守信 求实 好学 力行

烟台大学
YANTAI UNIVERSITY

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

报告人： 李营

2026年5月22日

In collaboration with: **Rui Zhou, Zhi-Tian Zou and Ya Li,**

aRxiv: 2604.17877 [hep-ph]

守信 求实 好学 力行

烟台大学 YANTAI UNIVERSITY

目录

CONTENT
S

PART 01

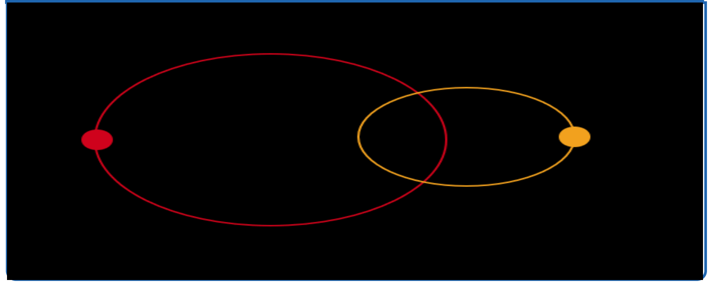
Motivation

Motivation

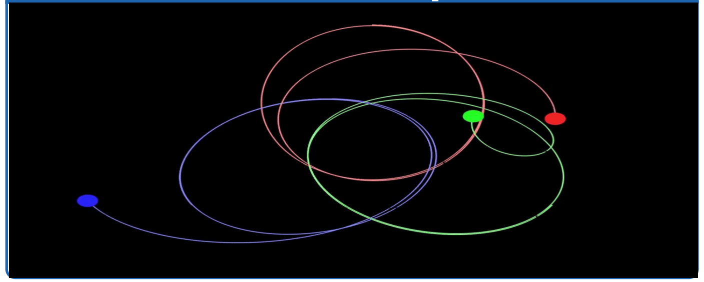
- CP violation Plays important roles for Universe evolution

Baryon number violation

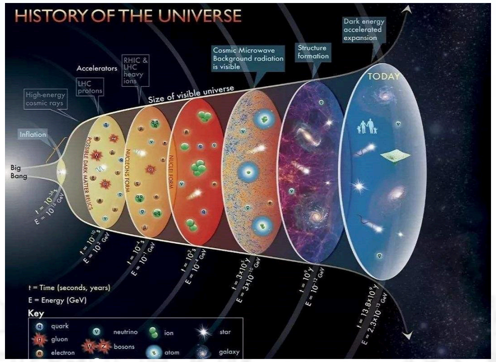
C and CP violation

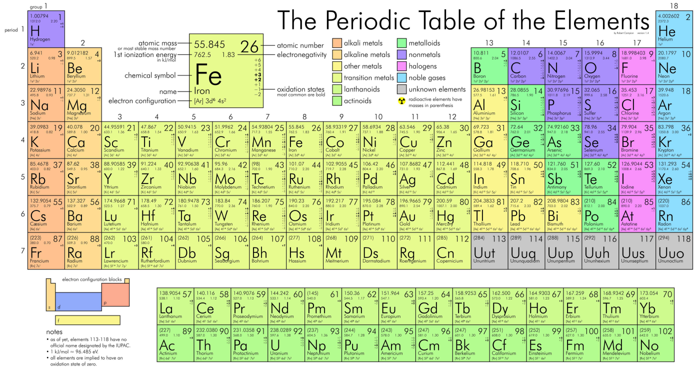


Out of hermal equilibrium



- 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!





Motivation

烟台大学 YANTAI UNIVERSITY

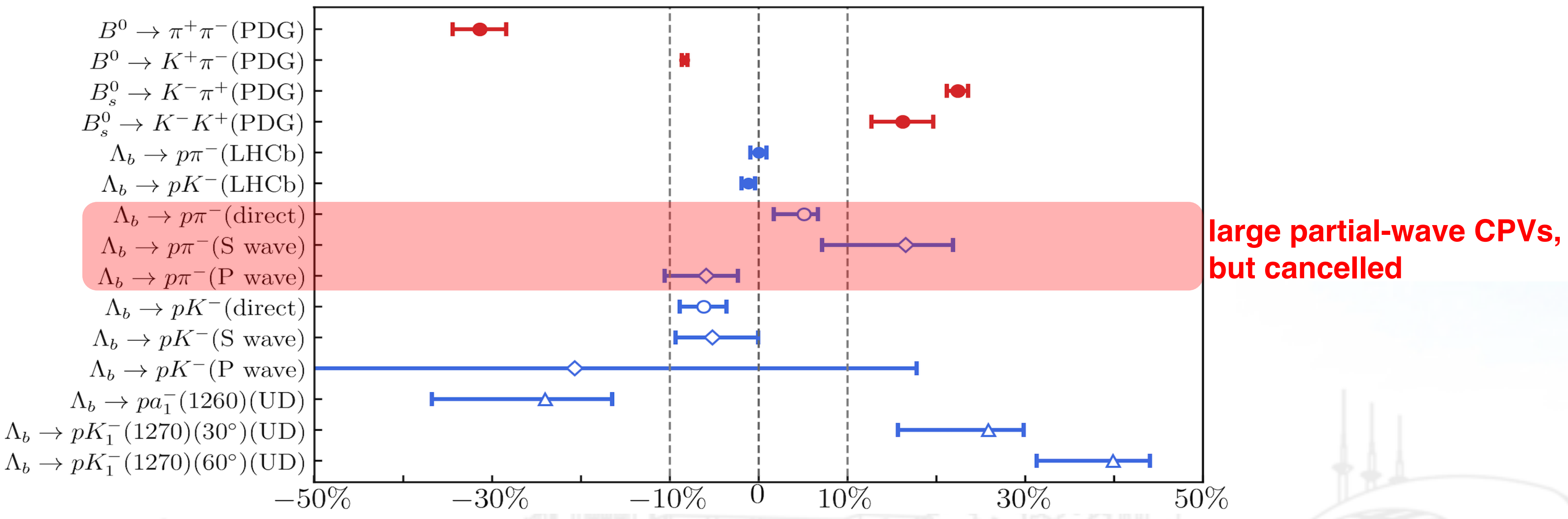
- **Hyperon CPV:**
  - SM: $\mathcal{O}\left(10^{-5} \sim 10^{-4}\right)$ [Donoghue, X.G.He, Pakvasa, 1986]
  - BESIII [Nature, 2022] $A_{CP}^{\alpha}(\Lambda \to p\pi^-) = (2.5 \pm 4.8) \times 10^{-3}$
- **Charm baryon CPV:**
  - SM: $\mathcal{O}\left(10^{-3} \sim 10^{-4}\right)$ [X.G.He, C.W.Liu, 2024] [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%**
  - $A_{CP}(\Lambda_b \to p\pi^-) = (0.2 \pm 0.8 \pm 0.4)\%$ [LHCb,2018,]
  - $A_{CP}(\Lambda_b \to pK^-) = (-1.1 \pm 0.7 \pm 0.4)\%$ [LHCb,2018,2024]

    $A_{CP}(\Lambda_b \to pK^-\pi^+\pi^-) = (2.45 \pm 0.46 \pm 0.10)\%$ [LHCb, 2024] — 5.2σ Evidence of CP violation
  - $A_{CP}(\Lambda_b^0 \to \Lambda K^+K^-) = (8.3 \pm 2.8)\%$ [LHCb,2025]
  - $A_{CP}(\Lambda_b^0 \to pK_S^0\pi^-) = (3.4 \pm 1.9 \pm 0.9)\%$ [LHCb,2025]

No evidence of CP violation is observed

Motivation

- 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 $\Lambda_b \to p\pi^-, pK^-$:tree-penguin interference [Han,PRL134, 221801 (2025)]

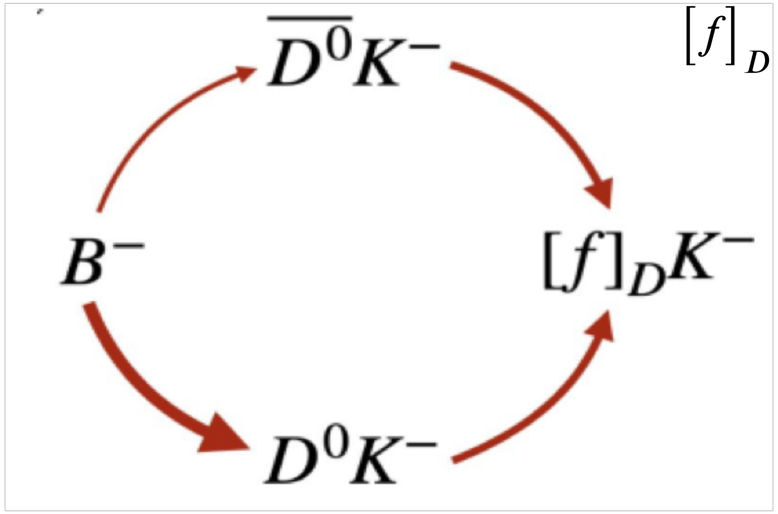


- What about the CPVs in the decays involving the tree-tree interference?

PART 02

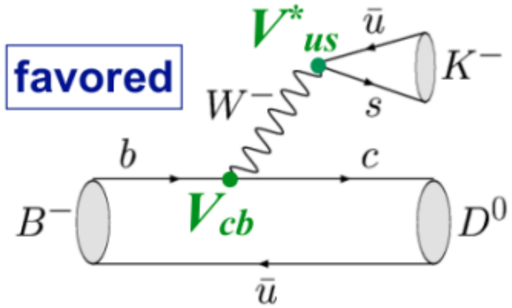
Large CPVs in $\Lambda_b \to \Lambda D$

Theoretical Framework

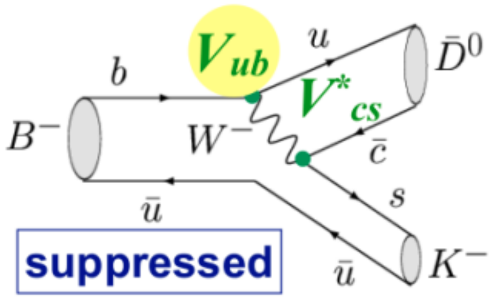


$$[f]_D = K^+K^-,\ K_S^0\pi^0$$

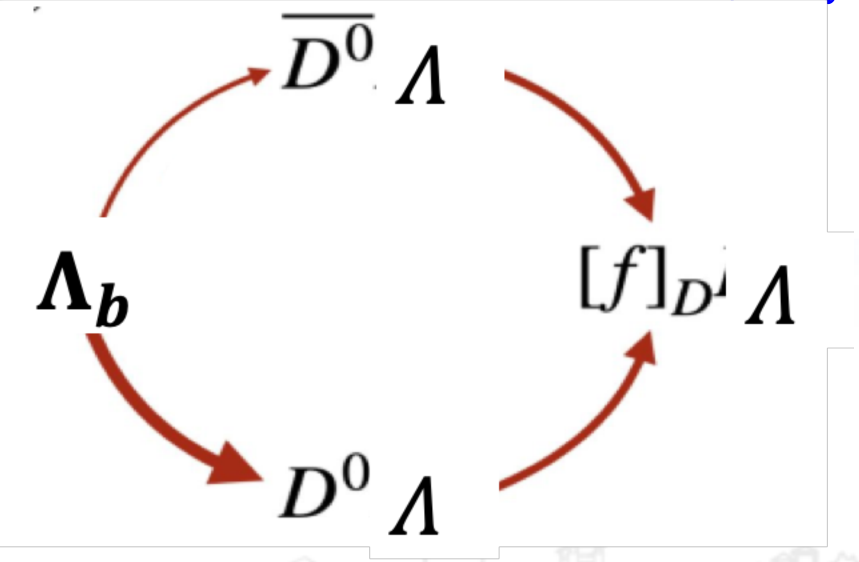
$B^- \rightarrow D^0 K^-$

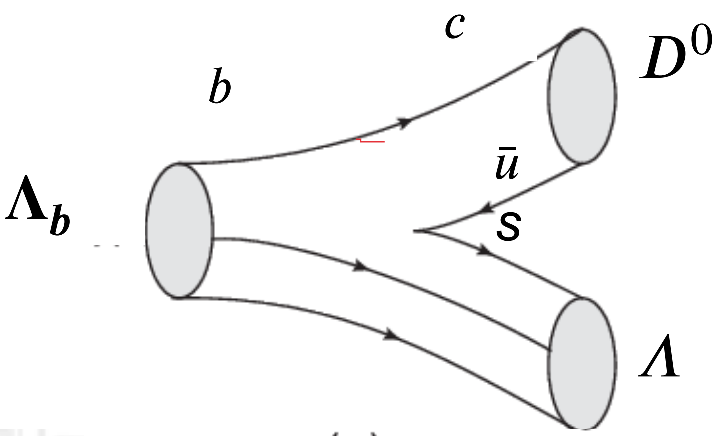


$B^- \rightarrow \overline{D^0} K^-$

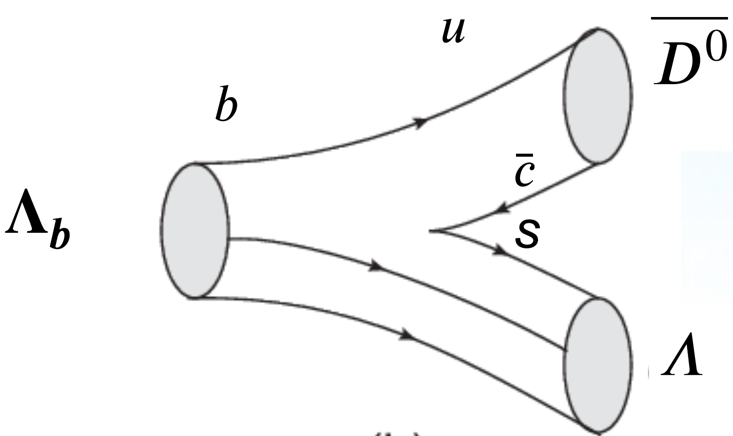


GLW, Phys. Lett. B 253, 483 (1991) .





(a)



(b)

Theoretical Framework

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

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

$$Q_+ = \left(M_{\Lambda_b} + M_\Lambda\right)^2 - M_D \qquad Q_- = \left(M_{\Lambda_b} - M_\Lambda\right)^2 - M_D$$

S wave *P wave*

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

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

There are no direct CP violations in both $\Lambda_b \to \Lambda D$ and $\Lambda_b \to \Lambda \bar{D}$

- Consider the CP eigenstates

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

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

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

- strong phase difference

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

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

- Ratios of amplitudes

$$r_S = \frac{S_{\bar{D}}}{S_D} \quad r_P = \frac{P_{\bar{D}}}{P_D}$$

Theoretical Framework

The global CP asymmetry is defined as

$$A_{CP}(\Lambda_b \to \Lambda D_{\pm}) \equiv \frac{|S_{\pm}|^2 + |P_{\pm}|^2 - |\bar{S}_{\pm}|^2 - |\bar{P}_{\pm}|^2}{|S_{\pm}|^2 + |P_{\pm}|^2 + |\bar{S}_{\pm}|^2 + |\bar{P}_{\pm}|^2},$$

$$= \kappa^{\pm} A_{\pm}^{S} + (1-\kappa^{\pm}) A_{\pm}^{P}$$

The weighted coefficients

$$\kappa^{\pm} = \frac{R_S^{\pm}}{R_S^{\pm} + R_P^{\pm}},$$

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

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

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

Theoretical Framework

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 $\dfrac{1}{x_i(1-x_j)Q^2+|k_{iT}|^2}$

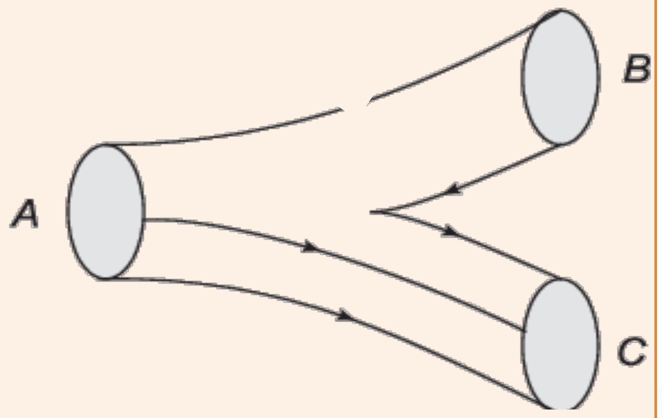
After resummation, Sudakov factors to suppress contribution from small k_T.

$$\mathscr{A} = \langle M_2 M_3 | \mathscr{H} | B \rangle$$
$$\sim \int \frac{d^4k_1}{(2\pi)^4}\frac{d^4k_2}{(2\pi)^4}\frac{d^4k_3}{(2\pi)^4}\Psi_B(k_1,\mu)\Psi_2(k_2,\mu)\Psi_3(k_3,\mu)\cdot H(k_1,k_2,k_3,\mu)C_i(\mu)$$
$$\sim \int_0^1 dx_2dx_2dx_3\int \frac{d^2k_{1T}}{(2\pi)^2}\frac{d^2k_{2T}}{(2\pi)^2}\frac{d^2k_{3T}}{(2\pi)^2}\phi_B(x_1,k_{1T},\mu)\phi_2(x_2,k_{2T},\mu)\phi_3(x_3,k_{3T},\mu)\cdot H(x_1,x_2,x_3,k_{1T},k_{2T},k_{3T},\mu)C_i(\mu)$$

Transition form factor is dominated from the perturbative region.

Nonfactorizable and annihilation diagrams can be calculated.

典型费曼图



Calculation based on PQCD Approach

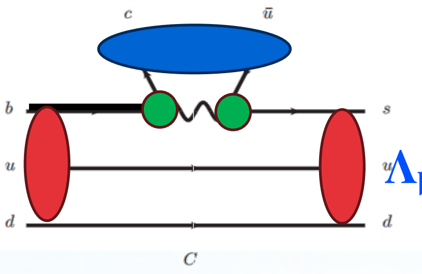
The effective Hamiltonian

$$\mathcal{H}_{eff} = \frac{G_F}{\sqrt{2}}\left[V_{cb}V_{us}^{*}\left(C_1 O_1^c + C_2 O_2^c\right) + V_{ub}V_{cs}^{*}\left(C_1 O_1^u + C_2 O_2^u\right)\right] + h.c.\,,$$

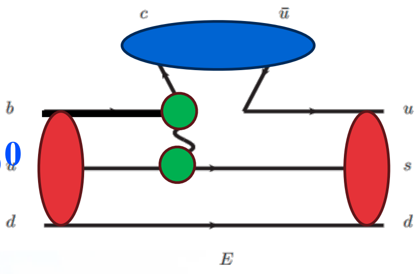
$$O_1^c = (\bar{c}_\beta u_\alpha)_{V-A}(\bar{d}_\alpha b_\beta)_{V-A}\,, \quad O_2^c = (\bar{c}_\alpha u_\alpha)_{V-A}(\bar{d}_\beta b_\beta)_{V-A}$$

$$O_1^u = (\bar{u}_\beta c_\alpha)_{V-A}(\bar{d}_\alpha b_\beta)_{V-A}\,, \quad O_2^u = (\bar{u}_\alpha c_\alpha)_{V-A}(\bar{d}_\beta b_\beta)_{V-A}$$

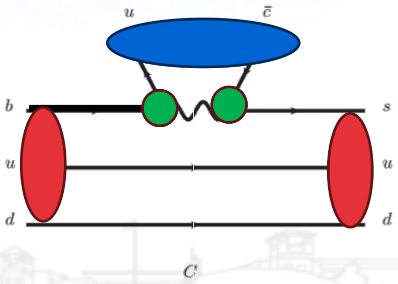
$b \to cs\bar{u}$



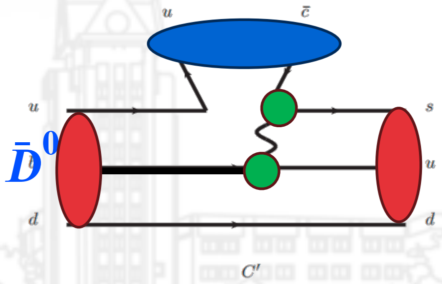
$\Lambda_b \to \Lambda D^0$



$b \to us\bar{c}$



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



- Besides the color suppressed diagrams, we should include the contributions from W-exchanged diagrams.
- Two hard gluons are needed, so the spectator quarks become collinear, which makes the calculations nontrivial.

Numerical Results

烟台大学 YANTAI UNIVERSITY

- Partial wave amplitudes of $\Lambda_b \to \Lambda D$ in PQCD without the CKM matrix elements, $\times 10^{-6}$

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

Numerical Results

烟台大学 YANTAI UNIVERSITY

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

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 $\bar{\mathrm{D}}^0$ 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.
- This patten cannot be generalized to $\Xi_b \to \Xi D_\pm$cases, as the W -exchange and internal W -emission diagrams are absent。

Numerical Results

烟台大学 YANTAI UNIVERSITY

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

Mode	This work	Zhu'19	Giri'02	Geng'22
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

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

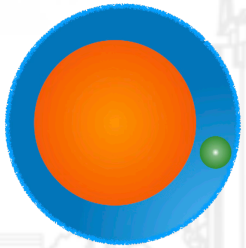
D	$\mathcal{B}(10^{-5})$	A_{CP}	κA^S_{CP}	$(1-\kappa)A^P_{CP}$
D^0	$3.1^{+1.8}_{-0.8}$	0	0	0
$\bar{D}^0$	$2.3^{+1.1}_{-0.7}$	0	0	0
D_+	$1.9^{+1.1}_{-0.4}$	$-0.44^{+0.10}_{-0.05}$	$-0.25^{+0.08}_{-0.01}$	$-0.19^{+0.04}_{-0.04}$
D_-	$3.5^{+1.9}_{-1.0}$	$0.72^{+0.06}_{-0.14}$	$0.42^{+0.01}_{-0.11}$	$0.30^{+0.05}_{-0.06}$

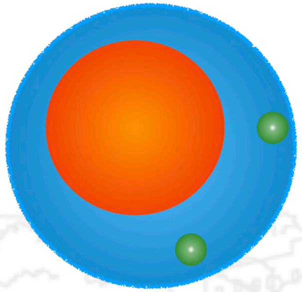
Uncertainties

- The theoretical calculation based on PQCD have many uncertainties.

$$\mathcal{A} = \int_0^1 [dx] \int [d^2b] \Psi_{\Lambda_b} T_H \Psi_p \Psi_h e^{-S}.$$

- Framework: **Factorization and soft gluons**
- Non-perturbative inputs: **wave functions for hadrons.**
- Higher power and high order corrections: **high-twist contributions of DAs; $O(\alpha_s^3)$**





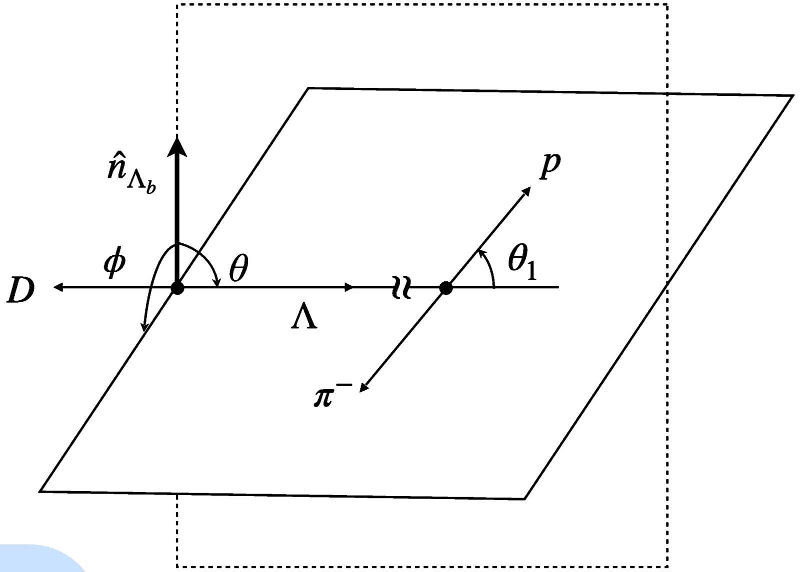
PART 03

Extraction of the CKM angle γ

Lee-Yang Parameters in $\Lambda_b \to \Lambda D$ Decays

- Three decay parameters for the $\Lambda_b \to \Lambda D$ decay, which characterize the strengths of the S- and P -waves, are defined in terms of the partial-wave amplitudes as

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



- We write $\mathcal{A}_\pm = |S_\pm|^2 + |P_\pm|^2$, then

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

- We obtain

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

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

Extraction of CKM γ

- **Similarly, we also have**

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 $\alpha'_\pm$.

守信 求实 好学 力行

烟台大学 YANTAI UNIVERSITY

PART 04

Summary

Summary

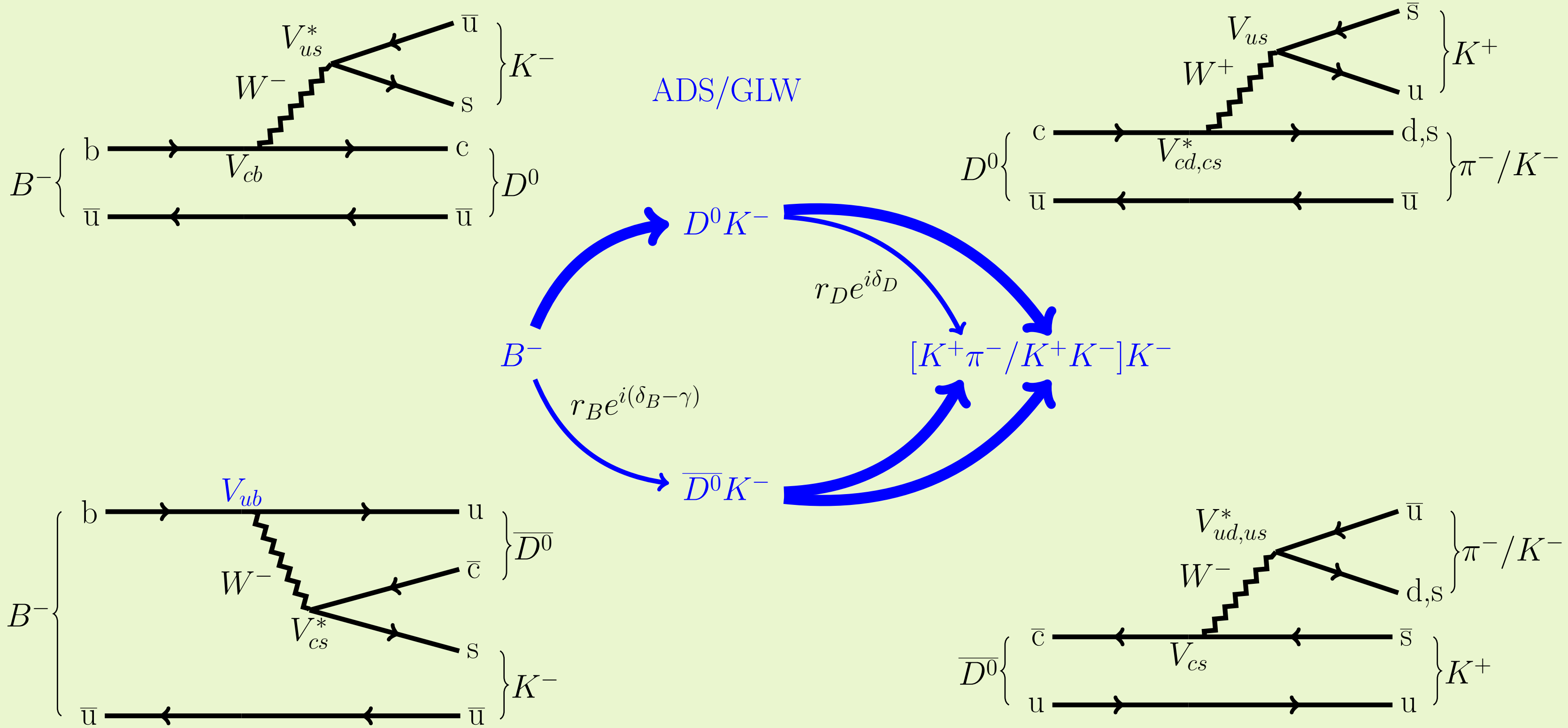
- Large CPV are predicted in the $\Lambda_b \to \Lambda D$ decays, which offers a direct measurement of γ in the baryon sector.

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

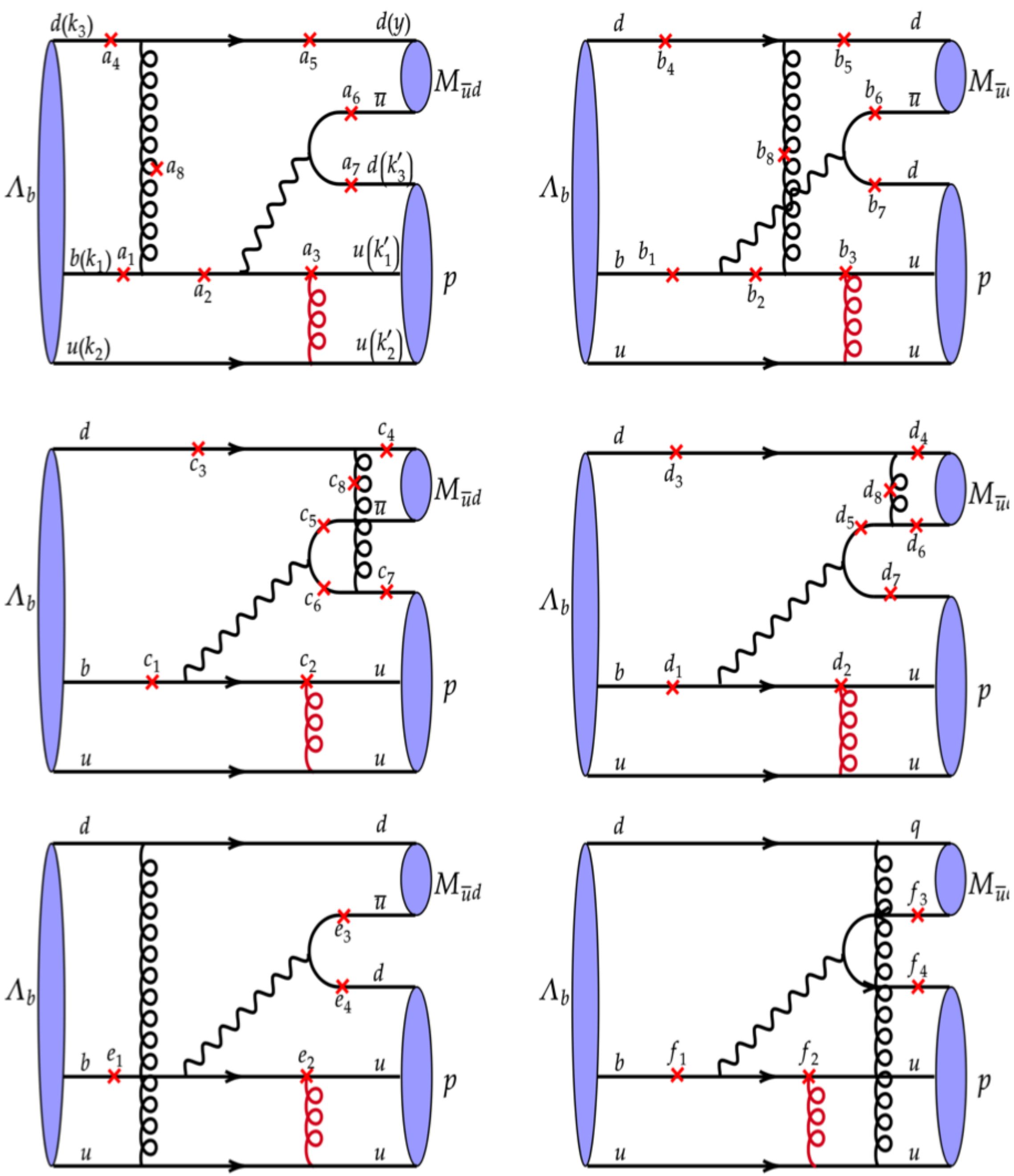
- First predictions of several nonzero CP-violating observables associated with angular distribution parameters.

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

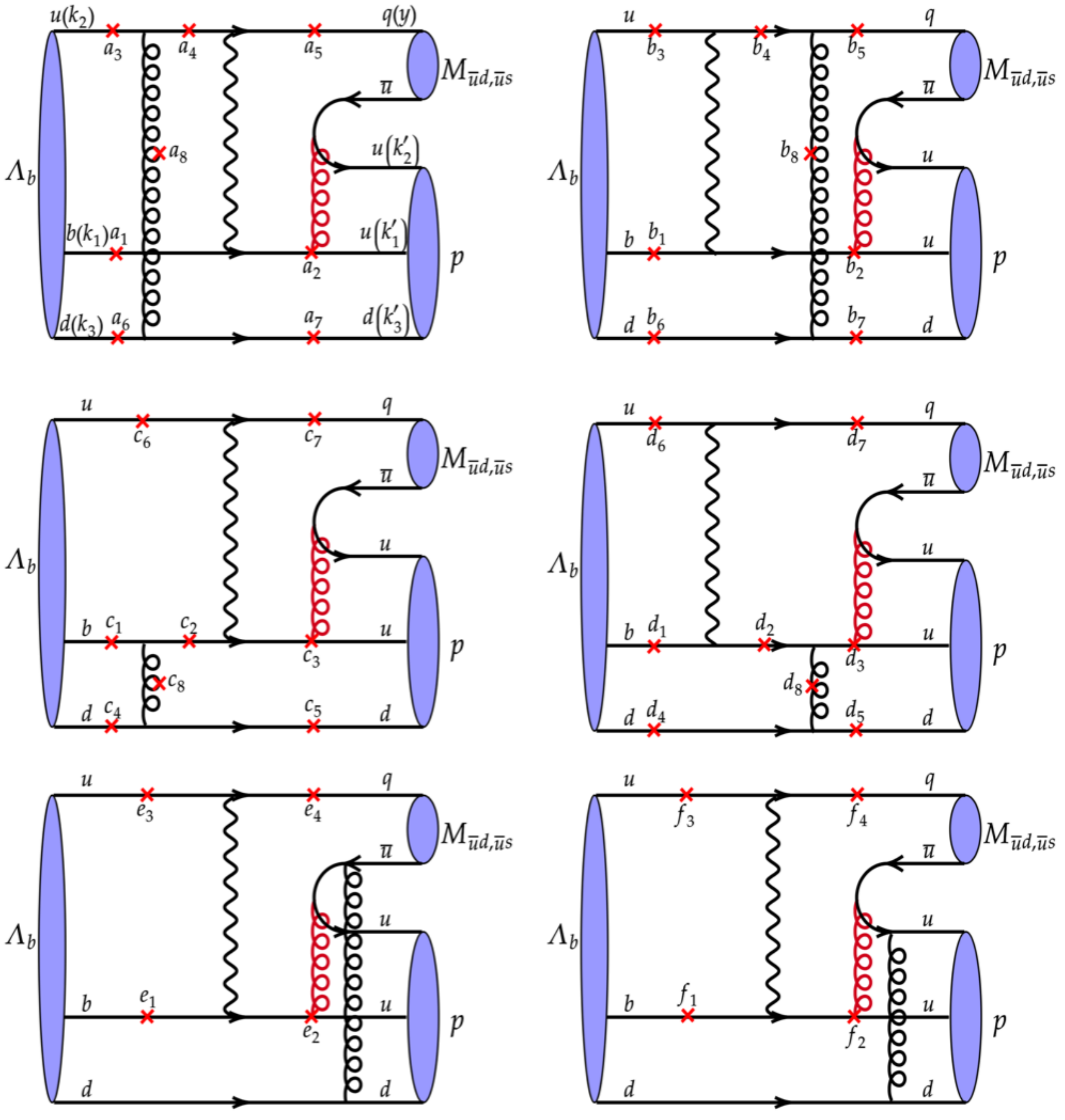
谢谢，敬请指正！



V^*_{us}
W^-
$\bar{u}$
s
K^-
B^-
b
c
V_{cb}
D^0
$\bar{u}$
$\bar{u}$
ADS/GLW
V_{us}
W^+
$\bar{s}$
u
K^+
D^0
c
d,s
$V^*_{cd,cs}$
π^-/K^-
$\bar{u}$
$\bar{u}$
D^0K^-
$r_De^{i\delta_D}$
B^-
$[K^+\pi^-/K^+K^-]K^-$
$r_Be^{i(\delta_B-\gamma)}$
$\overline{D^0}K^-$
V_{ub}
b
u
$\overline{D^0}$
W^-
$\bar{c}$
B^-
V^*_{cs}
s
K^-
$\bar{u}$
$\bar{u}$
$V^*_{ud,us}$
W^-
$\bar{u}$
d,s
π^-/K^-
$\overline{D^0}$
$\bar{c}$
$\bar{s}$
V_{cs}
K^+
u
u



Λb
p
M_ūd
d(k3) a4 a5 d(y)
a6 ū a7 d(k'3)
a8
b(k1) a1 a2 a3 u(k'1)
u(k2) u(k'2)
b1 b2 b3 b4 b5 b6 b7 b8
c1 c2 c3 c4 c5 c6 c7 c8
d1 d2 d3 d4 d5 d6 d7 d8
e1 e2 e3 e4
f1 f2 f3 f4
d u b ū q



Λb
p
M_ūd,ūs
u(k2) a3 a4 a5 q(y)
ū u(k'2)
a8
b(k1) a1 a2 u(k'1)
d(k3) a6 a7 d(k'3)
b1 b2 b3 b4 b5 b6 b7 b8
c1 c2 c3 c4 c5 c6 c7 c8
d1 d2 d3 d4 d5 d6 d7 d8
e1 e2 e3 e4
f1 f2 f3 f4
u b d ū q