CB - Note 281

Technical Report of the $p\bar{p} \to \omega\omega$, $\omega \to \pi^0\gamma$ - Analysis at Rest in LH_2

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1 Data and Preselection

For the analysis of the reaction $p\overline{p} \rightarrow \omega\omega,\ \omega \rightarrow \pi^0\gamma$ in liquid hydrogen at rest all - neutral data from the run - periods June, July and November 1990 have been taken. Preselection - cuts rejected events, which could not satisfy simplest requirements for this reaction:

- no residual charged tracks in the JDC
- exactly 6 PEDs ($E_{PED} > 20\,MeV$)
- no PEDs in crystal type #13
- no split - offs (identified by smart)
- energy- an momentum window of $\mid \Delta E \mid = c \mid \Delta p \mid \leq 150\,MeV$

The data - reduction is shown in table 1.

run - period	# phys. events	# no JDC tracks	# 6 PED - events	# no cry- stall #13	# without split - offs	# $E/\vec{p}$ - window
June/July 1990	5332785	4788480	1048240	887554	831958	628838
Nov. 1990	4287832	3888401	842795	726064	683812	553305

Table 1: Data - reduction by preselection

2 Kinematic Fitting and Further Selection

The remaining data were subjected to a kinematic fit with CBKFIT to following hypotheses:

1. hypothesis 6γ (phase - space)
2. hypothesis $p\overline{p} \rightarrow \omega\omega,\ \omega \rightarrow \pi^0\gamma$
3. hypothesis $\pi^0\pi^0\gamma\gamma$

background:

4. hypothesis $\pi^0\pi^0\pi^0$
5. hypothesis $\pi^0\pi^0\eta$
6. hypothesis $\pi^0\eta\eta$
7. hypothesis $\eta\eta\eta$
8. hypothesis $\pi^0\pi^0\eta'$
9. hypothesis $\pi^0\eta\eta'$
10. $\pi^0\pi^0\omega$ mit $\omega \rightarrow \gamma\gamma$ (one γ lost)

All mesons decay into photons. The error - factors were defined by normalized $\sqrt{E}$- and angular pulls of phase - space. Table 2 shows energy - resolution, error - factors for azimutal - angles Φ and polar - angles Θ and their standard - deviations. The distributions of pulls and confidence - levels (cl) are shown in

data	$\Delta\Phi$	σ_{Phi}	$\Delta\Theta$	σ_{Θ}	ΔE
June/July 90	1.06	1.017	1.06	1.035	2.8 %
November 90	1.02	0.995	1.10	0.992	2.2 %
MC	1.02	1.046	1.10	1.051	2.0 %

Table 2: Multiplicators for angular - and energy - errors and the resulting pull - widths for different run - periods and monte - carlo events

figures 1 and 2. All pulls except that of the energy are Gaussian - distributed with standard - deviations of ~ 1.

With the fit - results further selection - criteria were applied:

- Energy- and momentum conservation is guaranted by demanding a cl of 1% for the phase - space fit.

- The cl of hypothesis $\pi^0\pi^0\gamma\gamma$ must be higher than 10% and the cls of all background - hypotheses. The ω - mesons were reconstructed by their decay pions and -photons. The invariant $\pi^0\gamma$ masses show a clear omega - signal (figure 3). By fitting the peak with a voigt - profile one found an experimental width of $(14.76 \pm 0.20)MeV$.

From the two possible $\pi^0\gamma$ combinations that one was used, where the sum of squared deviations from the $\pi^0\gamma$ masses to the ω - mass is minimum:

$$(m_{\pi\gamma}^{c1} - m_\omega)^2 + (m_{\pi\gamma}^{c2} - m_\omega)^2 \stackrel{!}{=} Min$$

The very rare events, where both combinations lie in a circle of 40 MeV around the ω - mass, were rejected.

- In case of convergence of background hypotheses a cut demonstrated in figure 4 was applied. The cl of background hypotheses (in the example $\pi^0\pi^0\pi^0$) were plotted versus the cl of hypotheses 2. As selection - criteria a straight line were used. Slope and intercept have been adapted for each background - channel by means of MC studies.

- The energies of the pions and photons from the omega - decay have to lie in a window defined by kinematics. After this cut we receive the invariant $\pi^0\gamma$ - mass spectrum shown in figure 5.

- Having demanded a cl for hypothesis $p\overline{p} \rightarrow \omega\omega, \omega \rightarrow \pi^0\gamma$ of 1% we only lost 5% of good events, while background was reduced considerably.

- At last only events were used, where the invariant $\pi^0\gamma$ - masses lie in a circle of 40 MeV around the omega - mass.

run - period	# after presel.	# 4C - fit converges	# $(\pi\pi\gamma\gamma)-$ cl $\geq 10\%$	background: cl $\leq \ldots$	# $\omega\omega$- events	fraction of total #
November 90	553305	397574	208300	26319	4984	$11.6 \cdot 10^{-4}$
Juni/Juli 90	628838	483669	244255	35714	6596	$12.4 \cdot 10^{-4}$

Table 3: Further reduction of preselected events.

The reduction of data by this selection - process can be taken from table 3.

3 Monte - Carlo Studies

In order to determine the efficiency of the selection - process and feed - through for background events, some channels with 7,6 and 5 photons in the final state have been simulated by CBGEANT. The decay - products were simulated phase - space distributed. The data - reduction of the generated channels is shown in table 4. The detection - efficiency of reaction $p\overline{p} \rightarrow$

channel	# generated events	# after presel.	# $(\pi\pi\gamma\gamma)-$ cl $\geq 10\%$	background: cl $\leq \ldots$	# after last cut	detection probab.
$\omega\omega$	100000	43918	22667	21100	18477	18.48%
$\pi\pi\omega$	120000	16560	4577	2903	207	0.17%
$\pi\eta\omega$	80000	9770	539	381	18	$2.25 \cdot 10^{-4}$
$\pi\pi\pi$	100000	44089	20761	1331	1	10^{-5}
$\pi\pi\eta$	30000	13325	3168	248	0	0
$\pi\eta\eta$	20000	9264	323	58	5	$2.25 \cdot 10^{-4}$
$\eta\eta\eta$	5000	2486	23	6	0	0
$\pi\pi\eta'$	20000	8541	2041	157	1	$5 \cdot 10^{-5}$
$\pi\eta\eta'$	5000	2270	101	19	1	$2 \cdot 10^{-4}$
$\omega\pi$	5000	10	0	0	0	0
$\omega\eta$	5000	10	0	0	0	0
$\omega\eta'$	5000	10	0	0	0	0

Table 4: Reduction of monte - carlo data by the selection. The last column contains the probability for the identification of an event as reaction $p\overline{p} \rightarrow \omega\omega$, $\omega \rightarrow \pi^0\gamma$.

$\omega\omega$, $\omega \rightarrow \pi^0\gamma$ is $18.5 \pm 1.0\%$. All background channels, even the strong three pion channel, could be suppressed quite well. The only remarkable rest origines from the reaction $\pi^0\pi^0\omega$, where a low - energy photon has not been reconstructed. Five - photon channels do not contribute at all.

4 The Branching - Ratio of the Reaction $p\bar{p} \rightarrow \omega\omega$

Because of the enrichment of neutral events during the data - acquisition, first the corresponding total number of annihilations N_G had to be determined. The taken inverse enrichment - factor ϵ_0 was $(3.9\pm0.3)\%$[2]. Furthermore N_G

is reduced by two correction - factors, because not all annihilations happened at rest and in the target:

$$\begin{aligned} \epsilon_{Ruhe} &= (94.3 \pm 1.1)\% \\ \epsilon_{Target} &= (96.1 \pm 0.7)\% \end{aligned}$$

N_0 being the number of zero - prong events, N_G is calculated by

$$N_G = \frac{N_0 \cdot \epsilon_{Ruhe} \cdot \epsilon_{Target}}{\epsilon_0}$$

$$= (123.7 \pm 9.7) \cdot 10^6 \quad \text{for June/July 1990}$$
$$= (99.5 \pm 7.8) \cdot 10^6 \quad \text{for November 1990}$$

With the known background branching ratios (table 5) and feed - through probabilities received by monte - carlo (table 3), the contributing background in the final sample could be calculated. The error of the efficiencies was

channel	branching - ratio	fraction in 5, 6 or 7 photons
$\pi\pi\omega$	$(2.00 \pm 0.21) \cdot 10^{-2}$	$(0.164 \pm 0.027) \cdot 10^{-2}$
$\pi\eta\omega$	$(0.68 \pm 0.01 \pm 0.05) \cdot 10^{-2}$	$(0.022 \pm 0.002) \cdot 10^{-2}$
$\pi\pi\pi$	$(0.62 \pm 0.10) \cdot 10^{-2}$	$(0.60 \pm 0.16) \cdot 10^{-2}$
$\pi\pi\eta$	$0.66 \cdot 10^{-2}$	$0.25 \cdot 10^{-2}$
$\pi\eta\eta$	$(0.20 \pm 0.06) \cdot 10^{-2}$	$(0.030 \pm 0.010) \cdot 10^{-2}$
$\eta\eta\eta$		
$\pi\pi\eta'$		
$\pi\eta\eta'$	$(2.5 \pm 0.5) \cdot 10^{-4}$	$(2.1 \pm 0.6) \cdot 10^{-6}$
$\omega\pi$	$(5.73 \pm 0.47) \cdot 10^{-4}$	$(0.481 \pm 0.0286) \cdot 10^{-4}$
$\omega\eta$	$(1.51 \pm 0.12) \cdot 10^{-2}$	$(4.99 \pm 0.36) \cdot 10^{-4}$
$\omega\eta'$	$(0.78 \pm 0.08) \cdot 10^{-2}$	$(0.144 \pm 0.019) \cdot 10^{-4}$

Table 5: Possible background - channels and, if known, their branching - ratios into 5,6 or 7 photon final states

estimated by a statistic error and systematic part of 5.2% [1].

$$\begin{array}{rcl} \epsilon_{\omega\omega} & = & (18.5 \pm 0.1_{stat.} \pm 1.0_{syst.})\% \\ \hline \epsilon_{\pi\pi\omega} & = & (17.3 \pm 1.2_{stat.} \pm 0.9_{syst.}) \cdot 10^{-4} \\ \epsilon_{\pi\pi\pi} & = & (1 \pm 1_{stat.}) \cdot 10^{-5} \\ \epsilon_{\pi\eta\eta} & = & (2.3 \pm 1,0_{stat.} \pm 0.1_{syst.}) \cdot 10^{-4} \\ \epsilon_{\pi\eta\omega} & = & (2.3 \pm 0,5_{stat.} \pm 0.1_{syst.}) \cdot 10^{-4} \end{array}$$

Thus have following remaining background contribution:

	June/July 1990	November 1990
$N_{\pi\pi\omega}$	(352 ± 59)	(282 ± 42)
$N_{\pi\pi\pi}$	(11 ± 11)	(9 ± 9)
$N_{\pi\eta\eta}$	(9 ± 4)	(7 ± 3)
$N_{\pi\eta\omega}$	(6 ± 1)	(5 ± 1)

Subtracted from the surviving number of events one got $N_{\omega\omega} = (6218 \pm 154)$ good events for June/July 1990 and (4680 ± 125) for November, which can be regarded as "real" $\omega\omega$ - events. With the efficiency $\epsilon_{\omega\omega}$ and the decay - probabilities of the mesons the branching - ratio for $p\bar{p} \to \omega\omega$ is

$$BR(p\bar{p} \to \omega\omega) = \frac{N_{\omega\omega}}{N_G \cdot \epsilon_{\omega\omega} \cdot BR^2(\omega \to \pi^0\gamma) \cdot BR^2(\pi^0 \to \gamma\gamma)} =$$

$(3.86 \pm 0.55)\%$	for June/July 1990
$(3.62 \pm 0.52)\%$	for November 1990

(errors by gaussian error - propagation).

This results an average - value of $(3.74 \pm 0.54)\%$, consistent with the published value of $(3.32 \pm 0.34)\%$ [3]. Errors are strongly dominated by the systematic errors of $BR(\omega \to \pi^0\gamma) = (8.5 \pm 0.5)\%$ and $\epsilon_0 = (3.9 \pm 0.3)\%$, which are the same for both runs. Statistical errors are neglegable ($< 1\%$), so that the total errors of both run - periods must be averaged arithmetically.

5 Determination of Angular - Momenta

For determination of initial angular - momenta contribution of protonium the event - topology was fitted by a log - likelihood fit. The log - likelihood

l was defined by

$$l = -\underbrace{\log N!}_{\approx N(\log N - 1)} - \sum_{i=1}^{N} \log w_i + N \log\left(\Phi \frac{N}{N_c}\right) + \frac{1}{2}\left(\frac{\Phi}{N_c} - 1\right)^2 , \qquad (1)$$

where N and N_C are the number of data- and monte - carlo events and w_i the weights of the data - events. Φ is the sum over all monte - carlo weights. Thus defined log - likelihoods we need not care about efficiencies. The weights are products of a dynamical part and phase space. The former was calculated in the helicity - formalism from the angular - distribution in the reaction. The resulting scattering - amplitude $A^{JM}_{\lambda 1 \lambda 2}$ was squared and summed incoherent over the photon helicities and initial angular - momenta J of the assumed ${}^1S_0$, ${}^3P_0$, ${}^3P_1$, and ${}^3P_2$ - states:

$$A^{JM}_{\lambda 1 \lambda 2} = \sum_{\lambda \lambda_1 \lambda_2} \sqrt{2J+1}\,(2s+1) D^J_{M\lambda}(\Omega)^* D^s_{\lambda_1 \lambda_{d1}}(\Omega_1)^* D^s_{\lambda_2 \lambda_{d2}}(\Omega_2)^* F^J_{\lambda_1 \lambda_2}\; f^1_{\lambda_{d1}0} f^1_{\lambda_{d2}0} \qquad (2)$$

The angular dependent parts in the amplitude are given by the standard D - functions. Ω means the azimuthal and polar production - angle Φ and Θ of one of the ωs, Ω_i means the decay - angles of the i - th ω in its rest - system. An initial spin - density of $\frac{1}{2J+1}$ was assumed, so that the distributions of the production - angles should be flat because of the unitarity of the D - functions. In figure 6 the cosine of production polar - angle Θ, the cosines of the decay polar - angles ϑ_i and the sum and the difference of the decay azimutal - angles $\phi_\pm = \phi_1 \pm \phi_2$ are plotted. The lower pictures show the distributions corrected (one dimensional) by efficiencies. This is sufficient for recognizing the main structures. They are not consistent with a pure S - wave state, where following intensity - distributions are expected:

$$\mathcal{I}(\vartheta_{1/2}) = \int \mathcal{I} d\vartheta_{2/1} d\Phi_+ \sim 1 + \cos^2 \vartheta_{1/2} \qquad (3)$$

$$\mathcal{I}(\Phi_+) = \int \mathcal{I} d\vartheta_1 d\vartheta_2 \sim 3 + 2\sin^2 \Phi_+ \qquad (4)$$

(Φ_- - distribution should be flat)

More detailes result from the fit to the data. For minimazing l the MINUIT - package was used. Fit - parameters were the helicity - amplitudes $F^J_{\lambda_1 \lambda_2}$ from the omega production, developed in partial - wave amplitudes a^J_{ls}

according to the relation

$$F^J_{\lambda_1\lambda_2} = \sum_{ls} \sqrt{\frac{2l+1}{2J+1}}\, a_{ls}(J\lambda \mid l0s\lambda)(s\lambda \mid s_1\lambda_1 s_2 - \lambda_2). \tag{5}$$

The fit converged with the amplitudes and their statistical errors of table 6. With this amplitudes the fraction of angular - momentum states in protonium

a^0_{00}	a^0_{11}	a^0_{22}	a^1_{01}	a^1_{21}
0.737 ± 0.034	1.221 ± 0.050	0.153 ± 0.031	0.071 ± 0.092	0.099 ± 0.088
a^1_{22}	a^2_{02}	a^2_{20}	a^2_{21}	a^2_{21}
0.005 ± 0.070	0.151 ± 0.075	0.066 ± 0.043	0.000 ± 0.076	0.007 ± 0.105
a^2_{42}				
0.145 ± 0.048				

Table 6: Absolute values of the partial - wave amplitudes a^J_{ls}

could be determined:

$$\begin{array}{lcl} N(^1S_0) & = & (70.3 \pm 3.1)\% \\ N(^3P_0) & = & (26.7 \pm 2.1)\% \\ N(^3P_1) & = & (0.7 \pm 1.0)\% \\ N(^3P_2) & = & (2.4 \pm 1.3)\% \end{array}$$

Because of not having taken care of remaining background in this fit, these values may differ by about 5% due to the remaining $\pi^0\pi^0\omega$ events, under the assumption, that phase - space simulation for this background was sufficient. Demanding a cl of 10%, 20% or 30% for hypotheses $p\overline{p} \to \omega\omega$, $\omega \to \pi^0\gamma$ reduces $\pi^0\pi^0\omega$ - background by 30 to 50%, while fitted parameter - values do not change significantly.

Nevertheless, the contribution of P - wave is not neglegable in $p\bar{p}$ - annihilation to $\omega\omega$.

References

[1] M. Merkel, *Proton - Antiproton Vernichtung in* $\pi^0 X$, ηX *und* ωX *mit* $X = \pi^0$, η *und* η', Dissertation, Mainz (1993)

[2] The Crystal - Barrel Collaboration, $p\bar{p}$ - *Annihilation at Rest into* $\pi\pi\omega$, Phys. Let. B 311, 362-370 (1993)

[3] The Crystal - Barrel Collaboration, *Antiproton - Proton Annihilation at Rest in Two - Body Final States*, Z. Phys. C 58, 175-189 (1993)

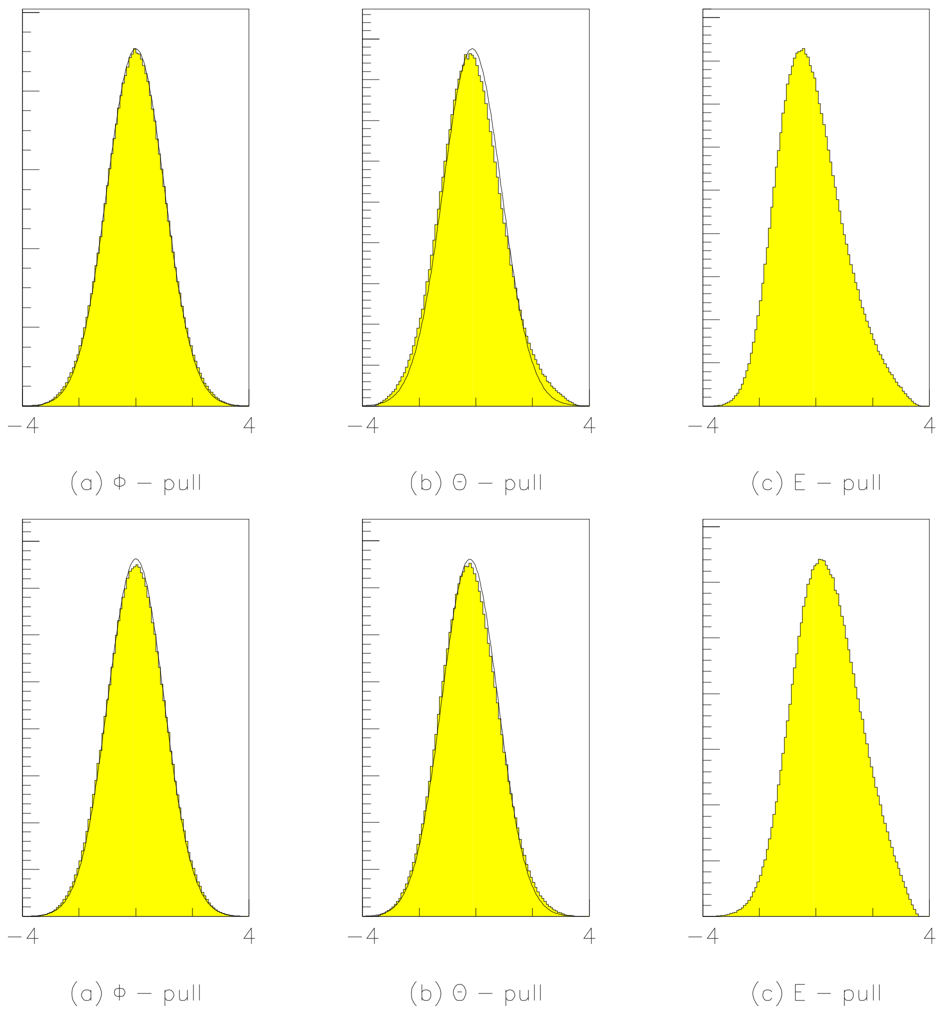

Figure 1: Distributions of pulls (above June/July 1990, below November 1990 data)

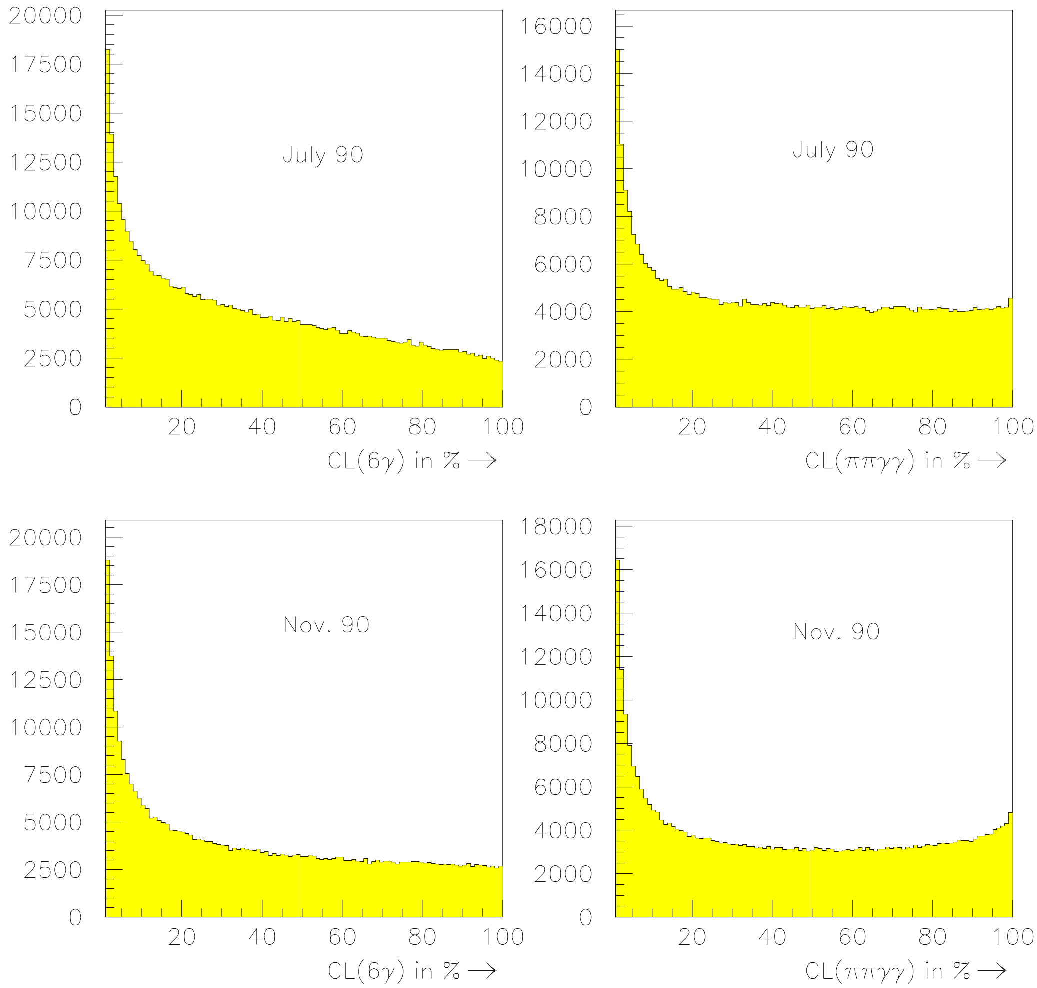

Figure 2: Distributions of confidence - levels

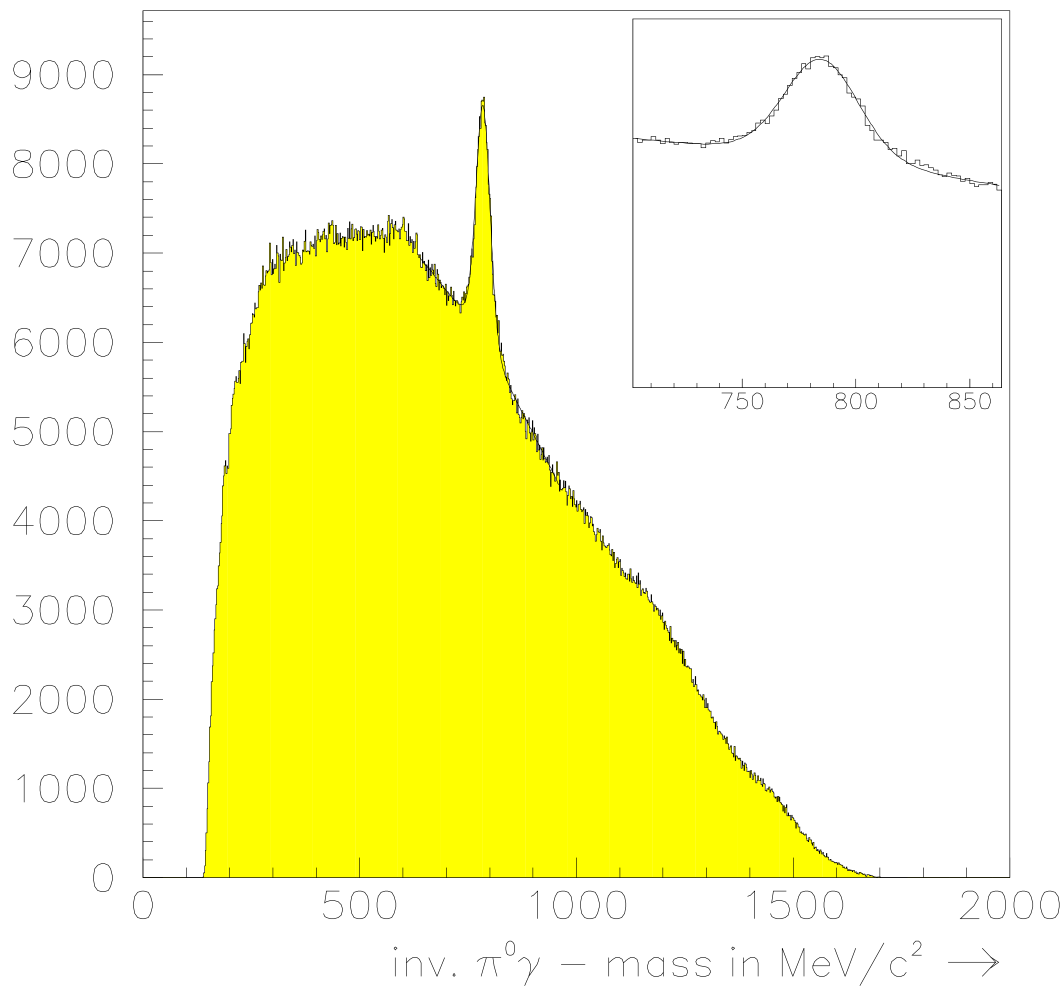

Figure 3: Invariant $\pi^0\gamma$ - masses (four entries per event) with a confidence - level for hypothesis $\pi^0\pi^0\gamma\gamma$ $> 10\%$

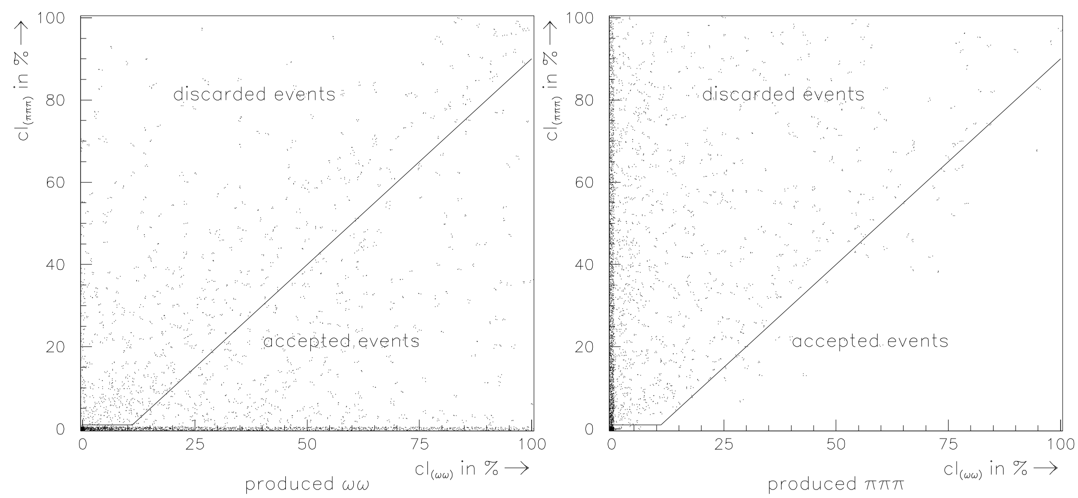

Figure 4: the cut in the confidence - level of background hypotheses $\pi^0\pi^0\pi^0$ versus hypothesis $p\overline{p} \rightarrow \omega\omega,\, \omega \rightarrow \pi^0\gamma$.

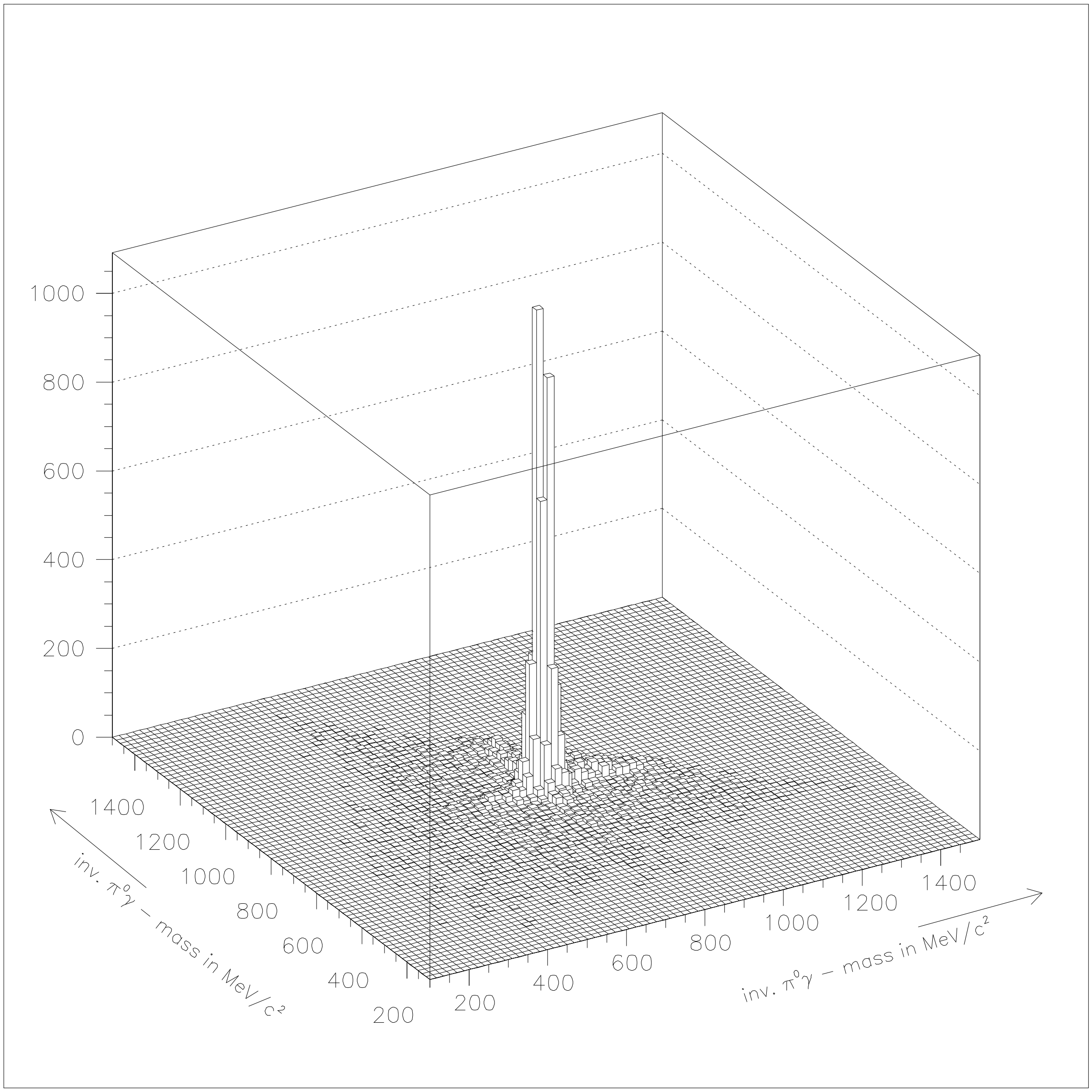

Figure 5: Invariant $\pi^0\gamma$ - masses

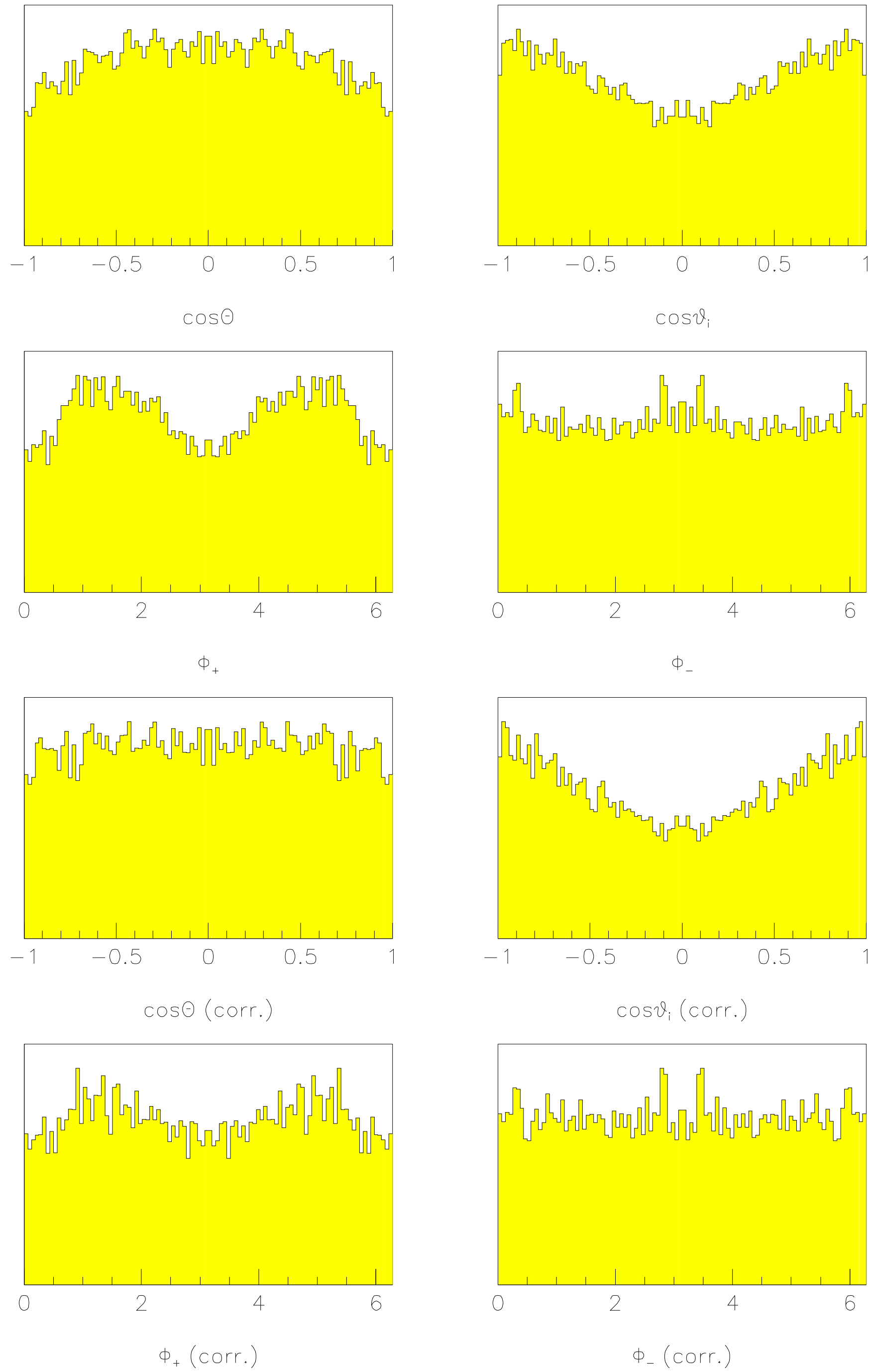

Figure 6: Angular - distributions of omegas and their decay - photons. The lower picture showes the distributions corrected on efficiencies.