Possible Large CP Violation in Charmed Λ_b Decays

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Why CP violation

- Symmetry violation is always intriguing
- Matter-antimatter asymmetry
- Our own origins

Why CPV in Baryon is interesting?

CPV in Meson

- CP violation was observed in the decay of K, B, and D mesons in turn.
- All experimental findings align remarkably well with the Standard Model (SM).

CPV in Baryon

- Most of the constituents of visible matter
- Yet still not be established in experiments.
- CKM mechanism has predicted substantial CPV in b-baryons.
- LHCb has yielded unprecedented b-baryons.
- A new *milestone* if discovered!

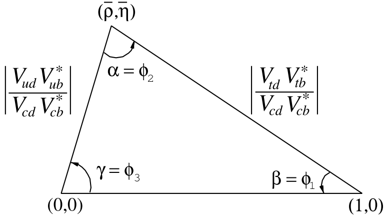
The CKM matrix

- The information on CPV is encoded in the CKM matrix, to find large CPV($\sim \sin\omega$), our focus should be on the matrix elements that have large weak phases ω.
- The CKM matrix can be parameterized as the following:

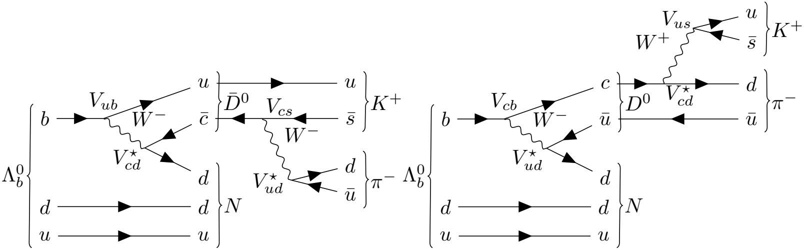
$$V_{\mathrm{CKM}} = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}|e^{-i\gamma} \\ -|V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}|e^{-i\beta} & -|V_{ts}|^{i\beta_s} & |V_{tb}| \end{pmatrix} + \mathcal{O}(\lambda^5), \qquad (1)$$

where the unitary angles are $\beta = 22.2°$, $\gamma = 65.9°$, $\beta_s = 1.4°$, and Wolfenstein parameter $\lambda = 0.225$.

- Decay associated with V_{ub}($\sin\gamma = 0.91$) can present large CPV.



Λ_b^0 Decay



- There are two amplitude will contribute, so we quantify them as:

$$\frac{\left\langle \bar{D}^0 N \middle| \Lambda_b^0 \right\rangle}{\left\langle D^0 N \middle| \Lambda_b^0 \right\rangle} = -r_B e^{i(\delta_B - \gamma)}, r_B \approx \left| \frac{V_{ub} V_{cd}^\star}{V_{cb} V_{ud}^\star} \right| = 0.0204, \gamma = 65.9^\circ \tag{2}$$

$$\frac{\left\langle K^+\pi^- \middle| D^0 \right\rangle}{\left\langle K^+\pi^- \middle| \bar{D}^0 \right\rangle} = -r_D e^{-i\delta_D}, r_D = 0.06, \delta_D = 7.2^\circ \tag{3}$$

$\Lambda_b \to D(\to K^+\pi^-)N$

- Given that $r_B = \left|\frac{\langle \bar{D}^0 N | \Lambda_b^0\rangle}{\langle D^0 N | \Lambda_b^0\rangle}\right| = \left|\frac{V_{ub} V_{cd}^\star}{V_{cb} V_{ud}^\star}\right| \approx 0.02, r_D = \left|\frac{\langle K^+\pi^- | D^0\rangle}{\langle K^-\pi^+ | D^0\rangle}\right| = 0.06, \sin\gamma = 0.91$, a large CPV induced by their interference can be expected, with the coherent immediate state $D \equiv D^0 + \bar{D}^0$.

$$\begin{tikzcd}
 & D^0 N \arrow[dr, "-r_D e^{-i\delta_D}"] & \\
\Lambda_b^0 \arrow[ur] \arrow[dr, "-r_B e^{i(\delta_B-\gamma)}"] & & (K^+\pi^-)N \\
 & \bar{D}^0 N \arrow[ur] &
\end{tikzcd}$$

N Resonances

- We consider the superposition of $N(1440)$ and $N(1520)$, with $S_{1440} = 1/2, S_{1520} = 3/2$.
- However, this necessitates the use of the helicity amplitude framework.
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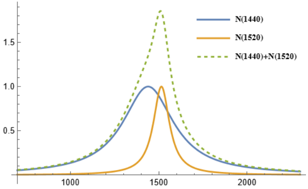
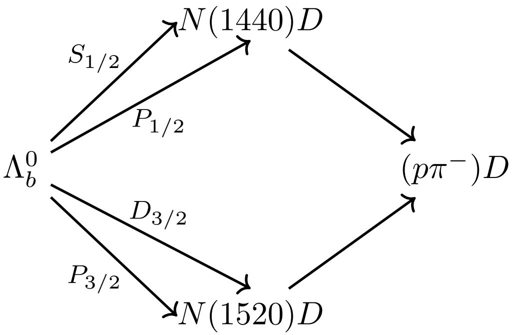
$$\mathcal{M}_{\lambda,\mu} \propto \left(J + \frac{1}{2}\right) \mathcal{H}_{\lambda,\mu} e^{i(\lambda-\mu)\phi} d^J_{\lambda,\mu}(\theta), \tag{4}$$

where λ, μ is the difference of helicity in the initial and final state, $d^J_{\lambda,\mu}(\theta)$ is the d-function of $SO(3)$ group.



Partial Wave Expansion

- Four partial waves will contribute due to the conservation of angular momentum.
- More observables can be constructed.

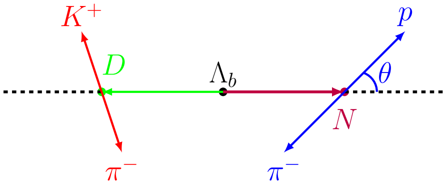


Observable

- The CP asymmetry is defined as:

$$A_{\mathrm{CP}} \equiv \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta} - \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}\cos\theta}\right) \Big/ \left(\frac{\mathrm{d}\Gamma}{\mathrm{d}\cos\theta} + \frac{\mathrm{d}\bar{\Gamma}}{\mathrm{d}\cos\theta}\right) \equiv \frac{\mathcal{N}(\theta)}{\mathcal{D}(\theta)}\,, \quad (5)$$

where θ is defined as illustrated in the below figure.



Observable

- Summing all polarizations in initial and final states, finally there are various parameters: $|S_{1/2}|, |P_{1/2}|, |P_{3/2}|, |D_{3/2}|, \{r_{Bi}, \delta_{Bi}\}, \delta_{PS}, \delta_{DP}$
- Conducting a complete analysis is horrible
- To streamline, we set: $|S_{1/2}| = |P_{1/2}| = |P_{3/2}| = |D_{3/2}|$ from now on.

Observable

- We define two observables, the first one is:

$$A_1 \equiv \frac{\int_{-1}^{1} \mathcal{N}(\theta)\,\mathrm{d}\cos\theta}{\int_{-1}^{1} \mathcal{D}(\theta)\,\mathrm{d}\cos\theta} \equiv \frac{\mathcal{N}_1}{\mathcal{D}_1}, \tag{6}$$

  where $\mathcal{N}_1 = \left|S_{1/2}\right|^2 \mathcal{N}_d(r_{B1}, \delta_{B1}) + \left|P_{1/2}\right|^2 \mathcal{N}_d(r_{B3}, \delta_{B3}) + 2\left|P_{3/2}\right|^2 \mathcal{N}_d(r_{B2}, \delta_{B2}) + 2\left|D_{3/2}\right|^2 \mathcal{N}_d(r_{B4}, \delta_{B4})$
- A_1 is expressed as the sum of contributions from four independent partial waves,

Observable

- The second one is:

$$A_2 \equiv \frac{\int_{-1}^{1} \mathrm{sgn}[\cos\theta] \cdot \mathcal{N}(\theta)\, \mathrm{d}\cos\theta}{\int_{-1}^{1} \mathcal{D}(\theta)\, \mathrm{d}\cos\theta} \equiv \frac{\mathcal{N}_2}{\mathcal{D}_1}, \tag{7}$$

  where $\mathrm{sgn}[x]$ is the sign function and
  $\mathcal{N}_2 = \left|S_{1/2}\right| \left|P_{3/2}\right| \mathcal{N}_i(r_{B1}, r_{B2}, \delta_{B1}, \delta_{B2}, \delta_{PS}) +$
  $\left|P_{1/2}\right| \left|D_{3/2}\right| \mathcal{N}_i(r_{B3}, r_{B4}, \delta_{B3}, \delta_{B4}, \delta_{DP})$
- A_2 is induced by the interference between distinct partial waves.

Numerical Results

- **Case 1:** A single N-resonance, and using a common phase to represent all the relevant strong phases $\{\delta_{Bi}\}$

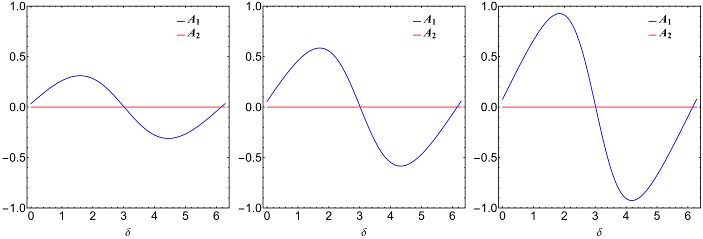


Figure 2: (a) $r_{B1} = r_{B3} = 0.5 r_B$; (b) $r_{B1} = r_{B3} = r_B$; and (c) $r_{B1} = r_{B3} = 2 r_B$

Numerical Results

- **Case 2:** Two N-resonances, and $\delta_{B1} = \delta_{B2} = \delta_{B3} = \delta_{B4}$ and $\delta_{PS} = \delta_{DP}$.

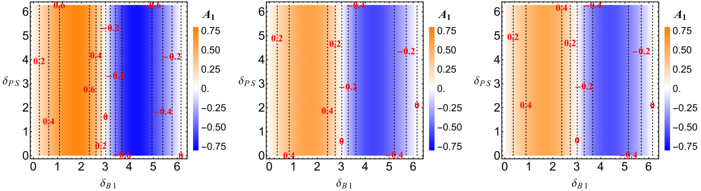


Figure 3: (a) $r_{B1} = r_{B3} = 0.5r_B, r_{B2} = r_{B4} = 2r_B$; (b) $r_{B1} = r_{B3} = r_{B2} = r_{B4} = r_B$; and (c) $r_{B1} = r_{B3} = 2r_B, r_{B2} = r_{B4} = 0.5r_B$

Numerical Results

- And the results of observable A_2 are:

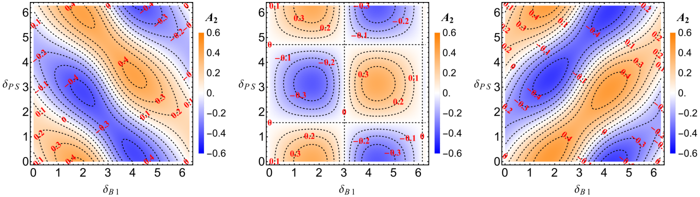


Figure 4: (a) $r_{B1} = r_{B3} = 0.5r_B, r_{B2} = r_{B4} = 2r_B$; (b) $r_{B1} = r_{B3} = r_{B2} = r_{B4} = r_B$; and (c) $r_{B1} = r_{B3} = 2r_B, r_{B2} = r_{B4} = 0.5r_B$

Numerical Results

- **Case 3:**, Two N-resonances, $\delta_{B1} = \delta_{B2} = -\delta_{B3} = -\delta_{B4}$, and $\delta_{PS} = \delta_{DP}$.

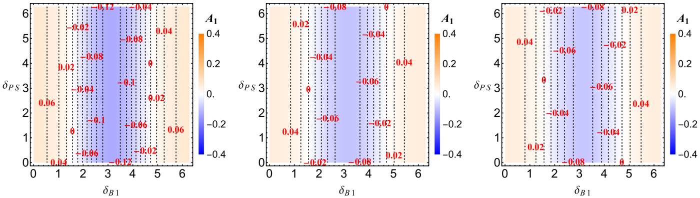


Figure 5: (a) $r_{B1} = r_{B3} = 0.5r_B, r_{B2} = r_{B4} = 2r_B$; (b) $r_{B1} = r_{B3} = r_{B2} = r_{B4} = r_B$; and (c) $r_{B1} = r_{B3} = 2r_B, r_{B2} = r_{B4} = 0.5r_B$

Numerical Results

- And the results of observable A_2 are:

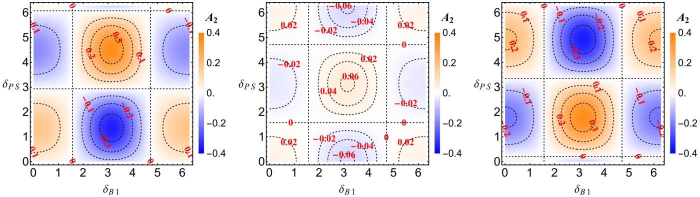


Figure 6: (a) $r_{B1} = r_{B3} = 0.5r_B, r_{B2} = r_{B4} = 2r_B$; (b) $r_{B1} = r_{B3} = r_{B2} = r_{B4} = r_B$; and (c) $r_{B1} = r_{B3} = 2r_B, r_{B2} = r_{B4} = 0.5r_B$

Discussion

- It is evident that the CP asymmetry reaches magnitudes of $\mathcal{O}(10\%)$ across a wide range of strong phases in most scenarios. Furthermore, in specific regions, the CP asymmetry can even exceed 50%.
- Given that the measurement results of LHCb in RUN 1(arXiv: 1311.4823), we estimate that $\mathcal{O}(10^2)$ can be collected following the completion of RUN 1-2.
- Such quantity of events can attain the confident level of 3σ if the CPV manifests about 40%.
- Similar decay modes such as $\Lambda_b \to D(\to K^+K^-)\Lambda$ can also be considered.

Acknowledgement

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Thank You