Three-body $CP$ Eigenstates

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Super B Factory Workshop
Opening Position

- $CP$ violation observed in a handful of modes
- KM scheme is *elegant* and *effective*, but is it *enough*?
- Already evidence for beyond SM $CP$ violation
- Desire multiple probes of $CPV$ phenomena
$b \rightarrow sqq$ Anomaly

<table>
<thead>
<tr>
<th>Charmionium Modes</th>
<th>OPAL 98</th>
<th>0.27 \pm 0.5</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>ALEPH 00</td>
<td>0.48 \pm 0.16</td>
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<tr>
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<td>CDF 00</td>
<td>0.79 \pm 0.44</td>
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<tr>
<td>BABAR 02</td>
<td>0.741 \pm 0.067 \pm 0.034</td>
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<tr>
<td>Belle 03</td>
<td>0.733 \pm 0.057 \pm 0.028</td>
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<tr>
<td>Average (charmonium)</td>
<td>0.736 \pm 0.049</td>
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| $\phi K_S^0$      | BABAR 03 | 0.45 \pm 0.43 \pm 0.07 |
|                   | Belle 03 | -0.96 \pm 0.5 \pm 0.09 |

| $\Upsilon K_S^0$  | BABAR 03 | 0.02 \pm 0.44 \pm 0.03 |
|                   | Belle 03 | 0.43 \pm 0.27 \pm 0.05 |

| $K K K^0$         | Belle 03 | 0.51 \pm 0.28 \pm 0.05 |
| Average (s penguin) | 0.24 \pm 0.15 |

Average (All) | 0.595 \pm 0.047 |

$\sin(2\beta_{(eff)})$
**CP Violation Analyses**

- Time-dependent studies of $B \to CP$ eigenstates have been very successful
  - Phenomenology rather straightforward
- $CP$ violation measurements from $B \to$ non-$CP$ final states have more unknown parameters
  - Analysis is harder, requires more statistics
  - Their time will certainly come
- Number of two-body $CP$ eigenstates is finite
$B^0 \rightarrow P^0 Q^0 X^0$

- $B^0$ is a neutral spin-0 particle
- Let $P^0, Q^0, X^0$ be neutral particles
- $L$ is orbital angular momentum between $P^0 - Q^0$
- $L'$ is orbital angular momentum between $(P^0 - Q^0) - X^0$
- Conservation of angular momentum:
\[ J_{B^0} = 0 = L + L' + S_{P^0} + S_{Q^0} + S_{X^0} \]
CP of $P^0Q^0X^0$

- $CP(P^0Q^0X^0) = CP(P^0) \ CP(Q^0) \ CP(X^0) \ (-1)^L \ (-1)^{L'}$

- If $P^0, Q^0, X^0$ are all spin-0 particles:
  
  conservation of angular momentum $\rightarrow L' = L$

- If $P^0, Q^0, X^0$ are all spin-0 CP eigenstates:
  
  final state is a CP eigenstate:
  
  $CP(P^0Q^0X^0) = CP(P^0) \ CP(Q^0) \ CP(X^0)$

- $P^0, Q^0, X^0$ candidates:
  
  $\pi^0, \eta, \eta', f_0, a_0, K_S, K_L, D_{CP}, \eta_c, \chi_{c0}$
Comments on $B^0 \rightarrow P^0 Q^0 X^0$

- Enormous number of possible final states!
- In general, more different quarks in final state
  $\rightarrow$ more amplitudes can contribute
- Concentrate on (hopefully cleaner) final states containing (at least) two identical particles
\[ B^0 \rightarrow P^0 P^0 X^0 \]

- \( B^0 \) is a neutral spin-0 particle
- Let \( P^0, X^0 \) be neutral spin-0 particles
- \( L \) is orbital angular momentum between \( P^0 - P^0 \)
- Bose-Einstein statistics \( \rightarrow L = 0, 2, 4, ... \)
- Conservation of angular momentum: \( L' = L \)

\[ CP(P^0 P^0 X^0) = CP(X^0) \]
Advantage of $B^0 \rightarrow P^0 P^0 X^0$ (?)

- $J^P(P^0 P^0) = 0^+, 2^+, 4^+, ...$
- Decays to similar final states (eg. $B^+ \rightarrow \chi_{c(0,2)} K^+$) forbidden in factorization (although observed)
- Does this help us?
- Expert input is welcome!
Possible $B^0 \rightarrow P^0 P^0 X^0$

<table>
<thead>
<tr>
<th>$X^0$</th>
<th>$\pi^0$</th>
<th>$\eta$</th>
<th>$\eta'$</th>
<th>$f_0$</th>
<th>$a_0$</th>
<th>$K_S$</th>
<th>$K_L$</th>
<th>$D_{CP}$</th>
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<td>$\pi^0$</td>
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Comments on $B^0 \rightarrow P^0 P^0 X^0$

- Try to judge which modes are (will be) useful now (at a Super $B$ factory)
- No reliable technique to estimate three-body BFs
- Base estimates of usefulness on measured quantities, where possible
- Measurements of three-body BFs provide useful information about hadronic $B$ decay
\[ B^0 \rightarrow K^+_S K^-_S \eta_c \]

- Modes \( B^0 \rightarrow P^0 P^0 (cc) \) probe \( b \rightarrow ccd \) transition with additional \( qq \) production
- Consider product BF's ... not very promising
Aside: $B^0 \rightarrow K_S K_S J/\psi$

- Cleaner signal and higher efficiency for $cc = J/\psi$
- Here, $X^0$ has spin-1 $\rightarrow$ final state is not a $CP$ eigenstate in general
- $J^P(K_S K_S) = 0^+, 2^+, 4^+, \ldots$
- If $0^+$ is dominant, final state is a $CP$ eigenstate
- Higher $L$ states suppressed by centrifugal barrier?
- Can determine from $(K_S K_S)$ helicity distribution
\[ B^0 \rightarrow K_S K_S D_{CP} \]

- Can use \( B^0 \rightarrow D_{CP}\pi^0 \) to measure \( \sin(2\varphi_f) \) or probe for (\( R \)-parity violating) new physics
- Same diagrams with \( ss \) production
- Expect smaller (but cleaner) signal than \( B^0 \rightarrow D_{CP}\pi^0 \)
\[ B^0 \rightarrow KK D \]

- No observation of \( B \rightarrow K_S K_S D \) yet, but ...
- Numerous similar \( B \rightarrow KK^{(*)} D^{(*)} \) modes observed
- Eg. \( B^- \rightarrow K_SK^-D^0 \)
  - from 29.4/fb

\[ \Delta E/\text{GeV} \]
These modes probe $b \rightarrow ccs / b \rightarrow ccd$

Negligible penguin contribution (?)

Tiny efficiency to reconstruct $2 \ast (D \rightarrow D_{CP})$
$B^0 \rightarrow KKK$

- Mode $B^0 \rightarrow (K^+K^-)_{non-\phi}K_S$ already used to probe $b \rightarrow sqq$
  (found to be mainly $CP+$)

- Suggests reasonable BF for $B^0 \rightarrow K_SK_SK_S$

- Indeed observed!
  - from 78/fb
\[ B^0 \rightarrow K_s K_s K_s \]

- Clean! No \( u \) quark in final state \( \rightarrow \) tiny tree pollution
- Probes \( b \rightarrow s \) better than \( B^0 \rightarrow (K^+ K^-)_{\text{non-}\varphi} K_s \) or \( B^0 \rightarrow \eta' K_s \)
- Clean! Good signal/background ratio.
- Little (negligible?) \( b \rightarrow c \) background
$K_s$ Vertexing

- To date, Belle has only announced results of time-dependent analyses with tracks that originate from the $B$ vertex ($egs. J/\psi K_s, \pi^+\pi^-, \varphi K_s$)
- BaBar has announced results on $D^{*+}D^-, D^{*+}D^{*-}, K_s\pi^0$
- It is possible to get vertex information from $K_s$ alone, with reasonable efficiency
- High vertex efficiency for $K_sK_sK_s$
\[ B^0 \rightarrow K_S K_S K_L \]

- Mode \( B^0 \rightarrow (K^+ K^-)_{\text{non-}\phi} K_S \) found to be mainly \( CP^+ \)
  \( (K^+ K^- \text{ has even } L) \)
- Suggests \( B^0 \rightarrow (K_SK_L)_{\text{non-}\phi} K_S \) should be small
- Good news! Use \( \phi \) mass constraint:
  - reduce continuum background
  - remove \( cc \) background
$B^0 \rightarrow \eta'\eta'K_S$

- $B \rightarrow \phi\phi K$ proposed as sensitive to new physics ...
- ... and observed
  - from 78/fb
- $\text{BF}(B \rightarrow \eta' K) > \text{expected}$
- $\text{BF}(B \rightarrow \eta' X_S) > \text{expected}$
\[ B^0 \rightarrow \pi^0 \pi^0 K_s, \text{ etc} \]

- \( B^0 \rightarrow \pi^0 K_s \) currently a hot topic
- Add \( \pi \pi \) production \( \rightarrow B^0 \rightarrow \pi^0 \pi^0 K_s \)
- Could also use \( B^0 \rightarrow P^0 Q^0 X^0 \) modes:
  \[ B^0 \rightarrow \pi^0 \eta K_s, \quad B^0 \rightarrow \pi^0 \eta' K_s \]
- Note that, \( eg., \) \( B^0 \rightarrow \pi^0 \eta' K_s \) includes \( B^0 \rightarrow \eta' K^{*0} \)
$B^0 \rightarrow K_S K_S \pi^0$

- Time-dependence of $B^0 \rightarrow \pi^0 \pi^0$ probes $\phi_2$ in principle
- In practise cannot measure vertex position
- Add $ss$ production $\rightarrow B^0 \rightarrow K_S K_S \pi^0$
- Expect this mode to be rather rare
  possibly enhanced if mediated by $B^0 \rightarrow f_0^0 \pi^0, a_0^0 \pi^0$ (??)
$B^0 \rightarrow \pi^0 \pi^0 \pi^0$

- Example of obtaining useful information without studying time-dependence
- No vertex information available
- BF can give a bound on the contribution of $B^0 \rightarrow \sigma^0 \pi^0$ to $B^0 \rightarrow \pi^+ \pi^- \pi^0$ (affects $B^0 \rightarrow \rho^+ \pi^-$ analysis)
Aside: $B^0 \rightarrow P^0 P^0 \gamma$

- $P^0 P^0 \gamma$ is not a CP eigenstate
- $P^0 P^0$ is a CP eigenstate
- Behaves as $B^0 \rightarrow M^0 \gamma$ ... a good probe for new physics
- $P^0 P^0$ cannot form $0^+$ state $\rightarrow$ suppressed (?)
- Probes $b \rightarrow d \gamma$ vertex
- No $b \rightarrow s \gamma$ background for $B^0 \rightarrow K_s K_s \gamma$
Conclusions

- Final state in $B^0 \rightarrow P^0 Q^0 X^0$ decays is a $CP$ eigenstate ($P^0, Q^0, X^0$ are spin-0 $CP$ eigenstates)
- Numerous possibilities for time-dependent studies
- Requiring $P^0 = Q^0$ adds useful (?) constraints
- Some modes which cannot be used for time-dependent analyses are still interesting
- $B^0 \rightarrow K_S K_S K_S$ may help solve the $b \rightarrow sqq$ riddle