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

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The production of $f_1$ ($J^{PC} = 1^{++}$) mesons in proton-proton collisions via pomeron-pomeron fusion is discussed. Two ways to construct the pomeron-pomeron-$f_1$ coupling are presented. Comparisons with data from the WA102 experiment are made and predictions for RHIC and LHC experiments are given.

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1. Introduction

In this contribution we will be concerned with central exclusive production (CEP) of \( f_1(1285) \) and \( f_1(1420) \) mesons in proton-proton collisions

\[
p (p_a) + p (p_b) \rightarrow p (p_1) + f_1 (k) + p (p_2).
\]

The presentation is based on [1] where all details and many more results can be found. At high energies the reaction (1) should be mainly due to double-pomeron exchange (figure 1).

![Diagram for the reaction (1) with double-pomeron exchange (i.e., PP-fusion mechanism).](image)

The relevant kinematic quantities are

\[
s = (p_a + p_b)^2 \quad \text{c.m. energy squared},
\]

\[
q_1 = p_a - p_1, \quad q_2 = p_b - p_2, \quad k = q_1 + q_2,
\]

\[
t_1 = q_1^2, \quad t_2 = q_2^2, \quad m_{f_1}^2 = k^2.
\]

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 pomeron and the charge-conjugation \( C = +1 \) reggeons as effective rank 2 symmetric tensor exchanges, the odderon and \( C = -1 \) reggeons as effective vector exchanges. A tensor character of the pomeron is also preferred in holographic QCD; see e.g. [4–6].

There are by now many applications of the tensor-pomeron model to two-body hadronic reactions [7], to photoproduction, to DIS structure functions at low \( x \), and especially to CEP reactions:

\[
p + p \rightarrow p + X + p, \quad \text{where} \ X = \eta, \eta', f_0, f_2, \pi^+\pi^-, 4\pi, p\bar{p}, K\bar{K}, K\bar{K}K\bar{K}, \rho^0, \phi, \phi\phi;
\]

see e.g. [8–10].

From these works we know the form of the effective \( F \) propagator and the \( Fppp \) vertex. The new quantity in figure 1, to be studied here, is the \( Ff_1 \) coupling.

2. The pomeron-pomeron-\( f_1 \) coupling

In this section we describe our ways to construct the Lagrangian for the \( Ff_1 \) coupling and the corresponding vertex function (figure 2).

We follow two strategies for constructing this vertex function.
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Figure 2: Diagram for the $\mathbb{PP} f_1$ vertex function $\Gamma_{i,t,\rho,\sigma,\alpha}^{(\mathbb{PP} f_1)}(q_1, q_2)$ where $q_1 + q_2 = k$.

(1) Phenomenological approach. First we consider a fictitious process: the fusion of two “real spin two pomeron” (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:

$$\mathbb{P} (m, \epsilon_1) + \mathbb{P} (m, \epsilon_2) \rightarrow f_1 (m_f, \epsilon).$$

The spin 2 of these “pomeron” can be combined to a total spin $S$ ($0 \leq S \leq 4$) and this must be combined with the orbital angular momentum $l$ to give the $J^{PC} = 1^{++}$ values of the $f_1$. There are exactly two possibilities for this, namely $(l, S) = (2, 2)$ and $(4, 4)$; see Appendix A of [8]. Corresponding $\mathbb{PP} f_1$ couplings are easily written down:

$$\mathcal{L}^{(2,2)}_{\mathbb{PP} f_1} = \frac{\kappa'_{\mathbb{PP} f_1}}{32 M_0^2} (\mathbb{P}_{k,\lambda} \bar{\partial}_\mu \mathbb{P}_{\rho,\sigma} \bar{\partial}_\nu \mathbb{P}_{\rho,\sigma} \bar{\partial}_\mu U_{\alpha} - \bar{\partial}_\rho U_{\alpha}) \Gamma^{(8)}_{k,\lambda,\rho,\sigma,\mu,\nu,\alpha,\beta},$$

$$\mathcal{L}^{(4,4)}_{\mathbb{PP} f_1} = \frac{\kappa''_{\mathbb{PP} f_1}}{24 \cdot 32 M_0^4} (\mathbb{P}_{k,\lambda} \bar{\partial}_\mu \mathbb{P}_{\rho,\sigma} \bar{\partial}_\mu \mathbb{P}_{\rho,\sigma} \bar{\partial}_\mu U_{\alpha} - \bar{\partial}_\rho U_{\alpha}) \Gamma^{(10)}_{k,\lambda,\rho,\sigma,\mu_1,\mu_2,\mu_3,\alpha,\beta},$$

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

(2) Our second approach uses holographic QCD, in particular the Sakai-Sugimoto model [11, 12]. There, the $\mathbb{PP} f_1$ coupling can be derived from the bulk Chern-Simons term requiring consistency of supergravity and the gravitational anomaly. From this we get the following

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

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

For our fictitious reaction (4) there is strict equivalence

$$\mathcal{L}^{\text{CS}} \equiv \mathcal{L}^{(2,2)} + \mathcal{L}^{(4,4)}$$

if the couplings satisfy the relations

$$g'_{\mathbb{PP} f_1} = -\kappa' \frac{M_0^2}{k^2} - \kappa'' \frac{M_0^2 (k^2 - 2m^2)}{2k^2},$$

$$g''_{\mathbb{PP} f_1} = \kappa'' \frac{2M_0^4}{k^2}.$$
3. Results for the WA102 experiment

Many experimental results for CEP in proton-proton collisions at a c.m. energy of $\sqrt{s} = 29.1$ GeV have been obtained by the WA102 collaboration in the years 1997–2000. They worked at the Omega spectrometer at CERN and they could measure the complete final state: the central meson plus the outgoing protons. They obtained for $\sqrt{s} = 29.1$ GeV the following total cross sections for a cut on the meson’s Feynman variable $|x_F| \lesssim 0.2$ (see [13]):

$$f_1(1285) : \quad \sigma_{\text{exp.}} = (6919 \pm 886) \text{ nb},$$
$$f_1(1420) : \quad \sigma_{\text{exp.}} = (1584 \pm 145) \text{ nb}. \quad (10)$$

The WA102 collaboration also gave distributions in $t$ and in $\phi_{pp}$ ($0 \leq \phi_{pp} \leq \pi$), the azimuthal angle between the transverse momenta of the two outgoing protons in the overall c.m. system. We are assuming that the reaction (1) is dominated by pomeron exchange (figure 1) already at $\sqrt{s} = 29.1$ GeV. Using this we have calculated in our tensor-pomeron approach the cross sections, the $t$ and $\phi_{pp}$ distributions for $f_1(1285)$ and $f_1(1420)$ CEP, and compared our results to the WA102 data. In figures 3–5 we show some of our results [1] which include - very important - absorptive corrections. Here $\Lambda_E$ is a form-factor parameter. We get a reasonable description of the WA102 data with $\Lambda_E = 0.7$ GeV and the following possibilities:

$$(l, S) = (2, 2) \text{ term only : } \quad g_{PPf_1}' = 4.89, \quad g_{PPf_1}'' = 0; \quad (11)$$
$$\quad (l, S) = (4, 4) \text{ term only : } \quad g_{PPf_1}' = 0, \quad g_{PPf_1}'' = 10.31; \quad (12)$$
$$\quad \text{CS terms : } \quad \chi' = -8.88, \quad \chi''/\chi' = -1.0 \text{ GeV}^{-2}. \quad (13)$$

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{wa102_data_fit}
\caption{Fit to the WA102 data using the (2, 2) term only, $|g_{PPf_1}'| = 4.89$; see (5).}
\end{figure}

Now we can use our equivalence relation (9) in order to see to which $(l, S)$ couplings (13) corresponds. Replacing in (9) $m^2$ by $t_1 = t_2 = -0.1$ GeV$^2$ and $k^2$ by $m^2_{f_1} = (1282 \text{ MeV})^2$ we get from (13)

$$g_{PPf_1}' = 0.42, \quad g_{PPf_1}'' = 10.81. \quad (14)$$

Thus, the CS couplings of (13) correspond to a nearly pure $(l, S) = (4, 4)$ coupling (12), and the corresponding values of $g_{PPf_1}''$ of (14) and (12) agree to within 5%.
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4. Conclusions

- We have discussed in detail the forms of the $Pf_1$ coupling.
- We obtain a good description of the WA102 data at $\sqrt{s} = 29.1$ GeV.
- Our results for higher energies indicate similar distributions as at the lower energy and cross sections for CEP of the $f_1(1285)$ of $\sigma \approx 30 - 140$ nb for the STAR experiment at RHIC and $\sigma \approx 6 - 40$ µb for the LHC experiments, depending on the assumed cuts.
- Detailed tests of the Sakai-Sugimoto model are possible.
- Experimental studies of single meson CEP reactions will allow to extract many pomeron-pomeron-meson coupling parameters. Their theoretical calculation is a challenging problem of nonperturbative QCD.

Figure 4: Fit to the WA102 data using the $(4, 4)$ term only, $|S_{PPf_1}'''| = 10.31$; see (6).

Figure 5: Fit to the WA102 data using the Chern-Simons coupling with $x' = -8.88, x''/x' = -1.0$ GeV$^{-2}$; see (7). The $x''$ contribution has been enhanced by a factor 10 for better visibility.
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