Charm Mixing - Theory
[Also Some CP-Violation]

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Charm Mixing thru the Years

1970's

Experiment – Discovery of Charm

Theory – Correlated D's via e+e- Production

1980's

SM Theory – Short distance D-mixing

SM Theory – Long distance D-mixing

1990's

Fixed-target Experiments (E687, E791)

FOCUS result y_{CP} ~ 3.4%

2000's

B-factory Experiments (BaBar, Belle, CLEO)

Dalitz studies (CLEO, Belle)

2007 (Wow!)

'Measurement' of D-mixing (BaBar, Belle, CLEO, CDF)

2008

Time for reflection? Futures planning ?

D^0 Mixing (2007)

HFAG Charm Subgroup values:

$$x = \frac{\Delta M}{\Gamma} \qquad x_D = (8.4^{+3.2}_{-3.4}) \cdot 10^{-3}$$

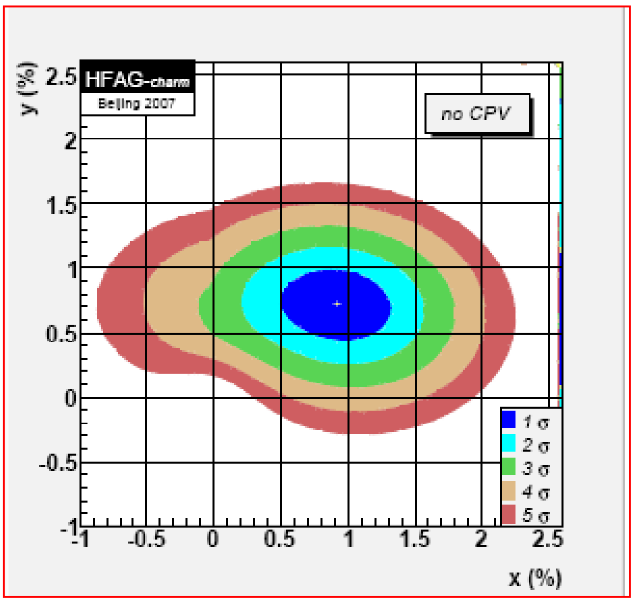
$$y = \frac{\Gamma_1 - \Gamma_2}{2\Gamma} \qquad y_D = (6.9 \pm 2.1) \cdot 10^{-3}$$

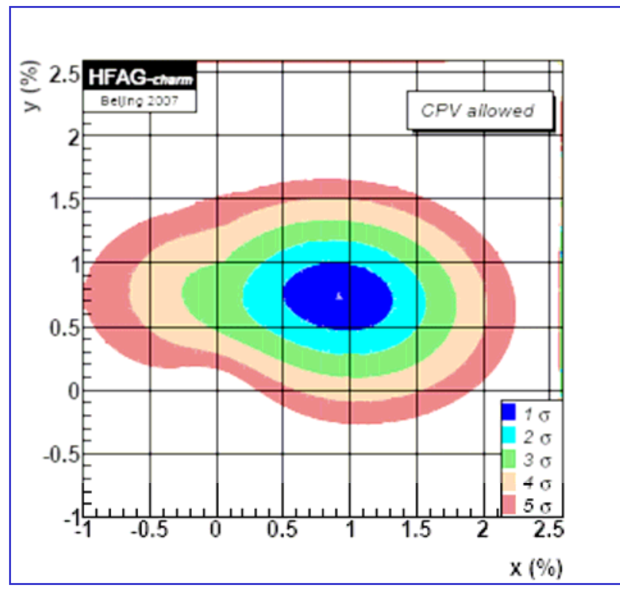
The above x_D is a 2.4 σ effect.

PRL discovery criteria are:
a) 'Observation': >5σ
b) 'Evidence': 3σ-to-5σ
c) 'Measurement': <3σ

D^0 Mixing (2008)

HFAG Group (Schwartz hep-ex/0803.0082v2)





Contours for y(%) vs x(%).

1] x differs from 0 by 3.0σ,

2] y differs from 0 by 4.1σ,

3] The point x=y=0 excluded by 6.7σ.

HFAG Global Fits (2008)

No CPV

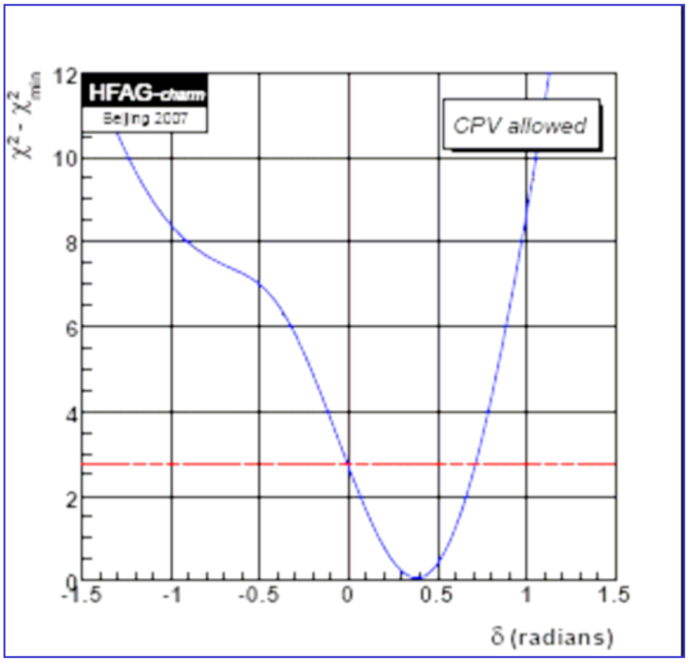
x(%)	$0.98^{+0.26}_{-0.27}$	
y(%)	0.75 ± 0.18	
$\delta(^\circ)$	$21.6^{+11.6}_{-12.6}$	← Strong phase!

CPV-allowed (95% C.L.)

x(%)	$0.39 \to 1.48$
y(%)	$0.41 \to 1.13$
$\delta(^\circ)$	$-6.3 \to 44.6$

Theories with x~y~0.1% untenable?

The Strong Phase δ



Defn: δ = relative phase between $D^0 \rightarrow K^+\pi^-$ and $D^0 \rightarrow K^-\pi^+$.

Origin of 'Wrong Sign' $K^+\pi^-$ in D^0 Decays: Via DCS decays and via mixing.

x' and y':

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

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

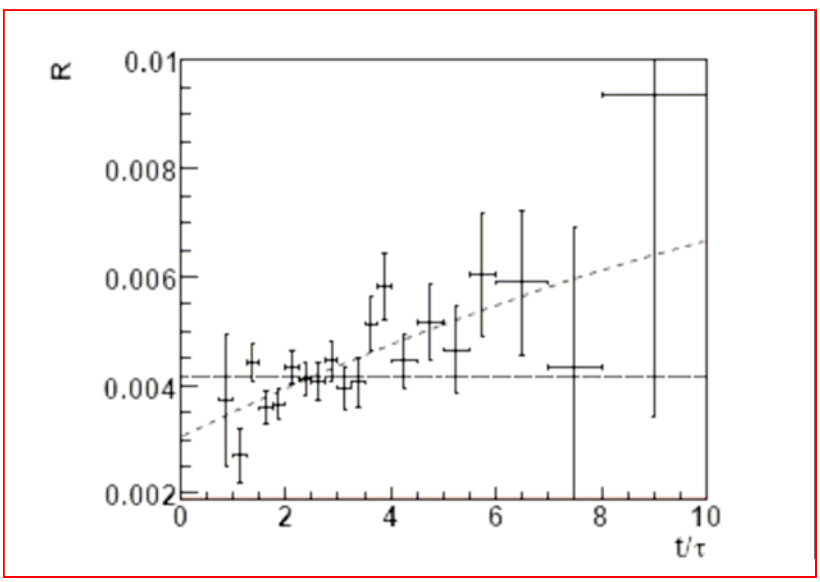
SU(3) invariant world: $\delta = 0$.

Recent Example: CDF

CDF (Phys. Rev. Lett. 100 (2008) 1218020)

Extract x', y', and R_D via fit to data of

$$R\left(\frac{t}{\tau}\right) = R_D + \sqrt{R_D}\, y' \frac{t}{\tau} + \frac{x'^2 + y'^2}{4}\left(\frac{t}{\tau}\right)^2$$



There is no fundamental physics in δ -- it is a detail of strong interactions. δ is actually an irritant, a nuisance.

δ and Resonance Model

Falk, Nir, Petrov JHEP 9912 (1999) 019

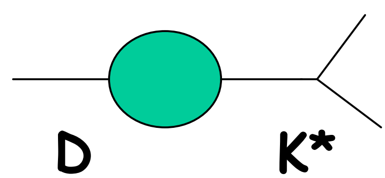
Consider $D^0 \rightarrow K\pi$ modes (DCS and CF).

Influence of near-by resonance?

For example, try K*(1945).

DCS: $A = A_T + A_R\, e^{i\varphi}$

CF: $B = B_T + B_R\, e^{i\varphi}$



$$\tan\varphi = -\frac{\Gamma_{K^*}\, m_D}{m_D^2 - m_{K^*}^2}$$

Regain $\delta = 0$: $A_T/A_R = B_T/B_R$

Sign of δ not determined.

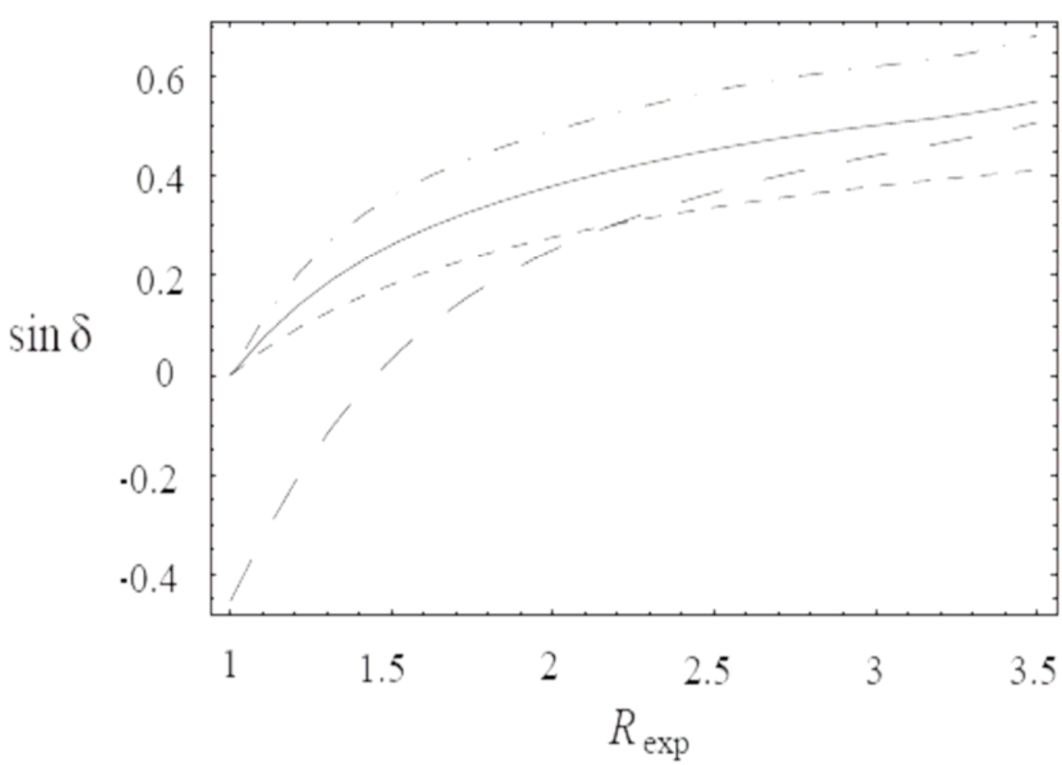
δ and Resonance Model (cont)

A Measure of SU(3) Breaking

$$R \equiv \frac{B(D^0 \to K^+\pi^-)}{B(\overline{D}^0 \to K^+\pi^-)} \bullet \frac{|V_{ud}\ V_{cs}|^2}{|V_{us}\ V_{cd}|^2}$$

Evaluation in 1999: R = 1.58 ± 0.49

Is SU(3) breaking large? Thus δ large?

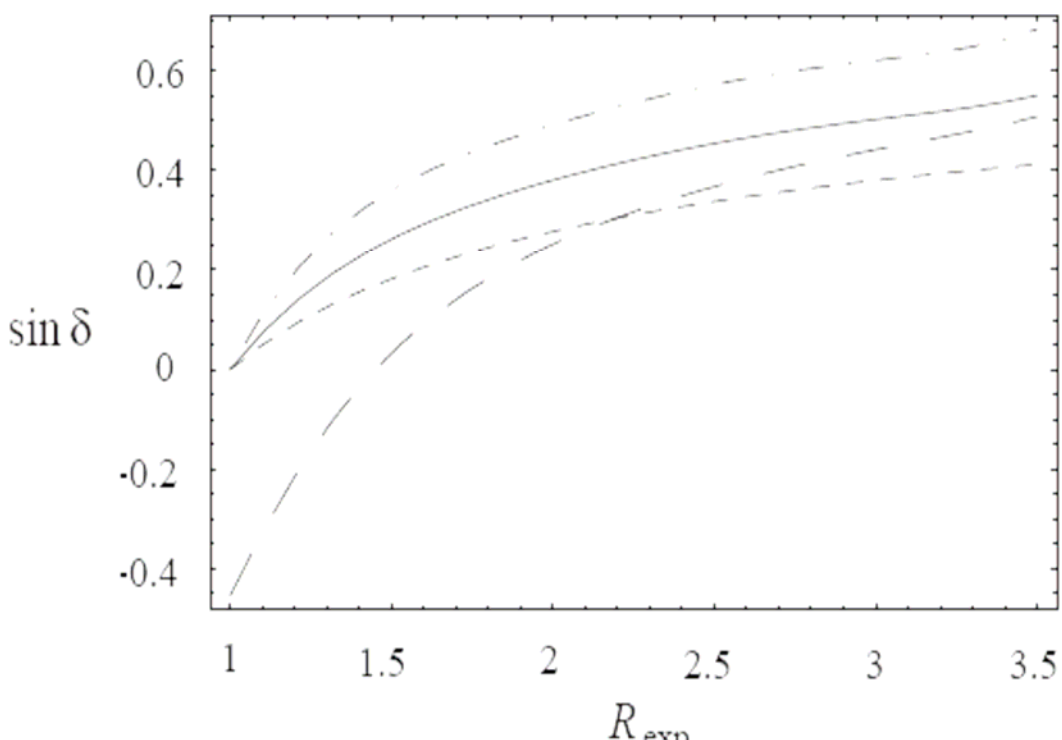


δ and Resonance Model (cont)

A Measure of SU(3) Breaking

$$R \equiv \frac{B(D^0 \to K^+\pi^-)}{B(\overline{D}^0 \to K^+\pi^-)} \bullet \frac{|V_{ud}\,V_{cs}|^2}{|V_{us}\,V_{cd}|^2}$$

Evaluation in 2008: R = 1.28 ± 0.05



So δ **not** 'very large'.

δ and Factorization Model

D-N Gao, Phys Lett B645 (2007) 59

Study 7 $D \to K\pi$ modes

A by-product is estimation of δ

Quark diagram topologies ($A \cong -0.4\ E$)

Factorization

Monopole form factors

SU(3) breaking mainly in f_K, f_π

Find: $|\delta| \cong 10^o \to 19^o$

Measuring δ

D. Asner and W. Sun [PR D73 (2006) 034024]

$$e^+e^- \rightarrow \psi(3770) \rightarrow D^0\overline{D}^0 \rightarrow i\,j$$

D^0 pair has P=C=-1

Define $CP|D_1\rangle = -|D_1\rangle$ $CP|D_2\rangle = +|D_2\rangle$

Quantum correlations and D_1, D_2 production

$$\begin{aligned}\Gamma(i,j) &\propto |\langle i|D^0\rangle\langle j|\overline{D}^0\rangle - (i \leftrightarrow j)|^2 \\ &= |\langle i|D_2\rangle\langle j|D_1\rangle - \langle j|D_2\rangle\langle i|D_1\rangle|^2\end{aligned}$$

To get sensitivity to δ, include CP eigenstates $S_\pm$

$$\begin{aligned}F^{cor}{}_{S_+/K\pi} &= |\langle S_+|D_2\rangle\langle K^-\pi^+|D_1\rangle|^2 \\ &= A^2_{S_+} A^2_{K^-\pi^+} |1 + re^{-i\delta}|^2\end{aligned}$$

D-mixing in the Standard Model

Quark-level Analysis ('SD')

Operator Product Expansion
QCD Perturbation Theory
Expansion in m_s/m_c
Evaluation of B-parameters

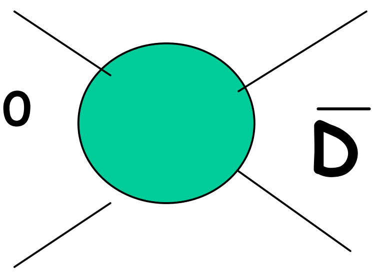
Hadron-level Analysis ('LD')

Focus on y_D
Direct Involvement of Data/Models
Role of SU(3) Breaking
Possible Large Effect

SD and the OPE

Georgi [PL B297 (1992) 353]

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

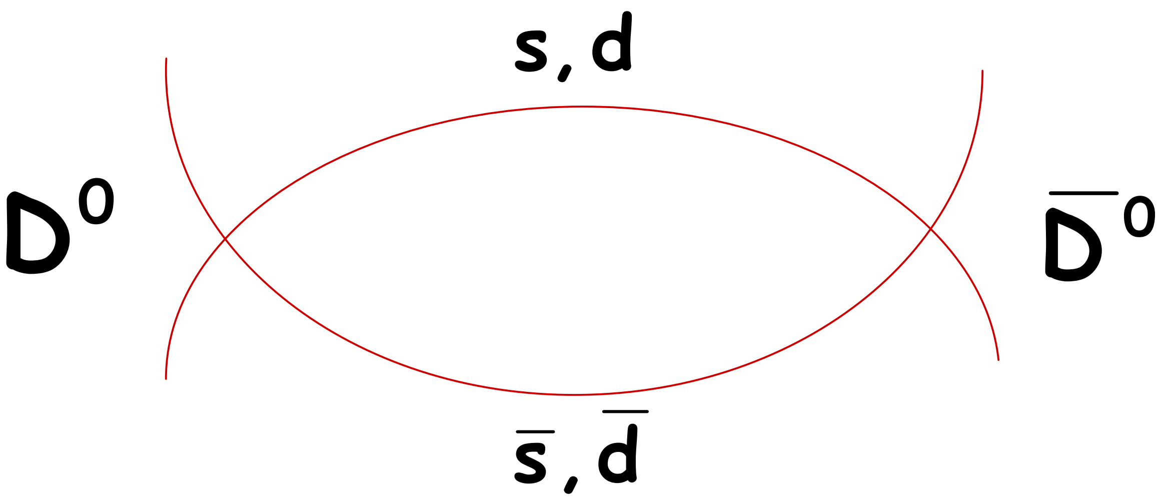
D=9: Fifteen local 6F operators

Etc

Dimension Six

Ignore b quark. Sum over

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



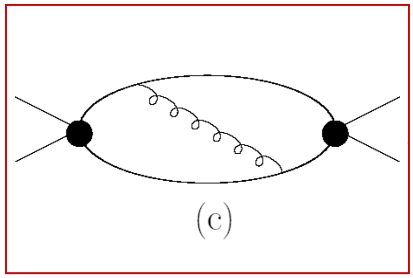
Expand in powers of

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

Status of Dimension Six

EG & Petrov [PLB 625 (2005) 53]

Expand in α_s:



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

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

SD Summary

Triple Expansion:

1. Operator dimensions d = 6, 9, 12, …

2. QCD factors $\alpha_s/4\pi$

3. Mass ratio $z = (m_s/m_c)^2$

Largest Claimed Effect ~ O(0.1%):

Bigi & Uraltsev, [NP B592 (2001) 92]

Evidently too small.

LD and y_D ($\Delta\Gamma$)

$$y_D = \frac{1}{2M_D\Gamma_D} \text{Im} < \bar{D}^0 \,|\, i\int d^4x \; T(H_w(x)H_w(0)) \,|\, D^0 >$$

Insert hadronic int. states: $\sum_n | n >< n |$

Require matrix elements: $< n \,|\, H_w \,|\, D^0 >$

1. Comprehensive model for D decays:
   Naples Group [PRD 51 (1995) 3478]

Find $y_D \sim 10^{-3}$
Evidently too small!

LD ($\Delta\Gamma$) cont.

2. Use data

(a) Early Work UMass [PRD 33 (1985) 178]

Choose $n = P^+P^-$

$$y_D \quad \propto \quad \Gamma_{\pi^+\pi^-} + \Gamma_{K^+K^-} - 2\sqrt{\Gamma_{K^+\pi^-}\Gamma_{K^-\pi^+}}$$

Back then, SU(3) breaking seemed large.
If so, 'y_D large'.

(b) Recent Work FGLNP [PRD 69 (2004) 114021]

SU(3) breaking 'small' (2^{nd} order).
But 4P sector cannot cancel.
'$y_D \sim 10^{-2}$ possible'.
But uncontrollable uncertainties,

New Physics and x_D

EG, Hewett, Pakvasa, Petrov [PR D76 (2007) 095009]

As the LHC era begins, many extras possible:

- 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)

GHPP study 21 NP models.

Results of x_D Analysis

Fourth Generation	$\|V_{ub'} V_{cb'}\| m_{b'} < 0.5$ GeV
Q=-1/3 Singlet Quark	$s_2 m_s < 0.27$ GeV
Q=+2/3 Singlet Quark	$\|\lambda_{uc}\| < 2.4\ 10^{-4}$
Little Higgs	Tree: Same as Q=-1/3 Singlet Qk
	Box: Can reach observed xD
Generic Z'	$M_{Z'}/C > 2.2\ 10^3$ TeV
Family Symmetries	$m_1/f > 1.2\ 10^3$ TeV
Left-Right Symmetries	No Constraint
Alternate L-R Symmetries	$M_R > 1.2$ TeV ($m_{D1} = 0.5$ TeV)
	$(\Delta m/m_{D1})/M_R > 0.4\ \text{TeV}^{-1}$
Vector Leptoquark Bosons	$M_{VLQ} > 55\ (\lambda_{PP}/0.1)$ TeV
Fl-Cons Two-Higgs Doublet	No Constraint
Fl- Change Neutral Higgs I	$m_H/C > 2.4\ 10^3$ TeV
Fl-Change Neutral Higgs II	$m_H/\|\Delta_{uc}\| > 600$ GeV
Scalar Leptoquark Bosons	See RPV SUSY
Higgless	$M > 100$ TeV
Universal Extra Dimensions	No Constraint
Split Fermion	$M/\Delta y\| > 600$ GeV
Warped Geometries	$M_1 > 3.5$ TeV
Minimal SUSY Standard	$\|(\delta^u{}_{12})_{LR,LR}\| < 0.035$
	$\|(\delta^u{}_{12})_{LL,RR}\| < 0.25$
SUSY Alignment	$M > 2$ TeV
SUSY with RPV	$\lambda'_{12k}\lambda'_{11k}/m < 1.8\ 10^{-4}/100$ GeV
Split SUSY	No Constraint

NP Constraints

Ineffective Models:

Four yield no constraints:

1. Split supersymmetry
2. Universal Extra Dimensions
3. Left-right symmetric
4. FC two-Higgs doublet

Ineffective because NP mass scale too large, severe cancellations operative, etc.

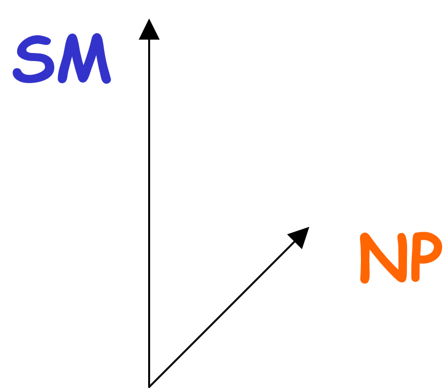
Constrainable Models:

There are 17 which can, in principle, exceed the observed x_D. For these, we can get constraints on masses and mixing parameters.

Is D-mixing NP or SM?

Observed mixing at roughly 1% level.
Could be NP (many NP models large enough).
Could be SM (but prediction might never be precise [lattice-QCD someday?]).

If both SM & NP, relative phase unknown.



Will lack of a clean separation between SM and NP remain a fact of life for D-mixing studies?

A Particular NP Model

$\not{R}_P$ VIOLATING SUSY

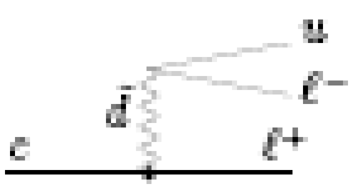
Introduce RPV Interaction $\mathcal{L}_{\not{R}}$

$$R_P = (-)^{3(B-L)+2S} = \begin{cases} +1 & \text{(particle)} \\ -1 & \text{(sparticle)} \end{cases}$$

$$\mathcal{L}_{\not{R}} = \lambda'_{ijk}\left[-\tilde{e}^i_L \bar{d}^k_R u^j_L - \tilde{u}^j_L \bar{d}^k_R e^i_L - (\tilde{d}^k_R)^* (\bar{e}^i_L)^c u^j_L + \ldots\right]$$

Constrain the $\{\lambda'_{ijk}\}$ via data (i,j,k generation labels).

Example: $c \to u\ell^+\ell^-$



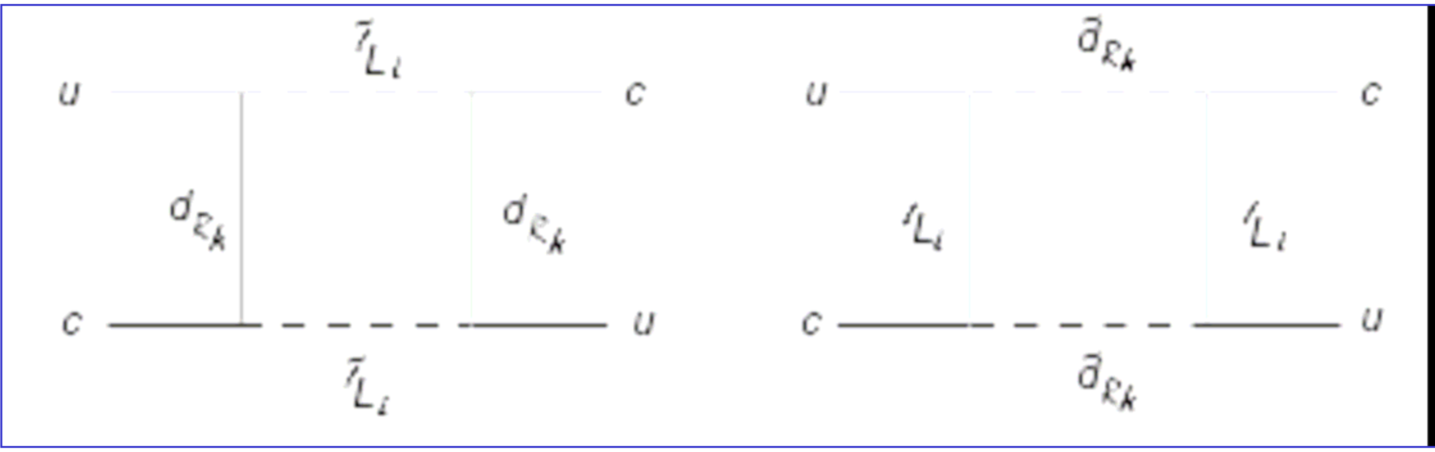
Tree-level non-electromagnetic process!

Mediated by exchange of down squark $\tilde{d}$.

Effect proportional to $\lambda'_{i1k} \cdot \lambda'_{i2k}$.

RPV SUSY (cont)

Feynman Diagrams for D-mixing:



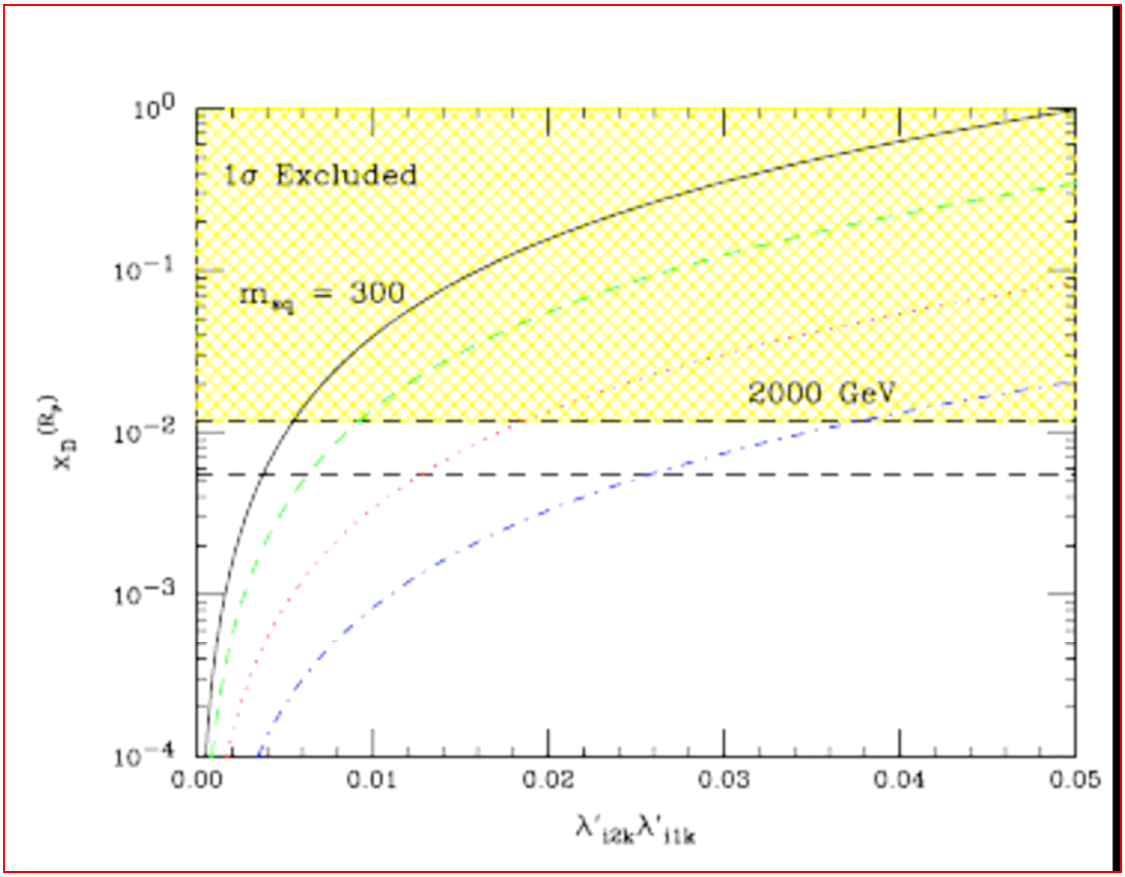
Effective Hamiltonian:

$$\mathcal{H}_{R_p} = \frac{1}{128\pi^2}(\tilde{\lambda}'_{i2k}\tilde{\lambda}'_{i1k})^2\left[\frac{1}{m^2_{\tilde{\ell}_{L,i}}} + \frac{1}{m^2_{\tilde{d}_{R,k}}}\right]Q_1,$$

Constrain Parameters: $\tilde{\lambda}'_{i1k}\ \tilde{\lambda}'_{i2k}$

RPV SUSY (cont)

Graph x_D vs RPV parameters:



Constraints tighten with improved limits on x_D.

At present, get $\tilde{\lambda}'_{i1k}\,\tilde{\lambda}'_{i2k} \leq 1.8\,10^{-3}\,\dfrac{\tilde{m}_d}{100\text{ GeV}}$

RPV SUSY (cont)

But the same RPV parameters occur in rare D decays such as $D^0 \rightarrow \mu^+\mu^-$ and $D^+ \rightarrow \pi^+\mu^+\mu^-$.

Burdman, EG, Hewett, Pakvasa, [PR D66 (2002) 014009]

Current PDG limit:

$$Br[D^0 \rightarrow \mu^+\mu^-] < 1.3\ 10^{-6}$$

which implies (preliminary)

$$\tilde{\lambda}'_{21k}\ \tilde{\lambda}'_{22k} \leq 7.\,10^{-3}\ \frac{\tilde{m}_d}{100\ \text{GeV}}$$

See that: D-mixing and rare decays both interesting, roughly competitive at present, and rare decay sensitivity can be improved.

Comment on NP Searches

My Choice: Discovery & Precision

1] Discovery at LHC

If NP revealed then:

a) Specific model identified, or
b) Situation unclear

2] Precision at Super-factory and/or LHC-B

Study Rare Modes:

a) Check/verify LHC finding
b) Clarification via pattern of rare effects

CPV Strategies

Later this morning (I trust).
CHARM 2007: A. Petrov, 'CPV in Charm Decay'.
Basic Formalism: Z-Z Xing, PR D55 (1997) 196

TWO RECENT PAPERS

1] Super B-factory: Li, Yang PR D74 (2006) 094016

Probe D-mixing and CPV using coherent $D^0 \overline{D}^0$ events from $\Upsilon(1S)$ decays.

Why? Boost factor in $\Upsilon(1S)$ rest frame ($\cong$ 2.33) allows precise determination of proper time interval t between the two D decays,

$$R(f_1, f_2; t) = d\Gamma[\Upsilon_{1S} \to f_1 f_2]/dt$$

Treat symmetric and asymmetric Υ(1S) factories
Various CPV asymmetries discussed. Estimate
$10^7 \to 10^8$ D-pairs per year.

CPV Strategies (cont)

2] $D \to K^*K$ Decays: Xing, Zhou PR D75 (2007) 114006

Run at $\psi(3770)$ and $\psi(4140)$ at τ-charm factory.

Note $C[\psi(3770)] = -1$, $C[\psi(4140)] = +1$

Define:

$\Gamma^{++}{}_C = \Gamma(K^{*+}K^-, K^{*+}K^-)_C$ $\Gamma^{--}{}_C = \Gamma(K^{*-}K^+, K^{*-}K^+)_C$

$\Gamma^{+-}{}_C = \Gamma(K^{*+}K^-, K^{*-}K+)_C$ $\Gamma^{-+}{}_C = \Gamma(K^{*-}K^+, K^{*+}K^-)_C$

"Favorable to measure decays of correlated D's into $(K^{*+}K^-, K^{*+}K^-)$, etc states on the $\psi(4140)$."

Ex: Probe CPV at $\psi(4140)$

CPV Observable $\dfrac{\Gamma_+^{++} - \Gamma_+^{--}}{\Gamma_+^{+-}}$

CPV Theory

Grossman, Kagan, Nir [PR D75 (2007) 036008]

Consider SCS:

$$c \rightarrow u\,\bar{q}\,q \qquad \text{with } q = s,d$$

Final States:

CP eigenstates: K^+K^-, $\pi^+\pi^-$, $\varphi\pi^0$, *etc.*
Non-CP eigenstates: KK^*, $\rho\pi$, *etc.*

Asymmetry Possibilities:

'Current' (as of 2006) limits at $O(10^{-2})$.
SM 'not much larger than $O(10^{-4})$'.
Thus NP window of opportunity!

CPV Asymmetries (HFAG 1/31/08)

Asymmetry	Mode	Value
$\frac{\Delta\Gamma}{2\Gamma}$	$D^0 \rightarrow K^+K^-$	$.0015 \pm .0034$
	$D^0 \rightarrow \pi^+\pi^-$	$.0002 \pm .0051$
	$D^0 \rightarrow K^-\pi^+\pi^0$	$.0016 \pm .0089$
	$D^+ \rightarrow K_S\pi^+$	$.0086 \pm .009$
	$D^+ \rightarrow K^+K^-\pi^+$	$.0059 \pm .0075$
$\frac{\Delta\tau}{2\tau}$	$D^0 \rightarrow K^+K, \pi^+\pi^-$	$.0012 \pm .0025$

CPV Theory (cont)

Time-integrated Asymmetries:

Ex: $$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}.$$ $(\bar{f} = f)$

Arising from decay, mixing, interference

$$a_f = a_f^d + a_f^m + a_f^i$$
$$a_f^d = 2 r_f \sin\varphi_f \sin\delta_f$$

Regarding NP Models

1] Some loop amplitudes can give $a_f^d \sim O(10^{-2})$
Tree amplitudes cannot (D-mixing constraints)

2] Some SUSY models can give $a_f^d \sim O(10^{-2})$
Models with Minimal Flavor Violation cannot.

3] Only SCS decays probe gluonic penguins. Large a_f^d seen in SCS unlikely for CD, DCS decays.

….plus more….

Concluding Remarks

Experiment on D-mixing:

Can now claim 'evidence' for x_D,y_D and 'observation' of D-Mixing. At long last! Mixing data starts to rule out some theoretical descriptions. Progress on 'strong phase' δ.

SM Theory on D-mixing:

Quarks (SD):

To date, find $x_D \cong y_D \cong 10^{-6}$ Tiny! But triple expansion very slowly convergent.

Hadrons (LD):

Might be that x_D , $y_D \sim 10^{-2}$ but hadronic physics messy as always.

NP Theory on D-mixing:

D-mixing values yield many NP constraints.
Rare D decays also of interest.

CPV Studies:

Charm CPV now at forefront of research. Window for detecting New Physics CPV asymmetries exists but is starting to narrow.