ψ' Decay To 5 γ Final State

Wei Yang
Department of Physics
Colorado State University
wyang@omega.physics.colostate.edu

January 25, 1999

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 satisfy the SU(3) flavor symmetry. The branching fraction of $\psi' \to \gamma f_2(1270)$ is also measured which is consistent with the prediction of the "15% rule".

1 Motivation

In the lowest order perturbative 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"[1]. This observation is confirmed by the BES collaboration which also found that decay to some vector-tensor modes are also suppressed from the "15% rule"[2].

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 [3].

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.

2 General Good γ Selection

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

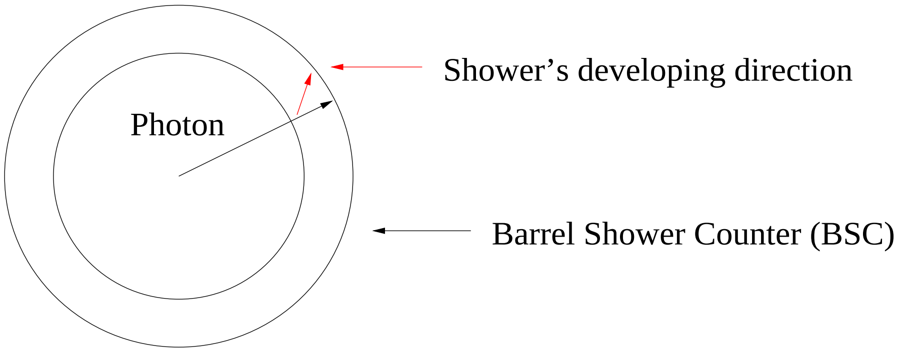

Figure 1: Angle between shower incident direction and shower developing direction.

- Hit at BSC for more than 2 layers and more than 3 cells.
- To avoid rib regions, we asked photons not hit at areas of $|z| < 4cm$ and $1.25m < |z| < 1.3m$.
- 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 $\theta_{ij} < 8^o$ and $E_j < E_i$, combine the shower energy of j into shower i and then remove shower j from the event. We require that after removing split showers, there are $5 \sim 6$ good γ's left. We then do a 6 constraint kinematic fit over $\gamma_1\pi^0\pi^0(\gamma_1\eta\eta) \rightarrow \gamma_1\gamma_2\gamma_3\gamma_4\gamma_5$. A the confidential level higher than 0.01 for the fit is imposed and the combination with smallest χ^2 is selected as the combining topology of $\gamma\pi^0\pi^0$ or $\gamma\eta\eta$. Extra photon's energy is required to be smaller than $150MeV$.

A 4 constraint fit is also done with the combination and the two pairs of $\gamma\gamma$ mass are recorded. We apply a cut of $|M_{\gamma\gamma} - M_{\pi^0}| < 70MeV$ and $|M_{\gamma\gamma} - M_\eta| < 75MeV$respectively. 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 2, are also calculated and $|cos(\theta_{boost})| < 0.99$ are imposed (see figure 3

One of the potential problem in the good γ selection is the possible overlay of the two γ's from a energetic π^0. Since the highest possible memontum of a single π^0 is less than 1.84 GeV, which is $\gg m_{\pi^0}$, 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 $\psi' \rightarrow \gamma\pi^0\pi^0$ and $\gamma\eta\eta$ via χ_{c0} and χ_{c2}

3.1 $\pi^0\pi^0$ mode

In the mode, the maximum angle for combining split showers is reduced to 5^o due to the high energy π^0 in this mode. Phase space Monte Carlo gives mass resulotion of $\sigma(\chi_{c0}) = 39.7MeV$ and $\sigma(\chi_{c2}) = 31.9MeV$ and efficiency of $\epsilon(\chi_{c0}) = 10.5\%$ and $\epsilon(\chi_{c2}) = 8.2\%$. Figure 4 shows

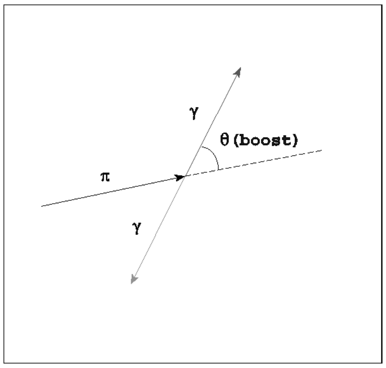

Figure 2: θ_{boost}

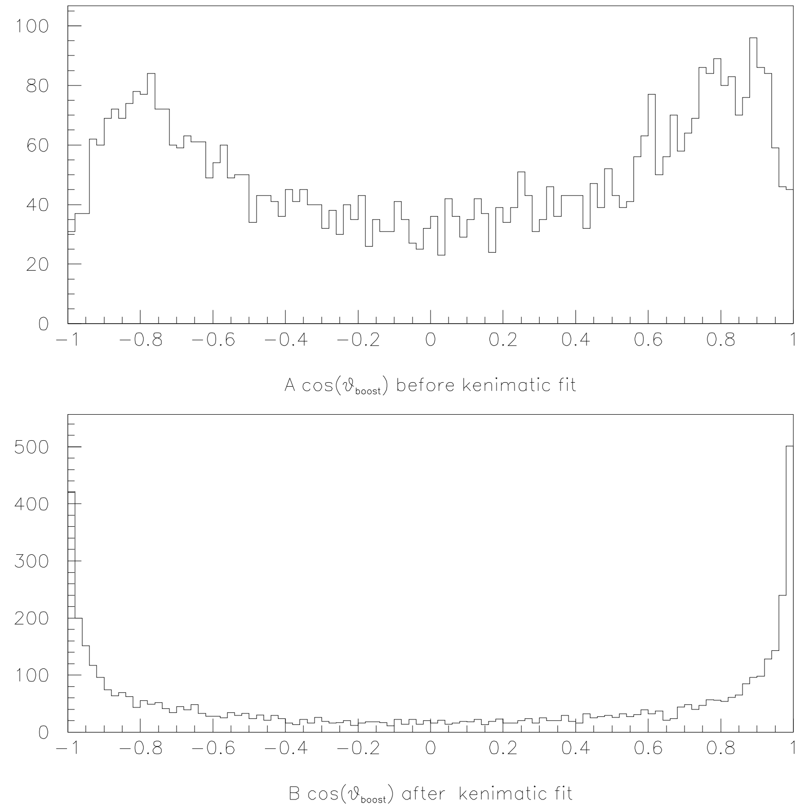

Figure 3: $cos\theta_{boost}$ distribution

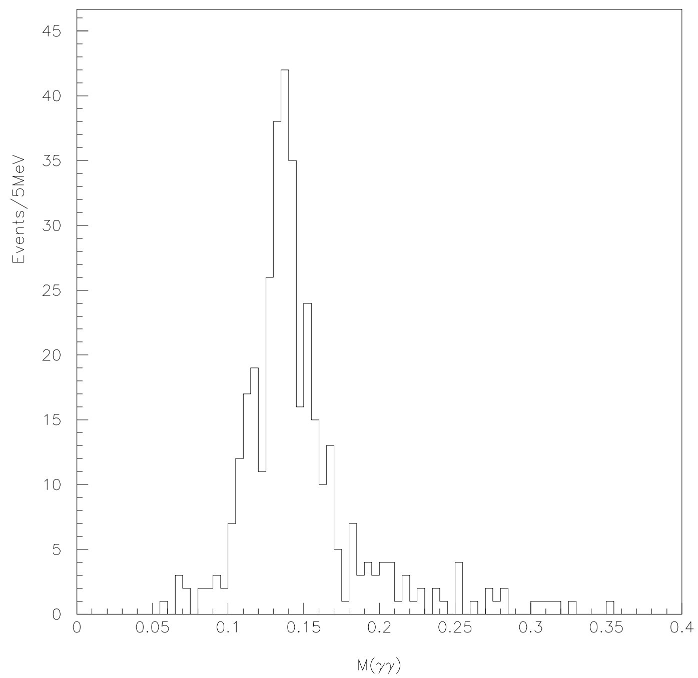

Figure 4: Mass of $\gamma\gamma$ in $\chi_c \to \pi^0\pi^0$ mode

the invariant mass of two photons. Figure 5 is the signal of χ_c's. Fitting figure 5 with two Breit-Wigners of form

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

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

$$N(\chi_{c0}) = 96.9 \pm 11.1$$

$$N(\chi_{c2}) = 20.8 \pm 5.8$$

$$Br(\chi_{c0} \to \pi^0\pi^0) = (2.80 \pm 0.32 \pm 0.51) \times 10^{-3}$$

$$Br(\chi_{c2} \to \pi^0\pi^0) = (9.2 \pm 2.7 \pm 5.2) \times 10^{-4}$$

We also imposed cuts of $|M_{\gamma\gamma} - M_{\pi^0}| < 50MeV$ and $P_{6C}(\chi^2) > 0.05$ to obtain more pure events and log out then. Other analyze on other modes won't use these events.

3.2 $\eta\eta$ mode

This mode used those cuts described in the section for good photon selection. Monte Carlo shows the efficiency $\epsilon(\chi_{c0}) = 11.9\%$ and $\epsilon(\chi_{c2}) = 10.5\%$ and the mass resolution of $\sigma(\chi_{c0}) = 43.6MeV$ and $\sigma(\chi_{c2}) = 29.2MeV$. The mass distribution is shown in figure 7. We fit the signal by using the same function we used for $\pi^0\pi^0$ mode and we obtain:

$$N(\chi_{c0}) = 12.7 \pm 5.3$$

$$N(\chi_{c2}) = 2.1 \pm 3.0$$

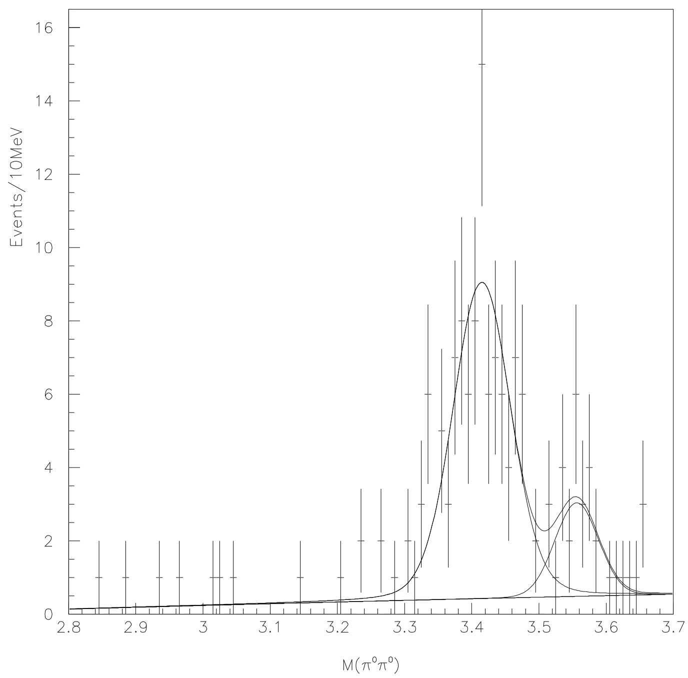

Figure 5: Mass of $\pi^0\pi^0$ at high mass region

$$Br(\chi_{c0} \to \eta\eta) = (2.03 \pm 0.84 \pm 0.58) \times 10^{-3}$$
$$Br(\chi_{c2} \to \eta\eta) < 2.5 \times 10^{-3} \quad (90\%\ C.L.)$$

4 $\psi' \to \gamma\pi^0\pi^0$ and $\gamma\eta\eta$ via non-charmonium mesons

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

For this mode, cuts are identical with cuts used in $\chi_{c0,2} \to \pi^0\pi^0$ studying except the split shower cut is reture to 8^o. 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 data is almost equals to our previous estimation of the detector's efficiency of detecting 5 γ's. Figure 9 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[4].

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

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 $f_2(1270)$.

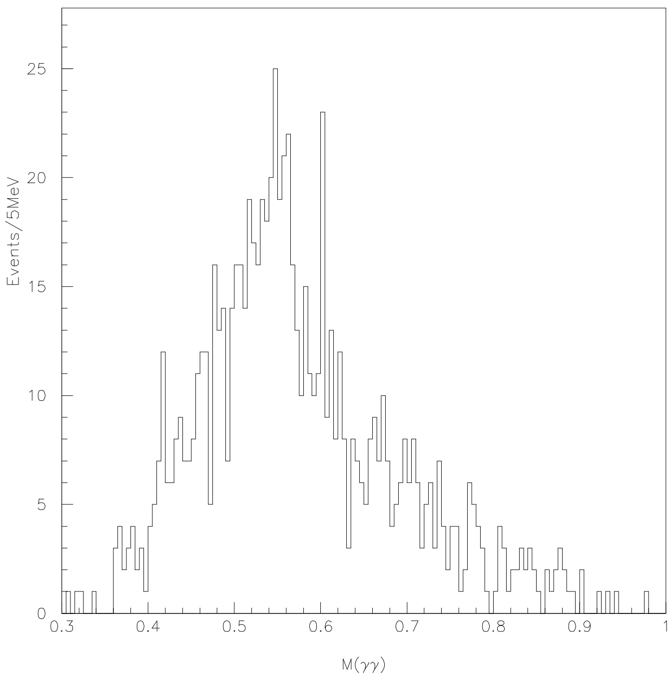

Figure 6: Mass of $\gamma\gamma$ in $\chi_c \to \eta\eta$ mode

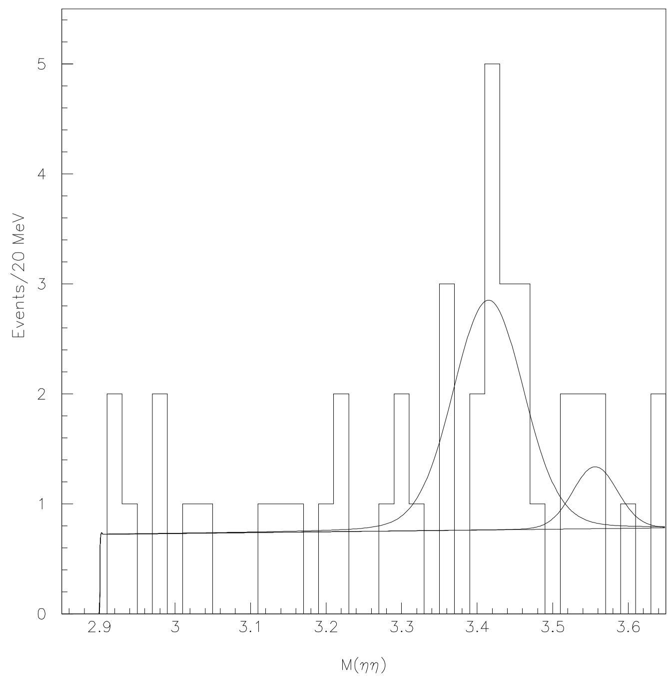

Figure 7: Mass of $\eta\eta$ at high mass region

Table 1: # of events survive various cuts

Cuts	Data	MC
# of events come in	3318477	42915
$Q_i = 0$; $5 \leq \#$ of γ's≤ 10	186455	19463
Good γ selection	38030	5500
4-C fit	5486	5210
6-C kinematic fit $P(\chi^2) > 0.01$	458	5034
$\lvert M_{\gamma\gamma} - M_{\pi^0} \rvert < 70 MeV$	266	4134
$E_{extra-\gamma} < 100 MeV$	117	4127

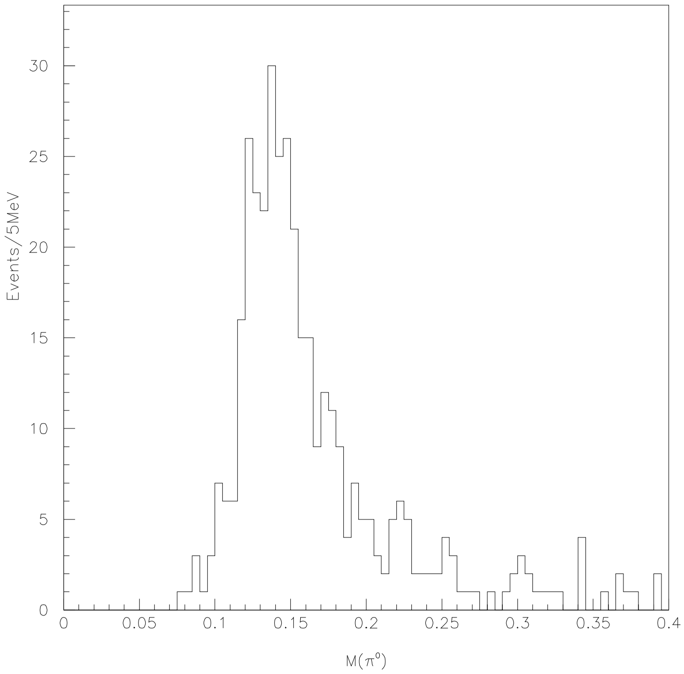

Figure 8: Mass of $\gamma\gamma$ in $f_2(1270)$ studying.

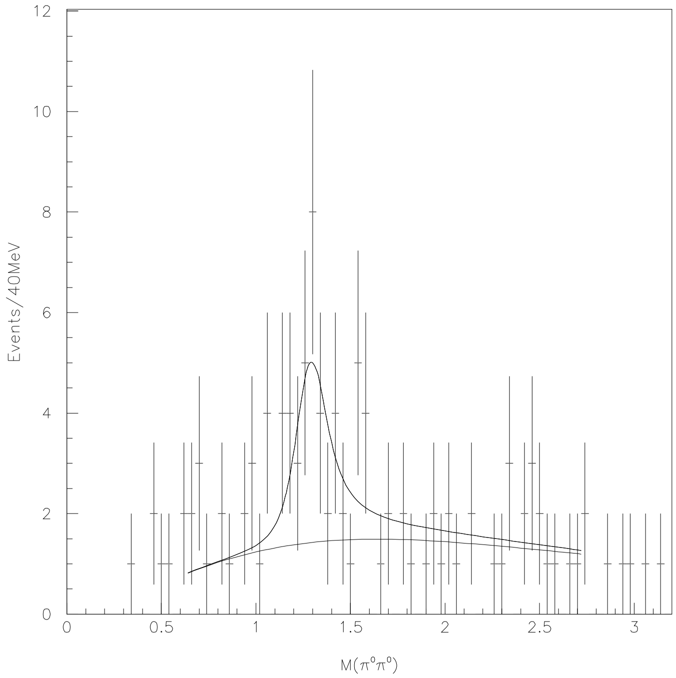

Figure 9: Mass of $\pi^0\pi^0$ at low mass region

- C is a constant.

If we think that T has form

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

and $BW_{prop} = m_0^2 - m^2 - i \times m_0 \times \Gamma_{total}(E)$, where s 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 $f_2(1270) \to \pi\pi$ and $K\overline{K}$ has 90% of its total decay branching ratio, we can make an approximation on $\Gamma_{total}(E)$

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

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

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.

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

Table 2: Systematic error estimation

Cuts	% change to $Br(\psi' \to \gamma f_2)$
# good γ's $= 6 \to 5$	2.8%
$P(\chi^2) > 0.01 \to 0.02$	3.1%
$\lvert M_{\gamma\gamma} - M_{\pi^0}\rvert < 70MeV \to 80MeV$	4.1%
$\lvert M_{\gamma\gamma} - M_{\pi^0}\rvert < 70MeV \to 60MeV$	3.0%
Extra photon energy $< 100MeV \to 150MeV$	13.0%
Remove the extra photon energy upper limit	32.8%
# of ψ' events error	6%
Background shape change	1.0%
χ_c contermination	11%
Total	35.6%

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

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

P and Q are here in order to ensure consistency of the Lorentz invariant phase space behavior. Normalization of $f(m)$ and $BG(m)$ are done numerically.

Sum all these together, we have

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

where α is the ratio of events. The logrithm 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, $b_1 \ldots b_n$.

A slightly modified uniform phase space Monte Carlo with the D-wave Breit-Wigner has been used to generate simulation data. It gives us $38.2MeV$ of mass resolution and 9.6% of efficiency. By fixing the mass and width of $f_2(1270)$ to PDG value, we have:

$$N(f_2(1270)) = 29.9 \pm 11.1$$

$$Br(\psi' \to \gamma f_2) = (3.01 \pm 1.12 \pm 1.07) \times 10^{-4}$$

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

$$Q = \frac{Br(\psi' \to \gamma f_2)}{Br(J/\psi \to \gamma f_2)} = (21.8 \pm 8.0 \pm 7.7)\%$$

where the first error is statistics and the second is systematic. Table 2 also list how various cuts contribute to systematic error estimation.

The polar angle distribution of a π^0 in the $\pi^0\pi^0$ system rest frame is showed in figure 10 alone with a curve showing the probability function describing $\psi' \to \gamma 2^{++}$ and $2^{++} \to 0^-0^-$:

$$P(cos(\theta_m) = \frac{4\pi}{3}(3cos^2\theta_m - 1)^2 + 8\pi x^2 cos^2\phi_x cos^2\theta_m sin^2\theta_m + 2\pi y^2 cos^2\phi_y sin^4\theta_m$$

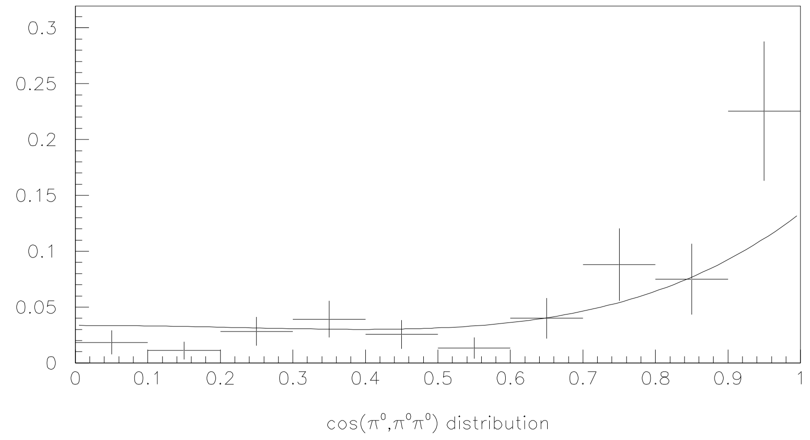

Figure 10: Polar angle of π^0 in $\pi^0\pi^0$ rest frame

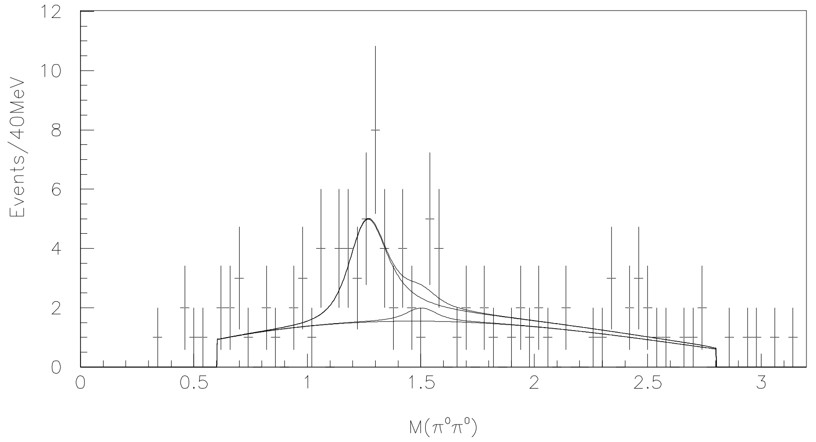

Figure 11: Fit the $\pi^0\pi^0$ mass with two peaks fixed at PDG value of $f_2(1270)$ and $f_0(1500)$

where

$$x = \frac{|A_{11}|}{|A_{10}|} = 0.88; y = \frac{|A_{21}|}{|A_{10}|} = 0.04; \phi_x = \phi_y = 0$$

are the ratio of helicities and their phase obtained from $J/\psi \to \gamma f_2(1270)$[5]

Finally we also tried to fit the small narrow peak at around $\sim 1.55GeV$ with a S-wave Breit-Wigner function with either the mass and width fixed at PDG value of $f_0(1500)$ or let them free. As showed in figure 11 and 12. They both give $Br(\psi' \to \gamma f_2) = (2.85 \pm 0.91) \times 10^{-4}$. They also give us ~ 2.4 and ~ 4.7 events underneath the peak ($1 \sim 1.6GeV$) respectively. From this we can estimate the upper limit of the branch fraction of ψ' radiative decay to X via two π^0's are 1.9×10^{-5} and 2.6×10^{-5}.

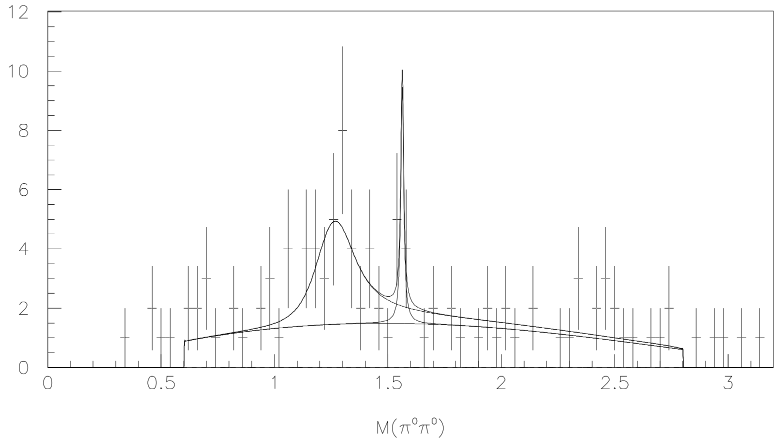

Figure 12: Fit the $\pi^0\pi^0$ mass with two peaks and the second peak's resonant parameters are free

4.2 $\eta\eta$ mode

All cuts used in this mode are the same as those used in $\chi_{c0,2} \to \eta\eta$. Figure 13 shows the $\eta\eta$ mass There are bumps below $2GeV$ in figure 13(e) but so far we can't claim anything from them.

5 Background Studying

5.1 $\psi' \to \eta J/\psi \to \gamma\eta\eta$, $\eta' \to 5\gamma$'s

The branching ratio of these two channels are $\sim 3.53\times10^{-6}$ and 9.62×10^{-7} respectly. Assuming that we have $\sim 3.7\times10^{6}$ 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.

5.2 $\chi_c \to \pi^0\pi^0$ contermination to $f_2(1270) \to \pi^0\pi^0$

Monte Carlo shows that there is around 1% of the χ_c events may be misidentified and have $\pi^0\pi^0$ invariant mass lower than $3GeV$ (figure 14), also noticed that the efficiency of selecting χ_c's is 10%, we estimate that there are $\sim$ 11 events conterminate in the $< 3GeV$ analysis, which further contribute $\sim$ 3.3 events, or 11% in $f_2(1270)$ signal. They have been enlisted in table 2.

6 Summary

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

$$Br(\psi' \to \gamma f_2) = (3.01 \pm 1.12 \pm 1.07) \times 10^{-4}$$

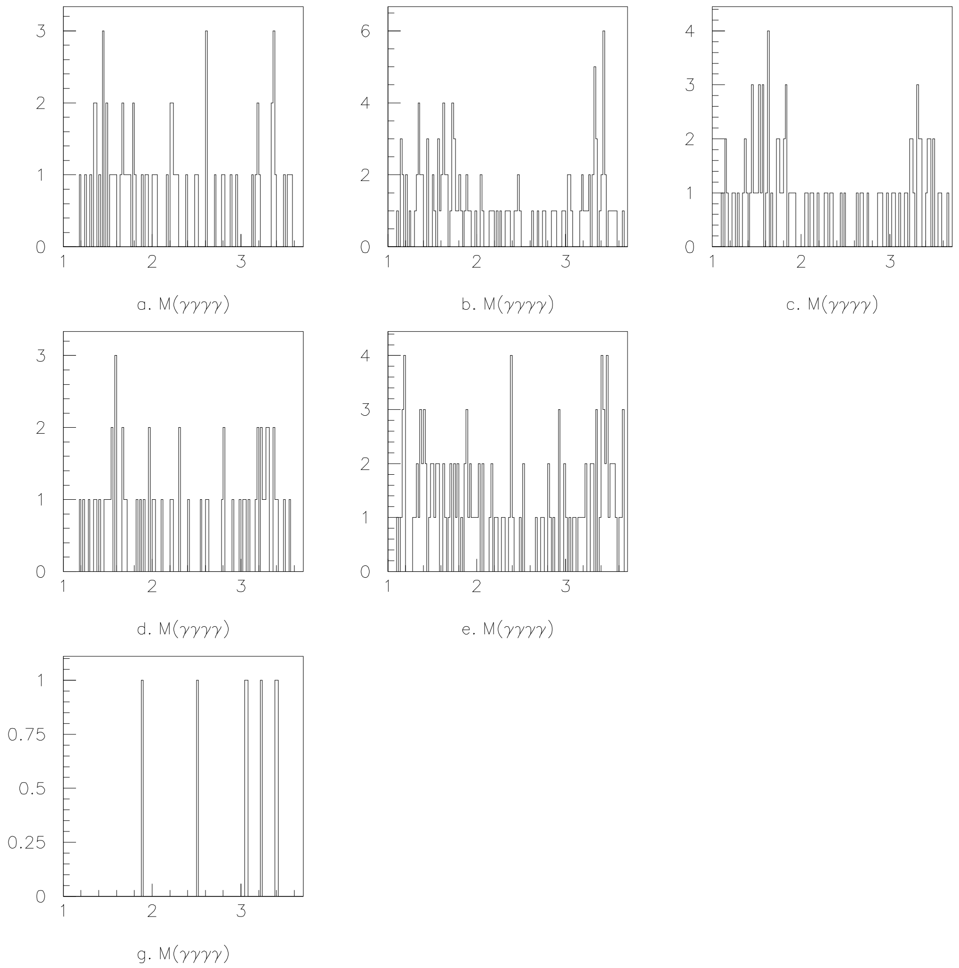

Figure 13: Mass of $\eta\eta$ a: $M_{\gamma_2\gamma_3} < 0.472MeV$ and $M_{\gamma_4\gamma_5} > 0.622MeV$; b: $0.472MeV < M_{\gamma_2\gamma_3} < 0.622MeV$ and $M_{\gamma_4\gamma_5} > 0.622MeV$; c: $M_{\gamma_2\gamma_3} > 0.622MeV$ and $M_{\gamma_4\gamma_5} > 0.622MeV$; d: $M_{\gamma_2\gamma_3} < 0.472MeV$ and $0.472MeV < M_{\gamma_4\gamma_5} < 0.622MeV$; e: $0.472MeV < M_{\gamma_2\gamma_3} < 0.622MeV$ and $0.472MeV < M_{\gamma_4\gamma_5} < 0.622MeV$; g: $M_{\gamma_2\gamma_3} < 0.472MeV$ and $M_{\gamma_4\gamma_5} < 0.472MeV$

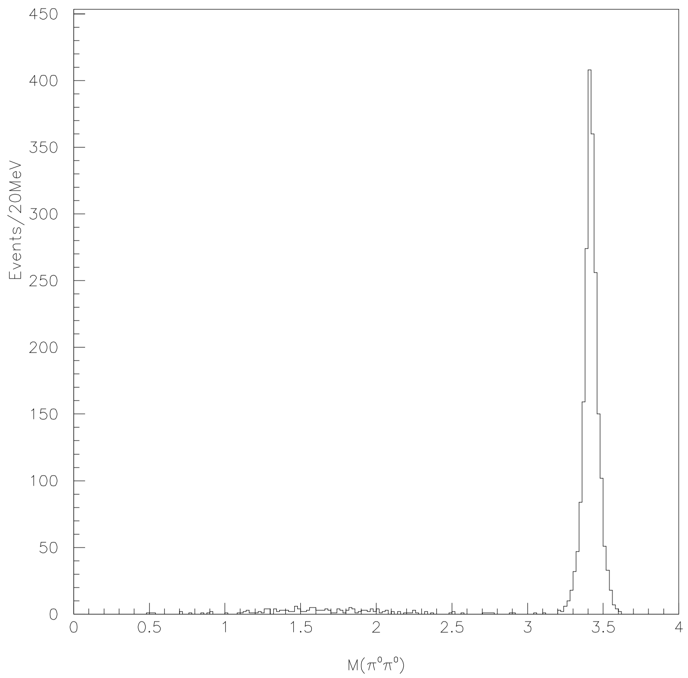

Figure 14: Feeding Monte Carlo $\chi_c \to \pi^0\pi^0$ to $f_2(1270) \to \pi^0\pi^0$ analysis program

$$Q = \frac{Br(\psi' \to \gamma f_2)}{Br(J/\psi \to \gamma f_2)} = (21.8 \pm 8.0 \pm 7.7)\%$$

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 $Br(J/\psi \to \gamma f_2) = (1.56 \pm 0.14) \times 10^{-3}$ [6], we then have

$$Q = \frac{Br(\psi' \to \gamma f_2)}{Br(J/\psi \to \gamma f_2)} = (19.8 \pm 7.3 \pm 6.9)\%$$

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:

$$Br(\chi_{c0} \to \pi^0\pi^0) = (2.80 \pm 0.32 \pm 0.51) \times 10^{-3}$$
$$Br(\chi_{c2} \to \pi^0\pi^0) = (9.2 \pm 2.7 \pm 5.2) \times 10^{-4}$$
$$Br(\chi_{c0} \to \eta\eta) = (2.03 \pm 0.84 \pm 0.56) \times 10^{-3}$$
$$Br(\chi_{c2} \to \eta\eta) < 2.5 \times 10^{-3} \quad (90\%\ C.L.)$$

Assuming the SU(3) flavor symmetry, the χ_{c0} and χ_{c2} decay to $\pi^0\pi^0$ and $\eta\eta$ should have the same branching fraction, except for a factor caused by the phase space differences and a barrier factor which is $p^{(2s+1)}$ where p is the momentum of the π^0 or η in χ's rest frame and s is the spin of χ's[7]. The theoretical prediction are 0.95 and 0.79 for χ_{c0} and χ_{c2} respectively. From the result we just archived, we have

$$\frac{Br(\chi_{c0} \to \eta\eta)}{Br(\chi_{c0} \to \pi^0\pi^0)} = 0.73 \pm 0.31 \pm 0.24$$

which approximately satisfy the prediction.

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