

UNIVERSIDADE DE SÃO PAULO

**INSTITUTO DE FÍSICA
CAIXA POSTAL 66318
05389-970 SÃO PAULO - SP
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INTERACTING GLUON MODEL**

F.O. Durães, F.S. Navarra, C.A.A. Nunes
Instituto de Física, Universidade de São Paulo

G. Wilk
Soltan Institute for Nuclear Studies, Nuclear Theory Department
ul. Hoza 69, 00-681 Warsaw, Poland

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LEADING CHARM PRODUCTION IN THE INTERACTING GLUON MODEL

F.O. Durães^{1*}, F.S. Navarra^{1,2†}, C.A.A. Nunes^{1‡} and G. Wilk^{2§}

¹Instituto de Física, Universidade de São Paulo
C.P. 20516, 01452-990 São Paulo, SP, Brazil

²Soltan Institute for Nuclear Studies, Nuclear Theory Department
ul. Hoża 69, 00-681 Warsaw, Poland

ABSTRACT

We discuss leading charm production in connection with energy deposition in the central rapidity region. Special attention is given to the correlation between production in central and fragmentation regions. If the fraction of the reaction energy released in the central region increases the asymmetry in the x_F distributions of charmed mesons will become smaller. We illustrate this quantitatively with simple calculations performed using the Interacting Gluon Model. Leading beauty production is also considered.

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*e-mail: dunga@uspif.if.usp.br

†e-mail: navarra@uspif.if.usp.br

‡e-mail: cnunes@uspif.if.usp.br

§e-mail: wilk@fuw.edu.pl

Several experiments have reported [1] a significant difference between the x_F dependence of leading and nonleading charmed mesons. It was not possible to explain these data with the usual perturbative QCD [2] or with the string fragmentation model contained in PYTHIA [3] and some alternative mechanisms have been advanced. The most detailed data analysis, including predictions for asymmetry and leading particle effect at higher energies, has been carried out with the intrinsic charm model [4] (ICM). In this model the essential ingredient for a good description of asymmetries is the recombination mechanism which binds together the intrinsic (fast) charm quarks and the valence quarks of the projectile. Apart from this fast component there is a slow one, which populates predominantly the central rapidity (low x_F) region and is given by perturbative QCD. The ICM is thus a two-component model where the central (parton fusion) and fragmentation (containing intrinsic charm) components are completely independent and added in a simple way. In particular, there is *no energy conservation constraint* imposed on both components, which would obviously result in some simple kinematical correlations between them.

The purpose of this work is to show that such kinematical correlation between central and non-central production is relevant for the study of the observed asymmetries in the production of charmed mesons and that it is also connected to another characteristic of high energy multiparticle production processes, namely to the inelasticity K of reaction. It defines the fraction of the initial energy \sqrt{s} which is released and deposited in the central region of reaction. In particular its energy (\sqrt{s}) dependence will be important here. All models that address charm production in the central region predict that there is no asymmetry in this region. Asymmetry comes from the fragmentation (large rapidity y) region. Therefore, if K increases with energy there will be less energy available in the large y region and this will result in a softening of the leading x_F distributions. Notice that this

is independent of all ingredients of the hadronization process since they are universal and energy independent (like, for example, the fragmentation functions). The x_F distributions of the leading charmed particles will thus eventually merge with the distribution of the centrally produced charmed particles, which will then become broader. The asymmetry will then not be observed! The opposite might also be true if K decreases with energy. In this case the leading system will carry proportionally more and more energy, implying a faster leading charm and resulting in stronger asymmetry [5].

The asymmetry problem can therefore be well formulated just in terms of kinematical considerations. All dynamics will show itself only in the way through which initial energy of projectiles will be distributed in rapidity space. For example, one would naively expect that, if perturbative QCD becomes more important at higher energies (due to, for example, increased minijet activity), the central production (and also energy deposition in central region) will become dominant and the asymmetry will decrease or even disappear. This goes along with the expected increase with energy of inelasticity deduced from the analysis of accelerator and cosmic ray data [6].

In what follows we shall therefore study leading charm production in terms of the Interacting Gluon Model (IGM) [7], which has been invented to describe the inelasticity and its energy behaviour and recently used also to successfully describe many aspects of multiparticle production (including its semi-hard minijets component, which can be important for charm production at high energies) [7].

Since the IGM has already been described previously in great detail [7] we shall provide here, for completeness, only the most basic formulas and concentrate our attention on the specific mechanisms of charm production and on the calculation of the asymmetries between leading and nonleading charm mesons. The asymmetry has been most accurately measured in the πp scattering, therefore we shall start discussing this process first [8]. In

Fig. 1a we show the IGM description of the energy flow in a hadron-hadron collision at high energies. Through the cooperative action of a certain number of soft gluons, carrying an overall momentum fraction x_1 of the incoming pion, colliding with a similar bunch of gluons coming from the target nucleon and carrying fraction x_2 of its momentum, an object called central fireball (CF) is formed. It will decay later on producing observed secondaries. In the IGM [7] the probability for this to happen is given by the function $\chi(x_1, x_2)$. The pion remnants leaving the central region (i.e., their valence quarks plus some gluons which did not interact) carrying momentum x_L are called in the IGM the *leading jet* (LJ) and, being themselves excited objects, may also produce particles (including D mesons). From the basic function $\chi(x_1, x_2)$ we can compute the Feynman momentum distributions of the CF, $\chi(x_{CF})$ ($x_{CF} = x_1 - x_2$), and of the LJ, $f(x_L)$, by a simple change of variables :

$$\chi(x_{CF}) = \int_0^1 dx_1 \int_0^1 dx_2 \delta(x_{CF} - x_1 + x_2) \chi(x_1, x_2) \theta(x_1 x_2 s - 4m_D^2) \quad (1)$$

$$f_{LJ}(x_L) = \int_0^1 dx_1 \int_0^1 dx_2 \delta(1 - x_1 - x_L) \chi(x_1, x_2) \theta(x_1 x_2 s - m_0^2) \quad (2)$$

where m_D (1.8 GeV) and m_0 are the masses of the D meson and of the lightest state produced in such collisions [7]. In the above equations we clearly see the connection between central and fragmentation production. The momentum distributions of the systems which will later give origin to charmed particles are derived from the same quantity $\chi(x_1, x_2)$. Moreover, $\chi(x_{CF})$ and $f(x_L)$ carry all the energy (\sqrt{s}) dependence of the process, which is both explicit, in the theta functions, and implicit, since $\chi(x_1, x_2)$ depends on \sqrt{s} . In Fig. 1b we show central $D\bar{D}$ meson production where $D(\bar{D})$ is any D meson carrying a $c(\bar{c})$ quark. Notice that, in the spirit of IGM, the central production ignores the valence quarks of target and projectile (defined here as those which carry the essential quantum numbers of the colliding pions and protons) which, in the first approximation, just "fly

through". Because of this, the centrally produced D 's will not show any leading particle effect. There are two distinct ways to produce D mesons out of LJ's: fragmentation and recombination. It is assumed here that, whenever energy allows, we shall have also $\bar{c}c$ pairs in the LJ (produced, for example, from the remnant gluons present there). These charmed quarks may undergo fragmentation into D mesons, as shown in Fig. 1c, but may also as well recombine with the valence quarks as depicted in Fig. 1d. It turns out that only this last process will produce asymmetry.

In the case of pion-nucleon scattering, the measured leading charmed mesons are D^- and the nonleading are D^+ . We shall now write the Feynman x_F single inclusive distribution of D^- mesons produced by the CF, by the fragmentation in the LJ (F) and by the recombination there (R):

$$\frac{d\sigma^{CF}}{dx_{D^-}} = \int_{x_{D^-}}^1 dx_{CF} \chi(x_{CF}) \int_{x_{D^-}}^{x_{CF}} dx_{\bar{c}} g(x_{\bar{c}}) D\left(\frac{x_{D^-}}{x_{\bar{c}}}\right) , \quad (3)$$

$$\frac{d\sigma^F}{dx_{D^-}} = \int_{x_{D^-}}^1 dx_L f_{LJ}(x_L) \int_{x_{D^-}}^{x_L} dx_{\bar{c}} g(x_{\bar{c}}) D\left(\frac{x_{D^-}}{x_{\bar{c}}}\right) , \quad (4)$$

$$\frac{d\sigma^R}{dx_{D^-}} = \int_{x_{D^-}}^1 dx_L f_{LJ}(x_L) \int dx_c \int dx_{\bar{c}} \int dx_{\bar{a}} \int dx_d g(x_c) g(x_{\bar{c}}) f(x_{\bar{a}}) f(x_d) \cdot \delta(x_{D^-} - x_{\bar{c}} - x_d) \delta(x_L - x_{\bar{c}} - x_c - x_d - x_{\bar{a}}) , \quad (5)$$

where $f(x)$ and $g(x)$ are distribution functions of valence and charm quarks respectively and the $D(z)$'s are charm quark fragmentation functions [4]. The D^+ momentum distributions are given by (3) and (4) with the replacements: $D^- \rightarrow D^+$, $\bar{c} \rightarrow c$. These nonleading mesons will not be produced by recombination (eq. (5)). The functions $f(x)$ and $g(x)$ are essentially unknown since they are momentum distributions of partons inside the CF and inside the LJ after the collision. Following our assumption that the valence quarks interact weakly we shall approximate $f(x)$ by the initial state valence quark distributions and take them from reference [9]. As for the charm quark distribution, $g(x)$,

the situation is less clear. The $c - \bar{c}$ pairs do not come directly from the sea: in the CF they are produced and in the LJ they may be excited. It is therefore reasonable to think that the charm quarks will be somewhat faster than ordinary sea quarks. Accordingly we shall use for $g(x)$ the ansatz proposed by Barger and collaborators [10]:

$$g(x) = \left(\frac{1-x}{x}\right)^{1/2} \quad (6)$$

which is less singular than $1/x$ but still much softer than an intrinsic charm distribution which behaves typically like $x(1-x)$. The fragmentation functions have the Peterson form [11]:

$$D_{c \rightarrow D}(z) = \frac{N}{z[1-1/z - \epsilon/(1-z)]^2} \quad (7)$$

where $\epsilon \simeq \frac{(m_q^2 + p_{qT}^2)}{(m_Q^2 + p_{QT}^2)}$, m_q, p_{qT}, m_Q, p_{QT} are mass and transverse momentum of the light and of the heavy quark respectively and N is a normalization constant. In the present case $\epsilon \simeq 0.06$. In Fig. 2a we show the (unnormalized) contributions coming from the three processes above (eqs. (3), (4) and (5)). As expected, central production (solid line) leads to the softest D meson x_F distribution, recombination in the leading jet (dotted line) leads to the hardest final distribution and leading jet fragmentation (dashed line) lies in between. This is so because $\chi(x_{CF})$ is softer than $f(x_L)$ and because recombination adds momenta whereas fragmentation causes always some deceleration. Note that, although flat, the dashed and dotted curves have a pronounced maximum at very low x_D . This is a direct consequence of the behaviour of $g(x)$. If instead of the form (6) we use an intrinsic charm distribution we will obtain a strong suppression at low x and a maximum around $x_D = 0.4 - 0.6$. A final comment on this figure is that our distribution of centrally produced D 's (solid line) is broader than the one obtained from perturbative QCD. This is so because the cooperative mechanism adds together soft gluons, increasing the energy released in the central region, favouring higher values of x_1 and x_2 (in fig. 1a) and

allowing for fluctuations with higher x_{CF} . Considering all that was said above we can conclude that the IGM (like the ICM) is a two component model in which the components are not very much different in shape from each other (in sharp contrast to what happens with the components of the ICM) and have some overlap. Because of this we expect to find smaller asymmetries than those found in ref. [4], but this depends, of course, on how one mixes the different components. In what follows we write the differential cross section as the sum of a central fireball (CF) and leading jet (LJ) component and the last one as the sum of a fragmentation (F) and a recombination (R) component, using a similar notation as in ref. [4]:

$$\frac{1}{\sigma} \frac{d\sigma}{dx_{D^-}} = (1-\eta) \frac{1}{\sigma^{CF}} \frac{d\sigma^{CF}}{dx_{D^-}} + \eta \frac{1}{\sigma^{LJ}} \frac{d\sigma^{LJ}}{dx_{D^-}}, \quad (8)$$

$$\frac{1}{\sigma^{LJ}} \frac{d\sigma^{LJ}}{dx_{D^-}} = (1-\xi) \frac{1}{\sigma^F} \frac{d\sigma^F}{dx_{D^-}} + \xi \frac{1}{\sigma^R} \frac{d\sigma^R}{dx_{D^-}} \quad (9)$$

where the mixture parameters are ξ ($0 \leq \xi \leq 1$) and

$$\eta = \frac{\sigma^{LJ}}{\sigma^{CF} + \sigma^{LJ}} \quad (10)$$

In the case of the D^+ distribution, the expressions above are the same but $\xi = 0$.

The ICM parameter η has been chosen 0.2 because of an analogy between σ_{ic} (our σ^{LJ}) and the diffractive charm cross section. On the other hand, in the Valon Model [12] the same data are addressed without any central component. This would correspond to taking $\eta = 1$. Here, because of the kinematical mixing between CF and LJ the value of η is essentially free. In what follows we will choose it to be $\eta = 0.7$. Note also that, in our case, $\xi = 0$ corresponds to no asymmetry. Since existing data on open charm production [1] apparently do not show nuclear effects [13], we use here (as all other models which address these data) the IGM for hadron-nucleon collisions [14].

In Fig. 3 we compare our calculations with WA-82 data. Fig. 3a and 3b show the x_F spectrum of D^+ and D^- , respectively, and Fig. 3c shows the asymmetry which is given by:

$$A(x_F) = \frac{\frac{d\sigma}{dx_{D^-}} - \frac{d\sigma}{dx_{D^+}}}{\frac{d\sigma}{dx_{D^-}} + \frac{d\sigma}{dx_{D^+}}} \quad (11)$$

In Fig. 3b and 3c solid, dashed and dotted lines correspond to $\xi = 0.8, 0.5$ and 0.2 respectively. Data points are from the WA-82, E769 and E791 [15] collaborations. As it can be seen, a satisfactory description of data can be obtained with the IGM. The best description can be obtained with a large amount of recombination ($\xi = 0.8$). This is ultimately due to our choice of $g(x)$. We have checked that the choice of an ordinary sea distribution for the charm quarks in the CF and LJ requires $\eta = 1.0$ and $\xi = 1.0$ for a reasonable fit. The choice of an intrinsic charm distribution allows for small values of η and ξ . The conclusion seems to be that although data do not rule out usual sea distributions as an input, good fits with more reasonable values of the parameters can be obtained using harder charm quark distributions like (6) or the one used in ref. 4.

We consider now the energy dependence of the asymmetry. All details concerning the particularities of charm production are energy independent. In equations (8) and (9) η , ξ and the differential distributions, i.e., respectively normalization and shape of the curves, can depend on \sqrt{s} . For simplicity we shall assume that ξ does not change with the energy. The distributions $\frac{d\sigma}{dx_{D^-}}$ will depend on \sqrt{s} through $\chi(x_{CF})$ and $f_{LJ}(x_L)$. The behaviour of these last functions with \sqrt{s} is shown in Fig. 4a and 4b respectively. We observe a very modest broadening of $\chi(x_{CF})$ implying a small increase of $\langle x_{CF} \rangle$ and a more pronounced softening of $f(x_L)$ with the corresponding reduction of $\langle x_L \rangle$. As for η , an extensive analysis [7] of charged particle production up to Tevatron energies has shown that it decreases by a factor 3 when we go from ISR to Tevatron energies. Assuming a similar reduction for the case of charmed particle production η will change from 0.7 to

0.25 . Considering what was said above we evaluate again all the expressions (1)-(9) at $\sqrt{s} = 1800$ GeV. The resulting asymmetry is shown in Fig. 4c with a dashed line. For comparison we show in the same figure (with a solid line) the asymmetry at $\sqrt{s} = 26$ GeV calculated with the same parameters. It decreases 20% in the region $x_F \geq 0.5$. Although this is not a very impressive change it illustrates the trend. Moreover, we know that the asymmetry goes asymptotically to zero since $\eta \rightarrow 0$. We emphasize that this is so because the IGM (in its version [7]) predicts that at higher energies, because of the action of minijets, the energy deposition in the central region will increase implying two effects : a growth of the central multiplicity (implying thus an increase of $1 - \eta$) and a softening of the leading jet momentum distribution. We can therefore conclude that, irrespective of details of charm production, these both effects combined will reduce the asymmetry. It is interesting to mention that the data collected in figure 3c come from three different collaborations E769,WA-82 and E791 with beam energies of 250,340 and 500 GeV respectively. In the CMS this corresponds to a variation of $\sqrt{s} = 23$ GeV to $\sqrt{s} = 33$ GeV. This energy change is small , the error bars are large and therefore no change in the asymmetry is visible yet. At higher energies there is a chance to experimentally verify this behaviour at RHIC or LHC.

As a straightforward extension of our analysis we calculate now the asymmetry in B meson production. This is done by simply replacing m_D by $m_B = 4.75$ GeV in (1) and $\epsilon = 0.06$ by $\epsilon = 0.006$ in (7). In principle we should also change $g(x)$ but in a first estimate we keep the ansatz (6) . If we would use an intrinsic distribution for $g(x)$ it would be very weakly dependent on the heavy quark mass [4]. In Fig. 5 we show the $\chi(x_{CF})$ distribution for charm (dashed line) and for beauty production (solid line) with the proper change in eq. (1) . The energy is $\sqrt{s} = 26$ GeV . The effect of increasing the production threshold ($m_D \rightarrow m_B$ in the theta function in eq.(1)) is to select events with a

more massive CF and with larger lower limits for x_1 and x_2 , suppressing thus larger values of $x_{CF} = x_1 - x_2$ with respect to charm production (in the limit of total energy deposition , i.e. , $x_1 = x_2 = 1$, the CF would be at rest) . This effect is however very small. This is expected and seen in Fig. 5. In Fig. 6a (6b) we show the x_F distributions of nonleading (leading) D and B mesons. The energy is the same as in Fig. 5 and the parameters are the same as before ($\eta = 0.7$ and $\xi = 0.8$). Nonleading spectra are calculated with eqs. (3) and (4) . The Peterson fragmentation functions , appearing in those equations , are very sensitive to the value of ϵ . In the case of beauty , the strong reduction of ϵ makes the fragmentation function strongly peaked at very large values of z . The emerging B's will therefore be much less decelerated than the D's . This effect compensates the previous one and the final nonleading B distribution is harder than the nonleading D one. The leading distributions include recombination , given by eq. (5) , which is not affected by the change in the heavy quark mass. Because of this , the spectra in Fig. 6b exhibit the same qualitative behaviour (B's faster than D's) seen in Fig. 6a but the difference between B's and D's is smaller. The asymmetries of B^-/B^+ and D^-/D^+ are shown in Fig. 7 with solid and dashed lines respectively for $\sqrt{s} = 26$ and 1800 GeV. The asymmetry in beauty is about 50% weaker than in charm at $x_F = 0.8$ and both show a similar decrease with energy.

In conclusion: the IGM describes the energy flow in high energy hadron collisions. It takes properly into account the correlation between energy deposition in the central region and the leading particle momentum distribution . It accounts for charmed meson production in a natural and satisfactory way and makes the prediction that at higher energies the increase of inelasticity K (see [7]) will lead to the decrease of the asymmetry in heavy quark production. It also predicts a weaker asymmetry for beauty.

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Figure Captions

- Fig. 1** (a) Illustration of a pion-nucleon collision: fractions x_1 and x_2 of the incoming hadrons momenta form a central fireball (CF) with probability $\chi(x_1, x_2)$. Fraction $1 - x_1 = x_L$ is carried by the leading jet (LJ). The leading jet momentum spectrum is $f(x_L)$; (b) Nonleading D meson production by central fireball fragmentation; (c) Nonleading D meson production by leading jet fragmentation; (d) Leading D meson production by leading jet recombination.
- Fig. 2** x_F distributions of D mesons calculated with the IGM. The solid line shows the contribution of the central fireball fragmentation. The dashed line shows the contribution of the leading jet fragmentation and the dotted line shows the contribution of the leading jet recombination.
- Fig. 3** (a) x_F distribution of D^+ mesons calculated with our model and compared with WA-82 data; (b) x_F distribution of D^- mesons calculated with our model and compared with WA-82 data. Solid line corresponds to $\xi = 0.8$ in eq. (9) while dashed and dotted lines correspond to $\xi = 0.5$ and $\xi = 0.2$ respectively; (c) the asymmetry calculated with the IGM and compared with WA-82 (solid circles), with E769 (open squares) and E791 (open triangles) data. Solid, dashed and dotted lines correspond to the same choices of ξ of 3b).
- Fig. 4** (a) Momentum distribution $\chi(x_{CF})$ of the central fireball at $\sqrt{s} = 26$ GeV (solid line) and at $\sqrt{s} = 1800$ GeV (dashed line); (b) momentum distribution $f_{LJ}(x_L)$ of the leading jet at $\sqrt{s} = 26$ GeV (solid line) and at $\sqrt{s} = 1800$ GeV (dashed line); (c) the asymmetry in pion - proton collision calculated with the IGM: solid line corresponds to $\sqrt{s} = 26$ GeV with $\eta = 0.7$ and dashed line corresponds to

$\sqrt{s} = 1800$ GeV with $\eta = 0.25$. In both cases $\xi = 0.8$.

ig. 5 x_F distribution ($\chi(x_{CF})$) of centrally produced $b - \bar{b}$ (solid line) and $c - \bar{c}$ (dashed line) quark pairs.

ig. 6 (a) x_F distribution of nonleading B (solid line) and D (dashed line) mesons; (b) the same as (a) for leading B (solid line) and D (dashed line) mesons. The energy is in both cases $\sqrt{s} = 26$ GeV.

ig. 7 B^-/B^+ (solid lines) and D^-/D^+ (dashed lines) asymmetries at $\sqrt{s} = 26$ and 1800 GeV.

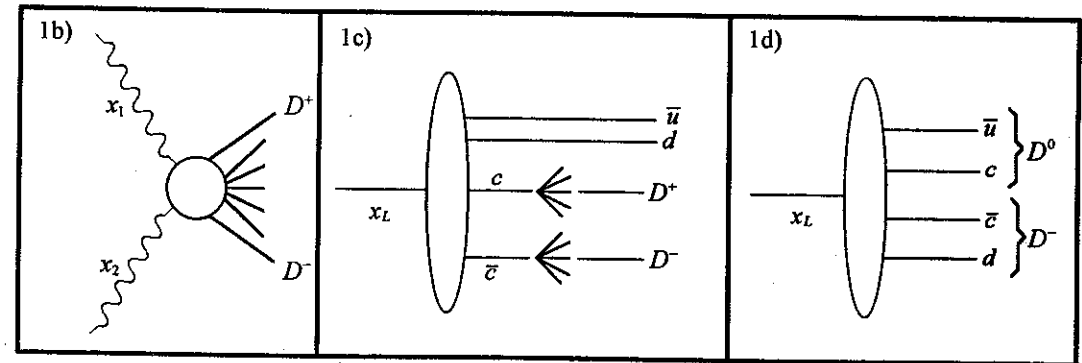
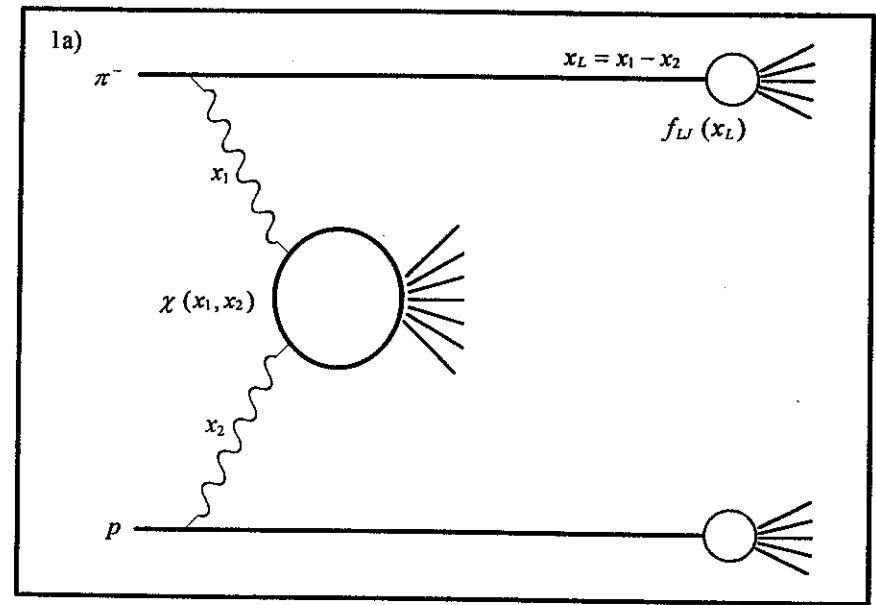


Figure 1

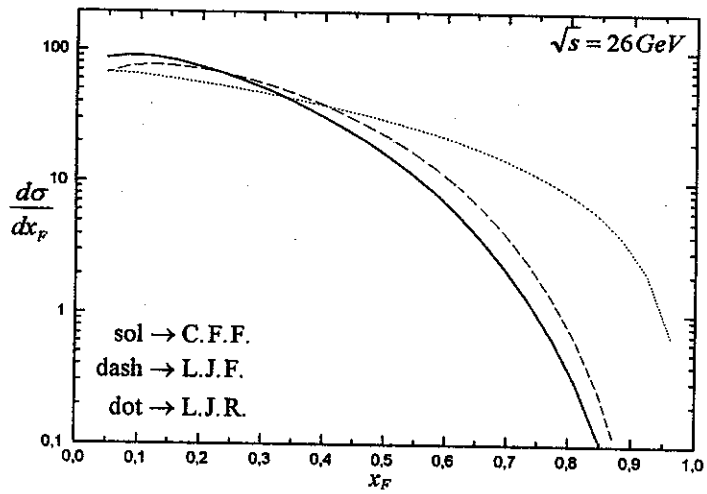


Figure 2

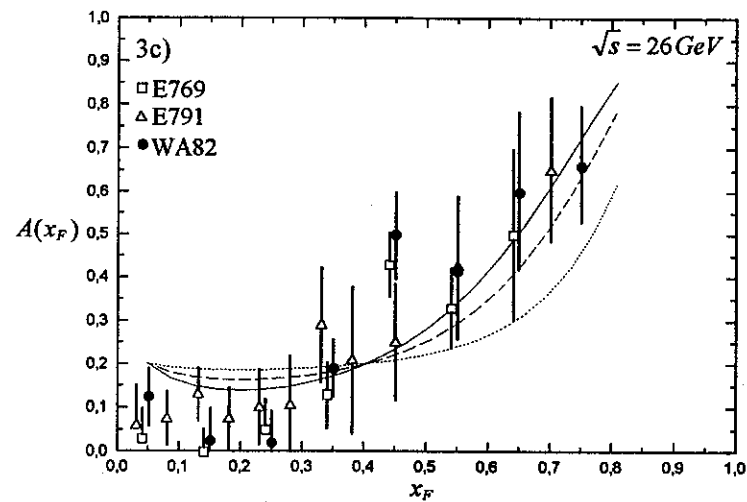
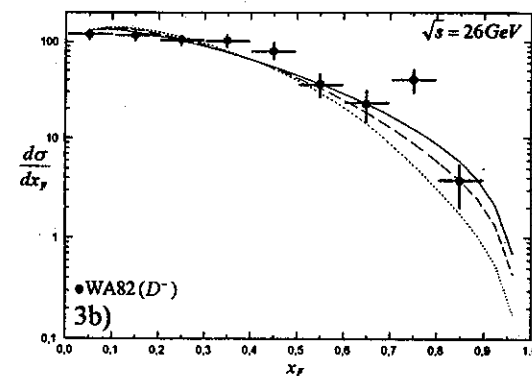
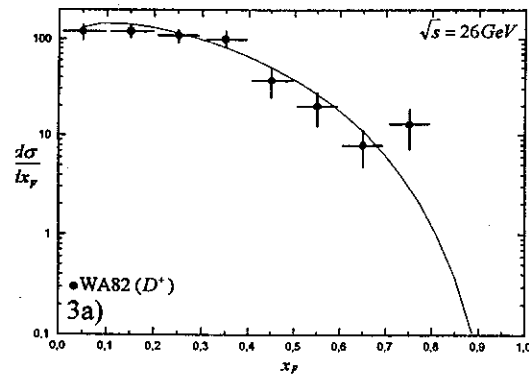


Figure 3

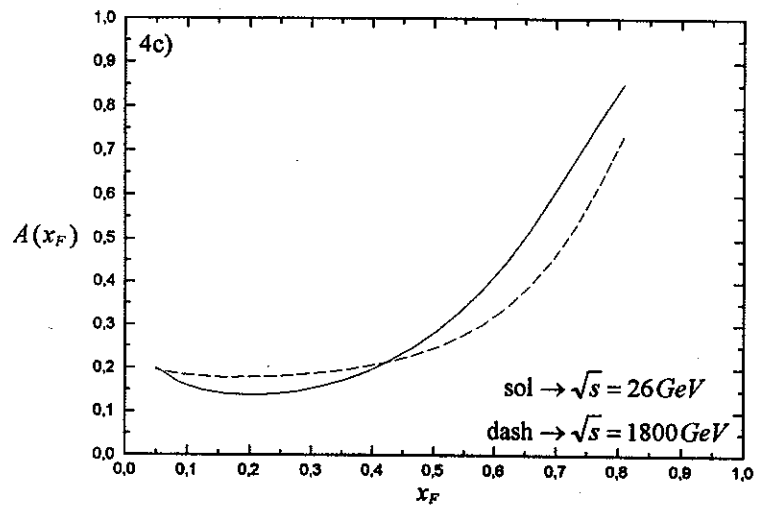
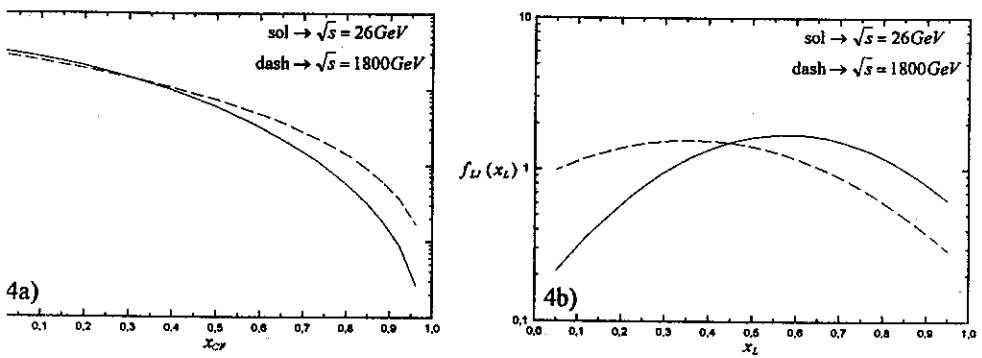


Figure 4

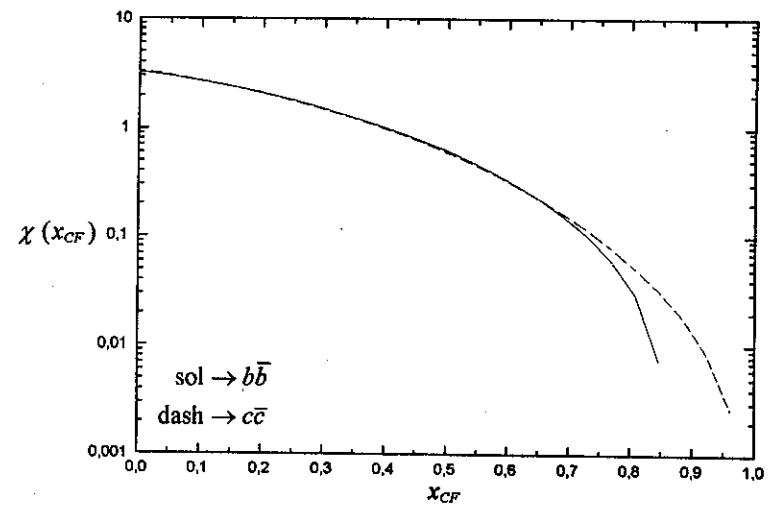


Figure 5

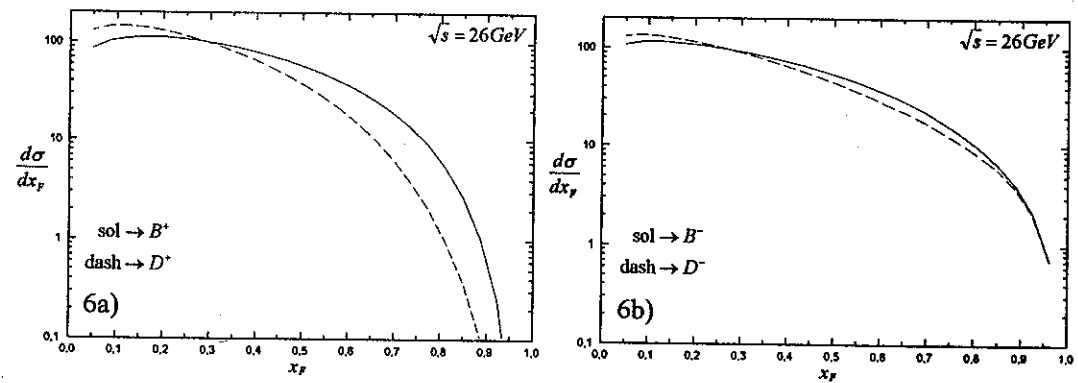


Figure 6

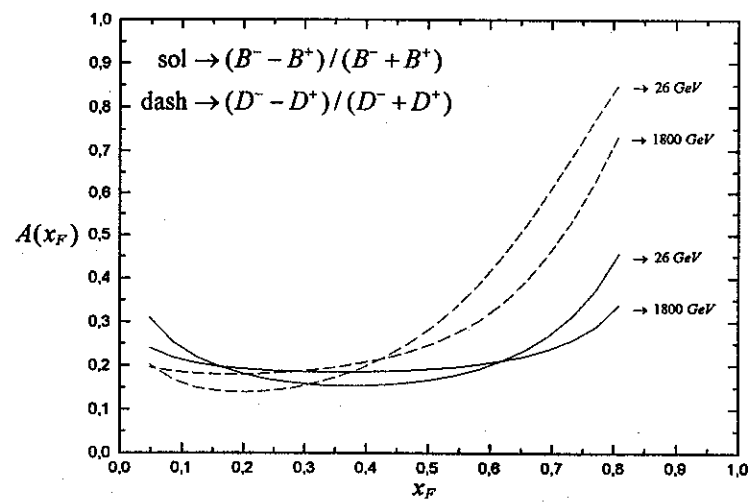


Figure 7