RECENT RESULTS FROM BABAR

Swagato Banerjee

University of Victoria
British Columbia • Canada
Recent Results From B Factory: PEP-II and BABAR

**PEP II** Delivered Luminosity: 364.79/fb

**BaBar** Recorded Luminosity: 350.86/fb

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**BaBar**

**PEP-II Records**

**Peak Luminosity**

$10.877 \times 10^{33}$ cm$^{-2}$sec$^{-1}$

- 1722 bunches
- 2700 mA LER
- 1775 mA HER

**Integration records of delivered luminosity**

- Best shift (8hrs, 0:00-8:00, 16:00): 280.9 pb$^{-1}$, Jun 3, 2006
- Best 3 shifts in a row: 760.0 pb$^{-1}$, May 25, 2006
- Best day: 713.5 pb$^{-1}$, May 22, 2006

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$E_{cm} = 10.58$ GeV

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**SLAC-Based B Factory: PEP-II and BABAR**
Canadian Collaborators in BaBar

University of British Columbia
- Asgeirsson, David J.
- Bruskiewich, Patrick S.
- De Silva, Asoka
- Donszelmann, Tulay
- Fulsom, Bryan
- Hearty, Christopher
- Mattison, Tom
- McKenna, Janis
- McGregor, Grant D.

Universite de Montreal
- Brunet, Sylvie
- Cote, David
- Sicard, Marie-Elisabeth
- Simard, Martin
- Taras, Paul
- Viaud, Benoit Francis

McGill University
- Campbell, Benjamin C.
- Harnois-Deraps, Joachim
- Kim, Hojeong
- Klemetti, Miika A.
- Mclachlin, Sheila
- Patel, Popat M.
- Robertson, Steven H.

University of Victoria
- Agarwal, Ashok K.
- Banerjee, Swagato
- Bhuyan, Bipul
- Choi, Herve H. F.
- Hamano, Kenji
- King, Gregory J.
- Kowalewski, Robert
- Lewczuk, Mateusz J.
- Nugent, Ian M.
- Roney, Michael
- Sobie, Randall J.

In this session

Facility
- RA/PostDoc
- Student
BaBar is more than a B-Factory:
\[ \sigma(b\bar{b}:c\bar{c}:\tau\bar{\tau}) = 1.1 : 1.3 : 0.9 \text{ nb} \]

**Outline**

In this talk:

- **CP violation in B system**
  - $\beta$
  - $\alpha$
  - $\gamma$

- **Charm Spectroscopy**
  - X (3872)
  - Y (4260)

- **$\tau$ Physics**
  - Lepton Flavour Violation
BaBar is more than a B-Factory: $\sigma(b\bar{b}:c\bar{c}:\tau\bar{\tau}) = 1.1 : 1.3 : 0.9$ nb

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CP Violation in Standard Model

- CKM Matrix (V): Mass eigenstates -> Flavour eigenstates
- 3x3 Unitary Matrix has 1 Complex Phase => CP violation

\[
V = \begin{pmatrix}
V_{ud} = 1 - \frac{1}{2} \lambda^2 \\
V_{cd} = -\lambda \\
V_{td} = A\lambda^3 (1 - \rho - i\eta)
\end{pmatrix}
\begin{pmatrix}
V_{us} = \lambda \\
V_{cs} = 1 - \frac{1}{2} \lambda^2 \\
V_{ts} = -A\lambda^2
\end{pmatrix}
\begin{pmatrix}
V_{ub} = A\lambda^3 (\rho - i\eta) \\
V_{cb} = A\lambda^2 \\
V_{tb} = 1
\end{pmatrix}
\]

- \( V^\dagger V = 1 \) => The Unitarity Triangle

\[
V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0
\]
CP Violation in several variants

- CP Violation in Mixing:
- CP Violation in Decay:
- CP Violation in Interference between decay without and with Mixing:

- $B^0$-$\bar{B}^0$ mixing factor in CPV:

\[
\frac{q}{p} = \frac{V_{tb}^* V_{td}}{V_{tb} V_{td}^*} = e^{-2i\beta}, \quad \Rightarrow \lambda_f = e^{-2i\beta} \frac{\bar{A}_f}{A_f} \text{ (with final state as CP eigenstate)}
\]
**Recent Results From BABAR**

**CPV : Time Dependent Analysis**

Coherent B meson production (L=1)

\[
\mathcal{B}_{\text{tag}} = \overline{B}^0(t) \\
\Rightarrow \mathcal{B}_{\text{rec}} = B^0(t)
\]

Exclusive B meson reconstruction

\[\Delta z \approx 260 \mu m\]

\[\sigma(\Delta z) \approx 170 \mu m\]

\[\Delta t \approx \Delta z / < \beta \gamma > c\]

\[\beta \gamma = 0.56 \text{ (PEP II)}\]

\[\sigma_s \propto 1/\sqrt{Q}\]

\[A_{CP}(t) = \frac{N(\overline{B}^0(t) \rightarrow f_{CP}) - N(B^0(t) \rightarrow f_{CP})}{N(\overline{B}^0(t) \rightarrow f_{CP}) + N(B^0(t) \rightarrow f_{CP})}\]

\[= S_f \sin(\Delta m t) - C_f \cos(\Delta m t)\]

\[Q = \varepsilon(1-2\omega)^2 = (30.5 \pm 0.5\%)\]
The angle $\beta$

**$b \rightarrow c \bar{c} s$**

Tree dominance

$$\bar{B}^0 \left\{ \begin{array}{c} b \\ \bar{d} \end{array} \right\} \xrightarrow{W^-} \left\{ \begin{array}{c} c \\ \bar{c} \end{array} \right\} J/\psi \left\{ \begin{array}{c} \frac{s}{d} \\ \bar{d} \end{array} \right\} \xrightarrow{t,c,u} \left\{ \begin{array}{c} \frac{s}{d} \\ \bar{s} \end{array} \right\} K^0$$

$$\lambda_{J/\psi} K^0_S = -\left( \frac{q}{p} \right) \left( \frac{V_{cb} V_{cs}^*}{V_{cb} V_{cs}} \right) \left( \frac{q}{p} \right) K = -e^{-2i\beta}$$

**$b \rightarrow s \bar{s} s$**

Penguin dominance

**internal penguin**

$$\bar{B} \left\{ \begin{array}{c} b \\ \bar{u}, \bar{d} \end{array} \right\} \phi \left\{ \begin{array}{c} s \\ \bar{s} \end{array} \right\} K$$

**flavour-singlet penguin**

$$\bar{B} \left\{ \begin{array}{c} b \\ \bar{u}, \bar{d} \end{array} \right\} \phi \left\{ \begin{array}{c} g \\ s \end{array} \right\} K$$

$$\lambda_{\phi} K^0_S = -\left( \frac{q}{p} \right) \left( \frac{V_{tb} V_{ts}^*}{V_{tb} V_{ts}} \right) \left( \frac{q}{p} \right) K \approx -e^{-2i\beta}$$

$S = \sin 2\beta$

$C = 0$

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Recent Results From BABAR
Independent measurements of $\beta$

- Important to check (in-)consistencies in different measurements

$A_{CP}(t) = \pm \text{Im} \lambda \sin(\Delta mt)$

$C_f = 0$

$S_f = \text{Im} \lambda = \sin(2\beta)$

$\sin(2\beta_{\text{eff}})$
Recent Results From BABAR

\[ \sin 2\beta \text{ from } B^0 \rightarrow \text{charmonium } K^0 \]

Latest measurement

\[
\sin 2\beta = 0.722 \pm 0.040 \pm 0.023
\]

[Recent measurement of BABAR](PRL94, 161803 (2005), 227MBB):
Recent Results From BABAR

Results consistent with SM expectation

\[ \sin 2\beta \text{ from } b \to c\bar{c}d : \text{summary} \]
**Sin2β_{eff} in b → s Penguins**

- **Search for New Physics in the loop**

  \[ B^0 \rightarrow (\phi, \eta', \rho, \omega, f_0, \pi^0, \pi^0\pi^0, K^+K^-, K^0_SK^0_S)K^0 \]

  .. look for deviations of Δsin2β from 0

- **New Results from BaBar:**
  - First measurement of \( \rho K_S \)
  - Update in \( \omega K_S \)
  - Pure Penguin mode: \( B \rightarrow K_SK_SK_S \)
    - No charged tracks from decay vertex: extrapolate back the \( K_S \)'s
  - Many BF and \( A_{CP} \) measurements in related modes control hadronic uncertainties in b → s penguins.

  - **B → \eta'\eta, (\eta',\eta)\pi^0**: Useful in reducing (by ~20%) theory uncertainty in \( \Delta\sin2\beta(\eta'K_S) \)

- **Phys.Rev.D73:071102,2006**
# Summary of \( \sin(2\beta) \) in Penguins

## Results

\[
\sin(2\beta_{\text{eff}})
\]

<table>
<thead>
<tr>
<th>( \bar{b} \to c \bar{c} s )</th>
<th>World Average</th>
<th>( \phi K^0 )</th>
<th>( \eta' K^0 )</th>
<th>( \pi^0 K_S )</th>
<th>( \omega K_S )</th>
<th>( \rho K_S )</th>
<th>( K^+ K_S K^0 )</th>
<th>( K^0 K_S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \bar{b} \to c \bar{c} s )</td>
<td>0.69 ± 0.03</td>
<td>0.50 ± 0.25</td>
<td>0.36 ± 0.13</td>
<td>-0.84 ± 0.71</td>
<td>0.50 ± 0.34</td>
<td>0.41 ± 0.18</td>
<td>0.63 ± 0.28</td>
<td>0.63 ± 0.32</td>
</tr>
<tr>
<td>BaBar</td>
<td>0.50 ± 0.25</td>
<td>0.44 ± 0.27</td>
<td>0.36 ± 0.13</td>
<td>-0.84 ± 0.71</td>
<td>0.50 ± 0.34</td>
<td>0.41 ± 0.18</td>
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</tr>
<tr>
<td>Belle</td>
<td>0.47 ± 0.19</td>
<td>0.47 ± 0.12</td>
<td>0.50 ± 0.09</td>
<td>0.75 ± 0.24</td>
<td>0.31 ± 0.26</td>
<td>0.17 ± 0.52</td>
<td>0.63 ± 0.30</td>
<td>0.58 ± 0.36</td>
</tr>
<tr>
<td>Average</td>
<td>0.47 ± 0.19</td>
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### Representative theory estimates

- **Naïve\(^2\) Average:** 0.50 ± 0.06 (2.8σ)

### New Physics?

Example from recent calculations (QCD factorization)
- 2-body: [Beneke; PL B620, 143 (2005)]
- 3-body: [Cheng,Chua,Soni; PRD72, 094003 (2005)]
Recent Results From BABAR

The angle alpha

- 2 body isospin analyses of $B \rightarrow \pi\pi$ and $B \rightarrow \rho\rho$ (discrete ambiguities)
- Dalitz plot analysis of $B \rightarrow \rho\pi$ (no ambiguity)

New BaBar measurement of $\rho^+\rho^0$:

$$B(B^\pm \rightarrow \rho^\pm\rho^0) = (17.2 \pm 2.5 \pm 2.8) \times 10^{-6}$$
$$A_{CP}(B^\pm \rightarrow \rho^\pm\rho^0) = 0.10 \pm 0.14 \pm 0.09.$$  

now fully compatible with a closed isospin triangle

new average $\alpha = (100.2^{+15.0}_{-8.8})^\circ$

hep-ex/0606046
The angle gamma

Use interference between $B^+ \rightarrow D^0 K^+$ and $B^+ \rightarrow \bar{D}^0 K^+$ with both $D^0$ and $\bar{D}^0$ decaying to the same final state $f$

- **Three Methods:**
  - GLW (Gronau, London, Wyler)
  - ADS (Atwood, Dunietz, Soni)
    - $A(D \rightarrow f)$: doubly Cabibbo suppressed
    - Need more data
  - Dalitz (Giri, Grossman, Soffer, Zupan)

New from BaBar: $D^0 \rightarrow K_S \omega, K_S \phi$


Currently most sensitive

$B^+ \rightarrow D^0 K^- (D^0 \rightarrow K_S \pi^+ \pi^-)$

$\gamma = (67 \pm 28 \pm 13 \pm 11)^\circ$

BABAR [PRL95, 121802 (2005), 227M BB]
Recent Results From BABAR

Evolution of Errors

\[ \sin(2\beta)[(c\bar{c})K^0] \]

\[ \sigma(\sin 2\beta) \] in penguins

Error on \( \alpha \)

Error on \( \gamma \)

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BaBar is more than a B-Factory:
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  - $\gamma$
- **Charm Spectroscopy**
  - $X (3872)$
  - $Y (4260)$
- **$\tau$ Physics**
  - Lepton Flavour Violation
BaBar is more than a B-Factory: \( \sigma(bb:cc:ττ) = 1.1 : 1.3 : 0.9 \text{ nb} \)

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- **Charm Spectroscopy**
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  - \( Y(4260) \)

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T. Barnes, S. Godfrey and E. S. Swanson

*Phys. Rev. D72 054026 (2005)*

Recent Results From BABAR
Recent Results From BABAR

- Observed by Belle (2003), confirmed by CDF, DØ, BABAR

\[ X(3872) \rightarrow J/\psi \pi^+\pi^- \]

- No charged partner observed $\rightarrow$ Initial state $X^0(3872)$ isospin = 0

\[ N = 61.2 \pm 15.3 \ (6.1\sigma) \]

- Combined Average:

\[ m_x = (3871.2 \pm 0.6) \text{ MeV/c}^2 \]

\[ \Gamma_x < 2.3 \text{ MeV} \ @ \ 90\% \ CL \]

\[ B(B^0 \rightarrow K^+ X^+(3872)) < 5 \times 10^{-4} \ @ \ 90\% \ CL \]

\[ B(B^0 \rightarrow K^+ X^\pm(3872), X^\pm \rightarrow \pi^\pm \pi^0 J/\psi) < 5.4 \times 10^{-6} \ @ \ 90\% \ CL \]

**New Physics!**


**X(3872) → J/ψ γ**

\[ B(B → K \ X(3872) \times X(3872) → γ \ J/ψ) = (3.4 ± 1.0 ± 0.3) \times 10^{-6} \]

- **Confirms 4σ evidence from Belle**
  - \( C(J/ψ) = -1, \ C(γ) = -1 \)
  - **X(3872) is a C=+1 state**

- \([\pi^+\pi^-]\) similar to \( γ \rightarrow I^G(J^{PC})[\pi^+\pi^-] = 1^+(1^-) : ρ^0\)
- **Isospin** \( (J/ψ) = 0 \rightarrow \) **Isospin** \( (J/ψ \ \pi^+\pi^-) = 1\)
  - **X(3872) \rightarrow \pi^+\pi^- J/ψ** **isospin-violating decay**
  - **Explains narrow width of X(3872)**
- **All (other) evidence** \( I=0, \ J^{PC}=1^{++} \) for **X(3872)**
Recent Results From BABAR

Y(4260) → J/ψ p⁺ p⁻

- Searching for X(3872) in ISR events but found Y(4260)
  - 233 fb⁻¹, PRL 95, 142001 (2005)
  - → J^PC = 1^{--}

Confirmed by CLEO in energy scan
(also in π⁰π⁰J/ψ mode) hep-ex/0602034

New Physics!

125±23 events
8 σ Significance

Γₑₑ × B(Y(4260) → π⁺π⁻ J/ψ )
= (5.5 ± 1.0^{+0.8}_{-0.7}) eV

BABAR: 232 fb⁻¹
PRD 73, 012005 (2006)

Peak cross section:
σ(e⁺e⁻→Y)=(51±12) pb

m_Y = (4259 ± 8^{+2}_{-6}) MeV/c²
Γ_Y = (88 ± 23^{+6}_{-4}) MeV
Y(4260) Searches in ISR Processes

\[ e^+e^- \rightarrow \gamma_{\text{ISR}} \overline{D}D \ (289 \text{ fb}^{-1}) \]

To b. subm. to PRL

\[ e^+e^- \rightarrow \gamma_{\text{ISR}} \phi p + p^- \ (232 \text{ fb}^{-1}) \]

To b. subm. to PRD

\[ e^+e^- \rightarrow \gamma_{\text{ISR}} \overline{p}p, \ (232 \text{ fb}^{-1}) \]

PRD 73, 012005 (2006)

\[ \text{BF}(Y(4260) \rightarrow D\overline{D}) \]

\[ \text{BF}(Y(4260) \rightarrow J/\psi \pi^+\pi^-) \]

\[ < 7.6 \text{(95\% CL)} \]

\[ \Gamma^Y_{ee} \times \text{B}(Y(4260) \rightarrow \pi^+\pi^-\phi) \]

\[ < 0.4 \text{ eV} \ \text{at} \ 90\% \text{ CL} \]

\[ \frac{\text{B}(Y(4260) \rightarrow p\overline{p})}{\text{B}(Y(4260) \rightarrow \pi^+\pi^-J/\psi)} \]

\[ < 0.13 \ \text{at} \ 90\% \text{ CL} \]

\[ \gamma_{\text{ISR}} \text{ detected} \]

\[ \gamma_{\text{ISR}} \text{ not required} \]
Indication of Y(4260) in B decays

BF(B⁺→Y(4260) K⁺, Y(4260)→π⁺π⁻J/ψ = (2.0±0.7±0.2) 10⁻⁵

3.1σ significance, assuming mass and width from ISR analysis; needs confirmation

PRD 73, 011101 (2006)
BaBar is more than a B-Factory:
\[ \sigma(b\bar{b}:c\bar{c}:\tau\bar{\tau}) = 1.1 : 1.3 : 0.9 \text{ nb} \]

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$\sigma(bb:cc:tt) = 1.1 : 1.3 : 0.9$ nb

**SM($\nu$ mixing) $\sim 10^{-14}$-$10^{-50}$**
BaBar is more than a B-Factory: \[ \sigma(b\bar{b}:c\bar{c}:\tau\bar{\tau}) = 1.1 : 1.3 : 0.9 \text{ nb} \]

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**SM(\( \nu \) mixing)** \( \sim 10^{-14} - 10^{-50} \)

**New Physics** \( \sim 10^{-8} - 10^{-10} \)
Lepton Flavour Violating $\tau$ decays

$\mathcal{B}(\tau^- \rightarrow e^- \gamma)$

$\mathcal{B}(\tau^- \rightarrow \mu^- \gamma)$

$\mathcal{B}(\tau^- \rightarrow e^- e^+ e^-)$

$\mathcal{B}(\tau^- \rightarrow \mu^- \mu^+ \mu^-)$

Recent Results From BABAR

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(\tau \rightarrow \mu \gamma) and S_{\phi K_S}

**SUSY SU(5) GUT:** Flavour changing right-handed currents \Rightarrow
Correlations between CP asymmetry in b-s penguins and \tau \rightarrow \mu \gamma

Current measurement: \( S(B \rightarrow \phi K_S) = 0.47 \pm 0.19 \) (HFAG, 2006).
More sensitive \( B(\tau \rightarrow \mu \gamma) < 6.8 \times 10^{-8} \) exclude some regions.

J. Hisano, Y. Shimizu (PLB565(2003)183)
\( \tan \beta = 10, A_0 = 0, \)
\( m_{\nu_R} = 5 \times 10^{14} \text{GeV}, \)
\( m_{\nu_\tau} = 5 \times 10^{-2} \text{eV} \)
“Last week the BaBar collaboration celebrated a major milestone: the submission of its 200th paper ... We have become a b-factory, a tau-factory and a charm-factory” (SLAC Press Release, May 2006).

➤ BaBar expects to double its data statistics over the next 2 years.

Please stay tuned for many more exciting results....