Charm Theory

[Mixing, Rare Decays]

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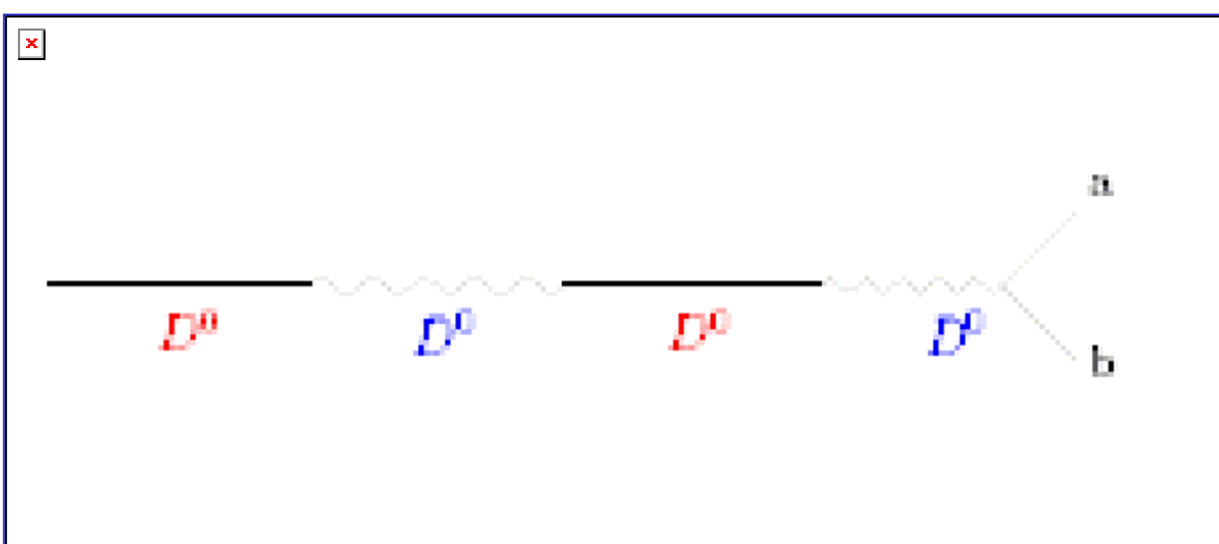


Mixing Outline

- Current Status of Mixing

  K, B_d, B_s, D

- D Mixing in the Standard Model

  (i) Quarks (ii) Hadrons

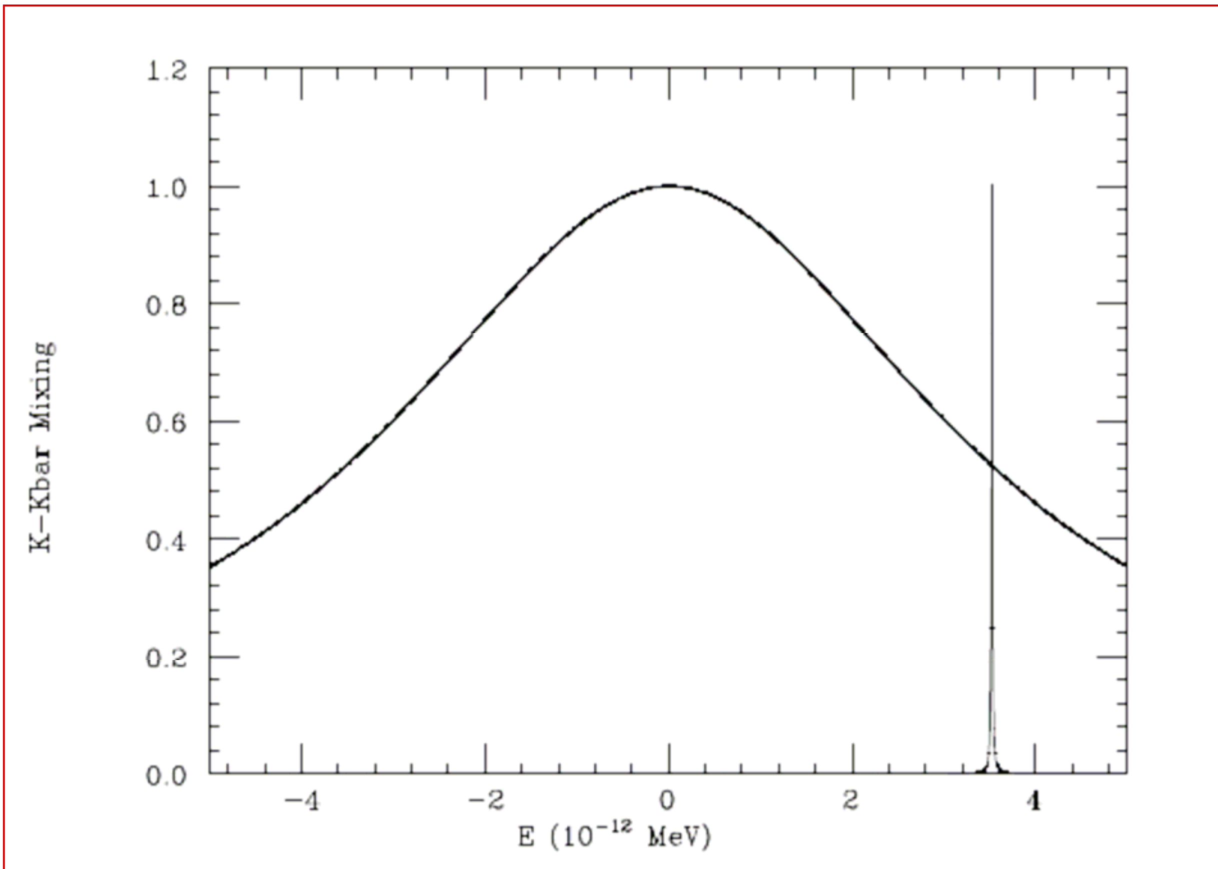
- New Physics and $\Delta\Gamma_D$

  GPP hep-ph/0610039

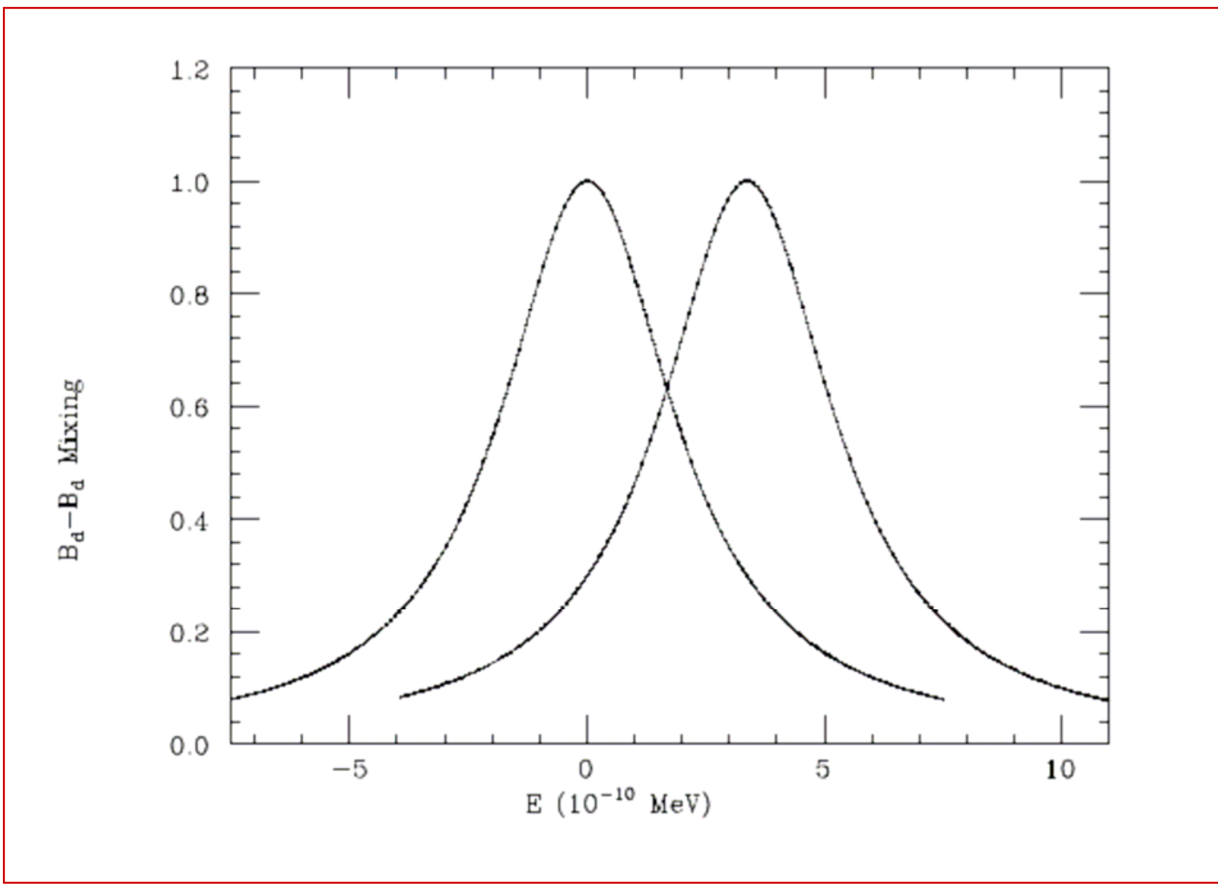
- New Physics and ΔM_D

  GHPP hep-ph/06xxxxx

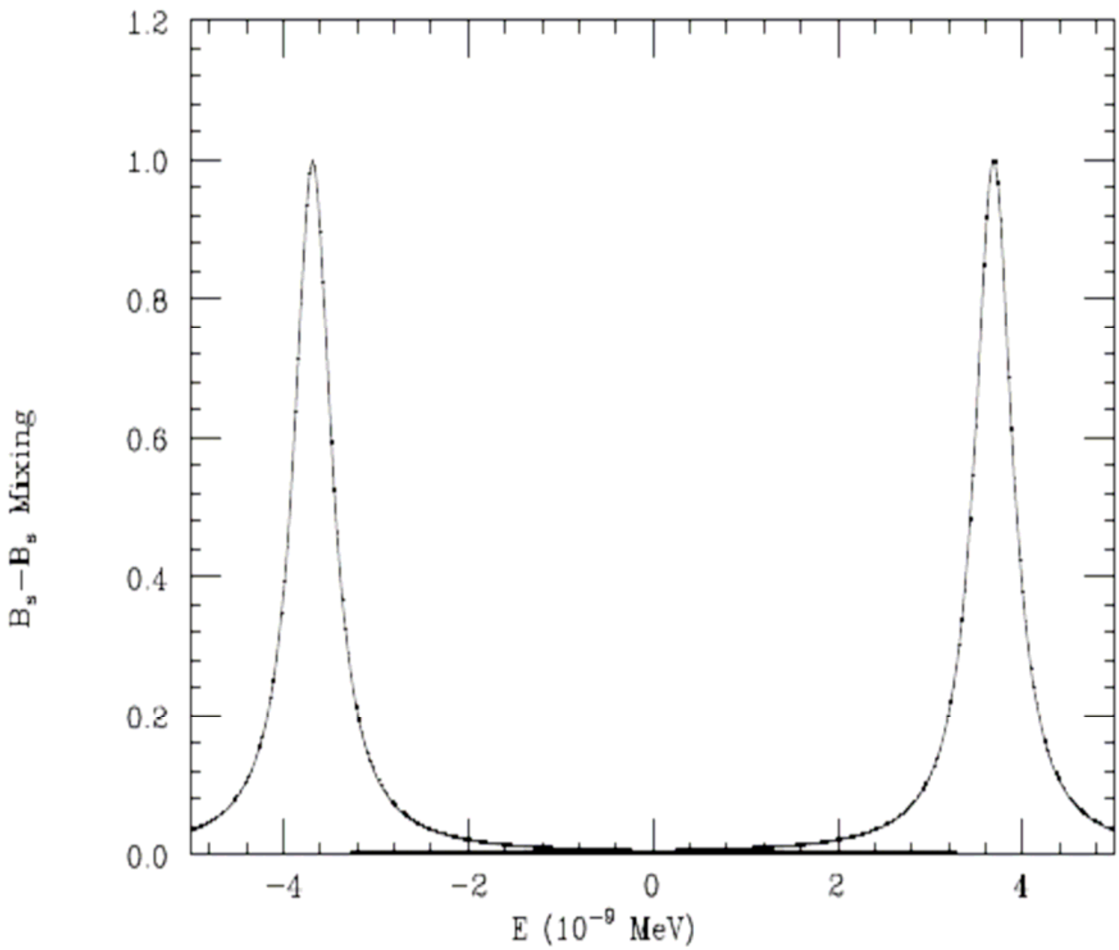
Mixing of K Mesons



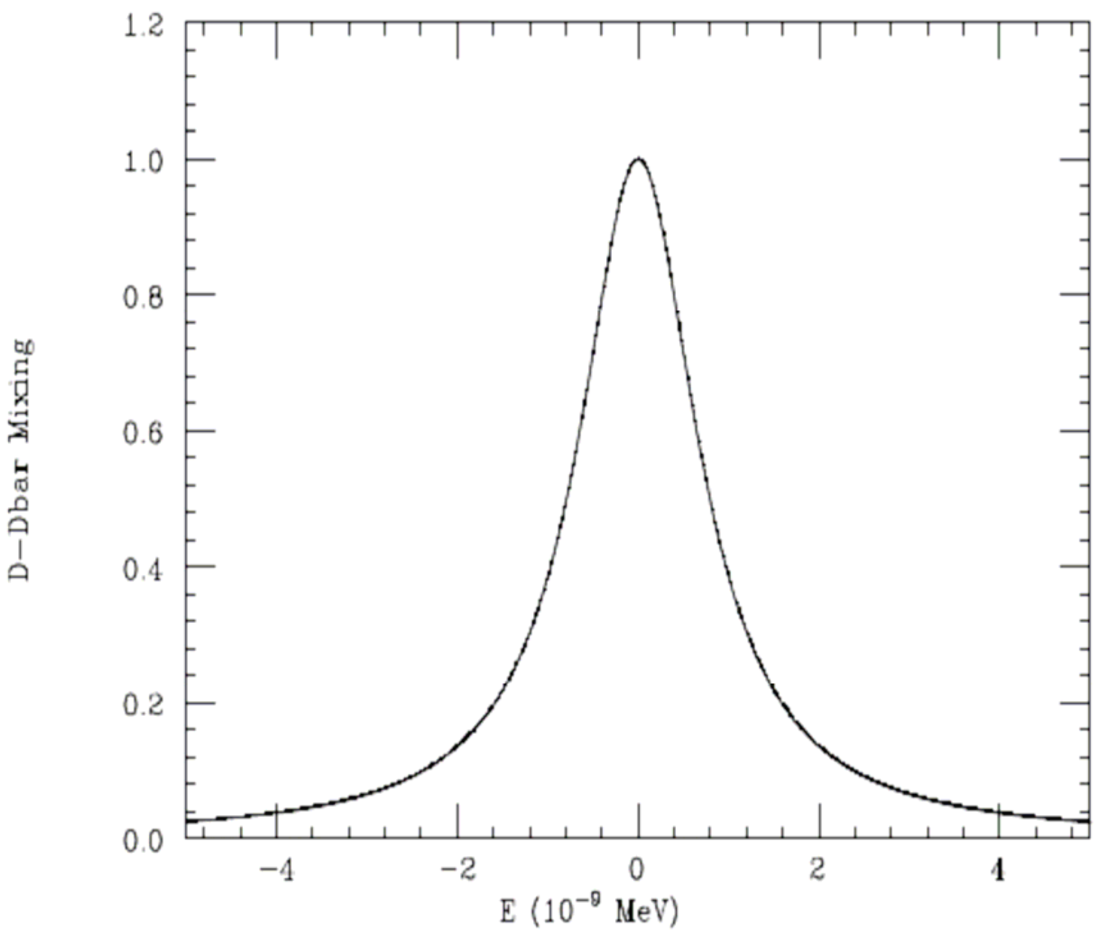
Mixing of B_d Mesons



Mixing of B_s Mesons



Mixing of D^0 Mesons



Existing D^0 Bounds

$$x = \frac{\Delta M}{\Gamma}$$

$x < 0.029$ (PDG)

$$y = \frac{\Delta\Gamma}{2\Gamma}$$

$y = 0.007 \pm 0.005$ (PDG)

y [in %] from Decay Rates

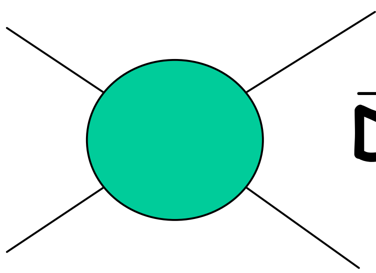
E791	0.8 ±2.9 ±1.0
FOCUS	3.4 ±1.4 ±0.7
CLEO	- 1.2 ±2.5 ±1.4
BaBar	0.8 ±0.4 ±0.4
Belle (tagged)	1.2 ±0.7 ±0.4
Belle (untggd)	- 0.5 ±1.0 ±0.8

(Average [%] = 0.9 ± 0.4)

[See also S. Stone (Belle), talk at FPCP 2006]

Charm Mixing in the SM

Quark Description (OPE*)

D^0  $\overline{D}^0$ $= \sum_n O_n^{(d=6)}$

$$+ \sum_n O_n^{(d=9)} + \ldots$$

D=6: Two local 4F operators

D=9: Fifteen local 6F operators

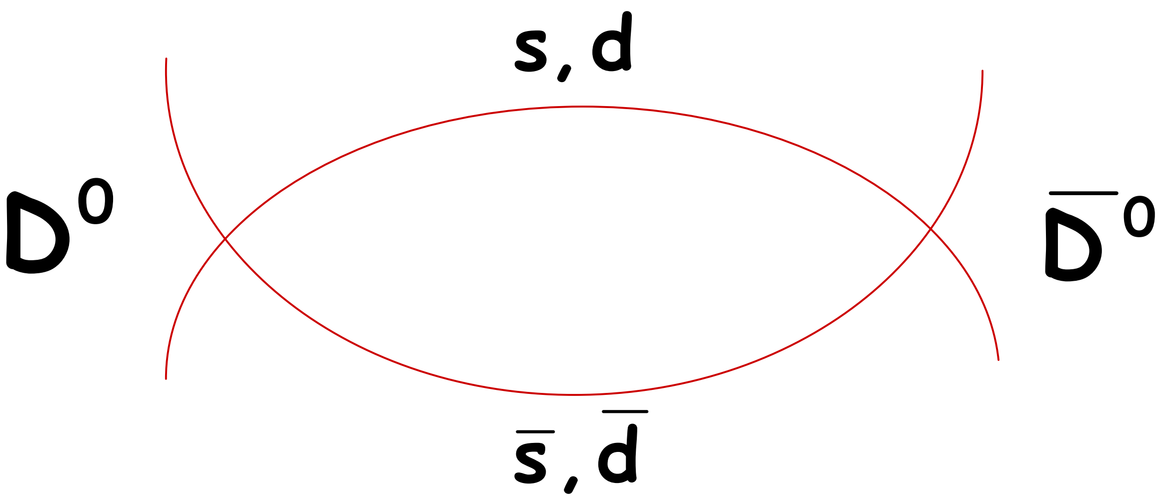
Etc

*[Georgi PL B297 (1992) 353]

Dimension Six

Ignore b quark. Sum over

$s\bar{s}$, $d\bar{d}$, $s\bar{d}$ + $d\bar{s}$ intermediate states.



Expand in powers of

$$z = \frac{m_s^2}{m_c^2} \cong 0.006$$

Flavor Cancellations

$\Delta\Gamma$ at d=6 (m_d=0):

	z^0	z^1	z^2
$s\bar{s}$	$\frac{1}{2}$		
$d\bar{d}$			
$s\bar{d} + d\bar{s}$			
Total			

Flavor Cancellations

$\Delta\Gamma$ at d=6 (m_d=0):

	z^0	z^1	z^2
$s\bar{s}$	$\frac{1}{2}$		
$d\bar{d}$	$\frac{1}{2}$		
$s\bar{d} + d\bar{s}$			
Total			

Flavor Cancellations

$\Delta\Gamma$ at d=6 (m_d=0):

	z^0	z^1	z^2
$s\bar{s}$	$\frac{1}{2}$		
$d\bar{d}$	$\frac{1}{2}$		
$s\bar{d} + d\bar{s}$	-1		
Total	0		

Flavor Cancellations

$\Delta\Gamma$ at d=6 (m_d=0):

	z^0	z^1	z^2
$s\bar{s}$	$\frac{1}{2}$	-3z	
$d\bar{d}$	$\frac{1}{2}$	0	
$s\bar{d} + d\bar{s}$	-1	3z	
Total	0	0	

Flavor Cancellations

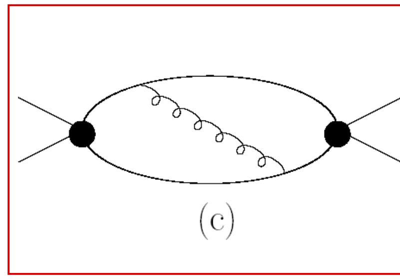
$\Delta\Gamma$ at d=6 (m_d=0):

	z^0	z^1	z^2
$s\bar{s}$	$\frac{1}{2}$	$-3z$	$3z^2$
$d\bar{d}$	$\frac{1}{2}$	0	0
$s\bar{d} + d\bar{s}$	-1	$3z$	$-3z^2$
Total	0	0	0

Allowing for QCD

Expand in α_s

[EG & Petrov PLB 625 (2005) 53]



	x	y	Comment
α_s^0 (LO)	z^2	z^3	$x^{(LO)} >> y^{(LO)}$
α_s^1 (NLO)	z^2	z^2	$x^{(NLO)} > y^{(NLO)}$

Quark LO + NLO Result: $x \cong y \approx 10^{-6}$

Current Bound $y < 0.007$ much larger!

Higher terms in QCD,OPE?

$\Delta\Gamma_D$ in the Standard Model

Hadron Description

$$\Delta\Gamma_D = -2\Gamma_{12} = -\frac{1}{M_D}\,\mathrm{Im}\,\langle \overline{D}^0 |\, i\int d^4x\, T\left\{\mathcal{H}_w^{\Delta C=1}(x)\,\mathcal{H}_w^{\Delta C=1}(0)\right\}|D^0\rangle$$

Insert hadronic int. states: $\sum_n |n\rangle\langle n|$

Require matrix elements: $\langle n | H_w | D^0 \rangle$

<u>Three approaches:</u>

a] Using a model:

$y \sim 10^{-3}$ [BLMPS PRD 51 (1995) 3478]

$\Delta\Gamma_D$ in the SM (cont)

b] Using data:

Basic Idea [UMass PRD 33 (1985)178]

Use experimental branching ratios

Divide out phase space

Take square root

Recent Work [FGLNP PRD 69 (2004) 114021]

Complete survey: n = PP,VP,VV,3P,4P

Conclude $0.01 > y > ?$

But analysis error-bar limited …(?)

c] Nearby Resonances: [GP PL B427 (1998) 172]

Can get enhancement if $M_R \cong M_D$

Promising idea but data inadequate

Mixing and New Physics

Standard Model (Historical)

$K^0 - \bar{K}^0 \rightarrow$ Charm quark

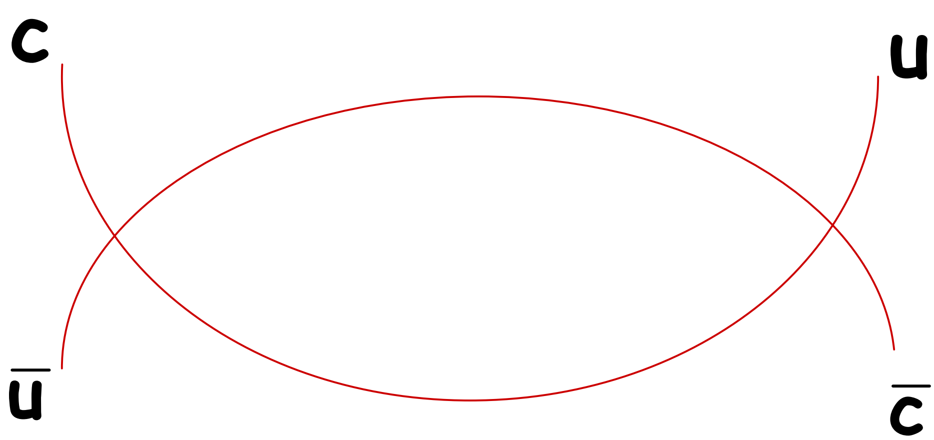
$B_d - \bar{B}_d \rightarrow$ Top quark

New Physics (Thus Far)

Nothing definite yet

Keep trying….

Propagating Particles



ΔM

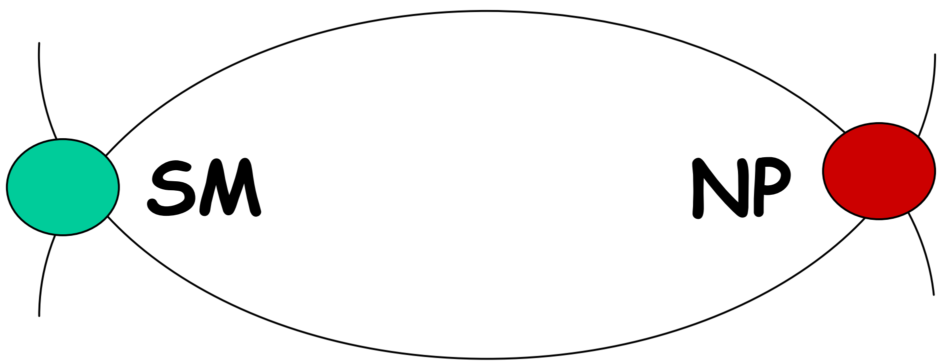
Both SM and NP particles propagate

ΔΓ

Only SM particles propagate

(Intermediate states are physical)

$\Delta\Gamma_D$ and New Physics*



NP can affect $\Delta\Gamma$

Via the $\Delta C = \pm 1$ interaction vertex.

Processes like $c\bar{u} \to q_1\bar{q}_2$

*EG, Pakvasa, Petrov [hep-ph/0610039]

The Calculation

INPUT

$$H_{NP}^{\Delta C=-1} = \sum_{q,q'} D_{qq'} \left[\overline{\mathcal{C}}_1(\mu) Q_1 + \overline{\mathcal{C}}_2(\mu) Q_2\right]$$

$$Q_1 = \overline{u}_i \overline{\Gamma}_1 q'_j \, \overline{q}_j \overline{\Gamma}_2 c_i \quad Q_2 = \overline{u}_i \overline{\Gamma}_1 q'_i \, \overline{q}_j \overline{\Gamma}_2 c_j$$

OUTPUT

$$y_D = -\frac{4\sqrt{2} G_F}{M_D \Gamma_D} \sum_{q,q'} V_{cq'}^* V_{uq} D_{qq'} \left(K_1 \delta_{ik} \delta_{j\ell}\right.$$

$$\left. + \quad K_2 \delta_{i\ell} \delta_{jk}\right) \sum_{\alpha=1}^{5} I_\alpha(x, x') \langle \overline{D}^0 | \, O_\alpha^{ijk\ell} \, | D^0 \rangle$$

SM Recovered (LO)

$$D_{qq'} \rightarrow -\frac{G_F}{\sqrt{2}} V^*_{cq} V_{uq'} \qquad \bar{C}_i \rightarrow C_i$$

$$\bar{\Gamma}_{1,2} \rightarrow \gamma_\mu (1+\gamma_5)/2$$

$$y_{SM} = \frac{G_F^2 m_c^2 \lambda^2 z^3}{2\pi M_D \Gamma_D} (K_2 - K_1) \langle Q_{eff} \rangle$$

$$Q_{eff} = Q + 4\, Q_S$$

LO Result tiny due mainly to z^3 and λ^2.

Some Results

Model	y_D	Comment
RPV-SUSY	$6\ 10^{-6}$ $-4\ 10^{-2}$	Squark Exch. Slepton Exch.
Left-right	$-5\ 10^{-6}$ $-9\ 10^{-5}$	‘Manifest’. ‘Nonmanifest’.
Multi-Higgs	$2\ 10^{-10}$	Charged Higgs
Extra Quarks -	10^{-8}	Not Little Higgs

ΔM_D and New Physics*

- Operator Basis

  Four-quark Operators

- D^0-to-anti D^0 Matrix Elements

  Two B parameters

- RG Running

  NP scale M $\rightarrow$ Charm scale m_c

- Menu of NP Possibilities

  The Usual Suspects

***EG, Hewett, Pakvasa, Petrov [in progress]**

Operator Basis

Total of eight local operators:

$$Q_1 = \bar{u}_L \gamma^\mu c_L \cdot \bar{u}_L \gamma_\mu c_L$$

$$Q_2 = \bar{u}_L \gamma^\mu c_L \cdot \bar{u}_R \gamma_\mu c_R$$

$$Q_3 = \bar{u}_L c_R \cdot \bar{u}_R c_L$$

$$Q_4 = \bar{u}_R c_L \cdot \bar{u}_R c_L$$

$$Q_5 = \bar{u}_R \sigma^{\mu\nu} c_L \cdot \bar{u}_R \sigma_{\mu\nu} c_L$$

$$Q_6 = \bar{u}_R \gamma^\mu c_R \cdot \bar{u}_R \gamma_\mu c_R$$

$$Q_7 = \bar{u}_L c_R \cdot \bar{u}_L c_R$$

$$Q_8 = \bar{u}_L \sigma^{\mu\nu} c_R \cdot \bar{u}_L \sigma_{\mu\nu} c_R$$

Matrix Elements

Just two nonperturbative constants:

$$\langle Q_1 \rangle = \tfrac{2}{3} f_D^2 M_D^2 B$$

$$\langle Q_2 \rangle = -\tfrac{1}{2} f_D^2 M_D^2 B + \tfrac{1}{3} f_D^2 B_S'$$

$$\langle Q_3 \rangle = \tfrac{1}{4} f_D^2 M_D^2 B - \tfrac{1}{2} f_D^2 B_S'$$

$$\langle Q_4 \rangle = \tfrac{1}{4} f_D^2 B_S'$$

$$\langle Q_5 \rangle = -f_D^2 B_S'$$

$$\langle Q_6 \rangle = \langle Q_1 \rangle$$

$$\langle Q_7 \rangle = \tfrac{5}{12} f_D^2 B_S'$$

$$\langle Q_8 \rangle = \langle Q_5 \rangle$$

RG Running

Ex: $Q_6 = \bar{u}_R \gamma^\mu c_R \bar{u}_R \gamma_\mu c_R$

Input $K(M)$ **Output** $K(m_c)$

Suppose NP scale M: $M > m_t$

Let $r(m_1, m_2) = \alpha_s(m_1)/\alpha_s(m_2)$

Then $K(m_c) = C[M, m_c]K(M)$

with

$$C[M, m_c] = r^{2/7}(M, m_t) r^{6/23}(m_t, m_b) r^{6/25}(m_b, m_c)$$

Menu of Possibilities

Extra gauge bosons

(LR models, etc)

Extra scalars

(Multi-Higgs models, etc)

Extra quarks

(Little Higgs, etc)

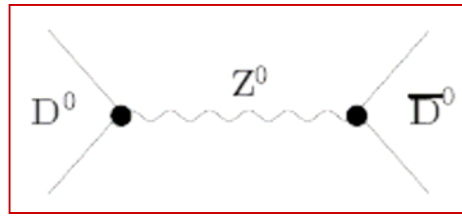
Extra dimensions

(Universal extra dimensions, etc)

Extra global symmetries

(SUSY, etc)

Ex: Extra Quarks



Tree diagram

Z^0 pole

Two flavor-changing vertices

Find $\Delta M_D = \dfrac{G_F (U_{uc})^2}{2\sqrt{2} M_D} K_1 \langle Q_1 \rangle$

Realizations:

Vector-like SU(2)-singlet quarks

E(6): Q = -e/3

Little Higgs: Q = 2e/3

Rare Charm Decays

Some are more interesting than others.

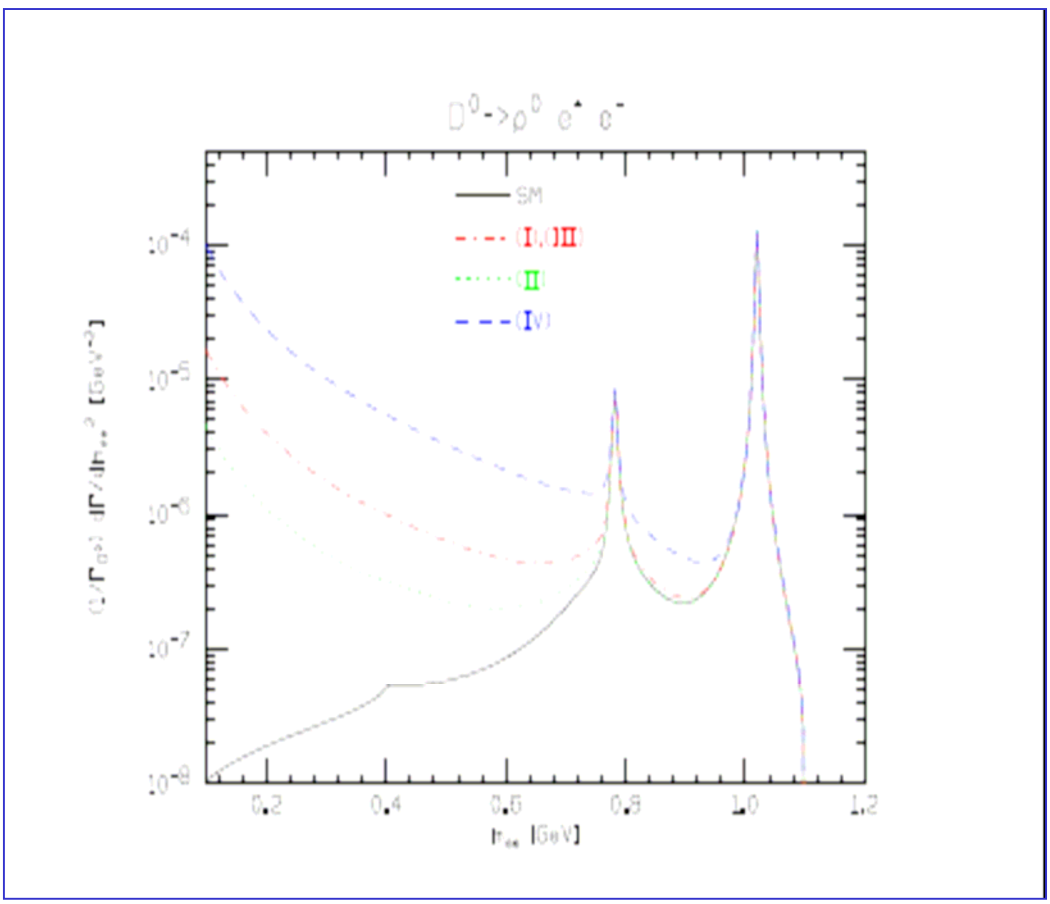
Ex: $D \to V\gamma$ dominated by SM effects.

[BGHP PR D52 (1996) 6383]

Ex: $D \to Ve^+e^-$ offers NP opportunities.

[BGHP PR D66 (2002) 014009]

Also see [FP PR D73 (2006) 054026]

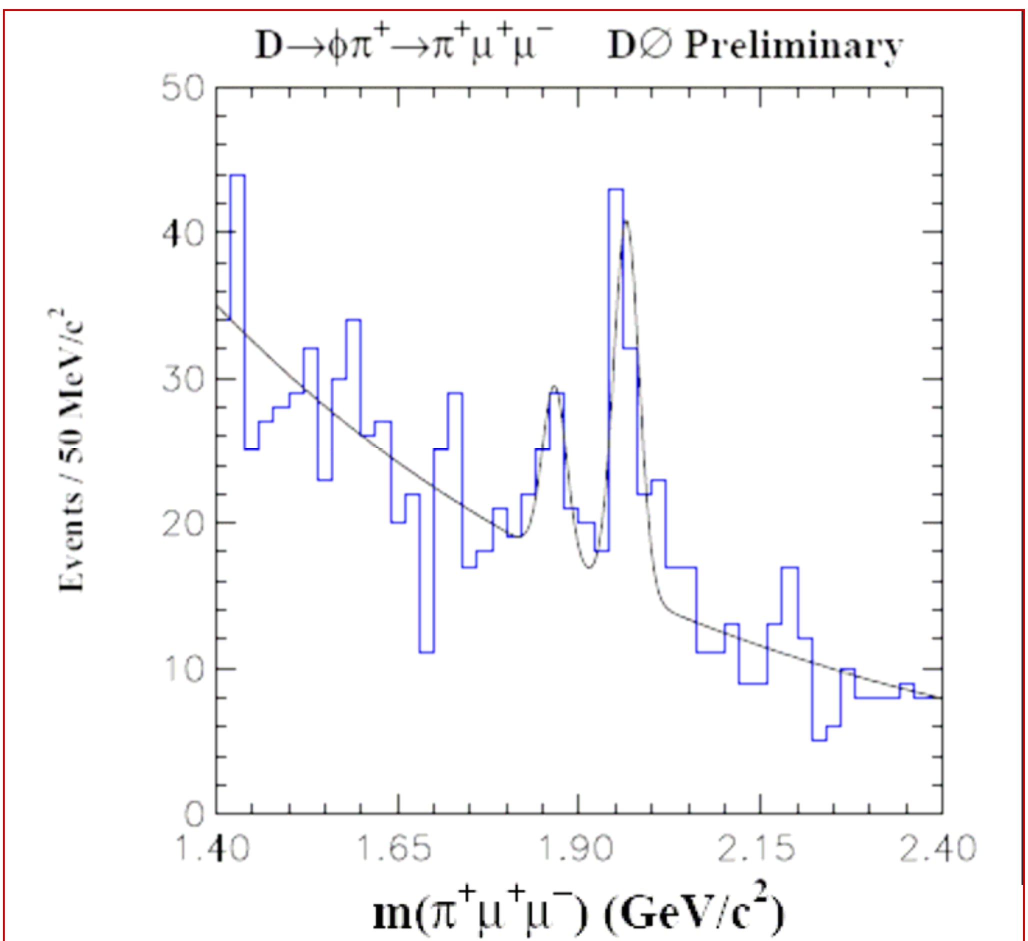


Rare Charm Decays (cont)

Experimental studies underway.

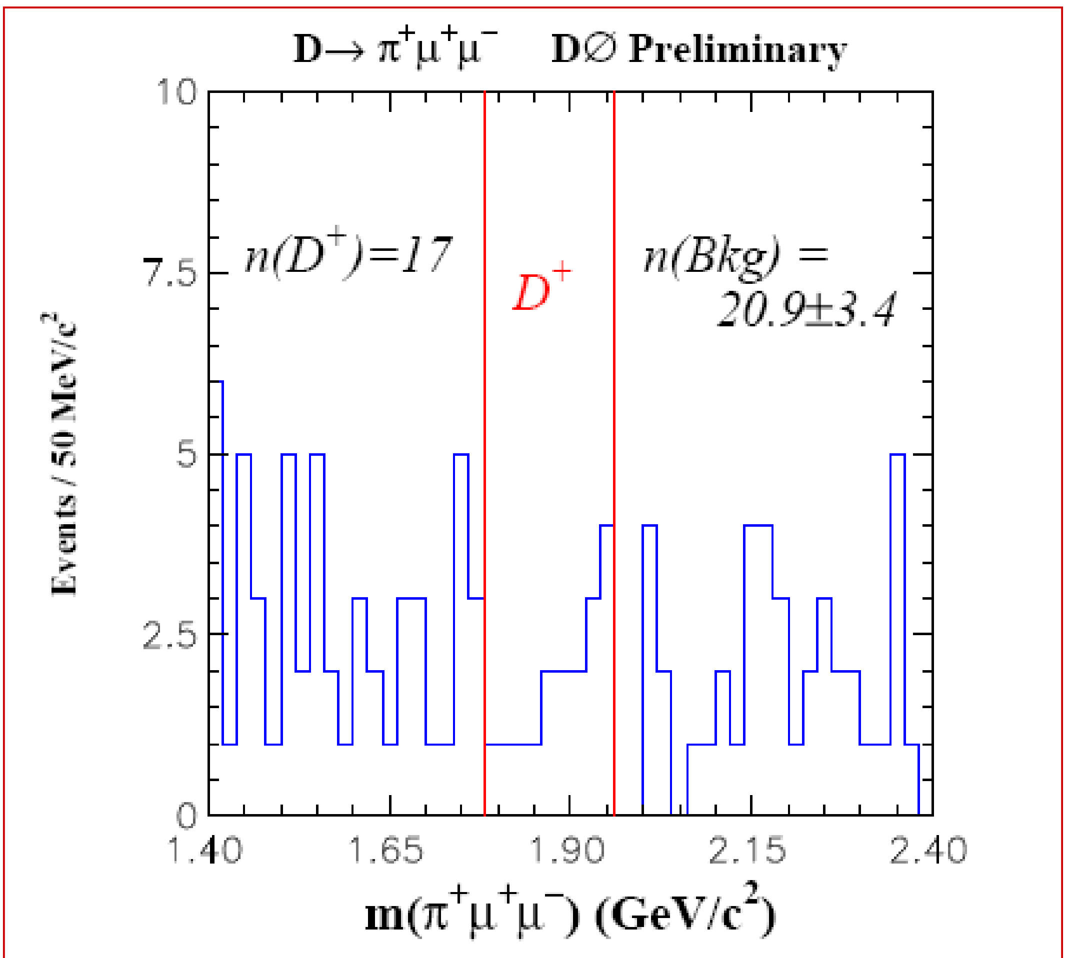
Below is a recent D0 result involving

$D^+, D_s^+ \rightarrow \pi^+\phi \rightarrow \pi^+\mu^+\mu^-$



Rare Charm Decays (cont)

But no signal yet in the continuum.
'Best' upper bound a good beginning.



Concluding Remarks

- **D^0 Mixing**

Experiment:

A number of studies underway (Good!)

But more sensitivity required.

One ultimate goal: Probe 0.01 > y > 0.001

Standard Model Theory:

Quarks:

Triple expansion (D, α_s , z)

Calculation to date to NLO with D=6

Find $x \cong y \cong 10^{-6}$

Higher terms in OPE (Difficult!)

Hadrons and $\Delta\Gamma$:

One specific theory model gives $y \cong 10^{-3}$

Phenomenology allows range 0.01 >y >?

Concluding Remarks (cont)

New Physics Theory:

Analysis of $\Delta\Gamma_D$ complete (New!)

Updated analysis of ΔM_D in progress.

- ## Rare Decays

Theory:

SM and NP analyses already in the literature

Experiment:

Experiments underway, esp $D \to M\ell^+\ell^-$

More sensitivity needed.