I discuss double-diffractive (double-elastic) production of the \(\eta'\) and \(\eta_c\) mesons in the \(pp \to pXp\) reaction within the formalism of unintegrated gluon distribution functions (UGDF). The contribution of \(\gamma^*\gamma^* \to \eta'\) fusion is estimated. The distributions in the Feynman \(x_F\) (or rapidity), transferred four-momenta squared between initial and final protons \((t_1, t_2)\) and azimuthal angle difference between outgoing protons \((\Phi)\) are calculated and discussed. The results are compared with the WA102 data. Predictions at higher energies are presented.

1. Introduction

Recently the exclusive production of \(\eta'\) meson in proton-proton collisions was intensively studied close to its production threshold at the COSY ring at KFA Jülich \(^1\) and at Saclay \(^2\). Here the dominant production mechanism is exchange of several mesons (so-called meson exchange currents) and reaction via \(S_{11}\) resonance \(^3\).

I present results of a recent study \(^4\) (done in collaboration with R. Pasechnik and O. Teryaev) of the same exclusive channel but at much larger energies \((W > 10\) GeV\)). Here diffractive mechanism may be expected to be the dominant process. In Ref.\(^7\) the Regge-inspired pomeron-pomeron fusion was considered as the dominant mechanism of the \(\eta'\) production. Here I present results obtained in the formalism with unintegrated gluon distribution functions. Similar formalism was used recently to calculate cross section for exclusive Higgs boson production \(^5,6\). There is a chance that the formalism used for Higgs can be tested quantitatively for exclusive (heavy) meson production where the corresponding cross section is expected to be much bigger.

In Fig.\(^1\) I show a sketch of the QCD mechanism of diffractive double-elastic production of \(\eta'\) meson (left diagram). For completeness, we include also photon-photon fusion mechanism (right diagram).
The above prescription is a bit arbitrary. It provides, however, an interpolation between different four-momentum transfers in the first and second proton line, respectively.

The vertex function \( V \) is the coupling of two virtual gluons to the pseudoscalar meson. The details concerning the function \( F \) become usual UGDFs. In the general case we do not know off-diagonal UGDFs very well. It seems reasonable, at least in the first approximation, to take the function \( F \) skewed (or off-diagonal) unintegrated gluon distributions. They are total four-momentum transfers in the first and second proton line, respectively.

The bare amplitude above is subjected to absorption corrections which depend on collision energy. The vertex function \( V(k_1, k_2, P_M) \) in the expression (1) describes the coupling of two virtual gluons to the pseudoscalar meson. The details concerning the function \( V(k_1, k_2, P_M) \) can be found in [5].

Following the formalism for the diffractive double-elastic production of the Higgs boson developed by Kaidalov, Khoze, Martin and Ryskin [56] (KKMR) we write the bare QCD amplitude for the process sketched in Fig. 1 as

\[
\mathcal{M}^{g^*g^*\to\gamma'p}_{pp\to pp} = i \pi^2 \int d^2k_{0,t} V(k_1, k_2, P_M) f_{g,1}^{off}(x_1, x'_1, k_{0,t}^2, k_{1,t}^2, t_1) f_{g,2}^{off}(x_2, x'_2, k_{0,t}^2, k_{2,t}^2, t_2)
\]

where \( F_1(t_1) \) and \( F_1(t_2) \) are usual Dirac isoscalar nucleon form factors and \( t_1 \) and \( t_2 \) are total four-momentum transfers in the first and second proton line, respectively. The above prescription is a bit arbitrary. It provides, however, an interpolation between different \( x \) and \( k_t \) values.

Neglecting spin-flipping contributions the average matrix element squared for

\[
\mathcal{M}^{g^*g^*\to\gamma'p}_{pp\to pp} = i \pi^2 \int d^2k_{0,t} V(k_1, k_2, P_M) f_{g,1}^{off}(x_1, x'_1, k_{0,t}^2, k_{1,t}^2, t_1) f_{g,2}^{off}(x_2, x'_2, k_{0,t}^2, k_{2,t}^2, t_2)
\]

The objects \( f_{g,1}^{off}(x_1, x'_1, k_{0,t}^2, k_{1,t}^2, t_1) \) and \( f_{g,2}^{off}(x_2, x'_2, k_{0,t}^2, k_{2,t}^2, t_2) \) appearing in formula (1) are skewed (or off-diagonal) unintegrated gluon distributions. They are non-diagonal both in \( x \) and \( k_t^2 \) space. Usual off-diagonal gluon distributions are non-diagonal only in \( x \). In the limit \( x_{1,2} \to x'_{1,2}, k_{0,t}^2 \to k_{1/2,t}^2 \) and \( t_{1,2} \to 0 \) they become usual UGDFs. In the general case we do not know off-diagonal UGDFs very well. It seems reasonable, at least in the first approximation, to take

\[
f_{g,1}^{off}(x_1, x'_1, k_{0,t}^2, k_{1,t}^2, t_1) = \sqrt{f_g^{(1)}(x'_1, k_{0,t}^2) \cdot f_g^{(1)}(x_1, k_{1,t}^2) \cdot F_1(t_1)},
\]

\[
f_{g,2}^{off}(x_2, x'_2, k_{0,t}^2, k_{2,t}^2, t_2) = \sqrt{f_g^{(2)}(x'_2, k_{0,t}^2) \cdot f_g^{(2)}(x_2, k_{2,t}^2) \cdot F_1(t_2)},
\]

where \( F_1(t_1) \) and \( F_1(t_2) \) are usual Dirac isoscalar nucleon form factors and \( t_1 \) and \( t_2 \) are total four-momentum transfers in the first and second proton line, respectively.
the \( p(\gamma^*)p(\gamma^*) \rightarrow pp\eta' \) process can be written as:

\[
|\mathcal{M}_{pp\rightarrow pp\eta'}|^2 \approx 4s^2 e^8 \frac{F_1^2(t_1)}{t_1^2} \frac{F_2^2(t_2)}{t_2^2} |F_{\gamma^*\gamma^*\rightarrow \eta'}(k_1^2, k_2^2)|^2 |k_{1,t}|^2 |k_{2,t}|^2 \sin^2(\Phi).
\]  

\(3\). Results

We have shown in Ref.\cite{4} that it is very difficult to describe the only existing high-energy \((W \sim 30 \text{ GeV})\) data measured by the WA102 collaboration\cite{8} in terms of the unintegrated gluon distributions. First of all, rather large cross section has been measured experimentally. Using prescription \cite{3} and on-diagonal UGDFs from the literature we get much smaller cross sections. Secondly, the calculated dependence on the azimuthal angle between the outgoing protons is highly distorted from the \(\sin^2\Phi\) distribution, whereas the measured one is almost a perfect \(\sin^2\Phi\). This signals that a rather different mechanism plays the dominant role at this energy.

![Fig. 2. \(\sigma_{tot}\) 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.](image)

In Fig.\cite{2} I show energy dependence of the total (integrated over kinematical variables) cross section for the exclusive reaction \(pp \rightarrow pn'p\) for different UGDFs.
Quite different results are obtained for different UGDFs. This demonstrates huge sensitivity to the choice of UGDF. The cross section with the Kharzeev-Levin type distribution (based on the idea of gluon saturation) gives the cross section which is 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. While the QED contribution can be reliably calculated, the QCD contribution cannot be at present fully controlled.

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.

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. In addition, it may interfere with the QCD mechanism.

In Table 1 I have collected cross sections (in nb) for $\eta'$ and $\eta_c$ mesons for $W = 1960$ GeV, integrated over broad range of kinematical variables specified in the table caption. The cross sections for $\eta_c$ are very similar to corresponding cross sections for $\eta'$ production and in some cases even bigger.
4. Conclusions

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 this “low” energy.

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 diffractive QCD mechanism and the photon-photon fusion lead to quite different pattern in the $(t_1, t_2)$ space.

Finally we have presented results for exclusive double elastic $\eta_c$ production. Similar cross sections as for $\eta'$ production were obtained. Also in this case the results depend strongly on the choice of UGDF.

Measurements of the reaction(s) in the title would help to limit or even pin down the UGDFs in the nonperturbative region of small gluon transverse momenta where these objects cannot be obtained as a solution of any perturbative evolution equation, but must be rather modelled.

References

1. P. Moskal, et al. (COSY11 collaboration), Phys. Rev. Lett. 80 (1998) 3202; P. Moskal, et al. (COSY11 collaboration), Phys. Lett. B474 (2000) 416. P. Moskal, et al. (COSY11 collaboration), Phys. Lett. B482 (2000) 356.
2. F. Balestra et al. (DISTO collaboration), Phys. Lett. B491 (2000) 29.
3. K. Nakayama and H. Haberzettl, Phys. Rev. C69 (2004) 065212.
4. A. Szczurek, R.S. Pasechnik and O.V. Teryaev, [hep-ph/0608302](http://arxiv.org/abs/hep-ph/0608302).
5. V.A. Khoze, A.D. Martin and M.G. Ryskin, Phys. Lett. B401 (1997) 330; V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C23 (2002) 311; A.B. Kaidalov, V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C31 (2003) 387; A.B. Kaidalov, V.A. Khoze, A.D. Martin and M.G. Ryskin, Eur. Phys. J. C33 (2004) 261.
6. J. Forshaw, [hep-ph/0508274](http://arxiv.org/abs/hep-ph/0508274).
7. N.I. Kochelev, T. Mori and A.V. Vinnikov, Phys. Lett. B457 (1999) 202.
8. D. Barberis et al. (WA102 collaboration), Phys. Lett. B422 (1998) 399.