Theory introduction to charm physics

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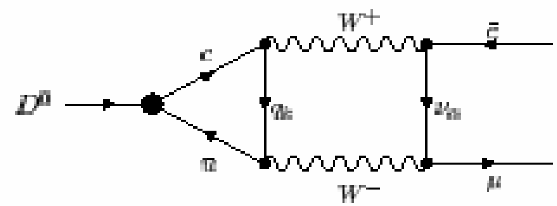
1. Charm transitions serve as excellent probes of New Physics

    1. Processes forbidden in the Standard Model to all orders (or very rare)

        Examples: $D^0 \to \mu^+ e^-$



    2. Processes forbidden in the Standard Model at tree level

        Examples: $D^0 - \overline{D^0}$ mixing, $D \to X\gamma$, $D \to X\nu\bar{\nu}$

    3. Processes allowed in the Standard Model

        Examples: relations, valid in the SM, but not necessarily in general

2. Provide unique QCD laboratory

Start from the bottom…

Introduction

Murphy's law:

Modern charm physics experiments acquire ample statistics; many decay rates are quite large.

THUS:

It is very difficult to provide model-independent theoretical description of charmed quark systems.

2. Charm Spectroscopy

- HQL: Charm spectroscopy is “simple”

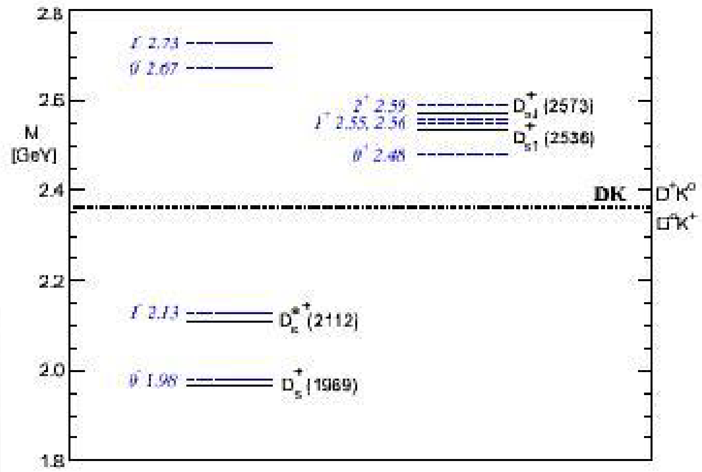
$$\vec{S} = \vec{J}_l + \vec{S}_Q, \quad \vec{J}_l = \vec{S}_l + \vec{L}_l$$

good quantum numbers — decouples

- All states appear as doublets classified by parity and spin of light DoF:

$$S^P = J_l^P \pm \frac{1}{2}$$

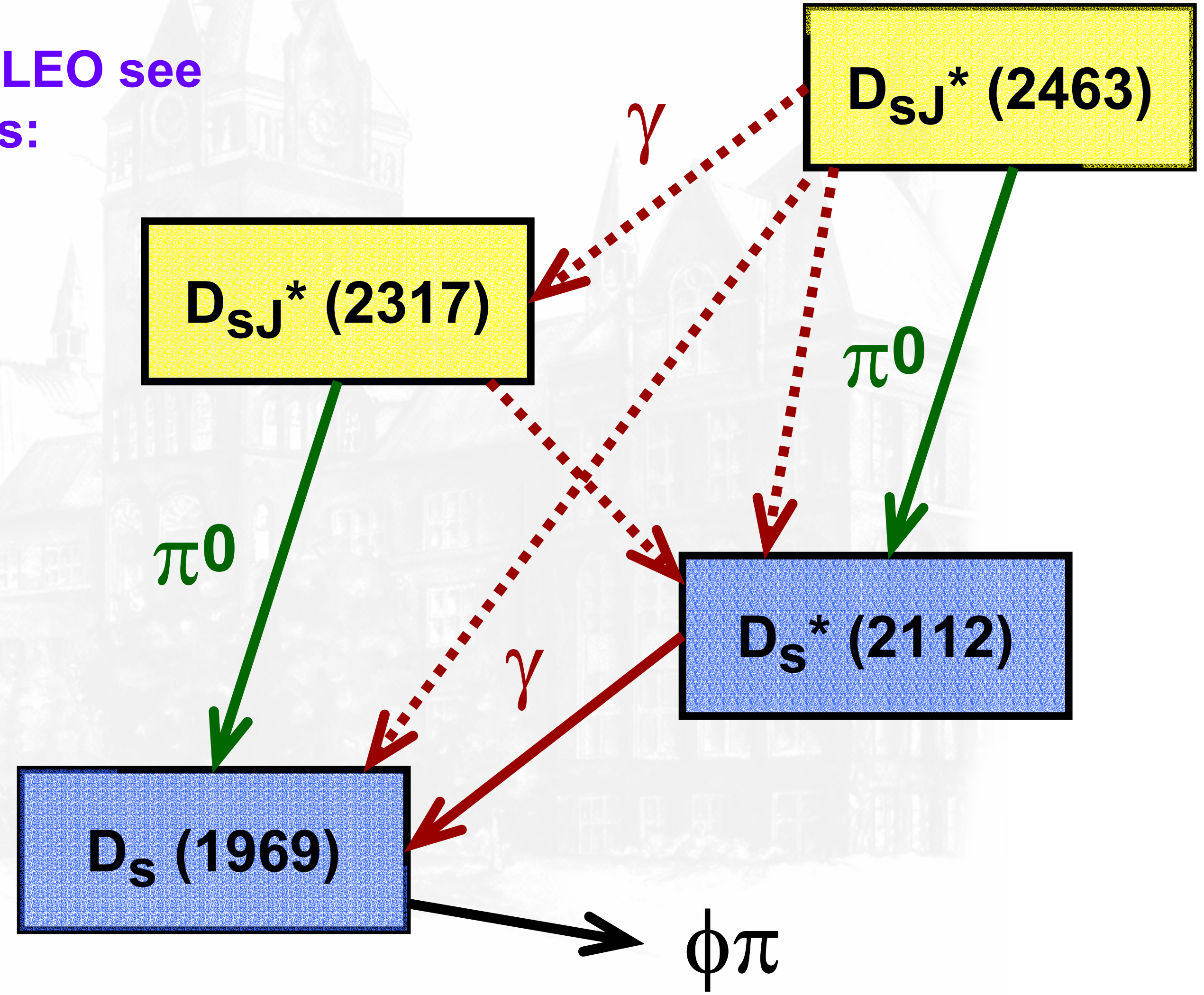
L	0	1		2	
J_l	1/2	1/2	3/2	3/2	5/2
S	0,1	0,1	1,2	1,2	2,3



Spin			Exp. Data, MeV	
J_l^P	S^P	state	M	Γ
$1/2^-$	0^-	D_s	1969	0.49 ps
	1^-	D_s^*	2110	<1.9
$1/2^+$	0^+	D_0^*		
	1^+	D_1'		
$3/2^+$	1^+	D_{s1}	2536	<2.3
	2^+	D_{s2}	2572	15

Charm Spectroscopy: new states

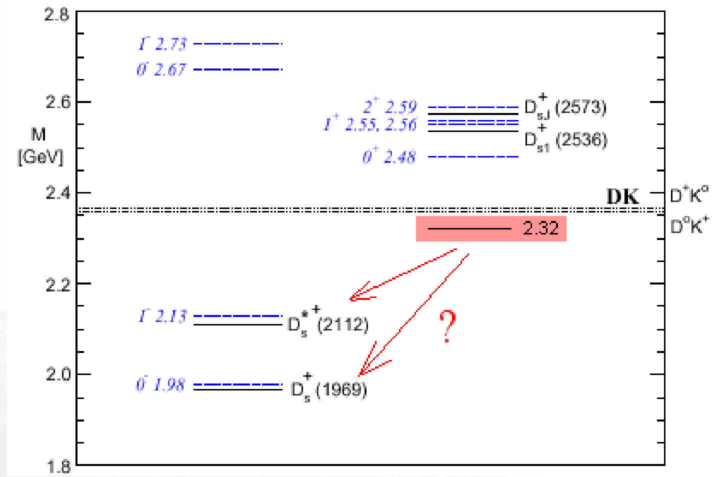
- BaBar/Belle/CLEO see new D_{sJ}^* states:



Charm Spectroscopy: problem?

- BaBar/Belle/CLEO report new D_{sJ} states

$$D_{sJ}^{*}(2317) \to D_s\, \pi^0,\; D_{sJ}(2463) \to D_s^{*}\, \pi^0$$
$$\not\to D_s^{*}\gamma,\; D_s^{*}\gamma\gamma,\; D_s\pi^+\pi^-$$



- Interpretation? 0^+ and 1^+ p-wave Qq states?

Possible problems:

1. Mass is too low?
2. Width is too narrow?

} non-Qq state?

Barnes, Close, Lipkin; Szczepaniak, Bali

4-quark ("baryonium") state

- DK or Dπ molecule?
  1. mass is naturally in the vicinity of DK threshold
  2. since $M(D_{sJ}(2130)) < M(D+K)$ width is naturally small

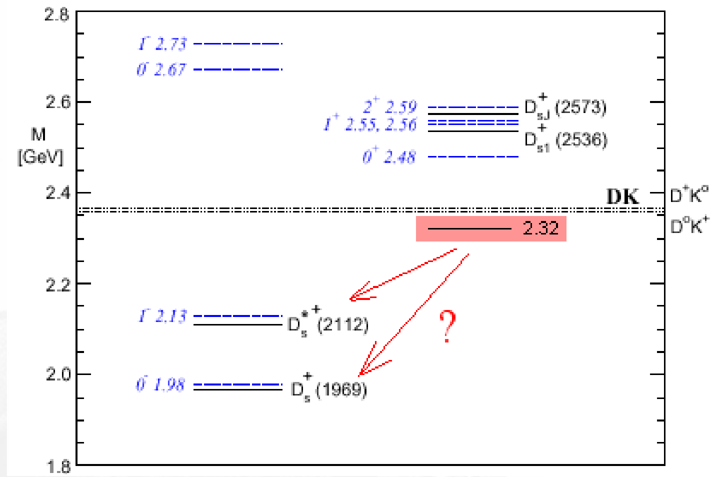
Charm Spectroscopy: problem?

- BaBar/Belle/CLEO report new D_{sJ} states

$$D_{sJ}^{*}(2317) \to D_s \pi^0,\ D_{sJ}(2463) \to D_s^{*} \pi^0$$

$$\not\to D_s^{*}\gamma,\ D_s^{*}\gamma\gamma,\ D_s \pi^+ \pi^-$$

- Interpretation? 0^+ and 1^+ p-wave Qq states!



Possible problems:

1. Mass is too low?
2. Width is too narrow?

Broken chiral symmetry: positive parity-partners of D_s D_s^*

Bardeen, Eichten, Hill

Reference	***Mass***
Ebert et. al. (98)	2.51 GeV
Godfrey-Isgur (85)	2.48 GeV
DiPierro-Eichten (01)	2.49 GeV
Gupta-Johnson (95)	2.38 GeV
Zeng et. al. (95)	2.38 GeV

Charm Spectroscopy

New states:

1. **Why is** $M(D_{sJ}^{*}(2130)) < M\ (D+K)$ and
   $M(D_{sJ}^{*}(2130)) < M\ (D^{*}+K)$?

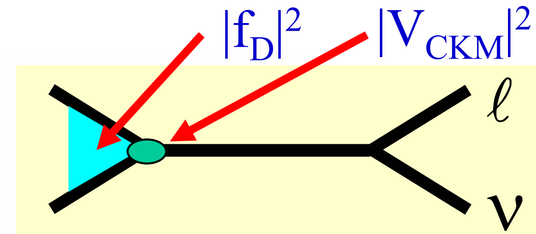
   Van Beveren and Rupp

2. **Interpretation? Radiative decays?**

   Godfrey; Colangelo and De Fazio

3. **Similar states in D and B systems?**

3. Leptonic and semileptonic decays



Form-factors and decay constants

- Heavy quark symmetry relates observables in B and D transitions

Example 1: decay constants

$$\langle 0|A_\mu(0)|X(p)\rangle = f_X p_\mu$$

HQS requires:

$$\frac{f_B}{f_D} = \sqrt{\frac{M_D}{M_B}} + O(1/M)$$

Large!

HQS+Chiral symmetry:

$$\frac{f_{B_s}/f_B}{f_{D_s}/f_D} = 1 + O(m_s) \times O(1/m_b - 1/m_c)$$

$$\frac{\Delta M_d}{\Delta M_s} \propto \left[\frac{\sqrt{B_{B_d}}\, f_{B_d}}{\sqrt{B_{B_s}}\, f_{B_s}}\right]^2 \left[\frac{|V_{td}|}{|V_{ts}|}\right]^2$$

$$\frac{f_{D_s}}{f_D} = 1 - \frac{5}{6}\left(1+3g^2\right)\frac{M_K^2}{16\pi^2 f^2}\log\left[M_K^2/\mu^2\right] + \ldots$$

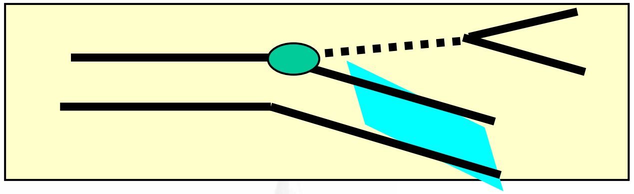
$D^* D\pi$ coupling constant

- CLEO-c is expected to provide accurate measurements

	Reaction	CLEO-c CM Energy (MeV)	L fb^{-1}	PDG	CLEO-c
f_{Ds}	$D_s^+ \to \mu\nu$	4140	3	17%	1.7%
f_{Ds}	$D_s^+ \to \tau\nu$	4140	3	33%	1.6%
f_{D+}	$D^+ \to \mu\nu$	3770	3	UL	2.3%

- If charm production data is used to obtain V_{cs} ($\delta V_{cs}/V_{cs} \sim 1.3\%$), the ratio gives information about decay constants
  - input for lattice calculations

$|V_{CKM}|^2 \; |f_+(q^2)|^2$



Form-factors and decay constants

- Heavy quark symmetry relates observables in B and D transitions

Example 2: decay form-factors

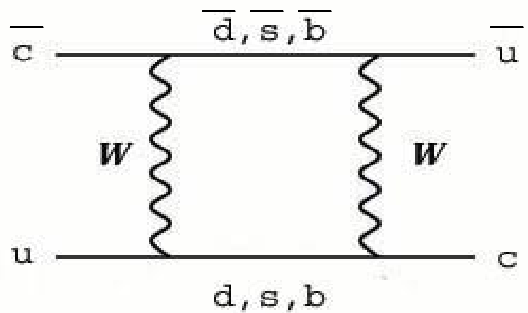
$$\langle P | j_\mu | X(p) \rangle = f_+^{XP}\left(q^2\right)\left(p_X + p_P\right)_\mu + f_-^{XP}\left(q^2\right)\left(p_X - p_P\right)_\mu$$

- If charm production data is used to obtain V_{cs} ($\delta V_{cs}/V_{cs} \sim 1.3\%$), the ratio gives information about decay form factors

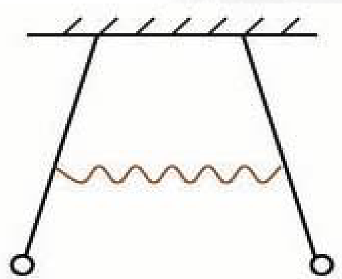
$$\frac{d\Gamma}{dq^2} = \frac{G_F^2}{24\pi^3} |V_{cs}|^2 \, p_K^3 \, |f_+(q^2)|^2$$

- q^2 shape can be measured
- input for lattice calculations

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



D-D mixing



Coupled oscillators

$\Delta Q=2$: only at one loop in the Standard Model: possible new physics particles in the loop

$\Delta Q=2$ interaction couples dynamics of D^0 and $\overline{D}^0$

$$\left| D(t) \right\rangle = \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = a(t)\left| D^0 \right\rangle + b(t)\left| \overline{D^0} \right\rangle$$

- Time-dependence: coupled Schrödinger equations

$$i\frac{\partial}{\partial t}\left| D(t) \right\rangle = \left(M - \frac{i}{2}\Gamma \right)\left| D(t) \right\rangle = \begin{bmatrix} A & p^2 \\ q^2 & A \end{bmatrix}\left| D(t) \right\rangle$$

- Diagonalize: mass eigenstates $\neq$ flavor eigenstates

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

Mass and lifetime differences of mass eigenstates: $x = \dfrac{M_2 - M_1}{\Gamma}, \; y = \dfrac{\Gamma_2 - \Gamma_1}{2\Gamma}$

CP violation in charm

- Possible sources of CP violation in charm:
  - CPV in decay amplitudes ("direct" CPV)

$$A\left(D \to f\right) \neq A\left(\overline{D} \to \overline{f}\right)$$

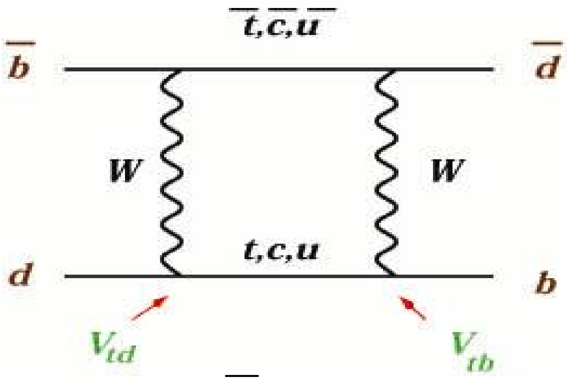
  - CPV in $D^0 - \overline{D^0}$ mixing matrix

$$R_m^2 = \left|\frac{p}{q}\right|^2 = \frac{2M_{12} - i\Gamma_{12}}{2M_{12}^* - i\Gamma_{12}^*} \neq 1$$

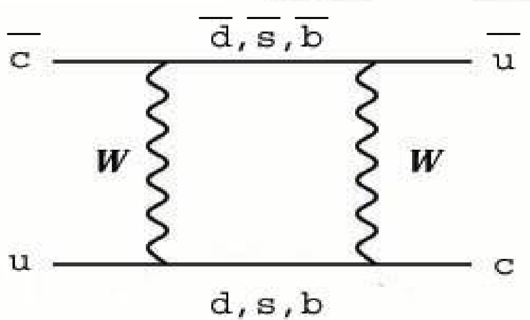
  - CPV in the interference of decays with and without mixing

$$\lambda_f = \frac{q}{p}\frac{\overline{A_f}}{A_f} = R_m e^{i(\phi+\delta)}\left|\frac{\overline{A_f}}{A_f}\right|$$

Mixing: why do we care?



B-$\overline{B}$ mixing



D-$\overline{D}$ mixing

$\overline{D^0} - D^0$ mixing	$\overline{B^0} - B^0$ mixing
• intermediate down-type quarks • SM: b-quark contribution is negligible due to V_{ub} • $rate \propto f(m_s) - f(m_d)$ (zero in the SU(3) limit) **Falk, Grossman, Ligeti, A.A.P. (Phys.Rev. D65, 054034, (2002)): 2nd order in SU(3) breaking!!!**	• intermediate up-type quarks • SM: t-quark contribution is dominant • $rate \propto m_t^2$ (expected to be large)
1. Sensitive to long distance QCD 2. Small in the SM: New Physics! (must know SM x and y)	1. Computable in QCD (*) 2. Large in the SM: CKM!

(*) up to matrix elements of 4-quark operators

How would new physics affect mixing?

- Look again at time development:

$$i\frac{\partial}{\partial t}\left|D(t)\right\rangle = \left(M - \frac{i}{2}\Gamma\right)\left|D(t)\right\rangle = \begin{bmatrix} A & p^2 \\ q^2 & A \end{bmatrix}\left|D(t)\right\rangle$$

- Expand $\overline{D^0} - D^0$ mass matrix:

$$\left(M - \frac{i}{2}\Gamma\right)_{ij} = m_D^{(0)}\delta_{ij} + \frac{1}{2m_D}\left\langle D_i^0\right| H_W^{\Delta C=2}\left|D_j^0\right\rangle + \frac{1}{2m_D}\sum_I \frac{\left\langle D_i^0\right| H_W^{\Delta C=1}\left|I\right\rangle\left\langle I\right| H_W^{\Delta C=1}\left|D_j^0\right\rangle}{m_D^2 - m_I^2 + i\varepsilon}$$

Local operator, affects x, possible **new phsyics**

Real intermediate states, affect both x and y ⇒ **Standard Model**

1. $x >> y$: signal for New Physics?
   $x \approx y$: Standard Model?

2. CP violation in mixing/decay

   new CP-violating phase ϕ

With b-quark contribution neglected: only **2** generations contribute
⇒ **real 2x2 Cabibbo matrix**

Experimental constraints

1. Time-dependent $D^0(t) \to K^+\pi^-$ analysis

$$\Gamma\left[D^0(t) \to K^+\pi^-\right] = e^{-\Gamma t}\left|A_{K^+\pi^-}\right|^2\left[R + \sqrt{R}R_m\left(y'\cos\phi - x'\sin\phi\right)\Gamma t + \frac{R_m^2}{4}\left(y^2+x^2\right)(\Gamma t)^2\right]$$

Sensitive to DCS/CF strong phase

2. Time-dependent $D^0(t) \to K^+K^-$ analysis (lifetime difference)

$$y_{CP} = \frac{\tau\left(D \to \pi^+K^-\right)}{\tau\left(D \to K^+K^-\right)} - 1 = y\cos\phi - x\sin\phi\frac{A_m}{2}$$

3. Semileptonic analysis $rate \propto x^2 + y^2$

Quadratic in x,y: not so sensitive

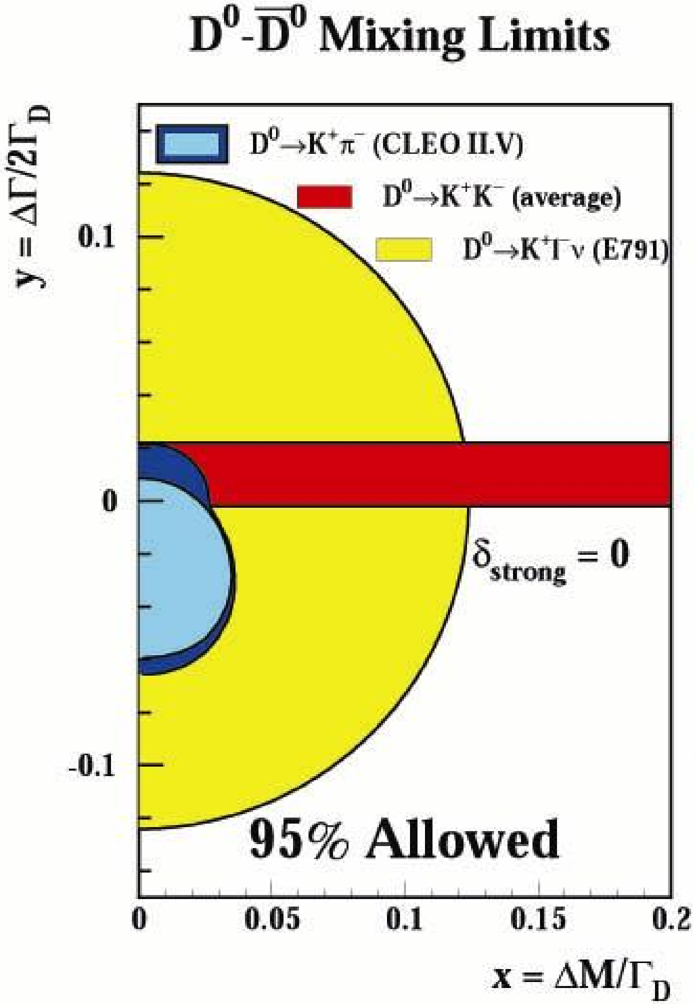
4. Time-independent analysis at tau-charm factory: (QM) entangled initial state

$$y\cos\phi = (-1)^L\sigma\frac{R_\sigma^L - 1}{R_\sigma^L}$$

$$R_\sigma^L = \frac{1}{Br\left(D^0 \to Xl\nu\right)}\frac{\Gamma[\psi_L \to (D \to [CP]_\sigma)(D \to Xl\nu)]}{\Gamma[\psi_L \to (D \to [CP]_\sigma)(D \to X)]}$$

D. Atwood and A.A.P., hep-ph/0207165

Experimental constraints 1



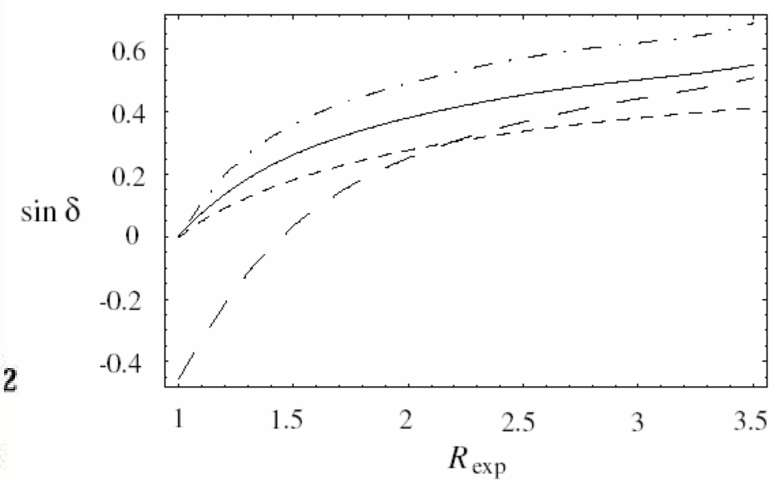
1. Time-dependent $D^0(t) \to K^+\pi^-$ analysis

$$\Gamma\left[D^0(t) \to K^+\pi^-\right] = e^{-\Gamma t}\left|A_{K^+\pi^-}\right|^2 \times \left[R + \sqrt{R}R_m\left(y'\cos\phi - x'\sin\phi\right)\Gamma t + \frac{R_m^2}{4}\left(y^2 + x^2\right)\left(\Gamma t\right)^2\right]$$

$$R = \left|\frac{A_{K^+\pi^-}}{\overline{A}_{K^+\pi^-}}\right|^2$$

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

for $D^0 \leftrightarrow \overline{D^0}$:
$R_m \leftrightarrow R_m^{-1}, \quad x' \leftrightarrow -x'$

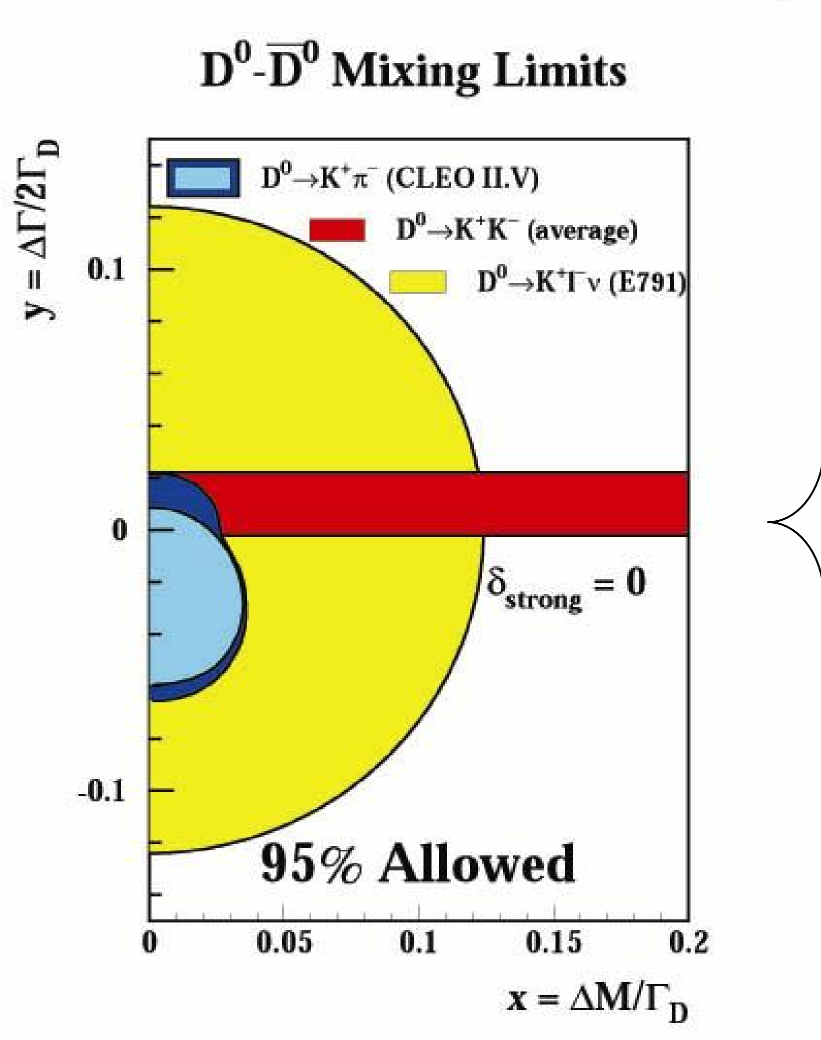


Strong phase is <u>zero</u> in the SU(3) limit

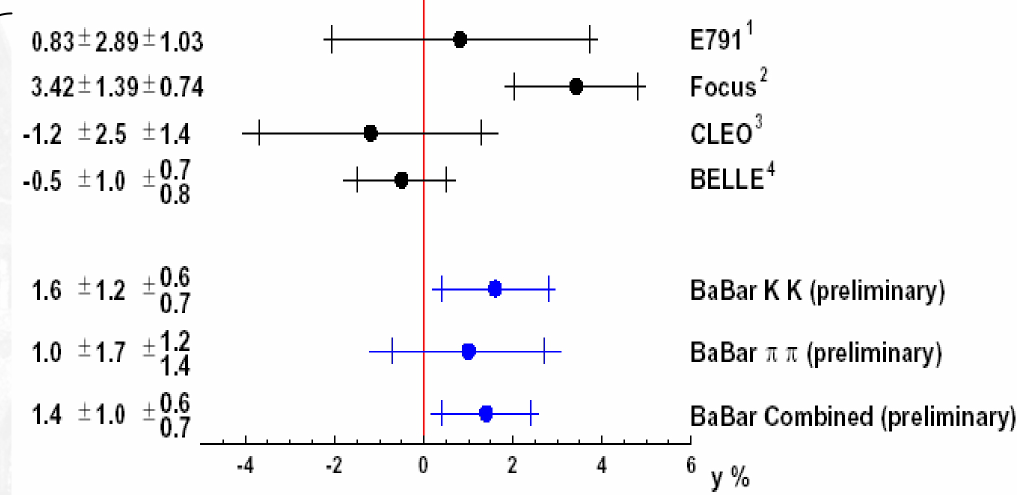
A. Falk, Y. Nir and A.A.P., JHEP 12 (1999) 019

Can be measured at CLEO-c!

Experimental constraints 2



2. Time-dependent $D^0(t) \to K^+K^-$ analysis

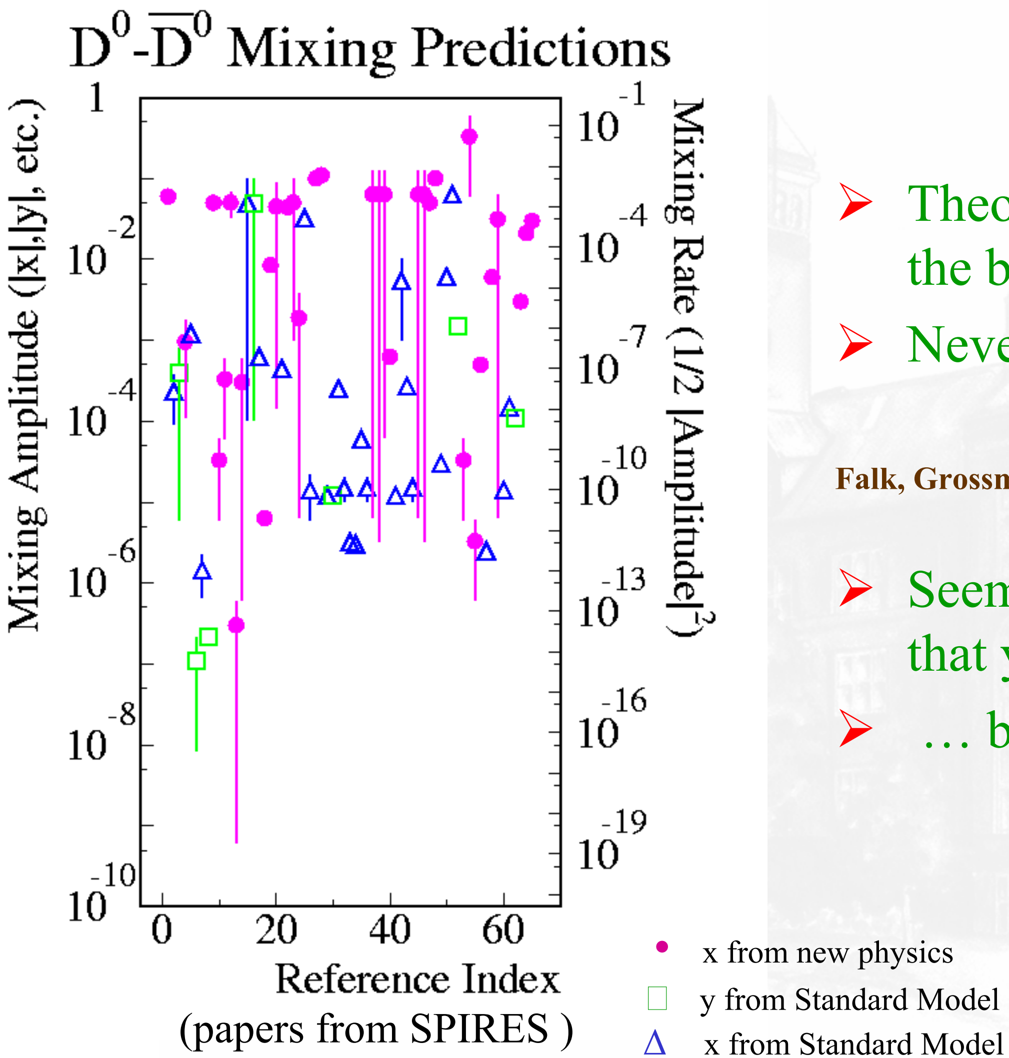


Experiment	Value
FOCUS (2000)	(3.42±1.39±0.74)%
E791(2001)	(0.8±2.9±1.0)%
CLEO (2002)	(-1.2±2.5±1.4)%
Belle (2002)	$(-0.5\pm1.0^{+0.7}_{-0.8})$%
BaBar (2002)	$(1.4\pm1.0^{+0.6}_{-0.7})$%

What are the expectations for x and y?

World average: $y_{CP} = (1.0\pm0.7)\%$

Theoretical estimates



- Theoretical predictions are all over the board…
- Nevertheless, it can be that y ~ 1%!

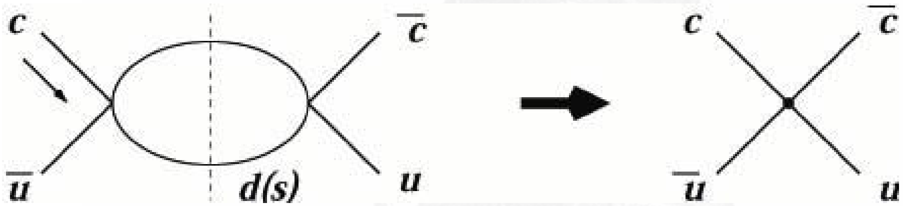
Falk, Grossman, Ligeti, A.A.P., Phys.Rev. D65, 054034, (2002)

- Seems like D-system is unique in that y >> x!
- … but sensitivity to new physics is reduced

Theoretical estimates I

m$_c$ IS large !!!

A. Short distance gives a tiny contribution, consider y as an example



$$y = \frac{1}{m_D \Gamma} \left\langle D^0 \middle| T \middle| \overline{D}^0 \right\rangle$$

… as can be seen form the straightforward computation…

$$y_{sd} = \frac{N_C + 1}{2\pi N_C \Gamma} X_D \frac{\left(m_s^2 - m_d^2\right)^2}{m_c^2} \frac{m_s^2 + m_d^2}{m_c^2} \left[C_2^2 + 2 C_1 C_2 + C_1^2 N_C \right.$$
$$\left. - \frac{2(2N_C - 1)}{1 + N_C} \frac{B_D'}{B_D} \frac{M_D^2 C_2^2}{(m_c + m_u)^2} \left(1 + \left(N_C \frac{C_1^2}{C_2^2} + 2 \frac{C_1}{C_2} \right) \frac{2 - N_C}{2 N_C - 1} \right) \right]$$

with $\left\langle D^0 \middle| \bar{u} \Gamma_\mu c \; \bar{u} \Gamma^\mu c \middle| D^0 \right\rangle = \frac{1 + N_C}{N_C} \frac{4 F_D^2 m_D^2}{2 m_D} B_D, \; etc.$

4 unknown matrix elements

similar for x (trust me!)

Theoretical estimates I

A. Short distance + "subleading corrections" (in $1/m_c$ expansion):

$$y_{sd}^{(6)} \propto \frac{\left(m_s^2 - m_d^2\right)^2}{m_c^2} \frac{m_s^2 + m_d^2}{m_c^2} \mu_{had}^{-2} \propto m_s^6 \Lambda^{-6}$$

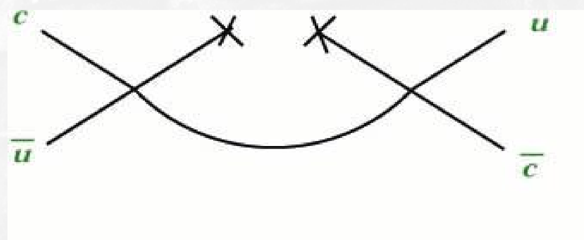
$$x_{sd}^{(6)} \propto \frac{\left(m_s^2 - m_d^2\right)^2}{m_c^2} \mu_{had}^{-2} \propto m_s^4 \Lambda^{-4}$$

4 unknown matrix elements

…subleading effects?

$$y_{sd}^{(9)} \propto m_s^3 \Lambda^{-3}$$

$$x_{sd}^{(9)} \propto m_s^3 \Lambda^{-3}$$



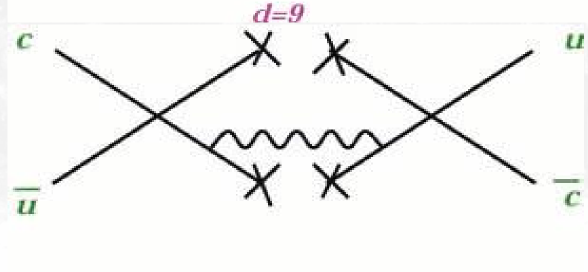
d=9

15 unknown matrix elements

Georgi, …
Bigi, Uraltsev

$$y_{sd}^{(12)} \propto \beta_0 \alpha_s^2(\mu) m_s^2 \Lambda^{-2}$$

$$x_{sd}^{(12)} \propto \alpha_s(\mu) m_s^2 \Lambda^{-2}$$



d=12

Twenty-something unknown matrix elements

Leading contribution!!!

Guestimate: $x \sim y \sim 10^{-3}$?

Resume: model-independent computation with model-dependent result

Theoretical estimates II

B. Long distance physics dominates the dynamics…

m$_c$ is NOT large !!!

$$y = \frac{1}{2\Gamma} \sum_n \rho_n \left[\left\langle D^0 \left| H_W^{\Delta C=1} \right| n \right\rangle \left\langle n \left| H_W^{\Delta C=1} \right| \overline{D}^0 \right\rangle + \left\langle \overline{D}^0 \left| H_W^{\Delta C=1} \right| n \right\rangle \left\langle n \left| H_W^{\Delta C=1} \right| D^0 \right\rangle \right]$$

… with n being all states to which D^0 and $\overline{D}^0$ can decay. Consider ππ, πK, KK intermediate states as an example…

Donoghue et. al.
Colangelo et. al.

$$y_2 = Br\left(D^0 \to K^+K^-\right) + Br\left(D^0 \to \pi^+\pi^-\right) - 2\cos\delta \sqrt{Br\left(D^0 \to K^+\pi^-\right) Br\left(D^0 \to \pi^+K^-\right)}$$

cancellation expected!

If every Br is known up to *O(1%)* ➡ the result is expected to be *O(1%)*!

The result here is a series of large numbers with alternating signs, SU(3) forces 0

x = ? Extremely hard… ➡ need to restructure the calculation…

Resume: model-dependent computation with model-dependent result

Theoretical expectations: SU(3) breaking

- Neglecting the third generation, mixing arises at second order in SU(3) breaking

$$x, y \sim \sin^2 \vartheta_C \ \varepsilon^2_{SU(3)}$$

- Known counter-example:

Does not work if there is a very narrow light quark resonance with $m_R \sim m_D$

$$x, y \sim \frac{g^2_{DR}}{m^2_D - m^2_R} \sim \frac{g^2_{DR}}{m^2_D - m^2_0 - 2m_0\delta_R}$$

Most probably don't exists…

see E.Golowich and A.A.P. Phys.Lett. B427, 172, 1998

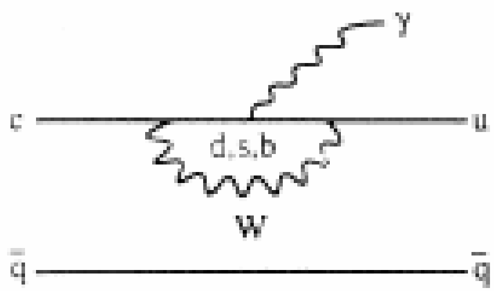
- What happens if part of the multiplet is kinematically forbidden?

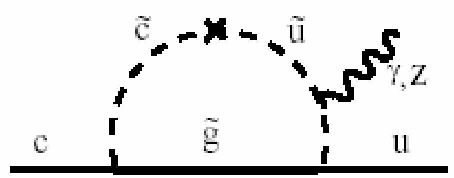
Example: both $D^0 \to 4\pi$ *and* $D^0 \to 4K$ are from the same multiplet, but the latter is kinematically forbidden

Mixing is dominated by 4-body intermediate state contribution, incomplete cancellations naturally imply that y ~ 1%

see A.F., Y.G., Z.L., and A.A.P. Phys.Rev. D65, 054034, 2002

FCNC in charm: why do we care?





Rare charm decays	Rare beauty decays
• intermediate down-type quarks • SM: b-quark contribution is very small due to V_{ub} • $rate \propto f(m_s) - f(m_d)$ (zero in the SU(3) limit)	• intermediate up-type quarks • SM: t-quark contribution is dominant • $rate \propto f(m_t^2)$ (expected to be large)
1. Sensitive to long distance QCD 2. Sensitive to New Physics!	1. Computable in QCD (*) 2. Large in the SM: CKM!

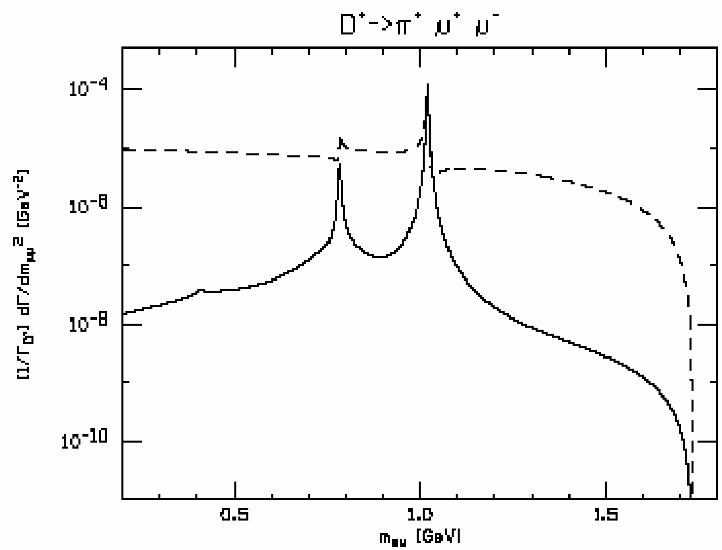
(*) depending on the process: OPE, factorization, …

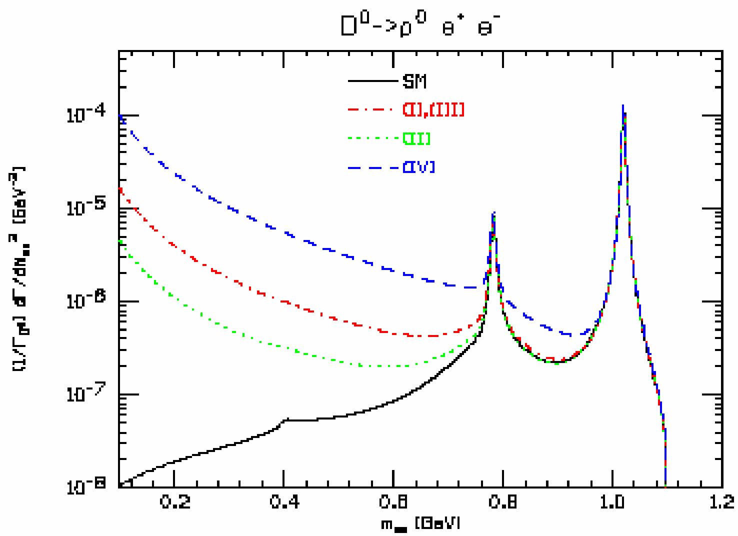
FCNC charm decays

1. In many cases NP contribution “gives a larger contribution” than the Standard Model

2. Example: $\not R$ SUSY

$$\delta H = -\frac{\tilde{\lambda}'_{i2k}\,\tilde{\lambda}'_{i1k}}{2m^2_{\tilde{d}^k_R}}\left(\bar{u}_L\gamma_\mu c_L\right)\left(\bar{l}_L\gamma^\mu l_L\right)$$





…or MSSM for different values of squark masses

see Burdman, Golowich, Hewett and Pakvasa Phys.Rev. D66, 014009, 2002

5. Conclusions

- Did not talk about:
  - Lifetimes and inclusive semileptonic decays
    - applications of 1/m techniques
  - Charmed baryons and double-charmed baryons
    - issues in double-charmed baryon production
  - Exclusive nonleptonic charm decays
    - direct CP violation
  - Charmonium production and polarization
    - J/ψ production in e^+e^- collisions
  - …

Conclusions

- Spectroscopy: what are the new D_{sJ}^* states?
  - low mass triggers many possible explanations
- Leptonic and semileptonic decays
  - important inputs to B-physics/CKM extractions
- Charm mixing:
  - x, y = 0 in the SU(3) limit (as $V^*_{cb}V_{ub}$ is very small)
  - it is a second order effect
  - it is quite possible that $y \sim 1\%$ with $x<y$
  - expect new data from BaBar/Belle/CLEO/CLEO-c/CDF
- Observation of CP-violation or FCNC transitions in the current round of experiments are still “smoking gun” signals for New Physics

Additional Slides

Questions:

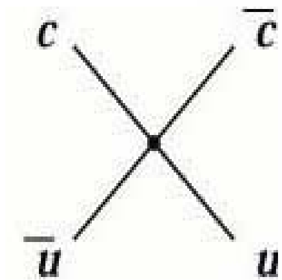
1. Can any model-independent statements be made for x or y ?

What is the order of SU(3) breaking?
i.e. if $x, y \propto m_s^n$ what is n?

2. Can one claim that $y \sim 1\%$ is natural?

Theoretical expectations

At which order in $SU(3)_F$ breaking does the effect occur? Group theory?



$$\langle D^0 | H_W \, H_W | \overline{D}^0 \rangle \Rightarrow \langle 0 | D \, H_W \, H_W \, D | 0 \rangle$$

is a singlet with $D \to D_i$ *that belongs to* ***3*** *of* $SU(3)_F$ *(one light quark)*

The $\Delta C=1$ part of H_W is $(\overline{q}_i c)(\overline{q}_j q_k)$, $i.e.\ 3 \times \overline{3} \times \overline{3} = \overline{15} + 6 + \overline{3} + \overline{3} \Rightarrow H^{ij}_k$

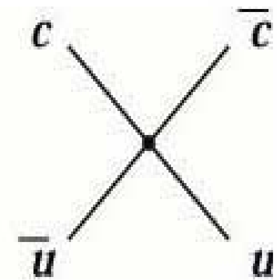
$$O_{\overline{15}} = (\overline{s} d)(\overline{u} d) + (\overline{u} c)(\overline{s} d) + s_1 (\overline{d} c)(\overline{u} d) + s_1 (\overline{u} c)(\overline{d} d) - s_1 (\overline{s} c)(\overline{u} s) - s_1 (\overline{u} c)(\overline{s} s) - s_1^2 (\overline{d} c)(\overline{u} s) - s_1^2 (\overline{u} c)(\overline{d} s)$$

$$O_6 = (\overline{s} d)(\overline{u} d) - (\overline{u} c)(\overline{s} d) + s_1 (\overline{d} c)(\overline{u} d) - s_1 (\overline{u} c)(\overline{d} d) - s_1 (\overline{s} c)(\overline{u} s) + s_1 (\overline{u} c)(\overline{s} s) - s_1^2 (\overline{d} c)(\overline{u} s) + s_1^2 (\overline{u} c)(\overline{d} s)$$

Introduce SU(3) breaking via the quark mass operator $M^i_j = diag\,(m_u, m_d, m_s)$

All nonzero matrix elements built of D_i, H^{ij}_k, M^i_j must be SU(3) singlets

Theoretical expectations



note that $D_i D_j$ *is symmetric* $\Rightarrow$ *belongs to* **6** *of* $SU(3)_F$

$$\langle D^0 | H_W H_W | \bar{D}^0 \rangle \Rightarrow \langle 0 | D H_W H_W D | 0 \rangle$$

Explicitly,

$$DD \Rightarrow D_6$$

$$H_W H_W \Rightarrow O_{\overline{60}} + O_{42} + O_{15'}$$

1. No $\bar{6}$ in the decomposition of $H_W H_W$ $\Rightarrow$ no SU(3) singlet can be formed

$\Rightarrow$ D mixing is prohibited by SU(3) symmetry

2. Consider a single insertion of $M^i_j \Rightarrow D_6 M$ transforms as $6 \times 8 = 24 + \overline{15} + 6 + \bar{3} \Rightarrow$ still no SU(3) singlet can be formed

$\Rightarrow$ NO D mixing at first order in SU(3) breaking

3. Consider double insertion of $M \Rightarrow DMM$: $6 \times (8 \times 8)_S = (60 + \overline{42} + 24 + \overline{15} + \overline{15} + 6) + (24 + \overline{15} + 6 + \bar{3}) + 6$

$\Rightarrow$ D mixing occurs only at the second order in SU(3) breaking

A.F., Y.G., Z.L., and A.A.P.
Phys.Rev. D65, 054034, 2002

Theoretical expectations: SU(3) breaking

- Two major sources of SU(3) breaking

1. phase space

$$m_K \neq m_\pi \neq m_\eta \ldots$$

2a. matrix elements (absolute value)

$$f_K \neq f_\pi \ldots$$

2b. matrix elements (phases a.k.a. FSI)

$$\mathrm{Im}\, \frac{A\left(D^0 \to K^+\pi^-\right)}{A(\overline{D}^0 \to K^+\pi^-)} \neq 0$$

Take into account only the first source…

SU(3) and phase space

- "Repackage" the analysis: look at the complete multiplet contribution

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

y for each SU(3) multiplet

Each is **0** in SU(3)

- Does it help? If only phase space is taken into account: **no** **(mild)** model dependence

$$y_{F,R} = \frac{\sum_{n \in F_R} \langle \overline{D}^0 | H_W | n \rangle \rho_n \langle n | H_W | D^0 \rangle}{\sum_{n \in F_R} \langle D^0 | H_W | n \rangle \rho_n \langle n | H_W | D^0 \rangle}$$

$$= \frac{\sum_{n \in F_R} \langle \overline{D}^0 | H_W | n \rangle \rho_n \langle n | H_W | D^0 \rangle}{\sum_{n \in F_R} \Gamma(D^0 \to n)}$$

if CP is conserved

Can consistently compute

Example: PP intermediate states

- *n=PP* transforms as $(8\times 8)_S = 27+8+1$, take 8 as an example:

Numerator:

$$A_{N,8} = |A_0|^2 s_1^2 \left[\frac{1}{2}\Phi(\eta,\eta) + \frac{1}{2}\Phi(\pi^0,\pi^0) + \frac{1}{3}\Phi(\eta,\pi^0) + \Phi(\pi^+,\pi^-) - \Phi(\overline{K}^0,\pi^0) \right.$$
$$\left. + \Phi(K^+,K^-) - \frac{1}{6}\Phi(\eta,K^0) - \frac{1}{6}\Phi(\eta,\overline{K}^0) - \Phi(K^+,\pi^-) - \Phi(K^-,\pi^+) \right]$$

Denominator:

phase space function

$$A_{D,8} = |A_0|^2 \left[\frac{1}{6}\Phi(\eta,K^0) + \Phi(K^+,\pi^-) + \frac{1}{2}\Phi(K^0,\pi^0) + O(s_1^2) \right]$$

- This gives a calculable effect!

$$y_{2,8} = \frac{A_{N,8}}{A_{D,8}} = -0.038\ s_1^2 = -1.8\times 10^{-4}$$

1. Repeat for other states
2. Multiply by Br_{Fr} to get y

Results

Final state representation		$y_{F,R}/s_1^2$	$y_{F,R}$ (%)
PP	8	−0.0038	−0.018
	27	−0.00071	−0.0034
PV	8_S	0.031	0.15
	8_A	0.032	0.15
	10	0.020	0.10
	$\overline{10}$	0.016	0.08
	27	0.040	0.19
$(VV)_{s\text{-wave}}$	8	−0.081	−0.39
	27	−0.061	−0.30
$(VV)_{p\text{-wave}}$	8	−0.10	−0.48
	27	−0.14	−0.70
$(VV)_{d\text{-wave}}$	8	0.51	2.5
	27	0.57	2.8

Final state representation		$y_{F,R}/s_1^2$	$y_{F,R}$ (%)
$(3P)_{s\text{-wave}}$	8	−0.48	−2.3
	27	−0.11	−0.54
$(3P)_{p\text{-wave}}$	8	−1.13	−5.5
	27	−0.07	−0.36
$(3P)_{\text{form-factor}}$	8	−0.44	−2.1
	27	−0.13	−0.64
$4P$	8	3.3	16
	27	2.2	9.2
	27′	1.9	11

- Product is naturally O(1%)
- No (symmetry-enforced) cancellations
- Does NOT occur for x

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

naturally implies that $y \sim 1\%$ and $x < y$!