D^0-$\bar{D}^0$ Mixing and CP Violation

Michael D. Sokoloff
University of Cincinnati

A Review and Preview

The oscillation in time of neutral D mesons into their antiparticles, and *vice versa*, commonly called D^0-$\bar{D}^0$ mixing, has been observed by several experiments in a variety of channels during the past four years. This has led to renewed interest in charm mixing and CP violation as possible signatures for new physics. First, I will review elements of charm mixing and associated CP violation. Then, I will review other searches for CP violation in the charm sector. Finally, I will project experimental sensitivities for the next generation of flavor factories.

Which are the sources of flavour symmetry breaking accessible at low energies?

$$\mathscr{L}_{\text{eff}} = \mathscr{L}_{\text{SM}} + \sum \frac{c_{ij}}{\Lambda^2} O_{ij}^{(6)}$$

G.I, Nir, Perez '10

Operator	Bounds on Λ (TeV)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ε_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ε_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert$, ϕ_D
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert$, ϕ_D
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2	1.1×10^2	7.6×10^{-5}	7.6×10^{-5}	Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2	3.7×10^2	1.3×10^{-5}	1.3×10^{-5}	Δm_{B_s}

↓

New flavor-breaking sources of O(1) at the TeV scale are definitely excluded

Mixing Phenomenology

Neutral *D* mesons are produced as *flavor eigenstates* D^0 and $\bar{D}^0$ and decay via

$$i\frac{\partial}{\partial t}\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix} = \left(\mathbf{M} - \frac{i}{2}\mathbf{\Gamma}\right)\begin{pmatrix} D^0(t) \\ \overline{D}^0(t) \end{pmatrix}$$

as *mass, lifetime eigenstates* D_1, D_2

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned}$$

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

$$\left(\frac{q}{p}\right)^2 = \frac{M_{12}^* - \frac{i}{2}\Gamma_{12}^*}{M_{12} - \frac{i}{2}\Gamma_{12}}$$

D_1, D_2 have masses M_1, M_2 and widths Γ_1, Γ_2

Mixing occurs when there is a *non-zero* mass

$$\Delta M = M_1 - M_2$$

or lifetime difference

$$\Delta\Gamma = \Gamma_1 - \Gamma_2$$

For convenience define, *x* and *y*

$$x = \frac{\Delta M}{\Gamma}, \quad y = \frac{\Delta\Gamma}{2\Gamma}$$

where

$$\Gamma = \frac{\Gamma_1 + \Gamma_2}{2}$$

and define the mixing rate

$$R_M = \frac{x^2 + y^2}{2}$$

CP Violation Simplified

CP violation in mixing originates in the difference between mixing and CP eigenstates:

$$\begin{aligned} |D_1\rangle &= p|D^0\rangle + q|\overline{D}^0\rangle \\ |D_2\rangle &= p|D^0\rangle - q|\overline{D}^0\rangle \end{aligned} \qquad q/p \neq 1$$

Direct CP violation originates in the difference between the magnitudes of CP-conjugate decays:

$$|\mathcal{A}(D \rightarrow f)| \neq |\overline{\mathcal{A}}(D \rightarrow \overline{f})|$$

If direct CP violation is absent, or small, then the four observables in mixing-related CPV

$$x, \quad y, \quad |q/p|, \quad \arg(q/p)$$

are related to three underlying parameters

$$x_{12} \equiv 2|M_{12}|/\Gamma, \quad y_{12} \equiv |\Gamma_{12}|/\Gamma, \quad \phi_{12} \equiv \arg(M_{12}/\Gamma_{12})$$

$$\left(M - \frac{i}{2}\Gamma\right)_{12} = \frac{1}{2m_D}\langle D^0|\mathcal{H}_w^{\Delta C=2}|\overline{D}^0\rangle + \frac{1}{2m_D}\sum_n \frac{\langle D^0|\mathcal{H}_w^{\Delta C=1}|n\rangle\,\langle n|\mathcal{H}_w^{\Delta C=1}|\overline{D}^0\rangle}{m_D - E_n + i\epsilon}$$

The first term is called the short distance contribution and the second the long distance contribution. Assuming the short distance contributions are small, and that CP is conserved, we can express y as the absorptive part of the second term

$$y = \frac{1}{\Gamma_{\rm D}}\sum_n \rho_n \langle \overline{D}^0|\mathcal{H}_w^{\Delta C=1}|n\rangle\langle n|\mathcal{H}_w^{\Delta C=1}|D^0\rangle,$$

where ρ_n is the phase space factor corresponding to the charmless intermediate state $|n\rangle$.

Points of theoretical consensus

- Short distance contributions to x and y are $\ll 10^{-2}$;
- CP is not significantly violated in the Standard Model;
- Large long-distance contributions to y may originate in the different phase spaces available for CP-even and CP-odd final states (but not in SM matrix elements); $y \sim \mathcal{O}(10^{-2})$ cannot be excluded in the Standard Model; $x \sim \mathcal{O}(10^{-2})$ is less likely, although it cannot be excluded absolutely.
- New Physics may contribute to mixing at the $x, y \sim \mathcal{O}(10^{-2})$ level.

Standard Model Mixing Predictions

Box diagram SM charm mixing rate naively expected to be very low (R_M~10^{-10}) (Datta & Kumbhakar)

Z.Phys. C**27**, 515 (1985)

CKM suppression → $|V_{ub}V^*_{cb}|^2$

GIM suppression → $(m^2_s-m^2_d)/m^2_W$

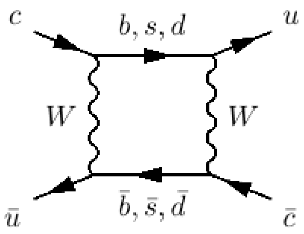
Di-penguin mixing, R_M~10^{-10}

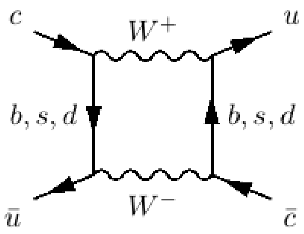
Phys. Rev. D **56**, 1685 (1997)

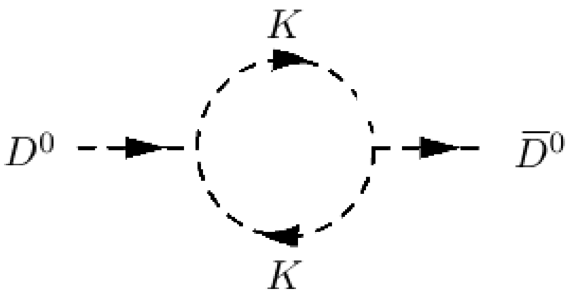
Enhanced rate SM calculations generally due to long-distance contributions:

first discussion, L. Wolfenstein

Phys. Lett. B **164**, 170 (1985)







Standard Model Mixing Predictions

Box diagram SM charm mixing rate naively expected to be very low ($R_M \sim 10^{-10}$) (Datta & Kumbhakar)

Z.Phys. C**27**, 515 (1985)

CKM suppression → $|V_{ub}V^*_{cb}|^2$

GIM suppression → $(m^2_s - m^2_d)/m^2_W$

Di-penguin mixing, $R_M \sim 10^{-10}$

Phys. Rev. D **56**, 1685 (1997)

Enhanced rate SM calculations generally due to long-distance contributions:

first discussion, L. Wolfenstein

Phys. Lett. B **164**, 170 (1985)

Partial History of Long-Distance Calculations

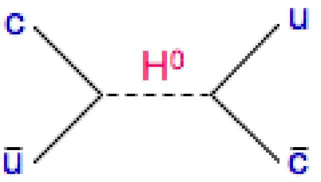
- Early SM calculations indicated long distance contributions produce $x \ll 10^{-2}$:
  - $x \sim 10^{-3}$ (dispersive sector)
    - PRD **33**, 179 (1986)
  - $x \sim 10^{-5}$ (HQET)
    - Phys. Lett. B **297**, 353 (1992)
    - Nucl. Phys. **B403**, 605 (1993)
- More recent SM predictions can accommodate x, y ~1% [of opposite sign] (Falk *et al.*)
  - $x,y \approx \sin^2 q_C \times [SU(3)\text{ breaking}]^2$
    - Phys.Rev. D **65**, 054034 (2002)
    - Phys.Rev. D **69**, 114021 (2004)
- For a discussion of local duality [Bigi & Uraltsev], see
  - Nucl. Phys. **B592**, 92-106 (2001)

New Physics Mixing Predictions

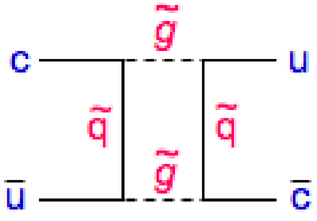
Possible enhancements to mixing due to new particles and interactions in new physics models

Most new physics predictions for *x*

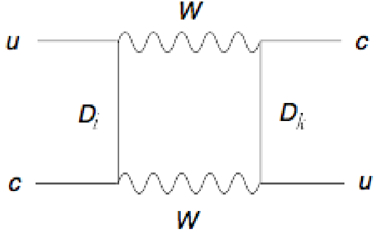
- Extended Higgs, tree-level FCNC
- Fourth generation down-type quarks
- Supersymmetry: gluinos, squarks
- Lepto-quarks



FCNC



supersymmetry



Heavy weak iso-singlet quarks

- Large possible SM contributions to mixing require observation of either a CP-violating signal or | *x* | >> | *y* | to establish presence of NP
- A recent survey (Phys. Rev. D76, 095009 (2007), arXiv:0705.3650) summarizes models and constraints:

Fourth generation	Vector leptoquarks
Q = -1/3 singlet quark	Flavor-conserving Two-Higgs
Q = +2/3 singlet quark	Flavor-changing neutral Higgs
Little Higgs	Scalar leptoquarks
Generic Z'	MSSM
Left-right symmetric	Supersymmetric alignment

and more

Lifetime Ratio Observables

In the *D tagged analysis, measure:**

$\tau_{K\pi} \equiv \tau(D^0 \to K^-\pi^+ + c.c.)$ *CP*-mixed right-sign Cabibbo-favored (CF) decay lifetime

$\tau_{hh}^{D^0} \equiv \tau(D^0 \to h^-h^+)$ *CP*-even singly Cabibbo-suppressed (SCS) decay lifetime

Construct mixing variable $\boxed{y_{CP} \equiv \frac{\tau_{K\pi}}{\tau_{hh}} - 1}$ **where** $\tau_{hh} = \frac{\tau_{hh}^{D^0} + \tau_{hh}^{\bar{D}^0}}{2}$

and CPV asymmetry: $\boxed{\Delta Y \equiv \frac{\tau_{K\pi}}{\tau_{hh}} A_\tau}$ **where** $A_\tau = \frac{\tau_{hh}^{D^0} - \tau_{hh}^{\bar{D}^0}}{\tau_{hh}^{D^0} + \tau_{hh}^{\bar{D}^0}} = -A_\Gamma$

In the untagged analysis, measure only:

$$\boxed{y_{CP} \equiv \frac{\tau_{K\pi}^{RS+WS}}{\tau_{hh}} - 1}$$

where $\tau_{K\pi}^{RS+WS}$ is the lifetime of the right-sign decay, with a small admixture of wrong sign decays

In the limit of CP conservation, $y_{CP} = y$ and $\Delta Y = 0$

Belle's ΔΓ Measurement

Phys. Rev. Lett. 98:211803 ,2007

540 fb^{-1}

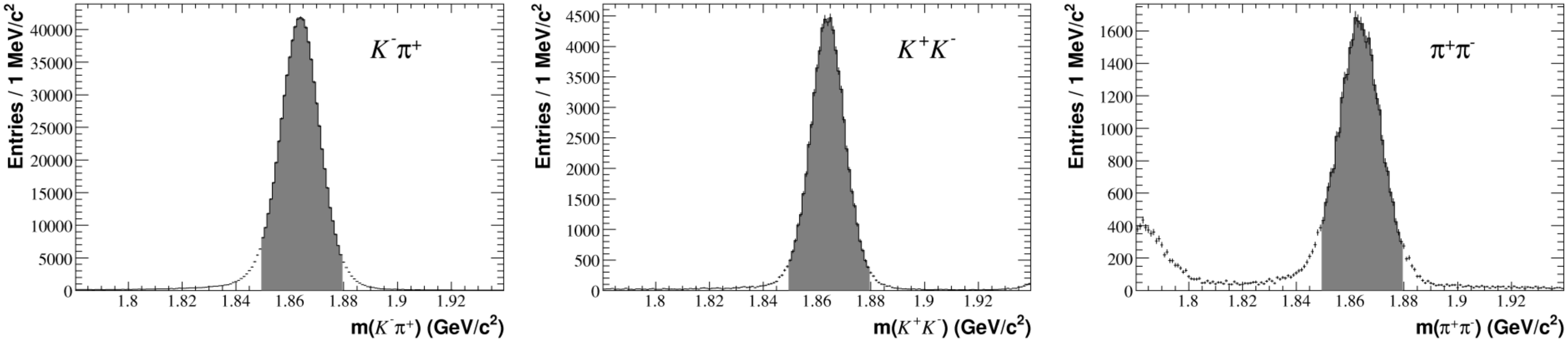
$$y_{CP} = (1.31 \pm 0.32\,(\text{stat.}) \pm 0.25\,(\text{syst.}))\%$$

$$A_{\Gamma} = (0.01 \pm 0.30\,(\text{stat.}) \pm 0.15\,(\text{syst.}))\%.$$

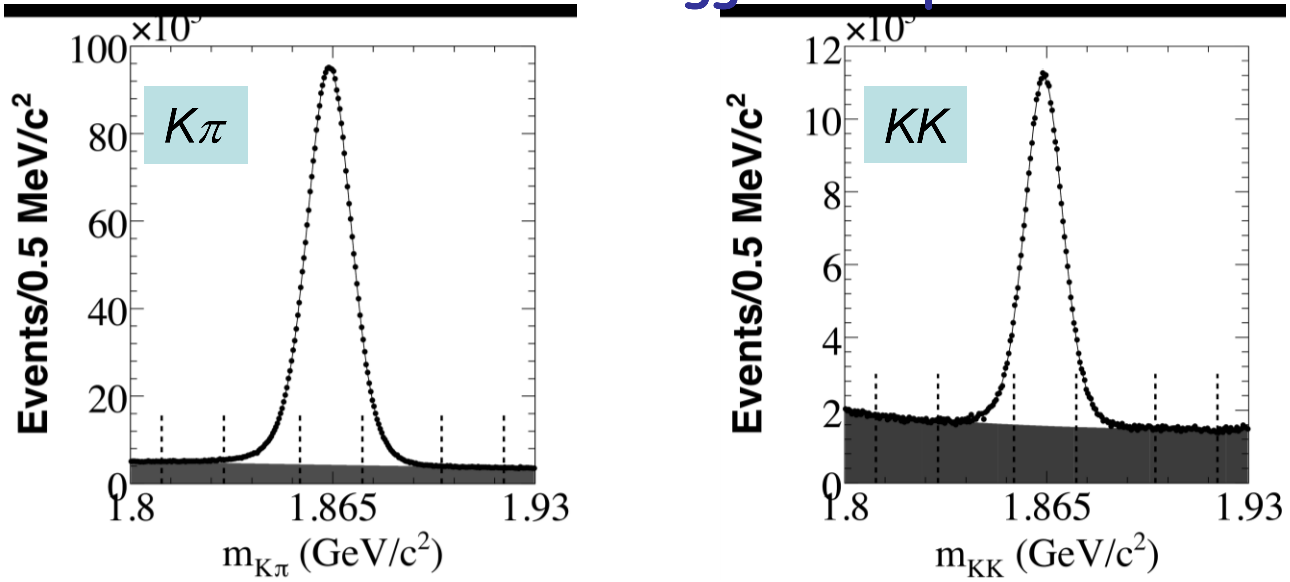
BaBar $\Delta\Gamma$ Samples

Phys. Rev. D78 011105 (2008) and **Phys. Rev. D80 071103 (2009)**

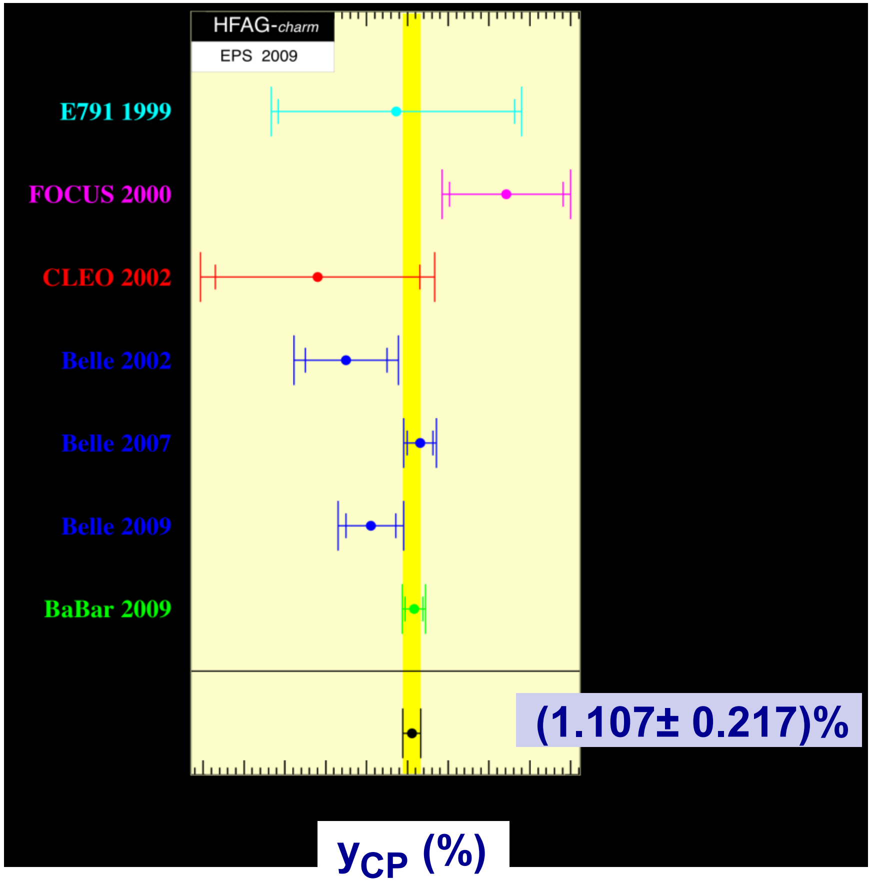
Mass projections from D*-tagged ($0.1447 < \Delta m < 0.1463$ GeV/c^2)



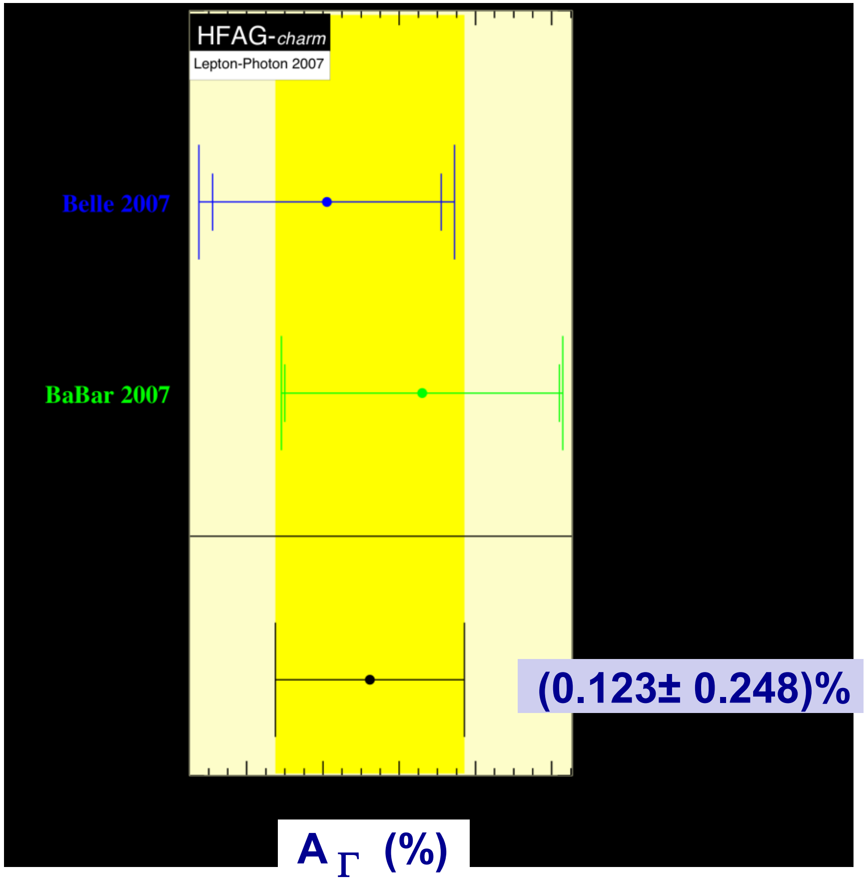
Mass distributions from the untagged samples



HFAG Lifetime Ratio Summaries

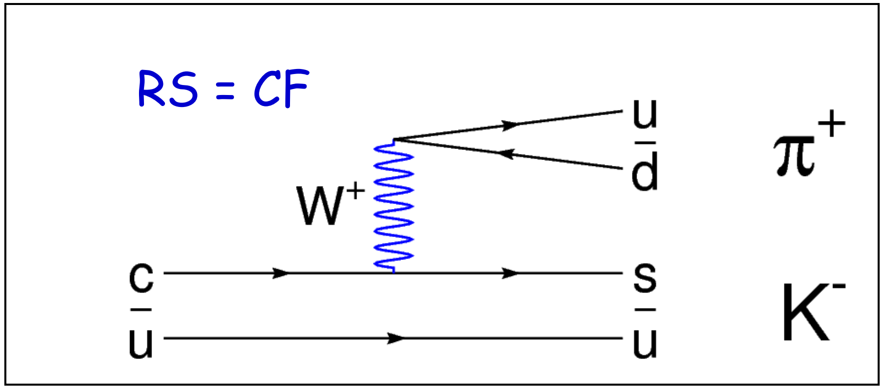


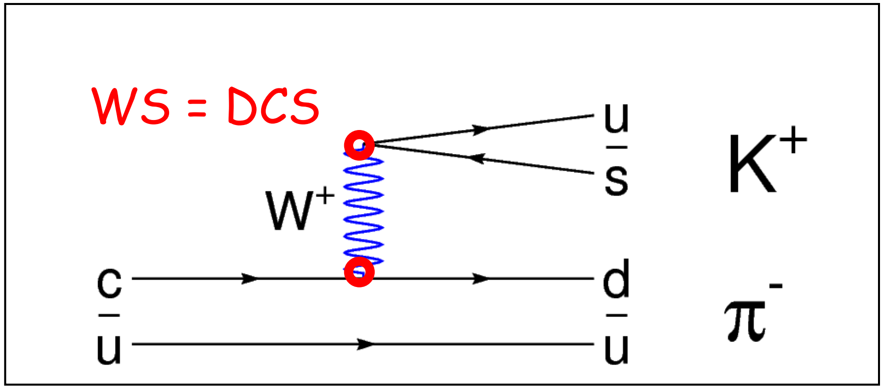
(1.107± 0.217)%



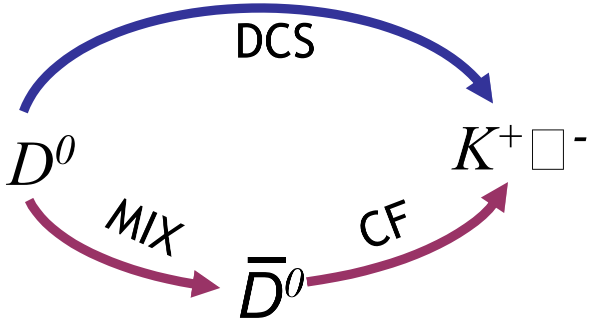
(0.123± 0.248)%

Time-Evolution of $D^0 \to K\pi$ Decays





DCS and mixing amplitudes interfere to give a "quadratic" WS decay rate (x, y << 1):



$$\frac{\Gamma_{WS}(t)}{e^{-t/\tau}} \propto R_D + \sqrt{R_D}y'\left(\frac{t}{\tau}\right) + \left(\frac{x'^2+y'^2}{4}\right)\left(\frac{t}{\tau}\right)^2$$

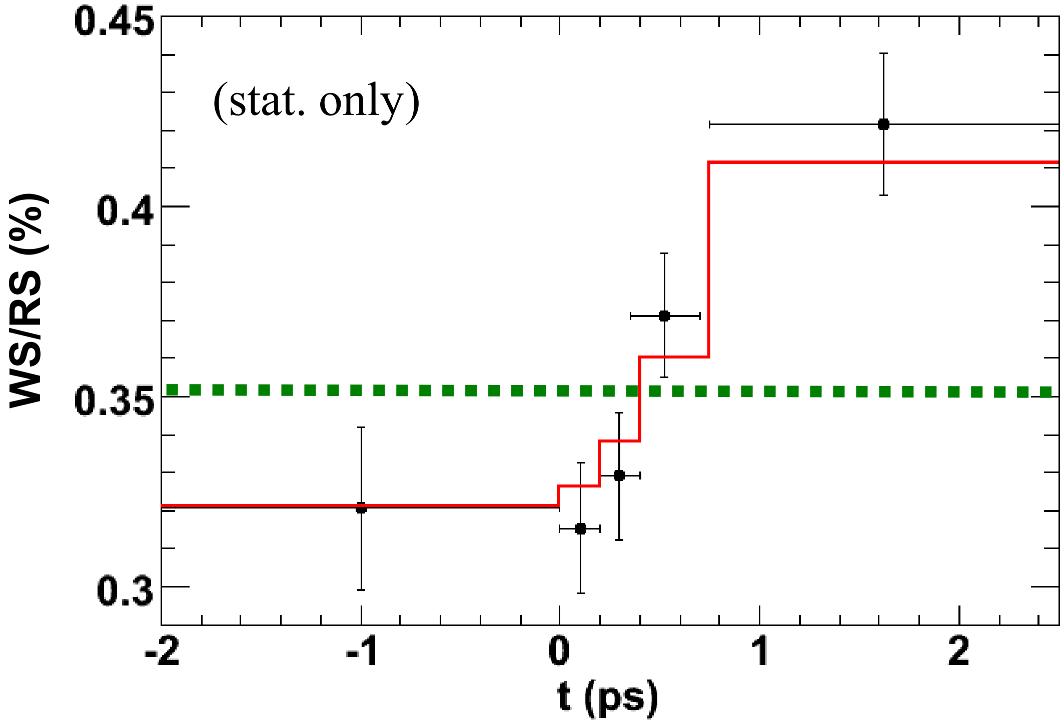
where $x' = x\cos\delta + y\sin\delta \qquad y' = y\cos\delta - x\sin\delta$

and □ is the phase difference between DCS and CF decays.

Simplified Fit Strategy & Validation

Rate of WS events clearly increases with time:

$$\frac{\Gamma_{WS}(t)}{e^{-t/\tau}} \propto R_D + \sqrt{R_D}y'\left(\frac{t}{\tau}\right) + \left(\frac{x'^2 + y'^2}{4}\right)\left(\frac{t}{\tau}\right)^2$$



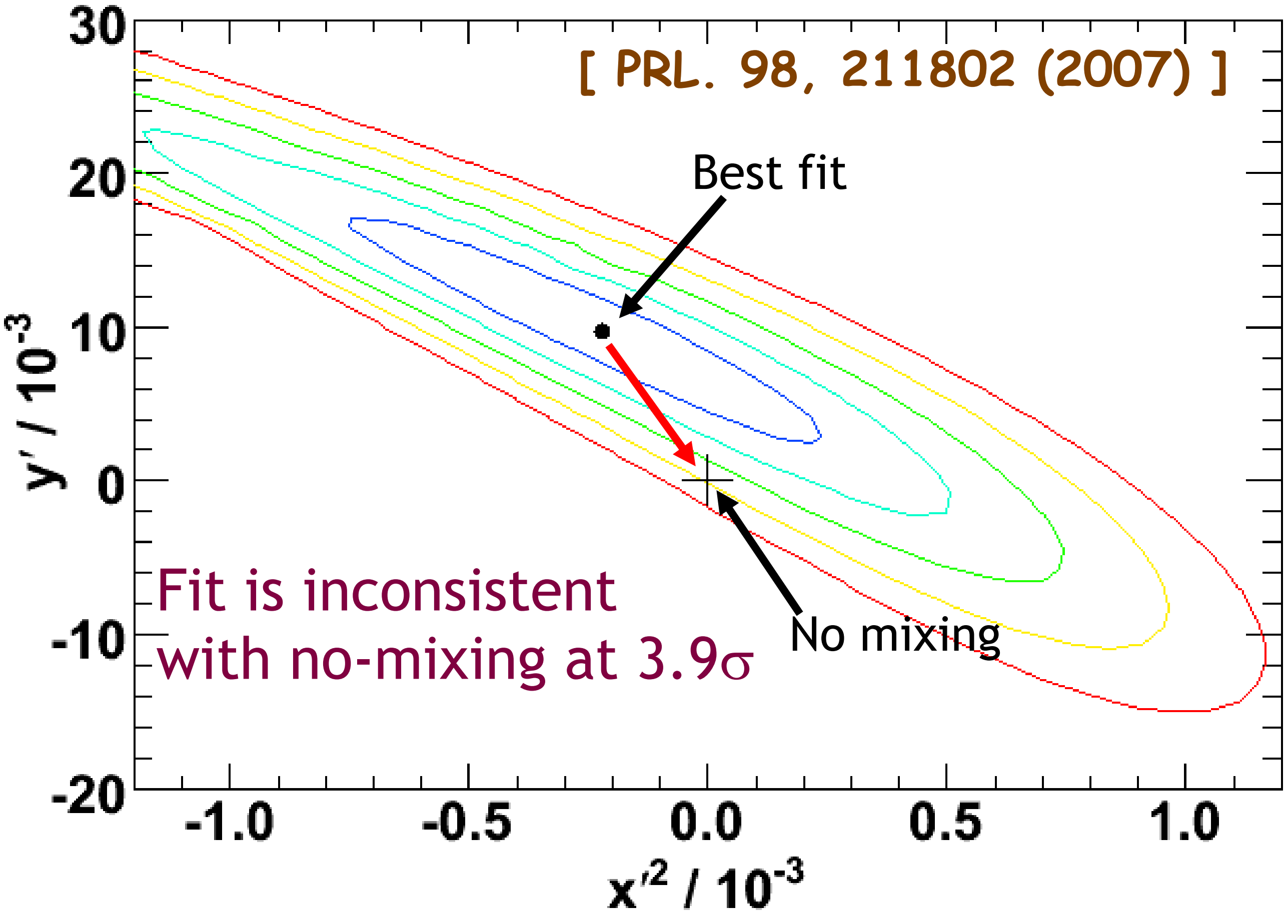
Consistent with prediction from full likelihood fit

□□□□□□□□□□^{2}=

Inconsistent with no-mixing hypothesis: χ^2=24

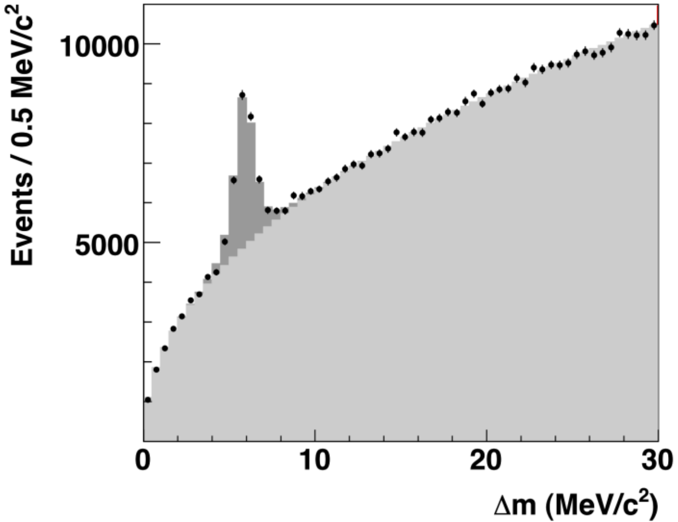
Signal Significance with Systematics

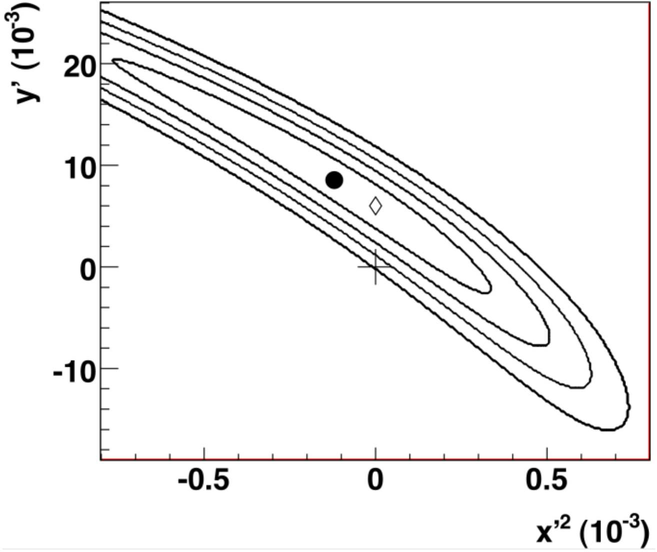
Including systematics (~ 0.7 x stat)
decreases signal significance

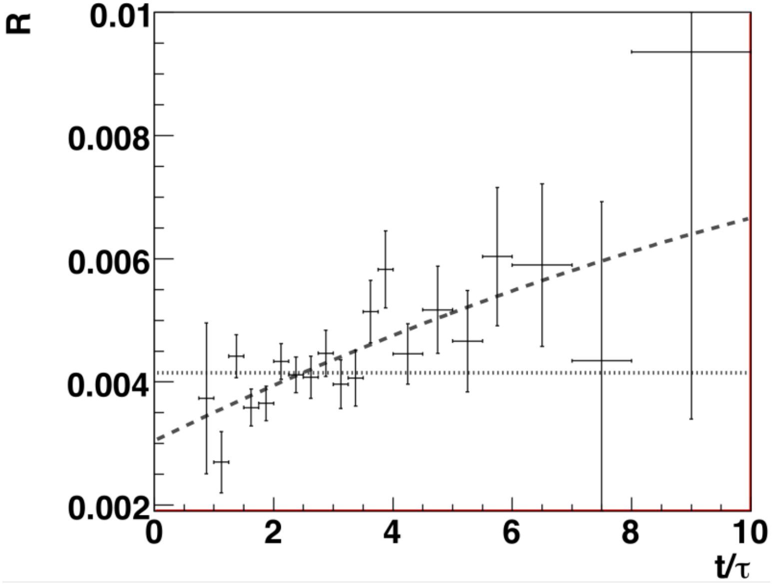


Fit is inconsistent
with no-mixing at 3.9σ

Kπ Mixing from CDF







Phys. Rev. Lett. 100:121802, 2008

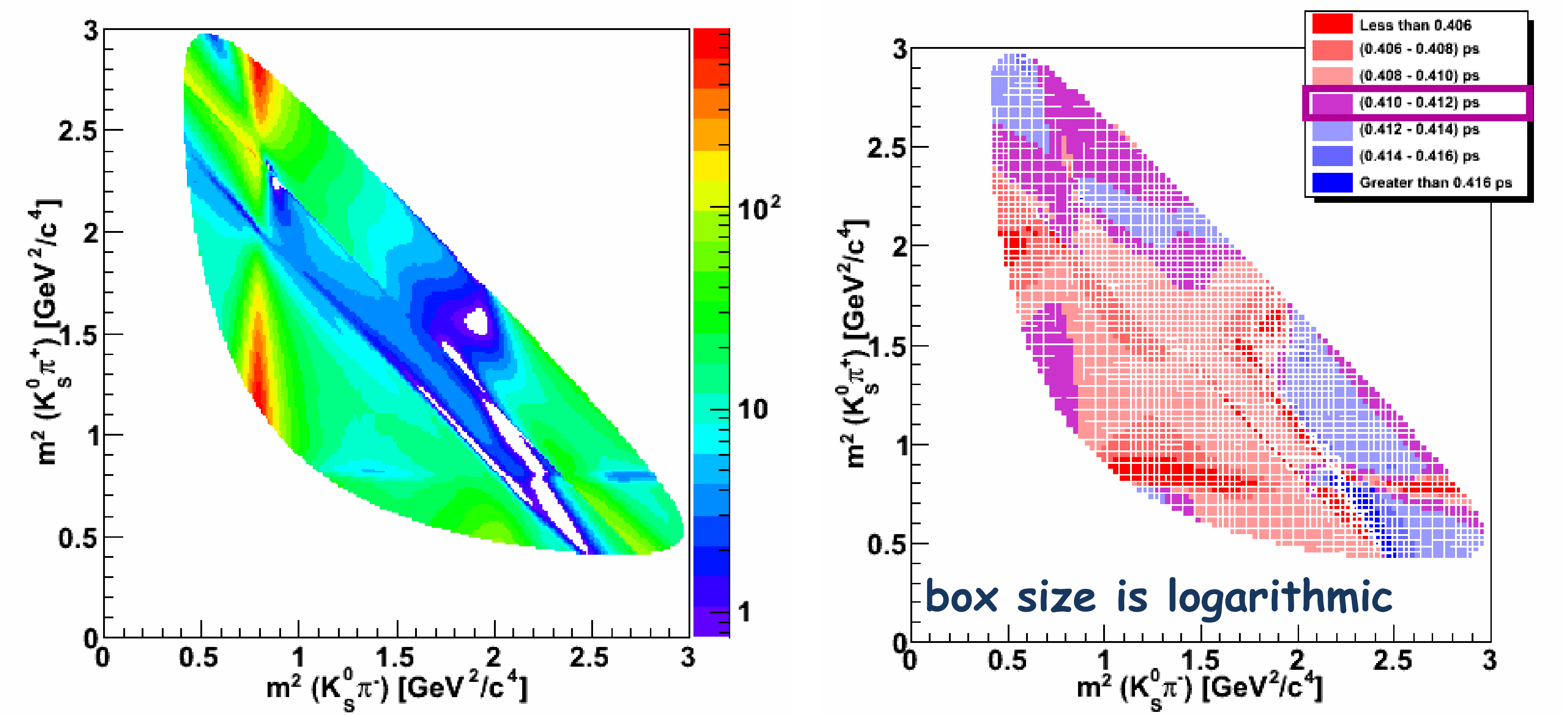
$$x'^2 = (-0.012 \pm 0.035) \times 10^{-2}$$

$$y' = (0.085 \pm 0.076) \times 10^{-2}$$

“data are inconsistent with the no-mixing hypothesis with a probability equivalent to 3.8 Gaussian standard deviations"

Time-Dependence in $D^0 \to K_S\pi^+\pi^-$

[Phys. Rev. Lett. 105, 081803 (2010)]

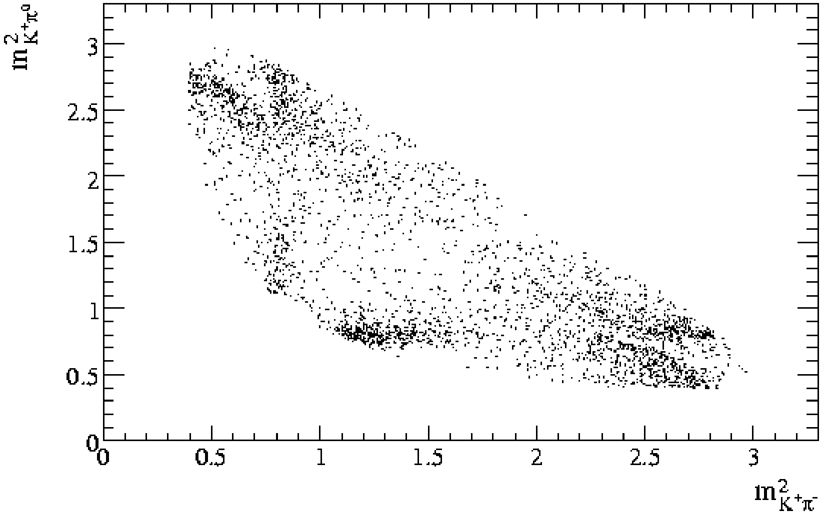


box size is logarithmic

These plots illustrate the time-integrated PDF and the average decay time as a function of position in the Dalitz plot for $(x,y) = (0.16\%, 0.57\%)$. The sizes of the boxes in the right-hand plot reflect the number of entries, and the colors reflect the average decay time.

$D^0 \rightarrow K^+\pi^-\pi^0$: Results

1483 ± 56 signal events



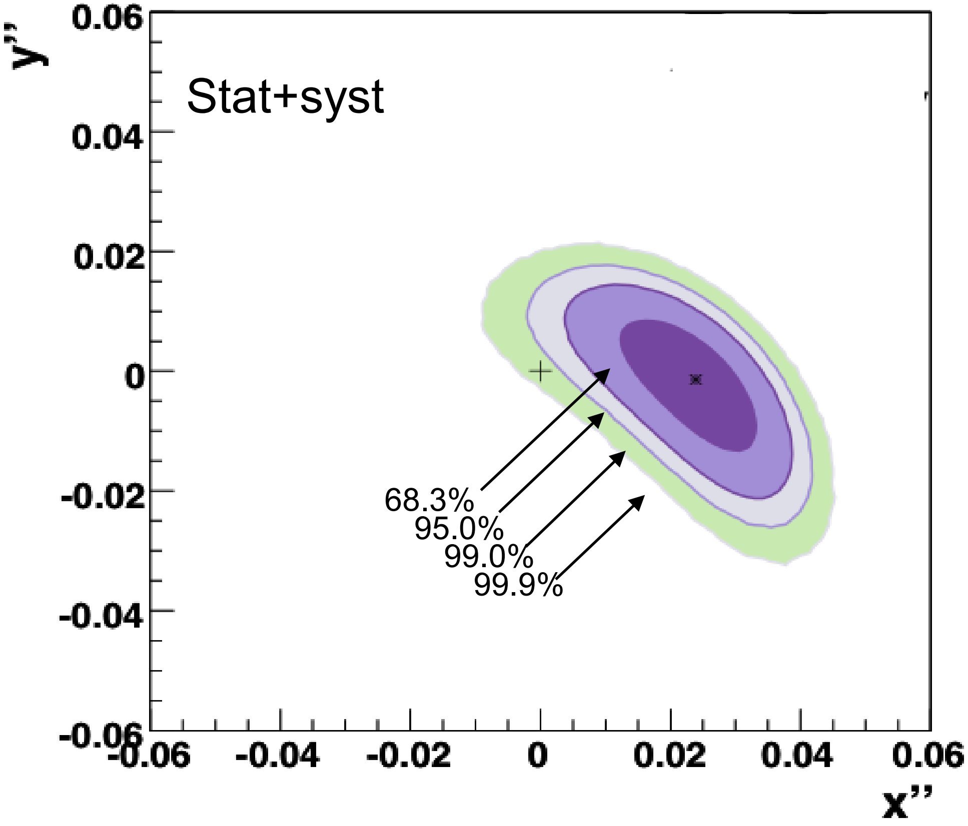
x''^{+}: $(2.53\ ^{+0.54}_{-0.63} \pm 0.39)$ %

y''^{+}: $(-0.05\ ^{+0.63}_{-0.67} \pm 0.50)$%

x''^{-}: $(3.55\ ^{+0.73}_{-0.83} \pm 0.65)$ %

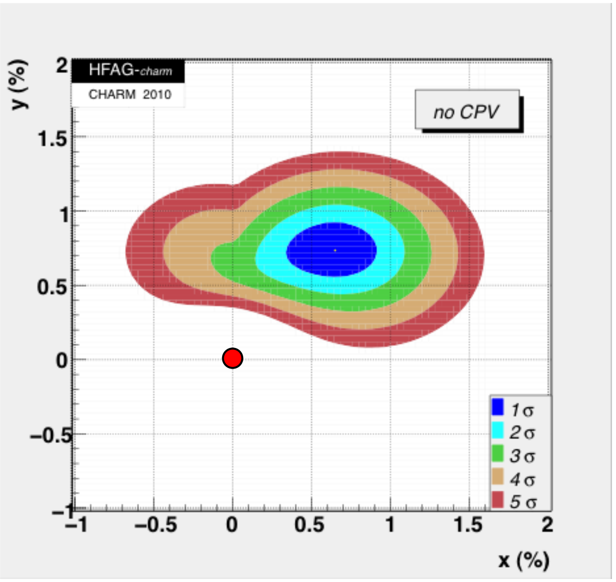
y''^{-}: $(-0.54\ ^{+0.40}_{-1.16} \pm 0.41)$%

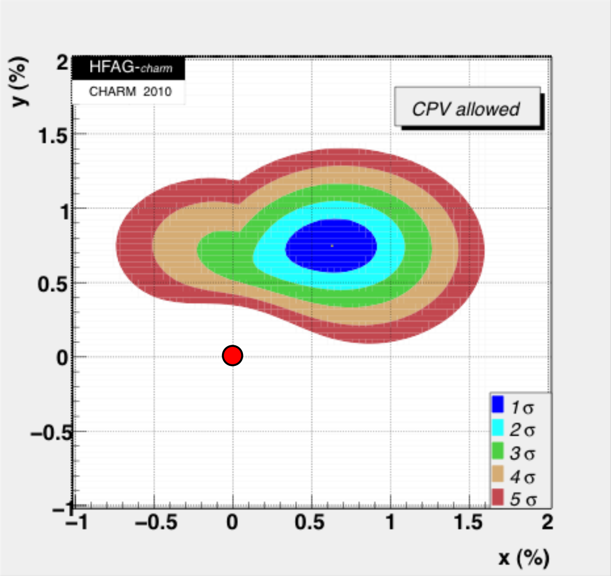
Phys. Rev .Lett. 103, 211801 (2009)

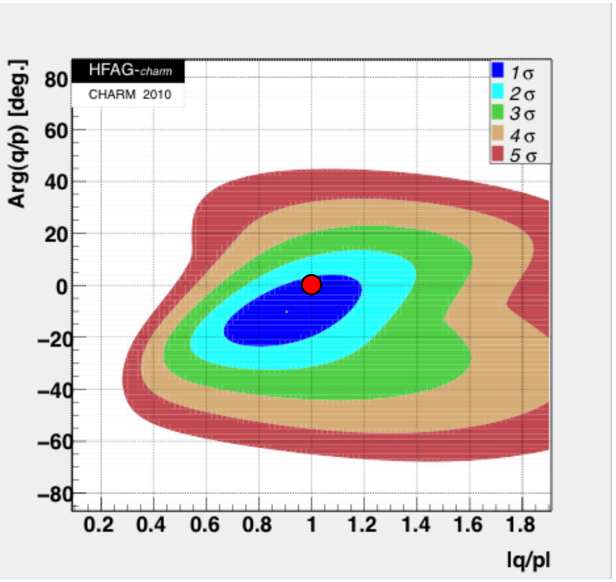


No mixing is excluded at the 99% confidence level.

HFAG Summary from October, 2010







Fit to all time-dependent CPV measurements.

CPV-allowed plot, no mixing (x,y) = (0,0) point: $\Delta\chi^2 = 109.6$, CL = 1.56 x 10^{-24}, no mixing excluded at 10.2σ

No CPV (|q/p|, φ) = (1,0) point: $\Delta\chi\ 2 = 1.218$, CL = 0.456 , consistent with CP conservation

Time-Integrated Charm CP Violation

- Three possible origins:
    - direct CPV
    - mixing-related CPV (universal – see Grossman, Kagan, Nir, PRD 75, 036008, 2007)
    - residual neutral kaon CPV

- Can study overall rate asymmetries
- Can study Dalitz plot structure differences
- Can study T-odd asymmetries in triple-product correlations (requires four-body decay)

- Need to account for forward-backward production asymmetries in e^+e^- experiments, A_{FB}.
- Need to account for differences in detection efficiencies.

Time Integrated CPV in $D^0 \to K^-K^+$, $\pi^-\pi^+$

Both BaBar and Belle use e+e- production of $D^{*+} \to D^0 \pi_s^+$ to tag flavor of neutral D

$$A_{CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)} = a_m + a_i + a_d$$

$$A_{rec}(f) = \frac{N(D^0 \to f) - N(\overline{D}^0 \to f)}{N(D^0 \to f) + N(\overline{D}^0 \to f)} = A_{CP}(f) + A_{FB} + A_\epsilon^{\pi_s}$$

Decay	BaBar (%)	Belle (%) (%)
$A_{CP}(D^0 \to K^-K^+)$	$0.00 \pm 0.34 \pm 0.13$	$-0.43 \pm 0.30 \pm 0.11$
$A_{CP}(D^0 \to \pi^-\pi^+)$	$-0.24 \pm 0.52 \pm 0.22$	$0.43 \pm 0.52 \pm 0.12$

BaBar Phys. Rev. Lett. 100, 061803 (2008)
Belle Phys. Lett. B670, 190 (2008)

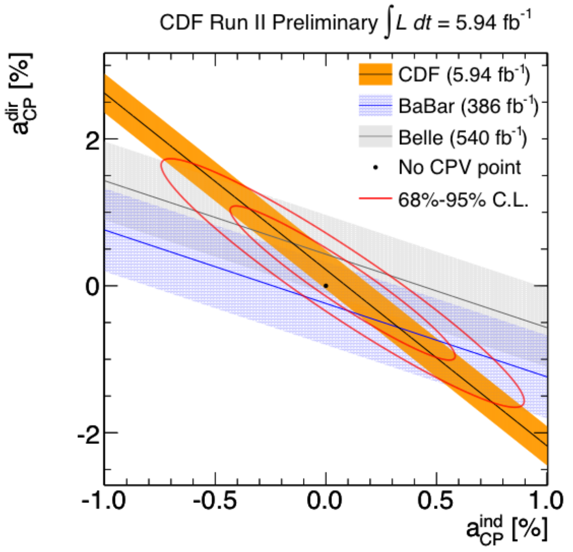
CDF's Time Integrated CPV in $D^0 \to \pi^-\pi^+$

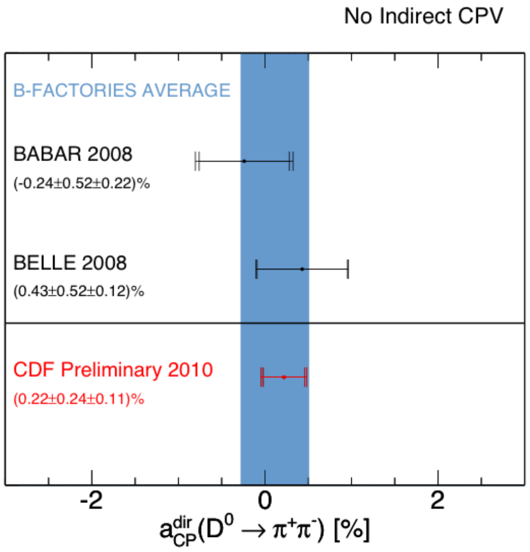
arXiv:1011.4892v3

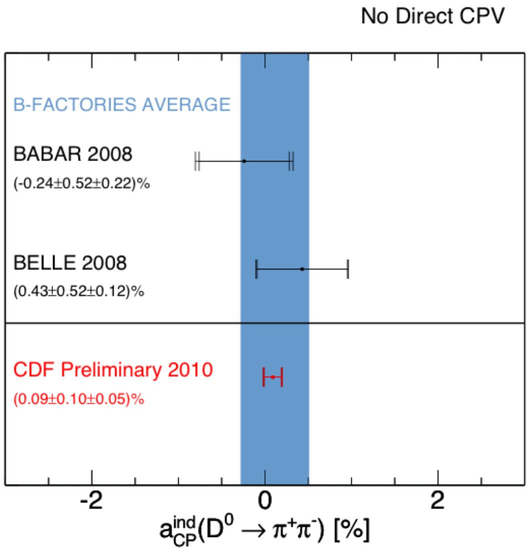
$$A_{CP}(D^0 \to \pi^-\pi^+) \approx a_d + \frac{\langle t \rangle}{\tau}(a_m + a_i)$$

$$\mathrm{CDF:} \quad A_{CP}(\pi^-\pi^+) = (0.22 \pm 0.24 \pm 0.11)\%$$

$$\langle t \rangle = (2.40 \pm 0.03)$$



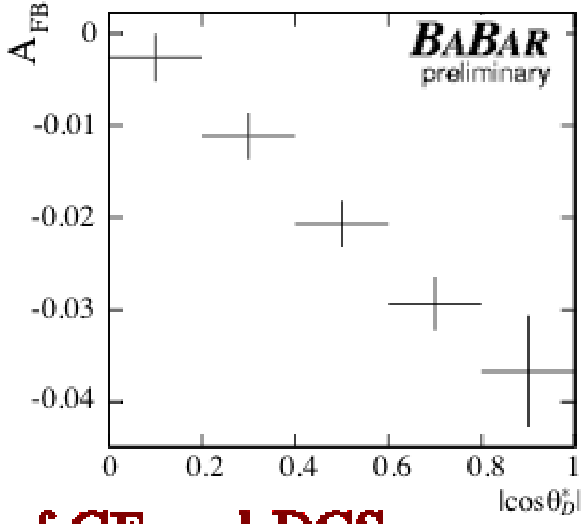




CPV in D^+, $D_S^+ \to K_S^0 K^+$, $K_S^0 \pi^+$

These are charged decays, so only direct CPV and residual neutral kaon CPV contribute.

Belle PRL 104, 181602 (2010)
BaBar arXiv:1011.5477v4



$D^+ \to K_S^0 K^+$ & $D_S^+ \to K_S^0 \pi^+$ are SCS

$D_S^+ \to K_S^0 K^+$ & $D^+ \to K_S^0 \pi^+$ are mixtures of CF and DCS

Decay	Belle (%)	BaBar (%) (preliminary)	SM (%)
$A_{CP}(D^+ \to K_S^0 \pi^+)$	$-0.71 \pm 0.019 \pm 0.20$	$-0.44 \pm 0.13 \pm 0.10$	-0.33
$A_{CP}(D_S^+ \to K_S^0 \pi^+)$	$+5.45 \pm 2.50 \pm 0.33$	–	$+0.33$
$A_{CP}(D^+ \to K_S^0 K^+)$	$-0.16 \pm 0.58 \pm 0.25$	–	-0.33
$A_{CP}(D_S^+ \to K_S^0 K^+)$	$+0.12 \pm 0.36 \pm 0.22$	–	-0.33

CPV in $\mathbf{D^0 \to K^0_S\,\pi^0,\ K^0_S\,\eta,\ K^0_S\,\eta'}$

These are neutral decays. To determine the flavor, only charged D* decay products are used. Mixing-related CPV, direct CPV, and residual neutral kaon CPV contribute all contribute to the observed asymmetries.

Belle arXiv:1101.3365v1 (791 fb^{-1})

$$\begin{aligned}
\mathcal{A}_{CP}(D^0 \to K^0_S\,\pi^0) &= -0.28 \pm 0.19 \pm 0.10 \\
\mathcal{A}_{CP}(D^0 \to K^0_S\,\eta\,) &= 0.54 \pm 0.51 \pm 0.16 \\
\mathcal{A}_{CP}(D^0 \to K^0_S\,\eta') &= 0.98 \pm 0.67 \pm 0.14
\end{aligned}$$

Standard Model predicts -0.33

CPV in T-odd correlations of $D^0 \to K^- K^+ \pi^- \pi^+$

$$C_T \equiv p_{K^+} \cdot (p_{\pi^+} \times p_{\pi^-})$$

$$\bar{C}_T \equiv p_{K^-} \cdot (p_{\pi^-} \times p_{\pi^+})$$

$$A_T \equiv \frac{\Gamma(C_T > 0) - \Gamma(C_T < 0)}{\Gamma(C_T > 0) + \Gamma(C_T < 0)}$$

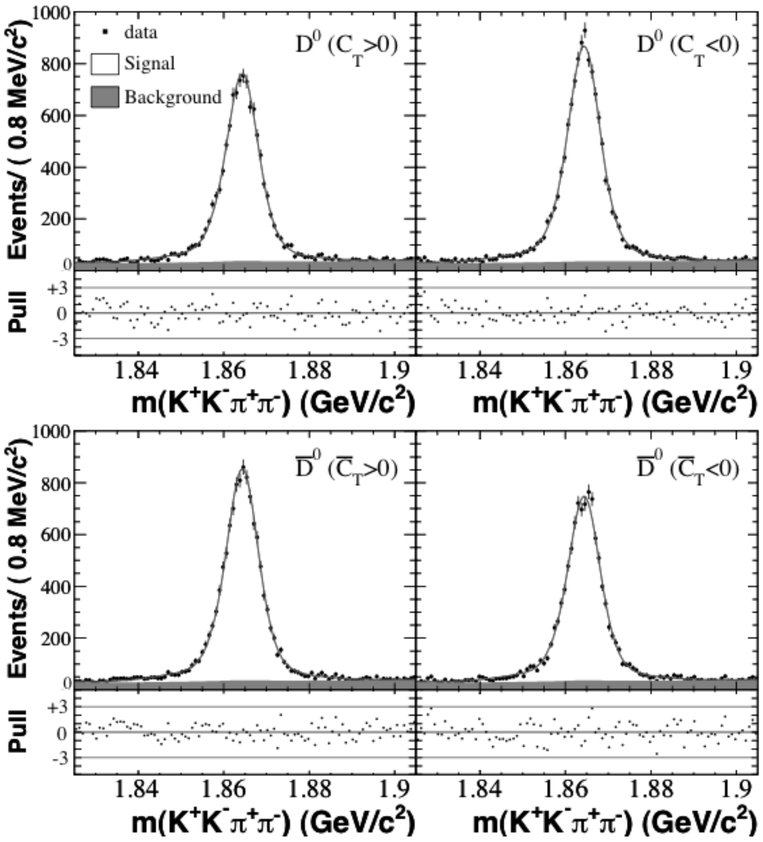
$$\bar{A}_T \equiv \frac{\Gamma(-\bar{C}_T > 0) - \Gamma(-\bar{C}_T < 0)}{\Gamma(-\bar{C}_T > 0) + \Gamma(-\bar{C}_T < 0)}$$

$$\mathcal{A}_T \equiv \frac{1}{2}\left(A_T - \bar{A}_T\right)$$

$$A_T = (-68.5 \pm 7.3 \pm 5.8) \times 10^{-3}$$

$$\bar{A}_T = (-70.5 \pm 7.3 \pm 3.9) \times 10^{-3}$$

$$\mathcal{A}_T = (1.0 \pm 5.1 \pm 4.4) \times 10^{-3}$$



BaBar PRD 81, 111103(R) , 2010

Why Next Generation Flavor Factories?

- Why build a high luminosity flavor factory in the era of the LHC?
  - What is the nature of electroweak symmetry breaking (EWSB)? Is it a simple Higgs, SUSY, a GUT, ETC, something else? The mass scale is probably somewhere in the 100 GeV - 1 TeV range.
  - What is cold dark matter? How does it couple to flavor? The concordance model of cosmology predicts a mass near that of the EWSB level.
  - Is there a fourth generation of quarks?
  - Is there other, new physics at 100 GeV – 1 TeV in mass?

- With 100 times the integrated luminosity of BaBar, CPV at SuperB will be sensitive to canonical interactions mediated by particles of mass up to about 1 TeV.
- SuperB will also be sensitive to new physics via very rare decays, lepton flavor violation, and lepton non-universality.

SuperB Accelerator Design Goals & Issues

$$\mathcal{L} = 10^{36}\ \ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1};\quad \int \mathcal{L}\,dt = 75\ \mathrm{ab}^{-1}\qquad \text{at the }\Upsilon(4S)$$

$$\mathcal{L} = 10^{35}\ \ \mathrm{cm}^{-2}\ \mathrm{sec}^{-1};\quad \int \mathcal{L}\,dt = 500\ \mathrm{fb}^{-1}\qquad \text{at the }\Psi(3770)$$

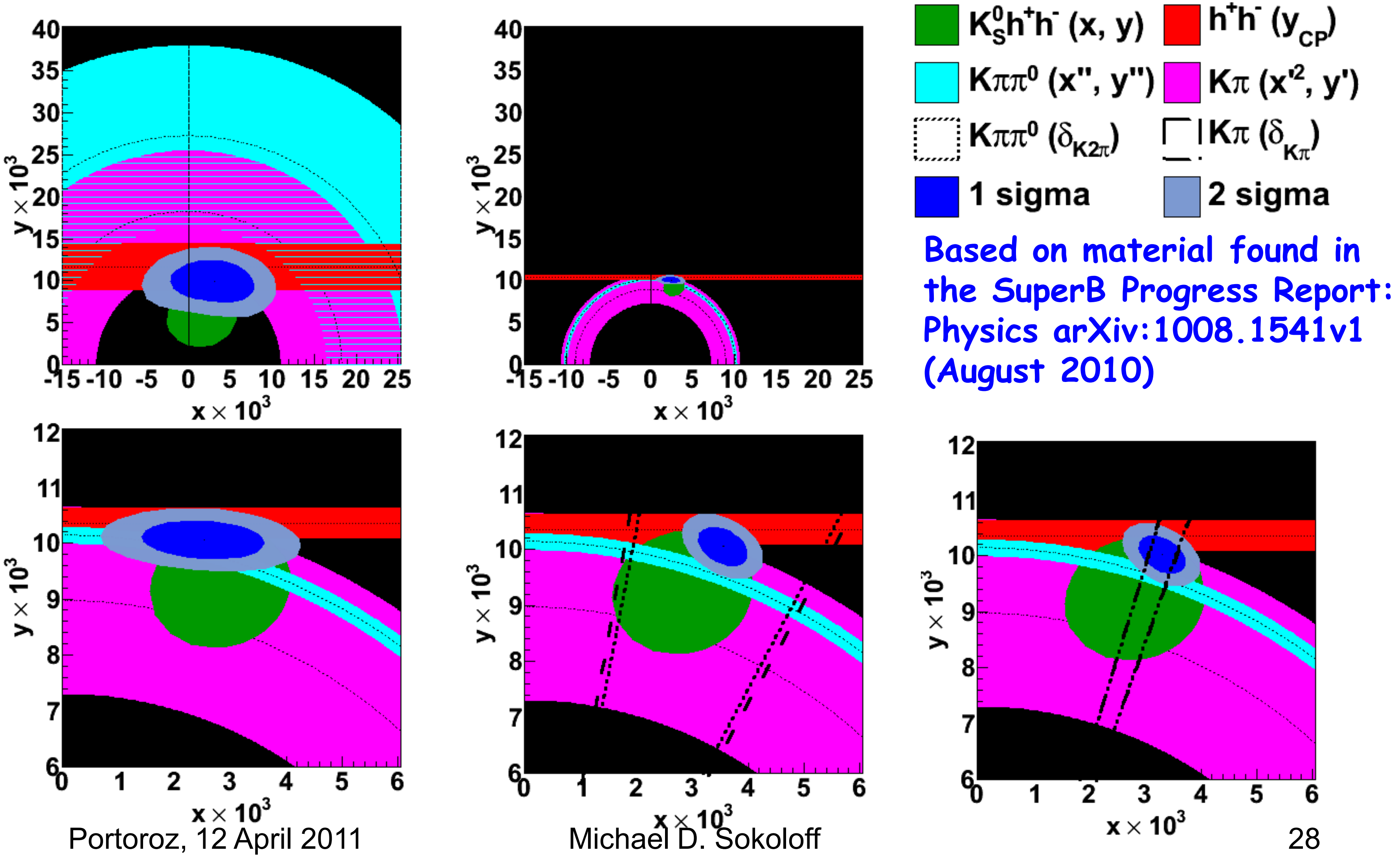
Baseline Design

- 6.7 GeV e^+ x 4.18 GeV e^- ($\beta\gamma \sim 0.24$)
- 1892 mA x 2410 mA
- 80% polarization of the electron beam
- beam size is ~ 7 μm horizontal x 35 nm vertical
- total RF power is 17 MW
- luminosity lifetimes are 4.82 & 6.14 minutes

  beam lifetimes ~ 4 minutes
- circumference 1258 meters (fits onto LNF site)
- designed to re-use PEP-II magnets and RF

Full funding approved by Italian Parliament

The Charm of SuperB



Based on material found in the SuperB Progress Report: Physics arXiv:1008.1541v1 (August 2010)

Conclusions

- Collective evidence for D^0-$\bar{D}^0$ mixing is compelling
  - The no-mixing point is excluded at >10σ, including systematic uncertainties. Results may be consistent with SM expectations.
  - No single measurement exceeds 5σ
- No evidence of CP violation
  - Sensitivity (1σ error) is better than 1% in many channels, and as low as 0.2% in several. SM predictions are as high as 0.3% for residual kaon CPV and (perhaps) 0.1% from CKM matrix elements for SCS decays.
- Future experiments (BES-III, LHCb, Belle-II, and SuperB) will improve measurements of x, y, |q/p| and arg(q/p) by an order of magnitude, reducing corresponding areas in the relevant 2-D plots by factors of 100.
- The LHC (and perhaps the Tevatron) will observe New Physics directly in the next 5 years. How can it be observed in the charm sector?

Backup Slides