$D^0\overline{D}^0$ Mixing and Other Charm Results from Babar

Brian Meadows

Representing the BaBar Collaboration

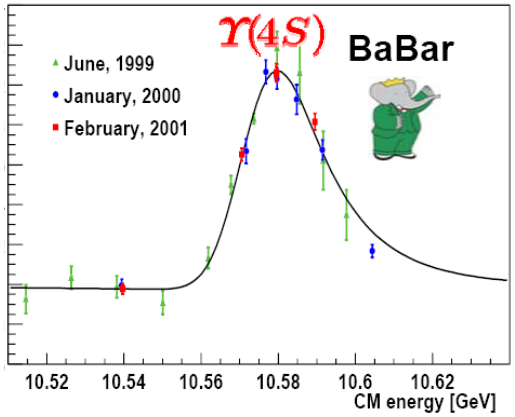
International Workshop on e^+e^- collisions from Phi to Psi ,
IHEP, Beijing, China, Oct 13-16, 2009

- Charm Studies at BaBar
- Mixing in the Charm Sector
- D_s Spectroscopy
- Summary

Charm Studies at BaBar

- Continuum cross sections are large → Can use "off peak" data

$e^+e^- \rightarrow$	σ
$b\bar{b}$	1.05 nb
$c\bar{c}$	1.30 nb
$s\bar{s}$	0.35 nb
$u\bar{u}$	1.39 nb
$d\bar{d}$	0.35 nb



E_{CM} (GeV)

- Very high statistical precision (~1.4 x 10^6 *D*'s/ fb^{-1}).
- Also:
  - B decays to charm – allow measurement of absolute BF's, and spins ?
  - D tagging - ~ 10^7 fully reconstructed D's.
  - Can study charm baryons

  …

Brian Meadows
UNIVERSITY OF Cincinnati

Mixing (Flavour Oscillations) In Neutral D Mesons

Brian Meadows
UNIVERSITY OF Cincinnati

Mixing Parameters

- Flavour oscillations in the neutral *D* system arise from the propagation of two mass eigenstates D_1 and D_2 that comprise the flavour states

$$i\frac{\partial}{\partial t}\begin{pmatrix} |D^0> \\ |\bar{D}^0> \end{pmatrix} = \left(\mathcal{M} - \frac{i}{2}\mathcal{G}\right)\begin{pmatrix} |D^0> \\ |\bar{D}^0> \end{pmatrix}$$

$$|D_1> \; = \; p|D^0> + q|\bar{D}^0> \qquad |D_1(t)> \; = \; |D_1> e^{-i(\Gamma_1/2 + im_1)t}$$
$$|D_2> \; = \; p|D^0> - q|\bar{D}^0> \qquad |D_2(t)> \; = \; |D_2> e^{-i(\Gamma_2/2 + im_2)t}$$

Eigenvalues are $m_{1,2} + i\Gamma_{1,2}/2$

with means: $M = (m_1 + m_2)/2$

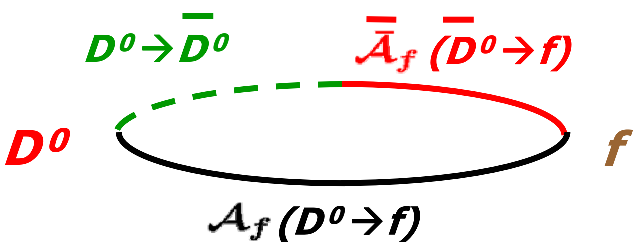
$\Gamma = (\Gamma_1 + \Gamma_2)/2$

- It is usual to define four mixing parameters:

$$x = \frac{m_1 - m_2}{\Gamma} \;\; ; \;\; y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \;\; ; \;\; \left|\frac{q}{p}\right| \;\; ; \;\; \phi_M = \mathrm{Arg}\left\{\frac{q}{p}\right\}$$

CPV signalled by $p \neq q$

- *CPV* from either the mixing, or from the decay (or both) can occur



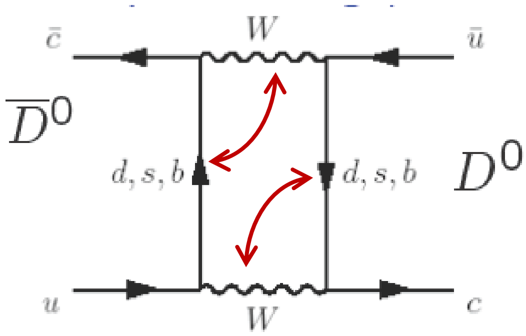
$$\lambda_f = \frac{q\bar{\mathcal{A}}_f}{p\mathcal{A}_f} \propto e^{i(\delta + \phi_f + \phi_M)}$$

strong weak mixing

Mixing in Standard Model is Very Small

- Off-diagonal mass matrix term – two leading terms:

$\Delta C=2$ (short-range)
(contributes mostly to x)



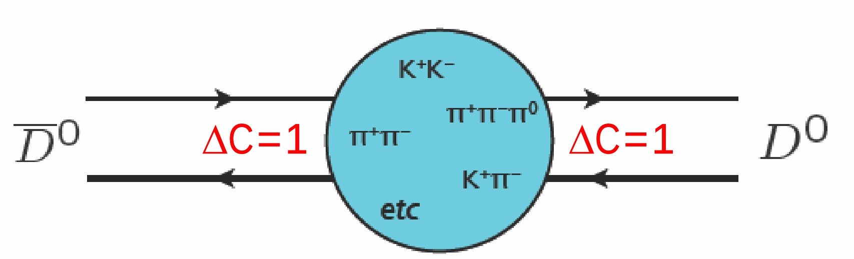
Down-type quarks in loop:

b : CKM-suppressed ($|V_{ub}V_{cb}|^2$)
d, s : GIM-suppressed

$$x \propto (m_s^2 - m_d^2)/m_c^2 \sim 10^{-5}$$

(almost 2 orders of magnitude less than current sensitivity)

Hadronic intermediate states (long-range)



Difficult to compute (need to know all the magnitudes and phases, ...)

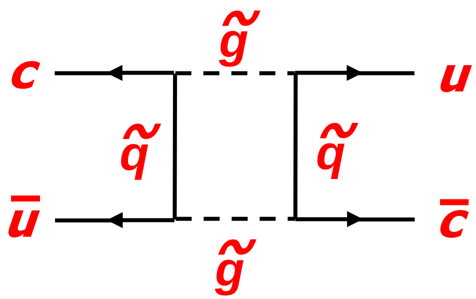
Most computations predict x and y in the range 10^{-3}–10^{-2} and $|x|<|y|$

Recent predictions: $|x| \leq 1\%$, $|y| \leq 1\%$

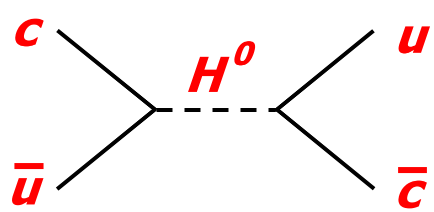
(consistent with current observation)

New Physics and Mixing

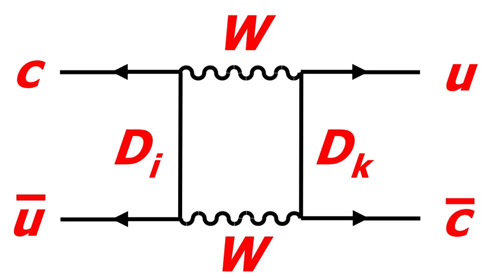
- Several extensions to the SM have been considered that can increase the value of **x** including:



Supersymmetry



FCNC



Heavy, weak iso-singlet quarks

[A recent survey: **Phys. Rev. D76, 095009 (2007), arXiv:0705.3650]**

- Generally agreed that signals for new physics are:
  - EITHER $|x| >> |y|$
  - OR Any evidence for *CPV*

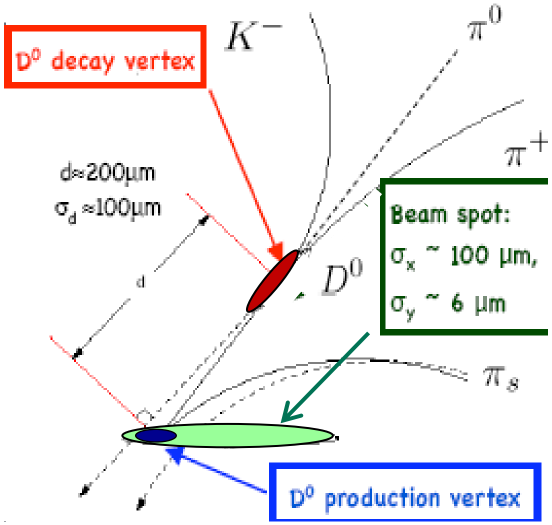
Phase in $\Delta C=1$ transitions tiny:

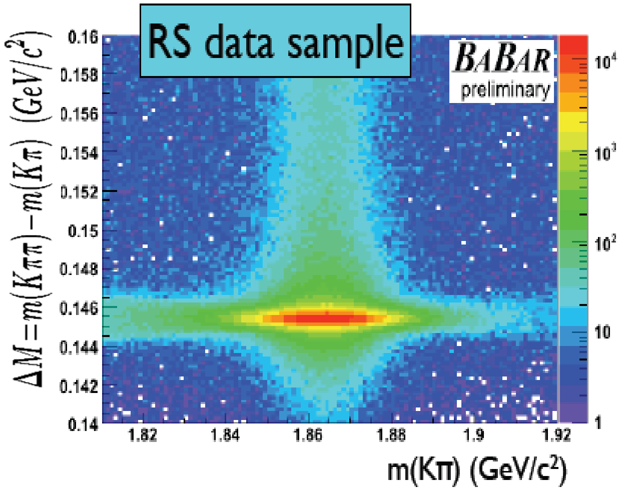
$V_{cs} \sim 1 - \lambda^2/2 - i\eta A^2\lambda^4$
$\to 0.97 - 6 \times 10^{-4}\, i$

Wolfenstein representation

Mixing Measurements at *BaBar*

- Good vertex resolution allows measurement of time-dependence of D^0 decays.
- Can eliminate distortion from B decays by cutting low momentum D^0's
- Excellent particle ID (Dirc and dE/dx) allows clean K/π separation

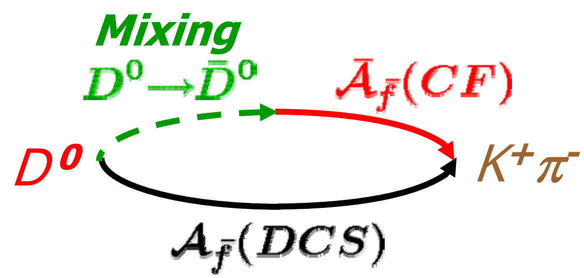




- D^0's from $D^{*+} \rightarrow D^0\pi^+$ decays:
  - Tag flavor of D^0 by the sign of the "slow pion" in D^* decays
  - Allow clean rejection of backgrounds
- **BUT untagged events can be used too !**

Hadronic Decays Accessible to D^0 or $\bar{D}^0$

- Two decay mechanisms interfere:
  - Mixing then Cabibbo-favoured (CF) decay
  - Doubly-Cabibbo-Suppressed (DCS) decay



- For $|x|, |y| \ll 1$, decay rate R_{WS} for wrong-sign *(WS)* decays $D^0 \to K^+\pi^-$:

DCS rate — **DCS-Mixing interference** — **Mixing rate**

$$\frac{R_{WS}}{e^{-\Gamma t}} \propto |A_{\bar{f}}|^2 + y'|A_{\bar{f}}||\bar{A}_{\bar{f}}|(\Gamma t) + \frac{x'^2 + y'^2}{4}|\bar{A}_{\bar{f}}|^2(\Gamma t)^2$$

BUT Recall Strong phase $\delta = \mathrm{Arg}\{A_{\bar{f}}/\bar{A}_{\bar{f}}\}$ **is unknown**

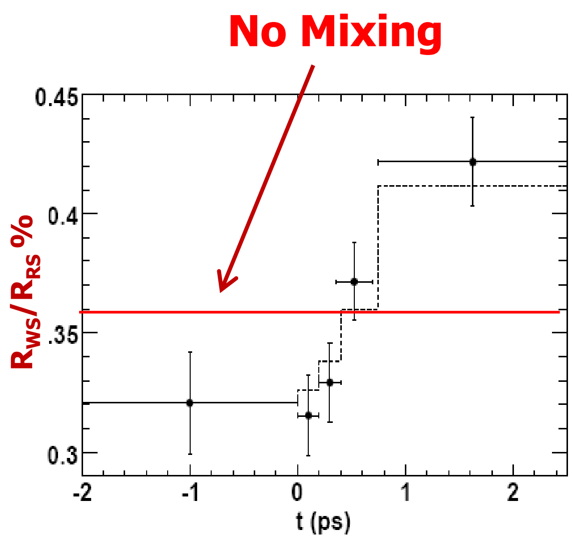
Can measure x'^2 **and** y'
NOT x **and** y

Define:
$x' = x\cos\delta + y\sin\delta$
$y' = y\cos\delta - x\sin\delta$

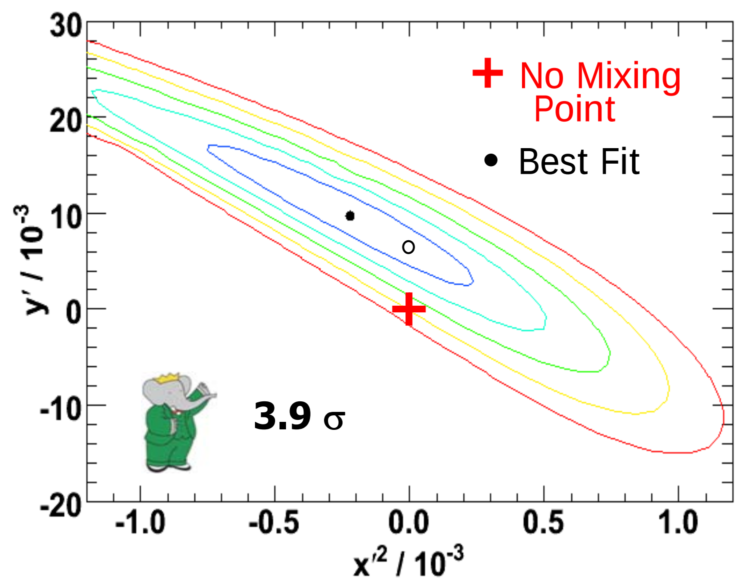
- "Right-sign" *(RS)* decays $D^0 \to K^-\pi^+$ dominated by A_f, so rate $R_{RS} \propto e^{-\Gamma t}$

Evidence for Mixing in $D^0 \rightarrow K^+\pi^-$

Tagged PRL 98:211802 (2007) – 384 fb^{-1}



Mixing signal clear in time-dependence of R_{WS}/R_{RS} ratio



Likelihood contours (expanded to account for systematic uncertainty of ~0.7 x statistical.)

Lifetime Difference Measurements

- In the absence of *CPV*,
  - D_1 is *CP*-even and D_2 is *CP*-odd
  - Measurement of lifetimes τ for D^0 decays to *CP*-even and *CP*-odd final states lead to a measurement of *y* !

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

Mixed *CP*. Assume τ is mean of *CP*-even and *CP*-odd

K^+K^- or $\pi^+\pi^-$ *CP*-even

- Allowing for *CPV*, measure the D^0 and $\bar{D}^0$ asymmetry

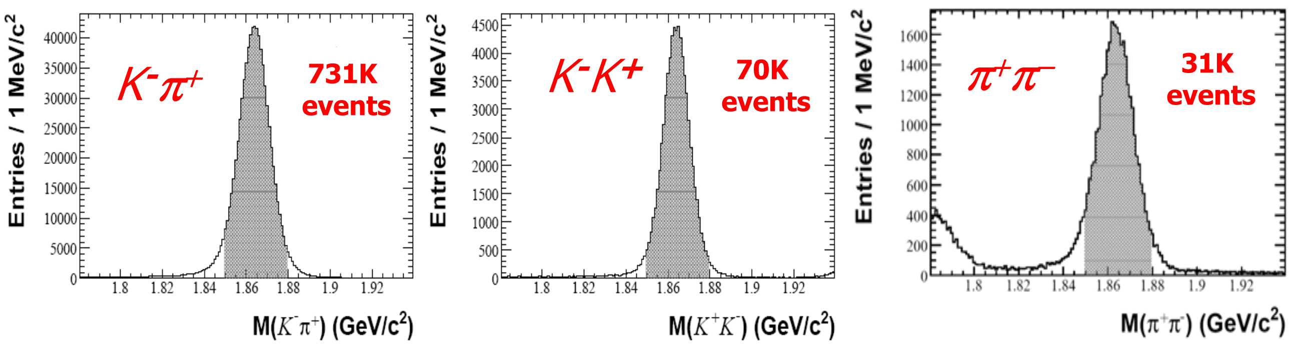
$$A_\tau = \frac{\tau^-(\bar{D}^0 \to h^+h^-) - \tau^+(D^0 \to h^+h^-)}{\tau^-(\bar{D}^0 \to h^+h^-) + \tau^+(D^0 \to h^+h^-)} = \frac{1}{2} A_M y \cos\phi_M - x \sin\phi_M$$

A_M: $|q/p|^2 - 1$

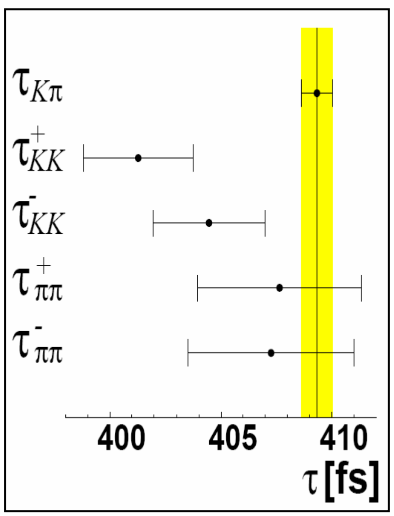
PRD 69,114021 (Falk, Grossman, Ligeti, Nir & Petrov)

Lifetime Difference (Flavor-Tagged D^0's)

Tagged PRD 78:011105 (2008) – 384 fb^{-1}



- Very clean samples
- Fit decays in shaded regions to exponential form convolved with resolution



Mode	y_{CP} (%)	$\Delta Y=(1-y_{CP})A_\tau$ (%)
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	$1.24 \pm 0.39 \pm 0.13$	$-0.26 \pm 0.36 \pm 0.08$

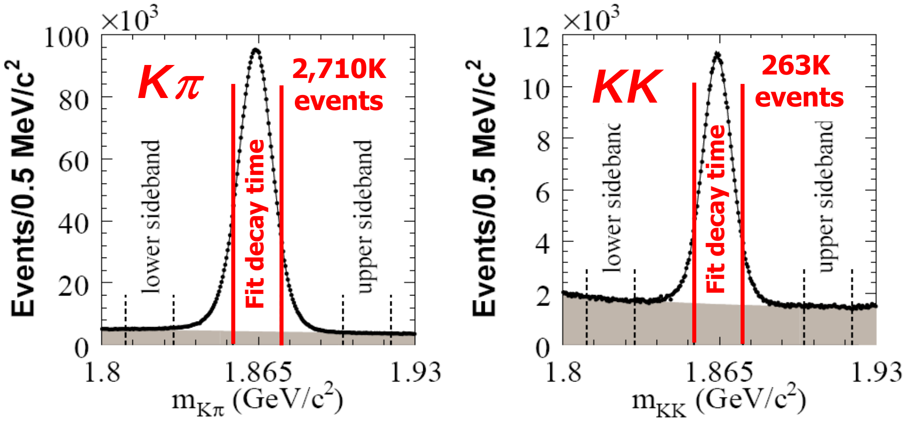
3.0 σ evidence - no *CPV*

- $\tau_{K\pi}$ differs from $\tau_{KK} = (\tau_{KK}^+ + \tau_{KK}^-)/2$
- BUT difference between $\tau^+(D^0)$ and $\tau^-(\overline{D}^0)$ insignificant

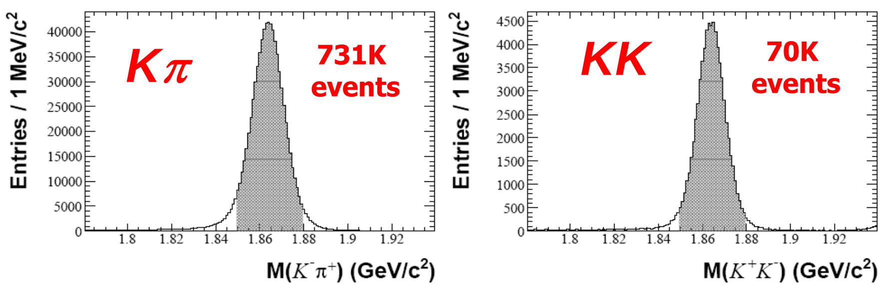
UNIVERSITY OF Cincinnati

Lifetime Difference (Untagged D^0's)

NEW
arXiv:0908.0761 – 384 fb^{-1} PRELIMINARY



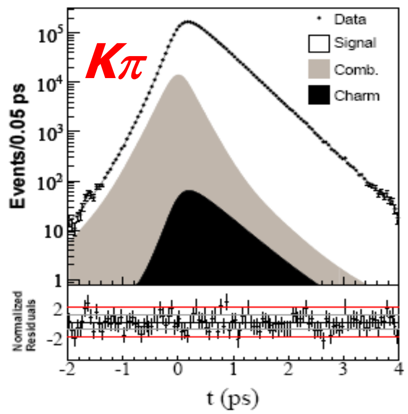
- Untagged K^+K^- decays are used
- Two main backgrounds
  - Combinatorial (largest)
    Examined in sidebands
  - From "broken charm" (small)
    Examined in simulations (MC)
- Fit decay time in narrow region

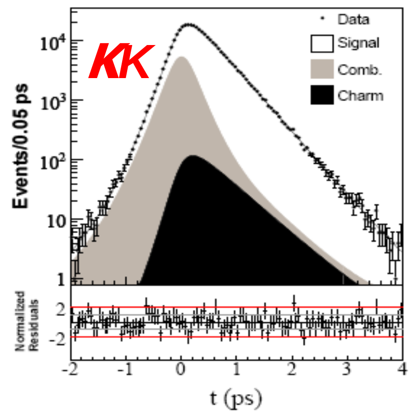


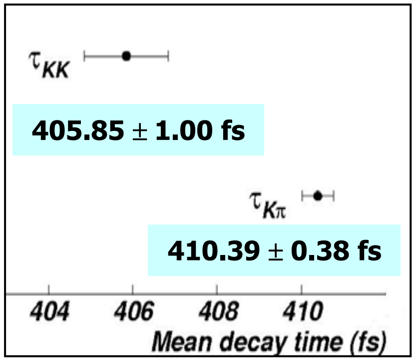
Tagged Sample – 384 fb^{-1}
(for comparison)

- These are dis-joint samples of *Kπ* and *KK* decays
- For each *Kπ* and *KK* pair, selection & reconstruction systematics ~cancel.

Fit t to exponential convoluted with resolution → KK NOT same as $K\pi$







- Major systematic uncertainties:
  - Time-dependence of Combinatorial background 0.115 %
  - Time-dependence of Charm background 0.086 %
  - Signal mass window 0.110 %
  - Detector effects (alignment) 0.093 %

Assuming correlation between systematic uncertainties is 100%

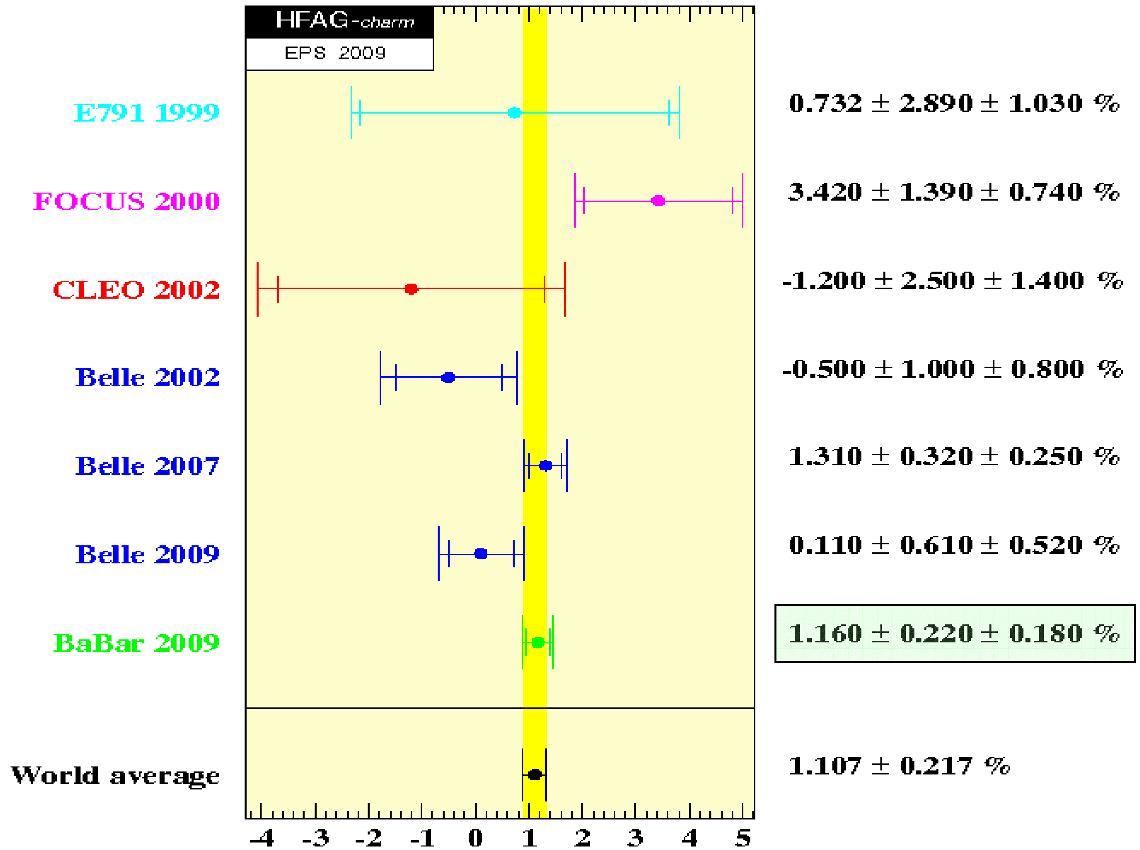
Results:

UNTAGGED	y_{CP} = [1.12 ± 0.26 (stat.) ± 0.22 (syst.)]%	(3.3 σ evidence)
TAGGED	y_{CP} = [1.24 ± 0.39 (stat.) ± 0.13 (syst.)]%	(3.0 σ evidence)

AVERAGE y_{CP} = [1.16 ± 0.22 (stat.) ± 0.18 (syst.)]% (4.1 σ evidence)

HFAG World Average for y_{CP}

A. Schwartz, et al. (updated, EPS 2009)



384 fb^{-1} tagged and untagged Combined

4.1 σ Effect

Supercedes earlier BaBar results.

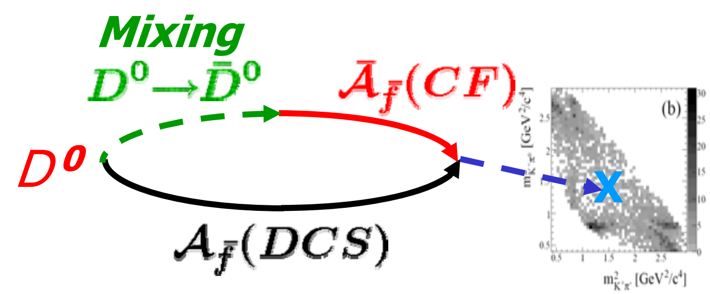
$y_{CP} = (1.107 \pm 0.217)\%$

Time-Dependent Amplitude Analysis of $D^0 \rightarrow K^+\pi^-\pi^0$

arXiv:0807.4544 – 384 fb^{-1}

Accepted by PRL

- Similar to $D^0 \rightarrow K^+\pi^-$ EXCEPT:
  f is now a point in the Dalitz Plot



- Again, for $|x|, |y| \ll 1$, decay rate R_{WS} is :

CF decay from **amplitude analysis of RS Dalitz plot**

DCS **DCS-Mixing interference** **Mixing**

$$\frac{R_{ws}}{e^{-\Gamma t}} \propto |A_{\bar{f}}|^2 + (y\cos\delta - x\sin\delta)|A_{\bar{f}}||\bar{A}_{\bar{f}}|(\Gamma t) + \frac{x^2+y^2}{4}|\bar{A}_{\bar{f}}|^2(\Gamma t)^2$$

BUT $\delta = \mathrm{Arg}\{A_{\bar{f}}/\bar{A}_{\bar{f}}\} = \delta_{K\pi\pi} + \delta_f$

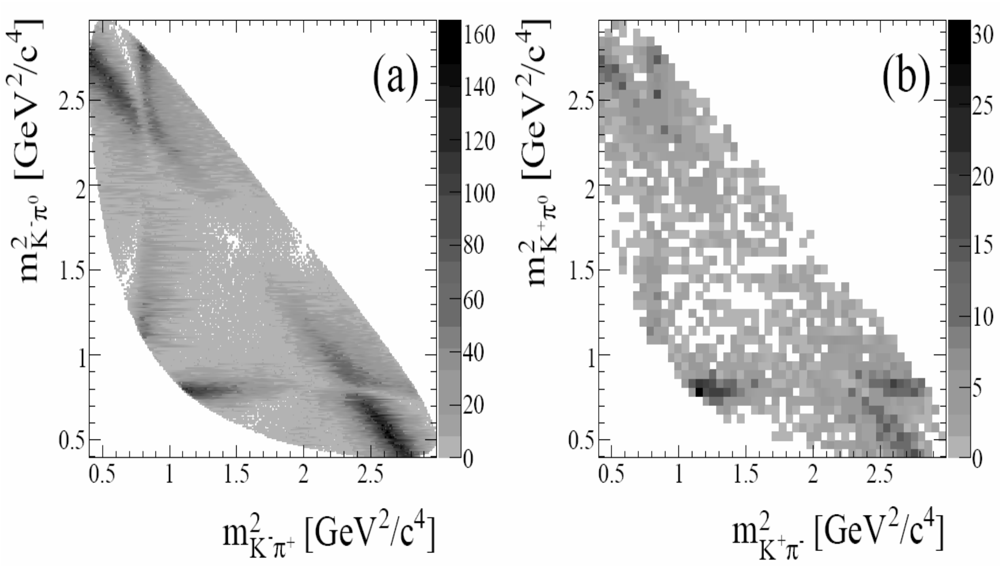
Unknown constant

Depends on position in Dalitz Plot
Determined by **t-dependent amplitude analysis of WS Dalitz plot**

- So the interference term permits measurement of

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

Evidence for Mixing - (*WS*) Tagged $D^0 \rightarrow K^+\pi^-\pi^0$



- Find *CF* amplitude $\bar{\mathcal{A}}_{\bar{f}}$ from time-integrated fit to RS Dalitz plot
  - isobar model expansion
- Use this in time-dependent amplitude analysis of WS plot → $\mathcal{A}_{\bar{f}}$ and mixing parameters.

$$x'' = [\ 2.61^{+0.57}_{-0.68}(\text{stat.}) \pm 0.39(\text{syst.})]\%$$
$$y'' = [-0.06^{+0.55}_{-0.64}(\text{stat.}) \pm 0.34(\text{syst.})]\%$$

Probability for no mixing 0.1% (3.2σ)

$|x''| > |y''|$

No evidence for *CPV*

D^0 only:

$$x''_+ = [\ 2.53^{+0.54}_{-0.63}(\text{stat.}) \pm 0.39(\text{syst.})]\%$$
$$y''_+ = [-0.05^{+0.63}_{-0.67}(\text{stat.}) \pm 0.50(\text{syst.})]\%$$

$\overline{D}^0$ only:

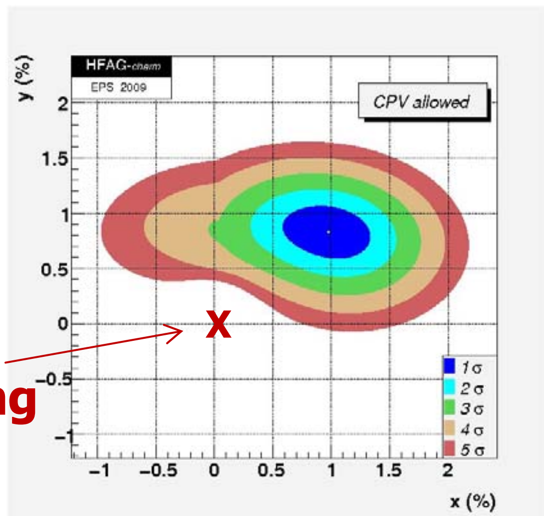
$$x''_- = [\ 3.55^{+0.73}_{-0.83}(\text{stat.}) \pm 0.65(\text{syst.})]\%$$
$$y''_- = [-0.54^{+0.40}_{-1.16}(\text{stat.}) \pm 0.41(\text{syst.})]\%$$

Brian Meadows
University of Cincinnati

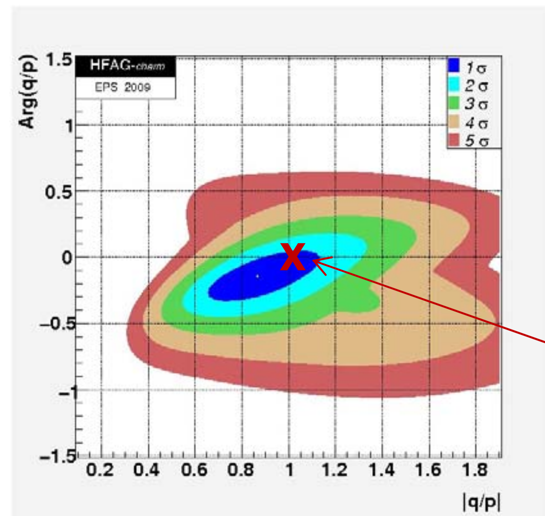
HFAG Mixing Summary

The HFAG collaboration have combined a wide range of these and other "mixing observables" to extract the underlying mixing parameters and their χ^2 contours:

No Mixing



A. Schwartz *et al.*
arXiv:0803.0082
(updated EPS 2009)



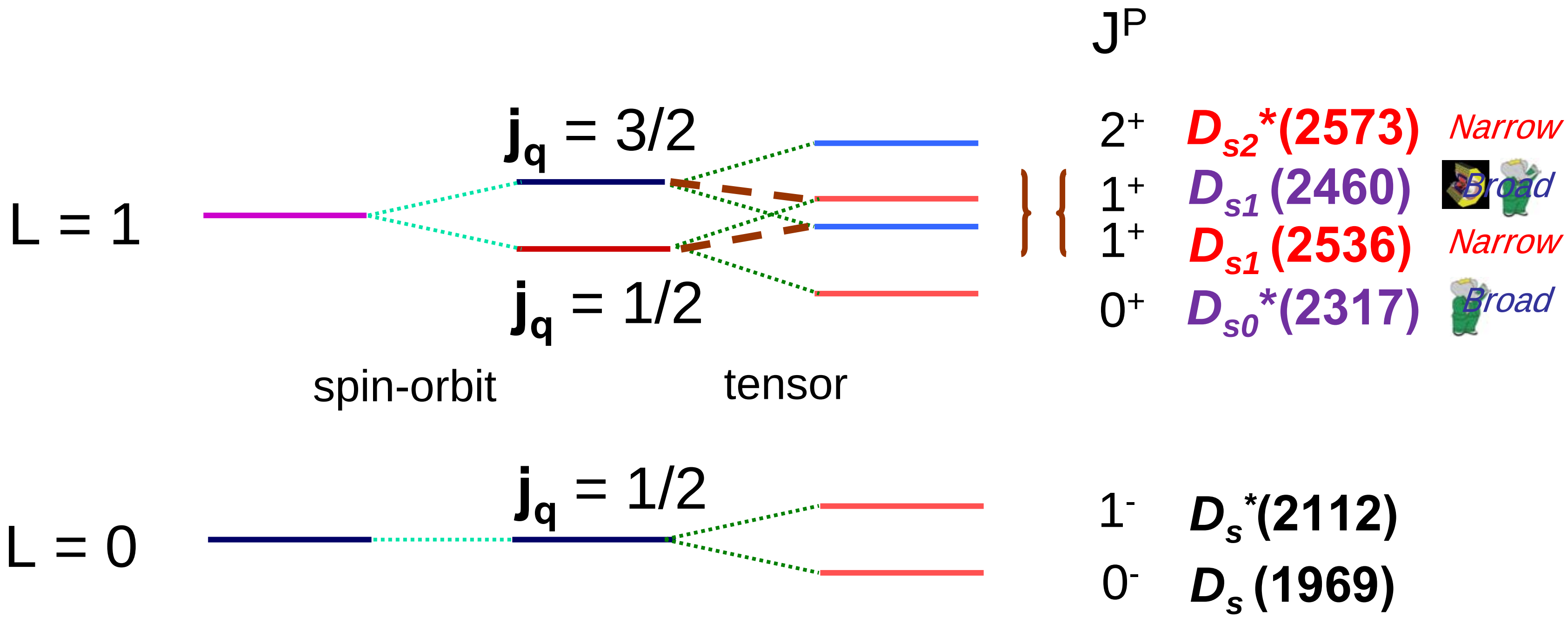
No CPV

x	$=$	$(0.98^{+0.24}_{-0.26})$	$\%$	y	$=$	(0.83 ± 0.16)	$\%$
$\lvert q/p \rvert$	$=$	$0.87^{+0.17}_{-0.15}$		ϕ	$=$	$(-8.5^{+7.4}_{-7.0})$	degrees
$\delta_{K\pi}$	$=$	$(26.4^{+9.6}_{-9.9})$	degrees	$\delta_{K\pi\pi}$	$=$	$(14.8^{+20.2}_{-22.1})$	degrees
R_D	$=$	(0.337 ± 0.009)	$\%$	A_D	$=$	(-2.2 ± 2.4)	$\%$

Charm-Strange Spectroscopy

Brian Meadows
UNIVERSITY OF Cincinnati

Lowest D_s States
("Heavy-Light" System)

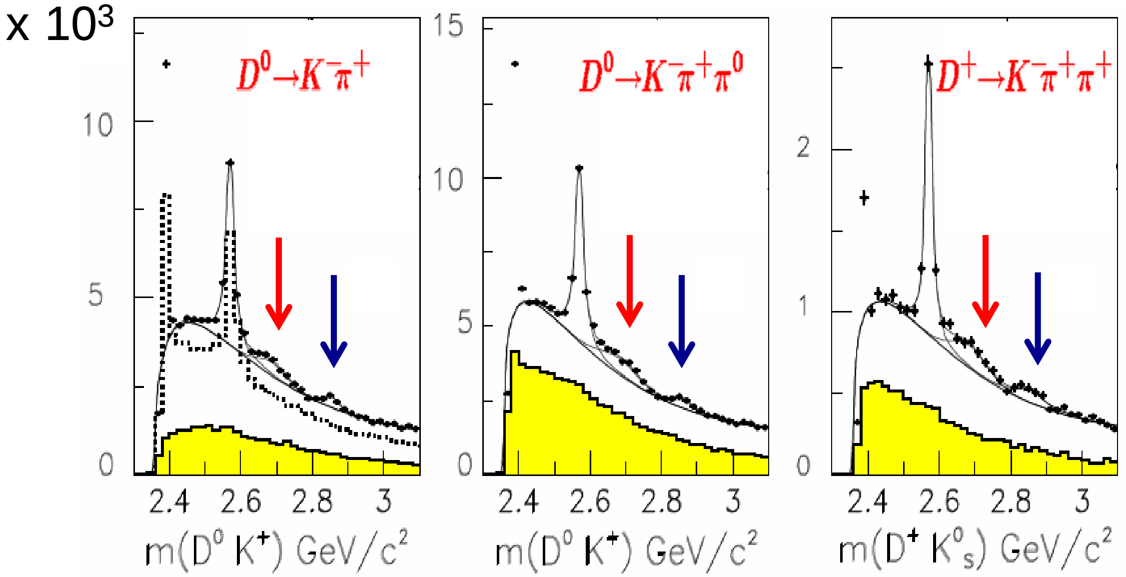


- Two "broad states" were found by BaBar and CLEO
- They were unexpectedly *narrow* AND *below K emission* threshold.
  - Much theoretical discussion still about this
  - → **Need more spectroscopic data to constrain the models**

Higher D_s States in DK System

(First reported by Babar at Charm06 here!)

Phys.Rev.Lett.97:222001,2006 – 240 fb^{-1}



- D meson invariant mass sidebands in yellow
- Narrow, low mass peaks due to $D_{s1}(2536)$ and $D_{s2}(2573)$

New peaks:

$$M_0 = [2688 \pm 4(\mathrm{stat.}) \pm 3(\mathrm{syst.})]\ \mathrm{MeV/c^2}$$
$$\Gamma_0 = [112 \pm 7(\mathrm{stat.}) \pm 36(\mathrm{syst.})]\ \mathrm{MeV/c^2}$$

> 6 σ

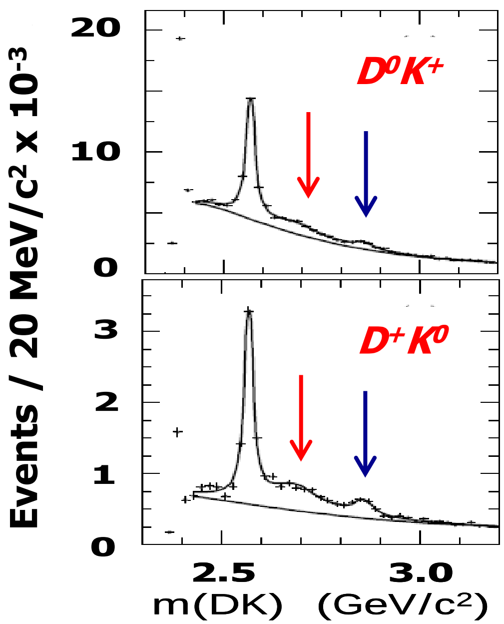
$$M_0 = [2856.6 \pm 1.5(\mathrm{stat.}) \pm 5.0(\mathrm{syst.})]\ \mathrm{MeV/c^2}$$
$$\Gamma_0 = [48 \pm 7(\mathrm{stat.}) \pm 10(\mathrm{syst.})]\ \mathrm{MeV/c^2}$$

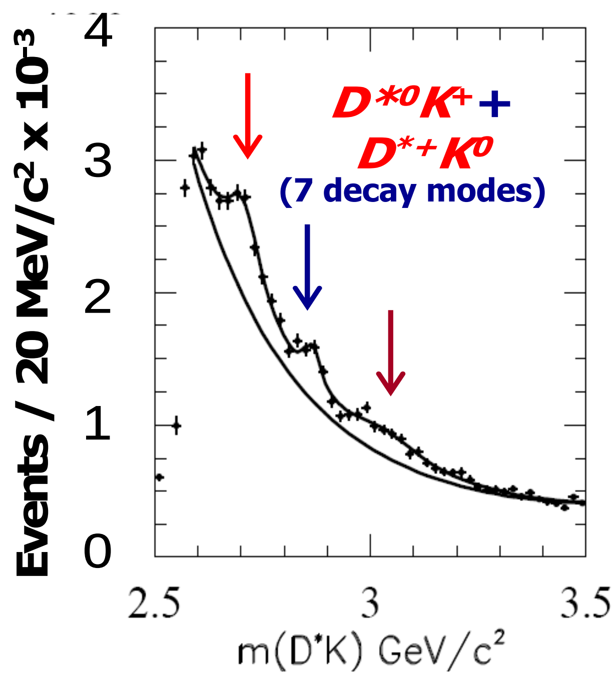
Also seen in B decay by BELLE with $J^P = 1^-$

D_s States in D^*K System

New study of whole BaBar sample of *DK* and *D*K* systems
States are seen in both charges and four *D* decay modes

NEW and PRELIMINARY
arXiv:0908.080 – 470 fb^{-1}





- Simultaneous fit to D^*K and *DK* spectra
  - Remove *D* sidebands
  - *D*K* background same shape as MC
- Strong hint of new signal only in D^*K near 3.0 GeV/c^2

PRELIMINARY

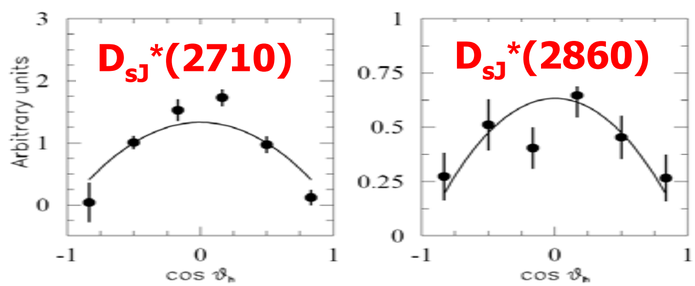
State	M_0 (MeV/c^2)	Γ_0 (MeV/c^2)
$D^*_{s1}(2710)^+$	$2710 \pm 2(\text{stat.})^{+12}_{-7}(\text{syst.})$	$149 \pm 7(\text{stat.})^{+39}_{-52}(\text{syst.})$
$D^*_{sJ}(2860)^+$	$2862 \pm 2(\text{stat.})\ ^{+5}_{-2}(\text{syst.})$	$48 \pm 3(\text{stat.}) \pm 6(\text{syst.})$
$D_{sJ}(3040)^+$	$3044 \pm 8(\text{stat.})^{+30}_{-5}(\text{syst.})$	$239 \pm 35(\text{stat.})^{+46}_{-42}(\text{syst.})$

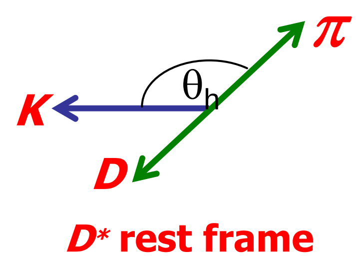
New State →

Brian Meadows
UNIVERSITY OF Cincinnati

Assignments for $D_{sJ}^{*}(2710)$ & $D_{sJ}^{*}(2860)$?

- Decay to $D^{*}K$ eliminates $J^{P}=0^{+}$
- Decay to BOTH modes hints that these 2 states have *natural parity*:
- Helicity angle distribution is also consistent with this





- Branching ratios may favour radial excitation $2^{3}S_{1}$ over orbital $1^{3}D_{1}$:

$$\frac{\mathcal{B}(D_{s1}^{*}(2710)^{+}\to D^{*}K)}{\mathcal{B}(D_{s1}^{*}(2710)^{+}\to DK)}=0.91\pm0.13_{\text{stat}}\pm0.12_{\text{syst}}$$

$$\frac{\mathcal{B}(D_{sJ}^{*}(2860)^{+}\to D^{*}K)}{\mathcal{B}(D_{sJ}^{*}(2860)^{+}\to DK)}=1.10\pm0.15_{\text{stat}}\pm0.19_{\text{syst}}$$

State	J^P	Level	$\mathcal{B}(D^*K)\div\mathcal{B}(DK)$	Ref.
$D_s(2710)$	1^-	1^3D_1	0.043 ± 0.002	[1]
"	1^-	2^3S_1	0.91 ± 0.04	[1]
"	1^-	2^3S_1	3.55	[2]
$D_s(2860)$	3^-	-	0.39	[3]

[1] P. Colangelo, et al., Phys. Rev. D77, 014012 (2008)
[2] F. Close, et al., Phys. Lett. B647, 159 (2007)
[3] P. Colangelo, et al., Phys. Lett. B642, 48 (2006)

Summary

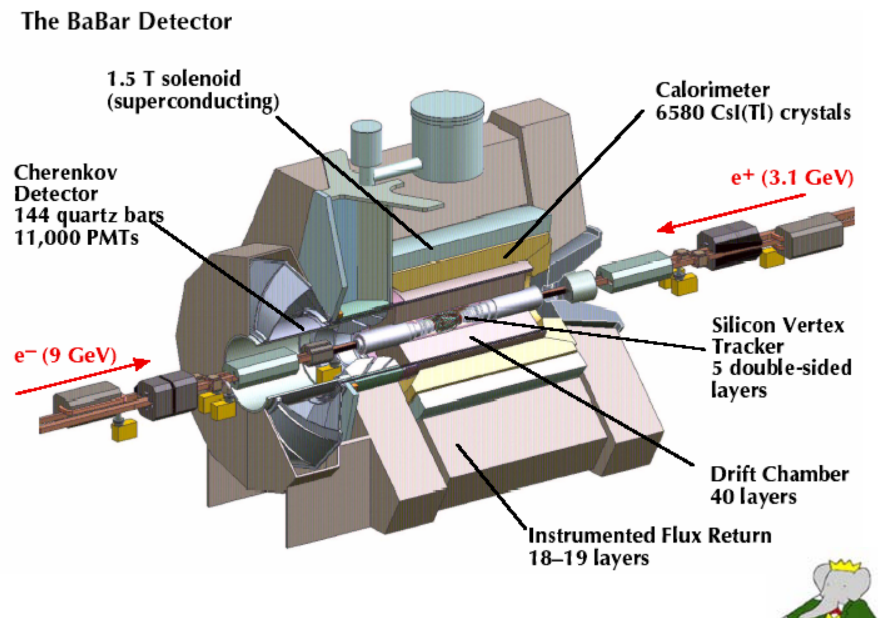
- Babar sees evidence for mixing in the D^0 meson system in four situations.
  - Two measurements of y_{CP} have a combined significance of 4.1¾ and agree well with one another and with other recent measurements.
  - Measurements of x and y, rotated by unknown strong phases, have been made for "WS" hadronic decays to $K^+\pi^-$ and to $K^+\pi^-\pi^0$.
  - There is no evidence for CPV in mixing.
- The most precise B factory mixing measurements are yet to come, as are results from BES III and LHCb.
  - Measurements of strong phases from BES III $\psi(3770)$ data are eagerly anticipated.
- A new D_{sJ} state has been observed in the D^*K system.

  M=3044± 8(stat.)$^{+30}_{-5}$(syst.) MeV/c^2 ; Γ=239 ± 35(stat.)$^{+46}_{-42}$(syst.) MeV/c^2.

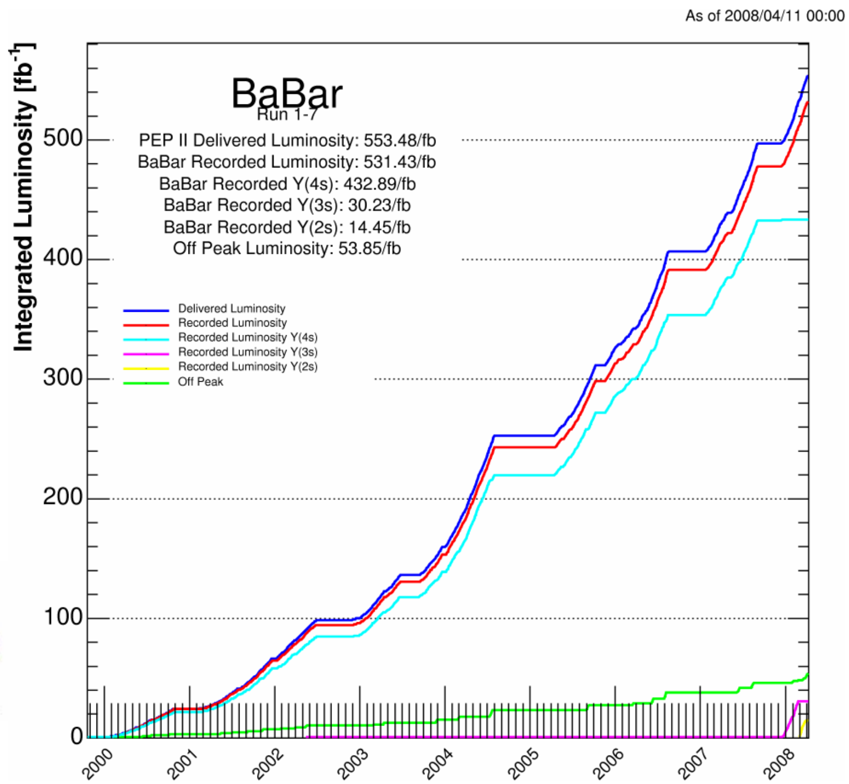
- $D_{s1}^*(2710)$ and $D_{sJ}^*(2860)$ are observed in both DK and D^*K systems with roughly equal branching fractions.
  - Requires natural parity AND $J^P=0^+$ is ruled out
  - Branching ratios may favor radial excitation 2^3S_1 assignment for $D_{s1}(2710)$
- Again, more information is on the way from BES III

Backup Here

BaBar



Peak luminosity 1.2×10^{34} cm^{-2}s^{-1}
Integrated luminosity 531 fb^{-1}



- Main purpose: Study CP violation in asymmetric $e^+e^- \to \Upsilon(4S) \to B\bar{B}$
- Experiment far exceeded the design goals
  - Luminosity order of magnitude larger
  - Many more measurements and discoveries.

Mixing in the D System

- Mixing (and CPV) in the D^0 system were discussed *over 30 years ago.*
  A. Pais and S.B. Treiman, Phys. Rev. **D12**, 2744 (1975).

- BUT evidence for mixing was only recently found

BABAR:	PRL 98 211802 (2007)	$D^0 \to K^+\pi^-$	decay time analysis	3.9σ
BELLE:	PRL 98 211803 (2007)	$D^0 \to K^+K^-, \pi^+\pi^- vs. K^+\pi^-$	lifetime difference	3.2σ
BELLE:	PRL 99 131803 (2007)	$D^0 \to K_S^0\pi^+\pi^-$	t-dep. Dalitz plot	2.2σ
CDF:	PRL 100 121802 (2008)	$D^0 \to K^+\pi^-$	decay time analysis	3.8σ
BABAR:	PRD 78:011105 (2008)	$D^0 \to K^+K^-, \pi^+\pi^-$ vs. $K^+\pi^-$	lifetime difference	3σ
BABAR:	arXiv:0807.4544 (2008)	$D^0 \to K^+\pi^-\pi^0$	t-dep. Dalitz plot	3.2σ
BABAR:	arXiv:0908.0761 (2009)	$D^0 \to K^+K^-$ vs. $K^+\pi^-$ (untagged)	lifetime difference	3.3σ
HFAG average:	arXiv:0803.0082 (updated)			$> 10\sigma$

- Of all neutral mesons, the D^0 system exhibits the least mixing

System (Year):	*x:*	*y:*
K^0 (1956)	0.95	0.99
B_d (1987)	0.78	≈0
B_s (2006)	26	0.15
D^0 (2007)	0.0098	0.0075

Recent Mixing and CPV Measurements

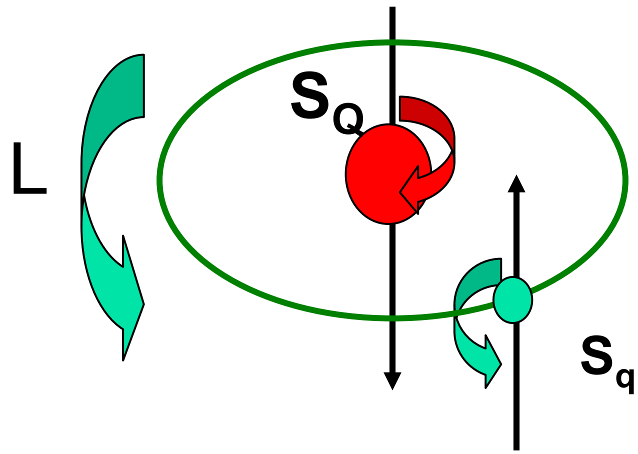
- Mixing measurements
  - $D^0 \to K^+\pi^-$
  - $D^0 \to K^+K^-, \pi^+\pi^-$
  - $D^0 \to K^{(*)-}l^+\nu$
  - $D^0 \to K^+\pi^-\pi^0$
  - $D^0 \to K_s\pi^+\pi^-$
  - $D^0 \to K_sK^+K^-$
  - Quantum Corr.
  - $D^0 \to K^+K^-$

New Result

Mixing Observed

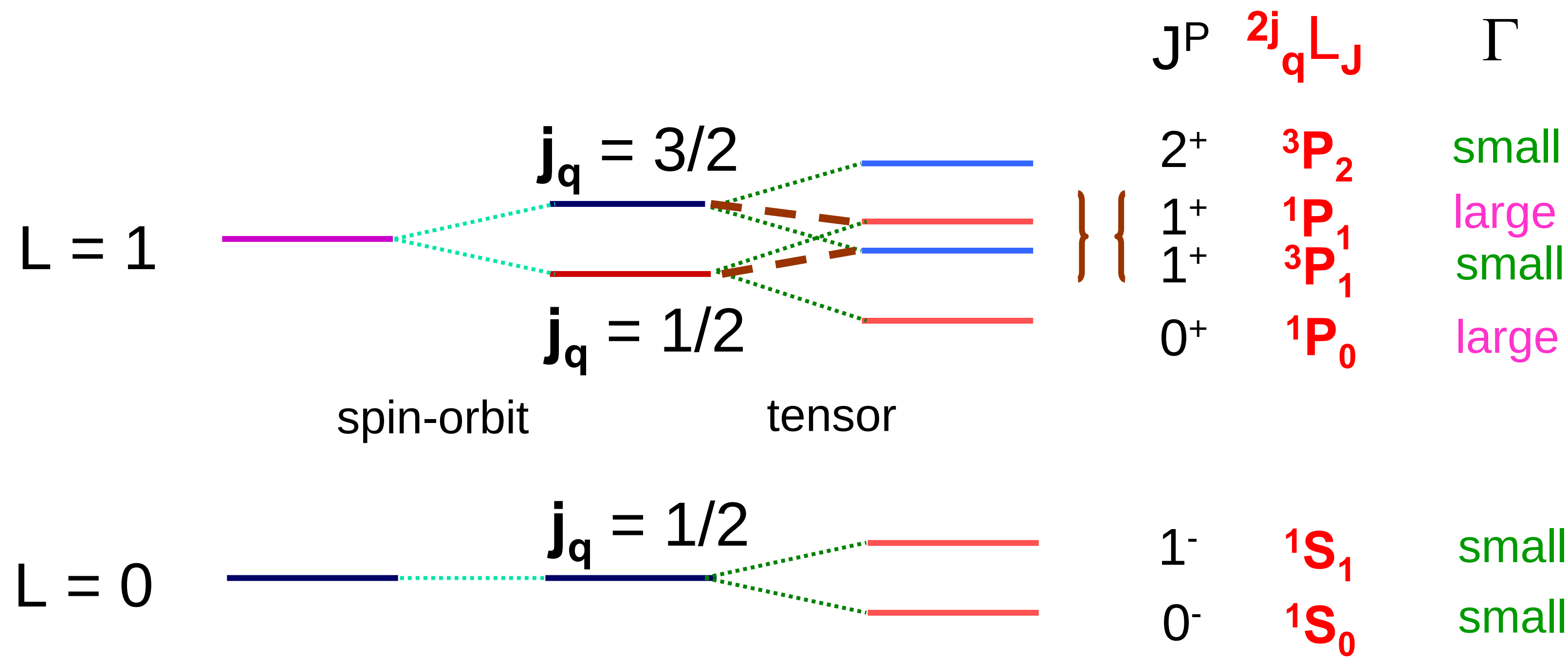
- Search for time integrated *CP* violation (*CPV*)
  - $D^0 \to K^+K^-, \pi^+\pi^-$
  - $D^0 \to \pi^+\pi^-\pi^0, K^+K^-\pi^0$

Heavy-Light Systems are Like the Hydrogen Atom

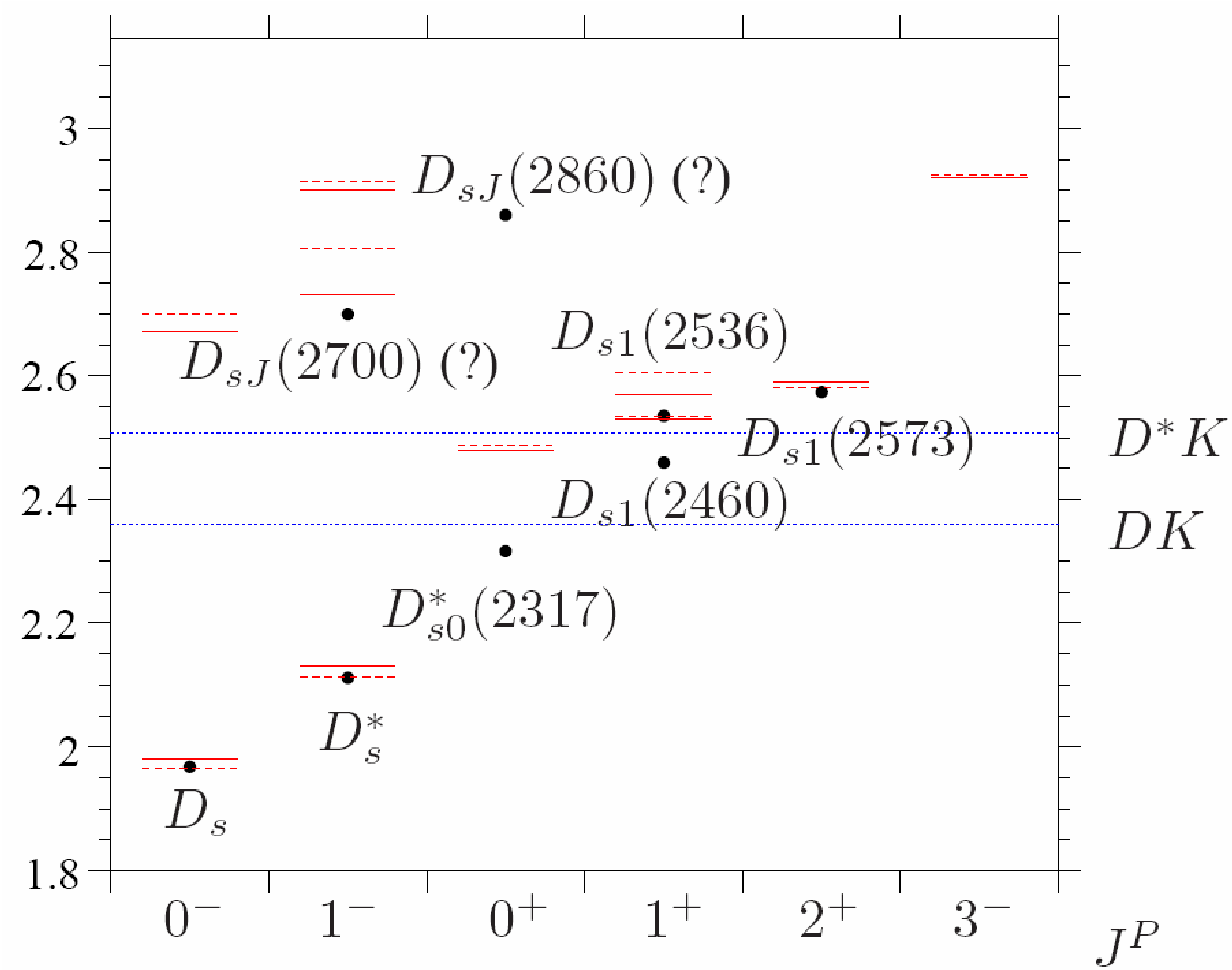


- When $\mathbf{m}_Q$ **! 1**, $\mathbf{s}_Q$ is fixed.
- So $\mathbf{j}_q = \mathbf{L} \otimes \mathbf{s}_q$ is separately conserved
- Total spin $\mathbf{J} = \mathbf{j}_q \otimes \mathbf{s}_Q$

Heavy-Light Systems (2)



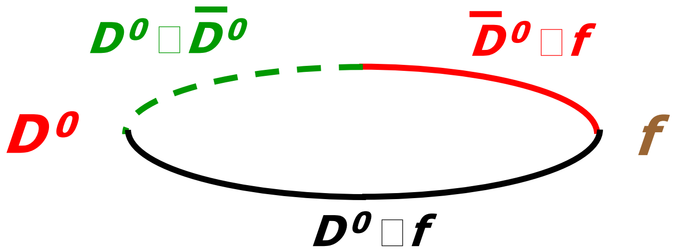
- Narrow states are easy to find.
- Two wide states are harder.
- Since charm quark is not infinitely heavy, some $\mathbf{j_q}$=1/2, 3/2 mixing can occur for the $\mathbf{J^P}$=1^+ states.



3
2.8
2.6
2.4
2.2
2
1.8
$D_{sJ}(2860)$ (?)
$D_{sJ}(2700)$ (?)
$D_{s1}(2536)$
$D_{s1}(2573)$
$D_{s1}(2460)$
$D^*_{s0}(2317)$
D^*_s
D_s
D^*K
DK
0^- 1^- 0^+ 1^+ 2^+ 3^-
J^P

Decays of Neutral *D* Mesons

- When final state *f* is accessible to both D^0 and $\bar{D}^0$, interference between mixing and direct decay will occur



$$
\begin{aligned}
\mathcal{A}_f &= < f|H|D^0 > \quad (D^0 \to f) \\
\bar{\mathcal{A}}_f &= < f|H|\bar{D}^0 > \quad (\bar{D}^0 \to f) \\
\mathcal{A}_{\bar{f}} &= < \bar{f}|H|D^0 > \quad (D^0 \to \bar{f}) \\
\bar{\mathcal{A}}_{\bar{f}} &= < \bar{f}|H|\bar{D}^0 > \quad (\bar{D}^0 \to \bar{f})
\end{aligned}
$$

Which leads to a time-dependence for decay

$$
\begin{aligned}
\mathcal{A}_f(t) &= \mathcal{A}_f e^{-(\Gamma+iM)t} \times [\cosh((y+ix)\Gamma t/2) + \lambda_f \sinh((y+ix)\Gamma t/2)] \\
\bar{\mathcal{A}}_{\bar{f}}(t) &= \bar{\mathcal{A}}_{\bar{f}} e^{-(\Gamma+iM)t} \times [\bar{\lambda}_{\bar{f}} \sinh((y+ix)\Gamma t/2) + \cosh((y+ix)\Gamma t/2)]
\end{aligned}
$$

$\lambda_f = \frac{q\bar{\mathcal{A}}_f}{p\mathcal{A}_f}$; $\bar{\lambda}_{\bar{f}} = \frac{p\mathcal{A}_{\bar{f}}}{q\bar{\mathcal{A}}_{\bar{f}}}$; { carry strong phase δ between the decays $D^0 \to f$ and $\bar{D}^0 \to f$

- The interference makes the mixing parameters measurable

BUT, for this, it is essential to know the strong phase δ

Measurement of y_{CP} in $D^0 \to K^0_S K^+ K^-$ decays

Belle

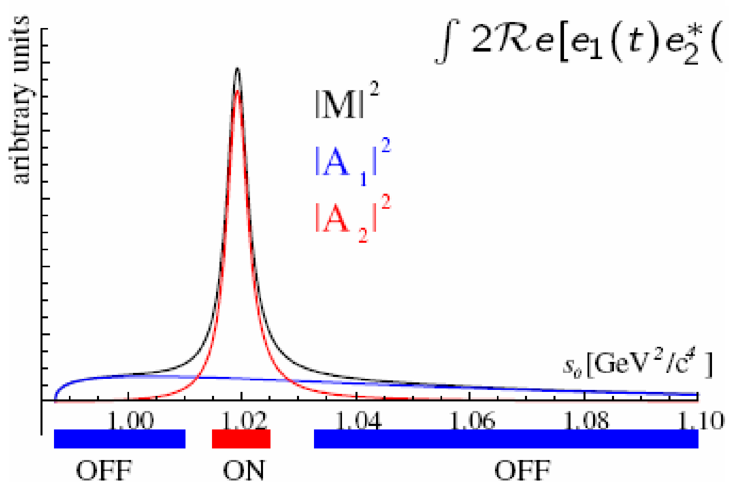
Time dependent decay rate: $|\mathcal{M}(s_0, s_+, t)|^2 =$

$$|e_1(t)|^2|\mathcal{A}_1(s_0, s_+)|^2 + |e_2(t)|^2|\mathcal{A}_2(s_0, s_+)|^2 + 2\mathcal{R}e[e_1(t)e_2^*(t)\mathcal{A}_1(s_0, s_+)\mathcal{A}_2^*(s_0, s_+)]$$

$$\mathcal{A}_1 = \sum \ CP = +1 \text{ and flavor eigenstates; } |e_1(t)|^2 = e^{-\frac{t(1+y)}{\tau}}$$

$$\mathcal{A}_2 = \sum \ CP = -1 \text{ and flavor eigenstates; } |e_2(t)|^2 = e^{-\frac{t(1-y)}{\tau}}$$

$$\int 2\mathcal{R}e[e_1(t)e_2^*(t)\mathcal{A}_1(s_0, s_+)\mathcal{A}_2^*(s_0, s_+)]ds_+ = 0$$



$[1.033, 1.100]$ GeV$/c^2$ OFF

$m(K^+K^-) \in [2m_{K^\pm}, 1.010]$ GeV$/c^2$ ON

$[2m_{K^\pm}, 1.010]$ GeV$/c^2$ OFF

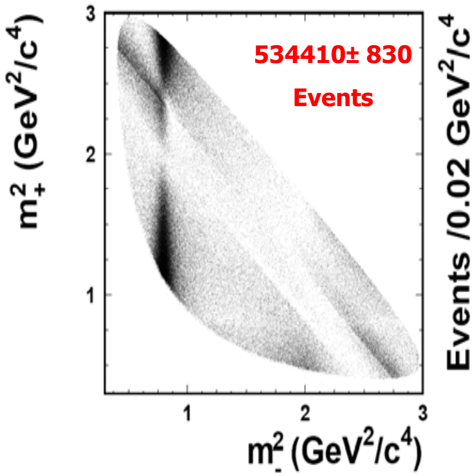
Compare lifetimes of D^0 candidates measured in different $m(K^+K^-)$ regions:

- $\tau_{ON/OFF} = f_1^{ON/OFF}\frac{\tau}{1+y} + (1 - f_1^{ON/OFF})\frac{\tau}{1-y}$
- $f_1^{ON/OFF} = \frac{\int_{ON/OFF}|\mathcal{A}_1|^2}{\int_{ON/OFF}|\mathcal{A}_1|^2+|\mathcal{A}_2|^2}$
- $\Delta_\tau = \frac{\tau_{OFF}-\tau_{ON}}{\tau_{OFF}+\tau_{ON}} = y_{CP}\frac{f_1^{ON}-f_1^{OFF}}{1+y_{CP}(1-f_1^{ON}-f_1^{OFF})}$

Time-Dependent Amplitude Analysis of $D^0 \to K_s\pi^+\pi^-$

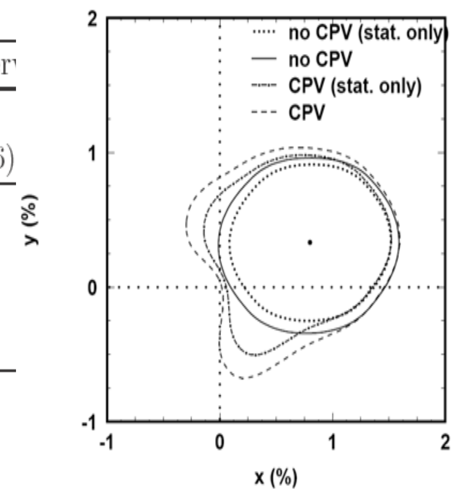
PRL 98:211803 (2007) 540 fb^{-1} | PRD 72:012001 (2005) 9 fb^{-1}

- Here, it is possible to measure *x, y,* |p/q| and arg {p/q} the D^0-$\bar{D}^0$ strong phase δ is fixed by presence of *CP* eigenstates in *f*
  - Strong phases of all points relative to *CP* eigenstates measured by time-dependent amplitude analysis of the *DP*.



Fit case	Parameter	Fit result	95% C.L. inter
No CPV	$x(\%)$	$0.80 \pm 0.29^{+0.09}_{-0.07}{}^{+0.10}_{-0.14}$	$(0.0, 1.6)$
	$y(\%)$	$0.33 \pm 0.24^{+0.08}_{-0.12}{}^{+0.06}_{-0.08}$	$(-0.34, 0.96)$
CPV	$x(\%)$	$0.81 \pm 0.30^{+0.10}_{-0.07}{}^{+0.09}_{-0.16}$	$\lvert x\rvert < 1.6$
	$y(\%)$	$0.37 \pm 0.25^{+0.07}_{-0.13}{}^{+0.07}_{-0.08}$	$\lvert y\rvert < 1.04$
	$\lvert q/p\rvert$	$0.86^{+0.30}_{-0.29}{}^{+0.06}_{-0.03} \pm 0.08$	-
	$\arg(q/p)(°)$	$-14^{+16}_{-18}{}^{+5}_{-3}{}^{+2}_{-4}$	-

NOTE – this is smaller than y_{CP}



Mixing only at 2.4 σ level.
Hint that x > y ??

Previous result from CLEO (9 fb^{-1})
$(-4.7 < x < 8.6)\%$
$(-6.1 < y < 3.5)\%$ at 95% CL.