D^0-mixing and CP Violation in Charm at Belle

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Outline

- Introduction
- Updates of D^0-mixing with our final data set ($\sim 1\ \mathrm{ab}^{-1}$)
    - $D^0 \to K^+\pi^-$
    - $D^0 \to K^+K^-, \pi^+\pi^-$
    - $D^0 \to K_s^0\pi^+\pi^-$
- Time-integrated CPV searches
    - $D^0 \to \pi^0\pi^0$ (latest one)
    - many more ...
- Conclusions

$D^0 - \overline{D}^0$ mixing

- Mass eigenstates differ from flavor eigenstates

$$|D^0_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$

  - $D^0_{1,2}$ with masses m_1, m_2 and partial widths Γ_1, Γ_2

- Mixing parameters:

$$x = \frac{\Delta m}{\Gamma} \qquad y = \frac{\Delta\Gamma}{2\Gamma}$$

- Time dependent decay rates of $D^0 \to f$ (since mixing is small):

$$\frac{dN_{D^0\to f}}{dt} \propto e^{-\Gamma t}\left|\langle f|\mathcal{H}|D^0\rangle + \frac{q}{p}(\frac{y+ix}{2}\Gamma t)\langle f|\mathcal{H}|\overline{D}^0\rangle\right|^2$$

  - exponential time dependency modulated with x and y, and q/p
  - modulation is final state dependent
  - different final states sensitive to different combinations of x and y

CP violation

$$\frac{dN_{D^0\to f}}{dt} \propto e^{-\Gamma t}\left|\langle f|\mathcal{H}|D^0\rangle + \frac{q}{p}\left(\frac{y+ix}{2}\Gamma t\right)\langle f|\mathcal{H}|\overline{D}^0\rangle\right|^2$$

- $q/p \neq 1 \;\Rightarrow$ indirect CP violation
- $q/p = |q/p| \cdot e^{i\phi}$:
  - $|q/p| \neq 1 \;\Rightarrow$ CP violation in mixing
  - $\phi \neq 0(\pi) \;\Rightarrow$ CP violation in interference of decays w/ and w/o mixing
- $|\mathcal{A}(D^0 \to f)|^2 \neq |\mathcal{A}(\bar{D}^0 \to \bar{f})|^2 \;\Rightarrow$ direct CP violation

Experimental techniques

- Time-dependent analysis:
  - difference in proper decay time distributions of $D^0 \to f$ and $\bar{D}^0 \to \bar{f}$
  - measure indirect CPV
- Time-integrated analysis:
  - difference in time-integrated decay rates of $D^0 \to f$ and $\bar{D}^0 \to \bar{f}$
  - measure direct+indirect CPV

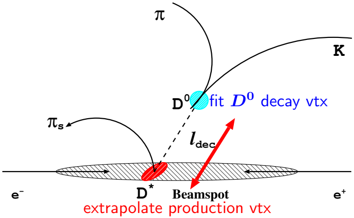
Experimental method at B-factories

- Usually using $D^{*+} \to D^0 \pi^+_{\rm slow}$
  - flavor tagging by $\pi_{\rm slow}$ charge
  - background suppression
- Observables:
  - D^0 invariant mass: $M \equiv m(K\pi)$
  - D^{*+} mass difference: $\Delta M \equiv m(K\pi\pi_{\rm slow}) - m(K\pi)$ or $Q \equiv \Delta M - m_\pi$
- Measurements performed mainly at $\Upsilon(4S)$
  - D^{*+} from B decays can be completely rejected with

$$p_{D^{*+}}^{CMS} > 2.5 \; GeV/c$$

- D^0 proper decay time measurement:

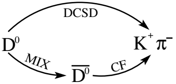
$$t = \frac{l_{dec}}{c\beta\gamma} \; , \qquad \beta\gamma = \frac{p_{D^0}}{M_{D^0}}$$



Wrong sign decays $D^0 \to K^+\pi^-$ (976 fb^{-1})

PRL 112, 111801 (2014)

- Wrong sign (WS) final state: via DCS decays or via mixing



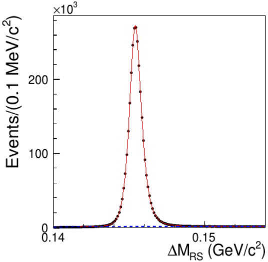
- Proper decay time distribution

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

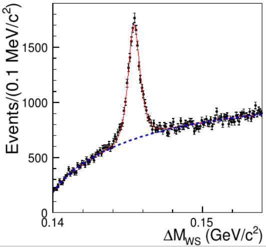
DCS interference mixing

R_D ratio of DCS/CF decay rates
$x' = x\cos\delta + y\sin\delta$
$y' = y\cos\delta - x\sin\delta$
δ strong phase between DCS and CF

RS events



WS events



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

- Fit of WS to RS decay rate ratio in bins of measured proper decay time t

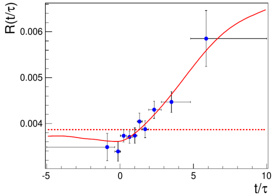
$$R(t) = \frac{\int \Gamma_{\rm WS}(t')\mathcal{R}(t-t')dt'}{\int \Gamma_{\rm RS}(t')\mathcal{R}(t-t')dt'}$$

- WS and RS signal yields in bins of t determined from fit to ΔM distributions
- Resolution function parameterized as a sum of four Gaussians

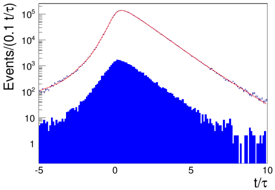
$$\mathcal{R}(t) = \sum_{i=1}^{4} f_i G_i(t;\mu_i,\sigma_i), \quad \mu_i = \mu_1 + a\sigma_i$$

- Parameters f_i, μ_1, a, σ_i determined from fit to sideband subtracted RS time distribution

WS to RS ratio



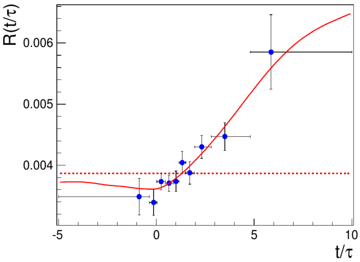
RS time distribution



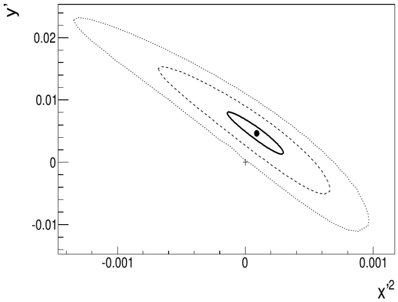
$\tau = (408.5 \pm 0.9)$ fs consistent with W.A.

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

Test hypothesis (χ^2/DOF)	Parameters	Fit results (10^{-3})	R_D	Correlation coefficient y'	x'^2
Mixing (4.2/7)	R_D	3.53 ± 0.13	1	-0.865	$+0.737$
	y'	4.6 ± 3.4		1	-0.948
	x'^2	0.09 ± 0.22			1
No Mixing (33.5/9)	R_D	3.864 ± 0.059			



systematics less that 1/10 of statistical error



← Best fit point and 1, 3, 5 σ contours

no-mixing point at 5.1σ
observation of D^0 mixing

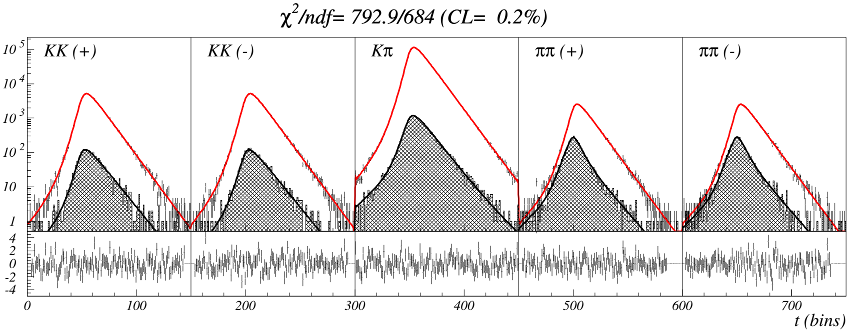
Decays to CP states $D^0 \to K^+K^-, \pi^+\pi^-$ (976 fb^{-1})

- Measurement of lifetime difference between flavor specific and decays into *CP* final states
  - choice of flavor specific: kinematically similar $D^0 \to K^-\pi^+$
- Timing distributions are exponential
  - mixing parameter: $$y_{CP} = \frac{\tau(K^-\pi^+)}{\tau(K^+K^-)} - 1$$
  - $y_{CP} = y$, if CP conserved
- If *CP* violated $\to$ difference in lifetimes of $D^0/\overline{D^0} \to K^+K^-, \pi^+\pi^-$
  - asymmetry in lifetimes: $$A_\Gamma = \frac{\tau(\overline{D}^0 \to K^-K^+) - \tau(D^0 \to K^+K^-)}{\tau(\overline{D}^0 \to K^-K^+) + \tau(D^0 \to K^+K^-)}$$
- If direct CPV negligible:
  - $y_{CP} = y\cos\phi - \frac{1}{2}A_M x \sin\phi$
  - $A_\Gamma = \frac{1}{2}A_M y \cos\phi - x\sin\phi$

$$A_M = 2(|q/p| - 1)$$

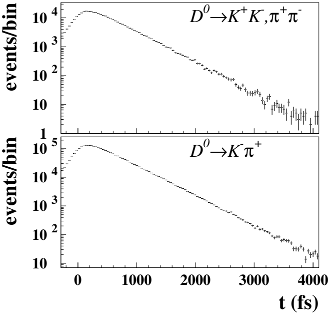
$D^0 \to K^+K^-, \pi^+\pi^-$: Method

- Simultaneous binned maximum likelihood fit of KK, $K\pi$ and $\pi\pi$
  - performed in bins of $cos\theta^*$, than weighted average to obtain y_{CP}, A_Γ
- Background estimated from sidebands in M
  - parameterized with two lifetime components (zero and non-zero τ)
- Resolution function: decay mode, run period, $cos\theta^*$ dependent

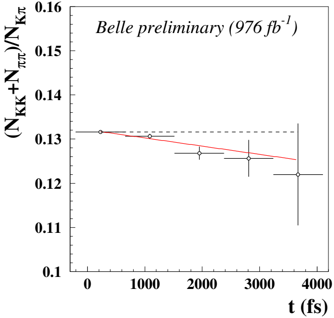


arXiv:1212.3478 (2012)

$$y_{CP} = (+1.11 \pm 0.22 \pm 0.11)\% \quad \text{4.5}\sigma \text{ evidence}$$
$$A_\Gamma = (-0.03 \pm 0.20 \pm 0.08)\% \quad \text{consistent with zero}$$



divide distributions
⟶



Self-conjugate decays: $D^0 \to K_s^0\,\pi^+\pi^-$ (921 fb^{-1})

PRD 89, 091103(R) (2014)

- This three body decay proceeds via many intermediate states, like
  - CF: $D^0 \to K^{*-}\pi^+$
  - DCS: $D^0 \to K^{*+}\pi^-$
  - CP: $D^0 \to \rho^0 K_s^0$
- Matrix element is Dalitz space dependent, so also time distribution is

$$\frac{dN_{D^0\to f}}{dt} \propto e^{-\Gamma t}\left|\mathcal{A}(m_-^2, m_+^2) + \frac{q}{p}(\frac{y+ix}{2}\Gamma t)\overline{\mathcal{A}}(m_-^2, m_+^2)\right|^2$$

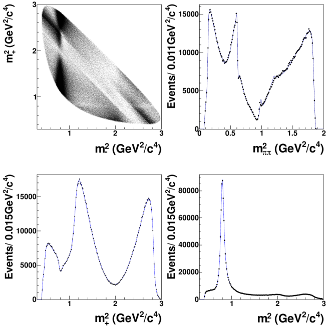
- Total amplitude $\mathcal{A}$ parametrized as a sum of quasi two-body amplitudes of resonances $\mathcal{A}_r$

$$\mathcal{A}(m_-^2, m_+^2) = \sum_r a_r e^{i\phi_r}\mathcal{A}_r(m_-^2, m_+^2)$$

- Both mixing parameters, x and y as well as CPV parameters ϕ and $|q/p|$ can be measured
- Requires 3D fit in (m_-^2, m_+^2, t); many free parameters

$D^0 \to K_s^0\, \pi^+\pi^-$: Method

- Unbinned maximum likelihood fit in 3D
- Dalitz model with 16 resonances
- Background estimated from sidebans
  - combinatorial: *M*-sideband
  - random $\pi_{\rm slow}$: *Q*-sideband
- Resolution function: 3 Gaussians

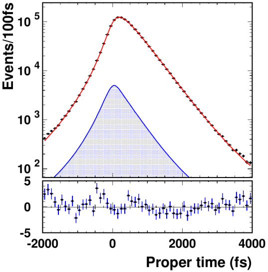


Resonance	Amplitude	Phase (deg)	Fit fraction
$K^*(892)^-$	1.590 ± 0.003	131.8 ± 0.2	0.6045
$K_0^*(1430)^-$	2.059 ± 0.010	-194.6 ± 1.7	0.0702
$K_2^*(1430)^-$	1.150 ± 0.009	-41.5 ± 0.4	0.0221
$K^*(1410)^-$	0.496 ± 0.011	83.4 ± 0.9	0.0026
$K^*(1680)^-$	1.556 ± 0.097	-83.2 ± 1.2	0.0016
$K^*(892)^+$	0.139 ± 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
$\pi\pi$ S-wave			0.1288
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 ± 0.3	
$f_{12}^{\rm prod}$	14.2 ± 0.2	-176.2 ± 0.6	
$f_{13}^{\rm prod}$	10.0 ± 0.5	-124.7 ± 2.1	
$K\pi$ 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)		
$\phi_R(rad)$	2.495 ± 0.009		
a(GeV/c^{-1})	0.172 ± 0.006		
r(GeV/c^{-1})	-20.6 ± 0.3		
$K^*(892)$	Parameters		
$M_{K^*(892)}$(MeV/c^2)	893.68 ± 0.04		
$\Gamma_{K^*(892)}$(MeV/c^2)	47.49 ± 0.06		

$D^0 \to K_s^0 \pi^+\pi^-$: Results

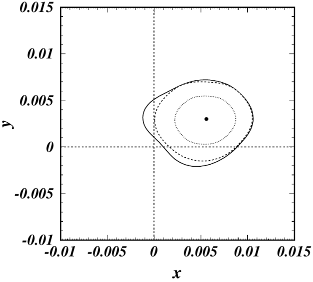
Fit type	Parameter	Fit result
No CPV	$x(\%)$	$0.56 \pm 0.19^{+0.03}_{-0.09}{}^{+0.06}_{-0.09}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04}_{-0.05}{}^{+0.03}_{-0.06}$
CPV	$x(\%)$	$0.56 \pm 0.19^{+0.04}_{-0.08}{}^{+0.06}_{-0.08}$
	$y(\%)$	$0.30 \pm 0.15^{+0.04}_{-0.05}{}^{+0.03}_{-0.07}$
	$\lvert q/p \rvert$	$0.90^{+0.16}_{-0.15}{}^{+0.05}_{-0.04}{}^{+0.06}_{-0.05}$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

error order: statistics, systematics, Dalitz model



$\tau = (410.3 \pm 0.6)$ fs

consistent with W.A.



← Best fit point, 68.3% and 95% contours

no-mixing point at 2.5σ

no evidence for CPV

Time-integrated measurements (A_{CP})

- Asymmetry in time-integrated decay rates of $D^0 \to f$ and $\overline{D}^0 \to \overline{f}$

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

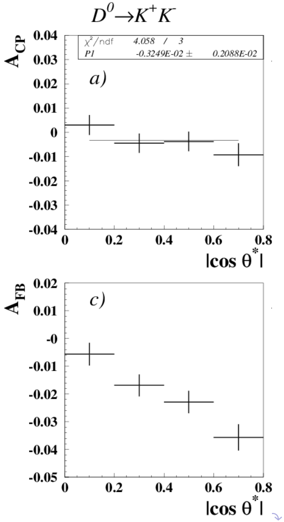
- Raw asymmetry

$$A_{\rm raw} = \frac{N - \overline{N}}{N + \overline{N}} = A_D + A^f_\epsilon + A^f_{CP}$$

  - A_D production asymmetry
  - A^f_ϵ asymmetry in efficiencies
- Production asymmetry at B-factory
  - odd function of CMS polar angle
    $A_D \equiv A_{FB}(cos\theta^*)$
  - can easily be disentangled

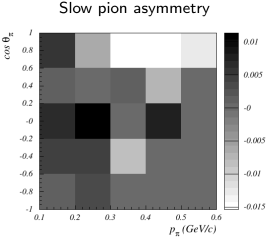
$$A_{CP} = \frac{A^{\rm cor}_{\rm raw}(cos\theta^*) + A^{\rm cor}_{\rm raw}(-cos\theta^*)}{2}$$

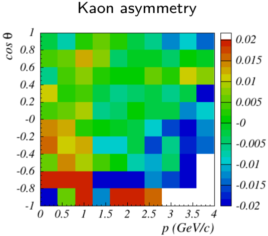
$$A_{FB} = \frac{A^{\rm cor}_{\rm raw}(cos\theta^*) - A^{\rm cor}_{\rm raw}(-cos\theta^*)}{2}$$



Detection asymmetries A_ϵ^f

- Asymmetries in detection efficiencies can be measured with sufficient precision using CF decays (CPV is very unlikely)
  - must be performed in bins of relevant phase-spaces
  - requires production asymmetries to be known
    $\rightarrow$ at B-factory: $A_D \equiv A_{FB}(cos\theta^*)$
- Slow pions: from tagged and untagged $D^0 \rightarrow K^-\pi^+$ decays
- Kaons: from decays $D^0 \rightarrow K^-\pi^+$ and $D_s^+ \rightarrow \phi\pi^+$
- Pions: from decays $D^+ \rightarrow K^-\pi^+\pi^+$ and $D^0 \rightarrow K^-\pi^+\pi^0$





A_{CP} in $D^0 \to \pi^0\pi^0$ and $D^0 \to K_S^0\pi^0$ (966 fb^{-1})

PRL 112, 211601 (2014)

- Flavor tag with $D^{*+} \to D^0\pi^+$
- Raw asymmetry:

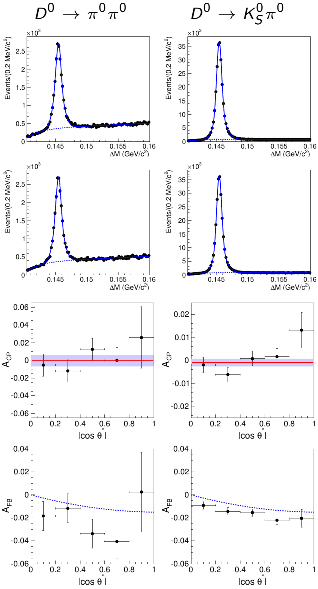
  $A_{\rm raw} = A_{CP} + A_{FB} + A_\epsilon^{\pi_{\rm slow}} \;(+\, A_{\rm mat}^{K^0})$

  - Last term due to different strong interactions of $K^0/\bar{K}^0$ in detector material $A_{\rm mat}^{K^0} = -0.11\%$, PRD 84, 111501 (2011)
- $D^0/\bar{D}^0$ yields from fit to ΔM distributions in bins of $(\cos\theta^*, p_T^{\pi_s}, \cos\theta^{\pi_s}) \to 10{\times}7{\times}8$
- Results consistent with no CPV:

  $$A_{CP}^{\pi^0\pi^0} = (-0.03 \pm 0.64 \pm 0.10)\%$$
  $$A_{CP}^{K_S^0\pi^0} = (-0.21 \pm 0.16 \pm 0.07)\%$$

- Modes with K_S^0:
  - CPV due to K^0-mixing: -0.34%,

    PRL 109, 021601 (2012); 109, 119903(E) (2012)



Time-integrated measurements: Summary

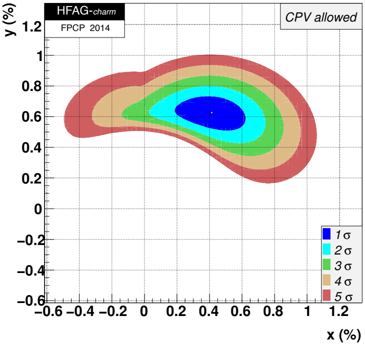
mode	$\mathcal{L}$ (fb^{-1})	A_{CP} (%)	paper
$D^0 \to K^+K^-$	976	$-0.32 \pm 0.21 \pm 0.09$	arXiv:1212.1975 (2012)
$D^0 \to \pi^+\pi^-$	976	$+0.55 \pm 0.36 \pm 0.09$	arXiv:1212.1975 (2012)
$D^0 \to \pi^0\pi^0$	966	$-0.03 \pm 0.64 \pm 0.10$	PRL 112, 211601 (2014)
$D^0 \to K_s^0\pi^0$	966	$-0.21 \pm 0.16 \pm 0.07$	PRL 112, 211601 (2014)
$D^0 \to K_s^0\eta$	791	$+0.54 \pm 0.51 \pm 0.16$	PRL 106, 211801 (2011)
$D^0 \to K_s^0\eta'$	791	$+0.98 \pm 0.67 \pm 0.14$	PRL 106, 211801 (2011)
$D^0 \to \pi^+\pi^-\pi^0$	532	$+0.43 \pm 1.30$	PLB 662, 102 (2008)
$D^0 \to K^+\pi^-\pi^0$	281	-0.60 ± 5.30	PRL 95, 231801 (2005)
$D^0 \to K^+\pi^-\pi^+\pi^-$	281	-1.80 ± 4.40	PRL 95, 231801 (2005)
$D^+ \to \phi\pi^+$	955	$+0.51 \pm 0.28 \pm 0.05$	PRL 108, 071801 (2012)
$D^+ \to \eta\pi^+$	791	$+1.74 \pm 1.13 \pm 0.19$	PRL 107, 221801 (2011)
$D^+ \to \eta'\pi^+$	791	$-0.12 \pm 1.12 \pm 0.17$	PRL 107, 221801 (2011)
$D^+ \to K_s^0\pi^+$	977	$-0.36 \pm 0.09 \pm 0.07$	PRL 109, 021601 (2012)
$D^+ \to K_s^0K^+$	977	$-0.25 \pm 0.28 \pm 0.14$	JHEP 02, 98 (2013)
$D_s^+ \to K_s^0\pi^+$	673	$+5.45 \pm 2.50 \pm 0.33$	PRL 104, 181602 (2010)
$D_s^+ \to K_s^0K^+$	673	$+0.12 \pm 0.36 \pm 0.22$	PRL 104, 181602 (2010)

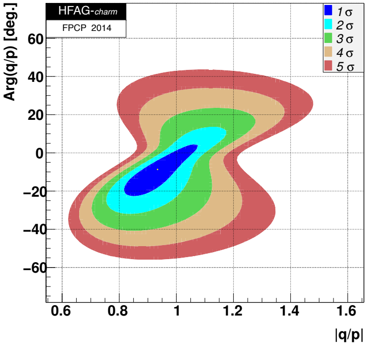
Conclusions

- D^0-mixing measurements in the three most sensitive decay modes were updated with the Belle final data set ($\sim 1\ \mathrm{ab}^{-1}$)
  - $D^0 \to K^+\pi^-$: 5.1σ observation
  - $D^0 \to K^+K^-, \pi^+\pi^-$: 4.5$\sigma$ evidence in y_{CP}
  - $D^0 \to K_s^0\pi^+\pi^-$: most stringent limits on x
- No evidence for indirect CP violation.
- CP violation was searched in many decay modes using time-integrated approach
  - no evidence found for CPV in the charm sector
  - can see CPV due to K^0-mixing in $D^+ \to K_S^0\pi^+$ decay

backup: HFAG averages

BaBar, Belle, CDF, CLEO, E791, FOCUS, LHCb





$$x = (0.41^{+0.14}_{-0.15})\%$$

$$y = (0.63^{+0.07}_{-0.08})\%$$

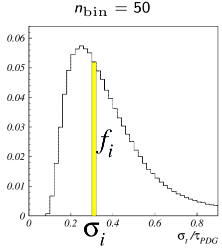
$$|q/p| = 0.93^{+0.09}_{-0.08}$$

$$\phi = (-8.7^{+8.7}_{-9.1})^{\rm o}$$

backup: $D^0 \to K^+K^-, \pi^+\pi^-$: Resolution function

Resolution function (for binned fit)

- Constructed from normalized distribution of σ_t
  - Using 2 or 3 Gaussian PDF for each σ_t bin
- PDF parameters determined in each $\cos\theta^*$ bin by fitting the distribution of pulls $(t - t_{\mathrm{gen}})/\sigma_t$
  - widths σ_k^{pull}, fractions w_k



$$R(t) = \sum_{i=1}^{n_{\mathrm{bin}}} f_i \sum_{k=1}^{n_g} w_k G(t; \mu_i, \sigma_{ik})$$

$$\sigma_{ik} = s_k \sigma_k^{\mathrm{pull}} \sigma_i \qquad \mu_i = t_0 + a\left(\sigma_i - \sum_{j=1}^{n} f_j \sigma_j\right)$$

- Free parameters:
  - width scaling factors: s_k, $k = 1, ..., n_g$ ($n_g = 2$ or 3)
  - resolution function offset: t_0
  - slope to model asymmetry: a

backup: Measurement strategies

$$\frac{dN_{D^0\to f}}{dt} \propto e^{-\Gamma t}\left|\langle f|\mathcal{H}|D^0\rangle + \frac{q}{p}\left(\frac{y+ix}{2}\Gamma t\right)\langle f|\mathcal{H}|\overline{D}^0\rangle\right|^2$$

- Wrong-sign semileptonic decays ($D^0 \to K^+\ell^-\nu$)
  - WS only via mixing: $\langle f|\mathcal{H}|D^0\rangle = 0$
  - measures time integrated mixing rate $R_M = \frac{x^2+y^2}{2} = \frac{N_{WS}}{N_{RS}}$
- Wrong-sign hadronic decays ($D^0 \to K^+\pi^-$)
  - WS via doubly Cabibbo suppressed (DCS) decays or mixing
  - interference between DCS and mixing (strong phase δ)
  - measures $x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$
- Decays to CP eigenstates ($D^0 \to K^+K^-, \pi^+\pi^-$)
  - if no direct CPV: $\langle f|\mathcal{H}|\overline{D}^0\rangle = -\langle f|\mathcal{H}|D^0\rangle$
  - measures y
- Decays to self-conjugate states ($D^0 \to K_s^0\pi^+\pi^-$)
  - time dependent Dalitz plot analysis
  - measures x and y