Central exclusive production of axial-vector f_1 mesons in proton-proton collisions within the tensor-pomeron approach

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Abstract

We discuss the central exclusive production of f_1 mesons in proton-proton collisions. The diffractive pomeron-pomeron fusion process within the tensor-pomeron approach is considered. Two ways to construct the pomeron-pomeron-f_1 coupling are discussed. The theoretical calculation of coupling constants is a challenging problem of nonperturbative QCD. We adjust the parameters of the model to the WA102 experimental data. The total cross section and differential distributions are presented. Predictions for LHC experiments are given. Detailed analysis of the distributions in ϕ_{pp} the azimuthal angle between the transverse momenta of the outgoing protons can help to check different models and to study real pattern of the absorption effects.

1 Introduction

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

$$p(p_a, \lambda_a) + p(p_b, \lambda_b) \rightarrow p(p_1, \lambda_1) + f_1(k, \lambda) + p(p_2, \lambda_2), \tag{1}$$

where $p_{a,b}$, $p_{1,2}$ and $\lambda_{a,b}$, $\lambda_{1,2} = \pm 1/2$ denote the four-momenta and helicities of the protons, and k and $\lambda = 0, \pm 1$ denote the four-momentum and helicity of the f_1 meson, respectively. Here f_1 stands for one of the axial-vector mesons with $J^{PC} = 1^{++}$, i.e. $f_1(1285)$ or $f_1(1420)$. This presentation summarises some of the key results of [1] to which we refer the reader for further details. CEP of $f_1(1285)$ and $f_1(1420)$ mesons was measured by WA102 Collaboration [2–4]. Their internal structure ($q\bar{q}$, tetraquark, $K\bar{K}$ molecule) remains to be established. At high energies the pomeron-pomeron fusion mechanism (Figure 1) is expected to be dominant. The pomeron ($\mathbb{P}$) is essential object for understanding diffractive phenomena. Within QCD is a color singlet, predominantly gluonic object, thus the CEP of mesons has long been regarded as a potential source of glueballs.
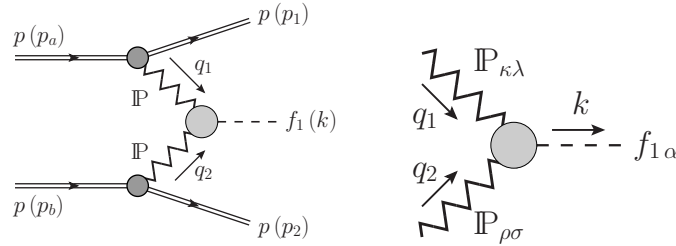
Figure 1: The diagram on the left corresponds to the Born-level pomeron-pomeron fusion mechanism contributing to the reaction (1) at high energies. The diagram on the right corresponds to the $\mathbb{P}\mathbb{P}f_1$ vertex [1].

For soft reactions, calculations of the pomeron from first principle are currently not possible, and one has to retreat to Regge models to describe soft high-energy diffractive scattering. Until recently, the spin structure of the pomeron has not received much attention. It is well known that the pomeron carries vacuum quantum numbers with regard to charge, color, isospin and charge conjugation. But what about spin? It has been shown some time ago that the charge-conjugation $C = +1$ pomeron can be regarded as a coherent sum of elementary spin $2 + 4 + 6 + \dots$ exchanges [5]. The tensor-pomeron model introduced in [6] assumes this property. We treat the reaction (1) in this model, in which the pomeron exchange is described as effective rank 2 symmetric tensor exchange. This approach has a good basis from nonperturbative QCD using functional integral techniques [5]. A tensor character of the pomeron is also preferred in holographic QCD models [7–10].

The tensor-pomeron model was applied to two-body hadronic reactions [6, 11, 12], to photoproduction of $\pi^+\pi^-$ pairs [13], to low-x deep inelastic lepton-nucleon scattering and photoproduction [14], and especially to CEP reactions

$$p + p \rightarrow p + X + p,$$
$$X = \eta, \eta', f_0, f_1, f_2, \pi^+\pi^-, K^+K^-, p\bar{p}, 4\pi, 4K, \rho^0, \phi, \phi\phi, K^{*0}\bar{K}^{*0}; \tag{2}$$

see e.g. [15–21]. In this model the $C = -1$ odderon [22] is described as effective vector exchange. Exclusive reactions suitable for studies of the odderon exchange at high energies were discussed in [13, 19, 20]. Conceptually, vector-type couplings of the pomeron turn out to be rather questionable. For example, a vector pomeron implies that the total cross sections

for pp and $p\bar{p}$ scattering at high energy have opposite sign [11]. But, of course, quantum field theory forbids negative cross sections. A further argument against a vector pomeron was shown in [14], mainly it does not give any contribution to photoproduction data. One may also ask about the possibility of a scalar coupling of the pomeron to external particles. While possible from the point of view of QFT, such a coupling is experimentally disfavoured. In [11] it was shown that STAR data [23] on polarised elastic pp scattering are compatible with the tensor-pomeron ansatz but clearly rule out a scalar character of the soft pomeron what its coupling concerns. Also some historical remarks on different views of the pomeron were made in [11]. In the light of our discussion here we cannot support the conclusions of [24, 25] that the pomeron behaves (couples) like vector current.

The theoretical calculation of $\mathbb{P}\mathbb{P}f_1$ coupling is a challenging problem of nonperturbative QCD. We argue that the pomeron couplings play an important role, and that they should be treated as tensor couplings. Using our model we perform a fit to the available WA102 data [2, 4] and we analyse whether our study could shed light on the $\mathbb{P}\mathbb{P}f_1$ couplings. In the future the model parameters ($\mathbb{P}\mathbb{P}f_1$ coupling constants, cutoff parameters in form factors) could be adjusted by comparison with precise experimental data from both RHIC and the LHC. The $\pi^+\pi^-\pi^+\pi^-$ channel seems well suited to measure the $f_1(1285)$ CEP at high energies. For a preliminary data of the reaction $pp \to pp2\pi^+2\pi^-$ measured at LHC@13TeV by the ATLAS Collaboration see [26].

2 Sketch of the formalism

2.1 The amplitude for the $pp \to ppf_1$ reaction

The Born-level amplitude for the reaction (1) via pomeron-pomeron fusion can be written as

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

The relevant kinematic quantities are

$$
\begin{aligned}
&s = (p_a + p_b)^2, \; s_1 = (p_a + q_2)^2 = (p_1 + k)^2, \; s_2 = (p_b + q_1)^2 = (p_2 + k)^2, \\
&k = q_1 + q_2, \; q_1 = p_a - p_1, \; q_2 = p_b - p_2, \; t_1 = q_1^2, \; t_2 = q_2^2, \; m_{f_1}^2 = k^2,
\end{aligned}
\tag{4}
$$

In (3) $\epsilon^\mu(\lambda)$ 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 [6]. The new quantity, to be discussed below, is the $\mathbb{P}\mathbb{P}f_1$ coupling.

In our analysis we should also include absorption effects to the Born amplitude. Then the full amplitude is

$$
\mathcal{M}_{pp \to ppf_1} = \mathcal{M}^{\text{Born}}_{pp \to ppf_1} + \mathcal{M}^{pp-\text{rescattering}}_{pp \to ppf_1}.
\tag{5}
$$

The amplitude including the pp-rescattering corrections can be written as (within the one-channel-eikonal approach)

$$
\mathcal{M}^{pp-\text{rescattering}}_{pp \to ppf_1}(s, \boldsymbol{p}_{t,1}, \boldsymbol{p}_{t,2}) = \frac{i}{8\pi^2 s} \int d^2\boldsymbol{k}_t \, \mathcal{M}^{\text{Born}}_{pp \to ppf_1}(s, \tilde{\boldsymbol{p}}_{t,1}, \tilde{\boldsymbol{p}}_{t,2}) \mathcal{M}_{pp \to pp}(s, t),
\tag{6}
$$

where $\boldsymbol{p}_{t,1}$ and $\boldsymbol{p}_{t,2}$ are the transverse components of the momenta of the outgoing protons and $\boldsymbol{k}_t$ is the transverse momentum carried around the pomeron loop. $\mathcal{M}^{\text{Born}}_{pp \to ppf_1}$ is the Born

amplitude given by (3) with $\tilde{p}_{t,1} = p_{t,1} - k_t$ and $\tilde{p}_{t,2} = p_{t,2} + k_t$. $\mathcal{M}_{pp \to pp}$ is the elastic pp scattering amplitude for large s and with the momentum transfer $t = -k_t^2$. In practice we work with the amplitudes in the high-energy approximation, i.e. assuming s-channel helicity conservation in the pomeron-proton vertex.

2.2 The pomeron-pomeron-f_1 coupling

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

(1) Phenomenological approach. 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: $\mathbb{P}(m, \epsilon_1) + \mathbb{P}(m, \epsilon_2) \to f_1(m_{f_1}, \epsilon)$. 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 [15]). Corresponding $\mathbb{P}\mathbb{P}f_1$ coupling Lagrangians are:

$$\mathcal{L}^{(2,2)}_{\mathbb{P}\mathbb{P}f_1} = \frac{g'_{\mathbb{P}\mathbb{P}f_1}}{32\, M_0^2} \left(\mathbb{P}_{\kappa\lambda} \overleftrightarrow{\partial}_\mu \overleftrightarrow{\partial}_\nu \mathbb{P}_{\rho\sigma} \right) \left(\partial_\alpha U_\beta - \partial_\beta U_\alpha \right) \Gamma^{(8)\,\kappa\lambda,\rho\sigma,\mu\nu,\alpha\beta}\,, \tag{7}$$

$$\mathcal{L}^{(4,4)}_{\mathbb{P}\mathbb{P}f_1} = \frac{g''_{\mathbb{P}\mathbb{P}f_1}}{24 \cdot 32 \cdot M_0^4} \left(\mathbb{P}_{\kappa\lambda} \overleftrightarrow{\partial}_{\mu_1} \overleftrightarrow{\partial}_{\mu_2} \overleftrightarrow{\partial}_{\mu_3} \overleftrightarrow{\partial}_{\mu_4} \mathbb{P}_{\rho\sigma} \right) \left(\partial_\alpha U_\beta - \partial_\beta U_\alpha \right) \Gamma^{(10)\,\kappa\lambda,\rho\sigma,\mu_1\mu_2\mu_3\mu_4,\alpha\beta}\,, \tag{8}$$

where $M_0 \equiv 1$ GeV is 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 pomeron effective field, U_α is the f_1 field, and $\Gamma^{(8)}$, $\Gamma^{(10)}$ are known tensor functions; see Appendix A of [1].

(2) Second approach uses holographic QCD, in particular the Sakai-Sugimoto model [27–29]. Here the $\mathbb{P}\mathbb{P}f_1$ coupling is determined by the mixed axial-gravitational anomaly of QCD; see Appendix B of [1]. In this approach:

$$\mathcal{L}^{\text{CS}} = \varkappa' U_\alpha\, \varepsilon^{\alpha\beta\gamma\delta}\, \mathbb{P}^\mu{}_\beta\, \partial_\delta \mathbb{P}_{\gamma\mu} + \varkappa'' U_\alpha\, \varepsilon^{\alpha\beta\gamma\delta} \left(\partial_\nu \mathbb{P}^\mu{}_\beta \right) \left(\partial_\delta \partial_\mu \mathbb{P}^\nu{}_\gamma - \partial_\delta \partial^\nu \mathbb{P}_{\gamma\mu} \right) \tag{9}$$

with $\varkappa'$ a dimensionless constant and $\varkappa''$ a constant of dimension GeV^{-2}.

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

$$g'_{\mathbb{P}\mathbb{P}f_1} = -\varkappa' \frac{M_0^2}{k^2} - \varkappa'' \frac{M_0^2 (k^2 - 2m^2)}{2k^2}\,, \qquad g''_{\mathbb{P}\mathbb{P}f_1} = \varkappa'' \frac{2M_0^4}{k^2}\,. \tag{10}$$

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]).

For the CEP reaction, we use the $\mathbb{P}\mathbb{P}f_1$ vertex derived from a corresponding coupling Lagrangian (7), (8), or (9) supplemented by a suitable form factor. We take the factorised ansatz

$$\tilde{F}^{(\mathbb{P}\mathbb{P}f_1)}(t_1, t_2, m_{f_1}^2) = \exp\left(\frac{t_1 + t_2}{\Lambda_E^2} \right)\,, \tag{11}$$

where the cutoff constant Λ_E should be adjusted to experimental data.

As discussed in Appendix B of [1], the prediction for the ratio $\varkappa''/\varkappa'$ obtained in the Sakai-Sugimoto model is

$$\varkappa''/\varkappa' = -(6.25 \cdots 2.44)\, \text{GeV}^{-2} \tag{12}$$

for $M_{\text{KK}} = (949 \cdots 1532)$ MeV. Usually [27] M_{KK} is fixed by matching the mass of the lowest vector meson to that of the physical ρ meson, leading to $M_{\text{KK}} = 949$ MeV. However, this

choice leads to a tensor glueball mass which is too low, $M_T \approx 1.5\,\text{GeV}$. The pomeron trajectory $[\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}}t$ with $\alpha_{\mathbb{P}}(0) = 1.0808$ and $\alpha'_{\mathbb{P}} = 0.25\,\text{GeV}^{-2}]$ corresponds to $M_T \approx 1.9\,\text{GeV}$, whereas lattice predictions correspond to $M_T \gtrsim 2.4\,\text{GeV}$.

3 Results

Below we compare our model results with the $pp \to ppf_1(1285)$ cross-section data measured at $\sqrt{s} = 29.1$ GeV by the WA102 Collaboration [2, 4]. We are assuming that the reaction (1) is dominated by pomeron exchange already at $\sqrt{s} = 29.1$ GeV. In the next stage, we present our predictions for the LHC experiments.

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 $|x_F| \leqslant 0.2$ [2]. 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 [4] 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 Figure 2 we show some of our results [1] which include absorptive corrections; see Eqs. (5), (6). We show the ϕ_{pp} distribution of events from [4] for $|t_1 - t_2| \leqslant 0.2\,\text{GeV}^2$ (left panels) and $|t_1 - t_2| \geqslant 0.4\,\text{GeV}^2$ (right panels). From the top panels, it seems that the $(l, S) = (4, 4)$ term (8) best reproduces the shape of the WA102 data. The absorption effects play a significant role there. In the bottom panels of Fig. 2 we examine the combination of two $\mathbb{P}\mathbb{P}f_1$ couplings $\varkappa'$ and $\varkappa''$ calculated with the vertex (9). The ratio (12) agrees with the fit $\varkappa''/\varkappa' = -1.0\,\text{GeV}^{-2}$ as far as the sign of this ratio is concerned, but not in its magnitude. This could indicate that the Sakai-Sugimoto model needs a more complicated form of reggeization of the tensor glueball propagator as indeed discussed in [29] in the context of CEP of η and η' mesons. It could also be an indication of the importance of secondary contributions with reggeon exchanges, i.e. $\mathbb{R}\mathbb{R}$-, $\mathbb{R}\mathbb{P}$-, and $\mathbb{P}\mathbb{R}$-fusion processes.

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

$$(l, S) = (2, 2) \text{ term}: \quad g'_{\mathbb{P}\mathbb{P}f_1} = 4.89, \, g''_{\mathbb{P}\mathbb{P}f_1} = 0; \tag{13}$$

$$(l, S) = (4, 4) \text{ term}: \quad g'_{\mathbb{P}\mathbb{P}f_1} = 0, \, g''_{\mathbb{P}\mathbb{P}f_1} = 10.31; \tag{14}$$

$$\text{CS couplings}: \quad \varkappa' = -8.88, \, \varkappa''/\varkappa' = -1.0\,\text{GeV}^{-2}. \tag{15}$$

Now we can use our equivalence relation (10) in order to see to which (l, S) couplings (15) corresponds. Replacing in (10) m^2 by $t_1 = t_2 = -0.1\,\text{GeV}^2$ and k^2 by $m_{f_1}^2 = (1282\,\text{MeV})^2$ we get from (15): $g'_{\mathbb{P}\mathbb{P}f_1} = 0.42 \; g''_{\mathbb{P}\mathbb{P}f_1} = 10.81$. Thus, the CS term corresponds to a nearly pure $(l, S) = (4, 4)$ coupling (14).

In Figure 3 we show the results for the ϕ_{pp} distributions for different cuts on $|t_1 - t_2|$ without and with the absorption effects included in the calculations. The results for the two (l, S) couplings are shown. The absorption effects lead to a large reduction of the cross section. We obtain the ratio of full and Born cross sections (the survival factor) as $\langle S^2 \rangle = 0.5$–$0.7$, depending on the kinematics. We can see a large damping of the cross section in the region of $\phi_{pp} \sim \pi$, especially for $|t_1 - t_2| \geqslant 0.4\,\text{GeV}^2$. Note that our results for the $(4, 4)$ term have similar shapes as those presented in [30], see Figs. 3(c) and 3(d), where the absorption effects was also considered.
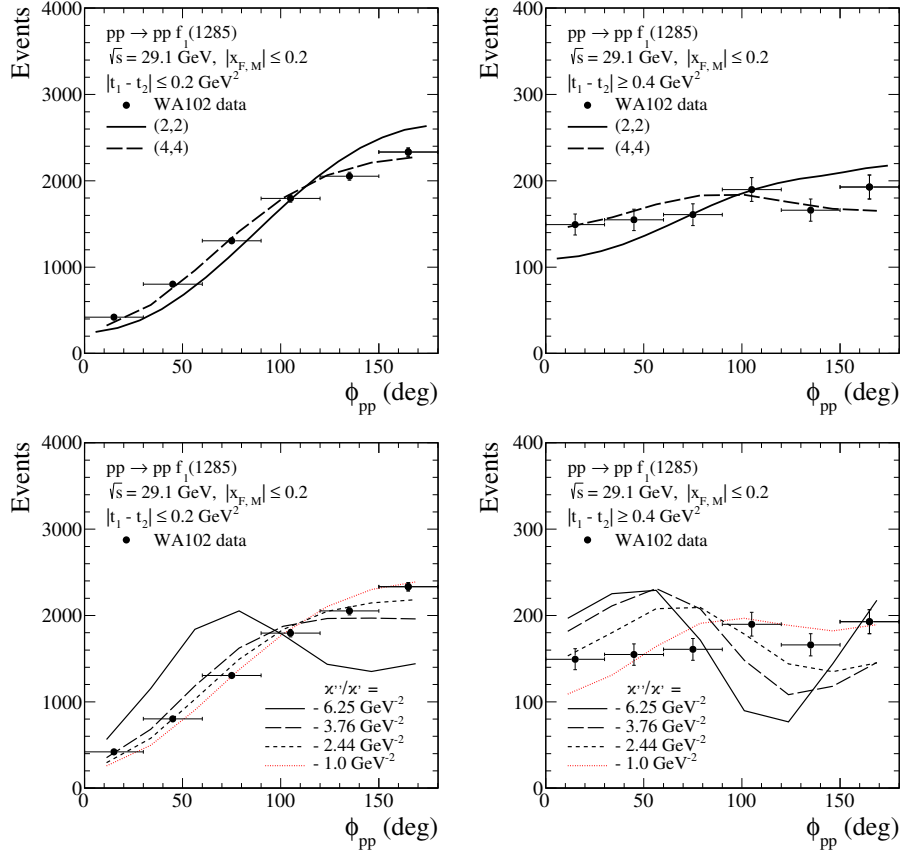
Figure 2: The ϕ_{pp} distributions for $f_1(1285)$ meson production at $\sqrt{s} = 29.1$ GeV, $|x_{F,M}| \leqslant 0.2$, and for $|t_1 - t_2| \leqslant 0.2$ GeV^2 (left panels) and $|t_1 - t_2| \geqslant 0.4$ GeV^2 (right panels); see Figs. 3 and 5 of [1]. The WA102 experimental data points are from Fig. 3 of [4]. 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 (11) are shown.

3.2 Predictions for the LHC experiments

Now we wish to show (selected) results for the $pp \to ppf_1(1285)$ reaction for the LHC; see [1] for many more results. Because of the possible influence of nonleading exchanges at low WA102 energies where we fixed the model parameters, the predictions at high energies should be regarded rather as an upper limit; see Appendix D of [1].

In Figure 4 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 (7), the $(4, 4)$ term (8), and for the $\varkappa'$ plus $\varkappa''$ terms obtained in the Sakai-Sugimoto model (9) (see also Appendix B of [1]) are shown. For comparison, the results for our fit to WA102 data ($\varkappa''/\varkappa' = -1.0$ 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 [26] and CMS-TOTEM, when both protons are measured. We obtain the ratio of full and Born cross sections as $\langle S^2 \rangle \simeq 0.3$ for $\sqrt{s} = 13$ TeV.

The four-pion decay channel seems well suited to measure the CEP of the $f_1(1285)$ at the LHC [26]. We predict a large cross section for the central exclusive $f_1(1285)$ production $\mathbb{PP} \to f_1(1285) \to 4\pi$ compared to $\mathbb{PP} \to f_2(1270) \to 4\pi$ [16, 18]. The diffractive processes of four-pion production in proton-proton collisions were discussed also in [17, 31].
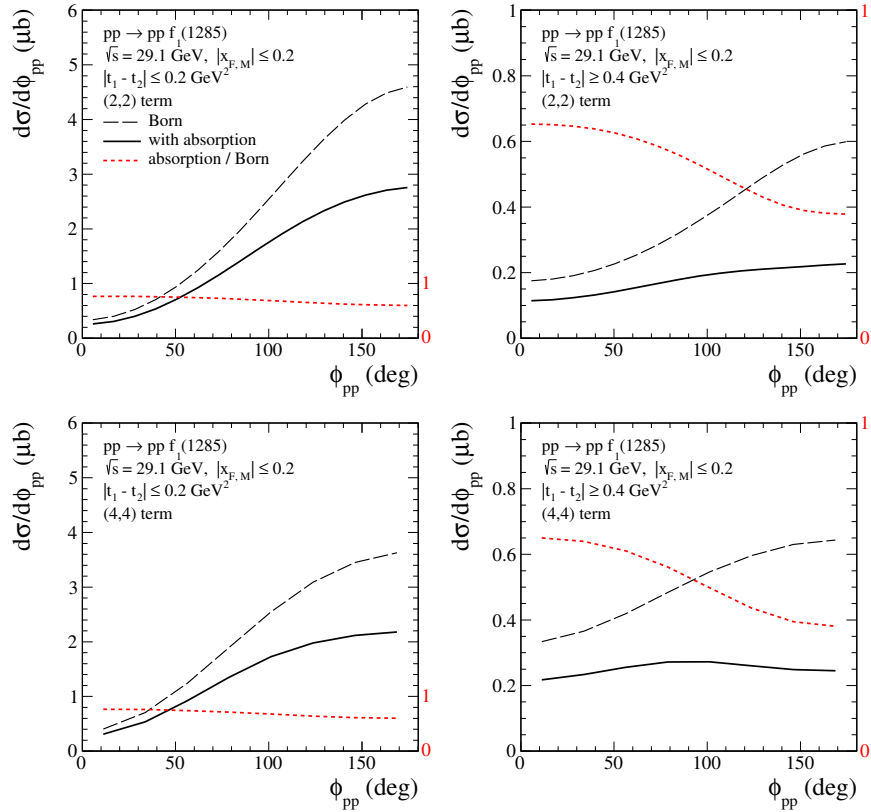
Figure 3: The ϕ_{pp} distributions for $f_1(1285)$ meson production at $\sqrt{s} = 29.1$ GeV, $|x_{F,M}| \leqslant 0.2$, for $|t_1 - t_2| \leqslant 0.2$ GeV^2 (left) and for $|t_1 - t_2| \geqslant 0.4$ GeV^2 (right); see Fig. 4 of [1]. The long-dashed black lines represent the Born results and the solid black lines correspond to the results with the absorption effects included. The ratio of full and Born cross sections represent the dotted red lines on the scale indicated on the r.h.s. of the panels.

4 Conclusion

- We have discussed the reaction $pp \to ppf_1(1285)$ in the tensor-pomeron approach [6]. We have used two different approaches for the $\mathbb{P}\mathbb{P}f_1$ coupling; see [1] for details. Assuming that the $f_1(1285)$ production is dominated by pomeron-pomeron fusion a good description of the WA102 data at $\sqrt{s} = 29.1$ GeV [2, 4] has been obtained.

- We predict a large cross section for CEP of the $f_1(1285)$ of $\sigma \cong 6 - 40$ μb for the ALICE, ATLAS-ALFA, CMS, and LHCb experiments, depending on the assumed cuts (see Table III of [1]). Predictions for the STAR experiments at RHIC are also given in [1]. The absorption effects were included.

- Experimental studies of single meson CEP reactions will allow to extract many $\mathbb{P}\mathbb{P}M$ coupling parameters. The holographic methods applied to QCD already give some predictions [1, 29].

- Detailed analysis of the distributions in ϕ_{pp} the azimuthal angle between the transverse momenta of the outgoing protons, can help to solve several important problems for soft processes, to check/study the real pattern of the interaction (absorption models), to understand the difference in the dynamics of production of $q\bar{q}$ mesons and glueballs (or more accurately, states which are believed to have a large glueball component), to disentangle f_1- and η-type resonances contributing to the same final channel.
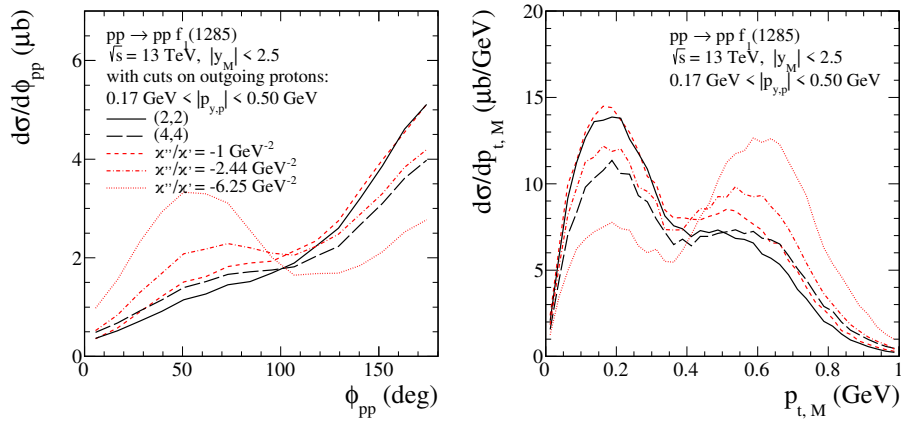
Figure 4: The differential cross sections for the $f_1(1285)$ production at $\sqrt{s} = 13$ TeV, $|y_M| < 2.5$, and with cuts on momenta of outgoing protons. The results for (l, S) and $(\varkappa', \varkappa'')$ terms are shown; see Fig. 8 of [1].

- 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 [32].

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