TAU DECAYS TO MULTIPHOTON FINAL STATES

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ABSTRACT

Present status and future prospects of measurements on τ decays to final states with π^0's and η's are discussed.

1 Introduction

Final states with multiple π^0's constitute a large fraction of all τ decays. Branching ratios for these decays are poorly measured because of experimental difficulties in reconstruction of many π^0's in a final state. Significant progress in this area is necessary in order to close the gap in our understanding of the τ as manifested by the deficit of 1-prong decays[2]. Present experimental status and prospects for the future are discussed.

2 Phenomenological Predictions

Table 1: Phenomenological predictions of branching ratios for τ decay modes which can contribute to 1-prong final states with photons. We have used $BR(\tau \to \nu e \nu)=(18.0\pm0.3)$ %[3], BR($\tau^- \to \nu\pi^-\pi^+\pi^-\pi^+\pi^-$)=(0.06±0.02) %[4], and BR($\tau^- \to \nu\pi^-\pi^+\pi^-$)=(7.1±0.4) %[7]. For a discussion of contributions from final states with one or more K mesons (not included here) see Ref.9,1.

decay mode	prediction			
$\tau^- \to \nu\pi^- \ldots$	BR [%]	input data	theorem	Ref.
π^0	22.1±2.2	$\sigma(e^+e^- \to \pi^+\pi^-)$, $BR(\tau \to \nu e \nu)$	CVC	[8,9]
$\pi^0\pi^0$	7.1±0.4	$=$ BR($\tau^- \to \nu\pi^-\pi^+\pi^-$)	isospin	[12]
$\pi^0\pi^0\pi^0$	1.00±0.15	$\sigma(e^+e^- \to \pi^+\pi^-\pi^+\pi^-)$, $BR(\tau \to \nu e \nu)$	CVC	[9]
$\pi^0\pi^0\pi^0\pi^0$	<0.06	$< \frac{3}{4}$ BR($\tau^- \to \nu\pi^-\pi^+\pi^-\pi^+\pi^-$)	isospin	[9]
η	10^{-3}	—	vector W, isospin	[10]
$\eta\pi^0$	0.13±0.02	$\sigma(e^+e^- \to \eta\pi^+\pi^-)$, $BR(\tau \to \nu e \nu)$	CVC	[13,14]
$\eta\pi^0\pi^0$	10^{-4}	—	phase space suppression	[10]
$\eta\eta$	10^{-7}	—	phase space, lack of production mechanism	[10]

There are rather firm phenomenological predictions for τ decays to final states with multiple photons coming from π^0, BR($\pi^0 \to \gamma\gamma$)=98.8 %, or η decays, BR($\eta \to \gamma\gamma$)=38.9 %, BR($\eta \to 3\pi^0$)=31.9 %. They are summarized in Table 1. Branching ratios for the decays proceeding through vector interaction ($\tau \to \nu\pi\pi^0$, $\tau \to \nu\pi 3\pi^0$, $\tau \to \nu\pi\pi^0\eta$) are predicted by the CVC theorem and the low energy e^+e^- data ($\sqrt{s} < m_\tau$) with a precision of about 10 %, which is limited by an error in absolute normalization of the e^+e^- cross section. Decays to odd number of pions are due to the axial vector interaction and their branching ratios cannot be precisely predicted. However, branching fractions for decays into final states with π^0's ($\tau \to \nu\pi 2\pi^0$, $\tau \to \nu\pi 4\pi^0$) can be related by strong isospin symmetry to branching fractions for decays into all-charged pions, which are easier to measure. In particular [12], BR($\tau \to \nu\pi 2\pi^0$)=BR($\tau \to \nu 3\pi$)=7.1±0.4 %. As there are inconsistences[7] in different measurements of BR($\tau \to \nu 3\pi$) the error given here to the world average value is probably

Table 2: The best experimental limits on τ decays to η.

decay mode	Upper Limit (95 % C.L.)	
$\tau^- \to \nu\pi^- \ldots$	BR [%]	Experiment
η	<0.3	Crystal Ball[15,16]
$\eta\pi^0$	<0.9	Crystal Ball[15]
$\eta\pi^0\pi^0$	<2.3	CLEO[18] ,HRS[17]
$\eta\eta$	<0.6	HRS[17]

underestimated. Among all τ decays to η the decay $\tau \to \nu\pi\pi^0\eta$ is expected to have the highest branching ratio, which is however rather small : 0.13±0.02 %. Note that the $e^+e^- \to \eta\pi^+\pi^-$ data used in the CVC estimate of this branching ratio have been recently improved[14) . Branching fractions for all other τ decays to η should be smaller by orders of magnitude.

3 Results on τ Decays to η

No confirmed experimental evidence for τ decay to η has been found. The best upper limits on branching ratios for different channels are given in Table 2. These limits imply that τ decays to η cannot account for the deficit of 1-prong branching ratio.

4 Results on $\tau \to \nu\pi\pi^0$

The decay $\tau \to \nu\pi\pi^0$, totally dominated by production of $\rho(770)$ resonance, was measured by many experiments. The world average value, 22.5±0.9 %[3) , agrees very well with the CVC prediction (Table 1). The CVC method correctly predicts also the differential shape of the invariant $\pi\pi^0$ mass distribution[19) . As pointed out by Hayes and Perl[3) , different measurements of BR($\tau \to \nu\pi\pi^0$) agree too well with each-other, which is evidence for biasing of measurements towards the previously published results or the CVC prediction. Therefore, the error on the world average BR($\tau \to \nu\pi\pi^0$) is probably underestimated, as it assumes that the measurements are all independent.

5 Indirect Measurements on High Photon Multiplicity Decays

Though the $\tau \to \nu\pi\pi^0$ decay has been rather precisely measured, experimental knowledge of $\tau \to \nu\pi 2\pi^0$ is still rather poor. Because of high boost of τ decay products at PEP and PETRA, which causes photons to overlap in the detector (see Fig.1), none of the experiments at these storage rings were able to measure BR($\tau \to \nu\pi 2\pi^0$) by the reconstruction of both π^0's in the final state. Indirect methods have been used instead. In the simplest approach, the number of neutral energy clusters ("showers") observed in the calorimeter is counted for 1-prong τ decays. Even though each decay mode has a fixed number of photons, the same decay mode contributes to a range of shower multiplicity, because of several reasons :

- Overlapping photons in the detector very often cannot be distinguished from single photon showers,
- Some photons can be undetected because of finite geometrical acceptance of the calorimeter or low energy cut off present in most of the detectors,
- Spurious neutral energy clusters can be produced by hadronic interaction of charge pions in the calorimeter or in the material in front of it.

Monte Carlo simulation of τ decays and of the detector response is used to find the efficiency of detecting a specific τ decay mode (e.g. $\tau \to \nu\pi 2\pi^0$) in the event class defined by the observed number of neutral energy clusters. As many different modes can contribute to the same event class, the τ decay mode cannot be identified on event-by-event basis. Therefore, such experiments are primarily sensitive to a sum of branching ratios for all modes contributing to the selected events. However, thanks to differences in the shower multiplicity distribution for each mode, the individual branching ratios can be determined on a statistical basis by a simultaneous fit to the observed shower multiplicity. To improve the resolution of individual decay modes and to reduce the background level, some experiments go beyond simple shower counting and impose additional requirements in the definition of event classes. Such as a pair of showers, assumed to be single photons, should combine to form the π^0 mass. This is however only a partial π^0 reconstruction as random combinations are not subtracted.

All measurements of τ decays to high photon multiplicity final states are summarized in Table 3.

The first analysis of this type was performed by the CELLO experiment[20) . The results were lacking precision because of poor statistics.

The TPC experiment[21) measured the branching ratio for $\tau \to \nu\pi + > 2\gamma$ to be significantly higher than predicted. A fit of individual branching ratios preferred the scenario in which all decays in this topology came from the $\tau \to \nu\pi 2\pi^0$ decay.

The Mark-II experiment presented two analyses of the same data. One of them[22) was lacking the necessary sensitivity to resolve individual branching ratios, thus only the inclusive BR($\tau \to \nu\pi + > 2\gamma$) was obtained. The result was consistent with the TPC value. The other analysis[23) was dedicated to resolution of the individual branching ratios. In contrast with the TPC result, the excess over the predicted branching ratios was found in high multiplicity modes like $\tau \to \nu\pi 3\pi^0$, $\tau \to \nu\pi\pi^0\eta$ rather than $\tau \to \nu\pi 2\pi^0$. The fit to the data had a very poor confidence level when branching ratios for $\tau \to \nu\pi 3\pi^0$ and $\tau \to \nu\pi\pi^0\eta$ were fixed at the predicted values.

Instead of looking at many different event classes in order to resolve various exclusive channels, the MAC experiment[24) chose to select only one event class getting the main contribution from the $\tau \to \nu\pi 2\pi^0$ decay. Nevertheless this analysis was no different from the other indirect measurements in its inability to separate the $\tau \to \nu\pi 2\pi^0$ channel from the other τ decay modes like $\tau \to \nu\pi\pi^0$, $\tau \to \nu\pi 3\pi^0$ or $\tau \to \nu\pi\pi^0\eta$. The branching ratio for $\tau \to \nu\pi 2\pi^0$ was obtained assuming the

Table 3: Measurements of τ decays to multiphoton final states. $\mathcal{L} \times \sigma^{\mathrm{QED}}_{\tau\tau}$ represents a crude estimate of the number of $\tau\tau$-pairs using the lowest order QED cross section for $e^+e^- \rightarrow \tau^+\tau^-$. The ratio of efficiencies is given to demonstrate how well experiments could separate $\tau \rightarrow \nu\pi 2\pi^0$ from the other τ decays (some numbers are only roughly estimated). The branching ratios in parentheses denote assumed values. All limits correspond to 95 % C.L.

Experiment	E_{CM} [GeV]	$\mathcal{L}$ [pb^{-1}]	$\mathcal{L} \times \sigma^{\mathrm{QED}}_{\tau\tau}$	efficiencies for event class with the maximal $\epsilon_{\pi 2\pi^0}$		BR [%]		
				$\epsilon_{\pi 2\pi^0}$ [%]	$\epsilon_{\pi\pi^0} : \epsilon_{\pi 2\pi^0} : \epsilon_{\pi 3\pi^0}$ (relative)	$\pi 2\pi^0$	$\pi 3\pi^0$	$\pi\pi^0\eta$
CELLO[20]	14	1						
	22	3	900	14	$\frac{1}{6.7} : 1 : \frac{1}{1.6}$	6.0±3.0±1.8	3.0±2.2±1.5	(0.0)
TPC[21]	29	72	7,400	7	$\frac{1}{6.2} : 1 : \frac{1.1}{1}$	$13.9 \pm 2.0^{+2.1}_{-2.4}$		
						>8.3	<3.5	<5.0
Mark-II[22,23]	29	220	22,700	11	$\frac{1}{9.6} : 1 : \frac{1}{1.0}$	12.0±1.4±2.5		
						6.2±0.6±1.2	0.0±1.4±1.1	$4.2^{+0.7}_{-1.2} \pm 1.6$
						6.7±0.5±?	2.2±0.4±?	(0.0)
						8.6±0.3±?	(1.0)	(0.0)
MAC[24]	29	216	22,300	12	$\frac{1}{3.5} : 1 : \frac{2.5}{1}$	8.7±0.4±1.1	(1.0)	(0.0)
CELLO[6]	35	87	6,200	11	$\frac{1}{23.} : 1 : \frac{1}{1.0}$	14.0±1.2±0.6		
						10.2±1.5±1.1	3.2±1.0±1.0	(0.0)
C. Ball[15,16]	≈ 10	256	222,000	0.4	$\frac{1}{35.} : 1 : \frac{1}{38.}$	7.4±0.6±1.3	<2.5	—

theoretically predicted values for the branching ratios for the other contributing τ decay modes. The obtained branching ratio was very close to the value obtained by Mark-II under the same assumptions, which fell in between the TPC and the Mark-II results from unconstrained fits.

Recently the CELLO group presented a preliminary analysis[6] of the data at higher energy and with higher statistics than previously analyzed. The BR($\tau \rightarrow \nu\pi + > 2\gamma$) was found again high compared to the expectations. Unfolding of the individual branching ratios resulted in high BR($\tau \rightarrow \nu\pi 2\pi^0$) favoring the TPC result over the Mark-II analysis. This branching ratio was significantly higher than expected from the world average BR($\tau \rightarrow \nu 3\pi$), but agreed within the errors with the value of BR($\tau \rightarrow \nu 3\pi$) measured by CELLO on the same data sample. The BR($\tau \rightarrow \nu\pi 3\pi^0$) was measured to be above the CVC prediction, but the disagreement was not significant because of the experimental errors.

In summary, all three measuremants of BR($\tau \rightarrow \nu\pi + > 2\gamma$) by TPC, Mark-II and CELLO agree. The average value BR($\tau \rightarrow \nu\pi + > 2\gamma$)=(13.7±1.1) % is significantly higher than expected theoretically : BR($\tau \rightarrow \nu\pi 2\pi^0$)+BR($\tau \rightarrow \nu\pi 3\pi^0$)+BR($\tau \rightarrow \nu\pi\pi^0\eta$)=(8.2±0.4) %. Unfortunately the experiments disagree on which decay mode should be blamed for this excess. TPC and CELLO favor high BR($\tau \rightarrow \nu\pi 2\pi^0$), whereas Mark-II finds evidence for excess in even higher photon multiplicity channels.

6 Direct Measurements on High Photon Multiplicity Decays

The indirect methods for determination of the branching ratios for multiphoton final states described in the previous section have several disadvantages, which all have their origin in the lack of reconstruction of all final state mesons. As demonstrated in Table 3 resolution of various exclusive modes is rather poor. Therefore, unfolded branching ratios are highly correlated. In case when some of the contributing branching ratios have been fixed at the predicted values, results become dependent on the validity of the predictions used. Results would be also invalid if an unexpected decay mode contributed to the selected events. As π^0's and η's are not identified, fake or background photons cannot be separated from genuine photons from the neutral meson decays. Therefore, one must heavily rely on Monte Carlo simulation of fakes and backgrounds. Dependence on many detailed aspects of the Monte Carlo simulation in the unfolding technique introduces systematic errors which are difficult to estimate. In fact the disagreement on the BR($\tau \rightarrow \nu\pi 2\pi^0$) indicates that there were some uncontrolled systematic errors in at least one of the indirect measurements.

All these problems can be overcome by identification of all final state neutral mesons. For large number of photons this is of course very difficult and requires an excellent photon detector and high statistics data. So far, the Crystal Ball experiment at DORIS was the only experiment which could achieve this goal for the $\tau \rightarrow \nu\pi 2\pi^0$ decay[15,16]. The Crystal Ball is a spherical shell of NaI(Tl) crystals, providing efficient detection of photons down to a few MeV energy region over a large solid angle with good energy resolution ($\sigma_E/E = 2.7\%/\sqrt[4]{E}$). The cross section for $\tau\tau$ production is higher by an order of magnitude at DORIS than at PEP or PETRA. This was directly reflected in the statistics of τ–pairs collected by the Crystal Ball as compared to the other experiments described in the previous section. The lower beam energy at DORIS as compared to PEP or PETRA, helped also by enlarging an opening angle between τ decay products (see Fig.1). Overlap of photons in the calorimeter was still, however, the main limitation on detection efficiency. The detection efficiency for the $\tau \rightarrow \nu\pi 2\pi^0$ decay was only a fraction of a percent in the Crystal Ball experiment. The advantage of reconstruction of the both π^0's is apparent from Table 3. With cuts designed to select $\tau \rightarrow \nu\pi 2\pi^0$ events, the indirect measurements could hardly get a $\tau \rightarrow \nu\pi 2\pi^0$ efficiency larger than the $\tau \rightarrow \nu\pi 3\pi^0$ feed-down efficiency. On the other hand, in the Crystal Ball measurement, the $\tau \rightarrow \nu\pi 3\pi^0$ feed-down efficiency was suppressed by a factor of 40 compared to the $\tau \rightarrow \nu\pi 2\pi^0$ efficiency. Therefore, for the first time, the branching ratio for $\tau \rightarrow \nu\pi 2\pi^0$ was measured independently of the branching ratios of even higher photon multiplicity decays. Background from fake photons or from any other non-π^0 photons was removed in the Crystal Ball data by π^0 sideband subtraction in the $M_{\gamma\gamma}$ distribution. Therefore, only $2\pi^0$ backgrounds had to be understood by the Monte Carlo simulation. This was the other big improvement over the indirect measurements which had to cope with backgrounds on the level of photons.

The Crystal Ball fully reconstructed about 200 $\tau \rightarrow \nu\pi 2\pi^0$ decays. The resulting $\tau \rightarrow \nu\pi 2\pi^0$ branching ratio was in very good agreement with the prediction by isospin symmetry and the world average BR($\tau \rightarrow \nu 3\pi$) (see Table 1 and 3). Unfortunately, the experimental errors, limited primary by the small detection efficiency, were such that the higher branching ratio as measured by TPC and CELLO could not be ruled out.

The Crystal Ball attempted to measure directly also the $\tau \rightarrow \nu\pi 3\pi^0$ mode. From 11.5±6.0 $3\pi^0$ events 7.5 events had to be attributed to the background. Thus, the $\tau \rightarrow \nu\pi 3\pi^0$ mode could not be really established and only the upper limit on the branching ratio was given.

7 Future Prospects

As far as the indirect measurements are concerned, one may expect some new results from the TPC experiment. TPC already has a sample with improved statistics and improved photon detection efficiency than the one analyzed originally. If PEP takes data in the future, the statistics will be improved even further.

Perhaps some indirect measurements can be done at the Z^0 peak at SLC and LEP. However, direct reconstruction of multiphoton final states will be prohibited by very high τ momentum (see Fig.1).

Significant progress in reconstruction of multiphoton τ decays should be accomplished in the next few years by the CLEO-II experiment25) at CESR. The CESR storage ring provides the same beam energy as DORIS but with higher luminosity. Further improvements in luminosity up to few times 10^{32} cm^{-2}s^{-1} are expected26) . Data samples by an order of magnitude larger than that used by the Crystal Ball are not unrealistic. The CLEO-II detector, which will start collecting data this year, is equipped with a CsI(Tl) calorimeter with a solid angle coverage and energy resolution comparable to the Crystal Ball detector. Individual crystals are about the same size, while the the inner radius of the CLEO-II calorimeter, $R \approx 100$ cm, is four times larger than that of the Crystal Ball calorimeter, $R \approx 25$ cm. Thus, reconstruction cut-off on photon overlap angle should be improved by a factor of 4. As overlap of photons was the main factor limiting the Crystal Ball efficiency, the CLEO-II reconstruction efficiency for the multiphoton final states should be better by at least factor of 10 (see Fig.1). A reconstrcution efficiency in the few percent region will be useful not only in obtaining better statistical errors, but also in decreasing systematic uncertainties. Assuming a factor of 100 in relative sensitivity of CLEO-II vs. Crystal Ball and the nominal branching ratios (Table 1), the CLEO-II should reconstruct 20,000 $\tau \rightarrow \nu\pi 2\pi^0$ events, 550 $\tau \rightarrow \nu\pi 3\pi^0$ events and 150 $\tau \rightarrow \nu\pi\pi^0\eta$ events. Thus, the corresponding branching ratios will be measured more precisely than the errors on the theoretical predictions (Table 1). Hopefully, this should be sufficient to resolve the origin of the discrepancy between the predictions and the inclusive measurements on multiphoton τ decays.

Beyond the CLEO-II experiment, further experiments in the 10 GeV region of e^+e^- energy (B-factories) can push the statistical sensitivity for multiphoton final states by another factor of 10–100. Experiments at a Tau-Charm Factory could do even better. Not only the $e^+e^- \rightarrow \tau^+\tau^-$ cross section can be made higher but also resolution of all final state photons should be easier as τ's are produced almost at rest (see Fig.1). Very rare τ decays, like the second class current process $\tau \rightarrow \nu\pi\eta$, should become detectable.

8 Conclusions

Three different experiments at PEP and PETRA measured the inclusive branching ratio for $\tau \rightarrow \nu\pi + > 2\gamma$ to be in excess of the theoretical predictions for the sum BR($\tau \rightarrow \nu\pi 2\pi^0$)+BR($\tau \rightarrow \nu\pi 3\pi^0$)+BR($\tau \rightarrow \nu\pi\pi^0\eta$). This suggests that the problem of missing exclusive τ decay modes can be resolved by measurements on various τ decays to final states with multiple photons. It is important to verify BR($\tau \rightarrow \nu\pi + > 2\gamma$) by experiments at different beam energies, which will have quite different systematic uncertainties. Futhermore, exclusive branching ratio for the individual decay modes in this topology should be measured. Unfortunately, the indirect determinations of the exclusive branching ratios for these decay modes disagree. The direct measurements by the Crystal Ball at DORIS were not precise enough to resolve this puzzle.

The forthcoming CLEO-II experiment at CESR will be able to measure all the above branching ratios with sufficient precision. Experiments at the proposed B and, especially, Tau-Charm Factories will investigate multiphoton τ decay modes even into much greater depth.

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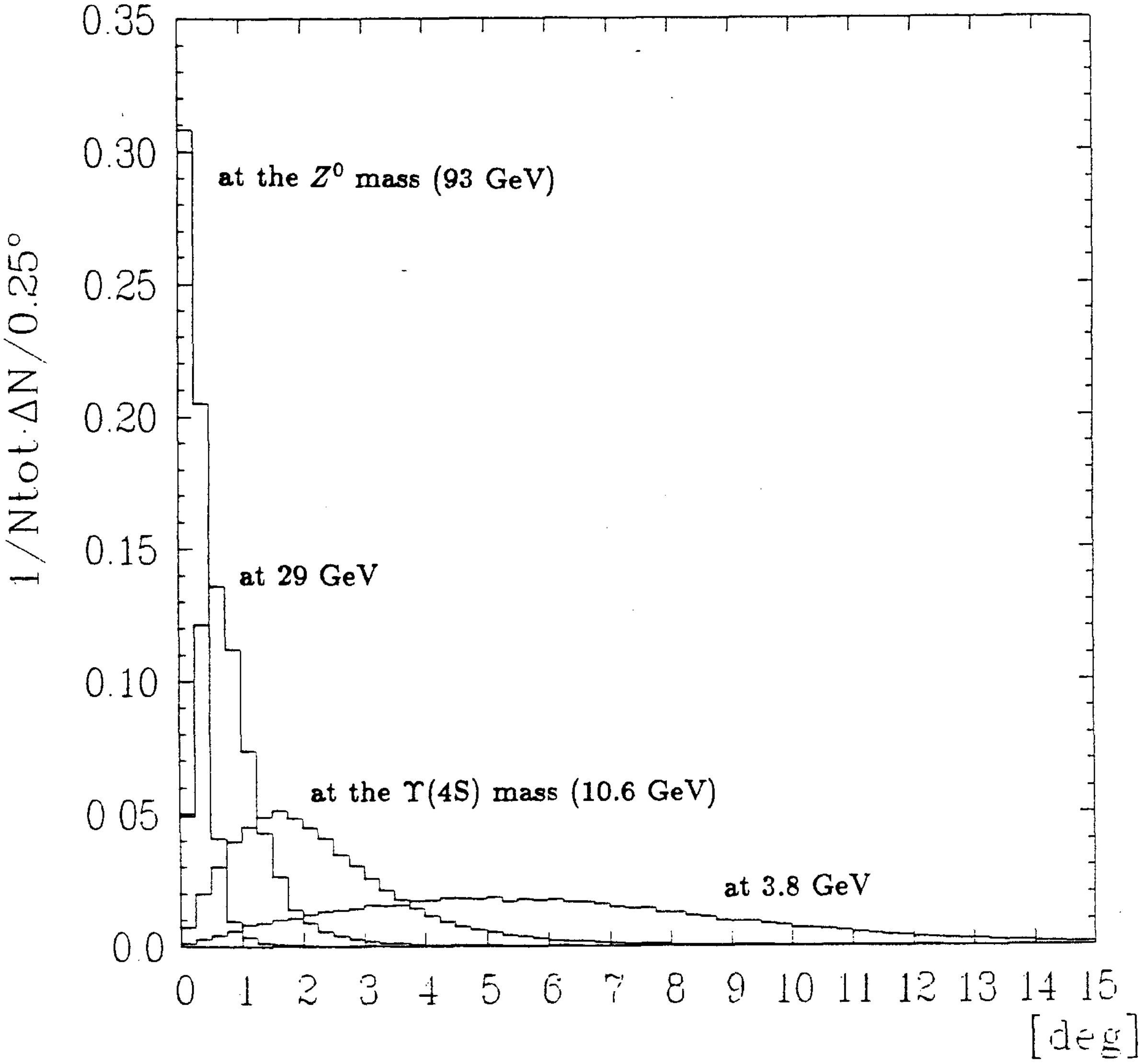

Figure 1: The maximal overlap angle between any of photons or charged tracks in $e^+e^- \rightarrow \tau^+\tau^-$, $\tau^+ \rightarrow \nu e^+\nu$, $\tau^- \rightarrow \nu\pi^-3\pi^0$ events at different e^+e^- energies. The $\tau \rightarrow \nu\pi 3\pi^0$ decay was modeled according to the phase space. The distribution at 29 GeV demonstrates why the experiments at PEP or PETRA could not reconstruct the final state π^0's. Such reconstruction will be even harder in experiments at the Z^0 mass (SLC, LEP). The opening angle is larger at the Υ(4S) resonance (DORIS, CESR, B-factory) but still limiting the reconstruction efficiency. For the Crystal Ball experiment at DORIS effective cut-off angle was about 10 degrees resulting in tiny detection efficiency much below 1 %. For the CLEO-II experiment at CESR the cut-off should be improved by a factor of 3-4 which will bring the reconstruction efficiency into the 10-20 % region. This gives improvement by a factor of 100 over the Crystal Ball analysis. The reconstruction of the all 3 π^0's would be easier at lower beam energies like proposed for the Tau-Charm Factory.