CP Violation in b-hadron Decays
b強子衰變中的CP破壞

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Outline

- Motivation
- ***Direct CP Violation in 3-body Baryonic B Decays***
- ***Direct CP Violation in Λ_b Decays***
- ***Summary***

• Motivation

The Standard Model:

Cabibbo, Kobayahsi and Maskawa (CKM) Quark Mixing Matrix

$$V_{CKM} = = \begin{pmatrix} c_1c_3 & s_1c_3 & s_3e^{-i\delta} \\ -s_1c_2 - c_1s_2s_3e^{i\delta} & c_1c_2 - s_1s_2s_3e^{i\delta} & s_2c_3 \\ s_1s_2 - c_1c_2s_3e^{i\delta} & -c_1s_2 - s_1c_2s_3e^{i\delta} & c_2c_3 \end{pmatrix}$$

a unique CP phase

CP violation

- **K^0 system: indirect (ε) and direct (ε′/ε) ($K_L \to \pi\pi$)**
- **B^0 system: mixed induced ($B^0 \to J/\psi K_s$)+ direct ($B^0 \to \pi\pi, K\pi$)**

Direct ~~CP~~ in charged systems: $K^{\pm}$? $B^{\pm}$?

Th: $\mathcal{A}_{CP}(\bar{B}^0 \to K^-\pi^+) \simeq \mathcal{A}_{CP}(B^- \to K^-\pi^0)$ but

$\mathcal{A}_{\overline{B}^0 \to K^-\pi^+} = -0.082 \pm 0.006$

$\mathcal{A}_{B^- \to K^-\pi^0} = 0.040 \pm 0.021$

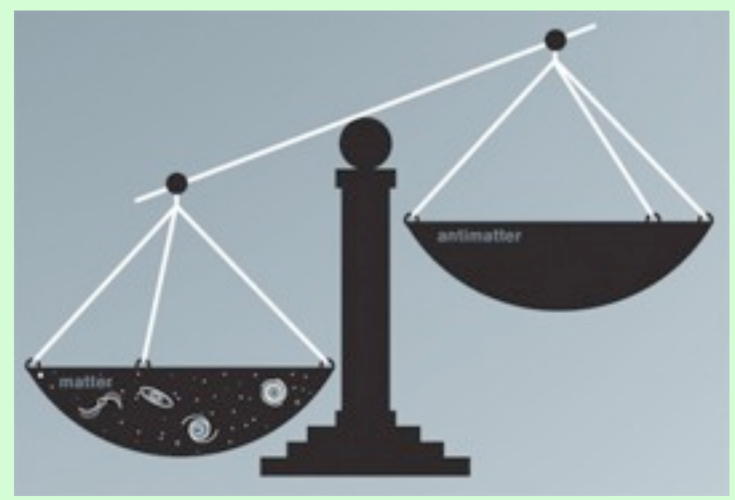
Matter-antimatter asymmetry

1. Baryon number violation

2. C and CP violation

3. A departure from thermal equilibrium

1967: Sakharov



?

See 舒菁's talk

The CP violating mechanism in the SM, i.e. the phase in the CKM, cannot account for the matter-antimatter asymmetry in the universe. → **New Physics**

To study *direct CP violation* in heavy flavor (b-hadron) systems

LHCb + SuperKEKB

Goal **To test the standard model and look for New Physics!**

Direct CP-violating asymmetry (CPA) in the B decays:

$$\mathcal{A}_{CP}(\bar{B} \to \bar{f}) = \frac{\Gamma(\bar{B}\to\bar{f})-\Gamma(B\to f)}{\Gamma(\bar{B}\to\bar{f})+\Gamma(B\to f)}$$

$$\mathcal{A}(B \to f) = ae^{i\delta_w} + be^{i\delta_s}$$

$$\mathcal{A}(\bar{B} \to \bar{f}) = ae^{-i\delta_w} + be^{i\delta_s}$$

$$\Gamma(B \to f) \neq \Gamma(\bar{B} \to \bar{f})$$

δ_w: $V_{ub} = A\lambda^3(\rho - i\eta)$ ← weak CP phase

δ_s: effective Wilson coefficients, final state interactions, ...

on-shell processes give the imaginary parts ← strong CP phase

See 何小刚,李新強, 張振華's talks

• Direct CP Violation in 3-body Baryonic B Decays

☺ Three-body charmless baryonic B decays:

$$Br(B^- \to p\bar{p}\pi^-) = (1.62 \pm 0.20) \times 10^{-6}$$
$$Br(\bar{B}^0 \to p\bar{p}K^0) = (2.7 \pm 0.3) \times 10^{-6}$$
$$Br(B^- \to p\bar{p}K^-) = (5.9 \pm 0.5) \times 10^{-6}$$
$$Br(\bar{B}^0 \to p\bar{p}\bar{K}^{*0}) = (1.2 \pm 0.3) \times 10^{-6}$$
$$Br(B^- \to p\bar{p}K^{*-}) = (3.6 \pm 0.8) \times 10^{-6}$$

$$Br(\bar{B}^0 \to p\bar{p}) = (1.47^{+0.71}_{-0.53}) \times 10^{-8} \quad \text{(LHCb)}$$

$$Br(B^- \to \Lambda\bar{p}\gamma) = (2.4 \pm 0.5) \times 10^{-6}$$
$$Br(B^- \to \Lambda\bar{p}\pi^0) = (3.0 \pm 0.7) \times 10^{-6}$$
$$Br(\bar{B}^0 \to \Lambda\bar{p}\pi^+) = (3.14 \pm 0.29) \times 10^{-6}$$

$$Br(B^- \to \Lambda\bar{p}) < 32 \times 10^{-8} \quad \text{(BELLE)}$$

$$Br(B^- \to \Lambda\bar{\Lambda}K^-) = (3.4 \pm 0.6) \times 10^{-6}$$
$$Br(\bar{B}^0 \to \Lambda\bar{\Lambda}\bar{K}^0) = (4.8 \pm 1.0) \times 10^{-6}$$
$$Br(\bar{B}^0 \to \Lambda\bar{\Lambda}\bar{K}^{*0}) = (2.5 \pm 1.0) \times 10^{-6}$$
$$Br(B^- \to \Lambda\bar{\Lambda}K^{*-}) = (2.2^{+1.2}_{-0.9}) \times 10^{-6}$$
$$Br(B^- \to \Lambda\bar{\Lambda}\pi^-) < 0.94 \times 10^{-6}$$

$$Br(\bar{B}^0 \to \Lambda\bar{\Lambda}) < 32 \times 10^{-8} \quad \text{(BELLE)}$$

• **Large BRs:** **Br(*B*→BB′P) >> Br(*B*→BB′) due to the threshold enhancements** ← Hou+Soni, PRL86(01)4247

• Direct CP Violation in 3-body Baryonic B Decays

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$$

Using the generalized factorization method along with QCD counting rule
+
SU(3)$_F$ & SU(2)$_S$ symmetries

Chua, Hou,Tsai, PRD66 (2002) 054004;
Chua,Hou, Eur. Phys. J. C 29 (2003) 27;
CQG, Hsiao, PLB610 (2005) 67;
CQG, Hsiao, PLB619 (2005) 305;
CQG, Hsiao, PRD72 (2005) 037901;
CQG, Hsiao, PRD74 (2006) 094023;
CQG, Hsiao, Ng, PRL98 (2007) 011801;
CQG, Hsiao, Ng, PRD75 (2007) 094005;
CQG, Hsiao, PRD85 (2012) 017501.
....

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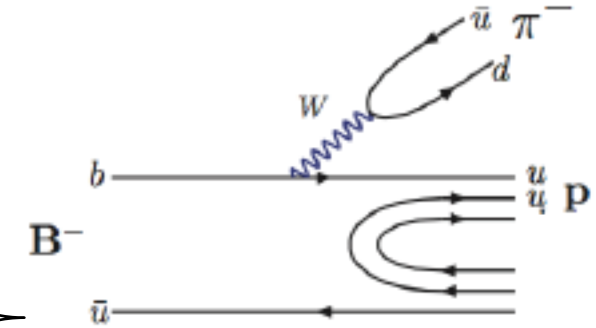

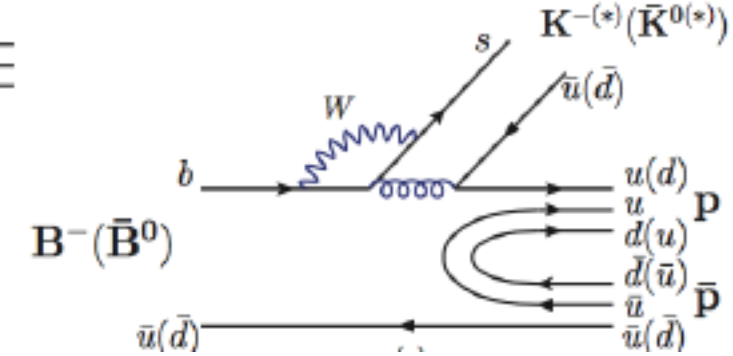

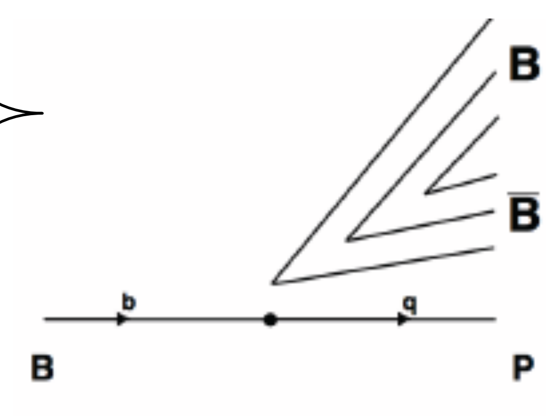

- **Large BRs:** Br(B→BB′P) >> Br(B→BB′) due to the threshold enhancements ← Hou+Soni, PRL86(01)4247

- **Large direct CP violation in charged B modes of** $B^\pm \to p\bar{p}K^{(*)\pm}$ ← CQG,Hsiao,Ng PRL98(07)011801

CQG+Hsiao+Ng, PRL98,011801 (2007)

The direct CP asymmetries in $B^\pm \to p\bar{p}M^\pm$ $(M = K, K^*)$:

$$A_{CP}(M) = \frac{\Gamma(B^- \to p\bar{p}M^-) - \Gamma(B^+ \to p\bar{p}M^+)}{\Gamma(B^- \to p\bar{p}M^-) + \Gamma(B^+ \to p\bar{p}M^+)}$$

$$A_{CP}(K^{(*)}) = \frac{|\alpha_{K^{(*)}}|^2 - |\bar{\alpha}_{K^{(*)}}|^2}{|\alpha_{K^{(*)}}|^2 + |\bar{\alpha}_{K^{(*)}}|^2}$$

Free of hadronic uncertainty

The amplitudes of $B^- \to p\bar{p}K^{(*)-}$:

$$\mathcal{A}_K = i\frac{G_F}{\sqrt{2}} m_b f_K \left[\alpha_K \langle p\bar{p}|\bar{u}b|B^-\rangle + \beta_K \langle p\bar{p}|\bar{u}\gamma_5 b|B^-\rangle\right]$$

$$\mathcal{A}_{K^*} = \frac{G_F}{\sqrt{2}} m_{K^*} f_{K^*} \varepsilon^\mu \alpha_{K^*} \langle p\bar{p}|\bar{u}\gamma_\mu(1-\gamma_5)b|B^-\rangle$$

$$\alpha_K(\beta_K) \equiv V_{ub}V_{us}^* a_1 - V_{tb}V_{ts}^*\left[a_4 \pm \frac{2m_K^2}{m_b m_s} a_6\right]$$

$$\alpha_{K^*} \equiv V_{ub}V_{us}^* a_1 - V_{tb}V_{ts}^* a_4$$

$(|\alpha_K|^2 \gg |\beta_K|^2)$

(N_c=3 at the scale m_b)

$$a_1 = c_1^{eff} + c_2^{eff}/N_c$$
$$a_4 = c_4^{eff} + c_3^{eff}/N_c$$
$$a_6 = c_6^{eff} + c_5^{eff} N_c$$

$$a_1 = 1.05$$

$$a_4 = [(-427.8 \mp 9.1\eta - 3.9\rho) + i(-83.2 \pm 3.9\eta - 9.1\rho)] \times 10^{-4}$$

$$a_6 = [(-595.5 \mp 9.1\eta - 3.9\rho) + i(-83.2 \pm 3.9\eta - 9.1\rho)] \times 10^{-4}$$

c_i^{eff} $(i = 1, 2, \ldots, 6)$ being effective Wilson coefficients (WC's)

for the $b \to s$ $(\bar{b} \to \bar{s})$ transition

Direct CP asymmetries in $B \to \mathbf{B}\bar{\mathbf{B}}'M$:

$B \to \mathbf{B}\bar{\mathbf{B}}'M$	$B^\pm \to p\bar{p}K^{*\pm}$	$B^\pm \to p\bar{p}K^\pm$	$B^\pm \to p\bar{p}\rho^\pm$	$B^\pm \to p\bar{p}\pi^\pm$
$\mathcal{A}_{CP}(M)$	0.22 ± 0.04	0.06 ± 0.01	-0.03	-0.06
Belle (2004)		-0.05 ± 0.11		
BaBar (2005)		-0.16 ± 0.09		
BaBar* (2006)	0.26 ± 0.19	$-0.13^{+0.08}_{-0.07}$		0.06 ± 0.02
BaBar (2007)	0.32 ± 0.14			0.04 ± 0.07
Belle (2008)	-0.01 ± 0.20	-0.02 ± 0.05		-0.17 ± 0.11
PDG (2014)	0.21 ± 0.16	-0.16 ± 0.07		0 ± 0.04
LHCb** (2014)		0.021 ± 0.020		-0.041 ± 0.039

CQG+Hsiao+Ng, PRL98,011801 (2007)

* T.B.Hryn'ova, SLAC-R-810 (2006)

** PRL113, 141801 (2014)

Large , Accessible to the LHCb as well as SuperKEKB!

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Large , Accessible to the LHCb as well as SuperKEKB!

Remarks:

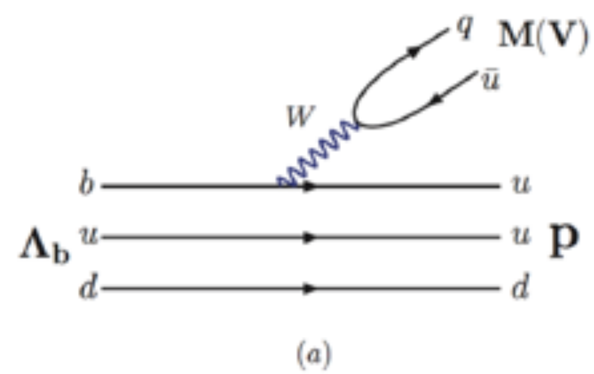
1. Independent of BR measurements+Free of hadronic uncertainties
2. $\Delta A_{CP}(K^{(*)})|_{CKM\ elements} \sim 0.01$
3. Small nonfactorizable contributions:

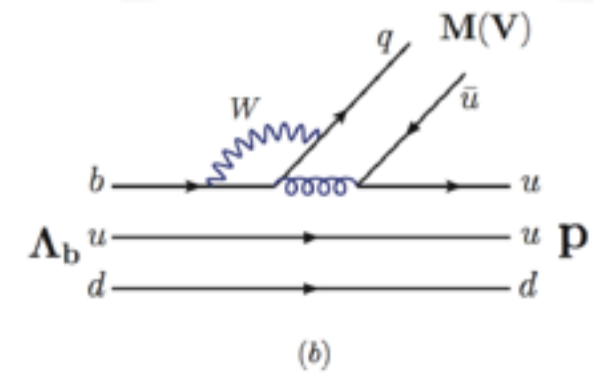
   $\Delta A_{CP}(K^{(*)}) \leq 0.005\ (0.04)$ for $N_c = 3 \to N_c^{eff} = 2$ and ∞
4. Annihilation contributions and final state interactions – suppressed

• *Direct CP Violation in Λ_b Decays:* $\Lambda_b \to pM(V)$

$M = \pi, K$
$V = \rho, K^*$

	pQCD[1]	data
$10^6\mathcal{B}(\Lambda_b \to pK^-)$	$2.0^{+1.0}_{-1.3}$	4.9 ± 0.9[2]
$10^6\mathcal{B}(\Lambda_b \to p\pi^-)$	$5.2^{+2.5}_{-1.9}$	4.1 ± 0.8[2]
$10^6\mathcal{B}(\Lambda_b \to pK^{*-})$	—	—
$10^6\mathcal{B}(\Lambda_b \to p\rho^-)$	—	—
$10^2\mathcal{A}_{CP}(\Lambda_b \to pK^-)$	$-5^{+26}_{-\ 5}$	$-10 \pm 8 \pm 4$[3]
$10^2\mathcal{A}_{CP}(\Lambda_b \to p\pi^-)$	$-31^{+43}_{-\ 1}$	$6 \pm 7 \pm 3$[3]
$10^2\mathcal{A}_{CP}(\Lambda_b \to pK^{*-})$	—	—
$10^2\mathcal{A}_{CP}(\Lambda_b \to p\rho^-)$	—	—



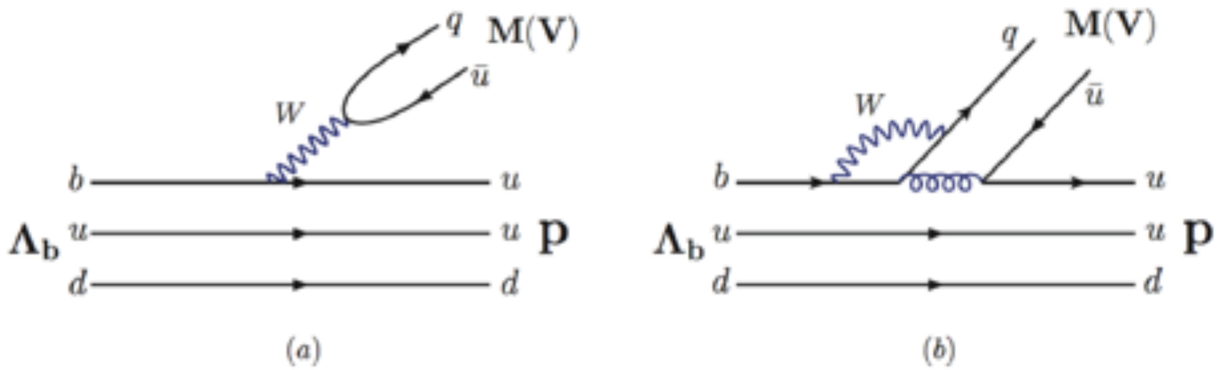


1. without annihilation
2. without color-suppressed tree amp

[1] **C.D. Lu, Y.M. Wang, H. Zou, A. Ali and G. Kramer, PRD80, 034011 (2009).**

[2] **PDG**

[3] **CDF, PRL106, 181802 (2011); arXiv:1403.5586 [hep-ex].**



$\Lambda_b \to pM(V)$

$M = \pi, K$
$V = \rho, K^*$

Y.K.Hsiao+CQG, PRD91,116007(2015)

$$\mathcal{A}(\Lambda_b \to pM) = i\frac{G_F}{\sqrt{2}}m_b f_M\left[\alpha_M\langle p|\bar{u}b|\Lambda_b\rangle + \beta_M\langle p|\bar{u}\gamma_5 b|\Lambda_b\rangle\right]$$

$$\langle M|\bar{q}_1\gamma_\mu\gamma_5 q_2|0\rangle = -if_M q_\mu$$
$$\langle V|\bar{q}_1\gamma_\mu q_2|0\rangle = m_V f_V \varepsilon^*_\mu$$

$$\mathcal{A}(\Lambda_b \to pV) = \frac{G_F}{\sqrt{2}}m_V f_V \varepsilon^{\mu *}\alpha_V\langle p|\bar{u}\gamma_\mu(1-\gamma_5)b|\Lambda_b\rangle$$

$$\alpha_M(\beta_M) = V_{ub}V^*_{uq}a_1 - V_{tb}V^*_{tq}(a_4 \pm r_M a_6)$$

$$\alpha_V = V_{ub}V^*_{uq}a_1 - V_{tb}V^*_{tq}a_4$$

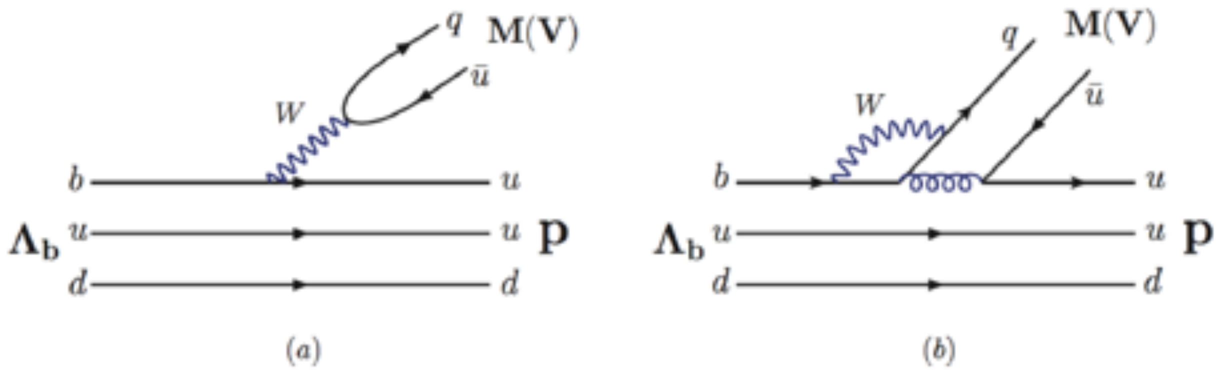
$$r_M \equiv 2m_M^2/[m_b(m_q+m_u)]$$
$$a_i \equiv c_i^{eff} + c_{i\pm 1}^{eff}/N_c^{(eff)} \text{ for } i = \text{odd (even)}$$

$$\langle p|\bar{u}\gamma_\mu b|\Lambda_b\rangle = \bar{u}_p[f_1\gamma_\mu + \frac{f_2}{m_{\Lambda_b}}i\sigma_{\mu\nu}q^\nu + \frac{f_3}{m_{\Lambda_b}}q_\mu]u_{\Lambda_b}$$
$$\langle p|\bar{u}\gamma_\mu\gamma_5 b|\Lambda_b\rangle = \bar{u}_p[g_1\gamma_\mu + \frac{g_2}{m_{\Lambda_b}}i\sigma_{\mu\nu}q^\nu + \frac{g_3}{m_{\Lambda_b}}q_\mu]\gamma_5 u_{\Lambda_b}$$
$$\langle p|\bar{u}b|\Lambda_b\rangle = f_S\bar{u}_p u_{\Lambda_b}$$
$$\langle p|\bar{u}\gamma_5 b|\Lambda_b\rangle = f_P\bar{u}_p\gamma_5 u_{\Lambda_b}$$

$$f_1 = g_1 \text{ and } f_{2,3} = g_{2,3} = 0$$

- By the SU(3) flavor and SU(2) spin symmetries or the heavy-quark and large-energy symmetries

Khodjamirian, Klein, Mannel, Wang, JHEP 1109, 106 (2011);
T. Mannel and Y. M. Wang, JHEP 1112, 067 (2011).



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$$\langle p|\bar{u}\gamma_\mu b|\Lambda_b\rangle = f_1 \bar{u}_p\gamma_\mu u_{\Lambda_b}$$
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$$f_1 = g_1 \text{ and } f_{2,3} = g_{2,3} = 0$$

$$f_1(q^2) = \frac{C_F}{(1-q^2/m^2_{\Lambda_b})^2}$$

- By the SU(3) flavor and SU(2) spin symmetries or the heavy-quark and large-energy symmetries

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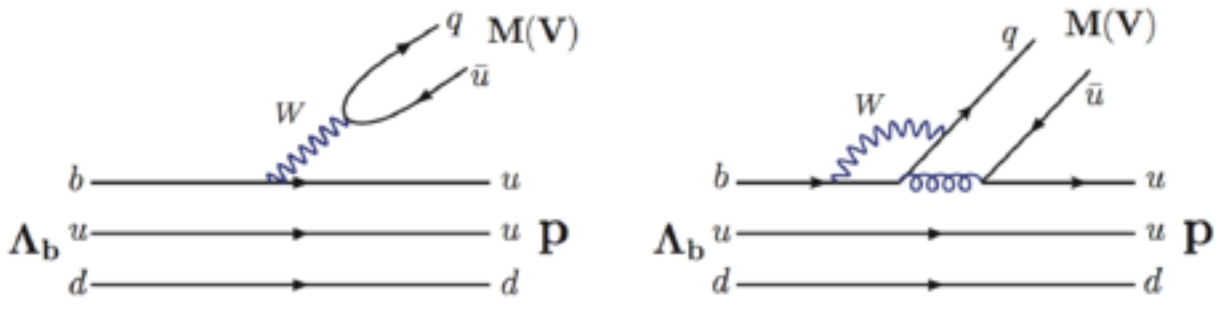

(a) (b)

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$$\langle p|\bar{u}\gamma_\mu b|\Lambda_b\rangle = f_1 \bar{u}_p\gamma_\mu u_{\Lambda_b}$$
$$\langle p|\bar{u}\gamma_\mu\gamma_5 b|\Lambda_b\rangle = g_1 \bar{u}_p\gamma_\mu\gamma_5 u_{\Lambda_b}$$
$$\langle p|\bar{u}b|\Lambda_b\rangle = f_S \bar{u}_p u_{\Lambda_b}$$
$$\langle p|\bar{u}\gamma_5 b|\Lambda_b\rangle = f_P \bar{u}_p\gamma_5 u_{\Lambda_b}$$

$$f_1 = g_1 \text{ and } f_{2,3} = g_{2,3} = 0$$
$$f_1(q^2) = \frac{C_F}{(1-q^2/m^2_{\Lambda_b})^2}$$

$$f_S = \frac{m_{\Lambda_b} - m_p}{m_b - m_u} f_1 \,, \quad f_P = \frac{m_{\Lambda_b} + m_p}{m_b + m_u} g_1$$

EoM

$$\mathcal{R}_{\pi K} \equiv \frac{\mathcal{B}(\Lambda_b \to p\pi^-)}{\mathcal{B}(\Lambda_b \to pK^-)} = \frac{f_\pi^2}{f_K^2} \frac{|\alpha_\pi|^2 + |\alpha_{\bar{\pi}}|^2}{|\alpha_K|^2 + |\alpha_{\bar{K}}|^2} \frac{1+\xi_\pi^+}{1+\xi_K^+}$$

$$\mathcal{R}_{\rho K^*} \equiv \frac{\mathcal{B}(\Lambda_b \to p\rho^-)}{\mathcal{B}(\Lambda_b \to pK^{*-})} = \frac{f_\rho^2}{f_{K^*}^2} \frac{|\alpha_\rho|^2 + |\alpha_{\bar{\rho}}|^2}{|\alpha_{K^*}|^2 + |\alpha_{\bar{K}^*}|^2}$$

$$\mathcal{A}_{CP}(\Lambda_b \to pM) = \left(\frac{|\alpha_M|^2 - |\alpha_{\bar{M}}|^2}{|\alpha_M|^2 + |\alpha_{\bar{M}}|^2} + \xi_M^- \right) \frac{1}{1+\xi_M^+}$$

$$\mathcal{A}_{CP}(\Lambda_b \to pV) = \frac{|\alpha_V|^2 - |\alpha_{\bar{V}}|^2}{|\alpha_V|^2 + |\alpha_{\bar{V}}|^2}$$

$$\xi_M^\pm \equiv \left(\frac{|\beta_M|^2 \pm |\beta_{\bar{M}}|^2}{|\alpha_M|^2 + |\alpha_{\bar{M}}|^2} \right) R_{\Lambda_b \to p}$$

$$R_{\Lambda_b \to p} = |\langle p|\bar{u}\gamma_5 b|\Lambda_b\rangle|^2 / |\langle p|\bar{u}b|\Lambda_b\rangle|^2$$

$$R_{\Lambda_b \to p} = 1.008\,,$$

CKM matrix elements + Effective Wilson Coeffs

$$(\xi_\pi^+,\, \xi_K^+) = (1.03 \pm 0.04 \pm 0.00,\ 0.11 \pm 0.01 \pm 0.02)\,,$$

$$(\xi_\pi^-,\, \xi_K^-) = (-4.0 \pm 0.3 \pm 0.0,\ -4.0 \pm 0.2 \pm 0.3) \times 10^{-3}$$

the CKM matrix elements

non-factorizable effects

$(f_\pi, f_K, f_\rho, f_{K^*}) =$

$(130.4 \pm 0.2,\ 156.2 \pm 0.7,\ 210.6 \pm 0.4,\ 204.7 \pm 6.1)$ MeV

$C_F = 0.136 \pm 0.009$

by fitting the two branching ratios

$C_F = 0.14 \pm 0.03$

from the light-cone sum rules

JHEP 1109, 106 (2011); JHEP 1112, 067 (2011)

	$\mathcal{R}_{\pi K}$	$\mathcal{R}_{\rho K^*}$
our result	$0.84 \pm 0.09 \pm 0.00$	$4.6 \pm 0.5 \pm 0.1$
pQCD [4]	$2.6^{+2.0}_{-0.5}$	—
CDF [14]	$0.66 \pm 0.14 \pm 0.08$	—
LHCb [15]	$0.86 \pm 0.08 \pm 0.05$	—

[4] C.D. Lu *et al.*, Phys. Rev. D **80**, 034011 (2009).

[14] T. Aaltonen *et al.* [CDF Collaboration], Phys. Rev. Lett. **103**, 031801 (2009).

[15] R. Aaij *et al.* [LHCb Collaboration], JHEP **1210**, 037 (2012).

	our result *	pQCD[1]	data
$10^6\mathcal{B}(\Lambda_b \to pK^-)$	$4.8 \pm 0.7 \pm 0.1 \pm 0.3$	$2.0^{+1.0}_{-1.3}$	4.9 ± 0.9[2]
$10^6\mathcal{B}(\Lambda_b \to p\pi^-)$	$4.2 \pm 0.6 \pm 0.4 \pm 0.2$	$5.2^{+2.5}_{-1.9}$	4.1 ± 0.8[2]
$10^6\mathcal{B}(\Lambda_b \to pK^{*-})$	$2.5 \pm 0.3 \pm 0.2 \pm 0.3$	—	—
$10^6\mathcal{B}(\Lambda_b \to p\rho^-)$	$11.4 \pm 1.6 \pm 1.2 \pm 0.6$	—	—
$10^2\mathcal{A}_{CP}(\Lambda_b \to pK^-)$	$5.8 \pm 0.2 \pm 0.1$	-5^{+26}_{-5}	$-10 \pm 8 \pm 4$[3]
$10^2\mathcal{A}_{CP}(\Lambda_b \to p\pi^-)$	$-3.9 \pm 0.2 \pm 0.0$	-31^{+43}_{-1}	$6 \pm 7 \pm 3$[3]
$10^2\mathcal{A}_{CP}(\Lambda_b \to pK^{*-})$	$19.6 \pm 1.3 \pm 1.0$	—	—
$10^2\mathcal{A}_{CP}(\Lambda_b \to p\rho^-)$	$-3.7 \pm 0.3 \pm 0.0$	—	—

* where the errors for $\mathcal{B}(\Lambda_b \to pM(V))$ arise from $f_{M(V)}$ and $f_1(g_1)$, the CKM matrix elements and non-factorizable effects while those for $\mathcal{A}_{CP}(\Lambda_b \to pM(V))$ are from the CKM matrix elements and non-factorizable effects

[1] C.D. Lu, Y.M. Wang, H. Zou, A. Ali and G. Kramer, PRD80, 034011 (2009).

[2] PDG

[3] CDF, PRL106, 181802 (2011); arXiv:1403.5586 [hep-ex].

Our approach can be extend to the two-body decays of other b-baryons

$$\mathcal{B}(\Xi_b \to \Sigma^+ K^{*-}) \sim 2.8 \times 10^{-6}$$
$$\mathcal{A}_{CP}(\Xi_b \to \Sigma^+ K^{*-}) \sim 20\%$$

See 何小刚's talks

• *Summary*

♥ **Direct CP violation in 3-body baryonic charged B and 2-body Λ_b baryon decays are large in the SM:**

our result	$B^\pm \to p\bar{p}K^\pm$	$B^\pm \to p\bar{p}\pi^\pm$	$B^\pm \to p\bar{p}K^{*\pm}$	$B^\pm \to p\bar{p}\rho^\pm$
$10^6\mathcal{B}$	5.9	1.6	3.6	10
$10^2\mathcal{A}_{CP}$	6	-6	22	-3
our result	$\Lambda_b \to pK^-$	$\Lambda_b \to p\pi^-$	$\Lambda_b \to pK^{*-}$	$\Lambda_b \to p\rho^-$
$10^6\mathcal{B}$	4.8	4.2	2.5	11.4
$10^2\mathcal{A}_{CP}$	6	-4	20	-4

small hadronic & other uncertainties

♥ **Some of CPAs are accessible to current experiments.**

☞ ♦ **Rich physics in b-hadron decays.**

More studies are needed at B-factories, especially, LHCb + *SuperKEKB*.

Thank you!

謝謝！