Four-body baryonic $B \to \mathbf{B_1}\bar{\mathbf{B}}'_1\mathbf{B_2}\bar{\mathbf{B}}'_2$ decays

Yu-Kuo Hsiao 萧佑国
Shanxi Normal University

The4thLHCbFrontierPhysicsWorkshop
2024.07.29
PLB845, 138158 (2023)

Outline:
1. Introduction
2. Formalism
3. Some results
4. Summary

Introduction

Four-body baryonic $B \to \mathbf{B}_1\bar{\mathbf{B}}'_1\mathbf{B}_2\bar{\mathbf{B}}'_2$ decays

- LHCb newly observed $\bar{B}^0 \to p\bar{p}p\bar{p}$ with

$\mathcal{B}(\bar{B}^0 \to p\bar{p}p\bar{p}) = (2.2 \pm 0.4 \pm 0.1 \pm 0.1) \times 10^{-8}$

[PRL131, 091901 (2023)].

- In comparison with

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

$\mathcal{B}(B^- \to p\bar{p}\pi^-) = (1.62 \pm 0.20) \times 10^{-6}$ (PDG),

$\mathcal{B}(\bar{B}^0 \to p\bar{p}\pi^0) = (5.0 \pm 1.9) \times 10^{-7}$ (PDG),

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

$\mathcal{B}(\bar{B}^0 \to p\bar{p}p\bar{p})$ is unexpectedly small.

Introduction

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

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. $B \to \mathbf{B}\bar{\mathbf{B}}'$, LHCb

$\mathcal{B}(B^- \to \Lambda(1520)\bar{p}) = (3.15 \pm 0.48 \pm 0.27) \times 10^{-7}$ (2014)

$\mathcal{B}(B^- \to \Lambda\bar{p}) = (2.4^{+1.0}_{-0.8} \pm 0.3) \times 10^{-7}$ (2017)

$\mathcal{B}(\bar{B}^0 \to p\bar{p}) = (1.25 \pm 0.27 \pm 0.18) \times 10^{-8}$ (2017)

Introduction

3. 1st observation of a baryonic $\bar{B}_s^0$ decay (LHCb, 2017)

$\mathcal{B}(\bar{B}_s^0 \to \Lambda\bar{p}K^+ + \bar{\Lambda}pK^-)$

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

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)

5. radiative and semileptonic

$\mathcal{B}(B^- \to \Lambda\bar{p}\gamma) = (2.16^{+0.58}_{-0.53} \pm 0.20) \times 10^{-6}$ (BELLE, 2005)

$\mathcal{B}(B^- \to p\bar{p}\ell^-\bar{\nu}_\ell) = (5.8^{+2.4}_{-2.1} \pm 0.9) \times 10^{-6}$ (BELLE, 2014)

Threshold effect

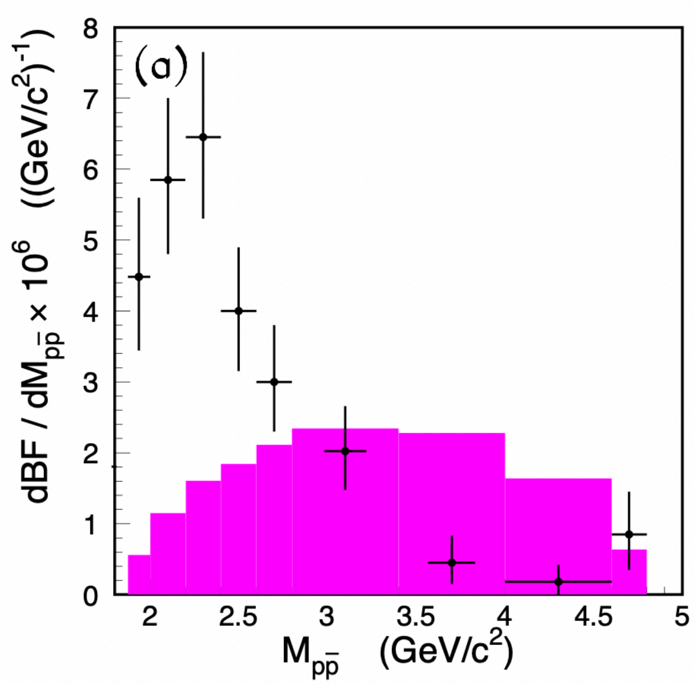
- From (non-)observation of $\bar{B}^0 \to n\bar{p}D^{*+}$ ($\bar{B}^0 \to p\bar{p}$),

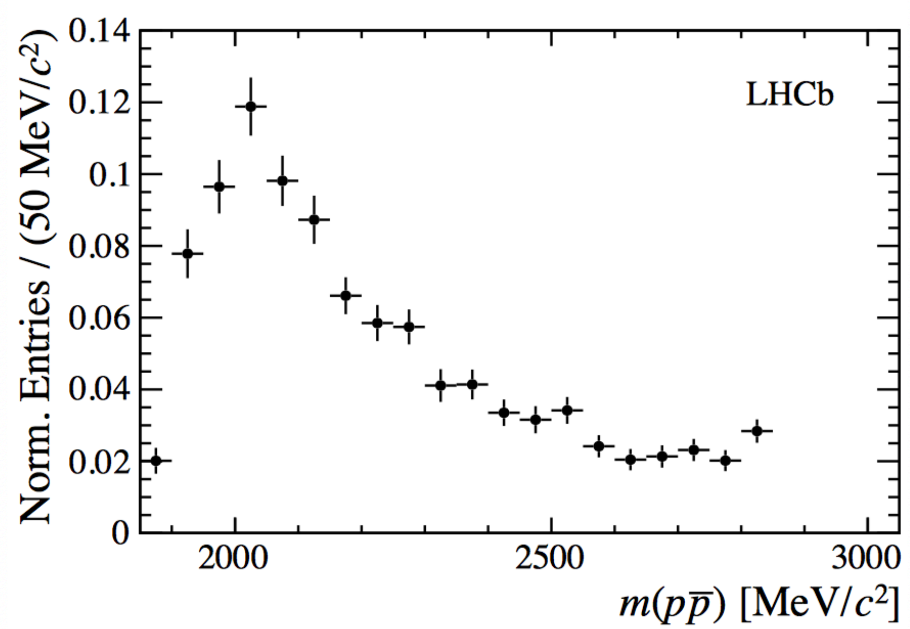
conjecturing a preference of $\mathbf{B}\bar{\mathbf{B}}'$ formation [Hou, Soni, PRL (2001)]

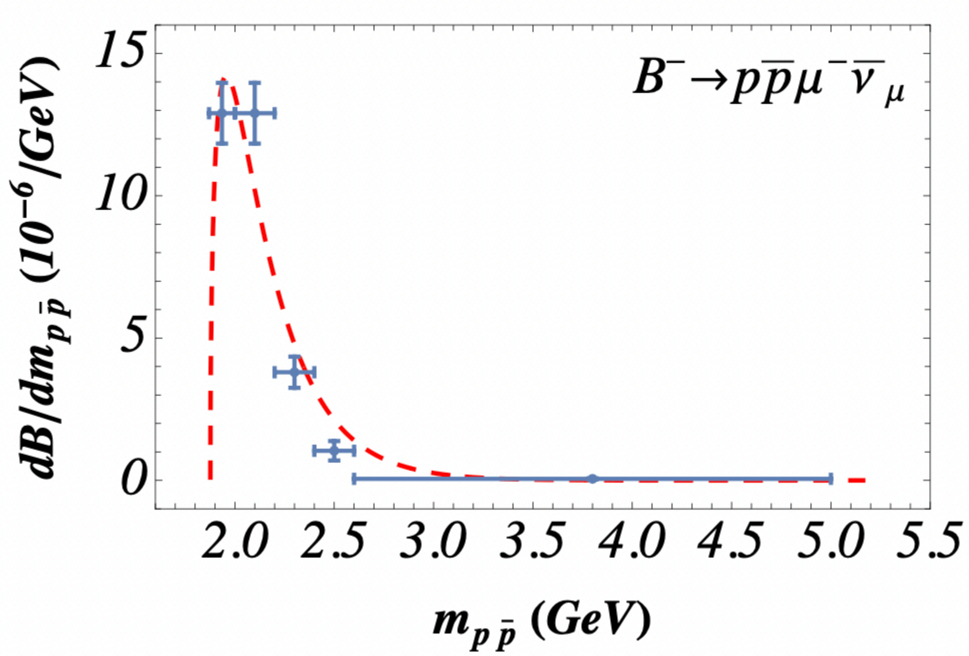
- Threshold effect, an enhancing factor

A peak near the threshold area of $m_{\mathbf{B}\bar{\mathbf{B}}'} \simeq m_{\mathbf{B}} + m_{\bar{\mathbf{B}}'}$

Observed in $B \to \mathbf{B}\bar{\mathbf{B}}'M$, $\mathbf{B}\bar{\mathbf{B}}'MM'$, $\mathbf{B}\bar{\mathbf{B}}'\gamma$, $\mathbf{B}\bar{\mathbf{B}}'L\bar{L}'$

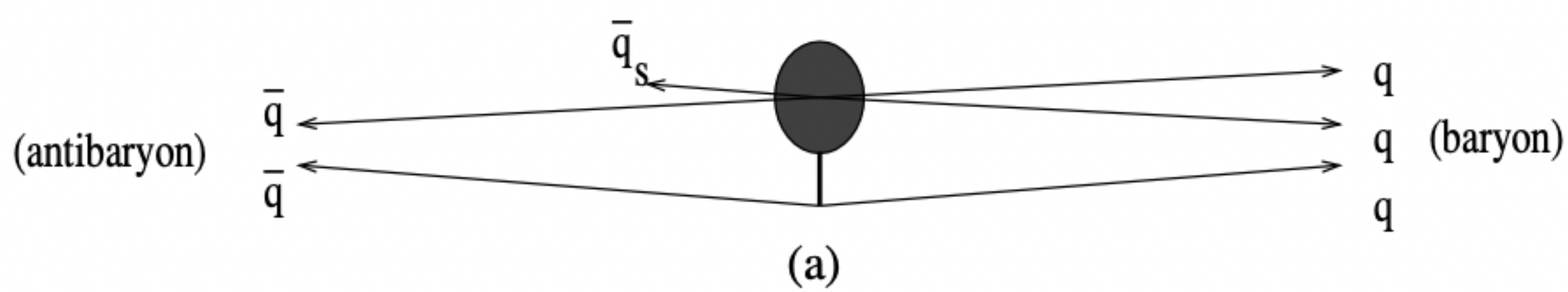




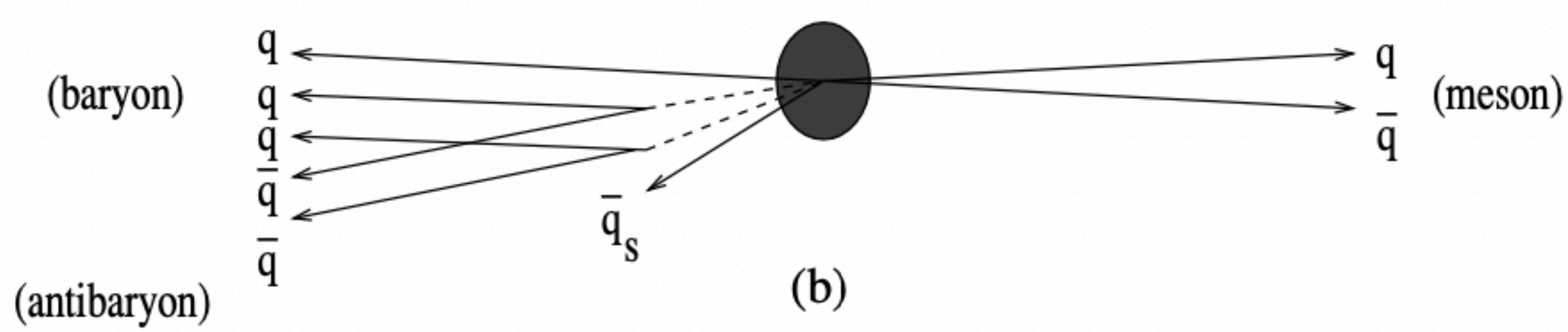


• The hard off-shell gluon suppresses

$\mathcal{M}(B \to \mathbf{B}\bar{\mathbf{B}}')$ by the power of α_s/q^2 [Suzuki, JPG **34**, 283 (2007)]



back-to-back $q\bar{q}$, energetic

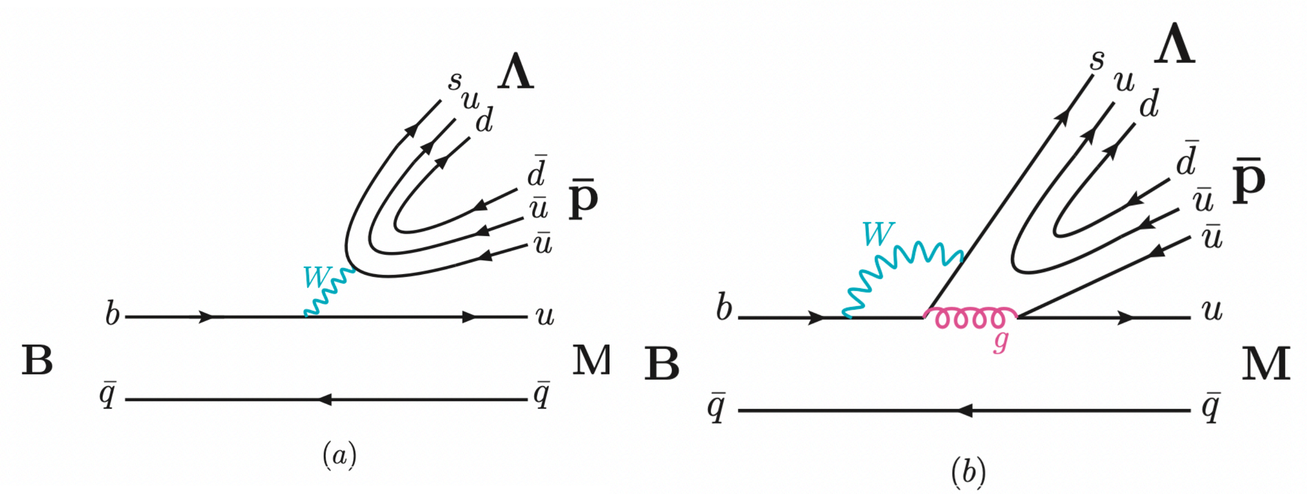


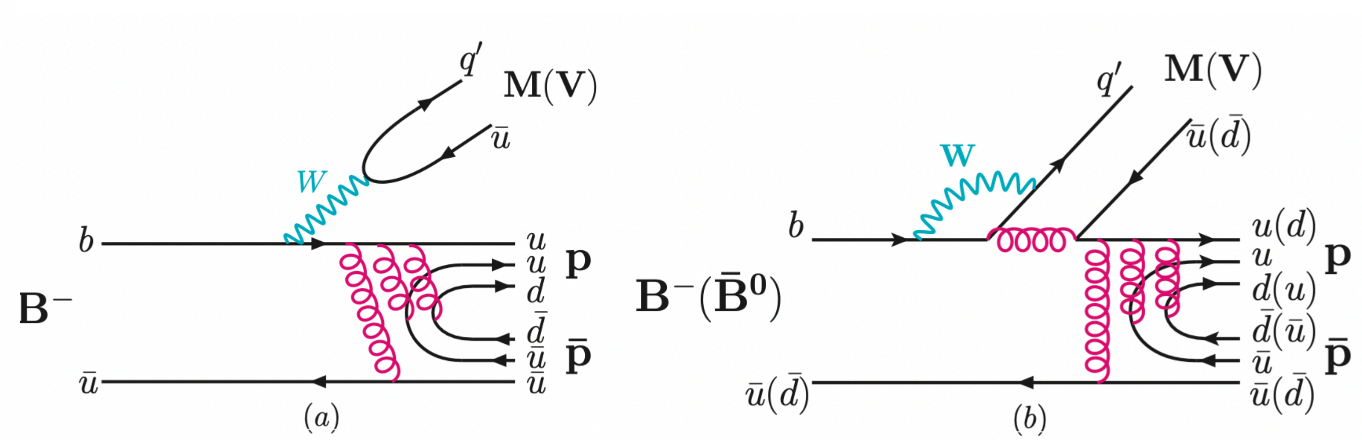
collinear $q\bar{q}$, not energetic

Factorization

$$\mathcal{M}_1(B \to \mathbf{B}\bar{\mathbf{B}}'M) \propto \langle \mathbf{B}\bar{\mathbf{B}}'|(\bar{q}q')|0\rangle\langle M|(\bar{q}b)|B\rangle$$

$$\mathcal{M}_2(B \to \mathbf{B}\bar{\mathbf{B}}'M) \propto \langle M|(\bar{q}q')|0\rangle\langle \mathbf{B}\bar{\mathbf{B}}'|(\bar{q}b)|B\rangle$$





pQCD counting rules

$\langle \mathbf{B}\bar{\mathbf{B}}'|(\bar{q}q')|0\rangle$, $F_{\mathbf{B}\bar{\mathbf{B}}'} \propto 1/t^2$ (Brodsky, Farrar, 1973)

$\langle \mathbf{B}\bar{\mathbf{B}}'|(\bar{q}b|B\rangle$, $F'_{\mathbf{B}\bar{\mathbf{B}}'} \propto 1/t^3$ (Chua, Hou, Tsai, 2002)

$B \to \mathbf{B_1\bar{B}'_1B_2\bar{B}'_2}$

- $\mathcal{M} \propto \langle \mathbf{B_1\bar{B}'_1}|(\bar{q}q')|0\rangle\langle \mathbf{B_2\bar{B}'_2}|(\bar{q}b)|B\rangle$
- Two dibaryon formations, threshold effect exists.
- anticipated to be of order 10^{-6}. In fact,

$\mathcal{B}(\bar{B}^0 \to p\bar{p}p\bar{p}) < 2.0 \times 10^{-7}$ (Babar, 2018)

$\mathcal{B}(\bar{B}^0 \to p\bar{p}p\bar{p}) = (2.2 \pm 0.4 \pm 0.1 \pm 0.1) \times 10^{-8}$ (LHCb, 2022)

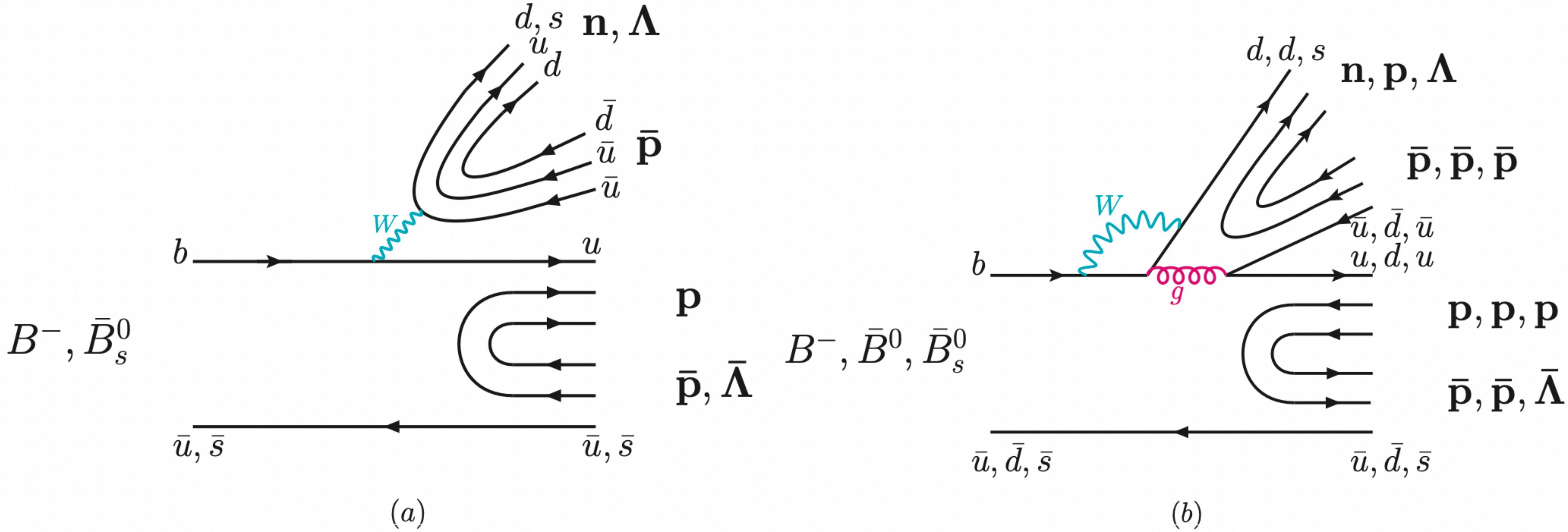
as small as $\mathcal{B}(\bar{B}^0 \to p\bar{p})$

- An interpretation is needed.
- Providing more $B \to \mathbf{B_1\bar{B}'_1B_2\bar{B}'_2}$ decay channels

for future measurements.

Amplitudes

$(B^-, \bar{B}^0_s) \to (n\bar{p}p\bar{p}, \Lambda\bar{p}p\bar{\Lambda})$



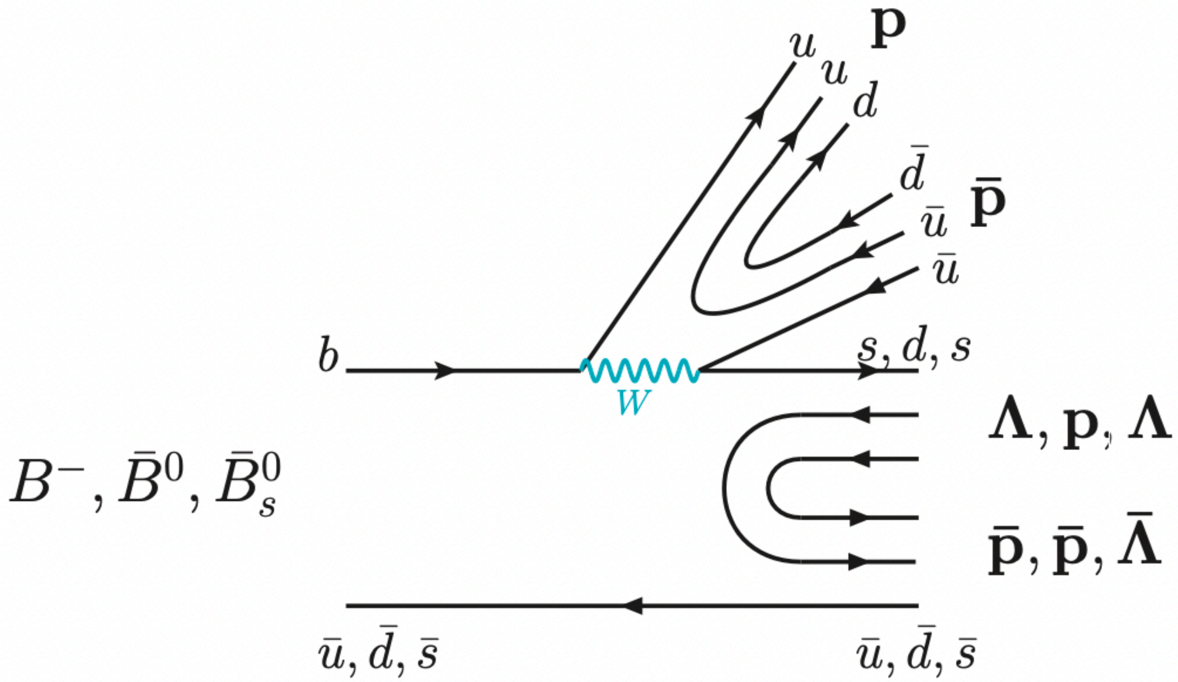
$$\bar{\mathcal{M}}(B^- \to n\bar{p}p\bar{p}) =$$

$$(\alpha_1^d + \alpha_4^d)\langle n\bar{p}|(\bar{d}u)_{V-A}|0\rangle\langle p\bar{p}|(\bar{u}b)_{V-A}|B^-\rangle$$

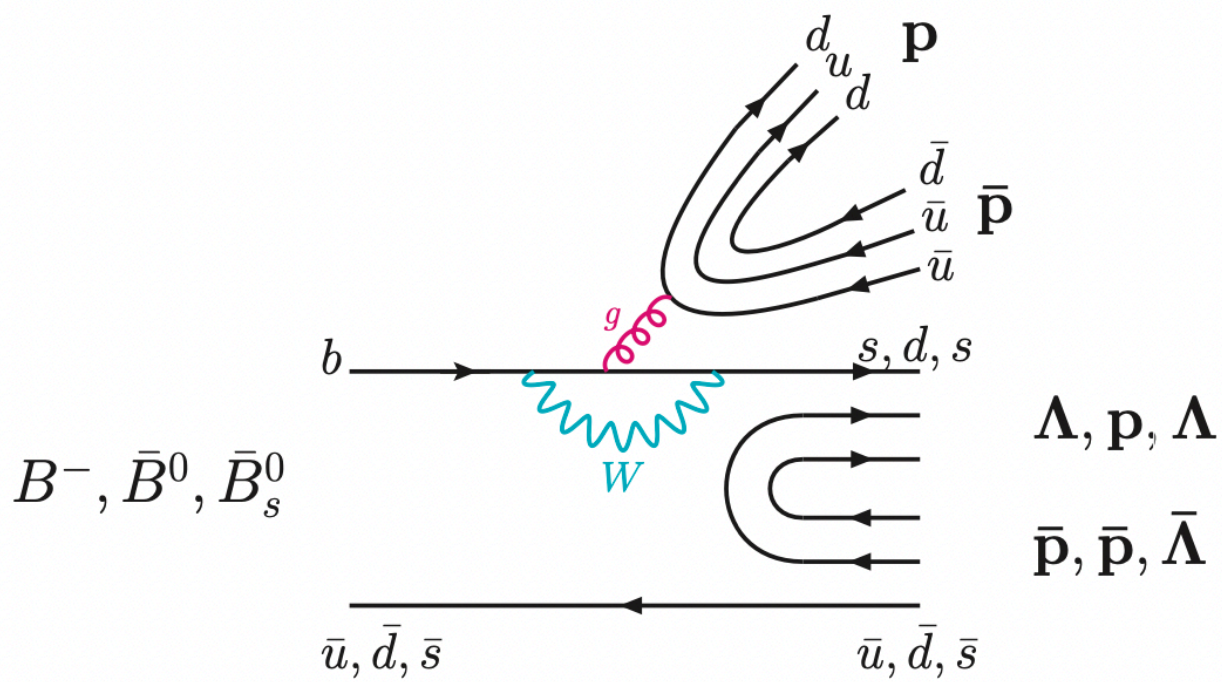
$$+\alpha_6^d\langle n\bar{p}|(\bar{d}u)_{S+P}|0\rangle\langle p\bar{p}|(\bar{u}b)_{S-P}|B^-\rangle$$

Amplitudes

$(B^-, \bar{B}^0, \bar{B}_s^0) \to p\bar{p}(\Lambda\bar{p}, p\bar{p}, \Lambda\bar{\Lambda})$



(c)



(d)

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

$$[\langle p\bar{p}|\alpha_+^d(\bar{u}u)_V - \alpha_-^d(\bar{u}u)_A|0\rangle + \langle p\bar{p}|\beta_+^d(\bar{d}d)_V - \beta_-^d(\bar{d}d)_A|0\rangle$$

$$+(\alpha_4^d - \alpha_{10}^d/2)\langle p\bar{p}|(\bar{d}d)_{V-A}|0\rangle]\ \langle p\bar{p}|(\bar{d}b)_{V-A}|\bar{B}^0\rangle$$

$$+\alpha_6^d\langle p\bar{p}|(\bar{d}d)_{S+P}|0\rangle\langle p\bar{p}|(\bar{d}b)_{S-P}|\bar{B}^0\rangle$$

Timelike baryonic form factors

$$\langle \mathbf{B_1}\bar{\mathbf{B}}'_\mathbf{1}|(\bar{q}q')_V|0\rangle = \bar{u}\left[F_1\gamma_\mu + \frac{F_2}{m_{\mathbf{B_1}}+m_{\bar{\mathbf{B}}'_\mathbf{1}}} i\sigma_{\mu\nu}q^\nu\right]v$$

$$\langle \mathbf{B_1}\bar{\mathbf{B}}'_\mathbf{1}|(\bar{q}q')_A|0\rangle = \bar{u}\left[g_A\gamma_\mu + \frac{h_A}{m_{\mathbf{B_1}}+m_{\bar{\mathbf{B}}'_\mathbf{1}}} q_\mu\right]\gamma_5 v$$

$$\langle \mathbf{B_1}\bar{\mathbf{B}}'_\mathbf{1}|(\bar{q}q')_S|0\rangle = f_S\bar{u}v$$

$$\langle \mathbf{B_1}\bar{\mathbf{B}}'_\mathbf{1}|(\bar{q}q')_P|0\rangle = g_P\bar{u}\gamma_5 v$$

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

$$s = (p_1 + p'_1)^2$$

$\bar{C}_i = C_i[\ln(t/\Lambda_0^2)]^{-\gamma}$ 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 $\bar{C}^*_{||} \equiv \bar{C}_{||} + \delta\bar{C}_{||}$.

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

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

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

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

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

$B \to \mathbf{B_2}\bar{\mathbf{B}}'_2$ transition form factors

$$\langle \mathbf{B_2}\bar{\mathbf{B}}'_\mathbf{2}|(\bar{s}b)_V|B\rangle = i\bar{u}[g_1\gamma_\mu + g_2 i\sigma_{\mu\nu}p^\nu + g_3 p_\mu + g_4 q_\mu + g_5(p_{\bar{\mathbf{B}}'_\mathbf{2}} - p_{\mathbf{B_2}})_\mu]\gamma_5 v$$

$$\langle \mathbf{B_2}\bar{\mathbf{B}}'_\mathbf{2}|(\bar{s}b)_A|B\rangle = i\bar{u}[f_1\gamma_\mu + f_2 i\sigma_{\mu\nu}p^\nu + f_3 p_\mu + f_4 q_\mu + f_5(p_{\bar{\mathbf{B}}'_\mathbf{2}} - p_{\mathbf{B_2}})_\mu]v$$

$$\langle \mathbf{B_2}\bar{\mathbf{B}}'_\mathbf{2}|(\bar{s}b)_S|B\rangle = i\bar{u}[\bar{g}_1\not{p} + \bar{g}_2(E_{\bar{\mathbf{B}}'_\mathbf{2}} + E_{\mathbf{B_1}}) + \bar{g}_3(E_{\bar{\mathbf{B}}'_\mathbf{2}} - E_{\mathbf{B_1}})]\gamma_5 v$$

$$\langle \mathbf{B_2}\bar{\mathbf{B}}'_\mathbf{2}|(\bar{s}b)_P|B\rangle = i\bar{u}[\bar{f}_1\not{p} + \bar{f}_2(E_{\bar{\mathbf{B}}'_\mathbf{2}} + E_{\mathbf{B_2}}) + \bar{f}_3(E_{\bar{\mathbf{B}}'_\mathbf{2}} - E_{\mathbf{B_2}})]v$$

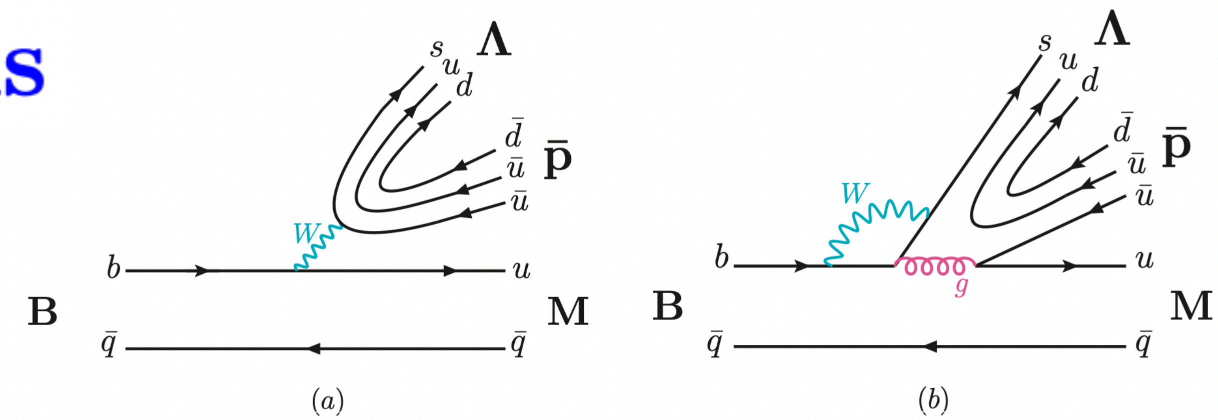
$$f_i = \frac{D_{f_i}}{t^3},\ g_i = \frac{D_{g_i}}{t^3},\ \bar{f}_i = \frac{D_{\bar{f}_i}}{t^3},\ \bar{g}_i = \frac{D_{\bar{g}_i}}{t^3},$$

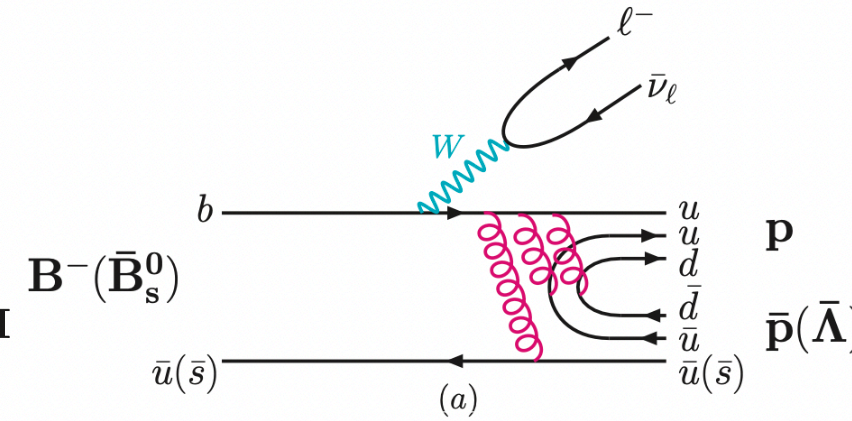
$$t = (p_2 + p'_2)^2$$

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

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

Extractions





$(C_{||}, \delta C_{||}, C_{\overline{||}}, \delta C_{\overline{||}}) =$

$(150.8 \pm 5.7, 31.9 \pm 7.1, 27.4 \pm 27.3, -317.8 \pm 169.1)\ \text{GeV}^4$

X. Huang, Hsiao, J. Wang and L. Sun,

"Angular asymmetries in $B \to \Lambda\bar{p}M$ decays," PRD105, 076016 (2022)

$(D_{||}, D_{\overline{||}}) = (11.2 \pm 43.5, 332.3 \pm 17.2)\ \text{GeV}^5$

$(D^2_{||}, D^3_{||}, D^4_{||}, D^5_{||}) =$

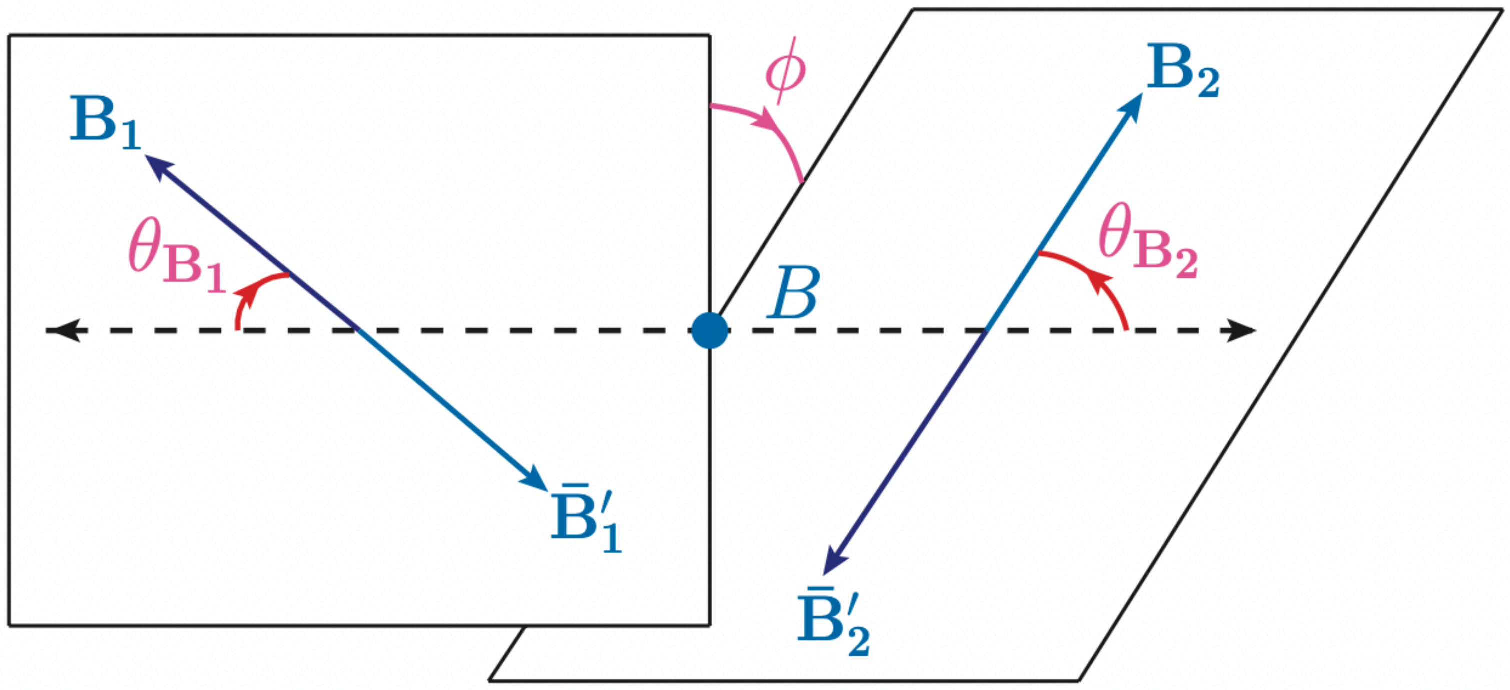
$(47.7 \pm 10.1, 442.2 \pm 103.4, -38.7 \pm 9.6, 80.7 \pm 27.2)\ \text{GeV}^4$

$(\bar{D}_{||}, \bar{D}_{\overline{||}}, \bar{D}^2_{||}, \bar{D}^3_{||}) =$

$(-59.9 \pm 12.9, 23.8 \pm 6.8, 90.9 \pm 11.1, 131.7 \pm 330.7)\ \text{GeV}^4$

Hsiao, "Semileptonic baryonic B decays," EPJC83, 300 (2023).

Phase space



$$d\Gamma = \frac{|\mathcal{M}|^2}{4(4\pi)^6 m_B^3} X \alpha_{\mathbf{B_1}} \alpha_{\mathbf{B_2}}\, ds\, dt\, d\cos\theta_{\mathbf{B_1}}\, d\cos\theta_{\mathbf{B_2}} d\phi$$

$$X = [(m_B^2 - s - t)^2/4 - st]^{1/2}$$

$$\alpha_{\mathbf{B_1}} = \lambda^{1/2}(s, m_1^2, m_1'^2)/s,\ \alpha_{\mathbf{B_2}} = \lambda^{1/2}(t, m_2^2, m_2'^2)/t$$

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

Allowed ranges

$$(m_1 + m_1')^2 \le\ s\ \le (m_B - \sqrt{t})^2,\ (m_2 + m_2')^2 \le t \le (m_B - m_1 - m_1')^2$$

$$0 \le \theta_{\mathbf{B_1},\mathbf{B_2}} \le \pi,\ 0 \le \phi \le 2\pi$$

Identical particles, indistinguishable amplitudes

• In our case

$(B^-, \bar{B}_s^0) \to (n\bar{p}p\bar{p}, \Lambda\bar{p}p\bar{\Lambda})$

$(B^-, \bar{B}^0, \bar{B}_s^0) \to p\bar{p}(\Lambda\bar{p}, p\bar{p}, \Lambda\bar{\Lambda})$

• By following the studies of $(\pi^0, K_L, \bar{B}_s^0) \to e^+e^-e^+e^-$:

1. T. Miyazaki and E. Takasugi, PRD8, 2051 (1973),

"Internal conversion of pseudoscalar mesons into lepton pairs."

2. L. Zhang and J. L. Goity, PRD57, 7031 (1998),

"The Decays $K_L \to \ell^+\ell^-\ell'^+\ell'^-$ revisited."

3. Dincer, Sehgal, PLB556, 169 (2003),

"Electroweak effects in the double Dalitz decay $B_s \to \ell^+\ell^-\ell'^+\ell'^-$."

4. Ivanov and Melikhov, PRD105, 094038 (2022),

"Theoretical analysis of the leptonic decays $B \to \ell\ell\ell\bar{\nu}_\ell$:

Identical leptons in the final state."

- $\bar{B}^0 \to p\bar{p}p\bar{p}$ **for illustration**

$\mathcal{M} = \mathcal{M}_{\rm dir} + \mathcal{M}_{\rm ex}$

$\mathcal{M}_{\rm dir}[\bar{B}^0 \to p(p_1)\bar{p}(p'_1)p(p_2)\bar{p}(p'_2)]$

$\mathcal{M}_{\rm ex}[\bar{B}^0 \to p(p_2)\bar{p}(p'_1)p(p_1)\bar{p}(p'2)]$

$\mathcal{B} = \mathcal{B}_{\rm dir} + \mathcal{B}_{\rm ex} + \mathcal{B}_{\rm dir} + \mathcal{B}_{\rm dir\times ex},$

where $\mathcal{B}_{\rm dir\times ex} \propto \mathcal{M}_{\rm dir}\mathcal{M}^*_{\rm ex} + \mathcal{M}^*_{\rm dir}\mathcal{M}_{\rm ex}$.

No doubt: $\mathcal{B}_{\rm dir} = \mathcal{B}_{\rm ex}$, but how to evaluate $\mathcal{B}_{\rm dir\times ex}$?

$\mathcal{M}_{\rm dir}$: $F_{\mathbf{B}\bar{\mathbf{B}}'} \propto 1/s^2$, $\hat{F}_{\mathbf{B}\bar{\mathbf{B}}'} \propto 1/t^3$.

$\mathcal{M}_{\rm ex}$: $F^{\rm ex}_{\mathbf{B}\bar{\mathbf{B}}'} \propto 1/s'^2$, $\hat{F}^{\rm ex}_{\mathbf{B}\bar{\mathbf{B}}'} \propto 1/t'^3$,

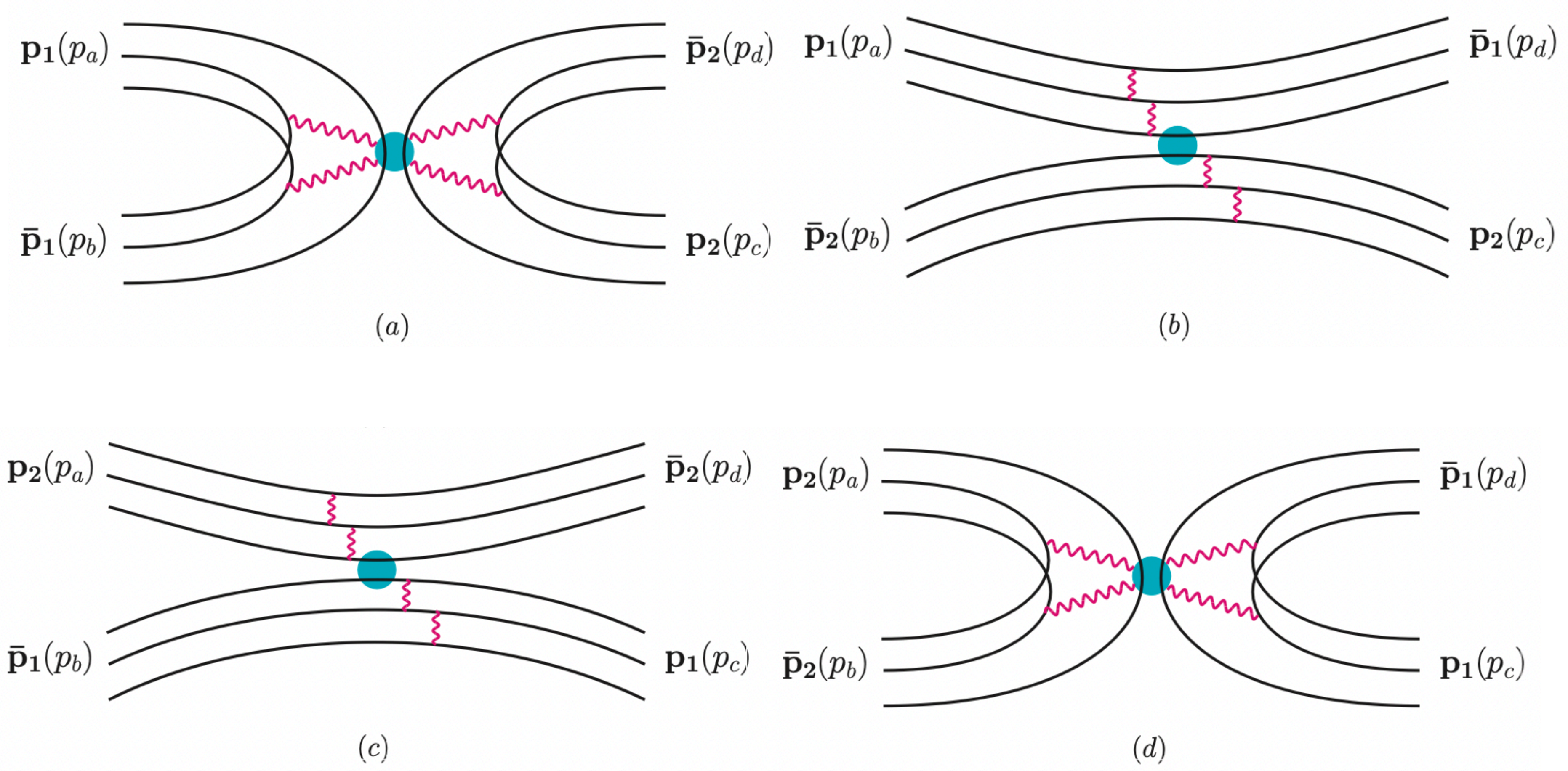
$s' \equiv (p_2 + p'_1)^2$ and $t' \equiv (p_1 + p'_2)$.

Approximation around the threshold

$\mathcal{B}_{\text{dir}\times\text{ex}} \sim 0.14 \times 10^{-8}$, negligible.

$\mathcal{B}(\bar{B}^0 \to p\bar{p}p\bar{p}) \simeq (\mathcal{B}_{\text{dir}} + \mathcal{B}_{\text{ex}})/4$,

1/4 for the 4 indistinguishable amplitudes.



Numerical results

decay mode	our work	data
$10^8\mathcal{B}(\bar{B}^0 \to p\bar{p}p\bar{p})$	$2.2 \pm 0.4 \pm 0.1 \pm 0.4$	2.2 ± 0.4
$10^8\mathcal{B}(B^- \to n\bar{p}p\bar{p})$	$8.4^{+2.1}_{-1.0} \pm 0.4^{+3.4}_{-1.9}$	—
$10^7\mathcal{B}(B^- \to \Lambda\bar{p}p\bar{p})$	$3.7^{+0.3}_{-0.1} \pm 0.02^{+1.8}_{-1.3}$	—
$10^7\mathcal{B}(\bar{B}^0_s \to \Lambda\bar{\Lambda}p\bar{p})$	$1.9^{+0.3}_{-0.1} \pm 0.01^{+1.1}_{-0.6}$	—

Errors come from non-factorizable QCD corrections, CKM matrix elements, and the form factors, in order.

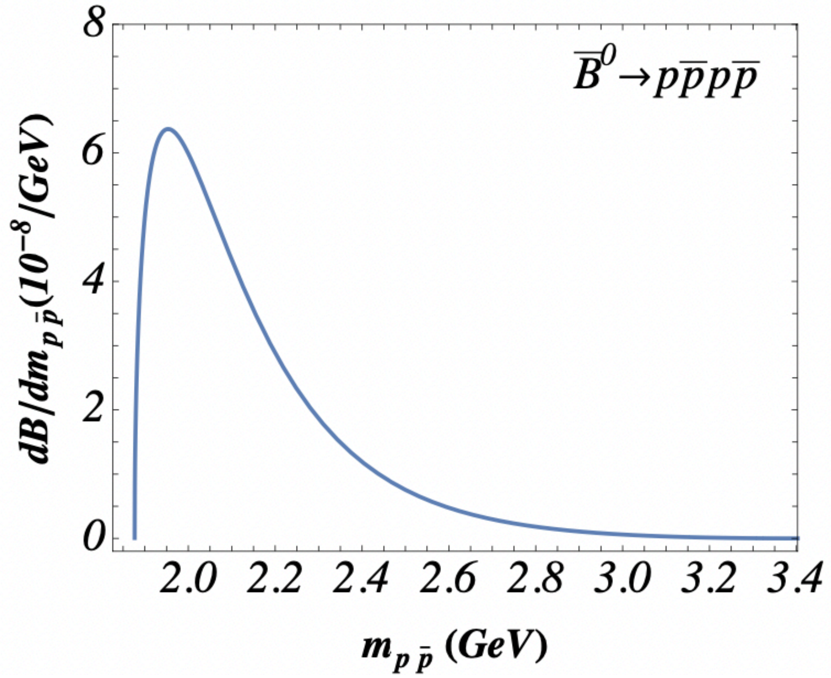
- Except for $\mathcal{B}(\bar{B}^0 \to p\bar{p}p\bar{p})$, $\mathcal{B}(B \to \mathbf{B_1\bar{B}'_1B_2\bar{B}'_2}) \sim 10^{-7}$ not as large as $\mathcal{B}(B \to \mathbf{B\bar{B}'}M) \sim 10^{-6}$.

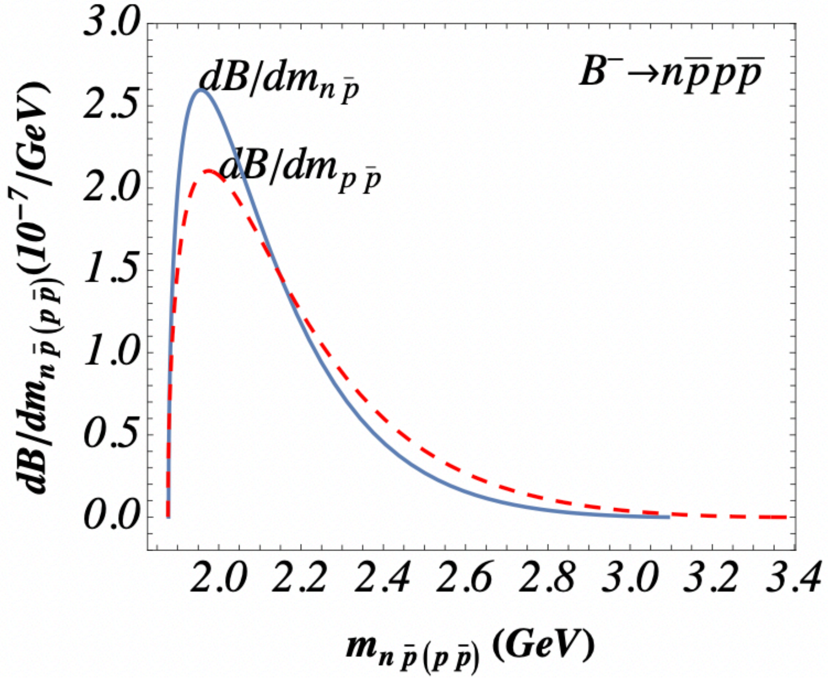
- "Double" threshold effect:

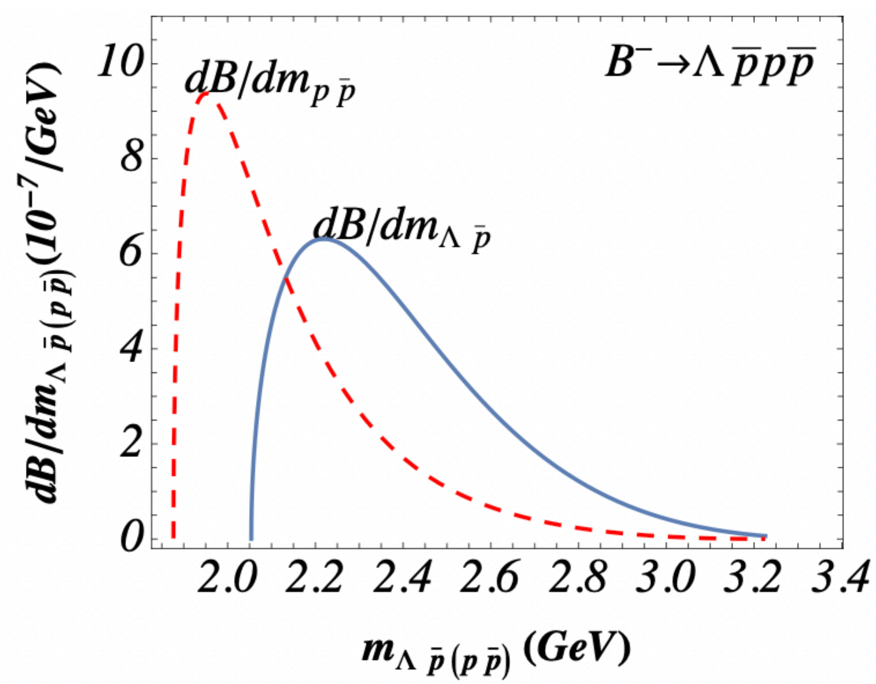
a strong preference of the phase space,

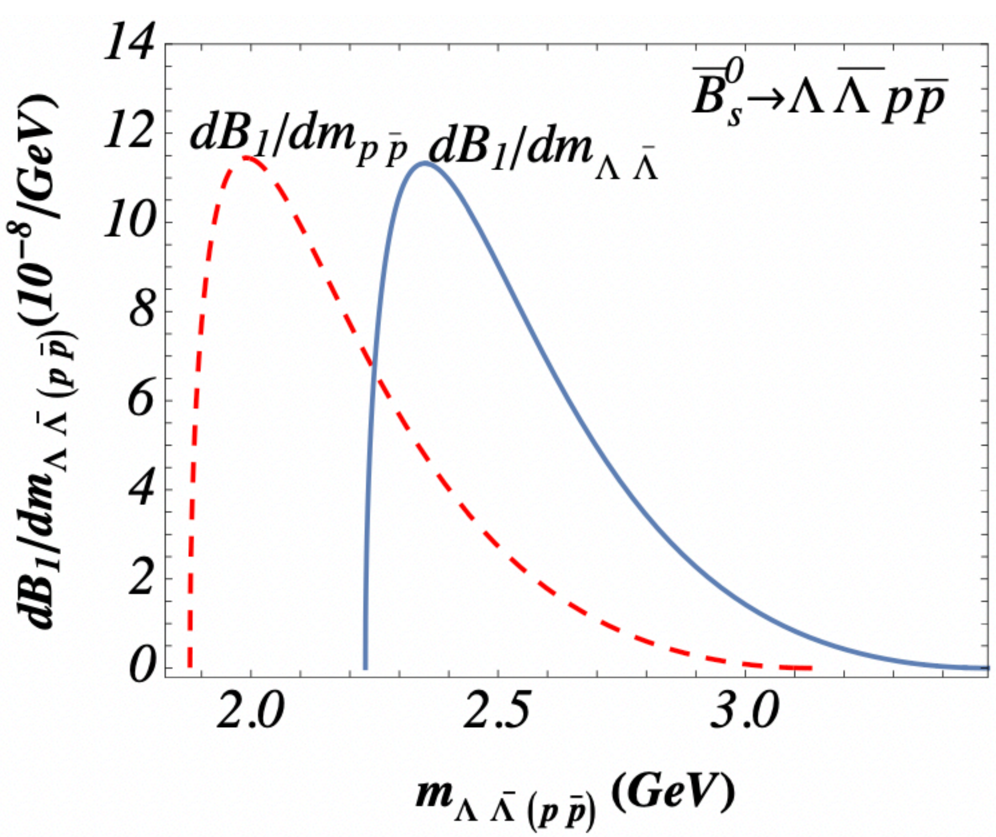
an unexpected restriction.

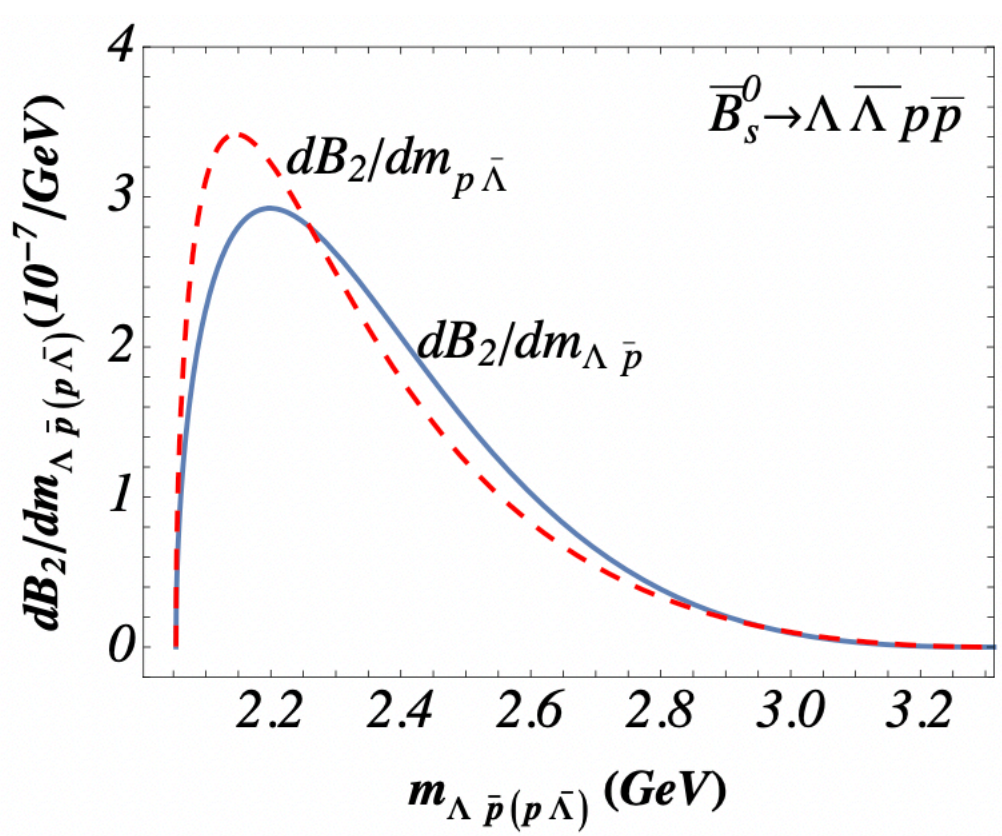
Double threshold effect











Summary

- We explained $\mathcal{B}(\bar{B}^0 \to p\bar{p}p\bar{p})$ as small as 10^{-8}.
- We predicted $\mathcal{B}(B^- \to n\bar{p}p\bar{p})$, $\mathcal{B}(B^- \to \Lambda\bar{p}p\bar{p})$, and

$\mathcal{B}(\bar{B}^0_s \to \Lambda\bar{\Lambda}p\bar{p})$ of order 10^{-7},

accessible to the LHCb and Belle II experiments.

- Double threshold effect,

used to test the theoretical model.

Thank You