Non B Physics from Belle

Kazuo Abe
KEK

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B factory is a powerful charm factory, and a powerful τ factory

Event shape variable $R_2$

\[ R_2 \]

326 million hadronic events
84.2 ± 0.5 million B meson pairs

$\sigma(B\bar{B}) \sim 1\ \text{nb}$

$\sigma(c\bar{c}) \sim \text{one half of continuum} \sim 1.3\ \text{nb}$

$e^+e^- \rightarrow \tau^-(\mu^-\nu_\mu\nu_\tau)\tau^+(\pi^+\pi^-\pi^+\bar{\nu}_\tau)$

\[ \sigma(\tau^+\tau^-) \sim 1\ \text{nb} \]
Charm Physics

• \( e^+ e^- \rightarrow J/\psi + X \): test of NRQCD

• New particles \( X(3872), D_sJ \): Potential model? or something else?

• \( D^0 \rightarrow \phi \gamma \): FCNC decay of \( D \) meson

• \( D^0 \bar{D}^0 \) mixing: New physics search

τ Physics

• \( \tau \rightarrow \mu \gamma, \tau \rightarrow \mu \mu \mu \): LFV decays

• \( \tau \) Electric Dipole Moment: CP violation in \( e^+ e^- \rightarrow \tau^+ \tau^- \)
Continuum $e^+e^- \rightarrow J/\psi + X$

- CDF $\sigma(\bar{p}p \rightarrow J\psi + X)$
  $\sim 30$ times larger than PQCD (LO color-singlet only)
  $\rightarrow$ development of NRQCD

- Agrees with CDF cross section.
  But HERA cross section data do not require color-octet.

- Disagrees with CDF polarization data.

NRQCD: Braaten, Fleming, Yuan, hep-ph/9602374v1

- Rigorous treatment of $c\bar{c}$ with similar momenta in all orders pf $\alpha_s$
  (both color-singlet and color-octet)

- Factorization of $c\bar{c} \rightarrow J/\psi$ using expansion of $\nu$ between $c$ and $\bar{c}$

$$d\sigma(J/\psi X) = d\hat{\sigma}(c\bar{c}[1,3S_1]) < O_1^{J/\psi} > + d\hat{\sigma}(c\bar{c}[8,2S+1S_{0,1},2S+1P_J]) < O_8^{J/\psi} >$$
Dominant Contributions to $e^+e^- \rightarrow J/\psi + X$:

**Color Single $J/\psi gg$**
\[
\begin{array}{c}
\varepsilon^+ \rightarrow \gamma \rightarrow \bar{c} c \rightarrow e^+ \rightarrow \bar{c} c \\
\varepsilon^- \rightarrow \bar{c} \rightarrow g \rightarrow e^- \rightarrow g \\
\sim 1 \text{ pb}
\end{array}
\]

**Color Octet $J/\psi g$**
\[
\begin{array}{c}
\varepsilon^+ \rightarrow \gamma \rightarrow \bar{c} c \rightarrow e^+ \rightarrow \bar{c} c \\
\varepsilon^- \rightarrow \bar{c} \rightarrow g \rightarrow e^- \rightarrow g \\
\sim 0.05 - 0.5 \text{ pb} \\
\text{peaks at } p_{J/\psi}^* \text{ endpoint}
\end{array}
\]

**Color Singlet $J/\psi c\bar{c}$**
\[
\begin{array}{c}
\varepsilon^+ \rightarrow \gamma \rightarrow \bar{c} c \rightarrow e^+ \rightarrow \bar{c} c \\
\varepsilon^- \rightarrow \bar{c} \rightarrow g \rightarrow e^- \rightarrow g \\
\sim 0.05 - 0.07 \text{ pb} \\
\text{extra charmed particles}
\end{array}
\]

**Belle (PRL 88, 052001 (2001))**

- $\sigma(e^+e^- \rightarrow J/\psi X) = (1.47 \pm 0.10 \pm 0.11) \text{ pb}$
- No endpoint structure in $p_{J/\psi}^*$ distr
- Next step is to look for $e^+e^- \rightarrow J/\psi c\bar{c}$

![Graphs](a) and (b) showing data for $\psi(2S) \rightarrow J/\psi X$.
Clear Signals for $e^+e^- \rightarrow J/\psi c\bar{c}$
Belle PRL 89 (2002) 142001

Recoil mass against $J/\psi$

\[ a) \]

\[ M_{\text{recoil}} \text{ GeV}/c^2 \quad N/0.2 \text{ GeV}/c^2 \]
\[ b) \]

\[ M_{\text{recoil}} \text{ GeV}/c^2 \quad N/20 \text{ MeV}/c^2 \]

Efficiency

\[ 0 \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \]
\[ 0 \quad 1 \quad 2 \quad 3 \quad 4 \quad 5 \quad 6 \]

\[ l^+l^- \text{ mass vs } D^* \text{ mass, } D \text{ mass} \]

\[ a) \]

\[ M(D^0) \text{ GeV}/c^2 \quad N/1 \text{ MeV}/c^2 \]
\[ b) \]

\[ M(K^-\pi^+) \text{ GeV}/c^2 \quad M(l^+l^-) \text{ GeV}/c^2 \]
\[ c) \]

\[ M(K^-\pi^+) \text{ GeV}/c^2 \quad N/4 \text{ MeV}/c^2 \]
\[ d) \]

\[ M(K^-\pi^+) \text{ GeV}/c^2 \]

- $\sigma(e^+e^- \rightarrow J/\psi \eta_c(\gamma)) \times B(\eta_c \rightarrow \leq 4\text{charged}) = (0.033^{+0.007}_{-0.006} \pm 0.009 \text{ pb})$
- $\sigma(e^+e^- \rightarrow J/\psi D^{*+}) = (0.53^{+0.19}_{-0.15} \pm 0.14) \text{ pb}$

\[ \frac{\sigma(e^+e^- \rightarrow J/\psi c\bar{c})}{\sigma(e^+e^- \rightarrow J/\psi X)} = 0.59^{+0.15}_{-0.13} \pm 0.12 \sim 10 \times \text{ larger than NRQCD!} \]
New Charmonium-like state $X(3872)$

$$B^+ \rightarrow K^+X^0 \rightarrow \pi^+\pi^-J/\psi$$

A small peak at $\sim 0.775$ GeV in addition to $0.589$ GeV peak corresponding to well known $\psi'$. 
Simultaneous fit to $M_{bc}$, $\Delta E$, and $M_{\pi^+\pi^- J/\psi}$ for $X(3872)$ region (and for $\psi'$ region as a calibration).

<table>
<thead>
<tr>
<th>$\psi'$ region</th>
<th>$X(3872)$ region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal Yield</td>
<td>489 ± 23</td>
</tr>
<tr>
<td>$M_{\pi^+\pi^- J/\psi}$ peak (MeV)</td>
<td>3685.5 ± 0.2</td>
</tr>
<tr>
<td>$\sigma_{M_{\pi^+\pi^- J/\psi}}$ (MeV)</td>
<td>3.3 ± 0.2</td>
</tr>
</tbody>
</table>

$M_X = 3872.0 \pm 0.6 \pm 0.5$ MeV

$\Gamma < 2.3$ MeV (90% C.L.)

$$\frac{\mathcal{B}(B^+ \rightarrow K^+ X(3872)) \times \mathcal{B}(X(3872) \rightarrow \pi^+\pi^- J/\psi)}{\mathcal{B}(B^+ \rightarrow K^+\psi') \times \mathcal{B}(\psi' \rightarrow \pi^+\pi^- J/\psi)} = 0.063 \pm 0.012 \pm 0.007$$
$\pi^+\pi^-$ Invariant Mass

Tends to cluster near the kinematic boundary (near $\rho$)

(shaded: background estimated from $M_{bc} - \Delta E$ sideband)
What is it?

- Decays to $\pi^+\pi^- J/\psi$
  - contains $c\bar{c}$ (charmonium-like)

- Above $D\bar{D}$ threshold, but narrow
  - $X(3872) \to D\bar{D}$ forbidden or suppressed

- Produced in exclusive $B^+ \to K^+ X(3872)$ decays
  - high $J$ values not likely
Godfrey, Isgur, PRD32 (1985) 189
Possible Charmonium States

Reject $D\bar{D}$-allowed states, disregard $L = 3$ or higher

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>state</th>
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</tr>
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<tbody>
<tr>
<td>1$^{+-}$</td>
<td>$h'_c$</td>
<td>1$^{++}$</td>
<td>$\chi'_{c1}$</td>
</tr>
<tr>
<td>2$^{--}$</td>
<td>$\psi_2$</td>
<td>0$^{-+}$</td>
<td>$\eta''_c$</td>
</tr>
<tr>
<td>3$^{--}$</td>
<td>$\psi_3$</td>
<td>2$^{-+}$</td>
<td>$\eta_{c2}$</td>
</tr>
</tbody>
</table>

- Data prefers $1^{--} \pi\pi$ ($\rho$-like) case. But they violate isospin (unlikely for charmonium)

- $X \rightarrow \pi^0\pi^0 J/\psi$ plays an important role (in progress)

$$\mathcal{B}(X \rightarrow \pi^0\pi^0 J/\psi) \simeq \frac{1}{2} \mathcal{B}(X \rightarrow \pi^+\pi^- J/\psi) \text{ for } 0^{++} \pi\pi$$

$$= 0 \text{ for } 1^{--} \pi\pi$$
No good Charmonium Candidate

\( \eta''_c \) Mass way off, should be wider

\( h'_c \) \( J/\psi \) angular distribution not consistent with \( 1^{+-} \)

\( \chi'_{c1} \) \( \Gamma(\gamma J/\psi) \) too small

\( \psi_2 \) \( \Gamma(\gamma \chi_{c1}) \) too small

\( \eta_{c2} \) \( \pi^+ \pi^- J/\psi \) decay not allowed

\( \psi_3 \) \( \Gamma(\gamma \chi_{c2}) \) too small

Eichten, Lane, Quigg, PRL 89, 162002(2002)
Interesting Possibility

- Observed $X(3872)$ mass is almost exactly equal to $D\bar{D}^*$ mass.

\[ M_X = 3872.0 \pm 0.6 \pm 0.5 \text{ MeV} \quad M_{D^0\bar{D}^{*0}} = 3871.3 \pm 0.5 \text{ MeV}. \]

A possibility of loosely bound $D\bar{D}^*$ molecular state?

- Some sort of threshold effect?
Two New $D_{sJ}$ Resonances

**BaBar**

$D_{sJ}(2317) \rightarrow D_s \pi^0$

**Belle**

$D_{sJ}(2457) \rightarrow D_s^* \pi^0$

<table>
<thead>
<tr>
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<th>$D_{sJ}(2317)$</th>
<th>$D_{sJ}(2457)$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Belle</strong></td>
<td>$2317.2 \pm 0.5 \pm 0.9$</td>
<td>$2456.5 \pm 1.3 \pm 1.3$</td>
</tr>
<tr>
<td><strong>BaBar</strong></td>
<td>$2317.3 \pm 0.4 \pm 0.8$</td>
<td>$2458.0 \pm 1.0 \pm 1.0$</td>
</tr>
<tr>
<td><strong>CLEO</strong></td>
<td>$2318.5 \pm 1.2 \pm 1.1$</td>
<td>$2463.1 \pm 1.7 \pm 1.2$</td>
</tr>
</tbody>
</table>

Widths less than 7 MeV for both states
Spin Parity Assignment

- \( D_{sJ}(2317) \) is \( 0^+ \)
  - \( D_{sJ}(2317) \rightarrow D_s(1969)\pi^0 \) has flat decay angle distribution
    BaBar
  - \( D_s(1969)\gamma \) and \( D_s(1969)\pi^+\pi^- \) not seen Belle

- \( D_{sJ}(2457) \) is consistent with \( 1^+ \)
  - \( D_{sJ}(2457) \rightarrow D_s(1969)\gamma \) is seen: rules out \( 0^+ \) and \( 0^- \) Belle
  - \( D_{sJ}(2457) \rightarrow D_s(1969)\pi^0 \) not seen: \( 1^- \) not likely Belle
  - \( B \rightarrow D_{sJ}(2457)D \) is seen: angular distr consistent with
    \( J = 1 \) Belle
Comparison with Potential Model


- Only mystery is the light masses. Spin-parity consistent with potential model. Narrow because the masses are below $D^{(*)}K$ threshold.
Interpretation with Chiral Symmetry


\[ m(0^+) - m(0^-) = 348 \text{ MeV} \]
\[ m(1^+) - m(1^-) = 345 \text{ MeV} \]

- All \( j_q = 1/2 \) masses are degenerate in the limit of \( m_c \rightarrow \infty \) and \( m_q \rightarrow 0 \)
- Mass-splitting occurs for finite \( m_c \) and \( m_q \)
  keeping a relation \( m(0^+) - m(0^-) = m(1^+) - m(1^-) \)
- Agrees well with observation
$D^0 \rightarrow \phi \gamma \ (85 \times 10^6 B\bar{B})$

- Flavor-changing radiative decay of $D$ meson
  - Long-distance effect should dominate but large uncertainty in estimation ($(0.04 - 3.4) \times 10^{-4}$)
  - Short distance effect in SM is small ($< 10^{-8}$)

- Important information for long-distance effect of $B(B \rightarrow X_d \gamma)$, thus for $V_{td}$ extraction.
Simultaneous Selection of $D^0 \to \phi\gamma, \phi\pi^0, \phi\eta$

$D^0 \to \phi\pi^0, \phi\eta$ are the major background.

- $1254 \pm 39 \ D^0 \to \phi\pi^0$ signal events
  
  ![Graph](image1)

- $31.1 \pm 9.8 \ D^0 \to \phi\eta$ signal events
  
  ![Graph](image2)

- $\cos^2 \theta_{\text{hel}}$ as expected for $P \to VP$

- $\mathcal{B}(D^0 \to \phi\eta) = (1.48 \pm 0.47 \pm 0.09) \times 10^{-4}$

- $\mathcal{B}(D^0 \to \phi\pi^0) = (8.01 \pm 0.26 \pm 0.47) \times 10^{-4}$
$D^0 \rightarrow \phi \gamma$ Result

$M(\phi\gamma)$ distribution
white dot: total background
dark: $\phi\pi^0$ background

Helicity angle distribution
white: $\phi\gamma$ signal
light: $\phi\pi^0$ background
dark: non-$\phi\gamma$ background

line of (c): MC

$B(D^0 \rightarrow \phi\gamma) = (2.60^{+0.70+0.15}_{-0.61-0.17}) \times 10^{-5}$

Evidence for significant long-distance contributions.
\( D^0 \bar{D}^0 \) Mixing

\[
x = \frac{\Delta m_D}{\Gamma_D} \leq 10^{-3} \text{ in SM box-diagram}
\]

- GIM cancellation for \( d \) and \( s \)
- Cabbibo suppression for \( b \)

\[
y = \frac{\Delta \Gamma_D}{2 \Gamma_D} \leq 10^{-3} \text{ (long distance effects)}
\]

**New physics signatures**

- \( |x| \gg |y| \)
- CP violation from \( x-y \) or \( x \)-decay interferences.

**Experimental approaches**

- Timed -dependence of “Wrong sign” \( D^0 \) decay (in progress)
- Effective lifetime of \( D^0 \) and \( \bar{D}^0 \) decaying to flavour specific states and CP states
Flavour Tagged $D^0(\bar{D}^0)$ Decays

$D^{*+} \rightarrow D^0 + \pi^+_s$ (tag)

$\leftarrow K^-\pi^+$ (CFD) “Right Sign”

$\leftarrow K^+\pi^-$ (DCSD) “Wrong Sign”

$\leftarrow \bar{D}^0 \rightarrow K^+\pi^-$ (MIX) “Wrong Sign”

Time-integrated Wrong Sign Rate:

$$R_{WS} = \frac{R_{DCSD} + R_{MIX}}{R_{CFD}} \approx 0.37\%$$

Established with better than 10% precision by Belle, BaBar, CLEO, FOCUS. Next step is to isolate $R_{MIX}$. 
\[ R_{WS} = R_{DCSD} + y'\sqrt{R_{DCSD}} + \frac{1}{2}(x'^2 + y'^2), \quad (R_{MIX} = \frac{1}{2}(x'^2 + y'^2)) \]

\[ R_{WS}(t) = \left[ R_{DCSD} + y'\sqrt{R_{DCSD}} \cdot \Gamma t + \frac{1}{4}(x'^2 + y'^2)\Gamma^2 t^2 \right] e^{-\Gamma t} \]

- \( x \) and \( y \) modified by \( \delta \) (strong phase dif. of DCSD and CFD)
  
  \[ x' = x \cos \delta + y \sin \delta \]
  \[ y' = y \cos \delta - x \sin \delta \]

- Isolate \( R_{MIX} \) using \( R_{WS}(t) \).

- Once non-zero \( R_{MIX} \) is established, measure CP violation.

From \( D^0(\bar{D}^0) \) data:

\[ x' \rightarrow x'\sqrt{1 \pm A_M}, \quad y' \rightarrow y'\sqrt{1 \pm A_M} \]

\[ \delta \rightarrow \delta \pm \phi \]

\( A_M, \phi \): real-value parameters describing CP violation
Lifetime Difference Measurements

\[ y_{CP} \equiv \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 \sim y \cos \phi - \left( \frac{|q|^2 - |p|^2}{|q|^2 + |p|^2} \right) x \sin \phi \]

- \( \tau(K^-\pi^+) \equiv (\tau(D^0 \to K^-\pi^+) + \tau(\bar{D}^0 \to K^+\pi^-))/2 \) (flavor-specific state)

- \( \tau(K^+K^-) \equiv (\tau(D^0 \to K^+K^-) + \tau(\bar{D}^0 \to K^+K^-))/2 \) (CP-even states)

- \( y_{CP} \to 0 \) for no mixing, \( y_{CP} \to y \) for no CPV

\[ A_{\Gamma} \equiv \frac{\tau(D^0 \to K^-K^+) - \tau(\bar{D}^0 \to K^-K^+)}{\tau(D^0 \to K^-K^+)} \sim (\frac{|q|^2 - |p|^2}{|q|^2 + |p|^2}) y \cos \phi - x \sin \phi \]

- \( A_{\Gamma} \to 0 \) for no mixing, \( A_{\Gamma} \to \left( \frac{|q|^2 - |p|^2}{|q|^2 + |p|^2} \right) y \) for no CPV
• $y_{CP} = (1.15 \pm 0.69 \pm 0.38)\%$ (Belle, hep-ex/0308034)
  
  $(0.8 \pm 0.4^{+0.5}_{-0.4})\%$ (BaBar, PRL 91, 121801 (2003))

  Consistent with zero.

• $A_{\Gamma} = (-0.20 \pm 0.63 \pm 0.30)\%$ (Belle, hep-ex/0308034)

  $\tau(K^-\pi^+)/\tau(K^-K^+)\cdot A_{\Gamma} = (-0.8\pm0.6\pm0.2)\%$ (BaBar, PRL 91, 121801(2003))

  Consistent with zero.
LFV Decays $\tau \to \mu \gamma$, $\tau \to \mu \mu \mu$

**“SM”**

$\tau \to \mu \gamma$

$\tau \to \mu \mu \gamma$

**SUSY with $\gamma$**

$\tau \to \mu \gamma$

**Higgs-mediation:**

$$\frac{\mathcal{B}(\tau \to \mu \mu \mu)}{\mathcal{B}(\tau \to \mu \gamma)} \approx 0.003 \text{ (no Higgs mediation)}$$

$$\mathcal{B}(\tau \to \mu \mu \mu) \approx 1 \times 10^{-7} \left(\frac{\tan \beta}{60}\right)^6 \times \left(\frac{100 \text{ GeV}}{m_A}\right)^4$$

As large as $10^{-7}$, within reach of B factory

**SUSY with higgs**

$h^0, H^0, A^0 \to \mu^+ \mu^-$
$\tau \to \mu \gamma$ candidates

$\tau \to l l l$ candidates

- Upper limits with $87 fb^{-1}$
  
  $\mathcal{B}(\tau \to \mu \gamma) < 3.1 \times 10^{-7}$ (90% C.L.)
  
  $\mathcal{B}(\tau^- \to l^- l^+ l^-) < (1.9 - 3.5) \times 10^{-7}$

- Order of magnitude improvement over next several years
Electric Dipole Moment of $\tau$ Lepton

8 different $\tau$ decay modes

$$(e\nu\bar{\nu})(\mu\nu\bar{\nu}) \quad (e\nu\bar{\nu})(\pi\nu) \quad (\pi\nu)(\pi\nu)$$

$$(\mu\nu\bar{\nu})(\pi\nu) \quad (\pi\nu)(\rho\nu) \quad (e\nu\bar{\nu})(\rho\nu)$$

$$(\mu\nu\bar{\nu})(\rho\nu)$$

"measure" $\vec{p}$, $\vec{k}$, $\vec{S}_+$, and $\vec{S}_-$

Spin density matrix including $d_\tau$

$$M_{\text{prod}}^2 = M_{\text{SM}}^2 + \text{Re}(d_\tau)M_{\text{Re}}^2 + \text{Im}(d_\tau)M_{\text{Im}}^2 + |d_\tau|^2 M^2 \{d^2\}$$

Determine the probabilities of each event being $M_{\text{SM}}^2$, $M_{\text{Re}}^2$, $M_{\text{Im}}^2$

New physics possibilities at $|d_\tau| \sim 10^{-19}$ ecm

Huang, Lu, Tao, PRD 55 (1997) 1643,

(Limit on $\mu \rightarrow e\gamma$ implies $|d_\tau| < 2.2 \times 10^{-25}$ ecm. But model dependent)
Results with $29 fb^{-1}$

$\text{Re}(d_\tau) = (1.15 \pm 1.70) \times 10^{-17}\text{ecm}$

$\text{Im}(d_\tau) = (-0.83 \pm 0.86) \times 10^{-17}\text{ecm}$

$\times 10$ improvement over previous direct measurements from LEP and ARGUS
Summary

- Several important findings from Belle’s charm studies
  - NRQCD description of $e^+e^- \rightarrow J/\psi + X$ is not satisfactory.
  - Observation of $\eta_c'(3594)$. Good agreement with potential models.
  - Detailed studies of $D_{sJ}(2317)$ and $D_{sJ}(2457)$. Spin-parity assignment of $D_{sJ}(2457)$ is $1^+$. 
  - Discovery of $X(3820)$. Difficulty for fitting into potential model scheme. New type of state?
  - Observation of the first FCNC $D^0$ decay.

- Sensitivity reach for new physics from $\tau$ is approaching an interesting region
  - $\tau \rightarrow \mu\mu\mu$ limit is within reach of some type of SUSY models.
  - $d_\tau$ limit is another factor of 100 away from some type of SUSY models.
Backup: $J/\psi$ Angular Distribution

\[ B \rightarrow K X(3872) \rightarrow J/\psi + (\pi \pi) \]

If $X(3872)$ is $1^{+-}$
\[ \frac{dN}{d \cos \theta_{J/\psi}} \propto \sin^2 \theta \]

$1^{+-}(h_c')$ is ruled out
Backup: $D_{sJ}(2457) \rightarrow D_s \gamma$ Helicity Distribution

$B \rightarrow D D_{sJ}(2457) \hookrightarrow D_s \gamma$

$\theta_{D_s \gamma}$: between $D_{sJ}(2457)$ momentum in $B$ rest frame and $D_s$ momentum in $D_{sJ}(2457)$ rest frame

solid line: $J = 1$ hypothesis
dotted line: $J = 2$ hypothesis

Belle, PRL 91 (2003) 262002
Backup: Observation of $D_{sJ}(2457) \to D_s \gamma, \; D_s \pi^+ \pi^-$