Snowmass 2020 Letter of Interest: Triple-Product Asymmetries

Bhubanjyoti Bhattacharya*
Department of Natural Sciences, Lawrence Technological University, Southfield, MI 48075, USA

Alakabha Datta†
Department of Physics and Astronomy, 108 Lewis Hall,
University of Mississippi, Oxford, MS 38677-1848, USA,
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Triple-product asymmetries in multi-body B decays can provide clean information about CP-violating new physics. This Letter of Interest aims at promoting theory progress needed to interpret future measurements of triple-product asymmetries, to identify appropriate models of new physics, and to create a road map for the discovery of new sources of CP violation beyond the Standard Model of particle physics.

I. Introduction

The Standard Model (SM) source of CP violation is a single complex phase in the Cabibbo-Kobayashi-Maskawa (CKM) matrix that governs the mixing between different flavors of quarks. Even though the fundamental origin of this phase is not known – it is a free parameter in the SM, experiments have already been successful in measuring it. In fact, soon we will have very precise measurements for the CP-violating phase in the CKM matrix. Yet, this poses a much greater challenge. It is well known that CP violation embedded in the CKM paradigm is not enough to explain the baryon-asymmetry problem of the universe, and that new-physics (NP) sources of CP violation beyond the SM are needed. In order to obtain concrete evidence for such NP we need two types of progress in the upcoming decade to occur concurrently. First, we need precise measurements of CP-violating observables from the experimental side, and second we need to identify and calculate new CP-violating observables from the theory side, both within the SM as well as in NP frameworks for comparison with data and explain deviations. This letter of interest will focus on ideas on making progress from the theory side.

CP-violation can manifest in the following ways: I) a time-independent asymmetry between the decay rates of a particle and its antiparticle in specific channels, also known as direct CP asymmetry, II) a time-dependent asymmetry between such decay rates, also known as indirect CP asymmetry, and III) an asymmetry that appears as a difference between angular distributions of a multi-body decay of a particle and its antiparticle. Triple-Product asymmetries (TPAs) that appear in angular distributions of particle decays are of the third kind. The TPAs are asymmetries involving scalar triple products of the type $\mathrm{TP} = \vec{\mathbf{v}}_1 \cdot (\vec{\mathbf{v}}_2 \times \vec{\mathbf{v}}_3)$, where the $\vec{\mathbf{v}}_{1,2,3}$ are momenta or polarizations of the final state particles. The TPAs can be constructed as $A_T \sim N(\mathrm{TP} > 0) - N(\mathrm{TP} < 0)$ where $N(\mathrm{TP} < (>) 0)$ are the number of events with TP less than or greater than 0. Our main focus in this Letter of Interest is to motivate theory progress on the topic of triple-product asymmetries in various multi-body B-meson decays[1–3]. Triple-product asymmetries involving baryon spins and momenta can also arise in baryon decays [4–6]. We focus on TPAs due to their relative cleanliness as indicators of new physics.

Any non-vanishing CP-violating observable requires an interference between two or more amplitudes with different weak (CP-odd) phases. Direct CP asymmetries, however, also require the two interfering amplitudes to have different strong (CP-even) phases. It is very likely that new sources of CP violation living at energies higher than the TeV scale only couple weakly to the SM. Therefore, the strong interactions being the only source of CP-even phases it is difficult to construct direct CP asymmetries, even with NP. TPAs, on the other hand, can be non-vanishing even if the two interfering amplitudes do not have different strong phases. This makes TPAs great targets for searches for CP-violating NP.

TPAs are generally T-odd observables. While many TPAs are CP violating – called "true" TPAs, many TPAs do not violate CP symmetry and are called "fake" TPAs. "Fake" TPAs are non-vanishing even when the two interfering amplitudes have the same weak phase. Measurement of both "True" (CP-violating) TPAs and "fake" (CP-conserving) TPAs can lead to a wealth of information on the CP properties of any new interaction [7]. In the following section we present a brief mathematical basis for TPAs.

II. Theory of Triple-Product Asymmetries

In angular distributions of multi-body decays of pseudocalar mesons (such as B mesons), where the final state spin information is not retained, TPAs appear as coefficients of terms that are proportional to a scalar triple product of the form $\vec{\mathbf{p}}_1 \cdot (\vec{\mathbf{p}}_2 \times \vec{\mathbf{p}}_3)$ (hence the name TPA), where $\vec{\mathbf{p}}_i$ represents the vector 3-momentum of the i^{th} final state particle. Clearly, a non-zero TPA requires the investigation of processes with at least four particles in the final state [8]. In the simplest possible situation, where there are only four particles in the final state, the

* bbhattach@ltu.edu
† datta@phy.olemiss.edu

distribution of events in the decay can be parametrized using three helicity angles. Fig. 1 presents an example for these angles using the decay $B \to D\pi\ell^-\bar{\nu}_{\ell^-}$.

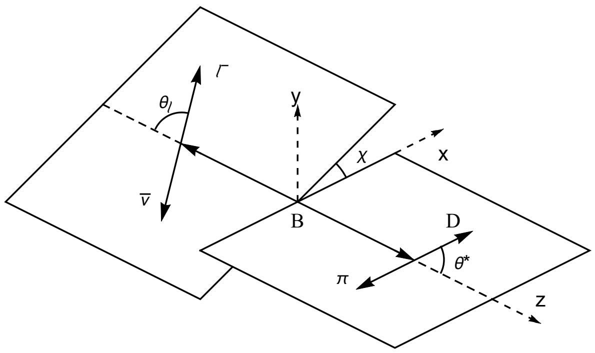

FIG. 1. Angles in the $\bar{B} \to D^*(\to D\pi)\,\ell^-\bar{\nu}_\ell$ distribution.

The full decay amplitude for a multi-body B decay can be broken down into several helicities. For example, in case of a decay that proceeds through two intermediate on-shell vector mesons the amplitude depends on three helcities. This decay can be represented in terms of helicity amplitudes $(A_0, A_\parallel, A_\perp)$ as,

$$\begin{aligned} A(B \to V_1 V_2) = A_0\ \vec{\epsilon}_1^{\,*L}\ \vec{\epsilon}_2^{\,*L} - A_\parallel\ \vec{\epsilon}_1^{\,*T} \cdot \vec{\epsilon}_2^{\,*T} \\ - i\ A_\perp\ (\vec{\epsilon}_1 \times \vec{\epsilon}_2) \cdot \hat{z}\ , \end{aligned} \quad (1)$$

where $\vec{\epsilon}^L(T)_i$ represents the longitudinal (transverse) part of the vector V_i. Allowing for time dependence due to neutral B-meson mixing, the angular distribution can be expressed as [9, 10],

$$\frac{d^4\Gamma}{dt d\theta_1 d\theta_2 d\chi} = \frac{9}{8\pi} \sum_i K_i(t) X_i(\theta_1, \theta_2, \chi)\ , \quad (2)$$

where θ_1, θ_2 are polar angles, χ is an azimuthal angle, X_i's denote angular functions, and K_i's denote time-dependent coefficient functions. The coefficient functions can be further represented using,

$$\begin{aligned} K_i(t) = a_i \cosh(\Delta\Gamma t/2) + b_i \sinh(\Delta\Gamma t/2) \\ + c_i \cos(\Delta m t) + d_i \sin(\Delta m t)\ , \end{aligned} \quad (3)$$

where the time-independent observables $a_i, b_i, c_i,$ and d_i are functions of the helicity amplitudes containing information about the underlying physics. These time-independent functions are of the form $\mathrm{Re}[A_i A_j^*]$ or $\mathrm{Im}[A_i A_j^*]$. Upon appropriately combining these observables with their CP-conjugate counterparts one can construct interesting CP-violating TPAs of the following form,

$$\mathrm{Im}[A_i A_j^* - \overline{A}_i \overline{A}_j^*] = 2|A_i||A_j| \cos(\Delta\delta) \sin(\Delta\phi)\ , \quad (4)$$

where $\Delta\delta$ and $\Delta\phi$ represent the respective differences between the strong and weak phases of the interfering amplitudes. In experiments such a TPA can be measured from an asymmetry in the distribution of decay events,

$$A_{\mathrm{TP}} = \frac{\Gamma(\sin\chi > 0) - \Gamma(\sin\chi < 0)}{\Gamma(\sin\chi > 0) + \Gamma(\sin\chi < 0)}\ . \quad (5)$$

The SM contributions to CP-violating TPs often vanish, making them clean signals for new physics weak phases. Once a non-vanishing TP is measured at an experiment, theory progress will be needed to identify the type of new physics responsible.

III. Future directions

One can systematically study the TPAs in various decays. Of particular interest are the semileptonic charged current and neutral current processes with the quark level transitions $b \to c\ell^-\bar{\nu}_\ell$ and $b \to s\ell^+\ell^-$ where evidence of lepton-flavor non-universal new physics have been accumulating over the past few years. It is possible that future experiments will see signatures of lepton flavor violating new physics. Measurement of nonzero true TPA in these decays is a sure sign of new physics and needs to be explored in greater details. Measurements and theoretical studies of TPAs in nonleptonic B decays is an important tool to probe possible new physics that may explain the polarization puzzle [11] or the $K\pi$ puzzle[12] in B decays. Below we identify some processes where the study TPAs can be very fruitful in the search for new physics.

1. $B \to K^*\mu^+\mu^-$. In [13, 14] it was shown that TPAs in this mode have distinguishing power between certain classes of leptoquarks and new heavy vector bosons. Progress is needed to identify the experimental precision necessary for the discovery of CP-violating new physics in this channel.
2. $B \to D^*\mu\nu$ [15] and $B \to D^*\tau\nu$ [16–18]. Modes involving the τ lepton are particularly interesting as the τ can be detected through its hadronic decay. Theory progress is needed to identify additional angular observables from multi-body decays of the τ coming from a semi-leptonic B decay.
3. $B \to K^*\bar{K}^*$ [10]. We consider this decay as an example where many TPAs occur. Reliable calculation of these asymmetries in the SM and in different models of new physics will be very useful to establish new physics and to distinguish among different new physics models.

[1] G. Valencia, Angular Correlations in the Decay $B \to VV$ and CP Violation, Phys. Rev. D **39**, 3339 (1989).

[2] A. Datta and D. London, Triple-product correlations in $B \to V_1 V_2$ decays and new physics, Int. J. Mod. Phys. A **19**, 2505 (2004), arXiv:hep-ph/0303159.

[3] M. Gronau and J. L. Rosner, Triple product asymmetries in K, $D_{(s)}$ and $B_{(s)}$ decays, Phys. Rev. D **84**, 096013 (2011), arXiv:1107.1232 [hep-ph].

[4] W. Bensalem, A. Datta, and D. London, T violating triple product correlations in charmless Λ_b decays, Phys. Lett. B **538**, 309 (2002), arXiv:hep-ph/0205009.

[5] W. Bensalem, A. Datta, and D. London, New physics effects on triple product correlations in Lambda(b) decays, Phys. Rev. D **66**, 094004 (2002), arXiv:hep-ph/0208054.

[6] X.-W. Kang, H.-B. Li, G.-R. Lu, and A. Datta, Study of CP violation in Λ_c^+ decay, Int. J. Mod. Phys. A **26**, 2523 (2011), arXiv:1003.5494 [hep-ph].

[7] A. Datta, M. Duraisamy, and D. London, Searching for New Physics with B-Decay Fake Triple Products, Phys. Lett. B **701**, 357 (2011), arXiv:1103.2442 [hep-ph].

[8] A three-body final state can be used as long as one or more of the final state particles is a vector. In this case the polarization of the vector particle, $\vec{\epsilon}$, can be used to construct the scalar triple product. However, often the vector polarization is itself studied through its decay, effectively increasing the multiplicity of the final state.

[9] A. Datta, M. Duraisamy, and D. London, New Physics in $b \to s$ Transitions and the $B^0_{d,s} \to V_1 V_2$ Angular Analysis, Phys. Rev. D **86**, 076011 (2012), arXiv:1207.4495 [hep-ph].

[10] B. Bhattacharya, A. Datta, M. Duraisamy, and D. London, Searching for new physics with $\bar{b} \to \bar{s} B^0_s \to V_1 V_2$ penguin decays, Phys. Rev. D **88**, 016007 (2013), arXiv:1306.1911 [hep-ph].

[11] S. Baek, A. Datta, P. Hamel, O. F. Hernandez, and D. London, Polarization states in B —¿ rho K* and new physics, Phys. Rev. D **72**, 094008 (2005), arXiv:hep-ph/0508149.

[12] N. B. Beaudry, A. Datta, D. London, A. Rashed, and J.-S. Roux, The $B \to \pi K$ puzzle revisited, JHEP **01**, 074, arXiv:1709.07142 [hep-ph].

[13] A. K. Alok, A. Datta, A. Dighe, M. Duraisamy, D. Ghosh, and D. London, New Physics in $b \to s\mu^+\mu^-$: CP-Violating Observables, JHEP **11**, 122, arXiv:1103.5344 [hep-ph].

[14] A. K. Alok, B. Bhattacharya, D. Kumar, J. Kumar, D. London, and S. U. Sankar, New physics in $b \to s\mu^+\mu^-$: Distinguishing models through CP-violating effects, Phys. Rev. D **96**, 015034 (2017), arXiv:1703.09247 [hep-ph].

[15] B. Bhattacharya, A. Datta, S. Kamali, and D. London, CP Violation in $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$, JHEP **05** (2019), 191, arXiv:1903.02567 [hep-ph].

[16] M. Duraisamy and A. Datta, The Full $B \to D^*\tau^-\bar{\nu_\tau}$ Angular Distribution and CP violating Triple Products, JHEP **09**, 059, arXiv:1302.7031 [hep-ph].

[17] M. Duraisamy, P. Sharma, and A. Datta, Azimuthal $B \to D^*\tau^-\bar{\nu_\tau}$ angular distribution with tensor operators, Phys. Rev. D **90**, 074013 (2014), arXiv:1405.3719 [hep-ph].

[18] B. Bhattacharya, A. Datta, S. Kamali, and D. London, A measurable angular distribution for $\overline{B} \to D^*\tau^-\overline{\nu}_\tau$ decays, JHEP **07** (2020), 194, arXiv:2005.03032 [hep-ph].