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Searching for odderon exchange in exclusive $pp \to pp\phi\phi$ reaction

Piotr Lebiedowicz
Institute of Nuclear Physics Polish Academy of Sciences, Radzikowskiego 152, PL-31342 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, Radzikowskiego 152, PL-31342 Cracow, Poland
E-mail: Antoni.Szczurek@ifj.edu.pl

We discuss the possibility to use the $pp \to pp\phi\phi$ process in identifying the odderon exchange. So far there is no unambiguous experimental evidence for the odderon, the charge conjugation $C = -1$ counterpart of the $C = +1$ pomeron. Last year results of the TOTEM collaboration suggest that the odderon exchange can be responsible for a disagreement of theoretical calculations and the TOTEM data for elastic proton-proton scattering. Here we present recent studies for central exclusive production (CEP) of $\phi\phi$ pairs in proton-proton collisions. We consider the pomeron-pomeron fusion to $\phi\phi$ ($\mathbb{P}\mathbb{P} \to \phi\phi$) through the continuum processes, due to the $\hat{t}$- and $\hat{u}$-channel reggeized ϕ-meson, photon, and odderon exchanges, as well as through the s-channel resonance process ($\mathbb{P}\mathbb{P} \to f_2(2340) \to \phi\phi$). This f_2 state is a candidate for a tensor glueball. The amplitudes for the processes are formulated within the tensor-pomeron and vector-odderon approach. Some model parameters are determined from the comparison to the WA102 experimental data. The odderon exchange is not excluded by the WA102 data for high $\phi\phi$ invariant masses. The measurement of large $M_{\phi\phi}$ or $\mathrm{Y_{diff}}$ events at the LHC would therefore suggest presence of the odderon exchange.

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∗Speaker.
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1. Introduction

Diffractive studies are one of the important parts of the physics program for the RHIC [1] and LHC experiments [2, 3]. A particularly interesting class is the central-exclusive-production (CEP) processes, where all centrally produced particles are detected. In recent years, there has been a renewed interest in exclusive production of $\pi^+\pi^-$ pairs at high energies related to successful experiments by the CDF [4] and the CMS [2] collaborations. Preliminary results of similar CEP studies have been presented by the ALICE and LHCb collaborations at the LHC. These measurements are important in the context of resonance production, in particular, in searches for glueballs. For a feasibility studies for the $pp \to pp\pi^+\pi^-$ process with tagging of the scattered protons as carried out for the ATLAS and ALFA detectors see [3].

In [5] the tensor-pomeron and vector-odderon concept was introduced for soft reactions. In this approach, the $C = +1$ pomeron and the reggeons $\mathbb{R}_+ = f_{2\mathbb{R}}, a_{2\mathbb{R}}$ are treated as effective rank-2 symmetric tensor exchanges while the $C = -1$ odderon and the reggeons $\mathbb{R}_- = \omega_{\mathbb{R}}, \rho_{\mathbb{R}}$ are treated as effective vector exchanges. For these effective exchanges a number of propagators and vertices, respecting the standard rules of quantum field theory, were derived from comparisons with experiments. This allows for an easy construction of amplitudes for specific processes. Applications of the tensor-pomeron and vector-odderon ansatz were given for photoproduction of pion pairs in [12] and for a number of central-exclusive-production (CEP) reactions in pp collisions in [13, 14, 15, 16, 17, 18, 19, 20, 21]. In [22] the helicity structure of small-$|t|$ proton-proton elastic scattering was considered in three models for the pomeron: tensor, vector, and scalar. Only the tensor ansatz for the pomeron was found to be compatible with the high-energy experiment on polarized pp elastic scattering [11].

So far there is no unambiguous experimental evidence for the odderon ($\mathbb{O}$), the charge conjugation $C = -1$ counterpart of the $C = +1$ pomeron, introduced on theoretical grounds in [6]. A hint of the odderon was seen in ISR results [7] as a small difference between the differential cross sections of elastic proton-proton (pp) and proton-antiproton ($p\bar{p}$) scattering in the diffractive dip region at $\sqrt{s} = 53$ GeV. Recently the TOTEM Collaboration has published data from high-energy elastic pp scattering experiments at the LHC [8].

As was discussed in [9] exclusive diffractive J/ψ and ϕ production from the pomeron-odderon fusion in high-energy pp and $p\bar{p}$ collisions is a direct probe for a possible odderon exchange. For a nice review of odderon physics see [10]. In the diffractive production of ϕ meson pairs it is possible to have pomeron-pomeron fusion with intermediate $\hat{t}/\hat{u}$-channel odderon exchange [21]; see the corresponding diagram in Fig. 1 (c). Thus, the $pp \to pp\phi\phi$ reaction is a good candidate for the $\mathbb{O}$-exchange searches, as it does not involve the coupling of the odderon to the proton [18].

Studies of different decay channels in central exclusive production would be very valuable also in the context of identification of glueballs. One of the promising reactions is $pp \to pp\phi\phi$ with both $\phi \equiv \phi(1020)$ mesons decaying into the K^+K^- channel. Structures in the $\phi\phi$ invariant-mass spectrum were observed by several experiments [23, 24, 25]. Three tensor states, $f_2(2010)$, $f_2(2300)$, and $f_2(2340)$, observed previously in [23], were also observed in the radiative decay $J/\psi \to \gamma\phi\phi$ [26]. The nature of these resonances is not understood at present. According to lattice-QCD simulations, the lightest tensor glueball has a mass between 2.2 and 2.4 GeV, see, e.g. [27]. The $f_2(2300)$ and $f_2(2340)$ states are good candidates to be tensor glueballs.

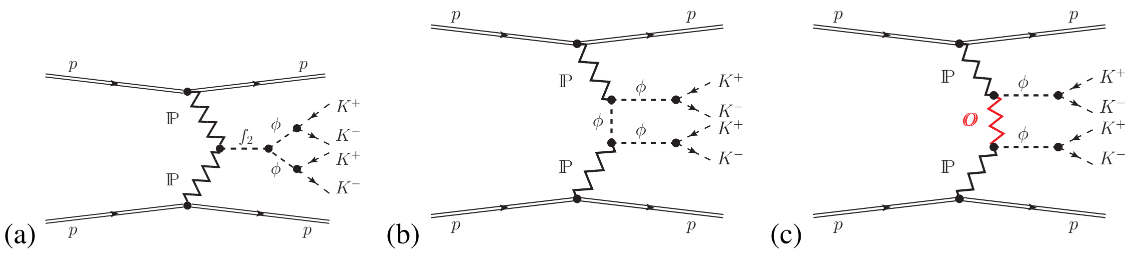

Figure 1: The Born-level diagrams for double pomeron central exclusive $\phi\phi$ production and their decays into $K^+K^-K^+K^-$: (a) $\phi\phi$ production via an f_2 resonance. Other resonances, e.g. of f_0- and η-type, can also contribute here. (b) and (c) continuum $\phi\phi$ production via an intermediate ϕ and odderon ($\mathbb{O}$) exchanges, respectively. $\mathbb{P}$-γ-$\mathbb{P}$ and $\mathbb{O}$-$\mathbb{P}$-$\mathbb{O}$ contributions are also possible but negligibly small.

2. A sketch of formalism

In [21] we considered the CEP of four charged kaons via the intermediate $\phi\phi$ state. Explicit expressions for the $pp \to pp\phi\phi$ amplitudes involving the pomeron-pomeron fusion to $\phi\phi$ ($\mathbb{P}\mathbb{P} \to \phi\phi$) through the continuum processes, due to the $\hat{t}$- and $\hat{u}$-channel reggeized ϕ-meson, photon, and odderon exchanges, as well as through the s-channel resonance reaction ($\mathbb{P}\mathbb{P} \to f_2(2340) \to \phi\phi$) were given there. The "Born-level" amplitude for the $pp \to pp\phi\phi$ reaction can be written as

$$\mathscr{M}^{\rm Born} = \mathscr{M}^{(f_2-{\rm exchange})} + \mathscr{M}^{(\phi-{\rm exchange})} + \mathscr{M}^{(\mathbb{O}-{\rm exchange})} . \tag{2.1}$$

Here we discuss shortly the continuum process with the odderon exchange [see Fig. 1 (c)] for the $pp \to pp\phi\phi$ reaction. The amplitude is a sum of $\hat{t}$- and $\hat{u}$-channel amplitudes. The $\hat{t}$-channel term (Born level) can be written as

$$\begin{aligned} \mathscr{M}^{(\hat{t})} = \; & (-i)\bar{u}(p_1,\lambda_1) i\Gamma^{(\mathbb{P}pp)}_{\mu_1\nu_1}(p_1,p_a) u(p_a,\lambda_a) i\Delta^{(\mathbb{P})\,\mu_1\nu_1,\alpha_1\beta_1}(s_{13},t_1) \\ & \times i\Gamma^{(\mathbb{P}\mathbb{O}\phi)}_{\rho_1\rho_3\alpha_1\beta_1}(\hat{p}_t,-p_3) \left(\varepsilon^{(\phi)\,\rho_3}(\lambda_3)\right)^* i\Delta^{(\mathbb{O})\,\rho_1\rho_2}(s_{34},\hat{p}_t) \\ & \times i\Gamma^{(\mathbb{P}\mathbb{O}\phi)}_{\rho_4\rho_2\alpha_2\beta_2}(p_4,\hat{p}_t) \left(\varepsilon^{(\phi)\,\rho_4}(\lambda_4)\right)^* i\Delta^{(\mathbb{P})\,\alpha_2\beta_2,\mu_2\nu_2}(s_{24},t_2) \\ & \times \bar{u}(p_2,\lambda_2) i\Gamma^{(\mathbb{P}pp)}_{\mu_2\nu_2}(p_2,p_b) u(p_b,\lambda_b) , \end{aligned} \tag{2.2}$$

where $p_{a,b}$, $p_{1,2}$ and $\lambda_{a,b}, \lambda_{1,2} = \pm\frac{1}{2}$ denote the four-momenta and helicities of the protons and $p_{3,4}$ and $\lambda_{3,4} = 0, \pm 1$ denote the four-momenta and helicities of the ϕ mesons, respectively. $\hat{p}_t = p_a - p_1 - p_3$, $\hat{p}_u = p_4 - p_a + p_1$, $s_{ij} = (p_i + p_j)^2$, $t_1 = (p_1 - p_a)^2$, $t_2 = (p_2 - p_b)^2$. $\Gamma^{(\mathbb{P}pp)}$ and $\Delta^{(\mathbb{P})}$ denote the proton vertex function and the effective propagator, respectively, for tensorial pomeron. The corresponding expressions are as follows [5]:

$$i\Gamma^{(\mathbb{P}pp)}_{\mu\nu}(p',p) = -i3\beta_{\mathbb{P}NN} F_1(t) \left\{ \frac{1}{2} \left[\gamma_\mu (p'+p)_\nu + \gamma_\nu (p'+p)_\mu \right] - \frac{1}{4} g_{\mu\nu} (\not{p}' + \not{p}) \right\} , \tag{2.3}$$

$$i\Delta^{(\mathbb{P})}_{\mu\nu,\kappa\lambda}(s,t) = \frac{1}{4s} \left(g_{\mu\kappa} g_{\nu\lambda} + g_{\mu\lambda} g_{\nu\kappa} - \frac{1}{2} g_{\mu\nu} g_{\kappa\lambda} \right) (-is\alpha'_{\mathbb{P}})^{\alpha_{\mathbb{P}}(t)-1} , \tag{2.4}$$

where $\beta_{\mathbb{P}NN} = 1.87$ GeV^{-1}. The pomeron trajectory $\alpha_{\mathbb{P}}(t)$ is assumed to be of standard linear form (see, e.g., [28]): $\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}} t$, $\alpha_{\mathbb{P}}(0) = 1.0808$, $\alpha'_{\mathbb{P}} = 0.25$ GeV^{-2}.

Our ansatz for the effective propagator of the $C = -1$ odderon is [5]

$$i\Delta^{(\mathbb{O})}_{\mu\nu}(s,t) = -ig_{\mu\nu}\frac{\eta_{\mathbb{O}}}{M_0^2}(-is\alpha'_{\mathbb{O}})^{\alpha_{\mathbb{O}}(t)-1} \quad \text{with} \quad M_0 = 1\ \text{GeV}\,,\ \eta_{\mathbb{O}} = \pm 1\,. \tag{2.5}$$

Here $\alpha_{\mathbb{O}}(t) = \alpha_{\mathbb{O}}(0) + \alpha'_{\mathbb{O}}\, t$ and we choose, as an example, $\alpha'_{\mathbb{O}} = 0.25\ \text{GeV}^{-2}$, $\alpha_{\mathbb{O}}(0) = 1.05$.

For the $\mathbb{P}\mathbb{O}\phi$ vertex we use an ansatz with two rank-four tensor functions $\Gamma^{(0,2)}$ [21]:

$$i\Gamma^{(\mathbb{P}\mathbb{O}\phi)}_{\mu\nu\kappa\lambda}(k',k) = iF^{(\mathbb{P}\mathbb{O}\phi)}((k+k')^2,k'^2,k^2)\left[2\,a_{\mathbb{P}\mathbb{O}\phi}\,\Gamma^{(0)}_{\mu\nu\kappa\lambda}(k',k) - b_{\mathbb{P}\mathbb{O}\phi}\,\Gamma^{(2)}_{\mu\nu\kappa\lambda}(k',k)\right], \tag{2.6}$$

$$F^{(\mathbb{P}\mathbb{O}\phi)}((k+k')^2,k'^2,k^2) = F((k+k')^2)\,F(k'^2)\,F^{(\mathbb{P}\mathbb{O}\phi)}(k^2)\,, \tag{2.7}$$

where we take $F(k^2) = (1-k^2/\Lambda^2)^{-1}$ and $F^{(\mathbb{P}\mathbb{O}\phi)}(m_\phi^2) = 1$. The coupling parameters $a_{\mathbb{P}\mathbb{O}\phi}$, $b_{\mathbb{P}\mathbb{O}\phi}$ and the cutoff parameter Λ^2 could be adjusted to the WA102 experimental data [25].

At low $\sqrt{s_{34}} = \mathrm{M}_{\phi\phi}$ the Regge type of interaction is not realistic and should be switched off. To achieve this we multiplied the $\mathbb{O}$-exchange amplitude by a purely phenomenological factor: $F_{\text{thr}}(s_{34}) = 1 - \exp[(s_{\text{thr}} - s_{34})/s_{\text{thr}}]$ with $s_{\text{thr}} = 4m_\phi^2$.

The amplitude for the process shown in Fig. 1 (b) has the same form as the amplitude with the $\mathbb{O}$ exchange but we have to make the following replacements:

$$i\Gamma^{(\mathbb{P}\mathbb{O}\phi)}_{\mu\nu\kappa\lambda}(k',k) \to i\Gamma^{(\mathbb{P}\phi\phi)}_{\mu\nu\kappa\lambda}(k',k)\,, \tag{2.8}$$

$$i\Delta^{(\mathbb{O})}_{\mu\nu}(s_{34},\hat{p}^2) \to i\Delta^{(\phi)}_{\mu\nu}(\hat{p})\,. \tag{2.9}$$

We have fixed the coupling parameters of the tensor pomeron to the ϕ meson based on the HERA experimental data for the $\gamma p \to \phi p$ reaction; see [19]. We should take into account the reggeization of the intermediate ϕ meson; see [21]. We take $\alpha_\phi(\hat{p}^2) = \alpha_\phi(0) + \alpha'_\phi\,\hat{p}^2$, $\alpha_\phi(0) = 0.1$ [29], and $\alpha'_\phi = 0.9\ \text{GeV}^{-2}$.

In order to give realistic predictions we shall include absorption effects calculated at the amplitude level and related to the pp nonperturbative interactions. The full amplitude includes the pp-rescattering corrections (absorption effects)

$$\mathcal{M}_{pp\to pp\phi\phi} = \mathcal{M}^{\text{Born}} + \mathcal{M}^{\text{absorption}}\,, \tag{2.10}$$

$$\mathcal{M}^{\text{absorption}}(s,p_{1t},p_{2t}) = \frac{i}{8\pi^2 s}\int d^2k_t\,\mathcal{M}^{\text{Born}}(s,\tilde{p}_{1t},\tilde{p}_{2t})\,\mathcal{M}^{(\mathbb{P})}_{\text{el}}(s,-k_t^2)\,, \tag{2.11}$$

where $\tilde{p}_{1t} = p_{1t} - k_t$ and $\tilde{p}_{2t} = p_{2t} + k_t$. $\mathcal{M}^{(\mathbb{P})}_{\text{el}}$ is the elastic pp-scattering amplitude with the momentum transfer $t = -k_t^2$.

3. Results

Figure 2 shows complete results including the $f_2(2340)$-resonance contribution and the continuum processes due to reggeized-ϕ, odderon, and photon exchanges. It is very difficult to describe the WA102 data for the $pp \to pp\phi\phi$ reaction including resonances and the ϕ-exchange mechanism only [21]. Inclusion of the odderon exchange improves the description of the WA102 data [25], see the left panel of Fig. 2. Having fixed the parameters of our quasi fit to the WA102 data we wish to show our predictions for the LHC. We show the results for the ATLAS (CMS) experimental conditions ($|\eta_K| < 2.5$, $p_{t,K} > 0.2$ GeV). The distribution in four-kaon invariant mass is shown in the center panel and the difference in rapidity between the two ϕ mesons ($\mathrm{Y_{diff}}$) in the right panel. The small intercept of the ϕ-reggeon exchange, $\alpha_\phi(0) = 0.1$ makes the ϕ-exchange contribution steeply falling with increasing M_{4K} and $|\mathrm{Y_{diff}}|$. Therefore, an odderon with an intercept $\alpha_{\mathbb{O}}(0)$ around 1.0 should be clearly visible in the region of large M_{4K} and for large rapidity distance between the ϕ mesons.

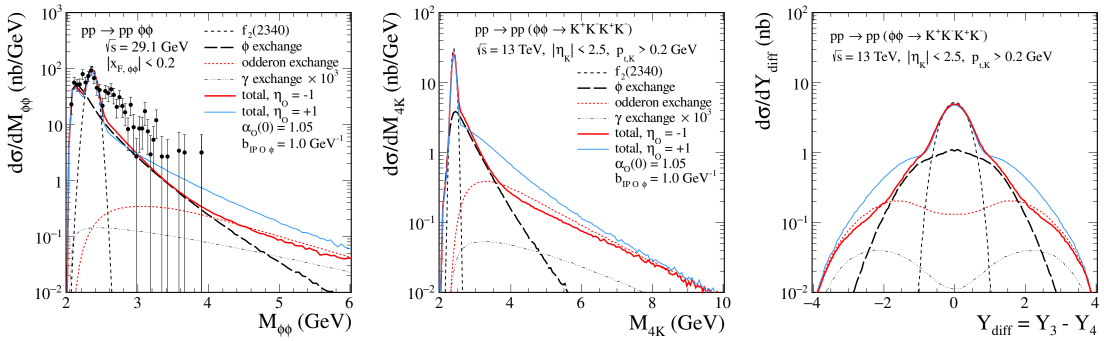

Figure 2: The distributions in $\phi\phi$ invariant mass (left), in M_{4K} (center), and in $\mathrm{Y_{diff}}$ (right). The WA102 experimental data from [25] are shown. The calculations were done for $\sqrt{s} = 29.1$ GeV and $|x_{F,\phi\phi}| \leqslant 0.2$, and for $\sqrt{s} = 13$ TeV and $|\eta_K| < 2.5$, $p_{t,K} > 0.2$ GeV. The black long-dashed line corresponds to the ϕ-exchange contribution and the black dashed line corresponds to the $f_2(2340)$ contribution. The red dotted line represents the odderon-exchange contribution for $a_{\mathbb{P}\mathbb{O}\phi} = 0$ and $b_{\mathbb{P}\mathbb{O}\phi} = 1.0\ \mathrm{GeV}^{-1}$ in (2.6). The coherent sum of all terms is shown by the red and blue solid lines for $\eta_{\mathbb{O}} = -1$ and $\eta_{\mathbb{O}} = +1$, respectively. The absorption effects are included in the calculations.

4. Conclusions

Taking into account typical kinematic cuts for LHC experiments in the $pp \to pp\phi\phi \to ppK^+K^-K^+K^-$ reaction we have found that the odderon exchange contribution should be distinguishable from other contributions for large rapidity distance between the outgoing ϕ mesons and in the region of large four-kaon invariant masses. Our results can be summarized in the following way:

- CEP is particularly interesting class of processes which provides insight to unexplored soft QCD phenomena. The fully differential studies of exclusive $pp \to pp\phi\phi$ reaction within the tensor-pomeron and vector-odderon approach was executed; for more details see [21]. Integrated cross sections of order of a few nb are obtained including the experimental cuts relevant for the LHC experiments. The distribution in rapidity difference of both ϕ-mesons could shed light on the $f_2(2340) \to \phi\phi$ coupling [15], not known at present.

- We find from our model that the odderon-exchange contribution should be distinguishable from other contributions for relatively large rapidity separation between the ϕ mesons. Hence, to study this type of mechanism one should investigate events with rather large four-kaon invariant masses, outside of the region of resonances. These events are then "three-gap events": proton–gap–ϕ–gap–ϕ–gap–proton. Experimentally, this should be a clear signature.

- Clearly, an experimental study of CEP of a ϕ-meson pair should be very valuable for clarifying the status of the odderon. At least, it should be possible to derive an upper limit on the odderon contribution in this reaction.

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