BES Analysis Memo
Results on Hadronic $\psi(2S)$ Decays into Vector–Pseudoscalar Mesons

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Abstract

The hadronic decays $\psi(2S) \to \pi^+\pi^-\pi^0$, $K^+K^-\pi^0$, $\rho\pi$, and $K^*\bar{K}$ have been studied in a sample of 3.7×10^6 produced $\psi(2S)$ events. Their branching fractions or upper limits are renewed in high statistics. The VP decay modes of the $\psi(2S)$ are further suppressed compared with the former results, and the upper limit of $\psi(2S)$ decay to $\rho\pi$ has been lower than any theoretical predictions. The "$\rho\pi$ puzzle" remains a puzzle.

I. INTRODUCTION

There exists a long standing puzzle in the study of the J/ψ and $\psi(2S)$ decays into vector–pseudoscalar exclusive final states. As early as 1983, by measuring the branching fractions of the J/ψ and $\psi(2S)$ decays to several hadronic final states, the MARK II Collaboration first found that two final states, $\rho\pi$ and $K^{*\pm}K^{\mp}$, are unobservable in the $\psi(2S)$ decays while both of them have a large branching fractions in the J/ψ decays [1]. The ratios of the branching fractions of the $\psi(2S)$ decays compared to those of corresponding J/ψ decays are

$$Q_{\rho\pi} < 0.63\% \quad \text{and} \quad Q_{K^{*\pm}K^{\mp}} < 1.1\%.$$

According to the perturbative QCD theorem [2], there is a direct parallel between the decay of $\psi(2S)$ and J/ψ to three massless gluons

$$Q_h \equiv \frac{B(\psi(2S) \to ggg)}{B(J/\psi \to ggg)} \approx \frac{B(\psi(2S) \to e^+e^-)}{B(J/\psi \to e^+e^-)} = (14.7 \pm 2.3)\%,$$

where the values of leptonic branching fractions are taken from the PDG listings [3]. For $p\bar{p}\pi^0$, 4π, $2(\pi^+\pi^-)\pi^0$, $3(\pi^+\pi^-)\pi^0$ etc. final states, this "15% rule" are conserved well except the above two VP states. This is the so–called "$\rho\pi$ puzzle".

Several theoretical explanations for this anomaly were proposed. One of them was provided by Brodsky, Lepage, and Tuan [4]. They assumed that the observed J/ψ decays to $\rho\pi$ and $K^*\bar{K}$ are mediated by an intermediate vector glueball with a mass near that of the

J/ψ. Such a vector glueball has been searched by an energy scan across the J/ψ resonance, and no evidence was found to support its existence [5].

Chaichian and Torngvist [6] hypothesized that the hadronic form factor exponentially decreases the two meson decays of the $\psi(2S)$ relative to the J/ψ. They predicted

$$B(\psi(2S) \rightarrow \rho\pi) = 7 \times 10^{-5}.$$

Another model suggested by Pinsky [7] postulated that the $\psi(2S) \rightarrow VP$, closely related to the hindered M1 transition $\psi(2S) \rightarrow \gamma\eta_c$, is in effect a generalized hindered M1 transition, and predicted

$$B(\psi(2S) \rightarrow \rho\pi) = 4 \times 10^{-5}.$$

The measurement of the branching fraction of the $\psi(2S)$ decay to $\rho\pi$ in high statistics may be crucial to test the above models. In this paper, we present the measurement of the $\psi(2S)$ decays to $\rho\pi$ and $K^*\bar{K}$ based on the 3.7×10^6 produced $\psi(2S)$ events taken with the Beijing Spectrometer (BES) [8] at the Beijing Electron–Positron Collider (BEPC).

II. EVENT SELECTION

The following preselection criteria are used for $\pi^+\pi^-\gamma\gamma$ state:

1. The number of charged tracks is required to be two with net charge zero and each track with one track fit quality $MFIT = 2$, -9, or -19.

2. The transverse momentum of each track $P_{xy} > 0.07$ GeV/c.

3. The polar angle of each track in MDC $|\cos\theta| < 0.8$.

4. Each charged track is identified as π by its dE/dx information $|XSPI| < 3.0$.

5. The acollinear angle between two charged track $\theta_{acol} > 10°$ and the total energy deposit in BSC $E^+_{BSC} + E^-_{BSC} < 1.6$ GeV to remove lepton pair events.

6. According to energy balance, define

$$ERRE = E_{cm} - \sum_{i=1}^{2} \sqrt{p_i^2 + m_{\pi^\pm}^2} - \sqrt{p_{miss}^2 + m_{\pi^0}^2},$$

   require $|ERRE| < 0.2$ GeV.

7. The number of neutral clusters is required to be between two and six, and the number of "good" photons $N_\gamma = 2$ or 3.

8. The "good" photon must satisfy:

   a. $|\cos\theta| < 0.75$,

   b. number of layers hit in BSC ≥ 2,

c. shower starts before layer 4,

d. $E_{BSC} > 50$ MeV,

e. angle between γ and the nearest charged track $> 16°$, and

f. angle between the cluster enters and goes through BSC $< 20°$.

9. The 4C fit to $\pi^+\pi^-\gamma\gamma$, require $\chi^2 < 30$.

Furthermore, the following cut conditions are applied to reject background:

1. The angle between two good photons $5° < \theta_{\gamma\gamma} < 50°$; the recoiling mass of $\pi^+\pi^- < 0.8$ GeV/c^2; when $10° < \theta_{acol} < 20°$, both $MUID \neq 1$; and the 4C fit to $K^+K^-\gamma\gamma$, $\mu^+\mu^-\gamma$, and $e^+e^-\gamma$, require $\chi^2_{\pi^+\pi^-\gamma\gamma} < \chi^2_{K^+K^-\gamma\gamma}$, $\chi^2_{\pi^+\pi^-\gamma\gamma} < \chi^2_{\mu^+\mu^-\gamma}$, $\chi^2_{\pi^+\pi^-\gamma\gamma} < \chi^2_{e^+e^-\gamma}$, and the probability of fit $P(\chi^2_{\pi^+\pi^-\gamma\gamma}) > 0.05$.

2. $N_\gamma = 2$.

3. At least one π is identified by code PARTID1 in the BES library combining TOF and dE/dx informations: $Prob(\pi) > Prob(K)$ and $Prob(\pi) > 0.05$.

For $K^+K^-\gamma\gamma$ state, the selection criteria are similar to those for $\pi^+\pi^-\gamma\gamma$ state. The different conditions are listed as follow:

1. K selection is instead of π selection, e.g., $|XSK| < 3.0$, $Prob(K) > Prob(\pi)$, and $Prob(K) > 0.05$.

2. $\theta_{acol} > 8°$.

3. The 4C fit to $K^+K^-\gamma\gamma$, $\pi^+\pi^-\gamma\gamma$ and $p\bar{p}\gamma\gamma$, require $\chi^2_{K^+K^-\gamma\gamma} < \chi^2_{\pi^+\pi^-\gamma\gamma}$, $\chi^2_{K^+K^-\gamma\gamma} < \chi^2_{p\bar{p}\gamma\gamma}$ and $P(\chi^2_{K^+K^-\gamma\gamma}) > 0.05$.

The selected events through the different cuts are shown in Table I. In Table I, '94 data means 1.3×10^6 $\psi(2S)$ events taken in 1993/94 running and '95 data means 2.4×10^6 $\psi(2S)$ events taken in 1995 running. The 6500, 11000 $\pi^+\pi^-\pi^0$ and $K^+K^-\pi^0$ events are generated in uniform phase space by MC simulations with the SOBER realization version 153, 154 and are reconstructed with the DRUNK version 85, 86, respectively. From this table, we can see that there is compatibility within the two data sets and the reconstruction efficiency for version 85 is lower than that for version 86. This difference has been found to be caused by reconstruction in BSC recently.

III. ANALYSIS

The $\gamma\gamma$ mass spectra for the selected $\pi^+\pi^-\gamma\gamma$ and $K^+K^-\gamma\gamma$ are shown in Fig. 1 and Fig. 2. A Gaussian function added a constant background is unbinnedly fitted to each spectrum . The fit results are listed in Table II. Backgrounds listed in this table are estimated by MC simulations. The main sources are listed in Table III and Table IV. Since the cross-section initial state radiation (ISR) at the $\psi(2S)$ mass which the resulting collision energy corresponds to the J/ψ mass is about 0.77 nb, one expects that the number of $\gamma J/\psi$

events corresponding to the 3.7×10^6 $\psi(2S)$ events is ~ 5000. It is shown by MC study that no π^0 signal in the $\gamma\gamma$ mass spectrum by a 4C fit to $\pi^+\pi^-\gamma\gamma$ for $J/\psi \to \rho\pi$ final state in the ISR $\gamma J/\psi$ process can be seen and the invariant masses of $\pi^\pm\gamma\gamma$ are almost higher than ρ mass.

The first error of each branching fraction is statistical error, and the second is systematic. The fractional systematic error is obtained by adding contributions from the following terms in quadrature: 10% from the normalization, 2% from the trigger and filter, 5% from the reconstruction, 15% from the selction criteria, and 5 — 10% resulting from the uncertainty on the background subtraction.

The Dalitz plots for $\psi(2S) \to \pi^+\pi^-\pi^0$ and $\psi(2S) \to K^+K^-\pi^0$ after the π^0 mass cut $|M_{\gamma\gamma} - 135| < 45$ MeV$/c^2$ are shown in Fig. 3 and Fig. 4. From these figures, we have not seen the dominant ρ and $K^{*\pm}$ signals in their mass bands. If we select ρ and $K^{*\pm}$ candidates by applying mass cuts $560 < M_{\pi\pi} < 980$ MeV$/c^2$ and $800 < M_{K^\pm\pi^0} < 1000$ MeV$/c^2$, we can see the mass spectra of two photons as Fig. 5 and Fig. 6. By fixing the π^0 mass and mass resolution coming from the fits of the $\gamma\gamma$ mass spectra of Fig. 1 and Fig. 2, a Gaussian function added a constant background fit to each $\gamma\gamma$ mass spectrum of Fig. 5 or Fig. 6 yields the number of events to be 7.5 or 2.5, or the upper limit of the $\rho\pi$ or $K^{*\pm}K^\mp$ events at the 90% confidence level to be 10.6 or 4.3. MC simulations yield the detection efficiencies for $\rho\pi$ and $K^{*\pm}K^\mp$ to be 10.1% and 5.85%, respectively. So we can get the upper limits of the branching fractions for $\rho\pi$ and $K^{*\pm}K^\mp$:

$$B(\psi(2S) \to \rho\pi) < 2.8 \times 10^{-5} \quad (90\% \text{ C.L.})$$

$$B(\psi(2S) \to K^{*+}\bar{K}^- + c.c.) < 5.9 \times 10^{-5} \quad (90\% \text{ C.L.}).$$

Combining the results from the $K^0_s K^\pm \pi^\mp$ channel:

$$B(\psi(2S) \to K^0_s K^\pm \pi^\mp) = (3.8 \pm 1.0 \pm 0.8) \times 10^{-5}$$

$$B(\psi(2S) \to K^{*+}\bar{K}^- + c.c.) < 3.0 \times 10^{-5} \quad (90\% \text{ C.L.}),$$

we give the following results:

$$B(\psi(2S) \to K\bar{K}\pi) = (1.29 \pm 0.19 \pm 0.26) \times 10^{-4}$$

$$B(\psi(2S) \to K^{*+}\bar{K}^- + c.c.) < 3.0 \times 10^{-5} \quad (90\% \text{ C.L.}).$$

On the other hand, the $K^{*0}\bar{K}^0$ decay is dominant in the $\psi(2S)$ decay to $K^0_s K^\pm \pi^\mp$ mode while only one K^* candidate is seen in the $K^0_s \pi^-$ mass spectrum, and then we have

$$B(\psi(2S) \to K^{*0}\bar{K}^0 + c.c.) = (8.1 \pm 2.4 \pm 1.6) \times 10^{-5}.$$

(In detail, see the analysis memo about $\psi(2S) \to K\bar{K}\pi$, author: Yuan Changzheng)

Otherwise, to obtain the number of $\rho\pi$ events, projections onto the mass axes are taken. The distribution of several events within ρ mass region looks like a ρ signal except that their mean mass is lower that the ρ mass. The careful checks have been done for these events. It appears that there is no instrumental explanation, or any reason related to the reconstruction that is causing the mass shift since the ρ^0 signal observed in the process of $\psi(2S) \to J/\psi +$ neutral and $J/\psi \to \rho^0\pi^0$ is consistent with a ρ mass listed in PDG. A logical interpretation seems to be that these events come from uniphase space $\pi^+\pi^-\pi^0$ process, and their $\pi\pi$ mass distribution in ρ mass region is a statistical fluctuation. A BW curve with a quadratic background fit to the $\pi\pi$ mass data by fixing the mass and width of ρ to PDG values yields the event number to be 0 and its upper limit to be 10.1 at the 90% confidence level. A MC simulation yields the detection efficiency to be 12.4%, and one gets

$$B(\psi(2S) \to \rho\pi) < 2.2 \times 10^{-5} \quad (90\% \text{ C.L.})$$

The upper limit of branching fraction of $\psi(2S) \to \rho\pi$ obtained by fitting the $\gamma\gamma$ mass data is greater than that by fitting the $\pi\pi$ mass data. This is comprehensible since the former includes the contribution of continuous $\pi^+\pi^-\pi^0$ process. So the former result is reserved.

IV. DISCUSSION

From the above results, we can see that:

a. The upper limit of the $\rho\pi$ decay is now lower than any theoretical predictions.

b.

$$\frac{B(\psi(2S) \to K^{*0}\bar{K}^0 + c.c.)}{B(\psi(2S) \to K^{*+}\bar{K}^- + c.c.)} > 1 \text{ while } \frac{B(J/\psi \to K^{*0}\bar{K}^0 + c.c.)}{B(J/\psi \to K^{*+}\bar{K}^- + c.c.)} < 1.$$

A possible interpretation to this phenomenon can be stated here.

The partial width of a charmonium state decay into a VP mode can be written as

$$\Gamma((c\bar{c}) \to VP) = |A|^2 p_V^3,$$

here p_V is the momentum of the vector meson in the rest frame of the charmonium state, and A is the amplitude coupled with strength g for the strong decay (OZI process via the three gluons), sg for possible SU(3) violation, and e for electromagnetic process via a virtual photon. These constants are relatively real, and the phase of e relative to g is defined to be θ_e. For $\rho\pi$, $K^{*\pm}K^{\mp}$, $K^{*0}\bar{K}^0$, and $\omega\pi^0$, the amplitude A's are shown in Table V.

In the case of the J/ψ, using $g = 1.10$, $s = 0.12$, $e = 0.12$, and $\theta_e = 72°$ [9], we find that $g(1-s) > e$ or the strong component is greater than the electromagnetic component, hence $B_{K^{*0}\bar{K}^0}/B_{K^{*\pm}K^{\mp}} < 1$.

In the case of the $\psi(2S)$, assuming $g(1-s) \ll e$, we predict

$$B(\psi(2S) \to K^{*\pm}K^{\mp}) \approx |\frac{e}{-2e}|^2 B(\psi(2S) \to K^{*0}\bar{K}^0) \sim 2.0 \times 10^{-5}.$$

If we take 4 $K^{*\pm}$ candidates as $K^{*\pm}K^{\mp}$ events and the fitted number of events 7.5 of Fig. 5 as $\rho\pi$ events, then we can get

$$B(\psi(2S) \to K^{*\pm}K^{\mp}) = (1.9 \pm 1.0 \pm 0.6) \times 10^{-5}$$

$$B(\psi(2S) \to \rho\pi) = (1.8 \pm 0.7 \pm 0.4) \times 10^{-5}.$$

If we assume that the electromagnetic process conserves the " 15% rule ", and denote A_e as electromagnetic amplitude, we can calculate $B^e_{J/\psi}$, the electromagnetic component for J/ψ decay mode, and $B^e_{\psi(2S)}$, the electromagnetic component for $\psi(2S)$ decay mode according to the following relations,

$$B^e_{J/\psi} = B_{J/\psi}|A_e|^2/|A|^2,$$

$$B^e_{\psi(2S)} = 15\% \times B^e_{J/\psi}.$$

These values are listed in Table V. As we know, because there is the continuous QED process, the measured branching fraction should be greater than the electromagnetic component, or these $B^e_{\psi(2S)}$ show us the lower limits for the measured branching fractions if our assumption can be proven out.

V. CONCLUSION

The measurements of the $\psi(2S)$ decays into $\pi^+\pi^-\pi^0$, $K^+K^-\pi^0$, $\rho\pi$, and $K^*\bar{K}$ are renewed in high statistics:

$$B(\psi(2S) \to \pi^+\pi^-\pi^0) = (1.03 \pm 0.13 \pm 0.16) \times 10^{-4}$$

$$B(\psi(2S) \to K^+K^-\pi^0) = (7.1 \pm 1.3 \pm 1.3) \times 10^{-5}$$

$$B(\psi(2S) \to \rho\pi) < 2.8 \times 10^{-5} \quad (90\% \text{ C.L.})$$

$$B(\psi(2S) \to K^{*\pm}K^{\mp}) < 3.0 \times 10^{-5} \quad (90\% \text{ C.L.})$$

$$B(\psi(2S) \to K\bar{K}\pi) = (1.29 \pm 0.19 \pm 0.26) \times 10^{-4}.$$

The $\psi(2S)$ decays into $\rho\pi$ and $K^{*\pm}K^{\mp}$ modes are now suppressed by factors of 67 and 24 compared with the corresponding J/ψ decays.

No theoretical model can stand so far.

It seems that, for the $\psi(2S)$ decays into VP modes, the three gluon process is severely suppressed while the electromagnetic process conserves the "15% rule".

The "$\rho\pi$ puzzle" remains a puzzle.

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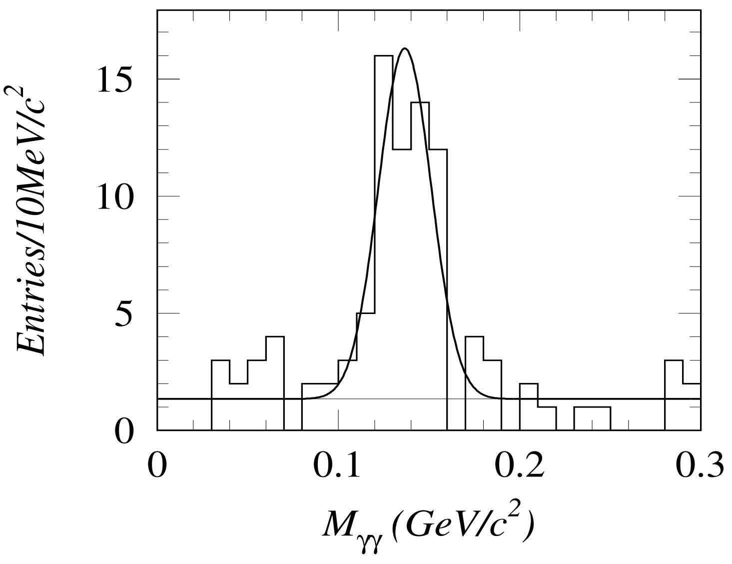

FIG. 1. The $\gamma\gamma$ mass spectrum in the final state $\pi^+\pi^-\gamma\gamma$.

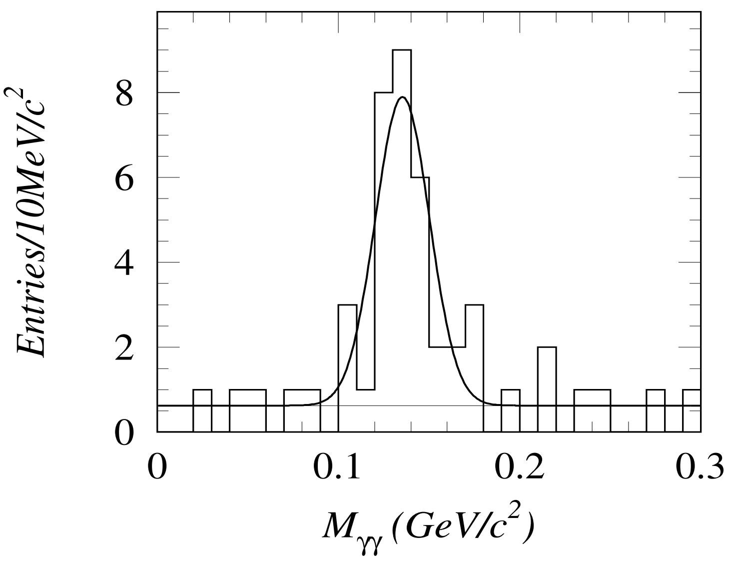

FIG. 2. The $\gamma\gamma$ mass spectrum in the final state $K^+K^-\gamma\gamma$.

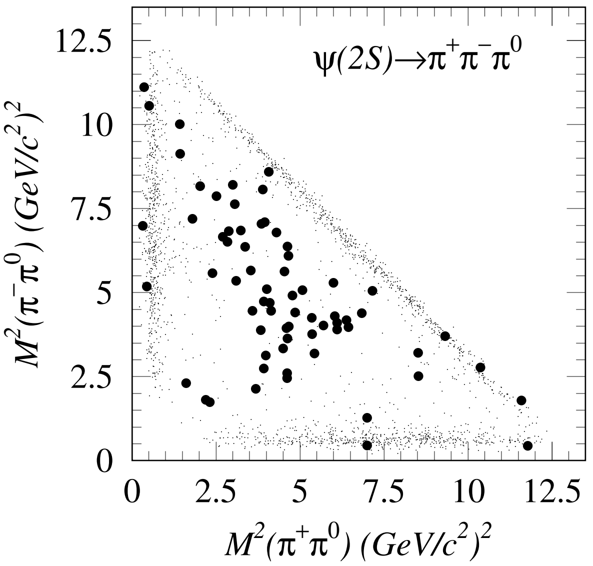

FIG. 3. The Dalitz plot for the $\psi(2S)$ decay to $\pi^+\pi^-\pi^0$.

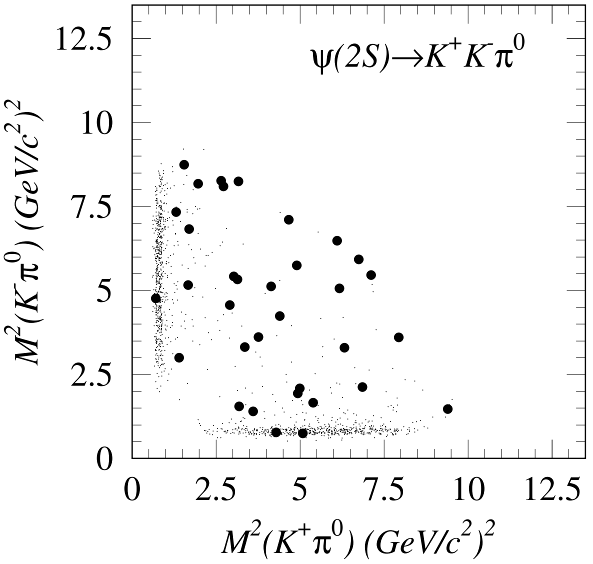

FIG. 4. The Dalitz plot for the $\psi(2S)$ decay to $K^+K^-\pi^0$.

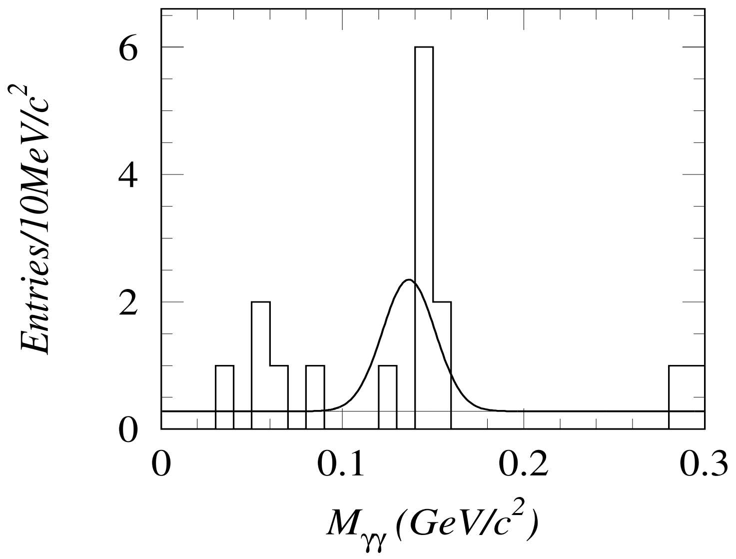

FIG. 5. The $\gamma\gamma$ mass spectrum by applying the ρ mass cut $560 < M_{\pi\pi} < 980$ MeV$/c^2$.

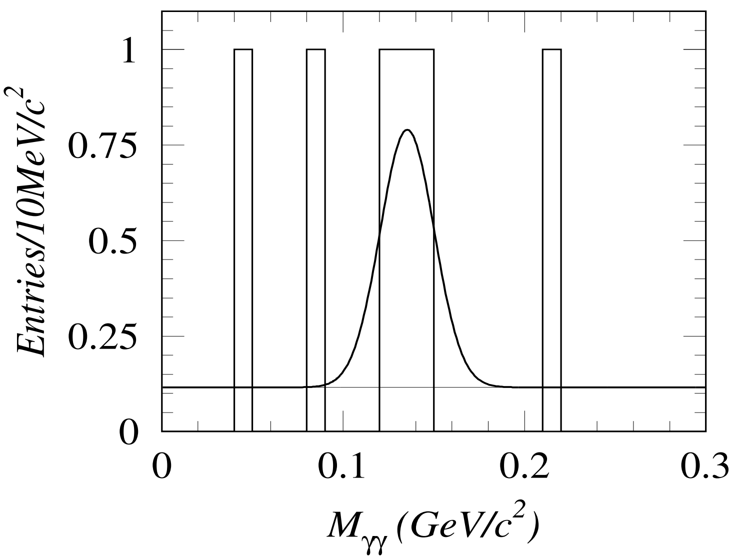

FIG. 6. The $\gamma\gamma$ mass spectrum by applying the $K^{*\pm}$ mass cut $800 < M_{K^{*\pm}\pi^0} < 1000$ MeV$/c^2$.

TABLES

TABLE I. The number of events through the different cuts for two data sets of the $\psi(2S)$.

Cut	'94 data		'95 data		MC V153		MC V154	
	$\pi^+\pi^-\gamma\gamma$	$K^+K^-\gamma\gamma$	$\pi^+\pi^-\gamma\gamma$	$K^+K^-\gamma\gamma$	$\pi^+\pi^-\pi^0$	$K^+K^-\pi^0$	$\pi^+\pi^-\pi^0$	$K^+K^-\pi^0$
preselection	529	1353	1025	2631	1445	1092	2196	1924
further cut 1	66	64	102	130	895	791	1749	1551
further cut 2	59	35	89	78	892	780	1734	1533
further cut 3	52	20	82	43	855	591	1684	1208

TABLE II. The fit results and branching fractions of the $\psi(2S)$ decays to $\pi^+\pi^-\pi^0$ and $K^+K^-\pi^0$.

Mode	M_{π^0} (MeV/c^2)	σ_M (MeV/c^2)	Events	Efficiency	Background	BR (10^{-5})
$\pi^+\pi^-\pi^0$	136.65	14.56	54.6 ± 6.7	14.2%	2.1	$10.3 \pm 1.3 \pm 1.6$
$K^+K^-\pi^0$	135.32	14.93	27.2 ± 4.7	10.2%	2.0	$7.1 \pm 1.3 \pm 1.3$

TABLE III. The estimated background through $\pi^+\pi^-\pi^0$ and $\rho\pi$ selection.

Channel	BR	No.	$\lvert M_{\gamma\gamma} - 135\rvert < 45$	BG	$560 < M_{\pi\pi} < 980$	BG
$K^+K^-\pi^0$	7.1×10^{-5}	17500	99	1.4	17	0.24
$\rho^0\pi^0\pi^0$	$\sim 2.1 \times 10^{-4}$[a]	3888	2	0.4	2	0.39
$f_2(\pi^+\pi^-)\gamma$	$2.2 \times 10^{-4} \times 0.85 \times 2/3$	18000	6	0.15	1	0.025
$\eta'(\gamma\rho^0)\gamma$	$1.53 \times 10^{-4} \times 0.302$	33500	11	0.05	11	0.05
$\omega\pi^0$	$\sim 6.6 \times 10^{-5}$[b]	2000	1	0.12	0	0
$J/\psi(\rho\pi)$neutral	$23.2\% \times 1.28\%$	10393	0	0	0	0

[a]The estimated value according to isospin conservation with the PDG listed value of $B(\psi(2S) \to \rho^0\pi^+\pi^-)$.
[b]The preliminary result on the BES measurement.

TABLE IV. The estimated background through $K^+K^-\pi^0$ and $K^{*\pm}K^{\mp}$ selection.

Channel	BR	No.	$\lvert M_{\gamma\gamma} - 135\rvert < 45$	BG	$800 < M_{K^\pm\pi^0} < 1000$	BG
$\pi^+\pi^-\pi^0$	1.03×10^{-4}	17500	45	0.95	5	0.11
$J/\psi(\rho\pi)$neutral	$23.2\% \times 1.28\%$	10393	1	1.03	0	0

TABLE V. Amplitudes and relative branching fractions.

Process	Amplitude	$B^{meas}_{J/\psi}(10^{-3})$	$B^{e}_{J/\psi}(10^{-3})$	$B^{e}_{\psi(2S)}(10^{-5})$	$B^{meas}_{\psi(2S)}(10^{-5})$
$\rho\pi$	$3*(g+e)$	12.8 ± 1.0	0.12	1.8	< 2.8
$K^{*+}K^{-} + c.c.$	$2*(g(1-s)+e)$	5.0 ± 0.4	0.070	1.1	< 3.0
$K^{*0}\bar{K^{0}} + c.c.$	$2*(g(1-s)-2e)$	4.2 ± 0.4	0.28	4.2	8.1 ± 2.8
$\omega\pi^{0}$	$3e$	0.42 ± 0.06	0.42	6.3	6.6 ± 1.4