Charm Lifetimes, $D^0 - \overline{D}^0$ Mixing and Double $c\bar{c}$ Production

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Outline

- Charm lifetimes and $D^0 - \overline{D}^0$ Mixing
  - Introduction
  - y_{CP} measurement from BaBar
  - Wrong-sign $D^0 \to K^+\pi^-$ update from Belle
  - New measurements of the D^0 and D^+ lifetimes from FOCUS
- Double $c\bar{c}$ continuum production from Belle
  - Evidence for $e^+e^- \to J/\psi +$ charmonium
  - Evidence for $e^+e^- \to J/\psi +$ charmed mesons
- Summary

Introduction: $D^0 - \overline{D}^0$ Mixing

D^0 mass eigenstates:

- different from flavour eigenstates: $\left|D^0_{1,2}\right\rangle = p\left|D^0\right\rangle \pm q\left|\overline{D}^0\right\rangle$
- characterized by mass splitting(ΔM), difference in widths ($\Delta\Gamma$)

$$\boxed{x \equiv \frac{\Delta M}{\Gamma}} \quad \rightarrow \quad \boxed{R_{\text{mix}} = \frac{1}{2}\sqrt{x^2+y^2}} \quad \leftarrow \quad \boxed{y \equiv \frac{\Delta\Gamma}{2\Gamma}}$$

Wrong-sign decays

Lifetime difference

Hadronic

Semileptonic

$y_{CP} \approx y$ (ignoring CPV)

$$\Downarrow$$

$$\boxed{D^0 \rightarrow K^+\pi^- \ vs\ K^-\pi^+}$$

$$\sim e^{-\Gamma t}\left(2R_{DCS} + 2y'\left(\frac{t}{\tau_D}\right)\sqrt{R_{DCS}} + \left(\frac{t}{\tau_D}\right)^2 \frac{x^2+y^2}{2}\right)$$

$$\boxed{D^0 \rightarrow X\ell^- \ vs\ X\ell^+}$$

$$\sim e^{-\Gamma t}\left(\frac{t}{\tau_D}\right)^2 \frac{x^2+y^2}{2}$$

$$\boxed{D^0 \rightarrow K^+K^- \ vs\ K^-\pi^+}$$

$$y_{CP} = \frac{\tau_{D^0\rightarrow K^-\pi^+}}{\tau_{D^0\rightarrow K^-K^+}} - 1$$

Introduction: $D^0 - \overline{D}^0$ Mixing

Standard Model: $x \lesssim 10^{-3}$ due to GIM mechanism and $m_s \ll m_c$;
$y \lesssim 10^{-3}$ based on $SU(3)$ symmetry and HQET

New Physics: new heavy particles involved into "mixing box" diagram can significantly enhance x

FSI and $SU(3)$ breaking: can enhance y

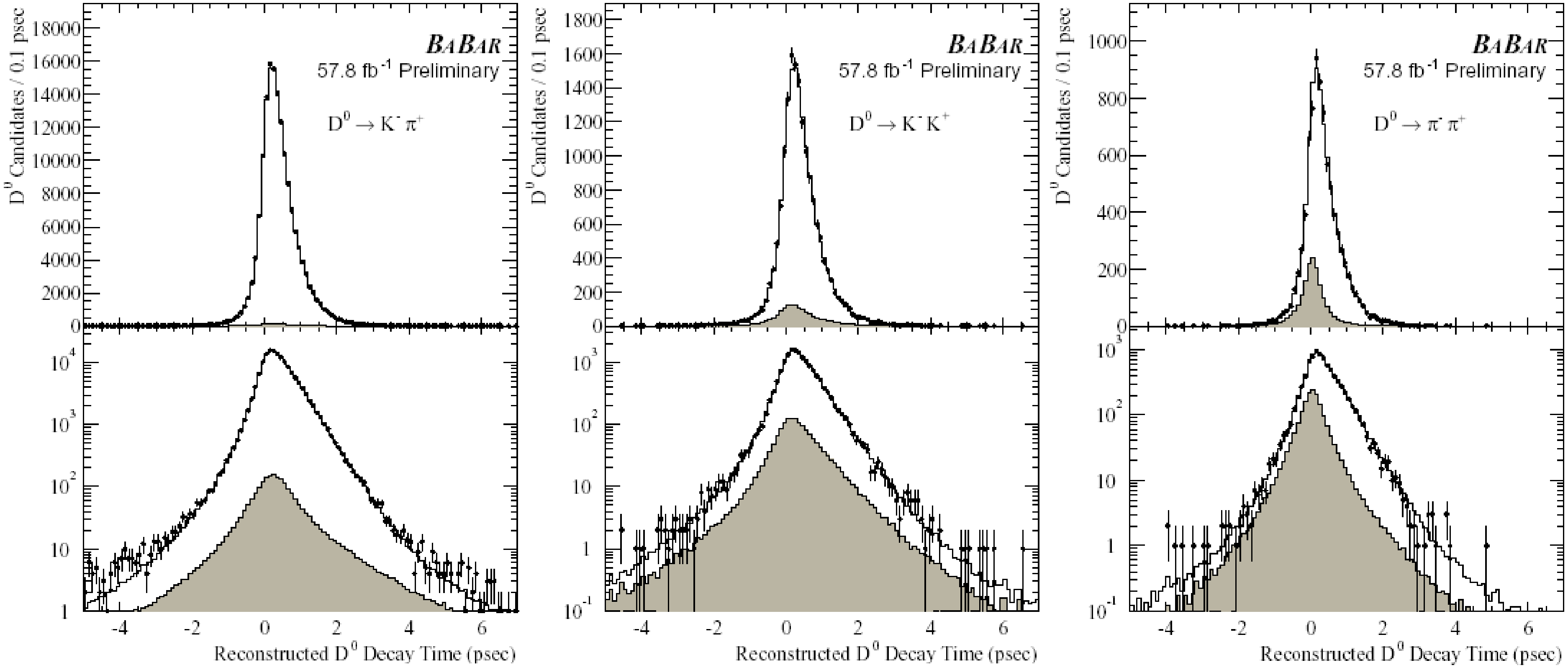
$\boxed{\text{Current experimental sensitivity} \sim 10^{-2} \text{ for both } x \text{ and } y}$

Observation of non-zero x would mean "New physics";
non-zero y would require better understanding of QCD models

New y_{CP} from BaBar

- $\mathcal{L} = 57.9\,\mathrm{fb}^{-1}$: statistics is huge; main problem – systematics
- Use D^{*+} tag:
  - reduce background systematics
  - step towards time-dependent CP violation search
  - at the expense of efficiency: factor $\sim 4 \downarrow$
- $D^0 \to K^-\pi^+ \sim 158,000$ with 99.5% purity
  $D^0 \to K^+K^- \sim 16,500$ with 97.1% purity
  $D^0 \to \pi^+\pi^- \sim 8,350$ with 92.4% purity
- Unbinned maximum likelihood fit
- SVT internal alignment systematics check done using
  $e^+e^- \to \gamma\gamma \to 4\, prongs$

New y_{CP} from BaBar



New y_{CP} from BaBar

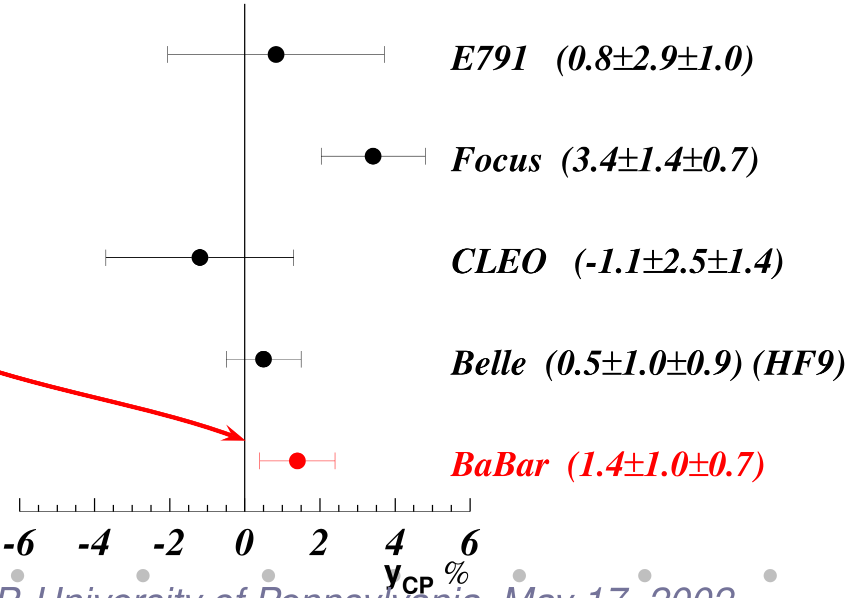
systematics

Source	K^+K^-	$\pi^+\pi^-$
MC statistics	$^{+0.4}_{-0.6}$	$^{+0.4}_{-0.9}$
Track reconstruction	±0.2	±0.9
Particle identification	±0.2	±0.4
Background and Fragmentation	±0.2	±0.6
Alignment and Vertexing	$^{+0.2}_{-0.1}$	$^{+0.3}_{-0.1}$
Total	$^{+0.6}_{-0.7}$	$^{+1.2}_{-1.4}$

$$y = 1.6 \pm 1.2^{+0.6}_{-0.7}\% \; (D^0 \to K^+K^-)$$

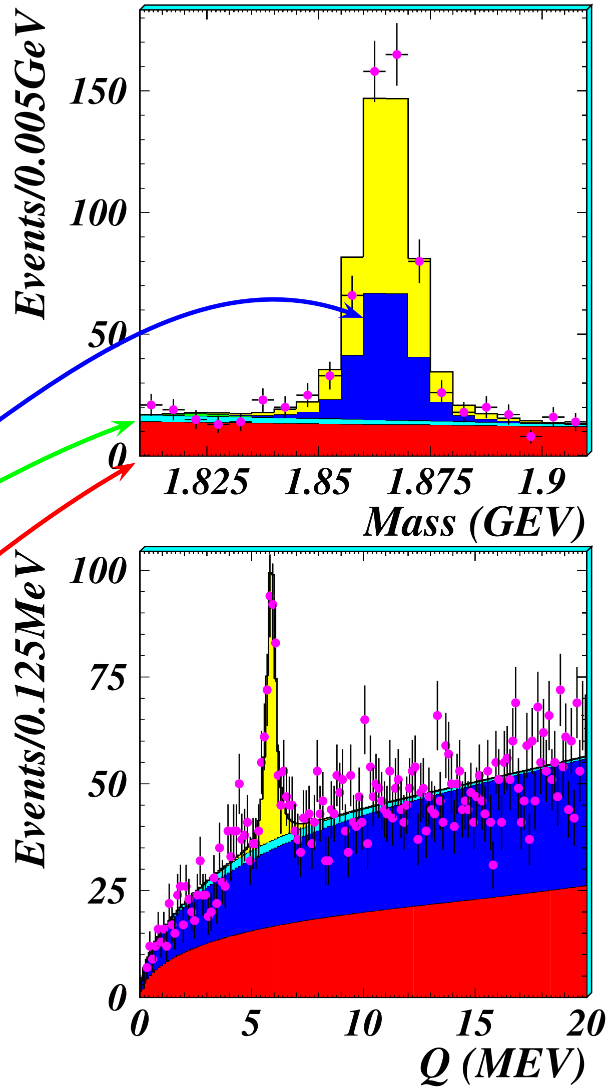
$$y = 1.0 \pm 1.7^{+1.2}_{-1.4}\% \; (D^0 \to \pi^+\pi^-)$$

$$y = (1.4 \pm 1.0^{+0.6}_{-0.7})\,\% \; \textit{Preliminary}$$



$D^0 \to K^+\pi^-$ from Belle

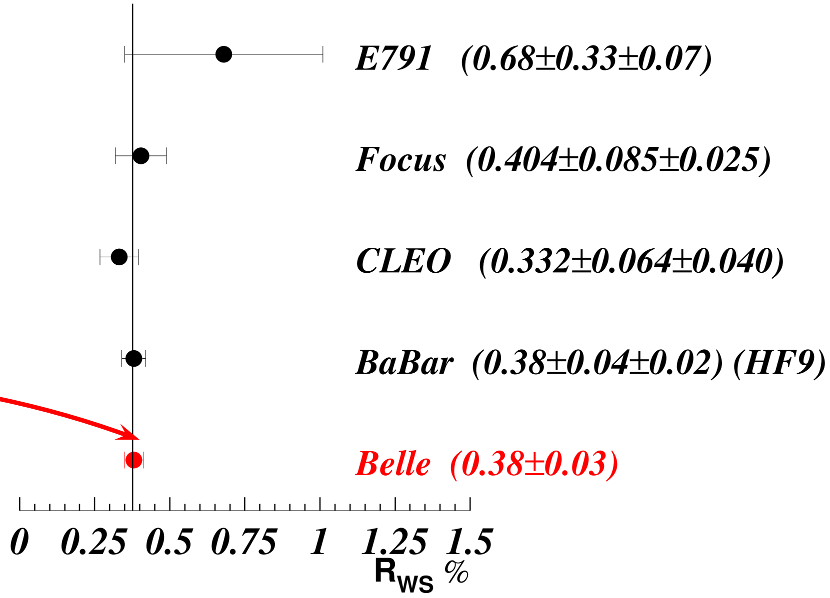
- Look for chain $D^{*+} \to D^0\pi^+_{slow}$; $D^0 \to K^+\pi^-$
- Two selective variables: $M_{D^0\to K^+\pi^-}$ and $Q \equiv M_{D^0\pi^+_{slow}} - M_{D^0} - M_{\pi^+}$
- Background classification
  - $D^0 \to h^-h^+$ (CA and SCS) with mis-id are rejected using kinematics
  - $D^0 \to K^-\pi^+$ with random π^+_{slow}
  - $D^0 \geq 3$ body
  - $D^+, D_s^+ \geq 3$ body
  - pure combinatorial background
- Each background shape is fixed from MC



$D^0 \to K^+\pi^-$ from Belle

- Fit to 2D distribution:
  $\boxed{N_{RS} = 82960 \pm 310}$
  $\boxed{N_{WS} = 317 \pm 26}$
- No estimates of the systematic errors yet
- No wrong-sign time fit yet

$\boxed{R_{WS} = (0.38 \pm 0.03)\ \%\ \textit{Preliminary}}$



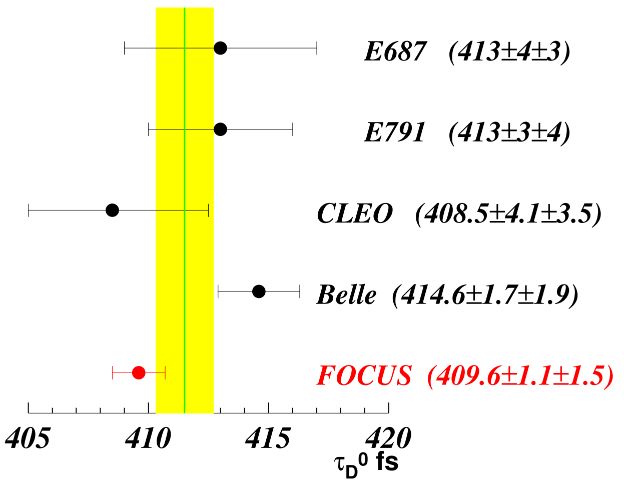
Lifetimes from FOCUS

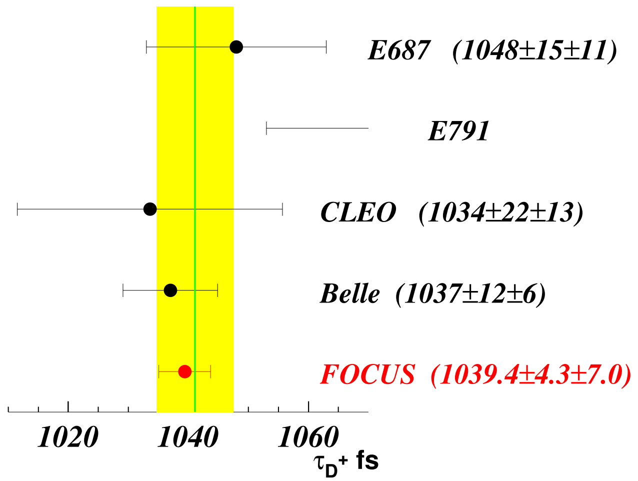
- FOCUS: *"New measurements of the D^0 and D^+ lifetimes"* (FERMILAB-Pub-0.2/059-E) *Submitted to PLB*
- Use $\sim 210,000$ $D^0 \rightarrow K^-\pi^+$; $\rightarrow K^-\pi^+\pi^+\pi^-$ and $\sim 110,000$ $D^+ \rightarrow K^-\pi^+\pi^+$ decays.
- The accuracy is better than World Average:

$$\boxed{\tau_{D^0} = (409.6 \pm 1.1 \pm 1.5)\ \text{fs}}$$

$$\boxed{\tau_{D^+} = (1039.4 \pm 4.3 \pm 7.0)\ \text{fs}}$$

- No new results since HF9 on D_s lifetime
- Charmed baryons lifetimes $\rightarrow$ Talk by John Yelton





Prompt J/ψ

CLEO: *Observation of* $\Upsilon(4S)$ *Decays into non-*$B\overline{B}$ *Final States Containing* ψ *mesons.* P.R.L.**64**, 2226 (1990)

BaBar: *"Measurement of* J/ψ *production in continuum* e^+e^- *annihilation near* $\sqrt{s} \approx 10.6$ *GeV"* (P.R.L. **87**, 162002 (2001))

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

Belle: *"Production of Prompt Charmonia in* e^+e^- *Annihilation at* $\sqrt{s} \approx 10.6$ *GeV"* (P.R.L. **88**, 052001 (2001)):

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

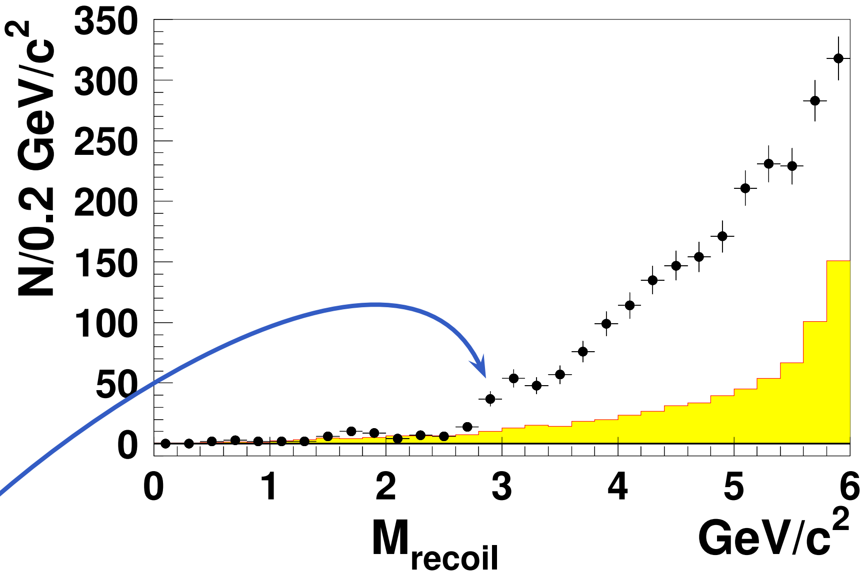
- NRQCD: mix of $J/\psi gg$(dominant) and $J/\psi\, c\bar{c}$
- Color-octet model: $J/\psi g$ could be large.
- *V.V.Kiselev et al.* (1994): $\sigma(e^+e^- \to J/\psi c\bar{c}) \approx 0.055$pb
  P.Cho and A.K.Leibovich (1996): $\sigma(e^+e^- \to J/\psi c\bar{c}) \approx 0.07$pb
  S.Baek et al. (1998): $\sigma(e^+e^- \to J/\psi c\bar{c}) \approx 0.15$pb

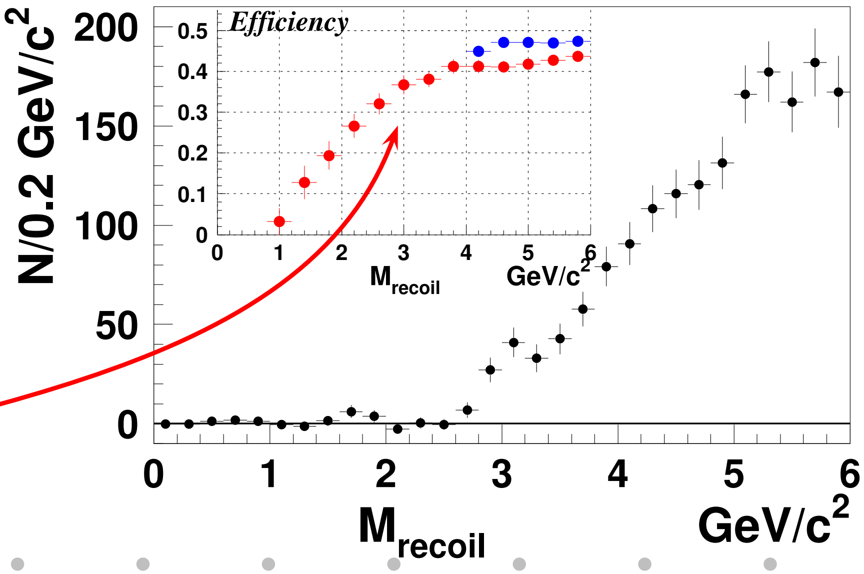
Hint for $e^+e^- \to J/\psi\, c\bar{c}$

- $\mathcal{L} = 46.2\,\mathrm{fb}^{-1}$; J/ψ selection identical to the previous paper
  - Suppress QED: > 4 charged tracks;
  - Remove J/ψ from $B\overline{B}$: $p^*_{J/\psi} > 2.0\,\mathrm{GeV}/c$.
- Look at the mass of the system recoiling against J/ψ candidates:

$$M_{\mathrm{recoil}} = \sqrt{(E_{\mathrm{CMS}} - E^*_{J/\psi})^2 - p^{*\,2}_{J/\psi}}$$

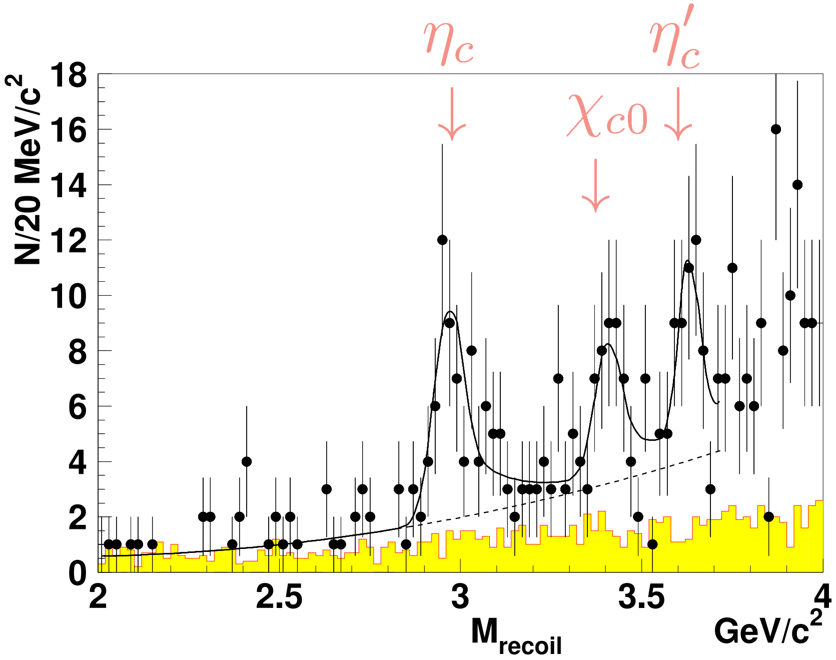
- Clear threshold around $2\,m_c$ for J/ψ signal window;
  Flat distribution for J/ψ sidebands
- The threshold very prominent after scaled sidebands subtraction (lower hist)
- Could this threshold be a result of selection bias ($N_{\mathrm{ch}} > 4$)?
  Toy MC ($e^+e^- \to J/\psi\, q\bar{q}$):
  efficiency smooth





Evidence for $e^+e^- \to J/\psi\,\eta_c$

Study the region $2\,m_c \lesssim M_{\mathrm{recoil}} < 2\,m_D$ in more detail



- Apply mass constrained fit to J/ψ, to improve resolution.
- Clear peak at $\approx 3\,\mathrm{GeV}/c^2$
- $e^+e^- \to J/\psi\,J/\psi$ is C-parity forbidden $\Rightarrow e^+e^- \to J/\psi\,\eta_c$ is the only possible interpretation.
- Additional peaks consistent with χ_{c0} and η_c' masses.
- Fit:
  - Signal shapes corrected on ISR taking into account that p-wave allowed for η_c and η_c', and s-wave for χ_{c0};
  - Background: second order polynomial

Evidence for $e^+e^- \to J/\psi\,\eta_c$

Fit results:

	η_c	χ_{c0}	η_c'
N	67^{+13}_{-12}	39^{+14}_{-13}	42^{+15}_{-13}
M [GeV$/c^2$]	2.962 ± 0.013	3.403 ± 0.014	3.622 ± 0.012
σ	6.7	3.3	3.4

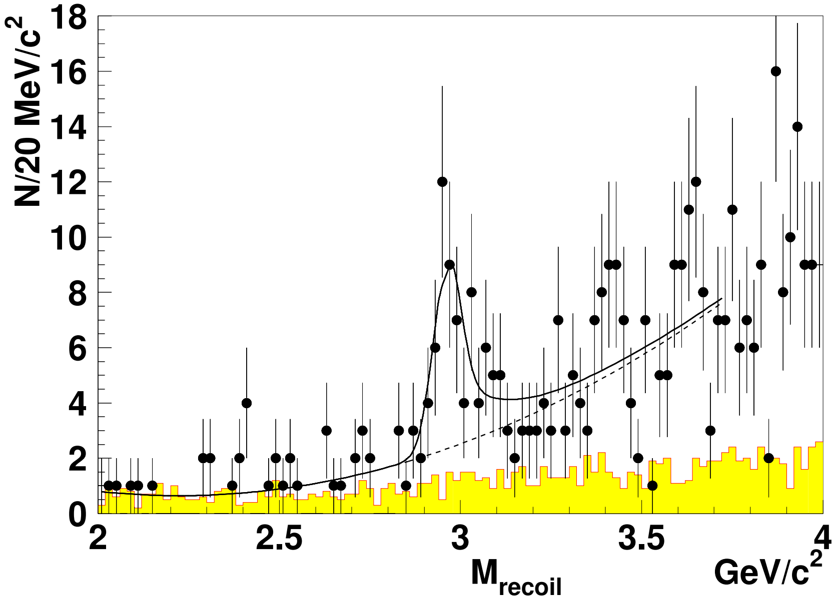
Perform additional fits to study fitting systematics:

- Ignore χ_{c0} and η_c' contributions:

  $$\boxed{N_{\eta_c} = 56^{+13}_{-12};\ \sigma = 5.9}$$

- Fix background shape to sidebands:

  $$\boxed{N_{\eta_c} = 75^{+14}_{-13};\ \sigma > 7}$$



Systematics/Cross-section

systematics study

Source	Systematic error (%)
ISR extrapolation	± 19
Fitting procedure	± 16
J/ψ polarization	± 11
Track reconstruction	± 5
Lepton identification	± 4
Total	± 28

problem

The requirement $N_{ch} > 4$ (to suppress huge QED contamination) removes all ($\eta_c \to 0, 2$ charged + neutrals); the branching fraction for such decays is unknown. We express our result in terms of the product:

$$\sigma(e^+e^- \to J/\psi\, \eta_c\, (\gamma)) \times \mathcal{B}(\eta_c \to \geq 4\,\text{charged}) =$$
$$(0.033\,^{+0.007}_{-0.006} \pm 0.009)\,\text{pb} \quad \textit{Preliminary}$$

$e^+e^- \to J/\psi$ charmed mesons

Look for J/ψ accompanied by D^{*+} or D^0

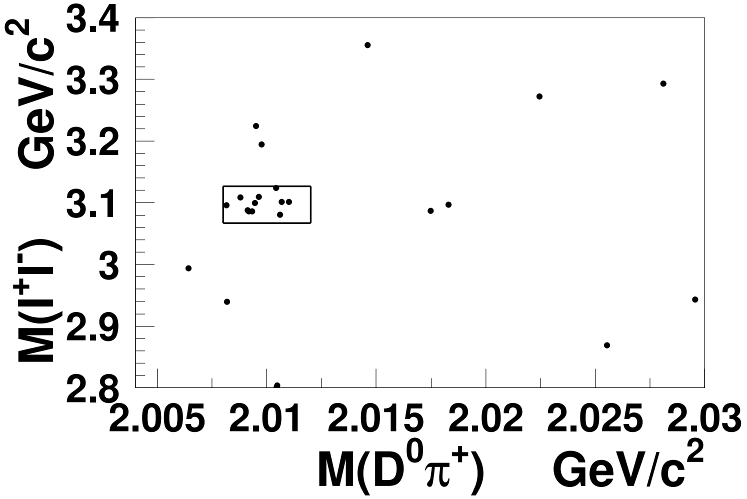
Main problem: The statistics is mostly collected at $\Upsilon(4S)$ resonance.

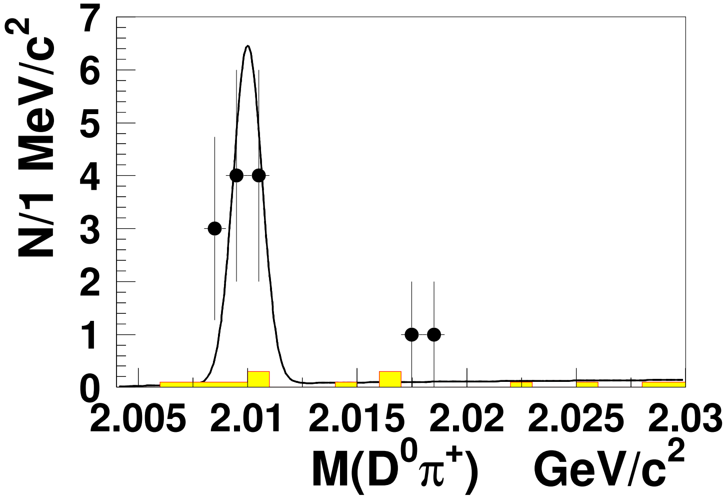
- $B \to J/\psi$ removed by $p^*_{J/\psi} > 2.0\,\mathrm{GeV}/c$;
- But a large D signal expected from $\begin{array}{l} B \to D\ \ell^-\bar{\nu} \\ \overline{B} \to X\ \ell^+\nu \end{array}$
- Remove this background: $p^*_{D^{*+}} > 2.6\,\mathrm{GeV}/c$ or $p^*_{\ell^\pm} > 2.6\,\mathrm{GeV}/c$.

D^{*+} and D^0 reconstruction

D^{*+}			D^0
$D^{*+} \to D^0\pi^+;\quad D^0 \to$	$K^-\pi^+$	$(\pm 10\,\mathrm{MeV}/c^2)$	$D^0 \to K^-\pi^+$
	K^-K^+	$(\pm 10\,\mathrm{MeV}/c^2)$	$D^0 \to K^-K^+$
	$K^-\pi^-\pi^+\pi^+$	$(\pm 10\,\mathrm{MeV}/c^2)$	
	$K_S\pi^+\pi^-$	$(\pm 10\,\mathrm{MeV}/c^2)$	
	$K^-\pi^+\pi^0$	$(\pm 20\,\mathrm{MeV}/c^2)$	

$e^+e^- \to J/\psi\, D^{*+} X$





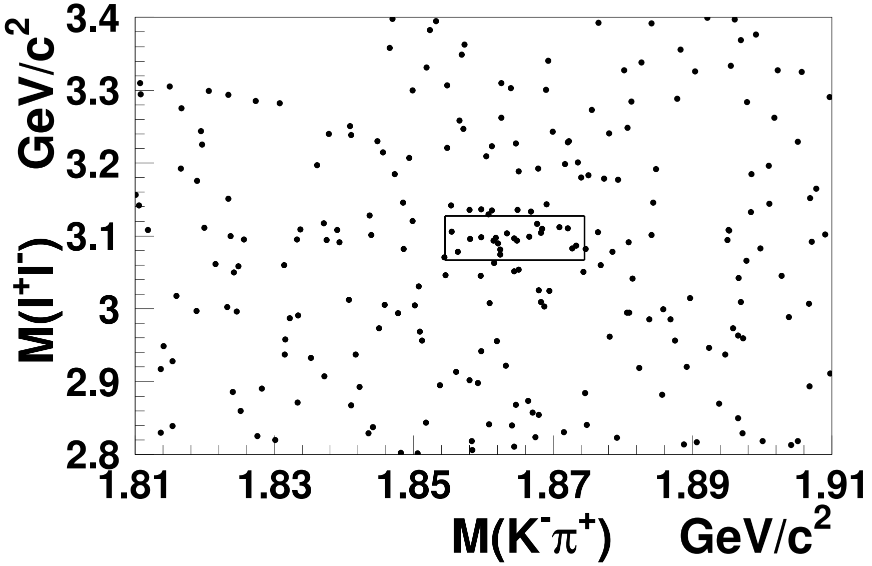
- Look at the scatter plot of dilepton mass versus $D^0\pi^+$ mass
- Signal box: $\pm 30\,\mathrm{MeV}/c^2$ for J/ψ; $\pm 2\,\mathrm{MeV}/c^2$ for D^{*+}
- 11 events in the signal box
- Fit with Gaussian $+A\sqrt{M_{D^0\pi^+} - M_{thres}}$ to $D^0\pi^+$ mass projection:

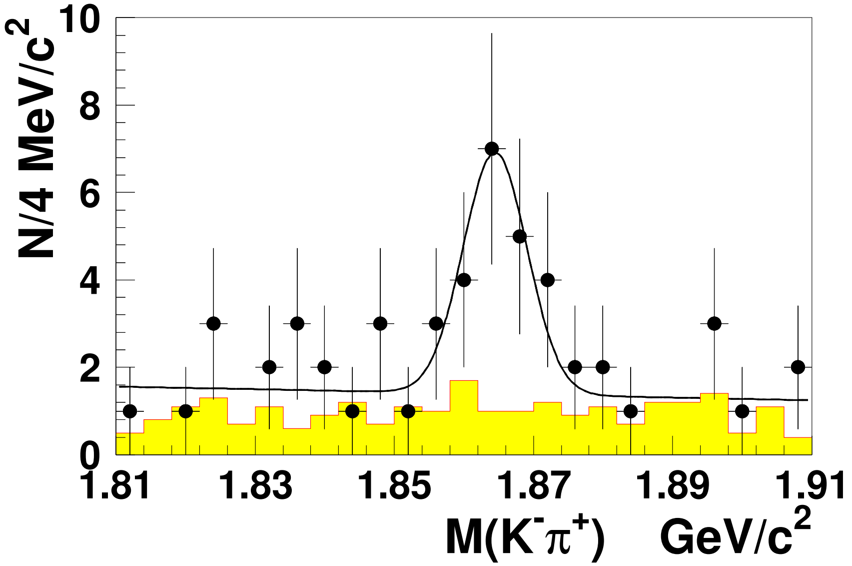
  $\boxed{10.5^{+3.6}_{-3.0}}$ for J/ψ signal window;

  $\boxed{0.4 \pm 0.3}$ for J/ψ sidebands
- Significance – $\boxed{5.3\sigma}$
- X-check: Fit to dilepton mass distribution for $D^0\pi^+$ signal window: $\boxed{9.6^{+3.6}_{-2.9}}$

$e^+e^- \to J/\psi\, D^0 X$

- Look at the scatter plot of dilepton mass versus $K^-\pi^+(K^+K^-)$ mass
- Signal box: $\pm 30\,\mathrm{MeV}/c^2$ for J/ψ; $\pm 10\,\mathrm{MeV}/c^2$ for D^0
- Fit with Gaussian linear background to $K^-\pi^+(K^+K^-)$ mass projection:
  $\boxed{15.9^{+5.4}_{-4.7}}$ for J/ψ signal window;
  $\boxed{1.0 \pm 0.8}$ for J/ψ sidebands
  Significance – $\boxed{3.7\sigma}$
- X-check: Fit to dilepton mass distribution for D^0 signal window: $\boxed{17.7^{+5.3}_{-4.6}}$ and D^0 sidebands: $\boxed{4.3 \pm 0.8}$





Efficiency/Systematics

BELLE

efficiency

MC: $e^+e^- \to J/\psi\, c\bar{c}$ with a simple model adapted from the QQ
The efficiency of both reconstruction and selection depends on kinematics:

- $Q^2(c\bar{c})$ (equivalent to J/ψ recoil mass)
- J/ψ production angle
- J/ψ helicity angle
- angle between $c\bar{c}$ axis ($\approx$ thrust of recoil system) and its boost

} corrected in MC using a large sample of continuum J/ψ

- $c\bar{c} \to D$ fragmentation $\to$ systematics

systematics

Source	$J/\psi\, D^0$	$J/\psi\, D^{*+}$
MC kinematics correction	± 11	± 10
$c\bar{c}$ fragmentation	± 8	± 15
Fitting procedure	± 10	± 5
Efficiency of $p^*_{J/\psi}$ cut	± 11	± 11
Reconstruction	± 8	± 12
Identification	± 6	± 6
Total	23	26

Results

$$\sigma(e^+e^- \to J/\psi D^{*+} X) = 0.53\,^{+0.19}_{-0.15} \pm 0.14\,\mathrm{pb}$$

$$\sigma(e^+e^- \to J/\psi D^0 X) = 0.87\,^{+0.32}_{-0.28} \pm 0.20\,\mathrm{pb}$$

$$\Downarrow$$

LUND rates $c\bar{c} \to D^{*\pm}(D^0)$

0.53 | 1.18

$$\Downarrow$$

$$\sigma(e^+e^- \to J/\psi c\bar{c} X) = 1.01\,^{+0.36}_{-0.30} \pm 0.26\,\mathrm{pb}$$

$$\sigma(e^+e^- \to J/\psi c\bar{c}) = 0.74\,^{+0.28}_{-0.24} \pm 0.17\,\mathrm{pb}$$

$$\Downarrow$$

$$\boxed{\sigma(e^+e^- \to J/\psi c\bar{c}) = 0.87^{+0.21}_{-0.19} \pm 0.21}$$

$$\Downarrow$$

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

preliminary

Summary

- Charm physics is not abandoned: all experiments show their interest in this field.
- At present:
  - BaBar measured $y_{CP} = (1.4 \pm 1.0^{+0.6}_{-0.7})\,\%$ with D^{*+} tag.
  - Belle updated $D^0 \to K^+\pi^-$: $R_{WS} = (0.38 \pm 0.03)\,\%$.
  - FOCUS: new measurement of D^0 and D^+ lifetimes: $\tau_{D^0} = (409.6 \pm 1.1 \pm 1.5)$ fs and $\tau_{D^+} = (1039.4 \pm 4.3 \pm 7.0)$ fs .
- Belle observed $e^+e^- \to 2(c\bar{c})$:
  - $\sigma(e^+e^- \to J/\psi\,\eta_c\,(\gamma)) \times \mathcal{B}(\eta_c \to \geq 4\,\text{charged}) = (0.033\,^{+0.007}_{-0.006} \pm 0.009)$ pb
  - $\sigma(e^+e^- \to J/\psi c\bar{c}) = 0.89^{+0.21}_{-0.19} \pm 0.21$ and $\sigma(e^+e^- \to J/\psi c\bar{c})/\sigma(e^+e^- \to J/\psi X) = 0.61^{+0.15}_{-0.13} \pm 0.12$
- Many new results are coming, and come soon.