$R_c$ measurement at B-factories

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Belle collaboration
Historical remarks on inclusive measurements

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

\( \psi(4415) \) \hspace{1em} \text{MARK-I 1976, DASP 1978}

\( \psi(3770) \) \hspace{1em} \text{MARK-I 1977, DELCO 1978, MARK-II 1980, BESII 2005}

\( \psi(4040) \) and \( \psi(4160) \) \hspace{1em} \text{DASP 1978}

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

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*

Resonance shapes $E_{cm}(\text{GeV})$ Interference term $R_{res}=R_{BW}+R_{int}$
Luminosity at B factories

Not only B-Factories but Charm-Factories as well

On resonance:
- $\Upsilon(5S)$: 121 $\text{fb}^{-1}$
- $\Upsilon(4S)$: 711 $\text{fb}^{-1}$
- $\Upsilon(3S)$: 3 $\text{fb}^{-1}$
- $\Upsilon(2S)$: 24 $\text{fb}^{-1}$
- $\Upsilon(1S)$: 6 $\text{fb}^{-1}$

Off resonance:
- $\sim 100$ $\text{fb}^{-1}$
- $\sim 550$ $\text{fb}^{-1}$
<table>
<thead>
<tr>
<th>State</th>
<th>$m$ (MeV)</th>
<th>$\Gamma$ (MeV)</th>
<th>$J^{PC}$</th>
<th>Process (mode)</th>
<th>Experiment (#$\sigma$)</th>
<th>Year</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(3872)$</td>
<td>3871.52±0.20</td>
<td>1.3±0.6</td>
<td>$1^{++}/2^{-+}$</td>
<td>$B \to K(\pi^+\pi^-J/\psi)$</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>(&lt;2.2)</td>
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<td>$p\bar{p} \to (\pi^+\pi^-J/\psi) + ...$</td>
<td>CDF [88-90] (np), DØ [91] (5.2)</td>
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<td>$B \to K(\omega J/\psi)$</td>
<td>Belle [92] (4.3), BABAR [93] (4.0)</td>
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<td>$B \to K(D^{0*}D^0)$</td>
<td>BABAR [94, 95] (6.4), BABAR [96] (4.9)</td>
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<td>$B \to K(\gamma J/\psi)$</td>
<td>BABAR [92] (4.0), BABAR [97, 98] (3.6)</td>
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<td>$B \to K(\gamma(2S))$</td>
<td>BABAR [98] (3.5), Belle [99] (0.4)</td>
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<td>$X(3915)$</td>
<td>3915.6 ± 3.1</td>
<td>28±10</td>
<td>0/2$^+$</td>
<td>$B \to K(\omega J/\psi)$</td>
<td>Belle [100] (8.1), BABAR [101] (19)</td>
<td>2004</td>
<td>OK</td>
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<td>$e^+e^- \to e^+e^- (\omega J/\psi)$</td>
<td>Belle [102] (7.7)</td>
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<td>$e^+e^- \to J/\psi(DD^*)$</td>
<td>Belle [103] (6.0)</td>
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<td>$e^+e^- \to J/\psi (...)$</td>
<td>Belle [54] (5.0)</td>
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<td>$G(3900)$</td>
<td>3943 ± 21</td>
<td>52±11</td>
<td>1$^-$</td>
<td>$e^+e^- \to \gamma(DD)$</td>
<td>BABAR [27] (np), Belle [21] (np)</td>
<td>2007</td>
<td>NC!</td>
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<td>$Y(4008)$</td>
<td>4008$^{+121}_{-49}$</td>
<td>226±97</td>
<td>1$^-$</td>
<td>$e^+e^- \to \gamma(\pi^+\pi^-J/\psi)$</td>
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<td>$Z_1(4050)^+$</td>
<td>4051$^{+24}_{-43}$</td>
<td>82$^{+51}_{-35}$</td>
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<td>$B \to K(\pi^+\chi_c(1P))$</td>
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<td>$Y(4140)$</td>
<td>4143.4 ± 3.0</td>
<td>15$^{+11}_{-7}$</td>
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<td>$B \to K(\phi J/\psi)$</td>
<td>BABAR [104] (7.4)</td>
<td>2007</td>
<td>NC!</td>
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<td>$X(4160)$</td>
<td>4156$^{+29}_{-25}$</td>
<td>139$^{+113}_{-65}$</td>
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<td>$e^+e^- \to J/\psi(DD^*)$</td>
<td>CDF [106, 107] (5.0)</td>
<td>2009</td>
<td>NC!</td>
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<td>$Z_2(4250)^+$</td>
<td>4248$^{+185}_{-45}$</td>
<td>177$^{+321}_{-72}$</td>
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<td>$Y(4260)$</td>
<td>4263 ± 5</td>
<td>108±14</td>
<td>1$^-$</td>
<td>$e^+e^- \to \gamma(\pi^+\pi^-J/\psi)$</td>
<td>BABAR [108, 109] (8.0)</td>
<td>2005</td>
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<td>$X(4274)$</td>
<td>4274.4$^{+6.7}_{-6.7}$</td>
<td>32$^{+4}_{-15}$</td>
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<td>CLEO [110] (5.4), Belle [104] (15)</td>
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<td>$X(4350)$</td>
<td>4350.6$^{+14.6}_{-9.2}$</td>
<td>13.3$^{+18.4}_{-10.0}$</td>
<td>0.2$^{++}$</td>
<td>$e^+e^- \to e^+e^- (\phi J/\psi)$</td>
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<td>$Y(4360)$</td>
<td>4353 ± 11</td>
<td>96±42</td>
<td>1$^-$</td>
<td>$e^+e^- \to \gamma(\pi^+\pi^-(2S))$</td>
<td>BABAR [113] (np), Belle [114] (8.0)</td>
<td>2007</td>
<td>OK</td>
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<td>$Z(4430)^+$</td>
<td>4443$^{+13}_{-18}$</td>
<td>107$^{+113}_{-71}$</td>
<td>?</td>
<td>$B \to K(\pi^+\chi_c(1P))$</td>
<td>BABAR [115, 116] (6.4)</td>
<td>2007</td>
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Radiative return in LO

\[
\frac{d\sigma^{(0)}}{dQ^2} = \frac{4\alpha^3}{3s} R(Q^2) \left[ \frac{s^2 + Q^4}{s(s - Q^2)} \ln \frac{1 + \cos \theta_{\text{min}}}{1 - \cos \theta_{\text{min}}} - \frac{s - Q^2}{s} \cos \theta_{\text{min}} \right]
\]
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: $\sigma(e^+e^- \rightarrow DD)$

- Good agreement between Belle и BaBar
- Wide structure near 3.9 GeV
- Agreement with coupled channel model
- Structure at 4.0 - 4.2 GeV
- $\psi(4040)$? $\psi(4160)$?
- First hint of $\psi(4415) \rightarrow DD$

CLEO: narrow range 3.97 - 4.26 GeV
no radiative corrections
problem of direct comparison with B-factories results
Belle, BaBar, CLEO: $\sigma(e^+e^-\rightarrow D(\ast)D(\ast))$

- Good agreement between Belle и 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

The single measurement of CLEO 2009
Energy scan with high accuracy but in narrow region 3.97 - 4.26 GeV

\[ e^+e^- \rightarrow D_s^{(*)}+D_s^{(*)} \]
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 $e^+e^- \rightarrow D^0D^-\pi^+$

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

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

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

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

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

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

In agreement with BES


PDG06, Barnes at.al

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

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

$\text{Br}(\psi(4415)\rightarrow D^0D^{*-}\pi^+)< 10.6\%$ 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>$\sigma(e^+e^-\rightarrow X)\times\mathcal{B}(X\rightarrow D^0D^{*-}\pi^+)$, [nb]</td>
<td>0.36</td>
<td>0.55</td>
<td>0.25</td>
<td>0.45</td>
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<tr>
<td>$\mathcal{B}_{ee}\times\mathcal{B}(X\rightarrow D^0D^{*-}\pi^+)$, [$\times 10^{-6}$]</td>
<td>0.42</td>
<td>0.72</td>
<td>0.37</td>
<td>0.66</td>
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<tr>
<td>$\mathcal{B}(X\rightarrow D^0D^{*-}\pi^+)/\mathcal{B}(X\rightarrow \pi^+\pi^-J/\psi)$</td>
<td>$\bigcirc$9</td>
<td>$\bigcirc$8</td>
<td>$\bigcirc$10</td>
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</table>
First final state with charm baryons

- $\psi(5S)$ or $\psi(4D)$ J.Segovia, A.M.Yasser, D.R.Entem, F.Fernandez
- $\psi(6S)$ B.Q.Li and K.T.Chao
- influence of $\psi(3D)$ E.Beveren, G.Rupp
- $\psi(2S)f_0(980)$ molecule F.K.Gou, C.Hanhart, S.Krewald, U.G.Meissner
- tetraquark D.Ebert, R.N.Faustov, V.O. Galkin
- hexaquark M.Abud, F.Bucella, F.Tramontano
- charm baryonium G.Gotugno, R.Faccini, A.Polosa

<table>
<thead>
<tr>
<th>State</th>
<th>$M$, MeV/c$^2$</th>
<th>$\Gamma_{tot}$, MeV</th>
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<tbody>
<tr>
<td>$X(4630)$</td>
<td>$4634^{+8+5}_{-7-8}$</td>
<td>$92^{+40+10}_{-24-21}$</td>
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<tr>
<td>$Y(4660)$</td>
<td>$4664 \pm 11 \pm 5$</td>
<td>$48 \pm 15 \pm 3$</td>
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22.09.2011
Exclusive cross sections contribution to the total cross section

Contributions of $D^+D^*$, $D^*D^*$, $D^0D^*\pi^+$ and $D^0\bar{D}^-\pi^+$ are scaled following isospin symmetry

22.09.2011
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

22.09.2011
Status and perspectives

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

22.09.2011