$\bar{B} \to D^* \ell^- \bar{\nu}_\ell$ Decays: Angular Distributions and New Physics

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Talk based on work done in collaboration with B. Bhattacharya, A. Datta and S. Kamali, (1903.02567 and 2005.03032), and with C. Burgess, S. Hamoudou and J. Kumar (2111.07421).

$b \to c\tau^-\bar{\nu}_\tau$ Anomalies

Measured $b \to c\tau^-\bar{\nu}_\tau$ observables:

$$R_{D^{(*)}} \equiv \frac{\mathcal{B}(\bar{B} \to D^{(*)}\tau^-\bar{\nu}_\tau)}{\mathcal{B}(\bar{B} \to D^{(*)}\ell^-\bar{\nu}_\ell)} \ , \ \ell = e, \mu \ , \quad R_{J/\psi} \equiv \frac{\mathcal{B}(B_c \to J/\psi\tau\nu_\tau)}{\mathcal{B}(B_c \to J/\psi\mu\nu_\mu)} \ ,$$

$$P_\tau(D^*) \equiv \frac{\Gamma(B \to D^*\tau^{\lambda=+1/2}\nu_\tau) - \Gamma(B \to D^*\tau^{\lambda=-1/2}\nu_\tau)}{\Gamma(B \to D^*\tau\nu_\tau)} \ ,$$

$$F_L(D^*) \equiv \frac{\Gamma(B \to D_L^*\tau\nu_\tau)}{\Gamma(B \to D^*\tau\nu_\tau)} \ .$$

Measurements of R_D and R_{D^*} (combined): deviation of 3.1σ from SM; measurement of $R_{J/\psi}$: deviation of 2.6σ. Fit to all the data within the SM: p-value is $\sim 0.1\% \Longrightarrow$ discrepancy of 3.3σ.

$\Longrightarrow$ hints of τ-μ and τ-e universality violation in $b \to c\ell^-\bar{\nu}$, suggests NP in $b \to c\tau^-\bar{\nu}_\tau$ decays.

New-Physics Explanations

Model approach: $\exists$ three types of NP explanations: (1) a new W' boson, (2) a leptoquark, (3) a charged Higgs boson.

EFT approach: assuming a LH ν, the most general effective Hamiltonian for $b \to c\tau^-\bar{\nu}_\tau$ is

$$
\begin{aligned}
H_{\text{eff}} \;=\; & \frac{4G_F}{\sqrt{2}} V_{cb} \left\{ \left[(1 + C_V^L)(\bar{c}\gamma^\mu P_L b) + C_V^R(\bar{c}\gamma^\mu P_R b) \right] (\bar{\tau}\gamma_\mu P_L \nu_\tau) \right. \\
& \left. + \left[C_S^R(\bar{c}P_R b) + C_S^L(\bar{c}P_L b) \right] (\bar{\tau}P_L\nu_\tau) + C_T(\bar{c}\sigma^{\mu\nu}P_L b)(\bar{\tau}\sigma_{\mu\nu}P_L\nu_\tau) \right\} + h.c.
\end{aligned}
$$

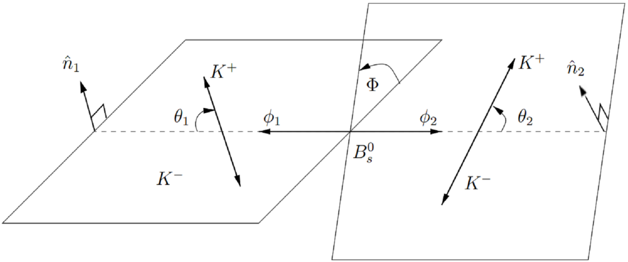
$C_{V,S,T}^{L,R}$ are generated only through NP.

How to distinguish these NP contributions? Suggestion: use angular distributions (sensitive to different Lorentz structures).

Angular Distributions

Quick reminder: $B \to V_1(\to P_1 P_1')V_2(\to P_2 P_2')$. Examples: $B_d \to \phi K^*$ (Belle) and $B_s^0 \to \phi\phi$ (LHCb). $\exists$ 3 helicity amplitudes: A_0, $A_\parallel$, $A_\perp$.

$B_s^0 \to \phi\phi$:



Differential decay rate is function of 3 angles, θ_1, θ_2, Φ. Note: Φ is angle between $V_1 \to P_1 P_1'$ and $V_2 \to P_2 P_2'$ decay planes.

Triple Products

$B \to V_1(\to P_1 P_1') V_2(\to P_2 P_2')$ decays are purely hadronic. Angular distribution used mainly to search for CP-violating (CPV) effects – smoking-gun signal of NP.

Suppose $A_\perp = |A_\perp| e^{i\phi_\perp} e^{i\delta_\perp}$ and $A_i = |A_i| e^{i\phi_i} e^{i\delta_i}$ $(i = 0, \|)$. Then $|A|^2$ may contain the term $\epsilon_{\mu\nu\rho\sigma} p_1^\mu p_2^\nu p_3^\rho p_4^\sigma$. This is a triple product (TP), with coefficient

$$\mathrm{Im}(A_\perp A_i^*) = |A_\perp||A_i|(\underbrace{\sin(\phi_\perp - \phi_i)\cos(\delta_\perp - \delta_i)}_{\text{true TP}} + \underbrace{\cos(\phi_\perp - \phi_i)\sin(\delta_\perp - \delta_i)}_{\text{fake TP}})$$

TPs are coefficients of P-odd terms in angular distribution $\Longrightarrow$ TP(anti-process) $=$ TP(process) $\Longrightarrow$ true (CPV) TP $=$ TP(process) $+$ TP(anti-process). TPs are sensitive to NP in the decay. TP terms $\propto \sin\Phi$ (Φ is angle between $V_1 \to P_1 P_1'$ and $V_2 \to P_2 P_2'$ decay planes).

$\bar{B} \to D^* \mu^- \bar{\nu}_\mu$

SM: $\bar{B} \to D^*(\to D\pi) W^*(\to \mu^- \bar{\nu}_\mu)$. Differences w.r.t. $B \to V_1(\to P_1 P_1') V_2(\to P_2 P_2')$:

1. Semileptonic decay $\Longrightarrow$ hadronic and leptonic currents factorize,
2. W^* virtual $\Longrightarrow \exists$ 4 helicity amplitudes: A_0, $A_\parallel$, $A_\perp$, A_t (timelike).

Add NP to $b \to c \mu \bar{\nu}_\mu$ (with LH ν_μ) $\Longrightarrow \bar{B} \to D^*(\to D\pi) N^*(\to \mu^- \bar{\nu}_\mu)$:

coupling	quarks	leptons	spin	type
$(1 + C_V^L)$	$\bar{c}\gamma_\mu P_L b$	$\bar{\mu}\gamma^\mu P_L \nu_\mu$	vector	SM + NP
C_V^R	$\bar{c}\gamma_\mu P_R b$	$\bar{\mu}\gamma^\mu P_L \nu_\mu$		NP
C_S^R	$\bar{c} P_R b$	$\bar{\mu} P_L \nu_\mu$	scalar	NP
C_S^L	$\bar{c} P_L b$	$\bar{\mu} P_L \nu_\mu$		NP
C_T	$\bar{c}\sigma^{\mu\nu} P_L b$	$\bar{\mu}\sigma_{\mu\nu} P_L \nu_\mu$	tensor	NP

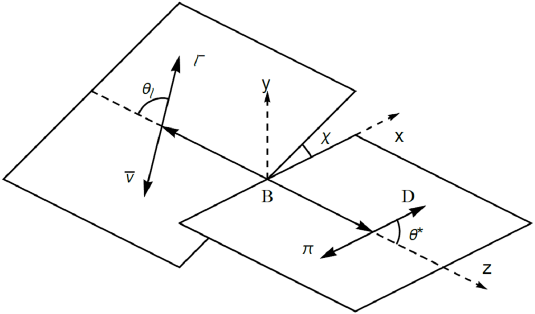
$\Longrightarrow$ add 4 new helicities: A_{SP}, $A_{0,T}$, $A_{\parallel,T}$, $A_{\perp,T}$.

Dependence of helicity amplitudes on NP parameters:

Helicity Amplitude	Coupling
A_0, $A_\parallel$, A_t	$1 + C_V^L - C_V^R$
$A_\perp$	$1 + C_V^L + C_V^R$
A_{SP}	$C_P \equiv \frac{1}{2}(C_S^R - C_S^L)$
$A_{0,T}$, $A_{\parallel,T}$, $A_{\perp,T}$	C_T

C_V^L, C_V^R, C_P and C_T each have a magnitude and a weak (CP-odd) phase. Key point: $\exists$ one hadronic transition in the decay: $\bar{B} \to D^* \Longrightarrow$ expect all helicity amplitudes to have the same strong (CP-even) phase. Thus, this process involves only 7 NP parameters: the four magnitudes of $1 + C_V^L$, C_V^R, C_P and C_T, and their three relative weak phases.

Compute differential decay rate as a function of the 8 helicity amplitudes.



Find:

1. Differential decay rate is function of q^2 and 3 angles, θ^*, θ_ℓ, χ.
2. Angular distribution contains 12 independent angular functions. 9 terms are CP-conserving and are present in the SM. 3 terms are CP-violating (TPs, proportional to $\sin\chi$) and arise only in the presence of NP.

Bottom line: for each q^2 bin, $\exists$ 12 observables (coefficients of the angular functions). All are functions of 7 NP parameters (or 8 unknowns if V_{cb} is included). More observables than unknowns $\Longrightarrow$ in principle, can extract *all* unknown parameters.

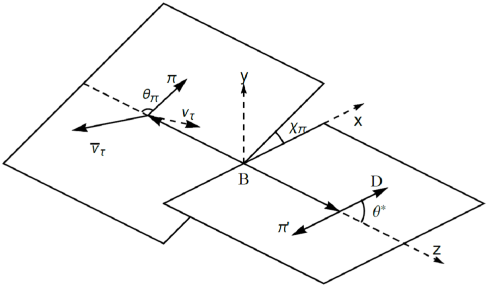
Note: $B \to V_1(\to P_1 P_1') V_2(\to P_2 P_2')$ decays purely hadronic $\Longrightarrow$ angular distribution can only be used to detect the presence of CP-violating NP. $\bar{B} \to D^* \mu^- \bar{\nu}_\mu$ decay is semileptonic, much cleanrer $\Longrightarrow$ angular distribution can also be used to detect the presence of CP-conserving NP.

In 1702.01521, Belle did an angular analysis of $\bar{B} \to D^* \ell^- \bar{\nu}_\ell$ with the purpose of extracting V_{cb}. Fit did not allow for NP contributions (e.g., TP terms not included). Suggestion: redo the analysis, including all NP terms (CP-conserving and CP-violating). Full fit $\Longrightarrow$ measure/constrain 7 $b \to c \mu^- \bar{\nu}_\mu$ NP parameters.

$\bar{B} \to D^* \tau^- \bar{\nu}_\tau$

$\bar{B} \to D^* \mu^- \bar{\nu}_\mu$ angular distribution: requires knowledge of p_μ. Cannot apply to $\bar{B} \to D^* \tau^- \bar{\nu}_\tau$ because p_τ not measurable (missing $\bar{\nu}_\tau$) $\Longrightarrow$ let τ^- decay. We choose $\tau^- \to \pi^- \nu_\tau \Longrightarrow$ process is series of 2-body decays: $\bar{B} \to D^* N^*$, $D^* \to D\pi'$. $N^* \to \tau^- \bar{\nu}_\tau$, $\tau^- \to \pi^- \nu_\tau$.

D^*, τ^- on shell $\Longrightarrow$ final state described by 6 kinematic parameters. Many unmeasurable (related to lack of knowledge of p_τ). Workaround:



Use π^- from τ^- decay: E_π, θ_π, χ_π measurable. q^2, θ^* measurable (as before). Can integrate over remaining unmeasurable angle.

Note: the two new angles, θ_π and χ_π, are formally defined as

$$\begin{aligned}
\cos(\pi - \theta_\pi) &= \frac{\vec{p}_{D^*} \cdot \vec{p}_\pi}{|\vec{p}_{D^*}||\vec{p}_\pi|} ~, \\
\sin\chi_\pi &= \frac{[(\vec{p}_{\pi'} \times \vec{p}_D) \times (\vec{p}_{D^*} \times \vec{p}_\pi)] \cdot \vec{p}_{D^*}}{|\vec{p}_{\pi'} \times \vec{p}_D||\vec{p}_{D^*} \times \vec{p}_\pi||\vec{p}_{D^*}|} ~, \\
\vec{p}_{D^*} &= \vec{p}_D + \vec{p}_{\pi'} ~, \\
\sin\chi_\pi &\propto (\vec{p}_{\pi'} \times \vec{p}_D) \cdot \vec{p}_\pi \qquad (\mathrm{TP}) ~.
\end{aligned}$$

Differential decay rate is function of q^2, E_π and 3 angles, θ^*, θ_π, χ_π.

Find: angular distribution can be written as

$$\sum_{i=1}^{9} f_i^R(q^2, E_\pi)\Omega_i^R(\theta^*, \theta_\pi, \chi_\pi) + \sum_{i=1}^{3} f_i^I(q^2, E_\pi)\Omega_i^I(\theta^*, \theta_\pi, \chi_\pi) \ .$$

The 9 $f_i^R \Omega_i^R$ terms are CP-conserving and are present in the SM. The f_i^R contain $|A_i|^2$ and $\mathrm{Re}[A_i A_j^*]$ pieces. The 3 $f_i^I \Omega_i^I$ terms are CP-violating; the f_i^I contain $\mathrm{Im}[A_i A_j^*]$ pieces. These terms are TPs, proportional to $\sin\chi_\pi$, and are smoking-gun signals of NP.

Point: the 7 $b \to c\tau^-\bar{\nu}_\tau$ NP parameters can be extracted. (Experimentalists will determine which type of analysis to use [q^2/E_π bins, fit to all data, ...].) If discrepancy with SM persists, this will tell us which NP parameters are nonzero. In turn, the knowledge of the Lorentz structure will be very helpful in identifying the NP.

Non-SMEFT NP

But there's more.

NP heavy $\Longrightarrow$ when integrated out, EFT respects $SU(2)_L \times U(1)_Y$. Symmetry can be realized linearly (SMEFT) or nonlinearly (e.g., HEFT). Discovery of Higgs $\Longrightarrow$ SMEFT is default assumption, but HEFT is still possible. Can distinguish through their predictions for the size of certain low-energy dimension-6 four-fermion operators.

In particular, consider $C_V^R(\bar{c}\gamma^\mu P_R b)(\bar{\tau}\gamma_\mu P_L \nu_\tau)$. HEFT predicts $|C_V^R| \sim O(1)/\Lambda_{\rm NP}^2$, like the other NP operators. But SMEFT predicts $|C_V^R| \sim O(1)/\Lambda_{\rm NP}^2 \times v^2/\Lambda_{\rm NP}^2$, much smaller than the other NP operators.

Point: measure NP parameters in angular distribution of $\bar{B} \to D^*(\to D\pi')\tau^-(\to \pi^-\nu_\tau)\bar{\nu}_\tau$. If find $|C_V^R|$ is much larger than the SMEFT prediction $\Longrightarrow$ non-SMEFT (non-decoupling) NP.

Conclusions

Presented measurable angular distributions for $\bar{B} \to D^* \mu^- \bar{\nu}_\mu$ and $\bar{B} \to D^* \tau^- (\to \pi^- \nu_\tau) \bar{\nu}_\tau$, including NP contributions. These are described by 7 NP parameters.

Although unrelated by LFU – the τ decays, the μ doesn't – the distributions have some similarities: both contain 12 independent angular functions. 9 terms are CP-conserving and are present in the SM. 3 terms are CP-violating (TPs) and are smoking-gun signals of NP.

In both cases, if the angular distributions can be measured, the 7 NP parameters can be extracted. In the case of $\bar{B} \to D^* \tau^- (\to \pi^- \nu_\tau) \bar{\nu}_\tau$, this is particularly interesting, as it would give us information about the NP hinted at in the $b \to c \tau^- \bar{\nu}_\tau$ anomalies.

Furthermore, these angular distributions have the ability to reveal the presence of non-SMEFT NP.