Looking for the Odderon in Photon Collisions

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We discuss the production of two pion pairs in photon collisions at high energies. We calculate the according matrix elements in k_T-factorization and discuss the possibility to reveal the existence of the perturbative Odderon by charge asymmetries.

1 Introduction

At high energies amplitudes of reactions with rapidity gaps in hadronic interactions are dominated by the exchange of a color singlet, C-even state – called the Pomeron. In the language of perturbative QCD – at lowest order – the Pomeron can be described as the exchange of two gluons in the color singlet state. In contrast to the very well settled notion of the Pomeron, the status of its C-odd partner – the Odderon – is less safe. Although it is needed *e.g.* to describe properly the different behaviors of pp and $\bar{p}p$ elastic cross sections [1], it still evades confirmation in the perturbative regime, where – again at lowest order – it can be described by the exchange of three gluons in the color singlet state.

The main reason lies in its smaller exchange amplitude in comparison to the Pomeron exchange such that in the cross section, obtained after squaring the sum of both amplitudes, the Pomeron amplitude squared dominates. In this contribution we present results of our study [2] of a charge asymmetry in the production of two pion pairs in photon-photon collisions where that Pomeron squared part vanishes. This observable is thus linearly sensitive to the Odderon contribution.

In the present analysis we deal with the hard Pomeron and the hard Odderon exchanges, *i.e.* both treated within perturbative QCD. This approach can be confronted with a description of the Pomeron-Odderon interference based on soft, non-perturbative physics and developed in Refs. [3]. The experimental observation of the P-O interference effects will thus shed a light on the important question which of the above mechanisms is more appropriate for the description of data.

2 Kinematics, amplitudes and GDAs

Figure 1 shows a sample diagram of the process under consideration. We consider large $\gamma\gamma$ energies such that the amplitude can be expressed in terms of two impact factors convoluted over the transverse momenta of the exchanged gluons. The impact factors are universal and consist of a perturbative part – describing the transition of a photon into a quark-antiquark
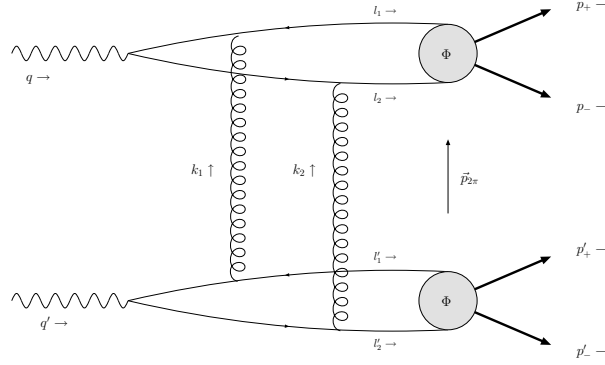
Figure 1: Kinematics of the reaction $\gamma\gamma \to \pi^+\pi^-\ \pi^+\pi^-$ in a sample Feynman diagram of the two gluon exchange process.

pair – and a non-perturbative part, the two pion generalized distribution amplitude (GDA) parametrizing the quark-antiquark hadronization into the the pion pair [4, 5]. This comes as a variant of the approach which has been previously proposed in the case of the electroproduction of a pion pair [6, 7, 8], and which is based on the fact that the $\pi^+\pi^-$-state does not have any definite charge parity. These GDAs which are functions of the longitudinal momentum fraction z of the quark, of the angle θ (in the rest frame of the pion pair) and of the invariant mass $m_{2\pi}$ of the pion pair are the only but nevertheless essential phenomenological inputs. In principle, they have to be extracted from experiments but this is a very challenging task and has not been done so far. However, after an expansion in Gegenbauer polynomials $C_n^m(2z-1)$ and in Legendre polynomials $P_l(\beta\cos\theta)$ (where $\beta = \sqrt{1 - 4m_\pi^2/m_{2\pi}^2}$) [4], it is believed that only the first terms give a significant contribution:

$$
\begin{aligned}
\Phi^{I=1}(z,\theta,m_{2\pi}) &= 6z\bar{z}\beta f_1(m_{2\pi})\cos\theta, \\
\Phi^{I=0}(z,\theta,m_{2\pi}) &= 5z\bar{z}(z-\bar{z})\left[-\frac{3-\beta^2}{2}f_0(m_{2\pi}) + \beta^2 f_2(m_{2\pi})P_2(\cos\theta)\right],
\end{aligned}
$$

where $f_1(m_{2\pi})$ can be identified with the electromagnetic pion form factor $F_\pi(m_{2\pi})$. For the $I = 0$ component we use different models. The first model follows Ref. [6] and expresses the functions $f_{0/2}$ in terms of the Breit-Wigner amplitudes of the according resonances. A second model has been elaborated in Ref. [8] and interprets the functions $f_{0/2}$ as corresponding Omnès functions for $S-$ and $D-$waves constructed by dispersion relations from the phase shifts of the elastic pion scattering. It has been argued [8, 9] that the actual phases of the GDA might be closer to the phases $\delta_{T,l}$ of the corresponding T matrix elements $\frac{\eta_l e^{2i\delta_l}-1}{2i}$, where η_l is the inelasticity factor. The third model for the $I = 0$ component of the GDA takes this into account by using the technique of model 2 with these phases $\delta_{T,l}$ of the T matrix elements. Indeed, measurements at HERMES [10] do not observe a resonance effect at the f_0-mass, but concerning the f_2 both phases (δ_2 and $\delta_{T,2}$) are compatible with data [8]. Having this in mind, we consider also a fourth model – a mixed description with the f_0 contribution from model 3 and the f_2 contribution from model 2.

Recently the BaBar experiment reported a new measurement of the reaction $\gamma^\star\gamma \to \pi^0$ up to photon virtualities squared of 40 GeV^2 [11]. In the latter study, the reaction $\gamma^\star\gamma \to \pi^0\pi^0$
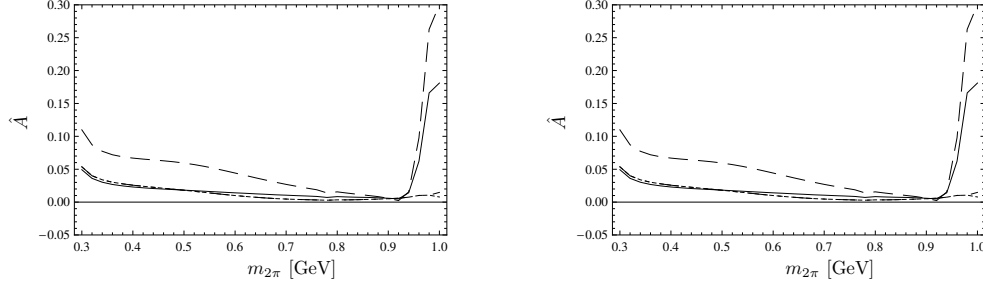
Figure 2: Asymmetry $\hat{A}$ at $t = -1\,\text{GeV}^2$ for model 1 (solid), 2 (dashed), 3 (dotted), and 4 (dash-dotted) – model 3 and 4 are nearly on top of each other. Left column has $m_{\text{min}} = .3\,\text{GeV}$ and $m_{\text{max}} = m_\rho$, while right column has $m_{\text{min}} = m_\rho$ and $m_{\text{max}} = 1\,\text{GeV}$.

was investigated in the $f_0(980)$ and $f_2(1270)$resonance regions as a potential background for the study of the π^0 transition form factor. This low-W^2 kinematical region should soon be analysed in the framework of generalised two-meson distribution amplitudes [12]. This will settle the question of the adequate model to be used.

3   Charge asymmetries and rates

The key to obtain an observable which linearly depends on the Odderon amplitude is the orthogonality of the C-even GDA (entering the Odderon process) and the C-odd one (entering the Pomeron process) in the space of Legendre polynomials in $\cos\theta$. Due to an additional multiplication by $\cos\theta$ before the angular integration only the interference term survives. We have to do this for both the pion pairs. Moreover we integrate over the invariant mass of one of the pion pairs to reduce the complexity of our observable. Finally, we define the charge asymmetry in the following way:

$$\hat{A}(t, m_{2\pi}^2; m_{\text{min}}^2, m_{\text{max}}^2) = \frac{\int_{m_{\text{min}}^2}^{m_{\text{max}}^2} dm_{2\pi}'^2 \int \cos\theta \, \cos\theta' \, d\sigma(t, m_{2\pi}^2, m_{2\pi}'^2, \theta, \theta')}{\int_{m_{\text{min}}^2}^{m_{\text{max}}^2} dm_{2\pi}'^2 \int \, d\sigma(t, m_{2\pi}^2, m_{2\pi}'^2, \theta, \theta')}$$

$$= \frac{\int_{m_{\text{min}}^2}^{m_{\text{max}}^2} dm_{2\pi}'^2 \int_{-1}^1 d\cos\theta \int_{-1}^1 d\cos\theta' \, 2\cos\theta \, \cos\theta' \, \text{Re}\left[\mathcal{M}_{\mathbb{P}}(\mathcal{M}_{\mathbb{O}} + \mathcal{M}_\gamma)^*\right]}{\int_{m_{\text{min}}^2}^{m_{\text{max}}^2} dm_{2\pi}'^2 \int_{-1}^1 d\cos\theta \int_{-1}^1 d\cos\theta' \left[|\mathcal{M}_{\mathbb{P}}|^2 + |\mathcal{M}_{\mathbb{O}} + \mathcal{M}_\gamma|^2\right]}.$$

An analytic calculation of the Odderon matrix element would demand the notion of analytic results for two-loop box diagrams, whose off-shellness for all external legs is different. With the techniques currently available such a calculation is not straightforward and we choose to rely on a numerical evaluation by Monte Carlo methods. In particular we make use of a modified version of VEGAS as it is provided by the CUBA library [13]. The result for $\hat{A}$ is shown in Fig. 2 where we took two different choices for the integrated region of the invariant mass of the two pions system. Since our framework is only justified for $m_{2\pi}^2 < -t$, (in fact strictly speaking, one even needs $m_{2\pi}^2 \ll -t$), we keep $m_{2\pi}$ below $1\,\text{GeV}$.

To answer the question whether it is possible to measure this asymmetry, we adress the two main issues here. First, one has to convolute the $\gamma\gamma$ cross section obtained by our calculations
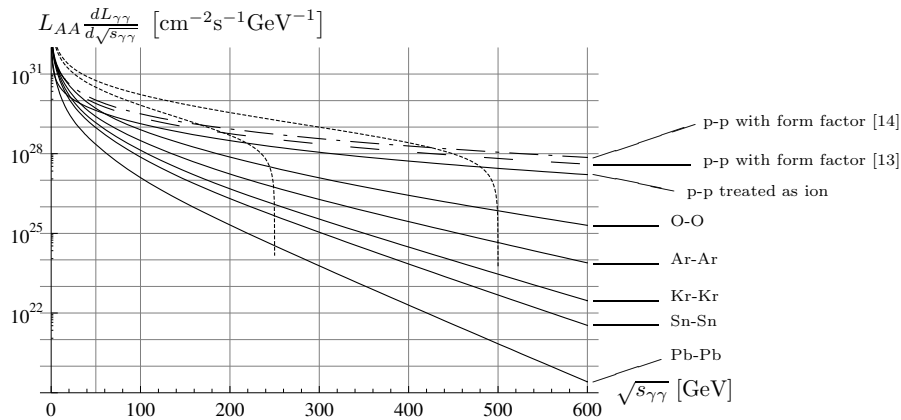
Figure 3: Effective $\gamma\gamma$ luminosities for the collision of p-p based on Ref. [15] (dash-dotted) and Ref. [16] (dashed). The results using the parametrization of Ref. [17] for ions are given by solid lines for p-p, O_{16}^8-O_{16}^8, Ar_{40}^{18}-Ar_{40}^{18}, Kr_{84}^{36}-Kr_{84}^{36}, Sn_{120}^{50}-Sn_{120}^{50}, Pb_{208}^{82}-Pb_{208}^{82} from top to bottom. For ions we used the average luminosities as given in Ref. [18], for proton we used $L_{pp} = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$. For comparison also effective $\gamma\gamma$ luminosities at the ILC are given for $\sqrt{s_{e^+e^-}} = 250\,\mathrm{GeV}$ and $\sqrt{s_{e^+e^-}} = 500\,\mathrm{GeV}$ (both as dotted lines).

with the effective photon flux at a certain collider. As we discuss in Ref. [2] in detail, the most recent review on this topic [14] presents an overview of photon fluxes for different colliding hadrons which is flawed by an inconsistency in the underlying hadron-hadron luminosities. Therefore, we show a consistent comparison for the design luminosities of different colliding particles in Fig. 3. For the proton case we display the different luminosities based on either the proton form factor [15, 16] or on the asymptotic formula for large nuclei.

Although photon fluxes are important in p-p collisions at the designed LHC luminosity ($10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$), data collected under these conditions will suffer from the pile up of events, which will prevent an analysis of the process considered here from being performed. At lower luminosity, rates may be marginally sufficient for values of $-t \approx 1\mathrm{GeV}^2$, but designing a trigger strategy to record interesting events seems very difficult: typical triggers on high p_t mesons demand a minimum p_T of a few GeV, which is incompatible with such low values of $-t$ and the corresponding limit of $m_{2\pi} < \sqrt{-t}$. Moreover, an important issue is the background in case of hadron colliders. In contrast to electromagnetic processes which have been proposed to be studied in ultraperipheral collisions, pions are produced by pure QCD processes as well. It is not easy to demonstrate quantitatively that one can separate these two processes by relying on the fact that ultraperipheral processes are strongly peaked at low t, contrarily to the flatter depence of the Pomeron induced ones [19].

In nucleus-nucleus collisions, the trigger problem is easily solved by detecting neutrons from giant dipole resonances in the Zero Degree Calorimeters, but the rates are much lower, especially for the heavier ions. The best compromise may be Oxygen-Oxygen collisions, which is by no means the priority of the heavy ion physics community.

In contrast, an electron-positron collider such as the projected ILC would be the ideal environment to study the process under consideration. Photon photon collisions are indeed the

dominant processes there and no pile up phenomenon can blur the picture of a scattering event. Studies of similar exclusive processes like diffractive double J/ψ [20] or double ρ production [21] show that high rates are expected. Maybe an alternative, which we did not study, is a large energy electron ion collider in its ultraperipheral mode.

In conclusion, our proposal to discover the perturbative Odderon through asymmetries in the production of two pion pairs in ultraperipheral collisions at the LHC seems to have a hard time to win over quite severe experimental constraints. Will the perturbative Odderon continue to escape detection for the next 10 years?

Acknowledgements

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