Charmless Two-body $B \to AP$ decays in the factorization approach

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2. $B \to AP$ in the naive factorization

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   - $B^- \to a_1^-\pi^0$ and $B^- \to a_1^0\pi^-$: large $|C/T|$ is required!
   - $\bar{B}^0 \to a_1^+K^-$ and $\bar{B}^0 \to b_1^+K^-$: too large theoretical predictions on branching fractions
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3. PQCD and SCET Predictions

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两种轴矢粒子

在经典的夸克模型中，一个介子由一对正反夸克构成。

正反夸克对的总自旋为1或者0。

如果正反夸克对没有轨道激发，那么总角动量为0，1，对应着基本的赝标和矢量粒子。

当轨道角动量为1时，自旋为0的正反夸克对可以构成总角动量为1的状态($J^{PC}=1^{+-}$)，自旋为1的正反夸克对也可以构成总角动量为1的状态($J^{PC}=1^{++}$)。它们对应着两种不同的轴矢粒子。

channel	QCDF	PQCD	SCET	Exp.
$\overline{B}^0 \to a_1^+\pi^-$	$9.1^{+0.2+2.2+1.7}_{-0.2-1.8-1.1}$	12.6	10.7	12.2 ± 4.5
$\overline{B}^0 \to a_1^-\pi^+$	$23.4^{+2.3+6.2+1.9}_{-2.2-5.5-1.3}$	15.8	17.0	21.0 ± 5.4
$B^0/\overline{B}^0 \to a_1^+\pi^-$	—	28.1	28.2	
$B^0/\overline{B}^0 \to a_1^-\pi^+$	—	28.7	27.1	
$\overline{B}^0 \to a_1^\pm\pi^\mp$	$32.5^{+2.5+8.4+3.6}_{-2.4-7.3-2.4}$	28.4	27.7	31.7 ± 3.7
$\overline{B}^0 \to a_1^0\pi^0$	$0.9^{+0.1+0.3+0.7}_{-0.1-0.2-0.3}$	0.1	5.5	
$B^- \to a_1^0\pi^-$	$7.6^{+0.3+1.7+1.4}_{-0.3-1.3-1.0}$	6.7	17.2	$20.4 \pm 4.7 \pm 3.4$
$B^- \to a_1^-\pi^0$	$14.4^{+1.4+3.5+2.1}_{-1.3-3.2-1.9}$	8.3	19.0	$26.4 \pm 5.4 \pm 4.1$
$\overline{B}^0 \to a_1^+K^-$	$18.3^{+1.0+14.2+21.1}_{-1.0-\ 7.2-\ 7.5}$	20.2	15.8	$16.3 \pm 2.9 \pm 2.3$
$\overline{B}^0 \to a_1^0\overline{K}^0$	$6.9^{+0.3+6.1+9.5}_{-0.3-2.9-3.2}$	7.9	6.3	
$B^- \to a_1^-\overline{K}^0$	$21.6^{+1.2+16.5+23.6}_{-1.1-\ 8.5-11.9}$	25.4	15.5	$34.9 \pm 5.0 \pm 4.4$
$B^- \to a_1^0K^-$	$13.9^{+0.9+9.5+12.9}_{-0.9-5.1-\ 4.9}$	13.2	10.5	
$\overline{B}^0 \to b_1^+\pi^-$	$11.2^{+0.3+2.8+2.2}_{-0.3-2.4-1.9}$	19.1	7.7	
$\overline{B}^0 \to b_1^-\pi^+$	$0.3^{+0.1+0.1+0.3}_{-0.0-0.1-0.1}$	1.4	0.6	
$B^0/\overline{B}^0 \to b_1^+\pi^-$	—	15.0	5.0	
$B^0/\overline{B}^0 \to b_1^-\pi^+$	—	25.9	11.6	
$\overline{B}^0 \to b_1^\pm\pi^\mp$	$11.4^{+0.4+2.9+2.5}_{-0.3-2.5-2.0}$	20.5	8.3	$10.9 \pm 1.2 \pm 0.9$
$\overline{B}^0 \to b_1^0\pi^0$	$1.1^{+0.2+0.1+0.2}_{-0.2-0.1-0.2}$	1.5	1.8	
$B^- \to b_1^-\pi^0$	$0.4^{+0.0+0.2+0.4}_{-0.0-0.1-0.2}$	1.0	$2.0^{+0.8+0.2}_{-0.6-0.2}$	
$B^- \to b_1^0\pi^-$	$9.6^{+0.3+1.6+2.5}_{-0.3-1.6-1.5}$	5.2	5.0	$6.7 \pm 1.7 \pm 1.0$
$\overline{B}^0 \to b_1^+K^-$	$12.1^{+1.0+9.7+12.3}_{-0.9-4.9-30.2}$	43.0	8.5	$7.4 \pm 1.0 \pm 1.0$
$\overline{B}^0 \to b_1^0\overline{K}^0$	$7.3^{+0.5+5.4+6.7}_{-0.5-2.8-6.5}$	24.0	4.0	
$B^- \to b_1^-\overline{K}^0$	$14.0^{+1.3+11.5+13.9}_{-1.2-\ 5.9-\ 8.3}$	54.8	8.6	
$B^- \to b_1^0K^-$	$6.2^{+0.5+5.0+6.4}_{-0.5-2.5-5.2}$	24.8	4.6	$9.1 \pm 1.7 \pm 1.0$

$B \to AP$的理论研究

C. H. Chen, C. Q. Geng, Y. K. Hsiao and Z. T. Wei, Productions of $K_0^*(1430)$ and K_1 in B decays, Phys. Rev. D ***72****, 054011 (2005) [arXiv:hep-ph/0507012].*

V. Laporta, G. Nardulli and T. N. Pham, Non leptonic B decays to axial-vector mesons and factorization, Phys. Rev. D ***74****, 054035 (2006) [arXiv:hep-ph/0602243].*

G. Calderon, J. H. Munoz and C. E. Vera, Nonleptonic two-body B-decays including axial-vector mesons in the final state, Phys. Rev. D ***76****, 094019 (2007) [arXiv:0705.1181 [hep-ph]].*

K. C. Yang, Branching Ratios and CP Asymmetries of $B \to a_1(1260)\pi$ and $a_1(1260)K$ Decays, Phys. Rev. D ***76****, 094002 (2007) [arXiv:0705.4029 [hep-ph]].*

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PQCD and SCET studies are required.

a_1衰变常数和$B \to a_1$形状因子的估计

For tree-dominated processes $B^0/\bar{B}^0 \to a_1^{\pm}\pi^{\mp}$, the factorization formulae can be written as:

$$\begin{aligned}
\mathcal{A}(\bar{B}^0 \to a_1^+\pi^-) &= \frac{G_F}{\sqrt{2}} m_B^2 f_\pi V_0^{B\to a_1} \{V_{ub}V_{ud}^*[a_1 + a_4 + a_{10} + r_\pi(a_6 + a_8)] \\
&\quad + V_{cb}V_{cd}^*[a_4 + a_{10} + r_\pi(a_6 + a_8)]\}\,, \\
\mathcal{A}(\bar{B}^0 \to \pi^+ a_1^-) &= \frac{G_F}{\sqrt{2}} m_B^2 f_{a_1} f_+^{B\to\pi} \{V_{ub}V_{ud}^*[a_1 + a_4 + a_{10}] + V_{cb}V_{cd}^*[a_4 + a_{10}]\}\,,
\end{aligned}$$

CKM matrix elements: $|V_{ub}V_{ud}^*| \sim 4 \times 10^{-3}$; $|V_{cb}V_{cd}^*| \sim 8 \times 10^{-3}$.

Wilson coefficients: $a_{3-10} \ll a_1$

$$\begin{aligned}
\mathcal{A}(\bar{B}^0 \to a_1^+\pi^-) &= \frac{G_F}{\sqrt{2}} m_B^2 f_\pi V_0^{B\to a_1} \{V_{ub}V_{ud}^* a_1\}\,, \\
\mathcal{A}(\bar{B}^0 \to \pi^+ a_1^-) &= \frac{G_F}{\sqrt{2}} m_B^2 f_{a_1} f_+^{B\to\pi} \{V_{ub}V_{ud}^* a_1\}\,,
\end{aligned}$$

a_1衰变常数和$B \to a_1$形状因子的估计

$$
\begin{aligned}
\mathcal{A}(\bar{B}^0 \to a_1^+ \pi^-) &= \frac{G_F}{\sqrt{2}} m_B^2 f_\pi V_0^{B\to a_1} \{V_{ub} V_{ud}^* a_1\}, \\
\mathcal{A}(\bar{B}^0 \to \pi^+ a_1^-) &= \frac{G_F}{\sqrt{2}} m_B^2 f_{a_1} f_+^{B\to\pi} \{V_{ub} V_{ud}^* a_1\}, \\
\mathcal{A}(\bar{B}^0 \to \pi^+ pi^-) &= \frac{G_F}{\sqrt{2}} m_B^2 f_\pi f_+^{B\to\pi} \{V_{ub} V_{ud}^* a_1\},
\end{aligned}
$$

利用实验上测量到的结果

$$
\begin{aligned}
\mathcal{BR}(\bar{B}^0 \to \pi^+ \pi^-) = (5.16 \pm 0.22) \times 10^{-6}, \\
\mathcal{BR}(\bar{B}^0 \to a_1^+ \pi^-) = (12.2 \pm 4.5) \times 10^{-6}, \\
\mathcal{BR}(\bar{B}^0 \to a_1^- \pi^+) = (21.0 \pm 5.4) \times 10^{-6},
\end{aligned} \tag{1}
$$

我们可以得到

$$
f_{a_1} = [2.02 \pm 0.26 \pm 0.04 + \mathcal{O}(\frac{a_{3-10}}{a_1})] f_\pi, \quad V_0^{B\to a_1} = (1.55 \pm 0.28 \pm 0.03 + \mathcal{O}(\frac{a_{3-10}}{a_1})) f_+^{B\to\pi}. \tag{2}
$$

As a rough estimation, we take $f_\pi = 131$ MeV and $f_+^{B\to\pi} = 0.25$ which corresponds to $f_{a_1} = (264 \pm 34 \pm 6)$ MeV and $V_0^{B\to a_1} = 0.39 \pm 0.07 \pm 0.01$.

$B \to b_1$的形状因子

b_1的量子数为$J^{PC} = 1^{+-}$，C宇称要求其衰变常数为0。

类似的，利用$B \to b_1^{\pm}\pi^{\mp}$和$B \to \pi^{+}\pi^{-}$的分支比，我们可以估计出$B \to b_1$的衰变常数:

$$|V_0^{B \to b_1}(q^2 = 0)| \simeq 0.35.$$

Large $|C/T|$ in $B^- \to a_1^- \pi^0$ and $B^- \to a_1^0 \pi^-$ decays

The factorization formulae of $B^- \to a_1^0 \pi^-$ and $B^- \to a_1^- \pi^0$ are given by:

$$\begin{aligned}
\sqrt{2}\mathcal{A}(B^- \to \pi^- a_1^0) &= \frac{G_F}{\sqrt{2}} m_B^2 f_\pi V_0^{B\to a_1} \{V_{ub}V_{ud}^*[a_1 + a_4 + a_{10} + r_\pi(a_6 + a_8)] \\
&\quad + V_{cb}V_{cd}^*[a_4 + a_{10} + r_\pi(a_6 + a_8)]\}, \\
&\quad + \frac{G_F}{\sqrt{2}} m_B^2 f_{a_1} f_+^{B\to\pi} \left\{V_{ub}V_{ud}^*[a_2 - a_4 + \frac{1}{2}a_{10}] + V_{cb}V_{cd}^*[-a_4 + \frac{1}{2}a_{10}]\right\}, \qquad (3) \\
\sqrt{2}\mathcal{A}(B^- \to \pi^0 a_1^-) &= \frac{G_F}{\sqrt{2}} m_B^2 f_\pi V_0^{B\to a_1} \left\{V_{ub}V_{ud}^*[a_2 - a_4 + \frac{1}{2}a_{10} + r_\pi(-a_6 + \frac{1}{2}a_8)] \right. \\
&\quad \left. + V_{cb}V_{cd}^*[-a_4 + \frac{1}{2}a_{10} + r_\pi(-a_6 + \frac{1}{2}a_8)]\right\}, \\
&\quad + \frac{G_F}{\sqrt{2}} m_B^2 f_{a_1} f_+^{B\to\pi} \{V_{ub}V_{ud}^*[a_1 + a_4 + a_{10}] + V_{cb}V_{cd}^*[a_4 + a_{10}]\}. \qquad (4)
\end{aligned}$$

Since the small values of a_{3-10}, the penguin contributions can be safely neglected:

$$\sqrt{2}\mathcal{A}(B^- \to \pi^- a_1^0) = \frac{G_F}{\sqrt{2}} m_B^2 V_{ub}V_{ud}^*[a_1 f_\pi V_0^{B\to a_1} + a_2 f_{a_1} f_+^{B\to\pi}], \qquad (5)$$

$$\sqrt{2}\mathcal{A}(B^- \to \pi^0 a_1^-) = \frac{G_F}{\sqrt{2}} m_B^2 V_{ub}V_{ud}^*[a_2 f_\pi V_0^{B\to a_1} + a_1 f_{a_1} f_+^{B\to\pi}]. \qquad (6)$$

Large $|C/T|$ in $B \to a_1\pi$ decays

If $a_2 \ll a_1$, branching ratios are required to satisfy the following relation:

$$\mathcal{BR}(\bar{B}^0 \to a_1^+\pi^-) = 2\mathcal{BR}(B^- \to \pi^- a_1^0), \quad \mathcal{BR}(\bar{B}^0 \to \pi^+ a_1^-) = 2\mathcal{BR}(B^- \to a_1^-\pi^0).$$

But the experimental data shows:

$$\mathcal{BR}(B^- \to \pi^- a_1^0) = 20.4 \pm 4.7 \pm 3.4 > \mathcal{BR}(\bar{B}^0 \to a_1^+\pi^-) = 12.2 \pm 4.5,$$
$$\mathcal{BR}(B^- \to \pi^0 a_1^-) = 26.4 \pm 5.4 \pm 4.1 > \mathcal{BR}(\bar{B}^0 \to a_1^-\pi^+) = 21.0 \pm 5.4,$$

If the Wilson coefficient a_2 can be enhanced to 0.5 (corresponding to large color-suppressed tree amplitude), the branching ratios of $\mathcal{BR}(B^- \to \pi^0 a_1^-)$ and $\mathcal{BR}(B^- \to \pi^- a_1^0)$ are predicted as 20.0×10^{-6} and 16.7×10^{-6}. These two predictions are well consistent with the experimental data.

Branching ratios of $\bar{B}^0 \to a_1^+ K^-$ and $\bar{B}^0 \to b_1^+ K^-$

Flavor structures of $\bar{B}^0 \to b_1^+ K^-$ and $\bar{B}^0 \to a_1^+ K^-$ are the same with each other, thus they have the same factorization formulae:

$$\begin{aligned} \mathcal{A}(\bar{B}^0 \to (a_1^+, b_1^+) K^-) &= \frac{G_F}{\sqrt{2}} m_B^2 f_K V_0^{B\to(a_1,b_1)} \{V_{ub}V_{us}^*[a_1 + a_4 + a_{10} + r_K(a_6 + a_8)] \\ &\quad + V_{cb}V_{cs}^*[a_4 + a_{10} + r_K(a_6 + a_8)]\}\,. \end{aligned} \tag{7}$$

The branching ratio of $\bar{B}^0 \to \pi^+ K^-$ has been measured as:

$$\mathcal{BR}(\bar{B}^0 \to \pi^+ K^-) = (19.4 \pm 0.6) \times 10^{-6}, \tag{8}$$

which implies:

$$\begin{aligned} \mathcal{BR}(\bar{B}^0 \to a_1^+ K^-) &= 19.4 \times \frac{12.2}{5.16} \times 10^{-6} = 45.9 \times 10^{-6}, \\ \mathcal{BR}(\bar{B}^0 \to b_1^+ K^-) &= 19.4 \times \frac{10.9}{5.16} \times 10^{-6} = 41.0 \times 10^{-6}. \end{aligned} \tag{9}$$

But experimentalists have given rather small decay rates:

$$\begin{aligned} \mathcal{BR}(\bar{B}^0 \to a_1^+ K^-) &= (16.3 \pm 2.9 \pm 2.3) \times 10^{-6}, \quad 2.8 \\ \mathcal{BR}(\bar{B}^0 \to b_1^+ K^-) &= (7.4 \pm 1.0 \pm 1.0) \times 10^{-6}. \quad 5.5 \end{aligned} \tag{10}$$

Isospin symmetry breaking in $B \to a_1(b_1)K$

Besides $\bar{B}^0 \to (a_1^+, b_1^+)K^-$, $B^- \to a_1^- \bar{K}^0$ and $B^- \to b_1^0 K^-$ decays have already been measured with the factorization formulae:

$$\begin{aligned}
\mathcal{A}(B^- \to a_1^- \bar{K}^0) &= \frac{G_F}{\sqrt{2}} m_B^2 f_K V_0^{B\to a_1} \Big\{ V_{ub}V_{us}^*[a_4 - \frac{1}{2}a_{10} + r_K(a_6 - \frac{1}{2}a_8)] \\
&\quad + V_{cb}V_{cs}^*[a_4 - \frac{1}{2}a_{10} + r_K(a_6 - \frac{1}{2}a_8)] \Big\}, \qquad (11)\\
\sqrt{2}\mathcal{A}(B^- \to b_1^0 K^-) &= \frac{G_F}{\sqrt{2}} m_B^2 f_K V_0^{B\to b_1} \{ V_{ub}V_{us}^*[a_1 + a_4 + a_{10} + r_K(a_6 + a_8)] \\
&\quad + V_{cb}V_{cs}^*[a_4 + a_{10} + r_K(a_6 + a_8)] \}. \qquad (12)
\end{aligned}$$

In order to characterize the magnitude from tree operators and symmetry breaking effects between B^- and $\bar{B}^0$ mesons, it is useful to define the two ratios:

$$R_1 \equiv \frac{\mathcal{BR}(B^- \to a_1^- \bar{K}^0)}{\mathcal{BR}(\bar{B}^0 \to a_1^+ K^-)} \times \frac{\tau_{\bar{B}^0}}{\tau_{B^-}}, \quad R_2 \equiv \frac{2\mathcal{BR}(B^- \to b_1^0 K^-)}{\mathcal{BR}(\bar{B}^0 \to b_1^+ K^-)} \times \frac{\tau_{\bar{B}^0}}{\tau_{B^-}}. \qquad (13)$$

Neglecting tree operators and electro-weak penguins, the ratios obey the limit:

$$R_1 = 1, \quad R_2 = 1, \qquad (14)$$

with large deviations from the experimental results:

$$R_1^{\text{exp.}} = 2.00 \pm 0.59, \quad R_2^{\text{exp.}} = 2.30 \pm 0.67. \qquad (15)$$

Puzzles in $B \to AP$ decays?

- Large $|C/T|$ is required in $B^- \to a_1^- \pi^0$ and $B^- \to a_1^0 \pi^-$ decays.

- Theoretical predictions on branching fractions of $\bar{B}^0 \to a_1^+ K^-$ and $\bar{B}^0 \to b_1^+ K^-$ decays are larger than the data by a factor of 2.8 and 5.5, respectively.

- Ratios R_1 and R_2 defined in $B^- \to a_1^- \bar{K}^0$, $B^- \to b_1^0 K^-$ and $\bar{B}^0 \to (a_1^+, b_1^+) K^-$ also have large deviations from the data.

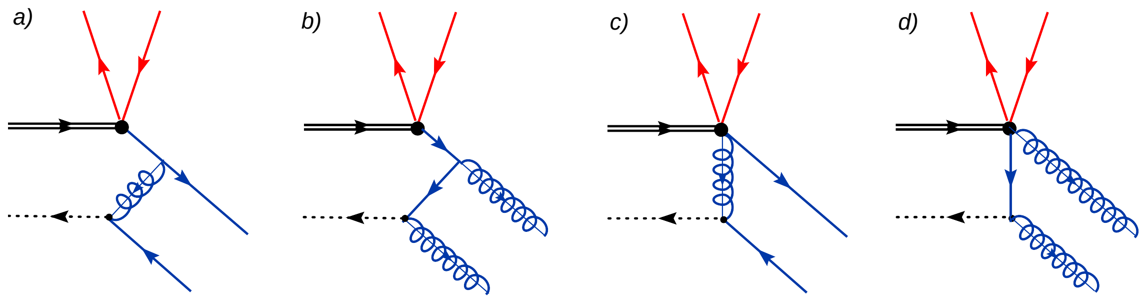
Characteristics of $B \to AP$ decays in PQCD approach

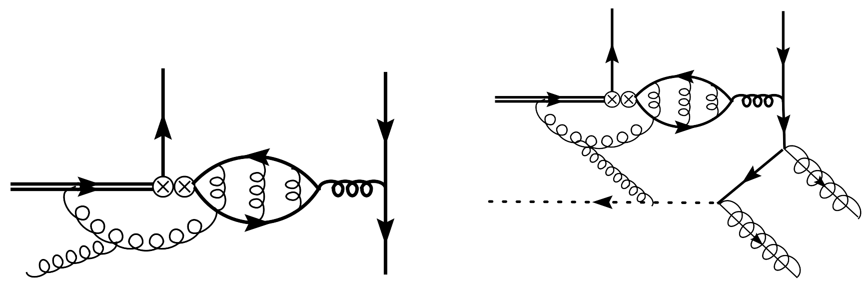
- $B \to a_1$的形状因子预言与实验抽取值基本符合（稍小一些），所以$\bar{B}^0 \to a_1^+\pi^-$和$\bar{B}^0 \to a_1^+K^-$的分支比与实验基本符合
- 色压低的树图较小(有效的Wilson系数a_2很小），不能解决$B^- \to a_1^0\pi^-$和$B^- \to a_1^-\pi^0$。
- $B \to b_1$形状因子的预言偏大,使得PQCD对$\mathcal{BR}(\bar{B}^0 \to b_1^+\pi^-)$和$\mathcal{BR}(\bar{B}^0 \to b_1^+K^-)$ 的预言会偏大
- 没有大的同位旋对称性破坏源，对比值R_1和R_2的预言不能改进

Factorization in SCET

在SCET$_I$的框架下，因子化公式为:

$$
\begin{aligned}
A(B\to M_1M_2) \quad = \quad & \frac{G_F}{\sqrt{2}}m_B^2\Big\{f_{M_1}\int du\phi_{M_1}(u)T_1(u)\zeta^{BM_2}+f_{M_1}\int du\phi_{M_1}(u)\int dzT_{1J}(u,z)\zeta_J^{BM_2}(z)\\
&+f_{M_1}\int du\phi_{M_1}(u)T_{1g}(u)\zeta_g+f_{M_1}\int du\phi_{M_1}(u)\int dzT_{1Jg}(u,z)\zeta_{Jg}(z)\\
&+\lambda_c^{(f)}A_{cc}^{M_1M_2}+1\leftrightarrow 2\Big\}, \qquad (16)
\end{aligned}
$$





Phenomenological studies

在树图层次下，因子化公式可以简化成:

$$A_{B\to M_1M_2} = \frac{G_F}{\sqrt{2}} m_B^2 \{ f_{M_1}\zeta_J^{BM_2}\int du\phi_{M_1}(u)T_{1J}(u) + f_{M_1}\zeta^{BM_2}T_{1\zeta} + (1\leftrightarrow 2) + \lambda_c^{(f)}A_{cc}^{M_1M_2}\}. \quad (17)$$

ζ, ζ_J and A_{cc} are treated as nonperturbative parameters which can be fit from experiment.

通过对$B\to PP, VP$衰变拟合的结果，我们得到经验:

- $\zeta\sim\zeta_J \to |C/T|$正比于$\zeta_J/(\zeta+\zeta_J)\sim 0.5$，可以很大。
- Charming penguins provide the dominant contributions in decays induced by the $b\to s$ transition. $\to$通过调节charming penguins，我们可以很好的预言$\bar{B}^0\to a_1^+K^-$和$\bar{B}^0\to b_1^+K^-$的分支比。
- 对很多非微扰参量采用了SU(3)对称性$\to$ 不能很好的预言上面讨论的比值R_1和R_2.

channel	QCDF	PQCD	SCET	Exp.
$\overline{B}^0 \to a_1^+\pi^-$	$9.1^{+0.2+2.2+1.7}_{-0.2-1.8-1.1}$	12.6	10.7	12.2 ± 4.5
$\overline{B}^0 \to a_1^-\pi^+$	$23.4^{+2.3+6.2+1.9}_{-2.2-5.5-1.3}$	15.8	17.0	21.0 ± 5.4
$B^0/\overline{B}^0 \to a_1^+\pi^-$	—	28.1	28.2	
$B^0/\overline{B}^0 \to a_1^-\pi^+$	—	28.7	27.1	
$\overline{B}^0 \to a_1^\pm\pi^\mp$	$32.5^{+2.5+8.4+3.6}_{-2.4-7.3-2.4}$	28.4	27.7	31.7 ± 3.7
$\overline{B}^0 \to a_1^0\pi^0$	$0.9^{+0.1+0.3+0.7}_{-0.1-0.2-0.3}$	0.1	5.5	
$B^- \to a_1^0\pi^-$	$7.6^{+0.3+1.7+1.4}_{-0.3-1.3-1.0}$	6.7	17.2	$20.4 \pm 4.7 \pm 3.4$
$B^- \to a_1^-\pi^0$	$14.4^{+1.4+3.5+2.1}_{-1.3-3.2-1.9}$	8.3	19.0	$26.4 \pm 5.4 \pm 4.1$
$\overline{B}^0 \to a_1^+K^-$	$18.3^{+1.0+14.2+21.1}_{-1.0-\ 7.2-\ 7.5}$	20.2	15.8	$16.3 \pm 2.9 \pm 2.3$
$\overline{B}^0 \to a_1^0\overline{K}^0$	$6.9^{+0.3+6.1+9.5}_{-0.3-2.9-3.2}$	7.9	6.3	
$B^- \to a_1^-\overline{K}^0$	$21.6^{+1.2+16.5+23.6}_{-1.1-\ 8.5-11.9}$	25.4	15.5	$34.9 \pm 5.0 \pm 4.4$
$B^- \to a_1^0K^-$	$13.9^{+0.9+9.5+12.9}_{-0.9-5.1-\ 4.9}$	13.2	10.5	
$\overline{B}^0 \to b_1^+\pi^-$	$11.2^{+0.3+2.8+2.2}_{-0.3-2.4-1.9}$	19.1	7.7	
$\overline{B}^0 \to b_1^-\pi^+$	$0.3^{+0.1+0.1+0.3}_{-0.0-0.1-0.1}$	1.4	0.6	
$B^0/\overline{B}^0 \to b_1^+\pi^-$	—	15.0	5.0	
$B^0/\overline{B}^0 \to b_1^-\pi^+$	—	25.9	11.6	
$\overline{B}^0 \to b_1^\pm\pi^\mp$	$11.4^{+0.4+2.9+2.5}_{-0.3-2.5-2.0}$	20.5	8.3	$10.9 \pm 1.2 \pm 0.9$
$\overline{B}^0 \to b_1^0\pi^0$	$1.1^{+0.2+0.1+0.2}_{-0.2-0.1-0.2}$	1.5	1.8	
$B^- \to b_1^-\pi^0$	$0.4^{+0.0+0.2+0.4}_{-0.0-0.1-0.2}$	1.0	$2.0^{+0.8+0.2}_{-0.6-0.2}$	
$B^- \to b_1^0\pi^-$	$9.6^{+0.3+1.6+2.5}_{-0.3-1.6-1.5}$	5.2	5.0	$6.7 \pm 1.7 \pm 1.0$
$\overline{B}^0 \to b_1^+K^-$	$12.1^{+1.0+9.7+12.3}_{-0.9-4.9-30.2}$	43.0	8.5	$7.4 \pm 1.0 \pm 1.0$
$\overline{B}^0 \to b_1^0\overline{K}^0$	$7.3^{+0.5+5.4+6.7}_{-0.5-2.8-6.5}$	24.0	4.0	
$B^- \to b_1^-\overline{K}^0$	$14.0^{+1.3+11.5+13.9}_{-1.2-\ 5.9-\ 8.3}$	54.8	8.6	
$B^- \to b_1^0K^-$	$6.2^{+0.5+5.0+6.4}_{-0.5-2.5-5.2}$	24.8	4.6	$9.1 \pm 1.7 \pm 1.0$

Charming penguins, annihilations and FSI

CKM matrix elements: The space-like annihilation ($(S-P)(S+P)$) is proportional to $V_{tb}V_{tD}^*$, while charming penguins and final state interactions are proportional to $V_{cb}V_{cD}^*$. Here D denotes a d or s quark.

Mixing-induced CP asymmetries S_f and H_f of $\bar{B}_s^0 \to \phi K_S$ are defined by:

$$\begin{aligned} S_f &= \eta_f \frac{2\text{Im}[\lambda]}{1+|\lambda|^2} = -2\frac{\text{Im}[\frac{q}{p}\frac{A(\bar{B}_s\to f)}{A(B_s\to \bar{f})}]}{1+|\lambda|^2}, \\ H_f &= \eta_f \frac{2\text{Re}[\lambda]}{1+|\lambda|^2} = -2\frac{\text{Re}[\frac{q}{p}\frac{A(\bar{B}_s\to f)}{A(B_s\to \bar{f})}]}{1+|\lambda|^2}, \end{aligned} \tag{18}$$

PQCD:

$$V_{tb}V_{td}^* \sim e^{i\beta} \to S_f = -\sin(2\beta + 2\epsilon), \;\; S_f = -\cos(2\beta + 2\epsilon), \tag{19}$$

SCET:

$$V_{cb}V_{cd}^* \sim 1 \to S_f = -\sin(+2\epsilon) \sim 0, \;\; S_f = -\cos(+2\epsilon) \sim -1, \tag{20}$$

Charming penguins, annihilations and FSI

Magnitudes: In $b \longrightarrow s$ transitions, the annihilation can be enhanced to be of the same order with penguins in emission diagrams in PQCD. And so is the contributions from final state interactions. But in SCET, charming penguins are larger than penguin operators.

Strong phase: In PQCD approach, the annihilation is dynamically enhanced and the dominant part is from the imaginary part. The contributions from the elastic final state interactions are also imaginary. But strong phase in charming penguin in SCET is not too large and the main contribution is from the real part.

Charming penguins, annihilations and FSI

Factorization properties: annihilations are factorizable in the PQCD approach; while final state interactions and charming penguins are non-perturbative in nature and can not factorized.

Power counting: annihilations are power suppressed by $1/m_b$; in the presence of form factors, final state interactions are also power suppressed; the charming penguins belong to the leading power term.

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Thank you for your attention.

Backup slides: Non-perturbative inputs in SCET

$$
\begin{aligned}
\zeta^{B\to\pi} &= 0.12, \quad \zeta_J^{B\to\pi} = 0.12, \\
\zeta^{B\to a_1} &= 0.17, \quad \zeta_J^{B\to a_1} = 0.17, \\
\zeta^{B\to b_1} &= -0.16, \quad \zeta_J^{B\to b_1} = -0.16, \\
|A_{cc}^{{}^3P_1P}| &= 40\times 10^{-4}, \quad arg[A_{cc}^{{}^3P_1P}] = 160^\circ, \\
|A_{cc}^{P^3P_1}| &= 40\times 10^{-4}, \quad arg[A_{cc}^{P^3P_1}] = 145^\circ, \\
|A_{cc}^{{}^1P_1P}| &= 40\times 10^{-4}, \quad arg[A_{cc}^{{}^1P_1P}] = 155^\circ, \\
|A_{cc}^{P^1P_1}| &= 35\times 10^{-4}, \quad arg[A_{cc}^{P^1P_1}] = 100^\circ.
\end{aligned}
$$

Backup slides

channel	QCDF	PQCD	SCET	Exp.
$\overline{B}^0 \to a_1^+ \pi^-$	$-3.6^{+0.1+0.3+20.8}_{-0.1-0.5-20.2}$	12.5	21.5	$7 \pm 21 \pm 15$
$\overline{B}^0 \to a_1^- \pi^+$	$-1.9 \pm 0.0 \pm 0.0^{+14.6}_{-14.3}$	11.7	10.4	$15 \pm 15 \pm 7$
$\overline{B}^0 \to a_1^0 \pi^0$	$60.1^{+4.6+6.8+37.6}_{-4.9-8.3-60.7}$	23.6	−29.5	
$B^- \to a_1^0 \pi^-$	$-4.3^{+0.3+1.4+14.1}_{-0.3-2.2-14.5}$	−0.7	5.7	
$B^- \to a_1^- \pi^0$	$0.5^{+0.3+0.6+12.0}_{-0.2-0.3-11.0}$	1.6	−5.4	
$\overline{B}^0 \to a_1^+ K^-$	$2.6^{+0.0+0.7+10.1}_{-0.1-0.7-11.0}$	−9.0	−17.7	$-16 \pm 12 \pm 1$
$\overline{B}^0 \to a_1^0 \overline{K}^0$	$-7.7^{+0.6+2.1+6.8}_{-0.6-2.2-7.0}$	−1.8	17.9	
$B^- \to a_1^- \overline{K}^0$	$0.8^{+0.0+0.1+0.6}_{-0.0-0.1-0.0}$	−1.0	0.3	$12 \pm 11 \pm 2$
$B^- \to a_1^0 K^-$	$8.4^{+0.3+1.4+10.3}_{-0.3-1.6-12.0}$	−5.8	−25.6	
$\overline{B}^0 \to b_1^+ \pi^-$	$-4.0^{+0.2+0.4+26.2}_{-0.0-0.6-25.5}$	−24.9	−42.3	
$\overline{B}^0 \to b_1^- \pi^+$	$66.1^{+1.2+7.4+30.3}_{-1.4-4.8-96.6}$	49.5	0	
$\overline{B}^0 \to b_1^0 \pi^0$	$53.4^{+6.4+9.0+5.2}_{-6.3-7.3-4.7}$	15.1	52.7	
$B^- \to b_1^0 \pi^-$	$0.9^{+0.6+2.3+18.0}_{-0.4-2.7-20.5}$	−64.2	−17.7	
$B^- \to b_1^- \pi^0$	$-36.5^{+4.4+18.4+82.2}_{-4.3-17.7-59.6}$	12.4	34.1	$5 \pm 16 \pm 2$
$\overline{B}^0 \to b_1^+ K^-$	$5.5^{+0.2+1.2+47.2}_{-0.3-1.2-30.2}$	16.6	46.3	$-7 \pm 12 \pm 2$
$\overline{B}^0 \to b_1^0 \overline{K}^0$	$-8.6^{+0.8+3.3+8.3}_{-0.8-4.2-25.4}$	−4.5	−0.8	
$B^- \to b_1^- \overline{K}^0$	$1.4^{+0.1+0.1+5.6}_{-0.1-0.1-0.1}$	−0.2	0.3	
$B^- \to b_1^0 K^-$	$18.7^{+1.6+7.8+57.7}_{-1.7-6.1-44.9}$	19.6	46.3	$-46 \pm 20 \pm 2$