Baryonic B decays

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Outline:
1. Introduction
2. Formalism
3. Results
4. Summary

Introduction

- $m_B > m_{\mathbf{B}} + m_{\bar{\mathbf{B}}'}$ **for $\mathbf{B\bar{B}'}$** ($D_s^+ \to p\bar{n}$, $\mathcal{B}$ of order 10^{-3})

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

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

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

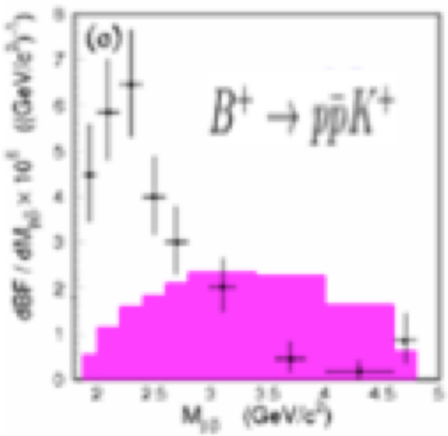
2. $B \to \mathbf{B\bar{B}'}$, 1st evidence in 2014 (LHCb)

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

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

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

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



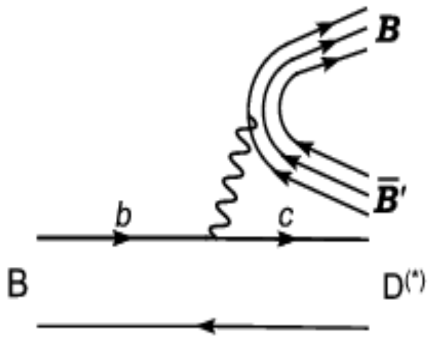
1. Accessibility of charmless cases
2. Smallness of $\mathcal{B}(\bar{B}^0_{(s)} \to p\bar{p}, \Lambda\bar{\Lambda}, B^- \to \Lambda\bar{p})$

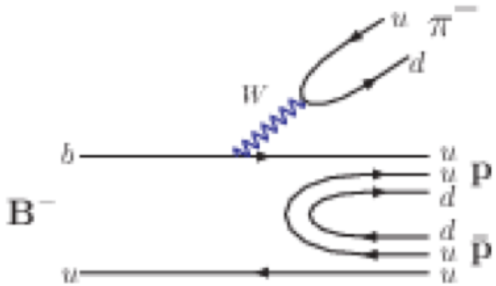
Conjecture by Hou and Soni, PRL86, 4247 (2001)
(Inspired by $\bar{B} \to D^* p\bar{n}$ and $\bar{B} \to D^* \pi p\bar{p}$)

• Factorization

The factorizable amplitudes

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





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 $B \to \mathbf{BB}$+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

• Approved to be reliable

decay mode	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	$1.5^{+0.9}_{-0.8}$

• Recent challenge from observations

Predictions (2008)

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

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.

- $B \to \mathbf{B\bar{B}'}$

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

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

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

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

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

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)

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

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

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

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

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

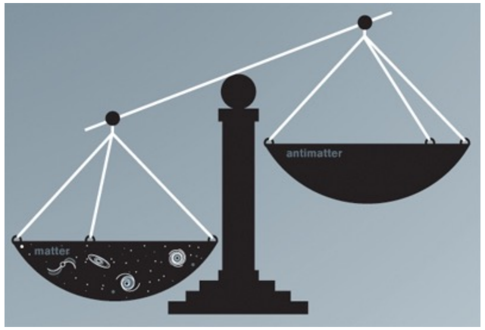
No constraints from CVC and PCAC!

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

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

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

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

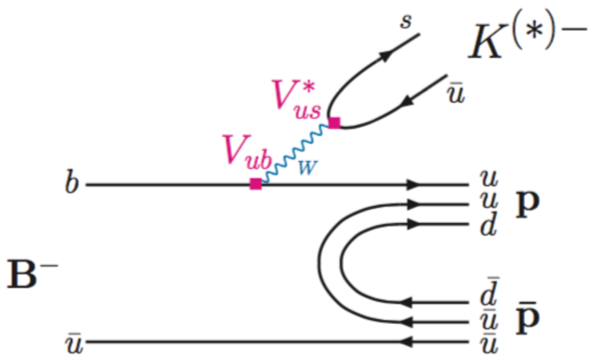
$$\mathcal{A}(\bar{B} \to \bar{f}) = ae^{-i\delta_w} + be^{i\delta_s}$$

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

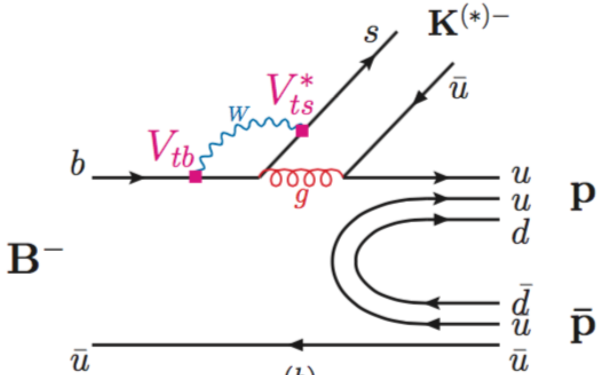
δ_w: $V_{ub} = A\lambda^3(\rho - i\eta)$

δ_s: on-shell processes

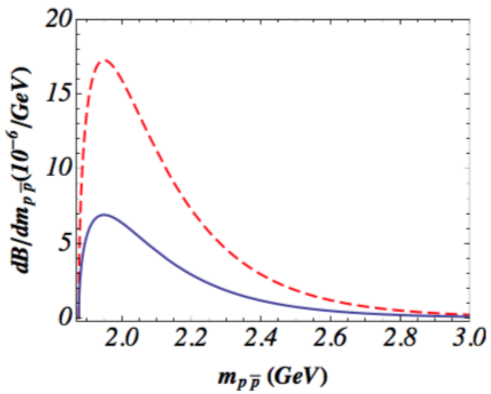
$B^- \to p\bar{p}K^{(*)-}$



(a)



(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 $m_{p\bar{p}} \simeq m_p + m_{\bar{p}}$

Direct CP violating asymmetries:

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

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

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

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

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

$$a_i \equiv c_i^{eff} + c_{i\pm 1}^{eff}/N_c^{(eff)} \text{ for } i = \text{odd (even)}$$

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

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

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

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)

Summary

- The theoretical approach is tested to be reliable to study the baryonic B decays.

- Consequently, it can be used
to explore the discrete symmetries like CPV, and
exotic states like glueballs
measured in the baryonic B decays.

Thanks for paying attention!