$D^0 - \overline{D}^0$ mixing in the SM (not assuming $m_c \gg \Lambda_{\rm QCD}$)

Zoltan Ligeti

- Introduction
- Group theory, long and short distance
- Numerical estimates and caveats

See: A. Falk, Y. Grossman, Z.L., A. Petrov, PRD **65** (2002) 054034 [hep-ph/0110317]
A. Falk, Y. Grossman, Z.L., Y. Nir, A. Petrov, PRD **69** (2004) 114021 [hep-ph/0402204]
S. Bergmann, Y. Grossman, Z.L., Y. Nir, A. Petrov, PLB **486** (2000) 418 [hep-ph/0005181]

déjà vu

Preliminaries

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  Alexey was right, and I remembered wrong... I can only guess that I only read "charm" in his email when accepting to give this talk

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- The good news is that all of you probably forgot those talks, just like I have...

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... unfortunately fixed eventually

First page of my last talk (CERN, 2003)

Summary

It is usually stated that $D^0 - \overline{D}^0$ mixing is small in the SM and therefore sensitive to new physics; i.e., $\Delta M, \Delta\Gamma \lesssim$ few $\times 10^{-3}\,\Gamma$ in the SM, and NP can easily enhance ΔM but would not affect $\Delta\Gamma$

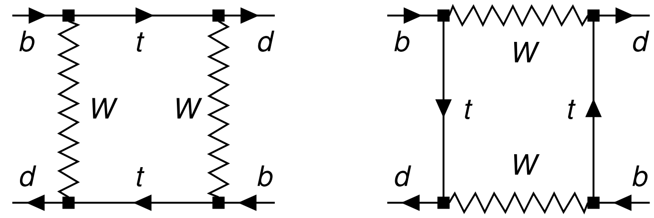
In this talk I argue that:

- It is likely that the SM predicts $\Delta\Gamma \sim 1\%$
- Then it is likely that $\Delta\Gamma > \Delta M$ in the SM
- If this is the case then the sensitivity to NP is reduced
- The central values of recent experimental results may be due to SM physics

Differences between B and D mixing

- Evolution: $i\,\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}|B^0(t)\rangle \\ |\overline{B}^0(t)\rangle\end{pmatrix} = \left(M - \frac{i}{2}\,\Gamma\right)\begin{pmatrix}|B^0(t)\rangle \\ |\overline{B}^0(t)\rangle\end{pmatrix}$

  $M,\ \Gamma$: 2×2 Hermitian matrices



  Mass eigenstates: $|B_{H,L}\rangle = p|B^0\rangle \mp q|\overline{B}^0\rangle$ $\qquad |B_{H,L}(t)\rangle = e^{-(iM_{H,L}+\Gamma_{H,L}/2)t}\,|B_{H,L}\rangle$

- General solution for q/p:

$$\frac{q^2}{p^2} = \frac{2M_{12}^* - i\Gamma_{12}^*}{2M_{12} - i\Gamma_{12}}$$

- $B^0_{d,s}$: $|\Gamma_{12}| \ll |M_{12}|$ model independently, so $q/p = e^{iX}$ to a good approximation

  X determined by M_{12} (up to phase conventions) $\Rightarrow$ sensitive to NP

- D^0: $|\Gamma_{12}/M_{12}| = \mathcal{O}(1)$, so q/p depends on both Γ_{12} and M_{12}

- In the D^0 system, $|q/p| - 1$ is much less constrained than in B^0 and K^0 mixing

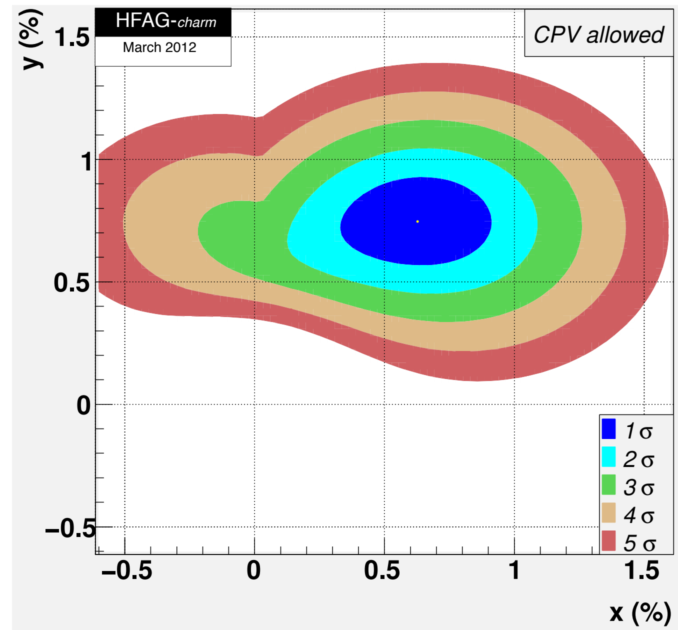
D^0: mixing in up sector

- Complementary to K, B: CPV, FCNC both GIM & CKM suppressed $\Rightarrow$ tiny in SM

- 2007: observation of mixing, now $\gtrsim 10\sigma$ [HFAG combination]

  Only meson mixing generated by down-type quarks (SUSY: up-type squarks)

  SM suppression: $\Delta m_D, \Delta\Gamma_D \lesssim 10^{-2}\,\Gamma$, since doubly-Cabibbo-suppressed & vanish in $SU(3)$ limit



- $y = (0.75 \pm 0.12)\%$ and $x = (0.63 \pm 0.20)\%$
  ... suggest long distance dominance

- How small CPV would unambiguously establish NP?

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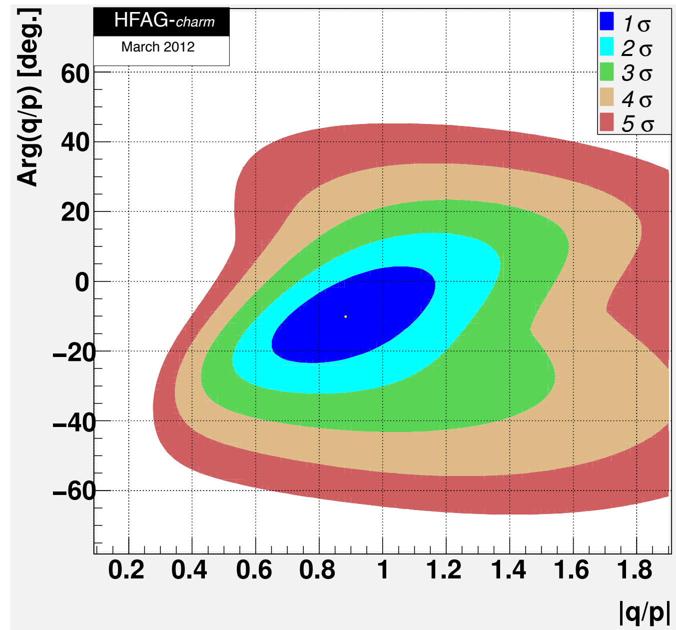

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- How small CPV would unambiguously establish NP?

Don't known yet if $|q/p|$ is near 1!

- Strong motivation to look for non-SM flavor and CP violation in c and t decays

  Can discover or rule out classes of well motivated models

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

$SU(3)$ analysis of D mixing

- Want to study: $\langle \overline{D}^0 | T\{H_w, H_w\} | D^0 \rangle = \langle 0 | D\, T\{H_w, H_w\} D | 0 \rangle$

  the field operator $D \in 3$ creates a D^0 or annihilates a $\overline{D}^0$

  $H(\Delta C = -1) = (\bar{q}_i\, c)(\bar{q}_j\, q_k) \in 3 \times \overline{3} \times \overline{3} = \overline{15} + 6 + \overline{3} + \overline{3}$

  Neglecting 3rd generation, only $\overline{15}$ and 6 appear in H ($\overline{3}$ = "penguins")

  $SU(3)$ breaking is introduced by $\mathcal{M}^i_j = \text{diag}(m_u, m_d, m_s) \sim \text{diag}(0, 0, m_s)$

- A pair of D operators is symmetric, so $D_i D_j \in 6$

  A pair of H is symmetric, so $H^{ij}_k H^{lm}_n \in \left[(\overline{15} + 6) \times (\overline{15} + 6)\right]_S \to \overline{60} + 42 + 15'$

  0. Since $\overline{6} \notin H_w H_w \;\Rightarrow\;$ mixing vanishes in $SU(3)$ limit
  1. $DD\mathcal{M} \in 6 \times 8 = 24 + \overline{15} + 6 + \overline{3} \;\Rightarrow\;$ no invariants with HH at $\mathcal{O}(m_s)$
  2. $DD\mathcal{M}\mathcal{M} \in 6 \times (8 \times 8)_S = 6 \times (27 + 8 + 1) = 60 + \overline{24} + \overline{15'} + \ldots$

  $\Rightarrow$ **D^0–$\overline{D}^0$ mixing only arises at $\mathcal{O}(m_s^2)$**

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Operator product expansion for D mixing

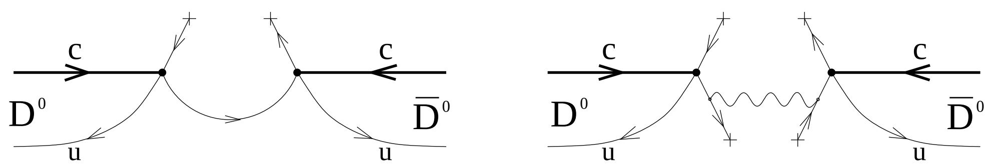
- It is hard to estimate x, y in the SM: vanish in the $SU(3)$ limit and doubly Cabibbo suppressed: $x, y \sim \sin^2\theta_C\, \epsilon^2_{SU(3)}$

  Short distance box diagram: $x \propto \dfrac{m_s^2}{m_W^2} \times \dfrac{m_s^2}{m_c^2} \to 10^{-5}$ (4-quark operator)

  y has additional m_s^2/m_c^2 helicity suppression

- Higher orders in OPE suppressed by fewer powers of m_s [Georgi '92; Ohl, Ricciardi, Simmons '93]

	4-quark	6-quark	8-quark
$\dfrac{\Delta M}{\Delta M_{\rm box}}$	1	$\dfrac{\Lambda^2}{m_s m_c}$	$\dfrac{\Lambda^4}{m_s^2 m_c^2}\,\dfrac{\alpha_s}{4\pi}$
$\dfrac{\Delta\Gamma}{\Delta M}$	$\dfrac{m_s^2}{m_c^2}$	$\dfrac{\alpha_s}{4\pi}$	$\dfrac{\alpha_s}{4\pi}\,\beta_0$



[Bigi & Uraltsev claimed ('00) that $x, y \propto m_s$ is possible; ... In conflict with our general proof from group theory]

- Dim. analysis $(\Lambda \sim 4\pi f_\pi)$ and estimates of matrix elements [Golowich & Petrov, Bobrowski *et al.*] give significant enhancements but still yield $x, y \lesssim 10^{-3}$

Long distance contributions to D mixing

- Maybe large, but hard to estimate — $SU(3)$ breaking has been argued to be $\mathcal{O}(1)$, based on $\mathcal{B}(D^0 \to K^+K^-)/\mathcal{B}(D^0 \to \pi^+\pi^-) \simeq 2.8$

  Cancellations sensitively depend on poorly known strong phases and DCS rates:

  $$y \approx \mathcal{B}(D \to \pi^+\pi^-) + \mathcal{B}(D \to K^+K^-) - 2\cos\delta\,\sqrt{\mathcal{B}(D \to K^-\pi^+)\,\mathcal{B}(D \to K^+\pi^-)}$$

  Current central values yield: $y \approx (5.36 - 4.78\cos\delta) \times 10^{-3}$

  In the $SU(3)$ limit $\cos\delta \sim 1$, and assuming that these intermediate states are representative, it was often stated that $x \lesssim y <$ few $\times 10^{-3}$

- The most important long distance effect may be due to phase space:
  - Contrary to $SU(3)$ breaking in matrix elements, this source of $SU(3)$ violation is calculable for certain final states with mild assumptions
  - Negligible for lightest PP states; important for states with mass near m_D

The saga whether m_c is heavy or light?

- Heavy quark limit works reasonably well for inclusive semileptonic charm decay
- Worse behavior expected for nonleptonic decays (confirmed by lifetime data)
- Recent ΔA_{CP} data $+$ growing literature on theorists' inability to unambiguously conclude (yet?) if central value would imply NP

  An enhancement as large as $\Delta I = \frac{1}{2}$ rule in K decay would be surprising
- If heavy quark limit is completely broken down at $\mu = m_c$, even limited successes at $\mu = m_b \sim 3m_c$ would be surprising

  Theory for $B \to D\pi$ uses $m_{c,b} \gg \Lambda_{\rm QCD}$ [relation of phases in $B \to D\pi$ & $D^*\pi$]
- Phase space differences are "threshold effects" — exponentially suppressed in the formal heavy quark limit, not included by dimension-9 and 12 terms in OPE

$\Delta\Gamma$ from $SU(3)$ breaking in phase space

- Phase space difference between final states containing fewer or more s quarks is a calculable source of $SU(3)$ breaking

- Let F_R denote final state F in representation R (e.g., PP can be in 8 or 27)

  Define: $$y_{F,R} = \frac{\sum_{n\in F_R} \langle \overline{D}^0 | H_w | n \rangle \rho_n \langle n | H_w | D^0 \rangle}{\sum_{n\in F_R} \Gamma(D^0 \to n)}$$

  This is the "would-be" value of y, if D only decayed to the states in F_R

- If the decay rates to all representations are known, we can reconstruct the value of y from $y_{F,R}$:

$$y = \frac{1}{\Gamma} \sum_{F,R} y_{F,R} \left[\sum_{n\in F_R} \Gamma(D^0 \to n) \right]$$

Simplest example: $D^0 \to PP$

- PP must be in $(8 \times 8)_S = 27 + 8 + 1$ — possible amplitudes:
  - $PP \in 27$ and $\mathcal{H}_w \in \overline{15}$: $A_{27}\,(PP_{27})^{km}_{ij}\,H^{ij}_k\,D_m$
  - $PP \in 8$ and $\mathcal{H}_w \in \overline{15}$: $A_8^{\overline{15}}\,(PP_8)^k_i\,H^{ij}_k\,D_j$
  - $PP \in 8$ and $\mathcal{H}_w \in 6$: $A_8^6\,(PP_8)^k_i\,H^{ij}_k\,D_j$

  } proportional to each other

  So effectively there are only two amplitudes — for example, we obtain for $y_{PP,8}$:

$$s_1^2 \left[\frac{1}{2}\,\Phi(\eta,\eta) + \frac{1}{2}\,\Phi(\pi^0,\pi^0) + \frac{1}{3}\,\Phi(\eta,\pi^0) + \Phi(\pi^+,\pi^-) + \Phi(K^+,K^-) - \frac{1}{6}\,\Phi(\eta,K^0) - \frac{1}{6}\,\Phi(\eta,\bar{K}^0) - \Phi(K^+,\pi^-) - \Phi(K^-,\pi^+) - \frac{1}{2}\,\Phi(K^0,\pi^0) - \frac{1}{2}\,\Phi(\bar{K}^0,\pi^0)\right] \times \left[\frac{1}{6}\,\Phi(\eta,\bar{K}^0) + \Phi(K^-,\pi^+) + \frac{1}{2}\,\Phi(\bar{K}^0,\pi^0) + \mathcal{O}(s_1^2)\right]^{-1}$$

- Result is explicitly proportional to $s_1^2 \equiv \sin^2\theta_C$ and vanishes in $SU(3)$ limit as m_s^2

Two-body final states

Final state representation		$y_{F,R}/s_1^2$
(PP) s-wave	$\mathbf{8}$	-0.0038
	$\mathbf{27}$	-0.00071
(PV) p-wave	$\mathbf{8}_S$	0.031
	$\mathbf{8}_A$	0.032
	$\mathbf{10}$	0.020
	$\overline{\mathbf{10}}$	0.016
	$\mathbf{27}$	0.040
(VV) s-wave	$\mathbf{8}$	-0.081
	$\mathbf{27}$	-0.061
(VV) p-wave	$\mathbf{8}$	-0.10
	$\mathbf{27}$	-0.14
(VV) d-wave	$\mathbf{8}$	0.51
	$\mathbf{27}$	0.57

Results for lightest multiplets, assuming no $SU(3)$ breaking in matrix elements

Contribution of PP final states is "anomalously" small

Widths of vector mesons are important and taken into account (straightforward)

PV and VV channels effectively include resonant part of 3- and 4-body final states

Larger $SU(3)$ breaking expected in heavier multiplets when some final states are not allowed at all

Multi-body final states

Final state representation		$y_{F,R}\,/\,s_1^2$
$(3P)_s$-wave	$\mathbf{8}$	-0.48
	$\mathbf{27}$	-0.11
$(3P)_p$-wave	$\mathbf{8}$	-1.13
	$\mathbf{27}$	-0.07
$(3P)$form-factor	$\mathbf{8}$	-0.44
	$\mathbf{27}$	-0.13
$4P$	$\mathbf{8}$	3.3
	$\mathbf{27}$	2.2
	$\mathbf{27'}$	1.9

Consider simplest representations only

Smaller representations tend to give larger effects

Assuming a "form factor suppression" in the matrix element, $\Pi_{i\neq j}(1-m_{ij}^2/Q^2)^{-1}$, where $m_{ij}^2 = (p_i + p_j)^2$ and $Q = 2\,\mathrm{GeV}$, changes the results only moderately

For $4P$, only consider fully symmetric final state

- For many final state representations, especially those close to threshold, "large" effects are possible, i.e., $y_{F,R}$ at the percent level is not unusual

Conclusions for $\Delta\Gamma$

- The 2-, 3-, and 4-body final states account for a large fraction of the D width

  Rounded to nearest 5%:

Final state	fraction
PP	5%
PV	10%
$(VV)_{s\text{-wave}}$	5%
$(VV)_{d\text{-wave}}$	5%
$3P$	5%
$4P$	10%

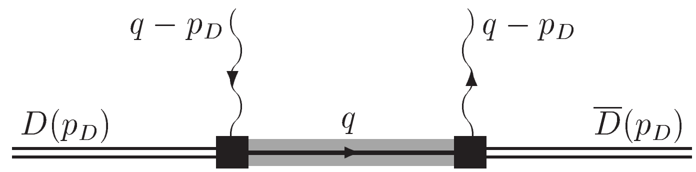
  There are other large rates near threshold, e.g.: $\mathcal{B}(D^0 \to K^- a_1^+) = (7.8 \pm 1.1)\%$

- There are final states that can contribute to y at the 1% level
- It would require cancellations to suppress y much below 1%

Dispersion relation for Δm_D

- Consider correlator (Only physical at $q = p_D$)

$$\Sigma_{p_D}(q) = i \int \mathrm{d}^4 z \langle \overline{D}(p_D) | T[\mathcal{H}(z)\mathcal{H}(0)] | D(p_D) \rangle \, e^{i(q-p_D)\cdot z}$$



- Can show, going over to HQET that

[See also: Grinstein, hep-ph/0112323]

$$\Delta m_D = -\frac{1}{2\pi} \, \mathrm{P} \int_{2m_\pi}^{\infty} \mathrm{d}E \, \frac{\Delta\Gamma(E)}{E - m_D} \left[1 + \mathcal{O}\left(\frac{\Lambda_{\mathrm{QCD}}}{E} \right) \right]$$

  Allows using the phase space model for $\Delta\Gamma$ to make a prediction for Δm_D

  Need assumptions about behavior of form factors; larger uncertainty than for $\Delta\Gamma$

  Concentrating on the $4P$ final states, we wrote:

  "if y is in the ballpark of $+1\%$ as expected if the $4P$ final states dominate y, then we should expect $|x|$ between 10^{-3} and 10^{-2}, and that x and y are of opposite sign."

- Clearly, we cannot predict the sign of x/y, only draw qualitative conclusions

Conclusions

- Identified a calculable source of long distance effects, and predicted that y and x can naturally be at the 1% level in the SM, without ad hoc assumptions
- I would like to see single measurements of y and especially x reach 5σ; $x/y = ?$
- Look for CP violation in mixing, which remains a potentially robust signal of NP
- There is still a lot to be learned from future data!


Exciting journey ahead!