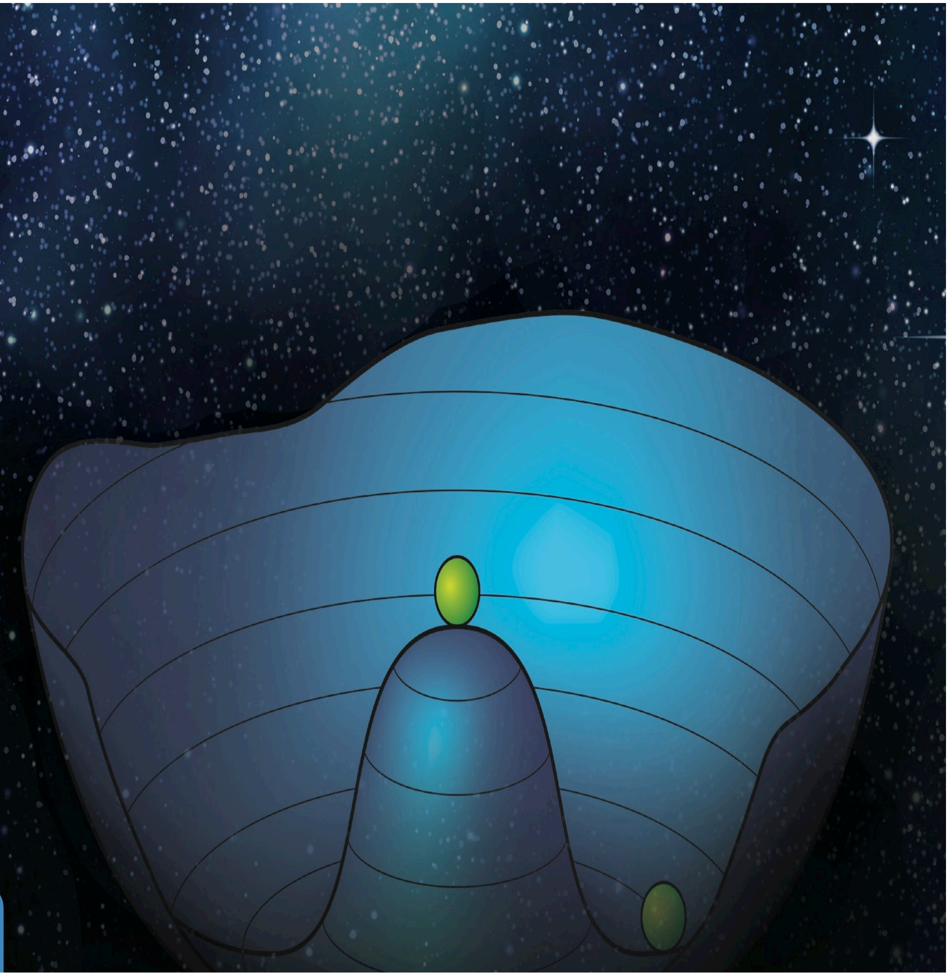
CP Violation in D decays at Belle:

a window on new physics



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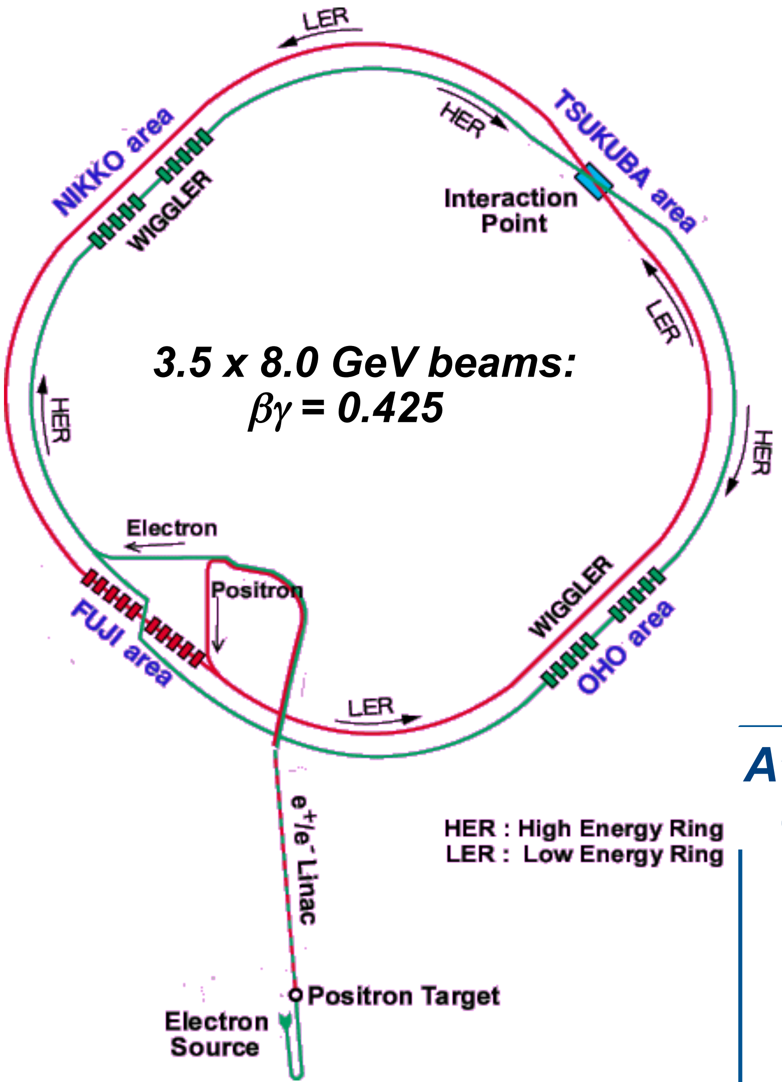
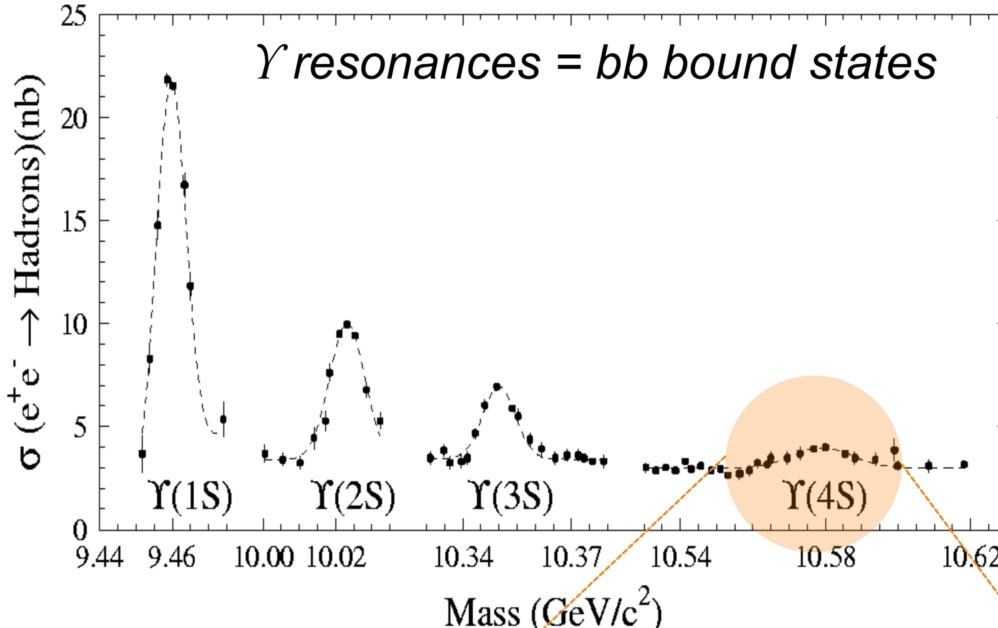
Brookhaven Forum 2013
May 1st, 2013

- *overview*
- *some formalism*
- *CPV in mixing or interference*
- *direct CPV*
- *HFAG global fit results*
- *Summary*

The Belle Experiment runs at KEKB:

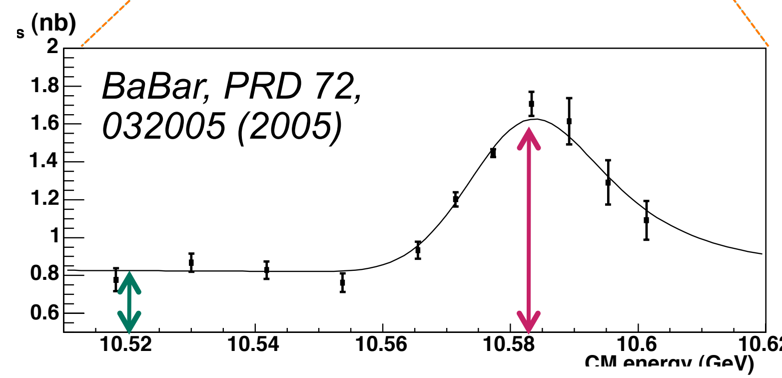
KEKB collider:





At Υ(4S) resonance:
($\sqrt{s}$ = 10.579 GeV)

$\sigma(bb) \approx 1.1$ nb
$\sigma(cc) \approx 1.3$ nb
$\sigma(uu) \approx 1.4$ nb
$\sigma(dd,ss) \approx 0.3$ nb



off-resonance on-resonance

Why study...

... CP Violation in D Decays?

- *As SM rates are very low, it is a good place to search for new physics [Most promising: singly Cabibbo-suppressed decays, see Grossman, Kagan, Nir, PRD 75, 036008 (2007)]*

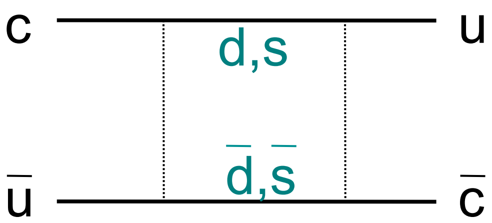
- *As it is now established that D^0/D^0bar undergo mixing, one wonders whether there exists CPV in the mixing, or CPV due to interference between mixed amplitudes and direct decay amplitudes*

... CPV in D Decays <u>at an e^+e^- machine (Belle/BaBar)?</u>

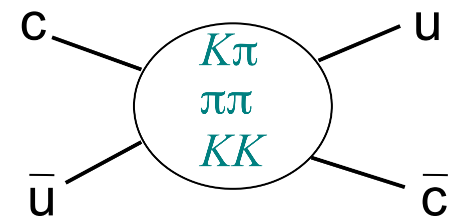
- *Final states with neutral particles (γ, K_S, π^0) can be reconstructed that are difficult/impractical to reconstruct at a hadron machine*

- *Low backgrounds, high trigger/reconstruction efficiencies, minimal decay time bias, roughly flat acceptance over Dalitz plots, several control samples*

Formalism I:



- doubly-Cabibbo-suppressed w/r/t Γ_D
- GIM mechanism cancellation
- long-distance contributions



Flavor eigenstates are not mass eigenstates:

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

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

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

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

Formalism II:

$$\frac{q}{p}\,\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} \;\equiv\; \left|\frac{q}{p}\right| \sqrt{R_D}\; e^{i(\phi+\delta)}$$

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

$$\begin{aligned}
\frac{N(D^0\!\to f)}{dt} &\propto e^{-\overline{\Gamma}\,t}\left\{R_D + \left|\frac{q}{p}\right|\sqrt{R_D}\,[\,y\,\cos(\phi+\delta) - x\,\sin(\phi+\delta)\,]\,(\overline{\Gamma}t) + \left|\frac{q}{p}\right|^2\frac{(x^2+y^2)}{4}(\overline{\Gamma}\,t)^2\right. \\
&= e^{-\overline{\Gamma}\,t}\left.\left\{R_D + \left|\frac{q}{p}\right|\sqrt{R_D}(y'\cos\phi - x'\sin\phi)(\overline{\Gamma}t) + \left|\frac{q}{p}\right|^2\frac{(x'^2+y'^2)}{4}(\overline{\Gamma}\,t)^2\right\}\right. \\
\frac{N(\overline{D}{}^0\!\to \bar{f})}{dt} &\propto e^{-\overline{\Gamma}\,t}\left\{\overline{R}_D + \left|\frac{p}{q}\right|\sqrt{\overline{R}_D} y'\cos\phi + x'\sin\phi)(\overline{\Gamma}t) + \left|\frac{p}{q}\right|^2\frac{(x'^2+y'^2)}{4}(\overline{\Gamma}\,t)^2\right\}
\end{aligned}$$

$$x' \equiv\; x\cos\delta + y\sin\delta \qquad\qquad y' \equiv\; y\cos\delta - x\sin\delta$$

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

No CPV ($R_D = \overline{R}_D$, $\lvert q/p\rvert = 1$, and $\phi = 0$):

$$\frac{dN(D^0\!\to f)}{dt} \;\propto\; e^{-\overline{\Gamma}\,t}\left\{R_D \;+\; \sqrt{R_D}\,y'(\overline{\Gamma}t) \;+\; \frac{(x'^2+y'^2)}{4}(\overline{\Gamma}\,t)^2\right\}$$

Formalism II:

$$\frac{q}{p}\,\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} \equiv \left|\frac{q}{p}\right| \sqrt{R_D}\, e^{i(\phi+\delta)}$$

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

$$\frac{N(D^0\to f)}{dt} \propto e^{-\overline{\Gamma}t}\left\{R_D + \left|\frac{q}{p}\right|\sqrt{R_D}\,[\,y\cos(\phi+\delta) - x\sin(\phi+\delta)\,]\,(\overline{\Gamma}t) + \left|\frac{q}{p}\right|^2 \frac{(x^2+y^2)}{4}(\overline{\Gamma}\,t)^2\right.$$

$$= e^{-\overline{\Gamma}t}\left\{R_D + \left|\frac{q}{p}\right|\sqrt{R_D}(y'\cos\phi - x'\sin\phi)(\overline{\Gamma}t) + \left|\frac{q}{p}\right|^2 \frac{(x'^2+y'^2)}{4}(\overline{\Gamma}\,t)^2\right\}$$

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

$$x' \equiv x\cos\delta + y\sin\delta \qquad\qquad y' \equiv y\cos\delta - x\sin\delta$$

$\lvert q/p\rvert$	CPV in mixing
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No CPV ($R_D = \overline{R}_D$, $|q/p| = 1$, and $\phi = 0$):

$$\frac{dN(D^0\to f)}{dt} \propto e^{-\overline{\Gamma}t}\left\{R_D + \sqrt{R_D}\,y'(\overline{\Gamma}t) + \frac{(x'^2+y'^2)}{4}(\overline{\Gamma}\,t)^2\right\}$$

Belle CPV in mixing or interference

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

[Zhang et al., PRL 96, 151801 (2006); Li et al., PRL 94, 071801 (2005)]

Fit for x'^2, y', $|q/p|$, ϕ = Arg(q/p)

$$A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$$

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

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

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

[Zhang et al., PRL 99, 131803 (2007)]

Fit for x, y, $|q/p|$, ϕ = Arg(q/p)

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

[Staric arXiv:1212.3478 (2012); Staric et al., PRL 98, 211803 (2007); Abe et al., hep-ex/0308034 (2003)]

Fit for y_{CP}, A_Γ

$$2\,y_{CP} = \big(|q/p| + |p/q|\big) y \cos\phi - \big(|q/p| - |p/q|\big) x \sin\phi$$

$$2\,A_\Gamma = \big(|q/p| - |p/q|\big) y \cos\phi - \big(|q/p| + |p/q|\big) x \sin\phi$$

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

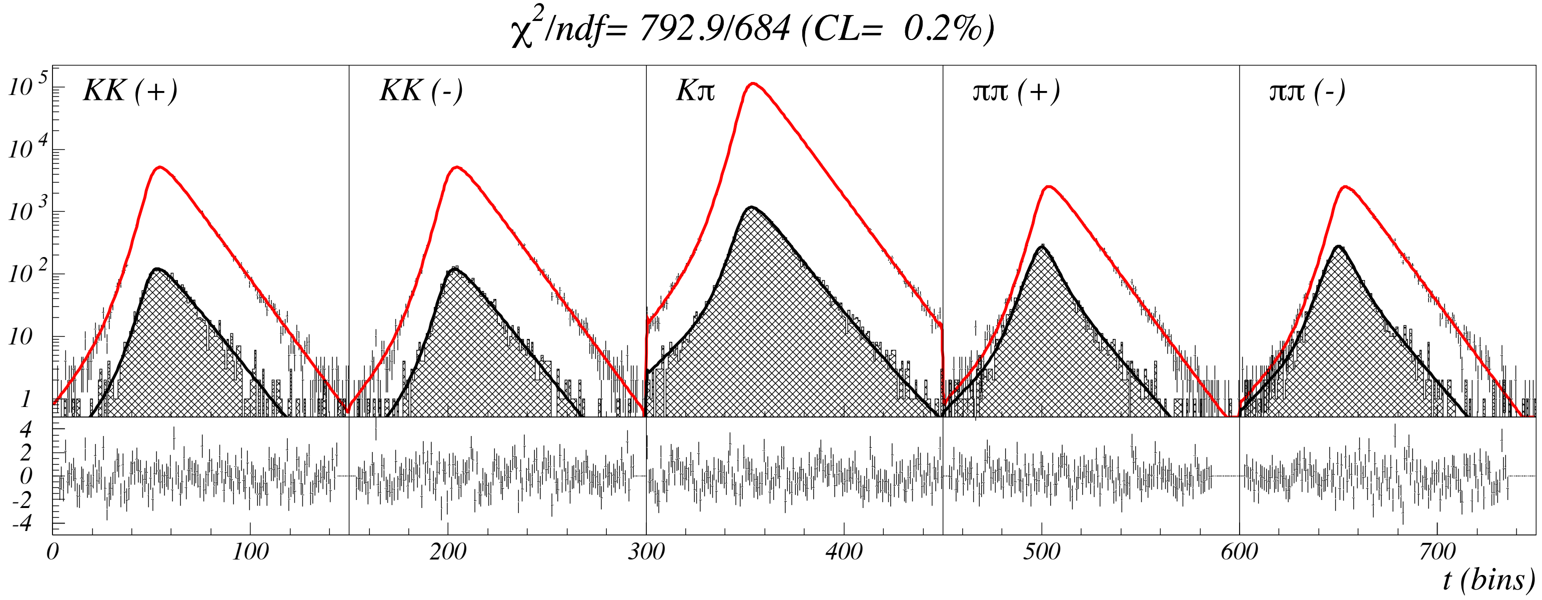
Staric, arXiv:1212.3478; Staric et al., PRL 98, 211803 (2007).

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

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

Method:

1) tag flavor via $D^{*+} \to D^0\pi^+$
2) determine resolution function from MC/data studies
3) do simultaneous binned fit to K^+K^-, $K^-\pi^+$, $\pi^+\pi^-$ samples

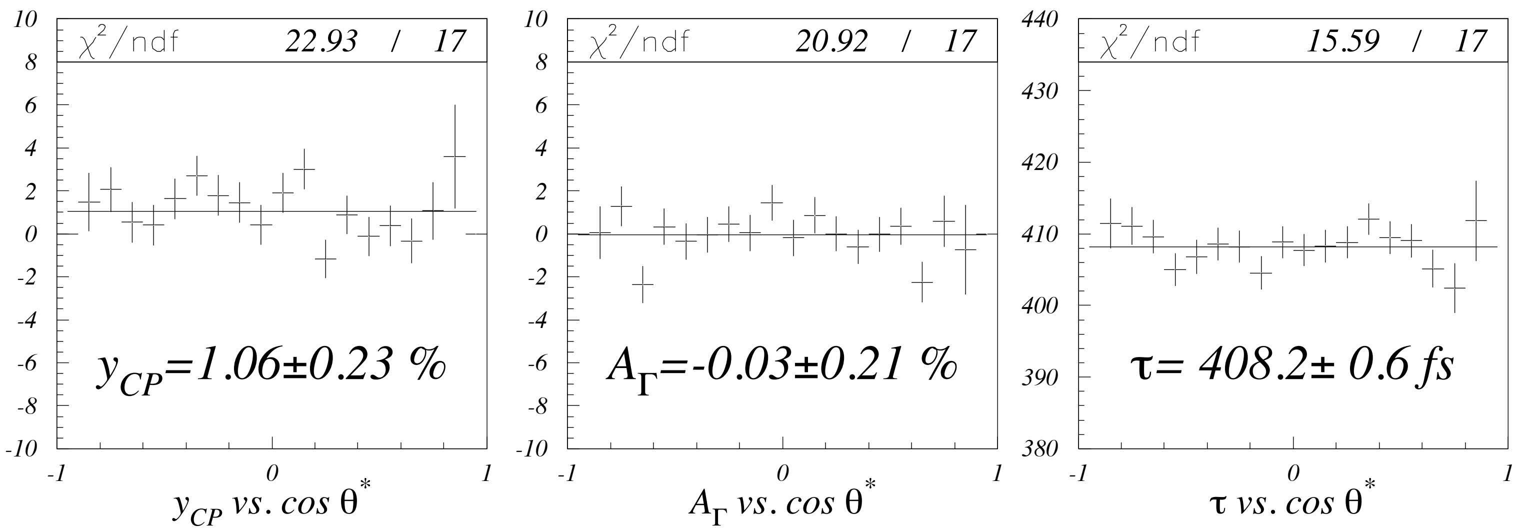


Belle time-dependent $D^0(t) \to K^+K^-, \pi^+\pi^-$ (cont'd)

Staric, arXiv:1212.3478; Staric et al., PRL 98, 211803 (2007).

Note: as resolution function depends on D^0 CMS angle (θ^*), fit is performed in bins of cos θ^*

976 fb^{-1} preliminary:



$$\boxed{\begin{aligned} y_{CP} &= (+1.11 \pm 0.22 \pm 0.11)\% \\ A_\Gamma &= (-0.03 \pm 0.20 \pm 0.08)\% \end{aligned}}$$

(world's most precise to-date)

Belle time-integrated $D^0 \rightarrow K^+K^-, \pi^+\pi^-$

Ko, arXiv:1212.1975; Staric et al., PLB 670, 190 (2008)

Method:

(1) tag flavor via $D^{*+} \rightarrow D^0\pi^+$

$$A^f_{CP} \equiv \frac{\Gamma(D^0 \rightarrow f) - \Gamma(\overline{D}^0 \rightarrow f)}{\Gamma(D^0 \rightarrow f) + \Gamma(\overline{D}^0 \rightarrow f)}$$

$$A^f_{\rm rec} = A^f_{CP} + A_{FB} + A^\pi_\varepsilon$$

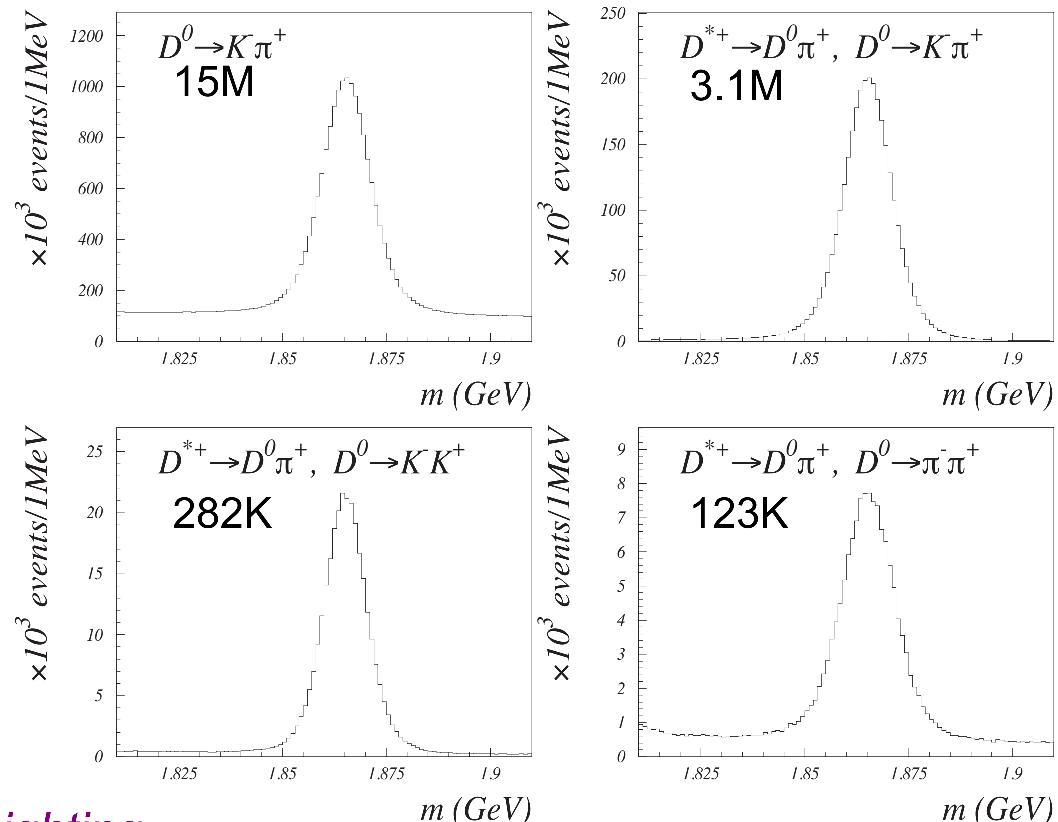
(2) measure tagging asym. using $D^0 \rightarrow K^+\pi^-$

$$\begin{aligned} A^{K\pi}_{\rm tagged} &= A^{K\pi}_{CP} + A_{FB} + A^{K\pi}_\varepsilon + A^\pi_\varepsilon \\ A^{K\pi}_{\rm untagged} &= A^{K\pi}_{CP} + A_{FB} + A^{K\pi}_\varepsilon \end{aligned}$$

(3) correct for $K^+\pi^-$ asym. by reweighting

$$\begin{aligned} u_{D^0} &= 1 - A^{K\pi}_{\rm untagged}(p_{D^0}, \cos\theta_{D^0}) \\ u_{\overline{D}^0} &= 1 + A^{K\pi}_{\rm untagged}(p_{\overline{D}^0}, \cos\theta_{\overline{D}^0}) \end{aligned}$$

Belle preliminary using 976/fb



(4) correct for tagging π+ asymmetry by reweighting

$$\begin{aligned} w_{D^0} &= 1 - A^\pi_\varepsilon(p_\pi, \cos\theta_\pi) \\ w_{\overline{D}^0} &= 1 + A^\pi_\varepsilon(p_\pi, \cos\theta_\pi) \end{aligned}$$

Belle time-integrated $D^0 \to K^+K^-$, $\pi^+\pi^-$ (cont'd)

Ko, arXiv:1212.1975; Staric et al., PLB 670, 190 (2008)

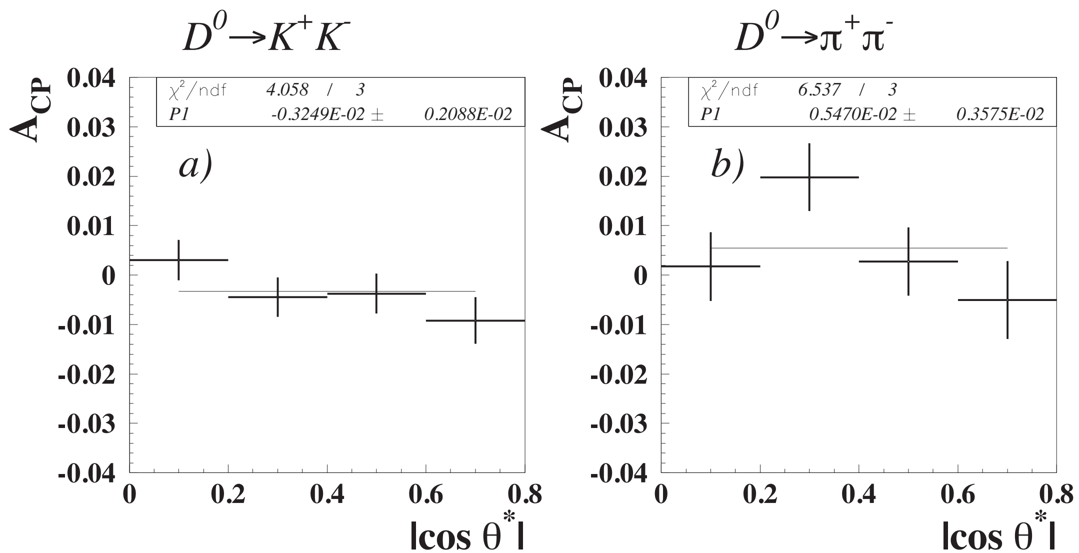
$$A_{CP}^{f} = \frac{A_{\rm rec}^{f,\rm corr}(\cos\theta^*) + A_{\rm rec}^{f,\rm corr}(-\cos\theta^*)}{2}$$

$$A_{FB} = \frac{A_{\rm rec}^{f,\rm corr}(\cos\theta^*) - A_{\rm rec}^{f,\rm corr}(-\cos\theta^*)}{2}$$

$$A_{CP}^{KK} = (-0.32 \pm 0.21 \pm 0.09)\%$$
$$A_{CP}^{\pi\pi} = (+0.55 \pm 0.36 \pm 0.09)\%$$

$$\Delta A_{CP} \equiv A_{CP}^{KK} - A_{CP}^{\pi\pi} = (-0.87 \pm 0.41 \pm 0.06)\%$$

Preliminary $976\ \mathrm{fb}^{-1}$:



Belle time-integrated $D^+ \to K_S\,\pi^+$

$$A_{\rm rec}^{K_S\pi^+} = \tilde{A}_{CP}^{K_S\pi^+} + A_{FB} + A_{\varepsilon}^{\pi^+} + A_{K^0}$$

Ko et al., PRL 109, 021601 (2012); Ibid., 119903 (2012)

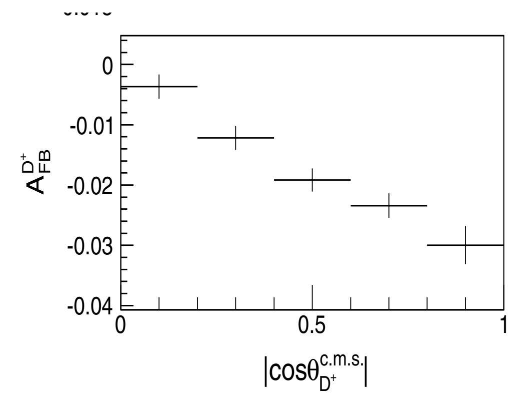
(1) *measure tagging asym. using $D \to K^+\pi^-\pi$*

$$A(D^+ \to K^-\pi^+\pi^+) = A_{FB} + A_{\varepsilon}^{K^-\pi^+} + A_{\varepsilon}^{\pi^+}$$
$$A(D^0 \to K^-\pi^+\pi^0) = A_{FB} + A_{\varepsilon}^{K^-\pi^+}$$

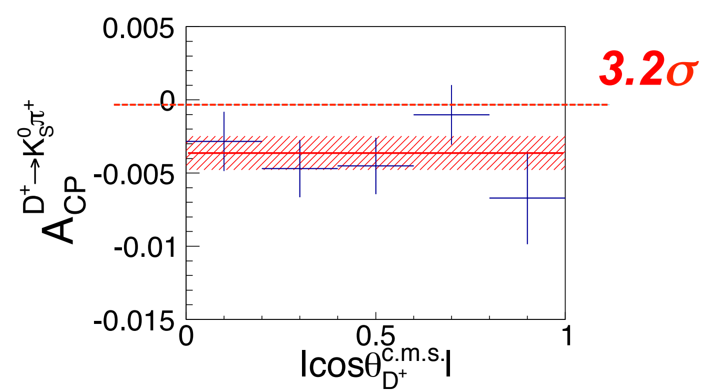
(2) *take sums and differences in bins of cosθ**

$$\tilde{A}_{CP}^{K_S\pi^+} = \frac{\tilde{A}_{\rm rec}^{K_S\pi^+,{\rm corr}}(\cos\theta^*) + \tilde{A}_{\rm rec}^{K_S\pi^+,{\rm corr}}(-\cos\theta^*)}{2}$$

$$A_{FB} = \frac{A_{\rm rec}^{K_S\pi^+,{\rm corr}}(\cos\theta^*) - A_{\rm rec}^{K_S\pi^+,{\rm corr}}(-\cos\theta^*)}{2}$$



$$\tilde{A}_{CP}^{K_S\pi^+} = A_{CP}^{K_S\pi^+} + A_{CP}^{\overline{K}^0} = (-0.363 \pm 0.094 \pm 0.067)\%$$
$$A_{CP}^{K_S\pi^+} = (-0.024 \pm 0.094 \pm 0.067)\%$$



Direct CP Violation Searches:

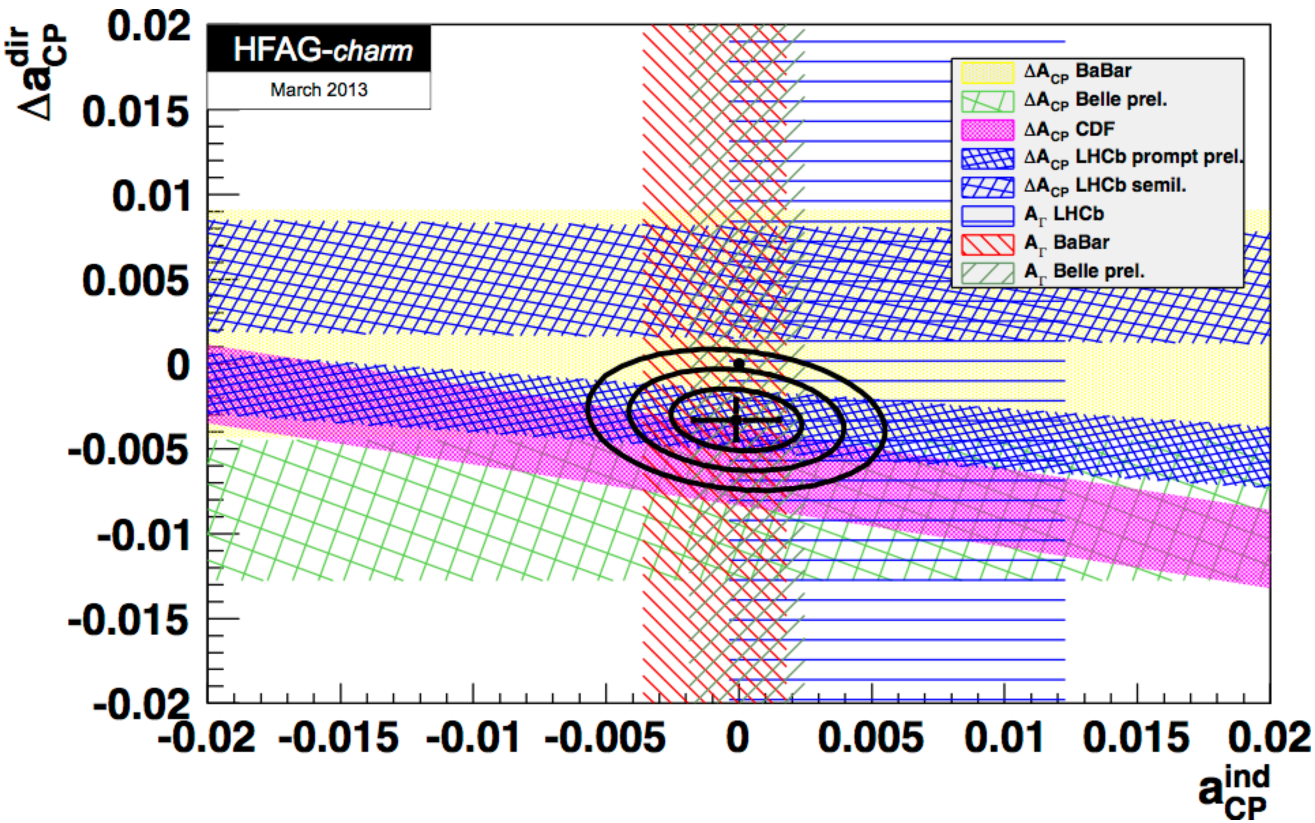
$D^0 \to \pi^+\pi^-$	976 fb^{-1}	$(+0.55 \pm 0.36 \pm 0.09)\%$	arXiv:1212.1975
$D^0 \to K^+K^-$	976 fb^{-1}	$(-0.32 \pm 0.21 \pm 0.09)\%$	arXiv:1212.1975
$D^0 \to K_S\,\pi^0$	791 fb^{-1}	$(-0.28 \pm 0.19 \pm 0.10)\%$	PRL 106, 211801 (2011)
$D^0 \to K_S\,\eta$	791 fb^{-1}	$(+0.54 \pm 0.51 \pm 0.16)\%$	PRL 106, 211801 (2011)
$D^0 \to K_S\,\eta'$	791 fb^{-1}	$(+0.98 \pm 0.67 \pm 0.14)\%$	PRL 106, 211801 (2011)
$D^0 \to K^+\pi^-\pi^0$	281 fb^{-1}	$(-0.6 \pm 5.3)\%$	PRL 95, 231801 (2005)
$D^0 \to K^+\pi^-\pi^+\pi^-$	281 fb^{-1}	$(-1.8 \pm 4.4)\%$	PRL 95, 231801 (2005)
$D^+ \to \pi^+\eta$	791 fb^{-1}	$(+1.74 \pm 1.13 \pm 0.19)\%$	PRL 107, 221801 (2011)
$D^+ \to \pi^+\eta'$	791 fb^{-1}	$(-0.12 \pm 1.12 \pm 0.17)\%$	PRL 107, 221801 (2011)
$D^+ \to K_S\,\pi^+$	977 fb^{-1}	$(-0.363 \pm 0.094 \pm 0.067)\%$ (3.2σ) $(-0.024 \pm 0.094 \pm 0.067)\%$	PRL 109, 021601 (2012)
$D^+ \to K^0\,K^+$	977 fb^{-1}	$(+0.08 \pm 0.28 \pm 0.14)\%$	JHEP 02 098 (2013)
$D^+ \to \phi\,\pi^+$	955 fb^{-1}	$(+0.51 \pm 0.28 \pm 0.05)\%$	PRL 108, 071801 (2012)
$D_s^+ \to K_S\,\pi^+$	673 fb^{-1}	$(+5.45 \pm 2.50 \pm 0.33)\%$	PRL 104, 181602 (2010)
$D_s^+ \to K_S\,K^+$	673 fb^{-1}	$(+0.12 \pm 0.36 \pm 0.22)\%$	PRL 104, 181602 (2010)

Fit for Direct CP Violation (HFAG):

$$A_\Gamma \equiv \frac{\tau(\overline{D}^0 \to f) - \tau(D^0 \to f)}{\tau(\overline{D}^0 \to f) + \tau(D^0 \to f)} \approx -a_{CP}^{\rm ind}$$

$$A_{CP}(f) \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)}$$

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = \left(1 + y\cos\phi \frac{\overline{\langle t \rangle}}{\tau}\right)\Delta a_{CP}^{\rm dir} + \left(\frac{\Delta\langle t \rangle}{\tau}\right) a_{CP}^{\rm ind}$$



$$a_{CP}^{\rm ind} = (-0.01 \pm 0.16)\%$$

$$\Delta a_{CP}^{\rm dir} = (-0.33 \pm 0.12)\%$$

No CPV (0,0) point:
$\Delta\chi^2 = 7.7$, CL=0.021,
CPV favored at 2.0σ

HFAG global fit

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

Fit to 41 measured observables for 10 parameters. Results:

Parameter	CPV-allowed	CPV-allowed 95% C.L.
x (%)	$0.49\,^{+0.17}_{-0.18}$	[0.10, 0.81]
y (%)	0.74 ± 0.09	[0.56, 0.92]
δ (°)	$19.5\,^{+8.6}_{-11.1}$	[−9.6, 35.4]
R_D (%)	$0.350\,^{+0.007}_{-0.006}$	[0.337, 0.362]
A_D (%)	-2.6 ± 2.2	[−6.9, 1.7]
$\lvert q/p \rvert$	$0.69\,^{+0.17}_{-0.14}$	[0.44, 1.07]
ϕ (°)	$-29.6\,^{+8.9}_{-7.5}$	[−44.6, −7.5]
$\delta_{K\pi\pi}$ (°)	$25.1\,^{+22.3}_{-23.0}$	[−20.6, 69.2]
A_π	0.16 ± 0.21	[−0.25, 0.57]
A_K	-0.16 ± 0.20	[−0.56, 0.23]
x_{12} (%)	–	[0.10, 0.80]
y_{12} (%)	–	[0.50, 0.85]
ϕ_{12}(°)	–	[−11.7, 35.9]

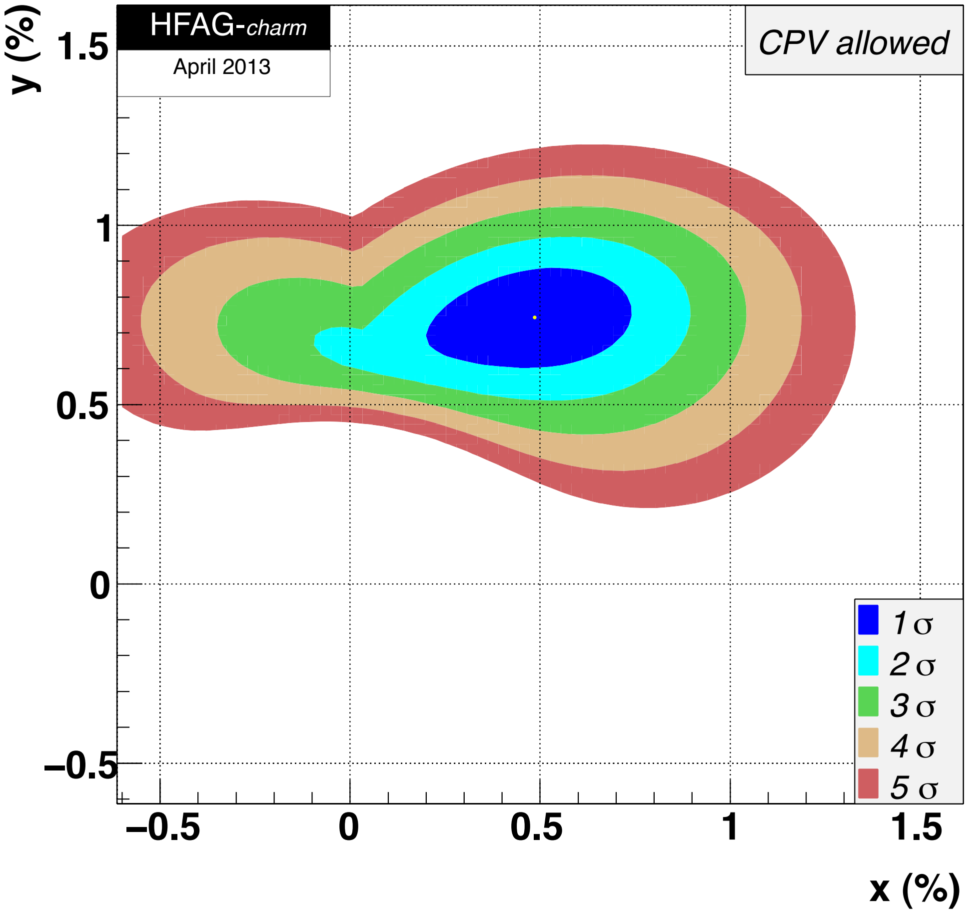
No direct CPV

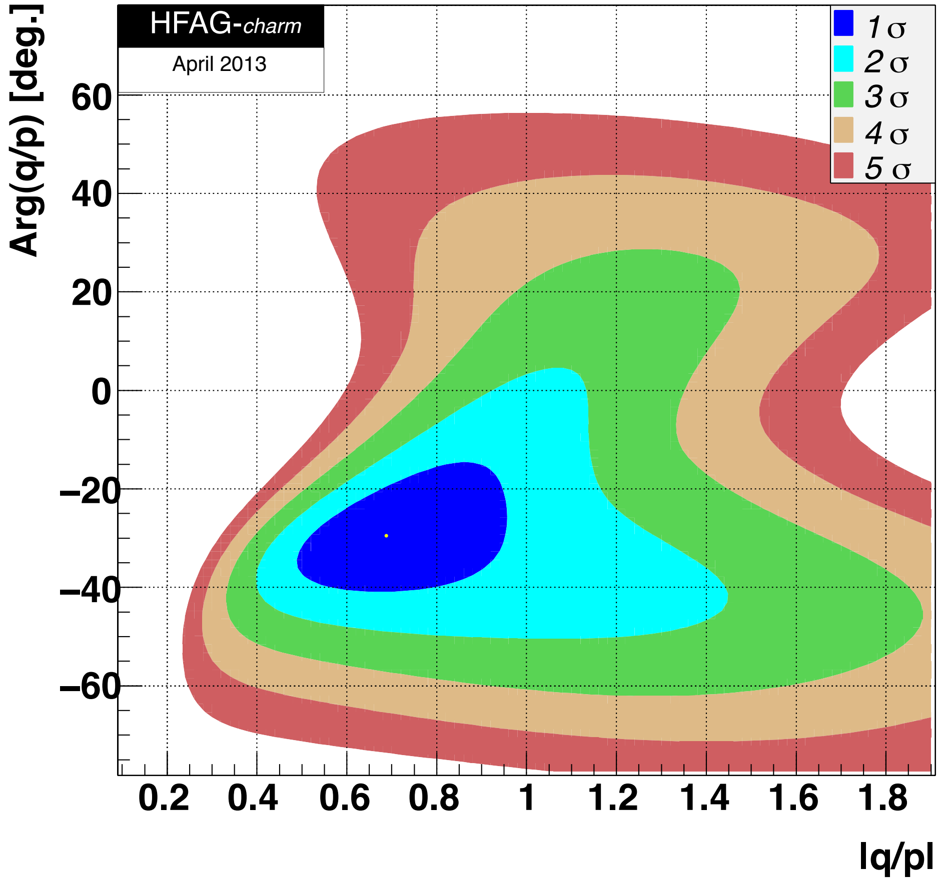
But χ^2 is high, driven by LHCb $D^0 \to K^+\pi^-$:

Observable	χ^2	$\sum\chi^2$
y_{CP}	2.90	2.90
A_Γ	0.03	2.94
$x_{K^0\pi^+\pi^-}$ Belle	0.87	3.81
$y_{K^0\pi^+\pi^-}$ Belle	1.63	5.44
$\lvert q/p \rvert_{K^0\pi^+\pi^-}$ Belle	0.30	5.74
$\phi_{K^0\pi^+\pi^-}$ Belle	0.98	6.72
$x_{K^0h^+h^-}$ BaBar	1.44	8.16
$y_{K^0h^+h^-}$ BaBar	0.39	8.55
$R_M(K^+\ell^-\nu)$	0.11	8.67
$x_{K^+\pi^-\pi^0}$ BaBar	6.26	14.93
$y_{K^+\pi^-\pi^0}$ BaBar	2.83	17.76
CLEOc $(x/y/R_D/\cos\delta/\sin\delta)$	10.83	28.59
$R_D^+/x'^{2+}/y'^+$ BaBar	7.76	36.34
$R_D^-/x'^{2-}/y'^-$ BaBar	5.59	41.93
$R_D^+/x'^{2+}/y'^+$ Belle	1.76	43.69
$R_D^-/x'^{2-}/y'^-$ Belle	0.66	44.35
$R_D/x'^2/y'$ CDF	11.46	55.81
$R_D/x'^2/y'$ LHCb	9.67	65.48
$A_{KK}/A_{\pi\pi}$ BaBar	0.71	66.19
$A_{KK}/A_{\pi\pi}$ Belle	1.56	67.75
$A_{KK} - A_{\pi\pi}$ CDF	1.57	69.33
$A_{KK} - A_{\pi\pi}$ LHCb (D^* tag)	0.01	69.33
$A_{KK} - A_{\pi\pi}$ LHCb ($B^0 \to D^0\mu X$ tag)	6.08	75.41

HFAG global fit: 2-d likelihood functions

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



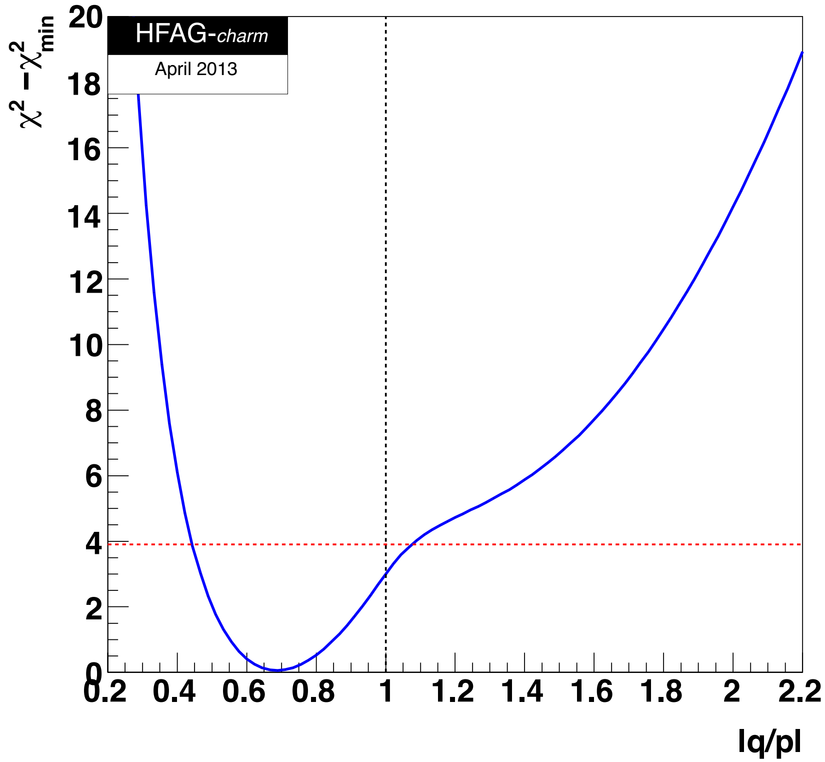


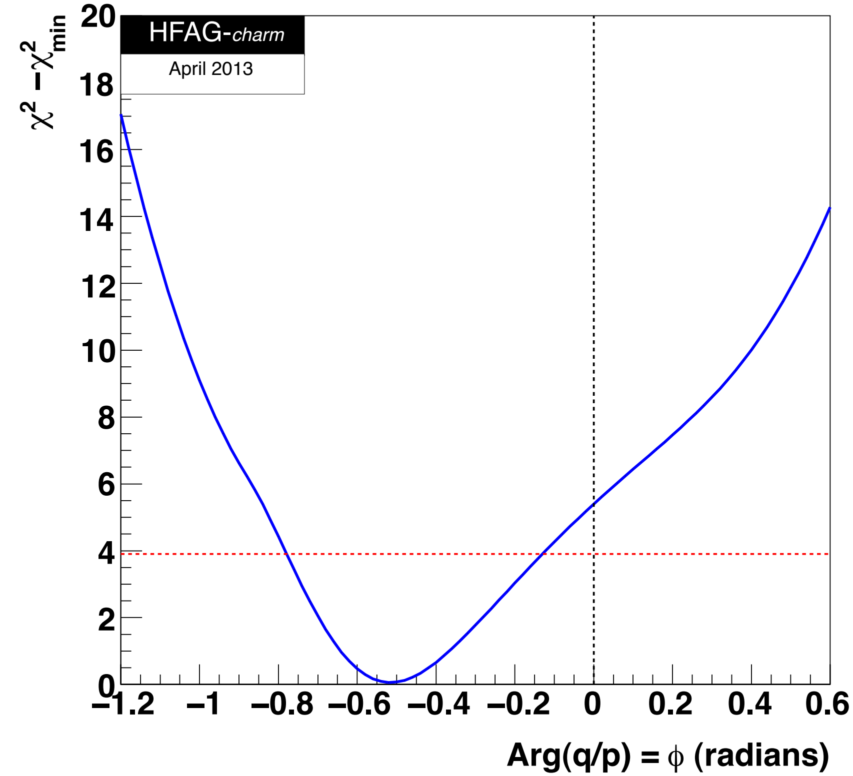
CPV-allowed plot, no mixing (x,y) = (0,0) point: $\Delta\chi^2 = 263.8$

No CPV (|q/p|, φ*) = (1,0) point:* $\Delta\chi^2 = 5.371$, *CL = 0.068 , CPV favored at* 1.8σ

HFAG global fit: 1-d likelihood functions

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





95% CL intervals:

|q/p| [0.44, 1.07]

Arg(q/p) [-44.6, -7.5] deg.

If no direct CPV:

Based on:
Ciuchini et al., PLB 655 (2007) 162; Y. Grossman, Y. Nir, G. Perez, PRL 103 (2009) 071602; Kagan and Sokoloff, Phys.Rev. D80 (2009) 076008.

New theory parameters:

$$\boxed{\begin{aligned} x_{12} &\equiv \frac{2|M_{12}|}{\Gamma} \\ y_{12} &\equiv \frac{|\Gamma_{12}|}{\Gamma} \\ \phi_{12} &\equiv \mathrm{Arg}\left(\frac{M_{12}}{\Gamma_{12}}\right) \end{aligned}}$$

If no direct CPV:

$$\mathrm{Im}\left(\Gamma^*_{12}\frac{\overline{A}_f}{A_f}\right) = 0$$

So one can derive:

$$\left.\begin{aligned} xy &= x_{12}y_{12}\cos\phi_{12} \\ x^2 - y^2 &= x_{12}^2 - y_{12}^2 \\ (x^2+y^2)|q/p|^2 &= x_{12}^2 + y_{12}^2 + 2x_{12}y_{12}\sin\phi_{12} \\ \tan(2\phi) &= \frac{-\sin(2\phi_{12})}{\cos(2\phi_{12}) + y_{12}^2/x_{12}^2} \end{aligned}\right\}$$

4 parameters (x,y,$|q/p|$,ϕ) now expressed in terms of 3 parameters (x_{12},y_{12},ϕ_{12}).

$\Rightarrow$

Additional constraint in fit:

$\tan\varphi = (1-|q/p|^2)/(1+|q/p|^2) \times (x/y)$

HFAG global fit: no direct CPV

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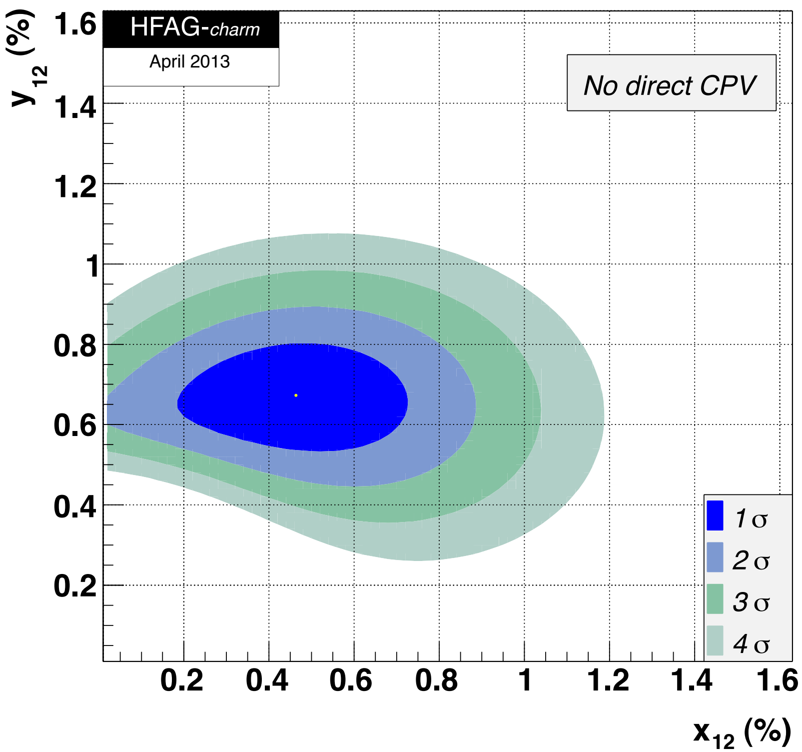
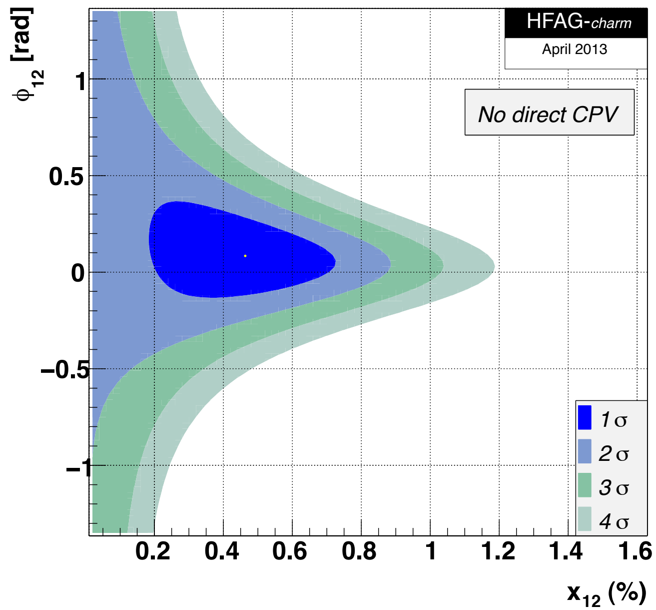
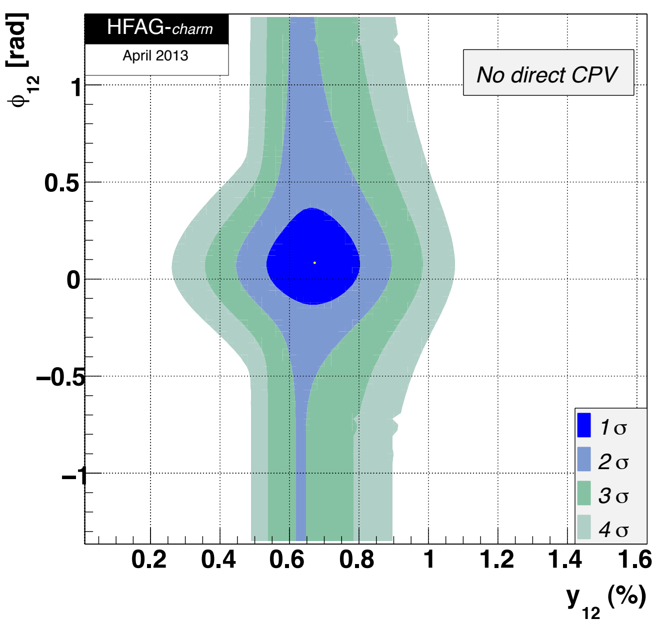
Fitting for x_{12}, y_{12}, ϕ_{12} directly:







$$
\begin{aligned}
x_{12} &= (0.46 \pm 0.18)\% \\
y_{12} &= (0.67 \pm 0.09)\% \\
\phi_{12} &= (4.8\,^{+9.2}_{-7.4})^\circ
\end{aligned}
$$

Summary

- The past two years have seen numerous new results in charm mixing/ CPV measurements.

- Belle, Babar, CDF, and LHCb have all observed mixing; combining all results gives a significance of mixing of >12σ (Note: χ^2 is now high)

- The question becomes: is there CPV in the charm system? This would be a strong sign of new physics.

- at present no sign of CPV, although |q/p| and ϕ prefer to be away from (1,0) at 1.8σ significance; possible direct CPV at 2.0σ significance

- Next advances:

  - Babar $D^0(t) \to K^0 \pi^+\pi^-$ (Dalitz plot) analysis for x, y, |q/p|, ϕ (480 fb^{-1})

  - updated Belle $D^0(t) \to K^0 h^+h^-$ Dalitz analyses for x, y, |q/p|, ϕ (970 fb^{-1})

  - updated Belle analysis of $D^0(t) \to K^+\pi^-$ for x, y, |q/p|, ϕ (970 fb^{-1})
  - CDF analysis of $D^0(t) \to K^+\pi^-$ for x, y, |q/p|, ϕ with all data (7-8 fb^{-1})
  - LHCb analysis of $D^0(t) \to K^0 \pi^+\pi^-$, $D^0(t) \to K^0 K^+K^-$

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