$B \to V_1 V_2$ and $B \to V l^+ l^-$ Angular Analysis

Alakabha Datta ^{a,*}, Murugeswaran Duraisamy ^{a,†}

a: *Department of Physics and Astronomy, 108 Lewis Hall, University of Mississippi, Oxford, MS 38677-1848, USA*

1 Motivation

To detect new physics (NP) in B decays one has to look at various final states as NP may affect different final states differently. The decay of B to one or two vector final state is interesting as one can devise many correlations that are sensitive to NP. In this write up we consider $B \to V_1 V_2$ and $B \to V l^+ l^-$ decays. When the final state can be reached by both B and $\bar{B}$ decays then mixing effects have to be taken into account leading to additional observables

2 $B \to V_1 V_2$ Angular Distribution

The most general Lorentz-covariant amplitude for the decay $B(p) \to V_1(k_1, \varepsilon_1) + V_2(k_2, \varepsilon_2)$ is given by [1, 2]

$$M = a\, \varepsilon_1^* \cdot \varepsilon_2^* + \frac{b}{m_B^2}(p \cdot \varepsilon_1^*)(p \cdot \varepsilon_2^*) + i\frac{c}{m_B^2}\epsilon_{\mu\nu\rho\sigma} p^\mu q^\nu \varepsilon_1^{*\rho} \varepsilon_2^{*\sigma} \ , \tag{1}$$

where $q \equiv k_1 - k_2$. The quantities a, b and c are complex and contain in general both CP-conserving strong phases and CP-violating weak phases. Three transversity amplitudes $A_i (i = 0, \|, \perp)$ are related to a, b and c of Eq. (1). For the CP-conjugate mode , $\bar{B}(p) \to \bar{V}_1(k_1, \varepsilon_1) + \bar{V}_2(k_2, \varepsilon_2)$ transversity amplitudes $\bar{A}_i (i = 0, \|, \perp)$ can be obtained from Eq. (1) by replacing $a \to \bar{a}$, $b \to \bar{b}$ and $c \to -\bar{c}$. Assuming that $V_{1,2}$ both decay into pseudoscalars, i.e. $V_1 \to P_1 P_1'$, $V_2 \to P_2 P_2'$, the time-independent angular distribution of the decay is then given in terms of the vector $\vec{\omega} = (\cos\theta_1, \cos\theta_2, \Phi)$ [3, 4]:

$$\frac{d^3\Gamma}{d\vec{\omega}} = \frac{9}{32\pi} \sum_{i=1}^{6} K_i f_i(\vec{\omega}) \ . \tag{2}$$

We are interested in two quantities $K_4 = \mathrm{Im}[A_\perp A_\|^*]$, and $K_6 = \mathrm{Im}[A_\perp A_0^*]$, which are related to CP-violating quantities called tripl products (TP's) [1, 2]. Two true (CP-violating) TP's are $\mathcal{A}_T^{(1)true} = \frac{1}{2}[\mathrm{Im}(A_\perp A_0^*) - \mathrm{Im}(\bar{A}_\perp \bar{A}_0^*)]$, $\mathcal{A}_T^{(2)true} = \frac{1}{2}[\mathrm{Im}(A_\perp A_\|^*) -$

*datta@phy.olemiss.edu

†duraism@phy.olemiss.edu

$\text{Im}(\bar{A}_\perp \bar{A}_\parallel^*)]$, and two fake (CP-conserving) TP's are fake $\mathcal{A}_T^{(1)fake} = \frac{1}{2}[\text{Im}(A_\perp A_0^*) + \text{Im}(\bar{A}_\perp \bar{A}_0^*)]$, $\mathcal{A}_T^{(2)fake} = \frac{1}{2}[\text{Im}(A_\perp A_\parallel^*) + \text{Im}(\bar{A}_\perp \bar{A}_\parallel^*)]$. It is straightforward to show that

$$\mathcal{A}_T^{true} \propto \cos(\delta_\perp - \delta_i)\sin(\phi_\perp - \phi_i), \ \mathcal{A}_T^{fake} \propto \sin(\delta_\perp - \delta_i)\cos(\phi_\perp - \phi_i). \qquad (3)$$

where $(\phi_\perp - \phi_i)$ and $(\delta_\perp - \delta_i)$ are, respectively, the relative weak and strong phases between $A_\perp$ and $A_i (i = 0, \|)$. Thus, the true TP requires nonzero CP-violating phase difference $(\phi_\perp - \phi_i)$ and is relatively insensitive to CP-conserving phase difference $(\delta_\perp - \delta_i)$. On the other hand, the fake TP requires nonzero CP-conserving phase difference $(\delta_\perp - \delta_i)$, and can be nonzero even if the CP-violating phase difference $(\phi_\perp - \phi_i)$ vanishes.

Both the true and fake triple products(T.P) are sensitive probes of new physics. In $b \to s$ transitions there is negligible CP violation in the SM and the true T.P is predicted to be almost zero. Many NP can produce non zero true T.P and so NP may be revealed via the measurements of the true T.P's.

Due to the fact that the weak interactions are left-handed, i.e. the couplings are $V - A$, the helicity amplitudes obey the hierarchy $|A_+/A_-| = \Lambda_{QCD}/m_b$. Thus, in the heavy-quark limit, A_+ is negligible compared to A_-, so that $A_\parallel = -A_\perp$. But in this case, $A_T^{(2)}$, which is proportional to $\text{Im}(A_\perp A_\parallel^*)$, vanishes. This means that if the large f_T/f_L observed in several $B \to V_1 V_2$ decays is due to the SM, $A_T^{(2)} = 0$ should be found. Any violation of this result with indicate new physics. This can be tested by measuring the fake T.P's

When the final state can be reached by both B and $\bar{B}$ decays, mixing effects come into play. Consider for example $B_s^0 \to \phi\phi$. Due to $B_s^0 - \bar{B}_s$ mixing, the amplitudes for the decay $B_s^0 \to \phi\phi$ become time-dependent. The time-dependent angular distribution in the presence of both the SM and NP contributions can be obtained from Eq.(2) by evaluating $K_i \equiv K_i(t = 0)$:

$$\frac{d^4\Gamma}{dt d\vec{\omega}} = \frac{9}{32\pi}\sum_{i=1}^{6} K_i(t) f_i(\vec{\omega}) \ , \qquad (4)$$

where $K_i(t)$'s depend on the mass difference Δm_s and the width difference $\Delta\Gamma_s$. The angular distribution for the CP-conjugate mode $\bar{B}_s^0 \to \phi\phi$ can be obtained by changing $K_i(t)$ to $\bar{K}_i(t)$ (i.e. $A_i \to \bar{A}_i$, $\sin\Delta m_s t \to -\sin\Delta m_s t$, and $\cos\Delta m_s t \to -\cos\Delta m_s t$). The time-dependent true TP's are given by the untagged observables $\mathcal{A}_T^{(1),(2)true}(t) = 1/2(K_{4,6}(t) + \bar{K}_{4,6}(t))$, and the time-dependent fake TP's are given by the tagged observables $\mathcal{A}_T^{(1),(2)fake}(t) = 1/2(K_{4,6}(t) - \bar{K}_{4,6}(t))$. In the absence of NP, $\mathcal{A}_T^{(1)true}(t)$ and $\mathcal{A}_T^{(2)true}(t)$ vanish. Recently, CDF Collaboration reported the first measurements for the true TP's [5] from the time-integrated angular distribution for the $B_s^0 \to \phi\phi$ decay: $A_u = -2/\pi\mathcal{A}_T^{(2)true} = (0.7 \pm 6.4(stat) \pm 1.8(syst))\%$; $A_v = -\sqrt{2}/\pi\mathcal{A}_T^{(1)true} = (12.0 \pm 6.4(stat) \pm 1.6(syst))\%$.

3 $B^0_{d,s} \to V(= K^*, \phi) l^+ l^-$ Angular Distribution

The complete three-angle distribution for the decay $\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+)\mu^+\mu^-$ in the presence of NP can be expressed in terms of q^2 and the vector $\vec{\Omega} = (\cos\theta_K, \cos\theta_l, \phi)$ [6]:

$$\frac{d^4\Gamma^{\bar{B}^0_d}}{dq^2 d\vec{\Omega}} = N_F \Big(\sum_{i=1}^{3} I_i^0(q^2) g_i^0(\vec{\Omega}) + \sum_{i=1}^{5} I_i^T(q^2) g_i^T(\vec{\Omega}) + \sum_{i=1}^{4} I_i^{LT}(q^2) g_i^{LT}(\vec{\Omega}) \Big) , \quad (5)$$

For the CP-conjugate decay $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$, the angular coefficients $\bar{I}$'s can be obtained from the I's by replacing $\theta_\mu \to \theta_\mu - \pi$ and $\phi \to -\phi$, and changing the signs of the weak phases.

By complete analogy to the angle distribution for the decay $\bar{B}^0 \to \bar{K}^{*0}(\to K^-\pi^+)\mu^+\mu^-$ in Eq. (5), one can obtain the expression for the $\bar{B}^0_s \to \phi(\to K^+K^-)l^+l^-$ angular distribution with the appropriate replacements in masses and hadronic parameters. As a result of $B^0_s - \bar{B}^0_s$, the angular distribution for becomes time-dependent. The untagged time dependent angular distribution is:

$$\frac{d^5(\Gamma^{\bar{B}^0_s} + \Gamma^{B^0_s})}{dt dq^2 d\vec{\Omega}} = N_F \Big(\sum_{i=1}^{3} (I_i^0(q^2,t) + \bar{I}_i^0(q^2,t)) g_i^0(\vec{\Omega}) + \sum_{i=1}^{5} (I_i^T(q^2,t) + \bar{I}_i^T(q^2,t)) g_i^T(\vec{\Omega}) + \sum_{i=1}^{4} (I_i^{LT}(q^2,t) + \bar{I}_i^{LT}(q^2,t)) g_i^{LT}(\vec{\Omega}) \Big) . \quad (6)$$

Many observables sensitive to NP can be defined from these distributions. These observables can be CP conserving as well as CP violating where the CP violating ones can be either direct CP violating or triple products. The prediction for these observables with the most general NP for the decay $B^0 \to K^{*0}(\to K^+\pi^-)\mu^+\mu^-$ is discussed in Ref .[6, 7].

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