Charmonium production in e^+e^- annihilation at $\sqrt{s} \sim 10.6\,\mathrm{GeV}$

P. Pakhlov

(ITEP, Moscow)

OUTLINE

- Introduction
- Inclusive prompt charmonium ( )
- Double charmonium production ( )
- J/ψ production with associated charm hadrons ( )
- Summary

D I S 2 0 0 3

XI International Workshop on Deep Inelastic Scattering St.Petersburg, 23-27 April 2003

Charmonium production in many processes
(B-decays; hadronic interactions; photoproduction; $\gamma\gamma$; e^+e^-)
remains a puzzle for many years.

''Tevatron $\psi(2S)$ surplus problem'':

- PQCD: Leading mechanism for high-p_T $\psi(2S)$:
  c–quark fragmentation
- The measured cross-section ~ 30 larger than PQCD calculations
- Include long-distance effects (Color Octet Mechanism):

$$g \to (cc)^8 \to \psi(2S)\, n\, g_{soft} \;\Rightarrow$$

good to describe cross-section and p_T spectrum (with few free parameters)
bad to describe J/ψ and $\psi(2S)$ polarization

Prompt J/ψ in e^+e^- continuum (history)

- First observed by *CLEO* (but misinterpreted as direct $\Upsilon(4S) \to J/\psi X$ decays):
  "Observation of $\Upsilon(4S)$ Decays into non-$B\overline{B}$ Final States Containing ψ mesons." P.R.L.**64**, 2226 (1990)

$$\boxed{\sigma(e^+e^- \to J/\psi X) \sim 2\,\mathrm{pb}}$$

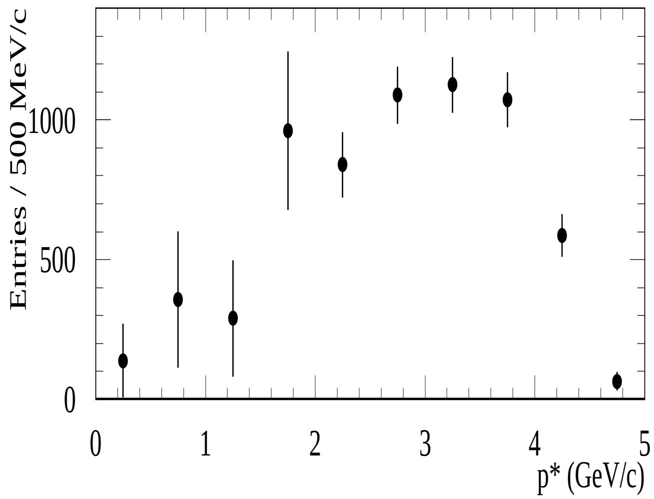
- Theory:
  - Color-signlet: $J/\psi gg$ is a leading mechanism
  - Color-octet: $J/\psi g$ could be significant at end-point of J/ψ spectrum
  - *V.V.Kiselev et al.* (1994): $\sigma(e^+e^- \to J/\psi c\bar{c}) \approx 0.055\,\mathrm{pb}$
    P.Cho and A.K.Leibovich (1996): $\sigma(e^+e^- \to J/\psi c\bar{c}) \approx 0.07\,\mathrm{pb}$
    S.Baek et al. (1998): $\sigma(e^+e^- \to J/\psi c\bar{c}) \approx 0.15\,\mathrm{pb}$

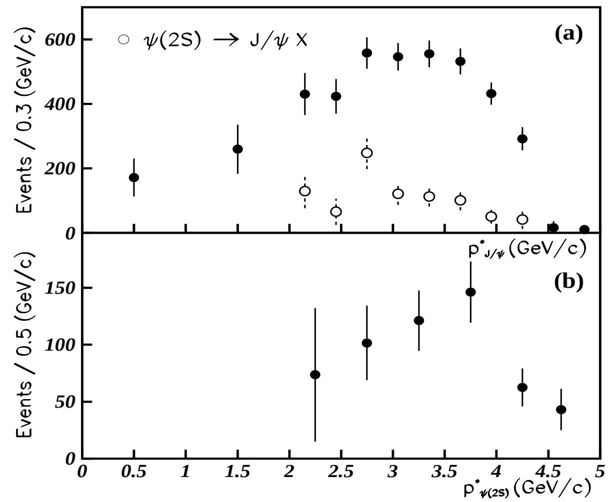
BaBar (P.R.L. **87**, 162002 (2001)):

$$\sigma(e^+e^- \to J/\psi X) = 2.52 \pm 0.21 \pm 0.21\,\mathrm{pb}$$

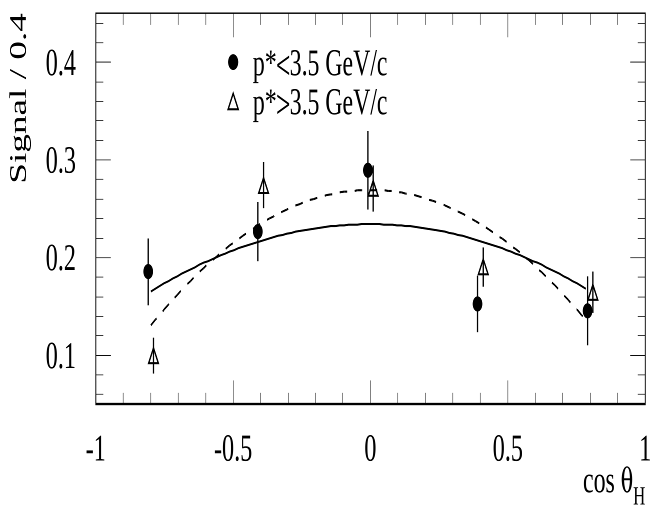
Belle (P.R.L. **88**, 052001 (2001)):

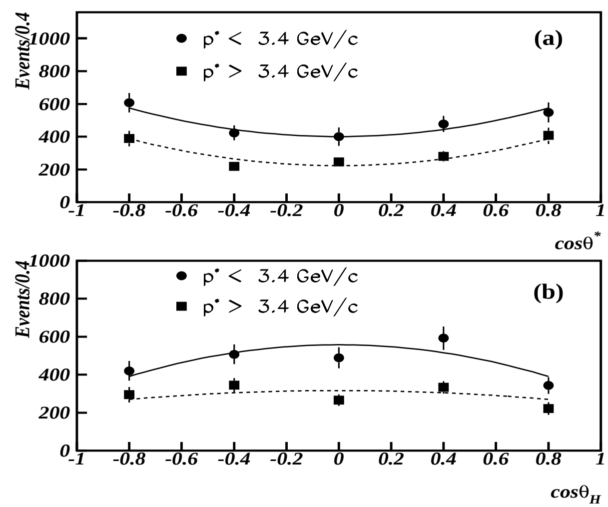
$$\sigma(e^+e^- \to J/\psi X) = 1.47 \pm 0.10 \pm 0.11\,\mathrm{pb}$$





momentum

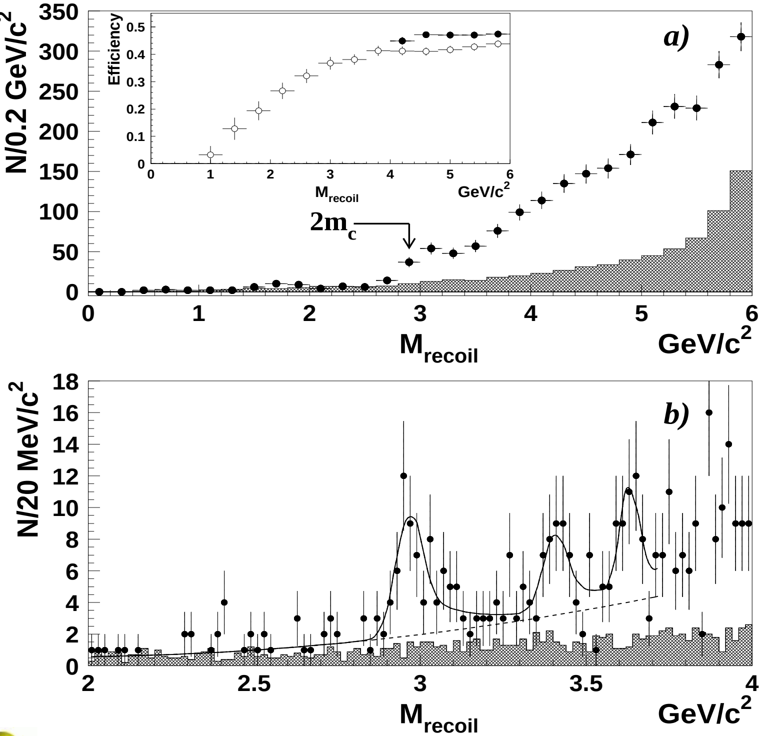




polarization

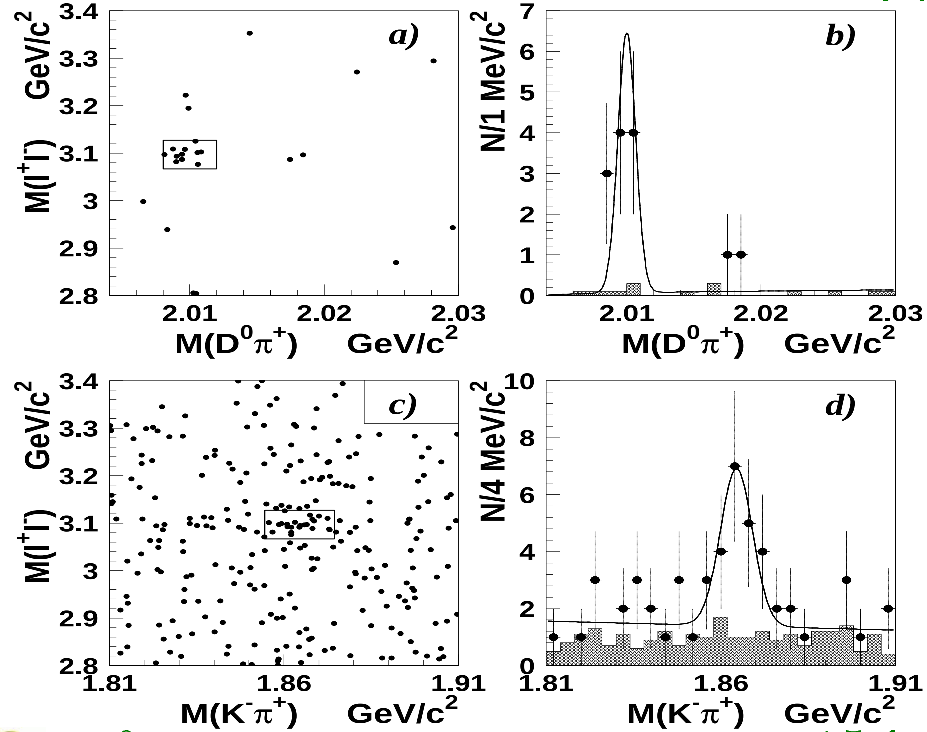
Belle (PRL 89, 142001 (2002)) observed many processes with prompt J/ψ accompanying by charm particles:

- Threshold in J/ψ recoil mass



- Charmonium peaks in J/ψ recoil mass spectrum

- D^{*+} in J/ψ events: $N = 10.5^{+3.6}_{-3.0}$



- D^0 in J/ψ events: $N = 14.9^{+5.4}_{-4.8}$

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

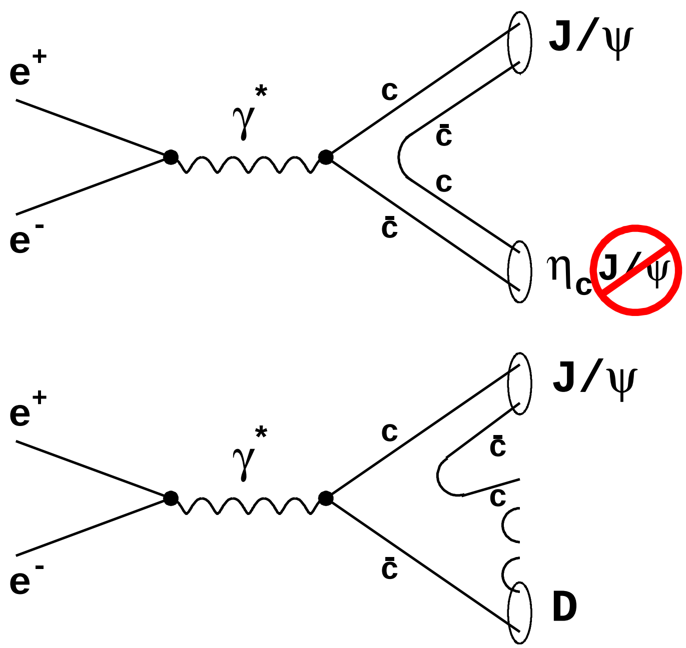
$$\sigma(e^+e^- \to J/\psi\, \eta_c) \times \mathcal{B}(\eta_c \to> 2\,\text{charged}) = (0.033^{+0.007}_{-0.006} \pm 0.009)\text{pb}$$

Can we explain Belle results?

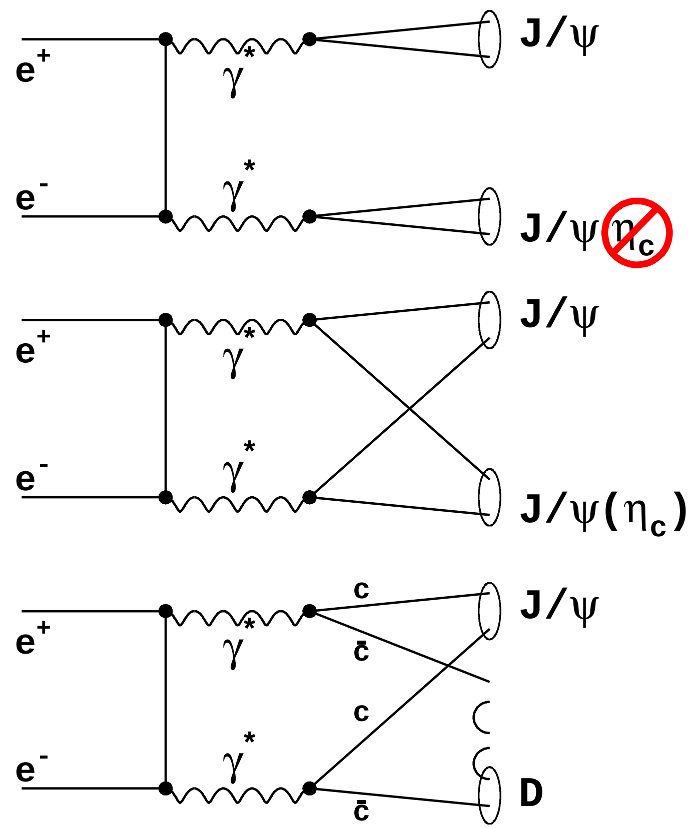
elle cross sections exceeds the theoretically predicted values by ~ 10

- for both $e^+e^- \to J/\psi\,\eta_c$ (E.Braaten & J.Lee (2003))
- and inclusive $e^+e^- \to J/\psi\,c\bar{c}$ (V.Kiselev *et al.* (1994); P.Cho & A.Leibovich (1996); E.Braaten & Y.Chen (1996))

These estimates are done for single virtual photon diagrams:



G.Bodwin, J.Lee, E.Braaten (2003) suggested new diagrams:

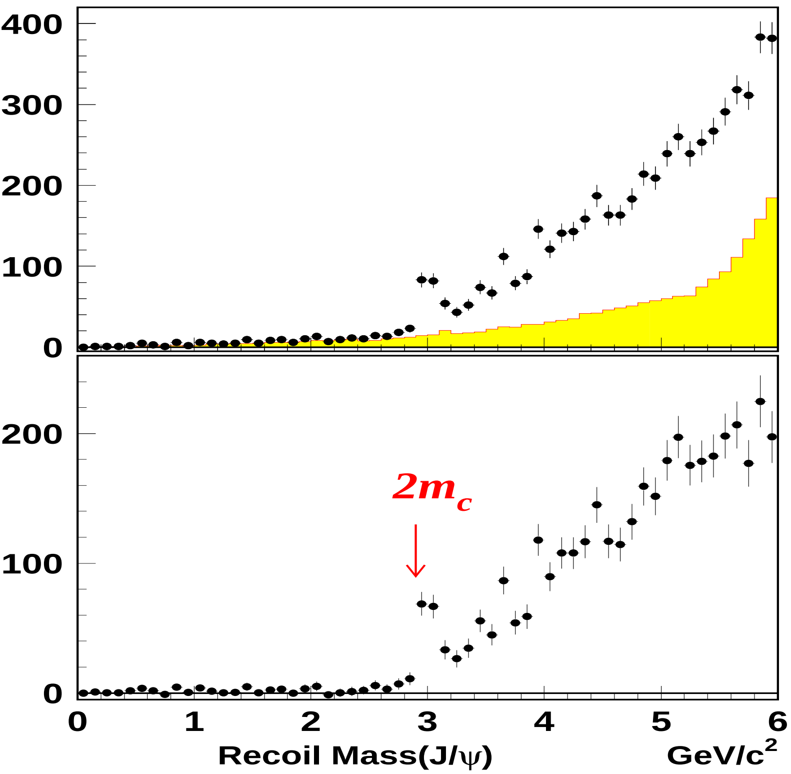


Study of recoil mass spectra

With new data ($\mathcal{L} = 101\,\mathrm{fb}^{-1}$) look at recoil mass against J/ψ and $\psi(2S)$

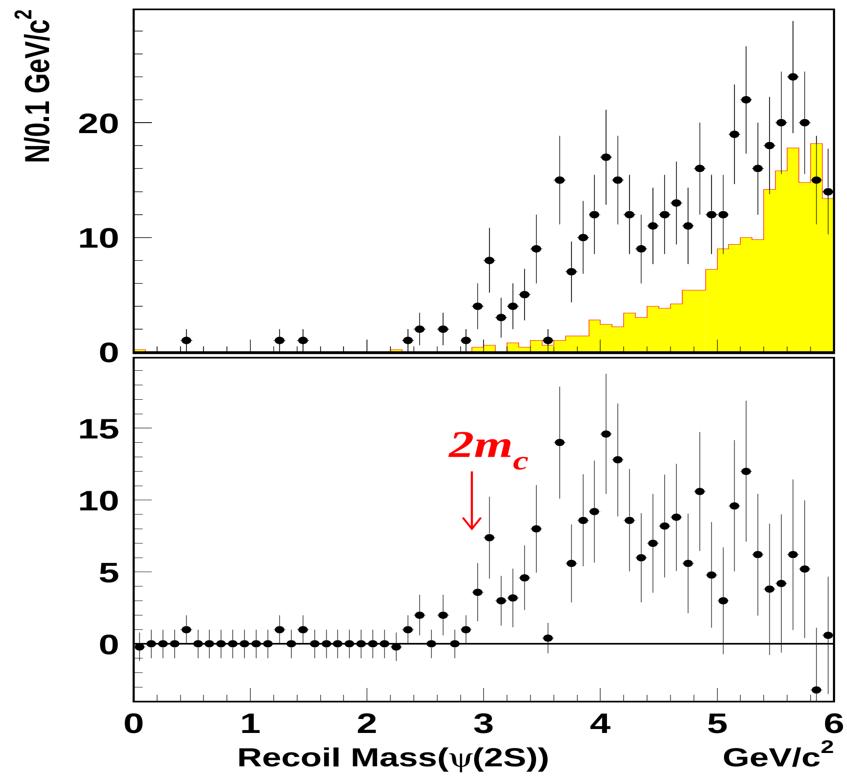
More than **2** additional charged tracks in the event required to suppress QED

$J/\psi \to \ell^+\ell^-$ $(N_{ch} > 4)$ & $\psi(2S) \to J/\psi\pi^+\pi^-$ $(N_{ch} > 6)$



$J/\psi(\psi(2S))$ signal and scaled sidebands

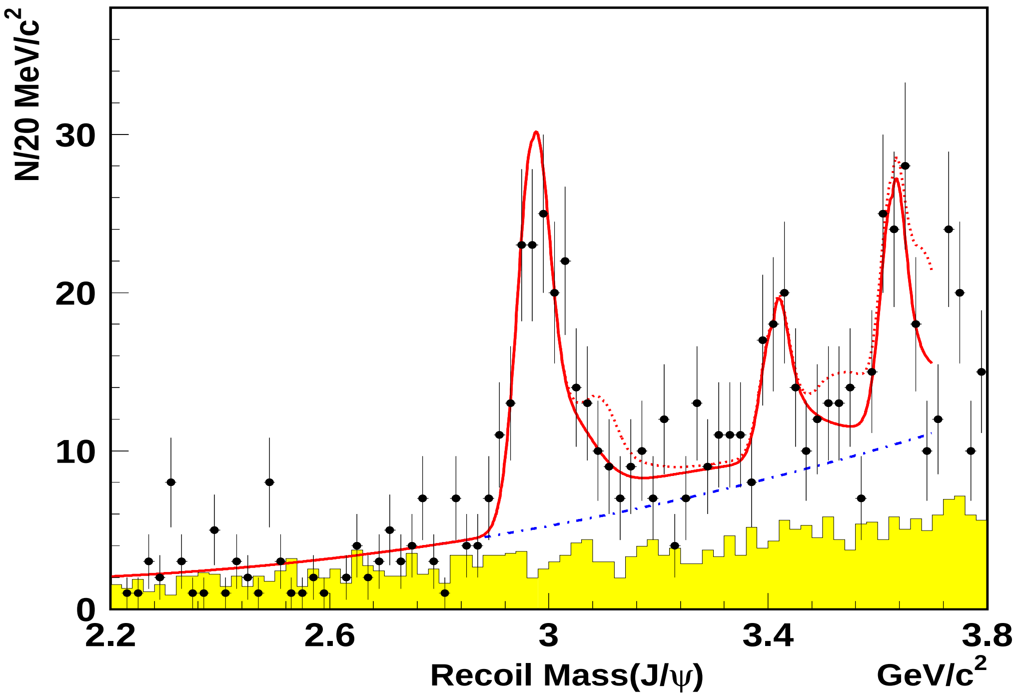
sidebands subtracted



Thresholds around $3\,\mathrm{GeV}/c^2$ are clearly seen

Study in detail J/ψ recoil mass spectrum around $\sim 3\,\mathrm{GeV}/c^2$

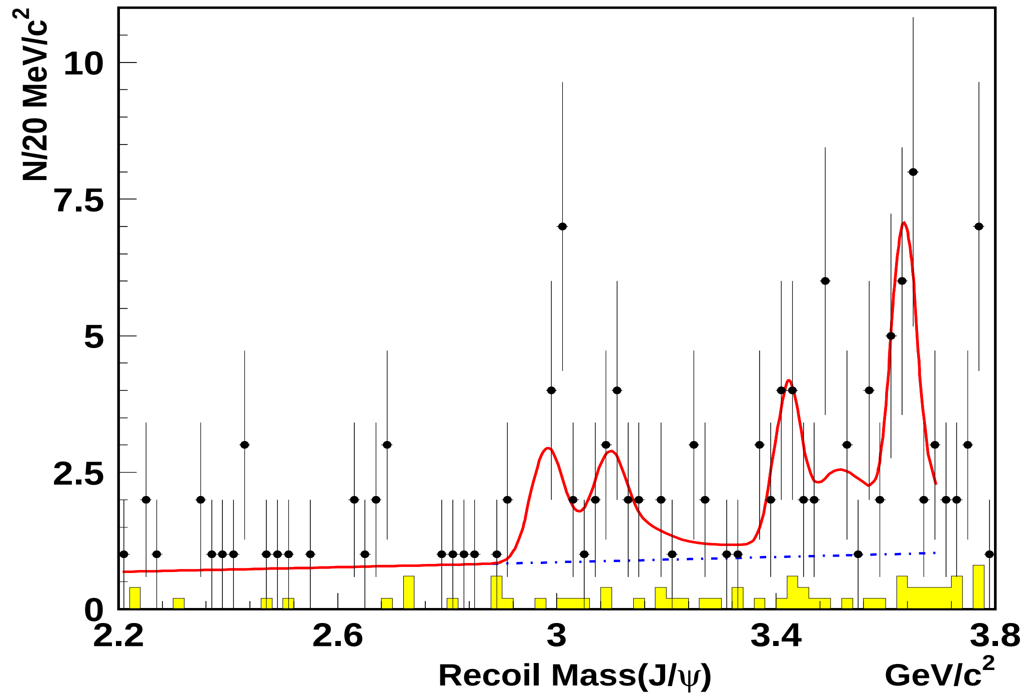
- Constrain J/ψ into nominal mass to improve resolution
- Check recoil mass scale:
  Use $e^+e^- \to \psi(2S)\gamma$ for calibration
  Find recoil mass bias is $< 3\,\mathrm{MeV}/c^2$
- Fit:
  - Include all known charmonium:
    η_c, J/ψ, χ_{c0}, χ_{c1}, χ_{c2}, $\eta_c(2S)$, $\psi(2S)$
  - Include ISR taking into account:
    η_c, $\eta_c(2S)$: p-wave; others: s-wave
  - Masses for η_c, χ_{c0}, $\eta_c(2S)$ free.



	N	M [GeV/c^2]	σ	N	M [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	--	0.0	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	--	0.0	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	--	0.0	fixed	--

Study in detail $\psi(2S)$ recoil mass spectrum around $\sim 3\,\mathrm{GeV}/c^2$

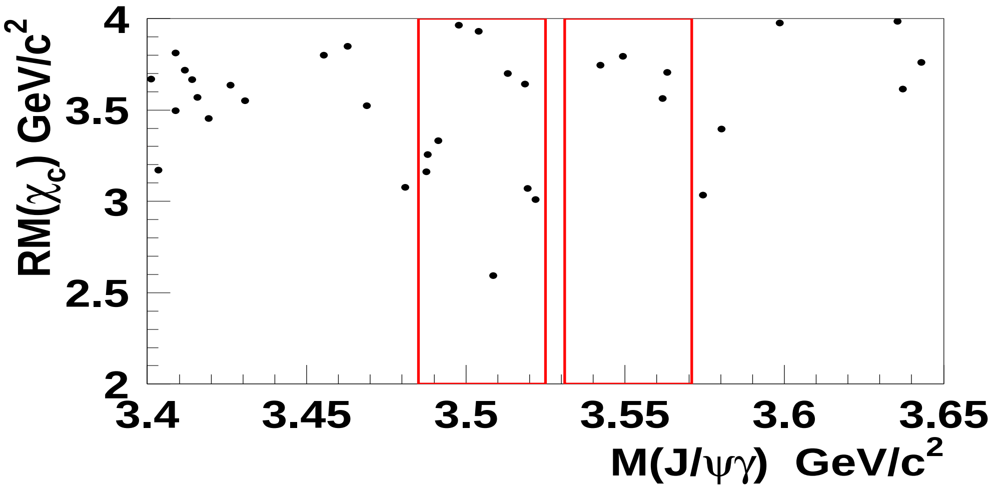
- Fit identical to the J/ψ recoil mass
  - Include all known charmonium: η_c, J/ψ, χ_{c0}, χ_{c1}, χ_{c2}, $\eta_c(2S)$, $\psi(2S)$
  - Masses for η_c, χ_{c0}, $\eta_c(2S)$ fixed: η_c, χ_{c0} to PDG values; $\eta_c(2S)$ to the J/ψ recoil mass fit

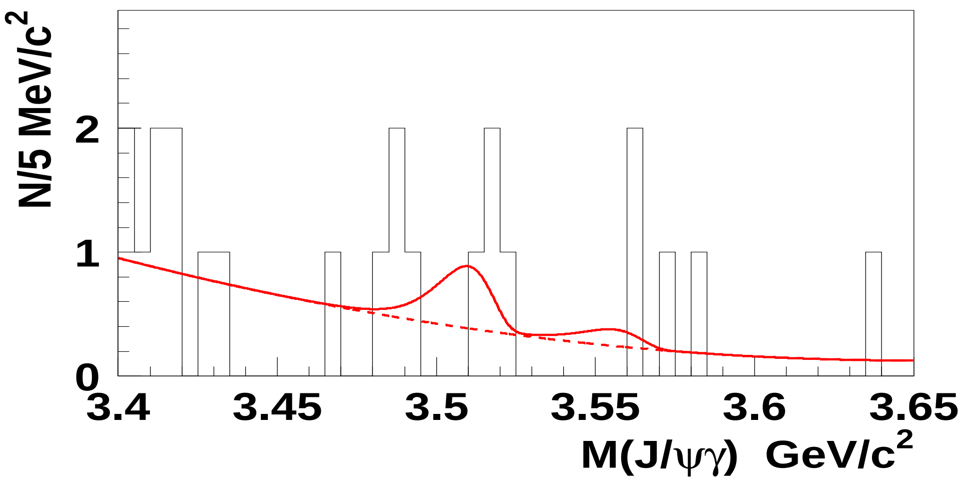


	N	σ	N	σ
η_c	15.8 ± 6.9	2.7	16.4 ± 7.3	2.7
J/ψ	13.3 ± 7.1	--	0.0	--
χ_{c0}	19.8 ± 8.3	3.0	17.8 ± 8.3	2.9
$\chi_{c1} + \chi_{c2}$	9.3 ± 8.1	--	0.0	--
$\eta_c(2S)$	32.8 ± 9.8	3.9	27.9 ± 9.0	3.7
$\psi(2S)$	-3.1 ± 6.8	--	0.0	--

tudy the spectrum of recoil masses against χ_c around charmonium masses

- χ_{c1}, $\chi_{c2} \to J/\psi\,\gamma$
- Look for χ_c signal while the recoil mass against χ_c candidate is in the region: $2.9 < M_{\text{recoil}} < 3.7\,\text{GeV}/c^2$
- Fit to the $J/\psi\gamma$ mass distribution:
  - $N_{\chi_{c1}} = 2.3^{+3.0}_{-2.3}$
  - $N_{\chi_{c2}} = 0.7^{+2.0}_{-1.4}$
- Set upper limit on $e^+e^- \to \chi_{c1(2)} + \textbf{any}\ \ charmonium$





Summary of double charmonium production X-section

PRELIMINARY!

$\sigma(e^+e^- \to charmonium_1\ charmonium_2) \times \mathcal{B}(charmonium_2 \to > 2\ charged)$ **(fb)**

(except for last column $\sigma(e^+e^- \to \psi(2S)\ charmonium_2) \times \mathcal{B}(charmonium_2 \to > 0\ charged)$)

	RECONSTRUCTED CHARMONIUM						
RECOIL 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

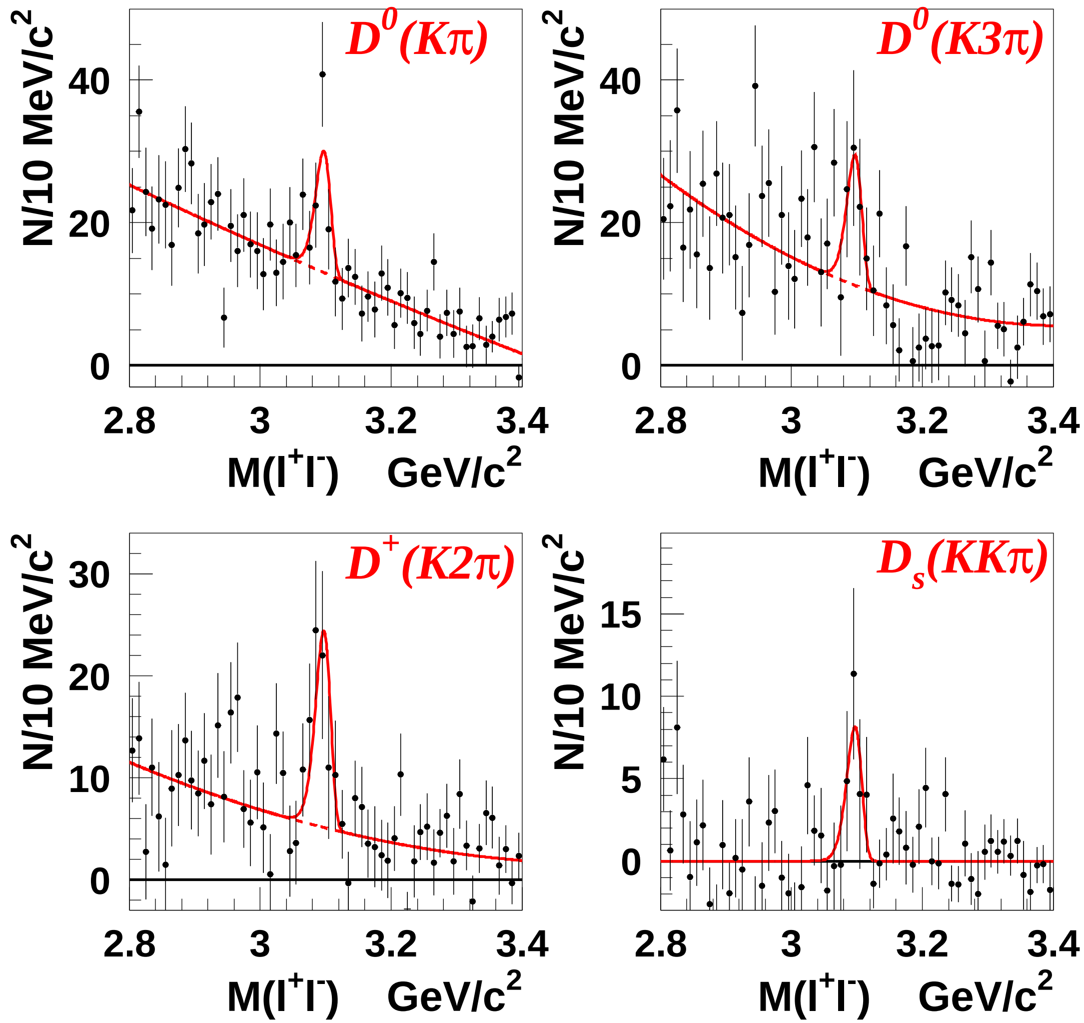
With $\mathcal{L} = 45\,\mathrm{fb}^{-1}$ statistics ***Belle*** observed charm mesons (D^{*+} and D^0) accompanying prompt J/ψ (PRL 89, 142001 (2002))

- Special kinematical cuts against large $B\bar{B}$ background
- To calculate cross-section for $e^+e^- \to J/\psi c\bar{c}$ from $e^+e^- \to J/\psi D^0(D^{*+})X$ we need to know fragmentation rates for $c\bar{c} \to D^0(D^{*+})$
- Large systematic uncertainty + unkonwn model dependence

Now we have more than double statistics ($\mathcal{L} = 101\,\mathrm{fb}^{-1}$) and try to reconstruct all ground state charm hadrons with no additional cuts

Reduce systematic error + remove model dependence

- Reconstruct $D^0 \to K\pi(K3\pi)$, $D^+ \to K2\pi$, $D_s^+ \to KK\pi$ and $\Lambda_c \to pK\pi$
- Fit Charm hadron signals in bins of $\ell^+\ell^-$ mass
- Plot the results of the fits in bins of $\ell^+\ell^-$ mass
- Fit $\ell^+\ell^-$ mass:



$$N_{D^0\to K\pi} = 49.6 \pm 13.3 \ \ (3.7\sigma)$$

$$N_{D^0\to K3\pi} = 53.0 \pm 21.2 \ \ (2.5\sigma)$$

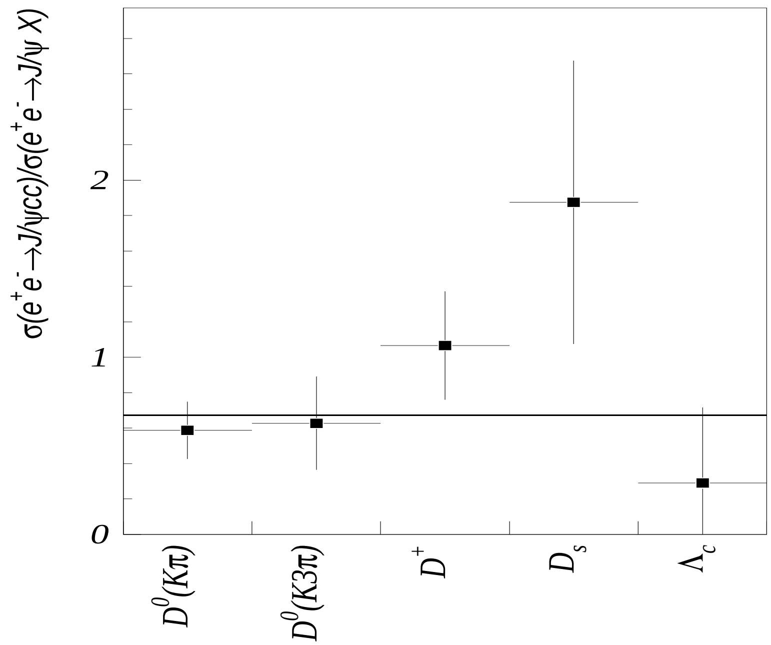
$$N_{D^+\to K2\pi} = 56.2 \pm 15.4 \ \ (3.6\sigma)$$

$$N_{D_s^+\to KK\pi} = 23.8 \pm 9.4 \ \ (2.6\sigma)$$

$$N_{\Lambda_c\to Kp\pi} = 3.0 \pm 4.2$$

Calculate X-section for $e^+e^- \to J/\psi\, c\bar{c}$

- Correct each of 5 measured yields on efficiency
- Average 5 results using LUND prediction for $f(c\bar{c} \to D(\Lambda_c))$



- Reasonable agreement with LUND prediciotn $\chi^2/n.d.f. = 1.25$

$$\frac{\sigma(e^+e^- \to J/\psi c\bar{c})}{\sigma(e^+e^- \to J/\psi X)} = 0.67 \pm 0.12$$

Sum D^0, D^+, D_s^+ and Λ_c yields corrected on the efficiency

$$\frac{\sigma(e^+e^- \to J/\psi c\bar{c})}{\sigma(e^+e^- \to J/\psi X)} = \frac{N_{D^0} + N_{D^+} + N_{D_s^+} + N_{\Lambda_c}}{2 \cdot N_{J/\psi}} =$$

$$\mathbf{0.82 \pm 0.15}$$

PRELIMINARY !

- The main results of the published *Belle* paper (PRL 89, 142001 (2002)) are confirmed with new data and analysis
- Cross-sections for many pairs of double charmonium production are calculated with better accuracy or for the first time:
  - $\sigma(\mathbf{e^+e^-} \to \mathbf{J}/\psi\,\eta_\mathbf{c}) \times \mathcal{B}(\eta_\mathbf{c} \to > \mathbf{2\ \ charged}) = (\mathbf{46} \pm \mathbf{6}^{+\mathbf{7}}_{-\mathbf{9}})\mathbf{fb}$
  - $\sigma(\mathbf{e^+e^-} \to \mathbf{J}/\psi\,\chi_\mathbf{c0}) \times \mathcal{B}(\chi_\mathbf{c0} \to > \mathbf{2\ \ charged}) = (\mathbf{16} \pm \mathbf{5} \pm \mathbf{4})\mathbf{fb}$
  - $\sigma(\mathbf{e^+e^-} \to \mathbf{J}/\psi\,\eta_\mathbf{c}(\mathbf{2S})) \times \mathcal{B}(\eta_\mathbf{c}(\mathbf{2S}) \to > \mathbf{2\ \ charged}) = (\mathbf{25} \pm \mathbf{6} \pm \mathbf{6})\mathbf{fb}$
  - $\sigma(\mathbf{e^+e^-} \to \psi(\mathbf{2S})\,\eta_\mathbf{c}(\mathbf{2S})) \times \mathcal{B}(\eta_\mathbf{c}(\mathbf{2S}) \to > \mathbf{0\ \ charged}) = (\mathbf{31} \pm \mathbf{9} \pm \mathbf{10})\mathbf{fb}$
- $\frac{\sigma(e^+e^- \to J/\psi c\bar{c})}{\sigma(e^+e^- \to J/\psi X)}$ is calculated with reduced systematics and removed model dependence:

$$\mathbf{0.82} \pm \mathbf{0.15} \pm \mathbf{0.14}$$

- All results are *preliminary*