Exclusive branching-fraction measurements of semileptonic tau decays into three charged hadrons, into \( \phi \pi^- \nu(\tau) \), and into \( \phi K^- \nu(\tau) \)

The BABAR Collaboration

Follow this and additional works at: https://scholarworks.umass.edu/cee_faculty_pubs

Recommended Citation

The BABAR Collaboration, "Exclusive branching-fraction measurements of semileptonic tau decays into three charged hadrons, into \( \phi \pi^- \nu(\tau) \), and into \( \phi K^- \nu(\tau) \)" (2008). *Physical Review Letters*. 50. https://doi.org/10.1103/PhysRevLett.100.011801
Exclusive Branching-Fraction Measurements of Semileptonic τ Decays into Three Charged Hadrons, into $\varphi\pi^-\nu_\tau$, and into $K^-\nu_\tau$.
(Received 19 July 2007; published 8 January 2008)

PRL 100, 011801 (2008) PHYSICAL REVIEW LETTERS week ending 11 JANUARY 2008

Technische Universität Dresden, Institut für Kern- und Teilchenphysik, D-01062 Dresden, Germany
Laboratoire Leprince-Ringuet, CNRS/IN2P3, Ecole Polytechnique, F-91128 Palaiseau, France
University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom
Università di Ferrara, Dipartimento di Fisica and INFN, I-44100 Ferrara, Italy
Laboratori Nazionali di Frascati dell'INFN, I-00044 Frascati, Italy
Università di Genova, Dipartimento di Fisica e INFN, I-16146 Genova, Italy
Harvard University, Cambridge, Massachusetts 02138, USA
Universität Heidelberg, Physikalisches Institut, Philosophenweg 12, D-69120 Heidelberg, Germany
Imperial College London, London, SW7 2AZ, United Kingdom
University of Iowa, Iowa City, Iowa 52242, USA
Johns Hopkins University, Baltimore, Maryland 21218, USA
Universität Karlsruhe, Institut für Experimentelle Kernphysik, D-76021 Karlsruhe, Germany
Lawrence Livermore National Laboratory, Livermore, California 94550, USA
University of Liverpool, Liverpool L69 7ZE, United Kingdom
McGill University, Montréal, Québec H3A 2T8, Canada
University of Milano, Dipartimento di Fisica and INFN, I-20133 Milano, Italy
University of Mississippi, University, Mississippi 38677, USA
Mount Holyoke College, South Hadley, Massachusetts 01075, USA
Università di Napoli Federico II, Dipartimento di Scienze Fisiche and INFN, I-80126, Napoli, Italy
NIKHEF, National Institute for Nuclear Physics and High Energy Physics, NL-1009 DB Amsterdam, The Netherlands
Ohio State University, Columbus, Ohio 43210, USA
University of Oregon, Eugene, Oregon 97403, USA
Università di Padova, Dipartimento di Fisica and INFN, I-35131 Padova, Italy
Laboratoire de Physique Nucléaire et de Hautes Energies, IN2P3/CNRS, Université Pierre et Marie Curie-Paris6, Université Denis Diderot-Paris7, F-75252 Paris, France
University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA
Università di Pisa, Dipartimento di Fisica, Scuola Normale Superiore and INFN, I-56127 Pisa, Italy
Prairie View A&M University, Prairie View, Texas 77446, USA
Princeton University, Princeton, New Jersey 08544, USA
Università di Roma La Sapienza, Dipartimento di Fisica and INFN, I-00185 Roma, Italy
Universität Rostock, D-18051 Rostock, Germany
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, OX11 0QX, United Kingdom
Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
University of Wisconsin, Madison, Wisconsin 53706, USA
Yale University, New Haven, Connecticut 06511, USA

(Received 19 July 2007; published 8 January 2008)
Using a data sample corresponding to an integrated luminosity of 342 fb\(^{-1}\) collected with the \textit{BABAR} detector at the SLAC PEP-II electron-positron storage ring operating at a center-of-mass energy near 10.58 GeV, we measure \(B(\tau^- \rightarrow \pi^- \pi^0 \pi^0 \nu_{\tau}, (\text{ex} K_{\pi}^0)) = (8.83 \pm 0.01 \pm 0.13)\%\), \(B(\tau^- \rightarrow K^- \pi^- \pi^0 \nu_{\tau}, (\text{ex} K_{\pi}^0)) = (0.273 \pm 0.002 \pm 0.009)\%\), \(B(\tau^- \rightarrow K^- K^+ \pi^0 \nu_{\tau}) = (0.1346 \pm 0.0010 \pm 0.0036)\%\), and \(B(\tau^- \rightarrow K^- K^- K^+ \nu_{\tau}) = (1.58 \pm 0.13 \pm 0.12) \times 10^{-5}\), where the uncertainties are statistical and systematic, respectively. These include significant improvements over previous measurements and a first measurement of \(B(\tau^- \rightarrow K^- K^- K^+ \nu_{\tau})\) in which no resonance structure is assumed. We also report a first measurement of \(B(\tau^- \rightarrow \phi \pi^0 \nu_{\tau}) = (3.42 \pm 0.55 \pm 0.25) \times 10^{-5}\), a first measurement of \(B(\tau^- \rightarrow \phi K^- \nu_{\tau}) = (3.39 \pm 0.20 \pm 0.28) \times 10^{-5}\) and a first upper limit on \(B(\tau^- \rightarrow K^- K^- K^+ \nu_{\tau}, (\text{ex} \phi))\).

The weak interaction coupling strength between the first and second quark generations \([1]\) can be probed with unprecedented precision in hadronic \(\tau\) decays having net strangeness of unity in the final state using \(e^+ e^- \rightarrow \pi^+ \tau^-\) data collected at the \(e^+ e^- \rightarrow B\) factories. Inclusive measurements of the strange spectral function, obtained from \(\tau\) lepton decays to final states containing kaons, provide a direct determination of the strange quark mass and Cabibbo-Kobayashi-Maskawa (CKM) matrix mixing element \(V_{ub}/V_{cb}\) \([2]\). A significant improvement on the precision of \(B(\tau^- \rightarrow K^- \pi^- \pi^0 \nu_{\tau})\) in particular, where one measurement \([3]\) disagrees by more than 2 standard deviations from the others \([4,5]\), will have the most immediate impact on the determination of these two fundamental Standard Model (SM) parameters using \(\tau\) decays \([6]\). Measurements of \(\tau^- \rightarrow \phi \pi^0 \nu_{\tau}\) and \(\tau^- \rightarrow \phi K^- \nu_{\tau}\) provide an interesting laboratory for studying Okubo-Zweig-Iizuka (OZI) suppression \([7]\).

Significant improvements on measurements of \(B(\tau^- \rightarrow \pi^- \pi^- \pi^0 \nu_{\tau})\), \(B(\tau^- \rightarrow K^- \pi^- \pi^+ \nu_{\tau})\), and \(B(\tau^- \rightarrow K^- \pi^- K^+ \nu_{\tau})\) are reported together with a first measurement of \(B(\tau^- \rightarrow K^- K^- K^+ \nu_{\tau})\) without resonance assumptions (charge conjugate decays are implied). The data sample corresponds to an integrated luminosity of \(L = 342 \text{ fb}^{-1}\) recorded at a center-of-mass (c.m.) energy \((\sqrt{s})\) near 10.58 GeV using the \textit{BABAR} detector at the SLAC PEP-II asymmetric-energy \(e^+ e^-\) storage ring. With a luminosity-weighted average cross-section of \(\sigma_{e^+ e^- \rightarrow \tau^+ \tau^-} = (0.919 \pm 0.003)\) nb \([8,9]\), this corresponds to the production of \(3.16 \times 10^8\) \(\tau\)-pair events.

The \textit{BABAR} detector \([10]\) has a silicon vertex tracker (SVT), drift chamber (DCH), ring-imaging Cherenkov detector (DIRC), and electromagnetic calorimeter (EMC) all contained in a 1.5-T solenoid. The iron flux return of the solenoid is instrumented to identify muons.

\(\tau\)-pair events are simulated with higher-order radiative corrections using the KK2F Monte Carlo (MC) generator \([8]\) with \(\tau\) decays simulated with \textsc{tautau} \([11,12]\) using measured rates \([13]\). The detector response is simulated with \textsc{geant4} \([14]\). Simulated events for signal as well as SM background processes \([8,11,12,15,16]\) are reconstructed in the same manner as data. The MC samples are used for selection optimization and systematic error studies. The number of simulated nonsignal events is comparable to the number expected in the data, with the exception of Bhabha and two-photon events, which are not simulated. Data studies demonstrate that these backgrounds are negligible.

The basic analysis strategy is to select a pure sample of \(\tau^- \rightarrow h^- h^- h^+ \nu_{\tau}\) decays from \(e^+ e^- \rightarrow \tau^+ \tau^-\) events by requiring the partner \(\tau^+\) to decay leptonically. Within this sample, each of the \(h^\pm\) mesons is uniquely identified as a charged pion or kaon and the decay categorized as \(\tau^- \rightarrow \pi^- \pi^- \pi^0 \nu_{\tau}\), \(\tau^- \rightarrow K^- \pi^- \pi^0 \nu_{\tau}\), \(\tau^- \rightarrow K^- K^- \pi^0 \nu_{\tau}\), or \(\tau^- \rightarrow K^- K^- K^+ \nu_{\tau}\). An efficiency migration matrix, \(E_{ij}\), initially obtained from MC simulations, is used to correct for efficiency losses from all stages of event selection and includes cross feed between the four signal channels where \(i\) (\(j\)) is the selected (true) decay mode index. The \(E_{ij}\) matrix is modified using data control samples of kaons and pions from \(D^{\pm} \rightarrow \pi^\pm D^0\), \(D^0 \rightarrow \pi^+ K^-\) decays to account for small differences between MC calculations and data. The number of decay mode \(j\) signal events measured in the sample, \(N_j^{\text{Sig}}\), is then

\[
N_j^{\text{Sig}} = \sum_i (E_i^{-1})_{ij} (N_i^{\text{Data}} - N_i^{\text{Bkg}})
\]

where \(N_i^{\text{Data}}\) is the number of data events selected in decay channel \(i\) and \(N_i^{\text{Bkg}}\) is the estimated number of background events in decay channel \(i\) arising from sources other than \(\tau^- \rightarrow h^- h^- h^+ \nu_{\tau}\). The branching fraction for decay mode \(j\) is then \(B_j = \frac{N_j^{\text{Sig}}}{N_j^{\text{Sig}} + N_j^{\text{Bkg}}}\).

The \(\tau^- \rightarrow h^- h^- h^+ \nu_{\tau}\) sample is obtained by selecting events with four well reconstructed tracks having zero total charge, where none of the tracks originate from the conversion of photons in the material of the detector. All four tracks are required to lie within the geometrical acceptance of the EMC and DIRC and, to ensure the tracks can reach the DIRC, are required to have a transverse momentum of at least 250 MeV/c. If any two photons in the event are identified as coming from \(\pi^\pm \rightarrow \gamma\gamma\), the event is removed from the sample. The event is divided into hemispheres in the c.m. by a plane perpendicular to the thrust axis \([17]\).

One of the hemispheres, the “leptonside,” is required to contain a \(\tau \rightarrow e\nu\bar{\nu}\) or \(\tau \rightarrow \mu\nu\bar{\nu}\) decay. If the hemisphere with an electron (muon) has any neutral particles with more than 1.0 (0.5) GeV, the event is not selected. The \(e^+ e^- \rightarrow q\bar{q}\) backgrounds are further reduced to ~0.1% of...
the $\tau^- \to h^- h^+ h^+ \nu_\tau$ sample by requiring a thrust magnitude $>0.85$.

Backgrounds from Bhabha and $e^+ e^- \to \mu^+ \mu^-$ events with photon conversions are suppressed by requiring the momentum of the leptonside track to be less than 80% of $\sqrt{s}/2$ and a requirement that none of the three signal-side tracks pass an electron identification algorithm. Remaining non-$\tau$ background events, including those from two-photon processes, are reduced by requiring the event missing c.m. transverse momentum to be $>0.009 \sqrt{s}$.

The remaining background in the sample is predominantly from other $\tau$ decays containing $\pi^0$ and $K^0_S$ mesons. Events containing a $K^0_S$ are identified and removed. Residual backgrounds from decays having a $\pi^0$ are reduced by requiring the total energy in the signalside hemisphere deposited in the EMC which is unassociated with the three charged hadron tracks to be $<200$ MeV. With these requirements, contributions from $\tau^- \to h^- n \pi^0 \nu$ and $\tau^- \to h^- h^+ 2\pi^0 \nu$ are negligible.

A track in the $\tau^- \to h^- h^- h^+ \nu_\tau$ sample is classified as a kaon using a likelihood approach to combine information from the DIRC, DCH, and SVT with a characteristic kaon identification efficiency of $\sim$80% and pion misidentification rate of $\sim$1%. If the track fails to be identified as a kaon, it is classified as a pion. Events are selected if the signalside decays are identified as $\tau^- \to \pi^- \pi^- \pi^+ \nu_\tau$, $\tau^- \to K^- \pi^- \pi^+ \nu_\tau$, $\tau^- \to K^- K^+ \nu_\tau$, or $\tau^- \to K^- \pi^- K^+ \nu_\tau$ with decays having a wrong charge combination removed.

The diagonal elements of $E_{ij}$ excluding particle identification ($e$), numbers of selected, background, and signal events determined using Eq. (1) are shown in Table I for all modes. The increase in $e$ with number of kaons in the decay is associated primarily with the transverse momentum requirement and the $K^0_S$ veto. The background fraction from $\tau$ decays to $\pi^- \pi^- \pi^- \pi^0 \nu$, $(K^- \pi^- \pi^- \pi^+ \nu$, $K^- \pi^- K^+ \pi^0 \nu$, $K^- K^- K^+ \pi^0 \nu$) in the $\pi^- \pi^- \pi^+$ ($K^- \pi^- \pi^+$, $K^- \pi^- K^+$, $K^- K^- K^+$) candidate sample is estimated to be $(3.6 \pm 0.3\%)$, $(2.3 \pm 0.4\%)$, $(0.4 \pm 0.1\%)$, $<5.0\%$. Non-$\tau$ backgrounds comprise less than 0.5% of each channel’s final event sample.

The component of $E_{ij}$ associated with the particle identification, $M_{ij}$, is shown in the first four rows of Table II. Note that this matrix includes efficiency losses associated with cross feed of the wrong charge combinations and small factors associated with data control sample corrections to the MC cross-feed efficiencies; therefore, the columns of the table are not expected to sum to 100%.

Systematic uncertainties are assigned for the following: luminosity; cross section; migration matrix elements, which includes MC statistical and systematic errors associated with the efficiency and particle identification; signal-mode modeling; modeling of the EMC and tracking response including scale and resolution uncertainties, the sensitivities of the measurements to the modeling of hadronic and electromagnetic showers in the EMC, and tracking efficiency; modeling of the trigger; and modeling of the backgrounds, including uncertainties on cross-sections and branching fractions. These are summarized in Table III along with the total error correlation matrix. The absolute normalization is a significant source of the correlations.

The branching-fraction results of this analysis are presented in Table I together with the world average values or limit published by the Particle Data Group (PDG) [13], with which they are consistent and significantly more precise. In all four channels, the results where the leptonside has an electron are consistent with those where it has a muon. Our measurement of $B(\tau^- \to \pi^- \pi^- \pi^+ \nu_\tau)$ is also consistent with a precision $B(\tau^- \to \pi^- \pi^- \pi^+ \text{(ex.}\omega))$ measurement [18] after accounting for the $\omega$. Our measurement of $B(\tau^- \to K^- \pi^- \pi^+ \nu_\tau)$ is in agreement with [3] and disagrees by more than 2 standard deviations from

| Candidates | $\pi\pi\pi$ | $K\pi\pi$ | $K\pi K$ | $KKK$
|------------|-----------|----------|----------|--------
| $\pi\pi\pi$ | 97.40     | 22.49    | 4.73     | 1.02   |
| $K\pi\pi$  | 1.42      | 74.87    | 16.43    | 6.38   |
| $K\pi K$   | 0.01      | 0.49     | 59.63    | 25.54  |
| $KKK$      | $\cdots$  | $\cdots$ | 0.26     | 50.87  |

| $\phi\pi$       | 72.54     | 19.20    |          |
| $\phi K$        | 0.83      |          | 66.06    |
We report a first measurement of $\mathcal{B}(\tau^\rightarrow K^- K^- K^+ \nu_\tau)$ in which no resonance structure is assumed and which has a significance in excess of 8$\sigma$.

A $\phi(1020)$ contribution is seen in both the $\tau^\rightarrow K^- \pi^- K^+ \nu_\tau$ and $\tau^\rightarrow K^- K^- K^+ \nu_\tau$ decay modes. The use of a kaon selection algorithm with higher efficiency, but less purity, provides significantly higher signal-to-background for $\tau^\rightarrow K^- \nu_\tau$. The $\tau^\rightarrow \phi \pi^- \nu_\tau$ ($\tau^\rightarrow K^- \nu_\tau$) signal has a 5.7$\sigma$ (9.8$\sigma$) level of significance. The last two rows of Table II lists the $M_{ij}$ matrix for this higher efficiency selection. The $K^+ K^-$ invariant mass distributions for the $\tau^\rightarrow K^- \pi^- K^+ \nu_\tau$ ($\tau^\rightarrow K^- K^+ \nu_\tau$) mode using this sample is shown in Fig. 1 and 2. Below 1.09 GeV (1.15 GeV), after background subtraction of the non-$K^+ K^-$ events, the $K^+ K^-$ invariant mass distribution from the $\tau^\rightarrow \phi \pi^- \nu_\tau$ ($\tau^\rightarrow \phi K^- \nu_\tau$) decay is well described by a Breit-Wigner function convoluted with a Gaussian resolution function for the signal and a third-order polynomial (function in [19]) for the background and is used to fit for the number of events. A binned maximum likelihood fit yields $344 \pm 42$ ($274 \pm 16$) $\tau^\rightarrow \phi \pi^- \nu_\tau$, ($\tau^\rightarrow \phi K^- \nu_\tau$) candidates. MC estimates of the subtracted $q\bar{q}$ background events with a $\phi$ contribute a 5.2% (0.7%) uncertainty. The $\phi \pi^-$ candidate sample has an additional 4.3% uncertainty arising from potentially peaking $\tau^\rightarrow \phi \pi^- \pi^0 \nu_\tau$ background. The fit parameterization contributes a 1.0% (2.0%) error. Accounting for $\mathcal{B}(\phi \rightarrow K^+ K^-)$ [13], $\mathcal{B}(\tau^\rightarrow \phi \pi^- \nu_\tau) = (3.42 \pm 0.55 \pm 0.25) \times 10^{-5}$ and $\mathcal{B}(\tau^\rightarrow \phi K^- \nu_\tau) = (3.39 \pm 0.20 \pm 0.28) \times 10^{-5}$ with a correlation of $-0.07$. From the fit, we find no evidence for $\tau^\rightarrow K^- K^- K^+ \nu_\tau$ without a $\phi$ and set a first upper limit on $\mathcal{B}(\tau^\rightarrow K^- K^- K^+ \nu_\tau, \text{ex.$\phi$}) < 2.5 \times 10^{-6}$ at 90% C.L.

This is the first measurement of $\mathcal{B}(\tau^\rightarrow \phi \pi^- \nu_\tau)$. It is consistent with aCLEO limit [20] and larger than the (1.20 $\pm$ 0.28) $\times 10^{-5}$ value predicted by a vector meson dominance model [7]. Our $\mathcal{B}(\tau^\rightarrow \phi K^- \nu_\tau)$ measurement is consistent with a recent Belle result [21]. Recent calculations using a meson dominance model [22] agree with our $\mathcal{B}(\tau^\rightarrow \phi \pi^- \nu_\tau)$ and $\mathcal{B}(\tau^\rightarrow \phi K^- \nu_\tau)$ measurements and with the ratio $\frac{\mathcal{B}(\tau^\rightarrow \phi \pi^- \nu_\tau)}{\mathcal{B}(\tau^\rightarrow \phi K^- \nu_\tau)} = 0.99 \pm 0.21$. Our measurements of $\mathcal{B}(\tau^\rightarrow K^- \pi^- \pi^0 \nu_\tau)$ and $\mathcal{B}(\tau^\rightarrow K^- K^- K^+ \nu_\tau)$, when combined with improved measurements of the other strange decays, will constrain the CKM element $|V_{us}|$ better than unitarity bounds [6,23].

<table>
<thead>
<tr>
<th>$L$</th>
<th>$\sigma_{e^+ e^- \rightarrow \tau^+ \tau^-}$</th>
<th>$M_{ij}$ and particle ID</th>
<th>signal modeling</th>
<th>EMC and DCH response</th>
<th>trigger</th>
<th>backgrounds</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi \pi \pi$</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
<td>0.9</td>
</tr>
<tr>
<td>$K \pi \pi$</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>$K \pi K$</td>
<td>0.4</td>
<td>3.0</td>
<td>1.9</td>
<td>4.9</td>
<td>2.0</td>
<td>5.5</td>
<td>7.8</td>
</tr>
</tbody>
</table>

FIG. 1 (color online). $K^+ K^-$ invariant mass in $\tau^\rightarrow K^- K^- K^+ \nu_\tau$ decays. Data are represented by points with error bars, MC of $\tau^\rightarrow K^- \pi^- K^+ \nu_\tau$ by the open histogram, cross feed from other $\tau^\rightarrow h^- h^+ \nu_\tau$ channels by the light shaded histogram, and non-$\tau$ backgrounds by the dark shaded histogram. The inset shows the background-subtracted data with the fit (solid line) and nonresonant component (dashed line).

FIG. 2 (color online). $K^+ K^-$ invariant mass in $\tau^\rightarrow K^- K^- K^+ \nu_\tau$ decays with two entries per event. Data are represented by points with error bars, the open histogram is the MC calculation of $\tau^\rightarrow \phi K^- \nu_\tau$, the light shaded histogram is the cross feed from the other $\tau^\rightarrow h^- h^+ \nu_\tau$ channels, primarily from $\tau^\rightarrow K^- \pi^- K^+ \nu_\tau$, and non-$\tau$ backgrounds by the dark shaded histogram. The inset shows the background-subtracted data with the fit (solid line) and nonresonant component (dashed line).
We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues, and for the substantial dedicated effort from the computing organizations that support BABAR. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), NFR (Norway), MIST (Russia), MEC (Spain), and PPARC (United Kingdom). Individuals have received support from the Marie Curie EIF (European Union) and the A. P. Sloan Foundation.

*Also with Universita di Perugia, Dipartimento di Fisica, Perugia, Italy.
†Also with Universita della Basilicata, Potenza, Italy.
‡Also with IPPP, Physics Department, Durham University, Durham DH1 3LE, United Kingdom.

[19] H. Albrecht et al. (ARGUS Collaboration), Phys. Lett. B 241, 278 (1990). $f(m) = [m - (2m_K)]^{[2m_K^2 - (2m_K^2)]} [m^2 - (2m_K^2)]^{[2m_K^2 - (2m_K^2)]}, m > 2m_K,: = 0, m < 2m_K.$