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

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We present simulation studies in preparation for analyzing $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ in data from the Belle experiment at the KEK e^+e^- collider. Analyzing this decay can shed light on the $a_1(1260)$ and $a_1(1420)$ resonances and yield results that improve measurement of the τ electric and magnetic dipole moments. We show that we can achieve a higher signal efficiency than previous analyses of the same decay. We also demonstrate that neural networks can model our complicated six-dimensional background distributions and that quasi-model-independent partial-wave analysis can extract resonance masses, widths, and production amplitudes and phases.

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In the decay $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$, hadrons are produced from unflavored axial-vector resonances [1]. This is an opportune setting in which to study such composite particles without strong interaction with other particles that may alter their resonance shapes. The dominantly produced resonance is the $a_1(1260)$, whose shape is much debated and whose mass and width are not well determined [2–4]. The COMPASS experiment observed an unexpected narrow axial-vector resonance, $a_1(1420)$, in partial-wave analysis (PWA) of three-pion final states produced in pion-proton scattering [5]. Whether this is a true particle resonance or an effect of K^*K scattering is debated [6].

A better model for $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$, driven by experimental measurement, will improve the simulation of this decay in existing MC generators, which is necessary for general τ studies at currently running experiments such as Belle II [7]. In particular, it will improve measurement of the tauon electric and magnetic dipole moments [8].

The Belle experiment, which ran for a decade at the 10.58-GeV e^+e^- collider KEKB in Tsukuba, Japan, can study the $a_1(1260)$ and $a_1(1420)$ and the general structure of $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ using partial-wave analysis and data containing 50×10^6 $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ decays [9]. This data size is comparable to that of the COMPASS experiment, five and fifty times larger than what the Belle and Babar experiments used to publish $\pi\pi\pi$ mass spectra, and one-thousand times larger than what the CLEO II experiment used to publish the only amplitude analysis of $\tau^- \to \pi\pi\pi\nu_\tau$ [3, 5, 10, 11].

We present preliminary studies of the applicability of PWA to $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ using simulated data. Since Belle cannot detect neutrinos and τ decays are measured in events with at least two neutrinos, we do not know the full coordinate of each decay in its eight-dimensional phase space. We analyze in a six-dimensional subspace spanned by the three-pion mass, $m_{3\pi}$, the two $\pi^+\pi^-$ squared masses, s_1 and s_2, and the three Euler angles, α, β, and γ, defined in [12]. We average decay rates over the unknown neutrino direction and calculate them from hadronic currents written in the relativistic tensor formalism of [13].

We study data simulated as if it is produced by the Belle experiment, with all known interactions originating from e^+e^- collision, including $e^+e^- \to \tau^+\tau^-$. To isolate $\tau^+\tau^-$ events containing $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$, we select events that each have four charged particles, having total charge zero, coming from the e^+e^- interaction region, each with transverse momentum in the lab frame above 100 MeV. We select events with a 3×1 topology relative to the thrust axis in the e^+e^- center-of-momentum (CM) frame.

We use a boosted-decision-tree algorithm (BDT) from the `ROOT TMVA` library to further select signal decays and veto background events; it looks at six event-wide kinematic variables. After selecting events by their BDT score, we further select for pion-identification quality and veto events in which any pair of oppositely charged pions are consistent with coming from a K^0_S or in which the total energy of photons in the signal hemisphere is consistent with the presence of one or more π^0. Photons counted for the veto must have energy above 40 MeV in the lab frame. Our signal efficiency is 31%, with a signal purity of 87%.

The other 13% of events are from $e^+e^- \to \tau^+\tau^-$ in which the three-prong tau decay is $\tau^- \to \pi^-\pi^+\pi^-\pi^0\nu_\tau$ (with possible further π^0) or $\tau^- \to K^-\pi^+\pi^-\nu_\tau$ or from $e^+e^- \to q\bar{q}$. The dynamic structure of these backgrounds in the 6D analysis space is too complicated to model parametrically. Instead we let a neural network learn the background shape, a method pioneered in amplitude analysis by LHCb in [14] to use a single neural network to parametrize the background in the entire phase space. We find it necessary to train multiple neural networks, each for a subregion

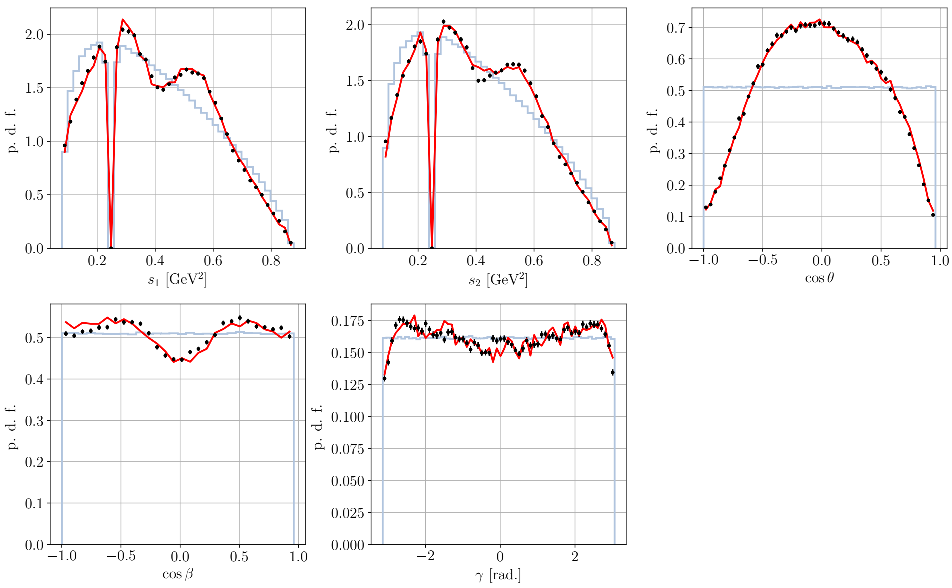

Figure 1: Distribution in simulation (black), from neural-network (red), and structureless (blue)

Wave	Amplitude		Phase [deg]	
	sim.	res.	sim.	res.
$[f_0(980)\pi]_P$	0.10	0.099 ± 0.001	-60	-55.485 ± 1.947
$[\rho(770)\pi]_S$	0.70	0.712 ± 0.005	0	reference phase
$[\rho(770)\pi]_D$	0.92	0.959 ± 0.025	120	120.546 ± 0.459
$[f_2(1270)\pi]_P$	0.53	0.514 ± 0.020	15	18.255 ± 2.525

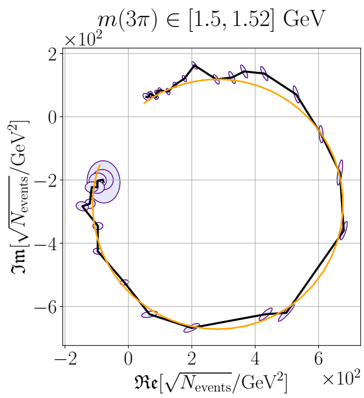

Table 1: Comparison of simulated values and fit results. **Figure 2:** QMIPWA (violet) and Breit-Wigner (orange) fit results for the $1^+[1^{--}\pi]_S$ wave in simulated data; ellipses show 68%-confidence intervals.

of $m(3\pi)$. Fig. 1 shows the resulting background shape for $m_{3\pi} \in (1.06, 1.08)$ GeV. The neural network prediction agrees with the simulated background.

We analyze the data in subregions of $m_{3\pi}$ with background modeled by the neural network and signal modeled with isobars and quasi-model-independent partial-wave analysis (QMIPWA) as described in [15]. To cross check the method, we analyze data simulated with only four partial waves: $1^+[f_0(980)\pi]_P$, $1^+[\rho(770)\pi]_S$, $1^+[\rho(770)\pi]_D$, and $1^+[f_2(1270)\pi]_P$. We use a QMIPWA isobar for the $1^+[1^{--}\pi]_S$ wave only, to avoid zero modes and simplify the test. We fit the QMIPWA complex amplitudes and a complex multiplier for each remaning wave. We then fit a Breit-Wigner function to the QMIPWA results (Fig. 2). The second fit determines the ρ's mass and width to be (769.8 ± 0.6) MeV and (155.2 ± 1.3) MeV, agreeing with the simulated values of 769.0 MeV and 150.9 MeV. The fit results (Table 1) all agree with their simulated values.

In conclusion, we have developed selection criteria with higher efficiency than previously achieved by the BaBar and Belle experiments [10, 11], though with a higher background contamination. However, we can still analyze this data well using a neural-network to parameterize background. We have also demonstrated that a fit algorithm using quasi-model-independent partial-wave analysis reproduces simulation inputs. This technique will be useful to study the $a_1(1260)$, $a_1(1420)$, $a_1(1640)$ and general structure of $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ independent of a model.

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