Inclusive and exclusive charmonium production at e^+e^- collisions

K. Hagiwara (KEK)

2004.3.10 @ KITP

Data from B factories :

- Babar : PRL 87 : 162002 (2001)
- Belle : PRL 88 : 052001 (2002) $d\sigma/dp^* \, d\cos\theta \, d\cos\theta^*$ •

$\sigma(e^+e^- \to J/\psi X) = 1.47 \pm 0.10 \pm 0.13$ pb

$p^* > 2$ GeV $\begin{cases} 1.05 \pm 0.04 \pm 0.09 \text{ pb} & \text{all } J/\psi \\ 0.72 \pm 0.08 \pm \ : \ \text{pb} & (J/\psi)_{direct} \\ 0.67 \pm 0.09 \pm \ : \ \text{pb} & \psi' \end{cases}$

- Belle : PRL 89 : 142001 (2002) $d\sigma/dM_X$ •

$\sigma(e^+e^- \to J/\psi \, \eta_c) \, B(\eta_c \to \geq 4 ch) = 33^{+7}_{-6} \pm 9$ fb

$\sigma(e^+e^- \to J/\psi \, c\bar{c}) / \sigma(e^+e^- \to J/\psi X) = 0.59^{+0.15}_{-0.13} \pm 0.12$

- Belle : hep-ex/0306015 $d\sigma/dM_X$
- B. Yabsley (Belle) @ APS (2003.4.7) "

$\sigma(e^+e^- \to J/\psi \, \eta_c) = 46 \pm 6^{+7}_{-9}$ fb •

$\sigma(e^+e^- \to \psi' \eta_c) = 18 \pm 8 \pm 7$ fb •

$\sigma(e^+e^- \to J/\psi \, c\bar{c}) / \sigma(e^+e^- \to J/\psi X) = 0.82 \pm 0.15 \pm 0.14$ •

> 0.48 (95%CL)

Our contributions :

- Exclusive : KH, E.Kou, C.F.Qiao, PLB570, 39(2003) HKQ
- Inclusive : KH, ZHLin, GHZhu, EKou, CFQiao, hep-ph/0401246 HLKQZ
- Exclusive : S.Dulat, KH, ZHLin, hep-ph/0402230 DHL

Belle : PRL 88 : 052001 (2002)

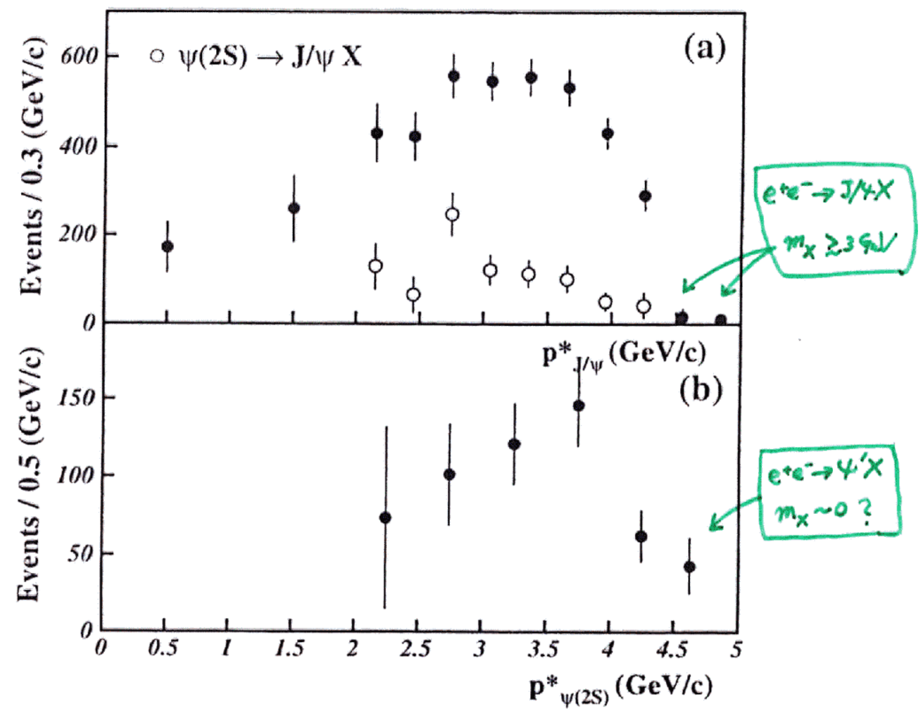


FIG. 3. c.m. momentum distributions of prompt charmonia, corrected for efficiency: (a) J/ψ (filled points) and J/ψ mesons from $\psi(2S) \to J/\psi X$ (open points); (b) $\psi(2S)$.

In the Color Singlet Model (CSM)

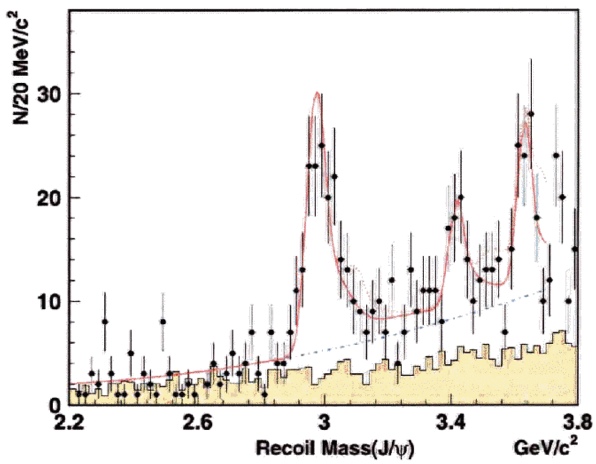
$$\frac{d\sigma(e^+e^- \to \psi' X)}{d\sigma(e^+e^- \to J/\psi_{direct} X)} \sim \frac{m_{\psi'}^2 \, \Gamma(\psi' \to ee)}{m_\psi^2 \, \Gamma(\psi \to ee)} \sim 0.6$$

⇒ We study $e^+e^- \to J/\psi_{direct} X$ first.

very small Color-Octet contribution?

New M_{recoil} fit with all charmonium states

- the fit allows all states: η_c, ψ, χ_{cJ}, $\eta_c(2S)$, $\psi(2S)$
- η_c, χ_{c0}, $\eta_c(2S)$ are confirmed
- *unaffected* by allowing for ψ
- no signif. ψ, $\chi_{c1,c2}$, $\psi(2S)$ [90% C.L. limits dotted]
- M_{recoil} scale calibrated to $< 3\,\text{MeV}/c^2$ [$e^+e^- \to \gamma\psi(2S)$]



	most general fit			default fit		
	N	$M\,[\text{GeV}/c^2]$	σ	N	$M\,[\text{GeV}/c^2]$	σ
η_c	175 ± 23	2.972 ± 0.007	9.9	179 ± 22	2.971 ± 0.006	10.6
J/ψ	-9 ± 17	fixed	--	0	fixed	--
χ_{c0}	61 ± 21	3.409 ± 0.010	2.9	72 ± 21	3.408 ± 0.009	3.8
$\chi_{c1} + \chi_{c2}$	-15 ± 19	fixed	--	0	fixed	--
$\eta_c(2S)$	108 ± 24	3.630 ± 0.008	4.4	97 ± 22	3.628 ± 0.007	4.9
$\psi(2S)$	-38 ± 21	fixed	--	0	fixed	--

APS 07–Apr–2003 $e^+e^- \to c\bar{c}c\bar{c}$ production at Belle *Bruce Yabsley*

Cross-sections for $e^+e^- \to (c\bar{c})_{res}(c\bar{c})_{res}$ (in fb)

$\frac{m_{\psi'}^2 \Gamma(\psi' \to ee)}{m_{\psi}^2 \Gamma(\psi \to ee)} \sim 0.6$

RECOIL CHARMONIUM	RECONSTRUCTED CHARMONIUM						
	η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	$\eta_c(2S)$	$\psi(2S)$
η_c	--	• $46 \pm 6^{+7}_{-9}$	--	< 18	< 20	--	• $18 \pm 8 \pm 7$
J/ψ	--	< 7 •	--	< 18	< 20	--	< 64
χ_{c0}	--	• $16 \pm 5 \pm 4$	--	< 18	< 20	--	• $17 \pm 8 \pm 7$
χ_{c1}	--	< 8	--	< 18	< 20	--	< 24
χ_{c2}	--	< 8	--	< 18	< 20	--	< 24
$\eta_c(2S)$	--	• $25 \pm 6 \pm 6$	--	< 18	< 20	--	• $31 \pm 9 \pm 10$
$\psi(2S)$	--	< 16	--	< 18	< 20	--	< 18

K∼20 ($J/\psi\,\eta_c$)
∼14 ($\psi'\eta_c$)
⇔ 3 fb (TH)

The $J/\psi\,\eta_c$ result is $O(10)\times$ NRQCD prediction;

the $J/\psi\,J/\psi$ limit is probing the region predicted by BLB.

APS 07–Apr–2003 $e^+e^- \to c\bar{c}c\bar{c}$ production at Belle *Bruce Yabsley*

Updated $\sigma(e^+e^- \to J/\psi\, c\bar{c})/\sigma(e^+e^- \to J/\psi\, X)$

Number of J/ψ from data

$p^* > 2.0$ GeV && $M_{\rm recoil} > 3.7$ GeV/c^2 $(4.44 \pm 0.09) \times 10^3$

associated state	$D^0 \to K\pi$	$D^0 \to K3\pi$	D^+	D_s^+	Λ_c^+
$N_{\rm data}^{\rm obs}$	49.6 ± 13.3	53.0 ± 21.2	56.2 ± 15.4	23.8 ± 9.4	3.0 ± 4.2
$N_{\rm data}^{0}$	$(3.10 \pm 0.83) \times 10^3$	$(3.31 \pm 1.32) \times 10^3$	$(2.08 \pm 0.57) \times 10^3$	$(1.83 \pm 0.72) \times 10^3$	$(0.17 \pm 0.23) \times 10^3$
LUND rate in $c\bar{c}$	1.19	1.19	0.43	0.22	0.13
$N(J/\psi\, c\bar{c})/N(J/\psi\, X))$	0.59 ± 0.16	0.62 ± 0.25	1.09 ± 0.30	1.87 ± 0.74	0.29 ± 0.41
AVERAGE			0.67 ± 0.12		

Can also determine the rate independent of $c\bar{c}$ fragmentation by taking

$$\frac{0.5 \times \sum N_i}{N_{J/\psi}} = 0.5 \times \frac{(7240 \pm 1240) \times 10^3}{(4438 \pm 88) \times 10^3}$$
$$= 0.82 \pm 0.15 \pm 0.14 \quad \Leftarrow \; 0.59^{+0.15}_{-0.13} \pm 0.12$$
$$> 0.48 \text{ at } 95\% \text{ CL}$$

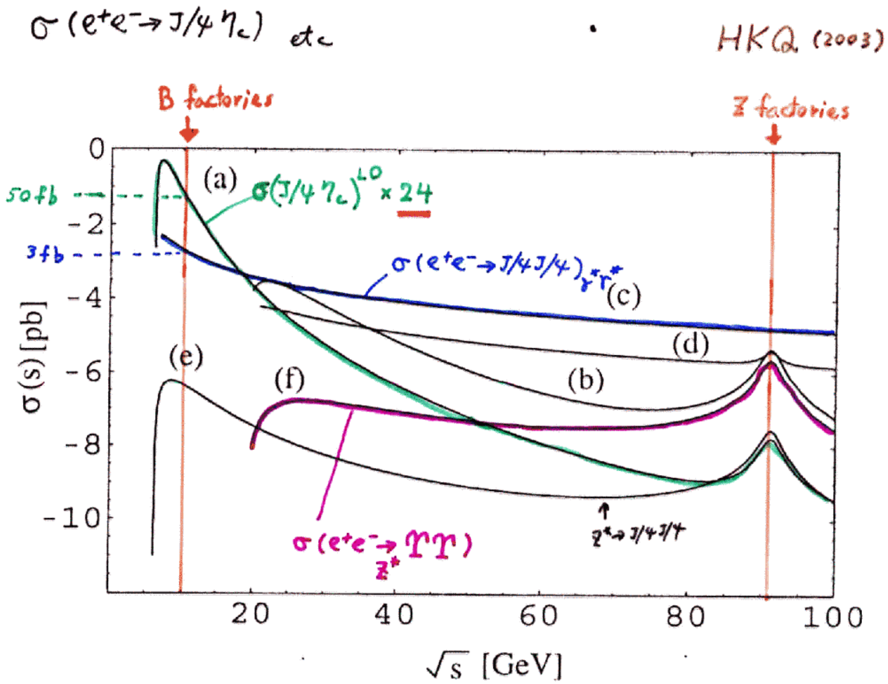
Belle : PRL 89 : 142001 (2002)

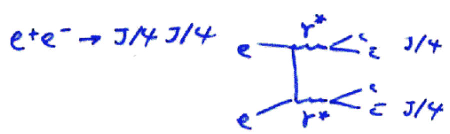
Notes:

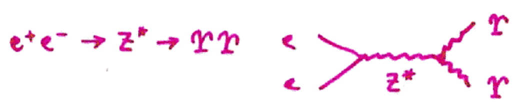
- this last number ignores Ξ_c, Ω_c^0 and $(c\bar{c})_{\rm res} X$ and is therefore conservative
- correction acc. to Lund is small (rate for other baryons is 0.03)

Summary

- Belle has updated its $e^+e^- \to c\bar{c}c\bar{c}$ study from *PRL 89, 142001 (2002)*, 46.2 fb^{-1} $\mapsto$ 101 fb^{-1}
- all previous results are confirmed
- we are beginning to probe the $e^+e^- \to \gamma^*\gamma^* \to \psi\psi$ prediction of Bodwin, Lee, Braaten
- however, our $\psi\eta_c$ yield is *unaffected* by allowing for $\psi\psi$
- we use an updated $\sigma(e^+e^- \to J/\psi\, c\bar{c})/\sigma(e^+e^- \to J/\psi\, X)$ method to reduce systematic error & model dependence
- $\sigma_{\psi c\bar{c}}/\sigma_{\psi X} = 0.82 \pm 0.15 \pm 0.14$ above 3.7 GeV/c^2
- all numbers are preliminary
- we plan a thorough study (incl. ≈ 150 fb^{-1}, angular analysis) for publication later this year
- it seems that NRQCD is in real trouble with charmonium ← !







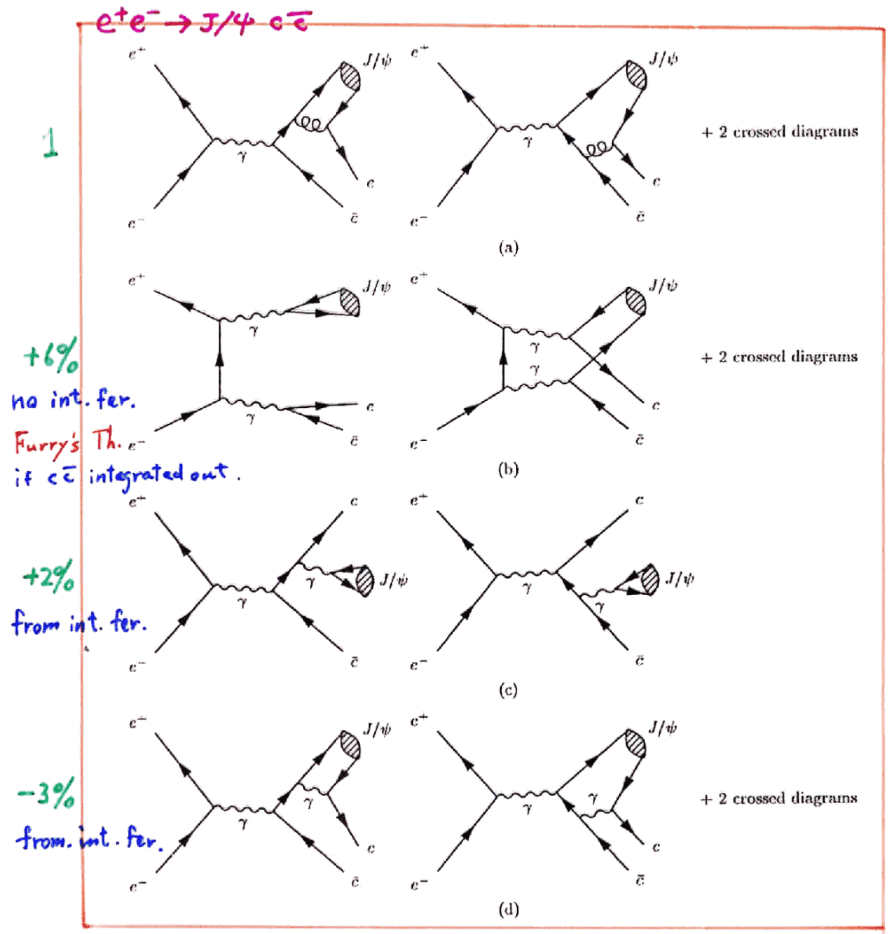
$Z \not\to \gamma\gamma$ Yang's Th. (Ang. mom. + Bose sym.)

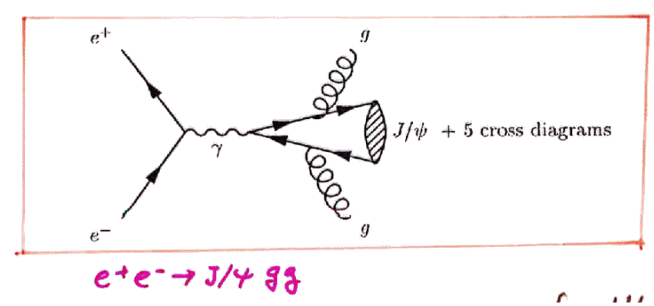
$\not\to V_T V_T$ ←

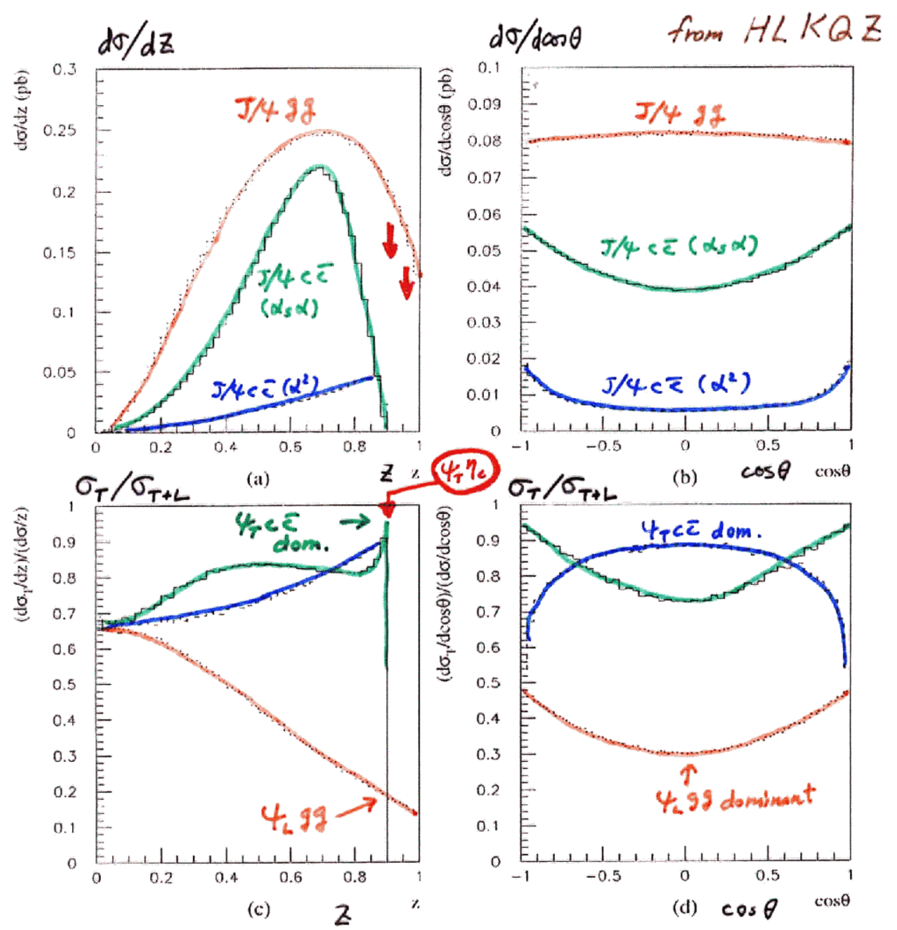
$\not\to V_L V_L$ ←

$\to V_T V_L$

But $B_r(Z \to \Upsilon\Upsilon) \simeq 5\times10^{-11}$!







σ(e⁺e⁻ → J/ψ gg) ~ 160 fb

σ(e⁺e⁻ → J/ψ cc̄) ~ 90 fb ×K

σ(e⁺e⁻ → J/ψ cc̄)_QED ~ 16 fb ×1

Contribution at large z should be suppressed.

K ~ 4 - 8

↑ Our attempt to explain

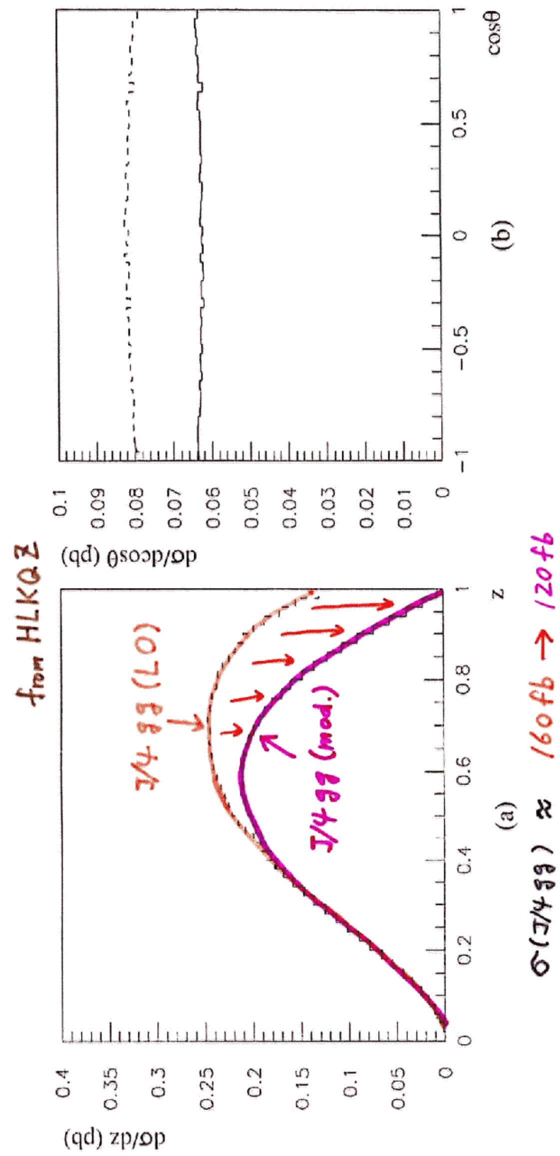
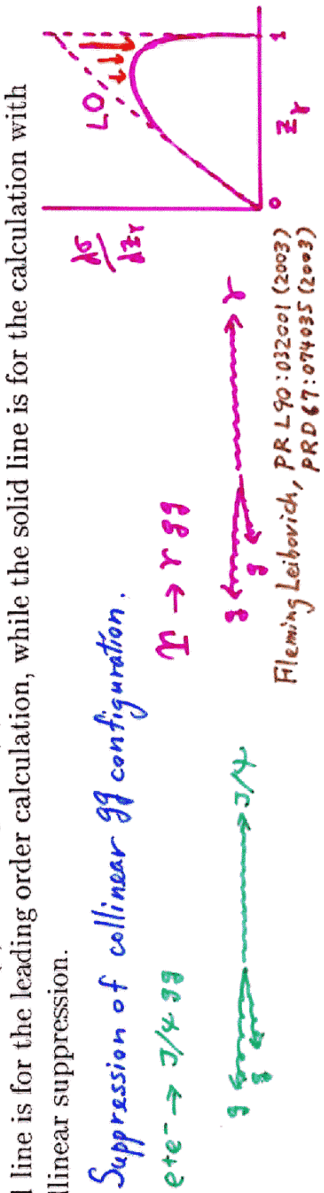
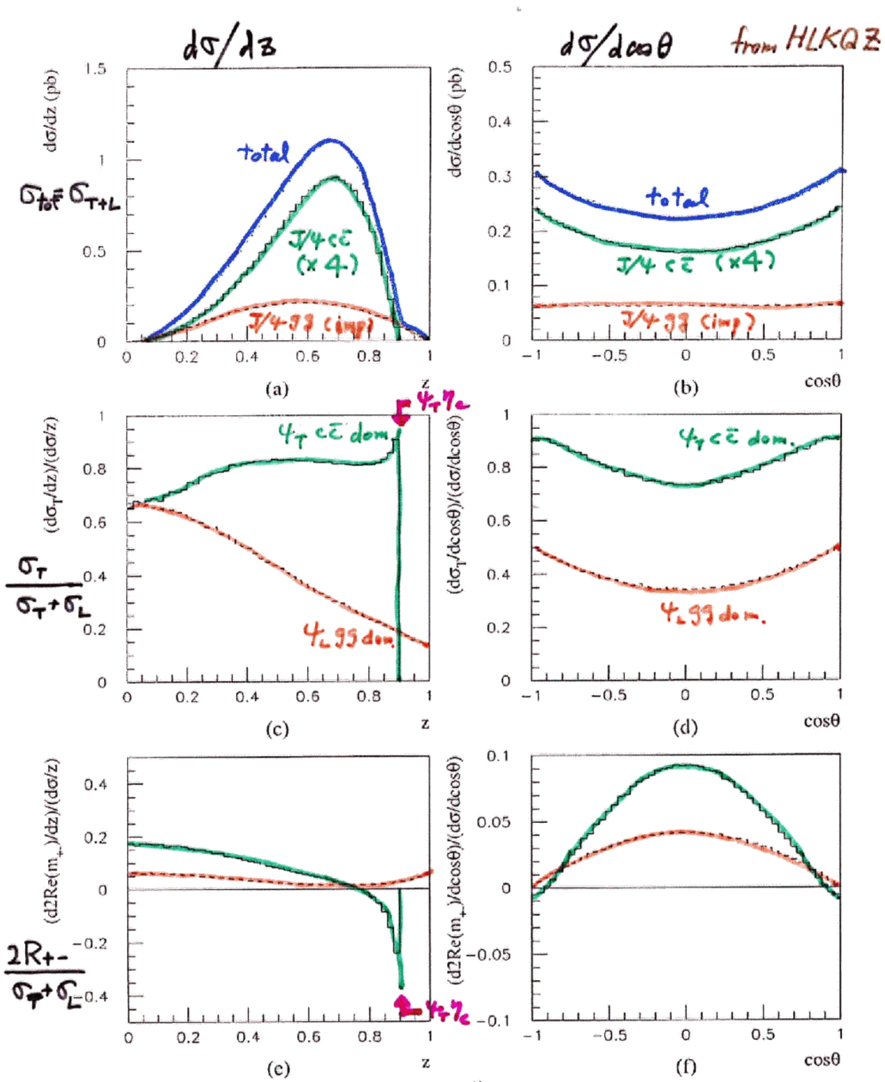


Figure 4: Momentum (a) and angular (b) distributions for the $J/\psi gg$ cross section. The dashed line is for the leading order calculation, while the solid line is for the calculation with the collinear suppression.





$$\frac{d\sigma}{dz\,d\cos\theta\,d\cos\theta^* d\phi^*} \sim \underbrace{(R_{++}+R_{--})}_{\sigma_T}\frac{1+\cos^2\theta^*}{2} + \underbrace{R_{00}}_{\sigma_L}\sin^2\theta^* + \underbrace{R_{+-}}_{\sigma_{+-}}\sin^2\theta^*\cos 2\phi^*$$

$$\frac{d\sigma(J/\psi\,\eta_c)}{d\cos\theta\,d\cos\theta^* d\phi^*} \sim 2(1+\cos^2\theta)\frac{(1+\cos^2\theta^*)}{2} - \sin^2\theta\,\sin^2\theta^*\cos 2\phi^*$$

Tentative Summary

in Seoul, 2003. 10. 7

B factory data on $e^+e^- \to J/\psi\, X$ (Babar+Belle)

$\sigma(e^+e^- \to (J/\psi)_{direct}\, X\, ;\, p^* > 2\,\mathrm{GeV}) = 720 \pm {}^{150}_{190}$ fb

$\sigma(e^+e^- \to J/\psi\, c\bar{c}) / \sigma(e^+e^- \to J/\psi X) = \begin{cases} 0.59 \pm 0.19 \\ 0.82 \pm 0.20 \end{cases}$ Belle

$\frac{d\sigma}{dz}(e^+e^- \to (J/\psi)_{direct}\, X)$ at high z (suppression at $M_X < M_{\eta_c}$) Belle

may be explained by Color Singlet Model whose LO predictions are

$\sigma(e^+e^- \to J/\psi\, c\bar{c})^{LO}_{\alpha\alpha_s} = 90$ fb

$\sigma(e^+e^- \to J/\psi\, gg)^{LO}_{\alpha\alpha_s} = 160$ fb

if we take into account (HLKQZ)

Collinear suppression of $\frac{d\sigma}{dz}(e^+e^- \to J/\psi gg)$ at large z.

Large K factor of $K \approx 4$ for $d\sigma(e^+e^- \to J/\psi c\bar{c})$.

$\Rightarrow \sigma(e^+e^- \to (J/\psi)_{direct}\, X) \approx (360 + 120)_{fb} = 480$ fb

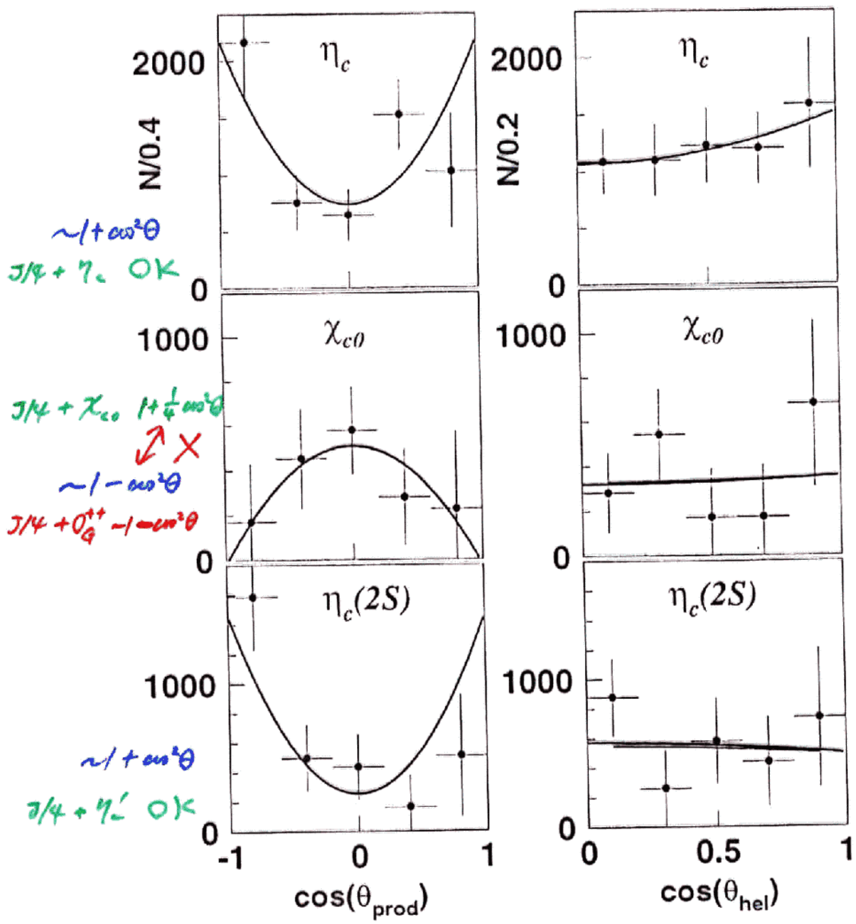
$\sigma(e^+e^- \to J/\psi c\bar{c}) / \sigma(e^+e^- \to J/\psi X) \approx \frac{360}{480} = 0.75$

$\Rightarrow$ Predictions on $\frac{d\sigma}{dz\,d\cos\theta\,d\cos\theta^* d\phi^*}$ depend on K

Large K factor for $d\sigma(e^+e^- \to J/\psi c\bar{c})$ matches more smoothly to

$\frac{\sigma(e^+e^- \to J/\psi\,\eta_c)^{EXP}}{\sigma(e^+e^- \to J/\psi\,\eta_c)^{LO}} \approx \frac{46 \pm 11\ \mathrm{fb}}{2.3\ \mathrm{fb}} \approx 20 \pm 5$ (HQZ)

- More data on inclusive distributions and more exclusive channels will be available soon.



prod^n & helicity angle distributions measured; used for eff^y estimates

APS 07–Apr–2003 $e^+e^- \to c\bar{c}c\bar{c}$

KEK-TH-943
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2004

Scalar charmonium and glueball mixing in $e^+e^- \to J/\psi X$

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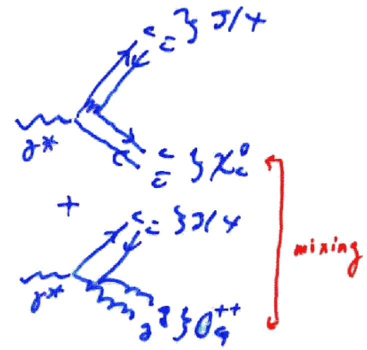
Abstract

We study the possibility of the scalar charmonium and glueball mixing in e^+e^- annihilation at $\sqrt{s}$ = 10.6 GeV. The effects can be used to explain the unexpected large cross section (12 ± 4 fb) and the anomalous angular distribution ($\alpha = -1.1^{+0.8}_{-0.6}$) of the exclusive $e^+e^- \to J/\psi\chi_{c0}$ process observed by Belle experiments at KEKB. We calculate the helicity amplitudes for the process $e^+e^- \to J/\psi H(0^{++})$ in NRQCD, where $H(0^{++})$ is the mixed state. We present a detailed analysis on the total cross section and various angular asymmetries which could be useful to reveal the existence of the scalar glueball state.

arXiv:hep-ph/0402230 v1 23 Feb 2004

PACS number(s): 12.39.Mk, 13.60.Le

$e^+e^- \to J/\psi + \chi_c^0$
$\searrow J/\psi + O_g^{++}$

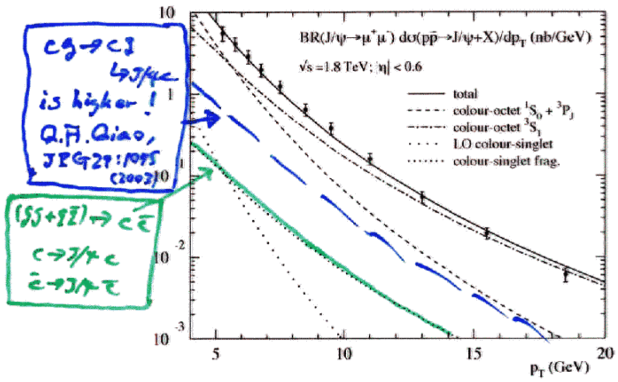


tests by { cross section / angular distribution

Two major constraints { known χ_c^0 EM properties → $\sin^2\xi < 0.1$ / no O_g^{++} signal in $\Upsilon \to \gamma gg$ → severe !

Transparency from K.Abe (Belle) lecture at the KEK PHENO meeting 2004 (3/1-3)

Continuum $e^+e^- \to J/\psi + X$



- CDF $\sigma(\bar{p}p \to J\psi + X)$ ~ 30 times larger than PQCD (LO color-singlet only)

  $\longrightarrow$ development of NRQCD

- Agrees with CDF cross section. But HERA cross section data do not require color-octet.
- Disagrees with CDF polarization data.

NRQCD: Braaten, Fleming, Yuan, hep-ph/9602374v1

- Rigorous treatment of $c\bar{c}$ with similar momenta in all orders pf α_s (both color-singlet and color-octet)
- Factorization of $c\bar{c} \to J/\psi$ using expansion of v between c and $\bar{c}$

$$d\sigma(J/\psi X) = d\hat{\sigma}(c\bar{c}[\underline{1}, {}^3S_1]) < O_1^{J/\psi} > + d\hat{\sigma}(c\bar{c}[\underline{8}, {}^{2S+1}S_{0,1}, {}^{2S+1}P_J]) < O_8^{J/\psi} >$$

Question : Can we account for 'direct' J/ψ production @ Tevatron without color 8 contribution? 4

$cg \to cg$, $cq \to cq$ } contribution $K \sim 2$? * $c \to J/\psi\, c$ fragmentation $K \sim 4$? ⇒ predict unpolarized J/ψ @ high p_T.

KH, ZHLin, CFQiao, JXWang, in prep.