Study of E/ι decay to $\eta\pi\pi$ in $\overline{p}p$ annihilation to $4\pi\eta$

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ABSTRACT

The annihilation channel $\overline{p}p \longrightarrow \pi^+\pi^-\pi^0\pi^0\eta$ was studied with the Crystal Barrel detector using antiprotons from LEAR stopping in liquid hydrogen. A sophisticated trigger allowed us to collect more than 100'000 kinematically fitted events. A clear resonance is seen in the E/ι region (around 1400 MeV) in both the $\pi^+\pi^-\eta$ and the $\pi^0\pi^0\eta$ invariant mass spectra. First attempts to determine spin and parity using the isobar model are presented.

1 History of the E/ι and motivation

In 1967 the CERN-Collège de France group saw a resonance at 1400 MeV in the K$\overline{K}\pi$ system [1], which they named E-meson. It was discovered in $\overline{p}p$ annihilation at rest into $K^{\pm}K_s\pi^{\mp}\pi^+\pi^-$. Its quantum numbers were determined to be 0^{-+}. The decay modes to K*(892)$\overline{K}$ and a$_0\pi$ had equal strengths. Since then other groups also found one or more resonances in the same energy region but spin, parity and decay modes remained controversial. Table 1 shows a selected overview of the experimental situation. For more details we refer to the compilation of the Particle Data Group. The E/ι is also observed by the Obelix Collaboration at LEAR [12] with results similar to those observed by Mark III [10].

[1] C. Amsler[1], D.S. Armstrong[2], I. Augustin[3], C.A. Baker[4], B.M. Barnett[5], C.J. Batty[4], K. Beuchert[6], P. Birien[7], P. Blüm[3], R. Bossingham[7], K. Braune[8], J. Brose[5], D.V. Bugg[9], M. Burchell[10], T. Case[7], S.U. Chung[5], A. Cooper[9], O. Cramer[8], K.M. Crowe[7], T. Degener[6], H.P. Dietz[8], S. v. Dombrowski[1], M. Doser[10], W. Dünnweber[8], D. Engelhardt[3], M. Englert[8], M.A. Faessler[8], C. Felix[8], R. Hackmann[5], R.P. Haddock[11], F.H. Heinsius[7], M. Herz[5], N.P. Hessey[10], P. Hidas[12],P. Illinger[8], D. Jamnik[8], H. Kalinowsky[5], B. Kämmle[13], T. Kiel[3], J. Kisiel[8], E. Klempt[14], M. Kobel[10], H. Koch[6], C. Kolo[8], K. Königsmann[8], M. Kunze[6], M. Lakata[7], R. Landua[10], F. Loser[13], J. Lüdemann[6], H. Matthäy[6], M. Merkel[5], J.P. Merlo[5], C.A. Meyer[15], L. Montanet[10], A. Noble[1], F. Ould-Saada[1], K. Peters[6], C.N. Pinder[4], G. Pinter[12], S. Ravndal[6], C. Regenfus[8], J. Salk[6], E. Schäfer[5], P. Schmidt[13], R. Seibert[13], S. Spanier[5], H. Stöck[6], C. Straßburger[14], U. Strohbusch[13], M. Suffert[16], U. Thoma[14], D. Urner[1], C. Völcker[8], F. Walter[5], D. Walther[6], U. Wiedner[13], N. Winter[3], J. Zoll[9], B.S. Zou[9] and Č. Zupančič[8]
Zurich[1] - William and Mary[2] - Karlsruhe[3] - RAL[4] - Mainz[5] - Bochum[6] - LBL[7] - Munich[8] - QMC[9] - CERN[10] - UCLA[11] - Budapest[12] - Hamburg[13] - Bonn[14] - Carnegie Mellon[15] - Strasbourg[16]

Table 1: The E/ι observed in various experiments

Experiment	Reaction	J^{PC}	E/ι decay	Mass MeV	Γ MeV	Ref
CCDF	$\overline{p}p \to K\overline{K}\pi\pi\pi$	0^{-+}	$a_0\pi \to K\overline{K}\pi$	1425 ± 7	80 ± 10	[1]
		0^{-+}	$\overline{K}K^*(892)$			
Crystal Ball	$J/\Psi \to \gamma K^0_s K^\pm\pi^\mp$	0^{-+}	$a_0\pi \to K\overline{K}\pi$	1440^{+10}_{-15}	50^{+30}_{-20}	[2]
MPS	$\pi^- p \to K\overline{K}\pi n$	0^{-+}	$a_0\pi \to K\overline{K}\pi$	1421 ± 2	60 ± 10	[3]
KEK	$\pi^- p \to \eta\pi^+\pi^- n$	0^{-+}	$a_0\pi \to \eta\pi\pi$	1420 ± 5	31 ± 7	[4]
Mark III	$J/\Psi \to \omega K\overline{K}\pi$	1^+	$K\overline{K}\pi$	1442^{+15}_{-18}	40^{+18}_{-14}	[5]
ASTERIX	$\overline{p}p \to$ $\pi^+\pi^- K^\pm\pi^\mp K^0$	0^{-+}	$a_0\pi \to K\overline{K}\pi$	1413 ± 8	62 ± 16	[6]
CELLO	$e^+e^- \to$ $e^+e^- K^0_s\overline{K}\pi$	1^{++}	$\gamma\gamma \to K^0_s K\pi$	1425 ± 10	42 ± 22	[7]
DM2	$J/\Psi \to \gamma K\overline{K}\pi$	0^{-+}	$a_0\pi \to K\overline{K}\pi$	1459 ± 5	75 ± 9	[8]
		0^{-+}	$\overline{K}K^*(892)$	1421 ± 14	63 ± 18	
		1^{++}	$\overline{K}K^*(892)$	1462 ± 20	129 ± 41	
WA 76	$(\pi^+/p)p \to$ $(\pi^+/p)K\overline{K}\pi p$	1^{++}	$\overline{K}K^*(892)$	1430 ± 4	58 ± 10	[9]
Mark III	$J/\Psi \to$ $\gamma K^0_s K^\pm\pi^\mp$	0^{-+}	$\overline{K}K^*(892)$	1490^{+14}_{-18}	91^{+69}_{-49}	[10]
		1^{++}	$\overline{K}K^*(892)$	1443^{+8}_{-6}	68^{+30}_{-20}	
		0^{-+}	$a_0\pi \to K\overline{K}\pi$	1416^{+11}_{-9}	54^{+39}_{-32}	
	$J/\Psi \to \gamma\eta\pi^+\pi^-$	0^{-+}	$a_0\pi \to \eta\pi\pi$	1400 ± 6	46 ± 13	[11]

We are investigating E/ι decay into $\pi\pi\eta$ to clarify the following questions:

- Can we confirm the 0^{-+} state at 1420 MeV?
- Do we also see the 0^{-+} state at 1490 MeV decaying to $\eta\pi\pi$?
- Is there a 1^{++} contribution?
- What are the branching ratios for the decay modes E/ι $\to$a$_0\pi$, E/$\iota \to \eta(\pi\pi)_{s-wave}$?

We collected a large data set on the $4\pi\eta$ final state, containing two E/ι samples with approximately 5000 reconstructed events for each $\overline{p}p$ $\to$E/$\iota(\to \pi^0\pi^0\eta)(\pi^+\pi^-)$ and $\overline{p}p$ $\to$E/$\iota(\to \pi^+\pi^-\eta)(\pi^0\pi^0)$.

2 Trigger on the $\pi^+\pi^-\pi^0\pi^0\eta$ final state

The Crystal Barrel experiment has a complex trigger system which is outlined in figure 1 and described in more details in ref [13]. To collect the present data we used, for the first time, all levels of the trigger system (including the hardwired FACE

Table 2: Trigger requirements for the $\pi^+\pi^-\pi^0\pi^0\eta$ final state

			Enrichment factor
Charged multiplicity	2	long tracks	4.0
FACE	8	clusters	5.2
Total energy	950-1700	MeV	1.1
Software trigger			3.1
	8	clusters	
Max $2\pi^0$ within mass window	121-149	MeV	
Max 2η within mass window	520-578	MeV	
Max 1 'none' outside π^0, η window			
Total enrichment			71

processor and software trigger). The enrichment factor for the hardware and software triggers is shown in table 2. The software trigger calculates the energy and the angles of the crystal clusters and selects exactly 8 clusters. Using the energies and angles of $\gamma\gamma$ pairs it then forms all possible invariant mass combinations of four-meson final states. An event is accepted if one combination is found to fulfil the requirements given in table 2. Since the software trigger uses only information from the crystals it cannot distinguish energy deposits from charged and neutral particles. An event with two charged tracks usually generates two clusters in the barrel which are not due to

PWC: 2 Proportional Wire Chambers, 90 resp. 150 anode wires

JDC: Jet Drift Chamber, 30 sectors each with 23 wires per layer

XTAL: CsI(Tl) Crystals, 1380 channels

Pil: Pileup: rejects the event if a second event is detected within -8 and +6 μs

Mult: Multiplicity logic: calculates the number of charged tracks

FACE: FAst Cluster Encoding: counts the number of clusters (using a bitmap) for crystals with more than 20 MeV energy deposit.

tot E: accepts the event if the total energy is in a given window

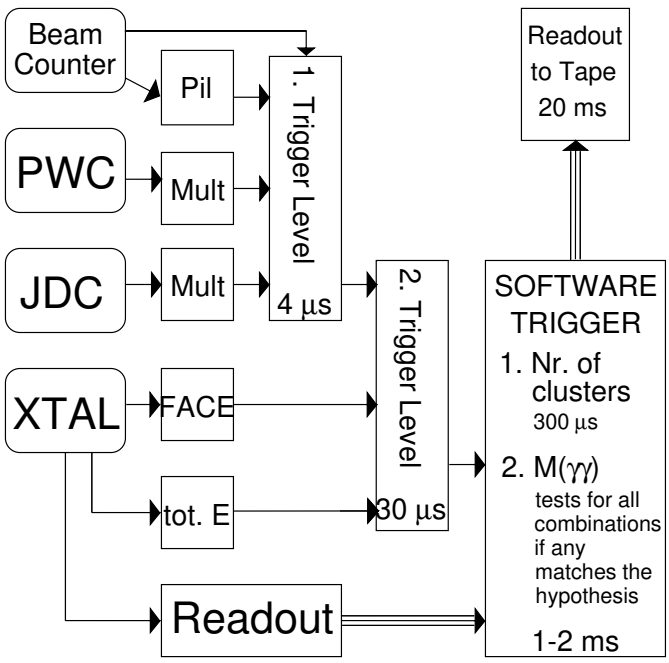

Figure 1: The Crystal Barrel Trigger Logic

photons and which therefore do not match the mass of a neutral meson decaying to $\gamma\gamma$. This is the reason for accepting 1 'none'. We have collected 5'832'000 triggered events in 8 days of beam time. This corresponds to 4.1×10^8 $\overline{p}p$ annihiliations at rest.

Figure 2 shows the momentum resolution for charged pions of the JDC, compared to the photon resolution, measured for events of the type $\pi^0\eta$ and $\pi^0\gamma$. The resolution of the JDC is almost at its design value (inset) and is comparable to or even better than the crystal resolution at low momenta.

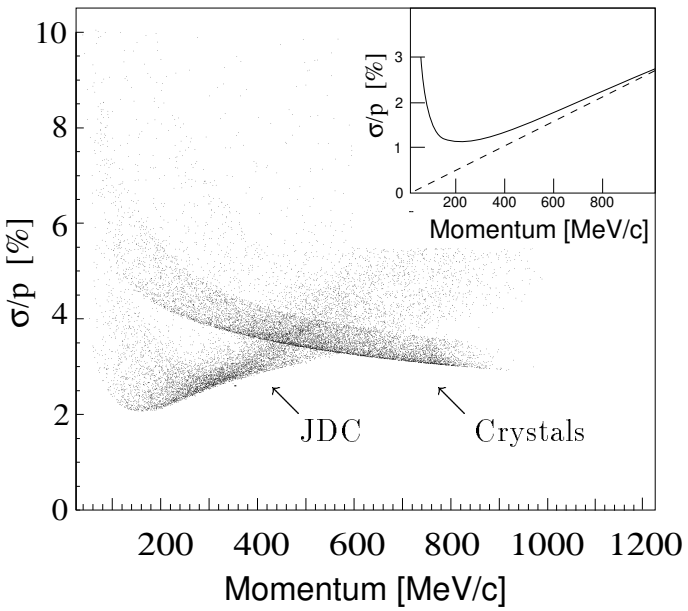

Figure 2: Resolution of the Crystal Barrel JDC, compared to the crystal resolution for photons. The inset shows the calculated JDC resolution [14].

3 Data reduction

After event reconstruction, a 7C kinematic fit was applied to select $\pi^+\pi^-\pi^0\pi^0\eta$ events satisfying the following three hypotheses:

- momentum and energy conservations, three $\gamma\gamma$ invariant masses consistent with $2\pi^0$'s and 1 η (signal events),
- momentum and energy conservations, three $\gamma\gamma$ invariant masses consistent with $3\pi^0$'s (background events),
- momentum and energy conservations, three $\gamma\gamma$ invariant masses consistent with $1\pi^0$ and 2 η's (background events).

An event was accepted if the confidence level for the signal hypothesis was above 20% and if the confidence level for both background hypotheses was smaller than 1%. This led to 370'000 $\pi^+\pi^-\pi^0\pi^0\eta$ events. Plotting the $2\pi\eta$ invariant mass distribution, one observes an enhancement around 1400 MeV (figure 3a and b).

Since we are working with a five particle final state, a two-dimensional scatterplot does not show all the structures. Plotting the $\pi^+\pi^-\pi^0$ vs. $\pi^0\eta$ mass distribution, one observes a strong ω signal (figure 3c and d). The main contribution stems from the annihilation channel $p\bar{p} \rightarrow a_0\omega$: there are indeed 212'000 events which satisfy an 8C kinematic fit to the $\omega\pi^0\eta$ hypothesis with a confidence level of more than 20%. Removing those events which satisfy the $\omega\pi^0\eta$ fit (and the hypothesis $\pi^0\eta(\rightarrow \gamma\gamma)\eta(\rightarrow \pi^+\pi^-\pi^0)$) with a confidence level of more than 1%, reduces the sample size to one third.

In the $\eta\pi\pi$ mass distribution (figure 3a and b) one observes a strong η' signal. For

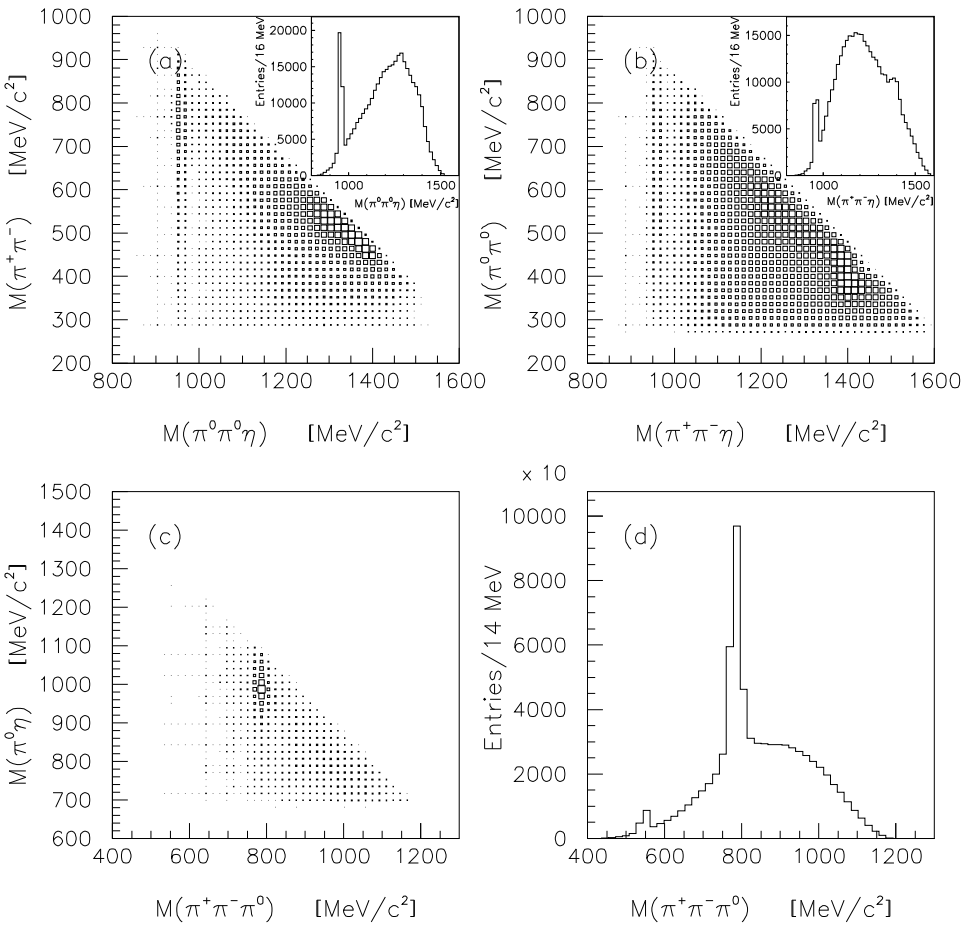

Figure 3: $\pi\pi\eta$ vs $\pi\pi$ mass scatterplots (a), (b). The insets shows the $\pi\pi\eta$ mass projections. $\pi^+\pi^-\pi^0$ vs $\pi^0\eta$ scatterplot (c) and $\pi^+\pi^-\pi^0$ mass distribution (d).

the preliminary fit presented here we removed the η' contribution for those events with a $\pi\pi\eta$ invariant mass in the mass range 958$\pm$10 MeV. This is a dangerous cut since events under the $\eta'(\rightarrow \pi^0\pi^0\eta(\pi^+\pi^-\pi^0))$ peaks also contribute to the $\pi^+\pi^-\eta(\pi^0\pi^0\eta)$ invariant mass spectrum in the 1400 MeV region. The final fit will have to include η' decay.

The 104'000 events surviving these cuts were used in the following fits. The $\pi\pi$ and $\pi\pi\eta$ distributions are shown in figure 4. The insets in figure 4 show the $\pi\pi\eta$ mass projections for recoiling $\pi\pi$ pairs with masses below 520 MeV. This cut enhances the E/ι signals but is not applied in the amplitude analysis, since events with recoiling $\pi^+\pi^-(\pi^0\pi^0)$ masses above 520 MeV also contribute to the $\pi^0\pi^0\eta(\pi^+\pi^-\eta)$ mass distributions in the E/ι region.

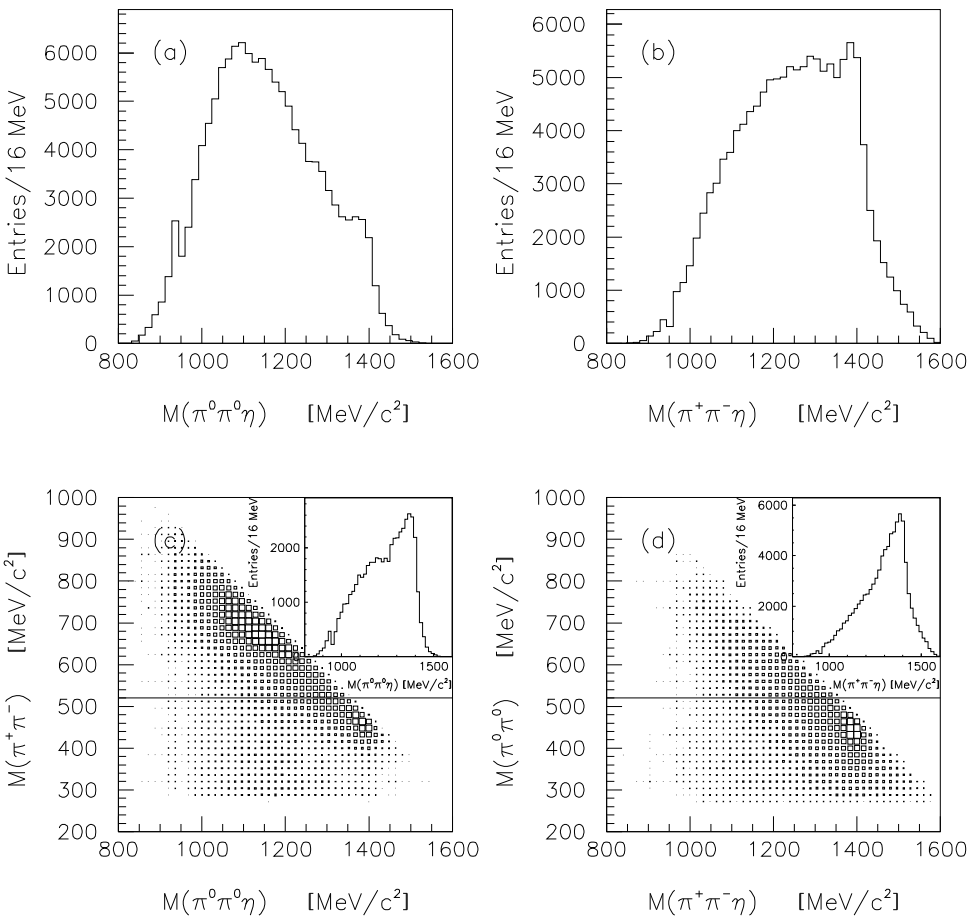

Figure 4: $\pi^0\pi^0\eta$ (a) and $\pi^+\pi^-\eta$ (b) invariant mass distributions and $\pi\pi$ vs. $\pi\pi\eta$ scatterplots (c)(d). Insets: $\pi\pi\eta$ distributions for recoiling $\pi\pi$ masses below 520 MeV (horizontal line in (c) and (d)).

4 Monte Carlo simulation

We have generated 5.8 million $\pi^+\pi^-\pi^0\pi^0\eta$ events with the Crystal Barrel Monte Carlo package (based on GEANT3.14) of which 1.1 million were accepted by the trigger simulator. Submitting these events to the same reconstruction procedure as real data (7C fit, ω cut, η' cut) we were left with 190'000 simulated events. The most prominent background channel is the $\pi^+\pi^-3\pi^0$ final state for which we generated 430'000 events. Only 50 events were however accepted as $\pi^+\pi^-\pi^0\pi^0\eta$ events. We therefore conclude that the contribution of $\pi^+\pi^-3\pi^0$ to the final data sample is about 3%, assuming a ratio of branching ratios ($\pi^+\pi^-3\pi^0/\pi^+\pi^-2\pi^0\eta$) of 10.

5 Preliminary spin-parity fit

The following fits use only about half of the available real and Monte Carlo data samples: 48'000 data and 98'000 Monte Carlo events. We analyze the data with the helicity formalism using the isobar model, in which the $\overline{p}p$ system is assumed to decay to $\pi^+\pi^-\pi^0\pi^0\eta$ through two-body intermediate states. The E/ι (0^{-+} or 1^{++}) can be produced in two different ways from the ${}^1S_0(J^{PC}=0^{-+})$ initial atomic state: $\overline{p}p \rightarrow$E/$\iota(\pi^+\pi^-)_s$ and $\overline{p}p \rightarrow$E/$\iota(\pi^0\pi^0)_s$, where the dipion is in a relative S-wave. Owing to parity and C- parity conservations, annihilation into E/$\iota(\pi\pi)_s$ cannot occur from the ${}^3S_1(J^{PC}=1^{--})$ initial state. We also assume, as usual, S-state annihilation dominance in liquid hydrogen and neglect annihilation from P states.

The data are fit using the maximum-likelihood method, by calculating a weight for every event in the 8-dimensional space of kinematic variables and minimising the quantity -2*log$L$ (Likelihood). We emphasize that the present fit is not satisfactory yet but some conclusions can already be drawn. The following three hypotheses were tried:

$$ {}^1S_0(J^{PC}=0^{-+}) \rightarrow \eta f_0(1365) \rightarrow (\pi^+\pi^-)_s(\pi^0\pi^0)_s \qquad (1) $$

$$ \begin{aligned} {}^1S_0(J^{PC}=0^{-+}) &\rightarrow (\pi\pi)_{s-wave}0^{-+}(M=1410\text{MeV})\,,\,\Gamma=60\text{ MeV}) \\ 0^{-+}(1410) &\rightarrow \eta(\pi^+\pi^-)_s \rightarrow \eta(\pi^0\pi^0)_s \\ &\rightarrow \pi^+a_0^-{}_{\rightarrow\eta\pi^-} \rightarrow \pi^-a_0^+{}_{\rightarrow\eta\pi^+} \\ &\rightarrow \pi_1^0a_0^0{}_{\rightarrow\eta\pi_2^0} \rightarrow \pi_2^0a_0^0{}_{\rightarrow\eta\pi_1^0} \end{aligned} \qquad (2) $$

$$ \begin{aligned} {}^1S_0(J^{PC}=0^{-+}) &\rightarrow (\pi\pi)_{s-wave}1^{++}(1380\text{ MeV}) \\ 1^{++}(1380) &\rightarrow \eta(\pi^+\pi^-)_s \rightarrow \eta(\pi^0\pi^0)_s \\ &\rightarrow \pi^+a_0^-{}_{\rightarrow\eta\pi^-} \rightarrow \pi^-a_0^+{}_{\rightarrow\eta\pi^+} \\ &\rightarrow \pi_1^0a_0^0{}_{\rightarrow\eta\pi_2^0} \rightarrow \pi_2^0a_0^0{}_{\rightarrow\eta\pi_1^0} \end{aligned} \qquad (3) $$

An incoherent contribution of Monte Carlo events (simulated according to phase space distribution) is also allowed in all fits.

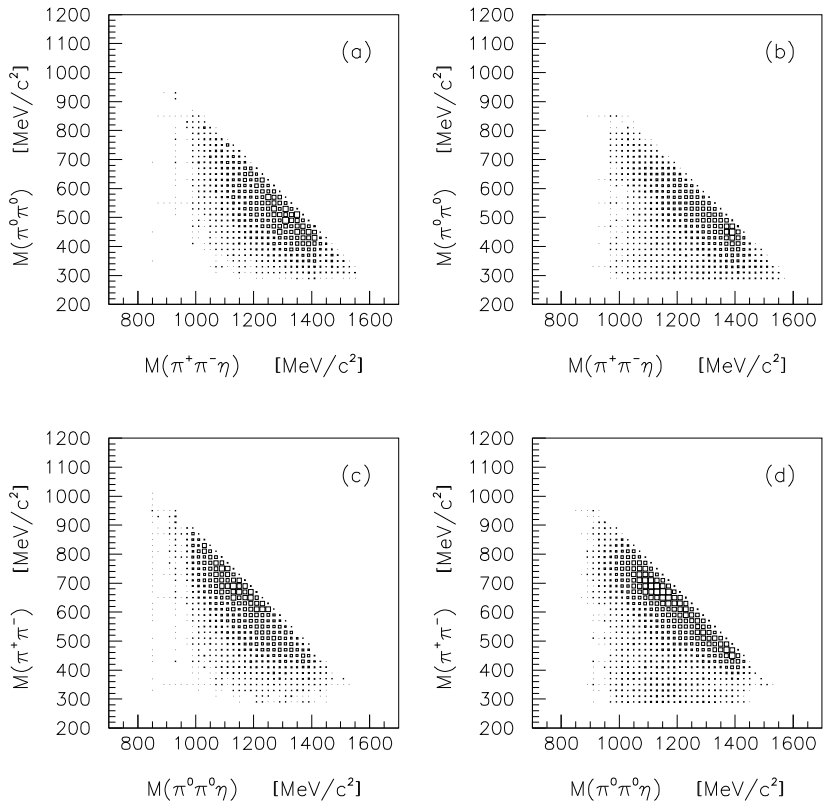

Figure 5: Fitted predictions for $\pi\pi\eta$ vs $\pi\pi$ mass scatterplots (left) compared to data (right).

The fit needs the $f_0(1365)$ (hypothesis (1)) with a large contribution. Without $f_0(1365)$ (e.g. hypothesis (2) only) the likelihood increases by 8000. By $f_0(1365)$ we mean the resonance that was observed earlier by this collaboration in the $\pi^+\pi^-3\pi^0$ final state [15], with a mass of 1365 MeV and a width of 280 MeV. Removing the $0^{-+}(1410)$ (hypothesis (2)) increases the likelihood by 2800. The fit accepts hypothesis (2) with 5% total contribution (figure 5) with reasonably stable mass and width.

Replacing the 0^{-+} (hypothesis (2)) by a 1^{++} state (hypothesis (3)) increases the likelihood by 2000, but using hypothesis (1) (2) and (3) decreases the likelihood by 800. We therefore cannot exclude a 1^{++} state at 1400 MeV. Other possible decay chains will have to be included and the full statistics used before definitive conclusions can be reached. Branching ratios for the two decay modes cannot be given yet, but the current fit needs both the $a_0\pi$ and the $\eta(\pi\pi)_{s-wave}$.

6 Conclusions

We have shown that final states with a small branching ratio can be enhanced by large factors with the online triggers of the Crystal Barrel apparatus. For $\pi^+\pi^-\pi^0\pi^0\eta$ the enhancement factor is 70. The resolution of the JDC has now achieved its design

value. The momentum resolution for charged particles and the energy resolution for photons are comparable.

A signal is observed in the $\pi^+\pi^-\eta$ and $\pi^0\pi^0\eta$ mass distributions ($\sim$5000 events each), consistent with E/ι. A preliminary maximum likelihood fit has been performed to determine spin, parity and decay modes. The results are still very preliminary, but the following can be stated:

- The fit requires the decay chain $p\overline{p} \to \eta$ f$_0$(1365) with a large contribution.
- The fit needs a 0^{-+} state with preliminary mass 1410 MeV and width 60 MeV, compatible with the E of Baillon et al.[1].
- The fit requires both decays $0^{-+} \to a_0\pi$ and $0^{-+} \to \eta(\pi\pi)_s$
- A 1^{++} contribution is not excluded.

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