New Physics and $B \to V_1 V_2$ Decays

David London
Université de Montréal

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A. Datta [hep-ph/0303159] and
N. Sinha and R. Sinha [hep-ph/0304230]

Triple Products

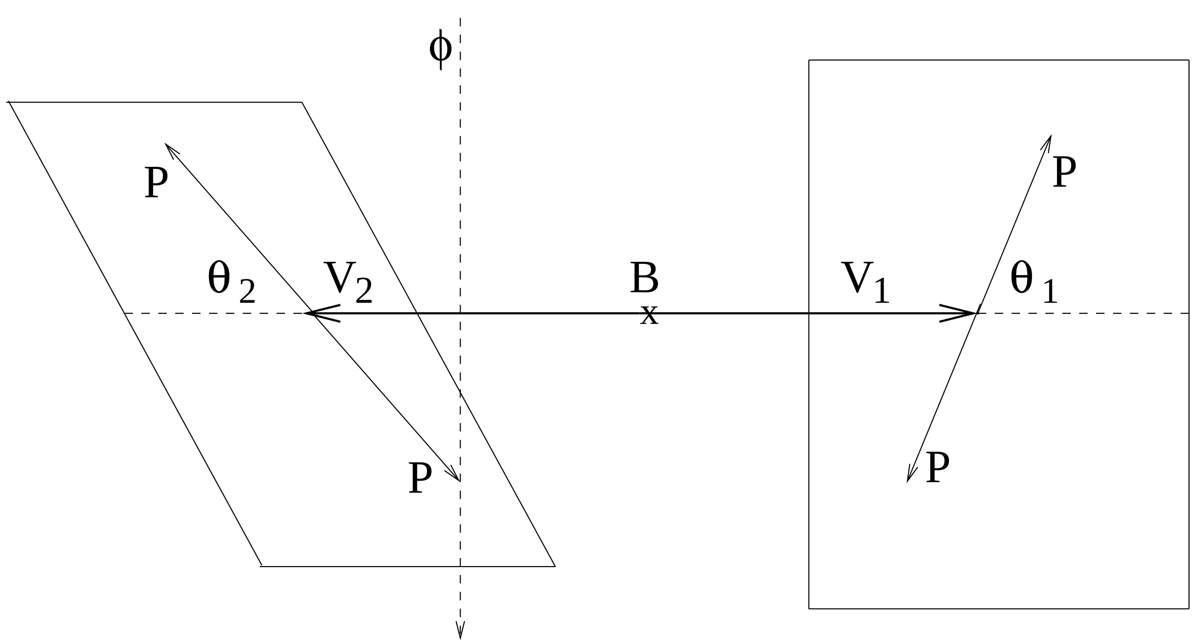
Problem with indirect CP violation in $B \to V_1 V_2$ decays: $V_1 V_2$ not a CP eigenstate.

3 helicity amplitudes: A_0, $A_\parallel$ (CP-even), $A_\perp$ (CP-odd):

$$M = A_0 \varepsilon_1^{*L} \cdot \varepsilon_2^{*L} - \frac{1}{\sqrt{2}} A_\parallel \vec{\varepsilon}_1^{*T} \cdot \vec{\varepsilon}_2^{*T} - \frac{i}{\sqrt{2}} A_\perp \vec{\varepsilon}_1^{*T} \times \vec{\varepsilon}_2^{*T} \cdot \hat{p} \, ,$$

where $\hat{p}$ is final-state momentum, and $\varepsilon_{1,2}$ are polarizations of vector mesons.

Well known: can separate helicity amplitudes using a (time-dependent) angular analysis. Can then measure indirect CP asymmetries in each helicity state.



However: angular analysis contains more information, due to interference of CP-even and CP-odd amplitudes. The time-integrated differential decay rate contains 6 angular terms:

$$\frac{d\Gamma}{d\cos\theta_1 d\cos\theta_2 d\phi} \sim |A_0|^2 \cos^2\theta_1 \cos^2\theta_2 + \frac{|A_\perp|^2}{2} \sin^2\theta_1 \sin^2\theta_2 \sin^2\phi + \frac{|A_\parallel|^2}{2} \sin^2\theta_1 \sin^2\theta_2 \cos^2\phi + \frac{\mathrm{Re}(A_0 A_\parallel^*)}{2\sqrt{2}} \sin 2\theta_1 \sin 2\theta_2 \cos\phi - \frac{\mathrm{Im}(A_\perp A_0^*)}{2\sqrt{2}} \sin 2\theta_1 \sin 2\theta_2 \sin\phi - \frac{\mathrm{Im}(A_\perp A_\parallel^*)}{2} \sin^2\theta_1 \sin^2\theta_2 \sin 2\phi \ .$$

The final two terms involve the *triple product* $\vec{\varepsilon}_1^{*T} \times \vec{\varepsilon}_2^{*T} \cdot \hat{p}$: odd under time reversal (T). (Note: full angular analysis not necessary to measure TP's.)

Well-known: triple product signals are not necessarily CP-violating – can be faked by strong phases. To obtain true CP-violating signal: compare TP in $B \to V_1 V_2$ with that in $\bar{B} \to \bar{V}_1 \bar{V}_2$. The CP-violating TP is found by adding the two T-odd asymmetries:

$$\mathcal{A}_T \equiv \frac{1}{2}(A_T + \bar{A}_T) \ .$$

Thus, neither tagging nor time dependence is necessary to measure TP's – can in principle combine measurements of charged and neutral B decays.

Triple products complementary to direct CP asymmetries:

$$\mathcal{A}_{CP}^{dir} \propto \sin\phi \sin\delta$$
$$\mathcal{A}_T \propto \sin\phi \cos\delta \ .$$

Unlike $\mathcal{A}_{CP}^{dir}$, triple product doesn't vanish if $\delta = 0$.

Triple products in SM

All CP-violating effects require the interference of two amplitudes, with different weak phases. Decays in the SM dominated by $b \to c\bar{c}s$ or $b \to s\bar{s}s$ do not satisfy this. E.g. no TP's expected in $B \to J/\psi K^*$, $B \to \phi K^*$, $B \to D_s^* D^*$, etc.

Other $B \to V_1 V_2$ decays: within factorization, amplitude is:

$$\sum_{\mathcal{O},\mathcal{O}'} \left\{ \langle V_1 | \, \mathcal{O} \, | 0 \rangle \, \langle V_2 | \, \mathcal{O}' \, | B \rangle + \langle V_2 | \, \mathcal{O} \, | 0 \rangle \, \langle V_1 | \, \mathcal{O}' \, | B \rangle \right\} \ .$$

TP's are a *kinematical* CP-violating effect $\Longrightarrow$ both amplitudes must be present, with a relative weak phase.

E.g. $B_d^0 \to D^{*+} D^{*-}$. There is a tree $(V_{cb}^* V_{cd})$ and a penguin $(V_{tb}^* V_{td})$ contribution. Two amplitudes, a relative weak phase $\Longrightarrow$ there is a triple product, right?

No: both amplitudes contribute to $\langle D^{*+} | \, \mathcal{O} \, | 0 \rangle \, \langle D^{*-} | \, \mathcal{O}' \, | B \rangle$; there is no $\langle D^{*-} | \, \mathcal{O} \, | 0 \rangle \, \langle D^{*+} | \, \mathcal{O}' \, | B \rangle$. (I.e. in the SM one has only $\bar{b} \to \bar{c}$; $\bar{b} \not\to c$.) Thus, there is no TP.

Which $B \to V_1 V_2$ decays are expected to yield large triple products in the SM? Answer: None!

1. If $V_1 = V_2$, no TP. Therefore, if V_1 and V_2 related by symmetry, TP is suppressed by size of symmetry breaking.
2. Longitudinal amplitude (A_0) much larger than transverse amplitudes $(A_{\|,\perp})$. Therefore, TP's suppressed by at least one power of m_V/m_B.
3. Interfering amplitudes typically different in size, leading to further suppression of TP's.

Upshot: we find all TP's involving light vector mesons are either expected to vanish or be very small in SM $\Longrightarrow$ excellent place to search for new physics! (Nonfactorizable effects do not change this conclusion.) If large TP found, indicates new physics with large couplings to the right-handed b-quark.

Example: $A_{CP}(J/\psi K_S) \neq A_{CP}(\phi K_S)$. One explanation: contributions to $B \to \phi K_S$ from SUSY with R-parity violation. If so, will also contribute to $B \to \phi K^* \Longrightarrow$ TP's. In SM, TP's vanish; in this model of new physics, can get very large TP asymmetries: 15–20%!

Time-dependent Angular Analysis

Consider B decays which in the SM are dominated by one decay amplitude (e.g. $B \to J/\psi K$, ϕK, etc.). Suppose there is a contributing new-physics amplitude, with a new weak phase. How to see it?

Direct CP violation + triple-product correlation. But can get much more information if a time-dependent angular analysis of the corresponding $B^0(t) \to V_1 V_2$ decay can be performed.

Write:

$$\begin{aligned} A_\lambda \equiv Amp(B \to V_1 V_2)_\lambda &= a_\lambda e^{i\delta_\lambda^a} + b_\lambda e^{i\phi} e^{i\delta_\lambda^b} , \\ \bar{A}_\lambda \equiv Amp(\bar{B} \to \overline{V}_1 \overline{V}_2)_\lambda &= a_\lambda e^{i\delta_\lambda^a} + b_\lambda e^{-i\phi} e^{i\delta_\lambda^b} , \end{aligned}$$

where $\lambda = \{0, \|, \perp\}$. The a_λ's and b_λ's are the SM and NP amplitudes, respectively.

The time-dependent decay rate is given by

$$\Gamma(\overset{(-)}{B}(t) \to V_1 V_2) \sim \sum_{\lambda \le \sigma} \Big(\Lambda_{\lambda\sigma} \pm \Sigma_{\lambda\sigma} \cos(\Delta M t) \mp \rho_{\lambda\sigma} \sin(\Delta M t) \Big) g_\lambda g_\sigma .$$

The g_λ are functions of the kinematic angles θ_1, θ_2, ϕ.

There are 18 observables, all functions of the A_λ and $\bar{A}_\lambda$. E.g.

$$\begin{aligned}\Lambda_{\lambda\lambda} &= \frac{1}{2}(|A_\lambda|^2 + |\bar{A}_\lambda|^2)\\ \Sigma_{\lambda\lambda} &= \frac{1}{2}(|A_\lambda|^2 - |\bar{A}_\lambda|^2)\\ \Lambda_{\perp i} &= -\mathrm{Im}\left(A_\perp A_i^* - \bar{A}_\perp \bar{A}_i^*\right)\\ \rho_{ii} &= -\mathrm{Im}\left(\frac{q}{p} A_i^* \bar{A}_i\right)\end{aligned}$$

If there is no new physics (i.e. $b_\lambda = 0$), there are 6 theoretical parameters: 3 a_λ's, 2 strong phase differences, and the phase of B^0–$\bar{B}^0$ mixing (q/p) $\Longrightarrow$ 12 relations among the observables:

$$\Sigma_{\lambda\lambda} = \Lambda_{\perp i} = \Sigma_{\|0} = 0$$

$$\frac{\rho_{ii}}{\Lambda_{ii}} = -\frac{\rho_{\perp\perp}}{\Lambda_{\perp\perp}} = \frac{\rho_{\|0}}{\Lambda_{\|0}}$$

$$\Lambda_{\|0} = \frac{1}{2\Lambda_{\perp\perp}}\left[\frac{\Lambda_{\lambda\lambda}^2 \rho_{\perp 0}\rho_{\perp\|} + \Sigma_{\perp 0}\Sigma_{\perp\|}(\Lambda_{\lambda\lambda}^2 - \rho_{\lambda\lambda}^2)}{\Lambda_{\lambda\lambda}^2 - \rho_{\lambda\lambda}^2}\right]$$

$$\frac{\rho_{\perp i}^2}{4\Lambda_{\perp\perp}\Lambda_{ii} - \Sigma_{\perp i}^2} = \frac{\Lambda_{\perp\perp}^2 - \rho_{\perp\perp}^2}{\Lambda_{\perp\perp}^2}\ .$$

The violation of any of these relations will be a smoking-gun signal of NP.

Constraints on New Physics

But there's more! Suppose that a signal for new physics is found. This implies $b_\lambda \neq 0$. Now there are 13 theoretical parameters: 3 a_λ's, 3 b_λ's, 5 strong phase differences, and two weak phases (ϕ and q/p).

However, at best one can measure the magnitudes and relative phases of the 6 decay amplitudes A_λ and $\bar{A}_\lambda \Longrightarrow$ only 11 independent observables.

11 measurements, 13 unknowns $\Longrightarrow$ even if there is a signal of NP, can't get any info, right? Not exactly: because equations are nonlinear, can constrain NP parameters.

E.g. if $\Sigma_{\lambda\lambda} \neq 0$,

$$b_\lambda^2 \geq \frac{1}{2}\Lambda_{\lambda\lambda}\left[1 - \sqrt{1 - \Sigma_{\lambda\lambda}^2/\Lambda_{\lambda\lambda}^2}\right].$$

If $\Sigma_{\lambda\lambda} = 0$, but $\Lambda_{\perp i} \neq 0$,

$$2(b_i^2 \mp b_\perp^2) \geq \Lambda_{ii} \mp \Lambda_{\perp\perp} - \sqrt{(\Lambda_{ii} \mp \Lambda_{\perp\perp})^2 \pm \Lambda_{\perp i}^2}\,.$$

Also

$$\Lambda_{ii}\cos\eta_i+\Lambda_{\perp\perp}\cos(\eta_\perp-2\eta_i) \leq \sqrt{(\Lambda_{ii}+\Lambda_{\perp\perp})^2-\Lambda_{\perp i}^2}\,,$$

$$\Lambda_{ii}\cos\eta_i-\Lambda_{\perp\perp}\cos\eta_\perp \leq \sqrt{(\Lambda_{ii}-\Lambda_{\perp\perp})^2+\Lambda_{\perp i}^2}\,,$$

where $\eta_\lambda \equiv 2\left(\frac{q}{p}{}_\lambda^{meas} - \frac{q}{p}^{mix}\right)$. If $\Lambda_{\perp i} \neq 0$, one cannot have $\eta_i = \eta_\perp = 0 \Longrightarrow$ obtain a lower bound on the difference between the measured value and the true value of the phase of B^0–$\bar{B}^0$ mixing.

In progress: full numerical analysis for the case where $\Sigma_{\lambda\lambda} \neq 0$.

Conclusion

$B \to V_1 V_2$ decays contain an enormous amount of information, especially if an angular analysis can be performed. One class of measurements which is very useful is triple-product correlations: $\vec{\varepsilon}_1^{\,*T} \times \vec{\varepsilon}_2^{\,*T} \cdot \hat{p}$. (Note: the full angular analysis is not necessary to obtain TP's.)

TP's are T-odd; a true CP-violating signal can be obtained by adding the TP's found in $B \to V_1 V_2$ and $\bar{B} \to \bar{V}_1 \bar{V}_2$. Neither tagging nor time dependence is necessary to measure TP's – can in principle combine measurements of charged and neutral B decays. TP's are complementary to direct CP asymmetries – they don't vanish if strong phases are zero.

In SM, all TP's involving light vector mesons are either expected to vanish or be very small $\Longrightarrow$ excellent place to search for physics beyond the SM! TP's which vanish in the SM can be huge (15–20%) in the presence of new physics.

If a full time-dependent angular analysis can be performed, there are many more signals of new physics. Should a signal for new physics be found, one can place a lower limit on the size of the new-physics parameters, as well as on their effect on the measurement of the phase of B^0–$\bar{B}^0$ mixing.