Measurements of τ hadronic branching fractions and spectra, and search for second class current τ decays at BaBar

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We present a set of preliminary and final results on tau branching fractions and invariant mass spectra, and a search for the second class current decay $\tau \to \pi\eta'(958)\nu_\tau$. The results include new studies of a large number 3 and 5-prong tau decay modes either inclusive or classified according the hadronic resonance content (K_S^0, η, ω, etc.). All results are based on the analysis of the complete *BABAR* data-set consisting on 430 million τ lepton pairs, corresponding to an integrated luminosity of 468 fb$^-$1, collected with the *BABAR* detector at the PEP-II asymmetric energy e^+e^- storage rings.

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1. Introduction

Although the PEP-II storage ring was designed as a factory for B mesons, its high luminosity made it an excellent machine for the production of τ leptons. The results presented here are based on up to 430 million τ pairs - almost one billion τ leptons – in the complete *BABAR* dataset. Such τ studies serve as a testbed for models of mesons, and for QCD in general.

The *BABAR* detector has been described elsewhere[1]. A particular feature of these τ analyses is the powerful π/K discrimination provided by the DIRC[2] and also by dE/dx measurements in the tracking chambers. The analyses presented here differ from each other in detail, but share use a similar broad technique: the event is divided in two using the thrust axis in the centre of mass. One hemisphere is used to *tag* the event as a τ, by requiring that it contain a single charged track. Further insisting that this track be identified as a lepton (electron or muon) increases the purity of the sample at the price of a lower efficiency.

2. τ to 3 charged particles

We have selected 3-prong τ decays – a 'prong' means any charged particle track, in this analysis they are either pions or kaons – and obtained branching ratios for the decays $\tau^- \to \pi^- \pi^+ \pi^- \nu_\tau$, $K^- \pi^+ \pi^- \nu_\tau$, $K^- K^+ \pi^- \nu_\tau$, and $K^- K^+ K^- \nu_\tau$. These have already been published[3]. Here also present (as preliminary results) the mass distributions for these channels.
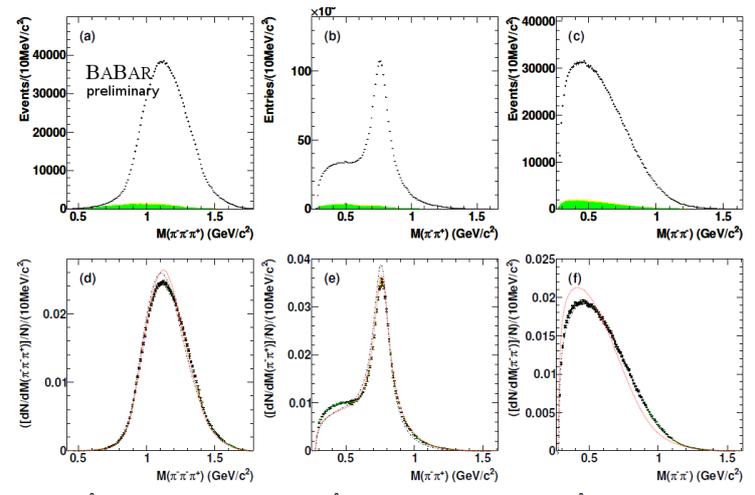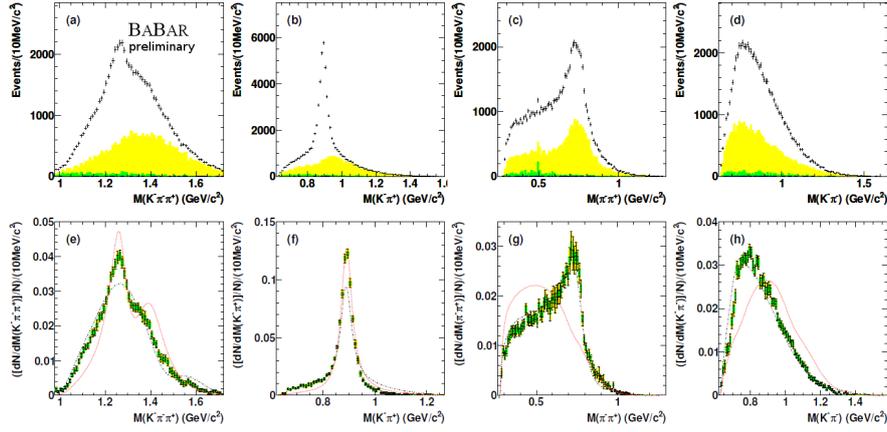

Figure 1: Mass combinations in $\pi^- \pi^+ \pi^-$ decays

Figure 1 presents the mass combinations of the three pions. The top row (a-c) gives the measured distributions for the 3π mass, the unlike-sign and like-sign 2π combinations. The small estimated backgrounds, which are from other τ decays, are shown in green.

The bottom row (d-f) presents the unfolded distributions, with the backgrounds subtracted and the resultion unfolded using a Bayesian technique[4]. The curves show the predictions of the Tauola Monte Carlo [5]. This is the current default tune, version 2.8, based on measurments at CLEO. The agreement is generally very good, though not perfect. This decay is basically modelled as occurring through the $a_1(1260)$, which in turn decays through the channel $a_1 \to \rho\pi$.
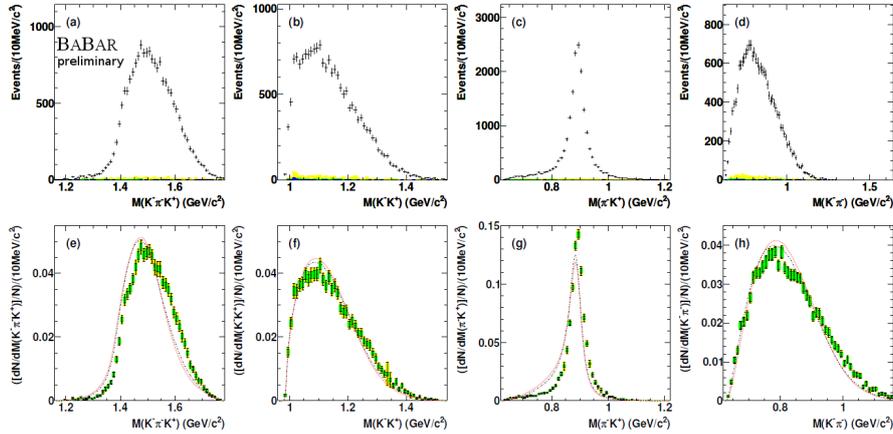
Figure 2: Mass combinations in $K^-\pi^+\pi^-$ decays

Figure 2 shows the mass combinations for the $K\pi^+\pi^-$ decays. Again, the top row shows the measured distributions and the lower the unfolded distributions. The background from other τ decays (green) is again small, but there are now also contributions from cross-feed from the 3π decay, shown in yellow.

Our results agree with those of Belle[6] except in the $K\pi\pi$ combination in the region around 1.4 GeV, where the shape is dominated by the background subtraction.

The agreement with the Tauola 2.8 predictions (the red curves) is not good. We have re-tuned the parameters and obtained better agreement, as shown in the black curves.

Figure 3: Mass combinations in $K^-K^+\pi^-$ decays

Figure 3 shows the mass combinations for the $K^+K^-\pi^-$ combinations. The inner error bars (green) show the statistical uncertainty, and the outer (yellow) ones have the systematic uncertainty added in quadrature. We have again retuned the Monte Carlo parameters, though the standard Tauola predictions are good. The decay is dominated by the channel $K^-K^{*0}(892)$
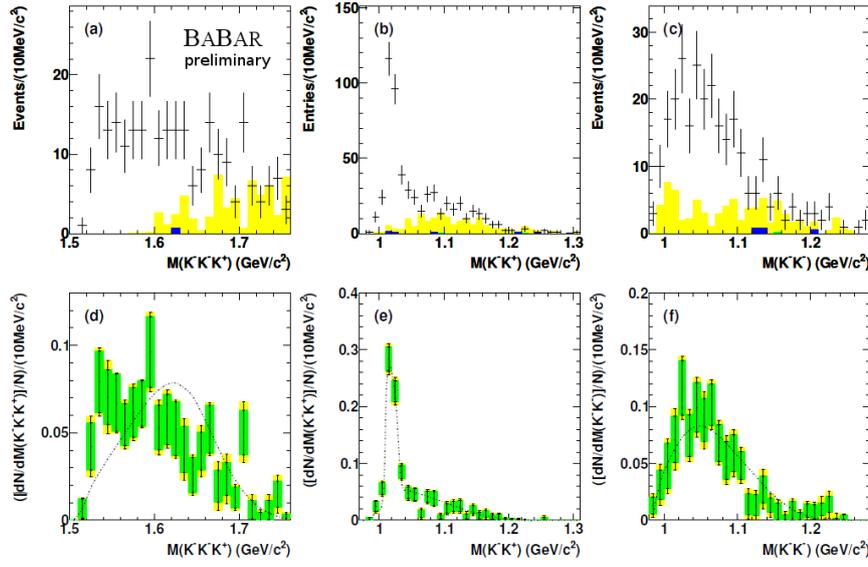
Figure 4: Mass combinations in $K^-K^+K^-$ decays

Figure 4 shows the mass distributions for 3 kaons. Here the dominant channel is $K^-\phi$

3. τ to 5 prongs

We have analysed a set of high multiplicity decays of the τ through a number of channels involving pions and multi-pion resonances[7]. The three intermediate states $\tau^- \to \pi^- f_1 \nu_\tau$, $\tau^- \to (3\pi)^- \eta \nu_\tau$, and $\tau^- \to (3\pi)^- \omega \nu_\tau$ produce the four final states $\pi^-\pi^-\pi^-\pi^+\pi^+$, $\pi^-\pi^+\pi^-\eta(\gamma\gamma)$, $\pi^-\pi^+\pi^-\pi^0\pi^0\pi^0$, and $\pi^-\pi^-\pi^-\pi^+\pi^+\pi^0$ by various routes:

The f_1 may decay to $\pi^+\pi^-\eta$ or $\pi^+\pi^-\pi^+\pi^-$.

The η may decay to $\pi^+\pi^-\pi^0$ or $3\pi^0$ or $\gamma\gamma$

The $(3\pi^-)$ system may be $\pi^-\pi^+\pi^-$ or $\pi^-\pi^0\pi^0$

The two different decay modes of the f_1 are clearly seen, including the three different decay modes of the η. These are shown in figure 5. A fit to the data give the world's best value for the mass of the f_1 as $1.28116 \pm 0.00039 \pm 0.00045 \text{GeV}/c^2$.
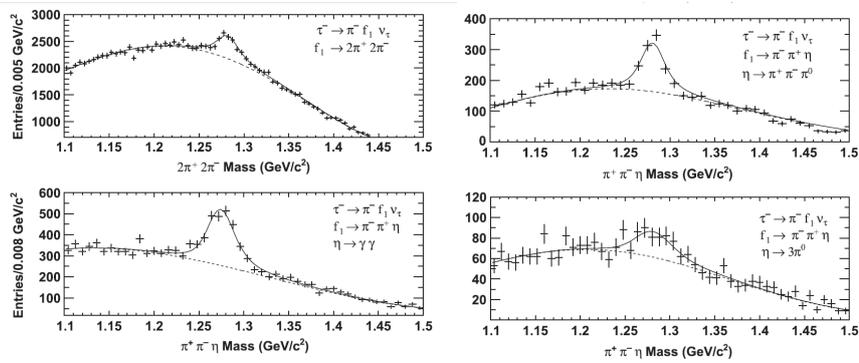

Figure 5: Decays of the f_1 meson

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Results for these branching ratios are shown in table 1. The branching ratios for the two f_1 decays are presented separately. If we take the ratio then we obtain (using isospin symmetry)

$$\frac{\mathscr{B}(f_1 \to \pi^+\pi^-\pi^+\pi^-)}{\mathscr{B}(f_1 \to \pi\pi\eta)} = 0.28 \pm 0.02 \pm 0.02$$

which agrees with the average value of 0.41 ± 0.14 obtained by the Particle Data Group, but not with their fitted value of 0.63 ± 0.06[8].

Channel	Branching Ratio
$\pi^-\pi^+\pi^-\eta\nu_\tau$	$(2.25 \pm 0.07 \pm 0.12) \times 10^{-4}$
$\pi^-\pi^0\pi^0\eta\nu_\tau$	$(2.01 \pm 0.34 \pm 0.22) \times 10^{-4}$
$\pi f_1, \nu_\tau, f_1 \to \pi^+\pi^-\pi^+\pi^-$	$(5.20 \pm 0.31 \pm 0.37) \times 10^{-5}$
$\pi f_1, \nu_\tau, f_1 \to \pi^+\pi^-\eta$	$(1.26 \pm 0.06 \pm 0.06) \times 10^{-4}$
$\pi^-\pi^+\pi^-\omega\nu_\tau$	$(8.4 \pm 0.4 \pm 0.6) \times 10^{-5}$
$\pi^-\pi^0\pi^0\omega\nu_\tau$	$(7.3 \pm 1.2 \pm 1.2) \times 10^{-5}$
$\pi^-\pi^+\pi^-\pi^+\pi^-\nu_\tau$ non-resonant	$(7.8 \pm 0.04 \pm 0.40) \times 10^{-4}$
$\pi^-\pi^+\pi^-\pi^+\pi^-\pi^0\nu_\tau$ non-resonant	$(3.6 \pm 0.3 \pm 0.9) \times 10^{-5}$
$\pi^-\pi^+\pi^-\pi^0\pi^0\pi^0\nu_\tau$ non-resonant	$< 5.8 \times 10^{-5}$ @ 90% CL
$\pi^-\eta'\nu_\tau$	$< 4.0 \times 10^{-6}$ @ 90% CL
$\pi^-\eta'\nu_\tau\pi^0$	$< 1.2 \times 10^{-5}$ @ 90% CL
$K^-\eta'\nu_\tau$	$< 2.4 \times 10^{-6}$ @ 90% CL
$K^-\pi^+\pi^-\pi^+\pi^-\nu_\tau$	$< 2.4 \times 10^{-6}$ @90%CL
$K^+\pi^-\pi^-\pi^+\pi^-\nu_\tau$	$< 5.0 \times 10^{-6}$ @90%CL
$K^-K^+\pi^-\pi^+\pi^-\nu_\tau$	$< 4.5 \times 10^{-7}$ @90%CL
$K^-\pi^+\pi^-\pi^+\pi^-\pi^0\nu_\tau$	$< 1.9 \times 10^{-6}$ @90%CL
$K^+\pi^+\pi^-\pi^+\pi^-\pi^0\nu_\tau$	$< 8 \times 10^{-7}$ @90%CL

Table 1: Values and limits of branching ratios for high multiplicity tau decay channels

We also searched for decays involving the η' meson, in its decays to $\pi^+\pi^-\eta$, again using all three η decay channels. A peak at the η' mass of 958 MeV is seen in the data, but it is compatible with the expected background from $q\bar{q}$ events. The decay $\tau^- \to \pi^-\eta'\nu_\tau$ is a Second Class current[9]. Such currents are forbidden by isospin/G-parity considerations or, equivalently, in the limit that the u and d quarks have equal mass. As this equality is not exact, the Standard Model predictions for such currents are small but non-zero, and we are now probing the values at which a signal might be expected, so this channel, and also the decay $\tau^- \to \pi^-\omega\nu_\tau$ channel [10] are of great interest. We have the world's best limits, but still have not observed a signal.

4. τ^- decays with a 1 prong plus two V topology.

K_s^0 particles from τ decays typically travel a short distance in the *BABAR* tracking chambers before decaying to two pions, giving (for the $\pi^+\pi^-$ decay mode) two charged tracks which intersect at a point away from the beam spot, with the invariant mass of the K_s^0.

We have analysed τ decays with two such K_s^0 decays, plus a possible additiional π^0[11]. A K_s^0 is selected as a pair of oppositely charged tracks which does not point to the beam spot, whose

vertex is at least 3 sigma displaced from it, and whose invariant mass lies between 0.475 and 0.525 Gev/c^2.

The numbers of events seen where the single prong is identified as a kaon rather than a pion are consistent with expected backgrounds (which come dominantly from the 1% probablity of a π being identified as a K), and we use them to give 90% confidence level upper limits.

Again, the standard Tauola package[5] does a good but not perfect job of describing the observed mass distributions. This is accounted for by re-weighting simulated events (needed for the calculation of efficiencies) according to the observed distribution in the two dimensional plot of the $\pi^- K_s^0$ masses. This is presented in Figure 6, which shows how the $\pi^- K_s^0 K_s^0$ state can be well described as going through the $K^0 K^*(892)$ channel
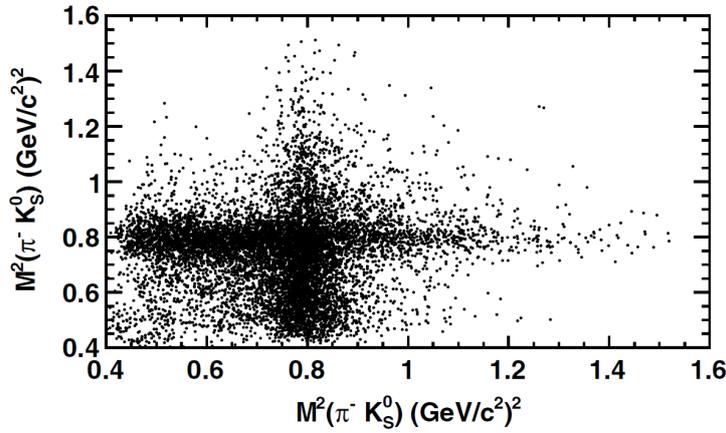

Figure 6: Mass plot of the two $\pi^- K_s^0$ combinations

Results are shown in table 2.

Channel	Branching Ratio
$\tau^- \to \pi^- K_s^0 K_s^0 \nu_\tau$	$(2.13 \pm 0.04 \pm 0.08) \times 10^{-4}$
$\tau^- \to \pi^- K_s^0 K_s^0 \pi^0 \nu_\tau$	$(1.60 \pm 0.20 \pm 0.22) \times 10^{-5}$
$\tau^- \to K^- K_s^0 K_s^0 \nu_\tau$	$< 6.3 \times 10^{-7}$ @ 90% CL
$\tau^- \to K^- K_s^0 K_s^0 \pi^0 \nu_\tau$	$< 4.0 \times 10^{-7}$ @ 90% CL

Table 2: Results

The precision of these measurements is a significant improvement on previous ones. They are interesting not only in their own right, but also as an important source of background to the $\tau^- \to \pi^- K_s^0 \nu_\tau$ decay channel, which is sensitive to new physics and will provide an important measurement at any future B factory.

5. Conclusions

The *BABAR* dataset is still providing a rich source of results on decays ot the τ. Further analyses are in progress and will be reported at future conferences.

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