D-mixing and indirect CPV at Belle, and prospects for Belle II

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- *motivation*
- $D^0(t) \to K^+\pi^-$
- $D^0(t) \to K_S\pi^+\pi^-$
- $D^0(t) \to K^+K^-, \pi^+\pi^-$
- *HFAG fit results*
- *Belle II prospects*

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 <u>at an e^+e^- machine (Belle/BaBar/Belle II)?</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

Belle CPV in mixing or interference

"Wrong-sign" $D^0(t) \to K^+\pi^-$
[Ko et al., PRL 112, 111801 (2014);
Zhang et al., PRL 96, 151801 (2006);
Li et al., PRL 94, 071801 (2005)]
Fit for x'^2, y', $|q/p|$, $\phi = Arg(q/p)$
[$x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$]

$D^0(t) \to K^0\pi^+\pi^-$ Dalitz plot analysis
[Peng et al., PRD 89, 091103(R) (2014);
Zhang et al., PRL 99, 131803 (2007)]

Fit for x, y, $|q/p|$, $\phi = Arg(q/p)$

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

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

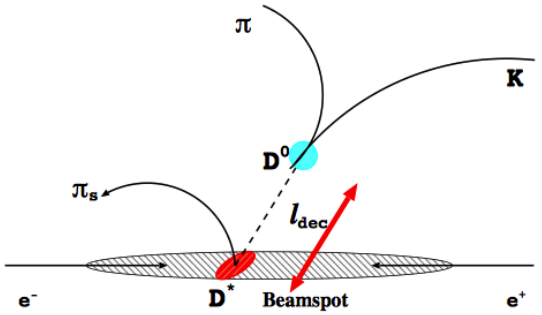
3 features in common:

a) *flavor is tagged via $D^{*-} \to \bar{D}^0\pi^-_{slow}$ or $D^{*+} \to D^0\pi^+_{slow}$*

b) *dominant background is typically "random π_{slow}" – include PDF for this in fits*

c) *decay time t calculated via*

$$t = \left(\frac{m_D}{p_D}\right)\vec{\ell}\cdot\hat{p}_D$$



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

Ko et al., PRL 112, 111801 (2014)

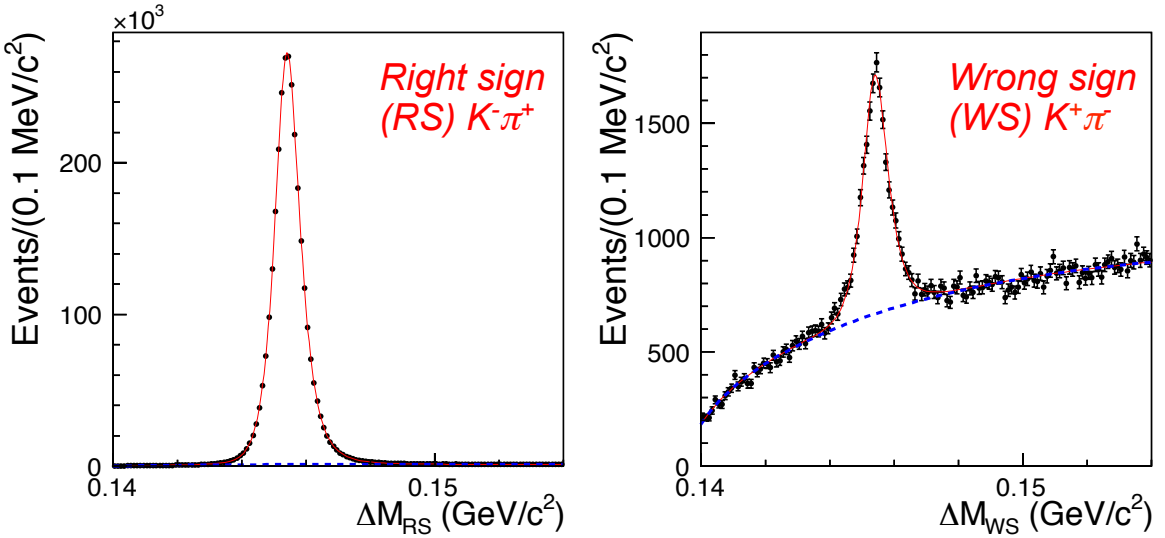
- 976 fb^{-1}, full data set
- double mis-ID background reduced with tight PID cuts if $|M_{swapped}-M_D| < 25$ MeV/c^2
- Method (opposite the usual):

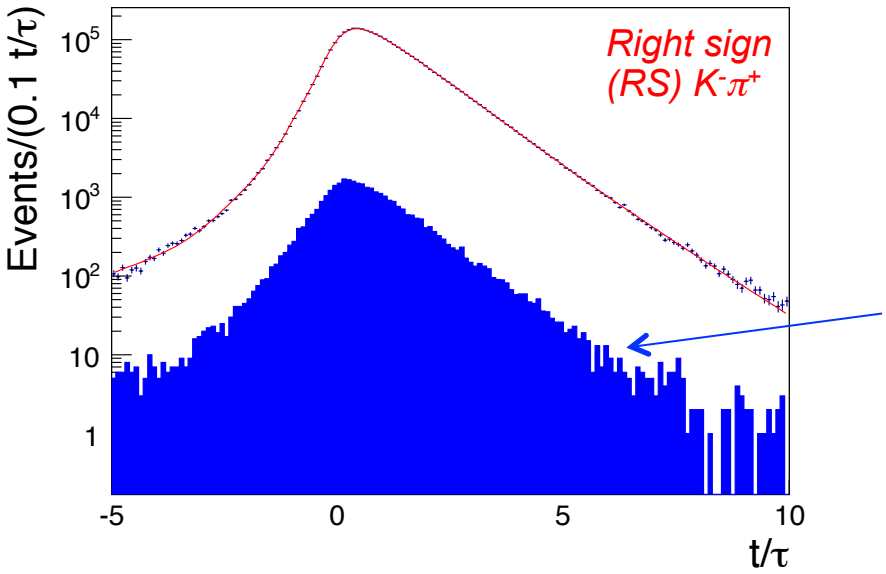
a) WS and RS samples are selected: $|M_{K\pi} - M_D| < 20$ MeV/c^2

b) Divide samples into 10 bins of decay time. For each bin, determine event yields by fitting $\Delta M = M_{K\pi\pi} - M_{K\pi}$ distribution

c) plot ratio of event yields, fit this distribution for R_D, x'^2, y'

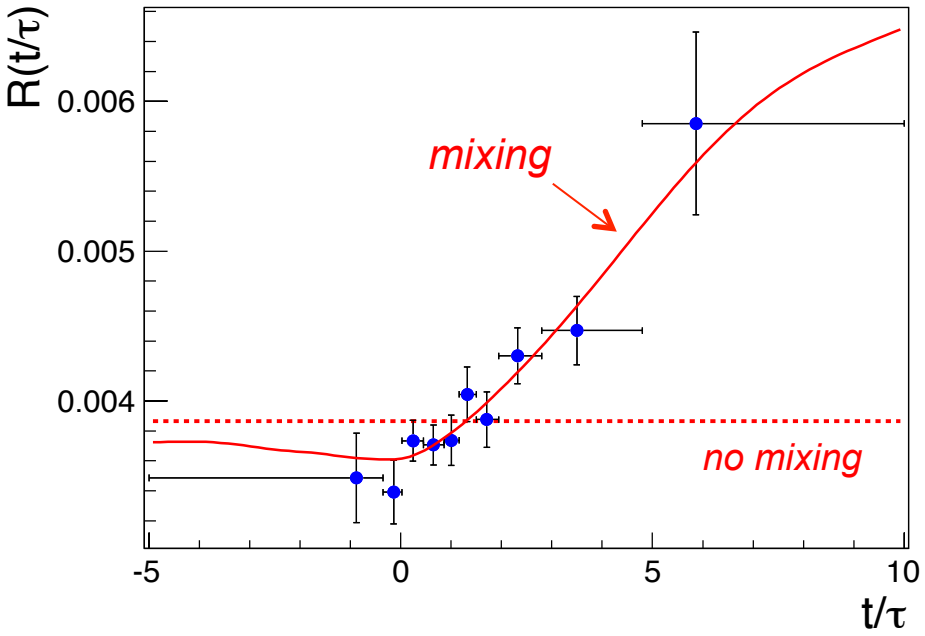
Advantage: as one fits to ratios of event yields, less sensitive to resolution function

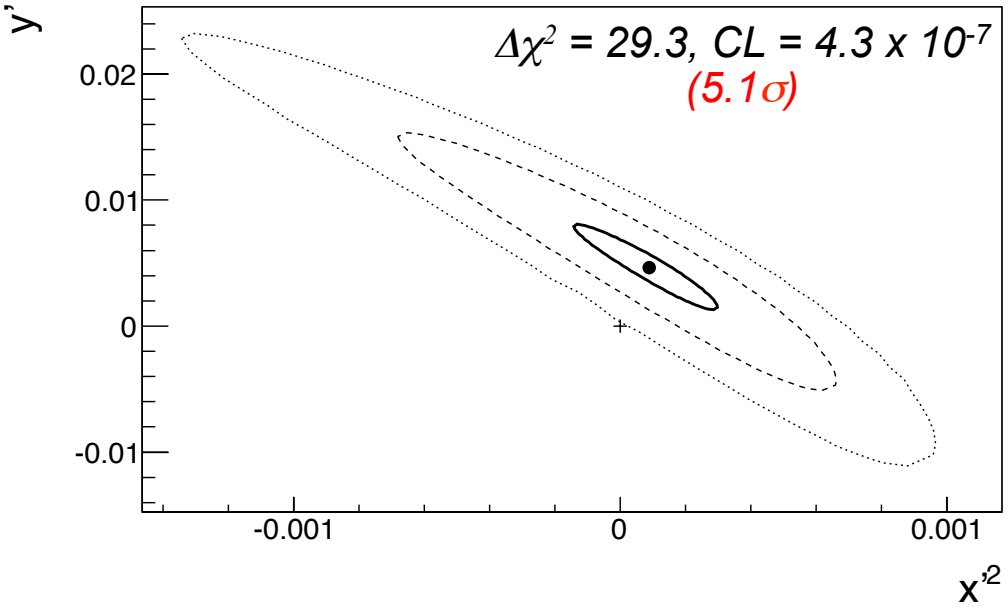




Time-dependent $D^0(t) \to K^+\pi^-$

Ko et al., PRL 112, 111801 (2014)





Test hypothesis (χ^2/d.o.f.)	Parameters	Fit results (10^{-3})
Mixing (4.2/7)	R_D	3.53 ± 0.13
	y'	4.6 ± 3.4
	x'^2	0.09 ± 0.22
No Mixing (33.5/9)	R_D	3.864 ± 0.059

Most precise results from e^+e^- experiments, But LHCb obtains:

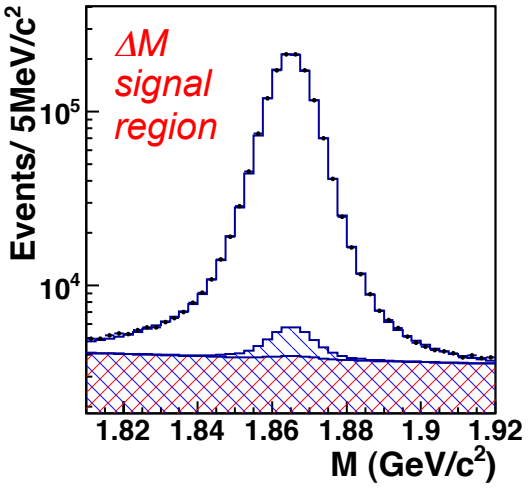
$R_D = 3.568 \pm 0.066$
$y' = 4.8 \pm 1.0$
$x'^2 = 0.055 \pm 0.049$
} $\times 10^{-3}$

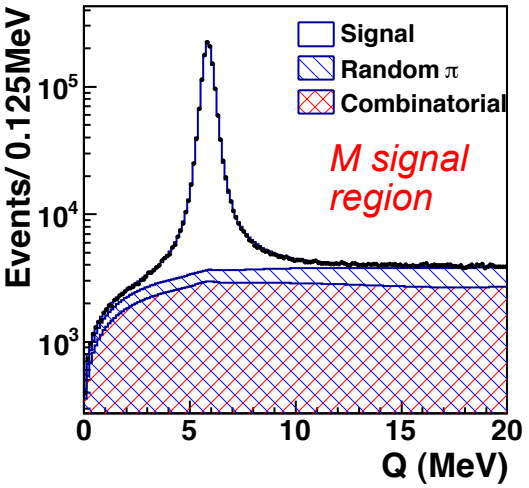
Time-dependent $D^0(t) \to K_S \pi^+\pi^-$

Peng et al., PRD 89, 091103(R) (2014)

Fitting the time-dependent Dalitz plot yields x, y, |q/p| and ϕ = Arg(q/p)

- *976 fb^{-1}, full data set*
- *Signal yield determined from 2-dim. fit to $M_{K\pi\pi}$ and $\Delta M = M_{K\pi\pi\pi} - M_{K\pi\pi}$. Yield is 1.2 x 10^6 events with a purity of 96%.*
- *Select events in signal region $|M_{K\pi\pi} - M_D| < 15$ MeV/c^2 and ΔM = (5.75, 5.95) MeV.*
- *For events in signal region, do unbinned ML fit to $m^+ = M(K\pi^+)^2$, $m^- = M(K\pi^-)^2$, and decay time t. Fit parameters are x, y, τ, resolution function parameters (2-3 Gaussians), and decay model: magnitudes and phases of 13 intermediate resonances.*
- *Do fit separately (+ simultaneously) for D^0 and D^0bar samples to obtain |q/p|, ϕ parameters.*





$$R_{D^0} = \frac{e^{-\Gamma t}}{2}\left\{\left(|\mathcal{A}_f|^2 + \left|\frac{q}{p}\right|^2 |\overline{\mathcal{A}}_f|^2\right)\cosh(yt) + \left(|\mathcal{A}_f|^2 - \left|\frac{q}{p}\right|^2 |\overline{\mathcal{A}}_f|^2\right)\cos(xt) + 2\mathrm{Re}\left(\frac{q}{p}\overline{\mathcal{A}}_f\mathcal{A}_f^*\right)\sinh(yt) - 2\mathrm{Im}\left(\frac{q}{p}\overline{\mathcal{A}}_f\mathcal{A}_f^*\right)\sin(xt)\right\}$$

$$R_{\overline{D}^0} = \frac{e^{-\Gamma t}}{2}\left\{\left(|\overline{\mathcal{A}}_f|^2 + \left|\frac{p}{q}\right|^2 |\mathcal{A}_f|^2\right)\cosh(yt) + \left(|\overline{\mathcal{A}}_f|^2 - \left|\frac{p}{q}\right|^2 |\mathcal{A}_f|^2\right)\cos(xt) + 2\mathrm{Re}\left(\frac{p}{q}\mathcal{A}_f\overline{\mathcal{A}}_f^*\right)\sinh(yt) - 2\mathrm{Im}\left(\frac{p}{q}\mathcal{A}_f\overline{\mathcal{A}}_f^*\right)\sin(xt)\right\}$$

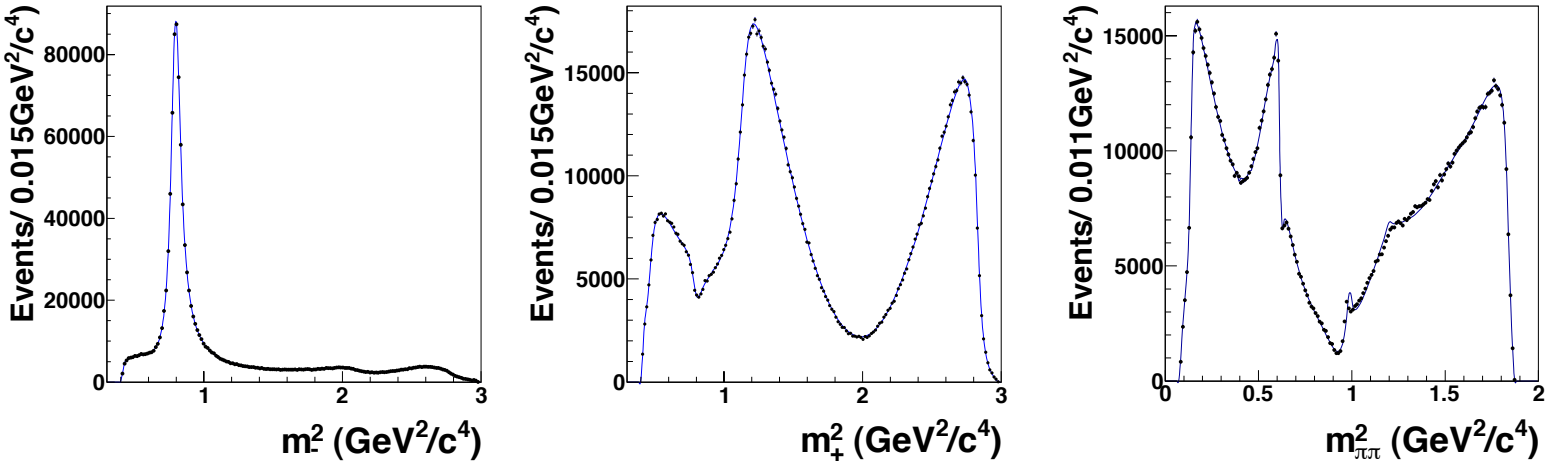
$$\text{If no } CPV: \quad \mathcal{A}_f(m_+^2, m_-^2) = \overline{\mathcal{A}}_f(m_-^2, m_+^2)$$

$D^0(t) \to K_S \pi^+\pi^-$: time-dependent Dalitz plot fit

Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.590 ± 0.003	131.8 ± 0.2	0.6045
$K_0^*(1430)^-$	2.059 ± 0.010	-194.6 ± 1.7	0.0702
$K_2^*(1430)^-$	1.150 ± 0.009	-41.5 ± 0.4	0.0221
$K^*(1410)^-$	0.496 ± 0.011	83.4 ± 0.9	0.0026
$K^*(1680)^-$	1.556 ± 0.097	-83.2 ± 1.2	0.0016
$K^*(892)^+$	0.139 ± 0.002	-42.1 ± 0.7	0.0046
$K_0^*(1430)^+$	0.176 ± 0.007	-102.3 ± 2.1	0.0005
$K_2^*(1430)^+$	0.077 ± 0.007	-32.2 ± 4.7	0.0001
$K^*(1410)^+$	0.248 ± 0.010	-145.7 ± 2.9	0.0007
$K^*(1680)^+$	1.407 ± 0.053	86.1 ± 2.7	0.0013
$\rho(770)$	1 (fixed)	0 (fixed)	0.2000
$\omega(782)$	0.0370 ± 0.0004	114.9 ± 0.6	0.0057
$f_2(1270)$	1.300 ± 0.013	-31.6 ± 0.5	0.0141
$\rho(1450)$	0.532 ± 0.027	80.8 ± 2.1	0.0012

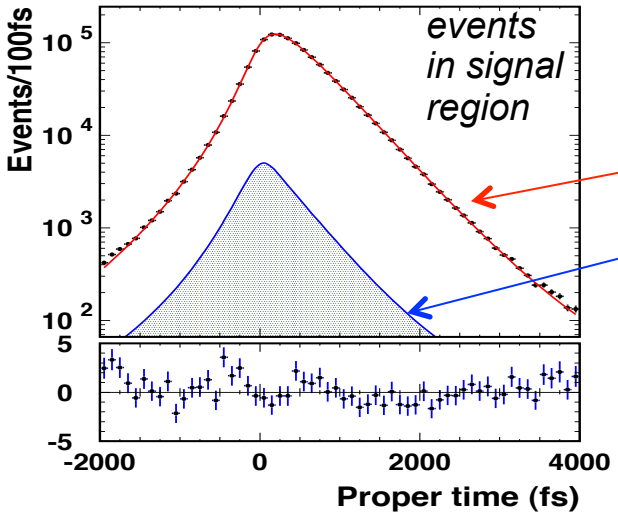
Resonance	Amplitude	Phase (deg
$\pi\pi$ S-wave		
β_1	4.23 ± 0.02	164.0 ± 0.2
β_2	10.90 ± 0.02	15.6 ± 0.2
β_3	37.4 ± 0.3	3.3 ± 0.4
β_4	14.7 ± 0.1	-8.9 ± 0.3
$f_{11}^{\rm prod}$	12.76 ± 0.05	$-161.1 \pm 0.$
$f_{12}^{\rm prod}$	14.2 ± 0.2	$-176.2 \pm 0.$
$f_{13}^{\rm prod}$	10.0 ± 0.5	$-124.7 \pm 2.$
$K\pi$ S-wave	**Parameters**	
M(MeV/c^2)	1461.7 ± 0.8	
Γ(MeV/c^2)	268.3 ± 1.1	
F	0.4524 ± 0.005	
$\phi_F(rad)$	0.248 ± 0.003	
R	1(fixed)	

Fit projections:
(fitted function describes the data well)



$D^0(t) \to K_S \pi^+\pi^-$: results

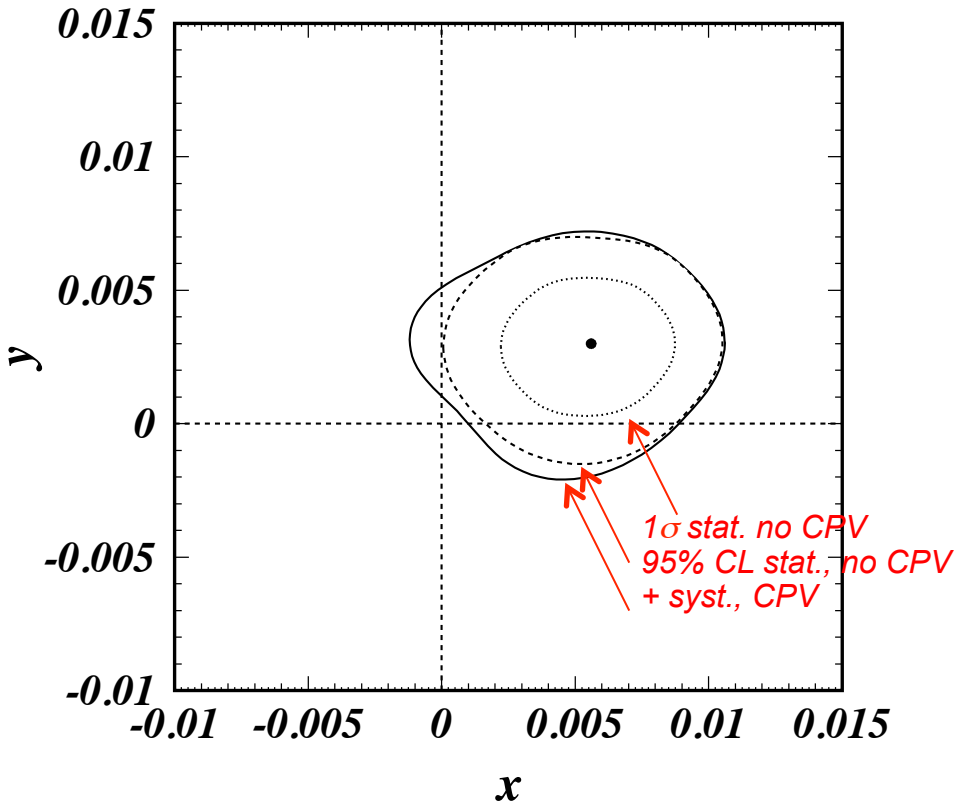
Peng et al., PRD 89, 091103(R) (2014)



Fit type	Parameter	Fit result
No CPV	x (%)	$0.56 \pm 0.19^{+0.03+0.06}_{-0.09-0.09}$
	y (%)	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.06}$
CPV	x (%)	$0.56 \pm 0.19^{+0.04+0.06}_{-0.08-0.08}$
	y (%)	$0.30 \pm 0.15^{+0.04+0.03}_{-0.05-0.07}$
	$\lvert q/p \rvert$	$0.90^{+0.16+0.05+0.06}_{-0.15-0.04-0.05}$
	$\arg(q/p)$ (°)	$-6 \pm 11 \pm 3^{+3}_{-4}$

τ = (410.3 ± 0.6) fs

2d likelihood contour:



$\Delta\chi^2$ ⇒ mixing significance = 2.5σ but no evidence for indirect or direct CPV

$D^0(t) \to K_S \pi^+\pi^-$: systematic errors

Peng et al., PRD 89, 091103(R) (2014)

Source	No *CPV* $\Delta x/10^{-4}$	No *CPV* $\Delta y/10^{-4}$	*CPV* $\Delta x/10^{-4}$	*CPV* $\Delta y/10^{-4}$	*CPV* $\lvert q/p\rvert/10^{-2}$	*CPV* $\arg(q/p)/^\circ$
Best candidate selection	$+1.0$	$+1.9$	$+1.3$	$+2.0$	-2.3	$+2.2$
Signal and background yields	±0.3	±0.3	±0.4	±0.4	±1.2	±0.8
Fraction of wrong tagged events	-0.7	-0.4	-0.5	$+0.4$	$+1.1$	$+0.8$
Time resolution of signal	-1.4	-0.9	-1.2	-0.8	$+0.8$	-1.2
Efficiency	-1.1	-2.1	-1.4	-2.2	$+3.1$	$+1.3$
→ Combinatorial PDF	$^{+1.9}_{-4.8}$	$^{+2.3}_{-3.9}$	$^{+2.4}_{-4.1}$	$^{+2.0}_{-4.4}$	$^{+1.2}_{-2.9}$	$^{+2.8}_{-2.3}$
$K^*(892)$ DCS/CF reduced by 5%	-7.3	$+2.3$	-6.9	$+3.1$	$+3.3$	-1.4
$K_2^*(1430)$ DCS/CF reduced by 5%	$+1.7$	-0.7	$+2.2$	-0.2	$+1.1$	$+0.4$
Total	$^{+2.8}_{-8.9}$	$^{+3.7}_{-4.6}$	$^{+3.6}_{-8.3}$	$^{+4.3}_{-5.1}$	$^{+5.0}_{-4.0}$	$^{+3.3}_{-3.0}$

Systematics due to decay model:

Source	No *CPV* $\Delta x/10^{-4}$	No *CPV* $\Delta y/10^{-4}$	*CPV* $\Delta x/10^{-4}$	*CPV* $\Delta y/10^{-4}$	*CPV* $\lvert q/p\rvert/10^{-2}$	*CPV* $\arg(q/p)/^\circ$
Resonance M & Γ	±1.4	±1.2	±1.2	±1.3	±2.1	±1.0
$K^*(1680)^+$ removal	-1.8	-3.0	-2.2	-2.8	$+2.1$	-1.2
$K^*(1410)^\pm$ removal	-1.2	-3.6	-1.7	-3.9	-1.3	$+1.4$
$\rho(1450)$ removal	$+2.1$	$+0.3$	$+2.1$	$+0.5$	-1.9	$+0.9$
Form factors	$+4.0$	$+2.4$	$+4.3$	$+2.0$	-2.4	-1.0
$\Gamma(q^2) =$ constant	$+3.3$	-1.6	$+4.1$	-2.3	-1.6	$+1.3$
Angular dependence	-8.5	-3.9	-7.4	-3.6	$+5.6$	-3.2
K-matrix formalism	-2.2	$+1.8$	-3.5	$+2.4$	-3.6	$+1.1$
Total	$^{+5.8}_{-9.1}$	$^{+3.2}_{-6.4}$	$^{+6.4}_{-8.4}$	$^{+3.4}_{-6.9}$	$^{+6.4}_{-5.1}$	$^{+2.5}_{-3.7}$

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

presented by Staric at CHARM 2012 (arXiv:1212.3478); update of Staric et al., PRL 98, 211803 (2007)

$$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1 = \frac{1}{2}\left(|q/p| + |p/q|\right) y\cos\phi - \frac{1}{2}\left(|q/p| - |p/q|\right) x\sin\phi$$

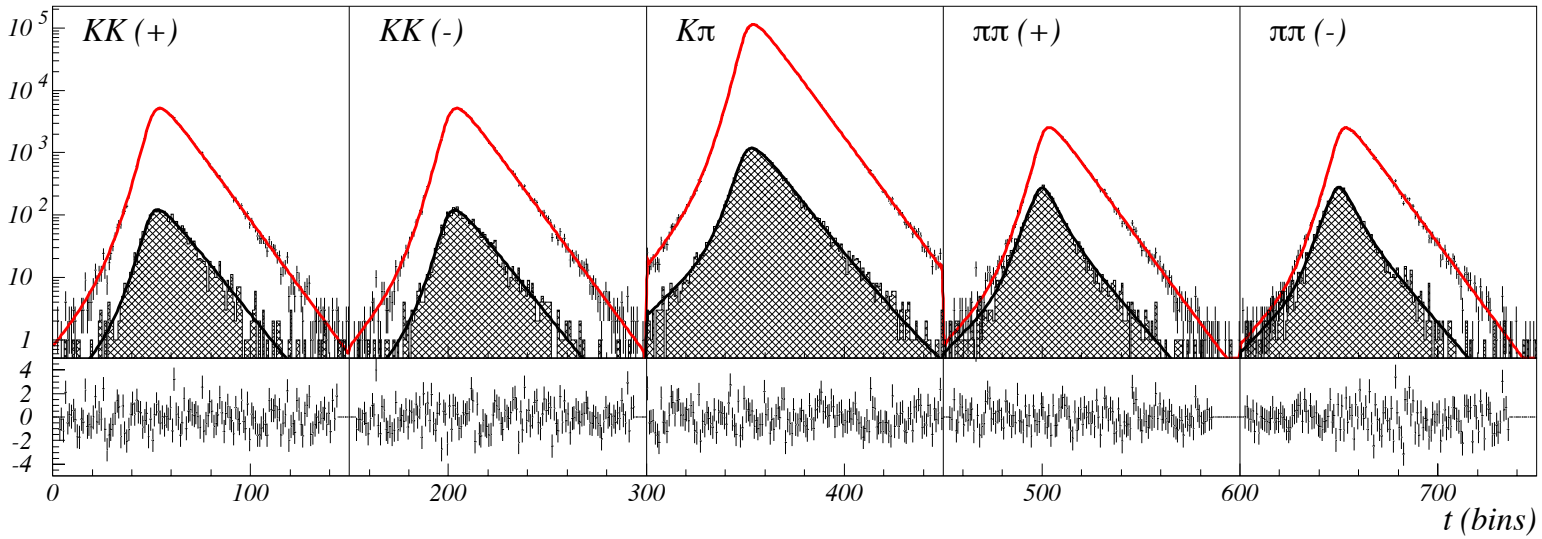
$$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^+K^-) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^+K^-) + \tau(D^0 \to K^+K^-)} = \frac{1}{2}\left(|q/p| - |p/q|\right) y\cos\phi - \frac{1}{2}\left(|q/p| + |p/q|\right) x\sin\phi$$

$= -a_{int} - a_{indirect}$ contribution to A_{CP}

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

$\chi^2/ndf = 792.9/684$ (CL= 0.2%)

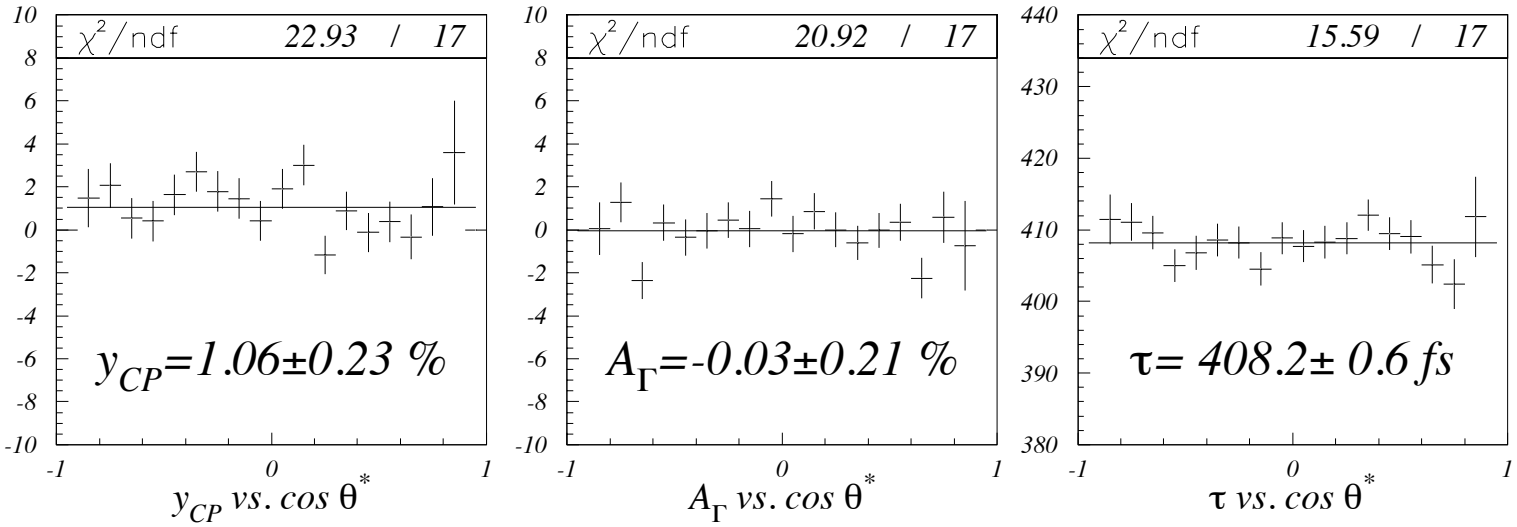


Belle time-dependent $D^0(t) \to K^+K^-, \pi^+\pi^-$ (cont'd)

arXiv:1212.3478; update of 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^**

977 fb^{-1} preliminary:



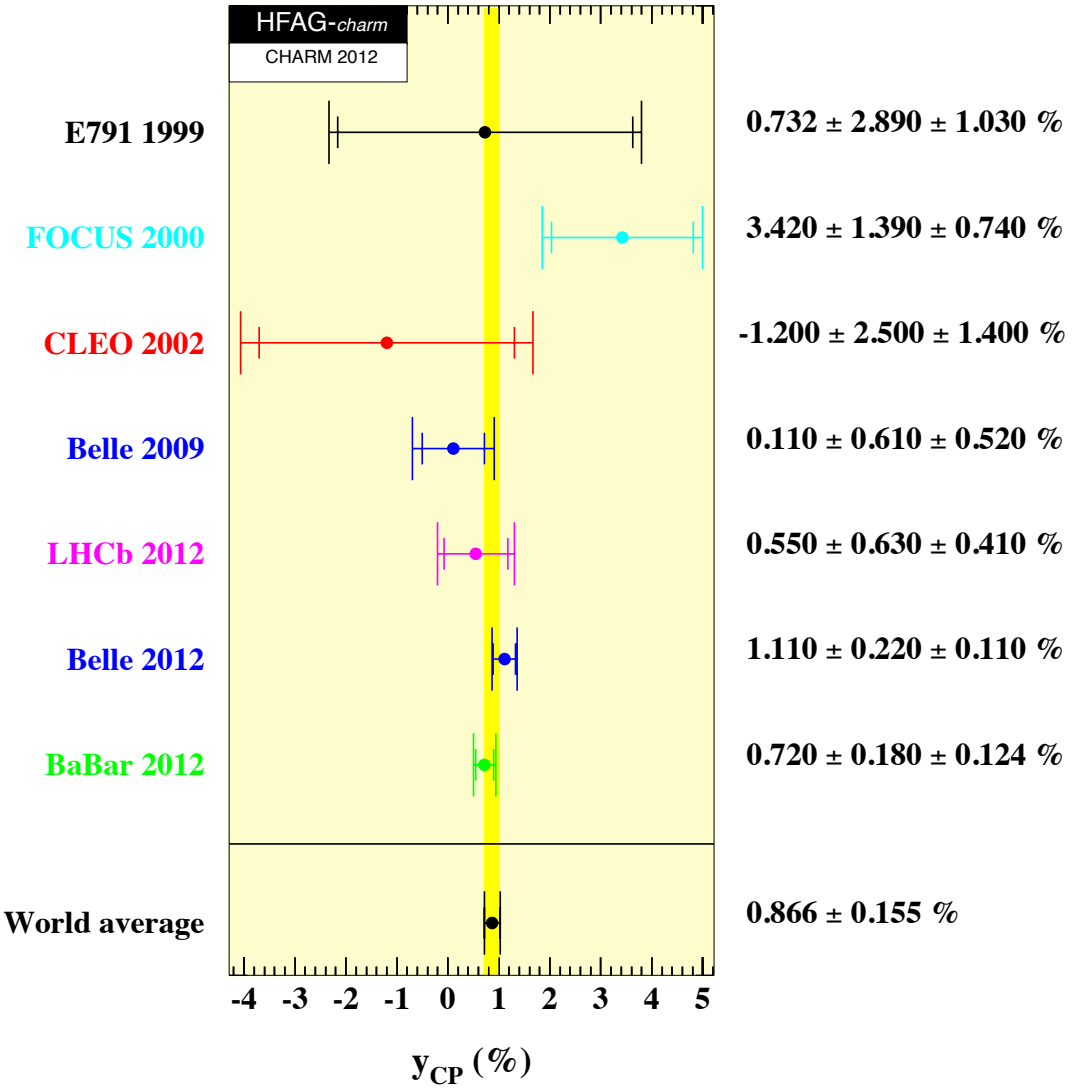
$$y_{CP} = (+1.11 \pm 0.22 \pm 0.11)\%$$
$$A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%$$

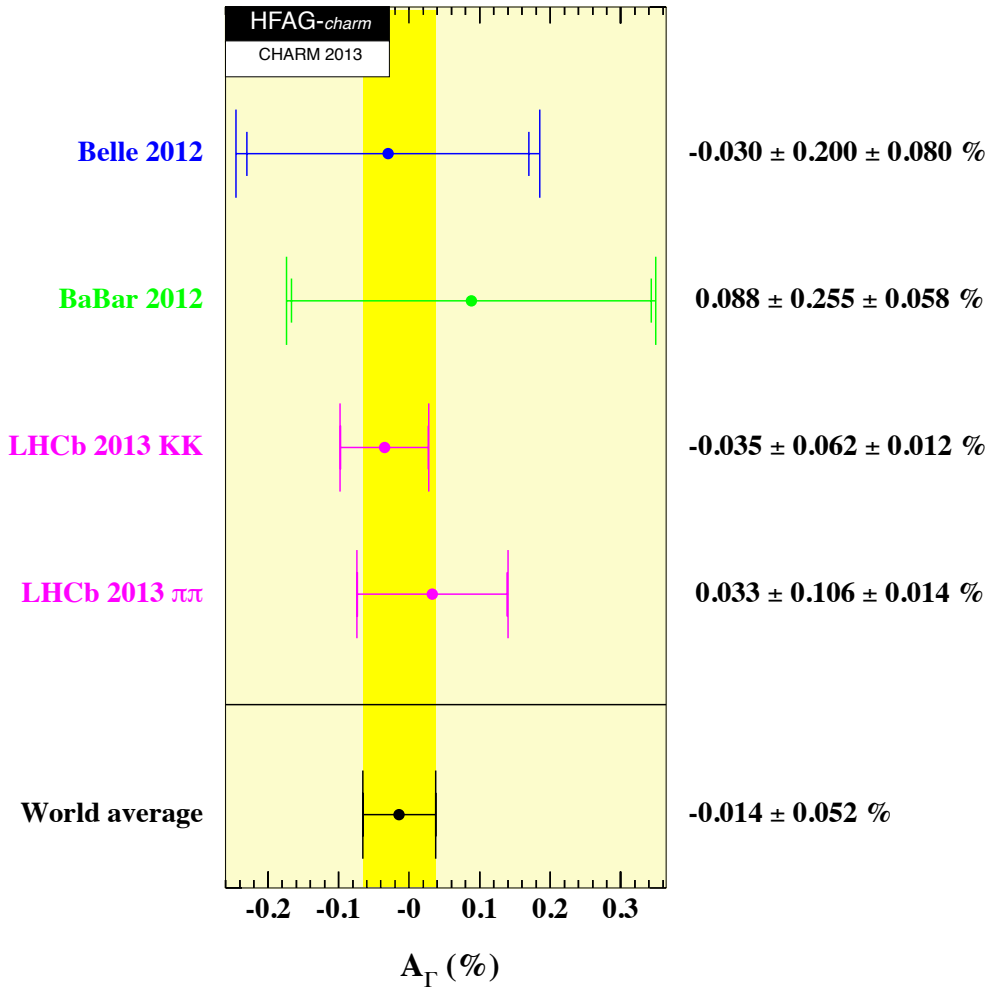
was

(world's most precise to-date)

HFAG World Averages

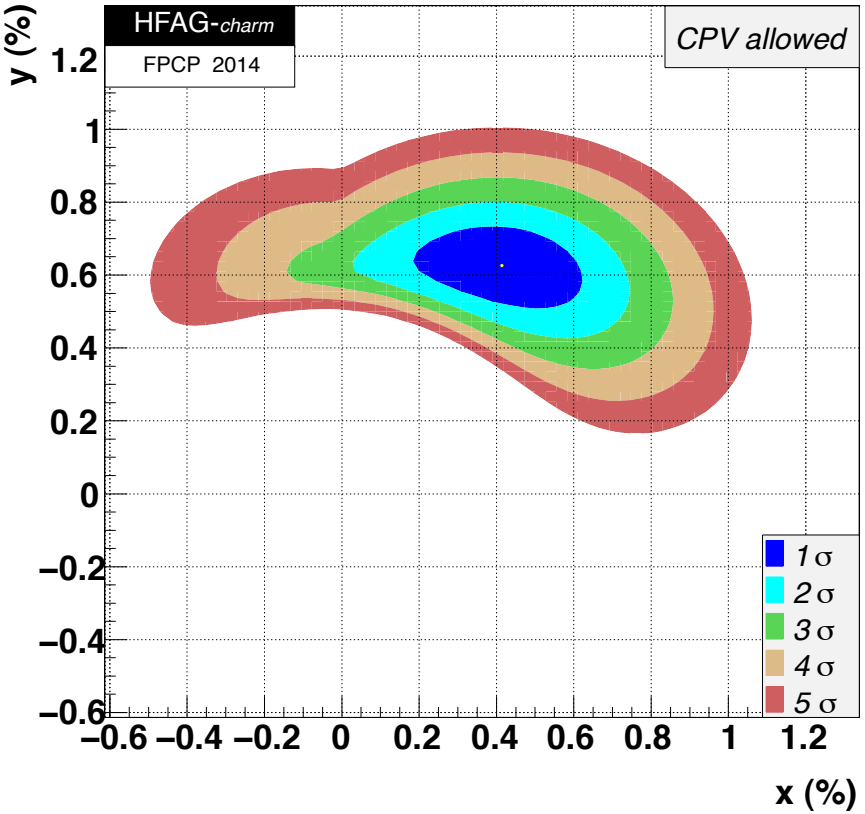
www.slac.stanford.edu/xorg/hfag/charm/index.html

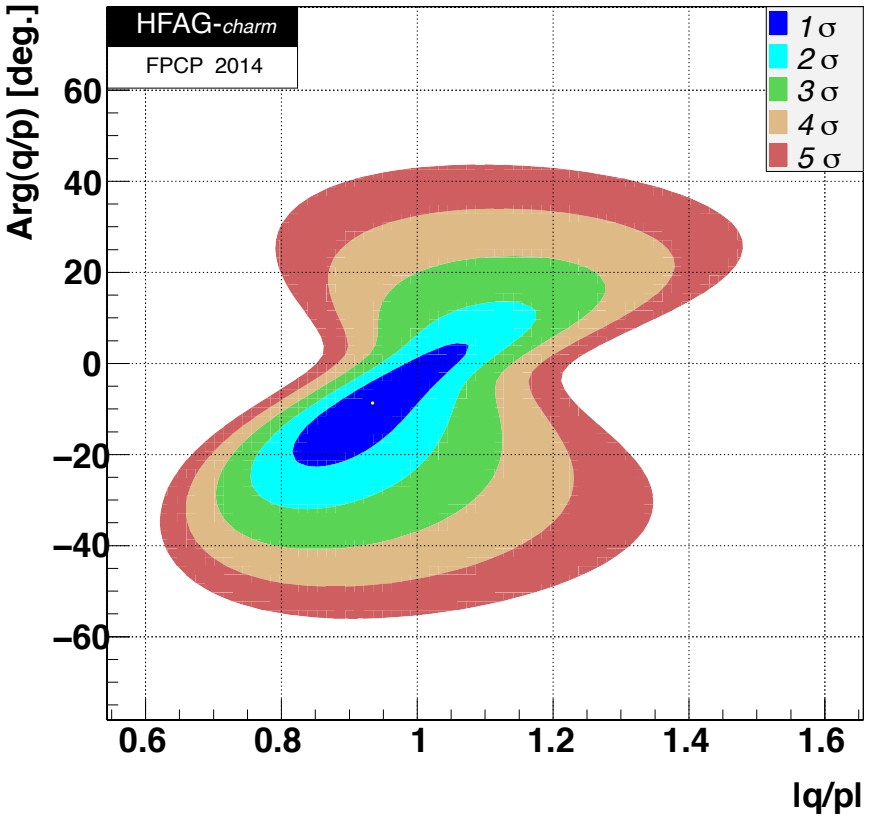




HFAG global fit to all available data

45 measured observables, 10 theoretical fitted parameters: x, y, δ, $\delta_{K\pi\pi}$, R_D, A_D, |q/p|, φ, A_K, A_π
(for details see Marco Gersabeck's talk & www.slac.stanford.edu/xorg/hfag/charm/index.html)





$\Delta\chi^2$ *at no mixing point (x,y) = (0,0)* > 420 $(>12\sigma)$ $[x: > 2.4\sigma, y: > 9.4\sigma]$
No CPV (|q/p|, φ) = (1,0) point: $\Delta\chi^2 = 1.32$, *CL = 0.48 , consistent with no CPV*

Belle II expectations for $\bar{D}^0$-D^0 mixing and CPV

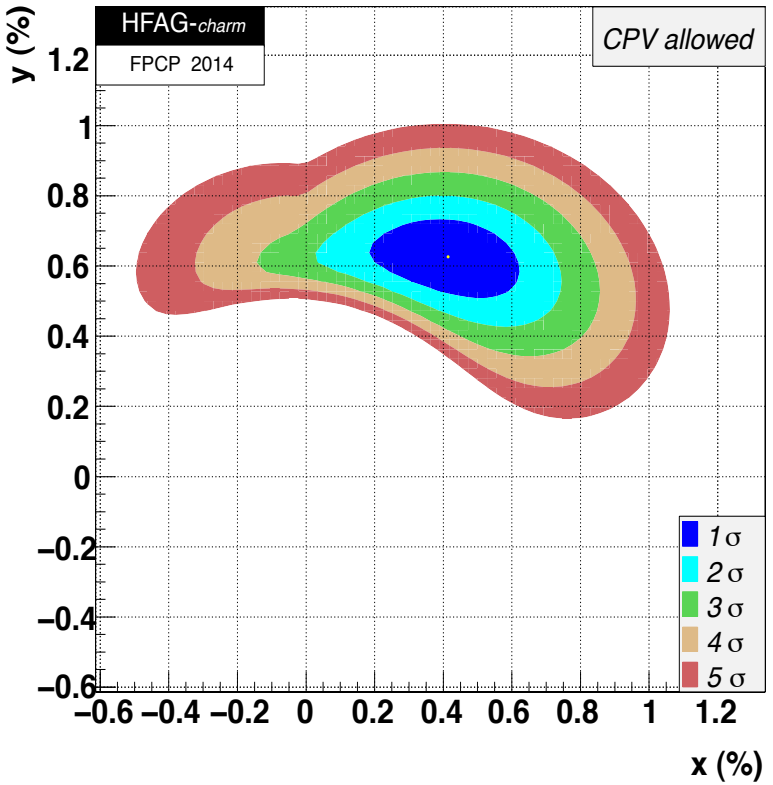
Expected Uncertaintes *(M. Staric, KEK FFW14)*:

Analysis	Observable	Uncertainty (%)		
		Now (~ 1 ab^{-1})	$\mathcal{L} = 50$ ab^{-1}	
$K^0_S \pi^+\pi^-$	x	0.19	0.08	
	y	0.15	0.05	*factor of ~3 better*
	$\lvert q/p \rvert$	16	6	
	ϕ	11°	4°	
$\pi^+\pi^-$, K^+K^-	y_{CP}	0.22	0.04	*factor of ~6 better*
	A_Γ	0.20	0.03	
$K^+\pi^-$	x'^2	0.022	0.003	
	y'	0.34	0.04	*factor of 8-10 better*
	$\lvert q/p \rvert$	0.6	0.06	
	ϕ	25°	2.3°	

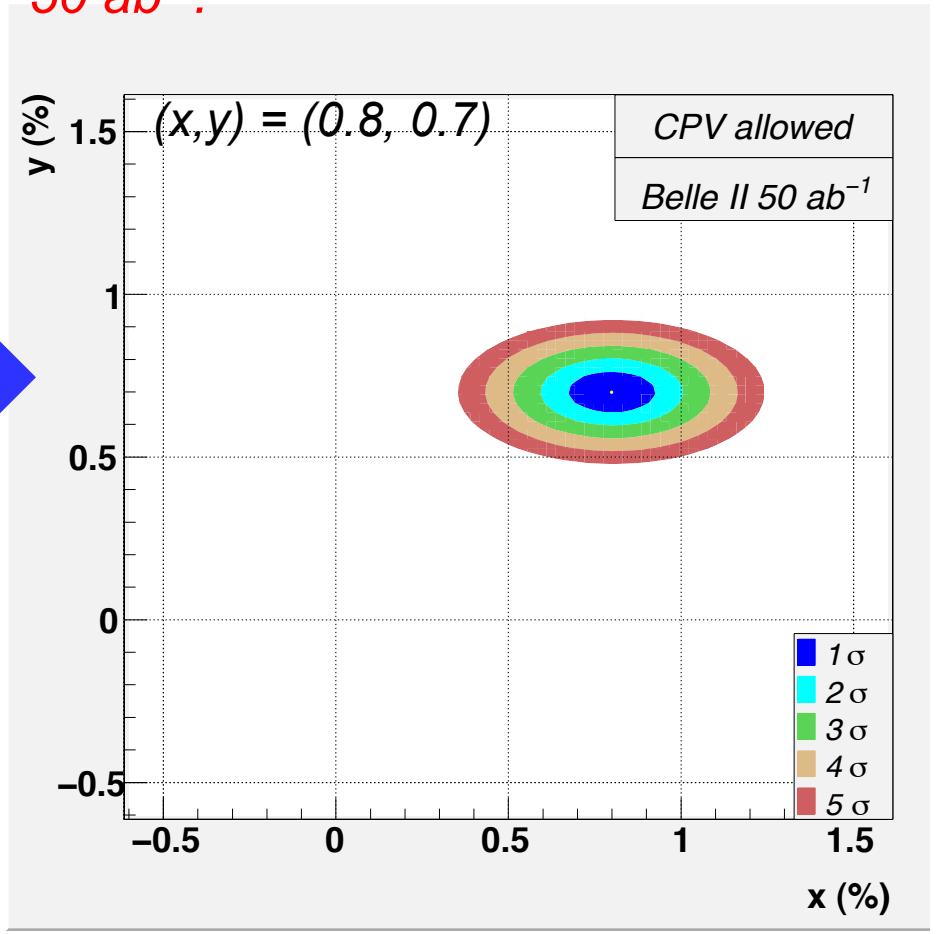
Note: *statistical error and some systematics scale by luminosity, but other systematics do not.*

Belle II expectations for $\bar{D}^0$-D^0 mixing

Now:



50 ab^{-1}:

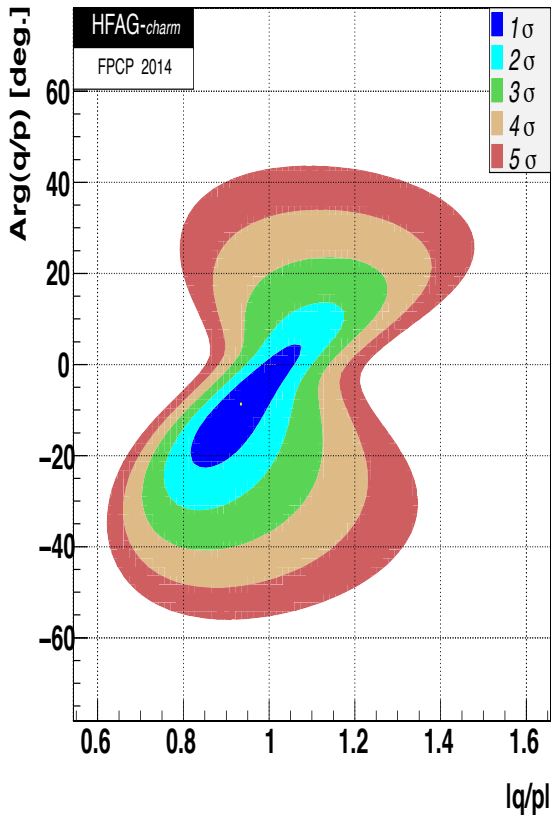


Current measurements of x, y give many constraints on NP models

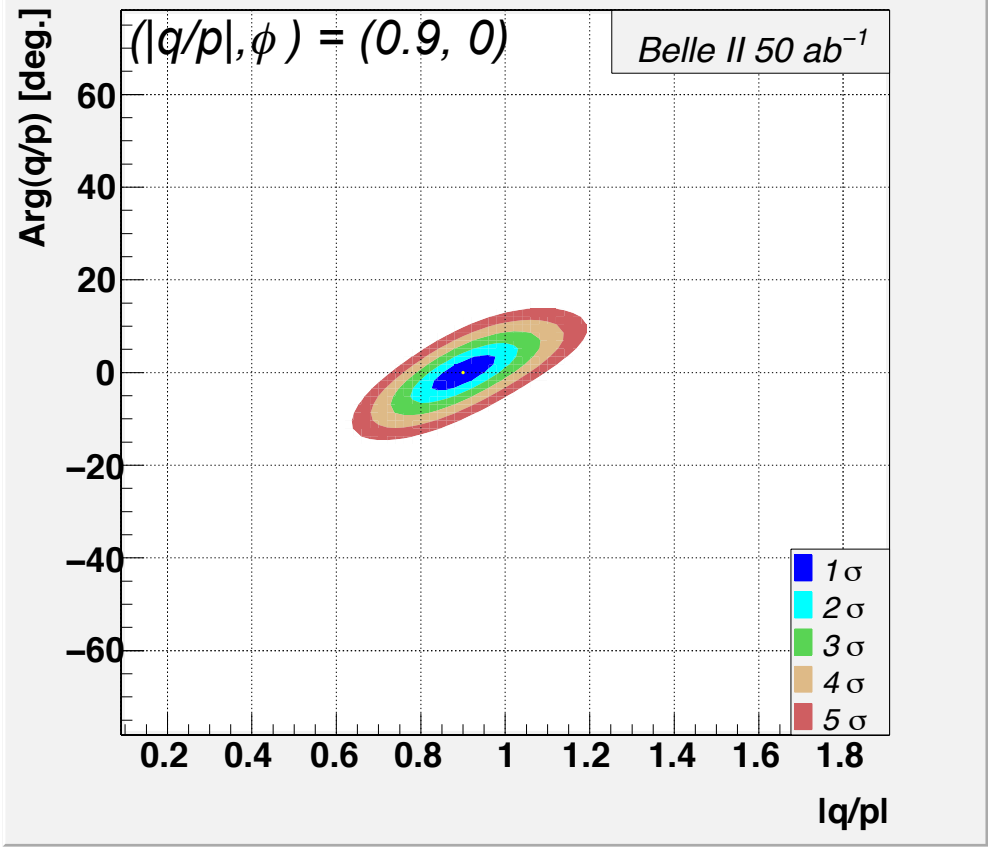
[see Golowich et al., PRD76, 095009 (2007); 21 models considered, e.g., 2-Higgs doublets, left-right models, little Higgs, extra dimensions, of which 17 give constraints]

Belle II expectations for $\bar{D}^0$-D^0 CPV

Now:



50 ab^{-1}:



Note: *LHCb will dominate most of these measurements, but Belle II should be competitive in y_{CP} and possibly in x'^2, y', $|q/p|$, ϕ (see Staric, KEK FFW14). If LHCb sees new physics, it would be important for Belle II to independently confirm.*

Summary

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

976 fb^{-1} published:
$R_D = (3.53 \pm 0.13) \times 10^{-3}$
$x'^2 = (0.09 \pm 0.22) \times 10^{-3}$
$y' = (0.46 \pm 0.34)\%$

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

921 fb^{-1} published:
$x = (0.56\ ^{+0.20}_{-0.22})\ \%$
$y = (0.30\ ^{+0.16}_{-0.17})\ \%$
$|q/p| = (0.90\ ^{+0.18}_{-0.16})\ \%$
$\phi = (-6 \pm 12)^o$

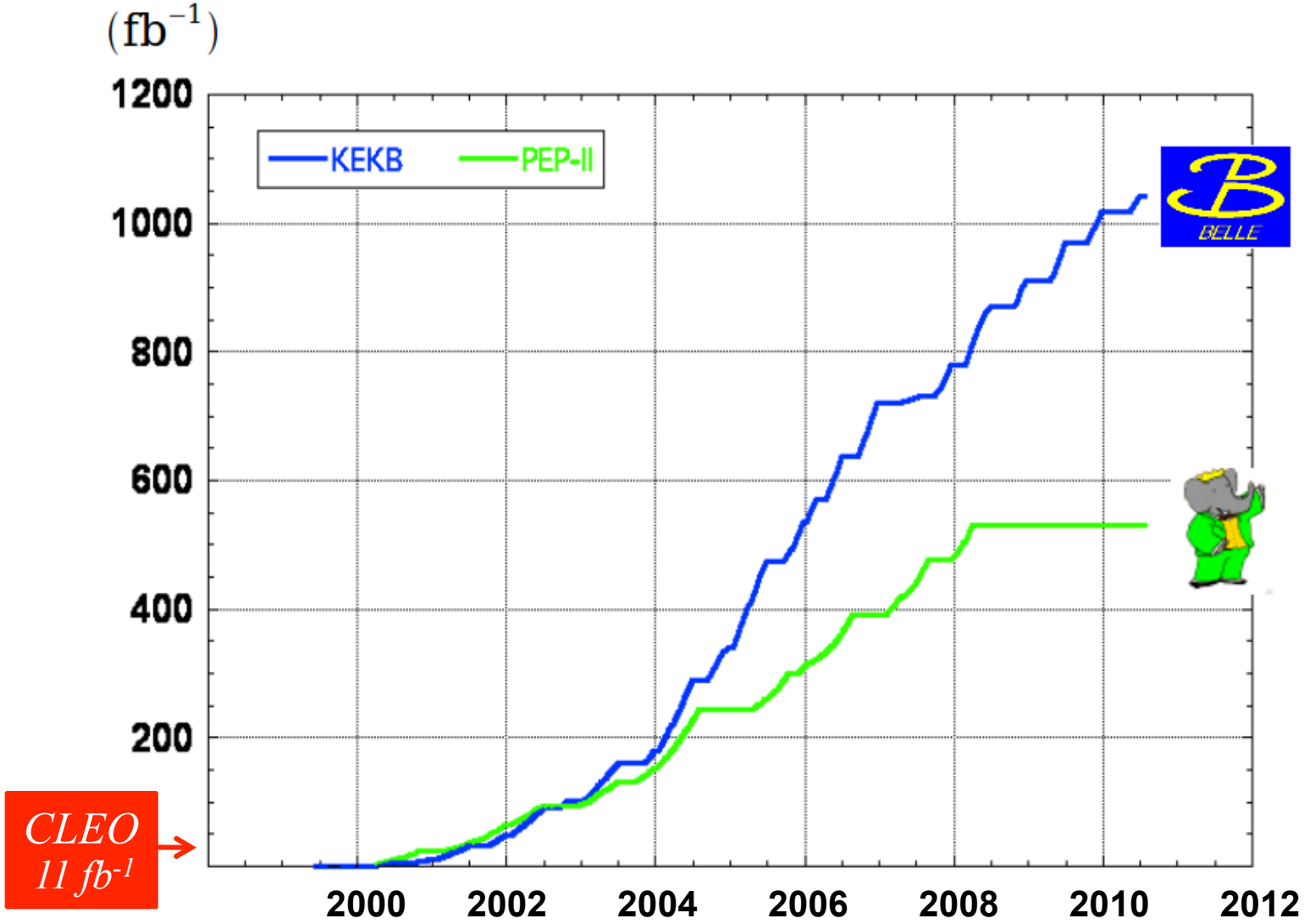
time-dependent $D^0(t) \to K^+K^-, \pi^+\pi^-$

977 fb^{-1} preliminary:
$y_{CP} = (1.11 \pm 0.22 \pm 0.11)\%$
$A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\%$

$\Rightarrow$ Evidence for mixing is unequivocal: $K^+\pi^-$ alone is 5.1σ; combined with all other world data is $>12\sigma$. No sign yet of indirect CPV. However, the sensitivity of these searches will greatly improve (factor of ~50 statistics) at Belle II

Extra/Backup

B factory performance – final tally:



> 1 ab^{-1}

On resonance:

Υ(5S): 121 fb^{-1}

Υ(4S): 711 fb^{-1}

Υ(3S): 3 fb^{-1}

Υ(2S): 25 fb^{-1}

Υ(1S): 6 fb^{-1}

Off reson./scan:

~ 100 fb^{-1}

~ 550 fb^{-1}

On resonance:

Υ(4S): 433 fb^{-1}

Υ(3S): 30 fb^{-1}

Υ(2S): 14 fb^{-1}

Off resonance:

~ 54 fb^{-1}