# $D^0$ mixing prospects at super B factory

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## Mixing

- Flavor eigenstates $\neq$ mass eigenstates (with $m_{1,2}$, $\Gamma_{1,2}$)

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

- $p/q \neq 1 \Rightarrow$ CP violation
- $D^0$ at $t = 0$ evolves as:

$$|D^0(t)\rangle = e^{-(\Gamma/2+im)t}[\cosh(\frac{y+ix}{2}\Gamma t)|D^0\rangle + \frac{q}{p}\sinh(\frac{y+ix}{2}\Gamma t)|\overline{D}^0\rangle]$$

with

$$x = \frac{m_2 - m_1}{\Gamma} \qquad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$

- $|x|, |y| \ll 1$:

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

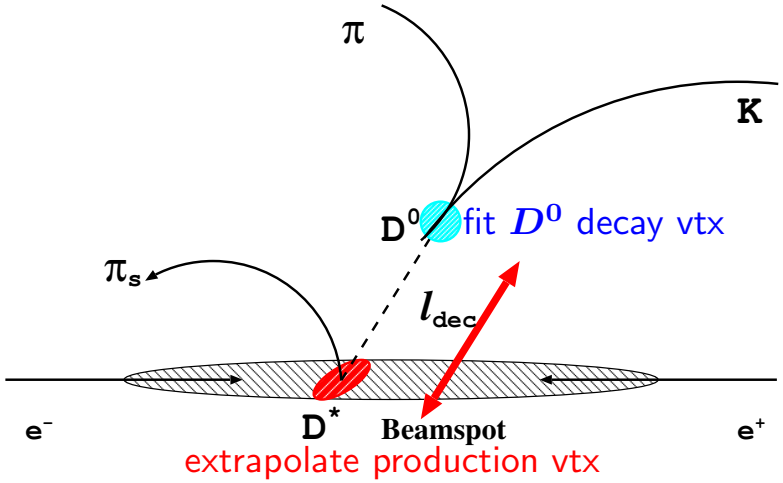
- Decay time distribution of different final states sensitive to different combinations of mixing parameters $x$ and $y$.

# Experimental method

- Hints:
  - ▷ tag the favor at production
  - ▷ measure proper decay time distribution
- $D^{*+} \to \pi^+ D^0$
  - ▷ flavor tagging by $\pi_{slow}$ charge
  - ▷ background suppression
- $D^0$ proper decay time $t$ measurement:

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

$\sigma_t$ ... decay-time uncertainty
(from vtx cov. matrices)




- Measurements performed at $\Upsilon(4S)$
  - ▷ to reject $D^{*+}$ from $B$ decays: $p^{CMS}_{D^{*+}} > 2.5\ GeV/c$
- Observables:

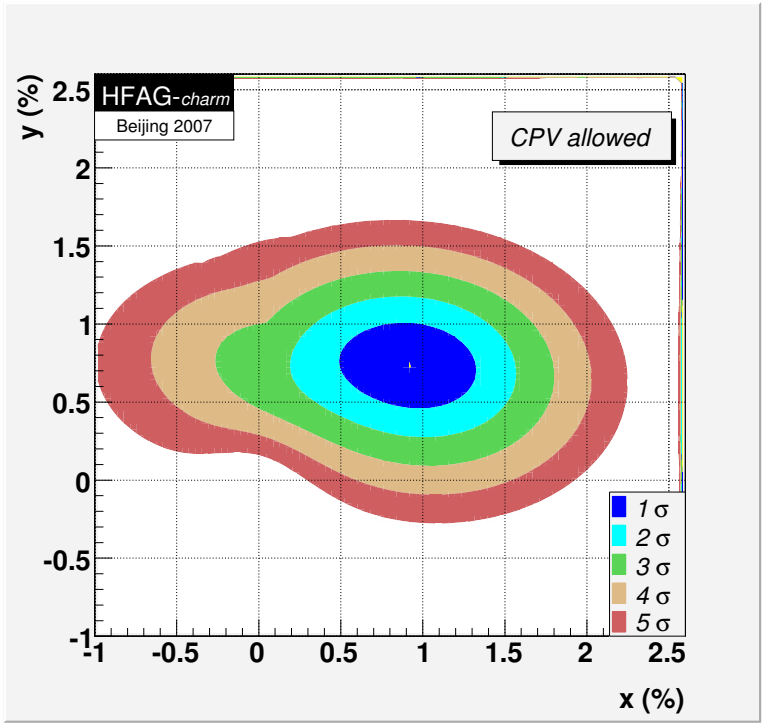
$$m = m(K\pi)$$
$$q = m(K\pi\pi_s) - m(K\pi) - m_\pi$$

## Some 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 $\delta$)
  - 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 charge-conjugate states ($D^0 \to K^0_s\pi^+\pi^-$)
  - time dependent Dalitz plot analysis
  - measures $x$ and $y$

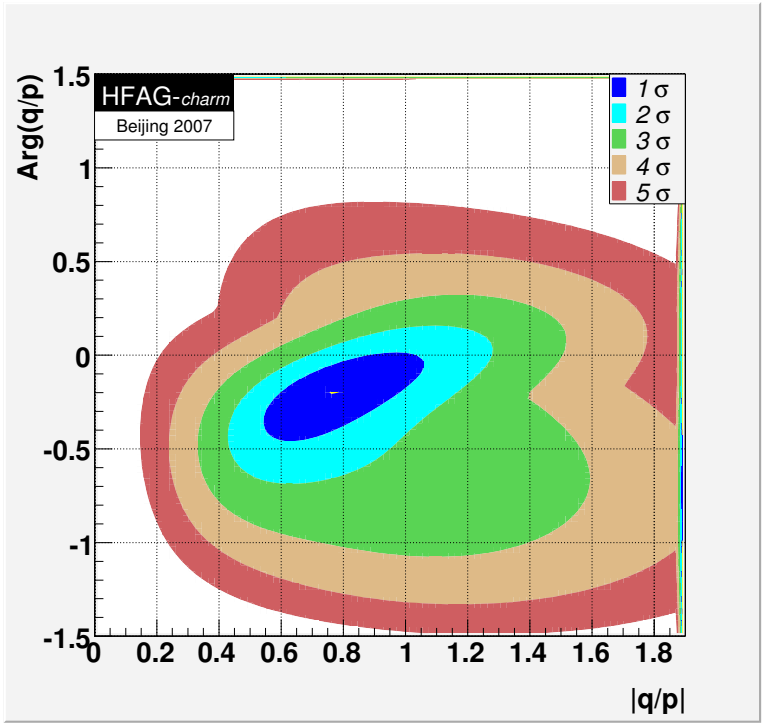
## HFAG averages




$x = (0.97^{+0.27}_{-0.29})\%$ $y = (0.78^{+0.18}_{-0.19})\%$

No mixing point > $5\sigma$

$x \sim y \sim 1\%$




$|q/p| = 0.86^{+0.18}_{-0.15}$ $\phi = -0.17^{+0.14}_{-0.16}$

No CPV point $\sim 1\sigma$

no CPV: $|q/p| = 1, \quad \phi = 0$

## Wrong-Sign semileptonic decays

$D^0 \to K^{(*)+} e^- \overline{\nu}_e$

- Belle, PRD72, 071101 (2005), 253 fb$^{-1}$:

$$R_M = (2.0 \pm 4.7 \pm 1.4) \times 10^{-4}$$

- non-scaling systematics: $0.7 \times 10^{-4}$
  - ▷ mainly Br's of some bkg. processes
  - ▷ equal to stat. error at 11 ab$^{-1}$
- extrapolated to 5 ab$^{-1}$: $\sigma(R_M) \approx \pm 1.3 \times 10^{-4}$
- including $\mu$ decay channel ($\sim 2\times$ larger statistics):

$$\boxed{\sigma(R_M) \approx 0.9 \times 10^{-4}}$$

- for comparison:
  - ▷ current HFAG average: $x \sim y \sim 1\% \Rightarrow R_M \sim 10^{-4}$

## Wrong-Sign semileptonic decays

$D^0 \to K^{(*)+} e^- \overline{\nu}_e$

- BaBar, PRD76, 014018 (2007), 344 fb$^{-1}$:
  - using double-tag method
  - observe 4780 RS events / 3 WS events (expected WS bkg.: 2.85)
- extrapolating to 5 ab$^{-1}$ and assuming $R_M = 10^{-4}$:
  - 70000 RS events $\to$ 7 WS signal events / 40 WS bkg. events
  - e.g.: $N_{WS} \approx 7 \pm \sqrt{7+40} = 7 \pm 7$
- expect to obtain $\sim 1\sigma$ sensitivity, similar to single-tag method

## Wrong-Sign hadronic decays

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

- Belle, PRL96, 151801 (2006), 400 fb$^{-1}$:

$$x'^2 = (1.8 \pm 2.2 \pm 1.1) \times 10^{-4}$$
$$y' = (0.06 \pm 0.40 \pm 0.20)\%$$
$$A_M = 0.67 \pm 1.2$$
$$|\phi| = 0.16 \pm 0.44$$

$$x' = x\cos\delta + y\sin\delta$$
$$y' = y\cos\delta - x\sin\delta$$

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

$A_M \ll 1$:
$|q/p| = 1 + \frac{1}{2}A_M$

- non-scaling systematics: none
- extrapolated to 5 ab$^{-1}$:

$$\sigma(x'^2) = 0.7 \times 10^{-4}$$
$$\sigma(y') = 0.13\%$$
$$\sigma(A_M) = 0.34$$
$$\sigma(\phi) = 0.14$$

## Wrong-Sign hadronic decays

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

- BaBar, LP 2007 (yet unpublished), 384 fb$^{-1}$:
- time-dependent Dalitz plot analysis

$$x'' = x\cos\delta_2 + y\sin\delta_2$$
$$y'' = y\cos\delta_2 - x\sin\delta_2$$

$$x'' = (2.39 \pm 0.61 \pm 0.32)\%$$
$$y'' = (-0.14 \pm 0.60 \pm 0.40)\%$$

- non-scaling systematics: Dalitz model

| | $x''$ | $y''$ |
|---|---|---|
| non-scaling syst. error | 0.13% | 0.25% |
| equal to stat. error at | 8 ab$^{-1}$ | 2 ab$^{-1}$ |

- extrapolated to 5 ab$^{-1}$:

$$\sigma(x'') = 0.23\%$$
$$\sigma(y'') = 0.31\%$$

## Decays to CP eigenstates

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

- Belle, PRL98, 211803 (2007), 540 fb$^{-1}$:

$$y_{CP} = (1.31 \pm 0.32 \pm 0.25)\%$$
$$A_\Gamma = (0.01 \pm 0.30 \pm 0.15)\%$$

$$y_{CP} = y\cos\phi - \tfrac{1}{2}A_M x \sin\phi$$
$$A_\Gamma = \tfrac{1}{2}A_M y\cos\phi - x\sin\phi$$

$$|q/p| = 1 + \tfrac{1}{2}A_M$$

- Assuming $\phi = 0 \Rightarrow A_M = \frac{2A_\Gamma}{y_{CP}}$

$$A_M = 0.02 \pm 0.46 \pm 0.22$$

- non-scaling systematics: 0.08% ($y_{CP}$ only)
  - ▷ 1/2 of equal $t_0$ (improved SVD alignment)
  - ▷ mass window position
  - ▷ equal to stat. error at 9 ab$^{-1}$
- extrapolated to 5 ab$^{-1}$:

$$\sigma(y_{CP}) = 0.15\%$$
$$\sigma(A_\Gamma) = 0.11\%$$
$$\sigma(A_M) = 0.17$$

## Decays to charge-conjugate states

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

- Belle, PRL99, 131803 (2007), 540 fb$^{-1}$:

$$x = (0.81 \pm 0.30 \pm 0.16)\%$$
$$y = (0.37 \pm 0.25 \pm 0.13)\%$$
$$|q/p| = 0.86 \pm 0.30 \pm 0.09$$
$$\phi = -0.24 \pm 0.30 \pm 0.09$$

- non-scaling systematics: Dalitz model

| | $x$ | $y$ | $\lvert q/p \rvert$ | $\phi$ |
|---|---|---|---|---|
| non-scaling syst. error | 0.13% | 0.08% | 0.08 | 0.06 |
| equal to stat. error at | 3 ab$^{-1}$ | 5 ab$^{-1}$ | 8 ab$^{-1}$ | 14 ab$^{-1}$ |

- extrapolated to 5 ab$^{-1}$:

$$\sigma(x) = 0.17\%$$
$$\sigma(y) = 0.12\%$$
$$\sigma(|q/p|) = 0.13$$
$$\sigma(\phi) = 0.12$$

## Other final states

- Decays to CP-odd eigenstates (measures $y_{CP}$ with opposite sign)

  $D^0 \to K^0_s\omega;\ \omega \to \pi^+\pi^-\pi^0 \quad Br = 0.68\%$

  $D^0 \to K^0_s\phi;\ \phi \to K^+K^- \quad Br = 0.15\%$

  (for comparison: $Br(K^+K^-) = 0.38\%$)

- Other decays to charge-conjugate final states (measures x and y)

  $D^0 \to \pi^+\pi^-\pi^0 \quad Br = 1.3\%$

  $D^0 \to K^0_s K^+K^- \quad Br = 0.3\%$

  (for comparison: $Br(K^0_s\pi^+\pi^-) = 1.9\%$)

- Results not reported yet
- Signal yields expected to be smaller ($Br$, $K^0_s$, $\pi^0$ efficiency)
  - ▷ probably less sensitive measurements

# Summary table

| extrapolated precision at 5 ab$^{-1}$ | | | | | | | |
|---|---|---|---|---|---|---|---|
| decay | $R_M$ ($\times 10^{-4}$) | $x$ (%) | $y$ (%) | $x'^2/x''$ ($\times 10^{-4}/\%$) | $y'/y''$ (%) | $\lvert q/p \rvert$ | $\phi$ (rad) |
| $K^{(*)+}l^-\nu$ | 0.9 | | | | | | |
| $K^+\pi^-$ | | (0.35)* | (0.13)* | 0.7 | 0.13 | 0.17 | 0.14 |
| $K^+\pi^-\pi^0$ | | (0.23)† | (0.31)† | 0.23 | 0.31 | | |
| $K^+K^-/\pi^+\pi^-$ | | | 0.15 | | | 0.09 | |
| $K_s\pi^+\pi^-$ | | 0.17 | 0.12 | | | 0.13 | 0.12 |
| combined | | 0.13 | 0.07 | | | 0.07 | 0.09 |

* assuming $\delta = 0$ and $x = 1\%$

† assuming $\delta_2 = 0$

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| HFAG(2007) | 3.9 | 0.28 | 0.19 | | | 0.17 | 0.15 |
| SuperB(5ab$^{-1}$) | 0.9 | 0.13 | 0.07 | | | 0.07 | 0.09 |
| gain | 4.3 | 2.2 | 2.6 | | | 2.4 | 1.7 |

## Conclusions

- Super B factory with 5 ab$^{-1}$ could measure $D^0$ mixing parameters $x$ and $y$ with precisions of 0.13% and 0.07%.
  - ▷ corresponds roughly to 10$\sigma$ (assuming $x \sim y \sim 1\%$).
- CPV parameters $|q/p|$ and $\phi$ could be constrained to 0.07 and 0.09
  - ▷ gain a factor of $\sim 2$ with respect to current W.A.
  - ▷ still not enough to reach SM predictions (<0.01)
  - ▷ any sign of CPV in this region would mean NP!
- The measurements except Dalitz t-dependent are not limited by systematics (improvements in the Dalitz model can be expected as well)