Diffractive Production of Vector Mesons and the Gluon at small *x*

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Abstract. The theory of diffractive production of vector mesons at HERA is briefly reviewed. Perturbative QCD calculations within the MRT model are discussed. The uncertainties of the predictions are scrutinized, and the strong sensitivity of the diffractive cross section to the gluon distribution at small *x* is emphasized.

Keywords: Diffraction, meson production, parton distribution functions
PACS: 12.38Bx, 12.38Aw, 13.60Le

Introduction

Diffractive high energy scattering is an unique laboratory to study QCD at various scales. Depending on the final state and kinematic variables diffraction can be a purely soft, semi-hard or even hard process, thus enabling us to study the transition from soft to hard QCD. While more and more precise data for different final states are analysed at various colliders, the theoretical description of diffraction has to be further refined and predictions must become quantitative. The motivation for this ranges from understanding the dynamics of QCD and measuring structure functions and parton distributions, to better predicting the structure of underlying events in hadron collisions or even the exciting possibility to first finding the Higgs in exclusive events at the LHC. In the following I will briefly review the prediction of diffractive vector meson (VM) production at HERA and discuss the main uncertainties. It will be demonstrated that the QCD predictions strongly depend on the gluon distribution required as input, which are, however, not well constrained in the region of small *x*.

Vector meson production in QCD beyond leading order

In leading order QCD, diffractive production of VMs through colourless two gluon exchange (in the forward limit) is given by [1]

$$\frac{\mathrm{d}\sigma}{\mathrm{d}t}\,(\gamma^* p\to V p)\Big|_{t=0} = \frac{\Gamma_{ee}^V M_V^3 \pi^3}{48\alpha}\,\frac{\alpha_s(\overline{Q}^2)^2}{\overline{Q}^8}\left[x g(x,\overline{Q}^2)\right]^2\left(1+\frac{Q^2}{M_V^2}\right), \qquad (1)$$

where M_V and Γ_{ee}^V are the mass and electronic width of the VM, $\overline{Q}^2=(Q^2+M_V^2)/4$ is the effective scale, and $x=(Q^2+M_V^2)/(Q^2+W^2)$ (W the c.m.s. energy of $\gamma^* p$). Eq. (1) is valid in the high energy (small x) regime, where quark contributions are negligible.

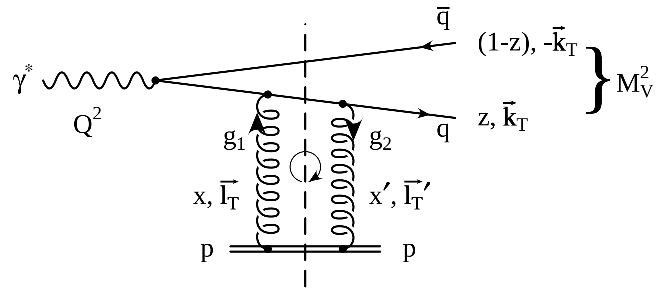

FIGURE 1. One of four leading order amplitudes for the diffractive process $\gamma^* p \rightarrow q\bar{q}\, p$.

The improvement of several other approximations as done e.g. in MRT predictions [2] will be discussed in the following.

Non-relativistic limit. Eq. (1) assumes that q and $\bar{q}$ forming the VM are produced with zero transverse momentum. This can be overcome by introducing the quark's transverse momentum k_T (see Fig. 1) and convoluting the k_T dependent amplitude with a suitable VM wave function, thus accounting for Fermi motion inside the VM. This introduces considerable uncertainties due to the limited knowledge of the form of the wave function. An alternative approach is to assume Parton Hadron Duality and to integrate *open* $q\bar{q}$ production over a given mass interval, $M_{q\bar{q}} \sim M_V$.[1] The size of the interval is a free parameter (though chosen universally for different VM in the MRT predictions) which results in an uncertainty of the overall normalization.

l_T of the gluons and skewing. The identification of the two gluons with the integrated, forward gluon is only valid in the limit $l_T^2 \ll \overline{Q}^2 + k_T^2$ and $x \simeq x'$, respectively. (Here l_T is the transverse momentum of the gluons and x, x' are the longitudinal momentum fractions of the gluons g_1, g_2, see Fig. 1.) However, beyond the leading $\log Q^2$ and $\log(1/x)$ approximations the amplitudes depend on generalized (unintegrated, non-forward) parton distributions (GPDs). In the predictions from MRT normal (integrated, forward) gluons $g(x, \mu^2)$ are used as input to derive unintegrated distributions, $f(x, l_T^2)$, thus replacing collinear with l_T factorization. For $t \sim 0$[2] and small x the effect of skewing comes mainly from evolution and can be determined from the unskewed (forward) gluon [3] (see also [4] for a different approach). Note that both effects, performing the l_T integral explicitely and applying skewing corrections, enhance the cross section considerably (typically by about a factor of two for electroproduction of J/ψ at HERA).

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[1] In addition, a projection of the $\gamma^*_{L,T}\, p \rightarrow q\bar{q}\, p$ amplitudes on the correct quantum numbers of the VM, $J^P = 1^-$, is performed which is crucial for the suppression of endpoint-singularities for transverse (T) photons, see [2] for details.

[2] As usual, the cross section is calculated in the forward limit $t \sim 0$, assuming an exponential t dependence $\sigma \sim \exp(-bt)$ with a slope b determined experimentally or by phenomenological models.

Real part and K factor corrections. The actual diagrammatic calculations of the amplitudes corresponding to Fig. 1 take into account only the imaginary parts (leading $\log(1/x)$ approximation). Assuming a power-like behaviour $\mathscr{A} \sim x^{-\lambda}$ of the amplitudes $\mathscr{A}_{L,T}$, the real part can be corrected for via the relation $\mathrm{Re}\mathscr{A} = \tan(\pi\lambda/2)\,\mathrm{Im}\mathscr{A}$ numerically and enhance the cross section for J/ψ by about 20%. Still missing at next-to-leading order (NLO) are full one-loop corrections to the coupling of the two gluons to the $q\bar{q}$ pair (impact factor at NLO). Such NLO corrections are not expected to significantly alter the Q^2 or W dependence of the cross section, or the ratio of longitudinal to transverse cross section, but could well lead to a sizeable change of the normalization (K factor). In [5] the K factor was estimated from π^2 enhanced terms, and MRT predictions are incorporating these contributions. First results for a full calculation of the NLO impact factors became available recently [6], so further improvement towards a complete NLO prediction seems in reach.

Results and discussion

Fig. 2 displays data from H1 [7] and ZEUS [8] for the cross section of diffractive photo- and electroproduction of J/ψ as a function of the $\gamma^* p$ c.m.s. energy. Also shown are predictions from MRT for different input gluon distributions, multiplied by (Q^2 independent) factors to fit the normalization which is not well predicted within the MRT model. Obviously the predictions strongly depend on the gluon distribution, as expected already from Eq. (1) with the quadratic dependence on g, further enhanced through skewing and real part corrections. The W behaviour of the cross section reflects the x dependence of the gluon in the range $x \sim 10^{-4} \ldots 10^{-2}$ at relatively small scales. Note that the scale assigment in $g(x, \mu^2 = \overline{Q}^2)$ only holds at leading order; applying l_T factorization and using the unintegrated gluon distribution $f(x, l_T^2)$ one samples all scales $l_T^2 = 0 \ldots \infty$ in the loop integral, see Fig. 1.[3] In diffractive J/ψ production at HERA typically 70% of the total cross section come from $l_T^2 < 10$ GeV^2, with a considerable contribution from low scales, where the gluon is not well constrained.[4] The HERA J/ψ data are therefore sensitive to scales relevant for diffractive (exclusive) Higgs production at the LHC, a topic discussed in detail at this workshop.

As pointed out, current fits of the gluon PDF using DIS and jet data are not well constrained at small x and scales, and allow for a wide range of shapes at small x, including non-monotonic behaviour or a falling gluon which even turns negative. As demonstrated, such a behaviour leads to QCD predictions incompatible with the diffractive data. Also note that the differences when using different gluon parametrizations as input well exceed the uncertainties as obtained through the error estimates of single parametrizations. Diffractive data therefore have a strong potential to constrain the gluon at small x. Due

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[3] In the infrared regime with scales l_T^2 smaller than the minimal value allowed in the gluon PDF fits (typically $\sim 1.5 - 2$ GeV^2) one has to extrapolate the gluon.[2] This introduces an additional uncertainty, which is, however, small compared to the uncertainties from the PDFs.

[4] For larger W and Q^2 (or M_V^2) the l_T^2 spectrum gets harder and the relative contribution from the regime of soft scales is suppressed.

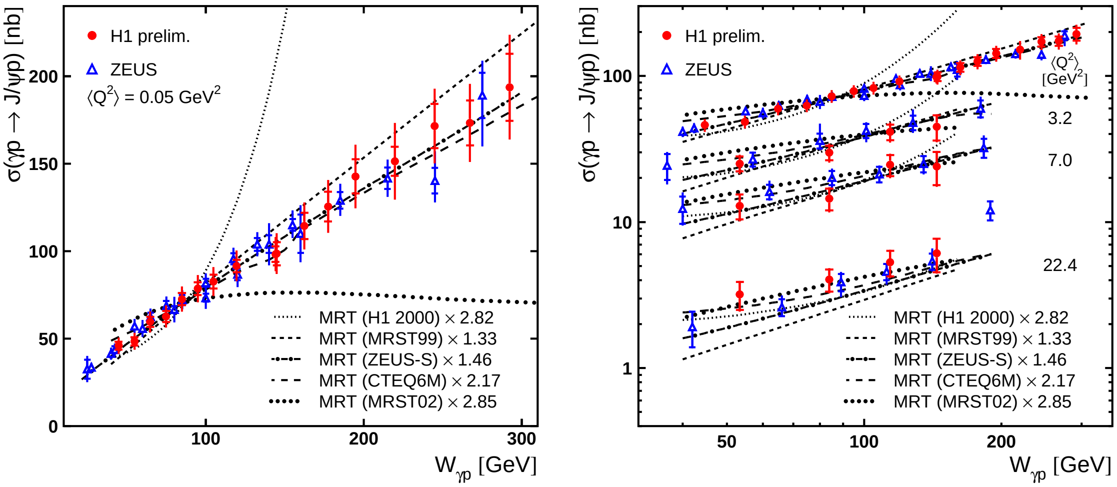

FIGURE 2. H1 [7] and ZEUS [8] data for diffractive J/ψ production compared to MRT predictions. (Figure provided by P. Fleischmann, H1 Collaboration.)

to the complicated relation between diffractive cross sections and the gluon distribution the determination of the gluon from diffractive data is non-trivial. However, with data for different VMs ($\rho, \omega, \phi, J/\psi, \Upsilon$) and different distributions (W, Q^2, t dependence, ratio σ_L/σ_T) one has a handle to disentangle the correlations between different scales and parameters, and we are looking forward to quantitative studies to improve PDFs at small x.

Acknowledgments

It is my pleasure to thank Alan Martin and Misha Ryskin for enjoyable collaboration on the subject of this talk and numerous members of the ZEUS and H1 Collaborations, especially Emmanuelle Perez, for very fruitful discussions.

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