Measurements of $\bar{D}^0$-D^0 mixing and searches for *CPV*:
HFAG combination of all data

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BES-Belle-CLEO-BaBar
Joint Workshop on Charm Physics
IHEP, Beijing
November 26th, 2007

- the HFAG charm group
- D^0 meson mixing
- old and new measurements
- combining all results assuming no *CPV*
- combining all results allowing for *CPV*

http://www.slac.stanford.edu/xorg/hfag/charm/index.html

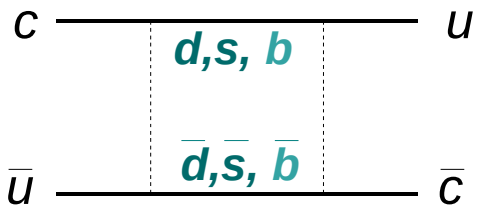
HFAG charm group http://www.slac.stanford.edu/xorg/hfag/charm/index.html

Began fall 2006 with representatives from relevant experiments:

BABAR	*Milind Purohit (+E791), Brian Petersen*
BELLE	*Bostjan Golob, Alan Schwartz*
BES	*Changzheng Yuan*
CDF	*Mark Mattson*
CLEO-c	*Lawrence Gibbons, David Asner*
D0	*Brendan Casey*
FOCUS	*Daniele Pedrini*

Although the "youngest" HFAG group, now one of the largest

Neutral meson mixing I:



Flavor eigenstates are not mass eigenstates:

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

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

$$|D^0\rangle = \frac{1}{2p}\left(|D_1\rangle+|D_2\rangle\right)\qquad\qquad |\overline{D}^0\rangle = \frac{1}{2q}\left(|D_1\rangle-|D_2\rangle\right)$$

$$\begin{aligned}|D^0(t)\rangle &= e^{-(\overline{\Gamma}/2+i\overline{m})\,t}\left\{\cosh\left[(\Delta\gamma/4+i\Delta m/2)t\right]|D^0\rangle+\left(\frac{q}{p}\right)\sinh\left[(\Delta\gamma/4+i\Delta m/2)t\right]|\overline{D}^0\rangle\right\}\\ |\overline{D}^0(t)\rangle &= e^{-(\overline{\Gamma}/2+i\overline{m})\,t}\left\{\left(\frac{p}{q}\right)\sinh\left[(\Delta\gamma/4+i\Delta m/2)t\right]|D^0\rangle+\cosh\left[(\Delta\gamma/4+i\Delta m/2)t\right]|\overline{D}^0\rangle\right\}\end{aligned}$$

$$\overline{m}\equiv\frac{1}{2}\left(m_1+m_2\right)\qquad \overline{\Gamma}\equiv\frac{1}{2}\left(\Gamma_1+\Gamma_2\right)\qquad \Delta m\equiv m_2-m_1\qquad \Delta\gamma\equiv\Gamma_2-\Gamma_1$$

Neutral meson mixing II

$$\langle f|H|D^0(t)\rangle = e^{-(\overline{\Gamma}/2+i\overline{m})\,t}\left\{\cosh\left[(\Delta\gamma/4+i\Delta m/2)t\right]\mathcal{A}_f + \left(\frac{q}{p}\right)\sinh\left[(\Delta\gamma/4+i\Delta m/2)t\right]\bar{\mathcal{A}}_f\right\}$$

$$\langle \bar{f}|H|\overline{D}^0(t)\rangle = e^{-(\overline{\Gamma}/2+i\overline{m})\,t}\left\{\left(\frac{p}{q}\right)\sinh\left[(\Delta\gamma/4+i\Delta m/2)t\right]\mathcal{A}_{\bar{f}} + \cosh\left[(\Delta\gamma/4+i\Delta m/2)t\right]\bar{\mathcal{A}}_{\bar{f}}\right\}$$

$$\mathcal{A}_f \equiv \langle f|H|D^0\rangle \qquad \bar{\mathcal{A}}_f \equiv \langle f|H|\overline{D}^0\rangle$$
$$\mathcal{A}_{\bar{f}} \equiv \langle \bar{f}|H|D^0\rangle \qquad \bar{\mathcal{A}}_{\bar{f}} \equiv \langle \bar{f}|H|\overline{D}^0\rangle$$

Since $\Delta m\, t \ll 1$ and $\Delta\gamma t \ll 1$, expand $\cos(\Delta m\, t)$, $\cosh(\Delta\gamma/2)t$, $\sin(\Delta m\, t)$, $\sinh(\Delta\gamma/2)t$:

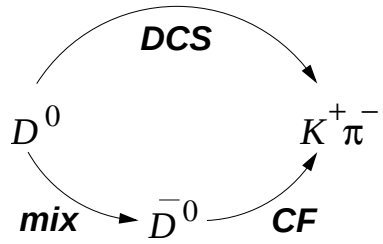
$$R(D^0(t)\to f) \propto e^{-\overline{\Gamma}t}\left\{1 + \left[\,y\,\mathrm{Re}(\lambda) - x\,\mathrm{Im}(\lambda)\,\right](\overline{\Gamma}t) + |\lambda|^2\frac{(x^2+y^2)}{4}(\overline{\Gamma}\,t)^2\right\}$$

$$R(\overline{D}^0(t)\to \bar{f}) \propto e^{-\overline{\Gamma}t}\left\{1 + \left[\,y\,\mathrm{Re}(\bar{\lambda}) - x\,\mathrm{Im}(\bar{\lambda})\,\right](\overline{\Gamma}t) + |\bar{\lambda}|^2\frac{(x^2+y^2)}{4}(\overline{\Gamma}\,t)^2\right\}$$

Direct **Interference** **Mixing**

$$x \equiv \frac{\Delta m}{\overline{\Gamma}} \qquad y \equiv \frac{\Delta\Gamma}{2\overline{\Gamma}} \qquad \lambda \equiv \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} \qquad \bar{\lambda} \equiv \frac{p}{q}\frac{\mathcal{A}_{\bar{f}}}{\bar{\mathcal{A}}_{\bar{f}}}$$

MIXING PARAM. ***CPV* enters here**



D^0 mixing measurements


Moriond'07

- **Wrong-sign semileptonic $D^0(t) \to K^+ l^- \nu$ decays**
  measures x^2+y^2, no *DCS* contamination


Moriond'07

- **Wrong-sign hadronic $D^0(t) \to K^+\pi^-$ decays**
  measures $x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$,
  where δ is a strong phase difference, and R_D


Moriond'07


LP'07

- **Decays to *CP* eigenstates: $D^0(t) \to K^+K^-, \pi^+\pi^-$**
  measures $y\cos\phi$ and $x\sin\phi$, where ϕ is a weak phase difference


Moriond'07

- **Dalitz plot analysis of $D^0(t) \to K^0\pi^+\pi^-$ decays**
  measures x, y, $|q/p|$, and ϕ


LP'07

- **Wrong-sign hadronic $D^0 \to K^+\pi^-\pi^+\pi^-$, $K^+\pi^-\pi^0$ decays**
  measures x^2+y^2 , x, y

CLEOc
CHARM'07

- **Quantum correlations in $e^+e^- \to D^0\bar{D}^0(n\pi^0)$, $D^0\bar{D}^0\gamma(n\pi^0)$**
  measures R_M, y, R_D, $\cos\delta$

HFAG references I

$D^0(t) \to K^+ l^- \nu$

* E. M. Aitala et al. (E791 Collab.), Phys. Rev. Lett. 77, 2384 (1996).
* C. Cawlfield et al. (CLEO Collab.), Phys. Rev. D 71, 077101 (2005).
* U. Bitenc et al. (Belle Collab.), Phys. Rev. D 72, 071101 (2005).
* B. Aubert et al. (BaBar Collab.), arXiv:0705.0704 (submitted to Phys. Rev. D).

not used (superseded):

* B. Aubert et al. (BaBar Collab.), Phys. Rev. D 70, 091102 (2004).

$D^0(t) \to K^+ \pi^-$

* E. M. Aitala et al. (E791 Collab.), Phys. Rev. D 57, 13 (1998).
* R. Godang et al. (CLEO Collab.), Phys. Rev. Lett. 84, 5038 (2000).
* J. M. Link et al. (E831 FOCUS Collab.), Phys. Lett. B 618, 23 (2005).
* L. M. Zhang et al. (Belle Collab.), Phys. Rev. Lett. 96, 151801 (2006).
* A. Abulencia et al. (CDF Collab.), Phys. Rev. D 74, 031109(R) (2006).
* B. Aubert et al. (BaBar Collab.), Phys. Rev. Lett. 98, 211802 (2007).

not used (low statistics/superseded/no preprint):

* J. C. Anjos et al. (E691 Collab.), Phys. Rev. Lett. 60, 1239 (1988).
* D. Cinabro et al. (CLEO Collab.), Phys. Rev. Lett. 72, 1406 (1994).
* R. Barate et al. (ALEPH Collab.), Phys. Lett. B 436, 211 (1998).
* J. M. Link et al. (E831 FOCUS Collab.), Phys. Rev. Lett. 86, 2955 (2001).
* J. Li et al. (Belle Collab.), Phys. Rev. Lett. 94, 071801 (2005).
* B. Aubert et al. (BaBar Collab.), Phys. Rev. Lett. 91, 171801 (2003).
* K. Tollefson (CDF Collab.), presented at LP'07, Daegu, S. Korea, 13 August 2007.

HFAG references II http://www.slac.stanford.edu/xorg/hfag/charm/index.html

$D^0 \to K^+\pi^-\pi^+\pi^-$, $K^+\pi^-\pi^0$

* X. C. Tian et al. (Belle Collab.), Phys. Rev. Lett. 95, 231801 (2005).
* B. Aubert et al. (BaBar Collab.), hep-ex/0607090 (unpublished).
* W. Lockman (BaBar Collab.), presented at LP'07, Daegu, S. Korea, 13 August 2007.

not used (low statistics/superseded):

* E. M. Aitala et al. (E791 Collab.), Phys. Rev. D 57, 13 (1998).
* G. Brandenburg et al. (CLEO Collab.), Phys. Rev. Lett. 87, 071802 (2001).
* S. A. Dytman et al. (CLEO Collab.), Phys. Rev. D 64, 111101 (2001).
* B. Aubert et al. (BaBar Collab.), Phys. Rev. Lett. 97, 221803 (2006).

$D^0(t) \to K^+K^-$, $\pi^+\pi^-$

* E. M. Aitala et al. (E791 Collab.), Phys. Rev. Lett. 83, 32 (1999).
* J. M. Link et al. (E831 FOCUS Collab.), Phys. Lett. B 485, 62 (2000).
* S. E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).
* K. Abe et al. (Belle Collab.), Phys. Rev. Lett. 88, 162001 (2002).
* M. Staric et al. (Belle Collab.), Phys. Rev. Lett. 98, 211803 (2007).
* W. Lockman (BaBar Collab.), presented at LP'07, Daegu, S. Korea, 13 August 2007.

not used (superseded):

* K. Abe et al. (Belle Collab.), hep-ex/0308034 (unpublished).
* B. Aubert et al. (BaBar Collab.), Phys. Rev. Lett. 91, 121801 (2003).

HFAG references III http://www.slac.stanford.edu/xorg/hfag/charm/index.html

Dalitz plot analysis of $D^0(t) \to K^0 \pi^+\pi^-$ decays

* D. M. Asner et al. (CLEO Collab.), Phys. Rev. D 72, 012001 (2005).
(hep-ex/0503045 revised April 2, 2007)
* L. M. Zhang et al. (Belle Collab.), Phys. Rev. Lett. 99, 131803 (2007).

$e^+e^- \to \psi(3770) \to D^0D^0(n\pi^0)$, $D^0D^0\gamma(n\pi^0)$

* W. Sun (CLEO Collab.), presented at Charm'07 Workshop, Cornell University, 5 August 2007.

not used (superseded):

* D. M. Asner et al. (CLEO Collab.), Int. J. Mod. Phys. A21 5456 (2006).

HFAG combination of all results

Two methods:

(1) ***convert all measurements to log(likelihood) functions in a 3-dimensional space of*** (x, y, δ)***. Add all log(likelihood) functions together. Final likelihood function can be projected onto axes to give (conservative) confidence intervals.***

ADVANTAGE: correlations and non-Gaussian errors are automatically accounted for

DISADVANTAGE: must obtain log(likelihood) function from experiments. Binning will be different ⇒ requires interpolation.

(2) ***do MINUIT fit of 8 parameters*** $(x, y, \delta, R_D, A_D, |q/p|, \phi, \delta_2)$ ***to 26 observables.***

ADVANTAGE: uses published measurements; easy to include/exclude *CPV*

DISADVANTAGE: must obtain correlation matrix from experiments. Does not account for non-Gaussian errors.

HFAG input values I:

$D^0 \to K^+K^-/\pi^+\pi^-$

$D^0 \to K^0_S\pi^+\pi^-$

$D^0 \to K^+l^-\nu$

Index	Observable	Value	Source
1	y_{CP}	(1.234 ± 0.275)%	World average (COMBOS combination) of $D^0 \to K^+K^-$ / $\pi^+\pi^-$ results
2	A_Γ	(0.123 ± 0.248)%	World average (COMBOS combination) of $D^0 \to K^+K^-$ / $\pi^+\pi^-$ results
(3-5) 6	x (no CPV)	(0.811 ± 0.334)%	No CPV: World average (COMBOS combination) of $D^0 \to K^0\pi^+\pi^-$ results CPV-allowed: Belle $D^0 \to K^0_S\pi^+\pi^-$ results; correlation coefficients: 1 −0.007 −0.255α +0.216 −0.007 1 −0.019α −0.280 −0.255α −0.019α 1 −0.128α +0.216 −0.280 −0.128α 1 (Note: $\alpha = (\lvert q/p\rvert+1)^2/2$ is a variable transformation factor)
	y (no CPV)	(0.309 ± 0.281)%	
	$\lvert q/p\rvert$ (no dCPV)	$0.95 \pm 0.22\,^{+0.10}_{-0.09}$	
	Arg(q/p)=φ (no dCPV)	(−0.035 ± 0.19 ± 0.09) radians	
	x	(0.81 ± $0.30\,^{+0.13}_{-0.17}$)%	
	y	(0.37 ± $0.25\,^{+0.10}_{-0.15}$)%	
	$\lvert q/p\rvert$	$0.86 \pm 0.30\,^{+0.10}_{-0.09}$	
	φ	(−0.244 ± 0.31 ± 0.09) radians	
7	R_M	(0.0173 ± 0.0387)%	World average (COMBOS combination) of $D^0 \to K^+l^-\nu$ results

HFAG input values II:

$D^0 \to K^+\pi^-\pi^0$

$D^0 \to K^+\pi^-\pi^+\pi^-$

CLEOc

$\psi(3770) \to D^0D^0(n\pi^0)$,
$D^0D^0\gamma(n\pi^0)$

$D^0 \to K^+\pi^-$

8	x'' y''	(2.39 ± 0.61 ± 0.32)% (−0.14 ± 0.60 ± 0.40)%	BaBar $K^+\pi^-\pi^0$ result; cortelation coefficient = −0.34. Note: $x'' = x\cos\theta'' + y\sin\theta''$, $y'' = y\cos\theta'' - x\sin\theta''$.
9	R_M	(0.019 ± 0.0161)%	BaBar $K^+\pi^-\pi^+\pi^-$ result
10	R_M y r^2 $r\cos\delta$	(0.199 ± 0.173 ± 0)% (−5.207 ± 5.571 ± 2.737)% (−2.395 ± 1.739 ± 0.938)% (8.878 ± 3.369 ± 1.579)%	CLEOc $\Psi(3770)$ results; cortelation coefficients: 1 −0.0644 0.0072 0.0607 −0.0644 1 −0.3172 −0.8331 0.0072 −0.3172 1 +0.3893 0.0607 −0.8331 +0.3893 1
11	R_D x'^{2+} y'^{+}	(0.303 ± 0.0189)% (−0.024 ± 0.052)% (0.98 ± 0.782)%	BaBar $K^+\pi^-$ results; cortelation coefficients: 1 +0.77 −0.87 +0.77 1 −0.94 −0.87 −0.94 1
12	A_D x'^{2-} y'^{-}	(−2.1 ± 5.4)% (−0.020 ± 0.050)% (0.96 ± 0.75)%	BaBar $K^+\pi^-$ results; cortelation coefficients same as above.

HFAG input values III:

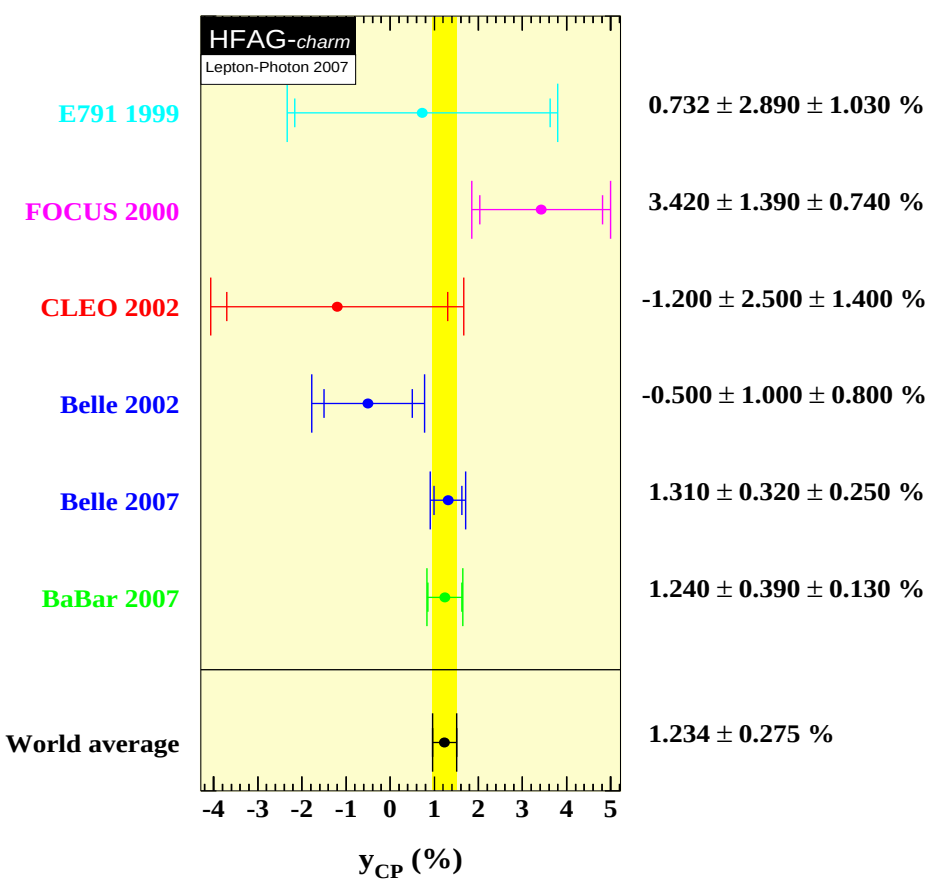
$D^0 \to K^+\pi^-$

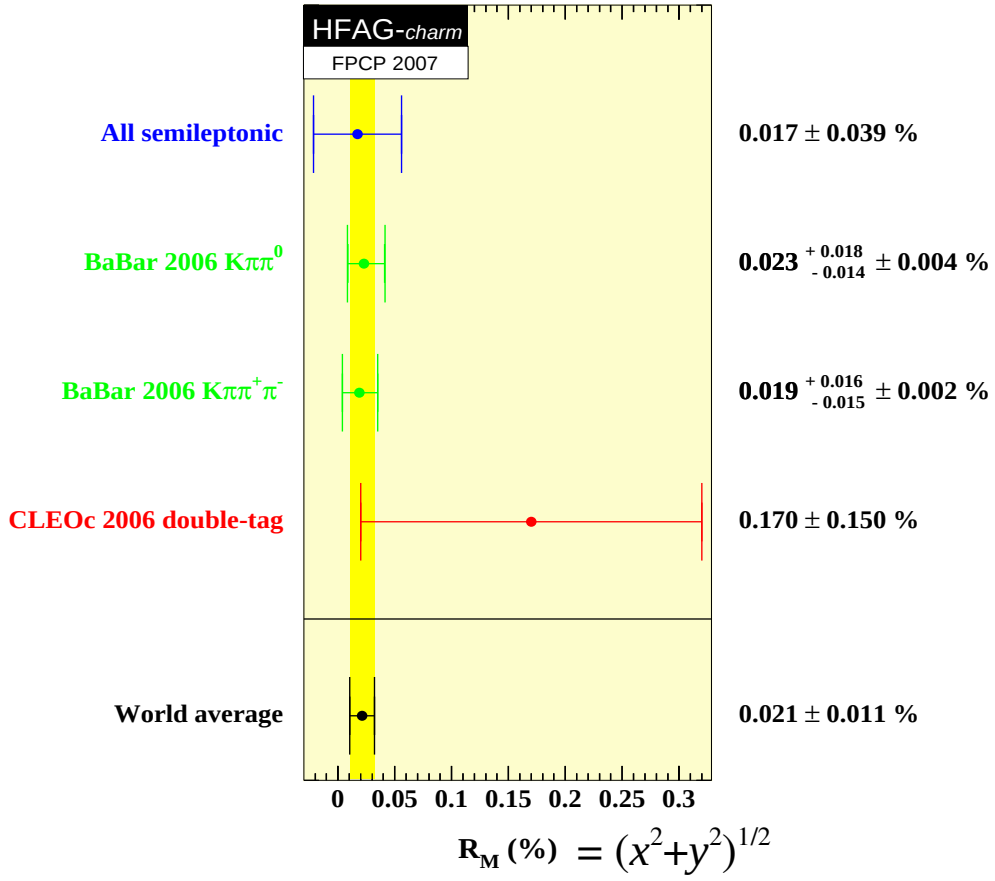
13	R_D x'^{2+} y'^{+}	(0.364 ± 0.018)% (0.032 ± 0.037)% (−0.12 ± 0.58)%	Belle $K^+\pi^-$ results; cottelation coefficients: 1 +0.655 −0.834 +0.655 1 −0.909 −0.834 −0.909 1
14	A_D x'^{2-} y'^{-}	(2.3 ± 4.7)% (0.006 ± 0.034)% (0.20 ± 0.54)%	Belle $K^+\pi^-$ results; cottelation coefficients same as above.

HFAG world average values:

We also calculate WORLD AVERAGE values of mixing parameters using the COMBOS program. We appy this to similar measurements from different experiments:

TO BE UPDATED:

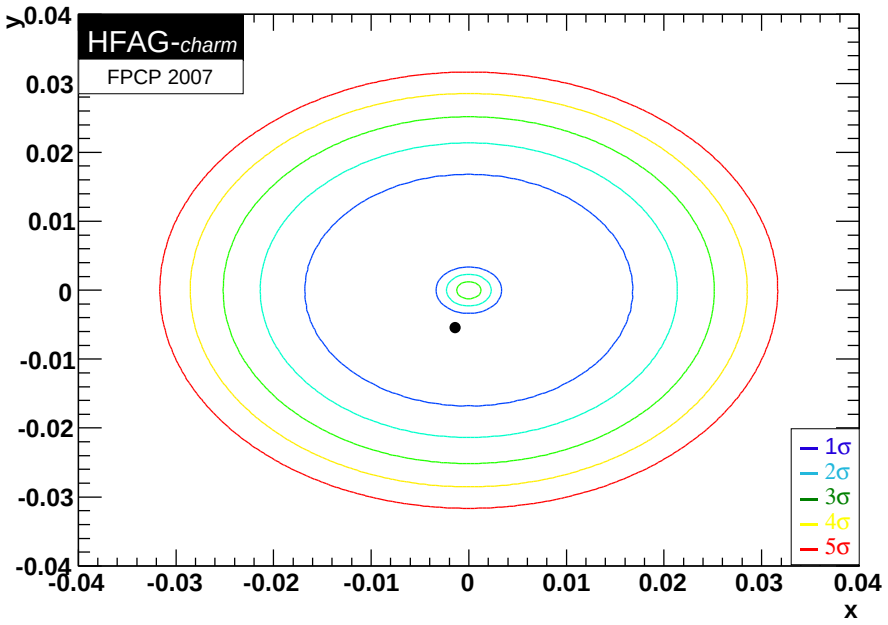




HFAG method #1: combining likelihood functions

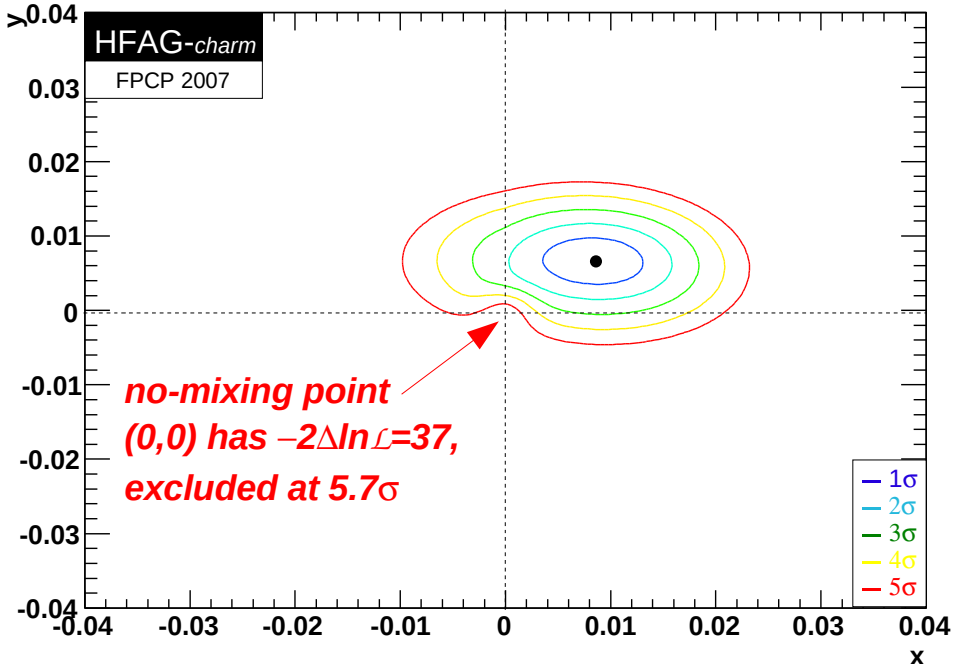
$\ln\mathcal{L}(R_D, x'^2, y')$ for $D^0(t)\to K^+\pi^-$ measurements:

- **project onto (x'^2, y') plane by allowing R_D to always take its preferred value**
- **map likelihood values to (x,y,δ) volume**
- **project onto (x,y) plane by allowing δ to always take its preferred value:**



$-2\ln\mathcal{L}$

Adding $-2\ln\mathcal{L}$ functions from $K^+\pi^-$, semileptonic decays, $K_S\pi^+\pi^-$, y_{CP}, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $\psi(3770)$:



$-2\ln\mathcal{L}$

HFAG method #2: MINUIT fit

Do global MINUIT fit: 8 parameters (x, y, δ, δ_2, R_D, A_D, |q/p|, φ), 26 observables:

$$R_M = \frac{1}{2}(x^2+y^2)$$

$$\begin{aligned} 2y_{CP} &= \big(|q/p|+|p/q|\big)y\cos\phi - \big(|q/p|-|p/q|\big)x\sin\phi \\ 2A_\Gamma &= \big(|q/p|-|p/q|\big)y\cos\phi - \big(|q/p|+|p/q|\big)x\sin\phi \end{aligned}$$

$$\begin{aligned} x_{K^0\pi\pi} &= x \\ y_{K^0\pi\pi} &= y \end{aligned}$$

$$\begin{aligned} |q/p|_{K^0\pi\pi} &= |q/p| \\ \mathrm{Arg}\,(q/p)_{K^0\pi\pi} &= \phi \end{aligned}$$

$$x'^{\pm} = \left(\frac{1\pm A_M}{1\mp A_M}\right)^{1/4}(x'\cos\phi \pm y'\sin\phi) \qquad A_M = \frac{|q/p|^2-|p/q|^2}{|q/p|^2+|p/q|^2}$$

$$y'^{\pm} = \left(\frac{1\pm A_M}{1\mp A_M}\right)^{1/4}(y'\cos\phi \mp x'\sin\phi) \qquad \begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix}\begin{pmatrix} x \\ y \end{pmatrix}$$

$$\frac{1}{2}\left[R(D^0\to K^+\pi^-)+\overline{R}(\overline{D}{}^0\to K^-\pi^+)\right] = R_D$$

$$\frac{R(D^0\to K^+\pi^-)-\overline{R}(\overline{D}{}^0\to K^-\pi^+)}{R(D^0\to K^+\pi^-)+\overline{R}(\overline{D}{}^0\to K^-\pi^+)} = A_D$$

HFAG method #2: MINUIT fit

FCN= 24.43161 FROM MINOS STATUS=SUCCESSFUL 2127 CALLS 150920 TOTAL
EDM= 0.26E-05 STRATEGY=1 ERROR MATRIX UNCERTAINTY= 4.4%

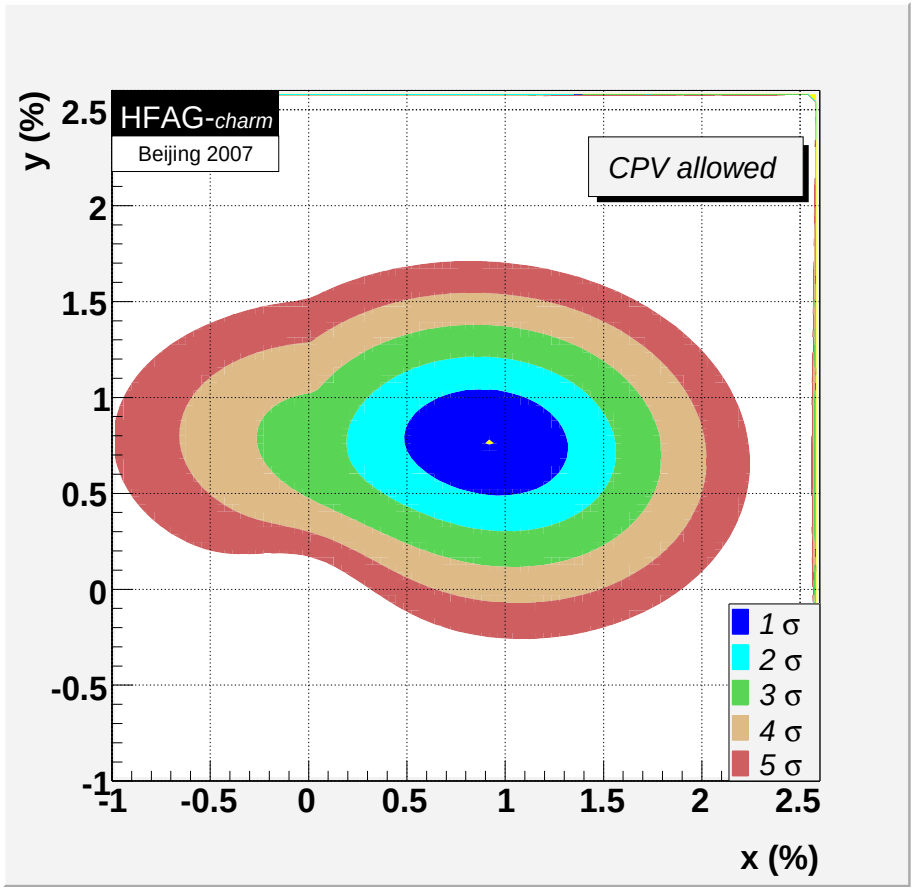
EXT PARAMETER			PARABOLIC	MINOS ERRORS	
NO.	NAME	VALUE	ERROR	NEGATIVE	POSITIVE
1	x	0.95990 %	0.24840	-0.28459	0.27081 %
2	y	0.81043 %	0.18261	-0.18719	0.18254 %
3	delta	0.41333 rad	0.19682	-0.21706	0.20009 rad
4	rd	0.33468 %	0.0061084	-0.0093041	0.0092887 %
5	ad	-2.2165	2.3845	-2.4993	2.4876
6	qovp	0.85944	0.16656	-0.14889	0.17661
7	phi	-0.16410	0.15085	-0.16173	0.14231
8	delta2	0.59056 rad	0.43650	-0.44818	0.43464 rad

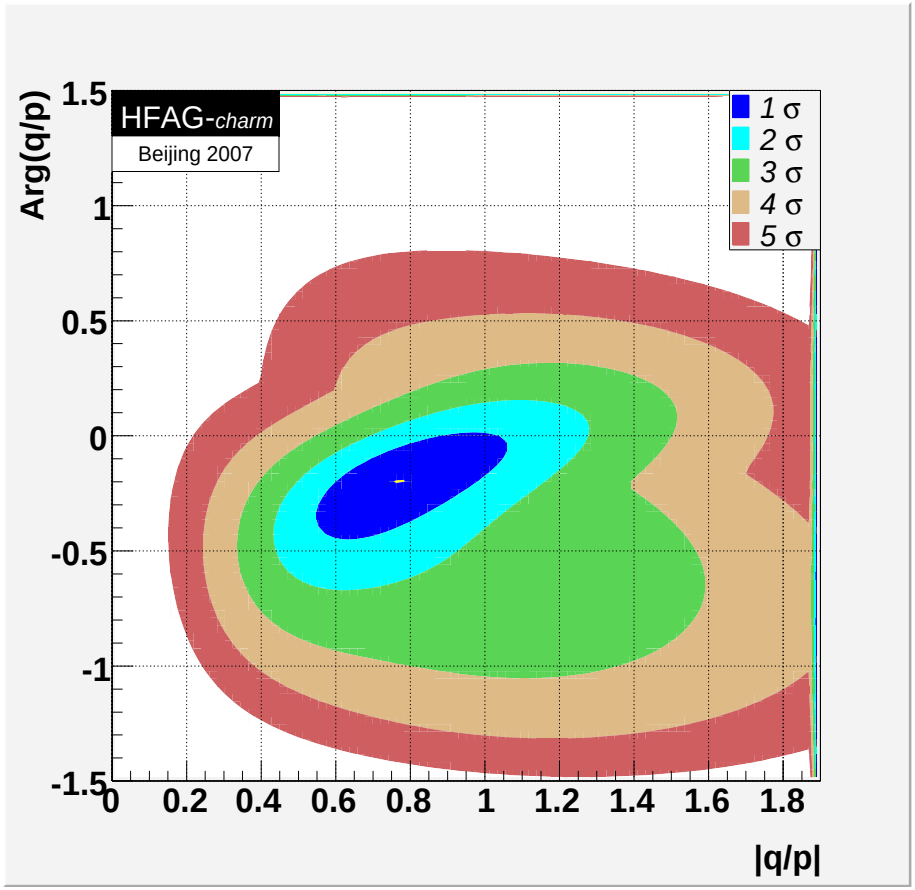
NO DIRECT CPV:

EXT PARAMETER			PARABOLIC	MINOS ERRORS	
NO.	NAME	VALUE	ERROR	NEGATIVE	POSITIVE
1	x	0.96523 %	0.27871	-0.28553	0.27196 %
2	y	0.81941 %	0.18589	-0.18754	0.18416 %
3	delta	0.44107 rad	0.20435	-0.21628	0.20215 rad
4	rd	0.33462 %	0.0092147	-0.0092496	0.0091855 %
5	ad	0.0000	fixed		
6	qovp	0.94615	0.14159	-0.13438	0.14883
7	phi	-0.046634	0.094019	-0.099127	0.092676
8	delta2	0.59479 rad	0.43535	-0.44674	0.43337 rad

Observable		χ^2	$\Sigma\chi^2$
f[y_CP	] =	2.66	2.66
f[A_Gamma	] =	0.12	2.78
f[x(K0p+p-)	] =	0.19	2.97
f[y(K0p+p-)	] =	2.26	5.23
f[|q/p| (K0p+p-)	] =	0.00	5.23
f[Arg(q/p) (K0p+p-)	] =	0.53	5.76
f[R_M(semilept)	] =	0.06	5.82
f[x(K+p-p0)	] =	1.04	6.86
f[y(K+p-p0)	] =	1.74	8.60
f[RM/ysq/rsq/rcd (psi_3770)]	=	5.64	14.24
f[K+pi- BaBar+	] =	2.55	16.79
f[K+pi- BaBar-	] =	1.77	18.55
f[K+pi- Belle+	] =	3.97	22.52
f[K+pi- Belle-	] =	1.44	23.96
f[R_M(K+p-p+p-)	] =	0.48	24.43

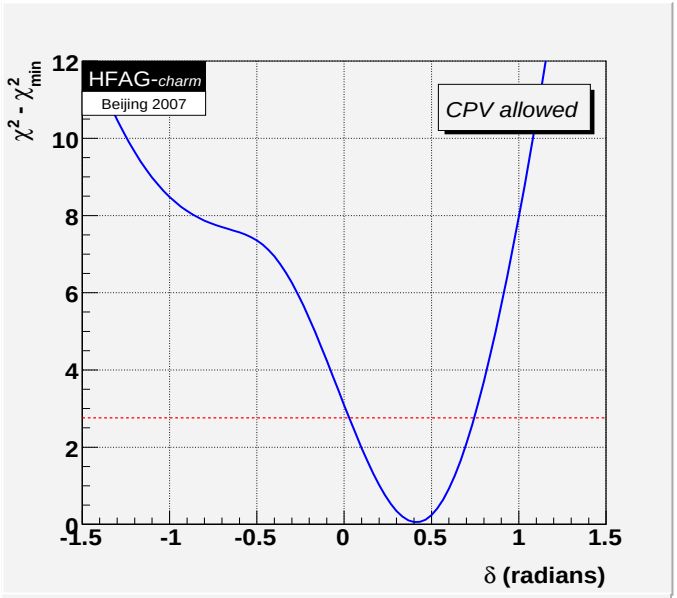
HFAG 2-dim. likelihood plots (MNCONTOUR-like) :



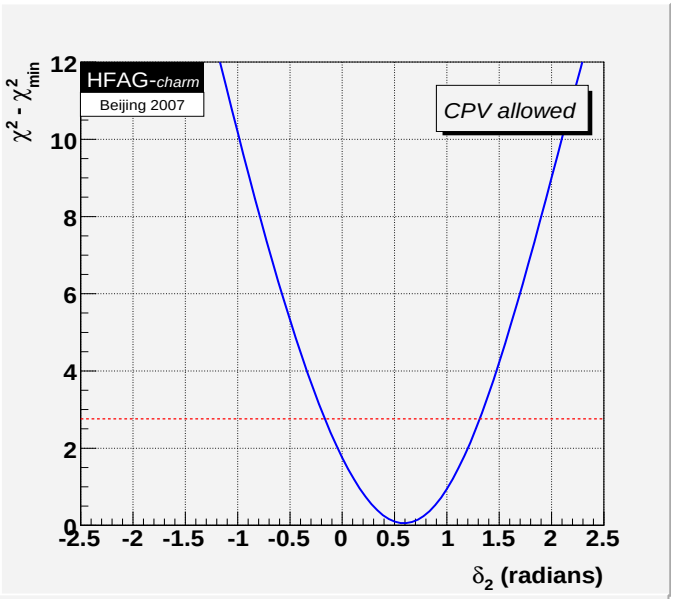


HFAG 1-dim. likelihood curves *(MNCONTOUR-like)*:

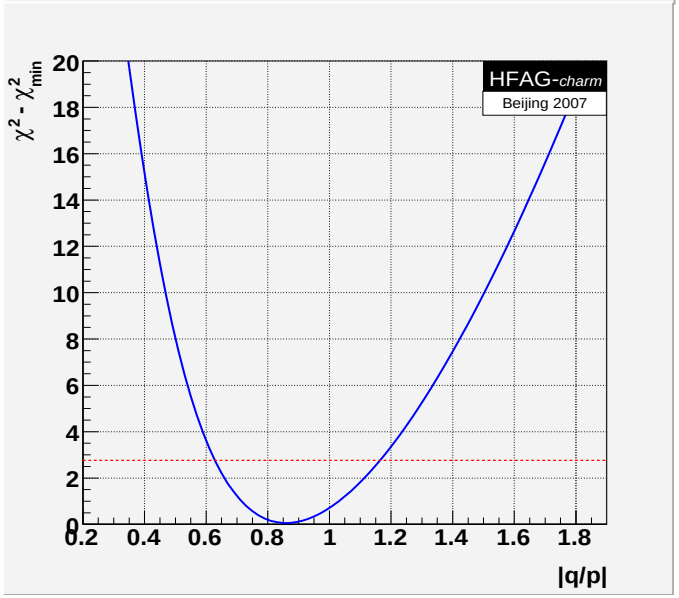
δ



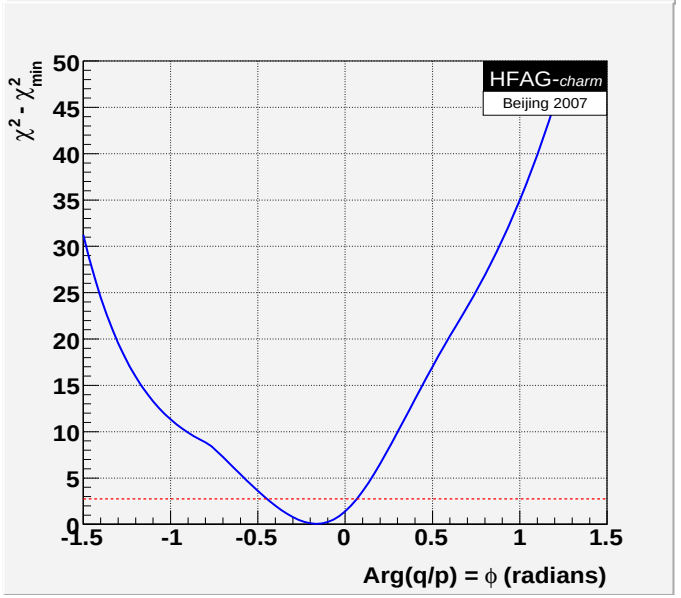
δ_2



$|q/p|$

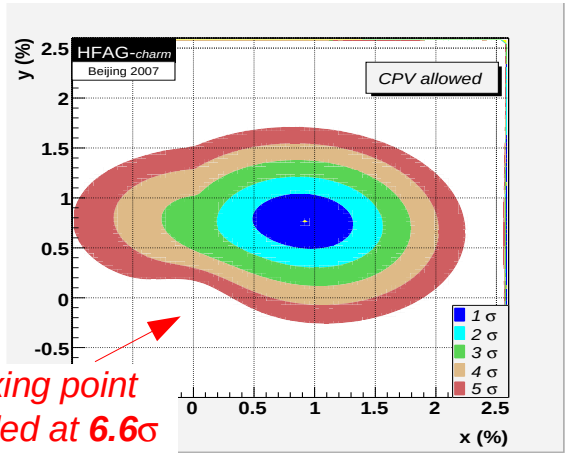


ϕ

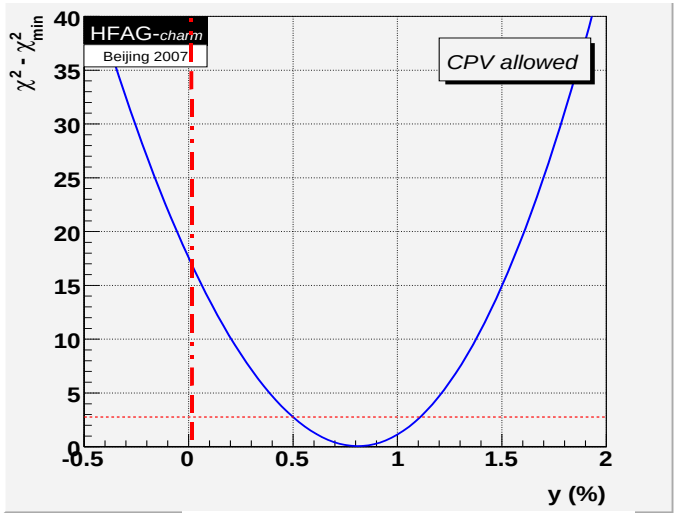


Summary

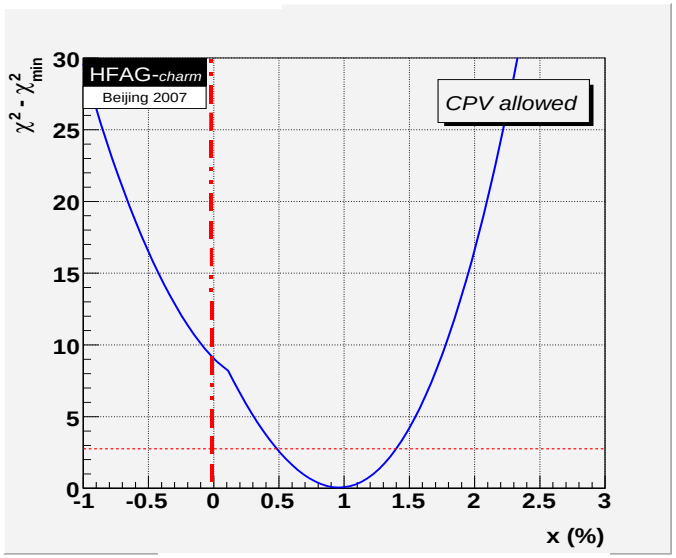
All data [semileptonic decays, $K^+\pi^-$, $K_S\pi\pi$, y_{CP}, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$, $\psi(3770)$]:



*no-mixing point excluded at **6.6**σ*



y projection



x projection

$x = (0.96\ ^{+0.27}_{-0.28})\%$
(3.4σ above zero)

$y = (0.81^{+0.18}_{-0.19})\%$
(4.3σ above zero)

$\delta = (24\ ^{+11}_{-12})^o$
(2σ above zero)

Conclusions:

Evidence is consistent and convincing that D^0's mix; effect is dominated by non-perturbative processes. Unless $|x|>>|y|$, may be hard to identify new physics.

Since y_{CP} is positive, CP-odd state is longer-lived (like other neutral meson systems); but positive x/y implies CP-odd is lighter (unlike K^0 system)

No evidence yet for CPV (a true sign of NP)

Belle $D^0(t) \to K^+\pi^-$ allowing for CPV (400 fb^{-1})

$$\lambda = \left(\frac{q}{p}\right)\frac{\overline{\mathcal{A}}_f}{\mathcal{A}_f} = \left|\frac{q}{p}\right|\sqrt{R_D}\, e^{i(\phi+\delta)} \qquad \bar{\lambda} = \left(\frac{p}{q}\right)\frac{\mathcal{A}_{\bar{f}}}{\overline{\mathcal{A}}_{\bar{f}}} = \left|\frac{p}{q}\right|\sqrt{\overline{R}_D}\, e^{i(-\phi+\delta)}$$

$$R_{D^0\to f} \propto e^{-\overline{\Gamma}t}\left\{R_D + \sqrt{R_D}\left|\frac{q}{p}\right|(y'\cos\phi - x'\sin\phi)(\overline{\Gamma}t) + \left|\frac{q}{p}\right|^2\frac{(x'^2+y'^2)}{4}(\overline{\Gamma}t)^2\right\}$$

$$R_{\overline{D}^0\to \bar{f}} \propto e^{-\overline{\Gamma}t}\left\{\overline{R}_D + \sqrt{\overline{R}_D}\left|\frac{p}{q}\right|(y'\cos\phi + x'\sin\phi)(\overline{\Gamma}t) + \left|\frac{p}{q}\right|^2\frac{(x'^2+y'^2)}{4}(\overline{\Gamma}t)^2\right\}$$

$A_D \equiv (R_D - \overline{R}_D)/(R_D + \overline{R}_D) \neq 0$	CPV in the decay amplitude (direct CPV)
$A_M \equiv (\lvert q\rvert^4 - \lvert p\rvert^4)/(\lvert q\rvert^4 + \lvert p\rvert^4) \neq 0$	CPV in mixing
$\phi \neq 0$	CPV in mixed/direct interference

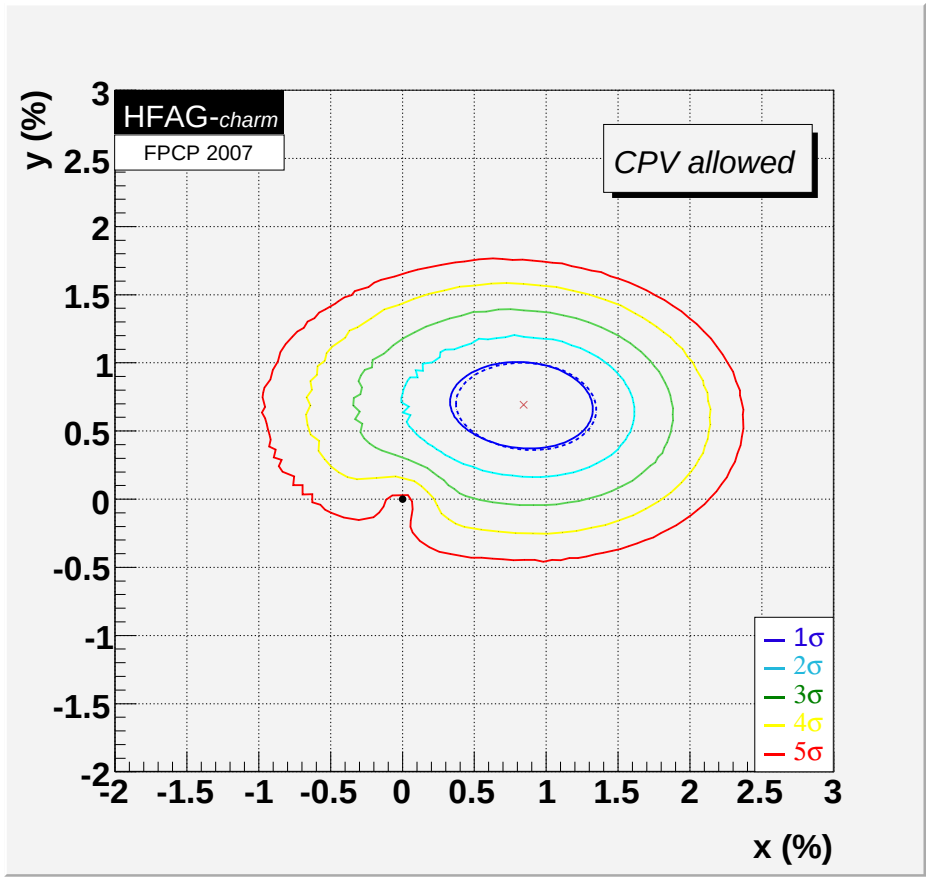
6 total parameters; in practice, we fit for R_D, $\overline{R}_D$ and

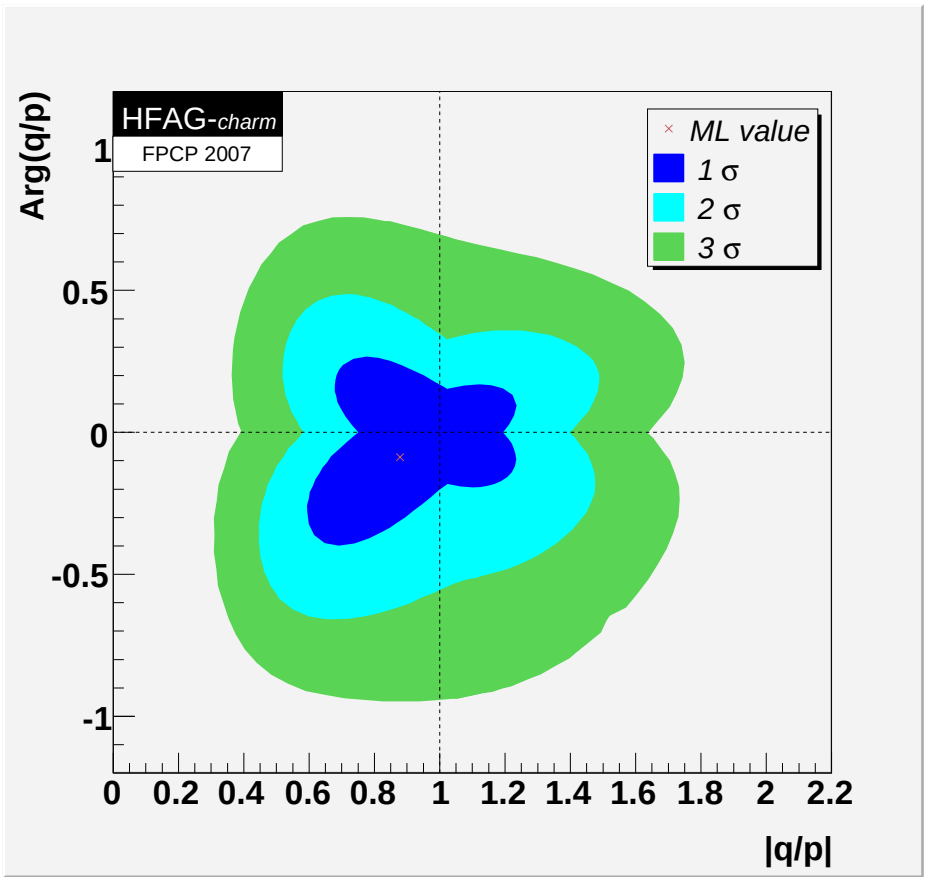
$$x'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4}(x'\cos\phi \pm y'\sin\phi)$$

$$y'^{\pm} = \left(\frac{1 \pm A_M}{1 \mp A_M}\right)^{1/4}(y'\cos\phi \mp x'\sin\phi)$$

from these we calculate A_D, A_M, ϕ, x' and y' *(note sign ambiguity for $x'^{\pm}$)*

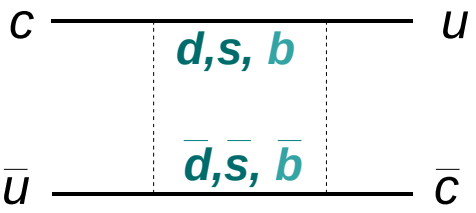
Older HFAG, with CPV

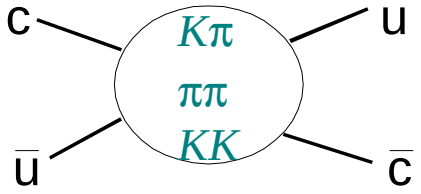




D^0 meson mixing:

e.g., Bianco *et al.*, Riv.Nuov.Cim.26N7-8 (2003)





"box" diagram: Δm

but mixing dominated by long-distance contributions (both Δm and $\Delta\Gamma$)

- *doubly-Cabibbo-suppressed w/r/t* Γ_D
- *GIM cancellation:* $V_{cd}^* V_{ud} + V_{cs}^* V_{us} + V_{cb}^* V_{ub} = 0$

Meson	flavors	$\Delta m/\Gamma$	$\Delta\Gamma/2\Gamma$	observed?
K^0	$\bar{s}d$	0.474	0.997	1958
B^0	$\bar{b}d$	0.77	$< 1\%$	1987
B_s^0	$\bar{b}s$	27	0.15 ± 0.07	2006
D^0	$c\bar{u}$	< 0.029	0.011 ± 0.005	March 2007

$$x \lesssim y \sim \begin{array}{ll} 10^{-6} - 10^{-3} & \text{(short distance)} \\ 10^{-3} - 10^{-2} & \text{(long distance)} \end{array}$$