Study of Charmonium-(like) states via ISR at Belle

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Outline

• Introduction
• Part I: the $Y$ states via $e^+e^- \rightarrow h^+h^- + \text{charmonium}$
  - $e^+e^- \rightarrow \pi^+\pi^- J/\psi$
  - $e^+e^- \rightarrow \pi^+\pi^- \psi(2S)$
  - $e^+e^- \rightarrow K^+K^- J/\psi$
• Part II: the $\psi$ states via $e^+e^- \rightarrow \text{charmed meson pair}$
  - $e^+e^- \rightarrow DD$
  - $e^+e^- \rightarrow DD^*$
  - $e^+e^- \rightarrow D^*D^*$
  - $e^+e^- \rightarrow DD_2(2460)$
• Summary
The KEKB Collider

World record:
L = 1.7 x 10^{34}/cm^2/sec

Since 1999

Mt. Tsukuba

KEKB

Belle

~ 1 km in diameter
R values/ψ states/Y states

The Y states should also appear in this plot (between 4.0 and 4.7 GeV!)

From PDG
Part I

Y states via $e^+e^- \rightarrow h^+h^- + \text{charmonium}$
$\pi^+\pi^- J/\psi$ Mass

$\mathbf{BaBar:}$

$232 \text{ fb}^{-1}$

$>8\sigma$ significance structure called $Y(4260)$

$M(J/\psi \pi \pi)$ of $\psi(2S)$ with $J/\psi$ constraint is well described by Cauchy shape funct.

- fit with Rel-BW $\times$ PhaseSpace $\otimes$ Reso + 2nd polynomial (BKGD)
- fit-probability ($\chi^2$) is about 2.6%, $N_{\text{events}} = 125 \pm 23$

$m = 4259 \pm 8^{+2}_{-6} \text{ MeV}$

$\Gamma = 88 \pm 23^{+6}_{-4} \text{ MeV}$

$\Gamma(Y \to e^+e^-) \cdot B(Y \to \pi^+\pi^- J/\psi) = 5.5 \pm 1.0^{+0.8}_{-0.7} \text{ eV}$
e^+e^- → ψ' as reference signal

From cross section, one gets partial width to e^+e^-.

Γ_{ee} = 2.54 ± 0.02 ± 0.15 keV

PDG’06

- Γ_{ee} = 2.48 ± 0.06 keV

Belle agrees with other experiments well.

ψ’ sample: Data vs MC

Good agreement between data and MC simulation.

(ISR events & background low & MC reliable)

We used Phokhara
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ via ISR

Clear signal of missed massless particle ($\gamma_{ISR}$)

- Polar angle distribution agrees well with ISR expectation
- Combinatorial background estimated by $J/\psi$ sidebands
- Backgrounds from real ($J/\psi \, \pi\pi$)$_{non \, ISR}$ or $J/\psi \, X_{non \, \pi\pi}$ are negligibly small

Lum=548 fb$^{-1}$

$J/\psi(\rightarrow l^+l^-)+\pi\pi$ + no extra tracks detection of $\gamma_{ISR}$ is not required

$120\pm14$ evts

$324\pm21$ evts

$e^+e^- \rightarrow \pi^+\pi^-J/\psi$ via ISR

- Background subtracted $M(J/\psi\pi\pi)$ corrected for efficiency and differential luminosity
- $M_{\pi\pi}$ spectra in different $\sqrt{s}$ regions:
  - $\sqrt{s} = 3.8 - 4.2$ & $4.4 - 4.6$ GeV in agreement with 3-body phase space
  - $Y(4260)$ region $\sqrt{s} = 3.8 - 4.15$ GeV: two clusters at low and high masses (scalars?)

$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ via ISR

- $\chi^2/\text{ndf} = 93/79$, CL = 13%
- $M = 4263 \pm 6$ MeV
- $\Gamma = 125 \pm 18$ MeV
- $\Gamma_{ee} \times \text{Br} = 9.7 \pm 1.1$ eV (fit errors only)

Background well above sidebands estimation.

Fit with function Babar used. Similar results are got.
$e^+e^- \rightarrow \pi^+\pi^- J/\psi$ via ISR

- Non resonant $J/\psi \pi \pi$?
- Re-scattering $ee \rightarrow D(*)D(*) \rightarrow J/\psi \pi \pi$?
- Another broad state?
  - Check the latter hypothesis and influence of interference of Y(4260) with non-Y contribution:
  - Fit with 2 coherent BWs
  - Two-fold ambiguity in amplitude (constructive-destructive interference) + model uncertainty due to $\psi'$ tail

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Solution I</th>
<th>Solution II</th>
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</thead>
<tbody>
<tr>
<td>$M(R1)$</td>
<td>$4008 \pm 40^{+114}_{-28}$</td>
<td></td>
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<tr>
<td>$\Gamma_{tot}(R1)$</td>
<td>$226 \pm 44 \pm 87$</td>
<td></td>
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<tr>
<td>$\mathcal{B} \cdot \Gamma_{e^+\bar{e}^-}(R1)$</td>
<td>$5.0 \pm 1.4^{+6.1}_{-0.9}$</td>
<td>$12.4 \pm 2.4^{+14.8}_{-1.1}$</td>
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<tr>
<td>$M(R2)$</td>
<td>$4247 \pm 12^{+17}_{-32}$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{tot}(R2)$</td>
<td></td>
<td>$108 \pm 19 \pm 10$</td>
</tr>
<tr>
<td>$\mathcal{B} \cdot \Gamma_{e^+\bar{e}^-}(R2)$</td>
<td>$6.0 \pm 1.2^{+4.7}_{-0.5}$</td>
<td>$20.6 \pm 2.3^{+9.1}_{-1.7}$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$12 \pm 29^{+7}_{-98}$</td>
<td>$-111 \pm 7^{+28}_{-31}$</td>
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$e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ via ISR at BaBar

$\sim 300 \text{fb}^{-1}$

single BW:
$M = (4324 \pm 24) \text{ MeV}$
$\Gamma = (172 \pm 33) \text{ MeV}$

BaBar: B. Aubert et al., PRL98, 212001 (2007)
$e^+e^- \rightarrow \pi^+\pi^-\psi(2S) \text{ via ISR}$

$\psi(\rightarrow J/\psi \pi\pi) + \pi\pi + \text{no extra tracks}$

detection of $\gamma_{\text{ISR}}$ is not required

Similar analysis: efficiency is smaller; bgs are almost negligible

- Clear signal of missed massless particle $(M_{\text{rec}}^2(\psi'\pi\pi)\sim0)$

- Polar angle distribution agrees well with ISR expectation

- Combinatorial background estimated by $\psi'$ sidebands

- Backgrounds from real $(\psi'\pi\pi)_{\text{non ISR}}$ or $\psi'$ $X_{\text{non }\pi\pi}$ are negligibly small

Two significant clusters: One is near BaBar reported enhancement PRL98, 212001 (2007) + NEW at $M \sim 4.7$ GeV

\[ e^+ e^- \rightarrow \pi^+ \pi^- \psi(2S) \text{ via ISR} \]

**Two solutions**

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<th>Solution two</th>
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<tr>
<td>( M(Y(4360)) )</td>
<td>4361 ± 9 ± 9</td>
<td>4364 ± 11 ± 5</td>
</tr>
<tr>
<td>( \Gamma_{\text{tot}}(Y(4360)) )</td>
<td>74 ± 15 ± 10</td>
<td>48 ± 15 ± 3</td>
</tr>
<tr>
<td>( \mathcal{B} \cdot \Gamma_{e^+ e^-}(Y(4360)) )</td>
<td>10.4 ± 1.7 ± 1.5</td>
<td>11.8 ± 1.8 ± 1.4</td>
</tr>
<tr>
<td>( M(Y(4660)) )</td>
<td>4664 ± 11 ± 5</td>
<td>4664 ± 11 ± 3</td>
</tr>
<tr>
<td>( \Gamma_{\text{tot}}(Y(4660)) )</td>
<td>48 ± 15 ± 3</td>
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</tr>
<tr>
<td>( \mathcal{B} \cdot \Gamma_{e^+ e^-}(Y(4660)) )</td>
<td>3.0 ± 0.9 ± 0.3</td>
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</tr>
<tr>
<td>( \phi )</td>
<td>39 ± 30 ± 22</td>
<td>-79 ± 17 ± 20</td>
</tr>
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Y(4360) – consistent with BaBar
Y(4660) – NEW (5.8\( \sigma \))
\( e^+e^- \rightarrow K^+K^-J/\psi \) via ISR

- CLEO-c observed 3 \( K^+K^-J/\psi \) at \( E_{cm}=4.26 \) GeV and assumed from \( Y(4260) \)

- Belle: first observation of \( e^+e^- \rightarrow J/\psi K^+K^- \) and evidence for \( e^+e^- \rightarrow J/\psi K_SK_S \)

\[
\sigma(e^+e^- \rightarrow J/\psi K_SK_S)/ \sigma(e^+e^- \rightarrow J/\psi K^+K^-) = 0.6^{+0.5}_{-0.4}
\]

Consistent with isospin (0.5)

Belle: C.Z.Y & C.P. Shen et al., arXive:0709.2565
$e^+e^- \rightarrow K^+K^-J/\psi$ via ISR

KK invariant mass tends to be large!

Belle:  C.Z.Y & C.P. Shen et al., arXiv:0709.2565
$e^+e^- \rightarrow K^+K^-J/\psi$ via ISR

New resonance or just continuum production, or other mechanism?

PDG $\psi(4415)$ + 1 BW:
$M = (4875\pm132)$ MeV
$\Gamma = (630\pm126)$ MeV

Single BW:
$M = (4430\pm38)$ MeV
$\Gamma = (254\pm49)$ MeV

$\Gamma \left( Y(4260) \rightarrow e^+e^- \right) \cdot B \left( Y \rightarrow K^+K^-J/\psi \right) < 1.2$ eV @ 90% C.L.

Belle: C.Z.Y & C.P. Shen et al., arXive:0709.2565
$\pi^+\pi^- J/\psi, \pi^+\pi^-\psi(2S), \text{ and } K^+K^- J/\psi$
Part II

e^+e^- → charmed meson pair
**exclusive \( \text{e}^+\text{e}^- \rightarrow D(*)D(*) \) cross-sections via ISR**

**Method**
- Hard ISR photon takes away significant fraction of energy
- Continuous ISR spectrum: access to whole \( \sqrt{s} \) interval
- \( \alpha_{\text{em}} \) suppression, but \( \sim 700/\text{fb} \) at Belle vs \( \sim 60/\text{pb} \) CLEO-c

**The first measurement:**
Belle: \( D^*+D^*-, D^+D^- \) with **partial reconstruction**
- Increase eff \( \sim 10-20 \) times
- Narrow peak in recoil mass difference
  \( M_{\text{rec}}(D^*+\gamma_{\text{ISR}}) - M_{\text{rec}}(D^*+\pi\gamma_{\text{ISR}}) \), because of cancelation of momentum smearing
  - Tight \( \Delta M_{\text{rec}} \) cut \( \Rightarrow \) small background

Belle: G. Pakhlova et al., PRL98, 092001 (2007)
Exclusive $e^+e^- \rightarrow D^{(*)}D^{(*)}$ cross-sections

- $ee \rightarrow D^*D^{(*)}$ with partial reconstruction: $D^{(*)} + \gamma_{ISR} + \pi_{slow}$ (from unreconstructed $D^*$)
- Use recoil mass difference to suppress bgs
- Use kinematic constraint $M_{recoil}(D^* \gamma_{ISR}) \rightarrow M_D$ to improve resolution

$\times 2$ to account for neutral $D^*D^{(*)}$

Belle: G. Pakhlova et al., PRL98, 092001 (2007)
Exclusive $e^+e^- \rightarrow D(\ast)D(\ast)$ cross-sections


Charged $D(\ast)D(\ast)$
$\frac{1}{2}$ from CLEOc

$\psi(4040)$ signal
$D^\ast D :$ hint, but not significant
$D^\ast D^* :$ clear dip (similar to inclusive $R$)

PRELIMINARY
$e^+e^- \rightarrow DD$ at $\sqrt{s} \sim 3.7-5$ GeV via ISR

- $D^0D^0$ or $D^+D^-$ + no extra tracks
  - detection of $\gamma_{\text{ISR}}$ is not required
  - if $\gamma_{\text{ISR}}$ is detected, $M(DD\gamma_{\text{ISR}})$ is required $\sim E_{\text{cm}}$

- Combinatorial background are estimated from D sidebands
- Other backgrounds are small and are taken into account

Belle: G. Pakhlova et al., arXiv:0708.0082
$e^+e^- \rightarrow DD$ at $\sqrt{s} \sim 3.7-5$ GeV via ISR

$M(DD)$ is in a qualitative agreement with BaBar

Belle: G. Pakhlova et al., arXiv:0708.0082

BaBar
arXiv:0710.1371

Y(4260) signal
DD: no signal
Broad structure around 3.9 GeV is in qualitative agreement with coupled-channel model. 


Cross section above 4 GeV has a similar shape to those measured for $e^+e^- \rightarrow D^*D^*$?

Belle: G. Pakhlova et al., arXiv:0708.0082
$e^+ e^- \rightarrow D^0 D^- \pi^+$ at $\sqrt{s} \sim 4-5$ GeV via ISR

- $D^0 D^- \pi^+$
- no extra tracks

Clear signal for $\psi(4415) \rightarrow DD \pi$!

- similar analysis and backgrounds
- no major bgs except for combinatorial.

Belle: G. Pakhlova et al., arXiv:0708.3313
**Resonant structure in $\psi(4415)\rightarrow DD\pi$**

- **M**($D^0\pi^+$) vs **M**($D^-\pi^+$) from $\psi(4415)$ region
  - Clear $D^*_2(2460)$ signals
  - Positive interference
  - Non $D^*_2(2460)$ contribution is not seen

**Consistent with BES, hep-ex/0705.4500, PDG06, Barnes at al. PRD72, 054026 (2005)**

**M** = 4411± 7 MeV  
$\Gamma_{\text{tot}}$ = 77±20 MeV  
$N_{\text{ev}}$ = 109± 25

\[ \sigma(e^+e^{-}\rightarrow\psi(4415)) \times \text{Br}(\psi(4415)\rightarrow DD^*_2(2460)) \times \text{Br}(D^*_2(2460) \rightarrow D\pi) = (0.74 \pm 0.17 \pm 0.07) \text{nb} \]

\[ \text{Br}(\psi(4415) \rightarrow D(D\pi)_{\text{non } D^*_2(2460)}/\text{Br}(\psi(4415) \rightarrow DD^*_2(2460)) < 0.22 \]

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Belle: G. Pakhlova et al., arXiv:0708.3313  
See also P. Pakhlov’s talk
DD, DD*, D*D*, DD^2

arXiv:0708.0082

arXiv:0708.3313

PRL98, 092001 (2007)

PRL98, 092001 (2007)
The decays of the $\psi$ states?

These 4 final states almost saturate inclusive cross section

A compilation of data by G. Pakhlova.
Y and ψ are studied via ISR at \( \sqrt{s} = 10.58 \text{ GeV} \) at Belle

- Observation of \( Y(4008), Y(4260), Y(4360), Y(4660) \)
- Observation of \( e^+e^- \rightarrow J/\psi K^+K^- \) & \( J/\psi K_SK_S \)
- Measurement of \( e^+e^- \rightarrow DD, DD^*, D^*D^*, DD\pi \)

- Nature of the \( Y \) states (charmonium, hybrid, …)?
- Resonance parameters of the excited \( \psi \) states?
- \( Y(xxxx) = \psi(xxxx) \)?

It is time for us to think more about them with all these Belle-BES-CLEOc-BaBar data!
Y and $\psi$ are studied via ISR at $\sqrt{s}=10.58$ GeV at Belle

- Observation of Y(4008), Y(4260), Y(4360), Y(4660)
- Observation of $e^+e^- \rightarrow J/\psi K^+K^-$ & $J/\psi K_SK_S$
- Measurement of $e^+e^- \rightarrow DD, DD^*, D^*D^*, DD\pi$

- Nature of the Y states (charmonium, hybrid, …)?
- Resonance parameters of the excited $\psi$ states?
- $Y(\text{xxxx})=\psi(\text{xxxx})$?

It is time for us to think more about them with all these Belle-BES-CLEOc-BaBar data!

Thanks a lot!
More information
Y(4260) in other experiments

BaBar, PRL 95, 142001 (2005)

125 ± 23 evts

CLEO, 2006, PRD74, 091104(R)

ψ(2S)

14 ± 5 evts

CLEO, PRL 96, 162003 (2006)

35 ± 7 evts
Y(4260) in other experiments

Using R-values from BES experiment.

\[ \Gamma_{ee} < 580 \text{ eV @ 90\% C.L.} \]

\[ N = 165 \pm 24 \]
\[ M = 4295 \pm 10^{10} \text{ MeV} \]
\[ \Gamma = 133 \pm 26^{+13}_{-6} \text{ MeV} \]
\[ \Gamma_{ee} \cdot B(Y \rightarrow \pi^+ \pi^- J/\psi) = 8.7 \pm 1.1^{+0.3}_{-0.9} \text{ eV} \]
Wilks’ theorem

If a population is described by the probability density $f(x; \lambda_1, \lambda_2, ..., \lambda_p)$ that satisfies reasonable requirements of continuity, and if $r$ of the $p$ parameters of the null hypothesis

$$H_0(\lambda_1 = \lambda_{10}, \lambda_2 = \lambda_{20}, ..., \lambda_r = \lambda_{r0}), \quad r \leq p,$$

are fixed then the statistic

$$-2 \ln T \ (T \text{ is the likelihood ratio})$$

follows a $\chi^2$-distribution with $p - r$ degrees of freedom for very large samples, i.e., for $N \to \infty$. For the case of a simple null hypothesis, i.e., $r = p$, then the number of degrees of freedom is equal to one.

S.S. Wilks, the Annals of Mathematical Statistics
Vol. 9, 60-62 (1938).
Less known states:
- $\psi(4040)$
- $\psi(4160)$
- $\psi(4415)$

New states from B-factories:
- $X(3872)=DD^*$ (?)
- $X(3940)=\eta_c(3S)$ (?)
- $Y(3940)=?$
- $Z(3930)=\chi_{c2}(2P)$
- $Y(3908)=\psi(3S)$ (?)
- $X(4160)=\chi_{c0}(3P)$ (?)
- $Y(4260)=\text{hybrid (?)}$
- $Y(4324)/Y(4360)=?$
- $Z(4430)=\text{tetraquark (?)}$
- $Y(4660)=\psi(5S)$ (?)

New states every year!
What are they?
Charmonia? Exotic states?