Charm Mixing - Theory
[CP-Conserving only]

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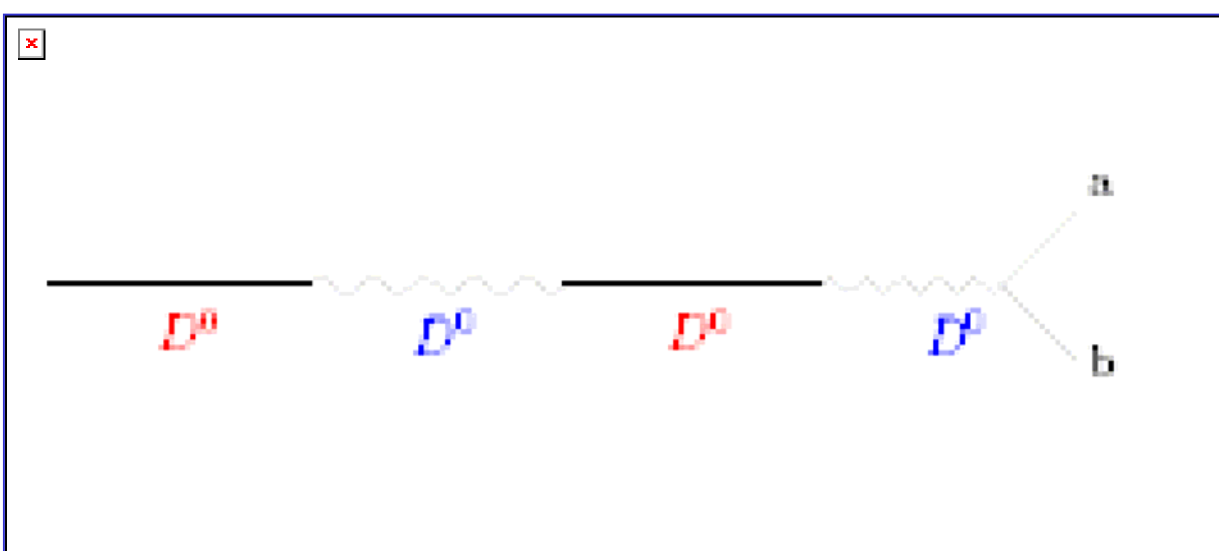

Our Thoughts on y_D and x_D

This talk will refer to:

1] y_D : PRL 98 (2007) 181808-1

New Physics contributions to the lifetime difference in D^0-$\overline{D}^0$ mixing

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2] x_D: arXiv:0705.3650 [hep-ph]

Implications of D^0-D^0 Mixing for New Physics

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Status of D^0 Mixing

At the time of our paper on x_D:

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

$$x_D = (8.7^{+3.0}_{-3.4}) \cdot 10^{-3}$$

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

$$y_D = (6.6 \pm 2.1) \cdot 10^{-3}$$

The above x_D is a 2.4 σ effect.

PRL discovery criteria are:

a) 'Observation': $>5\sigma$

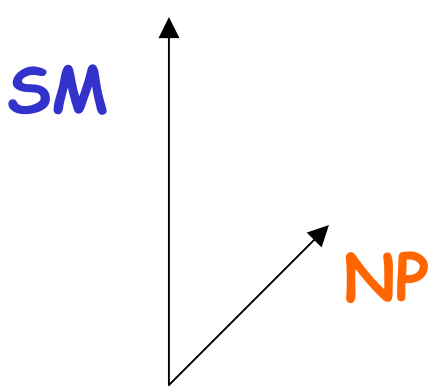
b) 'Evidence': 3σ-to-5σ

c) 'Measurement': $<3\sigma$

Basic Strategy for x_D

Observed Signal at roughly 1% level.
To some, this is 'large' for SM.
Or is it?

Our premise is to study both SM, NP.
We do not know the relative phase.



So we compare pure NP signals to values $x_D = (3.0 \rightarrow 15.0) \cdot 10^{-3}$

Standard Model

Quark-level Analysis

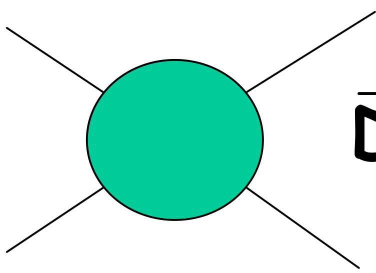
Operator Product Expansion
QCD Perturbation Theory
Expansion in m_s/m_c
Evaluation of B-parameters

Hadron-level Analysis

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

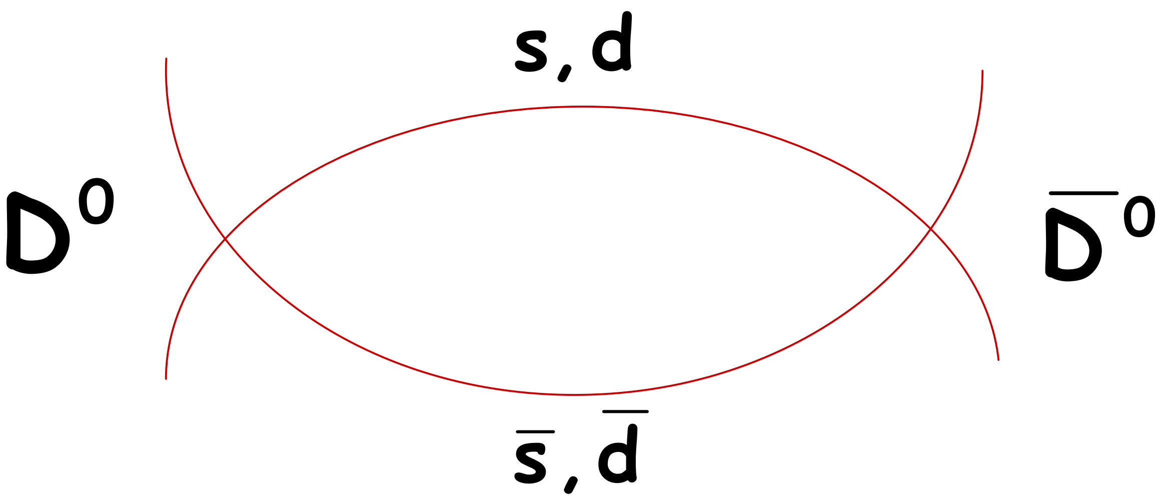
Etc

*[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			

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**	

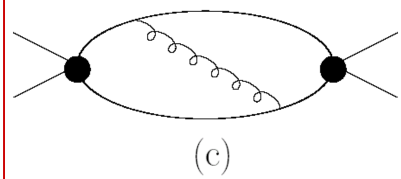
Flavor Cancellations

$\Delta\Gamma$ 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:



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

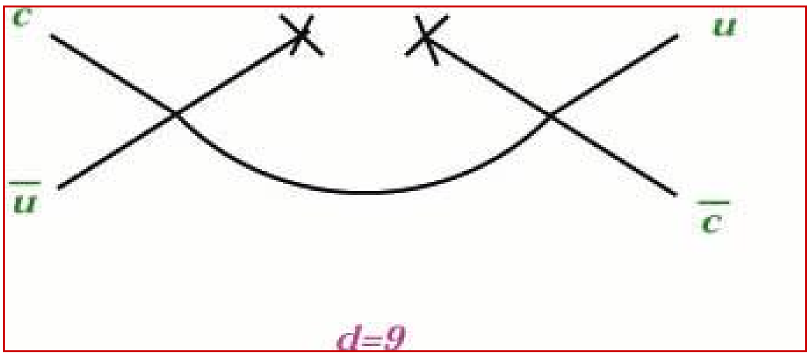
Main LO + NLO Result: $x \cong y \approx 10^{-6}$

(And find NLO > LO)

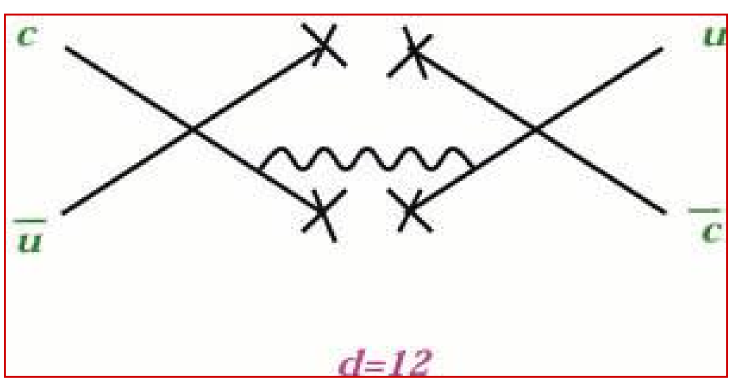
*EG & Petrov PLB 625 (2005) 53

Higher Terms in the OPE*

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



D = 12 ($\propto$ z)



*[Ohl, Ricciardi & Simmons NP B403 (1993) 605]

Quark-Level Summary

Triple Expansion:

1. Operator dimensions d = 6, 9, 12, …
2. QCD factors $\alpha_s/4\pi$
3. Mass ratio $z = (m_s/m_c)^2$

Status:

1. Scale thus far << 1%
2. Scale if all terms included, unknown.

Keep trying!

Bigi & Uraltsev, NP B592 (2001) 92

Gagik, Golowich, Petrov (in progress)

Hadron-level $(\Delta\Gamma)$

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

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

Require matrix elements $< n \mid H_w \mid D^0 >$

1. Use a model: $y_D \sim 10^{-3}$

Naples Group, PRD 51 (1995) 3478

Hadron-level ($\Delta\Gamma$) cont.

2. Use data

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

Choose $n = P^+P^-$

SU(3) Limit: Zero via cancellation

SU(3) breaking important?

Preliminary finding: 'y_D large'

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

Theorem: SU(3) breaking 2nd order

So maybe SU(3) breaking not large

But 4P sector cannot cancel.

Conclude '$y_D \sim 10^{-2}$ possible'

Quite possibly correct.

More persuasive than compelling

Uncontrollable uncertainties,

New Physics in D^0 Mixing

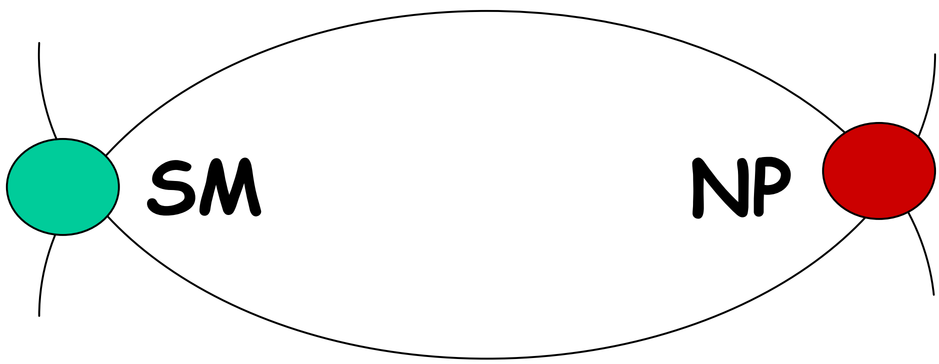
y_D

Intermediate states on-shell.
Thus only light particles propagate.
Can there be any NP effects?
Derive a 'master formula'.

x_D

Intermediate states off-shell.
Many possible NP candidates.
Which one to consider?
How to organize?

New Physics and $\Delta\Gamma$



NP can affect $\Delta\Gamma$!

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

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

Golowich, Pakvasa, Petrov, PRL 98 (2007) 181801.

[Comment]: Chen, Geng, Nam, PRL 99 (2007) 019101.

[Comment^2]: Yeghiyan, arXiv 0707.3285 [hep-ph].

The Master Formula

INPUT

$$\mathrm{H}_{NP}^{\Delta C=-1} = \sum_{q,q'} \mathrm{D}_{qq'} \left[\overline{\mathcal{C}}_1(\mu) \mathrm{Q}_1 + \overline{\mathcal{C}}_2(\mu) \mathrm{Q}_2 \right]$$

$$\mathrm{Q}_1 = \overline{u}_i \overline{\Gamma}_1 q'_j \; \overline{q}_j \overline{\Gamma}_2 c_i \quad \mathrm{Q}_2 = \overline{u}_i \overline{\Gamma}_1 q'_i \; \overline{q}_j \overline{\Gamma}_2 c_j$$

OUTPUT

$$\mathrm{y_D} \;=\; -\frac{4\sqrt{2} G_F}{M_\mathrm{D} \Gamma_\mathrm{D}} \sum_{q,q'} \mathrm{V}^*_{cq'} \mathrm{V}_{uq} \mathrm{D}_{qq'} \left(\mathrm{K}_1 \delta_{ik} \delta_{j\ell} \right.$$

$$\left. + \;\; \mathrm{K}_2 \delta_{i\ell} \delta_{jk} \right) \sum_{\alpha=1}^{5} \mathrm{I}_\alpha(x, x') \, \langle \overline{D}^0 | \, \mathrm{O}_\alpha^{ijk\ell} \, | D^0 \rangle$$

Some Results for y_D

Model	y_D	Comment
RPV-SUSY	$6\ 10^{-6}$	Squark Exch.
	$-4\ 10^{-2}$	Slepton Exch.
Left-right	$-5\ 10^{-6}$	‘Manifest’.
	$-8.8\ 10^{-5}$	‘Nonmanifest’.
Multi-Higgs	$2\ 10^{-10}$	Charged Higgs
Extra Quarks -	10^{-8}	Not Little Higgs

New Physics and x_D

As the LHC era begins, many extras possible (21 models in GHPP)*

- 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: arXiv 0705.3650 [hep-ph]

List of NP Models

Fourth Generation
Q=-1/3 Singlet Quark
Q=+2/3 Singlet Quark
Little Higgs
Generic Z'
Family Symmetries
Left-Right Symmetries
Alternate L-R Symmetries
Vector Leptoquark Bosons
Fl-Cons Two-Higgs Dblt
Fl-Chnge Neutral Higgs I
Fl-Chnge Neutral Higgs II
Scalar Leptoquark Bosons
Higgless
Universal Extra Dims
Split Fermion
Warped Geometries
Minimal SUSY Standard
SUSY Alignment
SUSY with RPV
Split SUSY

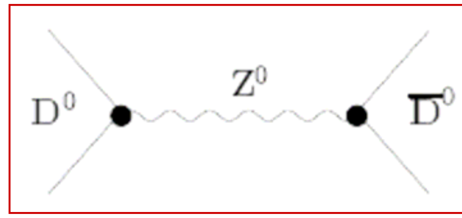
Challenge to the Audience*

Of the 21 NP models, how many turn out to yield contributions too small for D^0 mixing at the observed 10^{-2} level?

Comment: Note many NP models have been on the market for years (e.g., SUSY has been studied for over 30 yrs) and their parameter spaces have been steadily constrained.

* If you have already seen the paper, please keep quiet.

A NP Example



Diagram

Z^0 tree amplitude

Two flavor-changing vertices

Realizations:

Vector-like SU(2)-singlet quarks

E(6): Q = -e/3

Little Higgs: Q = 2e/3

Find $$x_D = \frac{G_F \lambda_{uc}^2}{\sqrt{2} M_D \Gamma_D} C_1(m_c) < \overline{D}^0 | Q_1 | D^0 >$$

Operator Basis

$$Q_1 = \overline{u}_L \gamma_\mu c_L \; \overline{u}_L \gamma^\mu c_L$$

$$Q_2 = \overline{u}_L \gamma_\mu c_L \; \overline{u}_R \gamma^\mu c_R$$

$$Q_3 = \overline{u}_L c_R \; \overline{u}_R c_L$$

$$Q_4 = \overline{u}_R c_L \; \overline{u}_R c_L$$

$$Q_5 = \overline{u}_R \sigma_{\mu\nu} c_L \; \overline{u}_R \sigma^{\mu\nu} c_L$$

$$Q_6 = \overline{u}_R \gamma_\mu c_R \; \overline{u}_R \gamma^\mu c_R$$

$$Q_7 = \overline{u}_L c_R \; \overline{u}_L c_R$$

$$Q_8 = \overline{u}_L \sigma_{\mu\nu} c_R \; \overline{u}_L \sigma^{\mu\nu} c_R$$

Operator Matrix Elements

In vacuum saturation, just two nonperturbative constants (B, B'_S)

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

$$\langle Q_2 \rangle = -\frac{1}{2} f_D^2 M_D^2 B - \frac{1}{3} f_D^2 M_D^2 B'_S$$

$$\langle Q_3 \rangle = \frac{1}{12} f_D^2 M_D^2 B + \frac{1}{2} f_D^2 M_D^2 B'_S$$

$$\langle Q_4 \rangle = -\frac{5}{12} f_D^2 M_D^2 B'_S$$

$$\langle Q_5 \rangle = f_D^2 M_D^2 B'_S$$

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

$$\langle Q_7 \rangle = \langle Q_4 \rangle$$

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

RG Factor

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

Two scales: $M \gg m_c$

Have $C_6(M)$ Need $C_6(m_c)$

Integrate RG equation

Obtain $C_6(m_c) = R[M, m_c] C_6(M)$

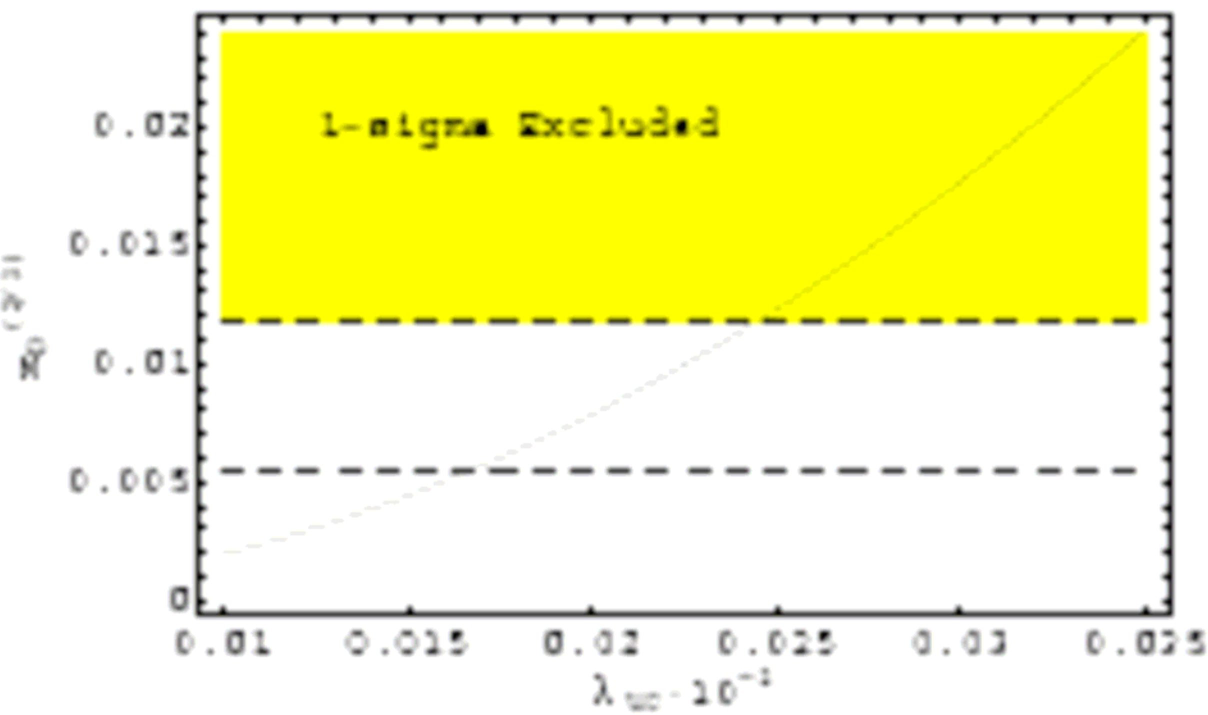
with

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

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

Limit on Q=2/3 Quark Singlet

Plot $x_D^{(2/3)}$ vs λ_{uc}:



D^0-mixing limit on λ_{uc} is about 10^2 better than that from 4x4 CKM unitarity.

Answer to Challenge

Ineffective Models:

Four yield no constraints:

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

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.

Split SUSY – Why So Small?

What 'is' Split SUSY?:

- New variant of SUSY (2003-4)
- SUSY breaks at $m_S >> 1000$ TeV
- Scalars (except Higgs) have mass ~ m_S
- Fermions have usual weak scale mass

Why So Small in D^0 Mixing?:

Large D^0 mixing in SUSY involves squark (i.e.scalar quarks) amplitudes. But squark masses are huge in Split SUSY. Thus the mixing is suppressed.

UEDs – Why So Small?

What 'are' Universal Extra Dimensions?

- Variant (2000) of having TeV^{-1}-sized extra dimensions
- No branes in this approach
- All SM fields reside in the bulk
- Usually one extra dimension

Why So Small in D^0 Mixing?:

Each SM field has an infinity of KK excitations. GIM cancellations affect all save a few b-quark KK terms, but these are CKM suppressed.

Results of x_D Analysis

Fourth Generation	$\lvert V_{ub'} V_{cb'} \rvert m_{b'} < 0.5$ GeV
Q=-1/3 Singlet Quark	$s_2 m_s < 0.27$ GeV
Q=+2/3 Singlet Quark	$\lvert\lambda_{uc}\rvert < 2.4\ 10^{-4}$
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)
	$(\Delta m/m_{D1})/M_R > 0.4$ 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	$m_H/\lvert\Delta_{uc}\rvert > 600$ GeV
Scalar Leptoquark Bosons	See RPV SUSY
Higgless	M > 100 TeV
Universal Extra Dimensions	No Constraint
Split Fermion	$M/\Delta y\rvert > 600$ GeV
Warped Geometries	$M_1 > 3.5$ TeV
Minimal SUSY Standard	$\lvert(\delta^u_{12})_{LR,LR}\rvert < 0.035$
	$\lvert(\delta^u_{12})_{LL,RR}\rvert < 0.25$
SUSY Alignment	M > 2 TeV
SUSY with RPV	$\lambda'_{12k}\lambda'_{11k}/m < 1.8\ 10^{-4}/100$ GeV
Split SUSY	No Constraint

Concluding Remarks

Experiment:

x_D and y_D signals at 1% level. Great!
But more sensitivity desired.
Ultimately attain PRL criterion?

SM Theory:

Quarks:

To date, find $x_D \cong y_D \cong 10^{-6}$ Tiny! But triple expansion not rapidly convergent.

Hadrons:

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

NP Theory:

We have found which NP models can yield sizable x_D and y_D and which cannot. Charm mixing data yield useful constraints. A most welcome addition to the NP community!