Large CP violation in $\Lambda_b \to \Lambda D$ decays and extraction of the CKM angle γ

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Outline

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Large CPVs in $\Lambda_b \to \Lambda D$

Extraction of the CKM angle γ

Summary

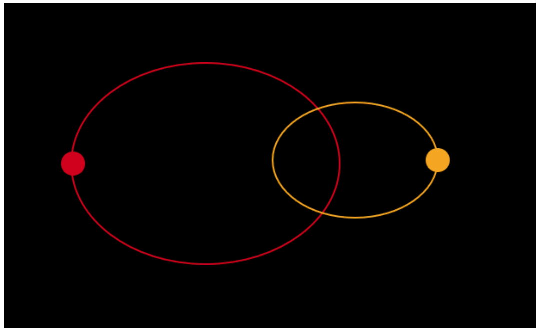
01

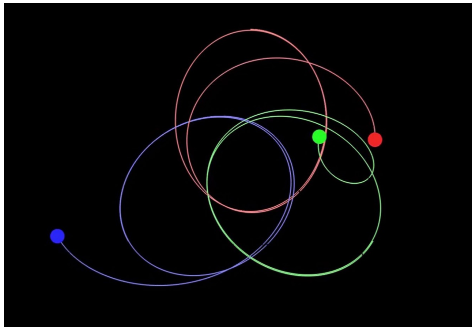
Motivation

Why baryon physics

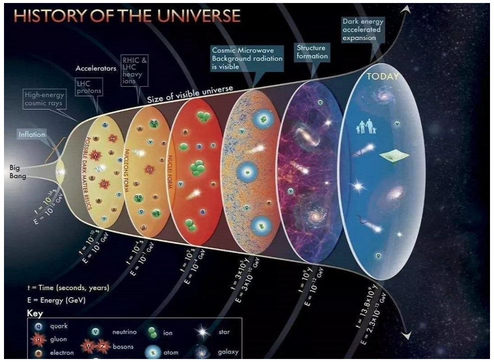
- CP violation for Universal evolution
  - Sakharov conditions for Baryogenesis:

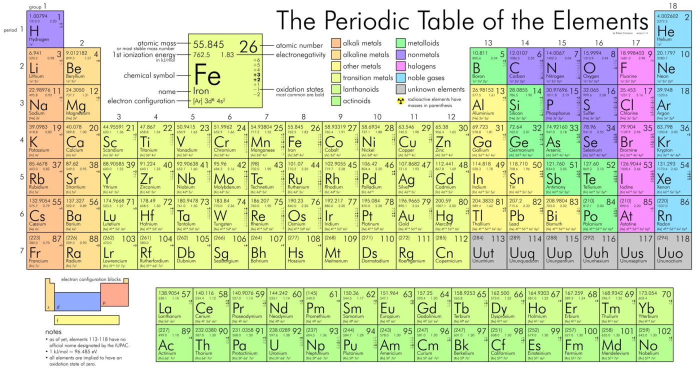
baryon number violation | C and CP violation | out of thermal equilibrium





- CPV relates to most of parameters of SM, is helpful to test SM and search NP;
- CPV has been established for *K*, *B* and *D* meson decays, CKM mechanism has been established for CPV in B meson decays;
- The visible universe is mainly made of baryons. It is of great significance to search for baryon CPV !





Opportunities

- Hyperon CPV:
  - SM: $\mathcal{O}(10^{-5} \sim 10^{-4})$ [Donoghue, X.G.He, Pakvasa, 1986]
  - BESIII [Nature, 2022] $A_{CP}^{\alpha}(\Lambda \to p\pi^-) = (2.5 \pm 4.8)\times 10^{-3}$

- Charm baryon CPV:
  - SM: $\mathcal{O}(10^{-3} \sim 10^{-4})$ [X.G.He, C.W.Liu, 2024] [C.P.Jia, H.Y.Jiang, J.P.Wang, F.S.Yu, 2024]
  - LHCb [JHEP, 2018] $A_{CP}(\Lambda_c \to pK^+K^-/p\pi^+\pi^-) = (3.0 \pm 9.1 \pm 6.1)\times 10^{-3}$

- Beauty hadron: SM estimates $\sim 10\%$ due to large weak phase difference

  $A_{CP}(B^0 \to K^+\pi^-) = (-8.34 \pm 0.32)\%$ $A_{CP}(B_s^0 \to K^-\pi^+) = (22.4 \pm 1.2)\%$

- Precision of b-baryon CPV measurement reached of order 1%

  $A_{CP}(\Lambda_b \to p\pi^-) = (0.2 \pm 0.8 \pm 0.4)\%$

  $A_{CP}(\Lambda_b \to pK^-) = (-1.1 \pm 0.7 \pm 0.4)\%$ [LHCb,2018,2024]

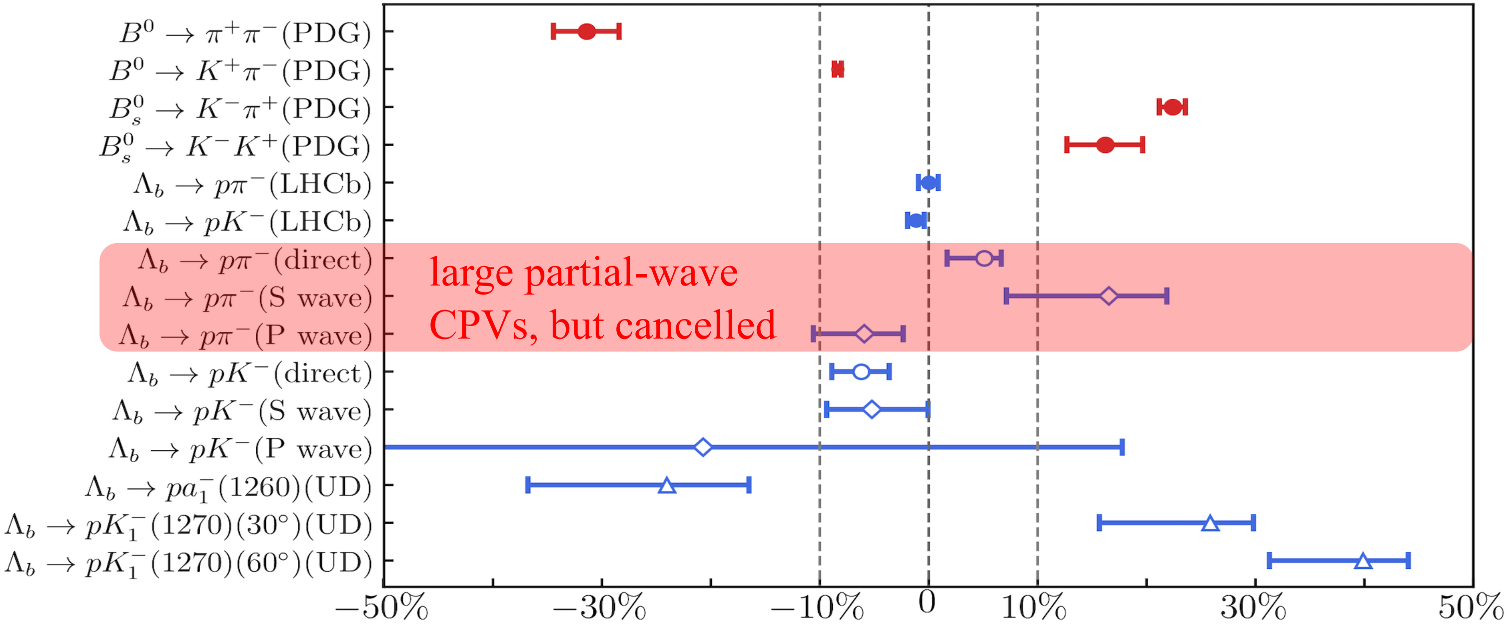
  $A_{CP}(\Lambda_b \to pK^-\pi^+\pi^-) = (2.45 \pm 0.46 \pm 0.10)\%$ 5.2σ [LHCb,Nature2025]

  $A_{CP}(\Lambda_b^0 \to \Lambda K^+K^-) = (8.3 \pm 2.8)\%$ [LHCb,2025] Evidence of *CP* violation

  $A_{CP}(\Lambda_b^0 \to pK_S^0\pi^-) = (3.4 \pm 1.9 \pm 0.9)\%$ [LHCb,2025] No evidence of *CP* violation

Challenges

- **Why the observed CPVs of b baryon decays are small ?** **(magnitude less than 10%)**
- **The current measurements are mainly focused on the decays involving tree-penguin interference.**
  - **the suppressed penguin-to-tree amplitude ratio**
  - **cancellations among partial wave**
- Small CPVs in $\Lambda_b \to p\pi^-$:**tree-penguin interference** **[PRL**134, 221801 (2025)**]**

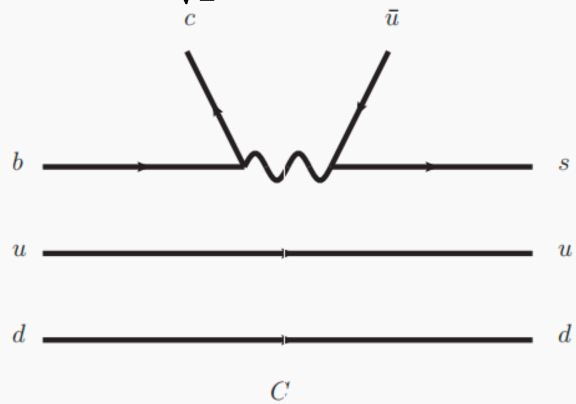


- **What about the CPVs in the decays involving the tree-tree interference?**

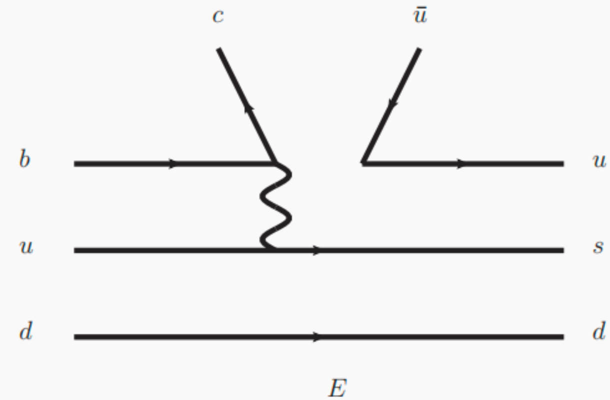
02 Large CPVs in $\Lambda_b \to \Lambda D$

CP eigenstate $D_\pm = \frac{1}{\sqrt{2}}(D^0 \pm \overline{D}^0)$ D_+:CP-even, D_-:CP-odd **tree-tree interference**

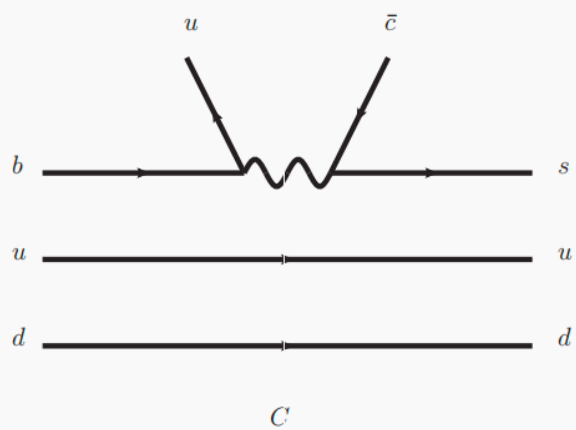
$b \to cs\bar{u}$



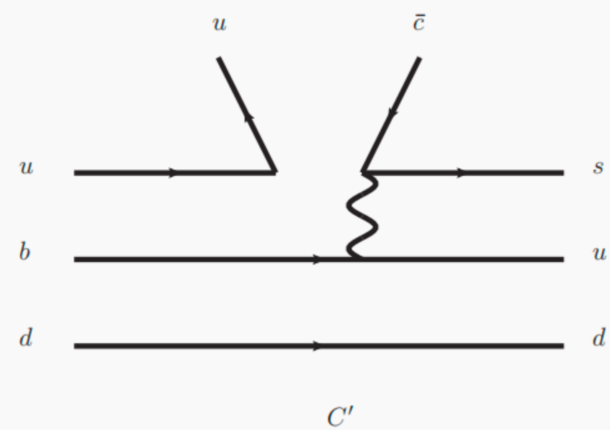
$\Lambda_b \to \Lambda D^0$



$b \to us\bar{c}$

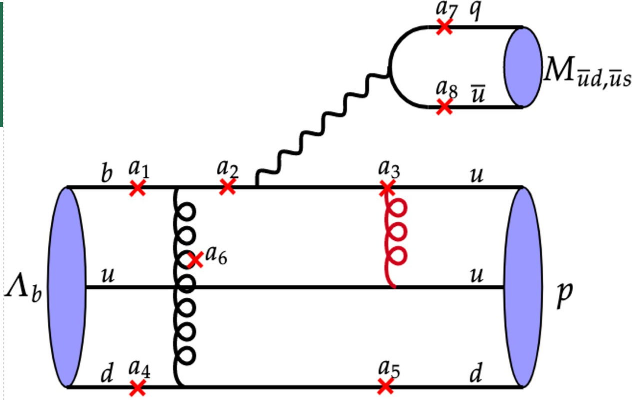


$\Lambda_b \to \Lambda \overline{D}^0$



- This CPV originates from tree-tree interference between the amplitudes $M(\Lambda_b \to \Lambda D^0)$ and $M(\Lambda_b \to \Lambda \overline{D}^0)$, induced by the $b \to cs\bar{u}$ and $b \to us\bar{c}$ transitions, respectively.
- Large strong phase from nonfactorizable diagrams which plays an important role in the CPV.

PQCD approach



- QCD studies on baryon are listed
  - GFA (Hsiao,Yao,Geng,2017; Liu,Geng,2021)
  - QCDF (Zhu,Ke,Wei,2016,2018)
  - PQCD (Lü,Wang,Zou,Ali,Kramer,2009; Zhou,et.al.,2022~2023)
  - quark model(Geng,Liu,Tsai,et.al.,2019~2022)
  - Light-cone Sum rule (Jiang,Cheng,Khodjamirian,Yu, in progress)

- PQCD approach, based on k_T factorization, retain transverse momentum k_T

  propagators $\sim \frac{1}{x_i(1-x_j)Q^2+|k_{iT}|^2}$ [Sterman,Hsiang-nan Li,1995~2000]

- After resummation, Sudakov factors to suppress contribution from small k_T

$$\mathscr{A} = \langle M_2 M_3 | \mathscr{H} | B \rangle$$
$$\sim \int \frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4}\frac{d^4k_3}{(2\pi)^4}\Psi_B(k_1,\mu)\Psi_2(k_2,\mu)\Psi_3(k_3,\mu)\cdot H(k_1,k_2,k_3,\mu)C_i(\mu)$$
$$\sim \int_0^1 dx_2 dx_2 dx_3 \int \frac{d^2k_{1T}}{(2\pi)^2}\frac{d^2k_{2T}}{(2\pi)^2}\frac{d^2k_{3T}}{(2\pi)^2}\phi_B(x_1,k_{1T},\mu)\phi_2(x_2,k_{2T},\mu)\phi_3(x_3,k_{3T},\mu)\cdot H(x_1,x_2,x_3,k_{1T},k_{2T},k_{3T},\mu)C_i(\mu)$$

- Transition form factor is dominated from the perturbative region
- Nonfactorizable and annihilation diagrams can be calculated

Establish CPVs in $\Lambda_b \to \Lambda D$ decays

- Baryons have half-integer spin, and thus two partial wave amplitudes.

$$\mathcal{M}(\Lambda_b \to \Lambda D) = i\bar{u}_\Lambda (A + B\gamma_5) u_{\Lambda_b} \qquad S = \sqrt{Q_+}A, \quad P = \sqrt{Q_-}B,$$

S wave *P wave*

$$S_D = |S_D| e^{i\delta_{S_D}}, \quad P_D = |P_D| e^{i\delta_{P_D}},$$

$$S_{\bar{D}} = |S_{\bar{D}}| e^{i(\delta_{S_{\bar{D}}} - \gamma)}, \quad P_{\bar{D}} = |P_{\bar{D}}| e^{i(\delta_{P_{\bar{D}}} - \gamma)},$$

consider the CP eigenstates

$$S_\pm = \frac{1}{\sqrt{2}}(S_D \pm S_{\bar{D}}), \quad P_\pm = \frac{1}{\sqrt{2}}(P_D \pm P_{\bar{D}})$$

$$r_{S(P)} = \left| \frac{S(P)_{\bar{D}}}{S(P)_D} \right|$$

$$A^S_\pm \equiv \frac{|S_\pm|^2 - |\bar{S}_\pm|^2}{|S_\pm|^2 + |\bar{S}_\pm|^2} = \frac{\pm 2 r_S \sin\gamma \sin\delta_{S_D S_{\bar{D}}}}{1 + r_S^2 \pm 2 r_S \cos\gamma \cos\delta_{S_D S_{\bar{D}}}},$$

$$A^P_\pm \equiv \frac{|P_\pm|^2 - |\bar{P}_\pm|^2}{|P_\pm|^2 + |\bar{P}_\pm|^2} = \frac{\pm 2 r_P \sin\gamma \sin\delta_{P_D P_{\bar{D}}}}{1 + r_P^2 \pm 2 r_P \cos\gamma \cos\delta_{P_D P_{\bar{D}}}},$$

strong phase difference

$$\delta_{S_D S_{\bar{D}}} = \delta_{S_{\bar{D}}} - \delta_{S_D}$$

$$\delta_{P_D P_{\bar{D}}} = \delta_{P_{\bar{D}}} - \delta_{P_D}$$

$$A_{CP}(\Lambda_b \to \Lambda D_\pm) = \kappa^\pm A^S_\pm + (1 - \kappa^\pm) A^P_\pm,$$

weights $$\kappa^\pm = \frac{R^\pm_S}{R^\pm_S + R^\pm_P},$$

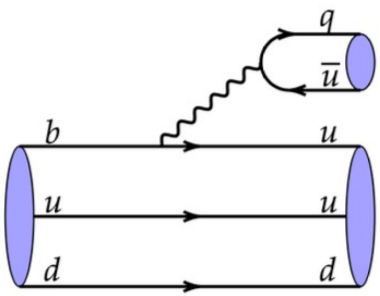
$$R^\pm_S = |S_D|^2 [1 + r_S^2 \pm 2 r_S \cos\gamma \cos\delta_{S_D S_{\bar{D}}}],$$

$$R^\pm_P = |P_D|^2 [1 + r_P^2 \pm 2 r_P \cos\gamma \cos\delta_{P_D P_{\bar{D}}}].$$

If the different partial wave CPVs share the same sign, the overall direct CP asymmetry increases!

Establish CPVs in $\Lambda_b \to \Lambda D$ decays

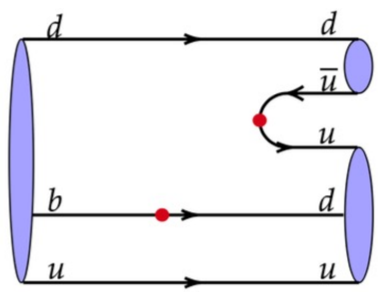
➢ Cancellation of partial wave CPVs exists in tree-penguin interference like $\Lambda_b \to p\pi$ decays.



T

$$\sim q^{\mu}\bar{u}_p\gamma_\mu(1-\gamma_5)u_{\Lambda_b} \sim \bar{u}_p(1+\gamma_5)u_{\Lambda_b}$$

$$\sim \bar{u}_p(1+\gamma_5)(\gamma_5 \not{p}_\pi)(\not{p}_{\Lambda_b}\gamma_5)\not{p}_p(1-\gamma_5)u_{\Lambda_b} \sim \bar{u}_p(1-\gamma_5)u_{\Lambda_b}$$



PC_2

$$\Delta\delta_{S-wave} = \delta_{PC_2}^{S-wave} - \delta_T^{S-wave}$$

$$\Delta\delta_{P-wave} = \delta_{PC_2}^{P-wave} - \delta_T^{P-wave}$$

different by π

✓ For tree-tree interference, where all contributing tree operators share the same (V −A)(V −A) structure, such cancellation that suppresses CPV in the tree-penguin scenario is absent.

Partial wave amplitudes of $\Lambda_b \to \Lambda D$ in PQCD

- without the CKM matrix elements, $\times 10^{-6}$GeV

Topology	S_D	$\lvert S_D \rvert$	δ_{S_D}	P_D	$\lvert P_D \rvert$	δ_{P_D}
C_f	1.8	1.8	0	1.8	1.8	0
C_{nf}	3.0-4.3i	5.2	-0.96	1.8-2.9i	3.4	-1.02
$C = C_f + C_{nf}$	4.8-4.3i	6.4	-0.73	3.6-2.9i	4.6	-0.68
E	-0.3-0.02i	0.3	-3.07	-0.3+0.5i	0.6	2.11
Total	4.5-4.3i	6.2	-0.76	3.3-2.4i	4.1	-0.63

Topology	$S_{\bar{D}}$	$\lvert S_{\bar{D}} \rvert$	$\delta_{S_{\bar{D}}}$	$P_{\bar{D}}$	$\lvert P_{\bar{D}} \rvert$	$\delta_{P_{\bar{D}}}$
C_f	1.8	1.8	0	1.8	1.8	0
C_{nf}	0.3-6.4i	6.4	-1.52	-0.4-5.0i	5.0	-1.65
$C = C_f + C_{nf}$	2.1-6.4i	6.7	-1.25	1.4-5.0i	5.2	-1.30
C'	1.0-5.9i	6.0	-1.40	0.8-6.1i	6.2	-1.44
Total	3.1-12.3i	12.7	-1.32	2.2-11.1i	11.3	-1.38

Large CPVs of $\Lambda_b \to \Lambda D$ in PQCD

$$A_{CP}(\Lambda_b \to \Lambda D_\pm) = \kappa^\pm A_\pm^S + (1-\kappa^\pm)A_\pm^P,$$

D	$\mathcal{B}(10^{-5})$	A_{CP}	κA_{CP}^S	$(1-\kappa)A_{CP}^P$
D^0	$3.1^{+1.8}_{-0.8}$	0	0	0
$\bar{D}^0$	$2.3^{+1.1}_{-0.7}$	0	0	0
D_+	$1.9^{+1.1}_{-0.4}$	$-0.44^{+0.10}_{-0.05}$	$-0.25^{+0.08}_{-0.01}$	$-0.19^{+0.04}_{-0.04}$
D_-	$3.5^{+1.9}_{-1.0}$	$0.72^{+0.06}_{-0.14}$	$0.42^{+0.01}_{-0.11}$	$0.30^{+0.05}_{-0.06}$

- Even in the presence of nonzero strong phases, the CPVs of the D^0 and $\bar{D}^0$ channels remain zero due to the vanishing weak phase difference.
- For both CP-even and CP-odd eigenstates, we observe sizeable CPVs with similar magnitudes.
- The CPVs of the S- and P-wave components accumulate coherently, leading to the large total CPVs in $\Lambda_b \to \Lambda D_\pm$ decays, which is different from the $\Lambda_b \to ph$ decays.

The first full QCD analysis on $\Lambda_b \to \Lambda D$ decays

Comparison of theoretical predictions on the branching fractions (10^{-6}) without the nonfactorizable contribution.

Mode	This work	[36]	[22]	[25]
D^0	$3.64^{+2.33}_{-1.53}$	$3.37^{+0.33+0.42+0.67}_{-0.19-0.47-0.23}$	4.56	6.6 ± 0.6
$\bar{D}^0$	$0.49^{+0.31}_{-0.21}$	$0.478^{+0.060+0.103+0.061}_{-0.027-0.108-0.047}$	0.829	0.9 ± 0.1
D_+	$2.48^{+1.58}_{-1.05}$	$\cdots$	$\cdots$	4.7 ± 0.5
D_-	$1.64^{+1.05}_{-0.69}$	$\cdots$	$\cdots$	2.9 ± 0.3

[36]PRD99,054020(2019)
[22]PRD65,073029(2002)
[25]PLB834,137429

The nonfactorizable topological diagrams C ′ and E are evaluated for the first time.

D	$\mathcal{B}(10^{-5})$	A_{CP}	κA^S_{CP}	$(1-\kappa)A^P_{CP}$
D^0	$3.1^{+1.8}_{-0.8}$	0	0	0
$\bar{D}^0$	$2.3^{+1.1}_{-0.7}$	0	0	0
D_+	$1.9^{+1.1}_{-0.4}$	$-0.44^{+0.10}_{-0.05}$	$-0.25^{+0.08}_{-0.01}$	$-0.19^{+0.04}_{-0.04}$
D_-	$3.5^{+1.9}_{-1.0}$	$0.72^{+0.06}_{-0.14}$	$0.42^{+0.01}_{-0.11}$	$0.30^{+0.05}_{-0.06}$

$$r_S = \left|\frac{V_{ub}V^*_{cs}}{V_{cb}V^*_{us}}\right| \times \left|\frac{S_{\bar{D}}}{S_D}\right| = 0.76,$$
$$r_P = \left|\frac{V_{ub}V^*_{cs}}{V_{cb}V^*_{us}}\right| \times \left|\frac{P_{\bar{D}}}{P_D}\right| = 1.05.$$

$r_{B\to DK} = 0.1$ (PDG)

- Owing to the significant nonfactorizable contributions, the branching fractions increase by an order of magnitude, reaching values on the order of 10^{-5}.

CP asymmetries in the angular distributions

$$\alpha' = -\frac{2\mathrm{Re}(S^* P)}{|S|^2 + |P|^2}, \beta' = -\frac{2\mathrm{Im}(S^* P)}{|S|^2 + |P|^2}, \gamma' = \frac{|S|^2 - |P|^2}{|S|^2 + |P|^2},$$

$$A_{CP}^{\alpha'} = \frac{\alpha' + \bar{\alpha}'}{2}, A_{CP}^{\beta'} = \frac{\beta' + \bar{\beta}'}{2}, A_{CP}^{\gamma'} = \frac{\gamma' - \bar{\gamma}'}{2},$$

Observable	$\Lambda_b \to \Lambda D^0$	$\Lambda_b \to \Lambda \bar{D}^0$	$\Lambda_b \to \Lambda D_+$	$\Lambda_b \to \Lambda D_-$
α'	$-0.90^{+0.06}_{-0.06}$	$-0.99^{+0.00}_{-0.01}$	$-0.90^{+0.05}_{-0.05}$	$-0.96^{+0.02}_{-0.03}$
β'	$-0.12^{+0.07}_{-0.10}$	$0.05^{+0.06}_{-0.03}$	$0.15^{+0.08}_{-0.11}$	$-0.16^{+0.07}_{-0.08}$
γ'	$0.41^{+0.10}_{-0.15}$	$0.11^{+0.01}_{-0.10}$	$0.40^{+0.09}_{-0.11}$	$0.22^{+0.06}_{-0.13}$
$A_{CP}^{\alpha'}$	0	0	$0.03^{+0.02}_{-0.01}$	$-0.11^{+0.06}_{-0.06}$
$A_{CP}^{\beta'}$	0	0	$0.12^{+0.05}_{-0.05}$	$-0.25^{+0.11}_{-0.09}$
$A_{CP}^{\gamma'}$	0	0	$0.08^{+0.05}_{-0.03}$	$-0.18^{+0.06}_{-0.09}$

It is observed that the CP asymmetries $A_{CP}^{\beta'}$ are prominent for both the CP-even and CP-odd modes.

03

Extraction of the CKM angle γ

Determination of γ via $\Lambda_b \to \Lambda D$

✓ The CKM angle γ is measurable via tree-level decays

- negligible theoretical uncertainty [JHEP 01(2014) 051]
- indirect search of BSM physics by comparing direct (tree-level) and indirect (loop-induced) measurements

$$\gamma_{\text{dir.}} = (65.9^{+3.3}_{-3.5})^{\circ}$$
$$\gamma_{\text{ind.}} = (66.23^{+0.60}_{-1.43})^{\circ}$$

✓ Probe γ via interference between $b \to u\bar{c}s$ and $b \to c\bar{u}s$ transitions

- most commonly used decays: $B \to \left(D^0, \overline{D^0}, D_{\pm}\right)h$ $(h = K, \pi)$ etc.
- applies to baryonic decay modes induced by the same transitions.

✓ Provide complementary and relatively independent constraints: pure tree decays of $\Lambda_b \to \Lambda\left(D^0, \overline{D^0}, D_{\pm}\right)$

- Large amplitude ratio
- Large CPVs as large as 50%

$$r_S = \left|\frac{V_{ub}V_{cs}^*}{V_{cb}V_{us}^*}\right| \times \left|\frac{S_{\bar{D}}}{S_D}\right| = 0.76,$$
$$r_P = \left|\frac{V_{ub}V_{cs}^*}{V_{cb}V_{us}^*}\right| \times \left|\frac{P_{\bar{D}}}{P_D}\right| = 1.05.$$

$$\mathrm{r}_{\mathrm{B \to DK}} = 0.1$$

- We propose a novel scheme to extract γ in **a model-independent** way by combining angular distribution parameters and the decay rates in $\Lambda_b \to \Lambda D_\pm$ decays.

α':

$$\mathcal{A}_\pm \alpha'_\pm = -2\mathrm{Re}(S^*_\pm P_\pm), \quad \mathcal{A}_\pm = |S_\pm|^2 + |P_\pm|^2$$

$$\mathcal{A}_\pm \alpha'_\pm + \bar{\mathcal{A}}_\pm \bar{\alpha}'_\pm = -2\mathrm{Re}(S^*_\pm P_\pm + \bar{S}^*_\pm \bar{P}_\pm).$$

$$\sin\gamma = \frac{\pm(\mathcal{A}_\pm \alpha'_\pm + \bar{\mathcal{A}}_\pm \bar{\alpha}'_\pm)}{2(|S_D||P_{\bar{D}}| \sin\delta_{S_D P_{\bar{D}}} + |P_D||S_{\bar{D}}| \sin\delta_{P_D S_{\bar{D}}})},$$

$$\cos\gamma = \pm \frac{\alpha'_D \mathcal{A}_D + \alpha'_{\bar{D}} \mathcal{A}_{\bar{D}} - (\mathcal{A}_\pm \alpha'_\pm - \bar{\mathcal{A}}_\pm \bar{\alpha}'_\pm)}{2(|S_D||P_{\bar{D}}| \cos\delta_{S_D P_{\bar{D}}} + |P_D||S_{\bar{D}}| \cos\delta_{P_D S_{\bar{D}}})}.$$

β':

$$\sin\gamma = \frac{\pm(\mathcal{A}_\pm\beta'_\pm + \bar{\mathcal{A}}_\pm\bar{\beta}'_\pm)}{2[|S_D||P_{\bar{D}}|\cos\delta_{S_D P_{\bar{D}}} - |P_D||S_{\bar{D}}|\cos\delta_{P_D S_{\bar{D}}}]},$$

$$\cos\gamma = \pm\frac{\beta'_D\mathcal{A}_D + \beta'_{\bar{D}}\mathcal{A}_{\bar{D}} - (\mathcal{A}_\pm\beta'_\pm - \bar{\mathcal{A}}_\pm\bar{\beta}'_\pm)}{2(|P_D||S_{\bar{D}}|\sin\delta_{P_D S_{\bar{D}}} - |S_D||P_{\bar{D}}|\sin\delta_{S_D P_{\bar{D}}})},$$

γ':

$$\sin\gamma = \frac{\pm(\mathcal{A}_\pm\gamma'_\pm - \bar{\mathcal{A}}_\pm\bar{\gamma}'_\pm)}{2[|P_D||P_{\bar{D}}|\sin\delta_{P_D P_{\bar{D}}} - |S_D||S_{\bar{D}}|\cos\delta_{S_D S_{\bar{D}}}]},$$

$$\cos\gamma = \mp\frac{\gamma'_D\mathcal{A}_D + \gamma'_{\bar{D}}\mathcal{A}_{\bar{D}} - (\mathcal{A}_\pm\gamma'_\pm + \bar{\mathcal{A}}_\pm\bar{\gamma}'_\pm)}{2(|S_D||S_{\bar{D}}|\cos\delta_{S_D S_{\bar{D}}} - |P_D||P_{\bar{D}}|\cos\delta_{P_D P_{\bar{D}}})}.$$

- Though measuring $\beta'_\pm$ and $\gamma'_\pm$ requires the initial polarization of b-baryons, these formulas provide valuable insights to extract γ with different dependencies on the strong phases.

- If the strong phases are obtained from model calculations, it is sufficient to determine by γ measuring the decay rates Γ± and the angular distribution parameters $\alpha'_\pm$.

04 Summary

Summary

Large CPV are predicted in the $\Lambda_b \to \Lambda D$ decays, which offers a direct measurement of γ in the baryon sector.

We propose a novel strategy to extract the CKM angle γ by combining angular distribution parameters and decay rates in a model-independent manner

First predictions of several nonzero CP-violating observables associated with angular distribution parameters

We strongly encourage the experiments to prioritize the measurement of $\Lambda_b \to \Lambda D$ decays as golden channels for CPV studies and CKM metrology in the baryon sector.

Thank you!

- Their relative ratios provide information about the relative strong phase between the S- and P-wave amplitudes.

$$\sin(\delta_P - \delta_S) = -\frac{\beta'}{\sqrt{1-\gamma'^2}}, \qquad \cos(\delta_P - \delta_S) = -\frac{\alpha'}{\sqrt{1-\gamma'^2}}.$$