D Mixing and CP Violation

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Part I

1. Introduction
2. Mixing phenomenology
3. Mixing measurements

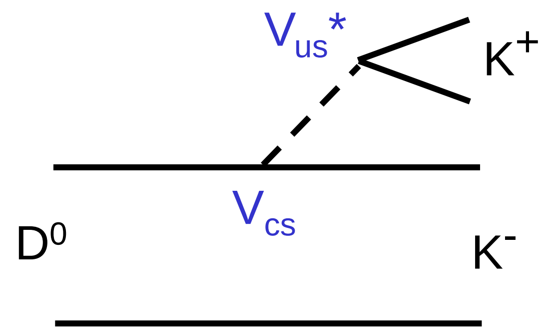
Part II

1. CPV phenomenology
2. CPV measurements
3. Constraints on NP
4. Outlook

Belle Analysis School,
KEK, Feb 10 – 12, 2011

CPV phenomenology

CP violation in charm



Magnitude of CPV ...is small. Why?

CPV: complex CKM matrix phase;
D^0 (and other processes involving charm hadrons):
first two quark generations;
CKM elements ≈ real;

$$\arg\left(\frac{\langle f|D^0\rangle}{\langle \bar f|\overline{D}^0\rangle}\right)=\arg\left(\frac{V_{cs}V_{us}^*}{V_{cs}^*V_{us}}\right)=2\arg\left[V_{cs}V_{us}^*\right]$$

$$\begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

$$2\arg\left[V_{cs}V_{us}^*\right]\underbrace{\approx}_{CKM unitarity}2\arg\left[-V_{cd}V_{ud}^*-V_{cb}V_{ub}^*\right]\approx$$

$$\approx -2\frac{A^2\lambda^5\eta}{\lambda}=-2A^2\lambda^4\eta=1.15\cdot 10^{-3}$$

CPV of $\mathcal{O}(10^{-3})$ is (just) bellow current exp. sensitivity;
larger CPV signals New Physics

CP violation in charm

Parametrization

...is sometimes messy

$R_D \neq 1$: Cabbibo suppression

$$\left|\frac{\langle \bar{f} | D^0 \rangle}{\langle f | D^0 \rangle}\right| \equiv \sqrt{R_D},$$

3 types of CPV:

$A_D \neq 0$: CPV in decay

appears only if two amplitudes with different weak and strong phases contributing; in D meson decays this is only the case for SCS decays, see p. II/26

$$\left|\frac{\langle f | D^0 \rangle}{\langle \bar{f} | \bar{D}^0 \rangle}\right| \equiv 1 + \frac{A_D}{2},$$

$$\frac{q}{p} \equiv (1 + \frac{A_M}{2}) e^{i\varphi}$$

$A_M \neq 0$: CPV in mixing

$\phi \neq 0$: CPV in interference

quantity appearing in decay rates ("λ_f"):

$$\frac{q}{p}\frac{\langle f | \bar{D}^0 \rangle}{\langle f | D^0 \rangle} \equiv -\frac{(1 + A_M/2)\sqrt{R_D}}{1 + A_D/2} e^{-i(\delta_f - \varphi)}$$

n.b.:
(R_D), A_D, A_M, $\phi \ll 1$

CP violation in charm

Observables

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

uncorrelated production

master formulas p. I/15, 16 still valid, need to keep *q/p* and write amplitudes A_f etc. in accordance with parametrization on previous slide

$$\Gamma(V \to D^0 \overline{D}^0 \to f_1 f_2) =$$
$$= \frac{1}{2}|a_-|^2 \left(\frac{1}{1-y^2} + \frac{1}{1+x^2} \right) + \frac{1}{2}|b_-|^2 \left(\frac{1}{1-y^2} - \frac{1}{1+x^2} \right)$$
$$a_- = A_{f1}\overline{A}_{f2} - \overline{A}_{f1}A_{f2}; \quad b_- = \frac{p}{q} A_{f1}A_{f2} - \frac{q}{p} \overline{A}_{f1}\overline{A}_{f2}$$

coherent production with C=-1

Decays to CP eigenstates

$$f=\bar{f};\quad A_f=A_{\bar{f}};\quad \bar{A}_f=\bar{A}_{\bar{f}};\quad \left|\frac{A_f}{\bar{A}_{\bar{f}}}\right|=1+\frac{A_D}{2}$$

Principle

t-dependent method

$$\frac{\left|\left\langle f\left|P^0(t)\right.\right\rangle\right|^2}{\left|A_f\right|^2 e^{-t}}=\left[1+(1+\frac{A_M}{2}-\frac{A_D}{2})(x\sin\varphi-y\cos\varphi)\,t\right]$$

$$\frac{\left|\left\langle f\left|\bar{P}^0(t)\right.\right\rangle\right|^2}{\left|A_f\right|^2 e^{-t}}=\left[1-A_D-(1-\frac{A_M}{2}-\frac{A_M}{2})\left(x\sin\varphi+y\cos\varphi\right)t\right]$$

measuring lifetime in $K^+K^-/\pi^+\pi^-$ state separately for D^0 and $\bar{D}^0$

following derivation on p. I/22 and keeping CPV parameters

$\tau_{KK}=\tau/(1+y_{CP})$; $\quad y_{CP}=(\tau/\tau_{KK})-1=y\cos\phi-(A_m/2)x\sin\phi$

no CPV: $y_{CP}=y$

$$\tau_{KK}\approx\tau\left[1+(1+\frac{A_M}{2}-\frac{A_D}{2})(x\sin\varphi-y\cos\varphi)\right],$$

$$\bar{\tau}_{KK}\approx\tau\left[1-(1-\frac{A_M}{2}-\frac{A_D}{2})(x\sin\varphi+y\cos\varphi)\right]$$

following same derivation separately for D and $\bar{D}$

$$A_\Gamma\equiv\frac{\bar{\tau}_{KK}-\tau_{KK}}{\bar{\tau}_{KK}+\tau_{KK}}=\frac{A_M}{2}y\cos\varphi-(1-\frac{A_D}{2})x\sin\varphi\approx\frac{A_M}{2}y\cos\varphi-x\sin\varphi$$

Decays to CP eigenstates

Results

t-dependent method

Belle, PRL 98, 211803 (2007), 540fb^{-1}

$$A_\Gamma = (0.01 \pm 0.30 \pm 0.15)\%$$

BaBar, PRD78, 011105 (2008), 384fb^{-1}

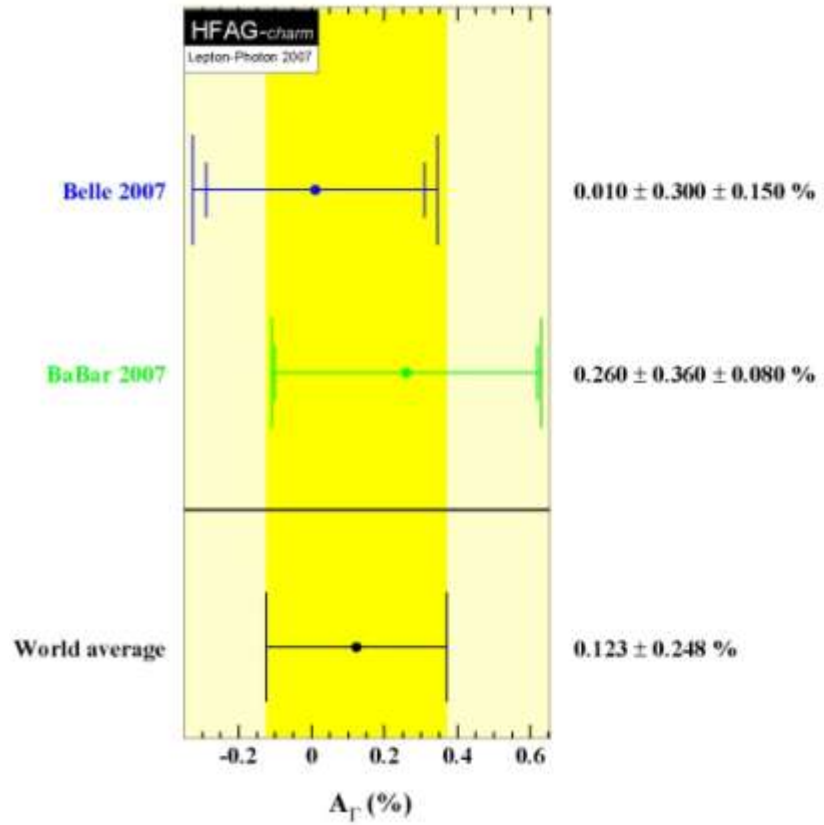
$$A_\Gamma = (0.26 \pm 0.36 \pm 0.08)\%$$

dominant syst.: same as for y_{CP}

$A_\Gamma = (A_M/2) y \cos\phi - x \sin\phi$

CPV in mixing and interference

HFAG, http://www.slac.stanford.edu/xorg/hfag/



no CPV at ~ $3 \cdot 10^{-3}$

Decays to CP eigenstates

Principle

t-integrated method

$$\frac{\Gamma(D^0 \to K^+K^-)}{|A_f|^2} = 1 + (1 + \frac{A_M}{2} - \frac{A_D}{2})(x\sin\varphi - y\cos\varphi)$$

$$\frac{\Gamma(\overline{D}^0 \to K^+K^-)}{|A_f|^2} = 1 - A_D - (1 - \frac{A_M}{2} - \frac{A_D}{2})(x\sin\varphi + y\cos\varphi)$$

asymmetry of
t-integrated rates;
CPV in decay, mixing and interference;

$$A_{CP}^{KK} = \frac{\Gamma(D^0 \to KK) - \Gamma(\overline{D}^0 \to KK)}{\Gamma(D^0 \to KK) + \Gamma(\overline{D}^0 \to KK)} \approx$$

$$\approx \frac{A_D}{2} + x\sin\varphi - \frac{A_M}{2}y\cos\varphi = \frac{A_D}{2} - A_\Gamma$$

However.....
measuring absolute rates instead of decay-t distrib. involves sensitivity to acceptance

n.b.: A_M and ϕ universal among various decay modes; A_D is decay mode specific

Decays to CP eigenstates

$$A^{meas} = \frac{N(D^0 \to KK) - N(\overline{D}^0 \to KK)}{N(D^0 \to KK) + N(\overline{D}^0 \to KK)} =$$

$$= A_\varepsilon^\pi + A_{FB} + A_{CP}^{KK}$$

Principle

t-integrated method

A_ε^π : π^+ / π^- detection eff. asymmetry
$D^{*+/-} \to D^0\pi^{+/-}$; e.g. due to different $\pi^{+/-}$ interactions on detect. material

→ comparison of tagged/untagged ($D^{*+} \to D^0\pi^+$), $D^0 \to K^-\pi^+$

$$A^{untag} = A_{FB}^{D^0} + A_{CP}^{K\pi} + A_\epsilon^{K\pi}$$

$$A^{tag} = A_{FB}^{D^{*+}} + A_{CP}^{K\pi} + A_\epsilon^{K\pi} + A_\epsilon^{\pi_{slow}}$$

assuming $A_{FB}^{D^*}=A_{FB}^D \Rightarrow$
$A^{tag}-A^{untag} = A_\varepsilon^\pi$;
need to perform meas. in bins of p_π, θ_π

A_{FB}: forward-backward asymmetry
$\gamma^*/Z^0 \to c\,\bar{c}$;
A_{FB} is an odd function of θ_D (in CMS);
vanishes if integrated over θ_D;
since working in bins of θ_π(correlated with θ_D) need to correct for it

$$A_{FB} = \frac{A^{meas}(\cos\theta_D) - A^{meas}(-\cos\theta_D)}{2}$$

A_{CP}^f: physical CPV asymmetry →

$$A_{CP} = \frac{A^{meas}(\cos\theta_D) + A^{meas}(-\cos\theta_D)}{2}$$

CPV measurements

Decays to CP eigenstates

Results

t-integrated method

BaBar, PRL 100, 061803 (2007), 386fb^{-1}

$$A_{CP}^{KK} = (0.00 \pm 0.34 \pm 0.13)\%$$

Belle, PLB670, 190 (2008), 540fb^{-1}

$$A_{CP}^{KK} = (-0.43 \pm 0.30 \pm 0.11)\%$$

stat. precission of $\pi\pi$ somewhat worse;
dominant syst.: stat. uncertainty of A_ε^π

world average:

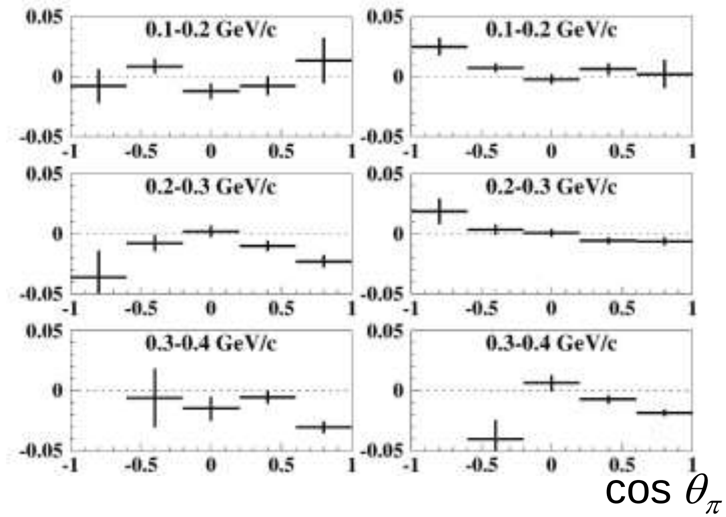
$$A_{CP}^{KK} = (-0.16 \pm 0.23)\ \%$$

HFAG, http://www.slac.stanford.edu/xorg/hfag/

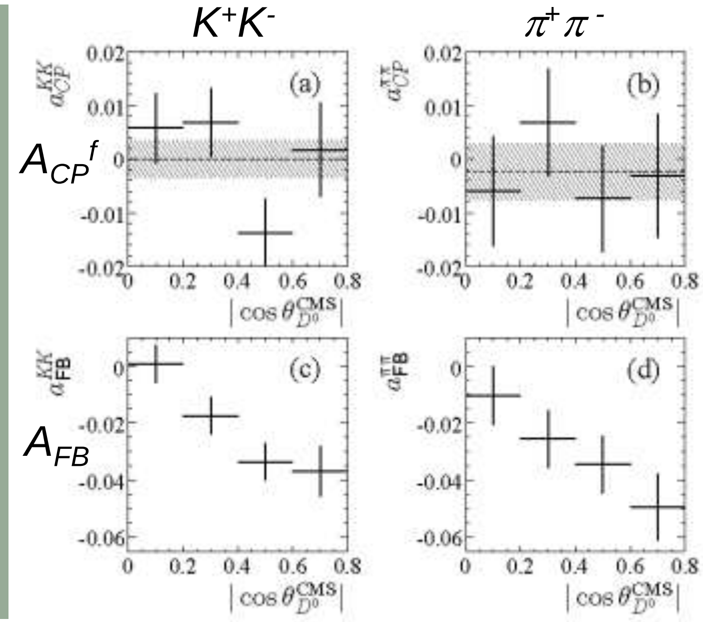
no CPV at ~ 2 ·10^{-3}

A_ε^π in bins of p_π, θ_π (n.b.: $\mathcal{O}(10^{-2})$)

Belle, PLB670, 190 (2008), 540fb^{-1}



BaBar, PRL 100, 061803 (2007), 386fb^{-1}



CPV measurements

DCPV in other $D_{(s)}^+$ decays

$$A_{CP} = \frac{\Gamma(M \to f) - \Gamma(\overline{M} \to \bar{f})}{\Gamma(M \to f) + \Gamma(\overline{M} \to \bar{f})}$$

t-integrated method;
same (similar) method of extracting detector induced asymmetries;

example: $D_{(s)}^+ \to K_S h^+$, $h=K, \pi$
charged mesons: CPV in decay only;

$$A_{rec}^{D\to K_S^0\pi^+} = A_{CP}^{D\to K_S^0\pi^+} + A_{FB}^{D} + A_{\varepsilon}^{\pi^+}$$

$$A_{rec}^{D\to K_S^0K^+} = A_{CP}^{D\to K_S^0K^+} + A_{FB}^{D} + A_{\varepsilon}^{K^+}$$

$$A_{rec}^{D^{*+}\to D^0\pi_s^+} = A_{CP}^{D^0\to K_S^0P^0} + A_{FB}^{D^{*+}} + A_{\varepsilon}^{\pi_s^+}$$

$$A_{rec}^{D_s^+\to \phi\pi^+} = A_{FB}^{D_s^+} + A_{\varepsilon}^{\pi^+}$$

$$A_{rec}^{untagged\ D^0\to K^-\pi^+} = A_{FB}^{D^0} + A_{\varepsilon}^{K^-} + A_{\varepsilon}^{\pi^+}$$

$$A_{rec}^{tagged\ D^0\to K^-\pi^+} = A_{FB}^{D^{*+}} + A_{\varepsilon}^{K^-} + A_{\varepsilon}^{\pi^+} + A_{\varepsilon}^{\pi_s^+}$$

example:
$A_{rec}(D \to K_S\pi^+)$ - $A_{rec}(D_s \to \phi\pi^+)$
$\Rightarrow A_{CP}(D \to K_S\pi^+)$
(technically much more involved due to p_π, θ_π, θ_D dependence)

Other states

$$A_K = \frac{\left|\langle \pi\pi | K^0 \rangle\right|^2 - \left|\langle \pi\pi | \bar{K}^0 \rangle\right|^2}{\left|\langle \pi\pi | K^0 \rangle\right|^2 + \left|\langle \pi\pi | \bar{K}^0 \rangle\right|^2} \approx$$

$$\approx \frac{1-\left|(p/q)_K\right|^2}{1+\left|(p/q)_K\right|^2} = \frac{2\,\mathrm{Re}(\varepsilon)}{1+|\varepsilon|^2} = 0.332\%$$

Principle

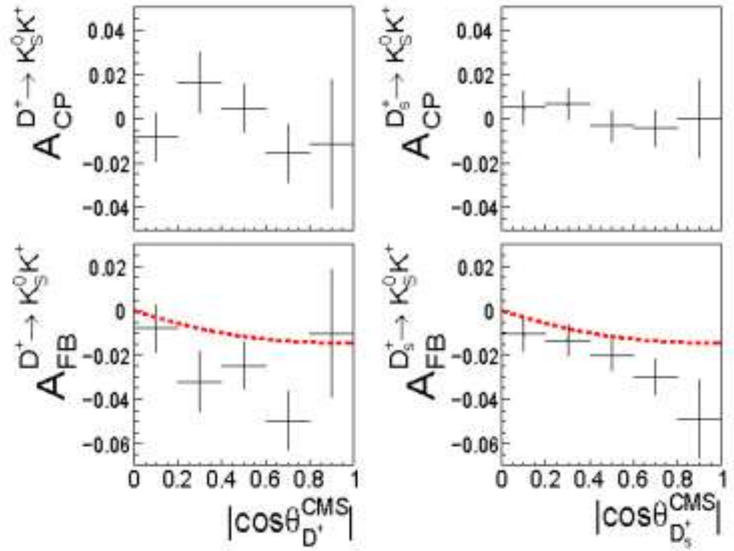
K_S in final state not a CP eigenstate itself;
in weak D decays K^0, $\overline{K^0}$ produced;
CPV in K^0 system $\Rightarrow$
even in absence of CPV in D system
some asymmetry expected

Results

Belle, PRL 104, 181602 (2010), 673fb^{-1}

		A_K
$A_{CP}^{D^+\to K_S^0\pi^+}$	$-0.71\pm0.19\pm0.20$	$-0.332^\dagger$
$A_{CP}^{D_s^+\to K_S^0\pi^+}$	$+5.45\pm2.50\pm0.33$	$+0.332$
$A_{CP}^{D^+\to K_S^0K^+}$	$-0.16\pm0.58\pm0.25$	-0.332
$A_{CP}^{D_s^+\to K_S^0K^+}$	$+0.12\pm0.36\pm0.22$	$-0.332^\dagger$

2.6 σ from 0, consistent with A_K



no CPV at $\geq 3\cdot10^{-3}$

CPV measurements

WS 2-body decays

Principle

$D^{*+} \to D^0 \; \pi_{slow}^+$

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

WS: $D^0 \to \overline{D}^0 \to K^+ \pi^-$ or DCS

$$\left|\langle K^+\pi^- | D^0(t)\rangle\right|^2 \propto \left[\underbrace{R_D^+}_{DCS} + \underbrace{\sqrt{R_D^+}\, y'^+\, t}_{interf.} + \underbrace{\frac{x'^{+2}+y'^{+2}}{4} t^2}_{mix}\right] e^{-t}$$

$$\left|\langle K^-\pi^+ | \overline{D}^0(t)\rangle\right|^2 \propto \left[\underbrace{R_D^-}_{DCS} + \underbrace{\sqrt{R_D^-}\, y'^-\, t}_{interf.} + \underbrace{\frac{x'^{-2}+y'^{-2}}{4} t^2}_{mix}\right] e^{-t}$$

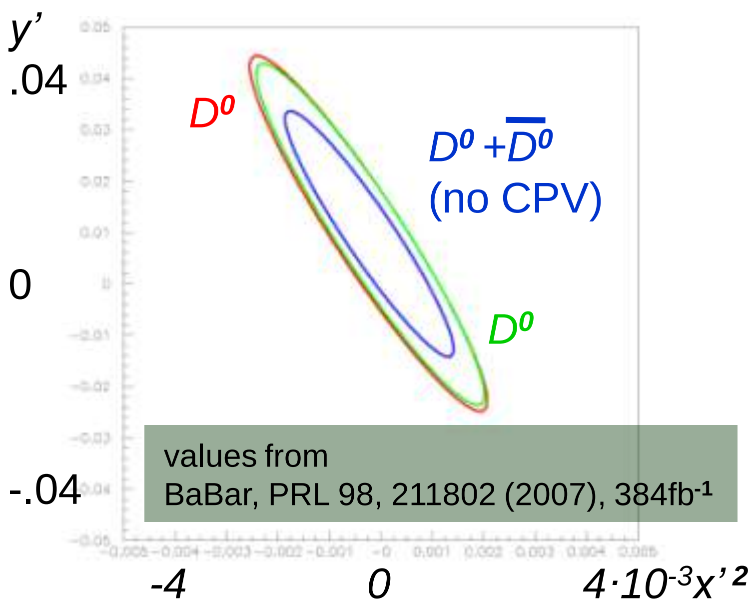
$$R_M^{\pm} = \frac{x^{\pm 2} + y^{\pm 2}}{2} \qquad A_M = \frac{R_M^+ - R_M^-}{R_M^+ + R_M^-} \qquad A_D = \frac{R_D^+ - R_D^-}{R_D^+ + R_D^-}$$

equivalent measurement separately for D^0, $\overline{D}^0$
$(x'^2, y', R_D) \to (x'^{\pm 2}, y'^{\pm}, R_D^{\pm})$;

CPV in decay and mixing

Belle, PRL 96, 151801 (2006), 400fb^{-1}

$A_D = (23 \pm 47) \cdot 10^{-3}$
$A_M = (670 \pm 1200) \cdot 10^{-3}$



Multi-body self conjugated states

same as eqs. on p. I/31 but including q/p

Principle

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

t-depedent matrix elements $\mathcal{M}$, $\overline{\mathcal{M}}$ are in case of CPV not trivially related;

$$\mathcal{M}(m_-^2, m_+^2, t) \equiv \langle K_S \pi^+ \pi^- | D^0(t) \rangle = \frac{1}{2} \mathcal{A}(m_-^2, m_+^2)\left[e^{-i\lambda_1 t} + e^{-i\lambda_2 t}\right] + \frac{1}{2}\frac{q}{p} \overline{\mathcal{A}}(m_-^2, m_+^2)\left[e^{-i\lambda_1 t} - e^{-i\lambda_2 t}\right]$$

$$\overline{\mathcal{M}}(m_-^2, m_+^2, t) \equiv \langle K_S \pi^+ \pi^- | \overline{D}^0(t) \rangle = \frac{1}{2} \overline{\mathcal{A}}(m_-^2, m_+^2)\left[e^{-i\lambda_1 t} + e^{-i\lambda_2 t}\right] + \frac{1}{2}\frac{p}{q} \mathcal{A}(m_+^2, m_-^2)\left[e^{-i\lambda_1 t} - e^{-i\lambda_2 t}\right]$$

no CPV: $\frac{q}{p} = 1, \overline{\mathcal{A}}(m_-^2, m_+^2) = \mathcal{A}(m_+^2, m_-^2) \Rightarrow \overline{\mathcal{M}}(m_-^2, m_+^2, t) = \mathcal{M}(m_+^2, m_-^2, t)$

CPV:

$$\mathcal{A}(m_-^2, m_+^2) = \sum a_r\, e^{i\Phi_r} B(m_-^2, m_+^2) + a_{NR}\, e^{i\Phi_{NR}}$$

$$\overline{\mathcal{A}}(m_-^2, m_+^2) = \sum \overline{a}_r\, e^{i\overline{\Phi}_r} B(m_+^2, m_-^2) + \overline{a}_{NR}\, e^{i\overline{\Phi}_{NR}}$$

$$\overline{\mathcal{M}}(m_-^2, m_+^2, t) \neq \mathcal{M}(m_+^2, m_-^2, t)$$

$\overline{a}_r$, $\overline{\phi}_r \neq a_r$, ϕ_r: direct CPV (in decay)

$|q/p| \neq 1$, $\phi \neq 0$: indirect CPV (in mixing and interference)

Multi-body self conjugated states

Results

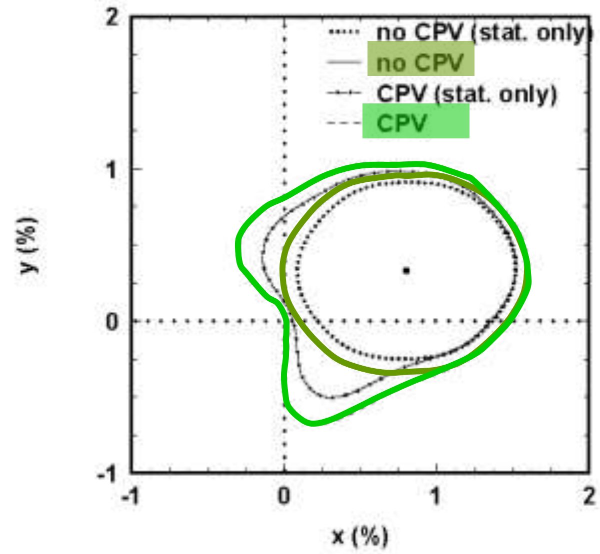
$D^0 \to K_S \pi^+ \pi^-$

Belle, PRL 99, 131803 (2007), 540fb^{-1}

$$|q/p| = 0.86 \pm^{0.30}_{0.29} \pm^{0.10}_{0.09}$$

$$\varphi = (-0.24 \pm^{0.28}_{0.30} \pm 0.09)\ rad$$

95% C.L. contour



no evidence of direct CPV;
x, y almost unchanged w.r.t. no CPV fit

BaBar, arXiv:1004.5053, 470 fb^{-1}

$K_S \pi^+ \pi^- / K_S K^+ K^-$
does not fit for CPV param.

CPV measurements

Averages

Results

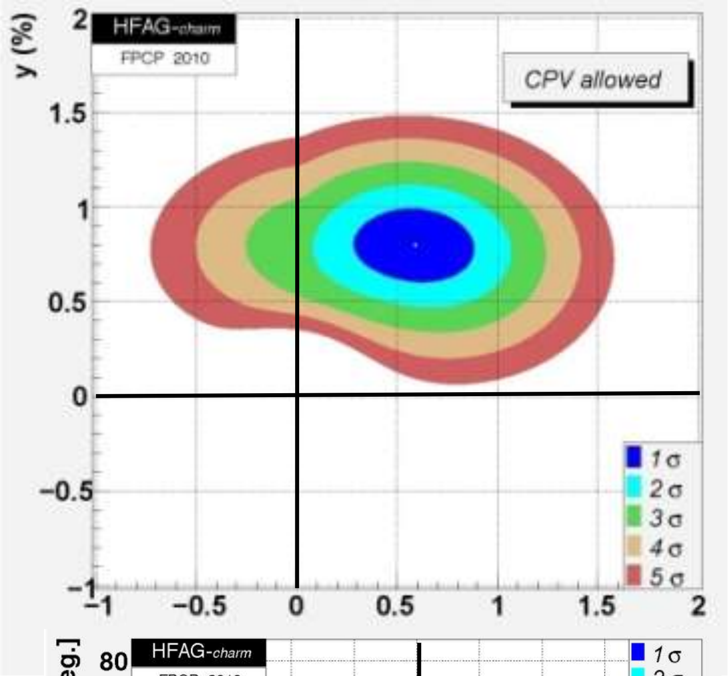
same fit as for the mixing parameters, + CPV parameters

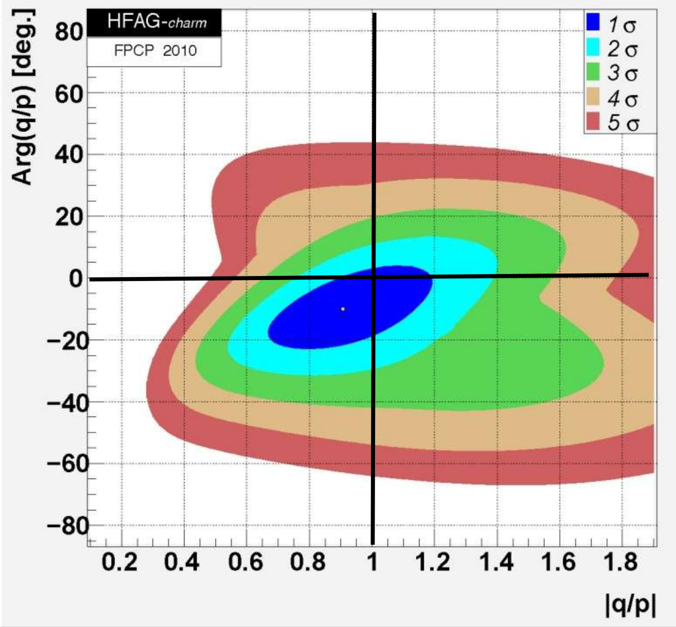
HFAG, http://www.slac.stanford.edu/xorg/hfag/

x	$(0.63 \pm 0.20)\%$
y	$(0.75 \pm 0.12)\%$
δ	$(22.0\ ^{+9.8}_{-11.2})°$
$\delta_{K\pi\pi}$	$(19.3\ ^{+21.8}_{-22.9})°$
R_D	$(0.331 \pm 0.008)\%$
A_D	$(-1.9 \pm 2.4)\%$
$\lvert q/p \rvert$	$0.91\ ^{+0.18}_{-0.16}$
ϕ	$(-10.2\ ^{+9.4}_{-8.9})°$

CPV: A_D, $|q/p|$, ϕ

χ^2/n.d.f.= 31.9/(30-8)= 31.9/22





Constraints from mixing

(examples from E. Golowich et al., PRD76, 095009 (2007))

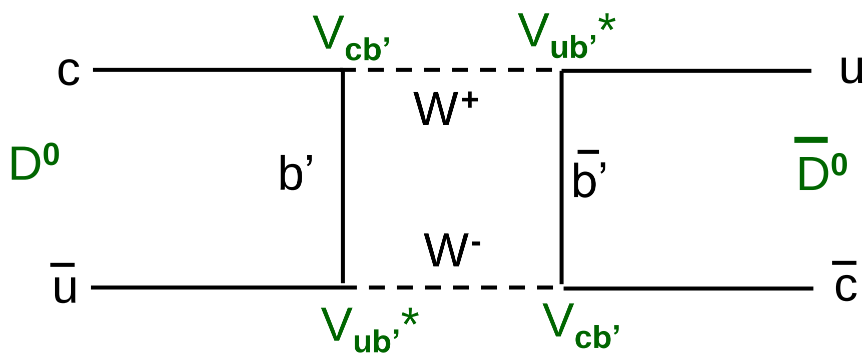
4th generation of fermions

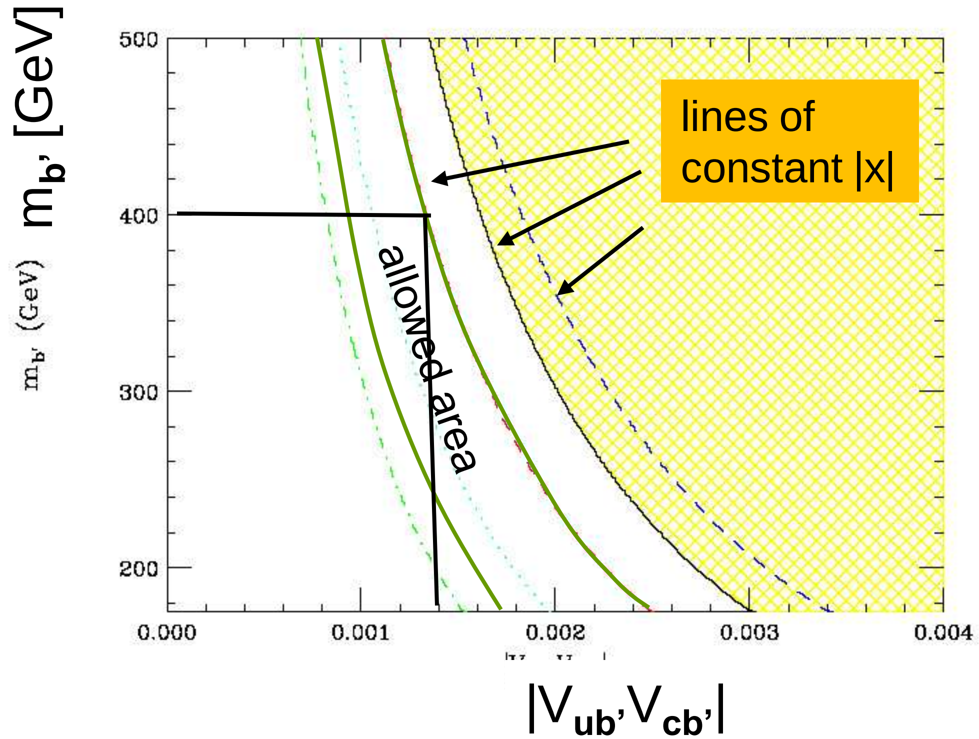
b' beside d,s,b exchanged in loop;

$|V_{ub'}V_{cb'}| < 1.4 \cdot 10^{-3}$
for $m_{b'} > 400$ GeV

more severe constraints than from CKM unitarity

complementarity of such constraints w.r.t. down-like FCNC obvious



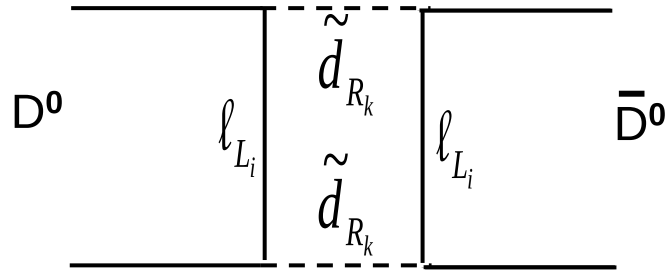


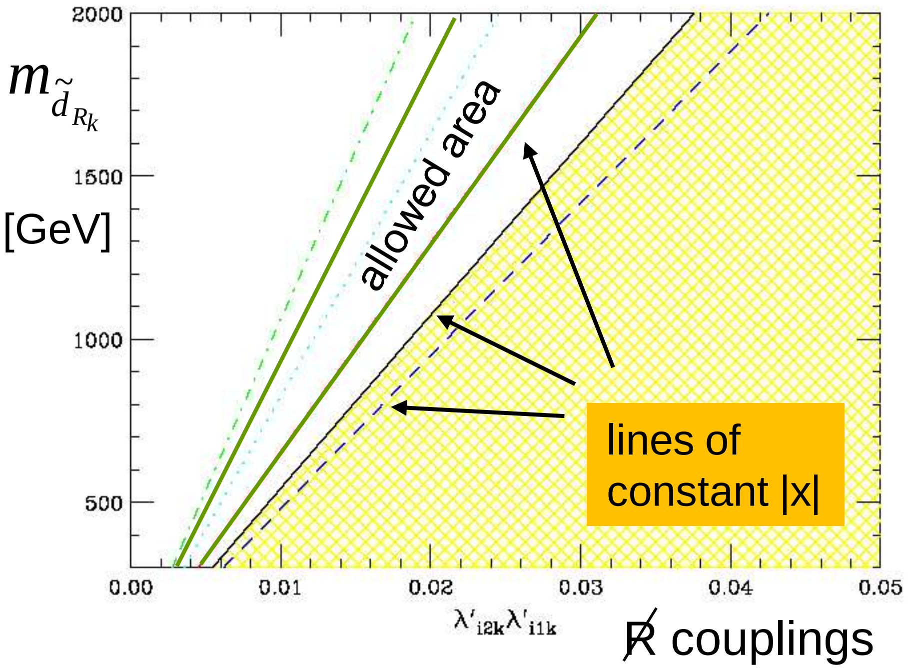
Constraints from mixing

E. Golowich et al., PRD76, 095009 (2007)

R-parity violating SUSY

squark-lepton (or vice versa) exchange in loop;





Outlook

Near future facilities

Charm-factories

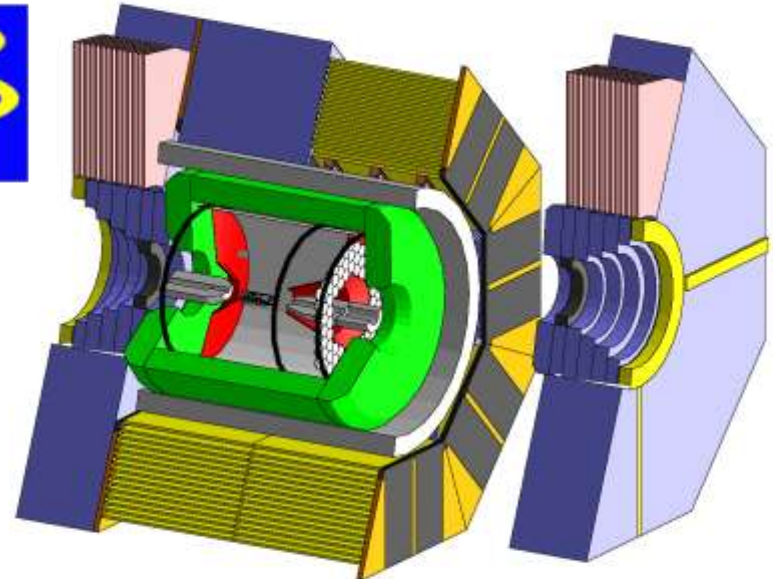
main results from BES-III expected in the near future;

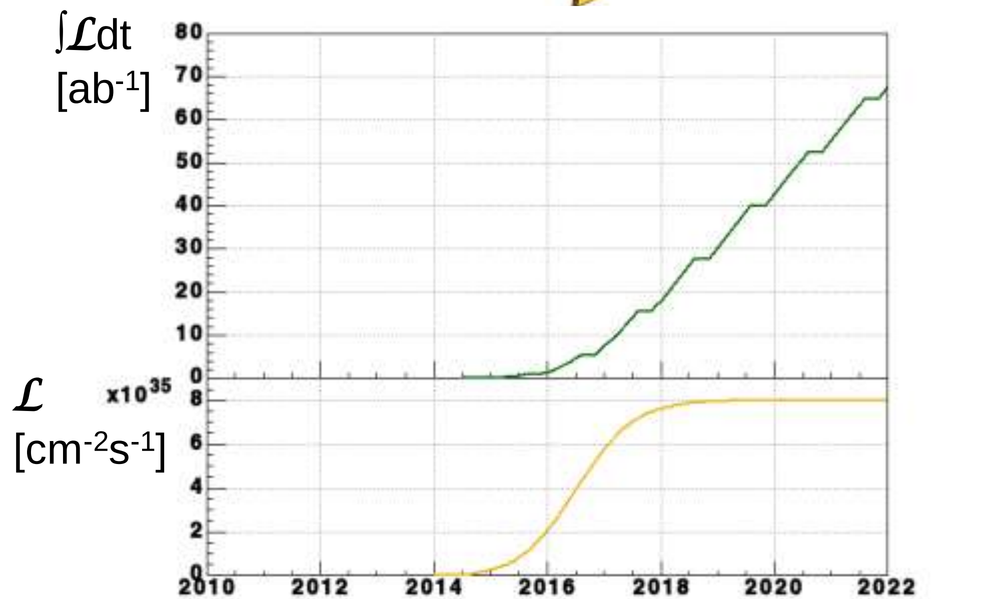
LHCb

great hopes for nice results, although 1 fb^{-1}(by end of 2011) may not be enough

Super B-factories

- Super KEKB, 5 ab^{-1} in 2016;
- SuperB, Frascati

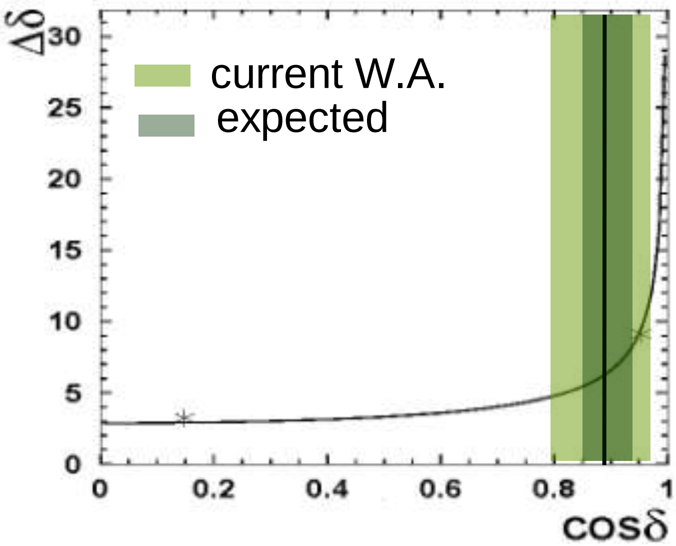




Outlook

Illustrative expected sensitivities

Mixing parameters



Charm-factories

BES III, arXiv:0809.1869

20 fb^{-1}: $\sigma(R_M) \sim 1 \cdot 10^{-4}$
(from $\psi(3770) \rightarrow K^-\pi^+, K^-\pi^+$) n.b.: p. I/51
(n.b.: $R_M \sim 1 \cdot 10^{-4}$);
$\sigma(y) \sim 0.3\%$
$\sigma(\cos\delta) \sim 0.04$

LHCb

G. Wilkinson et al., public note LHCb-2007-49

10 fb^{-1}: $\sigma(x) \sim 0.25\%$, $\sigma(y) \sim 0.05\%$
(estimated from precision on x'^2, y' and y_{CP})

Prediction is very difficult, especially of the future.

N. Bohr (1885 - 1962)

Super B-factories

A.G. Akeroyd et al., arXiv:1002.5012

Super-KEKB: 5 ab^{-1}: $\sigma(x)$, $\sigma(y) \sim 0.1\%$
(combined from $K\pi$, KK, $K_s\pi\pi$)

Illustrative expected sensitivities

CPV parameters

$$r \equiv \frac{\Gamma(S_+S_+)}{\Gamma(S_+X)} = 2R_M Br(S_+)\sin^2\varphi$$

$$A_{CP}^{C=+1} = \frac{\Gamma(S_+e^-)-\Gamma(S_+e^+)}{\Gamma(S_+e^-)+\Gamma(S_+e^+)} \approx$$

$$\approx y\frac{A_M}{2}\cos\varphi - x\sin\varphi = A_\Gamma$$

$$n.b.:\ A_{CP}^{C=-1} \approx R_M A_M$$

(neglecting direct CPV, i.e. A_D=0; see p. II/28 for other asymmetries)

Charm-factories

several possibilities;

- decays to same sign CP states;
  - not sensitive due to R_M suppression;
- C=+1 initial state ($D^0D^0\gamma$);
  - 20 fb^{-1}: $\sigma(A_\Gamma)$ ~ 0.6% (stat. only)

BES III, arXiv:0809.1869

Super B-factories

Super-KEKB:

5 ab^{-1}: $\sigma(\phi)$ ~ 5^o

$\sigma(A_\Gamma)$ ~ 0.1%-0.2%

A.G. Akeroyd et al., arXiv:1002.5012

Outlook

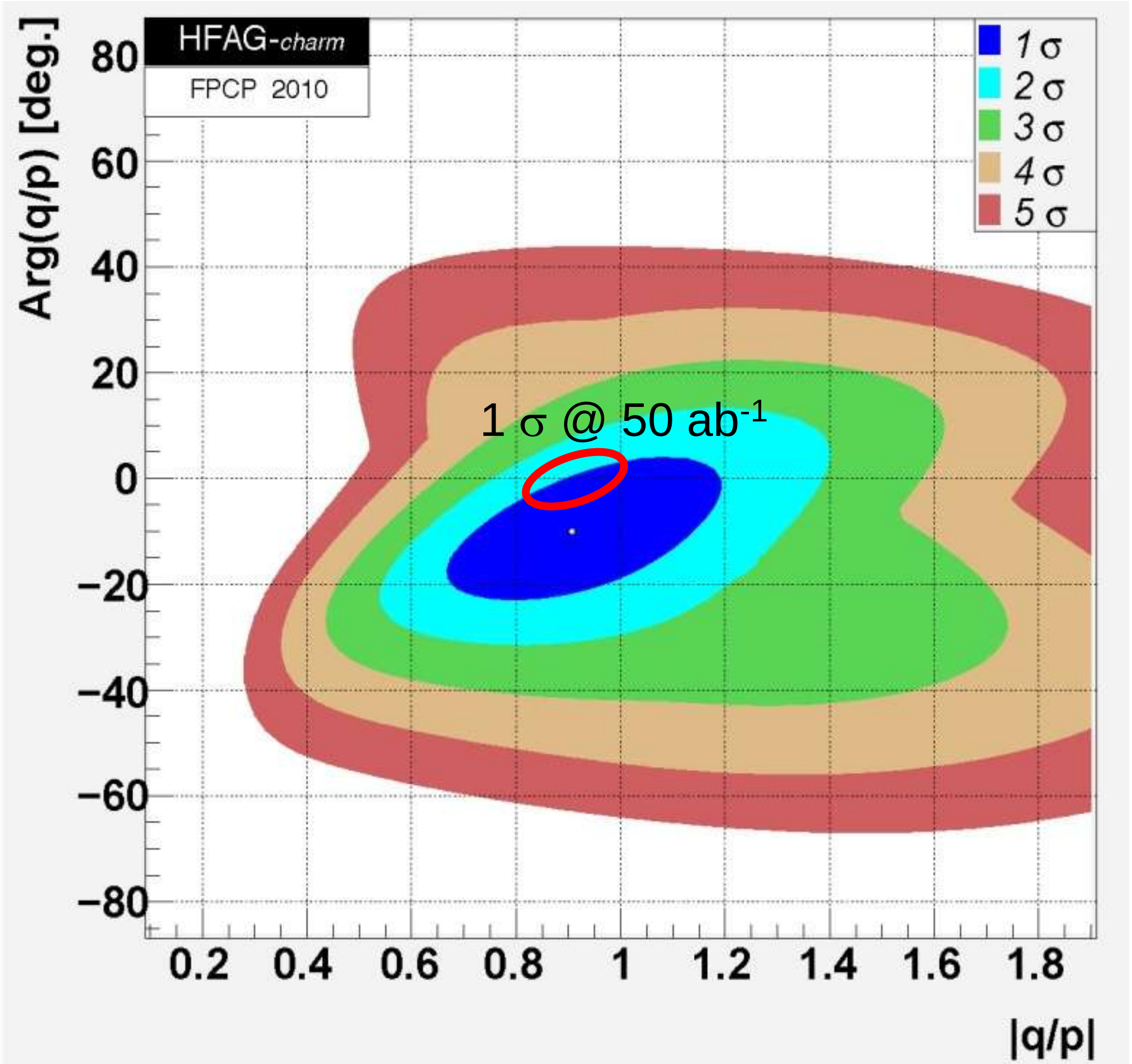
Illustrative expected sensitivities

CPV parameters

Belle II, 50 ab^{-1}

$$x = (0.832 \pm 0.095)\%$$
$$y = (0.813 \pm 0.064)\%$$
$$\delta_{K\pi} = 24.6° \pm 4.9°$$
$$R_D = (0.336 \pm 0.003)\%$$
$$\frac{|q|}{|p|} = 0.894 \pm 0.054$$
$$\varphi = -0.004 \pm 0.049\ rad$$
$$A_D = (-0.1 \pm 0.8)\%$$

only KK/ππ, Kπ and $K_s\pi\pi$ projected sensitivities included



Summary

- entering precision era in D^0 mixing and CPV (mixing only estab. in 2007)

- provide unique constraints/searches of NP in u-like FCNC

Today:

- B-factories (and Tevatron) still to say the final word

Tomorrow:

- Charm-factories, LHCb and Super-B factories

- will be able to search for NP effects (in CPV) in whole range down to SM predictions

Additional material

CP violation in charm

Parametrization
direct CPV

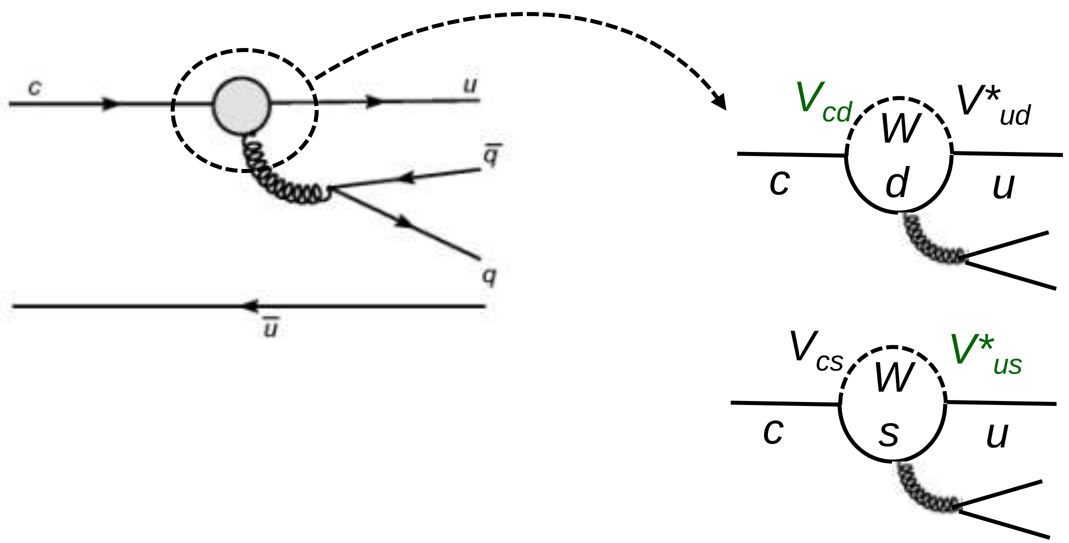
$$A_f = a_1 + a_2 = |a_1| e^{i(\delta_1+\varphi_1)} + |a_2| e^{i(\delta_2+\varphi_2)}$$

$$A_{CP} = \frac{\Gamma(M \to f) - \Gamma(\overline{M} \to \bar{f})}{\Gamma(M \to f) + \Gamma(\overline{M} \to \bar{f})} = \frac{|A_f/\overline{A}_{\bar{f}}|^2 - 1}{|A_f/\overline{A}_{\bar{f}}|^2 + 1} =$$

$$= \ldots = \frac{2|a_1 a_2| \sin(\delta_2 - \delta_1) \sin(\varphi_2 - \varphi_1)}{|a_1|^2 + |a_2|^2 + 2|a_1 a_2| \cos(\delta_2 - \delta_1)\cos(\varphi_2 - \varphi_1)}$$

for direct CPV two amplitudes with different strong and weak (CKM) phases are necessary;

in *D* meson decays this is only possible in CS decays with contribution of penguin decays (beside tree contrib.)



D mixing rate in exclusive approach

J.F. Donoghue et al., PRD33, 179 (1986)

$$(M - i\frac{\Gamma}{2})_{ij} = \frac{\langle D_i | H_{eff} | D_j \rangle}{2M_D} = M_D \delta_{ij} + \frac{1}{2M_D}\langle \overline{D}^0 | H_w^{\Delta C=-2} | D^0 \rangle +$$

$$+ \frac{1}{2M_D} \sum_n \frac{\langle \overline{D}^0 | H_w^{\Delta C=-1} | n \rangle \langle n | H_w^{\Delta C=-1} | D^0 \rangle}{M_D - E_n + i\varepsilon}$$

dominant contrib. to mixing;

take as example *PP* final states:

State	$\lvert \langle \overline{D}^0 \lvert H_w^{\Delta C=-1} \rvert n \rangle \rvert^2 \propto$	$\langle \overline{D}^0 \lvert H_w^{\Delta C=-1} \rvert n \rangle \langle n \lvert H_w^{\Delta C=-1} \rvert D^0 \rangle \propto$	measured Br	contrib. to mixing
$K^-\pi^+$	1	$-\lambda^2$	r_1	$-\sqrt{(r_1 r_4)}\,\lambda^2$
K^-K^+	λ^2	λ^2	$r_2\,\lambda^2$	$r_2\,\lambda^2$
$\pi^-\pi^+$	λ^2	λ^2	$r_3\,\lambda^2$	$r_3\,\lambda^2$
$K^+\pi^-$	λ^4	$-\lambda^2$	$r_4\,\lambda^4$	$-\sqrt{(r_1 r_4)}\lambda^2$
Σ		0		$\lambda^2(r_2+r_3-2\sqrt{(r_1 r_4)})$

minus sign due to relative sign of V_{us}/V_{cd} (see p. I/32);
summing over this states ⇒ 0 (GIM mechanism);

$$\Sigma = \lambda^2\left(r_2 + r_3 - 2\sqrt{r_1 r_4}\right) \neq 0$$

however, in D^0 decays SU(3) is broken;
in other words, measured Br's with $r_i \neq 1$

Mixing parameters

B mesons:
calculate M_{12}, Γ_{12} from box diagram; from that calculate Δm, $\Delta\Gamma$

$$M_{12} = -\frac{G_F^2 m_W^2 \eta_B m_{Bq} B_{Bq} f_{Bq}^2}{12\pi^2} S_0(m_t^2/m_W^2)(V_{tq}^* V_{tb})^2$$

$$\Gamma_{12} = \frac{G_F^2 m_b^2 \eta_B' m_{Bq} B_{Bq} f_{Bq}^2}{8\pi} (V_{tq}^* V_{tb})^2$$

q: d (B_d) or s (B_s)
B_{Bq}: bag parameter, $\langle B_q^0 | b\gamma^\mu(1-\gamma^5) q | B_q^0 \rangle$
f_{Bq}: decay constant
$\eta_B^{(')}$: QCD corr. $\mathcal{O}(1)$
$S_0(x_t)$: known kinematic function

$$\varphi_{12} = \arg\frac{M_{12}}{\Gamma_{12}} = \pi + \mathcal{O}(m_c^2/m_b^2)$$

$$\left|\frac{\Gamma_{12}}{M_{12}}\right| \approx \frac{3\pi}{2}\frac{m_b^2}{m_W^2}\frac{1}{S_0(m_t^2/m_W^2)} \sim \mathcal{O}(m_b^2/m_t^2)$$

$$\left|\frac{q}{p}\right|^2 = 1 + \left|\frac{\Gamma_{12}}{M_{12}}\right| \sin\varphi_{12} + \mathcal{O}(|\Gamma_{12}/M_{12}|^2)$$

Mixing parameters

B mesons:

$|\Gamma_{12}| << |M_{12}|$

measured x_d=0.776 ± 0.008

x_s=25.5 ± 0.6

from $M_{12}/\Gamma_{12} \Rightarrow y_d<1\%$

$y_s \sim 10\%$

$$\Delta m = 2|M_{12}|(1+\ldots)$$
$$\Delta\Gamma = -2|\Gamma_{12}|(1+\ldots)$$
$$\ldots \to \mathcal{O}(|\Gamma_{12}|/|M_{12}|)$$

D mesons:

$$\left|M_{12}^{D}\right| = \frac{\overline{\Gamma}x}{2}\sqrt{1+(A_M x/2y)^2}$$

G. Raz, PRD66, 057502 (2002)

Asymmetries at charm-factories

untagged asymmetry

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

$$A_{CP} \approx 2\sqrt{R_D}\,\sin\delta \left[y \sin\varphi + \frac{A_M}{2} x \cos\varphi \right] \approx 2\sqrt{R_D}\,\sin\delta\; y \sin\varphi$$

semileptonic asymmetry

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

$$A_{CP} \approx -2A_M$$

direct CPV

$$A_{CP} = \frac{\Gamma(\overline{D}^0 D^0 \to S_+ e^-) - \Gamma(\overline{D}^0 D^0 \to S_+ e^+)}{\Gamma(\overline{D}^0 D^0 \to S_+ e^-) + \Gamma(\overline{D}^0 D^0 \to S_+ e^+)} \approx \frac{A_D}{2}$$

(n.b.: A_D is decay mode specific, in this case represents direct CPV in S_+ decay mode)