GLUONIC MESON PRODUCTION

PETER MINKOWSKI*
Institute for Theoretical Physics, Univ. of Bern,
CH-3012 Bern, Switzerland
E-mail: mink@itp.unibe.ch

WOLFGANG OCHS
Max-Planck-Institut für Physik (Werner Heisenberg-Institut)
Föhringer Ring 6
D-80805 München, Germany
E-mail: wwo@mppmu.mpg.de

The existence of glueballs is predicted in QCD, the lightest one with quantum numbers $J^{PC} = 0^{++}$, but different calculations do not well agree on its mass in the range below 1800 MeV. Several theoretical schemes have been proposed to cope with the experimental data which often have considerable uncertainties. Further experimental studies of the scalar meson sector are therefore important and we discuss recent proposals to study leading clusters in gluon jets and charmless B-decays to serve this purpose.

1. Introduction

The existence of glueballs, i.e. bound states of two or more gluons, are among the early predictions of QCD. There is general agreement in that the lightest glueball should be in the scalar channel with $J^{PC} = 0^{++}$. The experimental situation is still controversial as the properties of scalar resonances are not well known. This can be illustrated by looking at the Particle Data Group[1] listing on the lightest scalar mesons (status end 2003). Glueballs can be searched for among the 5 isoscalar states with mass below 1800 MeV, listed in Table 1. The nature of two broad states $f_0(600)$ (also called σ) and $f_0(1370)$ is still controversial. Whereas quite a number of decay modes are "seen", no branching ratios are quoted for any one of these

*Work partially supported by grant 2-4570.5 of the Swiss National Science Foundation.

Table 1. Information on isoscalar mesons with $J^{PC} = 0^{++}$ from the Particle Data Group.

states	$f_0(600)$	$f_0(980)$	$f_0(1370)$	$f_0(1500)$	$f_0(1710)$
width [MeV]	600-1000	40-100	300-500	109 ± 7	125 ± 10
hadronic modes "seen"	1	2	11	13	3
ratios of rates published	-	1	13	18	5
"used" by PDG	-	0	0	5	2
from more than 1 exp.	-	0	0	2	0

particles. Only few ratios of rates are considered as acceptable of which altogether only two have been measured by two experiments independently.

Besides the decay branching ratios the production properties are important for the identification of gluonic mesons. Glueballs should be produced with enhanced rate in a "gluonic environment", such as central hadronic production (double Pomeron exchange), radiative J/ψ decay, proton antiproton annihilation, decay of excited Quarkonia into their respective ground states, whereas their production should be suppressed in $\gamma\gamma$ collisions.

There is not yet an agreement on the mass of the lightest 0^{++} glueball and its mixing with other states, it is even debated whether it has been seen at all. It is rather clear that the evidence for the scalar glueball will emerge only from a thorough experimental study of the low mass scalar channels and the identification of the scalar $q\bar{q}$ nonet in a parallel effort. Various channels should be probed with the aim to obtain more precise information on the production and decay of the scalar resonances.

A recent analysis of $K\bar{K}$ mass spectra at HERA[2] with a prominant peak near the mass of 1700 MeV (presumably $f_0(1710)$) has shown the potential for hadron spectroscopy at HERA. In this report we will discuss the recent proposal to search for glueballs in the leading part of the gluon jet[3] and first results[4] (see also discussions in[7,8,9]), which may be applicable at HERA. Furthermore we report on the possibility for glueball searches and results in B decays.[10]

2. QCD Expectations

The basic triplet of binary glueball states which can be formed by two "constituent gluons" corresponds to the three invariants which can be built from the bilinear expressions of gluon fields and carry quantum numbers $J^{PC} = 0^{++}$, 0^{-+} and 2^{++}.[11] Quantitative results are derived today from the QCD lattice calculations or QCD sum rules, both agree that the lightest glueball has quantum numbers $J^{PC} = 0^{++}$.

Lattice calculations in quenched approximation[12,13,14,15] (without light sea quark-antiquark pairs) suggest the lightest glueball to have a mass in the range 1400-1800 MeV.[16] Results from unquenched calculations still suffer from systematic effects, the large quark masses of the order of the strange quark mass and large lattice spacings. Typically, present results on the glueball mass are about 20% lower than the quenched results.[17,18] Another interesting result would be the mass of the light scalar $\bar{q}q$ mesons. A recent result[18] suggests the mass (1.0 ± 0.2) GeV for the scalar a_0; this is well consistent with the mass of $a_0(980)$ but in view of the systematic uncertainties it is not yet possible to exclude $a_0(1450)$ as the lightest isovector scalar particle.

Results on glueballs have also been obtained from QCD sum rules. Recent calculations[19] for the 0^{++} glueball yield a mass consistent with the quenched lattice result but in addition require a gluonic state near 1 GeV. A strong mixing with $q\overline{q}$ is suggested resulting finally in the broad σ and narrow $f_0(980)$. Similar results with a low glueball mass around 1 GeV are obtained also in other calculations.[20] On the other hand, it is argued[21] that the sum rules can also be saturated by a single glueball state with mass 1.25 ± 0.2 GeV.

In conclusion, there is agreement in the QCD based calculations on the existence of a 0^{++} glueball but the mass and width of the lightest state is not yet certain and phenomenological searches should allow a mass range of about 1000-1800 MeV.

There is also another class of gluonic mesons, the hybrid $q\bar{q}g$ states, both in the theoretical and experimental analysis, but we will not further consider these here (see, for example, review[23]).

3. Spectroscopy of Scalar Mesons - Phenomenology

In the mass range below 1800 MeV the PDG lists two isovectors $a_0(980)$ and $a_0(1450)$ as well as the strange $K_0^*(1430)$, furthermore, there is a possibility of a light strange particle $\kappa(800)$. From these particles and the isoscalars in Tab. 1 one should build the relevant multiplets, one (or more) $q\bar{q}$ nonets and a glueball. There are various schemes for the spectroscopy of the light scalars. We emphasize two different routes in the interpretation of the data, which are essentially different in the classification of the states, both with some further possibilities in details.

Route I: "Heavy" $q\bar{q}$ multiplet (above $f_0(980)$) and "heavy" glueball

One may start from the glueball assuming a mass around 1600 MeV

as found in the quenched lattice calculations emphasized above. In the isoscalar channel there are the states $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$ nearby in mass which are assumed to be mixtures of the two members of the nonet and the glueball. The multiplet of higher mass then includes furthermore the uncontroversial $q\bar{q}$ state $K^*(1430)$ and also the nearby $a_0(1450)$. After the original proposal[22] several such mixing schemes have been considered (review[23]) using different phenomenological constraints. There are schemes[22] with the largest gluon component residing in $f_0(1500)$ and others[13] where this role is taken by $f_0(1710)$. In these schemes $f_0(980)$ and $a_0(980)$ are sometimes superfluous, they are taken as multiquark bound states[24] or $K\overline{K}$ molecules[25] and then are removed from $q\bar{q}$ spectroscopy. An attractive possibility is the existence of an additional light nonet, which includes $\sigma/f_0(600)$, κ, $a_0(980)$ and $f_0(980)$ either as $q\bar{q}$ or $qq\bar{q}\bar{q}$ bound states. Such schemes appear in theories of meson meson scattering in a realization of chiral symmetry, for an outline, see review[26].

Route II: $q\bar{q}$ multiplet including $f_0(980)$ and "light" glueball

Alternatively, one may start from an identification of the lightest nonet and then look for the glueball among the remaining states.[27] Several approaches agree on a similar nonet with $f_0(980)$ as the lightest member,[28,27,29,19] although with different intrinsic structure. Also $K^*(1430)$ belongs to this nonet whereas the identification of the other members differs. There are arguments[27,28] for a strong flavour mixing similar to the pseudoscalar sector with the correspondence $f_0(980) \leftrightarrow \eta'$ near flavour singlet and $f_0(1500) \leftrightarrow \eta$ near flavour octet. The isovector could be $a_0(980)$[27] or $a_0(1450)$.[28] There is no room for κ in these schemes.

The remaining light scalars, the broad σ and $f_0(1370)$, are then candidates for the lightest glueball. The interpretation of σ which is related to the strong $\pi\pi$ scattering up to 1 GeV is subject to intense discussions and controversies.[30] In our phenomenological analysis[27] we consider both states as a single object with a width of about 500-1000 MeV.

Our arguments in favour of the glueball hypothesis include: the strong central production in pp collisions, the appearence in the Quarkonium decays $\psi', \psi'' \to J/\psi\pi\pi$, also in corresponding Y', Y'' decays, in $p\bar{p}$ annihilation and the suppression in $\gamma\gamma$ collisions;[31] on the other hand, contrary to expectation, there is no strong signal in radiative J/ψ decays. A glueball in this mass region is also located in the sum rule analyses[19,20,21] and the K matrix fits to a variety of production processes.[29] Alternatively, this broad $\pi\pi$ "background" has been viewed as due to non-gluonic exchange processes.[23]

As a common feature of the above schemes the lightest glueball is not expected to appear as a single narrow resonance but rather as a phenomenon spread over a mass range of around 500 MeV. Either it is mixed with several moderately narrow isoscalar resonances in a range from 1300-1800 MeV (route I) or it appears mainly as a broad state with a large width by itself (route II). In view of these different possibilities it is important to improve our knowledge on gluonic interactions and to look for further possibilities of glueball production.

4. Gluonic Meson Production in Gluon Jets

New information on gluonic mesons can be obtained from the comparative study of the leading particle systems in quark and gluon jets. The possible appearence of isoscalar particles in the leading system of a gluon jet has already been considered long ago.[7] More specifically, the production of glueballs in the fragmentation region at large Feynman x has been considered.[8] The search for glueballs applying a rapidity gap selection of events and charge distributions in quark and gluon jets has been suggested recently.[3]

There is a well established fragmentation phenomenology for quark jets: a particle which carries the primary quark as valence quark is produced with larger probability at high momentum fraction x than other particles. For example, the u-quark will produce more π^+ than π^- at large x. A natural extension of this phenomenology applies for gluon jets: particles with large Feynman x are predominantly those which carry the initial gluon as valence gluon, these are glueballs or hybrids if they exist.

Whether the idea can be transferred from quark to gluon jets in this way depends on the hadronization mechanism at the distances of about 1 fm, where the colour confinement forces become important, but there is no firm approach to deal with these non-perturbative processes. At the end of a parton cascade the valence quark will form a hadron by recombining with an anti-quark corresponding to an interaction between the colour triplets. In a simple case a primary pair of energetic q and $\bar{q}$ in a colour singlet state is neutralised by a soft $\bar{q}q$ pair, see Fig. 1a. For gluons there are in general two different possibilities. A pair of energetic valence gluons can be colour neutralized again by colour triplet forces (two soft $q\bar{q}$ pairs) or by colour octet forces (a pair of soft gluons), see Fig. 1b. Whereas the standard hadronization models support only the colour triplet neutralization, the second mechanism would allow glueball production.

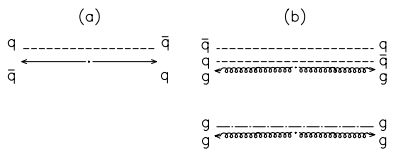

Figure 1. The colour neutralization (a) of an initial $q\overline{q}$ pair by $\overline{q}q$ and (b) of an initial gg pair by either double colour triplet $q\overline{q}$ or by colour octet gg.

It is not obvious to what extent the two types of neutralization mechanisms are realized in a given process. The octet neutralization could in general be a rare process enhanced only for particular kinematic configurations. We argued[3] that in a gluon jet with a large rapidity gap the octet mechanism should become visible if it exists. For large rapidity gaps the more complex multi-quark pair exchanges through the gap will be suppressed.

The relative importance of the colour octet mechanism can be tested by studying the distribution of electric charge of the leading hadronic cluster beyond the gap. These charges should approach for large gaps a limiting distribution corresponding to the minimal number of partons traversing the gap for the considered neutralization mechanism.

There is a clear distinction between the triplet and octet mechanisms: the leading charge in the minimal triplet $(q\bar{q})$ configuration is $Q = 0, \pm 1$ whereas for the octet configuration (gg) it is $Q = 0$. Note that this result is independent of the existence of glueballs. On the other hand, if no extra $Q = 0$ component is observed, then there is no evidence for the octet mechanism whose existence is a precondition for the production of glueballs: glueballs could exist in nature but not be produced in gluon jets.

An exploration of these possibilities has been performed in e^+e^- annihilation at LEP, first with the DELPHI data[4] and recently also with OPAL[5] and ALEPH data.[6] For illustration we show in Fig. 2 the results by DELPHI. The charge distribution has been obtained for the leading cluster, as defined by a rapidity gap $\Delta y = 2$, in quark and gluon jets. The data with this selection do not yet show the limiting charge distribution as can be concluded from the presence of charges $Q = \pm 2, \pm 3$ at the level of 10%. The data for quark jets are in a good agreement with the JETSET Monte Carlo[32] which is based on the triplet neutralization mechanism whereas in gluon jets there is a significant excess of events with charge $Q = 0$ above the MC expectation with a significance of about 4σ. A similar excess is found by OPAL, again for JETSET, but an even larger effect for ARIADNE[33]

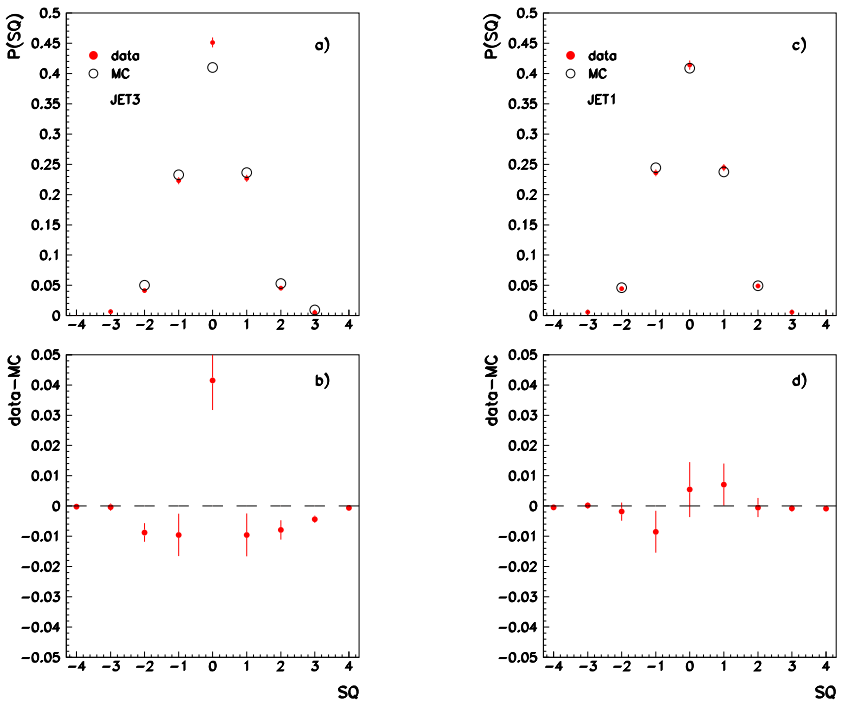

Figure 2. Sum of charges of leading system for a,b) gluon jets and c,d) quark jets (preliminary results by DELPHI[4]) showing the significant excess of data for gluon jets over the expectations from the JETSET MC.

and a smaller effect for HERWIG.[34] The same excesses in comparison to JETSET and ARIADNE have also been observed by ALEPH where the effect is also shown to increase with the size of the rapidity gap and appears mainly at the small multiplicities ≤ 4. These results show the inadequacy of MC's to describe the charge distribution of leading clusters in gluon jets. This may be taken as a hint towards the presence of the octet neutralization mechanism.

The next question to ask is whether the events with a leading cluster of charge $Q = 0$ show indeed a sign of a glueball which would be a natural explanation of the observed excesses. The mass spectra shown by DELPHI for quark jets are again in good agreement with the MC expectations. The mass distribution for events with charge $Q = 0$ in gluon jets in the mass region below 2 GeV show an excess near $f_0(980)$ and possibly in the mass

region around 1400 MeV.[a] OPAL observes a moderate excess in the region 1.0-2.5 GeV of 2σ significance with a coarse binning whereas ALEPH did not study mass spectra (however, their finding of the most sgnificant excess at low multiplicities indicates the main effect at low mass as well).

At present one cannot claim a significant signal in the mass spectra in view of insufficient statistics or the preliminary nature of the data. We want to stress therefore the importance of further dedicated studies.

If the finding of a significant excess of $f_0(980)$ in gluon jets is confirmed it would be a strong argument in favour of a large flavour singlet component of this meson[28,27,19] which could couple to two gluons and disfavour a flavour octet assignment.[36] It would also support the picture with the correspondence of $f_0(980)$ and η' both with gg coupling but not being a glueball; similar effects are discussed in charmless B-decays.[10] Also we note that such an excess is not what would be naturally expected from a 4 quark model for this state. Furthermore, there is the possibility of the broad 0^{++} glueball state above 1 GeV which may be indicated by the above findings.

For further improvements of the analysis it seems important to obtain a better separation of the leading cluster from the other particles in the event. This is not immediately garanteed if the rapidity gap is only applied to the particles inside one jet and not in the full event. This can be achieved if the gap is required for the gluon jet in a frame with a symmetric configuration and the same angle between the gluon and the two quark jets.[37] Then larger rapidity gaps can possibly be achieved with reasonable statistics which would reduce the background from non-minimal configurations.

5. Evidence for Scalar Glueball in Charmless B-Decay

The interest in charmless B-decays with strangeness has been stimulated through the observation of a large decay rate $B \to \eta' K$ and $B \to \eta' X$.[38] It has been suggested that these decays, at least partially, proceed through the b-quark decay $b \to sg$. This decay could be a source of mesons with large gluon affinity.[39,40,41,42] In consequence, besides η' also other gluonic states, in particular also glueballs could be produced in a similar way.

The total rate $b \to sg$ has been calculated perturbatively in leading[43] and next-to-leading order[44]

$$\mathrm{Br}(b \to sg) = \begin{cases} (2-5) \times 10^{-3} & \text{in LO (for } \mu = m_b \ldots m_b/2) \\ (5 \pm 1) \times 10^{-3} & \text{in NLO} \end{cases} \qquad (1)$$

[a]The significance of these excesses is still under experimental investigation.[35]

The energetic massless gluon in this process could turn entirely into gluonic mesons by a nonperturbative transition after neutralization by a second gluon. Alternatively, colour neutralization through $q\overline{q}$ pairs is possible as well (see also Sec. 4 and Fig. 1). This is to be distinguished from the short distance process $b \to s\overline{q}q$ with virtual intermediate gluon which has to be added to the CKM-suppressed decays $b \to q_1\overline{q}_2 q_2$. These quark processes with s have been calculated and amount to branching fractions of $\sim 2\times 10^{-3}$ each.[45,46,44]

Recently, the BELLE collaboration[47,48] has studied charmless decays $B \to Khh$ with $h = \pi, K$ showing a strong signal of the decay $B \to Kf_0(980)$ with decay rate comparable to $B \to K\pi$. Similar results have been obtained by BaBar.[49,50] These results show that scalar particles are easily produced and open the possibility to identify the scalar nonet related to $f_0(980)$ and to determine its properties.[10]

There is another interesting feature in the decays $B^+ \to K^+\pi^+\pi^-$ and $B^+ \to K^+K^-K^+$ observed by the BELLE collaboration.[47] The latter channel shows a broad enhancement in the K^+K^- mass spectrum in the region $1.0 - 1.7$ GeV. The flat distribution in the Dalitz plot of these events suggests this object to be produced with spin $J = 0$. Its contribution can be parametrized as scalar state $f_X(1500)$ with mass $M = 1500$ MeV and $\Gamma = 700$ MeV. More recent preliminary data[48] of higher statistics indicate a narrower substructure above the broad "background". In the $\pi\pi$ channel there is also some background under $f_0(980)$ which drops above 1400 MeV.

As discussed elsewhere[10] we consider the enhancements in $\pi\pi$ and $K\overline{K}$ observed by BELLE as a new manifestation of the broad scalar glueball discussed above under route II. Whereas the center of the peak in $\pi\pi$ is closer to 1 GeV, it is shifted to higher mass in the $K\overline{K}$ channel. The glueball decays with equal rates into $u\overline{u}$, $d\overline{d}$ and $s\overline{s}$ and also into $gb\ gb$. The strange quarks produce dominantly $K\overline{K}$, the nonstrange quarks produce $\pi\pi$ but also resonances in the 4π channel (like $\rho\rho$ or $\sigma\sigma$). We therefore interpret the drop in the $\pi\pi$ spectrum as consequence of the opening of the 4π channel for glueball decay. An important test of our glueball hypothesis is the verification of the expected branching ratios; with the published data there is no contradiction with the hypothesis.

Using the published B branching ratios[47] we have estimated the total production rate of the scalar glueball to be

$$\mathrm{Br}(B^+ \to gb(0^{++}) + X_s) \sim 1.2 \times 10^{-3}, \tag{2}$$

adding the gluonic part of $f_0(980)$ and η' production we estimate

$$\mathrm{Br}(B^+ \to gb(0^{++}) + f_0 + \eta' + X_s) \sim (1.5 \pm 0.5) \times 10^{-3} \qquad (3)$$

which is of the same size as the leading order result for the process $b \to sg$ in (1) and about 1/3 of the full rate obtained in NLO. Further gluonic contributions are expected from other glueballs, in particular, from the parity partner 0^{-+} so that the total production rate of the decay $b \to sg$ could be saturated by gluonic mesons and gluonic production of flavour singlet mesons.

6. Summary

1. Recent results from QCD calculations confirm the existence of glueballs, the lightest one with quantum numbers 0^{++}. The results for its mass vary in a range from 1000 to 1800 MeV.

2. There are different scenarios in the phenomenological interpretation of the data: the glueball has a mass around 1500 MeV and mixes with the isoscalar members of the nonet into observed isoscalars in the range 1300 - 1800 MeV. Alternatively, the glueball is around 1 GeV or a bit heavier with a large width of 500-1000 MeV. In any case, there is no single narrow resonance representing the glueball.

3. Many relevant data (decay branching ratios of f_0's, production rates and phases of f_0's in various production and decay channels have often large errors or are controversial. An improvement of this experimental situation by better measurements is essential for further progress. We think here in particular of improved measurements on the various f_0's (and gb) in central pp (double Pomeron) production, J/ψ decays ($\to f_0\omega,\ f_0\phi;\ \gamma 2\pi,\ \gamma 4\pi$) and D-decays ($f_0\pi$).

A crucial role is played by $f_0(980)$ which could be either a member of the higher mass or lower mass nonet. Its properties and flavour composition are still controversial.

4. An attractive new possibility to search for glueballs lies in the comparison of leading clusters in gluon and quark jets. Also new information on flavour singlet mesons can be obtained (η', $f_0(980)$?). First results from LEP show an additional neutral component in gluon jets not expected from standard MC's. The origin of this excess has to be understood in terms of hadronic states. Such studies are possible at HERA.

5. Charmless B-decays are an attractive source of glueballs and other gluonic mesons from the decay $b \to sg$ as well. Recent results have been

interpreted in terms of a broad scalar glueball decaying into $K\bar{K}$ in the mass range 1000-1600 MeV.

The recent results from B decays and gluon jets are quite promising. They allow to contrast quark and gluon structures in the same experiment. As we hope, there is a large potential to establish the light scalar $q\bar{q}$ nonet with its mixing and the lightest scalar glueball.

References

1. K.Hagiwara et al. (Particle Data Group), *Phys. Rev.* **D66**, 010001 (2002); URL: http://pdg.lbl.gov.
2. S. Chekanov et al. (ZEUS Collaboration), *Phys.Lett.* **B578**, 33 (2004).
3. P. Minkowski and W. Ochs, *Phys. Lett.* **B485**, 139 (2000).
4. B. Buschbeck and F.Mandl (DELPHI Collaboration), in Proc. of the Int. Symp. on Multiparticle Dynamics (ISMD 2001), Sept. 2001, Eds. Bai Yuting et al. (World Scientific, Singapore 2002), p.50.
5. G.Abbiendi et al. (OPAL Collaboration), arXiv:hep-ex/0306021, subm. to *Eur. Phys. J.C.* (2003).
6. ALEPH Collaboration (contact G. Rudolph), Contr. to Int. Europhysics Conf. on HEP, July 2003, Aachen, Germany, CONF 2003-005.
7. C. Peterson and T.F. Walsh, *Phys. Lett.* **B91**, 455 (1980).
8. P. Roy, K. Sridhar, *JHEP* **9907**, 013 (1999).
9. H. Spiesberger and P. Zerwas, *Phys. Lett.* **B481**, 236 (2000).
10. P. Minkowski and W. Ochs, arXiv:hep-ph/0304144.
11. H. Fritzsch and P. Minkowski, *Nuovo Cim.* **30A**, 393 (1975).
12. G. Bali et al., *Phys. Lett.* **B309**, 378 (1993).
13. J. Sexton, A. Vaccarino and D. Weingarten, *Phys. Rev. Lett.* **75**, 4563 (1995).
14. C.J. Morningstar and M. Peardon, *Phys. Rev.* **D60**, 034509 (1999).
15. B. Lucini and M. Teper, *JHEP* **0106**, 050 (2001).
16. G. Bali, arXiv:hep-lat/0308015.
17. A. Hart and M. Teper, *Phys. Rev.* **D65**, 034502 (2002).
18. A. Hart, C. McNeile and C. Michael, *Nucl. Phys. B (Proc. Suppl.)* **119**, 266 (2003).
19. S. Narison, *Nucl. Phys.* **B509**, 312 (1998); *Nucl. Phys. B (Proc. Suppl.)* **121**, 13 (2003).
20. E. Bagan and T.G. Steele, *Phys. Lett.* **B243**, 413 (1990); T.G. Steele, D. Harnett and G. Orlandini, arXiv:hep-ph/0308074.
21. H. Forkel, arXiv:hep-ph/0312049.
22. C. Amsler and F.E. Close, *Phys. Rev.* **D53**, 295 (1996); *Phys. Lett.* **B353**, 385 (1995).
23. E. Klempt, "*Meson Spectroscopy*", PSI Zuoz Summer School, Aug. 2000, arXiv:hep-ex/0101031.
24. R.L. Jaffe, *Phys. Rev.* **D 15** 267, 281 (1977).
25. J. Weinstein and N. Isgur, *Phys. Rev.* **D27**, 588 (1983).
26. F.E. Close and N.A. Törnqvist, *Phys. G* **28**, R249 (2002).

27. P. Minkowski and W. Ochs, *Eur. Phys. J.* **C9**, 283 (1999).
28. E. Klempt, B.C. Metsch, C.R. Münz and H.R. Petry, *Phys. Lett.* **B361**, 160 (1995).
29. V.V. Anisovich and A.V. Sarantsev, *Eur.Phys.J.* **A16**, 229 (2003).
30. W. Ochs, arXiv:hep-ph/0311144.
31. P. Minkowski and W. Ochs, in *Proc. Workshop on Hadron Spectroscopy*, Frascati, March 1999, Italy, Eds. T. Bressani et al. (Frascati Physics Series XV, 1999) p.245.
32. T. Sjöstrand, *Comp. Phys. Comm.* **82**, 74 (1994).
33. L. Lönnblad, *Comp. Phys. Comm.* **71**, 15 (1992).
34. G. Marchesini et al., *Comp. Phys. Comm.* **67**, 465 (1992); G. Corcella et al., *JHEP* **0101**, 010 (2001).
35. B. Buschbeck, private communication.
36. V.V. Anisovich, V.A. Nikonov and L. Montanet, *Phys. Lett.* **B480**, 19 (2000).
37. G. Abbiendi et al., (OPAL Collaboration) arXiv:hep-ex/0310048, subm. to *Phys.Rev.D.*
38. B.H. Behrens et al. (CLEO Collaboration), *Phys. Rev. Lett.* **80**, 3710 (1998); T.E. Browder et al., *Phys. Rev. Lett.* **81**, 1786 (1998).
39. D. Atwood and A. Soni, *Phys. Rev. Lett.* **79**, 5206 (1997).
40. H. Fritzsch, *Phys. Lett.* **B415**, 83 (1997).
41. X.-G. He, W.-S. Hou and C.-S. Huang, *Phys. Lett.* **B429**, 99 (1998).
42. A.S. Dighe, M. Gronau and J.L. Rosner, *Phys. Lett.* **B367**, 357 (1996); *Phys. Rev. Lett.* **79**, 4333 (1997).
43. M. Ciuchini, E. Franco, G. Martinelli, L. Reina and L. Silvestrini, *Phys. Lett.* **B334**, 137 (1994).
44. C. Greub and P. Liniger, *Phys. Rev.* **D63**, 054025 (2001).
45. G. Altarelli and S. Petrarca, *Phys. Lett.* **B261**, 303 (1991).
46. A. Lenz, U. Nierste, and G. Ostermaier, *Phys. Rev.* **D56**, 7228 (1997).
47. A. Garmash et al. (BELLE Collaboration), *Phys. Rev.* **D65**, 092005 (2002).
48. K. Abe et al., BELLE-CONF-0225, arXiv:hep-ex/0208030.
49. B. Aubert et al. (BaBar Collaboration), arXiv:hep-ex/0308065.
50. B. Aubert et al., BaBar-Conf-02/009, arXiv:hep-ex/0206004.