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RAPIDITY AND TRANSVERSE MOMENTUM DISTRIBUTIONS OF HEAVY QUARKS
PRODUCED BY DOUBLE POMERON EXCHANGE^{*)}

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Abstract. Rapidity and transverse momentum distributions of heavy quarks produced by double exchange of Donnachie-Landshoff pomeron are presented and discussed. In the limit of small transverse momentum of the pair, the cross-section is almost independent of the sum of q and $\bar{q}$ rapidities, but does depend on the rapidity difference and (rather strongly) on the transverse momenta of the produced quarks.

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1. INTRODUCTION.

It was pointed out recently [1] that the process of production of a pair of heavy quarks ($c\bar{c}$ or $b\bar{b}$) can serve as an useful test of the model of the pomeron proposed some time ago by Donnachie and Landshoff [2]. It was shown [1,3] that the double pomeron exchange mechanism gives a measurable cross-section for production of such pairs in the central rapidly region at Fermilab and LHC energies. In the present paper we give additional information on differential cross-section for this process, hoping that this shall facilitate the measurements and also allow a more precise comparison of the model with data.

The first calculations of the production of a heavy object by the double-pomeron-exchange mechanism in the Donnachie-Landshoff model were presented in [4] and [5] where the cross-section for production of the Higgs particle was estimated. Our calculation -which is described in some detail in Refs [1] and [3]- follows closely the method used in Ref. [5].

In the next section the results of Ref [1] are described and the necessary notation introduced. In Section 3 the formula for differential cross-section is worked out. The results are discussed in Section 4.

2. MATRIX ELEMENT.

In the Donnachie-Landshoff model, the pomeron exchange process is approximated by exchange of two non-perturbative gluons coupled to one of the quarks or antiquarks of the colliding hadron. The amplitude for pair production in such a model is given [5,6] by the sum of the s-channel discontinuities of the two diagrams of Fig.1 (where also kinematic variables are indicated). It was shown in [1] that this gives for the square of the amplitude (averaged over initial and summed over final spins) the following expression:

$$(1) \quad |W_q|^2 = C (s/m_{11} m_{12})^2 \rho(1-\rho) \delta^{2-2\alpha_1} \delta^{2-2\alpha_2} \exp[2(\rho t_1 + t_2)]$$

where C is a constant (defined below), s is the total cms energy squared and $\rho = (2m/M)^2$, m and M being the masses of the produced quark and of the pair, respectively. Transverse masses of the heavy quarks are denoted by m_{11} and m_{12} . $\alpha(t)$ is the pomeron trajectory taken in the form

$$(2) \quad \alpha(t) = 1 + \epsilon + \alpha' t$$

with $\epsilon = 0.08$ and $\alpha' = 0.25 \text{ GeV}^{-2}$. The phenomenological factor $\exp[2(\rho t_1 + t_2)]$ takes into account the effect of the momentum transfer dependence of the non-perturbative gluon propagator [2] (this factor was neglected in Refs [1] and [3], β is a constant of the order of 1 GeV^{-2}). The formula (1) is an approximation valid in the "double pomeron exchange limit".

$$(3) \quad \delta_i \equiv 1 - k_i \cdot p_i \ll 1 \quad ; \quad i=1,2$$

and for small momentum transfer between initial and final quarks. In the following we shall restrict ourselves to this phase-space region.

The constant C is given by

$$(4) \quad C = \frac{H}{162\pi^2} (G^2 D_0 \mu)^6 (g/G)^4 \mu^2$$

where g is the perturbative quark-gluon coupling at $q^2 = m^2$, G is the coupling of the non-perturbative gluon to a quark, μ is the range of the gluon propagator and D_0 its magnitude at vanishing momentum transfer. From data on elastic scattering of hadrons one infers $G^2 D_0 \mu = 30 \text{ GeV}^{-1}$ and $\mu = 1 \text{ GeV}$ [2]. $H = 1/243$ is the colour factor taking into account the summation over the heavy quark loops and the singlet nature of the pomeron. The non-perturbative coupling constant G is -unfortunately- not well determined by the elastic and diffractive cross-section (which are sensitive only to the product $G^2 D_0$). In the following we shall assume $G^2/4\pi = 1$. One should keep in mind, however, that this number is not really known at present and should be determined from the data [1].

For the experimentally observed process

$$(5) \quad p + p \rightarrow p + p + q + \bar{q}$$

the square of the amplitude is

$$(6) \quad |M_p|^2 = 81 |M_q|^2 [F(t_1) F(t_2)]^2$$

where the factor 81 takes into account the presence of 3 quarks in the proton and $F(t)$ is the nucleon form-factor which shall be approximated

by $F(t) = \exp(\lambda t)$ with $\lambda = 2 \text{ GeV}^{-2}$.

This completes the summary of the results of Ref. [1].

3. DIFFERENTIAL CROSS-SECTION.

Using (6) we obtain for the differential cross-section

$$(7) \quad d\sigma = (2s)^{-1} (2\pi)^{-9} |M_p|^2 d\Phi$$

where $d\Phi$ is the differential phase-space factor

$$(8) \quad d\Phi = d^4k_1 \delta(k_1^2) d^4k_2 \delta(k_2^2) d^4r_1 \delta(r_1^2 - m^2) d^4r_2 \delta(r_2^2 - m^2) * \\ * \delta^4(p_1 + p_2 - k_1 - k_2 - r_1 - r_2)$$

Our aim is to integrate the Eq.(7) over all variables except rapidities and transverse momenta of the heavy quarks. This task is facilitated by observation that the dependence of $|M_p|^2$ on transverse momenta v_1 and v_2 of the final hadrons is given by the gaussian factor

$$(9) \quad \delta(v_1, v_2) = \exp(-L_1 v_1^2 - L_2 v_2^2)$$

where

$$(10) \quad L_{1,2} = 2(\beta + \lambda - \alpha' \log \delta_{1,2}).$$

Consequently, the integral over transverse momenta gives

$$(11) \quad \int d^2v_1 d^2v_2 \delta(v_1, v_2) \delta^2(v_1 + v_2 + u_1 + u_2) = \\ = \frac{\pi}{L_1 + L_2} \exp\left(-\frac{L_1 L_2}{L_1 + L_2} (u_1 + u_2)^2\right) \equiv \delta(u_1 + u_2)$$

where u_1 and u_2 are the transverse momenta of the produced heavy quarks. As expected, the cut-off (9) on the transverse momenta of final protons implies a cut-off on the total transverse momentum of the produced pair.

Integration over longitudinal momenta of the final protons can be performed using the δ -functions expressing conservation of energy and longitudinal momentum. The result is

$$(12) \quad \int d^4k_1 d^4k_2 \delta(k_1^2 - m^2) \delta(k_2^2 - m^2) \delta^2(p_1 + p_2 - k_1 - k_2 - r_1 - r_2) = (2s)^{-1}$$

if

$$(13) \quad m_{i1} \exp(-y_1) + m_{i2} \exp(-y_2) = \delta_1 \gamma_s \\ m_{i1} \exp(-y_1) + m_{i2} \exp(-y_2) = \delta_2 \gamma_s$$

and zero otherwise.

As the next step, we observe that $2 d^2\delta(r^2 - m^2) = dy$, obtaining finally

$$(15) \quad d\sigma = C_E (s/4m^2)^{2\epsilon} m_{i1}^{-2} m_{i2}^{-2} \rho^{1+2\epsilon} (1-\rho) \psi(u_+) d^2u_+ d^2y_1 dy_2$$

where $C_E = 81 C (2\pi)^{-9}/16$, $u_+ = u_1 + u_2$, ψ is the function defined in (11), and $u = (u_1 - u_2)/2$. Furthermore, from (13) we find

$$(16) \quad 4 m^2 \rho^{-1} = s \delta \delta_{1,2} = m_{i1}^2 + m_{i2}^2 + 2 m_{i1} m_{i2} \cosh(y_1 - y_2).$$

The formula (15) is valid in the region of small u_+ , δ_1 and δ_2 . Using (13) this region can be translated into allowed region of transverse momenta and rapidities of the produced quarks.

This completes the calculation of the differential cross-section.

4. DISCUSSION OF THE RESULTS.

The formula (15) for the differential cross-section is only reliable for $u_+ \approx 0$. Furthermore, the function $\psi(u_+)$ gives a gaussian cut-off which limits u_+ to the region smaller than 0.5 GeV, even for moderate δ_1 and δ_2 and is much more effective for very small δ 's. We shall therefore restrict ourselves to the discussion of the formula (15) under the condition

$$(17) \quad u_+ = 0.$$

In this case $u = u_1 = -u_2$ is the transverse momentum of one of the produced quarks. Moreover, the transverse masses of the two quarks are equal to each other and the Eq.(15) simplifies substantially:

$$(18) \quad d\sigma/d^2u_+|_{u_+=0} = C_E (s/4m^2)^{2\epsilon} \pi^2 m_i^{-4} (L_1 + L_2)^{-1+2\epsilon} (1-\rho) dy_1 dy_2 dm_i^2$$

From the definition (10) of L_1 and L_2 one sees that the sum $L_1 + L_2$

depends only on the product $\hat{y}_1 \hat{y}_2$ and thus, as seen from (16) it is independent of the sum $y_1 + y_2$ of the rapidities of the quarks. Therefore the cross-section (18) depends only on the transverse momentum of the produced quarks and on the difference of their rapidities. It should be noted, however, that the kinematic limits of the double-pomeron-exchange region do depend on both the sum and the difference of rapidities, as is clearly seen from (13).

The behaviour of the cross-section is determined mostly by 3 factors:

(a) the threshold factor $(1-\rho)$ which provides a dip at vanishing difference of rapidities and of the momenta of the quarks, (b) the factor $m_1^{-\alpha_{\text{eff}}}$ which dominates the dependence on transverse mass, and (c) the factor $(\cosh(y_1 - y_2)/2)^{1-2\alpha_{\text{eff}}}$ dominating the dependence on difference of rapidities.

In Fig.2 the differential cross section for $b\bar{b}$ production, multiplied by $m_1^{\alpha_{\text{eff}}}$ at two c.m. energies is plotted vs rapidity difference and transverse mass of the quarks. The kinematical limits of the double pomeron exchange region are marked for two extreme cases $y_1 + y_2 = 0$ and $y_2 = 0$ in order to emphasize that, although the cross-section itself does not depend on the sum $y_1 + y_2$, the kinematic limits do.

In conclusion, we have presented the differential cross-section for the production of a pair of heavy quarks by double-pomeron exchange mechanism in the Donnachie-Landshoff model. The cross-section is concentrated at small total transverse momentum of the pair and only marginally depends on the sum of the rapidities of the produced quarks. On the other hand, it shows a rather fast power-law drop with the increasing transverse mass of the produced quarks (approximately as $m_1^{-\alpha_{\text{eff}}}$), and a moderate dependence on the difference of their rapidities. We hope that these results can be verified by future data and thus provide a further test of the Landshoff-Donnachie model of the pomeron.

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FIGURE CAPTIONS

Figure 1. Two diagrams contributing to the amplitude of the process of pair production by double pomeron exchange.

Figure 2. Differential cross-section for the production of a $b\bar{b}$ pair in the double pomeron-exchange process (5) at total c.m. energy 1.8 TeV. The figure shows the differential cross-section at vanishing total transverse momentum of the pair, multiplied by $m_1^{\alpha_{\text{eff}}}$. As explained in the text, this cross-section depends on transverse mass of a quark and on $\bar{b}$ rapidity difference, but does not depend on the sum of b and $\bar{b}$ rapidities. The kinematic limits, however, do depend on the sum of b and $\bar{b}$ rapidities. They are shown for symmetric ($y_1 + y_2 = 0$) and asymmetric ($y_2 = 0$) pairs. Note the uncertainty of about one order of magnitude in the vertical scale caused by the uncertainty in the non-perturbative quark-gluon coupling.

Fig.1

Fig.2