$CP$ violation in $B$ decays to charm and charmonium

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CP violation

- Difference between particle decay and anti-particle decay.
- CPV is incorporated in the SM.
- A large deviation w.r.t SM prediction is a sign for New Physics

Two new results in the charm and charmonium sector:

\[ b \to c \bar{c} d \]

1. \[ B^\pm \to \psi(2S)\pi^\pm \]
2. \[ \overline{B} \to D^{*-} D^{*-} \]

measured at Belle with \[ 657 \times 10^6 B\overline{B} \] events.
\[ B^\pm \rightarrow \psi (2S) \pi^\pm \]

Similar to the \( B^\pm \) decays to \( J/\psi K^\pm, J/\psi \pi^\pm \) and \( \psi (2S) K^\pm \)

Motivation

- small branching fraction $\sim O(10^{-5})$ due to color and Cabbibo suppression.

- has never been observed!!

Only possible due to the enormous amount of data!!
Possibility for direct CPV measurement.
Motivation

- small branching fraction \( \sim \mathcal{O}(10^{-5}) \) due to color and Cabbibo suppression.
- has never been observed!!

Only possible due to the enormous amount of data!!
Possibility for direct CPV measurement:

\[
\frac{\mathcal{B}(B^+ \to \psi(2S)\pi^+)}{\mathcal{B}(B^- \to \psi(2S)\pi^-)} \sim 5\%
\]

Contradicting results can be sign for New Physics.

**CP asymmetry:**

\[
\mathcal{B}(B^+ \to \psi(2S)\pi^+) \leftrightarrow \mathcal{B}(B^- \to \psi(2S)\pi^-)
\]

SM predicts no asymmetry
*(when penguins are neglected).*
$B^- \rightarrow \psi(2S)\pi^-$

or

$\rightarrow \ell^+\ell^-$

or

$J/\psi \pi^+\pi^-$

$\ell = e$ or $\mu$

**BACKGROUND:**

- $B^- \rightarrow J/\psi K^{*-} (K_S^0\pi^-)$
  same topology.
  $K_S^0$ veto (cut on $M_{\pi^+\pi^-}$).

- $B^- \rightarrow \psi(2S)K^-$
  $K^-$ mistaken as a $\pi^-$.  
  peak expected at $\Delta E \sim -0.07$ GeV.

- $B^- \rightarrow \psi(2S)K_S^0$
  one $\pi$ is missed.
  peak expected at $\Delta E \sim -0.18$ GeV.
$B^- \rightarrow \psi(2S)\pi^-$

$J/\psi \pi^+ \pi^-$

48.9±8.3  
9.5σ

44.0±8.1  
8.4σ

44.0±9.0  
7.3σ

43.5±7.7  
9.0σ

$\mathcal{B}(B^- \rightarrow \psi(2S)\pi^-) = \left(2.44 \pm 0.22 \pm 0.20\right) \times 10^{-5}$
$B^- \rightarrow \psi(2S)\pi^- \quad 657 \times 10^6 \text{ } B\overline{B}$

48.9±8.3
9.5σ

$J/\psi\pi^+\pi^-$

44.0±8.1
8.4σ

First observation

44.0±9.0
7.3σ

$\mathcal{B}(B^- \rightarrow \psi(2S)\pi^-) = (2.44 \pm 0.22 \pm 0.20) \times 10^{-5}$
SM factorization hypothesis implies: decay amplitude is product of two hadronic currents

\[ \frac{\mathcal{B}(B^- \to \psi(2S)\pi^-)}{\mathcal{B}(B^- \to \psi(2S)K^-)} \sim 5\% \]

\[ = 3.99 \pm 0.36 \pm 0.17\% \]

\textbf{CP asymmetry:} Small branching fraction \(\implies\) large sensitivity to N.P. if penguin contributions are negligible

\[ A = \frac{\mathcal{B}(B^- \to \psi(2S)\pi^-) - \mathcal{B}(B^+ \to \psi(2S)\pi^+)}{\mathcal{B}(B^- \to \psi(2S)\pi^-) + \mathcal{B}(B^+ \to \psi(2S)\pi^+)} \]

\[ = 0.022 \pm 0.085 \pm 0.016 \]

No indication for New Physics in this measurement.
$B^0 \rightarrow D^*+ D^*$

Cabibbo suppressed decay.
→ good place to look for New Physics.

Updated measurement.
The final state is $CP$ eigenstate: accessible by $B^0$ and $\bar{B}^0$

$CPV$ possible in decay, mixing and in interference between the decay and the mixing.

\[ A = \Gamma(B^0 \to D^{*+}D^{*-}) \propto \frac{e^{-t/\tau}}{4\tau} \{1 - (A \cos \Delta mt + S \sin \Delta mt)\} \]

\[ \bar{A} = \Gamma(\bar{B}^0 \to D^{*+}D^{*-}) \propto \frac{e^{-t/\tau}}{4\tau} \{1 + (A \cos \Delta mt + S \sin \Delta mt)\} \]

\[ A = \frac{1 - |\lambda|^2}{1 + |\lambda|^2} \xrightarrow{\text{SM}} 0 \quad \text{direct-}CP\, \text{violation} \]

\[ S = \frac{2 \Im \lambda}{1 + |\lambda|^2} \xrightarrow{\text{SM}} -\eta \sin 2\phi_1 \]

\[ \lambda_f = \frac{q}{p} \frac{\bar{A}_f}{A_f}. \]

We need to know the flavor, decay time and $CP$ eigenvalue.
How to measure $\sin 2\phi_1$ in practice?

$B$ mesons are entangled. The coherent oscillation implies that any given time, one is a $B^0$ and the other a $\bar{B}^0$.

\[
A_{CP}(\Delta t) = \frac{\Gamma_{\bar{B}^0}(\Delta t) - \Gamma_{B^0}(\Delta t)}{\Gamma_{B^0}(\Delta t) + \Gamma_{\bar{B}^0}(\Delta t)} = S \sin \Delta m \Delta t + A \cos \Delta m \Delta t
\]
Two $B$ mesons are produced in a boosted frame.

$\Delta t$ is measured from vertex positions

Determine flavor of $B^{\text{tag}}$ to know flavor of other $B$ at time $t = 0$.

\[
A_{CP}(\Delta t) \equiv \frac{\Gamma_{\bar{B}^0}(\Delta t) - \Gamma_{B^0}(\Delta t)}{\Gamma_{\bar{B}^0}(\Delta t) + \Gamma_{B^0}(\Delta t)}
= S \sin \Delta m \Delta t + A \cos \Delta m \Delta t
\]
Two $B$ mesons are produced in a boosted frame.

$\Delta t$ is measured from vertex positions

+ wrong tagging
+ detector resolution

$A_{CP}(\Delta t)$

$\equiv \frac{\Gamma_{B_0}(\Delta t) - \Gamma_{B^0}(\Delta t)}{\Gamma_{B_0}(\Delta t) + \Gamma_{B^0}(\Delta t)}$

$= S \sin \Delta m \Delta t + A \cos \Delta m \Delta t$
$YIELD \ 6.57 \times 10^6 \ B\overline{B}$

$B^0 \rightarrow D^{*+} D^{*-}$
$\rightarrow D^0 \pi^+$
$\rightarrow D^+ \pi^0$

550 ± 30 signal events
purity = 55%

**DETERMINE CP EIGENSTATE:**

- $D^{*+} D^{*-}$ are two vector mesons.

- Final state can have orbital momentum $l = 0, 1, 2$.

- $CP$ eigenvalue is admixture of $\eta = (-1)^l$.

Necessary to disentangle $CP$-odd states as they dilute the measurement of $\sin 2\phi_1$. 

$$\Delta E = E_{B}^{CM} - E_{beam}^{CM}$$

$$M_{bc} = \sqrt{(E_{beam}^{CM})^2 - (p_B^{CM})^2}$$

$$S = \frac{2\Im \lambda}{1 + |\lambda|^2} \xrightarrow{\text{SM}} -\eta \sin 2\phi_1$$
Angular analysis

transversity basis

<table>
<thead>
<tr>
<th>CP</th>
<th>cos $\theta_{tr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP even</td>
<td>$\sin^2(\cos \theta_{tr})$</td>
</tr>
<tr>
<td>CP odd</td>
<td>$\cos^2(\cos \theta_{tr})$</td>
</tr>
<tr>
<td>CP even</td>
<td>$\sin^2(\cos \theta_{tr})$</td>
</tr>
</tbody>
</table>

$R_\perp = 0.125 \pm 0.043^{\text{(stat)}} \pm 0.023^{\text{(syst)}}$

Consistent with previous measurements
**TIME-DEPENDENT CP ASYMMETRY**

\[
P_{\text{sig}} = \frac{e^{-|\Delta t|/\tau}}{4\tau} \left[ 1 - q w + q(1 - 2w)((1 - 2f_{\text{odd}})(S' \sin(\Delta m \Delta t) + A \cos(\Delta m \Delta t))) \right]
\]

- **Events / 2 ps**
  - 0.5 < r ≤ 1.0
  - \( B^0_{\text{tag}} \)
  - q = +1
  - \( \bar{B}^0_{\text{tag}} \)
  - q = -1

- **Δt (ps)**
  - -8 to 8

- **A**
  - SM \( \rightarrow 0 \)
  - \( S' = S/\eta \)
  - \( \rightarrow -\sin 2\phi_1 \)
  - \( \simeq -0.68 \pm 0.03 \) (charmonium)

- **A_{D^+D^-}**
  - 0.15 ± 0.13(stat) ± 0.04(syst),
  - **S'_{D^+D^-}**
  - -0.96 ± 0.25(stat)\(^{+0.12}_{-0.16}\) (syst),

**Consistent with SM prediction and previous \( B^0 \rightarrow D^{*+}D^{*-} \) result.**

Large direct CPV of \( B^0 \rightarrow D^+D^- \) is not observed here.
\[
P_{\text{sig}} = \frac{e^{-|\Delta t|/\tau}}{4\tau} \left[ 1 - qw + q(1 - 2w)(1 - 2f_{\text{odd}})(S' \sin(\Delta m \Delta t) + A \cos(\Delta m \Delta t)) \right]
\]

CP violation with 3.4 significance (stat. only)

\[
A \rightarrow 0
\]

\[
S' = \frac{S}{\eta}
\]

\[
A_{D^+D^-} = 0.15 \pm 0.13(\text{stat}) \pm 0.04(\text{syst}),
\]

\[
S'_{D^+D^-} = -0.96 \pm 0.25(\text{stat})^{+0.12}_{-0.16}(\text{syst}),
\]

Consistent with SM prediction and previous \(B^0 \rightarrow D^*+D^*\) result.

Large direct CPV of \(B^0 \rightarrow D^+D^-\) is not observed here.
Conclusion

- First measurement of branching fraction of $B^- \rightarrow \psi(2S)\pi^-$ thanks to large integrated luminosity at Belle.

- The branching fraction ratio measurement supports the factorization hypothesis.

- The obtained direct-$CP$ violation is within errors compatible with zero. (compatible with results of $B^-$ decays to $J/\psi K^-$, $J/\psi \pi^-$ and $\psi(2S)K^-$).
Conclusion

- First measurement of branching fraction of $B^- \rightarrow \psi(2S)\pi^-$ thanks to large integrated luminosity at Belle.

- The branching fraction ratio measurement supports the factorization hypothesis.

- The obtained direct-CP violation is within errors compatible with zero. (compatible with results of $B^- \rightarrow J/\psi K^-, J/\psi \pi^-$ and $\psi(2S)K^-$).

- Angular analysis performed to $B^0 \rightarrow D^{*+}D^{*-}$ and the measured CP-odd fraction is measured to be $R_\perp = 0.13 \pm 0.04 \pm 0.02$.


- CP violation is measured in this $b \rightarrow c\bar{c}d$ decay with a statistical significance of $\sigma = 3.4$.

Thank you.
BACKUP SLIDES
Overview of previous results

Belle

29.4 fb\(^{-1}\) data

TABLE V: Charge asymmetry for each mode. Errors are statistical only.

<table>
<thead>
<tr>
<th>Decay mode</th>
<th>Yield((-))</th>
<th>Yield((+))</th>
<th>(A_{K(\pi)})</th>
</tr>
</thead>
<tbody>
<tr>
<td>(B^{\pm} \rightarrow J/\psi\pi^{\pm})</td>
<td>21 ± 5</td>
<td>22 ± 5</td>
<td>-0.023 ± 0.164</td>
</tr>
<tr>
<td>(B^{\pm} \rightarrow J/\psi K^{\pm})</td>
<td>1024 ± 32</td>
<td>1078 ± 33</td>
<td>-0.026 ± 0.022</td>
</tr>
<tr>
<td>(B^{\pm} \rightarrow \psi(2S)(l^+l^-)K^{\pm})</td>
<td>79 ± 9</td>
<td>93 ± 10</td>
<td>-0.081 ± 0.078</td>
</tr>
<tr>
<td>(B^{\pm} \rightarrow \psi(2S)(J/\psi\pi^{+}\pi^-)K^{\pm})</td>
<td>68 ± 8</td>
<td>102 ± 10</td>
<td>-0.200 ± 0.075</td>
</tr>
<tr>
<td>Total ((B^{\pm} \rightarrow J/\psi(\psi(2S))K^{\pm}))</td>
<td>1171 ± 34</td>
<td>1273 ± 36</td>
<td>-0.042 ± 0.020</td>
</tr>
</tbody>
</table>
TABLE II: Summary of systematic errors on the $B^- \rightarrow \psi(2S)\pi^-$ branching fraction.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncertainty in yield</td>
<td>3.5</td>
</tr>
<tr>
<td>Tracking error</td>
<td>5.0</td>
</tr>
<tr>
<td>Lepton identification</td>
<td>4.2</td>
</tr>
<tr>
<td>Pion identification</td>
<td>1.6</td>
</tr>
<tr>
<td>MC statistics</td>
<td>0.3</td>
</tr>
<tr>
<td>Number of $B\bar{B}$ pairs</td>
<td>1.4</td>
</tr>
<tr>
<td>Daughter branching fractions</td>
<td>3.4</td>
</tr>
<tr>
<td>$\Delta M$ requirement</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>8.4</strong></td>
</tr>
</tbody>
</table>

\[
\frac{\mathcal{B}(B^- \rightarrow \psi(2S)\pi^-)}{\mathcal{B}(B^- \rightarrow \psi(2S)K^-)} = (3.99 \pm 0.36 \pm 0.17)\%, \quad (4)
\]

which is consistent with the expectations of the factorization hypothesis. Many sources of systematic errors cancel in the ratio of the branching fractions. Contributions to the systematic error come from the uncertainty in pion identification, signal extraction method, MC statistics from $B^- \rightarrow \psi(2S)\pi^- (K^-)$ decay, kaon identification and uncertainty on the background estimation from $B^- \rightarrow \psi(2S)K^-$ decay. The total uncertainty is 4.2%.
Overview of previous results

\[ B^0 \rightarrow D^{**} + D^{**} \]

\[ \mathcal{R}_\perp = 0.19 \pm 0.08 \pm 0.01 \]

\[ \mathcal{R}_\perp = 0.13 \pm 0.04 \pm 0.02 \]

\[ \mathcal{R}_\perp = 0.14 \pm 0.03 \pm 0.01 \]

\[ \text{Phys. Rev. D 76, 111102 (2007)} \]

\[ \text{Phys. Lett B 618, 34-42 (2005)} \]
Overview of previous results

- $B^0 \rightarrow D^+ D^-$: $(535 \times 10^6 B\bar{B})$
  $A = 0.91 \pm 0.23 \pm 0.06$
  $S = -1.13 \pm 0.37 \pm 0.06$

- $B^0 \rightarrow D^{*+} D^{*-}$: $(152 \times 10^6 B\bar{B})$
  $A = -0.26 \pm 0.26 \pm 0.06$
  $S = -0.75 \pm 0.56 \pm 0.12$
  *Phys. Lett B 618, 34-42 (2005)*

- $B^0 \rightarrow D^+ D^-$: $(383 \times 10^6 B\bar{B})$
  $A = -0.11 \pm 0.22 \pm 0.07$
  $S = -0.54 \pm 0.34 \pm 0.06$

- $B^0 \rightarrow D^{*+} D^{*-}$: $(383 \times 10^6 B\bar{B})$
  $A = 0.02 \pm 0.11 \pm 0.02$
  $S = -0.66 \pm 0.19 \pm 0.04$
  *Phys. Rev. D 76, 111102 (2007)*
systematic uncertainty on $R_\perp$

The systematic uncertainty on $R_\perp$ is obtained by varying the fixed parameters within their errors; contributions of 0.003, 0.003 and 0.009 arise from the signal shape, signal efficiency and the $R_0/(R_0 + R_\parallel)$ parameters respectively. A fast MC is used to estimate any possible fit bias; we find a small shift of 0.002. When tighter vertex quality cuts are applied a difference of 0.013 is obtained. Finally a peaking background contribution of 6.6% obtained from the MC, is added to which we conservatively assign a $CP$-odd behavior, leading to a 0.016 change in the central value. The different contributions are summed in quadrature to yield 0.023.
TABLE I: Systematic errors on the $CP$-violating parameters for $B^0 \to D^{*+}D^{*-}$ decays.

<table>
<thead>
<tr>
<th>source</th>
<th>$A$</th>
<th>$S'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>signal purity</td>
<td>$\pm 0.002$</td>
<td>$\pm 0.004$</td>
</tr>
<tr>
<td>standard resolution function</td>
<td>$\pm 0.004$</td>
<td>$+0.000 -0.102$</td>
</tr>
<tr>
<td>resolution from control sample</td>
<td>$\pm 0.002$</td>
<td>$\pm 0.030$</td>
</tr>
<tr>
<td>background shape</td>
<td>$\pm 0.000$</td>
<td>$\pm 0.006$</td>
</tr>
<tr>
<td>$CP$-odd fraction $R_\perp$</td>
<td>$\pm 0.004$</td>
<td>$\pm 0.109$</td>
</tr>
<tr>
<td>fit bias</td>
<td>$\pm 0.010$</td>
<td>$\pm 0.031$</td>
</tr>
<tr>
<td>$\Delta m_d, \tau_{B^0}$</td>
<td>$+0.002$</td>
<td>$+0.004$</td>
</tr>
<tr>
<td>flavour tagging</td>
<td>$\pm 0.011$</td>
<td>$\pm 0.020$</td>
</tr>
<tr>
<td>vertex cuts</td>
<td>$\pm 0.003$</td>
<td>$\pm 0.028$</td>
</tr>
<tr>
<td>$\Delta t$ fit range</td>
<td>$\pm 0.010$</td>
<td>$\pm 0.004$</td>
</tr>
<tr>
<td>peaking background</td>
<td>$\pm 0.010 +0.000 -0.027$</td>
<td></td>
</tr>
<tr>
<td>tag side interference</td>
<td>$\pm 0.034$</td>
<td>$\pm 0.007$</td>
</tr>
<tr>
<td>total</td>
<td>$\pm 0.040 +0.123 -0.162$</td>
<td></td>
</tr>
</tbody>
</table>

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