Measuring Cleanly
with
CP-Tagged $B_s$ Decays

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The Challenge:

Measure $\gamma$ with negligible theoretical uncertainty!

$$\gamma = \arg \left[ \frac{-V_{ud}V_{ub}^{*}}{V_{cd}V_{cb}^{*}} \right] \approx \arg \left[ \frac{-V_{cd}V_{ub}^{*}}{V_{ud}V_{cb}^{*}} \right] = \phi_3$$

= phase of $b \to u$ transition (Wolfenstein param.)

- Cleanliness requires decays mediated by a single weak amplitude – no penguins!

- Compare phases of $b \to u\bar{s}s$ and $b \to c\bar{u}s$:

$$\bar{B}_s \to D_s^- K^+ \quad \quad \bar{B}_s \to D_s^+ K^-$$

- Even though $s\bar{s}$ rescattering topologies do contribute, the signs of the $D_s$ and $K$ fix the weak phase of the decay amplitude.
The Strategy

- Fix final state $D_s^- K^+$. Define flavor-tagged amplitudes

$$A_1 = A(B_s \rightarrow D_s^- K^+) = a_1 e^{i\delta_1}$$

$$A_2 = A(B_s \rightarrow D_s^- K^+) = a_2 e^{-i\gamma} e^{i\delta_2}$$

$\delta_i$ are unknown strong phases

- CP eigenstate combination: $B_s^{CP} = B_s + \bar{B}_s$

(This assumes a phase convention, which is fixed for this talk.)

- Define CP-tagged amplitude

$$A_{CP} = A(B_s^{CP} \rightarrow D_s^- K^+) = (A_1 + A_2)/\sqrt{2}$$

- Compare to $D_s^+ K^-$ final state

$$\overline{A}_1 = A(\bar{B}_s \rightarrow D_s^+ K^-) = a_1 e^{i\delta_1}, \quad |\overline{A}_1| = |\overline{A}_1|$$

$$\overline{A}_2 = A(B_s \rightarrow D_s^+ K^-) = a_2 e^{i\gamma} e^{i\delta_2}, \quad |\overline{A}_2| = |\overline{A}_2|$$

$$\overline{A}_{CP} = A(B_s^{CP} \rightarrow D_s^+ K^-) = (\overline{A}_1 + \overline{A}_2)/\sqrt{2}$$

- Although $|A_{CP}| \neq |\overline{A}_{CP}|$ only if $\delta = \delta_2 - \delta_1 \neq 0$, the extraction of $\gamma$ does not depend on large $\delta$. 
• Extract $2\gamma$ from triangle relation. The triangles are not “squashed”:

\[ \sqrt{2} A_{cp} \]
\[ \sqrt{2} A_{cr} \]
\[ A_1 = \bar{A}_1 \]

• Analytic expression:

\[ \alpha = \frac{2|A_{cp}|^2 - |A_1|^2 - |A_2|^2}{2|A_1||A_2|} \]
\[ \bar{\alpha} = \frac{2|\bar{A}_{cp}|^2 - |\bar{A}_1|^2 - |\bar{A}_2|^2}{2|\bar{A}_1||\bar{A}_2|} \]

\[ 2\gamma = \arccos \alpha - \arccos \bar{\alpha} \quad (\ast \ast \ast) \]

\((\ast \ast \ast)\) expression is incorrect in published paper

• $\gamma$ has an eightfold ambiguity in the region $0 \leq \gamma < 2\pi$
CP tagging

• Need CP tagging to measure $\Gamma(B_s^{\text{CP}} \rightarrow D_s^- K^+)$

• Use $\Upsilon(5S) \rightarrow B_s \overline{B}_s$:

  $\Upsilon(5S)$ is CP-even, decay products in a $p$-wave

  $\downarrow$

  $B_s/\overline{B}_s$ combinations have anticorrelated CP

• Tagging mode should conserve CP in decay:

  $B_s^{\text{CP}} \rightarrow D_s^+ D_s^-$

• The CP value of tagging mode does not enter the analysis

• The $B_s$ and $\overline{B}_s$ mix before decaying. In the Standard Model, CP violation in $B_s$ is small, of order $\beta_s \sim \lambda^2$. But $\beta_s$ ought to be constrained independently.

• CP tagging is not possible in a hadronic environment

  This analysis is unique to a $B$ Factory at the $\Upsilon(5S)$!!
Is this feasible? Crude estimate only

- Goal is \( \sim 100 \) CP-tagged and reconstructed events

- Assume a luminosity-upgraded B Factory, with

\[
\mathcal{L} \approx 10^{35} \text{ cm}^{-2} \text{ sec}^{-1}
\]

\[
\frac{\sigma(B_s \bar{B}_s)}{\sigma(Y(4S))} \approx 10^{-2}
\]

\[
B(B_s^{\text{CP}} \rightarrow D_s^+ D_s^-) \approx 10^{-2}
\]

\[
B(B_s^{\text{CP}} \rightarrow D K) \approx 2 \times 10^{-4}
\]

\[
\downarrow
\]

100 events in \( \sim 1 \) year

- Assume flavor-tagged decays measured by BTeV or LHCb
This is much too optimistic!

- You need to reconstruct the $D_s$'s. Three of them, two of which are in the tagging mode.

- If efficiency is 10%, this is not good enough

- Combine many $D_s$ decay modes? Help!
This is too pessimistic!

- Use $B_s B_s^*$ and $B_s B_s^*$ combinations from $\Upsilon(5S)$:
  
  $$B_s^* \rightarrow B_s + \gamma,$$ magnetic $\gamma$ with $\text{CP} = -1$

  $\Downarrow$

  $B_s$ and $\bar{B}_s$ have correlated CP

- Similarly, $B_s^* \bar{B}_s^* \Rightarrow B_s$ and $\bar{B}_s$ with anticorrelated CP

  Gain at least an order of magnitude!

- Use additional final states:
  
  $$D_s K^*, \quad D_s^* K, \quad D_s^* K^*$$

- Use more CP tagging modes, some of which might require an angular analysis:
  
  $$\psi\eta, \quad D_s^* D_s^*, \quad \psi\phi$$
CP tagging in the $B_d$ system

- In the Standard Model, CP is violated in $B_d$ mixing, so the CP correlation depends on the decay time $t$.

- A complicated analysis is possible, if you
  1. know $\beta$ precisely
  2. measure $t$ for each decay

The amplitude analysis must then be performed at fixed $t$.

Extract a value of $\gamma$ for each $t$ bin, compare for consistency.

- In principle, $B$ Factories at the $\Upsilon(4S)$ could do this.

But could it be feasible?!
Summary

• The method is theoretically clean.

Good...

• The method is unique to the $\Upsilon(5S)$.

Intriguing!

• The method might even be feasible.

Experimental details?