PROCEEDINGS OF SCIENCE

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

$$p(p_a) + p(p_b) \to p(p_1) + f_1(k) + p(p_2)\,. \tag{1}$$

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).

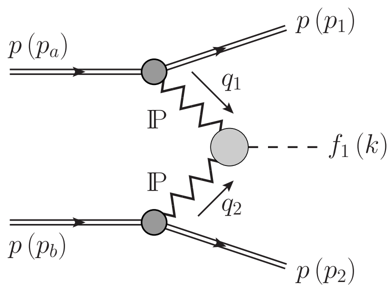

Figure 1: Diagram for the reaction (1) with double-pomeron exchange (i.e., $\mathbb{P}\mathbb{P}$-fusion mechanism).

The relevant kinematic quantities are

$$\begin{aligned} &s = (p_a + p_b)^2 \qquad \text{c.m. energy squared,} \\ &q_1 = p_a - p_1, \quad q_2 = p_b - p_2, \quad k = q_1 + q_2, \\ &t_1 = q_1^2, \quad t_2 = q_2^2, \quad m_{f_1}^2 = k^2\,. \end{aligned} \tag{2}$$

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:

$$p + p \to p + X + p, \quad \text{where} \;\; X = \eta,\, \eta',\, f_0,\, f_2,\, \pi^+\pi^-,\, 4\pi,\, p\bar{p},\, K\bar{K},\, K\bar{K}K\bar{K},\, \rho^0,\, \phi,\, \phi\phi\,; \tag{3}$$

see e.g. [8–10].

From these works we know the form of the effective $\mathbb{P}$ propagator and the $\mathbb{P}pp$ vertex. The new quantity in figure 1, to be studied here, is the $\mathbb{P}\mathbb{P}f_1$ coupling.

2. The pomeron-pomeron-f_1 coupling

In this section we describe our ways to construct the Lagrangian for the $\mathbb{P}\mathbb{P}f_1$ coupling and the corresponding vertex function (figure 2).

We follow two strategies for constructing this vertex function.

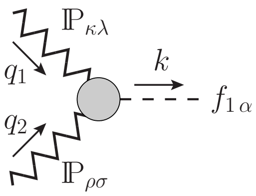

Figure 2: Diagram for the $\mathbb{P}\mathbb{P}f_1$ vertex function $i\Gamma^{(\mathbb{P}\mathbb{P}f_1)}_{\kappa\lambda,\rho\sigma,\alpha}(q_1, q_2)$ where $q_1 + q_2 = k$.

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

$$\mathbb{P}\,(m, \epsilon_1) + \mathbb{P}\,(m, \epsilon_2) \longrightarrow f_1\,(m_{f_1}, \epsilon)\,. \tag{4}$$

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 exactly two possibilities for this, namely $(l, S) = (2, 2)$ and $(4, 4)$; see Appendix A of [8]. Corresponding $\mathbb{P}\mathbb{P}f_1$ couplings are easily written down:

$$\mathcal{L}^{(2,2)}_{\mathbb{P}\mathbb{P}f_1} = \frac{g'_{\mathbb{P}\mathbb{P}f_1}}{32\,M_0^2}\left(\mathbb{P}_{\kappa\lambda}\,\overleftrightarrow{\partial}_\mu\,\overleftrightarrow{\partial}_\nu\,\mathbb{P}_{\rho\sigma}\right)\left(\partial_\alpha U_\beta - \partial_\beta U_\alpha\right)\Gamma^{(8)\,\kappa\lambda,\rho\sigma,\mu\nu,\alpha\beta}\,, \tag{5}$$

$$\mathcal{L}^{(4,4)}_{\mathbb{P}\mathbb{P}f_1} = \frac{g''_{\mathbb{P}\mathbb{P}f_1}}{24\cdot 32\cdot M_0^4}\left(\mathbb{P}_{\kappa\lambda}\,\overleftrightarrow{\partial}_{\mu_1}\,\overleftrightarrow{\partial}_{\mu_2}\,\overleftrightarrow{\partial}_{\mu_3}\,\overleftrightarrow{\partial}_{\mu_4}\,\mathbb{P}_{\rho\sigma}\right)\left(\partial_\alpha U_\beta - \partial_\beta U_\alpha\right)\Gamma^{(10)\,\kappa\lambda,\rho\sigma,\mu_1\mu_2\mu_3\mu_4,\alpha\beta}\,, \tag{6}$$

where $M_0 \equiv 1$ GeV (introduced for dimensional reasons), $\mathbb{P}_{\kappa\lambda}$ is the $\mathbb{P}$ effective field, U_α is the f_1 field, $g'_{\mathbb{P}\mathbb{P}f_1}$ and $g''_{\mathbb{P}\mathbb{P}f_1}$ 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 $\mathbb{P}\mathbb{P}f_1$ coupling can be derived from the bulk Chern-Simons term requiring consistency of supergravity and the gravitational anomaly. From this we get the following

$$\begin{aligned}\mathcal{L}^{\rm CS} \;=\;& \varkappa'\, U_\alpha\, \varepsilon^{\alpha\beta\gamma\delta}\, \mathbb{P}^\mu{}_\beta\, \partial_\delta \mathbb{P}_{\gamma\mu} \\ &+ \varkappa''\, U_\alpha\, \varepsilon^{\alpha\beta\gamma\delta}\left(\partial_\nu \mathbb{P}^\mu{}_\beta\right)\left(\partial_\delta\partial_\mu \mathbb{P}^\nu{}_\gamma - \partial_\delta\partial^\nu \mathbb{P}_{\gamma\mu}\right)\end{aligned} \tag{7}$$

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

For our fictitious reaction (4) there is strict equivalence

$$\mathcal{L}^{\rm CS} \mathrel{\widehat{=}} \mathcal{L}^{(2,2)} + \mathcal{L}^{(4,4)} \tag{8}$$

if the couplings satisfy the relations

$$\begin{aligned} g'_{\mathbb{P}\mathbb{P}f_1} &= -\varkappa'\,\frac{M_0^2}{k^2} - \varkappa''\,\frac{M_0^2(k^2 - 2m^2)}{2k^2}\,, \\ g''_{\mathbb{P}\mathbb{P}f_1} &= \varkappa''\,\frac{2M_0^4}{k^2}\,. \end{aligned} \tag{9}$$

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 relations (8), (9), will still be approximately true and we confirm this by explicit numerical studies.

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 $|x_F| \leqslant 0.2$ (see [13]):

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

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 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 ϕ_{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 Λ_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:

$$
(l,S) = (2,2)\ \text{term only}: \quad g'_{\mathbb{P}\mathbb{P}f_1} = 4.89\,,\ g''_{\mathbb{P}\mathbb{P}f_1} = 0; \tag{11}
$$

$$
(l,S) = (4,4)\ \text{term only}: \quad g'_{\mathbb{P}\mathbb{P}f_1} = 0\,,\ g''_{\mathbb{P}\mathbb{P}f_1} = 10.31; \tag{12}
$$

$$
\text{CS terms}: \quad \varkappa' = -8.88\,,\ \varkappa''/\varkappa' = -1.0\ \text{GeV}^{-2}\,. \tag{13}
$$

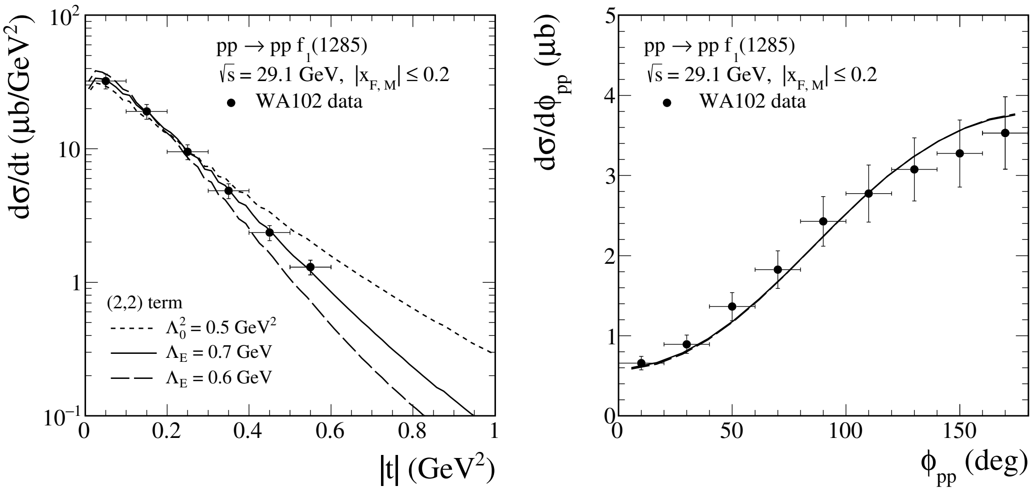

Figure 3: Fit to the WA102 data using the (2,2) term only, $|g'_{\mathbb{P}\mathbb{P}f_1}| = 4.89$; see (5).

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 $m_{f_1}^2 = (1282\ \text{MeV})^2$ we get from (13)

$$
g'_{\mathbb{P}\mathbb{P}f_1} = 0.42\,,\ g''_{\mathbb{P}\mathbb{P}f_1} = 10.81\,. \tag{14}
$$

Thus, the CS couplings of (13) correspond to a nearly pure $(l,S) = (4,4)$ coupling (12), and the corresponding values of $g''_{\mathbb{P}\mathbb{P}f_1}$ of (14) and (12) agree to within 5 %.

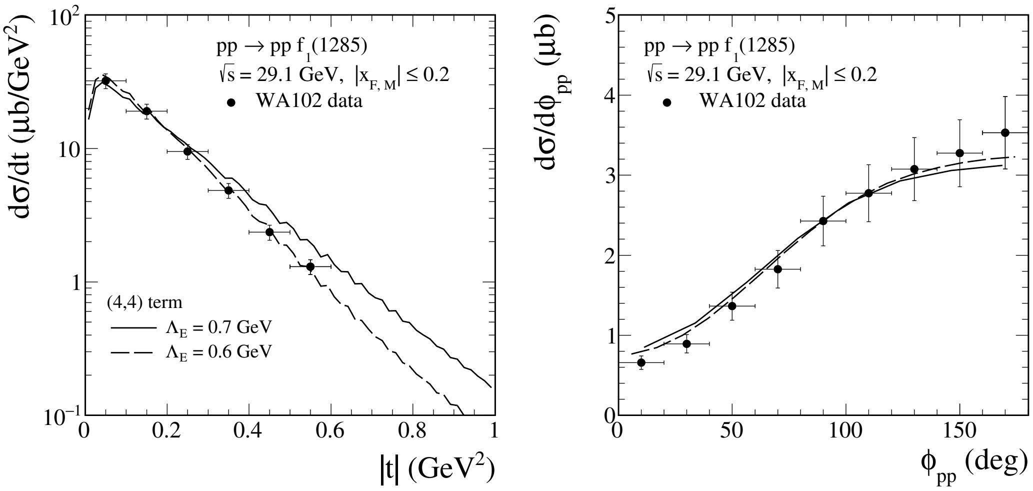

Figure 4: Fit to the WA102 data using the (4, 4) term only, $|g''_{\mathbb{P}\mathbb{P}f_1}| = 10.31$; see (6).

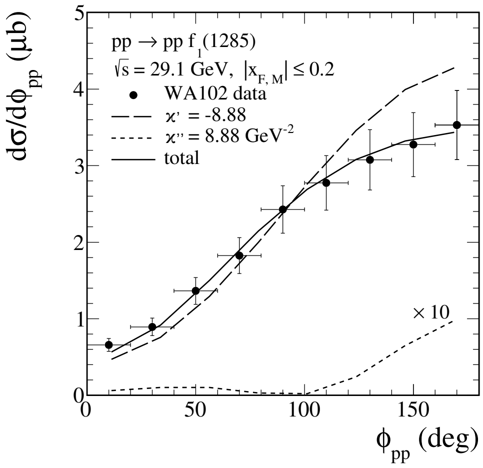

Figure 5: Fit to the WA102 data using the Chern-Simons coupling with $\varkappa' = -8.88$, $\varkappa''/\varkappa' = -1.0$ GeV^{-2}; see (7). The $\varkappa''$ contribution has been enhanced by a factor 10 for better visibility.

4. Conclusions

- We have discussed in detail the forms of the $\mathbb{P}\mathbb{P}f_1$ 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 $\sigma \cong 30 - 140$ nb for the STAR experiment at RHIC and $\sigma \cong 6 - 40$ 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.

Acknowledgments

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References

[1] P. Lebiedowicz, J. Leutgeb, O. Nachtmann, A. Rebhan, and A. Szczurek, *Central exclusive diffractive production of axial-vector $f_1(1285)$ and $f_1(1420)$ mesons in proton-proton collisions*, Phys. Rev. D **102** (2020) 114003 [hep-ph/2008.07452].

[2] C. Ewerz, M. Maniatis, and O. Nachtmann, *A model for soft high-energy scattering: Tensor pomeron and vector odderon*, Annals Phys. **342** (2014) 31 [hep-ph/1309.3478].

[3] O. Nachtmann, *Considerations concerning diffraction scattering in quantum chromodynamics*, Annals Phys. **209** (1991) 436.

[4] R. C. Brower, J. Polchinski, M. J. Strassler, and C.-I. Tan, *The Pomeron and gauge/string duality*, JHEP **12** (2007) 005 [hep-th/0603115].

[5] S. K. Domokos, J. A. Harvey, and N. Mann, *Pomeron contribution to pp and $p\bar{p}$ scattering in AdS/QCD*, Phys. Rev. D **80** (2009) 126015 [hep-ph/0907.1084].

[6] I. Iatrakis, A. Ramamurti, and E. Shuryak, *Pomeron interactions from the Einstein-Hilbert action*, Phys. Rev. D **94** (2016) 045005 [hep-ph/1602.05014].

[7] C. Ewerz, P. Lebiedowicz, O. Nachtmann, and A. Szczurek, *Helicity in Proton-Proton Elastic Scattering and the Spin Structure of the Pomeron*, Phys. Lett. **B763** (2016) 382 [hep-ph/1606.08067].

[8] P. Lebiedowicz, O. Nachtmann, and A. Szczurek, *Exclusive central diffractive production of scalar and pseudoscalar mesons; tensorial vs. vectorial pomeron*, Annals Phys. **344** (2014) 301 [hep-ph/1309.3913].

[9] P. Lebiedowicz, O. Nachtmann, and A. Szczurek, *Central exclusive diffractive production of the $\pi^+\pi^-$ continuum, scalar, and tensor resonances in pp and $p\bar{p}$ scattering within the tensor Pomeron approach*, Phys. Rev. D **93** (2016) 054015 [hep-ph/1601.04537].

[10] P. Lebiedowicz, O. Nachtmann, and A. Szczurek, *Searching for the odderon in $pp \to ppK^+K^-$ and $pp \to pp\mu^+\mu^-$ reactions in the $\phi(1020)$ resonance region at the LHC*, Phys. Rev. D **101** (2020) 094012 [hep-ph/1911.01909].

[11] T. Sakai and S. Sugimoto, *Low Energy Hadron Physics in Holographic QCD*, Prog. Theor. Phys. **113** (2005) 843 [hep-th/0412141].

[12] F. Brünner, D. Parganlija, and A. Rebhan, *Glueball Decay Rates in the Witten-Sakai-Sugimoto Model*, Phys. Rev. D **91** (2015) 106002 [hep-ph/1501.07906] [Erratum: Phys. Rev. D **93** (2016) 109903].

[13] D. Barberis *et al.*, (WA102 Collaboration), *A measurement of the branching fractions of the $f_1(1285)$ and $f_1(1420)$ produced in central pp interactions at 450 GeV/c*, Phys. Lett. **B440** (1998) 225 [hep-ex/9810003].