Study of the charmonium state χ_{c0} in $\psi(2S)$ decays — analysis memo

Yuan Changzheng

yuancz@bepc5.ihep.ac.cn

(Jun., 1996)

Abstract

$\gamma\pi^+\pi^-$, γK^+K^- and $\gamma p\bar{p}$ final states were studied with the $\psi(2S)$ data collected by BES/BEPC to measure the resonance parameters of the p-wave charmonium state χ_{c0}. The study gave the best estimate of the total width of χ_{c0} was $(15.0^{+3.2}_{-2.8})$MeV and the branching fractions of $\chi_{c0} \to p\bar{p}$ was $(14.5 \pm 3.9 \pm 3.1) \times 10^{-5}$. The branching fractions of $\chi_{cJ}(J = 0, 2)$ going to $\pi^+\pi^-$, K^+K^- and the branching fractions of $\chi_{cJ}(J = 1, 2)$ going to $p\bar{p}$ were measured too, the results were $B(\chi_{c0} \to \pi^+\pi^-) = (4.27 \pm 0.23 \pm 0.60) \times 10^{-3}$, $B(\chi_{c0} \to K^+K^-) = (3.44 \pm 0.21 \pm 0.47) \times 10^{-3}$, $B(\chi_{c2} \to \pi^+\pi^-) = (1.52 \pm 0.17 \pm 0.29) \times 10^{-3}$, $B(\chi_{c2} \to K^+K^-) = (5.2 \pm 1.1 \pm 1.8) \times 10^{-4}$, $B(\chi_{c1} \to p\bar{p}) = (8.3 \pm 2.9 \pm 2.7) \times 10^{-5}$ and $B(\chi_{c2} \to p\bar{p}) = (9.6 \pm 3.5 \pm 4.1) \times 10^{-5}$, where the first error was statistical and the second one systematic.

I. INTRODUCTION

The charmonium p-wave triplet states $\chi_{cJ}(J = 0, 1, 2)$ were found in 1970's and most of their decay parameters were measured before 1980's. By studying the charmonium states formed directly in proton-antiproton annihilation, Fermilab experiment E-760 gave a precision measurement of the total widths of χ_{c1} and χ_{c2} in 1992 [1], but χ_{c0} was still not studied because of its small branching fraction of going to electromagnet final states and its large total width.

The only available data on the total width of χ_{c0} was reported by Crystal Ball (CBAL) [2], which was measured in two different ways – the inclusive process $\psi(2S) \to \gamma X$ (13-21MeV) and the exclusive process $\psi(2S) \to \gamma\pi^0\pi^0 \to 5\gamma$ ($8.8 \pm 1.3 \pm 1.5$MeV), agree within 2.2 standard deviations. By combining these two measurements, CBAL gave the best estimate of the natural linewidth of the χ_{c0} was $13.5 \pm 3.3 \pm 4.2$MeV. The decay of $\chi_{c0} \to p\bar{p}$ was forbidden by the massless helicity conservation law, the only measurement of its branching fraction is an upper limit, with 90% confidence level, $B(\chi_{c0} \to p\bar{p}) < 9.0 \times 10^{-4}$.

Beijing Spectrometer (BES) running at Beijing Electron Positron Collider (BEPC) collected $3.5(1 \pm 0.10)$ million $\psi(2S)$'s in its 1993/94 and 1995 running. In this paper we report a measurement of the total width of χ_{c0} and the branching fraction of $\chi_{c0} \to p\bar{p}$ with these data.

The BES is a conventional cylindrical detector that is described in detail in Ref. [3]. A four-layer central drift chamber (CDC) surrounding the beampipe provides trigger information. A forty-layer main drift chamber (MDC), located radially outside the CDC, provides trajectory and energy loss (dE/dx) information on charged tracks over 85% of the total solid angle. The momentum resolution is $\sigma_p/p = 0.017\sqrt{1+p^2}$ (p in GeV/c), and the dE/dx resolution for hadron tracks is $\sim 11\%$. An array of 48 scintillation counters surrounding the MDC measures the time-of-flight (TOF) of charged tracks with a resolution of ~ 450 ps for hadrons. Outside the TOF system, a 12 radiation length, lead-gas barrel shower counter (BSC), operating in self-quenching streamer mode, measures the energies of electrons and photons over $\sim 80\%$ of the total solid angle with an energy resolution of $\sigma_E/E = 22\%/\sqrt{E}$ (E in GeV), and spatial resolutions of $\sigma_\phi = 7.9$ mrad, $\sigma_z = 3.6$ cm. Surrounding the BSC is a solenoidal magnet coil that provides a 0.4 Tesla magnetic field throughout the central tracking region of the detector. Three double layers of muon counters instrument the magnet flux return and serve to identify muons of momentum greater than 0.5 GeV/c. Endcap time-of-flight and shower counters extend coverage to the forward and backward regions.

II. TECHNIQUES

The most important techniques in determination of the total width of a resonance include two aspects: purely selected events and well determined mass resolution. The former make sure that the lineshape of the resonance is not distorted and the latter ensures that the width of the resonance determined is reliable.

To satisfy the above two requirements, the paired pseudoscalar mesonic decay modes of χ_{cJ} ($\pi^+\pi^-$ and K^+K^-) are used in our analysis, because it has the following advantages: 1. With four constrained kinematic fit, we can get relatively pure events. Although the cross contamination of the two channels we studied is inevitable, we can remove the contamination reliably according to Monte Carlo and the distributions got from data sample, so to get a pure distribution of each decay mode. 2. The Monte Carlo sometimes cannot describe the detector very well because the data taking procedure always going on for a long period of time and status of the detector changes much, while the Monte Carlo can only simulate the detector performance of some certain status. It will be risky to use the mass resolution completely determined from Monte Carlo. Instead in our analysis the mass resolution at χ_{c2} mass region was fitted out with the precisely measured width of χ_{c2} as input [4], and then it was used to calibrate the mass resolution function got from Monte Carlo simulation to give the mass resolution expected at χ_{c0} mass region, by fitting χ_{c0} with the mass resolution determined in this way, the reliable line width of χ_{c0} could be got. 3. The procedure of calibrating mass resolution function can not be used in some other decay modes of χ_{cJ}s although the branching fractions are larger, because χ_{c1} lies in the lower mass side of χ_{c2} and the possible existing η_c' lies in the higher mass side will fold together with χ_{c2} to make the procedure of getting the mass resolution χ_{c2} become very complicated. However, in the two modes selected, the J^Ps of χ_{c0} and χ_{c2} are $even^+$ while that of χ_{c1} and η_c' are 1^+ and 0^-, the decay of χ_{c1} and η_c' to 0^-0^- is forbidden by parity conservation, so we can get χ_{c0} and χ_{c2} resonances without any distortion due to the contamination from other resonances.

III. EVENT SELECTION

Events selection includes the identification of good photon, good charged tracks and separation of the events.

A neutral cluster is regarded as an photon candidate when its energy deposited in BSC greater than 50MeV and the cosine of the angle to the nearest charged track less than 0.96; the first hit of the cluster should be in the first three layers (about 3r.l.) of BSC and the hit cells at least in two layers. After identification, at least one and at most three photon candidates are allowed in one events. The candidate has the largest SC energy is considered to be the photon radiated from $\psi(2S)$.

The number of charged tracks in the events is required to be two with net charge zero and each track with high quality in track fitting; momentum of each track should greater than 1.0GeV/c and $|\cos\theta| < 0.8$, where θ is the polar angle relatives to the beam axis; to remove events with electron or with muon, we require at least one of the two tracks with $|\cos\theta| < 0.6$ and the total SC energy of the two charged tracks less than 1.4GeV and $Mustatus^{+} + Mustatus^{-} < 3$ [5]; TOF and dE/dx information is used for charged particle identification. The probabilities of the particle to be identified as a pion, kaon and proton were assigned to each track ($Prob_{\pi}, Prob_{K}, Prob_{p}$), both tracks must have $Prob_{\pi} > 0.01$ (for $\pi^+\pi^-$) or $Prob_K > 0.01$ (for K^+K^-); define $umiss = Emiss - Pmiss$, the difference between missing energy and missing momenta of the charged tracks, we require it lies in $\pm 2.575\sigma$ ($Prob_{\pi}^{umiss} > 1\%$ for $\pi^+\pi^-$ or $Prob_{K}^{umiss} > 1\%$ for K^+K^-) of the expected distribution of $umiss$; do four constrained kinematic fit to $\psi(2S) \to \gamma\pi^+\pi^-$ and $\psi(2S) \to \gamma K^+K^-$ with the photon candidate and the two charged tracks, the probability of the fit P^{χ^2} should greater than 1%.

To separate $\gamma\pi^+\pi^-$ and γK^+K^- from each other, we define

$$Prob_{all}^{\pi^+\pi^-} = Prob_{\pi}^{+} \cdot Prob_{\pi}^{-} \cdot Prob_{\pi}^{umiss} \cdot P_{\pi}^{\chi^2}$$

and

$$Prob_{all}^{K^+K^-} = Prob_{K}^{+} \cdot Prob_{K}^{-} \cdot Prob_{K}^{umiss} \cdot P_{K}^{\chi^2}.$$

If $Prob_{all}^{\pi^+\pi^-} > 2 \cdot Prob_{all}^{K^+K^-}$ the event is regarded as a $\gamma\pi^+\pi^-$ event, and if $Prob_{all}^{K^+K^-} > 2 \cdot Prob_{all}^{\pi^+\pi^-}$ is a γK^+K^- event. Figure 1 shows some of the distributions of the cuts.

After posing all above selections to the data, the invariant mass distributions are show in figure 2, fitting of the mass plots of $\pi^+\pi^-$ and K^+K^- with two Breit-Wigners folding a gaussian like mass resolution (all parameters free) shows that the mass of χ_{c0} and χ_{c2} in $\pi^+\pi^-$ mass plot is lower than the world average while that in K^+K^- mass plot is higher, which means that the events in our two samples are cross contaminated and the contaminated parts should be removed before fitting to get χ_c parameters.

We use Monte carlo simulation to get the probabilities of cross contamination of the two channels as well as the detection efficiencies and mass resolution. In the Monte carlo generator, the χ_{cJ}s are assumed to be generated via pure E1 transition of $\psi(2S)$ citee1, χ_{cJ} decaying to 0^-0^- meson pairs has only one independent helicity amplitude and so the whole process is determined. Events at different meson pair mass between 3.3 and 3.6GeV with a step of 10 to 30MeV and zero width were generated, assuming χ_{c1} is absolutely missing, the spin-parity of the resonance is assigned to 0^+ when mass less than 3.5GeV and to 2^+ when mass greater then 3.5GeV. After requiring the events satisfy the same selection criteria as for data, the detection efficiency, the probability of cross contamination and the mass resolution at each mass are got. Fitting all these values to the generated mass of meson pair, we get the detection efficiency, the probability of cross contamination and the mass resolution as a function of the mass of meson pair (see figure 3).

IV. FIT THE MASS PLOTS

After selection, besides the $\pi^+\pi^-$ mass plot of $\gamma\pi^+\pi^-$ and K^+K^- mass plot of γK^+K^- events, we can also calculate the K^+K^- mass of $\gamma\pi^+\pi^-$ candidates and $\pi^+\pi^-$ mass of γK^+K^- candidates, the latter two plots show us the mass distribution of the cross contamination, subtract these two plots (after renormalized to the events may contaminate calculated from Monte Carlo) from the former ones, the distributions of pure events are got. Correct them with the detection efficiency functions, the produced forms of $\psi(2S) \to \gamma\chi_{cJ} \to \gamma\pi^+\pi^-$ or γK^+K^- are then obtained. The procedure can be expressed with the following formula:

$$X^{prod} = \frac{X^{obs} - \frac{Prob_X^Y}{\varepsilon_Y} Y_X^{obs}}{\varepsilon_X}$$

where X^{obs}, X^{prod} are observed and produced events of γX channel, Y_X^{obs} is the observed mass plots of γY channel but the mass is calculated using the meson mass of γX channel, ε_X is the detection efficiency of γX channel, and $Prob_X^Y$ is the probability of γY channel events misidentified as γX channel events, X and Y are $\pi^+\pi^-$ or K^+K^-. It should be noted that the operations in above formula is used for plots, or the events in each bin of the plots.

The resonance we observed in the experiment is a Breit-Wigner folds a gaussian like mass resolution, caused by detector resolution, event kinematic fit procedure etc.. In the plots got above, there are two obvious resonances with almost none background, we estimate the mass resolution of the process we studied to be proportion to the resolution got from Monte Carlo, namely $\sigma(m) = cons_\sigma \cdot \sigma^{MC}(m)$ and the background of the shape of a first order polynomial, the mass plots were fitted with the following function:

$$f(m) = \int_0^\infty dx\{(\frac{cons_{\chi_{c0}}\Gamma^2_{\chi_{c0}}}{(x - m_{\chi_{c0}})^2 - (\frac{\Gamma_{\chi_{c0}}}{2})^2} + \frac{cons_{\chi_{c2}}\Gamma^2_{\chi_{c2}}}{(x - m_{\chi_{c2}})^2 - (\frac{\Gamma_{\chi_{c2}}}{2})^2})$$
$$\cdot \frac{1}{\sigma(x)} e^{-\frac{1}{2}(\frac{m-x}{\sigma(x)})^2}\} + poly_0 + poly_1 \cdot m$$

where $cons_{\chi_{c0}}$ and $cons_{\chi_{c2}}$, $m_{\chi_{c0}}$ and $m_{\chi_{c2}}$, $\Gamma_{\chi_{c0}}$ and $\Gamma_{\chi_{c2}}$ are the normalization factors, masses and widths of χ_{c0} and χ_{c2} respectively, $poly_0$ and $poly_1$ are the coefficients of the background polynomial and $cons_\sigma$ is the factor between the mass resolution of data and that of Monte Carlo.

Fix $\Gamma_{\chi_{c2}} = 2.00$MeV which was precisely measured by other experiments [4] and let other parameters free, fitting the plots with above function using maximum likelyhood method, we get $\Gamma_{\chi_{c0}} = 15.0 \pm 1.5$MeV from $\psi(2S) \to \gamma\pi^+\pi^-$, fit also gives $cons_\sigma = 1.21$ which means that the mass resolution estimated from Monte Carlo is about 20% smaller than the real one.

The results got from fitting K^+K^- mass plot of $\psi(2S) \to \gamma K^+K^-$ is not very reliable because of the limited statistics of $\psi(2S) \to \gamma\chi_{c2} \to \gamma K^+K^-$ (so we only use the $\Gamma_{\chi_{c0}}$ value fitted from $\pi^+\pi^-$ channel in the following discussion), but it in agreement with that got from $\pi^+\pi^-$ channel: $\Gamma_{\chi_{c0}} = 15.8 \pm 1.3$MeV and $cons_\sigma = 0.94$. The error quoted in $\Gamma_{\chi_{c0}}$ is from the fitting procedure only. The mass plots and fitted results are shown in figure 4.

The events number of $\chi_{cJ} \to \pi^+\pi^-$ and K^+K^- are also fitted out for determination of the branching fractions of each channel. we got $n^{prod}_{\chi_{c0}\to\pi^+\pi^-} = 1390 \pm 74$, $n^{prod}_{\chi_{c0}\to K^+K^-} = 1121 \pm 70$, $n^{prod}_{\chi_{c2}\to\pi^+\pi^-} = 414 \pm 45$ and $n^{prod}_{\chi_{c2}\to K^+K^-} = 141 \pm 29$, where the error is statistical.

V. $\psi(2S) \to \gamma P\bar{P}$

To select $\gamma p\bar{p}$ events, the same selection criteria are used for photon identification and charged tracks selection except that to remove radiative Bhabha and radiative dimu events we only require the SC energy of the positive track less than 0.7GeV or that of the negative track less than 0.8GeV and $Mustatus^+ + Mustatus^- < 3$; to identify the proton and anti-proton tracks, we require both tracks satisfy $prob_p > 0.05$ and at least one track $prob_p > prob_\pi$ and $prob_p > prob_K$. Do 4C-fit to $\psi(2S) \to \gamma p\bar{p}$ looping over all the photon candidates and the one combination with largest probability is kept and the χ^2 probability of the fit is required to be greater than 5%. Figure 5 shows the probabilities of PARTID and 4C fit of selected events. After above selection, the invariant mass of proton and anti-proton is shown in figure 6, clear χ_c states can be seen in the plot, after background subtraction (from the lower and higher sides of the mass plot), 14.1 ± 3.8, 8.3 ± 2.9 and 7.5 ± 2.7 events are got for χ_{c0}, χ_{c1} and χ_{c2} respectively.

Assuming the χ_{cJ} states are got via pure E1 transition of $\psi(2S)$, and the independent helicity amplitudes of charmonium decays to $p\bar{p}$ are equal, detection efficiencies of the three channels are $\varepsilon_{\chi_{c0}} = 29.8\%$, $\varepsilon_{\chi_{c1}} = 32.8\%$ and $\varepsilon_{\chi_{c2}} = 28.5\%$.

VI. ERROR ESTIMATION

The error of $\Gamma_{\chi_{c0}}$ may arise from the uncertainty of $\Gamma_{\chi_{c2}}$ which is used for mass resolution calibration, vary $\Gamma_{\chi_{c2}}$ a standard deviation from the nominal value, leads a deviation of $\Gamma_{\chi_{c0}}$ about 5%. Choosing of the bin width in the mass plot (from 5MeV to 2.5MeV or to 10MeV) cause a relative error of +7% or −1%, varying selection criteria a standard deviation from the values used, contribute +17% or −15% totally. Add all these errors and the error caused by the fitting procedure in quadrature, the total percentage error of $\Gamma_{\chi_{c0}}$ is +21% in the upper side and −19% in the lower side.

The systematic errors of the branching fractions arise from selection criteria are 4.7%, 3.6%, 13% and 31% for $B(\chi_{c0} \to \pi^+\pi^-)$, $B(\chi_{c0} \to K^+K^-)$, $B(\chi_{c2} \to \pi^+\pi^-)$ and $B(\chi_{c2} \to K^+K^-)$, and 13%, 29% and 41% for $B(\chi_{c0} \to p\bar{p})$, $B(\chi_{c1} \to p\bar{p})$ and $B(\chi_{c2} \to p\bar{p})$; the errors caused by the uncertainty of total events number are 10% for all the channels; the uncertainty of $B(\psi(2S) \to \gamma\chi_{cJ})$ cause 8.6% error to χ_{c0} decay channels, 9.2% error to χ_{c1} decay channels and 10.3% error to χ_{c2} decay channels. Add all these errors in quadrature, the total percentage errors of $B(\chi_{c0} \to \pi^+\pi^-)$, $B(\chi_{c0} \to K^+K^-)$, $B(\chi_{c2} \to \pi^+\pi^-)$ and $B(\chi_{c2} \to K^+K^-)$ are 14%, 14%, 19% and 35% respectively, and those of $B(\chi_{c0} \to p\bar{p})$, $B(\chi_{c1} \to p\bar{p})$ and $B(\chi_{c2} \to p\bar{p})$ are 21%, 33% and 42% respectively.

VII. CONCLUSION AND DISCUSSION

Combining above analysis, we got

$$\Gamma_{\chi_{c0}} = 15.0^{+3.2}_{-2.8}\mathrm{MeV},$$

This result is consistent with the world average, but with high precision. Compared with the theoretical predictions, it is consistent with the expectation of Ref. [7] but has large discrepancy to that of Ref. [8].

The results of the branching fractions of χ_{cJ} decays are listed in table I and table II. The branching fractions of $\chi_{c1} \to p\bar{p}$ and $\chi_{c2} \to p\bar{p}$ are in agreement with the values listed by PDG [4], which is got from $p\bar{p}$ experiment and with small error; $B(\chi_{c0} \to p\bar{p})$ is the first measurement in the world, which is consistent with the upper limit of PDG.

Backgrounds from $\psi(2S) \to \gamma\chi_{cJ} \to \gamma p\bar{p}$ are negligible according to Monte Carlo study. Backgrounds from $\psi(2S) \to \pi^+\pi^-\pi^0$ and $\psi(2S) \to K^+K^-\pi^0$ are estimated to be negligible according to their decay branching fractions.

REFERENCES

[1] T.A.Armstrong et al., Phys.Rev.Lett. **68** (1992) 1468.
[2] J.E.Gaiser et al., Phys.Rev., **D34** (1986) 711.
[3] BES Collab., Nucl. Inst. Meth., **A344** (1994) 319.
[4] Particle Data Group, Phys.Rev., **D50** part I (1994) and references therein.
[5] BES Collab., High Ener. Phys. and nucl. Phys. (in Chinese), bf 20 (1996) 97.
[6] G.Karl, S.Meshkov and J.L.rosner, Phys.Rev., **D13** (1976) 1203;
W.Tanenbaum et al., Phys.Rev., **D17** (1978) 731;
M.Oreglia et al., Phys.Rev., **D25** (1982) 2259.
[7] W.Kwong, P.B.Mackenzie, R.Rosenfeld and J.L.Rosner, Phys.Rev., **D37** (1988) 3210.
[8] G.T.Bodwin, E.Braaten and G.P.Lepage, Phys.Rev., **D46** (1992) 1914.

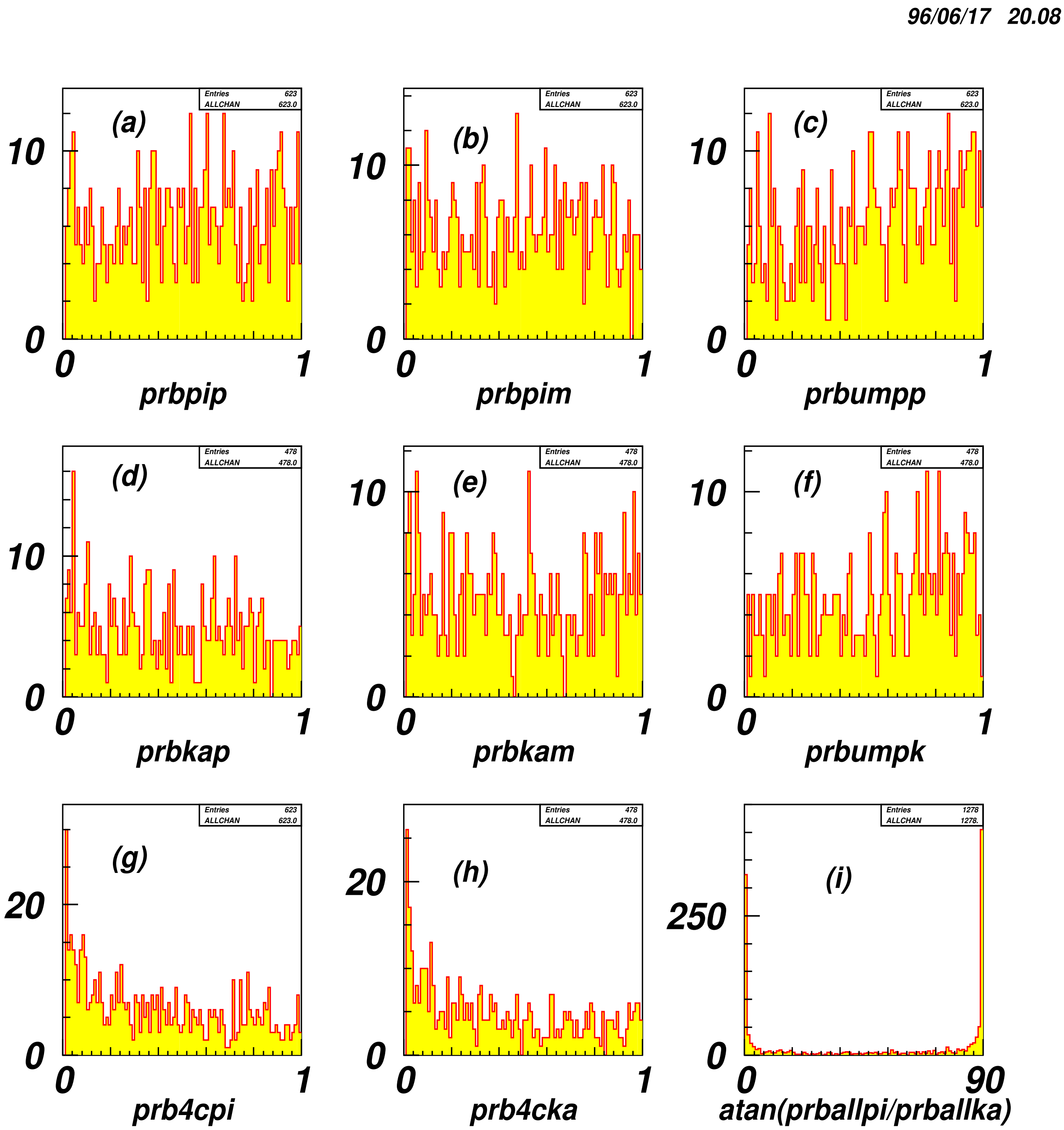

FIG. 1. Distributions of selected events, (a,b,c,g) for $\gamma\pi^+\pi^-$, (d,e,f,h) for γK^+K^-, (i) is the comparison of $Prob^{\pi}_{all}$ and $Prob^{K}_{all}$, events near 0 is γK^+K^- and near 90 is $\gamma\pi^+\pi^-$.

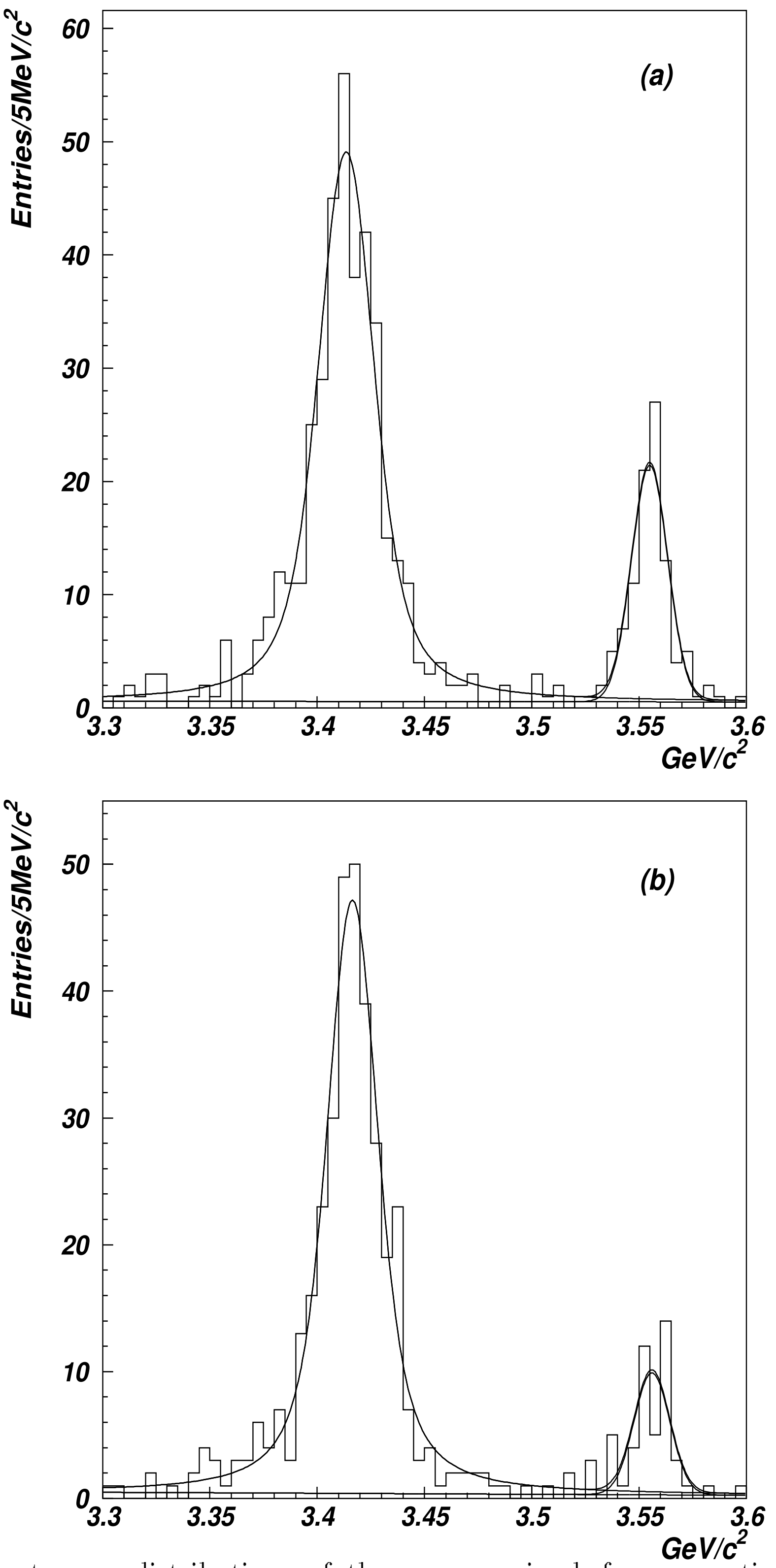

FIG. 2. invariant mass distributions of the meson pairs before correction, a) $\gamma\pi^+\pi^-$, b) γK^+K^-.

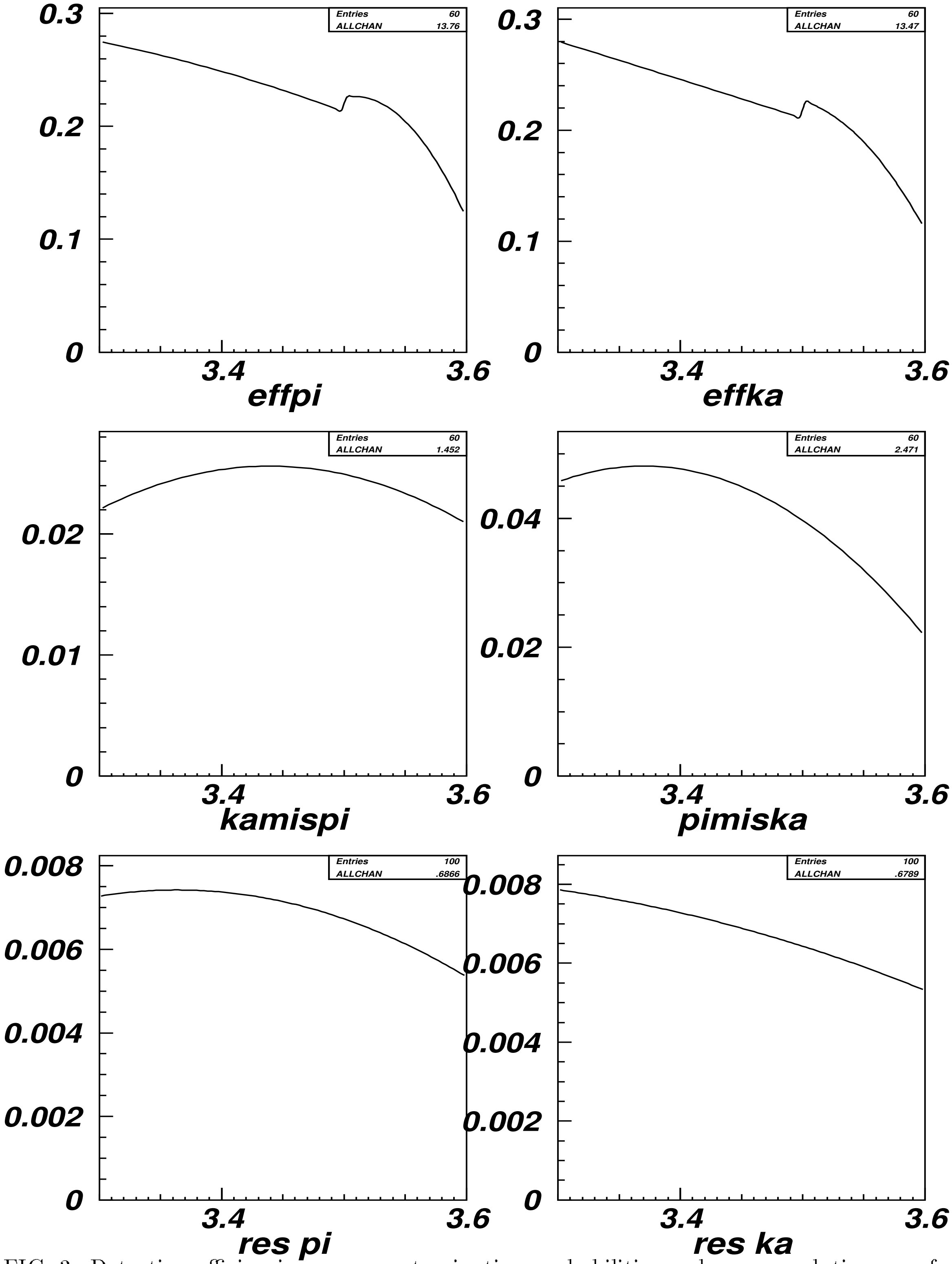

FIG. 3. Detection efficiencies, cross contamination probabilities and mass resolution as a function of the mass of meson pair

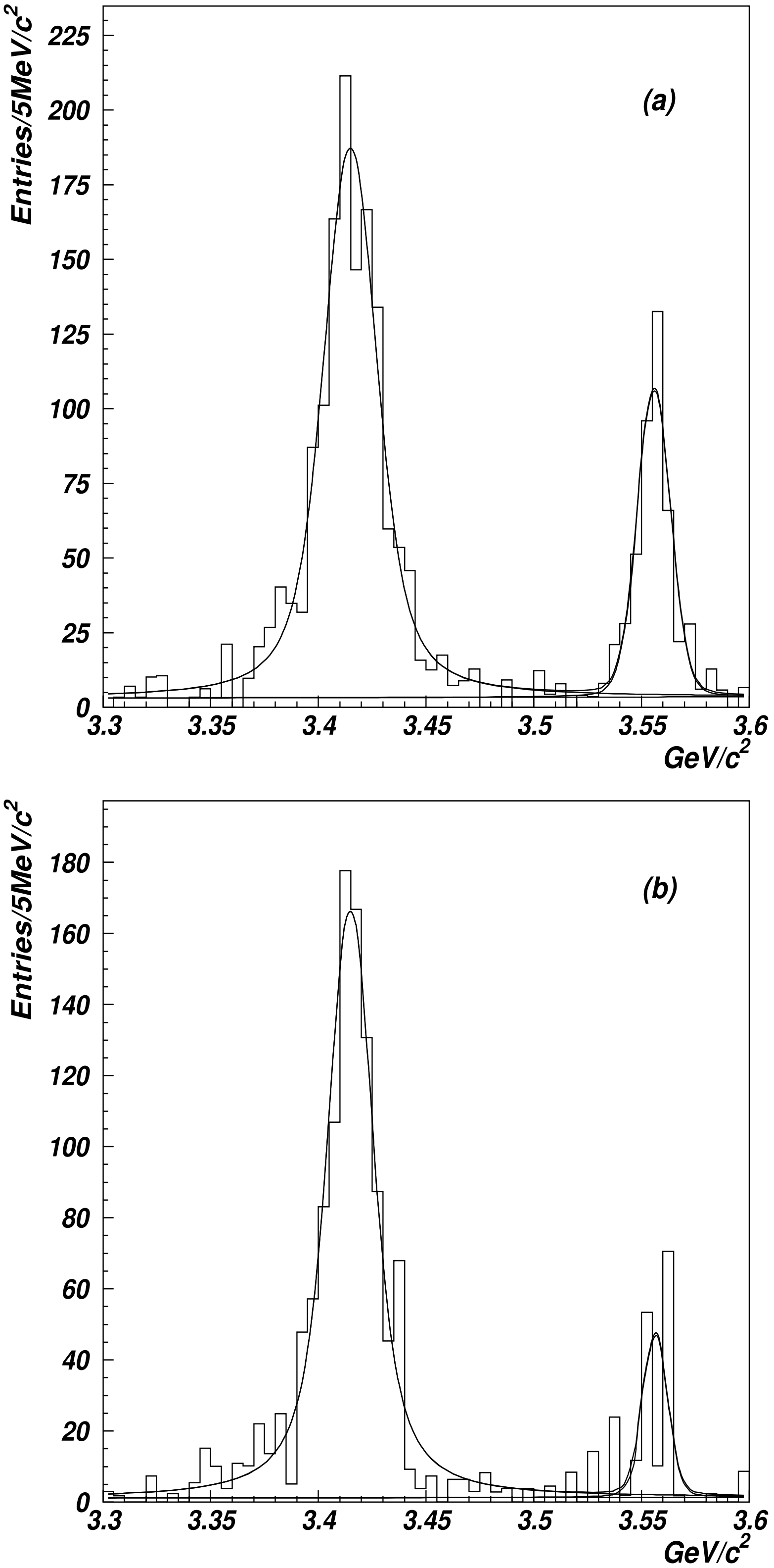

FIG. 4. Fitted results of the mass plots after correction, a) $\gamma\pi^+\pi^-$, b) γK^+K^-.

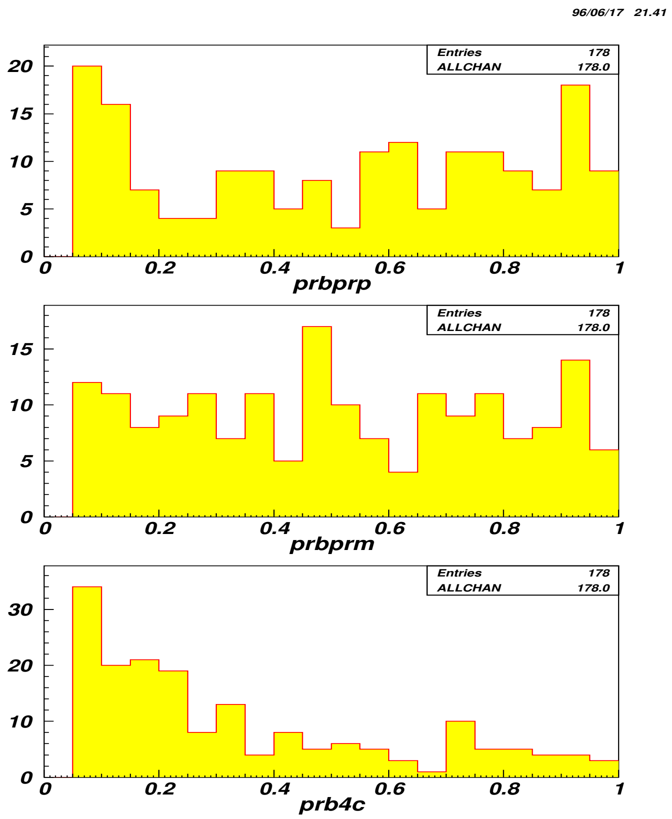

FIG. 5. some of the distributions of selected $\psi(2S) \to \gamma p\bar{p}$ events

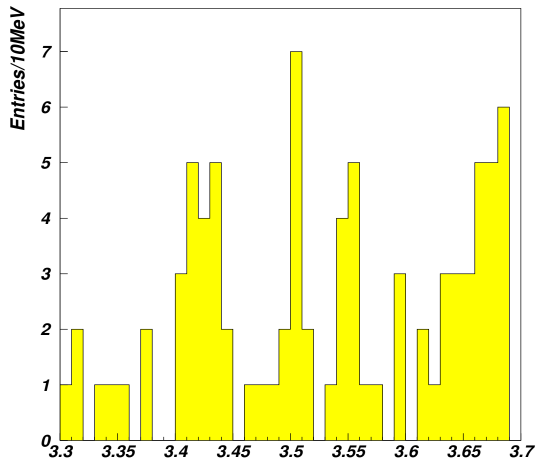

FIG. 6. $p\bar{p}$ mass distribution of $\psi(2S) \to \gamma p\bar{p}$

TABLES

decay modes	Branching Fractions($\times 10^{-5}$)	Observed Events
$\chi_{c0} \to p\bar{p}$	$14.5 \pm 3.9 \pm 3.1$	14.1 ± 3.8
$\chi_{c1} \to p\bar{p}$	$8.3 \pm 2.9 \pm 2.7$	8.3 ± 2.9
$\chi_{c2} \to p\bar{p}$	$9.6 \pm 3.5 \pm 4.1$	7.5 ± 2.7

TABLE I. Branching ratios of $\chi_{cJ} \to p\bar{p}$

decay modes	Branching Fractions($\times 10^{-3}$)	Observed Events
$\chi_{c0} \to \pi^+\pi^-$	$4.27 \pm 0.23 \pm 0.60$	350 ± 19
$\chi_{c0} \to K^+K^-$	$3.44 \pm 0.21 \pm 0.47$	258 ± 16
$\chi_{c2} \to \pi^+\pi^-$	$1.52 \pm 0.17 \pm 0.29$	84 ± 9
$\chi_{c2} \to K^+K^-$	$0.52 \pm 0.11 \pm 0.18$	24 ± 5

TABLE II. Branching ratios of $\chi_{cJ} \to 0^-0^-$