From the exclusive photoproduction of heavy quarkonia at HERA to the EDDE at TeVatron and LHC.

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Exclusive photoproduction of heavy quarkonia at HERA is analyzed in the framework of the Regge-eikonal approach together with the nonrelativistic bound state formalism. Total and differential cross-sections for the process $\gamma + \mathrm{p} \to (\mathrm{Q}\bar{\mathrm{Q}})_{1\mathrm{S}} + \mathrm{p}$ are calculated. The model predicts cross-sections of Exclusive Double Diffractive Events (EDDE) at TeVatron and LHC.

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1 Introduction

The study of properties of bound states of heavy quarks plays a central role in the understanding of strong interactions and verification of different QCD inspired and nonperturbative models, because such processes give a very exciting possibility to observe interplay of "hard" and "soft" regimes [1]. There have been intensive experimental studies of the J/Ψ and Υ photoproduction at HERA [2],[3] and also a lot of theoretical investigations [4]-[8].

In this paper we consider exclusive photoproduction of $\mathrm{V} = (\mathrm{Q}\bar{\mathrm{Q}})_{1\mathrm{S}}$ states from another viewpoint. There are some other interesting processes that will be investigated at present and future hadronic colliders. We need estimations of cross-sections for such processes and can use the data from HERA as a source of normalization of phenomenological models. Here we show that the extended Regge-Eikonal approach [9]-[12] gives not only a good description of the data on exclusive vector meson photoproduction but can be used also to predict rates of Exclusive Double Diffractive Events (EDDE) at LHC and Tevatron. The advantages of these events have been considered in [13],[14].

2 Calculations

In Fig. 1 we illustrate in detail the process $\gamma(q) + \mathrm{p}(p) \to \mathrm{V}(p_v) + \mathrm{p}(p')$. Off-shell proton-gluon amplitude T in Fig. 1 is treated by the method developed in Ref. [9],

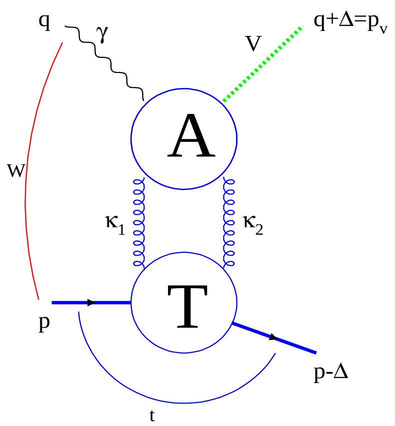

Fig. 1. Diagram for the process $\gamma + \mathrm{p} \to \mathrm{V} + \mathrm{p}$.

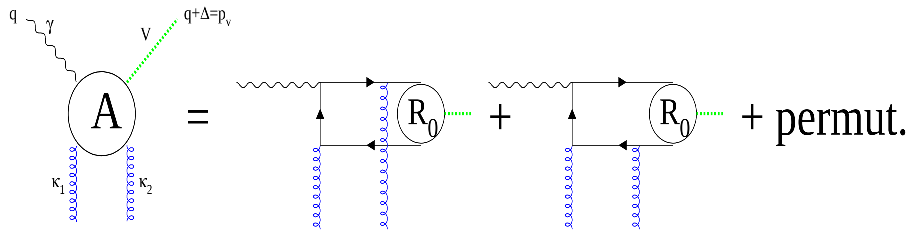

Fig. 2. Diagrams for the process $\gamma + \mathrm{g}^* \to \mathrm{V} + \mathrm{g}^*$.

which is based on the extension of Regge-eikonal approach, and succesfully used for the description of the data from hadron colliders [10]-[12]. The amplitude A of the process $\gamma(q) + \mathrm{g}(\kappa_1) \to \mathrm{V}(p_v) + \mathrm{g}(\kappa_2)$ (see Fig. 2) is calculated in the nonrelativistic bound state approximation(see [4]-[6] and ref. therein):

$$A = \frac{R_{v0}}{\sqrt{16\pi M_v}} \,\mathrm{Sp}\left[\hat{\mathcal{O}}(\hat{p}_v - M_v)\hat{\epsilon}_v\right] \qquad (1)$$

$$\hat{\mathcal{O}} = e_Q e g^2 \frac{\delta^{ab}}{2\sqrt{3}} \left(\frac{(p_{v\,\alpha} - 2\kappa_{1\,\alpha} + \hat{\kappa}_1\gamma_\alpha)\hat{\epsilon}_\gamma(p_{v\,\beta} + 2\kappa_{2\,\beta} - \gamma_\beta\hat{\kappa}_2)}{(-p_v\kappa_1 + \kappa_1^2 + \mathrm{i}0)(p_v\kappa_2 + \kappa_2^2 + \mathrm{i}0)} + 5\; perm. \right), \qquad (2)$$

where $p_v^2 = M_v^2$, e_Q is the charge of heavy quark, R_{v0} is the absolute value of the vector meson radial wave function at the origin, $\epsilon_{v,\gamma}$ are photon and vector meson polarization vectors correspondingly. Permutations are taken for all gauge bosons. Notations and vector decompositions that are used in the article are

$$\kappa_1 = \kappa + \frac{\Delta}{2} \ , \ \kappa_2 = \kappa - \frac{\Delta}{2} \ , \ p = p' + \frac{m_p^2}{s} q', \ q = q' - \frac{Q^2}{s} p', \tag{3}$$
$$Q^2 = -q^2 \ , \ p^2 = m_p^2 \ , \ q'^2 = p'^2 = 0 \ , \ s \simeq 2p'q' \ ,$$
$$\kappa = \frac{x_v}{2}(\alpha p' + \beta q') + \kappa_\perp \ , \ x_v = \frac{M_v^2}{s} \ , \ \kappa_\perp^2 = -\vec{\kappa}^2 \ , \ y = \frac{4\vec{\kappa}^2}{M_v^2} \ , \ y' = -\frac{4\kappa^2}{M_v^2} \ ,$$
$$\Delta = x_v\left([1 + y_Q + y_\Delta]\, p' - y_\Delta q'\right) + \Delta_\perp \ , \ y_Q = \frac{Q^2}{M_v^2} \ , \ t \simeq \Delta_\perp^2 = -\vec{\Delta}^2 \ , \ y_\Delta = \frac{\vec{\Delta}^2}{M_v^2} \ ,$$
$$p_v = q + \Delta \ , \ y_0 = \frac{m_p^2}{M_v^2}$$

Photon and vector meson polarization vectors in the general case ($Q \neq 0$) can be represented as follows:

$$\epsilon_{\gamma\perp} q = \epsilon_{\gamma 0} q = 0 \ , \ \epsilon_{\gamma\perp}^2 = -\epsilon_{\gamma 0}^2 = -1 \ , \ \epsilon_{\gamma 0} = \frac{1}{Q}(q' + x_v y_Q p') \ , \tag{4}$$
$$\epsilon_{v\perp} p_v = \epsilon_{v\parallel} p_v = 0 \ , \ \epsilon_{v\perp} = v_\perp + \frac{2(\vec{v}\vec{\Delta})}{s}(p' - q') \ , \ v_\perp^2 = -\vec{v}^2 \ ,$$
$$\epsilon_{v\parallel} = \frac{1}{M_v}(q' - x_v(1 - y_\Delta)p' + \Delta_\perp)$$

For the amplitude of the process $\gamma(q) + \mathrm{p}(p) \to \mathrm{V}(p_v) + \mathrm{p}(p')$ we have:

$$M = \int \frac{\mathrm{d}^4\kappa}{(2\pi)^4} \frac{1}{(\kappa_1^2 + \mathrm{i}0)(\kappa_2^2 + \mathrm{i}0)} A^{\alpha\beta,\, ab} T_{\alpha\beta,\, ab} \tag{5}$$

$$T_{\alpha\beta,\, ab} = \delta_{ab} \left(G_{\alpha\beta} - \frac{P_{1\alpha} P_{2\beta}}{P_1 P_2} \right) T^D_{gp\to gp} \ , \tag{6}$$
$$G_{\alpha\beta} = \mathrm{g}_{\alpha\beta} - \frac{\kappa_{2\alpha}\kappa_{1\beta}}{\kappa_1\kappa_2} \ , \tag{7}$$
$$P_1 = p - \frac{p\kappa_1}{\kappa_1\kappa_2}\kappa_2 \ , \ P_2 = p - \frac{p\kappa_2}{\kappa_1\kappa_2}\kappa_1 \ , \tag{8}$$

Generally the amplitude $T^D_{gp\to gp}$ can be represented in the Regge-eikonal form [10],[12] with fixed parameters of trajectories from Ref. [12] (see Table. 1), in which the eikonal is dominated by three vacuum trajectories (Pomerons with different properties). It follows from the analysis below that at small t the amplitude $T^D_{gp\to gp}$ takes the simple Regge form, which is dominated by the 3rd ("hard") Pomeron:

$$T^D_{gp\to gp} \simeq c_{gp} \left(\mathrm{e}^{-\mathrm{i}\frac{\pi}{2}} \frac{2p\kappa}{s_0 - \kappa^2} \right)^{\alpha_{P_3}(t)} \mathrm{e}^{b_0^{(3)} t} \ , b_0^{(3)} = \frac{r^2_{gP_3} + 0.5 r^2_{pP_3}}{4} \ , \tag{9}$$

Table 1. Parameters $\alpha_{P_i}(0)$, $\alpha'_{P_i}(0)$, $r^2_{pP_i}$ are obtained from the fit to the data on $\mathrm{p}(\bar{\mathrm{p}}) + \mathrm{p} \to \mathrm{p}(\bar{\mathrm{p}}) + \mathrm{p}$ [12] and remain fixed during the J/Ψ data fitting.

Pomeron$_i$	1	2	3
$\alpha_{P_i}(0) - 1$	0.0578 ± 0.0020	0.1669 ± 0.0012	0.2032 ± 0.0041
$\alpha'_{P_i}(0)$ (GeV^{-2})	0.5596 ± 0.0078	0.2733 ± 0.0056	0.0937 ± 0.0029
$r^2_{pP_i}$ (GeV^{-2})	6.3096 ± 0.2522	3.1097 ± 0.1817	2.4771 ± 0.0964

where $s_0 \simeq 1$ GeV is the scale parameter of the model that is used in the global fitting of the data on pp(p$\bar{\mathrm{p}}$) scattering [11],[12], $r^2_{pP_3}$, $\alpha_{P_3}(t) = \alpha_{P_3}(0) + \alpha'_{P_3}(0)t$ are defined in Table.1, $r^2_{gP_3}$ and c_{gp} are extracted by the procedure (16)-(21). With notations (3) we have:

$$d^4\kappa = \pi \frac{M_v^4 x_v}{32}\, \mathrm{d}\alpha \mathrm{d}\beta \mathrm{d}y = -\pi \frac{M_v^4 x_v}{64} \frac{\mathrm{d}\alpha}{\alpha}\, \mathrm{d}y' \mathrm{d}y \tag{10}$$

In the limit $Q \to 0$, $t \to 0$ only the amplitude $M_{\perp\perp}$ survives:

$$|M_{\perp\perp}|^2 \simeq K_v^2 I_v(t)^2 c_{gp}^2 \left(\frac{s}{s_0}\right)^{2\alpha_{P_3}(0)} \mathrm{e}^{2b_3 t}\ , \tag{11}$$

$$b_3 = b_0^{(3)} + \alpha'_{P_3}(0) \ln \frac{s}{s_0} \tag{12}$$

$$K_v^2 = \frac{4096\alpha_e \alpha_s^2 e_Q^2 |R_{v0}|^2}{3M_v^3 \pi^4} = \frac{1024\alpha_s^2 \Gamma(V \to e^+e^-) K_{NLO}}{3M_v \pi^4 \alpha_e}\ , \tag{13}$$

$$I_v(t) = \int \mathrm{d}\alpha \mathrm{d}y' \int_0^1 \mathrm{d}y \frac{f(\alpha, y, y')}{(\alpha - 1 - y' + \mathrm{i}0)(\alpha + 1 + y' - \mathrm{i}0)} \cdot \tag{14}$$

$$\cdot \frac{1}{(\alpha y' - y + y' - \mathrm{i}0)(\alpha y' + y - y' - \mathrm{i}0)}$$

$$f(\alpha, y, y') = \frac{1}{2\alpha^{\alpha_{P_3}(t)-1}} \left[\frac{\alpha^2 y y'}{(y-y')^2}\right] \left(\frac{y - y'}{2\left(1 + \frac{y'}{4y_0}\right)}\right)^{\alpha_{P_3}(t)} \tag{15}$$

Now let us extract the values of parameters from the fit to the data on elastic

J/Ψ photoproduction [2]. At first we write the amplitude $M_{\perp\perp}$ in the Regge-eikonal form with parameters from Table.1 and the coefficient that corresponds to the simple Vector Dominance Model (VDM):

$$M_{\perp\perp} = \sqrt{\frac{3\Gamma(\mathrm{V}\to \mathrm{e}^+\mathrm{e}^-)}{\alpha_e M_v}}\, 4\pi s \int_0^\infty \mathrm{d}b^2\, \mathrm{J}_0(b\sqrt{-t}) \frac{\mathrm{e}^{2\mathrm{i}(\delta_1+\delta_2+\delta_3)}-1}{2\mathrm{i}}\ , \tag{16}$$

where

$$\delta_i = \mathrm{i}\frac{c_{vp}^{(i)}}{s_0}\left(\mathrm{e}^{-\mathrm{i}\frac{\pi}{2}}\frac{s}{s_0}\right)^{\alpha_{P_i}(0)-1} \frac{\mathrm{e}^{\frac{-b^2}{\rho_i^2}}}{4\pi\rho_i^2}\ , \tag{17}$$
$$\rho_i^2 = 4\alpha'_{P_i}(0)\ln\left(\mathrm{e}^{-\mathrm{i}\frac{\pi}{2}}\frac{s}{s_0}\right) + r_{gP_i}^2 + 0.5 r_{pP_i}^2$$

As will be seen below, in our case the VDM plus Regge-eikonal approach representation (16) is applicable.

Results of this fit for J/Ψ meson are shown in Figs.3-6. As we see from figures, the main contribution to the cross-section is given by the Born term of the 3rd Pomeron. The 1st "soft" Pomeron gives no contribution. The term corresponding to the 2nd Pomeron vanishes faster with t, and gives the contribution less than 1%, when $t \le -0.2$ GeV^2. Numerical estimations show that absorbtive corrections play minor role at $t \simeq t^* = -1/2b_3$, where b_3 is obtained from (12). Using these facts, we keep in (16) only the Born term for the 3rd Pomeron with parameters

$$r_{gP_3}^2 = 2.54 \pm 0.41\ \mathrm{GeV}^{-2}\ ,\ c_{\mathrm{J}/\Psi\mathrm{p}}^{(3)} = 1.11 \pm 0.07\ ,\ \chi^2/dof = 1.48 \tag{18}$$

and take the integral I_v at $t = t^*$. Now we can estimate the constant c_{gp} in (11) from the comparison of two formulae for the amplitude $M_{\perp\perp}$:

$$c_{gp} = \frac{\sqrt{\frac{3\Gamma(\mathrm{V}\to\mathrm{e}^+\mathrm{e}^-)}{\alpha_e M_v}}}{K_v I_v(t^*)}\, c_{vp}^{(3)} = \frac{3\pi^2}{32\alpha_s I_v(t^*)\sqrt{K_{NLO}}}\, c_{vp}^{(3)}\ , \tag{19}$$

where α_e and α_s are electromagnetic and strong coupling constants correspondingly. K_{NLO} is the next to leading order correction coefficient.

Taking for J/Ψ mesons

$$M_{\mathrm{J}/\Psi} = 3.1\ \mathrm{GeV}\ ,\ \alpha_s(M_{\mathrm{J}/\Psi}^2) = 0.25\ , \tag{20}$$
$$I_{\mathrm{J}/\Psi}(t^*) \simeq 0.83\ ,\ 35\ \mathrm{GeV} < W = \sqrt{s} < 260\ \mathrm{GeV}\ ,$$
$$\Gamma(\mathrm{J}/\Psi \to \mathrm{e}^+\mathrm{e}^-) = 5.26 \pm 0.37\ \mathrm{keV}\ ,\ K_{NLO} \simeq 2\ \text{(see, for example, [15])}$$

we get from (19):

$$c_{gp} = 3.5 \pm 0.4 \tag{21}$$

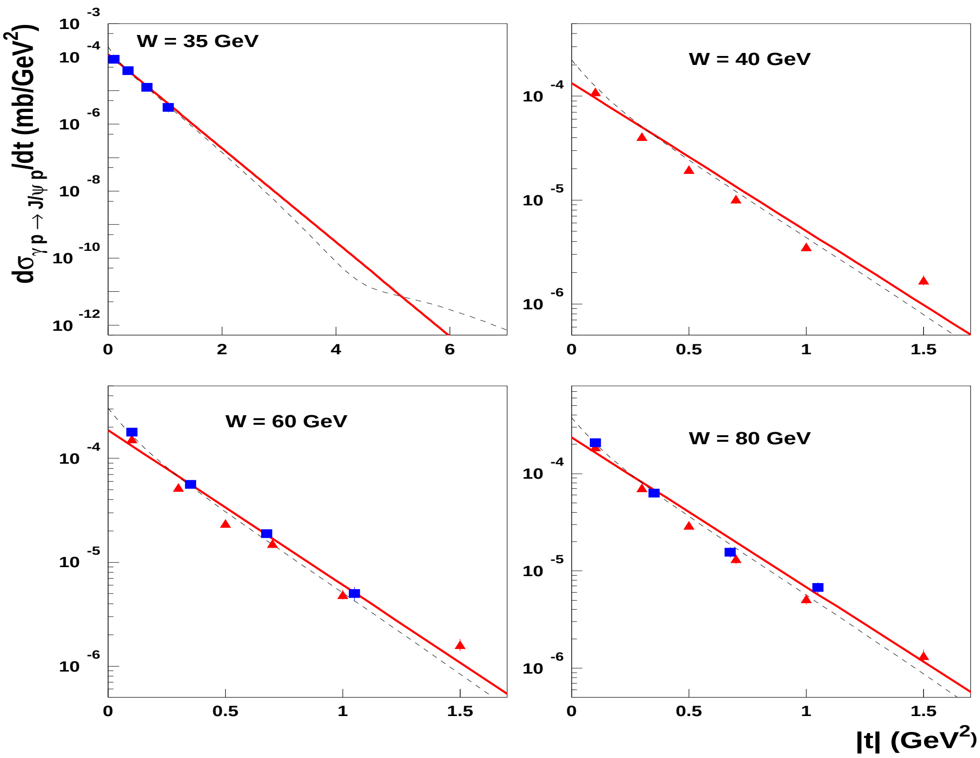

Fig. 3. Differential cross-sections of the process $\gamma + \mathrm{p} \to \mathrm{V} + \mathrm{p}$ at different values of W. Solid curve is the Born term for the 3rd Pomeron and dashed one is the unitarized result.

Here errors are estimated from uncertanties of quantities in (19).

The data on Υ production [3] gives the possibility to check the model predictions. The result of ZEUS collaboration for the ratio of total cross-sections of J/Ψ and Υ photoproduction:

$$\frac{\sigma_{\gamma\mathrm{p}\to\Upsilon\mathrm{p}}}{\sigma_{\gamma\mathrm{p}\to\mathrm{J}/\Psi\mathrm{p}}} = (4.8 \pm 2.2(\mathrm{stat.})\,{}^{+0.7}_{-0.6}(\mathrm{sys.}))\cdot 10^{-3} \qquad (22)$$

If we assume that the constant c_{gp} is the same for both processes, and the slope of the exponent does not change much with energy, then from the expression (11) we will get at the same value of W:

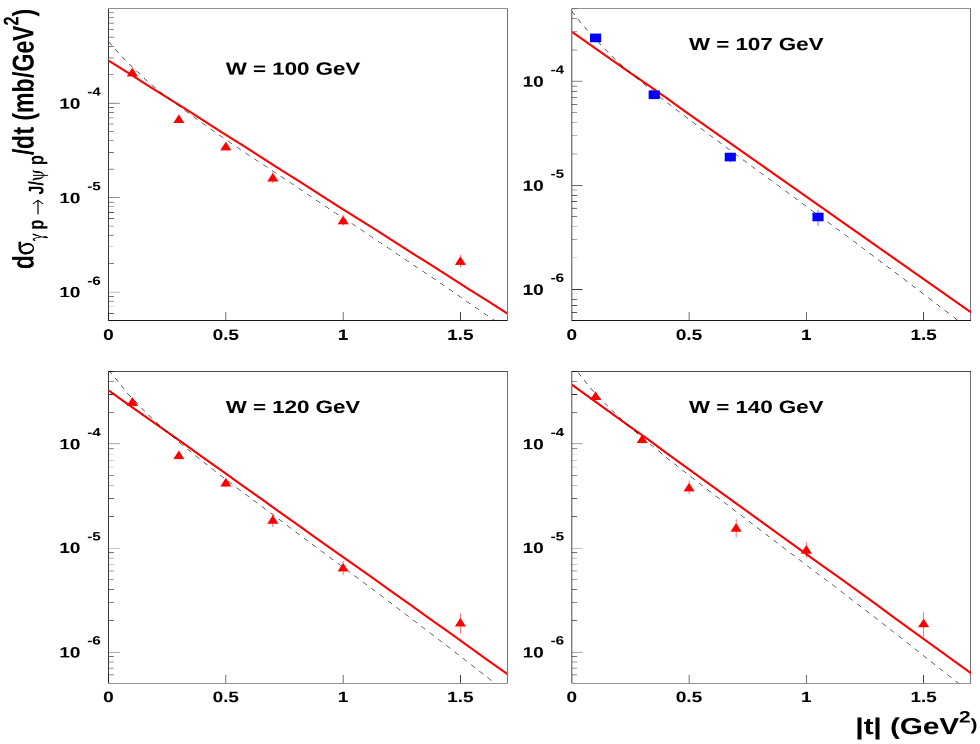

Fig. 4. Differential cross-sections of the process $\gamma + \mathrm{p} \to \mathrm{V} + \mathrm{p}$ at different values of W. Solid curve is the Born term for the 3rd Pomeron and dashed one is the unitarized result.

$$\frac{\sigma_{\gamma\mathrm{p}\to\Upsilon\mathrm{p}}}{\sigma_{\gamma\mathrm{p}\to\mathrm{J}/\Psi\mathrm{p}}} \simeq \left[\frac{\alpha_s(M_\Upsilon^2)I_\Upsilon}{\alpha_s(M_{\mathrm{J}/\Psi}^2)I_{\mathrm{J}/\Psi}}\right]^2 \frac{\Gamma(\Upsilon\to\mathrm{e^+e^-})K_{NLO}^{\Upsilon}M_{\mathrm{J}/\Psi}}{\Gamma(\mathrm{J}/\Psi\to\mathrm{e^+e^-})K_{NLO}^{\mathrm{J}/\Psi}M_\Upsilon} = (3.1\pm1.1)\cdot10^{-3}\ , \tag{23}$$

where

$$\Gamma(\Upsilon\to\mathrm{e^+e^-}) = 1.32\pm0.04\pm0.03\ \mathrm{keV}\ , \tag{24}$$
$$M_\Upsilon = 9.46\ \mathrm{GeV}\ ,\ \alpha_s(M_\Upsilon^2)\simeq0.2\ ,\ I_\Upsilon\simeq0.21\ ,$$
$$K_{NLO}\sim\frac{1}{1-\frac{16\alpha_s}{3\pi}}\ (\text{see Ref. [15]})\ ,$$

and uncertainty of the result originates from the errors of parameters in (23). The-

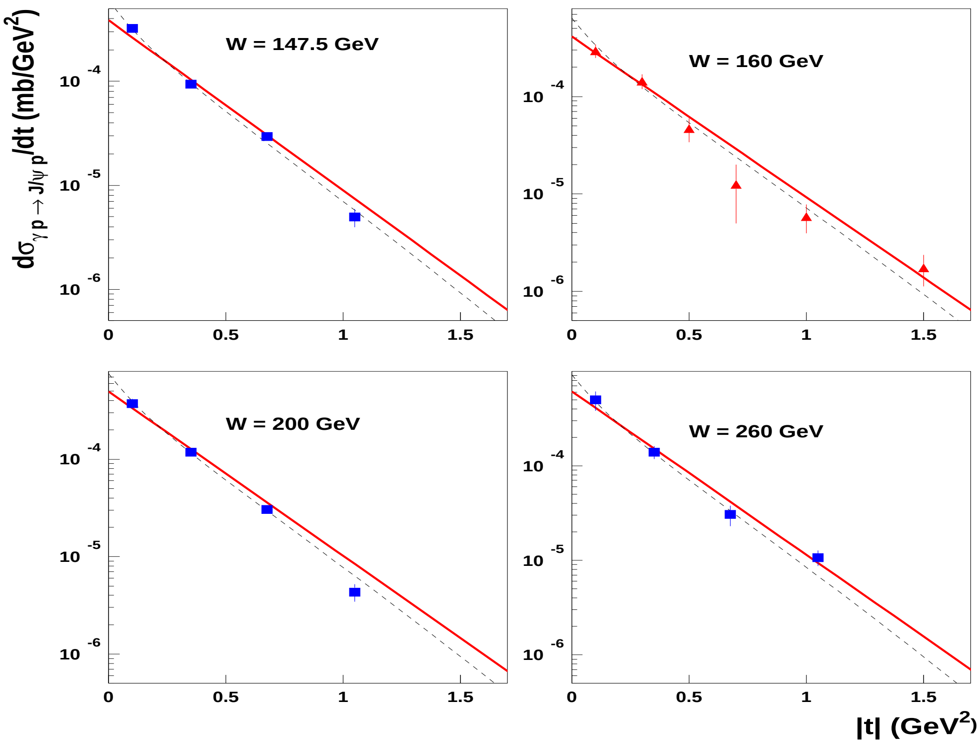

Fig. 5. Differential cross-sections of the process $\gamma + \mathrm{p} \to \mathrm{V} + \mathrm{p}$ at different values of W. Solid curve is the Born term for the 3rd Pomeron and dashed one is the unitarized result.

oretical estimation does not contradict the experimental value (22).

The second estimation can be done for the EDD dijet production at TeVatron energies. Recent CDF results [16],[17] for the upper bound of the cross-section of the process $\mathrm{p} + \mathrm{p} \to \mathrm{p} + \mathrm{jet} + \mathrm{jet} + \mathrm{p}$ are the following:

$$\begin{aligned} E_T &> 7\ \mathrm{GeV}\ ,\ \ \sigma < 3.7\ \mathrm{nb}\ , \\ E_T &> 10\ \mathrm{GeV}\ ,\ \ \sigma < 0.97 \pm 0.065\ (\mathrm{stat.}) \pm 0.272 (\mathrm{sys.})\ \mathrm{nb}\ , \\ E_T &> 25\ \mathrm{GeV}\ ,\ \ \sigma < 34 \pm 5\ (\mathrm{stat.}) \pm 10 (\mathrm{sys.})\ \mathrm{pb}\ , \end{aligned} \tag{25}$$

where E_T is the transverse momentum of the jet. After theoretical calculations by the method developed in Refs. [13],[18] we extract upper bounds for the parameter c_{gp} from (25):

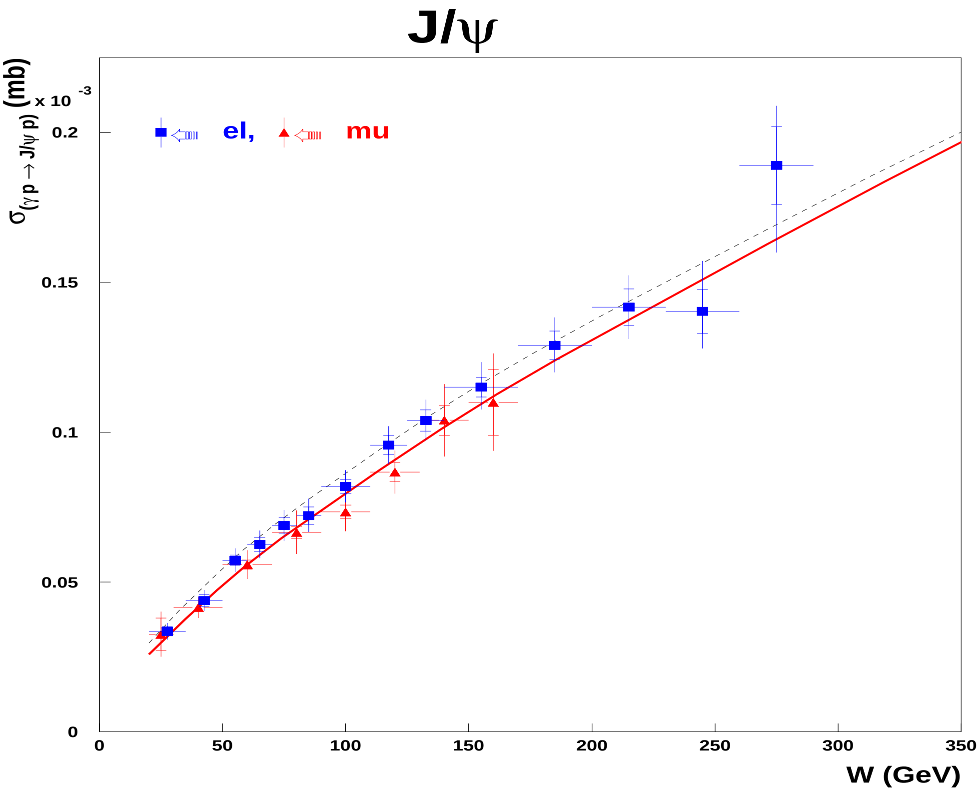

Fig. 6. Total cross-section of the process $\gamma + \mathrm{p} \rightarrow \mathrm{V} + \mathrm{p}$. Solid curve is the Born term for the 3rd Pomeron and dashed one is the unitarized result.

$$\begin{aligned} E_T &> 7 \text{ GeV} \; , \; c_{gp} < 3.3 \; , \\ E_T &> 10 \text{ GeV} \; , \; c_{gp} < 3.4 \; , \\ E_T &> 25 \text{ GeV} \; , \; c_{gp} < 4.2 \; . \end{aligned} \tag{26}$$

Values of c_{gp} are close to our estimation (21).

Conclusions

We can conclude that the generalized Regge-eikonal approach with 3 different Pomerons describes well the data on J/Ψ production. The main contribution to the cross-section comes from the term corresponding to the 3rd, so called, "hard" Pomeron. This makes possible to extract the corresponding parameter of the model.

The upper bound for the same parameter is found to be close to our result, when calculated from experimental estimations on EDD di-jet production made by CDF. It indicates once more the applicability of the Regge-eikonal approach and gives us the tool for further predictions.

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