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Glueball-$q\bar{q}$ filter in central hadron production

Frank E. Close [a,1], Andrew Kirk [b,2]

[a] *Rutherford Appleton Laboratory, Chilton, Didcot, OX11 0QX, UK*

[b] *School of Physics and Space Research, Birmingham University, Birmingham, UK*

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Abstract

Glueballs and $q\bar{q}$ of the same J^{PC} are distinguishable due to their boson versus fermion internal structure. This leads to a different topology for central production of glueballs and $q\bar{q}$. We apply this test to data from the WA102 experiment and find that the $f_0(1500)$ and the $f_2(1900)$ show behaviour consistent with glueballs and opposite to that expected if they were pure $q\bar{q}$ states. © 1997 Elsevier Science B.V.

We propose a method for filtering glueballs with $J^{PC} = (0,1,2)^{++}$ from their $^3P_{(J=0,1,2)}$ $q\bar{q}$ counterparts when they are produced in the central region of diffractive processes. The derivation is intuitive rather than rigorous, yet its application to data from the CERN WA102 experiment turns out to reveal some remarkable empirical regularities [1].

These matters are timely given the considerable current interest in the possibility that the lightest glueball is a scalar with a mass of about 1.5 GeV [2,3]. This is motivated both by predictions of lattice QCD [4] and by emerging hints in various experiments where glueball production has historically been expected to be favoured [3,5–7]. One such mechanism is "central production" where the produced mesons have no memory of the flavour of the initiating hadrons [8] and are excited via the gluonic fields of the "pomeron" [9]. Consequently it has been anticipated that production of glueballs may be especially favoured in such processes.

However, such anticipation requires some caution. First there is the well known problem that non-diffractive transfer of flavour (Regge exchange) can contaminate this simple picture and lead to the appearance of $q\bar{q}$ mesons in the central region. Furthermore, even for the diffractive production, momentum transfer between the gluons of the pomeron and the aligned constituents of the produced meson may lead to either gg or $q\bar{q}$ states. The former may be favoured relative to $q\bar{q}$ production due to colour factors but unless further cuts are made to enhance the gg signal, the appearance of novel states in central production is not of itself definitive evidence for a glueball.

However, there has been an interesting development with the recent empirical observation [10] that the states seen in central production are a function of the topology, and depend on whether events are classified as either LL or LR ("left left" or "left right" in the sense of how the beams scatter into the final state relative to the initial direction). Specifically, when the two beams scatter into opposing hemispheres (LR as defined in Ref. [10]) the $f_1(1285)$ $^3P_1$ $q\bar{q}$ state is clearly

[1] E-mail: fec@v2.rl.ac.uk

[2] E-mail: ak@hep.ph.bham.ac.uk

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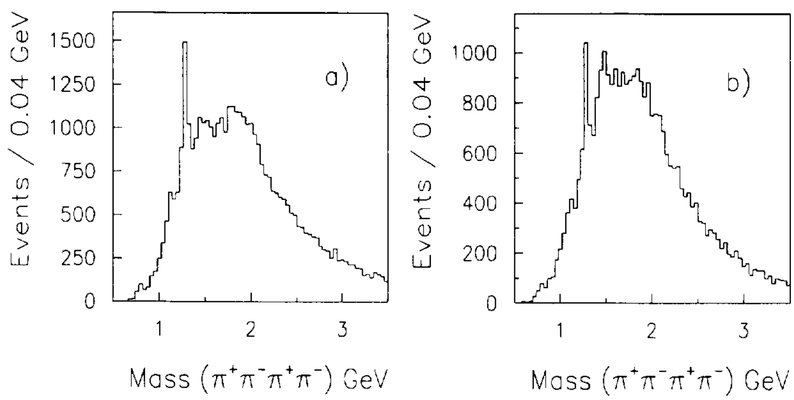

Fig. 1. The 4π mass spectra from Ref. 10 for (a) LR and (b) LL topologies.

visible (Fig. 1a) whereas in the same side configuration (LL) it is less prominent relative to the structures in the 1.4–2.0 GeV mass range (fig 1b). Such discrimination has also been seen for the $f_2(1270)$ $^3P_2$ $q\bar{q}$ state relative to the enigmatic $f_0(980)$ in the $\pi\pi$ channel [10]. Similar phenomena have recently been noted also in Fermilab data [11] and, in retrospect, at the ISR [12].

This phenomenon led us to reconsider the mechanisms for the production of gg and $q\bar{q}$ in the central region. Our notation is that in the centre of mass frame the initial protons have four-vectors

$$p = (P + M^2/2P; p_T = 0, p_L = P),$$
$$q = (P + M^2/2P; q_T = 0, q_L = -P),$$

the outgoing protons having respectively momenta

$$p' \equiv (p'_L = x_a p;\; p'_T), \quad q' \equiv (q'_L = x_b q;\; q'_T)$$

and $x_F \equiv x_a - x_b$. The data have historically been presented as a function of $M_R^2 \sim (1 - x_a)(1 - x_b)s$ with some separation as a function of

$$t_a \sim -\frac{(p'_T)^2}{1 - x_a}; \quad t_b \sim -\frac{(q'_T)^2}{1 - x_b}.$$

The topological separation into LL and LR is novel and independent of the magnitudes of $t_{a,b}$ [10]. We shall suggest that it is driven primarily by the variable $dP_T \equiv |\boldsymbol{p}'_T - \boldsymbol{q}'_T|$ and that gg configurations are enhanced in kinematic configurations where the gluons can flow "directly" into the final state with only small momentum transfer, in particular when $dP_T \to 0$.

A major uncertainty when analysing these processes is the modelling of the pomerons' interactions. While it is now rather generally accepted that a pomeron is a colour singlet gluonic system (see, e.g., Ref. [9]), an unknown feature is the topology of the individual constituent gluons in production processes. For example, Bialas and Landshoff [9] consider Higgs production by double pomeron exchange by treating each pomeron as a colour singlet system of two gluons; one gluon is "passive" and serves primarily to ensure overall colour singlet exchange (Fig. 2a) while the other gluon in each pomeron transfers (longitudinal) momentum which stimulates the Higgs production. This topology has some problems for the exclusive production of $q\bar{q}$ or a glueball. While it may be applicable to the pointlike Higgs, for the exclusive production of a spatially extended hadron, which is the case of interest in the present paper, one anticipates that it may be suppressed. The essential reason is the large rescattering that is required to turn the large relative longitudinal momenta of the "active" gluons into co-moving constituents necessary for the exclusive production of a composite hadron.

Specifically, consider the meson, R, to have an overall longitudinal momentum $P \equiv P_3$ and to be made of constituents (e.g. gluons or quarks) of mass m. The four momentum p^μ of a particle with mass m may be written

$$p^\mu = (p^+ \equiv p_0 + p_3; p^- = \frac{m^2 + p_T^2}{p^+}; p_T).$$

The momentum of the meson R is shared among its

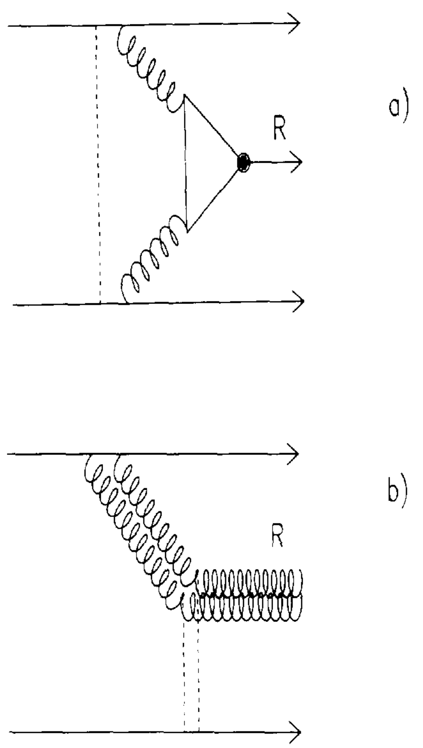

Fig. 2. (a) Two gluons with large p_L fuse to make a meson R. (b) Diffractive scattering of a gluonic pomeron to produce a glueball.

constituents, the j-th constituent carrying a fraction $x_j = p_j^+/P^+$ where the total (time-like) momentum $P^+ = \Sigma_j p_j^+$ is conserved, $\Sigma_j x_j = 1$. The relative momentum of the j-th constituent, $l_j = p_j - x_j P$, is space like with $l^2 = -l_T^2$ and $l^+ = 0$. For a meson that is an S-wave state in its rest frame, the light cone wavefunction will have a structure that may be parametrised in the form [13]

$$\phi_{LC}(x, l_T) \sim \exp(-\Sigma_j \frac{(l_T^2 + m^2) R^2}{x_j}),$$

where the sum is over the constituents, j, and R is a measure of the hadron's size. (Excitation of the l_T degree of freedom corresponds to P-wave (and higher orbitals) in the static limit [14].) For a system of two equal mass constituents with $\delta x \equiv x_1 - x_2$, the structure of the exponent becomes

$$\exp(-\frac{4(l_T^2 + m^2) R^2}{1 - \delta x^2})$$

which is suppressed if l_T is large or if $\delta x \to 1$. This is essentially the well known form factor suppression of asymmetric configurations [13,15] and becomes increasingly significant as M_R becomes large. It is manifested empirically in the sharp cut off of the M_R distribution in central hadron production (as for example when $M_R > 2$ GeV in Fig. 1 even though the kinematic reach of the experiment goes beyond this).

The above remarks are well known for the production of spatially extended $q\bar{q}$ and will also be expected to apply to the production of glueballs. However, in addition to these common features there can be generic differences between the production of glueballs and $q\bar{q}$ of the same J^{PC}. For example, a qualitative difference may result if glueballs are more pointlike than $q\bar{q}$ or have a hard gluonic component in their wavefunction, either of which would relatively enhance their production. The hard rescattering of $gg \to gg$ rather than $gg \to q\bar{q}$ is also aided by colour factors. There is also the possibility that the more singular behaviour of propagators for confined gluons relative to quarks at zero momentum [16] may lead to different production rates for $q\bar{q}$ and gg as a function of the kinematical variables, for example in dP_T and thereby in LL-LR.

The above description of the pomeron is an extreme case in the sense that its gluons are treated asymmetrically. The exclusive meson production then arises when one "hard" gluon from one pomeron fuses with a gluon from the other pomeron. These two gluons have a large relative p_L and in consequence are much separated in δx; this disfavours exclusive production. An alternative extreme, which can reduce this penalty, is where the two gluons within a single pomeron cooperate in being strongly aligned, both in p_L and p_T. In this case we can regard the initial proton beam as a source of pomerons, analogous to the way that an electron beam is a source of photons. Consider the process in the laboratory frame: the pomerons then scatter "diffractively" in the colour singlet gluonic field of the target (Fig. 2b) analogous to the diffractive photoproduction of vector mesons. With the pomeron having $C = +$ we anticipate that this mechanism will favourably produce $J^{PC} = 0^{++}, 2^{++}$ glueballs (which are the lightest according to lattice QCD). The pomeron can in principle also convert into $J^{PC} = 0^{++}, 2^{++}$ $q\bar{q}$ mesons in this process analogous to the photon turning into $J^{PC} = 1^{--}$ $q\bar{q}$. However, for t and $q_T^{\prime} \to 0$, diffractive photoproduction appears to produce only $^3S_1$ rather than $^3D_1$ configurations, suggesting that the excitation of internal angular momenta in the $q\bar{q}$ system is suppressed. If this is a guide to what happens with an initial pomeron "beam" in place of a photon, then one may expect that in this kinematic region the $^3P_{0,2}$ $q\bar{q}$ will be disfavoured relative to their glueball counterparts for which these J^{PC} can be realised in S-wave.

The kinematics and experimental triggers cannot access this "ideal" situation and require p'_T and q'_T to be non-zero. When the p'_T and q'_T are co-moving and of equal magnitude such that $dP_T \to 0$, they tend to produce an overall transverse boost of the meson R but with limited relative (internal) momentum: the resulting configuration for R will be strongly coupled to an S-state. By contrast, when the p'_T and q'_T are equal in magnitude but anti-aligned (so dP_T is large) then there can be significant relative l_T ($\sim dP_T$) within R. Note that in the laboratory frame R is moving overall with large p_L and that excitation of the l_T degree of freedom corresponds to P-wave (and higher orbitals) in the static limit. Thus by making the selection on data that $dP_T \to 0$, there is the possibility that $q\bar{q}$ with $J^{PC} = 0^{++}, 1^{++}, 2^{++}$ (which are all P-wave composites) will be suppressed relative to glueballs (or at least, relative to S-wave bound states of bosons with these J^{PC}). In effect, the Bialas-Landshoff topology encounters the penalty of mismatched p_L, which disfavours exclusive meson production at large M_R; the alternate topology dilutes this problem in p_L but in p_T it remains. It is this which is varied via dP_T and which can govern the relative importance of S and P (or higher) wave states.

If this is realised then we expect $f_1(1285)$, $f_2(1270)$ inter alia to be suppressed as $dP_T \to 0$; we expect f_0 $^3P_0$ $q\bar{q}$ to be suppressed similarly whereas $f_0(1500) \equiv gg$ or $f_0(980) \equiv K\bar{K}$ would be able to survive. Conversely, at larger dP_T the production of gg and $q\bar{q}$ can be competitive, their relative production rates being dependent on their detailed internal wavefunctions and the relative importance of the collinear versus asymmetric (hard gluon) production mechanisms.

The above intuitive picture is at best only a first sketch of the full dynamics but at least it provides a starting point that is qualitatively consistent with the pattern of the LL and LR topologies. Intuitively one expects that the LL configuration will contain a large sample with comparatively small relative transverse momentum and hence $dP_T \to 0$ favouring the glueballs. In contrast, the LR topology will have a tendency for rather larger relative transverse momentum, thereby necessitating greater momentum transfer in the exclusive meson production vertex; thus for this case one will expect both gg or $q\bar{q}$ production to occur. The relative emergence of the glueball candidates compared to the established $f_1(1285)$ $q\bar{q}$ in Fig. 1 are in accord with this. However, if it is the dP_T variable that underpins the $LL - LR$ effect, then there should be a more marked effect when the data are selected directly as a function of $dP_T = |p'_T - q'_T|$. Accordingly we have done so and present the results for the 4π channel in Fig. 3.

The $dP_T \geq 0.5$ GeV (Fig. 3a) is similar to the original LR sample as expected. The sample with 0.2 GeV $\leq dP_T \leq 0.5$ GeV (Fig. 3b) shows the $f_1(1285)$ becoming suppressed and a sharpening of the $f_0(1500)$ and $f_2(1900)$ structures. However, the most dramatic effect is seen in the $dP_T \leq 0.2$ GeV sample (Fig. 3c) where the $f_1(1285)$, a $q\bar{q}$ state, has essentially disappeared while the $f_0(1500)$ and $f_2(1900)$ structures have become more clear. (This is driven by $dP_T \to 0$ and is not an artifact of Bose symmetry, as might have occurred if the pomeron–photon analogy were exact: if we select $t_1 \neq t_2$, the $f_1(1285)$ still disappears as $dP_T \to 0$.) These surviving structures have been identified as glueball candidates: the $f_0(1500)$ is motivated by lattice QCD while the $f_2(1900)$ is noted to have the right mass to lie on the pomeron trajectory [17].

The $f_0(1500)$ is rather clean and appears at $dP_T \to 0$ with a shape and mass that are not inconsistent with what is seen in $p\bar{p}$ annihilation. This is in contrast to the full data sample of the present experiment where this state interfered with the $f_0(1370)$ and was shifted to a lower mass (~ 1440 MeV) [6] and with a much narrower width (~ 60 MeV). The emergence in Fig. 2c of a more canonical $f_0(1500)$ [7] suggests, at least implicitly, that the $f_0(1370)$ $q\bar{q}$ [18] state has become suppressed as $dP_T \to 0$ while the (gg candidate) $f_0(1500)$ has survived. It is important that experiments now verify if this is indeed the case.

Similar cuts have been applied to the $\pi\pi$, $K\bar{K}$ and $K\bar{K}\pi$ data (see the following paper [1]). The $f_1(1285)$ and $f_1(1420)$ are seen in the channel $K\bar{K}\pi$ when $dP_T > 0.5$ GeV but vanish when $dP_T \to 0$

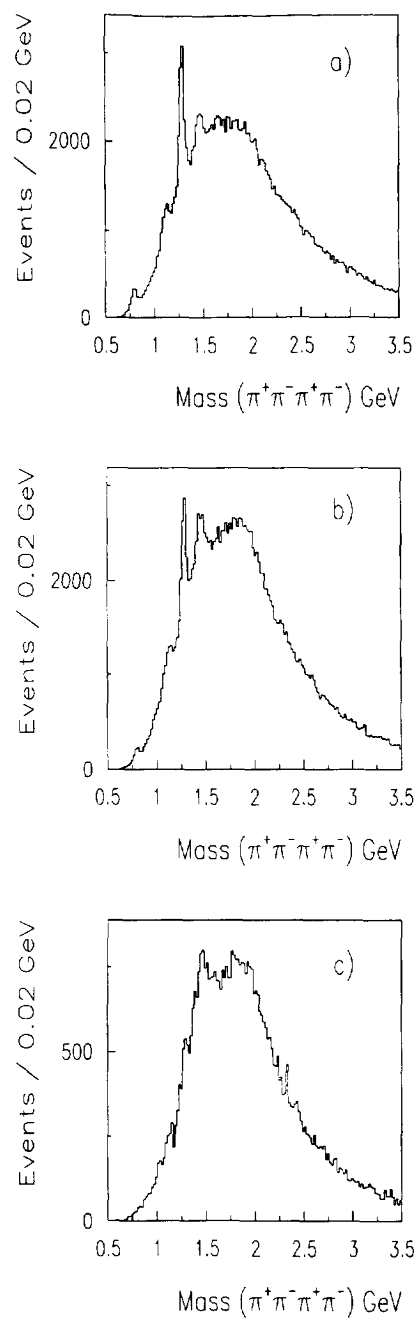

Fig. 3. The 4π mass spectra (i) With $dP_T > 0.5$ GeV exhibiting a clear $f_1(1285)$; (ii) $0.2 < dP_T < 0.5$ GeV (iii) $dP_T < 0.2$ GeV where the $f_1(1285)$ has disappeared while the $f_0(1500)$ is seen more clearly.

in line with $^3P_1$ $q\bar{q}$. We note that there are no 1^{++} resonances visible in this limit, in line with lattice QCD which predicts that there are no 1^{++} glueballs below $\sim$ 3.5 GeV [19]. In the $\pi\pi$ channel we see the $f_2(1270)$ when $dP_T > 0.5$ GeV. This vanishes as $dP_T \to 0$ as expected for $^3P_2$ $q\bar{q}$. The survival of $f_0(980)$ is significant and we suggest that this shows its affinity for coupling via S-wave bosons. This could be due to a gg presence or to $K\bar{K}$ in its wavefunction [20,21]; at the present level of analysis we are unable to distinguish between these alternatives.

Summarising, we have stumbled upon a remarkable feature of central meson production that does not appear to have been noticed previously. Although its extraction via the dP_T cut was inspired by intuitive arguments following the observation of an $LL - LR$ asymmetry, we have no simple dynamical explanation. Nonetheless, the empirical message is dramatic enough to stand alone and thereby we suggest that a systematic study of meson production as a function of $dP_T \equiv |p_T' - q_T'|$ holds special promise for isolating the systematics of meson production in the central region and in filtering $q\bar{q}$ mesons from those with significant *boson-boson* content. The latter include $K\bar{K}$ molecular bound states (or $s\bar{s}$ states with significant $K\bar{K}$ component in the wavefunction), *pomeron-pomeron* states and *glueballs*. Our selection procedure will need to be tested further in future experiments in order to determine the extent of its empirical validity. In turn we hope thereby that its dynamical foundations may be put on a sounder footing and the filtering of glueballs be made a practical reality.

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