Searching for odderon in exclusive vector meson hadroproduction

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In this talk\cite{1} estimates are presented of the odderon contributions to the exclusive $J/\psi$ and $\Upsilon$ production cross-sections at the Tevatron and the Large Hadron Collider. The obtained cross-sections are compared to cross-sections of the dominant background sub-processes mediated by the photon exchange. Possible experimental cuts are proposed that reduce the photon background.

1 Introduction

Color neutral gluonic exchanges in high energy hadron scattering are naturally classified according to their $C$-parity. The $C$-even component is usually called the Pomeron. It gives the dominant contribution to vast majority of the measured cross-sections at high energies. The $C$-odd partner of the Pomeron is the odderon. In contrast to the Pomeron, the effects of the odderon are so weak that a compelling experimental evidence for the non-vanishing odderon contribution has not been found yet. On the other hand, existence of the odderon exchange is guaranteed within perturbative QCD. In the lowest non-trivial order, the QCD odderon is made of three gluons with the symmetric color structure. Beyond the leading order, the odderon amplitude can be described in the leading logarithmic approximation (where $\sqrt{s}$ is the collisions energy) as a solution of the BKP evolution equation, a generalization of the famous BFKL equation for the Pomeron to a larger number of gluons. Thus, a successful measurement of the QCD odderon exchange should provide some important insight into the high energy evolution of multi-gluon amplitudes in QCD.

The main problem in odderon searches is the large background from the Pomeron which, if present, prohibits a measurement of the odderon contribution. In order to avoid this problem it is necessary to focus on processes in which, due to $C$-parity conservation, the Pomeron contribution vanishes. This condition is fulfilled in exclusive production of mesons with definite $C$-parity, at high energies. A number of such measurements was proposed and performed at HERA, unfortunately with negative results.

At hadron colliders, the Tevatron and the Large Hadron Collider (LHC) one expects to achieve an enhanced sensitivity to the odderon mediated processes, because of the strong coupling of proton projectiles to gluons. One of the simplest processes that should be sensitive to the odderon exchange in hadron collisions is the exclusive heavy vector meson production \cite{2}, \( p\bar{p} \rightarrow p\bar{p} + V \) or \( pp \rightarrow pp + V \) where \( V = J/\psi, \Upsilon \). In this talk\cite{1} an attempt \cite{3} to estimate the corresponding cross-sections for the Tevatron and the LHC is described and prospects for the measurements are discussed.

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2 Formalism

There are two main components of the exclusive vector meson hadroproduction amplitudes: one coming from the odderon-Pomeron fusion (Fig. 1a, 1b) and the other coming from the photon-Pomeron fusion (Fig. 1c, 1d). We estimated both contributions within the factorization approach, at the lowest order. In this approximation, the integrations over longitudinal components of loop momenta can be performed exactly, and the non-trivial process dependent features are encoded in the impact factors $\Phi(\ldots)$, that describe couplings of gluons to the scattering particles and depend only on the transverse momenta of the gluons, $k_i, l_i$. As an example, we give here the amplitude of the diagram shown in Fig. 1a,

$$
\mathcal{M}_{PO} = -i s \frac{2 \cdot 3}{2 \cdot 3} \frac{1}{(2\pi)^4} \int \frac{d^4l_1}{l_1^2} \frac{d^4l_2}{l_2^2} \delta^2(l_1 + l_2 - l) \frac{d^4k_1}{k_1^2} \frac{d^4k_2}{k_2^2} \frac{d^4k_3}{k_3^2} \delta^2(k_1 + k_2 + k_3 - k) 
\times \delta^2(k_3 + l_1) \frac{k_3^2}{k_3^2} \delta^{\lambda_1\kappa_3} \cdot \Phi_{\lambda_1\lambda_2}^{\lambda_1\kappa_2}(l_1, l_2) \cdot \Phi_{\lambda_3}^{\kappa_1\kappa_2\kappa_3}(k_1, k_2, k_3) \cdot \Phi_{J/\psi}^{\lambda_3\kappa_1\kappa_2}(l_2, k_1, k_2). 
$$

Here $k_i, l_i$ are gluon transverse momenta and $\lambda_i, \kappa_i$ are gluon color indices. $\Phi_{\lambda_1\lambda_2}^{\lambda_1\kappa_2}$ and $\Phi_{\lambda_3}^{\kappa_1\kappa_2\kappa_3}$ denote the impact factors of the proton, scattered via the Pomeron and odderon exchange respectively. Both the impact factors are obtained in the Fugugita-Kwieciński model of the proton, see [3] for details. The effective production vertex of the $J/\psi$ meson is denoted $\Phi_{J/\psi}^{\lambda_3\kappa_1\kappa_2}$. It results from the perturbatively calculable fusion of three gluons into $J/\psi$. In order to keep the notation of momenta $l_i$ and $k_i$ most symmetric, we introduced an additional, artificial vertex (denoted by the cross in Fig. 1) $\delta^2(k_3 + l_1) \frac{k_3^2}{k_3^2} \delta^{\lambda_1\kappa_3}$ connecting the spectator gluons $(l_1, \lambda_1)$ and $(k_3, \kappa_3)$. The ratio $\frac{2 \cdot 3}{2 \cdot 3} = \frac{1}{2}$ is a combinatorial factor. The factors $\frac{1}{2}$ and $\frac{1}{3}$ correct the over-counting of diagrams introduced by factorization in the scattering amplitudes of the impact factor with Pomeron and odderon exchanges, respectively. The factor $2 \cdot 3 = 6$ accounts for all possibilities to build the spectator gluon from the momenta $l_i$ and $k_j$.

3 Results

Diagrams shown in Fig. 1 give the lowest order amplitudes. A more realistic estimate of the production amplitudes requires taking into account the QCD evolution of the Pomeron. We represent this effect using a phenomenological enhancement factor $E(s, m_V)$, with $V = DIS 2008$
J/ψ, Υ. Besides that, it is necessary to take into account corrections coming from multiple scatterings, that may destroy the exclusive character of the process. Those effects will be expressed as a gap survival factor $S_{\text{gap}}^2$. An important model parameter that controls the magnitude of the proton impact factors is an effective strong coupling constant, $\bar{\alpha}_s$. This parameter enters the Pomeron–odderon fusion cross-section in the fifth power. Thus, a cross-section, that takes into account necessary phenomenological improvements may be written as $d\sigma^{\text{corr}} / dy|_{y=0} = \bar{\alpha}_s^5 S_{\text{gap}}^2 E(s, m_V) d\sigma / dy$, where $d\sigma / dy$ is the lowest order cross-section evaluated at $\bar{\alpha}_s = 1$. We approximate the effects of QCD evolution of the Pomeron amplitude by an exponential enhancement factor $\exp(\lambda \Delta y)$ where $\Delta y$ is the rapidity evolution length of the QCD Pomeron. Thus, for the central production one obtains $E(s, m_V) = (x_0 \sqrt{s}/m_V)^{2\lambda}$, and the initial $x$-value for the gluon evolution is assumed to be $x_0 = 0.1$. Following results from HERA, we take the effective Pomeron intercept $\lambda = 0.2$ ($\lambda = 0.35$) for the J/ψ (Υ) production.

Table 1: Estimates of cross-sections $d\sigma^{\text{corr}} / dy|_{y=0}$ given for the exclusive J/ψ and Υ production in pp and p¯p collisions by the odderon–Pomeron fusion and the photon-Pomeron fusion for the pessimistic–central–optimistic scenarios.

| $d\sigma^{\text{corr}} / dy$ | J/ψ         | Υ         |
|-----------------------------|-------------|-----------|
|                             | odderon     | photon    | odderon    | photon    |
| Tevatron                    | 0.3–1.3–5 nb| 0.8–5–9 nb| 0.7–4–15 pb| 0.8–5–9 pb|
| LHC                         | 0.3–0.9–4 nb| 2.4–15–27 nb| 1.7–5–21 pb| 5–31–55 pb|

The estimate of uncertainties introduced by $\bar{\alpha}_s$ and $S_{\text{gap}}^2$ is carried out together. By doing so, we follow the assumptions made in existing determinations of $\bar{\alpha}_s$. For instance, a low value of $\bar{\alpha}_s \simeq 0.3$ was obtained from an analysis of the elastic pp and p¯p scattering data in which $S_{\text{gap}}^2 = 1$ was taken. Analyzes of inclusive cross-sections and the exclusive vector meson photoproduction yielded $\bar{\alpha}_s \simeq 0.7 - 1$. Thus, we use $S_{\text{gap}}^2 = 1$ in our calculation if the low value of $\bar{\alpha}_s = 0.3$ is taken. This combination $S_{\text{gap}}^2 = 1$ and $\bar{\alpha}_s = 0.3$ gives low cross-sections and it is called the pessimistic scenario. In the optimistic scenario we use a $\bar{\alpha}_s = 1$, combined with the gap survival factors obtained in the Durham two-channel eikonal model: $S_{\text{gap}}^2 = 0.05$ for the exclusive production at the Tevatron and $S_{\text{gap}}^2 = 0.03$ for the LHC. The best estimates should follow from the central scenario defined by $\bar{\alpha}_s = 0.75$, $S_{\text{gap}}^2 = 0.05$ ($S_{\text{gap}}^2 = 0.03$) at the Tevatron (LHC). Within the same model, we also analyze the Pomeron–photon contribution in a way analogous to the Pomeron–odderon contribution. The values of the phenomenologically improved cross-sections are summarized in Table 1. The photon and the odderon contributions do not interfere in the lowest order approximation and the corresponding cross-sections may be treated independently. As seen from the table, the Pomeron–odderon contributions are found to be uncertain, with a multiplicative uncertainty factor of 3–5. The ambiguities, however, cancel partially in the ratio of the Pomeron–odderon contribution to the Pomeron–photon contribution evaluated in the same scenario. Thus, within the considered scenarios, the “odderon to photon ratio” $R = [d\sigma^{\text{corr}} / dy]/[d\sigma^{\gamma} / dy]$ varies between 0.3 and 0.6 for J/ψ production at the Tevatron, and between about 0.06 and 0.15 at the LHC. In the case of Υ, $R$ varies between about 0.8 and 1.7 at the Tevatron.

\* The photon cross-sections given in Table 1 are not meant to provide the most accurate estimate, but rather to assess the impact of model assumptions on the odderon/photon ratio.

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Figure 2: The normalized differential cross-section \( (d\sigma/dp_T^2)/\sigma \) for the exclusive production: a) \( p\bar{p} \to p\bar{p}J/\psi \), and b) \( pp \to ppJ/\psi \) as a function of meson \( p_T^2 \) for the odderon–Pomeron and the photon–Pomeron fusion.

and between about 0.15 and 0.4 at the LHC. These numbers suggest that the odderon contribution may well be of a similar magnitude to the photon contribution at the Tevatron and somewhat smaller than the photon contribution at the LHC.

The obtained results clearly indicate that the photon exchange background to the odderon mediated processes is important in the \( p_T \)-integrated cross-sections at central rapidities. Thus in the search for the odderon one should use also the available information on the transverse momentum distributions. In Fig. 2 normalized distributions of the meson \( p_T^2 \) are shown for the odderon and photon contributions to the exclusive \( J/\psi \) production (the results for \( \Upsilon \) are similar). As seen from this figure, the relative importance of the odderon contribution increases at larger meson \( p_T \), and the different \( p_T \)-shape of the odderon and the photon contributions may be used to perform an experimental separation between them. Another measurement with an enhanced sensitivity to the odderon should be possible using forward proton detectors. Assuming, that a forward detector at the LHC measures the proton \( A \) that lost about \( x_A \sim 0.01 \) of its energy in the \( pp \to pp\Upsilon \) process, one finds that the other proton, \( B \), should lose a tiny fraction of about \( x_B \sim 10^{-4} \) of its energy. Although proton \( B \) cannot be measured, the asymmetric kinematics implies that the proton \( B \) couples predominantly to the Pomeron and proton \( A \) couples to the photon or the odderon. The photon exchange is characterized by a steep \( 1/p_T^2 \) behavior and it leads to the \( p_T \) distribution of proton \( A \) that is concentrated at small momenta. The odderon induced \( p_T \)-distribution is much broader. Thus, for instance, a cut of \( p_T > 0.5 \text{ GeV} \) on the transverse momentum of proton \( A \) should increase the odderon to photon ratio in the data sample by a factor of about 10.

In summary, measurements of the exclusive heavy vector meson production at the Tevatron and the LHC may provide a viable opportunity to discover the odderon.

References

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