Physics Letters B; Volume 676; Issues 4-5; 8 June 2009; Pages 152-154
DESY 09-045

arXiv:0906.3147v1 [hep-ph] 17 Jun 2009

Touching on the gluon polarization in the Durham Pomeron

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Inclusive and exclusive production of scalar and pseudoscalar mesons via gluon-gluon fusion is considered. A new experimental test is proposed, which can probe the polarization state of the gluons in exclusive production processes and check the compatibility of the two-gluon exchange mechanism with the properties of conventional Pomeron.

Key words: Diffraction, polarization, Durham model
PACS: 12.38.Qk, 13.60.Le

1 Introduction

According to the present-day point of view, diffractive processes are to be understood in terms of two-gluon exchange mechanism, and the old concept of Pomeron has to be replaced with a new field theory object, the generalized two-gluon distribution function. It is not yet clear, however, to what extent does the two-gluon language fit the known properties of conventional Pomeron. In particular, since the Pomeron is considered to be a scalar object with positive parity, $J^{PC} = 0^{++}$, the polarization vectors of the both gluons must be parallel to each other. Do we have any chance to verify this prediction experimentally? The present Letter is devoted to this interesting issue, and, as far as the Durham model [1]-[4] is concerned, the answer is yes, as we will see in the next section.

2 Basic idea

In order to feel the correlation between the gluon polarization vectors, we have to compare the production cross sections of pseudoscalar and scalar mesons in inclusive and exclusive channels. Feynman diagrams representing

the inclusive inelastic and exclusive double diffractive production mechanisms are displayed in Fig. 1(a) and (b), respectively. Both these mechanisms have an important element in common, namely, the gluon-gluon fusion partonic subprocess. The properties of the corresponding matrix element $\mathcal{M}$ are such that, if the polarization vectors of the incident gluons are parallel to each other, then only the scalar states are produced, while the production of pseudoscalar states is forbidden. At the same time, if the polarization vectors of the initial gluons are perpendicular to each other, then the production of pseudoscalar states is allowed, while the production of scalar states is suppressed.

These properties follow immediately from the interaction Lagrangians, which read (for an ideal case of on-shell gluons)

$$Ł(gg0^+) \propto e_1^\mu e_2^\nu g_{\mu\nu} \tag{1}$$

for scalar states, and

$$Ł(gg0^-) \propto \epsilon_{\mu\nu\alpha\beta} e_1^\mu e_2^\nu k_1^\alpha k_2^\beta \tag{2}$$

for pseudoscalar states, with e_1 and e_2 being the gluon polarization vectors, and k_1 and k_2 the gluon momenta.

In the inelastic case, the gluons g_1 and g_2 in Fig. 1(a) are uncorrelated and contribute to the production of both pseudoscalar and scalar mesons. On the contrary, in the diffractive case, the presence of an additional gluon g_0 in Fig. 1(b) can induce positive correlations. If we assume that the emission of a gluon pair $g_0 g_1$ is equivalent to the emission of a Pomeron, then the gluons g_0 and g_1 are polarized in the same plane. For the same reason, the gluons g_0 and g_2 are also polarized in the same plane, and so, the gluons g_1 and g_2 have to be polarized in the same plane as well. Consequently, one can expect that the production of pseudoscalar mesons would be suppressed or forbidden in this case.

Thus, by comparing the pseudoscalar-to-scalar ratios in exclusive and inclusive production channels one probes the polarization of the interacting gluons. Though evident, the suppression of $J^P = 0^-$ states due to quantum number selection rules has not been taken into account in the literature [1]-[4] when considering the elastic production of non-standard Higgs bosons, η' and η_c mesons.

3 Numerical example

To illustrate the analysing power of the gluon-gluon fusion subprocess we show theoretical predictions on the inclusive production of $\eta_c\,(J^{PC}=0^{-+})$ and $\chi_c\,(J^{PC}=0^{++})$ mesons at the conditions of the Fermilab Tevatron ($p\bar{p}$ collisions at $\sqrt{s}=1960$ GeV) and Relativistic Heavy Ion Collider (RHIC, pp mode, $\sqrt{s}=200$ GeV).

Throughout this Letter we will be using the overall (proton-proton) center-of-mass system with the z axis oriented along the beam direction. Adopting the k_t-factorization prescription [5], we take the gluon polarization vectors in the form $e^\mu = k_t^\mu/|k_t|$, where k_t^μ is the component of the respective gluon momentum perpendicular to the beam axis. In this approach, the polarization vectors are real and lie entirely in the xy plane.

Our calculations are based on perturbative QCD and nonrelativistic bound state formalism [6, 7]. The creation of a heavy quark pair $c\bar{c}$ is treated as a purely perturbative process. The calculations are straightforward and follow the standard Feynman rules. The spin projection operators [6, 7]

$$\mathcal{P}(^1S_0) \equiv \mathcal{P}(S{=}0, L{=}0) = \gamma_5\,(\not{p}_c + m_c)/(2m_c)^{1/2} \quad (3)$$

$$\mathcal{P}(^3P_0) \equiv \mathcal{P}(S{=}1, L{=}1) = (\not{p}_{\bar{c}} - m_c)\;\not{\epsilon}_S\,(\not{p}_c + m_c)/(2m_c)^{3/2} \quad (4)$$

introduced in the amplitudes guarantee the proper quantum numbers of the $c\bar{c}$ states under consideration.

The formation of a final state meson is a non-perturbative process. Within the nonrelativistic approximation which we are using, its probability is determined by a single parameter related to the meson wave function at the origin of coordinate space. More precisely, the probability of forming an η_c meson is proportional to the radial wave function squared, $|\mathcal{R}_\eta(0)|^2$; the latter is taken to be the same as that of the J/ψ meson (known from the J/ψ leptonic decay width [8]) and set to $|\mathcal{R}_\eta(0)|^2 = 0.8$ GeV^3. The probability of forming a χ_c meson relates to the derivative of the radial wave function; the latter is taken from the potential model [9]: $|\mathcal{R}'_\chi(0)|^2 = 0.075$ GeV^5.

Finally, we obtain the meson production cross section by convoluting the matrix element squared with unintegrated gluon distribution functions. Here, we use the parametrization proposed by J.Blümlein [10], where the leading-order Glück-Reya-Vogt gluon density [11] was used for collinear input. The details of calculations from the first to the last step are explained in Ref. [12]. The full FORTRAN code is available from the author on request.

Fig. 2 displays our predictions on the transverse momentum spectra. All of the pseudoscalar η_c mesons come from gluons with perpendicular polarization vectors. Most of the scalar χ_c mesons come from gluons with parallel polarization vectors. As a result of the initial gluon off-shellness, the production of χ_c mesons by gluons with perpendicular polarization vectors is not totally forbidden (as it would follow from (1)), but is only suppressed by a large factor. This contribution comes from the interaction of the type $Ł(gg0^+) \propto (e_1k_2)(e_2k_1)$ which vanishes in the on-shell gluon limit.

The ratio of the production rates $d\sigma(\eta_c)/d\sigma(\chi_c)$ is exhibited in Fig. 3. As one can see, it stays almost constant at about $d\sigma(\eta_c)/d\sigma(\chi_c) \simeq 5$ both at the Tevatron and RHIC energies, neither showing dependence on the transverse momentum nor on rapidity. Any deviation from this number would indicate correlations between the gluon polarization states.

It is worth noting that many important theoretical uncertainties cancel out in the ratio: e.g., the predictions are insensitive to the choice of gluon distribution functions, the scale in the running coupling constant $\alpha_s(\mu^2)$, etc. Thus, we conclude that the gluon-gluon fusion mechanism can serve as a convenient tool probing the gluon polarization.

4 Comparison with other calculations

The properties of the gluon-gluon-meson vertex has been previously considered in Refs. [2, 3]. We fully agree with the mentioned papers in the general structure of this coupling (Eqs. (1) and (2) versus Eq. (22) in Ref. [2]). In the inelastic case, the angle between the gluon polarization vectors is at the same time the azimuthal angle between the recoil protons. This results in the $\cos^2\varphi$ and $\sin^2\varphi$ behavior of the production cross section for 0^+ and 0^- mesons, respectively. The behavior of double diffractive processes is less simple and strongly depends on the dynamics. Particularly essential is the relation between the internal transverse momentum Q_T in the loop (see Fig. 3 of Ref. [2]) and the transverse momenta of the outgoing protons p_t. The distribution of 0^+ mesons preserves its $\cos^2\varphi$ behavior for $Q_T << p_t$ (which is typical for comparatively light states) and becomes nearly flat for $Q_T >> p_t$ (for heavier states like Higgs bosons).

In the present Letter, we basically focus on the quantum number selection rules and avoid giving numerical predictions on the double diffractive processes, as they would be too much model dependent. First of all, the

very factorization principle is questionable. In order that the factorization be valid, both gluons attached to the 'upper' proton in Fig. 1 must only have positive light-cone momentum fraction, while the negative one must be close to zero. Also, both gluons attached to the 'lower' proton must only have negative light-cone momentum fraction, while the positive one must be close to zero. These two conditions are incompatible for the gluon connecting the both protons. A possible way out is in assuming that the positive and negative light-cone momenta are both close to zero, and only the transverse momentum is exchanged. But then it would be hard to believe that there exists a simple relation between the generalized two-gluon distribution functions and the ordinary gluon distributions measured in inclusive processes.

Instead, we give the first priority to clarifying the fundamental role of selection rules coming from gluon spin correlations, that may have dramatic effect on the production of all pseudoscalar states (including non-standard Higgs bosons) but yet had never been considered in the literature.

The first experimental observation of the double diffractive production of scalar χ_{c0} mesons is recently reported in [13]. This is an encouraging result showing that the test which we propose here is really feasible.

5 Summary

In the present Letter we draw attention to the fact that measuring the production cross sections of pseudoscalar and scalar mesons in inclusive and exclusive channels can yield important information on the polarization state of the interacting gluons. In addition, it would be extremely useful if these measurements are accompanied by measuring the azimuthal dependence of the cross section.

Whether or not will the Durham model receive support from the data, the information obtained by these measurements will shed more light on the nature of diffractive processes and, in particular, will stimulate further refinement of the concept of generalized gluon distributions.

Acknowledgements

This work was supported by DESY Directorate in the framework of Moscow-DESY project on Monte-Carlo implementation for HERA-LHC, by Russian

Foundation for Basic Research under Grant No. 08-02-00896-a and by FASI under Grant No. NS-1856.2008.2.

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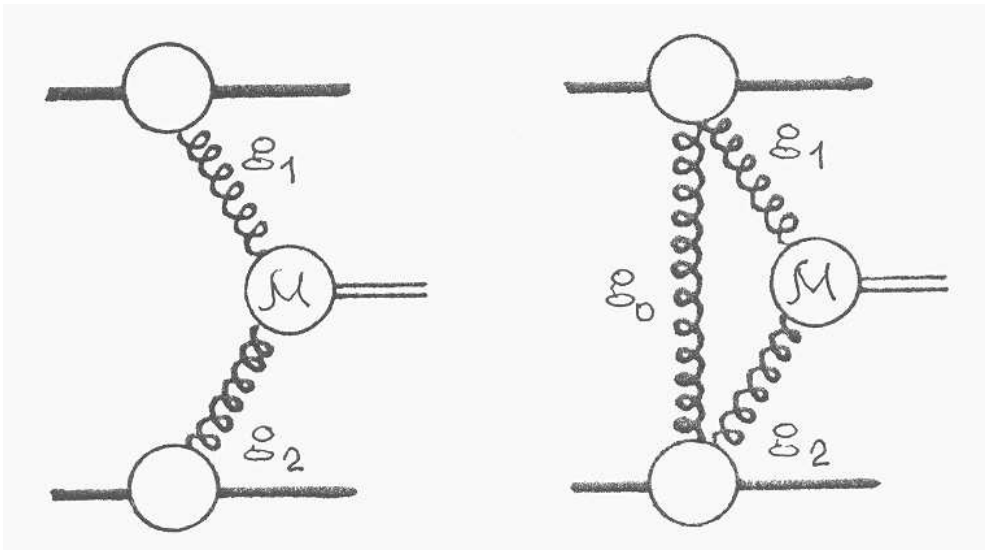

Figure 1: Diagrams representing the inclusive (left panel) and exclusive (right panel) production mechanisms. $\mathcal{M}$ denotes the gluon-gluon fusion matrix element; open circles stand for the gluon distribution functions in the proton.

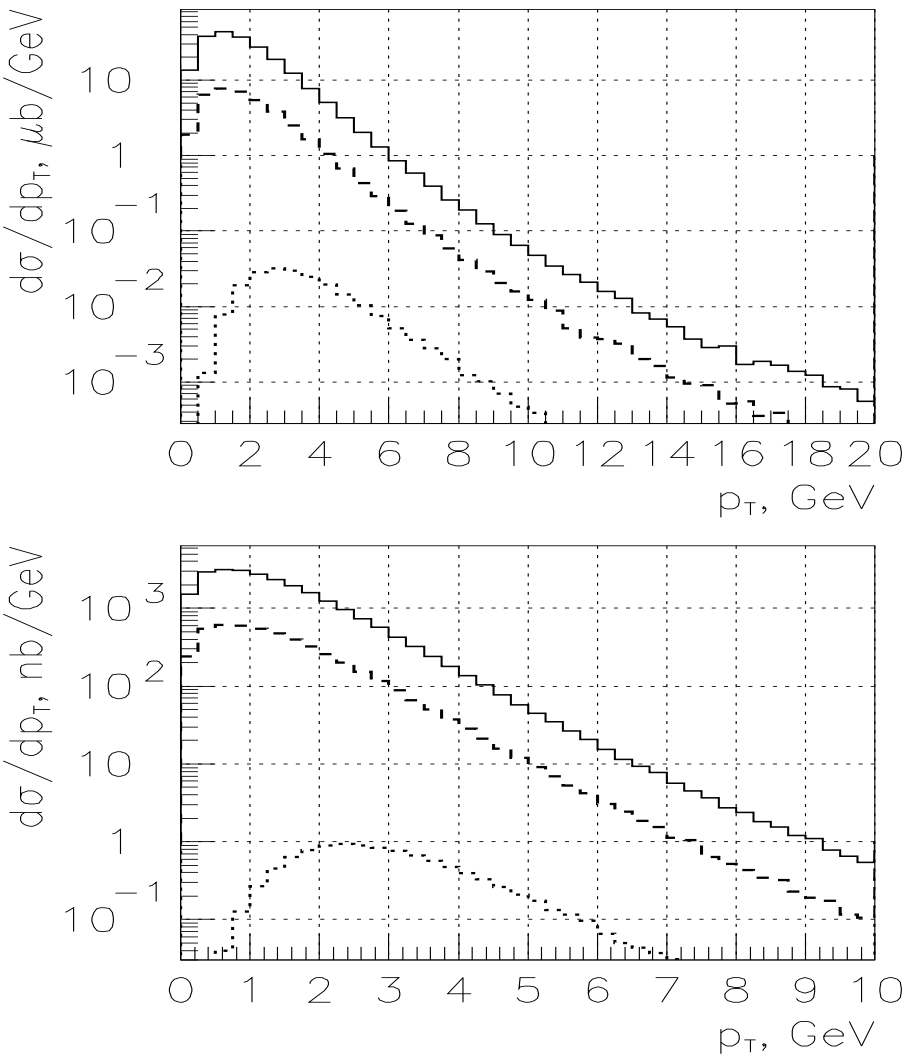

Figure 2: Inclusive transverse momentum distributions at the Tevatron (upper panel) and RHIC (lower panel) energies. Solid histograms, η_c mesons, all coming from the gluons with perpendicular polarization vectors; dashed and dotted histograms, χ_c mesons coming from the gluons with parallel and perpendicular polarization vectors, respectively.

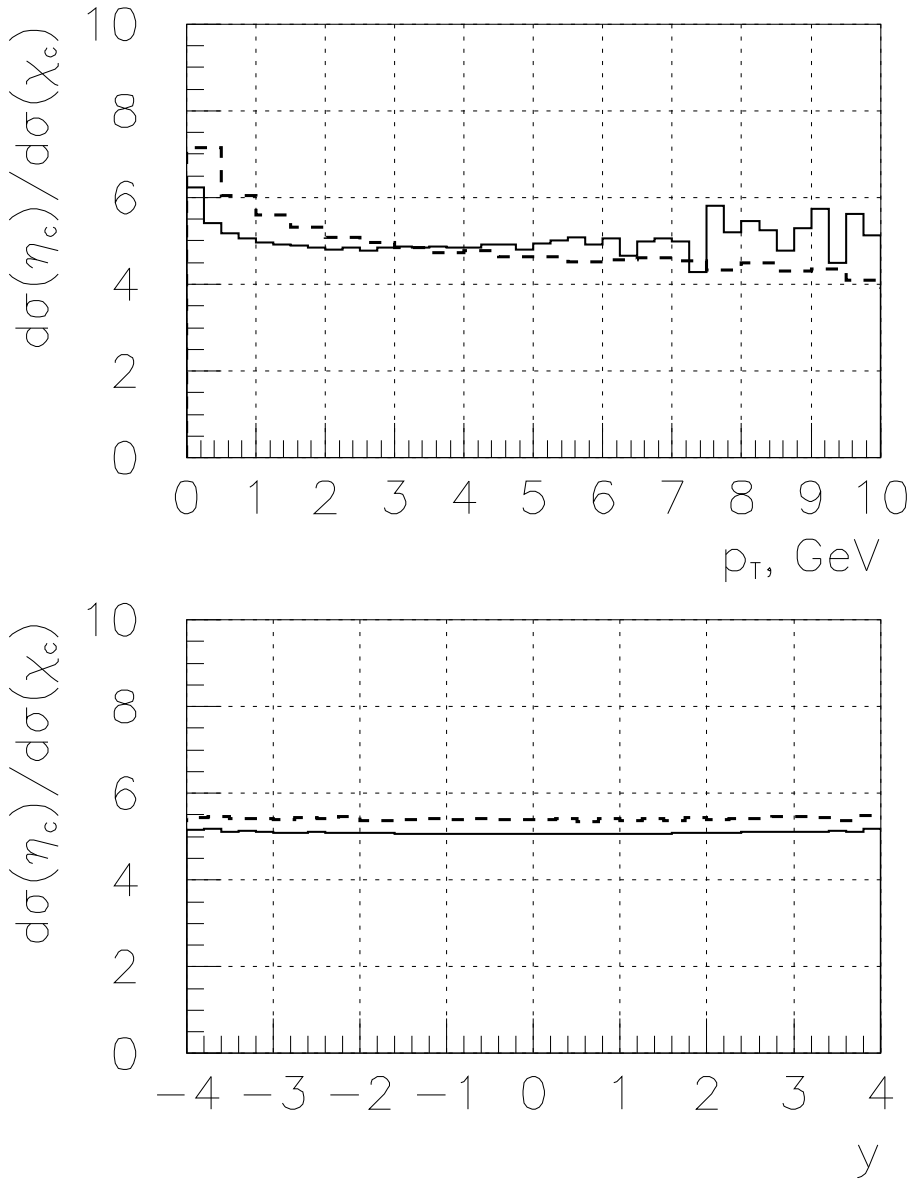

Figure 3: The ratio of the production rates $d\sigma(\eta_c)/d\sigma(\chi_c)$ as a function of the transverse momentum p_t (upper panel) and rapidity y (lower panel). Solid histograms, RHIC conditions; dashed histograms, Tevatron conditions.