Mixing Induced CP Violation at BaBar

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Representing the BaBar Collaboration
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Outline

- **First** direct measurement of time reversal violation
- **New** measurement of the time dependent CP violation parameters in $B^0 \rightarrow D^*+D^{*-}$ decays
T Reversal Violation

- **CPT** symmetry is a fundamental requirement of quantum field theories (like the SM)
  - No violation observed experimentally
- The Standard Model with three generations allows for **CP** violation to occur in mesons’ weak decays.
  - To conserve **CPT**, **CP** violation requires **T** violation
- The measurement of **CPV** in K and B decays therefore provides *indirect evidence* of **T**-violation
- Can *direct* evidence of **T** violation be obtained in **B** meson decays, where **CPV** is large?
Large CPV in B decays was measured precisely with golden channels (b\to c\bar{c}s transitions)

\begin{itemize}
  \item $B^0 \to J/\psi K_S$, CP = -1
  \item $B^0 \to J/\psi K_L$, CP = +1
\end{itemize}

The same CPV sample can be used to look for TRV

How?
“Flavor Tag”

\( \mathcal{I}^+ (B^0) \)

EPR Entanglement

\[ |i > = 1/\sqrt{2}[B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2)] \]

\( \Delta t = t_{CP} - t_{flav} \)

\( \Delta z = \beta \gamma c \Delta t \)

\( \langle \Delta z \rangle \sim 250 \, (200) \, \mu m \) BaBar (Belle)

\( J/\psi K_L^0 \) with \( l^+ \) tag

\( \Delta t > 0 \)

Reference: Physical Process (X, Y): Reconstructed Final States

Reference (X, Y)

Transformed (X, Y)

0

+ (\( l - L \))

0

- (\( l - S \))

0

+ (\( l + L \))

0

- (\( l + S \))

\( B^0 \) → \( B^+ \)

\( CP = +1 \equiv "B^+" \)

exclusive B meson reconstruction
If \( \Delta t < 0 \), we can exchange the roles of the two \( B \)'s in above picture: use reconstructed CP final state as “CP-tag” and look for flavor final state

- **\( \Delta t = t_{CP} - t_{flav} < 0 \)**
- **\( CP = +1 \equiv \text{“B+”} \)
- **\( \Delta z = \beta \gamma c \Delta t \)**
- **\( \langle \Delta z \rangle \approx 250 \, (200) \, \mu m \) BaBar (Belle)\**


Inclusive B flavor identification

**EPR Entanglement**

\[
|i| = \frac{1}{\sqrt{2}}[B^0(t_1)\bar{B}^0(t_2) - \bar{B}^0(t_1)B^0(t_2)]
\]

**J/\psi K_L^0 with \( l^+ \) tag**

\[ \Delta t > 0 \]

**J/\psi K_s^0 tag**

\[ \Delta t < 0 \]

**Exclusive B meson reconstruction**

T-conjugate transitions!
$T$-Reversal Processes

Define processes of interest and their T-transformed counterparts:

<table>
<thead>
<tr>
<th>Reference $(X,Y)$</th>
<th>$T$-Transformed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^0 \to B_+$ $(\ell^-, J/\psi K^0_L)$</td>
<td>$B_+ \to B^0 (J/\psi K^0_S, \ell^+)$</td>
</tr>
<tr>
<td>$B^0 \to B_-$ $(\ell^-, J/\psi K^0_S)$</td>
<td>$B_- \to B^0 (J/\psi K^0_L, \ell^+)$</td>
</tr>
<tr>
<td>$\bar{B}^0 \to B_+$ $(\ell^+, J/\psi K^0_L)$</td>
<td>$B_+ \to \bar{B}^0 (J/\psi K^0_S, \ell^-)$</td>
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<td>$\bar{B}^0 \to B_-$ $(\ell^+, J/\psi K^0_S)$</td>
<td>$B_- \to \bar{B}^0 (J/\psi K^0_L, \ell^-)$</td>
</tr>
</tbody>
</table>

$(X,Y)$ is the reconstructed final states (tag, reco.)

...and similar for CP, CPT

In total we can build:
- 4 independent $T$ comparisons
- 4 independent $CP$ comparisons
- 4 independent $CPT$ comparisons

$T$ implies comparison of:
1) Opposite $\Delta t$ sign
2) Different reco states ($\psi K_S$ v. $\psi K_L$)
3) Opposite flavor states ($B^0$ v. $\bar{B}^0$)
Fit parameters $\Delta S^\pm$ and $\Delta C^\pm$

8 Signal PDFs (assuming $\Delta \Gamma = 0$):

$$g_{\alpha,\beta}^\pm(\tau) \propto e^{-\Gamma|\tau|} \left\{ 1 + S_{\alpha,\beta}^\pm \sin(\Delta m_d \tau) + C_{\alpha,\beta}^\pm \cos(\Delta m_d \tau) \right\}$$

$\alpha \in \{ B^0, \bar{B}^0 \}$;
$\beta \in \{ K_S^0, K_L^0 \}$
$\tau = \pm \Delta t > 0$

Mistag dilutes the S, C parameters by a factor of (1-2w)

For T Violation

in the interference $\Delta S^+_T \neq 0$, $\Delta S^-_T \neq 0$
in the decay $\Delta C^+_T \neq 0$, $\Delta C^-_T \neq 0$
# TRV Results

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>(S_{\ell+ x, \bar{c}K^0_S}^+)</td>
<td>0.55 ± 0.08 ± 0.06</td>
</tr>
<tr>
<td>(S_{\ell+ x, \bar{c}K^0_S}^-)</td>
<td>−0.66 ± 0.06 ± 0.04</td>
</tr>
<tr>
<td>(C_{\ell+ x, \bar{c}K^0_S}^+)</td>
<td>0.11 ± 0.06 ± 0.05</td>
</tr>
<tr>
<td>(C_{\ell+ x, \bar{c}K^0_S}^-)</td>
<td>−0.05 ± 0.06 ± 0.03</td>
</tr>
<tr>
<td>(\Delta S_T^+ = S_{\ell- x, J/\psi K^0_S}^- - S_{\ell+ x, \bar{c}K^0_S}^+)</td>
<td>−1.37 ± 0.14 ± 0.06</td>
</tr>
<tr>
<td>(\Delta S_T^- = S_{\ell+ x, \bar{c}K^0_S}^- - S_{\ell- x, J/\psi K^0_S}^+)</td>
<td>1.17 ± 0.18 ± 0.11</td>
</tr>
<tr>
<td>(\Delta C_T^+ = C_{\ell- x, J/\psi K^0_S}^- - C_{\ell+ x, \bar{c}K^0_S}^+)</td>
<td>0.10 ± 0.16 ± 0.08</td>
</tr>
<tr>
<td>(\Delta C_T^- = C_{\ell+ x, \bar{c}K^0_S}^- - C_{\ell- x, J/\psi K^0_S}^+)</td>
<td>0.04 ± 0.16 ± 0.08</td>
</tr>
<tr>
<td>(\Delta S_{CP}^+ = S_{\ell- x, \bar{c}K^0_S}^- - S_{\ell+ x, \bar{c}K^0_S}^+)</td>
<td>−1.30 ± 0.10 ± 0.07</td>
</tr>
<tr>
<td>(\Delta S_{CP}^- = S_{\ell+ x, \bar{c}K^0_S}^- - S_{\ell- x, \bar{c}K^0_S}^+)</td>
<td>1.33 ± 0.12 ± 0.06</td>
</tr>
<tr>
<td>(\Delta C_{CP}^+ = C_{\ell- x, \bar{c}K^0_S}^- - C_{\ell+ x, \bar{c}K^0_S}^+)</td>
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</tr>
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<td>(\Delta C_{CP}^- = C_{\ell+ x, \bar{c}K^0_S}^- - C_{\ell- x, \bar{c}K^0_S}^+)</td>
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<td>(\Delta S_{CP}^{\text{CPT}} = S_{\ell+ x, J/\psi K^0_S}^- - S_{\ell+ x, \bar{c}K^0_S}^+)</td>
<td>0.16 ± 0.20 ± 0.09</td>
</tr>
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<td>(\Delta S_{CP}^{\text{CPT}} = S_{\ell+ x, J/\psi K^0_S}^- - S_{\ell+ x, \bar{c}K^0_S}^+)</td>
<td>−0.03 ± 0.13 ± 0.06</td>
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<td>(\Delta C_{CP}^{\text{CPT}} = C_{\ell+ x, J/\psi K^0_S}^- - C_{\ell+ x, \bar{c}K^0_S}^+)</td>
<td>0.15 ± 0.17 ± 0.07</td>
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<td>(\Delta C_{CP}^{\text{CPT}} = C_{\ell+ x, J/\psi K^0_S}^- - C_{\ell+ x, \bar{c}K^0_S}^+)</td>
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</table>

\[\sin 2\beta = 0.679\pm0.020 \text{ (HFAG winter'12)}\]
Independent $T$ Asymmetries

\[ A_T (\Delta t) \approx \frac{\Delta C^+}{2} \cos \Delta m \Delta t + \frac{\Delta S^+}{2} \sin \Delta m \Delta t \]

Points: data; red (blue) curves: projections of fits with (without) $T$ violation
$T$, $CP$ and $CPT$

\[ \Delta S_T^+ = -1.37 \pm 0.14 \pm 0.06 \]
\[ \Delta S_T^- = 1.17 \pm 0.18 \pm 0.11 \]
\[ \Delta C_T^+ = 0.10 \pm 0.16 \pm 0.08 \]
\[ \Delta C_T^- = 0.04 \pm 0.16 \pm 0.08 \]

$CP$ violating parameters

\[ \Delta S_{CP}^+ = -1.30 \pm 0.10 \pm 0.07 \]
\[ \Delta S_{CP}^- = 1.33 \pm 0.12 \pm 0.06 \]
\[ \Delta C_{CP}^+ = 0.07 \pm 0.10 \pm 0.03 \]
\[ \Delta C_{CP}^- = 0.08 \pm 0.09 \pm 0.04 \]

Significance

<table>
<thead>
<tr>
<th></th>
<th>$-2\Delta \ln L$</th>
<th>Signif.</th>
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<tbody>
<tr>
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</tr>
<tr>
<td>$CPT$</td>
<td>5</td>
<td>0.33 $\sigma$</td>
</tr>
</tbody>
</table>

(Include systematic)
$CPV\ in\ B^0 \rightarrow D^{*+} + D^{*-}$
**CPV in \( B^0 \rightarrow D^{*+}D^{*-} \)**

- In \( b \rightarrow c \bar{c}d \) transition like \( B \rightarrow D^{**}D^{*-} \), the TD CPV asymmetry is a measure of \( S_\eta \approx \eta \sin(2\beta) \), provided that the contribution from penguin diagrams to the tree amplitude can be neglected.

- Theoretical calculations, based on factorization and heavy quark symmetry, have shown that the penguin contributions lead to \( \sim \text{few} \% \) corrections to the determination of \( \sin^2\beta \) from the TD CPV asymmetry.

\[
P_{\eta}^{\text{tag}}(\Delta t) = \frac{e^{-|\Delta t|/\tau_b}}{4\tau_b} \cdot [1 + S_{\text{tag}} S_\eta \sin(\Delta m_d \Delta t) + S_{\text{tag}} C \cos(\Delta m_d \Delta t)], \quad S_{\text{tag}} = \frac{+1 (-1)}{B^0 (B^0)}
\]

\[
C = \frac{1 - |\lambda|^2}{1 + |\lambda|^2}; \quad S_\eta = -\eta \frac{2 \Im m(\lambda)}{1 + |\lambda|^2}; \quad \lambda = \frac{q A}{p A}
\]

- Large deviation in \( S_\eta \) from \( B^0 \rightarrow D^{**}D^{*-} \) with respect to that measured in \( b \rightarrow c \bar{c}s \) (\( J/\psi K \)) transitions could be an indication of physics beyond the SM.

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**Introduction**


Partial Reconstruction

- **VV final state not CP eigenstate:** admixture of $CP=+1$ and $CP=-1$ amplitudes. Angular analysis needed to disentangle components, possible with fully reconstructed events.

- **BaBar and Belle full reconstruction analyses** measured the $CP$ even component $CPV$ parameters $S^+$ and $C^+$, and the fraction $R_\perp$ of CP-odd amplitude: $R_{\perp}=0.158\pm0.028\pm0.006$.

- In a partial reconstruction analysis, we measure average $S$ and $C$ parameters which are related to $C^+$ and $S^+$ by the relations $C=C^+$ and $S=S^+(1-2R_\perp)$.

### Analysis Method

**Partial Reconstruction**

- Fully reconstruct one $D^*$ decaying to $D^0\pi$, with the $D^0$ decaying to one of 4 modes.
- Match reconstructed $D^*$ with a slow pion of opposite sign in the event.
- Select candidate if the kinematics is consistent with a $B^0$ decaying to a $D^*-D^0\pi$ combination with a missing $D^0$.
- Compute recoiling $D^0$ mass $m_{\text{rec}}$.

### Partial Reconstruction Method

- **Advantages:**
  - Gain is statistics
  - Almost independent sample

- **Disadvantages:**
  - Higher background
  - Larger systematic errors

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Analysis Variables

- Recoil mass, $m_{\text{rec}}$
  - Signal peaks at $D^0$ mass
  - Backgrounds from $B\bar{B}$ combinatorial and continuum $q\bar{q}$ doesn’t
  - Separate PDFs for different sample components: Signal, $B\bar{B}$ combinatorial, $q\bar{q}$ continuum
  - Require $m_{\text{rec}} \geq 1.835$ GeV/c$^2$

- Fisher Discriminant based on event shape variables
  - Help discriminate between spherical $B\bar{B}$ and jet-like continuum $q\bar{q}$ events
    - No cut: PDF used in fit
  - Separate PDFs for $B\bar{B}$ and continuum

- Time difference $\Delta t$
  - Separate PDFs for all sample components

- Tagging based on single track ($K$ or Lepton)
  - Additional dilution in partial reconstruction analysis due to tagging tracks from missing $D^0$
    - $(1-\alpha)$, where $\alpha$ is the fraction of tags from the unreconstructed $D^0$
CPV in $B^0 \rightarrow D^{*+}D^{*-}$

**Kin Fit Result - DATA**

- **BABAR preliminary**

**Δt Fit Result and Raw Asymmetry**

- **BABAR preliminary**

**Kaon Tags**

$$C = +0.12 \pm 0.11$$

$$S = -0.42 \pm 0.16$$
CPV in $B^0 \rightarrow D^{**+}D^{*-}$

Kin Fit Result - DATA

$\Delta t$ Fit Result and Raw Asymmetry

Lepton Tags

$C = +0.20 \pm 0.15$

$S = -0.21 \pm 0.20$

BABAR preliminary
Combined Kaon-Lepton Results

Combined $B^0 \to D^*+D^*$ Inclusive

\[
\begin{align*}
C &= +0.15 \pm 0.09 \pm 0.04 \\
S &= -0.34 \pm 0.12 \pm 0.05
\end{align*}
\]

Assuming negligible penguin contributions, then $S_+=-S_-$, and:

\[
\begin{align*}
C &= C_+ \\
S &= S_+ (1 - 2R_\perp)
\end{align*}
\]

and using\textsuperscript{[1]}: $R_\perp = 0.158 \pm 0.02$

\[
\begin{align*}
C_+ &= +0.15 \pm 0.09 \pm 0.04 \\
S_+ &= -0.49 \pm 0.18 \pm 0.07 \pm 0.04
\end{align*}
\]

All errors are statistical + systematic

This result is compatible with previous BaBar\textsuperscript{[1]} and Belle\textsuperscript{[2]} measurements and in agreement with SM predictions

\textsuperscript{[1]} B. Aubert et al. (BABAR collaboration), Phys. Rev. D79, 032002 (2009); Belle Collab. EPS 2011 Preliminary

\textsuperscript{[2]} B. Vervink et al. (Belle collaboration), Phys. Rev. D80, 111104 (2009); Belle Collab. EPS 2011 Preliminary
Summary

- **BaBar** has measured for the first time $T$-violating parameters in the time development of neutral $B$ mesons by comparing conjugate processes that can only be achieved by $T$ reversal, not $CP$.
  - This novel approach does not need $CPT$ invariance to link $T$ with $CP$
  - $T$ violation is observed at $>10 \sigma$ level.
  - Result is consistent with measurements of $CP$ violation assuming $CPT$ invariance.
- **BaBar** has made a new measurement of the $CP$-V parameters $S,C$ in $b \rightarrow c\bar{c}d$ transitions, from which the $CP$-even components $S_+,C_+$ have been extracted
  - Improves previous BaBar overall (stat+sys) error on $S,C$ by $\sim 20\%$
  - Results compatible with previous BaBar and Belle measurements using fully reconstructed decays
  - In agreement with SM predictions of small penguin contributions and $S_+ \approx \sin 2\beta$
SPARES
**T-Violation in Meson Decays**

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### Decay TRV searches

- **CP**
  - $B^0 \rightarrow K^+\pi^-$, $R_1$
  - $\bar{B}^0 \rightarrow K^-\pi^+$, $R_2$

- **CPT**
  - $K^-\pi^+ \rightarrow \bar{B}^0$, $R_1$
  - $K^+\pi^- \rightarrow B^0$, $R_2$

Unable to perform the T test:
- Preparation of the initial state.
- The strong processes will swamp the feeble weak processes.

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### Mixing TRV searches

- **CP**
  - $K^0 \rightarrow \bar{K}^0$
  - $B^0 \rightarrow \bar{B}^0$

- **T**
  - $\bar{K}^0 \rightarrow K^0$
  - $\bar{B}^0 \rightarrow B^0$

- Measured by CPLEAR in K system. Needs $\Delta \Gamma \neq 0$, too small in B system. [Phys. Lett. B 444, 43 (1998)]
- Cannot distinguish CP and T.

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### TRV in Interference

- Large $CPV$ observed in $B$ system.
- Expect large $T$ violation as well.

\[
\Gamma(B^0 \rightarrow f_{CP})(t) \neq \Gamma(\bar{B}^0 \rightarrow f_{CP})(t)
\]
Significance of $T$ violation

- Standard fit yields a likelihood value of the fit to S, C using the 8 independent samples.
- Repeat the fit, applying constraints to the parameters for T-conjugate processes.
- Difference in likelihood values yields the significance of $T$ violation.

\[
\Delta \chi^2 = -2 \left( \ln L_{\text{No TRV}} - \ln L \right)
\]
\[
\Delta \nu = 8 \text{ degrees of freedom}
\]

- CP and CPT significance can be determined the same way with proper constraints.
- Systematic uncertainties are included by calculating $2\Delta \ln L$ ($=m^2_j$) varying each parameter by $\pm 1 \sigma_{\text{syst.}}$ and reduce the overall statistical $-2\Delta \ln L$ by $1+\max(m^2_j)$.

<table>
<thead>
<tr>
<th>T-inv. constraints</th>
<th>$-2\Delta \ln L$</th>
<th>Signif.</th>
</tr>
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<tbody>
<tr>
<td>$\Delta S_T^{\pm} = \Delta C_T^{\pm} = 0$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta S_{CP}^{\pm} = \Delta S_{CPT}^{\pm}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\Delta C_{CP}^{\pm} = \Delta C_{CPT}^{\pm}$</td>
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</tr>
</tbody>
</table>
### TRV Systematics (for $\Delta S_T^{\pm}$)

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>$\Delta S_T^+$</th>
<th>$\Delta S_T^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>misID flavour</td>
<td>0.019</td>
<td>0.019</td>
</tr>
<tr>
<td>$\Delta t$ resolution function</td>
<td>0.02</td>
<td>0.05</td>
</tr>
<tr>
<td>Outlier’s scale factor</td>
<td>0.012</td>
<td>-0.013</td>
</tr>
<tr>
<td>$m_{ES}$ parameters</td>
<td>0.012</td>
<td>0.0018</td>
</tr>
<tr>
<td>$\Delta E$ parameters</td>
<td>0.017</td>
<td>0.017</td>
</tr>
<tr>
<td>$K_L$ systematics</td>
<td>0.03</td>
<td>0.03</td>
</tr>
<tr>
<td>Differences between $B_{CP}$ and $B_{flav}$</td>
<td>0.02</td>
<td>0.02</td>
</tr>
<tr>
<td>Background effects</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>Uncertainty on fit bias from MC</td>
<td>0.010</td>
<td>0.08</td>
</tr>
<tr>
<td>Detector and vertexing effects</td>
<td>0.011</td>
<td>0.04</td>
</tr>
<tr>
<td>$\Delta \Gamma \neq 0$ effects</td>
<td>0.004</td>
<td>0.003</td>
</tr>
<tr>
<td>External physics parameters</td>
<td>0.005</td>
<td>0.006</td>
</tr>
<tr>
<td>Normalization effects</td>
<td>0.012</td>
<td>0.009</td>
</tr>
<tr>
<td><strong>Total Systematics</strong></td>
<td><strong>0.06</strong></td>
<td><strong>0.11</strong></td>
</tr>
</tbody>
</table>

Similar tables for all others
### Fitting Fit results (Control Data Sample)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Delta C_{CP}$</td>
<td>$0.036 \pm 0.050$</td>
</tr>
<tr>
<td>$\Delta C_{CPT}$</td>
<td>$-0.0042 \pm 0.068$</td>
</tr>
<tr>
<td>$\Delta C_T$</td>
<td>$-0.0405 \pm 0.073$</td>
</tr>
<tr>
<td>$\Delta C_{CP}$</td>
<td>$-0.0044 \pm 0.049$</td>
</tr>
<tr>
<td>$\Delta C_{CPT}$</td>
<td>$-0.1586 \pm 0.070$</td>
</tr>
<tr>
<td>$\Delta C_T$</td>
<td>$-0.0237 \pm 0.073$</td>
</tr>
<tr>
<td>$\Delta S_{CP}$</td>
<td>$0.088 \pm 0.054$</td>
</tr>
<tr>
<td>$\Delta S_{CPT}$</td>
<td>$-0.1035 \pm 0.083$</td>
</tr>
<tr>
<td>$\Delta S_T$</td>
<td>$0.041 \pm 0.089$</td>
</tr>
<tr>
<td>$\Delta S_{CP}$</td>
<td>$0.041 \pm 0.053$</td>
</tr>
<tr>
<td>$\Delta S_{CPT}$</td>
<td>$0.030 \pm 0.086$</td>
</tr>
<tr>
<td>$\Delta S_T$</td>
<td>$0.155 \pm 0.094$</td>
</tr>
<tr>
<td>$C^-_{B^0,K^0}$</td>
<td>$0.025 \pm 0.032$</td>
</tr>
<tr>
<td>$C^+_{B^0,K^0}$</td>
<td>$0.038 \pm 0.031$</td>
</tr>
<tr>
<td>$S^-_{B^0,K^0}$</td>
<td>$-0.0072 \pm 0.038$</td>
</tr>
<tr>
<td>$S^+_{B^0,K^0}$</td>
<td>$-0.0002 \pm 0.038$</td>
</tr>
</tbody>
</table>

- $c\bar{c}K^\pm$ as $J/\psi K_S$
- $J/\psi K^{*+}$ as $J/\psi K_L$

1σ, 2σ 2D regions (68.3%, 95.4%)
### Evaluation of Systematic Errors

<table>
<thead>
<tr>
<th>Systematic source</th>
<th>kaon tags</th>
<th>lepton tags</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C$</td>
<td>$S$</td>
</tr>
<tr>
<td>Kinematic fit parameters</td>
<td>0.013</td>
<td>0.034</td>
</tr>
<tr>
<td>Continuum $\Delta t$ fit parameters</td>
<td>0.002</td>
<td>0.001</td>
</tr>
<tr>
<td>Signal $s_w$</td>
<td>0.0002</td>
<td>0.0007</td>
</tr>
<tr>
<td>$B\bar{B}$ Combinatoric $s_w$</td>
<td>0.017</td>
<td>0.0007</td>
</tr>
<tr>
<td>Signal tagging dilution: tag side ($w$)</td>
<td>0.012</td>
<td>0.045</td>
</tr>
<tr>
<td>Mistag difference ($\Delta w$)</td>
<td>0.007</td>
<td>0.0004</td>
</tr>
<tr>
<td>Signal tagging dilution: $CP$ side ($\alpha_{D^0}$)</td>
<td>0.006</td>
<td>0.017</td>
</tr>
<tr>
<td>Peaking background</td>
<td>0.0002</td>
<td>0.0003</td>
</tr>
<tr>
<td>Fit bias (MC statistics)</td>
<td>0.011</td>
<td>0.018</td>
</tr>
<tr>
<td>Tag interference from DCSD</td>
<td>0.030</td>
<td>0.002</td>
</tr>
<tr>
<td>$B^0$ lifetime variation</td>
<td>0.0002</td>
<td>0.002</td>
</tr>
<tr>
<td>$\Delta m_d$ variation</td>
<td>0.0003</td>
<td>0.001</td>
</tr>
<tr>
<td>SVT misalignment</td>
<td>0.003</td>
<td>0.007</td>
</tr>
<tr>
<td>Boost uncertainty</td>
<td>0.002</td>
<td>0.006</td>
</tr>
<tr>
<td>Total</td>
<td>0.042</td>
<td>0.062</td>
</tr>
</tbody>
</table>

= top contributions
The VV final state is a superposition of CP+ and CP- states depending on the angular momentum of the decay products.

Need angular analysis to distinguish the two components.

This has been done by BaBar (and Belle) with fully reconstructed events, measuring the CP-odd fraction \( R_\perp \) and the time dependent CP asymmetry

\[
R_\perp = \frac{|A_0^0|^2}{|A_0^0|^2 + |A_\perp|^2 + |A_\perp|^2}
\]
Probability Density Functions

- Overall PDF for the on-Peak sample is the sum of three components

\[ P_{\text{on}} = f_{B\bar{B}}[f_{\text{sig}}P_{\text{sig}} + (1 - f_{\text{sig}})P_{\text{comb}}] + (1 - f_{B\bar{B}})P_{q\bar{q}} \]

- Each component is the product of a kinematical and a \( \Delta t \) part

\[ P_i(m_{\text{rec}}, F, \Delta t, \sigma_{\Delta t}, S_{\text{tag}}) = M_i(m_{\text{rec}}) F_i(F) T_i'(\Delta t, \sigma_{\Delta t}, S_{\text{tag}}) \]

- \( \Delta t \) PDF: \[ T_i'(\Delta t, \sigma_{\Delta t}, S_{\text{tag}}) = \int d\Delta t_{\text{true}} T_i(\Delta t_{\text{true}}, S_{\text{tag}}) R_i(\Delta t - \Delta t_{\text{true}}, \sigma_{\Delta t}) \]

- Signal \( \Delta t \):

\[ T_{\text{sig}} = \frac{1}{4\tau_b} e^{-|\Delta t_{\text{true}}|/\tau_b} \cdot \left\{ (1 - S_{\text{tag}} \Delta \omega (1 - \alpha)) + S_{\text{tag}} (1 - 2\omega) (1 - \alpha) \cdot [C \cos(\Delta m_d \Delta t_{\text{true}}) + S \sin(\Delta m_d \Delta t_{\text{true}})] \right\} \]

\[ S = -\frac{2 \Im m(\lambda)}{1 + |\lambda|^2} \quad C = \frac{1 - |\lambda|^2}{1 + |\lambda|^2} \quad \lambda = \frac{q}{p} \frac{\bar{A}}{A} \]
Event Selection

4.7 Event Selection Summary

This is a summary of cuts used in our selection of events.

- Cuts in \( \Upsilon(4S) \) center-of-mass on \( D^* \) and soft pion momentum, and missing \( D^0 \) mass:
  \[
  1.3 \text{ GeV}/c \leq p_{D^*} \leq 2.1 \text{ GeV}/c
  \]
  \[
  p_\pi^* \leq 0.6 \text{ GeV}/c
  \]

- Continuum rejection cut:
  \[ R_2 \leq 0.3 \]

- “Quality” cuts on reconstructed \( D^* \) (see Sec. 4.3):
  \[ P_{D^*}^{\text{vert}} \text{ and } P_{D^0}^{\text{vert}} > 10^{-2} \]
  \[
  \text{Dch yes : } |Q_{D^*} - Q_{\text{PDG}}| = |M_{D^*} - M_{D^0} - M_\pi - 6 \text{ MeV}/c^2| \leq 1 \text{ MeV}/c^2
  \]
  \[
  \text{Dch no : } |Q_{D^*} - Q_{\text{PDG}}| = |M_{D^*} - M_{D^0} - M_\pi - 6 \text{ MeV}/c^2| \leq 1.5 \text{ MeV}/c^2
  \]
  \[
  |M_{D^0} - M_{\text{PDG}}| \leq [1. - 1.5] \cdot \sigma_i \text{ MeV}/c^2
  \]

- “PID” and flight-length cuts on Kaons in \( D^0 \) mesons (see Sec. 4.3)

- Slow pion \( dE/dx \) cuts:
  \[
  p_\pi^* \leq 0.150 \text{ GeV}/c^2 : \quad dE/dx \ (\text{MeV/cm}) \geq (\frac{0.25}{p_\pi^* - 0.030} + 1.0);
  \]
  \[
  0.150 \text{ GeV}/c^2 < p_\pi^* \leq 0.500 \text{ GeV}/c^2 : \quad dE/dx \ (\text{MeV/cm}) \leq (\frac{1.75}{p_\pi^*} + 2.0);
  \]

- Missed \( D^0 \) cuts:
  \[
  |\cos(\theta_{BD^*})| \leq 1
  \]
Tagging

- Mis-tag due to unreconstructed $D^0$ tracks
  - This introduces an additional dilution $D = (1 - \alpha)$, where $\alpha$ is the fraction of tags coming from the missing $D^0$
  - This fraction can be obtained from data with some input from signal MC
  - Can be reduced with a cut on the cosine of the opening angle between the tagging track and the missing $D^0$ direction $\theta_{\text{tag}}$

Figure 2.1: Signal Monte Carlo distributions of $\cos(\theta_{\text{tag}})$ for tracks from the missed $D^0$ (black) and from the other $B^0$ (red); lepton tags on the left, kaon tags on the right.