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Theory of Vector Meson Production

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Abstract

I discuss the theoretical status of the 'soft' pomeron and its place in describing generic diffractive processes. The role of perturbative QCD (pQCD) corrections is considered, in particular in the context of quasi-elastic vector meson production at high Q^2. In those processes where short distances are dominant, the 'hard' (pQCD) pomeron is expected to reveal itself, such a process may well be that of diffractive vector meson production at high-t and I discuss this.

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1 Introduction

I will talk about the theoretical status of high energy diffractive/elastic physics. As my theme I will attempt to address the questions: "What 'tools' do we presently have?"and "How well do they/should they work?". But, I will not attempt to discuss the most important question: "How are they related?"! I start with a review of the 'soft' pomeron of Donnachie and Landshoff before moving to the role of perturbative QCD corrections in the context of quasi-elastic vector meson production in high-Q^2 ep collisions at $t = 0$ (when the proton usually remains intact). To conclude, I talk about a much rarer process which ought to shed light on the perturbative (or 'BFKL') pomeron, namely that of vector meson production at high t (where the proton will usually break up).

2 The 'Soft' Pomeron

Motivated largely by the success of the additive quark rule in describing the ratios of the total cross sections (of light hadrons) at high energies and the rising of the individual cross sections with increasing energy, Donnachie and Landshoff (DL) proposed the exchange of a single Regge pole which couples directly to on-shell valence quarks [1]. This simple proposition works exceedingly well for a wide range of circumstances: total cross sections, elastic scattering at low t and quasi-elastic vector meson production at high Q^2 (at least at EMC/NMC energies) are all successfully described by a pomeron pole of trajectory $\alpha_P(t) \simeq 1.08 + 0.25t$ [2]. We would like to understand this picture in terms of QCD, and progress in this direction has been made by Landshoff and Nachtmann (LN) [3] who proposed that the pomeron is simply the exchange of two non-perturbative gluons, see fig.1 (the blobs denote the non-perturbative gluons). The
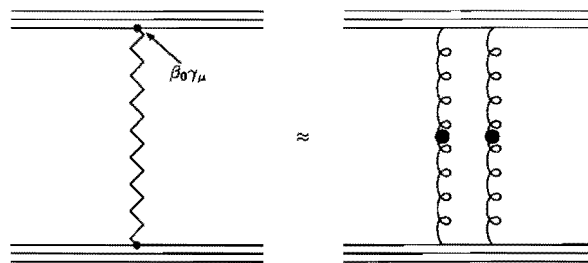

Figure 1

two-point Green function that defines the gluon propagator was shown to pick up a contribution

from non-perturbative physics which arises due to a non-zero vacuum expectation value of the gluon condensate, $\langle G_{\mu\nu}^a G_a^{\mu\nu} \rangle \sim M_c^4$. The new mass scale is related to the pomeron-quark coupling, β_0, via a correlation length, a, i.e. $\beta_0 \sim M_c^4 a^5$. QCD sum rules give M_c and the DL pomeron phenomenology fixes β_0. As a result, the correlation length is found to satisfy the inequality $a \ll R$, where R is a typical light-hadron radius. Interpreting a as the typical separation of the two non-perturbative gluons then we can appreciate that this inequality is responsible for guaranteeing the preservation of the additive quark rule. Unfortunately, the LN formalism is in an Abelian theory and rigorous contact with QCD still eludes us.

The arrival of HERA meant, for the first time, data which are not compatible with the DL picture. The steep rise of $F_2^p(x, Q^2)$ at small x [4] and the largeness of the high-Q^2 quasi-elastic ρ production cross section [5] along with a similar enhancement for the quasi-elastic photoproduction of J/Ψ's [6] are all evidence for physics beyond the DL pomeron. In particular they are evidence for significant perturbative corrections. Such corrections were not unexpected, since the presence of a hard scale opens up the phase space for perturbative corrections, e.g. $\sim \alpha_s \ln Q^2$. A very brief word on why the diffractive contribution to the inclusive DIS cross section appears not to rise as fast as one might naively expect (i.e. it appears more consistent with the 'soft' pomeron approach [7]) is perhaps in order. In fact, it is the only small x deep inelastic process seen at HERA which does not appear to contain very large perturbative corrections. The very asymmetric partition of the longitudinal momentum of the incoming photon between the quark and anti-quark to which it couples (in the proton rest frame) is responsible for selecting dominantly non-perturbative configurations and so we should not be surprised by these HERA data (see [8, 9] for more details).

3   QCD corrections

Since the perturbative calculation (of processes which involve hadrons in the initial state) usually introduces collinear divergences it follows that any sensible calculation must address the interface with non-perturbative physics. Fortunately, it is known that for inclusive cross sections these divergences can be factorised into some a priori unknown boundary condition [10]. Fig.2 illustrates how the perturbative corrections enter in a calculation of $F_2(x, Q^2)$.

What about the rapidly rising cross section for quasi-elastic vector meson production at high Q^2 which has been seen in the HERA data? In fig.3, the lowest order QCD contribution is
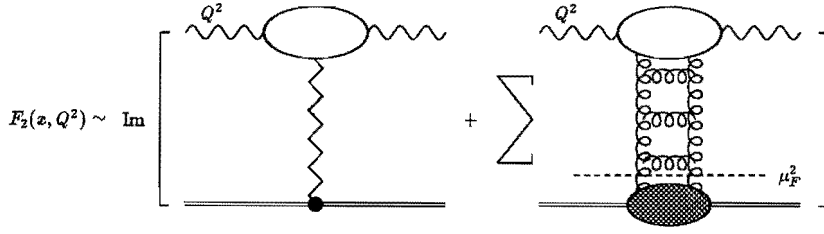
Figure 2

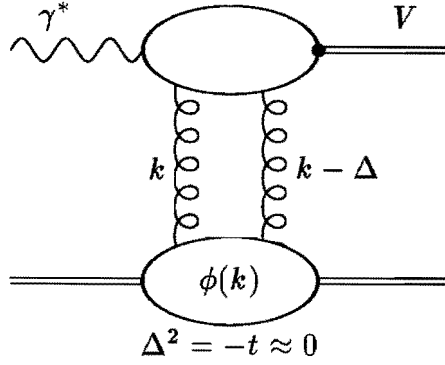shown. According to Ryskin [11], the amplitude for scattering longitudinal photons to produce

Figure 3

longitudinal mesons (it is the dominant contribution) can be written (for small enough t):

$$\frac{\mathrm{Im}\,A(s,t)}{s} \approx F(t)\alpha_s \left[\frac{\Gamma_{ee}^V m_V^3 \pi^3}{3\alpha_{\mathrm{em}}}\right]^{1/2} \frac{1}{Q^4} \frac{\sqrt{Q^2}}{m_V}$$
$$\times \int^{\sim Q^2} \frac{dk^2}{k^4} \phi(k^2). \tag{1}$$

Where $F(t)$ is a form factor associated with the elastic scattering of the proton (it is unity at $t = 0$). The collinear divergence of pQCD is present, since $\phi(k^2) \sim k^2 R^2$ at small k^2. It is of the same nature as the factorisable logarithmic divergence in F_2 and as such Ryskin replaces the integral over k^2 with the gluon parton density, $G(x, Q^2/4)$. By evaluating the gluon density at a scale $\sim Q^2$, the infinity of $\ln Q^2$ corrections to fig.3 are summed up. Consequently, the cross section can be written (for $Q^2 \gg m_V^2$):

$$\frac{d\sigma}{dt} \sim \frac{1}{Q^6}[G(x, Q^2/4)]^2. \tag{2}$$

Essentially the same result has been obtained by Brodksy et al [12] and Nikolaev et al [13]. Since the gluon density rises rapidly at small x, so the cross section for $\gamma^* p \to \rho p$ rises (but twice as fast) and we have an explanation of the HERA data. However, we should be careful

in taking this result too literally: there are huge theoretical uncertainties in the normalisation. These uncertainties arise since eq.(2) is derived in the double logarithmic approximation (i.e. only $\ln Q^2 \ln 1/x$ terms are summed up). This approximation is necessary in order to allow us to write the cross section simply as the square of the gluon density, evaluated at the double leading log scales, Q^2/W^2 and Q^2. For more discussion on the dangers associated with this expression see Peter Landshoff's talk [14].

4 The Hard 'Pomeron'

As well as a large transverse momentum phase space (which led to the large logs in Q^2), at high enough CM energies there is also a large longitudinal momentum phase space. This generates logs in W^2/Q^2 which lead to the much cited BFKL corrections [15]. The logs exponentiate to deliver a power law growth (in W^2) of total cross sections. In fig.4, the 'definitive' BFKL process is shown: short distances are dominant and the pomeron (i.e. that object which determines the behaviour of total cross sections at high energies) can be described using perturbation theory. The dashed lines represent 'reggeized' gluons (the bare t-channel gluons having been dressed
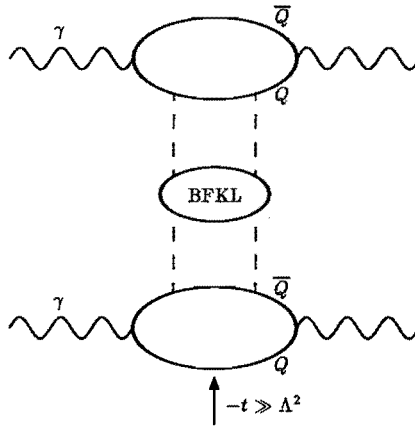

Figure 4

by virtual corrections). The process, $\gamma\gamma \rightarrow \gamma\gamma$ through heavy quark loops at high-t, is not something likely to be measured in the near future! Even so, one can imagine turning down the heavy quark mass and the momentum transfer t until we eventually arrive (as we must) at the DL pomeron. Our goal must be to understand this transition. Fortunately this is not a purely theoretical exercise, there is a very similar process that can be measured (with decent statistics) at HERA. This is the process, $\gamma^{(*)}p \rightarrow V + X$, where X denotes the proton dissociation [16], see

fig.5. The photon need not be highly virtual, providing t is sufficiently large. Large t provides
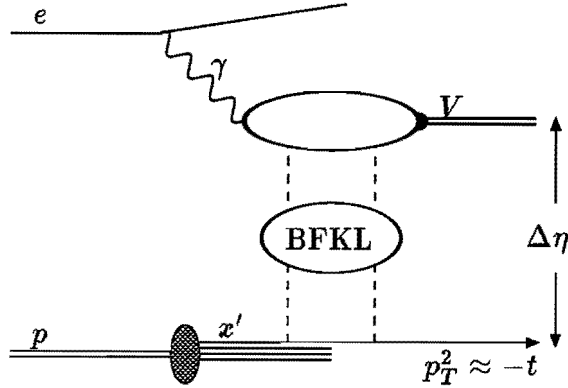

Figure 5

a dynamical infra-red cut-off so there is no need to worry about unknown non-perturbative physics (the theory allows a consistency check, since one can, in principle, always look to see how much of a contribution comes from a particular region of phase space), it also suppresses vector dominance contributions. High t is also vital in ensuring that the simple picture of the proton dissociation shown in fig.5 is valid, i.e. the pomeron couples to a single parton line [17]. The non-perturbative physics associated with the proton bound state is then factorised into the parton densities (which are evaluated at large x' since we require a large CM energy across the pomeron and $\mu_F^2 \sim -t$) and are known. Another bonus is that, although a single parton is struck and emerges to form a jet at $p_T^2 \approx -t$ we do not have to see it. The interesting cross section, $d\sigma/dt$, can be measured by observing the decay of the vector meson (and the scattered electron in DIS). By not requiring to see any of the proton dissociation, we can use much more of the 820 GeV that the proton carries into the scatter and hence pick up contributions from the largest possible rapidity gaps that HERA can deliver (the ultimate limitation is due to the $\sim (1-x)^5$ fall off of parton densities as $x \to 1$). This large reach in rapidity is vital in ensuring that the whole BFKL summation is necessary. To understand the importance of large $\Delta\eta$, recall that the BFKL expansion is an expansion in

$$ z = \frac{3\alpha_s}{2\pi} \ln\left(\frac{x'W^2}{Q_H^2}\right) \sim \alpha_s\Delta\eta, $$

where Q_H^2 is the hard scale (e.g $Q_H^2 \approx -t$ for $-t \gg Q^2, m_V^2$). Ryskin and I found that for $z \lesssim 0.1$, there is no need to go beyond two-gluon exchange and that the full BFKL dynamics reveals itself only for $z \gtrsim 0.8$. At HERA, for $2 \le -t \le 5$ GeV^2, $W = 100$ GeV and $x' \ge 0.1$ (this means that X is unseen) $0.1 \le z \le 1$. So there is the possibility to get into the most

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interesting regime of large z. The scale invariance of the BFKL kernel means that the exchange dynamics is specified only by z and the ratio $\tau \equiv -t/(Q^2 + m_V^2)$ (providing we assume a non-relativistic form for the vector meson wavefunction). Going from DIS J/Ψ's to photoproduction ρ's corresponds to varying τ from 0.1 to 5 which means that we can probe the dynamics over a wide range.

The rate for this process is promising. Since, at large z, we feel the full force of the BFKL power, the cross section is expected to rise rapidly with increasing W^2, i.e. $\sim (W^2/Q_H^2)^{2\omega_0}$ where $\omega_0 = 12 \ln 2 \alpha_s/\pi$. For example, for $Q^2 = 0$, $-t \geq 2$ GeV^2 and $W = 100$ GeV we estimate that $\sigma(\gamma p \to J/\Psi + X) \approx 5$nb and that the mean $z \approx 0.6$. This is more than an order of magnitude larger than the prediction based on two-gluon exchange and as such would show up rather dramatically in the data. Note that there will be many more ρ's produced and that the high-t excess should be present even in ρ photoproduction. I should note that Ryskin and I performed our calculation for the production of transversely polarised mesons off transversely polarised photons and assumed a small contribution from the end-points of the associated wavefunctions. This approximation is known to be a poor one [9, 12], but our conclusions easily generalise to the case of longitudinal photons and more realistic wavefunctions.

Not only is it interesting to study the dynamics of the exchange: understanding the dynamics responsible for the formation of the vector meson also challenges the theorists. The comparison of rates for ρ, ω, ϕ and J/Ψ will provide important tests. For example, DIS ρ production and photoproduction of J/Ψ's can have the same τ value. Theoretically the only difference is related to the different dynamics associated with their formation. At $t = 0$, such comparisons can be done with relative ease and puzzles such as why $\sigma(\phi) : \sigma(\rho) \approx 0.1$ (NMC [18]) whilst theory predicts naively 2/9 (or larger!) can be addressed.

Aknowledgements

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