Exclusive production of meson pairs and resonances in proton-proton collisions

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Abstract.
We report a study of the central exclusive production of π⁺π⁻ and K⁺K⁻ pairs in high energy hadron-hadron collisions. The amplitude is calculated in the Regge approach including both pomeron and secondary reggeon exchanges and absorption effects due to proton-proton interaction and ππ (KK) rescattering. We discuss a measurement of exclusive production of a scalar χc₀ meson via χc₀ → π⁺π⁻, K⁺K⁻ decay. We find that the relative contribution of resonance states and the ππ (KK) continuum strongly depend on the cut on pion (kaon) transverse momentum. We compare the results with the existing experimental data and present predictions for the RHIC, Tevatron and LHC colliders. We discuss also the f₂(1270) meson production mediated by an effective tensor pomeron exchanges.

Keywords: Exclusive production, pomeron, two-pion continuum, resonance states, χc₀ → π⁺π⁻
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INTRODUCTION

Central exclusive production (CEP) processes of the type pp → pXp, where X represents the centrally produced state separated from the two very forward protons by large rapidity gaps, provide a very promising way to study the properties of resonance states. We have studied recently the four-body pp → ppp⁺π⁻ [1, 2, 3], ppK⁺K⁻ [4] reactions which constitute an irreducible background to resonance states (e.g. φ, f₂(1270), f₀(1500), f₂(1525), χc₀). As discussed in [5, 6], the measurement of χc₀ CEP via two-body decay channels to light mesons is of special interest for both studying the dynamics of heavy quarkonia and for testing the QCD framework of CEP.

CEP processes have been successfully observed at the Tevatron by selecting events with large rapidity gaps [7]. At the Tevatron the measurement of exclusive production of χc via decay in the J/ψ + γ channel cannot provide production cross sections for different species of χc [8]. It may be possible to isolate the χcJ CEP contribution via hadronic decay channels, especially to π⁺π⁻ [5] and K⁺K⁻ [4]. In particular the branching fraction to these channels are relatively larger for scalar meson than for the tensor meson and σ(χc₀) > σ(χc₂) from theoretical calculation means that only χc₀ will contribute to the signal [9, 5].

A new area of experimental studies of CEP with tagged forward protons has just started. It is expected that large CEP data sample will be available in the near future

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from measurements performed by the STAR Collaboration at RHIC [10]. In Ref. [11] a possibility of measuring exclusive $\pi^+\pi^-$ production at the LHC with tagged forward protons (ALFA detectors) during special low-luminosity runs has been studied. The $pp \rightarrow nn\pi^+\pi^+$ [12] and $pp \rightarrow pp\omega$ [13] processes are also very interesting for possible future experiments at high energies.

**SKETCH OF FORMALISM**

![Representative diagrams for the non-perturbative exclusive production of pion (kaon) pairs (panel a) and $f_2(1270)$ meson (panel b). The absorptive corrections due to proton-proton interactions and $\pi\pi$-rescattering are indicated and the perturbative mechanism of $\chi_{c0}$ meson production (panel c).](image)

The dominant mechanism of the exclusive production of light meson pairs at high energies is sketched in Fig. 1a. The formalism used to calculate of non-resonant background amplitude is explained in detail in Refs [3, 4]. The Regge parametrization of the scattering amplitude includes both pomeron and subleading reggeon exchanges. Our model with the parameters taken from the Donnachie-Landshoff analysis of the total $\pi N$ or $KN$ cross sections sufficiently well describes the elastic data for $\sqrt{s} > 3$ GeV. The form factors correcting for the off-shellness of the intermediate pions/kaons are parametrized as $F_{\pi/K}(\hat{t}/\hat{u}) = \exp\left(\frac{\hat{t}/\hat{u} - m^2_{\pi/K}}{\Lambda^2_{\text{off}}}\right)$, where the parameter $\Lambda^2_{\text{off}} = 2 \text{ GeV}^2$ is obtained from a fit to the CERN-ISR data [14, 15].

In Fig. 1b the exclusive dipion production through the $s$-channel $f_2$-meson exchange and double tensor pomeron exchange is presented [16]. The theoretical arguments for an effective tensorial answer for the nonperturbative pomeron are sketched in [17] and will be discussed in detail [18].

The QCD amplitude for exclusive central diffractive $\chi_{c0}$ meson production, sketched in Fig. 1c, was calculated within the $k_t$-factorization approach including virtualities of active gluons [9] and the corresponding cross section is calculated with the help of unintegrated gluon distribution functions (UGDFs). In Ref. [5] we have performed detailed studies of several differential distributions of $\chi_{c0}$ meson production.

**RESULTS**

In Fig. 2 we compare our results with CERN ISR experimental data [15] at $\sqrt{s} = 62$ GeV. One can see two-pion invariant mass spectrum with strong resonance structures attributed to $f_0$ and $f_2$ states and distribution in pion rapidity when all (solid line)
and only some components in the amplitude are included. In the right panel the cross sections for the \( f_2(1270) \) meson production was calculated according to the diagram in Fig.1b with an effective tensor pomeron exchanges [16]. In principle, the resonance and continuum contributions should be added coherently together leading to the distortion of the \( f_2 \) line shape as observed e.g. for the \( \gamma\gamma \rightarrow f_2(1270) \rightarrow \pi^+\pi^- \) reaction [19]. This requires a consistent model of the resonances and the backgrounds.

\[
\frac{d\sigma}{dp} (\mu b/GeV) \quad t, \pi
\]

\( \chi_{c0} \rightarrow 1.96 \text{ TeVs} \quad |p| \leq 1.5 \text{ GeV} \)

\( \chi_{c0} \rightarrow 62 \text{ GeVs} \quad |p| \rightarrow 0.9, |y| \leq 1.5 \text{ GeV} \)

\( M = 62 \text{ GeV} (ISR) \quad |x| > 0.9, |y| > 0.9 \)

\( \chi_{c0} \rightarrow 2.5 \text{ GeV} \quad |x| > 0.9 \)

\( \chi_{c0} \rightarrow 14 \text{ TeV} \quad |x| > 2.5 \text{ GeV} \)

\( \chi_{c0} \rightarrow 1.96 \text{ TeVs} \quad p < 14 \text{ TeV} \)

\( \chi_{c0} \rightarrow 1.5 \text{ GeV} \quad |p| > 2.5 \text{ GeV} \)

\( \chi_{c0} \rightarrow 14 \text{ TeV} \quad |p| > 2.5 \text{ GeV} \)

\( \chi_{c0} \rightarrow 1.96 \text{ TeVs} \quad |p| > 1.5 \text{ GeV} \)

In addition to the signal, the background ratio [5]. Measurements of other decay channels, e.g. \( K^+K^- \), are possible as well [4].

\[
\frac{d\sigma}{dM_{\pi\pi}} (\mu b/GeV) \quad p_{t,\pi}
\]

\( \chi_{c0} \rightarrow 1.96, 14 \text{ TeV} \quad |p_{t,\pi}| > 1.5 \text{ GeV} \)

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CONCLUSIONS

We have calculated several differential observables for the $pp \to pp\pi^{+}\pi^{-}$ [1, 2, 3] and $ppK^{+}K^{-}$ [4] reactions. The full amplitude of central diffractive process was calculated in a simple model with parameters adjusted to low energy data. At high energies the pions or kaons from the presented CEP mechanism are emitted preferentially in the same hemispheres, i.e. $y_{\pi^{+}}, y_{\pi^{-}} > 0$ or $y_{\pi^{+}}, y_{\pi^{-}} < 0$. We have predicted large cross sections for RHIC, Tevatron and LHC which allows to hope that presented by us distributions will be measured in near future. We have calculated also contributions of several diagrams where pions/kaons are emitted from the proton lines. These mechanisms contribute at forward and backward regions and do not disturb the observation of the central DPE component which dominates at midrapidities.

We have analyzed a possibility to measure the exclusive production of $\chi_{c0}$ meson in the proton-(anti)proton collisions at the RHIC, Tevatron and LHC via $\chi_{c0} \to \pi\pi, KK$ decay channels. For a more detailed discussion of this issue see [5, 4, 6].

Future experimental data on exclusive meson production at higher energies may provide a better information on the spin structure of the pomeron and its coupling to the nucleon and mesons. The relevant measurements at high energies are possible and could provide useful information e.g. about $f_{0}(980)$, glueball candidate $f_{0}(1500)$ [1], $f_{2}(1270)$ and $\chi_{c0}$ meson CEP production.

REFERENCES

1. A. Szczurek and P. Lebiedowicz, Nucl. Phys. A826 (2009) 101.
2. P. Lebiedowicz, A. Szczurek and R. Kamiński, Phys. Lett. B680 (2009) 459.
3. P. Lebiedowicz and A. Szczurek, Phys. Rev. D81 (2010) 036003.
4. P. Lebiedowicz and A. Szczurek, Phys. Rev. D85 (2012) 014026.
5. P. Lebiedowicz, R. Pasechnik and A. Szczurek, Phys. Lett. B701 (2011) 434.
6. L.A. Harland-Lang, V.A. Khoze, M.G. Ryskin and W.J. Stirling, Eur. Phys. J. C72 (2012) 2110.
7. M. Albrow, talk at this conference (Diffraction2012).
8. T. Aaltonen et al. [CDF Collaboration], Phys. Rev. Lett. 102 (2009) 242001.
9. R.S. Pasechnik, A. Szczurek and O.V. Teryaev, Phys. Rev. D78 (2008) 014007; Phys. Lett. B680 (2009) 62; Phys. Rev. D81 (2010) 034024.
10. L. Adamczyk, for the STAR Collaboration, talk at this conference (Diffraction2012).
11. R. Stašzewski, P. Lebiedowicz, M. Trzebiński, J. Chwastowski and A. Szczurek, Acta Phys. Polon. B42 (2011) 1861.
12. P. Lebiedowicz and A. Szczurek, Phys. Rev. D83 (2011) 076002.
13. A. Cisek, P. Lebiedowicz, W. Schäfer and A. Szczurek, Phys. Rev. D83 (2011) 114004.
14. A. Breakstone et al. [ABCDHW Collaboration], Z. Phys. C42 (1989) 387.
15. A. Breakstone et al. [ABCDHW Collaboration], Z. Phys. C48 (1990) 569.
16. P. Lebiedowicz, O. Nachtmann and A. Szczurek, paper in preparation.
17. O. Nachtmann, talk ”A model for high-energy soft reactions” at ECT* workshop on Exclusive and diffractive processes in high energy proton-proton and nucleus-nucleus collisions, Trento, February 27 - March 2, 2012.
18. C. Everz, M. Maniatis and O. Nachtmann, paper in preparation.
19. A. Szczurek and J. Speth, Nucl. Phys. A 728 (2003) 182.
20. A. Kirk, Phys. Lett. B489 (2000) 29.
21. R. Waldi, K.R. Schubert and K. Winter, Z. Phys. C18 (1983) 301.
22. M. Glück, E. Reya and A. Vogt, Z. Phys. C67 (1995) 433.
23. M. Glück, D. Jimenez-Delgado, E. Reya and C. Schuck, Phys. Lett. B664 (2008) 133.