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The Glueball Filter in Central Production and Broken Scale Invariance

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Abstract

We propose a possible explanation of the kinematical dependence of the central production of the scalar glueball candidate observed recently by the WA91 and WA102 Collaborations, and discussed by Close and Kirk, in the context of the broken scale invariance of QCD. The dependences of glueball production on the transverse momenta and azimuthal angles of the final-state protons may be related to the structure of the trace anomaly in QCD.

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Confinement and the non-Abelian structure of QCD imply the existence of bound states of gluons. Clearly, finding and recognizing such glueball states is very important. One intriguing possibility is to identify the observed $f_0(1500)$ state with the lightest scalar glueball [1]. To verify the gluonic nature of this state, one has to check in particular if the mechanisms of its production are consistent with those expected for glueball states. This suggests in particular that one looks for its production in gluon-rich environments. It was suggested long time ago [2] that the glueballs should be produced copiously in the central production process

$$pp \to p_f X p_s \tag{1}$$

This may be dominated by double-Pomeron exchange when the final-state protons carry large fractions of the initial-state proton momenta in the centre-of-mass frame. In fixed-target experiments, this requires the presence of fast (p_f) and slow (p_s) protons in the final state.

Recently, a big step in the investigation of this process has been taken by the WA91 and WA102 Collaborations, which have reported remarkable kinematical dependences of central meson production [3, 4]. Specifically, it was observed [4] that the the production of glueball candidates depends strongly on the relative transverse momenta of the final-state protons p_f and p_s. The variable suggested in [4, 5] was the difference between the transverse momenta $\vec{p\prime}_t$ and $\vec{q\prime}_t$ of the final-state protons:

$$dP_t = |\vec{p_t}\prime - \vec{q_t}\prime|. \tag{2}$$

The dependence of central meson production on this variable appears to be very non-trivial: namely, it was found that at small dP_t the production of glueball candidates, in particular the $f_0(1500)$, was significantly enhanced over the production of conventional $\bar{q}q$ mesons. It was proposed [5] that this remarkable feature of central production could be related to the intrinsic structure of glueball states, and that the selection of events with small dP_t could act effectively as a glueball filter. So far, no dynamical explanation of this important empirical observation has been suggested, so the challenge for theory is to understand the dynamics behind this glueball filter.

In this Letter, we suggest a possible dynamical explanation of this empirical observation, based on the concept of broken scale invariance in QCD [6, 7, 8]. This framework requires the existence of a scalar glueball, which plays the role of the dilaton, saturating the matrix elements of the trace of the energy-momentum tensor of QCD Θ_μ^μ. This operator includes an anomalous piece containing gluon field strengths, and we propose that the kinematic structure of the effective Pomeron-Pomeron-glueball vertex may reflect that of the gluon-gluon piece in Θ_μ^μ, which is proportional to $F^{\mu\nu}F_{\mu\nu}$. We demonstrate that this mechanism reproduces qualitatively the observed dependence of the candidate scalar glueball production on dP_t and the relative angles of $\vec{p_t}\prime, \vec{q_t}\prime$.

In central production at sufficiently high energies, mesons are believed to be produced via Pomeron-Pomeron fusion, as shown in the top two diagrams of Fig. 1, although other models are possible, such as that illustrated in the bottom diagram of Fig. 1. The Pomeron is known to couple to light hadrons effectively as a vector particle [9, 10]. Moreover, it is also generally accepted that the Pomeron has a large gluon component, and this picture is supported by analyses of diffraction at HERA. The strongest from of this hypothesis is the leading-gluon model, which postulates a hard distribution of gluons inside the Pomeron, as suggested by the H1 Collaboration [11]. Within this model, it is natural to describe meson production in Pomeron-Pomeron collisions via the fusion of two leading gluons from the interacting Pomerons, as shown in the central diagram of Fig. 1. Other interpretations of the H1 and ZEUS data are possible [12], but the success in other applications of the vector-dominance model for Pomeron couplings [13] also motivates the suggestion that the central production of scalar glueballs occurs via the coupling between the scalar dilaton field and two vector fields.

This coupling has been known since 1972, when the concept of the canonical trace anomaly was introduced [6, 7, 8]. This concept was later given legitimacy by QCD, which was explicitly shown to possess an anomalous term $\propto F^{\mu\nu}F_{\mu\nu}$ in the energy-momentum tensor [14]. If one assumes that matrix elements of the trace of the energy-momentum tensor are dominated by a scalar glueball field Θ, its resulting coupling to two vector fields would also have the form $\sim \Theta F^{\mu\nu}F_{\mu\nu}$. In an effective theory where the effective coupling of the Pomeron is that of a vector particle, $F^{\mu\nu}$ can be considered as an effective 'Pomeron field'. In the leading-gluon model of the Pomeron structure, this is closely related to the gluon field strength $G_a^{\mu\nu}(x)$.

Based on the above arguments, we propose the following form for the coupling responsible for scalar glueball production in Pomeron-Pomeron collisions:

$$Ł \sim \Theta(x) G_a^{\mu\nu}(x) G^a_{\mu\nu}(x), \tag{3}$$

In momentum space, this coupling leads to an amplitude that is proportional to the square of the scalar product of the four-momenta of the colliding gluons g_1 and g_2:

$$\mathcal{M} \sim (g_1.g_2 g^{\mu\nu} - g_1^\mu g_2^\nu)(g_1.g_2 g_{\mu\nu} - g_{1\mu} g_{2\nu}) \sim (g_1.g_2)^2. \tag{4}$$

whose implications for the WA91 and WA102 experiments we now evaluate, assuming that the Pomeron-Pomeron-glueball vertex has a similar structure.

Denoting the initial and final four-momenta of the colliding protons by p,q and $p\prime$, $q\prime$, respectively, and denoting their initial c.m.s. momentum by P, we can write

$$p \simeq \left(P + \frac{M^2}{2P},\ \vec{p_t} = 0,\ p_L = P \right),$$

$$q \simeq \left(P + \frac{M^2}{2P},\ \vec{q_t} = 0,\ q_L = -P \right)$$

and

$$p\prime \simeq \left(x_1 P + \frac{M^2}{2x_1 P},\ \vec{p_t}\prime,\ p_L\prime = x_1 P \right),$$

$$q\prime \simeq \left(x_2 P + \frac{M^2}{2x_2 P},\ \vec{q_t}\prime,\ q_L\prime = -x_2 P \right).$$

We now assume that the dependence of the production vertex on the Pomeron momenta is proportional to that on the gluon momenta in (4). This assumption would be trivial in the leading-gluon model, since the colliding gluons would carry essentially all of the transfered momentum, with the other gluon(s) in the Pomerons merely compensating the colour, which is assumed not to alter the kinematic structure:

$$g_1.g_2 \propto (p - p\prime).(q - q\prime) = -\vec{p_t}\prime \vec{q_t}\prime = -p_t\prime.q_t\prime cos\phi, \tag{5}$$

where ϕ is the azimuthal angle between the directions of the final-state protons. This proportionality assumption may also hold in a more general approach to the vector-like couplings of the Pomeron, and even in the different

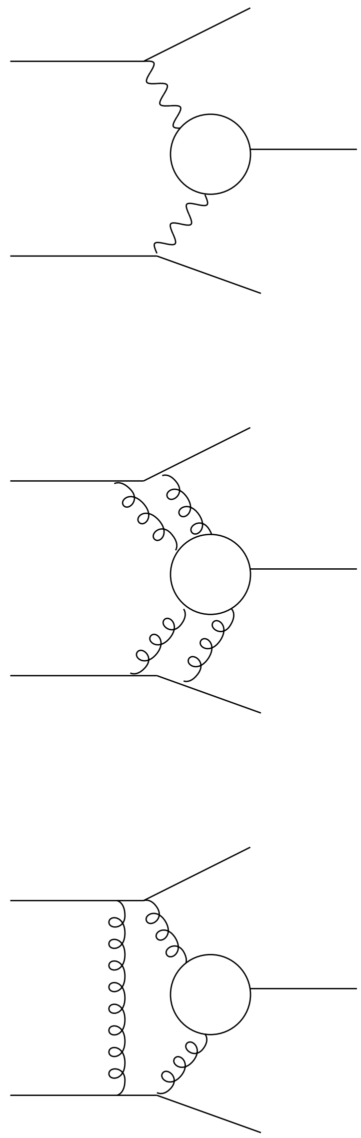

Figure 1: Diagrams describing double-diffractive production. Top diagram: Pomeron-Pomeron fusion, with the zigzag lines denoting the Pomeron exchanges. Central diagram: as previously, with two-gluon models for the Pomerons. Bottom diagram: another pattern of gluon exchange that may lead to the same form of glueball production vertex.

production mechanism displayed in the bottom diagram of Fig. 1. Making this proportionality assumption, the central glueball production rate contains a factor

$$\hat{\sigma} \sim |\mathcal{M}|^2 \sim (p_t\prime q_t\prime)^4 cos^4\phi, \tag{6}$$

This suggests that the production of the scalar glueball should be most efficient when the two protons scatter in parallel or antiparallel directions in the transverse plane, and with significant tranverse momenta, although these should not exceed the limit beyond which the validity of the Pomeron-Pomeron fusion picture breaks down.

In addition to the rate (6) for the glueball production subprocess, one must also take into account the kinematics and the appropriate Pomeron flux factors. In particular, we must ensure the mass-shell condition

$$[(p - p\prime) + (q - q\prime)]^2 = m^2, \tag{7}$$

where m is the glueball mass. In terms of our kinematical variables, this condition may be rewritten as

$$\left(P(2 - x_1 - x_2) + \frac{M^2}{2P}\left(2 - \frac{1}{x_1} - \frac{1}{x_2}\right)\right)^2 - (\vec{p_t}\prime + \vec{q_t}\prime)^2 - (x_2 - x_1)^2 P^2 = m^2. \tag{8}$$

When $x_1 = x_2 = x$ is close to unity, one has

$$s(1 - x)^2 - (\vec{p_t}\prime + \vec{q_t}\prime)^2 \simeq m^2. \tag{9}$$

This requirement must be combined with the kinematic dependence of the production rate (6).

Assuming that $x_1 = x_2 = x \equiv x_P - 1$, one can write down the cross section for double-diffractive glueball production in the following form (note that $t_{1,2} \simeq -\vec{p_t}\prime^2, \vec{q_t}\prime^2$):

$$\frac{d^2\sigma}{dt_1 dt_2 d\phi} = f_P(x_P, t_1) f_P(x_P, t_2) \frac{d^2\hat{\sigma}}{dt_1 dt_2 d\phi}, \tag{10}$$

where $\hat{\sigma}$ is defined in (6) and the Pomeron flux factors are given by [17]

$$f_P(x_P, t) = \frac{9\beta_0^2}{4\pi^2}\,[F_1(t)]^2\, x_P^{1-2\alpha(t)}, \tag{11}$$

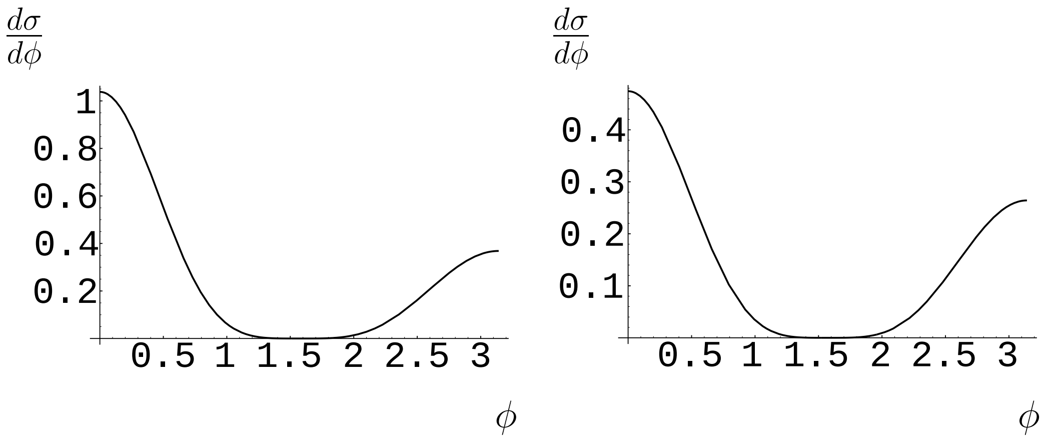

Figure 2: Distribution in the azimuthal angle ϕ (in radians) between the final-state protons in double-diffractive production of the $f_0(980)$ (left panel) and $f_0(1500)$ (right panel) states, calculated for the center-of-mass energy of the WA91 and WA102 experiments, and with $t = -0.5$ GeV^2 for both final-state protons.

with the Pomeron trajectory $\alpha(t) = 1 + \epsilon + \alpha\prime t$, where $\epsilon \simeq 0.085$ and $\alpha\prime \simeq 0.25$ GeV^2, and $|F_1(t)|$ is the elastic form factor of the proton. The value of x_P is fixed by the kinematical constraint (9):

$$x_P = \frac{\left(m^2 - t_1 - t_2 + 2\sqrt{t_1 t_2}\ cos\phi\right)^{1/2}}{\sqrt{s}}. \tag{12}$$

In the case when $t_1 \simeq t_2 = t$, one can write down a simple formula for the distribution in the relative azimuthal angle ϕ :

$$\frac{d\sigma}{d\phi} \sim \left(\frac{s}{m^2 - 2t(1 - cos\phi)}\right)^{1+2\epsilon+2\alpha\prime t} cos^4\phi. \tag{13}$$

The distribution (13) for $f_0(980)$ and $f_0(1500)$ production in the WA91 and WA102 experiments when $t = -0.5$ GeV^2 is shown in Fig. 2, and has two interesting features. First, it favours the production of the glueball when the transverse momenta of the outcoming protons are parallel, in qualitative accord with the experimental observation [3, 4]. Secondly, it vanishes when the azimuthal angle $\phi = \pi/2$. We would expect this second feature to be washed out in a more realistic model calculation which takes account of the internal structure of the Pomeron, deviations from the leading-gluon picture, etc.. Nevertheless, we note that the angular dependence we find is very different from that found in [13] for other mesons. It would be interesting to study this azimuthal-angle dependence in more detail experimentally, remembering that the detailed shape of the azimuthal dependence should depend on the kinematic selection, according to the expression (10). It would also be interesting to extend the studies of azimuthal-angle dependences in double diffractive processes to collider (RHIC or LHC) energies, where the dominance of the Pomeron exchange is better justified.

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