Central exclusive diffractive production
of axial-vector f_1 mesons in proton-proton collisions

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Abstract

Exclusive production of axial-vector $f_1(1285)$ meson in proton-proton collisions via pomeron-pomeron fusion within the tensor-pomeron approach is discussed. Two ways to construct the pomeron-pomeron-f_1 coupling are presented. We adjust the parameters of our model to the WA102 experimental data and compare with predictions of the Sakai-Sugimoto model. Predictions for LHC experiments are given.

1 Introduction

In this contribution we discuss central exclusive production (CEP) of f_1 ($J^{PC} = 1^{++}$) mesons in proton-proton collisions

$$p(p_a) + p(p_b) \rightarrow p(p_1) + f_1(k) + p(p_2). \qquad (1)$$

As a concrete example we shall consider the $f_1(1285)$ meson. The presentation is based on [1] where all details and many more results can be found. At high energies the $\mathbb{P}\mathbb{P}$ fusion process (figure 1) is expected to be dominant. The relevant kinematic quantities are

$$s = (p_a + p_b)^2, \ q_1 = p_a - p_1, \ q_2 = p_b - p_2, \ k = q_1 + q_2, \ t_1 = q_1^2, \ t_2 = q_2^2, \ m_{f_1}^2 = k^2. \qquad (2)$$
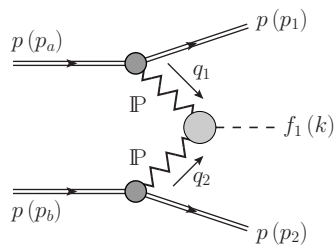
Figure 1: Diagram for the reaction (1) with double-pomeron exchange.

We treat our reaction in the tensor-pomeron approach as introduced in [2]. This approach has a good basis from nonperturbative QCD using functional integral techniques [3]. We describe the charge-conjugation $C = +1$ pomeron as effective rank 2 symmetric tensor exchange. A tensor character of the pomeron is also preferred in holographic QCD.

There are by now many applications of the tensor-pomeron model to two-body hadronic reactions [4], to photoproduction, to DIS structure functions at low x, and especially to CEP reactions $p + p \rightarrow p + X + p$, where $X = \eta, \eta', f_0, f_2, \pi^+ \pi^-, K \bar{K}, p \bar{p}, 4\pi, 4K, \rho^0, \phi, \phi \phi, K^{*0} \bar{K}^{*0}$; see e.g. [5–10].

2 Brief overview of the formalism

2.1 The amplitude for the $pp \rightarrow pp f_1$ reaction

The Born-level $\mathbb{P}\mathbb{P}$-fusion amplitude for the reaction (1) can be written as

$$
\begin{aligned}
\mathcal{M}^{(\mathbb{P}\mathbb{P} \rightarrow f_1)}_{\lambda_a \lambda_b \rightarrow \lambda_1 \lambda_2 \lambda} &= (-i)(\epsilon^\mu(\lambda))^* \bar{u}(p_1, \lambda_1) i \Gamma^{(\mathbb{P}pp)}_{\mu_1 \nu_1}(p_1, p_a) u(p_a, \lambda_a) \\
&\times i \Delta^{(\mathbb{P})\mu_1 \nu_1, \alpha_1 \beta_1}(s_1, t_1) i \Gamma^{(\mathbb{P}\mathbb{P}f_1)}_{\alpha_1 \beta_1, \alpha_2 \beta_2, \mu}(q_1, q_2) i \Delta^{(\mathbb{P}) \alpha_2 \beta_2, \mu_2 \nu_2}(s_2, t_2) \\
&\times \bar{u}(p_2, \lambda_2) i \Gamma^{(\mathbb{P}pp)}_{\mu_2 \nu_2}(p_2, p_b) u(p_b, \lambda_b).
\end{aligned}
\tag{3}
$$

Here $\epsilon^\mu(\lambda)$ is the polarisation vector of the f_1 meson, $\Delta^{(\mathbb{P})}$ and $\Gamma^{(\mathbb{P}pp)}$ denote the effective propagator and proton vertex function, respectively, for the tensor-pomeron exchange [2]. The new quantity, to be studied here, is the $\mathbb{P}\mathbb{P}f_1$ coupling. In practice we work with the amplitudes in the high-energy approximation. In our analysis we include absorptive corrections within the one-channel-eikonal approach.

2.2 The pomeron-pomeron-f_1 coupling

We follow two strategies for constructing the $\mathbb{P}\mathbb{P}f_1$ coupling and the vertex function.

(1) Phenomenological approach. First we consider a fictitious process: the fusion of two "real spin-2 pomerons" (or tensor glueballs) of mass m giving an f_1 meson of $J^{PC} = 1^{++}$. We make an angular momentum analysis of this reaction in its c.m. system, the rest system of the f_1 meson: $\mathbb{P}(m, \epsilon_1) + \mathbb{P}(m, \epsilon_2) \rightarrow f_1(m_{f_1}, \epsilon)$. The spin 2 of these "pomerons" can be combined to a total spin S ($0 \leqslant S \leqslant 4$) and this must be combined with the orbital angular momentum l to give the $J^{PC} = 1^{++}$ values of the f_1. There are two possibilities, $(l, S) = (2, 2)$ and $(4, 4)$

(see Appendix A of [5]), and corresponding bare coupling Lagrangians $\mathbb{P}\mathbb{P}f_1$ are:

$$\mathcal{L}^{(2,2)}_{\mathbb{P}\mathbb{P}f_1} = \frac{g'_{\mathbb{P}\mathbb{P}f_1}}{32\,M_0^2}\left(\mathbb{P}_{\kappa\lambda}\overset{\leftrightarrow}{\partial}_\mu\overset{\leftrightarrow}{\partial}_\nu\mathbb{P}_{\rho\sigma}\right)\left(\partial_\alpha U_\beta - \partial_\beta U_\alpha\right)\Gamma^{(8)\,\kappa\lambda,\rho\sigma,\mu\nu,\alpha\beta}\,, \tag{4}$$

$$\mathcal{L}^{(4,4)}_{\mathbb{P}\mathbb{P}f_1} = \frac{g''_{\mathbb{P}\mathbb{P}f_1}}{24\cdot 32\cdot M_0^4}\left(\mathbb{P}_{\kappa\lambda}\overset{\leftrightarrow}{\partial}_{\mu_1}\overset{\leftrightarrow}{\partial}_{\mu_2}\overset{\leftrightarrow}{\partial}_{\mu_3}\overset{\leftrightarrow}{\partial}_{\mu_4}\mathbb{P}_{\rho\sigma}\right)\left(\partial_\alpha U_\beta - \partial_\beta U_\alpha\right)\Gamma^{(10)\,\kappa\lambda,\rho\sigma,\mu_1\mu_2\mu_3\mu_4,\alpha\beta}\,, \tag{5}$$

where $M_0 \equiv 1$ GeV (introduced for dimensional reasons), $g'_{\mathbb{P}\mathbb{P}f_1}$ and $g''_{\mathbb{P}\mathbb{P}f_1}$ are dimensionless coupling constants, $\mathbb{P}_{\kappa\lambda}$ is the $\mathbb{P}$ effective field, U_α is the f_1 field, and $\Gamma^{(8)}$, $\Gamma^{(10)}$ are known tensor functions [1]. We use then these couplings, supplemented by suitable form factors, for the $f_1(1285)$ CEP reaction (1).

(2) Our second approach uses holographic QCD, in particular the Sakai-Sugimoto model [11, 12] where the $\mathbb{P}\mathbb{P}f_1$ coupling is determined by the mixed axial-gravitational anomaly of QCD. In this approach

$$\mathcal{L}^{\text{CS}} = \varkappa' U_\alpha\,\varepsilon^{\alpha\beta\gamma\delta}\,\mathbb{P}^\mu_{\ \beta}\,\partial_\delta\mathbb{P}_{\gamma\mu} + \varkappa'' U_\alpha\,\varepsilon^{\alpha\beta\gamma\delta}\left(\partial_\nu\mathbb{P}^\mu_{\ \beta}\right)\left(\partial_\delta\partial_\mu\mathbb{P}^\nu_{\ \gamma} - \partial_\delta\partial^\nu\mathbb{P}_{\gamma\mu}\right)\,, \tag{6}$$

with $\varkappa'$ a dimensionless constant and $\varkappa''$ a constant of dimension GeV^{-2}; see Appendix B of [1].

For our fictitious reaction ($\mathbb{P} + \mathbb{P} \to f_1$) there is strict equivalence $\mathcal{L}^{\text{CS}} \cong \mathcal{L}^{(2,2)} + \mathcal{L}^{(4,4)}$ if the couplings satisfy the relations

$$g'_{\mathbb{P}\mathbb{P}f_1} = -\varkappa'\frac{M_0^2}{k^2} - \varkappa''\frac{M_0^2(k^2-2m^2)}{2k^2}\,, \qquad g''_{\mathbb{P}\mathbb{P}f_1} = \varkappa''\frac{2M_0^4}{k^2}\,. \tag{7}$$

For our CEP reaction (1) we are dealing with pomerons of mass squared $t_1, t_2 < 0$ and, in general, $t_1 \neq t_2$. Then, the equivalence relation for small values $|t_1|$ and $|t_2|$ will still be approximately true and we confirm this by explicit numerical studies (see Fig. 11 of [1]).

3 Results

3.1 Comparison with the WA102 data

The WA102 collaboration obtained for the $pp \to ppf_1(1285)$ reaction the total cross section of $\sigma_{\text{exp.}} = (6919 \pm 886)$ nb at $\sqrt{s} = 29.1$ GeV and for a cut on the central system $|x_F| \leqslant 0.2$ [13]. The WA102 collaboration also gave distributions in t and in ϕ_{pp} ($0 \leqslant \phi_{pp} \leqslant \pi$), the azimuthal angle between the transverse momenta of the two outgoing protons. In [14] an interesting behaviour of the ϕ_{pp} distribution for $f_1(1285)$ meson production for two different values of $|t_1 - t_2|$ was presented. In Fig. 2 we show some of our results [1] which include - very important - absorptive corrections. We show the ϕ_{pp} distribution of events from [14] for $|t_1 - t_2| \leqslant 0.2$ GeV^2 (left panels) and $|t_1 - t_2| \geqslant 0.4$ GeV^2 (right panels). We are assuming that the reaction (1) is dominated by pomeron exchange already at $\sqrt{s} = 29.1$ GeV. From the top panels, it seems that the $(l, S) = (4, 4)$ term (5) best reproduces the shape of the WA102 data. The absorption effects play a significant role there. In the bottom panels we examine the combination of two $\mathbb{P}\mathbb{P}f_1$ couplings $\varkappa'$ and $\varkappa''$ calculated with the vertex (6). As discussed in Appendix B of [1], the prediction for $\varkappa''/\varkappa'$ obtained in the Sakai-Sugimoto model is

$$\varkappa''/\varkappa' = -(6.25\cdots 2.44)\,\text{GeV}^{-2} \tag{8}$$

for $M_{\text{KK}} = (949\cdots 1532)$ MeV. This agrees with the fit ($\varkappa''/\varkappa' = -1.0$ GeV^{-2}) as far as the sign of this ratio is concerned, but not in its magnitude. This could indicate that the
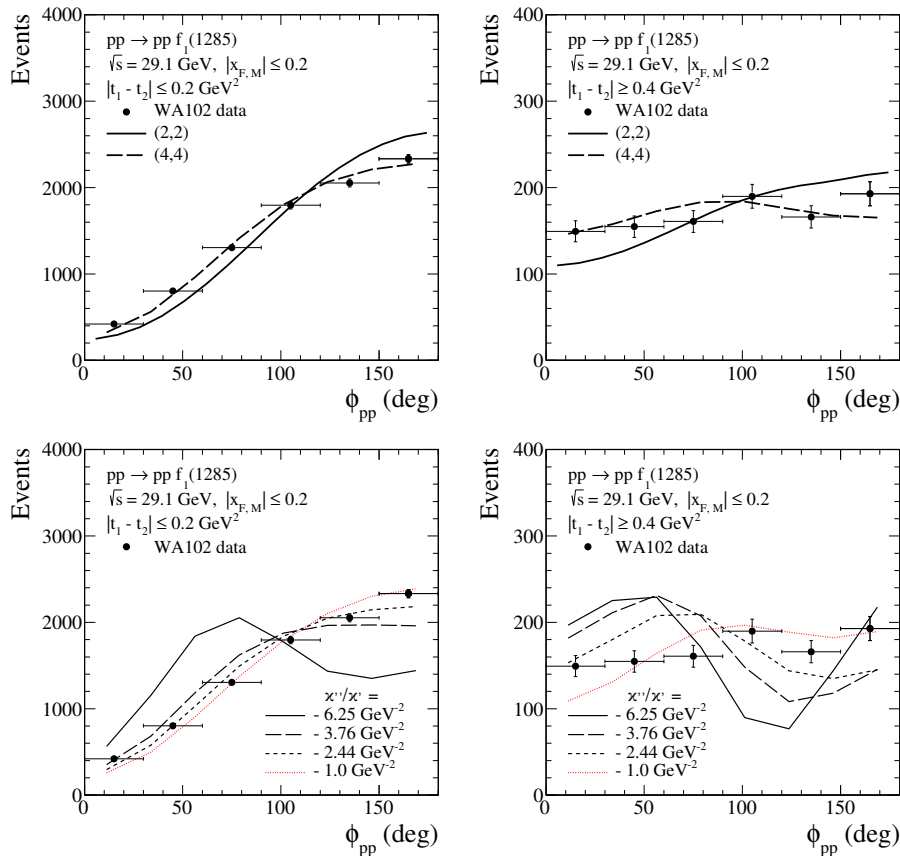
Figure 2: The ϕ_{pp} distributions for $f_1(1285)$ meson production at $\sqrt{s} = 29.1$ GeV, $|x_{F,M}| \leqslant 0.2$, and for $|t_1 - t_2| \leqslant 0.2$ GeV^2 (left panels) and $|t_1 - t_2| \geqslant 0.4$ GeV^2 (right panels). The WA102 experimental data points are from Fig. 3 of [14]. The theoretical results have been normalised to the mean value of the number of events. The results for $\Lambda_E = 0.7$ GeV a form-factor parameter are shown.

Sakai-Sugimoto model needs a more complicated form of reggeization of the tensor glueball propagator as indeed discussed in [15] in the context of CEP of η and η' mesons. It could also be an indication of the importance of secondary reggeon exchanges.

We get a reasonable description of the WA102 data with $\Lambda_E = 0.7$ GeV and the following possibilities:

$$(l,S) = (2,2) \text{ term only}: \quad g'_{\mathbb{P}\mathbb{P}f_1} = 4.89, \ g''_{\mathbb{P}\mathbb{P}f_1} = 0; \tag{9}$$

$$(l,S) = (4,4) \text{ term only}: \quad g'_{\mathbb{P}\mathbb{P}f_1} = 0, \ g''_{\mathbb{P}\mathbb{P}f_1} = 10.31; \tag{10}$$

$$\text{CS terms}: \quad \varkappa' = -8.88, \ \varkappa''/\varkappa' = -1.0 \text{ GeV}^{-2}. \tag{11}$$

Now we can use our equivalence relation (7) in order to see to which (l,S) couplings (11) corresponds. Replacing in (7) m^2 by $t_1 = t_2 = -0.1$ GeV^2 and k^2 by $m^2_{f_1} = (1282 \text{ MeV})^2$ we get from (11)

$$g'_{\mathbb{P}\mathbb{P}f_1} = 0.42, \ g''_{\mathbb{P}\mathbb{P}f_1} = 10.81. \tag{12}$$

Thus, the CS couplings of (11) correspond to a nearly pure $(l,S) = (4,4)$ coupling (10).

Having fixed the parameters of the model in this way we will give predictions for the LHC experiments. Because of the possible influence of nonleading exchanges at low energies, these predictions for cross sections at high energies should be regarded rather as an upper limit. The secondary reggeon exchanges should give small contributions at high energies and in the

midrapidity region. As discussed in Appendix D of [1] we expect that they should overestimate the cross sections by not more than a factor of 4.

3.2 Predictions for the LHC experiments

Now we wish to show (selected) results for the $pp \to pp f_1(1285)$ reaction for the LHC; see [1] for many more results. In Fig. 3 we show our predictions for the distributions of ϕ_{pp} and the transverse momentum of the $f_1(1285)$ for $\sqrt{s} = 13$ TeV, $|y_M| < 2.5$, and for the cut on the leading protons of 0.17 GeV $< |p_{y,p}| < 0.50$ GeV. The results for the $(l, S) = (2, 2)$ term (4), the $(4, 4)$ term (5), and for the $\varkappa'$ plus $\varkappa''$ terms calculated with (6) for $\varkappa''/\varkappa' = -(6.25 \cdots 2.44)$ GeV^{-2} obtained in the Sakai-Sugimoto model (see Appendix B of [1]) are shown. For comparison, the results for $\varkappa''/\varkappa' = -1.0$ GeV^{-2} are also presented. The contribution with $\varkappa''/\varkappa' = -6.25$ GeV^2 gives a significantly different shape. This could be tested in experiments, such as ATLAS-ALFA [16], when both protons are measured. The four-pion decay channel seems well suited to measure the CEP of the $f_1(1285)$ at the LHC. We predict a large cross section for the exclusive axial-vector $f_1(1285)$ production compared to the CEP of the tensor $f_2(1270)$ meson [6,7] in the $\pi^+ \pi^- \pi^+ \pi^-$ channel.
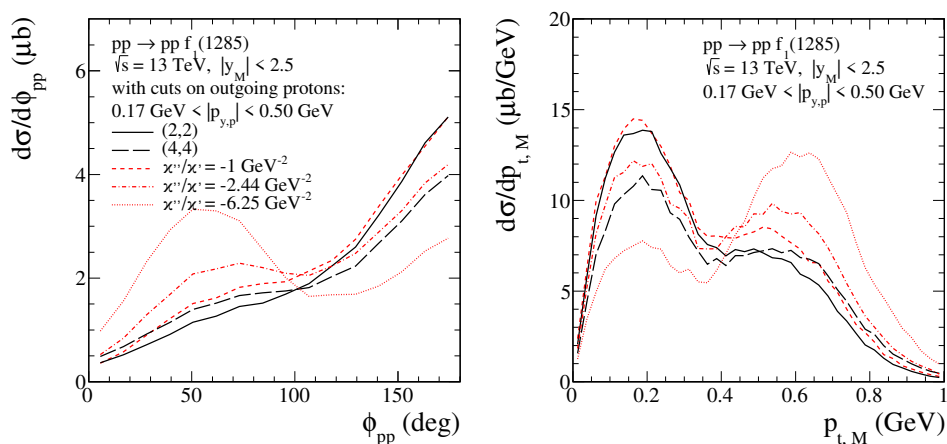
Figure 3: The differential cross sections for the $f_1(1285)$ production at $\sqrt{s} = 13$ TeV, $|y_M| < 2.5$, and with cuts on both outgoing protons: 0.17 GeV $< |p_{y,p}| < 0.50$ GeV. The results for $(l, S) = (2, 2)$, $(4, 4)$, and $(\varkappa', \varkappa'')$ contributions are shown.

4 Conclusions

- The calculations for the $pp \to pp f_1(1285)$ reaction have been performed in the tensor-pomeron approach [2]. We have discussed in detail the forms of the $\mathbb{P}\mathbb{P}f_1$ coupling. Detailed tests of the Sakai-Sugimoto model are possible.

- We obtain a good description of the WA102 data at $\sqrt{s} = 29.1$ GeV [13, 14] assuming that the $pp \to pp f_1(1285)$ reaction is dominated by pomeron-pomeron fusion.

- We obtain a large cross section for CEP of the $f_1(1285)$ of $\sigma \cong 6-40$ μb for the ALICE, AT-LAS, CMS, and LHCb experiments, depending on the assumed cuts (see Table III of [1]). Predictions for the STAR experiment at RHIC are given in Table IV of [1]. In all cases the absorption effects were included.

- Experimental studies of single meson CEP reactions will allow to extract many $\mathbb{P}\mathbb{P}M$ coupling parameters. Their theoretical calculation is a challenging problem of nonperturbative QCD.

- Such studies could be extended, for instance by the COMPASS experiment where presumably one could study the influence of reggeon-pomeron and reggeon-reggeon fusion terms. Future experiments available at the GSI-FAIR with HADES and PANDA should provide new information about the $\rho\rho f_1$ and $\omega\omega f_1$ couplings [17].

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