XYZ from Belle

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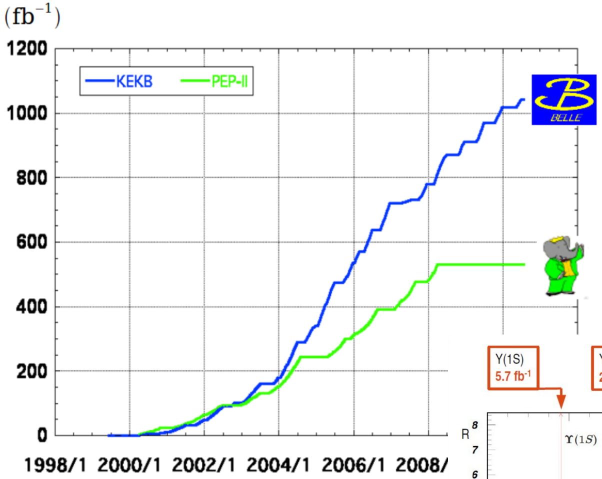
$5^{\rm th}$ **Workshop on the XYZ particles**
10/21/2018, 郑州大学

KEKB and Belle

The data samples



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

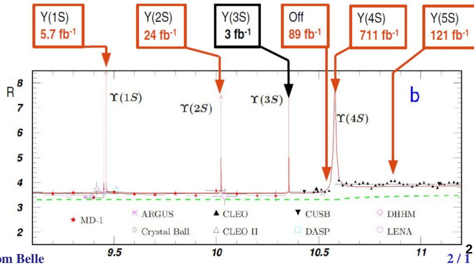
Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}



Huge data samples for quarkonium(-like) state.

Outline

- $e^+e^- \to \gamma + \chi_{cJ}/\eta_c$
- Observation of $\chi_{c0}(2P)$ in $e^+e^- \to J/\psi + D\overline{D}$
- Inclusive $B \to X_{cc}K$ and $\mathcal{B}(X(3872) \to f)$
- η-transitions between quarkonim(-like) states

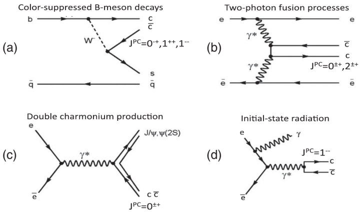


FIG. 12. Processes that produce $c\bar{c}$ pairs in e^+e^- collisions near $E_{\mathrm{c.m.}} = 10.6$ GeV: (a) $B \to K(c\bar{c})$ decays, (b) two-photon fusion processes, (c) e^+e^- annihilation into $c\bar{c}c\bar{c}$, and (d) initial state radiation.

More than these!
Pictures from Rev. Mod. Phys. 90, 1(2018)

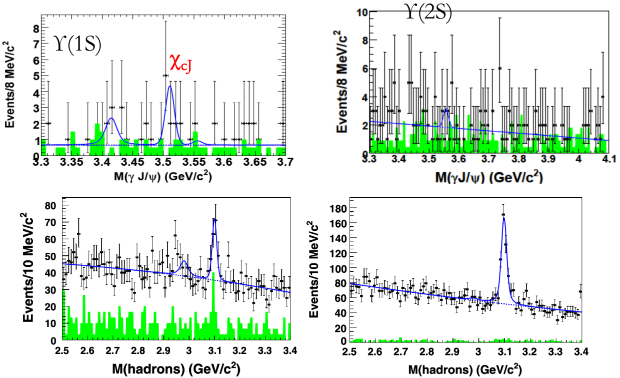
I. $e^+e^- \to \gamma + \chi_{cJ}/\eta_c$ near 1.058 GeV

Motivation (I)

- Searching for C-even charmonium(-like) states in $\Upsilon(1,2S)$ decays: 1.02×10^8 $\Upsilon(1S)$ and 1.58×10^8 $\Upsilon(2S)$

process	$\Upsilon \to \chi_{c2}\gamma$	$\Upsilon \to \chi_{c1}\gamma$	$\Upsilon \to \chi_{c0}\gamma$	$\Upsilon \to \eta_c\gamma$
BR_{QCD}	5.1×10^{-6}	4.5×10^{-6}	4.0×10^{-6}	2.9×10^{-5}
$BR_{QCD+QED}$	5.6×10^{-6}	9.8×10^{-6}	3.2×10^{-6}	4.9×10^{-5}

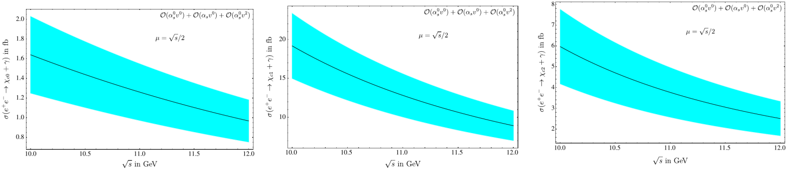
$\mathcal{B}(2S)/\mathcal{B}(1S) \approx 0.77$, Y. J. Gao, Y. J. Zhang, K. T. Chao: hep-ph/0701009v2



C.P. Shen *et al.*, PRD82,051504(2010); X.L. Wang *et al.*, PRD84,071107(2011)

Motivation (II)

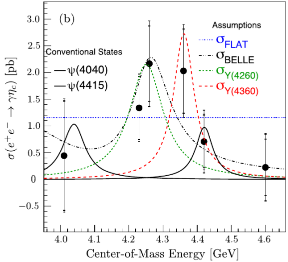
- Continuum production predictions by NRQCD (for Belle II):



N. Brambilla *et al.*, PRD**97**, 096001(2018)

- We can study with Belle data at first:
  - $\sigma(e^+e^- \to \chi_{c0} + \gamma) = (1.4 \pm 0.3)$ fb;
  - $\sigma(e^+e^- \to \chi_{c1} + \gamma) = (15.0 \pm 3.3)$ fb;
  - $\sigma(e^+e^- \to \chi_{c2} + \gamma) = (4.5 \pm 1.4)$ fb.
- $e^+e^- \to \gamma + \chi_{cJ}/\eta_c$ measured by BESIII: PRD96,051101(2017) and Chin.Phys.C39, 041001(2015)

$E_{\rm CM}$ (GeV)		$N^{\rm obs}$	significance (σ)	$\sigma^{\rm UP}$ (pb)	$\sigma^{\rm B}$ (pb)
4.009	χ_{c0}	7.0 ± 6.6	1.6	182	$65.0 \pm 61.3 \pm 5.3$
	χ_{c1}	4.4 ± 2.6	2.2	5.3	$2.4 \pm 1.4 \pm 0.2$
	χ_{c2}	1.8 ± 1.7	1.5	18	$4.7 \pm 4.4 \pm 0.6$
4.230	χ_{c0}	0.2 ± 2.3	0.0	26	$0.7 \pm 8.0 \pm 0.1$
	χ_{c1}	6.7 ± 4.3	1.9	1.7	$0.7 \pm 0.5 \pm 0.1$
	χ_{c2}	13.3 ± 5.2	2.9	5.0	$2.7 \pm 1.1 \pm 0.3$
4.260	χ_{c0}	0.1 ± 1.9	0.0	26	$0.5 \pm 8.8 \pm 0.1$
	χ_{c1}	3.0 ± 3.0	1.1	1.1	$0.4 \pm 0.4 \pm 0.1$
	χ_{c2}	7.5 ± 3.9	2.3	4.2	$2.0 \pm 1.1 \pm 0.2$
4.360	χ_{c0}	0.1 ± 0.7	0.0	23	$0.7 \pm 5.0 \pm 0.1$
	χ_{c1}	5.2 ± 4.9	2.4	2.9	$1.4 \pm 1.3 \pm 0.1$
	χ_{c2}	4.4 ± 4.5	2.0	5.0	$2.3 \pm 2.3 \pm 0.2$



Data samples and expected signals based on NRQCD

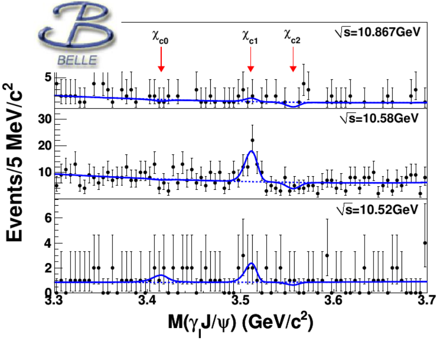
TABLE I: The numbers of expected events in $e^+e^- \to \gamma\chi_{cJ}$ and $e^+e^- \to \gamma\eta_c$ at $\sqrt{s} = 10.52$, 10.58 and 10.867 GeV.

Channel	$\sqrt{s}$ GeV	σ_B (fb) predicted in Ref. [12] by NRQCD with all leading relativistic corrections included	$\mathcal{L}$ (fb^{-1})	$\mathcal{B}_{decay}$ ($\times 10^{-4}$)	ε(%)	$N_{expected}$
$e^+e^- \to \gamma\chi_{c0}$		1.4		7.6	19.0	0.1
$e^+e^- \to \gamma\chi_{c1}$	10.52	15.5	89.5	202.1	20.8	5.8
$e^+e^- \to \gamma\chi_{c2}$		4.7		114.4	19.9	1.0
$e^+e^- \to \gamma\chi_{c0}$		1.4		7.6	18.9	0.1
$e^+e^- \to \gamma\chi_{c1}$	10.58	15.1	711.0	202.1	19.9	43.2
$e^+e^- \to \gamma\chi_{c2}$		4.5		114.4	19.8	7.2
$e^+e^- \to \gamma\chi_{c0}$		1.3		7.6	17.7	0.1
$e^+e^- \to \gamma\chi_{c1}$	10.867	13.5	121.4	202.1	16.8	5.6
$e^+e^- \to \gamma\chi_{c2}$		4.0		114.4	16.3	0.9

Channel	$\sqrt{s}$ GeV	σ_B (fb) by LO QCD/σ_B (fb) by NLO QCD in Ref. [14]	$\mathcal{L}$ (fb^{-1})	$\Sigma_i \mathcal{B}_i \varepsilon_i$(%)	$N_{expected}$
$e^+e^- \to \gamma\eta_c$	10.52	0.38/0.13	89.5	0.79	0.3/0.1
$e^+e^- \to \gamma\eta_c$	10.58	0.37/0.12	711.0	0.78	2.1/0.7
$e^+e^- \to \gamma\eta_c$	10.867	0.32/0.10	121.4	0.76	0.3/0.1

$e^+e^- \to \gamma + \chi_{cJ}$ from Belle

- $\chi_{cJ} \to \gamma J/\psi,\ J/\psi \to \mu^+\mu^-$ for reconstruction;
- 5C constraints: 4C to initial e^+e^- collision system &. 1C to J/ψ mass
- ISR events $e^+e^- \to \gamma_{\rm ISR}\psi(2S) \to \gamma_{\rm ISR}\gamma\chi_{cJ}$ removed by $M(\gamma_{\rm ext}\gamma\mu^+\mu^-) < 3.60$ GeV$/c^2$ or > 3.78 GeV$/c^2$:
  - $N^{\rm residual}(\chi_{c1}) = 0.84 \pm 0.15$ and $N^{\rm residual}(\chi_{c2}) = 0.43 \pm 0.05$.



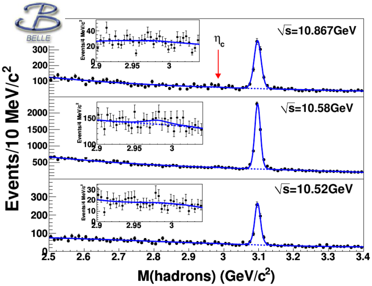
A significant χ_{c1} signal in 10.58 GeV data sample:

- $N^{\rm obs}(\chi_{c1}) = 39.0^{+9.5}_{-8.8}$ with $\varepsilon = 19.9\%$;
- The significance: 5.1σ including systematic uncertainties;
- $\sigma^{\rm Born}(e^+e^- \to \gamma + \chi_{c1}) = (17.3^{+4.2}_{-3.9}(stat.) \pm 1.7(syst.))$ fb.

Going to be submitted to PRD(RC)

ULs of $e^+e^- \to \gamma\chi_{cJ}/\eta_c$

- η_c reconstructed in $K_S^0 K^+\pi^-$, $\pi^+\pi^- K^+ K^-$, $2(\pi^+\pi^-)$, $2(K^+K^-)$ and $3(\pi^+\pi^-)$;
- ULs of χ_{c0}, χ_{c2} and η_c are determined at 90% C.L.



Channel	$\sqrt{s}$ (GeV)	$N^{\rm obs}$	$N^{\rm UL}$	$\Sigma(\sigma)$	$\varepsilon(\%)$	$\lvert 1-\prod\rvert^2$	$(1+\delta)_{\rm ISR}$	$\sigma_{\rm syst}(\%)$	$\sigma_{\rm B}$ (fb)	$\sigma_{\rm B}^{\rm UL}$ (fb)
$e^+e^- \to \gamma\chi_{c0}$	10.52	$2.9^{+4.0}_{-3.3}$	9.6	0.9	19.0	0.931	0.732868	10.7	$286.2^{+394.7}_{-325.6} \pm 30.7$	957.2
$e^+e^- \to \gamma\chi_{c1}$		$4.8^{+3.6}_{-2.9}$	10.4	1.9	20.8		0.733432	8.9	$16.2^{+12.1}_{-9.8} \pm 1.4$	34.9
$e^+e^- \to \gamma\chi_{c2}$		$-0.8^{+2.3}_{-1.6}$	4.5	-	19.9		0.733675	12.8	$-5.0^{+14.3}_{-10.0} \pm 0.6$	28.9
$e^+e^- \to \gamma\eta_c$		$6.8^{+14.8}_{-14.3}$	30.8	0.5	0.79		0.732788	11.3	$9.0^{+19.5}_{-18.8} \pm 1.0$	40.6
$e^+e^- \to \gamma\chi_{c0}$	10.58	$-1.6^{+9.8}_{-8.9}$	16.5	-	18.9	0.930	0.732725	13.1	$-20.0^{+122.3}_{-111.0} \pm 2.6$	205.9
$e^+e^- \to \gamma\chi_{c1}$		$39.0^{+9.5}_{-8.8}$	-	5.2	19.9		0.73329	10.0	$17.3^{+4.2}_{-3.9} \pm 1.7$	-
$e^+e^- \to \gamma\chi_{c2}$		$-8.7^{+5.7}_{-5.0}$	7.2	-	19.8		0.733532	20.9	$-6.8^{+4.5}_{-3.9} \pm 1.4$	5.7
$e^+e^- \to \gamma\eta_c$		$67.2^{+42.0}_{-39.2}$	125.9	1.8	0.78		0.732645	13.0	$11.3^{+7.0}_{-6.6} \pm 1.5$	21.1
$e^+e^- \to \gamma\chi_{c0}$	10.867	$-1.3^{+4.0}_{-3.2}$	7.0	-	17.7	0.929	0.732054	9.4	$-101.4^{+312.0}_{-249.6} \pm 9.5$	543.7
$e^+e^- \to \gamma\chi_{c1}$		$1.9^{+3.4}_{-2.6}$	7.9	0.7	16.8		0.73262	13.4	$5.8^{+10.5}_{-8.0} \pm 0.8$	24.3
$e^+e^- \to \gamma\chi_{c2}$		$-2.8^{+3.2}_{-2.4}$	5.3	-	16.3		0.732863	14.4	$-15.7^{+17.9}_{-13.4} \pm 2.3$	30.3
$e^+e^- \to \gamma\eta_c$		$12.3^{+18.2}_{-17.4}$	42.3	0.9	0.76		0.731974	9.1	$12.3^{+17.3}_{-18.1} \pm 1.1$	42.2

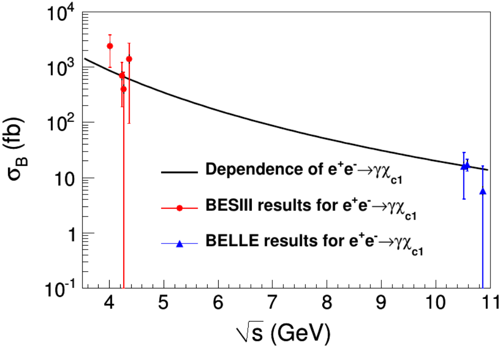
$\sigma(e^+e^- \to \gamma\chi_{c1})$ vs. $\sqrt{s}$

- Assuming $\sigma(e^+e^- \to \gamma\chi_{cJ}/\eta_c) \propto 1/s^n$, the prediction:

charmonium	χ_{c0}	χ_{c1}	χ_{c2}	η_c
n	1.4	2.1	2.4	1.3

L.B. Chen, Y. Liang and C.F. Qiao, JHEP1801,091(2018)

- Combining measurements from BESIII and Belle.
- Fitting yields $n = 2.1^{+0.3}_{-0.4}$.



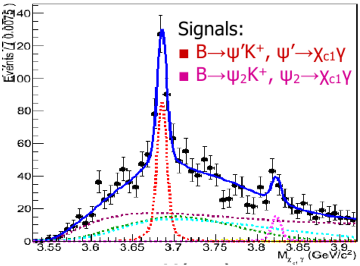
- Can we use NRQCD to predict the productions of XYZ particles for Belle II?

More about $\chi_{c1}(\gamma)$

- $B^+ \to \gamma\chi_{c1}K^+$ with $\chi_{c1} \to \gamma J/\psi$ using 772×10^6 $B\bar{B}$.
- $\psi_2 \to \gamma\chi_{c1}$ was predicted, $(\Gamma(\psi_2 \to \gamma\chi_{c1}) = 260$ keV).

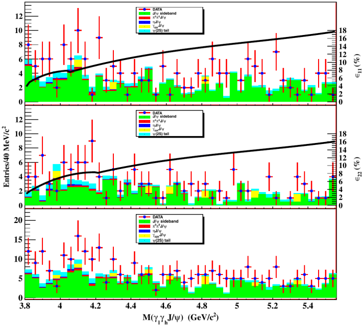
Godfrey-Isgur, PRD21,189(1985); Eichten-Lane-Quigg, PRL89, 162002(2002) and PRD69, 094019(2004)

	yield	Mass[MeV]	$BR(B^+ \to \psi(\to\chi_{c1}\gamma)K^+)$
ψ'	193 ± 18	3685.3 ± 0.6	$(7.7\pm0.8\pm0.9)\times10^{-4}$
ψ_2	33 ± 9	3823.5 ± 2.8	$(9.7^{+2.8}_{-2.5}\pm1.1)\times10^{-6}$



- ψ_2 significance 4.2σ w/syst.
- $\Gamma(\psi_2) = 4 \pm 6$ MeV$/c^2$ if fitted.

Searching for $e^+e^- \to \gamma\chi_{cJ}$ via ISR



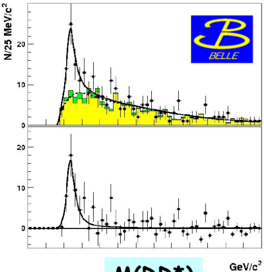
Y.L. Han *et al.*, Belle Coll.: PRD92,012011(2015)

II. Observation of $\chi_{c0}(2P)$ in $e^+e^- \to J/\psi + D\overline{D}$

Begin with states near 3940 MeV at Belle

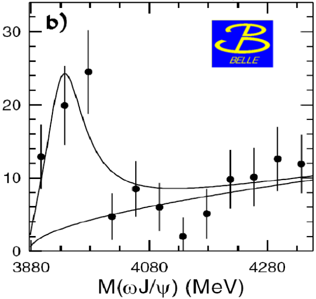
not seen in $\omega J/\psi$	probably different	not seen in DD^*	Probably the χ_{c2}'

X(3940) — $e^+e^- \to J/\psi\ DD^*$

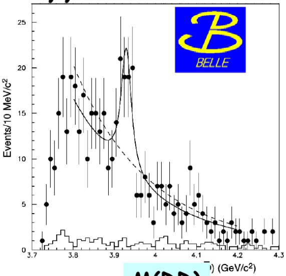


M(DD*)

Y(3940) — $B \to K\ \omega J/\psi$



Z(3930) — $\gamma\gamma \to DD$



M(DD)

$M = 3942\ ^{+7}_{-6} \pm 6$ MeV
$\Gamma_{tot} = 37\ ^{+26}_{-15} \pm 12$ MeV

693/fb, PRL 100, 202001

$M \approx 3943 \pm 11 \pm 13$ MeV
$\Gamma_{tot} \approx 87 \pm 22 \pm 26$ MeV

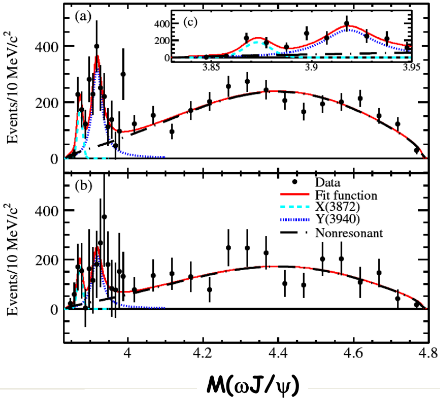
253/fb, PRL 94, 182002

$M = 3929 \pm 5 \pm 2$ MeV
$\Gamma_{tot} = 29 \pm 10 \pm 2$ MeV

395/fb, PRL 96, 082003

States near $3940\ \mathrm{MeV}/c^2$ at BaBar

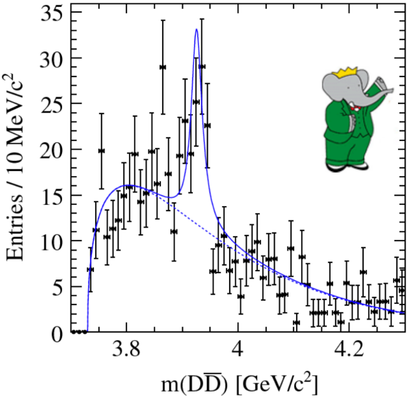
Y(3940), $B \to K\,\omega J/\psi$



$M \approx 3919.1^{+3.8}_{-3.5} \pm 2.0$ MeV
$\Gamma \approx 31^{+10}_{-8} \pm 5$ MeV

426/fb: PRD 82, 011101

Z(3930), $\gamma\gamma \to D\bar{D}$



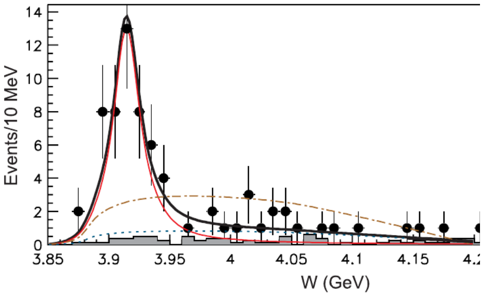
$M = 3926.7 \pm 2.7 \pm 1.1$ MeV

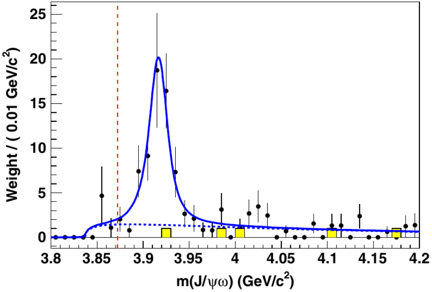
$\Gamma_{tot} = 21.3 \pm 6.8 \pm 3.6$ MeV

19

384/fb: PRD 81, 092003

$X(3915)$ in $\gamma\gamma^* \to \omega J/\psi$





$X(3915)$ from Belle:

- $M = (3915 \pm 3 \pm 2)$ MeV;
- $\Gamma = (17 \pm 10 \pm 3)$ MeV
- $N^{\rm sig} = 49 \pm 14 \pm 4$ events
- Signif. = 7.7σ.

Belle: PRL104, 092001(2010)

$X(3915)$ was expected to be $\chi_{c0}(2P)$ candidate.

$X(3915)$ From BaBar:

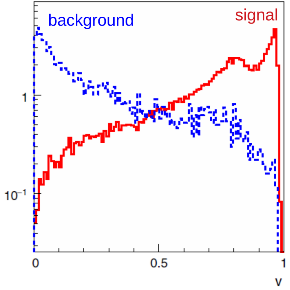
- $M = (3919.4 \pm 2.2 \pm 1.6)$ MeV$/c^2$;
- $\Gamma = (13 \pm 6 \pm 3)$ MeV;
- $N^{\rm sig} = 59 \pm 10$;
- Signif. = $7.6\ \sigma$.
- Data largely prefer $J^P = 0^\pm$ over 2^+.

BaBar: PRD86,072002(2012)

$\chi_{c0}(2P)$ in $e^+e^- \to J/\psi D\overline{D}$

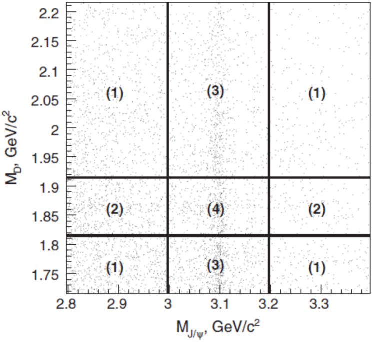
- $X(3915)$ observed by Belle in $B \to K + J/\psi\omega$, and was identified as the $\chi_{c0}(2P)$ in PDG2014, but disappear in PDG2016.
  - The main decay mode of $\chi_{c0}(2P)$ is expected to be $D\overline{D}$.
  - $X(3915) \to \omega J/\psi$ would be OZI suppressed for the $\chi_{c0}(2P)$.
  - $\chi_{c0}(2P) \to D\overline{D}$ in an S-wave, it's naively expected $\Gamma > 100$ MeV.
  - Mass of $X(3915)$ is high, if $Z(3930) = \chi_{c2}(2P)$ in $\gamma\gamma \to D\overline{D}$ is expected. $M_{Z(3930)} = (3838 \pm 12)\ \mathrm{MeV}/c^2$ and $\Gamma = (211 \pm 19)$ MeV.
- So, we search for $\chi_{c1}(2P)$ in $e^+e^- \to J/\psi + D\overline{D}$.

- Only one D-meson is reconstructed, while the other one is identified by $M_{recoil}(J/\psi D)$.
- Reconstruction channels:
  - D^+: $K_S^0\pi^+$, $K^-\pi^+\pi^+$, $K_S^0\pi^+\pi^0$, $K^-\pi^+\pi^+\pi^0$, and $K_S^0\pi^+\pi^+\pi^-$.
  - D^0: $K^-\pi^+$, $K_S^0\pi^+\pi^-$, $K^-\pi^+\pi^0$ and $K^-\pi^+\pi^+\pi^-$.
  - J/ψ: e^+e^-, $\mu^+\mu^-$.
- Multivariable analysis to suppress background.



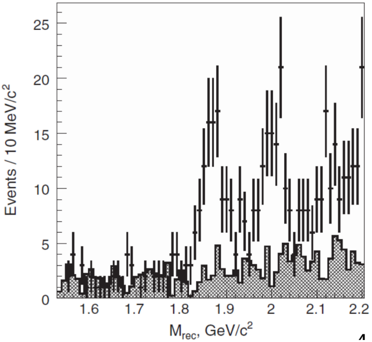
PRD95, 112003(2017)

J/ψ and D signals



- Background contribution is estimated using J/ψ and D invariant masses:
  1. pure combinatorial background
  2. real D, combinatorial J/ψ
  3. real J/ψ, combinatorial D
  4. signal

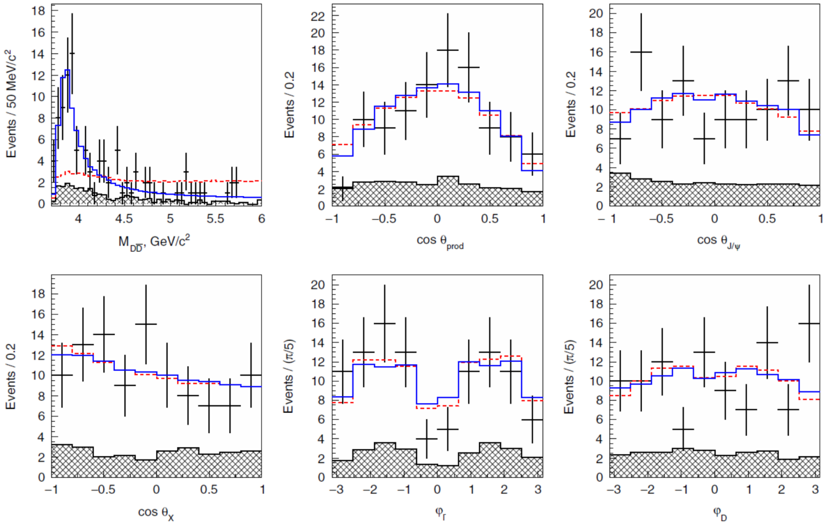
- Signal yield is extracted from the fit to the $M_{recoil}(J/\psi D)$ distribution.



Phy. Rev. D95, 112003(2017)

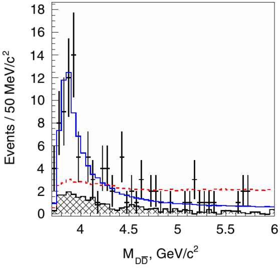
Amplitude analysis

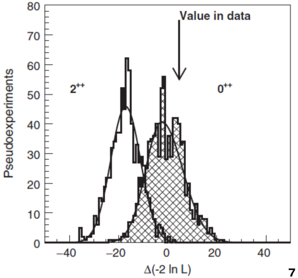
- 6-D amplitude analysis: $M_{D\overline{D}}, \theta_{\mathrm{prod}}, \theta_J/\psi, \theta_{X^*}, \phi_{l^-}, \phi_D$.
- Fit to data: Signal, non-resonant only, background



$X^*(3860)$ **in** $e^+e^- \to J/\psi + D\overline{D}$

- A new charmonium-like state is observed at Belle, called $X^*(3860)$.
  - $M = 3862^{+26+40}_{-32-13}$ MeV$/c^2$;
  - $\Gamma = 201^{+154+88}_{-67-82}$ MeV.
- The $J^{PC} = 1^{++}$ is preferred from 2^{++} at the level of 2.5σ.
- $X^*(3860)$ is consistent with $\chi_{c0}(2P)$ hypotheses.
- The measured mass is close to potential model expectations for the $\chi_{c0}(2P)$.



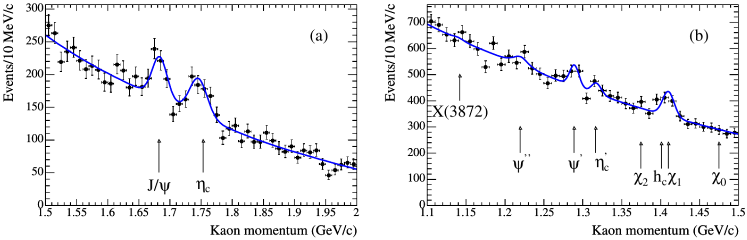


Phys. Rev. D95, 112003(2017)

New question: What is $X(3915)$ observed in $\omega J/\psi$?

III. Inclusive $B \to X_{c\bar{c}}K$ and $\mathcal{B}(X(3872) \to f)$

Measurements of the absolute $\mathcal{B}$s of $B^{\pm} \to K^{\pm} X_{c\bar{c}}$



- Clear signals of J/ψ, χ_{c1}, $\psi(2S)$, etc.
- $\mathcal{B}(B \to X(3872)K) < 3.2 \times 10^{-4}$ at 90% C.L.

BaBar: PRL96, 052002(2006)

Decays of $X(3872)$

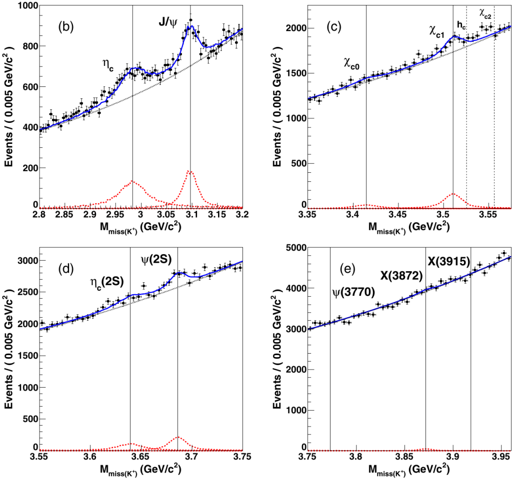
$$Bf(B^- \to XK^-)Bf(X \to J/\psi\pi^+\pi^-) = (8.20 \pm 0.93)\times 10^{-6}$$
$$Bf(B^- \to XK^-)Bf(X \to J/\psi\pi^+\pi^-\pi^0) = (8.2 \pm 4.2)\times 10^{-6}$$
$$Bf(B^- \to XK^-)Bf(X \to J/\psi\gamma) = (2.8 \pm 0.8 \pm 0.1)\times 10^{-6}$$
$$Bf(B^- \to XK^-)Bf(X \to \psi(2S)\gamma) = (9.5 \pm 2.7 \pm 0.6)\times 10^{-6}$$
$$Bf(B^- \to XK^-)Bf(X \to D^0\overline{D^{0*}} + c.c.) = (1.67 \pm 0.36 \pm 0.47)\times 10^{-4}$$
$$\ldots$$
$$\Rightarrow Bf(X \to J/\psi\pi^+\pi^-) < \frac{8.2+1\sigma}{8.2+8.2+2.8+9.5+167-1\sigma} \approx 6.6\% \quad @90\%\ \mathrm{C.L.}$$

$$2.3\% < Bf\left(X \to J/\psi\pi^+\pi^-\right) < 6.6\%$$
$$1.4\times 10^{-4} < Bf\left(B^- \to X(3872)K^-\right) < 3.2\times 10^{-4} \qquad \text{at } 90\%\ \mathrm{C.L.}$$

$$Bf\left(B^- \to \psi(2S)K^-\right) = \left(6.48 \pm 0.35\right)\times 10^{-4}$$
$$Bf\left(B^- \to \chi_{c1}K^-\right) = \left(4.9 \pm 0.5\right)\times 10^{-4}$$
$$Bf\left(B^- \to \eta_c K^-\right) = \left(9.1 \pm 1.3\right)\times 10^{-4}$$

15

$B^+ \to X_{c\bar{c}}K$ at Belle



- Fully reconstruct one of the two charge B mesons ($B_{\rm tag}$) and require at least one K.
- Scanning for charmonium states in $M_{\rm miss(K)}$.

$$M_{\rm miss(K)} = \sqrt{(p^*_{e^+e^-} - p^*_{\rm tag} - p^*_{\rm h})}/c \quad (1)$$

Y. Kato *et al.*, PRD97,012005(2018)

$B^+ \to X_{cc}K^+$

- $B^+ \to X_{cc}K^+$ branching fractions have been measured.
- We significantly improve knowledge for η_c and $\eta_c(2S)$.
- Results for J/ψ, χ_{c0}, χ_{c1} and $\psi(2S)$ are consistent with world average.
- No significant signals are observed for $\psi(3770)$, $X(3872)$, $X(3915)$. ULs at 90% C.L. have been set.

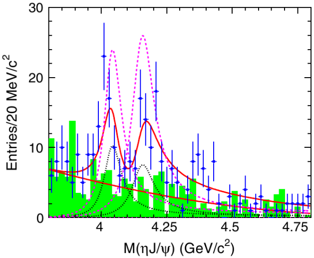
Mode	Yield	Significance (σ)	$\epsilon(10^{-3})$	$\mathcal{B}$ (10^{-4})	World average for $\mathcal{B}$ (10^{-4}) [10]
η_c	2590 ± 180	14.2	2.73 ± 0.02	$12.0 \pm 0.8 \pm 0.7$	9.6 ± 1.1
J/ψ	1860 ± 140	13.7	2.65 ± 0.02	$8.9 \pm 0.6 \pm 0.5$	10.26 ± 0.031
χ_{c0}	430 ± 190	2.2	2.67 ± 0.02	$2.0 \pm 0.9 \pm 0.1$ (< 3.3)	$1.50^{+0.15}_{-0.14}$
χ_{c1}	1230 ± 180	6.8	2.68 ± 0.02	$5.8 \pm 0.9 \pm 0.5$	4.79 ± 0.23
$\eta_c(2S)$	1050 ± 240	4.1	2.77 ± 0.02	$4.8 \pm 1.1 \pm 0.3$	3.4 ± 1.8
$\psi(2S)$	1410 ± 210	6.6	2.79 ± 0.02	$6.4 \pm 1.0 \pm 0.4$	6.26 ± 0.24
$\psi(3770)$	-40 ± 310	-	2.76 ± 0.02	$-0.2 \pm 1.4 \pm 0.0$ (< 2.3)	4.9 ± 1.3
$X(3872)$	260 ± 230	1.1	2.79 ± 0.01	$1.2 \pm 1.1 \pm 0.1$ (< 2.6)	(< 3.2)
$X(3915)$	80 ± 350	0.3	2.79 ± 0.01	$0.4 \pm 1.6 \pm 0.0$ (< 2.8)	-

- $1.4 \times 10^{-4} < \mathcal{B}(B \to X(3872)K) < 2.6 \times 10^{-4}$ at 90% C.L.
- On the way to get the absolute $\mathcal{B}$s of $X(3872)$.

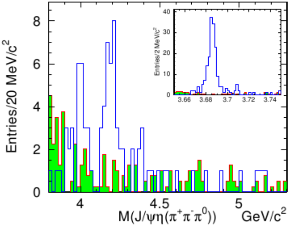
IV: η-transitions between quarkonim(-like) states

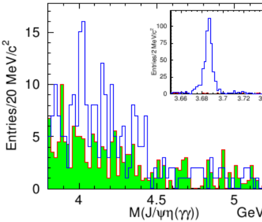
$\eta J/\psi$ via ISR at Belle

- Search for hadronic transition via emitting η.
- Reconstructions: $\eta \to \gamma\gamma/\pi^+\pi^-\pi^0$.



- This is the first time to found ψ states in charmonium transition. ($> 6.0\sigma$ for $\psi(4040)$; $> 6.5\sigma$ for $\psi(4160)$.)
- Large $\mathcal{B}(\psi \to \eta J/\psi)$! $\mathcal{B}(\psi(2S) \to \eta J/\psi) = (3.28 \pm 0.07)\%$
- Unlike $\pi^+\pi^-$ transition, no significant Y signal!!!



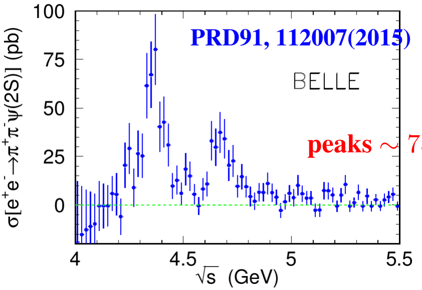


Parameters	Solution I	Solution II
$M_{\psi(4040)}$	4039 (fixed)	
$\Gamma_{\psi(4040)}$	80 (fixed)	
$\mathcal{B} \cdot \Gamma^{\psi(4040)}_{e^+e^-}$	$4.8 \pm 0.9 \pm 1.5$	$11.2 \pm 1.3 \pm 2.1$
$M_{\psi(4160)}$	4153 (fixed)	
$\Gamma_{\psi(4160)}$	103 (fixed)	
$\mathcal{B} \cdot \Gamma^{\psi(4160)}_{e^+e^-}$	$4.0 \pm 0.8 \pm 1.4$	$13.8 \pm 1.3 \pm 2.1$
ϕ	$336 \pm 12 \pm 14$	$251 \pm 4 \pm 7$

$\Gamma_{e^+e^-}(\psi(4040)) = (0.86 \pm 0.07)$ keV from PDG $\to$
$\mathcal{B}(\psi(4040) \to \eta J/\psi) = (0.56 \pm 0.10 \pm 0.18)\%$ or
$\mathcal{B}(\psi(4040) \to \eta J/\psi) = (1.30 \pm 0.15 \pm 0.26)\%$.
$\Gamma_{e^+e^-}(\psi(4160)) = (0.83 \pm 0.07)$ keV from PDG $\to$
$\mathcal{B}(\psi(4160) \to \eta J/\psi) = (0.48 \pm 0.10 \pm 0.17)\%$ or
$\mathcal{B}(\psi(4160) \to \eta J/\psi) = (1.66 \pm 0.16 \pm 0.29)\%$.

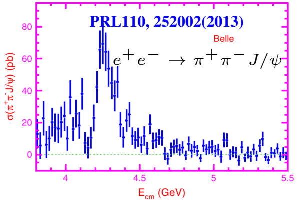
Cross sections from some ISR studies

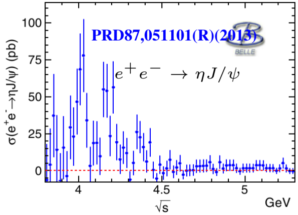
$e^+e^- \to \pi^+\pi^-\psi(2S)$



peaks $\sim$ 75 pb!

$\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ **and** $\sigma(e^+e^- \to \eta J/\psi)$





The $\sigma(e^+e^- \to \pi^+\pi^- J/\psi)$ at $Y(4260)$, $\sigma(e^+e^- \to \pi^+\pi^-\psi(2S))$ at $Y(4360)$ and $\sigma(e^+e^- \to \eta J/\psi)$ at $\psi(4040)$ are almost the same!!! WHY?

$\to$ Need BelleII data, or more BESIII data.

Hadronic transitions

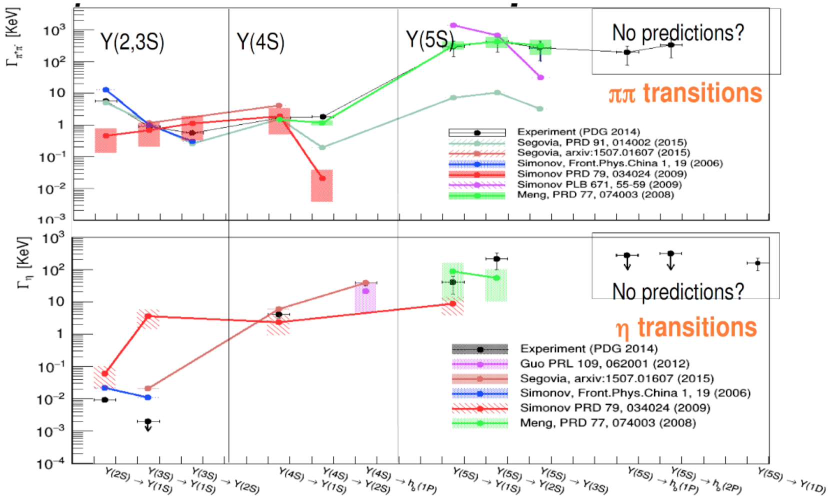
- Important informations on bottomonium given also by the **study of transitions** between its states.
- These transitions can be predicted by effective potential models, rather well established in the case of the dominant radiative transitions
- Instead BRs not well predicted in particular in the 2-body hadronic transitions (η, π^0)
- In quarkonia below open-bottom threshold, should be explained by **QCDME** (analogy with the QED multiple expansion) in terms of momentum of the emitted gluons
- From Heavy Quark Spin Symmetry (HQSS), the spin-flipping η-transtions between bottomonia are suppress by a factor $(\Lambda_{\text{QCD}}/m_b)^2$ comparing to $\pi^+\pi^-$-transitions:

$$\mathcal{R}^{\eta-tran}_{\pi^+\pi^- -tran}(n,m) = \frac{\mathcal{B}(\Upsilon(nS) \to \eta\Upsilon(mS))}{\mathcal{B}(\Upsilon(nS) \to \pi^+\pi^-\Upsilon(mS))} \approx 10^{-3} \tag{2}$$

- Expectations:
  - **suppression of spin-flipping transitions**
    (i.e. mS$\to$ η+nS wrt mS$\to$ $\pi^+\pi^-$+nS, and mS$\to$ $\pi^+\pi^-$+nP wrt mS$\to$ $\pi^+\pi^-$nS)
  - **further suppression of isospin-violating transitions**
    (i.e. mS$\to$ π^0+nS wrt others)

Some slides from QWG2017, but focus on η transitions.

The η vs $\pi^+\pi^-$ transitions from $\Upsilon(nS)$: theory vs exp



More hadronic transitions

The partial width in units of keV:

Limited by available channels

$\Upsilon(4S) \to$	
$\Upsilon(1S)\pi^+\pi^-$	1.7 ± 0.2
$\Upsilon(1S)\eta$	4.0 ± 0.8
$\Upsilon(2S)\pi^+\pi^-$	1.8 ± 0.3
$h_b(1P)$	45 ± 7

$\mathcal{B}(\Upsilon(4S) \to \eta\Upsilon(1S)) > \mathcal{B}(\Upsilon(4S) \to \pi^+\pi^-\Upsilon(1S))$!!!

Limited by available statistics

$\Upsilon(6S) \to$	
$\Upsilon(1S)\pi^+\pi^-$	137 ± 32
$\Upsilon(2S)\pi^+\pi^-$	183 ± 43
$\Upsilon(3S)\pi^+\pi^-$	77 ± 28
$Z_b(10610, 10650)^\pm\pi^\mp$	$1300 - 6600$

$\Upsilon(5S)$ **transitions**

$\Upsilon(5S) \to$	
$\Upsilon(1S)\pi^+\pi^-$	238 ± 41
$\Upsilon(1S)\eta$	39 ± 11
$\Upsilon(1S)K^+K^-$	33 ± 11
$\Upsilon(2S)\pi^+\pi^-$	428 ± 83
$\Upsilon(2S)\eta$	204 ± 44
$\Upsilon(3S)\pi^+\pi^-$	153 ± 31
$\chi_{b1}(1P)\omega$	84 ± 20
$\chi_{b1}(1P)(\pi^+\pi^-\pi^0)_{\mathrm{non}-\omega}$	28 ± 11
$\chi_{b2}(1P)\omega$	32 ± 15
$\chi_{b2}(1P)(\pi^+\pi^-\pi^0)_{\mathrm{non}-\omega}$	33 ± 20
$\Upsilon_J(1D)\pi^+\pi^-$	~ 60
$\Upsilon_J(1D)\eta$	150 ± 48
$Z_b(10610)^\pm\pi^\mp$	2070 ± 440
$Z_b(10650)^\pm\pi^\mp$	1200 ± 300

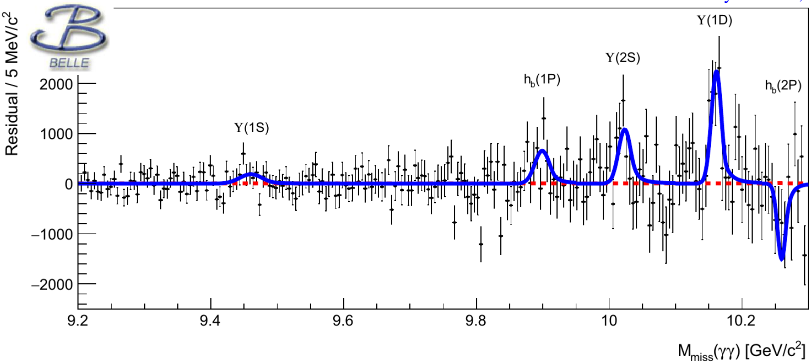
$\pi^+\pi^-$-transition is enhanced by Z_b states.

Bondar et al. **Mod. Phys. Lett. A32(2017), 1750025**

η transitions from $\Upsilon(5S)$

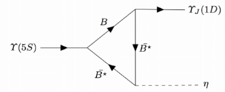
- η reconstructed in $\eta \to \gamma\gamma$, look at the missing mass spectrum, after combinatorial background subtraction

Eur. Phys. J. C78,633(2018)



- In particular, $\mathcal{B}(\Upsilon(5S) \to \eta\Upsilon(1D))$ in compatible with the prediction
- Observation of $\Upsilon(5S) \to \eta\Upsilon(1D)$: $\mathcal{B} = (4.82 \pm 0.92 \pm 0.67) \times 10^{-3}$

Process	ϵ (%)	σ_v (pb)	$1+\delta_{\mathrm{ISR}}$	σ_B (pb)
$e^+e^- \to \eta\Upsilon(1S)$	20.1	< 0.34	0.644 ± 0.007	< 0.49
$e^+e^- \to \eta h_b(1P)$	22.2	< 0.52	0.644 ± 0.007	< 0.76
$e^+e^- \to \eta\Upsilon(2S)$	16.5	$0.70 \pm 0.21 \pm 0.12$	0.644 ± 0.007	$1.02 \pm 0.30 \pm 0.17$
$e^+e^- \to \eta\Upsilon_J(1D)$	17.2	$1.14 \pm 0.22 \pm 0.15$	0.643 ± 0.006	$1.64 \pm 0.31 \pm 0.21$
$e^+e^- \to \eta h_b(2P)$	16.7	< 0.44	0.636 ± 0.005	< 0.64

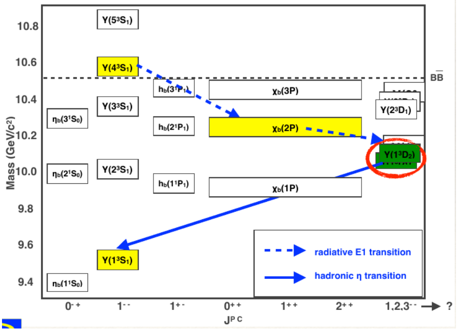


Wang et al., PRD94, 094039(2016)

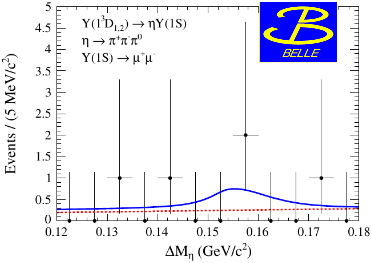
$\Upsilon(1D) \to \eta\Upsilon(1S)$

- $\eta \to \pi^+\pi^-\pi^0$ and $\pi^0 \to \gamma\gamma$, $\Upsilon(1S) \to \mu^+\mu^-$
- Predicted to be enhanced with respect to the transition $\Upsilon(1D) \to \pi^+\pi^-\Upsilon(1S)$ by the axial anomaly in QCD

Voloshin PLB562, 68(2003)



Belle: PRD96,052005(2017)



- $\Upsilon(1D)$ could be produced via double-radiative transitions from $\Upsilon(4S)$ through $\chi_{bJ}(2P)$ states
- $\mathcal{B}(\Upsilon(4S) \to \gamma\gamma\Upsilon(1D)) \times \mathcal{B}(\Upsilon(1D) \to \eta\Upsilon(1S)) < 2.3 \times 10^{-5}$ at 90% C.L.

Summary

- $e^+e^- \to \gamma + \chi_{cJ}/\eta_c$ are measured by Belle, χ_{c1} signal is observed at $\sqrt{s} = 10.58$ GeV with 5.1σ significance.
- $X^*(3860)$ is observed in $e^+e^- \to J/\psi + D\overline{D}$, which shows that $X^*(3860)$ is a good candidate of $\chi_{c0}(2P)$. The following question is the nature of $X(3915)$ observed in $\omega J/\psi$.
- $B \to X_{c\bar{c}} + K$ measurement has been improved by Belle. It's on the way to get the absolute $\mathcal{B}$s of $X(3872)$ decays.
- η-transitions for quarkonium(-like) states have been reviewed. It looks η-transition is a good way to study XYZ particles.

Thank you!

Backup

MVA in $e^+e^- \to J/\psi D\overline{D}$

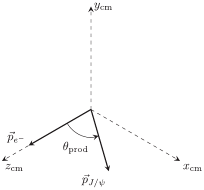


FIG. 8. Definition of the production angle (in the e^+e^- center-of-mass frame).

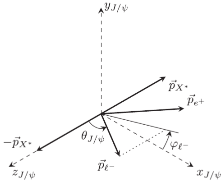


FIG. 9. Definitions of the J/ψ helicity angle and the angle φ_{ℓ^-} (in the J/ψ rest frame).

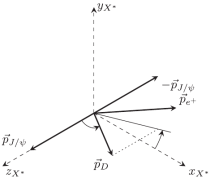


FIG. 10. The coordinate system $(x_{X^*}, y_{X^*}, z_{X^*})$ (in the X^* rest frame).

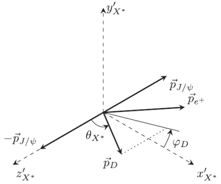


FIG. 11. Definitions of the X^* helicity angle and the angle φ_D (in the X^* rest frame).