Received: *June 5, 1999*, Accepted: *July 10, 1999*

A new proposal for glueball exploration in hard gluon fragmentation

Probir Roy and K. Sridhar

Department of Theoretical Physics, Tata Institute of Fundamental Research, Homi Bhabha Road, Bombay 400 005, India
E-mail: probir@theory.tifr.res.in, sridhar@theory.tifr.res.in

Abstract: An unambiguous identification of glueballs in experiments will be of great significance, because their existence is an important test of QCD. The proposal, advanced here, is to experimentally search for glueballs as peaks in the invariant mass of a leading K_S-pair fragmenting from an energetic gluon jet out of high-statistics three-jet events in hadronic decays of the weak neutral Z boson. Using a physically motivated model of the gluon-glueball fragmentation function, we find a substantial fragmentation rate into a leading glueball. It is very likely that a search, along the lines suggested here by any of the four groups at the Large Electron Positron collider at CERN, will prove fruitful.

Keywords: QCD, Phenomenological Models.

JHEP07(1999)013

Gluons, the confined colour-octet mediators of strong interactions in quantum chromodynamics (QCD), 'shine [1] in their own light'. They have self-interactions as a consequence of non-abelian gauge symmetry. At short distances $\ll 1$ GeV^{-1}, their coupling strength decreases via renormalisation group evolution to yield an asymptotically free [2] weak-coupling description. But at distances $\geq (\Lambda_{\rm QCD})^{-1}$, where $\Lambda_{\rm QCD}$ is the QCD scale ~ 200 MeV, the coupling strength increases to a strong enough value to cause colour confinement. With such strong couplings, colour-singlet gluonic bound states or *glueballs* [1] are expected to form. Indeed, there exist strong theoretical arguments [3] favouring such formation.

Simple representations of scalar, pseudoscalar and tensor glueball fields are $G(x) \sim {\rm Tr}\, F_{\mu\nu}(x)F^{\mu\nu}(x)$, $\tilde{G}(x) \sim {\rm Tr}\, F_{\mu\nu}(x)\tilde{F}^{\mu\nu}(x)$, and $G^{\nu}_{\mu}(x) \sim {\rm Tr} F_{\mu\rho}(x)F^{\rho\nu}(x)$, respectively. Here $F_{\mu\nu}(x)$ is the covariant colour-contracted gluon field-strength tensor in standard notation [2] and $\tilde{F}^{\mu\nu}(x)$ is its dual. Theoretical studies, carried out over two decades, suggest the existence of glueball states in the few GeV mass-range. Such considerations cover bag [4], quasiparticle [5] and instanton [6] models and even those on supergravity [7]. There have also been glueball simulations [8] on the lattice which fall in the same ambit.

All of the above studies predict the lightest member of the glueball spectrum to be a scalar. In fact, the lattice approach [8] pins down its mass within the window 1.5–1.7 GeV. A scalar mass of 1.5 GeV or so is suggested anyway from the square-root of the inverse of the slope $\simeq 0.4/{\rm GeV}^2$ of the Pomeron trajectory, describing high-energy diffraction, if the latter is identified as the grandparent of the scalar glueball trajectory. However, there is controversy over the predicted spin, parity of the lightest glueball. Estimates [9] from QCD sum-rules show preference for the latter being a pseudo-scalar, while some field-theoretic models [10] suggest that it could be tensor. Glueballs will, of course, be unstable against hadronic decay. But, on account of the $\sqrt{OZI}$ rule [1], their width should not be much more than 100 MeV or so. Thus they are expected to be narrower than typical $q\bar{q}$ resonances in that mass range, though this characteristic feature may get diluted due to glueball-meson mixing.

Since glueballs are inherently quantum chromodynamic in nature, the confirmation of a glueball would constitute direct evidence for QCD. Much effort, as reviewed in refs. [1, 11, 12], has gone into the production and detection of such states. First of all, glueballs need glue-rich production channels. They are scarcely produced in usual quark-antiquark creation, annihilation and rearrangement subprocesses. A further complication is that [13] glueballs are expected to mix significantly with flavour-singlet $q\bar{q}$ mesons of the same spin and parity. For instance, the central region of hadroproduction is characterised by the gg production channel. Nevertheless, careful filtering procedures [14] have to be devised to avoid misidentifying flavour singlet mesons as glueballs among resonances produced here. There have been several quests in this direction [15]. Another probe [16, 17] has been the radiative decay

JHEP07(1999)013

of charmonium (J/ψ) where the photon could recoil against a glueball. However, the reduced statistics of a radiative process constitute a limiting factor here. Several interesting candidates have emerged from both of these studies: $f_0(1500)$, $f_J(1710)$ with $J = 0, 2$, $\xi(2230)$, etc. The glueball interpretation of these flavour singlet mesons is quite plausible. Still, statistically significant clinching evidence for a conclusive glueball identification has been lacking so far and alternative avenues need to be explored. This motivates us to propose a new way of gathering such evidence.

We are guided by the simple idea that a sufficiently hard gluon, hadronizing as an energetic jet, will naturally fragment first into a leading glueball. Because of the reasonably large mass of the glueball, a sizable amount of rapidity will be taken up in the process of lifting a glueball from the vacuum, leaving the residual gluon as quite soft (figure 1). Such a possibility was first mooted [18] two decades ago in the context of collinear hadronic decays of a heavy quarkonium. Subsequent experimental searches on the Υ resonance were unsuccessful, but then the three gluons emerging from the bound $b\bar{b}$ annihilation in hadronic Υ decay are not sufficiently energetic to form isolated jets, which are necessary for the fragmentation process. With higher energy gluon jets, fragmentation processes become important as is evidenced by the study of J/ψ production via gluon fragmentation at the Tevatron [19]. In fact, at high energy colliders gluon fragmentation becomes dominant and becomes an important discovery channel for new particles. We are thus naturally led to direct our attention to hard, isolated gluon jets in the sample of $Z \to q\bar{q}g$ three-jet events at LEP. The least energetic of the three jets in the sample is taken, with a high degree of reliability (with an efficiency of about 70%), to be a gluon jet. Indeed, this is what is borne out in simulations [20] based on perturbative QCD. Even after the imposition of a cut of $E_{\text{jet}} > 15$ GeV in the Z rest-frame, one should still be left with nearly hundred thousand events from the LEP1 Z sample. This is a rich repository of events containing isolated hard gluon jets. One is likely to get an observational handle on any glueball produced in them if one can estimate the gluon-glueball fragmentation probability, multiplied by the branching ratio for the glueball decaying into a K_S-pair, that is credible even within an order of magnitude. The glueball will show up as a peak in the $K_S K_S$ invariant mass spectrum, studied in the gluon (but not in the $q-$ or $\bar{q}-$) jet. For a scalar or pseudoscalar glueball, no correlations are expected between the K_S-directions and the jet axis; for a tensor one there will, in general, be such correlations.

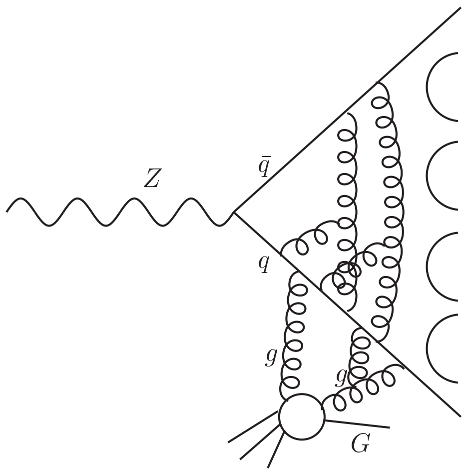

Figure 1: Glueball fragmentation from a hard gluon in $Z \to q\bar{q}g$ decay.

Let us quantitatively consider the question of the glueball fragmentation of a hard gluon in the three-jet final state of Z hadronic decay at LEP. We will consider the quantity $\Gamma(Z \to q\bar{q}GX)$, the partial width for the Z to decay into a $q\bar{q}$ pair plus a glueball state, G, and other soft gluons. These soft gluons will produce soft hadrons which in this inclusive mode we denote by X. The hardness of the fragmenting gluon can be ensured by a cut on the energy of the gluon jet in the rest frame of the Z. It is expedient to write $\Gamma(Z \to q\bar{q}GX)$, in terms of the $q\bar{q}$ partial width, $\Gamma(Z \to q\bar{q})$. This can be done using the well-known expressions for $\Gamma(Z \to q\bar{q}g)$ in terms of $\Gamma(Z \to q\bar{q})$, given as

$$\frac{d\Gamma(Z \to q\bar{q}g)}{dx_2 dx_3} = \frac{2\alpha_s}{3\pi}\Gamma(Z \to q\bar{q})\frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}\,, \tag{1}$$

where $x_i = 2E_i/M_Z$ with $E_i = 1, 2, 3$ denoting the energy (in the Z rest frame) of the antiquark, quark and the gluon jet, respectively. We note that $x_1+x_2+x_3 = 2$. Using this expression, we can write down the corresponding expression for $\Gamma(Z \to q\bar{q}GX)$. It is more convenient to write this width in terms of z, which is the fraction of the parent gluon energy carried by the glueball, rather than in terms of x_3. After this transformation of variables, we fold $\Gamma(Z \to q\bar{q}g)$ with the fragmentation function $D(z, Q^2)$, where Q^2 is the scale at which the fragmentation function is evaluated. The resultant expression is

$$\Gamma(Z \to q\bar{q}GX) = \frac{2\alpha_s}{3\pi}\Gamma(Z \to q\bar{q})\int dx_2 \int dz \frac{x_3}{z}\frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}D(z, Q^2)\,, \tag{2}$$

where the limits of integration in the above expression are chosen in a way consistent with the experimental cuts to be specified in detail below.

To estimate the glueball production rate, we need to make an ansatz for the glueball fragmentation function. The simplest assumption is to consider the fragmentation of a high energy gluon into a glueball as being analogous to the fragmentation of a valence quark into a meson. This may appear unusual at first sight. We know that all quark jets predominantly fragment into mesons whereas in most of the gluon jets — studied in three-jet samples in e$^+$e$^-$ machines at CM energies far below the Z-mass — the parent gluon first goes into a $q\bar{q}$ pair which hadronize in terms of π's, η's, ρ's, etc. Unlike the former, which is a zeroth order process, the latter is $O(\alpha_s)$ in the rate; but the large mass of the glueball makes it impossible for such a gluon to effect a zeroth order fragmentation into it. Our claim is that, once a gluon is very energetic, as is the case for the one emitted by the Z via $Z \to q\bar{q}g$, it will easily overcome this threshold effect; its fragmentation into a glueball state would then become a 'valence-like' process. For such a gluon, fragmentation via the transition first into a $q\bar{q}$ pair would be comparatively down by an $O(\alpha_s)$ factor just as quark fragmentation via gluon radiation is smaller as compared with the direct fragmentation into a meson of a valence quark.

There is more justification for the above assumption. A calculation [21], based on QCD sumrules, of the exclusive distribution of gluons inside a glueball (i.e., the wavefunction) shows that the results are very similar to that of the meson wavefunction. In fact, these calculations suggest a somewhat larger normalisation for the glueball wavefunction and it is possibly true of the inclusive fragmentation function too. But without dwelling too much on these finer points, let us point out that this ansatz for the fragmentation function is being made with the idea of estimating the rate of glueball production via fragmentation at LEP2 energies. The assumption we make allows us to make a rough estimate for the number of glueball events we expect to see at LEP2. Taking this number as given, we can then try to understand whether it is feasible to attempt a search for the glueball state through its decay into mesons. In that sense, we should take the numerical results presented here as a rough guide to decide on what kind of search strategies will be appropriate in the experimental situation. Moreover, we also present results with a different fragmentation function and study the effect on our results of varying this input. For the pion fragmentation function, we use the parametrisation of ref. [22] (which is a $1-z$ distribution with the normalisation obtained from a fit to pion production data) and use this as the glueball fragmentation function at the input scale $\mu_0 \sim 2$ GeV. To take into account the fact that the glueball mass is quite substantial, we multiply this fragmentation function with a multiplicative threshold factor $(1-4M_{\rm G}^2/E_{\rm g}^2)$, where $M_{\rm G}$ is the mass of the glueball and $E_{\rm g}$ is the lab-frame gluon energy. The fragmentation function is then evolved to the scale typical of the fragmenting gluon using Altarelli-Parisi evolution. In the evolution, we have neglected the non-diagonal anomalous dimensions, since their effects are sub-leading. When we vary the fragmentation function, we choose a $(1-z)^2$ distribution instead, but we normalise the distribution in such a way that the integrated probability is the same as in the case of the $1-z$ distribution.

In order to make contact with the experimental jet selection criteria used in the LEP experiments, we require that the lowest energy parton is identified as the gluon and that is the fragmenting parton. Also, it is usual to select the jet sample by requiring a minimum cut, $d_{\rm min}$ on the quantities d_{ij}, defined as

$$d_{ij} = \frac{2E_iE_j \sin\theta_{ij}/2}{E_i+E_j}\,, \tag{3}$$

where the i, j indices refer to the three partons in the three-jet final state. Following the experimental cuts, we take $d_{\rm min}$ to be 7 GeV. In addition, we also require that the gluon energy be above a minimum value, $E_{\rm cut}$. Since $\Gamma(Z \to q\bar{q}GX)$ is a function of $E_{\rm cut}$, we study this functional dependence by varying $E_{\rm cut}$.

Because of the good reconstruction efficiency for the K_S at LEP, we focus on the decay of the glueball into K_SK_S, rather than for its decay into η's for which the efficiency is rather poor. Theoretical estimates [23] for the decay branching ratio of the glueball in the K_SK_S channel suggest that this could be conservatively placed

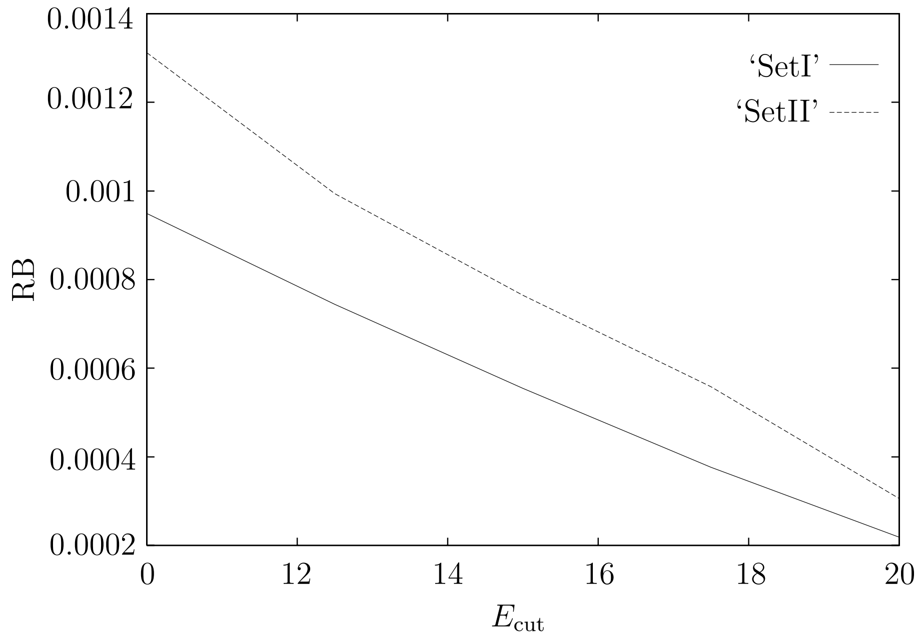

Figure 2: Branching ratio into $q\bar{q}G$ final state times branching fraction of the $G \to K_S K_S$ decay.

at about 2.5%. We present our results in terms of the branching ratio into the $q\bar{q}G$ final state, with the branching ratio of the glueball decay into $K_S K_S$ also folded in. Thus we define

$$\mathrm{BR} = \frac{\Gamma(Z \to q\bar{q}\, GX)}{\Gamma(Z \to q\bar{q})} \cdot \frac{\Gamma(G \to K_S K_S)}{\Gamma(G \to \ \text{all})}\,. \tag{4}$$

In figure 2, we have shown our results for this branching ratio as a function of the cut on the energy of the gluon jet denoted as $E_{\rm cut}$. These are shown for both sets of input fragmentation functions — the curve marked Set I is with the pion fragmentation function and that marked Set II is the $(1-z)^2$ fragmentation function. Assuming four million hadronic Z's and folding in a K_S reconstruction efficiency factor (which is taken to be 18%), we find that with a $E_{\rm cut}$ of about 15 GeV one would expect of the order of 100 events in the $K_S K_S$ channel, for the Set I fragmentation function. For the Set II fragmentation function, this number varies by about 10%. Thus it should be possible for any of the four LEP groups to mount a glueball search on their three-jet hadronic events from the Z. As mentioned earlier, we have made a rather conservative choice for the normalisation of the fragmentation function. If the normalisation of the exclusive distribution amplitude for glueballs relative to that of the pion [21] is taken as a bench-mark, then we could expect a larger normalisation for the fragmentation function and a correspondingly larger number of glueball events in the hadronic decay of the Z.

We also find, from our computations, that the z values that are sampled in the fragmentation process lie in a not very broad range at relatively small z between

0.05 and 0.25. The lower value of z accessed, is close to the kinematic lower limit. The existence of the upper cut-off on z suggests that it may be able to improve the efficiency of the glueball search by restricting the lab energies of the glueball to be less than about a quarter of the energy in the gluon jet. As mentioned earlier, we had used a multiplicative threshold factor in the fragmentation function. But we find that the cuts on d_{ij} and on the gluon energy ensure that the energies involved in the fragmentation process are large enough, so that the effect of this factor is negligible. A similar kinematic behaviour results in the production of quarkonia through fragmentation of high energy gluons [19].

We would like to emphasise that the search we have proposed in this paper is for a pure glueball state. It is, however, quite likely that a glueball state in the mass range of 1.5 or 2 GeV may mix with scalar isosinglet $q\bar{q}$ states in the same mass region. Indeed, such a mixing has been invoked in the analysis of the $f_0(1500)$ — a glueball candidate. It has been pointed out [24] that the mixing of the scalar glueball state with a $q\bar{q}$ state nearly degenerate in mass can change the glueball couplings so that the decays of the mixed state need not be such as to give equal fraction of π's and K's, as would be expected in the case of the decays of the pure glueball state. [1] In the event that the mixing is substantial, we would expect that the $K_S K_S$ branching ratio of the mixed state to be reduced from the value used in the present calculation by the square of the cosine of the mixing angle.

We have, in this letter, proposed a new way of exploring a glueball in the fragmentation of hard gluon jets at LEP. Our estimated numbers do look sufficiently encouraging for any of the four LEP experiments to mount a glueball search in this channel. The observation of the glueball state will provide a confirmation of one of the important non-perturbative predictions of quantum chromodynamics.

Acknowledgments

This work germinated during the Workshop on High Energy Physics Phenomenology V (WHEPP V) held at IUCAA, Pune, India under the sponsorship of the S.N. Bose National Centre for Basic Sciences. We thank Sunanda Banerjee for many helpful discussions. We thank the referee for drawing our attention to ref. [25].

References

[1] F. Close, *Contemp. Phys.* **38** (1997) 1.

[2] M.E. Peskin and D.V. Schroeder, *An introduction to quantum field theory*, Addison-Wesley, 1995.

[1] The expectation that a pure glueball state would decay into equal fractions of π's and K's is rather naive and ignores the decay dynamics. The lattice calculation in ref. [25], in fact, shows that these rates are unequal and, in particular, in agreement with the experimental data on $f_J(1710)$.

[3] G.B. West, *The Glueball; The fundamental particle of non-perturbative QCD*, Paris, 1996, hep-ph/9608258.

[4] M. Chanowitz and S. Sharpe, *Nucl. Phys.* **B 222** (1983) 211.

[5] A. Szczepaniak et al., *Phys. Rev. Lett.* **76** (1996) 2011 [hep-ph/9511422].

[6] T. Schiffer and E.V. Shuryak, *Phys. Rev. Lett.* **75** (1995) 1707 [hep-ph/9410372].

[7] C. Csaki, H. Ooguri, Y. Oz and J. Terning, *J. High Energy Phys.* **01** (1999) 017 [hep-th/9806021].

[8] G. Bali et al., *Phys. Lett.* **B 309** (1993) 378 [hep-lat/9304012];
D. Weingarten, *Nucl. Phys.* **34** *(Proc. Suppl.)* (1994) 29 [hep-lat/9401021];
H. Chen, J. Sexton, A. Vaccarino and D. Weingarten, *Nucl. Phys.* **34** *(Proc. Suppl.)* (1994) 357 [hep-lat/9401020];
X.Q. Luo et al., *Nucl. Phys.* **53** *(Proc. Suppl.)* (1997) 243 [hep-ph/9609389];
M. Teper, *What lattice calculations tell us about the glueball spectrum*, hep-ph/9711299.

[9] S. Narison, *Z. Physik* **C 26** (1984) 209;
S. Narison and G. Veneziano, *Int. J. Mod. Phys.* **A 4** (1989) 2751.

[10] M. Schaden and D. Zwanzigar, New York University Preprint, NYU-94-5141, 1994.

[11] M.R. Pennington, *Glueballs: the naked truth*, hep-ph/9811276.

[12] F. Close, *Nucl. Phys.* **56A** *(Proc. Suppl.)* (1997) 248 [hep-ph/9610426];
B-.S. Zou, *Search for glueballs from three-body annihilation of antiproton-proton in-flight*, hep-ex/9812007.

[13] F.E. Close, G.R. Farrar and Z. Li, *Phys. Rev.* **D 55** (1997) 5749 [hep-ph/9610280];
C-.S. Gao, *Way to discriminate between mesons and glueballs for* $I = 0, J^{PC} =$ *even*$^{++}$ *unflavored hadrons*, hep-ph/9901367.

[14] F.E. Close and A. Kirk, *Phys. Lett.* **B 397** (1997) 333 [hep-ph/9701222].

[15] S. Abatzis et al., *Phys. Lett.* **B 324** (1994) 509;
V. Anisovich et al., *Phys. Lett.* **B 323** (1994) 233;
C. Amslev et al., *Phys. Lett.* **B 291** (1992) 347; *Phys. Lett.* **B 340** (1994) 259; *Phys. Lett.* **B 342** (1995) 433; *Phys. Lett.* **B 355** (1995) 425;
T.A. Armstrong et al., *Phys. Lett.* **B 307** (1993) 394, 399;
M.A. Reyes et al., *Phys. Rev. Lett.* **81** (1998) 4079.

[16] P.D. Barnes et al., *Phys. Lett.* **B 309** (1993) 469;
J. Bai et al., *Phys. Rev. Lett.* **76** (1996) 3502;
M.S. Alam et al., *Phys. Rev. Lett.* **81** (1998) 3328 [hep-ex/9805033].

[17] X-Q. Li and P.R. Page, *Eur. Phys. J.* **C 1** (1998) 579.

[18] P. Roy and T.F. Walsh, *Phys. Lett.* **B 78** (1978) 62.

[19] E. Braaten, M.A. Doncheski, S. Fleming and M. Mangano, *Phys. Lett.* **B 333** (1994) 548 [hep-ph/9405407];
D.P. Roy and K. Sridhar, *Phys. Lett.* **B 339** (1994) 141 [hep-ph/9406386];
M. Cacciari and M. Greco, *Phys. Rev. Lett.* **73** (1994) 1586 [hep-ph/9405241].

[20] M. Acciari et al., *Phys. Lett.* **B 407** (1997) 389.

[21] A.B. Wakely and C.E. Carlson, *Phys. Rev.* **D 45** (1992) 338; *Phys. Rev.* **D 45** (1992) 1796.

[22] P. Chiappetta et al., *Nucl. Phys.* **B 412** (1998) 3 [hep-ph/9301254].

[23] X. He, W. Hou and C.S. Huang, *Phys. Lett.* **B 429** (1998) 99 [hep-ph/9712478].

[24] C. Amsler and F.E. Close, *Phys. Rev.* **D 53** (1996) 295 [hep-ph/9507326].

[25] J. Sexton, A. Vaccarino and D. Weingarten, *Phys. Rev. Lett.* **75** (1995) 4563 [hep-lat/9510022].

JHEP07(1999)013