Not for Beauty Alone: Highlights on Charm from Babar and Belle

- motivations
- charm in the Upsilon region
- selected results
  - D^0 mixing
  - first radiative D decay
  - surprises in spectroscopy
- summary

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Belle Collaboration

Motivations for Charm Studies

Standard Model

weak force - CKM elements

strong "

hadronic models, HQ symmetry:

spectroscopy, production, decay.

New physics

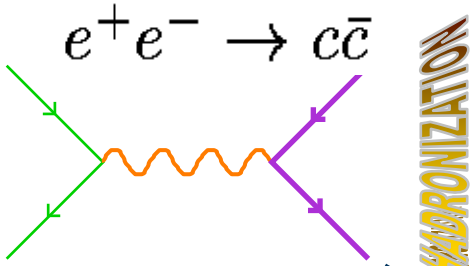
cancellations in SM -> probe for new physics

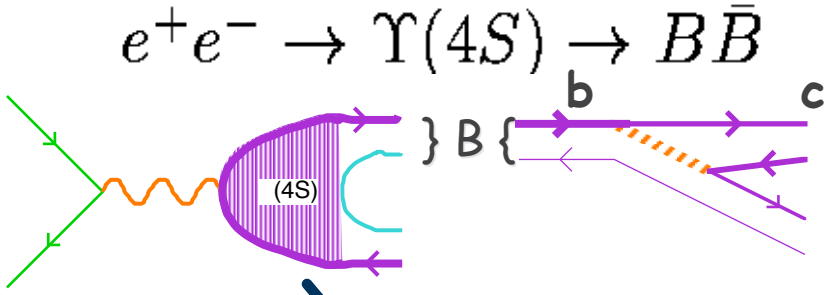
{Service}

for B physics: c-hadron branching fractions,

form factors via HQ symmetry

Charm in the Region





in cms, $E_c=E_e$, □~1 nb

most c-hadrons have p>(kinematic limit for b->c)

in cms, $E_B=E_e$, □~1 nb

unrestricted J^{PC} for cc

Well-defined (& measureable!) production rate, energy, clean:

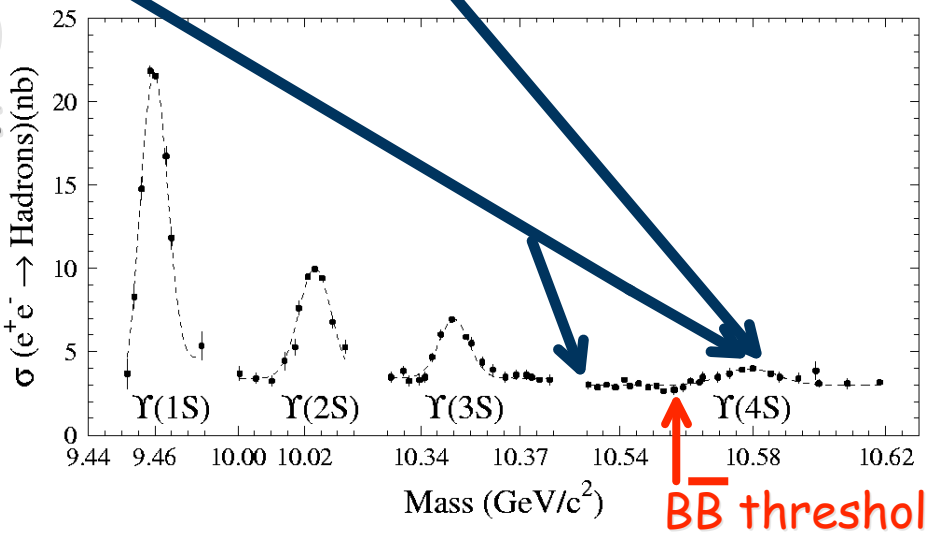
(Continuum and B, each)

Trigger efficiency ~ 100%

Rate $\mathcal{L}$x□~10^{34}x10^{-33}=10 Hz

Raw S/B ~1/3

Data sample >10^8 events



At B factories, $\int\mathcal{L}$(<4S)dt/$\int\mathcal{L}$(4S)dt~0.10

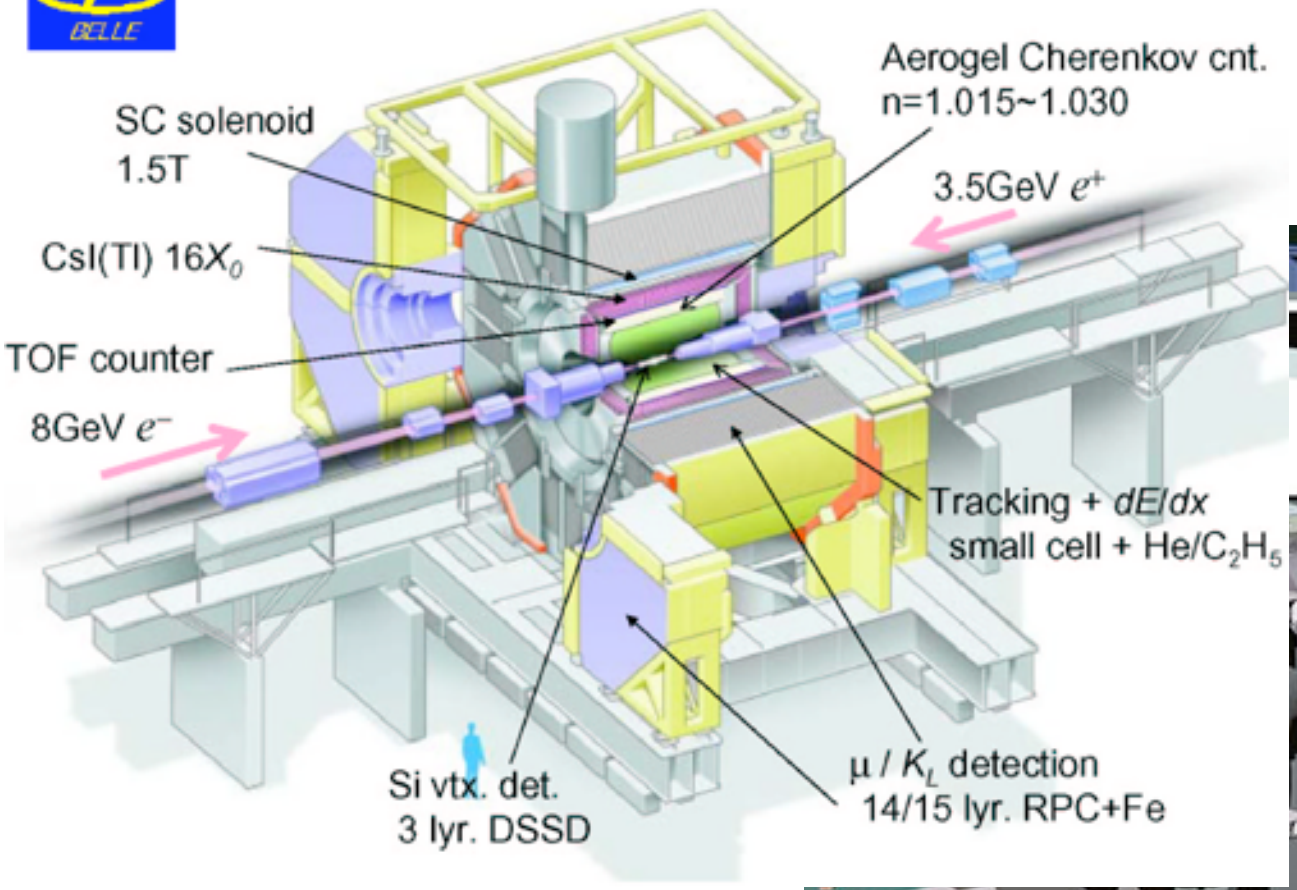
more reasons to study charm @ beauty factory

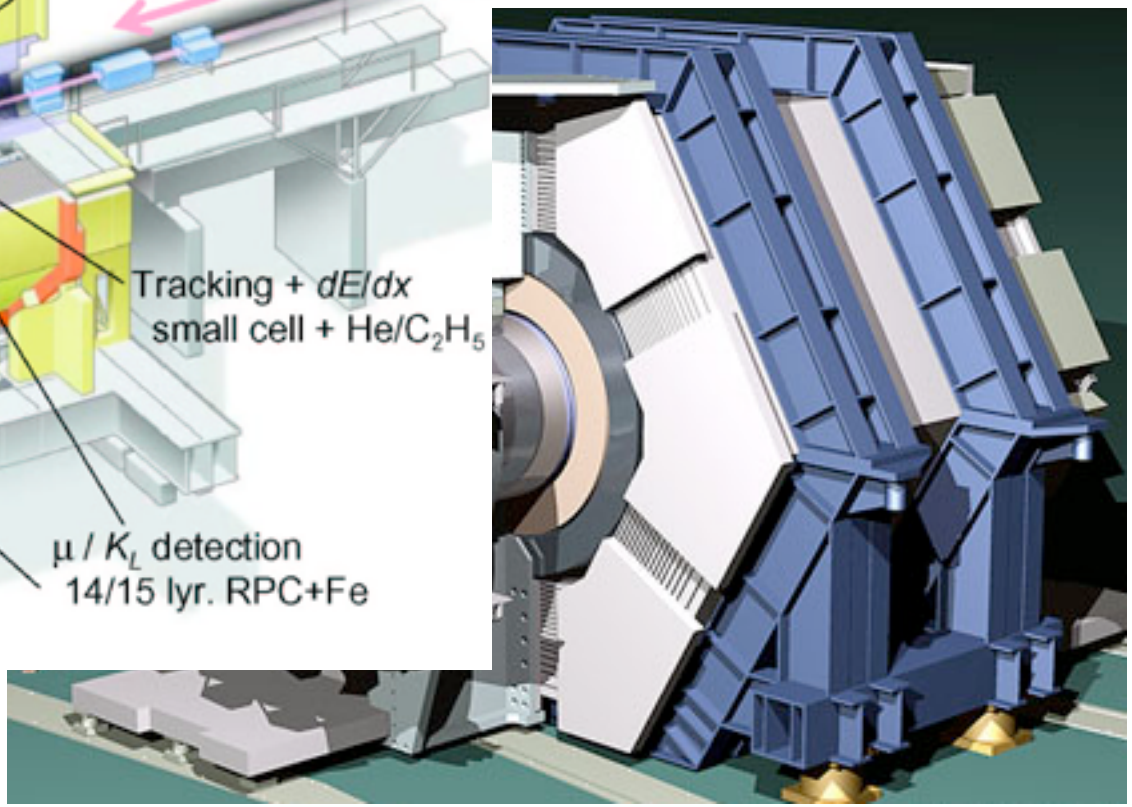
High luminosity has produced many exciting results:

- gluon-mediated production – NRQCD models rate observed at TeVatron
  not supported by e^+e^- data:
  - Prompt J/□ softer than expectation (Belle: PRL 88, 052001 (2002))
  - major source of J/□ is double c-pairs, counter to expectation (Belle: PRL 89, 142001 (2002))
  - observation of exclusive $e^+e^- \to D^{(*)}\overline{D}^{(*)}$ (Belle: hep-ex/0401040)
- Hadronic insights
  - new particles found thru reconstruction of B decay:
    - η_c' (Belle: PRL 89, 102001 (2002); 41.8 fb^{-1})
    - new excited D states
    - charmonium surprise: X(3872)
  - surprises in D_s
  - $D^0 \to$ □□ - first radiative D decay
- improved sensitivity to $D\overline{D}$ mixing

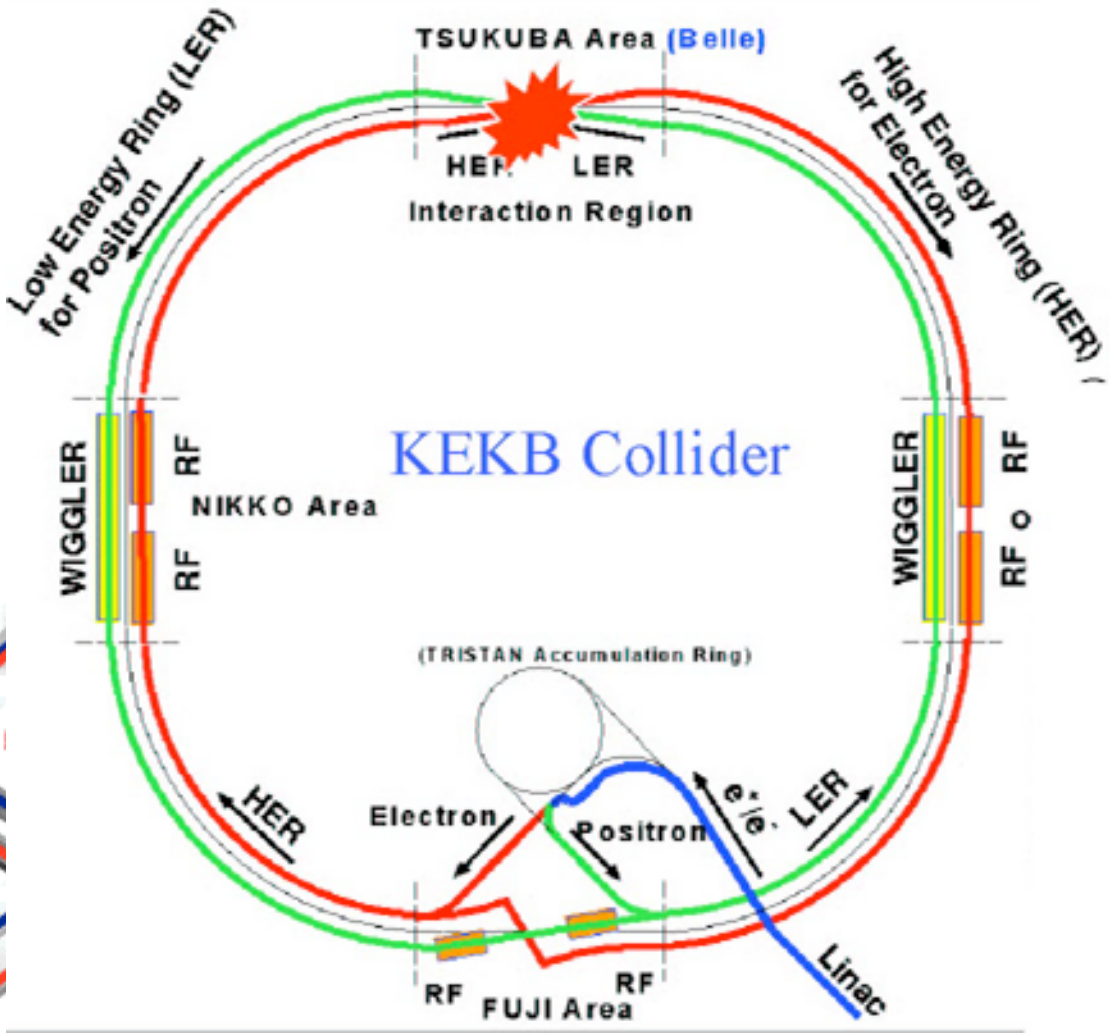
  Presented here

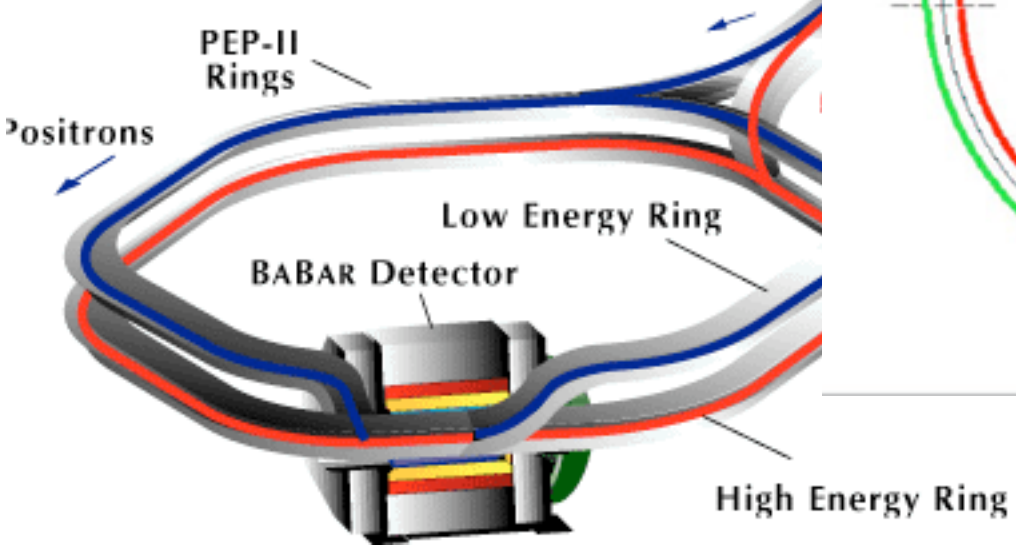
The Detector





e^+e^- rings


TSUKUBA Area (Belle)
Low Energy Ring (LER) for Positron
High Energy Ring (HER) for Electron
HER
LER
Interaction Region
KEKB Collider
WIGGLER
RF
NIKKO Area
(TRISTAN Accumulation Ring)
HER
Electron
Positron
e-/e+ LER
Linac
RF
FUJI Area


PEP-II Rings
Positrons
Low Energy Ring
BABAR Detector
High Energy Ring

D^0 mixing/CP

expect: D^0 mass eigenstate ~ CP eigenstate

CP=+1, -1 -> different final states

-> nonzero mixing $x \equiv \frac{m_1 - m_2}{(\Gamma_1 + \Gamma_2)/2}$ $y \equiv \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$

in SM: x, y= $O(10^{-3})$ highly suppressed -> window on new physics

Methods:

1) Lifetimes, different modes

$D^0 \to K^+K^-$, $\pi^+\pi^-$ (pure CP=+1), $\Gamma = 1/\tau_1$

$D^0 \to K^-\pi^+$ (mixed CP), $\Gamma = 1/[(\tau_1+\tau_2)/2]$ (if CP conserved)

=> $y \approx \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 = \frac{\tau(K^-\pi^+)}{\tau(\pi^-\pi^+)} - 1 \equiv y_{CP}$

2) Time evolution of wrong-flavor decays

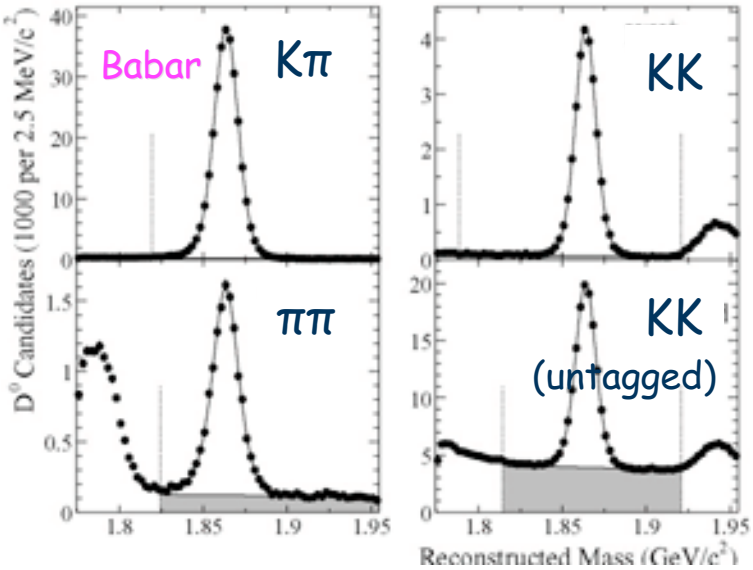
$D^0 \to K^+\pi^-$ - doubly Cabibbo-suppressed (DCS),

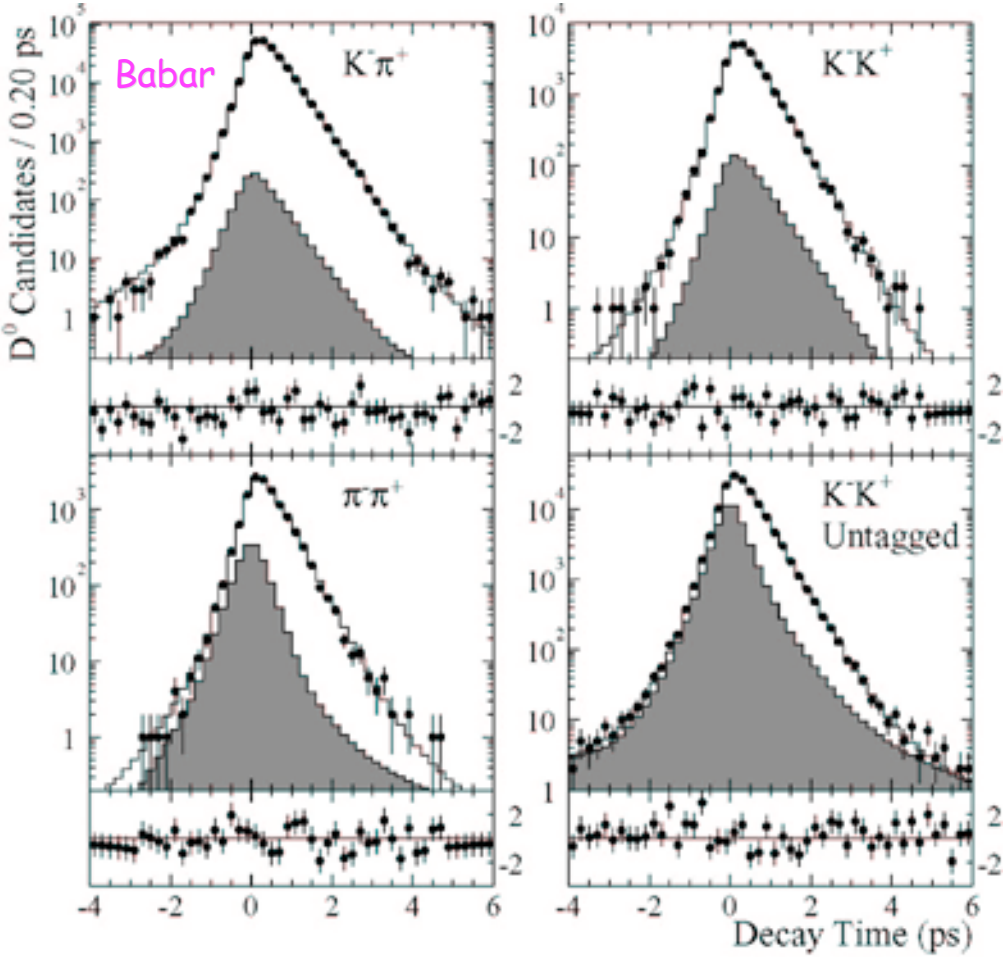
favored (CF)+mixing - interference

D^0 mixing via lifetime ratio

Modes D->KK, Kπ, ππ

Tagged: $D^{*+}\to D^0\pi^+$





Babar 91 fb^{-1}: PRL 91, 121801 (2003)

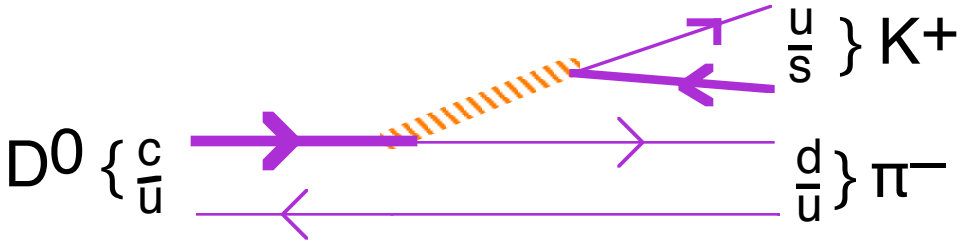
$y_{CP}=(0.8\pm0.4^{+0.5}_{-0.4})\%$

Belle 158 fb^{-1}: hep-ex/0308034

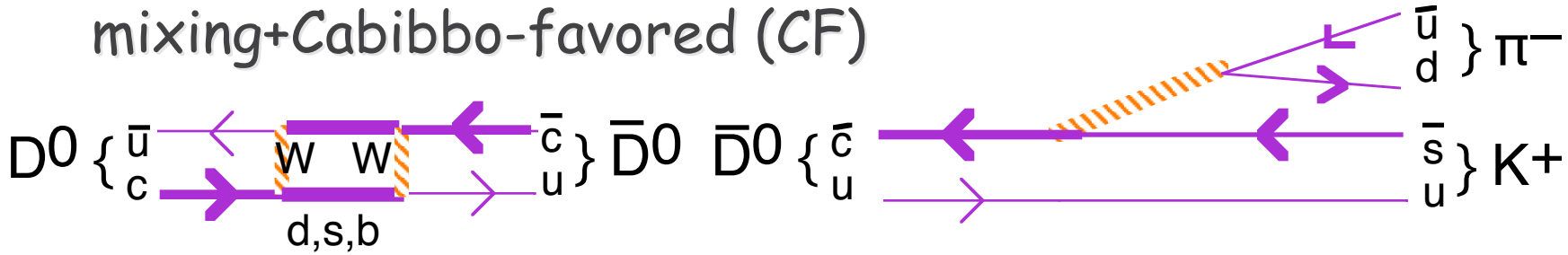
$y_{CP}=(1.15\pm0.69\pm0.38)\%$ (preliminary)

Mixing via time-dependent $D^0 \to K^-\pi^+$

"wrong-sign" (WS) $D^0 \to K\pi$ occurs via double-Cabibbo-suppression (DCS):



mixing+Cabibbo-favored (CF)



Tag D flavor (WS/RS) by $D^{*+} \to D^0\pi^+$

Mixing via time-dependent $D^0 \to K^+\pi^-$

Rate depends on DCS vs CF amplitudes +mixing:

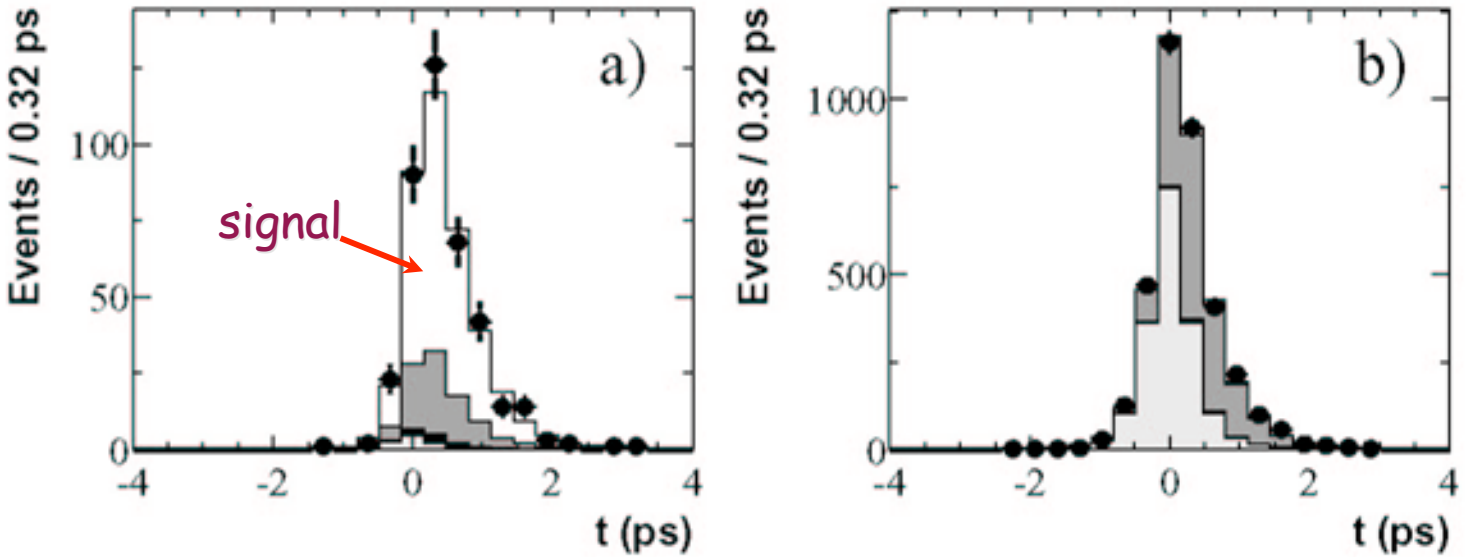
$$\sqrt{R_D} \equiv \frac{|\mathcal{A}_{DCS}|}{|\mathcal{A}_{CF}|} \qquad \begin{aligned} x' &= x\cos\delta_{K\pi} + y\sin\delta_{K\pi} \\ y' &= -x\sin\delta_{K\pi} + y\cos\delta_{K\pi} \end{aligned}$$

strong phase diff=$\delta_{K\pi}$

Bottom line:

$$T_{WS}(t) \approx T_{RS}(t)[R_D + \sqrt{R_D}\, y't + \frac{x'^2 + y'^2}{4}t^2]$$

Babar 57.1 fb^{-1}: PRL 91, 171801 (2003)

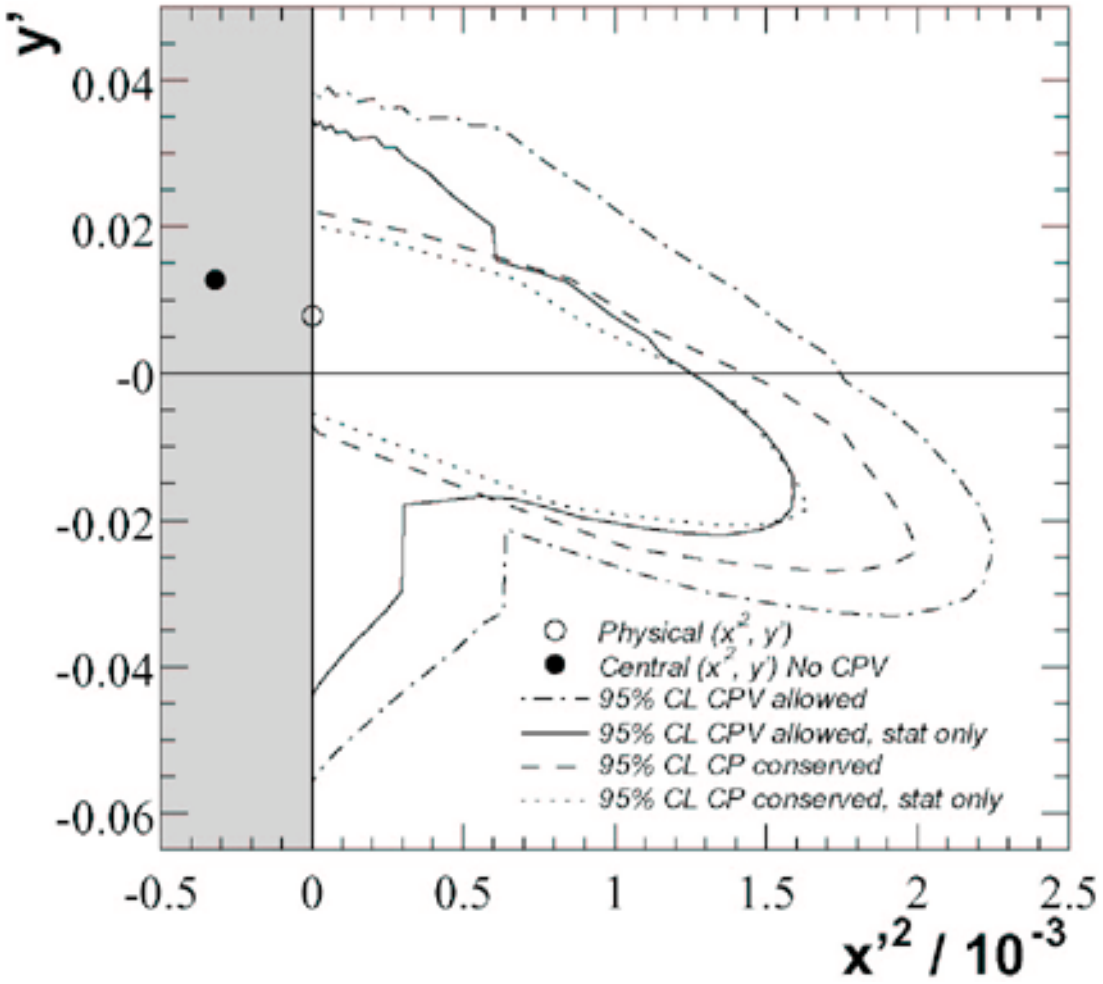


Babar 57.1 fb^{-1}: PRL 91, 171801 (2003)

Results: fitted under assumptions w/wo mixing, CP violation

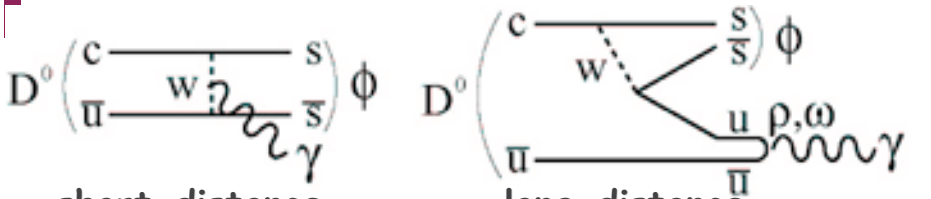
Fit case	Parameter	Central value ($x'^2=0$) ($/10^{-3}$)	95% CL interval ($/10^{-3}$)
CP violation allowed	R_D	3.1	$2.3 < R_D < 5.2$
	A_D	1.2	$-2.8 < A_D < 4.9$
	x'^2	0	$x'^2 < 2.2$
	y'	8.0	$-56 < y' < 39$
	R_M		$R_M < 1.6$
No *CP* violation	R_D	3.1	$2.4 < R_D < 4.9$
	x'^2	0	$x'^2 < 2.0$
	y'	8.0	$-27 < y' < 22$
	R_M		$R_M < 1.3$
No mixing	$R_D = (0.357 \pm 0.022$ (stat.) ± 0.027 (syst.))%		
	$A_D = 0.095 \pm 0.061$ (stat.) ± 0.083 (syst.)		
No *CP* viol. or mixing	$R_D = (0.359 \pm 0.020$ (stat.) ± 0.027 (syst.))%		

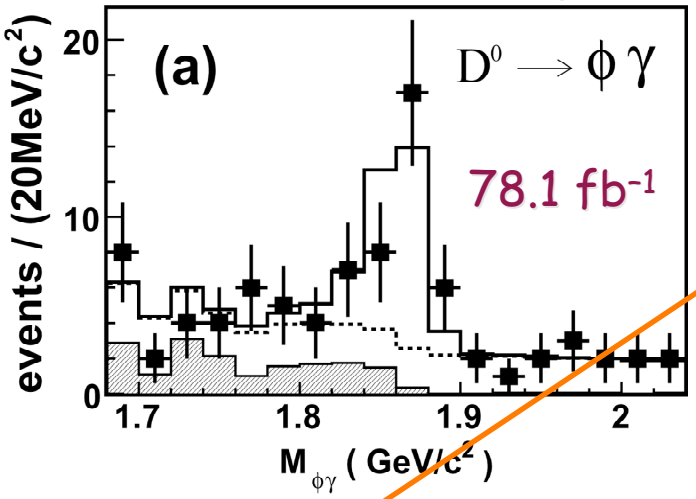
Babar 57.1 fb^{-1}: PRL 91, 171801 (2003)

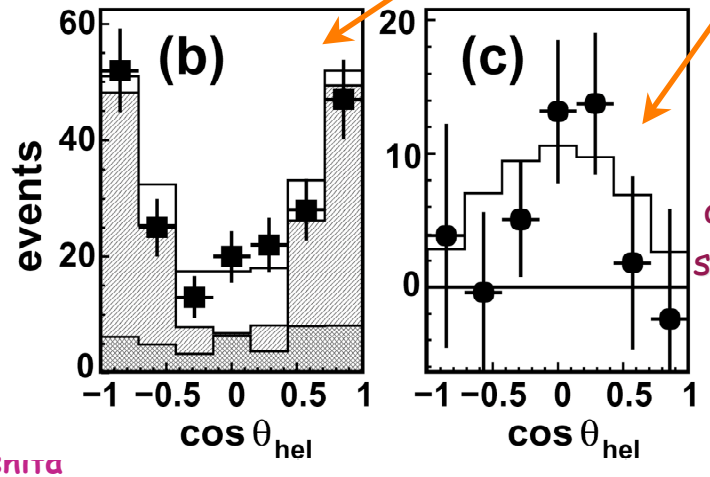


Observation of first radiative D decay

(Belle hep-ex/0308037 accepted by PRL)







after bg subtraction

$D^0 \to \phi\phi$ ($\phi \to K^+K^-$)

- large bg from $D^0 \to \phi\pi^0$ (also first observation) distinguish by $\phi \to KK$ helicity angle distribution

$$B = [2.60^{+0.70\ +0.15}_{-0.61\ -0.17}] \times 10^{-5}$$

(mainly long-distance proc; HQ symmetry <-> $B \to \phi\phi$)

Also observed:
$D^0 \to \phi\pi^0$ (Cabibbo-suppressed)
$B = [8.01 \pm 0.26 \pm 0.47] \times 10^{-4}$
$D^0 \to \phi\phi$ (color-suppressed)
$B = [1.48 \pm 0.47 \pm 0.09] \times 10^{-5}$

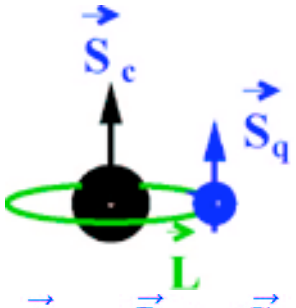
Hadron spectroscopy: new $\{c\bar{s}\}$ states

lowest D_s states:

S-wave: $^1S_0$ ($M=1968$ MeV/c^2), $^3S_1$ (2112 MeV/c^2)

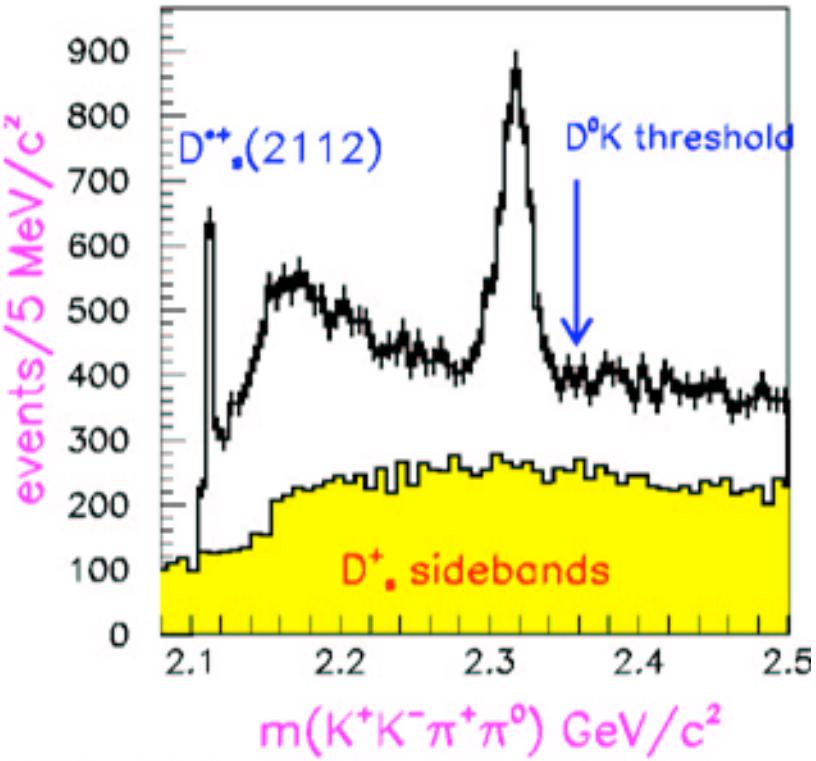
P-wave: $\{j=3/2;\ J^P=1^+$ (2536 MeV/c^2), $J^P=2^+$ (2573 MeV/c^2)

$\{j=1/2;\ J^P=1^+, 0^+$ (theory: $M=2400$-2600 MeV/c^2)



4/03 observation (Babar 91 fb^{-1} : PRL 90, 242001 (2003);

$D_{sJ}(2317)$:->$D_s^+\pi^0$, D_s^+->{□π^+,$K^{*0}K^+$}->$K^+K^-\pi^+$, π^0->□□



- tentative: j=1/2, $J^P=0^+$
- mass lower than predicted (exotic?)

observation/mass confirmed:

(CLEO 13.5 fb^{-1} : PR D68, 032002 (2003))

$M(D_{sJ})-M(D_s)=350.0\pm1.2\pm1.0$ MeV/c^2

($M(D_{sJ})=2318.1\pm1.2\pm1.1$ MeV/c^2)

(Belle 86.9 fb^{-1} : PRL 92, 012002 (2004))

$M(D_{sJ})=2317.2\pm0.5\pm0.9$ MeV

(Babar 91 fb^{-1}: hep-ex/0310050)

$M(D_{sJ})=2317.3\pm0.4\pm0.8$ MeV/c^2

More new $\{c\bar{s}\}$:

Candidate for $J^P=1^+$ partner

$D_{sJ}(2457)$:->$D_s^{*+}\pi^0$, D_s^{*+}->D_s^+□

(CLEO 13.5 fb^{-1} : PR D68, 032002 (2003))

$M(D_{sJ})-M(D_s^*)=351.2\pm1.7\pm1.0$ MeV/c^2

($M(D_{sJ})=2463.1\pm1.7\pm1.2$ MeV/c^2)

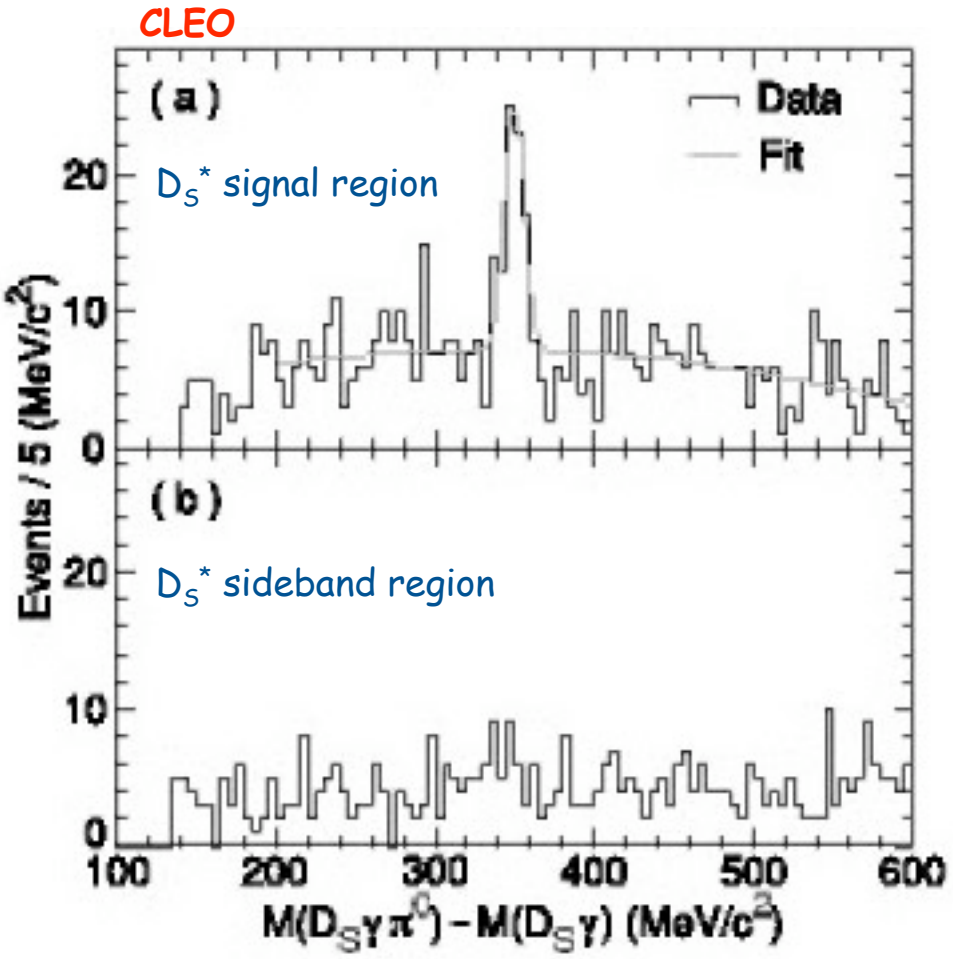
(Belle 86.9 fb^{-1} : PRL 92, 012002 (2004))

$M(D_{sJ})-M(D_s^*)=344.1\pm1.3\pm1.0$ MeV/c^2

($M(D_{sJ})=2456.5\pm1.3\pm1.3$ MeV/c^2)

(Babar 91 fb^{-1}: hep-ex/0310050)

$M(D_{sJ})=2458.0\pm1.0\pm1.0$ MeV/c^2



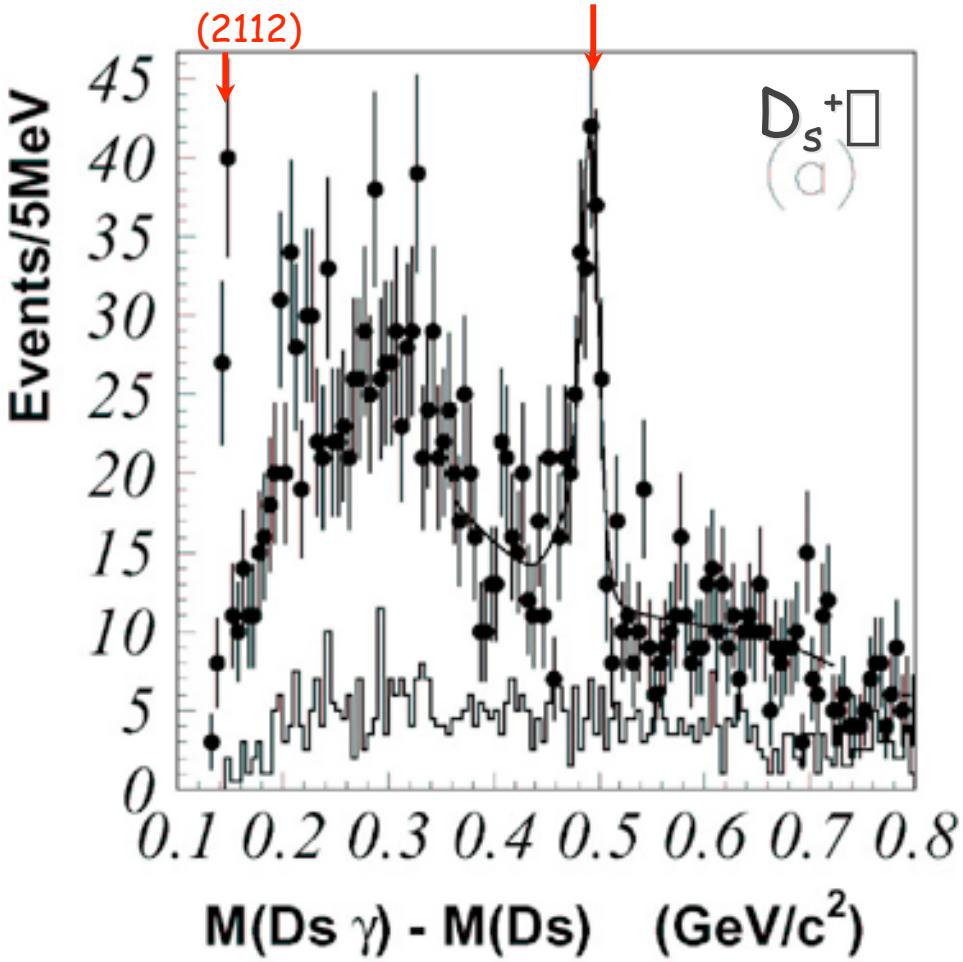
Masses are lower than predicted;

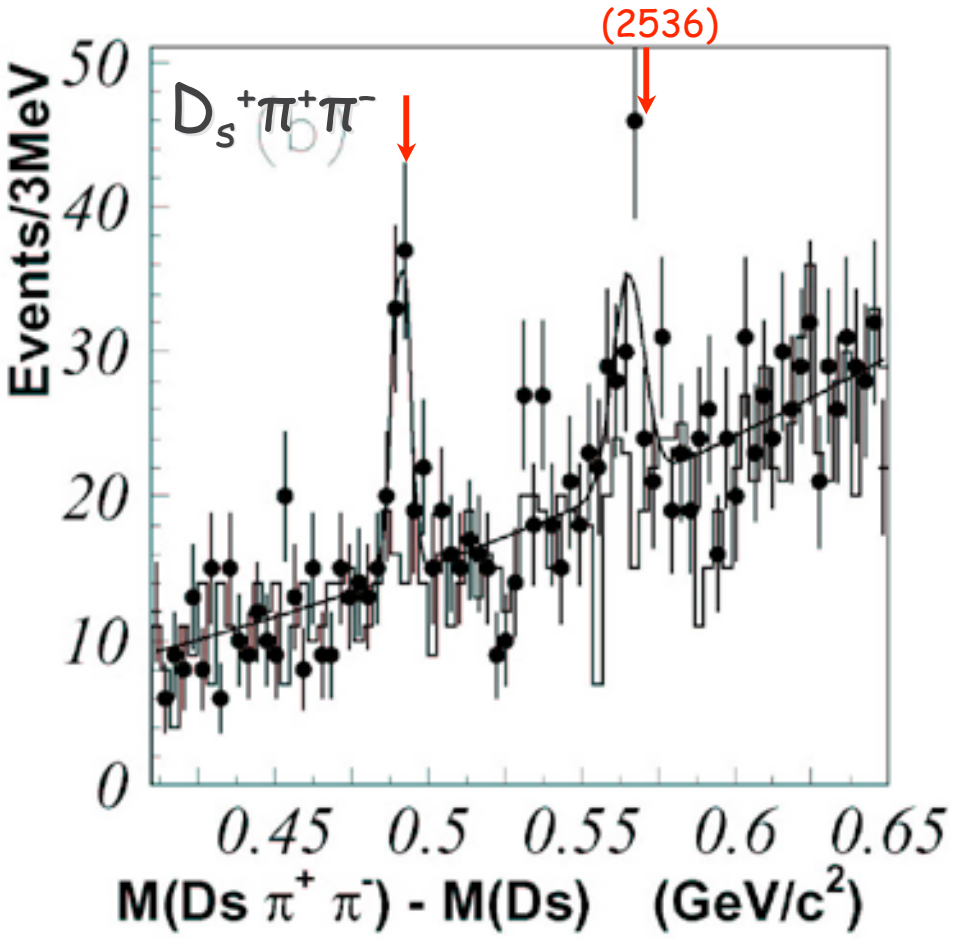
$D_{sJ}(2457)$-$D_{sJ}(2317)$ splitting is consistent w potential model predictions for 1^+-0^+

More new {$c\bar{s}$}:

$D_{sJ}(2357)$:->$D_s^+\gamma$ ->$D_s^+\pi^+\pi^-$; existence rules out 0^+

(Belle 86.9 fb^{-1} : PRL 92, 012002 (2004))





More new {cs}: rate ratios

(Belle 86.9 fb^{-1} : PRL 92, 012002 (2004))

$D_{sJ}^+(2457)$

$$\frac{\mathcal{B}_{D_s^+\gamma}}{\mathcal{B}_{D_s^{*+}\pi^0}} = 0.55 \pm 0.13 \pm 0.08$$

$$\frac{\mathcal{B}_{D_s^{*+}\gamma}}{\mathcal{B}_{D_s^{*+}\pi^0}} \leq 0.31\ (90\%\ CL)$$

$$\frac{\mathcal{B}_{D_s^+\pi^+\pi^-}}{\mathcal{B}_{D_s^{*+}\pi^0}} = 0.14 \pm 0.04 \pm 0.02$$

$$\frac{\mathcal{B}_{D_s^+\pi^0}}{\mathcal{B}_{D_s^{*+}\pi^0}} \leq 0.21\ (90\%\ CL)$$

$D_{sJ}^+(2317)$

$$\frac{\mathcal{B}_{D_s^+\gamma}}{\mathcal{B}_{D_s^+\pi^0}} \leq 0.05\ (90\%\ CL)$$

$$\frac{\mathcal{B}_{D_s^{*+}\gamma}}{\mathcal{B}_{D_s^+\pi^0}} \leq 0.18\ (90\%\ CL)$$

$$\frac{\mathcal{B}_{D_s^+\pi^+\pi^-}}{\mathcal{B}_{D_s^+\pi^0}} \leq 4 \times 10^{-3}\ (90\%\ CL)$$

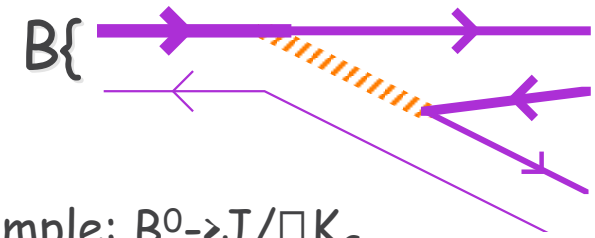
(Babar 91 fb^{-1}: hep-ex/0310050)

$D_{sJ}^+(2458)$

$$\frac{\mathcal{B}_{D_{sJ}^+(2317)\gamma}}{\mathcal{B}_{D_s^{*+}\pi^0}} \leq 0.22\ (95\%\ CL)$$

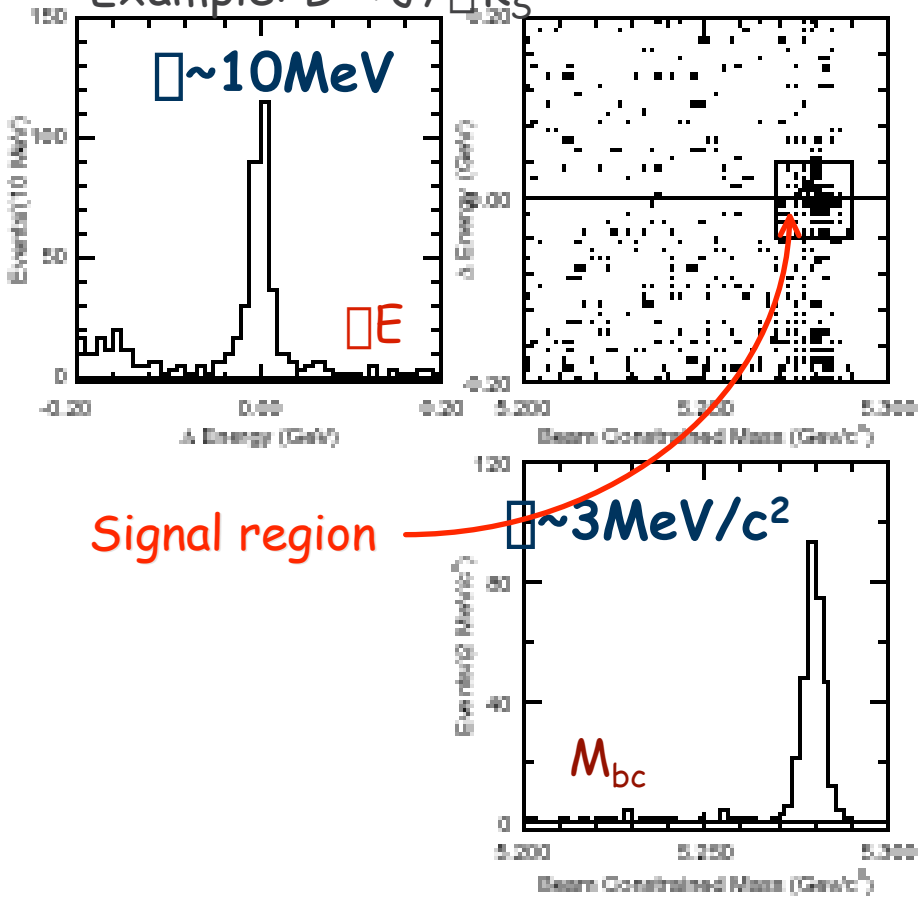
New particles in B decays reconstructed at (4S)

In B decay:



Unrestricted in J,P,C
-> spectroscopy

Example: $B^0 \to J/\psi K_S$



Powerful background rejection:
exploit

- exclusive pair production of B
- narrow resolution of collision energy

$\Delta E = E^*_{cand} - E^*_{beam} = 0$ ($E^*_{beam} = s^{1/2}/2$)

ΔE~10-50 MeV, depending on mode

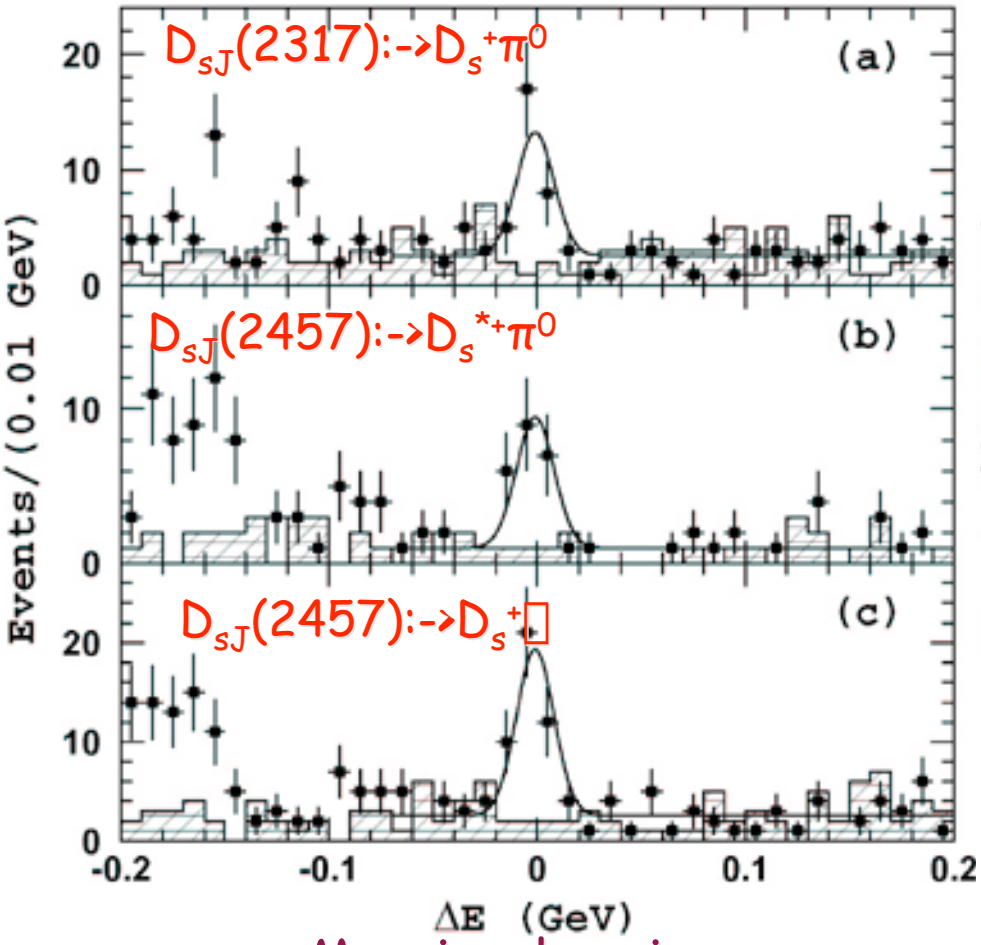
M_{bc} (Beam-constrained mass)

$$M_{bc} = (E^{*2}_{beam} - p^{*2}_{cand})^{1/2}$$

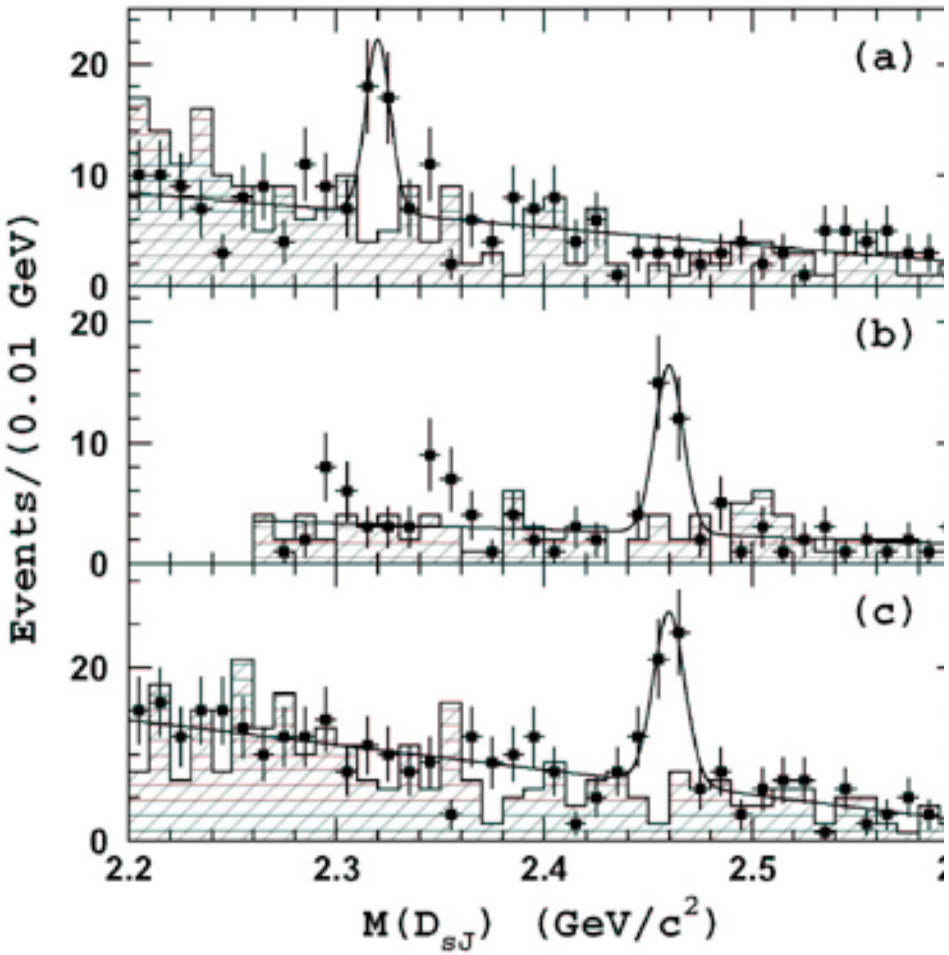
First identified in B:
$\eta_c(2S)$ (Belle: PRL **89**, 102001 (2002))

$D_{sJ}(2317), D_{sJ}(2457)$ in B decay (Belle 114 fb^{-1} on-res: PRL **91**, 262002 (2003))

In B-> DD_{sJ} {D^0->$K^+\pi^-$, $K^+\pi^-\pi^-\pi^+$, D^-->$K^+\pi^-\pi^-$}, 123.8M B pairs



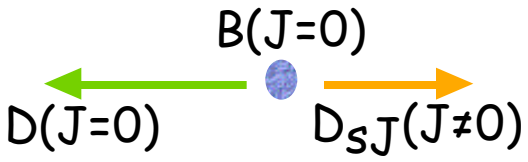
M_{bc} signal region



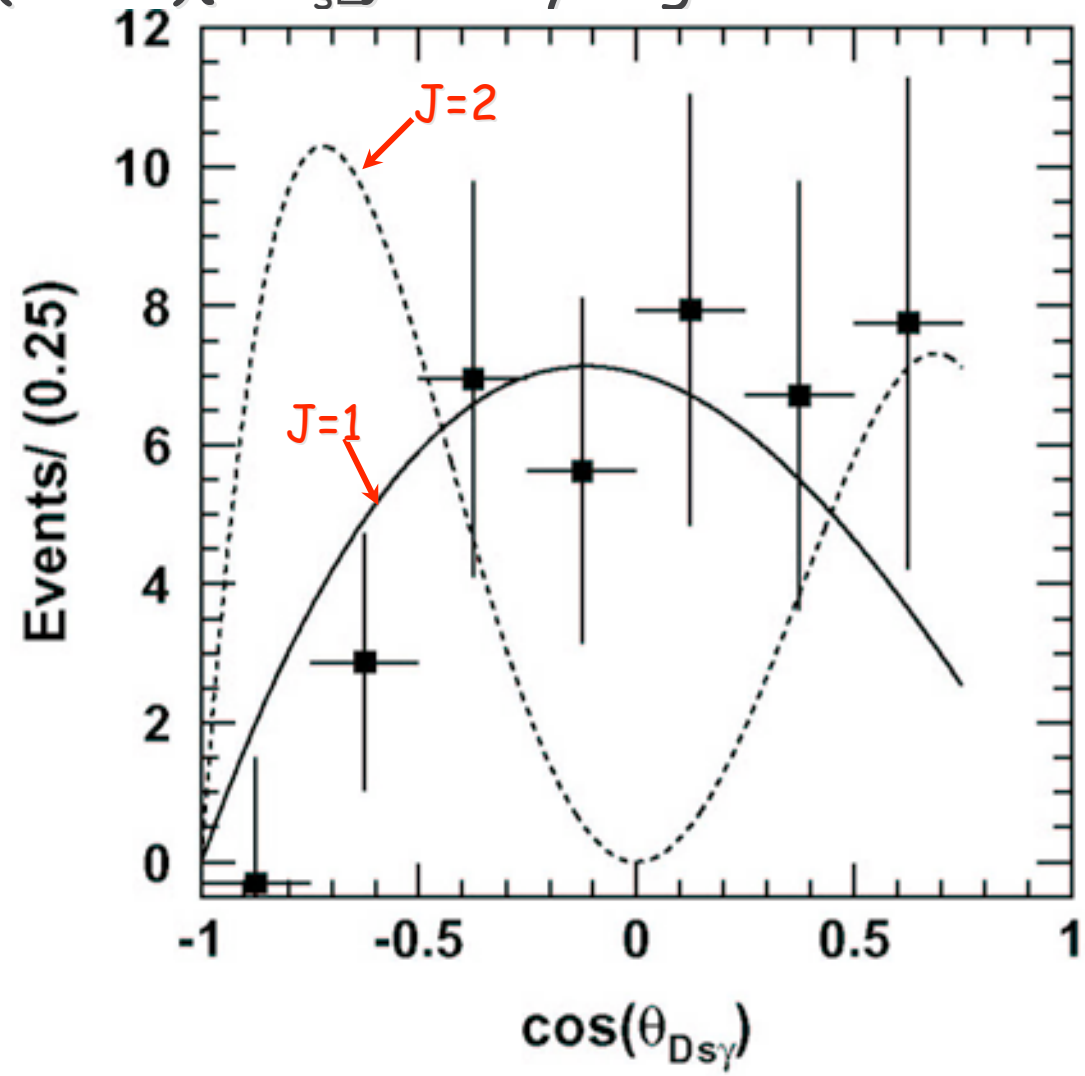
(Belle 125 fb^{-1}: PRL **91**, 262002 (2003))

Determine J: B-> $DD_{sJ}(2457)\{->D_s\gamma\}$ decay angle distribution

Conservation of J: flight direction correlates w. spin



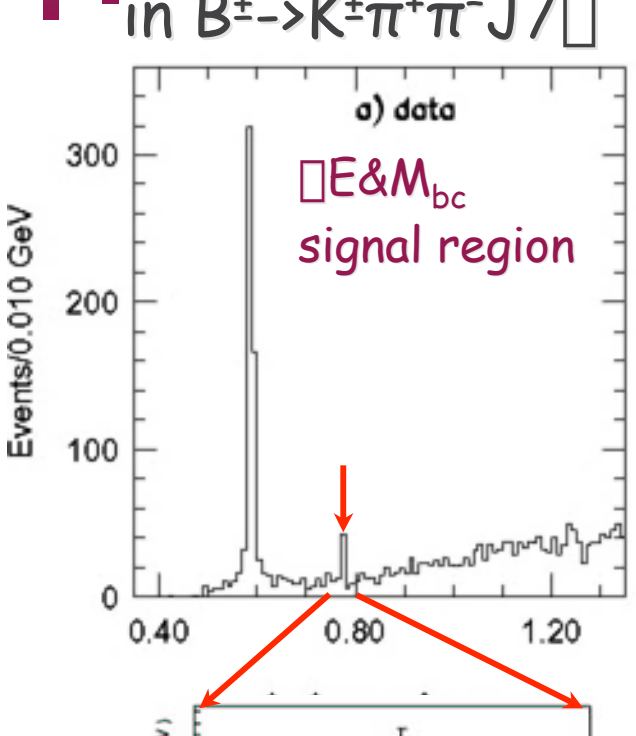
supports $J^P=1^+$

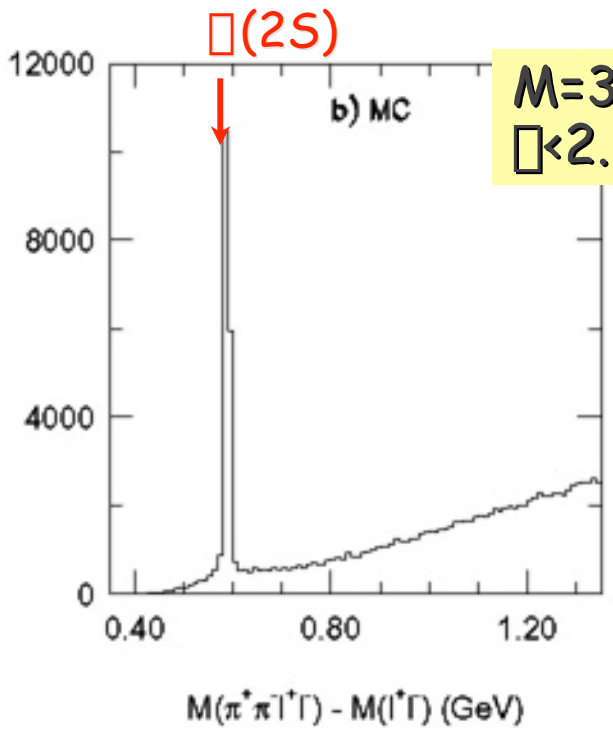


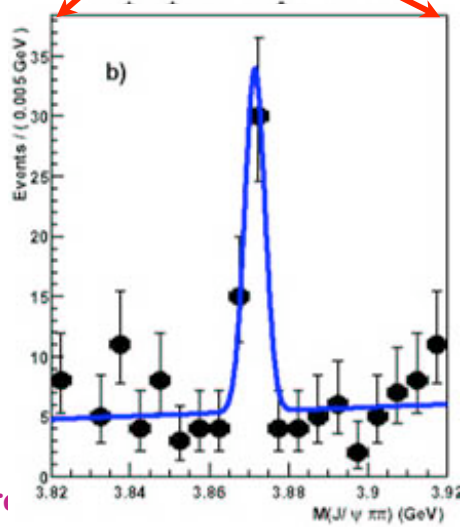
New charmonium-like state in B decay

(Belle: PRL **91**, 262001 (2003))

in $B^{\pm} \to K^{\pm}\pi^{+}\pi^{-}J/\psi$







M=3872.0±0.6±0.5 MeV/c²
Γ<2.3 MeV (90% CL)

Also searched:

$B^{\pm} \to K^{\pm}\chi_{c1}$ --> $\dfrac{\mathcal{B}_{\gamma\chi_{c1}}}{\mathcal{B}_{\pi^+\pi^- J/\psi}} \leq 0.89\ (90\%\ CL)$

(not consistent w $^3D_{c2}$ charmonium;
Eichten, Lane & Quigg PRL 89, 162002 (2002);
mass higher than potential model expectations)

Summary

Charm thrives at the e^+e^- beauty factories!

- 2 sources, e^+e^-->cc, b->c >10^8 events each
- high Lum, clean events -> many new and unexpected results
- D mixing and CP - into interesting region of sensitivity
  several methods, more to come
- rare D decays - first radiative mode
- challenges to QCD models: c production, spectroscopy
  charm and double charm - rates ~ 10X prediction
  new D_s states - fits j=1/2, except masses
  "charmoniumlike" - what is it?

More to come - luminosity, expanded studies – stay tuned!