Charm Theory (Mixing, etc)

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CKM2008 Workshop

Topics and Abbreviations

Topics

1] A look at the data

2] Charm mixing and SM

3] Charm mixing and NP

The Usual Abbreviations

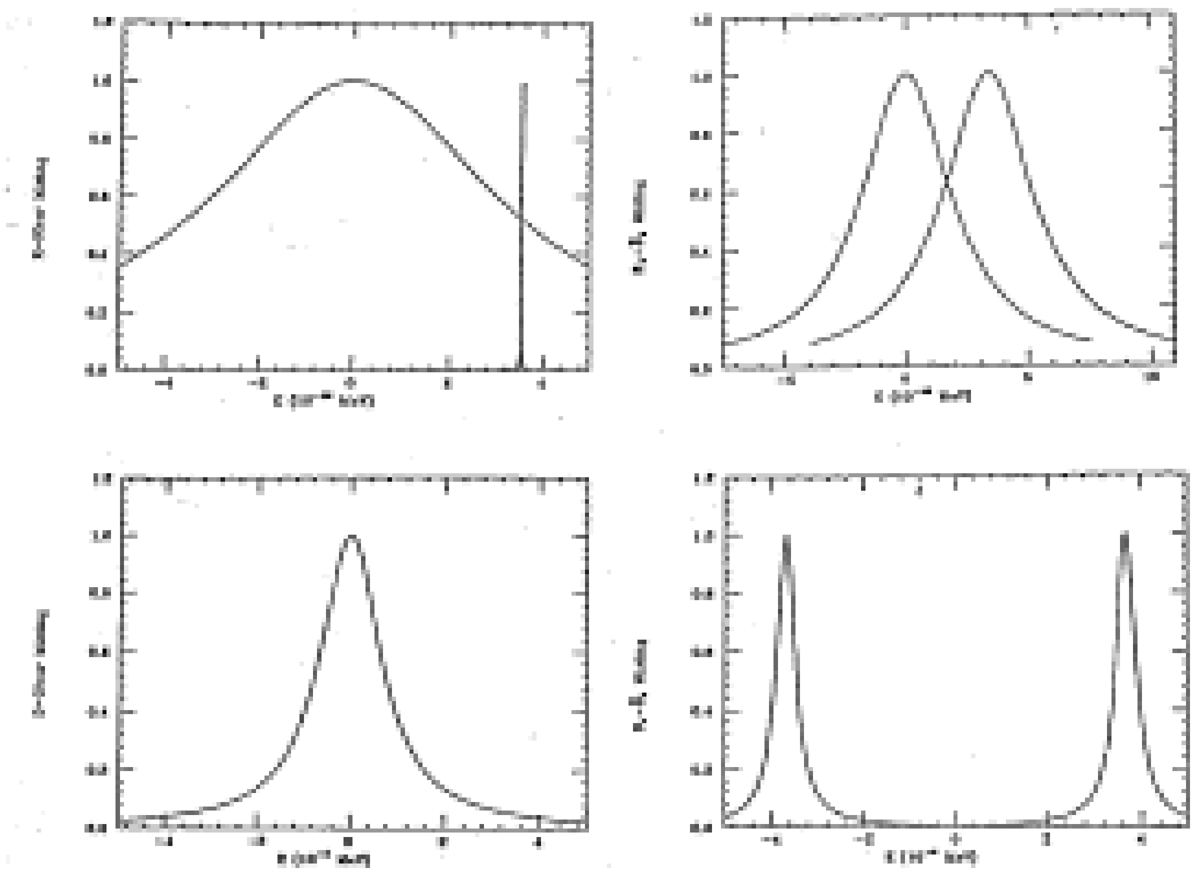
1] SM = Standard Model

2] NP = New Physics

3] CPV = CP Violations

4] HFAG = Heavy Flavor Averaging Group

Profiles of Mixing



Mixing in K, B_d, D and B_s Mesons.

x and y in Charm

ICHEP 2008 HFAG values (CPV-allowed fit):

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

$$x = 0.0100^{+0.0024}_{-0.0026}$$

$$y = \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2}$$

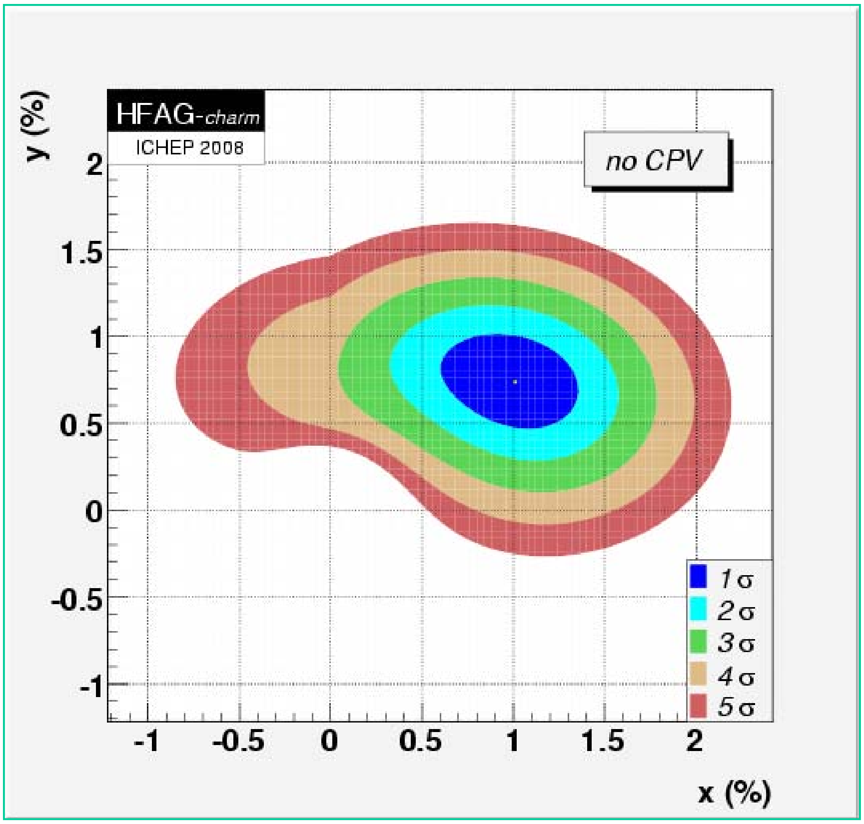
$$y = 0.0076^{+0.0017}_{-0.0018}$$

Other systems have:

	x	y	Lesson
K:	.540	.997	m_c
B_d:	.78	Tiny	m_t
B_s:	26	.15	$(V_{td}/V_{ts})^2$

Contour Plot: 'No CPV' Fit

HFAG (ICHEP 2008)



y(%) vs x(%) (No CPV Fit)

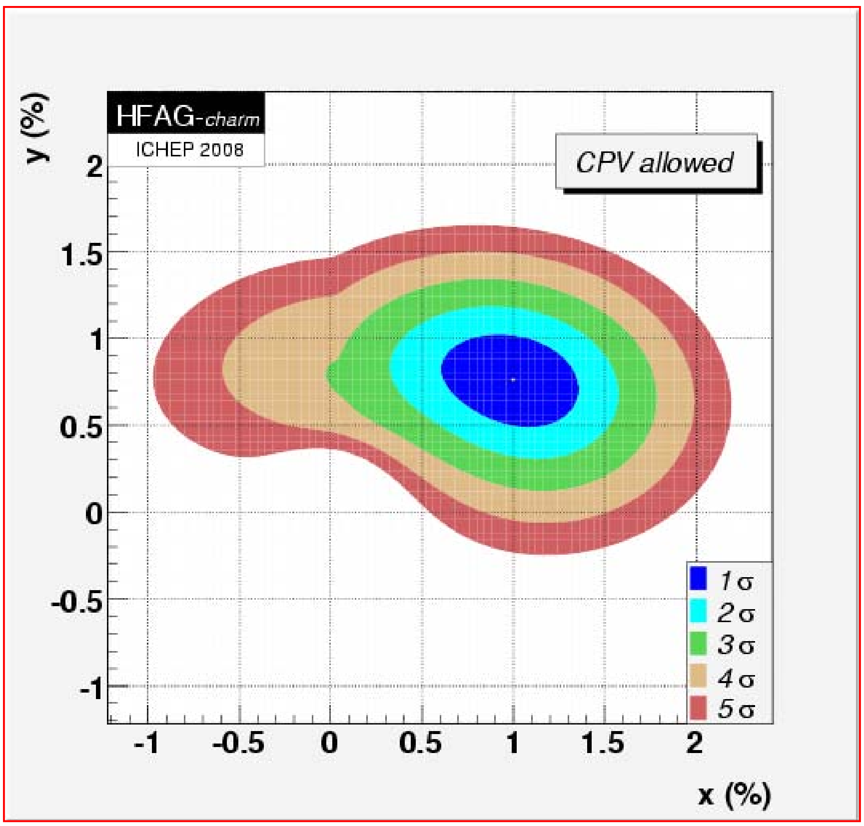
1] The point x=y=0 excluded by 6.7σ.

2] x,y differ from 0 by more than 3σ.

3] x>0 and y>0 favored (await direct determination for sign of x).

Contour Plot: ‘CPV allowed’ Fit

HFAG (ICHEP 2008)



No significant difference from ‘No-CPV Fit’.

Testing for CPV in Mixing

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

$$q/p \;=\; |q/p|\,e^{i\varphi}$$

CP Invariance: |q/p| = 1 and φ=0

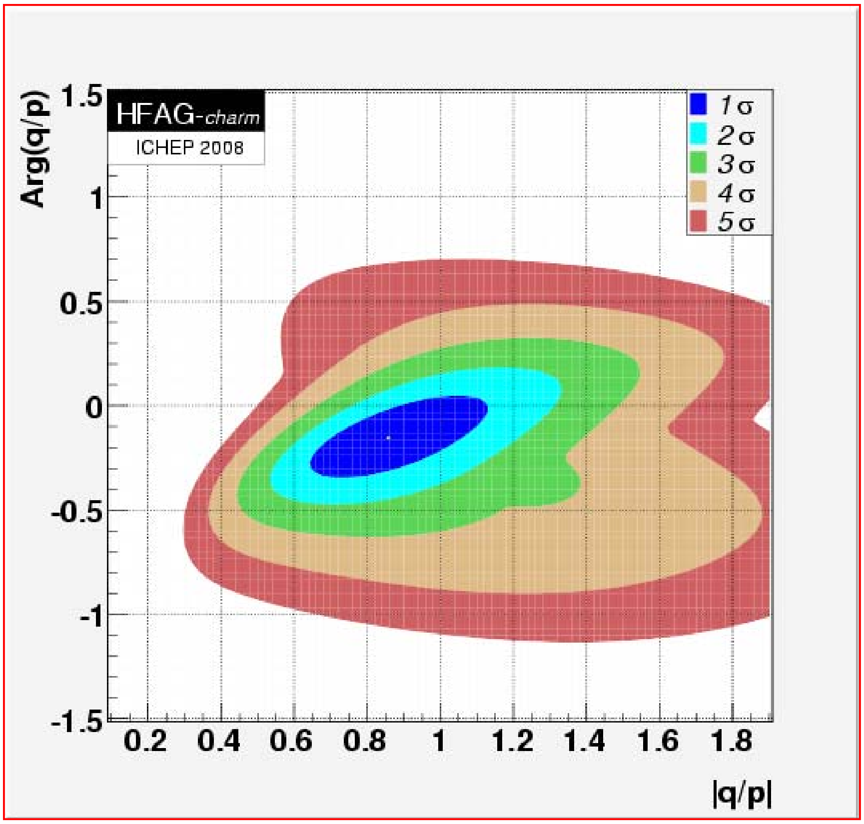
HFAG Values (8/08):

$$|q/p| = 0.86^{+0.17}_{-0.15}$$

$$\varphi\,(\text{deg}) = -\,8.8^{+7.6}_{-7.2}$$

Consistent with CP Invariance.

Contour Plot: ϕ vs $|q/p|$



The 'no-CPV' point $|q/p|=1$, $\varphi=0$ lies within the 1σ (blue) contour.

CPV in Decay*

Here: Time-integrated CPV Asymmetry a_f

$$a_f = \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to \bar{f})}$$

Possible Sources

Can arise from decay, mixing, interference

$$a_f = a_f^d + a_f^m + a_f^i$$

Some Previous Estimates as Large as

SM, NP: $a_f \sim 10^{-3} \to 10^{-2}$

* Talk by B. Winters at ICHEP 2008

Testing CPV in Decay (HFAG)

Asymmetry	Mode	Value
$\frac{\Delta\Gamma}{2\Gamma}$	$D^0 \rightarrow K^+K^-$	$.0016 \pm .0023$
	$D^0 \rightarrow \pi^+\pi^-$	$.0022 \pm .0037$
	$D^0 \rightarrow K^- \pi^+\pi^0$	$.0016 \pm .0089$
	$D^+ \rightarrow K_S\pi^+$	$.0086 \pm .009$
	$D^+ \rightarrow K^+ K^-\pi^+$	$.0059 \pm .0075$
$\frac{\Delta\tau}{2\tau}$	$D^0 \rightarrow K^+K,\pi^+\pi^-$	$.0012 \pm .0025$

SM and Charm Mixing

Quark-level Analysis

Expansions in:

1] Operator Dimension D

2] QCD α_s

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

Discuss: CKM vis-à-vis observed mixing.

Hadron-level Analysis

Focus on y_D

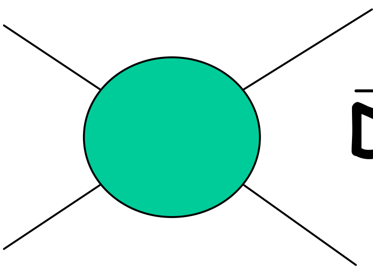
Direct Involvement of Data/Models

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

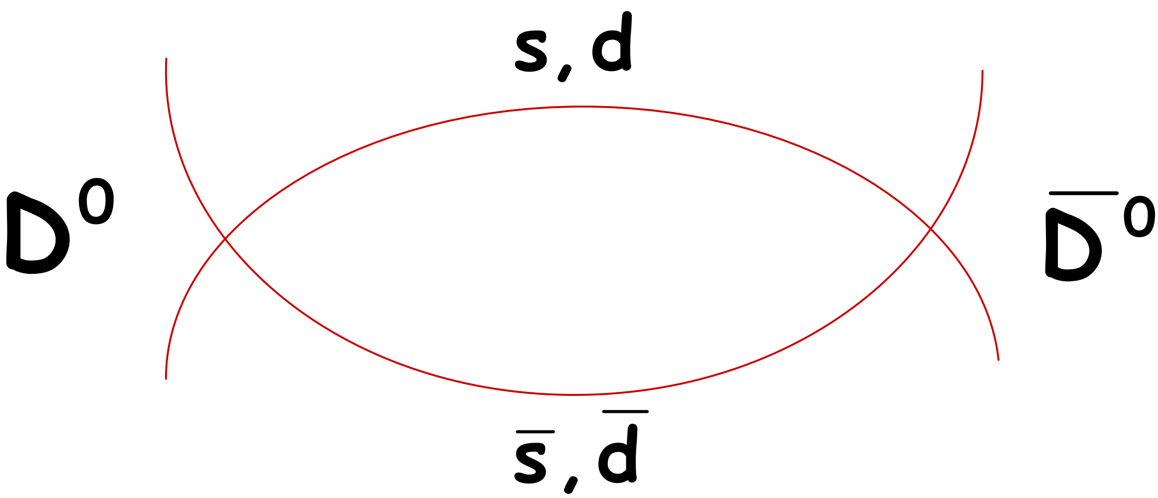
D=9: Fifteen local 6F operators

Etc

*[Georgi PL B297 (1992) 353]

Dimension Six

Ignore b quark. Int. states $s\bar{s}, d\bar{d}, s\bar{d} + d\bar{s}$.



CKM? $y_D \propto (V_{us}/V_{cs})^2 F(z) \sim$ 0.01 F(z) (!)

Expand F(z) 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

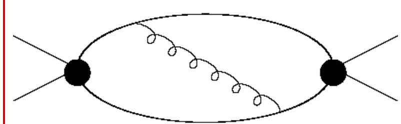
$\Delta\Gamma$ at d=6 $(m_d=0)$:

	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

Status of Dimension Six

EG & Petrov [PLB 625 (2005) 53]

Expand in α_s:

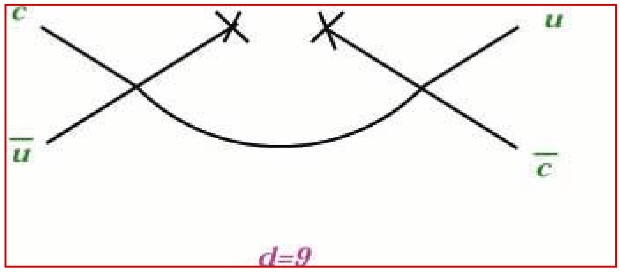

(c)

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

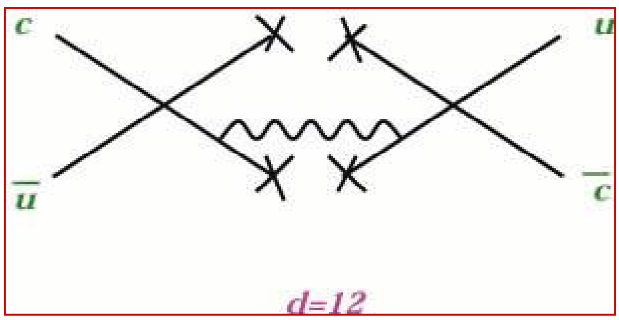
D=6 LO + NLO Result: $x \approx y \approx 10^{-6}$

Higher Terms in the OPE*

D = 9



D = 12



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

Large number of D >6 operators (Bad!).
Can have reduced z-dependence (Good!).
Evaluate matrix elements?
Cancellations?

Hadron Analysis and y_D

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

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

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

1] Model the Matrix Elements

Ex: B_s Mixing (Orsay Group [PLB 316 (1993) 567])

D Mixing: (Buccella et al [PRD 51 (1995) 3478])

Find $y_D \sim 10^{-3}$

LD ($\Delta\Gamma$) cont.

2. Use data

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

Choose n = P^+P^-

$$y_D^{(P^+P^-)} \propto \Gamma_{\pi^+\pi^-} + \Gamma_{K^+K^-} - 2\sqrt{\Gamma_{K^+\pi^-}\Gamma_{K^-\pi^+}}$$

Back then, SU(3) breaking seemed large.

If so, 'y_D large'.

(b) Recent Work Falk et al [PRD 69 (2004) 114021]

SU(3) breaking 'small' (2^{nd} order).

But 4P sector cannot cancel.

'$y_D \sim 10^{-2}$ possible' (but hadronic uncerts.)

Can even get x_D from dispersion relation.

'Conclude x_D and y_D are of opposite sign with $x_D/y_D \sim -\ (0.1 \rightarrow 1.0)$.'

New Physics in D^0 Mixing?

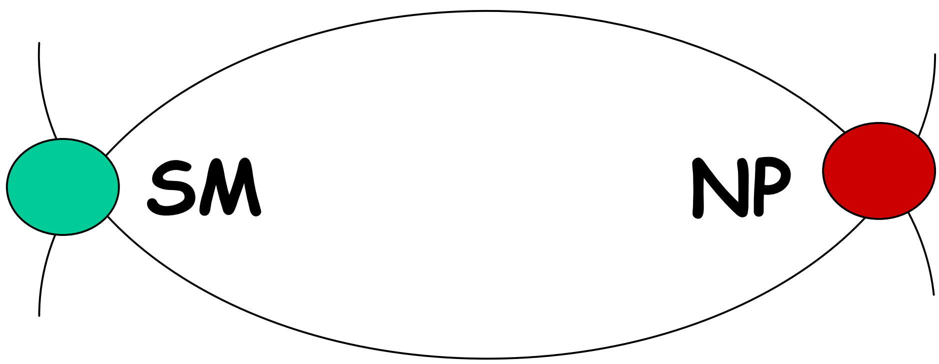
Width Difference y_D

Intermediate states on-shell.
Thus only light particles propagate.
Can there be any NP effects?
In principle, the answer is 'yes'!

Mass Difference 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 $c\bar{u} \rightarrow q_1\bar{q}_2$

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

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

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

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

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.

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

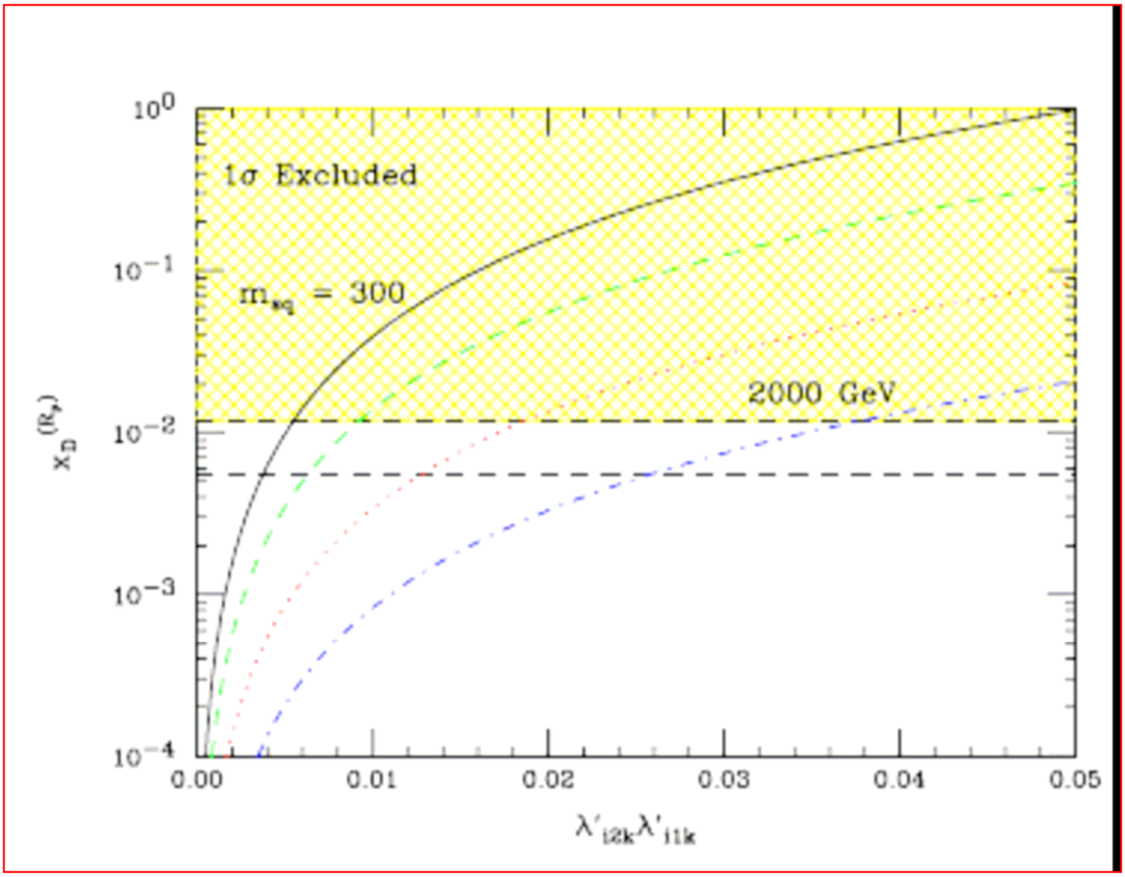
Question to Ourselves

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.

NP Example: RPV SUSY

Graph x_D vs RPV parameters:



Constraints tighten with improved limits on x_D.

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

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)
	$(\Delta m/m_{D1})/M_R > 0.4\ \mathrm{TeV}^{-1}$
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

Answer to Question

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?:

- 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 quark) 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.

Concluding Remarks

Experiment:

x_D and y_D signals at 1%. Await direct meas. of x_D sign via Dalitz studies (BABAR, BELLE).
No CPV seen in charm mixing or decay.

SM Theory (Hadron Analysis):

Estimate $y_D \sim 10^{-2}$ but hadronic physics messy; x_D problematic (wrong sign!).

NP Theory:

Many NP models can yield sizable x_D but a few cannot. Charm mixing data yield useful constraints. Could x_D have a NP component?

Theory - Things to Do:

Sign of SM prediction for x_D.
Relate charm mixing to charm rare decays.
Keep working on CPV in charm.
Respond to LHC findings!