ψ' Decay To 5 γ Final State

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Abstract

The ψ' radiative decay to 5 γ final states via $\pi^0\pi^0$ and $\eta\eta$ have been studied. Preliminary results of the branching fractions of the χ_{c0} and χ_{c2} decay to $\pi^0\pi^0$ and $\eta\eta$ are given which are consistent with the PDG value. The branching fraction of $f_2(1270)$ decay to $\pi^0\pi^0$ is also measured which is consistent with the prediction of the "15% rule". We are doing more studying with looser cuts.

1 Motivation

In the lowest order perturvative QCD, the dominant process of the J/ψ and ψ' decay are via three gluons. If we assume that the α_s doesn't vary significantly from the J/ψ mass to ψ' mass, we then have the relation:

$$\frac{Br(\psi' \to X)}{Br(J/\psi \to X)} = \frac{Br(\psi' \to ggg)}{Br(J/\psi \to ggg)} = \frac{Br(\psi' \to l^+l^-)}{Br(J/\psi \to l^+l^-)} = (14.6 \pm 2.2)\%$$

where X is an arbitrary non-charmonium state. This is the so called "15% rule". It is generally valid for any process involving the initial annihilation of the quarks.

The Mark II collaboration found that while most of the channels follow the theoretical prediction, the ψ' decay to vector-pseudoscalar modes such as $\rho\pi$ and K^*K are severely suppressed from the "15% rule". This observation is confirmed by the BES collaboration which also found that decay to some vector-tener modes are also suppressed from the "15% rule".

It has been noticed for many years that since the partial width of a quarkonium state radiative decay with one of the above gluons replaced by a photon is given by a similar expression to the first order perturbative QCD process, the "15% rule" should hold for radiative decay modes also [1].

In this studying, we used the 3.7×10^6 ψ' events collected by the BES detector and we studied the $\psi' \to \gamma\pi^0\pi^0$ while $\pi^0\pi^0$ come from $f_2(1270)$ and χ_{c0} and χ_{c2}. The $\psi' \to \gamma\eta\eta$ with $\eta \to \gamma\gamma$ final states have also been studied.

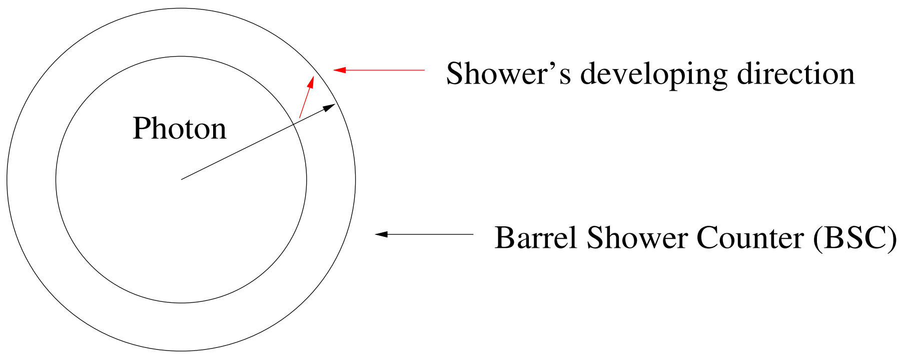

Figure 1: Angle between shower incident direction and shower developing direction.

2 General Good γ Selection

Here we briefly describe cuts we used in selecting good γ's. We start from events with no charged track and with 5 to 10 γ's. For each neutral track, we require:

- Hit at BSC and $E > 50MeV$.
- Hit more than 2 layers in BSC and more than 3 cells in BSC.
- Angle between γ incident direction and the shower's developing direction $< 60^o$ (see figure 1).

In order to remove split showers. We require that for γ_i and γ_j:

if $\theta_{ij} < 10^o$ and $E_i < \frac{E_j}{4}$	reject γ_i
else if $\theta_{ij} < 5^o$	reject both γ_i and γ_j

We require that after removing split showers, there are 5 good γ's left and

$$E_1 + E_2 + E_3 + E_4 + E_5 < 5GeV$$

We then do a 6 constraint kinematic fit over $\gamma_1\pi^0\pi^0(\gamma_1\eta\eta) \rightarrow \gamma_1\gamma_2\gamma_3\gamma_4\gamma_5$ combination that satisfy

- $E_1 > 100MeV$ for $\pi^0\pi^0$ and $\eta\eta$ modes via non-charmoniumstates or:
  $E_1 < 600MeV$ for decay via charmonium states.
- $\theta_{23} < \theta_A$ and $\theta_{45} < \theta_A$.
- At least one of the $\theta_{12}, \theta_{13}, \theta_{14}, \theta_{15} > \theta_B$.

and we select the combination with smallest χ^2 as the combining topology of $\gamma\pi^0\pi^0$ or $\gamma\eta\eta$. Cuts θ_A and θ_B vary from modes to modes and the selection of θ_A and θ_B are generally loose enough that they won't cut out many events.

A 4 constraint fit is also done with the combination and the two pairs of $\gamma\gamma$ mass are record, as shown in figure 2. We apply a cut of $|M_{\gamma\gamma} - M_{\pi^0}| < 50MeV$ and $|M_{\gamma\gamma} - M_\eta| < 40MeV$ on the figure respectly. The angle between a γ and the π^0's boost direction from which the γ decay in that π^0's rest frame, called θ_{boost} as indicated in figure 3, is also calculated for further use.

One of the potential problem in the good γ selection is the possible overlay of the two γ's from a energetic π^0. Figure 4 shows π^0's momentum distribution from $\psi' \rightarrow \gamma f_2(1270)$ and $\psi' \rightarrow \gamma\chi_{c0,2}$.

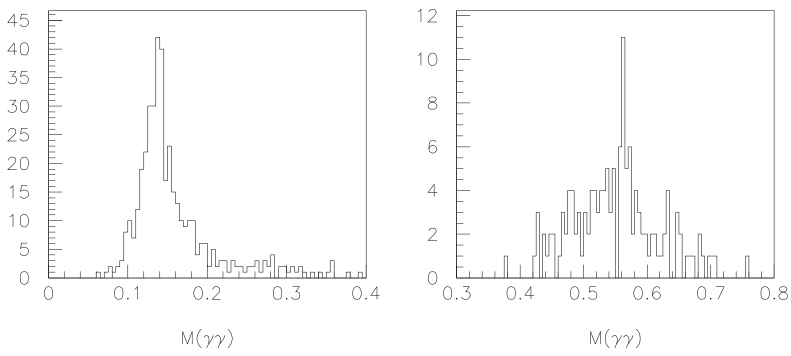

Figure 2: Mass of $\gamma\gamma$. Left: $\pi^0 \to \gamma\gamma$; Right: $\eta \to \gamma\gamma$.

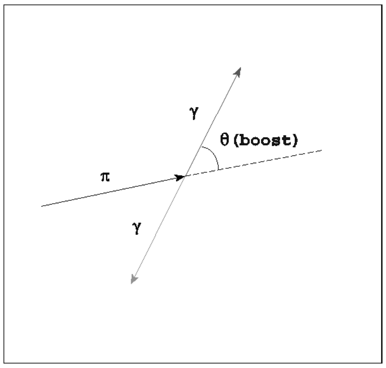

Figure 3: θ_{boost}

The maxinum momentums on both of the two plots are roughly 1.9 GeV. Since $1.9GeV \gg m_{\pi^0}$, the corresponding minimum opening angle of the two γ's from the π^0 is

$$\sim \frac{2m_{\pi^0}}{p_{\pi^0}} \cong 8.4^o$$

which has no problem to be seperated by the BSC. So the γ overlay problem can be ignored.

3 Background Studying

3.1 $\psi' \to \eta J/\psi \to \gamma\eta\eta$, $\eta' \to 5\gamma$'s

The branching ratio of these two channels are $\sim 3.53 \times 10^{-6}$ and 9.62×10^{-7} respectly. Assuming that we have $\sim 3.7 \times 10^6$ ψ' events and the maxinum detection efficiency is 17% for 5γ's events, we will end up with 2.2 and 0.6 events for these channels, which means we can safety ignored them.

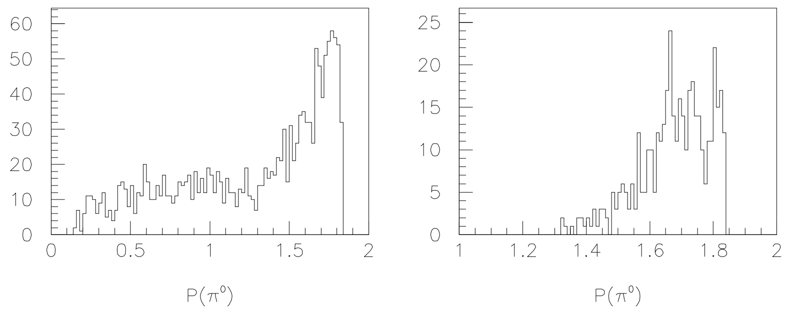

Figure 4: π^0's momentum distribution. Left: $\psi' \to \gamma f_2(1270) \to \gamma\pi^0\pi^0$ from MC data; Right: $\psi' \to \gamma\chi_{c0,2} \to \gamma\pi^0\pi^0$ from real data

3.2 $e^+e^- \to \gamma\gamma(\gamma)$

This is a pure QED process. The QED calculation shows that at $\sqrt{S} = M_{\psi'} = 3.686GeV$

$$\sigma(e^+e^- \to \gamma\gamma) = 188nb$$

The integrated luminosity for ψ' data collected by BES are

- 93/94 data set: $2.25pb^{-1}$
- 95 data set: $4.19pb^{-1}$
- total integrated luminosity: $6.44pb^{-1}$

So the number of $e^+e^- \to \gamma\gamma$ is $\sigma \times L = 1.21 \times 10^6$, compare to the $\sim 3.7 \times 10^6$ ψ' data. These energetic γ's may create split shower in BSC. So problem raises that whether this can contaminate 5γ events. This contamination may be small but we may not completely ignore it.

In order to understand the influence, we tried to select them. We select events with at least 3 good γ's and do a 4-C kinematic fit over all possible 3 γ combination and select the combination with smallest χ^2. We plot the energy of the three γ's and the sum of two out of the three, as are shown in figure 5. The angle among these three γ's are also plotted in figure 6. These plots clearly show that many of these three γ's are either back to back and have the energy equals to the beam energy, or in the the same direction and have the total energy equals the beam energy, which are split shows.

How many of these $e^+e^- \to \gamma\gamma(\gamma)$ are real $e^+e^- \to \gamma\gamma$? Let's feed these events with at least 5 good γ's to our $\gamma\pi^0\pi^0$ 6-C fit program and look at the angle between the two π^0's identified by the program. The peak in figure 7 around -1 is actually from $\psi' \to \gamma\chi_{c0,2} \to \pi^0\pi^0$ because the radiative γ is a rather soft γ and the two π^0's are almost back to back. They can pass the $e^+e^- \to \gamma\gamma(\gamma)$ selection simply because of the BSC's poor energy resolution.

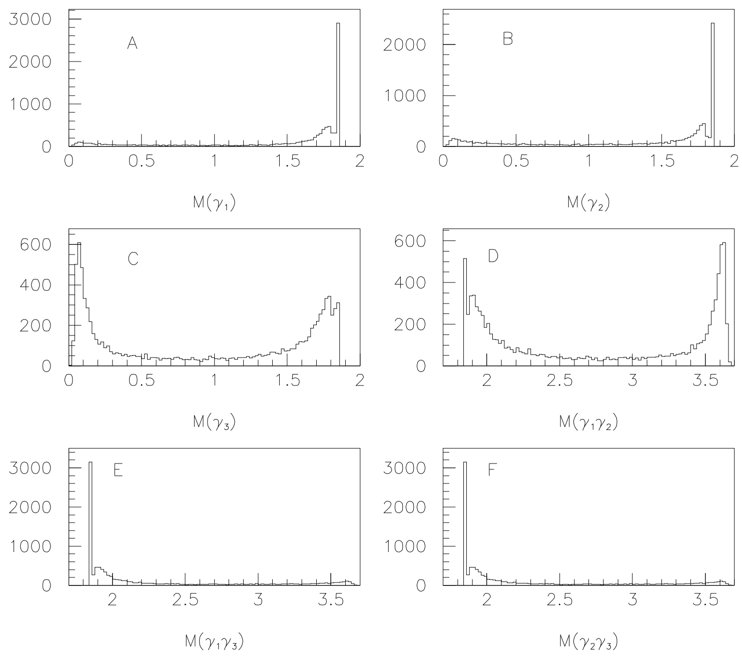

Figure 5: γ energy in $e^+e^- \to \gamma\gamma(\gamma)$.

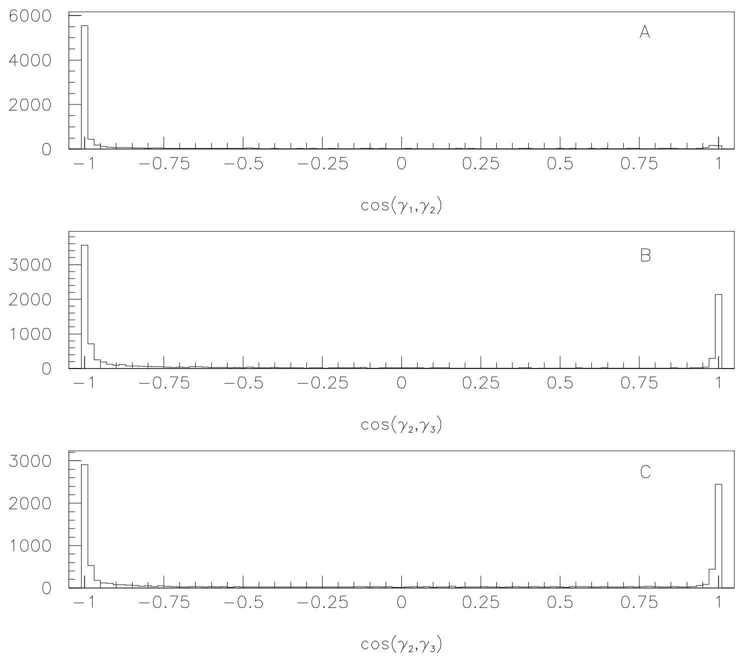

Figure 6: Angles among γ's in $e^+e^- \to \gamma\gamma(\gamma)$.

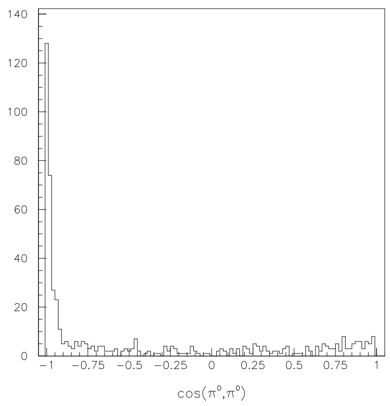

Figure 7: Angle between $\pi^0\pi^0$ from $e^+e^- \to \gamma\gamma(\gamma)$ data.

4 $\psi' \to \gamma\pi^0\pi^0$ and $\gamma\eta\eta$ via χ_{c0} and χ_{c2}

4.1 $\pi^0\pi^0$ mode

We require that $\theta_A = 60^o$, $\theta_B = 70^o$, $|cos(\theta_{boost})| < 0.97$ and χ^2 from the 6-C fit < 20. Phase space Monte Carlo gives mass resulotion of $\sigma(\chi_{c0}) = 39.7 MeV$ and $\sigma(\chi_{c2}) = 31.9 MeV$ and efficiency of $\epsilon(\chi_{c0}) = 11.9\%$ and $\epsilon(\chi_{c2}) = 9.5\%$. We fit figure 8 with two Breit-Wigners of form

$$\frac{1}{\pi}\frac{\Gamma/2}{(m-m_0)^2+\Gamma^2/4}$$

plus polynomial background function with $\Gamma_{\chi_{c0}}$, $\Gamma_{\chi_{c2}}$ and $M_{\chi_{c2}}$ fixed at PDG values, and we get

$$M_{\chi_{c0}} = (3420.4 \pm 4.4 \pm 1.3) MeV$$
$$Br(\chi_{c0} \to \pi^0\pi^0) = (3.18 \pm 0.15 \pm 0.56) \times 10^{-3}$$
$$Br(\chi_{c2} \to \pi^0\pi^0) = (1.17 \pm 0.22 \pm 0.20) \times 10^{-3}$$

These results are consistent with the PDG values.

4.2 $\eta\eta$ mode

We require that $\theta_A = 90^o$, $\theta_B = 45^o$, $|cos(\theta_{boost})| < 0.97$ and χ^2 from the 6-C fit < 10. Monte Carlo shows the efficiency $\epsilon(\chi_{c0}) = 4.8\%$ and $\epsilon(\chi_{c2}) = 4.0\%$. The mass distribution is shown in figure 9. We fit the narrow peaks with two Gauss function and polynomial background function and we obtain:

$$M_{\chi_{c0}} = (3409.8 \pm 5.7 \pm 1.6) MeV$$
$$N(\chi_{c0}) = 4.9 \pm 1.5$$
$$N(\chi_{c2}) = 3.4 \pm 1.7$$
$$Br(\chi_{c0} \to \eta\eta) = (2.08 \pm 0.62 \pm 0.54) \times 10^{-3}$$
$$Br(\chi_{c0} \to \eta\eta) < 3.5 \times 10^{-3} \ \ (90\% \ C.L.)$$

These results are also consistent with the PDG values.

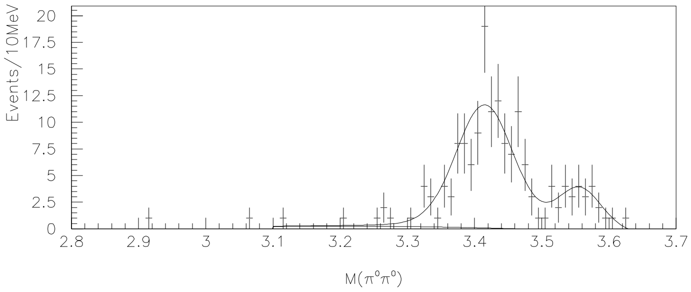

Figure 8: Mass of $\pi^0\pi^0$ at high mass region

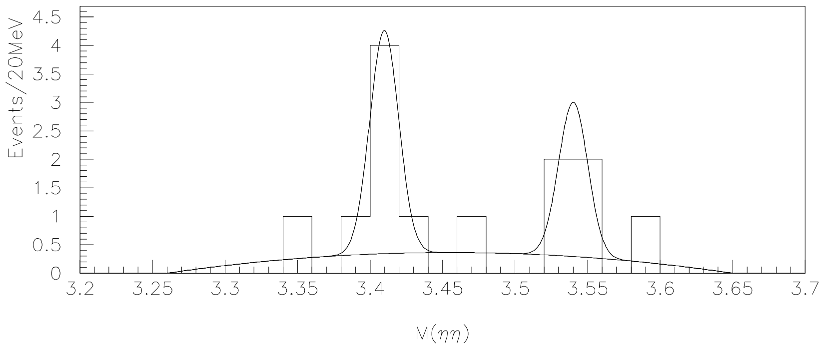

Figure 9: Mass of $\eta\eta$ at high mass region

Table 1: # of events survive various cuts

Cuts	**Data**	**MC**
# of events come in	11725	42915
Surviving $e^+e^- \to \gamma\gamma(\gamma)$ cut	9217	41524
$Q_i = 0$; 5 $\leq$# of γ's$\leq$ 7	3971	18229
Good γ selection	2469	8407
Kinematic fit	769	6569
$\|M_{\gamma\gamma} - M_{\pi^0}\| < 50MeV$	224	5482
6-C fit $chi^2 < 20$	198	5240
$M_{\pi^0\pi^0} < 3GeV$	120	5123
$E_{extra-\gamma} < 100MeV$	73	4906

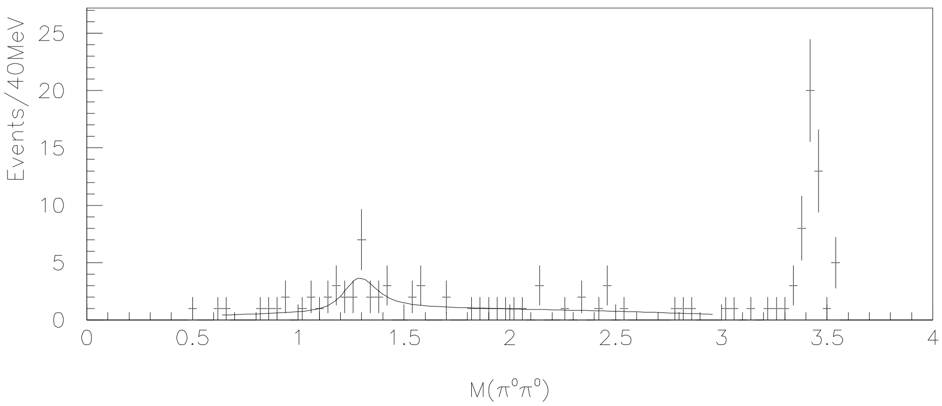

Figure 10: Mass of $\pi^0\pi^0$ at low mass region

5 $\psi' \to \gamma\pi^0\pi^0$ and $\gamma\eta\eta$ via non-charmonium mesons

5.1 $\pi^0\pi^0$ mode

For this mode, we require $\theta_A = 90^o$ and $\theta_B = 90^o$. The rest cuts are identical with cuts used in $\chi_{c0,2} \to \pi^0\pi^0$ studying. Table 1 list number of events survive major cuts with both real data and Monte Carlo data. Note that the ration of number of event surviving the 4th cut and the number of events events comming in in Monte Carlo is almost equals to our previous estimation of the detector's efficiency to detect 5 γ's. Figure 10 shows the $\pi^0\pi^0$ signal.

The $f_2(1270)$ signal is rather broad. We use the following function to fit the mass plot[2].

$$\frac{d\sigma}{dm^2} = C|T|^2 \frac{P}{m_{\psi'}} \frac{Q}{m} \tag{1}$$

where:

- P is the momentum of the $\pi^0\pi^0$.
- Q is the momentum of π^0 in $\pi^0\pi^0$'s rest frame.
- T is the invariant amplitude describing the production and decay of $f_2(1270)$.
- C is a constant.

If we think that T has form

$$T = \frac{Q^l}{BW_{prop}}$$

and $BW_{prop} = m_0^2 - m^2 - i \times m_0 \times \Gamma_{total}(E)$, where l is the spin of the resonant which is 2 here for $f_2(1270)$ ($J^{PC} = 2^{++}$). $\Gamma_{total}(E)$ is the energy dependent width.

Consider that $f_2(1270) \to \pi^0\pi^0$ and $K\overline{K}$ has 90% of its total decay branching ratio, we can make an approximation on $\Gamma_{total}(E)$

$$\Gamma_{total}(E) = \Gamma_0 \frac{m_0}{m} \frac{Br(f_2 \to \pi^0\pi^0)[\frac{Q_\pi(m)}{Q_\pi(m_0)}]^{2l+1} + \theta Br(f_2 \to K\overline{K})[\frac{Q_K(m)}{Q_K(m_0)}]^{2l+1}}{Br(f_2 \to \pi^0\pi^0) + Br(f_2 \to K\overline{K})} \tag{2}$$

$$\theta = \theta(m - (m_K + m_{\overline{K}}))$$

Γ_0 is the width of $f_2(1270)$ on PDG. By putting Eq. 2 and the expression of BW_{prop} and T back to Eq. 1, we get a D-wave Breit-Wigner describing the mass distribution of $f_2(1270)$. It is then folded with a Gauss function that describe the mass resolution

$$f(m) = \int \frac{d\sigma}{dm'} \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(m'-m)^2}{2\sigma^2}} dm'$$

The rest of the likelihood function is a rather standard technique. We use Legendre polynomial to describe the background sharp.

$$BG(m) = \frac{1}{m_{max} - m_{min}} \sum_{i=1}^{N_{poly}} b_i p_i(x) P(m) Q(m)$$

where $p_i(x)$'s are Legendre polynomial and $b_0 = 1$ for normalization reason. m_{max} and m_{min} are fitting range and

$$x = 2\frac{m - m_{min}}{m_{max} - m_{min}} - 1; \;\; x \in [-1, 1]$$

P and Q are here in order to ensure consistency of the Lorentz invariant plase space behavior.

Summer all these togather, we have

$$prob(m) = \alpha f(m) + (1 - \alpha) BG(m)$$

where α is the ratio of events. The loarithm likelihood function we are going to maximum is

$$\ln(\mathcal{L}) = \ln(\prod_{events} prob(m)) = \sum_{i=1}^{N_{poly}} \ln(prob(m_i))$$

in which parameters to fit are σ, m_0, Γ_0, α, $b_1 \ldots b_n$.

Table 2: Systematic error estimation

Cuts	Shift from $M_{\pi^0\pi^0} = 1274.8MeV$	% change to $Br(\psi' \to \gamma f_2)$
# good γ's = $5 \to 6$	$-16.9MeV$	12.4%
$\chi^2 < 20 \to 30$	$1.9MeV$	7.5%
$\chi^2 < 30 \to 40 \to 50$	None	None
$\lvert M_{\gamma\gamma} - M_{\pi^0}\rvert < 50MeV \to 60MeV$	$-5.6MeV$	6.7%
$\lvert M_{\gamma\gamma} - M_{\pi^0}\rvert < 50MeV \to 40MeV$	$+5.3MeV$	7.1%
$Icode > 1 \to 0$	$-2.7MeV$	
# of ψ' events error	N/A	6%
Background shape change		11.3%
Total	$18.1MeV$	20.5%

A slightly modified uniform phase space Monte Carlo with the D-wave Breit-Wigner has been used to generate simulation data. It gives us $23.0MeV$ of mass resolution and 10.5% of efficiency. Fitting the data with above function gives us,

$$M_{\pi^0\pi^0} = (1274.8 \pm 39.0 \pm 18.1)MeV$$

$$Br(\psi' \to \gamma f_2) = (2.38 \pm 0.70 \pm 0.49) \times 10^{-4}$$

Comparing with the PDG value of $Br(J/\psi \to \gamma f_2) = (1.38 \pm 0.14) \times 10^{-3}$, we also have

$$Q = \frac{Br(\psi' \to \gamma f_2)}{Br(J/\psi \to \gamma f_2)} = (17.2 \pm 5.1 \pm 3.9)\%$$

where the first error is statistics and the second is systematic. Table 2 list how various cuts contribute to systematic error estimation. The mass of $f_2(1270)$ we measured is well consistent with the value on PDG.

One question is whether it is appropriate to use $e^+e^- \to \gamma\gamma(\gamma)$ cut in this mode. Figure 11 shows the $\pi^0\pi^0$ mass with and without rejecting events being regarded as $e^+e^- \to \gamma\gamma(\gamma)$. It shows that the cut effects a lot on χ_c's signal while it can clean up background a little at mass region lower than $3GeV$.

5.2 $\eta\eta$ mode

Most cuts used in this mode are the same as those used in $\chi_{c0,2} \to \eta\eta$ except that $\theta_A = 60^o$ and $\theta_B = 150^o$ are required. There are bumps at $\sim 1.4GeV$ and $1.75 \sim 1.8GeV$ in figure 12 but so far we can't claim anything from them.

6 Summary

In this studying we measured the ψ' charmonium decay and non-charmonium decay to 5γ final states. For ψ' non-charmonium radiative decay, we have:

$$M_{\pi^0\pi^0} = (1274.8 \pm 39.0 \pm 18.1)MeV$$

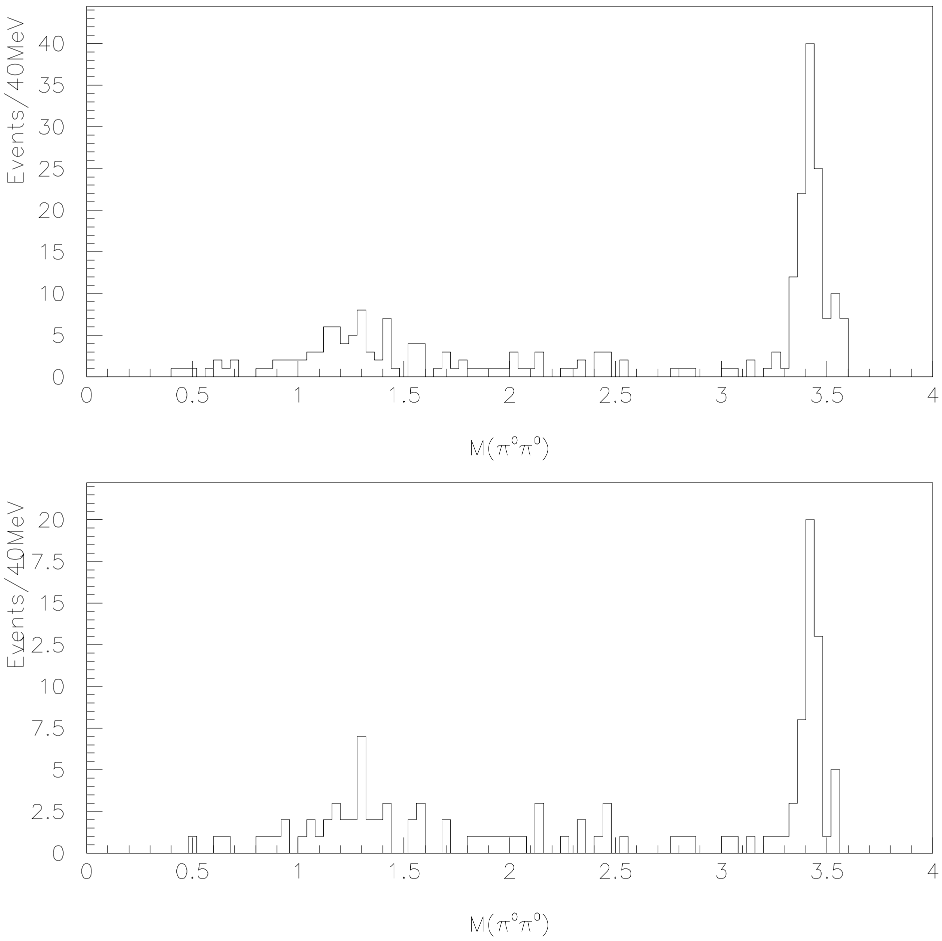

Figure 11: Up: Mass of $\pi^0\pi^0$ without $e^+e^- \to \gamma\gamma(\gamma)$ cut. Down: Mass of $\pi^0\pi^0$ with $e^+e^- \to \gamma\gamma(\gamma)$ cut.

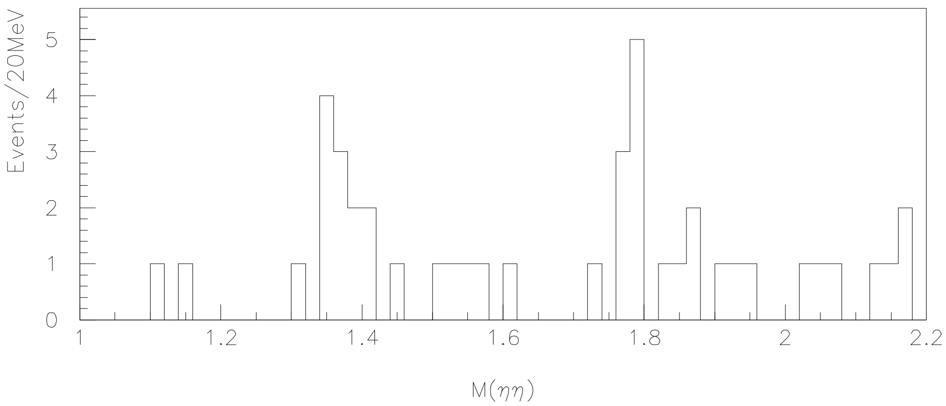

Figure 12: Mass of $\eta\eta$

$$Br(\psi' \to \gamma f_2) = (2.38 \pm 0.70 \pm 0.49) \times 10^{-4}$$
$$Q = \frac{Br(\psi' \to \gamma f_2)}{Br(J/\psi \to \gamma f_2)} = (17.2 \pm 5.1 \pm 3.9)\%$$

The PDG value of $Br(J/\psi \to \gamma f_2)$ is actually from a slightly improperly handled analysis. If we use Mark III's result $Br(J/\psi \to \gamma f_2) = (1.56 \pm 0.14) \times 10^{-3}$ [3], we then have

$$Q = \frac{Br(\psi' \to \gamma f_2)}{Br(J/\psi \to \gamma f_2)} = (15.3 \pm 4.5 \pm 3.4)\%$$

This shows that the "15% rule" hold for ψ' radiative decay to heavy meson $f_2(1270)$.

We have also obtained from this studying that:

$$Br(\chi_{c0} \to \pi^0\pi^0) = (3.18 \pm 0.15 \pm 0.56) \times 10^{-3}$$
$$Br(\chi_{c2} \to \pi^0\pi^0) = (1.17 \pm 0.22 \pm 0.20) \times 10^{-3}$$
$$Br(\chi_{c0} \to \eta\eta) = (2.08 \pm 0.62 \pm 0.54) \times 10^{-3}$$
$$Br(\chi_{c0} \to \eta\eta) < 3.5 \times 10^{-3} \;\; (90\% \; C.L.)$$

They are consistent with PDG values.

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[1] T. Appelquist, A. De Rújula, H.D. Politzer. S.L. Glashow. Phys. Rev. Lett. 3.4 (1975) 363; M. Chanowitz. Phys. Rev. D 12(1975) 918; L. Okun and M. Voloshin, ITEP-95-1976(unpublished); S.J. Brodsky, T.A. DeGrand, R.R. Horgun, D.G. Coyne, Phys. Lett. 73B (1978) 203; K. Koller and T. Walsh. Nucl. Phys. B140 (1978) 449.

[2] Private communication with Bill Dunwoodie.

[3] Bill Dunwoodie and Liangpeng Chen, SLAC-PUB 7163.