BES Analysis Memo
Search for $\psi(2S)$ Decays to Vector plus Tensor Mesons

Li Xinhua
email: LIXH@bepc5.ihep.ac.cn
(Revised July 11, 1997)

Abstract

The hadronic decays $\psi(2S) \to \omega f_2$, ρa_2 $K^{*0}K_2^{*0}$ and $\phi f_2'(1525)$ have been studied in a sample of 3.7×10^6 $\psi(2S)$ events. Measurements of their branching fractions are presented. All channels violate the "15% *rule*" predicted by perturbative QCD compared with the corresponding J/ψ decays. As vector-tensor pair combinations, they provide the first anomalous example of non-vector-pseudoscalar decays of charmonium.

I. INTRODUCTION

There exists a long standing puzzle in the study of charmonium decays. According to Applequist and Politzer [1], there is a direct parallel between the decay of $\psi(2S)$ and J/ψ to three massless gluons

$$Q_h \equiv \frac{B(\psi(2S) \to ggg)}{B(J/\psi \to ggg)} = \frac{B(\psi(2S) \to e^+e^-)}{B(J/\psi \to e^+e^-)} = (14.6 \pm 2.2)\%$$

where the leptonic branching fractions from PDG [2] are used.

The Mark II first revealed unexpected small values for the ratios of $\psi(2S)$ to J/ψ branching fractions for decays to $\rho\pi$ and $K^{*\pm}K^{\mp}$. With a data sample of 1.02×10^6 produced $\psi(2S)$ events, it was found that $Q_{\rho\pi} < 0.63\%$ (90% *C.L.*) and $Q_{K^{*\pm}K^{\mp}} < 2.07\%$ (90% C.L.) [3].

Following Mark II, several radiative decays were measured by the Crystal Ball experiment [4]. Radiative decays of $\psi(2S)$ to the tensor f_2 was observed but neither to the η nor the η'. These results, in combination with the Mark II results, immediately led to a conclusion that the suppressed modes are just vector-pseudoscalar decays of $\psi(2S)$. Ever since it becomes popular in the literature to refer to the puzzle as "*vector − pseudoscalar puzzle*".

A number of theoretical models [5] have been suggested to explain the puzzle, but none of them are satisfactory.

This paper extends to the observation of vector-tensor combination decays, $\psi(2S) \to \omega f_2$, ρa_2 and $\phi f_2'$. Data were taken during 1993-1995 at the BEPC. The total event number of $\psi(2S)$ is $(3.7 \pm 0.3) \times 10^6$ got by observing the inclusive production of J/ψ in the process $\psi(2S) \to \pi^+\pi^- J/\psi$ and using the branching fraction of $\psi(2S) \to \pi^+\pi^- J/\psi$ of PDG [2].

II. $\psi(2S) \to \pi^+\pi^-\pi^+\pi^-\pi^0$ SELECTION

Events with four charged tracks (MFIT=2) in the polar angle region $-0.8 < \cos\theta < 0.8$ and with zero net charge have been selected. Moreover, at least two neutral tracks with polar angle $-0.75 < \cos\theta < 0.75$ and also not hitting the central ribbon range ($Z_{sc} < -4cm$ or $Z_{sc} > 4cm$) are required for photon candidates.

Magnetic field correction is made to the momentum of charged track. Momentum corrections are further made for energy loss and multiple Coulomb scattering in the material before charged particles enter the drift volume in BES inner detector. So are photon directions entering shower counter for beam position dispersion in the colliding zone.

Events are kinematically $4C2\gamma$ fitted with all photon pairs. The pair with highest probability of fit are selected and it is also required to be greater than 0.01. The π^0 is selected by requiring the invariant mass of two photons to be $85 < M_{\gamma\gamma} < 205\ MeV$. Its side band is defined as the mass range $40 < M_{\gamma\gamma} < 80\ MeV$ and $210 < M_{\gamma\gamma} < 290\ MeV$. Several steps are processed to remove fake photon contamination. The angle between photon and charged track is larger than 13^o. The distance between photon and charged track hitting shower counter is larger than 35cm. The fitted energy of photon is higher than 60MeV.

Furthermore, the J/ψ contamination of e^+e^- or $\mu^+\mu^-$ from $\psi(2S) \to \eta J/\psi$ where η decays to $\pi^+\pi^-\pi^0$ and J/ψ decays to leptons are removed by $M(\pi^+\pi^-) < 2.9\ GeV/c^2$. The dE/dx measurements are used to select pion tracks with confidence level larger than 0.003 for each track and 0.01 for all tracks combined. So are the TOF measurements when hit qualities are good ($T_{qual} = 1$) (at least one track with $T_{qual} = 1$ is required). No $\pi^+\pi^-$ combination is allowed to recoil to J/ψ within $50MeV/c^2$ of J/ψ mass to exclude the background $\psi(2S) \to \pi^+\pi^- J/\psi$ with J/ψ decaying to $\pi^+\pi^-\pi^0$.

The effects of the various selection cuts on the data are summarized in Table 1. Included in the table are the results that obtain when the same analysis is applied to samples of Monte Carlo simulated events $\psi(2S) \to \omega\pi^+\pi^-$, ωf_2 and ρa_2.

Table 1. A tabulation of the $\psi(2S) \to 2(\pi^+\pi^-)\pi^0$ selection cuts.

a). Samples of $\omega\pi^+\pi^-$, ωf_2 and ρa_2 are the Monte Carlo simulated events;
b). The MDC cut is Nchrg=4, $\sum q = 0$ and $|\cos\theta| < 0.8$;
c). The cuts of dE/dx and TOF are not applied to the simulated sample;
d) 141 events survive the ω selection when $CL(TOF)$ is not applied to the data.

	data	$\omega\pi^+\pi^-$	ωf_2	ρa_2
Generated		12000	12000	19200
MDC	440698	4566	4751	7037
$N_\gamma > 1$	359933	2324	2490	4066
$CL(4C) > 0.01$	23489	1712	1824	2932
$\cos\theta_{\gamma ch} < 0.975$	15990	1448	1508	2841
$d_{\gamma ch} > 35cm$	14605	1307	1347	2769
$E_\gamma^{fit} > 60MeV$	12225	1041	1101	2442
$m_{\pi^+\pi^-} < 2.9GeV$	11934	1038	1099	2439
$CL(dE/dx) > 0.01$	9519			
$CL(TOF) > 0.01$	8547			
Remove $\pi^+\pi^- J/\psi$	1206	985	1077	2340
$85 < m_{\gamma\gamma} < 205MeV$	939	979	1061	2305
Select ω	128	891	964	
Select $\rho^0\rho^\pm\pi^\mp$	301			1601

III. ANALYSIS OF $\psi(2S) \to \omega\pi^+\pi^-$

The $\pi^+\pi^-\pi^0$ mass spectrum (figure 1) shows significant ω signal. The similar plot of π^0 side band (figure 2) shows invisible ω signal. The mass distribution is fitted to a Breit-Wigner curve with width fixed to PDG [2] and float mass added to a quaduatical background. Mass resolution is 13.4 MeV got from simulation and 10.4 ± 1.5 MeV from data. Figure 3 shows the fit plot of data. The fit quality is $\chi^2 = 43.36/35dof$. It gives 114.0 ± 12 events and mass of ω $(781.7 \pm 2.0)MeV/c^2$ well consistent with PDG [2]. Figure 4 is the corresponding fit plot of Monte Carlo simulation. The efficiency is 0.079 calculated by Monte Carlo simulation with uniform phase space distribution. The branching fraction is obtained

$$B(\psi(2S) \to \omega\pi^+\pi^-) = (4.6 \pm 0.5 \pm 0.9) \times 10^{-4},$$

where the first error is statistical and second systematic. The systematic error mainly dues to the cut on kinematic fit. It also contains signal fit to different background line, the simulation of analysis efficiency, total number of $\psi(2S)$, and the branching fraction of $\omega \to \pi^+\pi^-\pi^0$ given by PDG [2]. So are calculated for the other systematic errors in this memo.

The $\omega\pi^+\pi^-$ candidates are selected by requiring $740 < m_{\pi^+\pi^-\pi^0} < 820\ MeV/c^2$. $680 < m_{\pi^+\pi^-\pi^0} < 720MeV/c^2$ and $840 < m_{\pi^+\pi^-\pi^0} < 880MeV/c^2$ are chosen for the ω side band. The Dalitz plot of $\omega\pi^+$ versus $\omega\pi^-$ are in figure 5 for ω mass region and figure 6 for the side band.

The $\omega\pi^\pm$ mass spectrum figure 7 shows a clear $b_1^\pm$ signal owing to the proximity of the phase space limit. The similar plot for the ω side band figure 8 shows very few $b_1^\pm$ signals.

The decay $\psi(2S) \to \omega f_2$ is investigated on the $\pi^+\pi^-$ mass plot recoiling to the ω mass band (figure 10) and also to the ω side band (figure 9). The $f_2(1270)$ signal is invisible on both plots. It has been fitted to a Breit-Wigner curve with width and mass fixed to PDG [2] added to quadratic background. Mass resolution is 12.3 MeV got by simulation. The fit leads to 8.8 ± 9.2 events. At the 90% confidence level the event number is less than 23.8. The fit quality is $\chi^2 = 66.56/51\ dof$. The fit plot is shown in figure 10. The corresponding fit plot of Monte Carlo is in figure 11. The efficiency is 0.074 calculated by simulation with uniform phase space distribution. Considering an isospin ratio 2:1 for f_2 decays into $\pi^+\pi^-$ or $\pi^0\pi^0$, one gets the branching fraction

$$B(\psi(2S) \to \omega f_2) < 1.8 \times 10^{-4} \qquad \text{(C.L.=90\%)}$$

IV. ANALYSIS OF $\psi(2S) \to \rho A_2$

This decay channel is analyzed in $\rho^0\rho^\pm\pi^\mp$ combination which decays to $\pi^+\pi^-\pi^+\pi^-\pi^0$ final state. The $\rho^0\rho^\pm\pi^\mp$ candidate is selected by minimizing a quantity

$$\Delta = \sqrt{(m_{\pi^+\pi^-} - m_{\rho^0})^2 + (m_{\pi^0\pi^\pm} - m_{\rho^\pm})^2}$$

and a cut $\Delta_{min} < 110\ MeV/c^2$ is applied. Another range $130 < \Delta_{min} < 170\ MeV/c^2$ is selected as the side band of $\rho^\pm\pi^\mp\rho^0$ combination. Figure 12 shows the simulated Δ_{min}

plot. The resolution of the Δ_{min} quantity is shown on figure 13 where the widths of $\rho^{\pm}$ and ρ^0 are set to zero in the event generation of $\psi(2S) \to \rho a_2 \to \rho^0\rho^{\pm}\pi^{\mp}$. The dalitz plots of $\rho^0\pi^{\pm}$ versus $\rho^{\mp}\pi^{\pm}$ are in figure 14 for the signal region and figure 15 for the side band. The $a_2(1320)$ signal is very marginal on the combining $\rho^0\pi^{\pm}$ and $\rho^{\pm}\pi^{\mp}$ mass plot from both $\rho^0\rho^{\pm}\pi^{\mp}$ candidate (figure 17) and $\rho^0\rho^{\pm}\pi^{\mp}$ side band (figure 16). The a_2 mass resolution is 10.3 MeV got from simulation. A fit to a Breit-Wigner curve with a_2 mass and width fixed to PDG [2] over a quadratic background yields ρa_2 event number 6.4 ± 9.0. The event number is less than 21.2 at 90% confidence level. The fit quality is $\chi^2 = 52.03/58\ dof$. Simulation with uniform phase space distribution gives 0.048 detection efficiency. Assuming an isospin ratio of $a_2^+\rho^- : a_2^-\rho^+ : a_2^0\rho^0 = 1:1:1$ for $\psi(2S)$ decay, one calculates

$$B(\psi(2S) \to \rho a_2) < 2.7 \times 10^{-4}.$$

V. ANALYSIS OF $\psi(2S) \to \pi^+\pi^-K^+K^-$

Four charged track net charge zero events have been selected if each track with high quality in track fitting (MFIT=2) and polar angle in the region $|\cos\theta| < 0.8$. Magnetic field correction is made to momentum of charged track. Momentum correction is further made for energy loss and multiple Coulomb scattering in the material before track enters the drift volume in BES inner detector. Events are 4C fitted to $\psi(2S) \to \pi^+\pi^-K^+K^-$ for all track assignments and the fit with largest probability is selected as $\pi^+\pi^-K^+K^-$ candidate. The probability of the fit is required to be larger than 0.01. The $\pi^+\pi^-$ recoiling mass which is calculated using the reconstructed track momentum is required to be lower than 3.0 GeV or higher than 3.2 GeV to exclude contamination of $\psi(2S) \to \pi^+\pi^-J/\psi$ with J/ψ decaying to lepton pair. The dE/dx measurements are used to select π and K tracks with confidence level larger than 0.003 for each track and 0.01 for all tracks combined. So are the TOF measurements when the hit qualities are good ($T_{qual} = 1$) (at least one track with $T_{qual} = 1$ is required). Electron is removed by $E_{BSC}/P > 0.6$ when $P > 1GeV/c$ and muon by μ hit less than 2. K^{*0} is selected by $800 < m(k^{\pm}\pi^{\mp}) < 1000\ MeV/c^2$. $680 < m(k^{\pm}\pi^{\mp}) < 780\ MeV/c^2$ and $1020 < m(k^{\pm}\pi^{\mp}) < 1120\ MeV/c^2$ are selected as the side band. The resulting plots are in figure 19, the upper left is the scatter plot of $K^+\pi^-$ vs $K^-\pi^+$; the lower left the mass of $K^{\pm}\pi^{\mp}$; the upper right $m(K^{\pm}\pi^{\mp})$ recoiling to K^{*0}; the lower right $m(K^{\pm}\pi^{\mp})$ recoiling to K^{*0} side band.

The effects of the various selection cuts on the data $\psi(2S) \to \pi^+\pi^-K^+K^-$ are summarized in Table 2. Included in the table are the results that obtain when the same analysis is applied to samples of Monte Carlo simulated events $\psi(2S) \to K^{*0}K_2^{*0}$.

The mass plot of $K^{\pm}\pi^{\mp}$ recoiling to K^{*0} is fitted with two Breit-Wigner curves of K^{*0} and K_2^{*0} over a quadratic background (figure 20). Monte Carlo simulation gives mass resolutions 4.9 MeV for the K^{*0} and 6.7 MeV for the K_2^{*0}. The mass and width of K_2^{*0} are set to PDG. So is the width of K^{*0}. The fit quality is $\chi^2 = 58.57/60\ dof$. The fit yields mass of K^{*0} $886.5 \pm 5.3\ MeV$, K^{*0} numbers 47.9 ± 8.1, and K_2^{*0} numbers 0 ± 7.9. At the 90% confidence level, the numbers of K_2^{*0} is less than 20.8. The efficiency is 12.5% calculated by simulation with uniform phase space distribution. Applying $K^{\pm}\pi^{\mp} : K^0\pi^0 = 2:1$ for both K^{*0} and K_2^{*0} decay, one gets

$$B(\psi(2S) \to K^{*0}K_2^{*0}) < 2.1 \times 10^{-4} \qquad (C.L. = 90\%)$$

Table 2. A tabulation of the $\psi(2S) \to \pi^+\pi^-K^+K^-$ and $K^+K^-K^+K^-$ selection cuts.

a). Samples of $K^{*0}K_2^{*0}$ and $\phi f_2'$ are the Monte Carlo simulated events;
b). The MDC cut is Nchrg=4, $\sum q = 0$ and $|\cos\theta| < 0.8$;
c). The cuts of dE/dx and TOF are not applied to the simulated sample;
d). The cut of $\pi^+\pi^- J/\psi$ is not applied to $K^+K^-K^+K^-$ and $\phi f_2'$.

	$\pi^+\pi^-K^+K^-$	$K^+K^-K^+K^-$	$K^{*0}K_2^{*0}$	$\phi f_2'$
Generated			10000	6000
MDC	440698	440698	3674	1837
$CL(4C) > 0.01$	18116	664	2830	1172
$CL(dE/dx) > 0.01$	7199	42		
$CL(TOF) > 0.01$	6670	41		
Remove electron	6651	41	2829	1172
Remove $\pi^+\pi^- J/\psi$	508		2771	
Remove muon	492	41	2760	1171
best 4C fits	463	41	2745	1171

VI. ANALYSIS OF $\psi(2S) \to K^+K^-K^+K^-$

Events with four charged tracks (MFIT=2) in the polar angle region $-0.8 < \cos\theta < 0.8$ and with zero net charge have been selected. Magnetic field correction is made to momentum of charged track. Momentum correction is further made for energy loss and multiple Coulomb scattering in the material before track enters the drift volume in BES inner detector. Events are kinematically $4C$ fitted to improve mass resolution and exclude background. The probability of fit is required to be higher than 0.01. The dE/dx measurements are used to select kaon tracks with confidence level larger than 0.003 for each track and 0.01 for all tracks combined. So are the TOF measurements when hit qualities are good ($T_{qual} = 1$) (at least one track with $T_{qual} = 1$ is required). There remains 41 events after the above selections. No track seems to be electron ($E_{BSC}/P > 0.6$ when $P > 1GeV/c$) or muon (μ hit less than 2). The effects of the various selection cuts on the data are summarized in Table 2. Included in the table are the results that obtain when the same analysis is applied to the Monte Carlo simulated $\phi f_2'$ events.

The resulting dalitz plot (figure 21) shows ϕ signals. Figure 22 is the mass plot of K^+K^- (4 entries/event). The ϕ candidate is selected as $m_{K^+K^-} < 1040\ MeV/c^2$ to investigate the recoiling part. The mass plot of K^+K^- pair recoiling to ϕ (figure 23) shows ϕ signal but $f_2'(1525)$ is absent. Two events with double counting (2 entries/event) are in the ϕ mass range ($m_{K^+K^-} < 1040\ MeV/c^2$). Based on these two events, the number of $\phi\phi$ events is less than 5.32 at the 90% confidence level. The f_2' signal is fitted to a Breit-Wigner curve added to linear background with mass and width fixed to PDG. The mass resolution is 6 MeV. The fitted number of f_2' is 1.1 ± 2.3. At the 90% confidence level the number is less than 4.9.

Simulations result in efficiencies 0.231 for $\phi\phi$, 0.181 for $\phi f_2'(1525)$ respectively. The branching fractions are calculated

$$B(\psi' \to \phi\phi) < 2.6 \times 10^{-5}$$

$$B(\psi' \to \phi f_2'(1525)) < 3.4 \times 10^{-5}$$

VII. SUMMARY AND DISCUSSION

The decays of $\psi(2S)$ to $2(\pi^+\pi^-)\pi^0$, $\pi^+\pi^-K^+K^-$ and $K^+K^-K^+K^-$ have been studied from a high statistics constrained and fully reconstructed events. Four vector-tensor combinations, ωf_2, ρa_2, $K^{*0}K_2^{*0}$ and $\phi f_2'(1525)$ are measured in $\psi(2S)$ decays. Table 3 summarizes the results of branching ratios measured for $\psi(2S)$ decays into vector plus tensor combinations and also the PDG [2] values for the corresponding J/ψ decays. All four channels give values of the ratio of branching fractions of the $\psi(2S)$ to the J/ψ much lower than the prediction of perturbative QCD. As vector-tensor combinations, their suppressions provide a striking deviation from the expectation [1] and as yet there is no satisfactory theoretical explanation.

Table 3 Experimental ratios of $\psi(2S)$ compared to J/ψ (limits at 90% confidence level).

	$B(\psi(2S))$	$B(J/\psi)$	$B(\psi(2S))/B(J/\psi)$
$\omega\pi^+\pi^-$	$(4.6 \pm 0.5 \pm 0.9) \times 10^{-4}$	$(7.2 \pm 1.0) \times 10^{-3}$	0.064 ± 0.015
ωf_2	$< 1.8 \times 10^{-4}$	$(4.3 \pm 0.6) \times 10^{-3}$	< 0.042
ρa_2	$< 2.7 \times 10^{-4}$	$(10.9 \pm 2.2) \times 10^{-3}$	< 0.025
$K^{*0}K_2^{*0} + c.c.$	$< 2.1 \times 10^{-4}$	$(6.7 \pm 2.6) \times 10^{-3}$	< 0.032
$\phi f_2'$	$< 3.4 \times 10^{-5}$	$(8 \pm 4) \times 10^{-4}$	< 0.045

REFERENCES

[1] T. Applequist and D. Politzer, Phys. Rev. Lett. 34, 43(1975).
[2] R.M.Barnett et al. (Particle Data Group), Phys. Rev. D54, 1(1996).
[3] M.E.B.Franklin et al., Phys. Rev. Lett. 51, 963(1983).
[4] R.A.Lee, SLAC-PUB-3676, May 1985.
[5] G.Karl and W.Roberts, Phys. Lett. B144, 263(1984);
G.Karl and S.F.Tuan, Phys. Rev. D34, 1629(1986);
M.Chaichian et al., Nucl. Phys. B323, 75(1989);
S.S.Pinsky, Phys. Lett. B236, 479(1990);
W.S.Hou and A.Soni, Phys. Rev. Lett. 50, 569(1983);
S.J.Brodsky et al., Phys. Rev. Lett. 59, 621(1987);
X.Q.Li et al., Phys. Rev. D55, (1997) 1241;
S.J.Brodsky et al., hep-ph/9704379.

FIGURES

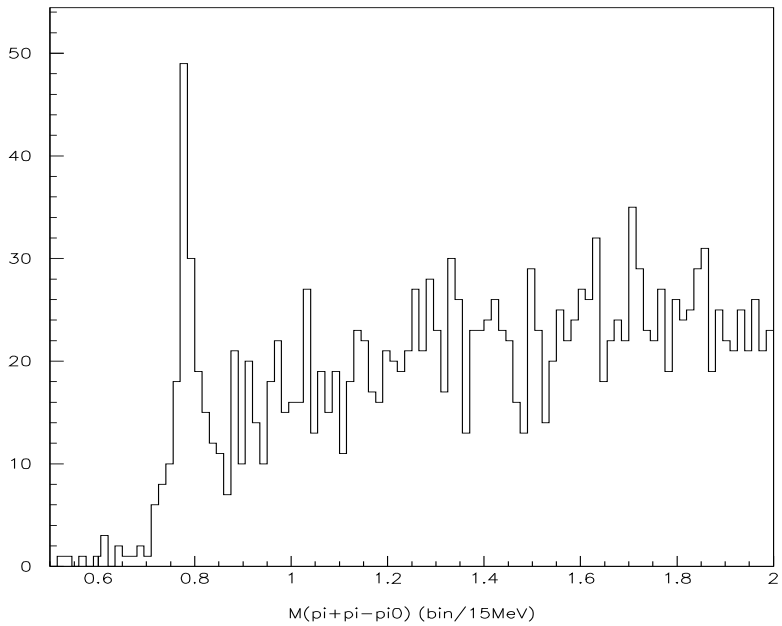

FIG. 1. Mass plot of $\pi^+\pi^-\pi^0$ in $\psi' \to \pi^+\pi^-\pi^+\pi^-\pi^0$

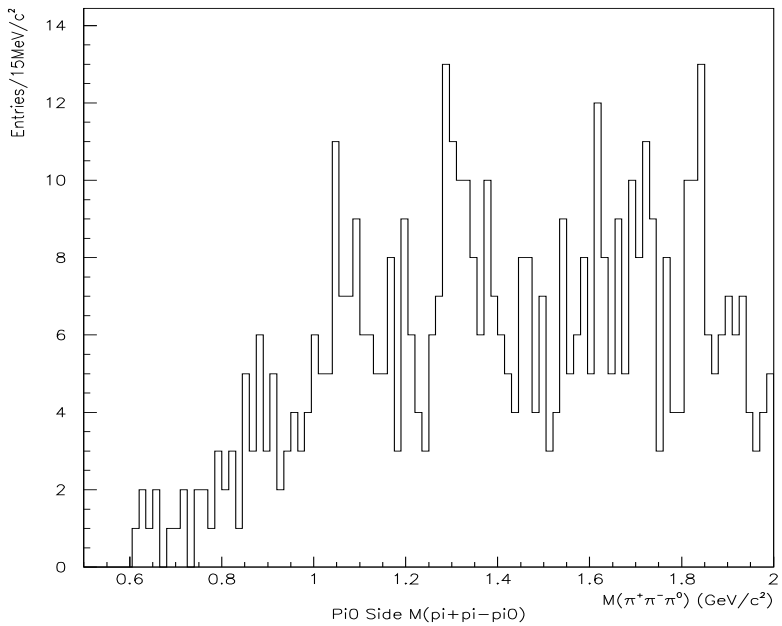

FIG. 2. Mass plot $\pi^+\pi^-\pi^0$ for the π^0 side band

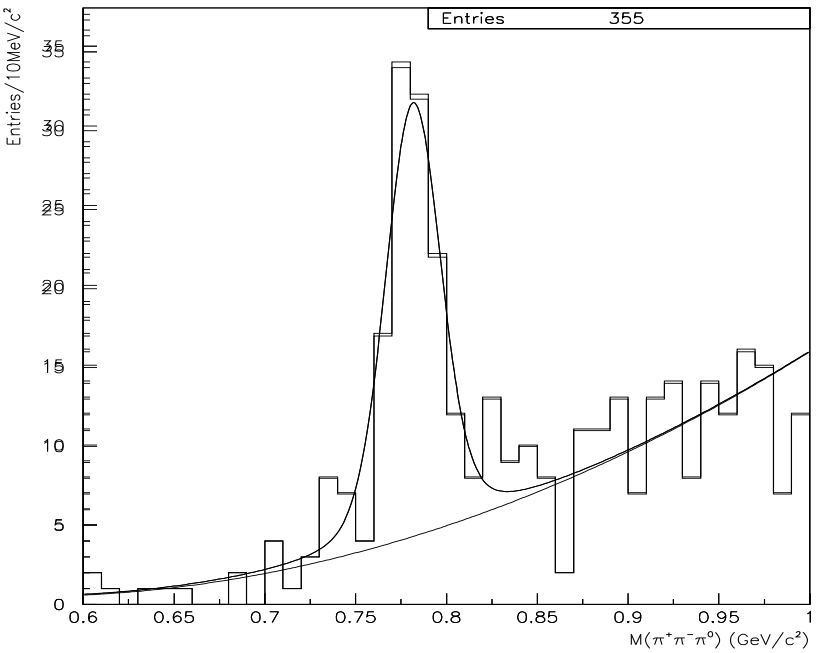

FIG. 3. The ω fit to the $\pi^+\pi^-\pi^0$ mass plot

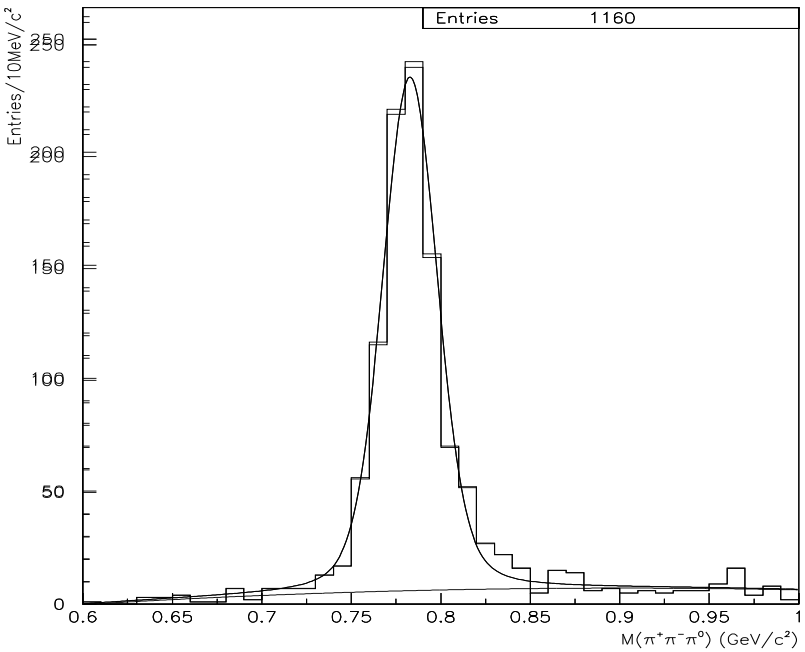

FIG. 4. Fit to the $\pi^+\pi^-\pi^0$ mass plot for the simulation $\psi' \to \omega\pi^+\pi^-$.

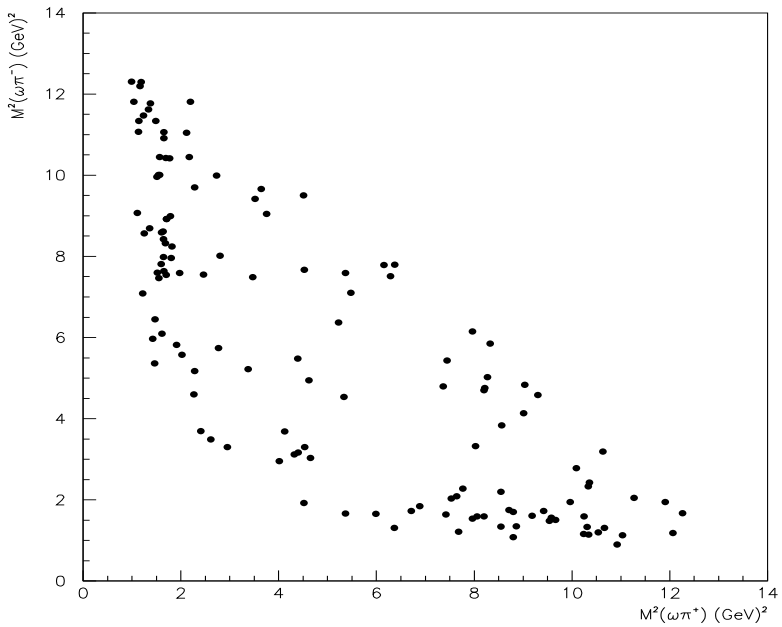

FIG. 5. Dalitz plot of $\omega\pi^+$ vs. $\omega\pi^-$.

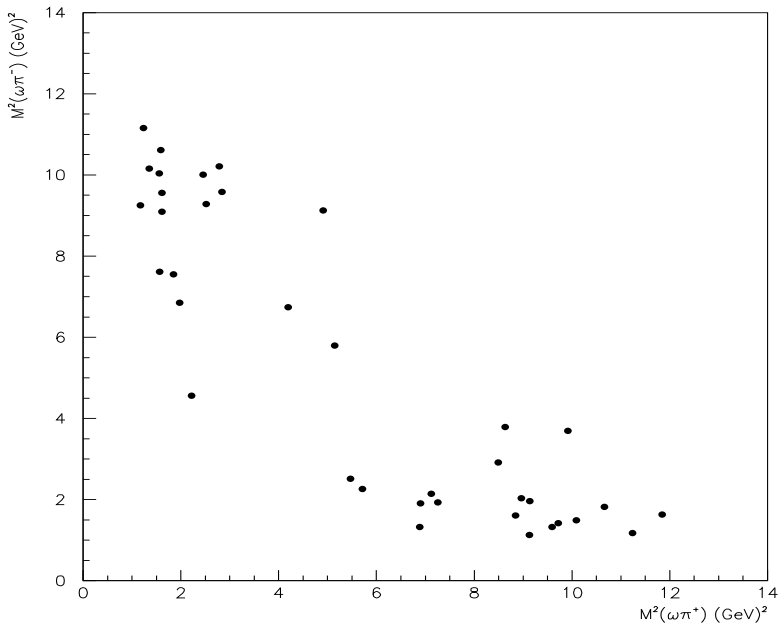

FIG. 6. Dalitz plot of $\omega\pi^+$ vs. $\omega\pi^-$ for ω side band.

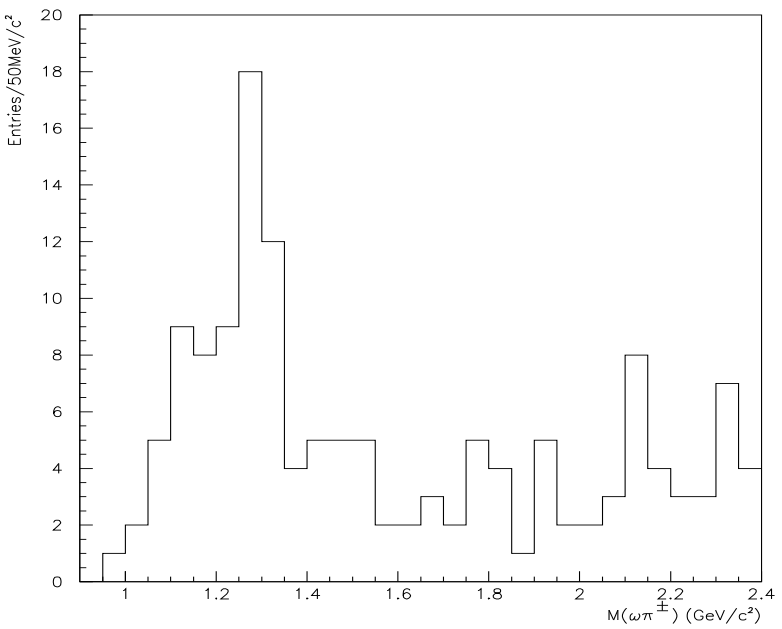

FIG. 7. $\omega\pi^{\pm}$ mass in $\psi' \to \omega\pi^{+}\pi^{-}$

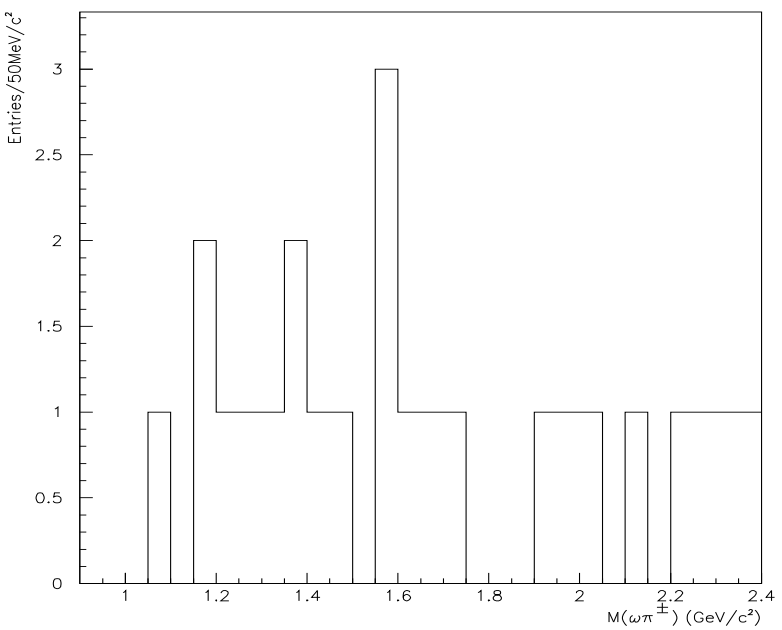

FIG. 8. $\omega\pi^{\pm}$ mass plot for the ω side band.

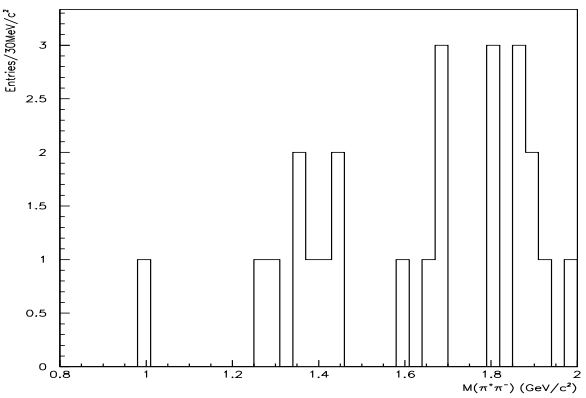

FIG. 9. Mass plot of $\pi^+\pi^-$ recoiling to ω side band

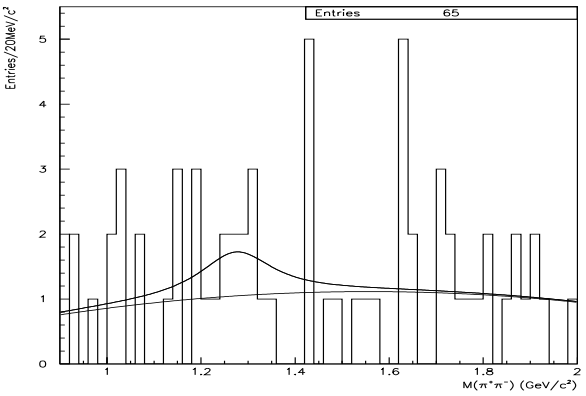

FIG. 10. Fit to plot of $m(\pi^+\pi^-)$ recoiling to ω.

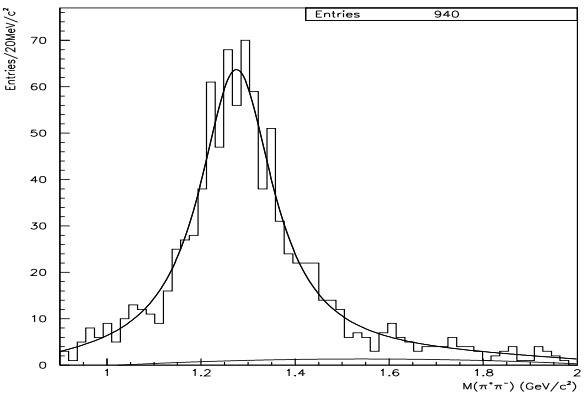

FIG. 11. Fit to plot of $m(\pi^+\pi^-)$ recoiling to ω for the simulation of $\psi' \to \omega f_2$

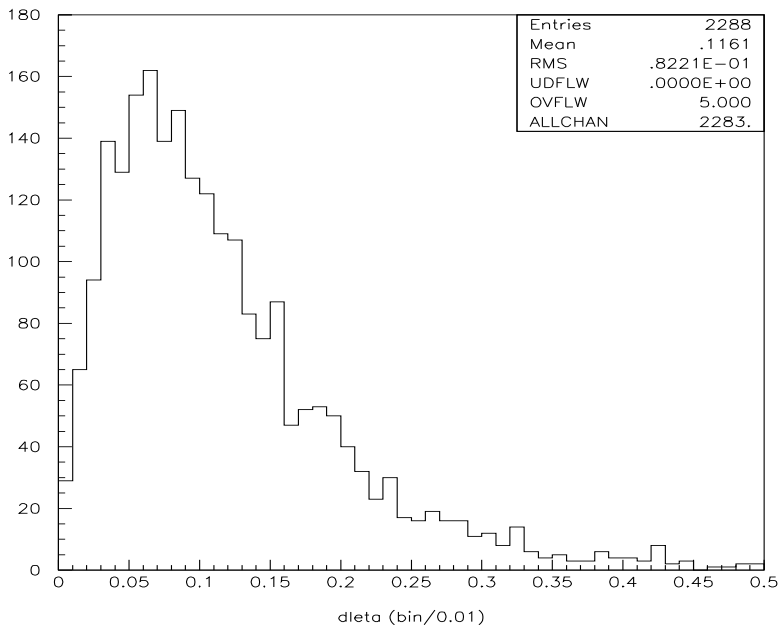

FIG. 12. Δ_{min} plot of the simulation $\psi' \to \rho a_2 \to \rho^0 \rho^{\mp} \pi^{\pm}$

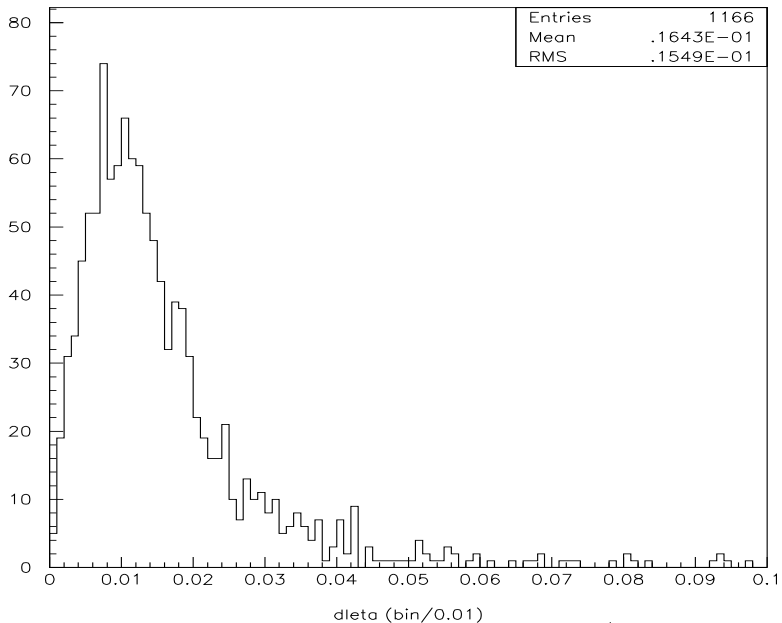

FIG. 13. Resolution plot of Δ_{min} quantity: the widths of $\rho^{\pm}$ and ρ^0 are set to zero in the simulation $\psi' \to \rho a_2 \to \rho^0 \rho^{\mp} \pi^{\pm}$

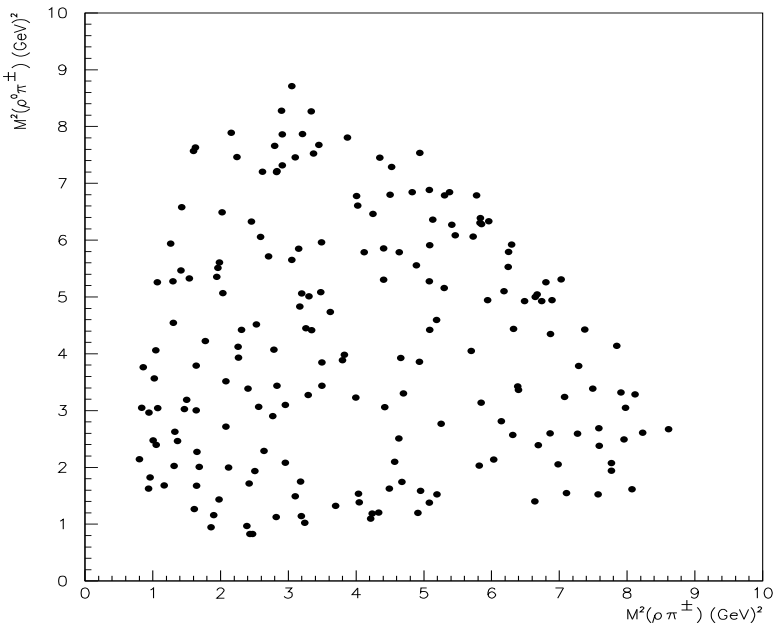

FIG. 14. Dalitz plot of $\rho^0\pi^\pm$ vs $\rho^\mp\pi^\pm$ in $\psi' \to \rho^0\rho^\mp\pi^\pm$

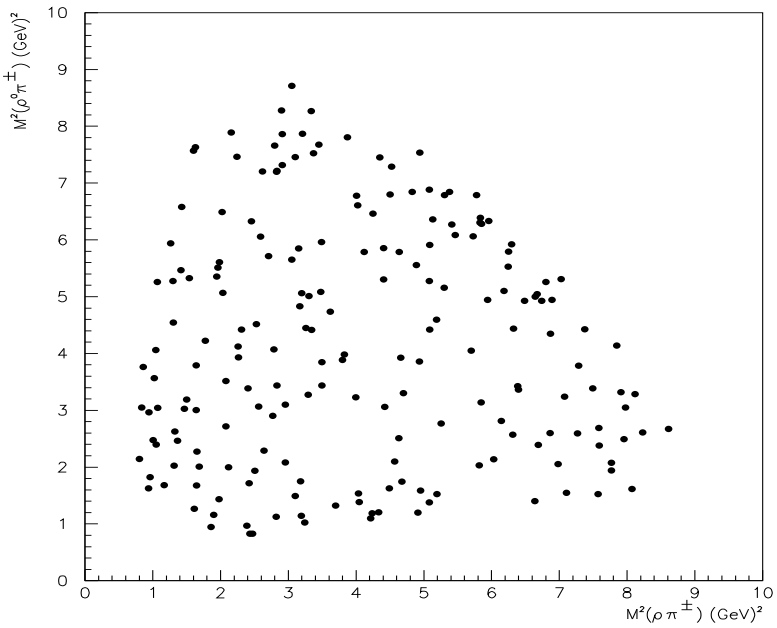

FIG. 15. Dalitz plot of $\rho^0\pi^\pm$ vs $\rho^\mp\pi^\pm$ for the side band of $\rho^0\rho^\mp\pi^\pm$ combination

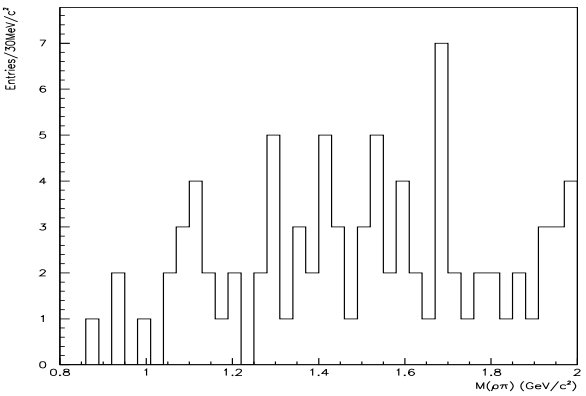

FIG. 16. Mass plot of $\rho\pi$ for the side band of $\rho^0\rho^{\mp}\pi^{\pm}$ combination

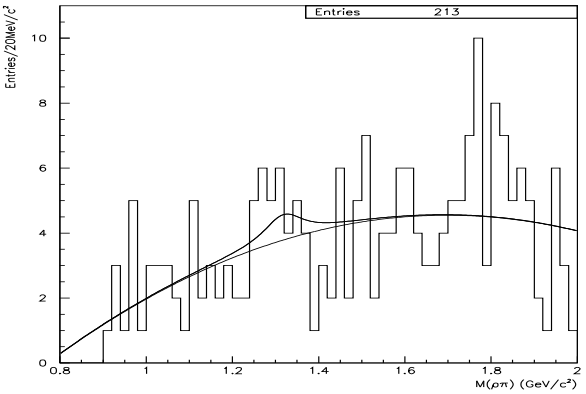

FIG. 17. Fit to plot of $m(\rho\pi)$ in $\psi' \to \rho^0\rho^{\mp}\pi^{\pm}$

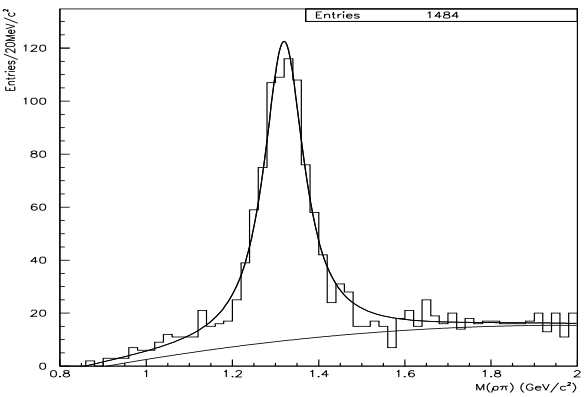

FIG. 18. Fit to plot of $m(\rho\pi)$ in the simulation of $\psi' \to \rho a_2 \to \rho^0\rho^{\mp}\pi^{\pm}$

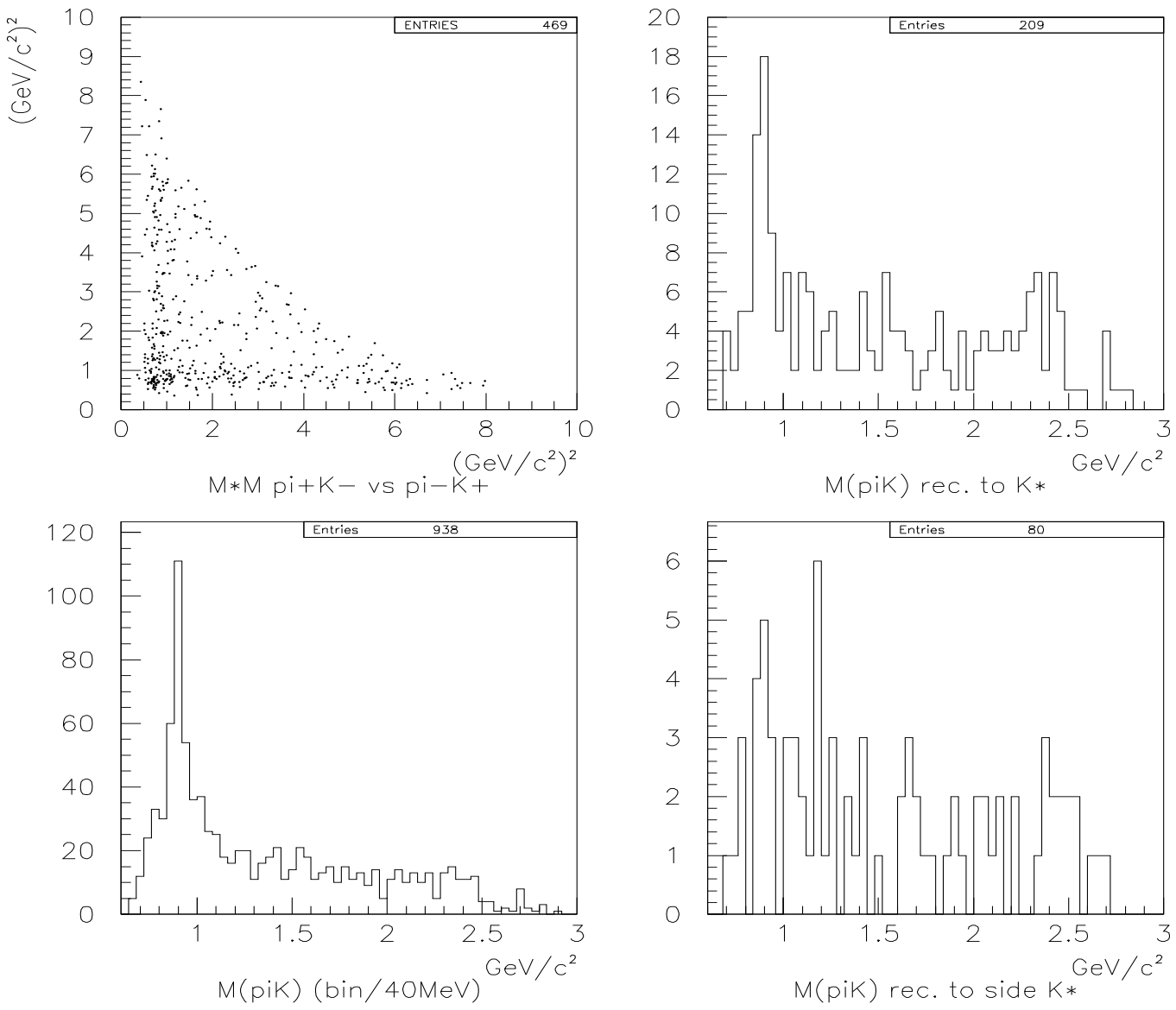

FIG. 19. Plots of $\psi' \to \pi^+\pi^- K^+ K^-$.

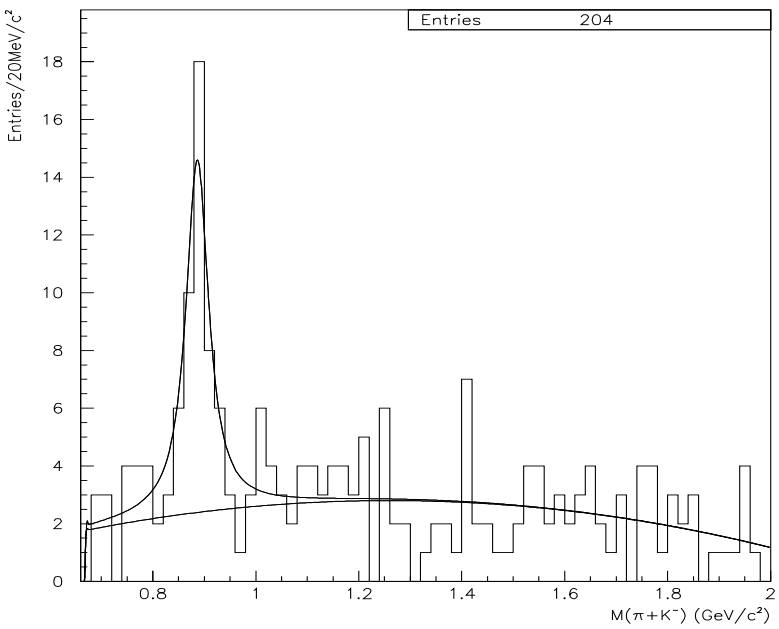

FIG. 20. Fit plot of $m(K^{\pm}\pi^{\mp})$ recoiling to the K^{*0}.

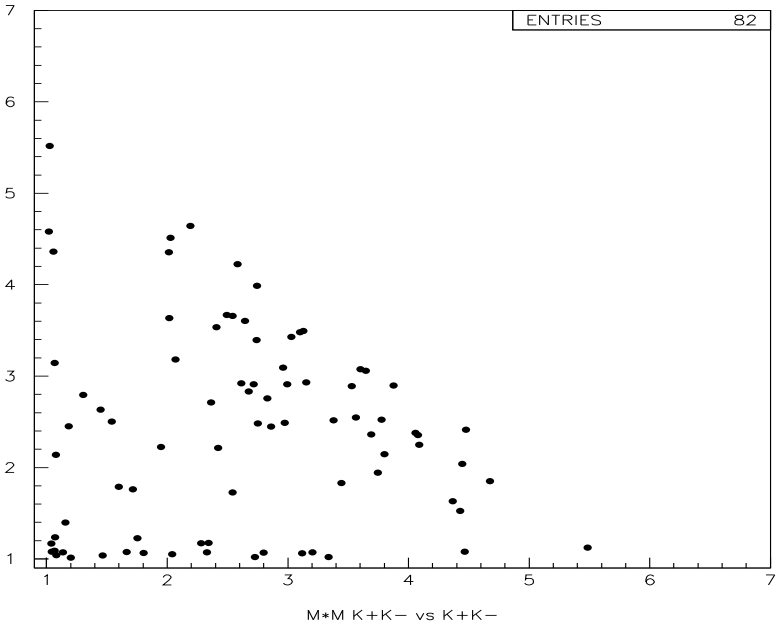

FIG. 21. Dalitz plot in $\psi' \to K^+K^-K^+K^-$

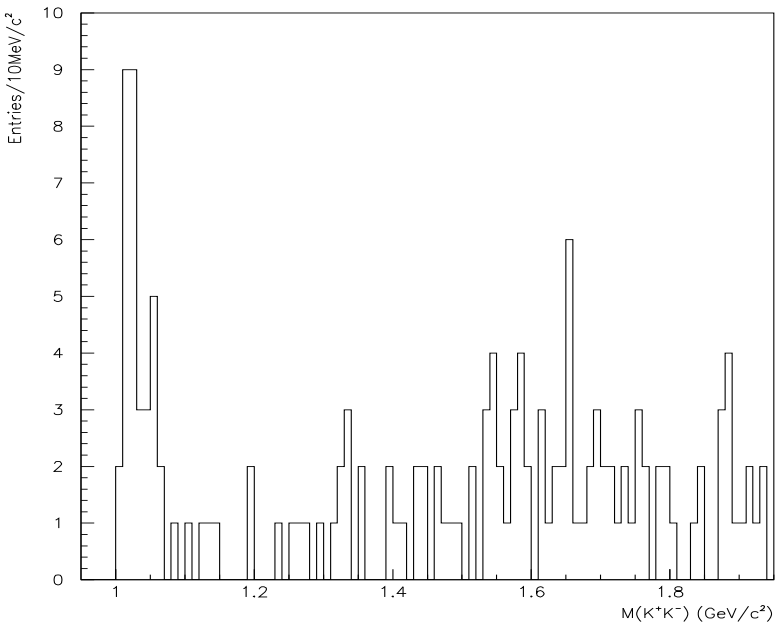

FIG. 22. K^+K^- mass in $\psi' \to K^+K^-K^+K^-$

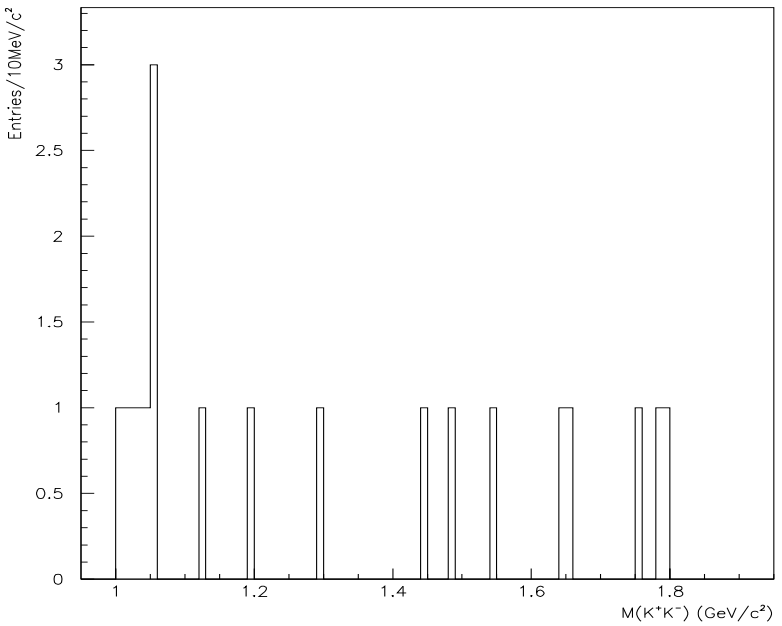

FIG. 23. Mass plot of K^+K^- recoiling to ϕ in $\psi' \to K^+K^-K^+K^-$