We discuss how triple product asymmetries can be used to discover and constrain new physics in $B \to V_1 V_2$ decays.

1 Introduction

One of the main goals in $B$ physics experiments is to find new physics (NP) by observing deviations from the standard model (SM) predictions [1]. The $b \to s$ transitions are interesting as the SM CP violation in these decays is tiny. Hence these decays are good places to search for NP. Two main probes of CP violation (CPV) are direct CP violation (DCPV) and indirect CP violation. In $B \to V_1 V_2$ decays there is another probe of CPV - the triple product asymmetries (TPA) [2, 3, 4]. As shown in [3] they can provide useful information about the structure of NP. In this talk I will discuss TPA in the the rare processes $b \to s\bar{q}q$, where $q$ are light quarks, that lead to $VV$ final states.

$B \to V_1 V_2$ decays are really three transitions because there are 3 polarization final states. One can construct direct CP violation (DCPV) asymmetries by taking the rate differences of the various polarization amplitudes. Interference between the different polarization amplitudes produce TPA. As is well known, DCPV $\sim \sin \phi \sin \delta$ where $\phi$ and $\delta$ are the weak and strong phase differences. TPA on the other hand are proportional to $\sim \sin \phi \cos \delta$. Hence DCPV and TPA complement each other. If the strong phases are small then TPA are maximized. There is another measurement involving triple products that is not CP violating which is called the fake triple product [5]. This quantity goes as $\sim \cos \phi \sin \delta$ and requires tagging for measurement. This observable can constrain NP if the NP has the same weak phase as the SM in which case DCPV and TPA vanish.
We will first discuss triple products in $B \rightarrow V_1V_2$ decays in general. To motivate new physics we will consider the polarization measurements in $b \rightarrow s$ transitions that differ significantly from naive standard model (SM) predictions. There are SM solutions to these polarization puzzles which can be tested but we will focus on the NP solutions and discuss how triple product asymmetries can constrain the size and structure of this new physics. Finally, we will discuss polarization fractions and triple products in decays where the final states can be reached by both $B$ and $\bar{B}$ decays and so mixing effects have to be included.

## 2 Triple Products

In the $B$ rest frame we can construct a triple product, $TP$

$$TP = \vec{p} \cdot (\vec{\epsilon}_1 \times \vec{\epsilon}_2),$$

where $\vec{\epsilon}_{1,2}$ are the polarization vectors of the final state vector mesons and $\vec{p}$ is the three momentum of one of the vector mesons in the $B$ rest frame. We can define a T-odd asymmetry

$$A_T = \frac{\Gamma[TP > 0] - \Gamma[TP < 0]}{\Gamma[TP > 0] + \Gamma[TP < 0]}.$$  

For true CP violation, we need to compare $A_T$ and $\overline{A_T}$. One can define the true and the fake TPA as

$$A_{T, true} = A_T + \overline{A_T} \propto \sin \phi \cos \delta,$$

$$A_{T, fake} = A_T - \overline{A_T} \propto \cos \phi \sin \delta.$$  

The TPA appear in the angular distribution of $B \rightarrow V_1V_2 \rightarrow (V_1 \rightarrow P_1P_1')(V_2 \rightarrow P_2P_2')$. We can define two T.P's

$$A_T^{(1)} \equiv \frac{\text{Im}(A_\perp A_0^*)}{A_0^2 + A_\parallel^2 + A_\perp^2}, \quad A_T^{(2)} \equiv \frac{\text{Im}(A_\perp A_0^*)}{A_0^2 + A_\parallel^2 + A_\perp^2}. $$

Here the amplitudes are longitudinal ($A_0$), or transverse to the directions of motion and parallel ($A_\parallel$) or perpendicular ($A_\perp$) to one another.

For the CP conjugate decay one defines two TPA

$$\overline{A_T}^{(1)} \equiv -\frac{\text{Im}(\overline{A_\perp A_0})}{A_0^2 + A_\parallel^2 + A_\perp^2}, \quad \overline{A_T}^{(2)} \equiv -\frac{\text{Im}(\overline{A_\perp A_0})}{A_0^2 + A_\parallel^2 + A_\perp^2}. $$

2
Polarization fractions
\[ f_L = 0.480 \pm 0.030 \quad f_\perp = 0.241 \pm 0.029 \]

Phases
\[ \phi_\parallel (\text{rad}) = 2.40^{+0.04}_{-0.14} \quad \phi_\perp (\text{rad}) = 2.39 \pm 0.13 \]
\[ \Delta \phi_\parallel (\text{rad}) = 0.11 \pm 0.13 \quad \Delta \phi_\perp (\text{rad}) = 0.08 \pm 0.13 \]

CP asymmetries
\[ A_{\parallel}^{\text{CP}} = 0.04 \pm 0.06 \quad A_{\perp}^{\text{CP}} = -0.11 \pm 0.12 \]

Table 1: \( B_d \to \phi K^{*0} \) polarization observables.

3 Testing NP with Triple Products

In the SM there is prediction for one of the triple products in the heavy \( b \) quark limit for \( B \) decays to light final states. Let us write the transverse amplitudes in terms of the helicity amplitudes, \( A_\pm \)
\[
A_\parallel = \frac{1}{\sqrt{2}} (A_+ + A_-), \\
A_\perp = \frac{1}{\sqrt{2}} (A_+ - A_-). \tag{6}
\]

Due to the fact that the weak interactions are left-handed, the helicity amplitudes obey the hierarchy
\[
\left| \frac{A_+}{A_-} \right| = r_T \sim \frac{\Lambda_{\text{QCD}}}{m_b}. \tag{7}
\]

Thus, in the heavy-quark limit, \( A_\parallel = -A_\perp \) which means \( A_T^{(2)} \), which is proportional to \( \text{Im}(A_\perp A_\parallel^*) \), vanishes [5] and so we can conclude that the corresponding fake and true TPA vanish in this limit. Corrections to the heavy quark limit can be calculated and within QCD factorization this is at most around 10% [5]. The other triple product \( A_T^{(1)} \) does not vanish in the heavy quark limit and can be sizeable.

In table the measurements for \( B_d \to \phi K^{*0} \) polarization observables [7] are shown. Using the numbers in the table we can calculate the fake and true TPA:
\[
A_{T,P,2}^{\text{fake}} = \frac{1}{2} (A_{T,B}^{(2)} - \overline{A}_{T,B}^{(2)}) = 0.002 \pm 0.049, \\
A_{T,P,1}^{\text{fake}} = \frac{1}{2} (A_{T,B}^{(1)} - \overline{A}_{T,B}^{(1)}) = -0.23 \pm 0.03. \tag{8}
\]

The measured values of the fake TPA are in agreement with the SM prediction in the heavy quark limit. The true T.P are
\[
A_{T,P,2}^{\text{true}} = \frac{1}{2} (A_{T,B}^{(2)} + \overline{A}_{T,B}^{(2)}) = -0.004 \pm 0.025,
\]

3
\begin{align*}
A^\text{true}_{T,P,1} &= \frac{1}{2} (A^{(1)}_{T,B} + \overline{A}^{(1)}_{T,P}) = 0.013 \pm 0.053. \tag{9}
\end{align*}

These are consistent with SM or with NP with the same weak phase as the SM amplitude.

If one assumes NP is responsible for the large transverse polarization \( f_T \) observed in penguin/penguin dominated decays like \( B \rightarrow \phi K^* \) then the NP operators must have the structures \[ S_{LL} = (1 - \gamma_5) \otimes (1 - \gamma_5) \text{ or } T_{LL} = \sigma^{\mu\nu} (1 - \gamma_5) \otimes \sigma_{\mu\nu}(1 - \gamma_5), \]
\[ S_{RR} = (1 + \gamma_5) \otimes (1 + \gamma_5) \text{ or } T_{RR} = \sigma^{\mu\nu} (1 + \gamma_5) \otimes \sigma_{\mu\nu}(1 + \gamma_5). \tag{10} \]

With the assumption \( f_{SM}^T = 0 \) one can draw the following conclusions. In the heavy-quark limit, \( A_{\perp} = 0 \) for the \( LL \) operators, so that \( A_{\parallel} = -A_{\perp} \) (as in the SM) and \( A^{(2)}_{T} = 0 \) which in turn implies the corresponding TPA vanish. Similarly, for the \( RR \) operators \( A_{\perp} = 0 \), so that \( A_{\parallel} = A_{\perp}, A^{(2)}_{T} = 0 \) and the corresponding TPA vanish. However both \( LL \) and \( RR \) operators cannot be present. If the SM produces a large \( f_T \) from penguin annihilation and/or re scattering (which is left handed) then the \( RR \) operator cannot be present. Thus, the measurement of \( A^{(2)}_{T} \simeq 0 \) rules out \( RR \) operators, or at least strongly constrains them.

### 4 Time Dependent Angular Distribution

We consider decays like \( B_s \rightarrow \phi \phi (\bar{b} \rightarrow s s \bar{s} s), K^* K^* (\bar{b} \rightarrow s d d) \). Here the final state can be reached by both \( B_s \) and \( \overline{B}_s \) decays so mixing effects have to be included \[9\]. Assuming that \( V_{1,2} \) both decay into pseudoscalars (i.e. \( V_1 \rightarrow P_1 P_1', V_2 \rightarrow P_2 P_2' \)), the angular distribution of the decay is given in terms of the vector \( \vec{\omega} = (\cos \theta_1, \cos \theta_2, \Phi) \)
\[ \frac{d^3 \Gamma(t)}{d\vec{\omega}} = \frac{9}{32\pi} \sum_{i=1}^{6} K_i(t) f_i(\vec{\omega}) . \tag{11} \]

Here, \( \theta_1(\theta_2) \) is the angle between the directions of motion of \( P_1(P_2) \) in the \( V_1(V_2) \) rest frame and \( V_1(V_2) \) in the \( B \) rest frame, and \( \Phi \) is the angle between the normals to the planes defined by \( P_1 P_1' \) and \( P_2 P_2' \) in the \( B \) rest frame. The functions \( K_i(t) \) are expressed in terms of the \( B_s \) oscillation parameters, \( \phi_s, \Gamma_s, \Delta \Gamma_s, \Delta m_s \) and the transversity amplitudes \( A_{i=0,\parallel,\perp} \) \[9\]. The time-integrated untagged angular distribution can be obtained by integrating the \( K_i(t) + \overline{K}_i(t) \) observables over time:
\[ \frac{d^3 \langle \Gamma(B_s^0 \rightarrow f) \rangle}{d\vec{\omega}} = \frac{9}{32\pi} \sum_{i=1}^{6} \langle K_i \rangle f_i(\vec{\omega}) , \tag{12} \]

where
\[ \langle \Gamma(B_s^0 \rightarrow f) \rangle = \frac{1}{2} \int_0^\infty dt (\Gamma^{B_s} + \Gamma^{\overline{B}_s} ), \quad \langle K_i \rangle = \frac{1}{2} \int_0^\infty dt (K_i(t) + \overline{K}_i(t)) . \tag{13} \]
The general structure is

\[ \langle K_i \rangle \propto A^{ch}_i + A^{sh}_i y_s \]

where \( y_s = \frac{\Delta \Gamma_s}{2 \Gamma_s} \). The \( A^{ch}_i \) can be used to extract the polarization fractions and triple products. The details can be found in Ref. [9]. The key point is that the TPA can be measured with untagged time integrated measurements.

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