Partial-wave analysis of $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ at BELLE

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Summary. — We present preliminary results of a partial-wave analysis of $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ in data from the Belle experiment at the KEKB e^+e^- collider. We demonstrate the presence of the $a_1(1420)$ and $a_1(1640)$ resonances in tauon decays and measure their masses and widths. We also present validation of our findings using a model-independent approach. Our results can improve modeling in simulation studies necessary for measuring the tauon electric and magnetic dipole moments and Michel parameters.

Studies of the correlated spins of tauons in $e^+e^- \to \tau^+\tau^-$, such as measurement of the tauon electric and magnetic dipole moments, look at events in which tauons decay to $\pi^-\pi^-\pi^+\nu_\tau$([1]) [2, 3]. However, lack of knowledge about the dynamics of $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$, which have never been experimentally measured in detail, limits the sensitivity of such measurements.

This decay proceeds mostly through the $a_1(1260)$ resonance, a ground state unflavoured axial-vector meson [1] whose mass and width are poorly known [5, 6, 7]. Also poorly understood is what other resonances are present and in which admixture they contribute. The COMPASS experiment observed a narrow, unflavoured axial-vector resonance, $a_1(1420)$, in pion-proton scattering [4]. If it exists, it should be present in $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$. Whether it is a particle or an artifact of K^*K scattering can be clarified by studying it in tauon decay [8]

We perform a partial-wave analysis (PWA) of $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ using $980\,\text{fb}^{-1}$ of data collected by the Belle experiment at the asymmetric e^+e^- collider KEKB.

$\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ is parameterized by seven phase-space variables: the mass of three pions, $m_{3\pi}$; the squared masses of the two $\pi^+\pi^-$ pairs, s_1 and s_2; the three Euler angles of the decay plane; and the helicity angle of the neutrino in the tauon rest frame [14]. One of the Euler angles is immeasurable because we cannot detect the ν_τ. We average the decay rate over this angle. We studied the effect of the averaging procedure and found it introduces no biases [9].

([1]) We imply the charge-conjugated mode throughout this text.

Our event selection criteria [9] are optimized, using simulated data, to maximize efficiency and purity, but chosen not to distort the phase-space variables. In each event, we define two hemispheres defined by the plane perpendicular the thrust axis of all charged particles and photons. We require three charged particles be present in one hemisphere, the signal hemisphere, and one be present in the other, the tag hemisphere.

Using simulated data, we train a boosted decision tree (BDT) to remove events from processes other than $e^+e^- \to \tau^+\tau^-$. It looks at six event variables: the thrust, the sum of charged-particle and photon momenta in the center-of-momentum (CM) frame, the mass and cosine of the polar angle of the missing four-momentum in the CM frame, the total energy measured in the Belle's electromagnetic calorimeter, and the sum of the energies of charged particles in the CM frame. The thrust is the most discriminating of the variables.

We veto the presence of charged kaons in the signal hemisphere by requiring the particles with the same charge be consistent with being pions. We veto the presence of neutral kaons by requiring $|\sqrt{s_i} - m_{K^0}| > 12\,\mathrm{MeV}$, $i = 1, 2$. Finally, we veto the presence of neutral pions by requiring the sum of photon energies in the signal hemisphere to be below 480 MeV.

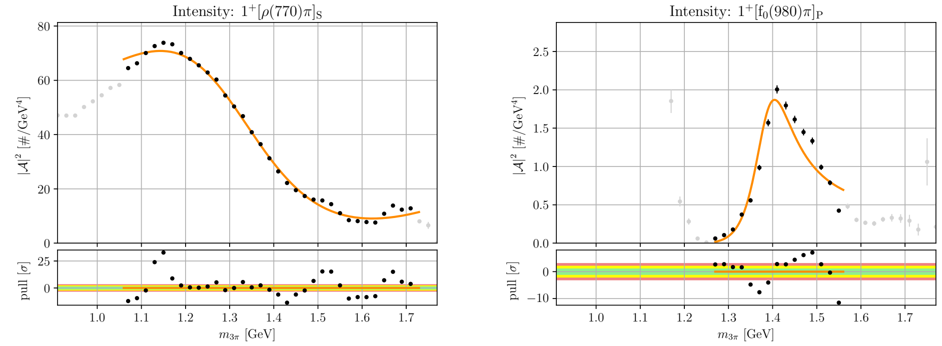
We select 55×10^6 events, with a signal-decay efficiency of 32% and a purity of 82%. This is the largest sample of $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ to date. However, it is contaminated with 10×10^6 background events, mostly originating from $\tau^- \to \pi^-\pi^-\pi^+\pi^0\nu_\tau$ and $e^+e^- \to q\bar{q}$, where q can be a u-, d-, s-, or c-quark. To account for it, we train a neural network on simulated data to describe the multidimensional distribution of the background as described in [10, 9]. We add the neural network's prediction of the background intensity to our partial-wave analysis.

We split the data into bins of $m_{3\pi}$ and perform a partial-wave decomposition independently in each bin using the isobar model and tensor formalism described in [11]. It assumes that the decay proceeds through a resonance X^- that decays to three charged pions via a sequence of two-body decays, $X^- \to \xi^0\pi^-$ and $\xi^0 \to \pi^-\pi^+$, where ξ^0 is an isobar. We ignore the nature of the resonance X^- in the partial-wave decomposition, but we require it have $J^P = 1^+$, 0^-, or 1^- quantum numbers. In the $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ process, a decay amplitude with $J^P = 1^-$ violates G parity.

For ξ^0 we include $\rho(770)$, $\rho(1450)$, $f_0(500)$, $f_0(980)$, $f_0(1500)$, $f_2(1270)$, and $\omega(782)$. We model all but $f_0(500)$ with the relativistic Breit-Wigner function with masses and widths taken from [13] and $f_0(500)$ with the broad $[\pi\pi]_S$ component described in [12]. We allow angular momenta between ξ^0 and the remaining pion in the $[0, 3]$ range.

We observe the $1^+[\rho(770)\pi]_S$ wave shown in Fig. 1a, which has a fit fraction around 100%. The second most present partial wave is the $1^+[\sigma\pi]_P$ wave with a fit fraction around 20%. Fit fractions need not sum to unity due to the interferences between partial waves. Our results agree with those of CLEO II for $\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$ in [6].

We fit a model for the X^- to the results of the partial-wave decomposition, accounting for the phase-space volume and efficiency in each $m_{3\pi}$ bin. We use the Bowler parameterization [16] for $a_1(1260)$ and a relativistic Breit-Wigner function for $a_1(1640)$ and $a_1(1420)$. In the resonance-model fit shown in Fig. 1, we measure the masses and widths of $a_1(1260)$ and $a_1(1420)$, which are shown in Table I. The mass and width of $a_1(1260)$ agree with the COMPASS results within their systematic uncertainties. Fig. 1b demonstrates the fit projection of the $1^+[f_0(980)\pi]_P$ wave. The $a_1(1420)$ resonance appears as a narrow peak near 1400 MeV. Its mass and width are smaller than those measured by COMPASS. This could be explained by the presence of coherent background in COM-



a) $1^+[\rho(770)\pi]_S$ wave.

b) $1^+[f_0(980)\pi]_P$ wave.

Fig. 1.: Intensities as functions of $m_{3\pi}$ for the partial-wave decompositions (black and grey points), with statistical uncertainties shown, and the prediction of the resonance-model fit (orange lines) to the black points.

TABLE I.: Resonance-model fit results (statistical uncertainties only).

	mass [MeV]	width [MeV]
$a_1(1260)$	1328.9 ± 0.1	388.4 ± 0.1
$a_1(1420)$	1387.8 ± 0.3	109.2 ± 0.6

PASS which dominates the low $m_{3\pi}$ region.

For the fit to converge, we fix the mass and width of $a_1(1640)$ to the nominal values from the PDG [7] because of the phase-space suppression in the region of the $a_1(1640)$. We justify the inclusion of $a_1(1640)$ by the intensity excess at the high-mass tail of the $a_1(1640)$ resonance in the $1^+[\rho(770)\pi]_S$ intensity plot in Fig. 1a.

We verify the presence of $a_1(1420)$ using the quasi-model-independent PWA technique developed in [15]. At the partial-wave decomposition stage, we parameterize the $[\pi\pi]_S$ wave with a complex-valued step-like function and let the fit find the $[\pi\pi]_S$ wave amplitude as a function of $m_{2\pi}$. To reduce the bias caused by the $1^+[\rho(770)\pi]_S$ model, we similarly parameterize the $1^+[\rho(770)\pi]_S$ wave. We observe the presence of the $f_0(980)$ isobar in the $[\pi\pi]_S$ wave in the narrow region of $m_{3\pi}$ and extract its amplitude in the isobar fit. The amplitude's intensity and phase have similar features to those from the conventional PWA.

We conducted a preliminary study of the systematic uncertainties on 20% of the data. We varied the neural network coefficients to study the uncertainty on the background parameterization and find that its tantamount to the statistical uncertainty for $m_{3\pi} > 1\,\mathrm{GeV}$.

In conclusion, we observe the $a_1(1420)$ resonance in both conventional and quasi-model-independent PWA. After finalizing the systematic uncertainty studies, we will provide an updated model for the $\tau^- \to \pi^-\pi^-\pi^+\nu_\tau$ with 15 partial waves, which can be used by the TAUOLA software library for simulating tauon decay and in future measurements of the tau electrical and magnetic dipole moments at Belle II.

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