

Exclusive diffractive production of $\pi^+\pi^-$ pairs within tensor pomeron approach

Piotr LEBIEDOWICZ*

Institute of Nuclear Physics, Polish Academy of Sciences, PL-31-342 Cracow, Poland

E-mail: Piotr.Lebiedowicz@ifj.edu.pl

Otto NACHTMANN

Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, D-69120

Heidelberg, Germany

E-mail: O.Nachtmann@thphys.uni-heidelberg.de

Antoni SZCZUREK

Institute of Nuclear Physics, Polish Academy of Sciences, PL-31-342 Cracow, Poland[†]

E-mail: Antoni.Szczurek@ifj.edu.pl

We discuss exclusive central diffractive production of $\pi^+\pi^-$ in proton-(anti)proton collisions at high energies. Based on a tensor pomeron model we present results of the purely diffractive dipion continuum, the scalar $f_0(500)$, $f_0(980)$ and tensor $f_2(1270)$ resonances decaying into the $\pi^+\pi^-$ pairs as well as the photoproduction mechanism (ρ^0 , Drell-Söding). We discuss how two pomerons couple to the tensor meson $f_2(1270)$ and the interference effects of resonance and dipion continuum contributions. The theoretical results are compared with existing STAR, CDF, and CMS experimental data. Predictions for planned or being carried out experiments (ALICE, ATLAS) are presented. We find that the relative contribution of resonant $f_2(1270)$ and dipion continuum strongly depend on the cut on proton transverse momenta (or four-momentum transfer squared $t_{1,2}$) which may explain some controversial observations made by different ISR experiments in the past. The cuts may play then the role of a $\pi\pi$ resonance filter.

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*Speaker.

[†]Also at University of Rzeszów, PL-35-959 Rzeszów, Poland.

1. Introduction

Recent theoretical [1, 2, 3] and experimental [4, 5, 6, 7, 8] studies have demonstrated that the exclusive dipion production can be important in the context of resonance production, in particular, in searches for glueballs. For a related work see [9]. The experimental data on central exclusive $\pi^+\pi^-$ production measured at the energies of the ISR, RHIC, Tevatron, and the LHC colliders all show visible structures in the $\pi^+\pi^-$ invariant mass. Some time ago two of us have formulated a Regge-type model of the dipion continuum for the exclusive reaction $pp \rightarrow pp\pi^+\pi^-$ with parameters fixed from phenomenological analysis of total and elastic NN and πN scattering [10]. The number of free model parameters is then limited to a parameter of form factor describing off-shellness of the exchanged pion. The model was extended to include rescattering corrections due to pp nonperturbative interaction [11, 12]. The largest uncertainties in the model are due to the unknown off-shell pion form factor and the absorption effects discussed recently in [13]. Such an approach gives correct order of magnitude cross sections, however, does not include resonance contributions which interfere with the continuum contribution.

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 was performed in Ref. [2]. Here we based on the tensor-pomeron model formulated in [14]; see also [15]. In this model pomeron exchange is effectively treated as the exchange of a rank-2 symmetric tensor. In [16] we show that the tensor pomeron is consistent with the STAR pp elastic scattering data [17]. The corresponding couplings of the tensorial object to proton and pion were worked out; see [14]. In Ref. [18] the model was applied to the diffractive production of several scalar and pseudoscalar mesons in the reaction $pp \rightarrow ppM$. We discussed there differences between results obtained with the "tensorial" and "vectorial" pomeron approaches. In most cases one has to add coherently amplitudes for two pomeron-pomeron-meson couplings with different orbital angular momentum and spin of two "pomeron particles" ¹. In [19] an extensive study of the photoproduction reaction $\gamma p \rightarrow \pi^+\pi^- p$ was presented. The resonant ($\rho^0 \rightarrow \pi^+\pi^-$) and non-resonant (Drell-Söding) photon-pomeron/reggeon $\pi^+\pi^-$ production in pp collisions was studied in [1]. Recently, in Ref. [3], we analysed also the exclusive diffractive production of $\pi^+\pi^-\pi^+\pi^-$ via the intermediate $\sigma\sigma$ and $\rho\rho$ states.

2. Sketch of formalism

This amplitude for central exclusive $\pi^+\pi^-$ production is believed to be given by the "fusion" of two exchanged objects. The Born level diagrams for the continuum and resonant production are shown in Fig. 1. The full amplitude of $\pi^+\pi^-$ production is a sum of continuum amplitude and the amplitudes with the s -channel resonances:

$$\mathcal{M}_{pp \rightarrow pp\pi^+\pi^-} = \mathcal{M}_{pp \rightarrow pp\pi^+\pi^-}^{\pi\pi\text{-continuum}} + \mathcal{M}_{pp \rightarrow pp\pi^+\pi^-}^{\pi\pi\text{-resonances}}. \quad (2.1)$$

¹We wish to emphasize that the tensorial pomeron can, at least, equally well describe the WA102 experimental data on the exclusive meson production as the less theoretically justified vectorial pomeron frequently used in the literature. The existing low-energy experimental data do not allow to clearly distinguish between the two models as the presence of subleading reggeon exchanges is at low energies very probable for many $pp \rightarrow ppM$ reactions.

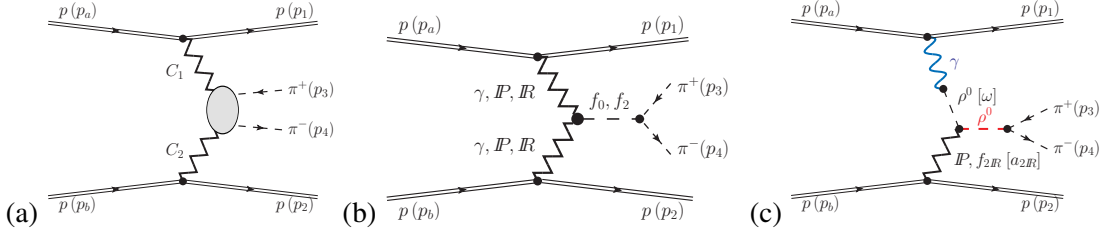


Figure 1: Diagram (a): Generic Born level diagram for central exclusive continuum $\pi^+\pi^-$ production in proton-(anti)proton collisions. Here we labelled the exchange objects by their charge conjugation numbers $C_1, C_2 \in \{+1, -1\}$. Diagram (b): The double-pomeron/reggeon and photon mediated central exclusive scalar and tensor resonances production and their subsequent decays into $\pi^+\pi^-$. Diagram (c): The $\rho(770) \rightarrow \pi^+\pi^-$ photoproduction mechanism.

The formulae for amplitudes are presented and discussed in detail in Refs. [18, 1, 2]. For instance, the amplitude for the $\pi\pi$ production through the s -channel f_2 -meson exchange can be written as

$$\begin{aligned} \mathcal{M}_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 \pi^+ \pi^-}^{(\mathbb{P}\mathbb{P} \rightarrow f_2 \rightarrow \pi^+ \pi^-)} &= (-i) \bar{u}(p_1, \lambda_1) i\Gamma_{\mu_1 \nu_1}^{(\mathbb{P}pp)}(p_1, p_a) u(p_a, \lambda_a) i\Delta^{(\mathbb{P})\mu_1 \nu_1, \alpha_1 \beta_1}(s_1, t_1) \\ &\quad \times i\Gamma_{\alpha_1 \beta_1, \alpha_2 \beta_2, \rho\sigma}^{(\mathbb{P}\mathbb{P}f_2)}(q_1, q_2) i\Delta^{(f_2)\rho\sigma, \alpha\beta}(p_{34}) i\Gamma_{\alpha\beta}^{(f_2\pi\pi)}(p_3, p_4) \\ &\quad \times i\Delta^{(\mathbb{P})\alpha_2 \beta_2, \mu_2 \nu_2}(s_2, t_2) \bar{u}(p_2, \lambda_2) i\Gamma_{\mu_2 \nu_2}^{(\mathbb{P}pp)}(p_2, p_b) u(p_b, \lambda_b), \end{aligned} \quad (2.2)$$

where $t_1 = (p_1 - p_a)^2$, $t_2 = (p_2 - p_b)^2$, $s_1 = (p_a + q_2)^2 = (p_1 + p_{34})^2$, $s_2 = (p_b + q_1)^2 = (p_2 + p_{34})^2$, and $p_{34} = p_3 + p_4$. $\Delta^{(\mathbb{P})}$ and $\Gamma^{(\mathbb{P}pp)}$ denote the effective propagator and proton vertex function, respectively, for the tensorial pomeron. For the explicit expressions, see Sec. 3 of [14]. The pomeron-pomeron- f_2 vertex is the most complicated element of our amplitude (2.2). In Ref. [2] we have considered all possible tensorial structures for the $\mathbb{P}\mathbb{P}f_2$ coupling (see Appendix A of [2])

$$i\Gamma_{\mu\nu, \kappa\lambda, \rho\sigma}^{(\mathbb{P}\mathbb{P}f_2)}(q_1, q_2) = \left(i\Gamma_{\mu\nu, \kappa\lambda, \rho\sigma}^{(\mathbb{P}\mathbb{P}f_2)(1)}|_{bare} + \sum_{j=2}^7 i\Gamma_{\mu\nu, \kappa\lambda, \rho\sigma}^{(\mathbb{P}\mathbb{P}f_2)(j)}(q_1, q_2)|_{bare} \right) \tilde{F}^{(\mathbb{P}\mathbb{P}f_2)}(q_1^2, q_2^2, p_{34}^2). \quad (2.3)$$

We take here the same form factor $\tilde{F}^{(\mathbb{P}\mathbb{P}f_2)}$ for each vertex with index j ($j = 1, \dots, 7$). Other details as form of form factors, the tensor-meson propagator $\Delta^{(f_2)}$ and the $f_2\pi\pi$ vertex are given in Refs. [14, 2]. The production of the f_2 meson via $\mathbb{P}f_{2\mathbb{R}}$, $f_{2\mathbb{R}}\mathbb{P}$, and $f_{2\mathbb{R}}f_{2\mathbb{R}}$ fusion can be treated in a completely analogous way to the $\mathbb{P}\mathbb{P}$ fusion.

We consider also the production of $\rho(770)$ resonance produced by photon-pomeron/reggeon mechanism studied in detail in [1], see the panel (c) in Fig. 1. In the amplitude for the $\gamma p \rightarrow \rho^0 p$ subprocess we included both pomeron and $f_{2\mathbb{R}}$ exchanges. The $\mathbb{P}\rho\rho$ vertex is given in [14] by formula (3.47). The coupling parameters of tensor pomeron/reggeon exchanges was fixed based on the HERA experimental data for the $\gamma p \rightarrow \rho^0 p$ reaction. In [1] we showed that the resonant contribution interfere with the non-resonant (Drell-Söding) $\pi^+\pi^-$ continuum and produces a skewing of the $\rho(770)$ -meson line shape. 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 momentum transfer.

3. Selected results

In our recent preliminary analysis [2] we tried to understand whether one can approximately describe the dipion invariant mass distribution observed by different experiments assuming only one of seven possible $\mathbb{P}\mathbb{P}f_2$ tensorial couplings. 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 $\hat{F}_\pi(k^2) = \frac{\Lambda_{off.M}^2 - m_\pi^2}{\Lambda_{off.M}^2 - k^2}$ and $\Lambda_{off.M} = 0.7$ GeV. As can be clearly seen from Fig. 2 different couplings generate different interference patterns. For detailed study of f_2 production see Ref. [2]. We found that the pattern of visible structures depends in addition on the cuts used in a particular experiment (usually the t cuts are different for different experiments). In Fig. 4 there we show that only in two cases ($j = 2$ and 5) the cross section $d\sigma/d|t|$ vanishes when $|t| \rightarrow 0$. We can observe that the $j = 2$ coupling gives results close to those observed by the CDF Collaboration [5]. In this preliminary study we did not try to fit the existing data [5] by mixing different couplings because the CDF data are not fully exclusive (the outgoing p and \bar{p} were not measured).

In Fig. 3 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 ($\rho^0 \rightarrow \pi^+\pi^-$, Drell-Söding mechanism), as well as the $f_0(500)$ resonant contribution. Our predictions are compared with the CMS preliminary data [7]. The CMS measurement [7] is not fully exclusive and the $M_{\pi\pi}$ spectrum contains therefore contributions associated with one or both protons undergoing dissociation. Here the absorption effects lead to 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 term, especially at higher energies.

4. Conclusions

In our recent paper 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. 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 [2] all (seven) possible pomeron-pomeron- f_2 couplings and the corresponding amplitudes using the effective field theoretical approach proposed in [14]. The different couplings (tensorial structures) give different results due to different interference effects of the f_2 resonance and the dipion continuum contributions. By assuming dominance of one of the couplings we can get only a rough description of the recent CDF and preliminary STAR experimental data. The model parameters of the optimal coupling ($j = 2$) have been roughly adjusted to recent CDF data and then used for the predictions for the STAR, ALICE, and CMS experiments. In the future they could be adjusted by a comparison with precise experimental data. We have shown some differential distributions related to produced pions as well as some observables related to final state protons, e.g., different dependence on proton transverse momenta and azimuthal angle correlations between outgoing protons could be used to separate the photoproduction term, see [2].

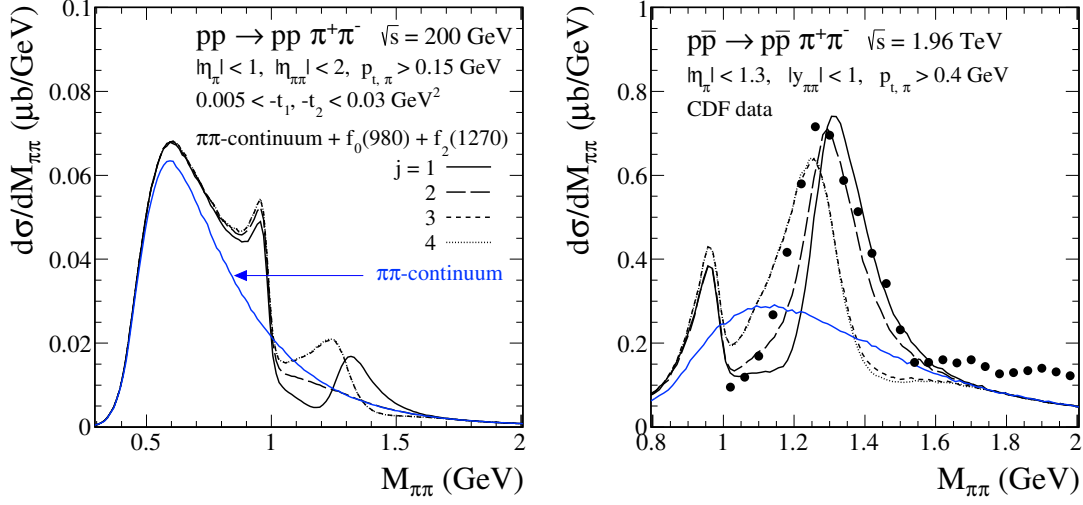


Figure 2: Two-pion invariant mass distribution for the STAR [4] and CDF [5] kinematics. The Born calculations for $\sqrt{s} = 200$ GeV and $\sqrt{s} = 1.96$ TeV were multiplied by the gap survival factors $\langle S^2 \rangle = 0.2$ and $\langle S^2 \rangle = 0.1$, respectively. The blue solid lines represent the non-resonant continuum contribution only while the black lines represent a coherent sum of non-resonant continuum, $f_0(980)$ and $f_2(1270)$ resonant terms. The individual contributions of different $\mathbb{P}\mathbb{P}f_2$ couplings ($j = 1, \dots, 4$) are compared with the CDF data [5] (right panel).

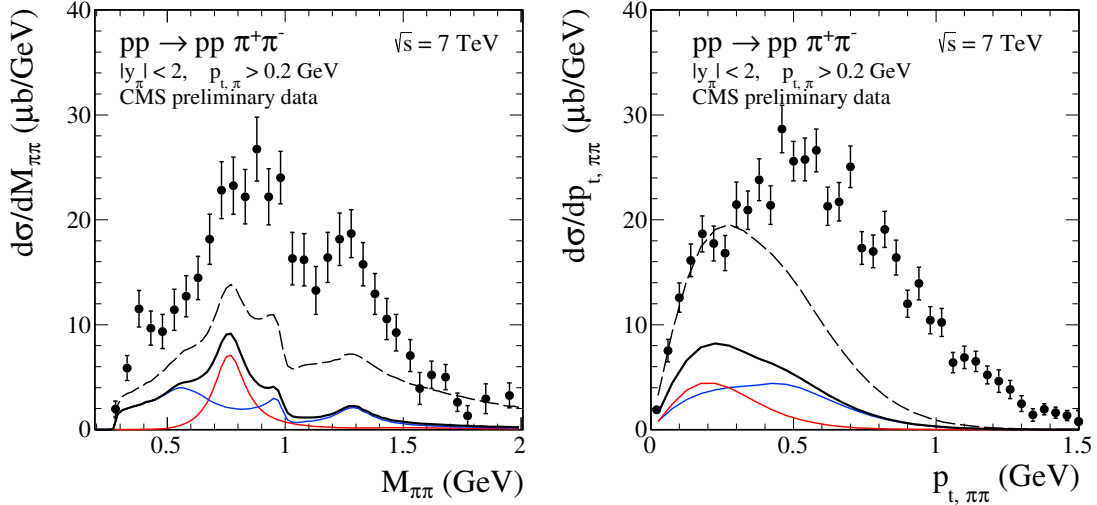


Figure 3: The distributions for two-pion invariant mass (left panel) and transverse momentum of the pion pair (right panel) for the CMS kinematics at $\sqrt{s} = 7$ TeV. Both photoproduction (red line) and purely diffractive (blue line) contributions multiplied by the gap survival factors $\langle S^2 \rangle = 0.9$ 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 dashed line ($\Lambda_{off,M} = 1.2$ GeV). The CMS preliminary data [7] are shown for comparison.

The measurement of forward/backward protons which should be possible for CMS-TOTEM and ATLAS-ALFA is crucial in better understanding of the mechanism of the $pp \rightarrow pp\pi^+\pi^-$ reaction. The absorption effects due to pp and πp interactions lead to a significant modification

of the shape of the distributions in ϕ_{pp} and $p_{t,p}$ and could also be tested by these experimental groups. Future experimental data on exclusive meson production at high energies should thus provide good information on the spin structure of the pomeron and on its couplings to the nucleon and the mesons.

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