# Charm Theory

## [Mixing, Rare Decays, CP-Violation]

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Beach 2006
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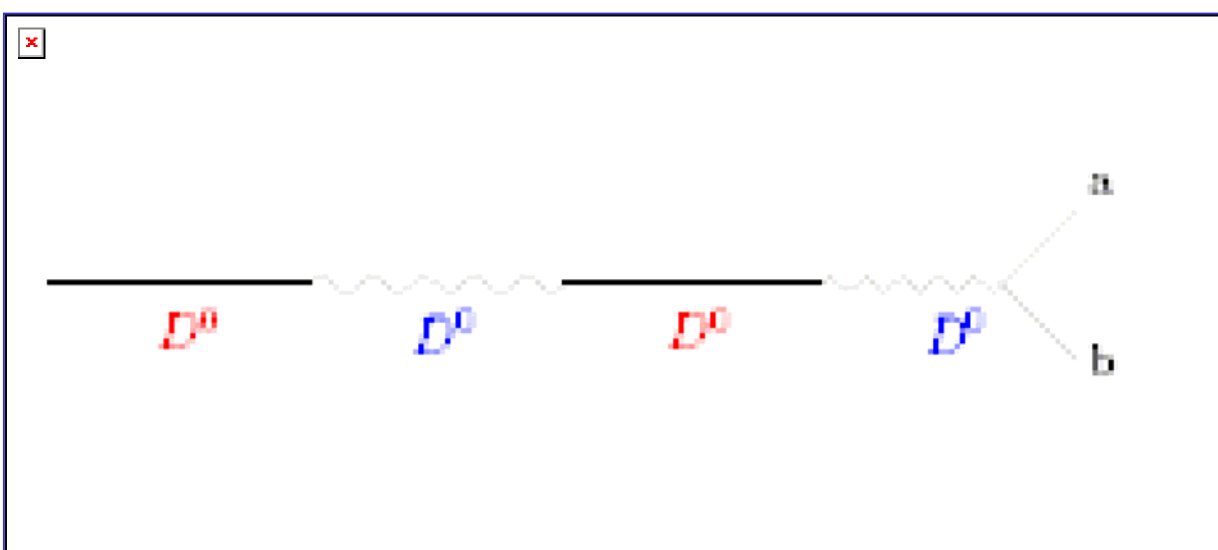
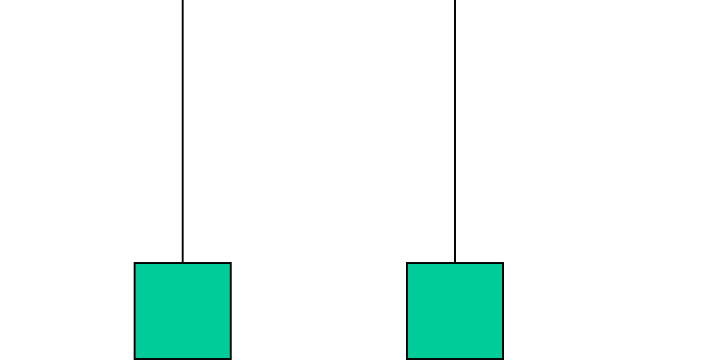
2-8 July 2006



# Math of Mixing I

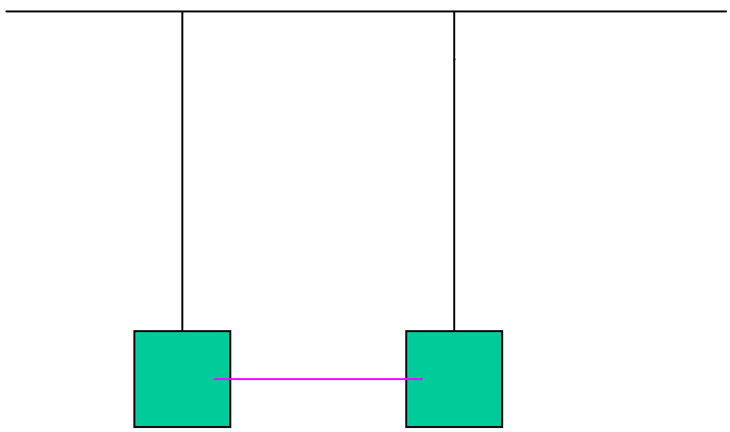
## Uncoupled Pendulums



$\omega_1 = \omega_2$ $\Gamma_1 = \Gamma_2$

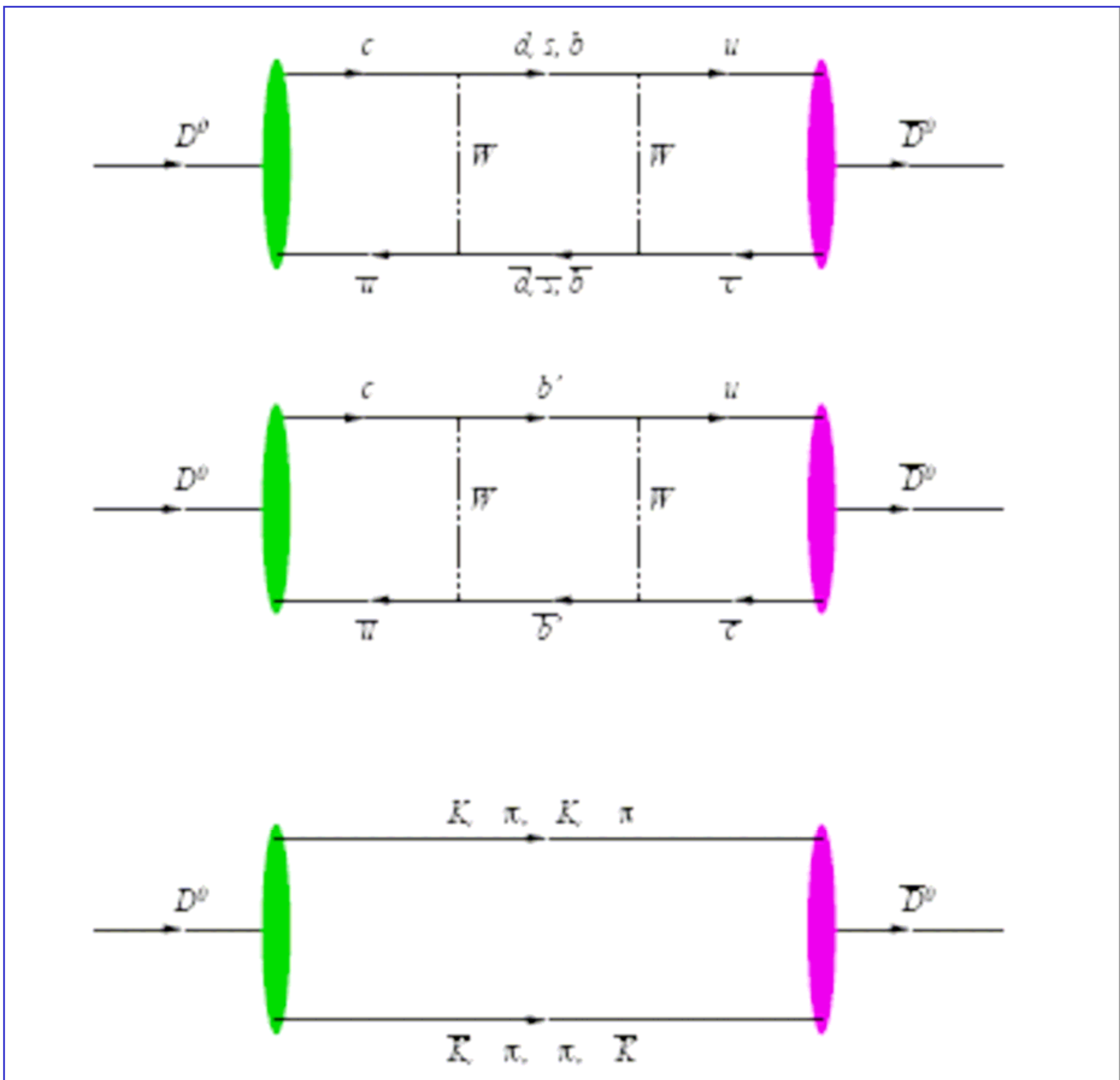
# Math of Mixing II

## Coupled Pendulums

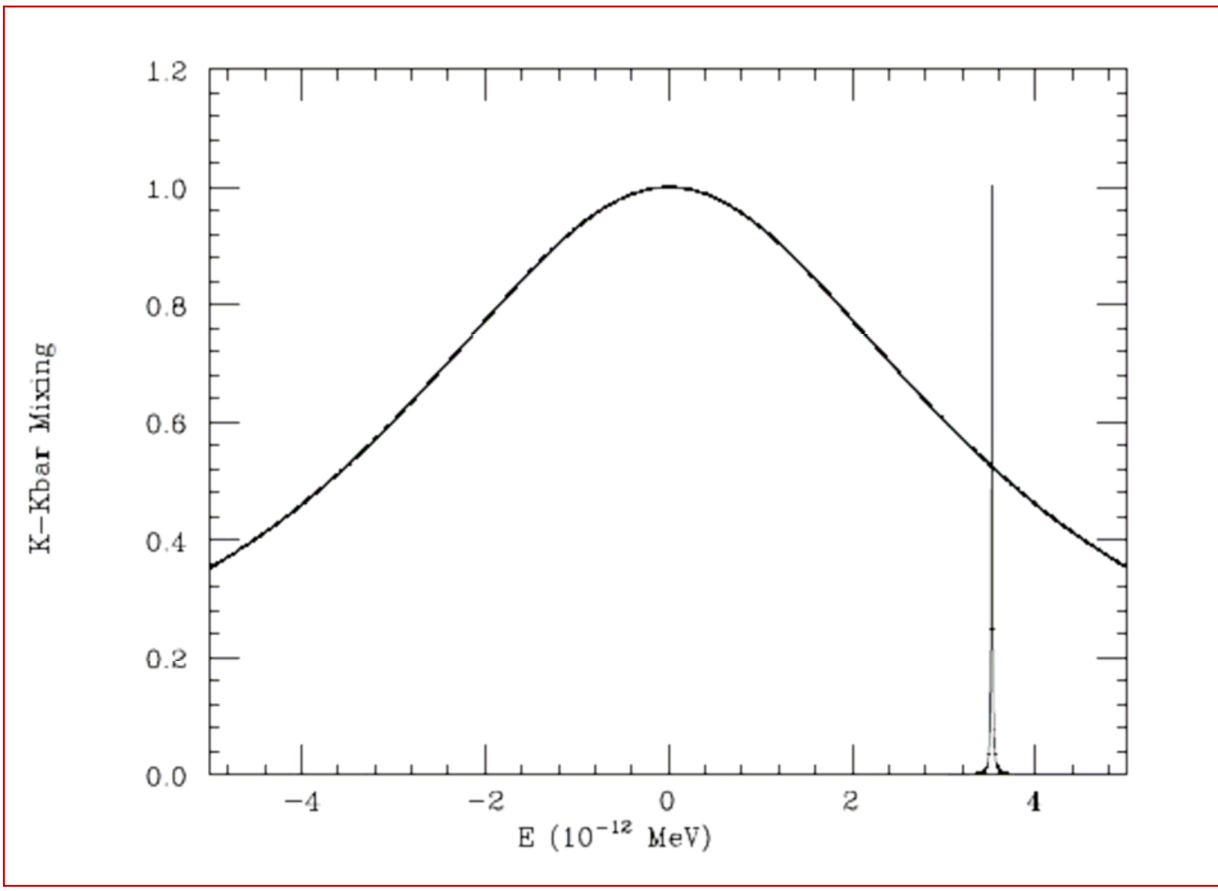


$\Delta\omega = \omega_1 - \omega_2$ $\Delta\Gamma = \Gamma_1 - \Gamma_2$

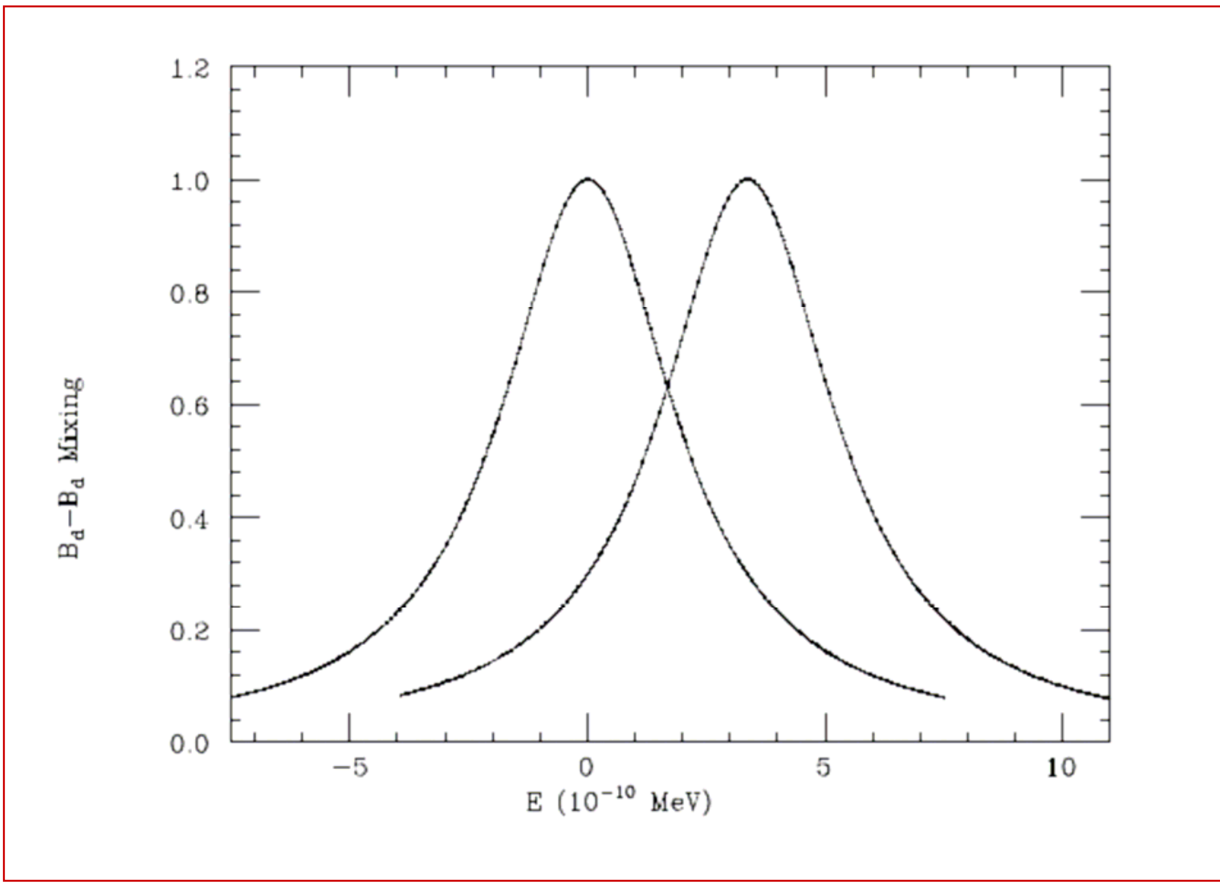
# The 'Coupling Spring'



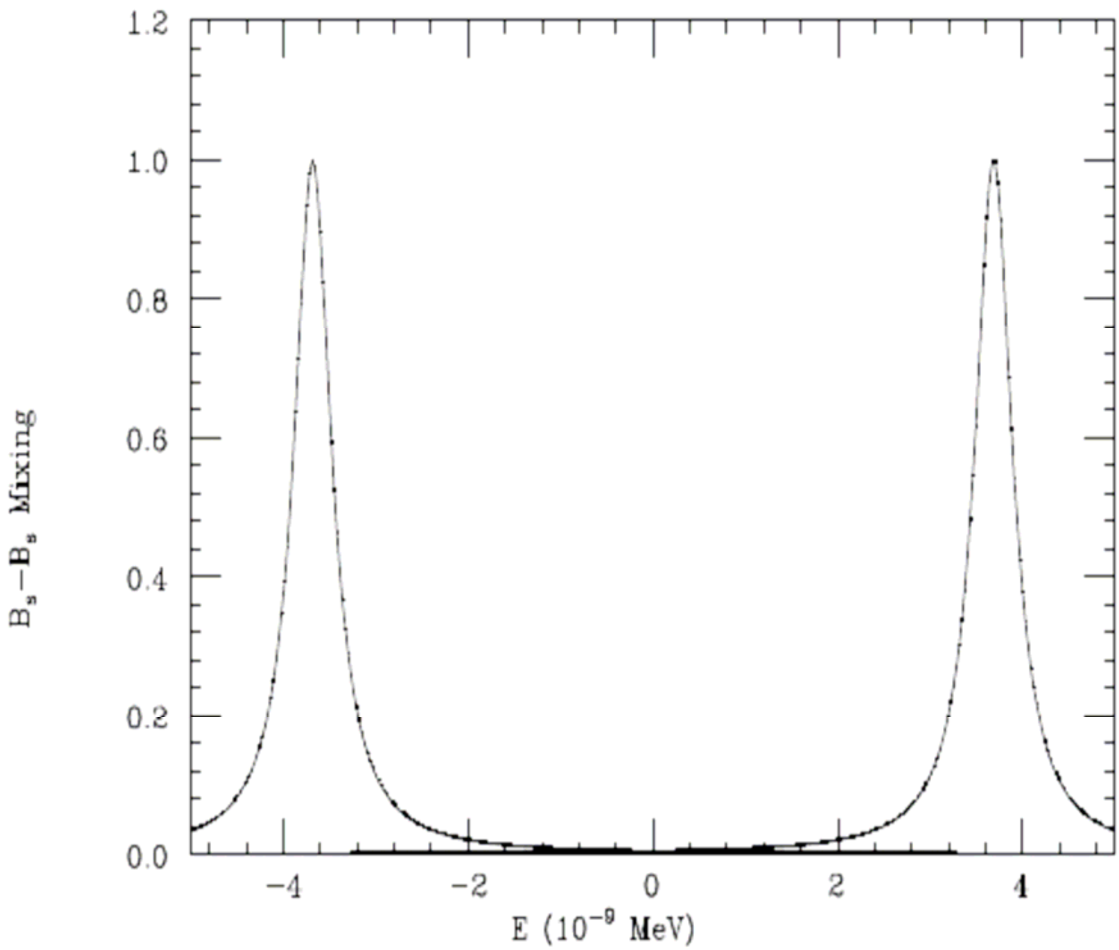
# Mixing of K Mesons



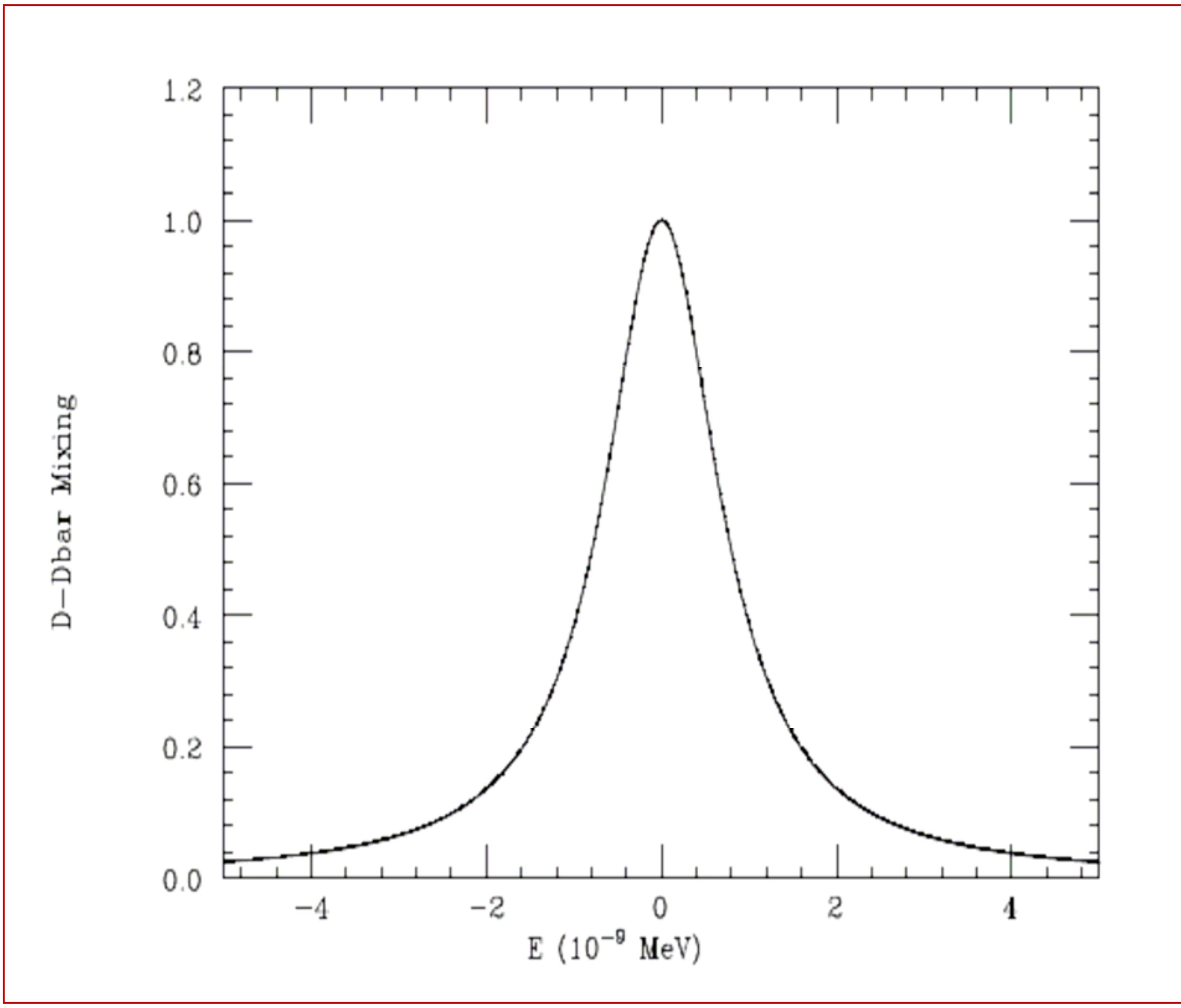
# Mixing of $B_d$ Mesons



# Mixing of $B_s$ Mesons



# Mixing of $D^0$ Mesons



# Existing $D^0$ Bounds

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

x < 0.029 (PDG)

$$y \cong \frac{\Gamma_1 - \Gamma_2}{2\Gamma}$$

y = 0.008 ± 0.00 (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 = 0.009 ± 0.004)

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

# Theory of $D^0$ Mixing

1] Why is $D^0$ mixing so small?

We know why!

2] Just how small is it?

We don't know this yet ….

3] Theoretical Studies

a) Mixing in Standard Model (SM)

Quark level

Hadron level

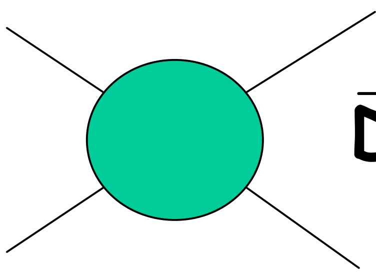
b) Mixing for New Physics (NP)

Motivated by small SM effect!

# Charm Mixing and the OPE*

**Expand in increasing operator dimension:**

$D^0$



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

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

**D=6: Two local 4F operators**

**D=9: Fifteen local 6F operators**

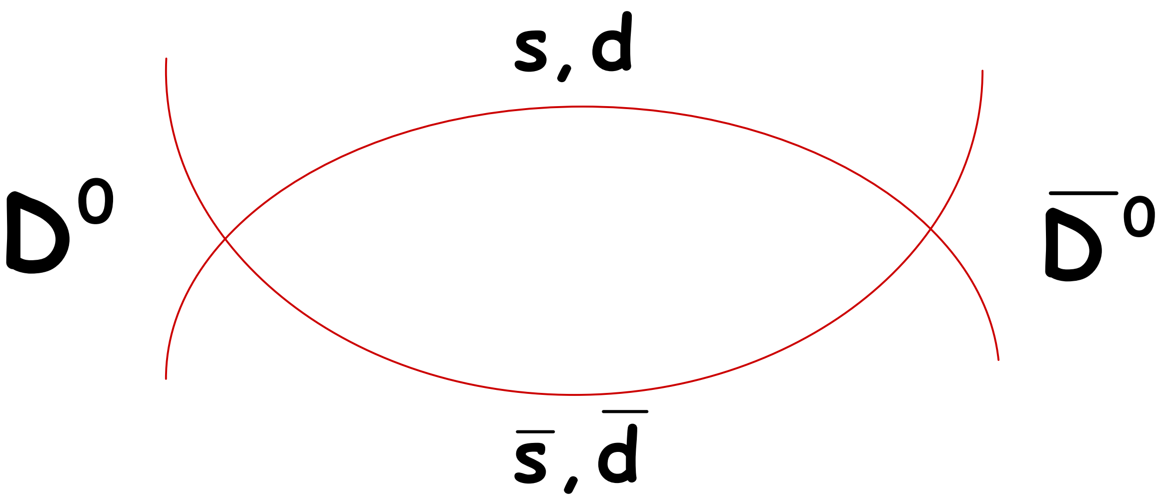
**Etc**

*[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** | | | |

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# Flavor Cancellations

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| $s\bar{s}$ | $\frac{1}{2}$ | | |
| $d\bar{d}$ | $\frac{1}{2}$ | | |
| $s\bar{d} + d\bar{s}$ | -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

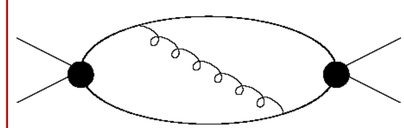
$\Delta\Gamma$ at d=6 $(m_d=0)$:

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

# Allowing for QCD

**Expand in $\alpha_s$**

[EG & Petrov PLB 625 (2005) 53]



(c)

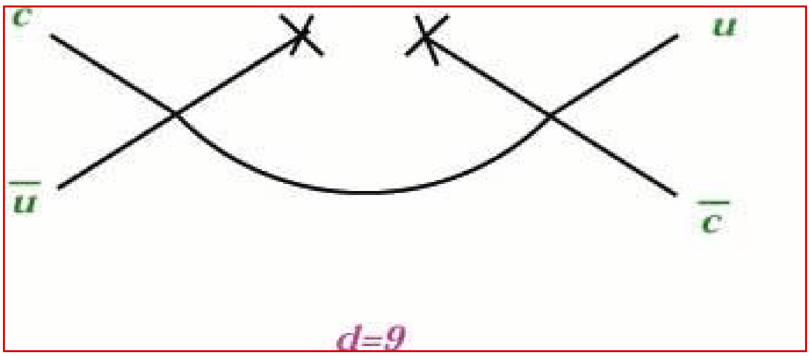
| | x | y | Comment |
|---|---|---|---|
| $\alpha_s^0$ (LO) | $z^2$ | $z^3$ | $x^{(LO)} >> y^{(LO)}$ |
| $\alpha_s^1$ (NLO) | $z^2$ | $z^2$ | $x^{(NLO)} > y^{(NLO)}$ |

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

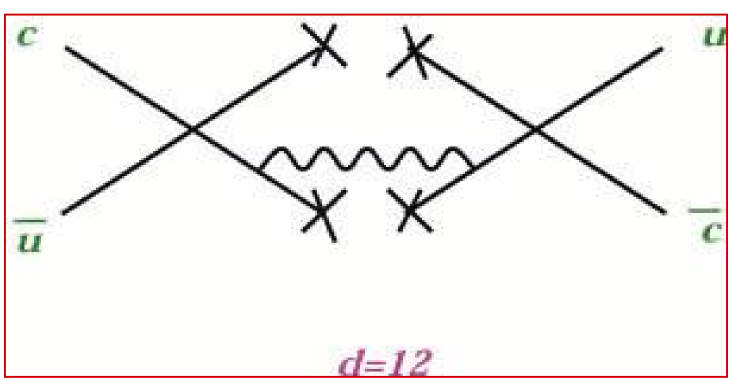
**Note NLO > LO (!)**

# Higher Terms in the OPE*

## D = 9 ($\propto$ $z^{3/2}$ )




## D = 12 ($\propto$ z )





*[Ohl, Ricciardi & Simmons NP B403 (1993) 605]
[Bigi & Uraltsev, NP B592 (2001) 92]

# Status of Quark-level Theory*

1. **OPE:** Expand in operator dimensions d = 6, 9, 12, …

2. **QCD:** Expand in $\frac{\alpha_s}{4\pi}$

3. **CKM:** Expand in $z = \frac{m_s^2}{m_c^2}$

## Triple Expansion!

*[Gagik, Golowich, Petrov (in progress)]

# $\Delta\Gamma$ and Hadrons

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

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

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

**Using a model:**

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

# $\Delta\Gamma$ and Hadrons (cont)

## Using data:

### (a) Basic Idea

Use experimental branching ratios
Divide out phase space
Take square root

### (b) Early Work [UMass PRD 33 (1985)178]

Choose $n = P^+P^-$
$= K^+K^-, \pi^+\pi^-, K^-\pi^+, K^+\pi^-$
Have $K^+K^- + \pi^+\pi^- - 2\,[\,K^-\pi^+\ \ K^+\pi^-\,]^{1/2}$
SU(3) Limit: Zero via cancellation
Real World: SU(3) is broken!
Effect seemed large
Preliminary finding: 'y large'
But data uncertain in 1985 ( esp. $K^+\pi^-$ )

# $\Delta\Gamma$ and Hadrons (cont)

## (c) Recent [FGLNP PRD 69 (2004) 114021]

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

Data much improved by 2004

Analyze the various sectors

Find SU(3) breaking not so large

4P sector cannot cancel (4K state absent)

Conclude ’$y \sim 10^{-2}$ possible’

But analysis error-bar limited …(?)

## (d) Nearby Resonance [GP PL B427 (1998) 172]

Can get enhancement if $M_D \cong M_R$

Promising idea but data inadequate

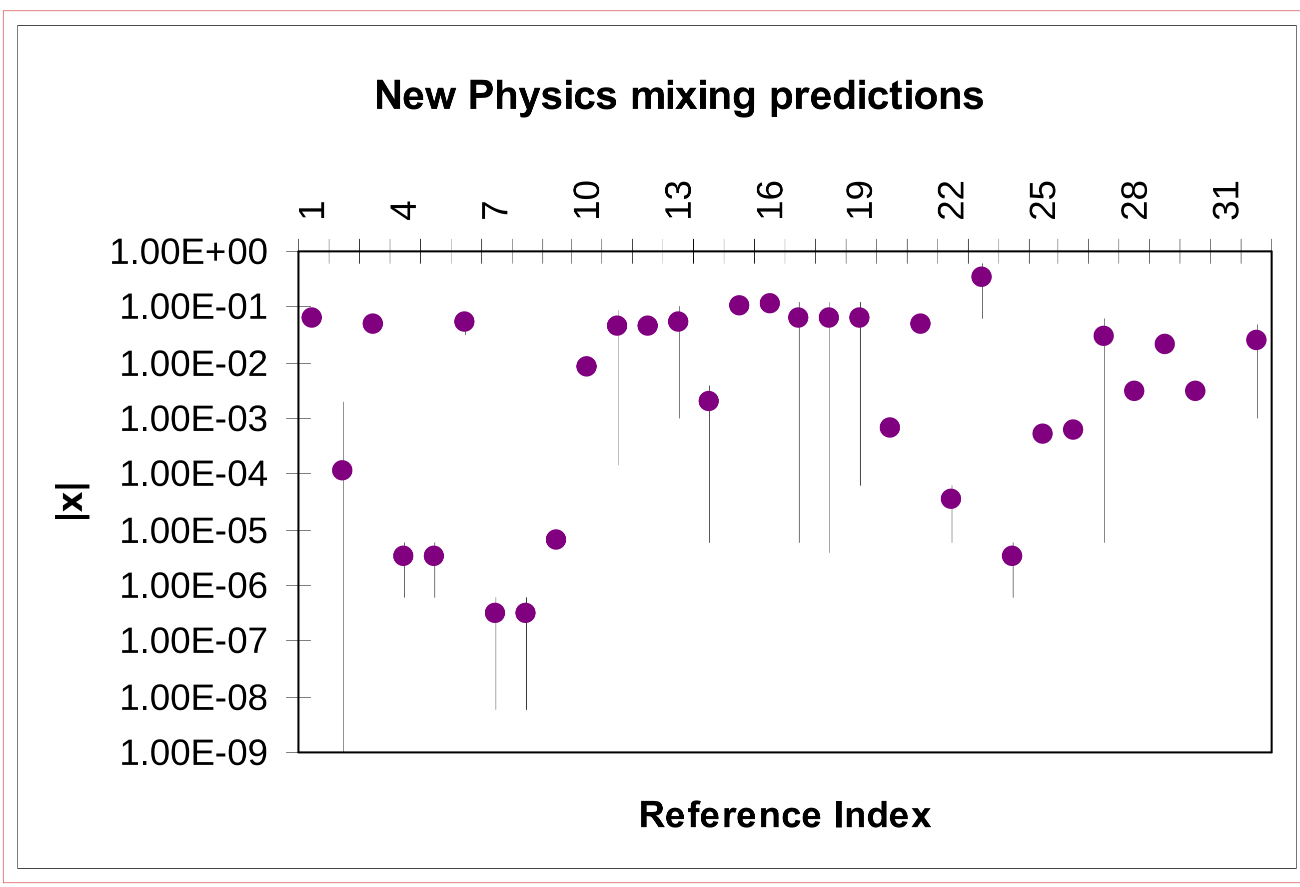
# New Physics

**Motivations**

- **It should be there!**
- **SM mixing is relatively small.**

**Problems**

- **Which new physics?**
- **Whom to believe?**



# Unified Analysis*

## a] Spectrum of Possibilities

- **Extra gauge bosons**

  **(LR models, etc)**
- **Extra scalars**

  **(Multi-Higgs models, etc)**
- **Extra fermions**

  **(Little Higgs, etc)**
- **Extra dimensions**

  **(Universal extra dimensions, etc)**
- **Extra global symmetries**

  **(SUSY, etc)**

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

# b] Low-E Description of NP

## Ex: New Physics Operator

$$O_{NP} = K(m_c)\bar{u}_R \gamma^\mu c_R \bar{u}_R \gamma_\mu c_R$$

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

**Suppose NP scale M:** $m_t > M > m_b$

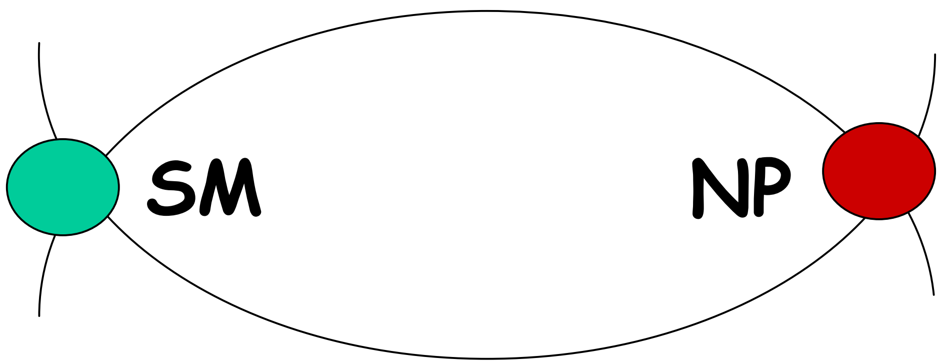
**Let** $r(m_1, m_2) = \alpha_s(m_1)/\alpha_s(m_2)$

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

**Where** $C(M, m_c) = r^{6/23}(M, m_b) r^{6/25}(m_b, m_c)$

[EG, Hewett, Pakvasa, Petrov (in progress)]
[CFLMSS NP B523 (1998) 501]

# c] $\Delta\Gamma$ and New Physics*




**NP can affect $\Delta\Gamma$ !**

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

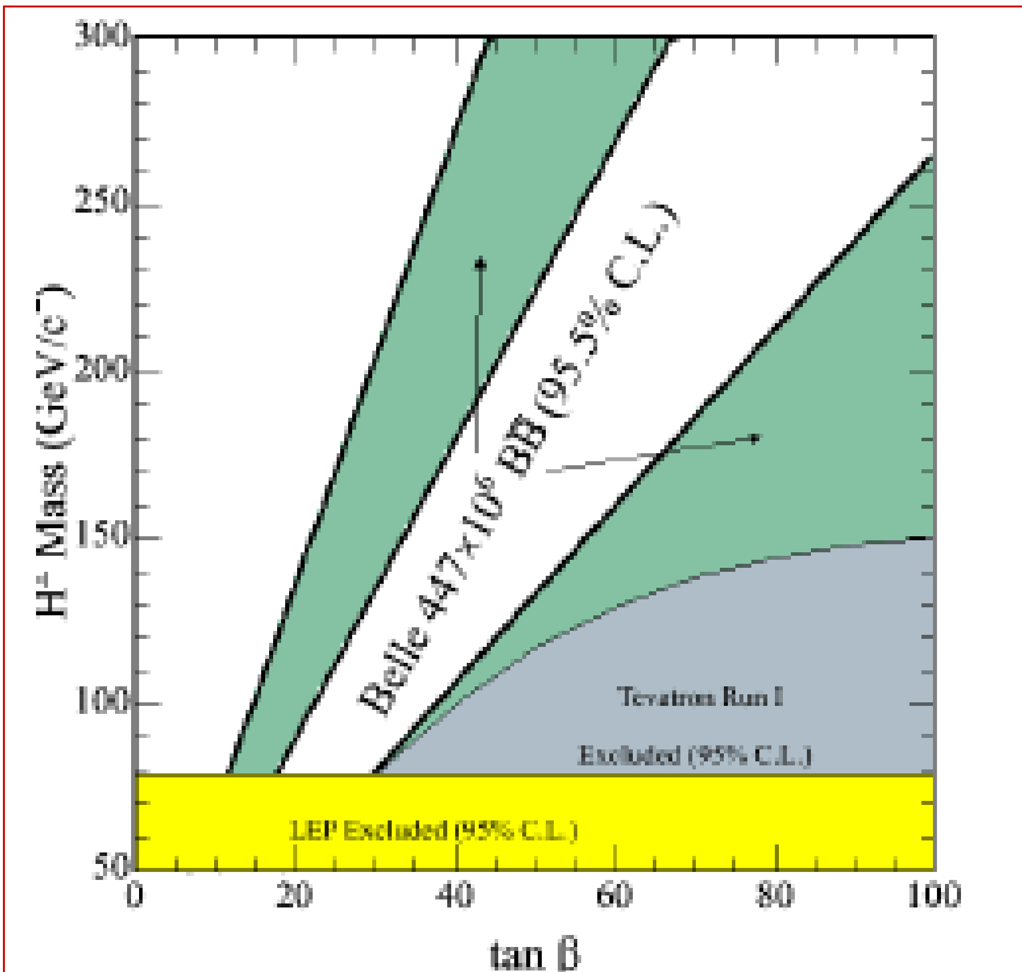
**Processes like $c\bar{u} \to q_1 \bar{q}_2$**

**Paper in preparation**

*[Golowich, Pakvasa, Petrov]

# d] Constraining NP Parameters

**Slow progress continues in this area.**
**Broad, community-wide effort.**
**Not glamorous, ultimately important!**




[K. Ikado (Belle), talk on $B \to \tau\nu_\tau$ at FPCP 2006]

# Rare Charm Decays

**Some are more interesting than others.**

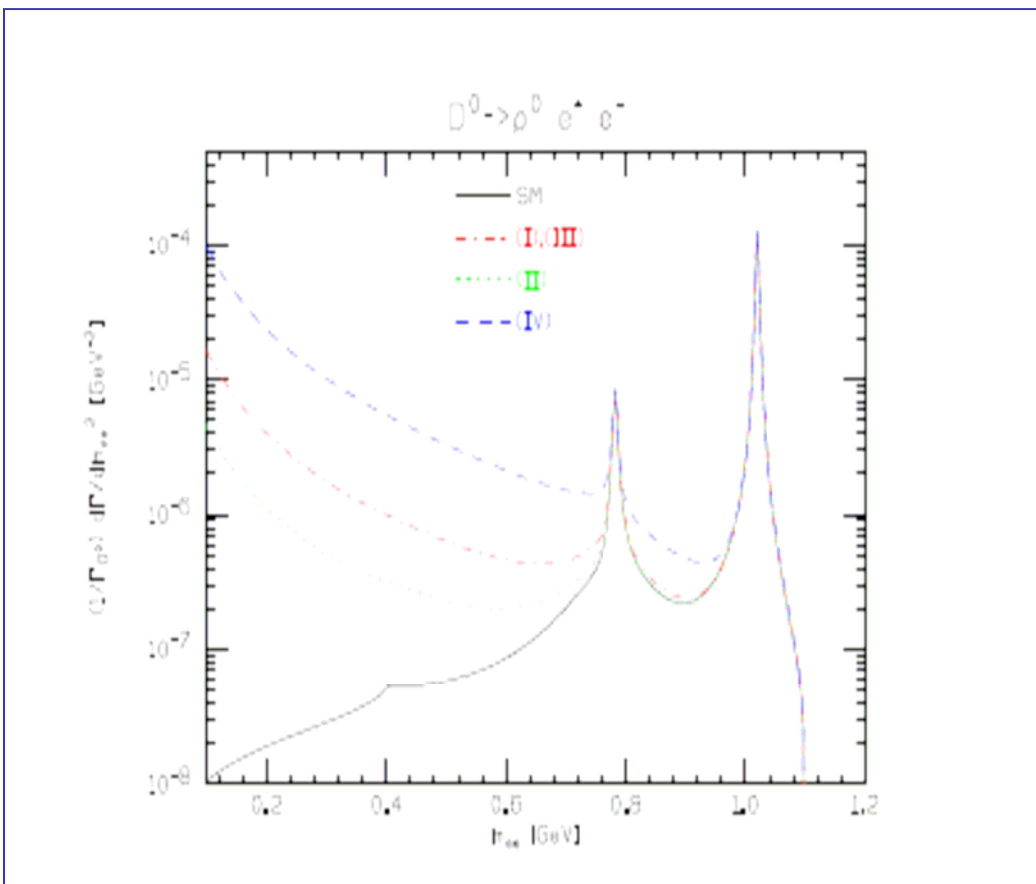
**Ex: D $\rightarrow V\gamma$ dominated by SM effects.**

**[BGHP PR D52 (1996) 6383]**

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

**[BGHP PR D66 (2002) 014009]**

**Also see [FP PR D73 (2006) 054026]**

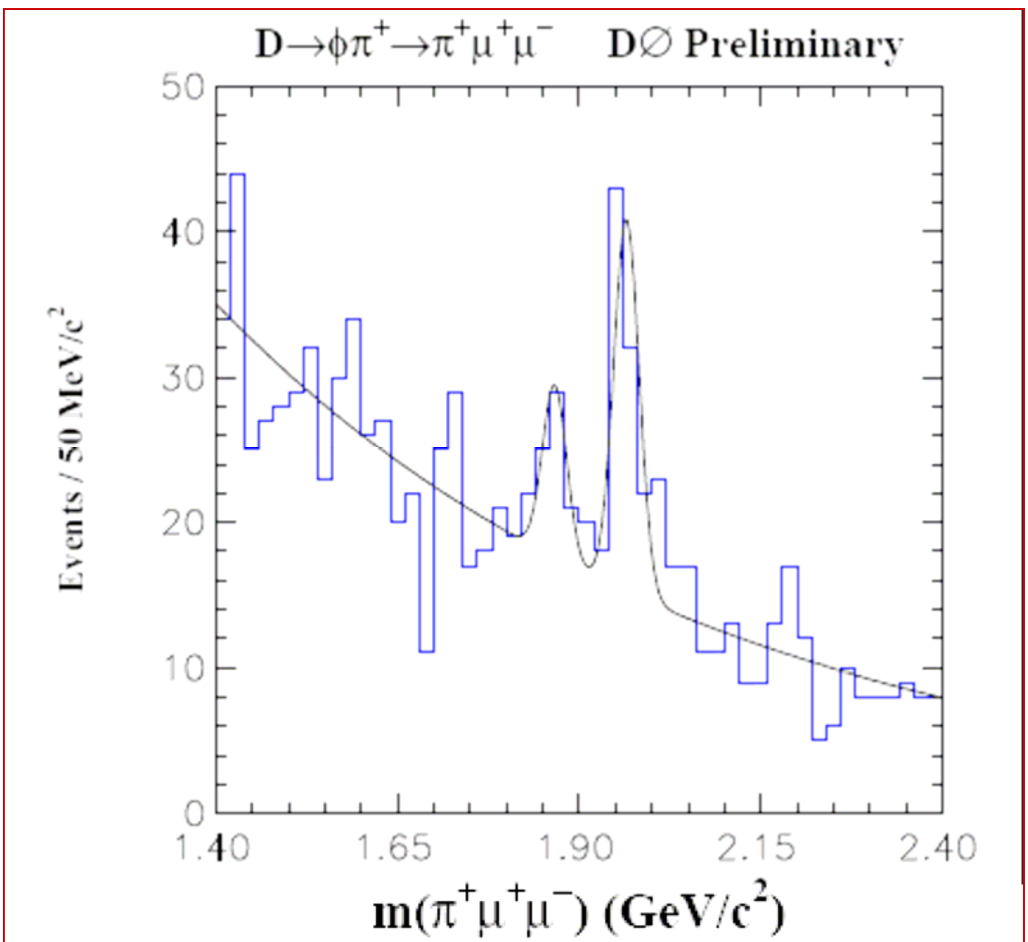


# Rare Charm Decays (cont)

**Experimental studies underway.**

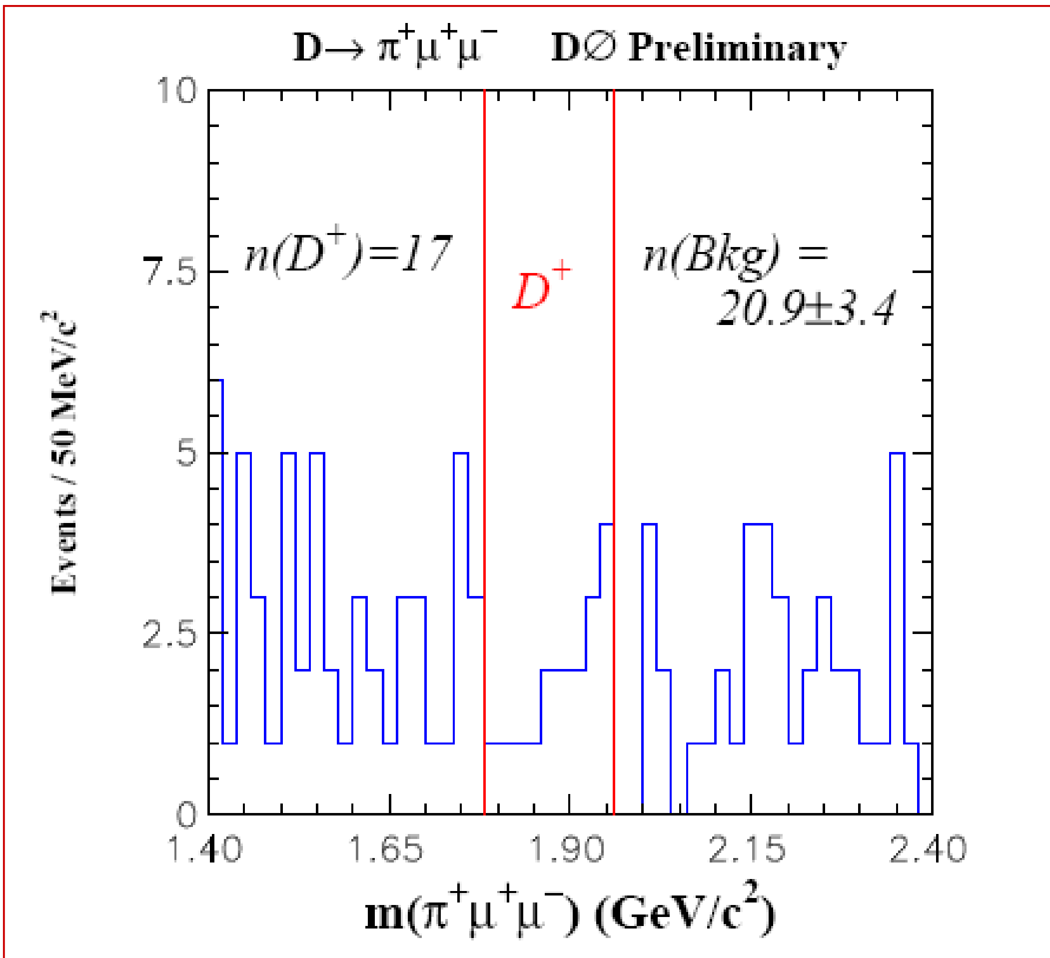
**Below is a recent D0 plot involving**

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



# Rare Charm Decays (cont)

**But no signal yet in the continuum.**
**A good beginning: 'Best' bound yet**




**Data is 500 times above SM and 10 times above Little Higgs, but already probes RPV SUSY**

# CP Violations

## 'Direct' CP-violations

### Two-body Decay Asymmetries

$$\frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})}$$

### Some Decay Asymmetries

| Neutral | PDG | Charged | PDG |
|---|---|---|---|
| $D^0 \to K^+K^-$ | **0.005 ± 0 .016** | $D^\pm \to \phi\pi^\pm$ | **-.014 ± .033** |
| $D^0 \to \pi^+\pi^-$ | **0.021 ± 0 .026** | $D^\pm \to \pi^\pm K^+K^-$ | **0.002 ± 0 .011** |
| $D^0 \to K_S\pi^0$ | **0.001 ± 0 .013** | $D^\pm \to K^\pm K^{*0}$ | **-0.02 ± 0 .05** |
| $D^0 \to \pi^0\pi^+K^-$ | **-.031 ± 0 .086** | | |

### First Principles Calculation?

### Amplitude Phases Problematic!

# Dalitz Plots

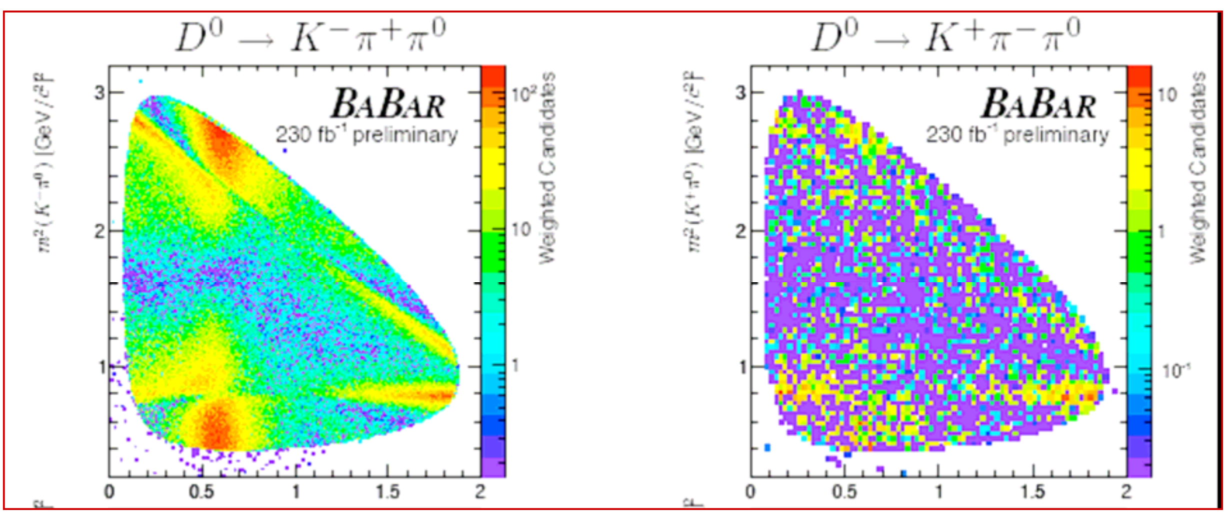
## Sensitive to both Mixing and CPV.
## Studies by CLEO-c, Belle, BaBar

- CLEO performed an analysis of $D^0 \to K_S^0 \pi^+ \pi^-$

  $-4.5\% < x < 9.3\%$

  $-6.4\% < y < 3.6\%$

  (statistically limited)




## Suggestions for future experiments

**[Asner & Sun PR D73 (2006) 034024]**

**[Petrov PR D69 (2004)111901]**

# Concluding Remarks

- **$D^0$ Mixing**

**Experiment:**

**A number of studies underway (Good!)**
**More sensitivity required.**
**Desired goal: To probe $0.001 < y < 0.01$**
**Hints already seen at Belle and BaBar?**

**Theory:**

**SM [Quarks]: Triple expansion (D, $\alpha_s$ , z)**
**Calculation to date to NLO with D=6**
**Find $x \cong y \cong 10^{-6}$**
**More to come (Difficult!)**

**$\Delta\Gamma$ [Hadrons]:**
**One theory model gives $y \cong 10^{-3}$**
**Phenomenology seems to allow a larger value**

**New Physics:**
**Updated theory analysis on the way**

# Concluding Remarks (cont)

- **Rare Decays**

**Theory:**
**SM and NP analyses already in the literature**

**Experiment:**
**Experiments underway, esp** $D \to M\ell^+\ell^-$
**More sensitivity needed.**

- **CP Violations**

**Experiment:**
**More sensitivity needed.**
**Detection strategies being formulated:**
**(I) Quantum correlations**
**(Ii) Single-tagged *vs* Double-tagged**
**(iIi) Time-dependent *vs* time-integrated**