LEADING PARTICLES AND DIFFRACTIVE SPECTRA IN THE INTERACTING GLUON MODEL

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Abstract. We discuss the leading particle spectra and diffractive mass spectra from the novel point of view, namely by treating them as particular examples of the general energy flow phenomena taking place in the multiparticle production processes. We argue that they show a high degree of universality what allows for their simple description in terms of the Interacting Gluon Model developed by us some time ago.

1. Introduction

The multiparticle production processes are the most complicated phenomena as far as the number of finally involved degrees of freedom is concerned. They are also comprising the bulk of all inelastic collisions and therefore are very important - if not per se than as a possible background to some other, more specialized reactions measured at high energy collisions of different kinds. The high number of degrees of freedom calls inevitably for some kind of statistical description when addressing such processes. However, all corresponding models have to be supplemented by information on the fraction of the initial energy deposited in the initial object(s) (like fireball(s)) being then the subject of further investigations.

Some time ago we have developed a model describing such energy deposit (known sometimes as inelasticity) and connecting it with the apparent
dominance of multiparticle production processes by the gluonic content of the impinging hadrons, hence its name: Interacting Gluon Model (IGM) (Fowler et al., 1989). Its classical application to description of inelasticity (Duraes et al., 1993) and multiparticle production processes in hydrodynamical model approach (Duraes et al., 1994) was soon followed by more refined applications to the leading charm production (Duraes et al., 1995) and to the (single) diffraction dissociation, both in hadronic reactions (Duraes et al., 1997a) and in reactions originated by photons (Duraes et al., 1997b). These works allowed for providing the systematic description of the leading particle spectra (which turned out to be very sensitive to the presence of diffractive component in the calculations, not accounted for before) (Duraes et al., 1998a) and clearly demonstrated that they are very sensitive to the amount of gluonic component in the diffracted hadron (Duraes et al., 1998b) and (Duraes et al., 1998a). We have found it amusing that all the results above were obtained using the same set of basic parameters with differences arising essentially only because of different kinematical limits present in each particular application (i.e., in different allowed phase space). All this points towards the kind of universality of energy flow patterns in all the above mentioned reactions.

Two recent developments prompted us to return again to the IGM ideas of energy flow: one was connected with the new, more refined data on the leading proton spectra in $e p \rightarrow e' p X$ obtained recently by ZEUS collaboration\footnote{Private information from A. Garfagnini, see also ZEUS Collab. presentation in these proceedings.} (which are apparently different from what has been used by us before in (Duraes et al., 1998a), (Duraes et al., 1998b) and (Duraes et al., 1998a)). The other was recent work on the central mass production in Double Pomeron Exchange (DPE) process reported in (Brandt et al., 2002) allowing in principle for deduction of the Pomeron-Pomeron total cross section $\sigma_{IP-IP}$. In what follows we shall therefore provide a brief description of IGM, stressing the universality of energy flow it provides and illustrating it by some selected examples from our previous works. The new results of ZEUS will be then shown again and commented. Finally, we shall present our recent application of the IGM to the DPE processes as well (Duraes et al., 2002).

2. IGM and some of its earlier applications

The main idea of the model is that nucleon-nucleon collisions (or any hadronic collisions in general) at high energies can be treated as an incoherent sum of multiple gluon-gluon collisions, the valence quarks playing a secondary role in particle production. While this idea is well accepted for
large momentum transfer between the colliding partons, being on the basis of some models of minijet and jet production (for example HIJING (Wang et al., 92)), in the IGM its validity is extended down to low momentum transfers, only slightly larger than $\Lambda_{QCD}$. At first sight this is not justified because at lower scales there are no independent gluons, but rather a highly correlated configuration of color fields. There are, however, some indications coming from lattice QCD calculations, that these soft gluon modes are not so strongly correlated. One of them is the result obtained in (Giacomo et al., 1992), namely that the typical correlation length of the soft gluon fields is close to 0.3 fm. Since this length is still much smaller than the typical hadron size, the gluon fields can, in a first approximation, be treated as uncorrelated. Another independent result concerns the determination of the typical instanton size in the QCD vacuum, which turns out to be of the order of 0.3 fm (Shaefer et al., 1998). As it is well known (and has been recently applied to high energy nucleon-nucleon and nucleus-nucleus collisions) instantons are very important as mediators of soft gluon interactions (Shaefer, 1998). The small size of the active instantons lead to short distance interactions between soft gluons, which can be treated as independent.

These two results taken together suggest that a collision between the two gluon clouds (surrounding the valence quarks) may be viewed as a sum of independent binary gluon-gluon collisions, which is the basic idea of our model. The interaction follows then the usual IGM picture (Fowler et al., 1989) and (Duraes et al., 1998a), namely: the valence quarks fly through essentially undisturbed whereas the gluonic clouds of both projectiles interact strongly with each other (by gluonic clouds we understand a sort of “effective gluons” which include also their fluctuations seen as $\bar{q}q$ sea pairs) forming a kind of central fireball (CF) of mass $M$. The two impinging projectiles (usually protons/antiprotons and mesons) loose fractions $x$ and $y$ of their original momenta and get excited forming what we call leading jets (LJ’s) carrying $x_p = 1 - x$ and $x_{\bar{p}} = 1 - y$ fractions of the initial momenta. Depending on the type of the process under consideration one encounters different situation depicted in Fig. 1. In non-diffractive (ND) processes one is mainly interested only in CF of mass $M$, in single diffractive (SD) ones in masses $M_X$ or $M_Y$ (comprising also the mass of CF) whereas in double Pomeron exchanges (DPE) in a special kind of CF of mass $M_{XY}$. The only difference between ND and SD or DPE processes is that in the later ones the energy deposition is done by a restricted bunch of gluons which in our language are forming what is regarded as a kind of “kinematical” Pomeron (IP), the name which we shall use in what follows.

The central quantity in IGM is then the probability to form a CF carrying momentum fractions $x$ and $y$ of two colliding hadrons (Fowler et al.,
Figure 1. Left panel: schematic IGM pictures for (a) non-diffractive (ND), (b) and (c) single diffractive (SD) and (d) double Pomeron exchange (DPE) processes. Their corresponding phase space limits are displayed on the right panel. The $\frac{1}{2} \ln \frac{5}{y}$ line in the right (a) panel indicates the rapidity $Y$ of the produced mass $M$.

1989) and (Duraes et al., 1998a) which is given by:

$$\chi(x, y) = \frac{\chi_0}{2\pi \sqrt{D_{xy}}} \cdot \exp \left\{ -\frac{1}{2D_{xy}} \left[ (y^2)(x - \langle x \rangle)^2 + (x^2)(y - \langle y \rangle)^2 \right] \right\}$$

$$\times \exp \left\{ -\frac{1}{D_{xy}} (xy)(x - \langle x \rangle)(y - \langle y \rangle) \right\}, \quad (1)$$

where $D_{xy} = \langle x^2 \rangle \langle y^2 \rangle - \langle xy \rangle^2$ and

$$\langle x^n y^m \rangle = \int_0^{x_{\text{max}}} dx' x'^n \int_0^{y_{\text{max}}} dy' y'^m \omega(x', y'), \quad (2)$$

with $\chi_0$ defined by the normalization condition, $\int_0^1 dx \int_0^1 dy \chi(x, y) \theta(xy - K_{\text{min}}^2) = 1$, where $K_{\text{min}} = \frac{m_0}{\sqrt{s}}$ is the minimal inelasticity defined by the mass $m_0$ of the lightest possible CF. The spectral function, $\omega(x', y')$, contains all the dynamical input of the IGM. Their soft and semihard components are given by (cf. (Duraes et al., 1993)):

$$\omega(x', y') = \omega^{(S)}(x', y') + \omega^{(H)}(x', y') \quad (3)$$

with

$$\omega^{(i)}(x', y') = \frac{\hat{\sigma}_{gg}^{(i)}(x'y's)}{\sigma(s)} G(x') G(y') \theta \left(x'y' - [K_{\text{min}}^{(i)}]^2\right), \quad (4)$$
where \( i = S, H \), and \( K_{\text{min}}^{(S)} = K_{\text{min}} \) whereas \( K_{\text{min}}^{(H)} = 2p_{T_{\text{min}}} / \sqrt{s} \). The values of \( x_{\text{max}} \) and \( y_{\text{max}} \) depend on the type of the process under consideration (cf. Fig. 2). For ND processes \( x_{\text{max}} = y_{\text{max}} = 1 \) (all phase space above the minimal one is allowed) whereas for SD and DPE there are limitations seen in Fig. 2 and discussed in more detail in the appropriate sections below. Here \( G \)'s denote the effective number of gluons from the corresponding projectiles (approximated in all our works by the respective gluonic structure functions), \( \hat{\sigma}_{gg}^{S} \) and \( \hat{\sigma}_{gg}^{H} \) are the soft and semihard gluonic cross sections, \( p_{T_{\text{min}}} \) is the minimum transverse momentum for minijet production and \( \sigma \) denotes the impinging projectiles cross section.

Let us close this section by mentioning that, as has been shown in (Fowler et al., 1989), (Duraes et al., 1994) and (Duraes et al., 1995), IGM can describe both the hadronic and nuclear collision data (providing initial conditions for the Landau Hydrodynamical Model of hadronization (Duraes et al., 1994)) as well as some peculiar, apparently unexpected features in the leading charm production (Duraes et al., 1995) (mainly via its strict energy-conservation introducing strong correlations between production from the CF and LJ). It was done with the same form of the gluonic structure function in the nucleon used: \( G(x) = p(m + 1)(1 - x)^{m} / x \) with defold value of \( m = 5 \) and with the fraction of the energy-momentum allocated to gluons equal to \( p = 0.5 \) and with \( \sigma_{gg}^{(i)}(xys) = \text{const} \) (notice that results are sensitive only to the combination of \( p^{2}\sigma_{gg} / \sigma \)).

3. Single Diffractive processes in the IGM

In the last years, diffractive scattering processes received increasing attention mainly because of their potential ability to provide information about the most important object in the Regge theory, namely the Pomeron (IP), its quark-gluonic structure and cross sections. Not entering the whole discussion (Goulianos, 1983) \(^2\) we would like to show here the possible approach, based on the IGM, towards the mass(\( M_{X} \)) distributions provided by different experiments. In Figs. 1b and 1c the understanding of what such mass means in terms if the IGM is clearly shown: it contains both the central fireball and the LJ from the initial particle which got excited. The only difference between it and, say, the corresponding object which could be formed also in Fig. 1a is that the energy transfer from the diffracted projectile is now done by the highly correlated bunch of gluons denoted IP which are supposed to be in the colour singlet state. The other feature also seen in Fig. 1 (right panel) is that now only the limited part of

\(^2\)See also talk by K.Goulianos in these proceedings.
the phase space supporting the \( \chi(x, y) \) distribution is allowed and that the limits depend on the mass \( M_X \) we are going to produce (and observe).

Figure 2. Examples of diffractive mass spectra for (a) \( p\bar{p} \) collisions compared with Tevatron data (Abe et al., 1994) (Fig. 4 from (Duraes et al., 1997a)) and for (b) \( \gamma p \) collisions compared with H1 data (Adloff et al., 1997) (Fig. 2b from (Duraes et al., 1997b), Vector Dominance Model has been used here with \( G_\rho(x) = G_\pi(x) = 2p(1-x)/x \); the different curves correspond to different choices of \((m_0 \text{ GeV}, \sigma \text{ mb })\): I= (0.31, 2.7), II= (0.35, 2.7), III= (0.31, 5.4) and IV= (0.35, 5.4)).

In technical terms it means that in comparison to the previous applications of the IGM we are free to change both the possible shape of the function \( G_{IP}(x) \) (telling us the number of gluons participating in the process) and the cross section \( \sigma \) in the spectral function \( \omega \) in eq. (4) above. Actually we have found that we can keep the shape of \( G(x) \) the same as before and the only change necessary (and sufficient) to reach agreement with data is the amount of energy-momentum \( p = p_{IP} \) allocated to the impinging hadron and which will find its way in the object we call \( IP \). It turns out that \( p_{IP} \approx 0.05 \) (to be compared with \( p \approx 0.5 \) for all gluons encountered so far). In Fig. 3 we provide a sample of results taken from (Duraes et al., 1997a) and (Duraes et al., 1997b). They all have been obtained by putting \( x_{\text{max}} = 1 \) and \( y_{\text{max}} = M_X^2/s \) in eq. (2) above and by writing

\[
\frac{dN}{dM_X^2} = \int_0^1 dx \int_0^1 dy \chi(x, y) \delta \left( M_X^2 - sy \right) \Theta \left( xy - K_{\text{min}}^2 \right). \tag{5}
\]

As can be explicitly shown the characteristic \( 1/M_X^2 \) behaviour of diffractive mass spectra are due to the \( G(x) \sim 1/x \) behaviour of the gluonic structure functions for small \( x \). The full formula results in small deviations following precisely the trend provided by experimental data (and usually attributed
in the Regge model approach to the presence of additional Reggeons (Goulianos, 1983)).

4. Leading Particle spectra in the IGM

With the above development of the IGM one can now think about the systematic survey of the leading particle spectra, both in hadronic and in $\gamma p$ collisions (Duraes et al., 1998a) (cf. Figs. 4 and 5). The specific prediction of the IGM connected with the amount of gluons in the hadron available for interactions (i.e., for the slowing down of the original quark content of the projectile) has been discussed in (Duraes et al., 1997a), (Duraes et al., 1997b) and (Duraes et al., 1998b), (Duraes et al., 1998a), and shown here in Fig. 6. The leading particle can emerge from different regions of the phase space (cf. Figs. 1) and distribution of its momentum fraction $x_L$ is given by (Duraes et al., 1997a):

$$F(x_L) = (1 - \alpha) \int_{x_{min}}^{1} dx \chi^{(nd)}(x; y = 1 - x_L) +$$
$$\sum_{j=1,2} \alpha_j \int_{x_{min}}^{1} dx \chi^{(d)}(x; y = 1 - x_L),$$

(6)

where $\alpha = \alpha_1 + \alpha_2$ is the total fraction of single diffractive ($d$) events (from the upper and lower legs in Fig. 1, respectively, both double DD and DPE events are neglected here) and where

$$x_{min} = \text{Max} \left[ \frac{m_0^2}{(1 - x_L)s}; \frac{(M_{LP} + m_0)^2}{s} \right]$$

(7)

with $M_{LP}$ being the mass of the LP under consideration. Notice that the $\alpha$ is essentially a new parameter here, which should be of the order of the ratio between the total diffractive and total inelastic cross sections (Duraes et al., 1997a). All other parameters leading to results in Fig. 4 are the same as established before.

We want to stress here the fact that the fair agreement with data observed in the examples shown in Figs. 4 and 5 is possible only because the diffraction processes have been properly incorporated in calculating the LP spectra (Duraes et al., 1997a). As far as the energy flow is concerned the IGM works extremely well (including the pionic LP not shown here but

3In what concerns comparison with ZEUS data see also presentation of ZEUS Collab. in these proceedings. Our present results differ from Fig. 4 in (Duraes et al., 1997a) where the preliminary ZEUS data were used instead. The only difference between the two fits is that whereas in (Duraes et al., 1997a) we were assuming that 30% of the LP comes from diffraction, now it is only 10%.
Figure 3. (a) Example of comparison of our LP spectra $F(x_L)$ with data from (Barton et al., 1983) and (Brenner et al., 2002) (Fig. 2a from (Duraes et al., 1997a)). (b) Comparison between our calculation and the new data on the leading proton spectrum measured at HERA by the ZEUS Collab. (c) Fits to leading $J/\Psi$ spectra as given by ZEUS and H1 groups (Aid et al., 1996), (Derrick et al., 1995) and (Breitweg et al., 1997) (cf. (Duraes et al., 1998b) and (Duraes et al., 1998a); the fixed value of $\sigma^{inel}_{J/\Psi - p} = 9 \text{ mb}$ has been used and results for three different choices of $p_{J/\Psi}$ are displayed: 0.066 - dashed line, 0.033 - solid line and 0.016 - dotted line).

discussed in (Duraes et al., 1997a)) with essentially two parameters only: the nonperturbative gluon-gluon cross section and the fraction of diffractive events. At the same time, assuming the Vector Dominance Model and replacing impinging photon by its hadronic component (as in Fig. 3b), we are able to describe also the leading proton spectra observed in $e - p$ reactions. Also here the inclusion of diffractive component turns out to be crucial factor to get agreement with data. We can also describe fairly well pionic LP (not shown here, cf. (Duraes et al., 1997a)) and the observed differences turns out to be due to their different gluonic distributions. The
crucial role played by the parameter $p$ representing the energy-momentum fraction of a given hadron allocated to gluons is best seen in the Fig. 3c example showing fit to data for leading $J/\Psi$ photoproduction (Aid et al., 1996), (Derrick et al., 1995) and (Breitweg et al., 1997). It turns out that (after accounting for the proper kinematics in (7) and presence of diffraction processes as discussed above) the only parameter to which results are really sensitive is $p = p^{J/\Psi}$ which, as shown in Fig. 3c, has to be astonishingly small, $p^{J/\Psi} = 0.033$. However, closer scrutiny shows us that this is exactly what could be expected from the fact that charmonium is a non-relativistic system and almost all its mass comes from the quark masses leaving therefore only small fraction,

$$p^{J/\Psi} = \frac{M_{J/\Psi} - 2m_c}{M_{J/\Psi}} \simeq 0.033,$$

for gluons (here $m_c = 1.5$ GeV and $M_{J/\Psi} = 3.1$ GeV).

5. Double Pomeron Exchange in the IGM

Our latest application of the IGM discussed here will be for the DPE processes seen as a specific energy flow (cf. Fig. 1d) taking place from both colliding particles and directed into the central region. The difference between it and the "normal" energy flow as represented by Fig. 1a is that now the gluons involved in this process must be confined to what is usually referred to as Pomeron ($IP$). Such process was recently measured by UA8 (Brandt et al., 2002) and used (using the normal Reggeon calculus

![Figure 4](image_url). Our fits to two types of DPE diffractive mass distribution given by (Brandt et al., 2002) with $\sigma_{IP-IP} = 1$ mb (solid lines) and 0.5 mb (dashed lines).
arguments) to deduce the \( IP - IP \) cross section, \( \sigma_{IP-IP} \). It turned out that using this method one gets \( \sigma_{IP-IP} \) which apparently depends on the produced mass \( M_{XY} \). This fact was tentatively interpreted as signal of glueball formation (Brandt et al., 2002). However, when seen from the IGM point of view mentioned above, where

\[
\frac{1}{\sigma} \frac{d\sigma}{dM_{XY}} = \frac{2M_{XY}}{s} \int_{\frac{M_{XY}^2}{x}}^{1} \frac{dx}{x} \chi \left( x, y = \frac{M_{XY}^2}{xs} \right) \Theta \left( M_{XY}^2 - m_0^2 \right),
\]

the (Brandt et al., 2002) data can be fitted (see Fig. 4) with the same set of parameters as used previously to describe the SD processes (Duraes et al., 1997a) and (Duraes et al., 1997b) and with constant value of \( \sigma_{IP-IP} = 0.5 \) mb (which is new parameter here). No glueball concept is needed here.

6. Summary and conclusions

The picture which is emerging from the above discussion is that the energy flows, which are present in all multiparticle production reactions, are apparently a kind of universal phenomenon in the following sense: they are all sensitive mainly to the gluonic content of the colliding projectiles (i.e., both to the number of gluons as given by the form of the function \( G(x) \) and to the amount of energy-momentum of the hadron, \( p \), they carry and to the gluonic cross section which defines the actual effectiveness of the gluonic component in the energy transfer phenomenon). Their sensitivity to other aspects of the production process (except of kinematical limits provided by the observed masses, as illustrated in Fig. 1) is only of secondary importance.

To close our arguments two other applications of IGM should be, however, tested: whether it can also describe the final, yet unchecked energy flow pattern as the one provided by the Double Diffraction Dissociation processes and whether it can be applied in such simple form also to reactions with nuclei (first attempts were already done at the very beginning of the history of IGM in (Fowler et al., 1989), but they were too crude to be convincing at present). We plan to address these questions elsewhere.

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