CPV in Charm Mixing
Belle, BaBar and Tevatron

Brian Meadows

Representing the BaBar Collaboration

CKM 2010
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Outline

- Mixing (particle - anti-particle oscillations).
- Brief review of evidence for mixing
- A New result
- Prospects for observing *CPV* in mixing

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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

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

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

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:

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

CPV signalled by $p \neq q$

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

Define decay amplitudes:

$$\begin{aligned}&\mathcal{A}_f(D^0\to f)\\ &\bar{\mathcal{A}}_f(\bar{D}^0\to f)\end{aligned}$$

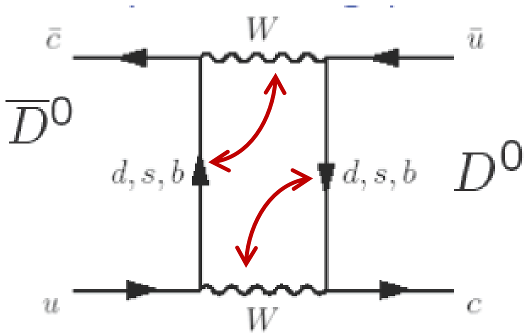
$$\lambda_f = \frac{q\bar{\mathcal{A}}_f}{p\mathcal{A}_f} \propto e^{i(\delta_f+\phi_f+\phi_M)}$$

strong   Weak decay   mixing

Mixing in Standard Model is Very Small

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

ΔC=2 (short-range)
(contributes mostly to *x*)



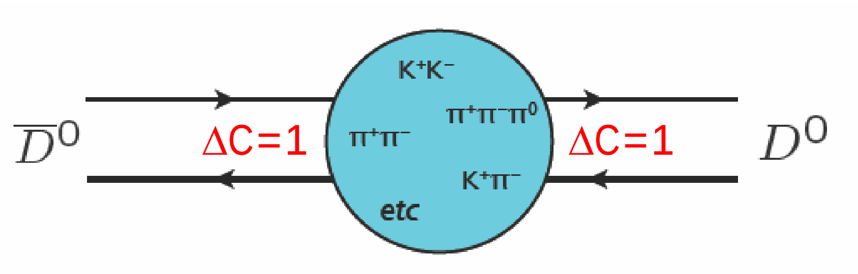
Down-type quarks in loop:

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|

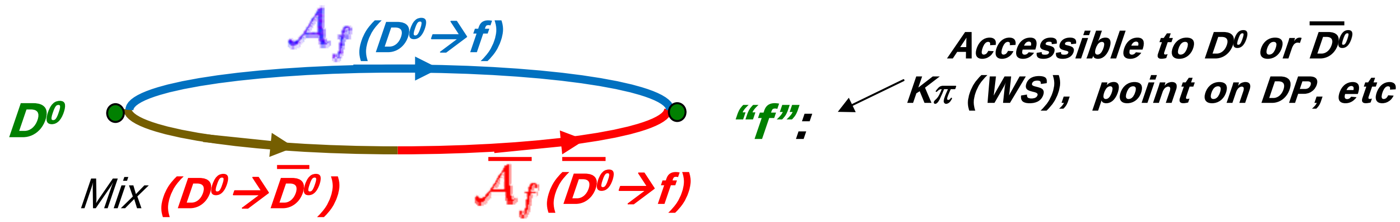
Recent predictions: $|x| \leq 1\%, \quad |y| \leq 1\%$

(consistent with current observation)

x_D, y_D at 1% consistent with SM, BUT
CPV at 10^{-3} levels would be signal for NP

Mixing Measurements

- All current measurements, so far, exploit interference between direct decays $D^0 \rightarrow f$ and decays through mixing:



- Time-dependence (no CPV, to 2nd order in x and y)

$$\frac{e^{\Gamma t}}{|\mathcal{A}_f|^2}\frac{dN}{dt} \propto 1 + \lambda_f(y_D\cos\delta_f - x_D\sin\delta_f)\Gamma t + \frac{|\lambda_f|^2}{4}(x_D^2 + y_D^2)(\Gamma t)^2$$

Direct decay — Interference — Decay through Mixing

- Interference term is approximately linear in small quantities x_D, y_D

  BUT λ_i *and* δ_i *are, generally, unknown*

- So can usually only measure the rotated quantities

  $x'_D = x_D \cos\delta_i + y_D \sin\delta_i$ D Q G $y'_D = y_D \cos\delta_i - x_D \sin\delta_i$

  unless measurements of δ_i from charm threshold are available.

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Wrong Sign (WS) Decays $D^0 \rightarrow K^+\pi^-$

- The *WS* decay rate R_{WS} is:

$$R_{WS} = e^{-\Gamma t}|\mathcal{A}_{\bar{f}}|^2 \left[1 \;+\; \lambda_{\bar{f}} y'_D(\Gamma t) \;+\; \frac{|\lambda_{\bar{f}}|^2}{4}(x'^2_D + y'^2_D)(\Gamma t)^2 \right]$$

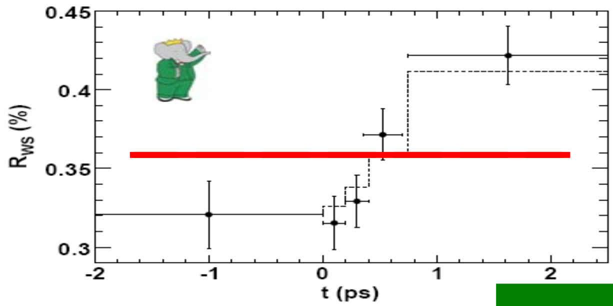
Direct decay — Interference — Decay through Mixing

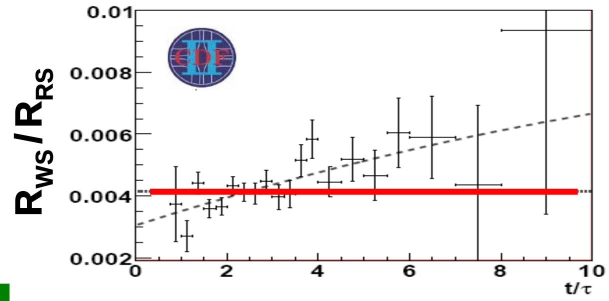
- Since $|\lambda_{\bar{f}}|>>1$, all three terms are comparable

- For "right-sign" (*RS*) decays $D^0 \rightarrow K^-\pi^+$ though, $|\lambda_f|<<1$, so 2nd two terms are negligible and R_{RS} is approximately exponential. $R_{RS} \approx e^{-\Gamma t}|\mathcal{A}_f|^2$

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

Mixing seen by Babar and CDF in time-dependence of the R_{WS}/R_{RS} ratio

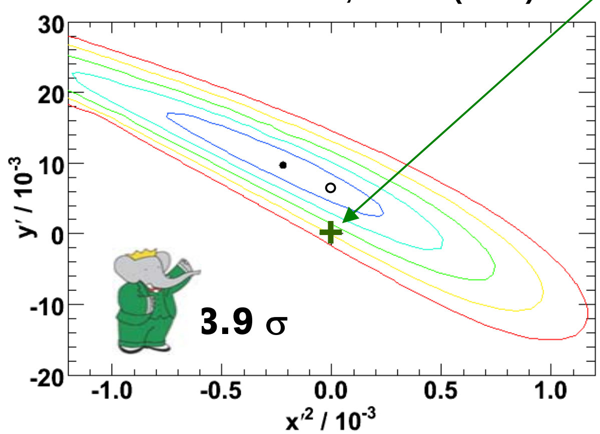




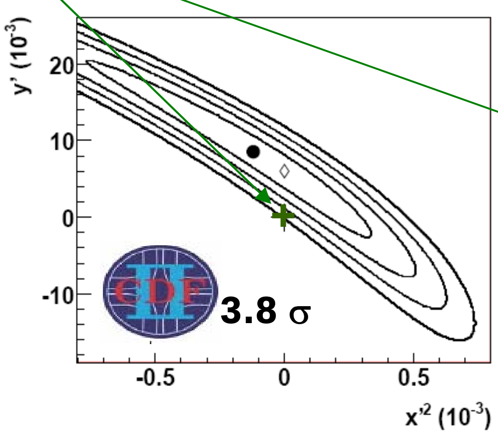
No Mixing

No Mixing

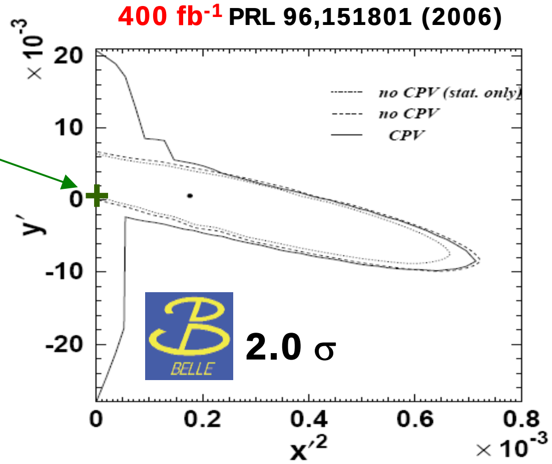
384 fb^{-1} PRL 98,211802 (2007)



1.5 fb^{-1} PRL 100,121802 (2008)



400 fb^{-1} PRL 96,151801 (2006)



Belle result was the most sensitive, BUT evidence for mixing not significant !

Mixing and CPV Parameters for $D^0 \to K^+\pi^-$

Fit type	Parameter	Fit results/10^{-3}		
		BaBar[a]	CDF[b]	Belle[c]
No CPV or mixing	R_D	3.53 ± 0.09	–	3.77 ± 0.01
	R_D	3.03 ± 0.19	3.04 ± 0.55	3.64 ± 0.17
No CPV	x'^2	–0.22 ± 0.37	–0.12 ± 0.35	$0.18^{+0.21}_{-0.23}$
	y'	9.7 ± 5.4	8.5 ± 7.6	$0.6^{+4.0}_{-3.9}$
	R_D	3.03 ± 0.19	–	–
	a_D	–21 ± 54	–	23 ± 47
	a_M	–	–	670 ± 1200
CPV allowed	x'^{2+}	–0.24 ± 0.52	–	<0.72
	x'^{2-}	–0.20 ± 0.50	–	–
	y'^+	9.8 ± 7.8	–	$-28 < y' < 21$
	y'^-	9.6 ± 7.5	–	–

Same for D^0 and $\overline{D}^0$

Consistent with zero

$$R_D = \lambda_f^2 \quad \text{(Ratio of DCS to CF decays)}$$
$$a_D = (R_D - R_{\bar{D}})/(R_D + R_{\bar{D}})$$

$$R_M = (x_D^2 + y_D^2)/2$$
$$a_M = (R_M - R_{\bar{M}})/(R_M + R_{\bar{M}})$$

Lifetime Ratio 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

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

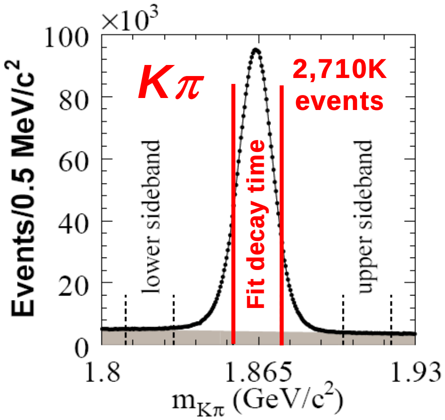
A_M: $|q/p|^2 - 1$

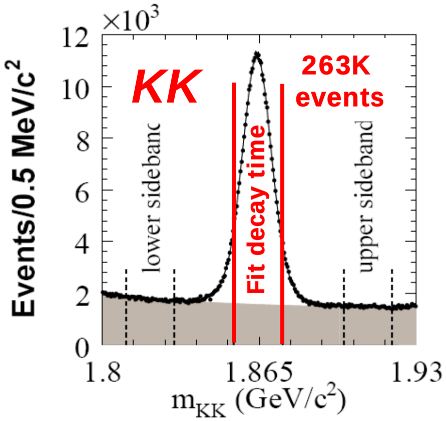
PRD 69,114021 (Falk, Grossman, Ligeti, Nir & Petrov)

Recent result

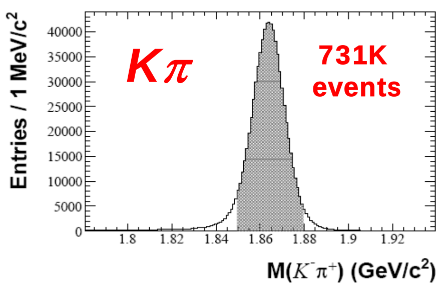
Lifetime Ratio (Untagged D^0's)

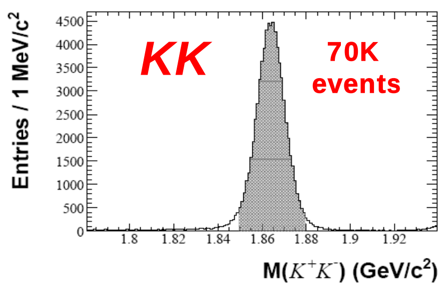
Phys.Rev.D80:071103,2009 – 384 fb^{-1}





- 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



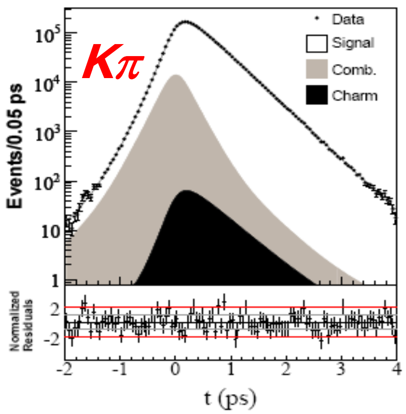


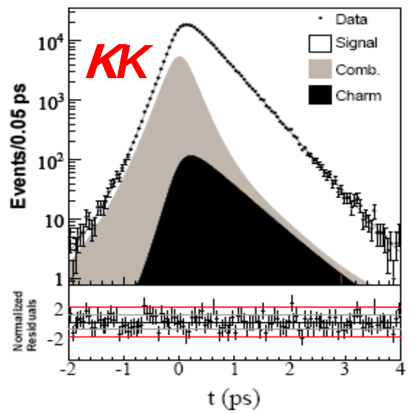
Tagged Sample – 384 fb^{-1}

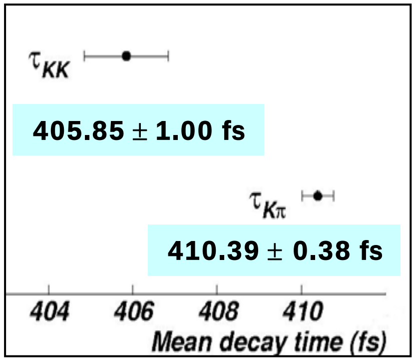
(for comparison)

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

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







- 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%

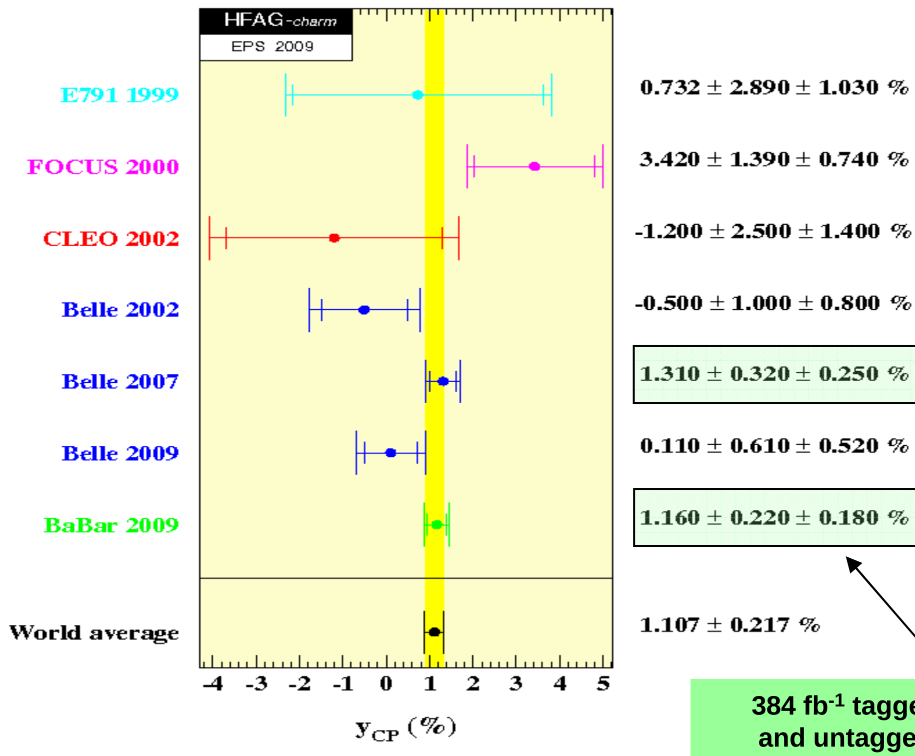
Results:

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)



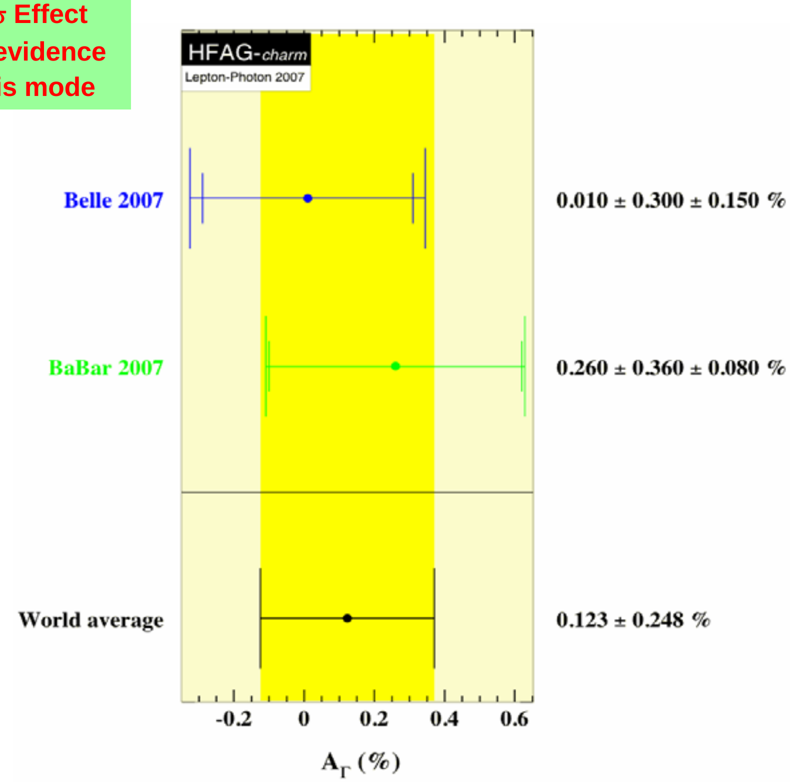
540 fb^{-1} tagged

3.2 σ Effect
First evidence
In this mode

384 fb^{-1} tagged and untagged Combined

4.1 σ Effect

Supercedes earlier BaBar results.



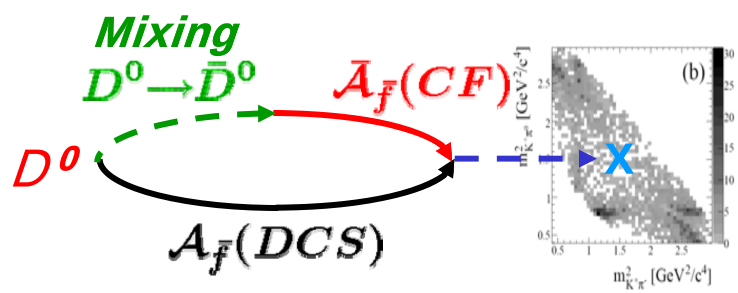
$y_{CP} = (1.107 \pm 0.217)\%$

$A_\Gamma = -A_{\sim} = (0.123 \pm 0.248)\%$

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

Phys.Rev.Lett.103:211801,2009 – 384 fb^{-1}

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



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

$$R_{ws} = e^{-\Gamma t}|A_{\bar{f}}|^2 \left[1 + \lambda_{\bar{f}}(y\cos\delta - x\sin\delta)|\lambda_{\bar{f}}|(\Gamma t) + \frac{x^2+y^2}{4}|\lambda_{\bar{f}}|^2(\Gamma t)^2\right]$$

Models for WS ($A_{\bar{f}}$) and RS ($\bar{A}_{\bar{f}}$) decay amplitudes define $|\lambda_{\bar{f}}|$ and $\delta_{\bar{f}}$

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

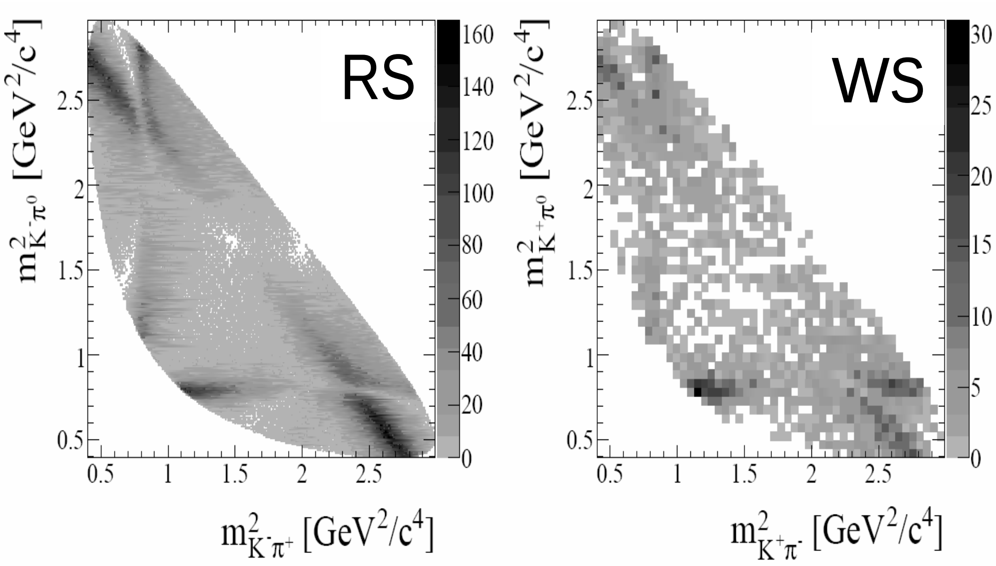
Unknown constant

Comes from the model.
Depends on position in 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 $\bar{A}_{\bar{f}}$ from time-integrated fit to RS Dalitz plot
  - isobar model expansion
- Use this in time-dependent amplitude analysis of WS plot $\rightarrow A_{\bar{f}}$ and mixing parameters.

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

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

Significance of mixing signal 3.2σ

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:

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

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

No evidence for *CPV*

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Amplitude Analysis of $D^0(t) \rightarrow K_S h^+ h^-$

- Similar to $D^0 \rightarrow K^+\pi^-\pi^0$ BUT final states are self-conjugate (sum of odd and even CP-eigenstates):
  - "Unknown" overall strong phase "$\delta_{K\pi\pi}$" is zero
  - So x_D and y_D can be determined directly
- Dalitz plot described by decay amplitude $\mathcal{A}_f(s_-, s_+)$
- If there is no direct *CPV*, then

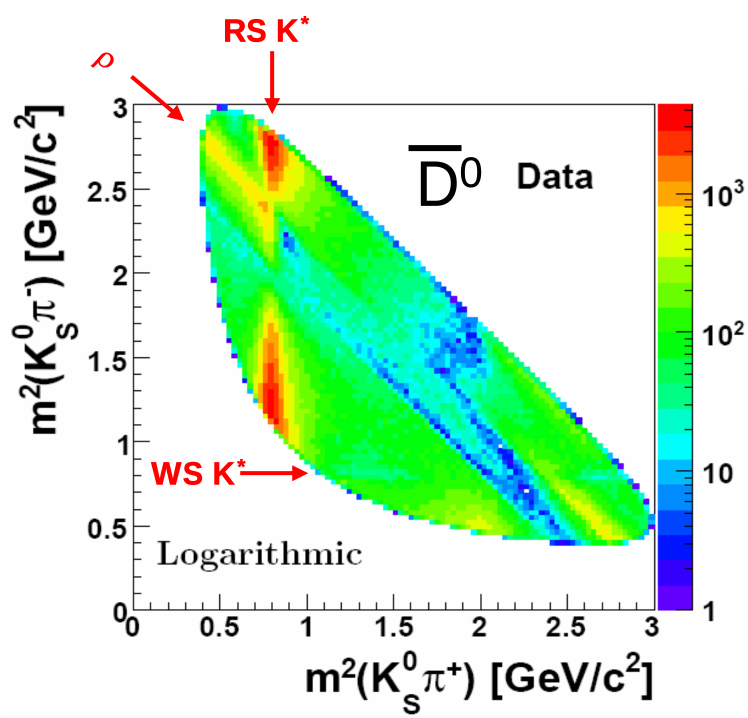
$$\bar{\mathcal{A}}_f(s_-, s_+) = \mathcal{A}_{\bar{f}}(s_-, s_+) = \mathcal{A}_f(s_+, s_-)$$

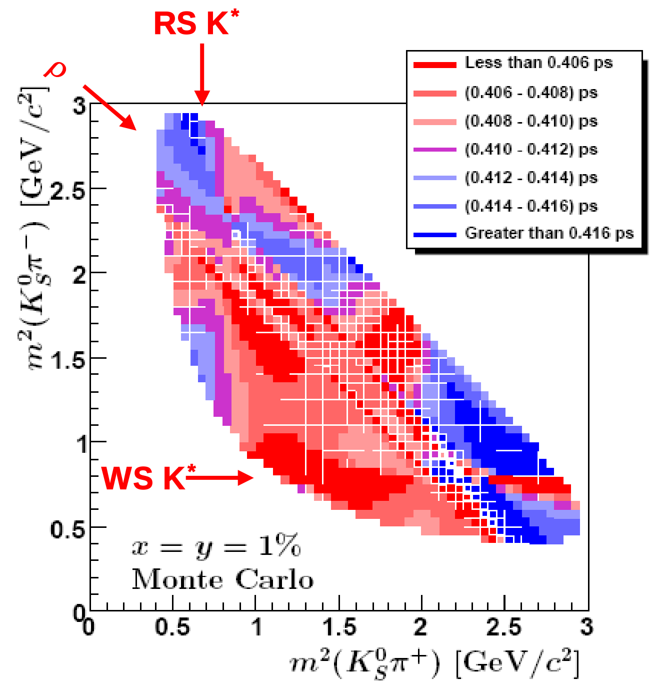
- Can also determine |q/p| and arg{q/p}.
- Method pioneered by CLEO: Phys.Rev.D72:012001,2005

  Used with 60x data by Belle: Phys.Rev.Lett.99:131803,2007

Amplitude Analysis of $D^0(t)\rightarrow K_S h^+ h^-$

Phys.Rev.Lett.105:081803 (2010) – 468.5 fb^{-1}



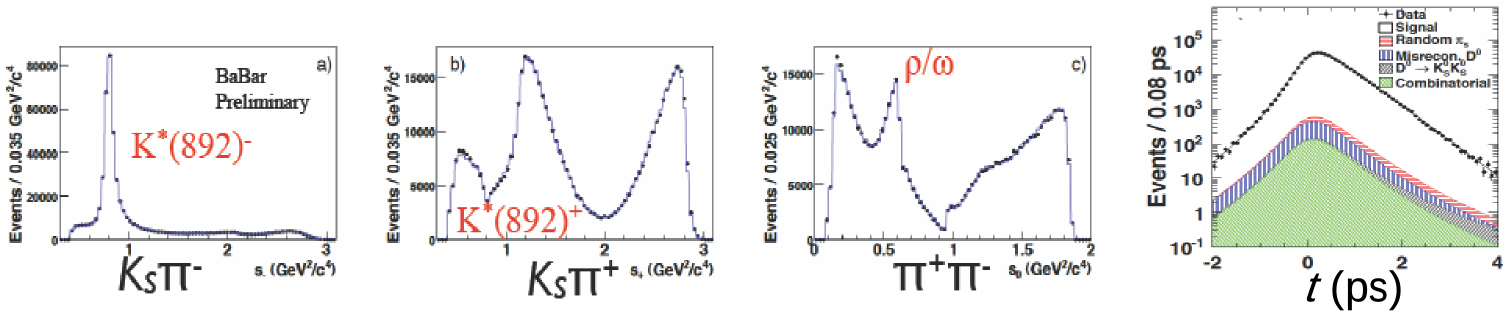


- Mean decay time differs by Δt - depends upon position in Dalitz plot
- Sensitivity to x_D and y_D also depends on density of points
  - Product Δt N^{½} is maximum in WS K* and in ρ bands

Large and pure samples from $D^{*+} \rightarrow D^0 \pi^+$ decays fit to combined $K_s\pi\pi$ and K_sKK samples give most precise measurement to date

$K_s \pi^+ \pi^-$

Signal : 541K
purity 98.5%



$\mathcal{A}_f$:

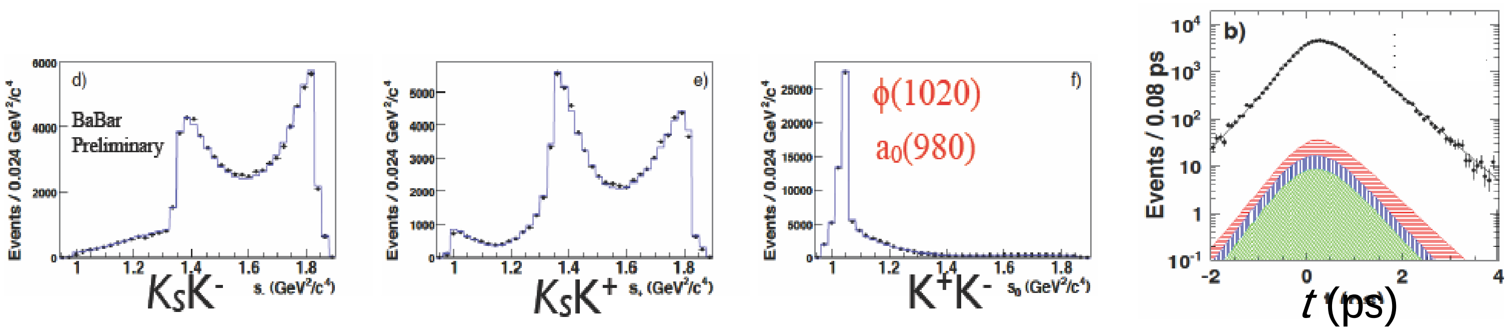
S-wave $\pi^+\pi^-$ — K-matrix model

S-wave $K^0\pi^-$ — LASS model

P- and D-waves — Breit-Wigner model

$K_s K^+ K^-$

Signal : 80K
purity 99.2%



$\mathcal{A}_f$:

S-wave K^+K^- — Coupled-channel Breit-Wigner a0(980)

All other waves — Breit-Wigners

Comparison with Previous Analyses

Experiment	Sample	Result
CLEO 2.5	$9\ fb^{-1}$	$x = (1.9^{+3.2}_{-3.3} \pm 0.4 \pm 0.4)\ \%$ $y = (-1.4 \pm 2.4 \pm 0.8 \pm 0.4)\ \%$
BELLE (Allowing CPV)	$540\ fb^{-1}$ Signal: $534K$ Purity: 95%	$x = (0.81 \pm 0.30^{+0.10}_{-0.07}{}^{+0.09}_{-0.16})\ \%$ $y = (0.37 \pm 0.25^{+0.07}_{-0.13}{}^{+0.07}_{-0.08})\ \%$ $\lvert q/p \rvert = 0.86^{+0.30}_{-0.29}{}^{+0.06}_{-0.03} \pm 0.08$ $\arg\{q/p\} = (-14^{+16}_{-18}{}^{+5}_{-3}{}^{+2}_{-4})^{\circ}$
BaBar	$486.5\ fb^{-1}$ Signal: $540K$ Purity: 98.5%	$x = (0.16 \pm 0.23 \pm 0.12 \pm 0.08)\ \%$ $y = (0.57 \pm 0.20 \pm 0.13 \pm 0.07)\ \%$ $x^+ = (0.00 \pm 0.33)\ \%$ $y^+ = (0.55 \pm 0.27)\ \%$ $x^+ = (0.33 \pm 0.33)\ \%$ $y^+ = (0.59 \pm 0.28)\ \%$

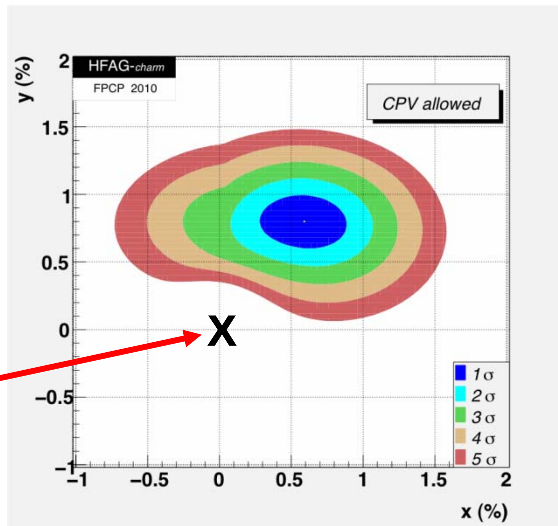
Third error is irreducible model ($\mathcal{A}_f$) uncertainty (IMU):

- ~10^{-3} in x_D and y_D
- ~8% in |q/p| and
- ~3^0 in arg{q/p}.

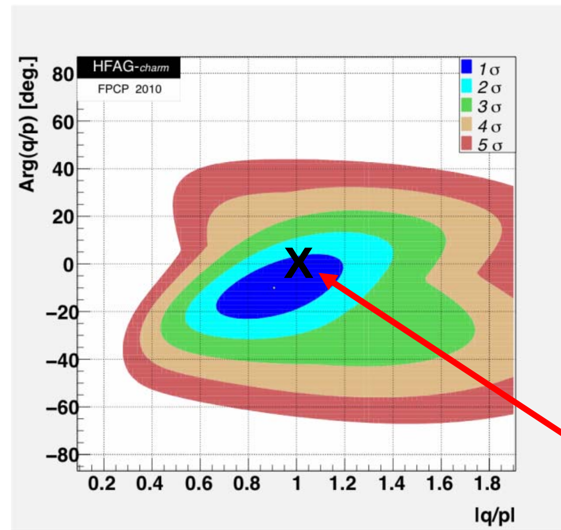
HFAG Mixing Summary

The HFAG collaboration combine 30 “mixing observables” to extract the 8 underlying mixing parameters and their χ^2 contours:

No Mixing



A. Schwartz *et al.*
arXiv:0803.0082
(updated FPCP 2010)



No CPV

EPS 2009	FPCP 2010
$x = (0.976 \pm 0.249)\%$	$x = (0.59 \pm 0.20)\%$
$y = (0.833 \pm 0.160)\%$	$y = (0.80 \pm 0.13)\%$
$\lvert q/p \rvert = 0.866 \pm 0.160$	$\lvert q/p \rvert = 0.91^{+0.19}_{-0.16}$
$\varphi = -0.148 \pm 0.126$ rad	$\varphi = -10^{+9.3}_{-8.7}$ deg
	($\varphi = -0.175^{+0.162}_{-0.152}$ rad)

New $D^0 \to K_s\pi^+\pi^- + K_sK^+K^-$ results from BaBar significantly reduce average x

Evidence for mixing is $>10\sigma$
No evidence for *CPV*

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Prospects for Observing CPV in Mixing

- The experimental challenge is shifted to observing *CPV* AND to investigating whether it is in *mixing, decay or both*.
- Best strategy may be to improve precision in x_D & y_D - say to ~1×10^{-4}
  - D^0-$\overline{D}^0$ asymmetries ~ $|q/p|^2-1$

Dependence on decay mode would indicate direct CPV?

- Several possibilities for this exist. Most likely are:
  - LHCb (or CDF, Atlas, CMS ?)
  - Super B factories

LHC performance not yet established

Machines do not yet exist !

- A rather safe estimate for performance can be made by using Babar as basis to project to integrated luminosity of 75 ab^{-1} at $\Upsilon(4S)$ anticipated for SuperB *(Similarly for Belle and Super KEKB)*
- We can also speculate on what "SuperD[1]" [500 fb^{-1} at $\psi(3770)$] might accomplish

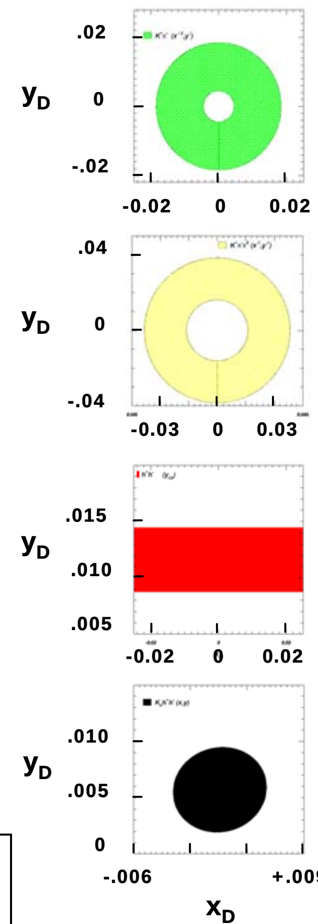
[1]See SuperB white paper: *http://arxiv.org/abs/1008.1541)*

BaBar Mixing Measurements

x_D *vs.* y_D

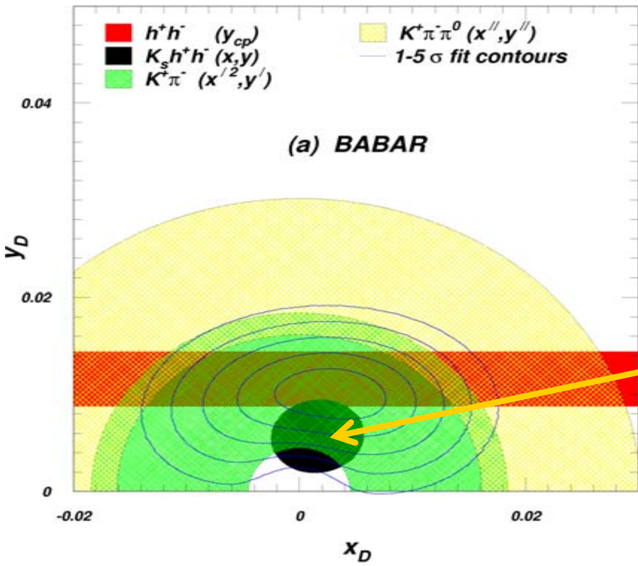
- WS decays $D^0 \rightarrow K^+\pi^-$: PRL 98,211802 (2007)
  - δ_f unknown, $\lambda_f^2 = R_{DCS}$ – measure $(x_D'^2, y_D')$
- WS decays $D^0 \rightarrow K^+\pi^-\pi^0$: PRL 103:211801 (2009)
  - δ_f unknown, λ_f from decay model – measure (x_D'', y_D'')
- "Lifetime" diff for $D^0 \rightarrow h^+h^-$: PRD 78:011105 (2008) PRD 80:071103 (2009)
  - Measure y_{CP}
- "Golden" $D^0 \rightarrow K_s h^+h^-$ PRL 105:081803 (2010)
  - $\delta = 0$ - measure (x_D, y_D) directly,

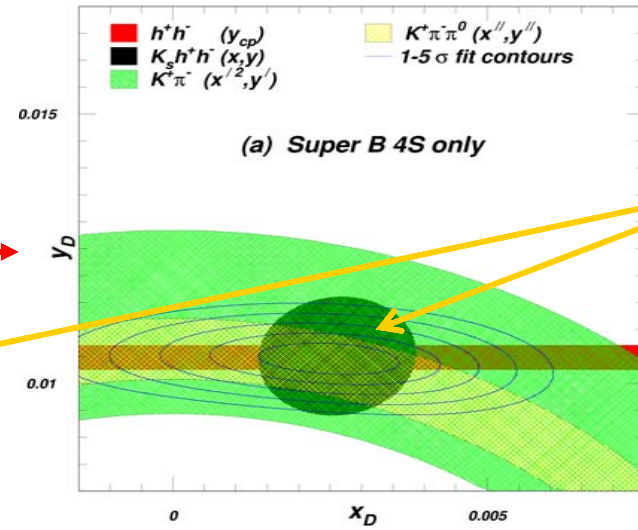
ALSO measures $|q/p|$ and $Arg\{q/p\}$ BUT
Introduces irreducible model uncertainty , IMU



Project BaBar Average to 75ab^{-1}@Υ(4S):

480 fb^{-1} → **75 ab^{-1}**





Golden channels

Min. χ^2 fits *(similar to HFAG fits)* Represented by blue contours

$$x_D = (3.01^{+3.12}_{-3.38}) \times 10^{-3}$$
$$y_D = (10.10^{+1.69}_{-1.72}) \times 10^{-3}$$

Unofficial average !!

→

$$x_D = (xxx^{+0.72}_{-0.75}) \times 10^{-3}$$
$$y_D = (xxx \pm 0.19) \times 10^{-3}$$

Uncertainties shrink: but are limited by the IMU (biggest effect on x_D)

Strong phase measurements from ψ(3770) can greatly reduce this.

$D\bar{D}$ Threshold Measurements

- Data from $\psi(3770) \to D\bar{D}$ at charm threshold provide measurement of strong phases such as $\delta_{K\pi}$.
- They <u>also</u> provide measured values of λ in Dalitz plot bins[1]

  These can be used to significantly reduce uncertainties from the Dalitz plot model used in the golden channel analyses.

- As basis for projection, we take uncertainties from CLEO-c:

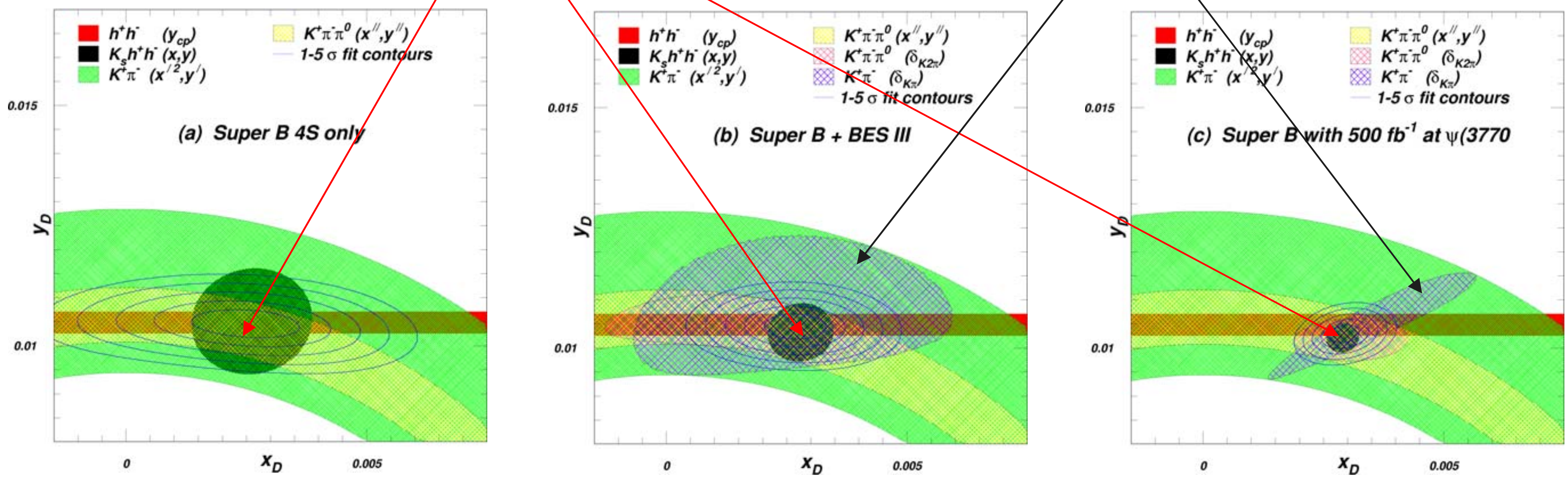
  N. Lowrey et al, PRD80, 031105 (2009), 0903.4853

- Our assumption is that <u>new data</u> from threshold will reduce the uncertainties in model uncertainty IMU:
  - <u>BES III:</u> IMU x 1/3 (Factor 3 improvement)
  - <u>SuperD 500 fb^{-1}</u> @$D\bar{D}$ threshold: IMU x 1/10 (Factor 10 improvement)

[1] **Bondar, Poluektov & Vorobiev, Phys. Rev. D82, 034033 (2010)**

Value of Strong Phase Measurements

- Two improvements in mixing precision come from threshold data:
  - Dalitz plot model uncertainty shrinks
  - Information on overall strong phase $\delta_{K\pi}$ is added



$$x_D = (xx^{+7.2}_{-7.5}) \times 10^{-4}$$
$$y_D = (xx \pm 1.9) \times 10^{-4}$$

BES III →

$$x_D = (xx \pm 4.2) \times 10^{-4}$$
$$y_D = (xx \pm 1.7) \times 10^{-4}$$

SuperD →

$$x_D = (xx \pm 2.0) \times 10^{-4}$$
$$y_D = (xx \pm 1.2) \times 10^{-4}$$

Uncertainty in x_D improves more than that of y_D

CPV Parameters $|q_D/p_D|$, ϕ_M=Arg{q/p}

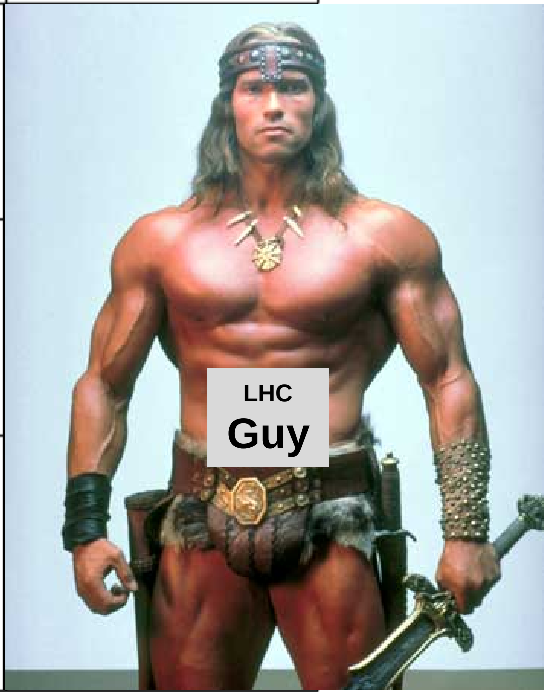
- Several strategies:

Strategy		Decay mode	$\sigma(\lvert q/p\rvert)$ x 100	$\sigma(\phi_M)^0$
Current World Averages (HFAG):	Global χ^2 Fit to all modes: (HFAG - direct CPV allowed)		« 18	« 9
D^0- $\overline{D}^0$ parameter asymmetries: $a_z = (z_+-z_-)/(z_++z_-) \sim \lvert q\rvert^2-\lvert p\rvert^2$ where z is x, y, x', y', x'', y'', x'^2	Asymmetries a_z:			
	x	<All modes>	±1.8	–
	y	<All modes>	±1.1	–
	y_{CP}	K^+K^-	±3.8	–
	y'	$K^+\pi^-$	±4.9	–
	x'^2	$K^+\pi^-$	±4.9	–
	x''	$K^+\pi^-\pi^0$	±5.4	–
	y''	$K^+\pi^-\pi^0$	±5.0	–
Time-dependent amplitude analysis of Golden channels	Model for $\mathcal{A}_f$	$K_s h^+h^-$	±8.4	±3.3
	BES III DP model	$K_s h^+h^-$	±3.7	±1.9
	SuperB DP model	$K_s h^+h^-$	±2.7	±1.4
Semi-leptonic asymmetry $a_{SL} = \frac{1-\lvert q/p\rvert^4}{1-\lvert q/p\rvert^4}$	75 ab^{-1} at $\Upsilon(4S)$	$X\ell\nu_\ell$	±10	
	500 fb^{-1} at $\psi(3770)$	$K\pi$-$K\pi$	±10	
	500 fb^{-1} at $\psi(3770)$	$X\ell\nu_\ell$	??	

Improve present precision by order of magnitude
Also improve distinction between decay modes ~ 5%

What About LHCb (10 fb^{-1}) ?

Decay Mode	*BABAR* (480 fb^{-1})	SuperB/Belle (75 ab^{-1})	+ LHCB (10 fb^{-1})
$\boldsymbol{K^+K^-}$ **($\boldsymbol{D^*}$-tag):**			
N (Events)	88×10^3	13.7×10^6	
Δy_{CP} (stat)	$\pm 3.5 \times 10^{-3}$	0.28×10^{-3}	
$\boldsymbol{K^+K^-}$ **(no tag):**			
N (Events)	330×10^3	51.4×10^6	
Δy_{CP} (stat)	$\pm 2.3 \times 10^{-3}$	0.19×10^{-3}	
$\boldsymbol{K^+\pi^-}$ **(WS):**			
N (Events)	5.1×10^3	0.79×10^6	
$\Delta y'$ (stat)	$\pm 4.4 \times 10^{-3}$	0.31×10^{-3}	
$\Delta x'^2$ (stat)	$\pm 3.0 \times 10^{-4}$	0.21×10^{-4}	



+ G. Wilkinson P. M. Spradlin CERN-lhcb-2007-049.
P. M. Spradlin (2007), Arxiv: 0711.1661.

LHCb is running now (and doing well)
Wait for next talk by Marco Gersabeck

Summary

- There is strong evidence for mixing in the D^0 meson system in four types of analyses:
  - Measurements of y_{CP} agree well with one another.
  - Measurements of x_D and y_D, rotated by unknown strong phases, have been made for "WS" hadronic decays to $K^+\pi^-$ and to $K^+\pi^-\pi^0$.
  - Measurement of x_D and y_D, from CP self-conjugate $K_s h^+ h^-$ decays

  BUT there is no evidence for CPV in mixing.
- More 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.
- If Super B factories can produce luminosities ~ 75 ab^{-1}, it may be possible to see CPV as a few percent in $|q/p| \neq 1$ and |˘$_M$| $\geq 5^0$.

Backup Here

Time-Integrated CPV from TeVatron

Work in progress – Mark Mattson, ICHEP 2010

Experiment	N ($D^0 \to \pi^+\pi^-$)	$A_{CP}(D^0 \to \pi^+\pi^-)$ (%)
CDF(0.123/fb)	7.3K	1.0 ± 1.3(stat) ± 0.6 (syst)
CDF(4.8/fb)	273K	xxx $\pm$ 0.19(stat) $\pm$ xxx (syst)
Babar (386/fb)	64K	-0.24 ± 0.52(stat) ± 0.22(syst)
Belle(540/fb)	51K	$+0.43 \pm 0.52$(stat) ± 0.12 (syst)

Experiment	N ($D^0 \to K^+K^-$)	$A_{CP}(D^0 \to K^+K^-)$ (%)
CDF(0.123/fb)	7.3K	1.0 ± 1.3(stat) ± 0.6 (syst)
CDF(4.8/fb)	781K	xxx $\pm$ 0.11(stat) $\pm$ xxx (syst)
Babar (386/fb)	129K	$0. \pm 0.34$(stat) ± 0.13(syst)
Belle(540/fb)	120K	-0.43 ± 0.30(stat) ± 0.11 (syst)

Systematic uncertainty is expected to be O(0.1%), comparable to statistical uncertainty.

Techniques pioneered by Babar, extended and used by Belle, virtually eliminate major systematic effects:

- F-B production asymmetry
  - Use odd moments
- Charge efficiency asymmetry
  - Use data to calibrate, NOT Monte Carlo

Now used by CDF.

Interesting → interestinger ...

New Time-Integrated CPV Results from Belle

PRL 104,181602 (2010)

Summary-cont.

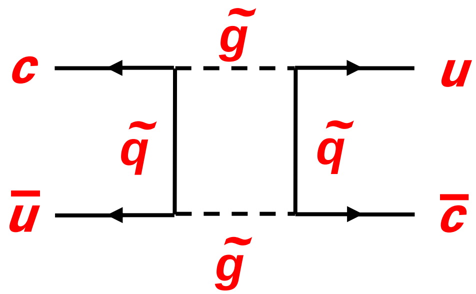
Decay Mode	A_{CP} (%) (Belle)	A_{CP} (%)(other)	A_{CP} (%) (SM from K_S^0)
$D^+ \to K_S^0 \pi^+$	$-0.71 \pm 0.19 \pm 0.20$	$-1.3 \pm 0.7 \pm 0.3$	-0.332
$D^+ \to K_S^0 K^+$	$-0.16 \pm 0.58 \pm 0.25$	$-0.2 \pm 1.5 \pm 0.9$	-0.332
$D_s^+ \to K_S^0 \pi^+$	$+5.45 \pm 2.50 \pm 0.33$	$+16.3 \pm 7.3 \pm 0.3$	$+0.332$
$D_s^+ \to K_S^0 K^+$	$+0.12 \pm 0.36 \pm 0.22$	$+4.7 \pm 1.8 \pm 0.9$	-0.332
$D^0 \to K_S^0 \pi^0$	$-0.28 \pm 0.19 \pm 0.10$	$+0.1 \pm 1.3$	-0.332
$D^0 \to K_S^0 \eta$	$+0.54 \pm 0.51 \pm 0.13$	N.A.	-0.332
$D^0 \to K_S^0 \eta'$	$+0.90 \pm 0.67 \pm 0.15$	N.A.	-0.332

• $A_{CP}^{D^+\to\phi\pi^+} - A_{CP}^{D_s^+\to\phi\pi^+} = (+0.62 \pm 0.30 \pm 0.15)\%$ {PDG: $A_{CP}^{D^+\to\phi\pi^+} = (-0.1 \pm 1.5)\%$}

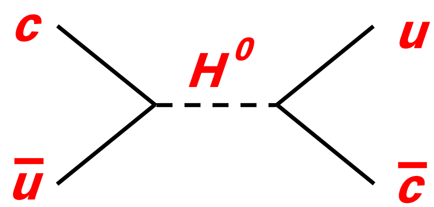
Preliminary results

New Physics and Mixing

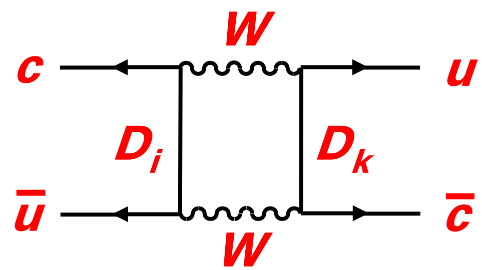
- Several extensions to the SM have been considered that can increase the value of { including:



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 |{|>>|y|
  - OR Any evidence for *CPV*

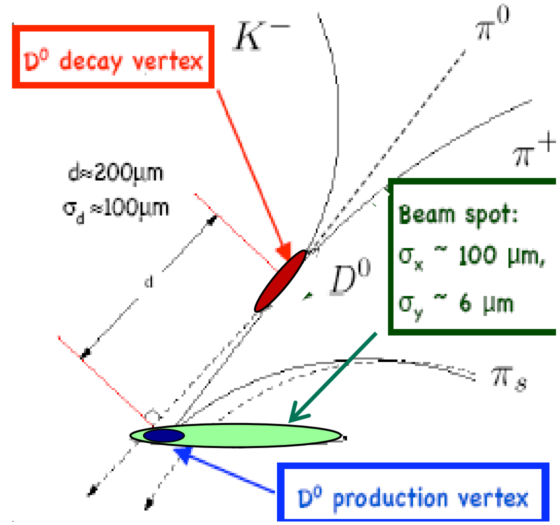
Phase in $\Delta C=1$ transitions tiny:

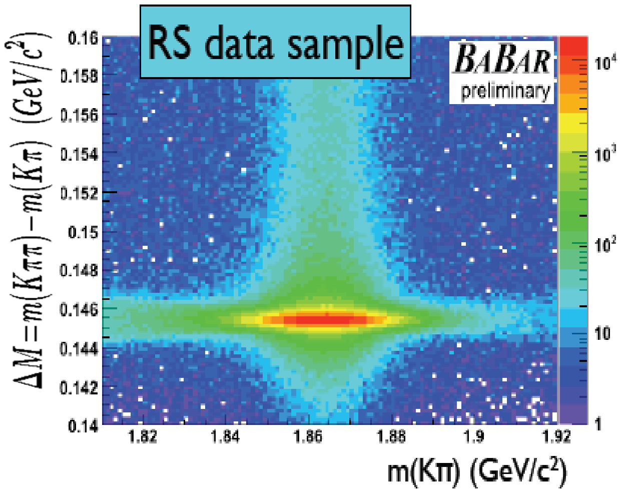
$V_{cs} \sim 1 - \lambda^2/2 - i\eta A^2\lambda^4$
$\rightarrow 0.97 - 6\times 10^{-4}\, i$

Wolfenstein representation

Mixing Measurements at *BaBar* and *Belle*

- 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

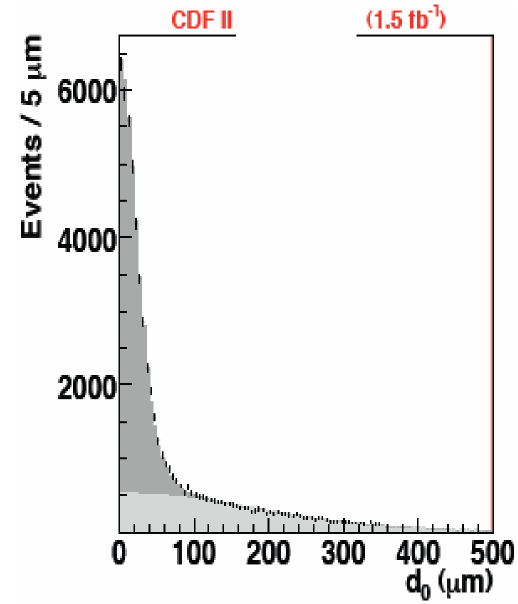


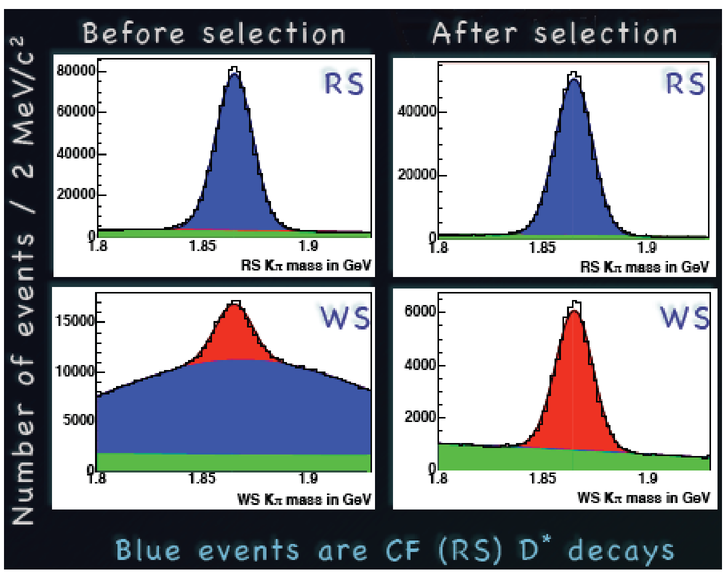


- D^0's from $D^{*+} \rightarrow D^0\pi^+$ decays:
  - Tag flavor of D^0 by the sign of the "slow pion" in D^* decays
  - Allow clean rejection of backgrounds
- **BUT untagged events can be used too !**

Mixing Measurements at *CDF*

- Use 2-track displaced vertex trigger
- Must contend with D^0 from B decay
- Can eliminate distortion from B decays by cutting out events with large impact parameter.

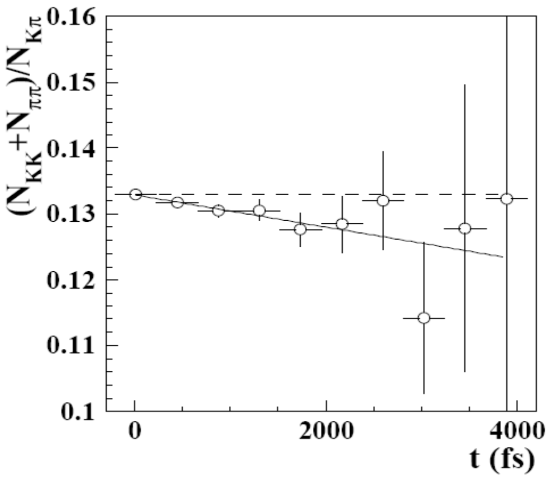




- Doubly mis-ID'd WS events require a RS mass cut
- D^0's from $D^{*+} \to D^0\pi^+$ decays: Untagged events are not used

Brian Meadows

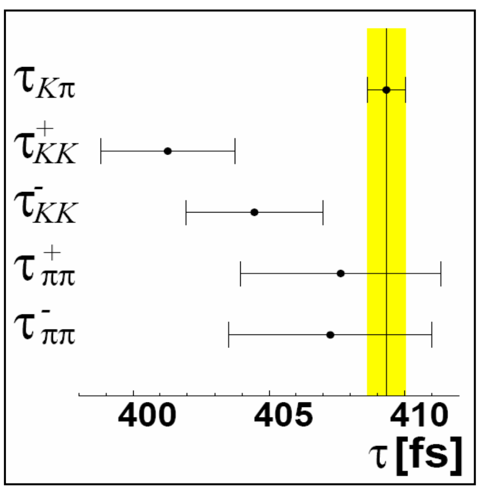
Lifetime Ratio (D^*-tagged Samples)



Mode	y_{CP} (%)	A_τ (%)
K^+K^-	$1.25 \pm 0.39 \pm 0.28$	$0.15 \pm 0.34 \pm 0.16$
$\pi^+\pi^-$	$1.44 \pm 0.57 \pm 0.42$	$-0.28 \pm 0.52 \pm 0.30$
Combined	$1.31 \pm 0.32 \pm 0.25$	$0.01 \pm 0.30 \pm 0.15$

3.2 σ evidence - no *CPV*

PRL 98:211803,2007 540 fb^{-1}



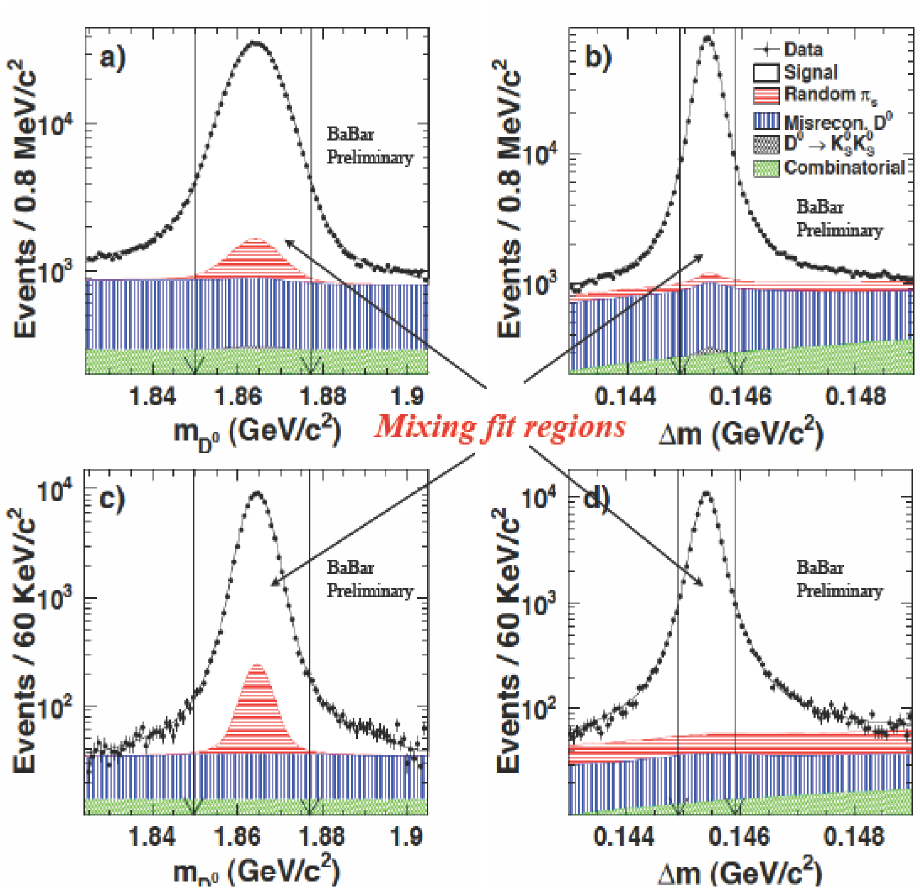
Mode	y_{CP} (%)	$\Delta Y = (1-y_{CP})A_\tau$ (%)
K^+K^-	$1.60 \pm 0.46 \pm 0.17$	$-0.40 \pm 0.44 \pm 0.12$
$\pi^+\pi^-$	$0.46 \pm 0.65 \pm 0.25$	$0.05 \pm 0.64 \pm 0.32$
Combined	$1.24 \pm 0.39 \pm 0.13$	$-0.26 \pm 0.36 \pm 0.08$

3.0 σ evidence - no *CPV*

Phys.Rev.D78:011105,2008 384 fb^{-1}

TD Amplitude Analysis of $D^0 \rightarrow K_S h^+ h^-$

Phys.Rev.Lett.105:081803 (2010) – 468 fb^{-1}



Very clean samples from $D^{*+} \rightarrow D^0 \pi^+$ decays

$\underline{K_S \pi^+ \pi^-}$:

Signal $(540.8 \pm 0.8) \times 10^3$ events

Purity 98.5 %

Fit to combined $K_s\pi\pi$ and K_sKK samples give

$x = [0.16 \pm 0.23(\text{stat.}) \pm 0.12(\text{syst.}) \pm 0.08(\text{model})]\%$

$y = [0.57 \pm 0.20(\text{stat.}) \pm 0.13(\text{syst.}) \pm 0.07(\text{model})]\%$

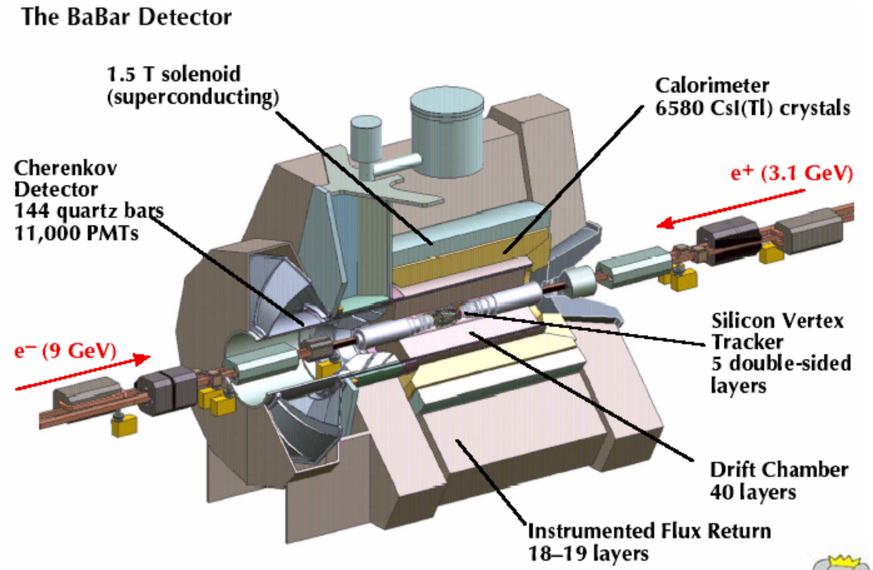
Most precise measurement to date:

$\underline{K_S K^+ K^-}$:

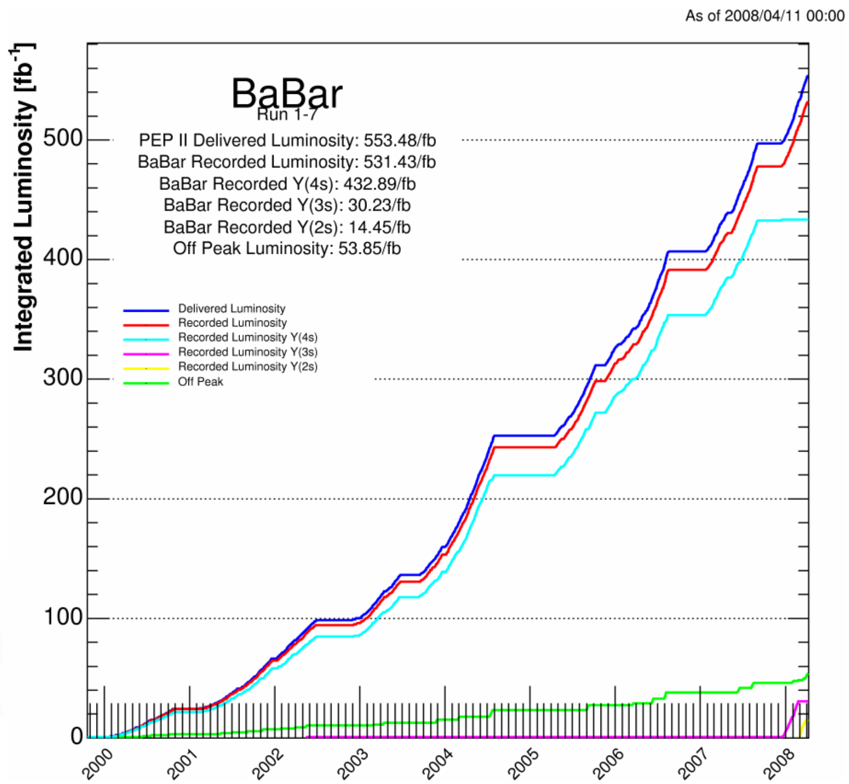
Signal $(79.9 \pm 0.3) \times 10^3$ events

Purity 99.2 %

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.