Continuum double ($c\bar{c}$) and $D^{(*)}\overline{D}^{(*)}$ production at Belle

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(ON BEHALF OF BELLE COLLABORATION)

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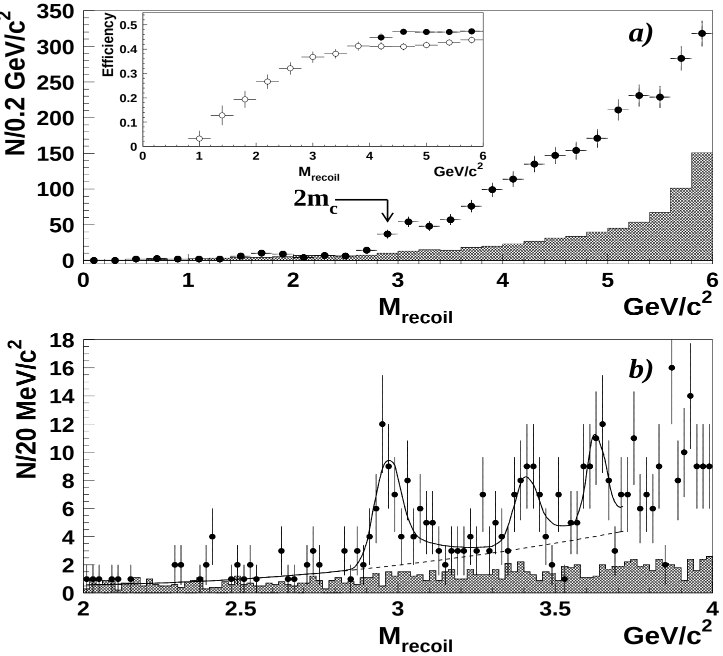
OUTLINE

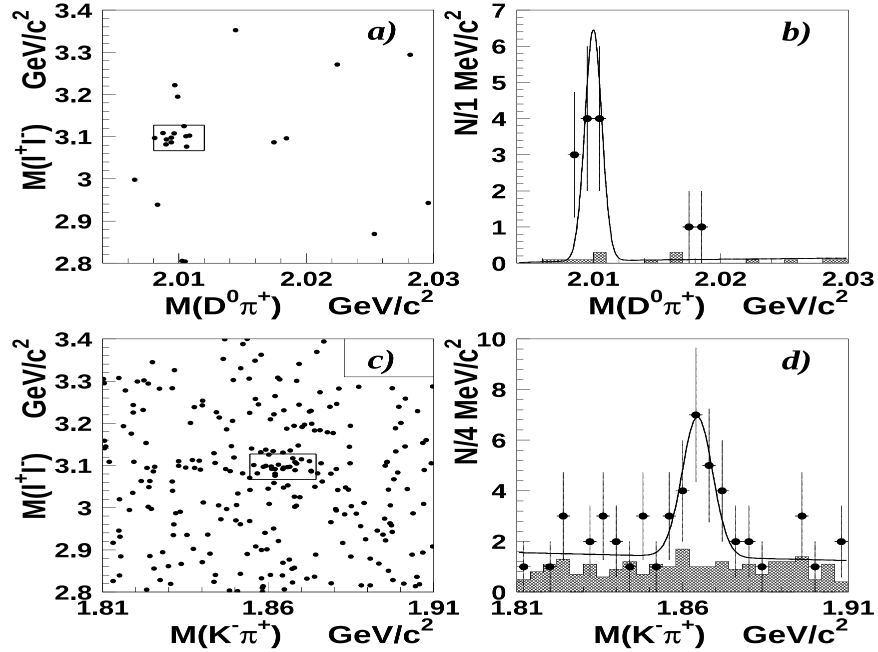
- Double $c\bar{c}$ production
  - Inclusive prompt charmonium
  - Double charmonium production
  - J/ψ production with associated charm hadrons
- $e^+e^- \to D^{(*)}\overline{D}^{(*)}$
  - Motivation
  - Method
  - Results
- Summary

First observation of $e^+e^- \to J/\psi c\bar{c}$

Belle (*PRL 89, 142001 (2002)*) observed many processes with prompt $J/\psi \to \ell^+\ell^-$ ($P_{J/\psi} > 2\,\mathrm{GeV}/c$) accompanied by charm particles ($\mathcal{L} = 45\,\mathrm{fb}$):

- Threshold in J/ψ recoil mass
- D^{*+} in J/ψ events





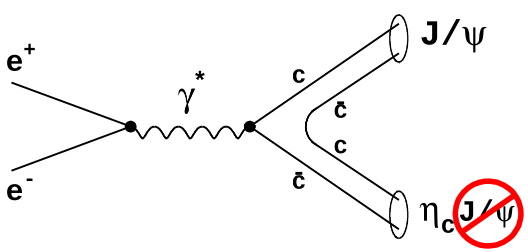
- η_c, χ_{c0}, η_c' in J/ψ recoil mass spectrum
- D^0 in J/ψ events

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

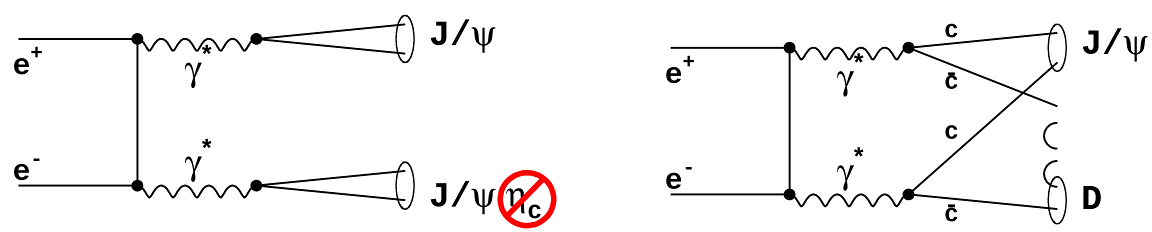
$$(\mathbf{e^+e^- \to J/\psi\, \eta_c) \times \mathcal{B}(\eta_c \to> 2\ charged) = (0.033^{+0.007}_{-0.006} \pm 0.009)}\mathrm{pb}$$

- Cross sections are an order of magnitude larger than predicted by theory:
  - for inclusive $e^+e^- \to J/\psi\, c\bar{c}$ (V.Kiselev *et al.* (1994); P.Cho & A.Leibovich (1996) predict $\sigma \sim 0.05 - 0.07$ pb; Belle measured $\sigma \sim 0.9$ pb)
  - for $e^+e^- \to J/\psi\, \eta_c$ (E.Braaten & J.Lee (2003)) predict $\sigma \sim 0.002$ pb; Belle measured $\sigma \gtrsim 0.033$ pb)
- PQCD and NRQCD predict dominant cross-sections from $e^+e^- \to J/\psi\, gg$ and $e^+e^- \to J/\psi\, g$ processes, while we observed $e^+e^- \to J/\psi\, c\bar{c}$ to be leading mechanism.

The estimates are for single virtual photon diagrams:



G.Bodwin, J.Lee, E.Braaten (2003) suggest new contribution to explain descrepancy:

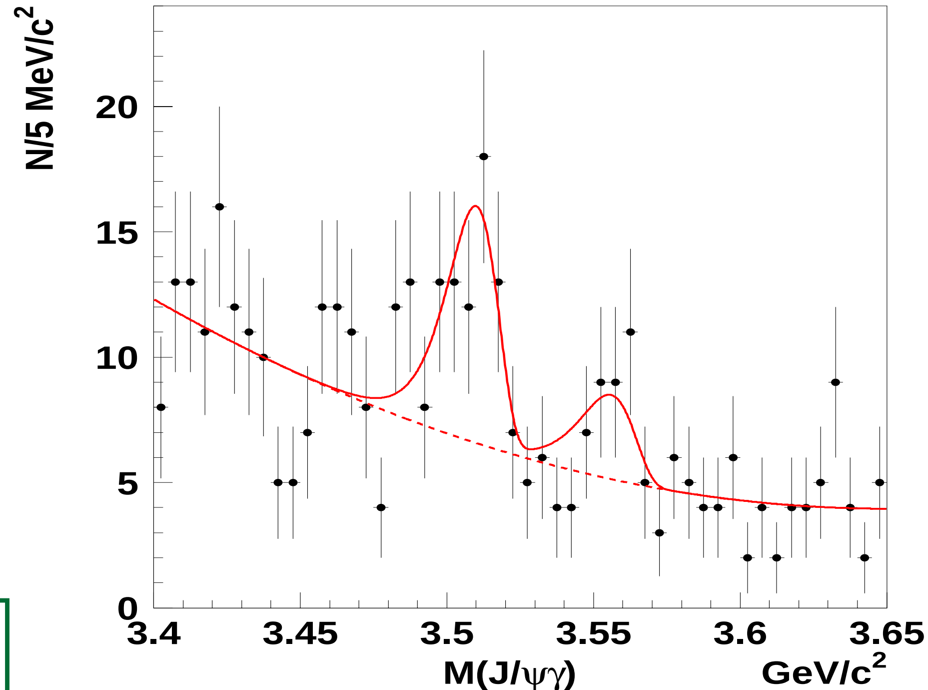


Large $2(c\bar{c})$ is due to QED $e^+e^- \to 2\gamma^* \to 2(c\bar{c})$ with large fraction of $e^+e^- \to 2\gamma^* \to 2J/\psi$

ook for $\chi_{c1(2)}$ in $J/\psi\gamma$ mass spectrum

$\mathcal{L} = 101\,\mathrm{fb}^{-1}$)

- Remove $B\bar{B}$ contribution:
  $p(J/\psi) > 2\,\mathrm{GeV}/c$
- To suppress soft γ background require γ in forward hemisphere in $J/\psi\gamma$ rest frame
- $N^{fit}_{\chi_{c1}} = 42.7^{+10.5}_{-9.8}$ $\quad$ $N^{fit}_{\chi_{c2}} = 16.4^{+8.2}_{-7.5}$

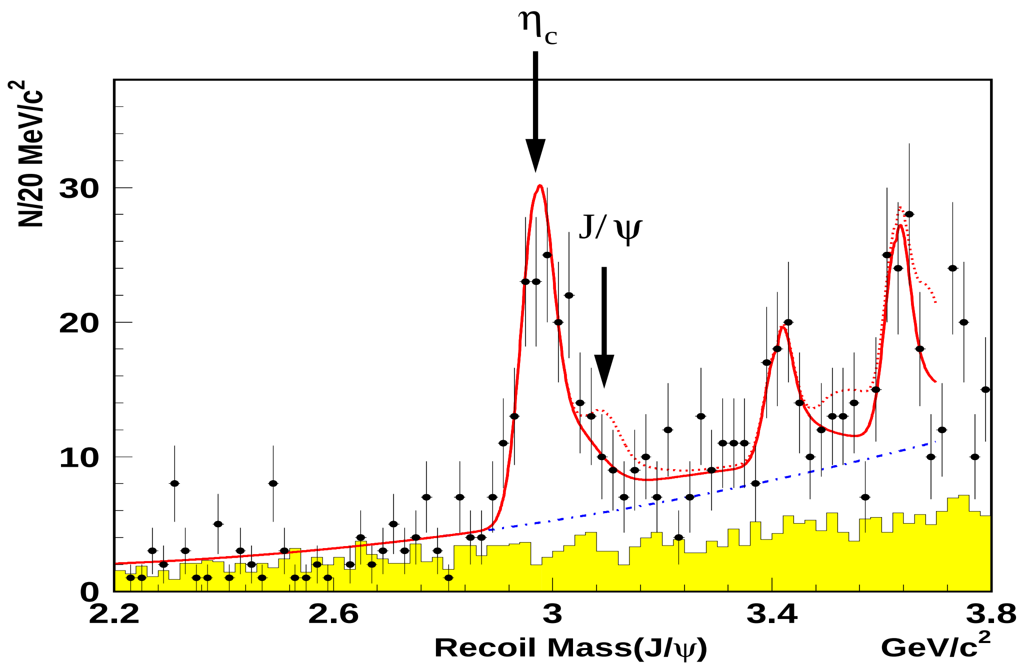


- Subtract $\psi(2S) \to \chi_{c1}\,\gamma$ using reconstructed $\psi(2S) \to J/\psi\pi^+\pi^-$:
  $N_{\psi(2S)\to\chi_{c1}} = 9.5 \pm 1.5$
- After $\psi(2S)$ feed down subtraction $N^{prompt}_{\chi_{c1}} = 33.2^{+10.6}_{-9.8}$ $\quad (3.5\sigma)$

First evidence for prompt χ_{c1} production in e^+e^- annihilation

Study in detail J/ψ recoil mass spectrum around $\sim 3\,\mathrm{GeV}/c^2$ ($\mathcal{L} = 101\,\mathrm{fb}^{-1}$)

- Calibrate M_{recoil} scale before fit:
  Use $e^+e^- \to \psi(2S)\gamma$;
  $\psi(2S) \to J/\psi\pi^+\pi^-$
  Find M_{recoil} bias $< 3\,\mathrm{MeV}/c^2$
- Fit includes all known charmonium states.
- No significant J/ψ, $\chi_{c1,2}$, $\psi(2S)$: 90% CL is shown with dotted line
- η_c, χ_{c0}, $\eta_c(2S)$ are confirmed.

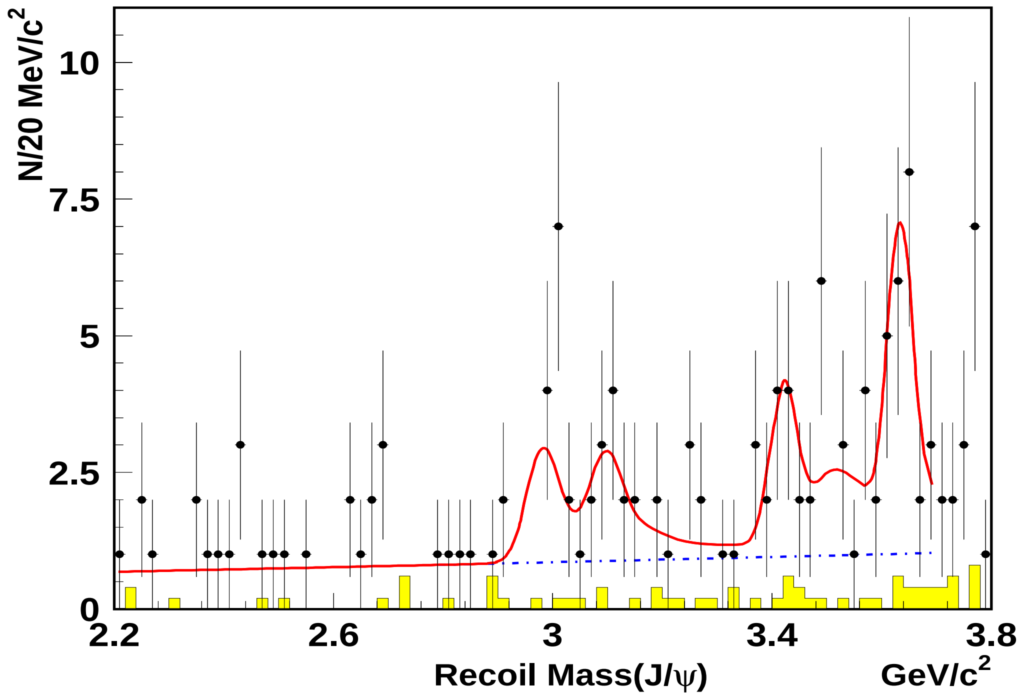


	N	$M\,[\mathrm{GeV}/c^2]$	σ	N	$M\,[\mathrm{GeV}/c^2]$	σ
η_c	175 ± 23	2.972 ± 0.007	9.9	179 ± 22	2.971 ± 0.006	10.6
J/ψ	-9 ± 17	fixed	--	0.0	fixed	--
χ_{c0}	61 ± 21	3.409 ± 0.010	2.9	72 ± 21	3.408 ± 0.009	3.8
$\chi_{c1} + \chi_{c2}$	-15 ± 19	fixed	--	0.0	fixed	--
$\eta_c(2S)$	108 ± 24	3.630 ± 0.008	4.4	97 ± 22	3.628 ± 0.007	4.9
$\psi(2S)$	-38 ± 21	fixed	--	0.0	fixed	--

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

Study $\psi(2S) \to J/\psi\pi^+\pi^-$ recoil mass spectrum around $\sim 3\,\mathrm{GeV}/c^2$

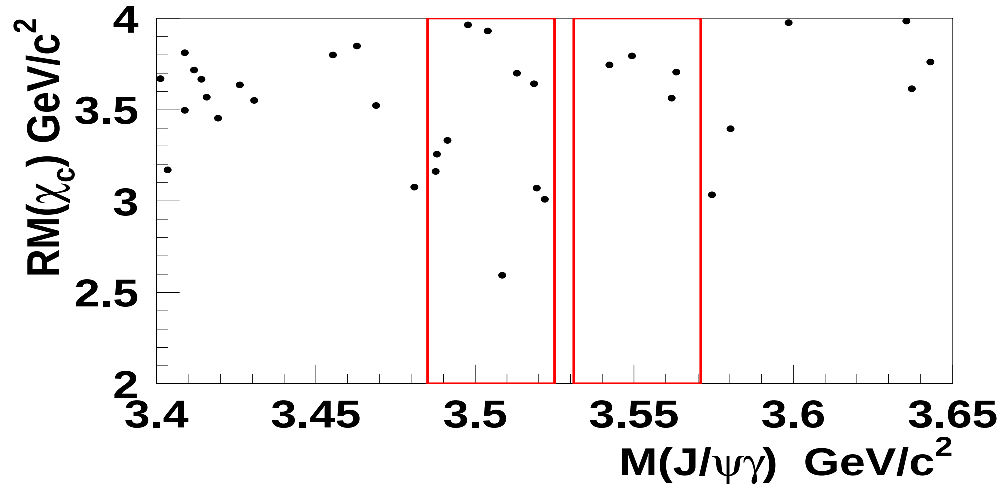
- Fit identical to that for J/ψ (M fixed)
- Statistics is still poor:
  - we can not still find or exclude J/ψ, χ_{cJ}, $\psi(2S)$
  - signals of η_c, χ_{c0}, $\eta_c(2S)$ are $\sim 3\sigma$
- Qualatively behavior is similar to that for J/ψ

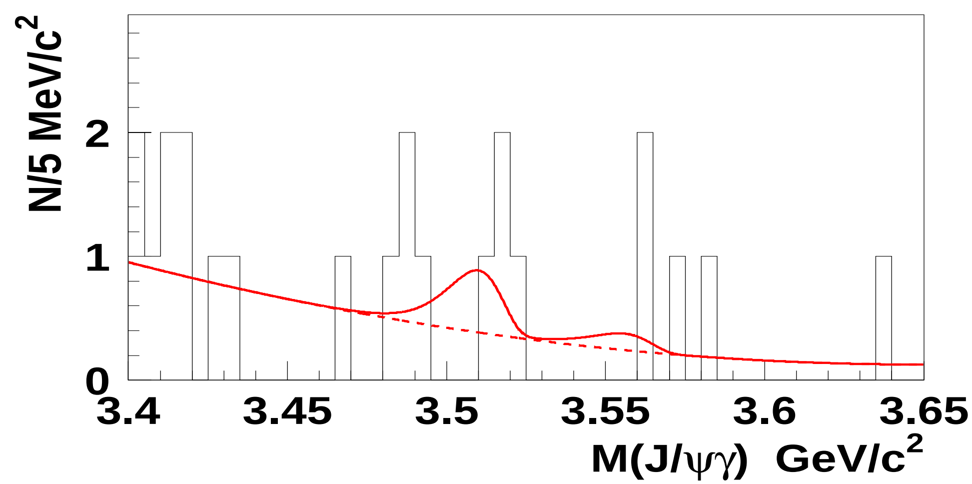


	N	σ	N	σ
η_c	15.8 ± 6.9	2.7	16.4 ± 7.3	2.7
J/ψ	13.3 ± 7.1	--	0.0	--
χ_{c0}	19.8 ± 8.3	3.0	17.8 ± 8.3	2.9
$\chi_{c1} + \chi_{c2}$	9.3 ± 8.1	--	0.0	--
$\eta_c(2S)$	32.8 ± 9.8	3.9	27.9 ± 9.0	3.7
$\psi(2S)$	-3.1 ± 6.8	--	0.0	--

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 given recoil mass against χ_c candidate is in the region: $2.9 < M_{\text{recoil}} < 3.7\,\text{GeV}/c^2$
- Fit to $J/\psi\gamma$ 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-sections

PRELIMINARY!

$$\sigma\Big(e^+e^- \to (\bar{c}c)_1\,(c\bar{c})_2\Big) \times \mathcal{B}\Big((c\bar{c})_2 \to > 2\ charged\Big) \qquad \textbf{(fb)}$$

		RECONSTRUCTED CHARMONIUM						
		η_c	J/ψ	χ_{c0}	χ_{c1}	χ_{c2}	$\eta_c(2S)$	$\psi(2S)$
RECOIL CHARMONIUM	η_c	--	$46 \pm 6^{+7}_{-9}$	--	< 18	< 20	--	$18 \pm 8 \pm 7$
	J/ψ	--	< 8	--	< 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

$\mathcal{L} = 101\,\mathrm{fb}^{-1}$

Reconstruct all charm ground states: D^0, D^+, D_s^+, Λ_c

Fit $D(\Lambda_c)$ signals in $M_{\ell^+\ell^-}$ bins

Fit J/ψ to yields distributions:

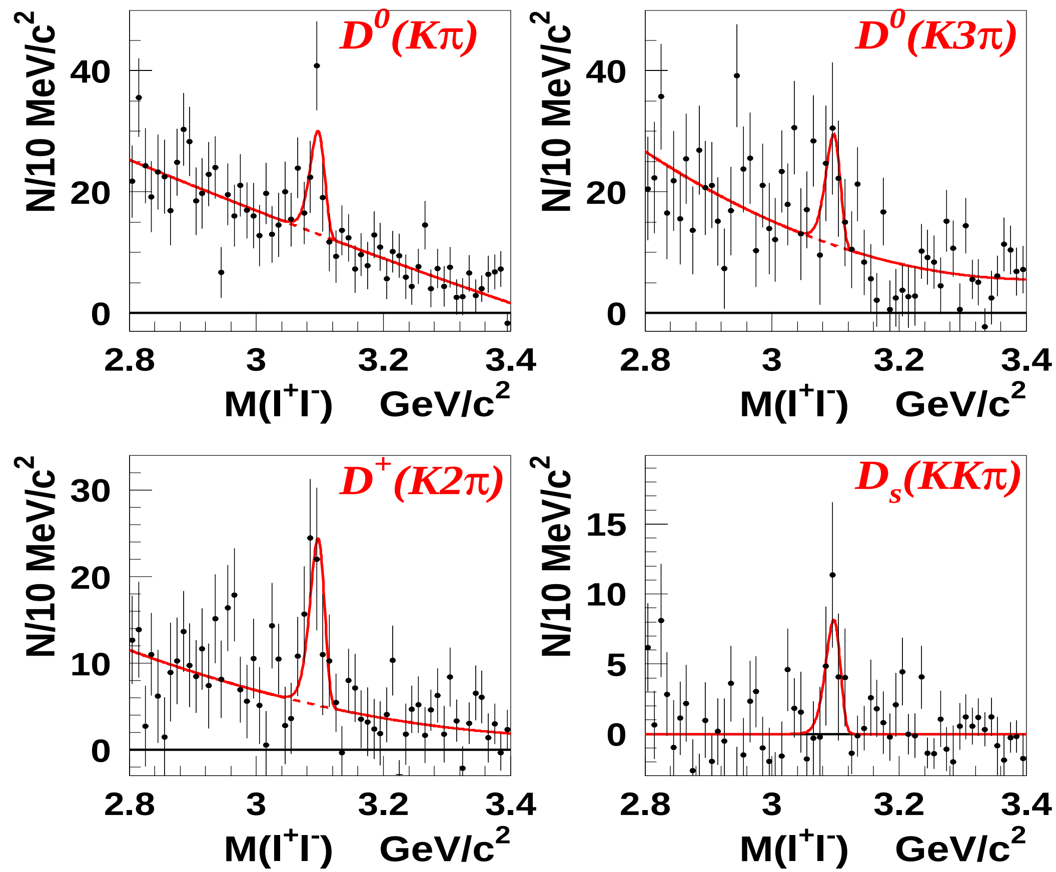
$N_{D^0\to K\pi} = 49.6 \pm 13.3 \ \ (3.7\sigma)$

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

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

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

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



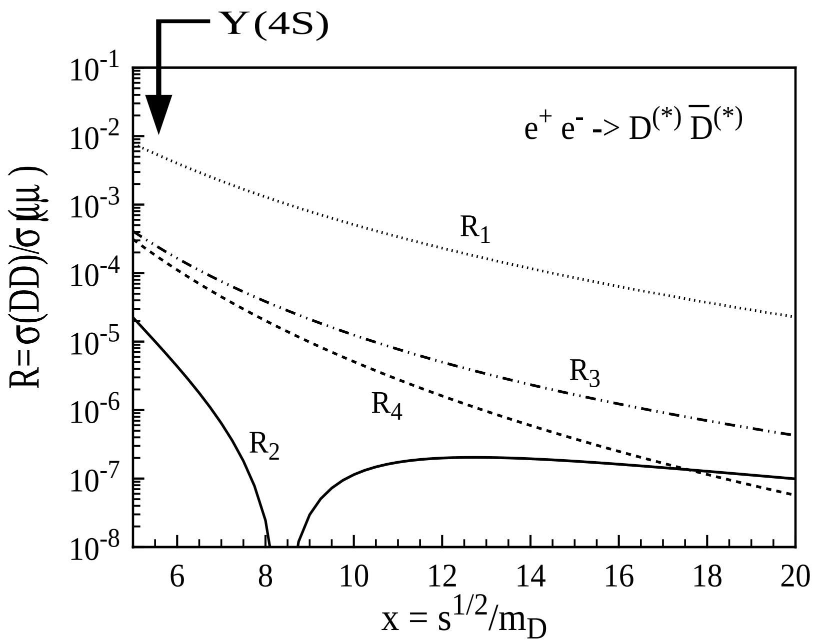
All $c\bar{c}$ final states except for Ξ_c reconstructed $\Rightarrow$ Do not need model to calculate $2(c\bar{c})$ X-section!

$$\frac{(e^+e^- \to J/\psi c\bar{c})}{(e^+e^- \to J/\psi X)} = \frac{N_{D^0} + N_{D^+} + N_{D_s^+} + N_{\Lambda_c} + 2\cdot N_{(c\bar{c})_{res}}}{2\cdot N_{J/\psi}} = 0.82 \pm 0.15 \pm 0.14$$

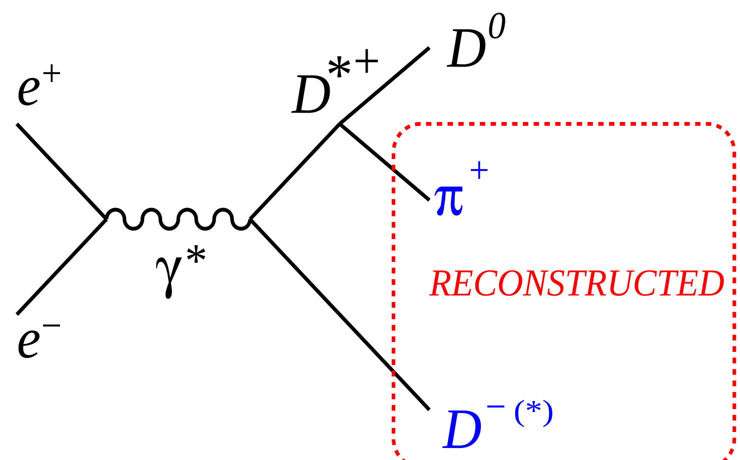
- Coherent continuum $D^{(*)}\overline{D}^{(*)}$ production has been never observed before at large $\sqrt{s}$ ($\gg 2M_D$)
- $\sigma\left(e^+e^- \to D^{(*)}\overline{D}^{(*)}\right)$ measures $D^{(*)}$ form-factors at $q^2 = s \equiv 4 \cdot E^2_{beam}$
- In $m_Q \to \infty$ limit can be related to $B \to D^{(*)}$ form-factors
- M.Neubert, A.Grozin ''Asymptotics of Heavy Meson formfactors'' (*P.R.D 55, 272 (1997)*): quantative predictions for cross-sections and helicity decomposition for $D^*\overline{D}^*$:

$$\sigma\left(e^+e^- \to D^*_T\overline{D}^*_L\right) \simeq \sigma\left(e^+e^- \to D^*\overline{D}\right) \simeq 5 \text{ pb}$$

Other final states have vanishing cross-sections at $\sqrt{s} \simeq 10.58$ GeV



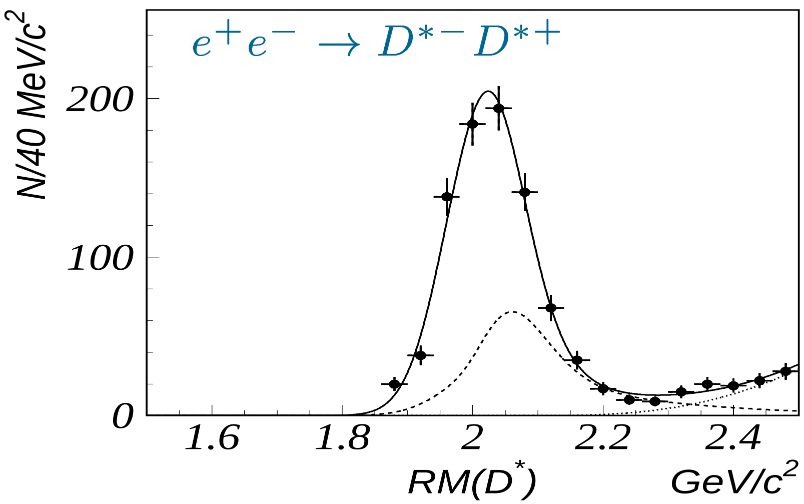
- Study only $D^{*+}\overline{D}^{*-}$, $D^{*+}\overline{D}^{-}$ and $D^{+}D^{-}$ final states (no neutral particles)
- Can be reconstructed fully: two $D^{(*)}$ with total energy $= E_{CMS}$, but efficiency is too small in this case
  Process monochromatic $\Rightarrow$ *partial reconstruction* is sufficient
- Reconstruct $D^{-} \to K^{+}\pi^{-}\pi^{-}$ or $D^{*-} \to \overline{D}^{0}(K\pi, K3\pi)\pi^{-}$
- Mass constraint on D^{-} or $\overline{D}^{0}$ to improve resolution
- Form recoil mass (RM) against reconstructed $D^{(*)-}$



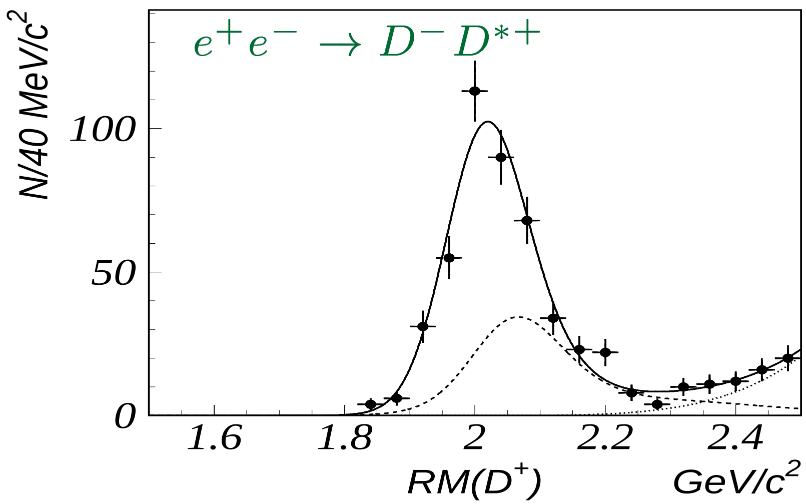
- Reconstruct π^{+} from recoiling D^{*+} decay.
- Form recoil mass difference:
  $RMD \equiv RM(D^{(*)-}\pi^{+}) - RM(D^{(*)-}) \approx M_{D^{*+}} - M_{D^{0}} \equiv \delta_{M} \Leftarrow$ Extremelly efficient in background rejection

$e^+e^- \to D^{*-}D^{*+}$ and $e^+e^- \to D^{*-}D^+$

Apply RMD cut: $|RMD - \delta_M| < 2$ MeV/c^2. Resolution is ~ 1 MeV/c^2!

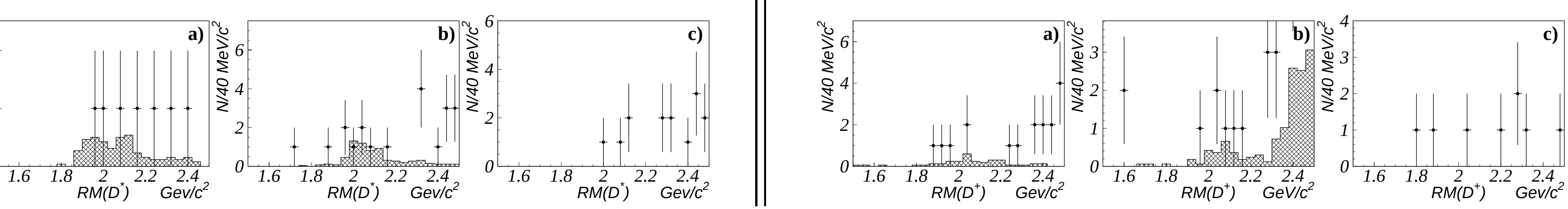


$N = 812 \pm 28$



$N = 423 \pm 20$

Check $D^{(*)-}$, RMD sidebands and wrong sign to estimate backgrounds

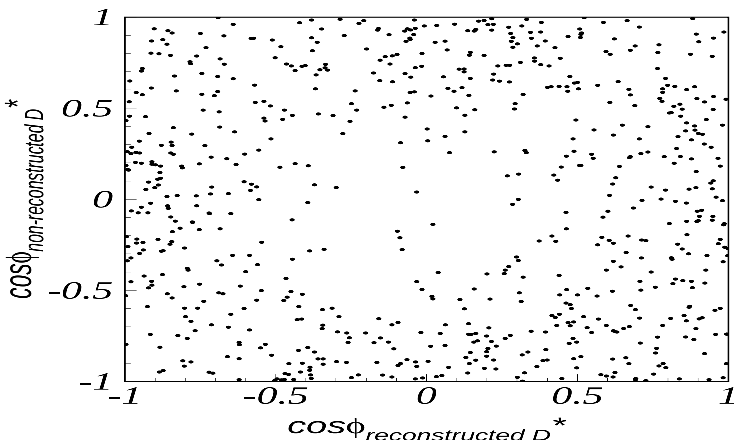


$\mathcal{O}(1\%)$ level backgrounds below 2.1 GeV/c^2 !!!

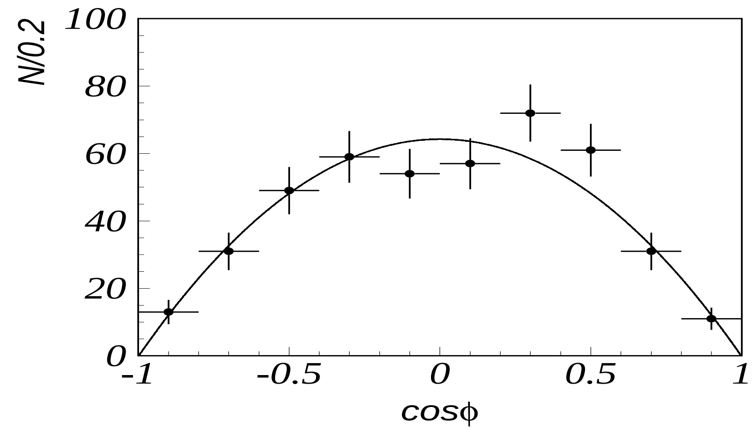
Angular analysis

D^* helicity

$e^+e^- \to D^{*-}D^{*+}$



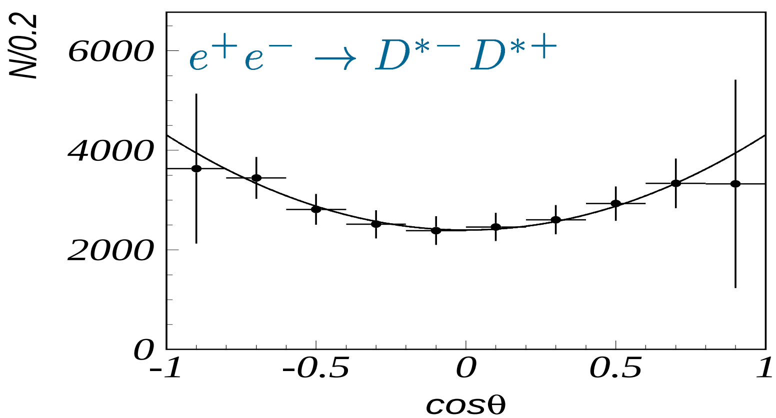
$e^+e^- \to D^-D^{*+}$

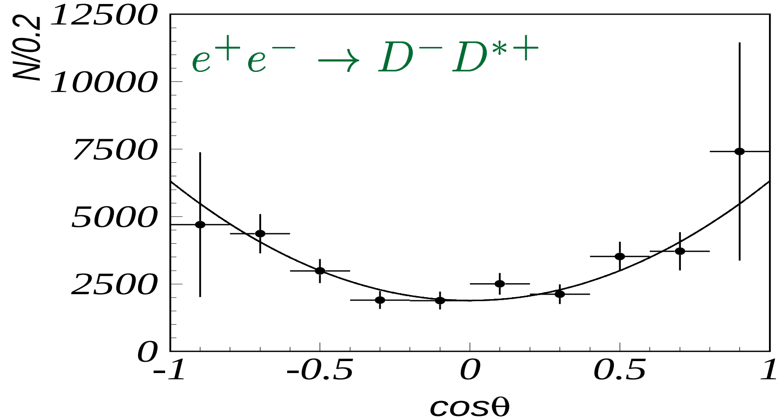


$f_{TT} = 1.5 \pm 3.6\%; \quad f_{TL} = 97.2 \pm 4.8\%; \quad f_{LL} = 1.3 \pm 4.7\%;$

$f_T = 100 \pm 5\%$

D^* production





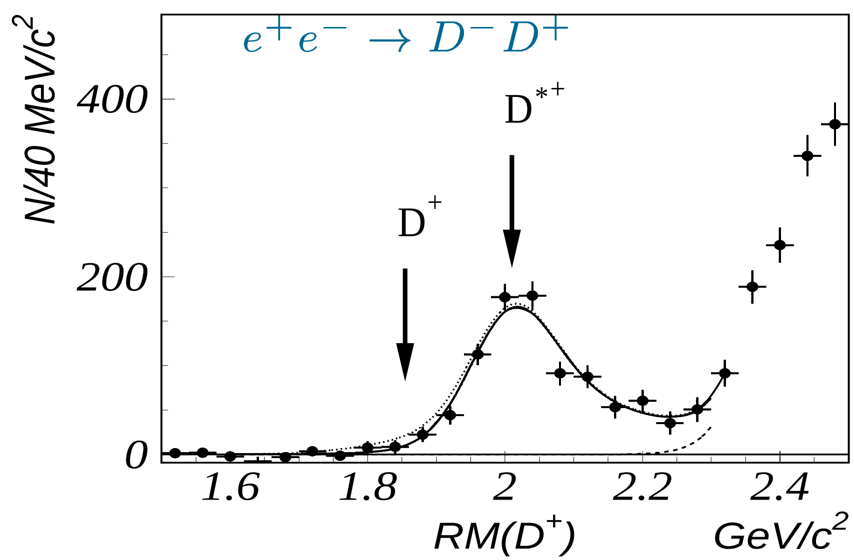
$\alpha = 0.79^{+0.34}_{-0.30}$

Fit: $\sim (1 + \alpha \cos^2 \theta_{prod})$

$\alpha = 2.3^{+0.8}_{-0.7}$

$e^+e^- \to D^-D^+$

- For $e^+e^- \to D^-D^+$, trick with Recoil Mass Difference is no longer applicable
- Study D^- recoil mass spectrum accepting more backgrounds
- No $e^+e^- \to D^-D^+$ signal is found: $N = -17 \pm 22$
- 90% UL is shown with dotted line



RESULTS:

$e^+e^- \to$	$D^{*+}D^{*-}$	$D^{*+}D^-$	D^+D^-
X-section (pb)	$0.65 \pm 0.04 \pm 0.07$	$0.71 \pm 0.05 \pm 0.09$	< 0.02 at 90% CL
Theory (pb)	~ 5	~ 5	~ 0.002

Summary

- Double $(c\bar{c})$ continuum production is not yet understood one year after first experimental observation. The suggestion by BLB that observed large cross-section is a result of pure QED contribution of $e^+e^- \to \gamma^*\gamma^* \to (c\bar{c})(c\bar{c})$ is ruled out by new study
- The main results of the published *Belle* paper (*PRL 89, 142001 (2002)*) are confirmed with new data:
  - Cross-sections for many charmonium pairs production are calculated with better accuracy or for the first time
  - $\frac{\sigma(e^+e^-\to J/\psi c\bar{c})}{\sigma(e^+e^-\to J/\psi X)}$ is calculated with reduced systematics and with less model dependence
- $e^+e^- \to D^{*+}\overline{D}^{*-}$ and $e^+e^- \to D^{*+}\overline{D}^{-}$ are observed for the first time
- The hierarchy of $D^{*+}D^{*-}$, $D^{*+}D^{-}$ and $D^{+}D^{-}$ production cross-sections and $D^{*\pm}$ helicity are in good agreement with HQET; while measured cross-sections are one order of magnitude smaller than theoretical predictions

ook at $D^{(*)-}$ invariant mass and at RMD for the $RM(D^{(*)-}) < 2.1\,\mathrm{GeV}/c^2$ region (expected to be pure signal)