Hadronic Decays of χ_c States —BES analysis memo

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Abstract

The hadronic decays of the P-wave spin triplet charmonium states $\chi_{cJ}(J = 0, 1, 2)$ are studied using the ψ' data collected by BES/BEPC. $\chi_{c1} \to K_s^0 K^+ \pi^- + c.c.$, $\chi_{c0} \to K_s^0 K_s^0$, $\chi_{c2} \to K_s^0 K_s^0$, $\chi_{c0} \to \phi\phi$, $\chi_{c2} \to \phi\phi$ and $\chi_{cJ} \to K^+K^-K^+K^-$ are first observed and the corresponding branching fractions are determined; $\mathcal{B}(\chi_{cJ} \to \pi^+\pi^-\pi^+\pi^-)$, $\mathcal{B}(\chi_{cJ} \to \pi^+\pi^-K^+K^-)$, $\mathcal{B}(\chi_{cJ} \to \pi^+\pi^-p\bar{p})$, $\mathcal{B}(\chi_{cJ} \to K^+K^-K^+K^-)$ and $\mathcal{B}(\chi_{cJ} \to 3(\pi^+\pi^-))$ are measured with high statistics, some of the mean values are changed significantly and the precisions are improved compared with previous measurements.

1 Introduction

Although many decay modes of the $c\bar{c}$ P-wave spin-triplet states χ_{cJ} are listed by PDG [7], most of the hadronic decays were measured in only one experiment based on 30,000 produced ψ's [8], where the ability of detecting photons were restricted and a 1C kinematic fit was then applied to the events to reconstruct the χ_{cJ}s. BES detector running at BEPC collected 3.7 million ψ' data in its 1993/94 and 1995 runs, which provides a sole place to study the χ_{cJ} decays in high precision.

In this note, we report the analyses of almost all the all-charged-track final states of the χ_{cJ} decays, including $\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-K^+K^-$, $\pi^+\pi^-p\bar{p}$, $K^+K^-K^+K^-$, $K_s^0K^+\pi^- + c.c.$ and $3(\pi^+\pi^-)$, $\pi^+\pi^-$, K^+K^- and $p\bar{p}$ decays of the χ_{cJ} were also analyzed and summarized and the detailed description can be found elsewhere [3, 4].

2 Data sample and the Detector

The data sample used in this analysis was taken by BES at BEPC in 1993/94 and 1995 runs, reconstructed in University of Hawaii and IHEP respectively with V86 BES code. The total produced ψ' events is $3.7(1 \pm 10\%) \times 10^6$ calculated with inclusive $\psi' \to \pi^+\pi^-J/\psi$ events.

The BES is a conventional cylindrical detector that is described in detail in Ref. [5]. 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.

3 Monte Carlo

We use Monte Carlo simulation to get the detection efficiencies as well as the mass resolutions.

In the Monte Carlo generator, the χ_{cJ}'s are assumed to be generated via pure E1 transition of ψ' [6], namely $1+\cos^2\theta$, $1-\frac{1}{3}\cos^2\theta$ and $1+\frac{1}{13}\cos^2\theta$ for $J=0,1$ and 2 respectively. Muiltihadron decays of χ_{cJ}s are simulated according to phase space distribution. 10000 or 5000 events are generated for each channel according to the statistics of corresponding mode from real data.

4 Events selection

4.1 γ Identification

A neutral cluster is regarded as a photon candidate when the angle in xy plane between the nearest charged track and the cluster greater than 15°, the first hit should be in the beginning 6 radiation length, and the cosine of the angle between cluster develop direction and its emit direction greater than 0.80. When these selection criteria used to select γ candidates in $\psi' \to \pi^+\pi^-\pi^+\pi^-$ and $\psi' \to \pi^+\pi^-K^+K^-$, less than 20% events can find γ's. After identification, The number of photon candidates N_γ is required to be one, two, three or four in one events. The candidate has the largest BSC energy is considered to be the photon radiated from ψ' and then subjected to a four-constraint kinematic fit to the hypothesis $\psi' \to \gamma +$ charged tracks assignment.

4.2 Charged Particle Identification

Charged particles are identified using the sketch of the D_s official partid program—PARTID1 with TOF and dE/dx correction parameters got from two ψ' data sets. A correction of the deviations of dE/dx XS is introduced instead of using the default value of one for the D_s data. The Monte Carlo simulated data is treated in different way and with different correction parameters. The codes are checked with $\psi' \to \pi^+\pi^- J/\psi$, $J/\psi \to \rho\pi$ and $J/\psi \to K^+K^-$, the partid probability of the tracks in different momentum range distributes uniformly between zero and one as expected and the branching fraction of $J/\psi \to K^+K^-$ in good agreement with the world average listed by PDG [7]. The probabilities of the particle to be identified as a pion, kaon or proton are assigned to each track ($Prob_\pi, Prob_K, Prob_p$) for further use, typically the PARTID probability of each track is required to be greater than 1%.

4.3 Events Selection Criteria

Following lists the generally used events selection criteria for all channels:

1. Run status > 0, namely, only very bad RUNs are rejected;
2. The number of charged tracks is required to be four or six with net charge zero and each track with high quality in track fitting(MFIT=2 or -19);
3. $|\cos\theta_{MDC}| < 0.8$ for all the tracks in the event;
4. $0 < NNEU < 9$ and $0 < N_\gamma < 5$;
5. The total momentum of the lower momentum π^+ and π^- should be greater than 550MeV to remove the contamination from $\psi' \to \pi^+\pi^- J/\psi$ events;
6. The χ^2 probability of four-constraint kinematic fit Prob4C > 0.01;
7. PARTID probability of each charged track ProbID > 0.01;

Tables 1 and 2 show the events number after each step of the cut in pre-selection.

Table 1: Events number after each cut for data and Monte Carlo (pre-selection, four prongs).

Cut	data	$\gamma\pi^+\pi^-\pi^+\pi^-$	$\gamma K^0_s K^0_s$	$\gamma\pi^+\pi^- K^+K^-$	$\gamma\pi^+\pi^- p\bar{p}$	$\gamma K^+K^-K^+K^- + \gamma\phi\phi$	$\gamma K^0_s K^+\pi^- + c.c.$
Total evts	2507071	35000	10000	35000	20000	30000	30000
IJK>0	2442918	35000	10000	35000	20000	30000	30000
Nchrg=4	1171865	22223	6887	20835	11794	17126	18323
0<NNEU<9	1063620	22223	6887	20835	11794	17125	18323
MFIT=2,-19	1041633	22166	6849	20712	11775	16967	18205
$\Sigma Q = 0$	810834	21757	6431	19631	11576	15422	17352
$0 < N_\gamma < 5$	534434	10822	3294	10319	5653	8751	9276

Table 2: Events number after each cut (pre-selection, six prongs).

Cut	data	$\gamma 3(\pi^+\pi^-)$ MC
Total events	1932794	30000
IJK .GT. 0	1900576	30000
NCHRG=6	598562	13867
0<NNEU<9	558252	13867
MFIT=2,-19	546433	13801
$\Sigma Q = 0$	406940	13282
0< N_γ <5	315495	5856

4.3.1 $\gamma\pi^+\pi^-\pi^+\pi^-$ and $\gamma\pi^+\pi^-K^+K^-$

A combined probability of the four-constraint kinematic fit and particle identification is used to separate $\gamma\pi^+\pi^-\pi^+\pi^-$ and different particle assignments of $\gamma\pi^+\pi^-K^+K^-$ assumptions. The combined probability $Prob_{all}$ is defined as

$$Prob_{all} = Prob(\chi^2_{\text{all}}, ndf_{\text{all}}),$$

where $\chi^2_{\text{all}} = \chi^2_{4C} + \chi^2_{ID^+_{p_h}} + \chi^2_{ID^-_{p_h}} + \chi^2_{ID^+_{p_l}} + \chi^2_{ID^-_{p_l}}$ and $ndf_{\text{all}} = ndf_{4C} + ndf_{ID^+_{p_h}} + ndf_{ID^-_{p_h}} + ndf_{ID^+_{p_l}} + ndf_{ID^-_{p_l}}$ are the total χ^2 and corresponding number of degrees of the freedom of the χ^2 distributions; χ^2_{4C} and $\chi^2_{ID^{+,-}_{p_h,p_l}}$ are the χ^2's of four-constrain kinematic fit and of the PARTID of the high momentum (p_h) or low momentum (p_l) positive (+) or negative (−) tracks; ndf_{4C} and $ndf_{ID^{+,-}_{p_h,p_l}}$ are the corresponding number of degrees of the freedom of the χ^2 distributions.

The particle assignment with largest $Prob_{all}$ is regarded as the right assumption and further cuts on kinematic fit probability and PARTID probability are imposed.

Tables 3, 4 and Figures 1, 2 show the events numbers after each step of the cut and the effect of the cuts on the invariant mass spectrum of all the charged tracks.

Table 3: Events numbers after each cut (after pre-selection, $\gamma\pi^+\pi^-\pi^+\pi^-$ mode, (3.2<m<3.6)).

Cut	data	χ_{c0} MC	χ_{c1} MC	χ_{c2} MC	$\chi_{c0} \to K^0_sK^0_s$ MC	$\chi_{c2} \to K^0_sK^0_s$ MC
Generated Evts		10000	10000	10000	5000	5000
Prob4C > 0.01	3966	2506	2661	2314	1179	1120
ProbID > 0.01	3367	2412	2549	2221	1115	1055
$\lvert\cos\theta\rvert < 0.8$	2423	1624	1726	1522	934	892
Remove J/ψ	1808	1606	1706	1494	892	858
$K^0_sK^0_s$ selection	59	–	–	–	720	668

Figure 3 shows the invariant mass of the two pairs of $\pi^+\pi^-$, it is obvious that $K^0_sK^0_s$ exists, a fit to the $\pi^+\pi^-$ mass gives the mass of K^0_s is 499.3 ± 1.2MeV and mass resolution is 11.8 ± 1.0MeV. To select $\gamma K^0_sK^0_s$ events, the mass of the two combinations of $\pi^+\pi^-$ is required to lie in a 2σ region around K^0_s nominal mass.

After above selection, the invariant mass distributions of $\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-K^+K^-$ and $K^0_sK^0_s$ are shown in figures 4, 5 and 6, clear χ_c signals can be seen in the plots.

Table 4: Events numbers after each cut (after pre-selection, $\gamma\pi^+\pi^-K^+K^-$ mode, (3.2<m<3.6)).

Cut	Real data	χ_{c0} MC	χ_{c1} MC	χ_{c2} MC
Generated Evts		10000	10000	10000
Prob4C > 0.01	2512	1772	1948	1794
ProbID > 0.01	2071	1684	1862	1702
$\|\cos\theta\| < 0.8$	1383	1143	1302	1142
Remove J/ψ	1224	1132	1290	1131

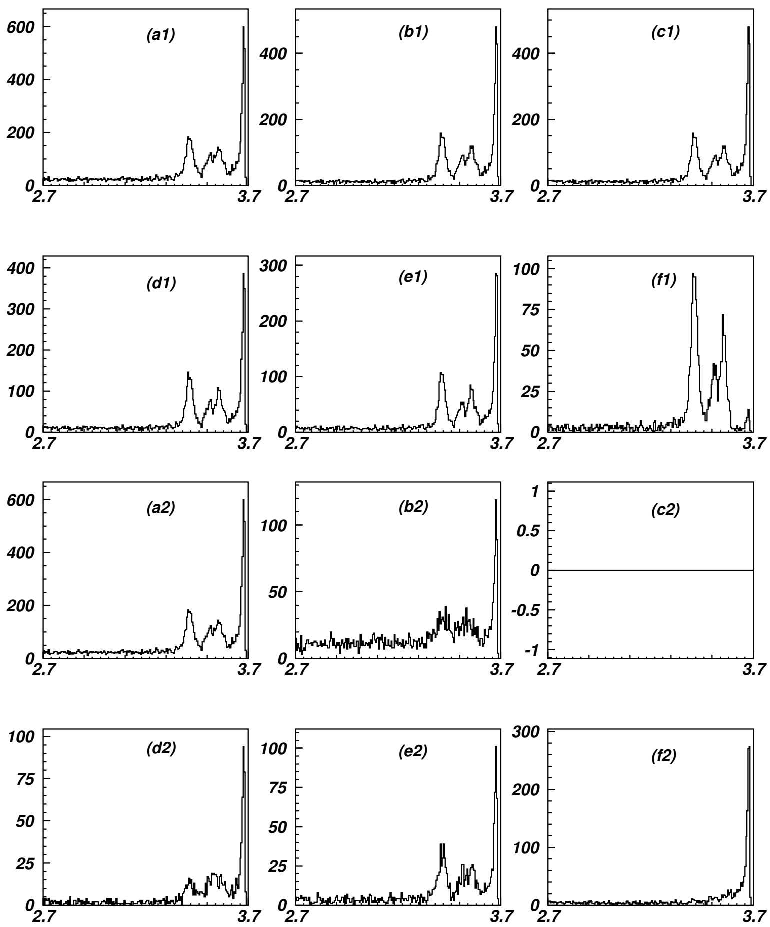


Figure 1: $\pi^+\pi^-\pi^+\pi^-$ mass distribution of $\gamma\pi^+\pi^-\pi^+\pi^-$ mode after each cut, (a1,b1,c1,d1,e1,f1) events survived the cut, (a2,b2,c2,d2,e2,f2) events removed by the cut. a) after preselection, b) Prob4C cut, c) number of gamma cut, d) ProbID cut, e) polar angle cut, f) Remove J/ψ.

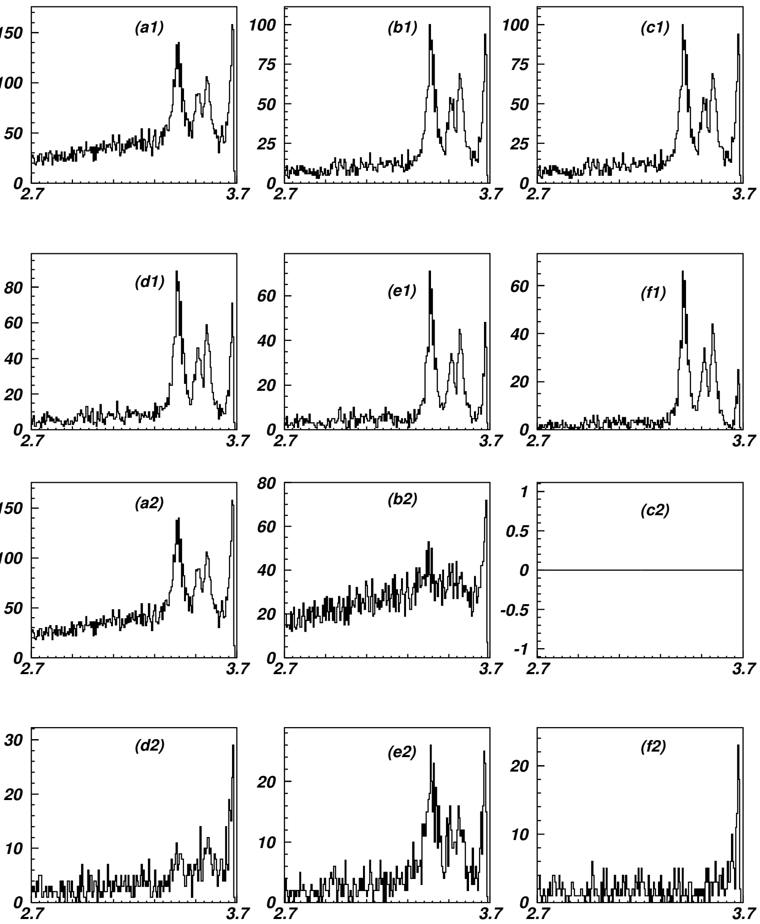


Figure 2: $\pi^+\pi^-K^+K^-$ mass distribution of $\gamma\pi^+\pi^-K^+K^-$ mode after each cut, (a1,b1,c1,d1,e1,f1) events survived the cut, (a2,b2,c2,d2,e2,f2) events removed by the cut. a) after preselection, b) Prob4C cut, c) number of gamma cut, d) ProbID cut, e) polar angle cut, f) Remove J/ψ.

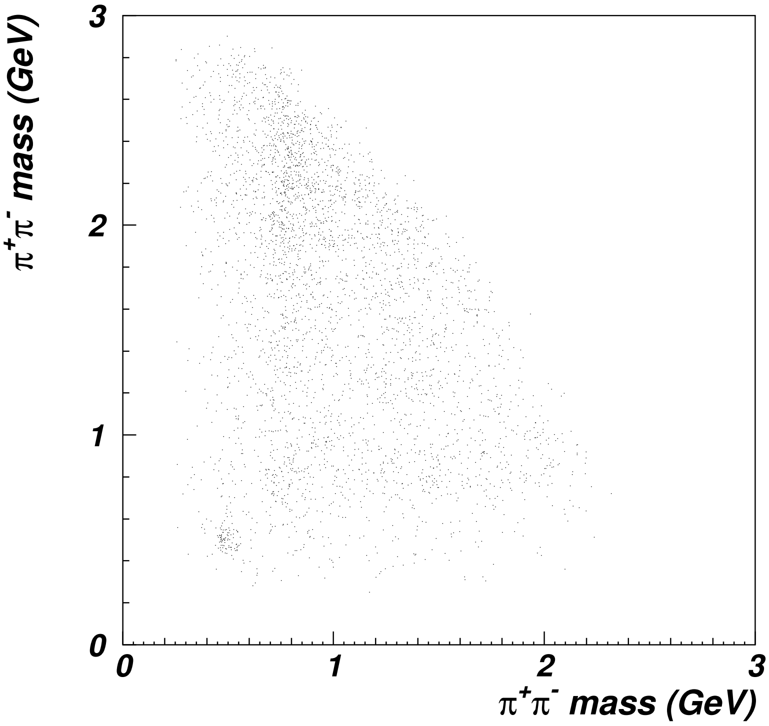


Figure 3: $\pi^+\pi^-$ mass distribution of $\gamma\pi^+\pi^-\pi^+\pi^-$ events, clear $K_s^0 K_s^0$ concentration can be seen (Two entries per event).

The final selected events with $\pi^+\pi^-\pi^+\pi^-$, $\pi^+\pi^-K^+K^-$ or $K_s^0 K_s^0$ mass between 3.20 and 3.65GeV are fitted with three Breit-Wigner resonances smeared by Gaussian like mass resolution functions together with a linear background using unbinned maximum likelihood method. In the fit, the mass resolutions are fixed to the Monte Carlo values and the width of χ_{c1} and χ_{c2} is fixed to the world average of 0.88 and 2.00MeV coming from PDG [7]. Fitted out results as well as the efficiencies and the mass resolutions get from Monte Carlo are listed in Table 5 and are shown in figures 4, 5 and 6.

4.3.2 $\gamma\pi^+\pi^-p\bar{p}$

If one of the four tracks is identified as proton or antiproton the event is assumed to be $\gamma\pi^+\pi^-p\bar{p}$, to separate the two particle assignments, the same philosophy as that of separating different combinations of $\pi^+\pi^-K^+K^-$ are used, the combination with high probability is selected as the real one.

Table 6 and Figure 7 show the events numbers after each step of the cut and the effect of the cuts on the invariant mass spectrum of all the charged tracks.

After above selection, the invariant mass distribution of $\pi^+\pi^-p\bar{p}$ is shown in figure 8, clear χ_c signals can be seen in the plot.

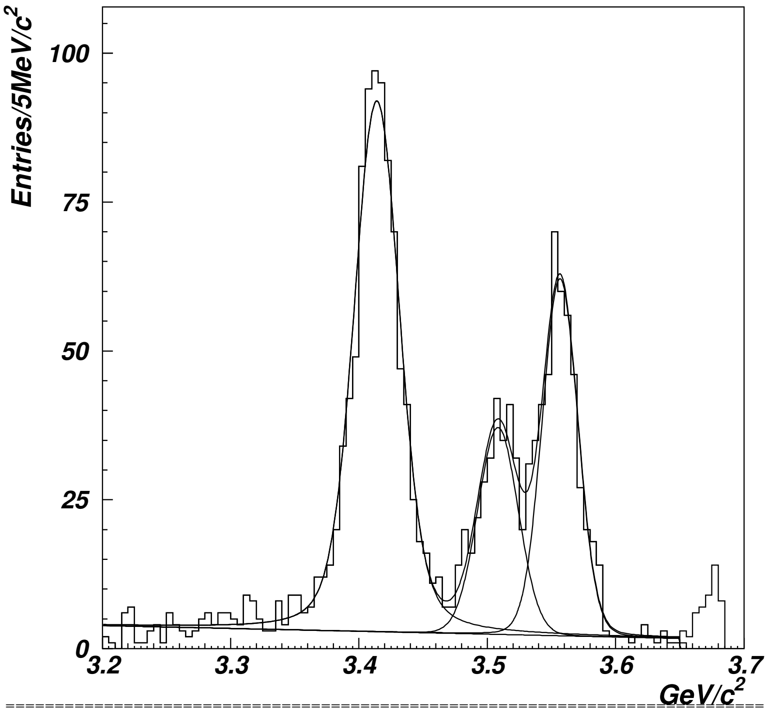
The final selected events with $\pi^+\pi^-p\bar{p}$ mass between 3.20 and 3.65GeV are fitted with three Breit-Wigner resonances smeared by Gaussian like mass resolution functions together with a linear background using unbinned maximum likelihood method. In the fit, the mass resolutions are fixed to the Monte Carlo values and the width of χ_{c1} and χ_{c2} is fixed to the world average of 0.88 and 2.00MeV coming from

Table 5: Fitted results of $\chi_{cJ} \to \pi^+\pi^-\pi^+\pi^-, \pi^+\pi^-K^+K^-andK_s^0K_s^0$

	events number	Efficiency (%)	Mass resolution (MeV)	Branching fraction ($\times 10^{-3}$)
$\chi_{c0} \to \pi^+\pi^-\pi^+\pi^-$	874 ± 30	16.06	15.1	15.82 ± 0.54
$\chi_{c1} \to \pi^+\pi^-\pi^+\pi^-$	277 ± 19	17.06	15.6	5.05 ± 0.35
$\chi_{c2} \to \pi^+\pi^-\pi^+\pi^-$	425 ± 21	15.09	13.4	9.77 ± 0.49
$\chi_{c0} \to K_s^0K_s^0$	49.3 ± 7.0	15.16	10.9	2.01 ± 0.29
$\chi_{c2} \to K_s^0K_s^0$	11.7 ± 3.2	13.92	9.4	0.62 ± 0.17
$\chi_{c0} \to \pi^+\pi^-K^+K^-$	587 ± 27	11.32	14.4	15.06 ± 0.70
$\chi_{c1} \to \pi^+\pi^-K^+K^-$	192 ± 16	12.91	15.3	4.63 ± 0.40
$\chi_{c2} \to \pi^+\pi^-K^+K^-$	267 ± 18	11.42	15.1	8.11 ± 0.55

Table 6: Events numbers after each cut (after pre-selection, $\gamma\pi^+\pi^-p\bar{p}$ mode, (3.2<m<3.6)).

Cut	Real data	χ_{c0} MC	χ_{c1} MC	χ_{c2} MC
Generated Evts		5000	5000	5000
Prob4C > 0.01	589	1247	1319	1183
ProbID > 0.01	403	1108	1181	1069
$\lvert\cos\theta\rvert < 0.8$	305	758	858	715
Remove J/ψ	234	731	835	694

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I                        Summary Of BWFIT Results                        I
========================================================================
Histogram ID=     1  UnBinned Breit-Wigner Fit using 1828 Points
Fit Parameters:Npoly=   2 Nbw=   3 Namp=   0 Range=    3.200 To    3.650
Hist. Chisq =      75.92 for   8 params &  81 DF.
Chisquare Probability =  63.89%. Mean and S.D. for pulls:   .0044   .9184
Likelihood ratio and probability             :     79.655      52.14%
Final Value of Log Likelihood                :    -2494.66
Error Correspond to a Function Chage         :      .50
Phase Space limits for tails corrections     :   .280GEV     2.817GEV
Breit-Wigner efficiency correction factors   :   .984       .999    .996
Include Breit-Wigner tails outside fit region :   .002       .000    .000
Efficiency-corrected events in fit region    : 1828.[average eff. :1.000]
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   LEG_1Value : -.38582    Error(Cov,-/+):    .151      -.146      .150
   AREA0Value :  .47837    Error(Cov,-/+):    .163E-01 -.163E-01  .164E-01
   RESL0Value :  .15120E-01Error(Cov,-/+):    .000E+00 -.194E-02  .206E-02
   GAMA0Value :  .11298E-01Error(Cov,-/+):    .200E-02 -.757E-03  .758E-03
   MASS0Value :  3.4139    Error(Cov,-/+):    .757E-03 -.103E-01  .106E-01
   AREA1Value :  .15159    Error(Cov,-/+):    .105E-01 -.148E-02  .150E-02
   RESL1Value :  .15580E-01Error(Cov,-/+):    .000E+00 -.116E-01  .118E-01
   GAMA1Value :  .88000E-03Error(Cov,-/+):    .000E+00 -.906E-03  .906E-03
   MASS1Value :  3.5084    Error(Cov,-/+):    .149E-02  .000E+00  .000E+00
   AREA2Value :  .23270    Error(Cov,-/+):    .117E-01  .000E+00  .000E+00
   RESL2Value :  .13410E-01Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   GAMA2Value :  .20000E-02Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   MASS2Value :  3.5567    Error(Cov,-/+):    .906E-03  .000E+00  .000E+00
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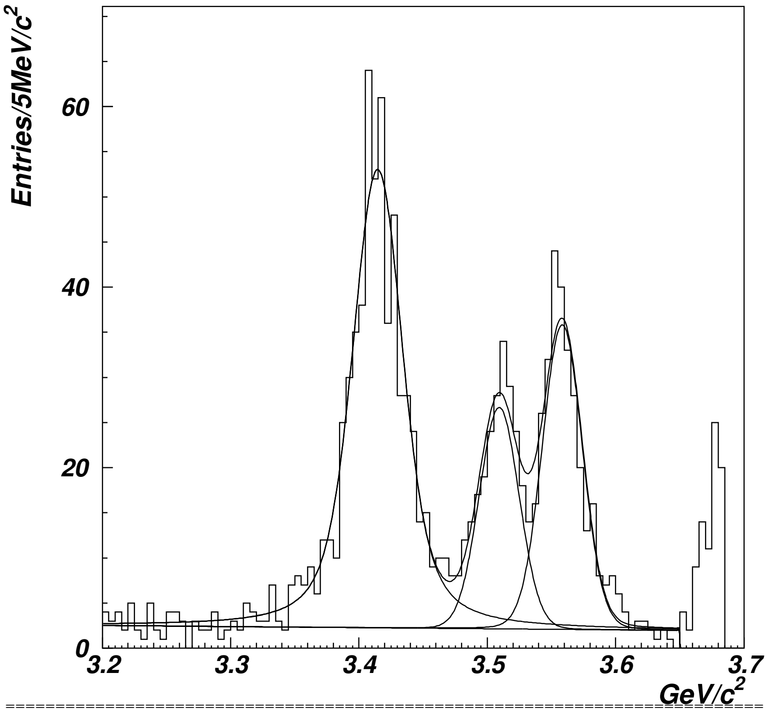
Figure 4: Fitted results of the $\pi^+\pi^-\pi^+\pi^-$ invariant mass spectrum. Mass resolutions are fixed to Monte Carlo values, width of χ_{c1} and χ_{c2} is fixed to PDG values.

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======================================================================
Histogram ID=     1  UnBinned Breit-Wigner Fit using 1248 Points
Fit Parameters:Npoly=   2 Nbw=   3 Namp=   0 Range=   3.200 To      3.650
Hist. Chisq =      67.26 for   8 params &  81 DF.
Chisquare Probability =  86.30%. Mean and S.D. for pulls:  -.0265   .8641
Likelihood ratio and probability             :    67.729       85.37%
Final Value of Log Likelihood                :    -1560.22
Error Correspond to a Function Chage         :      .50
Phase Space limits for tails corrections     :   .280GEV    2.817GEV
Breit-Wigner efficiency correction factors   :   .970   .999   .996
Include Breit-Wigner tails outside fit region :   .005   .000   .000
Efficiency-corrected events in fit region    :  1248.[average eff. :1.000]
---THE FITTED VALUES AND ERRORS OF THE PARAMETERS:---
   LEG_1Value : -.11978    Error(Cov,-/+):    .173      -.176      .169
   AREA0Value :  .47007    Error(Cov,-/+):    .217E-01 -.216E-01  .217E-01
   RESL0Value :  .14430E-01Error(Cov,-/+):    .000E+00 -.305E-02  .328E-02
   GAMA0Value :  .21094E-01Error(Cov,-/+):    .316E-02 -.114E-02  .114E-02
   MASS0Value :  3.4146    Error(Cov,-/+):    .114E-02 -.130E-01  .133E-01
   AREA1Value :  .15425    Error(Cov,-/+):    .132E-01 -.176E-02  .176E-02
   RESL1Value :  .15320E-01Error(Cov,-/+):    .000E+00 -.143E-01  .146E-01
   GAMA1Value :  .88000E-03Error(Cov,-/+):    .000E+00 -.142E-02  .140E-02
   MASS1Value :  3.5093    Error(Cov,-/+):    .176E-02  .000E+00  .000E+00
   AREA2Value :  .21417    Error(Cov,-/+):    .145E-01  .000E+00  .000E+00
   RESL2Value :  .15060E-01Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   GAMA2Value :  .20000E-02Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   MASS2Value :  3.5584    Error(Cov,-/+):    .141E-02  .000E+00  .000E+00
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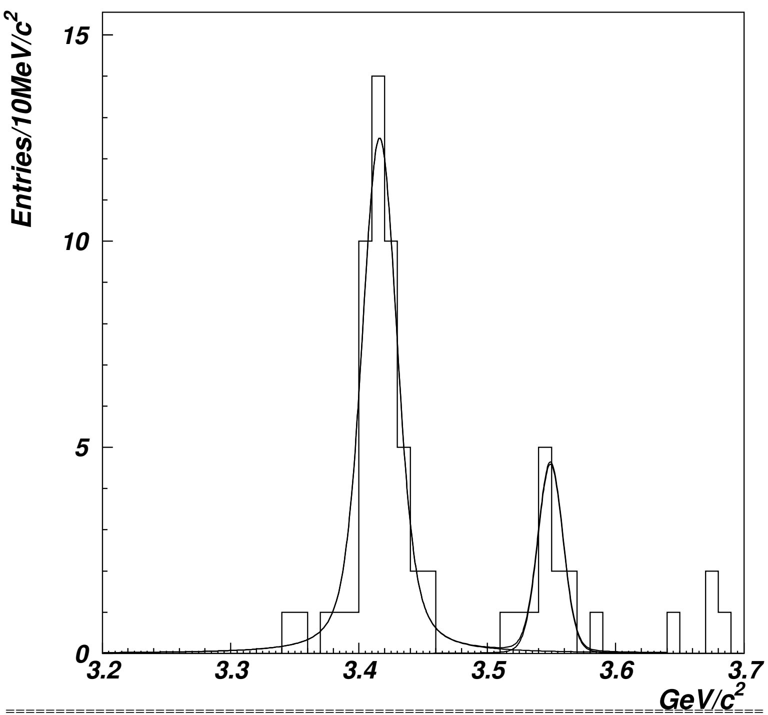
Figure 5: Fitted results of the $\pi^+\pi^-K^+K^-$ invariant mass spectrum. Mass resolutions are fixed to Monte Carlo values, width of χ_{c1} and χ_{c2} is fixed to PDG values.

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=====================================================================
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Fit Parameters:Npoly=   0 Nbw=   2 Namp=   0 Range=   3.200 To   3.640
Hist. Chisq =      30.40 for   4 params &  39 DF.
Chisquare Probability =  83.63%. Mean and S.D. for pulls:   .0277   .8307
Likelihood ratio and probability              :     21.915   98.76%
Final Value of Log Likelihood                 :      -123.43
Error Correspond to a Function Chage          :      .50
Phase Space limits for tails corrections      :     .280GEV     2.817GEV
Breit-Wigner efficiency correction factors    :    .983         .996
Include Breit-Wigner tails outside fit region :    .003         .000
Efficiency-corrected events in fit region     :  61.[average eff. :1.000]
---THE FITTED VALUES AND ERRORS OF THE PARAMETERS:---
   RESL0Value :  .10920E-01Error(Cov,-/+):    .000E+00 -.381E-02  .483E-02
   GAMA0Value :  .11810E-01Error(Cov,-/+):    .429E-02 -.243E-02  .242E-02
   MASS0Value :  3.4161    Error(Cov,-/+):    .242E-02 -.491E-01  .559E-01
   AREA2Value :  .19103    Error(Cov,-/+):    .525E-01 -.355E-02  .359E-02
   RESL2Value :  .93600E-02Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   GAMA2Value :  .20000E-02Error(Cov,-/+):    .000E+00 -.418E-02  .426E-02
   MASS2Value :  3.5492    Error(Cov,-/+):    .356E-02 -.325E-01  .337E-01
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Figure 6: Fitted results of the $K_s^0 K_s^0$ invariant mass spectrum. Mass resolutions are fixed to Monte Carlo values, width of χ_{c0} and χ_{c2} is fixed to PDG values.

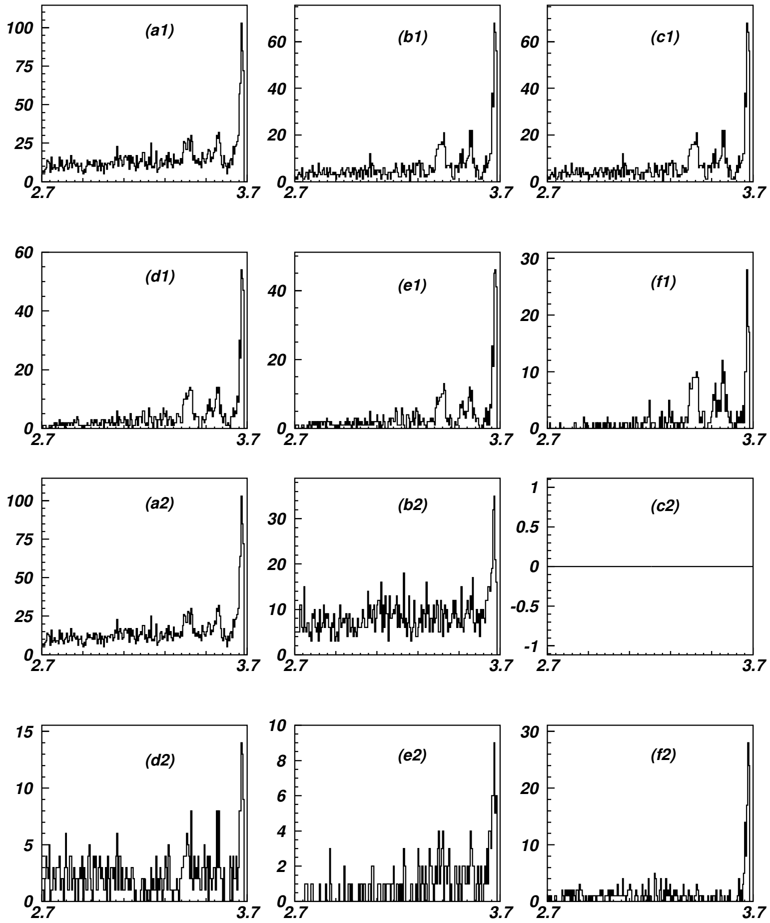


Figure 7: $\pi^+\pi^-p\bar{p}$ mass distribution of $\gamma\pi^+\pi^-p\bar{p}$ mode after each cut, (a1,b1,c1,d1,e1,f1) events survived the cut, (a2,b2,c2,d2,e2,f2) events removed by the cut. a) after preselection, b) Prob4C cut, c) number of gamma cut, d) ProbID cut, e) polar angle cut, f) Remove J/ψ.

PDG [7]. Fitted out results as well as the efficiencies and the mass resolutions get from Monte Carlo are listed in Table 7 and are shown in figure 8.

Table 7: Fitted results of $\chi_{cJ} \to \pi^+\pi^- p\bar{p}$

	events number	Efficiency (%)	Mass resolution (MeV)	Branching fraction ($\times 10^{-3}$)
$\chi_{c0} \to \pi^+\pi^- p\bar{p}$	81 ± 10	14.62	13.9	1.61 ± 0.21
$\chi_{c1} \to \pi^+\pi^- p\bar{p}$	27.1 ± 6.9	16.72	14.3	0.50 ± 0.13
$\chi_{c2} \to \pi^+\pi^- p\bar{p}$	50.9 ± 8.1	13.98	13.0	1.26 ± 0.20

4.3.3 $\gamma K^+K^-K^+K^-$

Since all the tracks are kaon, the contamination coming from $\pi^+\pi^- J/\psi$ is not important background, so no cut on removing $\pi^+\pi^- J/\psi$ is performed.

After selection, the events numbers and the corresponding mass spectra are listed in Table 8 and are shown in Figure 9.

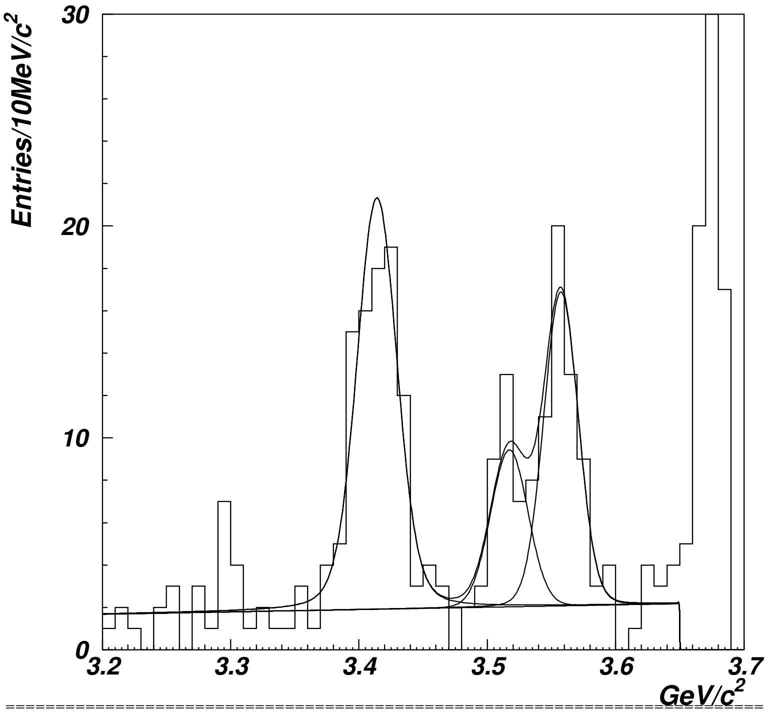
Table 8: Events number after each cut (after pre-selection, $\gamma K^+K^-K^+K^-$ mode, (3.2<m<3.6)).

Cut	Real data	χ_{c0}	χ_{c1}	χ_{c2}	$\chi_{c0} \to \phi\phi$	$\chi_{c2} \to \phi\phi$
Generated Evts		5000	5000	5000	5000	5000
Prob4C > 0.01	1227	600	695	603	698	667
ProbID > 0.01	161	534	620	549	579	562
$\lvert\cos\theta\rvert < 0.8$	125	369	426	382	503	488
$\phi\phi$ selection	24	1	1	0	489	477

Figure 10 shows the invariant mass of the two pairs of K^+K^-, it is obvious that $\phi\phi$ exists, a fit to the K^+K^- mass gives the mass of ϕ is 1021.9 ± 0.8MeV and mass resolution is 5.3 ± 0.6MeV. To select $\gamma\phi\phi$ events, the mass of the two combinations of K^+K^- is required to be greater than 0.99 and less than 1.05GeV.

After above selection, the invariant mass distributions of $K^+K^-K^+K^-$ and $\phi\phi$ are shown in figures 11 and 12, clear χ_c signals can be seen in the plots.

Using the Monte Carlo generator described in previous section, 5000 events are generated for each χ_c state in $\gamma K^+K^-K^+K^-$ and $\gamma\phi\phi$ modes, after the same selection procedure as that of the real data, the corresponding detection efficiencies and mass resolutions are determined and listed in Table 9, it should be noted that because of the large fraction of $\phi\phi$ intermediate events in $K^+K^-K^+K^-$ mode and the significance difference between phase space events efficiency and $\phi\phi$ intermediate events efficiency, the detection efficiency of total $K^+K^-K^+K^-$ events should be a weighted average of phase space decay efficiency and $\phi\phi$ intermediate decay efficiency.




```
===========================================================================
I                       Summary Of BWFIT Results                          I
===========================================================================
Histogram ID=      1  UnBinned Breit-Wigner Fit using  246 Points
Fit Parameters:Npoly=   2 Nbw=   3 Namp=   0 Range=  3.200 To   3.650
Hist. Chisq =      45.66 for   8 params &  36 DF.
Chisquare Probability =  12.99%. Mean and S.D. for pulls:  -.0189    1.0071
Likelihood ratio and probability            :     46.577    11.15%
Final Value of Log Likelihood               :   -291.27
Error Correspond to a Function Chage        :       .50
Phase Space limits for tails corrections    :    .280GEV     2.817GEV
Breit-Wigner efficiency correction factors  :   .990    .998    .996
Include Breit-Wigner tails outside fit region :   .002    .000    .000
Efficiency-corrected events in fit region   :   246.[average eff. :1.000]
---THE FITTED VALUES AND ERRORS OF THE PARAMETERS:---
   LEG_1Value :  .12881    Error(Cov,-/+):    .212      -.215      .207
   AREA0Value :  .33022    Error(Cov,-/+):    .428E-01 -.421E-01  .435E-01
   RESL0Value :  .13920E-01Error(Cov,-/+):    .000E+00 -.545E-02  .635E-02
   GAMA0Value :  .70962E-02Error(Cov,-/+):    .586E-02 -.230E-02  .232E-02
   MASS0Value :  3.4140    Error(Cov,-/+):    .230E-02 -.270E-01  .293E-01
   AREA1Value :  .11031    Error(Cov,-/+):    .281E-01 -.418E-02  .426E-02
   RESL1Value :  .14290E-01Error(Cov,-/+):    .000E+00 -.325E-01  .337E-01
   GAMA1Value :  .88000E-03Error(Cov,-/+):    .000E+00 -.271E-02  .268E-02
   MASS1Value :  3.5172    Error(Cov,-/+):    .419E-02  .000E+00  .000E+00
   AREA2Value :  .20685    Error(Cov,-/+):    .331E-01  .000E+00  .000E+00
   RESL2Value :  .12960E-01Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   GAMA2Value :  .20000E-02Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   MASS2Value :  3.5574    Error(Cov,-/+):    .269E-02  .000E+00  .000E+00
```

Figure 8: Fitted results of the $\pi^+\pi^-p\bar{p}$ invariant mass spectrum. Mass resolutions are fixed to Monte Carlo values, width of χ_{c1} and χ_{c2} is fixed to PDG values.

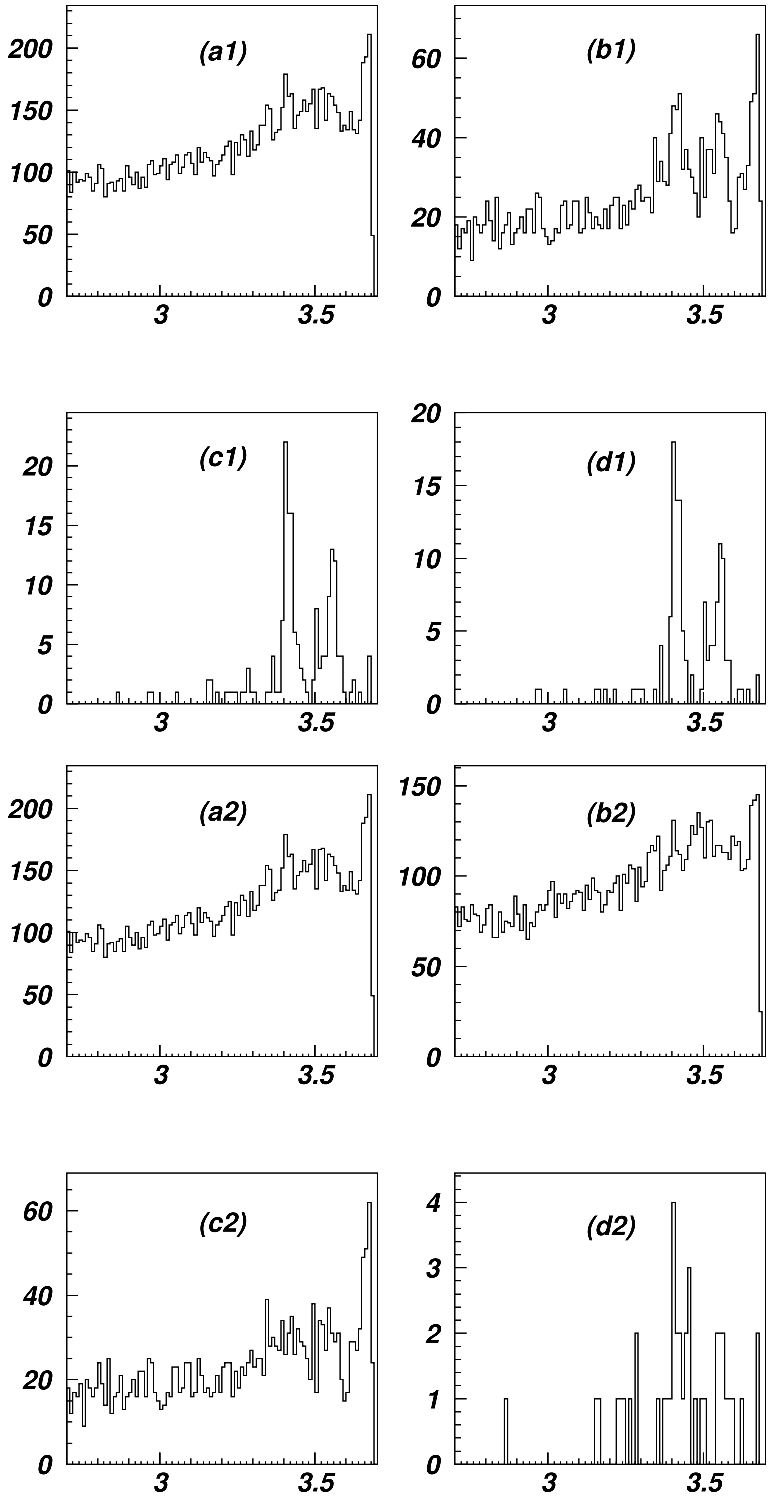


Figure 9: $K^+K^-K^+K^-$ mass distribution of $\gamma K^+K^-K^+K^-$ mode after each cut, (a1,b1,c1,d1) events survived the cut, (a2,b2,c2,d2) events removed by the cut. a) after preselection, b) Prob4C cut, c) ProbID cut, d) polar angle cut.

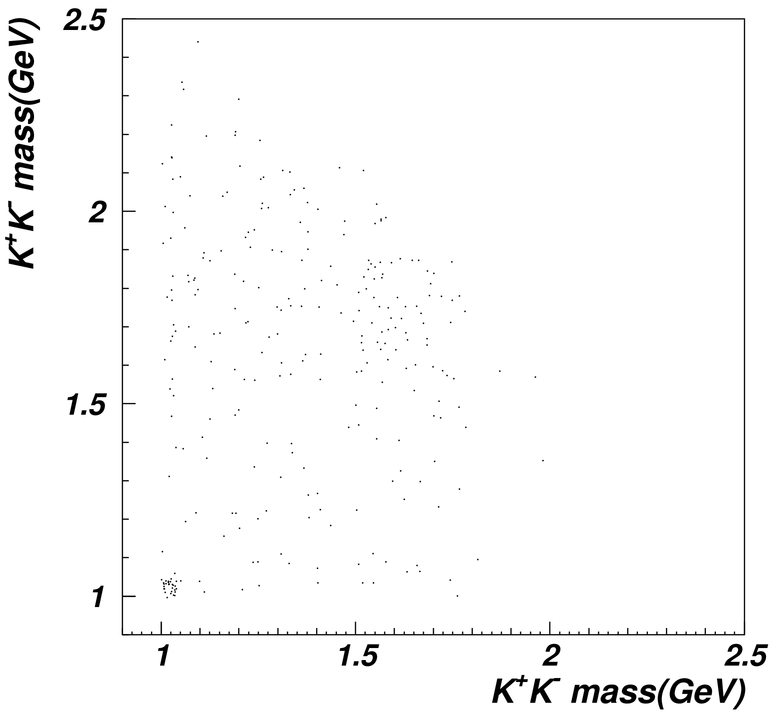
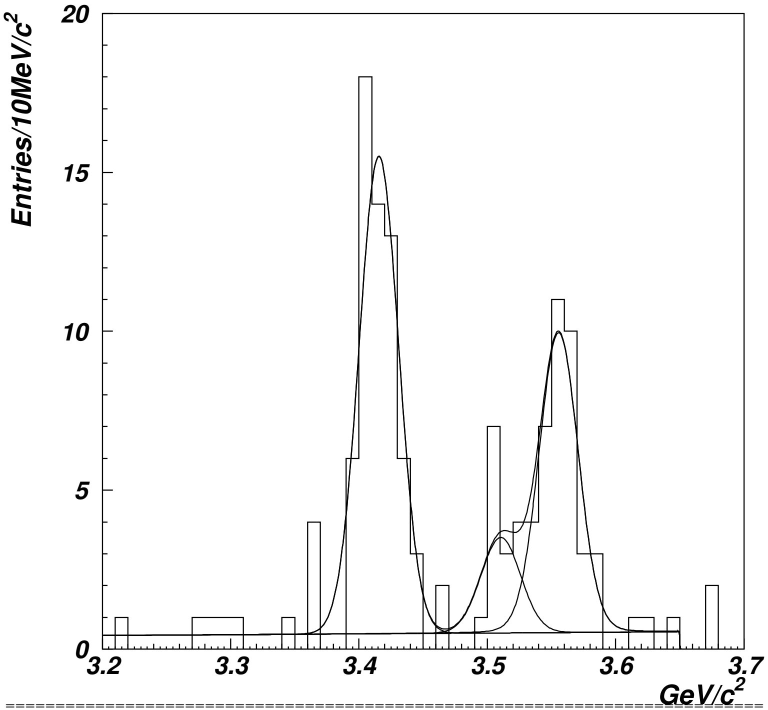


Figure 10: K^+K^- mass distribution of $\gamma K^+K^-K^+K^-$ events, clear $\phi\phi$ concentration can be seen (Two entries per event).

The final selected events with $K^+K^-K^+K^-$ or $\phi\phi$ mass between 3.20 and 3.65GeV are fitted with three Breit-Wigner resonances smeared by Gaussian like mass resolution functions together with a linear background using unbinned maximum likelihood method. In the fit, the mass resolutions are fixed to the Monte Carlo values and the width of χ_{c1} and χ_{c2} is fixed to the world average of 0.88 and 2.00MeV coming from PDG [7]. Fitted out results are listed in Table 9 and are shown in figures 11 and 12.

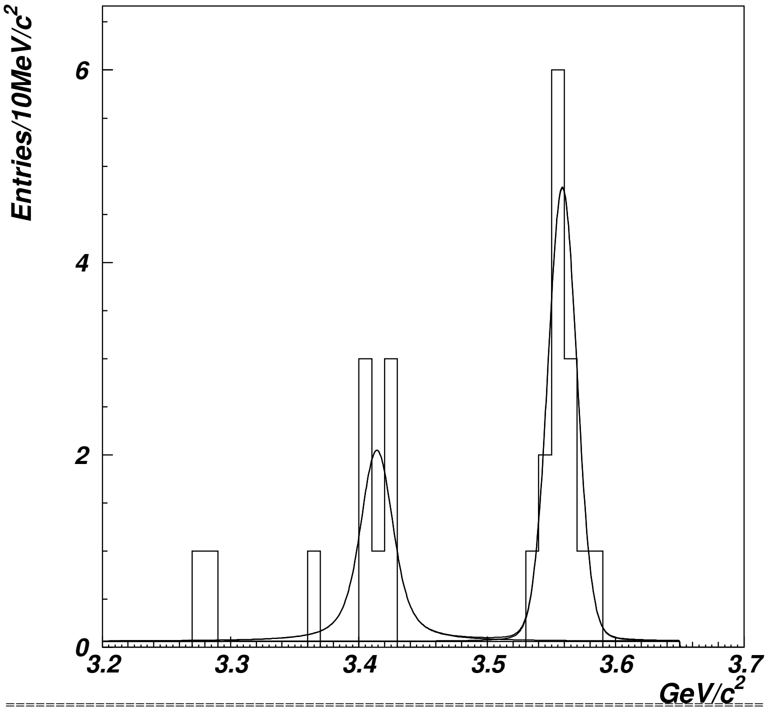
Table 9: Fitted results of $\chi_{cJ} \to K^+K^-K^+K^-and\phi\phi$

	events number	Efficiency (PS/$\phi\phi$)(%)	Mass resolution (MeV)	Branching ratio ($\times 10^{-3}$)
$\chi_{c0} \to K^+K^-K^+K^-$	57.8 ± 6.9	7.38/10.06	15.4	2.19 ± 0.27
$\chi_{c1} \to K^+K^-K^+K^-$	11.7 ± 4.2	8.52/no	15.2	0.43 ± 0.15
$\chi_{c2} \to K^+K^-K^+K^-$	36.6 ± 5.9	7.64/9.76	14.7	1.52 ± 0.27
$\chi_{c0} \to \phi\phi$	7.6 ± 2.8	9.78	8.9	0.94 ± 0.35
$\chi_{c2} \to \phi\phi$	13.6 ± 3.7	9.54	10.8	2.05 ± 0.56




```
=========================================================================
I                        Summary Of BWFIT Results                        I
=========================================================================
Histogram ID=     1  UnBinned Breit-Wigner Fit using  128 Points
Fit Parameters:Npoly=   3 Nbw=   3 Namp=   0 Range=    3.200 To   3.650
Hist. Chisq =      52.68 for   7 params &  37 DF.
Chisquare Probability =   4.55%. Mean and S.D. for pulls:  -.0193  1.0818
Likelihood ratio and probability              :     50.450    6.92%
Final Value of Log Likelihood                 :   -197.62
Error Correspond to a Function Chage          :       .50
Phase Space limits for tails corrections      :     .280GEV     2.817GEV
Breit-Wigner efficiency correction factors    :   1.000   .999   .996
Include Breit-Wigner tails outside fit region :    .000   .000   .000
Efficiency-corrected events in fit region     : 128.[average eff. :1.000]
---THE FITTED VALUES AND ERRORS OF THE PARAMETERS:---
   LEG_1Value :  .11895    Error(Cov,-/+):    .469      -.469      .440
   LEG_2Value :  .00000E+00Error(Cov,-/+):    .000E+00 -.470E-01  .606E-01
   AREA0Value :  .45173    Error(Cov,-/+):    .542E-01 -.543E+05  .000E+00
   RESL0Value :  .15360E-01Error(Cov,-/+):    .000E+00 -.232E-02  .223E-02
   GAMA0Value :  .15764E-06Error(Cov,-/+):    .686      -.306E-01  .351E-01
   MASS0Value :  3.4155    Error(Cov,-/+):    .225E-02 -.451E-01  .472E-01
   AREA1Value :  .91406E-01Error(Cov,-/+):    .329E-01 -.307E-02  .305E-02
   RESL1Value :  .15215E-01Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   GAMA1Value :  .88000E-03Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   MASS1Value :  3.5105    Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   AREA2Value :  .28603    Error(Cov,-/+):    .463E-01  .000E+00  .000E+00
   RESL2Value :  .14744E-01Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   GAMA2Value :  .20000E-02Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   MASS2Value :  3.5556    Error(Cov,-/+):    .305E-02  .000E+00  .000E+00
```

Figure 11: Fitted results of the $K^+K^-K^+K^-$ invariant mass spectrum. Mass resolutions are fixed to Monte Carlo values, width of χ_{c1} and χ_{c2} is fixed to PDG values.




```
=====================================================================
I                       Summary Of BWFIT Results                    I
=====================================================================
Histogram ID=     1  UnBinned Breit-Wigner Fit using   24 Points
Fit Parameters:Npoly=    2 Nbw=    2 Namp=    0 Range=   3.200 To    3.650
Hist. Chisq =       39.27 for   4 params &  40 DF.
Chisquare Probability =  50.31%. Mean and S.D. for pulls:  -.0096   .9341
Likelihood ratio and probability             :     23.812    98.02%
Final Value of Log Likelihood                :       -45.73
Error Correspond to a Function Chage         :       .50
Phase Space limits for tails corrections     :     .280GEV     2.817GEV
Breit-Wigner efficiency correction factors   :     .979          .996
Include Breit-Wigner tails outside fit region :      .003          .000
Efficiency-corrected events in fit region     :   24.[average eff. :1.000]
---THE FITTED VALUES AND ERRORS OF THE PARAMETERS:---
   LEG_1Value :  .00000E+00Error(Cov,-/+):     .000E+00 -.100       .111
   AREA0Value :  .31769    Error(Cov,-/+):     .106      -.549E-02  .541E-02
   RESL0Value :  .89310E-02Error(Cov,-/+):     .000E+00 -.107       .102
   GAMA0Value :  .15000E-01Error(Cov,-/+):     .000E+00 -.326E-02  .324E-02
   MASS0Value :  3.4140    Error(Cov,-/+):     .544E-02 -.306E-01  .351E-01
   AREA2Value :  .56722    Error(Cov,-/+):     .103      -.451E-01  .472E-01
   RESL2Value :  .10762E-01Error(Cov,-/+):     .000E+00 -.307E-02  .305E-02
   GAMA2Value :  .20000E-02Error(Cov,-/+):     .000E+00  .000E+00  .000E+00
   MASS2Value :  3.5585    Error(Cov,-/+):     .322E-02  .000E+00  .000E+00
```

Figure 12: Fitted results of the $\phi\phi$ invariant mass spectrum. Mass resolutions are fixed to Monte Carlo values, width of χ_{c0} and χ_{c2} is fixed to BES result and PDG value.

4.3.4 $\gamma K_s^0 K^+ \pi^- + c.c.$

The most crucial aspect of the selection of this kind of events is K_s^0 finding, compared with the large background from $\gamma\pi^+\pi^-\pi^+\pi^-$ (including $\gamma K_s^0 K_s^0$) and $\gamma\pi^+\pi^- K^+ K^-$, the characteristic of $K_s^0 K^+ \pi^- + c.c.$ events is the existence of one and only one K_s^0 with secondary vertex.

Of every two charged tracks with net charge zero and effective mass lies between $M_{K^0} - 0.200$ and $M_{K^0} + 0.200$ when they are assumed to be π, the combination with mass most near K_s^0 nominal energy is considered to be K_s^0 candidate, the number of combinations in the event is counted as NKSHORT. K_s^0 vertex is got by crossing these two tracks and the primary vertex is estimated with the cross point of another two charged tracks assuming one of them is kaon and another pion. Two parameters are defined to identify the K_s^0: the distance between primary vertex and secondary vertex in R-ϕ plain L_{xy} and the cosine of the angle between the K_s^0 momentum and its vertex direction $CSKS$ which is expected to be very near one for a real K_s^0 event.

The number of K_s^0 candidate NKSHORT equals one, L_{xy} greater than 5mm and CSKS greater than 0.98 are required for a successful $\gamma K_s^0 K^+ \pi^- + c.c.$ event candidate in addition to the requirement of the mass of K_s^0 candidate after 4C-fit lies in 2σ(28MeV) region around K_s^0 nominal mass.

After each step of the selection, the events numbers and the corresponding mass spectra are shown in Table 10 and Figure 13.

Table 10: Events numbers after each cut (after pre-selection, $\gamma K_s^0 K^+ \pi^- + c.c.$ mode, (3.2<m<3.6)).

Cut	Real data	χ_{c0} MC	χ_{c1} MC	χ_{c2} MC
Generated Evts		10000	10000	10000
$M^{4C}_{K_s^0}$ cut	1876	2272	2515	2133
CSKS > 0.98	422	1039	1135	968
LXY > 0.005	370	1003	1098	935
NKSHORT $= 1$	197	808	908	782
ProbID > 0.01	157	770	873	755
Prob4C > 0.01	87	693	804	694
Remove J/ψ	73	678	788	685
$\lvert\cos\theta\rvert < 0.8$	54	495	563	488

The mass spectrum of the final selected events is shown in figure 14, only the signal of χ_{c1} is significant, Monte Carlo also shows the still remaining background from $\gamma\pi^+\pi^-\pi^+\pi^-$, $\gamma K_s^0 K_s^0$ and $\gamma\pi^+\pi^- K^+ K^-$ is compatible to the statistics in the χ_{c0} and χ_{c2} mass region, to get the results conservatively, we intend to give the upper limits on the branching fractions of χ_{c0} and $\chi_{c2} \to K_s^0 K^+ \pi^- + c.c.$.

The events with $K_s^0 K^+ \pi^- + c.c.$ mass between 3.20 and 3.65GeV are fitted with three Breit-Wigner resonances smeared by Gaussian like mass resolution functions together with a linear background using unbinned maximum likelihood method. In the fit, the mass resolutions are fixed to the Monte Carlo values and the width of

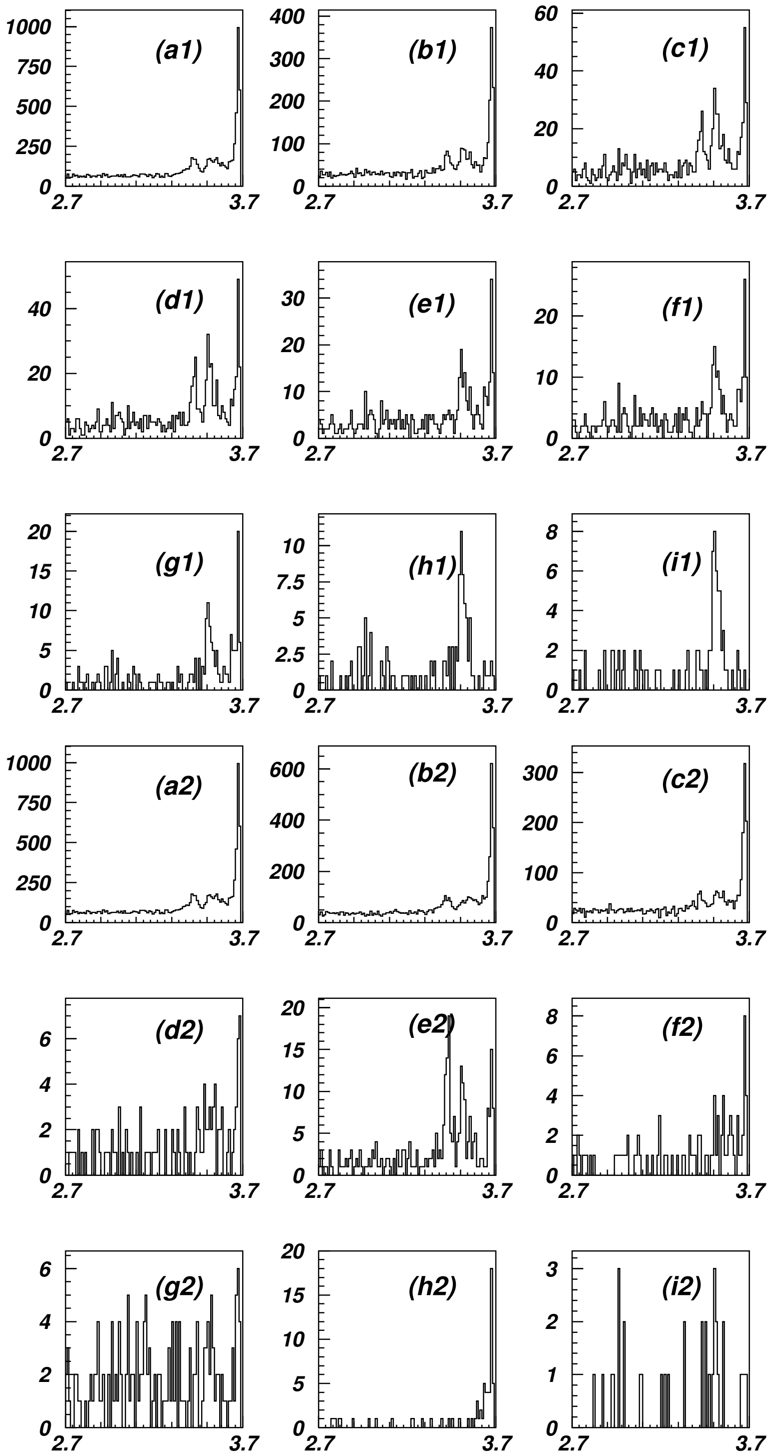


Figure 13: $K_s^0 K^+ \pi^- + c.c.$ mass distribution of $\gamma K_s^0 K^+ \pi^- + c.c.$ mode after each cut, (a1,b1,c1,d1,e1,f1,g1,h1,i1) events survived the cut, (a2,b2,c2,d2,e2,f2,g2,h2,i2) events removed by the cut. a) after preselection, b) K_s^0 mass cut, c) CSKS cut, d) LXY cut, e) NKSHORT cut, f) ProbID cut, g) Prob4C cut, h) Remove J/ψ, i) polar angle cut.

χ_{c0}, χ_{c1} and χ_{c2} is fixed to the BES result of 14.3MeV and the world average of 0.88 and 2.00MeV coming from PDG [7] respectively. The mass of the three χ_c states are also fixed to PDG [7] values. Fitted out results as well as the efficiencies and the mass resolutions get from Monte Carlo are listed in Table 11 and are shown in figure 14.

Table 11: Fitted results of $\chi_{cJ} \to K_s^0 K^+ \pi^- + c.c.$, upper limits at 90% confidence level

	events number	Efficiency (%)	Mass resolution (MeV)	Branching fraction ($\times 10^{-3}$)
χ_{c0}	< 8.5	4.94	10.3	< 0.73
χ_{c1}	31.4 ± 5.6	5.64	14.2	2.51 ± 0.45
χ_{c2}	< 10.6	4.93	14.7	< 1.09

4.3.5 $\gamma 3(\pi^+\pi^-)$

After kinematic fit and particle ID, the main background comes from the decay chain $\psi' \to \pi^+\pi^- J/\psi, J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$, the requirement on the total momentum of the two lower momentum $\pi^+\pi^-$ pair remove one third of the Monte Carlo events while reject almost all the remaining background in real data sample.

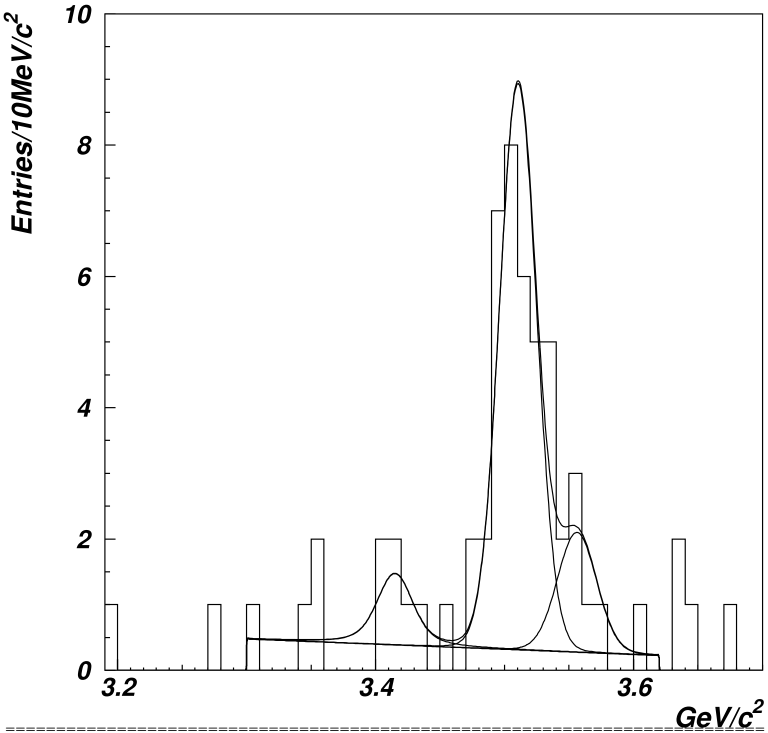
Table 12 and Figure 15 show the events number after each step of the cut and the effect of the cut on the invariant mass spectrum of all the charged tracks.

Table 12: Events number after each cut (after pre-selection, $\gamma 3(\pi^+\pi^-)$ mode, (3.2<m<3.6)).

Cut	Real data	χ_{c0} MC	χ_{c1} MC	χ_{c2} MC
Generated Evts		10000	10000	10000
Prob4C > 0.01	2607	1337	1475	1227
ProbID > 0.01	2035	1223	1359	1118
Remove J/ψ	880	813	925	798
$\lvert\cos\theta\rvert < 0.8$	476	462	520	418

After above selection, the invariant mass distribution of $3(\pi^+\pi^-)$ is shown in figure 16, clear χ_c signals can be seen in the plot.

The final selected events with $3(\pi^+\pi^-)$ mass between 3.20 and 3.65GeV are fitted with three Breit-Wigner resonances smeared by Gaussian like mass resolution functions together with a linear background using unbinned maximum likelihood method. In the fit, the mass resolutions are fixed to the Monte Carlo values and the width of χ_{c1} and χ_{c2} is fixed to the world average of 0.88 and 2.00MeV coming from PDG [7]. Fitted out results as well as the efficiencies and the mass resolutions get from Monte Carlo are listed in Table 13 and are shown in figure 16.




```
=======================================================================
I                        Summary Of BWFIT Results                     I
=======================================================================
Histogram ID=      1  UnBinned Breit-Wigner Fit using   54 Points
Fit Parameters:Npoly=   3 Nbw=   3 Namp=   0 Range=   3.300 To   3.620
Hist. Chisq =      20.21 for   4 params &  27 DF.
Chisquare Probability =  82.20%. Mean and S.D. for pulls:  -.0336  .7939
Likelihood ratio and probability            :     20.875     79.21%
Final Value of Log Likelihood               :    -91.99
Error Correspond to a Function Chage        :       .50
Phase Space limits for tails corrections    :       .280GEV   2.817GEV
Breit-Wigner efficiency correction factors  :   .969      .998      .993
Include Breit-Wigner tails outside fit region :   .003      .000      .000
Efficiency-corrected events in fit region   : 54.[average eff. :1.000]
---THE FITTED VALUES AND ERRORS OF THE PARAMETERS:---
   LEG_1Value : -.36199    Error(Cov,-/+):    .662      -.582      .648
   LEG_2Value :  .00000E+00Error(Cov,-/+):    .000E+00 -.490E-01  .592E-01
   AREA0Value :  .81320E-01Error(Cov,-/+):    .538E-01 -.834E-01  .790E-01
   RESL0Value :  .10348E-01Error(Cov,-/+):    .000E+00 -.586E-01  .674E-01
   GAMA0Value :  .14300E-01Error(Cov,-/+):    .000E+00 -.474E-02  .434E-02
   MASS0Value :  3.4151    Error(Cov,-/+):    .000E+00 -.913E-01  .110
   AREA1Value :  .58056    Error(Cov,-/+):    .813E-01 -.931E-02  .973E-02
   RESL1Value :  .14175E-01Error(Cov,-/+):    .000E+00 -.943E-02  .982E-02
   GAMA1Value :  .88000E-03Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   MASS1Value :  3.5105    Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   AREA2Value :  .13075    Error(Cov,-/+):    .626E-01  .000E+00  .000E+00
   RESL2Value :  .14720E-01Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   GAMA2Value :  .20000E-02Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   MASS2Value :  3.5562    Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
```

Figure 14: Fitted results of the $K_s^0K^+\pi^- + c.c.$ invariant mass spectrum. Mass resolutions, width and mass of the three χ_c states is fixed as described in the text.

Table 13: Fitted results of $\chi_{cJ} \rightarrow 3(\pi^+\pi^-)$

	events number	Efficiency (%)	Mass resolution (MeV)	Branching fraction ($\times 10^{-3}$)
$\chi_{c0} \rightarrow 3(\pi^+\pi^-)$	191 ± 16	4.62	15.8	12.02 ± 0.99
$\chi_{c1} \rightarrow 3(\pi^+\pi^-)$	98 ± 12	5.20	15.0	5.86 ± 0.69
$\chi_{c2} \rightarrow 3(\pi^+\pi^-)$	112 ± 12	4.23	14.7	9.20 ± 0.99

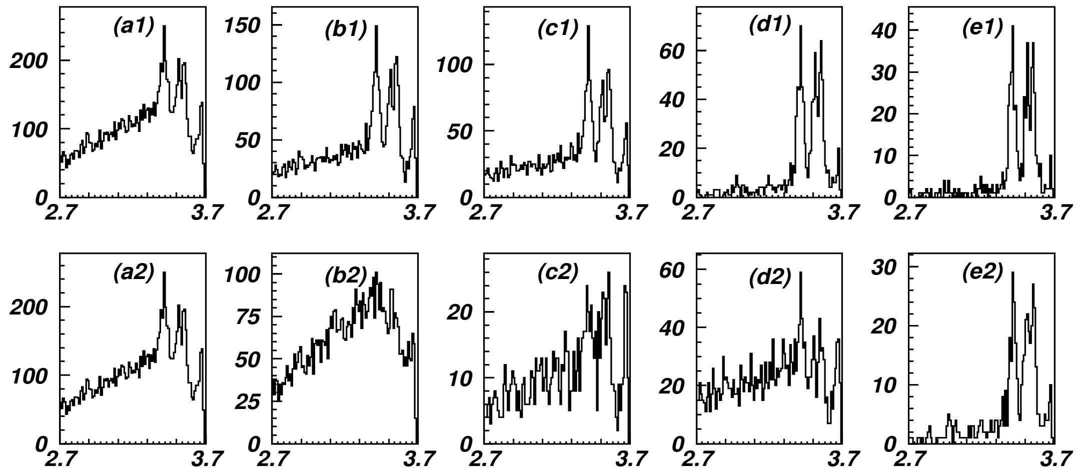


Figure 15: $3(\pi^+\pi^-)$ mass distribution of $\gamma 3(\pi^+\pi^-)$ mode after each cut, (a1,b1,c1,d1,e1) events survived the cut, (a2,b2,c2,d2,e2) events removed by the cut. a) after preselection, b) Prob4C cut, c) ProbID cut, d) polar angle cut, e) Remove J/ψ.

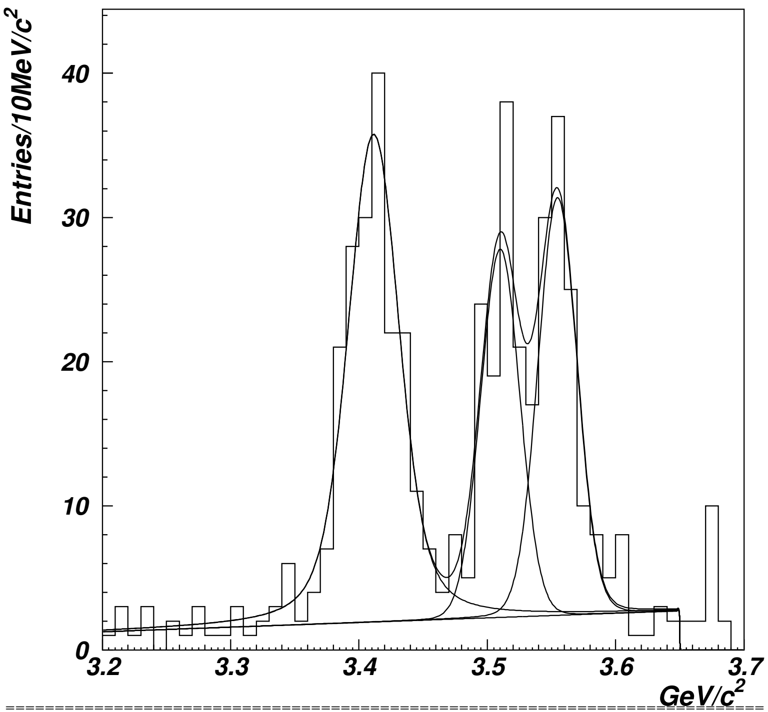
5 Systematic error

The systematic errors of the branching fractions arise from many sources, those from the selection of the cut points are about 10% for those high statistics decay modes and around 25% for those channels with low statistics; the systematic errors due to the statistics of the Monte Carlo simulated data sample vary from 2% to 5% based on the efficiencies of the channels; we estimate an percentage error of 15% for the usage of pure phase space Monte Carlo generator and without considering the possible intermediate states in many of the decay modes we analyzed; the variance of the events numbers caused by the uncertainties of the mass resolutions and the total width of χ_{cJ}s is about 7% and that caused by the assumption of the background shape is less than 5%. We include an relative error of 10% to all the channels for the usage of the TELESIS codes for kinematic fit (according to our study, the error matrix elements determined in the track finding, which are essential for kinematic fit, are not the same for real data and Monte Carlo events, so cause a different confidence level distribution and then introduce systematic error). The uncertainty of the total number of ψ' is 10% and we also include the errors of the branching fractions of $\psi' \to \gamma + \chi_{cJ}$, which are 8.6%, 9.2% and 10.3% for χ_{c0}, χ_{c1} and χ_{c2} respectively.

Add all the systematic errors in quadrature, the total systematic errors vary from 25% to 35% from channel to channel.

6 Summary

Table 14 summarizes the branching fractions of χ_{cJ} decays, including some channels measured at BES but described in detail elsewhere [3, 4], previous measurements used by PDG to evaluate the world average is also listed. From the table we can see




```
===========================================================================
I                        Summary Of BWFIT Results                         I
===========================================================================
Histogram ID=     1  UnBinned Breit-Wigner Fit using  491 Points
Fit Parameters:Npoly=   3 Nbw=   3 Namp=   0 Range=   3.200 To      3.650
Hist. Chisq =      46.63 for   8 params &  36 DF.
Chisquare Probability =  11.05%. Mean and S.D. for pulls:  -.0450  1.0170
Likelihood ratio and probability             :     44.563     15.48%
Final Value of Log Likelihood                :      -626.91
Error Correspond to a Function Chage         :       .50
Phase Space limits for tails corrections     :  .280GEV     2.817GEV
Breit-Wigner efficiency correction factors   :  .976     .999     .996
Include Breit-Wigner tails outside fit region :  .004     .000     .000
Efficiency-corrected events in fit region    :   491.[average eff. :1.000]
---THE FITTED VALUES AND ERRORS OF THE PARAMETERS:---
   LEG_1Value :  .36453    Error(Cov,-/+):    .213      -.224      .201
   LEG_2Value :  .00000E+00Error(Cov,-/+):    .000E+00 -.319E-01  .325E-01
   AREA0Value :  .38929    Error(Cov,-/+):    .322E-01 -.503E-02  .565E-02
   RESL0Value :  .15842E-01Error(Cov,-/+):    .000E+00 -.196E-02  .198E-02
   GAMA0Value :  .16843E-01Error(Cov,-/+):    .532E-02 -.231E-01  .238E-01
   MASS0Value :  3.4115    Error(Cov,-/+):    .197E-02 -.235E-02  .234E-02
   AREA1Value :  .19987    Error(Cov,-/+):    .235E-01 -.241E-01  .249E-01
   RESL1Value :  .14995E-01Error(Cov,-/+):    .000E+00 -.219E-02  .218E-02
   GAMA1Value :  .88000E-03Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   MASS1Value :  3.5101    Error(Cov,-/+):    .234E-02  .000E+00  .000E+00
   AREA2Value :  .22864    Error(Cov,-/+):    .245E-01  .000E+00  .000E+00
   RESL2Value :  .14724E-01Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   GAMA2Value :  .20000E-02Error(Cov,-/+):    .000E+00  .000E+00  .000E+00
   MASS2Value :  3.5548    Error(Cov,-/+):    .218E-02  .000E+00  .000E+00
```

Figure 16: Fitted results of the $3(\pi^+\pi^-)$ invariant mass spectrum. Mass resolutions are fixed to Monte Carlo values, width of χ_{c1} and χ_{c2} is fixed to PDG values.

some new decay modes are observed and branching fractions are measured, and some other channels, branching fractions with high precision are given. It is notable that some of the branching fractions got from this analysis give a lower value compared with the values listed by PDG (typically a factor of 1/2 lower than PDG values).

Table 14: Summary of χ_{cJ} decay branching fractions.

	BES		PDG 96		
	evts number	result	evts number	World average	Reference
$\mathcal{B}(\chi_{c0} \to \pi^+\pi^-)$	720 ± 32	$(4.79 \pm 0.27 \pm 0.73) \times 10^{-3}$	11	$(7.5 \pm 2.1) \times 10^{-3}$	[12]
			32 ± 6		[8]
$\mathcal{B}(\chi_{c2} \to \pi^+\pi^-)$	185 ± 16	$(1.52 \pm 0.15 \pm 0.24) \times 10^{-3}$	4	$(1.9 \pm 1.0) \times 10^{-3}$	[12]
$\mathcal{B}(\chi_{c0} \to K^+K^-)$	774 ± 38	$(5.82 \pm 0.36 \pm 0.94) \times 10^{-3}$	6	$(7.1 \pm 2.4) \times 10^{-3}$	[12]
			27 ± 5.5		[8]
$\mathcal{B}(\chi_{c2} \to K^+K^-)$	115 ± 13	$(0.81 \pm 0.14 \pm 0.14) \times 10^{-3}$	2	$(1.5 \pm 1.1) \times 10^{-3}$	[12]
$\mathcal{B}(\chi_{c0} \to p\bar{p})$	15.2 ± 4.1	$(16.3 \pm 4.4 \pm 5.4) \times 10^{-5}$		$< 9.0 \times 10^{-4}$	[12]
$\mathcal{B}(\chi_{c1} \to p\bar{p})$	4.2 ± 2.2	$(4.3 \pm 2.3 \pm 2.9) \times 10^{-5}$	513	$(8.6 \pm 1.2) \times 10^{-5}$	[9]
$\mathcal{B}(\chi_{c2} \to p\bar{p})$	4.7 ± 2.5	$(5.9 \pm 3.1 \pm 3.3) \times 10^{-5}$	585[9]	$(10.0 \pm 1.0) \times 10^{-5}$	[9, 10]
$\mathcal{B}(\chi_{c0} \to \pi^+\pi^-\pi^+\pi^-)$	874 ± 30	$(15.8 \pm 0.5 \pm 3.9) \times 10^{-3}$	181 ± 16	$(3.7 \pm 0.7) \times 10^{-2}$	[8]
$\mathcal{B}(\chi_{c1} \to \pi^+\pi^-\pi^+\pi^-)$	277 ± 19	$(5.0 \pm 0.4 \pm 1.3) \times 10^{-3}$	72 ± 12	$(1.6 \pm 0.5) \times 10^{-2}$	[8]
$\mathcal{B}(\chi_{c2} \to \pi^+\pi^-\pi^+\pi^-)$	425 ± 21	$(9.8 \pm 0.5 \pm 2.5) \times 10^{-3}$	89 ± 12	$(2.2 \pm 0.5) \times 10^{-2}$	[8]
$\mathcal{B}(\chi_{c0} \to K^0_s K^0_s)$	49.3 ± 7.0	$(2.01 \pm 0.29 \pm 0.55) \times 10^{-3}$			
$\mathcal{B}(\chi_{c2} \to K^0_s K^0_s)$	11.7 ± 3.2	$(0.62 \pm 0.17 \pm 0.17) \times 10^{-3}$			
$\mathcal{B}(\chi_{c0} \to \pi^+\pi^-K^+K^-)$	587 ± 27	$(15.1 \pm 0.7 \pm 4.0) \times 10^{-3}$	83 ± 11	$(3.0 \pm 0.7) \times 10^{-2}$	[8]
$\mathcal{B}(\chi_{c1} \to \pi^+\pi^-K^+K^-)$	192 ± 16	$(4.6 \pm 0.4 \pm 0.1.2) \times 10^{-3}$	24 ± 7	$(9 \pm 4) \times 10^{-3}$	[8]
$\mathcal{B}(\chi_{c2} \to \pi^+\pi^-K^+K^-)$	267 ± 18	$(8.1 \pm 0.6 \pm 2.2) \times 10^{-3}$	47 ± 8	$(1.9 \pm 0.5) \times 10^{-2}$	[8]
$\mathcal{B}(\chi_{c0} \to \pi^+\pi^-p\bar{p})$	81 ± 11	$(1.61 \pm 0.21 \pm 0.56) \times 10^{-3}$	23 ± 6	$(5.0 \pm 2.0) \times 10^{-3}$	[8]
$\mathcal{B}(\chi_{c1} \to \pi^+\pi^-p\bar{p})$	27.1 ± 6.9	$(0.50 \pm 0.13 \pm 0.18) \times 10^{-3}$	6 ± 4	$(1.4 \pm 0.9) \times 10^{-3}$	[8]
$\mathcal{B}(\chi_{c2} \to \pi^+\pi^-p\bar{p})$	50.9 ± 8.1	$(1.26 \pm 0.20 \pm 0.37) \times 10^{-3}$	13 ± 5	$(3.3 \pm 1.3) \times 10^{-3}$	[8]
$\mathcal{B}(\chi_{c0} \to K^+K^-K^+K^-)$	57.8 ± 6.9	$(2.19 \pm 0.27 \pm 0.43) \times 10^{-3}$			
$\mathcal{B}(\chi_{c1} \to K^+K^-K^+K^-)$	11.7 ± 4.2	$(0.43 \pm 0.15 \pm 0.13) \times 10^{-3}$			
$\mathcal{B}(\chi_{c2} \to K^+K^-K^+K^-)$	36.6 ± 5.9	$(1.52 \pm 0.27 \pm 0.34) \times 10^{-3}$			
$\mathcal{B}(\chi_{c0} \to \phi\phi)$	7.6 ± 2.8	$(0.94 \pm 0.35 \pm 0.39) \times 10^{-3}$			
$\mathcal{B}(\chi_{c2} \to \phi\phi)$	13.6 ± 3.7	$(2.05 \pm 0.56 \pm 0.64) \times 10^{-3}$			
$\mathcal{B}(\chi_{c0} \to K^0_s K^+\pi^- + c.c.)$	< 8.5	$< 0.73 \times 10^{-3}$			
$\mathcal{B}(\chi_{c1} \to K^0_s K^+\pi^- + c.c.)$	31.4 ± 5.6	$(2.52 \pm 0.45 \pm 0.68) \times 10^{-3}$			
$\mathcal{B}(\chi_{c2} \to K^0_s K^+\pi^- + c.c.)$	< 10.6	$< 1.09 \times 10^{-3}$			
$\mathcal{B}(\chi_{c0} \to 3(\pi^+\pi^-))$	191 ± 16	$(12.0 \pm 1.0 \pm 2.5) \times 10^{-3}$	37 ± 8	$(1.5 \pm 0.5) \times 10^{-2}$	[8]
$\mathcal{B}(\chi_{c1} \to 3(\pi^+\pi^-))$	98 ± 12	$(5.9 \pm 0.7 \pm 1.3) \times 10^{-3}$	48 ± 15	$(2.2 \pm 0.8) \times 10^{-2}$	[8]
$\mathcal{B}(\chi_{c2} \to 3(\pi^+\pi^-))$	112 ± 12	$(9.2 \pm 1.0 \pm 2.1) \times 10^{-3}$	23 ± 15	$(1.2 \pm 0.8) \times 10^{-2}$	[8]

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