Scalar and Tensor Meson Spectroscopy at a τ-charm Factory

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1. Introduction

While the clear identification of a glueball would be universally accepted as a fundamental discovery, all such searches have thus far produced ambiguous results. Simplified analyses based on low statistics data samples collected with low acceptance detectors have possibly introduced as much confusion as understanding. However, there is a "correct" way to do spectroscopy, especially in the two pseudoscalar channel. Several ingredients are necessary:

- High statistics - ~1000 events per 25 MeV/c^2 mass bin– to make partial wave analyses statistically meaningful.
- High acceptance – $\gtrsim$95% of the 4π solid angle– so that spin analyses are not confused.
- A clean and well-understood production mechanism, to both aid the analysis and assist in the interpretation.
- The ability to simultaneously study as many final states as possible to allow cross checking of results and to assist in their interpretation.

For the remainder of this report, it will be shown that each of these requirements can be met by building the appropriate detector at a τ-charm factory and adopting the right approach to analyzing the data.

2. The Physics Advantages of the J/ψ as a Meson Factory

Existing experimental and theoretical evidence supports the idea that radiative J/ψ decays proceeds through the emission of a photon and two or more gluons. It was conjectured that these multi-gluon intermediate states would couple preferentially to glueballs. Indeed, such hopes seemed to be justified by the discoveries of the $\iota(1440)$[1] and $\theta(1720)$[2] in the $\gamma K\bar{K}\pi$ and $\gamma\eta\eta, \gamma K\bar{K}$ final states, respectively. Unfortunately, a simple interpretation of the ι or θ as glueballs appears unlikely. The θ will be discussed in more depth later to amplify on this point.

While the J/ψ may not be an obvious "glueball factory", it nonetheless serves as a useful laboratory for studying spectroscopy in the γ-two-pseudoscalar ($\gamma P\bar{P}$) channel. Besides the gluon-dominated production mechanism, one enjoys the following advantages in studying $\gamma P\bar{P}$ decays of the J/ψ produced in e^+e^- collisions:

- The $P\bar{P}$ final state is constrained to have $J^{PC} = even^{++}$.
- The initial state is a pure $SU(3)$ flavor singlet.
- The initial state 4-momentum is well defined: $(E, \overrightarrow{p}) = (M_{J/\psi}, \overrightarrow{0})$.
- The initial state polarization density is well defined, $J_{J/\psi} = 1, \lambda_{J/\psi} = \pm 1$ with equal probability.
- States with invariant mass up to the J/ψ mass can be produced without strong kinematic suppression.
- The $SU(3)$ flavor related $\pi^+\pi^-, \pi^\circ\pi^\circ, K^+K^-, K^\circ_S K^\circ_S, \eta\eta, \eta'\eta$, and $\eta'\eta'$ final states can be detected and reconstructed with high efficiency using one detector and one data set.

These points may be compared with a traditional $\pi^- p \to P\bar{P}n$ experiment in which:

- The intermediate state is generally believed to be a $q\bar{q}$ meson, suggesting no strong preference for gluonic final states.

- $J^{PC} = 0^{++}, 1^{--}, 2^{++}, \ldots$ states are produced together in the $\pi^+\pi^-$ and K^+K^- channels, effectively doubling the density of possible final states.
- A mixture of SU(3) singlet and octet states is produced.
- Strong cuts must be placed on the momentum transfer t so that dominance of the one-pion-exchange mechanism is assured, which reduces acceptance for higher mass states.
- N^* resonance production further reduces acceptance and increases backgrounds at high $P\bar{P}$ invariant mass.
- No detector has been built that can handle both charged particle and multi-photon final states.

The fixed target experiments do enjoy a huge statistics advantage. As an example of the disparity in statistics, the Mark III $\gamma K^\circ_S K^\circ_S$ data sample consists of about 600 reconstructed events, whereas a recent $\pi^- p \to K^\circ_S K^\circ_S n$ experiment[3] has accumulated over 20,000 reconstructed $K^\circ_S K^\circ_S$ events. All J/ψ experiments to date have been unable to acquire large enough event samples to compensate for the $\lesssim 10^{-3}$ J/ψ branching ratios to particular $\gamma P\bar{P}$ final states; thus, the J/ψ experiments have been unable to effectively apply the rigorous partial wave analyses used in fixed target experiments. Since the $J/\psi \to \gamma P\bar{P}$ final states are dominated by several broad, overlapping, and coherently produced states in the 1-3 GeV/c^2 resonance region, such sophisticated analyses are mandated. A τ-charm factory would allow J/ψ data sets of 10^9 produced events, the factor of statistical improvement over existing results needed.

Before describing a more rigorous spin measurement methodology for use in J/ψ decays, the requirements placed upon detector performance will be briefly discussed.

3. Detector Requirements for $J/\psi \rightarrow \gamma P\bar{P}$

The detector must be able to trigger on and measure efficiently the following $\gamma P\bar{P}$ final states:

1. $J/\psi \rightarrow \gamma\pi^+\pi^-$.
2. $J/\psi \rightarrow \gamma K^+K^-$.
3. $J/\psi \rightarrow \gamma\pi^+\pi^-\pi^+\pi^-$ $(\gamma K^\circ_S K^\circ_S)$.
4. $J/\psi \rightarrow 5\gamma$ $(\gamma\pi^\circ\pi^\circ$ and $\gamma\eta\eta)$.
5. $J/\psi \rightarrow 5\gamma\pi^+\pi^-$ $(\gamma\eta\eta, \gamma\eta'\eta, \gamma K^\circ_S K^\circ_S)$.

At center-of-mass energy equal to the J/ψ mass, the total detection efficiency for any particular final state is roughly proportional to ϵ^n, where ϵ is the angular acceptance of the detector and n is the number of final state particles. Since final states (3)-(5) above contain at least five particles, as complete as possible solid angle coverage is necessary for both charged and neutral tracks to maintain high overall efficiency. As will be shown, the need for complete solid angle coverage is even more important to perform spin-parity analyses. A reasonable goal for a τ-charm detector is 95% of 4π coverage for both charged particles and photons.

Because of the availability of multi-constraint kinematic fitting at the J/ψ, there is no real need for exceptional momentum resolution for either charged particles or photons. Despite Mark III's relatively poor photon energy resolution $(\frac{\sigma_E}{E} = 18\%/\sqrt{E})$, it proved possible, with kinematic fitting, to reconstruct final states with up to five photons. However, backgrounds in such final states were typically quite high. A factor of two in photon energy resolution, without loss of angular resolution, is required. A Mark III type drift chamber resolution $(\frac{\sigma_p}{p} = 1.5\%\sqrt{1+p^2})$ should be adequate.

The more important consideration for a photon detector is the maximization of the low energy photon detection efficiency. The energy spectrum from π° and η decays is typically quite soft, thus $\gtrsim 2$ reductions in raw detection efficiency result if the minimum detectable energy is around 75 MeV/c^2, as was the case at Mark III and DM2. Even more important is the ability to "tag" π°'s, both for event reconstruction purposes and, especially, background rejection. The dominant source of background in radiative J/ψ decay is due to asymmetric π° decay, where one of the decay $\gamma's$ carries nearly all of the π° energy while the photon that is emitted in the "backwards" direction is very soft. The fraction of π° that will be mis-identified as photons is roughly $E_\gamma^{min}/E_{\pi^\circ}$, where E_γ^{min} is the minimum energy of a photon that can be efficiently detected. Reducing E_γ^{min} from the Mark III/DM2 value of $\sim$ 75 MeV to 10 MeV would result in an approximate seven-fold reduction of π° misidentification background.

To appreciate fully the desirability of reducing π° misidentification background, one need only look at previous analyses of the $\gamma\pi^+\pi^-$ and γK^+K^- final states. These final states suffer large backgrounds from the prominent decays $J/\psi \rightarrow \pi^+\pi^-\pi^\circ$ and $J/\psi \rightarrow K^+K^-\pi^\circ$. Furthermore, the dominance of pseudoscalar-vector intermediate states causes a concentration of the background in the regions of phase space which are most crucial for spin analyses. This is evident in Fig. 1, which shows the Dalitz plot for the $\gamma\pi^+\pi^-$ final state obtained from the Mark III experiment.[4] The diagonal bands in the plot indicate the presence of resonant $\pi^+\pi^-$ substructure; equally prominent, however, are the bands along the horizontal axes which are due to π° misidentification background of the $J/\psi \rightarrow \rho\pi$ final state. Since it is the extremes of the angular distributions, ie the edges of the Dalitz plot, which are most important to spin measurement, it is important to minimize the π° mis-identification.

The $\gamma\pi^\circ\pi^\circ$, $\gamma K_S^\circ K_S^\circ$, $\gamma\eta\eta$, $\gamma\eta'\eta$ and $\gamma\eta'\eta'$ decays are "protected" by charged conjugation invariance. All J/ψ decays obtained by replacing the γ with a π° for these cases are forbidden. The ability to reconstruct these particular final states is especially importance.

To complete the detector requirements, particle identification is necessary to cleanly separate the γK^+K^- final state from $\gamma\pi^+\pi^-$. A time-of-flight system with

Mark III resolution $\sigma_t \simeq 200\ ps$ is adequate if the solid angle coverage of this system matches that of the tracking system. Finally, a neutral trigger is required for the all photon final states.

4. Spin Measurements and the Need for 4π Coverage

Nearly all spin measurements performed in J/ψ decay experiments used the following recipe:

1. Identify a bump in an invariant mass distribution.
2. Make invariant mass cuts to isolate this bump as much as possible from the "background".
3. Using a maximum likelihood procedure, find the spin whose angular distribution best describes the observed angular distribution in the invariant mass region of interest.

Such a procedure may fail in the spin analysis of hadronic systems because it neglects important physics. The $P\bar{P}$ spectrum in the 1-3 GeV/c^2 invariant mass region is dominated by many broad, overlapping states; and the J/ψ decays coherently to many final states with the different spin amplitudes present interfering with each other.

Most $\pi^- p$ and $K^- p$ production experiments perform partial wave analyses in which the spin content of the $P\bar{P}$ system is extracted mass-bin-by-mass-bin without *apriori* assumptions. The procedure generally involves measuring the spherical harmonics moments for each mass bin, then fitting appropriate amplitudes to the moments. Resonances can be more-or-less rigorously identified by the observation of Breit-Wigner phase motion in one amplitude accompanied by peaking in the corresponding intensity distribution.

This analysis technique has been adapted for $P\bar{P}$ spectroscopy in J/ψ decay.[4] In general, the $J/\psi \to \gamma P\bar{P}$ amplitude can be decomposed into a sum of partial amplitudes corresponding to spin ℓ and helicity m. The observed joint kinematic distribution function then depends bilinearly on the helicity amplitudes and can be written:

$$W(\mu_{P\bar{P}}, \cos\theta_\gamma, \Omega_P^*) = \sum_{\ell,m}\sum_{\ell',m'} \Re(A_{\ell,m}(\mu_{P\bar{P}})A^*_{\ell',m'}(\mu_{P\bar{P}})\times \\ G_{m,m'}(\cos\theta_\gamma)\Re(Y_{\ell m}(\Omega_P^*)Y^*_{\ell' m'}(\Omega_P^*)). \tag{4.1}$$

All of the physics of interest is contained in this equation. The four kinematic variables needed to describe the final state are $\mu_{P\bar{P}}$, the $P\bar{P}$ invariant mass; $\cos\theta_\gamma$, the cosine of the angle of the radiated photon in the laboratory frame; and $\Omega_P^* = \cos\theta_P^*, \phi_P^*$, where $\cos\theta_P^*$ is the angle between one of the pseudoscalars and the radiated photon in the $P\bar{P}$ rest frame and ϕ_P^* is the angle between the $e^+e^-\gamma$ production plane and the $\gamma P\bar{P}$ decay plane. The intensity function W is a function of these variables, and is parametrized by the helicity amplitudes $A_{\ell,m}$. The spin index ℓ runs over all even spins and the helicity index m can be constrained to run over the values 0,1, and 2. A typical analysis would present the values of the square of each helicity amplitude and the phase of the each amplitude relative to a reference phase for a series of mass bins.

4.1. A Partial Wave Analysis of the $\gamma K\bar{K}$ System

The only published measurement of the spin of the $\theta(1720)$,[5] based on the simplified hypothesis test model described previously, yielded a strong preference for spin 2 over spin 0. A newer measurement from the same experiment with approximately two times higher statistics and using a true partial wave analysis technique shows that the original spin 2 resonance interpretation is probably too simple. This is shown in Fig. 2 and Fig. 3, where the measured intensities of the spin 0 and spin 2 partial waves are shown as a function of $K\bar{K}$ mass. Due to low statistics, the phases were essentially unmeasurable, and the intensities have large error bars. More details of this analysis may be found in Ref. 4; the results are given here as a prototype for a future very high statistics measurement.

While the statistics are low, the data suggest that a spin 0 structure exists in the vicinity of the $\theta(1720)$. Indeed, it is possible that the spin of the $\theta(1720)$ is 0. If this is true, then one of the strongest arguments in favor of the glueball interpretation of the $\theta(1720)$ would be weakened. A spin 2 $\theta(1720)$ is difficult to identify as a conventional $q\bar{q}$ meson since the ground state tensors are well known and the $\theta(1720)$ mass is too low for a radial excitation. This argument for an exotic interpretation is not as strong for a scalar $\theta(1720)$, mostly because of the extremely poor understanding of the 0^{++} $q\bar{q}$ states. However, a possible interpretation of a spin 0 $\theta(1720)$ would be its identification as the lightest scalar glueball.[6] A definitive partial wave analysis would thus be extremely interesting.

Another issue that would be further clarified with much higher statistics is the SU(3) flavor couplings of the $\theta(1720)$. If the $\theta(1720)$ were a glueball, then the first guess is that it would decay in an $SU(3)$ symmetric fashion. Although $K\bar{K}$, $\pi^+\pi^-$, and $\eta\eta$ decays of the $\theta(1720)$ have been "observed", no spin determinations at all exist for the $\pi^+\pi^-$ and $\eta\eta$ modes. Hence, the very existence of non-$K\bar{K}$ decays of the $\theta(1720)$ is not yet established. Nevertheless, interpreting existing results at face value, the $K\bar{K}$ rate compared to the $\pi\pi$ rate is several times larger than the $SU(3)$ prediction. While the $K\bar{K}$ and $\eta\eta$ rates are consistent with $SU(3)$, the evidence that the "$\theta(1720)$" seen in $K\bar{K}$ and the "$\theta(1720)$" seen in $\eta\eta$ are in fact the same state is weak. Only two experiments have even observed $J/\psi \rightarrow \gamma\eta\eta$. The Crystal Ball originally observed one broad structure centered at a mass of 1.64 GeV/c^2. They were later able to fit the structure to a sum of $f_2'(1525)$ ans $\theta(1720)$ Breit-Wigner shapes with parameters taken from the $K\bar{K}$ final state.[7] This fit was not significantly better than their single structure fit. Furthermore, it implied an $f_2'(1525) \rightarrow \eta\eta$ branching ratio far out of line with $SU(3)$ flavor predictions. The Mark III observation of $J/\psi \rightarrow \gamma\eta\eta$[4] had roughly the same statistical significance of the Crystal Ball measurement, but higher background. Again, a broad bump centered at 1.64 GeV/c^2 was observed, with no indication for a split $f_2'(1525) - \theta(1720)$ structure. Thus, the $SU(3)$ couplings of the $\theta(1720)$ are up in the air, and again a definitive measurement is required.

4.2. The Effects of Acceptance

Besides statistics, the major region that spin 0 and spin 2 hypotheses are not clearly separated for the $\theta(1720)$ is the lack of 4π acceptance. Acceptance losses are caused mainly by the limited drift solid angle coverage in existing detectors. In Figures 4-6, the distributions of the $\cos\theta_\gamma$, $\cos\theta^*_P$, and ϕ^*_P angles are shown for three different spin hypotheses and three different levels of charged particle solid angle coverage. The three spin hypotheses are: spin 0, spin 2 with all three helicity states equally populated, and spin 2 with one helicity state not populated. The second case corresponds to a spin 2 $\theta(1720)$, while the last is a reasonable approximation to what is seen for the $f_2(1270)$ and $f'_2(1525)$ produced in radiative J/ψ decay. The three solid angle coverages are $|cos\theta| < 0.8$, the acceptance of the Mark III, $|\cos\theta| < 0.9$, and $|\cos\theta| < 0.99$.

For nearly complete acceptance, the angular distributions of different spin hypotheses differ substantially. However, with Mark III acceptance, the spin 2 $\theta(1720)$ and spin 0 distributions look very much alike. The more polarized $f_2(1270)/f'_2(1525)$ case can still be separated because its $\cos\theta^*_P$ distribution is dramatically different from the other two cases, and this kinematic variable is the least affected by lack of acceptance. Acceptance effects are not small even for $|\cos\theta| < 0.9$, hence the justification for charged particle tracking out to $|\cos\theta| \leq 0.95$.

5. Conclusions

A τ-charm factory with 10^{33} $cm^{-2}s^{-1}$ luminosity, coupled with a 95% of 4π charged particle and photon detector will provide the level of statistics needed and the control over systematics required to perform definitive measurements of the $P\bar{P}$ spectrum in the 1-3 GeV/c^2 region. There is a reasonable possibility of unambiguously identifying non-$q\bar{q}$ scalar and tensor mesons at such a facility. In particular, the discovery of the scalar glueball– perhaps the $\theta(1720)$? – would test QCD at a fundamental level in the strong coupling regime.

REFERENCES

1. D. Scharre *et al.*, *Phys. Lett.* **97B**, 329, 1980.
2. C. Edwards *et al.*, *Phys. Rev. Lett.* **48**, 458, 1982.
   M.E.B. Franklin, Thesis, SLAC-0282, 1982.
3. R.S. Longacre *et al.*, *Phys. Lett.* **177B**, 223, 1986.
4. T. Bolton, Thesis, Massachusetts Institute of Technology, 1988.
5. R.M. Baltrusaitus *et al.*, *Phys. Rev.* **D35**, 2077, 1987.
6. For another perspective on the question of spin 0 vs. spin 2 of the $K\bar{K}$ system in the $\theta(1720)$ region, see Ref. 3.
7. R. Lee, Thesis, SLAC-0282, 1985.

FIGURE CAPTIONS

1) Dalitz plot for $J/\psi \rightarrow \gamma\pi^+\pi^-$ from Mark III.

2) Spin 0 and spin 2 helicity amplitude intensities for the $J/\psi \rightarrow \gamma K_S^o K_S^o$ final state. See Ref. 4 for details.

3) Spin 0 and spin 2 helicity amplitude intensities for the $J/\psi \rightarrow \gamma K^+K^-$ final state. See Ref. 4 for details.

4) The effects of charged particle acceptance on the $\cos\theta_\gamma$ kinematic variable. The columns represent different parent distributions: spin 0, spin 2 with all helicity states equally populated ("spin 2 $\theta(1720)$"), and spin 2 with one helicity state not populated ("$f_2'(1525)$"). The top row shows the distributions for the three different cases with 99% charged particle acceptance, the second row with 90% acceptance, and the third row with the 80% acceptance characteristic of the existing e^+e^- experiments.

5) The effects of charged particle acceptance on the $\cos\theta_P^*$ kinematic variable. The individual plot descriptions are the same as in Fig. 4.

6) The effects of charged particle acceptance on the ϕ_P^* kinematic variable. The individual plot descriptions are the same as in Fig. 4.

FIGURE 1

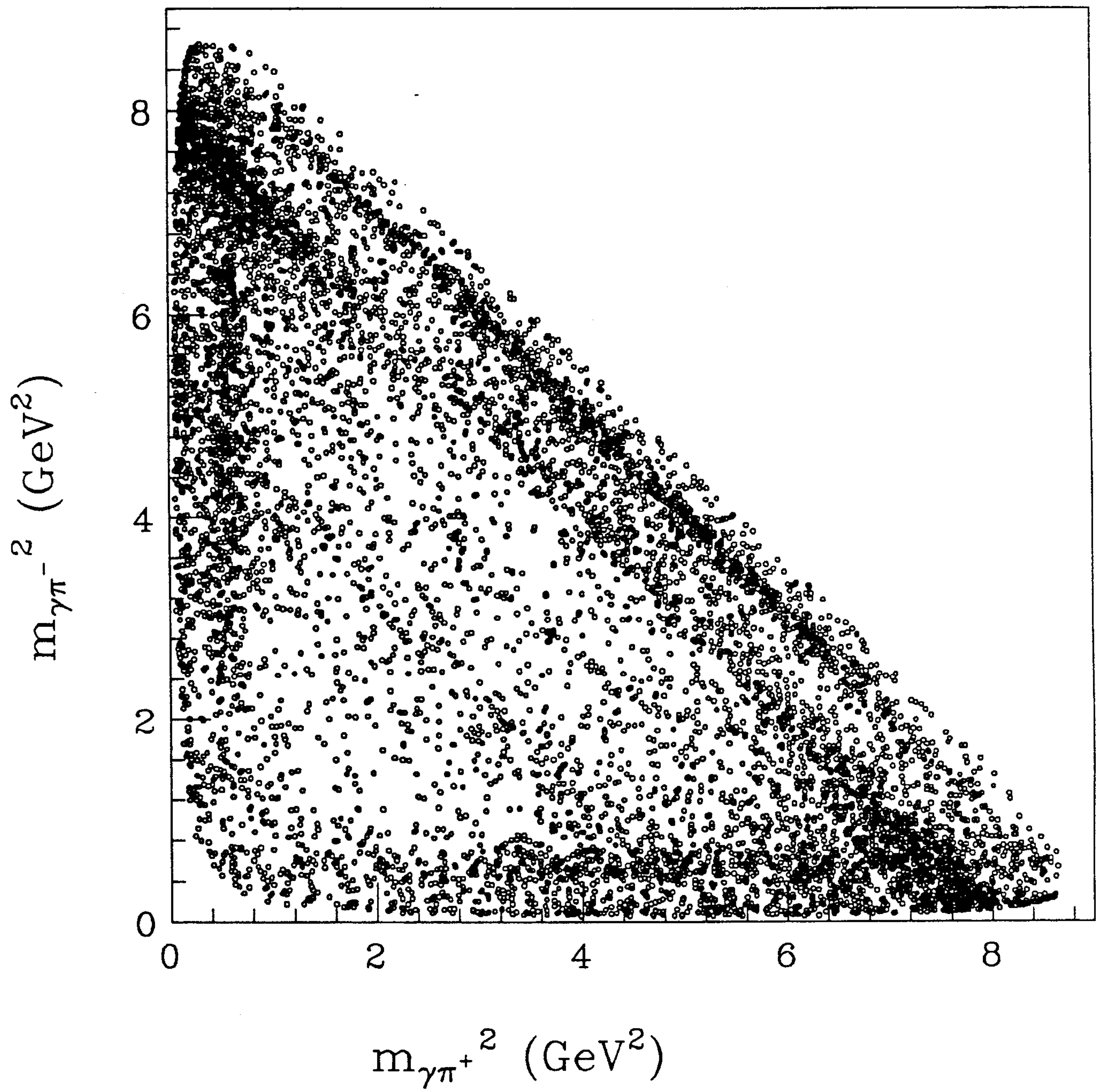
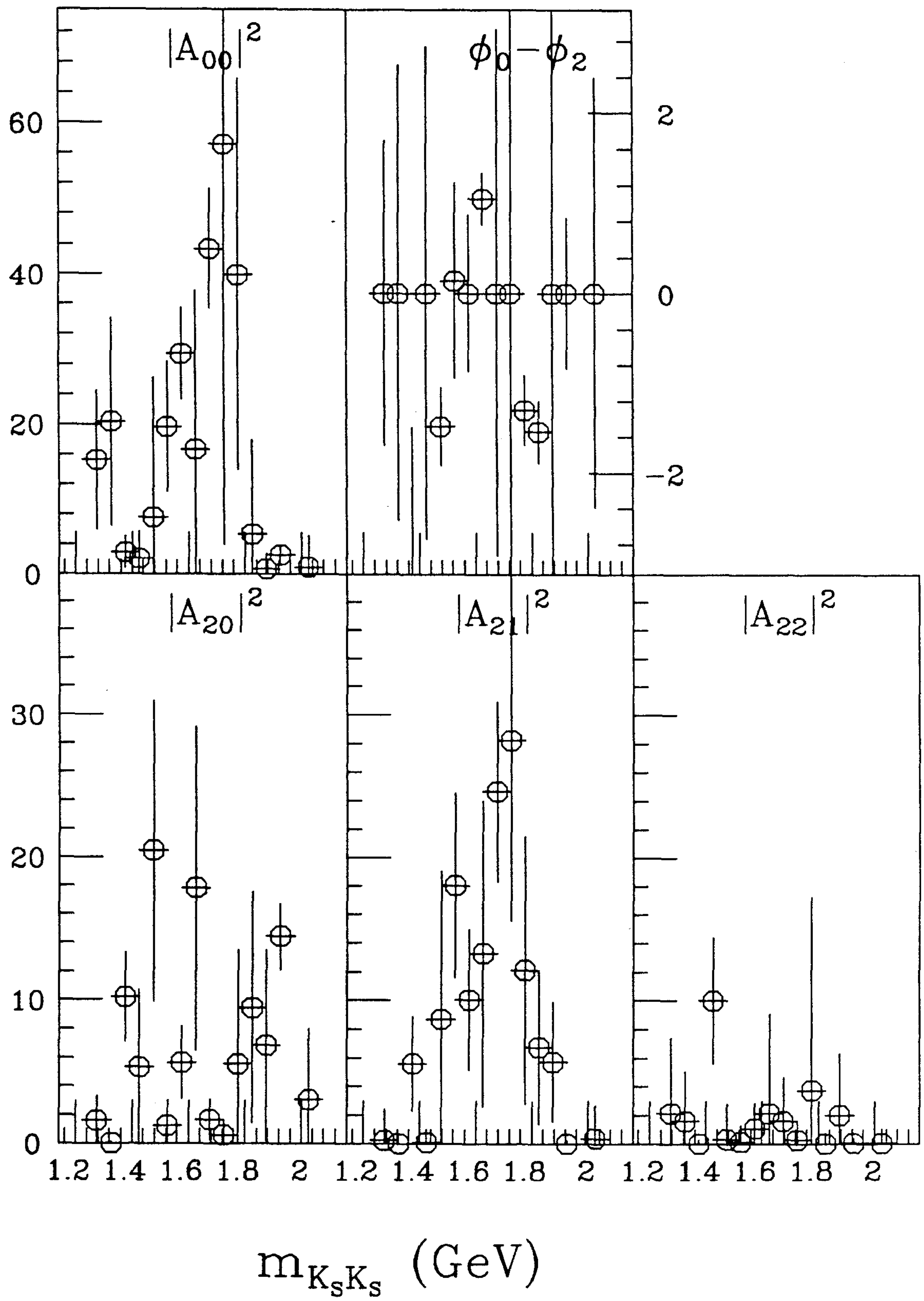
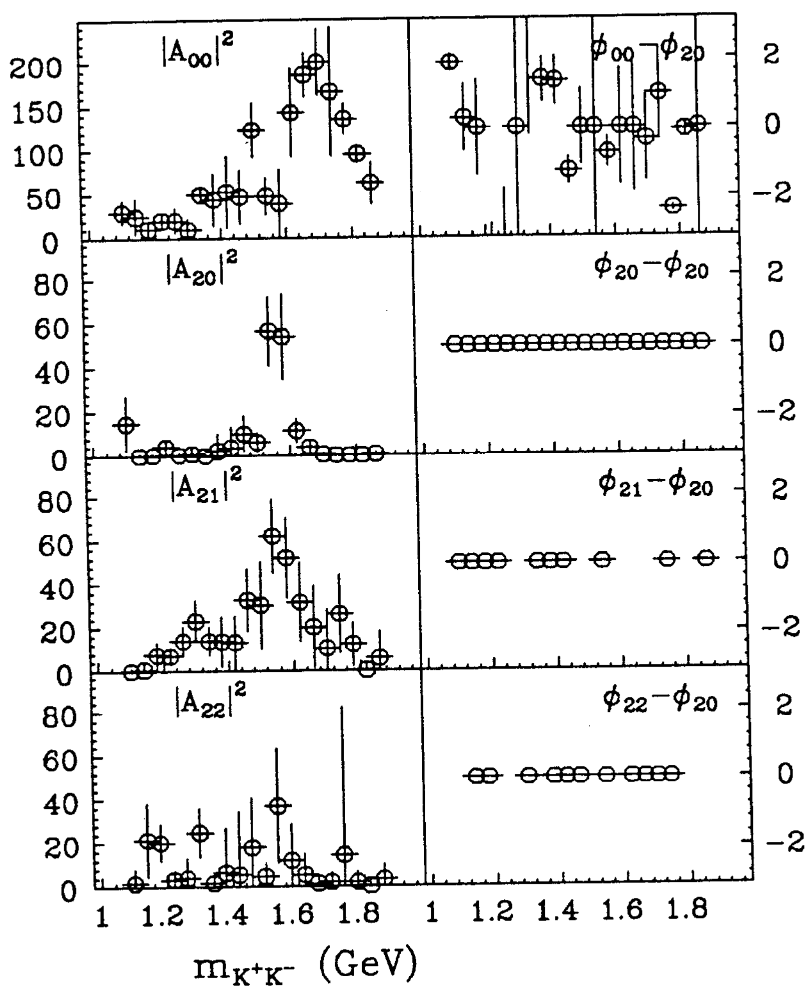


FIGURE 2



$|A_{00}|^2$
$\phi_0 - \phi_2$
$|A_{20}|^2$
$|A_{21}|^2$
$|A_{22}|^2$
60
40
20
0
2
0
−2
30
20
10
0
1.2 1.4 1.6 1.8 2
1.2 1.4 1.6 1.8 2
1.2 1.4 1.6 1.8 2
$m_{K_sK_s}$ (GeV)

FIGURE 3



spin 0x2, rel. complex amps

FIGURE 4

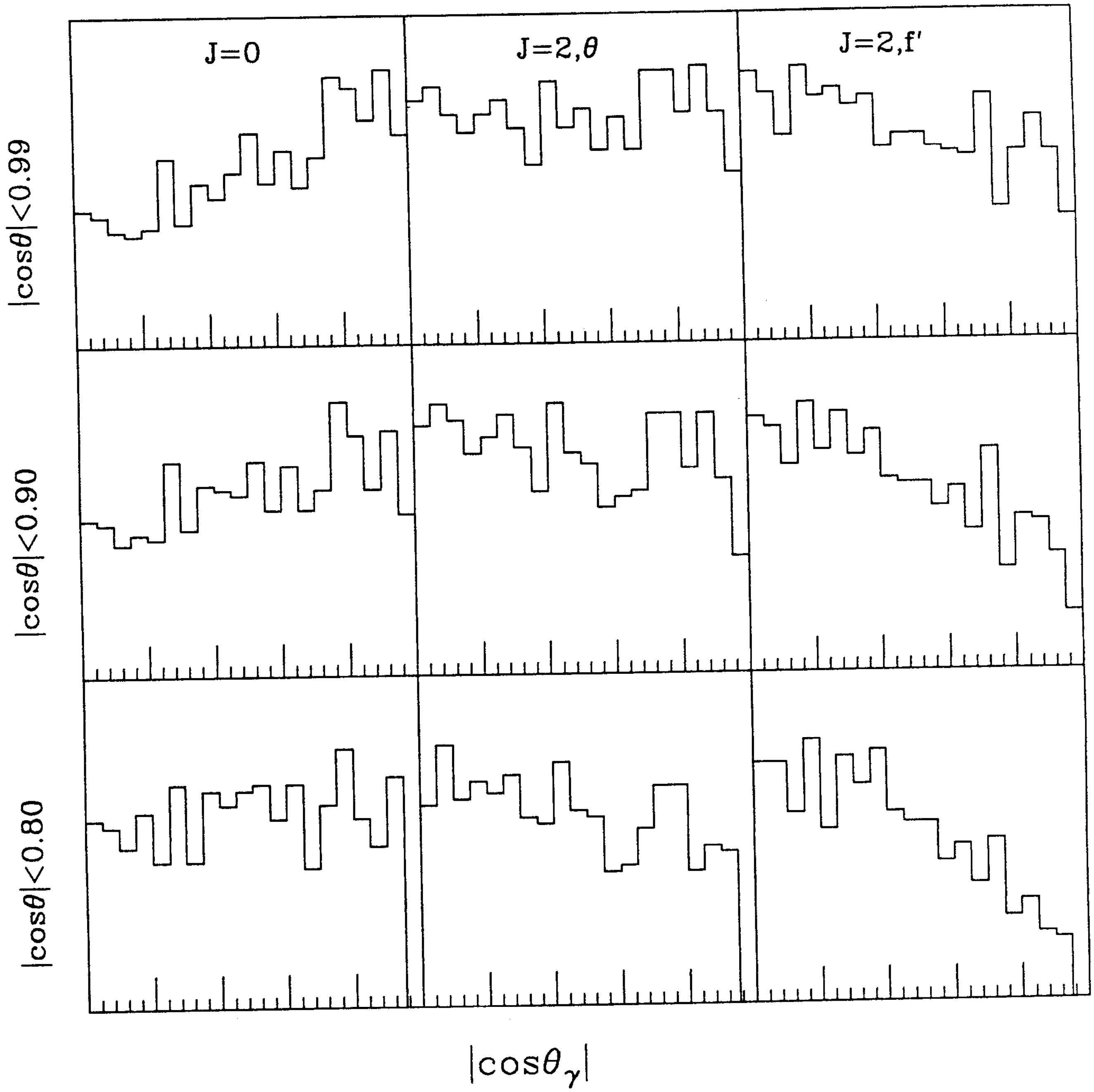


FIGURE 5

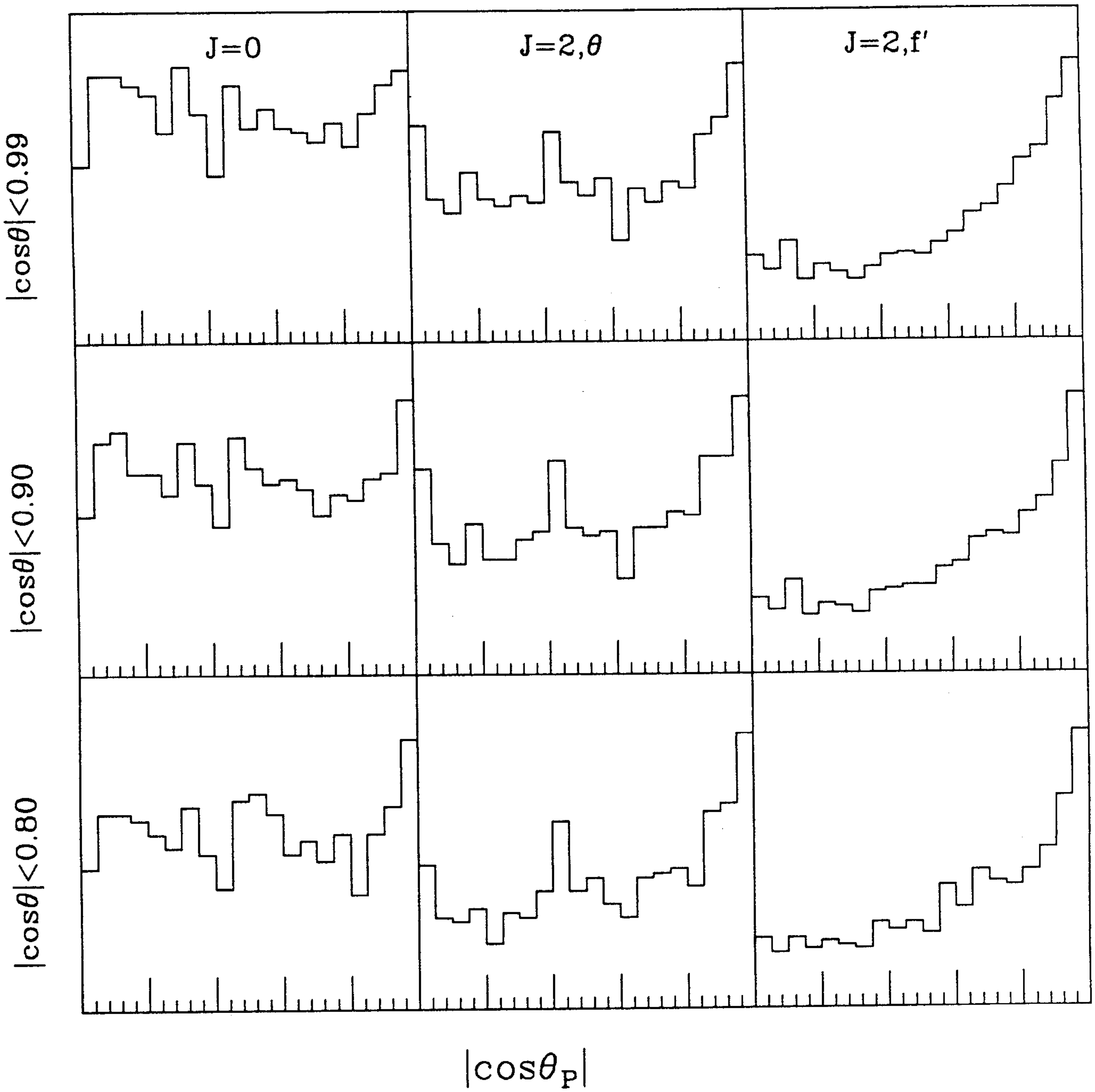


FIGURE 6