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A comparison of the Berkeley and Zurich $\omega \rightarrow \eta\gamma$ Analyses

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Abstract

We compare the analyses of Berkeley (BB3) and Zurich (ZZ3) for the $\omega \rightarrow \eta\gamma$ decay measurement, which currently disagree by two standard deviations. We attempt to find the causes of the disagreement by doing a detailed reanlysis (BZ0) using the Zurich technique. We find that a reanalysis using the Zurich technique but with a new background (BZ1) agrees with the BB3 analysis. However, we are unable to reproduce the details of the Zurich analysis.

Chapter 1

Overview and Introduction

The Berkeley and Zurich independent analyses of BR($\omega \rightarrow \eta\gamma$), using the same 0-prong dataset from the Crystal Barrel, disagree by more than two standard deviations.

Analysis	result
Zurich	$(6.6 \pm 1.7) \times 10^{-4}$
Berkeley	$(2.1 \pm 1.3) \times 10^{-4}$

In order to sort this out, we repeated the original Zurich analysis (ZZ3)[1] , using the the same cuts as advertised in the technical report (here called the **BZ0** analysis). In addition to this, we also modified the analysis with the inclusion of a new background (BZ1).

Analysis	result	
ZZ3	$(6.5 \pm 1.1) \times 10^{-4}$	(no ρ^0 correction)
BZ0	$(5.0 \pm 0.8) \times 10^{-4}$	(no ρ^0 correction, stat. error only)
BZ1	$(2.8 \pm 0.8) \times 10^{-4}$	(no ρ^0 correction, stat. error only)
BB3	$(2.5 \pm 1.0) \times 10^{-4}$	(incoherent ρ^0 correction)
BB3	$(2.1 \pm 1.3) \times 10^{-4}$	(final value)

1. We see that the BZ0 reanalysis does not agree well with the Zurich analysis (ZZ3) when one takes into account that both analyses were done on the same data set; the reasons are not exactly known because we didn't do the Zurich analysis but we speculate on the differences in section 5.1. Some of this difference can be attributed to the confidence level tuning (or lack thereof), but this does not account for all. BZ0 does not agree with BB3.

2. A new background was introduced in the BB3 analysis, namely $p\overline{p} \rightarrow \eta\eta\gamma$ (with no resonant intermediate) to improve the quality of the fits. There is experimental evidence that this channel exists, but it is not definitive. Thus we increase our systematic error by 20% to reflect our ignorance

[1] The notation of BZ, ZZ and BB is described later

of whether the background exists or not. However, if we include this background with the same intensity in the BZ0 analysis, the result for BR($\omega \to \eta\gamma$) is reduced by a factor of two in section 2.0.2. Now there is bad agreement with ZZ3, but perfect agreement with BB3.

In other words, without the $\eta\eta\gamma$ background, the BB3 analysis has slightly worse fits and does not agree with the BZ0 analysis. With the $\eta\eta\gamma$ background, the BB3 analysis has better fits and agrees with the BZ1 analysis.

Because of this good agreement between BB3 and BZ1, we believe that the ZZ3 value (as published) is not accurate and that a new paper superceding the ZZ3 value needs to be published.

1.1 History

We present the history of the Zurich and Berkeley preliminary results on this measurement for the reader may have be confused by earlier results. This section is not important for any of the arguments of this paper.

The Berkeley and Zurich groups of the Crystal Barrel experiment undertook two independent analyses of the same branching ratio, BR($\omega \to \eta\gamma$). Mark Lakata was working on his project for his PhD thesis, and Claudio Pietra was working on his project for his Diplom thesis. For notational simplicity, we call the two analyses BB and ZZ. The first letter indicates the group that did the analysis and the second letter indicates which method was used. In this paper, we will describe the BZ analysis and its connection to the other two.

The history of the analyses is as follows. **ZZ0** was completed at the end of 1995 and the preliminary results were presented at a CB meeting. However, a significant background was neglected, and a reanalysis **ZZ1** was presented at the 1996 Jamboree. At the same Jamboree, the first preliminary results of **BB0** were presented, using a subset of the full data set. Both results were preliminary and did not agree well.

In the fall of 1996, **ZZ2** was completed and submitted to the collaboration for publication. A full analysis of all the zero-prong data, **BB1**, was not finished in time for inclusion in a merged paper, and there were still differences in the results. After some time, a "problem" was found in the BB analysis regarding the fitting method, and a change in the fit method changed the results such that **BB2** and **ZZ2** agreed. The preliminary results of **BB2** were presented at the APS April Meeting, 1997.

However, both analyses suffered from some unexplained phenomena, and the analyses continued. Even though **BB2** now agreed with **ZZ2**, the reason for the sudden change due to the fitting procedure was not understood. The difference was a switch from 1-D fitting of the peak to a fit of the 2-D Dalitz plot. Several tests with MC showed that the Dalitz fit was more reliable than the 1-D fit, but the visual evidence contradicted this – the visible peak was clearly not as big as the fit claimed. Perhaps prematurely, we assumed the agreement with **ZZ2** and the MC tests mean the 2-D fit was correct. With hindsight, it turns out that

Analysis	Date	BR($\omega \rightarrow \eta\gamma$) $\times 10^{-4}$		BR($\rho^0 \rightarrow \eta\gamma$)$\times 10^{-4}$
		ρ^0 uncorrected	ρ^0 corrected	
PDG	94	N/A	8.3 ± 2.1	3.8 ± 0.7
ZZ0*	95	29 ± 5	–	–
ZZ1	96/4/9	7.2 ± 1.6	–	–
ZZ2	96/10/10	7.1 ± 1.2	6.6 ± 1.7	9.1 ± 6.8
ZZ3	97/6/5	6.5 ± 1.1	6.6 ± 1.7	12.2 ± 10.6
BB0	96/4/9	4.5 ± 2.0	–	–
BB1	96/10/23	4.1±N/A	–	–
BB2*	97/4	6.8 ± 1.4	6.2 ± 1.4	–
BB3	97/10/28	2.5 ± 1.3	$(2.1 \pm 1.3) \times 10^{-4}$	–

Table 1.1: History of analyses. B= Berkeley, Z=Zurich, *= Recognized by the original authors as faulty.

this decision was wrong. The Dalitz plot fit was done using a poor definition of log-likelihood, ignoring empty bins in the Dalitz plot (in both MC and data) and thereby biasing the fit too high. The MC tests used a subset of the MC data as "fake" real data to test the behavior of the fit. However, because the fake data was a subset of the same MC data used as the hypothesis, they are 100% correlated, and there is always at least one MC event (as theory) for each fake MC event, meaning that there are no bins where the (fake) data exists but there is no MC data. In the real world, there DO exist many bins where the MC theory has zero events, but there are a few data events. For these bins, the likelihood is undefined, and by not dealing with this problem, the results were incorrect. Using a improved definition of log-likelihood that solves this problem (see forth coming paper for description and reference), the **ZZ2** data was refit. The 1-D and 2-D fits agree very well, and (not surprisingly), the fit values are smaller than in **BB2**, but agree well with **BB1**. Thus we believe **BB2** was seriously in error and should not be used at all.

ZZ3 was ultimately finished in the spring of 1997, and published[2] with little change from **ZZ2**.

In the meantime, **BB3** was completely redone, including all new code and a new kinematic fit. This ultimate analysis is statistically better than **BB2** because of the effect of the kinematic fit, and many systematic problems were clearly found and well understood. Because of higher statistics, the contribution from ρ^0 could be handled. Unfortunately, the results do not agree well with **ZZ3**.

This paper is the result of an attempt to recreate the ZZ analysis using the Berkeley software. **BZ0** attempts to reproduce **ZZ3** as closely as possible by using the same cuts, while **BZ1** subtracts one more background ($\eta\eta\gamma$) that was not subtracted in ZZ3 or BZ0. We will show that **BZ0** marginally agrees with **ZZ3** in the final result, but many of the partial results are very different. We will also show that BZ1 agrees perfectly with BB3.

[2] Phys. Lett. B411 (1997) 361.

1.2 Problems with the Zurich analysis

This section describes some of the general shortcomings of the Zurich analysis, explaining why the new background ($p\overline{p}\rightarrow\eta\eta\gamma$) was not included, as well as some technical problems with the analysis.

Because the Zurich data is no longer available, we redid the analysis based on the description in the technical report[3]. This reanalysis is called **BZ0** henceforth.

1.2.1 Background appears indistinguishable from signal

The fundamental problem of any of the ZZ analyses is that it makes a kinematic fit on the ω, forcing the background to look like the signal. Once the ω mass is enforced, any random η caught in it makes a peak in the γ energy. *One can not simply do a "side-bin" subtraction, or a gaussian plus polynomial fit to the peak, because the peak is not pure signal.* Only by relying on the Monte Carlo to model the background accurately can one subtract from peak, which is not just under but also *in* the peak. [4]

(We note in passing that the latest GAMS result ($\pi^{\mp}\rightarrow\omega$n) on this branching ratio does not use the Zurich technique.)

This technique suffers from two problems. First, the Monte Carlo is required to accurately model a feedthrough background channel. There is no way of testing this accuracy. Second, there is no way of checking of the existence of other backgrounds that may exist, for example the channel $p\overline{p}\rightarrow\eta\eta\gamma$ ("flat" 3-body phasespace) which has not been measured before.

We have evidence that both of these problems may be manifest in the ZZ analysis. We believe that the Monte Carlo in this particular mode is very sensitive to the choice of PED parameters, see section 1.4. We also believe there is evidence for the existence of the $p\overline{p}\rightarrow\eta\eta\gamma$ ("flat" 3-body phasespace) channel, see section 2.0.2. By "flat" we mean that it does not have any sharp resonances, such as ω or ϕ, but may contain some resonances that are sufficiently broad as to be flat to first order.

The figures given in this paper show that background shape has a very clear peak under the signal (see figure 1.2).

We acknowledge that the background as shown in ZZ3 (see figure 1.1 does not appear to have as large a peak at 200 MeV as that of BZ0. The Monte Carlo statistics of the ZZ3 analysis are not as high as that of the BZ0, and thus the absence of a sharp peak could be just due to statistics.

We also acknoledge that the data below 180 MeV appears to be well described by the background Monte Carlo, and thus it has been said that because the side-bins are described well by the $\pi^0\eta\eta$ Monte Carlo, then the $\pi^0\eta\eta$ Monte

[3] CB Note 308

[4] With the knowledge that the background consists of events with lots of π^0's and η's, it makes much more sense to kinematically fit the π^0's and the η's, and then looking for a peak in the $\eta\gamma$ spectrum. Because the backgrounds are non-resonant under the ω, the fit can clearly distinguish between signal and background.

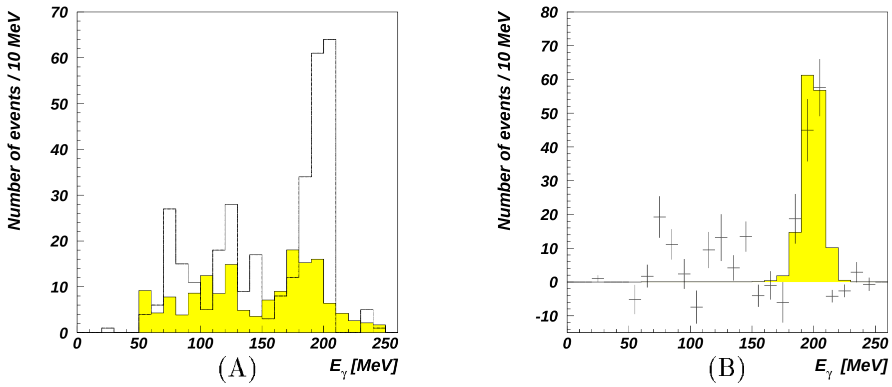


Figure 1.1: The final plots of the ZZ3 analysis, $\eta\omega$ channel. (A) Unsubtracted data (solid) and MC background (shaded) from $\pi^0\eta\eta$. (B) Subtracted data (solid) and MC signal (shaded) using BR($\omega\to\eta\gamma$)=6.6e-4. Figure taken from Phys. Lett. B411 (1997) 361 preprint.

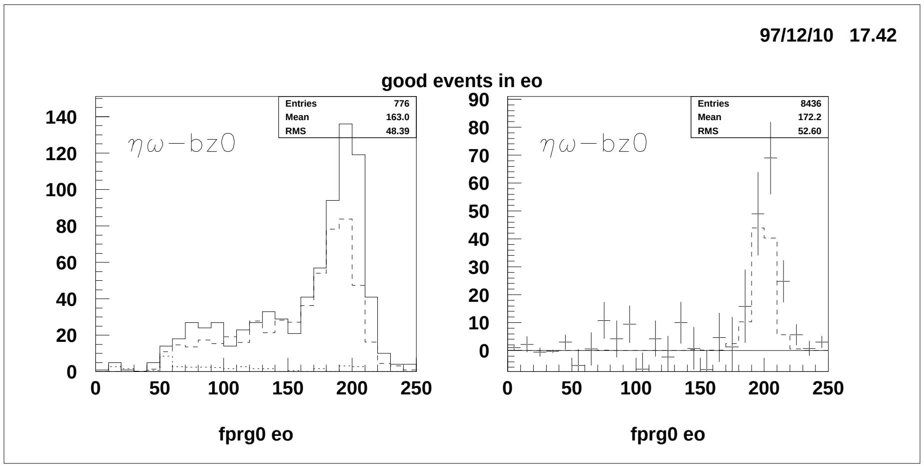
Carlo describes the entire background well. *However, the data points in the sidebins (< 180 MeV) are produced by a different mechanism than the events under the peak (at 200 MeV), and thus no such statement can be made.* We show in section 1.4 that a small change in the reconstruction PED threshold parameters could change the event count under the peak differently than the event count in the side-bins. It is as if there were two independent efficiencies for each 3 pseudoscalar background; a perfect MC would have the same efficiency, but the two efficiencies may not be the same CBGEANT.

1.2.2 Reference measurements of $\omega\to\pi^0\gamma$ are slightly off

The measurement of BR($\omega\to\pi^0\gamma$) as a reference neglected some sources of background. This reference was measured by fitting a gaussian plus polynomial to the E_γ peak at 379 MeV, under the assumption that all events were from either $\eta(\omega\to\pi^0\gamma)$ or $\pi^0(\omega\to\pi^0\gamma)$ in $\eta\omega$ or $\pi^0\omega$ respectively. However, there is a significant background from $\pi^0\pi^0\eta$ and $\pi^0\pi^0\pi^0$.

	background to $\eta(\omega\to\pi^0\gamma)$	background to $\pi^0(\omega\to\pi^0\gamma)$
$\pi^0\pi^0\eta$	2200 ± 70 events	–
$\pi^0\pi^0\pi^0$	600 ± 60 events	5240 ± 200 events
total	2800 (6%)	5240 (9%)

These corrections (6% and 9%) are small to compared to the final result, however.



(A) (B)

Figure 1.2: The final plots of the BZ0 analysis, $\eta\omega$ channel. (A) Unsubtracted data (solid) and MC background (dashed) from $\pi^0\eta\eta$ and $\eta\eta\gamma$. (B) Subtracted data (solid) and MC signal of $\eta(\omega\rightarrow\eta\gamma)$(dashed), using BR($\omega\rightarrow\eta\gamma$)=$2.2\times10^{-4}$ with ρ^0 correction (raises peak).

1.2.3 Pulls and Confidence Levels are poor

From section 3.2 of C.Pietra's technical report, pages 17 and 18, figures 12 through 19, the pull distributions have widths of approximately 0.89 ± 0.05 instead of 1. The confidence levels in figures 15 and 19 (see figure 1.3 in this report) are not flat, but this is not *a priori* bad. Because of background and because the ω has a measurable width, the confidence levels should not be perfectly flat, for either MC or data.

However, we tuned our pull distributions and confidence levels by adjusting the PED errors $(\sigma(\theta), \sigma(\phi)\sigma(\sqrt{E}))$ and the neutral vertex positions on the 5-gamma phase space hypothesis, and were able to obtain very flat looking confidence levels as well as pull distributions with widths consistent with unity, as shown in figure 1.3, subfigures (C) and (D). Because we tuned the 5-gamma phase space (4-C fit), the width of the ω is not important. The confidence levels given in the figure are for the 6-C hypotheses ($\eta\omega$ or $\pi^0\omega$) though, and flat nevertheless.

If the confidence levels are not flat, then cuts made on it are called into question. The two cuts made on the confidence level for the $\eta\omega$ channel were CL($\eta\omega$)$>10\%$ and CL($\pi^0\omega$)$<1\%$. If the confidence level is biased too low, then the first cut will lower the signal efficiency, while the second cut will increase the background efficiency. Both these affects will affect the final result.

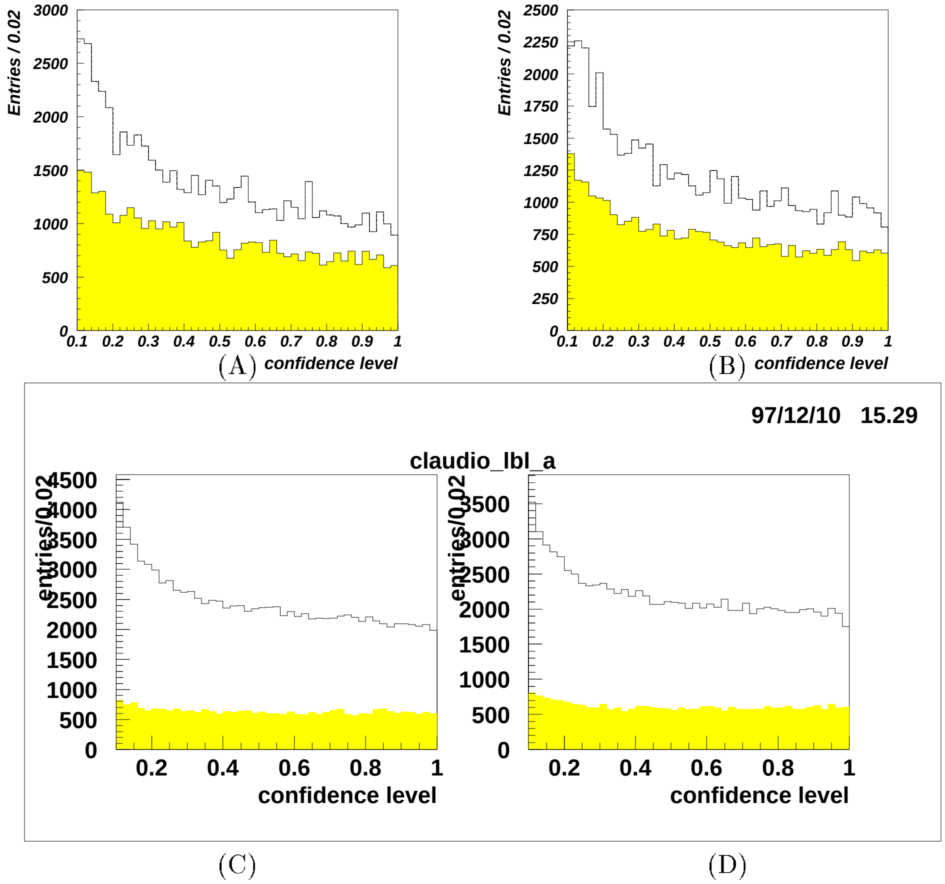


Figure 1.3: Confidence levels for (left) $\pi^0\omega$ and (right) $\eta\omega$. The solid line is data, while the shaded histograms are signal MC. (A) and (B) are Figures 15 and 19 reproduced from C. Pietra's technical report (ZZ3). (C) and (D) are Figures from the BZ0 analysis.

	ZZ3	BZ0
Total Number of Events Read	15.46M	20.30M
Split-off software	custom	Dolby-C
Kinematic Fitter	CBKFIT	KinFit++
error scalings	different	
PED thresholds 1st pass	?	20,20 MeV
PED thresholds 2nd pass	10,10 MeV	10,10 MeV
CBOFF Software	same	
Cuts	same	
ω angular decay parameter b	0.82	1.0
All $p\overline{p}\to\eta\omega$ events	72,000 (54,865)	99,184
All $p\overline{p}\to\pi^0\omega$ events	82,500 (62,853)	110,118

Table 1.2: Summary of differences in **ZZ3** and **BZ0**. The values for ZZ3 are corrected because of the different number of total events; the original numbers are given in parentheses.

1.3 The BZ0 analysis

Because the data for the **ZZ3** analysis is not available, we endevored to reproduce the analysis using similar cuts and software. Because of time constraints, it was not practical to exactly redo the ZZ analysis, but every cut or reconstruction parameter was chosen to be as close as possible.

Table 1.2 summarizes the differences in the analyses and the differences in the results. The split-off package used in **ZZ** is not Dolby-C, but appears to be similar. A custom kinematic fit program (written in C++) was used in **BZ**, as well as **BB** and other analyses of Berkeley. The necessary error scalings used in **BZ** were that of **BB**, and probably different than **ZZ**. First skimming pass of **BZ** used different PED thresholds (20, 20 MeV) than the final pass. This does not affect the final result.

1.3.1 The reference decay $\omega\to\pi^0\gamma$

The reference decay BR($\omega\to\pi^0\gamma$) was measured using the same technique as in ZZ3. For consistency with ZZ3, the background was not subtracted as it should be, but this is only a 6% effect for the $\eta\omega$ channel.

	$\eta(\omega\to\pi^0\gamma)$ reference	$\pi^0(\omega\to\pi^0\gamma)$ reference
data	$89,300\pm400$	$101,100\pm400$
$\pi^0\pi^0\eta$ bkg	2900 ± 100	–
$\pi^0\pi^0\pi^0$ bkg	790 ± 80	$6,700\pm300$
net	$85,600\pm400$	$94,400\pm400$
MC expected	$85,900\pm12,000$	$87,000\pm12,000$

	ZZ3	BZ0
	$\eta\omega$ analysis	
All $p\overline{p}\rightarrow\eta\omega$ events	72,000 (54,865)	99,184
MC efficiency $\eta(\omega\rightarrow\pi^0\gamma)$	21.3%	32.7 %
MC Expected $\eta(\omega\rightarrow\pi^0\gamma)$	56,000 (42,600)	85,900
Data $\eta(\omega\rightarrow\pi^0\gamma)$	$66,200 \pm 300 (50,430)$	$89,336 \pm 390$
	$\pi^0\omega$ analysis	
All $p\overline{p}\rightarrow\pi^0\omega$ events	82,500 (62,853)	110,152
MC efficiency $\pi^0(\omega\rightarrow\pi^0\gamma)$	23.9%	34.5%
MC Expected $\pi^0(\omega\rightarrow\pi^0\gamma)$	60,200 (45,855)	87,000
Data $\pi^0(\omega\rightarrow\pi^0\gamma)$	$72,700 \pm 500$ (55,340)	$101,118 \pm 430$

Table 1.3: A comparison of BZ0 and ZZ3 for the reference measurement, $\omega\rightarrow\pi^0\gamma$.

1.4 Special Comments on $\pi^0\eta\eta$ and $\pi^0\pi^0\eta$

These two backgrounds appear in the signal by "losing" a γ. However, there are two different ways of losing a γ. ZZ is sensitive to both, while BB is sensitive to one. Refer to figure 1.4 regarding this section.

The first way is if two hard γ's hit the same neighborhood of crystals and become merged, as in figure 1.4-a. The 2 γ's must come from different mesons due to the kinematics. Thus if a γ from a η and a γ from a π^0 merge, that η and π^0 are essentially no longer identifiable because the reconstructed $\gamma\gamma$ invariant mass will be incorrect. It then appears that the measured 3 PEDs will not reconstruct to any meson pairwise, or in otherwords that the reaction appears as $p\overline{p}\rightarrow X\gamma\gamma\gamma$, where X is π^0 or η and the 3 γ's are non-resonant. This method of merging should be relatively well described by the Monte Carlo, because its is a simple geometric problem and the shower widths seem to be well modelled. Remember, both γ's that merge are not necessarily soft and *thus not sensitive to the PED thresholds.* This method of background is seen significantly in ZZ but not significantly in BB, because the BB analysis requires that pairwise combinations of γ's form exactly two mesons.

The second way is if the π^0 decays into a hard and soft photon, and the soft photon is lost in the noise, figure 1.4-b. In this case, the other mesons are not affected, and it appears as if this background is a 2-meson plus 1-photon channel. This form of background can appear in both ZZ and BB, and *it is sensitive to the PED thresholds chosen because of the soft* γ. Unfortunately, since the lost photon is soft, it is nearly impossible to separate this background channel from a flat 3-body decay, $p\overline{p}\rightarrow\pi^0\pi^0\gamma$ or $p\overline{p}\rightarrow\eta\pi^0\gamma$, except by looking at χ^2 values which are slightly worse for the lost-γ channels than the flat 3-body channels. In the ZZ analysis, the problem with this process is that it fakes an ω decay, either $\omega\rightarrow\eta\gamma$ or $\omega\rightarrow\pi^0\gamma$ depending on the initial state. It then appears as a peak in the E_γ plot at 200 MeV (or 379 MeV) just as the desired signal

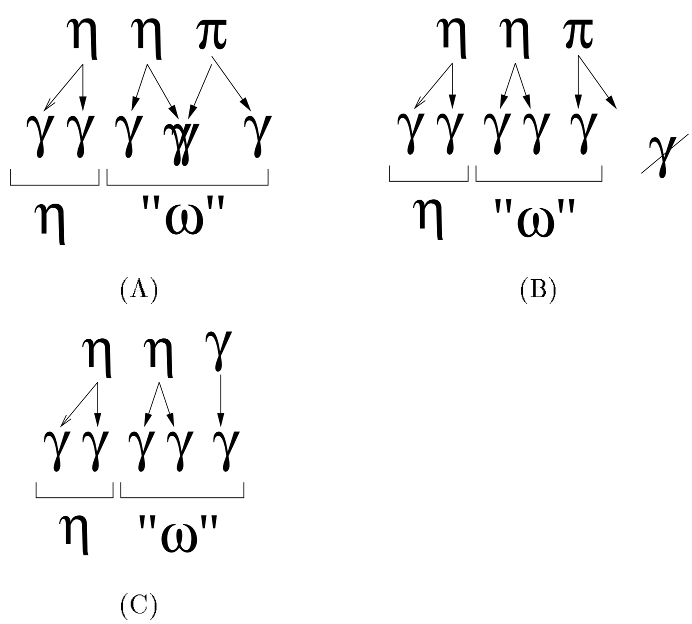


Figure 1.4: (A), (B) The two processes for the three pseudoscalar backgrounds to appear in the five-γ channels. (C) The $\eta\eta\gamma$ background appearing as an ω

does. It is absolutely critical to understand this process in order to legitimately subtract it from the data. In the BB analysis, this background does not fake anything and is thus not a problem.

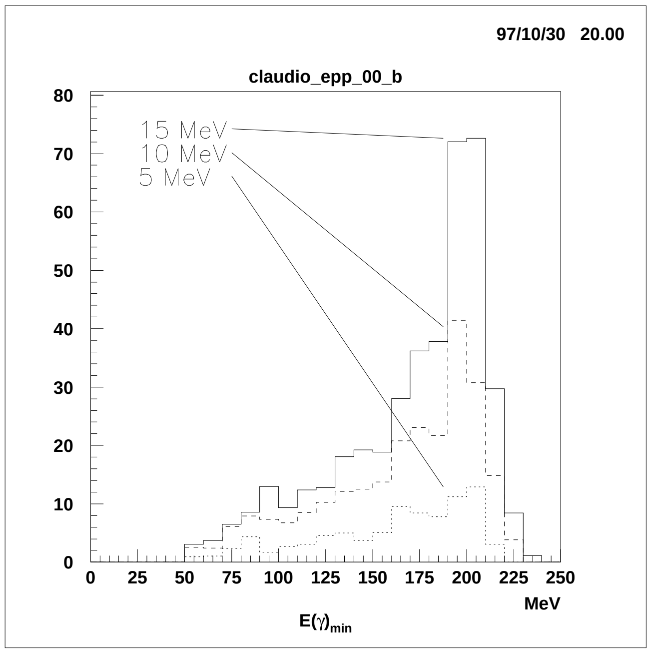
Because these two processes are so different, it is possible that the Monte Carlo may not simulate them with the same efficiencies. In fact, it appears in the BZ analysis that the former process (of merged γ's) is well described by the MC, but the later process (of lost soft γ's) is underdescribed by the MC, by 20 to 50%. This is supported in the BB analysis as well.

The two processes differ in there dependence on the PED thresholds. The merged PED process doesn't depend as much on the thresholds as the soft photon process does. Figure 1.5 shows the effect of varying the Cluster and Secondary PED thresholds in the analysis. The conclusion is that the peak contribution can vary independently of the shoulder background, and can increase quickly with threshold. *To increase the peak background by 50%, the threshold need only be increased from 10 MeV to about 12.5 MeV.*

On the other hand, we have seen that this underestimation of the background may instead not be a manifestation of the poorness of the MC, but may actually be evidence for the direct 3-body reactions, $p\overline{p}\rightarrow\eta\pi^0\gamma$ and $p\overline{p}\rightarrow\pi^0\pi^0\gamma$. However, the data is not sensitive enough to rule out one or the other. In the BB analysis, it is not relevant, because either background is relatively linear (non-resonant) under the peak. In the ZZ analysis, it is significant, because both backgrounds are resonant under the peak, and the contributions are calculated via the MC, so the MC and tabulated branching ratios must be trusted in order to correctly subtract the right amount.

We can see in figure 1.2 that the data is described by a peak at 200 MeV and a shoulder for $E\gamma < 200$ MeV. Any event with a real η in it will have a γ recoiling at 200 MeV, so the peak is caused by events with an η within the $\omega\rightarrow\gamma\gamma\gamma$, while the shoulder is caused by events with no η within the $\omega\rightarrow\gamma\gamma\gamma$. Thus the shoulder is due only to the "merged" process from $\pi^0\eta\eta$ or $\pi^0\pi^0\eta$. We can see that the data is well described in the shoulders by the MC. However, the peak does not appear to be described well if the backgrounds are simply scaled by their published branching ratios.

We summarize this section by stating that without some external checks of the performance of the Monte Carlo, it is very dangerous to blindly subtract the $\pi^0\pi^0\eta$ or $\pi^0\eta\eta$ backgrounds from the data, because both of these backgrounds have a component that is similar to the signal (so it is impossible to distinguish signal from background) and this component is strongly correlated to the PED thresholds which may not be handled perfectly by the MC.



Threshold	N(peak)	N(shoulder)	Ratio
5 MeV	35	53	0.67
10 MeV	109	134	0.81
15 MeV	212	190	1.12

Figure 1.5: The contribution of the $\pi^0\pi^0\eta$ channel is compared at three different PED thresholds, 5, 10 and 15 MeV. Note that the ratio of the peak to the shoulder is NOT constant. Peak background increases faster than shoulder background as the thresholds increase. The event counts are for the intervals [0,180] MeV and [180,220] MeV for shoulder and peak respectively.

Chapter 2

Details of the $p\bar{p}\to\eta\omega$ analysis

The procedure in **ZZ3** was followed for **BZ0** as closely as practical, but some differences exist. In **ZZ3**, only the 3 bins from 180 MeV to 210 MeV were integrated, mostly because there were no events in 210-220 MeV. However, the MC predicts an even spread around 200 MeV, so actually the range 180-220 should be used for a better estimate, although ultimately it doesn't matter if the efficiency is correctly for each case.

The first cut is the anti-$\omega\to\pi^0\gamma$ cut, which cuts off the large peak of E_γ at 379 MeV. The second cut is the "XPI" cut.

The event counts are shown in table 2.1. Because BB3 analyzed 33% more data, the equivalents for **ZZ3** are given. The original counts are given in parentheses. The difference between **BZ0** and **BZ1** is described later in the text.

The result is 159 events, which leads to a BR of

$$BR(\omega\to\eta\gamma) = BR(\omega\to\pi^0\gamma) * \frac{159 \pm 25}{25.3\%}\frac{32.7\%}{89,336} * \frac{1}{BR(\eta\to\gamma\gamma)} = 5.0 \pm 0.8 \times 10^{-4}$$

	ZZ3	**BZ0**	**BZ1**
Events in 180:220 MeV	212(159)	390 ± 20	390 ± 20
Background from $\pi^0\eta\eta$	48(37)	225 ± 15	225 ± 15
Background from $\eta(\omega\to\pi^0\gamma)$	0	6 ± 2	6 ± 2
Background from $\eta\eta\gamma$	0	–	69 ± 8
Subtracted	$164(123 \pm 19)$	159 ± 25	89 ± 26
MC efficiency	17.0%	25.3%	25.3%
BB3 Expected	–	100 ± 10	100 ± 10

Table 2.1: Event counts for $\eta\omega$ analysis

2.0.1 Confidence level check

The confidence levels are the final check for consistency of the data. If done properly, the background-subtracted data should have a flat confidence level distribution. The 4C CL (phase-space) are reasonably flat (A and B). The 6C CL for $\omega \rightarrow \pi^0\gamma$ selected events (C and D) is not quite flat, but reasonable when the width of the ω and the presence of background is considered. However, the 6C CL distributions for final selected events (E and F) are clearly not flat, indicating a large background.

2.0.2 The BZ1 analysis

In the BZ1 analysis, we add a new background channel to the fit, namely the reaction $p\overline{p} \rightarrow \eta\eta\gamma$, where there is no resonant 2-body intermediate state, and the events are scattered flatly across the Dalitz plot. The motivation for this background is given in the technical report of BB3. We summarize the results here.

A simple calculation of the expected branching ratio from $p\overline{p}$ annihilation was done, invoking VDM and phase space considerations. We arrive at the following order-of-magnitude predictions, which compare reasonably to the measured rates for the radiative channels.

Reaction	BR (10^{-5})	
	prediction	seen
$p\overline{p} \rightarrow \pi^0\pi^0\gamma$	12	$8.8^{+6.2}_{-8.8}$
$p\overline{p} \rightarrow \pi^0\eta\gamma$	8	$25.0^{+5.0}_{-25.0}$
$p\overline{p} \rightarrow \eta\eta\gamma$	2 - 4	$1.9^{+1.6}_{-1.9}$

Secondly, the $\eta\eta\gamma$ background improves the fit by a change in χ^2 from 165 to 129, with DOF = 133. Also, the fit value for the pseudoscalar background was improved when the new background was added. Because $\pi^0\eta\eta$ is missing a particle, it is biased to have too low an energy and thus a bad confidence level distribution that falls with increasing confidence level. On the other hand, $\eta\eta\gamma$ is a perfect match for the kinematic fit and thus has a perfectly flat confidence level. By describing the background as a sum of $\pi^0\eta\eta$(with a falling CL) and $\eta\eta\gamma$(with a flat CL), the fit values were constant regardless of what CL was used. Without the $\eta\eta\gamma$ background, the fit value for $\pi^0\eta\eta$ rose significantly as the CL cut was increased.

Thirdly, the amount of pseudoscalar background in the three data groups ($\eta\eta\gamma$, $\eta\pi^0\gamma$, and $\pi^0\pi^0\gamma$) was higher than predicted from tabulated values, especially in the case of $\eta\pi^0\gamma$ where the $\pi^0\pi^0\eta$ background needed to be scaled 50% higher than predicted, when the error of the tabulated values is only 10-20%. With the flat $\eta\pi^0\gamma$ background, the $\pi^0\pi^0\eta$ background need only be scaled down by -13%, within the allowed tabulated error.

We would like to emphasize that the existence of this $\eta\eta\gamma$ has only a minor impact on the BB3 analysis. It was included to reduced the χ^2 of the side bins. It does not significantly impact the measurement of the ω peak above the

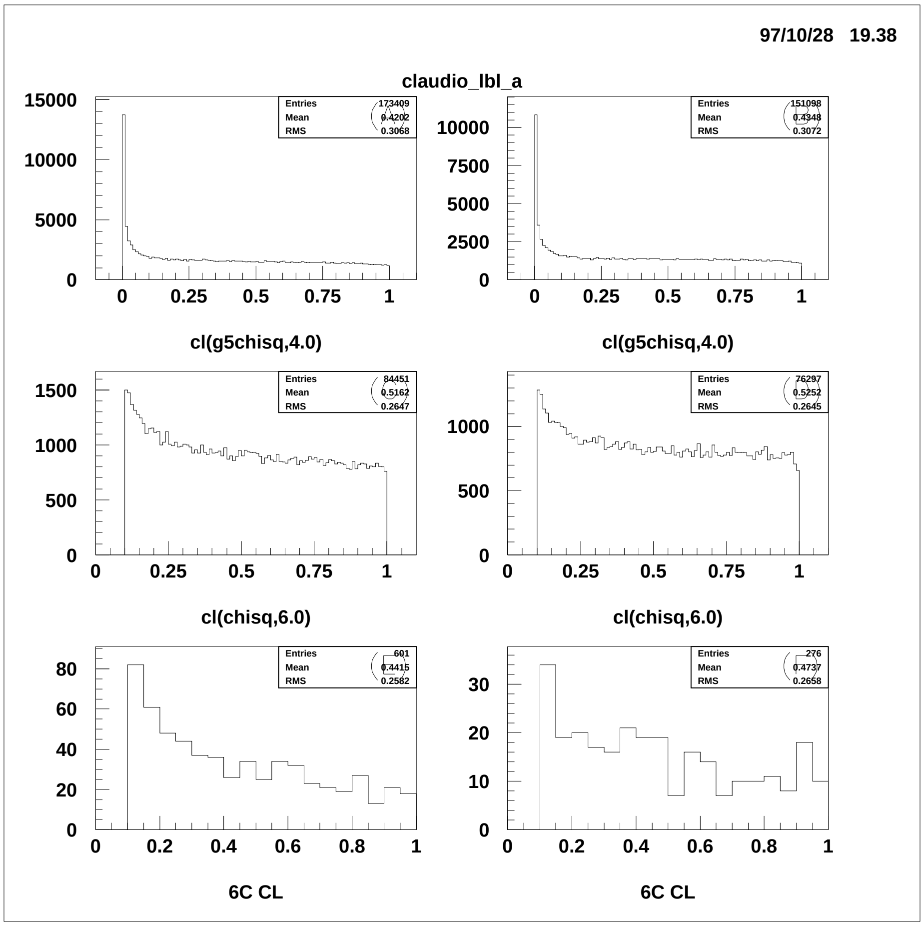
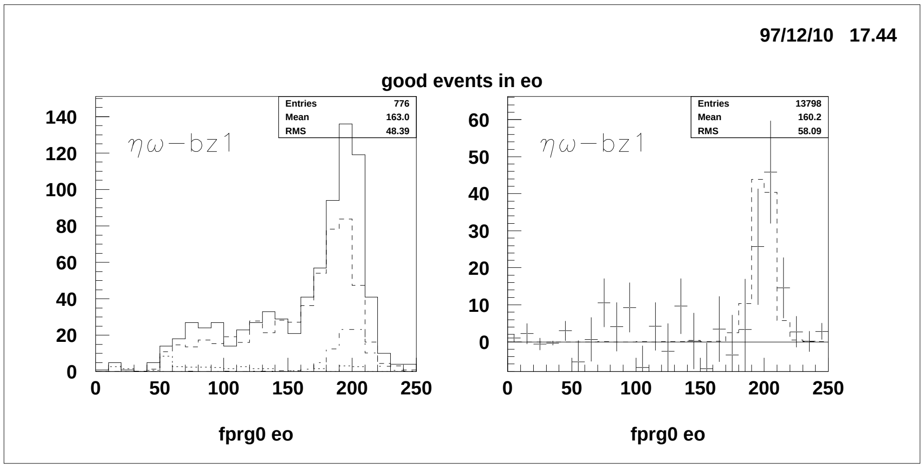


Figure 2.1: (A),(B) The 4C confidence level for $\pi^0\omega$ and $\eta\omega$, respectively. (C), (D) The 6C confidence level for $\pi^0\omega$ and $\eta\omega$, where $E_{max} > 369$ MeV, to select $\omega\rightarrow\pi^0\gamma$ events. (E), (F) The 6C confidence level for $\pi^0\omega$ and $\eta\omega$, with all cuts applied and $180 < E_{min} < 220$ MeV.



(A) (B)

Figure 2.2: The final plots of the BZ1 analysis, $\eta\omega$ channel. (A) Unsubtracted data (solid) and MC background (dashed) from $\pi^0\eta\eta$. (B) Subtracted data (solid) and MC signal of $\eta(\omega\rightarrow\eta\gamma)$(dashed), using the branching ratio from BB3 (including ρ^0 effect).

background. This is entirely not the case for the ZZ3 analysis, which is totally unable to measure this background, and the final result is 100% correlated to the size of the $\eta\eta\gamma$ branching ratio.

The **BZ1** analysis results in 89 ± 26 background-subtracted events between 180:220 MeV. Thus the naive BR (without ρ^0 interference) is

$$BR(\omega\rightarrow\eta\gamma) = BR(\omega\rightarrow\pi^0\gamma) * \frac{89 \pm 26}{25.3\%}\frac{32.7\%}{89,336} * \frac{1}{BR(\eta\rightarrow\gamma\gamma)} = 2.8 \pm 0.8 \times 10^{-4}$$

The MC simulation of $\eta((\omega/\rho^0)\rightarrow\eta\gamma)$ using the branching ratio values of **BB3** (namely BR($\omega\rightarrow\eta\gamma$)= $(2.1 \pm 1.3) \times 10^{-4}$ results in 100 events in the same interval, a good agreement between the two methods.

2.0.3 Summary of lost events

We can follow the path from the ZZ3 result to the BB3 result by applying the correction necessary for each problem. We start with the ZZ3 results of BR($\omega\rightarrow\eta\gamma$) $= 6.5 \times 10^{-4}$ and apply each correction sequentially. Because some of the lower event counts affect both the data and the efficiency, some corrections cancel each other in part.

Value	change	Reason
$(6.5 \pm 1.1) \times 10^{-4}$	$\rightarrow$	ZZ3 value as published, with no correction for ρ^0.
	-4%	Detuning the confidence levels by decreasing the errors by 10%. A minor effect.
	-20%	*UNKNOWN* difference between BZ0 and ZZ3.
	-44%	Loss of signal in BZ1 analysis over BZ0 analysis, by subtracting the additional $\eta\eta\gamma$ background.
$(2.8 \pm 0.8) \times 10^{-4}$	$\leftarrow$	result of BZ1 analysis
$(2.1 \pm 1.3) \times 10^{-4}$	$\rightarrow$	result of BB3

Chapter 3

Details of the $p\bar{p}\rightarrow\pi^0\omega$ Analysis

Unfortunately, we have found that it is essentially impossible to extract any significant signal from the $\pi^0\omega$ channel, because of the enormous backgrounds. We believe that it is coincidence that the ZZ3 analysis even achieves anything reasonable. The result from the BZ1 analysis is consistent with zero, because nearly all of the "peak" is actually background from $\eta\pi^0\gamma$.

The first of two critical cuts is a cut on the maximum γ energy, to remove the very strong $\omega\rightarrow\pi^0\gamma$ decay from the Dalitz plot. This is easy to remove and there is a very clear reason for this cut. The second cut is the decay angle cut.

3.0.4 The decay angle cut

The decay angle cut was introduced in **ZZ3**, removing events that have any of the three γ's within 45 degrees of the ω's momentum direction. (We assume that this is measured in the rest frame of the ω). We show a plot of the minimum angle in figure 3.1. It shows a very broad distribution, and the resultant number of events is highly sensitive to the exact value chosen. The motivation behind the cut is clear, but the importance of the cut is not so clear, because 50% of the signal is thrown away.

3.0.5 Shoulders and peaks

$\pi^0\pi^0\eta$ and $\eta(\omega\rightarrow\pi^0\gamma)$ were subtracted from the data. Using the published values for the branching ratios, the shoulder to the left of the 200 MeV peak is well described by the $\pi^0\pi^0\eta$ MC, in both efficiency and shape, see figure 1.2. However, the broad peak at 200 MeV is not consistent with the prediction from MC – note the high counts in the 180-190 and 210-220 bins. This is characteristic of fake ω events that are not truly resonant at 781 MeV, and thus do not form a sharp recoil peak in the γ energy against the η. However, as noted before, it is

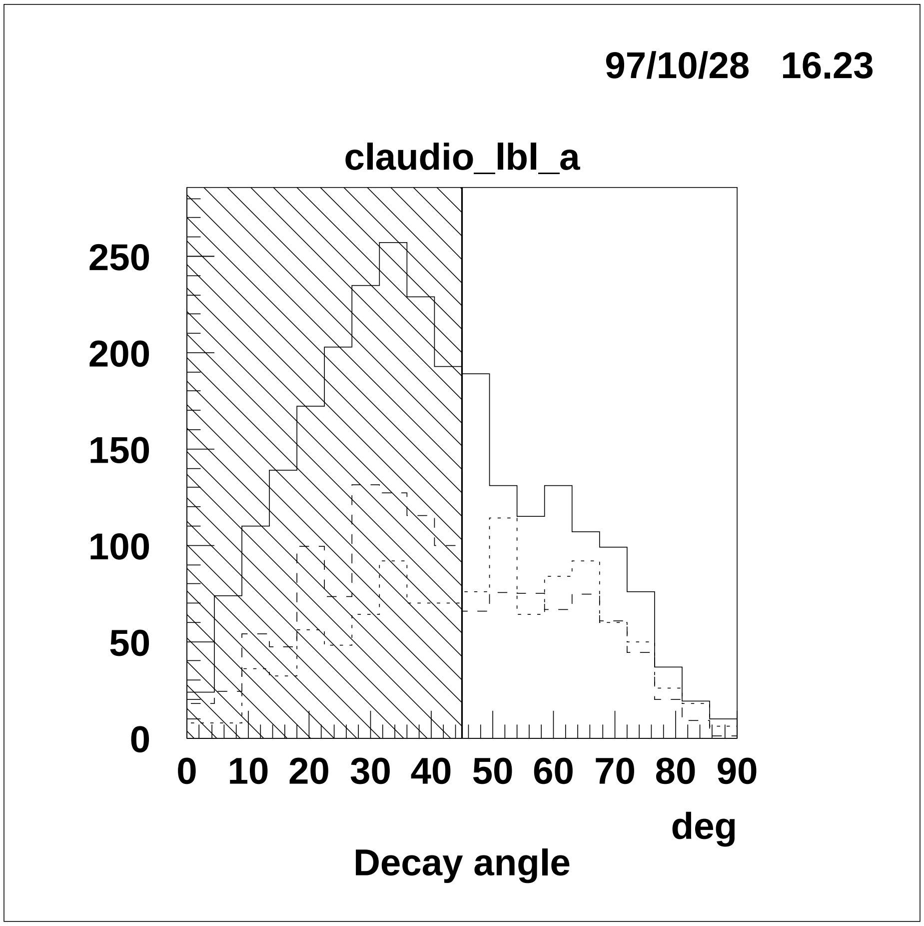


Figure 3.1: The distribution of the smallest angle between any gamma and the ω momentum direction, in the ω rest frame. The solid line is the data, the dashed line is the MC $\pi^0\pi^0\eta$ background, and the dotted line is the MC $\pi^0((\omega/\rho^0)\rightarrow\eta\gamma)$ signal. *Both MC's have arbitrary vertical scales.*

	ZZ3	**BZ0**	**BZ1**
Events in 180:220 MeV	690 (525)	830 ± 30	830 ± 30
Background from $\pi^0\pi^0\eta$	410 (311)	400 ± 20	400 ± 20
Background from $\pi^0\eta\eta$		6 ± 2	6 ± 2
Background from $\eta(\omega\rightarrow\pi^0\gamma)$	90 (67)	168 ± 13	168 ± 13
Background from $\pi^0\eta\gamma$		–	340 ± 170
Subtracted	$193 \pm 33(147)$	255 ± 38	-80 ± 170
MC efficiency	10.4%	n/a%	n/a%
BB3 Expected	–	78 ± 9	78 ± 9

Table 3.1: Event counts for $\pi^0\omega$ analysis

not clear if these events are feedthrough from $p\overline{p}\rightarrow\pi^0\pi^0\eta$ or simply (unresonant) $p\overline{p}\rightarrow\pi^0\eta\gamma$ direct decays. There is no way of knowing in the ZZ or BZ analysis.

3.0.6 Results of BZ1

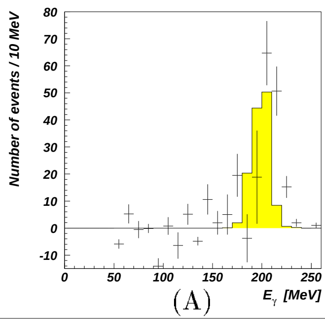
We have seen that the shoulder is well described, but the peak is not, because it is wider than the narrow signal is predicted. It is probably the case that the peak is mostly background from either $\pi^0\pi^0\eta$ or $p\overline{p}\rightarrow\pi^0\eta\gamma$. In the **BB3** analysis, these backgrounds both form similar broad backgrounds under the ω peak. In order to fit this broad background, one of two things was necessary. Either the background from $\pi^0\pi^0\eta$ was increased manually by 50%, or the new background from $p\overline{p}\rightarrow\pi^0\eta\gamma$ was introduced. Either greatly increases the quality of the fit, with the later slightly better. In either case, *in the BB3 analysis the absolute size of the background is independent of the measurement of the $\omega\rightarrow\eta\gamma$ peak which sits on top.*

However, in the ZZ3 and BZ1 analyses, both of these backgrounds form a "peak" at the same spot as the signal does. In fact, it appears from figure 3.2 that the wide width of the peak is better described by the $\eta\pi^0\gamma$ background (FWHM = 3-4 bins) than the desired signal (FWHM = 2 bins). Except for the fact that the peak from background is slightly wider, it is impossible to "fit" the data to signal plus background, because the background entirely swallows up the data.

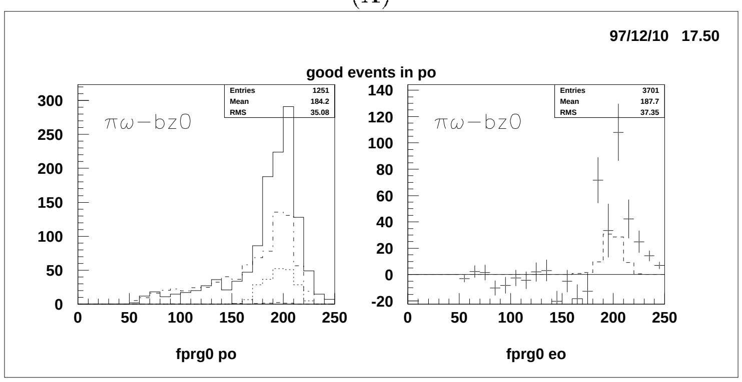
In the BZ1 analysis, we use a value of BR($\eta\pi^0\gamma$) of

$$BR(p\overline{p}\rightarrow\pi^0\eta\gamma) = 2.3 \times 10^{-4}$$

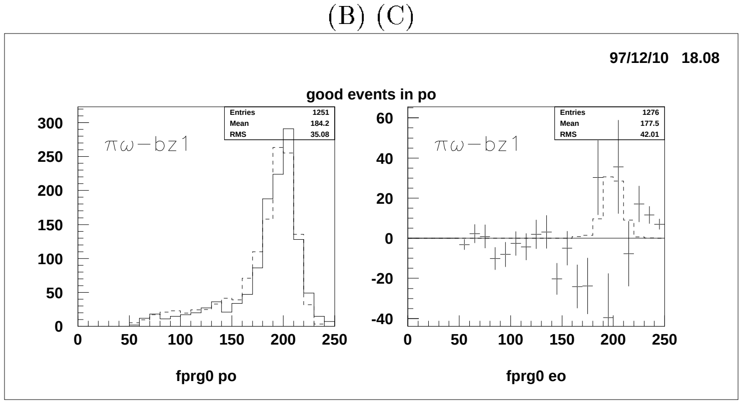
that is slightly (10%) less than that as determined in the BB3 technical report of BR($p\overline{p}\rightarrow\pi^0\eta\gamma$)= 2.5×10^{-4}, because it visually fits better. *Note that the background subtracted data is totally consistent with zero, including many negative-value bins!*



(A)



(B) (C)



(D) (E)

Figure 3.2: Final plots for $\pi^0\omega$. (A) Figure reproduced from C.Pietra's paper. (B) and (C) are the BZ0 analysis. (B) is before background subtraction, with the data (solid) and background (dashed). (C) is after background subtraction, with data (solid) and expected $\eta(\omega\rightarrow\eta\gamma)$ (from BB3 values) (dashed). (D) and (E) follow (B) and (C) for the BZ1 analysis.

Chapter 4

BB3 Analysis

To demonstrate the quality of the BB3 data, we include the mass spectra of the $\eta\gamma$ system, along with six different values of branching ratio for BR($\omega \rightarrow \eta\gamma$) (see figure 4.1). We fix BR($\rho^0 \rightarrow \eta\gamma$) = 4.0×10^{-4}, although this does not affect the result very much. The contributions to the data are as follows:

Channel	nickname	Events
$\eta((\omega/\rho^0) \rightarrow \eta\gamma)$	`ereog`	126
$\pi^0\eta\eta$	`eep`	970
$\eta\eta\gamma$	`eeg`	190 ± 40
$\eta(\omega \rightarrow \pi^0\gamma)$	`eopg`	15
$\pi^0\pi^0\eta$	`epp`	109
$\eta\eta$	`ee`	14

Each fit only has one free fit parameter, the intensity of BR($\eta\eta\gamma$). The intensity of BR($\pi^0\eta\eta$) was allowed to be free in other fits, without much affect on the final result. Because it's shape is similar to $\eta\eta\gamma$, the contributions from each are hard to accurately determine, so we fix one without significantly increasing the χ^2.

The last three contributions ($\eta(\omega \rightarrow \pi^0\gamma)$, $\pi^0\pi^0\eta$, and $\eta\eta$) have too few MC events to allow to be free in the fit, but they are distributed roughly evenly across the spectrum and do not contribute significantly to the peak.

The six values for BR($\omega \rightarrow \eta\gamma$) are as follows

BR($\omega \rightarrow \eta\gamma$)	comment
0.3×10^{-4}	lower limit on final value
0.8×10^{-4}	"visual" lower limit on final value
2.2×10^{-4}	Final value (from Dalitz plot fit)
3.3×10^{-4}	"visual" upper limit on final value
6.6×10^{-4}	Zurich final value
8.3×10^{-4}	PDG value (GAMS experiment)

It is clear that the GAMS values of 8.3×10^{-4} is clear incompatible with our data. It is also clear that the Zurich value of 6.6×10^{-4} does not appear to fit the data well.

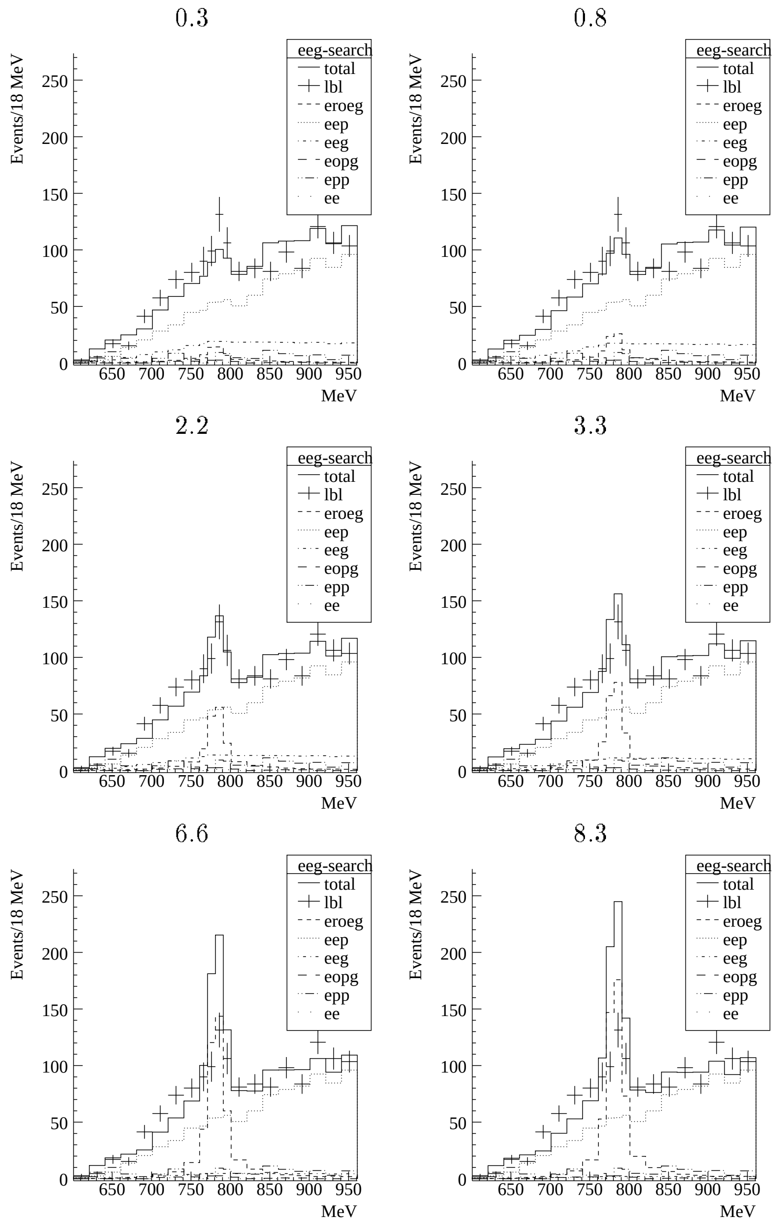


Figure 4.1: The invariant mass of $\eta\gamma$ in the $\eta\eta\gamma$ group, with MC predictions using different values of BR($\omega\rightarrow\eta\gamma$) ($10^{-4}$). Data is shown as points with error bars, the fit total is the solid line histogram. Other contributions are given in the legend.

Chapter 5

Discussion

5.1 ZZ3 vs BZ0, problems with intermediate results

The ρ^0-uncorrected values for ZZ3, $(6.5\pm1.1)\times10^{-4}$, and BZ0, $(5.0\pm0.8)\times10^{-4}$ disagree by more than one sigma, when they should be identical because they are from the same data set. However, on closer inspection, the intermediate results differ even more, especially the efficiencies. We list the troubling intermediate results:

1. The efficiencies are 50% different.

$$\frac{\epsilon(\eta(\omega\to\pi^0\gamma), BZ0)}{\epsilon(\eta(\omega\to\pi^0\gamma), ZZ3)} = \frac{32.7\%}{21.3\%} = 1.53$$

$$\frac{\epsilon(\eta(\omega\to\eta\gamma), BZ0)}{\epsilon(\eta(\omega\to\eta\gamma), ZZ3)} = \frac{25.3\%}{17.0\%} = 1.48$$

   Even though not unity which they should be, they essentially cancel to 3%, so this 50% effect is invisible in the final ratio. It still needs to be explained.

2. After correcting for the different efficiencies and size of the total data sets (LBL used 31% more data), both reference and signal channels are lower in ZZ3 as compared to BZ0, i.e. the efficiency corrected ratios are less than 1.0.

$$\frac{1}{1.31}\frac{N(\omega\to\pi^0\gamma, BZ0)\epsilon(\eta(\omega\to\pi^0\gamma), ZZ3)}{N(\omega\to\pi^0\gamma, ZZ3)\epsilon(\eta(\omega\to\pi^0\gamma), BZ0)} = \frac{89336}{1.31\cdot 50430\cdot 1.53} = 0.88$$

$$\frac{1}{1.31}\frac{N(\omega\to\eta\gamma, BZ0)\epsilon(\eta(\omega\to\eta\gamma), ZZ3)}{N(\omega\to\eta\gamma, ZZ3)\epsilon(\eta(\omega\to\eta\gamma), BZ0)} = \frac{159}{1.31\cdot 123\cdot 1.48} = 0.67\pm0.14$$

Because both are lower, the net effect for the final result is only 0.88/0.67 (i.e. $6.5 \times 10^{-4}/5.0 \times 10^{-4}$) or 31%.

3. Why the number of expected background events from $\pi^0\eta\eta$ are a factor of 6 different (225 vs 37), when it should be in a ratio of 1.31.

4. Why the total data events (signal + background) are a factor of 2.45 different (390 vs 159), when they should be in a ratio of 1.31.

The factors that were different in the analyses are summarized as follows:

1. A small fraction can be explained by the poorness of the confidence level in the Zurich analysis. We detuned the χ^2 values to mimic the worse confidence levels. By dividing the errors globally by $\sqrt{1.5}$, the efficiencies drop to

$$\frac{\epsilon(\omega \rightarrow \pi^0\gamma, BZ0')}{\epsilon(\omega \rightarrow \pi^0\gamma, ZZ3)} = \frac{24.1}{21.3} = 1.13$$

$$\frac{\epsilon(\omega \rightarrow \eta\gamma, BZ0')}{\epsilon(\omega \rightarrow \eta\gamma, ZZ3)} = \frac{18.7}{17.0} = 1.10$$

   However, the event counts also drop in a similar ratio, so this is not the answer. The confidence level distributions become much worse than shown in the Zurich paper, so this can not be the only answer.

2. The "split-off" software used in the Zurich analysis. From the description in the technical report, this does not appear to be any of the official suppression packages in the CBOFF library (Dolby-C, Brain, Taxi, Smart).

3. Problems in either CBKFIT (CBOFF) or KinFit++ (Lakata/LBL). While CBKFIT has been used more, CBKFIT is not the epitome of good software writing. In defense of KinFit++, it has been shown to work excellently in charge channels, with a high efficiency. A direct comparison of the two would be desirable, but involves a lot of work.

4. Because reanalyzing the entire data set with different cuts would take too long, we used the skim tape from BB3 which provided 5-γ events reconstructed with a 20 MeV PED threshold. By reanalyzing the skim data with 10 MeV PED thresholds, we lost some events. A check with MC data shows that double analyzing the data and MC lost about 12% of the events. *This means that the disagreement between Zurich and Berkeley MC efficiencies is even worse, or 68% instead of 50%.*

Without any help, we can only speculate on the problems. We encourage Zurich to release their raw data so that an event by event comparison can be made. We offer our summary data of the BZ0 analysis as well as the BB3 analysis to whomever wishes to check our data.

5.2 BZ0 vs BZ1, existence of background

The sole difference between BZ0 and BZ1 is the introduction of the "flat" background, $\eta\eta\gamma$. The evidence for this background is significant:

1. The measured value of the background agrees with a simply VDM calculation.

2. In the BB3 analysis, it improves the χ^2 of the fit significantly ($\Delta\chi^2 = 36$ for 133 DOF). It also stabilizes the scaling factors for the background as a function of CL cut.

3. "flat" backgrounds such as $\pi^0\eta\gamma$ and $\pi^0\pi^0\gamma$ improve the fits to their relative Dalitz plots too, and compare to VDM calculations also.

4. The measurements the pseudoscalar backgrounds, $\pi^0\eta\eta$, $\pi^0\pi^0\eta$ and $\pi^0\pi^0\pi^0$, are all too high as compared to prediction tabulated values, about 3 sigmas in the case of $\pi^0\pi^0\eta$.

5. *Without it, the BZ0 analysis does not agree with BB3. With it, the BZ1 analysis agrees perfectly with BB3.*

The BB3 analysis is superior to BZ or ZZ analyses, because it has little dependence on the existence of this background. *The results of the ZZ and BZ analyses are 100% correlated to the size of this $\eta\eta\gamma$ background, and can not decide the question.* The uncertainty alone is reason enough to chose BB3 over ZZ3.

5.3 Final remarks

We feel that we have shown that the BZ analyses are internally consistent for the measurement of the reference signal ($\omega \rightarrow \pi^0\gamma$), and that the BZ1 is consistent with the BB3 analysis. We feel we have also shown that the Zurich technique can not check background contamination, and is sensitive to any background that was not explicitly included in the calculation. The 31% difference in BZ0 and ZZ3 can only be resolved by an event-by-event comparison of the two data sets, which we are willing to try if the Zurich data is available.

We would like to see the Crystal Barrel publish a paper that supercedes its previous paper with the new result, on the grounds that it

1. Does not rely on any pre-measured branching ratios for backgrounds (or absolute MC calculations of the background)

2. Is self-consistent with a reanalysis using the Zurich method.

3. Has higher statistics

4. The Zurich result is called into question because of experimental evidence and some theoretical support for the evidence of a $p\overline{p} \rightarrow \eta\eta\gamma$ "flat" background.