Partial Wave Analysis of $J/\psi \to \gamma K^+K^-$

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Abstract

A partial wave analysis of BESI $J/\psi \to \gamma K^+K^-$ data has been performed through two independent analysis methods. For the first time, a large spin zero component in the $f_J(1710)$ mass region is observed. This structure is attributed to the production of an S wave resonance, of mass and width M= $1735 \pm 15 \pm 15$ MeV/c^2, $\Gamma = 145 \pm 25 \pm 20$ MeV/c^2 (Analysis #1); M= 1763^{+22}_{-23} MeV/c^2, $\Gamma = 140^{+100}_{-65}$ MeV/c^2 (Analysis #2) respectively. However, a small amount ($\sim 20-25\%$) of spin two component which is peaked at the low mass region cannot be ruled out with the present statistics.

Quantum Chromodynamics(QCD) admits the possibility of colorless bound states of two or more gluons which have been named glueballs. Radiative decays of the J/ψ have been suggested [1] as promising modes for glueball searches. It has calculated [2] that $J^{PC} = 0^{++}, 0^{-+}, 2^{++}$ dominate the $J/\psi \to \gamma X$ final state and that $J^{PC} = 1^{--}$ and 1^{-+} are suppressed. The final states most accessible are those containing two or three pseudoscalars. Two pseudoscalars can combine to produce states with $J^{PC} = 0^{++}, 2^{++}$, while three pseudoscalars can form $J^{PC} = 0^{-+}$ states.

Since the $f_J(1710)$, one of the glueball candidates, was first discovered by the Crystal Ball Collaboration in $J/\psi \to \gamma\eta\eta$ [3], there has been considerable interests in its experimental and theoretical studies. Current theoretical predictions based on lattice gauge calculations indicate that the lowest lying scalar glueball should be in the mass range 1500-1700 MeV [4]. The $f_J(1710)$ displays clear glueball characteristic in that it's produced in glue-rich production mechanisms and is either not seen or is heavily suppressed in normal hadronic interactions. In addition, the $f_J(1710)$ is observed to decay dominantly to $K\bar{K}$ and yet it is not produced in K^-p interaction [5]. However, the spin of the $f_J(1710)$ is still uncertain and controversial with $J = 0$ or 2 being possible. Tab. 1 shows the experimental results of the $f_J(1710)$ study in chronological order. During 1990s, especially in recent years, the spin analysis of the $f_J(1710)$ has been performed continuously via different processes [6, 7, 8, 9, 10, 11]. From the results shown in Tab. 1, we can find such an interesting and important tendency: nearly all the analyses reached the same conclusion that spin zero is preferred over two whereas no reports favor 2^{++} are given correspondingly.

It is essential to know the spin of the $f_J(1710)$ because measurements of its production rate in J/ψ decays indicate that if it has spin two then it would be consistent with being a

Process	Collaboration	M(MeV)	Γ(MeV)	J^{PC}
$J/\psi \to \gamma\eta\eta$	C. B.(82)	1640 ± 50	200^{+100}_{-70}	2^{++}
$\pi^- p \to K^0_s K^0_s n$	BNL(82)	1771^{+77}_{-53}	200^{+156}_{-9}	0^{++}
$\pi^- N \to K^0_s K^0_s n$	FNAL(84)	1742 ± 15	57 ± 38	——
$\pi^- p \to \eta\eta N$	GAMS(86)	1755 ± 8	< 50	0^{++}
$J/\psi \to \gamma K^+K^-$	MARKIII(87)	1720 ± 14	130 ± 20	2^{++}
$J/\psi \to \gamma K^+K^-$	DM2(88)	1707 ± 10	166 ± 33	——
$pp \to p(K\bar{K})p$	WA76(89)	1713 ± 10	181 ± 30	2^{++}
$J/\psi \to \gamma K\bar{K}$	MARKIII(91)	1710 ± 20	186 ± 30	0^{++}
$p\bar{p} \to \pi^0\eta\eta$	E760(93)	1748 ± 10	264 ± 25	$(even)^{++}$
$J/\psi \to \gamma 4\pi$	MARKIII data D. Bugg(95)	1750 ± 15	160 ± 40	0^{++}
$J/\psi \to \gamma K^+K^-$	BES(96)	$1696 \pm 5^{+9}_{-34}$ $1781 \pm 8^{+10}_{-31}$	$103 \pm 18^{+30}_{-11}$ $85 \pm 24^{+22}_{-19}$	2^{++} 0^{++}
$J/\psi \to \gamma K\bar{K}$	MARKIII data W. Dunwoodie(97)	1704^{+16}_{-23}	124^{+52}_{-44}	0^{++}
$pp \to p(K\bar{K})p$	WA102(99)	1730 ± 15	100 ± 25	0^{++}
$pp \to p(\pi^+\pi^-)p$	WA102(99)	1750 ± 25	105 ± 34	0^{++}
$pp \to p(\pi^+\pi^-)p$	WA76(99)	1710 ± 20	160 ± 30	0^{++}
$J/\psi \to \gamma 4\pi$	BES(99)	1740^{+20}_{-25}	135^{+40}_{-25}	0^{++}

Table 1: The experimental results of the $f_J(1710)$ study in chronological order.

normal $q\bar{q}$ meson whereas if it has spin zero it would be consistent with having a significant glueball component [12].

Thus, the reaction $J/\psi \to \gamma K^+K^-$ would be a very important channel to investigate the $f_J(1710)$, because the production of a scalar glueball with a relative large K^+K^- branching ratio is assumed to be enhanced in this reaction. During our work, using about 8×10^6 J/ψ events from the BES experiment at the Beijing electron-positron collider (BEPC), a partial wave analysis of the $f_J(1710)$ will be done in the radiative decay $J/\psi \to \gamma K^+K^-$. Here two independent analyses with different data samples, different analysis methods, one called covariant tensor amplitude analysis where the formulae are provided by B. S. Zou, another called covariant helicity amplitude analysis where the formulae are provided by N. Wu, are performed at the same time and so it's easy to cross check the respective results. We hope to be able to determine the J^{PC} of the $f_J(1710)$ through our analyses.

Fig. 1 shows the K^+K^- invariant mass spectra obtained by Z. J. Guo and N. Wu respectively. From the figures, clear $f_2'(1525)$ and $f_J(1710)$ signals are observed.

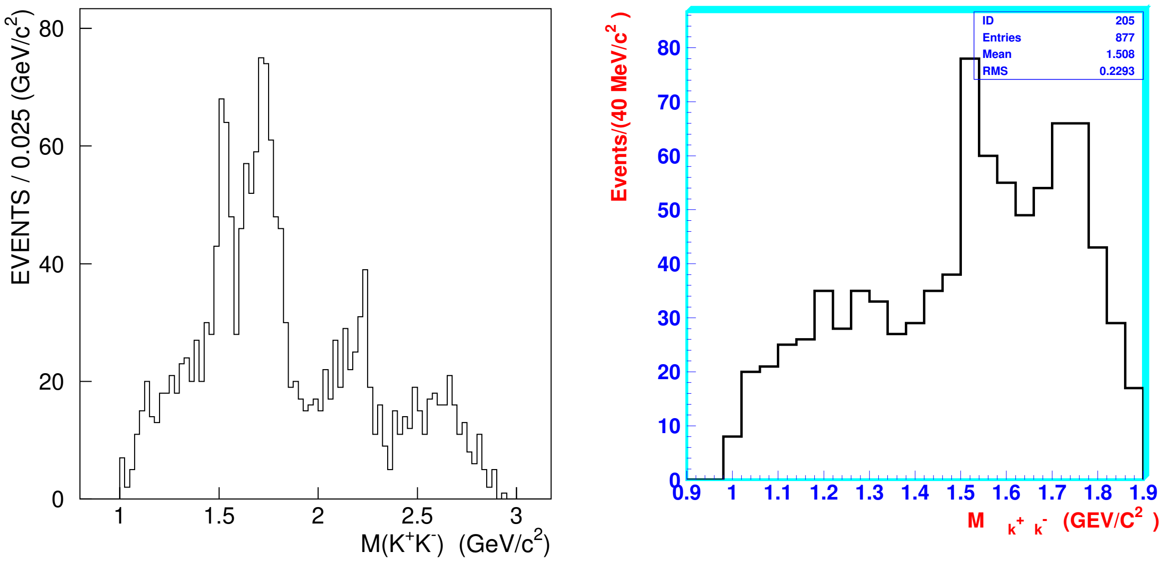

Figure 1: $J/\psi \to \gamma K^+K^-$ sample (Left: selected by Z. J. Guo, Right: selected by N. Wu)

The maximum likelihood method is employed to fit the data. The probability density function $f(x_i;\alpha)$ with x_i as a set of independently measured quantities and α as a set of unknown parameters is given as below

$$f(x_i;\alpha) = \frac{d\sigma}{d\Phi}/\sigma,$$

where the total cross section $\sigma = \int \mid A_{total} \mid^2 d\Phi$ is calculated by using the Monte Carlo integration. The differential cross section is given by

$$\frac{d\sigma}{d\Phi} = \mid A^{0+} + A^{2+} + \cdots \mid^2 + BG,$$

here, BG is the background term, A^{0+}, A^{2+} are the amplitudes for scalar and tensor components respectively.

Fit is made to the data in order to maximize the value of

$$\mathcal{L} = \prod_{i=1}^{N_{event}} f(x_i;\alpha).$$

Actually, $S = -\ln \mathcal{L}$ is minimized in the fit.

In order to calculate the total cross section σ, 1,600,000 $J/\psi \to \gamma K^+K^-$ Monte Carlo events are generated uniformly as the phase space. As we know, the 8M J/ψ events have been taken during four different periods and there are four versions of realization for the Monte Carlo simulation. Therefore, such ratio is adopted: 25 : 25 : 20 : 10 in the simulation procedure. For the four batches of J/ψ real data, we use the sample reconstructed with the old version(< 8) to perform the partial wave analysis.

Analysis #1 is finished by Z. J. Guo with the covariant tensor amplitude method. Since resonances with spin higher than 2 are possible in the region $m_{K^+K^-} > 2$ GeV/c^2, a complete PWA analysis would have to incorporate many spin and helicity states. However, the number of events in this region is small, but with high background, and, as a result, no reliable PWA analysis can be carried out with the available statistics. Therfore, the present study will cover only the region $m_{K^+K^-} \in (1.2, 2.0)$ GeV/c^2.

Using the partial wave formulae, all the clearly known or possible existing resonances in the channel $J/\psi \to \gamma K^+K^-$ are added one by one during the fit. For each partial wave, we determine its contribution to this process and the necessarity to introduce it through comparing the change of $ln\mathcal{L}$. If the partial wave improves $ln\mathcal{L}$ significantly, we will keep it after careful mass and width scans, otherwise, the partial wave will be dropped. There exist two obvious resonances $f_2'(1525)$ and $f_J(1710)$ in the K^+K^- mass region from 1.2 to 2.0 GeV/c^2. For the bump at the low mass region, it is complicated to be described because of the pollution from the $\rho^0\pi^0$, $\gamma\eta(1440)$ background channels. Therefore, we make different tests to discuss the effect of its tail on the $f_J(1710)$ region. First, a wide 0^{++} structrue σ [13] which interferes with the $f_J(1710)$ is used in the fit. Since the $f_2'(1525)$ has been studied carefully through different experiments and its spin is two confirmed, we will describe it with the 2^{++} partial waves. Our mass and width scan give $M_{f_2'(1525)} = 1530$ MeV/c^2, $\Gamma_{f_2'(1525)} = 75$ MeV/c^2 which are very similar to PDG values. So we just fix the mass and width of the $f_2'(1525)$ in the fit with the values given by PDG. As for the $f_J(1710)$ which we're mostly interested in, we assume that there only exists one structure 0^+ or 2^+, or exist two ones 0^+ and 2^+ to perform the mass and width scans.

$$\begin{cases} \text{only } 0^{++}: S = 604.12 \\ \text{M} = 1730 \text{ MeV},\ \Gamma = 165 \text{ MeV} \\[1ex] \text{only } 2^{++}: S = 615.22 \\ \text{M} = 1715 \text{ MeV},\ \Gamma = 155 \text{ MeV} \\[1ex] 0^{++} + 2^{++} \text{ together:} \quad S = 595.28 \\ \text{M}_{0^{++}} = 1735 \text{ MeV},\ \Gamma_{0^{++}} = 145 \text{ MeV} \\ \text{M}_{2^{++}} = 1635 \text{ MeV},\ \Gamma_{2^{++}} = 80 \text{ MeV} \end{cases}$$

The scan results show that for the $f_J(1710)$, the 0^{++} partial wave will give a better decription($S = 604.12$) compared with the 2^{++} ones($S = 615.22$). We get such a preliminary concept that in the $f_J(1710)$ region spin zero is preferred over spin two. Fig. 2 shows the projections of theoretical distributions on K^+K^- invariant mass with the fit values to data. Here we use the solution: $\sigma + f_2'(1525) + f_0(1735) + f_2(1635) + B.G.$. These partial waves fit well to data within the fluctuations of statistics.

Continuously, a series of checks from different ways have been done to guarantee our analysis correct and precise.

We compare the variations of the Likelihood values to get the significances of different structures and a no-signal-hypothesis is used here. The results of significance study are displayed in Tab. 2. If the 0^{++} structrue is removed from the best solution of 0^{++}, 2^{++}

combined scan, reducing $ln\mathcal{L}$ value 19.94 and the statistics significance is greater than 5σ while the 2^{++} one's significance is low, only 3.2σ.

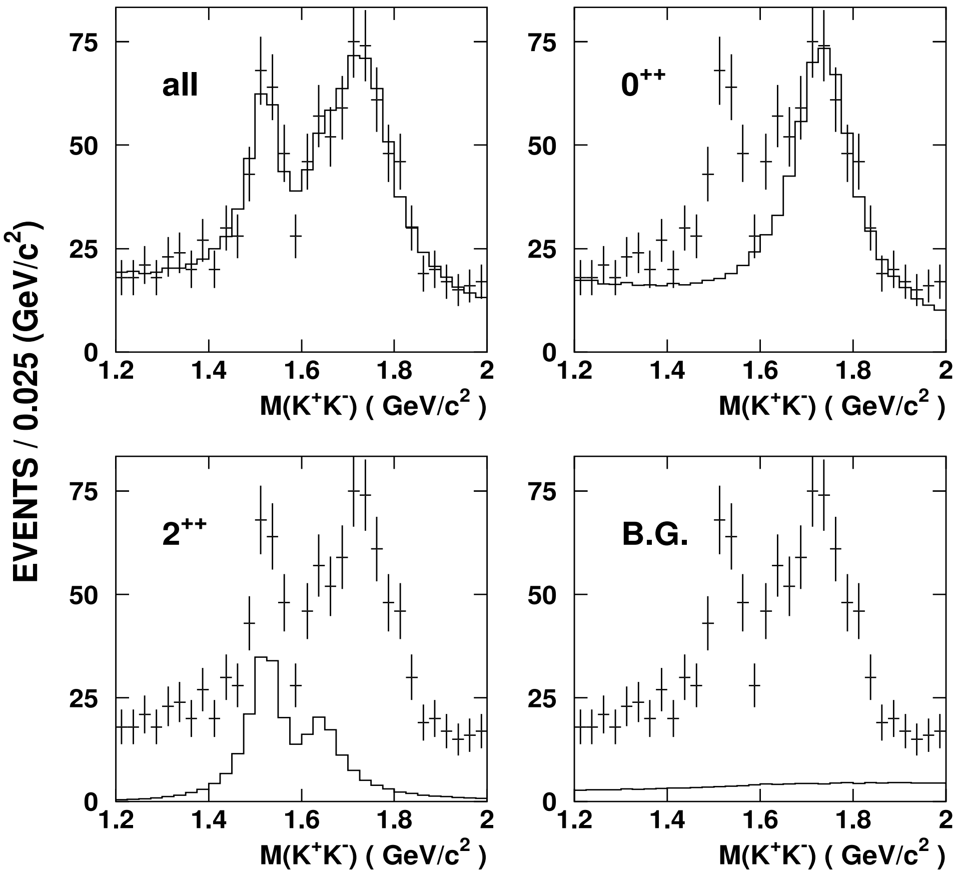

Figure 2: Projections of the different components on the K^+K^- mass. Points with error bars are the data and the histogram is the fit result.

Resonance	$-\,ln\mathcal{L}$	ΔS	ndf	Significance
0^{++} removed	615.22	19.94	4	$> 5\sigma$
2^{++} removed	604.12	8.84	4	3.2σ
$0^{++}\ +\ 2^{++}$	595.28	——	——	——

Table 2: Significance study of the 0^{++} and 2^{++} resonances.

As discussed previously, we're not very clear about the bump at the low K^+K^- region, so we try to use an non-interference background to describe it and perform the partial wave analysis again just as before. At the beginning, a Breit-Wigner fit to K^+K^- mass spectrum is done. The background shape shown in Fig. 3 is adopted with about 421 events.We hope to understand the effect of the bump's tail on the $f_J(1710)$ region farther.

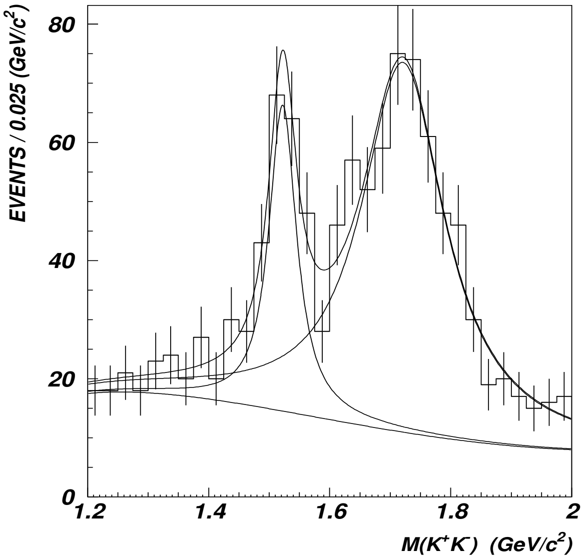

Figure 3: Breit-Wigner fitted invariant mass spectrum of K^+K^-.

$$\begin{cases} \text{only } 0^{++}: S = 612.59 \\ \text{M} = 1720 \text{ MeV},\ \Gamma = 175 \text{ MeV} \\ \text{only } 2^{++}: S = 647.97 \\ \text{M} = 1725 \text{ MeV},\ \Gamma = 180 \text{ MeV} \\ 0^{++} + 2^{++} \text{ together:} \quad S = 605.78 \\ \text{M}_{0^{++}} = 1725 \text{ MeV},\ \Gamma_{0^{++}} = 180 \text{ MeV} \\ \text{M}_{2^{++}} = 1640 \text{ MeV},\ \Gamma_{2^{++}} = 85 \text{ MeV} \end{cases}$$

Above results support our former analysis, so we needn't worry about the uncertainty of the effect of the low mass region. Through different tests we obtain nearly same conclusion.

Resonance | Bin (MeV)	50	60	70	80
$f_2'(1525)$	~ 0	26/126	42/127	19/169
$f_J(1710)$	127/27	143/37	156/42	204/21

Table 3: Slice fit resluts

Besides the global fit, we also perform slice fit at the same time. Here this kind of fit is done in the different bins of $m_{K^+K^-}$. Because of the limit of statistics, we only study two bins under the peaks of $f_2'(1525)$ and $f_J(1710)$ and the bin width is tried from 50 to 80 MeV respectively. Slice fit could avoid the effect of the terms in PWA formulae which vary with the energy flatly. From the fit results shown in Tab. 3, we find that the 2^{++} component is dominant under the $f_2'(1525)$ and 0^{++} component dominant under the $f_J(1710)$. It again supports the previous results.

In order to understand the character of the $f_J(1710)$ well, it's also necessary to study the angular distribution except the K^+K^- invariant mass. Here we adopt the polar angle of K^+ in the K^+K^- center-mass system, $cos\theta^*_{K+}$ and the polar angle of photon in J/ψ center-mass system, $cos\theta_V$. For $cos\theta^*_{K+}$, if we assume the $f_J(1710)$ is a pure scalar or tensor resonance respectively, we could get such projections as shown in Fig. 4 (left), where points with error bars are the data and the histogram is the fit result. Theoretical formulae indicate that the $cos\theta^*_{K+}$ of 0^{++} resonance is flat, however, the interference between the $f_2'(1525)$ and $f_J(1710)$ makes it looks like the distribution of 2^{++} one. So during the spin-parity analysis of the $f_J(1710)$ in his channel, the consideration of interference is very important. Moreover, from this figure, it's impossible to distinguish 0^{++} and 2^{++}. Hence, we must use the complete information of the final states. From the projections on $cos\theta_V$ (right), the above puzzle could be solved easily. Obviously, 0^{++} fits better to data than 2^{++}.

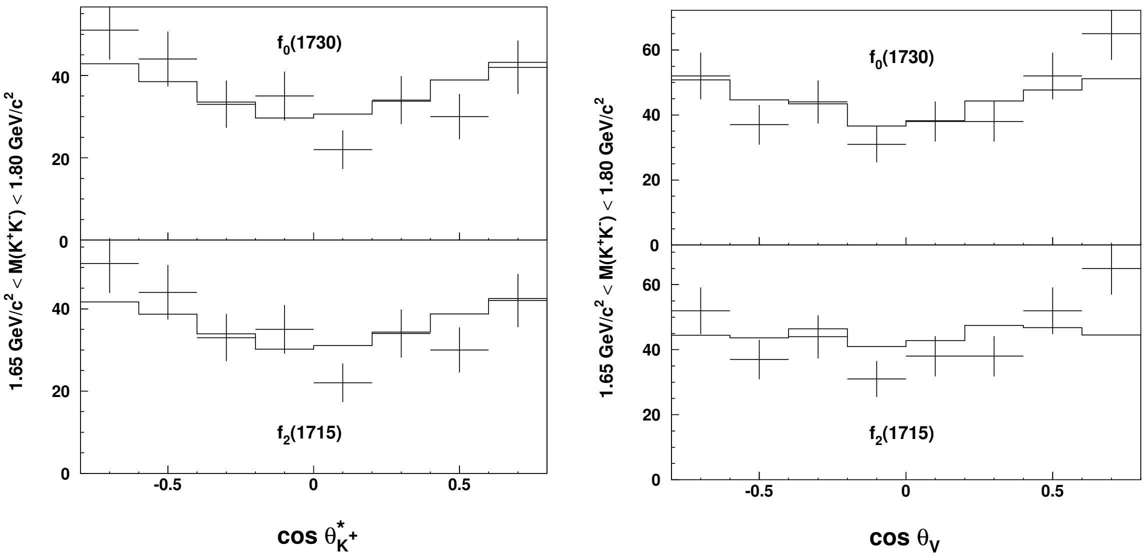

Figure 4: Projections on the $cos\theta^*_{K+}$ and $cos\theta_V$.

Spin	Mass (MeV)	Width (MeV)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma K^+K^-)$ (10^{-4})
0^{++}	$1735 \pm 15 \pm 15$	$145 \pm 25 \pm 20$	$1.8 \pm 0.1^{+1.8}_{-0.4}$
2^{++}	$1635^{+20}_{-15} \pm 25$	$80^{+20}_{-30} \pm 30$	$0.45 \pm 0.05 \pm 0.21$
$f_2'(1525)$	1525	76	$1.5 \pm 0.1 \pm 0.4$

Table 4: The masses, widths, and branching ratios of the $X_{0^{++}}, X_{2_{++}}$ and $f_2'(1525)$.

Tab. 4 shows the mass, width and branching ratio values after our final scan. The 0^{++} component is at the higher mass region of the $f_J(1710)$ while 2^{++} at lower region. And the ratio of these two components is about 4:1.

Analysis #2 is finished by N. Wu with the covariant helicity amplitude method. Here the study covers the region $m_{K^+K^-} \in (0.9, 1.9)$ GeV/c^2 and a wide 0^{++} Breit-Wigner structure is used to describe the bump of the low mass region and Tab. 5 gives the scan values of the mass, width and branching ratio. From the results of independent Analysis #2. we also see that in the $f_J(1710)$ region, the 0^{++} component is dominant, the ratio of 0^{++} and 2^{++} components is about 3:1. Fig. 5 shows the projections on K^+K^- invariant mass.

Spin	Mass (MeV)	Width (MeV)	$\mathcal{B}(J/\psi \to \gamma X \to \gamma K^+K^-)$ (10^{-4})
0^{++}	1763^{+22}_{-23}	140^{+100}_{-65}	$2.3 \pm 0.1 \pm 0.7$
2^{++}	1722^{+38}_{-48}	154^{+60}_{-41}	$0.68 \pm 0.19 \pm 0.18$
$f_2'(1525)$	1525	76	$1.6 \pm 0.1 \pm 0.5$
$f_2(1270)$	1275	185.5	$0.52 \pm 0.07 \pm 0.15$

Table 5: The mass, width, and branching ratio values obtained by Analysis #2.

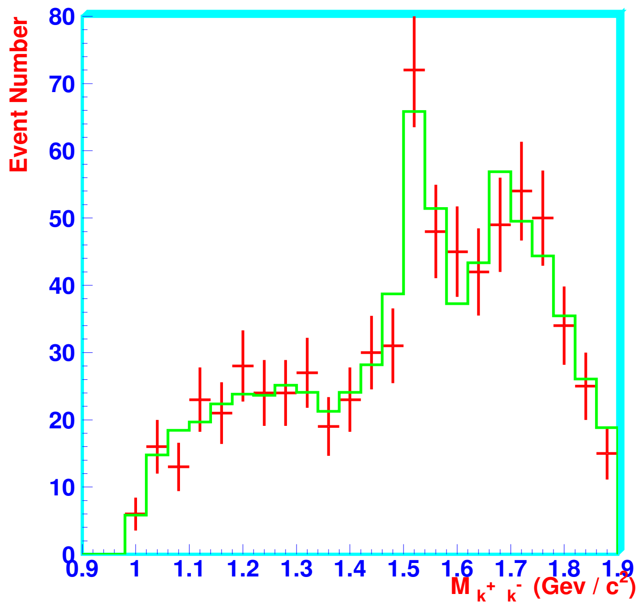

Figure 5: Projection on the K^+K^- mass obtained by Analysis #2.

In summary, our two independent analyses give similar results of the spin-parity in the $f_J(1710)$ region: there is a strong 0^{++} structure which is dominant while with another 2^{++} component is about 20-25%. The mass of the scalar structure is higher than the tensor one's. From our study, we could summarize the key to analyze the spin-parity of the $f_J(1710)$ in the radiative decay $J/\psi \to \gamma K^+K^-$ to two points: First, we must consider the interference between $f_2'(1525)$ and $f_J(1710)$ correctly; Second, we must use the complete information of the final states: the $cos^*_{K^+}$ and cos_V projections have shown these two points clearly. The partial wave amplitudes of our analyses are described by the four-momentum of the final state particles and the two points emphasized above could be satisfied totally. As for the strong scalar resonance, just as the previous introduction, are also observed by some other experiments. It may be a mixture of the ground 0^{++} glueball and $q\bar{q}$ meson. Of course, for understanding its character confirmly, more experimental facts and more data are welcome.

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