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

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Abstract

We discuss the possibility to use the $\mathbf{pp \to pp\phi\phi}$ process in identifying the odderon exchange. So far there is no unambiguous experimental evidence for the odderon, the charge conjugation $\mathbf{C = -1}$ counterpart of the $\mathbf{C = +1}$ pomeron, introduced on theoretical grounds in [1]. 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 [2]. Here we present recent studies for central exclusive production (CEP) of $\phi\phi$ pairs in proton-proton collisions [3].
We consider the pomeron-pomeron fusion to $\phi\phi$ ($\mathbb{PP} \to \phi\phi$) through the continuum processes, due to the $\hat{\mathbf{t}}$- and $\hat{\mathbf{u}}$-channel reggeized ϕ-meson, photon, and odderon exchanges, as well as through the $\mathbf{s}$-channel resonance process ($\mathbb{PP} \to \mathbf{f_2(2340)} \to \phi\phi$). This $\mathbf{f_2}$ state is a candidate for a tensor glueball. The amplitudes for the processes are formulated within the tensor-pomeron and vector-odderon approach [4]. Some model parameters are determined from the comparison to the WA102 experimental data [6]. The odderon exchange is not excluded by the WA102 data for high $\phi\phi$ invariant masses. The process is advantageous as here the odderon does not couple to protons. The observation of large $\mathbf{M_{\phi\phi}}$ and the rapidity difference $|\mathbf{Y_{diff}}|$ seems well suited to identify odderon exchange.

Formalism

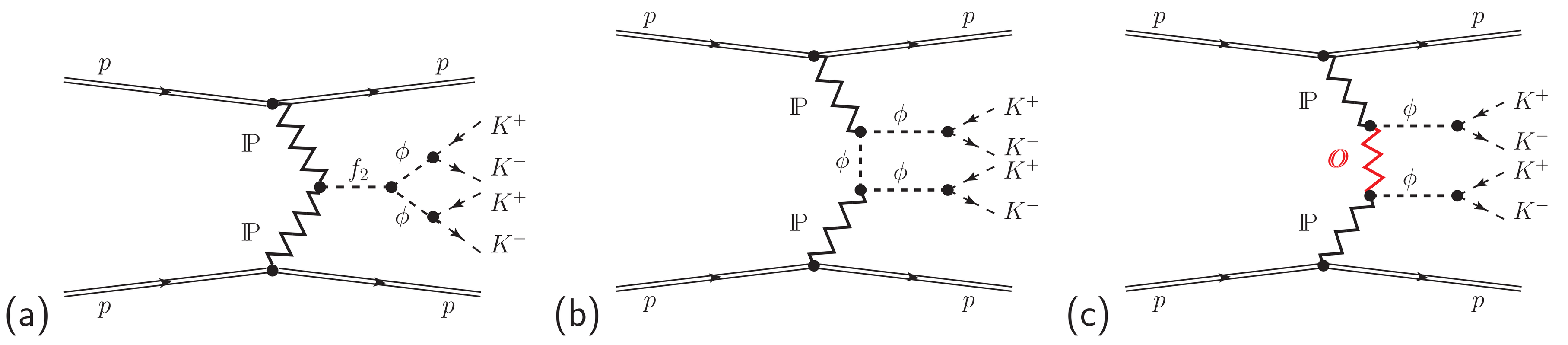

Fig.1 "Born-level" diagrams for double pomeron central exclusive $\phi\phi$ production and their decays into $K^+K^-K^+K^-$: (a) $\phi\phi$ production via an f_2 resonance. Other resonances, e.g. of f_0- and η-type, can also contribute here. (b) and (c) continuum $\phi\phi$ production via an intermediate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

The "Born-level" amplitude for the $\mathbf{pp \to pp\phi\phi}$ reaction is

$$\mathcal{M}^{\rm Born} = \mathcal{M}^{(f_2-\rm exchange)} + \mathcal{M}^{(\phi-\rm exchange)} + \mathcal{M}^{(\mathbb{O}-\rm exchange)}\,.$$

The full amplitude includes the $\mathbf{pp}$-rescattering corrections (absorption effects)

$$\mathcal{M}_{pp\to pp\phi\phi} = \mathcal{M}^{\rm Born} + \mathcal{M}^{\rm absorption}\,,$$
$$\mathcal{M}^{\rm absorption}(s,p_{1t},p_{2t}) = \frac{i}{8\pi^2 s}\int d^2k_t\, \mathcal{M}^{\rm Born}(s,\tilde{p}_{1t},\tilde{p}_{2t})\, \mathcal{M}^{(\mathbb{P}-\rm exchange)}_{pp\to pp}(s,-k_t^2)\,,$$

where $\tilde{p}_{1t} = p_{1t} - k_t$ and $\tilde{p}_{2t} = p_{2t} + k_t$. $\mathcal{M}^{(\mathbb{P}-\rm exchange)}_{pp\to pp}$ is the elastic $\mathbf{pp}$-scattering amplitude with the momentum transfer $t = -k_t^2$.
For continuum process with the odderon exchange [diagram (c)] the amplitude is a sum of $\hat{\mathbf{t}}$- and $\hat{\mathbf{u}}$-channel amplitudes. The $\hat{\mathbf{t}}$-channel term can be written as

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

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 [4]:

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

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., [5]): $\alpha_{\mathbb{P}}(t) = \alpha_{\mathbb{P}}(0) + \alpha'_{\mathbb{P}}\,t$, $\alpha_{\mathbb{P}}(0) = 1.0808$, $\alpha'_{\mathbb{P}} = 0.25\ \mathrm{GeV}^{-2}$.
Our ansatz for the effective propagator of the $\mathbf{C = -1}$ odderon is [4]

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

Here $\alpha_{\mathbb{O}}(t) = \alpha_{\mathbb{O}}(0) + \alpha'_{\mathbb{O}}\,t$ and we choose, as an example, $\alpha'_{\mathbb{O}} = 0.25$ 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 [3]:

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

We take the factorized form for the $\mathbb{P}\mathbb{O}\phi$ form factor:

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

where we adopt the monopole form $F(k^2) = (1 - k^2/\Lambda^2)^{-1}$ 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 exp. data.
At low $\sqrt{s_{34}} = M_{\phi\phi}$ 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:
$F_{\rm thr}(s_{34}) = 1 - \exp[(s_{\rm thr} - s_{34})/s_{\rm thr})]$ with $s_{\rm thr} = 4m_\phi^2$.

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:

$$i\Gamma^{(\mathbb{P}\mathbb{O}\phi)}_{\mu\nu\kappa\lambda}(k',k) \to i\Gamma^{(\mathbb{P}\phi\phi)}_{\mu\nu\kappa\lambda}(k',k)\,, \qquad i\Delta^{(\mathbb{O})}_{\mu\nu}(s_{34},\hat{p}^2) \to i\Delta^{(\phi)}_{\mu\nu}(\hat{p})\,.$$

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 [7].
We should take into account the reggeization of the intermediate ϕ meson. We consider the two prescriptions of reggeization (only expected to hold in $|\hat{p}^2|/s_{34} \ll 1$ regime):

$$\Delta^{(\phi)}_{\mu\nu}(\hat{p}) \to \Delta^{(\phi)}_{\mu\nu}(\hat{p})\left(\exp(i\phi(s_{34}))\,\frac{s_{34}}{s_{\rm thr}}\right)^{\alpha_\phi(\hat{p}^2)-1}\,,$$
$$\phi(s_{34}) = \frac{\pi}{2}\exp\left(\frac{s_{\rm thr} - s_{34}}{s_{\rm thr}}\right) - \frac{\pi}{2}\,, \quad s_{\rm thr} = 4m_\phi^2\,; \qquad \text{Eq. (3.21)}$$
$$\Delta^{(\phi)}_{\rho_1\rho_2}(\hat{p}) \to \Delta^{(\phi)}_{\rho_1\rho_2}(\hat{p})\,F(Y_{\rm diff}) + \Delta^{(\phi)}_{\rho_1\rho_2}(\hat{p})\,\left[1 - F(Y_{\rm diff})\right]\left(\exp(i\phi(s_{34}))\,\frac{s_{34}}{s_{\rm thr}}\right)^{\alpha_\phi(\hat{p}^2)-1}\,,$$
$$F(Y_{\rm diff}) = \exp\left(-c_y|Y_{\rm diff}|\right)\,. \qquad \text{Eq. (3.25)}$$

We take (from Collins [5]): $\alpha_\phi(\hat{p}^2) = \alpha_\phi(0) + \alpha'_\phi\,\hat{p}^2$, $\alpha_\phi(0) = 0.1$, and $\alpha'_\phi = 0.9\ \mathrm{GeV}^{-2}$.

Results

Comparison with the WA102 data

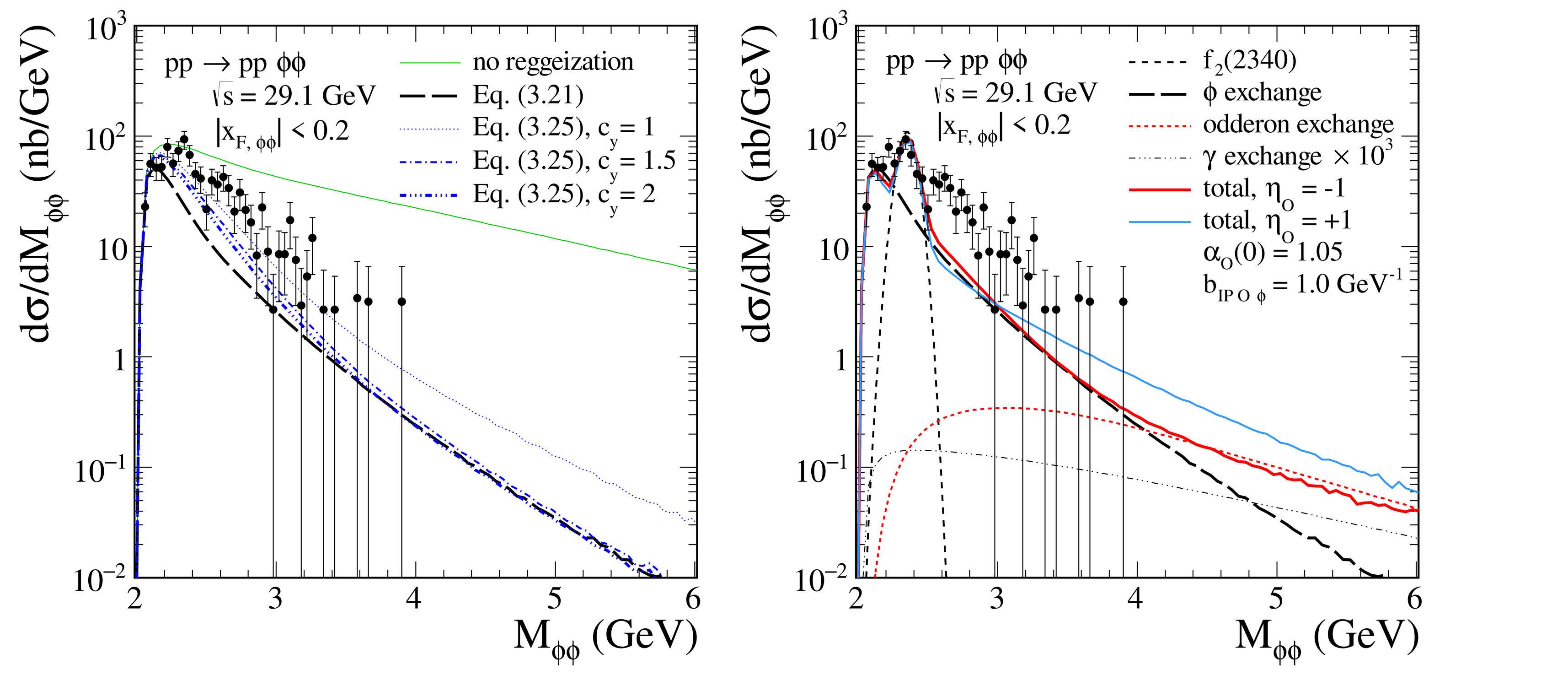

Fig.2 The distributions in $\phi\phi$ invariant mass. The calculations were done for $\sqrt{s} = 29.1$ GeV and $|x_{F,\phi\phi}| \leqslant 0.2$. The WA102 experimental data from [6] are shown. In the left panel, the green solid line corresponds to the non-reggeized ϕ-exchange contribution. The results for the two prescriptions of reggeization are shown by the black and blue lines. In the right panel we show the complete results including the $\mathbf{f_2(2340)}$-resonance contribution and the continuum processes due to reggeized-ϕ, odderon, and photon exchanges.

Predictions for the LHC experiments

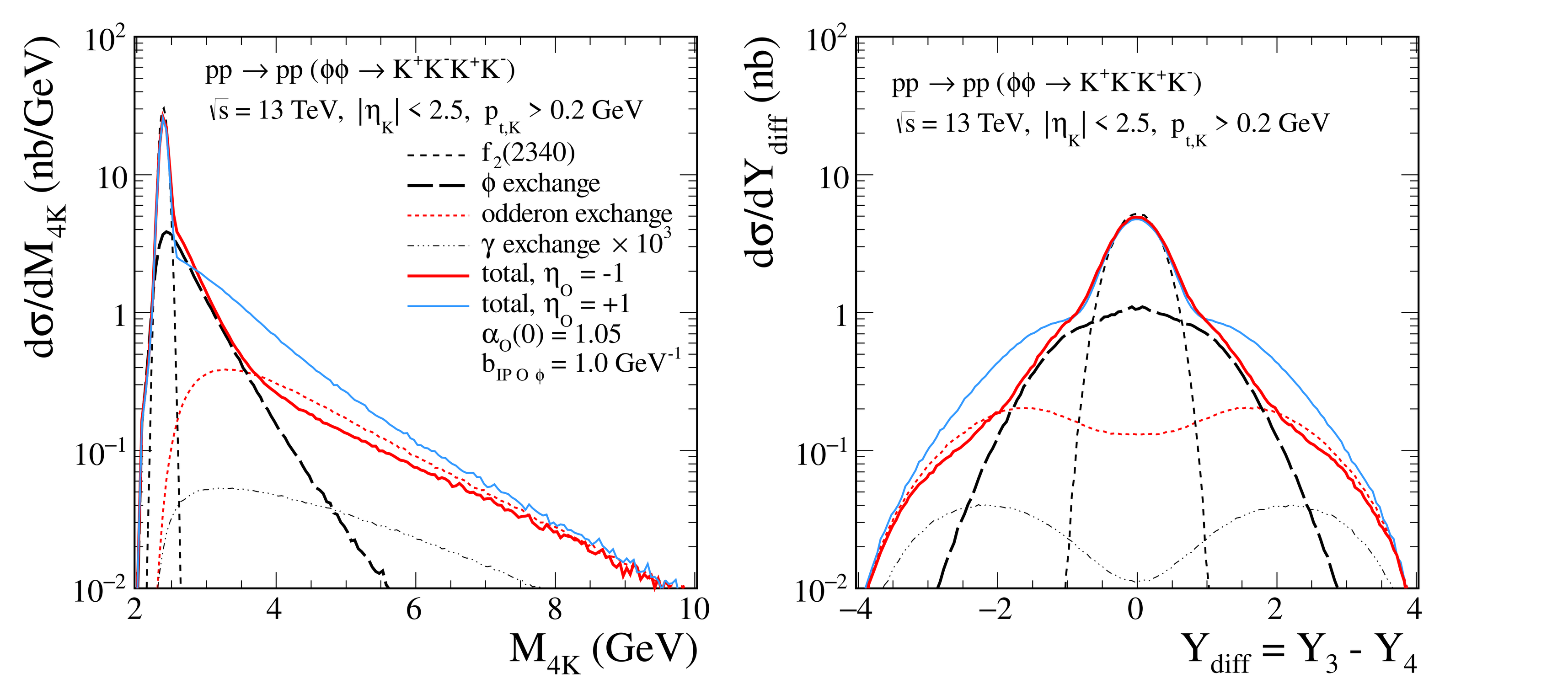

Fig.3 The distributions in $\mathbf{M_{4K}}$ (left) and in $\mathbf{Y_{diff}}$ (right) for the $\mathbf{pp \to pp(\phi\phi \to K^+K^-K^+K^-)}$ reaction calculated for $\sqrt{s} = 13$ TeV and $|\eta_K| < 2.5$, $p_{t,K} > 0.2$ GeV. The small intercept of the ϕ-reggeon exchange, $\alpha_\phi(0) = 0.1$ makes the ϕ-exchange contribution steeply falling with increasing $\mathbf{M_{4K}}$ and $|\mathbf{Y_{diff}}|$. Therefore, an odderon with an intercept $\alpha_{\mathbb{O}}(0)$ around 1.0 should be clearly visible in the region of large four-kaon invariant masses and for large rapidity distance between the ϕ mesons.

Conclusions

- CEP is particularly interesting class of processes which provides insight to unexplored soft QCD phenomena. The fully differential studies of exclusive $\mathbf{pp \to pp\phi\phi}$ reaction within the tensor-pomeron and vector-odderon approach was executed; for more details see [3].
- 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 $\mathbf{f_2(2340)} \to \phi\phi$ coupling, not known at present. Here we used only one type of $\mathbb{PP}\mathbf{f_2}$ coupling (out of 7 possible; see [8]). We have checked that for the distributions studied here the choice of $\mathbb{PP}\mathbf{f_2}$ coupling is not important. This is a different situation compared to the one observed by us for the $\mathbf{pp \to pp(\mathbb{PP} \to f_2(1270) \to \pi^+\pi^-)}$ reaction in [8].
- 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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