Recent results in charm physics

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FPCP 2014
Marseille, May 28, 2014

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- In the following, some groups (one including the speaker) argued that this value can plausibly be accommodated within the SM.
- Recent world average [HFAG]: $\Delta\mathcal{A}_{CP} = (-0.253 \pm 0.104)\%$

Introduction – Why charm physics?

$$|V_{\rm CKM}| = \begin{pmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{pmatrix} \approx \begin{pmatrix} 1 & \lambda & \lambda^3 \\ \lambda & 1 & \lambda^2 \\ \lambda^3 & \lambda^2 & 1 \end{pmatrix} \text{, where } \lambda \approx 0.23$$

- "Two-generation dominance" and efficient GIM mechanism – SM contribution to mixing and CP violation is small.
- Large long-distance contributions make theory predictions difficult.
- Not suited for precision extractions of CKM elements.
- Search for new physics in the up-quark sector!

Weak effective Hamiltonian for charm

$$\mathcal{H}_{\text{eff}} = \frac{G_F}{\sqrt{2}} \sum_i C_i Q_i$$

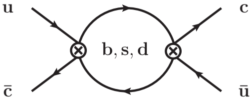
- Wilson coefficients can be computed perturbatively
- Hadronic matrix elements $\langle K\pi|\mathcal{H}_{\text{eff}}|D\rangle$ dominated by nonperturbative QCD
- QCD factorization expected to work badly ($\Lambda_{\text{QCD}}/m_c \lesssim 1$)
- Could compute matrix elements on the lattice (in the not so near future)
- Flavor symmetries ($SU(3)_F$, isospin, U spin ...) can help at least qualitatively

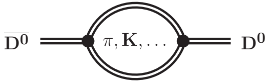
Outline

- $D^0 - \bar{D}^0$ mixing
- CP violation, $\Delta\mathcal{A}_{CP}$
  - $SU(3)_F$ and sum rules
- Implications for γ from tree decays

Mixing

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





$$i\frac{d}{dt}\begin{pmatrix}|D(t)\rangle\\|\bar{D}(t)\rangle\end{pmatrix} = \left(M - i\frac{\Gamma}{2}\right)\begin{pmatrix}|D(t)\rangle\\|\bar{D}(t)\rangle\end{pmatrix}$$

Diagonalize to get eigenstates

$$|D_{H,L}\rangle = p|D^0\rangle \mp q|\bar{D}^0\rangle$$

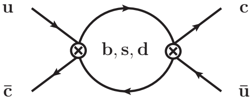
$$\Gamma_D \equiv \frac{\Gamma_H + \Gamma_L}{2}, \quad x \equiv \frac{M_H - M_L}{\Gamma_D}, \quad y \equiv \frac{\Gamma_H - \Gamma_L}{2\Gamma_D}.$$

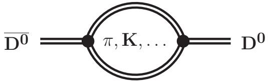
$D^0 - \bar{D}^0$ mixing

- Using $SU(3)$ decomposition of $\langle \bar{D} | \mathcal{H}_{\text{eff}} \mathcal{H}_{\text{eff}} | D \rangle$ can show [Falk et al. 2002]

$$x, y \sim \sin^2 \theta_C \times m_s^2$$

- (Argument neglects third generation)





$D^0 - \bar{D}^0$ mixing – SM estimates

"Inclusive approach":

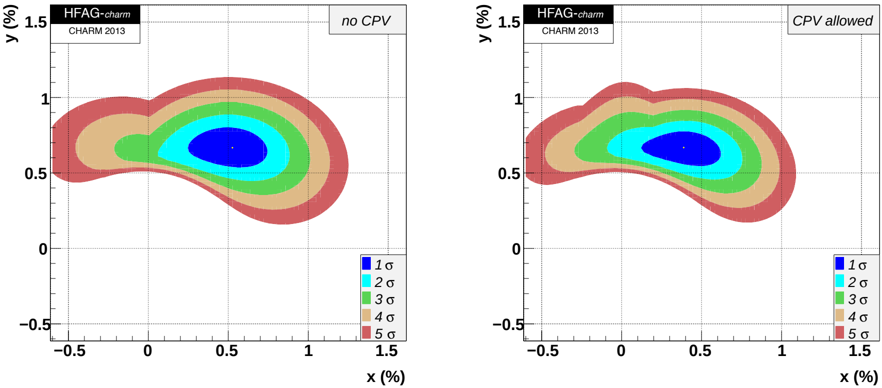
- OPE expansion in powers of "Λ/m_c"
- LO gives $x \sim 10^{-5}$, $y \sim 10^{-7}$
- Higher order $x \sim y \lesssim 10^{-3}$ [Georgi 1992; Ohl et al. 1993; Bigi et al. 2000]
- Cannot exclude $y \sim 10^{-2}$ ($V_{ub} \neq 0$) [Bobrowski et al. 2010]

"Exclusive approach":

- Sum over on-shell intermediate states
- Mainly $D \to PP, PV$ leads to $x \sim y \lesssim 10^{-3}$ [Cheng et al. 2010]
- $SU(3)_F$ breaking in phase space $y \sim 10^{-2}$ [Falk et al. 2002]
- Get $x \sim 10^{-2}$ from a dispersion relation [Falk et al. 2004]

Large uncertainties; use experimental values to set upper bounds

$D^0 - \bar{D}^0$ mixing – HFAG



CP violation

Three types of CP violation

Time-integrated CP asymmetry for decay into CP eigenstate f

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} = a_f^d + a_f^m + a_f^i \,.$$

- a^m and a^i are universal to good approximation
- Indirect CP violation is expected to be $\mathcal{O}(10^{-4})$ in the SM ($V_{ub} \neq 0$ and $SU(3)$) [Grossman et al., work in progress]

$\Delta\mathcal{A}_{CP}$: Definitions

$$A_f \equiv A(D^0 \to f) = A_f^T \left[1 + r_f e^{i(\delta_f - \phi_f)}\right],$$
$$\bar{A}_f \equiv A(\overline{D^0} \to f) = A_f^T \left[1 + r_f e^{i(\delta_f + \phi_f)}\right]$$

$r_f = A_f^P / A_f^T$, δ_f strong phase, ϕ_f weak phase.

$$a_f^d := \frac{|A_f|^2 - |\bar{A}_f|^2}{|A_f|^2 + |\bar{A}_f|^2} = 2 r_f \sin\phi_f \sin\delta_f$$

Indirect contribution $a^m + a^i$ cancels to good approximation in

$$\Delta\mathcal{A}_{CP} := a^d_{K^+K^-} - a^d_{\pi^+\pi^-}$$

$\Delta\mathcal{A}_{CP}$: Measurements

CDF [arXiv:1207.2158]:

$$\Delta\mathcal{A}_{CP} = (-0.62 \pm 0.21 \pm 0.10)\%$$

Belle [arXiv:1212.1075]:

$$\Delta\mathcal{A}_{CP} = (-0.87 \pm 0.41 \pm 0.06)\%$$

LHCb prompt [LHCb-CONF-2013-003]:

$$\Delta\mathcal{A}_{CP} = (-0.34 \pm 0.15 \pm 0.10)\%$$

LHCb muon tag NEW [arXiv:1405.2797]:

$$\Delta\mathcal{A}_{CP} = (+0.14 \pm 0.16 \pm 0.08)\%$$

leading to new world average (including individual BaBar measurements) [HFAG May 2014]:

$$\Delta\mathcal{A}_{CP} = (-0.253 \pm 0.104)\%$$

Three U-spin relations

- $s \leftrightarrow d$ symmetry – expect breaking of order $(f_K/f_\pi - 1) \sim 20\%$

$$\frac{|A(D^0 \to K^+K^-)|}{|A(D^0 \to \pi^+\pi^-)|} - 1 = (82 \pm 2)\%$$

$$\frac{|A(D^0 \to K^-\pi^+)|}{|A(D^0 \to K^+\pi^-)|} - 1 = (15 \pm 3)\%$$

$$\frac{|A(D^0 \to K^+K^-)| + |A(D^0 \to \pi^+\pi^-)|}{|A(D^0 \to K^+\pi^-)| + |A(D^0 \to K^-\pi^+)|} - 1 = (4.0 \pm 1.6)\%$$

U-spin decomposition

- D^0 is U-spin singlet
- triplet $(\langle K^+\pi^-|, (\langle K^+K^-| - \langle\pi^+\pi^-|)/\sqrt{2}, \langle K^-\pi^+|)$,
  singlet $(\langle K^+K^-| + \langle\pi^+\pi^-|)/\sqrt{2}$
- triplet $(Q_i^{\bar{d}s}, (Q_i^{\bar{s}s} - Q_i^{\bar{d}d})/\sqrt{2}, Q_i^{\bar{s}d})$,
  singlet $(Q_i^{\bar{s}s} + Q_i^{\bar{d}d})/\sqrt{2}$
- Write down U-spin amplitudes
- Include breaking $\propto m_s$ via spurion method

U-spin analysis

[Brod, Grossman, Kagan, Zupan; see also Pirtskhalava et al., Feldmann et al., Franco et al., Jung et al. 2011-12]

- $\epsilon \sim (f_K/f_\pi - 1) \sim 0.2$, $\xi = |V_{cb}^* V_{ub}/V_{cs} V_{us}^*| \sim 6 \times 10^{-4}$

$$A(\bar{D}^0 \to K^+\pi^-) = t_0 - \epsilon t_1$$

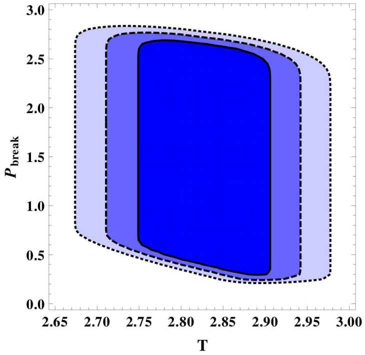
$$A(\bar{D}^0 \to \pi^+ K^-) = t_0 + \epsilon t_1$$

$$A(\bar{D}^0 \to K^+ K^-) = t_0 - \epsilon p_1 - \xi p_0$$

$$A(\bar{D}^0 \to \pi^+\pi^-) = t_0 + \epsilon p_1 + \xi p_0$$

- $\Delta\mathcal{A}_{CP} \sim (p_0/t_0) \sin\delta$
- Branching ratio data imply $p_1 \gg t_1$
- Expect $p_1 \sim p_0$ (“$\Delta U = 0$ rule”)

Fit to branching ratios



- Fit to branching ratios only shows $\epsilon p_1 \sim t_0/2$
- For $\epsilon = 20\%$:

$$r_f = \frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|}\frac{p_0}{|t_0 \pm \epsilon p_1|}$$

$$\sim \frac{|V_{cb}V_{ub}|}{|V_{cs}V_{us}|}\frac{1}{2\,\epsilon} \sim 0.2\%$$

- Can comfortably explain $\Delta\mathcal{A}_{CP}$!

- (Expect similar size in $D^+ \to K^+\bar{K}^0$, $D_s^+ \to \pi^+ K^0$ by exchanging spectator quark)

Future directions

- Global SU(3) fit
  - Dortmund group: Use input from factorization

    [Hiller, Schacht et al., work in progress]
- Progress in lattice calculations
  - Recent progress in $K \to \pi\pi$ matrix element
  - Multiple-channel generalization of Lellouch-Lüscher formula

    [Hansen, Sharpe; Briceño, Davoudi 2012]
  - Channels with multiple particles

    [E.g. Polejaeva, Rusetsky 2012]

Isospin sum rules

Basic idea [Grossman, Kagan, Zupan, PRD 85 (2012) 114036]:

- Tree-level $\mathcal{H}_{\text{eff}}$ for $D \to \pi\pi$ has both $\Delta I = 1/2$ and $\Delta I = 3/2$:

$$Q_T \sim (\bar{d}c)(\bar{u}d)$$

- QCD penguin operators are purely $\Delta I = 1/2$:

$$Q_P \sim (\bar{c}u) \otimes (\bar{u}u + \bar{d}d + \bar{s}s)$$

- $\Delta I = 3/2$ direct CP-violating transitions are absent in SM.

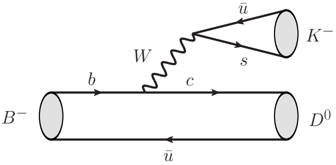
Isospin sum rules for $D \to \pi\pi$

$$
\begin{aligned}
A_{\pi^+\pi^-} &= \frac{1}{\sqrt{6}}\mathcal{A}_{3/2} + \frac{1}{\sqrt{3}}\mathcal{A}_{1/2}\,, \\
A_{\pi^0\pi^0} &= \frac{1}{\sqrt{3}}\mathcal{A}_{3/2} - \frac{1}{\sqrt{6}}\mathcal{A}_{1/2}\,, \\
A_{\pi^+\pi^0} &= \frac{\sqrt{3}}{2}\mathcal{A}_{3/2}\,.
\end{aligned}
$$

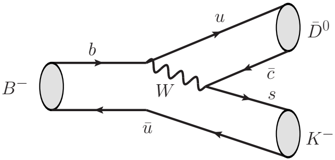
- $D^+ \to \pi^+\pi^0$ purely $\Delta I = 3/2$
- $\Rightarrow$ any CP asymmetry would be NP
- Converse is not true
- Can write down sum rules also for $D \to \rho\pi$, $D \to K^{(*)}\bar{K}^{(*)}\pi(\rho)$, $D_s^+ \to K^*\pi(\rho)$ [Grossman, Kagan, Zupan, PRD 85 (2012) 114036].

Implications for γ from tree decays

γ from tree decays – general idea

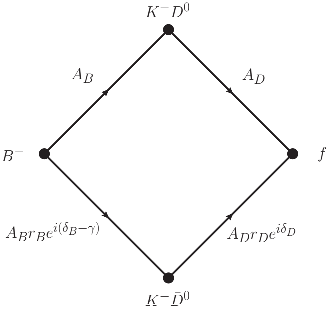


$\propto V_{cb}V_{us}^*$



$\propto V_{ub}V_{cs}^*$

- $b \to c\bar{u}s$, $b \to u\bar{c}s$
- pure tree-level transition
- interference from common D^0, $\bar{D}^0$ final states



Including direct CP violation

[Martone, Zupan 1212.0165; also Wang 2012, Bhattacharya et al. 2013, Bondar et al., 2013]

- B decay amplitude gets modified:

$$A(B^\pm \to f_D K^\pm) = A_B A_f^T \left[1 + r_B^\pm e^{i(\delta_B' \pm \gamma \pm \delta\gamma)}\right]$$

- What is the size of the effect?

$$\delta\gamma = \mathcal{O}(r_f/r_B)\,, \quad \delta_B' - \delta_B = \mathcal{O}(r_f/r_B)\,, \quad r_B^\pm - r_B = \mathcal{O}(r_f)$$

- $r_B(DK) = \mathcal{O}(10\%)\,, \quad \delta\gamma = \mathcal{O}(\text{few}\,\%)$
- $r_B(D\pi) = \mathcal{O}(0.5\%)\,, \quad \delta\gamma = \mathcal{O}(1)$

$$A_{CP}(B \to f_D K) = 2 r_B \sin\delta_B \sin\gamma - a_f^{\text{dir}}$$

Including direct CP violation

- Unknowns: $2n_{\mathrm{SCS}} + 3n_B + 1$
- Observables: $2n_B(n_{\mathrm{CA}} + n_{\mathrm{SCS}})$
- Shift symmetry $\gamma \to \gamma + \phi$, $\alpha_f \to \alpha_f - \phi$:

$$|A(B^\pm \to f_D K^\pm)|^2 = |A_B|^2 \left[|A_f|^2 + 2r_B |A_f||\bar{A}_f| \cos(\delta_B \pm \gamma \pm \alpha_f) + \dots \right]$$

- $\alpha_f \equiv \arg(A_f/\bar{A}_f) = -a_f^{\mathrm{dir}} \cot \delta_f$
- Cannot extract γ from $B \to DK$ alone without assumptions
- Measure δ_f at charm factories, or extract from $D - \bar{D}$ mixing

Summary

- Charm physics is theoretically and experimentally challenging
- Some observables in principle very sensitive to NP
- Important input for B physics

Backup

U-spin decomposition – $\mathcal{O}(1)$

$$
\begin{aligned}
A(\bar{D}^0 \to K^+\pi^-) =& V_{cs} V_{ud}^* \, T (1 - \tfrac{1}{2}\epsilon'_{1T}), \\
A(\bar{D}^0 \to \pi^+\pi^-) =& - V_{cs} V_{us}^* \big[\, T (1 + \tfrac{1}{2}\epsilon_{1T}) - P_{\text{break}} (1 - \tfrac{1}{2}\epsilon_{sd}^{(2)}) \big] \\
& - V_{cb}^* V_{ub} (T/2 (1 + \tfrac{1}{2}\epsilon_{1T}) + P (1 - \tfrac{1}{2}\epsilon_P)), \\
A(\bar{D}^0 \to K^+K^-) =& V_{cs} V_{us}^* \big[\, T (1 - \tfrac{1}{2}\epsilon_{1T}) + P_{\text{break}} (1 + \tfrac{1}{2}\epsilon_{sd}^{(2)}) \big] \\
& - V_{cb}^* V_{ub} (T/2 (1 - \tfrac{1}{2}\epsilon_{1T}) + P (1 + \tfrac{1}{2}\epsilon_P)), \\
A(\bar{D}^0 \to \pi^+K^-) =& V_{cd} V_{us}^* \, T (1 + \tfrac{1}{2}\epsilon'_{1T}).
\end{aligned}
$$

$$
\begin{aligned}
T &= -\frac{1}{2}\big(\langle K^+K^- | C_i (Q_i^{\bar{s}s} - Q_i^{\bar{d}d}) | \bar{D}^0 \rangle - \langle \pi^+\pi^- | C_i (Q_i^{\bar{s}s} - Q_i^{\bar{d}d}) | \bar{D}^0 \rangle \big) \\
&= \langle K^+\pi^- | C_i Q_i^{\bar{d}s} | \bar{D}^0 \rangle = \langle \pi^+K^- | C_i Q_i^{\bar{s}d} | \bar{D}^0 \rangle \sim \mathcal{O}(1)\,.
\end{aligned}
$$

U-spin decomposition – $\mathcal{O}(1/\epsilon')$

$$
\begin{aligned}
A(\bar{D}^0 \to K^+\pi^-) =& V_{cs} V_{ud}^* T(1 - \tfrac{1}{2}\epsilon'_{1T}), \\
A(\bar{D}^0 \to \pi^+\pi^-) =& - V_{cs} V_{us}^* \big[T(1 + \tfrac{1}{2}\epsilon_{1T}) - P_{\text{break}}(1 - \tfrac{1}{2}\epsilon_{sd}^{(2)}) \big] \\
& - V_{cb}^* V_{ub} (T/2(1 + \tfrac{1}{2}\epsilon_{1T}) + P(1 - \tfrac{1}{2}\epsilon_P)), \\
A(\bar{D}^0 \to K^+K^-) =& V_{cs} V_{us}^* \big[T(1 - \tfrac{1}{2}\epsilon_{1T}) + P_{\text{break}}(1 + \tfrac{1}{2}\epsilon_{sd}^{(2)}) \big] \\
& - V_{cb}^* V_{ub} (T/2(1 - \tfrac{1}{2}\epsilon_{1T}) + P(1 + \tfrac{1}{2}\epsilon_P)), \\
A(\bar{D}^0 \to \pi^+K^-) =& V_{cd} V_{us}^* T(1 + \tfrac{1}{2}\epsilon'_{1T}).
\end{aligned}
$$

$$
\begin{aligned}
P &= \langle K^+K^- | C_i Q_i^{\bar{d}d} | \bar{D}^0 \rangle = \langle \pi^+\pi^- | C_i Q_i^{\bar{s}s} | \bar{D}^0 \rangle \sim \mathcal{O}(1/\epsilon')\,, \\
T + P &= \langle K^+K^- | C_i Q_i^{\bar{s}s} | \bar{D}^0 \rangle = \langle \pi^+\pi^- | C_i Q_i^{\bar{d}d} | \bar{D}^0 \rangle \sim \mathcal{O}(1/\epsilon')\,.
\end{aligned}
$$

U-spin decomposition – $\mathcal{O}(\epsilon_U/\epsilon')$

$$
\begin{aligned}
A(\bar{D}^0 \to K^+\pi^-) =& V_{cs}V_{ud}^* T(1 - \tfrac{1}{2}\epsilon'_{1T}),\\
A(\bar{D}^0 \to \pi^+\pi^-) =& - V_{cs}V_{us}^*\big[T(1 + \tfrac{1}{2}\epsilon_{1T}) - P_{\rm break}(1 - \tfrac{1}{2}\epsilon_{sd}^{(2)})\big]\\
& - V_{cb}^*V_{ub}(T/2(1 + \tfrac{1}{2}\epsilon_{1T}) + P(1 - \tfrac{1}{2}\epsilon_P)),\\
A(\bar{D}^0 \to K^+K^-) =& V_{cs}V_{us}^*\big[T(1 - \tfrac{1}{2}\epsilon_{1T}) + P_{\rm break}(1 + \tfrac{1}{2}\epsilon_{sd}^{(2)})\big]\\
& - V_{cb}^*V_{ub}(T/2(1 - \tfrac{1}{2}\epsilon_{1T}) + P(1 + \tfrac{1}{2}\epsilon_P)),\\
A(\bar{D}^0 \to \pi^+K^-) =& V_{cd}V_{us}^* T(1 + \tfrac{1}{2}\epsilon'_{1T}).
\end{aligned}
$$

$$
\begin{aligned}
P_{\rm break} =& \frac{1}{2}\big(\langle K^+K^-|C_i(Q_i^{\bar{s}s} - Q_i^{\bar{d}d})|\bar{D}^0\rangle + \langle\pi^+\pi^-|C_i(Q_i^{\bar{s}s} - Q_i^{\bar{d}d})|\bar{D}^0\rangle\big)\\
& \sim \mathcal{O}(\epsilon_U/\epsilon')\,.
\end{aligned}
$$

U-spin decomposition – $\mathcal{O}(\epsilon_U)$

$$
\begin{aligned}
A(\bar{D}^0 \to K^+\pi^-) =& V_{cs}V_{ud}^* T(1 - \tfrac{1}{2}\epsilon'_{1T}),\\
A(\bar{D}^0 \to \pi^+\pi^-) =& - V_{cs}V_{us}^*\big[T(1 + \tfrac{1}{2}\epsilon_{1T}) - P_{\text{break}}(1 - \tfrac{1}{2}\epsilon_{sd}^{(2)})\big]\\
& - V_{cb}^* V_{ub}(T/2(1 + \tfrac{1}{2}\epsilon_{1T}) + P(1 - \tfrac{1}{2}\epsilon_P)),\\
A(\bar{D}^0 \to K^+K^-) =& V_{cs}V_{us}^*\big[T(1 - \tfrac{1}{2}\epsilon_{1T}) + P_{\text{break}}(1 + \tfrac{1}{2}\epsilon_{sd}^{(2)})\big]\\
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A(\bar{D}^0 \to \pi^+K^-) =& V_{cd}V_{us}^* T(1 + \tfrac{1}{2}\epsilon'_{1T}).
\end{aligned}
$$