CP Asymmetries in Penguin-Dominated Decays

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7 reasons for excitement ...

<table>
<thead>
<tr>
<th>s-penguin</th>
<th>Charmonium</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi K^0$</td>
<td>$0.726 \pm 0.037$</td>
</tr>
<tr>
<td>$\eta' K_S^0$</td>
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Average (s-penguin) $0.43 \pm 0.07$
Basic relations

- Decay amplitudes:

\[ A(\bar{B} \to f) = V_{cb} V_{cs}^* a_f^c + V_{ub} V_{us}^* a_f^u \propto 1 + e^{-i\gamma} d_f \]

where:

\[ d_f = \epsilon_{\text{KM}} \frac{a_f^u}{a_f^c} = \epsilon_{\text{KM}} \hat{d}_f \quad \text{with} \quad \epsilon_{\text{KM}} = \left| \frac{V_{ub} V_{us}^*}{V_{cb} V_{cs}^*} \right| \sim 0.025 \]

- Parameter \( \epsilon_{\text{KM}} \) determines smallness of the effects
Basic relations

- CP asymmetries:

\[
\Delta S_f \equiv \frac{2 \text{Re}(d_f) \cos(2\beta) \sin \gamma + |d_f|^2 (\sin(2\beta + 2\gamma) - \sin(2\beta))}{1 + 2 \text{Re}(d_f) \cos \gamma + |d_f|^2}
\]

\[
A_{CP,f} \equiv -C_f = \frac{2 \text{Im}(d_f) \sin \gamma}{1 + 2 \text{Re}(d_f) \cos \gamma + |d_f|^2}.
\]

- If \(d_f\) is small, then both involve independent hadronic parameters
Sub-leading amplitudes

- **QCD Factorization:**
  - Model-independent approach in heavy-quark limit (derived from QCD)
  - Final-state rescattering phases are included
  - Uncertainties from input parameters (form factors, LCDAs, quark masses ...) and power corrections can be large, but affect different observables to a different degree
Sub-leading amplitudes

- **Topological amplitudes:**
  - Well understood: $T$ (irrelevant), $P_{EW}$
  - Less certain: $P$ for PP, $P_{EW,C}$ (negligible)
  - Rather uncertain: $P$ for PV, $C, S$

- Instructive to look at dominant sub-leading amplitudes and their signs (real parts)
Pattern of dominant terms

\[ \begin{align*}
\pi^0 K_S & \quad \hat{d}_f \sim \frac{[-P^u] + [C]}{[-P_c]} & \rho^0 K_S & \quad \hat{d}_f \sim \frac{[P^u] - [C]}{[P_c]} \\
\eta' K_S & \quad \hat{d}_f \sim \frac{[-P^u] - [C]}{[-P_c]} & \phi K_S & \quad \hat{d}_f \sim \frac{[-P^u]}{[-P_c]} \\
\eta K_S & \quad \hat{d}_f \sim \frac{[P^u] + [C]}{[P_c]} & \omega K_S & \quad \hat{d}_f \sim \frac{[P^u] + [C]}{[P_c]}
\end{align*} \]

- \(|P^u/P_c|\) roughly process independent, but \(|P_{c,u}|\) vary significantly
- As a result, influence of C differs between modes
## Results: 200000 parameter scans

- Require that BRs are reproduced within $3\sigma$

<table>
<thead>
<tr>
<th>Mode</th>
<th>$\Delta S_f$ (Theory)</th>
<th>$\Delta S_f$ [Range]</th>
<th>Experiment [3] (BaBar/Belle)</th>
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<tr>
<td>$\pi^0 K_S$</td>
<td>$0.07^{+0.05}_{-0.04}$</td>
<td>[+0.02, 0.15]</td>
<td>$-0.39^{+0.27}<em>{-0.29}$ ($-0.38^{+0.30}</em>{-0.33}$/$-0.43^{+0.60}_{-0.60}$)</td>
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<td>$\rho^0 K_S$</td>
<td>$-0.08^{+0.08}_{-0.12}$</td>
<td>[$-0.29$, 0.02]</td>
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<td>$\eta' K_S$</td>
<td>$0.01^{+0.01}_{-0.01}$</td>
<td>[+0.00, 0.03]</td>
<td>$-0.30^{+0.11}<em>{-0.11}$ ($-0.43^{+0.14}</em>{-0.14}$/$-0.07^{+0.18}_{-0.18}$)</td>
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<td>$0.10^{+0.11}_{-0.07}$</td>
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<td>$\omega K_S$</td>
<td>$0.13^{+0.08}_{-0.08}$</td>
<td>[+0.01, 0.21]</td>
<td>$-0.18^{+0.30}<em>{-0.32}$ ($-0.23^{+0.34}</em>{-0.38}$/$+0.02^{+0.65}_{-0.66}$)</td>
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Theory vs. Experiment

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\[-\eta_f \times S_f\]
\( \Delta S_f - C_f \) Correlation

In red: points that pass 3\( \sigma \) BR cut

Measurement of \( C_f \) can help support estimate of magnitude of effects!
Discussion

- How do we know that QCDF is not grossly wrong?
- Can we establish that $\Delta S_f$ is positive (except for $\rho K_S$)?
  - Direct CP asymmetry of not much use
  - SU(3) of not much help (only weak bounds; also, $\eta - \eta'$ and $\rho - \omega$ mixing indicate large SU(3) breaking effects)

[see Beneke’s paper for further discussion]
Discussion

- To get large effects (focus on $\Phi K_S$ and $\eta' K_S$), would need to enhance amplitude ratio $\text{Re}(a_f^u/a_f^c)$ significantly
  - Option 1: strong suppression of $a_f^c$
    - Excluded by BR measurements
  - Option 2: enhance $a_f^u$ by factor of several
    - Not possible in QCDF (in conflict with any even remotely decent HQ expansion!)
Discussion

- Sign of effect can be trusted assuming that QCDF correctly predicts the signs of the various sub-amplitudes
  - Follows if imaginary parts are small
  - Model-independent prediction of HQ limit
Conclusions

- Except for $\rho K_S$, QCDF predicts positive $\Delta S_f$, enforcing the disagreement with data.
- Very small effect and uncertainty for $\Phi K_S$ and $\eta' K_S$, reliable predictions.
- Enhancement of color-suppressed amplitudes ($C, P_{EW,C}$) suggested by $\pi\pi\pi\pi$ and $\pi K$ data, if true, would not change results significantly.