CP Violation in $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$

David London
Physique des Particules, Université de Montréal,
C.P. 6128, succ. centre-ville, Montréal, QC, Canada H3C 3J7

At present, there are discrepancies with the predictions of the standard model in $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ decays, hinting at the presence of new physics (NP) in $b \to c\tau^-\bar{\nu}$. Various NP models have been proposed to explain the data. In this talk, I discuss how the measurement of CP-violating observables in $\bar{B}^0 \to D^{*+}\ell^-\bar{\nu}_\ell$ can be used to differentiate the NP scenarios.

This talk is based on work done in collaboration with B. Bhattacharya, A. Datta and S. Kamali [1].

At the present time, there are discrepancies with the predictions of the standard model (SM) in the measurements of $R_{D^{(*)}} \equiv \mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)/\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)$ ($\ell = e, \mu$) and $R_{J/\psi} \equiv \mathcal{B}(B_c^+ \to J/\psi\tau^+\nu_\tau)/\mathcal{B}(B_c^+ \to J/\psi\mu^+\nu_\mu)$. The experimental results from before Moriond, 2019 are shown in Table I. The deviation from the SM in R_D and R_{D^*} (combined) was $\sim 3.8\sigma$ [6, 8–10], while in $R_{J/\psi}$ it is 1.7σ [11].

TABLE I: Measured values of $b \to c\tau^-\bar{\nu}$ observables from before Moriond, 2019.

Observable	Measurement/Constraint
$R_{D^*}^{\tau/\ell}/(R_{D^*}^{\tau/\ell})_{\rm SM}$	1.18 ± 0.06 [2–5]
$R_{D}^{\tau/\ell}/(R_{D}^{\tau/\ell})_{\rm SM}$	1.36 ± 0.15 [2–5]
$R_{D^*}^{\mu/e}/(R_{D^*}^{\mu/e})_{\rm SM}$	1.00 ± 0.05 [6]
$R_{J/\psi}^{\tau/\mu}/(R_{J/\psi}^{\tau/\mu})_{\rm SM}$	2.51 ± 0.97 [7]

At Moriond, 2019, Belle announced new results [12]:

$$R_{D^*}^{\tau/\ell}/(R_{D^*}^{\tau/\ell})_{\rm SM} = 1.10 \pm 0.09 ,$$
$$R_{D}^{\tau/\ell}/(R_{D}^{\tau/\ell})_{\rm SM} = 1.03 \pm 0.13 . \quad (1)$$

These are in better agreement with the SM, so that the deviation from the SM in R_D and R_{D^*} (combined) has been reduced from $\sim 3.8\sigma$ to 3.1σ.

Even so, taken together, these measurements still hint at the presence of new physics (NP) in $b \to c\tau^-\bar{\nu}$ decays.

$b \to c\tau^-\bar{\nu}$ is a charged-current process. The NP explanations that have been examined include a $W'^{\pm}$, an $H^{\pm}$, or several different types of leptoquarks (LQs). It was shown in Ref. [13] that considerations of the rate for $B_c^- \to \tau^-\bar{\nu}$ disfavour NP models involving an $H^{\pm}$. Still, this leaves a variety of different NP explanations. Assuming that NP is indeed present in $b \to c\tau^-\bar{\nu}$, how can we distinguish among these possibilities? One idea is to use measurements of CP violation (CPV) in $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ [1].

The best-known CPV signal is direct CPV, in which the direct CP asymmetry A_{dir} is proportional to $\Gamma(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau) - \Gamma(B^0 \to D^{*-}\tau^+\nu_\tau)$. Now, CPV can only arise due to the interference of (at least) two amplitudes with a relative weak (CP-odd) phase. But $A_{dir} \neq 0$ only if the interfering amplitudes also have different strong (CP-even) phases. In $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$, the only hadronic transition is $\bar{B} \to D^*$. This means that the strong phases of all amplitudes, both SM and NP, are approximately equal, which then implies that, even if A_{dir} is nonzero, it is expected to be small.

Instead, as we will see, the main CPV effects are CPV asymmetries in the angular distribution of $\bar{B}^0 \to D^{*+}(\to D^0\pi^+)\tau^-\bar{\nu}_\tau$. Such asymmetries are a generalization of triple-product asymmetries [14–16], and are kinematical effects. That is, they can be nonzero only if the interfering amplitudes have different Lorentz structures. This allows us to distinguish different NP explanations.

Unfortunately, there is a practical problem. The $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ angular distribution requires the knowledge of the three-momentum $\vec{p}_\tau$. However, this cannot be measured, due to the missing final ν_τ in the decay of the τ^-. A full analysis will need to include information from the decay products of the τ. My collaborators and I are looking at this (it is work in progress), but as a first step we examined the NP contributions to CPV angular asymmetries in $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ [1]. Since $\vec{p}_\mu$ is measurable, this angular distribution can be reconstructed. There are two reasons for starting with this process. First, LHCb has announced [17] that it will perform a detailed angular analysis of this decay, with the aim of extracting the coefficients of the CPV angular asymmetries. It is therefore important to show exactly what the implications of these measurements are for NP. Second, NP that contributes to $b \to c\tau^-\bar{\nu}$ may well also contribute to $b \to c\mu^-\bar{\nu}$, leading to deviations from the SM in $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$.

Below, I sketch out the derivation of the angular distribution. For all the details, the reader should consult Ref. [1].

We begin by examining $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ within the SM. The decay is interpreted as $\bar{B}^0 \to D^{*+}(\to D^0\pi^+)W^{*-}(\to \mu^-\bar{\nu}_\mu)$, and the amplitude is written as

$$\mathcal{M}_{(m;n)}(B \to D^*W^*) = \epsilon^{*\mu}_{D^*}(m)\, M_{\mu\nu}\, \epsilon^{*\nu}_{W^*}(n) . \quad (2)$$

Here, the (real) D^{*+} has 3 polarizations, $m = +, -, 0$, while the (virtual) W^{*-} has 4 polarizations, $n = +, -, 0, t$ (t = timelike).

Of the twelve D^{*+}-W^{*-} polarization combinations, only four are allowed by conservation of angular momentum: $++$, $--$, 00, $0t$. This implies that the decay is governed by four helicity amplitudes: $\mathcal{A}_+$, $\mathcal{A}_-$, $\mathcal{A}_0$, $\mathcal{A}_t$. The decay amplitude can then be written as

$$\mathcal{M}(B \to D^*(\to D\pi) W^*(\to \mu^- \bar{\nu}_\mu)) \propto \sum_{m=t,\pm,0} g_{mm}\, \mathcal{H}_{D^*}(m)\, \mathcal{A}_m\, \mathcal{L}_{W^*}(m) \ , \quad (3)$$

where $\mathcal{H}_{D^*}$ and $\mathcal{L}_{W^*}$ are, respectively, the hadronic and leptonic matrix elements.

We now add NP. There are two effects. First, we take $W^* \to N^*$, where $N = S - P$ ($\equiv SP$), $V - A$ ($\equiv VA$), and T represent new interactions involving the left-handed neutrino. (Note that VA includes the SM.) In the presence of these new interactions, there are now more helicities. Previously, we had only VA, leading to the helicity amplitudes $\mathcal{A}_+$, $\mathcal{A}_-$, $\mathcal{A}_0$, and $\mathcal{A}_t$. Now, there are four more helicity amplitudes. The SP interaction leads to $\mathcal{A}_{SP}$, while the T interaction generates $\mathcal{A}_{+,T}$, $\mathcal{A}_{0,T}$, and $\mathcal{A}_{-,T}$.

Second, there are new contributions to the hadronic current:

$$\begin{aligned}\mathcal{H}_{eff} \ = \ & \frac{G_F V_{cb}}{\sqrt{2}} \Big\{ [g_S\, \bar{c}b + g_P\, \bar{c}\gamma_5 b]\, \bar{\ell}(1-\gamma_5)\nu_\ell \\ & + \ [(1+g_L)\, \bar{c}\gamma_\mu(1-\gamma_5)b + g_R\, \bar{c}\gamma_\mu(1+\gamma_5)b] \\ & \quad \times \ \bar{\ell}\gamma^\mu(1-\gamma_5)\nu_\ell \\ & + \ g_T\, \bar{c}\sigma^{\mu\nu}(1-\gamma_5)b \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell + h.c. \Big\} \ . \quad (4)\end{aligned}$$

Including both SM and NP contributions, we now write

$$\begin{aligned}& \mathcal{M}(B \to D^*(\to D\pi) N^*(\to \mu^- \bar{\nu}_\mu)) \\ & \qquad = \mathcal{M}^{SP} + \mathcal{M}^{VA} + \mathcal{M}^{T} \ , \qquad (5)\end{aligned}$$

where each term includes a sum over the relevant D^* and N^* helicities. The point is that, in the presence of NP, the amplitude now contains a variety of Lorentz structures. (In the SM, we had only $\mathcal{M}^{VA}$ [Eq. (3)].)

We now compute $|\mathcal{M}|^2$. This generates two types of terms: (i) $|\mathcal{A}_i|^2 f_i$(momenta) and (ii) the interference terms $\mathrm{Re}[\mathcal{A}_i \mathcal{A}_j^* f_{ij}$(momenta)]. The momenta are defined in Fig. 1. The computation of the quantities f_i and f_{ij} yields the angular distribution.

Here is the key point: in the interference terms, sometimes there is an additional factor of i in f_{ij}(momenta) (e.g., from $\mathrm{Tr}[\gamma_\mu\gamma_\nu\gamma_\rho\gamma_\sigma\gamma_5] = 4i\epsilon_{\mu\nu\rho\sigma}$). In this case, the coefficient is $\mathrm{Im}[\mathcal{A}_i\mathcal{A}_j^*]$, which is sensitive to phase differences.

Furthermore, in this decay, the SM and NP strong phases are all approximately equal. This implies that $\mathrm{Im}[\mathcal{A}_i\mathcal{A}_j^*]$ involves only the weak-phase difference. Such terms are therefore, by themselves, signals of CP violation!

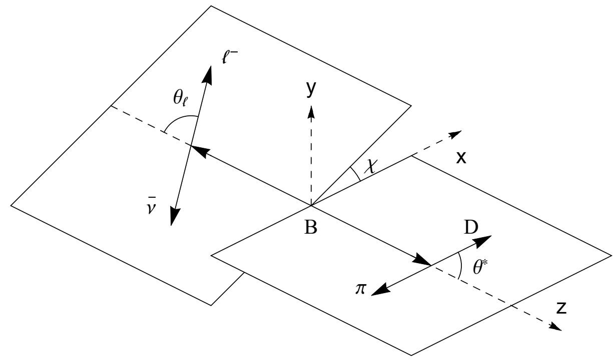

FIG. 1: Definition of the angles in the $\bar{B} \to D^*(\to D\pi)\ell^-\bar{\nu}_\ell$ distribution.

The complete angular distribution contains many CPV observables: some are suppressed by m_μ^2/q^2 or $m_\mu/\sqrt{q^2}$, and some are unsuppressed. q^2 is typically of $O(m_b^2)$, so that the suppression is significant. (On the other hand, if measurements can be made in that region of phase space where $q^2 = O(m_\mu^2)$, here the suppression is removed.) The unsuppressed observables are given in Table II.

TABLE II: Unsuppressed CPV observables.

Coefficient	Angular Function
$\mathrm{Im}(\mathcal{A}_\perp \mathcal{A}_0^*)$	$-\sqrt{2}\sin 2\theta_\ell \sin 2\theta^* \sin\chi$
$\mathrm{Im}(\mathcal{A}_\parallel \mathcal{A}_\perp^*)$	$2\sin^2\theta_\ell \sin^2\theta^* \sin 2\chi$
$\mathrm{Im}(\mathcal{A}_0 \mathcal{A}_\parallel^*)$	$-2\sqrt{2}\sin\theta_\ell \sin 2\theta^* \sin\chi$
$\mathrm{Im}(\mathcal{A}_{SP} \mathcal{A}_{\perp,T}^*)$	$-8\sqrt{2}\sin\theta_\ell \sin 2\theta^* \sin\chi$

Which NP couplings are involved in these observables? $\mathrm{Im}(\mathcal{A}_\perp\mathcal{A}_0^*)$, $\mathrm{Im}(\mathcal{A}_\parallel\mathcal{A}_\perp^*)$ and $\mathrm{Im}(\mathcal{A}_0\mathcal{A}_\parallel^*)$ are all generated by $\mathrm{Im}[(1+g_L+g_R)(1+g_L-g_R)^*]$, while $\mathrm{Im}(\mathcal{A}_{SP}\mathcal{A}_{\perp,T}^*)$ is related to $\mathrm{Im}(g_P g_T^*)$.

If the $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ angular distribution is measured, here is the NP information that it yields:

- Most proposed NP models contribute only to g_L (like the SM). If any CPV observables are found to be nonzero, these simple models are ruled out.
- Suppose that the angular distribution contains, for example, a CPV $\sin 2\theta_\ell \sin 2\theta^* \sin\chi$ term. This implies that $g_R \neq 0$. In this case, one also expects to see nonzero $\sin^2\theta_\ell \sin^2\theta^* \sin 2\chi$ and $\sqrt{2}\sin\theta_\ell \sin 2\theta^* \sin\chi$ terms.
- On the other hand, if the $\sin 2\theta_\ell \sin 2\theta^* \sin\chi$ term were found to vanish, this would imply that $g_R = 0$ (or that its phase is the same as that of $(1+g_L)$). In this case, the measurement of a nonzero $\sqrt{2}\sin\theta_\ell \sin 2\theta^* \sin\chi$ term would imply that $\mathrm{Im}(g_P g_T^*) \neq 0$.

- In all cases, additional information comes from the measurement of the CP-conserving pieces of the angular distribution. For example, both $|\mathcal{A}_{SP}|^2$ and $|\mathcal{A}_{\perp,T}|^2$ can be determined from the angular distribution, so in principle we will know if they are nonzero (though we will have no information about their phases).

- If measurements can be made in that region of phase space where $q^2 = O(m_\mu^2)$, removing the suppression factors m_μ^2/q^2 or $m_\mu/\sqrt{q^2}$ from some CPV observables, additional information can be obtained.

Another question is: what NP models can generate the new hadronic couplings g_R, g_P, g_T?

1. The R_2 and S_1 LQ models generate g_T, while the U_1, R_2, S_1 and V_2 LQ models generate g_P. Thus, if $\text{Im}(g_P g_T^*) \neq 0$ is found, this points to a model containing two (different) LQs.

2. LQ models do not produce g_R. This coupling can arise, for example, in a model that includes both a W'_L and a W'_R that mix.

Finally, I report on some work in progress. Earlier, it was argued that a full analysis of the angular distribution of $\bar{B}^0 \to D^{*+}(\to D^0\pi^+)\tau^-\bar{\nu}_\tau$ must include information from the decay products of the τ^-. My collaborators and I have looked at this, focusing on the decays $\tau^- \to \pi^-\nu_\tau$ and $\tau^- \to \rho^-\nu_\tau$, with $\rho^- \to \pi^-\pi^0$ and $\pi^-\pi^+\pi^-$. When one takes into account the momenta of the decay products of the τ^-, there are now new angular observables, so that we expect that the angular distributions using these τ^- decays will furnish complementary information to that obtained from $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$. Our preliminary results confirm this. For example, in $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$, CPV terms proportional to $\text{Im}(g_P(1+g_L)^*)$ are suppressed by $m_\mu/\sqrt{q^2}$. But in $\bar{B}^0 \to D^{*+}\tau^-(\to \pi^-\nu_\tau)\bar{\nu}_\tau$, they are unsuppressed.

To summarize, the anomalies in $R_{D^{(*)}}$ and $R_{J/\psi}$ hint at NP in $b \to c\tau^-\bar{\nu}$. A variety of NP models have been proposed to explain the data. It has been suggested that these models can be distinguished through the measurement of CP violation in $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ [1]. In this talk, I have described the first step, namely looking at the NP contributions to CPV angular asymmetries in $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$, which will be measured by LHCb.

Our results can be summarized as follows:

1. Model-independent analysis: We allow for NP with new Lorentz structures. The interference of two contributions with different Lorentz structures leads to CP-violating angular asymmetries. We identify the CPV asymmetries in $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$, and show how they depend on the NP parameters.
2. Model-dependent analysis: There are two classes of models that have been proposed to explain the data, involving a W' or a LQ. In the simplest (most popular) models, the NP couples only to LH particles. If CPV is observed, these models are ruled out. We show how the other models can be distinguished, depending on which CPV asymmetries are found to be nonzero.

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