Measuring α using $B \to K^{(*)} \bar{K}^{(*)}$ Decays

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Flavor Physics and CP Violation (FPCP)

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Measure CP violation in the B system $\Longrightarrow$ test the SM $\Longrightarrow$ find New Physics.

Smoking-gun signals for new physics:

- $B_d^0(t) \to \Psi K_S$ vs. $B_d^0(t) \to \phi K_S$ (β)
- $B^\pm \to D K^\pm$ vs. $B_s^0(t) \to D_s^\pm K^\mp$ (γ)
- $B_s^0(t) \to \Psi \phi$ (0)

Probes new physics in the $b \to s$ FCNC (B_s^0–$\bar{B}_s^0$ mixing or the $b \to s$ penguin). No hadronic uncertainties.

Question: are there clean probes of new physics in the $b \to d$ FCNC?

NO.

Consider $b \to d$ penguin:

$$A = P_u V_{ub}^* V_{ud} + P_c V_{cb}^* V_{cd} + P_t V_{tb}^* V_{td}$$

Can eliminate any one CKM combination in terms of the other two:

$$\begin{aligned}
&(P_u - P_c) V_{ub}^* V_{ud} + (P_t - P_c) V_{tb}^* V_{td} \quad (\alpha) \\
&(P_c - P_u) V_{cb}^* V_{cd} + (P_t - P_u) V_{tb}^* V_{td} \quad (\beta) \\
&(P_u - P_t) V_{ub}^* V_{ud} + (P_c - P_t) V_{cb}^* V_{cd} \quad (\gamma)
\end{aligned}$$

There is a "CKM ambiguity": don't know the relative weak phase.

In order to test for new physics in the $b \to d$ FCNC, need a theoretical assumption to break the CKM ambiguity.

(D.L., N. Sinha, R. Sinha)

$B_d^0 \to K^0 \bar{K}^0$

Pure $b \to d$ penguin:

$$\begin{aligned} A &= P_u\, V_{ub}^* V_{ud} + P_c\, V_{cb}^* V_{cd} + P_t\, V_{tb}^* V_{td} \\ &= \mathcal{P}_{uc}\, e^{i\gamma}\, e^{i\delta_{uc}} + \mathcal{P}_{tc}\, e^{-i\beta}\, e^{i\delta_{tc}} \end{aligned}$$

Note: $\mathcal{P}_{uc}$ and $\mathcal{P}_{tc}$ include CKM info.

4 parameters: $\mathcal{P}_{uc}$, $\mathcal{P}_{tc}$, $\Delta \equiv \delta_{uc} - \delta_{tc}$, α

Recall:

$$\Gamma(B_d^0(t) \to f) \sim X + Y \cos\Delta m t - Z_I \sin\Delta m t$$

where

$$X \equiv \frac{|A|^2 + |\bar{A}|^2}{2} \quad , \quad Y \equiv \frac{|A|^2 - |\bar{A}|^2}{2} \ ,$$

$$Z_I \equiv \mathrm{Im}\left(e^{-2i\beta} A^* \bar{A}\right) \quad , \quad Z_R \equiv \mathrm{Re}\left(e^{-2i\beta} A^* \bar{A}\right) \ .$$

$(Z_R^2 = X^2 - Y^2 - Z_I^2.)$

3 OBSERVABLES, 4 UNKNOWNS.

Can express 3 theoretical parameters in terms of 4^{th}:

$$\mathcal{P}_{tc}^2 = \frac{Z_R \cos 2\alpha + Z_I \sin 2\alpha - X}{\cos 2\alpha - 1} \ .$$

$B_d^0 \to K^* \bar{K}^*$

K^* is $K^*(892)$, $K_1(1270)$, ...

Similar analysis as for $B_d^0 \to K^0 \bar{K}^0$:

$$\mathcal{P}_{tc}'^{\,2} = \frac{Z_R' \cos 2\alpha + Z_I' \sin 2\alpha - X'}{\cos 2\alpha - 1} ~.$$

Therefore

$$\frac{\mathcal{P}_{tc}^2}{\mathcal{P}_{tc}'^{\,2}} = \frac{Z_I \sin 2\alpha + Z_R \cos 2\alpha - X}{Z_I' \sin 2\alpha + Z_R' \cos 2\alpha - X'} ~.$$

Note: CKM info in $\mathcal{P}_{tc}$ and $\mathcal{P}_{tc}'$ cancels in the ratio.

If we knew the value of $\mathcal{P}_{tc}^2/\mathcal{P}_{tc}'^{\,2}$, we could extract α.

$B_s^0 \to K^{(*)}\bar{K}^{(*)}$

$B_s^0 \to K^0\bar{K}^0$: pure $b \to s$ penguin:

$$\begin{aligned} A &= P_u^{(s)}\, V_{ub}^* V_{us} + P_c^{(s)}\, V_{cb}^* V_{cs} + P_t^{(s)}\, V_{tb}^* V_{ts} \\ &= \mathcal{P}_{uc}^{(s)}\, e^{i\gamma}\, e^{i\delta_{uc}^{(s)}} + \mathcal{P}_{tc}^{(s)}\, e^{i\delta_{tc}^{(s)}} \end{aligned}$$

Note: $\mathcal{P}_{uc}^{(s)}$ is negligible compared to $\mathcal{P}_{tc}^{(s)}$. Therefore the measurement of $B(B_s^0 \to K^0\bar{K}^0)$ gives $|\mathcal{P}_{tc}^{(s)}|$.

Similarly, the measurement of $B(B_s^0 \to K^*\bar{K}^*)$ gives $|\mathcal{P}_{tc}^{\prime(s)}|$.

CLAIM:

$$\frac{{\mathcal{P}_{tc}^{(s)}}^2}{{\mathcal{P}_{tc}^{\prime(s)}}^2} = \frac{\mathcal{P}_{tc}^2}{{\mathcal{P}_{tc}^{\prime}}^2} \ .$$

Note: CKM matrix elements cancel in ratios, so this is a statement about hadronic parameters – breaks CKM ambiguity.

A similar method applies to non-CP-conjugate decays of the form $K^0\bar{K}^*$, $K^*\bar{K}^0$.

IN ALL CASES, THE THEORETICAL ERROR IS SMALL, AT MOST 5% (AND MAY WELL BE EVEN SMALLER).

Experimental considerations:

- Branching ratios $\sim 10^{-6}$.
- K^*, $\bar{K}^*$ detected through their decays to charged π's and K's only $\Longrightarrow$ good K/π separation.
- No π^0 detection needed.

Discrete ambiguities:

Potentially a serious drawback: method allows extraction of α with a 16-fold (!) ambiguity.

- Can be reduced to 4-fold by considering two different pairs of $K^{(*)}\bar{K}^{(*)}$ final states (e.g. $K^0\bar{K}^0$ and $K^*\bar{K}^*$; $K^0\bar{K}^*$ and $K^*\bar{K}^0$).
- We expect P_u, P_c in $b \to d$ penguins to be at most 50% of $P_t \Longrightarrow \mathcal{P}_{uc}/\mathcal{P}_{tc} < 0.5$ for all decays. This reduces the ambiguity to 2-fold: α, $\alpha + \pi$.

Other methods for measuring α: $B_d^0(t) \to \pi^+\pi^-$ ($+$ isospin analysis), $B \to \rho\pi$ ($+$ Dalitz-plot analysis). These methods have their difficulties. Could the $B \to K^{(*)}\bar{K}^{(*)}$ method be first? Unlikely. But: a discrepancy between the values of α would point to new physics in the $b \to d$ penguin.

Theoretical Error

We claim the equality of a double ratio of matrix elements:

$$\frac{r_t}{r_t^*} \equiv \frac{\left\langle K^0 \bar{K}^0 \right| H_d \left| B_d^0 \right\rangle / \left\langle K^0 \bar{K}^0 \right| H_s \left| B_s^0 \right\rangle}{\left\langle K^* \bar{K}^* \right| H_d \left| B_d^0 \right\rangle / \left\langle K^* \bar{K}^* \right| H_s \left| B_s^0 \right\rangle} = 1 \ .$$

The two decays in r_t are related by $SU(3)$ (U-spin). Same for r_t^*:

$$\begin{aligned} r_t &= \frac{\left\langle K^0 \bar{K}^0 \right| H_d \left| B_d^0 \right\rangle}{\left\langle K^0 \bar{K}^0 \right| H_s \left| B_s^0 \right\rangle} = 1 + C_{SU(3)} \ , \\ r_t^* &= \frac{\left\langle K^* \bar{K}^* \right| H_d \left| B_d^0 \right\rangle}{\left\langle K^* \bar{K}^* \right| H_s \left| B_s^0 \right\rangle} = 1 + C^*_{SU(3)} \ , \end{aligned}$$

so that

$$\frac{r_t}{r_t^*} = 1 + \left(C_{SU(3)} - C^*_{SU(3)} \right) \ .$$

Although there is no symmetry limit in which $(C_{SU(3)} - C^*_{SU(3)}) \to 0$, we expect significant cancellations between $C_{SU(3)}$ and $C^*_{SU(3)}$.

We write

$$
\begin{aligned}
r_t &= \left\langle K^0\bar{K}^0\right| H_d \left|B_d^0\right\rangle / \left\langle K^0\bar{K}^0\right| H_s \left|B_s^0\right\rangle \\
&= \left\langle K^0\bar{K}^0\right| H_d \left|B_d^0\right\rangle / \left\langle K^0\bar{K}^0\right| U^\dagger H_d U \left|B_s^0\right\rangle \ ,
\end{aligned}
$$

Two main sources of error:

- "final-state" corrections, $U\left|K^0\bar{K}^0\right\rangle \neq \left|K^0\bar{K}^0\right\rangle$
- "initial-state" corrections, $U\left|B_s^0\right\rangle \neq \left|B_d^0\right\rangle$

Will examine these in turn.

But note: sources of $SU(3)$ breaking in r_t^* are very similar to those in r_t: $U\left|K^*\bar{K}^*\right\rangle \neq \left|K^*\bar{K}^*\right\rangle$ and $U\left|B_s^0\right\rangle \neq \left|B_d^0\right\rangle \Longrightarrow$ not unreasonable to expect sizeable cancellations between $C_{SU(3)}$ and $C_{SU(3)}^*$.

Final-state corrections

$K^0 = \bar{s}d \Longrightarrow$ write

$$p_s \approx x p_K \ , \ p_d \approx (1-x) p_K \ .$$

U-spin transformation exchanges $\bar{s}$ and d quarks:

$$U\psi_K = \psi(d(xp_K)\bar{s}(1-xp_K)) \ .$$

Final-state U-spin correction due to the presence of a piece in the kaon light-cone distribution (LCD) which is antisymmetric under the exchange $x \to 1-x$.

We know that the kaon LCD is symmetric in the high-energy limit $E_{\scriptscriptstyle K} \to \infty$. What about at $E_{\scriptscriptstyle K} \sim m_{\scriptscriptstyle B}/2$?

- Pion LCD is extremely close to its asymptotic form, $\phi_\pi(x) \sim x(1-x)$, at $\mu^2 \sim 10~\mathrm{GeV}^2 \Longrightarrow$ kaon LCD may also be very close to its (symmetric) asymptotic form.
- Can test this experimentally: measure the kaon LCD. If symmetric, no final-state corrections. Model independent.
- Model calculations: an antisymmetric piece of the kaon LCD tends not to contribute much to the overall amplitude $\Longrightarrow$ final-state corrections unimportant.

Initial-state corrections

Need framework to perform calculations. Within QCD factorization, write

$$r_t = \frac{A^d_{fac}\left[1 + x^d\right]}{A^s_{fac}\left[1 + x^s\right]} \ .$$

A^d_{fac} and A^s_{fac} are the factorizable contributions to $B^0_d \to K^0 \bar{K}^0$ and $B^0_s \to K^0 \bar{K}^0$; x^d and x^s are the corresponding nonfactorizable contributions.

• $SU(3)$ corrections due to nonfactorizable corrections negligible.

• Write factorizable contributions as

$$A^d_{fac} = f_K \, F_{B_d \to K} \int T(x) \phi_{\bar{K}}(x) dx \ ,$$

$$A^s_{fac} = f_K \, F_{B_s \to \bar{K}} \int T(x) \phi_K(x) dx \ .$$

$SU(3)$ breaking due to kaon LCD's is negligible $\Longrightarrow$ main contribution to $SU(3)$ breaking comes from the form factors $F_{B_d \to K}$ and $F_{B_s \to \bar{K}}$.

Form factors

$B \to K$ form factors related to $D \to K$ form factors: in chiral limit and heavy-quark limit

$$\frac{F_{B_d \to K} / F_{B_s \to \bar{K}}}{F_{\bar{D} \to K} / F_{\bar{D}_s \to \bar{K}}} = 1 \ .$$

$\Longrightarrow$ measurement of $D \to K$ form factors determines $B \to K$ form factors to $O(\Delta M_{\scriptscriptstyle D} / M_{\scriptscriptstyle D}) \simeq 5\%$.

Also:

$$\begin{aligned} \frac{F_{B_d \to K} / F_{B_s \to \bar{K}}}{F_{\bar{D} \to K} / F_{\bar{D}_s \to \bar{K}}} &= 1 + a \, \frac{\Delta M_D}{M_D} \ , \\ \frac{F_{B_d \to K^*} / F_{B_s \to \bar{K}^*}}{F_{\bar{D} \to K^*} / F_{\bar{D}_s \to \bar{K}^*}} &= 1 + a^* \, \frac{\Delta M_D}{M_D} \ . \end{aligned}$$

a and a^* are $O(1)$.

So:

$$\frac{F_{B_d \to K} / F_{B_s \to \bar{K}}}{F_{B_d \to K^*} / F_{B_s \to \bar{K}^*}} = \frac{F_{\bar{D} \to K} / F_{\bar{D}_s \to \bar{K}}}{F_{\bar{D} \to K^*} / F_{\bar{D}_s \to \bar{K}^*}} \times \left[1 + (a - a^*) \frac{\Delta M_D}{M_D} \right] \ .$$

But B decays similar, expect $a \simeq a^*$. Model calculations:

$$(a - a^*) \left(\frac{\Delta M_D}{M_D}\right) < 1\% \ .$$

$\Longrightarrow$ measurement of $D \to K$ form factors determines $B \to K$ form factors to $\lesssim 1\%$.

Theory: in limit $m_b \to \infty$ and $E_K \to \infty$, $B \to K$ and $B \to K^*$ transitions are described by 3 form factors. Calculate form factors in QCD sum rules. Find

$$\frac{F_{B_d \to K} / F_{B_s \to \bar{K}}}{F_{\bar{D} \to K} / F_{\bar{D}_s \to \bar{K}}} = 1 \ ,$$

i.e. initial-state $SU(3)$ breaking cancels in numerator and denominator $\Longrightarrow$ combined with QCD factorization, $r_t / r_t^* = 1$, up to corrections of $O(\Delta M_B / M_B) \simeq 2\%$.

Bottom line: cannot *prove* that initial-state corrections to $r_t / r_t^* = 1$ are small. However, all model calculations suggest this to be the case. This can be tested experimentally.

Conclusions

New method for measuring α: $B^0_{d,s}(t) \to K^{(*)}\bar{K}^{(*)}$ decays.

Good for hadron colliders: branching ratios $\sim 10^{-6}$; K^*, $\bar{K}^*$ detected through their decays to charged particles; no π^0 detection needed.

Compare with α as obtained in $B \to \pi\pi$ or $B \to \rho\pi$. Can find new physics in $b \to d$ FCNC.

Requires theoretical input. But model calculations suggest that the error is at most 5%, and could well be quite a bit less. Can be tested experimentally. So the method is quite clean.