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**CRYSTAL BALL RESULTS ON TAU DECAYS\***

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**ABSTRACT**

This report reviews measurements and upper limit determinations for a number of exclusive 1-prong  $\tau$  decay modes using the Crystal Ball detector. These results are important input to the apparent discrepancy between the topological and sum-of-exclusive branching fractions in 1-prong  $\tau$  decays.

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**MASTER**

1. Introduction

Since its discovery in 1975<sup>[2]</sup> experiments have confirmed the assignment of the  $\tau$  as the third sequential charged lepton. There is, however, an increasingly apparent discrepancy in our understanding of 1-prong tau decays. Table 1 shows the measured values for the known or expected decay modes, along with the topological 1-prong branching fraction. The theoretical estimates of decay rates for various decay modes, normalized to the  $\tau^- \rightarrow \nu_\tau \nu_e e^-$  mode (along with additional experimental input) are also shown and are in good agreement with the measured values. To the extent of this agreement, we have confidence in the theoretical estimates of the expected, but unmeasured modes also shown. The apparent discrepancy then shows itself as about a 7% difference between the inclusive and sum-of-exclusive 1-prong branching fractions. When averaging results from several experiments to obtain the values shown, the systematic errors were assumed independent. This assumption is not strictly correct and leads to an underestimate of the error on the 7% difference. Thus the apparent discrepancy may be due to correlated systematic errors between different experiments or, more interestingly, it could be a signal of new physics. In any case, a resolution to this problem is necessary for a complete understanding of the tau.

Last year both the HRS and Crystal Ball collaborations presented preliminary evidence for  $\tau \rightarrow \eta X$  at the few percent level<sup>[4]</sup> but no branching fraction was given in the Crystal Ball analysis due to possible backgrounds from hadronic events. Both groups observed an enhancement at the eta mass in an inclusive  $M_{\tau\gamma}$  mass spectrum. It was pointed out by Gilman<sup>[6]</sup> earlier this year that, in the Standard Model, a 1-prong eta decay mode of a few percent is not consistent with other measurements. At about this time HRS reanalyzed their data and concluded their eta signal was only consistent with the  $\tau \rightarrow \nu\pi\eta$  mode. Their published branching ratio<sup>[5]</sup> of  $5.1 \pm 1.5\%$  seemed to resolve the 1-prong puzzle but, because this decay can only proceed via a second class current, it is negligible in the Standard Model. The Crystal Ball has also reanalyzed their data and found their signal completely disappears under more stringent selection criteria, resulting in upper limits for various eta decays modes<sup>[7]</sup>

Before the new Crystal Ball inclusive analysis was complete, an independent exclusive analysis was begun to determine which decays, if any, were contributing to the inclusive eta signal. A primary goal was to accurately measure the known decay  $\tau \rightarrow \nu\pi$  and the expected but unseen modes  $\tau \rightarrow \nu\pi\pi^0\pi^0$  and  $\tau \rightarrow \nu\pi\pi^0\pi^+\pi^-$ . This exclusive analysis is reported here; Reference 7 summarizes the new inclusive results. The decay modes studied are  $\tau \rightarrow \nu\pi X$ , where  $X$  is one to three  $\pi^0$ s or etas, in all possible combinations kinematically allowed. The  $\pi^0$ s and etas are detected only through their  $\gamma\gamma$  decay modes

Decay Mode $\tau \rightarrow \nu +$	1-Prong Branching Ratio (%)	
	Experiment	Theory
$\nu e$	$17.7 \pm 0.4$	17.7
$\nu \mu$	$17.6 \pm 0.4$	17.2
$\pi$	$10.9 \pm 0.6$	10.7
$K$	$0.7 \pm 0.2$	0.7
$\rho$	$22.7 \pm 1.0$	21.8
$K^*$	$1.4 \pm 0.1$	1.1
$\pi\omega$	$0.14 \pm 0.03$	0.1-0.2
$\pi\pi^0\pi^0$	$7.4 \pm 0.8$	7.1
$\pi 3\pi^0$	"1.0"	1.0
$\pi\pi^0\eta$	"0.15"	0.15
$\pi\pi^0\pi^0\eta$		< 0.40
$\pi\eta\eta$		< 1.5
$\pi 4\pi^0 + \pi 5\pi^0$		< 0.22
Sum	$79.7 \pm 1.5$	
Topological 1-prong	$86.8 \pm 0.3$	
Difference	$7.1 \pm 1.5$	

Table 1 The average of the known one-prong exclusive and inclusive measurements<sup>[2]</sup> Numbers in quotes are copied from theory.

Several aspects of the Crystal Ball detector<sup>[1]</sup> are important for this analysis and in how these results are used in combination with those from other experiments. The primary strengths of the Crystal Ball are its energy and angular resolution for electromagnetically showering particles;  $\sigma_E/E = 2.7 \pm 0.2\% / \sqrt{E(\text{GeV})}$  and 1-2 degrees, respectively. The low energy cut-off for photons is 10 MeV and is important for the higher multiplicity final states; a higher cut-off would drastically reduce the efficiency for these modes. Tube chambers near the interaction region separate charged from neutral particles, but because the Crystal Ball has no magnetic field, the momentum of the charged particles is not measured. Thus particle identification for charged particles is performed by examining the energy deposition pattern in several adjacent NaI crystals.

## 2. The $\tau^+\tau^-$ Data Sample

The data used for this analysis were collected at the DORIS II storage ring from 1982-1986. These data were collected on the  $\Upsilon(1S)$ ,  $\Upsilon(2S)$ ,  $\Upsilon(4S)$  and the continuum near the  $4S$ . The integrated luminosity, calculated from large-angle Bhabhas and the known cross-section, was found to be about  $260 \text{ pb}^{-1}$ . Using the known  $\tau^+\tau^-$  cross-section, corrected for direct leptonic decays of the  $\Upsilon$  states and some radiative corrections gives  $265 \pm 9K$  produced  $\tau^+\tau^-$  events.

Events are selected which are consistent with  $e^+e^- \rightarrow \tau^+\tau^-$  where one tau decays to  $\nu\bar{\nu}e$ ,  $\nu\bar{\nu}\mu$ ,  $\nu\bar{\nu}\pi$  or  $\nu\bar{\nu}K$ ; modes with undetected neutrinos plus a single charged particle which tags the tau decay. The other tau then decays to  $\nu\bar{\nu}X$  where  $X$  is 2, 4 or 6 photons.

## 3. Two-Photon Final State Analysis

The two decay modes studied with 2 photons in the final state are  $\tau \rightarrow \nu\rho \rightarrow \nu\pi\pi^0$  and  $\tau \rightarrow \nu\pi\eta$ . Because the  $\pi$  momentum is not measured, the  $\rho$  mass cannot be reconstructed. Thus,  $\text{BR}[\tau \rightarrow \nu\pi\pi^0]$  is measured assuming the  $\pi\pi^0$  system is a  $\rho$ .

Figure 1 shows  $M_{\pi\pi}$  for events passing the  $\nu\pi\pi^0$  analysis criteria. A clear  $\pi^0$  peak is evident and a fit to the histogram results in  $2262 \pm 52$  counts. From Monte Carlo studies, 154 of these events are estimated to come from other  $\tau^+\tau^-$  decays feeding into this channel. The branching ratio derived from this analysis is  $\text{BR}[\tau \rightarrow \nu\pi\pi^0] = 22.6 \pm 0.5 \pm 1.4\%$ , where the first error is statistical and the second systematic. This result depends on no significant contributions from non-tau processes. Several checks have been performed to verify this is true:

- If the charged tag is required to be an electron, a consistent result is obtained ( $23.9 \pm 0.7 \pm 1.8\%$ ).
- The branching ratio is very flat as the analysis cuts are applied. If a significant background were present, the branching ratio should drop as the cuts are applied.
- If the  $\pi^\pm$  candidate is required to be minimum ionizing in the NaI, a consistent result is obtained.
- If the events in the final  $\pi^0$  peak, for both the data and Monte Carlo are run through the analysis a second time, the distributions which were cut on appear the same (there is no observed pile-up near a cut boundary, for example).

The other two-photon final state is  $\tau \rightarrow \nu\pi\eta$ . The histogram in Figure 2 shows the data along with the expected signal for a 5% branching ratio, approximately the value published

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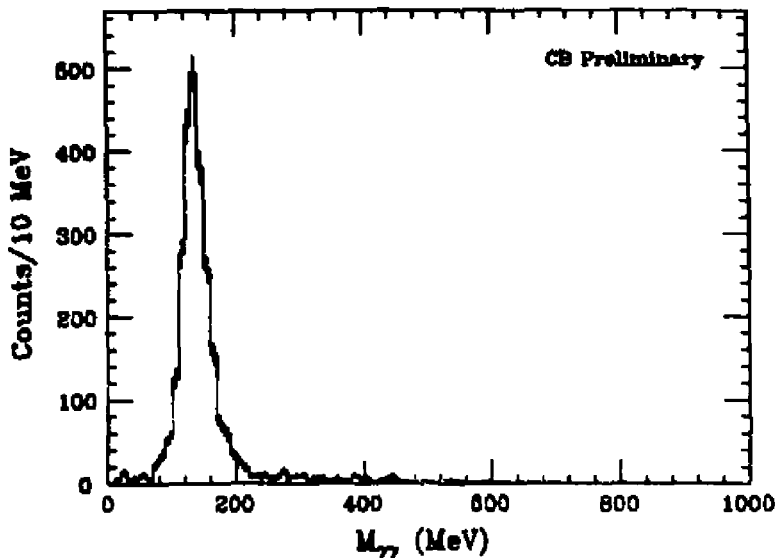


Fig. 1  $M_{\gamma\gamma}$  for the  $\nu\pi\pi^0$  analysis. A clear  $\pi^0$  signal is evident.

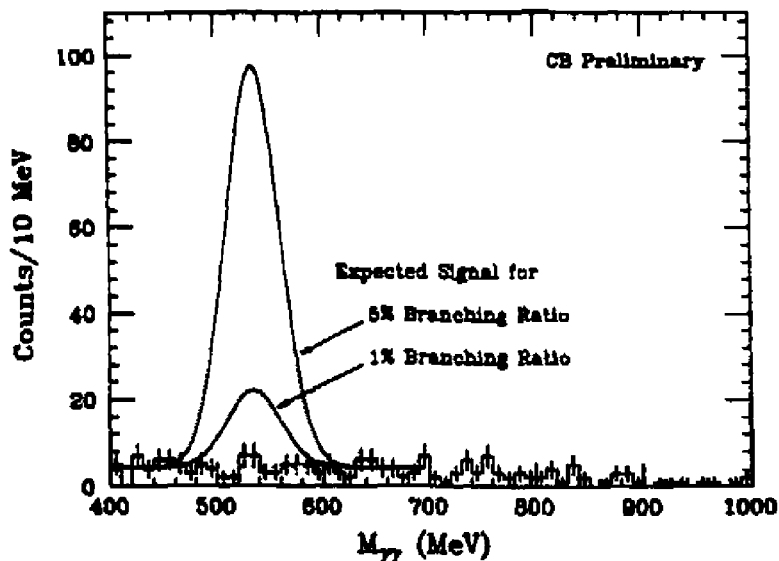


Fig. 2  $M_{\gamma\gamma}$  for the  $\nu\pi\eta$  analysis. The expected amplitude for a 5% and 1% branching ratio are shown for comparison.

by HRS, and a 1% branching ratio for comparison. The nominal width of 25 MeV used here is determined from the  $\eta$  signal seen in inclusive hadronic events and in exclusive  $\gamma\gamma$  interactions. Because the data show no enhancement at the  $\eta$  mass, an upper limit of  $\text{BR}[\tau \rightarrow \nu\pi\eta] < 0.3\%$  at the 95% confidence level is derived.

#### 4. Four-Photon Final State Analysis

Three tau decay modes leading to a four-photon final state are analyzed;  $\tau \rightarrow \nu\pi\pi^0\pi^0$ ,  $\tau \rightarrow \nu\pi\pi^0\eta$  and  $\tau \rightarrow \nu\pi\eta\eta$ . The  $\nu\pi\pi^0\eta$  decay products are assumed to be distributed either flat in phase space or the  $\pi\pi^0$  system may proceed via a  $\rho$ ; both cases are treated here.

Figure 3 shows  $M_{\gamma\gamma}(\text{high})$  vs  $M_{\gamma\gamma}(\text{low})$  and the diagonal projection. A clear  $\pi^0$  peak is seen with a width  $\sqrt{2}$  narrower than the nominal value due to the diagonal projection. Note that this is the first direct evidence for the existence of this tau decay mode. A fit to this peak gives  $210 \pm 17$  counts where 29 are expected from other tau decay modes, mostly  $\tau_{1,2} \rightarrow \nu\rho$  because of the identical final state and large branching fraction to the  $\rho$ . The derived branching ratio is then  $\text{BR}[\tau \rightarrow \nu\pi\pi^0\pi^0] = 7.4 \pm 0.6 \pm 1.3\%$ . To check for non-tau backgrounds in this sample, the tagging charged particle was split into three classes based on the energy deposition pattern; electron, minimum ionizing (muons and some pions), and "other." All three classes give a consistent branching ratio, indicating this result is insensitive to non-tau backgrounds.

A similar analysis for the  $\nu\pi\pi^0\eta$  mode shows no evidence for an  $\eta$  signal. The detection efficiency, assuming the decay products are distributed flat in phase space, is 0.29% while the efficiency is 0.30% if the  $\pi\pi^0$  system forms a  $\rho$ . This leads to the 95% confidence level upper limits  $\text{BR}[\tau \rightarrow \nu\pi\pi^0\eta] < 2.5\%$  and  $\text{BR}[\tau \rightarrow \nu\rho\eta] < 2.5\%$ . The  $\tau \rightarrow \nu\pi\eta\eta$  mode similarly shows no evidence for an  $\eta$  signal, leading to the upper limit  $\text{BR}[\tau \rightarrow \nu\pi\eta\eta] < 1.4\%$  at the 95% confidence level.

#### 5. Six-Photon Final State Analysis

The six-photon final state analysis is designed primarily to study the decay  $\tau \rightarrow \nu\pi\pi^0\pi^0\pi^0$ . Two other decay modes are also examined,  $\tau \rightarrow \nu\pi\pi^0\pi^0\eta$  and  $\tau \rightarrow \nu\pi\pi^0\eta\eta$ , but are not the primary thrust of this analysis.

Figure 4 shows the invariant mass of one  $\gamma\gamma$  pair, where the mass of the other 2 pairs were each required to be consistent with the  $\pi^0$  mass. A fit to the histogram with the mean and width constrained to the expected values results in  $11.5 \pm 6.0$  counts. From Monte Carlo studies one can estimate that of the 11.5 events seen, 4.0 are expected from the signal and

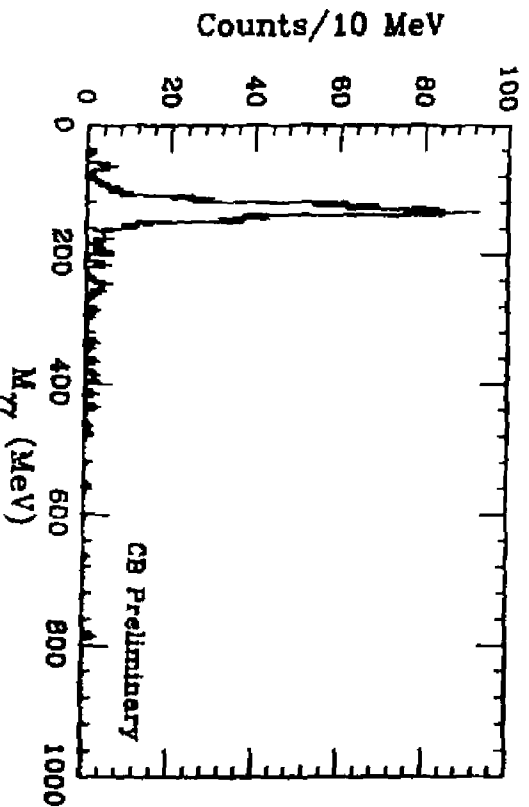
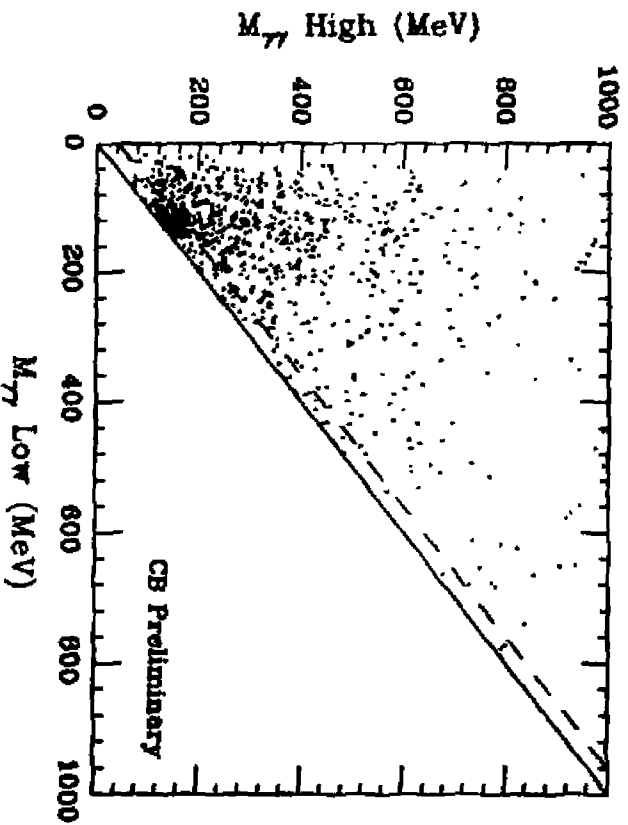


Fig. 5 Scatter plot of  $M_{\gamma\gamma}$ (high) vs  $M_{\gamma\gamma}$ (low) and the diagonal projection for the  $\nu\pi\pi^0\gamma^0$  analysis. A clear  $\pi^0$  signal is evident. This is the first proof that this  $\tau$  decay mode exists.



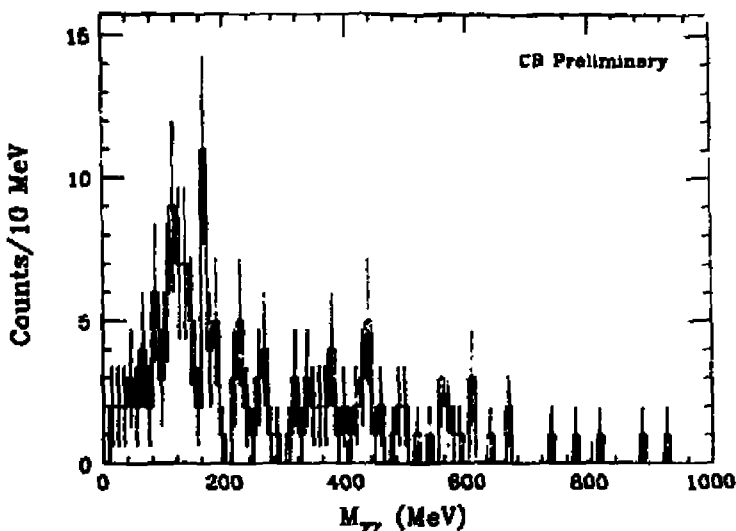


Fig. 4  $M_{\tau\tau}$  for the  $\nu\pi 3\pi^0$  analysis. One  $M_{\tau\tau}$  pair is plotted if the other two  $\pi^0$  candidates are consistent with the  $\pi^0$  mass.

7.5 are backgrounds expected from other  $\tau^+\tau^-$  decays. This results in a branching ratio of  $\text{BR}(\tau \rightarrow \nu\pi\pi^0\pi^0\pi^0) = 0.54 \pm 0.28 \pm 1.06$  which we prefer to quote as an upper limit of 2.5% at the 95% confidence level.

No evidence of an eta is seen in the  $\tau \rightarrow \nu\pi\pi^0\pi^0\eta$  and  $\tau \rightarrow \nu\pi\pi^0\eta\eta$  analyses. This leads to the upper limits  $\text{BR}(\tau \rightarrow \nu\pi\pi^0\pi^0\eta) < 5.9\%$  and  $\text{BR}(\tau \rightarrow \nu\pi\pi^0\eta\eta) < 9.8\%$  respectively. In both cases, the acceptance uncertainty is completely dominated by Monte Carlo statistics, leading to these non-constraining upper limits.

## 6. Summary and Conclusions

The results from the above analyses are summarized in Table 2. Also shown are other preliminary results from the Crystal Ball derived from the new inclusive analysis.<sup>(7)</sup> Note that several of these results are the best reported to date.

If one calculates the difference between the inclusive and sum-of-exclusive 1-prong decay modes, the difference moves from  $7.1 \pm 1.6\%$  to  $7.3 \pm 1.3\%$  with the inclusion of these results. Although these errors are almost surely underestimated, one can conclude that there still remains a notable difference. Upper limits on the eta decay modes presented here constrain them from contributing greatly to the exclusive sum. Thus, the eta decay modes are probably not the solution to this problem.

Summary of Crystal Ball Tau Results

$\tau$ Decay Mode	Exclusive Analysis	Inclusive Analysis <sup>(1)</sup>
$\nu\pi\pi^0$ *	$22.6 \pm 0.5 \pm 1.4\%$	
$\nu\pi\pi^0\pi^0$ †	$7.4 \pm 0.6 \pm 1.3\%$	
$\nu\pi\pi^0\pi^0\pi^0$ *	$< 2.5\%$	
$\nu\pi\eta$ *	$< 0.3\%$	$< 0.3\%$
$\nu\pi\pi^0\eta$ *	$< 2.5\%$	$< 0.9\%$
$\nu\pi\eta\eta$	$< 1.4\%$	$< 2.5\%$

\* World's best measurement/upper limit at present  
 † First proof this decay mode exists

Table 2 The measured branching fractions/upper limits for the 1-prong decays studied here. Upper limits from the Crystal Ball inclusive analysis are also shown. Upper limits are at the 95% confidence level.

One likely solution to the 1-prong puzzle is that there is some common systematic which biases the results from all experiments measuring the same quantity, making the average systematically high or low. This is especially worrisome because most of the information from tau decays comes from magnetic detectors. Because the Crystal Ball is optimized for photon detection, the systematics are quite different. The results from the  $\nu\pi\pi^0$  and  $\nu\pi\pi^0\pi^0$  analyses agree well with those from the magnetic detectors making the case for a common systematic much less likely for these exclusive modes.

In conclusion, these results do not resolve the 1-prong discrepancy. Many solutions, like  $\eta$  decay modes or some possible sources of common systematics between experiments can be ruled out or made much less likely. For the future it would be very helpful, and interesting in its own right, to check the assumption of lepton universality for taus to a higher precision. It might also help if the 1-prong inclusive branching fraction were checked by a neutrals detector.

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