THE IOTA IN RADIATIVE J/ψ DECAYS

by
Mark Burchell
Santa Cruz Institute of Particle Physics
Univ. of California

SECTION I: INTRODUCTION

The continued study of light meson spectroscopy holds out two inviting prospects: (A) We can discover more about the mesons with masses 1 → 2 GeV/c^2, (B) if anomalous mesons are identified we will have found either **exotics** (states with quantum numbers not permitted by the standard quark model), **hybrids** (states which are quark-gluon mixtures) or **glueballs** (bound gluon states). Both these objectives are intimately related as the experimental evidence for many of the light mesons expected in the quark model is poor. Only four nonets are unambiguously known, the $0^{-+}, 1^{--}, 2^{++}$ and 3^{--}. In the other nonets there are problems, e.g. in the 0^{++} nonet there are still questions about the true nature of the $a_0(980)$ and $f_0(975)$. Further we also lack firm predictions for the exotics/hybrids/glueballs. There is therefore a great need for systematic studies of light mesons, concentrating on measurements not just of mass and width but also of spin and parity.

The decays of the J/ψ produced at rest, are a good laboratory for such studies. Given the OZI suppression of strong J/ψ decays, the electromagnetic decays are equally accessible. Radiative J/ψ decays (see figure 1) offer a particularly clean environment for searches for light mesons. Several experiments (MarkII, Crystal Ball, DM2 and MarkIII) have accumulated large samples of J/ψ decays at rest and have searched for decay modes down to branching ratios of some 10^{-4}. Clean, strong signals are seen for many mesons of interest. One of the glueball candidate states that has emerged in the last 10 years or so is the "iota" (mass around 1440 MeV/c^2, width 40 → 80 MeV/c^2). This is seen very well in radiative J/ψ decays in the $KK\pi$ final state. Below I review the reported observations of this state, then, using MarkIII data, I'll discuss the current status of our studies of the "iota" and also point to future directions for such work at a high statistics (10^9 J/ψ /month) τ-charm factory.

SECTION II: E/Iota ? A Brief History

This is not a full review of all observations of the "iota", but rather points out significant/typical results in hadroproduction, two-photon physics and J/ψ decays. The first report which included a J^{PC}determination, of a signal in $KK\pi$ around 1440 was made by Baillon *et al.*[1]. They studied $pp \rightarrow X^0\pi^+\pi^-, X^0 \rightarrow K^0K^\pm\pi^\mp$, and found that there was a signal X (which they called the E) with mass 1425±7 MeV/c^2, width 80±10 MeV/c^2 and J^{PC} 0^{-+}. They also found that the E decayed to $KK\pi$ almost 100% via an intermediate two-body decay involving K^* or $a_0(980)$ in the ratio 50:50. The authors determined the J^{PC} by assuming the data to be primarily due to certain amplitudes contributing to the decay matrix element. They used this normalization to predict the signal strengths due to related amplitudes in other channels, and compared these expectations to their observations. They also fit to a number of angular distributions arising from various amplitudes. At each stage in their work more than one amplitude is likely, but they dismiss all but 0^- on physical grounds (e.g. 'not satisfactory situation', or 'not..very natural'). Later fixed target experiments found a resonance in $KK\pi$ with similar mass and width, but favoured $J^{PC}= 1^{++}$. These experiments used π^- beams[2] (3.75 GeV/c^2) or π^+ and p beams[3][4] (85 GeV/c^2) on hydrogen targets, and determined J^{PC} via fits of angular distributions in the data to various amplitudes possibly contributing to the matrix element for the process (e.g. $0^{-+}, 1^{++}$, S or D wave, involving K^*or $a_0(980)$ etc). These experiments were considered more reliable than the original one and thus the resonance in $KK\pi$ came to be identified with $J^{PC}=$ 1^{++} and was called the E.

However, more recent fixed target experiments by Rath *et al.*,[5] (who use a 21 GeV π^- beam on a hydrogen target) and Birman *et al.*[6] (who study 8 GeV π^-p interactions) also produce strong signals in $KK\pi$ around 1440 MeV/c^2, but clearly favour $J^{PC}= 0^{-+}$. This state is identified as the iota. Again their analyses consider all possible contributing amplitudes to describe the data. It is interesting to note that Birman *et al.* find both 0^{-+} and 1^{++} contributions in the $1.4 \rightarrow 1.5$ GeV/c^{2}mass region, with 0^{-+} dominating around 1.42 GeV/c^2. Both K^* and $a_0(980)$ contribute to the 0^{-+} amplitudes.

The situation in hadroproduction is clearly complicated. A possible explanation is that there are two resonances similar in mass and width but with differing J^{PC}. However why one experiment is sensitive to one such resonance and not the other is not obvious. Also the degree to which the decays occur via K^* and $a_0(980)$ isobars varies from experiment to experiment.

In two photon physics (using tagged $\gamma\gamma^*$ events) several experiments (TPC[7], MarkII,[8]Jade[9] and Cello[10]) report low statistics signals in $KK\pi$ around 1420 → 1440 MeV/c^2 which are interpreted (via Yangs-Mills theorm) as spin 1. They find that decays via K^*K dominate. Interestingly they find no equivalent in their untagged (real $\gamma\gamma$) data samples. They conclude that there is a lack of an even spin resonance produced with equal strength.

In J/ψ decays the $KK\pi$ system recoiling against γ, ω or ϕ has been studied in search of the iota. Strong signals are seen in the radiative decays by several experiments (MarkII,[11] DM2[12] and MarkIII[13]); figure 2 is typical and shows the $KK\pi$ mass distribution in MarkIII data. The signal was quickly interpreted as 0^{-+} and the product branching ratio found to be $BR(J/\psi \rightarrow \gamma i)BR(i \rightarrow KK\pi) = 0.0047 \pm 0.0006$[14]. This is a surprisingly large value, and is indeed the largest two-body radiative decay mode of the J/ψ (the next largest two-body radiative decay is to $\gamma\eta'$ with BR $= 0.0042 \pm 0.0004$, while the radiative transition to $\gamma\eta_c$ has a BR $= 0.0127 \pm 0.0036$). The intention of the studies in hadronic J/ψ decays was to look for flavour correlations in iota production. Figure 3 shows possible diagrams leading to such correlations, where the quark content of the recoiling meson is tagged as strange (by the ϕ) or up/down (by the ω). The $KK\pi$ mass seen recoling from ϕ and ω in MarkIII data is shown in figure 4. A signal around 1440 MeV/c^2 is seen with the ω (and not with the ϕ). Figure 4d) shows the acceptance corrected distribution of the angle of normal to the ω decay plane in the ω helicity system, along with the prediction for a 0^{-+} resonance (solid curve). A clear difference is seen, and more detailed analysis favours a 1^{++} interpretation.[15] This analysis is however greatly limited by low statistics, and the search for flavour correlations and the assignment of J^{PC} would be much improved if repeated with the higher statistics of a τ-charm factory.

Taken as a whole these results seem to indicate the existance of two resonances around 1420 and 1440 MeV/c^2. One of these, the 1^{++}, would be the E (now known as the $f_0(1420)$) and the other, the 0^{-+}, as the iota (now known as the $\eta(1430)$). Also, considering all the evidence, the iota has been identified as a glueball candidate. This is mainly because

- Small two gamma width
- Strong production in radiative J/ψ decays (figure 1 shows how such decays couple via two gluons)
- The poor understanding of its appearance in some rather than all hadronic interactions.

None of these arguments is individually convincing, nor is their sum. To improve this situation I present the following list of questions which await definitive answers:

- If there are two resonances around 1420/1400 MeV/c^2 which is seen in which experiments and why ?
- What are the mass, width and $J^{PC}$of each resonance ?
- How does each resonance decay ?
- What is the quark content of each resonance ?
- Can either/both resonances be easily fit into conventional ($q\overline{q}$) nonets ?

In the next few pages I give the status of current studies of J/ψ decays (using the MarkIII data as being typical of all experiments) and discuss how future work at a τ-charm factory can answer some of these questions.

SECTION III: $J/\psi \rightarrow \gamma K K \pi$

Figure 3 shows that the data for 5.8 $\times 10^6$ J/ψ produced in the MarkIII experiment yields strong $KK\pi$ signals on low backgrounds in a variety of final states. I give in table I the number of events in the signal in $K_s K^+ \pi^-$, and assuming an equal efficiency for analysis, I predict how many such events will be available for 10^9 produced J/ψ . This assumption of equal efficiency is clearly an underestimate, as we hope a new detector will have improved acceptance for both charged tracks and photons, will have improved particle identification over a larger solid angle and more uniform photon acceptance (i.e. no barrel-endcap gap in calorimetry) etc. The result will be a very large number of events for analysis.

Table I. Number Of Accepted Events In Present And Future Work

Decay	Mass (MeV/c^2)	MarkIII	τ-charm
$K_s K^+ K^-$	1440	1,235	212,000
$\eta \pi^+ \pi^-$	1285	80	13,790
$\eta \pi^+ \pi^-$	1390	112	19,310
$\gamma \rho$	1440	130	22,410

Current analysis has tried fitting one or two Breit-Wigners to the mass plot (one BW is insufficient to describe the signal shape). A decay plane analysis has been tried, which involves a fit to various angles assuming a prediction for the resonance as 0^{-+} or 1^{++} (the main angles are θ_γ, the angle of the radiative photon to the beam direction, and the normal to the $KK\pi$ decay plane). Finally the most comprehensive type of analysis involves a simultaneous fit to the predictions of angular distributions arising from any amplitude for the decay $J/\psi \rightarrow \gamma X, X \rightarrow KK\pi$, where the decay of X proceeds via an appropriate isobar (K^*or $a_0(980)$). The amplitudes are constructed using the Zemach tensor formalism.[16] Such amplitudes contain both the angular dependence for a decay and the momentum dependence. To obtain the maximum advantage from such an analysis, high statistics signals are needed, combined with uniform (and preferably complete) acceptance in all angular distributions. This latter point is illustrated in figure 5 where the acceptance corrected distributions for $cos\theta_\gamma$ are shown for 0^{-+} and 1^{++} (for the latter this is not uniquely predicted, it is dependent on x, the ratio of the ψ helicity amplitudes, and two possibilities are shown). Shown in figure 5d) are the dead regions in $cos\theta_\gamma$ in MarkIII analysis. Clearly the resolving power in this angle is greatly increased not only by extending the coverage to $cos\theta_\gamma = \pm 1$ but also by eliminating the cuts due to the barrel/endcap gap and the need for supporting spars for the barrel.

For this analysis key requirements for a new detector are :

- The extended, uniform $cos\theta_\gamma$ coverage discussed above.
- Charged particle tracking over as much of 4π as possible
- Photon detection with high (and uniform) efficiency down to photon energies of at least 50 MeV/c^2. To illustrate this need figure 6 shows the lowest photon energy per event in a MC of $J/\psi \to \gamma X, X \to K^{*0}\pi^0, \pi^0 \to \gamma\gamma$. A cut at 100 MeV/c^2 (as needed in present MarkIII analysis due to falling efficiency) would remove 48% of events.
- Particle id in the momentum range 100 → 1000 MeV/c. The kaon momentum in the same MC is shown in figure 7, and the distribution is well within limits achievable with dE/dx or TOF. However, such particle id should cover as much of 4π as possible.

Finally I note that the J^{PC} determination described earlier is carried out in mass bins. To see the variation with mass of the contributions from different amplitudes (and hence reveal each resonance) binning on the order of 10 MeV/c^2 is required. A mass resolution smaller than this is thus required. Using a MC simulation of the 'perfect' detector ($(\delta E/E)^2 = 2\%/\sqrt{E}$, $(\delta p/p)^2 = 0.4\% p$ in GeV) the reconstructed $KK\pi^0$ mass has a mass resolution at 1440 MeV/c^2 of 9.9 ± 0.3 MeV/c^2. This is already sufficient and after a 4c kinematic fit will improve further.

SECTION IV: $J/\psi \rightarrow \gamma\eta\pi^+\pi^-$

This channel is of interest as several experiments reported that the iota decayed to $KK\pi$ via $a_0(980)\pi$, and the $a_0(980)$ is known to decay to both KK and $\eta\pi$. Thus $\eta\pi^+\pi^-$ has been studied for evidence of the E/iota. The results are confusing at first glance. Figure 8 shows the $\eta\pi^+\pi^-$ mass distribution in MarkIII data after a cut is made requiring an $\eta\pi$ mass compatible with the $a_0(980)$ (data for two η decays are shown, to $\pi^+\pi^-\pi^0$ and to $\gamma\gamma$). No signal is seen around 1440 MeV/c^2, but a new signal is seen at 1390 MeV/c^2 . Again detailed analysis is underway but the lack of statistics and a large background present problems.

Table I gives estimates for the yield at a τ-charm factory for both the signals seen in figure 8a) (at 1285 and 1390 MeV/c^2). Both will be observed with greater than 10,000 events. In this analysis high photon detection efficiency at low photon energies will be important. Figure 9 shows the distribution of energy for the lowest energy photon in a MC of $J/\psi \rightarrow \gamma\eta\pi^+\pi^-, \eta \rightarrow \pi^+\pi^-\pi^0, \pi^0 \rightarrow \gamma\gamma$. The current MarkIII analysis imposes a cut at 100 MeV, if good efficiency can be maintained down to 30 MeV the acceptance increases dramatically. The only new detector requirement not mentioned in the previous section is that for a neutral trigger, here this would permit access to the $\eta' \rightarrow \eta\pi^0\pi^0, \eta \rightarrow \gamma\gamma$ decays. It is also worth noting that any improvement in mass resolution will improve the separation of the 1285 and 1390 signals.

SECTION V: $J/\psi \rightarrow \gamma\gamma\rho$

The possible decay of the iota to $\gamma\rho$ has been suggested[17] as an interesting test of the nature of the iota. MarkIII's current data is shown in figure 10 and a signal is seen at 1440 MeV/c^2, along with one at 1285 MeV/c^2. The ideal analysis will again be a J^{PC} determination using a fit to the amplitudes possibly contributing to the matrix element for the decay process. The existing low statistics make this difficult, but table I shows that at a τ-charm factory the signal strengths will be more suitable for such an analysis. There are no new detector requirements desirable that are not already covered in the previous sections.

SECTION VI: Summary

The main objective of this work has been to show that in $KK\pi$ (and $\eta\pi^+\pi^-$) there may be two resonances in the mass range 1400 → 1500. There is thus a need to be able to be able to disentangle possible contributions to the invariant mass distribution from at least two mesons with similar masses and widths but differing J^{PC}'s. The analysis methods currently in use by both DM2 and MarkIII are sufficient for this. However the current analyses are limited by the signal statistics and difficulties in fully resolving angular distributions caused by incomplete and non-uniform acceptances. A τ-charm factory will provide both the necessary statistics and the improved acceptance. We can thus expect to be able to answer the questions concerning the number of resonances around 1440 MeV/c^2, their masses, widths and J^{PC}'s, as well as their favoured decay modes. To obtain the full benefit of this work the results should be combined with studies of hadronic J/ψ decays. Also depending on the masses of the resonances it may be possible to look for threshold effects in the decays $J/\psi \rightarrow \gamma\rho\rho$ or $J/\psi \rightarrow \gamma\omega\omega$.

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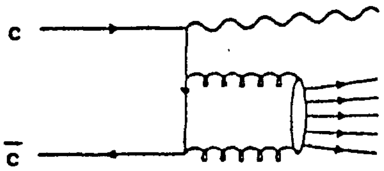
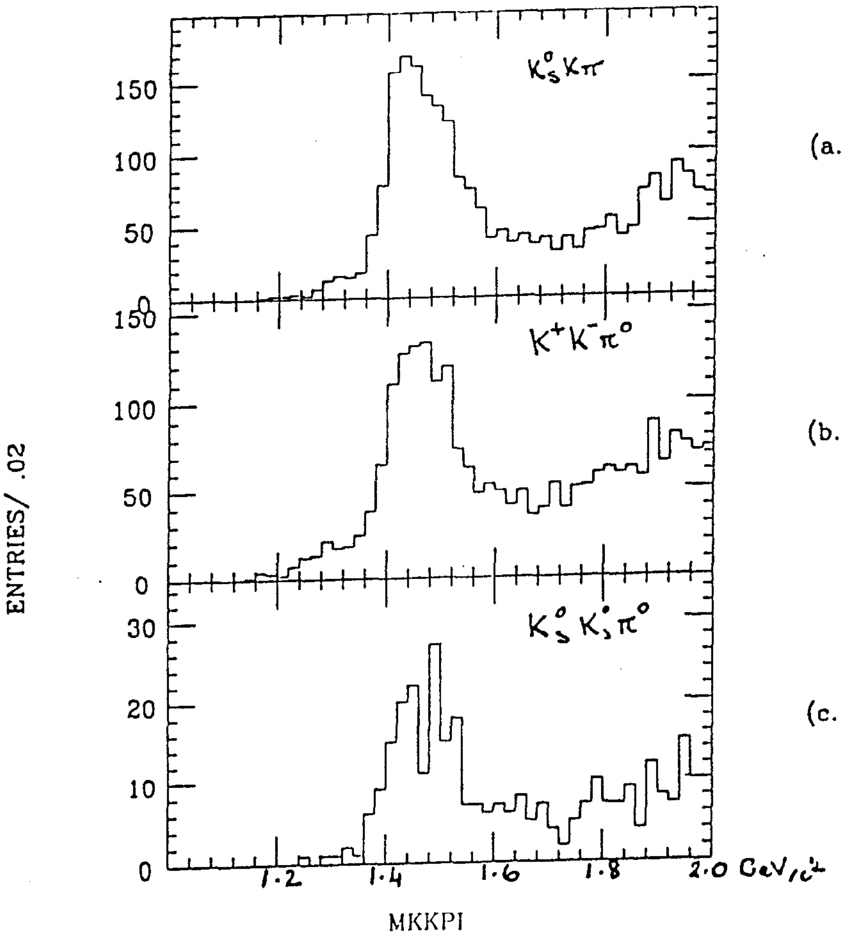
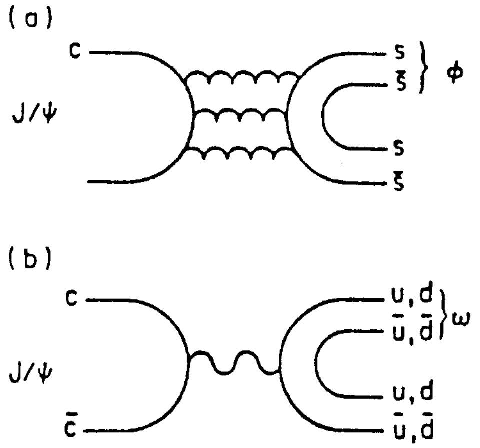


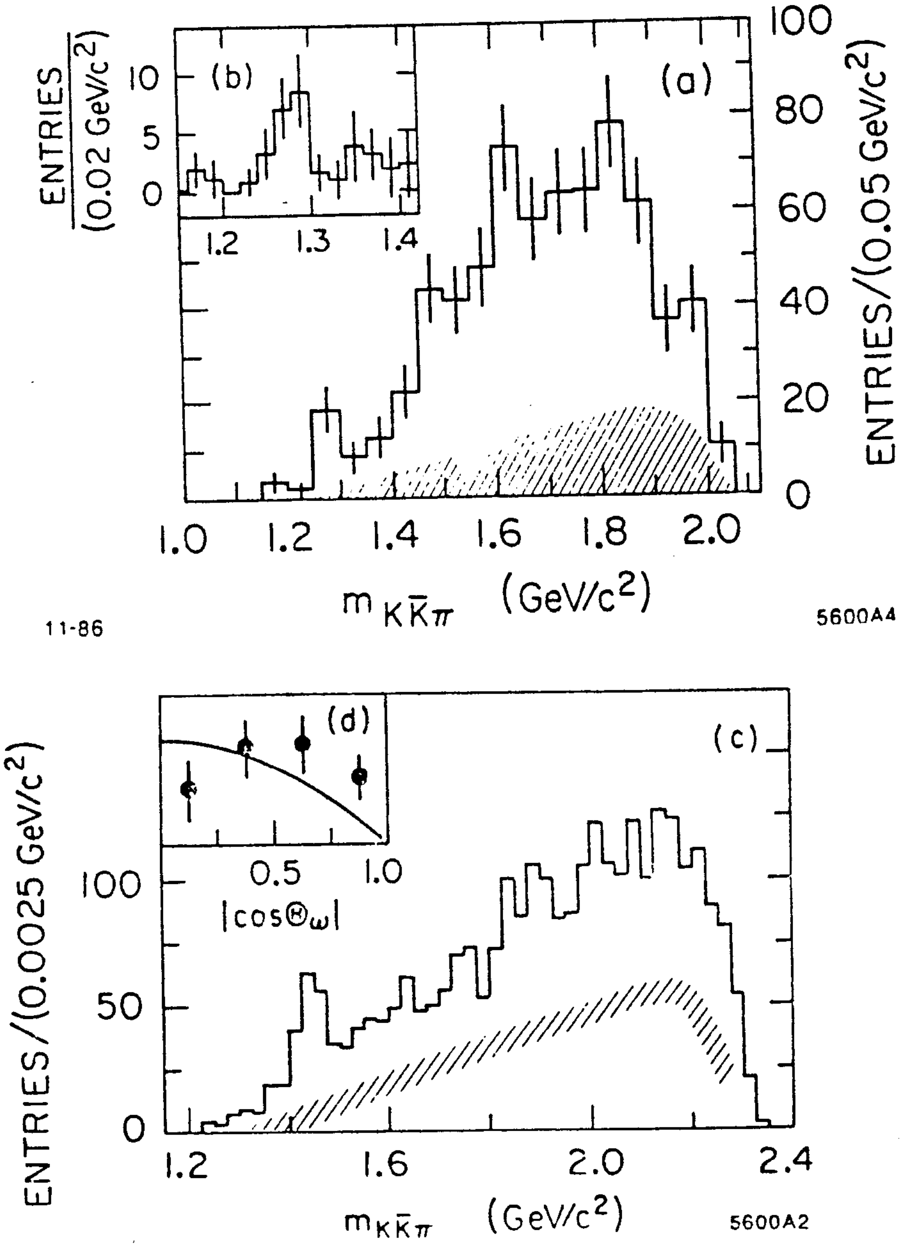
Fig. 1. Radiative J/ψ Decays



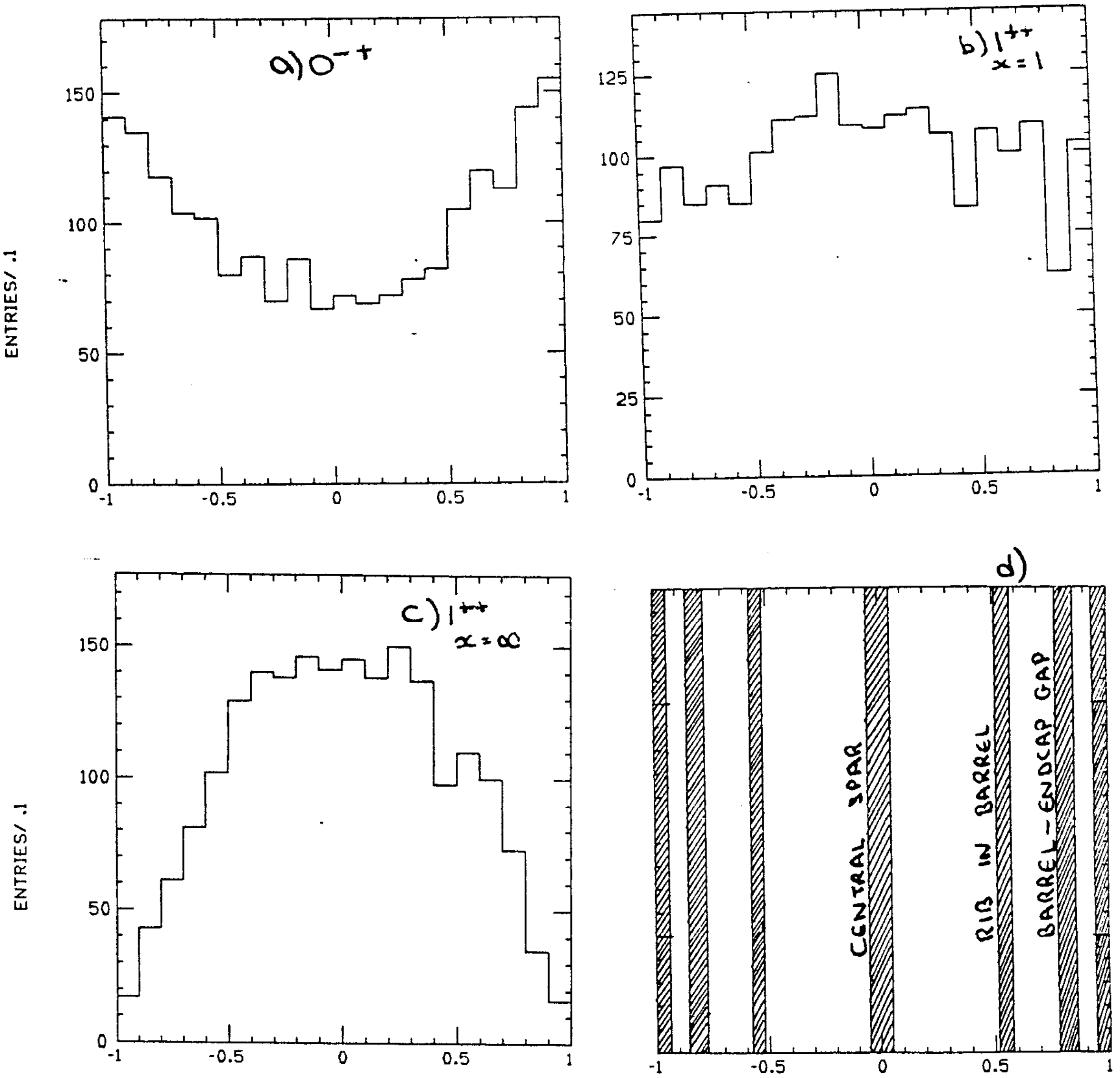
2) $KK\pi$ invariant mass in radiative J/ψ decays seen in MarkIII



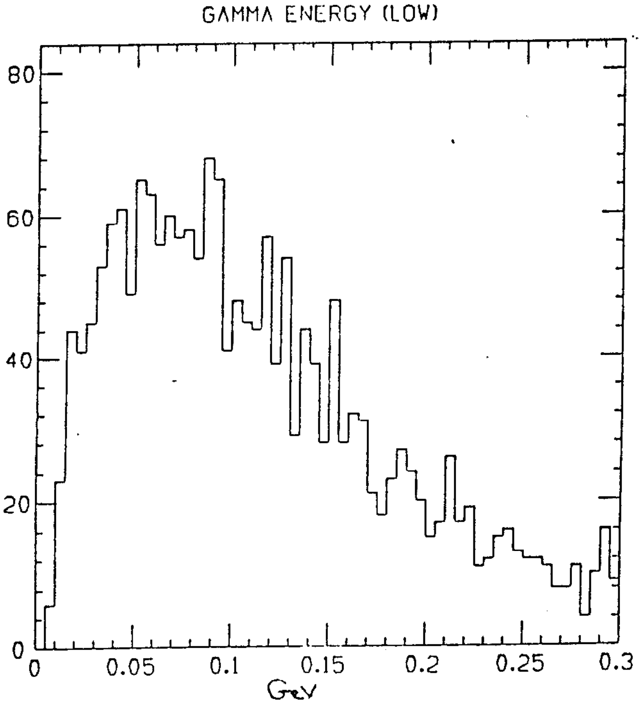
3) Quark line diagram for flavour correlation in hadron J/ψ decays.



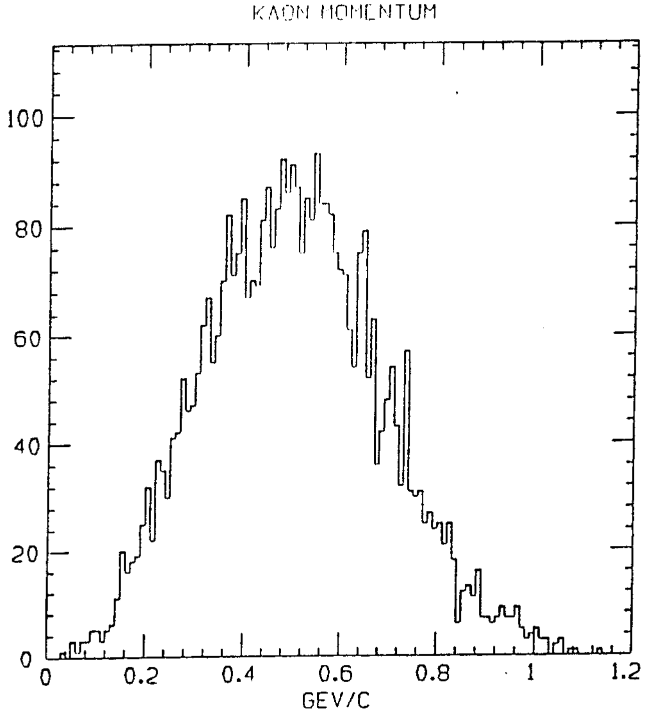
4) Hadronic J/ψ decays; a) $KK\pi$ recoiling from ϕ signal, the 1285 region is shown expanded in b); c) $KK\pi$ recoiling from ω.



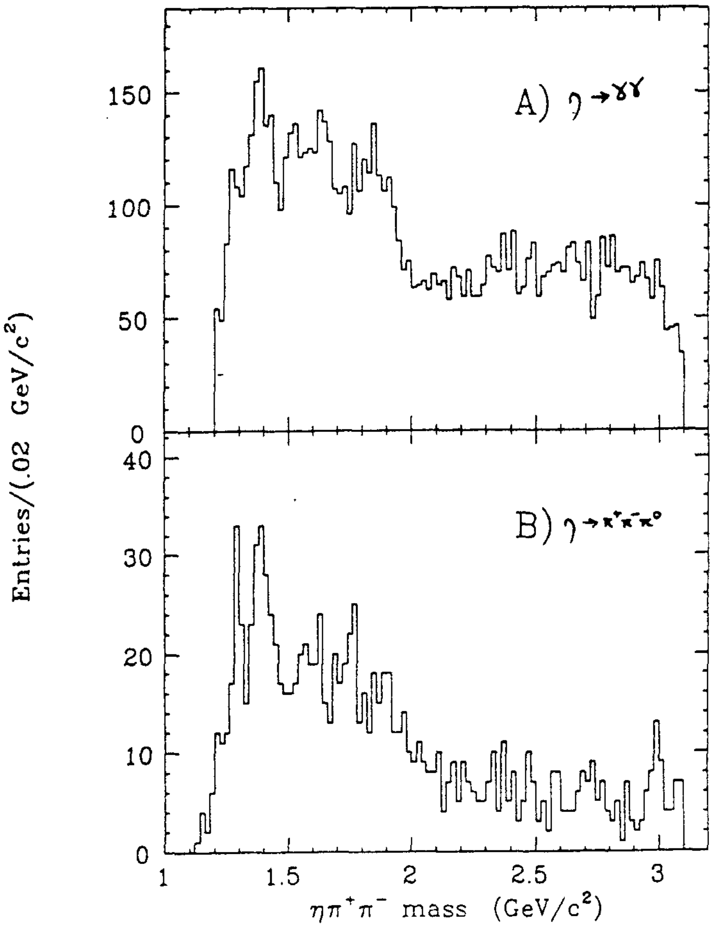
5) $cos\theta_\gamma$ in $J/\psi \rightarrow \gamma K_s^0 K^+ \pi^-$ MC for a) 0^{-+}, b) 1^{++} x = 1.0, c) 1^{++} x = infinity, d) acceptance



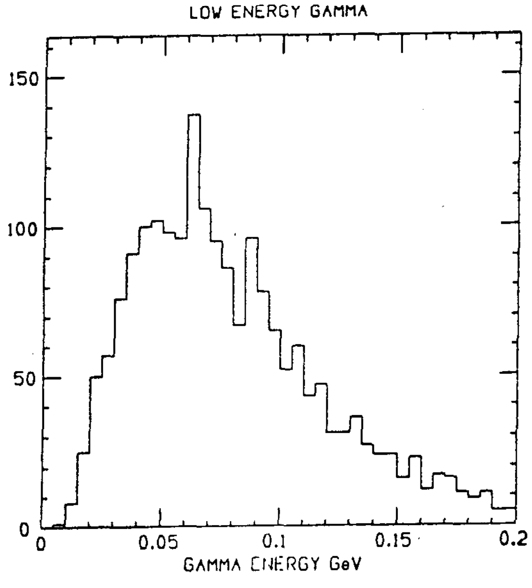
6) Distribution of lowest E_γ in MC of $J/\psi \rightarrow \gamma K^{*0}\pi^0$, $K^{*0} \rightarrow K^+\pi^-, \pi^0 \rightarrow \gamma\gamma$.



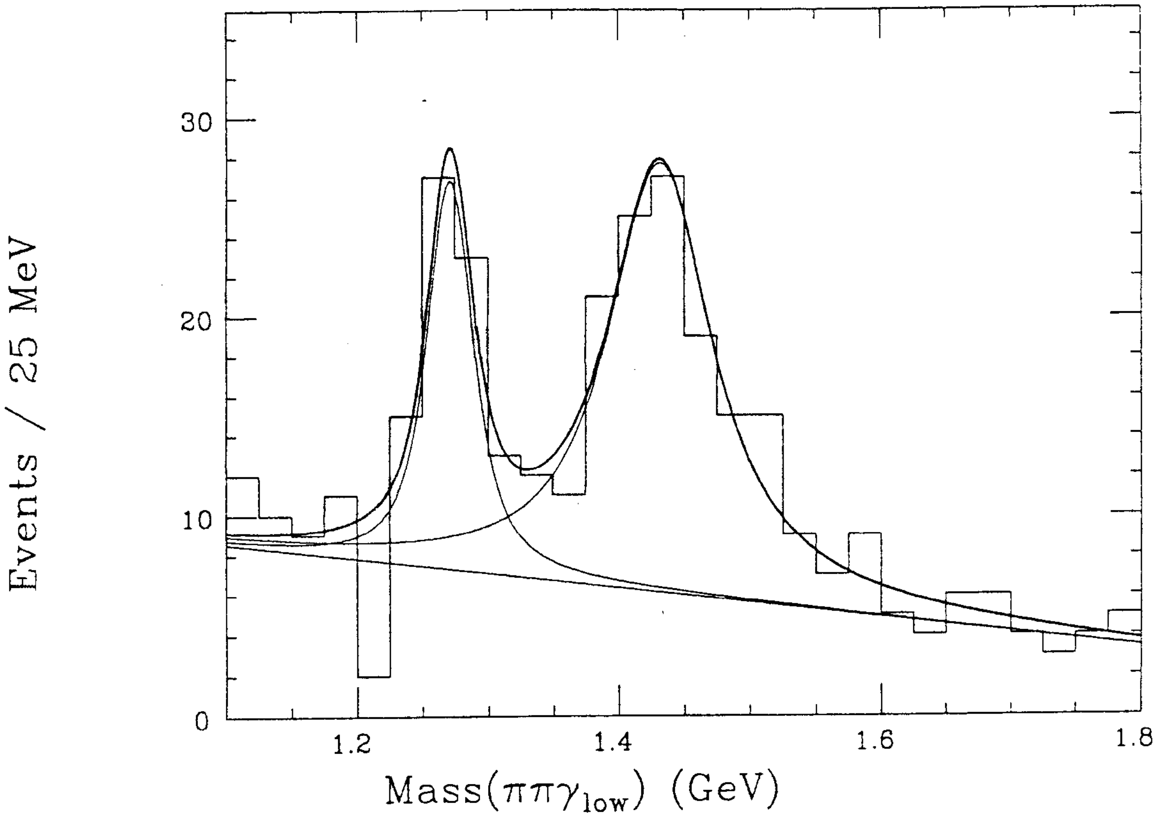
7) Momentum of K^+ in MC used in figure 6.



8) Mass $\eta\pi^+\pi^-$ in MarkIII.



9) Distribution of lowest E_γ in MC of $J/\psi \to \gamma\eta\pi^+\pi^-$, $\eta \to \pi^+\pi^-\pi^0, \pi^0 \to \gamma\gamma$.



10) Mass $\gamma\rho$ in radiative J/ψ decays seen in MarkIII.