Searching for the Odderon at HERA and the LHC

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Abstract
We review the present status of the odderon, focusing in particular on searches at HERA and the prospects for finding the odderon in exclusive processes at the LHC.

1 The odderon

The odderon is the negative charge parity ($C=-1$) partner of the well-known pomeron. Therefore, it is the t-channel exchange that gives rise to the difference between a particle-particle scattering cross section and the corresponding particle-antiparticle cross section at high center-of-mass energy $\sqrt{s}$. The concept of the odderon was introduced and its existence conjectured in [1] in the context of Regge theory. It was subsequently realized that in QCD a colorless exchange in the t-channel with negative C-parity can be constructed from three gluons in a symmetric color state. In recent years considerable progress in understanding the odderon has been made in particular in perturbative QCD. The nonperturbative odderon, on the other hand, remains poorly understood.

In perturbative QCD the odderon is described by the Bartels-Kwieciński-Praszałowicz (BKP) equation [2] which resums the leading logarithms of $\sqrt{s}$, corresponding to the pairwise interaction of the three gluons exchanged in the t-channel. One finds that also compound states of more than three gluons with odderon quantum numbers can be constructed, which are also described by the BKP equation. The BKP equation exhibits interesting mathematical properties like conformal invariance in impact parameter space and holomorphic separability [3], and even turns out to be an integrable system [4]. Two explicit solutions to the BKP equation have been found, one with intercept $\alpha_{\mathbb{O}}=1$ [5] and one with a slightly smaller intercept [6], giving rise to a high-energy behavior of the cross section $\sim s^{\alpha_{\mathbb{O}}-1}$. The main difference of the two solutions lies in their different coupling to external particles rather than in their intercepts which for all practical purposes can be considered equal.

While the perturbative odderon is at least theoretically rather well understood, our picture of the odderon in the nonperturbative regime is not at all satisfying. The main reason is the lack of experimental data which does not even allow us to test models of nonperturbative odderon exchange. This is in strong contrast to the nonperturbative pomeron which is theoretically equally hard to describe, but for the pomeron a rather clear picture has emerged at least on the phenomenological level from the study of a variety of high energy scattering data.

In the following we discuss some aspects of the odderon which are particularly relevant for HERA and LHC. A detailed review of the odderon and further references can be found in [7].

2 Experimental evidence

It would seem natural to expect that odderon exchange is suppressed relative to pomeron (two-gluon) exchange only by a power of α_s due to the requirement to couple an additional gluon to the external particles. And at moderately low momenta α_s is not too small, such that – given the ubiquitous pomeron – one expects odderon exchange to appear in many processes. Surprisingly, the contrary is true.

So far the only experimental evidence for the odderon has been found in a small difference in the differential cross sections for elastic proton-proton and proton-antiproton scattering at $\sqrt{s} = 53\,\text{GeV}$. Figure 1 shows the data taken at the CERN ISR in the dip region around $t = -1.3\,\text{GeV}^2$. The proton-proton data have a dip-like structure, while the proton-antiproton data

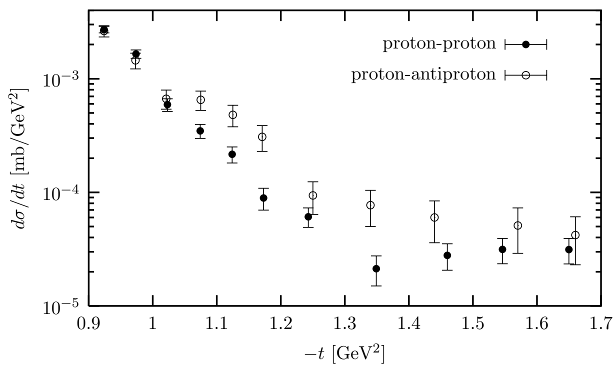

Fig. 1: Differential cross section for elastic pp and $p\bar{p}$ scattering in the dip region for $\sqrt{s} = 53\,\text{GeV}$; data from [8]

only level off at the same $|t|$. This difference between the two data sets can only be explained by invoking an odderon exchange. However, the difference relies on just a few data points with comparatively large error bars.

The data at various energies are well described by models that take into account the various relevant exchanges between the elastically scattering particles [9], [10]. Both of these models involve of the order of twenty parameters that need to be fitted. The structure in the region around $|t| = 1 - 2\,\text{GeV}^2$ is the result of a delicate interference between different contributions to the scattering amplitude including the odderon. Therefore it is rather difficult to extract the odderon contribution unambiguously. In fact it turns out that the two odderon contributions obtained in [9] and [10], respectively, are not fully compatible with each other [11] (see also [7]). In [12] it was shown that assuming a perturbative odderon (three gluon exchange) in the context of the model of [9] requires to choose a very small coupling of the odderon to the proton. This small coupling can be either due to a small relevant value of $\alpha_s \simeq 0.3$ or due to a small average distance of two of the constituent quarks in the proton corresponding to a diquark-like structure.

Unfortunately, $\sqrt{s} = 53\,\text{GeV}$ is the only energy for which data for both reactions are available. The comparison of data taken at different energies rather strongly relies on theoretical models. Given the large number of parameters in these models it is not possible to arrive at firm conclusions about the odderon on the basis of the presently available data.

3 Odderon searches at HERA

The cross section for elastic pp and $p\bar{p}$ scattering is a typical example in which the odderon exchange is only one of many contributions to the scattering amplitude. It was recently realized that the chances for a clean identification of the odderon should be better in exclusive processes in which the odderon is the only exchange (usually besides the well-understood photon) that can give rise to the final state to be studied. This strategy was chosen at HERA.

Searches for the odderon at HERA have concentrated on the exclusive diffractive production of pseudoscalar mesons ($M_{\rm PS}$) as depicted in Figure 2. In addition to that diagram only the exchange of a photon instead of the odderon is possible at high energies. (Similarly also tensor mesons can be produced only by odderon and photon exchange.) This process had been suggested in [13]. The photon exchange contribution is rather well understood and is expected

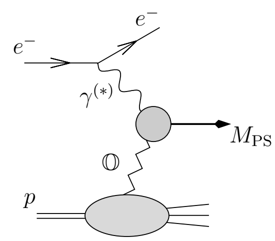

Fig. 2: Diffractive production of a pseudoscalar meson in ep scattering

to have a much steeper t-dependence than the odderon exchange.

The process which has been studied in most detail experimentally is the exclusive diffractive production of a single neutral pion, $\gamma^{(*)}p \to \pi^0 X$. Early theoretical considerations [14] had led to an estimate of the total photoproduction cross section for that process of $\sigma(\gamma p \to \pi^0 X) \simeq 300\,$nb, with a possible uncertainty of a factor of about two. The experimental search for that process, however, was not successful and resulted in an upper limit of $\sigma(\gamma p \to \pi^0 X) < 49\,$nb [15], obviously ruling out the prediction of [14]. The smallness of the cross section is a striking result since of all processes at HERA in which hadrons are diffractively produced this is the one with the largest phase space. Therefore a strong suppression mechanism must be at work here. One possibility is again a potentially small coupling of the odderon to the proton. Further possible causes for the failure of the prediction of [14] were discussed in [16]. The most important among them is probably the suppression of pion production due to approximate chiral symmetry, as has been discussed in detail in [17]. In fact it turns out that the odderon contribution to the amplitude for diffractive single-pion production vanishes exactly in the chiral limit. This suppression had not been taken into account properly in [14].

Also searches for similar processes in which instead of the pion some other pseudoscalar or tensor meson is produced diffractively have been performed, although only on a preliminary basis [18]. Again, no evidence for the odderon was found. However, for these processes the experimental bounds are closer to the theoretical estimates of [14], and hence the situation is less clear.

4 Prospects for the LHC

At the LHC one can in analogy to the ISR try to look for the odderon in elastic pp scattering. The measured differential cross section can be compared to models which are fitted to the differential cross section at lower energies and extrapolated to LHC energies, see for example [19]. Although these models involve a large number of fit parameters and some uncertainty in the extrapolation to a new energy range it is argued in [19] that there is a chance to see evidence of the odderon. Also the spin dependence of elastic scattering is sensitive to the odderon and can be used to search for it, see [20]. In both cases the odderon is again one of several contributions to the scattering amplitude, which makes an unambiguous identification unlikely.

Recent proposals for odderon searches at the LHC (and analogously at the Tevatron) have therefore again focussed on exclusive processes in which the odderon is (except for the photon) the only contribution to the cross section. Here the mere observation of the process can already be sufficient to confirm odderon exchange. The most prominent of these exclusive processes at LHC is the double-diffractive production of a vector meson M_V in pomeron-odderon fusion, that is $p + p \to X + M_V + Y$ with the vector meson separated from the forward hadronic systems X and Y by rapidity gaps, see Figure 3. This process was first proposed and discussed in the

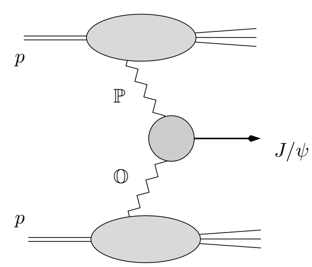

Fig. 3: Pomeron-odderon fusion mechanism for double-diffractive J/ψ production in $p\bar{p}$ scattering

framework of Regge theory in [21]. In particular heavy vector mesons, $M_V = J/\psi, \Upsilon$, are well suited for odderon searches since here the reggeon exchange contribution (in place of the odderon) is suppressed by Zweig's rule. (In the production of ϕ mesons that contribution could still be relevant – especially if the odderon contribution is small.) At the LHC in particular the ALICE detector appears to be best suited for the observation of centrally produced J/ψ or Υ mesons and can in addition identify rapidity gap events [22].

In [23] a detailed study of this process has been performed in perturbation theory. The leading perturbative diagram contains the fusion of two of the three gluons in the odderon with one from the two in the pomeron to the J/ψ or Υ, and an additional ('spectator') gluon exchange between the two protons. There are two important uncertainties in the calculation of this process. One is again the coupling of the odderon to the proton which might be small. The other main uncertainty is the survival probability for the rapidity gaps in the final state. Presently, a full understanding of the gap survival is still lacking. In hadronic collisions the gap survival is very different from ep scattering, and extrapolations from Tevatron energies to the LHC energy contain a considerable uncertainty. Depending on the assumptions about these uncertainties the expected cross sections $d\sigma/dy|_{y=0}$ at mid-rapidity y for J/ψ production are between 0.3 and 4 nb at the LHC. For the Υ one expects 1.7 – 21 pb. One has to keep in mind that also photon instead of odderon exchange can give rise to the same final state. A possibility to separate the two contributions is to impose a cut on the squared transverse momentum p_T^2 of the vector meson. The photon dominates at small p_T^2 but then falls rapidly towards higher p_T^2. The odderon contribution does not fall so quickly and for the J/ψ dominates above $p_T^2 \simeq 0.3\,\mathrm{GeV}^2$.

It is possible that the negative result of all odderon searches to date is caused by a small coupling of the odderon to the proton. If that coupling is indeed so small also the process just described will not be observable at the LHC. A possibility to find the odderon nevertheless might then be to look for the production of two heavy vector mesons in triple-diffractive events, $p+p \to X + M_V + M_V + Y$ (with the $+$-signs indicating rapidity gaps), as suggested in [7]. This process is shown in Figure 4. For small odderon-proton coupling the right hand diagram can be neglected.

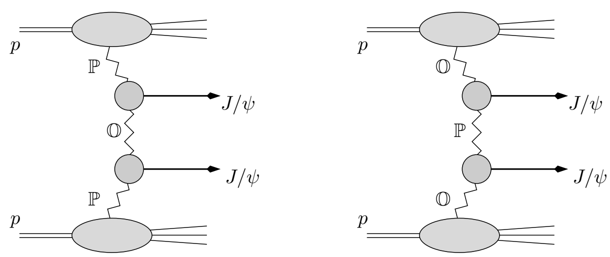

Fig. 4: Diagrams contributing to the triple-diffractive production of two J/ψ mesons in $p\bar{p}$ scattering

In the left hand diagram – which does not involve the $\mathbb{O}p$ coupling – the middle rapidity gap can only be produced by odderon (or photon) exchange and the mere observation of the process could finally establish the existence of the odderon.

5 Summary

The existence of the odderon is a firm prediction of perturbative QCD. But also in the nonperturbative regime we do not have good reasons to expect the absence of the odderon. A possible obstacle in finding it might be its potentially small coupling to the proton. As we have pointed out there are exclusive processes that can give a clear indication of the odderon at the LHC – including some which do not involve the potentially small odderon-proton coupling. If the odderon remains elusive also in these processes we might have to reconsider our picture of QCD at high energies.

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