CP Violation & Mixing Results in D decays from Belle:

a window on new physics

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- *motivation and formalism*
- *CPV in mixing or interference*
- *direct CPV*
- *HFAG fit results*
- *Summary*

Why study...

... CP Violation in D Decays?

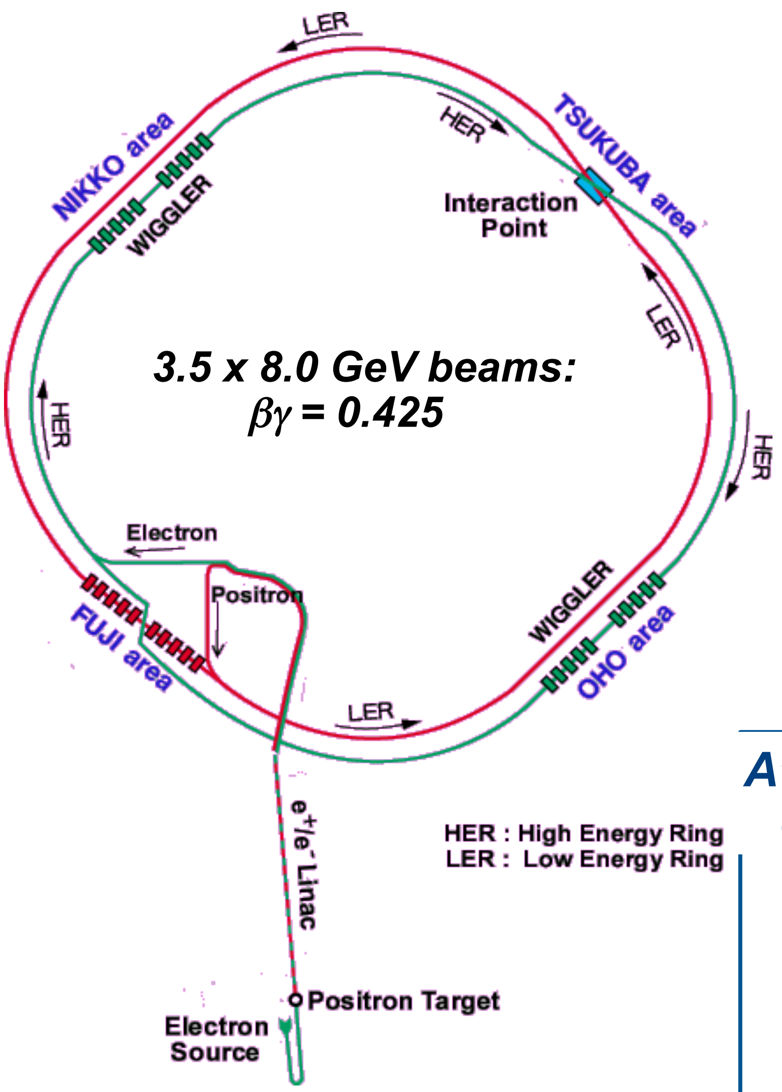
- SM rates are very low ⇒ a good place to search for new physics [Most promising: singly Cabibbo-suppressed decays, see Grossman, Kagan, Nir, PRD 75, 036008 (2007)]
- Now established that D^0/D^0bar mesons mix ⇒ is there CPV in the mixing? or CPV due to interference between mixed and direct decay amplitudes?

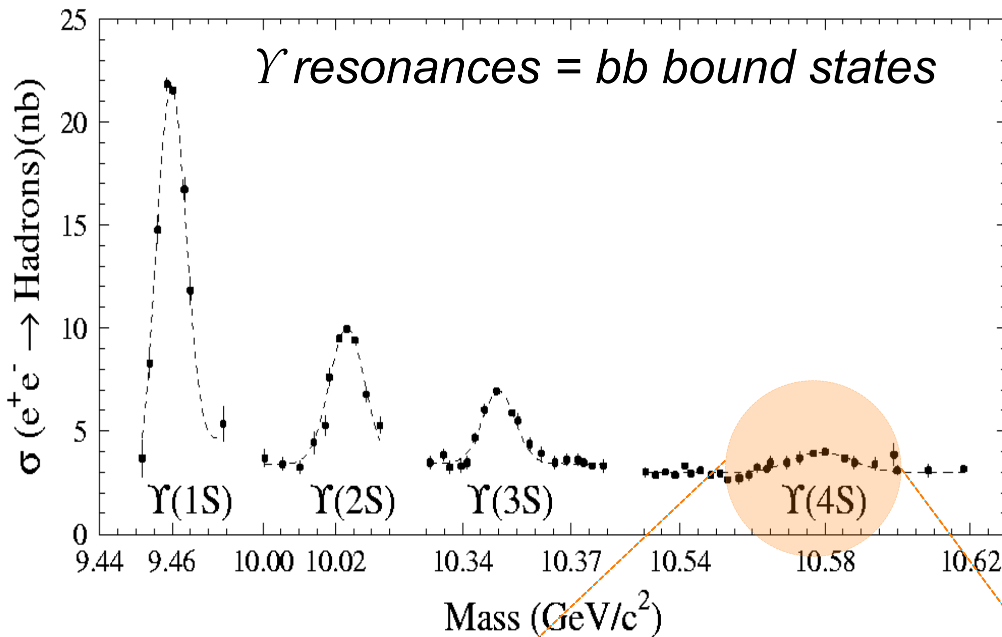
... CPV in D Decays at an e^+e^- machine (Belle/BaBar)?

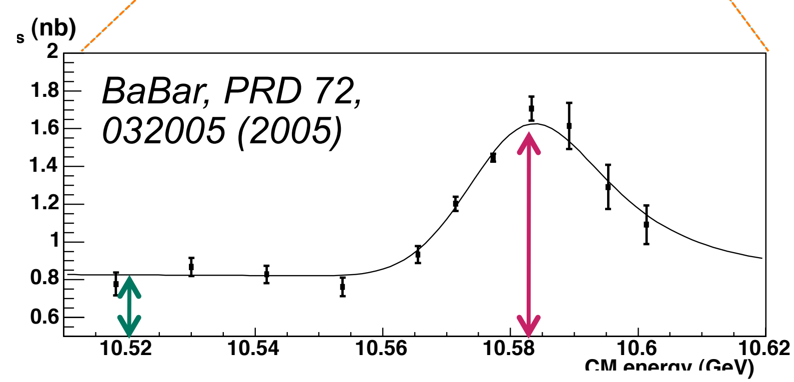
- Final states with neutral particles (γ, K_S, π^0) can be reconstructed that are difficult/impractical to reconstruct at a hadron machine
- Low backgrounds, high trigger/reconstruction efficiencies, minimal decay time bias, roughly flat acceptance over Dalitz plots, several control samples

The Belle Experiment runs at KEKB:

KEKB collider:





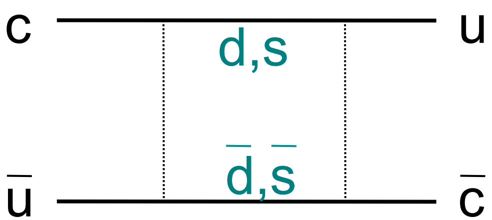


off-resonance *on-resonance*

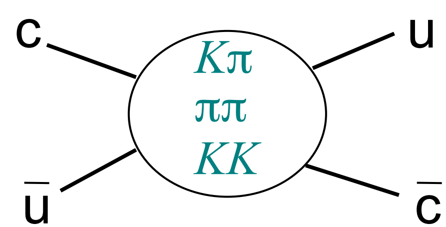
At $\Upsilon(4S)$ resonance:
($\sqrt{s}$ = 10.579 GeV)

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

Formalism I:



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



Flavor eigenstates are not mass eigenstates:

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

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

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

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

Formalism II:

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

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

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

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

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

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

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

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

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

Formalism II:

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

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

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

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

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

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

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

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

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

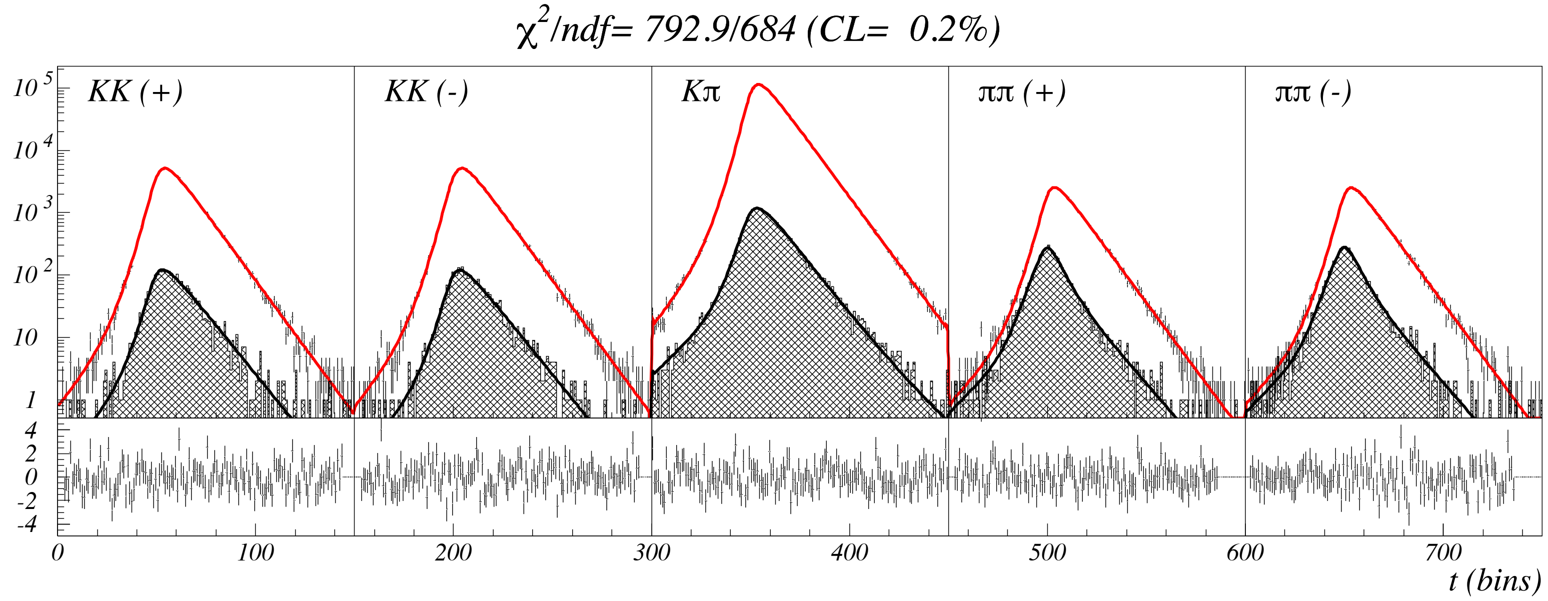
Staric, arXiv:1212.3478; Staric et al., PRL 98, 211803 (2007).

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

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

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*

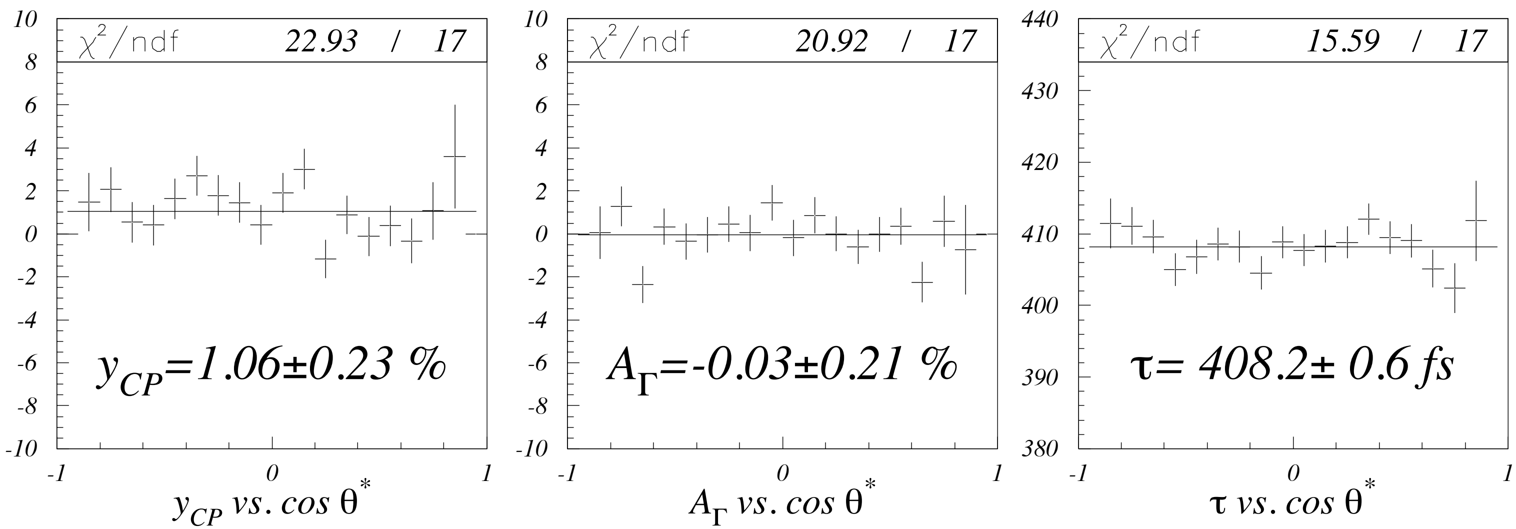


Belle time-dependent $D^0(t) \rightarrow K^+K^-, \pi^+\pi^-$ (cont'd)

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

Method:

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

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

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

$$A_{\rm rec}^{f} = A_{CP}^{f} + A_{FB} + A_{\varepsilon}^{\pi}$$

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

$$A_{\rm tagged}^{K\pi} = A_{CP}^{K\pi} + A_{FB} + A_{\varepsilon}^{K\pi} + A_{\varepsilon}^{\pi}$$
$$A_{\rm untagged}^{K\pi} = A_{CP}^{K\pi} + A_{FB} + A_{\varepsilon}^{K\pi}$$

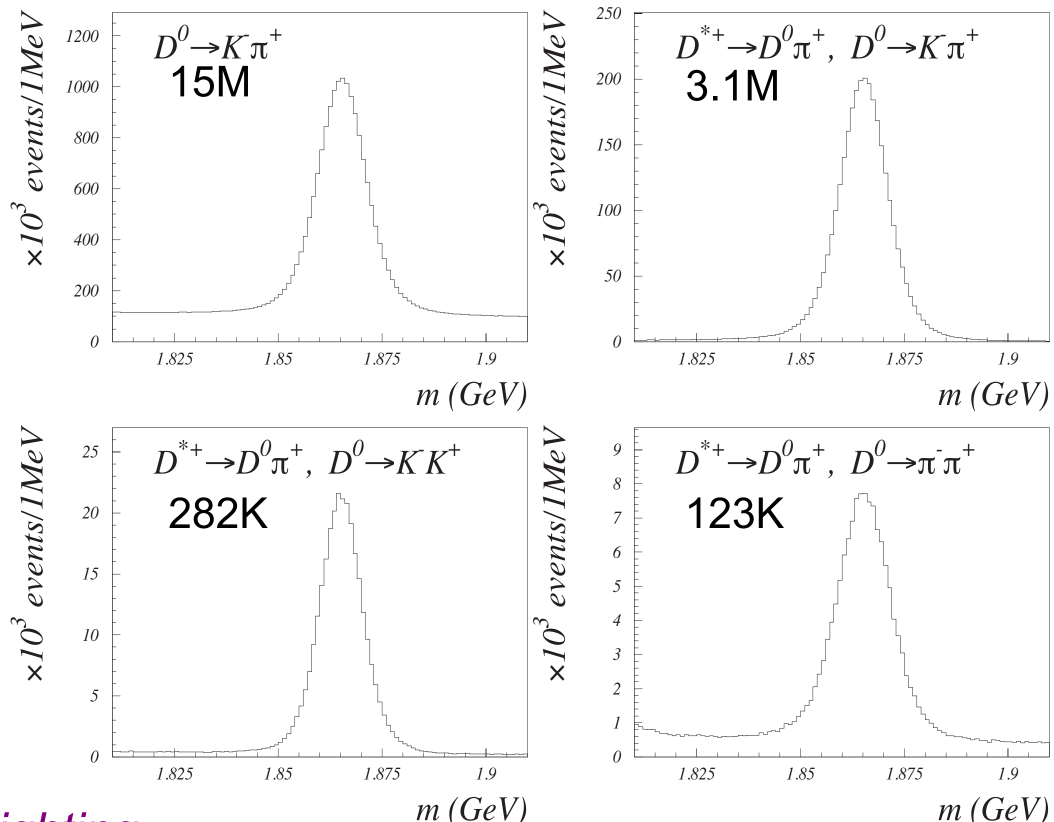
(3) correct for $K^+\pi^-$ asym. by reweighting

$$u_{D^0} = 1 - A_{\rm untagged}^{K\pi}(p_{D^0}, \cos\theta_{D^0})$$
$$u_{\overline{D}^0} = 1 + A_{\rm untagged}^{K\pi}(p_{\overline{D}^0}, \cos\theta_{\overline{D}^0})$$

(4) correct for tagging $\pi+$ asymmetry by reweighting

$$w_{D^0} = 1 - A_{\varepsilon}^{\pi}(p_\pi, \cos\theta_\pi)$$
$$w_{\overline{D}^0} = 1 + A_{\varepsilon}^{\pi}(p_\pi, \cos\theta_\pi)$$

Belle preliminary using 976/fb



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

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

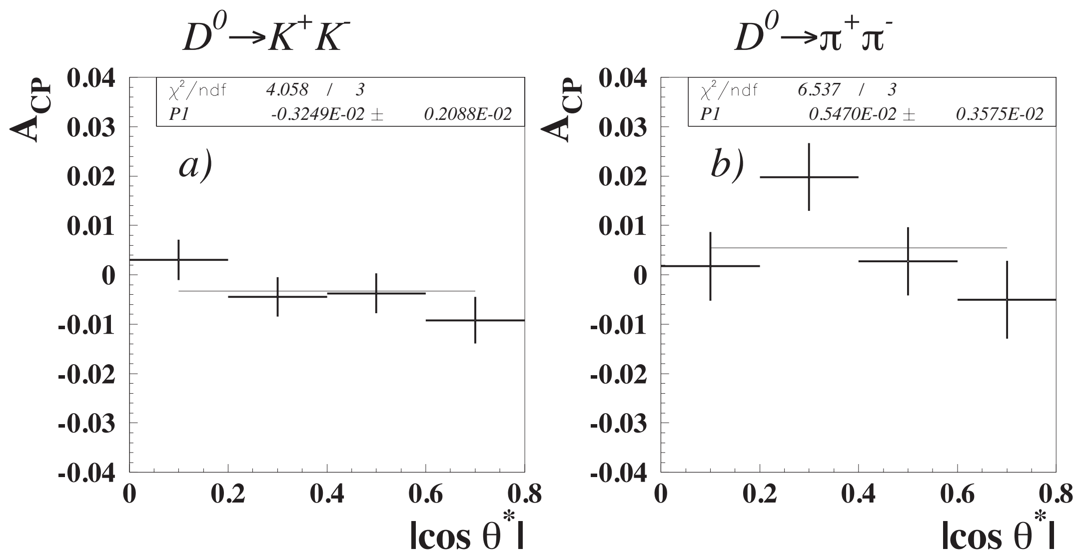
$$A_{CP}^{f} = \frac{A_{\rm rec}^{f,\rm corr}(\cos\theta^*) + A_{\rm rec}^{f,\rm corr}(-\cos\theta^*)}{2}$$

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

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

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

Preliminary 976 fb^{-1} :

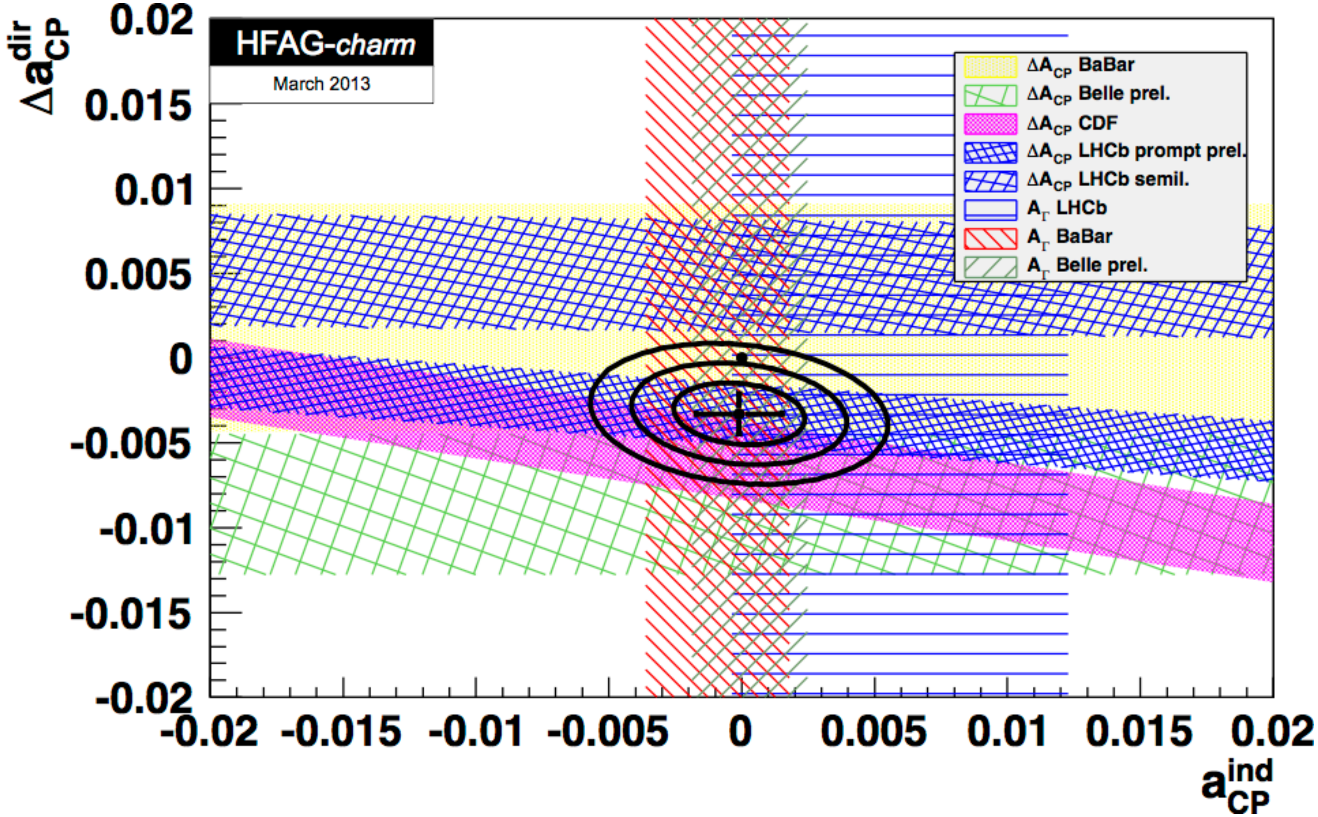


Fit for Direct CP Violation (HFAG):

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

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

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



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

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

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

Belle time-integrated $D^+ \rightarrow K_S K^+$

Ko et al., JHEP 1302, 098 (2013)

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

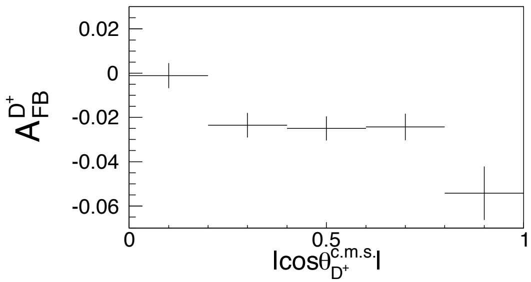
(1) *measure tagging asym. using* $D^0 \rightarrow K^- \pi^+$

$$A(D^0 \rightarrow K^- \pi^+) = A_{FB} + A_{\varepsilon}^{K^-} + A_{\varepsilon}^{\pi^+}$$
$$A(D_s^+ \rightarrow \phi\, \pi^+) = A_{FB} + A_{\varepsilon}^{\pi^+}$$

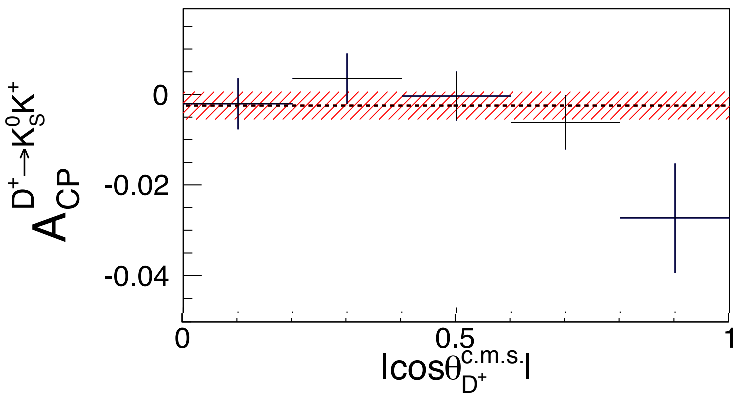
(2) *take sums and differences in bins of* $\cos\theta^*$

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

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

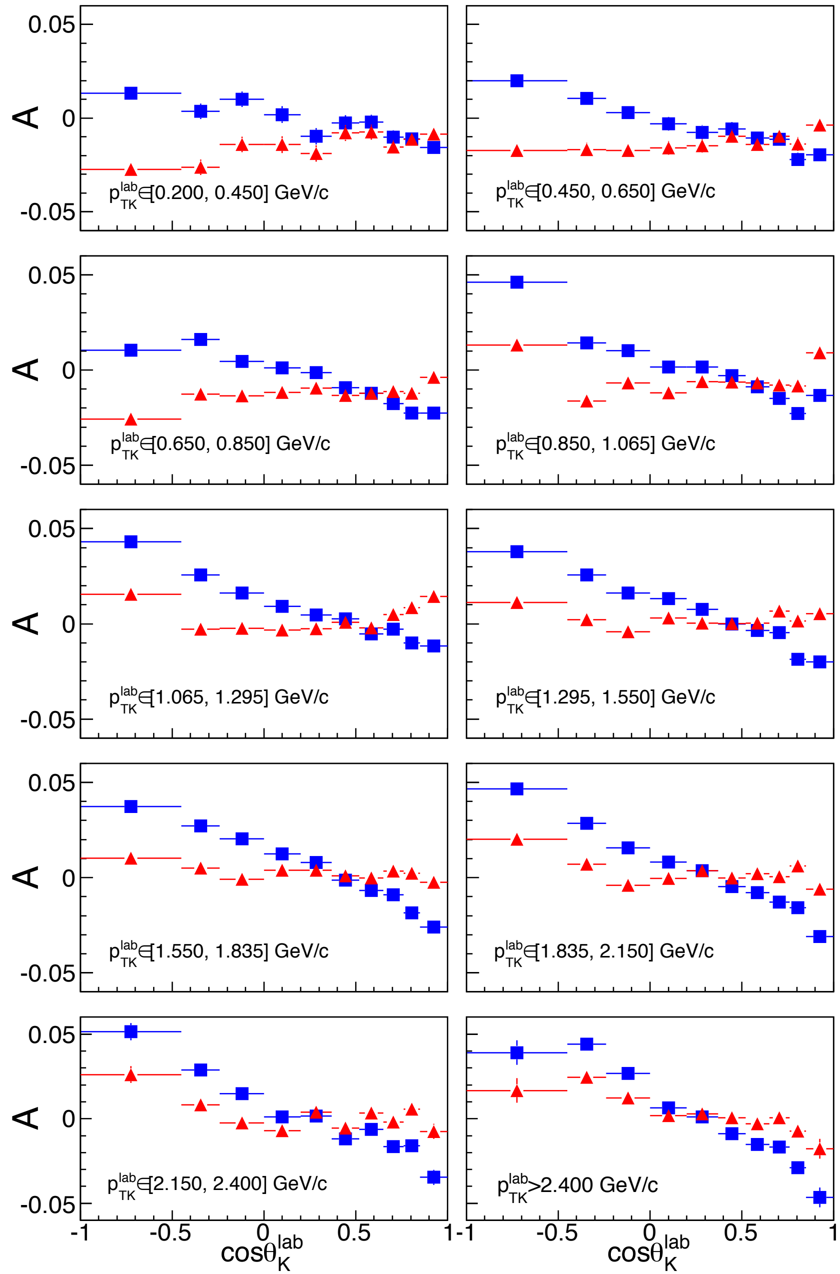


$$\tilde{A}_{CP}^{K_S K^+} = A_{CP}^{K_S K^+} + A_{CP}^{\overline{K}^0} = (-0.25 \pm 0.28 \pm 0.14)\%$$
$$A_{CP}^{K_S K^+} = (+0.08 \pm 0.28 \pm 0.14)\%$$



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

Ko et al., JHEP 1302, 098 (2013)



■ $A_{FB} + A_\varepsilon^{K^-} + A_\varepsilon^{\pi^+}$

▲ $A_\varepsilon^{K^-}$

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

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

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

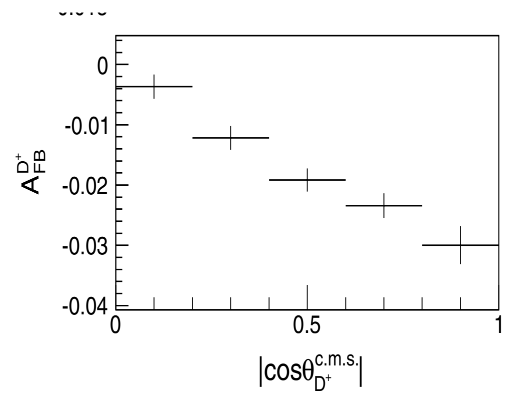
(1) *measure tagging asym. using $D \to K^+\pi^-\pi$*

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

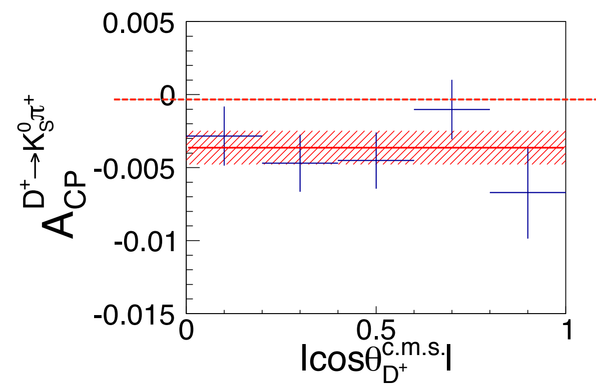
(2) *take sums and differences in bins of $\cos\theta^*$*

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

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



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



3.2σ

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)

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

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

White et al., arXiv:1307.5935, submitted to PRD

New result, 791 fb^{-1} :

$D^0 \to K^+\pi^- \pi^+ \pi^-$ "wrong-sign" decays are due to both a doubly-Cabibbo suppressed amplitude and mixing:

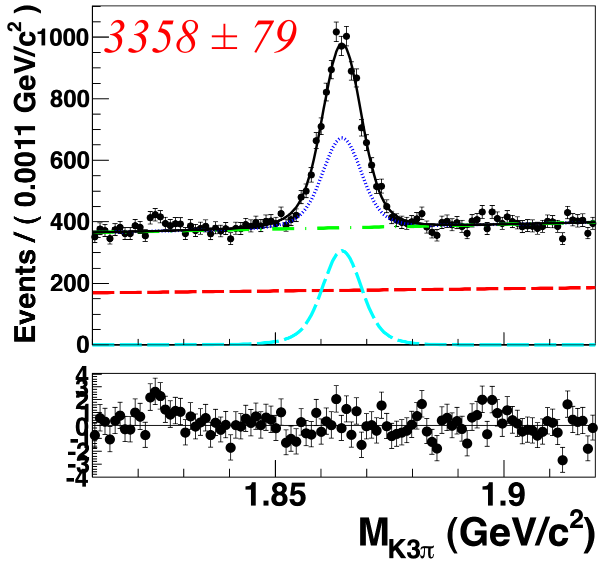
$$R_{\rm WS} = \frac{\Gamma(D^0 \to K^+\pi^-\pi^+\pi^-)}{\Gamma(D^0 \to K^-\pi^+\pi^-\pi^+)}$$

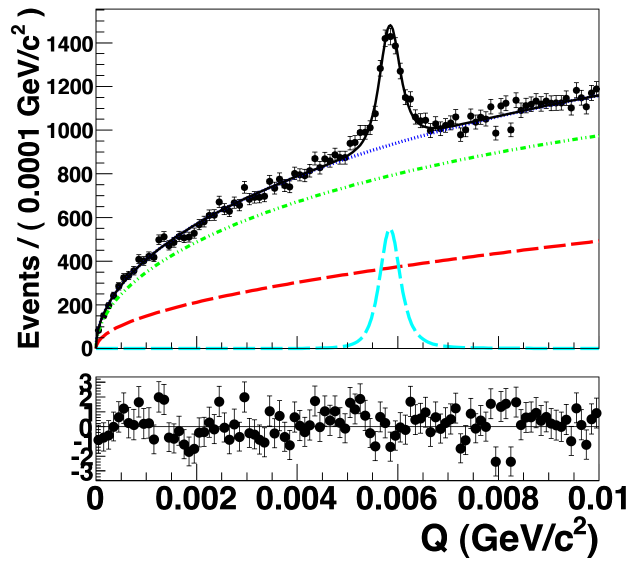
$$= R_D + \alpha y' \sqrt{R_D} + \frac{1}{2}(x^2 + y^2)$$

$$(y' = y\cos\delta - x\sin\delta)$$

Normalize to Cabibbo-favored $D^0 \to K^-\pi^+ \pi^+ \pi^-$ decays

2-d binned fit to $M_{K3\pi}$ and $Q = M_{D^*\pi} - M_D$





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

$$R_{\rm WS} = R'_{\rm WS} \cdot \frac{\varepsilon(K^-\pi^+\pi^+\pi^-)}{\varepsilon(K^+\pi^-\pi^+\pi^-)}$$

$$N'(K\pi\pi\pi) = \sum_{i=1}^{576} \left[\frac{N_i - N_{\rm bkg} \cdot f_i}{\varepsilon_i} \right]$$

$$\Rightarrow \quad R_{\rm WS} = \frac{N'(K^+\pi^-\pi^+\pi^-)}{N'(K^-\pi^+\pi^+\pi^-)}$$

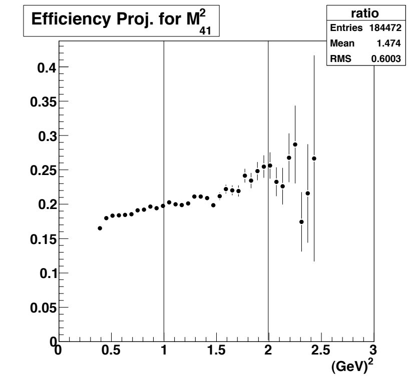
$$N'(K^+\pi^-\pi^+\pi^-) = 37\,297 \pm 881$$
$$N'(K^-\pi^+\pi^+\pi^-) = 11\,510\,000 \pm 20\,000$$

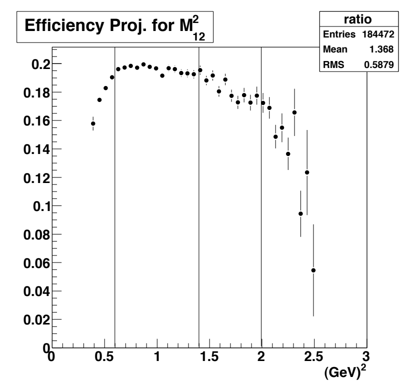
$$\Rightarrow \quad R_{\rm WS} = (0.324 \pm 0.008 \pm 0.007)\%$$
$$B_{D^0 \to K^+\pi^-\pi^+\pi^-} = (2.61 \pm 0.06\,^{+0.09}_{-0.08}) \times 10^{-4}$$

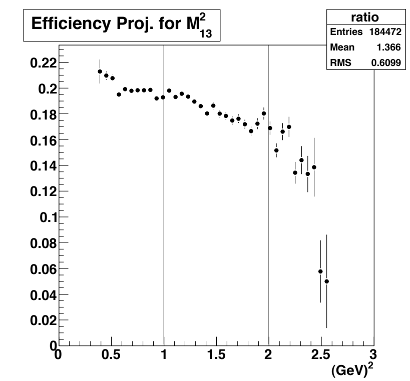
Take α and strong phase δ from CLEOc:

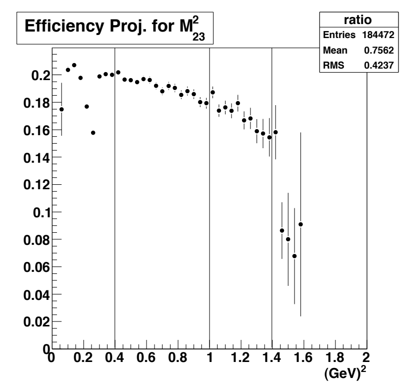
$$R_D = (0.327\,^{+0.019}_{-0.016})\%$$

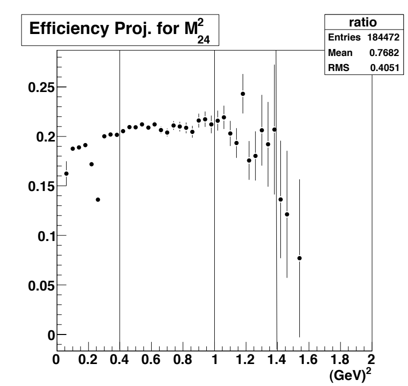
Acceptance calculated in 5-dimensional space of m_{h+h^-} bins (576 bins total):











Summary

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

976 fb^{-1} preliminary: y_{CP} =(1.11 ± 0.22 ± 0.11)%
A_Γ = (-0.03 ± 0.20 ± 0.08)%

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

976 fb^{-1} preliminary: $\Delta A \equiv A_{KK} - A_{\pi\pi}$ = (−0.87 ± 0.41 ± 0.06)%

time-integrated $D^+ \to K_S K^+$

977 fb^{-1} final: A = (+0.08 ± 0.28 ± 0.14)%

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

977 fb^{-1} final: A = (−0.024 ± 0.094 ± 0.067)%
[A + A(K^0) = (−0.363 ± 0.094 ± 0.067)%]

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

791 fb^{-1} preliminary: $B = (2.61 \pm 0.06\ ^{+0.09}_{-0.08}) \times 10^{-4}$
Taking α and δ from CLEO: R_D = (0.327 ± 0.019)%

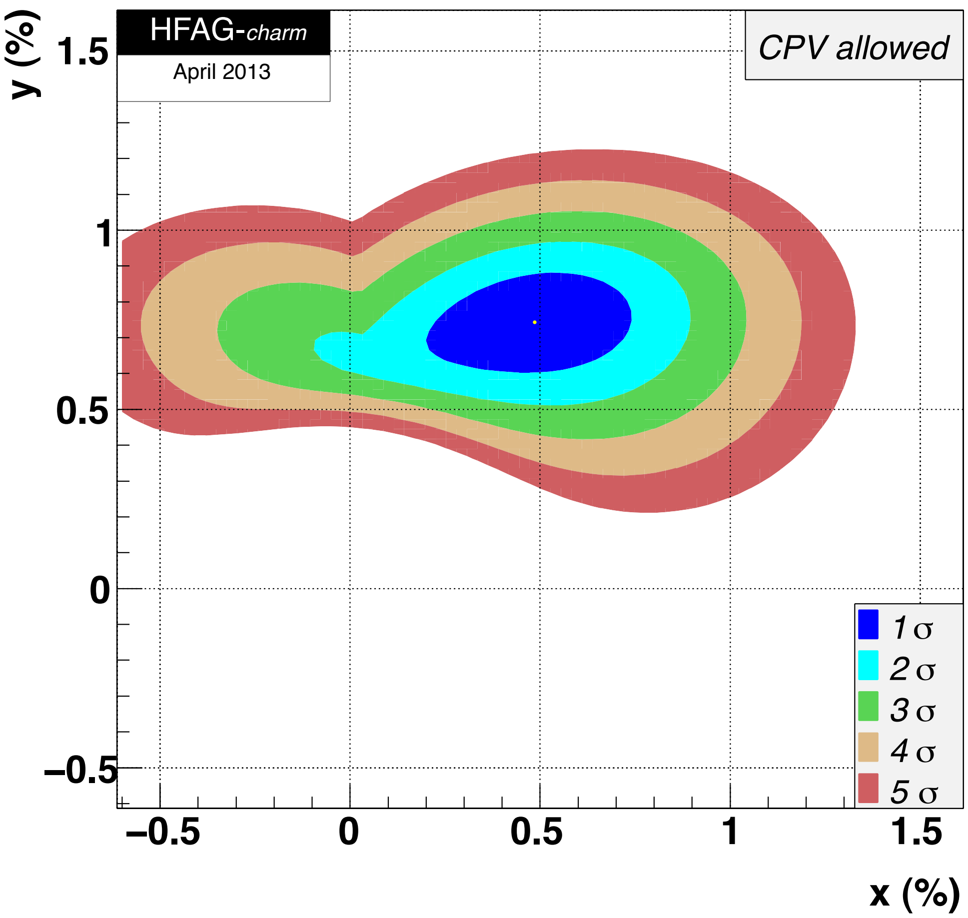
⇒ *No sign of new physics, but:*
these searches represent "low-lying fruit" and will be extended by a factor of ~50 with the upcoming Belle II experiment

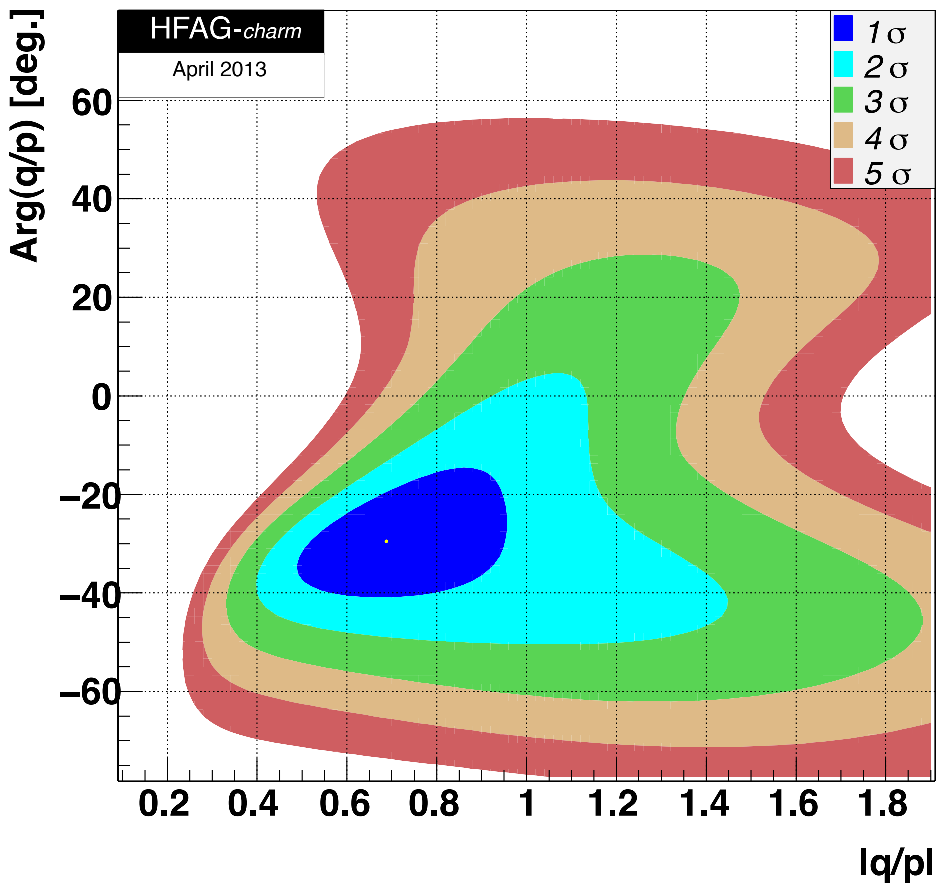
Extra/Backup

BELLE

HFAG global fit: 2-d likelihood functions

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

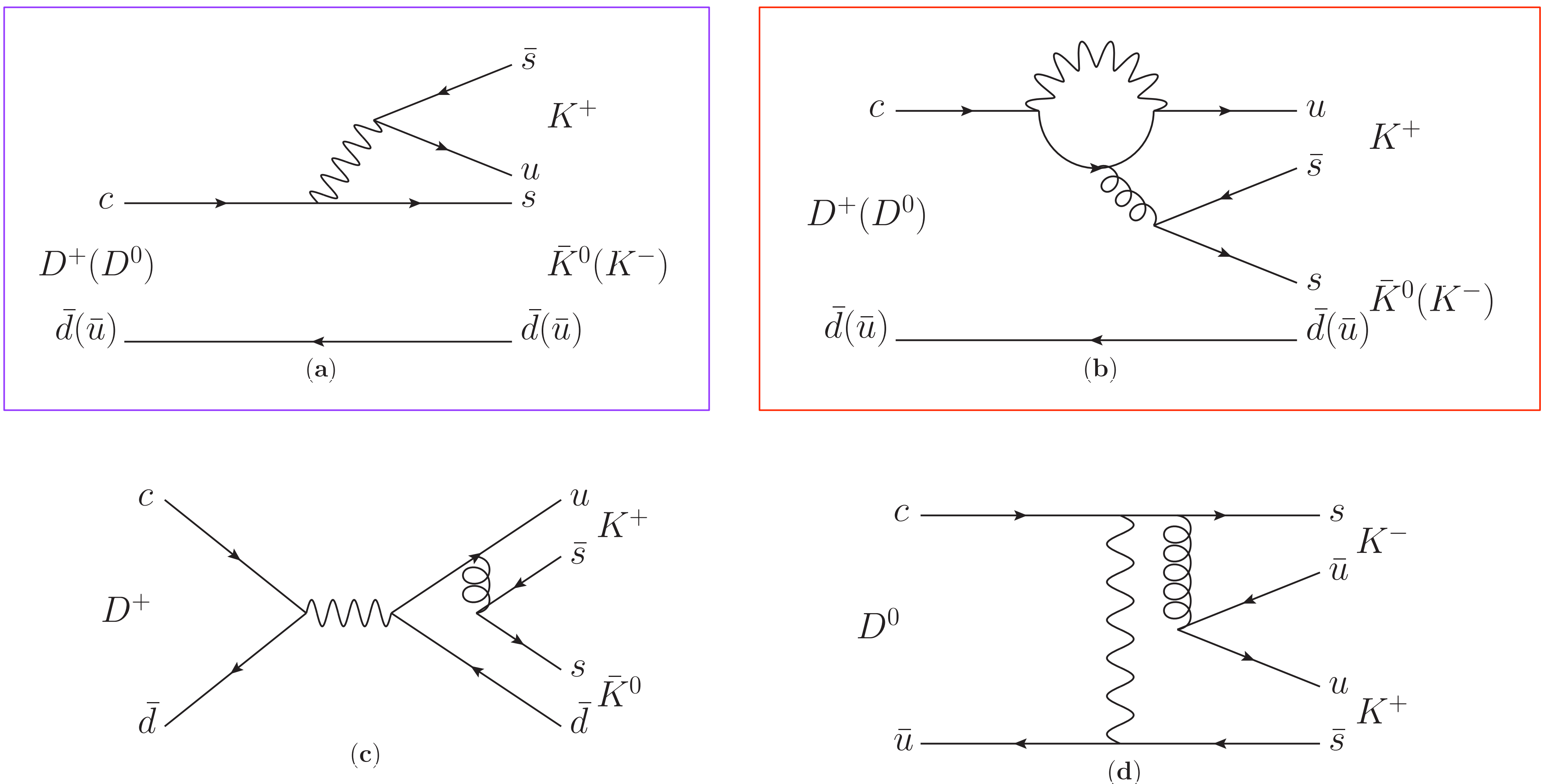




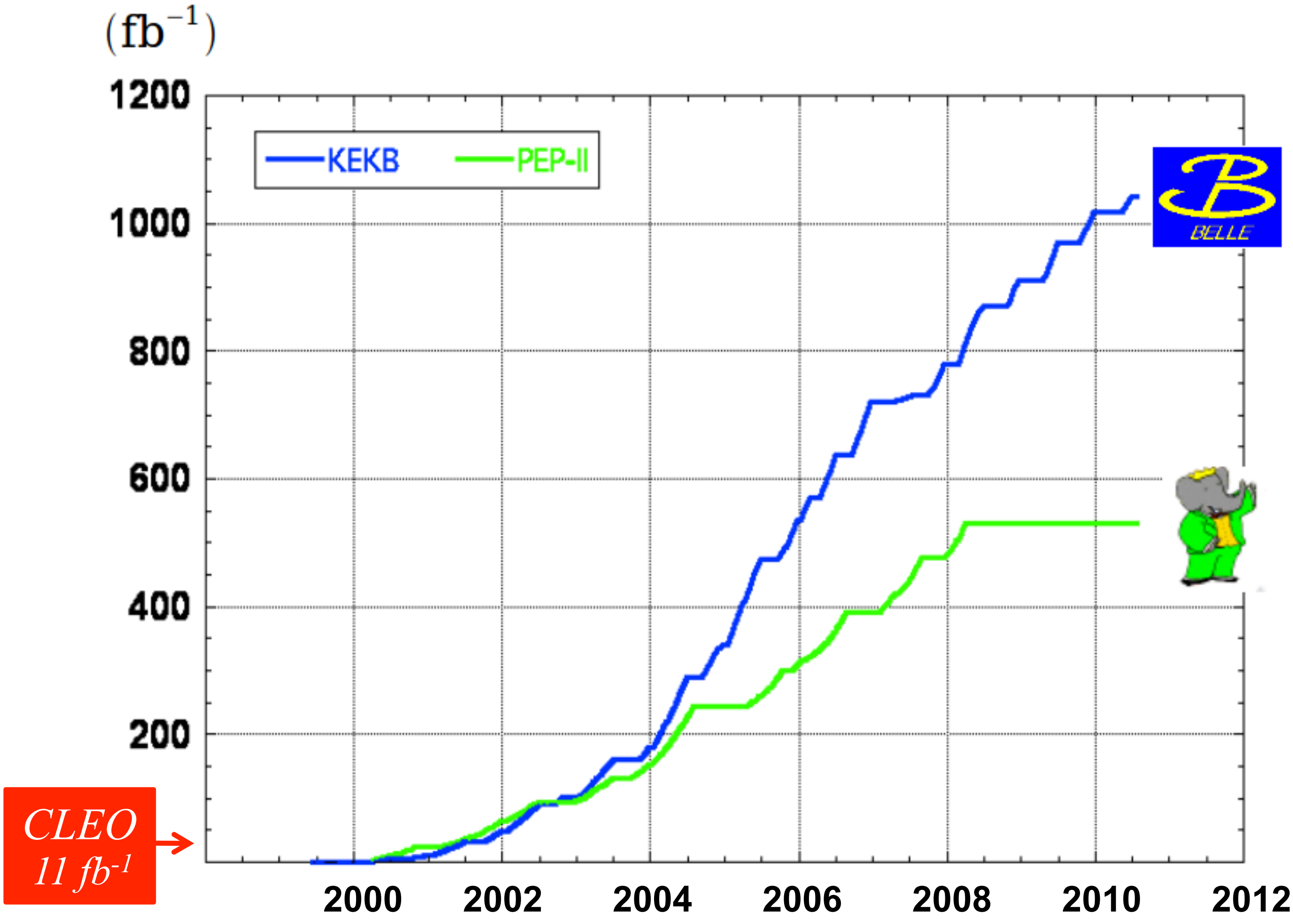
CPV-allowed plot, no mixing (x,y) = (0,0) point: $\Delta\chi^2 = 263.8$
No CPV (|q/p|, φ*) = (1,0) point:* $\Delta\chi^2 = 5.371$, *CL = 0.068 , CPV favored at* 1.8σ

Belle time-integrated $D^+ \to K_S K^+$

Same underlying direct CPV as $D^0 \to K^+K^-$: **(can check for new physics)**



B factory performance – final tally:



> 1 ab^{-1}

On resonance:

$\Upsilon(5S)$: 121 fb^{-1}

$\Upsilon(4S)$: 711 fb^{-1}

$\Upsilon(3S)$: 3 fb^{-1}

$\Upsilon(2S)$: 25 fb^{-1}

$\Upsilon(1S)$: 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

$\Upsilon(4S)$: 433 fb^{-1}

$\Upsilon(3S)$: 30 fb^{-1}

$\Upsilon(2S)$: 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}