Theory of D-meson decays

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14^{th} International Conference on B-Physics at Hadron Machines
Bologna, April 10, 2013

Recent excitement – $\Delta\mathcal{A}_{CP}$

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- (This story hides some details . . . !)

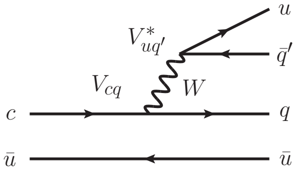
Introduction – Why charm physics?

- "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!
- $D^0 - \bar{D}^0$ system exhibits mixing. Interesting connections to top physics.

Outline

- Hadronic two-body decays
- $D^0 - \bar{D}^0$ mixing
- CP violation, $\Delta\mathcal{A}_{CP}$
- Looking for NP:
  - Sum rules
  - Radiative decays
- Outlook

Hadronic two-body decays



- CKM hierarchy leads to two-generation dominance:

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

- Cabibbo-favored (CF) decays: for instance, $D^0 \to K^-\pi^+$.
- Singly Cabibbo-suppressed (SCS) decays:
  for instance, $D^0 \to \pi^+\pi^-, K^+K^-, K^0\bar{K}^0$; $D^+ \to \pi^+\pi^0$
- Doubly Cabibbo-suppressed (DCS) decays: for instance, $D^0 \to K^+\pi^-$.

Weak effective Hamiltonian

- Effective Field Theory formalism allows to separate long and short distances
- Easy to include large ("leading-log") QCD effects

$$H_{\text{eff}}^{|\Delta C|=1} = \frac{G_F}{\sqrt{2}} \left\{ V_{cp} V_{up'}^* \sum_{i=1,2} C_i Q_i^{\bar{p}p'} - V_{cb} V_{ub}^* \sum_{i=3}^{6} C_i Q_i + C_{8g} Q_{8g} \right\} + \text{h.c.}$$

$$Q_1^{\bar{p}p'} = (\bar{p}c)_{V-A}(\bar{u}p')_{V-A} \qquad Q_2^{\bar{p}p'} = (\bar{p}_\alpha c_\beta)_{V-A}(\bar{u}_\beta p'_\alpha)_{V-A}$$

$$Q_3 = (\bar{u}c)_{V-A} \sum_{q=u,d,s} (\bar{q}q)_{V-A} \qquad Q_4 = (\bar{u}_\alpha c_\beta)_{V-A} \sum_{q=u,d,s} (\bar{q}_\beta q_\alpha)_{V-A}$$

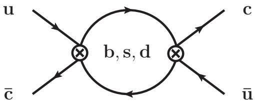
$$Q_5 = (\bar{u}c)_{V-A} \sum_{q=u,d,s} (\bar{q}q)_{V+A} \qquad Q_6 = (\bar{u}_\alpha c_\beta)_{V-A} \sum_{q=u,d,s} (\bar{q}_\beta q_\alpha)_{V+A}$$

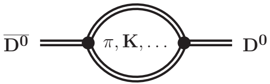
$$Q_{8g} = -\frac{g_s}{8\pi^2} m_c \bar{u} \sigma_{\mu\nu} (1+\gamma_5) c G^{\mu\nu}$$

Hadronic matrix elements

- Wilson coefficients can be computed perturbatively
- Hadronic matrix elements $\langle K\pi|\mathcal{H}_{\text{eff}}|D\rangle$ dominated by nonperturbative QCD
- QCD factorization is expected to work badly, due to large Λ_{QCD}/m_c
- Flavor symmetries ($SU(3)_F$, isospin, U spin ...) can help
- Lattice QCD could compute matrix elements (in the not so near future)

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

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

with eigenvalues

$$M_{H,L} - i\Gamma_{H,L}\,.$$

It is conventional to define

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

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

Can express

$$y = \frac{1}{2\Gamma_D} \sum_n \rho_n [\langle D^0|\mathcal{H}|n\rangle\langle n|\mathcal{H}|\bar{D}^0\rangle + \langle \bar{D}^0|\mathcal{H}|n\rangle\langle n|\mathcal{H}|D^0\rangle] \,,$$

$$x = \frac{1}{\Gamma_D} \left[\langle D^0|\mathcal{H}|\bar{D}^0\rangle + P \sum_n \frac{\langle D^0|\mathcal{H}|n\rangle\langle n|\mathcal{H}|\bar{D}^0\rangle + \langle \bar{D}^0|\mathcal{H}|n\rangle\langle n|\mathcal{H}|D^0\rangle}{M_D^2 - E_n^2} \right] .$$

"Inclusive approach":

- OPE expansion in powers of "Λ/m_c"
- $x \sim y \lesssim 10^{-3}$ [Georgi 1992; Ohl et al. 1993; Bigi et al. 2000]
- Cannot exclude $y \sim 10^{-2}$ [Bobrowski et al. 2010]
- Violation of quark-hadron duality

"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 alone leads to $y \sim 10^{-2}$ [Falk et al. 2002]
- Get $x \sim 10^{-2}$ from a dispersion relation [Falk et al. 2004]

Three types of CP violation

I $|\bar{A}_{\bar{f}}/A_f| \neq 1$ (CP violation in decay)

$$a_f^d := \frac{\Gamma(D \to f) - \Gamma(\bar{D} \to \bar{f})}{\Gamma(D \to f) + \Gamma(\bar{D} \to \bar{f})} = \frac{|A_f|^2 - |\bar{A}_{\bar{f}}|^2}{|A_f|^2 + |\bar{A}_{\bar{f}}|^2}$$

II $|q/p| \neq 1$ (CP violation in mixing)

$$a_{sl} := \frac{\Gamma(\bar{D}^0(t) \to \ell^+ X) - \Gamma(D^0(t) \to \ell^- X)}{\Gamma(\bar{D}^0(t) \to \ell^+ X) + \Gamma(D^0(t) \to \ell^- X)} = \frac{|p/q|^2 - |q/p|^2}{|p/q|^2 + |q/p|^2}$$

III $\mathrm{Im}(\lambda_f) \equiv \mathrm{Im}(\frac{q}{p}\frac{\bar{A}_f}{A_f}) \neq 0$ (interference-type CP violation)

$$a_{f_{CP}} := \frac{\Gamma(\bar{D}^0(t) \to f_{CP}) - \Gamma(D^0(t) \to f_{CP})}{\Gamma(\bar{D}^0(t) \to f_{CP}) + \Gamma(D^0(t) \to f_{CP})}$$

Three types of CP violation

Look at the time-integrated CP asymmetry for final CP eigenstate f

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

Using the experimental constraints x, y, we find the simplified expressions [Grossman et al., PRD 75 (2007) 036008]:

$$a^m = -\frac{y}{2}\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\cos\phi_D \,,$$

$$a^i = \frac{x}{2}\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\sin\phi_D \,,$$

where ϕ_D is the phase of λ_f.

- a^m and a^i are universal to good approximation
- Indirect CP violation is expected to be very small in the SM

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

Let us focus on direct CP violation:

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

r_f relative magnitude of subleading (penguin) amplitude with relative strong phase δ_f, weak phase ϕ_f. Recall

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

(Universal) 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 semileptonic [LHCb-PAPER-2013-003, arXiv:1303.2614]:

$$\Delta\mathcal{A}_{CP} = (+0.49 \pm 0.30 \pm 0.14)\%$$

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

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

leading to new world average (including individual BaBar measurements) [HFAG March 2013]:

$$\Delta\mathcal{A}_{CP} = (-0.329 \pm 0.121)\%$$

$\Delta\mathcal{A}_{CP}$ in the standard model

- Have still almost 3σ evidence for non-zero direct CP violation.
- Estimation of hadronic matrix elements in $m_c \to \infty$ limit ("leading power") yields $\Delta\mathcal{A}_{CP}$ factor 3 below measurement.
- From $SU(3)$ fits [Cheng et al. 1001.0987, 1201.0785; Bhattacharya et al. 1201.2351; Pirtskhalava et al. 1112.5451] we know that power corrections are large.
  Signals breakdown of $1/m_c$ expansion
- Penguin contraction matrix elements can be large [Savage PLB 257 (1991) 414]
- Penguin contractions can account for $\Delta\mathcal{A}_{CP}$ and decay rate difference, with nominal U-spin breaking [Brod et al. PRD 86 (2012) 014023]
- Various groups found at least marginal consistency of old value with SM [Pirtskhalava et al., Feldmann et al., Franco et al., Jung et al. 2011-12]
- New value can likely be accommodated within SM.
- Can still have NP contributions!

SM or NP? – $\Delta I = 3/2$

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

- Tree-level effective Hamiltonian for $D \to \pi\pi$ has both $\Delta I = 1/2$ and $\Delta I = 3/2$ contributions:

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

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

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

- $\Delta I = 3/2$ direct *CP*-violating transitions are absent in SM.
- Isospin breaking effects:
  - Breaking by quark masses and QED is *CP* conserving
  - *CP*-violating contribution of electroweak penguins is down by $\alpha/\alpha_s \approx 1\%$ w.r.t. already small QCD penguin contribution.

SM or NP? – Isospin sum rules for $D \to \pi\pi$

The isospin decomposition of the amplitudes is

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

- $D^+ \to \pi^+\pi^0$ is purely $\Delta I = 3/2$, so any CP asymmetry would be NP.
- The converse is not true: The strong phase could be smaller between the SM and NP $\Delta I = 3/2$ amplitudes than between the $\Delta I = 1/2$ and $\Delta I = 3/2$ amplitudes.

SM or NP? – Isospin sum rules for $D \to \pi\pi$

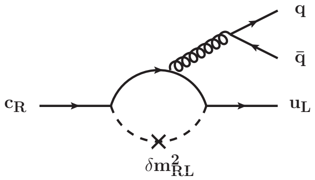
Another test:

$$|A_{\pi^+\pi^-}|^2 - |\bar{A}_{\pi^-\pi^+}|^2 + |A_{\pi^0\pi^0}|^2 - |\bar{A}_{\pi^0\pi^0}|^2 - \frac{2}{3}(|A_{\pi^+\pi^0}|^2 - |\bar{A}_{\pi^-\pi^0}|^2)$$
$$= \frac{1}{2}(|\mathcal{A}_{1/2}|^2 - |\bar{\mathcal{A}}_{1/2}|^2)\,.$$

- If sum is zero, while individual rate differences are nonzero, CP asymmetries are likely dominated by $\Delta I = 3/2$ NP.
- Analogous rules for each polarization state of $D^+ \to \rho^+\rho^0$
- 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].

NP in the gluon penguin

- Isospin rules test only for $\Delta I = 3/2$ NP. What about NP penguins?
- E.g. left-right squark mixing in supersymmetric models [Grossman et al. 2006; Guidice et al., Hiller et al. 2012]



- δ_{LR} contributions to Q_{8g} enhanced by $m_{\tilde{g}}/m_c$
- No such enhancement of $\Delta C = 2$ operators
- Can have $\mathcal{O}(10^{-2})$ effects in a_f^d and still evade bounds from $D^0 - \bar{D}^0$ mixing
- See also overview [Altmannshofer et al., arxiv:1202.2866]

SM or NP? – Radiative decays

Radiative decays can help testing for $\Delta I = 1/2$ NP. [Isidori, Kamenik; arXiv:1205.3164]

First key observation:

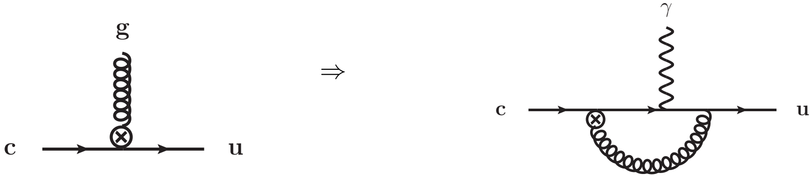
NP models with large chromo-magnetic penguin

$$Q_{8g} = \frac{m_c}{4\pi^2} \bar{u}_L \sigma_{\mu\nu} T^a g_s G_a^{\mu\nu} c_R$$

typically also have large electromagnetic dipole operator

$$Q_{7\gamma} = \frac{m_c}{4\pi^2} \bar{u}_L \sigma_{\mu\nu} Q_u e F^{\mu\nu} c_R \,.$$

Can also be generated by loops (mixing):



SM or NP? – Radiative decays

Second key observation:

$Q_{7\gamma}$ has large matrix element in $D \to (V = \rho^0, \omega)\gamma$ and $D \to (\phi \to K^+K^-)\gamma$.

- Detailed analysis [Isidori, Kamenik; arXiv:1205.3164]: asymmetries as large as

$$\approx 10\%\,, \quad D \to \rho^0\gamma\,, D \to \omega\gamma\,;$$
$$\approx 2\%\,, \quad D \to K^+K^-\gamma \,\text{(above } \phi \text{ resonance).}$$

- One order of magnitude above SM
- Caveat: strong phases might be small.

Summary and outlook

- Charm physics is theoretically and experimentally challenging
- Some observables in principle very sensitive to NP
- Full of surprises
- Many more modes which I did not talk about:
  - $D^+ \to \ell^+ \nu$ helicity suppressed. $\text{Br}(D^+ \to e^+ \nu) = \mathcal{O}(10^{-8})$
  - $D^0 \to \mu^+ \mu^-, e^+ e^-, \gamma\gamma$ FCNC transitions, long-distance dominated in SM. $\text{Br}(D^0 \to \mu^+ \mu^-) \sim 3 \times 10^{-13}$, $\text{Br}(D^0 \to \gamma\gamma) \sim 10^{-8}$
  - $D^0 \to \mu^\pm e^\mp$ forbidden in the SM

Backup

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

Understand the basics of $D^0 - \bar{D}^0$ mixing in terms of flavor symmetries
[Georgi, PLB 297 (1992) 353]

- $SU(6)_L \times SU(6)_R \times U(1)$ symmetry of massless QCD with six quarks broken by m_t, m_b, m_c, as well as γ, Z to approximate $SU(2)_{D_L} \times SU(2)_{D_R}$
- Write $\Delta C = 1$ Hamiltonian as

$$H_{\text{eff}} = \frac{G_F}{\sqrt{2}} (\bar{\psi}_L \gamma^\mu u_L) \ \boldsymbol{\kappa} \cdot \boldsymbol{\tau} \ (\bar{c}_L \gamma^\mu \psi_L)$$

where

$$\psi_L = \begin{pmatrix} s_L \\ d_L \end{pmatrix}, \quad \boldsymbol{\kappa} = \frac{1}{2} \begin{pmatrix} \cos^2\theta_c - \sin^2\theta_c \\ i \\ 2\cos\theta_c \sin\theta_c \end{pmatrix}, \quad \tau^i = \frac{1}{2}\sigma^i, \quad \cos\theta_c \equiv |V_{us}|.$$

- $\Delta C = 1$ Hamiltonian proportional to $\boldsymbol{\kappa}$
- $\boldsymbol{\kappa} \cdot \boldsymbol{\kappa} = 0 \Rightarrow$ GIM suppression of $D - \bar{D}$ mixing

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

- Need symmetry-breaking spurion $\mathbf{A}$ to form nonvanishing $(\mathbf{A} \cdot \boldsymbol{\kappa})(\mathbf{A} \cdot \boldsymbol{\kappa})$.
- Related to mass matrix

$$\mathcal{M} = \begin{pmatrix} m_s & 0 \\ 0 & m_d \end{pmatrix} .$$

- At short distances, $\mathcal{M}$ transforms as (2,2) under $SU(2)_{D_L} \times SU(2)_{D_R}$.
- Breaking is proportional to $SU(2)_{D_R}$ singlet combination

$$\mathbf{A} \propto \mathrm{tr}(\tau^3 \mathcal{M} \mathcal{M}^\dagger) = m_s^2 - m_d^2 \approx m_s^2 .$$

- At long distances, can form U-spin triplet $\mathcal{M}\Sigma^\dagger$ from chiral condensate Σ
- Can have larger contributions $\propto m_s^2$
- Can show from $SU(3)_{\text{flavor}}$ that breaking starts indeed with m_s^2
  [Falk et al., PRD 65 (2002) 054034]