Results on $R_c$ from Belle, BaBar and CLEO

Galina Pakhlova
ITEP, Belle collaboration
Historical remarks on inclusive measurements

\( \psi \) states were discovered at \( e^+e^- \) colliders

- \( \psi(4415) \) MARK-I 1976, DASP 1978
- \( \psi(3770) \) MARK-I 1977, DELCO 1978, MARK-II 1980, BESII 2005
- \( \psi(4040) \) and \( \psi(4160) \) DASP 1978

Total cross section \( e^+e^- \rightarrow \) hadrons

Crystal Ball 1986
BESII 2005
CLEO 2009
Exclusive measurements of $\psi$ state decays

- Only $\psi(3770)$ non-DD decays problem

- The single measurement of D and D* meson production at $E_{cm} = 4.028$ GeV Phys.Lett.B 69, 503 1977

- The single measurement of $\Lambda_c$ production at $E_{cm} = 5.2$ GeV Phys.Rev. Lett. 44, 10 1980


  All possible two-body decays of $\psi(3770)$, $\psi(4040)$, $\psi(4160)$, $\psi(4415)$

  model-dependent results
Luminosity at B factories

> 1 ab$^{-1}$
On resonance:
$Y(5S)$: 121 fb$^{-1}$
$Y(4S)$: 711 fb$^{-1}$
$Y(3S)$: 3 fb$^{-1}$
$Y(2S)$: 24 fb$^{-1}$
$Y(1S)$: 6 fb$^{-1}$
Off res./scan:
$\sim$ 100 fb$^{-1}$

$\sim$ 550 fb$^{-1}$
On resonance:
$Y(4S)$: 433 fb$^{-1}$
$Y(3S)$: 30 fb$^{-1}$
$Y(2S)$: 14 fb$^{-1}$
Off resonance:
$\sim$ 54 fb$^{-1}$

Not only B-Factories but Charm-Factories as well

07.10.2011

QWG 2011 - 8th International Workshop on Heavy Quarkonium
<table>
<thead>
<tr>
<th>State</th>
<th>m (MeV)</th>
<th>Γ (MeV)</th>
<th>J^{PC}</th>
<th>Process (mode)</th>
<th>Experiment (νσ)</th>
<th>Year</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(3872)</td>
<td>3871.5 ± 0.20</td>
<td>1.3 ± 0.6</td>
<td>1^{++}/2^{−−}</td>
<td>B → K(π^{+}π^{−}J/ψ)</td>
<td>Belle [85, 86] (12.8), BABAR [87] (8.6)</td>
<td>2003</td>
<td>OK</td>
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<td></td>
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<td>p → (π^{+}π^{−}J/ψ) + ...</td>
<td>CDF [88–90] (np), DØ [91] (5.2)</td>
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<td>B → K(ωJ/ψ)</td>
<td>Belle [92] (4.3), BABAR [93] (4.0)</td>
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<td></td>
<td>B → K(D^{0}D^{0})</td>
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<td>B → K(γJ/ψ)</td>
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<td>B → K(γ(2S))</td>
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<tr>
<td>X(3915)</td>
<td>3915.6 ± 3.1</td>
<td>28 ± 10</td>
<td>0/2^{++}</td>
<td>B → K(ωJ/ψ)</td>
<td>Belle [100] (8.1), BABAR [101] (19)</td>
<td>2004</td>
<td>OK</td>
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<td></td>
<td>e^{+}e^{-} → e^{+}e^{-}(ωJ/ψ)</td>
<td>Belle [102] (7.7)</td>
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<td></td>
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<td></td>
<td>e^{+}e^{-} → J/ψ(2D^{*})</td>
<td>Belle [103] (6.0)</td>
<td>2007</td>
<td>NC!</td>
</tr>
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<td>Belle [54] (5.0)</td>
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<tr>
<td>G(3900)</td>
<td>3943 ± 21</td>
<td>52 ± 11</td>
<td>1^{−−}</td>
<td>e^{+}e^{-} → γ(DD)</td>
<td>BABAR [27] (np), Belle [21] (np)</td>
<td>2007</td>
<td>OK</td>
</tr>
<tr>
<td>Y(4008)</td>
<td>4008^{+121}_{−49}</td>
<td>226±97</td>
<td>1^{−−}</td>
<td>e^{+}e^{-} → γ(π^{+}π^{−}J/ψ)</td>
<td>Belle [104] (7.4)</td>
<td>2007</td>
<td>NC!</td>
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<tr>
<td>Z_{1}(4050)^{+}</td>
<td>4051^{+24}_{−43}</td>
<td>82^{+51}_{−55}</td>
<td>?</td>
<td>B → K(π^{+}X_{c1}(1P))</td>
<td>Belle [105] (5.0)</td>
<td>2008</td>
<td>NC!</td>
</tr>
<tr>
<td>Y(4140)</td>
<td>4143 ± 3.0</td>
<td>15 ± 11</td>
<td>?^{++}</td>
<td>B → K(φJ/ψ)</td>
<td>CDF [106, 107] (5.0)</td>
<td>2009</td>
<td>NC!</td>
</tr>
<tr>
<td>X(4160)</td>
<td>4156^{+29}_{−25}</td>
<td>139^{+113}_{−65}</td>
<td>?^{++}</td>
<td>e^{+}e^{-} → J/ψ(2D^{*})</td>
<td>Belle [103] (5.5)</td>
<td>2007</td>
<td>NC!</td>
</tr>
<tr>
<td>Z_{2}(4250)^{+}</td>
<td>4248^{+185}_{−45}</td>
<td>177^{+321}_{−72}</td>
<td>?</td>
<td>B → K(π^{+}X_{c1}(1P))</td>
<td>Belle [105] (5.0)</td>
<td>2008</td>
<td>NC!</td>
</tr>
<tr>
<td>Y(4260)</td>
<td>4263 ± 5</td>
<td>108 ± 14</td>
<td>1^{−−}</td>
<td>e^{+}e^{-} → γ(π^{+}π^{−}J/ψ)</td>
<td>BABAR [108, 109] (8.0)</td>
<td>2005</td>
<td>OK</td>
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<td>CLEO [110] (5.4)</td>
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<td>Belle [104] (15)</td>
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<td>CLEO [111] (11)</td>
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<td></td>
<td>CLEO [111] (5.1)</td>
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<tr>
<td>Y(4274)</td>
<td>4274.4 ± 6.7</td>
<td>32 ± 15</td>
<td>?^{++}</td>
<td>B → K(φJ/ψ)</td>
<td>CDF [107] (3.1)</td>
<td>2010</td>
<td>NC!</td>
</tr>
<tr>
<td>X(4350)</td>
<td>4356^{+146}_{−51}</td>
<td>13.3^{+18.4}_{−10.9}</td>
<td>0.2^{++}</td>
<td>e^{+}e^{-} → e^{+}e^{-}(φJ/ψ)</td>
<td>Belle [112] (3.2)</td>
<td>2009</td>
<td>NC!</td>
</tr>
<tr>
<td>Y(4360)</td>
<td>4353 ± 11</td>
<td>96 ± 42</td>
<td>1^{−−}</td>
<td>e^{+}e^{-} → γ(π^{+}π^{−}ψ(2S))</td>
<td>BABAR [113] (np), Belle [114] (8.0)</td>
<td>2007</td>
<td>OK</td>
</tr>
<tr>
<td>Z(4430)^{+}</td>
<td>4443^{+24}_{−18}</td>
<td>107^{+113}_{−71}</td>
<td>?</td>
<td>B → K(π^{+}ψ(2S))</td>
<td>Belle [115, 116] (6.4)</td>
<td>2007</td>
<td>NC!</td>
</tr>
<tr>
<td>X(4630)</td>
<td>4634^{+11}_{−11}</td>
<td>92^{+113}_{−71}</td>
<td>1^{−−}</td>
<td>e^{+}e^{-} → γ(Λ_{c}^{+}Λ_{c}^{-})</td>
<td>Belle [25] (8.2)</td>
<td>2007</td>
<td>NC!</td>
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<td>Y(4660)</td>
<td>4664 ± 12</td>
<td>48 ± 15</td>
<td>1^{−−}</td>
<td>e^{+}e^{-} → γ(π^{+}π^{−}ψ(2S))</td>
<td>Belle [114] (5.8)</td>
<td>2007</td>
<td>NC!</td>
</tr>
</tbody>
</table>
ISR measurements at B-factories

- Fixed quantum numbers of final state $J^{PC} = 1^{--}$
- Study of open charm final states from threshold in wide energy region
- Huge accumulated luminosity at B factories

- Limited statistics
  - strong electromagnetic suppression
  - typical events topology: fast photon with small $p_t$

- Specific reconstruction methods
  - e.g. $D^+D^- \& D^*D^-$
    - partial reconstruction of $D^-$ to increase efficiency by 10-20
    - reconstruction of ISR photon
    - measurements of recoil mass against $\gamma_{ISR} \equiv$ mass of $D(^*)+D^{*-}$
    - translation of $D(^*)+D^{*-}$ mass spectrum to cross section
  - e.g. $D^+D^-$
    - full reconstruction of hadronic part
    - no reconstruction of ISR photon
Two-body final states
Belle, BaBar, CLEO: \( \sigma(e^+e^- \rightarrow DD) \)

\[ \sigma(nb) \]

\begin{align*}
\text{Belle} & \quad \text{BaBar} \\
\text{e}^+\text{e}^- & \rightarrow D^0 \overline{D}^0 \\
\text{e}^+\text{e}^- & \rightarrow D^+ D^- \\
\end{align*}

\text{CLEO: narrow range 3.97 - 4.26 GeV}
\text{no radiative corrections}
\text{problem of direct comparison with B-factories results}

\begin{itemize}
\item Wide structure near 3.9 GeV
\item agreement with coupled channel model
\item Structure at 4.0 - 4.2 GeV
\item \( \psi(4040)? \ \psi(4160)? \)
\item First hint of \( \psi(4415) \rightarrow DD \)
\end{itemize}
Belle, BaBar, CLEO: $\sigma(e^+e^-\rightarrow D^{(*)}D^{(*)})$

- Good agreement between Belle and BaBar
- Belle measurements more accurate than BaBar

CLEO: $3.97 - 4.26$ GeV
- no radiative correction
- problem of direct comparison with B-factories results
Problems

- Cross sections of *charm strange mesons* were found to be order of magnitude less than cross sections of $D^{(*)}D^{(*)}$
- $D_s^* \rightarrow D_s \gamma_{\text{slow}}$
  - very low efficiency of soft photons at threshold
  - multiple counting due to lots of soft photons in event
Belle measurements of $e^+e^- \rightarrow D_s^{(*)+}D_s^{(*)-}$

*Full reconstruction method similar to DD*

- $D_s^{+}D_s^{-}$ peak at threshold near $\psi(4040)$
- $D_s^{+}D_s^{*-}$ peak at threshold near $\psi(4160)$ and $\psi(4415)$
- Dip near $Y(4260)$ mass
Belle, BaBar, CLEO: $e^+e^- \rightarrow D_s^{(*)}+D_s^{(*)-}$

**BaBar**: Bin size of 100 MeV is too large to observe relatively narrow structures

**Belle & BaBar** are in agreement within errors

**CLEO**: 3.97 - 4.26 GeV

*no radiative corrections*
Three-body final states

$D^0 D^{(*)-} \pi^+$

Full reconstruction method
Cross section of $e^+e^- \rightarrow D^0D^-\pi^+$

$\psi(4415) \rightarrow D^0D^-\pi^+$

$\sigma(e^+e^- \rightarrow \psi(4415)) \times Br(\psi(4415) \rightarrow DD_2(2460)) \times Br(D_2(2460) \rightarrow D\pi) = (0.74 \pm 0.17 \pm 0.07)\text{nb}$

$\text{Br}(\psi(4415) \rightarrow D(D\pi)_{\text{non } D_2(2460)}/\text{Br}(\psi(4415) \rightarrow DD_2(2460)) < 0.22$

$M = 4411 \pm 7 \text{ MeV}$

$\Gamma_{\text{tot}} = 77 \pm 20 \text{ MeV}$

$N_{\text{ev}} = 109 \pm 25$

In agreement with BES


PDG06, Barnes et al

Cross section of $e^+e^- \rightarrow D^0D^{*-}\pi^+$

Upper limit

$\psi(4415)$

$\sigma(e^+e^- \rightarrow \psi(4415)) \times Br(\psi(4415) \rightarrow D^0D^{*-}\pi^+) < 0.76 \text{ nb at 90\% CL}$

$Br(\psi(4415) \rightarrow D^0D^{*-}\pi^+) < 10.6 \% \text{ at 90\% CL}$

<table>
<thead>
<tr>
<th>UL at 90% CL</th>
<th>$Y(4260)$</th>
<th>$Y(4350)$</th>
<th>$Y(4660)$</th>
<th>$X(4630)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sigma(e^+e^- \rightarrow X) \times B(X \rightarrow D^0D^{*-}\pi^+)$, [nb]</td>
<td>0.36</td>
<td>0.55</td>
<td>0.25</td>
<td>0.45</td>
</tr>
<tr>
<td>$B_{ee} \times B(X \rightarrow D^0D^{*-}\pi^+)$, [$\times 10^{-6}$]</td>
<td>0.42</td>
<td>0.72</td>
<td>0.37</td>
<td>0.66</td>
</tr>
<tr>
<td>$B(X \rightarrow D^0D^{*-}\pi^+)/B(X \rightarrow \pi^+\pi^-J/\psi)$</td>
<td>9</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B(X \rightarrow D^0D^{*-}\pi^+)/B(X \rightarrow \pi^+\pi^-\psi(2S))$</td>
<td></td>
<td>8</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>
First final state with charm baryons

\[ e^+e^- \rightarrow \Lambda_c^+\Lambda_c^- \]

\[ X(4630) \equiv Y(4660)? \quad J^{PC}=1^{--} \]

<table>
<thead>
<tr>
<th>State</th>
<th>M, MeV/c^2</th>
<th>\Gamma_{tot}, MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>X(4630)</td>
<td>4634^{+8+5}_{-7-8}</td>
<td>92^{+40+10}_{-24-21}</td>
</tr>
<tr>
<td>Y(4660)</td>
<td>4664 \pm 11 \pm 5</td>
<td>48 \pm 15 \pm 3</td>
</tr>
</tbody>
</table>

- \( \psi(5S) \) or \( \psi(4D) \) \quad J.Segovia, al
- \( \psi(6S) \) \quad B.Q.Li and K.T.Chao
- influence of \( \psi(3D) \) \quad E.Beveren, G.Rupp
- \( \psi(2S)f_0(980) \) molecule \quad F.K.Guo et al
- tetraquark \quad D.Ebert et al
- hexaquark \quad M.Abud,F.Bucella, F.Tramontano
- charm baryonium \quad G.Gotugno, R.Faccini, A.Polosa
- baryon-antibarion production via \( \psi(4S) \) intermediate state

Yu.Simonov hep-ph 1109.5545

07.10.2011
Exclusive cross sections contribution to the total cross section

Contributions of $D^+D^*$, $D^*+D^*$, $D^0D^-\pi^+$ and $D^0D^*-\pi^+$ are scaled following isospin symmetry
In conclusion...
Search for charmonium-like states

Y family

- no peaks near Y states mass in exclusive open charm cross sections
  - X(4630) ?
- minima near Y(4260) mass in cross sections of $e^+e^- \rightarrow D^*+D^{*-}$, $D_s^*(*)+D_s^{(*)-}$

- predictions of dominant decays of $Y(4260) \rightarrow DD^{(*)}\pi$ were not confirmed

X(4630)

- quantum numbers, mass and width are in agreement with $Y(4660)$
  - does not mean that $X(4630) \equiv Y(4660)$
- lots of interpretations – absence of clear understanding of X(4630) nature
Status and perspectives

- Almost all measured cross sections are included into Durham Hep Data Base.
- Parameters and branchings of observed decays of $\psi(4415)$, $\sigma(\text{ee} \rightarrow \text{D}^0\text{D}^0)/\sigma(\text{ee} \rightarrow \text{D}^+\text{D}^-)$ for $\psi(3770)$, upper limits on $Y \rightarrow \text{DD}^*\pi$ are included to PDG tables.

Obtained results are important for physical programs of experiments at $e^+e^-$ colliders:
- KEDR at VEPP-4M
- BESIII at BEPCII
- c-$\tau$ factory in Novosibirsk
- Belle II at SuperKEKB

- ... and for theory
Thank you!