Radiative decays of the J/ψ meson

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I have measured the branching ratio of the decay $\psi(2S) \rightarrow \pi^+\pi^- J/\psi \rightarrow \gamma\pi^+\pi^-\pi^+\pi^-$ using data consisting of 25.9 ± 0.5 million $\psi(2S)$ events from the CLEO-c detector at LEPP during my summer REU at Cornell University. I modified a C++ program that had been designed for a reasonably similar analysis in order to perform my analysis. I used several methods to deal with the issue of π^0 ($\psi(2S) \rightarrow \pi^+\pi^- J/\psi \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0$) contamination in the signal, as well as to avoid losing as few as possible good events. The branching ratio has been measured as: $(2.64 \pm 0.02 \pm 0.14) \times 10^{-3}$.

I. INTRODUCTION

Studying radiative J/ψ events is a possible way to study gluons, as well as possibly the theorized "glueball." This particle is predicted by quantum chromodynamics (QCD), but has not been found. Radiative J/ψ decays are conducive to gluon study because the photon allows for the creation of only two gluons while maintaining quantum number conservation.

This analysis can also be compared with one performed by the BES-II collaboration [1]. Their analysis considered 58 million J/ψ events while the CLEO-c data contains only 8 million or so; however, the CLEO-c dectector is superior to the BES-II detector in terms of photon detection, which is a vital aspect of the analysis. CLEO-c is the first detector operating at relevant energies which has state-of-the-art detection of both tracks and showers.

In this analysis a C++ program is used to select signal events from the CLEO-c data. This program was created by modifiying an existing program that had been used in photon resolution studies with CLEO-c data. A variety of methods are used to weed out non-signal events. In a signal event, six pion tracks and a photon shower are detected. Energy, charge, and momentum are required to be conserved, in order to reduce backgrounds from other reactions. Vertex and 4-momentum fits are performed, and cuts made on the resulting reduced chisquare values. The program was run with loose chisquare cuts, and tighter cuts imposed afterwards by means of ntuples. The events which passed all these cuts are considered signal events. The number of signal events is then used to calculate the branching ratio according to the equation:

$$\text{Branching Ratio} = (\text{signal events observed}/(\text{efficiency} \times \psi(2\text{S}) \text{ events}) \qquad (1)$$

Efficiency is calculated using signal Monte Carlo to model the detector response. The number of $\psi(2S)$'s produced is estimated for the data used [2].

This branching ratio has been previously measured, but these measurements have had relatively high error and did not agree well among each other. These measurements yielded a branching ratio of $(2.8 \pm 0.5) \times 10^{-3}$[3].

The largest background decay that affected this analysis is: $\psi(2S) \rightarrow \pi^+\pi^- J/\psi \rightarrow \pi^+\pi^-\pi^+\pi^-\pi^0$, with the π^0 then decaying to $\gamma\gamma$. This decay occurs about four times more often than $\psi(2S) \to \pi^+\pi^- J/\psi \to \pi^+\pi^-\pi^+\pi^-\gamma$, so differentiating between the two decays is a vital part of the analysis.

II. CUTS

Every event recorded in the data set is considered by the program. In choosing only signal events (which are used to calculate the branching ratio), all nonsignal events must be discarded. Various "cuts" or criteria of signal events are used to achieve this.

I initially consider all events that contain six to eight tracks. After Trkman[6] analyzes the tracks, I reject any events that do not have exactly six tracks that have been labeled "good" and "valid" by Trkman. Charge conservation is required. Events lacking exactly one $\pi^+\pi^-$ recoil combination with recoil mass 3.097 ± 0.020 GeV are discarded.

Signal events have a photon as well as the six pion tracks. The photons are detected in the crystal calorimeter. Photons which were detected by "hot" crystals, have an energy of less than 50 MeV, or which are identified as bremsstrahlung photons are discarded. Since photons from the π^0 decay mentioned earlier form a serious background, a π^0 veto was tested for use in this analysis. Its purpose is to identify photons which were daughters of π^0 decays and to exclude them from further consideration. If more than one photon is detected, the photon whose 4-momentum most closely matches the missing 4-momentum calculated from the six pion tracks is selected.

Energy conservation is required within 300 MeV. The mass recoiling against the transition pions is required to be within 10 MeV of the J/ψ mass, 3.097 GeV [3]. The 4-pion mass is capped at a maximum value of 2.9 GeV so that the photon will have energy greater than 200 MeV, to guard against noise photons. The event then undergoes three kinematic fits. The first fit is a vertex fit which ensures that the pions originated from the same vertex. The vertex reduced chisquare values are required to be less than fifty. The second fit is a missing mass fit that calculates how close the missing mass of the event (calculated using the six pion tracks and the initial $\psi(2S)$) is to zero. If the missing mass is not zero this may indicate the presence of another particle in the decay...such as a π^0! The missing mass reduced chisquare of the missing mass fit (ChisqFit) is initially required to be less than twenty, and I have tightened this cut to ten by using the ntuples stored by the program. The third fit is a 4-momentum fit, and it calculates the overall energy-momentum conservation of the event. The reduced chisquare value from the 4-momentum fit (Chi4MFit)was initially set at twenty but has been reduced to a maximum of 5. The chisquare values were chosen to eliminate as many π^0 events (as well as any other backgrounds) and include as many signal events as possible.

All these cuts represent a best effort to choose signal events, and while they are generally successful there is of course systematic error associated with the process which is addressed in the Error section of this paper.

III. "EXTRA" TRACKS AND SHOWERS

Signal events have 6 tracks (4 pions from the J/ψ decay, plus 2 transition pions). I wanted to determine the effect of considering more than six initial tracks on the number of events that passed cuts. To do this, I first modified the program to select events that have six to eight initial tracks. I then demanded that the number of tracks which are approved by Trkman be exactly six. Trkman weeds out "curlers," low-energy tracks, and other types of unsatisfactory tracks. Of the tracks rejected by Trkman that had passed Chi4MFit < 5 and ChisqFit < 20, approximately half were curlers (as determined from the MC decay tree printouts). The other half were mostly classified as "other". My analysis of "extra" tracks shows that the number of six-track events recovered from events with 7 initial tracks is about 8.5 percent of the number of regular six-track events; the corresponding value for the events with 8 initial tracks is about 3 percent. I also looked at how many of these events with more than six initial tracks actually passed the cuts to contribute to the signal. It turns out that none of the events with seven initial tracks passed the cuts, even with loose chisquare cuts. Very few events with eight initial tracks passed cuts. These events formed 0.13 percent of the signal events. Thus, allowing more than 8 initial tracks is not likely to change the signal significantly, and allowing up to eight does have some impact on the signal, although only very slightly. The program used to measure the branching ratio does, therefore, include this selection structure for the charged particle tracks.

For events which have more than one shower, it is necessary to determine which photon is the "best;" that is, to decide which photon actually resulted from the J/ψ decay. To do this, the missing 4-momentum vector is calculated from the six pion tracks and the known information from the $\psi(2S)$ via energy and momentum conservation. The photon whose 4-momentum deviates least from this calculated vector is chosen as the best photon. To check how well this method works, I modified the program to select the second-best photon instead. No satisfactory fits resulted using the second-best photon, although only very loose chisquare cuts were used. This shows that the method of selecting the photon is satisfactory; no good events are excluded by this cut. I therefore used this method in the final calculation of the branching ratio.

IV. THE π^0 PROBLEM

The π^0 ($\psi(2S) \to \pi^+\pi^- J/\psi \to \pi^+\pi^-\pi^+\pi^-\pi^0$) events are difficult to eliminate from the signal ($\psi(2S) \to \pi^+\pi^- J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$). One of the photons resulting from $\pi^0 \to \gamma\gamma$ is often very low energy, and may either not be picked up by the detector or may be indistinguishable from noise. I have used three primary methods to reduce π^0 contamination in the signal.

The code for the "π^0 veto" explicitly excludes photons from π^0 decays. I initially ran the program without the π^0 veto, but since the MC results indicated that the chisquare fits were not as effective as desired in excluding π^0 events, the π^0 veto was reinstated (having been written into but commented out of the original program). The veto is not highly effective; when cutting at 4Mchisquare less than 5, the veto makes less than 6 percent difference in the number of Monte Carlo events which pass cuts, and less than 5 percent difference in the number of data events. I then ran the code over signal Monte Carlo while using the π^0 veto. I found that efficiency decreased more than 3 percent when the veto was used. This indicated that the π^0 veto actually cut away more signal events than π^0 events, due to the limitations of the veto process. The veto was therefore not used in the final calculation of the branching ratio.

Signal events will have a missing mass recoiling against the six pions which is equal to zero, and thus a low value for ChisqFit, the chisquare value of the missing momentum fit. If the missing mass is equal to the π^0 mass (134.98 MeV [3]) indicates a π^0 event. Since it is actually the square of the missing mass that is calculated in the fit and the π^0 mass is small in comparison to the $\psi(2S)$ or J/ψ, this chisquare value is less useful than Chi4MFit.

Cutting on Chi4MFit, the chisquare value of the 4-momentum fit requires the total momentum and energy of the event to be conserved more closely. In a π^0 event, one of the daughter photons of the π^0 is lost, resulting in a poorer 4-momentum conservation for the event. The cut on Chi4MFit is the most effective of the methods of reducing π^0 contamination. Since the π^0 may decay asymmetrically into one high-energy photon and one low-energy photon, loss of the low-energy photon may not result in significant enough 4-momentum conservation violation to be eliminated by the Chi4MFit cut. Error in measuring the photon energy is also large enough to play a role. So a stubborn background remains, but many π^0 events are identified and excluded by this cut.

V. SYSTEMATIC AND STATISTICAL ERROR

Statistical error is calculated by:

$$\text{Error } = (\text{number of events observed})^{1/2} \ / \ (\text{number of events observed}) \tag{2}$$

Since 13471 signal events were found, the statistical error is only about 0.8 percent.

There are numerous sources of systematic error in this analysis. They include uncertainty in detecting tracks and photons, error in the fitting process, and others which are buried within the code of the program and in the calculation of the branching ratio. Many of the errors have been calculated elsewhere; I calculated the error of the fitting procedure by looking at the variation in the branching ratio when each of the chisquare values is varied by one unit from their final cutting values. To do this, I averaged the change which resulted in the branching ratio when I varied the reduced chisquare cut by one unit. I used the two values I got (one for Chi4MFit and one for ChisqFit) as the error in my measurement. I added these two errors in quadrature to find the overall fitting error. See Table I for a listing of the various sources of systematic error and their corresponding percentages, as well as the sum of the errors, added in quadrature.

There is one particular source of systematic error which I did not have time to analyze during this project. Demanding only one set of transition pions which have appropriate characteristics to recoil from the J/ψ in the intermediate phase of the decay has error associated with it because it is possible that two of the pions which decay from the J/ψ may have similar properties as the transition pions themselves. Any event fitting these circumstances is still a good, signal event, but would be discarded because of this cut. I was not able to determine how often a mistake like this might occur. This is something that will need to be analyzed in the future. For now, I have left it as a question mark in the table.

VI. RESULTS

Figures 1 and 2 refer to [1], and are comparisons to similar plots shown in that paper.

In figures 3, 4 and 5, I refer to the final pion tracks as first, second, etc. The numbering convention is that track one is the higher energy positive pion, track two the higher energy negative pion, and tracks three and four are similarly the positive and negative lower energy pions. The transition pions are classified as tracks 5 and 6, for the positive and negative pions, respectively.

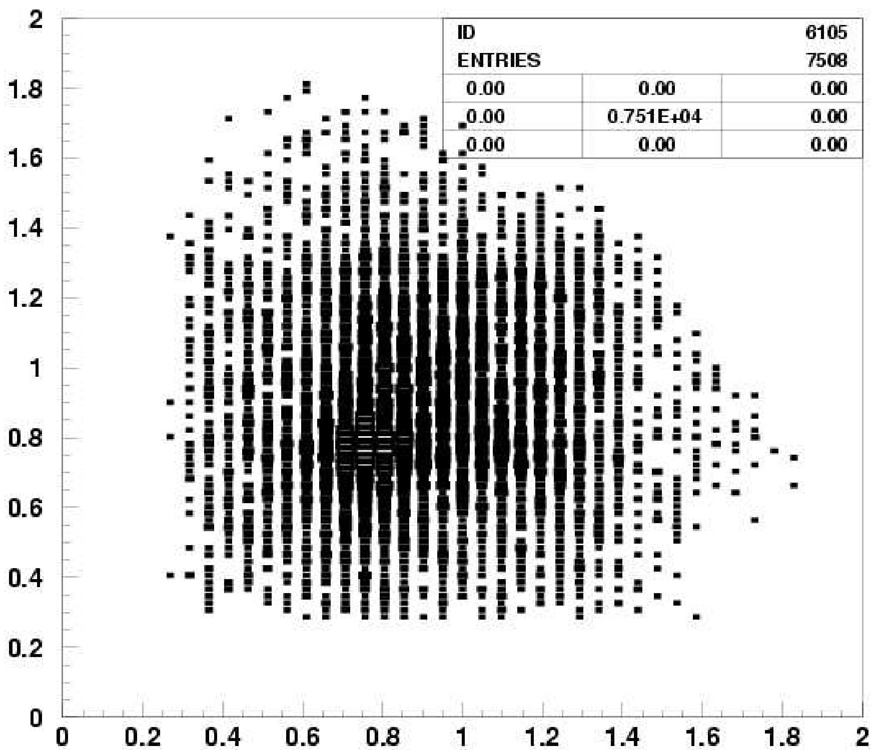

FIG. 1: 2-D histogram plotting 2-pion mass of the second and third tracks versus the 2-pion mass of the first and fourth tracks, with a cut on the 4-pion mass of 2.0 GeV or greater. Recall that the 4-pion mass is also constrained to be 2.9 GeV or less. This plot corresponds to Figure 1a in [1]. The peak seen at (0.75,0.75) is evidence for $J/\psi \to \gamma\rho^0\rho^0$ production.

TABLE I: Sources and values of systematic uncertainties

Source of error	Percent error
Fitting procedure	3.5
Photon detection	2 [4]
Track detection	1.8 [5]
Number of $\psi(2S)$	2 [2]
Branching ratio of $\psi(2S) \to \pi^+\pi^- J/\psi$	1.9 [3]
Demanding one set of transition pions	?
Total: (added in quadrature)	**5.2**

In choosing which chisquare cuts were best to impose in the code, I created many plots of efficiency (for signal Monte Carlo) and branching ratio (for generic Monte Carlo and data) versus chisquare values (both for ChisqFit and Chi4MFit). A sample plot from this process is shown in Figure 6.

I also performed a Monte Carlo analysis regarding the effectiveness of the two chisquare fits in cutting away π^0 events. I calculated the number of events that passed cuts (of varying chisquare values) whose photons were daughters of π^0's. I divided this number by the total number of events considered, and plotted this ratio versus the two chisquare values. One of

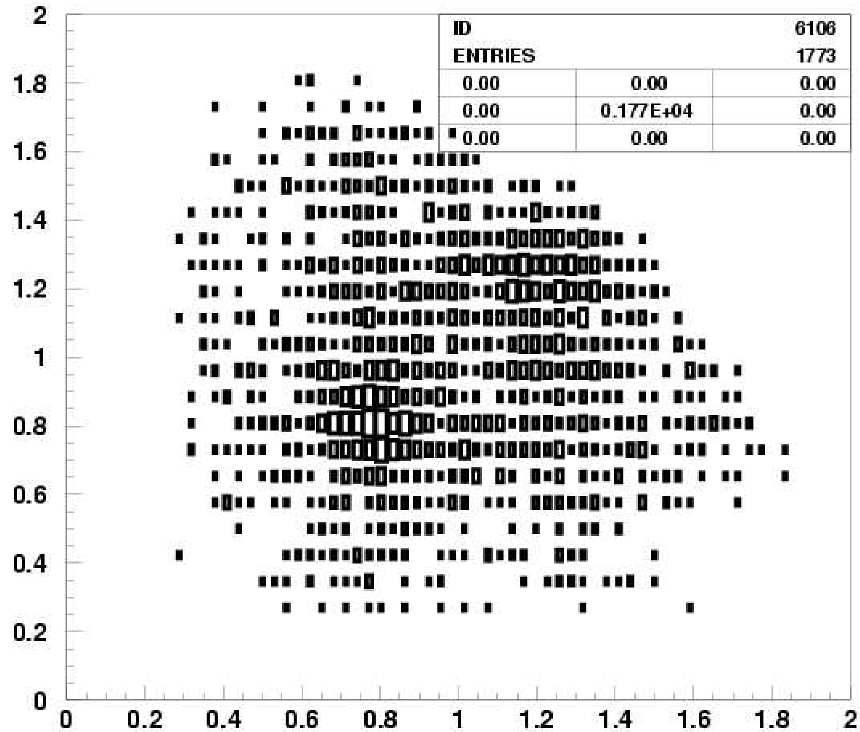

FIG. 2: 2-D histogram plotting 2-pion mass of the second and third tracks versus the 2-pion mass of the first and fourth tracks, with a cut on the 4-pion mass of 2.6 GeV or greater. Recall that the 4-pion mass is also constrained to be 2.9 GeV or less. This plot corresponds to Figure 1b in [1]. The $J/\psi \to \gamma\rho^0\rho^0$ peak seen in Fig. 1 is still visible, as well as the peak found at (1.270, 1.270), which is evidence for$J/\psi \to \gamma f_0(1270) f_0(1270)$ production.

these plots is shown in Figure 7. The plots were used to see which reduced chisquare cut was more effective in rejecting π^0 events, as well as to get a feel for how many π^0 events might slip through even with tight chisquare cuts.

One conclusive result of this analysis is that the method of selecting the "best" photon is very effective. I also found that "curler" tracks are somewhat common in the events encountered in this analysis, but that Trkman appears to be able to identify them effectively and discard the tracks accordingly. My analysis of "extra" tracks indicates that it is not necessary to consider events with tracks that initially number more than 8.

VII. CONCLUSIONS

My analysis has produced the desired calculation of the branching ratio of $\psi(2S) \to \pi^+\pi^- J/\psi \to \gamma\pi^+\pi^-\pi^+\pi^-$, but the uncertainty is obviously high. The π^0 background problem has proved to be very difficult to conquer. The 4-momentum chisquare cut, which had proven very effective in the analysis for which the original program was written, was not very effective at eliminating π^0 events from the signal in this analysis. Therefore, an explicit π^0 analysis will likely be necessary in order to increase the effectiveness of the program in weeding out π^0 events. The branching ratio I calculated is within the error margins of the previous value ($(2.8\pm0.5)\times10^{-3}$ [3]), and has significantly smaller error, despite the π^0 problem. The

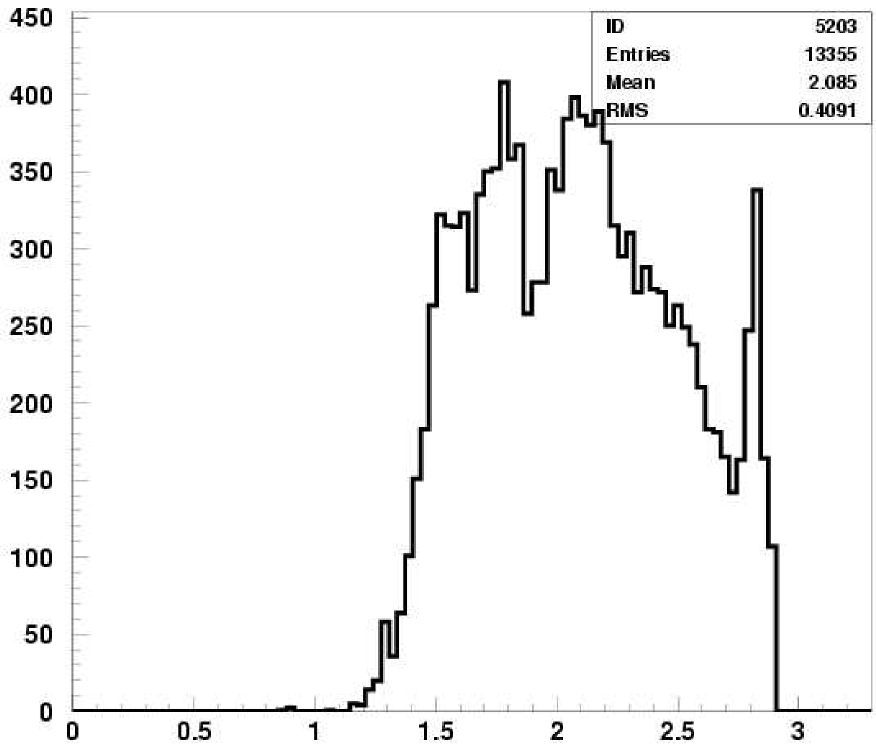

FIG. 3: 4-pion mass histogram under final chisquare cuts.

final value that I have calculated for the branching ratio is: $(2.64 \pm 0.02 \pm 0.14) \times 10^{-3}$.

VIII. ACKNOWLEDGMENTS

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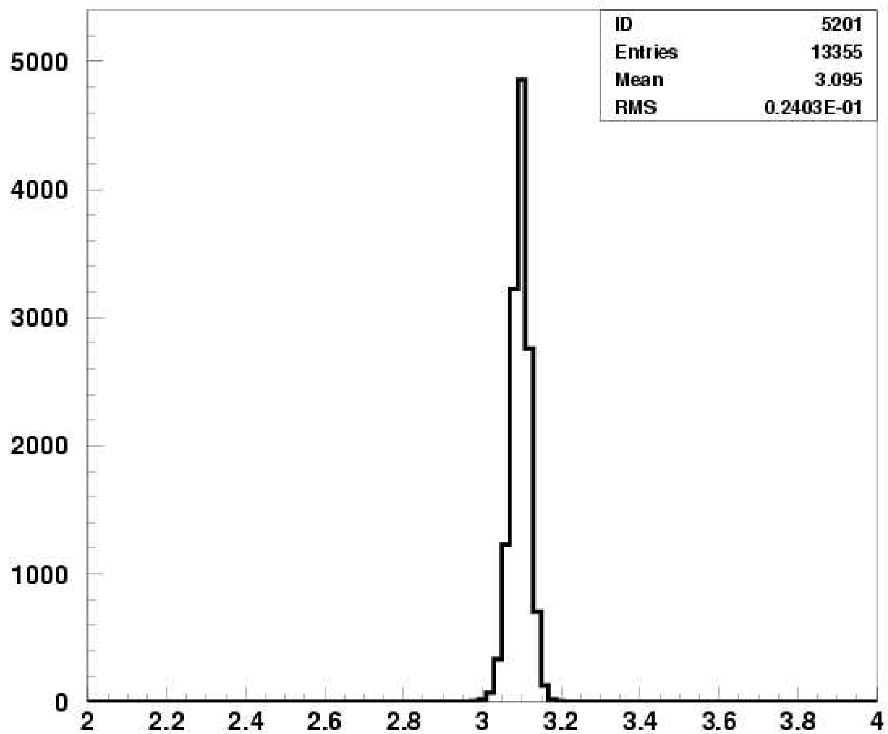

FIG. 4: 4-pion plus photon mass under final chisquare cuts.

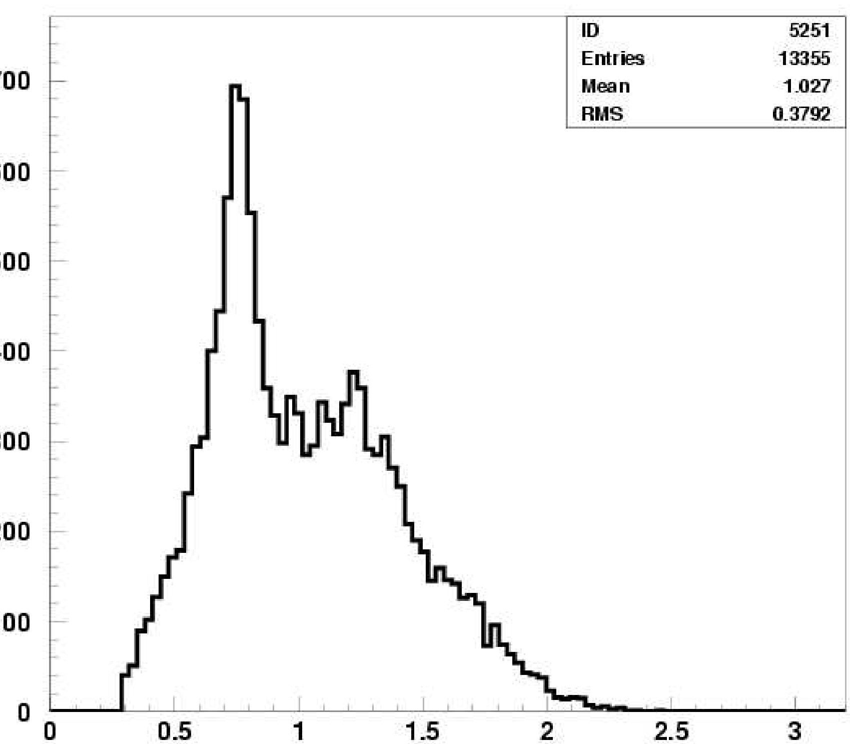

FIG. 5: 2-pion mass of first and second tracks under final chisquare cuts.

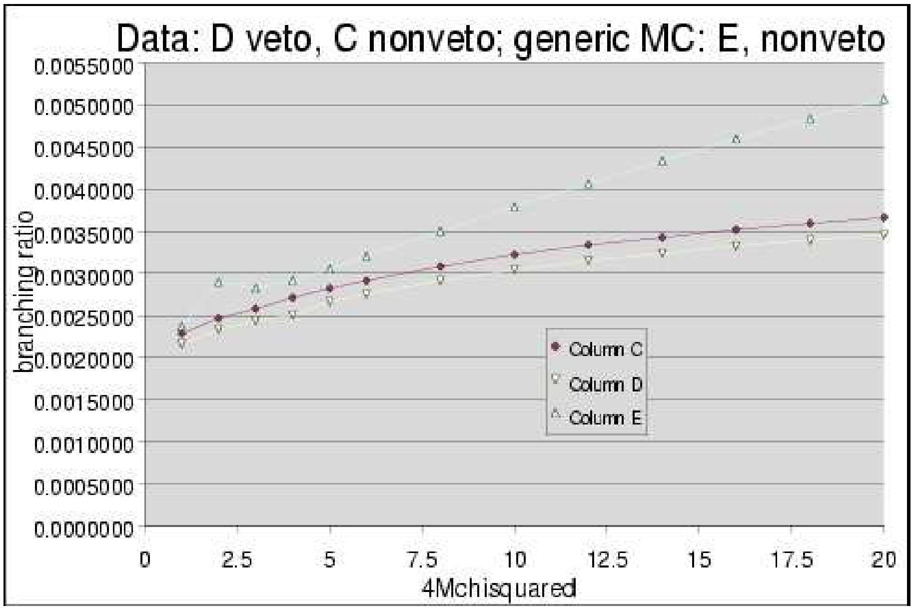

FIG. 6: This plot shows the extent to which the branching ratio varies with Chi4MFit when ChisqFit is constrained to be less than ten. The top curve is from Monte Carlo events; the π^0 veto was not used. The π^0 veto was not used in the middle curve either, which was calculated from data. The lowest curve is from data events; the π^0 veto was used for this curve.

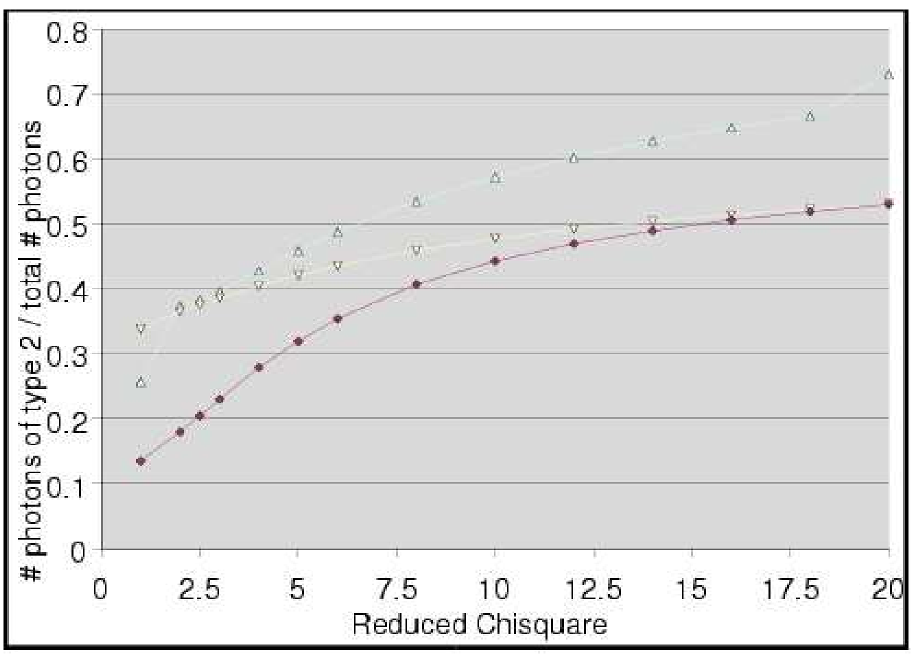

FIG. 7: Generic Monte Carlo events; looking at effectiveness of chisquare values for ChisqFit and Chi4MFit. The value on the y-axis is the ratio of photons identified in Monte Carlo to be daughters of π^0's divided by the total number of photons. The top curve does not include the π^0 veto; the ratio is plotted against Chi4MFit. The two lower curves both use the π^0 veto; the higher of the two has the photon ratio plotted against ChisqFit, while the lowest curve has the ratio plotted against Chi4MFit.