Analysis memo of $\psi(2S) \to \gamma\eta'(958)$

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Abstract

The branching ratio of $\psi(2S) \to \gamma\eta'$ is measured via two decay chains $\eta' \to \gamma\rho^o$ and $\eta' \to \pi^+\pi^-\eta$ using about 3.73 millions of $\psi(2S)$ data at BES. The decay chain of $\gamma\eta'(\to \gamma\rho^o)$ gives $\mathcal{B}(\ \psi(2S) \to \gamma\eta'\ ) = (1.17 \pm 0.25 \pm 0.35) \times 10^{-4}$ while the decay chain of $\gamma\eta'(\to \pi^+\pi^-\eta)$ gives $\mathcal{B}(\ \psi(2S) \to \gamma\eta'\ ) = (7.8 \pm 3.7 \pm 2.6) \times 10^{-5}$. The result indicates that $\psi(2S) \to \gamma\eta'$ is also suppressed in regard to the "15%" rule comparing with $J/\psi \to \gamma\eta'$. In addition, prediction and measurement on $\mathcal{B}(\psi(2S) \to \gamma\eta)$ at BES are given thereby.

1 Introduction

The mixing angle between η and η' has been a subject of discussion for a long time and is still of great interest to physicists. In the simplest possible situation where one assumes the presence of only octet and singlet, the quadratic Gell-Mann-Okubo mass formalua yields [1] a pseudoscalar mixing angle of $\theta_p \simeq -10^o$. With the same assumption, a Gell-Mann-Okubo mass which is linear in the masses gives [1] $\theta_p \simeq -23^o$.

But using the data on $\psi(2S) \to \eta(\eta')\gamma$ and $\eta(\eta') \to \gamma\gamma$ favor [2] a mixing angle of $\theta_p \simeq -20^o$.

Supposing that the processes $\psi \to \gamma\eta$ and $\psi \to \gamma\eta'$ occur primarily through radiation of the photon from the charmed quark or charmed antiquark in the initial state, and assuming the applicability of SU(3) symmetry for SU(3)-singlet part of the pseudoscalar, one find [2],

$$\frac{\Gamma(J/\psi \to \gamma\eta')}{\Gamma(J/\psi \to \gamma\eta)} = \left[\frac{p_{\eta'}}{p_\eta}\right]^3 \frac{1}{\tan^2\theta_p} \tag{1}$$

Hence, $\theta_p = -22^o \pm 1^o \pm 4^o$, where $p_\eta(p_{\eta'})$ stands for the momentum of $\eta(\eta')$.

At J/ψ, the branching fraction of $\gamma\eta'$ is much larger than $\gamma\eta$

$$\frac{\mathcal{B}(J/\psi\to\gamma\eta')}{\mathcal{B}(J/\psi\to\gamma\eta)}\frac{p_\eta^3}{p_{\eta'}^3}=6.2\pm0.7$$

on the contrary, the branching fraction of hadronic decay $\omega\eta(\phi\eta)$ is smaller than $\omega\eta'(\phi\eta')$

$$\frac{\mathcal{B}(J/\psi\to\omega\eta')}{\mathcal{B}(J/\psi\to\omega\eta)}\frac{p_\eta^3}{p_{\eta'}^3}=0.14\pm0.02$$

$$\frac{\mathcal{B}(J/\psi\to\phi\eta')}{\mathcal{B}(J/\psi\to\phi\eta)}\frac{p_\eta^3}{p_{\eta'}^3}=0.7\pm0.1$$

2 Event selection

The decay chains in determining $\mathcal{B}(\psi(2S)\to\gamma\eta')$ under investigation are

$$\psi(2S)\to\gamma\,\eta' \quad \eta'\to\gamma\,\rho^o \quad \rho^o\to\pi^+\pi^-$$

and

$$\psi(2S)\to\gamma\,\eta' \quad \eta'\to\pi^+\pi^-\eta \quad \eta\to2\gamma$$

For the case of $\gamma\eta'(\to\gamma\rho^o)$, the final states are $\pi^+\pi^-2\gamma$, the branching fraction $\mathcal{B}(\eta'\to\gamma\rho^o)=30.2\%$. While for $\gamma\eta'(\to\pi^+\pi^-\eta)$, the final states are $\pi^+\pi^-3\gamma$, and the branching fraction $\mathcal{B}(\eta'\to\pi^+\pi^-\eta)=43.7\%$, $\mathcal{B}(\eta\to2\gamma)=39.25\%$. For both cases, define good-gamma as those satisfying the criteria:

$$\boxed{N_{scht}\geq3;\ N_{scl}\geq2;\ \Delta\theta<40^o;\begin{cases}\theta_{vsc}>10^o;\ \theta_{vsn}>110^o & \text{for } \eta'\to\gamma\rho^o\\ \theta_{vsc}>5^o;\ \theta_{vsn}>30^o & \text{for } \eta'\to\pi^+\pi^-\eta\end{cases}}$$

after careful study using MC data. For convenience, defines "dir-vs" as the direction from vertex to the hitting-position of 1st layer in BSC, and "dir-dv" as the cluster's developing direction in BSC. Where N_{scht} is the number of hits in BSC, and N_{scl} is the number of layers hit in BSC, $\Delta\theta$ the angle between "dir-dv" and "dir-vs" of a gamma, θ_{vsc} the angle between "dir-vs" of gamma and that of charged tracks, θ_{vsn} the angle between "dir-vs" of gammas. See figure 1 and figure 2. Where figure 1-a is the distribution of θ_{vsc} in MC sample of $\gamma\eta'(\to\gamma\rho^o)$, and figure 1-b refers to $\gamma\eta'(\to\pi^+\pi^-\eta)$. Figure 2-a is the distribution of θ_{vsn} in MC sample of $\gamma\eta'(\to\gamma\rho^o)$, and figure 2-b refers to $\gamma\eta'(\to\pi^+\pi^-\eta)$.

Then impose on the following cuts shared by both cases:

- $Nchrg=2;\ Nneu=2\sim10;\ \sum Q_i=0$

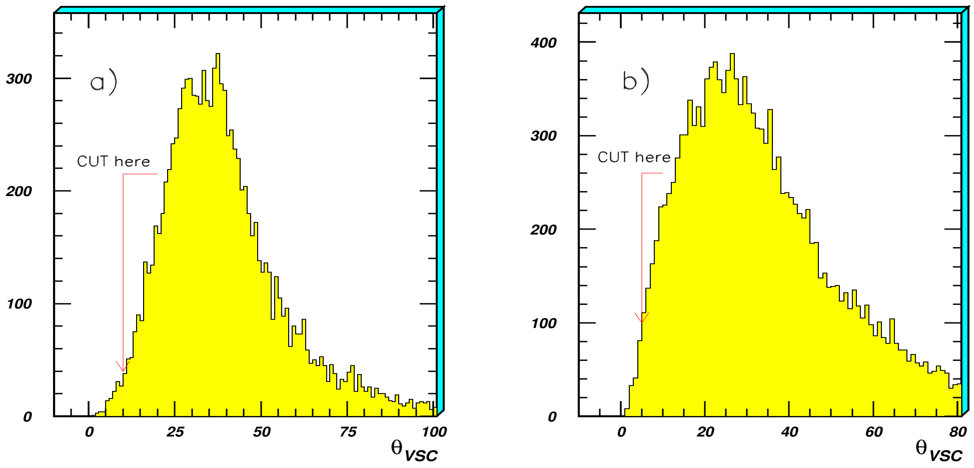

Figure 1: Distribution of θ_{vsc} in $\gamma\eta'$, figure-a for $\gamma\eta'(\rightarrow\gamma\rho^o)$, figure-b for $\gamma\eta'(\rightarrow\pi^+\pi^-\eta)$

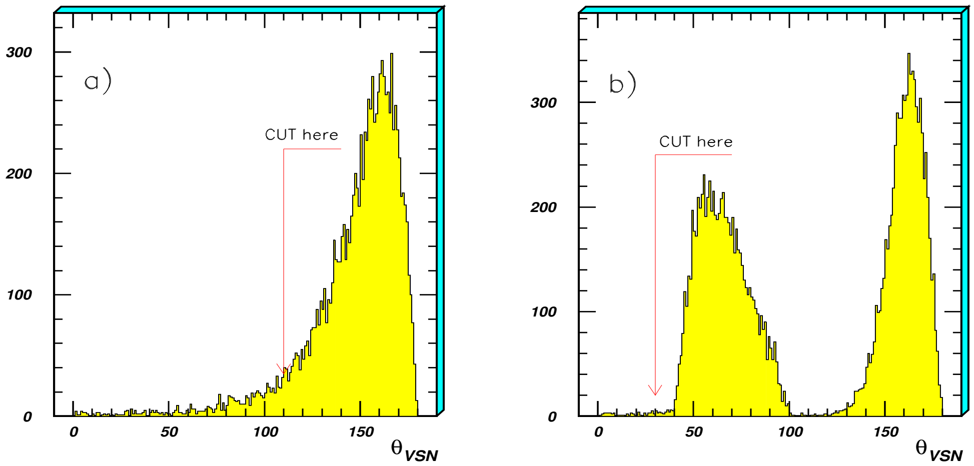

Figure 2: Distribution of θ_{vsn} in $\gamma\eta'$, figure-a for $\gamma\eta'(\rightarrow\gamma\rho^o)$, figure-b for $\gamma\eta'(\rightarrow\pi^+\pi^-\eta)$

- Vertex: $R_{xy} < 10mm$; $|z| < 15cm$; $|z_1 - z_2| < 6cm$
- Mfit $= 2$, $p_{xy} > 80MeV$, $|\cos\theta| < 0.8$

2.1 Selection of $\gamma\eta'(\rightarrow\gamma\rho^o)$

As for $\gamma\eta'(\rightarrow\gamma\rho^o)$ process, then specifically require further:

- $\theta_{acol} > 50^o$, it is the acollinear angle between two charged tracks. See figure 3-a for the distribution of θ_{acol} in the corresponding MC sample.

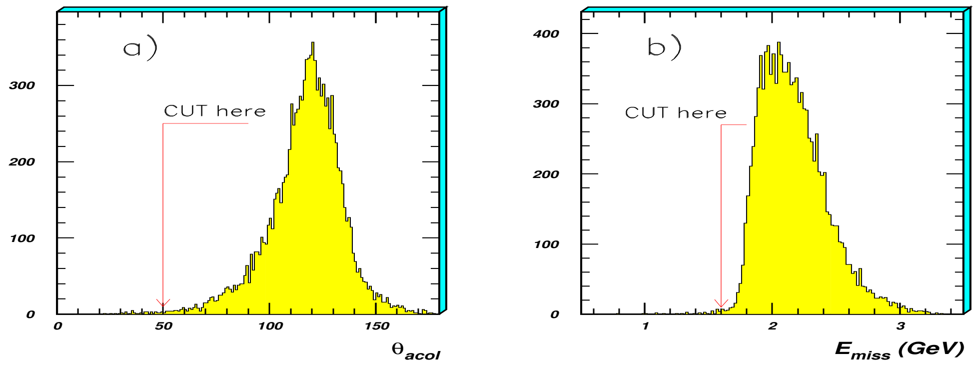

Figure 3: Distribution of θ_{acol} and E_{mis} in $\gamma\eta'(\rightarrow\gamma\rho^o)$, figure-a refers to θ_{acol}, figure-b refers to E_{mis}

- $E_{mis} > 1.6GeV$, where $E_{mis} = Ecm - E_1 - E_2$, E_1 and E_2 are the energies of two charged tracks under the hypothesis of $\pi^{\pm}$. See figure 3 - b for the distribution of E_{mis} in MC sample.
- $N_{good-\gamma} = 2 .or. 3$ $Enunk < 0.2GeV$, $N_{good-\gamma}$ is the number of good-gamma defined above, and $Enunk$ is the total energy of other gammas excluding those feeding into the kinematic fit.
- Kinematic 4C-fit with $\chi^2 < 15$
- $XSE_1 + XSE_2 < -2$, to remove the background from $ee(\gamma's)$.
- $0.40GeV/c^2 < m_{\pi^+\pi^-} < 0.90GeV/c^2$. See figure 4 for the distribution of $m_{\pi^+\pi^-}$ in MC sample.

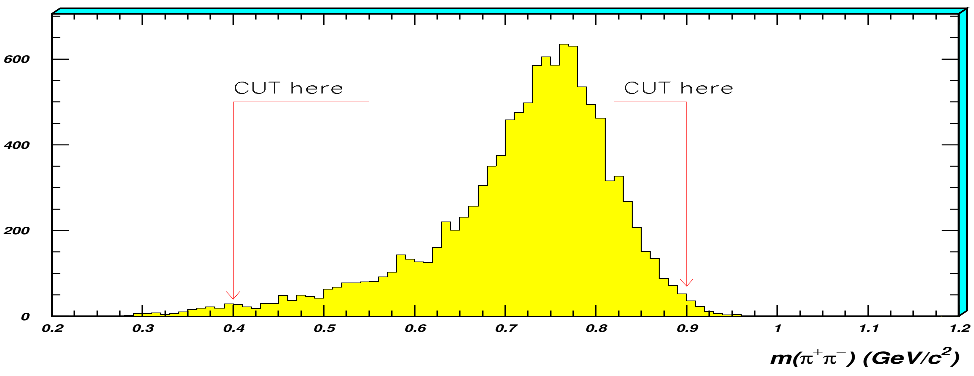

Figure 4: Distribution of $m_{\pi^+\pi^-}$ in $\gamma\eta'(\rightarrow\gamma\rho^o)$

After the cuts above, we make a combination of $2\pi^\pm$ and the gamma closer to $\pi^\pm$, and calculate their invariant mass $m_{\pi^+\pi^-\gamma_1}$ whose distribution is in figure 5-a. An obvious peak can be seen around the position of mass of $\eta'(958)$. Figure 5-b is a scatter plot of $m_{\pi^+\pi^-\gamma_1}$ versus $m_{\pi^+\pi^-}$, and figure 5-

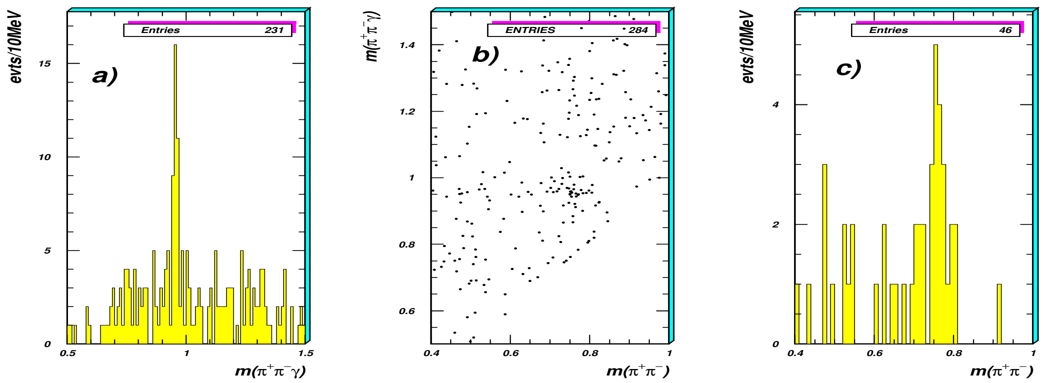

Figure 5: Some distributions for $\gamma\eta'(\rightarrow\ \gamma\rho^o)$ in $\psi(2S)$ data, figure-a for $m_{\pi^+\pi^-\gamma_1}$, figure-b for the scatter plot of $m_{\pi^+\pi^-\gamma_1}$ versus $m_{\pi^+\pi^-}$, and figure-c for $m_{\pi^+\pi^-}$

c for the plot of $m_{\pi^+\pi^-}$ after requiring $|m_{\pi^+\pi^-\gamma_1} - 0.958| < 0.05GeV/c^2$ in which the signal of ρ^0 can also be found.

With a function of the Breit-Wigner shape and the polynomial, the Breit-Wigner fit yields $N_{evts} = 30.1\pm6.2$, $M = 956.0\pm1.8MeV$, $\sigma_m = 7.2\pm1.5MeV$ with the width of η' fixed at $0.201MeV$ and resolution free, see figure 6-a.

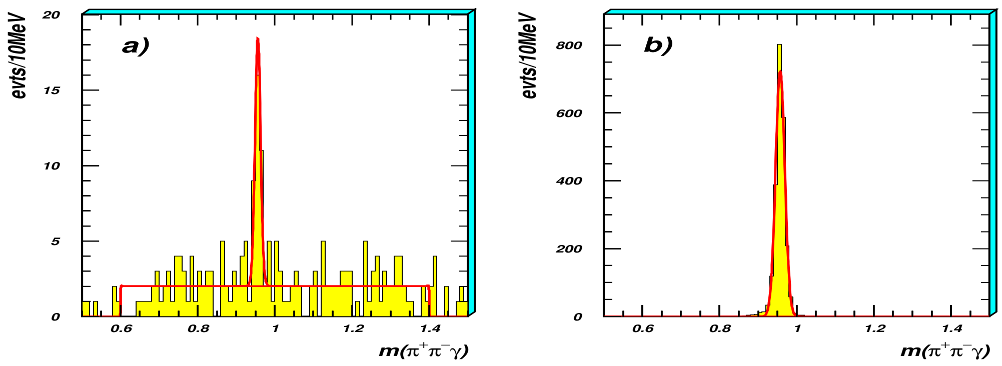

Figure 6: Fitting with $m_{\pi^+\pi^-\gamma_1}$ in $\gamma\eta'(\rightarrow\gamma\rho^o)$, figure-a refers to data, figure-b refers to MC

And figure 6-b is the distribution for MC sample.

2.2 Selection of $\gamma\eta'(\rightarrow\pi^+\pi^-\eta)$

As for $\gamma\eta'(\rightarrow\pi^+\pi^-\eta)$ process, then specifically require:

- $\theta_{acol} > 110^o$, see figure 7-a for its distribution in $\gamma\eta'(\rightarrow\pi^+\pi^-\eta)$ (Monte Carlo study).

- $E_{mis} > 2.5GeV$, see figure 7-b for its distribution in $\gamma\eta'(\rightarrow\pi^+\pi^-\eta)$ (Monte Carlo study).

- $N_{good-\gamma} = 3\,.or.\,4$; $Enunk < 0.2GeV$.

- $\chi^2_{4C} < 15$ for the kinematic fit.

- $m_{\pi^+\pi^-} < 0.42GeV/c^2$, see figure 8-a for its distribution in MC sample.

- $|m_{2\gamma_1} - 0.5475| < 0.05GeV/c^2$, where $2\gamma_1$ are 2 out of 3 gammas closer to $\pi^\pm$. See figure 8-b for its distribution in MC sample.

After the cuts above, we combine two gammas out of three closer to $\pi^\pm$, noted as $2\gamma_1$, to calculate the invariant mass $m_{2\gamma_1}$, and unite them further with $2\pi^\pm$ to obtain the invariant mass $m_{\pi^+\pi^-2\gamma_1}$. The distribution of $m_{\pi^+\pi^-2\gamma_1}$ is in the figure 9-a in which signal of η' can be seen almost free from background. Figure 9-b is a scatter plot of $m_{\pi^+\pi^-2\gamma_1}$ versus $m_{2\gamma_1}$, and figure 9-c for the plot of $m_{2\gamma_1}$ after requiring $|m_{\pi^+\pi^-\gamma_1} - 0.958| < 0.05GeV/c^2$

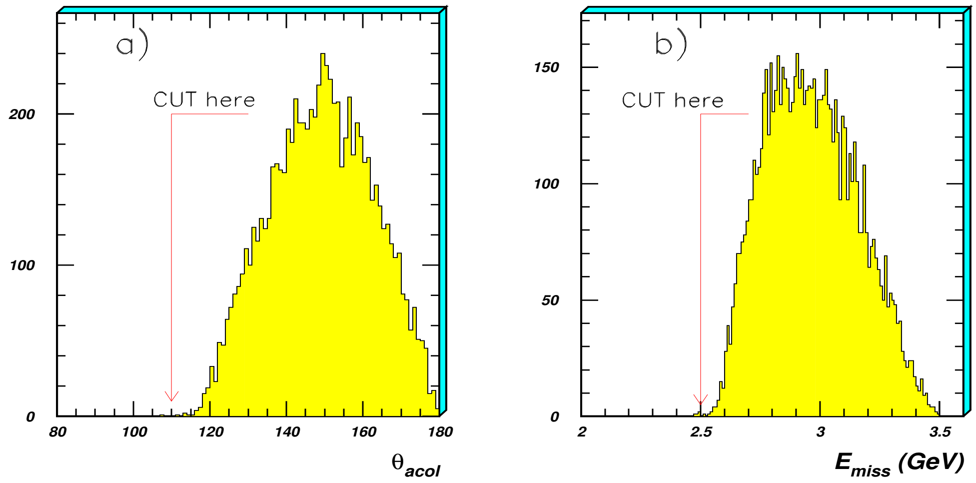

Figure 7: Distribution of θ_{acol} and E_{mis} in $\gamma\eta'(\to\pi^+\pi^-\eta)$, figure-a for θ_{acol}, figure-b for E_{mis}

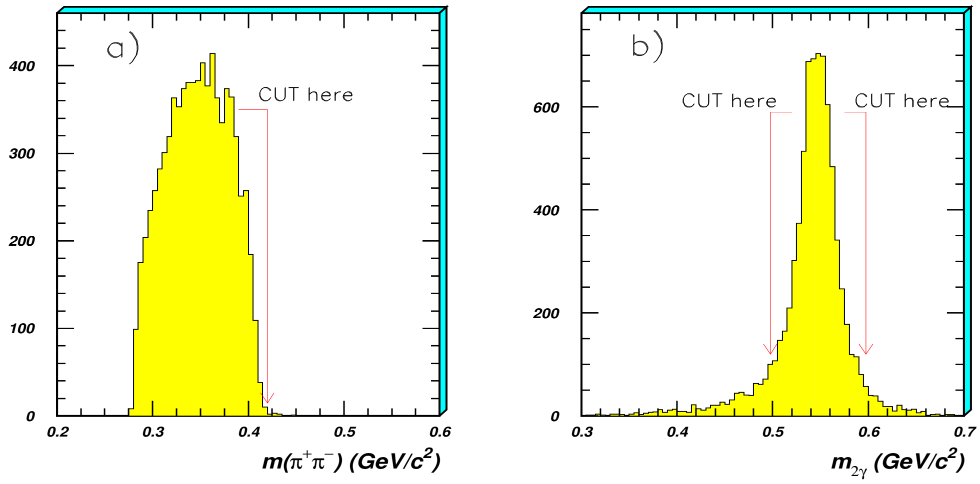

Figure 8: Distribution of $m_{\pi^+\pi^-}$ and $m_{2\gamma_1}$ in $\gamma\eta'(\to\pi^+\pi^-\eta)$, figure-a for $m_{\pi^+\pi^-}$, figure-b for $m_{2\gamma_1}$

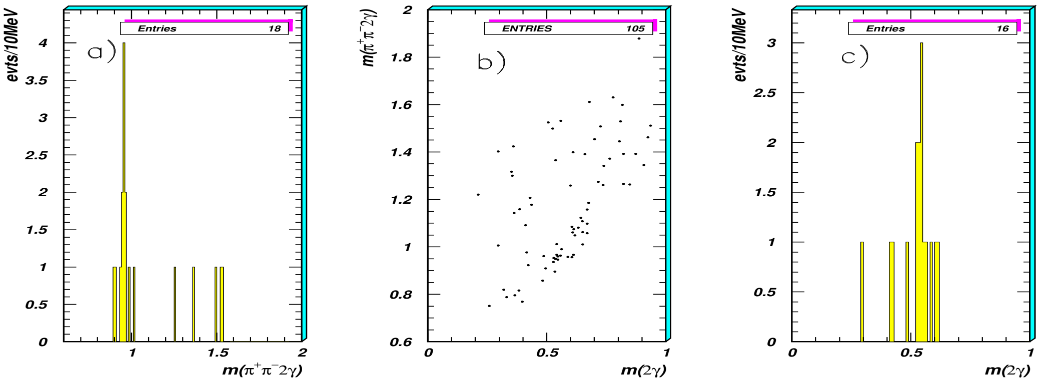

Figure 9: Some distributions for $\gamma\eta'(\to\pi^+\pi^-\eta)$ in $\psi(2S)$ data, figure-a for $m_{\pi^+\pi^-2\gamma_1}$, figure-b for scatter plot of $m_{\pi^+\pi^-2\gamma_1}$ versus $m_{2\gamma_1}$, figure-c for $m_{2\gamma_1}$

in which a heap of events at $\eta(548)$ can be seen. Since the statistics is so low, an alternative method instead of BW-fit is applied here. That is, count the events in the window of $|m_{\pi^+\pi^-2\gamma_1}-0.958|<0.03$ in the central band of $|m_{2\gamma_1}-0.5475|<0.05$, then subtract from it the events in the sidebands of $m_{2\gamma_1}$. The residual number is 7.5 ± 3.4.

3 Background study

Backgrounds from $\psi(2S)\to anything+J/\psi$ while $J/\psi\to\gamma\eta',\rho\pi$ are studied with samples equivalent to 10 times of $\psi(2S)$ data. See figure 10 for the decay chain of $\gamma\eta'(\to\gamma\rho^o)$, and see figure 11 for $\gamma\eta'(\to\pi^+\pi^-\eta)$. The background in $\gamma\eta'(\to\gamma\rho^o)$ is estimated as 1.4 ± 0.50 while 0.35 ± 0.30 in $\gamma\eta'(\to\pi^+\pi^-\eta)$. The background will be subtracted in the signal number obtained above.

4 Determination of $\mathcal{B}(\psi(2S)\to\gamma\eta')$

4.1 Acceptance for the process $\gamma\eta'(\to\gamma\rho^o)$

To determine the acceptance, two samples of 10000 simulated Monte Carlo events, corresponding to $\psi(2S)$ data of 93+94 and 95 each, are used with a angular distribution $1+\cos^2\theta$ for $\psi(2S)\to\gamma\eta'$ and $\sin^2\theta$ for $\rho\to\pi^+\pi^-$. The acceptance is given as 22.1%. The resolution given by the MC sample is $12.0MeV$ using the Breit-Wigner-shape fit.

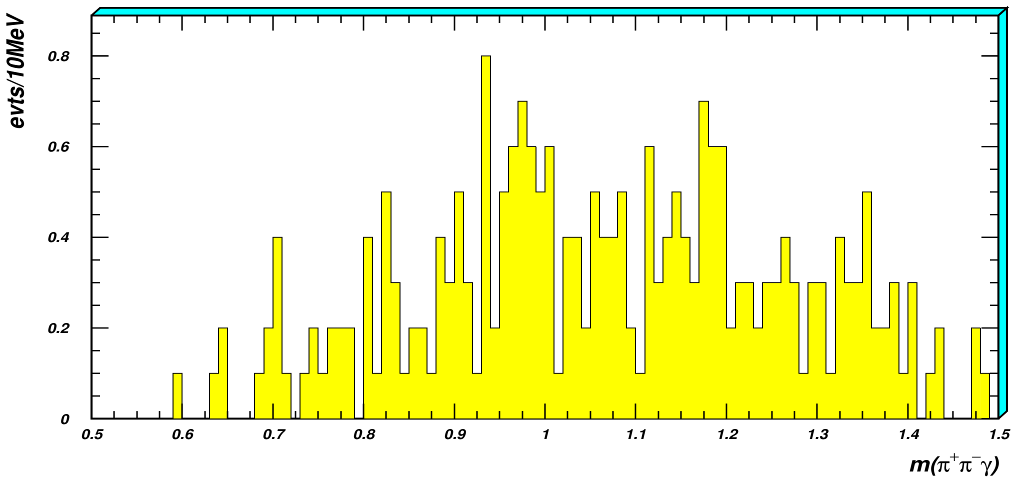

Figure 10: Background in $\gamma\eta'(\to\gamma\rho^o)$

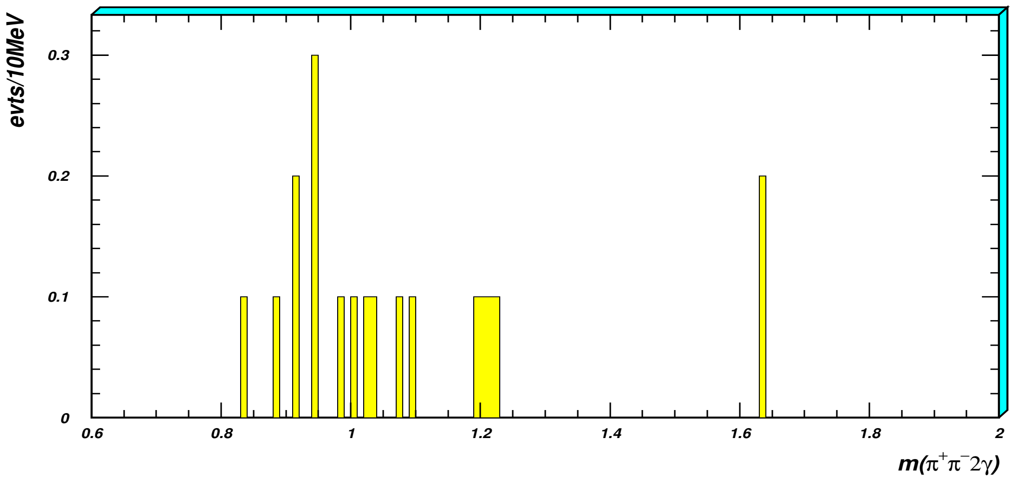

Figure 11: Background in $\gamma\eta'(\to\pi^+\pi^-\eta)$

4.2 Result from process of $\gamma\eta'(\rightarrow\gamma\rho^o)$

With the event number $N_{evts} = 30.1 \pm 6.2$, $N_{bkg} = 1.40 \pm 0.50$, $\mathcal{B}(\eta' \rightarrow \gamma\rho^o) = 0.302 \pm 0.013$, $\varepsilon_{acc} = 22.1\%$ and $N_{\psi(2S)} = (3.730 \pm 0.309) \times 10^6$, the branching fraction of $\psi(2S) \rightarrow \gamma\eta'$ via $\eta' \rightarrow \gamma\rho^o$ is got as follows:

$$\boxed{\mathcal{B}(\psi(2S) \rightarrow \gamma\eta') = (1.15 \pm 0.25 \pm 0.35) \times 10^{-4}}$$

where ± 0.25 is the statistic error, and ± 0.35 the systematic error including the uncertainty of $N_{\psi(2S)}$, $\mathcal{B}(\eta' \rightarrow \gamma\rho^o)$, background estimate, acceptance determination.

4.3 Acceptance for the process $\gamma\eta'(\rightarrow\pi^+\pi^-\eta)$

To determine the acceptance, two samples of 10000 simulated Monte Carlo events, corresponding to $\psi(2S)$ data of 93+94 and 95 each, Similarly, two samples of 10000 simulated Monte Carlo events, corresponding to $\psi(2S)$ data of 93+94 and 95 respectively, also with the angular distribution $1 + \cos^2\theta$, gives an acceptance of 15.0%.

4.4 Result from process of $\gamma\eta'(\rightarrow\pi^+\pi^-\eta)$

Again, With the event number $N_{evts} = 7.5 \pm 3.4$, $N_{bkg} = 0.35 \pm 0.30$, $\mathcal{B}(\eta' \rightarrow \pi^+\pi^-\eta) = 0.437 \pm 0.015$, $\mathcal{B}(\eta \rightarrow 2\gamma) = 0.3925 \pm 0.0031$, $\varepsilon_{acc} = 18.9\%$ and $N_{\psi'} = (3.730 \pm 0.309) \times 10^6$, the branching ratio of $\psi(2S) \rightarrow \gamma\eta'$ via $\eta' \rightarrow \pi^+\pi^-\eta$ including the systemtic error is given:

$$\boxed{\mathcal{B}(\psi(2S) \rightarrow \gamma\eta') = (7.8 \pm 3.7 \pm 2.6) \times 10^{-5}}$$

which is consitent with the result via $\eta' \rightarrow \gamma\rho^o$ within the measuring error.

5 Discussion

5.1 Comparison with J/ψ

Using the result of $\mathcal{B}(\psi(2S) \rightarrow \gamma\eta')$ via $\eta' \rightarrow \gamma\rho^o$ and the PDG96 value of $\mathcal{B}(J/\psi \rightarrow \gamma\eta')$, we find the ratio:

$$\begin{aligned} Q_{\gamma\eta'} &= \frac{\mathcal{B}(\psi(2S) \rightarrow \gamma\eta')}{\mathcal{B}(J/\psi \rightarrow \gamma\eta')} \\ &= \frac{(1.15 \pm 0.25 \pm 0.35) \times 10^{-4}}{(4.31 \pm 0.30) \times 10^{-3}} \\ &= 0.027 \pm 0.010 \end{aligned}$$

Obviously, it is also suppressed though not pronouncedly as that for $\rho\pi$ and K^*K.

5.2 Prediction and measurement of $\mathcal{B}(\psi(2S)\to\gamma\eta)$

If the equation (1) on the relation between the branching fraction of $\gamma\eta$ and $\gamma\eta'$, still holds true for $\psi(2S)$, we can predict the branching fraction on $\psi(2S)\to\gamma\eta$. Using the result above on $\psi(2S)\to\gamma\eta'$ and $\theta_p = -20^o$, we find $\mathcal{B}(\psi(2S)\to\gamma\eta) = 1.8\times 10^{-5}$.

Similarly with the selection for $\gamma\eta'(\to\pi^+\pi^-\eta)$, we choose the decay chain of $\gamma\eta(\to\pi^+\pi^-\pi^0)$ and get an acceptance of 12.0%. In the 3.73 millions of $\psi(2S)$ data accumulated by BES, 2 events is found around the mass of η, see figure 12, while the expectation is 1.8. The upper limit for 2 observed events

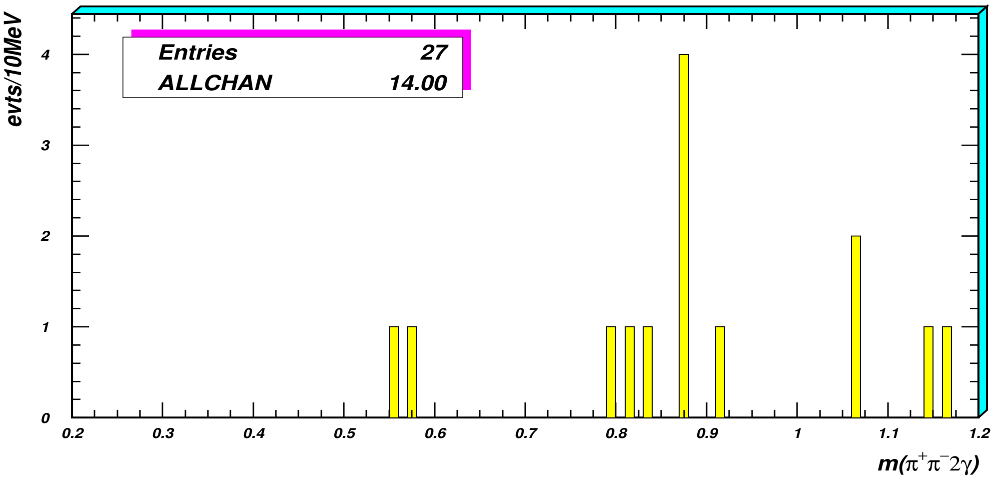

Figure 12: Background in $\gamma\eta'(\to\gamma\rho^o)$

is 5.32 at 90% confidence level. Hence, the upper limit on $\psi(2S)\to\gamma\eta$ is

$$\mathcal{B}(\psi(2S)\to\gamma\eta) < \frac{5.32}{3.73E6\times 12\%\times 0.223\times 0.988}$$
$$= 5.4\times 10^{-5}\ (90\%\ \mathrm{CL})$$

Where 0.223 is $\mathcal{B}(\eta\to\pi^+\pi^-\pi^0)$, and 0.988 for $\mathcal{B}(\pi^0\to 2\gamma)$.

The main criteria in the selection are

- $\theta_{acol} > 150^o,\quad E_{mis} > 2.0GeV,\ m_{\pi^+\pi^-} < 0.45GeV/c^2.$
- $|m_{2\gamma_1} - 0.13498| < 0.05GeV/c^2$, as a π^0.

- $N_{good-\gamma} = 3\,.or.\,4\ Enunk < 1.0GeV$. Good-$\gamma$ satisfies with

$$\boxed{N_{scht} \geq 3;\ N_{scl} \geq 2;\ \Delta\theta\ <\ 40^o; \theta_{vsc} > 5^o;\ \ \theta_{vsn} > 5^o}$$

- Kinematic 4C-fit with $\chi^2 < 15$.
- $XSE_1 + XSE_2 < -2$.

With more data of $\psi(2S)$, for example, 5 times as much as now, it is possible to give a certain branching fraction for this decay $\psi(2S) \to \gamma\eta$.

References

[1] R.M.Barnett et al., Phys. Rev. D54, 1(1996)

[2] F.Gilman and R.Kauffman, Phys. Rev. D36, 276(1987)