CPV in baryonic decays

Yu-Kuo Hsiao 萧佑国
Shanxi Normal University
第一届 LHCb 前沿物理研讨会
2019.12.14

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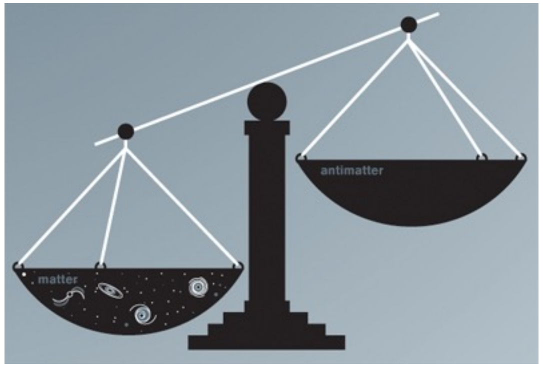
Introduction



- To explain the matter-antimatter asymmetry, CPV is needed. (one of Sakharov conditions)

- In SM, the CKM matrix elements
provide the unique source,
explaining CPV in the K, B and D systems.

- Baryonic CPV for baryonic universe.

Two-body $B \to MM$ decays

- To explain $\mathcal{A}_{CP}(\bar{B}^0 \to K^- \pi^+) = -0.082 \pm 0.006$,

one needs the penguin annihilation amp
to flip the naive results based on the factorization.

Y.Y. Keum, H.n. Li, A.I. Sanda, PRD63, 054008 (2001);
H.Y. Cheng, C.K. Chua, PRD80, 074031 (2009).

- The naive result of $\mathcal{A}_{CP}(\bar{B}^0 \to K^- \pi^+) \simeq \mathcal{A}_{CP}(B^- \to K^- \pi^0)$

NOT approved by the data of

$\mathcal{A}_{CP}(B^- \to K^- \pi^0) = 0.037 \pm 0.021$.

One needs the color-suppressed tree amp to flip the sign again.

H.Y. Cheng, C.K. Chua, PRD80, 074031 (2009);
H.n. Li, S. Mishima, PRD83, 034023 (2011).

• Direct CPA in $\mathbf{B}_b$ decays:

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

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

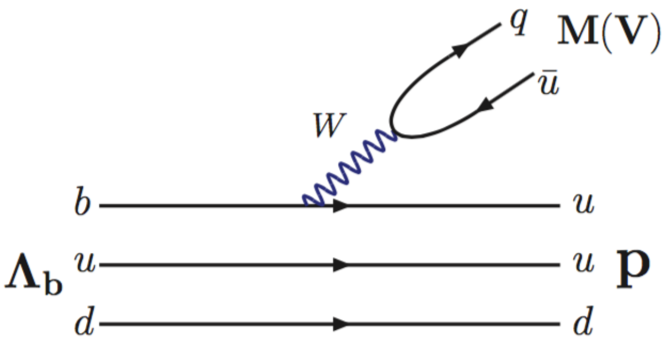
$$\mathcal{A}(\bar{\mathbf{B}}_b \to \bar{f}) = ae^{-i\delta_w} + be^{i\delta_s}$$

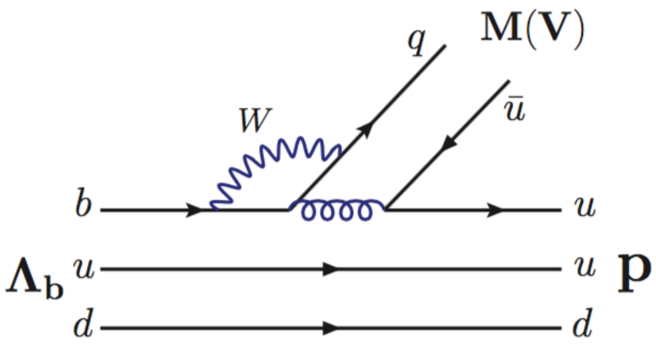
$$\Gamma(\mathbf{B}_b \to f) \neq \Gamma(\bar{\mathbf{B}}_b \to \bar{f})$$

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

δ_s: effective Wilson coefficients (quark rescattering)

• Factorization





- Amplitudes

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

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

- $\Lambda_b \to p$ transition form factors

$$\langle \mathcal{B}|\bar{q}\gamma_\mu b|\mathcal{B}_b\rangle = \bar{u}_\mathcal{B}[f_1\gamma_\mu + \frac{f_2}{m_{\mathcal{B}_b}} i\sigma_{\mu\nu}q^\nu + \frac{f_3}{m_{\mathcal{B}_b}} q_\mu]u_{\mathcal{B}_b}$$

$$\langle \mathcal{B}|\bar{q}\gamma_\mu\gamma_5 b|\mathcal{B}_b\rangle = \bar{u}_\mathcal{B}[g_1\gamma_\mu + \frac{g_2}{m_{\mathcal{B}_b}} i\sigma_{\mu\nu}q^\nu + \frac{g_3}{m_{\mathcal{B}_b}} q_\mu]\gamma_5 u_{\mathcal{B}_b}$$

$$\langle \mathcal{B}|\bar{q}b|\mathcal{B}_b\rangle = f_S\bar{u}_\mathcal{B}u_{\mathcal{B}_b},\ \langle \mathcal{B}|\bar{q}\gamma_5 b|\mathcal{B}_b\rangle = f_P\bar{u}_\mathcal{B}\gamma_5 u_{\mathcal{B}_b}$$

In equation of motion:

$$f_S = \frac{m_{\mathcal{B}_b}-m_\mathcal{B}}{m_b-m_q}f_1,\ f_P = \frac{m_{\mathcal{B}_b}+m_\mathcal{B}}{m_b+m_q}g_1.$$

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

$$f_1(q^2) = \frac{C_F}{(1-q^2/m^2_{\mathcal{B}_b})^2},\ g_1(q^2) = \frac{C_F}{(1-q^2/m^2_{\mathcal{B}_b})^2}$$

$$C_F = 0.14 \pm 0.03$$

from the light-cone sum rules
JHEP 1109, 106 (2011); JHEP 1112, 067 (2011)

$$\mathcal{B}(\Lambda_b \to pK^-) = (5.1^{+2.4}_{-2.0}) \times 10^{-6}$$

$$\mathcal{B}(\Lambda_b \to p\pi^-) = (4.4^{+2.1}_{-1.7}) \times 10^{-6}$$

- We fit C_F to reduce the uncertainty.

$$C_F = 0.136 \pm 0.009$$

$$\mathcal{B}(\Lambda_b \to pK^-) = (4.8 \pm 0.7 \pm 0.1 \pm 0.3) \times 10^{-6}$$

$$\mathcal{B}(\Lambda_b \to p\pi^-) = (4.2 \pm 0.6 \pm 0.4 \pm 0.2) \times 10^{-6}$$

- $\mathcal{R}_{\pi K} \equiv \frac{\mathcal{B}(\Lambda_b \to p\pi^-)}{\mathcal{B}(\Lambda_b \to pK^-)} = 0.84 \pm 0.22$ (CDF and LHCb)

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

$$\mathcal{R}_{\pi K} = \frac{f_\pi^2}{f_K^2} \frac{|\alpha_\pi|^2+|\alpha_{\bar{\pi}}|^2}{|\alpha_K|^2+|\alpha_{\bar{K}}|^2} \frac{1+\xi_\pi^+}{1+\xi_K^+}$$

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

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

$$R_{\Lambda_b \to p} = |\langle p|\bar{u}\gamma_5 b|\Lambda_b\rangle|^2 / |\langle p|\bar{u}b|\Lambda_b\rangle|^2 = 1.008$$

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

$\mathcal{R}_{\pi K} \simeq 2\frac{f_\pi^2}{f_K^2} \frac{|\alpha_\pi|^2+|\alpha_{\bar{\pi}}|^2}{|\alpha_K|^2+|\alpha_{\bar{K}}|^2}$, nearly model-indepent

$$\mathcal{R}_{\pi K} = 0.84 \pm 0.09 \pm 0.00.$$

- The direct CP asymmetry: $\mathcal{A}_{CP} = \frac{\Gamma_{M(V)} - \Gamma_{\bar{M}(\bar{V})}}{\Gamma_{M(V)} + \Gamma_{\bar{M}(\bar{V})}}$

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

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

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

$$\mathcal{A}_{CP}(\Lambda_b \to pK^-) = (5.8 \pm 0.2 \pm 0.1)\%$$

$$\mathcal{A}_{CP}(\Lambda_b \to p\pi^-) = (-3.9 \pm 0.2 \pm 0.0)\%$$

- The vector mode:

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

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

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

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

$$\mathcal{B}(\Lambda_b \to pK^{*-}) = (2.5 \pm 0.5) \times 10^{-6}$$

$$\mathcal{B}(\Lambda_b \to p\rho^-) = (11.4 \pm 2.1) \times 10^{-6}$$

$$\mathcal{R}_{\rho K^*} = 4.6 \pm 0.5$$

$$\mathcal{A}_{CP}(\Lambda_b \to pK^{*-}) = (19.6 \pm 1.6)\%$$

$$\mathcal{A}_{CP}(\Lambda_b \to p\rho^-) = (-3.7 \pm 0.3)\%$$

- Summary:

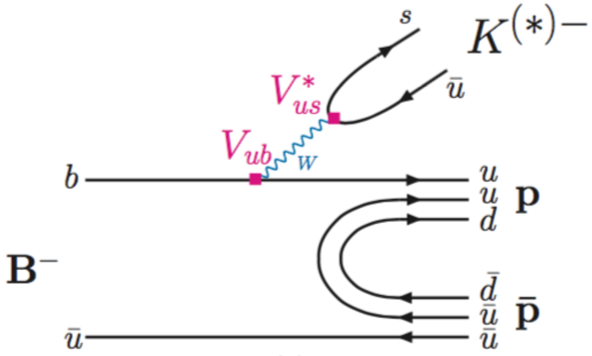
	our result	pQCD[1]	data
$10^6\mathcal{B}(\Lambda_b \to pK^-)$	$4.8 \pm 0.7 \pm 0.1 \pm 0.3$	$2.0^{+1.0}_{-1.3}$	4.9 ± 0.9[2]
$10^6\mathcal{B}(\Lambda_b \to p\pi^-)$	$4.2 \pm 0.6 \pm 0.4 \pm 0.2$	$5.2^{+2.5}_{-1.9}$	4.1 ± 0.8[2]
$10^6\mathcal{B}(\Lambda_b \to pK^{*-})$	$2.5 \pm 0.3 \pm 0.2 \pm 0.3$	—	—
$10^6\mathcal{B}(\Lambda_b \to p\rho^-)$	$11.4 \pm 1.6 \pm 1.2 \pm 0.6$	—	—
$10^2\mathcal{A}_{CP}(\Lambda_b \to pK^-)$	$5.8 \pm 0.2 \pm 0.1$	$-5^{+26}_{-\ 5}$	$-10 \pm 8 \pm 4$[3] ($-2.0 \pm 1.3 \pm 1.9$[4])
$10^2\mathcal{A}_{CP}(\Lambda_b \to p\pi^-)$	$-3.9 \pm 0.2 \pm 0.0$	$-31^{+43}_{-\ 1}$	$6 \pm 7 \pm 3$[3] ($-3.5 \pm 1.7 \pm 2.0$[4])
$10^2\mathcal{A}_{CP}(\Lambda_b \to pK^{*-})$	$19.6 \pm 1.3 \pm 1.0$	—	—
$10^2\mathcal{A}_{CP}(\Lambda_b \to p\rho^-)$	$-3.7 \pm 0.3 \pm 0.0$	—	—

[1] **PRD80, 034011 (2009).**
[2] **PDG (2014)**
[3] **CDF, PRL106, 181802 (2011); 113, 242001 (2014).**
[4] **LHCb, PLB787, 124 (2018).**

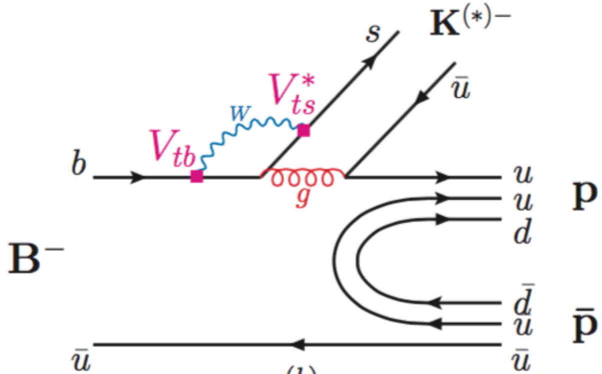
$$A_{CP}^{pK^-} - A_{CP}^{p\pi^-} = 0.014 \pm 0.022 \pm 0.010,$$

$$A_{CP}(\Lambda_b^0 \to \overline{K}^0 p\pi^-) = 0.22 \pm 0.13\,(\text{stat}) \pm 0.03\,(\text{syst})\,.$$ LHCb **JHEP 1404 (2014) 087**

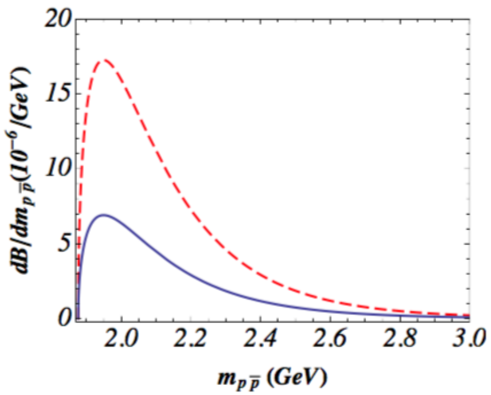
$B^- \to p\bar{p}K^{(*)-}$



(a)



(b)



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

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

$$\mathcal{B}(B^- \to p\bar{p}(K^-, K^{*-})) = (5.8 \pm 1.7, 2.2 \pm 0.6) \times 10^{-6}$$

Threshold effect:

Sharply raising peak around $m_{p\bar{p}} \simeq m_p + m_{\bar{p}}$

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

$$A_{CP}(K) \simeq \frac{|\alpha_K|^2 - |\bar{\alpha}_K|^2}{|\alpha_K|^2 + |\bar{\alpha}_K|^2} \quad (\alpha_K \gg \beta_K)$$

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

Hadronic uncertainties eliminated!

- Direct CP violation in $B \to p\bar{p}M$

Geng, Hsiao, Ng, PRL98, 011801 (2007)

$A_{CP}(M)$	$A_{CP}(K^{*\pm})$	$A_{CP}(K^{\pm})$	$A_{CP}(\pi^{\pm})$
Our result (2007)	0.22 ± 0.04	0.06 ± 0.01	-0.06
BELLE (2004)	—	-0.05 ± 0.11	—
BABAR (2005)	—	-0.16 ± 0.09	—
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

* PRL113, 141801 (2014)

$\mathcal{B}_b \to \mathcal{B}_n M$	$\mathcal{B} \times 10^6$	$\mathcal{A}_{CP} \times 10^2$
$\Lambda_b \to p\pi^-$	$4.25^{+1.04}_{-0.48} \pm 0.74 \pm 0.56$	$-3.9^{+0.0}_{-0.0} \pm 0.4$
$\Lambda_b \to pK^-$	$4.49^{+0.84}_{-0.39} \pm 0.26 \pm 0.59$	$6.7^{+0.3}_{-0.2} \pm 0.3$
$\Lambda_b \to n\pi^0$	$0.10^{+0.03}_{-0.03} \pm 0.01 \pm 0.01$	$8.0^{+1.2}_{-1.4} \pm 0.3$
$\Lambda_b \to n\bar{K}^0$	$4.61^{+1.31}_{-0.58} \pm 0.31 \pm 0.61$	$1.1^{+0.0}_{-0.0} \pm 0.0$
$\Lambda_b \to \Lambda\pi^0$	$(3.4^{+0.8}_{-0.4} \pm 0.1 \pm 0.4) \times 10^{-2}$	$0.0^{+0.0}_{-0.0} \pm 0.0$
$\Lambda_b \to \Lambda K^0$	$(9.4^{+2.3}_{-3.8} \pm 0.4 \pm 1.3) \times 10^{-3}$	$0.2^{+0.1}_{-0.0} \pm 0.0$

$$\mathcal{A} = Te^{i\delta_W} + Pe^{i\delta_S}$$

$$R = P/T$$

$$\mathcal{A}_{CP} = \frac{2R \sin\delta_W \sin\delta_S}{1 + 2R\cos\delta_W \cos\delta_S + R^2}$$

$\mathcal{B}_b \to \mathcal{B}_n M$	$\mathcal{B} \times 10^6$	$\mathcal{A}_{CP} \times 10^2$
$\Lambda_b \to p\rho^-$	$11.03^{+2.72}_{-1.25} \pm 1.97 \pm 1.46$	$-3.8^{+0.0}_{-0.0} \pm 0.4$
$\Lambda_b \to pK^{*-}$	$2.86^{+0.62}_{-0.29} \pm 0.11 \pm 0.51$	$19.7^{+0.4}_{-0.3} \pm 1.4$
$\Lambda_b \to n\rho^0$	$0.18^{+0.09}_{-0.09} \pm 0.02 \pm 0.02$	$14.0^{+1.8}_{-1.8} \pm 1.0$
$\Lambda_b \to n\omega$	$0.22^{+0.16}_{-0.10} \pm 0.03 \pm 0.03$	$-18.2^{+24.4}_{-\ \ 4.2} \pm 1.6$
$\Lambda_b \to n\phi$	$0.02^{+0.17}_{-0.02} \pm 0.00 \pm 0.00$	$-8.8^{+7.4}_{-5.1} \pm 0.3$
$\Lambda_b \to n\bar{K}^{*0}$	$3.09^{+1.57}_{-0.67} \pm 0.21 \pm 0.41$	$1.3^{+0.1}_{-0.1} \pm 0.0$
$\Lambda_b \to \Lambda\rho^0$	$(9.5^{+3.0}_{-1.3} \pm 0.4 \pm 1.3) \times 10^{-2}$	$2.3^{+0.7}_{-0.8} \pm 0.2$
$\Lambda_b \to \Lambda\omega$	$0.71^{+1.59}_{-0.70} \pm 0.04 \pm 0.09$	$3.6^{+4.8}_{-4.0} \pm 0.2$
$\Lambda_b \to \Lambda\phi$	$1.77^{+1.65}_{-1.68} \pm 0.12 \pm 0.23$	$1.4^{+0.7}_{-0.1} \pm 0.1$
$\Lambda_b \to \Lambda K^{*0}$	$(9.2^{+4.7}_{-2.0} \pm 0.4 \pm 1.2) \times 10^{-2}$	$1.3^{+0.1}_{-0.1} \pm 0.0$
$\Lambda_b \to n\eta$	$(6.9^{+2.7}_{-2.4} \pm 0.9 \pm 0.9) \times 10^{-2}$	$-16.8^{+2.1}_{-2.1} \pm 1.3$
$\Lambda_b \to n\eta'$	$(4.2^{+1.8}_{-1.8} \pm 0.6 \pm 0.6) \times 10^{-2}$	$-15.7^{+4.0}_{-5.6} \pm 1.3$
$\Lambda_b \to \Lambda\eta$	$1.59^{+0.38}_{-0.17} \pm 0.11 \pm 0.21$	$0.4^{+0.2}_{-0.2} \pm 0.0$
$\Lambda_b \to \Lambda\eta'$	$1.90^{+0.68}_{-0.23} \pm 0.13 \pm 0.25$	$1.6^{+0.1}_{-0.1} \pm 0.1$

CPV in internal W-emission dominated baryonic B decays

$$\mathcal{A} = T e^{i\delta_W} + P e^{i\delta_S}$$

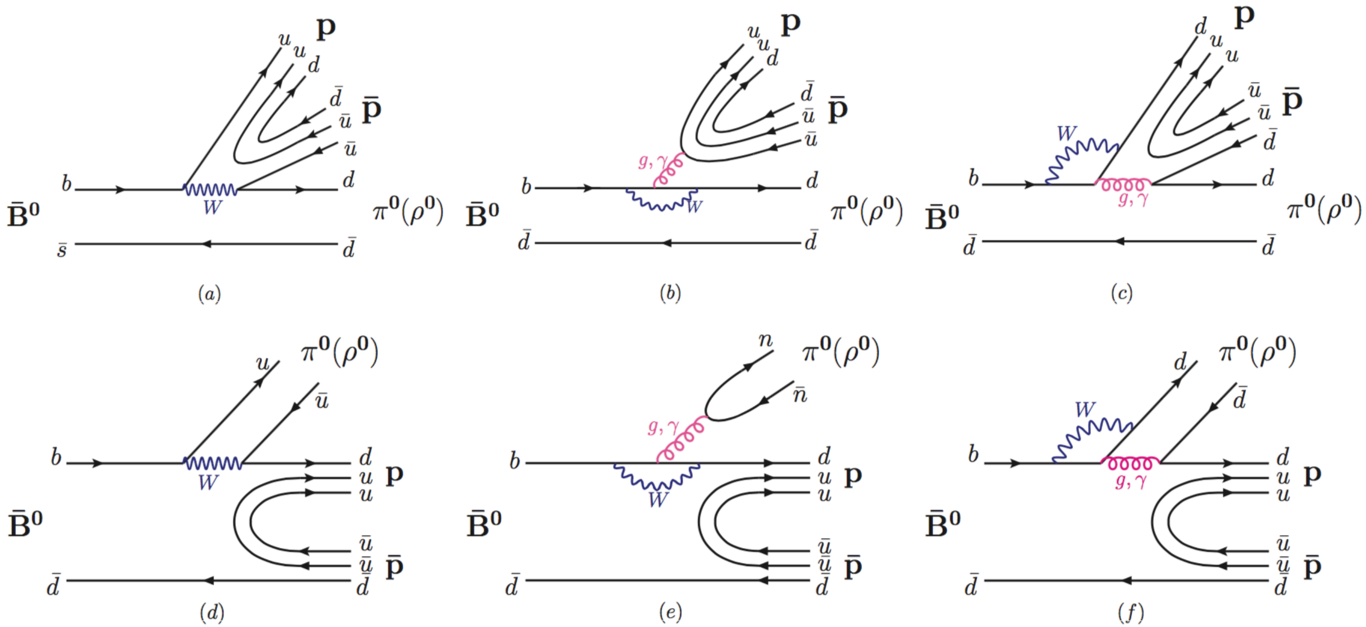
$$R = P/T$$

$$\mathcal{A}_{CP} = \frac{2R \sin\delta_W \sin\delta_S}{1 + 2R\cos\delta_W \cos\delta_S + R^2}$$

$$\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^0) = (5.0 \pm 1.8 \pm 0.6) \times 10^{-7},$$

$$\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^+\pi^-) = (2.7 \pm 0.1 \pm 0.1 \pm 0.2) \times 10^{-6},$$

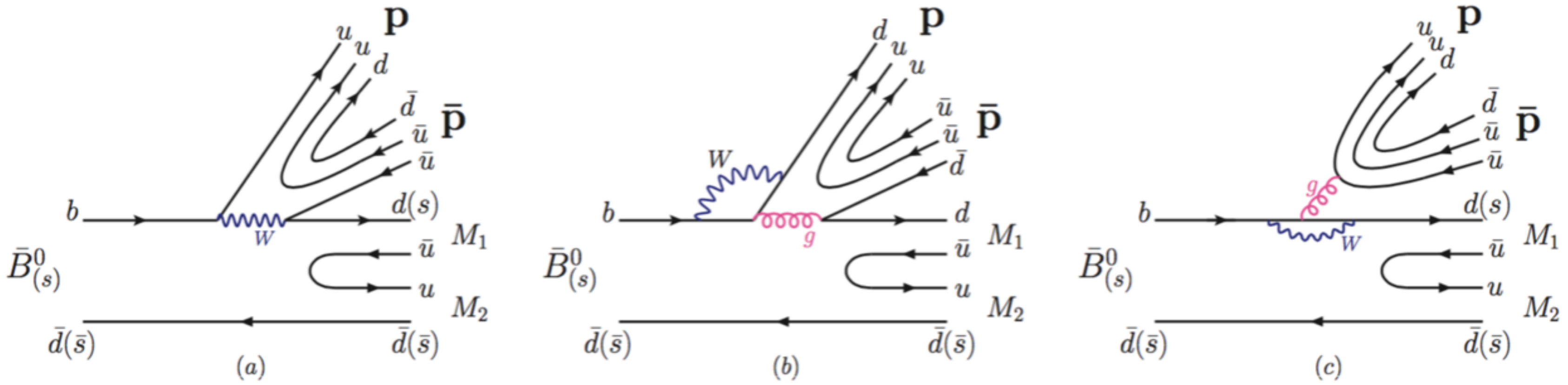
$$\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^0) = (5.0 \pm 1.8 \pm 0.6) \times 10^{-7}$$



$$\mathcal{A}_1(X_M) = \frac{G_F}{\sqrt{2}}\Big\{\Big[\langle p\bar{p}|\bar{u}\gamma^\mu(\alpha_2^+ - \alpha_2^-\gamma_5)u|0\rangle + \langle p\bar{p}|\bar{d}\gamma^\mu(\alpha_3^+ - \alpha_3^-\gamma_5)d|0\rangle\Big]$$
$$\times \langle X_M|\bar{d}\gamma_\mu(1-\gamma_5)b|\bar{B}^0\rangle + \alpha_6\langle p\bar{p}|\bar{d}(1+\gamma_5)d|0\rangle\langle X_M|\bar{d}(1-\gamma_5)b|\bar{B}^0\rangle\Big\}\,,$$

$$\mathcal{A}_2(X_M) = \frac{G_F}{\sqrt{2}}\Big\{\Big[\langle X_M|\bar{u}\gamma^\mu(\alpha_2^+ - \alpha_2^-\gamma_5)u|0\rangle + \langle X_M|\bar{d}\gamma^\mu(\alpha_3^+ - \alpha_3^-\gamma_5)d|0\rangle\Big]$$
$$\times \langle p\bar{p}|\bar{d}\gamma_\mu(1-\gamma_5)b|\bar{B}^0\rangle + \alpha_6\langle X_M|\bar{d}(1+\gamma_5)d|0\rangle\langle p\bar{p}|\bar{d}(1-\gamma_5)b|\bar{B}^0\rangle\Big\}\,,$$

$$\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^+\pi^-) = (2.7 \pm 0.1 \pm 0.1 \pm 0.2) \times 10^{-6}$$



$$\mathcal{A}_1(\bar{B}^0_{(s)} \to p\bar{p}M_1M_2) = \frac{G_F}{\sqrt{2}}\Big\{\Big[\langle p\bar{p}|\alpha^q_+(\bar{u}u)_V - \alpha^q_-(\bar{u}u)_A|0\rangle + \langle p\bar{p}|\beta^q_+(\bar{d}d)_V - \beta^q_-(\bar{d}d)_A|0\rangle$$

$$+(\alpha^q_4 - \alpha^q_{10}/2)\langle p\bar{p}|(\bar{q}q)_{V-A}|0\rangle\Big]\langle M_1M_2|(\bar{q}b)_{V-A}|\bar{B}^0_{(s)}\rangle$$

$$+\alpha^q_6\langle p\bar{p}|(\bar{q}q)_{S+P}|0\rangle\langle M_1M_2|(\bar{q}b)_{S-P}|\bar{B}^0_{(s)}\rangle\Big\},$$

• $B \to M_1 M_2$ transition form factors

$\langle M_1 M_2 | \bar{q}_1 \gamma_\mu (1-\gamma_5) b | B \rangle =$

$h \epsilon_{\mu\nu\alpha\beta} p_B^\nu p^\alpha (p_{M_2} - p_{M_1})^\beta + i r q_\mu + i w_+ p_\mu + i w_- (p_{M_2} - p_{M_1})$

$h = \frac{C_h}{t^2}, \; w_- = \frac{D_{w_-}}{t^2}$

Chua, Hou, Shiau and Tsai,

"Evidence for factorization in three-body anti-$B \to D^{(*)} K^- K^0$ decays,"

PRD67, 034012 (2003); EPJC33, S253 (2004).

$(C_h, C_{w_-})|_{B\to\pi\pi} = (3.6 \pm 0.3, 0.7 \pm 0.2)\,\mathrm{GeV}^3$

$(C_h, C_{w_-})|_{B\to KK(K\pi)} = (-38.9 \pm 3.3, 14.2 \pm 2.3)\,\mathrm{GeV}^3$

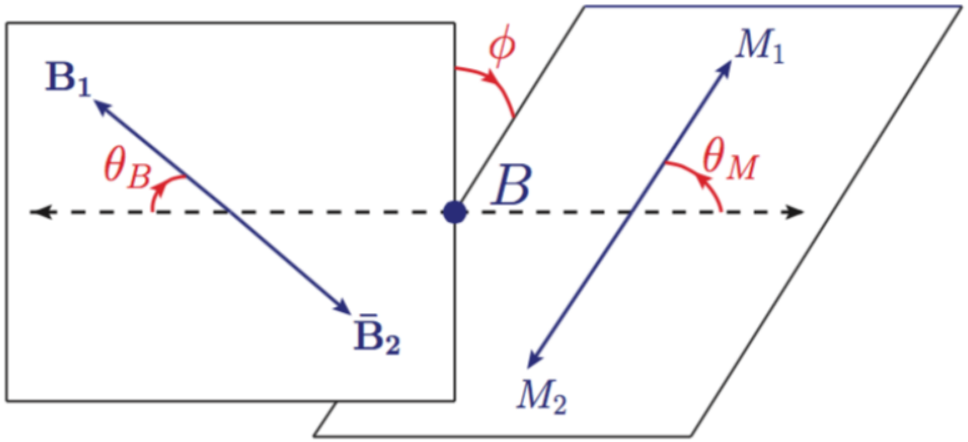
phase space

$$d\Gamma = \frac{|\bar{\mathcal{A}}|^2}{4(4\pi)^6 m_B^3} X \alpha_{\mathbf{B}} \alpha_{\mathbf{M}}\, ds\, dt\, d\cos\theta_{\mathbf{B}}\, d\cos\theta_{\mathbf{M}}\, d\phi$$

$$X = \left[\frac{1}{4}(m_B^2 - s - t)^2 - st\right]^{1/2},$$

$$\alpha_{\mathbf{B}} = \frac{1}{t}\lambda^{1/2}(t, m_{\mathbf{B_1}}^2, m_{\bar{\mathbf{B}}_2}^2),$$

$$\alpha_{\mathbf{M}} = \frac{1}{s}\lambda^{1/2}(s, m_{M_1}^2, m_{M_2}^2),$$



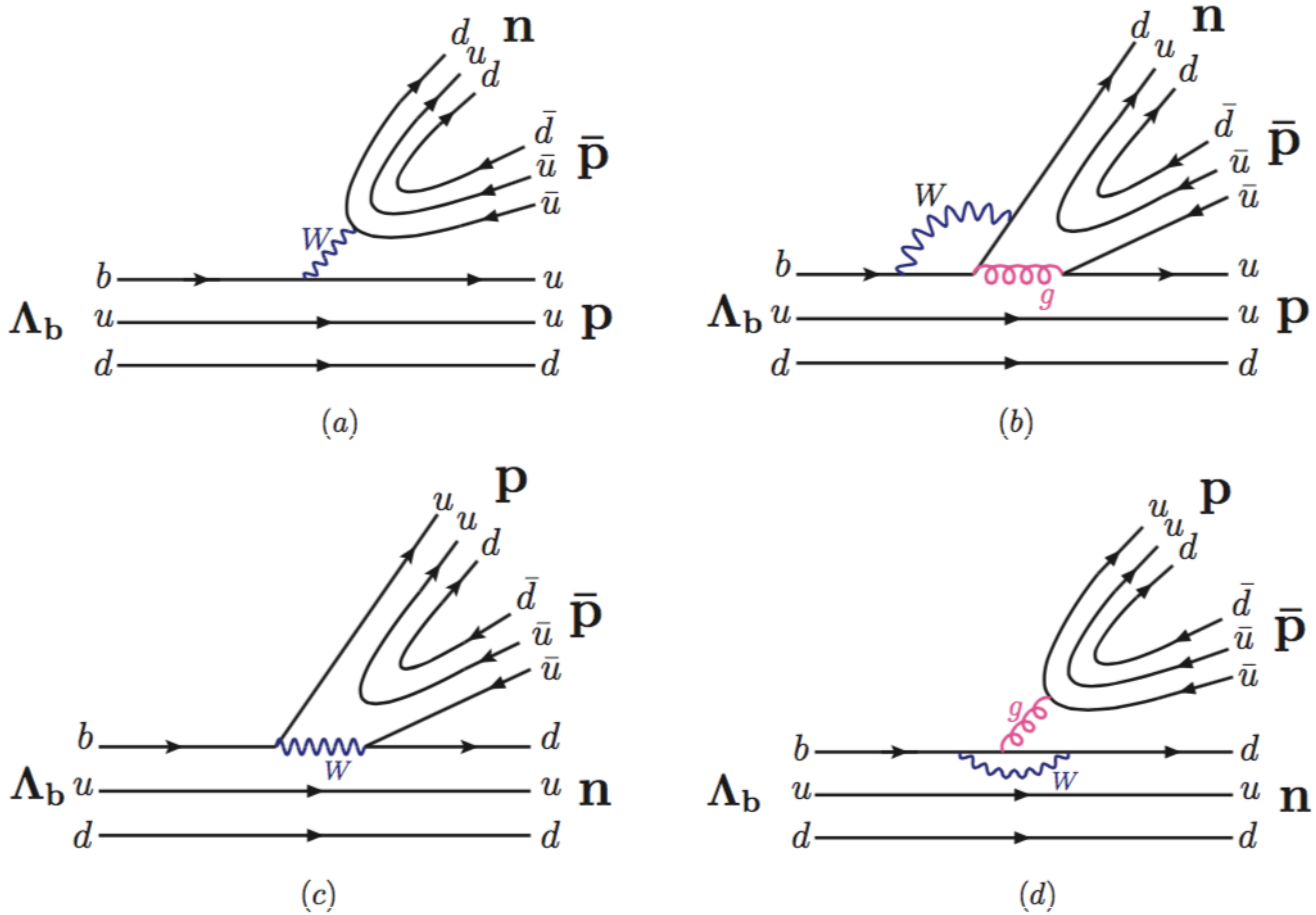
$$\lambda(a,b,c) = a^2 + b^2 + c^2 - 2ab - 2bc - 2ca,$$

$$(m_{M_1} + m_{M_2})^2 \le s \le (m_B - \sqrt{t})^2, \quad (m_{\mathbf{B_1}} + m_{\bar{\mathbf{B}}_2})^2 \le t \le (m_B - m_{M_1} - m_{M_2})^2,$$

$$0 \le \theta_{\mathbf{B}}, \theta_{\mathbf{M}} \le \pi, \quad 0 \le \phi \le 2\pi.$$

	our result	data
$10^7\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^0)$	$5.5 \pm 0.3 \pm 1.0$	5.0 ± 1.9 [23]
$10^7\mathcal{B}(\bar{B}^0 \to p\bar{p}\rho^0)$	$1.9 \pm 0.1 \pm 0.4$	—
$10^6\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^+\pi^-)$	$2.7 \pm 0.2 \pm 0.7$	2.7 ± 0.2 [18]
$\mathcal{A}_{CP}(\bar{B}^0 \to p\bar{p}\pi^0)$	$(-16.0 \pm 1.6 \pm 1.7)\%$	—
$\mathcal{A}_{CP}(\bar{B}^0 \to p\bar{p}\rho^0)$	$(-12.2 \pm 1.2 \pm 1.7)\%$	—
$\mathcal{A}_{CP}(\bar{B}^0 \to p\bar{p}\pi^+\pi^-)$	$(-11.5 \pm 1.2 \pm 1.4)\%$	—

The $\Lambda_b^0 \to p\bar{p}n$ decay



$$\mathcal{A}(\Lambda_b^0 \to p\bar{p}n) \simeq \frac{G_F}{\sqrt{2}} V_{ub} V_{ud}^* a_1 \langle n\bar{p}|(\bar{d}u)_{V-A}|0\rangle \langle p|(\bar{u}b)_{V-A}|\Lambda_b^0\rangle$$

$$\mathcal{A}(\Lambda_b^0 \to p\bar{p}n) \simeq \frac{G_F}{\sqrt{2}} V_{ub} V_{ud}^* a_1 \langle n\bar{p}|(\bar{d}u)_{V-A}|0\rangle \langle p|(\bar{u}b)_{V-A}|\Lambda_b^0\rangle$$

Theoretical tools, well developed!

$$\langle n\bar{p}|\bar{d}\gamma_\mu(1-\gamma_5)u|0\rangle = \bar{u}_n[F_1\gamma_\mu - (g_A\gamma_\mu + \frac{h_A}{m_n+m_{\bar{p}}}q_\mu)\gamma_5]v_{\bar{p}}$$

$$\langle p|\bar{u}\gamma_\mu(1-\gamma_5)b|\Lambda_b\rangle = \bar{u}_p\left[f_1\gamma_\mu - g_1\gamma_\mu\gamma_5\right]u_{\Lambda_b}$$

$$F_1(g_A) = C_{F_1(g_A)}/t^2[\ln(t/\Lambda_0^2)]^{-\gamma}$$

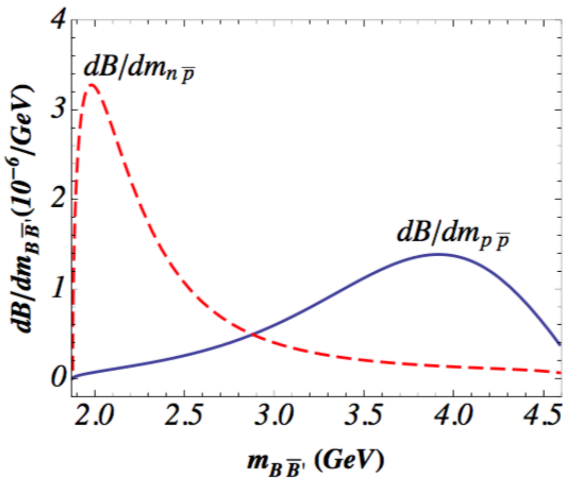
$h_A = C_{h_A}/t^2$, $\gamma = 2.148$, $\Lambda_0 = 0.3$ GeV and $t \equiv q^2$

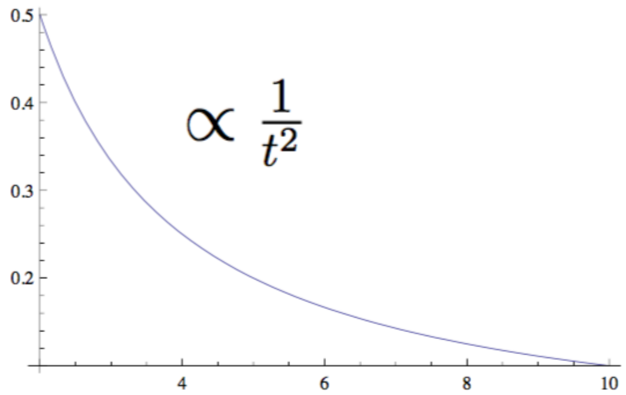
$$f_1(g_1) = C_{f_1(g_1)}/(1-t/m_{\Lambda_b}^2)^2$$

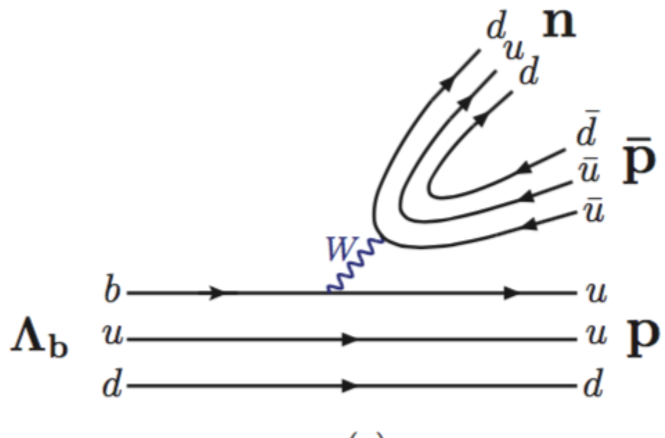
Numerical results

$$\mathcal{B}(\Lambda_b^0 \to p\bar{p}n) = (2.0^{+0.3}_{-0.2} \pm 0.1 \pm 0.1) \times 10^{-6}$$

$\mathcal{A}_{CP}$ and $\mathcal{A}_T$ estimated to be around -4%, undetectable due to n.







(a)

$d\mathcal{B}/dm_{n\bar{p}}$, threshold effect:

sharply raising peak around $m_{n\bar{p}} \simeq m_n + m_{\bar{p}}$

for the $n\bar{p}$ production: $F_1(g_A) \propto \frac{1}{t^2} = 1/(p_n + p_{\bar{p}})^4$

reshape the phase space

$p\bar{p}$ and np not produced in pairs: NO threshold effect

CPV in $\mathbf{B}_c \to \mathbf{B}M$

- Abundant measurements for $\Lambda_c^+ \to \mathbf{B}M$ at BESIII.

More data coming.

Theoretical study should be renewed also;

besides, giving predictions.

- Non-factorizable effects, significant in $\mathbf{B}_c$ decays.
- The search for CP violation.

$\Delta\mathcal{A}_{CP} \equiv \mathcal{A}_{CP}(D^0 \to K^+K^-) - \mathcal{A}_{CP}(D^0 \to \pi^+\pi^-)$

$= (-15.4 \pm 2.9) \times 10^{-4}$ (LHCb).

Future studies

- $\Lambda_b^0 \to p\bar{p}\Lambda$, $\Lambda_b^0 \to \Lambda\bar{p}\Lambda$, $\Lambda_b^0 \to \Lambda\bar{\Lambda}\Lambda$, $\Xi_b^{+,0} \to \mathbf{B_1\bar{B}_2B_3}$
- **DCPA in $\mathbf{B}_b \to \mathbf{B_1\bar{B}_2B_3}$**
- **Time reversal violating asymmetries**

via triple product correlations (rich baryon spins)

- **DCPA in $\mathbf{B}_c \to \mathbf{B}M$**

Thank You