Exclusive diffractive production of hadrons in pp collisions

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We discuss central exclusive diffractive dihadron production in proton-proton collisions at high energies. The calculation is based on a tensor pomeron model and the amplitudes for the processes are formulated in an effective field-theoretic approach. We include a purely diffractive dipion continuum, and the scalar and tensor resonances decaying into the $\pi^+\pi^-$ pairs as well as the photoproduction contributions (ρ^0, Drell-Söding). We discuss how two pomerons couple to tensor meson $f_2(1270)$ and the interference effects of the scalar and tensor resonances and the dipion continuum. The theoretical results are compared with existing CDF and CMS experimental data. We discuss also the Drell-Hiida-Deck type mechanism with centrally produced ρ^0 meson associated with a very forward/backward πN system. For the $pp \to pp\pi^+\pi^-\pi^+\pi^-$ reaction we consider both the $\sigma\sigma$ and $\rho\rho$ contributions as well as the triple Regge exchange mechanism. Predictions for planned or being carried out experiments (STAR, ALICE, ATLAS, CMS) are presented. We show the influence of the experimental cuts on the integrated cross section and on various differential distributions for outgoing particles.

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1 Introduction

Central production mediated by the "fusion" of two exchanged pomerons is an important diffractive process for the investigation of properties of resonances, in particular, for search of gluonic bound states (glueballs) [1, 2]. This is closely related to experimental studies of the COMPASS [3], ISR [4], STAR [5], CDF [6], LHCb [7], ALICE [8], CMS [9], ATLAS [10]. On the theoretical side, the exclusive diffractive dihadron continuum production can be understood as due to the exchange of two pomerons between the external protons and the centrally produced hadronic system. One of the first calculations were concerned with the $pp \to pp\pi^+\pi^-$ reaction [11, 12, 13]. The Born amplitude was written in terms of pomeron/reggeon exchanges with parameters fixed from phenomenological analyses of NN and πN total and elastic scattering. Such calculations make sense for the continuum production of pseudoscalar meson pairs. First calculations of central exclusive diffractive production of $\pi^+\pi^-$ continuum together with the dominant scalar $f_0(500)$, $f_0(980)$, and tensor $f_2(1270)$ resonances were performed in [1] within the tensor-pomeron model formulated in [15]. In this model the soft pomeron exchange is described as an effective rank-2 symmetric tensor exchange; see [16, 15]. There, all reggeon exchanges with charge conjugation $C = +1$ ($C = -1$) were described as effective tensor (vector) exchanges. Recently, in [17], three models for the soft pomeron, tensor, vector, and scalar, were compared with the STAR data on polarised high-energy pp scattering [18]. Only the tensor-pomeron model was found to be consistent with the general rules of quantum field theory and the data from [18]. This model was applied to the diffractive production of several scalar and pseudoscalar mesons in the reaction $pp \to ppM$; see [19].

The exclusive ρ^0 and non-resonant (Drell-Söding) photon-pomeron/reggeon $\pi^+\pi^-$ production in pp collisions was studied in [20]. In [20] we showed that the resonant contribution interferes with the non-resonant $\pi^+\pi^-$ continuum leading to a skewing of the $\rho(770)$-meson line shape; see also [21]. Due to the photon propagators occurring in diagrams, we expect these processes to be most important when at least one of the protons undergoes only a very small $|t_{1,2}|$. We discussed also the Drell-Hiida-Deck type mechanism with centrally produced ρ^0 meson associated with a very forward/backward πN system in the $pp \to pp\rho^0\pi^0$ and $pp \to pn\rho^0\pi^+$ reactions [24].

2 Sketch of formalism

The total diffractive amplitude is a sum of continuum amplitude and the amplitudes with the s-channel resonances (with quantum numbers $I^G J^{PC} = 0^+(\text{even})^{++}$):

$$\mathcal{M}_{pp\to pp\pi^+\pi^-} = \mathcal{M}^{\pi\pi-\text{continuum}}_{pp\to pp\pi^+\pi^-} + \mathcal{M}^{(I\!PI\!P\to f_0\to\pi^+\pi^-)}_{pp\to pp\pi^+\pi^-} + \mathcal{M}^{(I\!PI\!P\to f_2\to\pi^+\pi^-)}_{pp\to pp\pi^+\pi^-}\,. \quad (1)$$

For instance, the Born (no absorption effects) amplitude for the process $pp \to pp(I\!\!P I\!\!P \to f_2 \to \pi^+\pi^-)$ can be written as

$$\begin{aligned}\mathcal{M}^{(I\!\!P I\!\!P \to f_2 \to \pi^+\pi^-)}_{\lambda_a\lambda_b \to \lambda_1\lambda_2\pi^+\pi^-} = & (-i)\,\overline{u}(p_1,\lambda_1) i\Gamma^{(I\!\!P pp)}_{\mu_1\nu_1}(p_1,p_a) u(p_a,\lambda_a)\; i\Delta^{(I\!\!P)\,\mu_1\nu_1,\alpha_1\beta_1}(s_1,t_1) \\ & \times i\Gamma^{(I\!\!P I\!\!P f_2)}_{\alpha_1\beta_1,\alpha_2\beta_2,\rho\sigma}(q_1,q_2)\; i\Delta^{(f_2)\,\rho\sigma,\alpha\beta}(p_{34})\; i\Gamma^{(f_2\pi\pi)}_{\alpha\beta}(p_3,p_4) \\ & \times i\Delta^{(I\!\!P)\,\alpha_2\beta_2,\mu_2\nu_2}(s_2,t_2)\,\overline{u}(p_2,\lambda_2) i\Gamma^{(I\!\!P pp)}_{\mu_2\nu_2}(p_2,p_b) u(p_b,\lambda_b)\,, \end{aligned} \tag{2}$$

where $t_1 = (p_1 - p_a)^2$, $t_2 = (p_2 - p_b)^2$, $s_1 = (p_a + q_2)^2 = (p_1 + p_{34})^2$, $s_2 = (p_b + q_1)^2 = (p_2 + p_{34})^2$, $p_{34} = p_3 + p_4$. $\Delta^{(I\!\!P)}$ and $\Gamma^{(I\!\!P pp)}$ denote the effective propagator and proton vertex function, respectively, for the tensor pomeron exchange. For the explicit expressions see section 3 of [15]. In [1] we considered all (seven) possible tensorial structures for the $I\!\!P I\!\!P f_2$ coupling. Other details as form of form factors, the tensor-meson propagator $\Delta^{(f_2)}$ and the $f_2\pi\pi$ vertex are given in [15, 1]. In reality the Born approximation is usually not sufficient and absorption corrections (rescattering effects) have to be taken into account, see e.g. [14, 13]. The absorption effects due to pp and πp interactions, discussed in [13], lead to a significant modification of the shape of the distributions in ϕ_{pp}, $p_{t,p}$, $t_{1,2}$ and could be tested by the CMS-TOTEM and ATLAS-ALFA groups.

3 Some selected results

In [1] we tried to describe the dipion invariant mass distribution observed by different experimental groups. As can be clearly seen from Fig. 1 (a) - (c) different $I\!\!P I\!\!P f_2$ couplings generate different interference patterns around $M_{\pi\pi} \sim 1.27$ GeV. A sharp drop around $M_{\pi\pi} \sim 1$ GeV is attributed to the interference of $f_0(980)$ and continuum. We found that the shape of the $\pi^+\pi^-$ distribution depends on the cuts used in a particular experiment (usually the t cuts are very different for different experiments). We can observe that the $j = 2$ coupling gives results close to those observed by the CDF Collaboration [6]. In this preliminary study we did not try to fit the CDF data [6] by mixing different couplings because the data are not fully exclusive (the outgoing p and $\overline{p}$ were not measured). The calculations were done at Born level and the absorption corrections were taken into account by multiplying the cross section by a common factor $\langle S^2 \rangle$ obtained from [13]. The two-pion continuum was fixed by choosing a form factor for the off-shell pion $\hat{F}_\pi(k^2) = \frac{\Lambda^2_{off,M} - m_\pi^2}{\Lambda^2_{off,M} - k^2}$ and $\Lambda_{off,M} = 0.7$ GeV.

In panel (d) of Fig. 1 we show results including in addition to the non-resonant $\pi^+\pi^-$ continuum, the $f_2(1270)$ and the $f_0(980)$ resonances, the contribution from photoproduction ($\rho^0 \to \pi^+\pi^-$, Drell-Söding mechanism), as well as the $f_0(500)$ resonant contribution. Our predictions are compared with the CMS preliminary data [9]. We assume only one of the seven possible $I\!\!P I\!\!P f_2$ tensorial couplings, that is $j = 2$

coupling; see [1]. Here the absorption effects lead to a huge damping of the cross section for the purely diffractive term (the blue lines) and relatively small reduction of the cross section for the photoproduction term (the red lines). Therefore we expect one could observe the photoproduction contribution. The CMS measurement [9] is not fully exclusive and the experimental spectra contain contributions associated to other processes, e.g., when one or both protons undergo dissociation. In addition we show that the results with $\Lambda_{off,M} = 1.2$ GeV better describe the preliminary CMS data (see the dashed line). If we used this set for the STAR or CDF measurements our results there would be above the preliminary STAR data [5] at $M_{\pi\pi} > 1$ GeV and in complete disagreement with the CDF data from [6]. Only purely central exclusive data expected from CMS-TOTEM and ATLAS-ALFA will allow to draw definite conclusions.

4 Summary of our recent results

In [1] we have analysed the exclusive central production of dipion continuum and resonances contributing to the $\pi^+\pi^-$ pair production in proton-(anti)proton collisions in an effective field-theoretic approach with tensor pomerons and reggeons proposed in [15]. We have included the scalar $f_0(500)$ and $f_0(980)$ resonances, the tensor $f_2(1270)$ resonance and the vector $\rho(770)$ resonance in a consistent way. In the case of $f_2(1270)$-meson production via "fusion" of two tensor pomerons we have found [1] all possible $I\!P I\!P f_2$ tensorial couplings. The different couplings give different results due to different interference effects of the f_2 resonance and the dipion continuum contributions. We have shown that the resonance structures in the measured two-pion invariant mass spectra depend on the cut on proton transverse momenta and/or on four-momentum transfer squared $t_{1,2}$ used in an experiment. The cuts may play then the role of a $\pi\pi$ resonance filter. The model parameters of the optimal $I\!P I\!P f_2$ coupling ($j = 2$) have been roughly adjusted to the recent CDF and preliminary STAR experimental data and then used for the predictions for the ALICE, and CMS experiments. We have made estimates of cross sections for both the diffractive and photoproduction contributions and we have presented several interesting correlation distributions which could be checked by the experiments.

The $pp \to pN\rho^0\pi$ processes constitute an inelastic (non-exclusive) background to the $pp \to pp\rho^0$ reaction in the case when only the centrally produced ρ^0 meson decaying into $\pi^+\pi^-$ is measured, the final state protons are not observed, and only rapidity-gap conditions are checked experimentally. We have estimated the size of the proton diffractive-dissociative background to the exclusive $pp \to pp\rho^0$ process at LHC energies [24]. The ratio of integrated cross sections for the inelastic $pp \to pN\rho^0\pi$ processes to the reference reaction $pp \to pp\rho^0$ is of order of (7–10)%.

Also the studies of different decay channels in central exclusive production would be very valuable. One of the possibilities is the reaction $pp \to pp\pi^+\pi^-\pi^+\pi^-$ being analysed at the LHC. In Ref. [22] we analysed the reaction $pp \to pp\pi^+\pi^-\pi^+\pi^-$ proceeding via the intermediate $\sigma\sigma$ and the $\rho\rho$ states. The results for processes with the exchange of heavy mesons (compared to pion) strongly depend on the details of the hadronic form factors. By comparing the theoretical results and the cross sections found in the ISR experiment [23] we fixed the parameters of the off-shell meson form factor and the $I\!\!P\sigma\sigma$ and $f_{2I\!\!R}\sigma\sigma$ couplings. The exclusive $\pi^+\pi^-\pi^+\pi^-$ continuum production was discussed recently in [25]. A measurable cross section of order of a few μb was obtained including the experimental cuts relevant for the LHC experiments.

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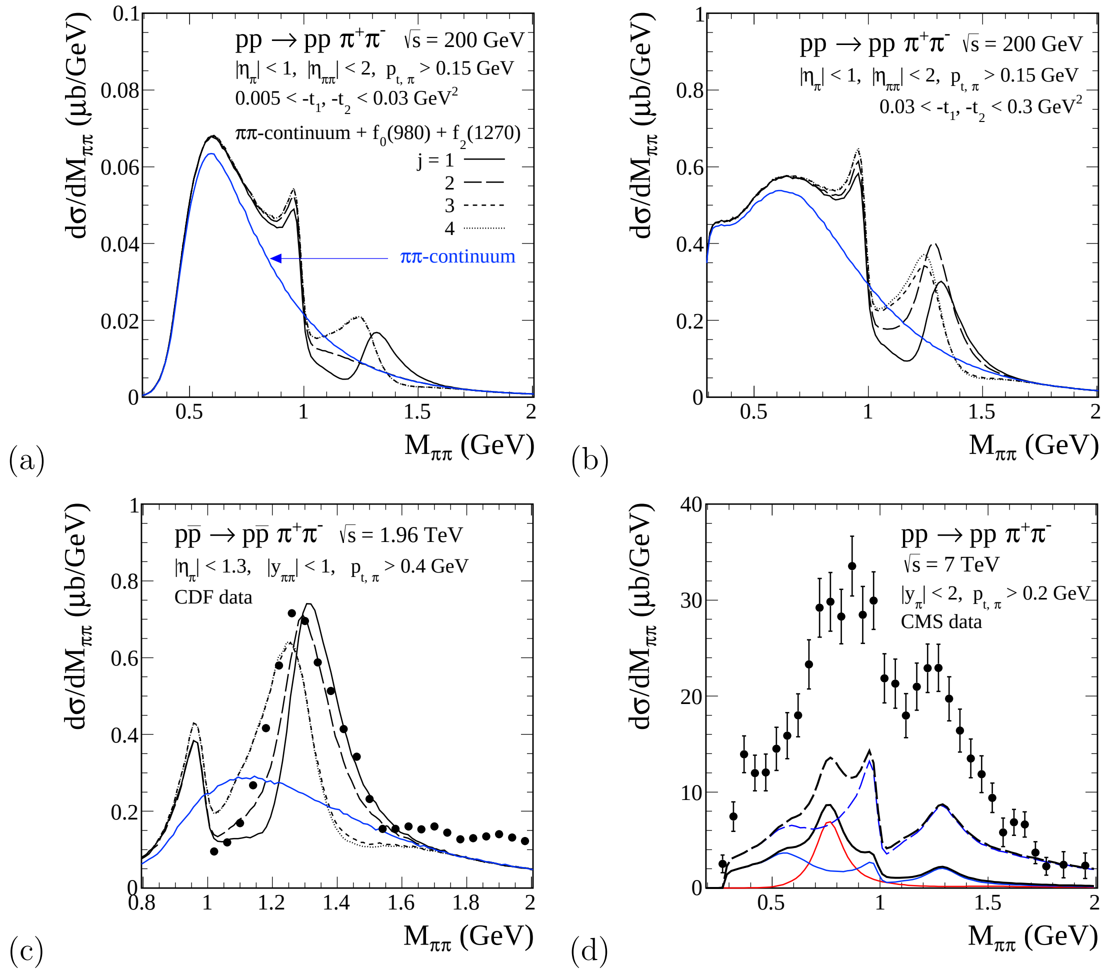

Figure 1: Two-pion invariant mass distributions for the STAR [5] ((a) and (b) panels), the CDF [6] ((c) panel) and the CMS [9] ((d) panel) kinematics. In the panels (a) - (c) the individual contributions of different $I\!P I\!P f_2$ couplings ($j = 1, ..., 4$) are shown. The Born calculations for $\sqrt{s} = 0.2, 1.96$ TeV were multiplied by the gap survival factor $\langle S^2 \rangle = 0.2, 0.1$, respectively. The blue solid lines represent the non-resonant continuum contribution only ($\Lambda_{off,M} = 0.7$ GeV) while the black lines represent a coherent sum of non-resonant continuum, $f_0(980)$ and $f_2(1270)$ resonant terms. The CDF data are from [6]. In the panel (d) both the photoproduction (red line) and purely diffractive (blue line) contributions multiplied by the factors $\langle S^2 \rangle = 0.9$ and $\langle S^2 \rangle = 0.1$, respectively, are included. The complete results correspond to the black solid line ($\Lambda_{off,M} = 0.7$ GeV) and the black dashed line ($\Lambda_{off,M} = 1.2$ GeV). The CMS preliminary data scanned from [9] are shown for comparison.