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A Precise Measurement of the Branching Fraction for the Decay $\tau \rightarrow \nu_\tau \pi$*

W. T. Ford, N. Qi, A. L. Read, Jr.,[a] and J. G. Smith
Department of Physics, University of Colorado, Boulder, Colorado 80309

T. Camporesi,[b] I. Peruzzi, and M. Piccolo
I. N. F. N., Laboratori Nazionali di Frascati, Frascati, Italy

R. B. Hurst, K. H. Lau, J. Pyrlik, J. P. Venuti, H. B. Wald, and R. Weinstein
Department of Physics, University of Houston, Houston, Texas 77004

H. R. Band, M. W. Gettner, G. P. Goderre,[c] J. H. Moromisato,
W. D. Shambroom,[d] J. C. Sleeman, and E. von Goeler
Department of Physics, Northeastern University, Boston, Massachusetts 02115

W. W. Ash, G. B. Chadwick, R. E. Leedy, R. L. Messner,
L. J. Moss, F. Muller,[e] H. N. Nelson, D. M. Ritson,
L. J. Rosenberg,[f] D. E. Wiser, and R. W. Zdarko
Department of Physics and Stanford Linear Accelerator Center,
Stanford University, Stanford, California 94305

D. E. Groom and P. G. Verdini
Department of Physics, University of Utah, Salt Lake City, Utah 84112

M. C. Delfino, J. R. Johnson, T. L. Lavine, T. Maruyama, and R. Prepost
Department of Physics, University of Wisconsin, Madison, Wisconsin 53706

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ABSTRACT

A sample of events from the process $e^+e^- \rightarrow \tau^+\tau^-$ observed with the MAC detector operating at the SLAC storage ring PEP is used for a precise measurement of B_π, the branching fraction for the decay $\tau \rightarrow \nu_\tau \pi$. The result $B_\pi = 0.107 \pm 0.004 \pm 0.008$ is obtained from a sample of events with 798 identified pions.

A measurement of the ratio of branching fractions (relative to all tau decays) for the decays $\tau \rightarrow \nu_\tau \pi$ (B_π) and $\tau \rightarrow \nu_\tau e \bar{\nu}_e$ (B_e) can be used to determine the coupling of the τ lepton to the pion. The ratio B_π/B_e is calculable from well measured quantities, if the assumption is made that the same weak charged current participates in the decays $\pi \rightarrow \mu\bar{\nu}_\mu$ and $\tau \rightarrow \nu_\tau \pi$. In addition, recent theoretical progress in the understanding of tau decays[1] has motivated precise measurements of tau branching fractions. Two measurements of the pion branching fraction from the reaction $e^+e^- \rightarrow \tau^+\tau^-$ are presented, where one tau decays into $\nu_\tau \pi$ and the other into one or three charged particles. The data for these measurements were obtained with the MAC detector operating at the SLAC storage ring PEP at $\sqrt{s} = 29$ GeV. The integrated luminosity for the data sample is 212.7 ± 3.3 pb^{-1}, corresponding to approximately 27 000 produced tau-pair events.

The central element of the MAC detector[2] is a ten layer cylindrical drift chamber (CD) inside a solenoid with a magnetic field strength of 0.57 T, providing a momentum resolution $\delta p/p = 0.065\, p \sin\theta (\mathrm{GeV/c})^{-1}$ for polar angles θ such that $|\cos\theta| < 0.9$. Surrounding the solenoid is a hexagonal barrel calorimeter of lead sheets interspersed with proportional wire chambers (PWC's) for measuring electromagnetic showers with $|\cos\theta| < 0.8$. Surrounding this electromagnetic calorimeter is a hadronic calorimeter of 5.5 nuclear interaction lengths of iron instrumented with PWC's. The ends of the detector are closed by endcaps consisting entirely of iron plates interspersed with PWC's. The energy resolutions for electromagnetic showers are $\sigma_E/E = 20\%/\sqrt{E(\mathrm{GeV})}$ in the central section and $45\%/\sqrt{E}$ in the endcaps. The hadronic calorimeters have energy resolutions of about $75\%/\sqrt{E}$. The electromagnetic calorimeters have azimuthal and polar angular resolutions of $\sigma_\phi = 0.6^\circ$ and $\sigma_\theta = 1.2^\circ$ in the central section, and $\sigma_\phi = 1.2^\circ$ and $\sigma_\theta = 1.5^\circ$ in the endcaps. The calorimeters are enclosed by a hexagonal barrel of four layers of cylindrical drift tubes oriented transverse to the beam, except for the plane under the detector which consists of three layers of planar drift chambers. The ends of the detector are covered with six planes of drift tubes, covering the angular range $0.80 < |\cos\theta| < 0.97$. The iron calorimeters are toroidally magnetized and the outer drift system (OD) measures the polar bend angle of a charged particle emerging from the iron. Scintillators, placed immediately inside the central hadron calorimeter and near electromagnetic shower maximum in the endcaps, provide triggering and time of flight information.

The trigger for the experiment consists of the logical OR of (1) scintillator hits in opposite sextants or endcap quadrants; (2) scintillator hits on three or more of the eight faces of the detector (six hexagon faces and two endcap planes); (3) showers of at least 2 GeV in any two of six shower chamber sextants, two endcaps, or the central hadron calorimeter; (4) one or more penetrating tracks, defined by a cluster of CD hits in azimuthal coincidence with energy deposition of more than 400 MeV in the matching calorimeter sextant and a signal in one of the corresponding scintillators. Events satisfying this hardware trigger must also pass a simple software filter. The data were written to magnetic tapes and then processed by a loose first-pass analysis that rejected 90% of the original triggers leaving about 4×10^6 events (mostly due to Bhabha scattering) for subsequent analysis.

The selection of events with one τ decaying to $\nu_\tau \pi$ and the other to one or three charged particles, starts from a sample of tau-pair events whose selection is described in detail elsewhere.[3] These events have either two or four reconstructed tracks in the central drift chamber, one of which is separated from the others by at least 120°. The requirements that are most important for reducing the background are the following: (1) The total energy must be greater than 6 GeV; (2) the total energy of the electromagnetic showers must be less than 23 GeV; (3) the charged particle sphericity must be less than 0.05; (4) the net transverse momentum relative to the thrust axis measured with the calorimeters must be less than 1.5 GeV/c; (5) identified electrons must have an energy less than 5 GeV or a large angle from the beam axis; (6) events with two charged tracks (1-1 events) and neutrals must not be consistent with a kinematic fit to an $ee\gamma$ or $\mu\mu\gamma$ hypothesis. These cuts reduce the background from sources without a τ in the final state to about 4%. In order to restrict the sample to the part of the CD with the best performance, both tracks in 1-1 events and the isolated track in four track events (1-3 events) are required to have $|\cos\theta| < 0.9$. The 1-3 events must meet the further requirement that at least two of the 3-prong CD tracks are fitted to the primary vertex with a satisfactory χ^2. This reduces the background from τ-pair events with an e^+e^- pair from a photon conversion in the 0.036 radiation lengths of material inside the CD.

For a track to be identified as a pion, it is required that: (1) the CD momentum be greater than 2 GeV/c; (2) the extrapolation of the CD track penetrate active areas of the both the calorimeters and the OD; (3) there be no match between the CD track and an OD track; (4) more than 25% of the track calorimeter energy be in the hadron calorimeters; (5) there be a single shower in the vicinity of the CD track with a total energy in the first layer of the electromagnetic calorimeters (0.1 and 0.5 nuclear interaction lengths in the central section and endcaps respectively) that does not exceed the expectation for a minimum ionizing particle. These requirements reduce the particle identification backgrounds from all decays except $\tau \rightarrow \nu_\tau \rho$ and $\tau \rightarrow \nu_\tau K$ to negligible levels. The former is significant because the π^0 from ρ decay sometimes escapes detection. The latter cannot be eliminated since the MAC detector has no π/K separation capabilities, but this is not a serious problem since the branching fraction B_K has been measured to be only about 6% of B_π.[4]

Estimates of the background and efficiencies for selection of the various data samples are made with Monte Carlo techniques. A Monte Carlo calculation provides the only estimate of the pion identification efficiency since there is no pure source of pions in the data with which to measure the efficiency. Cross section calculations and event generation are done with the computer programs of Smith and co-workers[5] for all two-photon processes, Sjöstrand[6] for $e^+e^- \rightarrow q\overline{q}$, and Berends *et al.*[7] for $e^+e^- \rightarrow l^+l^-(\gamma), (l = e, \mu, \tau)$. Events thus generated are run through a Monte Carlo simulation of the MAC detector.[8] The simulation includes all the physical and electronic properties of the detector and describes the data well. Monte Carlo events are required to pass a simulation of the trigger requirements and are analyzed by the same computer programs used for the data.

The branching fraction B_π is extracted from the 1-3 sample by measurement of the fraction of the events with an identified pion on the 1-prong side of the event, namely

$$B_\pi = B_1\,(N_{\pi-3}/\epsilon_{\pi-3})/(N_{1-3}/\epsilon_{1-3}),$$

where N_{1-3} and $N_{\pi-3}$ are the background-subtracted numbers of observed 1-3 and π-3 events, ϵ_{1-3} and $\epsilon_{\pi-3}$ are efficiencies for observing these types of events, and B_1 is the branching fraction for τ decaying to one charged particle and any number of neutrals, $B_1 = 0.865 \pm 0.003$.[4] This has several advantages compared with the method in which the number of π-3 events is measured and then the branching fraction is calculated from the integrated luminosity. The integrated luminosity and its error do not enter in the above method, and many other systematic errors tend to cancel, including those for the 1-3 selection efficiency (the ratio $\epsilon_{\pi-3}/\epsilon_{1-3}$ is just the pion identification efficiency for 1-3 events) and the background due to unidentified photon conversion pairs.

The pion branching fraction is measured from the 1-1 sample by observation of the fraction of tracks in the 1-1 sample that are identified pions, that is,

$$B_\pi = \frac{B_1}{2}(N_\pi/\epsilon_\pi)/(N_{1-1}/\epsilon_{1-1}),$$

where N_π is the number of tracks identified as pions, ϵ_π is the efficiency for detecting a pion in the 1-1 sample, N_{1-1} is the number of 1-1 events, and ϵ_{1-1} is the efficiency for detecting 1-1 events. As in the 1-3 case, this method tends to reduce systematic effects common to all 1-1 events such as uncertainties in the trigger efficiency, the background rejection cuts, and the measurement of the integrated luminosity. A total of 798 identified pions are found in the two samples. Table I shows the numbers relevant to the calculation of B_π for both samples. The branching fraction is computed with an iterative procedure in which the backgrounds which are dependent on B_π are adjusted.

Since the most significant background is from the decay $\tau \rightarrow \nu_\tau \rho$, the study of systematic errors focuses on how well these decays can be rejected from the sample. By variation of the criteria that define a detected neutral particle (an electromagnetic shower which is not aligned with a CD track), it is estimated that the uncertainties in the number of false showers and the detection efficiency for neutrals contribute 0.004 to the systematic error in B_π. Uncertainty in the efficiency of the other pion identification criteria contributes 0.005 to the systematic error, as determined by variation of the minimum allowed momentum, the maximum allowed $|\cos\theta|$, and the minimum allowed fraction of the track energy in the hadron calorimeters. Uncertainties in the branching fractions of decay modes which are significant sources of particle identification background, 25% uncertainty in B_K[4] and 5.4% in B_ρ[9–11], contribute 0.0017 and 0.001 respectively to the systematic error. A comparison of results from the method described above and those from the luminosity method is used to estimate that the systematic errors due to the selection efficiencies for the 1-1 and 1-3 samples are .001 and .003 respectively.

The final pion branching fraction results are

$$B_\pi = \begin{cases} 0.108 \pm 0.005 \pm 0.008 & \text{(1-1 sample)} \\ 0.106 \pm 0.010 \pm 0.007 & \text{(1-3 sample)} \end{cases},$$

where the first errors are statistical and the second are systematic (all the systematic errors discussed above were added in quadrature). These two results are combined to yield

$$B_\pi = 0.107 \pm 0.004 \pm 0.008,$$

where the statistical and systematic errors have been combined in a way which reflects the fact that most of the systematic uncertainty is common to the two measurements. This result is consistent with previous measurements made by Blocker *et al.*,[12] 0.117±0.004±0.018, and Behrend *et al.*,[13] 0.099±0.017±0.013.

Assuming universality of the weak charged current, the ratio of the pion and electron branching fractions of the tau is given by[14]

$$\frac{B_\pi}{B_e} = \frac{(f_\pi \cos\theta_c)^2}{m_\tau^2} 12\pi^2 \left(1 - \frac{m_\pi^2}{m_\tau^2}\right)^2 = 0.607,$$

where the quantity $f_\pi \cos\theta_c$, the form factor at the W-π vertex, is precisely determined in the decay $\pi \to \mu\bar{\nu}_\mu$. The ratio of the present result for B_π to the world average value of $B_e = 0.176 \pm 0.006$[4] is $B_\pi/B_e = 0.61 \pm 0.05$, where the errors, including the contribution due to the total error in the average value of B_e, have been added in quadrature. This result is in good agreement with the theoretical prediction given above.

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Table I. Numbers relevant to the calculation of B_π for the 1-1 and 1-3 samples (errors are statistical only). A 1-1 event with two identified pions was counted twice in the π_{1-1} column.

	1-1	π_{1-1}	1-3	π-3
No. of observed events	5432 ± 74	646 ± 25	3337 ± 58	152 ± 12
Efficiency (%)	25.2 ± 0.1	9.6 ± 0.2	47.4 ± 0.3	14.0 ± 0.5
Backgrounds:				
1-1	...	...	144 ± 6	8 ± 1
1-3	28 ± 2	14 ± 2	...	...
3-3	1 ± 1	$<< 1$	5 ± 1	$<< 1$
$\tau \to \nu_\tau \rho$	...	76 ± 4	...	20 ± 2
$\tau \to \nu_\tau K$	...	32 ± 3	...	7 ± 2
other tau decays	...	7 ± 1	...	2 ± 1
$ee\tau\tau$	77 ± 8	10 ± 3	52 ± 6	3 ± 1
$eeq\bar{q} + q\bar{q}$	33 ± 9	12 ± 6	140 ± 13	4 ± 2
$eeee + ee\mu\mu$	73 ± 11	$<< 1$	$<< 1$	$<< 1$
$\mu\mu$ + cosmic rays	45 ± 15	$<< 1$	$<< 1$	$<< 1$

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(a) Present address: University of Oslo, N-0316 Oslo 3, Norway.

(b) Present Address: CERN, Geneva, Switzerland.

(c) Present Address: Texas Accelerator Center, The Woodlands, Texas 77380.

(d) Joint appointment: Department of Physics and College of Computer Science, Northeastern University, Boston, Massachusetts 02115.

(e) Permanent address: CERN, Geneva, Switzerland.

(f) Present Address: Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637.

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