$B$-meson decay into a proton and dark antibaryon from QCD light-cone sum rules

Alexander Khodjamirian, Marcel Wald
June 14, 2022

CPPS - Theoretische Physik 1 (TP1) - Universität Siegen
Motivation

- **$B$-Mesogenesis scenario** [Elor, Escudero, Nelson; 2019], [Alonso-Alvarez, Elor, Escudero; 2021], [Alonso-Alvarez et. al.; 2021]
- solves the problem of matter-antimatter asymmetry in the Universe
- explains the relic dark matter abundance
- predicts a dark sector containing a Dirac fermion $\Psi$ coupled to Standard Model (SM) quarks via heavy scalar mediator $Y$
- mechanism relates baryon asymmetry of the Universe to $CP$-violation in the neutral $B$-meson mixing
- baryon number conservation restored by assigning the dark fermion a baryon number $B = -1$
  $\rightarrow$ visible SM sector violates symmetry, but visible and dark sector combined restore baryon number conservation
Motivation

Effective Lagrangian:

\[ \mathcal{L}_{(-1/3)} = -y_{ud} \epsilon_{ijk} Y^* i \bar{u}^j_R d^c_R - y_{ub} \epsilon_{ijk} Y^* i \bar{u}^j_R b^c_R - y_{\psi d} Y_i \bar{\psi} d^c_R - y_{\psi b} Y_i \bar{\psi} b^c_R + \text{h.c.} \]

<table>
<thead>
<tr>
<th>Field</th>
<th>Spin</th>
<th>( Q_{EM} )</th>
<th>( B )</th>
<th>color</th>
<th>mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>( Y )</td>
<td>0</td>
<td>(-\frac{1}{3})</td>
<td>(-\frac{2}{3})</td>
<td>3</td>
<td>( \mathcal{O}(\text{TeV}) )</td>
</tr>
<tr>
<td>( \psi )</td>
<td>( \frac{1}{2} )</td>
<td>0</td>
<td>(-1)</td>
<td>1</td>
<td>( \mathcal{O}(\text{GeV}) )</td>
</tr>
</tbody>
</table>

- model exhibits rich phenomenology, but we restrict ourselves to the decay mode \( B \to \psi p \)
- in [Alonso-Alvarez, Elor, Escudero; 2021], branching fraction for this decay has been roughly estimated from phase space counting
- we suggest to use light-cone sum rule (LCSR) approach to calculate the \( B \to p \) hadronic matrix element, e.g. similar to the calculation of \( \Lambda_b \to p \) form factors [Khodjamirian, Klein, Mannel, Wang; 2011]
Process $B \rightarrow p\psi$

- we are interested in the process $B \rightarrow p\psi$

$$\mathcal{A}_{(d)}(B^+ \rightarrow p\psi) = G_{(d)} \langle p(P)|\tilde{\mathcal{O}}_{(d)}|B^+(P + q)\rangle u_\Psi^c(q)$$

- decomposed in terms of four form factors multiplying independent kinematical structures

$$\langle p(P)|\tilde{\mathcal{O}}_{(d)}|B^+(P + q)\rangle = F^{(d)}_{B\rightarrow p_R}(q^2)\bar{u}_{pR}(P) + F^{(d)}_{B\rightarrow p_L}(q^2)\bar{u}_{pL}(P) + \tilde{F}^{(d)}_{B\rightarrow p_R}(q^2)\bar{u}_{pR}(P)\phi + \tilde{F}^{(d)}_{B\rightarrow p_L}(q^2)\bar{u}_{pL}(P)\phi$$

- the relevant three-quark operator coupled to the fermion $\psi$

$$\tilde{\mathcal{O}}_{(d)} = i\epsilon_{ijk} \left( \bar{u}^i_R b^{cj}_R \right) \bar{d}^k_R, \quad \mathcal{O}_{(d)} = i\epsilon_{ijk} d^i_R \left( \bar{b}^{cj}_R u^k_R \right) , \quad (d \leftrightarrow b)$$
Basics of the LCSR approach

- combination of the ordinary QCD sum rule approach by [Shifman, Vainshtein, Zakharov; 1979] with theory of hard-exclusive processes [Balitsky, Braun, Kolesnichenko; 1986], [Chernyak, Zhitnitsky; 1990]
- use of correlation function calculated in terms of light-cone OPE in the deep spacelike region
- separating a hard perturbatively calculable Wilson coefficient from the long distance part encoded in distribution amplitudes of increasing twist
- in our problem, we use the nucleon distribution amplitudes [Braun, Fries, Mahnke, Stein; 2000], [Braun, Lenz, Mahnke, Stein; 2001]
- the spacelike momentum region is:

\[(P + q)^2 \ll m_b^2 \quad \text{and} \quad q^2 = m_{\psi}^2 \ll m_b^2\]
Obtaining LCSR

\[
\Pi^{(d),(b)}(P, q) = i \int d^4x \ e^{i(P+q) \cdot x} \langle 0 | \ T \{j_B(x), O_{(d),(b)}(0)\} | p(P) \rangle
\]

- correlation function:

- with the \( B \)-meson interpolating current \( j_B(x) = m_b \bar{b} i\gamma_5 u \) and the effective 3-quark operator from the \( B \)-Mesogenesis model

- we consider the inverted hadronic matrix element of the \( p \to B \) transition

\to advantage: directly using definition of DAs from literature, a global phase compared to \( B \to p \) transition is inessential
Obtaining LCSR

- follow the usual steps: matching the OPE result to hadronic dispersion relation using quark-hadron duality, Borel transformation
- sum rule for the form factor:

\[
m_B^2 f_B F_{B \rightarrow p_R}^{(d)}(q^2) e^{-m_B^2/M^2} = \frac{1}{\pi} \int_{m_b^2}^{s_0^B} ds \ e^{-s/M^2} \Im \Pi_{R}^{(d)OPE}(s, q^2)
\]

- evaluating the diagram and confining ourselves by the leading twist-3 approximation, we obtain:

\[
F_{B \rightarrow p_R}^{(d)}(q^2) = \frac{m_b^3}{4m_B^2 f_B} \int_0^{\alpha_0^B} d\alpha e^{(m_B^2-s(\alpha))/M^2} \left(1 + \frac{(1-\alpha)^2 m_{p}^2 - q^2}{m_b^2} \right) \frac{\tilde{V}(\alpha)}{(1-\alpha)^2}
\]
• for the \((b)\) - model, we derive the form factors:

\[
F_{B \rightarrow p_R}^{(b)}(q^2) = \frac{m_b^2 m_p}{4 m_B^2 f_B} \int_0^{\alpha^B_0} d\alpha \, e^{(m_B^2 - s(\alpha))/M^2} \left( \frac{m_p}{m_b} \tilde{V}(\alpha) - \frac{3}{1 - \alpha} \tilde{T}(\alpha) \right)
\]

\[
F_{B \rightarrow p_L}^{(b)}(q^2) = \frac{m_b^2 m_p}{4 m_B^2 f_B} \int_0^{\alpha^B_0} d\alpha \, e^{(m_B^2 - s(\alpha))/M^2} \frac{\tilde{V}(\alpha)}{(1 - \alpha)}
\]

• combination of two twist-3 DAs, \(\alpha\) is the momentum fraction of the u-quark in the DA

\[
\tilde{V}(\alpha) = 20 f_N \alpha (1 - \alpha)^3 \left( 1 + \frac{7}{4} \left[ 3(V_1^d + A_1^u) - 1 \right] (1 - 3\alpha) \right)
\]

\[
\tilde{T}(\alpha) = 20 f_N \alpha (1 - \alpha)^3 \left( 1 - \frac{21}{8} \left[ V_1^d - \frac{1}{3} + A_1^u \right] (1 - 3\alpha) \right)
\]

• all other form factors vanish at leading twist
z-expansion of the form factor

- large $m_\psi$ region is not accessible by LCSR
- $z$-expansion is needed in order to extrapolate the sum rule to the whole region of the possible antibaryon $\Psi$ masses $m_p + m_e \leq m_\psi \leq m_B - m_p$
- isolating the subthreshold pole of $\Lambda_b$ with $m_{\Lambda_b} = 5.62$ GeV
- after $z$-expansion, the form factor looks like:

$$F_{B \rightarrow p R}^{(d)}(q^2) = \frac{F_{B \rightarrow p R}^{(d)}(0)}{1 - q^2 / m_{\Lambda_b}^2} \left\{ 1 + b_{B \rightarrow p R}^{(d)} \left[ z(q^2) - z(0) + \frac{1}{2} (z(q^2)^2 - z(0)^2) \right] \right\}$$

$$z(q^2) = \frac{\sqrt{t_+ - q^2} - \sqrt{t_+ - t_0}}{\sqrt{t_+ - q^2} + \sqrt{t_+ - t_0}}$$

$$t_+ = (m_B + m_p)^2, \quad t_0 = (m_B + m_p) \cdot (\sqrt{m_B} - \sqrt{m_p})^2$$
Preliminary numerical analysis

- the numerical input parameters are:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>default value (interval)</th>
<th>[Ref.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$ quark $\overline{MS}$ mass</td>
<td>$\bar{m}<em>b(3 \text{ GeV}) = 4.47^{+0.04}</em>{-0.03}$ GeV</td>
<td>[1]</td>
</tr>
<tr>
<td>Renormalization scale</td>
<td>$\mu = 3.0^{+1.5}_{-0.5}$ GeV</td>
<td></td>
</tr>
<tr>
<td>Borel parameter squared</td>
<td>$M^2 = 16.0 \pm 4.0$ GeV</td>
<td>[2],[3]</td>
</tr>
<tr>
<td>Duality threshold</td>
<td>$s^B_0 = 39.0^{+1.0}_{-1.5}$ GeV</td>
<td></td>
</tr>
<tr>
<td>$B$-meson decay constant</td>
<td>$f_B = 190.0 \pm 1.3$ MeV</td>
<td>[4]</td>
</tr>
<tr>
<td>Nucleon decay constant</td>
<td>$f_N(\mu = 2$ GeV) = $(3.54^{+0.06}_{-0.04}) \times 10^{-3}$ GeV^2</td>
<td></td>
</tr>
<tr>
<td>Parameters of twist-3 DAs</td>
<td>$\phi_{10}(\mu = 2$ GeV) = $0.182^{+0.021}_{-0.015}$</td>
<td>[5]</td>
</tr>
<tr>
<td></td>
<td>$\phi_{11}(\mu = 2$ GeV) = $0.118^{+0.024}_{-0.023}$</td>
<td></td>
</tr>
</tbody>
</table>

**Table 1:** The input parameters in the LCSR.

- [1]: [Zyla et. al.; 2020], [2]: [Khodjamirian, Rusov; 2017], [3]: [Khodjamirian, Melic, Wang, Wei; 2021], [4]: [Aoki et. al.; 2021], [5]: [Bali et. al.; 2019]
Preliminary numerical analysis

- fit parameter:

<table>
<thead>
<tr>
<th>$F_{B\rightarrow p_R}(0)$</th>
<th>$b_{B\rightarrow p_R}$</th>
<th>$F_{B\rightarrow p_R}(0)$</th>
<th>$b_{B\rightarrow p_R}$</th>
<th>$F_{B\rightarrow p_L}(0)$</th>
<th>$b_{B\rightarrow p_L}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0.026^{+0.002}_{-0.002}$</td>
<td>$6.807^{+1.437}_{-0.850}$</td>
<td>$-0.008^{+0.002}_{-0.001}$</td>
<td>$-2.080^{+0.283}_{-0.287}$</td>
<td>$0.0008^{+0.0002}_{-0.0001}$</td>
<td>$0.396^{+1.531}_{-0.409}$</td>
</tr>
</tbody>
</table>

- decay width for (d) - model:

$$\Gamma_{(d)}(B^+ \rightarrow p\Psi) = |G_{(d)}|^2 |F_{B\rightarrow p_R}(m_\Psi^2)|^2 (m_B^2 - m_p^2 - m_\Psi^2) \cdot \frac{\lambda^{1/2}(m_B^2, m_p^2, m_\Psi^2)}{16\pi m_B^3}$$

- decay width for (b) - model:

$$\Gamma_{(b)}(B^+ \rightarrow p\Psi) = |G_{(b)}|^2 \left\{ \left[ F_{B\rightarrow p_R}(m_\Psi^2) \right]^2 + \frac{m_\Psi^2}{m_p^2} \left( \tilde{F}_{B\rightarrow p_L}(m_\Psi^2) \right)^2 \right\} (m_B^2 - m_p^2 - m_\Psi^2) \cdot \frac{\lambda^{1/2}(m_B^2, m_p^2, m_\Psi^2)}{16\pi m_B^3}$$
Preliminary: Form factor and branching fraction from $O(d)$
Preliminary: Form factors and branching fraction from $\mathcal{O}(b)$
new application of LCSRs with nucleon DAs providing the first QCD based estimate of $B \rightarrow \Psi$ decay amplitudes

leading order in $\alpha_s$ and leading twist

we obtained the branching fractions for the decay $B \rightarrow p\Psi$ initiated by two different operators which do not mix

branching fractions lie within the sensitivity of Belle-II

future perspectives: other versions of the $B$-Mesogenesis model, more accurate LCSRs including higher twist and radiative corrections
Appendix: Renormalization of twist-3 DA parameters

\[ f_N(\mu) = \left( \frac{\alpha_s(\mu)}{\alpha_s(\mu_0)} \right)^{\frac{2}{3\beta_0}} f_N(\mu_0) \quad \phi_{10}(\mu) = \left( \frac{\alpha_s(\mu)}{\alpha_s(\mu_0)} \right)^{\frac{20}{9\beta_0}} \phi_{10}(\mu_0) \]

\[ \phi_{11}(\mu) = \left( \frac{\alpha_s(\mu)}{\alpha_s(\mu_0)} \right)^{\frac{8}{3\beta_0}} \phi_{11}(\mu_0) \]

\[ V_1^d(\mu) - \frac{1}{3} + A_1^u(\mu) = \frac{4}{3} \left( \frac{\alpha_s(\mu)}{\alpha_s(\mu_0)} \right)^{\frac{8}{3\beta_0}} \phi_{11}(\mu_0) \]