SciPost Physics Submission

Measurement of the presence of $a_1(1420)$ and $\omega(782)$ in $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ at Belle

A. Rabusov[1*], D. Greenwald[1], and S. Paul[1]

1 Technical University of Munich, Munich, Germany
* a.rabusov@tum.de

June 12, 2024

The 17th International Workshop on Tau Lepton Physics
Louisville, USA, 4-8 December 2023
doi:10.21468/SciPostPhysProc.?

Abstract

We present preliminary results of a partial-wave analysis of $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ using data from the Belle experiment at the KEKB e^+e^- collider. We validate our model with a model-independent analysis. We see the $a_1(1420)$ and a G-parity-violating $1^-[\omega(782)\,\pi]_P$ wave in tauon decays. Our results will improve models used in simulation studies necessary for measuring the electric and magnetic dipole moments and Michel parameters of the τ.

1 Introduction

Many studies of spin correlation in $e^+e^- \to \tau^+\tau^-$, such as measuring the electric and magnetic dipole moments of the τ, analyze tauon decay to $\pi^-\pi^+\pi^-\nu_\tau$ [1].[1] However, lack of knowledge about $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$, which has never been analyzed for intermediate resonances, limits the precision of such measurements.

This decay proceeds predominantly through $a_1(1260)$, a broad unflavored ground-state axial-vector meson [2], whose resonance shape is poorly known [3–5]. What other resonances are present and in what amounts is also poorly known. The COMPASS and VES experiments observed the $a_1(1420)$, potentially a narrow unflavored axial-vector meson, in pion-proton scattering [6, 7]. Seeing it in $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ and measuring how present it is in the decay will clarify whether it is a particle or an artifact of K^*K scattering [8].

To study such matters, we perform a partial-wave analysis (PWA) of $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ using 980 fb^{-1} of data collected by the Belle experiment [9] at the asymmetric e^+e^- collider KEKB [10]. Consult [9] for details of the Belle detector.

2 Event selection

Using simulated data, we optimized our event selection to maximize efficiency and purity without introducing significantly uneven detection efficiency across the decay's phase space. Each event has two hemispheres defined by the axis that minimizes the thrust of all detected charged particles and photons. We require there be three charged particles in one, the signal hemisphere, and one in the other, the tag hemisphere.

---

[1] Inclusion of charge-conjugated decays is assumed throughout.

We use a boosted decision tree (BDT), implemented with ROOT's TMVA software [11], to remove events not coming from $e^+e^- \to \tau^+\tau^-$. It is trained on simulated data and bases its decision on the sum of the momenta of charged particles and photons, the sum of energies of charged particles, the missing mass, the cosine of the polar angle of the missing momentum, the energy detected in the electromagnetic calorimeter, and the event thrust; the last is the most discriminating. All frame-dependent variables are calculated in the center-of-momentum frame.

We veto the presence of charged kaons in the signal hemisphere by requiring the two particles with like charges be consistent with being pions. We veto the presence of neutral kaons by requiring the mass of each pair of oppositely charged pions in the signal hemisphere be more than 12 MeV from the known K^0 mass [5]. And we reduce the presence of neutral pions by requiring the sum of photon energies in the signal hemisphere be below 480 MeV.

We find 55×10^6 events, with 82% purity and 32% efficiency to find signal—the largest sample of $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ yet analyzed. Background events come mostly from $e^+e^- \to q\bar{q}$, with $q = \mathrm{u,d,s,c}$, and from $e^+e^- \to \tau^+\tau^-$ with the τ in the signal hemisphere decaying to $\pi^-\pi^+\pi^-\pi^0$. We use a neural network to model the background in our partial-wave analysis; see [12, 13] for more details.

3 Partial-wave analysis

The phase space of $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ has seven dimensions. We parameterize our model intensity in the helicity angle of the ν_τ, the Euler angles of the three pions in the τ rest frame, the $\pi^+\pi^-$ squared masses, s_1 and s_2, and the mass of the three pions, $m_{3\pi}$ [14]. We average the intensity over the Euler angle that is unmeasurable because the ν_τ cannot be detected [13].

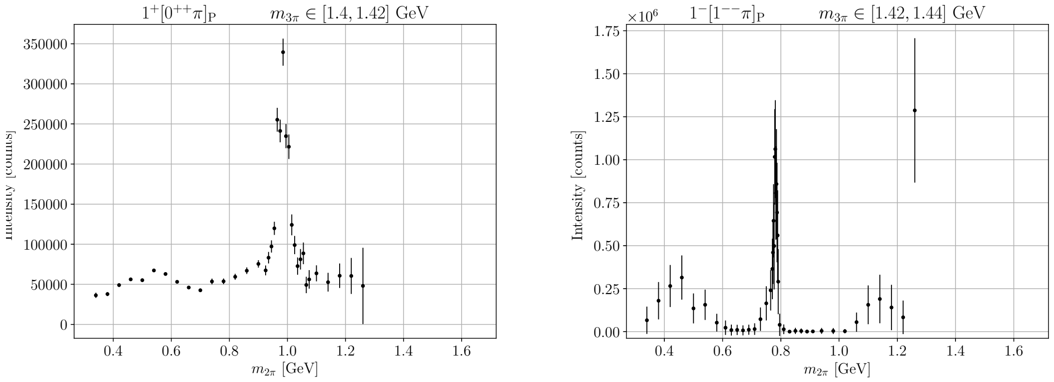
We fit to the data independently in disjoint contiguous bins of $m_{3\pi}$ to decompose it into partial waves using an isobar model and the tensor formalism of [15]. We assume that the decay proceeds through a resonance X^- that decays to three charged pions via a sequence of two-body decays, $X^- \to \xi^0\pi^-$ and $\xi^0 \to \pi^-\pi^+$, where ξ^0 is an isobar. The only requirement on X^- in the partial-wave decomposition is that its spin and parity, J^P, be 0^-, 1^+, or 1^-; the presence of the last would violate G parity.

We allow ξ^0 to be $\rho(770)$, $\rho(1450)$, $f_0(500)$, $f_0(980)$, $f_0(1500)$, $f_2(1270)$, or $\omega(782)$. We model them all with the relativistic Breit-Wigner function with masses and widths the same as in the COMPASS PWA [3], except for the $f_0(500)$, which we model with the broad $(\pi\pi)_S$ component described in [16]. Angular momentum up to 3 is allowed between ξ^0 and the remaining pion. We denote a partial wave by $J^P[\xi^0\pi]_L$ for specific isobar resonances ξ^0 and $J^P[(\pi\pi)_j\pi]_L$ for generic isobars with spin j; L is the total angular momentum of the three pions.

The preliminary results of the PWA were presented in [17]. Here we present an update that includes systematic uncertainties. We observe that the most intense partial wave is the $1^+[\rho(770)\pi]_S$ wave, with a fit fraction of $(76.42 \pm 0.05 \pm 3.29)\%$, where the first uncertainty is statistical, and the second uncertainty is systematic. The next most intense is the $1^+[\sigma\pi]_P$ wave with a fit fraction of $(8.40 \pm 0.02 \pm 1.16)\%$. The fit fraction of a partial wave is the integral over $m_{3\pi}$ of the intensity of that wave alone divided by the same integral of the intensity of the full PWA model. These fractions agree with those measured by CLEO II in $\tau^- \to \pi^-\pi^0\pi^0\nu_\tau$ [4].

We use quasi-model-independent PWA (QMIPWA) [18] to verify our model. We replace the $(\pi\pi)_S$ and $1^+[\rho(770)\pi]_S$ models with complex step functions, letting the fit optimize their values [17]. We observe the narrow peak of the $f_0(980)$ in the $(\pi\pi)_S$ wave, as shown in Fig. 1a.

In [19], Mirkes and Urech stated that 1^- intensity in $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ comes from the



a) $1^+[(\pi\pi)_S\,\pi]_P$ wave.

b) $1^-[(\pi\pi)_P\,\pi]_P$ wave.

Figure 1: QMIPWA intensities as functions of $m_{2\pi}$ with statistical uncertainties.

G-violating decay of $\omega(782) \to \pi^+\pi^-$, where $\omega(782)$ is produced by decay of a $\rho(770)$, $\rho(1450)$, or $\rho(1700)$. We free the $1^-[(\pi\pi)_P\,\pi]_P$ wave in our QMIPWA and observe a narrow peak at 782 MeV, as shown in Fig. 1b. We include the $1^-[\omega(782)\,\pi]_P$ wave in the conventional PWA and measure a fit fraction of $(2.95\pm0.04)\times10^{-3}$, consistent with the prediction of 4×10^{-3} in [19].

4 Conclusion

We will soon provide an updated model for $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$ with about 15 partial waves and statistical and systematic uncertainties. It will be useful for simulating $\tau^- \to \pi^-\pi^+\pi^-\nu_\tau$, necessary for measurement of the electric and magnetic dipole moments of the τ. We see the $a_1(1420)$ and $1^-[\omega(782)\,\pi]_P$ wave in tauon decays in both conventional PWA and QMIPWA; this is their first sighting in tauon decay.

Acknowledgments

We acknowledge Florian Kaspar for providing his code to train a neural network on simulated background data, Dmitrii Ryabchikov for providing his code to resolve ambiguities in QMIPWA, and Stefan Wallner for cross checking our acceptance correction scheme.

References

[1] E. Kou *et al.*, *The Belle II Physics Book*, Progress of Theoretical and Experimental Physics **2019**(12) (2019), doi:10.1093/ptep/ptz106, 123C01.

[2] G. Alexander *et al.*, *Evidence for the $\tau \to \nu\rho\pi$ decay mode*, Physics Letters B **73**(1), 99 (1978), doi:https://doi.org/10.1016/0370-2693(78)90181-8.

[3] M. Aghasyan *et al.*, *Light isovector resonances in $\pi^- p \to \pi^-\pi^-\pi^+ p$ at* 190 GeV/c, Phys. Rev. D **98**, 092003 (2018), doi:10.1103/PhysRevD.98.092003.

[4] D. M. e. Asner, *Hadronic structure in the decay $\tau^- \rightarrow \nu_\tau \pi^- \pi^0 \pi^0$ and the sign of the tau neutrino helicity*, Phys. Rev. D **61**, 012002 (1999), doi:10.1103/PhysRevD.61.012002.

[5] P. A. Zyla *et al.*, *Rev. of Particle Physics*, PTEP **2020**(8), 083C01 (2020), doi:10.1093/ptep/ptaa104.

[6] C. e. Adolph, *Observation of a new narrow axial-vector meson $a_1(1420)$*, Phys. Rev. Lett. **115**, 082001 (2015), doi:10.1103/PhysRevLett.115.082001.

[7] D. Ryabchikov, *Meson spectroscopy at VES and COMPASS*, EPJ Web Conf. **212**, 03010 (2019), doi:10.1051/epjconf/201921203010.

[8] M. Mikhasenko, B. Ketzer and A. Sarantsev, *Nature of the $a_1(1420)$*, Phys. Rev. D **91**, 094015 (2015), doi:10.1103/PhysRevD.91.094015.

[9] A. Abashian *et al.*, *The Belle Detector*, Nucl. Instrum. Meth. A **479**, 117 (2002), doi:10.1016/S0168-9002(01)02013-7.

[10] S. Kurokawa and E. Kikutani, *Overview of the KEKB accelerators*, Nucl. Instrum. Meth. A **499**, 1 (2003), doi:10.1016/S0168-9002(02)01771-0.

[11] A. Hocker *et al.*, *TMVA - Toolkit for Multivariate Data Analysis*, Tech. rep. (2007), physics/0703039.

[12] A. Mathad, D. O'Hanlon, A. Poluektov and R. Rabadan, *Efficient description of experimental effects in amplitude analyses*, JINST **16**(06), P06016 (2021), doi:10.1088/1748-0221/16/06/P06016, 1902.01452.

[13] A. Rabusov, D. Greenwald and S. Paul, *Partial wave analysis of $\tau^- \rightarrow \pi^- \pi^+ \pi^- \nu_\tau$ at Belle*, In *41st International Conference on High Energy Physics* (2022), 2211.11696.

[14] J. H. Kühn and E. Mirkes, *Structure functions in tau decays*, Zeitschrift für Physik C Particles and Fields **67**(2), 364 (1995), doi:10.1007/BF01571299.

[15] F. Krinner and S. Paul, *Hadronic Currents and Form Factors in three-body Semileptonic τ Decays* (2021), 2107.04295.

[16] I. Kachaev and Ihep, *Modified S-wave $\pi\pi$ scattering amplitude for multiparticle PWA* (2023), 2305.11711.

[17] A. Rabusov, D. Greenwald and S. Paul, *Partial-wave analysis of $\tau^- \rightarrow \pi^- \pi^- \pi^+ \nu_\tau$ at Belle*, In *20th International Conference on Hadron Spectroscopy and Structure* (2023), 2310.09155.

[18] F. Krinner, D. Greenwald, D. Ryabchikov, B. Grube and S. Paul, *Ambiguities in model-independent partial-wave analysis*, Phys. Rev. D **97**, 114008 (2018), doi:10.1103/PhysRevD.97.114008.

[19] E. Mirkes and R. Urech, *Isospin violation in tau —> 3 pi tau-neutrino*, Eur. Phys. J. C **1**, 201 (1998), doi:10.1007/BF01245809, hep-ph/9702382.