Charmonium Studies in $\gamma\gamma$ Collisions at Belle

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Outline

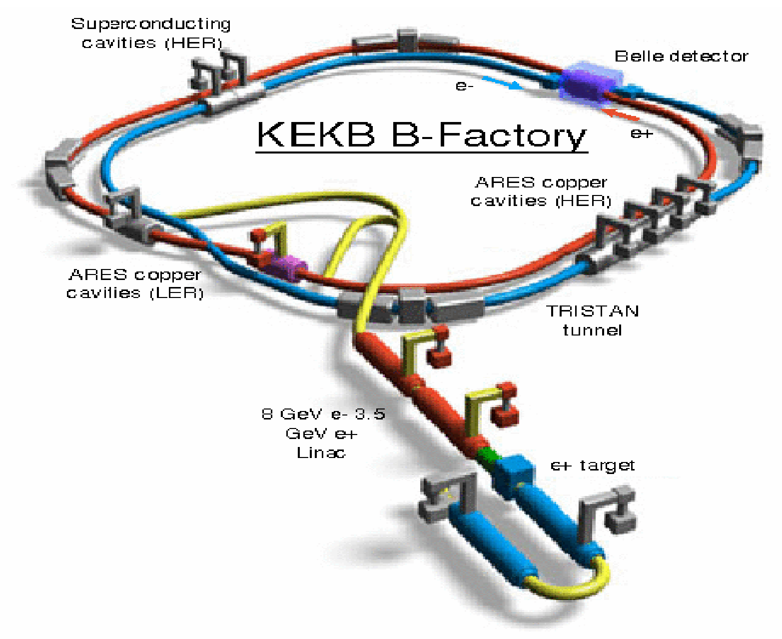
1. New charmonium states and decay modes
2. Learning more about charmonia
3. $\gamma\gamma \to \pi^0\pi^0$
4. Conclusions

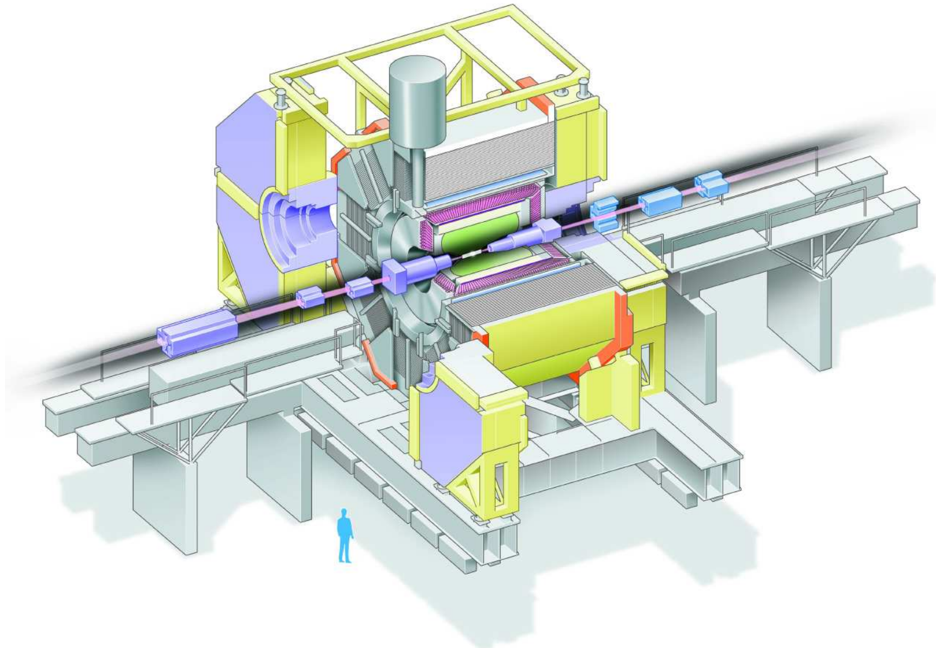
Belle Geography

International Collaboration: Belle

14 countries, 55 institutes, ~400 collaborators

KEKB, Belle Detector

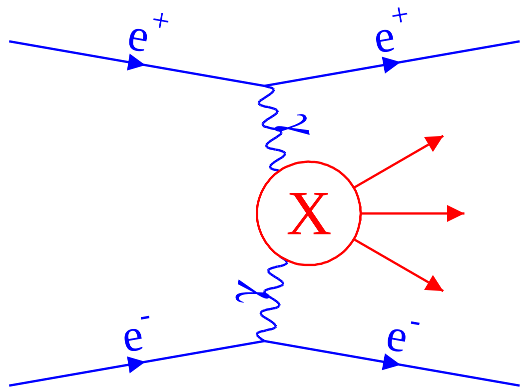




3.5 GeV e^+ × 8.0 GeV e^- $\mathcal{L}_{\mathbf{max}} = \mathbf{1.71 \times 10^{34} cm^{-2} s^{-1}}$

Continuous injection $\Rightarrow$ **1.2 fb^{-1}**/day $\int \mathcal{L}dt \approx \mathbf{715\, fb^{-1}}$

Charmonium Production in $\gamma\gamma$ Collisions



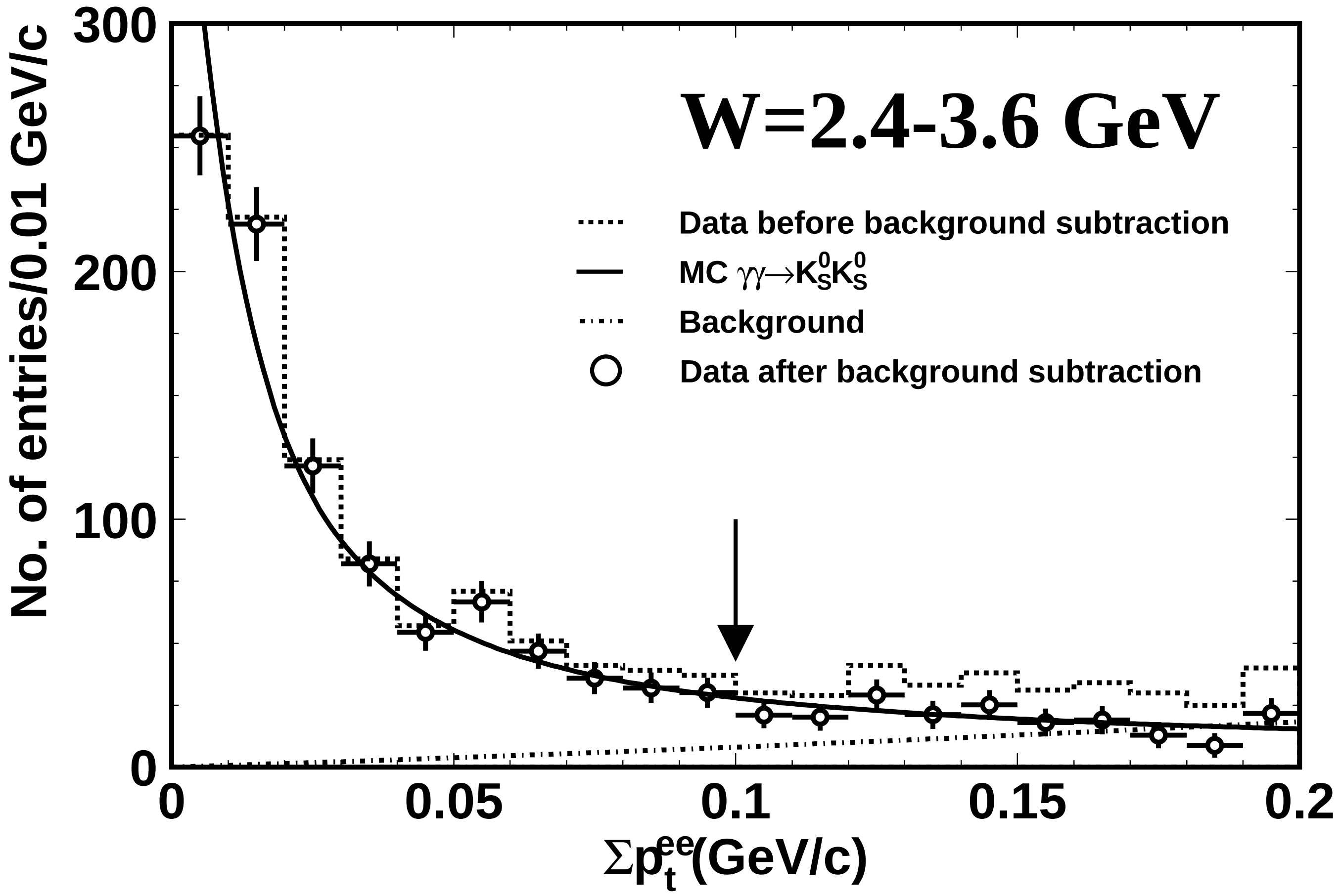
- $\gamma\gamma$ is a good laboratory to study hadrons under clean conditions
- No (single, double)-tag = 0(1,2) scattered $e^{\pm}$ detected
- For no-tag the allowed quantum numbers are $J^{PC} = 0^{-+},\ 0^{++},\ 2^{-+},\ 2^{++}, \ldots$
- Two-photon width $\Gamma_{\gamma\gamma}$ – important parameter predicted by theory

How are $\gamma\gamma$ Events Selected

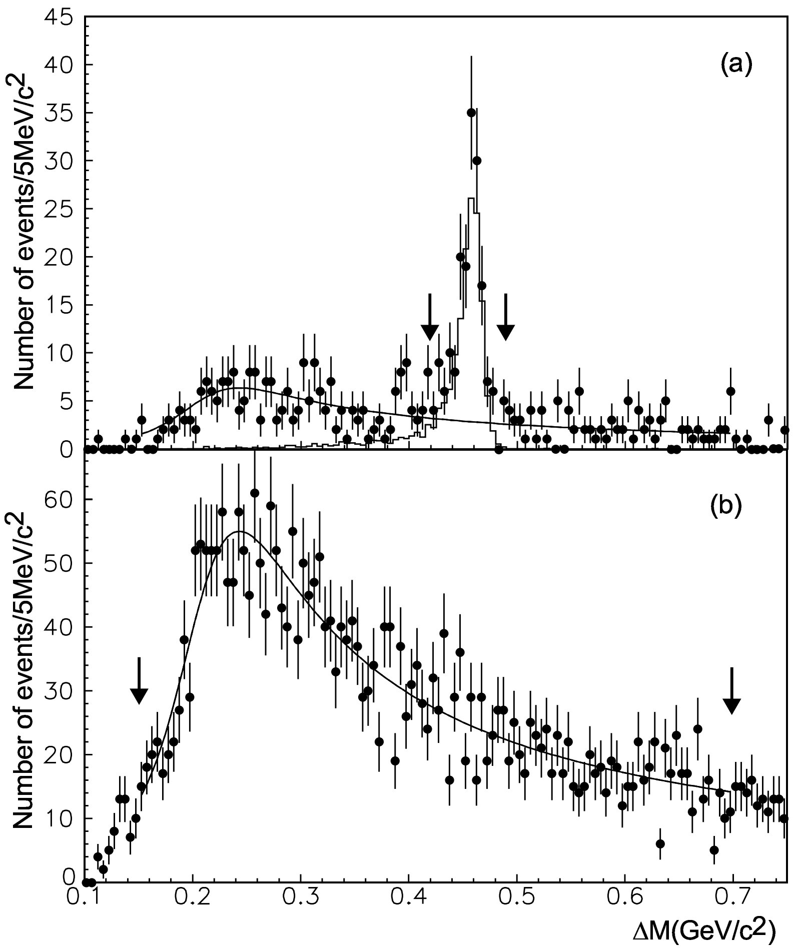
- No-tag, i.e. only products of the $\gamma\gamma$ collision detected
- Total momentum and energy restricted
- Good transverse momentum balance: $|\Sigma \vec{p}_t^{\,*}|$ restricted
- Particle identification criteria applied
- Background subtracted
- From the number of events $\mathcal{G}$ obtained

$$\mathcal{G}(R \to X) \equiv \Gamma_{\gamma\gamma}\mathcal{B}(R \to X) \propto \frac{N_{\rm ev} m_R^2}{\int L dt \; dL_{\gamma\gamma}/dW_{\gamma\gamma} \; \epsilon}$$

Background Determination in $\gamma\gamma$ Analysis

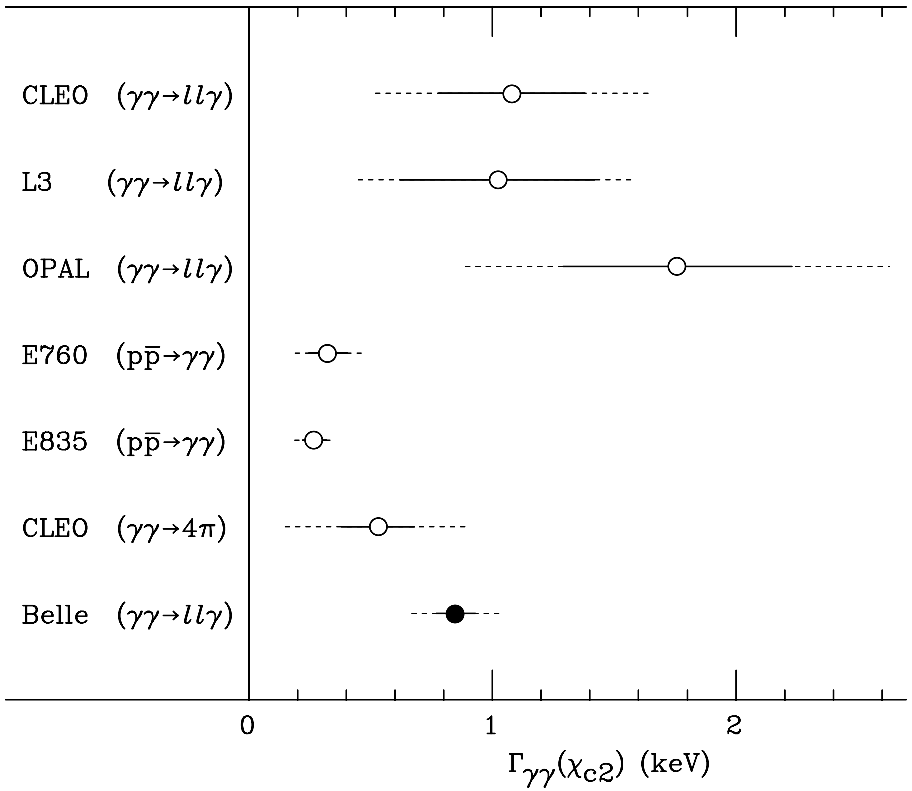


$\chi_{c2} \to J/\psi\gamma$ – I



K. Abe et al., PLB 540, 33 (2002) $32.6\ \mathrm{fb}^{-1}$

$\chi_{c2} \to J/\psi\gamma$ – II



Big spread of $\Gamma_{\gamma\gamma}(\chi_{c2})$, possible conflict of e^+e^- vs. $p\bar{p} \to \gamma\gamma$

$\chi_{c2} \to J/\psi\gamma$ – III

C. Patrignani, PRD 64, 034017 (2001):

Determinations of $\Gamma_{\gamma\gamma}$ suffer from strong correlations and different assumptions for the intermediate $\mathcal{B}$'s of the J/ψ, $\psi(2S)$ and χ_{cJ}

Since 2002 correlations between different PDG quantities removed

Mode	PDG-2001	PDG-2007
$\mathcal{B}(J/\psi\gamma), \%$	13.5 ± 1.1	20.3 ± 1.0
$\mathcal{B}(\gamma\gamma), 10^{-4}$	1.42 ± 0.24	2.58 ± 0.19

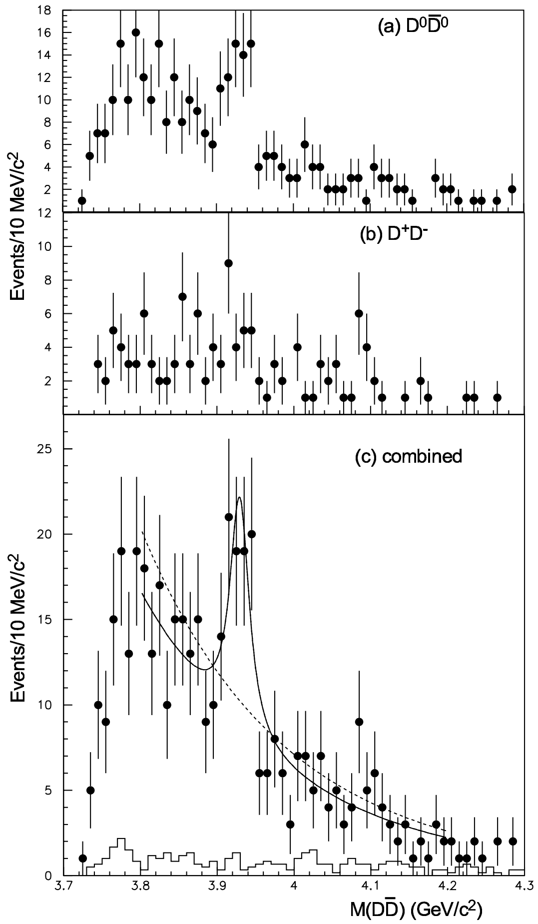
$\Gamma_{\gamma\gamma}\mathcal{B}(J/\psi\gamma)$ for the χ_{c2}

Directly measured parameters should be quoted by authors!

Group	$\Gamma_{\gamma\gamma}(\chi_{c2})\mathcal{B}(\chi_{c2} \to J/\psi\gamma)$, eV
TPC-2γ - 1993	$470 \pm 240 \pm 120$
CLEO - 1994	$150 \pm 42 \pm 36$
OPAL - 1998	$242 \pm 65 \pm 51$
L3 - 1999	$139 \pm 55 \pm 21$
Belle - 2002	$114 \pm 11 \pm 9$
CLEO - 2006	$111 \pm 12 \pm 9$
PDG-2007 (av.)	117 ± 10
PDG-2007 (fit)	108 ± 8

No conflict observed by comparing $\Gamma_{\gamma\gamma}(\chi_{c2})\mathcal{B}(\chi_{c2} \to J/\psi\gamma)$

Observation of $\chi_{c2}(2P)$



395 fb^{-1}

64 ± 18 ev. (5.3σ)

$M = 3929 \pm 5 \pm 2$ MeV

$\Gamma = 29 \pm 10 \pm 2$ MeV

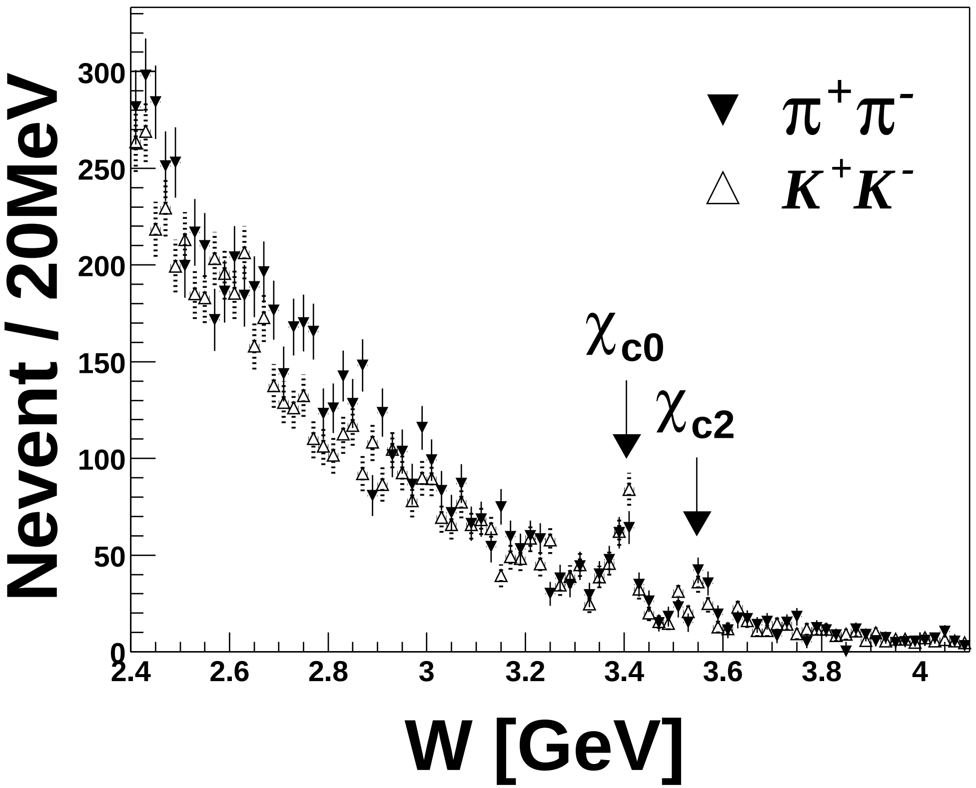
$\Gamma_{\gamma\gamma}\mathcal{B}(D\bar{D}) = 0.18 \pm 0.05 \pm 0.03$ keV

$\mathcal{B}(D^+D^-)/\mathcal{B}(D^0\bar{D}^0) = 0.74 \pm 0.43 \pm 0.16$

Angular analysis $\Rightarrow$ spin=2

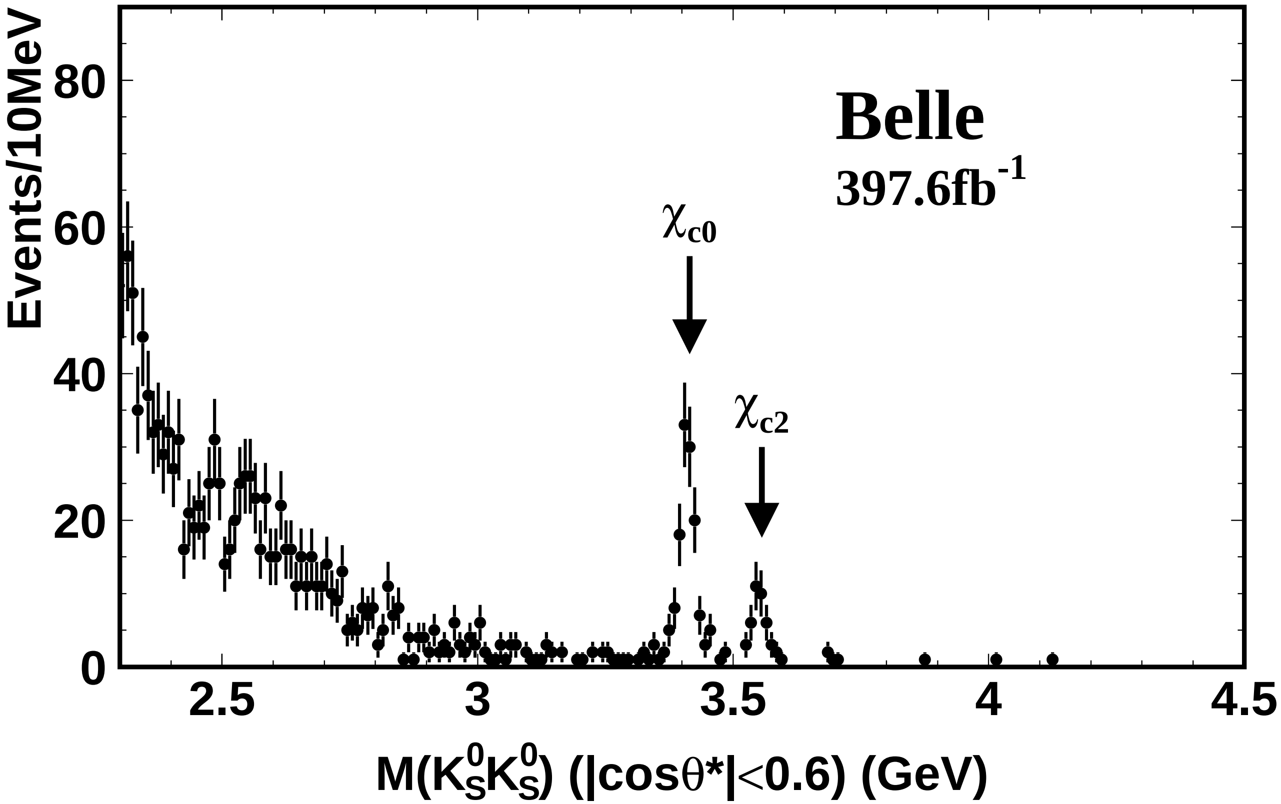
S. Uehara et al., PRL 96, 082003 (2006)

$\gamma\gamma \to \chi_{c0(2)} \to \pi^+\pi^-, \; K^+K^-$



H. Nakazawa et al., PLB 615, 39 (2005) 87.7 fb^{-1}

$\gamma\gamma \to \chi_{c0(2)} \to K_S^0 K_S^0$



W.-T. Chen et al., PLB 651, 15 (2007) 397.6 fb^{-1}

$\gamma\gamma \longrightarrow \chi_{c0(2)} \longrightarrow \pi^+\pi^-, K^+K^-, K^0_S K^0_S$

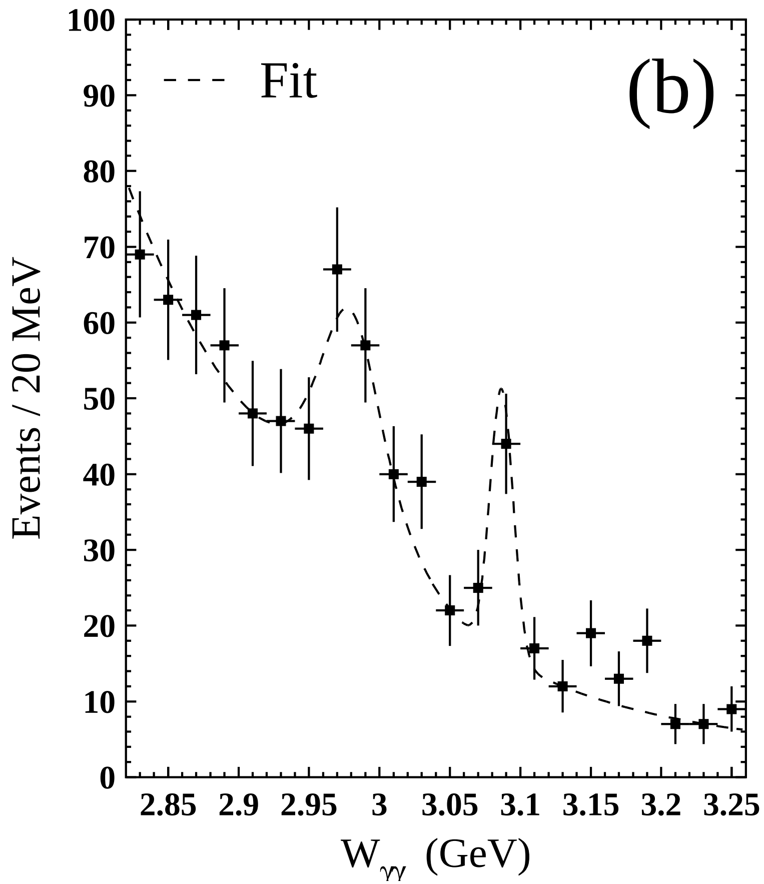
$\mathcal{G} \equiv \Gamma_{\gamma\gamma}\mathcal{B}$, eV

Mode	χ_{c0}	χ_{c2}
$\pi^+\pi^-$	$15.1 \pm 2.1 \pm 2.3$	$0.76 \pm 0.14 \pm 0.11$
K^+K^-	$14.3 \pm 1.6 \pm 2.3$	$0.44 \pm 0.11 \pm 0.07$
$K^0_S K^0_S$	$7.00 \pm 0.65 \pm 0.71$	$0.31 \pm 0.05 \pm 0.03$

$R \equiv \mathcal{B}_1/\mathcal{B}_2$

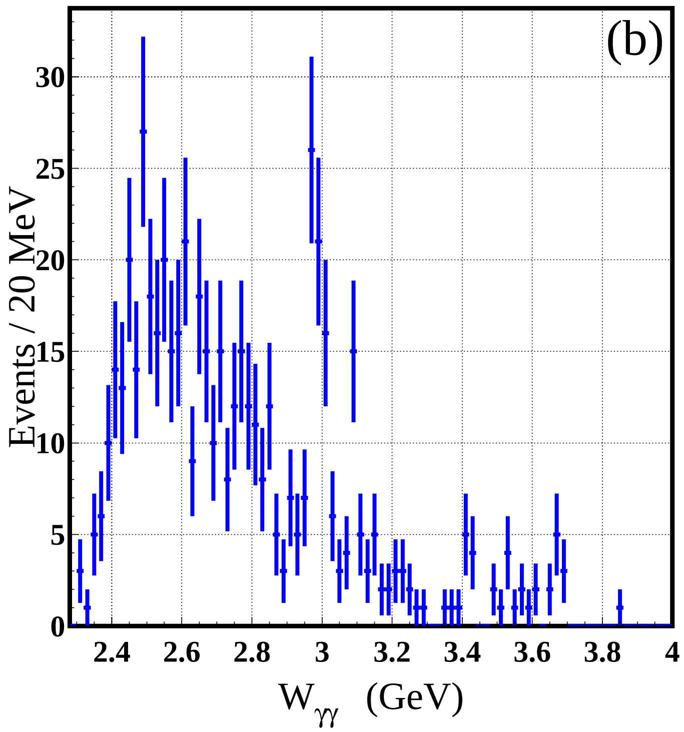
Modes	$R(\chi_{c0})$	$R(\chi_{c2})$
$K^0_S K^0_S/\pi^+\pi^-$	$0.46 \pm 0.08 \pm 0.07$	$0.40 \pm 0.10 \pm 0.06$
$K^0_S K^0_S/K^+K^-$	$0.49 \pm 0.07 \pm 0.08$	$0.70 \pm 0.21 \pm 0.12$

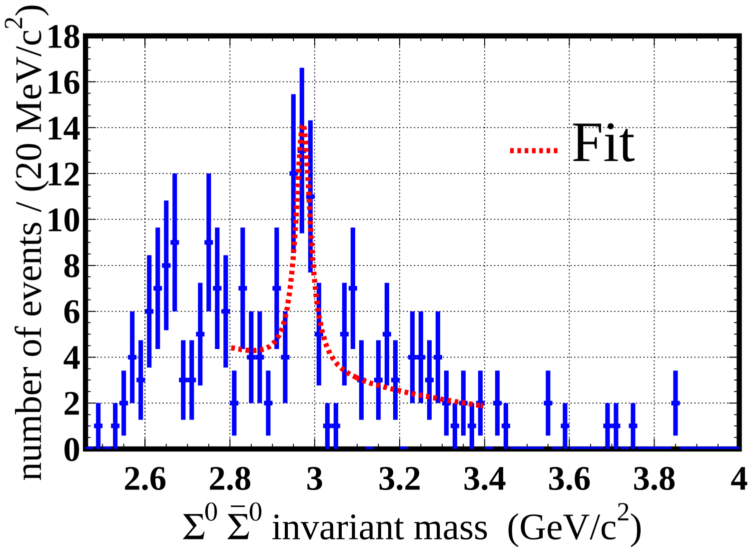
$\gamma\gamma \to \eta_c \to p\bar{p}$



C.-C. Kuo et al., PLB 621, 41 (2005) 89 fb^{-1}

$\gamma\gamma \to \eta_c \to \Lambda\bar{\Lambda},\ \Sigma^0\bar{\Sigma}^0$





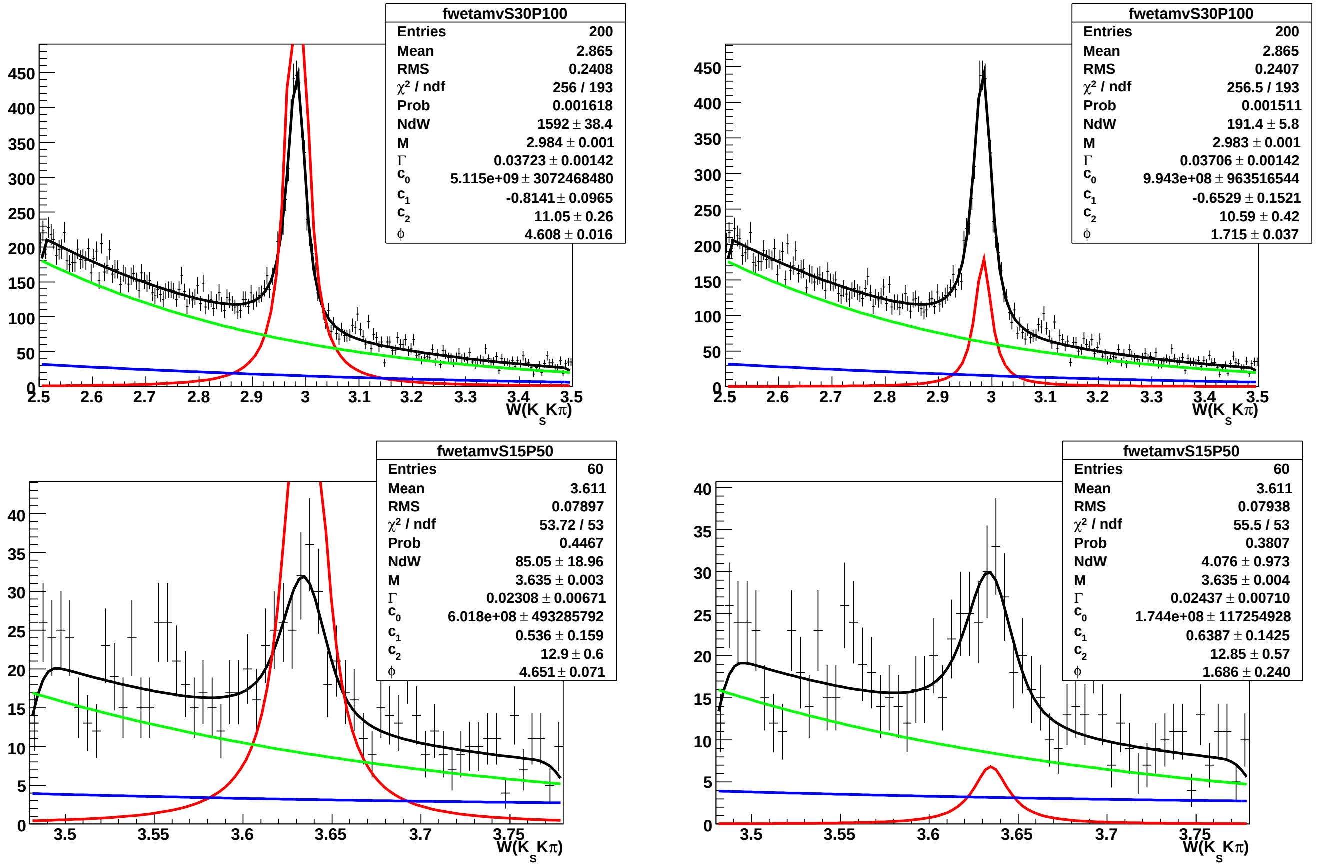
C.-C. Kuo et al., hep-ex/0609048 464 fb^{-1}

$$\gamma\gamma \to \eta_c \to p\bar{p},\ \Lambda\bar{\Lambda},\ \Sigma^0\bar{\Sigma}^0$$

Mode	$N_{\rm ev}$ (σ)	$\mathcal{G}$, eV
$p\bar{p}$	157 ± 33 (5.3)	$7.20 \pm 1.53^{+0.67}_{-0.75}$
$\Lambda\bar{\Lambda}$	101.2 ± 16.5 (6.6)	$6.21 \pm 1.01^{+0.49}_{-0.52}$
$\Sigma^0\bar{\Sigma}^0$	36.1 ± 9.3 (3.9)	$9.80 \pm 2.50^{+0.98}_{-1.03}$

First evidence for $\eta_c \to \Sigma^0\bar{\Sigma}^0$

η_c and $\eta_c(2S)$ in $\gamma\gamma \to K^0_S K\pi$ – I



483fb^{-1} Interference effects extremely important

H. Nakazawa, talk at PHOTON 07

η_c and $\eta_c(2S)$ in $\gamma\gamma \to K_S^0 K\pi$ – II

M, MeV	Group	η_c	$\eta_c(2S)$
	Belle	$2981.4 \pm 0.5 \pm 0.4$	$3633.7 \pm 2.3 \pm 1.9$
	PDG-07	2979.8 ± 1.2	3637.0 ± 4.0
	CLEO	$2981.8 \pm 1.3 \pm 1.5$	$3642.9 \pm 3.1 \pm 1.5$
	BaBar	$2982.5 \pm 1.1 \pm 0.9$	$3630.8 \pm 3.4 \pm 1.0$
Γ, MeV	Group	η_c	$\eta_c(2S)$
	Belle	$36.6 \pm 1.5 \pm 2.0$	$19.1 \pm 6.9 \pm 6.0$
	PDG-07	25.5 ± 3.4	14.0 ± 7.0
	CLEO	$24.8 \pm 3.4 \pm 3.5$	$6.3 \pm 12.4 \pm 4.0$ (< 31)
	BaBar	$34.3 \pm 2.3 \pm 0.9$	$17.0 \pm 8.3 \pm 2.5$
$\Gamma_{\gamma\gamma}\mathcal{B}$, eV	Group	η_c	$\eta_c(2S)$
	Belle	$142 \pm 4 \pm 14$	$11.2 \pm 2.4 \pm 2.7$

Two-photon Width for the η_c and $\eta_c(2S)$

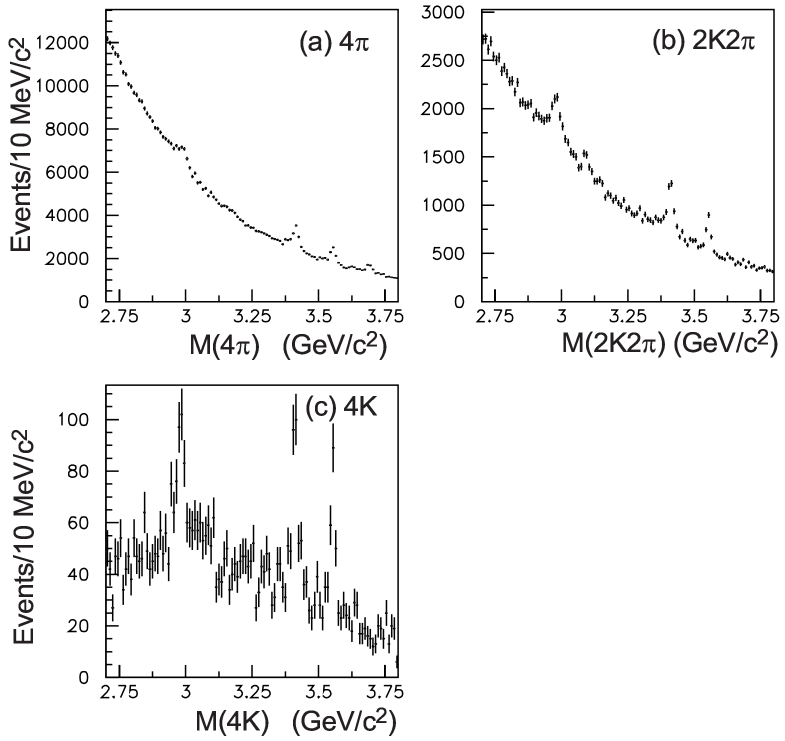
Assuming that $\mathcal{B}(\eta_c \to K_S^0 K^\pm \pi^\mp) = \mathcal{B}(\eta_c(2S) \to K_S^0 K^\pm \pi^\mp)$

Group	$\Gamma_{\gamma\gamma}(\eta_c)$, keV	$\Gamma_{\gamma\gamma}(\eta_c(2S))$, keV
Belle	$7.48 \pm 0.20 \pm 0.73$	$0.59 \pm 0.13 \pm 0.14$
PDG-07	$6.7^{+0.9}_{-0.8}$	–
CLEO	$7.7 \pm 0.4 \pm 0.5 \pm 2.2$	1.4 ± 0.6

η_c and $\eta_c(2S)$ in $\gamma\gamma \to K_S^0 K\pi$ – Interference

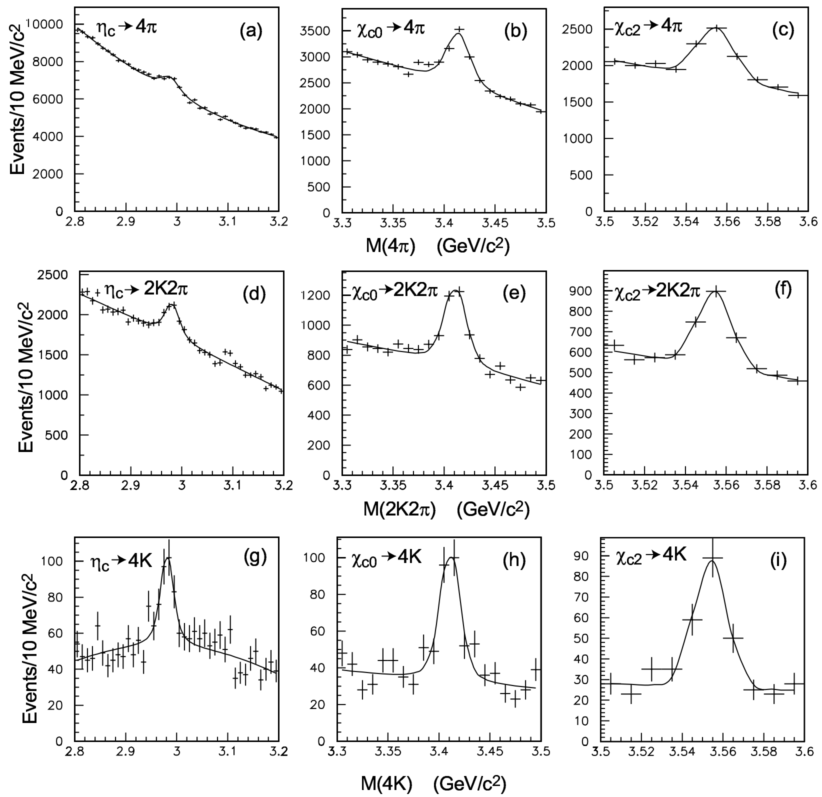
		η_c	$\eta_c(2S)$
M, MeV	no int.	2981.4 ± 0.5	3633.7 ± 2.3
	$\phi > \pi$	2983.6 ± 0.7	3634.8 ± 3.2
	$\phi < \pi$	2983.5 ± 0.7	3634.8 ± 3.2
Γ, MeV	no int.	36.6 ± 1.5	19.1 ± 6.9
	$\phi > \pi$	37.2 ± 1.4	23.0 ± 6.7
	$\phi < \pi$	37.1 ± 1.4	23.0 ± 7.1
$\Gamma_{\gamma\gamma}$, keV	no int.	7.48 ± 0.20	0.59 ± 0.13
	$\phi > \pi$	16.5 ± 0.4	2.16 ± 0.49
	$\phi < \pi$	1.99 ± 0.06	0.22 ± 0.05
ϕ	$\phi > \pi$	4.61 ± 0.02	4.65 ± 0.07
	$\phi < \pi$	1.71 ± 0.04	1.67 ± 0.22

$\gamma\gamma \to 2\pi^+2\pi^-,\ \pi^+\pi^-K^+K^-,\ 2K^+2K^-$ – I



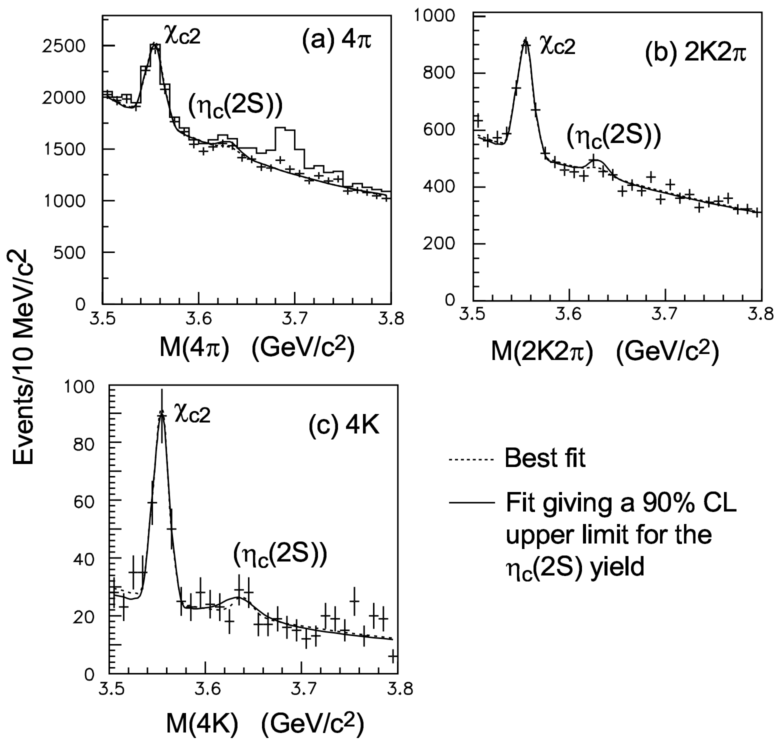
S. Uehara et al., arXiv:0706.3955, EPJC; $395\ \mathrm{fb}^{-1}$

$\gamma\gamma \to 2\pi^+2\pi^-,\ \pi^+\pi^-K^+K^-,\ 2K^+2K^-$ – II



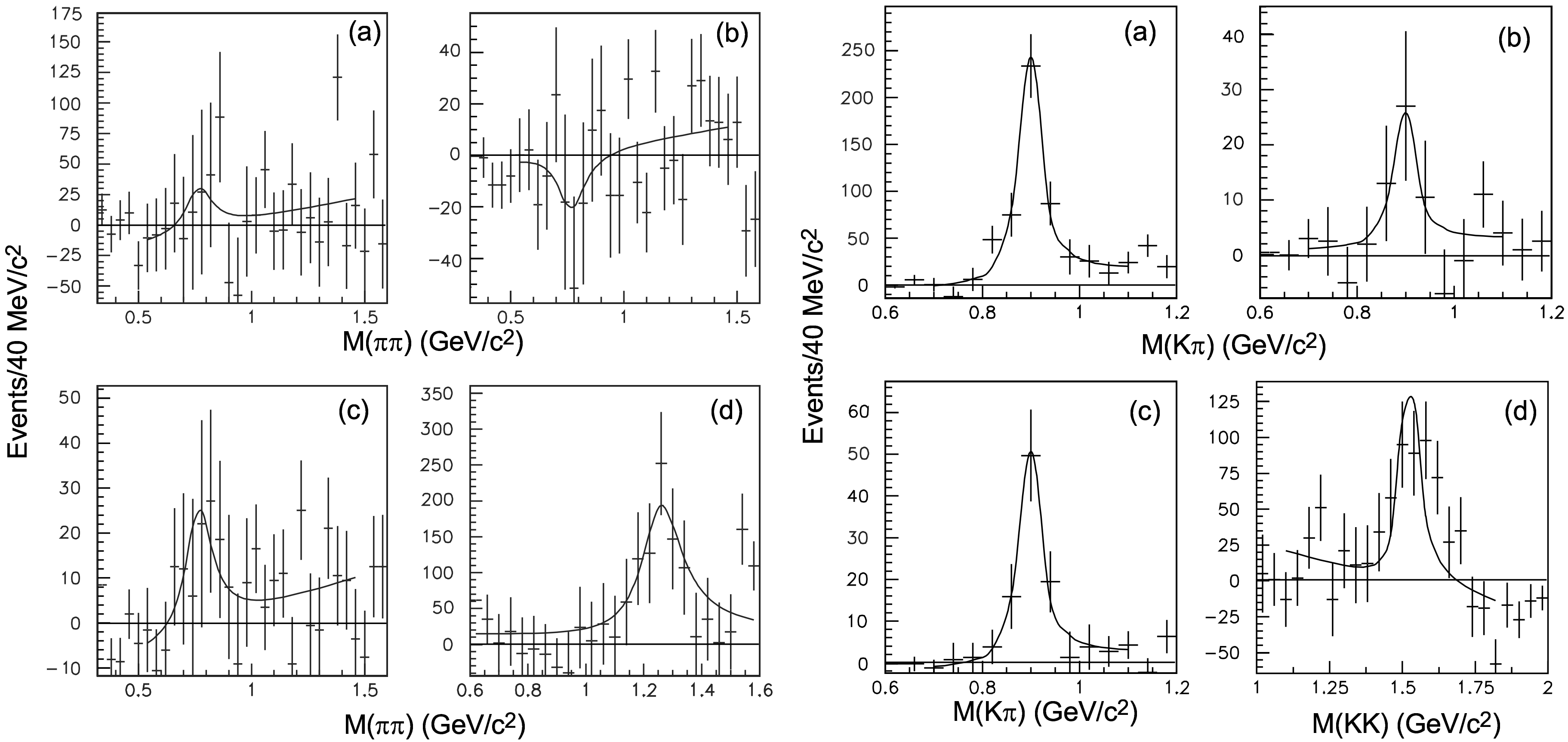
The new $\Gamma_{\gamma\gamma}(\eta_c)\mathcal{B}$ values are a few times smaller than previously

$\gamma\gamma \to 2\pi^+2\pi^-,\ \pi^+\pi^-K^+K^-,\ 2K^+2K^-$ – III



For the $\eta_c(2S)$ UL's on $\Gamma_{\gamma\gamma}\mathcal{B}$ are 2–5 times smaller compared to the $\eta_c(1S)$

$\gamma\gamma \to 2\pi^+2\pi^-,\ \pi^+\pi^-K^+K^-,\ 2K^+2K^-$ – IV



$\eta_c,\ \chi_{c0},\ \chi_{c2} \to \rho^0\rho^0$ not observed

$\eta_c,\ \chi_{c2} \to K^{*0}\bar{K}^{*0},\ \ \eta_c \to f_2 f_2,\ f_2 f_2'$ seen

$\gamma\gamma \to 2\pi^+2\pi^-,\ \pi^+\pi^-K^+K^-,\ 2K^+2K^-$ – V

$$\mathcal{G}(R \to X) = \mathcal{B}(R \to X)\frac{\mathcal{G}(R \to A)}{\mathcal{B}(R \to A)}$$

Mode	$\mathcal{G}^{\eta_c}_{\rm Belle}$, eV	$\mathcal{G}^{\eta_c}_{\rm dir}$, eV	$\mathcal{G}^{\eta_c}_{\rm indir}$, eV	$\mathcal{G}^{\eta_c'}$, eV
$\pi^+\pi^-\pi^+\pi^-$	$40.7 \pm 3.7 \pm 5.3$	$180 \pm 70 \pm 20$	83 ± 24	< 6.5
$K^+K^-\pi^+\pi^-$	$25.7 \pm 3.2 \pm 4.9$	210 ± 70	102 ± 30	< 5.0
$K^+K^-K^+K^-$	$5.6 \pm 1.1 \pm 1.6$	280 ± 70	11 ± 5	< 2.9

Significantly smaller $\mathcal{G}(\eta_c)$ than before!

Upper limits for $\mathcal{G}(\eta_c(2S))$ 2–5 smaller than $\mathcal{G}(\eta_c)$

Two-body Decays of the η_c

Mode	$\mathcal{G}^{\eta_c}_{\rm Belle}$, eV	$\mathcal{G}^{\eta_c}_{\rm dir}$, eV	$\mathcal{G}^{\eta_c}_{\rm indir}$, eV
$\rho\rho$	< 39	–	130 ± 43
$f_2 f_2$	$69 \pm 17 \pm 12$	–	74 ± 36
$K^*\bar{K}^*$	$32.4 \pm 4.2 \pm 5.8$	–	66 ± 22
$f_2 f_2'$	$49 \pm 9 \pm 13$	–	–
$\phi\phi$	$6.8 \pm 1.2 \pm 1.3$	–	19 ± 5

More precise and smaller two-body $\mathcal{B}$'s

$\rho\rho$ not seen, first evidence for $f_2 f_2'$

$\gamma\gamma \to \chi_{c0(2)} \to 2\pi^+2\pi^-,\ \pi^+\pi^-K^+K^-,\ 2K^+2K^-$

χ_{c0} Mode	$\mathcal{G}_{\rm Belle}$, eV	$\mathcal{G}_{\rm dir}$, eV	$\mathcal{G}_{\rm indir}$, eV
$\pi^+\pi^-\pi^+\pi^-$	$44.7 \pm 3.6 \pm 4.9$	$75 \pm 13 \pm 8$	69 ± 13
$K^+K^-\pi^+\pi^-$	$38.8 \pm 3.7 \pm 4.7$	–	53 ± 12
$K^+K^-K^+K^-$	$7.9 \pm 1.3 \pm 1.1$	–	7.8 ± 1.6

χ_{c2} Mode	$\mathcal{G}_{\rm Belle}$, eV	$\mathcal{G}_{\rm dir}$, eV	$\mathcal{G}_{\rm indir}$, eV
$\pi^+\pi^-\pi^+\pi^-$	$5.01 \pm 0.44 \pm 0.55$	$6.4 \pm 1.8 \pm 0.8$	7.2 ± 1.2
$K^+K^-\pi^+\pi^-$	$4.42 \pm 0.42 \pm 0.53$	–	5.8 ± 2.1
$K^+K^-K^+K^-$	$1.10 \pm 0.21 \pm 0.15$	–	1.03 ± 0.18

Knowledge of the $\mathcal{B}$'s improved

More on χ_{c0} Decays

Mode	$\mathcal{G}^{\eta_c}_{\mathrm{Belle}}$, eV	$\mathcal{G}^{\eta_c}_{\mathrm{dir}}$, eV	$\mathcal{G}^{\eta_c}_{\mathrm{indir}}$, eV
$K^{*0}K^-\pi^+$ + c.c.	$16.7 \pm 6.1 \pm 3.0$	–	34 ± 13
$\rho\rho$	< 12	–	–
$K^*\bar{K}^*$	< 18	–	5.1 ± 1.9
$\phi\phi$	$2.3 \pm 0.9 \pm 0.4$	–	2.7 ± 0.8

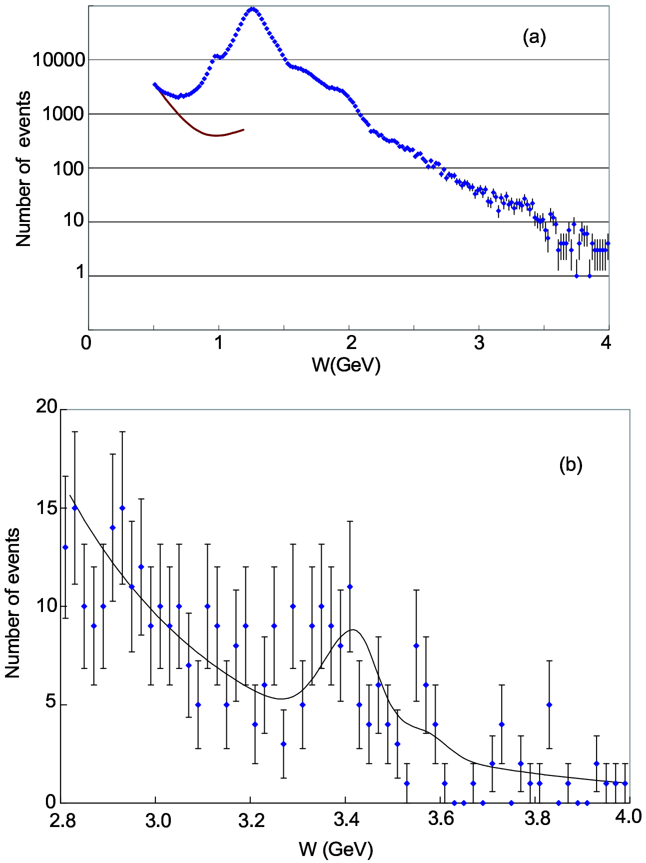
$\rho\rho$, $K^*\bar{K}^*$ not seen, $\phi\phi$ confirmed

More on χ_{c2} Decays

Mode	$\mathcal{G}^{\eta_c}_{\rm Belle}$, eV	$\mathcal{G}^{\eta_c}_{\rm dir}$, eV	$\mathcal{G}^{\eta_c}_{\rm indir}$, eV
$\rho^0\pi^-\pi^+$	$3.2 \pm 1.9 \pm 0.5$	–	3.9 ± 2.3
$\rho\rho$	< 7.8	–	–
$K^*\bar{K}^*$	$2.4 \pm 0.5 \pm 0.8$	–	2.2 ± 0.5
$\phi\phi$	$0.58 \pm 0.18 \pm 0.16$	–	1.0 ± 0.3

$\rho\rho$ not seen, $K^*\bar{K}^*$, $\phi\phi$ confirmed

$\gamma\gamma \to \pi^0\pi^0$



$95\ \text{fb}^{-1}$, $0.6\ \text{GeV} < W < 4.0\ \text{GeV}$

R	N_{ev}	$\Gamma_{\gamma\gamma}\mathcal{B}$, eV
χ_{c0}	35.3 ± 9.2	$8.4 \pm 2.2 \pm 0.8$
χ_{c2}	8.2 ± 6.4	$0.29 \pm 0.23 \pm 0.03$ (< 0.75 at 90% CL)

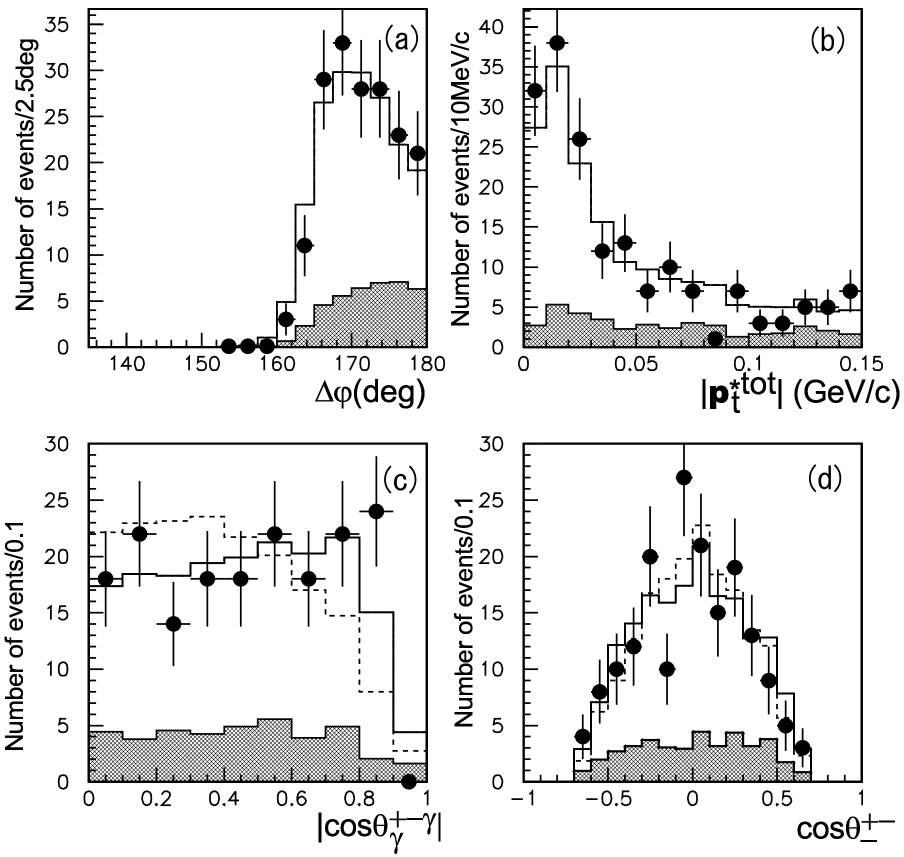
$$\Gamma_{\gamma\gamma}\mathcal{B}(\pi^0\pi^0) \approx 0.5\Gamma_{\gamma\gamma}\mathcal{B}(\pi^+\pi^-)$$

S. Uehara, talk at PHOTON 07

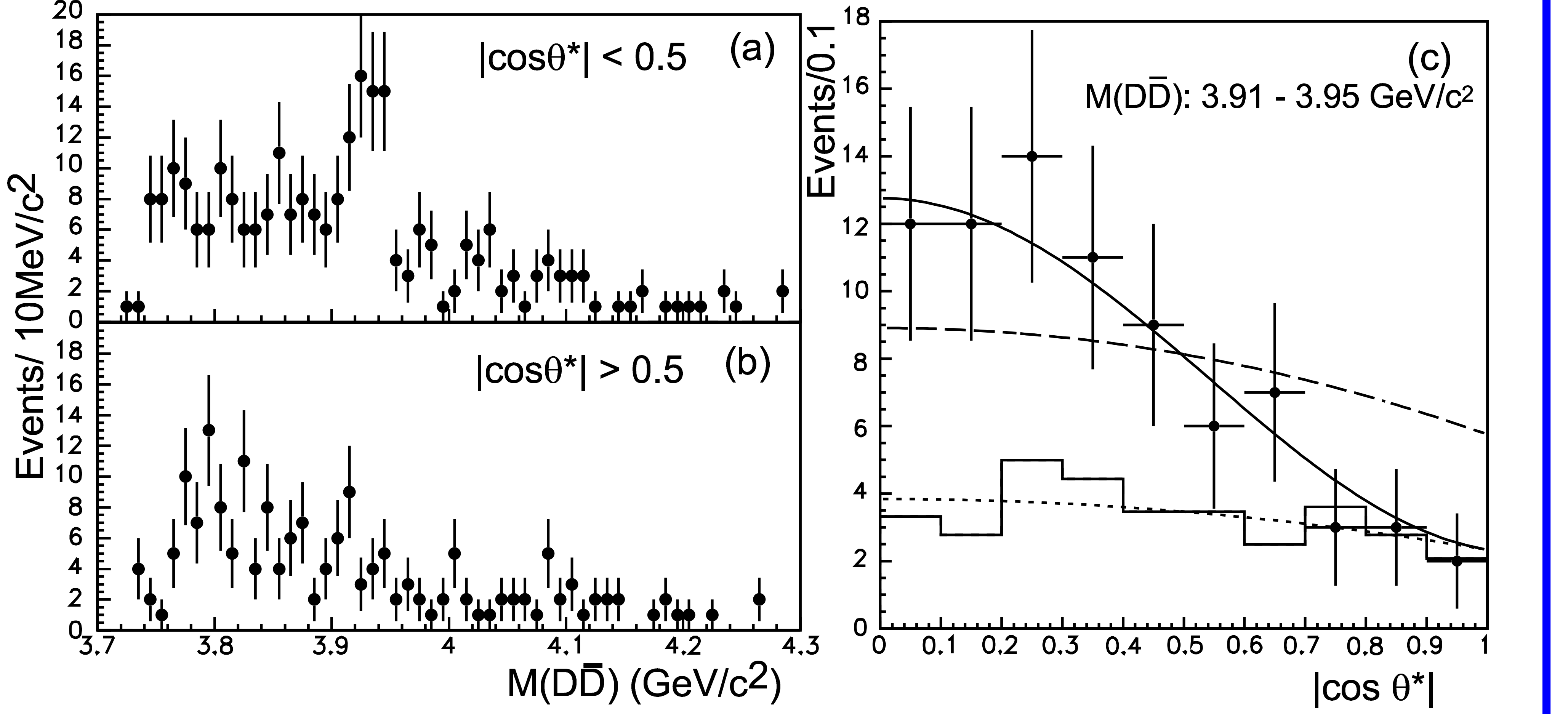
Conclusions

- A $\chi_{c2}(2P)$ candidate observed
- New decay modes are observed or first evidence shown ($\eta_c \to \Sigma^0\bar{\Sigma}^0,\ f_2 f_2'$)
- $\eta_c(2P)$ decays to $K_S^0 K^\pm \pi^\mp$ only?
- Better understanding of the $\eta_c(1S),\ \eta_c(2S),\ \chi_{c0},\ \chi_{c2}$ from $\gamma\gamma$
- Interference effects seriously affect $\Gamma_{\gamma\gamma}$
- First promising results on $\gamma\gamma \to \pi^0\pi^0$
- $\gamma\gamma$ is a very convenient laboratory to study various charmonia

$\chi_{c2} \to J/\psi\gamma$ – II



More on the $\chi_{c2}(2P)$



Mass and Width of η_c, χ_{c0} and χ_{c2} from $\gamma\gamma \to$ Four Tracks

	Belle (4T)	PDG-07
$M(\eta_c)$, MeV	$2986.1 \pm 1.0 \pm 2.5$	2979.8 ± 1.2
$\Gamma(\eta_c)$, MeV	$28.1 \pm 3.2 \pm 2.2$	26.5 ± 3.5
$M(\chi_{c0})$, MeV	$3414.2 \pm 0.5 \pm 2.3$	3414.75 ± 0.35
$\Gamma(\chi_{c0})$, MeV	$10.6 \pm 1.9 \pm 2.6$	10.4 ± 0.7
$M(\chi_{c2})$, MeV	$3555.3 \pm 0.6 \pm 2.2$	3556.20 ± 0.09
$\Gamma(\chi_{c2})$, MeV	–	2.05 ± 0.12