Double $c\bar{c}$ production in e^+e^- annihilations at high energy

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Belle collaboration / University of Sydney

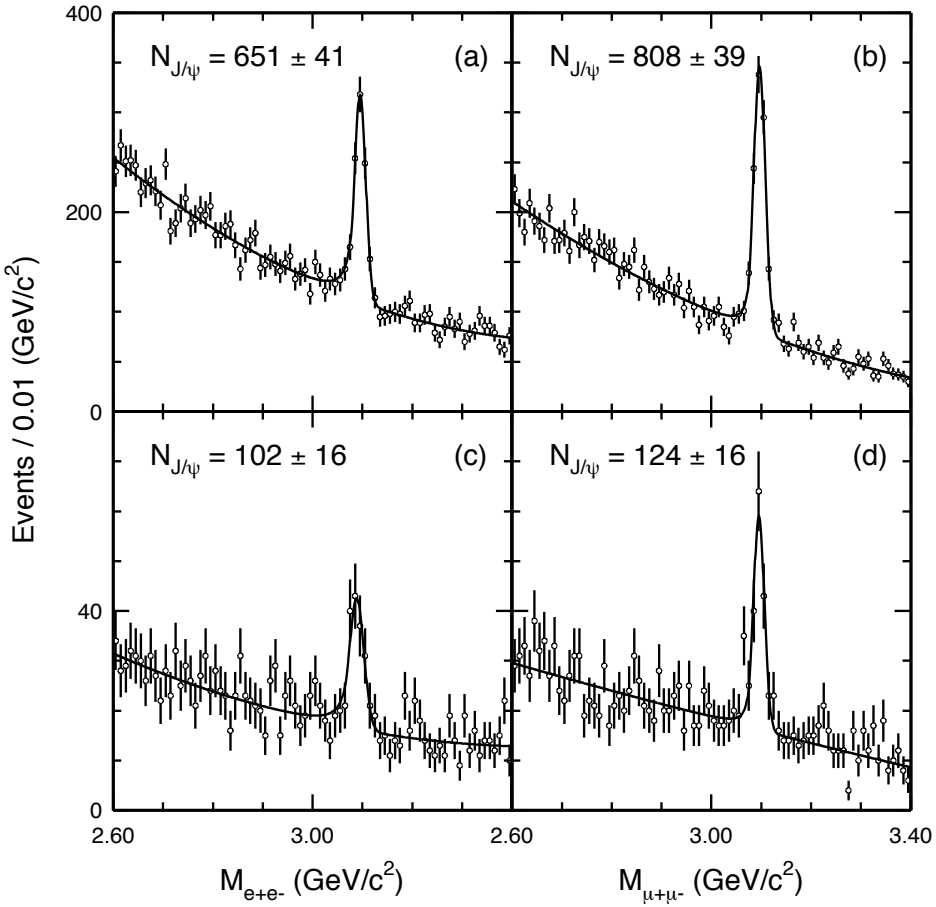
Charm 2007 Workshop, Cornell University, 5th August 2007

Outline

$e^+e^- \to \psi X$ production: How we came to study it

Belle: K. Abe et al., Phys. Rev. Lett. 88, 052001 (2002)

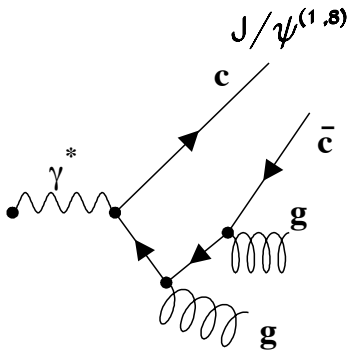
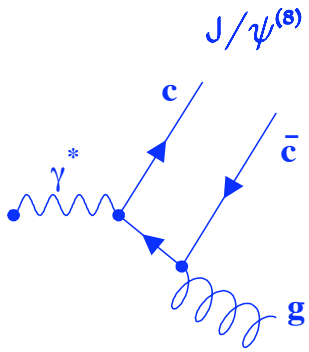
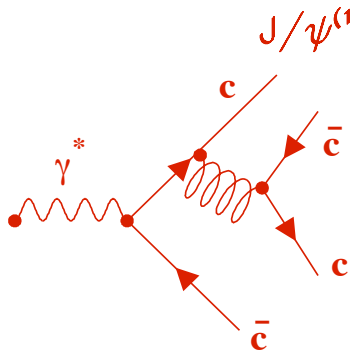
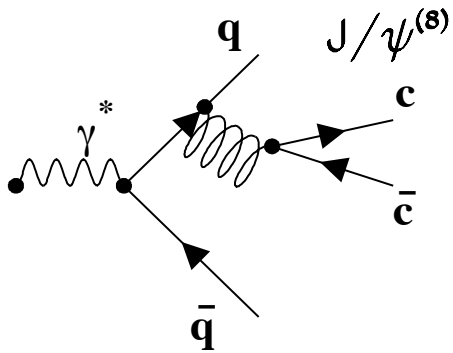
search for direct $\Upsilon(4S) \to J/\psi X$ production (*cf.* old CLEO result)



- $p^*_\psi > 2.0\,\mathrm{GeV}$ cut:
  veto $\Upsilon(4S) \to B\overline{B}[\to \psi X]$
- ψ yield on-resonance [top]
  $-$ ψ yield off-resonance [bottom]
  $\times$ on/off scale factor
  $=$ ψ yield from $\Upsilon(4S)$
- $\mathcal{B}(\Upsilon(4S) \to J/\psi X)$
  $< 1.9 \times 10^{-4}$ @ 95% C.L.
- *i.e.* all of these J/ψ are from continuum production

$e^+e^- \to \psi X$ production: What was expected

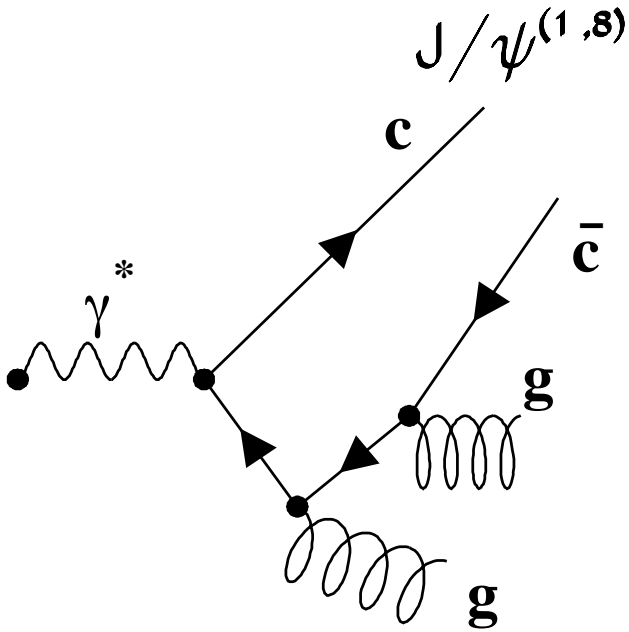
contributions from various processes (according to NRQCD):

$e^+e^- \to \psi gg$	$\to \psi g$	$\to \psi c\bar{c}$	$\to \psi q\bar{q}$
			
	[octet]		[octet]
DOMINANT for $\sqrt{s} \approx 10.6\,\mathrm{GeV}$	dominant at p^* endpoint	$\mathcal{O}(10\%)$	small

so we expect the p^*_ψ spectrum to have two components . . .

$e^+e^- \to \psi X$ production: What was expected

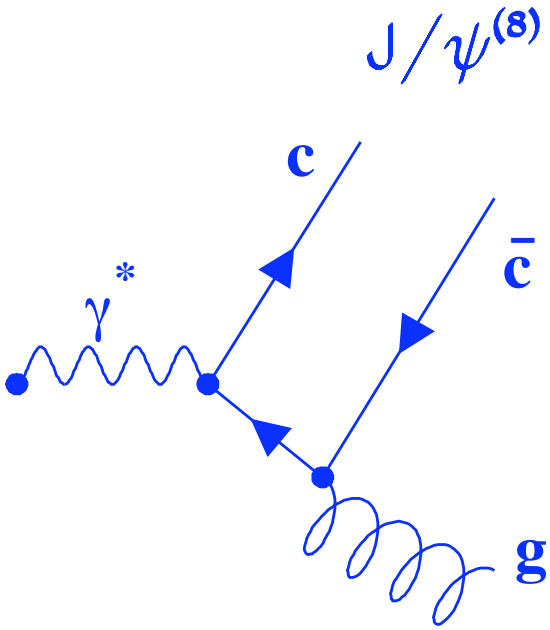
$e^+e^- \to \psi gg$



continuous component

[maybe some $\psi c\bar{c}$ modification]

$e^+e^- \to \psi g$



peak/spike at endpoint

across a range $p^*_\psi \in [0, p^*_{max}]$, $p^*_{max} = \frac{s - m^2_\psi}{2\sqrt{s}} = 4.84\,\mathrm{GeV}/c$

$e^+e^- \to \psi X$ production: What we saw

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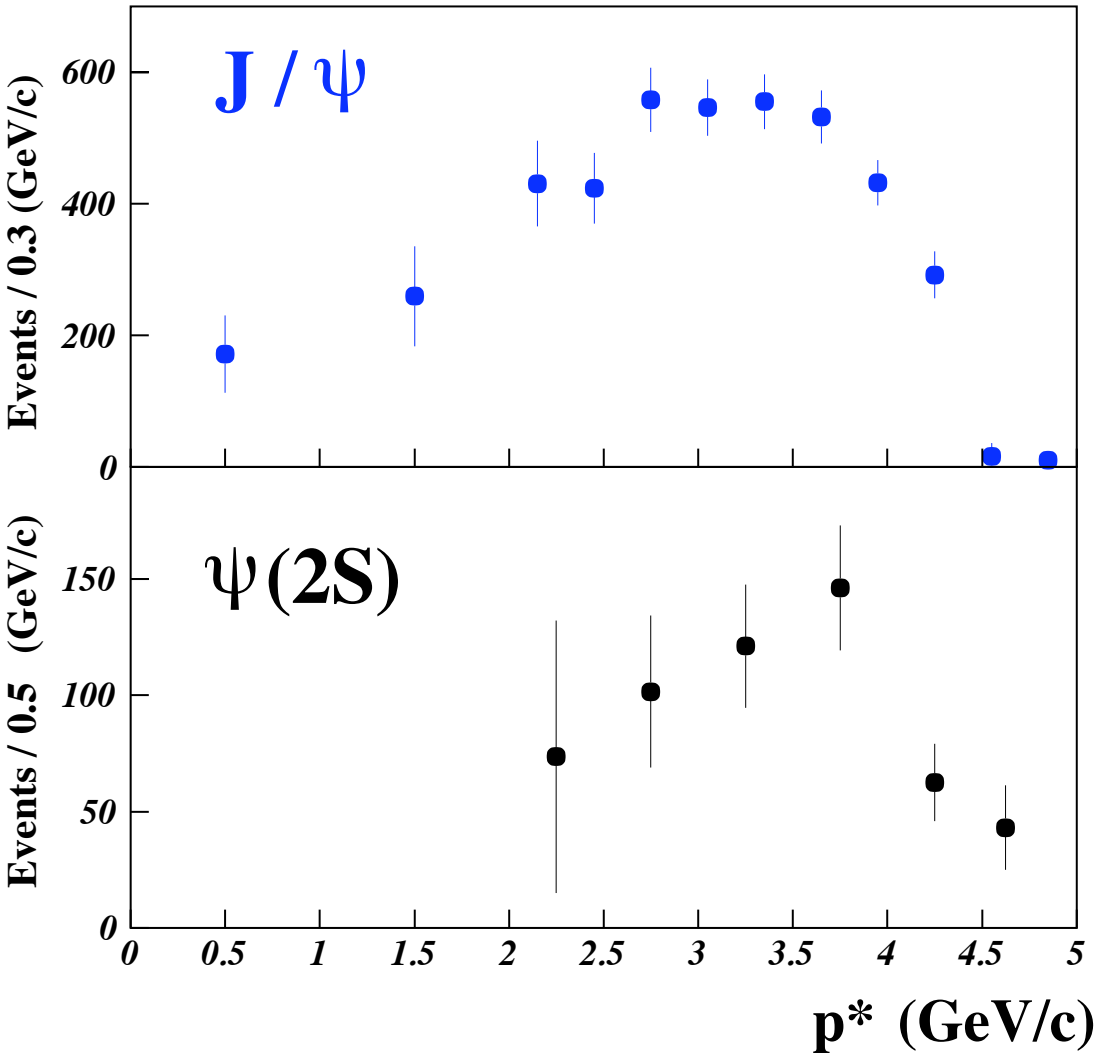

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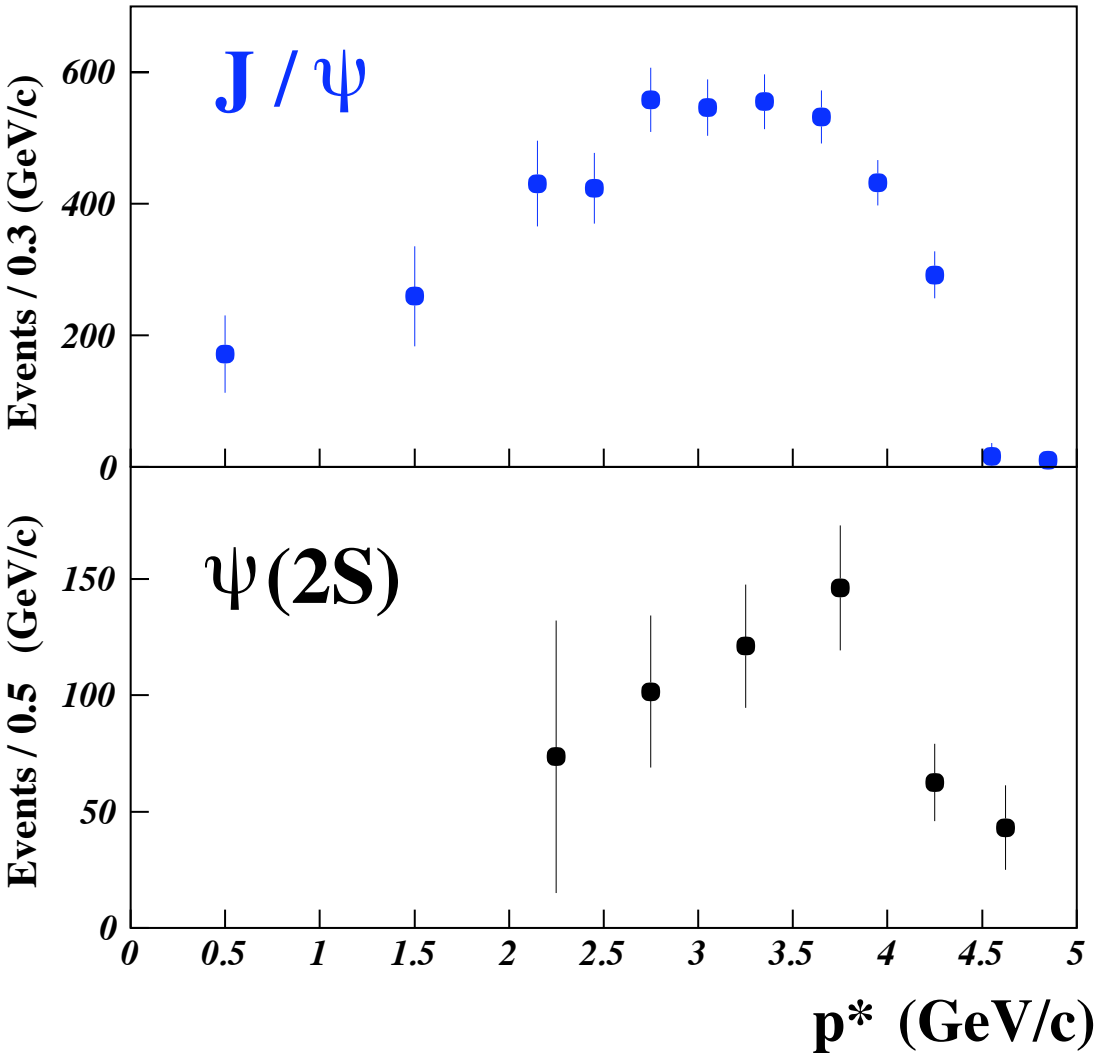

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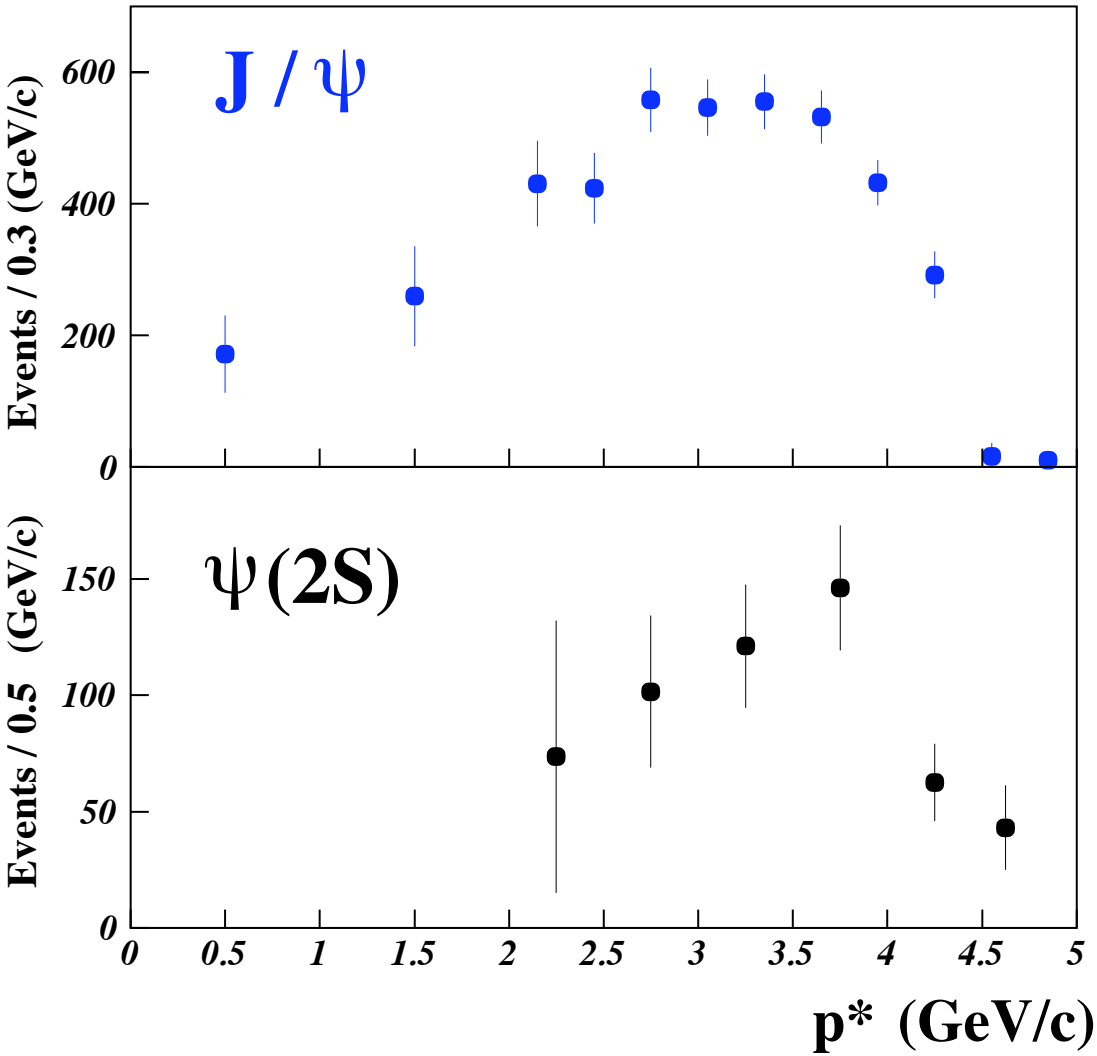

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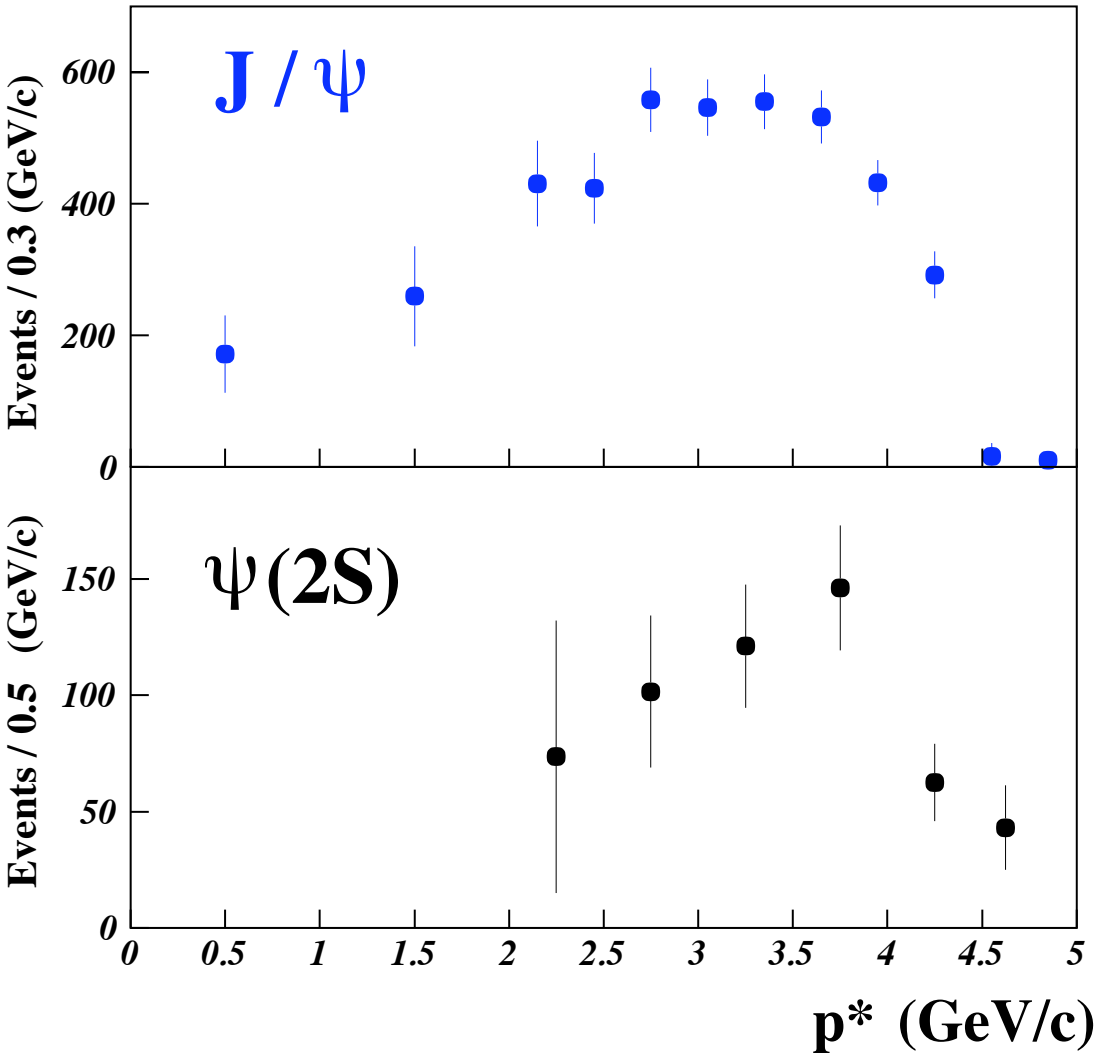

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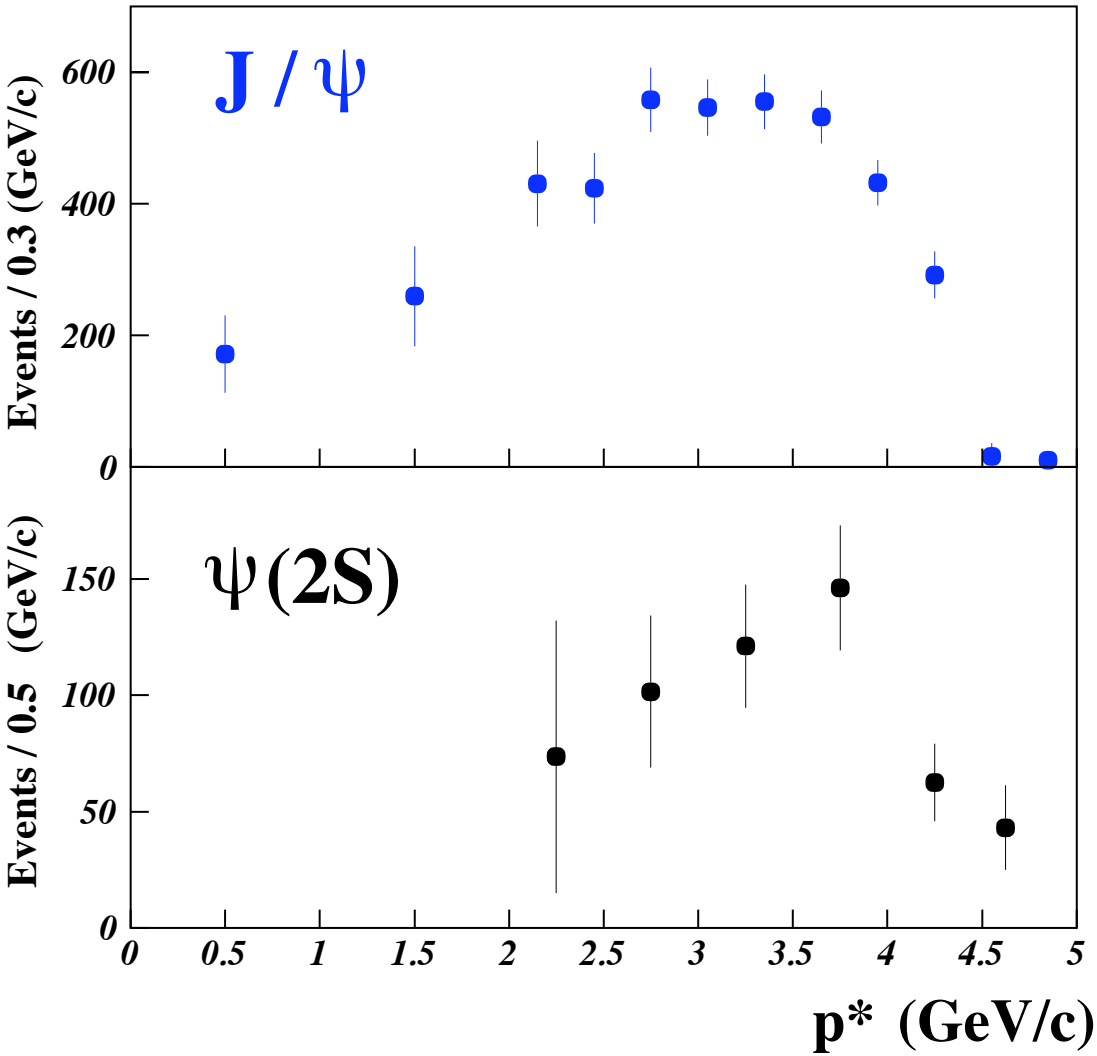

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- but there is no spike at the p^*_ψ endpoint
  [we'll return to this later]
- more striking:
  $\sigma \to 0$ before endpoint
- idea:
  p^*_ψ may not be the most natural representation of the data

$e^+e^- \to \psi (c\bar{c})_{res}$: The method

- study the **recoil mass** $M_{\text{recoil}}(\psi) = \sqrt{(\sqrt{s} - E^*_\psi)^2 - (p^*_\psi)^2}$

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- study the **recoil mass** $M_{\text{recoil}}(\psi) = \sqrt{(\sqrt{s} - E^*_\psi)^2 - (p^*_\psi)^2}$
- production at fixed $\sqrt{s} = 10.58$ (and 10.52) GeV
  - 1–1 mapping between p^*_ψ and $M_{\text{recoil}}(\psi)$
  - nontrivial upper bound on $p^*_\psi \equiv$ lower bound on $M_{\text{recoil}}(\psi)$

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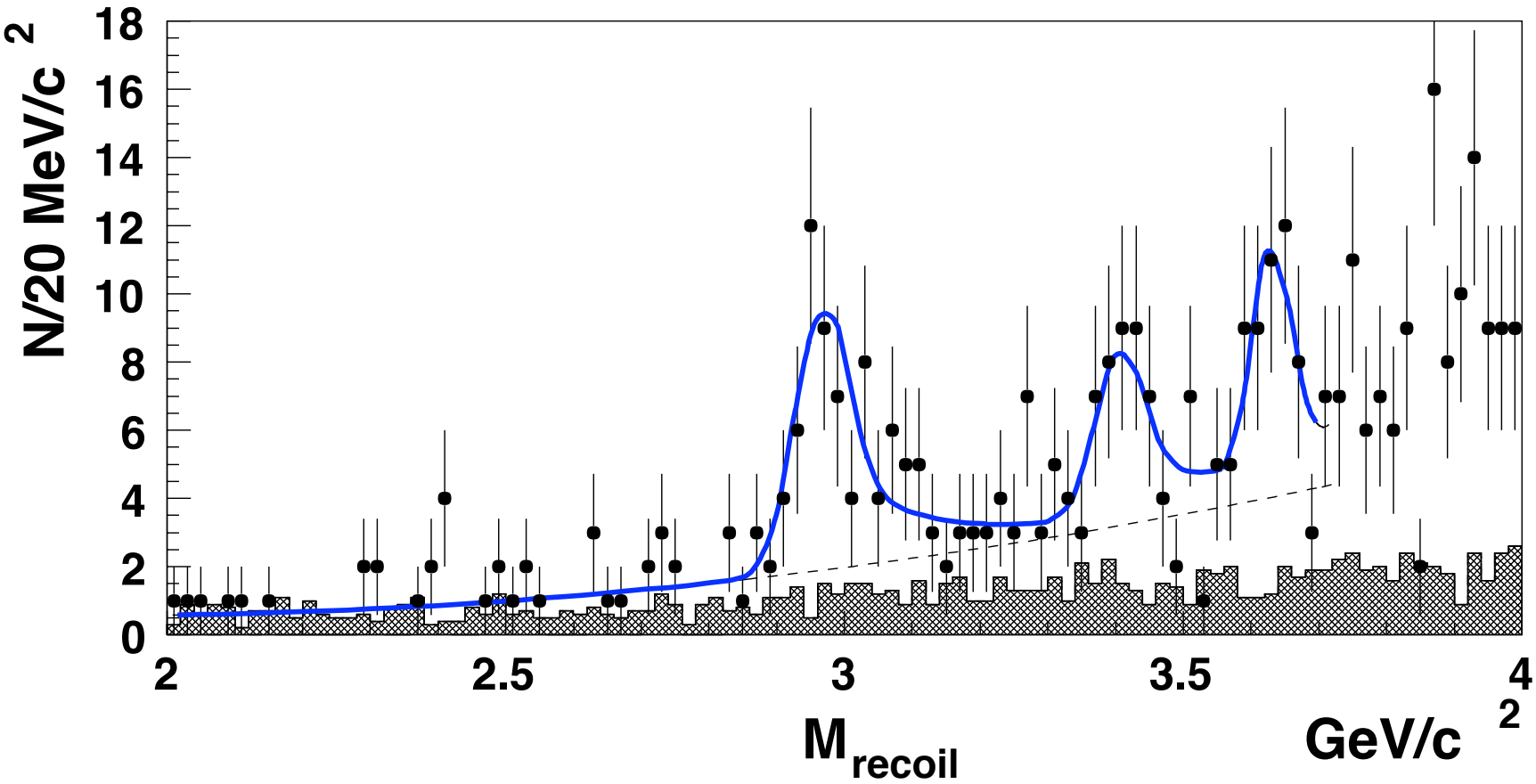
  - ISR $\longrightarrow$ high-$M_{\rm recoil}$ tail on any structure

$e^+e^- \to \psi (c\bar{c})_{res}$: The (unexpected) results

Belle: K. Abe et al., Phys. Rev. Lett. 89, 142001 (2002)

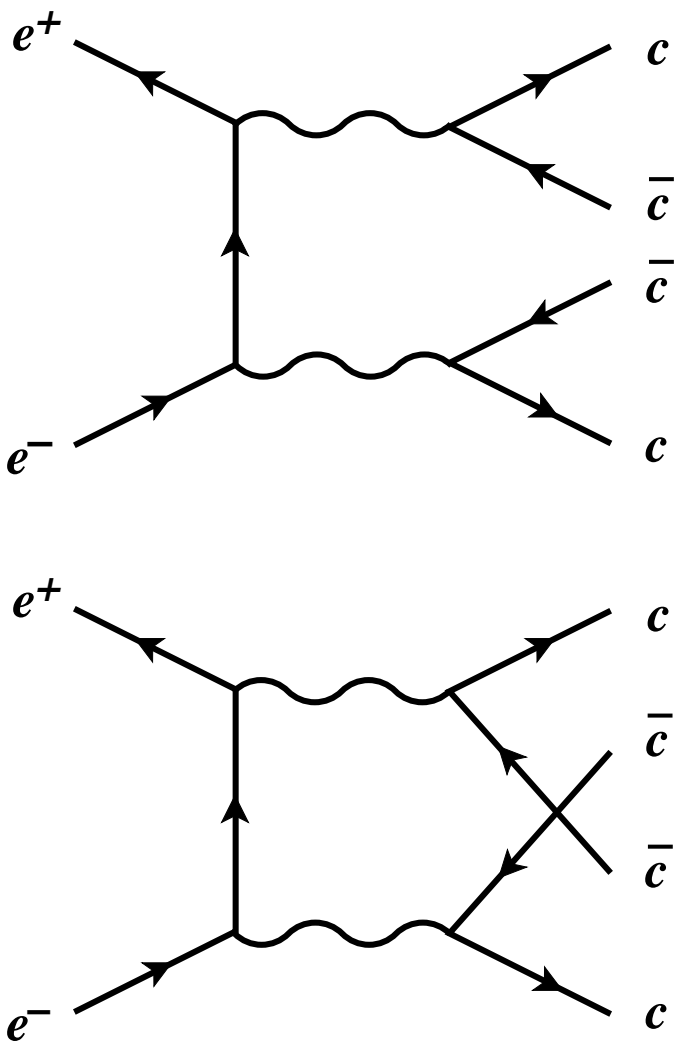


below $c\bar{c}$ threshold: *nothing*

above $c\bar{c}$ threshold: *charmonia*

$e^+e^- \to \psi (c\bar{c})_{res}$ *vs* alternative interpretations

(1) Bodwin, Lee, And Braaten, Phys. Rev. D 67, 054023 (2003)



- straightforward diagrams neglected
  - in interpretation of data
  - in previous theoretical work
- e^+e^- annihilation

  $\to \gamma^* \quad \to \psi X \quad$ requires $\quad \xi_C^X = +1$

  $\to \gamma^*\gamma^* \to \psi X \quad$ allows $\quad \xi_C^X = \pm 1$
- only $\psi \eta_c$ significant in 2002 PRL
- idea: *"... there are probably $J/\psi + J/\psi$ events that contribute to the $J/\psi + \eta_c$ signal ... if these were taken into account, they would increase the compatibility between the NRQCD prediction and the Belle measurement"*

$e^+e^- \to \psi\,(c\bar{c})_{res}$ *vs* alternative interpretations

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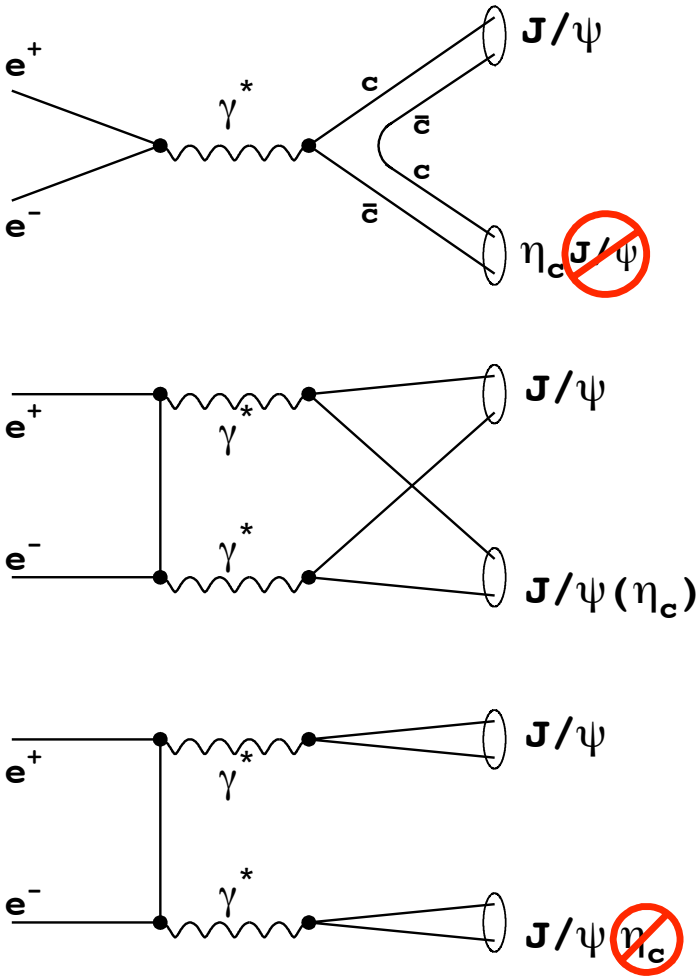
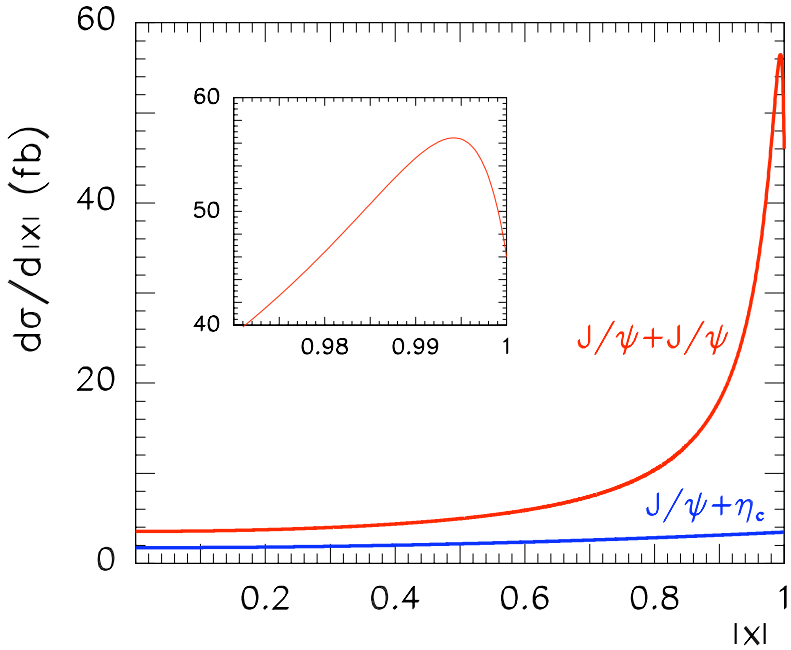


distributions in $x = \cos\theta_{\text{prod}}$:



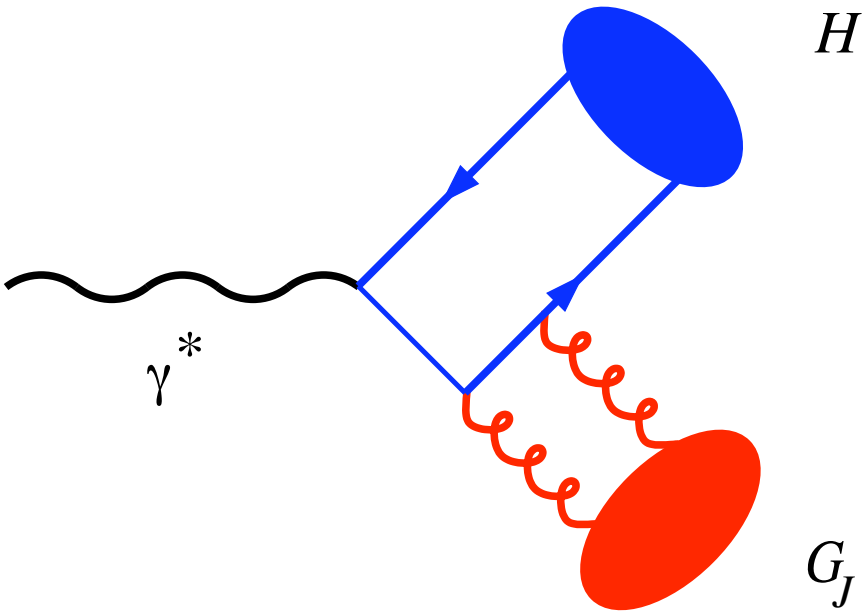
$\psi\,\eta_c$ close to $1 + \cos^2\theta_{\text{prod}}$ [γ^* case]

$\psi\,\psi$ distinctive forward peak

$e^+e^- \to \psi (c\bar{c})_{res}$ *vs* alternative interpretations

(2) Brodsky, Goldhaber, and Lee, Phys. Rev. Lett. 91, 112001 (2003)

mirror-image of the previous proposal . . .

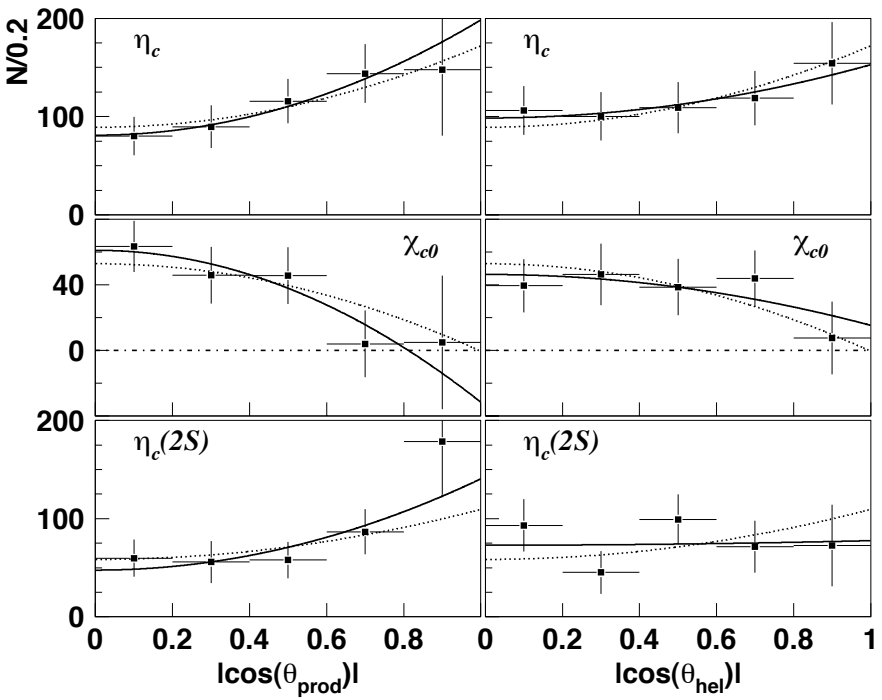


- $e^+e^- \to \psi\, gg$ process *really does* dominate
- $\exists$ heretofore unknown glueball state
- it's sitting at the η_c mass
- the gg are coupling to it . . .
- . . . and that's our signal

$e^+e^- \to \psi (c\bar{c})_{res}$ *vs* alternative interpretations

(nemesis) Belle: K. Abe et al., Phys. Rev. D 70, 071102(R) (2004)

1. full reconstruction of 3 $\psi\eta_c$ events (*cf.* 2.6 ± 0.8 expectation)
2. full reconstruction of 0 $\psi\psi$ events (limit is weak)
3. M_{recoil} bias $\lesssim 3\,\text{MeV}$
4. angular analysis of ψ production (θ_{prod}) & helicity (θ_{hel}):



	α_{prod}	α_{hel}
η_c	$1.4^{+1.1}_{-0.8}$	$0.5^{+0.7}_{-0.5}$
χ_{c0}	-1.7 ± 0.5	$-0.7^{+0.7}_{-0.5}$
$\eta_c(2S)$	$1.9^{+2.0}_{-1.2}$	$0.3^{+1.0}_{-0.7}$

no $\cos\theta_{\text{hel}} \to 1$ feature; consistent with $\alpha_{\text{prod}} = \alpha_{\text{hel}}$ (per $e^+e^- \to \gamma^*$)

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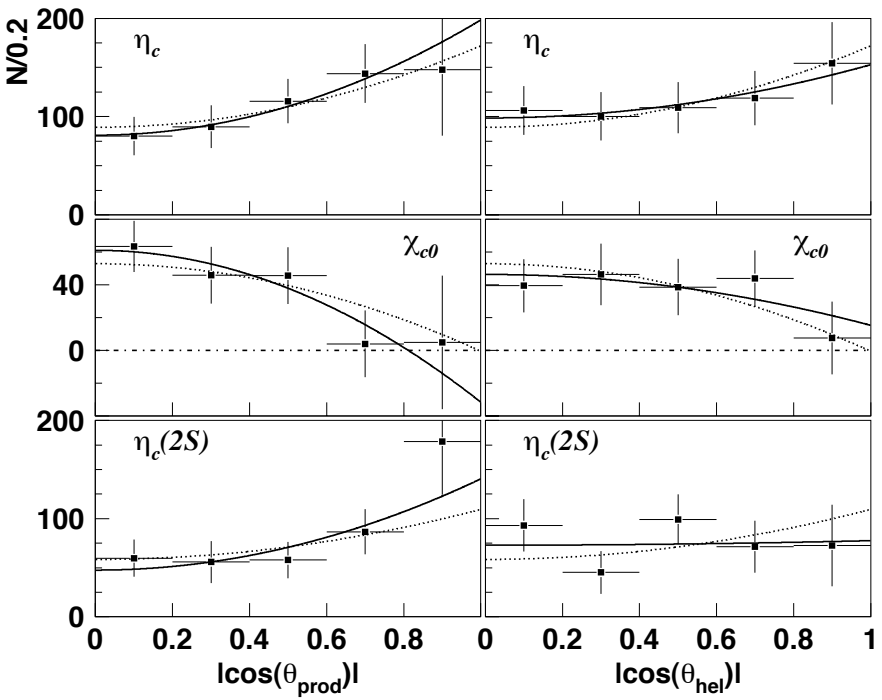

	$\alpha_{\text{hel}} \equiv \alpha_{\text{prod}}$	expect^n
η_c	$0.93^{+0.57}_{-0.47}$	+1 (P)
χ_{c0}	$-1.01^{+0.38}_{-0.33}$	−1 (S)
$\eta_c(2S)$	$0.87^{+0.86}_{-0.63}$	+1 (P)

cf. $\alpha \simeq -0.87$ for glueball $\mathcal{G}_0$

cf. $\alpha \simeq +0.25$ for χ_{c0} in NRQCD

Results: $e^+e^- \to \psi\,(c\bar{c})_{res}$ production

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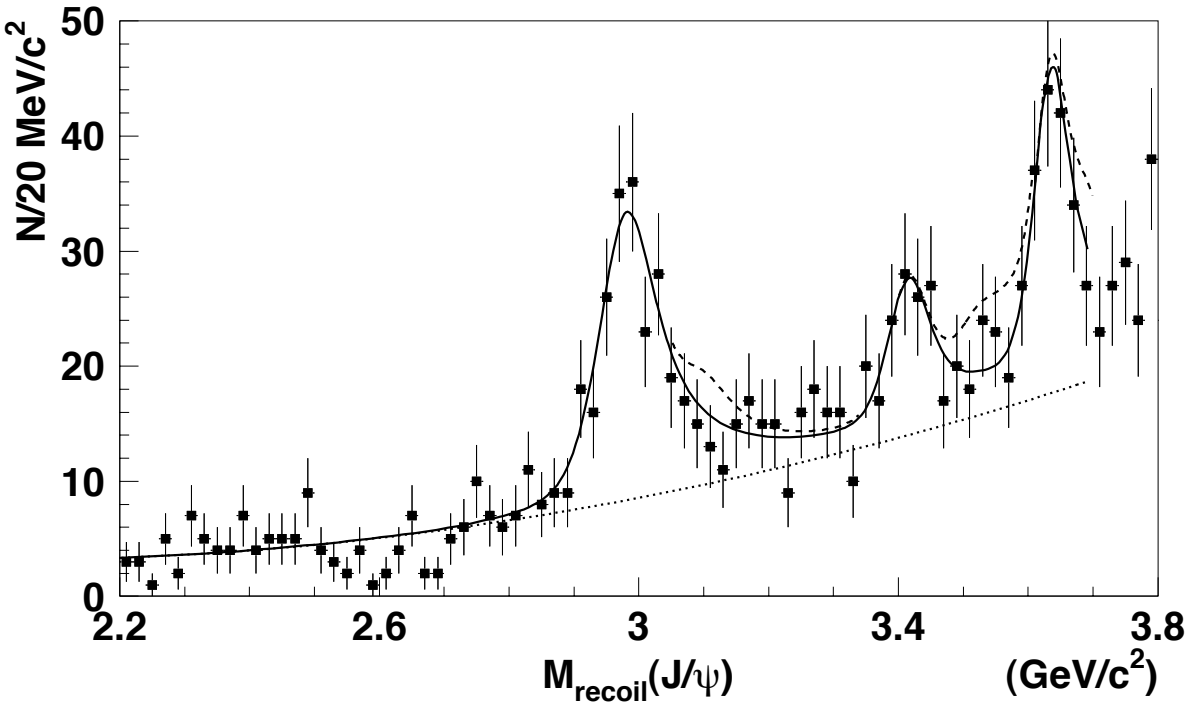

systematics $\ni$ fits $\begin{cases} \text{with the } J/\psi,\ \psi(2S),\ \chi_{c1,c2} & \text{(dashed: UL)} \\ \text{without } \xi_C = -1 \text{ or } \chi_{c1,c2} \text{ states} & \text{(solid)} \end{cases}$

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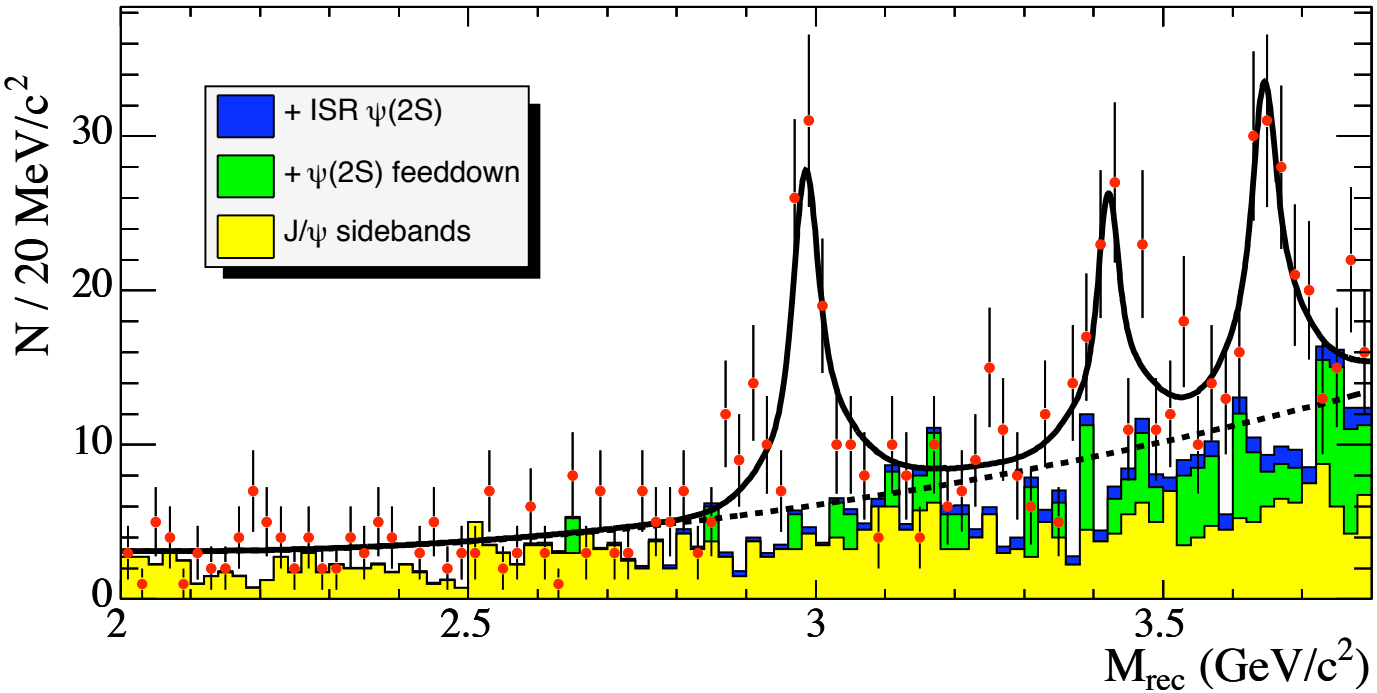
BaBar: B. Aubert et al., Phys. Rev. D 72, 031101(R) (2005)



J/ψ, $\chi_{c1,c2}$, $\psi(2S)$ added to the fit in turn: none is significant

Results: $e^+e^- \to \psi\,(c\bar{c})_{res}$ production

[Belle and BaBar]

$(c\bar{c})_{res}$	N (fit yield)		M (MeV/c^2)	
	Belle	BABAR	Belle	BABAR
$\eta_c(1S)$	235 ± 26	126 ± 20	2972 ± 7	2985 ± 4
χ_{c0}	89 ± 24	81 ± 20	3407 ± 11	3421 ± 5
$\eta_c(2S)$	164 ± 30	121 ± 27	3630 ± 8	3645 ± 6
J/ψ	-14 ± 20	-26 ± 13	fixed	
χ_{c1}	10 ± 27	-5 ± 16	fixed	
χ_{c2}		-12 ± 16	fixed	
$\psi(2S)$	-26 ± 29	30 ± 27	fixed	

Results: $e^+e^- \to \psi(c\bar{c})_{res}$ production

[Belle and BaBar]

$J/\psi(c\bar{c})_{res}$		$\eta_c(1S)$	χ_{c0}	$\eta_c(2S)$
Belle	$\sigma \times \mathcal{B}_{>2}$ [fb]	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$
BABAR	$\sigma \times \mathcal{B}_{>2}$ [fb]	$17.6 \pm 2.8^{+1.5}_{-2.1}$	$10.3 \pm 2.5^{+1.4}_{-1.8}$	$16.4 \pm 3.7^{+2.4}_{-3.0}$
NRQCD:	σ [fb]			
Braaten&Lee[1]		3.78 ± 1.26	2.40 ± 1.02	1.57 ± 0.52
...with relativistic corr^{ns}:		$7.4^{+10.9}_{-4.1}$	–	$7.6^{+11.8}_{-4.1}$
Liu,He,&Chao[2]		5.5	6.9	3.7
Zhang,Gao,&Chao[3]		14.1	–	–
Bondar&Chernyak[4] light cone		33	–	–

[1 PRD 67, 054007 & 72, 099901(E); 2 hep-ph/0408141; 3 PRL 96, 092001; 4 PLB 612, 215–222 (2005)]

- low-order perturbative calculations still don't reproduce the data
- theoretical postdiction is actively pursued with varying approaches; no longer easy to characterise the issues at stake (*e.g.* see discussion Bodwin, Kang, & Lee, PRD 74, 114028 (2006) re NRQCD *vs* light cone)
- data is still in the driving seat ...

Results: $e^+e^- \to \psi(2S)\,(c\bar{c})_{res}$ production

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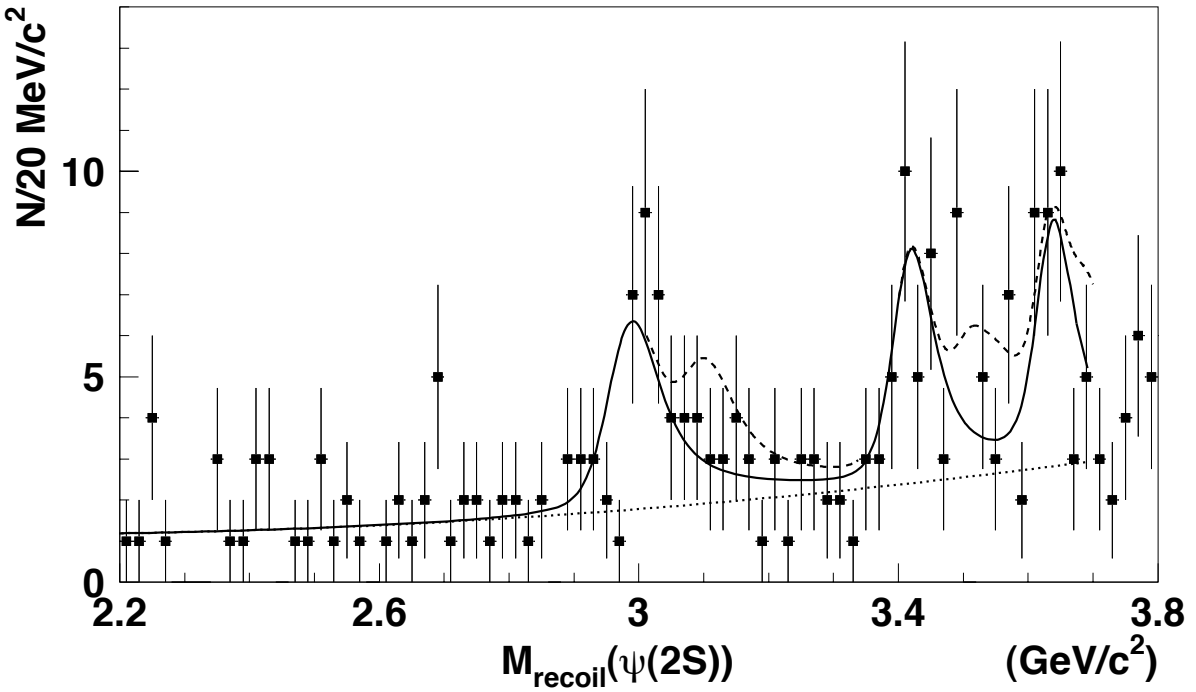

	$\eta_c(1S)$	χ_{c0}	$\eta_c(2S)$
significance	4.2	3.5	3.4
$\sigma(\psi(2S)\,(c\bar{c})_{res}) \times \mathcal{B}_{>0}$ [fb]	$16.3 \pm 4.6 \pm 3.9$	$12.5 \pm 3.8 \pm 3.1$	$16.0 \pm 5.1 \pm 3.8$

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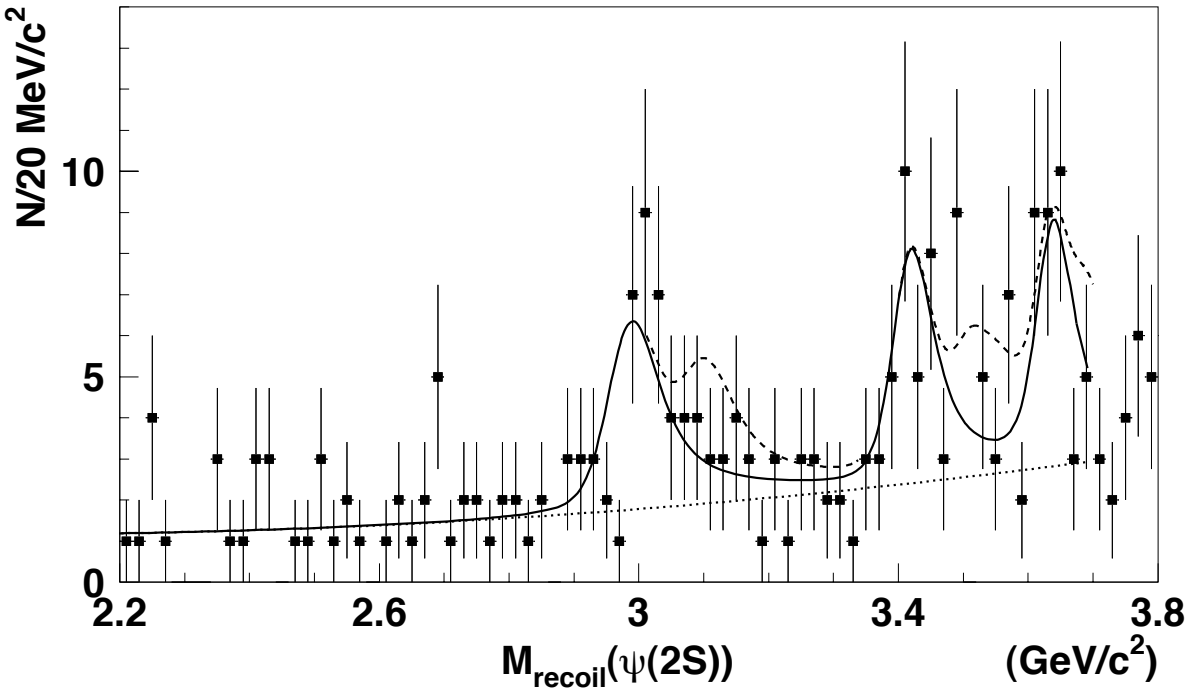

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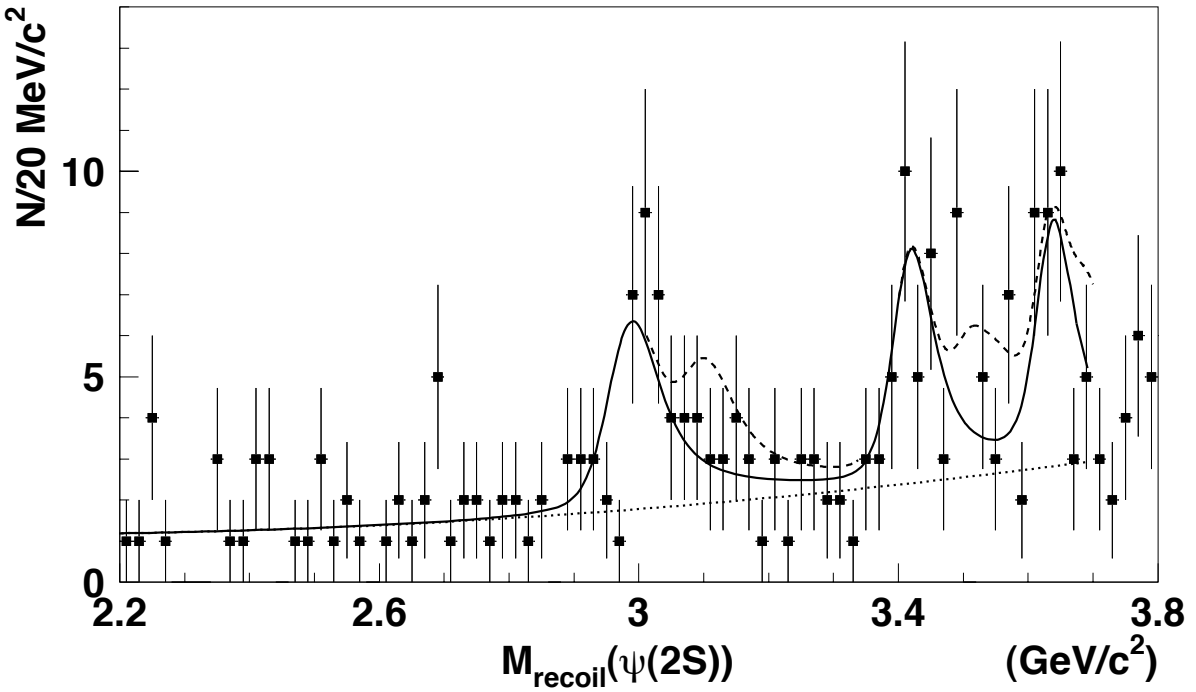


	$\eta_c(1S)$	χ_{c0}	$\eta_c(2S)$
significance	4.2	3.5	3.4
$\sigma(\psi(2S)\,(c\bar{c})_{res}) \times \mathcal{B}_{>0}$ [fb]	$16.3 \pm 4.6 \pm 3.9$	$12.5 \pm 3.8 \pm 3.1$	$16.0 \pm 5.1 \pm 3.8$
cf. $\sigma(\psi(1S)\,(c\bar{c})_{res}) \times \mathcal{B}_{>2}$ [fb]	$25.6 \pm 2.8 \pm 3.4$	$6.4 \pm 1.7 \pm 1.0$	$16.5 \pm 3.0 \pm 2.4$

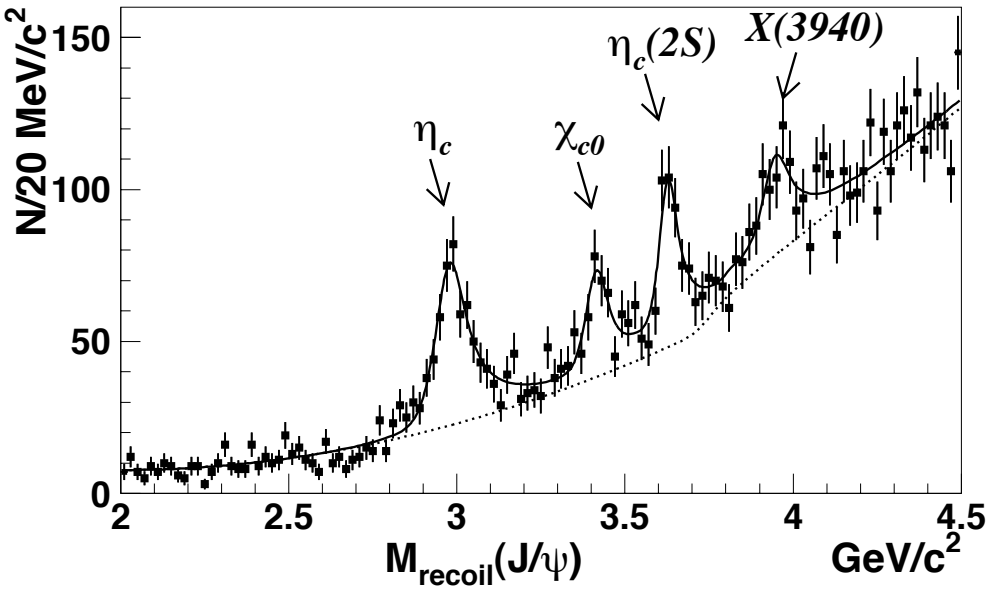
! no suppression of radially-excited states !

Published: new "X(3940)" state

[Belle: K. Abe et al., Phys. Rev. Lett. 98, 082001 (2007)]

standard analysis:

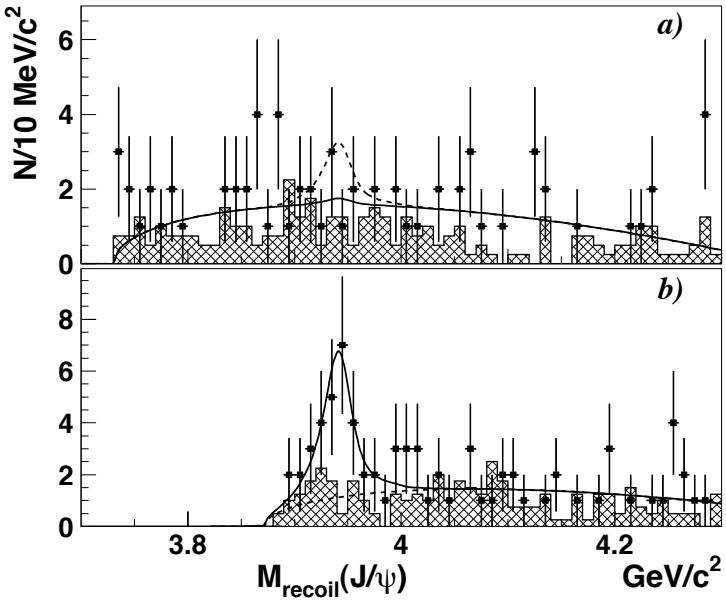
inclusive $M_{\text{recoil}}(\psi)$ spectrum



5.0σ peak at $(3936 \pm 14)\,\text{MeV}$

extra tag & constraint:

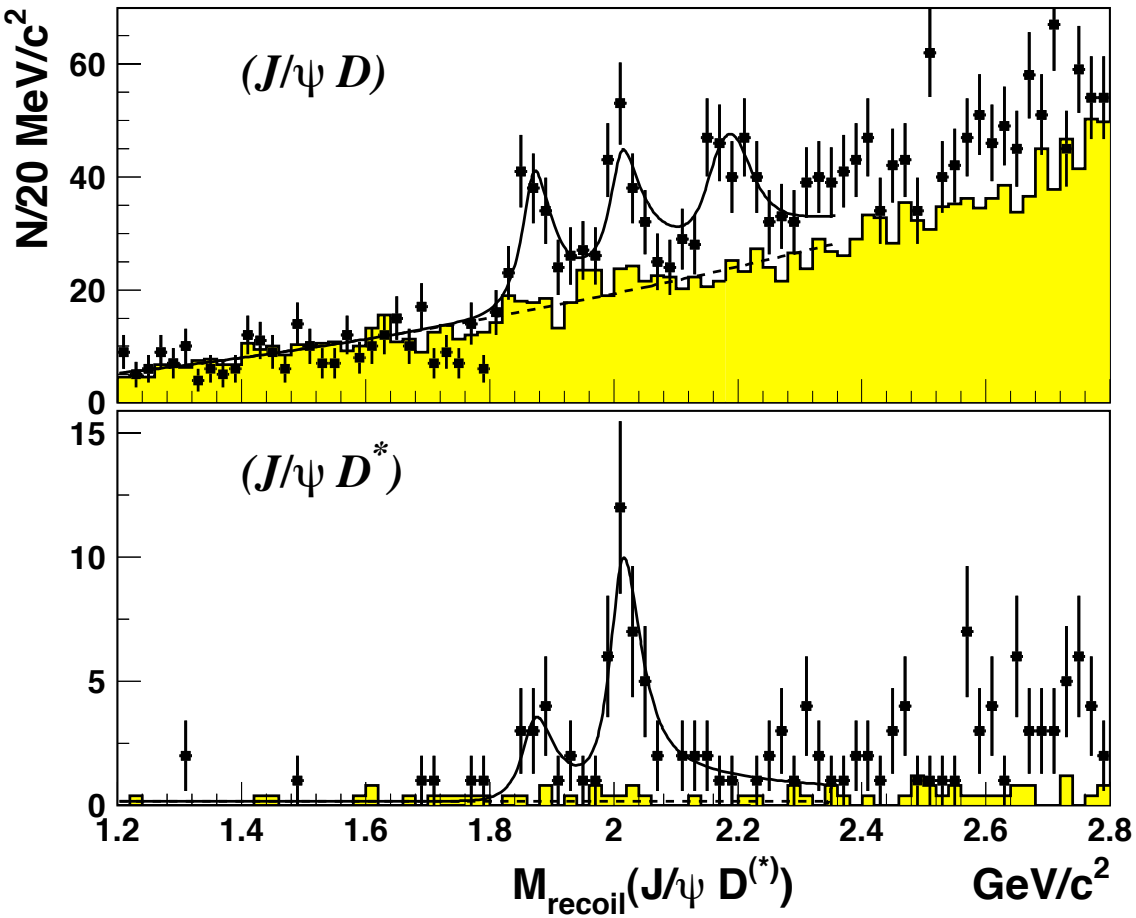
$M_{\text{recoil}}(\psi\,\text{D}) \to m_{\text{D}^{(*)}}$



$X(3940) \to \text{D}^*\overline{\text{D}}$; $\not\to \text{D}^*\overline{\text{D}}$

Updated: Systematic use of $\mathrm{D}^{(*)}$ tagging

[BELLE–CONF–0705: PRELIMINARY]



DATA:

- ψ recon, constraint
- D^0, D^+ recon
- D refit $\rightarrow m_{\mathrm{D}}$
- select $\psi\,\mathrm{D}$ or $\psi\,\mathrm{D}^*$
- form $M_{\mathrm{recoil}}(\psi\,\mathrm{D}^{(*)})$
- simultaneous fit with D-sidebands
- $> 5\sigma$ peaks: $\psi\,\mathrm{D}\overline{\mathrm{D}}$, $\psi\,\mathrm{D}^*\overline{\mathrm{D}}$, and $\psi\,\mathrm{D}^*\overline{\mathrm{D}}^*$

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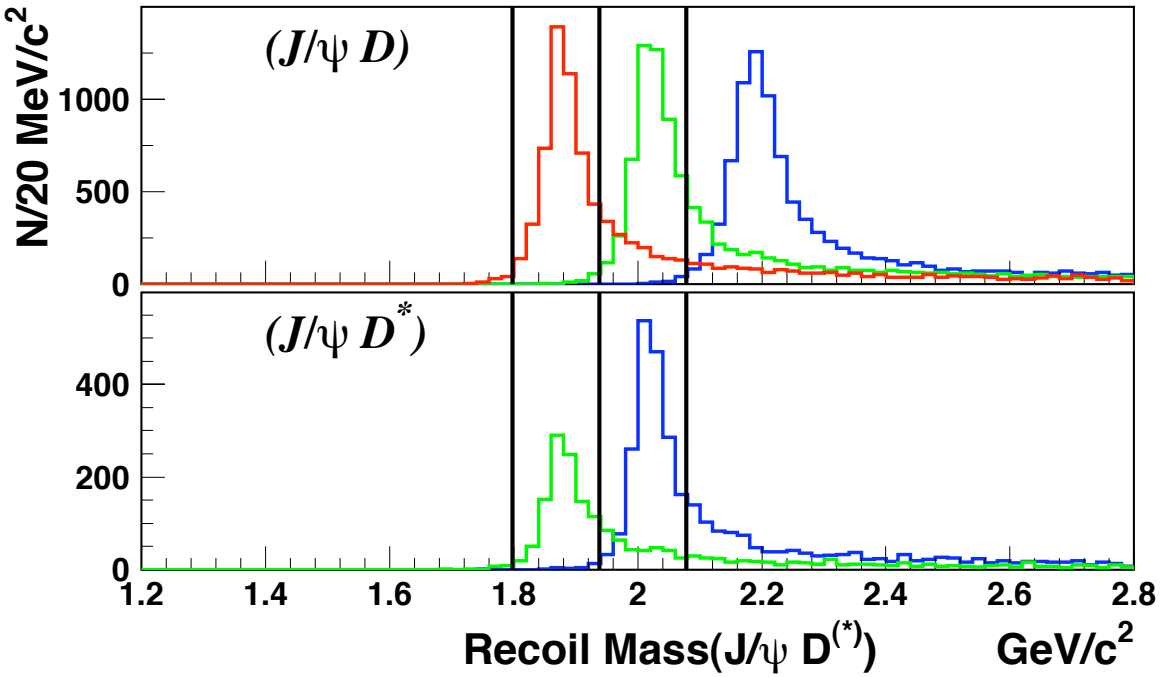

MONTE CARLO:

- $\mathrm{e^+e^-} \to \psi \mathrm{D}\overline{\mathrm{D}}$
  $\mathrm{e^+e^-} \to \psi \mathrm{D^*}\overline{\mathrm{D}}$
  $\mathrm{e^+e^-} \to \psi \mathrm{D^*}\overline{\mathrm{D}}^*$
- $\sigma \sim 30\,\mathrm{MeV}$
  $< (m^*_{\mathrm{D}} - m_{\mathrm{D}})$

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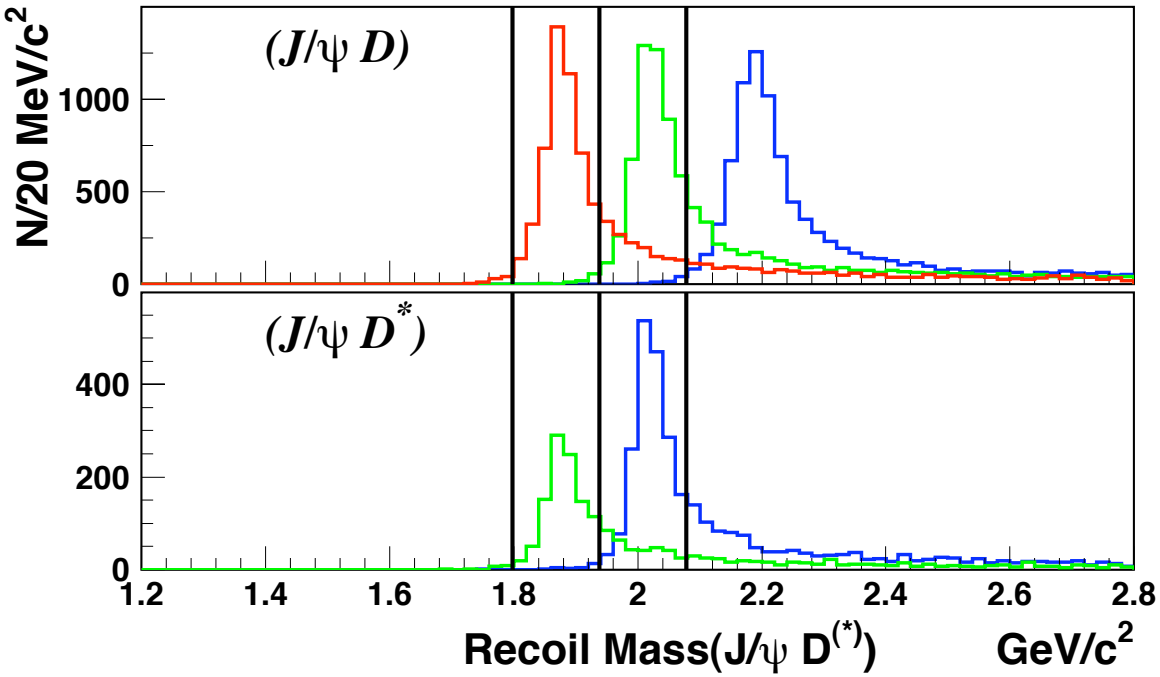
[BELLE–CONF–0705: PRELIMINARY]



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- tag processes requiring $\left| M_{\mathrm{recoil}}(\psi\,\mathrm{D}^{(*)}) - m_{\mathrm{tag}} \right| < 70\,\mathrm{MeV}$

Updated: Systematic use of $\mathrm{D}^{(*)}$ tagging

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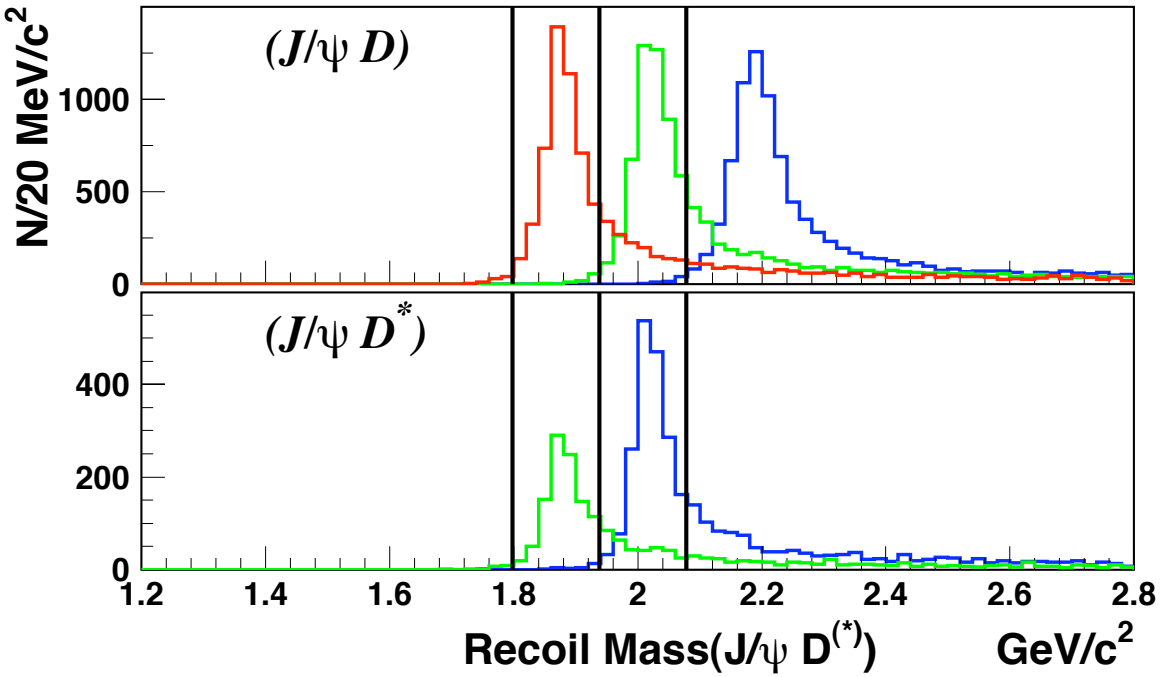

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- ISR produces (*e.g.*) 10% $\psi\mathrm{D}\overline{\mathrm{D}} \to \psi\mathrm{D}\overline{\mathrm{D}}^*$ cross-feed

Updated: Systematic use of $\mathrm{D}^{(*)}$ tagging

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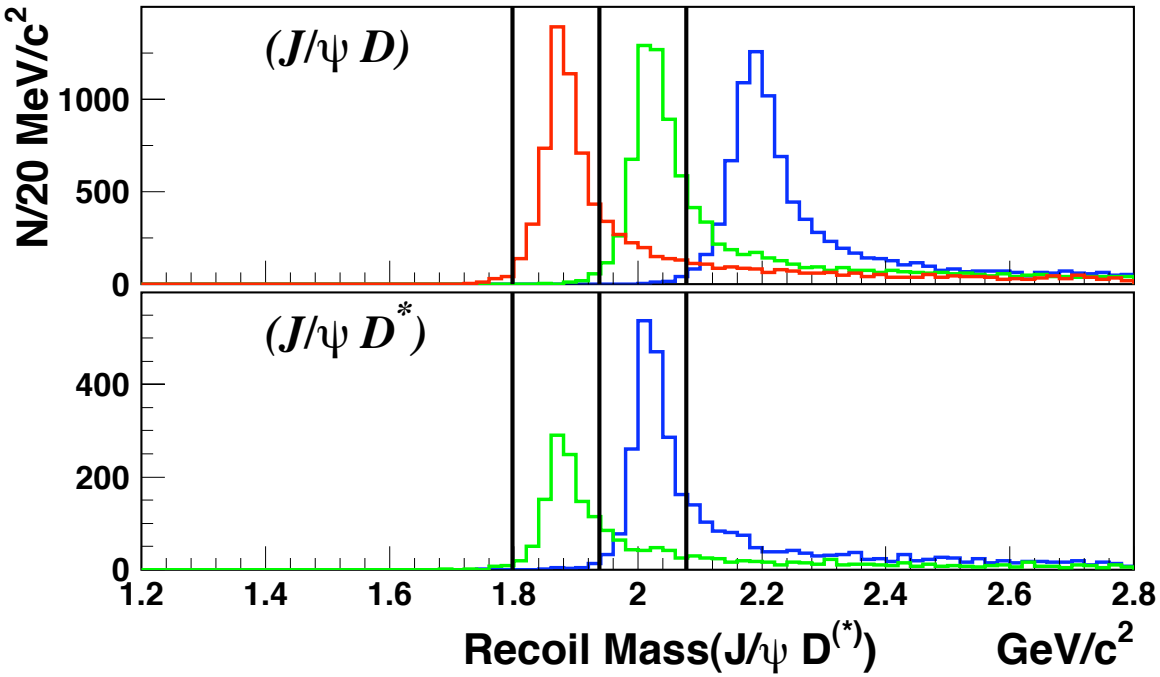

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- constrain $M_{\mathrm{recoil}}(\psi\,\mathrm{D}^{(*)}) \to m_{\mathrm{tag}}$ . . .

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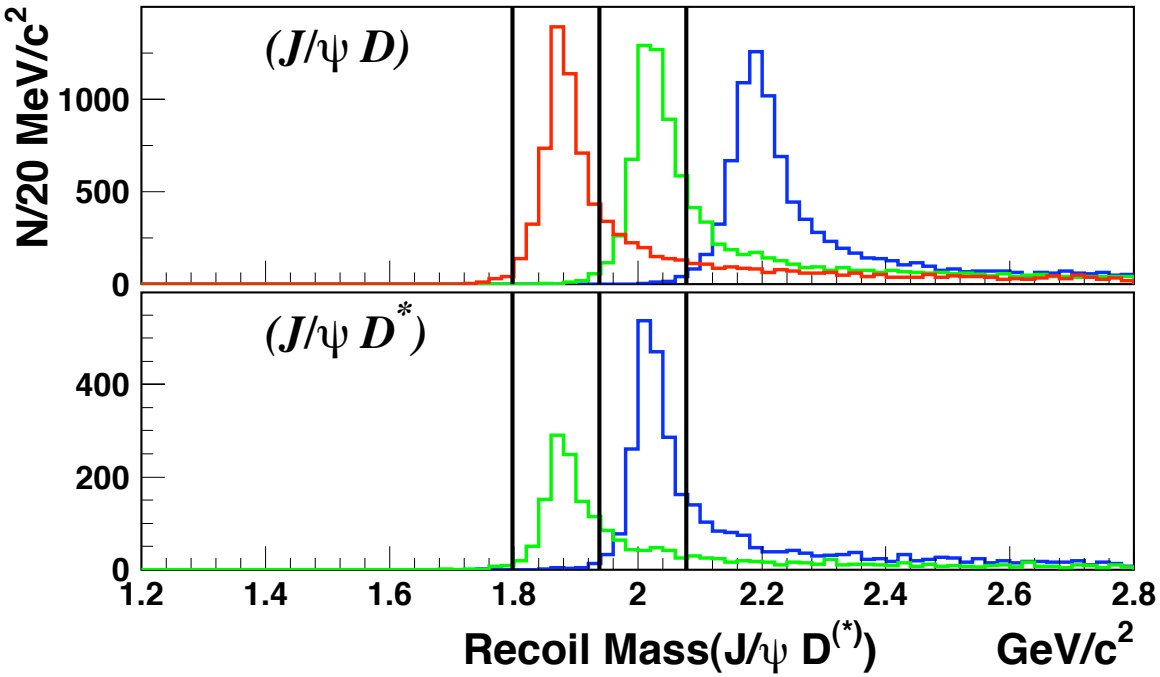

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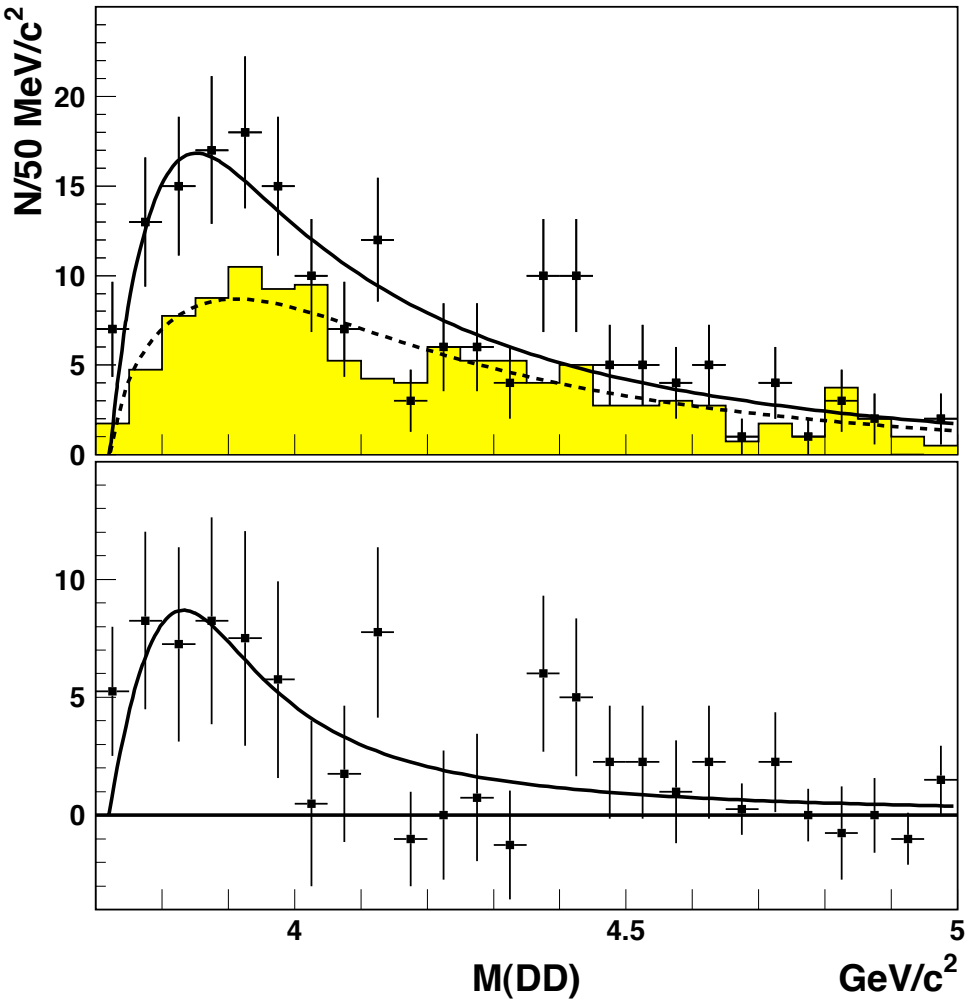
- constrain $M_{\mathrm{recoil}}(\psi\,\mathrm{D}^{(*)}) \to m_{\mathrm{tag}}$ . . .
  resolution on $M(\mathrm{D}^{(*)}\overline{\mathrm{D}}^{(*)})$ improves by a factor of 3–10

Updated: $X \to D\overline{D}$

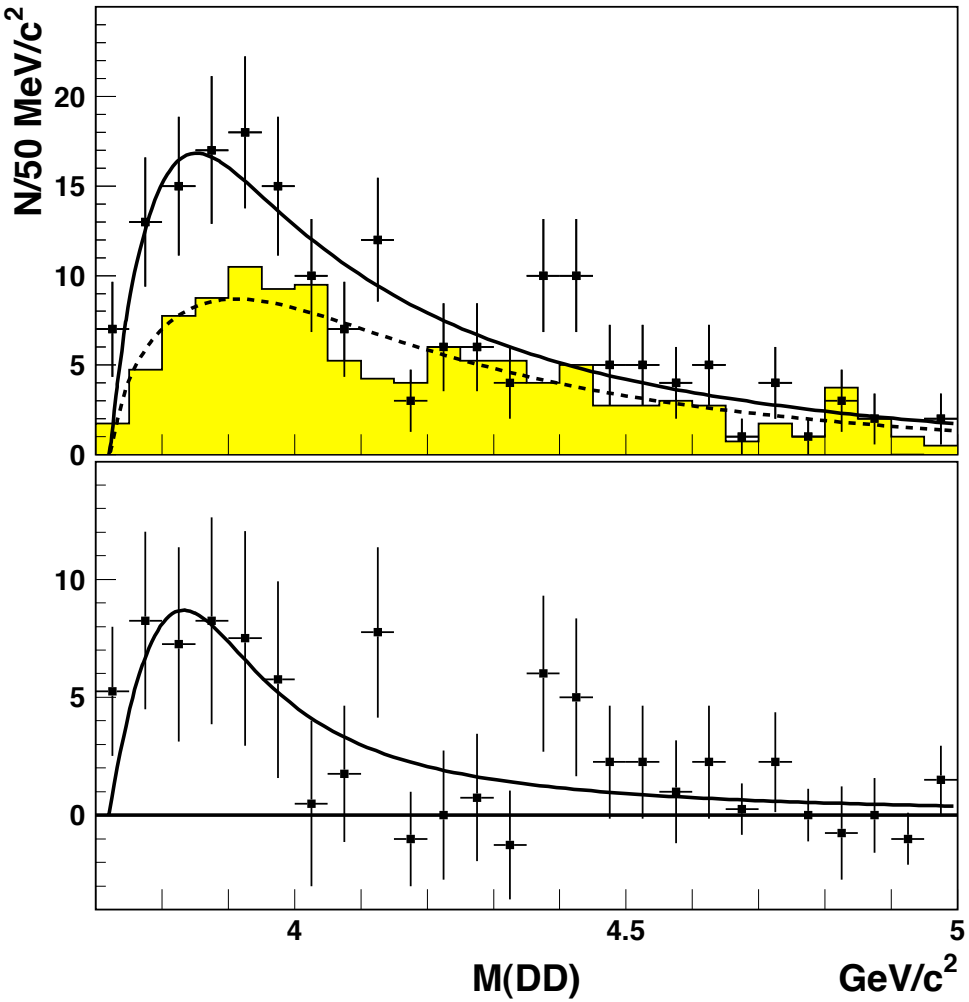
[BELLE–CONF–0705: PRELIMINARY]



- yellow: D_{rec} sidebands
- dashed: rel. B-W fit
- points: data (D_{rec} signal)
- solid: simultaneous fit to background (sideband) + threshold function + rel. S-wave B-W

Updated: $X \to D\overline{D}$

[BELLE–CONF–0705: PRELIMINARY]



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- solid: simultaneous fit to
  background (sideband)
  + threshold function
  + rel. S-wave B-W

- insignificant threshold term
- 4.4σ resonant term

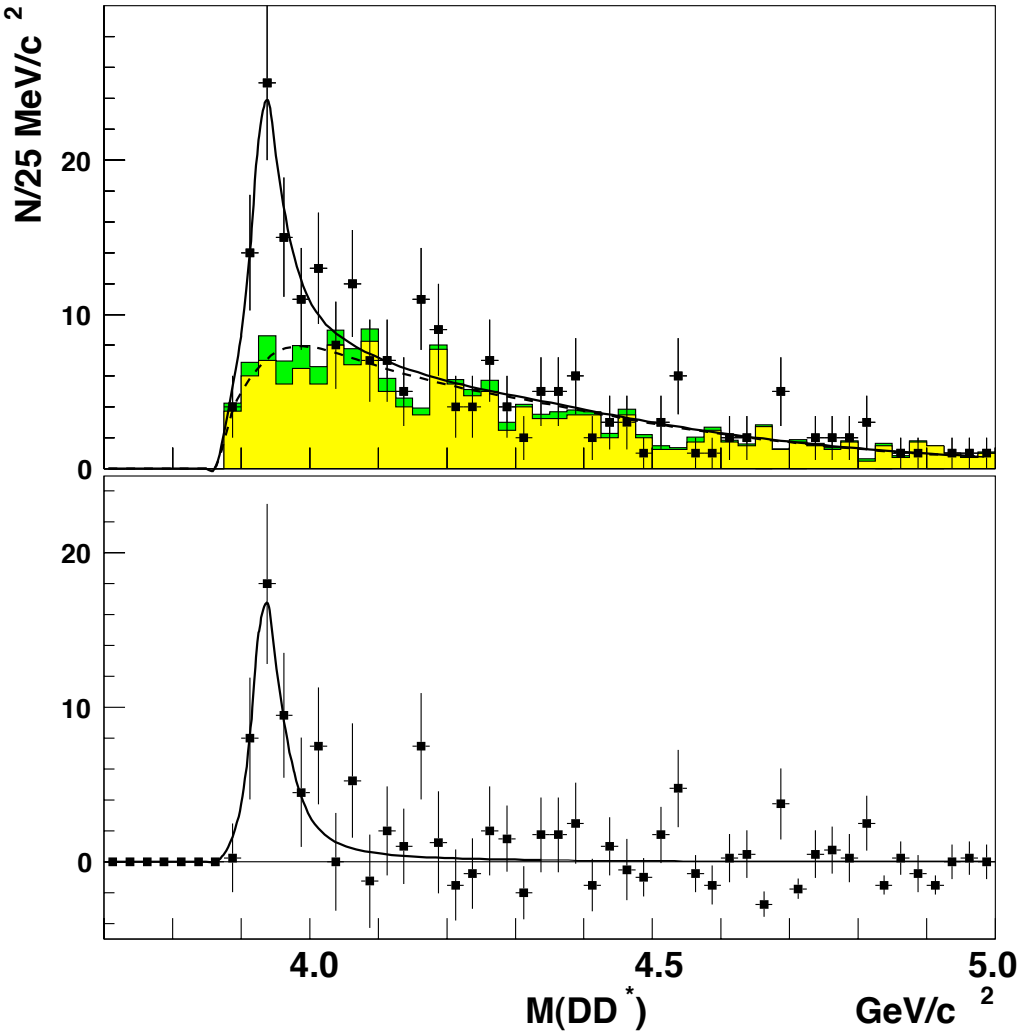
$$M = (3878 \pm 48)\,\mathrm{MeV}$$

$$\Gamma = (347^{+316}_{-143})\,\mathrm{MeV}$$

- unstable under:
  — bkgd param^n changes
  — bin-width changes
  — extra B-W term

Updated: $X \to \mathrm{D}\overline{\mathrm{D}}^*$ (D recon.; $\overline{\mathrm{D}}^*$ constraint)

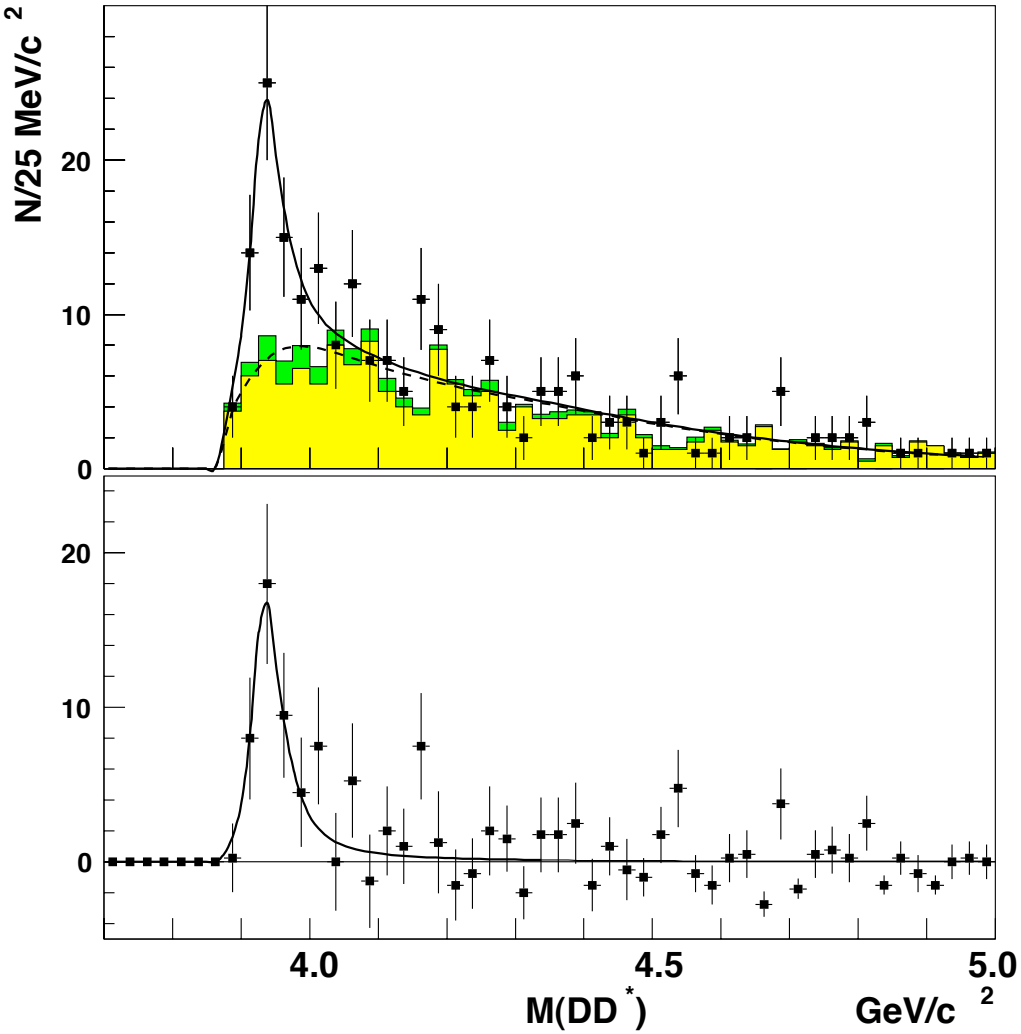
[BELLE–CONF–0705: PRELIMINARY]



- yellow: $\mathrm{D}_{\mathrm{rec}}$ sidebands
- green: $\mathrm{D}\overline{\mathrm{D}}$ reflection
- dashed: $A\sqrt{M-2m_{\mathrm{D}}}\cdot e^{-BM}+$ reflection fit
- points: data ($\mathrm{D}_{\mathrm{rec}}$ signal)
- solid: simultaneous fit to
  background (sideband)
  $+$ reflection
  $+$ threshold function
  $+$ rel. S-wave B-W
  $\otimes$ resolution function (MC)

Updated: $X \to \mathrm{D}\overline{\mathrm{D}}^*$ (D recon.; $\overline{\mathrm{D}}^*$ constraint)

[BELLE–CONF–0705: PRELIMINARY]



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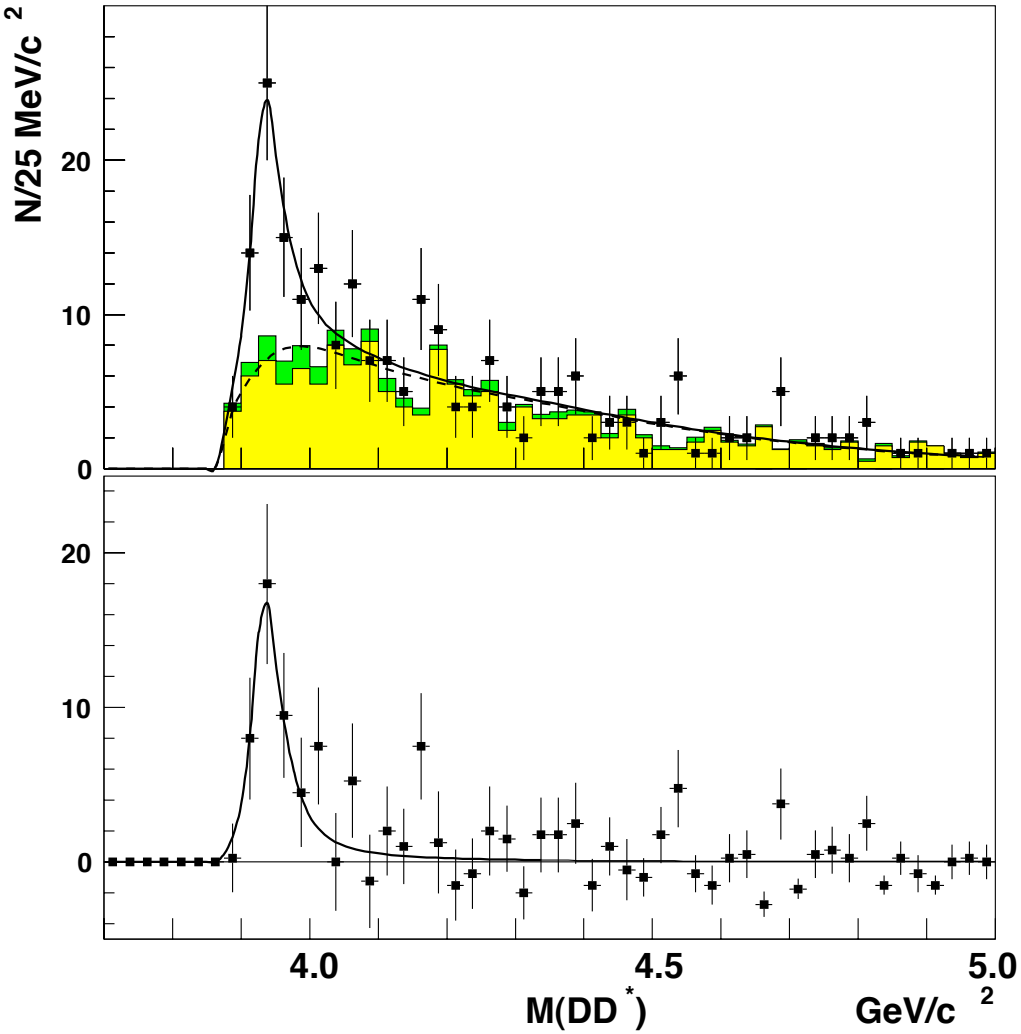
- green: $\mathrm{D}\overline{\mathrm{D}}$ reflection
- dashed: $A\sqrt{M-2m_{\mathrm{D}}}\cdot e^{-BM}+$ reflection fit
- points: data ($\mathrm{D}_{\mathrm{rec}}$ signal)
- solid: simultaneous fit to
  background (sideband)
  $+$ reflection
  $+$ threshold function
  $+$ rel. S-wave B-W
  $\otimes$ resolution function (MC)

- threshold term < 0
- fix to zero and refit:

Updated: $X \to D\overline{D}^*$ (D recon.; $\overline{D}^*$ constraint)

[BELLE–CONF–0705: PRELIMINARY]



- solid: simultaneous fit to
  background (sideband)
  $+$ reflection
  $+$ rel. S-wave B-W
  $\otimes$ resolution function (MC)

- 6.0σ resonant term

$$M = (3942^{+7}_{-6})\,\mathrm{MeV}$$

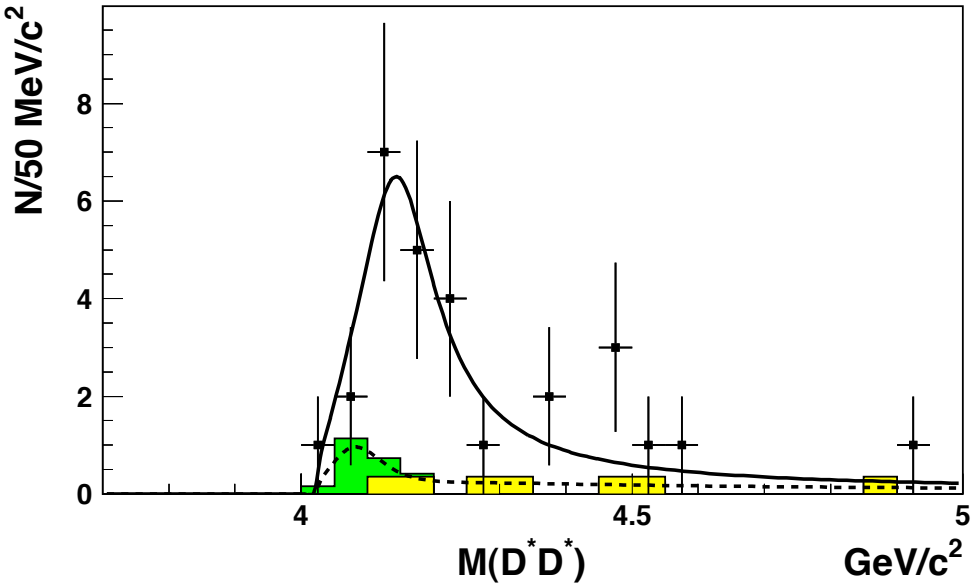
$$\Gamma = (37^{+26}_{-15})\,\mathrm{MeV}$$

$$< 76\,\mathrm{MeV} \text{ @ } 90\% \text{ C.L.}$$

- consistent PRL mass & yield
- *cf.* published width:
  $15.1 \pm 10.1\ (< 52$ @ $90\%)\,\mathrm{MeV}$
  (non-parabolic $\mathcal{L}$ function)

Updated: $X \to \mathrm{D}^*\overline{\mathrm{D}}^*$

[BELLE–CONF–0705: PRELIMINARY]



- yellow: $\mathrm{D}^*_{\mathrm{rec}}$ sidebands
- green: $X(3940)$ reflection
- points: data ($\mathrm{D}^*_{\mathrm{rec}}$ signal)
- similar fit performed
- 5.5σ NEW resonant term

$$M = (4156^{+25}_{-20})\,\mathrm{MeV}$$

$$\Gamma = (139^{+111}_{-61})\,\mathrm{MeV}$$

Born cross-section calculations per published analysis:

$$\sigma(\mathrm{e}^+\mathrm{e}^- \to \psi\, X(3940)) \times \mathcal{B}(X(3940) \to \mathrm{D}\overline{\mathrm{D}}^*) = (13.9^{+6.4}_{-4.1})\,\mathrm{fb}$$

$$\sigma(\mathrm{e}^+\mathrm{e}^- \to \psi\, X(4160)) \times \mathcal{B}(X(4160) \to \mathrm{D}^*\overline{\mathrm{D}}^*) = (24.7^{+12.8}_{-8.3})\,\mathrm{fb}$$

Again: comparable to $\psi\,\eta_c$ and other $2(c\overline{c})_{res}$ cross-sections

Updated: systematics

[BELLE–CONF–0705: PRELIMINARY]

Source	$X(3940)$			$X(4160)$		
	M	Γ	σ	M	Γ	σ
Fitting procedure	± 4	± 6	± 5	± 12	± 18	± 2
Selection	± 4	± 5	± 4	± 8	± 11	± 5
Momentum scale	± 3	—	—	± 3	—	—
Angular distributions	—	—	± 12	—	—	± 16
Reconstruction	—	—	± 6	—	—	± 8
Identification	—	—	± 4	—	—	± 4
$\mathcal{B}(D^{(*)})$	—	—	± 3	—	—	± 4
Total	± 6	± 8	± 16	± 15	± 21	± 20

Updated: cross-checks

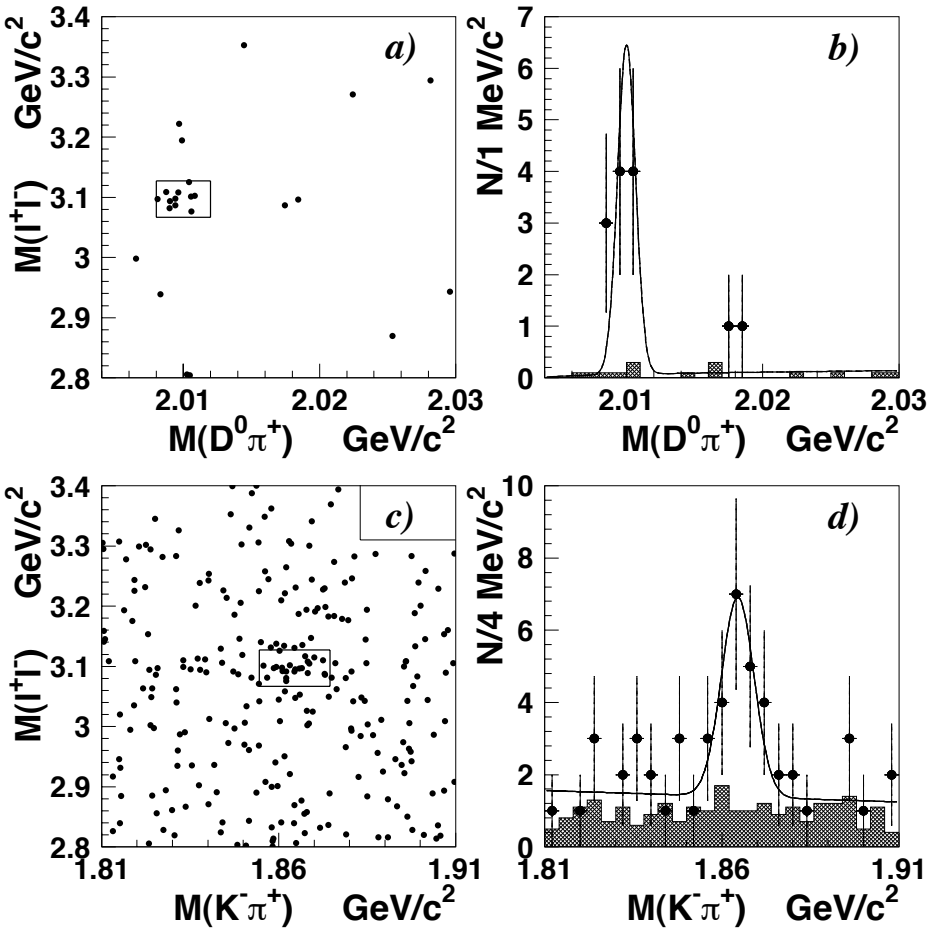
[BELLE–CONF–0705: PRELIMINARY]

1. D-sidebands represent D-window backgrounds well:
   - in MC: for backgrounds due to non-signal $\psi\,\mathrm{D}^{(*)}\overline{\mathrm{D}}^{(*)}$
   - in data: under various subsample tests
2. charged and neutral D-subsamples agree
3. for $X(3940) \to \mathrm{D}\overline{\mathrm{D}}^{*}$: the D^{*} recon, D constraint analysis gives consistent results (ϵ is low)

Sideline (1): the inclusive $\psi\, c\bar{c}/\psi\, X$ fraction

Belle: K. Abe et al., Phys. Rev. Lett. 89, 042001 (2002) — model-dependent

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



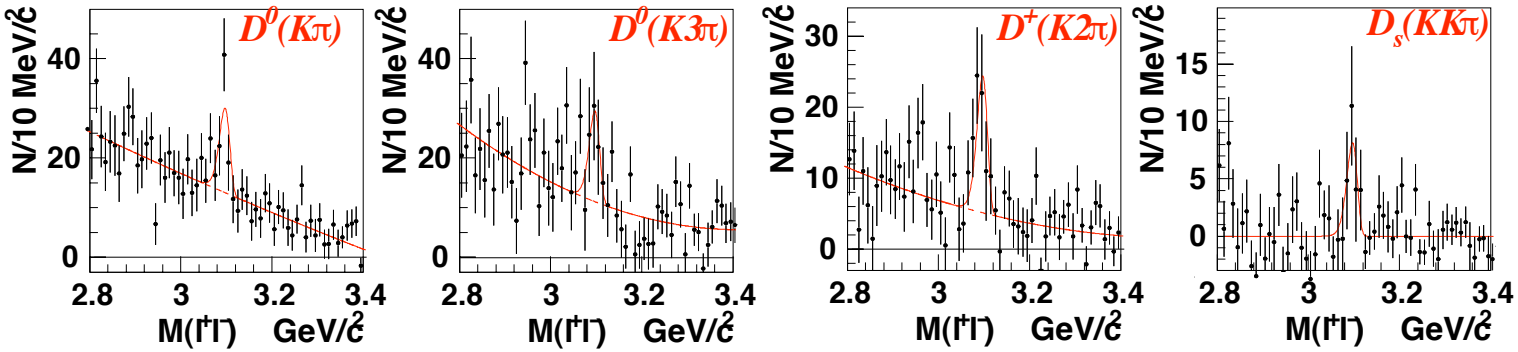
method:

- recon+constrain ψ
- recon+constrain $D^{(*)}$
- veto B-daughters: p^*_D or $p^*_\ell > 2.6\, gev$
- 2D fit to obtain $\psi\, D^{(*)}\, X$ yields
- fragment^n per PYTHIA
- deduce σ

Sideline (1): the inclusive $\psi\, c\bar{c}/\psi\, X$ fraction

Belle: unpublished conference results 2003ff — model-INDEPENDENT

use instead minimal cuts $p^*_\psi > 2.0\,\text{GeV}$ && $M_{\text{recoil}} > 3.7\,\text{GeV}/c^2$, fit backgrounds:



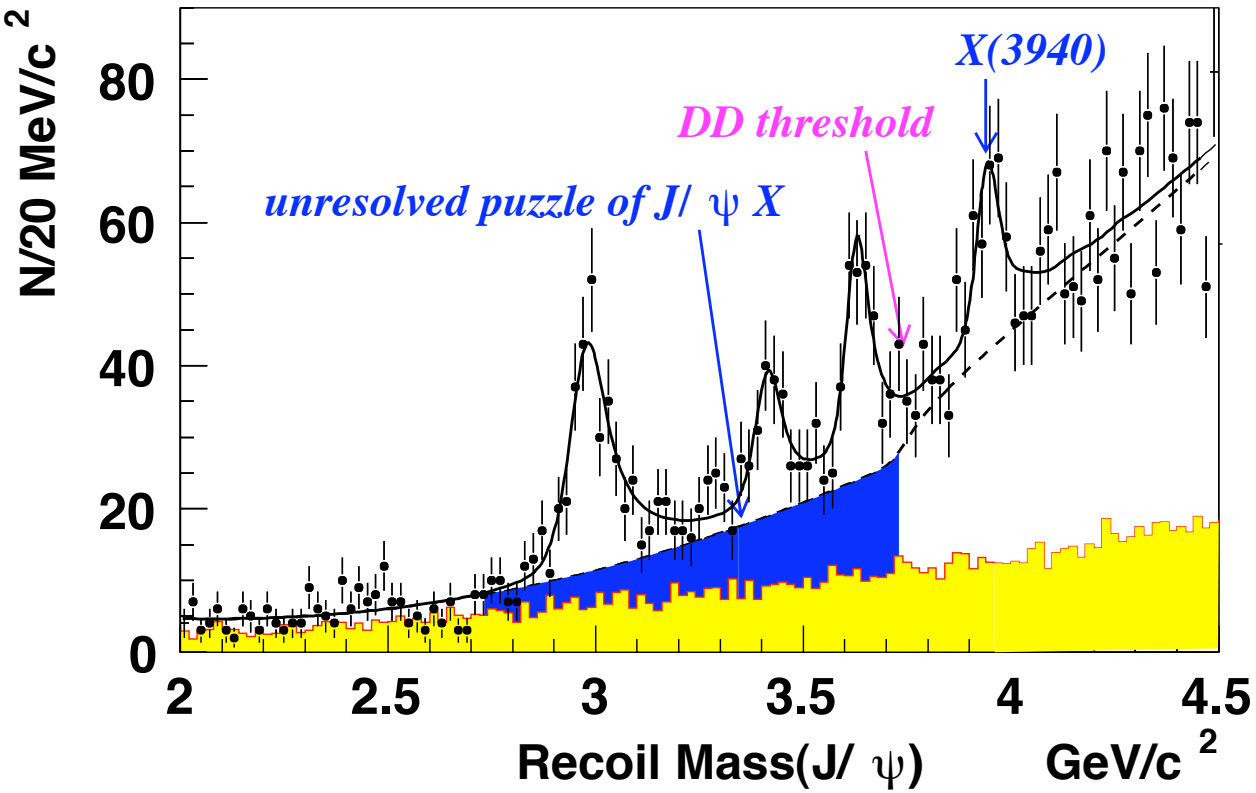
associated state	$D^0 \to K\pi$	$D^0 \to K3\pi$	D^+	D_s^+	Λ_c^+
$N^{\text{obs}}_{\text{data}}$	49.6 ± 13.3	53.0 ± 21.2	56.2 ± 15.4	23.8 ± 9.4	3.0 ± 4.2
N^{0}_{data}	$(3.10 \pm 0.83) \times 10^3$	$(3.31 \pm 1.32) \times 10^3$	$(2.08 \pm 0.57) \times 10^3$	$(1.83 \pm 0.72) \times 10^3$	$(0.17 \pm 0.23) \times 10^3$
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		

Determine double-charm fraction independent of $c\bar{c}$ fragmentation:

$$\frac{\sigma(e^+e^- \to J/\psi\, c\bar{c})}{\sigma(e^+e^- \to J/\psi\, X)} \simeq \frac{0.5 \times \sum N_i}{N_{J/\psi}} = 0.5 \times \frac{(7240 \pm 1240) \times 10^3}{(4438 \pm 88) \times 10^3}$$
$$= 0.82 \pm 0.15 \pm 0.14$$
$$> 0.48 \text{ at } 95\% \text{ CL}$$

cf. perturbative QCD (*esp.* NRQCD): hard to "move the prediction" above 0.1
[expectation: dominance of $e^+e^- \to \gamma^* \to \psi\, gg$ (bulk) and $\psi\, g$ (endpoint)]

Sideline (2): the $e^+e^- \to \psi\, g$ process



- $\exists$ residual component which seems not to be $\psi\,(c\bar{c})_{res}$
- it is only above $c\bar{c}$ threshold
- is this $e^+e^- \to \psi\, g$? if so, why the coincidence?

Summary

- What's over
- What's established
- What's new
- What's needed from theory

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$D\overline{D}$ amplitude	broad 3880–4200 MeV structure	
$X(3940) \to D\overline{D}^*$	$(3942^{+7}_{-6} \pm 6)$	$\Gamma = (37^{+26}_{-15} \pm 8)\,\mathrm{MeV}$
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  - predictive account of $e^+e^- \to \psi(nS)\,X$ amplitudes

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- What's needed from theory
  - interpretation & tests of the new states (already underway)
  - predictive account of $e^+e^- \to \psi(nS)\,X$ amplitudes
  - implications for prod^n of quarkonium-like states at the LHC?

Supporting results: $e^+e^- \to 2\gamma^* \to V\,V'$ [BaBar]