Implications of charm mixing for New Physics

Alexey A. Petrov

WSU & MCTP

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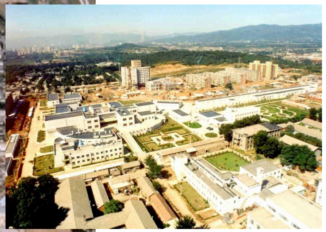
Introduction: identifying New Physics



"Inverse LHC problem"

The LHC ring is 27km in circumference

How can KEK or other older machines help with New Physics searches?

Introduction: charm and New Physics

Charm transitions serve as excellent probes of New Physics

Unique access to up-quark sector

1. Processes forbidden in the Standard Model to all orders

   Examples: $D^0 \to p^+ \pi^- \nu$

2. Processes forbidden in the Standard Model at tree level

   Examples: $D^0 - \overline{D}^0, \; D^0 \to X\gamma, \; D \to X\nu\bar{\nu}$

3. Processes allowed in the Standard Model

   Examples: relations, valid in the SM, but not necessarily in general

CKM triangle relations

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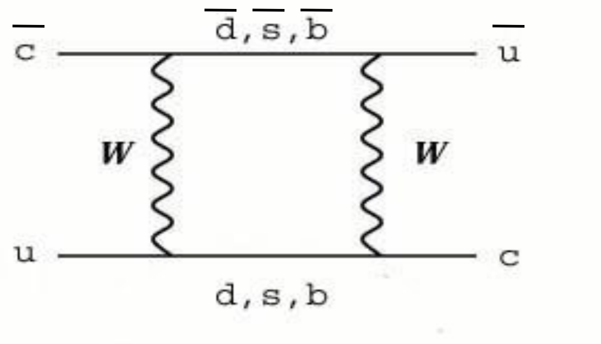
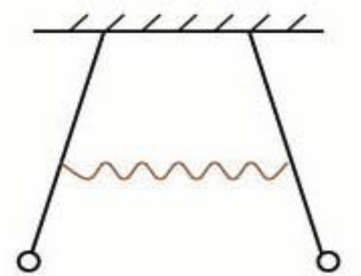
Introduction: mixing



D-$\bar{D}$ mixing


Coupled oscillators

$\Delta Q=2$: only at one loop in the Standard Model: possible new physics particles in the loop

$\Delta Q=2$ interaction couples dynamics of D^0 and $\overline{D^0}$

$$|D(t)\rangle = \begin{pmatrix} a(t) \\ b(t) \end{pmatrix} = a(t)|D^0\rangle + b(t)|\overline{D}^0\rangle$$

- Time-dependence: coupled Schrödinger equations

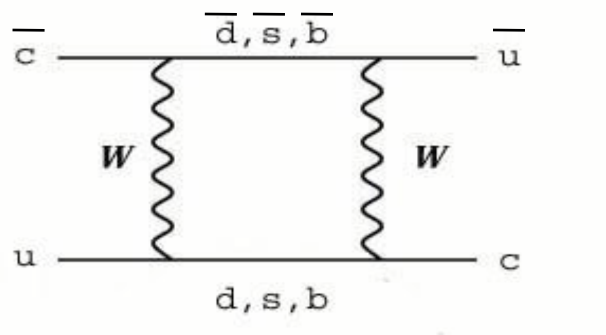
$$i\frac{\partial}{\partial t}|D(t)\rangle = \left(M - \frac{i}{2}\Gamma\right)|D(t)\rangle = \begin{bmatrix} A & p^2 \\ q^2 & A \end{bmatrix}|D(t)\rangle$$

- Diagonalize: mass eigenstates $\neq$ flavor eigenstates

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

Mass and lifetime differences of mass eigenstates: $x = \frac{M_2 - M_1}{\Gamma}$, $y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$

Introduction: mixing



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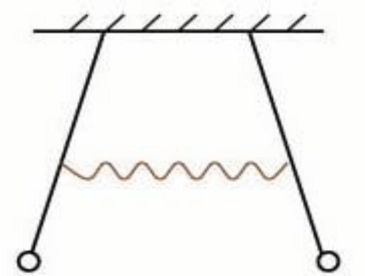

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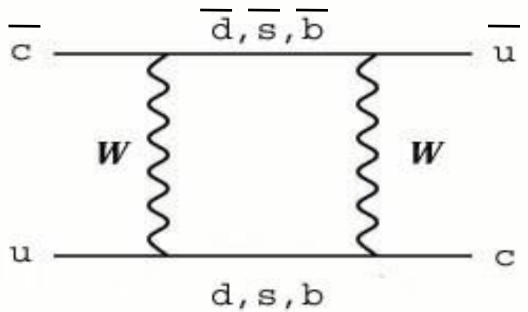
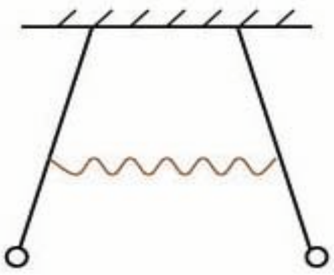


D-D̄ mixing



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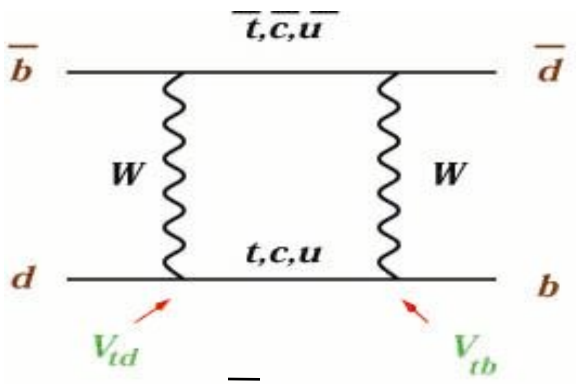
- Diagonalize: mass eigenstates $\neq$ flavor eigenstates

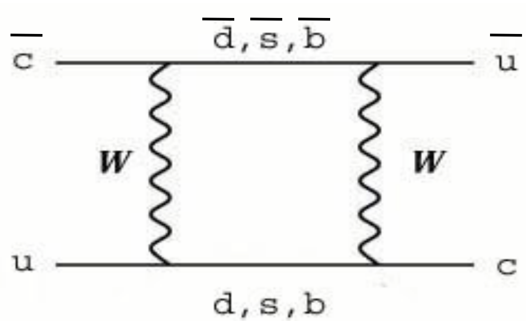
$$\text{No CPV:} \quad \left|D_{1,2}\right\rangle \Rightarrow \left|D_{CP\pm}\right\rangle = \frac{1}{\sqrt{2}}\left[\left|D^0\right\rangle \pm \left|\overline{D^0}\right\rangle\right]$$

Mass and lifetime differences of mass eigenstates: $x = \dfrac{M_2 - M_1}{\Gamma}, \; y = \dfrac{\Gamma_2 - \Gamma_1}{2\Gamma}$

Introduction: why do we care?



B-$\bar{B}$ mixing



D-$\bar{\text{D}}$ mixing

$\overline{D^0} - D^0$ mixing	$\overline{B^0} - B^0$ mixing
• intermediate down-type quarks • SM: b-quark contribution is negligible due to $V_{cd}V_{ub}^*$ • $rate \propto f(m_s) - f(m_d)$ (zero in the SU(3) limit) Falk, Grossman, Ligeti, and A.A.P. Phys.Rev. D65, 054034, 2002 2nd order effect!!!	• intermediate up-type quarks • SM: t-quark contribution is dominant • $rate \propto m_t^2$ (expected to be large)
1. Sensitive to long distance QCD 2. Small in the SM: New Physics! (must know SM x and y)	1. Computable in QCD (*) 2. Large in the SM: CKM!

(*) up to matrix elements of 4-quark operators

Experimental constraints on mixing

Idea: look for a wrong-sign final state

1. Time-dependent or time-integrated semileptonic analysis

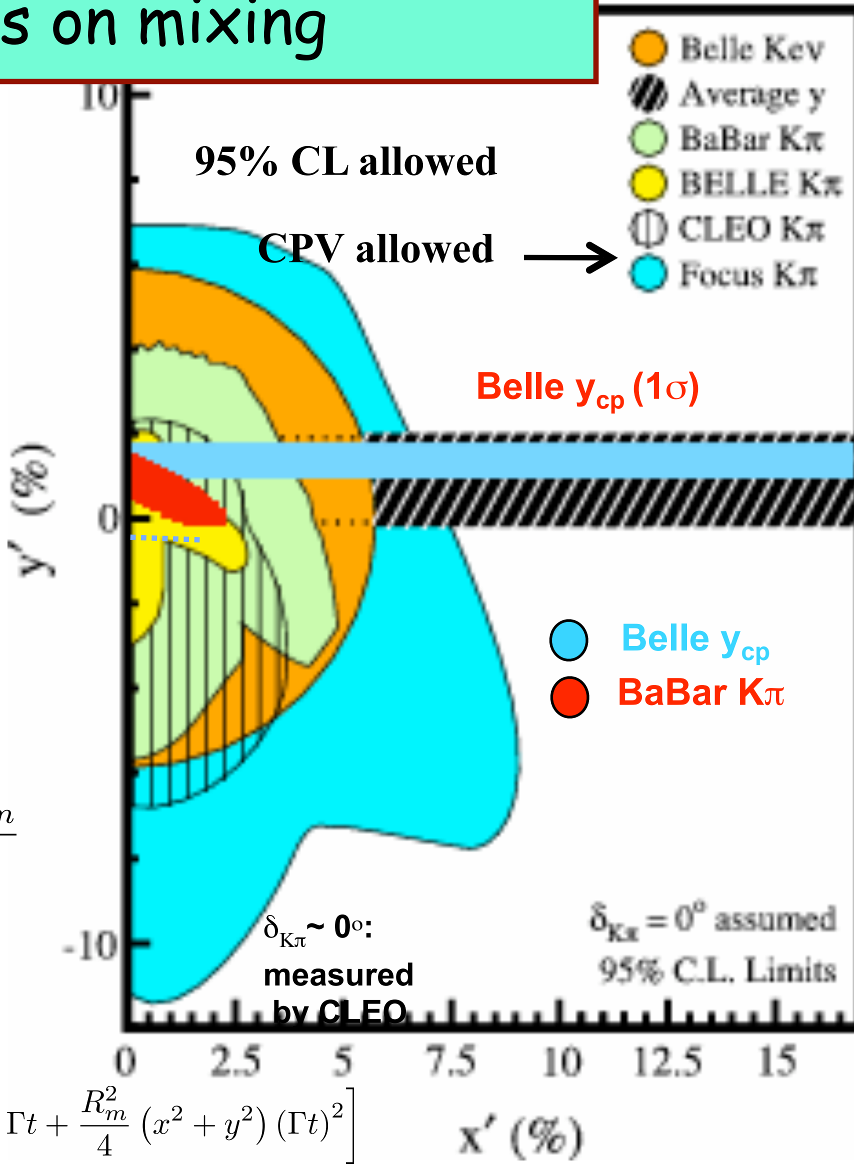
$$rate \propto x^2 + y^2$$

Quadratic in x,y: not so sensitive

2. Time-dependent $D^0 \to K^+K^-$ analysis (lifetime difference)

$$y_{CP} = \frac{\tau(D \to \pi^+ K^-)}{\tau(D \to K^+ K^-)} - 1 = y\cos\phi - x\sin\phi \frac{1-R_m}{2}$$

3. Time-dependent $D^0(t) \to K^+\pi^-$ analysis



$$\Gamma[D^0(t) \to K^+\pi^-] = e^{-\Gamma t} |A_{K^+\pi^-}|^2 \left[R + \sqrt{R}R_m (y'\cos\phi - x'\sin\phi)\Gamma t + \frac{R_m^2}{4}(x^2+y^2)(\Gamma t)^2\right]$$

$$R_m^2 = \left|\frac{q}{p}\right|^2, \; x' = x\cos\delta + y\sin\delta, \; y' = y\cos\delta - x\sin\delta$$

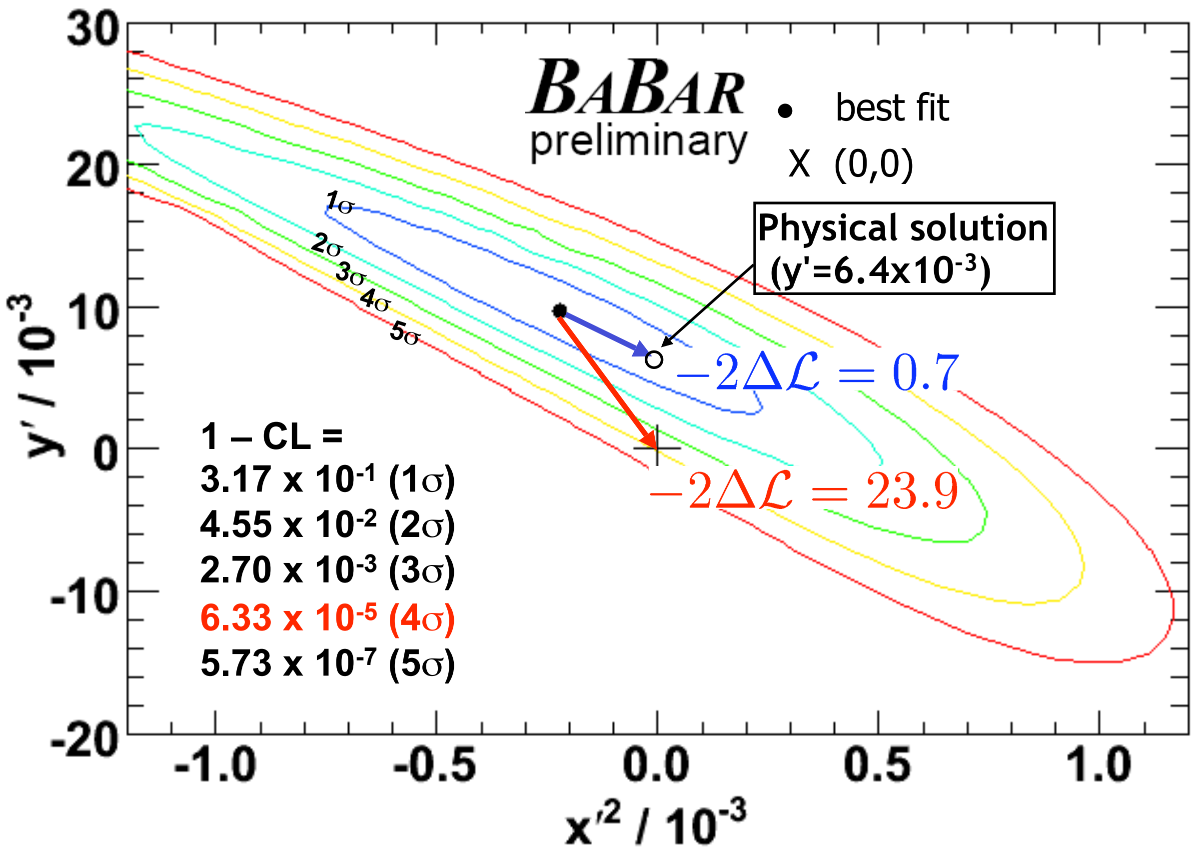
Sensitive to DCS/CF strong phase δ

Recent results from BaBar

- Time-dependent $D \to K\pi$ analysis

$$\Gamma_{WS}(t) = e^{-\Gamma t}\left(R_D + y'\sqrt{R_D}(\Gamma t) + \left(\frac{x'^2 + y'^2}{4}\right)(\Gamma t)^2\right)$$

- No evidence for CP-violation
- Accounting for systematic errors, the no-mixing point is at 3.9-sigma contour



Evidence for $D\bar{D}$ mixing !

R_D: $(3.03 \pm 0.16 \pm 0.10) \times 10^{-3}$

x'^2: $(-0.22 \pm 0.30 \pm 0.21) \times 10^{-3}$

y': $(9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$

Recent results from Belle

- Time-dependent D →KK/ππ analysis

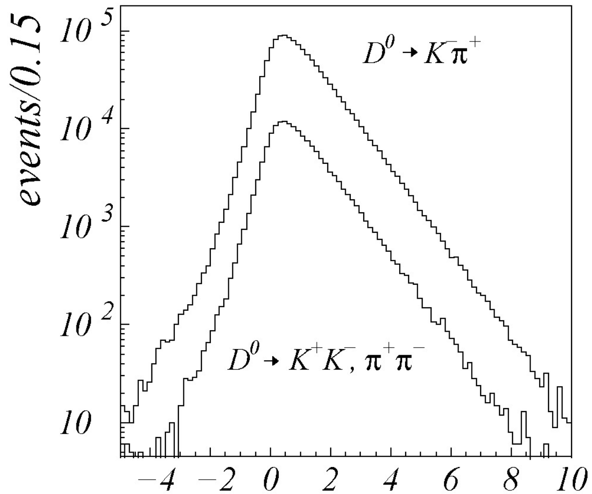
$$y_{CP} \equiv \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1 \underset{no\ CPV}{=} y = \frac{\Delta\Gamma}{2\Gamma}$$

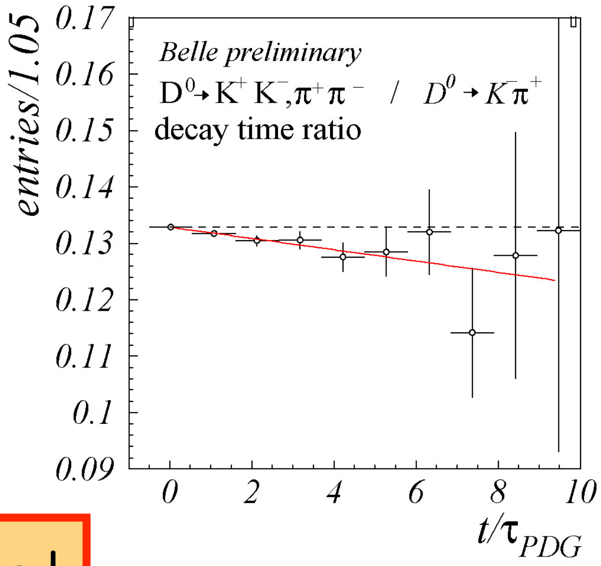
$$CPV : A_\Gamma = \frac{\Gamma(D^0 \to K^-K^+) - \Gamma(\bar{D}^0 \to K^-K^+)}{\Gamma(D^0 \to K^-K^+) + \Gamma(\bar{D}^0 \to K^-K^+)}$$

	y_{CP} (%)	A_Γ (%)
KK	1.25±0.39±0.28	0.15±0.34±0.16
$\pi\pi$	1.44±0.57±0.42	-0.28±0.52±0.30
$KK+\pi\pi$	1.31±0.32±0.25	0.01±0.30±0.15

y_{CP} = 1.31 ± 0.32 ± 0.25 %

- No evidence for CP-violation





(courtesy of A. Rahimi)

Evidence for $D\bar{D}$ mixing !

Recent experimental results

- BaBar, Belle and CDF results

$$y'_{\rm D} = (0.97 \pm 0.44 \pm 0.31) \cdot 10^{-2} \qquad ({\rm BaBar}) \ ,$$

$$y_{\rm D}^{\rm (CP)} = (1.31 \pm 0.32 \pm 0.25) \cdot 10^{-2} \qquad ({\rm Belle}) \ .$$

$$y'_D = (0.85 \pm 0.76) \cdot 10^{-2} \qquad ({\rm CDF})$$

- Belle Dalitz plot result ($D^0 \to K_S \pi^+ \pi^-$)

$$x_{\rm D} = (0.80 \pm 0.29 \pm 0.17) \cdot 10^{-2} \ ,$$

$$y_{\rm D} = (0.33 \pm 0.24 \pm 0.15) \cdot 10^{-2} \ .$$

- Preliminary HFAG numbers

$$x_{\rm D} = 8.5^{+3.2}_{-3.1} \cdot 10^{-3} \ ,$$

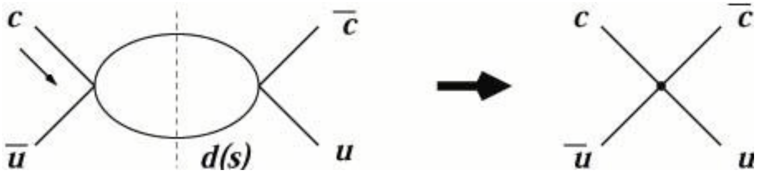
$$y_{\rm D} = 7.1^{+2.0}_{-2.1} \cdot 10^{-3} \qquad (\cos \delta_{K\pi} = 1.09 \pm 0.66)$$

What about theoretical predictions?

Theoretical estimates I

A. Short distance gives a tiny contribution

m_c IS large !!!



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

… as can be seen from a "straightforward computation"…

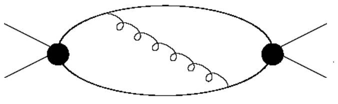
$$y_{\rm LO}^{(z^3)} = \frac{G_F^2 m_c^2 f_D^2 M_D}{3\pi\Gamma_D}\ \xi_s^2\ z^3\ \left(C_2^2 - 2C_1C_2 - 3C_1^2\right)\left[B_{\rm D} - \frac{5}{2}\overline{B}_{\rm D}^{(S)}\right] \propto m_s^6\ \Lambda^{-6}$$

$$x_{\rm LO}^{(z^2)} = \frac{G_F^2 m_c^2 f_D^2 M_D}{3\pi^2\Gamma_D}\ \xi_s^2\ z^2\ \left[C_2^2 B_{\rm D} - \frac{5}{4}(C_2^2 - 2C_1C_2 - 3C_1^2)\overline{B}_{\rm D}^{(S)}\right] \propto m_s^4\ \Lambda^{-4}$$

… $x_{LO} \gg y_{LO}$!!!

with $\langle D^0 | \bar{u}\Gamma_\mu c\ \bar{u}\Gamma^\mu c | D^0\rangle = \frac{1+N_C}{N_C}\frac{4F_D^2 m_D^2}{2m_D} B_D$, *etc.*

Notice, however, that at NLO in QCD $(x_{NLO}, y_{NLO}) \gg (x_{LO}, y_{LO})$:



(c)

Example of NLO contribution

$$y_{\rm NLO}^{(2)} = \frac{G_F^2 m_c^2 f_D^2 M_D}{3\pi\Gamma_D}\ \xi_s^2\ \frac{\alpha_s}{4\pi}\ z^2 \Bigg(B_{\rm D}\left[-\left(\frac{77}{6} - \frac{8\pi^2}{9}\right) C_2^2 + 14\ C_1C_2 + 8\ C_1^2\right]$$
$$- \frac{5}{2}\overline{B}_{\rm D}^{(S)}\ \left[\left(\frac{8\pi^2}{9} - \frac{25}{3}\right) C_2^2 + 20\ C_1C_2 + 32\ C_1^2\right]\Bigg) ,$$

$x_{NLO} \sim y_{NLO}$!

Similar for x (trust me!)

E. Golowich and A.A.P.
Phys. Lett. B625 (2005) 53

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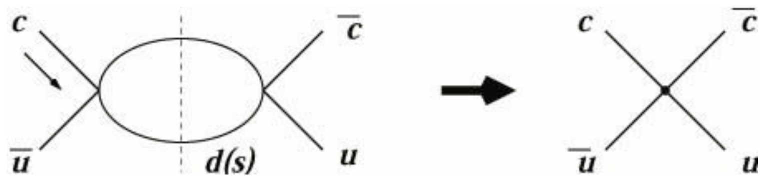

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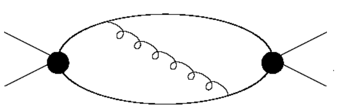

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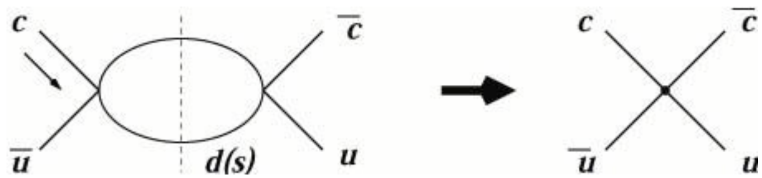

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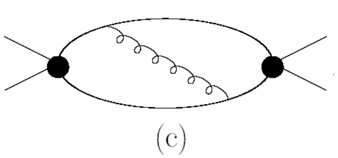

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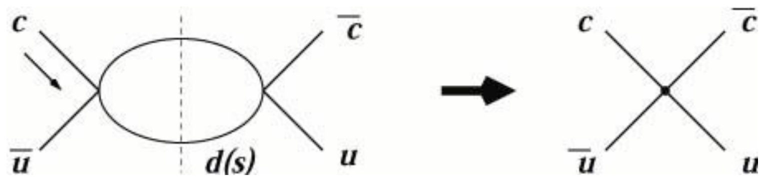

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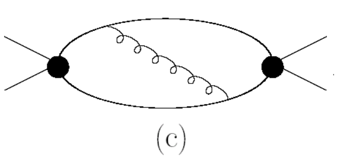

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E. Golowich and A.A.P. Phys. Lett. B625 (2005) 53

Theoretical estimates I

A. Short distance + "subleading corrections" (in $\{m_s, 1/m_c\}$ expansion):

$$y_{sd}^{(6)} \propto \frac{\left(m_s^2 - m_d^2\right)^2}{m_c^2} \frac{m_s^2 + m_d^2}{m_c^2} \mu_{had}^{-2} \propto m_s^6 \; \Lambda^{-6}$$

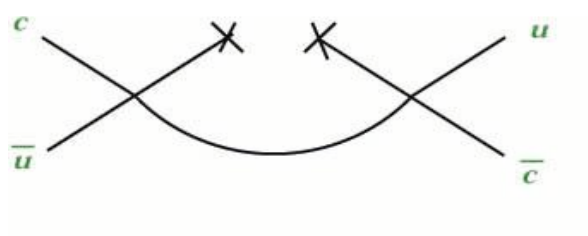
$$x_{sd}^{(6)} \propto \frac{\left(m_s^2 - m_d^2\right)^2}{m_c^2} \mu_{had}^{-2} \propto m_s^4 \; \Lambda^{-4}$$

4 unknown matrix elements

…subleading effects?

$$y_{sd}^{(9)} \propto m_s^3 \; \Lambda^{-3}$$

$$x_{sd}^{(9)} \propto m_s^3 \; \Lambda^{-3}$$



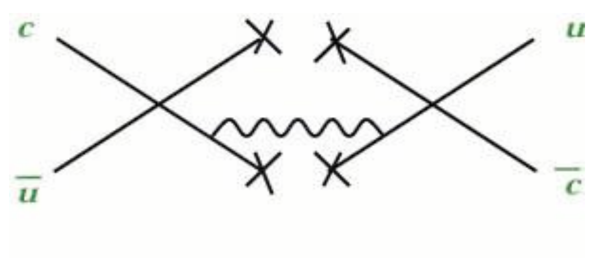
d=9

15 unknown matrix elements

H. Georgi, …
I. Bigi, N. Uraltsev

$$y_{sd}^{(12)} \propto \beta_0 \alpha_s^2(\mu) m_s^2 \; \Lambda^{-2}$$

$$x_{sd}^{(12)} \propto \alpha_S(\mu) m_s^2 \; \Lambda^{-2}$$



d=12

Twenty-something unknown matrix elements

Leading contribution!!!

Guestimate: $x \sim y \sim 10^{-3}$?

Resume: model-independent computation with model-dependent result

Theoretical estimates II

B. Long distance physics dominates the dynamics…

m_c is NOT large !!!

$$y = \frac{1}{2\Gamma} \sum_n \rho_n \left[\langle D^0 | H_W^{\Delta C=1} | n \rangle \langle n | H_W^{\Delta C=1} | \overline{D}^0 \rangle + \langle \overline{D}^0 | H_W^{\Delta C=1} | n \rangle \langle n | H_W^{\Delta C=1} | D^0 \rangle \right]$$

… with n being all states to which D^0 and $\overline{D}^0$ can decay. Consider $\pi\pi$, πK, KK intermediate states as an example…

J. Donoghue et. al.
P. Colangelo et. al.

$$\begin{aligned} y_2 &= Br(D^0 \to K^+ K^-) + Br(D^0 \to \pi^+ \pi^-) \\ &- 2\cos\delta \sqrt{Br(D^0 \to K^+ \pi^-) Br(D^0 \to \pi^+ K^-)} \end{aligned}$$

If every Br is known up to *O(1%)* ⇒ the result is expected to be *O(1%)*!

The result here is a series of large numbers with alternating signs, <u>SU(3) forces 0</u>

x = ? Extremely hard…

Need to "repackage" the analysis: look at the <u>complete</u> multiplet contribution

Theoretical estimates II

m_c is NOT large !!!

B. Long distance physics dominates the dynamics…

$$y = \frac{1}{2\Gamma} \sum_n \rho_n \left[\langle D^0 | H_W^{\Delta C=1} | n \rangle \langle n | H_W^{\Delta C=1} | \overline{D}^0 \rangle + \langle \overline{D}^0 | H_W^{\Delta C=1} | n \rangle \langle n | H_W^{\Delta C=1} | D^0 \rangle \right]$$

… with n being all states to which D^0 and $\overline{D}^0$ can decay. Consider $\pi\pi$, πK, KK intermediate states as an example…

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cancellation expected!

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SU(3) and phase space

- "Repackage" the analysis: look at the <u>complete</u> multiplet contribution

$$y = \sum_{F_R} y_{F,R}\ Br(D^0 \to F_R) = \sum_{F_R} y_{F,R} \frac{1}{\Gamma} \sum_{n \in F_R} \Gamma(D^0 \to n)$$

y for each SU(3) multiplet

Each is **0** in SU(3)

- Does it help? If only phase space is taken into account: **no** **(mild)** model dependence

$$y_{F,R} = \frac{\sum_{n \in F_R} \langle \overline{D}^0 | H_W | n \rangle \rho_n \langle n | H_W | D^0 \rangle}{\sum_{n \in F_R} \Gamma(D^0 \to n)}$$

$$= \frac{\sum_{n \in F_R} \langle \overline{D}^0 | H_W | n \rangle \rho_n \langle n | H_W | D^0 \rangle}{\sum_{n \in F_R} \langle D^0 | H_W | n \rangle \rho_n \langle n | H_W | D^0 \rangle}$$

Can consistently compute

Example: PP intermediate states

- *n=PP* transforms as $(8\times 8)_S = 27 + 8 + 1$, take 8 as an example:

Numerator:

$$A_{N,8} = |A_0|^2 s_1^2 \left[\frac{1}{2}\Phi(\eta,\eta) + \frac{1}{2}\Phi(\pi^0,\pi^0) + \frac{1}{3}\Phi(\eta,\pi^0) + \Phi(\pi^+,\pi^-) - \Phi(\overline{K}^0,\pi^0) \right.$$
$$\left. + \Phi(K^+,K^-) - \frac{1}{6}\Phi(\eta,K^0) - \frac{1}{6}\Phi(\eta,\overline{K}^0) - \Phi(K^+,\pi^-) - \Phi(K^-,\pi^+) \right]$$

Denominator:

phase space function

$$A_{D,8} = |A_0|^2 \left[\frac{1}{6}\Phi(\eta,K^0) + \Phi(K^+,\pi^-) + \frac{1}{2}\Phi(K^0,\pi^0) + O(s_1^2) \right]$$

- This gives a calculable effect!

$$y_{2,8} = \frac{A_{N,8}}{A_{D,8}} = -0.038 s_1^2 = -1.8\times 10^{-4}$$

1. Repeat for other states
2. Multiply by Br_{Fr} to get y

Results

Final state representation		$y_{F,R}/s_1^2$	$y_{F,R}$ (%)
PP	8	−0.0038	−0.018
	27	−0.00071	−0.0034
PV	8_S	0.031	0.15
	8_A	0.032	0.15
	10	0.020	0.10
	$\overline{10}$	0.016	0.08
	27	0.040	0.19
$(VV)_{s\text{-wave}}$	8	−0.081	−0.39
	27	−0.061	−0.30
$(VV)_{p\text{-wave}}$	8	−0.10	−0.48
	27	−0.14	−0.70
$(VV)_{d\text{-wave}}$	8	0.51	2.5
	27	0.57	2.8

Final state representation		$y_{F,R}/s_1^2$	$y_{F,R}$ (%)
$(3P)_{s\text{-wave}}$	8	−0.48	−2.3
	27	−0.11	−0.54
$(3P)_{p\text{-wave}}$	8	−1.13	−5.5
	27	−0.07	−0.36
$(3P)_{\text{form-factor}}$	8	−0.44	−2.1
	27	−0.13	−0.64
$4P$	8	3.3	16
	27	2.2	9.2
	$27'$	1.9	11

Final state	fraction
PP	5%
PV	10%
$(VV)_{s\text{-wave}}$	5%
$(VV)_{d\text{-wave}}$	5%
$3P$	5%
$4P$	10%

- Product is naturally O(1%)
- No (symmetry-enforced) cancellations
- Disp relation: compute x (model-dependence)

naturally implies that *x,y ~ 1%* is expected in the Standard Model

A.F., Y.G., Z.L., Y.N. and A.A.P. Phys.Rev. D69, 114021, 2004

E.Golowich and A.A.P. Phys.Lett. B427, 172, 1998

Resume: a contribution to x and y of the order of 1% is natural in the SM

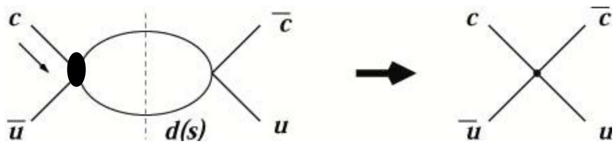
What about New Physics?

How New Physics affects x and y

- Local ΔC=2 piece of the mass matrix affects x:

$$\left(M-\frac{i}{2}\Gamma\right)_{ij}=m_D^{(0)}\delta_{ij}+\frac{1}{2m_D}\left\langle D_i^0\right|H_W^{\Delta C=2}\left|D_j^0\right\rangle+\frac{1}{2m_D}\sum_I\frac{\left\langle D_i^0\right|H_W^{\Delta C=1}\left|I\right\rangle\left\langle I\right|H_W^{\Delta C=1}\left|D_j^0\right\rangle}{m_D^2-m_I^2+i\varepsilon}$$

- Double insertion of ΔC=1 affects x and y:



Amplitude $A_n=\left\langle D^0\right|\left(H_{SM}^{\Delta C=1}+H_{NP}^{\Delta C=1}\right)\left|n\right\rangle\equiv A_n^{SM}+A_n^{NP}$

Suppose $\left|A_n^{NP}\right|/\left|A_n^{SM}\right|: O(\text{exp. uncertainty})\le 10\%$

Example: $y=\frac{1}{2\Gamma}\sum_n\rho_n\left(\overline{A}_n^{SM}+\overline{A}_n^{NP}\right)\left(A_n^{SM}+A_n^{NP}\right)\approx\frac{1}{2\Gamma}\sum_n\rho_n\overline{A}_n^{SM}A_n^{SM}+\frac{1}{2\Gamma}\sum_n\rho_n\left(\overline{A}_n^{SM}A_n^{NP}+\overline{A}_n^{NP}A_n^{SM}\right)$

phase space

How New Physics affects x and y

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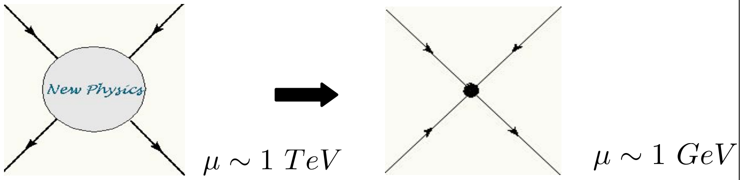

$$\left(M - \frac{i}{2}\Gamma\right)_{ij} = m_D^{(0)}\delta_{ij} + \frac{1}{2m_D}\left\langle D_i^0 \right| H_W^{\Delta C=2} \left| D_j^0 \right\rangle + \frac{1}{2m_D}\sum_I \frac{\left\langle D_i^0 \right| H_W^{\Delta C=1} \left| I \right\rangle \left\langle I \right| H_W^{\Delta C=1} \left| D_j^0 \right\rangle}{m_D^2 - m_I^2 + i\varepsilon}$$

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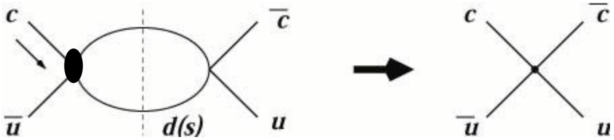

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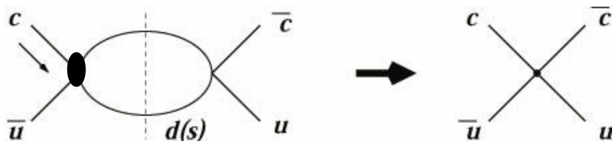

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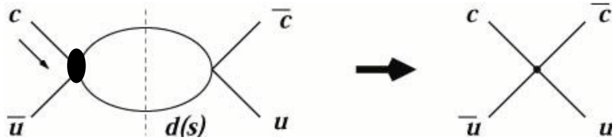

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phase space

Zero in the SU(3) limit

Falk, Grossman, Ligeti, and A.A.P.
Phys.Rev. D65, 054034, 2002

2nd order effect!!!

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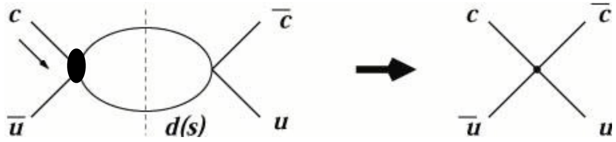

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phase space

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Phys.Rev. D65, 054034, 2002
2nd order effect!!!

Can be significant!!!

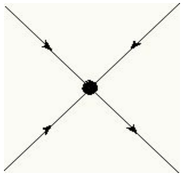
Global Analysis of New Physics: $\Delta C=1$

E. Golowich, S. Pakvasa, A.A.P.
Phys. Rev. Lett. 98, 181801, 2007

- Let's write the most general $\Delta C=1$ Hamiltonian

$$\mathcal{H}_{\rm NP}^{\Delta C=-1} = \sum_{q,q'} D_{qq'}[\bar{\mathcal{C}}_1(\mu)Q_1 + \bar{\mathcal{C}}_2(\mu)Q_2],$$

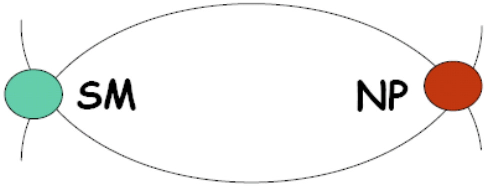
$$Q_1 = \bar{u}_i \bar{\Gamma}_1 q'_j \bar{q}_j \bar{\Gamma}_2 c_i, \qquad Q_2 = \bar{u}_i \bar{\Gamma}_1 q'_i \bar{q}_j \bar{\Gamma}_2 c_j,$$



$\mu \le 1\, TeV$

Only light on-shell (propagating) quarks affect $\Delta\Gamma$:

$$y = -\frac{4\sqrt{2}G_F}{M_D \Gamma_D} \sum_{q,q'} \mathbf{V}^*_{cq'} \mathbf{V}_{uq} D_{qq'} (K_1 \delta_{ik}\delta_{j\ell} + K_2 \delta_{i\ell}\delta_{jk}) \times \sum_{\alpha=1}^{5} I_\alpha(x,x') \langle \bar{D}^0 | \mathcal{O}_\alpha^{ijk\ell} | D^0 \rangle,$$



with $K_1 = [\mathcal{C}_1\bar{\mathcal{C}}_1 N_c + (\mathcal{C}_1\bar{\mathcal{C}}_2 + \bar{\mathcal{C}}_1\mathcal{C}_2)], \qquad K_2 = \mathcal{C}_2\bar{\mathcal{C}}_2$ and

$$\begin{aligned}
\mathcal{O}_1^{ijk\ell} &= \bar{u}_k \Gamma_\mu \gamma_\nu \bar{\Gamma}_2 c_j \bar{u}_\ell \bar{\Gamma}_1 \gamma^\nu \Gamma^\mu c_i \\
\mathcal{O}_2^{ijk\ell} &= \bar{u}_k \Gamma_\mu \not{p}_c \bar{\Gamma}_2 c_j \bar{u}_\ell \bar{\Gamma}_1 \not{p}_c \Gamma^\mu c_i \\
\mathcal{O}_3^{ijk\ell} &= \bar{u}_k \Gamma_\mu \bar{\Gamma}_2 c_j \bar{u}_\ell \bar{\Gamma}_1 \not{p}_c \Gamma^\mu c_i \\
\mathcal{O}_4^{ijk\ell} &= \bar{u}_k \Gamma_\mu \not{p}_c \bar{\Gamma}_2 c_j \bar{u}_\ell \bar{\Gamma}_1 \Gamma^\mu c_i \\
\mathcal{O}_5^{ijk\ell} &= \bar{u}_k \Gamma_\mu \bar{\Gamma}_2 c_j \bar{u}_\ell \bar{\Gamma}_1 \Gamma^\mu c_i,
\end{aligned}$$

This is the master formula for NP contribution to lifetime differences in heavy mesons

Global Analysis of New Physics: $\Delta C=1$

- Some examples of New Physics contributions

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

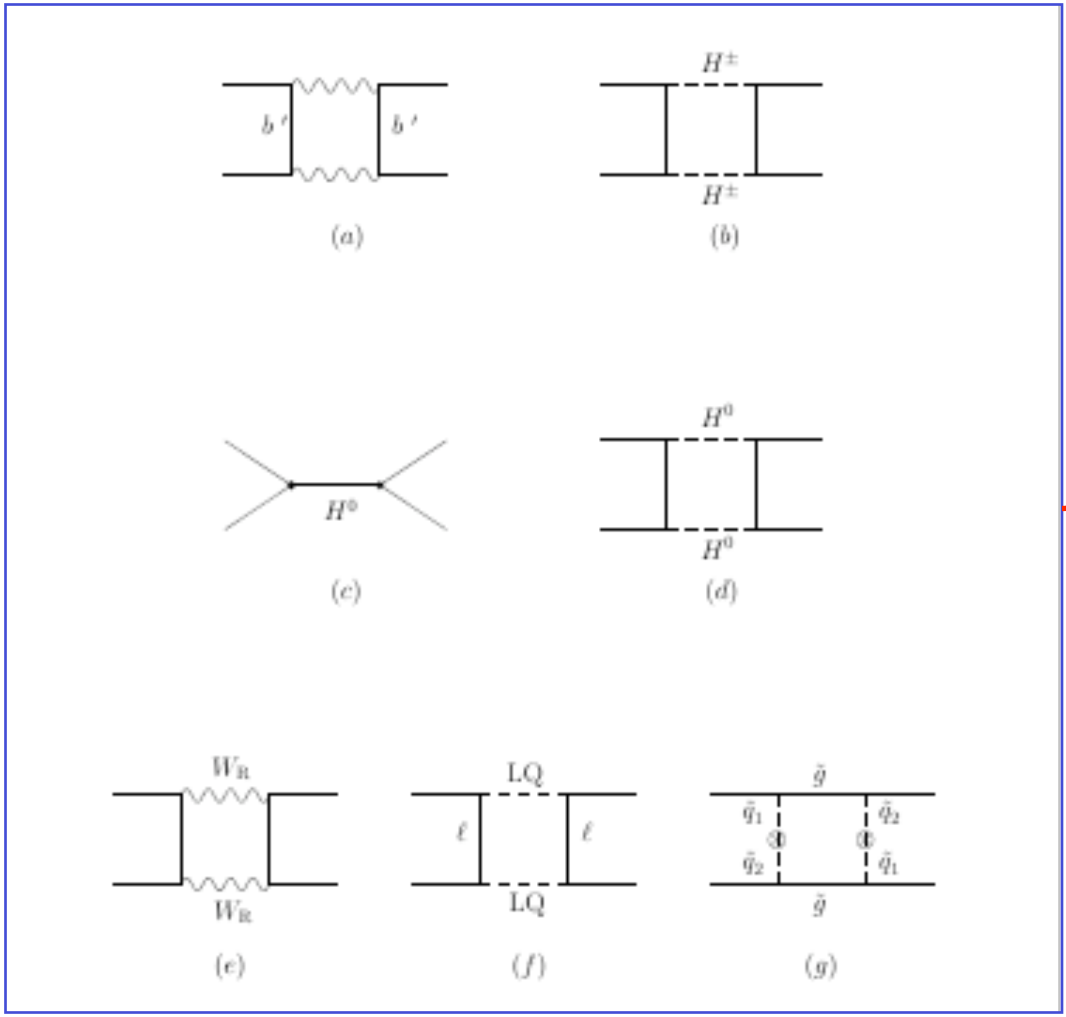
E. Golowich, S. Pakvasa, A.A.P.
Phys. Rev. Lett. 98, 181801, 2007

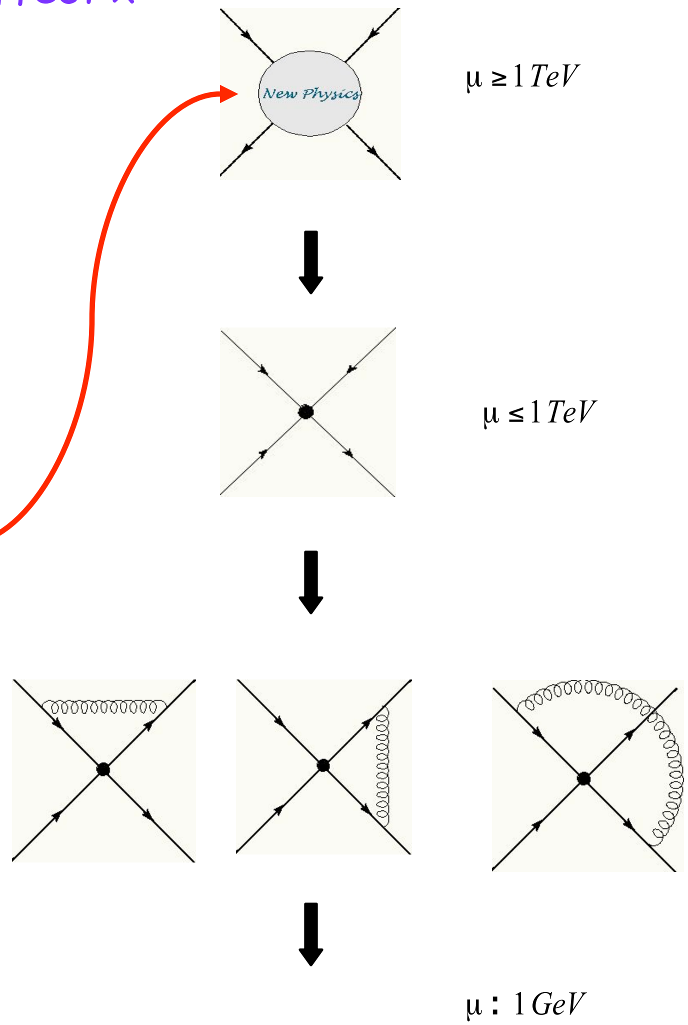
A.A.P. and G. Yeghiyan
Phys. Rev. D77, 034018 (2008)

For considered models, the results are smaller than observed mixing rates

Global Analysis of New Physics: $\Delta C=2$

- Multitude of various models of New Physics can affect x





Global Analysis of New Physics: $\Delta C=2$

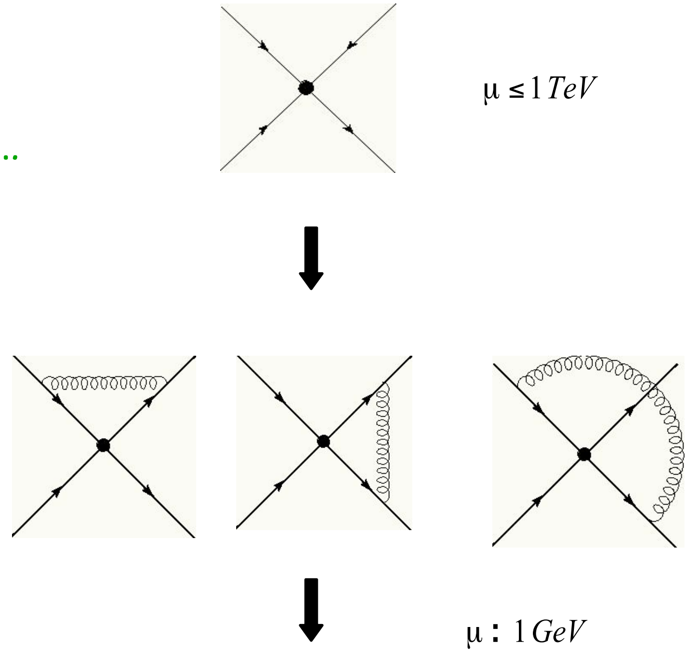
E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
Phys. Rev. D76:095009, 2007

- Let's write the most general $\Delta C=2$ Hamiltonian

$$\langle f|\mathcal{H}_{NP}|i\rangle = G\sum_{i=1} \mathrm{C}_i(\mu)\ \langle f|Q_i|i\rangle(\mu)$$

… with the following set of 8 independent operators…

$$Q_1 = (\overline{u}_L\gamma_\mu c_L)\ (\overline{u}_L\gamma^\mu c_L)\ , \qquad Q_5 = (\overline{u}_R\sigma_{\mu\nu} c_L)\ (\overline{u}_R\sigma^{\mu\nu} c_L)\ ,$$
$$Q_2 = (\overline{u}_L\gamma_\mu c_L)\ (\overline{u}_R\gamma^\mu c_R)\ , \qquad Q_6 = (\overline{u}_R\gamma_\mu c_R)\ (\overline{u}_R\gamma^\mu c_R)\ ,$$
$$Q_3 = (\overline{u}_L c_R)\ (\overline{u}_R c_L)\ , \qquad Q_7 = (\overline{u}_L c_R)\ (\overline{u}_L c_R)\ ,$$
$$Q_4 = (\overline{u}_R c_L)\ (\overline{u}_R c_L)\ , \qquad Q_8 = (\overline{u}_L\sigma_{\mu\nu} c_R)\ (\overline{u}_L\sigma^{\mu\nu} c_R)\ .$$



RG-running relate C_i(m) at NP scale to the scale of m ~ 1 GeV, where ME are computed (on the lattice)

$$\frac{d}{d\log\mu}\vec{C}(\mu) = \hat{\gamma}^T(\mu)\vec{C}(\mu)$$

Each model of New Physics provides unique matching condition for $C_i(L_{NP})$

New Physics in x: lots of extras

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
Phys. Rev. D76:095009, 2007

New Physics contributions do not suffer from QCD uncertainties as much as SM contributions since they are short-distance dominated.

- Extra gauge bosons
  - Left-right models, horizontal symmetries, etc.
- Extra scalars
  - Two-Higgs doublet models, leptoquarks, Higgsless, etc.
- Extra fermions
  - 4^{th} generation, vector-like quarks, little Higgs, etc.
- Extra dimensions
  - Universal extra dimensions, split fermions, warped ED, etc.
- Extra symmetries
  - SUSY: MSSM, alignment models, split SUSY, etc.

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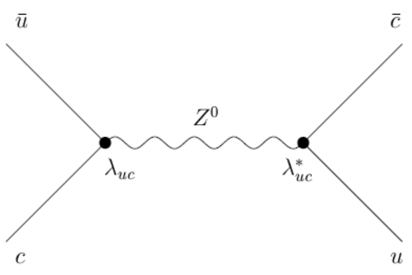
Total: 21 models considered

Dealing with New Physics-I

- Consider an example: FCNC Z^0-boson



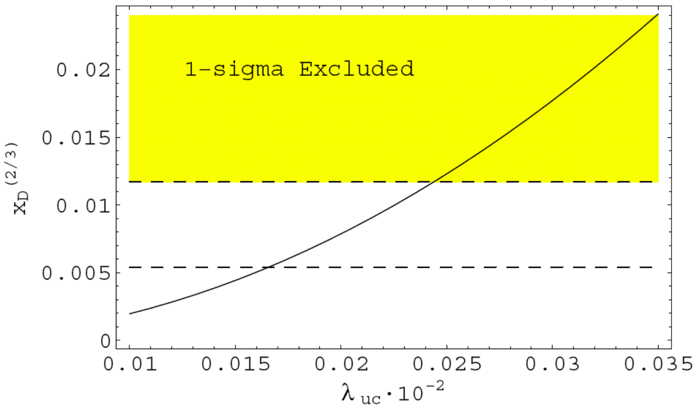
appears in models with
extra vector-like quarks
little Higgs models

1. Integrate out Z: for $\mu < M_Z$ get

$$\mathcal{H}_{2/3} = \frac{g^2}{8\cos^2\theta_w M_Z^2} (\lambda_{uc})^2 \, \bar{u}_L \gamma_\mu c_L \bar{u}_L \gamma^\mu c_L$$

2. Perform RG running to $\mu \sim m_c$ (in general: operator mixing)

$$\mathcal{H}_{2/3} = \frac{g^2}{8\cos^2\theta_w M_Z^2} (\lambda_{uc})^2 \, r_1(m_c, M_Z) Q_1$$



3. Compute relevant matrix elements and x_D

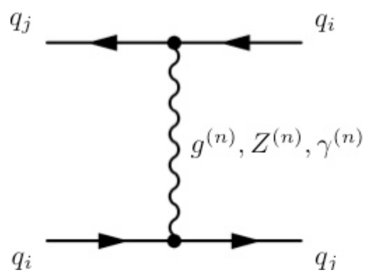
$$x_D^{(2/3)} = \frac{2G_F f_D^2 M_D}{3\sqrt{2}\Gamma_D} B_D (\lambda_{uc})^2 \, r_1(m_c, M_Z)$$

4. Assume no SM - get an upper bound on NP model parameters (coupling)

Dealing with New Physics - II

- Consider another example: warped extra dimensions

FCNC couplings via KK gluons



1. Integrate out KK excitations, drop all but the lightest

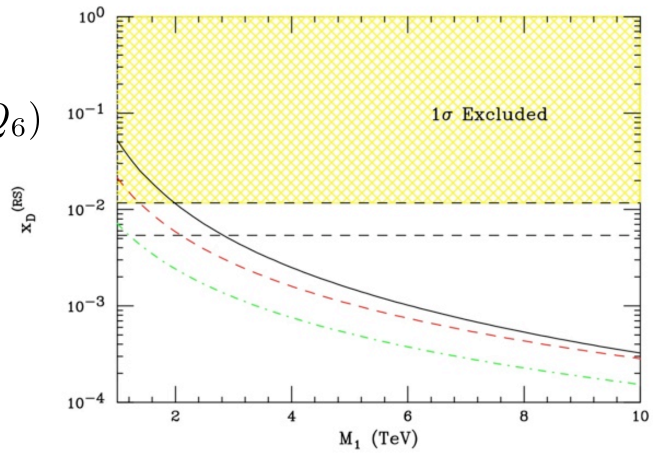
$$\mathcal{H}_{RS} = \frac{2\pi k r_c}{3M_1^2} g_s^2 \left(C_1(M_n)Q_1 + C_2(M_n)Q_2 + C_6(M_n)Q_6\right)$$

2. Perform RG running to $\mu \sim m_c$

$$\mathcal{H}_{RS} = \frac{g_s^2}{3M_1^2} \left(C_1(m_c)Q_1 + C_2(m_c)Q_2 + C_3(m_c)Q_3 + C_6(m_c)Q_6\right)$$

3. Compute relevant matrix elements and x_D

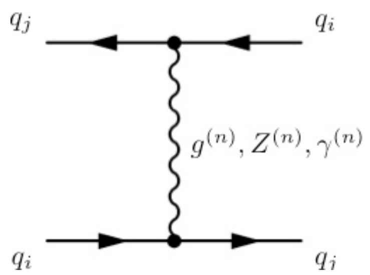
$$x_D^{(RS)} = \frac{g_s^2}{3M_1^2} \frac{f_D^2 B_D M_D}{\Gamma_D} \left(\frac{2}{3}[C_1(m_c) + C_6(m_c)] - \frac{1}{6}C_2(m_c) - \frac{5}{12}C_3(m_c)\right)$$



Dealing with New Physics - II

- Consider another example: warped extra dimensions

FCNC couplings via KK gluons



1. Integrate out KK excitations, drop all but the lightest

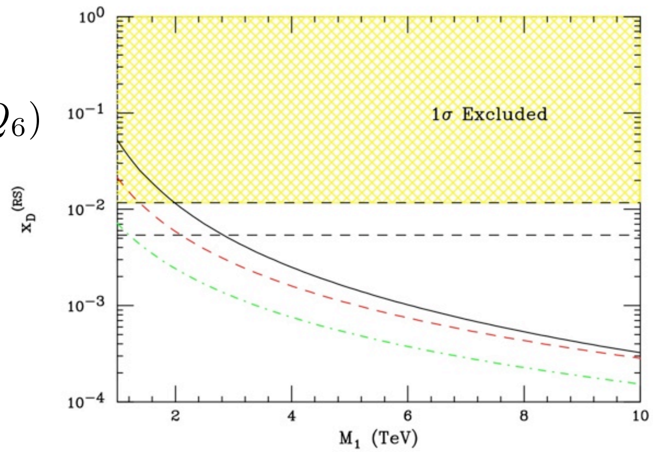
$$\mathcal{H}_{RS} = \frac{2\pi k r_c}{3M_1^2} g_s^2 \left(C_1(M_n)Q_1 + C_2(M_n)Q_2 + C_6(M_n)Q_6\right)$$

2. Perform RG running to $\mu \sim m_c$

$$\mathcal{H}_{RS} = \frac{g_s^2}{3M_1^2} \left(C_1(m_c)Q_1 + C_2(m_c)Q_2 + C_3(m_c)Q_3 + C_6(m_c)Q_6\right)$$

3. Compute relevant matrix elements and x_D

$$x_D^{(RS)} = \frac{g_s^2}{3M_1^2} \frac{f_D^2 B_D M_D}{\Gamma_D} \left(\frac{2}{3}[C_1(m_c) + C_6(m_c)] - \frac{1}{6}C_2(m_c) - \frac{5}{12}C_3(m_c)\right)$$

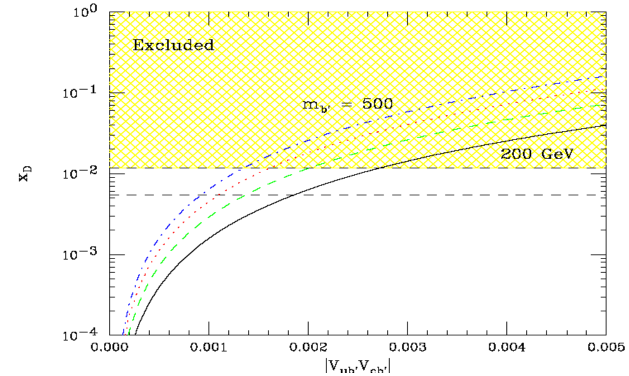


Implies: $M_{1KKg} > 3.5$ TeV!

New Physics in x: extra fermions

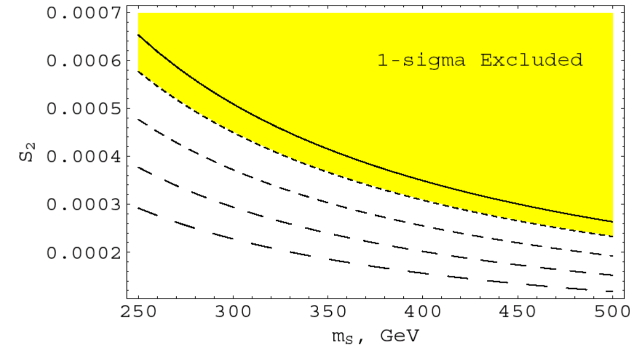
- Fourth generation

$$x_{\rm D}^{(4^{th})} = \frac{G_F^2 M_W^2}{6\pi^2 \Gamma_D} f_D^2 M_D B_D \lambda_{b'}^2 S(x_{b'}, x_{b'}) r_1(m_c, M_W)$$



- Vector-like quarks (Q=+2/3)

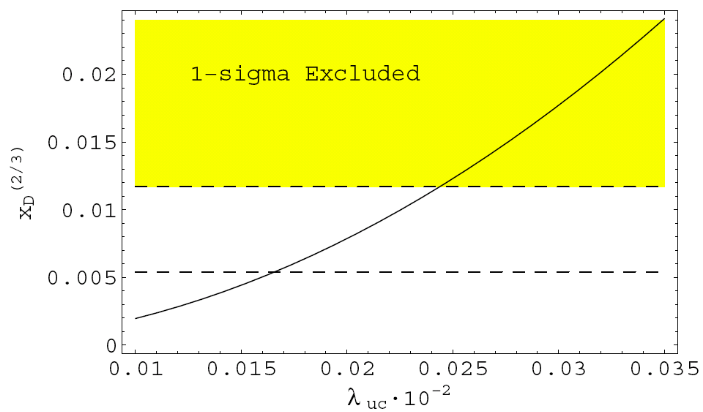
$$x_{\rm D}^{(-1/3)} \simeq \frac{G_F^2}{6\pi^2 \Gamma_D} f_D^2 B_D r_1(m_c, M_W) M_D M_W^2 \left(V_{cS}^* V_{uS}\right)^2 f(x_S)$$



- Vector-like quarks (Q=-1/3)

$$x_{\rm D}^{(2/3)} = \frac{2G_F}{3\sqrt{2}\Gamma_D} \left(\lambda_{uc}\right)^2 r_1(m_c, M_Z) f_{\rm D}^2 M_{\rm D} B_1$$

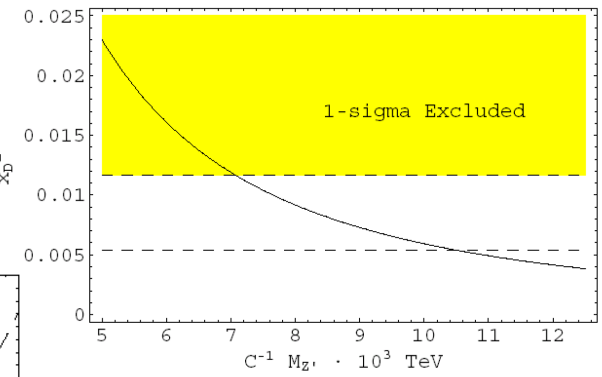
$$\lambda_{uc} \equiv -\left(V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb}\right)$$



New Physics in x: extra vector bosons

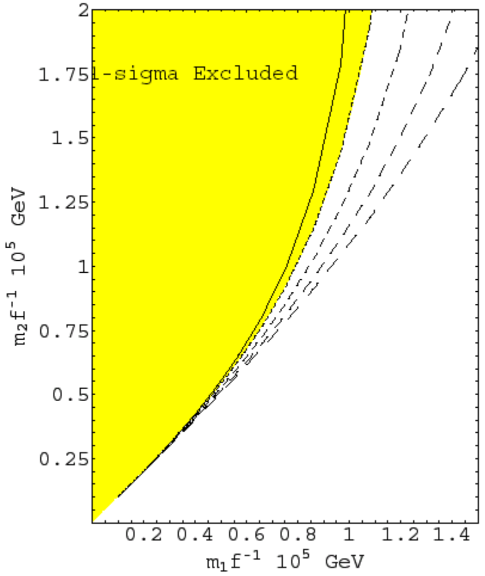
- Generic Z′ models

$$x_{\rm D}^{(Z')} = \frac{f_D^2 B_D}{2\Gamma_D}\frac{M_D}{M_{Z'}^2}\left[\frac{2}{3}\left(C_1(m_c)+C_6(m_c)\right)+C_2(m_c)\left(-\frac{1}{2}+\frac{\eta}{3}\right)+C_3(m_c)\left(\frac{1}{12}-\frac{\eta}{2}\right)\right]$$



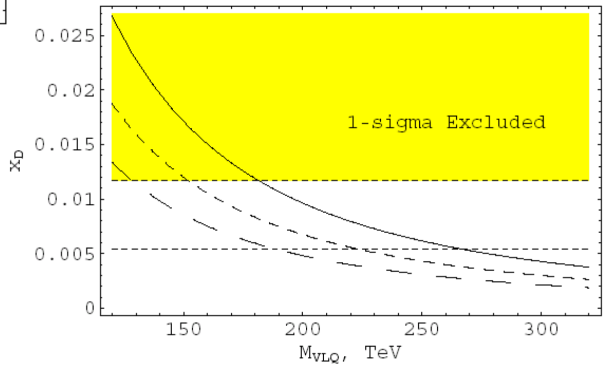
- Family symmetry

$$x_{\rm D}^{(FS)} = \frac{2}{3\Gamma_D} r_1(m_c, M)\left(\frac{f^2}{m_1^2}-\frac{f^2}{m_2^2}\right) f_D^2 M_D B_D$$



- Vector leptoquarks

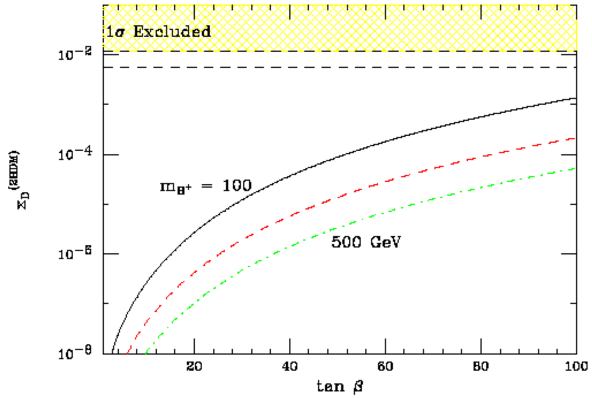
$$x_{\rm D}^{(VLQ)} = -\frac{1}{8\pi^2 m_{LQ}^2 \Gamma_D M_D}\left[\left(\lambda_L\langle Q_1\rangle+\lambda_R\langle Q_6\rangle\right)+\frac{10}{9}\frac{m_c^2}{m_{LQ}^2}\left(\lambda_L\langle Q_7\rangle+\lambda_R\langle Q_4\rangle\right)\right]$$
$$= -\frac{f_D^2 M_D B_D}{12\pi^2 m_{LQ}^2\Gamma_D}\left(\lambda_L+\lambda_R\right)\left(1+\frac{5\eta}{3}\frac{m_c^2}{m_{LQ}^2}\right),$$



New Physics in x: extra scalars

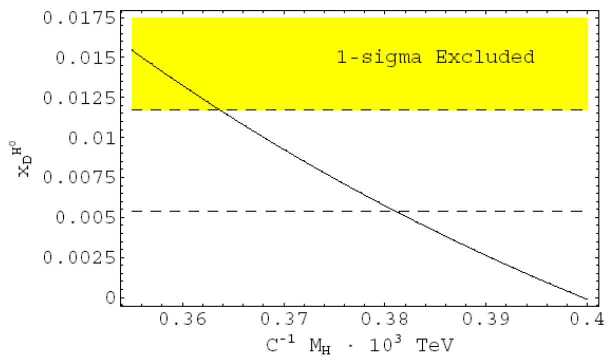
- 2-Higgs doublet model

$$x_{\rm D}^{(2{\rm HDM})} = \frac{G_F^2 M_W^2}{6\pi^2 \Gamma_D} f_D^2 M_D B_D r_1(m_c, M_{H^\pm}) \times \sum_{i,j} \lambda_i \lambda_j \left[\tan^4\beta A_{HH}(x_i, x_j, x_H) + \tan^2\beta A_{WH}(x_i, x_j, x_H)\right]$$



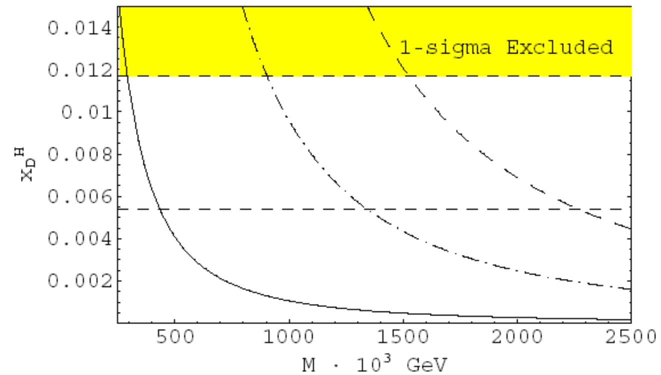
- Flavor-changing neutral Higgs

$$x_{\rm D}^{(\rm H)} = \frac{5 f_D^2 M_D B_D}{24 \Gamma_D M_H^2} \left[\frac{1-6\eta}{5} C_3(m_c) + \eta \left(C_4(m_c) + C_7(m_c)\right) - \frac{12\eta}{5} \left(C_5(m_c) + C_8(m_c)\right)\right]$$



- Higgsless models

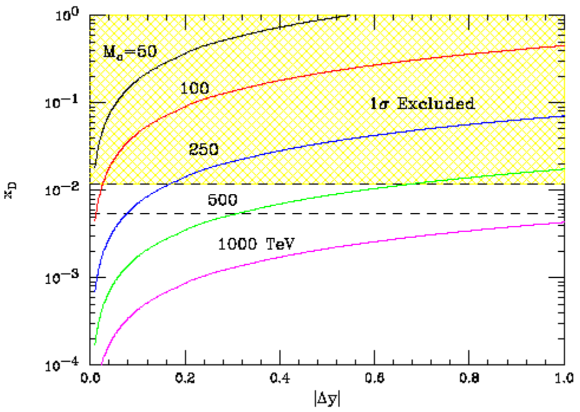
$$x_{\rm D}^{(\not H)} = \frac{f_D^2 M_D B_D}{\Gamma_D} (c_L^c s_L^c)^2 \frac{g^2}{M^2} \left[\frac{2}{3}\left(C_1(m_c) + C_6(m_c)\right) + C_2(m_c)\left(-\frac{1}{2} + \frac{\eta}{3}\right) + \frac{1}{12} C_3(m_c)(1-6\eta)\right] \quad .$$



New Physics in x: extra dimensions

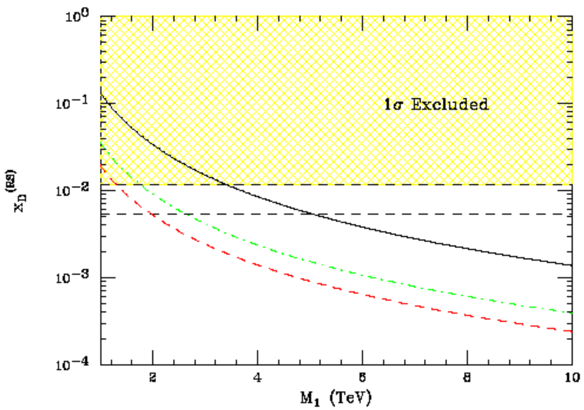
- Split fermion models

$$x_D^{(split)} = \frac{2}{9\Gamma_D} g_s^2 R_c^2 \pi^2 \Delta y \; r_1(m_c, M) |V^u_{L\,11} V^{u*}_{L\,12}|^2 f_D^2 M_D B_1$$



- Warped geometries

$$x_D^{(RS)} = \frac{g_s^2}{3M_1^2} \frac{f_D^2 B_D M_D}{\Gamma_D} \left(\frac{2}{3}[C_1(m_c) + C_6(m_c)] - \frac{1}{6} C_2(m_c) - \frac{5}{12} C_3(m_c) \right)$$



+ others…

Summary: New Physics

Model	Approximate Constraint
Fourth Generation (Fig. 2)	$\lvert V_{ub'}V_{cb'}\rvert \cdot m_{b'} < 0.5$ (GeV)
$Q = -1/3$ Singlet Quark (Fig. 4)	$s_2 \cdot m_S < 0.27$ (GeV)
$Q = +2/3$ Singlet Quark (Fig. 6)	$\lvert\lambda_{uc}\rvert < 2.4 \cdot 10^{-4}$
Little Higgs	Tree: See entry for $Q = -1/3$ Singlet Quark
	Box: Region of parameter space can reach observed $x_{\rm D}$
Generic Z' (Fig. 7)	$M_{Z'}/C > 2.2 \cdot 10^3$ TeV
Family Symmetries (Fig. 8)	$m_1/f > 1.2 \cdot 10^3$ TeV (with $m_1/m_2 = 0.5$)
Left-Right Symmetric (Fig. 9)	No constraint
Alternate Left-Right Symmetric (Fig. 10)	$M_R > 1.2$ TeV ($m_{D_1} = 0.5$ TeV)
	$(\Delta m/m_{D_1})/M_R > 0.4$ TeV^{-1}
Vector Leptoquark Bosons (Fig. 11)	$M_{VLQ} > 55(\lambda_{PP}/0.1)$ TeV
Flavor Conserving Two-Higgs-Doublet (Fig. 13)	No constraint
Flavor Changing Neutral Higgs (Fig. 15)	$m_H/C > 2.4 \cdot 10^3$ TeV
FC Neutral Higgs (Cheng-Sher ansatz) (Fig. 16)	$m_H/\lvert\Delta_{uc}\rvert > 600$ GeV
Scalar Leptoquark Bosons	See entry for RPV SUSY
Higgsless (Fig. 17)	$M > 100$ TeV
Universal Extra Dimensions	No constraint
Split Fermion (Fig. 19)	$M/\lvert\Delta y\rvert > (6 \cdot 10^2$ GeV)
Warped Geometries (Fig. 21)	$M_1 > 3.5$ TeV
Minimal Supersymmetric Standard (Fig. 23)	$\lvert(\delta^u_{12})_{\rm LR,RL}\rvert < 3.5 \cdot 10^{-2}$ for $\tilde m \sim 1$ TeV
	$\lvert(\delta^u_{12})_{\rm LL,RR}\rvert < .25$ for $\tilde m \sim 1$ TeV
Supersymmetric Alignment	$\tilde m > 2$ TeV
Supersymmetry with RPV (Fig. 27)	$\lambda'_{12k}\lambda'_{11k}/m_{\tilde d_{R,k}} < 1.8 \cdot 10^{-3}/100$ GeV
Split Supersymmetry	No constraint

- ✓ Considered 21 well-established models
- ✓ Only 4 models yielded no useful constraints
- ✓ Consult paper for explicit constraints

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
Phys. Rev. D76:095009, 2007

Conclusions

- Indirect effects of New Physics at flavor factories help to distinguish among models possibly observed at the LHC
  - a combination of bottom/charm sector studies
  - don't forget measurements unique to tau-charm factories
- Charm provides great opportunities for New Physics studies
  - unique access to up-type quark sector
  - large available statistics
  - mixing: x, y = 0 in the SU(3) limit (as $V^*_{cb}V_{ub}$ is very small)
  - mixing is a second order effect in SU(3) breaking
  - it is conceivable that $y \sim x \sim 1\%$ in the Standard Model
  - large contributions from New Physics are possible
  - out of 21 models studied, 17 yielded competitive constraints
  - additional input to LHC inverse problem
- Observation of CP-violation in the current round of experiments provide "smoking gun" signals for New Physics

Meeting of the Division of Particles and Fields of the American Physical Society (DPF 2009)

July 26-31, 2009, Detroit, Michigan

The 2009 Meeting of the Division of Particles and Fields of the American Physical Society will be held on campus of Wayne State University in Detroit, Michigan.

http://www.dpf2009.wayne.edu/

Please consider attending!!!

Additional slides

Questions:

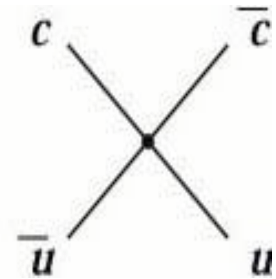
1. Can any model-independent statements be made for x or y ?

What is the order of SU(3) breaking?
i.e. if $x, y \propto m_s^n$ what is n?

2. Can one claim that y ~ 1% is natural?

Theoretical expectations

At which order in $SU(3)_F$ breaking does the effect occur? Group theory?



$$\langle D^0 | H_W H_W | \overline{D}^0 \rangle \Rightarrow \langle 0 | D H_W H_W D | 0 \rangle$$

is a singlet with D ® D_i *that belongs to **3** of* $SU(3)_F$ *(one light quark)*

The $\Delta C=1$ part of H_W is $\left(\overline{q}_i c\right)\left(\overline{q}_j q_k\right)$ $i.e.\ 3 \times \overline{3} \times \overline{3} = \overline{15} + 6 + \overline{3} + \overline{3} \Rightarrow H_k^{ij}$

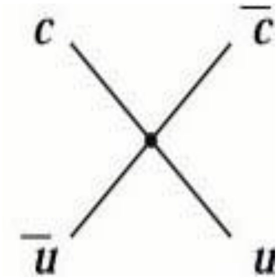
$$O_{\overline{15}} = (\overline{s}d)(\overline{u}d) + (\overline{u}c)(\overline{s}d) + s_1(\overline{d}c)(\overline{u}d) + s_1(\overline{u}c)(\overline{d}d) - s_1(\overline{s}c)(\overline{u}s) - s_1(\overline{u}c)(\overline{s}s) - s_1^2(\overline{d}c)(\overline{u}s) - s_1^2(\overline{u}c)(\overline{d}s)$$

$$O_6 = (\overline{s}d)(\overline{u}d) - (\overline{u}c)(\overline{s}d) + s_1(\overline{d}c)(\overline{u}d) - s_1(\overline{u}c)(\overline{d}d) - s_1(\overline{s}c)(\overline{u}s) + s_1(\overline{u}c)(\overline{s}s) - s_1^2(\overline{d}c)(\overline{u}s) + s_1^2(\overline{u}c)(\overline{d}s)$$

Introduce SU(3) breaking via the quark mass operator $M_j^i = diag(m_u, m_d, m_s)$

All nonzero matrix elements built of D_i, H_k^{ij}, M_j^i must be SU(3) singlets

Theoretical expectations



note that $D_i D_j$ is symmetric $\Rightarrow$ *belongs to **6** of $SU(3)_F$*

$$\langle D^0 | H_W H_W | \bar{D}^0 \rangle \Rightarrow \langle 0 | D H_W H_W D | 0 \rangle$$

Explicitly,

$$DD \Rightarrow D_6$$
$$H_W H_W \Rightarrow O_{\overline{60}} + O_{42} + O_{15'}$$

1. No $\bar{6}$ in the decomposition of $H_W H_W \Rightarrow$ no SU(3) singlet can be formed

$\Rightarrow$ D mixing is prohibited by SU(3) symmetry

2. Consider a single insertion of $M^i_j \Rightarrow D_6 M$ transforms as $6 \times 8 = 24 + \overline{15} + 6 + \bar{3} \Rightarrow$ still no SU(3) singlet can be formed

$\Rightarrow$ NO D mixing at first order in SU(3) breaking

3. Consider double insertion of $M \Rightarrow DMM$: $6 \times (8 \times 8)_S = (60 + \overline{42} + 24 + \overline{15} + \overline{15} + 6) + (24 + \overline{15} + 6 + \bar{3}) + 6$

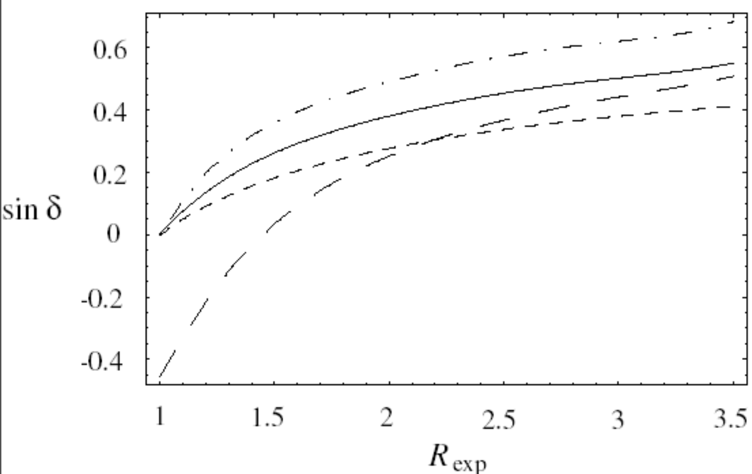
$\Rightarrow$ D mixing occurs only at the second order in SU(3) breaking

A.F., Y.G., Z.L., and A.A.P. Phys.Rev. D65, 054034, 2002

Quantum coherence: supporting measurements

Time-dependent $D^0(t) \to K^+\pi^-$ analysis

$$\Gamma\left[D^0(t) \to K^+\pi^-\right] = e^{-\Gamma t}\left|A_{K^+\pi^-}\right|^2 \left[R + \sqrt{R}R_m\left(y'\cos\phi - x'\sin\phi\right)\Gamma t + \frac{R_m^2}{4}\left(y^2 + x^2\right)(\Gamma t)^2\right]$$



where $R = \left|\frac{A_{K^+\pi^-}}{\overline{A}_{K^+\pi^-}}\right|^2$ and $x' = x\cos\delta + y\sin\delta$, $y' = y\cos\delta - x\sin\delta$

Strong phase δ is zero in the SU(3) limit and strongly model-dependent

A. Falk, Y. Nir and A.A.P., JHEP 12 (1999) 019

Strong phase can be measured at CLEO-c!

$$\sqrt{2}\,A\left(D_{CP\pm} \to K^-\pi^+\right) = A\left(D^0 \to K^-\pi^+\right) \pm A\left(\overline{D^0} \to K^-\pi^+\right)$$

$$\cos\delta = \frac{Br\left(D_{CP+} \to K^-\pi^+\right) - Br\left(D_{CP-} \to K^-\pi^+\right)}{2\sqrt{R}\,Br\left(D^0 \to K^-\pi^+\right)}$$

With 3 fb^{-1} of data $\cos\delta$ can be determined to $|\Delta \cos\delta| < 0.05$!

Silva, Soffer;
Gronau, Grossman, Rosner

Theoretical expectations

- If SU(3) breaking enters perturbatively, it is a second order effect…

$$A_i = A_{SU(3)} + \delta_i$$

A. Falk, Y. Grossman, Z. Ligeti, and A.A.P. Phys.Rev. D65, 054034, 2002

- Known counter-example:

1. Very narrow light quark resonance with $m_R \sim m_D$

$$x, y \sim \frac{g_{DR}^2}{m_D^2 - m_R^2} \sim \frac{g_{DR}^2}{m_D^2 - m_0^2 - 2m_0\delta_R}$$

Most probably don't exists…

see E.Golowich and A.A.P. Phys.Lett. B427, 172, 1998

- What happens if part of the multiplet is kinematically forbidden?

Example: both D^0 ® 4π *and* D^0 ® $4K$ are from the same multiplet, but the latter is kinematically forbidden

see A.F., Y.G., Z.L., and A.A.P. Phys.Rev. D65, 054034, 2002