Charm mixing in the Standard Model and Beyond

Alexey A. Petrov
Wayne State University

Table of Contents:

- Introduction
- Mixing: current/future experimental constraints
- Mixing: theoretical expectations
    - Standard Model
    - New Physics
- Conclusions and outlook

Introduction: identifying New Physics

"Inverse
LHC problem"

The LHC ring is 27km in circumference

How can SLAC and 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

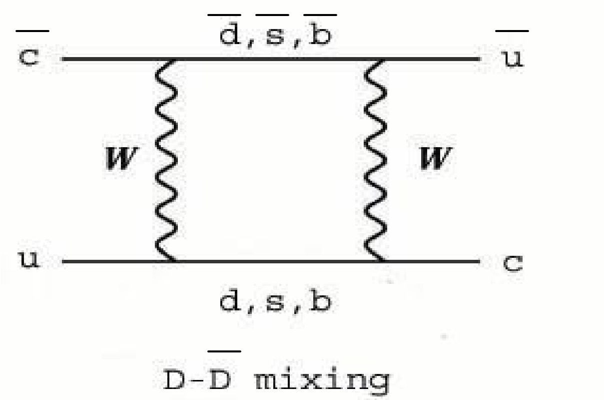
   Examples: $D^0 - \overline{D^0}$ mixing, $D \to X\gamma$, $D \to X\nu\overline{\nu}$

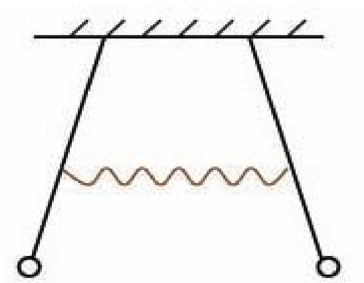
3. Processes allowed in the Standard Model

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

   CKM triangle relations

Introduction: 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 $\overline{D}^0$

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

- Time-dependence: coupled Schrödinger equations

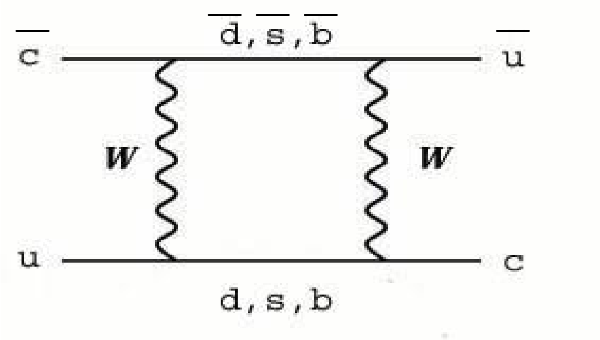
$$i \frac{\partial}{\partial t} \left| D(t) \right\rangle = \left(M - \frac{i}{2} \Gamma \right) \left| D(t) \right\rangle = \begin{bmatrix} A & p^2 \\ q^2 & A \end{bmatrix} \left| D(t) \right\rangle$$

- 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: $x = \frac{M_2 - M_1}{\Gamma}, \quad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$

Introduction: mixing



D-$\overline{D}$ mixing

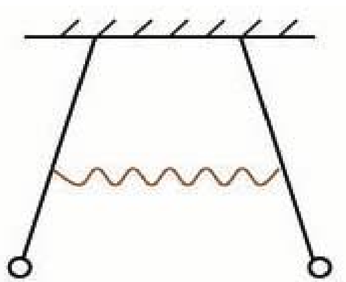
$\Delta Q=2$: only at one loop in the Standard Model: possible new physics particles in the loop

$\Delta Q=2$ 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

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



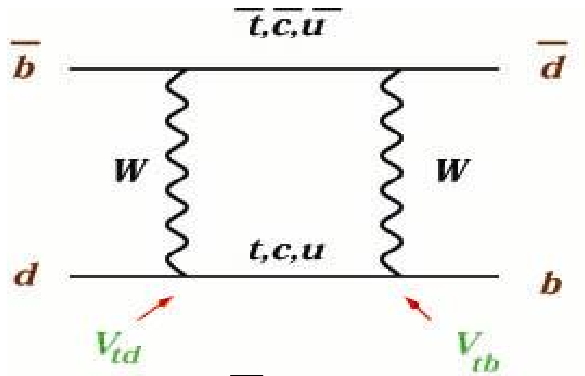
Coupled oscillators

- Diagonalize: mass eigenstates $\neq$ flavor eigenstates

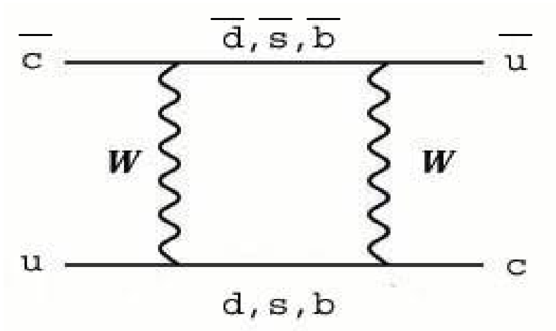
$$\text{No CPV:} \quad |D_{1,2}\rangle \Rightarrow |D_{CP\pm}\rangle = \frac{1}{\sqrt{2}}\left[|D^0\rangle \pm |\overline{D^0}\rangle\right]$$

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

Introduction: why do we care?



$B\text{-}\overline{B}$ mixing



$D\text{-}\overline{D}$ 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

How would new physics affect mixing?

- Look again at time development:

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

- Expand $\overline{D^0} - D^0$ mass matrix:

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

Local operator, affects x, possible ΔC=2 **new physics**

Real intermediate states, affect both x and y ⇒ **SM, ΔC=1 NP!**

1. $x >> y$: signal for New Physics?
   $x \approx y$: Standard Model?

2. CP violation in mixing/decay

new CP-violating phase ϕ

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 $D^0(t) \to K^+K^-$ analysis (lifetime difference)

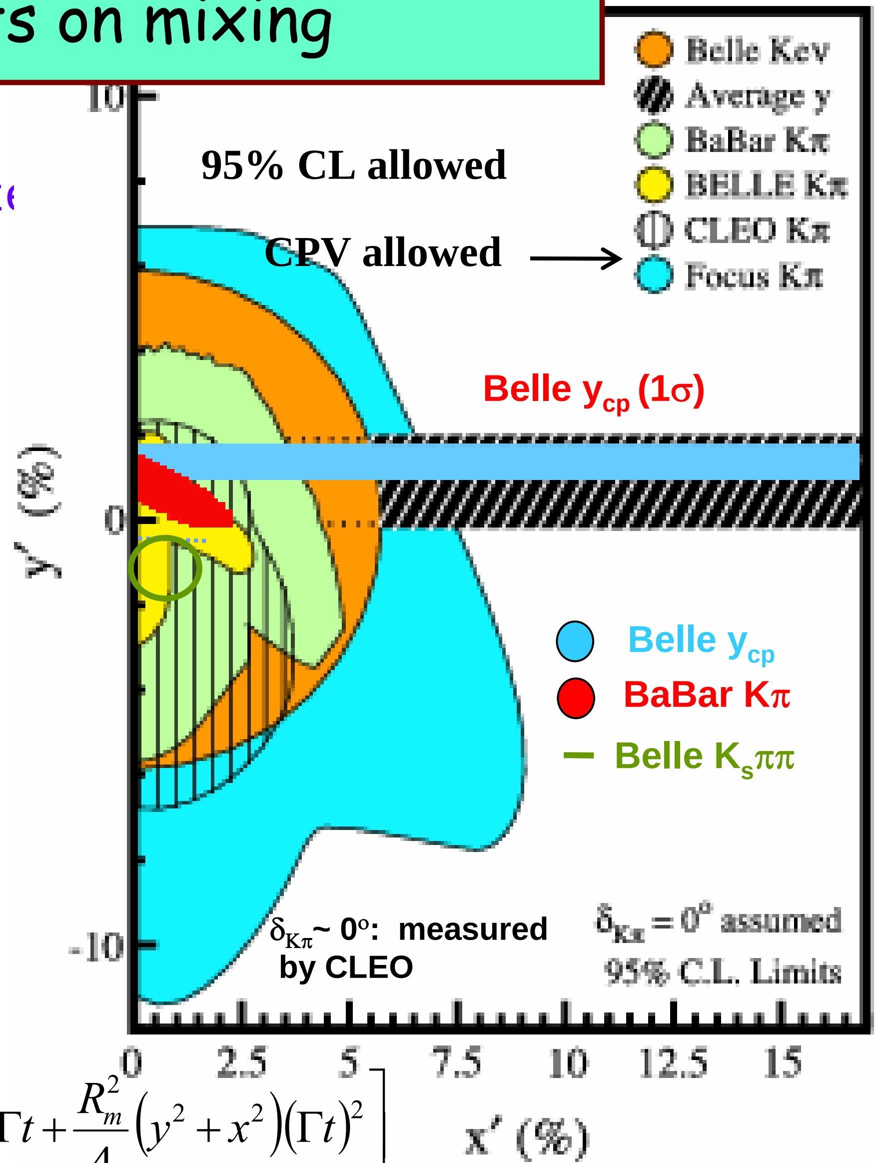
$$y_{CP} = \frac{\tau(D \to \pi^+ K^-)}{\tau(D \to K^+ K^-)} - 1 = y \cos\phi - x \sin\phi \frac{1-R_m}{2}$$

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

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

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

Sensitive to DCS/CF strong phase δ

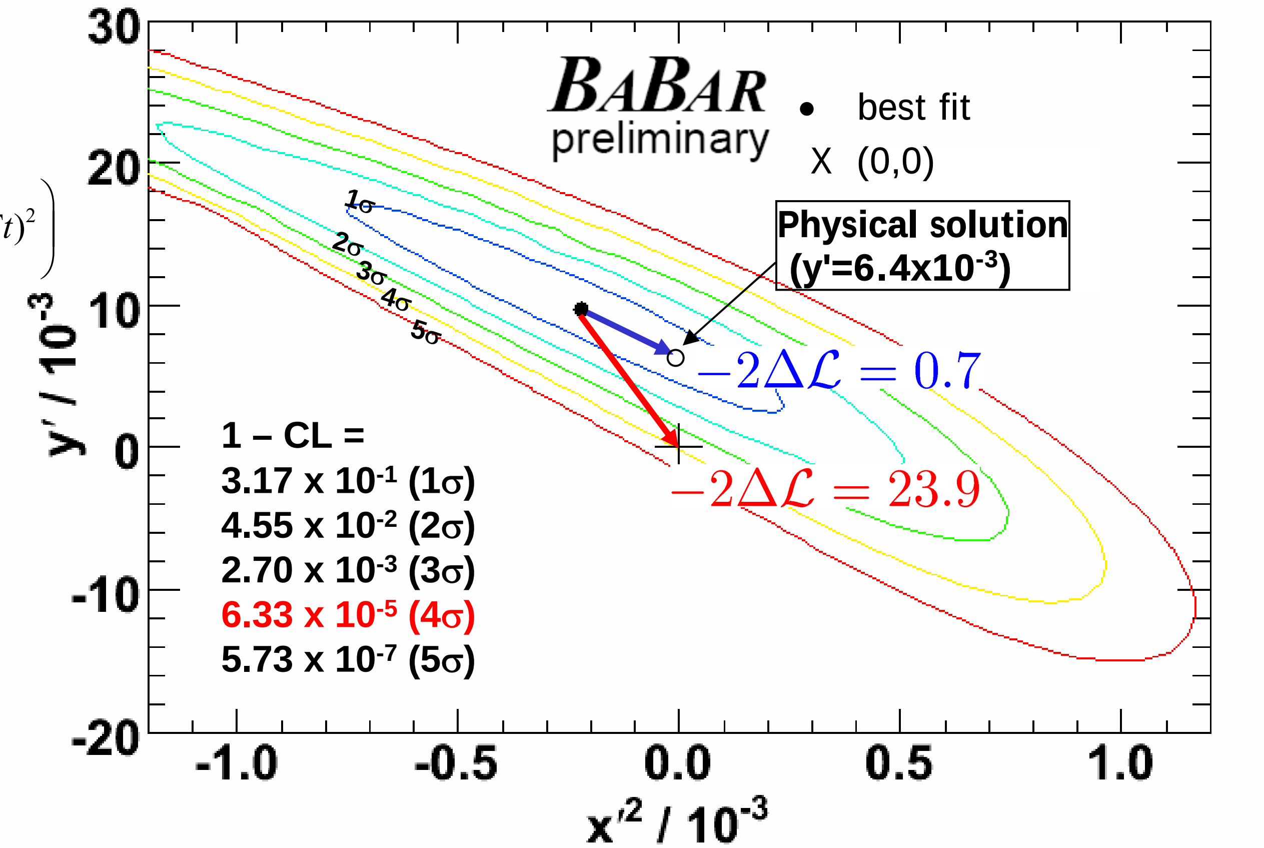


Recent results from BaBar

- 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

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

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

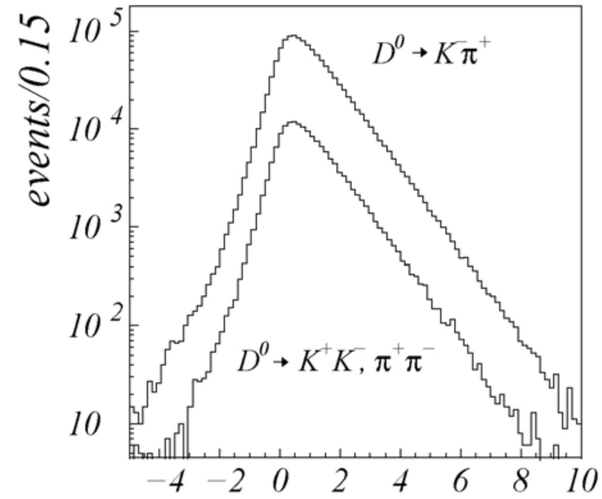
- Belle data

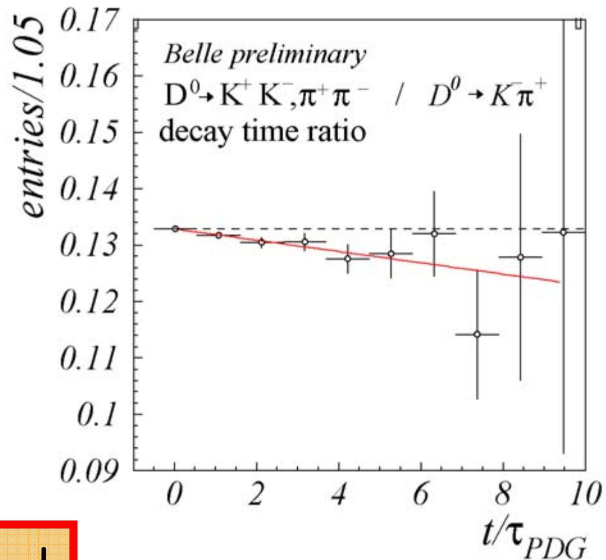
	y_{CP} (%)	A_Γ (%)
KK	1.25±0.39±0.28	0.15±0.34±0.16
$\pi\pi$	1.44±0.57±0.42	-0.28±0.52±0.30
$KK+\pi\pi$	1.31±0.32±0.25	0.01±0.30±0.15

y_{CP} = 1.31 ± 0.32 ± 0.25 %

- No evidence for CP-violation

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





(courtesy of A. Rahimi)

Recent results: summary

- BaBar and Belle results

$$y'_D = (0.97 \pm 0.44 \pm 0.31) \cdot 10^{-2} \qquad \text{(BaBar)} ,$$
$$y_D^{(CP)} = (1.31 \pm 0.32 \pm 0.25) \cdot 10^{-2} \qquad \text{(Belle)} .$$

Similar results from CDF

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

$$x_D = (0.80 \pm 0.29 \pm 0.17) \cdot 10^{-2} ,$$
$$y_D = (0.33 \pm 0.24 \pm 0.15) \cdot 10^{-2} .$$

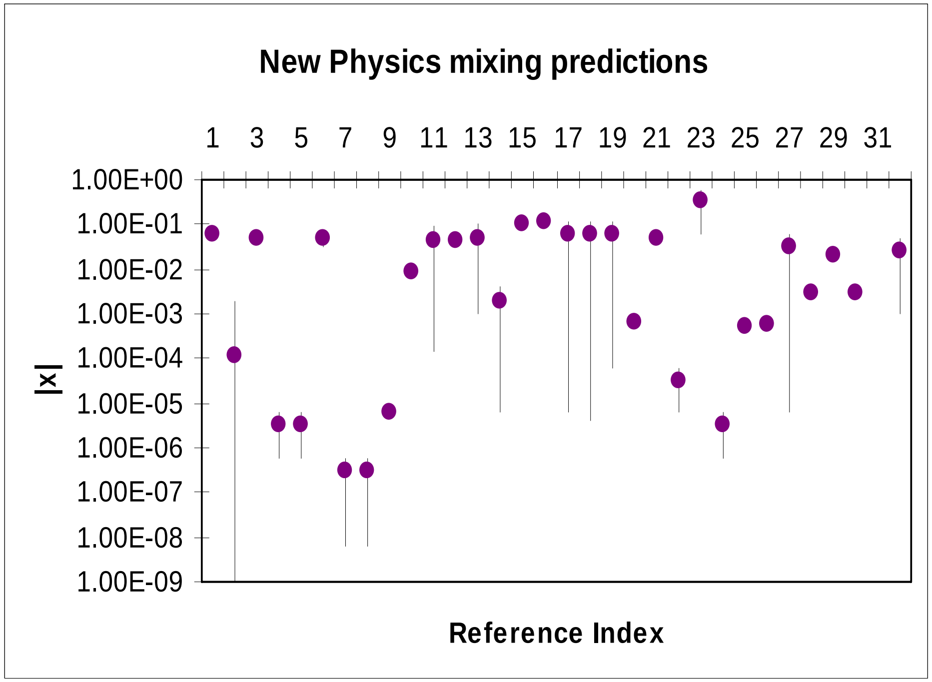
- Preliminary HFAG numbers

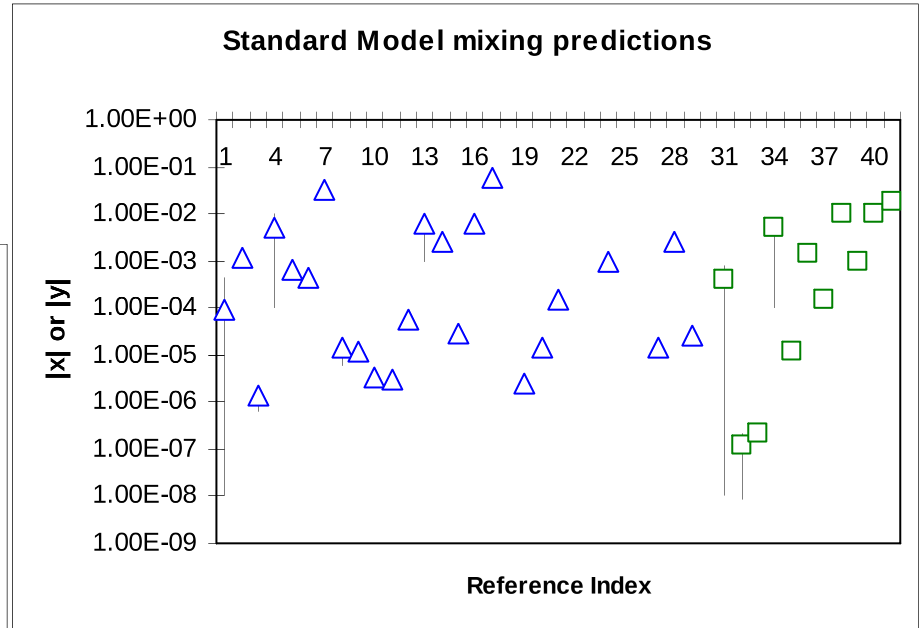
$$x_D = 8.5^{+3.2}_{-3.1} \cdot 10^{-3} ,$$
$$y_D = 7.1^{+2.0}_{-2.1} \cdot 10^{-3} \qquad (\cos \delta_{K\pi} = 1.09 \pm 0.66)$$

Mixing: theoretical estimates

Updated predictions

A.A.P. hep-ph/0311371





- Theoretical predictions are all over the board… so:
- Can x,y ~ 1% be a SM signal?
- What is the relationship between x and y (x ~ y, x > y, x < y?) in the Standard Model?

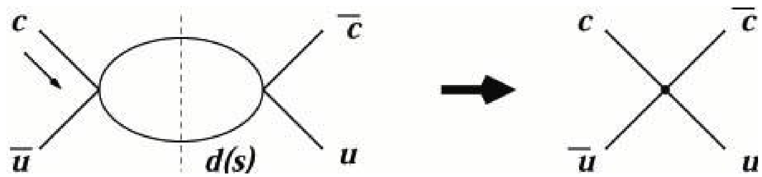
(papers from SPIRES)

- ● x from new physics
- □ y from Standard Model
- Δ x from Standard Model

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"...

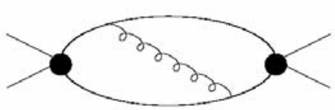
$$\Rightarrow \quad y_{\rm LO}^{(z^3)} = \frac{G_F^2 m_c^2 f_D^2 M_D}{3\pi\Gamma_D}\,\xi_s^2\, z^3 \left(C_2^2 - 2C_1C_2 - 3C_1^2\right)\left[B_{\rm D} - \frac{5}{2}\overline{B}_{\rm D}^{(S)}\right] \propto m_s^6\,\Lambda^{-6}$$

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

... $x_{LO} \gg y_{LO}$!!!

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

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

Theoretical estimates I

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

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

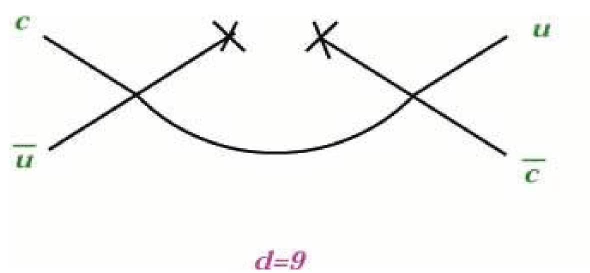
$$x_{sd}^{(6)} \propto \frac{\left(m_s^2 - m_d^2\right)^2}{m_c^2} \mu_{had}^{-2} \propto m_s^4 \Lambda^{-4}$$

4 unknown matrix elements

...subleading effects?

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

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

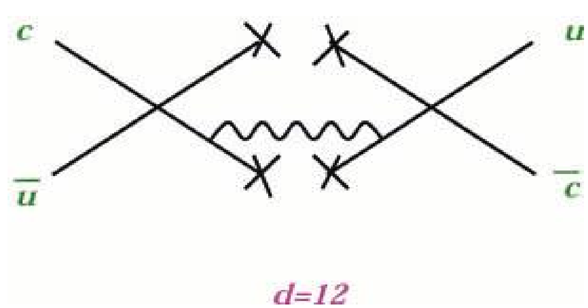


15 unknown matrix elements

H. Georgi, …
I. Bigi, N. Uraltsev

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

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



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 !!!

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

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

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

$$y_2 = Br\left(D^0 \to K^+K^-\right) + Br\left(D^0 \to \pi^+\pi^-\right) - 2\cos\delta \sqrt{Br\left(D^0 \to K^+\pi^-\right) Br\left(D^0 \to \pi^+K^-\right)}$$

cancellation expected!

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

SU(3) and phase space

- "Repackage" the analysis: look at the complete multiplet contribution

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

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

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

if CP is conserved

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

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

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

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

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

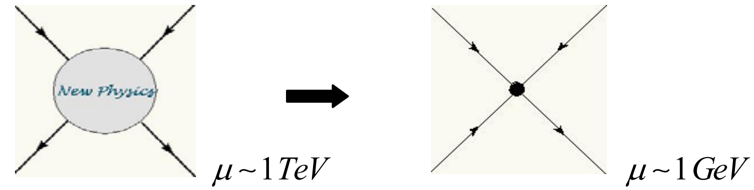
E.Golowich and A.A.P.
Phys.Lett. B427, 172, 1998

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

What about New Physics?

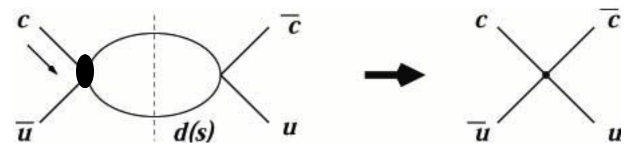
New Physics in x and y

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



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

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



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

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

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

Zero in the SU(3) limit

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

Can be significant!!!

2nd order effect!!!

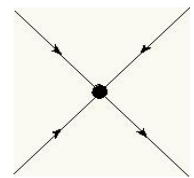
Global Analysis of New Physics: ΔC=1

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

- Let's write the most general ΔC=1 Hamiltonian

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

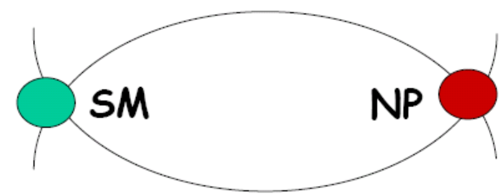
$$Q_1 = \bar{u}_i\bar{\Gamma}_1 q'_j \bar{q}_j \bar{\Gamma}_2 c_i, \qquad Q_2 = \bar{u}_i\bar{\Gamma}_1 q'_i \bar{q}_j \bar{\Gamma}_2 c_j,$$



$\mu \leq 1 TeV$

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

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

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

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

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

A.A.P. and G. Yeghiyan
arXiv:0710.4939 [hep-ph]

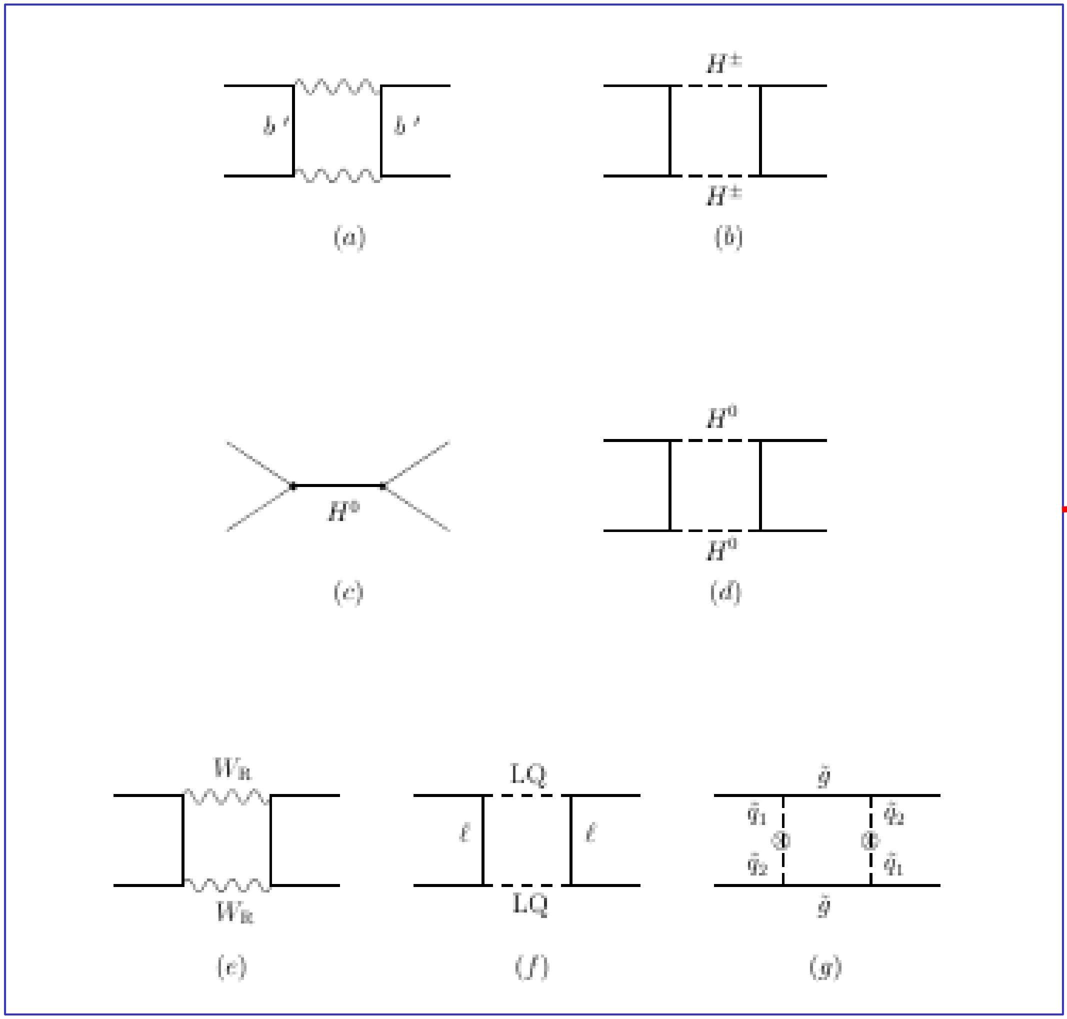
- Some examples of New Physics contributions

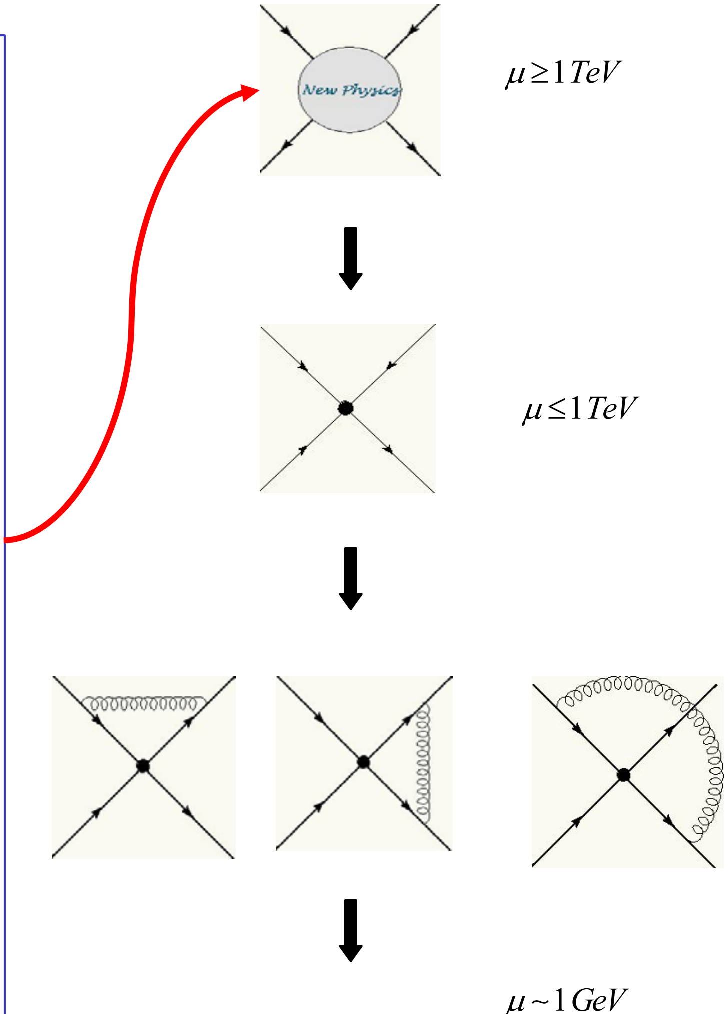
Model	y_D	Comment
RPV-SUSY	$6\ 10^{-6}$ $-4\ 10^{-2}$	Squark Exch. Slepton Exch.
Left-right	$-5\ 10^{-6}$ $-8.8\ 10^{-5}$	'Manifest'. 'Nonmanifest'.
Multi-Higgs	$2\ 10^{-10}$	Charged Higgs
Extra Quarks -	10^{-8}	Not Little Higgs

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



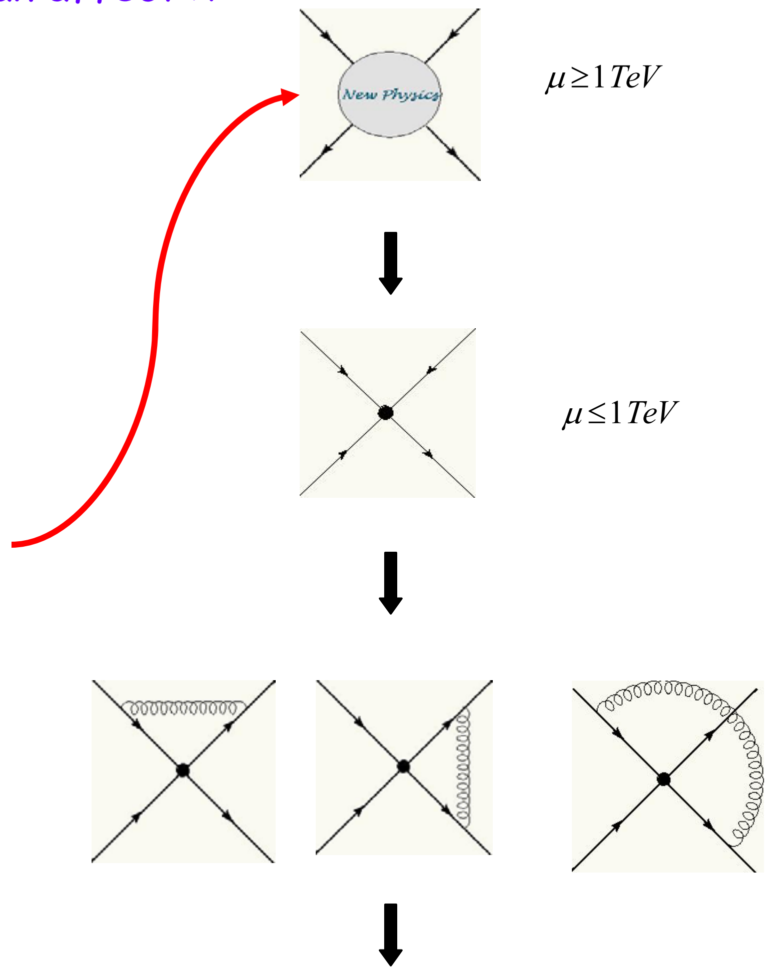


Global Analysis of New Physics: $\Delta C=2$

- Multitude of various models of New Physics can affect x

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.

"Four amigos"



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

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
arXiv:0705.3650 [hep-ph], PRD, to appear

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

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

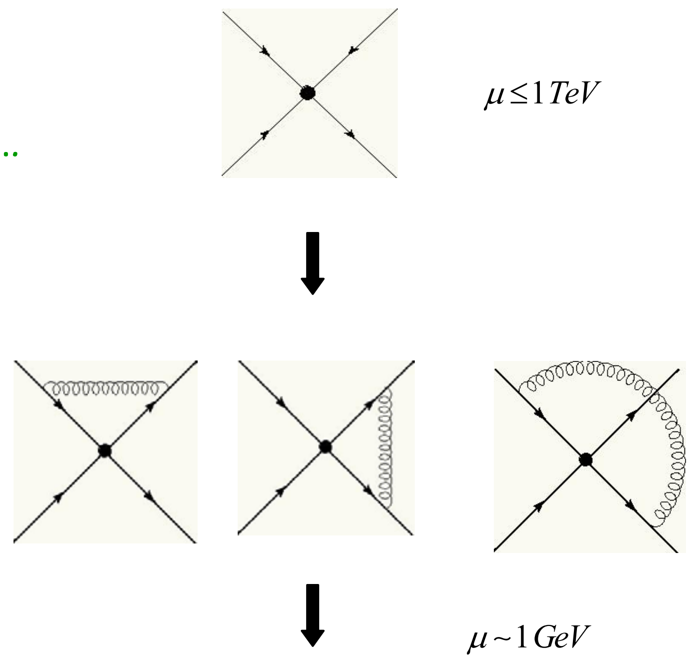
… with the following set of 8 independent operators…

$$Q_1 = (\overline{u}_L\gamma_\mu c_L)\ (\overline{u}_L\gamma^\mu c_L)\ , \qquad Q_5 = (\overline{u}_R\sigma_{\mu\nu} c_L)\ (\overline{u}_R\sigma^{\mu\nu} c_L)\ ,$$

$$Q_2 = (\overline{u}_L\gamma_\mu c_L)\ (\overline{u}_R\gamma^\mu c_R)\ , \qquad Q_6 = (\overline{u}_R\gamma_\mu c_R)\ (\overline{u}_R\gamma^\mu c_R)\ ,$$

$$Q_3 = (\overline{u}_L c_R)\ (\overline{u}_R c_L)\ , \qquad Q_7 = (\overline{u}_L c_R)\ (\overline{u}_L c_R)\ ,$$

$$Q_4 = (\overline{u}_R c_L)\ (\overline{u}_R c_L)\ , \qquad Q_8 = (\overline{u}_L\sigma_{\mu\nu} c_R)\ (\overline{u}_L\sigma^{\mu\nu} c_R)\ .$$



RG-running relate $C_i(\mu)$ at NP scale to the scale of μ ~ 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 $C_i(\Lambda_{NP})$

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

New Physics in x: lots of extras

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
arXiv:0705.3650 [hep-ph], PRD, to appear

- Extra gauge bosons

  Left-right models, horizontal symmetries, etc.

- Extra scalars

  Two-Higgs doublet models, leptoquarks, Higgsless, etc.

- Extra fermions

  4th generation, vector-like quarks, little Higgs, etc.

- Extra dimensions

  Universal extra dimensions, split fermions, warped ED, etc.

- Extra symmetries

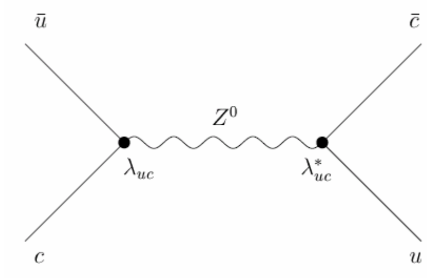
  SUSY: MSSM, alignment models, split SUSY, etc.

Total: 21 models considered

Dealing with New Physics

- 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

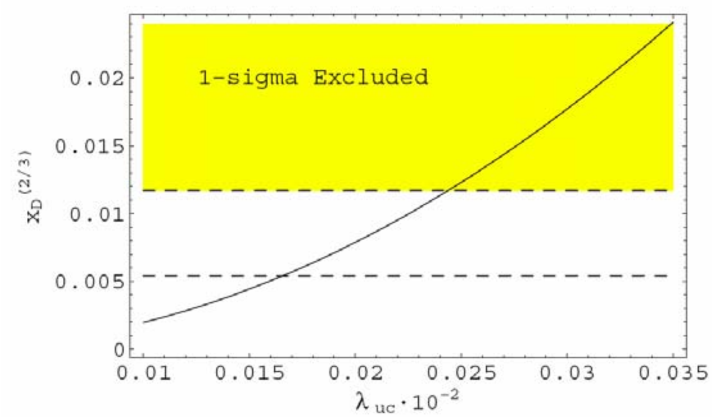
$$\mathcal{H}_{2/3} = \frac{g^2}{8\cos^2\theta_w M_Z^2} \left(\lambda_{uc}\right)^2 \bar{u}_L \gamma_\mu c_L \bar{u}_L \gamma^\mu c_L$$

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

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

3. Compute relevant matrix elements and x_D

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



New Physics in x: extra fermions

- Fourth generation

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

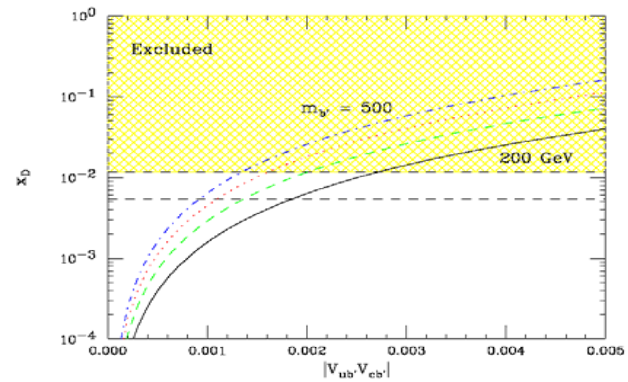
- Vector-like quarks (Q=+2/3)

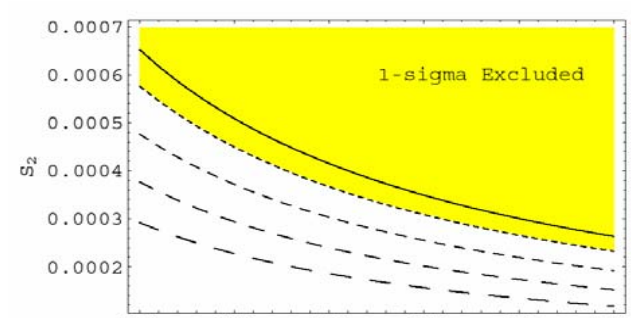
$$x_{\rm D}^{(-1/3)} \simeq \frac{G_F^2}{6\pi^2 \Gamma_D} f_D^2 B_D r_1(m_c, M_W) M_D M_W^2 \left(V_{cS}^* V_{uS}\right)^2 f(x_S)$$

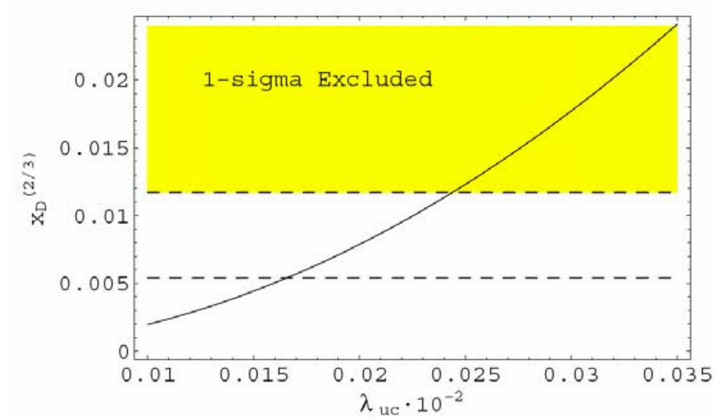
- Vector-like quarks (Q=-1/3)

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

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



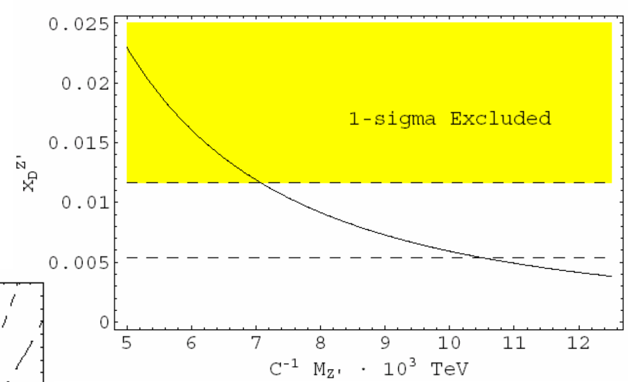




New Physics in x: extra vector bosons

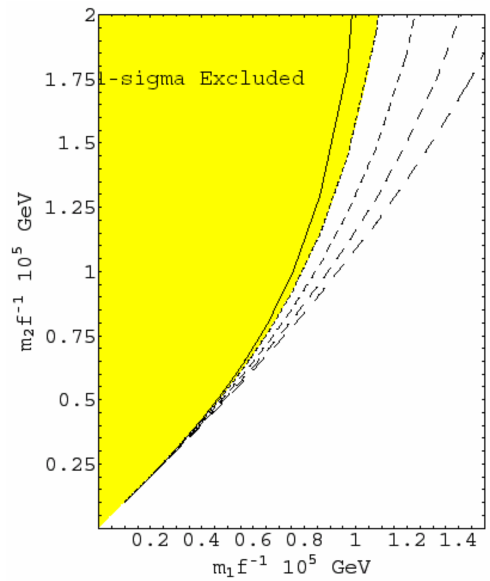
- Generic Z′ models

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



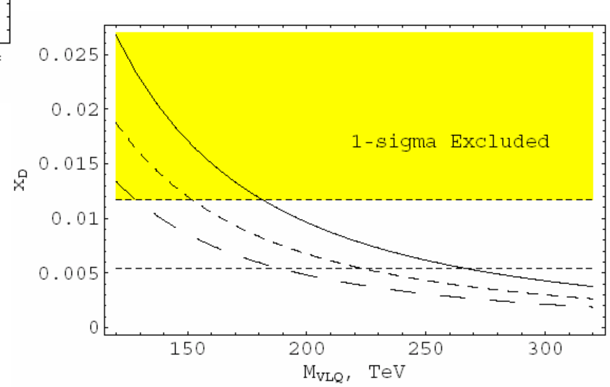
- Family symmetry

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



- Vector leptoquarks

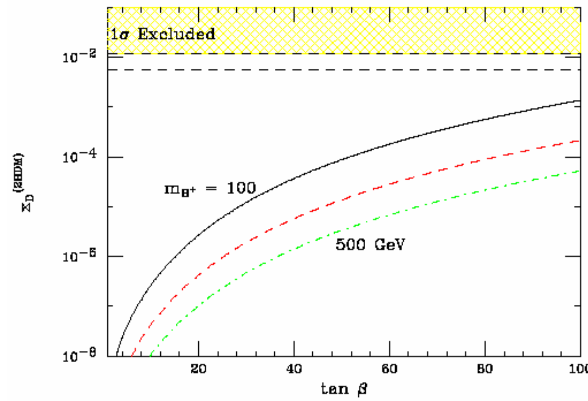
$$x_{\rm D}^{\rm (VLQ)} = -\frac{1}{8\pi^2 m_{LQ}^2 \Gamma_D M_D}\left[\left(\lambda_L\langle Q_1\rangle+\lambda_R\langle Q_6\rangle\right)+\frac{10}{9}\frac{m_c^2}{m_{LQ}^2}\left(\lambda_L\langle Q_7\rangle+\lambda_R\langle Q_4\rangle\right)\right]$$
$$= -\frac{f_D^2 M_D B_D}{12\pi^2 m_{LQ}^2 \Gamma_D}\left(\lambda_L+\lambda_R\right)\left(1+\frac{5\eta}{3}\frac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



New Physics in x: extra scalars

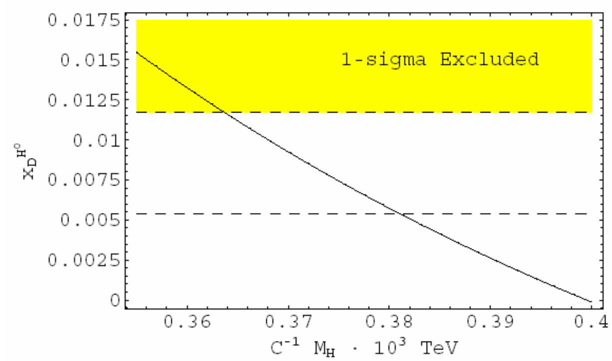
- 2-Higgs doublet model

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



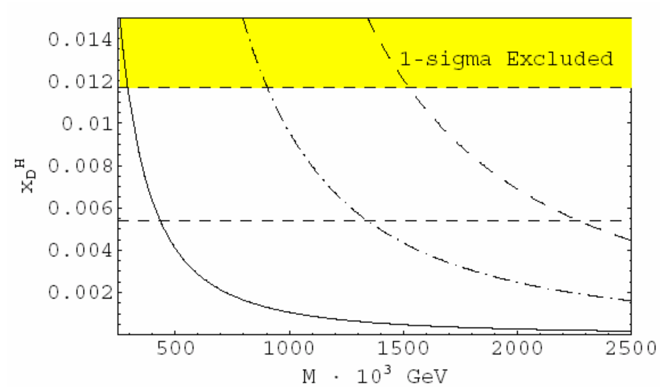
- Flavor-changing neutral Higgs

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



- Higgsless models

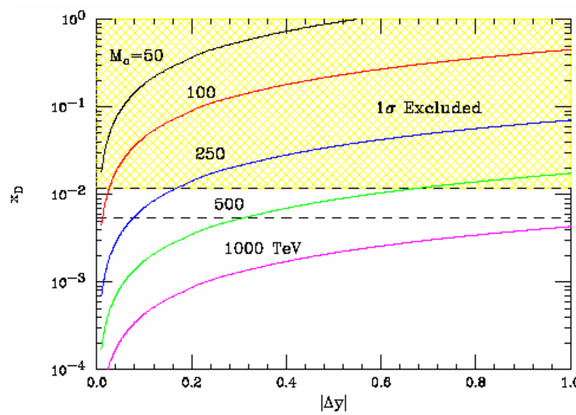
$$x_{\rm D}^{(\not{H})} = \frac{f_D^2 M_D B_D}{\Gamma_D}\left(c_L^c s_L^c\right)^2 \frac{g^2}{M^2}\left[\frac{2}{3}\left(C_1(m_c) + C_6(m_c)\right) + C_2(m_c)\left(-\frac{1}{2} + \frac{\eta}{3}\right) + \frac{1}{12} C_3(m_c)\left(1 - 6\eta\right)\right] .$$



New Physics in x: extra dimensions

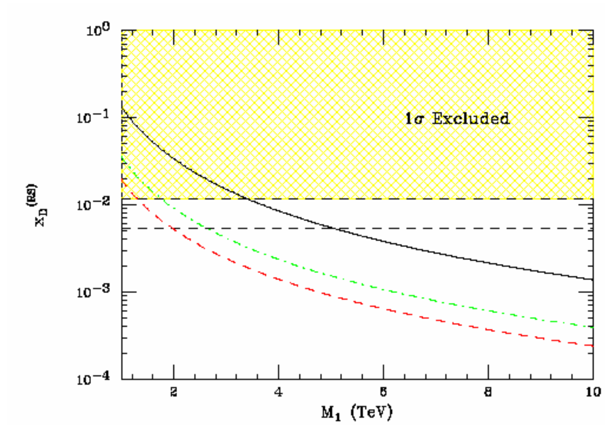
- Split fermion models

$$x_{\rm D}^{(split)} = \frac{2}{9\Gamma_D} g_s^2 R_c^2 \pi^2 \Delta y \ r_1(m_c, M) |V_{L\,11}^u V_{L\,12}^{u*}|^2 f_D^2 M_D B_1$$



- Warped geometries

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



+ others…

Summary: New Physics

Model	Approximate Constraint
Fourth Generation (Fig. 2)	$\|V_{ub'}V_{cb'}\| \cdot m_{b'} < 0.5$ (GeV)
$Q = -1/3$ Singlet Quark (Fig. 4)	$s_2 \cdot m_S < 0.27$ (GeV)
$Q = +2/3$ Singlet Quark (Fig. 6)	$\|\lambda_{uc}\| < 2.4 \cdot 10^{-4}$
Little Higgs	Tree: See entry for $Q = -1/3$ Singlet Quark
	Box: Region of parameter space can reach observed x_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)	$m_H/\|\Delta_{uc}\| > 600$ GeV
Scalar Leptoquark Bosons	See entry for RPV SUSY
Higgsless (Fig. 17)	$M > 100$ TeV
Universal Extra Dimensions	No constraint
Split Fermion (Fig. 19)	$M/\|\Delta y\| > (6 \cdot 10^2$ GeV)
Warped Geometries (Fig. 21)	$M_1 > 3.5$ TeV
Minimal Supersymmetric Standard (Fig. 23)	$\|(\delta^u_{12})_{\rm LR,RL}\| < 3.5 \cdot 10^{-2}$ for $\tilde{m} \sim 1$ TeV
	$\|(\delta^u_{12})_{\rm LL,RR}\| < .25$ 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.
arXiv:0705.3650 [hep-ph], PRD, to appear

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 ~ x ~ 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

Additional slides

Questions:

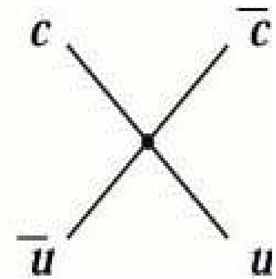
1. Can any model-independent statements be made for *x* or *y*?

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 $D \to D_i$ *that belongs to* **3** *of* $SU(3)_F$ *(one light quark)*

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

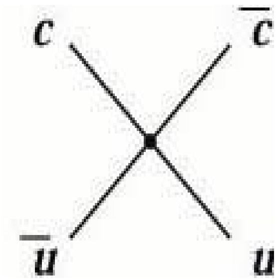
$$O_{\overline{15}} = (\bar{s}d)(\bar{u}d) + (\bar{u}c)(\bar{s}d) + s_1(\bar{d}c)(\bar{u}d) + s_1(\bar{u}c)(\bar{d}d) - s_1(\bar{s}c)(\bar{u}s) - s_1(\bar{u}c)(\bar{s}s) - s_1^2(\bar{d}c)(\bar{u}s) - s_1^2(\bar{u}c)(\bar{d}s)$$

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

Introduce SU(3) breaking via the quark mass operator $M^i_j = diag\,(m_u, m_d, m_s)$

All nonzero matrix elements built of D_i, H^{ij}_k, M^i_j must be SU(3) singlets

Theoretical expectations



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

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

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

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

➡ D mixing is prohibited by SU(3) symmetry

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

➡ NO D mixing at first order in SU(3) breaking

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

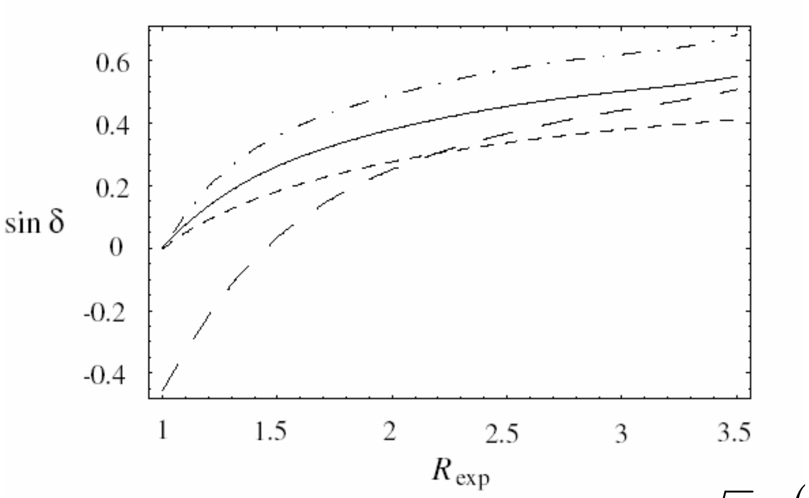
➡ D mixing occurs only at the second order in SU(3) breaking

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

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



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 δ can be determined to |Δ cos δ| < 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 $D^0 \to 4\pi$ *and* $D^0 \to 4K$ 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

CP violation: new experimental possibilities 1

1. Time dependent $D^0(t) \to K^+K^-$ (lifetime difference analysis): separate datasets for D^0 and $\overline{D}^0$

$$A_{CP}(f) = \frac{\Gamma'\left(D^0 \to K^+K^-\right) - \Gamma'\left(\overline{D^0} \to K^+K^-\right)}{\Gamma'\left(D^0 \to K^+K^-\right) + \Gamma'\left(\overline{D^0} \to K^+K^-\right)} = \frac{A_m}{2} y \cos\phi - x \sin\phi$$

This analysis requires

1. time-dependent studies
2. initial flavor tagging ("the D* trick")

Cuts statistics/sensitivity

How would CP violation manifest itself in charm?

- Possible sources of NP in CP violation in charm transitions:

  - CPV in decay amplitudes ("direct" CPV)

$$A(D \to f) \neq A(\overline{D} \to \overline{f})$$

  - CPV in $D^0 - \overline{D^0}$ mixing matrix

$$R_m^2 = \left|\frac{p}{q}\right|^2 = \frac{2M_{12} - i\Gamma_{12}}{2M_{12}^* - i\Gamma_{12}^*} \neq 1$$

With b-quark contribution neglected:
only 2 generations contribute
⇒ **real 2x2 Cabibbo matrix**

  - CPV in the interference of decays with and without mixing

$$\lambda_f = \frac{q}{p}\frac{\overline{A_f}}{A_f} = R_m e^{i(\phi+\delta)}\left|\frac{\overline{A_f}}{A_f}\right|$$

At this point CP-violating signal is a "smoking gun" signature of New Physics

A bit more about CP violation in charm

CP violation: experimental constraints

1. Standard analysis: rate asymmetries

$$A_{CP}(f) = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})} = \frac{1 - \left|\overline{A}_{\overline{f}} / A_f\right|^2}{1 + \left|\overline{A}_{\overline{f}} / A_f\right|^2}$$

Mode	E791, %	FOCUS, %	CLEO, %
$D^0 \to K^+K^-$	-1.0±4.9±1.2	-0.1±2.2±1.5	0.0±2.2±0.8
$D^0 \to \pi^+\pi^-$	-4.9±7.8±3.0	4.8±3.9±2.5	1.9±3.2±0.8
$D^0 \to K_S\pi^0$			0.1±1.3
$D^0 \to \pi^0\pi^+K^-$			-3.1±8.6

… which is of the first order in CPV parameters, but requires tagging

2. Recall that CP of the states in $D^0\overline{D^0} \to (F_1)(F_2)$ are anti-correlated at $\psi(3770)$:

- a simple signal of CP violation: $\psi(3770) \to D^0\overline{D^0} \to (CP\pm)(CP\pm)$

$$\Gamma_{F_1F_2} = \frac{\Gamma_{F_1}\Gamma_{F_2}}{2R_m^2}\left[\left(2 + x^2 + y^2\right)\left|\lambda_{F_1} - \lambda_{F_2}\right|^2 + \left(x^2 + y^2\right)\left|1 - \lambda_{F_1}\lambda_{F_2}\right|^2\right]$$

$$\lambda_f = \frac{q}{p}\frac{\overline{A}_f}{A_f}$$

… which is of the second order in CPV parameters, i.e. tiny

CP violation: new experimental possibilities

Look for CPV signals that are

1. first order in CPV
2. do not require flavor tagging

Consider the final states that can be reached by both $\overline{D^0}$ and D^0, but are not CP eigenstates ($\pi\rho$, KK^*, $K\pi$, $K\rho$, …)

$$A_{CP}^{U}\left(f,t\right)=\frac{\Sigma_f-\Sigma_{\overline{f}}}{\Sigma_f+\Sigma_{\overline{f}}}$$

where

$$\Sigma_f=\Gamma\left(D^0\to f\right)[t]+\Gamma\left(\overline{D^0}\to f\right)[t]$$

A.A.P., PRD69, 111901(R), 2004
hep-ph/0403030

CP violation: untagged asymmetries

Expect time-dependent asymmetry…

$$A_{CP}^{U}(f,t) = \frac{1}{D(t)} e^{-\Gamma t}\left[A + B(\Gamma t) + C(\Gamma t)^2\right]$$

… and time-integrated asymmetry

$$A_{CP}^{U}(f,t) = \frac{1}{D}\left[A + B + 2C\right]$$

… whose coefficients are computed to be

$$A = |A_f|^2\left[\left(1 - |\overline{A}_{\overline{f}}|^2 / |A_f|^2\right) + R\left(1 - |A_{\overline{f}}|^2 / |\overline{A}_f|^2\right)\right],$$

$$B = -2y\sqrt{R}\left[\sin\phi\sin\delta\left(|\overline{A}_f|^2 + |A_{\overline{f}}|^2\right) - \cos\phi\cos\delta\left(|\overline{A}_f|^2 - |A_{\overline{f}}|^2\right)\right],$$

$$C = \frac{x^2}{2}A.$$

$$\frac{A(D^0 \to f)}{A(\overline{D^0} \to f)} = \sqrt{R}e^{i\delta}$$

This is true for any final state f

CP violation: untagged asymmetries ($K^+\pi^-$)

For a particular final state $K\pi$, the time-integrated asymmetry is simple

$$A_{CP}^{U}\left(K^{+}\pi^{-}\right)=-y\sin\delta\sin\phi\sqrt{R}$$

This asymmetry is

1. non-zero due to large SU(3) breaking
2. contains no model-dependent hadronic parameters (R and δ are experimental observables)
3. could be as large as 0.04% for NP

Note: larger by O(100) for SCS decays ($\pi\rho$, ...) where R ~ 1

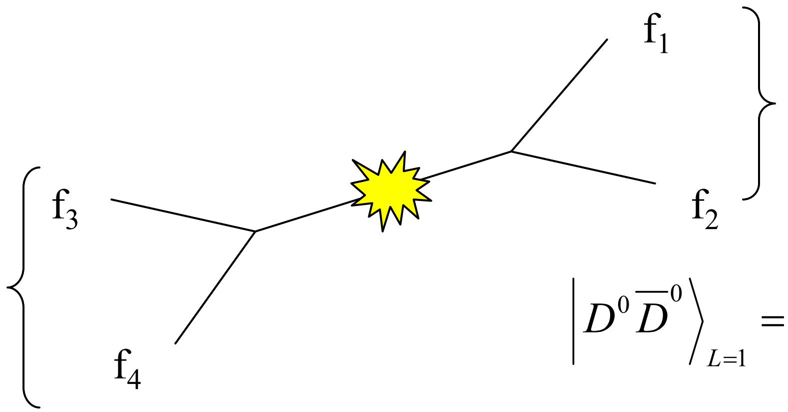
A.A.P., PRD69, 111901(R), 2004
hep-ph/0403030

What if time-dependent studies are not possible I?

τ-charm factory (BES/CLEO-c)

Time-integrated $D^0 \to K^+\pi^-$ analysis: DCSD contribution cancels out for double-tagged $D^0\overline{D^0} \to (K^-\pi^+)(K^-\pi^+)$ decays!

$D \to f_3 f_4$



$D \to f_1 f_2$

$$\left|D^0\overline{D}^0\right\rangle_{L=1} = \frac{1}{\sqrt{2}}\left[\left|D^0(k_1)\overline{D}^0(k_2)\right\rangle - \left|D^0(k_2)\overline{D}^0(k_1)\right\rangle\right]$$

$$A\left(D^0\overline{D^0} \to (K^-\pi^+)^2\right) = \frac{1}{\sqrt{2}}\left\langle (K^-\pi^+)(K^-\pi^+)\right|H_{eff}\left|D^0\overline{D^0}\right\rangle - \frac{1}{\sqrt{2}}\left\langle (K^-\pi^+)(K^-\pi^+)\right|H_{eff}\left|\overline{D^0}D^0\right\rangle$$

CF *DCS*

$$R\left(\frac{(K^-\pi^+)(K^-\pi^+)}{(K^-\pi^+)(K^+\pi^-)}\right) = \frac{x^2+y^2}{2}\left|\frac{p}{q}\right|^2 = r_D^2\left|\frac{p}{q}\right|^2$$

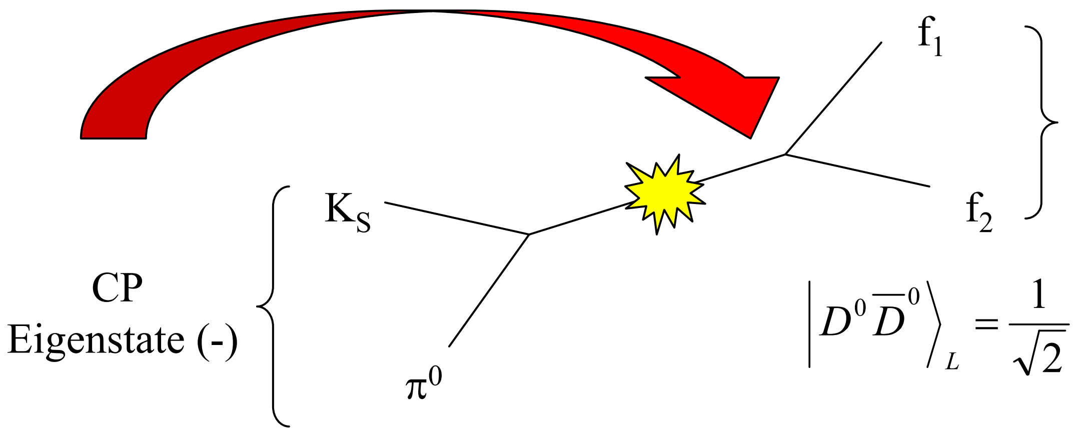
Quadratic in x,y: not so sensitive
wanted: *linear* in x or y

H. Yamamoto; I. Bigi, A. Sanda

What if time-dependent studies are not possible II?

τ-charm factory (BES/CLEO-c)

- If CP violation is neglected: mass eigenstates = CP eigenstates
- CP eigenstates do NOT evolve with time, so can be used for "tagging"



$$D_{CP(+)} \to f_1 f_2$$

$$\left| D^0 \overline{D}^0 \right\rangle_L = \frac{1}{\sqrt{2}} \left[\left| D^0(k_1) \overline{D}^0(k_2) \right\rangle + (-1)^L \left| D^0(k_2) \overline{D}^0(k_1) \right\rangle \right]$$

- τ-charm factories have good CP-tagging capabilities

  CP anti-correlated ψ(3770): $CP(tag)\,(-1)^L = \overbrace{[CP(K_S)\,CP(\pi^0)]}^{(-)}\,(-1) = +1$

  CP correlated ψ(4140)

Can still measure y:

$$B_\pm^l = \frac{\Gamma\left(D_{CP\pm} \to X l \nu\right)}{\Gamma_{tot}}$$

$$y \cos\phi = \frac{1}{4}\left(\frac{B_+^l}{B_-^l} - \frac{B_-^l}{B_+^l} \right)$$

D. Atwood, A.A.P., hep-ph/0207165
D. Asner, W. Sun, hep-ph/0507238