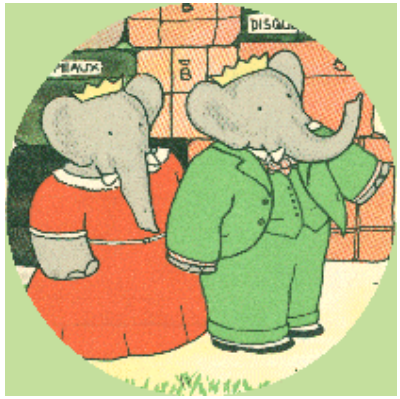


Charm and Charm spectroscopy

Valentina Santoro
University of Ferrara & INFN
On behalf of the BaBar Collaboration

Outline

- ✓ The BaBar detector and Data sample
- ✓ D mixing
  - ✓ Why is it so important?
  - ✓ How to measure the D-mixing
  - ✓ Hadronic D^0 decays
  - ✓ Semi-leptonic decays
  - ✓ Lifetime differences
  - ✓ Analysis of 3-body decays
- ✓ Charm meson spectroscopy
  - ✓ Overview of the current situation
  - ✓ D_{sJ} states
- ✓ Summary

Not mentioned in this talk: charm baryon spectroscopy

The BaBar Detector

BaBar is also a c factory: 1.3 million Charm events per fb^{-1}

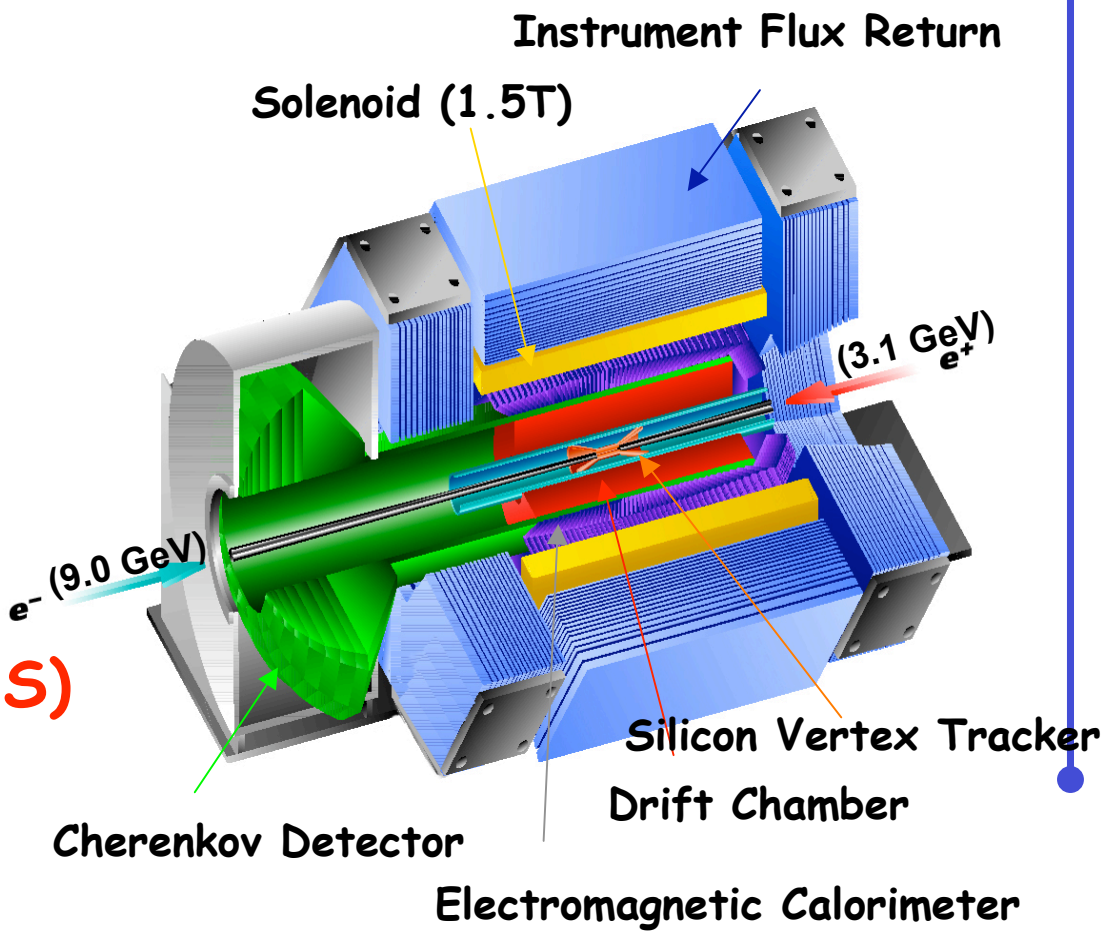
Data collected:

Y(4S): 432 fb^{-1}
Y(3S): 30.2 fb^{-1}
Y(2S): 14.5 fb^{-1}

OffPeak (10.54GeV) + Scan above Y(4S): 53.9 fb^{-1}

The largest world samples on Y(3S) and Y(2S)

Data-taking ended in april 2008



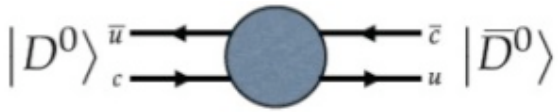
D^0-mixing

Why the D mixing is it so interesting?

- It completes the quark mixing picture already seen in the K, B_d, B_s systems
- The charm sector is the only place where the contribution to the CP violation of down-type quarks in the mixing diagram can be explored .
  - Flavor physics provides strong constraints on models.
  - Many models poorly tested in Q=+2/3 quark sector
- Depending on the measured values of the parameters it could indicate new physics
- It is an important prerequisite in the search of CP violation in the charm sector

D mixing theory(1)

Neutral D mesons (D^0 and D^0bar) are produced as flavor eigenstates, but they can mix through weak interaction:



Time evolution is given by the Schrodinger equation:

$$-i\frac{\partial}{\partial t}\begin{pmatrix}|D^0(t)\rangle\\ |\bar{D}^0(t)\rangle\end{pmatrix}=\left(M-i\frac{\Gamma}{2}\right)_{weak}\times\begin{pmatrix}|D^0(t)\rangle\\ |\bar{D}^0(t)\rangle\end{pmatrix}$$

The mass eigenstates are related to the flavour eigenstates:

(1) $$\boxed{|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D^0}\rangle}$$

$|q^2|+|p^2|=1$

and they propagate according to

(2) $$\boxed{|D_{1,2}(t)\rangle = e^{-i\left(m_{1,2}-\frac{-i\Gamma_{1,2}}{2}\right)t}|D_{1,2}(t=0)\rangle}$$

The mixing parameters are

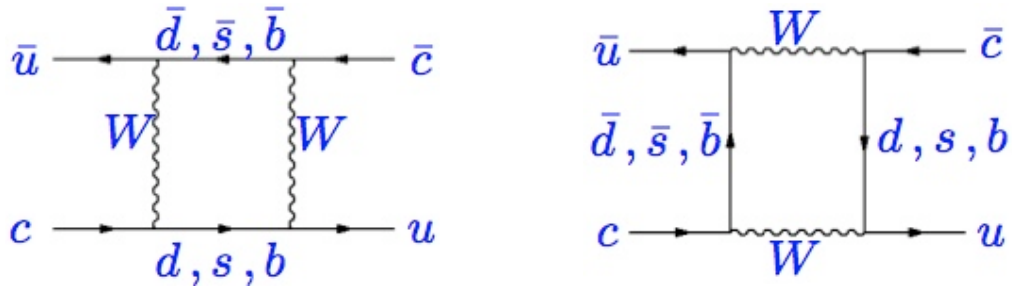
(3) $x=(m_1-m_2)/\Gamma$ (4) $y=(\Gamma_1-\Gamma_2)/2\Gamma$ (5) $\Gamma=(\Gamma_1+\Gamma_2)/2\Gamma$

Mixing will occur if either x or y is non zero

D mixing theory(2)

The SM contribution to meson mixing is well described in the K, B_s and B_d cases by box diagram with W and up-type quarks:

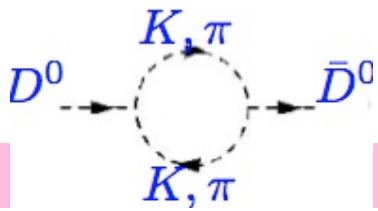
In the D meson one has: $D^0 = (c, \bar{u})$ so that the box contribution for D^0-mixing is given by d-type quarks in the loop



with down-type quarks in the loop GIM suppression is extremely effective. The b-quark contribution is CKM suppressed and the s-quark contribution is suppressed by SU(3) breaking

Good news: SM box is tiny: a lot of room for new Physics to show up

Bad news: There are long distance contributions due to the fact $m_c \sim$ hadronic scale $K\pi$ intermediate states likely dominate



How to measure D-mixing

There are several ways to measure D-mixing :

- ✓ Wrong sign semi-leptonic decays (WS) ($D^0 \to K^+\pi^-$) and right-sign (RS) Cabibbo-Favored (CF) decays ($D^0 \to K^-\pi^+$)
- ✓ Multibody decays ($K\pi\pi^0$) or ($K_S\pi\pi$)
- ✓ Decays to CP eigenstates (K^+K^- or $\pi^+\pi^-$)

I will focus on the BaBar experimental results:

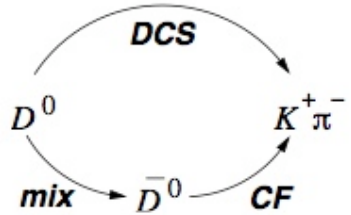
- ✓ First evidence of the D^0-mixing (hadronic D^0 decays)
- ✓ Semi-leptonic D^0 decays
- ✓ Lifetime difference
- ✓ Time-dependent Dalitz plot analysis of $D^0 \to K^+\pi^-\pi^0$

Hadronic D^0 decays

Look for wrong sign decays, e.g. $D^{*+} \to D^0\pi^+, D^0 \to K^+\pi^-$:

Two contributions to wrong sign decays:

- ✓ Doubly-Cabibbo-Supressed (DCS) Decay
- ✓ Mixing then Cabibbo-favored (CF) decays



Discriminate DCS and mixing using temporal distribution

$$\Gamma_{WS}(t) = e^{-\Gamma t}\left(\underbrace{R_D}_{DCS} + \underbrace{\sqrt{R_D}\,y'\Gamma t}_{interference} + \underbrace{\frac{x'^2 + y'^2}{4}(\Gamma t)^2}_{mixing}\right)$$

Assuming $|x|<<1, |y|<<1$ and no CPV

$$x' = x\cos\delta_{K\pi} + y\sin\delta_{K\pi}, \quad y' = -x\sin\delta_{K\pi} + y\cos\delta_{K\pi}$$

$\delta_{K\pi}$ is the strong relative phase between DCS and CF amplitudes

Hadronic D^0 decays: results

(PRL98,211802 (2007))

Fitting procedure :

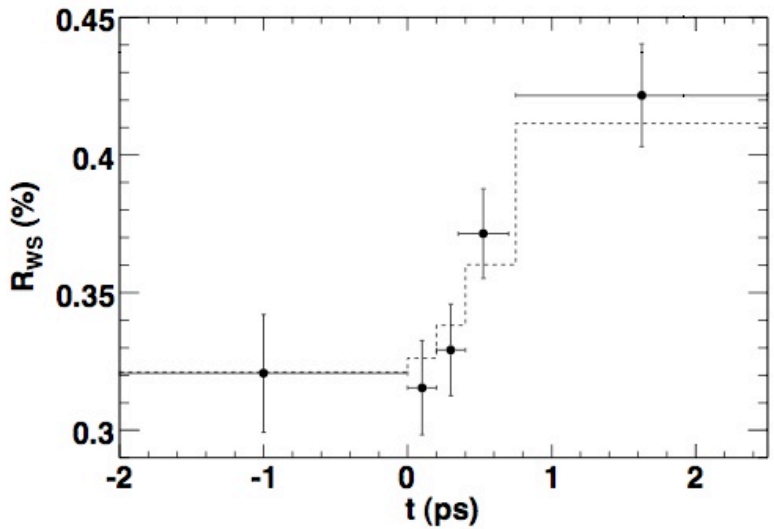
- ✓ Fit $m(K\pi)$, $\Delta m(m_{D^{*+}}-m_{K\pi})$ distribution to separate signal and backgrounds
- ✓ Fit to RS proper time distribution to determine proper time signal resolution function
- ✓ Fit to WS proper time distribution to determine x'^2 and y'

384fb^{-1}

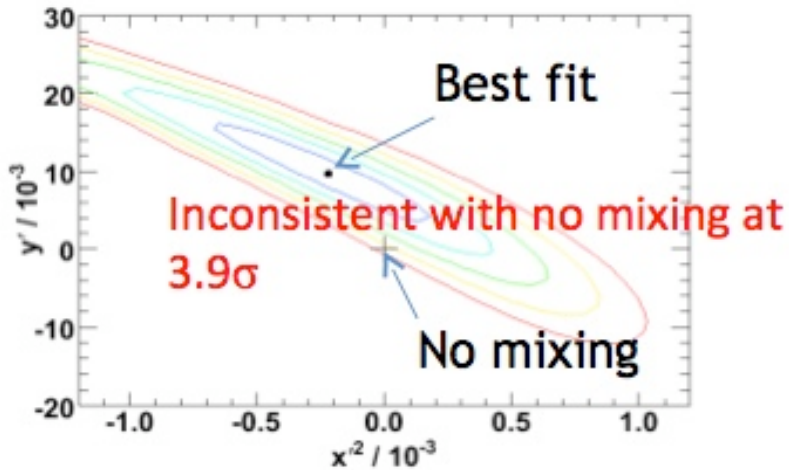
First evidence of D mixing

$X'^2=(-0.22 \pm 0.30 \pm 0.21)\times10^{-3}$
$Y'=(9.7 \pm 4.4 \pm 3.1)\times10^{-3}$

Correlation $x'^2,y' = -0.94$
Significance from $\Delta\log L$



The WS branching fractions from independent $\{m_{K\pi}, \Delta m\}$ fits to slices in measured proper time (points)



D^0 mixing life time difference

- Study D^0 mixing by means of life time difference among $D^0 \to K^+K^-$, $\pi^+\pi^-$ and $D^0 \to K^-\pi^+$

$$y_{CP} = \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to h^-h^+)} - 1$$

Mixture of CP odd and CP even states

h=(K,π)

CP even states

$$y_{CP} = y\cos\phi - \frac{1}{2}A_M x \sin\phi \qquad A_M = \left|\frac{q}{p}\right|^2 - 1$$

ϕ is a weak phase

- If CP conserved, $A_M = \phi = 0$, $y_{CP} = y$

BaBar:hep-ex/0712.2249

Also search for CPV by measuring:

$$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)}$$

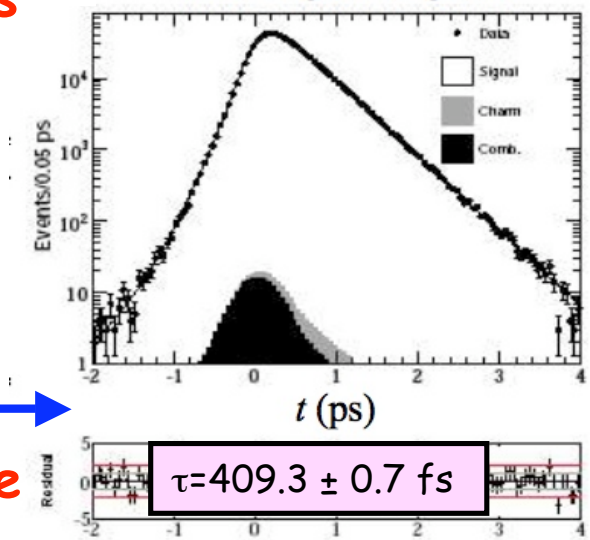
$$\Delta Y = -\frac{\tau(D^0/\overline{D}^0 \to K^-\pi^+)}{(\tau(D^0 \to K^+K^-) + \tau(\overline{D}^0 \to K^+K^-))/2} A_\Gamma$$

Lifetime ratio measurement

Events

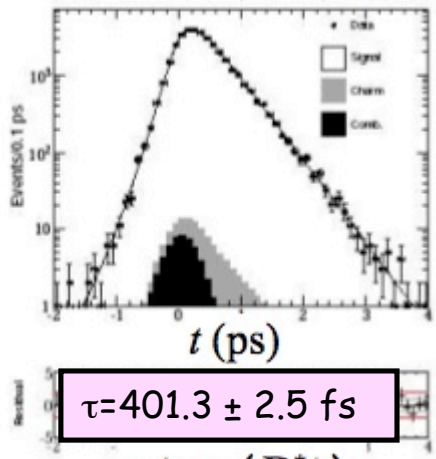
time

π^+K^- signal region:



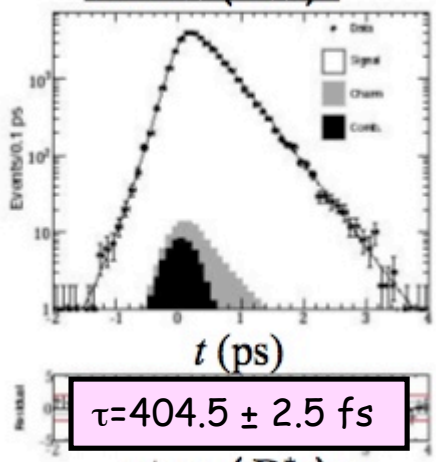
τ=409.3 ± 0.7 fs

K^+K^- (D^{*+}):



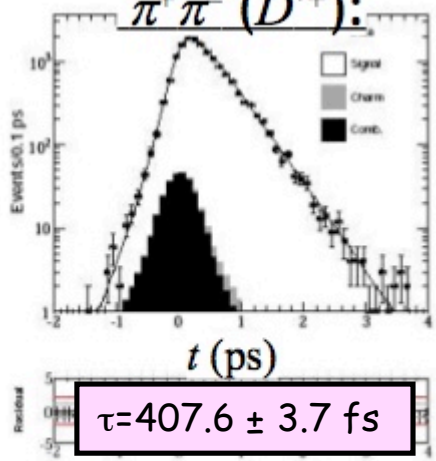
τ=401.3 ± 2.5 fs

K^+K^- (D^{*-}):



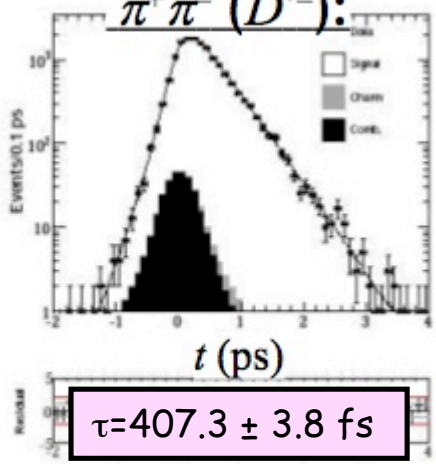
τ=404.5 ± 2.5 fs

$\pi^+\pi^-$ (D^{*+}):



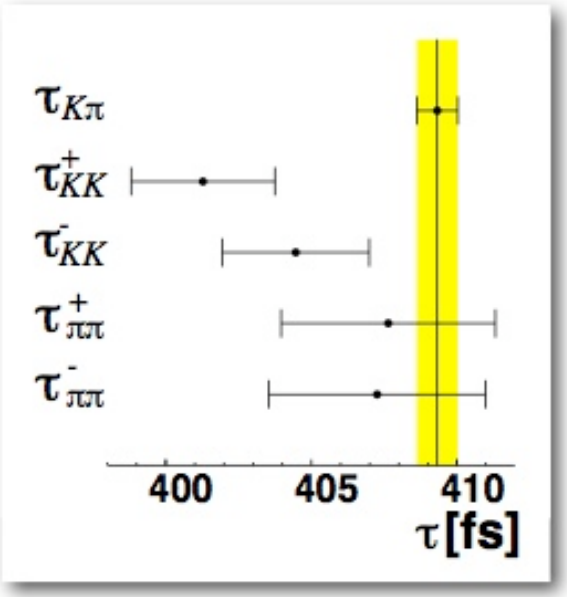
τ=407.6 ± 3.7 fs

$\pi^+\pi^-$ (D^{*-}):



τ=407.3 ± 3.8 fs

Kπ and KK lifetimes differ!



Sample	y_{CP}	ΔY
K^-K^+	$(1.60 \pm 0.46 \pm 0.17)\%$	$(-0.40 \pm 0.44 \pm 0.12)\%$
$\pi^-\pi^+$	$(0.46 \pm 0.65 \pm 0.25)\%$	$(\ \ 0.05 \pm 0.64 \pm 0.32)\%$
Combined	$(1.24 \pm 0.39 \pm 0.13)\%$	$(-0.26 \pm 0.36 \pm 0.08)\%$

3 σ evidence for D^0-$\bar{D}^0$ mixing

Three body decay analysis: $D^0 \to K^+\pi^-\pi^0$

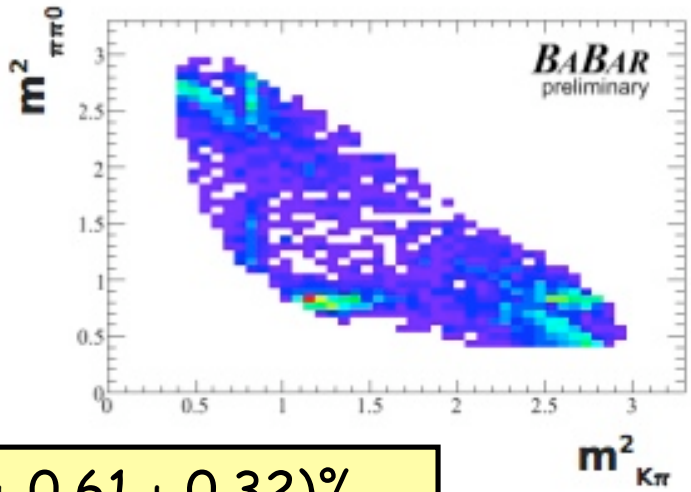
Approach similar to $K\pi$, except the time dependence is a function of position in the Dalitz plot :

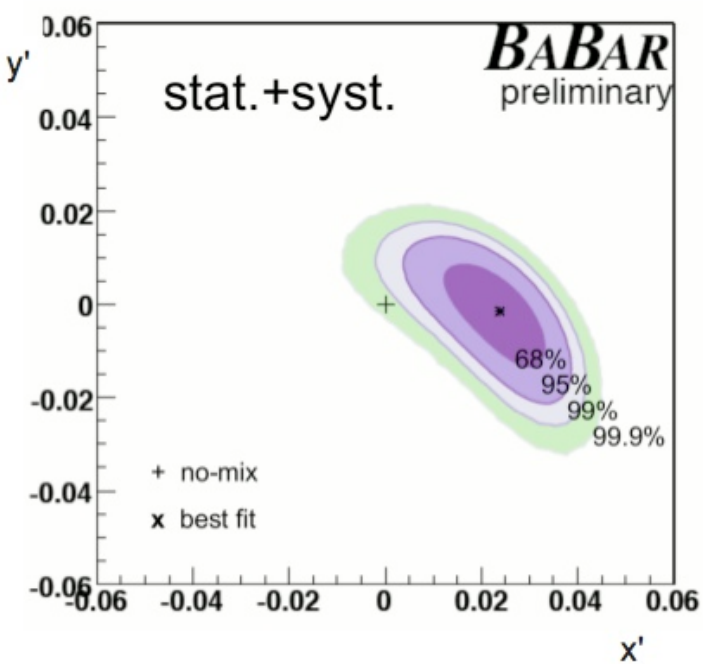
$$\Gamma_{\bar{f}}(m_{12}, m_{13}, t) = e^{-\Gamma}\{|A_{\bar{f}}|^2 + |A_{\bar{f}}||\bar{A}_{\bar{f}}|[y''\cos\delta_{\bar{f}} - x''\sin\delta_{\bar{f}}](\Gamma t) + \frac{x''^2 + y''^2}{4}|\bar{A}_{\bar{f}}|^2(\Gamma t)^2\}$$

$$y'' = y\cos\delta_{K\pi\pi^0} - x\sin\delta_{K\pi\pi^0}$$
$$x'' = x\cos\delta_{K\pi\pi^0} + y\sin\delta_{K\pi\pi^0}$$

384fb^{-1}

x,y are rotated of a strong phase for final state





$X''=(2.39 \pm 0.61 \pm 0.32)\%$
$Y''=(-0.14 \pm 0.6 \pm 0.4)\%$

$R_{mix}=(x''^2+y''^2)/2=(2.9 \pm .6)\times10^{-4}$

No mixing is excluded at 99% confidence level

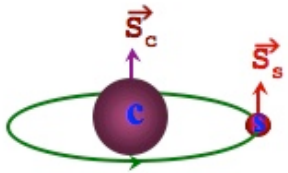
William Lockman LP07

D-mixing summary

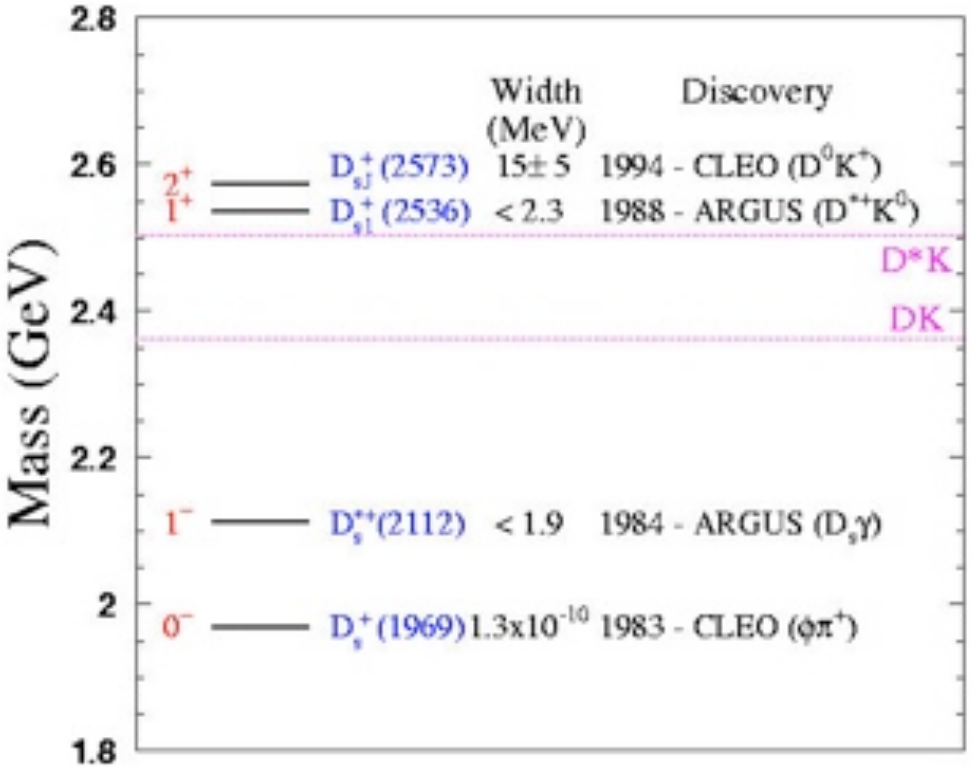
- ✓ Evidence for charm mixing represents an outstanding experimental achievement
- ✓ Combined world average is **inconsistent** with no mixing at 6.7 σ
- ✓ No evidence for CPV in charm mixing yet
- ✓ Lot of analysis still on-going

Charm spectroscopy: $c\bar{s}$ mesons

Brief history of $c\bar{s}$ spectroscopy before 2003



A D_{sJ} charmed-strange meson is composed of a ***c*** and a $\bar{\boldsymbol{s}}$ quarks.



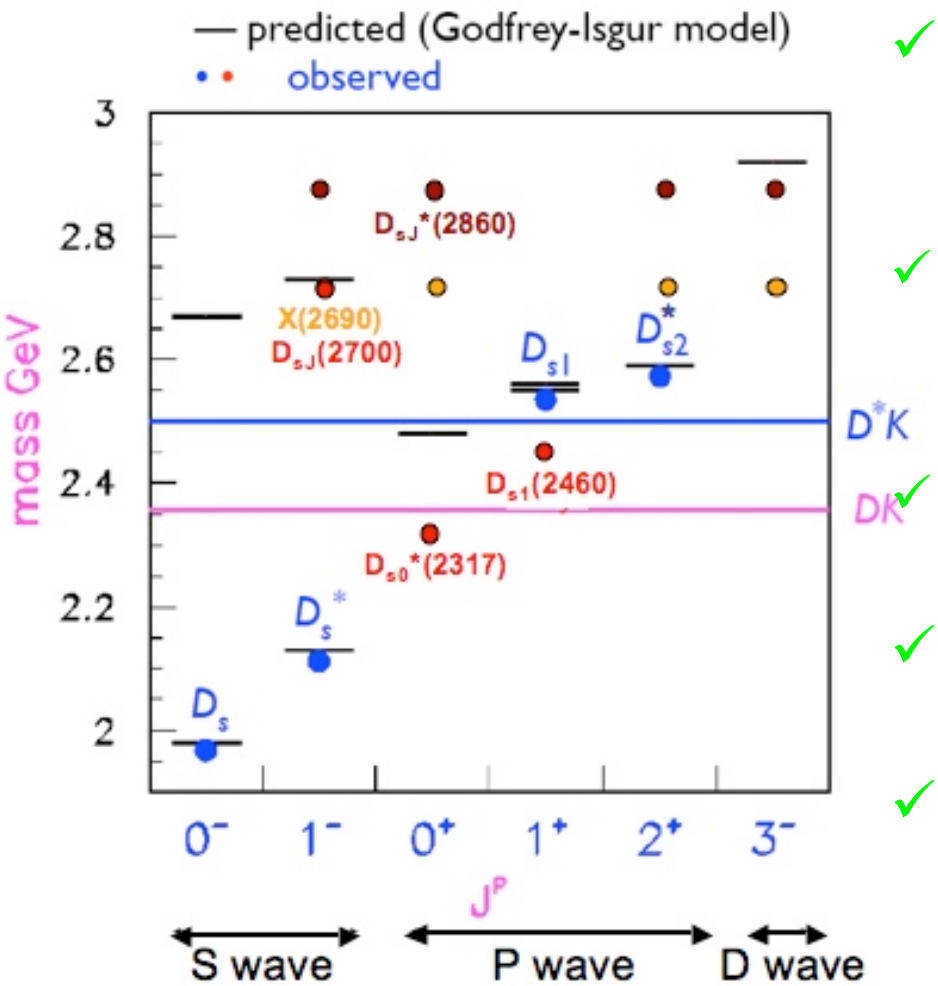
- ✓ All 4 discovered states are very narrow
- ✓ D_s through weak decay
- ✓ $D_s^* \to D_s\gamma$ & $D_s\pi^0$
- ✓ $D_{s1}(2536)$
- ✓ $D_{sJ}(2573)$

D_s^*,$D_{s1}(2536)^+$,$D^*_{sj}(2573)^+$ well known, but J^P only inferred not measured

Current situation

The discovery of the new D_{sJ} states has brought into question potential models .

2 Mass positions of $D^*_{sJ}(2317)^+$ and $D_{sJ}(2460)^+$ very much lower than expected and below the DK and D^*K thresholds respectively .



- ✓ $D_{s0}^*(2317)^+$, Apr. 2003: unexpected observation of a narrow resonance in **BaBar**
- ✓ $D_{s1}(2460)$, May. 2003: CLEO **BaBar** observed a new narrow resonance
- ✓ $D_{sJ}^*(2860)^+$, Jul. 2006: new state discovered by **BaBar**
- ✓ $X(2690)^+$, Jul. 2006: broad enhancement seen in **BaBar**
- ✓ $D^*_{sJ}(2700)^+$, Jul. 2006: new state discovered by **Belle** (≡ X(2690)?)

$D_{s1}(2536)$

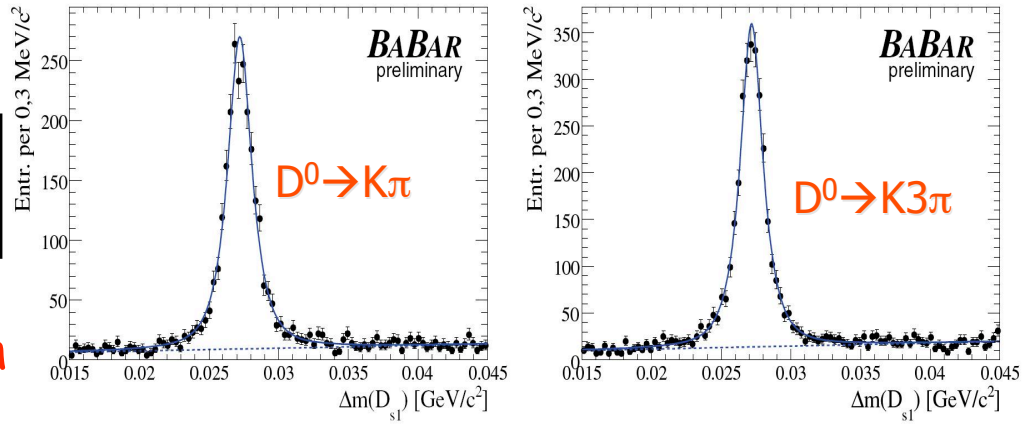
BaBar:hep-ex/0607084

Precision measurement of $D_{S1} \to D^{*+}K^0$ in continuum $D^{*+} \to D^0\pi^+$ $D^0 \to K^-\pi^+$ or $K^-\pi^+\pi^+\pi^-$

232fb^{-1}

$M(D_{s1}^+)=(2534.85 \pm 0.02 \pm 0.40)$MeV/c^2
$\Gamma(D_{s1}^+)=(1.03 \pm 0.05 \pm 0.12)$ MeV

First measurement of the width



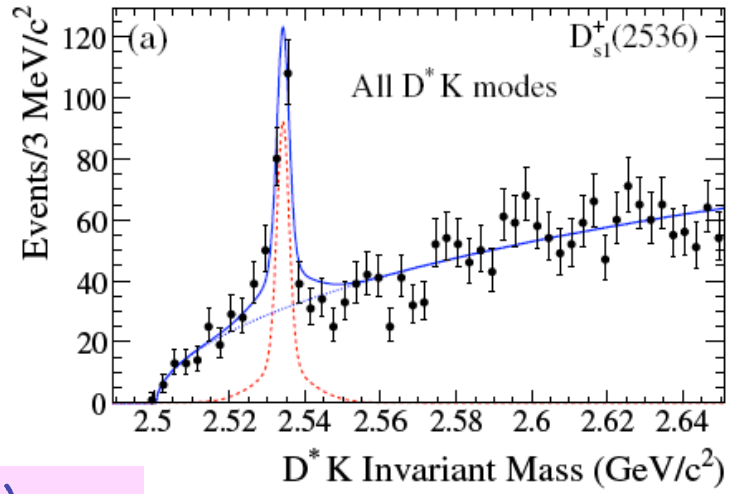
NEW

347fb^{-1}

$B \to D(^*)D_{s1}^+$ (8 modes) $D_{s1}^+ \to D^{*0}K$

First observation of D_{s1} in B decays

N=182 ± 19 events 12 σ
$M(D_{s1}^+)=(2534.78 \pm 0.31 \pm 0.40)$MeV/c^2
J=1 is favored



Phys.Rev.D77:011102, (2008)

$D_{s0}^*(2317)^+$ and $D_{s1}(2460)^+$

- Discovered 4 years ago in $e^+e^- \to c\bar{c}$ events: subsequently observed in B decays
- comprehensive study of decays to D_s^+, plus one or two $\pi^{+/-}, \pi^0$ or γ
- Masses and tight upper limit on widths

$M(D_{s0}^*)=(2319.6 \pm 0.2 \pm 1.4)\,MeV/c^2$
$\Gamma(D_{s0}^*) < 3.8\,MeV$ @ 95% CL
$M(D_{s1}^+)=(2460.2 \pm 0.2 \pm 0.8)\,MeV/c^2$
$\Gamma(D_{s1}^*) < 3.5\,MeV$ @ 95% CL

- A search for neutral and doubly charged partners of $D^*_{s0}(2317)^+$ mesons has been done (tetra quark model). No evidence of such states near 2317 MeV.
- J^P:0^+ for $D_{s0}^*(2317)$ and 1^+ for $D_{s1}(2460)$
- Interpretation of these new states still unclear because the masses of these 2 states are very unusual:
  - Identify them as the 0^+ and 1^+ $c\bar{s}$ states (strong difficulties with potential model)
  - 4 quark states? DK molecule? $D\pi$ atom? Chiral symmetry?

BaBar:Phys.Rev.D74 (2006) 032007
BaBar:Phys.Rev.D74 (2006) 031103

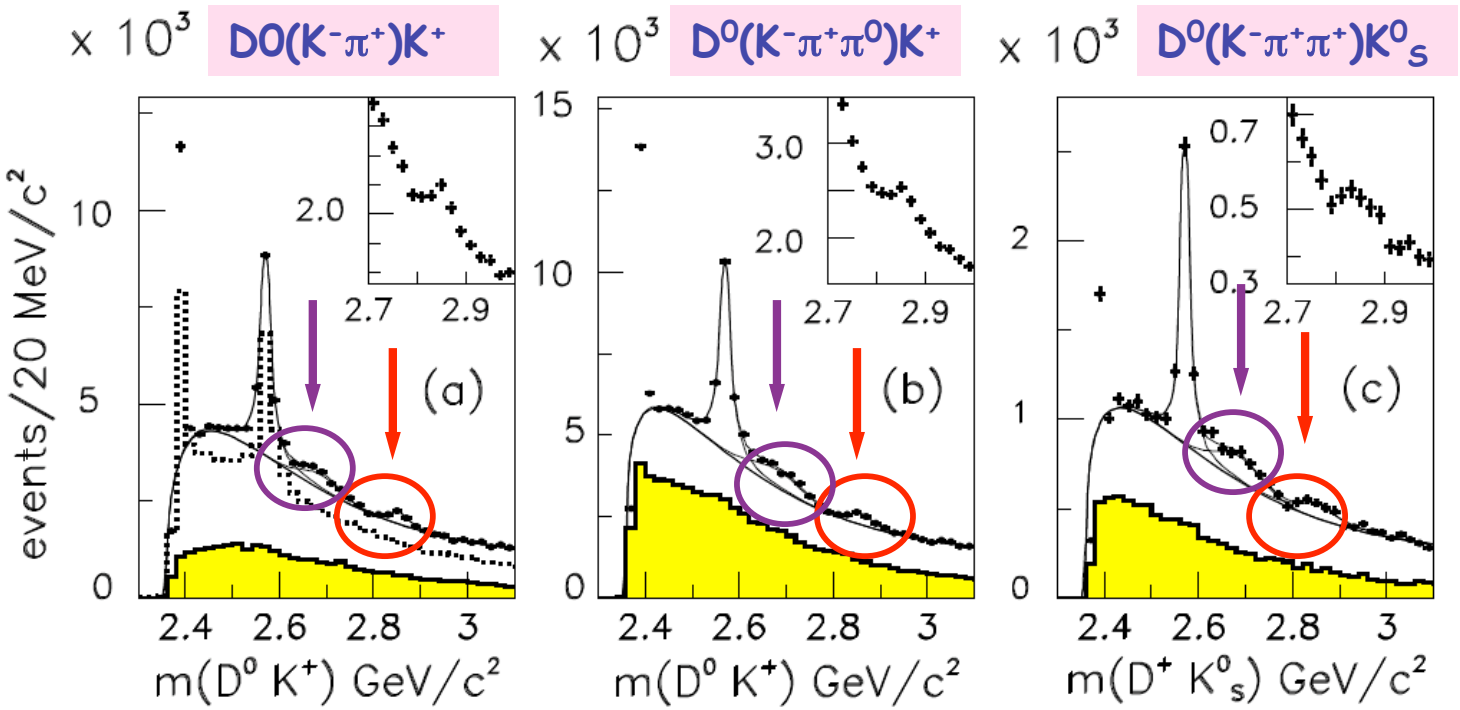
$D_{sJ}^*(2860)$ and $X(2690)$?

240fb^{-1}

Looking to very small cross section in the $c\bar{c}$ continuum:

$e^+e^- \to D^0(K^-\pi^+, K^-\pi^+\pi^0)K^+X$ and $e^+e^- \to D^+(K^-\pi^+\pi^+)K^0_S X$

BaBar discovered a new structure at 2.86 GeV/c^2



There was also a bump at 2690 MeV/c^2 is another resonance? Probably X(2690)

BaBar:Phys.Rev.D97 (2006) 222001

$M(D_{sJ}^*)=(2856.6 \pm 1.5 \pm 5.4)$MeV/c^2
$\Gamma(D_{sJ}^*)=(47 \pm 7 \pm 10)$MeV

$M(X?)=(2688 \pm 4 \pm 3)$MeV/c^2
$\Gamma(X?)=(112 \pm 7 \pm 36)$MeV

$D^*_{sJ}(2700)$

Belle discovered new resonance in $B^+ \to D^0 D_{sJ}, D_{sJ} \to (D^0 K^+)$

$M(D_{sJ}) = (2708 \pm 9^{+11}_{-10}) MeV/c^2$
$\Gamma(D_{sJ}) = (108 \pm 23^{+36}_{-31}) MeV$
$J^P = 1^-$ favored

Belle:hep-ex/0707.3491

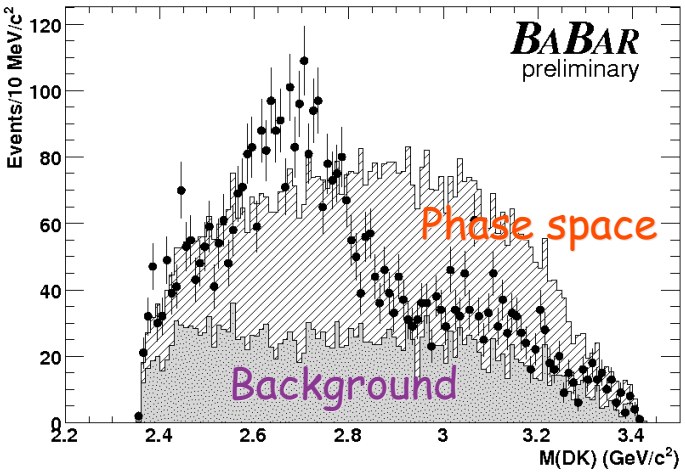
Same resonance as seen by BaBar in continuum, X(2690)?

Mass and width are consistent, same decay mode

Study of $B \to D^{(*)} \bar{D}^{(*)} K$ decays in BaBar (22modes)

Enhancement observed around 2690 MeV/c^2 in DK and D*K

Dalitz plot analysis in progress



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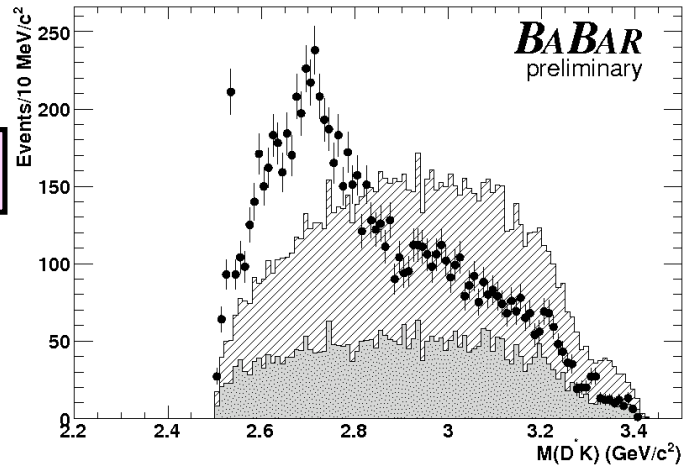


No signal of $D^*_{sJ}(2860)$ in B decays

hep-ex/0705.3716
V.Poireau, DIS 2007 p.10

Charm mesons spectroscopy summary

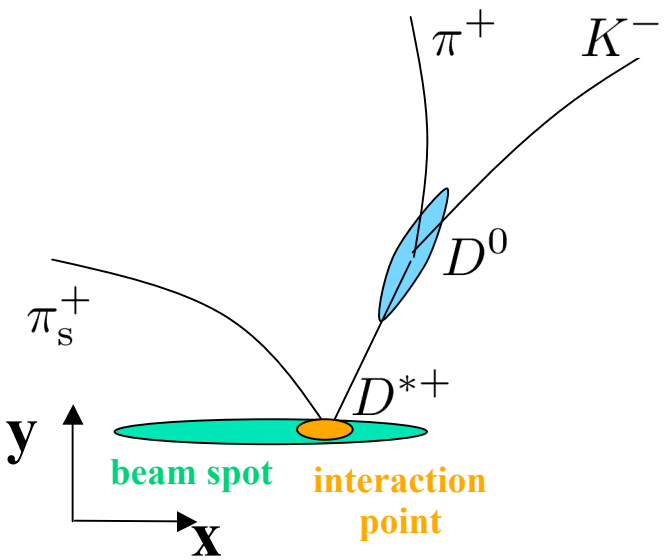
- ✓ Several new charmed states discovered in the last few years.
- ✓ Many new states are waiting for a classification in the quark model (potential models are in trouble)
- ✓ More information is needed
- ✓ Spectroscopy will provide more surprises !

Back-up slides

Event selection in the D-mixing analysis

There are two keys sperimental features used in D^0-mixing analysis:

- The flavor tag by D*
- p(D*)>~2.5 GeV to eliminate D^0 from B decays



Beam-constrained vertex fits of K, π, π_{tag} tracks as show in figure..

π_{tag} charge gives D flavor at production.

Semileptonic D^0 decays: $D^0 \to K^* l \nu$

In the limit of small mixing and no CP violation mixed D^0 states decaying semi-leptonically have a simpler time dependence:

- WS time-dependence for semi-leptonic analyses is well-distinguished from exponential
- No DCS decays in the semi-leptonic D^0 decays
- Missing neutrino makes D^0 reconstruction harder
- semileptonic decays gives direct access to mixing rate R_M

$$\mathcal{P}(D^0 \to \overline{D}^0 \to X^+ \ell^- \overline{\nu}_\ell) \propto R_M \; t^2 \; e^{-\Gamma t}$$

$$R_M = \frac{\int_0^\infty dt \; \mathcal{P}(D^0 \to \overline{D}^0 \to X^+ \ell^- \overline{\nu}_\ell)}{\int_0^\infty dt \; \mathcal{P}(D^0 \to X^- \ell^+ \nu_\ell)} \approx \frac{x^2 + y^2}{2}$$

No evidence for mixing

$344 fb^{-1}$

$R_M = (-13,12) \times 10^{-4}$ @ 90% C.L.

(PRD76,014018)