 1$ GeV, where direct soft photon emission agrees with inner bremsstrahlung. One may ask whether the mechanism we propose to explain the high energy effect is compatible with the celebrated Low theorems [22], which states that inner bremsstrahlung must necessarily dominate in the limit of vanishing photon momentum. Our mechanism is compatible with the theorems in the sense that the ultrasmall globs of the IPS, as a consequence of their finite size and lifetime, do not emit photons in the vanishing momentum limit. For some $p_T$ far below the mean parton momentum $p_T \sim 30$ MeV/c emission by incident and outgoing charged particles, i.e., inner bremsstrahlung, must become dominant. The data of [21], esp. Figs. 3 and 4, suggest that the relevant $p_T$ range may be as low as $p_T \lesssim 5$ MeV/c. As to the absence of additional ultrasmall photons in the [21] data, it implies in the framework of our model that a c.m. energy of 4.5 GeV is too low for production of a sizable parton shower of the type occurring in the mid-rapidity region at higher energies.

5. CONCLUDING REMARKS

Our proposed explanation of the ultrasmall effects i-iii listed in the Introduction has two essential ingredients:

A. Following [14], we propose that multiparticle production reactions, also soft ones, involve an Intermediate Parton System (IPS) produced by a QCD parton shower process.

B. Departing from the usual formulations of QCD shower models, we propose that parts of the shower extend very far into the infrared domain and produce globs of ultrasmall partons, i.e., partons of very low virtuality (perhaps $\lesssim 10$ MeV) with very low momenta (perhaps $\lesssim 50$ MeV/c) in the glob restframe. The matter in such an ultrasmall glob can be described as a Cold Quark Gluon Plasma (CQGP), of sizable parton number density but very low mean energy per parton.

In our model, the hadronic effects i and iii are due to the hadronization of ultrasmall globs. Quark-antiquark annihilation and the Compton-like process (7) are proposed to account for the electromagnetic effects ii, more exactly for the (dominant) part of these effects which is in excess of inner bremsstrahlung.
Conventional QCD parton shower models stop the shower development at a parton virtuality $Q^2$ far above $Q^2_{\text{QCD}} \sim 200$ MeV, usually at $Q^2 \sim 1$ GeV. They then proceed by applying an assumed hadronization mechanism for the final partons of the shower, e.g., the Lund string fragmentation which was also used in [13,14]. The reason to stop the shower development at high $Q^2$ is the desire to remain within the domain of applicability of the perturbative parton splitting equations of QCD, i.e., the Altarelli-Parisi equations. Contrary to this, we assume that parton showers can continue down to virtualities in the MeV range, which is very deep into the non-perturbative domain of QCD, with the unavoidable consequence that we have no reliable equations at our disposal.

Evidently, the fact that non-perturbative QCD is still largely an area of ignorance in the Standard Model cannot be taken as an argument against the possible occurrence of ultra-soft parton showers in high energy reactions. On the contrary, our model, if qualitatively correct, could lead to the extraction of new insights in non-perturbative QCD from the various ultra-soft effects which are becoming widely accessible to experimental study. The difficulty remains, however, that no reliable equations are available a priori, with the consequence that all our considerations have to remain qualitative. To go further and propose equations which can be tested quantitatively, one has to make more specific assumptions, keeping in mind that they could easily be wrong even if the qualitative model is correct. This has not been attempted in the present paper.

It is probably in the area of the ultra-soft electromagnetic effects ii that this can be done most readily, since they are less sensitive to the unknown hadronization mechanism of soft and ultra-soft partons. Concerning the latter, simple guesses will have to be tried out, and we expect that useful guidance will be provided by the generalized local parton-hadron duality proposed in [13], which can be extended to low virtuality partons.

As to direct experimental tests of the model at the present qualitative level, some are provided by the fact that it implies positive correlations between all effects i,ii,iii, since they are claimed to have a common origin. In addition there is the relationship to $dN_{\pi^0}/dy$ mentioned in Subsections 4.2 and 4.3. If some of these qualitative predictions turn out to be incorrect, much if not all of the model will have to be abandoned. If they are found to be correct, this will not be enough to establish the validity of the model as such, because other explanations may be found, but it will provide guidance for making the model more quantitative.

We end with two remarks. Firstly, the ultra-soft effect i should have small but perhaps non-negligible consequences for elastic scattering, since the ultra-soft pions should affect the overlap function and give it a small and sharp peak at very small momentum transfer. This could have consequences for the extraction of the real part of the forward scattering amplitude from its interference with the Coulomb amplitude, possibly leading to a reduction of the real part.

Our second remark concerns the relation of our IPS model with the problem of quark-gluon plasma formation in ultra-relativistic nuclear collisions. As repeatedly stressed, our IPS and its ultra-soft components are assumed to occur in elementary collisions. Evidently,
they would also appear in nuclear collisions, giving rise to larger globs of non-thermal QGP with the possibility of long lifetimes. As remarked in [23] this could readily account for the observed $3\gamma$ suppression phenomenon by a non-thermal extension of the Matsui-Satz mechanism based on Debye screening [24]. The main question in our framework is then whether such large globs of plasma would thermalize before their hadronization. A careful study of soft and ultrasonof direct photons and dileptons in nucleus-nucleus collisions may provide a valuable source of information in this respect.

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