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:
\[ L = 1.7 \times 10^{34}/\text{cm}^2/\text{sec} \]

Since 1999

Mt. Tsukuba

~ 1 km in diameter
The Y states should also appear in this plot (between 4.0 and 4.7 GeV!)
Part I

Y states via $e^+e^- \rightarrow h^+h^- + \text{charmonium}$
BaBar: 232 fb⁻¹

$\pi^+\pi^-J/\psi$ Mass

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

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

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

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

| N^{obs} | Lum (/fb) | Cross section (pb) |
|---------|-----------|--------------------|
| 15,444  | 547.8     | 15.42±0.12±0.89    |

- From cross section, one gets partial width to $e^+e^-$. 
- $\Gamma_{ee} = 2.54\pm0.02\pm0.15$ keV 
- PDG’06 
  - $\Gamma_{ee} = 2.48 \pm 0.06$ keV 
- Belle agrees with other experiments well.

Belle: C.Z.Y & C.P. Shen et al., PRL99, 182004 (2007)
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 ($\gamma_{\text{ISR}}$)

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

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

$120\pm14$ evts $324\pm21$ evts

$Lum=548$ fb$^{-1}$

Belle: C.Z.Y & C.P. Shen et al., PRL99, 182004 (2007)
\[ e^+e^- \rightarrow \pi^+\pi^-J/\psi \text{ via ISR} \]

- 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?)

Belle: C.Z.Y & C.P. Shen et al., PRL99, 182004 (2007)
\[ e^+e^- \rightarrow \pi^+\pi^- J/\psi \text{ via ISR} \]

- \[ \chi^2/\text{ndf}=93/79, \text{ CL}=13\% \]
- \[ M=4263\pm6 \text{ MeV} \]
- \[ \Gamma=125\pm18 \text{ MeV} \]
- \[ \Gamma_{ee}\times\text{Br}=9.7\pm1.1 \text{ eV (fit errors only)} \]

**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

| Parameters            | Solution I                      | Solution II                     |
|-----------------------|---------------------------------|---------------------------------|
| $M(R1)$               | $4008 \pm 40^{+114}_{-28}$      |                                 |
| $\Gamma_{tot}(R1)$    | $226 \pm 44 \pm 87$            |                                 |
| $\mathcal{B} \cdot \Gamma_{e^+e^-}(R1)$ | $5.0 \pm 1.4^{+6.1}_{-0.9}$   | $12.4 \pm 2.4^{+14.8}_{-1.1}$  |
| $M(R2)$               | $4247 \pm 12^{+17}_{-32}$      |                                 |
| $\Gamma_{tot}(R2)$    | $108 \pm 19 \pm 10$            |                                 |
| $\mathcal{B} \cdot \Gamma_{e^+e^-}(R2)$ | $6.0 \pm 1.2^{+4.7}_{-0.5}$   | $20.6 \pm 2.3^{+9.1}_{-1.7}$   |
| $\phi$                | $12 \pm 29^{+7}_{-98}$         | $-111 \pm 7^{+28}_{-31}$       |

2-BW fit with interference better describes the data: $Y(4260)$ parameters are different (especially peak cross section – large uncertainty)

Belle: C.Z.Y & C.P. Shen et al., PRL99, 182004 (2007)
$e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ 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)
$e^+e^- \rightarrow \pi^+\pi^-\psi(2S)$ via ISR

\[ \psi(\rightarrow J/\psi \pi\pi) + \pi\pi \quad + \text{no extra tracks} \]

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

Belle: X.L. Wang & C.Z.Y et al., PRL99, 142002 (2007)
$e^+e^- \rightarrow \pi^+\pi^- \psi(2S)$ via ISR

Two solutions

| Parameters                      | Solution one     | Solution two     |
|---------------------------------|------------------|------------------|
| $M(Y(4360))$                    | $4361 \pm 9 \pm 9$|                  |
| $\Gamma_{\text{tot}}(Y(4360))$ | $74 \pm 15 \pm 10$|                  |
| $\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4360))$ | $10.4 \pm 1.7 \pm 1.5$ | $11.8 \pm 1.8 \pm 1.4$ |
| $M(Y(4660))$                    | $4664 \pm 11 \pm 5$ |                  |
| $\Gamma_{\text{tot}}(Y(4660))$ | $48 \pm 15 \pm 3$ |                  |
| $\mathcal{B} \cdot \Gamma_{e^+e^-}(Y(4660))$ | $3.0 \pm 0.9 \pm 0.3$ | $7.6 \pm 1.8 \pm 0.8$ |
| $\phi$                          | $39 \pm 30 \pm 22$ | $-79 \pm 17 \pm 20$ |

Belle: X.L. Wang & C.Z.Y et al., PRL99, 142002 (2007)

Y(4360) – consistent with BaBar
Y(4660) – NEW (5.8$\sigma$)
e^+e^- \rightarrow K^+K^-J/\psi \text{ via ISR}

- CLEO-c observed 3 K^+K^-J/\psi at E_{cm}=4.26 \text{ 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_S K_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., arXive: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

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

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

e^+e^- \rightarrow \text{charmed meson pair}
**Method**

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

$M_{rec}(D^{*+}\gamma_{ISR}) - M_{rec}(D^{*+}\pi\gamma_{ISR})$, because of cancelation of momentum smearing

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

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

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

**CHARM 2007**

- $D^*D^*$
- $D^*D$ (PRELIMINARY)
- $\psi(4160)$
- $\psi(4040)$

**Phys. Rev. Lett. 98, 092001 (2007)**

- Charged $D^{(*)}D^{(*)}$ half from CLEOc
- $D^*D^*$: hint, but not significant
- $D^*D$: clear dip (similar to inclusive $R$)

**Y(4260) signal**
- $D^*D$: hint, but not significant
- $D^*D^*$: clear dip (similar to inclusive $R$)

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

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

- 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
Broad structure around 3.9 GeV is in qualitative agreement with coupled-channel model, Phys. Rev. D21, 203 (1980).

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

σ($e^+e^- \rightarrow DD$)

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

- **D$^0$ D$^-$ π$^+$**
- **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 $\psi(4415) \to DD\pi$

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

\[ M = 4411 \pm 7 \text{ MeV} \]
\[ \Gamma_{\text{tot}} = 77 \pm 20 \text{ MeV} \]
\[ N_{\text{ev}} = 109 \pm 25 \]

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

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

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

Belle: G. Pakhlova et al., arXiv:0708.3313

See also P. Pakhlov’s talk
DD, DD*, D*D*, DD₂

- arXiv:0708.0082
- arXiv:0708.3313
- PRL 98, 092001 (2007)
- PRL 98, 092001 (2007)

$E_{cm}$ (GeV)
The decays of the $\psi$ states?

These 4 final states almost saturate inclusive cross section.
Y and ψ are studied via ISR at √s=10.58 GeV at Belle

- Observation of Y(4008), Y(4260), Y(4360), Y(4660)
- Observation of e⁺e⁻ → J/ψ K⁺K⁻ & J/ψ KSKS
- Measurement of e⁺e⁻ → DD, DD*, D*D*, DDπ

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

It is time for us to think more about them with all these Belle-BES-CLEOc-BaBar data!
Y and ψ are studied via ISR at √s=10.58 GeV at Belle

- Observation of Y(4008), Y(4260), Y(4360), Y(4660)
- Observation of e^+e^- → J/ψ K^+K^- & J/ψ K_SK_S
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- Nature of the Y states (charmonium, hybrid, …)?
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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, PRL96, 162003 (2006)

35±7 evts

ψ(0)+ψ(2S) data

K+K− J/ψ

π0π0 J/ψ

π+π− J/ψ
Y(4260) in other experiments

X.H. Mo et al, PLB 640, 182 (2006)
Using R-values from BES experiment.

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

\[ N = 165 \pm 24 \]
\[ M = 4295 \pm 10_{-5}^{+10} \text{ MeV} \]
\[ \Gamma = 133 \pm 26_{-6}^{+13} \text{ MeV} \]
\[ \Gamma_{ee} \cdot B(Y \rightarrow \pi^+ \pi^- J/\psi) = 8.7 \pm 1.1_{-0.9}^{+0.3} \text{ eV} \]
Wilks’ theorem

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

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

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:
- $X(3872) = D\bar{D}^*$ (?)
- $X(3940) = \eta_c(3S)$ (?)
- $Y(3940) = ?$
- $Z(3930) = \chi_c^2(2P)$
- $Y(4008) = \psi(3S)$ (?)
- $X(4160) = \chi_c^0(3P)$ (?)
- $Y(4260) = \text{hybrid (?)}$
- $Y(4324)/Y(4360) = ?$
- $Z(4430) = \text{tetraquark (?)}$
- $Y(4660) = \psi(5S)$ (?)

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