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

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Talk based on work done in collaboration with A. Datta, B. Bhattacharya and S. Kamal, (arXiv:1903.02567 [hep-ph]).

Discrepancies with SM

$\exists$ discrepancies with predictions of SM in

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

$$R_{J/\psi} \equiv \mathcal{B}(B_c^+ \to J/\psi \tau^+ \nu_\tau)/\mathcal{B}(B_c^+ \to J/\psi \mu^+ \nu_\mu) \ .$$

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Pre-Moriond:

Observable	Measurement/Constraint	
$R_{D^*}^{\tau/\ell}/(R_{D^*}^{\tau/\ell})_{\rm SM}$	1.18 ± 0.06	(BaBar, Belle, LHCb)
$R_{D}^{\tau/\ell}/(R_{D}^{\tau/\ell})_{\rm SM}$	1.36 ± 0.15	(BaBar, Belle, LHCb)
$R_{D^*}^{\mu/e}/(R_{D^*}^{\mu/e})_{\rm SM}$	1.00 ± 0.05	(Belle)
$R_{J/\psi}^{\tau/\mu}/(R_{J/\psi}^{\tau/\mu})_{\rm SM}$	2.51 ± 0.97	(LHCb)

Deviation from SM is $\sim 3.8\sigma$ in R_D and R_{D^*} (combined), 1.7σ in $R_{J/\psi}$.

At Moriond, Belle announced new results (see 1904.08794):

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

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

$\Longrightarrow$ There is still a suggestion of NP in $b \to c\tau^-\bar{\nu}$ decays.

New Physics

$b \to c\tau^-\bar{\nu}$ is charged-current process $\Longrightarrow$ NP is $W'^{\pm}$, $H^{\pm}$ or LQ (several different possibilities). $H^{\pm}$ disfavoured by constraints from $B_c^- \to \tau^-\bar{\nu}_\tau$. How to distinguish remaining NP models? Suggestion: measure CP violation in $\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau$.

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Direct CPV: $A_{dir} \propto \Gamma(\bar{B}^0 \to D^{*+}\tau^-\bar{\nu}_\tau) - \Gamma(B^0 \to D^{*-}\tau^+\nu_\tau)$. $A_{dir} \neq 0$ only if interfering amplitudes have different strong phases. Only hadronic transition is $\bar{B} \to D^*$: SM and NP strong phases $\sim$equal $\Longrightarrow$ A_{dir} is small.

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Main CPV effects: CPV asymmetries in angular distribution of $\bar{B}^0 \to D^{*+}(\to D^0\pi^+)\tau^-\bar{\nu}_\tau$. Requires that interfering amplitudes have different Lorentz structures $\Longrightarrow$ can distinguish different NP explanations.

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Practical problem: requires knowledge of $\vec{p}_\tau$, which cannot be measured (missing final ν_τ) $\Longrightarrow$ need to include information from decay products of τ. Will do (work in progress), but first step: look at NP contributions to CPV angular asymmetries in $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$ (will be measured by LHCb).

$\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$: Angular Distribution

1. SM: decay is interpreted as $\bar{B}^0 \to D^{*+}(\to D^0\pi^+)W^{*-}(\to \mu^-\bar{\nu}_\mu)$. Write

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

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

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Of 12 D^{*+}-W^{*-} polarization combinations, only 4 allowed (conservation of angular momentum): $++$, $--$, 00, $0t$
$\Longrightarrow \exists$ 4 helicity amplitudes: $\mathcal{A}_+$, $\mathcal{A}_-$, $\mathcal{A}_0$, $\mathcal{A}_t$. Decay amplitude is

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

$\mathcal{H}_{D^*}$: hadronic matrix element, $\mathcal{L}_{W^*}$: leptonic matrix element.

2. NP: change $W^* \to N^*$, where $N = S - P$ ($\equiv SP$), $V - A$ ($\equiv VA$), T represent new interactions involving LH neutrino (VA includes SM). Hadronic piece:

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

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Effect: $\exists$ more helicities. Previously, VA only: $\mathcal{A}_+$, $\mathcal{A}_-$, $\mathcal{A}_0$, $\mathcal{A}_t$. Now, add 4 more: $SP \to \mathcal{A}_{SP}$, $T \to \mathcal{A}_{+,T}$, $\mathcal{A}_{0,T}$, $\mathcal{A}_{-,T}$.

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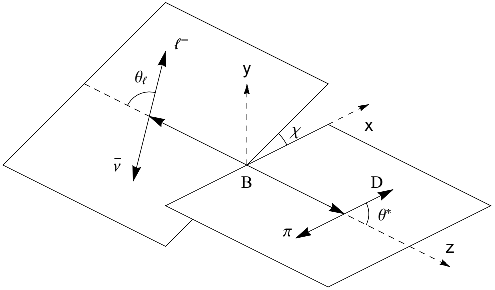
With both SM + NP contributions, write

$$\mathcal{M}(B \to D^*(\to D\pi)W^*(\to \mu^- \bar{\nu}_\mu)) = \mathcal{M}^{SM} + \mathcal{M}^{VA} + \mathcal{M}^T .$$

Each term includes sum over relevant D^* and N^* helicities. [Before had only $\mathcal{M}^{VA} \sim \sum_{m=t,\pm,0} g_{mm}\, \mathcal{H}_{D^*}(m)\, \mathcal{A}_m\, \mathcal{L}_{W^*}(m)$.]

Now, compute $|\mathcal{M}|^2$, obtain terms $|\mathcal{A}_i|^2 f_i(\mathrm{momenta})$ and $\mathrm{Re}[\mathcal{A}_i \mathcal{A}_j^* f_{ij}(\mathrm{momenta})]$. Momenta defined using angles shown on the right



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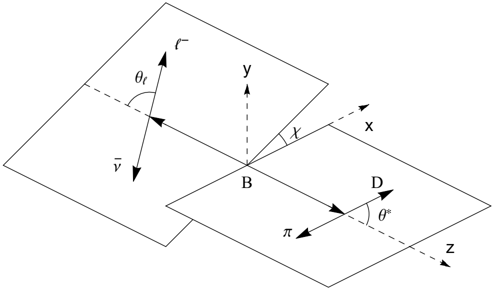

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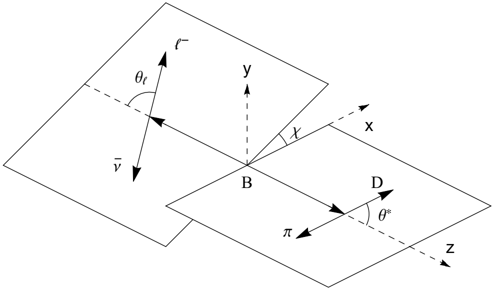

Key point: in interference terms, sometimes $\exists$ an additional factor of i in $f_{ij}(\mathrm{momenta})$ (e.g., from $\mathrm{Tr}[\gamma_\mu \gamma_\nu \gamma_\rho \gamma_\sigma \gamma_5] = 4i\epsilon_{\mu\nu\rho\sigma}$) $\Longrightarrow$ coefficient is $\mathrm{Im}[\mathcal{A}_i \mathcal{A}_j^*]$,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

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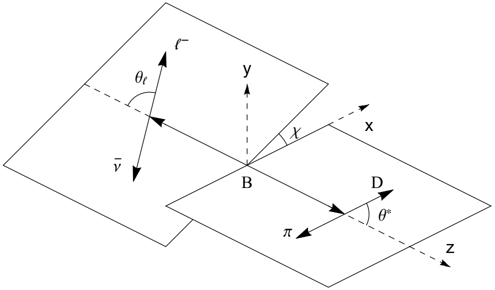

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Recall: in this decay, SM and NP strong phases $\sim$equal $\Longrightarrow$ $\mathrm{Im}[\mathcal{A}_i \mathcal{A}_j^*]$ involves only the weak-phase difference. Such terms are signals of CP violation!

CP-Violating Observables

Complete angular distribution contains many CPV observables, some suppressed by m_μ^2/q^2, some suppressed by $m_\mu/\sqrt{q^2}$, and some unsuppressed. q^2 typically $O(m_b^2) \Longrightarrow$ suppression significant. (But if measurements can be made in region of phase space where $q^2 = O(m_\mu^2)$, can get more information.)

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The unsuppressed observables are

Coefficient	Angular Function
$\mathrm{Im}(\mathcal{A}_\perp \mathcal{A}_0^*)$	$-\sqrt{2}\sin 2\theta_\ell \sin 2\theta^* \sin\chi$
$\mathrm{Im}(\mathcal{A}_\parallel \mathcal{A}_\perp^*)$	$2\sin^2\theta_\ell \sin^2\theta^* \sin 2\chi$
$\mathrm{Im}(\mathcal{A}_0 \mathcal{A}_\parallel^*)$	$-2\sqrt{2}\sin\theta_\ell \sin 2\theta^* \sin\chi$
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Which NP couplings are involved? $\mathrm{Im}(\mathcal{A}_\perp \mathcal{A}_0^*)$, $\mathrm{Im}(\mathcal{A}_\parallel \mathcal{A}_\perp^*)$ and $\mathrm{Im}(\mathcal{A}_0 \mathcal{A}_\parallel^*)$ are 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 $\mathrm{Im}(g_P g_T^*)$.

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1. R_2 and S_1 LQ models generate g_T. U_1, R_2, S_1 and V_2 LQ models generate $g_P \Longrightarrow$ if $\mathrm{Im}(g_P g_T^*) \neq 0$ is found, points to model with two (different) LQs.

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$\exists$ other possibilities if suppressed CPV observables can be measured, and there is also information from CP-conserving observables.

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Finally, work in progress: look at angular distribution of $\bar{B}^0 \to D^{*+} \tau^- \bar{\nu}_\tau$, including products of τ decay.

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(i) $\tau^- \to \pi^-\nu_\tau$. Here, $\vec{p}_\pi$ is measured, providing information beyond that found in the angular distribution of $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$. E.g., in $\bar{B}^0 \to D^{*+}\mu^-\bar{\nu}_\mu$, CPV terms proportional to $\mathrm{Im}(g_P(1+g_L)^*)$ 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.

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(ii) We will also examine the angular distributions of $\bar{B}^0 \to D^{(*)+}\tau^-(\to \rho^-\nu_\tau)\bar{\nu}_\tau$, with $\rho^- \to \pi^-\pi^0$ and $\pi^-\pi^+\pi^-$.

Conclusions

$\exists$ anomalies in $R_{D^{(*)}}$ and $R_{J/\psi} \Longrightarrow$ suggestion of NP in $b \to c\tau^- \bar{\nu}$. A variety of NP models have been proposed. Suggestion: distinguish models through measurement of CP violation in $\bar{B}^0 \to D^{*+}\tau^- \bar{\nu}_\tau$.

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2. Model-dependent: $\exists$ two classes of models, involving a W' or a LQ. Most popular: couplings only to LH particles. If CPV observed, these models ruled out. Depending on which CPV asymmetries found to be nonzero, can distinguish other models.