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STATUS OF GLUONIUM SEARCHES

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Abstract

Quantum chromodynamics predicts the existence of quarkless mesons. The search for these hadrons has been ingenious and persevering. Early hints for candidate states have been investigated in the light of recent data, mostly from the Mark III Collaboration, in radiative charmonium decay. No 'smoking-gun' candidate stands out.

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1. MOTIVATION

Quantum chromodynamics (QCD) is an integral part of our Standard Model of elementary-particle interactions. Its application to problems accessible to a perturbative approach stands unchallenged.

The non-Abelian character of the theory manifests itself in the implication that gluons must bind together to form hadrons without quark content. Although quantitative aspects of QCD applied to 'soft' phenomena are uncertain, the qualitative features of this prediction are not doubted. It is therefore natural that we look in the preferred interaction channels for evidence on the existence of such quarkless 'gluonia' (two-gluon bound states). In the following, we review the evidence that has recently accumulated on those states which, over the past several years, have appeared particularly promising as ground states of the gluonic matter in various spin–parity combinations. We will see that, while criteria for the identification of gluonia are fairly well established, refinement in quality and statistical significance has not led to a strengthening of our confidence in the existing candidates.

This does not, however, exclude that the next generation of experiments sort out the various tantalizing hints: there are clearly more mesonic states in the $J^{PC} = 0^{-+}$ and 2^{++} channels than the lowest-lying quark–antiquark nonets can accommodate; it remains to be decided whether they can all be classified as radial excitations or need new degrees of freedom such as those implied by the gg, $q\bar{q}g$, or $q\bar{q}q\bar{q}$ constituencies. We estimate that it will take a very significant increase (by a factor of 100 or so) in data to decide on these questions.

For the present review, we forgo all model-dependent theoretical prejudice when searching for specific states. We note that, for instance, the mass of the scalar gg ground state has been predicted over a fairly wide range between 0.5 and 2.5 GeV/c^2. We will simply content ourselves with the rather general argument, formulated in terms of QCD sum-rule techniques, that the expansion of the vacuum-polarization function [1]

$$T_{\mu\nu}\Pi^j(Q^2) = i\int \mathrm{d}^4x\ \mathrm{e}^{iqx}\langle 0|Tj(x)j'(0)|0\rangle$$
$$= \sum_i a_i\ \langle 0|O_i|0\rangle\ ,$$

where $T_{\mu\nu}$ denotes the current in question (scalar, pseudoscalar, tensor), the O_i are local operators made up out of the quark and gluon fields, and the a_i are Wilson coefficients hiding the details of QCD, contains only two types of dimension-4 operators:

- the quark condensate
$$\langle 0|mg\bar{g}|0\rangle\ ;$$
- the gluon condensate
$$\langle 0|(\alpha_s/\pi)\ \mathrm{G}^{\mu\nu}\mathrm{G}_{\mu\nu}|0\rangle\ .$$

This means, given the successful QCD Lagrangian, that it is well-nigh impossible to avoid the appearance of the gluon condensate in the mesonic mass spectrum.

2. GLUONIUM TAGS

We reiterate the strategy for identifying mesonic states that have no quark content. In so doing, we enumerate criteria that apply specifically to the most simple-minded ground-state gluonia, i.e. mesons made up out of two transverse-vector-gluon constituents. We thus look for

- singlets in SU_3 (flavour) and SU_3 (colour);
- mass range between 0.5 and 2.5 GeV/c^2;
- width anywhere between a few MeV/c^2 and normal hadronic widths;
- spin/parity/charge conjugation: $J^{PC} = 0^{++}, 0^{-+}, 2^{++}$;
- no obvious accommodation in unfilled slots of $q\bar{q}$ SU_6 multiplets;
- evidence for flavour-independent decay coupling;
- preferential observation in two-hard-gluon-dominated production channels;
- production mechanism that may be telling for two massless (transverse) vectors;
- suppressed coupling to electromagnetic current.

3. CLASSICAL GLUONIUM CANDIDATES

Tall claims have been made in years past about a number of states [2]. It is useful to review quickly the situation as it presented itself some five years ago.

3.1 Scalars

Depending on the available rest mass, a $J^{PC} = 0^{++}$ meson will tend to decay into two or four pseudoscalar mesons. Since, in contrast to $q\bar{q}$ states, gg scalar gluonia can be formed in $\ell = 0$ configurations, they may well be the lowest-mass gg states. For masses below 1 GeV/c^2, the $\pi^+\pi^-$ and $\pi^0\pi^0$ decay channels will be of particular importance. The higher masses, $K\bar{K}$, qq, $\eta\eta'$ are attractive final states to study.

The classical 'gluonium reaction', $J/\psi \to \gamma X$, has not been too fruitful for a study of the scalar system in π pair production ($X \to \pi^+\pi^-, \pi^0\pi^0$); nevertheless, there have been repeated claims for low-mass scalar candidates, the most creditable of which stems from a study of transversality amplitudes in πp_{pol} scattering [3], where a $\sigma(750)$ state was reported at three different energies. This state would probably be drowned out in $J/\psi \to \pi^+\pi^-$ decay, where no evidence was found, by feedthrough from the $\pi^0\pi^+\pi^-$ final state.

At higher mass there have been the well-documented claims by the GAMS Collaboration [4] for a scalar state observed in $\pi^- p \to \eta\eta n$, with mass $m(G) = 1590$ MeV/c^2.

3.2 Pseudoscalars

The 'E'/ι mass region has been the subject of much study and controversy. The pseudoscalar system $\iota(1460)$, first reported in 1967 by Baillon et al. [26] in $p\bar{p}$ annihilation, by the Crystal Ball Collaboration [5] in radiative J/ψ decay, has been a prime gluonium candidate thanks to its apparent prominence in this gluon-rich channel and its lack of a natural habitat in the $q\bar{q}$ meson nonets. Detailed investigations of its appearance in this channel and in hadronic J/ψ decay into $V^0 K\bar{K}\pi$ [6], as shown in Fig. 1, permitted the inference that at least part of the signal was not correlated with the non-strange quark content of the ω meson shown in Fig. 1b. This is illustrated in Fig. 2.

Similar data exist for the $\eta\pi\pi$ system emitted in analogous J/ψ decays (see Fig. 2). If $\iota(1460)$ were a gluonium singlet SU_3 state, it would be expected to show up here equally. No clear inferences are possible at this level. The picture was further confused by the observation of both pseudoscalar and axial-vector $K\bar{K}\pi$ states in this mass region in hadronic and $\gamma\gamma$ interactions. A thorough investigation imposed itself.

3.3 Tensors with $J^{PC} = 2^{++}$

QCD calculations of the J^{PC} content in two-transverse-gluon hadronization had singled out this channel as the third locus for gluonium identification [7]. Early reports by the Crystal Ball Collaboration showed [8] heretofore unseen 2^{++} meson in $J/\psi \to \gamma\eta\eta$ at a mass around 1700 MeV/c^2. The Mark III Collaboration performed a quark correlation (Fig. 3) study [6] as for the $K\bar{K}\pi, \eta\eta\pi$ states above. It is shown in Fig. 4. The two well-resolved peaks for $m(K\bar{K})$ in the $\gamma K\bar{K}$ final state appear to be quark-correlated. A further question was raised when the $\theta(1700)$ state was not observed in the $\eta\eta$ mode by Mark III, and the $\pi\pi$ final state was observed much below the level expected from a $\mathbf{1}(SU_3)$ state.

At higher masses, there has long been the claim [9] for three broad states, overlapping in energy, which resulted from a partial-wave decomposition of the large $\phi\phi$ signal observed above threshold in the Cabibbo-suppressed reaction $\pi^- p \to \phi\phi n$. Figure 5 shows the signal and its decomposition into three waves, all with $J^{PC} = 2^{++}$. It was pointed out early on [10] that such a state, if a gluonium, would have to be seen in radiative J/ψ decay, where no such signal was observed.

4. RECENT EVIDENCE ON LEADING GLUONIUM CANDIDATES

In the following, we report on recent work that reflects on the viability of the candidate states described in Section 3. Most of this comes from the final analysis work of the Mark III Collaboration at SPEAR, which has a well-understood sample of 5.6×10^6 J/ψ decays in its data bank. We compare these, where useful, with hadronically produced data, mostly from the WA76 experiment at CERN and from the GAMS Collaboration.

4.1 Recent evidence—Scalars

The reported $\sigma(750) \to \pi\pi$ is an intriguing possibility for a scalar gluonium ground state. The π^0 feedthrough from the $\pi^+\pi^-\pi^0$ final state makes it a difficult system to study in radiative J/ψ decay; nevertheless, a careful investigation, by T. Bolton, of Mark III data [11] shows (see Fig. 6) no action at all below $m(\pi\pi) \simeq 0.7$ GeV/c^2, then ρ feedthrough and $f_2(1220)$ in the mass plot. He quotes an upper limit for an unresolved *narrow* $\pi^+\pi^-$ state ($\Gamma < 2$ MeV/c^2), at masses below 0.6 GeV/c^2, of $< 2.1 \times 10^{-5}$ (90% CL). The well-known quark-based scalar $f_0(975)$ is not seen either, with branching limit

$$B[J/\psi \to \gamma f_0(975)](f_0 \to \pi^+\pi^-) < 1.4 \times 10^{-5} \qquad (90\%\ \mathrm{CL})\ .$$

For a broader $\pi^+\pi^-$ enhancement, the limit is still impressive:

$$B(J/\psi \to \gamma\ \mathrm{scalar})(\mathrm{scalar} \to \pi^+\pi^-) < 4.7 \times 10^{-5} \qquad (90\%\ \mathrm{CL})\ .$$

A full amplitude analysis gives a broad scalar enhancement just above the $K\bar{K}$ threshold (Fig. 6b–e) at a low level ($B \simeq 8 \times 10^{-5}$). This compares with a much stronger signal for $f_2(1270)$ production (Fig. 6b, c), which comes in at

$$B[J/\psi \to \gamma f_2(1270)](f_2 \to \pi^+\pi^-) \simeq 8 \times 10^{-4}\ .$$

For the $K\bar{K}$ final state, Bolton shows again a limit for sharp peaks in the threshold region at a $< 3 \times 10^{-5}$ level, below the pronounced $f_2(1525)$ signal (Fig. 7a). Instead, the region from 1.1 to 1.4 GeV/c^2 appears to be populated by a broad signal that shows up in K^+K^- and K_SK_S. Figure 7b shows the angular distribution to be typical of scalar decays. This $\ell = 0$ component is a significant signal,

$$\begin{aligned} B(J/\psi \to K^+K^-) &= (1.7 \pm 0.1 \pm 0.3) \times 10^{-4} \\ B(J/\psi \to K_SK_S) &= (1.7 \pm 0.3 \pm 0.3) \times 10^{-4}\ , \end{aligned}$$

for $m(\mathrm{K^+K^-})$ between 1.1 and 1.4 GeV/c^2. It may well be due to the decay of the broad $\mathrm{f_0}(1300)$ isoscalar.

If investigation of the $\pi\pi$ system is hard in the radiative J/ψ decay channel, hadronic decay permits again the quark correlation study. Figures 8a and b show J/ψ decays into $\phi\pi^+\pi^-$ and $\phi\pi^0\pi^0$, respectively. In both channels, there is no evidence for low-mass structure, but a good signal for $\mathrm{f_0}(975)$, plus a good hint of $\mathrm{f_2}(1525)$. For the $\phi\mathrm{K^+K^-}$ system, there is evidence only for $\mathrm{f_2}(1525)$, as expected.

At still higher masses, the all-neutrals detection methods of the GAMS detector show [12] evidence for $\mathrm{f_2}(1270)$ in the $4\pi^0$ system $J^{PC} = 2^{++}$, together with a state at 1700–1800 MeV/c^2 (Fig. 9b), and evidence for the G(1590) state in the $J^{PC} = 0^{++}$ sample (Fig. 9c). The well-known $\eta\eta$ decay of G(1590) sticks out clearly in Fig. 9a—so clearly indeed that we feel very confident it will have to be seen in radiative J/ψ decay as well. This would certainly add to its credibility.

4.2 Recent evidence—Pseudoscalar

The iota signal in the pseudoscalar sector has been, for years, the focal point for discussion of likely evidence for gluonium—if only because of its large total branching ratio of some 0.5% in the radiative process [2]

$$\mathrm{J}/\psi \to \gamma\mathrm{K}\bar{\mathrm{K}}\pi ,$$

and of its large ratio for the gluonium quality criterion [13]:

$$S = \frac{|\langle \mathrm{X}|\mathrm{gg}\rangle|^2}{|\langle \mathrm{X}|\gamma\gamma\rangle|^2} \simeq \frac{\Gamma(\mathrm{J}/\psi \to \gamma\mathrm{X})}{\Gamma(\mathrm{X} \to \gamma\gamma)} .$$

Comparable values were reported to be $S(\iota) \geq 65,\ S(\eta') = 2.5, S(\pi^0) = 0.02$.

The Mark III Collaboration has made a concerted effort to resolve this issue: the $\mathrm{K}\bar{\mathrm{K}}\pi$ and $\eta\pi\pi$ signals in this mass region were subjected to a full partial-wave analysis (PWA), singling out the quasi-two-body decays that showed resonant activity.

For the $\mathrm{K}\bar{\mathrm{K}}\pi$ final state in radiative J/ψ decay, the charge modes $\mathrm{K^0_S K^\pm \pi^\mp}$, $\mathrm{K^+K^-\pi^0}$, and $\mathrm{K_S K_S \pi^0}$ were independently investigated [14]. The amplitudes considered are shown in Table 1: they lead to $0^{++}, 0^{-+}, 1^{-+}$, and 1^{++} final states through intermediate channels of

$$\begin{aligned} \mathrm{J}/\psi &\to \gamma\mathrm{K^*K} &&\to \gamma\mathrm{K}\bar{\mathrm{K}}\pi \\ &\to \gamma\mathrm{a_0}(980)\pi &&\to \gamma\mathrm{K}\bar{\mathrm{K}}\pi , \end{aligned}$$

in relative S, P, D waves of the intermediate two-body systems. This procedure is suggested by a closer look at the broad ι structure in Fig. 10a: dividing it up into a lower and a higher mass regions, clear $\mathrm{K^*}$ bands become apparent in the higher-mass sample (Fig. 10c); they cross in a manner typical of a pseudoscalar decay into $\mathrm{K^*K}$. Also, the depopulation in the middle of the $\mathrm{K^*}$ bands indicates helicity-zero $\mathrm{K^*}$'s. The lower-mass region (Fig. 10b) has none of these features, and is easily compatible with $\mathrm{a_0}\pi$ decay structure.

Fits of the data to the various hypotheses of Table 1 were performed in 25 MeV/c^2 bins [15]. The results are compatible for all charge modes; for $\mathrm{K_S K^\pm \pi^\mp}$, they are shown in Fig. 11. The summed signal (Fig. 11f) is clearly made up of three components that show resonance-type motion. There is an axial-vector component with central mass value at 1443 GeV/c^2, decaying via $\mathrm{a_0}\pi$; a pseudoscalar with the same decay mode at 1416, and another pseudoscalar at 1490, visible in the $\mathrm{K^*K}$ channel. These results are quite stable with respect to cuts applied to the data, binning, etc., and were verified by extensive Monte Carlo calculations, using the resulting waves to reproduce the data. The branching fractions, remarkably, are roughly comparable in the $< 10^{-3}$ range; they are summarized in Table 2.

Before discussing these results, let us look at complementary information from the $J/\psi \rightarrow \gamma\eta\pi^+\pi^-$ data sample. In a comparable procedure [16], two data sets were treated independently, with $\eta \rightarrow 2\gamma$ or $\eta \rightarrow \pi^+\pi^-\pi^0$. Figures 12a and b show that, in both sets, there is a strong $\eta' \rightarrow \eta\pi\pi$ signal at low mass, which we were able to use for checks on our analysis procedure. These signals are of considerable statistical significance and correspond to branching ratios of some 4.5×10^{-3}.

The detailed analysis procedure assumed four amplitudes: $J^{PC} = 0^{-+}$ and 1^{++} via intermediate two-body states $a_0\pi$ and $f_0(1400)\eta$. The latter was included in the fits notwithstanding its high rest mass, due to the great width of $f_0(1400)$, to permit more variety to the fit; no f_0 signal was observed.

The full data set (Figs. 12c, d) in both η decay modes was subjected to this analysis, with the results shown in Fig. 13: the only significant action in both data sets is in the 1^{++} and 0^{-+} $a_0\pi$ waves; the other waves are included in the background waves (Figs. 13c, f) which, significantly, show a very different behaviour owing to the different processes that feed into them. Resonant behaviour is seen to be indicated in the $a_0\pi$ pseudoscalar and axial-vector channels. We identify the axial-vector state with $f_1(1285)$, then find a pseudoscalar state at 1400 MeV/c^2 with the parameters

$$m(a_0\pi) = (1400 \pm 6)\ \mathrm{MeV}/c^2\ ,$$

$$\Gamma(a_0\pi) = (45 \pm 13)\ \mathrm{MeV}/c^2\ ,$$

and a branching ratio commensurate with the $f_0(1285)$ signal, as shown in Table 2. The phase motion, shown in Fig. 14, confirms—notwithstanding the still limited statistics—that there is resonant behaviour in the two mentioned channels, in both data sets.

Table 2 then shows the full results of these fits in the $K\bar{K}\pi$ and $\eta\pi\pi$ data samples, together with $f_1(1285)$: there are compatible signals in both samples for the existence of a pseudoscalar of mass 1.4 GeV/c^2 and width $\sim$ 50 MeV/c^2, decaying via $a_0\pi$; only in the $K\bar{K}\pi$ sample do we see further evidence for two states— an axial-vector at 1440 MeV/c^2, easily identified with E(1426) as variously observed in hadroproduction and $\gamma\gamma$ scattering, and another pseudoscalar at mass 1486 MeV/c^2, decaying via K^*K, with a branching ratio higher than the others.

What do these three components of the ι signal imply? A comparison with hadronic interactions shows evidence for the pseudoscalar at 1400 (see, for instance, the recent work of Fukui et al. [17] in $\pi^-p \rightarrow \eta\pi^+\pi^-n$, who see it in the $a_0\pi \rightarrow \eta\pi\pi$ mode, and the previous work of Ando et al. [18]. Compatibly with the axial-vector state at somewhat higher mass, we show in Fig. 15a the axial-vector signal in $K\bar{K}\pi$ from the WA76 Collaboration at CERN [19]. Figure 15b, from the same experiment, gives a good signal for $f_1(1285) \rightarrow \eta\pi\pi$, but shows no higher structure in this channel.

The implication thus imposes itself that a quark-based state $\eta(1400)$ is compatibly seen in J/ψ radiative decay and in hadronic interactions, decaying via K^*K or $a_0\pi$. An axial-vector state $f_1(1420)$, only decaying via $a_0\pi$, is equally observed in various interactions, with comparable branching ratios, but has only now been identified in the gluon-rich J/ψ radiative decay. Finally, a higher-mass state is seen at 1490 MeV/c^2, in the pseudoscalar sector, with large branching fraction, and in K^*K only.

Present theoretical interest [20] therefore concentrates on this higher-mass pseudoscalar, but the interpretation is in terms of a generic (multi-gluon) glueball rather than the 'ground-state gg' configuration that we set out to discover.

4.3 Recent evidence—Tensors

The principal candidates in this sector, $\theta(1700)$ and $g_T^{1,2,3}$, have not done well under close investigation: for one thing, $\theta(1700)$ was never confirmed in the $\eta\eta$ final state, which was routinely written off to the lack of a neutral trigger in the Mark III experiment. The confirmations in the $K\bar{K}$ channel by the Mark II and Mark III Collaborations were recently put to a rigorous test by a full amplitude analysis of K pairs from the radiative J/ψ decay processes

$$J/\psi \to \gamma K^+K^-,\ \gamma K_S K_S$$

in the Mark III detector. A moment analysis method [21] was worked out for the mass region $1.075 \leq m(K\bar{K}) \leq 2.075$, for which we show the mass plots in Figs. 16a, b, by studying the angular distributions in terms of spherical harmonics:

$$W(\Omega_X, \Omega_K^*) = \sum_{j,\ell,m} T_{\ell m}^j\ Y_{jm}(\Omega_X)\ Y_{\ell m}(\Omega_K^*)\ ,$$

with $T_{\ell m}^j$ the moments of angular distributions. These moments and the resulting helicity amplitudes were determined in 100 MeV bins; the latter are shown in Fig. 17 for both $K\bar{K}$ charge modes. While still preliminary, these data permit important inferences: the $|a_2|^2$ intensities confirm $f_2(1525)$ prominence in this channel, as consistently observed by Mark III. At $m(K\bar{K}) \sim 1700$ MeV/c^2, there is a strong signal in the $|a_0|^2$, *scalar*, amplitudes. Only the $K_S K_S$ sample gives the hint of some possible tensor admixture in this mass range.

This result is fatal to the interpretation of '$\theta(1700)$' as a tensor gluonium candidate. Also, the quoted mass resolution makes it unlikely that the observed scalar action at $m(K\bar{K}) \simeq 1{,}700$ MeV/c^2 is related to the G(1590) scalar put forward by the GAMS Collaboration. Data from hadron production do not add clarity to the picture: WA76 results on central production [19] of K^+K^- and $K_S K_S$ systems show (Fig. 18) good evidence for $f_2(1525)$ and '$\theta(1700)$' production, quoted to be fully compatible with $J^{PC} = 2^{++}$ assignments. It will take, at the very least, a high-statistics $\eta\eta$ study, in both radiative J/ψ decays and central hadronic production, to shed light on this situation!

Moving on to higher masses, we will finally investigate the $\phi\phi$ system in the reaction

$$J/\psi \to \gamma\phi\phi\ .$$

The final Mark III analysis of the 4K final states $K_S K_S K^+K^-$ and $K^+K^-K^+K^-$ has permitted a very detailed evaluation of the spin–parity content of the observed signal [22]. It is 'calibrated' by the clear observation, at the upper end of the 4K mass distributions, of the well-known pseudoscalar charmonium ground state η_c, which decays into this channel. The resulting mass distributions are shown, after background subtraction, in Fig. 19. In both charge samples, there is not only a clear η_c signal, but also a strong enhancement above threshold. Parametrized as a resonance, this enhancement gives compatible results from both data samples:

$$
\begin{aligned}
m(\mathrm{X} \to \mathrm{K^+K^-K^+K^-}) &= (2230 \pm 25 \pm 15)\ \mathrm{MeV}/c^2 \\
\text{with } \Gamma &\cong 150\ \mathrm{MeV}/c^2 \\
\mathrm{B}(\mathrm{J}/\psi \to \gamma\mathrm{X}) \times 10^4 &= 3.3 \pm 0.8 \pm 0.5\ ,
\end{aligned}
$$

and

$$
\begin{aligned}
m(\mathrm{X} \to \mathrm{K^+K^-K_SK_S}) &= (2214 \pm 20 \pm 15)\ \mathrm{MeV}/c^2 \\
\text{with } \Gamma &\cong 150\ \mathrm{MeV}/c^2 \\
\mathrm{B}(\mathrm{J}/\psi \to \gamma\mathrm{X}) \times 10^4 &= 2.7 \pm 0.6 \pm 0.6\ .
\end{aligned}
$$

As Figs. 20a and b conclusively show, the spin–parity structure of this enhancement is pseudoscalar, $J^{PC} = 0^{-+}$, as are all other $\mathrm{V\bar{V}}$ enhancements observed above their respective threshold values in radiative J/ψ decays [23]. This is illustrated in the 'calibration signals' that show the corresponding angular distributions of the η_c peak.

The inference is inescapable that the claimed $\mathrm{g_T}$ resonances are not visible in this gluon-rich channel; in fact, we can establish [22] an upper limit for $\mathrm{g_T}$ production, at the 90% CL, of $\mathrm{B} < 1.16 \times 10^{-4}$—none too restrictive, but not at all confirming what badly needs confirmation!

5. WHERE DO WE STAND TODAY?

The detailed studies reported in Section 4 did not strengthen a single one of the promising candidates of Section 3; in fact, all of them were considerably weakened, if not outright removed.

Crudely speaking, there is no 'smoking-gun' candidate for gluonium left: low-mass scalars look as elusive as ever, there is no gluonic behaviour in evidence. There are still more pseudoscalar terms than the simple-minded quark model/$\mathrm{SU_6}$ phenomenology can accommodate in its ground state—but there is no dearth of available slots for radial excitation of η, η'. The precision studies of the ι region in the $\mathrm{K\bar{K}}\pi$ and $\eta\pi\pi$ systems have discredited their gluonium candidacy: $\eta(1400)$ and $\mathrm{f_1}(1420)$ are neatly found here as in hadronic reactions, only the pseudoscalar (1490), nearly identified here, may have interesting implications.

The pseudoscalar $\mathrm{V\bar{V}}$ states above threshold have been seen in $\phi\phi$ with $J^{PC} = 0^{-+}$, as previously in $\rho^0\rho^0, \rho^+\rho^-, \omega\omega, \mathrm{K^*\bar{K}^*}$. Their dynamical origin remains unclear, but looks hardly gluonic [23].

As for $\theta/\mathrm{f_2}(1720)$, it refuses to hold up as a credible candidate; its reappearance in the scalar sector of $\mathrm{K\bar{K}}$ is disturbing, and a large sample of $\eta\eta$ is not available at present.

The G(1590) needs to be identified by a non-GAMS experiment. The g_{T} states remain unconfirmed: if gluonic, they must be present in $\mathrm{J}/\psi \to \gamma\phi\phi$.

There is clearly room in the observed meson yield X of $\mathrm{J}/\psi \to \gamma\mathrm{X}$ for surprises with masses $m(\mathrm{X}) \geq 1.5\ \mathrm{GeV}/c^2$, but this is a question for future analysis, with better statistics and systematics.

6. WHAT IS NEXT?

Of those projects active at present, we expect new data from the Beijing electron collider and from the Crystal Barrel experiment ($\mathrm{p\bar{p}}$ annihilation) at CERN. The latter has the advantage of being able to see entirely neutral final states—but the disadvantage of ill-defined space–time properties of the initial state. The former will have higher luminosities than SPEAR, but probably not by a large amount. An interesting niche may be filled, with a precision look at low-mass pion pairs, by the e^+e^- collider at $\sqrt{s} = m(\phi)$, looking for $\phi \to \gamma X$, $X \to \pi^+\pi^-$ or $\pi^0\pi^0$.

Beyond that, a big step in statistics *and* in reduced systematic uncertainties will open up with the operation of a Tau-Charm Factory [24], a '1000 SPEARs'. That facility will not only profit from these obvious improvements; it will also permit an independent approach to the gluonium question by the availability of a large sample of tagged η' decays [25].

And maybe, just maybe, our concepts of how clearly gluonic matter will show up in our data samples are too simplistic.

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REFERENCES

[1] See the review in S. Narison, World Scientific Lecture Series in Physics, Vol. 26 (1989).

[2] See, for instance, C.A. Heusch, *in* Multiparticle dynamics 1986 (World Scientific, Singapore, 1987), p. 247.

[3] M. Sveč, J. Phys. France **46**, C2, Suppl. 2 (1985).

[4] D. Alde et al., Nucl. Phys. **B269**, 485 (1986).

[5] C.D. Edwards et al., Phys. Rev. Lett. **49**, 259 (1982).

[6] See discussion in Ref. [2].

[7] A. Billoire et al., Phys. Lett. **80B**, 381 (1979); R. Lacaze and H. Navelet, Nucl. Phys. **B165**, 67 (1980).

[8] C.D. Edwards et al., Phys. Rev. Lett. **48**, 458 (1982).

[9] A. Etkin et al., Phys. Rev. Lett. **49**, 1620 (1982).

[10] C.A. Heusch, in Quarks, leptons, and their constituents, ed. A. Zichichi (Plenum Press, New York, 1988), p. 440.

[11] T. Bolton (Mark III Collab.), private communication, to be published (1991).

[12] J.P. Stroot, preprint CERN–PPE/91–02, Invited talk given at QCD '90, Montpellier, 1990.

[13] M. Chanowitz, Proc. VIth Int. Workshop on Photon–Photon Collisions, Granlibakken (Lake Tahoe), 1984, ed. R. Lander (World Scientific, Singapore, 1985), p. 95.

[14] Z. Bai et al. (Mark III Collab.), Phys. Rev. Lett. **65**, 2507 (1990).

[15] For details, see J. Drinkard, Ph.D. Thesis, Univ. California at Santa Cruz report SCIPP 90/04 (1990), unpublished.

[16] Z. Bai et al. (Mark III Collab.), to be published (1991). A preliminary version was shown in C.A. Heusch and M. Burchell, Proc. Hadron '89, Ajaccio, 1989, eds. F. Binon et al. (Editions Frontières, Gif-sur-Yvette, 1990), p. 61.

[17] S. Fukui et al., preprint KEK 90–191, submitted to Phys. Lett. B (1991).

[18] A. Ando et al., Phys. Rev. Lett. **57**, 1296 (1986).

[19] T.A. Armstrong et al., Proc. Hadron '89, Ajaccio, 1989, eds. F. Binon et al. (Editions Frontières, Gif-sur-Yvette, 1990), p. 91.

[20] C. Gounaris and J.E. Paschalis, Phys. Lett. **B251**, 639 (1990).

[21] L.P. Chen et al., Stanford preprint SLAC-PUB 5378 (1990), presented at Rheinfels Workshop on Hadron Mass Spectrum, St. Goar, 1990.

[22] Z. Bai et al. (Mark III Collab.), Phys. Rev. Lett. **65**, 1309 (1990).

[23] C.A. Heusch, *in* Current issues in hadron physics, ed. J. Tran Thanh Van (Editions Frontières, Gif-sur-Yvette, 1988).

[24] M. Davier, these Proceedings.

[25] C.A. Heusch, *in* Proc. Tau-Charm Factory Workshop, Stanford, 1989 (SLAC Report 343 , Stanford, 1989).

[26] P. Baillon et al., Nuovo Cimento **50A**, 393 (1967).

Table 1
Partial waves used for analysis of the process $J/\psi \to \gamma K\bar{K}\pi$
via two-body intermediate states

J^{PC} (X)	Decay mode	Definition
0^{-+}	$K^*\bar{K} + c.c.$	K*K P-wave
1^{++}	$K^*\bar{K} + c.c.$	K*K S-wave, K*K D-wave
1^{-+}	$K^*\bar{K} + c.c.$	$1^{-+}K^*K$
0^{-+}	$a_0(980)\pi$	$a_0\pi$ S-wave
1^{++}	$a_0(980)\pi$	$a_0\pi$ P-wave

Table 2
Resonance signals extracted from PWA of the radiative
processes $J/\psi \to K\bar{K}\pi$ and $\eta\pi\pi$ for the mass range 1.2–1.5 GeV/c^2;
$f_1(1285)$ was not fitted, but is shown for comparison.

State	J^{PC}	Mode	Γ [MeV/c^2]	$B^3R\times10^4$
$f_1(1285)$	1^{++}	$\to a_0\pi$		$2.6 \pm 0.28 \pm 0.6$
		$\to \eta\pi\pi$		
$\eta(1400)$	0^{-+}	$\to a_0\pi$		
		$\to \eta\pi\pi$	$45 \pm 13 \pm 9$	$3.4 \pm 0.33 \pm 0.6$
		$\to \bar{K}K\pi$	$54 \pm 30 \pm 17$	$6.8 \pm 0.8 \pm 1.4$
$f_1(1440)$	1^{++}	$\to K^*K$		
		$\to K\bar{K}\pi$	$68 \pm 21 \pm 8$	$6.6 \pm 27 \pm 1.9$
X(1486)	0^{-+}	$\to K^*K$	$91 \pm 50 \pm 25$	$10.3 \pm 2.0 \pm 2.3$
		$\to K\bar{K}\pi$		

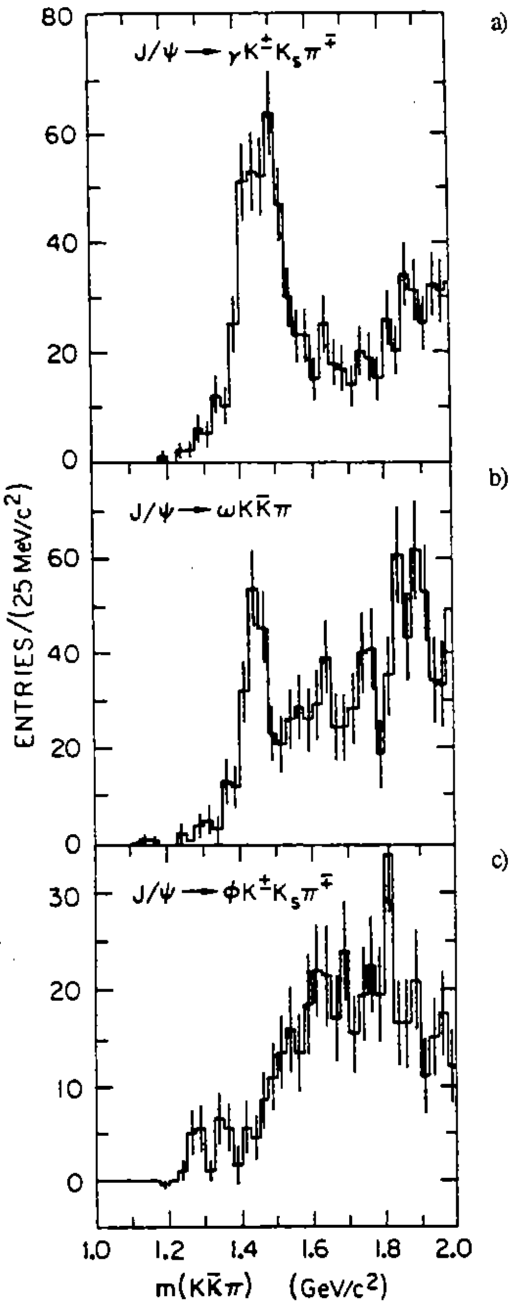


Fig. 1 a) Radiative decay, and b) and c) hadronic decays of J/ψ into a vector and a K$\bar{K}\pi$ system. The broad structure in (a) cannot be fitted to one Breit–Wigner resonance term. The narrower state visible in (b) is clearly correlated with the (u, d) quark content of the accompanying W. No such quark correlation is visible in (c). Mark III data.

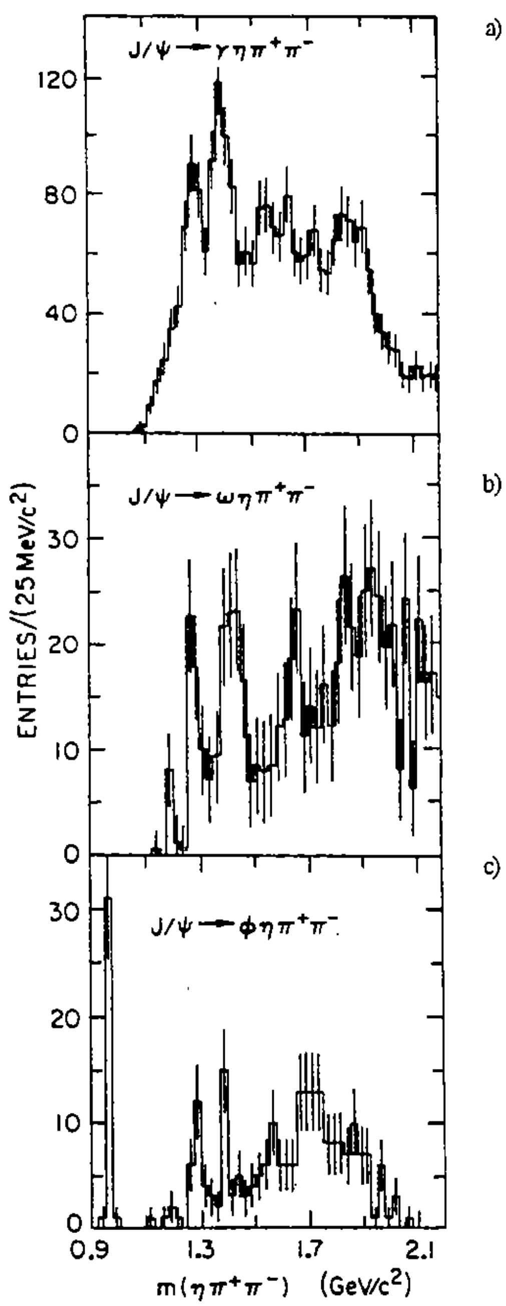


Fig. 2 Same as Fig. 1 for J/$\psi \to$ vector + $\eta\pi\pi$. The two peaks seen in (a) appear to be correlated with the quark-based structure in (b), but only the lower one also appears in (c). Possible interpretation is a (u, d)-based structure at $\sim$ 1400 MeV/c^2, a mixed (u, d, and s) state at $m \leq 1300$ MeV/c^2. Mark III data.

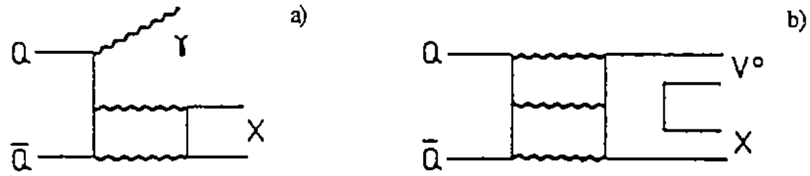


Fig. 3 Quark correlation graphs. V stands for ω ($u\bar{u}$, $d\bar{d}$) or ϕ ($s\bar{s}$).

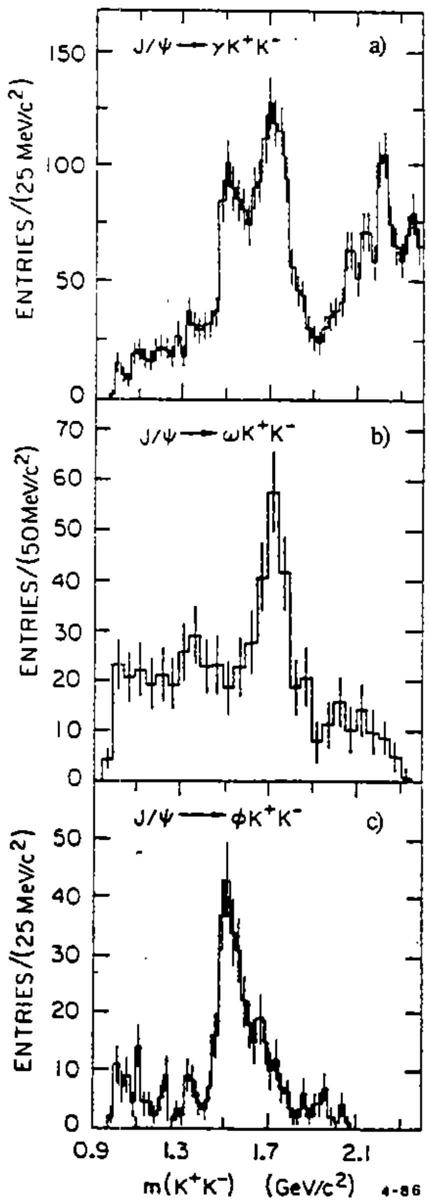
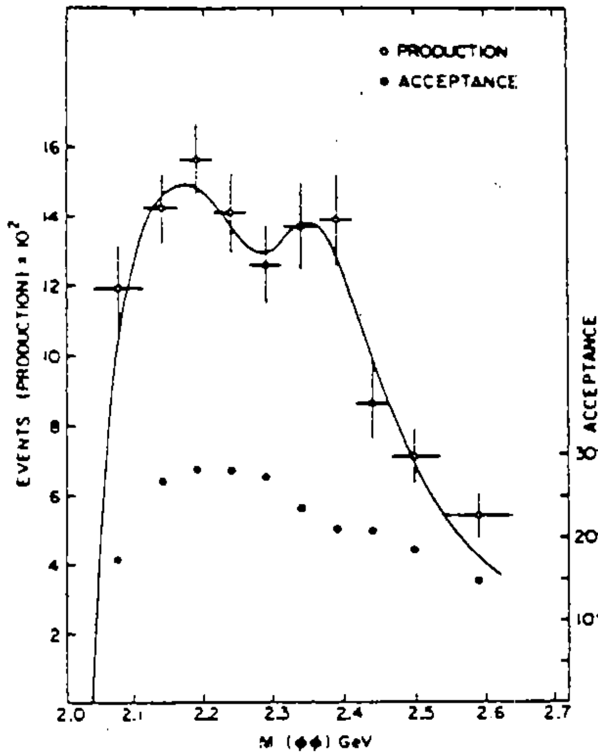
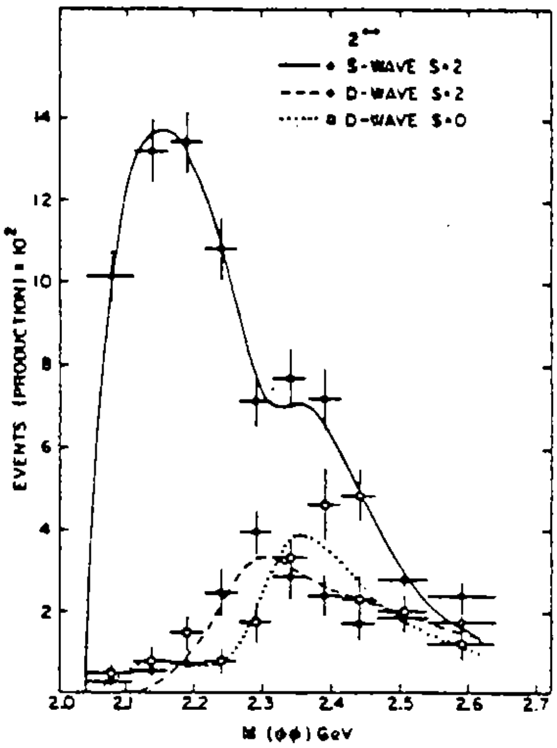


Fig. 4 Same as Fig. 1 for $J/\psi \rightarrow$ vector + K^+K^-; a) shows two well-resolved peaks; b) shows a narrower upper structure, obviously correlated with (u, d) quark content; c) shows that $f_2(1525)$ is s-quark based. Mark III data.



a)



b)

Resonance parameters reported for $\phi\phi$ system in $\pi^- p \to \phi\phi n$

State	Mass [MeV/c²]	Width [MeV/c²]
$g_T^{(1)}$	$2,050^{+90}_{-50}$	200^{+160}_{-50}
$g_T^{(2)}$	$2,300^{+20}_{-10}$	200^{+60}_{-50}
$g_T^{(3)}$	$2,350^{+20}_{-30}$	270^{+90}_{-130}

c)

Fig. 5 A strong $\phi\phi$ production enhancement (a), reported by various groups, was interpreted by Etkin et al. (b) in terms of three resonant waves, all in the $J^{PC} = 2^{++}$ channel. The resonance parameters are given in (c).

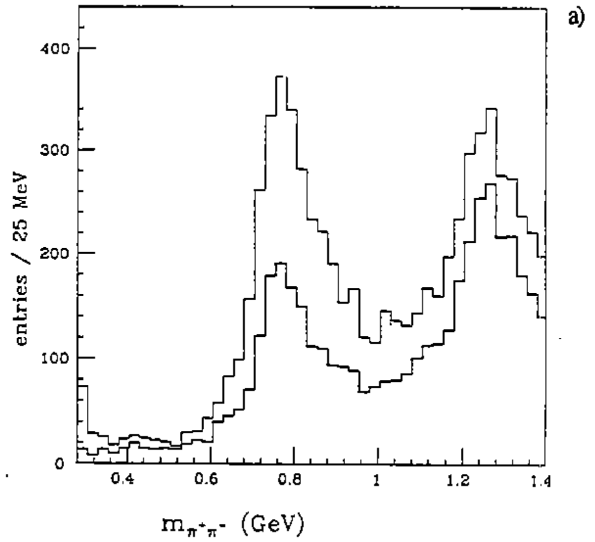
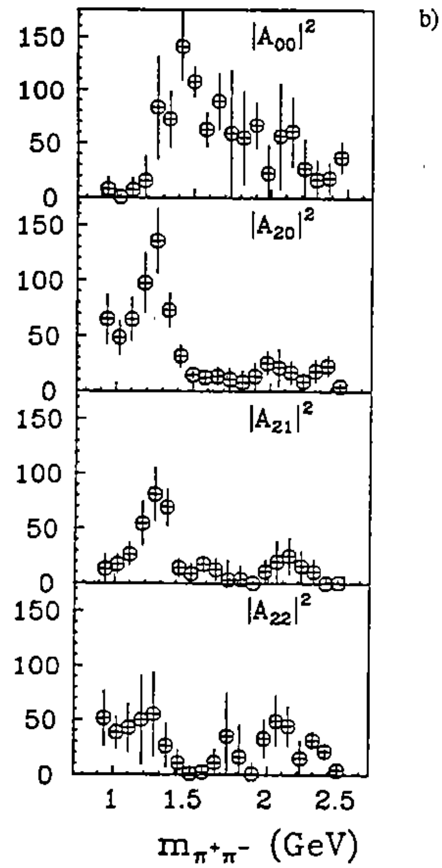


Fig. 6 The $\pi^+\pi^-$ mass spectrum (a) and amplitude fit (b) for the process $J/\psi \to \gamma\pi^+\pi^-$. Stringent selection criteria do not fully suppress the $\rho^0 \to \pi^+\pi^-$ feedthrough signal from the process $J/\psi \to \pi^0\pi^+\pi^-$, where one photon is lost from $\pi^0 \to 2\gamma$. At higher masses, the amplitude fits show a broad scalar enhancement above the $K\bar{K}$ threshold, with a total branching fraction of $\leq 8 \times 10^{-5}$. By comparison, the $f_2(1270)$ signal in the lower graphs of (b) translates into $B \sim 8 \times 10^{-4}$.



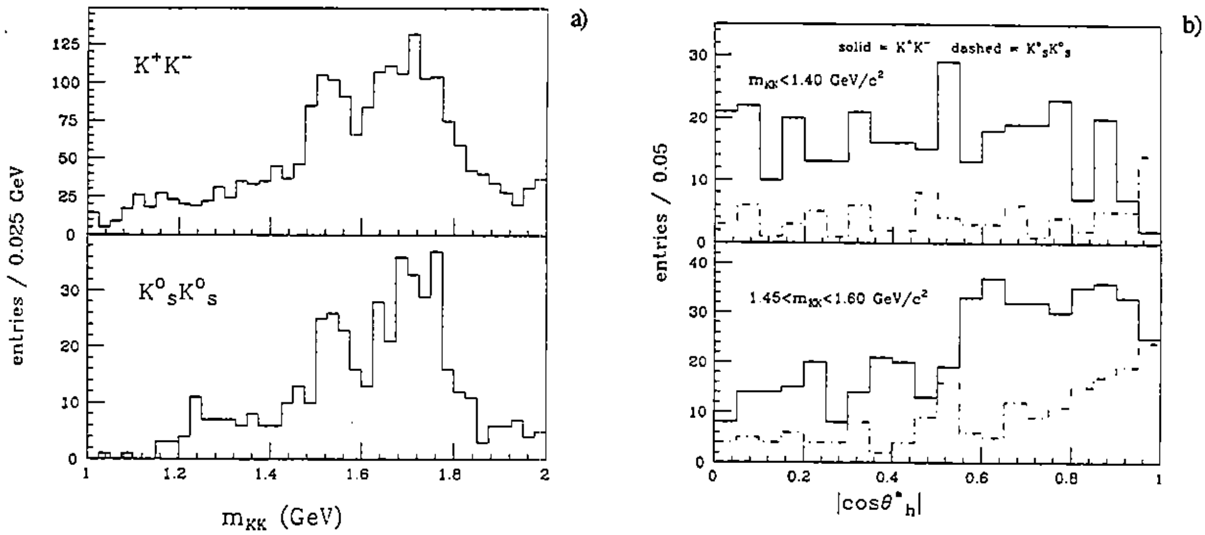


Fig. 7 New Mark III analysis of $J/\psi \to \gamma K\bar{K}$: a) mass distributions give evidence for $f_2(1525)$ and one higher state, b) angular distributions support a broad scalar continuum above threshold.

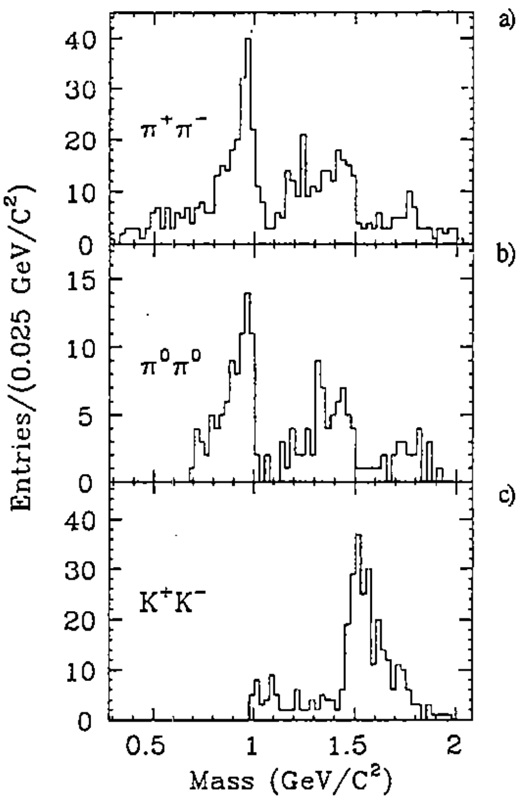
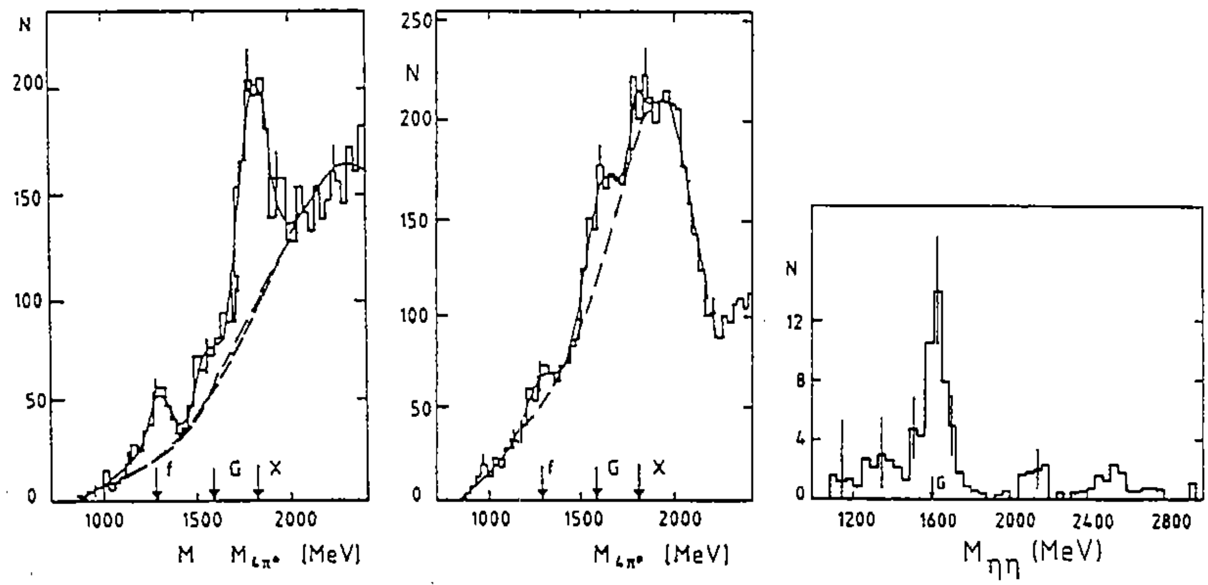


Fig. 8 a) $\pi^+\pi^-$, b) $\pi^0\pi^0$, and c) K^+K^- mass distributions from the Mark III data sample of the decays $J/\psi \to \phi(\pi^+\pi^-)$, etc. There is no structure in the low-mass $\pi\pi$ yield (which is clearly uncorrelated with the quark content of the ϕ).



a) b) c)

Fig. 9 New results from the GAMS Collaboration: a) $\eta\eta$ systems emitted in central production of $\pi^- p \to \eta\eta n$. The background subtraction leaves a clear G(1590) signal; $4\pi^0$ mass spectrum from $\pi^- p \to X^0 n$ central production: cuts favour $J^P = 2^+$ states, b) same for $J^P = 0^+$, c) scalar projection of $\eta\eta$ final state.

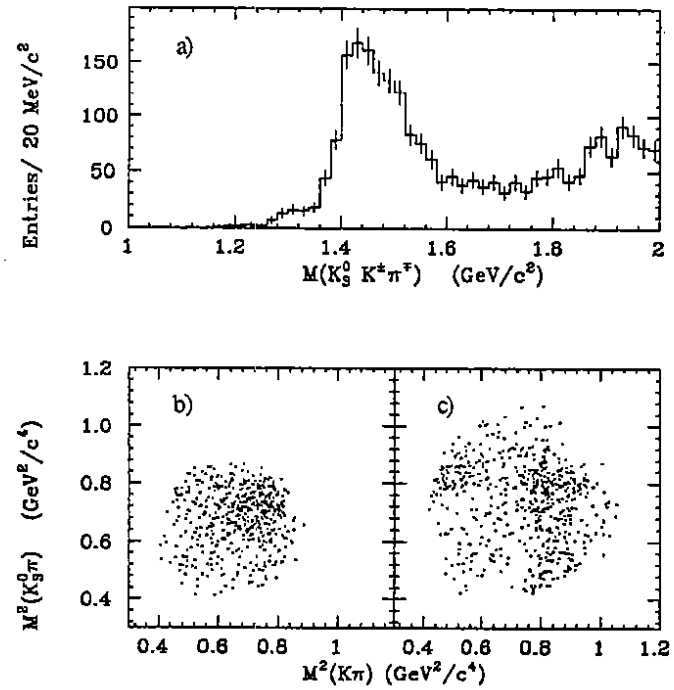


Fig. 10 $K\bar{K}\pi$ system emitted in radiative J/ψ decay: a) mass plot, b) and c) Dalitz plots for $K\pi$ systems in lower and upper mass bands, respectively.

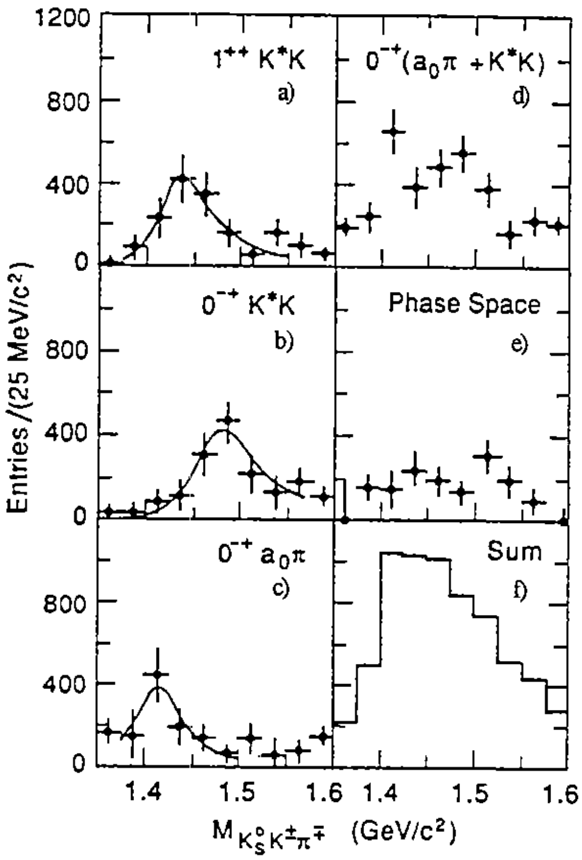


Fig. 11 Results of a partial-wave analysis of the $K\bar{K}\pi$ systems: a), b), and c) give the relevant partial waves, while d) shows the full pseudoscalar sample.

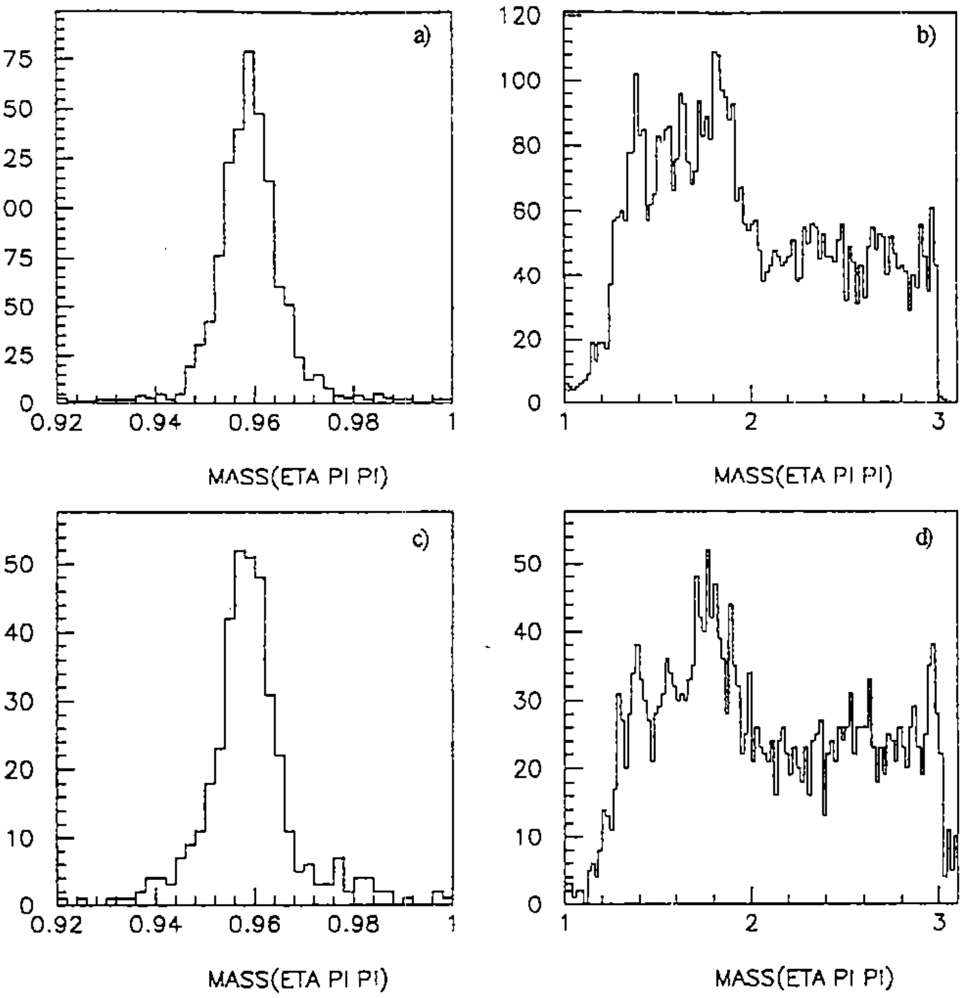


Fig. 12 The $\eta\pi\pi$ system emitted in $J/\psi \to \gamma\eta\pi^+\pi^-$: a) and b) show the η' peak for 2η decay modes; c) and d) the mass distributions.

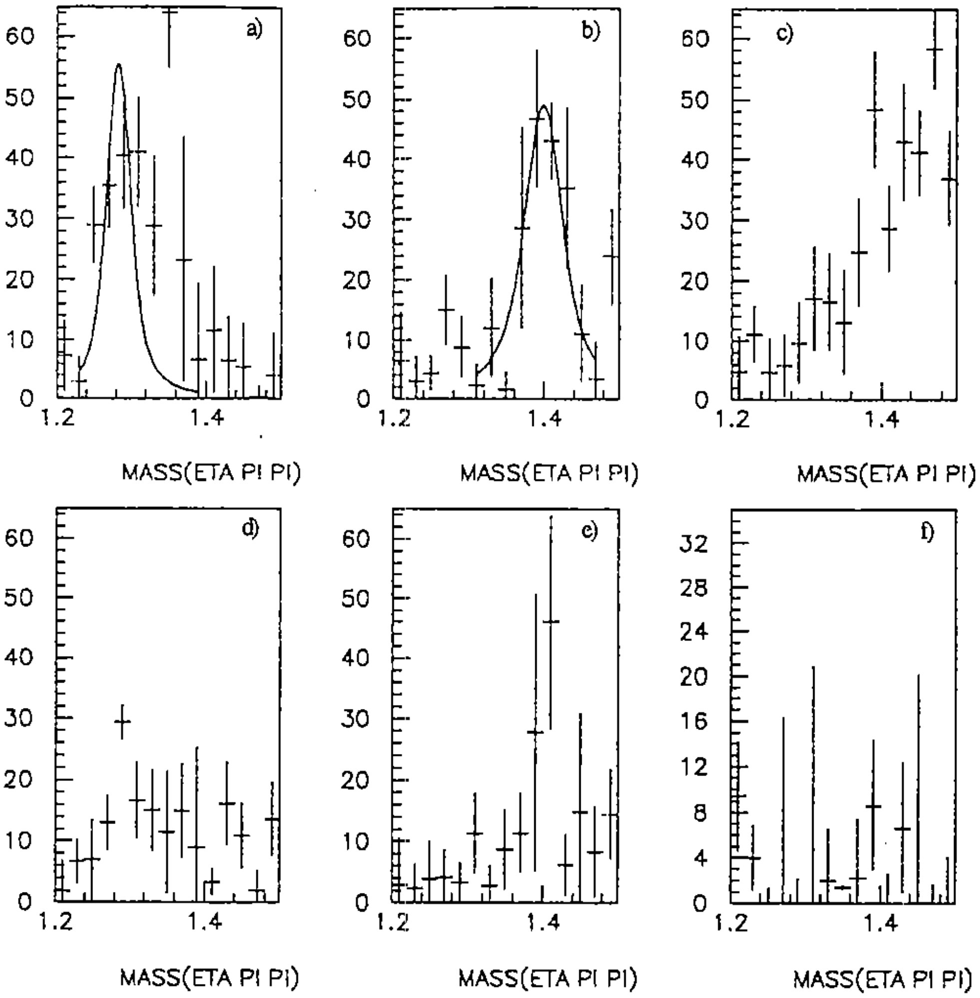


Fig. 13 Results of the partial-wave analysis: the activity in the $J^{PC} = 1^{++}$ $a^0\pi$ and 0^{-+} $a_0^0\pi$ channels is interpreted in terms of one resonant term each (a, b for $\eta \to 2\gamma$; d, e for $\eta \to \pi^+\pi^-\pi^0$). Note that the background terms are smooth, but very different for the 2η decay topologies (c, f). Mark III data.

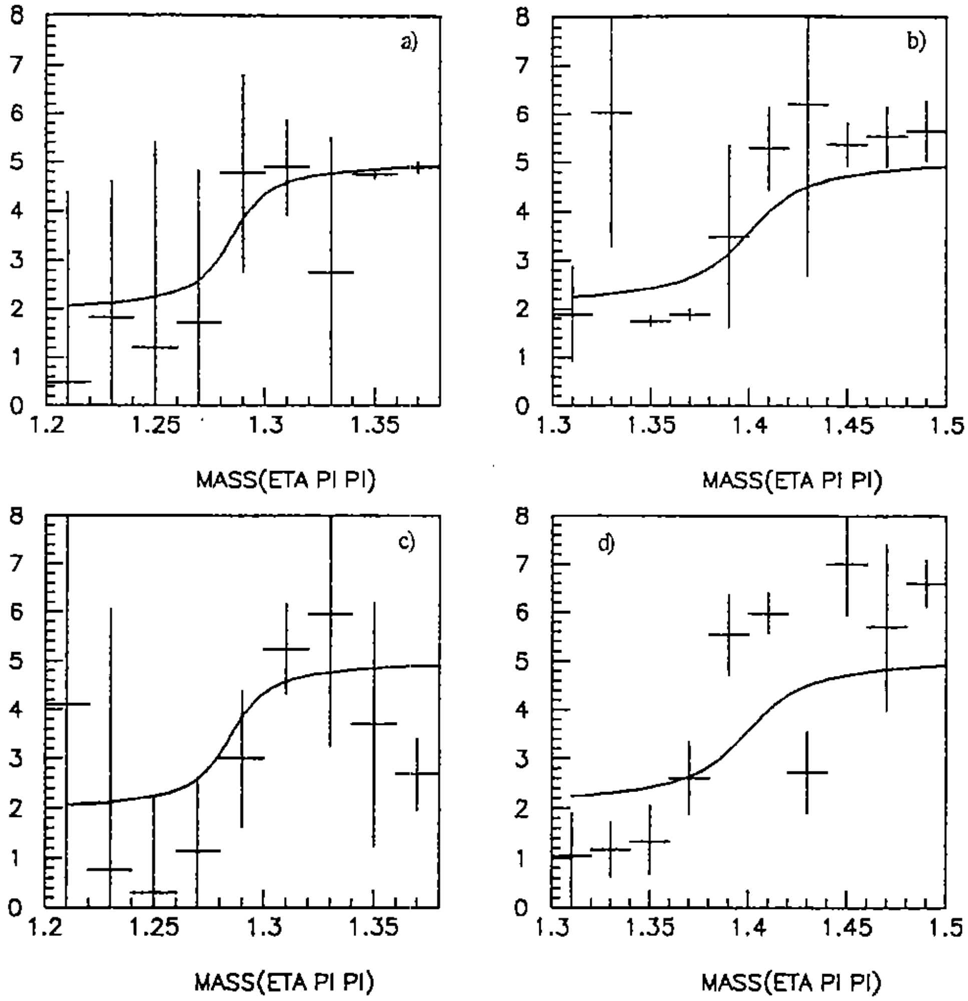


Fig. 14 Phase motion for the 'resonant' waves of Fig. 13: there is unmistakable evidence for relative changes at the energies corresponding to the mass peaks of Fig. 13.

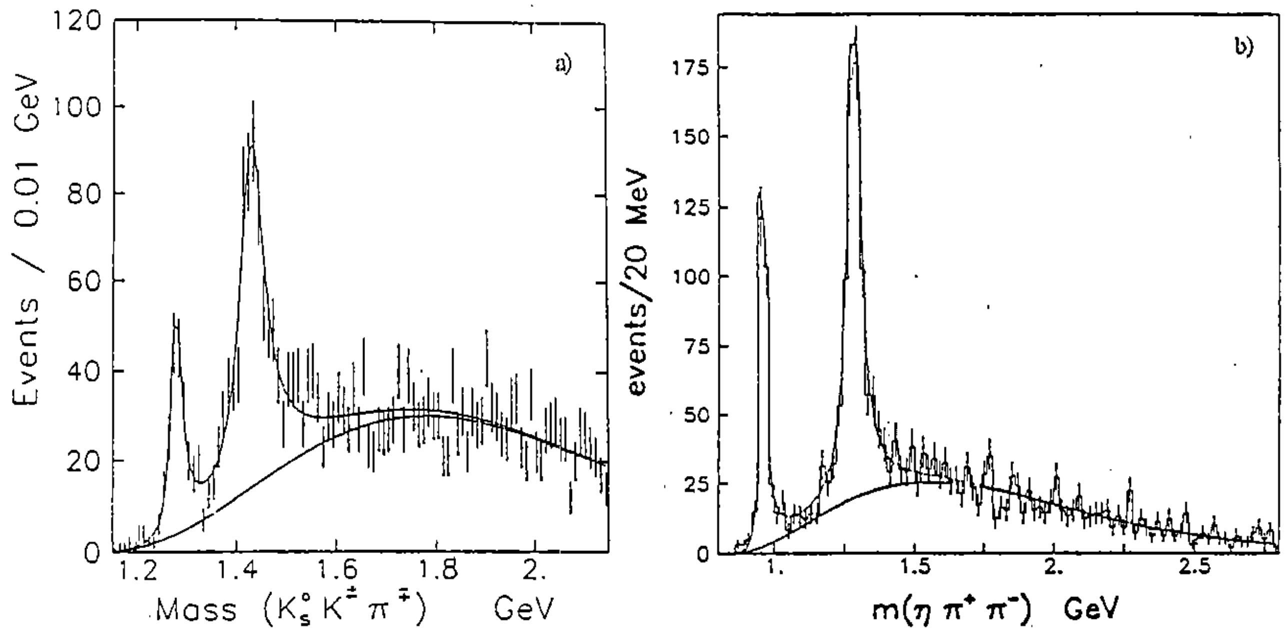


Fig. 15 Recent evidence from hadronic production in CERN Expt. WA76: a) the $K\bar{K}\pi$ mass spectrum is compatible with results from J/ψ decay, but shows no hint of structure at 1480 MeV/c^2; b) the $\eta\pi^+\pi^-$ mass spectrum has only η' and $f_1(1285)$ peaks.

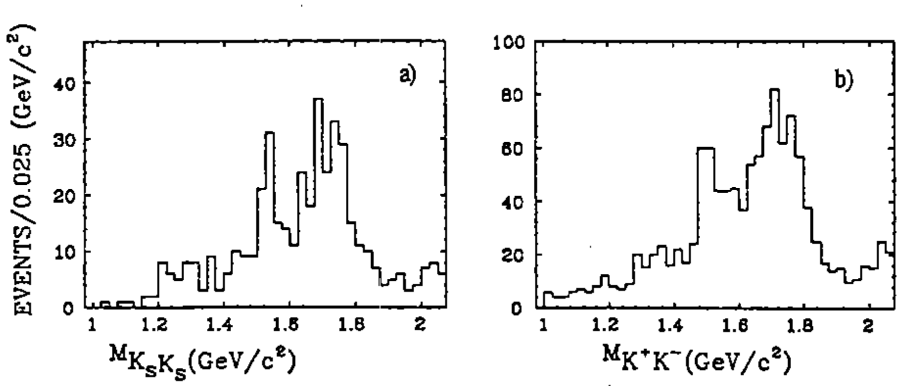


Fig. 16 New Mark III analysis of the $K\bar{K}$ system in radiative J/ψ decay: a) and b) give limits of f_2 and 'θ' in the K^+K^- and K_SK_S spectra.

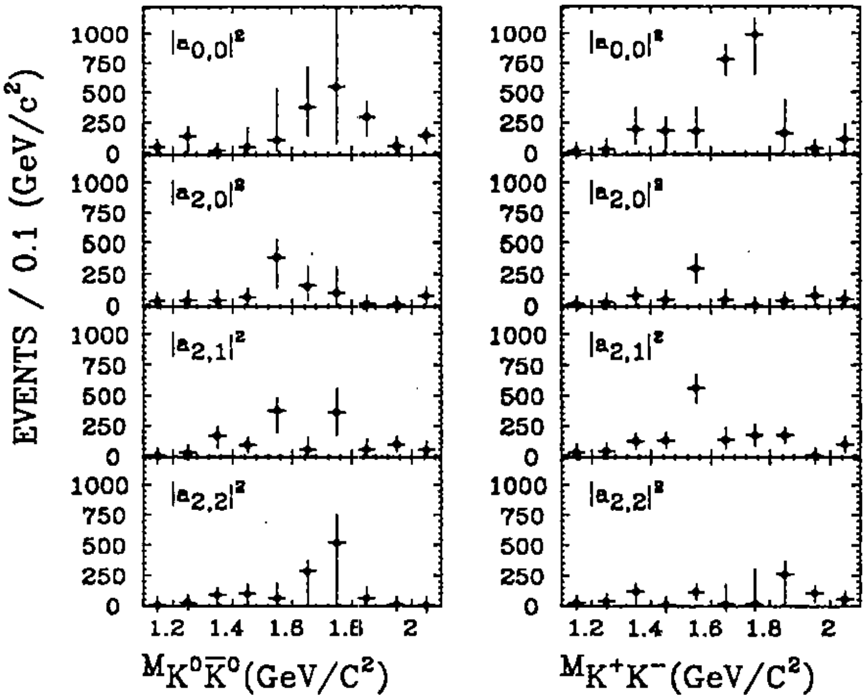


Fig. 17 The data from Fig. 16 show mostly tensor activity at the f_2 mass, mostly scalar at the mass of the 'θ' peak.

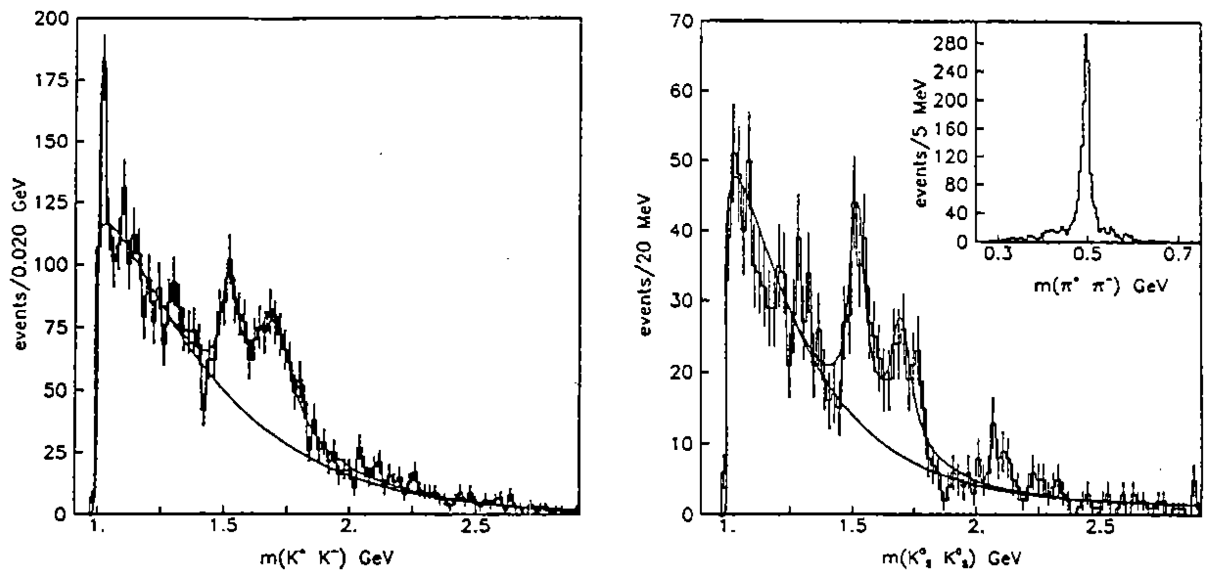


Fig. 18 Comparison with hadronic production data: WA76 shows a structure at f_2 and θ energies in the K^+K^- and $K^0_SK^0_S$ systems. Both appear to prefer $J^{PC}=2^{++}$.

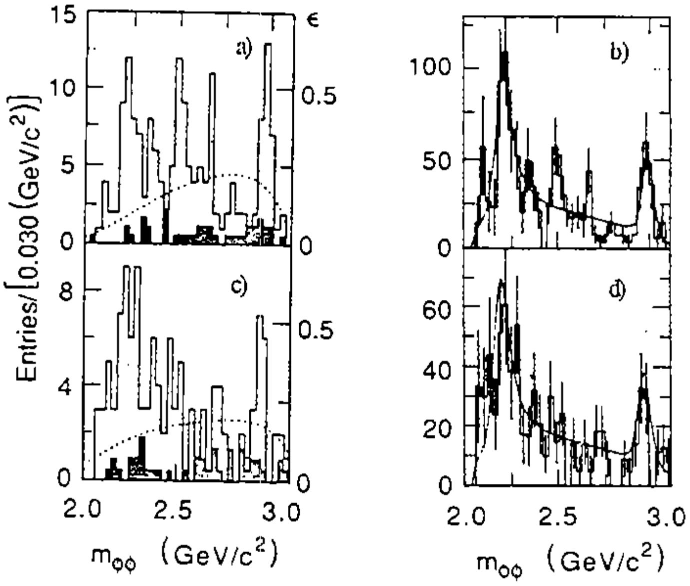


Fig. 19 Mark III data on $m(\phi\phi)$ in radiative J/ψ decay. There is an enhancement above threshold in a) the all-charged decays, b) the semi-neutral decays. The η_c peaks provide normalization.

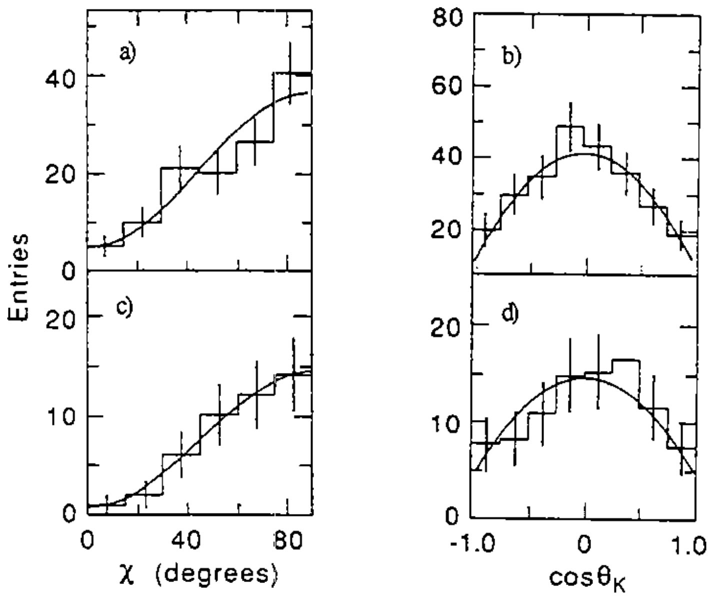


Fig. 20 Mark III data as above: both the lower-mass signals show clear $J^{PC} = 0^{-+}$ behaviour, just like η_c at the upper end of the mass spectrum in Fig. 19.

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