Charm Mixing and Rare Decays: Looking for New Physics

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Table of Contents:

1. Introduction: identifying New Physics

"Inverse LHC problem"

The LHC ring is 27km in circumference

KEKb - 3 km...

How can BaBar/Belle/BES 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, $D \to \ell^+ \ell^-$, $D \to X\gamma, ...$

3. Processes allowed in the Standard Model

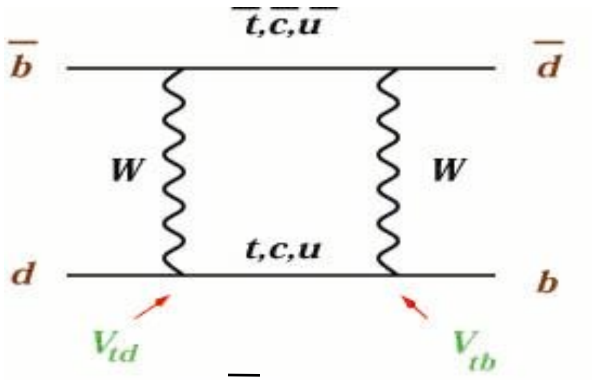
   Examples: 1. relations, valid in the SM, but not necessarily in general

   CKM triangle relations

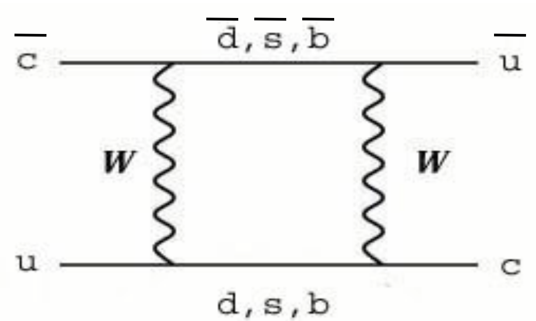
   2. SM rates and uncertainties are known

Unique feature: not-so-heavy quark

2. $\overline{D}^0$-D^0 mixing?



B-$\overline{B}$ mixing



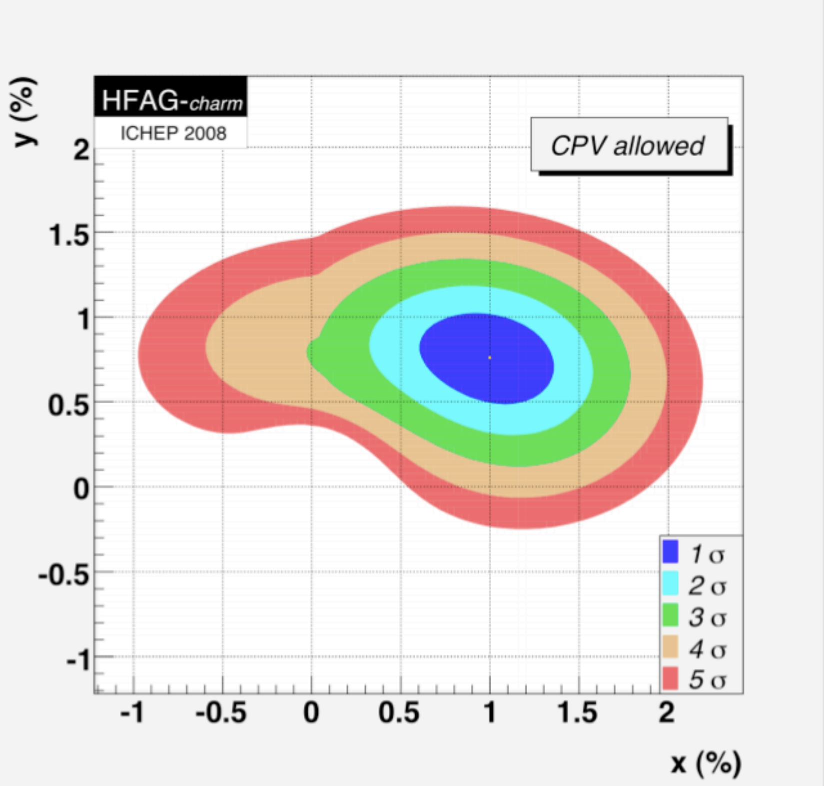
D-$\overline{D}$ mixing

$\overline{D^0} - D^0$ 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

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

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

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

4. Dalitz analyses $D^0(t) \to K\pi\pi, KKK$
5. Quantum correlations analyses

Sensitive to DCS/CF strong phase δ

Recent experimental results

★ Recent experimental data

[287] **Charm mixing and CPV at CDF** by Nagesh KULKARNI (Wayne State University) (17:18 - 17:42)	slides
[452] **Measurement of D0-D0bar mixing and search for CP violation at Babar** by Prof. Michael SOKOLOFF (University of Cincinnati) (17:42 - 18:06)	slides
[320] **Quantum Correlated Neutral D Meson Decays** by Dr. Adam LINCOLN (Wayne State University) (18:06 - 18:30)	slides

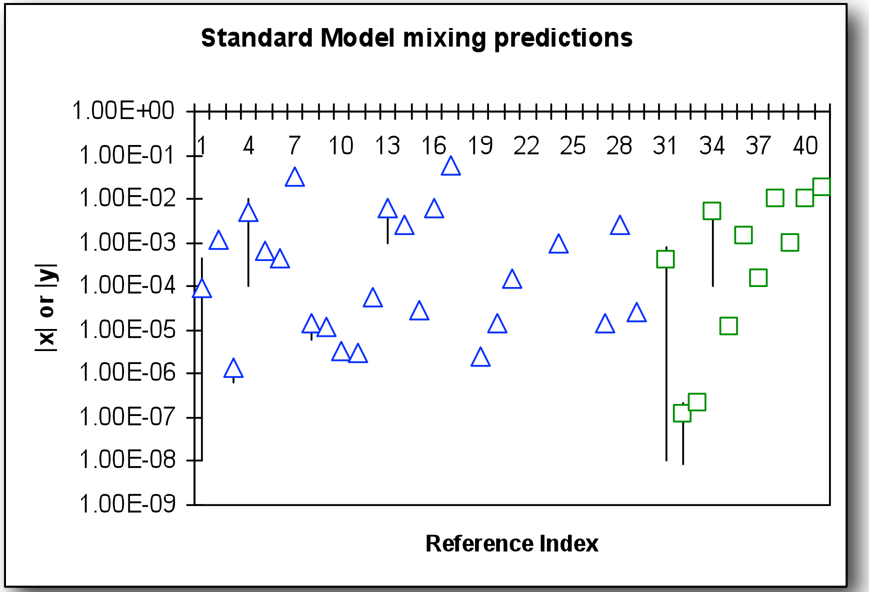
★ Recent HFAG numbers

$$x_D \equiv \frac{\Delta M_D}{\Gamma_D} = 0.0100^{+0.0024}_{-0.0026} \quad \text{and} \quad y_D \equiv \frac{\Delta\Gamma_D}{2\Gamma_D} = 0.0076^{+0.0017}_{-0.0018}$$

See talks above for additional details

|x| >> |y| is NO LONGER a signal for New Physics

Standard Model predictions



* Not an actual representation of theoretical uncertainties. Objects might be bigger then what they appear to be...

★ Predictions of x and y in the SM are complicated

- second order in flavor SU(3) breaking
- m_c is not quite large enough for OPE
  - x, y << 10^{-3} ("short-distance")
  - x, y ~ 10^{-2} ("long-distance")

★ Short distance:

- assume m_c is large
  - combined m_s, $1/m_c$, a_s expansions
  - leading order: m_s^2, $1/m_c^6$!

H. Georgi; T. Ohl, …
I. Bigi, N. Uraltsev;
M. Bobrowski et al

★ Long distance:

- assume m_c is NOT large
  - sum of large numbers with alternating signs, SU(3) forces zero!
  - multiparticle intermediate states dominate

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

Falk, Grossman, Ligeti, Nir. A.A.P.
Phys.Rev. D69, 114021, 2004
Falk, Grossman, Ligeti, and A.A.P.
Phys.Rev. D65, 054034, 2002

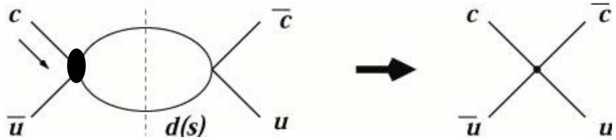
Resume: a contribution to x and y <u>of the order of 1%</u> is natural in the SM

How New Physics affects x and y

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

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

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



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

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

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

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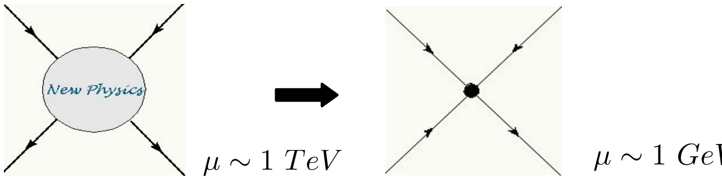

$$\left(M - \frac{i}{2}\Gamma\right)_{ij} = m_D^{(0)}\delta_{ij} + \frac{1}{2m_D}\left\langle D_i^0 \middle| H_W^{\Delta C=2} \middle| D_j^0 \right\rangle + \frac{1}{2m_D}\sum_I \frac{\left\langle D_i^0 \middle| H_W^{\Delta C=1} \middle| I \right\rangle \left\langle I \middle| H_W^{\Delta C=1} \middle|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

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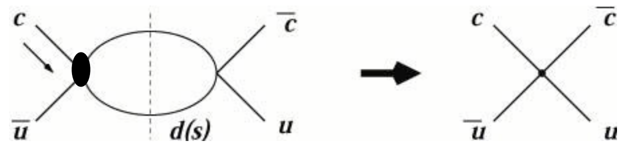

Amplitude $A_n = \left\langle D^0 \middle| \left(H_{SM}^{\Delta C=1} + H_{NP}^{\Delta C=1}\right) \middle| n \right\rangle \equiv A_n^{SM} + A_n^{NP}$

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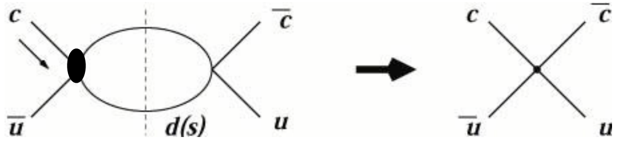

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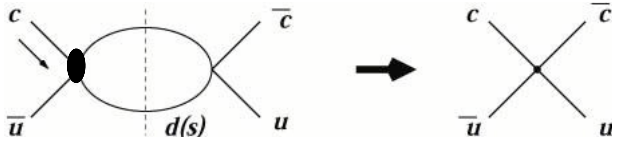

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phase space

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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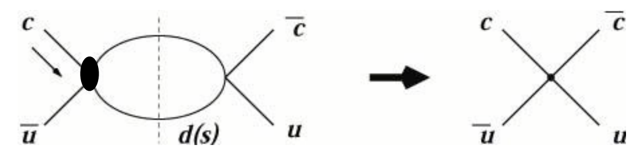

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2nd order effect!!!

Can be significant!!!

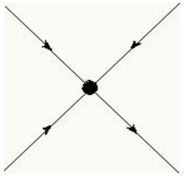
Global Analysis of New Physics: $\Delta C=1$

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

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

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

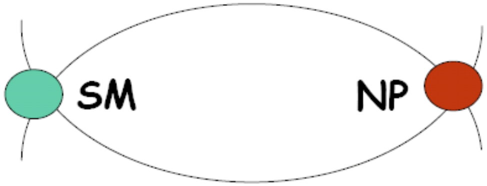
$$Q_1 = \bar{u}_i \bar{\Gamma}_1 q'_j \bar{q}_j \bar{\Gamma}_2 c_i, \qquad Q_2 = \bar{u}_i \bar{\Gamma}_1 q'_i \bar{q}_j \bar{\Gamma}_2 c_j,$$



$\mu \le 1\,TeV$

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

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

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

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

- 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

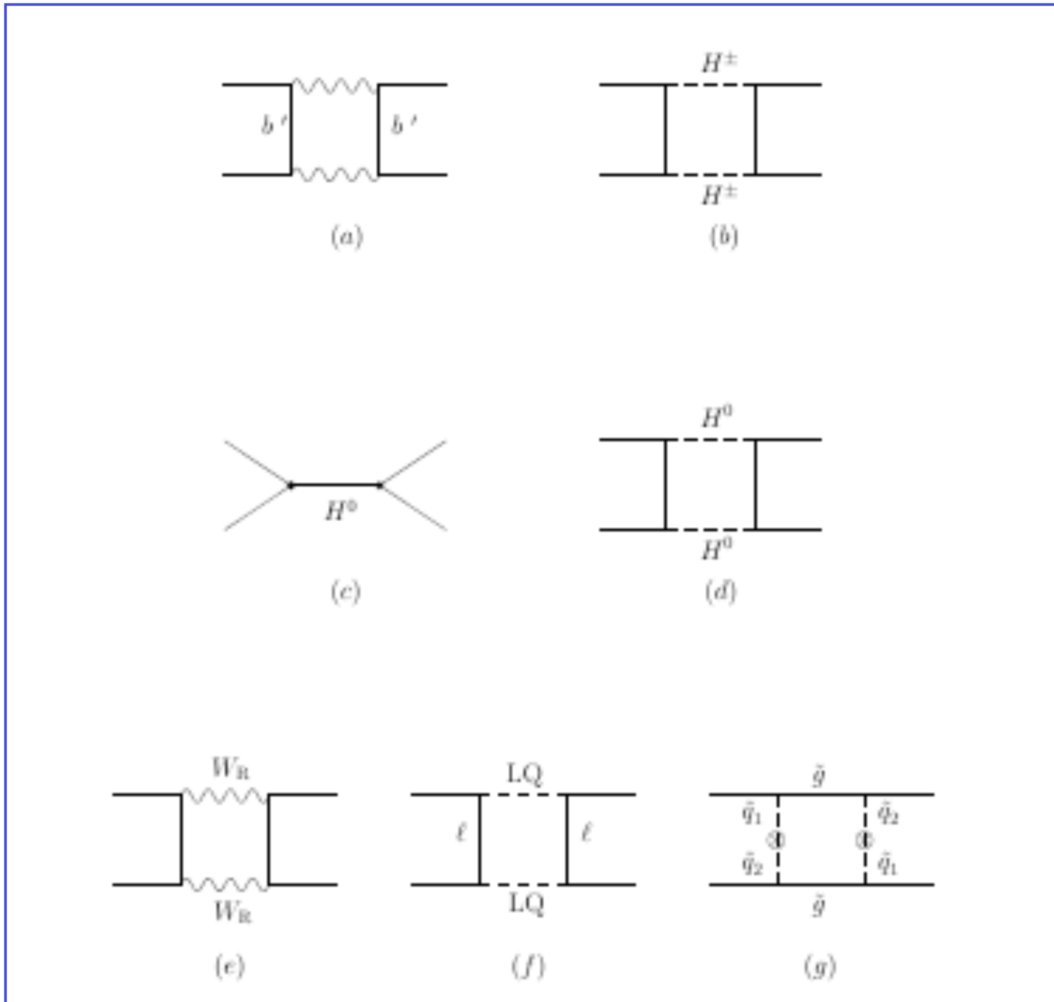
A.A.P. and G. Yeghiyan
Phys. Rev. D77, 034018 (2008)

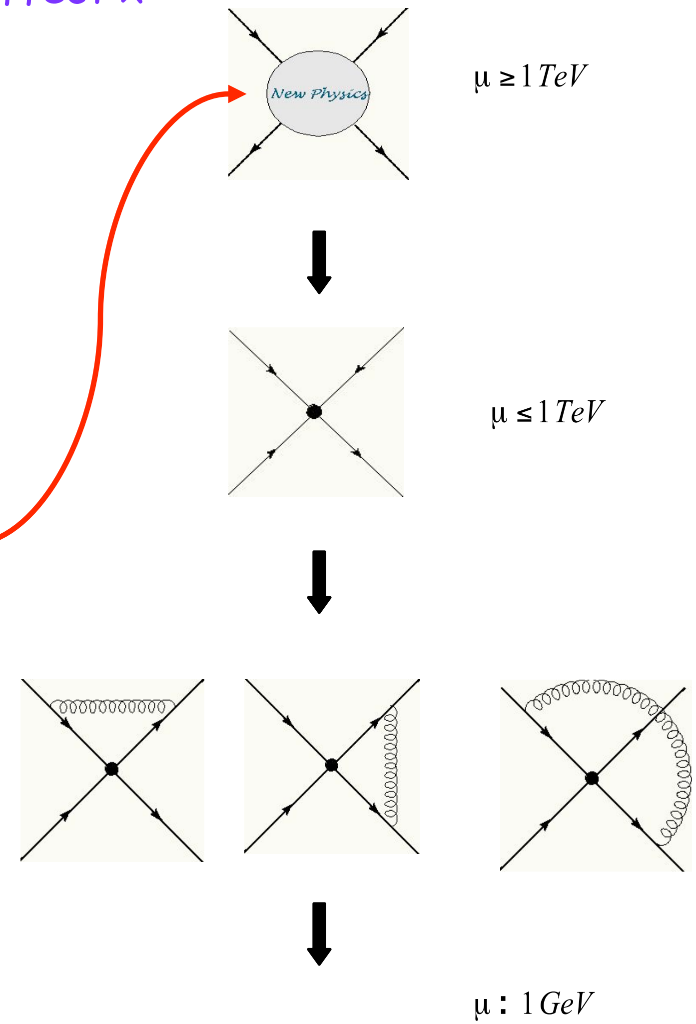
M. Bobrowski et al
arXiv: 0904.3971 [hep-ph]

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



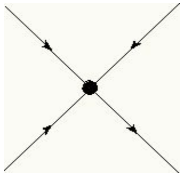


Global Analysis of New Physics: $\Delta C=2$

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

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



$\mu \le 1\, TeV$

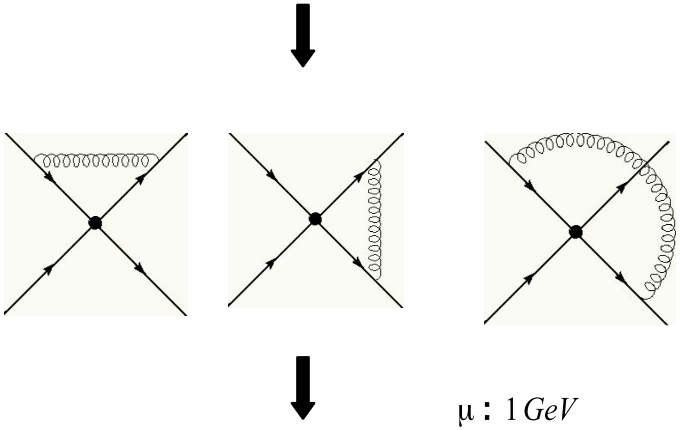
… with the following set of 8 independent operators…

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

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

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

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



$\mu \sim 1\, GeV$

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 $C_i(\Lambda_{NP})$

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.

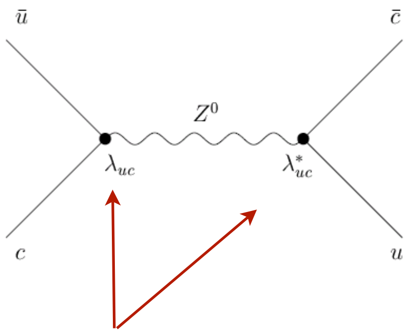
- Extra gauge bosons
  - Left-right models, horizontal symmetries, etc.
- Extra scalars
  - Two-Higgs doublet models, leptoquarks, Higgsless, etc.
- Extra fermions
  - 4^{th} generation, vector-like quarks, little Higgs, etc.
- Extra dimensions
  - Universal extra dimensions, split fermions, warped ED,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

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



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

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

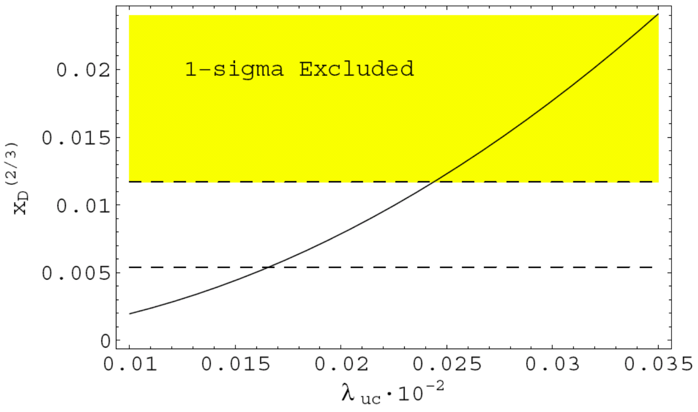
$$\mathcal{H}_{2/3} = \frac{g^2}{8\cos^2\theta_w M_Z^2}\left(\lambda_{uc}\right)^2 \bar{u}_L\gamma_\mu c_L \bar{u}_L\gamma^\mu c_L$$

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

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

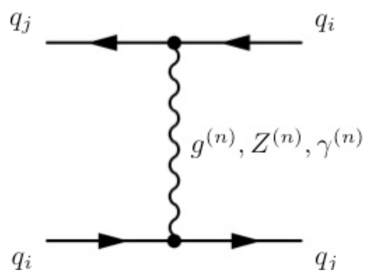


4. Assume no SM - get an upper bound on NP model parameters (coupling)

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

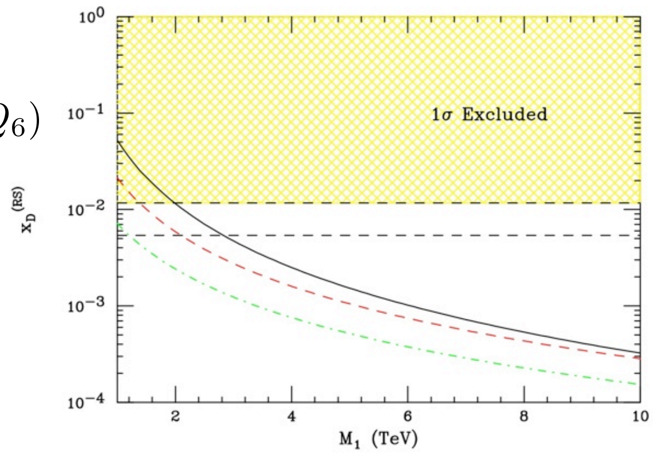
$$\mathcal{H}_{RS} = \frac{2\pi k r_c}{3M_1^2} g_s^2 \left(C_1(M_n)Q_1 + C_2(M_n)Q_2 + C_6(M_n)Q_6\right)$$

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

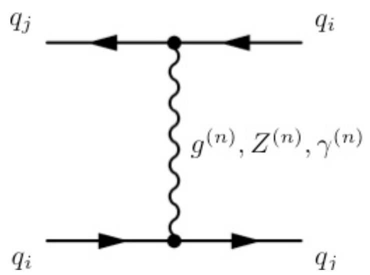
$$x_D^{(RS)} = \frac{g_s^2}{3M_1^2} \frac{f_D^2 B_D M_D}{\Gamma_D} \left(\frac{2}{3}[C_1(m_c) + C_6(m_c)] - \frac{1}{6}C_2(m_c) - \frac{5}{12}C_3(m_c)\right)$$



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

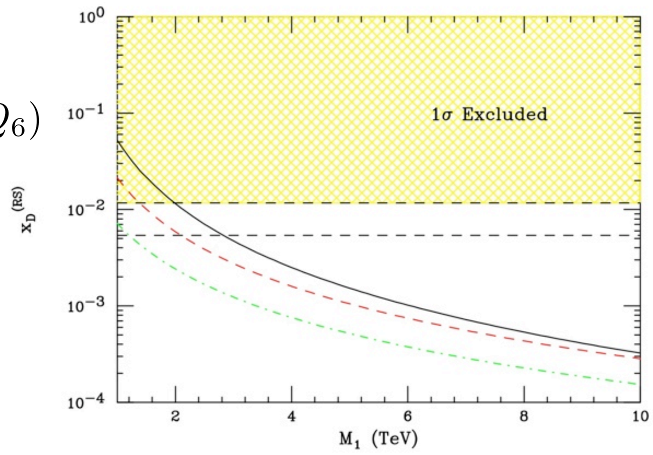
$$\mathcal{H}_{RS} = \frac{2\pi k r_c}{3M_1^2} g_s^2 \left(C_1(M_n) Q_1 + C_2(M_n) Q_2 + C_6(M_n) Q_6 \right)$$

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

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

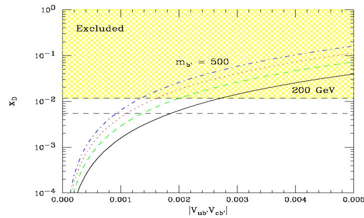


Implies: M_{1KKg} > 2.5 TeV!

Constraints on New Physics from x

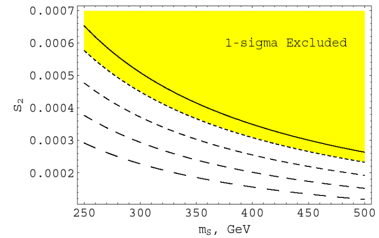
- Extra fermions
- Extra vector bosons
- Extra scalars

4th generation



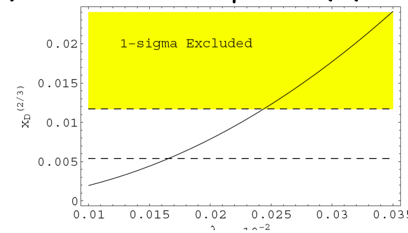
$$x_D^{(4^{th})} = \frac{G_F^2 M_W^2}{6\pi^2 \Gamma_D} f_D^2 M_D B_D \lambda_{b'}^2 S(x_{b'}, x_{b'}) r_1(m_c, M_W)$$

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



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

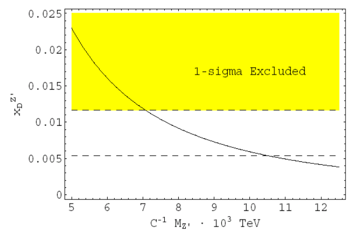
Vector-like quarks (Q=-1/3)



$$x_D^{(2/3)} = \frac{2G_F}{3\sqrt{2}\Gamma_D} \left(\lambda_{uc}\right)^2 r_1(m_c, M_Z) f_D^2 M_D B_1$$

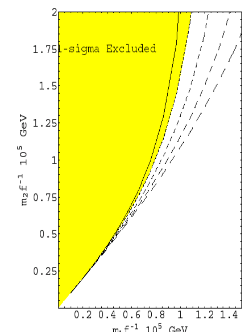
$$\lambda_{uc} \equiv -\left(V_{ud}^* V_{cd} + V_{us}^* V_{cs} + V_{ub}^* V_{cb}\right)$$

Generic Z' models



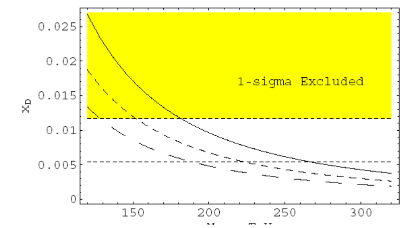
$$x_D^{(Z')} = \frac{f_D^2 B_D}{2\Gamma_D} \frac{M_D}{M_{Z'}^2} \left[\frac{2}{3}\left(C_1(m_c) + C_6(m_c)\right) + C_2(m_c)\left(-\frac{1}{2} + \frac{\eta}{3}\right) + C_3(m_c)\left(\frac{1}{12} - \frac{\eta}{2}\right)\right]$$

Family symmetry



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

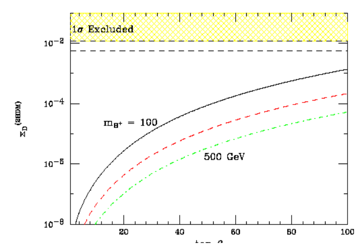
Vector leptoquarks



$$x_D^{(VLQ)} = -\frac{1}{8\pi^2 m_{LQ}^2 \Gamma_D M_D} \left[\left(\lambda_L \langle Q_1 \rangle + \lambda_R \langle Q_6 \rangle\right) + \frac{10}{9} \frac{m_c^2}{m_{LQ}^2} \left(\lambda_L \langle Q_7 \rangle + \lambda_R \langle Q_4 \rangle\right)\right]$$

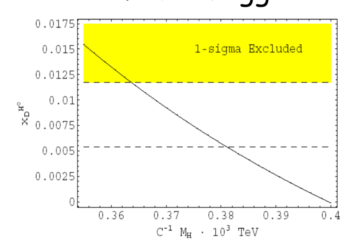
$$= -\frac{f_D^2 M_D B_D}{12\pi^2 m_{LQ}^2 \Gamma_D} \left(\lambda_L + \lambda_R\right)\left(1 + \frac{5\eta}{3} \frac{m_c^2}{m_{LQ}^2}\right),$$

2 Higgs doublet



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

FCNC Higgs



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

Extra dimensions, extra symmetries, etc...

Summary: New Physics in mixing

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_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)	$\lvert(\delta^u_{12})_{LR,RL}\rvert < 3.5 \cdot 10^{-2}$ for $\tilde{m} \sim 1$ TeV
	$\lvert(\delta^u_{12})_{LL,RR}\rvert < .25$ 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

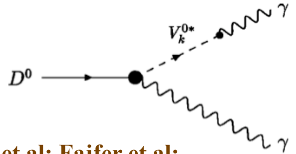
- ✓ Considered 21 well-established models
- ✓ Only 4 models yielded no useful constraints
- ✓ Consult paper for explicit constraints on your favorite model!

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

3. Mixing vs rare decays

- These decays only proceed at one loop in the SM; GIM is very effective
  - SM rates are expected to be small

★ Radiative decays $D \to \gamma X$, $\gamma\gamma$ mediated by $c \to u\,\gamma$
- SM contribution is dominated by LD effects
- dominated by SM anyway: useless?



+ others

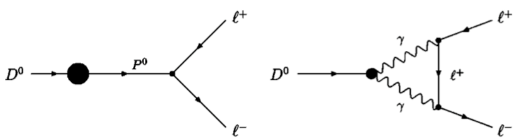
Burdman et al; Fajfer et al;
Greub, Hurth, Misiak, Wyler

★ Rare decays $D \to e^+e^-/\mu^+\mu^-/\tau^+\tau^-$ mediated by $c \to u\,ll$

$$\mathcal{L}_{\rm eff}^{\rm SD} = \frac{G_F}{\sqrt{2}} V_{cb}^* V_{ub} \sum_{i=7,9,10} C_i Q_i,$$

$$Q_7 = \frac{e}{8\pi^2} m_c F_{\mu\nu} \bar{u} \sigma^{\mu\nu}(1+\gamma_5)c, \qquad Q_9 = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell}\gamma^\mu \ell,$$

$$Q_{10} = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell}\gamma^\mu \gamma_5 \ell,$$



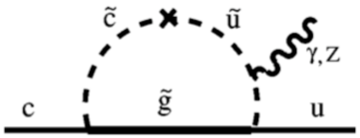
- SM contribution is dominated by LD effects
- could be used to study NP effects and correlate to mixing

★ Rare decays $D \to M\, e^+e^-/\mu^+\mu^-/\tau^+\tau^-$ mediated by $c \to u\,ll$
- SM contribution is dominated by LD effects
- could be used to study NP effects

Burdman, Golowich, Hewett, Pakvasa;
Fajfer, Prelovsek, Singer

Rare and radiative decays

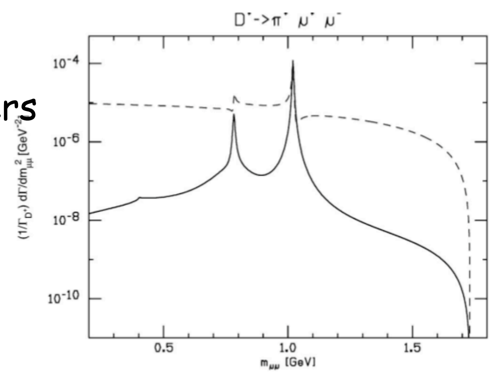
- Some examples of New Physics contributions
  - ★ R-partity-conserving SUSY
    - operators with the same mass insertions contribute to D-mixing
    - feed results into rare decays: NP is smaller than LD SM!

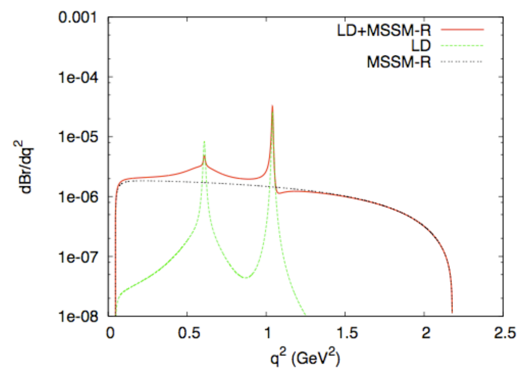


Bigi, Gabbiani, Masiero; Prelovsek, Wyler; Ciuchini et al; Nir; Golowich et al.

  - ★ R-partity-violating SUSY
    - operators with the same parameters contribute to D-mixing
    - feed results into rare decays

Fajfer, Kosnik, Prelovsek





  - ★ Same for other models...

Mode	LD	Extra heavy q	LD + extra heavy q
$D^+ \to \pi^+ e^+ e^-$	2.0×10^{-6}	1.3×10^{-9}	2.0×10^{-6}
$D^+ \to \pi^+ \mu^+ \mu^-$	2.0×10^{-6}	1.6×10^{-9}	2.0×10^{-6}
Mode	MSSM$\not{R}$	LD + MSSM$\not{R}$	
$D^+ \to \pi^+ e^+ e^-$	2.1×10^{-7}	2.3×10^{-6}	
$D^+ \to \pi^+ \mu^+ \mu^-$	6.5×10^{-6}	8.8×10^{-6}	

Impact of NP is reduced...

Mixing vs rare decays

Basics of rare decays

★ Most general effective Hamiltonian:

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

$$\widetilde{Q}_1 = (\overline{\ell}_L\gamma_\mu\ell_L)\ (\overline{u}_L\gamma^\mu c_L)\ ,\qquad \widetilde{Q}_4 = (\overline{\ell}_R\ell_L)\ (\overline{u}_R c_L)\ ,$$

$$\widetilde{Q}_2 = (\overline{\ell}_L\gamma_\mu\ell_L)\ (\overline{u}_R\gamma^\mu c_R)\ ,\qquad \widetilde{Q}_5 = (\overline{\ell}_R\sigma_{\mu\nu}\ell_L)\ (\overline{u}_R\sigma^{\mu\nu} c_L)\ ,$$

$$\widetilde{Q}_3 = (\overline{\ell}_L\ell_R)\ (\overline{u}_R c_L)\ ,$$

plus L ↔ R

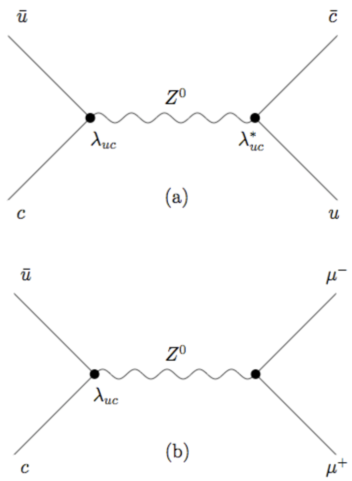
★ ... thus, the amplitude for D → $e^+e^-/\mu^+\mu^-/\tau^+\tau^-$ decay is

$$\mathcal{B}_{D^0\to\ell^+\ell^-} = \frac{M_D}{8\pi\Gamma_\mathrm{D}}\sqrt{1-\frac{4m_\ell^2}{M_D^2}}\left[\left(1-\frac{4m_\ell^2}{M_D^2}\right)|A|^2+|B|^2\right]\ ,$$

$$\mathcal{B}_{D^0\to\mu^+e^-} = \frac{M_D}{8\pi\Gamma_\mathrm{D}}\left(1-\frac{m_\mu^2}{M_D^2}\right)^2\left[|A|^2+|B|^2\right]\ ,$$

$$|A| = G\frac{f_D M_D^2}{4m_c}\left[\widetilde{C}_{3-8}+\widetilde{C}_{4-9}\right]\ ,$$

$$|B| = G\frac{f_D}{4}\left[2m_\ell\left(\widetilde{C}_{1-2}+\widetilde{C}_{6-7}\right)+\frac{M_D^2}{m_c}\left(\widetilde{C}_{4-3}+\widetilde{C}_{9-8}\right)\right]$$



Important: many NP models give contributions to both D-mixing and D → $e^+e^-/\mu^+\mu^-/\tau^+\tau^-$ decay: correlate!!!

Mixing vs rare decays

★ Recent experimental constraints

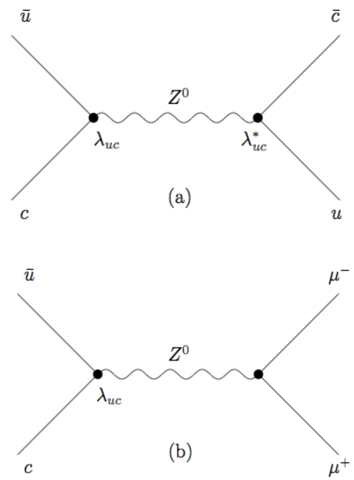
$$\mathcal{B}_{D^0\to\mu^+\mu^-} \leq 1.3\times 10^{-6}, \qquad \mathcal{B}_{D^0\to e^+e^-} \leq 1.2\times 10^{-6},$$

$$\mathcal{B}_{D^0\to\mu^\pm e^\mp} \leq 8.1\times 10^{-7} \quad ,$$

E.Golowich, J. Hewett, S. Pakvasa and A.A.P. arXiv: 0903.2830

★ Relating mixing and rare decay

- consider an example: heavy vector-like quark (Q=+2/3)
    - appears in little Higgs models, etc.



Mixing:

$$\mathcal{H}_{2/3} = \frac{g^2}{8\cos^2\theta_w M_Z^2}\lambda_{uc}^2\, Q_1 \;=\; \frac{G_F\lambda_{uc}^2}{\sqrt{2}}Q_1$$

$$x_{\rm D}^{(+2/3)} = \frac{2G_F\lambda_{uc}^2 f_D^2 M_D B_D r(m_c, M_Z)}{3\sqrt{2}\Gamma_D}$$

Rare decay:

$$A_{D^0\to\ell^+\ell^-} = 0 \qquad B_{D^0\to\ell^+\ell^-} = \lambda_{uc}\frac{G_F f_{\rm D} m_\mu}{2}$$

$$\mathcal{B}_{D^0\to\mu^+\mu^-} = \frac{3\sqrt{2}}{64\pi}\,\frac{G_F m_\mu^2 x_{\rm D}}{B_{\rm D} r(m_c, M_Z)}\left[1-\frac{4m_\mu^2}{M_{\rm D}}\right]^{1/2}$$
$$\simeq\; 4.3\times 10^{-9} x_{\rm D} \;\leq\; 4.3\times 10^{-11} \quad .$$

Note: a parameter-free relation!

Mixing vs rare decays

★ Correlation between mixing/rare decays
- possible for tree-level NP amplitudes
- some relations possible for loop-dominated transitions

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
arXiv: 0903.2830 [hep-ph]

★ Considered several popular models

Model	$\mathcal{B}_{D^0\to\mu^+\mu^-}$
Standard Model (SD)	$\sim 10^{-18}$
Standard Model (LD)	$\sim$ several $\times 10^{-13}$
$Q=+2/3$ Vectorlike Singlet	4.3×10^{-11}
$Q=-1/3$ Vectorlike Singlet	$1 \times 10^{-11}\ (m_S/500\ \text{GeV})^2$
$Q=-1/3$ Fourth Family	$1 \times 10^{-11}\ (m_S/500\ \text{GeV})^2$
Z' Standard Model (LD)	$2.4 \times 10^{-12}/(M_{Z'}(\text{TeV}))^2$
Family Symmetry	$0.7\ 10^{-18}$ (Case A)
RPV-SUSY	$1.7 \times 10^{-9}\ (500\ \text{GeV}/m_{\tilde{d}_k})^2$

Upper limits on rare decay branching ratios

Same idea can be employed to relate D-mixing to K-mixing

Blum, Grossman, Nir, Perez
arXiv:0903.2118 [hep-ph]

Things to take home

- 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/in many cases small SM background
  - D-mixing is a second order effect in SU(3) breaking ($x,y \sim 1\%$ in the SM)
  - large contributions from New Physics are possible
  - out of 21 models studied, 17 yielded competitive constraints
- Can correlate mixing and rare decays with New Physics models
  - signals in D-mixing vs rare decays help differentiate among models
- Observation of CP-violation in the current round of experiments provide "smoking gun" signals for New Physics
  - Different observables should be used to disentangle CP-violating contributions to $\Delta c=1$ and $\Delta c=2$ amplitudes

There is always something new in charm!

Additional slides

Theoretical estimates I

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

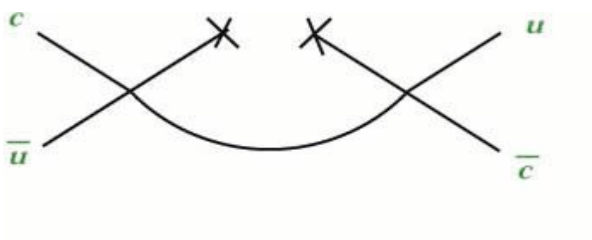
$$y_{sd}^{(6)} \propto \frac{\left(m_s^2 - m_d^2\right)^2}{m_c^2} \frac{m_s^2 + m_d^2}{m_c^2} \mu_{had}^{-2} \propto m_s^6 \Lambda^{-6}$$

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

4 unknown matrix elements

…subleading effects?

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

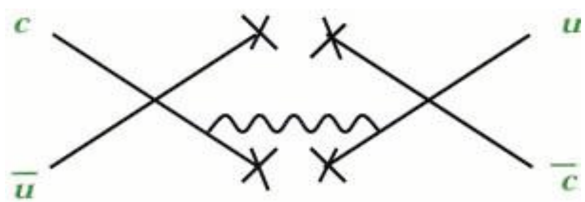


d=9

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

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 ππ, 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, SU(3) forces 0

x = ? Extremely hard…

Need to "repackage" the analysis: look at the complete multiplet contribution

Theoretical estimates II

mc 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 ππ, πK, KK intermediate states as an example…

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

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

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