Vector Meson Production From Gauge/Gravity Duality

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We use gauge/gravity duality to study the production of ρ, Ω, J/Ψ and ϕ mesons, in the limit of high center of mass energy at fixed momentum transfer, corresponding to the limit of low Bjorken x, where the process is dominated by the exchange of the pomeron. At strong coupling the pomeron is described as the graviton Regge trajectory, in AdS space, with a hard wall to mimic confinement effects. This is an extension of our previous work on deep inelastic scattering and deeply virtual Compton scattering. We compare our AdS/CFT calculations to experimental data collected at HERA, both for differential and exclusive cross sections.

1 Introduction

Vector meson production (VMP) is one of the diffractive processes studied in electron-proton collisions at HERA. It is conceptually similar to deeply virtual Compton scattering (DVCS), but instead of an outgoing photon a vector meson is produced. The vector mesons have the same J^{PC} values as the photon (i.e. 1^{--}), so the process is kinematically similar. The key difference comes from the vector mesons' structure functions. In the limit of high center of mass energy at fixed momentum transfer, corresponding to the limit of low Bjorken x, this process is dominated by the exchange of the pomeron Regge trajectory between the photon and the proton. Here we will study processes where the final state is a $\rho, \phi, J/\psi$ or Ω, and apply gauge/gravity duality methods. This is a continuation of our work presented at Moriond on DIS[1,2,3] and DVCS[4]. Due to the briefness of this note, very few details will be given, and we direct the interested reader to the aforementioned references, as well as the paper that this work is based on[18]. A number of authors [5,6,7,8,9,10,11] have studied vector meson production using the weak coupling analysis providing a decent fit to the data. More recently, the analysis in [12] uses AdS wave functions within a dipole approximation to fit ρ production. A new key aspect of our gauge/gravity duality description of VMP, in comparison with DIS and DVCS, will be to use a very simple holographic model for the vector mesons which gives the holographic wave function of the mesons as a function of their mass. These wave functions are normalisable modes of the AdS $U(1)$ gauge field dual to the electromagnetic current operator $j_f^a = i\bar{\psi}_f\gamma^a\psi_f$. The meson wave functions are determined in terms of the scale z_f, but we fix this by the observed meson mass. The parameters we have in our model are the scale of the proton state, z_*, the intercept j_0 of the BPST[13] Pomeron, and g_0^2 which is determined by the coupling of the pomeron to the external states (and is therefore different

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for each vector final state). A fit to the data assuming the conformal propagator hence depends on three parameters and we find already a good fit. A fourth parameter can be introduced to represent confinement in the propagator, a hard-wall cut off at large $z_0 > z_f$. We also make fits including this adjustment and find a better overall χ^2 fit.

To compute the total cross section for vector meson production we need first to compute the following hadronic tensor

$$W_a{}^{\lambda}(k_j) = i \int d^4y\, e^{ik_1\cdot y}\, \langle k_3, \lambda; k_4 |\, j_a(y)\, | k_2 \rangle \,, \tag{1}$$

where λ is the polarization of the outgoing vector meson. Contracting with the polarization of the incoming photon, the amplitude for the transition between a photon of polarization λ and a vector meson of polarization λ' is given by

$$W^{\lambda\lambda'}(k_j) = (n^{\lambda})^a W_a{}^{\lambda'}(k_j)\,. \tag{2}$$

We will average over the incoming polarizations and sum over the final ones. The differential cross-section is then given by

$$\frac{d\sigma}{dt}(x, Q^2, t) = \frac{1}{16\pi s^2}\,\frac{1}{3}\sum_{\lambda,\lambda'=1}^{3} |W^{\lambda\lambda'}|^2\,. \tag{3}$$

The different polarizations of the amplitude above can be shown to be represented by

$$W_{TT} = (n^{\lambda})^a\, W_a{}^{\lambda'}(k_j) = (\epsilon_\lambda \cdot \epsilon_{\lambda'})\, Qm\, W_1\,, \qquad (\lambda, \lambda' = 1, 2) \tag{4}$$

$$W_{LL} = (n^{\lambda})^a\, W_a{}^{\lambda'}(k_j) = -Qm\, W_0\,, \qquad (\lambda = \lambda' = 3) \tag{5}$$

where

$$W_n = 2is \int dl_\perp\, e^{iq_\perp\cdot l_\perp} \int \frac{dz}{z^3}\,\frac{d\bar{z}}{\bar{z}^3}\, \Psi_n(z)\, \Phi(\bar{z})\, \mathcal{B}(S, L)\,. \tag{6}$$

$\mathcal{B}(S, L)$ above is the propagator for Pomeron exchange in AdS, the Regge trajectory of the graviton. In this paper we are interested in the limit of large 't Hooft coupling $\lambda \gg 1$, but with sufficiently high energies such that $\sqrt{\lambda}/\ln S \ll 1$. In this limit all fields in the graviton Regge trajectory contribute to the amplitude [14], and we have

$$\mathcal{B}(S, L) = g_0^2 \left(1 + i \cot\left(\frac{\pi\rho}{2}\right)\right) (\alpha' S)^{1-\rho}\, \frac{e^{-\frac{L^2}{\rho \ln(\alpha' S)}}}{(\rho \ln(\alpha' S))^{3/2}}\, \frac{L}{\sinh L}\,, \tag{7}$$

where

$$\alpha' S = \frac{z\bar{z}s}{\sqrt{\lambda}}\,, \qquad \rho = 2 - j_0 = \frac{2}{\sqrt{\lambda}}\,, \qquad \cosh L = \frac{z^2 + \bar{z}^2 + l_\perp^2}{2z\bar{z}}\,. \tag{8}$$

$\Psi_n(z)$ and $\Phi(\bar{z})$ are functions of the external states, in this case

$$\Psi_n(z) = -\left(\sqrt{\frac{C\pi^2}{6}}\, z^2 K_n(Qz)\right)\left(\frac{\sqrt{2}}{\xi J_1(\xi)}\, z^2 J_n(mz)\right), \Phi(z) = z^3 \delta(z - z_*)\,, \tag{9}$$

The first of these is a product of the incoming photon and the outgoing vector meson wave functions. They were found by solving the Maxwell equation, in the gauge $D_\mu A^\mu = 0$, given by $D^2 A_\mu = 0$. The photon corresponds to the non-normalizable mode, and the vector meson to the normalizable. To fix the asymptotic normalization of the mode we must impose a large z (IR) boundary condition on the solution. We simply include a "fermion hard-wall" at the scale $z_f \sim m_f^{-1}$ for each fermion flavour and impose Neumann boundary conditions on the field at the wall. The value of z_f is phenomenologically fixed by the measured vector meson mass and the model contains no free parameters in the mesonic sector.

In equation (7) we use the Pomeron propagator in the conformal model. In the hardwall model, following [3], we use the approximation (with $\tau = \log(\alpha' S)$)

$$\chi_{hw}(\tau, l_\perp, z, \bar{z}) = C(\tau, z, \bar{z})\, D(\tau, l_\perp)\, \chi^{(0)}_{hw}(\tau, l_\perp, z, \bar{z})\,, \tag{10}$$

where

$$D(\tau, l_\perp) = \min\left(1, \frac{\exp[-m_1 l_\perp - (m_0 - m_1)^2 l_\perp^2/4\rho\tau]}{\exp[-m_1 z_0 - (m_0 - m_1)^2 z_0^2/4\rho\tau]}\right), \tag{11}$$

is an exponential cutoff at large $l_\perp$, known to be present asymptotically and determined by the first glueball masses m_0 and m_1, and

$$\chi^{(0)}_{hw}(\tau, l_\perp, z, \bar{z}) = \chi_c(\tau, l_\perp, z, \bar{z}) + \mathcal{F}(\tau, z, \bar{z})\, \chi_c(\tau, l_\perp, z, z_0^2/\bar{z})\,. \tag{12}$$

The function

$$\mathcal{F}(\tau, z, \bar{z}) = 1 - 4\sqrt{\pi\tau}\, e^{\eta^2} erfc(\eta)\,, \qquad \eta = \frac{-\log(z\bar{z}/z_0^2) + 4\tau}{\sqrt{4\tau}}\,, \tag{13}$$

is set by the boundary conditions at the wall and represents the relative importance of the two terms and therefore confinement.

2 Results

Using the above equations, we perform a fit to the data collected at HERA by the H1 collaboration [15,16], except for the Ω meson, where only ZEUS data is available[17]. In Table 1 we see a summary of all our fits. We show fits to the full cross-section and the differential cross-sections for each process. N labels the number of available data points.

		σ [nb]				dσ/dt [nb/GeV²]		
		ρ	φ	Ω	J/ψ	ρ	φ	J/ψ
	m [GeV]	0.77549	1.019445	0.78265	3.096916	0.77549	1.019445	3.096916
	N	48	27	6	38	35	21	84
Conformal	χ^2	0.92	0.60	0.0099	0.28	1.7	1.3	2.9
	g_0^2	4.6	1.8	0.53	0.62	1.6	0.25	0.56
	ρ	0.76	0.73	0.64	0.70	0.65	0.54	0.72
	z* [GeV⁻¹]	3.4	3.0	1.8	0.98	2.1	2.5	2.2
Hardwall	χ^2	0.88	0.61	0.015	0.30	1.7	1.4	1.8
	g_0^2	4.1	1.8	0.67	0.75	2.2	0.38	0.69
	ρ	0.76	0.73	0.66	0.71	0.69	0.59	0.75
	z* [GeV⁻¹]	3.6	3.6	1.5	0.87	2.2	2.5	2.4
	z_0 [GeV⁻¹]	4.8	4.4	7.3	5.3	7.7	8.6	4.6

Table 1: Output data for our fits.

We list the χ^2 per degree of freedom in the fit and the best fit values of the parameters. Firstly, the fits to the full cross-sections provide very good $\chi^2 < 1$ in all cases. Note the Ω

production fit is only to 6 data points. The best fit for the intercept $j_0 = 2 - \rho$ is in the range $0.64 < \rho < 0.76$ across the fits, which seems fairly stable, and consistent with the intercepts found in DIS [3] and DVCS [4]. The fits are less good than for the full cross-section data but still have $\chi^2 < 2$ in each case. To claim such a good fit for the J/Ψ meson we do need to include the hard-wall parameter z_0 and this is the only place in our fits where it makes a significant impact. For this process the momentum transfer energies t go as low as 0.05 GeV^2, which is already below the hard-wall cut off scale set by $1/z_0$. We therefore might need to improve the hard-wall model in order to obtain a better fit for this meson. We also note that these fits are not quite as good as the equivalent ones to DIS and DVCS data using the AdS methods, presumably reflecting the additional complication of fitting the mesonic wave functions holographically. In conclusion we find that the strong coupling AdS/CFT inspired model of low x vector meson production gives a very good fit to the data, providing further evidence for the strength of gauge gravity duality methods. Full details can be found in [18].

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