The Pomeron as Massive Gluons

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ABSTRACT

A QCD-Pomeron composed by two non-perturbative gluons with a dynamically generated mass, is constructed in a gauge invariant way. The gluon propagator is infrared-finite. The model properly describes data on elastic scattering, exclusive $\rho$ production in deep inelastic scattering (DIS) and the $J/\Psi$-nucleon total cross-section in terms of a single gluon mass $m_g \simeq 0.37$ GeV. The total cross sections of hadrons with small radii, such as $J/\Psi$, are very sensitive on the effective gluon mass.

1. Introduction.

The Pomeron exchange describes well the diffractive scattering. Within QCD the Pomeron is considered as the exchange of two (or more) gluons.\textsuperscript{3} However, two perturbative gluons cannot reproduce the experimental results, as can be done with the exchange of two non-perturbative gluons (NPG).\textsuperscript{4} Relating their properties with the QCD vacuum,\textsuperscript{5} the NPG have a finite correlation length, or a mass, associated to the gluon field, which can be understood in terms of gluon condensates (LN model).

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We proposed a QCD Pomeron model using a solution of the Schwinger-Dyson equation for the gluon propagator, which contains a dynamically generated gluon mass. This solution is obtained in a gauge invariant way and it is finite at $k^2 = 0$.

This model describes the data on $\rho$ meson production in DIS, which is claimed as a good test for the non-perturbative Pomeron and the $J/\Psi$-nucleon total cross section, in terms of the same gluon mass derived from elastic $pp$ scattering. Also, the $J/\Psi$-nucleon total cross-section presents a strong dependence on the dynamical gluon mass.

2. The NPG exchange model

In the LN model, Pomeron exchange between quarks has a structure similar to a photon exchange diagram with amplitude $i\beta_0^2(\bar{u}\gamma_\mu u)(\bar{u}\gamma^\mu u)$, where $\beta_0$ is the strength of the Pomeron coupling to quarks

$$\beta_0^2 = \frac{1}{36\pi^2} \int d^2k \left[ g^2 D(k^2) \right]^2,$$  \hspace{1cm} (1)

where $g^2/4\pi$ is the strength of the non-perturbative coupling ($\beta_0^2 = 4 \text{ GeV}^{-2}$). For an infrared-finite propagator the integral in Eq. (1) converges, as required to reproduce the additive quark rule for total cross sections.

Cornwall associates to the gluon a dynamically generated mass by means of a gauge invariant truncation of the gluonic Schwinger-Dyson equation. This solution is given by $D_{\mu\nu} = -ig_{\mu\nu}D(k^2)$, in the Feynman gauge, and

$$D^{-1}(k^2) = \left[ k^2 + m^2(k^2) \right] bg^2 \ln \left[ \frac{k^2 + 4m^2(k^2)}{\Lambda^2} \right],$$  \hspace{1cm} (2)

with the momentum-dependent dynamical mass given by $m^2(k^2) = m_g^2 \left[ \ln \left( \frac{k^2 + 4m_g^2}{\Lambda^2} \right) / \ln \left( \frac{4m_g^2}{\Lambda^2} \right) \right]^{-12/11}$. In these expressions $m_g$ is the gluon mass, and $b = (33 - 2n_f)/48\pi^2$ is the leading order coefficient of the $\beta$ function of the renormalization group equation, where $n_f$ is the number of flavors taken as 3. The effect of fermion loops is included in $b$. Formally, $g^2 D(k^2)$ is independent of the coupling $g$, which is frozen...
and required to be in the range 1.5–2. This constraint and the value of the Pomeron coupling to quarks, see Eq. (1), fixes the non-perturbative propagator.

In Fig. 1 we show the determination of $\beta_0^2$ as a function of the gluon mass using Eq. (2) for three different values of $\Lambda$. For $\Lambda = 300$ MeV and $m_g = 380$ MeV we obtain $\beta_0 \simeq 2$ GeV$^{-1}$. This value of the gluon mass is consistent with $m_g = 370$ MeV obtained from fits to the $pp$ total cross-section, shown in Fig. 2. We find that a gluon mass $m_g = 1.2 - 2\Lambda_{QCD}$ is in agreement with experiment. We choose $\Lambda = 0.3$ GeV, and we obtain that a variety of experimental data requires a gluon mass $m_g \simeq 0.37$ GeV.

3. Exclusive $\rho$ production in DIS.

The exclusive DIS process $\gamma^* p \rightarrow \rho p$ can measure the Pomeron-quark coupling off-shellness. The amplitude for this process behaves as

$$A \propto \int \frac{d^2k}{(k^2 + Q^2 - t)(-4k^2 + Q^2 + m_\rho^2)} \left[4\pi\alpha_n D(k^2 + t/4)\right]^2,$$

where $\alpha_n = g^2/4\pi$, $q$, $P$ and $P'$ are the four-momenta of the photon, incoming and outgoing proton, $Q^2 = -q^2$, $t = (P - P')^2$ and $m_\rho$ is the $\rho$ meson mass. The QCD motivated propagator of Eq. (2) is valid for the entire range of momentum with $g = 1.5$.

We will assume $g^2(k^2) \simeq g^2/(1 + bg^2 ln\frac{k^2 + m_\rho^2}{\Lambda^2})$, i.e. for $k^2 \rightarrow 0$, $g^2(k^2)$ approaches the frozen value of $g$, and the perturbative coupling is recovered at high momentum.

The differential cross section is given by

$$\frac{d\sigma}{dt} = \left[\frac{\alpha_{elm}}{4w^4} |A|^2 \Phi^2\right] Z^2 [3F_1(t)]^2,$$

where $\alpha_{elm}$ is the electromagnetic coupling constant, $\Phi$ gives the strength of the $q\bar{q}\rho$ vertex, $F_1(t)$ is the proton elastic form factor, and $Z = (w^2/w_0^2)^{0.08 + \alpha' t}$, where $w^2 = (P + q)^2$, $w_0^2 \simeq 1/\alpha'$ and $\alpha' = (2 GeV)^{-2}$. This factor introduces the Pomeron exchange dependence on energy and the two-gluon exchange reproduces a Pomeron trajectory $1 + 0t$. Since at $t = 0$ the energy dependence is very small we can compare the value of $\beta_0$ with the experimental one.
The total cross section for $\gamma^* p \rightarrow \rho p$, which is the sum of the transverse and longitudinal parts $\sigma_{\text{total}} = \sigma_T + \epsilon \sigma_L$, is shown in Fig. 3 for $\Lambda = 0.3$ GeV, $\langle w \rangle = 12$ GeV and $\epsilon = 0.85$. We conclude that $m_g = 0.37$ GeV describes the data. There is a strong variation of the cross section with the gluon mass and that, once $\Lambda$ is fixed, this is a one-parameter fit. Some disagreement is expected as we move towards low values of $Q^2$, due to non-perturbative effects.

4. $J/\Psi$ - nucleon scattering.

The amplitude for meson-nucleon scattering in the NPG model is given by

$$A = i \frac{32}{9} s \alpha^2 \int d^2 k D(k^2) D((2Q - k)^2) 2 \left[ f_M(Q^2) - f_M((Q - k)^2) \right]$$

$$\times 3 \left[ f_N(Q^2) - f_N(Q^2 - \frac{3}{2} Q \cdot k + \frac{3}{4} k^2) \right],$$

where $s$ is the square of the center of mass energy and $f_M$ and $f_N$ are respectively the meson and nucleon form factors. The total cross section is related to this amplitude by $\sigma_T = \text{Im} A(s, t = 0)/s$, and we use form factors in the pole approximation in the calculation. In our picture of the Pomeron, the relation between cross section and effective radii of hadrons modifies for heavy mesons as $J/\Psi$, since it strongly depends on the gluon mass.

In our calculation we compute the coefficient of the term $s^{0.08}$ in the total cross section and not the growth with energy. Then, for the ratio of cross sections $\sigma_{\Psi p}/\sigma_{\pi p}$ we expect a factor of approximately 1/3 for the $s^{0.0808}$ coefficients. The total $J/\Psi - p$ cross section is 4 mb. The ratio of cross sections depends on the propagators and form factors. We used the following mean squared radii, $\langle r_{\pi}^2 \rangle = 0.67$ fm$^2$, $\langle r_K^2 \rangle = 0.44$ fm$^2$, $\langle r_{\rho}^2 \rangle = 0.35$ fm$^2$, $\langle r_{\Psi}^2 \rangle = 0.04$ fm$^2$, and also from a non-relativistic quark model calculation $\langle r_{\Psi}^2 \rangle = 0.06$ fm$^2$.

The ratios $\sigma_{K p}/\sigma_{\pi p}$ and $\sigma_{\Psi p}/\sigma_{\pi p}$ are shown in Fig. 4 as a function of the gluon mass. The ratio $\sigma_{K p}/\sigma_{\pi p}$ is practically constant, and $\sigma_{\Psi p}/\sigma_{\pi p}$ exhibits an appreciable variation with $m_g$. This can be understood since for a perturbative propagator with zero gluon mass, and the form-factor in the pole approximation the cross section dependence
on hadron radius, e.g. for the collision of two identical mesons, is given by $\sigma_M = \frac{64}{27} \pi \alpha_s^2 \langle r_M^2 \rangle$, where $\langle r_M^2 \rangle$ sets the scale of the cross section. In the $J/\Psi$ case, the scale $\langle r_M^2 \rangle$ is too small creating a strong dependence of $\sigma_T$ and $m_g$. This result can be tested experimentally. The curves of Fig. 4 are obtained for $\Lambda = 0.3$ GeV. With $m_g = 0.37$ GeV we have $\sigma_{Kp}/\sigma_{\pi p} \simeq 0.92$ (to be compared with 0.87), and $\sigma_{\Psi p}/\sigma_{\pi p} \simeq 0.29$ with $\langle r_{\Psi}^2 \rangle \simeq 0.04$ fm$^2$. We predict the Pomeron contribution to $\sigma_{\Psi p}$ to be equal to $3.95 s^{0.0808}$.

5. Conclusions.

The NPG model describes the Pomeron as the exchange of two non-perturbative gluons. At low $k^2$ the gluon propagator shows the presence of a dynamically generated gluon mass, and at high $k^2$ has the correct QCD asymptotic behavior. It was computed the elastic cross section for $pp$ scattering, finding agreement with experiment for $m_g = 0.37$ GeV, when $\Lambda = 0.3$ GeV, which is consistent with Cornwall’s determination of $m_g$ through the gluon condensate. Here we obtain the Pomeron coupling to quarks, the exclusive $\rho$ production in DIS, the ratio of total cross section of $J/\Psi$-$p$ to $\pi$-$p$ scattering, and determined the behavior $3.95 s^{0.0808}$ for the Pomeron contribution to $J/\Psi$-$p$ scattering. The results are consistent with a gluon mass of 0.37 GeV when $\Lambda_{QCD} = 0.3$ GeV.

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Figure Captions

Fig. 1. Pomeron coupling to quarks ($\beta^2_0$) as a function of the gluon mass $m_g$ for different values of $\Lambda$.

Fig. 2. Total cross section for $pp$ as a function of the gluon mass for different values of $\Lambda$.

Fig. 3. Total cross section for exclusive $\rho^0$ production as a function of the gluon mass $m_g$. Data from Ref. [7].

Fig. 4. Ratios of total cross sections: $\sigma_{Kp}/\sigma_{\pi p}$ (dashed curve), $\sigma_{\Psi p}/\sigma_{\pi p}$ with $\langle r^2_{\Psi}\rangle = 0.04$ fm$^2$ (solid curve), and $\langle r^2_{\Psi}\rangle = 0.06$ fm$^2$ (dotted curve). The curves were determined for $\Lambda = 0.3$ GeV.