Searching for odderon exchange in exclusive $pp \rightarrow pp\phi$ and $pp \rightarrow pp\phi\phi$ reactions at the LHC

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The possibility to use the exclusive $pp \rightarrow pp\phi$ and $pp \rightarrow pp\phi\phi$ reactions in identifying the odderon exchange is discussed. So far there is no unambiguous experimental evidence for the odderon, the charge conjugation $C = -1$ counterpart of the $C = +1$ pomeron. Recently proposed tensor-pomeron and vector-odderon model for soft high-energy reactions is applied. For the $pp \rightarrow pp\phi$ reaction at high energies the photon-pomeron fusion is the dominant process and the odderon-pomeron fusion is an interesting alternative. Adding odderon exchange improves considerably description of the proton-proton angular correlations measured by the WA102 collaboration. The $pp \rightarrow pp\phi\phi$ process via pomeron-pomeron fusion is advantageous one as here the odderon does not couple to protons. The observation of large $M_{\phi\phi}$ and the rapidity difference $Y_{\phi\phi}$ seems well suited to identify odderon exchange. Comparisons with data from the WA102 experiment are made and predictions for LHC experiments are given.

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1. Introduction

The odderon was introduced on theoretical grounds in [1]. It was predicted in QCD as a colourless charge-conjugation C-odd three-gluon bound state exchange [2, 3]. Recent experimental results by the TOTEM Collaboration [4, 5] have brought the odderon question in proton-proton elastic scattering to the forefront again. It is of great importance to study possible odderon effects in other reactions. As was discussed in [6] exclusive diffractive $J/\psi$ and $\phi$ production from the pomeron-odderon fusion in high-energy $pp$ and $p\bar{p}$ collisions is a direct probe for a possible odderon exchange. We shall argue here that the central exclusive production (CEP) of a $\phi\phi$ state offers a very nice way to look for odderon effects as suggested in [7].

In this contribution we will be concerned with CEP of single and double $\phi(1020)$ meson production observed in the $K^+ K^-$ or $\mu^+ \mu^-$ channels in $pp$ collisions as a possible source of information for soft odderon exchange (see figure 1). The presentation is based on [8] where all details and many more results can be found. At high energies the $pp \to pp\phi$ reaction should be mainly due to photon-pomeron exchange. The odderon-pomeron fusion mechanism is an interesting alternative. The $pp \to pp\phi\phi$ reaction should be mainly due to double-pomeron exchange with resonant production at low $\phi\phi$ invariant masses and the continuum processes (reggeized-$\phi$-meson and odderon exchanges) at higher $M_{\phi\phi}$. The process with an intermediate $\hat{t}/\hat{u}$-channel odderon exchange ($P^{-O-P^{-}}$) is a good candidate for the odderon searches, as it does not involve the coupling of the odderon to the proton.

Figure 1: Diagrams for (a) single $\phi$ production and for (b) double $\phi$ production with odderon ($O$) exchange. There are also diagrams with the role of the protons interchanged, $(p(p_a), p(p_1)) \leftrightarrow (p(p_b), p(p_2)).$

We treat our reactions in the tensor-pomeron and vector-odderon approach as introduced in [9]. This approach has a good basis from nonperturbative QCD using functional integral techniques [10]. We describe the pomeron and the $C = +1$ reggeons as effective rank 2 symmetric tensor exchanges, the odderon and $C = -1$ reggeons as effective vector exchanges. There are by now many applications of the tensor-pomeron model to two-body hadronic reactions [11], to photoproduction, to DIS structure functions at low $x$, and especially to CEP reactions: $p + p \to p + X + p$, where $X = \eta, \eta', f_0, f_1, f_2, \pi^{\pm}\pi^{\mp}, p\bar{p}, K\bar{K}, 4\pi, 4K, p^0, \phi, \phi\phi$; see e.g. [8, 12-15].

2. A sketch of formalism

As an example, we consider the reaction

$$p(p_a) + p(p_b) \to p(p_1) + [\phi(p_{34}) \to K^+(p_3) + K^-(p_4)] + p(p_2), \tag{1}$$

where $p_{a,b}, p_{1,2}$ denote the four-momenta of the protons and $p_{3,4}$ denote the four-momenta of the $K$ mesons, respectively. For high energies and central $\phi$ production we expect the reaction (1) to
be dominated by the fusion processes $\gamma \Phi \rightarrow \phi$ and $\mathcal{O} \Phi \rightarrow \phi$. For the first process all couplings are, in essence, known. The parameters of $\phi$ photoproduction were fixed to describe the HERA data taking into account the $\phi$-$\omega$ mixing effect [8]. For the odderon-exchange process we shall use the ansätze from [9] and we shall try to get information on the odderon parameters and couplings from the comparison to the WA102 data for the $pp \rightarrow pp\phi$ and $pp \rightarrow pp\Phi\phi$ reactions. Of course, at the relatively low c.m. energy of the WA102 experiment, $\sqrt{s} = 29.1$ GeV, we have to include also subleading contributions with reggeized-vector-meson (or reggeon) exchanges discussed in [8].

The Born-level amplitude for the diffractive production of the $\phi(1020)$ via odderon-pomeron fusion [figure 1(a)] can be written as

$$M^{(\Phi)}_{pp \rightarrow ppK^+K^-} = (-i)\bar{u}(p_1, \lambda_1)\Gamma^{(\Phi pp)}_\mu(p_1, p_a)u(p_1, \lambda_1)i\Delta^{(\Phi)}_{\mu}(s_1, t_1)i\Gamma^{(PO\phi)}_\mu(p_{q1}, q_1) \times i\Delta^{(\Phi)}_{\nu}(s_{34})\Gamma^{(\Phi KK)}_\nu(p_{34}, p_\nu)i\Delta^{(\Phi)}_{\nu}(s_2, t_2)\bar{u}(p_2, \lambda_2)i\Gamma^{(ppp)}_\nu(p_{b2}, p_b)u(p_\nu, \lambda_b).$$

(2)

The kinematic variables are $p_{34} = p_3 + p_4$, $q_1 = p_a - p_1$, $q_2 = p_b - p_2$, $t_1 = q_1^2$, $t_2 = q_2^2$, $s = (p_a + p_b)^2$, $s_1 = (p_1 + p_{34})^2$, $s_2 = (p_2 + p_{34})^2$. The effective pomeron propagator and the pomeron-proton vertex function are as follows [9]:

$$i\Delta^{(\Phi)}_{\mu\nu}(s, t) = \frac{1}{4s} \left[ g_{\mu\nu} g_{\nu\lambda} + g_{\mu\lambda} g_{\nu\kappa} - \frac{1}{2} g_{\mu\nu} g_{\kappa\lambda} \right] (-i\alpha' \rho^{2}(t))^{-1},$$

(3)

$$i\Gamma^{(ppp)}_\mu(p', p) = -i\beta_{\Phi NN} F_1((p' - p)^2) \left[ \frac{1}{2} \left[ \gamma_\mu (p' + p) + \gamma_\nu (p' - p) \right] \right],$$

(4)

where $\beta_{\Phi NN} = 1.87$ GeV$^{-1}$ and $t = (p' - p)^2$. For simplicity we use the electromagnetic Dirac form factor $F_1(t)$ of the proton. The pomeron trajectory $\alpha_\Phi(t)$ is assumed to be of standard linear form: $\alpha_\Phi(t) = \alpha_\Phi(0) + \alpha_\Phi' t$, with $\alpha_\Phi(0) = 1.0808$ and $\alpha_\Phi' = 0.25$ GeV$^{-2}$.

Our ansatz for the $C = -1$ odderon follows (3.16), (3.17) and (3.68), (3.69) of [9]:

$$i\Delta^{(\Phi)}_{\mu\nu}(s, t) = -ig_{\mu\nu} \frac{\eta_\Phi}{M_0} (-i\alpha' \rho^{2}(t))^{-1},$$

(5)

$$i\Gamma^{(ppp)}_\mu(p', p) = -i\beta_{\Phi pp} M_0 F_1((p' - p)^2) \gamma_\mu,$$

(6)

where $\eta_\Phi$ is a parameter with value $\eta_\Phi = \pm 1$; $M_0 = 1$ GeV is inserted for dimensional reasons. We assumed $\beta_{\Phi pp} = 0.1 \times \beta_{\Phi NN}$. We take $\alpha_\Phi(t) = \alpha_\Phi(0) + \alpha_\Phi' t$. In our calculations we shall choose as default values $\alpha_\Phi(0) = 1.05$, $\alpha_\Phi' = 0.25$ GeV$^{-2}$, and $\eta_\Phi = -1$; see [8].

For the $PO\phi$ vertex we use an ansatz analogous to the $\Phi\phi$ vertex (see (3.48)–(3.50) of [14])

$$i\Gamma^{(PO\phi)}_\mu(p_{q1}, q_1) = i \left[ 2 a_{PO\phi} \Gamma^{(0)}_{\mu\nu\lambda\alpha}(p_{34}, -q_1) - b_{PO\phi} \Gamma^{(2)}_{\mu\nu\lambda\alpha}(p_{34}, -q_1) \right] \times F_M(q_1^2) F_M(q_2^2) F(\Phi)(p_{34}^2).$$

(7)

Here we use the relations (3.20) of [9] and as in (3.49) of [14] we take the factorised form for the $PO\phi$ form factor; see [8]. The coupling parameters $a_{PO\phi}$, $b_{PO\phi}$ in (7) and the cut-off parameter $\Lambda^2_{0, PO\phi}$ in $F_M(t) = 1/(1-t/\Lambda^2_{0, PO\phi})$ could be adjusted to experimental data. The WA102 data allow us to determine the respective coupling constants as $a_{PO\phi} = -0.8$ GeV$^{-3}$, $b_{PO\phi} = 1.6$ GeV$^{-1}$, and $\Lambda^2_{0, PO\phi} = 0.5$ GeV$^2$ [8]. We have checked that these parameters are compatible with our analysis of the WA102 data for the $pp \rightarrow pp\Phi\phi$ reaction in [14].

The full amplitude includes the $pp$-rescattering corrections in the eikonal approximation; see [8].
3. Results

It is very difficult to describe the WA102 data from [16] for the $pp \rightarrow pp\phi$ reaction including the $\gamma\phi$-fusion mechanism only. As was presented in [8] inclusion of the odderon-exchange contribution significantly improves the description of the $pp$ azimuthal correlations ($\phi_{pp}$ is angle between the transverse momentum vectors $p_{t,1}$, $p_{t,2}$ of the outgoing protons) and the $dP_t = |p_{t,2} - p_{t,1}|$ dependence of $\phi$ CEP measured by the WA102 collaboration. The absorption effects - very important - were included in the calculations. In the left panel of figure 2 we present the $O\cdot\mathcal{P}$ contribution (approach II of [8]) together with the $\gamma\cdot\mathcal{P}$ contribution and with the subleading terms. Adding odderon exchange term improves description of the proton-proton angular correlations. Having fixed the parameters of our model to the WA102 data we show our predictions at $\sqrt{s} = 13$ TeV for the LHC. Here we focus on the limited invariant mass region around the $\phi(1020)$ resonance.

![Figure 2](image_url)

Figure 2: Left panel: The distributions in $\phi_{pp}$ together with the WA102 experimental data points for $\sqrt{s} = 29.1$ GeV normalized to the central value of the total cross section $\sigma_{exp} = 60$ nb from [16]. The coherent sum of all terms is shown by the black solid line. Right panel: The distribution in rapidity difference between kaons for the $pp \rightarrow pp(\phi \rightarrow K^+K^-)$ reaction for the ATLAS-ALFA kinematics.

In the right panel of figure 2 we show the results for the $pp \rightarrow pp(\phi \rightarrow K^+K^-)$ reaction for experimental conditions relevant for ATLAS-ALFA or CMS-TOTEM. The $O\cdot\mathcal{P}$ contribution dominates at larger $p_{t,K^+K^-}$ (or transverse momentum of the $K^+K^-$ pair) and $|y_{diff}|$ compared to the $\gamma\cdot\mathcal{P}$ contribution. For the ATLAS-ALFA kinematics the absorption effects lead to a large damping of the cross sections for both the mechanisms; see Table II of [8].

Now we discuss the $pp \rightarrow pp\mu^+\mu^-$ reaction at forward rapidities and without measurement of protons relevant for LHCb. Figure 3 shows the distribution in transverse momentum of the $\mu^+\mu^-$ pair. We can see that the low-$p_{t,\mu^+\mu^-}$ cut can be helpful to reduce the dimuon-continuum and $\gamma\cdot\mathcal{P}$-fusion contributions. In the right panel we show the $y_{diff}$ (rapidity difference between muons) distribution when imposing in addition a cut $p_{t,\mu^+\mu^-} > 0.8$ GeV. The $\gamma\gamma \rightarrow \mu^+\mu^-$ continuum contribution is now very small. At $y_{diff} = 0$ the $O\cdot\mathcal{P}$ term should win with the $\gamma\cdot\mathcal{P}$ term. In contrast to dikaon CEP here there is for both contributions a maximum at $y_{diff} = 0$.

Now we go to the $pp \rightarrow pp\phi\phi$ reaction. Figure 4 shows the results including the $f_2(2340)$ term and the continuum processes due to reggeized-$\phi$ and odderon exchanges. For the details how to calculate these processes see [14]. Inclusion of the odderon exchange improves the description...
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Figure 3: The distributions in transverse momentum of the $\mu^+\mu^-$ pair (left) and in rapidity difference between muons (right) for the $pp \rightarrow ppm^+\mu^-$ reaction for $\sqrt{s} = 13$ TeV and $M_{\mu^+\mu^-} \in (1.01, 1.03)$ GeV. Results for the $\gamma$-P and $O$-P fusion terms, the continuum term as well as their coherent sum are shown.

of the WA102 data [17] for the $pp \rightarrow pp\phi\phi$ reaction; see the left panel of figure 4. Here we showed results for the odderon-exchange contribution with the parameters of our model fixed to the WA102 data [16] on single CEP of $\phi$; see section IV A of [8]. In the right panel we show the distribution in four-kaon invariant mass for the LHCb experimental conditions. The small intercept of the $\phi$-reggeon exchange, $\alpha_{\phi}(0) = 0.1$ makes the $\phi$-exchange contribution steeply falling with increasing $M_{4K}$. Therefore, an odderon with an intercept $\alpha_{O}(0)$ around 1.0 should be clearly visible in the region of large $M_{4K}$ (and also for large rapidity distance between the $\phi$ mesons).

Figure 4: The distributions in $\phi\phi$ invariant mass (left) for $\sqrt{s} = 29.1$ GeV together with the WA102 data from [17] and (right) in $M_{4K}$ for the LHCb kinematics. The short-dashed line corresponds to the reggeized-$\phi$-exchange contribution, the dotted line corresponds to the $f_2(2340)$ contribution, the red long-dashed line represents the $O$-exchange contribution. The coherent sum of all terms is shown by the black solid line.
4. Conclusions

We have discussed in detail the $pp \rightarrow pp\phi$ and $pp \rightarrow pp\phi\phi$ reactions. For single $\phi$ CEP at the LHC there are two basic processes: the relatively well known $\gamma\text{-}P$ fusion and the rather elusive $O\text{-}P$ fusion. We fixed the parameters of the pomeron-odderon contribution to obtain a good description of the WA102 data \cite{16, 17}. Then we have estimated the integrated cross sections and several differential distributions at the LHC; see Table II of \cite{8}. It is a main result of our analysis that, the $y_{\text{diff}}$ distributions are very different for the $\gamma\text{-}P$- and $O\text{-}P$-fusion processes. The $\mu^+\mu^-$ channel seems to be less promising in identifying the odderon exchange at least when only the $p_t,\mu^+\mu^-$ cuts are imposed. To observe a sizeable deviation from photoproduction a $p_t,\mu^+\mu^+ > 0.8$ GeV cut on the transverse momentum of the $\mu^+\mu^-$ pair seems necessary. A combined analysis of both the $K^+K^-$ and the $\mu^+\mu^-$ channels should be the ultimate goal in searches for odderon exchange.

The $pp \rightarrow pp\phi\phi$ process via odderon exchange [figure 1(b)] seems promising as here the odderon does not couple to protons. We find from our model that the odderon-exchange contribution should be distinguishable from other contributions for relatively large four-kaon invariant masses (outside of the region of resonances) and for large rapidity distance between the $\phi$ mesons. Hence, to study this type of mechanism one should investigate “three-gap events” (proton–gap–$\phi$–gap–$\phi$–proton). Experimentally, this should be a clear signature.

We are looking forward to first experimental results on single and double $\phi$ CEP at the LHC.

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References