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Measurement of the $\tau \to \eta\pi\pi^0\nu_\tau$ branching ratio using $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ final states

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Using Aleph data until 1993 (159.000 tau pairs), an η signal is observed in τ decays in both $\eta \to \gamma\gamma$ and $\eta \to \pi^+\pi^-\pi^0$ final states. The corresponding branching ratio for τ into $\eta\pi\pi^0$ is measured to be: $0.23 \pm 0.06_{stat} \pm 0.02_{syst}$%. It rests on independent measurements which are together consistent ($\chi^2/d.o.f = 0.4$) and amount to a total statistical significance of about 4 σ.

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1 Theoretical and Experimental Overview

1.1 Theoretical interest

The $\eta\pi\pi^0$ final state, having positive G-parity, should be produced from the vector part of the charged hadronic current. It turns out that this vector part, in the chiral limit, couples exclusively to even numbers of pseudo-scalars. The $\eta\pi\pi^0$ decay channel thus provides direct evidence for the chiral anomaly of QCD and can be computed from the "anomalous" Wess-Zumino effective left current [1]: $\mathcal{L}_\mu^{(ano)} = -i\frac{N_c}{24\pi^2 f^6}\epsilon_{\mu\nu\alpha\beta}\mathcal{L}^\nu\mathcal{L}^\alpha\mathcal{L}^\beta$ where $\mathcal{L}_\mu = if^2 U\partial_\mu U^\dagger$ $(U = \exp(i\lambda_a\pi^a/f))$ is the ordinary, chirally symmetric, effective left current. The rate is still difficult to compute because of its sensitivity to various resonance assumptions: [2] gives $Br\ (\tau \rightarrow \eta\pi\pi^0\nu_\tau) \simeq 0.2 \sim 0.3\%$ while [3] is more vague. An alternative way consists in using CVC which relates this decay to the $e^+e^- \rightarrow \eta\pi^+\pi^-$ annihilation. One thus obtains [4]: $Br\ (\tau \rightarrow \eta\pi\pi^0\nu_\tau) = 0.13 \pm 0.02\%$.

1.2 Experimental status

The decay has only been observed by the CLEO collaboration [5]. Their study was able to make use of all 3 main η decay channels, namely $\eta \rightarrow \gamma\gamma$, $\pi^+\pi^-\pi^0$ or $3\pi^0$, with the result: $Br\ (\tau \rightarrow \eta\pi\pi^0\nu_\tau) = 0.17 \pm 0.02_{stat.} \pm 0.02_{syst.}\%$ based on 125 events. In Aleph, only the first 2 final states with 39% and 24% respective branching fractions are used. The technique will be identical to that of [5] except that, due to higher photon losses, one missing photon is allowed and thus two sub-cases coexist in each final state. Note that the $\eta\pi^\pm\gamma$ states will be deliberately interpreted as $\eta\pi\pi^0$ with one photon lost and not as $\eta\pi^\pm$ (2^{nd}-class current) with one additional photon.

2 Event Selection

2.1 Methods common to both η decay channels

The starting point is a standard dilepton pre-selection of 99.6% efficiency inside the geometrical acceptance. Then each di-lepton is split in 2 opposite hemispheres which are treated separately. The pions (1 or 3) are selected through standard quality cuts and particle identification. All photons within 30° of this pion(s), including conversions, are first counted. Then, other quality cuts are applied to sort out the so-called "fake" photons coming either from electro-magnetic shower fluctuations or hadronic interaction residuals.

A simple acollinearity cut disposes of the two photon background and two probability likelihood variables cut away the Bhabha and hadronic ($Z^0 \rightarrow q\bar{q}$) events. One is based on particle identification and momentum value, the other on charged multiplicity, opening angles and track momenta. Both bear solely on the recoil hemisphere which not only ensures absence of bias but also allows efficiency checks on the data. The Bhabha background is negligible for $\eta \rightarrow \pi^+\pi^-\pi^0$ and around 0.7% for $\eta \rightarrow \gamma\gamma$ while the hadronic one is respectively 30% and 10%. The cut on the second variable will thus be complemented by maximum photon-tracks angle and/or total invariant mass demands to reach the per mille contamination level in both cases. The selected topologies are thus:

$$\begin{array}{lll} \pi^{\pm}, 4\gamma\ (3\gamma) & for\ the\ \ \eta \to \gamma\gamma & decay \\ (3\pi)^{\pm}, 2\pi^0\ (\pi^0\gamma) & for\ the\ \ \eta \to \pi^+\pi^-\pi^0 & decay \end{array}$$

From now on, calorimetric photon issues only are discussed.

2.2 Selection of the $\pi^{\pm}$, $4\gamma(3\gamma)$ topology

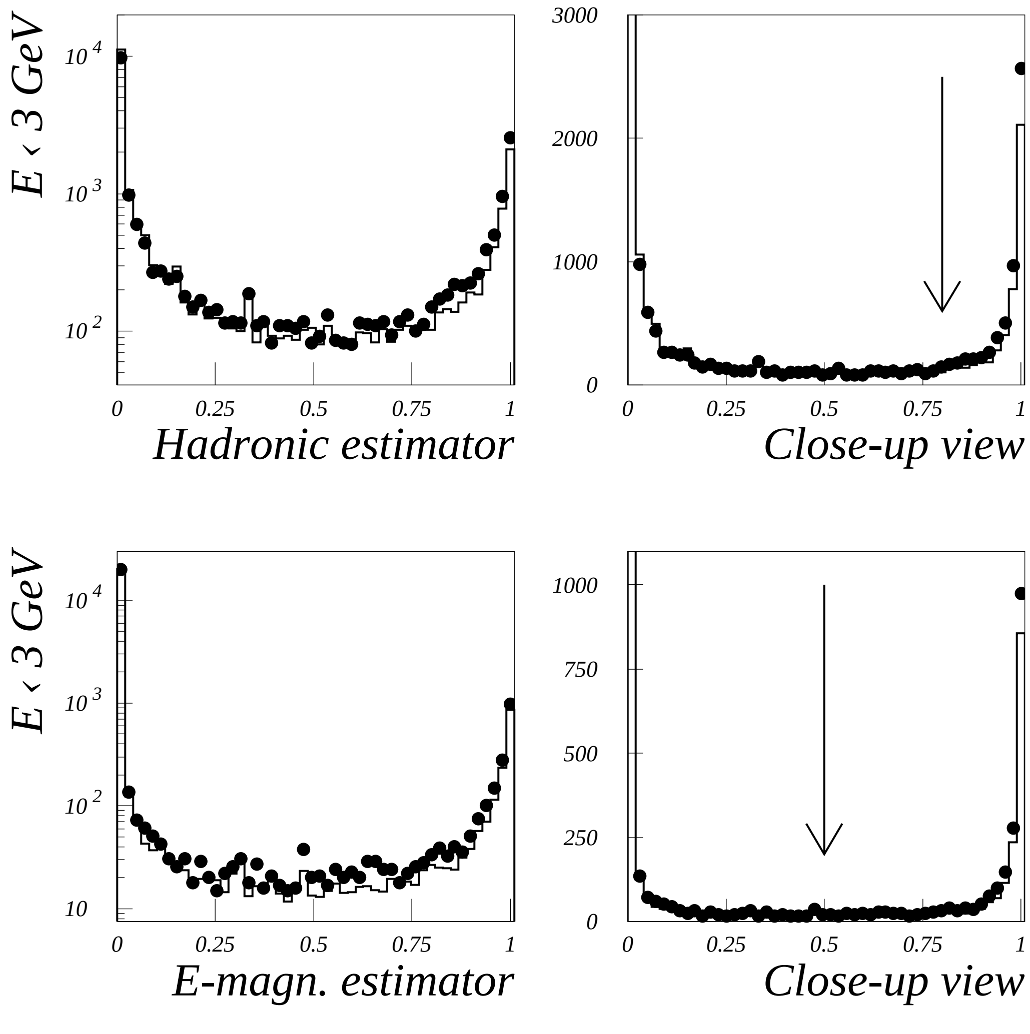

Figure 1: Estimator's distributions in the $\pi^{\pm}, 4\gamma\ (3\gamma)$ topology for photons below 3 GeV with cut values indicated. "Good" photons stand on the left side, "fakes" on the right.

Two probability likelihood estimators are used to distinguish between authentic and "fake" photons (figure 1). One analyses the shape of two neighbour electro-magnetic

clusters to determine whether one is born of the other or really independent. A 95% efficiency-98% rejection value is chosen, the proportion of these fake photons being originally between 3 and 4%. The other estimator tackles the more delicate problem of tagging hadronic interaction residuals. These are more elusive and numerous so that, the same efficiency-rejection performance being chosen, the same precision is not guaranteed. An additional "fake" photon is thus allowed, making the overall efficiency safe at the cost of entangling 3 and 4 photons, which is not embarrassing.
In the 4 photons topology, the photons are further required to be sufficiently disjoint and "massive" clusters are discarded by an analysis of the moments of the transverse energy deposition. This results in 26.8% and 17.4% respective efficiencies for 3 and 4 photons. The background, which consists mainly of $\pi 2\pi^0$ and $\pi\pi^0$ τ-decays, is clearly overwhelming in absolute number but sharply peaked at the π^0 ((π^0, π^0)) mass. A χ^2 to this π^0 ((π^0, π^0)) hypothesis will thus allow to veto it as shown on figure 2.

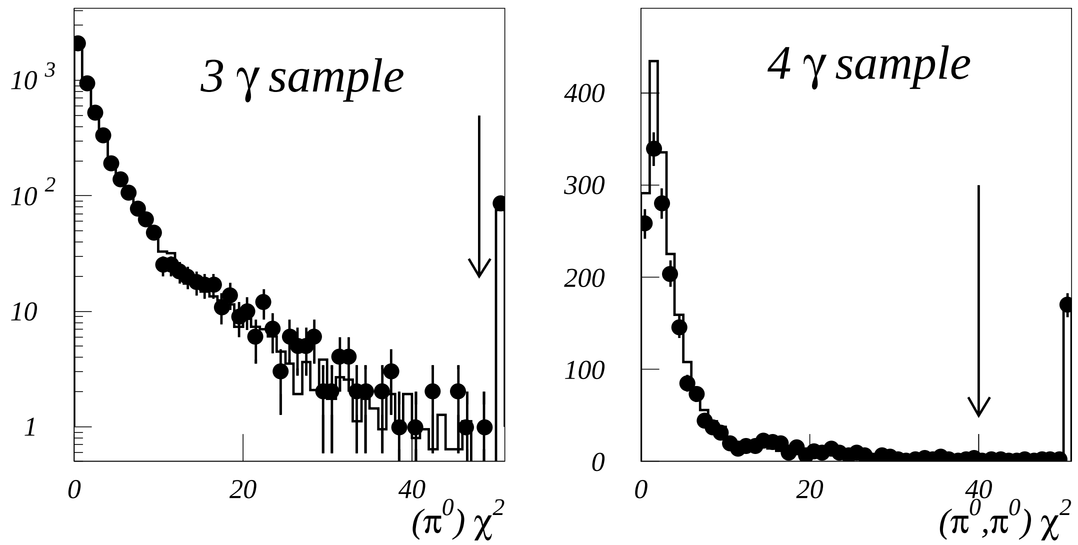

Figure 2: χ^2s to π^0 (left) and (π^0, π^0) (right) hypothesis. The arrow indicates the cut value.

2.3 Selection of the $3\pi^\pm$, $2\pi^0(\pi^0\gamma)$ topology

To disentangle the $3\pi^\pm 2\pi^0$ signal from a background that differs only in the number of photons, the estimator for electro-magnetic fake photons is again used. However, a different, simpler, approach to the hadronic residuals is preferred because of the presence of 3 charged pions. Two-dimensional cuts in the (distance to charged track - energy) plane of the calorimetric photons are applied, depending on the number (3 to 5) of photons. The π^0 quality is estimated from the goodness of a fit of the photon's energies under the constraint of a π^0 invariant mass. Special care has been taken to establish a precise overall calibration and agreement between data and Monte-carlo in low-energy pairs invariant mass has been arranged. The overall efficiencies are now 16% and 17% for respectively one and two reconstructed π^0(s). Again the non-η $3\pi^\pm 2\pi^0$ decays are dominant but fortunately, the η resonance, being narrow and lying in a low background mass region, emerges from them. From a Monte-Carlo of $\tau \to \eta\pi\pi^0$ events, and after refitting the π^0, a width of only 10 MeV is indeed observed.

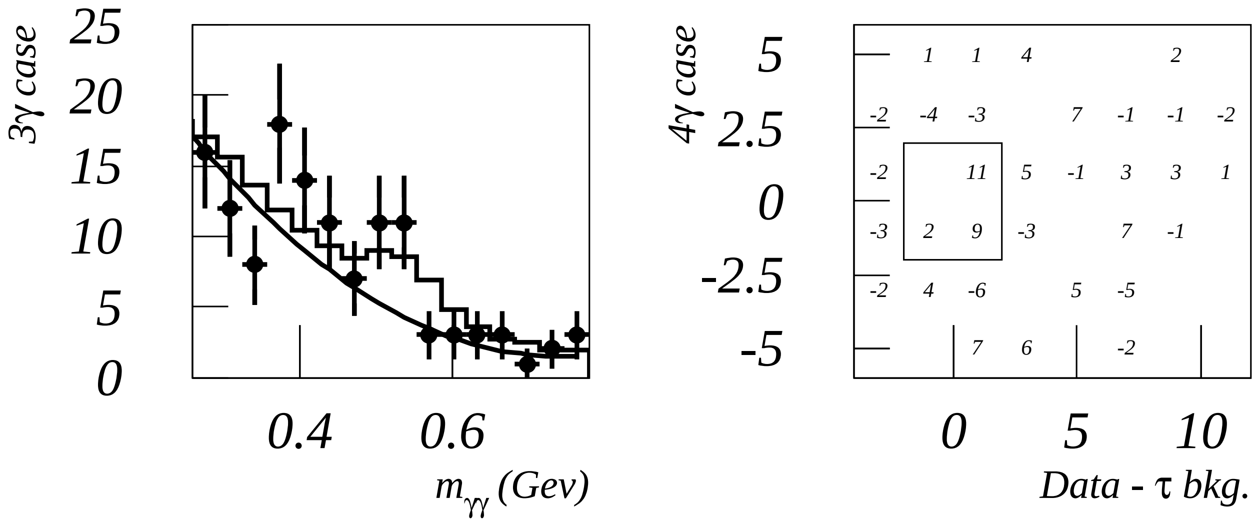

Figure 3: 1 and 2 dimensional plots showing the $\eta \to \gamma\gamma$ resonance. Left: Parabola + signal fit. Right: Data - Monte-Carlo with 2 σ box around (m_η, m_{π^0}).

3 Branching ratio by $\eta \to \gamma\gamma$

3.1 Case of 3 photons

Rejecting all events with a good π^0 (figure 2), a factor $\simeq$ 25 in the signal to noise ratio is gained while 57% of the signal is lost. However, most of that loss is from events where the missing photon came from the η and thus should not be regretted. The rejected events allow to check the efficiency to $\pi^\pm 3\gamma$ and the location and resolution of the π^0 peak between data and Monte-Carlo. In the selected events, all 3 pair masses are plotted and the relative contributions of background (flattish) and signal (η peak of $\simeq$ 55 MeV's width) are fitted. Performing a binned maximum likelihood fit between 260 and 780 MeV , region unaffected by the preceding anti-π^0 cut, a $20 \pm 20\%$ larger than expected background is found. The fitted signal represents $\alpha_3 = 24 \pm 13$ entries (figure 3) i.e. 19% of the total. From this figure and the $\eta\pi\pi^0$ Monte-Carlo, the following branching fraction is derived:

$$Br\ (\tau \to \eta\pi\pi^0)_3 = 1.7 \pm 0.9_{stat}\ 10^{-3}$$

3.2 Case of 4 photons

Similarly, absence of any good π^0 pair among the 4 photons (figure 2) is required. The signal to noise factor is improved by a factor 12 only because of the $\pi^\pm 3\pi^0$ background which, due to combinatorics, is less efficiently tagged than $\pi^\pm 2\pi^0$. A 2-dimensional binned maximum likelihood fit is performed on the data which again estimates the relative proportions of a flattish background versus a (η, π^0) peaked signal. The background is found $6 \pm 8\%$ lower than predicted by the simulation and the signal represents $\alpha_4 = 64 \pm 27$ entries (figure 3). Using the same procedure as for 3 photons yields:

$$Br\ (\tau \rightarrow \eta\pi\pi^0)_4 = 2.5 \pm 1.0_{stat}\ 10^{-3}$$

3.3 Systematic errors

The common systematic errors due to the luminosity, $\eta \rightarrow \gamma\gamma$ branching fraction or selection procedure, outside of the photon's issues, are negligible in the face of $40 - 50\%$ statistical errors. The decisive anti-π^0(s) cut and background shape uncertainty only are considered. The background level was indeed fitted and thus accounted for in the fit error but that assumed knowledge of its shape hence the latter error. Both fits turn out to be quite insensitive to the background shape (and thus composition) and robust towards variations in the value of the anti-π^0 χ^2 cut, that variation being conservatively carried out as far as the background predominance allows. The stability against variations in the fit range is also checked. The table below summarizes the systematic errors:

	$bkg.shape$	χ^2	$range$	$TOTAL$
$\frac{\Delta B_3}{B_3}$ (%)	12	$\simeq 12$	≤ 5	18
$\frac{\Delta B_4}{B_4}$ (%)	3	$\simeq 13$	6	15

And consequently:

$$\begin{cases} Br\ (\tau \rightarrow \eta\pi\pi^0)_3 = 1.7 \pm 0.9_{stat} \pm 0.3_{syst}\ 10^{-3} \\ Br\ (\tau \rightarrow \eta\pi\pi^0)_4 = 2.5 \pm 1.0_{stat} \pm 0.4_{syst}\ 10^{-3} \end{cases}$$

4 Branching ratio by $\eta \rightarrow \pi^+\pi^-\pi^0$

4.1 Fit of the η resonance

To account for a possible lost photon, both $3\pi^\pm\pi^0\gamma$ and $3\pi^\pm 2\pi^0$ situations are selected. In the first case, there are only two combinations per event but the η meson is lost about half of the time. In the second case, there are four combinations but one should always correspond to the η decay products. This causes the two situations to have similar $(\pi^+\pi^-\pi^0)$ invariant mass spectra. Figure 4 indeed shows their similarity and the presence of an η signal in both. For simplicity, only the sum of the two spectra is fitted, using a binned maximum likelihood method to estimate the relative proportions of entries coming from a linear distribution and a gaussian one. The fit is performed on the largest possible

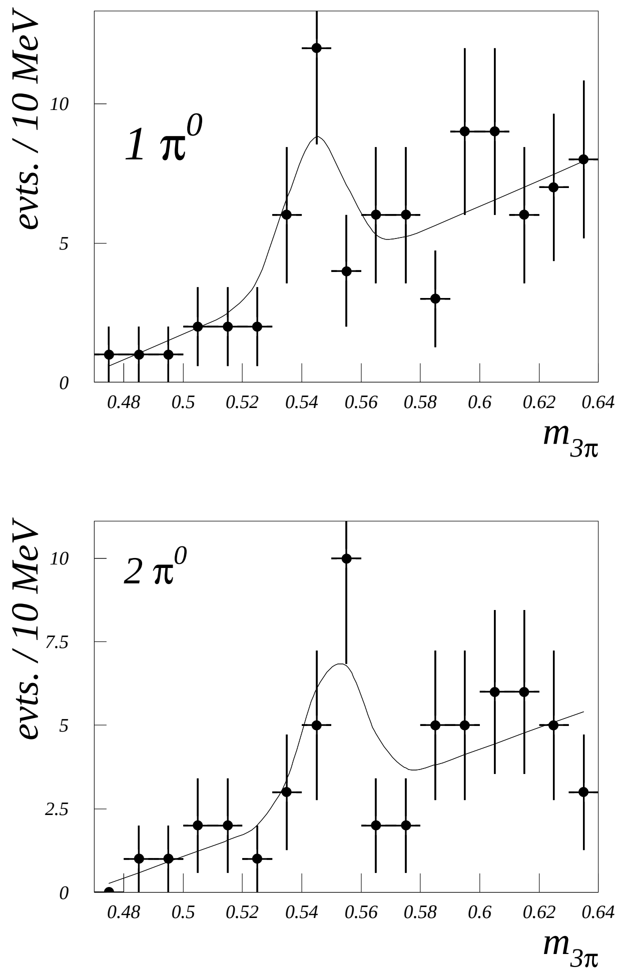

Figure 4: Data $(\pi^+\pi^-\pi^0)$ mass spectra for 1 and 2 π^0 cases with fit result superimposed. Close-up view around m_η

range of linearity of the background which is up to the beginning of the ω resonance (745 MeV). The width of 10 MeV is taken from a $\tau \to \eta\pi\pi^0$ Monte-Carlo since data statistics are not sufficient to evaluate it. Gaussian center, background slope and relative proportion are simultaneously fitted. The fitted resonance mass is $m = 543 \pm 4\ MeV$, the slope $p = 2.18 \pm 0.05$ and proportion of signal: $f = 5.6 \pm 1.9\%$. The number of analysed $\tau \to \eta\pi\pi^0$ decays is derived from that fraction and the $\tau \to \eta\pi\pi^0$ Monte-Carlo. Figure 5 shows the background linearity, the peak from which the η width is extracted and the result is:

$$Br\ (\tau \to \eta\pi\pi^0) = 3.0 \pm 1.0_{stat}\ 10^{-3}$$

4.2 Systematic errors

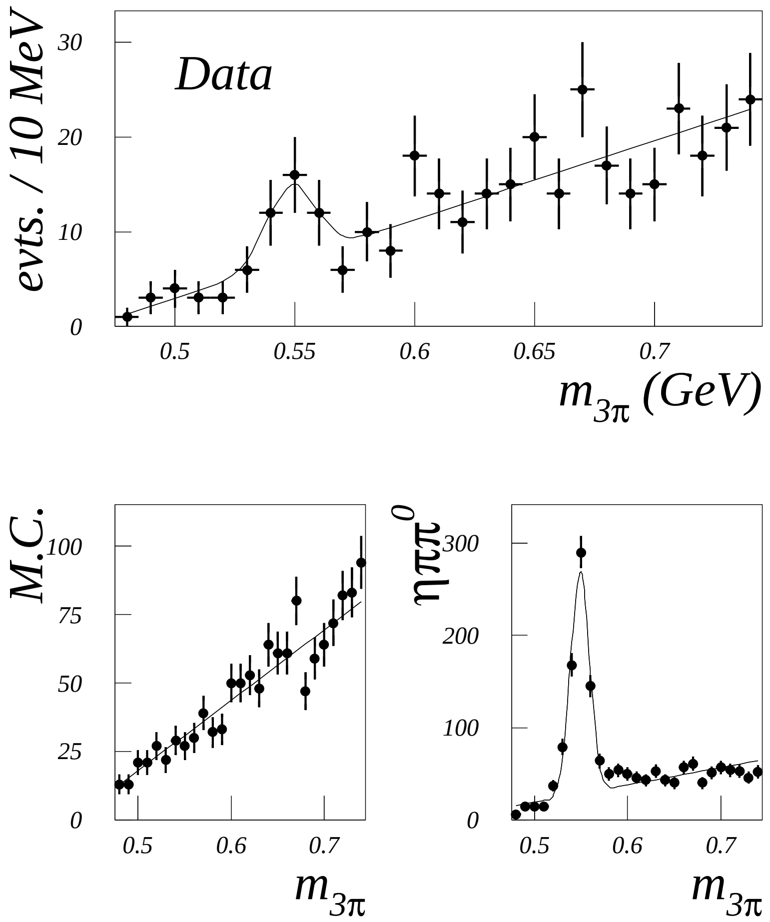

Figure 5: Top: Data ($\pi^+\pi^-\pi^0$) invariant mass spectrum with straight line + gaussian fit superimposed. Bottom: Expected mass spectra for non-η τ events and η signal.

As in the $\eta \to \gamma\gamma$ case, the relative statistical error is quite large (34%) which makes the common systematic errors like non-τ background contributions or luminosity normalisation rather negligible. The error on the slope allows for an 8% variation in the result. Note that shortening the fit range simply modifies that background slope within errors already taken into account hereabove. The extrapolation from the gaussian content to the number of signal events suffers mainly from the limited $\eta\pi\pi^0$ Monte-Carlo statistics and a small relative uncertainty on Br $(\eta \to \pi^+\pi^-\pi^0)$ of 2.5% is added. Finally, the branching ratio is re-computed for different sets of good photon selection cuts to check the sensitivity. The cuts are moved in a way that reflects the detector resolution on the used variables: distance and energy. All these errors are summarized in the table below.

	Br $(\eta \to \pi^+\pi^-\pi^0)$	$slope$	$extrapolation$	$(d, E) cuts$	$TOTAL$
$\frac{\Delta B}{B}$ (%)	2.5	8	5	$\simeq 9$	13

And consequently:

$$Br\ (\tau \to \eta\pi\pi^0) = 3.0 \pm 1.0_{stat} \pm 0.4_{syst}\ 10^{-3}$$

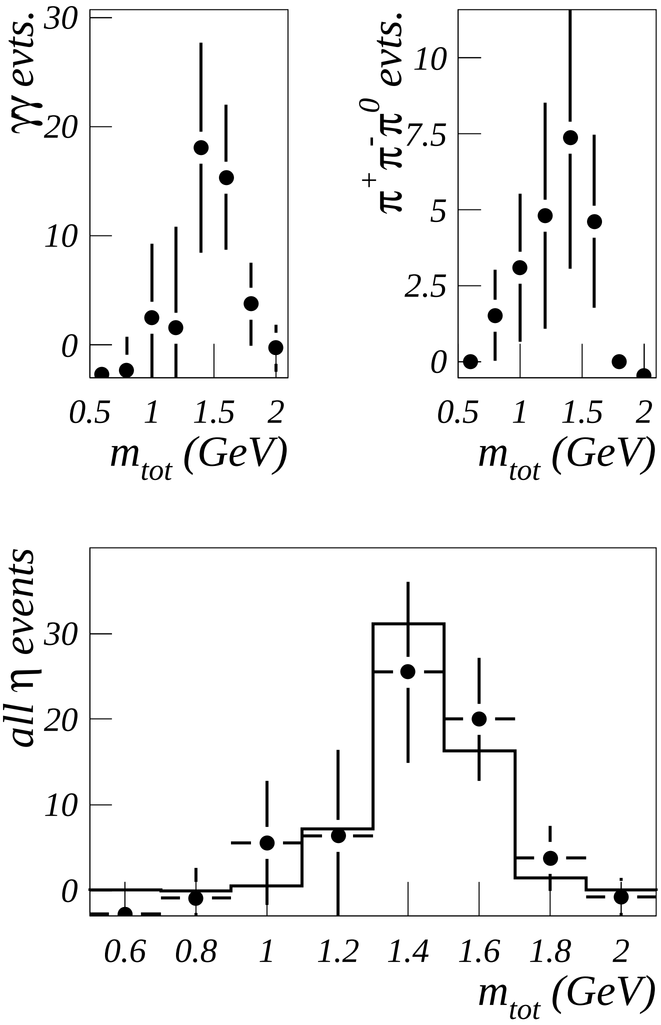

Figure 6: Top: Total mass for $\eta \rightarrow \gamma\gamma$ (left) and $\eta \rightarrow \pi^+\pi^-\pi^0$ (right) candidates. Bottom: Sum of the 2 channels compared to the Monte-Carlo (fitted on e^+e^-) expectation for a $\tau \rightarrow \eta\pi\pi^0$ decay.

5 Conclusion

An $\eta\pi\pi^0$ signal in τ decays was observed in both $\eta \rightarrow \gamma\gamma$ and $\eta \rightarrow \pi^+\pi^-\pi^0$ final states. Invariant mass spectra identify and quantify the η meson resonance, yielding 3 independent measurements. Their consistency, given by a χ^2 per d.o.f. of 0.4, allows to combine them. The result is:

$$\boldsymbol{Br\ (\tau \rightarrow \eta\pi\pi^0) = 0.23 \pm 0.06_{stat} \pm 0.02_{syst}\%}$$

It is consistent with the only available measurement [5] (figure 7) and so is the total mass of the candidate events, shown on figure 6. The Monte-Carlo spectrum on that figure (from the KORALZ library) is the result of a fit to the e^+e^- annihilation data [6].

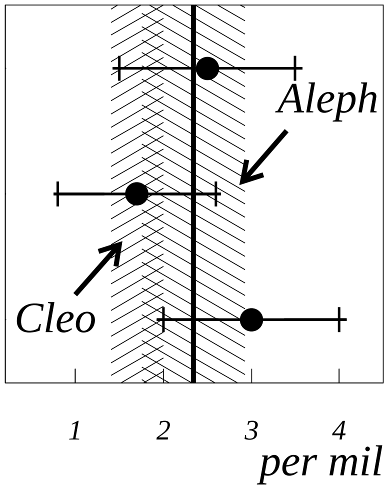

Figure 7: The three results of this paper with full error bars. The wide band shows their combination while the narrower one represents the CLEO value. The ticks on the error bars mark the (dominant) statistical error contribution.

References

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