Diffractive production of quarkonia

Antoni Szczurek\textsuperscript{1,2}
\textsuperscript{1}Institute of Nuclear Physics Polish Academy of Sciences, Cracow, Poland
\textsuperscript{2}Institute of Physics, University of Rzeszów, Rzeszów, Poland

Abstract

I discuss two selected examples of diffractive production of quarkonia: \(pp \rightarrow p\eta'/p\) and \(pp \rightarrow pJ/\psi p\). In the first case I consider diffractive pQCD approach and \(\gamma\gamma\) fusion, in the second case the amplitude is linked to the amplitude of the process for \(J/\psi\) photoproduction at HERA. Absorption effects are discussed briefly for the second reaction.

1 Introduction

Exclusive production of mesons was studied in details only at fixed target collisions at CERN. At present, there is ongoing investigations at Tevatron aiming to measure the exclusive production of both vector and scalar quarkonia, but no result is yet publicly available. Only an upper limit for \(\chi_c\) was given up to now [1].

There is a long standing debate about the nature of the pomeron. The approximate \(\sin^2(\Phi)\) (\(\Phi\) is the azimuthal angle between outgoing protons) dependence observed experimentally for \(pp \rightarrow p\eta'/p\) [2] was interpreted in Ref. [3] as due to (vector pomeron)-(vector pomeron)-(pseudoscalar meson) coupling. The QCD-inspired calculation for diffractive production of pseudoscalar mesons was presented only recently in Ref. [4]. Here I shall present some results from that analysis obtained within the pQCD approach of Khoze-Martin-Ryskin (KMR) [5].

Recently the \(J/\psi\) exclusive production in proton-proton and proton-antiproton collisions was suggested as a candidate in searches for odderon exchange [6]. In order to identify the odderon exchange one has to consider all other possible processes leading to the same final channel. One of such processes, probably dominant, is pomeron-photon or photon-pomeron fusion [7].

The diffractive photoproduction of \(J/\psi\)-mesons has been recently a subject of thorough studies at HERA [8, 9], and serves to elucidate the physics of the QCD pomeron and/or the small-\(x\) gluon density in the proton (for a recent review and references, see [10]). Being charged particles, protons/antiprotons available at RHIC, Tevatron and LHC are a source of high energy Weizsäcker–Williams photons. Those photons interact with the other nucleon. In some cases such an interaction leads to elastical (ground state proton) production of \(J/\psi\). In the approach presented here the amplitude for the \(pp \rightarrow ppJ/\psi\) reaction is related to the amplitude of the photoproduction \(\gamma p \rightarrow J/\psi p\) [7]. Such a method of calculating cross section is expected to be much more precise than any QCD approach which does not refer to the \(ep\) HERA data.
2 Diffractive production of $\eta'$

Following the formalism for the diffractive double-elastic production of the Higgs boson one can write the amplitude from Fig.1 as

$$\mathcal{M}_{pp \rightarrow pp'p} = i \pi^2 \int d^2 k_{0,t} V(k_1, k_2, P_M) \frac{f^off(x_1, x_1', k_{0,t}^2, t_1) f^off(x_2, x_2', k_{0,t}^2, k_{2,t}^2, t_2)}{k_{0,t}^2 k_{1,t}^2 k_{2,t}^2}, \quad (1)$$

where $f'$s are skewed unintegrated gluon distributions. For more details see [4].

As an example in Fig. 2 I show the results of calculations obtained with several models of UGDF (for details see [4]) for relatively low energy $W = 29.1$ GeV. For comparison I show also the contribution of the $\gamma^*\gamma^*$ fusion mechanism. The contribution of the last mechanism is much smaller than the contribution of the diffractive QCD mechanism.

The diffractive and $\gamma^*\gamma^*$ contributions have very different dependence on four-momentum transfers. In Fig.3 I present two-dimensional maps $t_1 \times t_2$ of the cross section for the QCD mechanism (KL UGDF) and the QED mechanism (Dirac terms only) for the Tevatron energy $W = 1960$ GeV. If $|t_1|, |t_2| > 0.5$ GeV$^2$ the QED mechanism is clearly negligible. However, at $|t_1|, |t_2| < 0.2$ GeV$^2$ the QED mechanism may become equally important or even dominant. However, the details depend strongly on UGDFs.

Finally in Fig.4 I show energy dependence of the total cross section for the $pp \rightarrow pp'p$ reaction for different UGDFs. Quite different results are obtained for different UGDFs. The cross section with the Kharzeev-Levin type distribution (based on the idea of gluon saturation) gives the cross section which is relatively small and almost independent of beam energy. In contrast, the BFKL distribution leads to strong energy dependence. The sensitivity to the transverse momenta of initial gluons can be seen by comparison of the two solid lines calculated with the Gaussian UGDF with different smearing parameter $\sigma_0 = 0.2$ and 0.5 GeV. The contribution of the $\gamma^*\gamma^*$ fusion mechanism (red dash-dotted line) is fairly small and only slowly energy dependent.
3 Photoproduction of $J/\psi$

The basic mechanisms leading to the exclusive production of $J/\psi$ are shown in Fig. 5. The amplitude for the corresponding $2 \rightarrow 3$ process can be written as

$$
\mathcal{M}_{h_1 h_2 \rightarrow h_1 h_2 V}^{\lambda_1 \lambda_2 \rightarrow \lambda_V \lambda_V}(s, s_1, s_2, t_1, t_2) = \mathcal{M}_{\gamma p} + \mathcal{M}_{\gamma \gamma}
$$

$$
= \langle p_1', \lambda_1' | J_\mu | p_1, \lambda_1 \rangle \epsilon_\mu^*(q_1, \lambda_V) \frac{\sqrt{4\pi \alpha_{em}}}{t_1} \mathcal{M}_{\gamma^* h_2 \rightarrow V h_2}^{\lambda_2 \lambda_2 \rightarrow \lambda_V \lambda_V}(s_2, t_2, Q_1^2) + \langle p_2', \lambda_2' | J_\mu | p_2, \lambda_2 \rangle \epsilon_\mu^*(q_2, \lambda_V) \frac{\sqrt{4\pi \alpha_{em}}}{t_2} \mathcal{M}_{\gamma^* h_1 \rightarrow V h_1}^{\lambda_1 \lambda_1 \rightarrow \lambda_V \lambda_V}(s_1, t_1, Q_1^2) .
$$

After some algebra it can be written in the compact form:

$$
\mathcal{M}(p_1, p_2) = e_1 \frac{2}{z_1} \frac{p_1}{t_1} \mathcal{F}_{\lambda_1 \lambda_1}(p_1, t_1) \mathcal{M}_{\gamma^* h_2 \rightarrow V h_2}(s_2, t_2, Q_1^2)

+ e_2 \frac{2}{z_2} \frac{p_2}{t_2} \mathcal{F}_{\lambda_2 \lambda_2}(p_2, t_2) \mathcal{M}_{\gamma^* h_1 \rightarrow V h_1}(s_1, t_1, Q_1^2) .
$$
Fig. 3: Two-dimensional distribution in $t_1 \times t_2$ for the diffractive QCD mechanism (left panel), calculated with the KL UGDF, and the $\gamma^*\gamma^*$ fusion (right panel) at the Tevatron energy $W = 1960$ GeV. No absorption corrections were included here.

The differential cross section is given in terms of $M$ as

$$d\sigma = \frac{1}{512\pi^4s^2}|M|^2dydt_1dt_2d\phi,$$

where $y$ is the rapidity of the vector meson, and $\phi$ is the angle between $p_1$ and $p_2$. Notice that the interference between the two mechanisms $\gamma IP$ and $IP\gamma$ is proportional to $e_1e_2(p_1 \cdot p_2)$ and introduces a charge asymmetry as well as an angular correlation between the outgoing protons.

In Fig.6 I collect rapidity distributions for different energies relevant at RHIC, Tevatron and LHC. One observes an occurrence of a small dip in the distribution at midrapidities at LHC energy. One should remember, however, that the distribution for the LHC energy is long-distance extrapolation of the $\gamma^*p \rightarrow J/\psi p$ amplitude (or cross section) to unexplored yet experimentally energies $W_{\gamma p}$. Therefore a real experiment at Tevatron and LHC would help to constrain cross sections for $\gamma p \rightarrow J/\psi p$ process.

In Fig.7 I show two-dimensional distributions in rapidity and the azimuthal angle. Surprisingly, the interference effect between both diagrams is significant over broad range of $J/\psi$ rapidity. One can see that even at large $J/\psi$ rapidities one observes anisotropic distributions in the azimuthal angle. This means that interference between photon-pomeron and pomeron-photon mechanisms survives up to large rapidities.

The parametrization of the $\gamma^*p \rightarrow Vp$ amplitude which describes corresponding experimental data (see [7]) includes effectively absorption effects due to final state $Vp$ interactions. In the $pp \rightarrow ppJ/\psi$ ($p\bar{p} \rightarrow p\bar{p}J/\psi$) reaction the situation is more complicated as here $pp$ (or $p\bar{p}$) strong rescatterings occur in addition. In Ref. [7] we have included only elastic rescatterings shown schematically in Fig.8.

In order to demonstrate the effect of the absorption in Fig.9 I show the ratio of the cross section with absorption to that without absorption as a function of $t_1$ and $t_2$, for $p\bar{p}$ (left) and $pp$ (right). Generally, the bigger $t_1$ and/or $t_2$ the bigger the absorption. On average, the absorption for the $p\bar{p}$ reaction is smaller than the absorption for the $pp$ reactions.
Fig. 4: $\sigma_{tot}$ as a function of center of mass energy for different UGDFs. The $\gamma^*\gamma^*$ fusion contribution is shown by the dash-dotted (red) line. The world experimental data are shown for reference. No absorption corrections were included here.

Fig. 5: The sketch of the two mechanisms considered in the present paper: photon-pomeron (left) and pomeron-photon (right). Some kinematical variables are shown in addition.
Fig. 6: $d\sigma/dy$ for exclusive $J/\psi$ production as a function of $y$ for RHIC, Tevatron and LHC energies. No absorption corrections were included here.

Fig. 7: $d\sigma/dy d\Phi$ for $W = 1960$ GeV and for $p\bar{p}$ (left panel) and $pp$ (right panel) collisions. No absorption corrections were included here.

4 Summary

In contrast to diffractive Higgs production, in the case of light meson production the main contribution to the diffractive amplitude comes from the region of very small gluon transverse momenta and very small longitudinal momentum fractions. In this case application of Khoze-Martin-
Ryskin UGDFs seems not justified and we have to rely on UGDFs constructed for this region.

The existing models of UGDFs predict cross section much smaller than the one obtained by the WA102 collaboration at the center-of-mass energy $W = 29.1$ GeV. This may signal presence of subleading reggeons at the energy of the WA102 experiment or suggest a modification of UGDFs in the nonperturbative region of very small transverse momenta.

Due to a nonlocality of the loop integral our model leads to sizeable deviations from the $\sin^2 \Phi$ dependence (predicted in the models of one-step fusion of two vector objects). The $\gamma^*\gamma^*$ fusion may be of some importance only at extremely small four-momentum transfers squared.

It was shown in [7] that at the Tevatron energy one can study the exclusive production of $J/\psi$ at the photon-proton center-of-mass energies $70$ GeV < $W_{\gamma p}$ < 1500 GeV, i.e. in the unmeasured region of energies, much larger than at HERA. At LHC this would be correspondingly 200 GeV < $W_{\gamma p}$ < 8000 GeV. At very forward/backward rapidities this is an order of magnitude more than possible with presently available machines.

An interesting azimuthal-angle correlation pattern has been obtained due to the interference of photon-pomeron and pomeron-photon helicity-preserving terms.

We have estimated also absorption effects. In some selected configurations the absorption effects may lead to the occurrence of diffractive minima. The exact occurrence of diffractive minima depends on the values of the model parameters. Such minima are washed out when integrated over the phase space or even its part. We have found that on average the rescattering effects in proton-antiproton reactions are much bigger than in proton-proton reactions. In this case the obvious isospin violation is of electromagnetic origin due to the interference of diagrams with photon exchange.

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Fig. 9: The ratio of the cross sections with absorption to that without absorption for $p\bar{p}$ (left panel) and $pp$ (right panel) scattering. Here the integration over $-1 \text{ GeV}^2 < t_1, t_2 < 0.0$ and $-1 < y < 1$ is performed.

References


