Baryonic B decays

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Introduction

- $m_B > m_{\mathbf{B}} + m_{\bar{\mathbf{B}}'}$ **for $\mathbf{B}\bar{\mathbf{B}}'$**

$(D_s^+ \to p\bar{n}$, $\mathcal{B}$ of order $10^{-3})$

$(D_s^+ \to p\bar{p}e^+\nu_e$, Cheng and Kang, [PLB780, 100 (2018)])

1. $B \to \mathbf{B}\bar{\mathbf{B}}'M$

$\mathcal{B}(\bar{B}^0 \to n\bar{p}D^{*+}) \simeq 10^{-3}$ observed in 2001 (CLEO)

$\mathcal{B}(B^- \to p\bar{p}K^-) \simeq 10^{-6}$ observed in 2002 (BELLE)

2. $B \to \mathbf{B}\bar{\mathbf{B}}'$, 1st observation in 2017 (LHCb)

$\mathcal{B}(\bar{B}^0 \to p\bar{p}) = (1.25 \pm 0.27 \pm 0.18) \times 10^{-8}$

$\mathcal{B}(\bar{B}_s^0 \to p\bar{p}) < 1.5 \times 10^{-8}$

[PRL119, 232001 (2017)]

Introduction

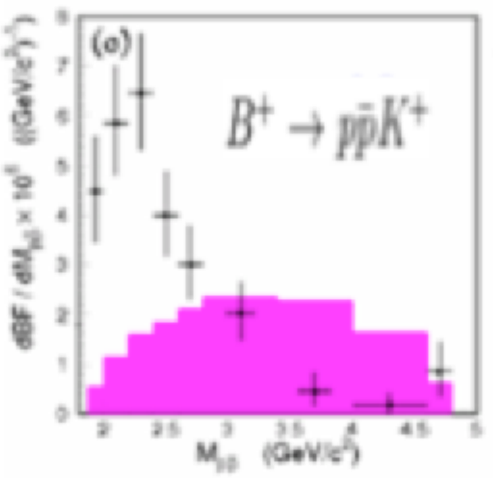
3. First observation of a baryonic $\bar{B}_s^0$ decay (LHCb)

$\mathcal{B}(\bar{B}_s^0 \to \Lambda\bar{p}K^+ + \bar{\Lambda}pK^-)$
$= (5.46 \pm 0.61 \pm 0.57 \pm 0.50 \pm 0.32) \times 10^{-6}$
[PRL119, 232001 (2017)]

4. $B_{(s)} \to \mathbf{B}\bar{\mathbf{B}}' MM'$
$\mathcal{B}(B^- \to \Lambda\bar{p}\pi^+\pi^-) = (5.92^{+0.88}_{-0.84} \pm 0.69) \times 10^{-6}$ (BELLE, 2009)
$\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^+\pi^-) = (3.0 \pm 0.2 \pm 0.2 \pm 0.1) \times 10^{-6}$ (LHCb, 2017)
$\mathcal{B}(\bar{B}^0 \to p\bar{p}K^\mp\pi^\pm) = (6.6 \pm 0.3 \pm 0.3 \pm 0.3) \times 10^{-6}$ (LHCb, 2017)
Review: "17.12 B decays to baryons"
in "The Physics of the B Factories" (Cheng, EPJC)

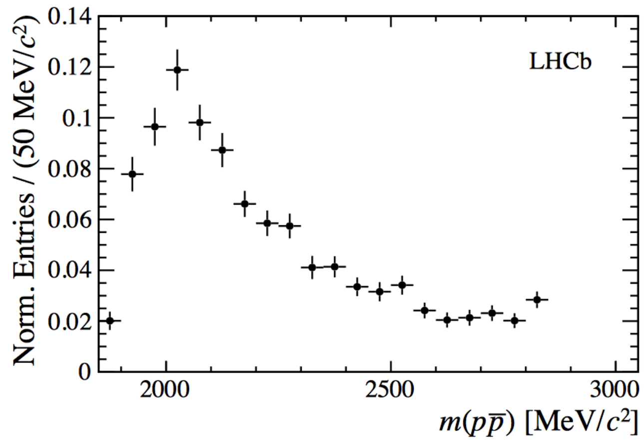
• The threshold effect in the $m_{\mathbf{B}\bar{\mathbf{B}}'}$ spectrum

Peak near the threshold area of
$m_{\mathbf{B}\bar{\mathbf{B}}'} \simeq m_{\mathbf{B}} + m_{\bar{\mathbf{B}}'}$
as the difference between
$B \to \mathbf{B}\bar{\mathbf{B}}'$ and $B \to \mathbf{B}\bar{\mathbf{B}}'M$.



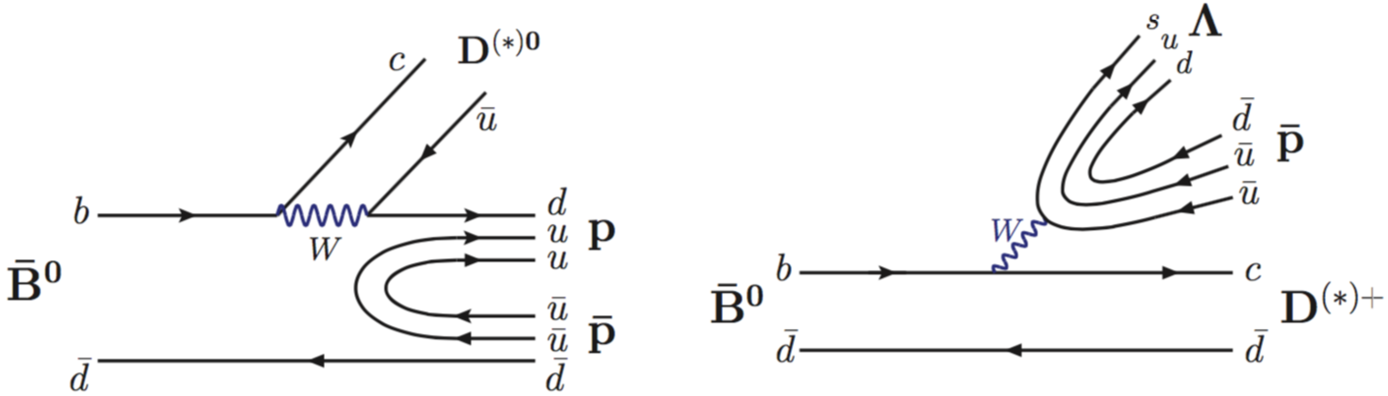
1. Accessibility of charmless cases
2. Smallness of $\mathcal{B}(\bar{B}^0_{(s)} \to p\bar{p}, \Lambda\bar{\Lambda}, B^- \to \Lambda\bar{p})$

Conjecture by Hou and Soni, PRL86, 4247 (2001)
(Inspired by $\bar{B} \to D^* p\bar{n}$ and $\bar{B} \to D^*\pi p\bar{p}$)



• Factorization

$$\mathcal{A}_{\mathcal{T}} \propto \langle M|(\bar{q}_1 q_2)|0\rangle\langle \mathbf{B}\bar{\mathbf{B}}'|(\bar{q}_3 b)|\bar{B}\rangle \quad \mathcal{A}_{\mathcal{C}} \propto \langle \mathbf{B}\bar{\mathbf{B}}'|(\bar{q}_1 q_2)|0\rangle\langle M|(\bar{q}_3 b)|\bar{B}\rangle$$



(a) (b)

A. matrix elements of the $\mathbf{B}\bar{\mathbf{B}}'$ formation

$0 \to \mathbf{B}\bar{\mathbf{B}}'$: timelike baryonic form factors $(ee \to p\bar{p})$

$B \to \mathbf{B}\bar{\mathbf{B}}'$: B meson transition form factors, new term

$B^- \to \Lambda\bar{p}\gamma$ (2005, BELLE), $B^- \to p\bar{p}\ell^-\bar{\nu}_\ell$ (2014, BELLE)

B. approaches under factorization

1. pole model:

H.Y. Cheng, K.C. Yang, PRD66, 014020; 094009 (2002)

2. paramterization of $B \to \mathbf{B}\mathbf{B}$+pQCD counting rules:

W.S. Hou, A. Soni, PRL86, 4247 (2001);

C.K. Chua, W.S. Hou, S.Y. Tsai, PRD66, 054004 (2002);

C.K. Chua, W.S. Hou, EPJC29, 27 (2003).

- Timelike baryonic form factors

$$\langle \mathbf{B}\bar{\mathbf{B}}'|V_\mu|0\rangle = \bar{u}\left\{F_1\gamma_\mu + \frac{F_2}{m_{\mathbf{B}}+m_{\bar{\mathbf{B}}'}} i\sigma_{\mu\nu}q_\mu\right\}v$$

$$\langle \mathbf{B}\bar{\mathbf{B}}'|A_\mu|0\rangle = \bar{u}\left\{g_A\gamma_\mu + \frac{h_A}{m_{\mathbf{B}}+m_{\bar{\mathbf{B}}'}} q_\mu\right\}\gamma_5 v$$

$$\langle \mathbf{B}\bar{\mathbf{B}}'|S|0\rangle = f_S\bar{u}v,\ \langle \mathbf{B}\bar{\mathbf{B}}'|P|0\rangle = g_P\bar{u}\gamma_5 v$$

- pQCD counting rules (Lepage and Brodsky, 1979)

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

The $B \to \mathbf{B}\bar{\mathbf{B}}'$ transition form factors

$$\langle \mathbf{B}\bar{\mathbf{B}}'|(\bar{q}'b)_V|\bar{B}\rangle =$$

$$i\bar{u}(p_{\mathbf{B}})[g_1\gamma_\mu + g_2 i\sigma_{\mu\nu}p^\nu + g_3 p_\mu + g_4 q_\mu + g_5(p_{\bar{\mathbf{B}}'} - p_{\mathbf{B}})_\mu]\gamma_5 v(p_{\bar{\mathbf{B}}'})$$

$$\langle \mathbf{B}\bar{\mathbf{B}}'|(\bar{q}'b)_A|\bar{B}\rangle =$$

$$i\bar{u}(p_{\mathbf{B}})[f_1\gamma_\mu + f_2 i\sigma_{\mu\nu}p^\nu + f_3 p_\mu + f_4 q_\mu + f_5(p_{\bar{\mathbf{B}}'} - p_{\mathbf{B}})_\mu]v(p_{\bar{\mathbf{B}}'})$$

$$q = p_{\mathbf{B}} + p_{\bar{\mathbf{B}}'},\ p = p_{\bar{B}} - p_{\mathbf{B}} - p_{\bar{\mathbf{B}}'},$$

$$f_i = \frac{D_{f_i}}{t^n},\quad g_i = \frac{D_{g_i}}{t^n}$$

$n = 3$ for 3 gluon propagators

- Predictions to be consistent with data.

decay modes	predictions	data
$10^6\mathcal{B}(B^- \to \Lambda\bar{\Lambda}K^-)$	2.8 ± 0.2	$3.38^{+0.41}_{-0.36} \pm 0.41$
$10^6\mathcal{B}(\bar{B}^0 \to \Lambda\bar{\Lambda}\bar{K}^0)$	2.5 ± 0.3	$4.76^{+0.84}_{-0.68} \pm 0.61$
$10^7\mathcal{B}(B^- \to \Lambda\bar{\Lambda}\pi^-)$	1.7 ± 0.7	< 9.4
$10^5\mathcal{B}(B^- \to \Lambda\bar{p}D^0)$	1.14 ± 0.26	$1.43^{+0.28}_{-0.25} \pm 0.18$
$10^5\mathcal{B}(B^- \to \Lambda\bar{p}D^{*0})$	3.23 ± 0.32	$1.53^{+1.12}_{-0.85} \pm 0.47\ (< 4.8)$
$10^5\mathcal{B}(\bar{B}^0 \to \Sigma^0\bar{\Lambda}D^0)$	1.8 ± 0.5	$1.5^{+0.9}_{-0.8}$
$10^6\mathcal{B}(\bar{B}^0 \to \Lambda\bar{p}\phi)$	1.5 ± 0.3	$0.818 \pm 0.215 \pm 0.078$

• Challenge from observations

Predictions (Cheng, Geng and Hsiao, 2008)

$\mathcal{B}(\bar{B}^0 \to \Lambda\bar{p}D^+, \Lambda\bar{p}D^{*+}) = (3.4 \pm 0.2, 11.9 \pm 2.7) \times 10^{-6}$

Observations [PRL115, 221803 (2015), BELLE]

$\mathcal{B}(\bar{B}^0 \to \Lambda\bar{p}D^+) = (25.1 \pm 2.6 \pm 3.5) \times 10^{-6}$

$\mathcal{B}(\bar{B}^0 \to \Lambda\bar{p}D^{*+}) = (33.6 \pm 6.3 \pm 4.4) \times 10^{-6}$

$\mathcal{A}_\theta(\bar{B}^0 \to \Lambda\bar{p}D^+) = -0.08 \pm 0.10$

$\mathcal{A}_\theta(\bar{B}^0 \to \Lambda\bar{p}D^{*+}) = +0.55 \pm 0.17$

• Comment from BELLE:

"The measured branching fractions are clearly
incompatible with the theoretical predictions ...
This indicates that the model parameters
used in the calculation need to be revised and, perhaps,
some modification of the theoretical framework is required."

• Underestimation of the baryonic form factors

due to the information of $ee \to p\bar{p}$

(electromagnetic interaction only)

• With the new extractions of BFFs from baryonic B decays, we obtain

decay mode	data	our results
$10^5\mathcal{B}(\bar{B}^0 \to \Lambda\bar{p}D^+)$	2.51 ± 0.44	1.85 ± 0.30
$10^5\mathcal{B}(\bar{B}^0 \to \Lambda\bar{p}D^{*+})$	3.36 ± 0.77	2.75 ± 0.24
$\mathcal{A}_\theta(\bar{B}^0 \to \Lambda\bar{p}D^+)$	-0.08 ± 0.10	-0.030 ± 0.002
$\mathcal{A}_\theta(\bar{B}^0 \to \Lambda\bar{p}D^{*+})$	$+0.55 \pm 0.17$	$+0.150 \pm 0.000$

1. The data of $\bar{B}^0 \to \Lambda\bar{p}D^{(*)+}$ are not involved in the extractions.
2. Factorization still works.

Extractions of the baryonic form factors

1. Timelike baryonic form factors:

$$\langle \mathbf{B}\bar{\mathbf{B}}'|(\bar{q}q')_V|0\rangle = \bar{u}\left[F_1\gamma_\mu + \frac{F_2}{m_{\mathbf{B}}+m_{\bar{\mathbf{B}}'}} i\sigma_{\mu\nu}q^\nu\right]v$$

$$\langle \mathbf{B}\bar{\mathbf{B}}'|(\bar{q}q')_A|0\rangle = \bar{u}\left[g_A\gamma_\mu + \frac{h_A}{m_{\mathbf{B}}+m_{\bar{\mathbf{B}}'}} q_\mu\right]\gamma_5 v$$

$$\langle \mathbf{B}\bar{\mathbf{B}}'|(\bar{q}q')_S|0\rangle = f_S\bar{u}v$$

$$\langle \mathbf{B}\bar{\mathbf{B}}'|(\bar{q}q')_P|0\rangle = g_P\bar{u}\gamma_5 v$$

$$F_1 = \frac{\bar{C}_{F_1}}{t^2}\,,\ g_A = \frac{\bar{C}_{g_A}}{t^2}\,,\ f_S = \frac{\bar{C}_{f_S}}{t^2}\,,\ g_P = \frac{\bar{C}_{g_P}}{t^2}$$

$\bar{C}_i = C_i[\ln(t/\Lambda_0^2)]^{-\gamma}$ with $\gamma = 2.148$ and $\Lambda_0 = 0.3$ GeV.

$(C_{F_1}, C_{g_A}, C_{f_S}, C_{g_P}) = \sqrt{\frac{3}{2}}(C_{||}, C^*_{||}, -\bar{C}_{||}, -\bar{C}^*_{||})$ (for $\langle\Lambda\bar{p}|(\bar{s}u)_{V,A,S,P}|0\rangle$)

with $C^*_{||(\overline{||})} \equiv C_{||(\overline{||})} + \delta C_{||(\overline{||})}$ and $\bar{C}^*_{||} \equiv \bar{C}_{||} + \delta\bar{C}_{||}$.

$\chi^2/d.o.f \simeq 2.3$ (20 data points)

$(C_{||},\ \delta C_{||}) = (154.4 \pm 12.1,\ 19.3 \pm 21.6)$ GeV^4

$(C_{\overline{||}},\ \delta C_{\overline{||}}) = (18.1 \pm 72.2,\ -477.4 \pm 99.0)$ GeV^4

$(\bar{C}_{||},\ \delta\bar{C}_{||}) = (537.6 \pm 28.7,\ -342.3 \pm 61.4)$ GeV^4

2. $B \to \mathbf{B}\bar{\mathbf{B}}'$ transition form factors:

$$\langle \mathbf{B}\bar{\mathbf{B}}'|(\bar{s}b)_V|B\rangle = i\bar{u}[g_1\gamma_\mu + g_2 i\sigma_{\mu\nu}p^\nu + g_3 p_\mu + g_4 q_\mu + g_5(p_{\bar{\mathbf{B}}'} - p_{\mathbf{B}})_\mu]\gamma_5 v$$

$$\langle \mathbf{B}\bar{\mathbf{B}}'|(\bar{s}b)_A|B\rangle = i\bar{u}[f_1\gamma_\mu + f_2 i\sigma_{\mu\nu}p^\nu + f_3 p_\mu + f_4 q_\mu + f_5(p_{\bar{\mathbf{B}}'} - p_{\mathbf{B}})_\mu]v$$

$$\langle \mathbf{B}\bar{\mathbf{B}}'|(\bar{s}b)_S|B\rangle = i\bar{u}[\bar{g}_1 \not{p} + \bar{g}_2(E_{\bar{\mathbf{B}}_2} + E_{\mathbf{B}_1}) + \bar{g}_3(E_{\bar{\mathbf{B}}_2} - E_{\mathbf{B}_1})]\gamma_5 v$$

$$\langle \mathbf{B}\bar{\mathbf{B}}'|(\bar{s}b)_P|B\rangle = i\bar{u}[\bar{f}_1 \not{p} + \bar{f}_2(E_{\bar{\mathbf{B}}'} + E_{\mathbf{B}}) + \bar{f}_3(E_{\bar{\mathbf{B}}'} - E_{\mathbf{B}})]v$$

$$f_i = \frac{D_{f_i}}{t^3}\,,\; g_i = \frac{D_{g_i}}{t^3}\,,\; \bar{f}_i = \frac{D_{\bar{f}_i}}{t^3}\,,\; \bar{g}_i = \frac{D_{\bar{g}_i}}{t^3}$$

$\langle \Lambda\bar{p}|(\bar{s}b)_{V,A}|B^-\rangle$:

$$D_{g_1} = D_{f_1} = \sqrt{\frac{3}{2}}D_{||}\,,\; D_{g_{4,5}} = -D_{f_{4,5}} = -\sqrt{\frac{3}{2}}D_{||}^{4,5}$$

$\chi^2/d.o.f \simeq 0.8$ (28 data points)

$$D_{||} = (45.7 \pm 33.8)\ \text{GeV}^5\,, (D_{||}^4, D_{||}^5) = (6.5 \pm 18.1, -147.1 \pm 29.3)\ \text{GeV}^4$$

$$(\bar{D}_{||}, \bar{D}_{||}^2, \bar{D}_{||}^3) = (35.2 \pm 4.8, -22.3 \pm 10.2, 504.5 \pm 32.4)\ \text{GeV}^4$$

$$C_{F_1} = \frac{5}{3}C_{||} + \frac{1}{3}C_{\overline{||}}\,,\ C_{g_A} = \frac{5}{3}C^*_{||} - \frac{1}{3}C^*_{\overline{||}}\,, \quad (\text{for } \langle p\bar{p}|\bar{u}\gamma_\mu(\gamma_5)u|0\rangle)$$

$$C_{F_1} = \frac{1}{3}C_{||} + \frac{2}{3}C_{\overline{||}}\,,\ C_{g_A} = \frac{1}{3}C^*_{||} - \frac{2}{3}C^*_{\overline{||}}\,, \quad (\text{for } \langle p\bar{p}|\bar{d}\gamma_\mu(\gamma_5)d|0\rangle)$$

$$C_{f_S} = \frac{1}{3}\bar{C}_{||}\,,\ C_{g_P} = \frac{1}{3}\bar{C}^*_{||}\,, \quad (\text{for } \langle p\bar{p}|\bar{d}(\gamma_5)d|0\rangle)$$

$$C_{F_1} = \sqrt{\frac{3}{2}}C_{||}\,,\ C_{g_A} = \sqrt{\frac{3}{2}}C^*_{||}\,, \quad (\text{for } \langle \Lambda\bar{p}|\bar{s}\gamma_\mu(\gamma_5)u|0\rangle)$$

$$C_{f_S} = -\sqrt{\frac{3}{2}}\bar{C}_{||}\,, C_{g_P} = -\sqrt{\frac{3}{2}}\bar{C}^*_{||}\,, \quad (\text{for } \langle \Lambda\bar{p}|\bar{s}(\gamma_5)u|0\rangle)$$

- Angular distribution asymmetries

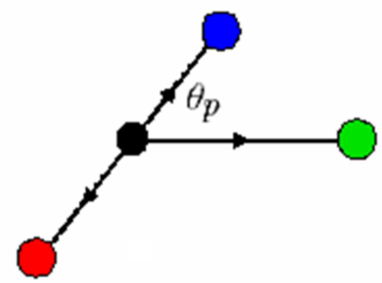
$\mathcal{A}_\theta$ for $B^+ \to p\bar{p}K^+$, $B^+ \to p\bar{p}\pi^+$, $B^0 \to p\bar{\Lambda}\pi^-$

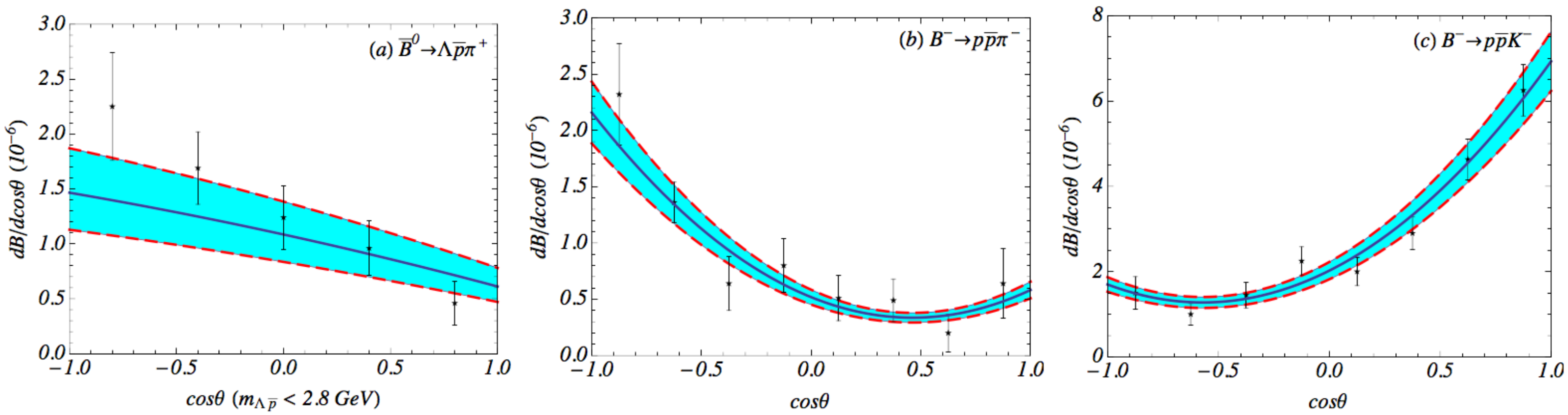
0.45 ± 0.06, -0.47 ± 0.12, -0.41 ± 0.11,

measured by BELLE

large and unexpected.

[PRD76, 052004 (2007), PLB659, 80 (2008)]





• $B \to \mathbf{B}\bar{\mathbf{B}}'$

1st evidence (2014, LHCb)

$\mathcal{B}(\bar{B}^0 \to p\bar{p}) = (1.47^{+0.62+0.35}_{-0.51-0.14}) \times 10^{-8}$

$\mathcal{B}(\bar{B}^0_s \to p\bar{p}) = (2.84^{+2.03+0.85}_{-1.68-0.18}) \times 10^{-8}$

with the statistical significances to be 3.3σ and 1.9σ, respectively.

Factorization

Annihilation mechanism

$$\mathcal{A}(\bar{B}^0 \to p\bar{p}) = \frac{G_F}{\sqrt{2}} V_{ub} V_{ud}^* \, a_2 \langle p\bar{p}|(\bar{u}u)_{V-A}|0\rangle \langle 0|(\bar{d}b)_{V-A}|\bar{B}^0\rangle$$

$$= \frac{G_F}{\sqrt{2}} V_{ub} V_{ud}^* \, a_2 \, i f_B \left(\langle p\bar{p}|q^\mu V_\mu|0\rangle - \langle p\bar{p}|q^\mu A_\mu|0\rangle \right)$$

$$\langle 0|\bar{d}\gamma_\mu\gamma_5 b|\bar{B}^0\rangle = i f_B q_\mu$$

$$V_\mu = \bar{u}\gamma_\mu u, \; A_\mu = \bar{u}\gamma_\mu\gamma_5 u$$

1. CVC: $q^\mu V_\mu = 0$
2. PCAC: $q^\mu A_\mu = 2 f_\pi m_\pi^2 \phi_\pi$ (ϕ_π: pion field)

$\mathcal{B}(\bar{B}^0 \to p\bar{p}) \simeq 0$

- In at least 13 papers,

nonfactorizable effects as the main contributions:

diquark model

C.H.V. Chang and W.S. Hou, EPJC23, 691 (2002),

sum rule,

flavor symmetry

X. G. He, B. H. McKellar and D. d. Wu, PRD41, 2141 (1990),

pole model

H.Y. Cheng, K.C. Yang, PRD66, 014020 (2002)

topological approach

C.K. Chua, PRD68, 074001 (2003); 89, 056003 (2014)

$B^- \to \Lambda\bar{p}$

$$\mathcal{A} = \frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \, 2a_6 \langle \Lambda\bar{p}|(\bar{s}u)_{S+P}|0\rangle \langle 0|(\bar{u}b)_{S-P}|B^-\rangle$$

$$= -i\frac{G_F}{\sqrt{2}} V_{tb} V_{ts}^* \, 2a_6 f_B \frac{m_B^2}{m_b} \left(\langle \Lambda\bar{p}|\bar{s}u|0\rangle + \langle \Lambda\bar{p}|\bar{s}\gamma_5 u|0\rangle \right)$$

$$\langle \Lambda\bar{p}|\bar{s}u|0\rangle = f_S \bar{u} v$$

$$\langle \Lambda\bar{p}|\bar{s}\gamma_5 u|0\rangle = g_P \bar{u}\gamma_5 v$$

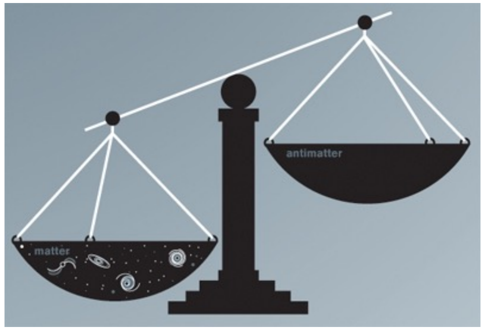
No constraints from CVC and PCAC!

$\mathcal{B}(B^- \to \Lambda\bar{p}) = (3.5^{+0.7}_{-0.5}) \times 10^{-8}$,

to be used to test factorization.

$\mathcal{B}(\bar{B}^- \to \Lambda(1520)\bar{p}) = (3.1 \pm 0.6) \times 10^{-7}$

(2013, LHCb)



CP violation in baryonic B decays

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

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

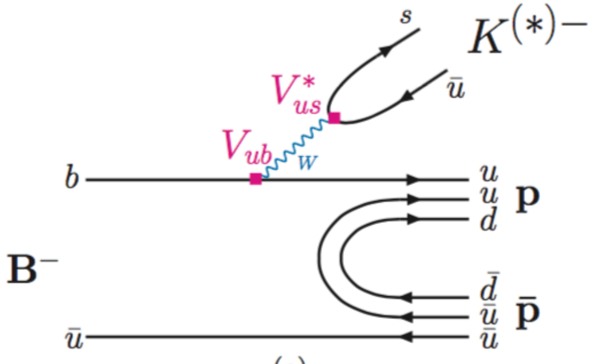
$$\mathcal{A}(\bar{B} \to \bar{f}) = ae^{-i\delta_w} + be^{i\delta_s}$$

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

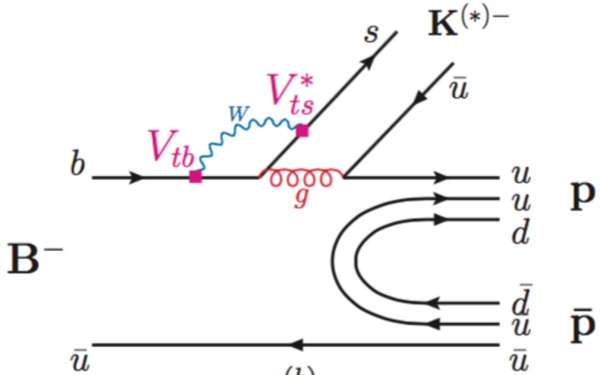
δ_w: $V_{ub} = A\lambda^3(\rho - i\eta)$

δ_s: on-shell processes

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



(a)



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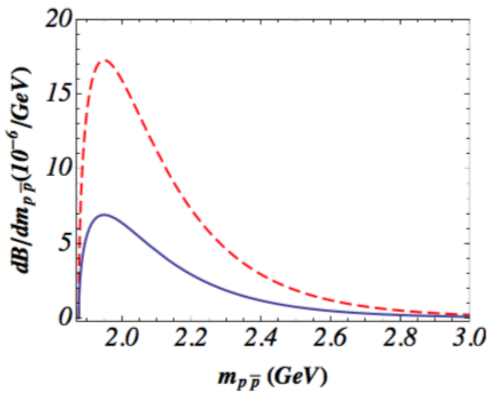


$$\mathcal{A}_K = i\frac{G_F}{\sqrt{2}} m_b f_K [\alpha_K \langle p\bar{p}|\bar{u}b|B^-\rangle + \beta_K \langle p\bar{p}|\bar{u}\gamma_5 b|B^-\rangle]$$

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

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

Threshold effect:

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

Direct CP violating asymmetries:

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

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

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

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

$$r_M \equiv 2m_M^2/[m_b(m_q + m_u)]$$

$a_i \equiv c_i^{eff} + c_{i\pm1}^{eff}/N_c^{(eff)}$ for i =odd (even)

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

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

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

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)

The resonant states

1. $\Sigma_c(2800)$, $\Lambda_c(2880)$, $\Lambda_b(2940)$, and $\mathbf{B}_c(3212)$ in $\bar{B}^0 \to p\bar{p}D^{(*)0}$

H.Y. Cheng, C.Q. Geng and Y.K. Hsiao, PRD89, 034005 (2014)

2. Identifying the glueball state at 3.02 GeV in $\bar{B}^0 \to p\bar{p}D^{(*)0}$

Y.K. Hsiao, C.Q. Geng, PLB727, 168 (2013)

3. resonant $f_J(2220)$ to explain $\mathcal{B}(\bar{B}^0_s \to p\bar{p}J/\psi) = 3 \times 10^{-6}$

Y.K. Hsiao, C.Q. Geng, EPJC75, 101 (2015)

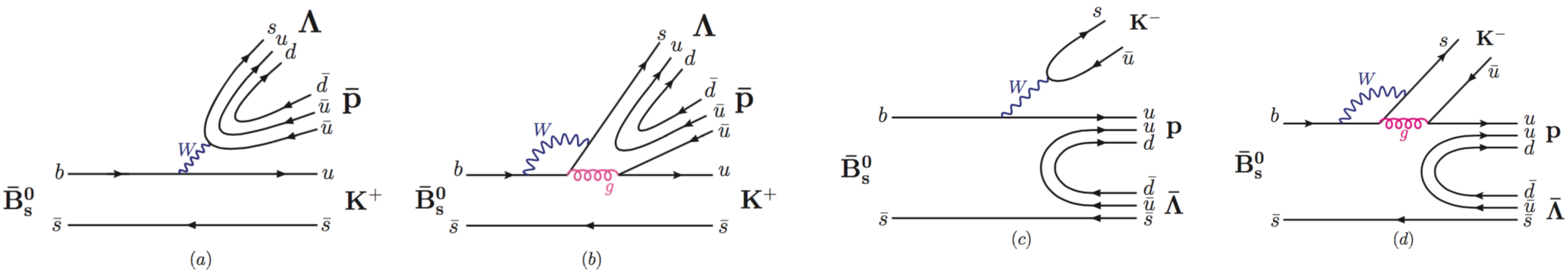
$\bar{B}^0_s \to s\bar{s} \to p\bar{p}$ encounters the OZI suppression
$\bar{B}^0_s \to s\bar{s} \to f_J(2220) \to p\bar{p}$
$f_J(2220)$ as the tensor glueball candidate
$B^- \to K^-(f_J(2220) \to)p\bar{p}$, suggested by

W.S. Hou *et al.*, PLB544, 139 (2002)

• Baryonic $\bar{B}_s^0$ decay

First observation of a baryonic $\bar{B}_s^0$ decay (LHCb)

$\mathcal{B}(\bar{B}_s^0 \to \Lambda\bar{p}K^+ + \bar{\Lambda}pK^-)$
$= (5.46 \pm 0.61 \pm 0.57 \pm 0.50 \pm 0.32) \times 10^{-6}$
[PRL119, 232001 (2017)]



• Naive inference

$\mathcal{B}(\bar{B}_s^0 \to \bar{p}\Lambda K^+) \simeq \mathcal{B}(\bar{B}^0 \to \bar{p}\Lambda\pi^+)$, 3.1×10^{-6}

$\mathcal{B}(\bar{B}_s^0 \to p\bar{\Lambda}K^-) \simeq \mathcal{B}(B^- \to p\bar{p}K^-)$, 5.9×10^{-6}

$\mathcal{B}(\bar{B}_s^0 \to p\bar{\Lambda}\pi^-) \simeq \mathcal{B}(B^- \to p\bar{p}\pi^-)$, 1.6×10^{-6}

• our results [PLB767, 205 (2017)]

$$\mathcal{B}(\bar{B}^0_s \to \bar{p}\Lambda K^+) = (3.75 \pm 0.81^{+0.67}_{-0.31} \pm 0.01) \times 10^{-6}$$

$$\mathcal{B}(\bar{B}^0_s \to p\bar{\Lambda} K^-) = (1.31 \pm 0.32^{+0.22}_{-0.10} \pm 0.01) \times 10^{-6}$$

$$\mathcal{B}(\bar{B}^0_s \to p\bar{\Lambda}\pi^-) = (2.79 \pm 1.37^{+0.64}_{-0.30} \pm 0.17) \times 10^{-7}$$

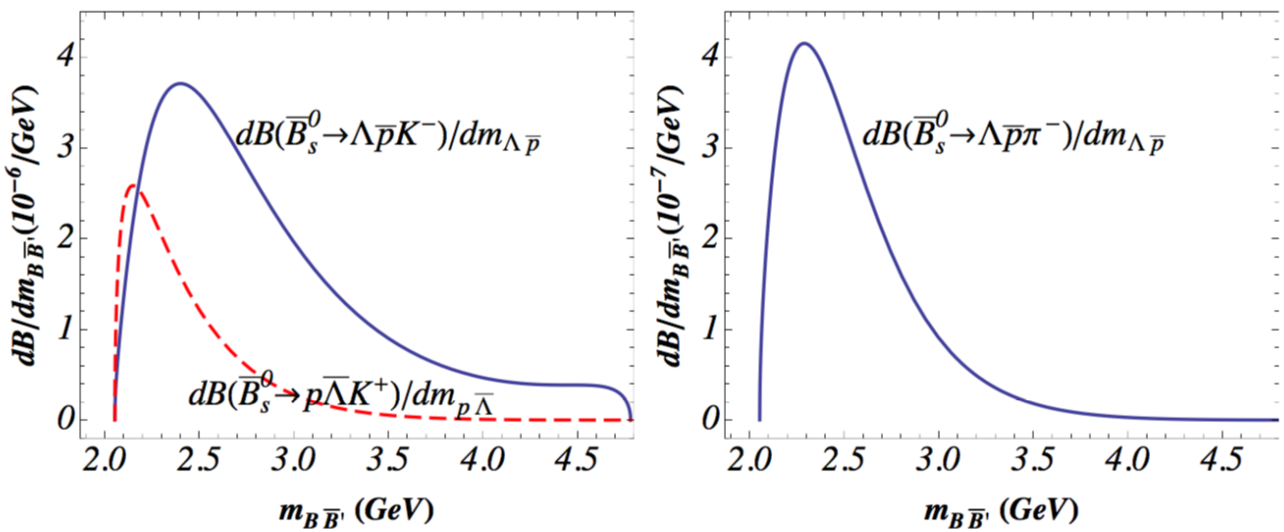
errors: the form factors, non-factorizable effects, and CKM matrix elements.

$\mathcal{B}(\bar{B}^0_s \to \bar{p}\Lambda K^+ + p\bar{\Lambda} K^-) = (5.1 \pm 1.1) \times 10^{-6}$, to agree with the data of

$(5.46 \pm 0.61 \pm 0.57 \pm 0.50 \pm 0.32) \times 10^{-6}$.

$$\mathcal{B}(\bar{B}^0_s \to \bar{p}\Lambda K^+) \simeq (f_K/f_\pi)^2(\tau_{B^0_s}/\tau_{B^0})\mathcal{B}(\bar{B}^0 \to \bar{p}\Lambda\pi^+)$$

$$\frac{\mathcal{B}(\bar{B}^0_s \to p\bar{\Lambda}\pi^-)}{\mathcal{B}(\bar{B}^0_s \to p\bar{\Lambda}K^-)} \simeq \frac{\mathcal{B}(B^- \to p\bar{p}\pi^-)}{\mathcal{B}(B^- \to p\bar{p}K^-)}$$

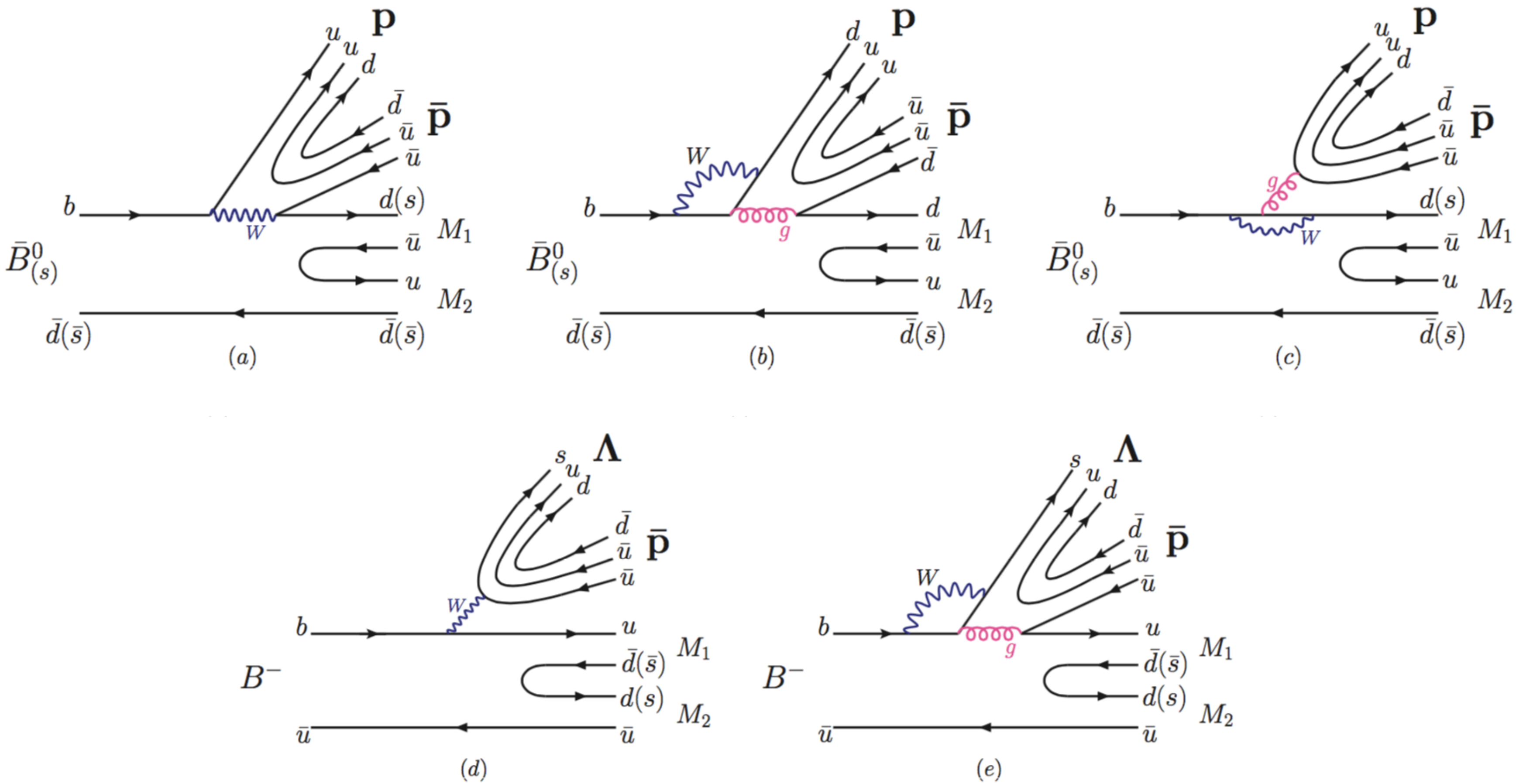


• Four-body Baryonic $B_{(s)}$ decays

$$\mathcal{B}(B^- \to \Lambda\bar{p}\pi^+\pi^-) = (5.92^{+0.88}_{-0.84} \pm 0.69) \times 10^{-6} \text{ (BELLE, 2009)}$$

$$\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^+\pi^-) = (3.0 \pm 0.2 \pm 0.2 \pm 0.1) \times 10^{-6} \text{ (LHCb, 2017)}$$

$$\mathcal{B}(\bar{B}^0 \to p\bar{p}K^\mp\pi^\pm) = (6.6 \pm 0.3 \pm 0.3 \pm 0.3) \times 10^{-6} \text{ (LHCb, 2017)}$$



• $B \to M_1 M_2$ 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).

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

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

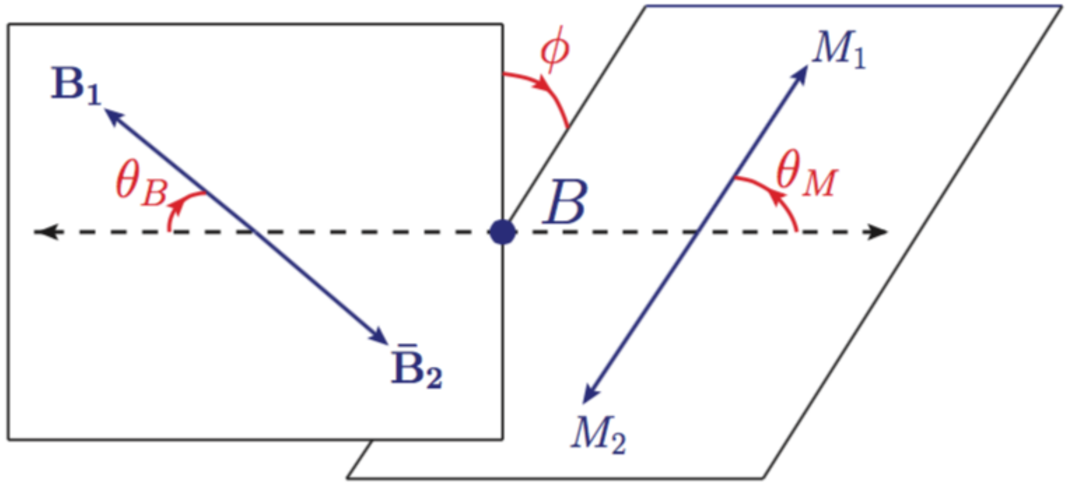
phase space

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

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

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

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

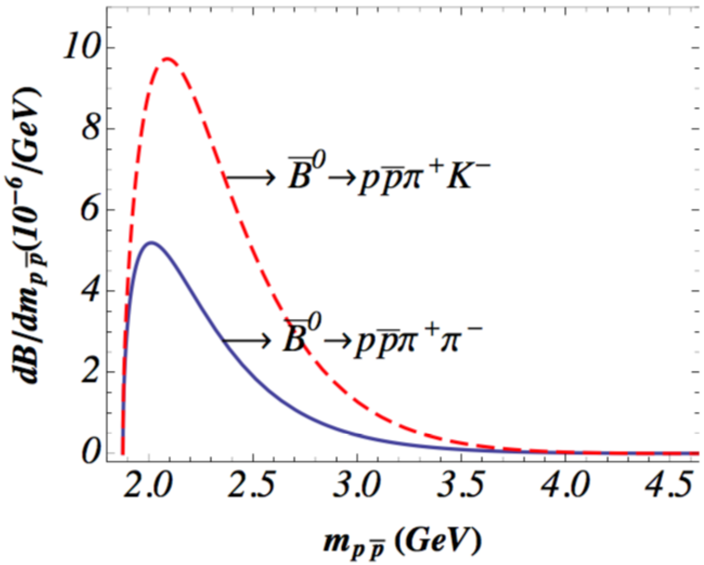


$$\lambda(a, b, c) = a^2 + b^2 + c^2 - 2ab - 2bc - 2ca,$$

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

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

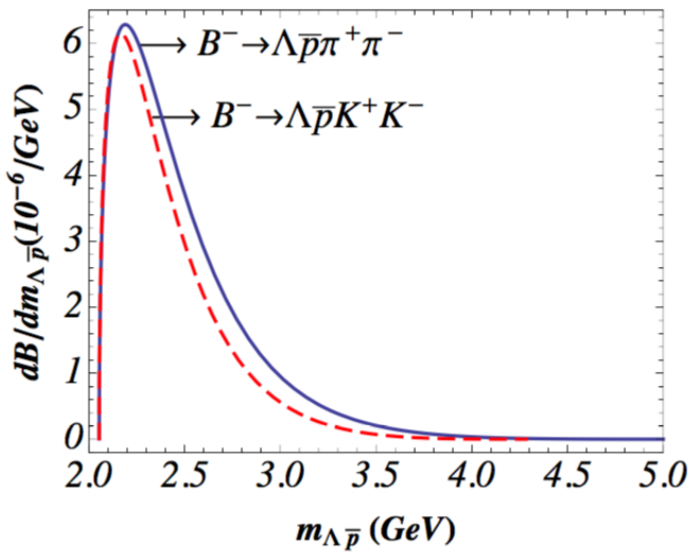
branching ratios	our results	data
$10^6\mathcal{B}(B^- \to \Lambda\bar{p}\pi^+\pi^-)$	$3.7^{+1.2}_{-0.5} \pm 0.1 \pm 0.9$	5.9 ± 1.1
$10^6\mathcal{B}(B^- \to \Lambda\bar{p}K^+K^-)$	$3.0^{+1.1}_{-0.5} \pm 0.1 \pm 0.7$	—
$10^6\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^+\pi^-)$	$3.0^{+0.5}_{-0.3} \pm 0.3 \pm 0.7$	3.0 ± 0.3
$10^6\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^\pm K^\mp)$	$6.6 \pm 0.5 \pm 0.0 \pm 2.3$	6.6 ± 0.5



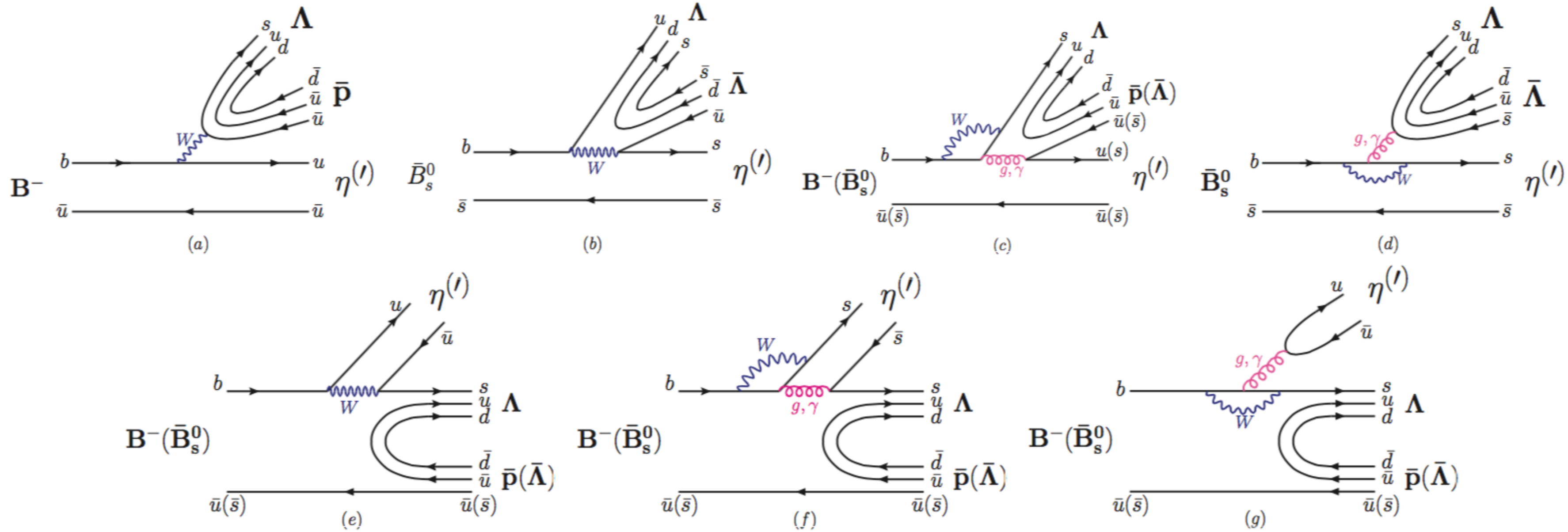
The errors come from the non-factorizable effects, CKM matrix elements, and form factors, respectively.

arXiv:1807.10503 [hep-ex], [Belle]

$$\mathcal{B}(B^+ \to p\bar{\Lambda}K^+K^-) = (4.22^{+0.45}_{-0.44} \pm 0.51) \times 10^{-6}$$



Study of $B^- \to \Lambda\bar{p}\eta^{(\prime)}$ and $\bar{B}_s^0 \to \Lambda\bar{\Lambda}\eta^{(\prime)}$ decays



branching ratios	$\mathcal{B}_+$	$\mathcal{B}_-$
$10^6\mathcal{B}(B^- \to \Lambda\bar{p}\eta)$	$5.3 \pm 0.7 \pm 1.2$	$4.0 \pm 0.6 \pm 0.4$
$10^6\mathcal{B}(B^- \to \Lambda\bar{p}\eta')$	$3.3 \pm 0.6 \pm 0.4$	$4.6 \pm 0.7 \pm 0.9$
$10^6\mathcal{B}(\bar{B}_s^0 \to \Lambda\bar{\Lambda}\eta)$	$1.2 \pm 0.2 \pm 0.2$	$2.1 \pm 0.4 \pm 0.5$
$10^6\mathcal{B}(\bar{B}_s^0 \to \Lambda\bar{\Lambda}\eta')$	$2.6 \pm 0.5 \pm 0.6$	$1.5 \pm 0.1 \pm 0.4$

Summary

- The factorization, together with
the determination of the baryonic form factors,
can be used to study the baryonic B decays.

- Particularly, we have explained
$\bar{B}^0_s \to \bar{p}\Lambda K^+ + p\bar{\Lambda}K^-$,
$B \to \mathbf{B_1 B_2} M_1 M_2$.

Thank You