Charm(ed) Phenomenology

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1. Instead of introduction

Applications of Murphy's law to charm physics:

Modern charm physics experiments acquire ample statistics; many decay rates are quite large.

THUS:

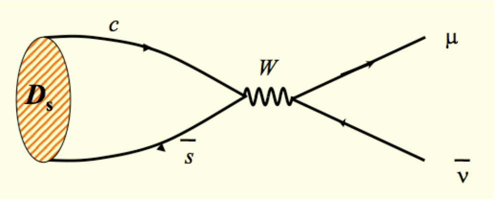
It is very difficult to provide model-independent theoretical description of charmed quark systems.

1a. Leptonic decays of D^+ and D_s

★ In the Standard Model probes meson decay constant/CKM matrix element

$$\langle 0|\bar{s}\gamma^\mu\gamma_5 c|D_s\rangle = i f_{D_s} p^\mu_{D_s}$$

$$\Gamma(D_q \to \ell\nu) = \frac{G_F^2}{8\pi} f_{D_q}^2 m_\ell^2 M_{D_q}\left(1-\frac{m_\ell^2}{M_{D_q}^2}\right)^2 |V_{cq}|^2$$



… so theory can be compared to experiment by comparing $|f_{Dq} V_{cq}|$

Table 1 Theoretical predictions for f_{D^+}, $f_{D_s^+}$, $f_{D_s^+}/f_{D^+}$

Source	f_{D^+} (MeV)	$f_{D_s^+}$ (MeV)	$f_{D_s^+}/f_{D^+}$
Unquenched lattice calculations			
HPQCD, UKQCD	208 ± 4	241 ± 3	1.162 ± 0.009
FNAL, MILC, HPQCD	$201 \pm 3 \pm 17$	$249 \pm 3 \pm 16$	$1.24 \pm 0.01 \pm 0.07$
Quenched lattice QCD calculations			
Taiwan	$235 \pm 8 \pm 14$	$266 \pm 10 \pm 18$	$1.13 \pm 0.03 \pm 0.05$
UKQCD	$210 \pm 10^{+17}_{-16}$	$236 \pm 8^{+17}_{-14}$	$1.13 \pm 0.02^{+0.04}_{-0.02}$
Becirevic et al.	$211 \pm 14^{+2}_{-12}$	$231 \pm 12^{+6}_{-1}$	1.10 ± 0.02
QCD sum rules and other approximations			
J. Bordes et al.	177 ± 21	205 ± 22	$1.16 \pm 0.02 \pm 0.03$
S. Narison	203 ± 10	235 ± 24	1.15 ± 0.04
Field correlators	210 ± 10	260 ± 10	1.24 ± 0.03
Isospin splitting		262 ± 29	

Table 2 Results for decay branching fractions $\mathcal{B}_{\phi\pi} \equiv \mathcal{B}(D_s \to \phi\pi^+)$, $\mathcal{B}(D_s \to \mu^+\nu_\mu)$, $\mathcal{B}(D_s \to \tau^+\nu_\tau)$, an

Name of experiment	Mode	$\mathcal{B}(\times 10^3)$	$\mathcal{B}_{\phi\pi}(\%)$	$f_{D_s^+}$ (MeV)
CLEO-c	$\mu^+\nu_\mu$	$5.94 \pm 0.66 \pm 0.31$		$264 \pm 15 \pm 7$
CLEO-c	$\tau^+\nu_\tau$	$80.0 \pm 13.0 \pm 4.0$		$310 \pm 25 \pm 8$
CLEO-c	$\tau^+\nu_\tau$	$61.7 \pm 7.1 \pm 3.6$		$273 \pm 16 \pm 8$
CLEO-c	combined			$274 \pm 10 \pm 5$
Belle	$\mu^+\nu_\mu$	$6.44 \pm 0.76 \pm 0.52$		$275 \pm 16 \pm 12$
Average				275 ± 10
CLEO	$\mu^+\nu_\mu$	$6.2 \pm 0.8 \pm 1.3 \pm 1.6$	3.6 ± 0.9	$273 \pm 19 \pm 27 \pm 33$
BEATRICE	$\mu^+\nu_\mu$	$8.3 \pm 2.3 \pm 0.6 \pm 2.1$	3.6 ± 0.9	$312 \pm 43 \pm 12 \pm 39$
ALEPH	$\mu^+\nu_\mu$	$6.8 \pm 1.1 \pm 1.8$	3.6 ± 0.9	$282 \pm 19 \pm 40$
ALEPH	$\tau^+\nu_\tau$	$58 \pm 8 \pm 18$		
L3	$\tau^+\nu_\tau$	$74 \pm 28 \pm 16 \pm 18$		$299 \pm 57 \pm 32 \pm 37$
OPAL	$\tau^+\nu_\tau$	$70 \pm 21 \pm 20$		$283 \pm 44 \pm 41$
BaBar	$\mu^+\nu_\mu$	$6.74 \pm 0.83 \pm 0.26 \pm 0.66$	4.71 ± 0.46	$283 \pm 17 \pm 7 \pm 14$

see Artuso, Meadows, AAP

Theory (lattice, HPQCD): $f_{D_s}^{lat} = 241 \pm 3$ MeV Experiment (CLEO-c/Belle): $f_{D_s}^{exp} = 274 \pm 10$ MeV

2008: about 3 sigma discrepancy...

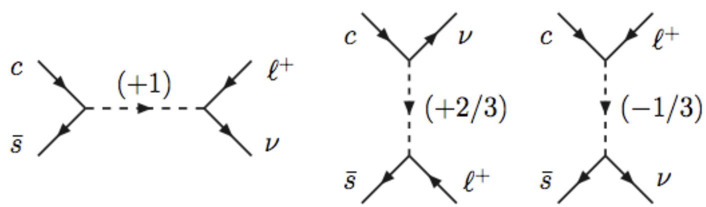
Leptonic decays of D^+ and D_s

➢ What is the reason for this discrepancy?

★ New physics contribution to $D_s \to l\nu$ decay

- possible heavy NP mediators

Akeryod; Hou; Hewett
Dobrescu, Kronfeld



see Dorsner, Fajfer, Kamenik and Kosnik

- ultra-light NP particle emission in the final state?

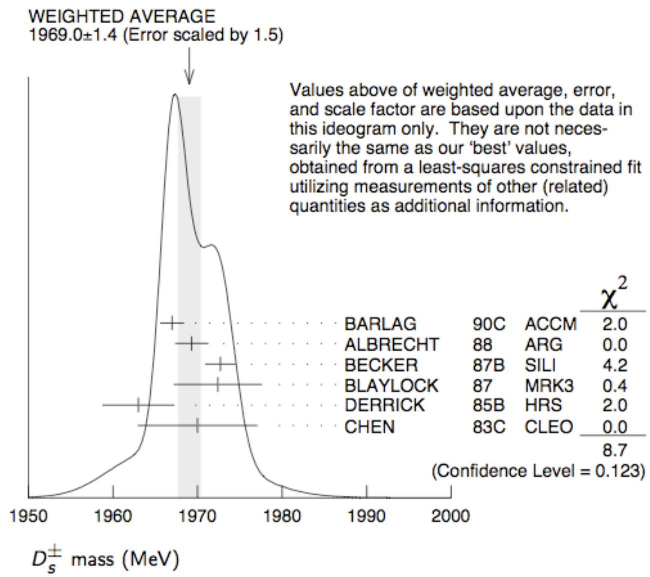
No helicity suppression !!!

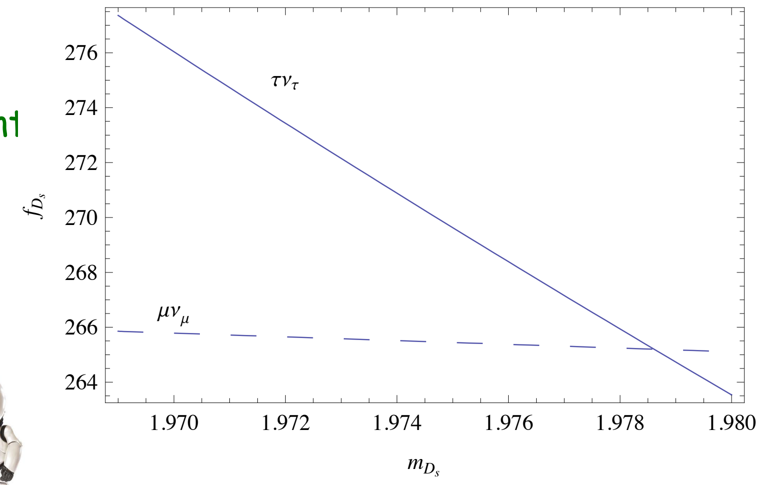
★ Problems with experimental determination of decay constant

- why systematic errors for $\mu\nu$ are larger than for $\tau\nu$?
- how well do we know m_{D_s}?
- new CLEOc results?

★ Problems with (lattice) calculations of the decay constant

- systematic uncertainties in HPQCD result?
- new lattice results?





Leptonic decays of D^+ and D_s

★ New results in both theory and experiment

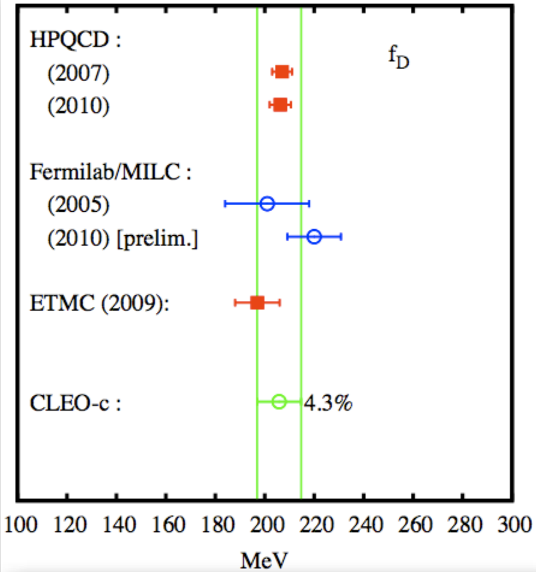
- 2008: 3.6 σ discrepancy

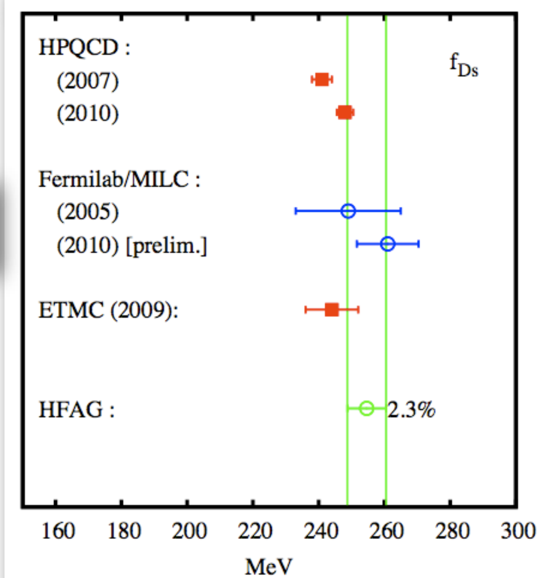
The discrepancy is in D_s only!

- Jan 2009: new CLEOc result
- July 2009: new FNAL/MILC result

1. better statistics
2. improved charm mass
3. improved scale setting

- 2010: new HPQCD result





No discrepancy between theory and experiment

J. Shigemitsu, CKM-2010

★ Can we push it a bit further?

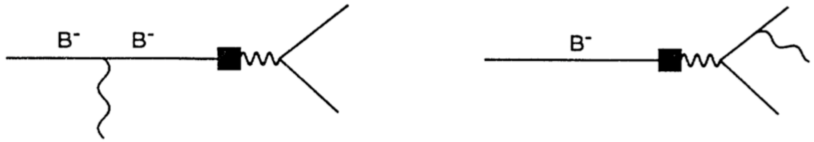
Radiative leptonic decays of D^+ and D_s

★ Recall that purely leptonic decays are helicity suppressed in the SM
- add photon to the final state to lift helicity suppression

$$\mathcal{A}(D \to \mu\bar{\nu}\gamma) = \langle \mu\bar{\nu}\gamma(k)|H_w(0)|D(p)\rangle \sim \int d^4x e^{-ikx}\epsilon^{*\alpha}\ell^{\beta}\langle 0|T\left[J_{\alpha}^{em}(x)J_{\beta}(0)\right]|D(p)\rangle$$

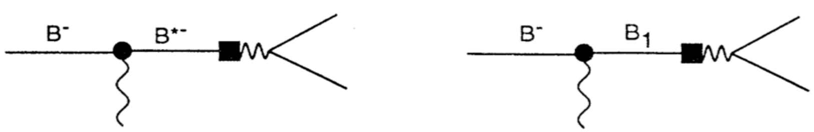
LSZ reduction + e/m perturbation theory

★ This correlator can be estimated phenomenologically



Internal Brehmsstrahlung (IB)

still helicity-suppressed



Structure-dependent (SD)

★ Define
$$R_D^{\ell} = \frac{\Gamma(D \to \ell\nu\gamma)}{\Gamma(D \to \ell\nu)} = \frac{\alpha}{6\pi}\left(\frac{m_D}{m_{\ell}}\right)^2 \mu_V^2\ I(\Delta, m_D, \gamma_i)$$

Burdman, Goldman, Wyler

Radiative leptonic decays of D^+ and D_s

★ Estimate $R_D^\mu \approx (1-10) \times 10^{-2} \mu_V^2 \ \mathrm{GeV}^2$

- results in $B(D \to \mu\nu\gamma) \sim 10^{-5}$ and $B(D_s \to \mu\nu\gamma) \sim 10^{-4}$ with $B(D \to e\nu\gamma) \gg B(D \to e\nu)$
- for B-mesons, QCD-based calculations are possible

Lunghi, Pirjol, Wyler
Korchemsky, Prjol, Yan

★ Is lattice prediction for $D \to \mu\nu\gamma$ possible?

- charmonium radiative decays — Dudek, Edwards; Dudek, Edwards, Roberts
- photon structure functions, pion form-factor, etc. — X. Ji, C. Jung

$$\mathcal{A}(D \to \mu\bar{\nu}\gamma) = \langle \mu\bar{\nu}\gamma(k)|H_w(0)|D(p)\rangle \sim \int d^4x e^{-ikx} \epsilon^{*\alpha} \ell^\beta \langle 0|T\left[J_\alpha^{em}(x) J_\beta(0)\right]|D(p)\rangle$$

LSZ reduction + e/m perturbation theory

Wishes for the lattice:

i) confirm SM numbers for leptonic decays
ii) use them to constrain NP
iii) can one compute $D \to \mu\nu\gamma$ on the lattice?

1b. Semileptonic decays of D-mesons

★ In the Standard Model probes meson form factor/CKM matrix element

- direct access to V_{cs} and V_{cd}
- lattice QCD: exclusive transitions

★ Decay rate depend on form factors

- parameterization of q^2 dependence defines a model

$$\frac{d\Gamma(D \to K(\pi) e \nu_e)}{dq^2} = \frac{G_F^2 |V_{cq}|^2}{24\pi^3} p_{K(\pi)}^3 |f_+(q^2)|^2$$

where $\langle K(\pi)|\bar{q}\Gamma^\mu c|D\rangle = f_+(q^2)P^\mu + f_-(q^2)q^\mu$

★ Dispersive representation of a form factor

$$f_+(q^2) = \frac{f_+(0)}{1-\alpha}\left(1 - \frac{q^2}{m_{D*}^2}\right)^{-1} + \frac{1}{\pi}\int_{t_+}^{\infty} dt \frac{\mathrm{Im} f_+(t)}{t - q^2 - i\epsilon}$$

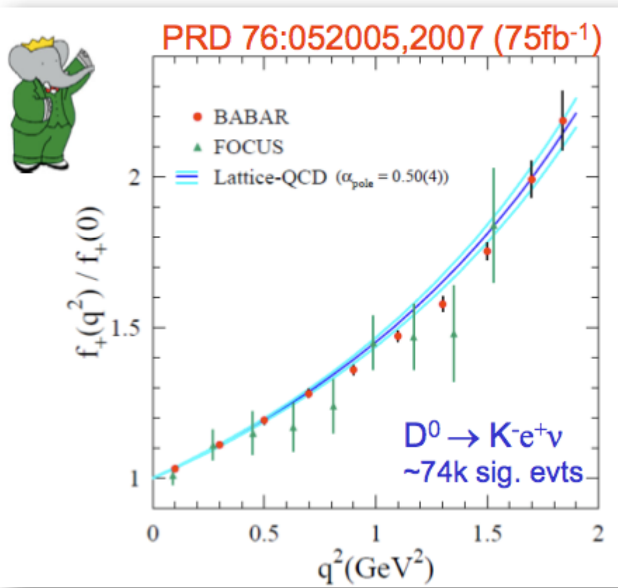
Becher, Hill

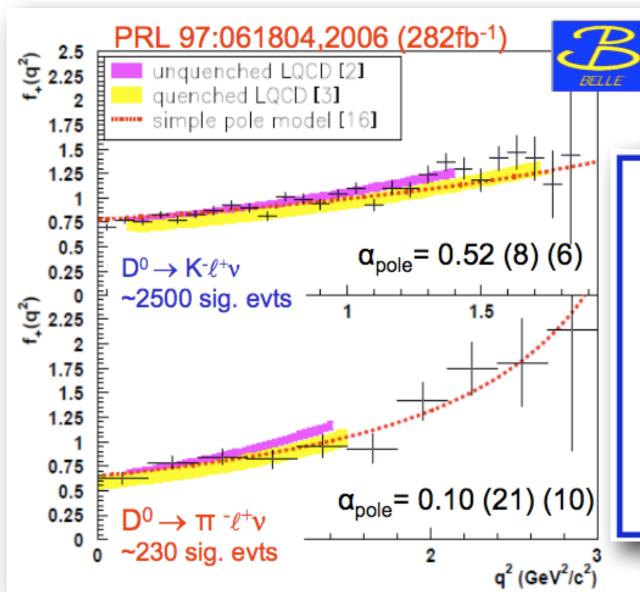
Semileptonic decays of D-mesons

★ Representation of a dispersive integral define a model

$$f_+(q^2) = \frac{f_+(0)}{(1-\alpha)} \frac{1}{1-(q^2/m_V^2)} + \sum_{k=1}^{N} \frac{\rho_k}{1-\frac{1}{\gamma_k}\frac{q^2}{m_V^2}}$$

★ Experiments fit to a particular model





Modified pole parametrization:

$$f_+(q^2) = \frac{f_+(0)}{\left(1-\frac{q^2}{m_{D_s^*}^2}\right)\left(1-\alpha_{pole}\frac{q^2}{m_{D_s^*}^2}\right)}$$

α_{pole}= 0.38 (2) (3) BaBar
α_{pole}= 0.30 (3) (1) CLEO-c
[α_{pole}= 0.21 (4) (3) CLEO-c 281pb^{-1}]
α_{pole}= 0.52 (8) (6) Belle

J. Serrano, CKM-2010

Semileptonic decays of D-mesons

★ Can success of LQCD calculations of $D \to K$ and $D \to \pi$ form factors be replicated for other systems?

- calculations of D_s form factors
- calculations of semileptonic decays of baryons

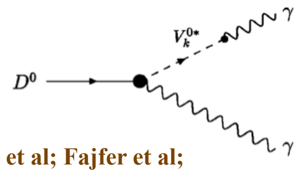
Wishes for the lattice:

i) compute form factors for $D \to \eta(\eta')\mu\nu$
ii) compute form factor for $\Lambda_c \to \Lambda\mu\nu$

2a. Radiative and rare decays

- Hope to isolate penguin-like contribution: BUT SM GIM is very effective
  - SM penguin contributions are expected to be small

★ Radiative decays $D \to \gamma X$, $\gamma\gamma$: FCNC transition $c \to u\,\gamma$



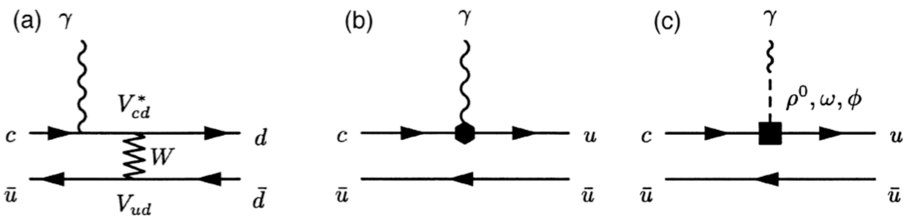
+ others

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

$$Q_7 = \frac{e}{8\pi^2} m_c F_{\mu\nu} \bar{u} \sigma^{\mu\nu} (1+\gamma_5) c,$$

- SM contribution is dominated by LD effects
- dominated by SM anyway: useless for NP studies?

★ Consider exclusive decays $D \to \gamma\rho$, $\gamma\omega$: $\omega^{(I=0)} = \frac{1}{\sqrt{2}}(\bar{u}u + \bar{d}d)$, $\rho^{(I=1)} = \frac{1}{\sqrt{2}}(\bar{u}u - \bar{d}d)$



$V_{cd}^* V_{ud} \sim \lambda$ $V_{cb}^* V_{ub} \sim \lambda^5$

- Extract $c \to uu\,\gamma$: LD contribution cancels in $R_{uu\gamma} = \frac{\Gamma(D^0 \to \omega\gamma) - \Gamma(D^0 \to \rho\gamma)}{\Gamma(D^0 \to \omega\gamma)}$

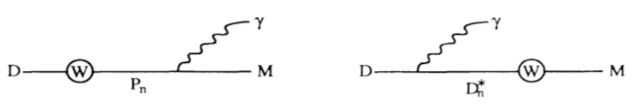
Radiative decays

★ Theoretical predictions and experimental bounds (x 10^5)

$D \to V\gamma$	Burdman et al	Fajfer et al	Khodjamirian et al	Experimental bound
$D_s^+ \to \rho^+\gamma$	6–38	20–80	4.4	
$D^0 \to \bar{K}^{*0}\gamma$	7–12	6–36	0.18	32.8±3.4
$D^0 \to \rho^0\gamma$	0.1–0.5	0.1–1	0.38	< 240
$D^0 \to \omega^0\gamma$	$\simeq$0.2	0.1–0.9	—	< 240
$D^0 \to \phi^0\gamma$	0.1–3.4	0.4–0.9	—	2.70±0.35
$D^+ \to \rho^+\gamma$	2–6	0.4–6.3	0.43	
$D_s^+ \to K^{*+}\gamma$	0.8–3	1.2–5.1	—	

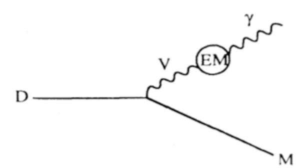
K. Nakamura et al. (Particle Data Group), J. Phys. G 37, 075021 (2010)

★ All of those transitions are dominated by long-distance contributions



(a) (b)

pole amplitudes (WA/WS)



VMD amplitudes

What about New Physics?

Radiative decays

- Some examples of New Physics contributions

  ★ R-partity-conserving SUSY

  - operators with the same mass insertions contribute to D-mixing

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

  - feed results into rare decays: NP is smaller than LD SM!

- Can one estimate the size of Weak Annihilation on the lattice?

Done in QCD sum rules

Khoddjamirian, Stoll, Wyler
Ali, Braun
Eilam, Halperin, Mendel

$$\mathcal{A}(D \to \rho\gamma) \sim \int d^4x e^{-ikx} \epsilon^{*\alpha} \langle \rho(p_\rho) | T \left[J_\alpha^{em}(x) H_w(0) \right] | D(p_D) \rangle$$

Wishes for the lattice:

i) calculate WA in $D \to \gamma V$ (neglect dipole)
ii) calculate $B \to \gamma D^*$ as a test

2b. Rare decays

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

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

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

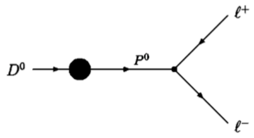
Burdman, Golowich, Hewett, Pakvasa;
Fajfer, Prelovsek, Singer

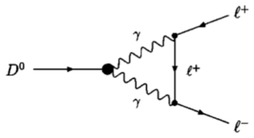
$$Q_9 = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \ell, \quad Q_{10} = \frac{e^2}{16\pi^2} \bar{u}_L \gamma_\mu c_L \bar{\ell} \gamma^\mu \gamma_5 \ell,$$

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

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

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





- only Q_{10} contribute, but SM contribution is dominated by LD effects
- could be used to study NP effects in correlation with D-mixing

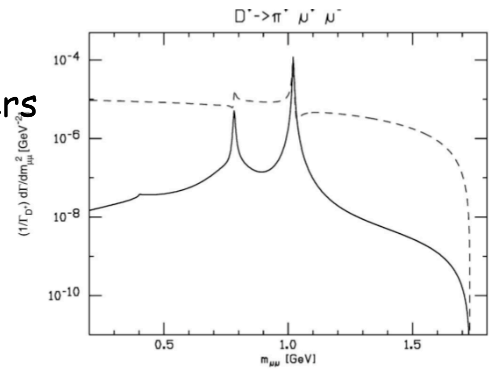
Rare decays

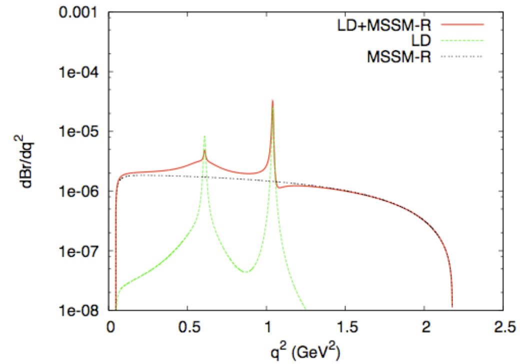
➢ Some examples of New Physics contributions

★ 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...

Rare decays

Basics of rare decays

★ Most general effective Hamiltonian:

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

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

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

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

plus L ↔ R

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

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

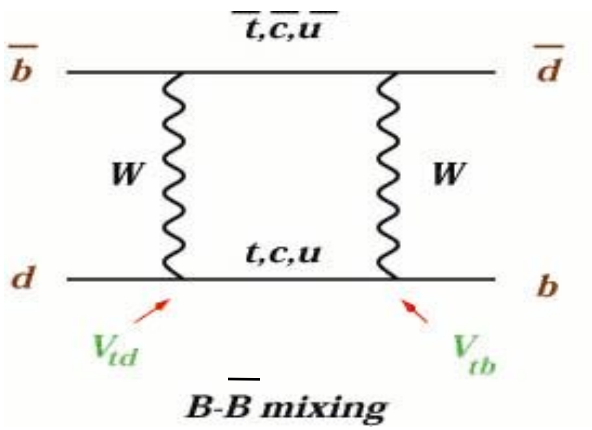
$$\mathcal{B}_{D^0\to\mu^+e^-} = \frac{M_D}{8\pi\Gamma_D}\left(1-\frac{m_\mu^2}{M_D^2}\right)^2\left[|A|^2+|B|^2\right]\ ,$$

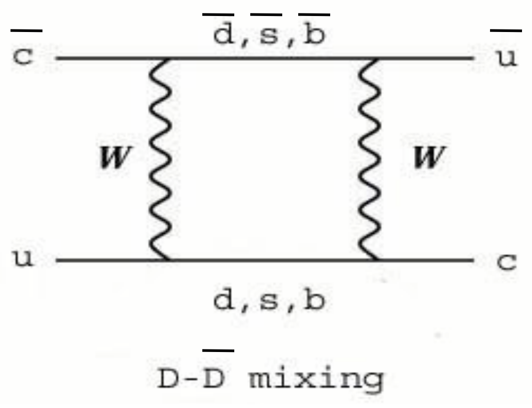
$$|A| = G\frac{f_D M_D^2}{4m_c}\left[\widetilde{C}_{3-8}+\widetilde{C}_{4-9}\right]\ ,$$

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

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

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

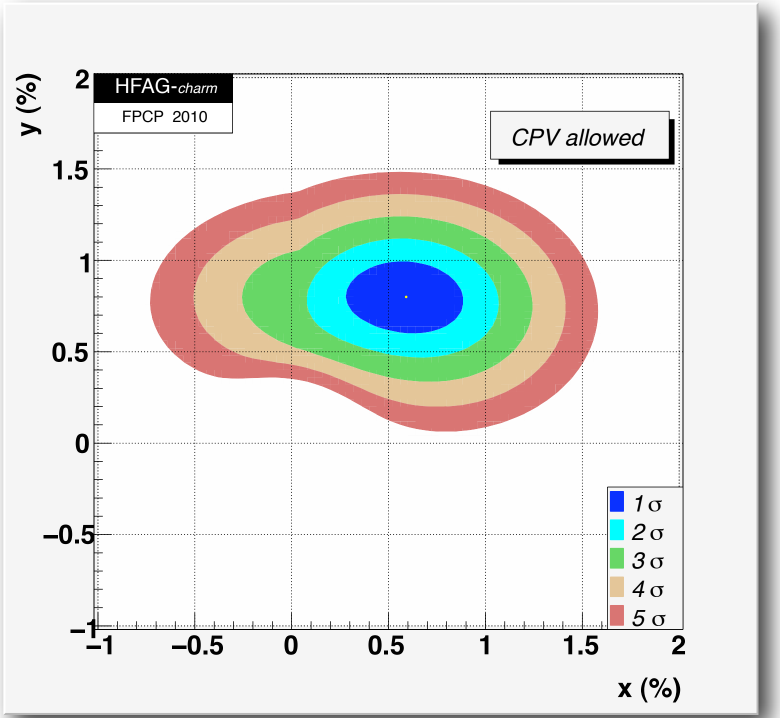
Experimental constraints on mixing

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

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

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

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

- ★ Some definitions:

$$m \equiv \frac{m_1 + m_2}{2}, \qquad \Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2},$$

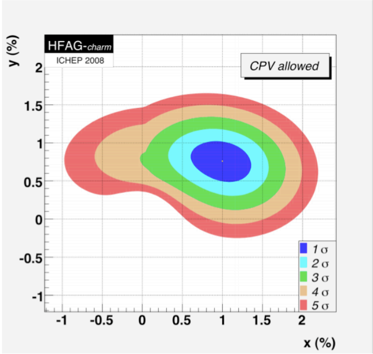
$$x \equiv \frac{m_2 - m_1}{\Gamma}, \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}.$$

"experimental" parameters

$$y_{12} \equiv |\Gamma_{12}|/\Gamma, \qquad x_{12} \equiv 2|M_{12}|/\Gamma, \qquad \phi_{12} \equiv \arg(M_{12}/\Gamma_{12}).$$

"theoretical" parameters

- ★ Recent experimental data and future experimental prospects



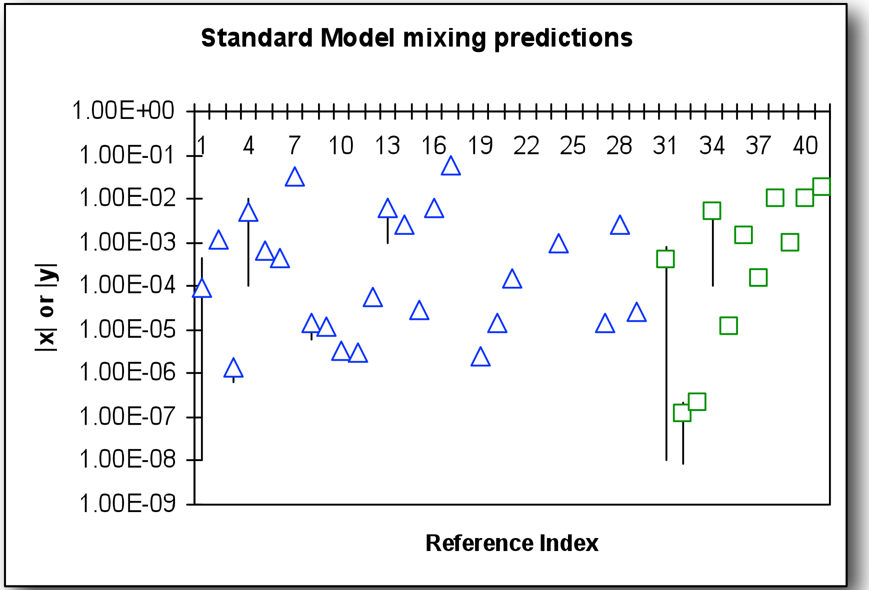
- ★ Recent HFAG numbers

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

A. Schwartz, CHARM-2009

|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

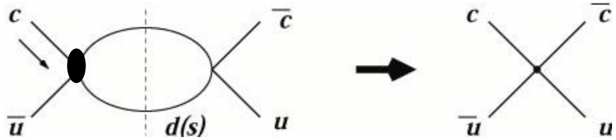
Resume: a contribution to x and y <u>of the order of 1%</u> is natural in the SM

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

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

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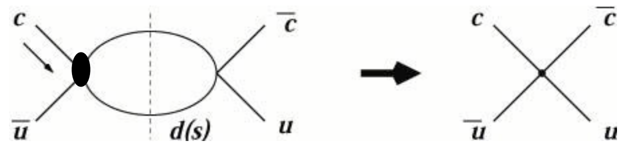

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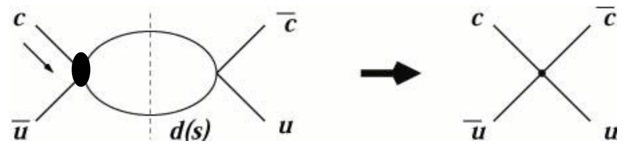

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phase space

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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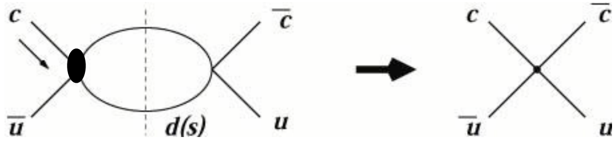

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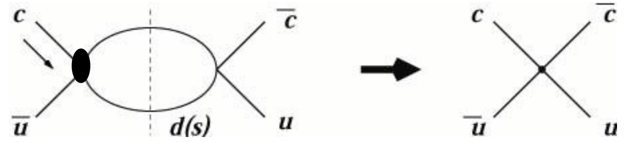

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Phys. Rev. Lett. 98, 181801, 2007

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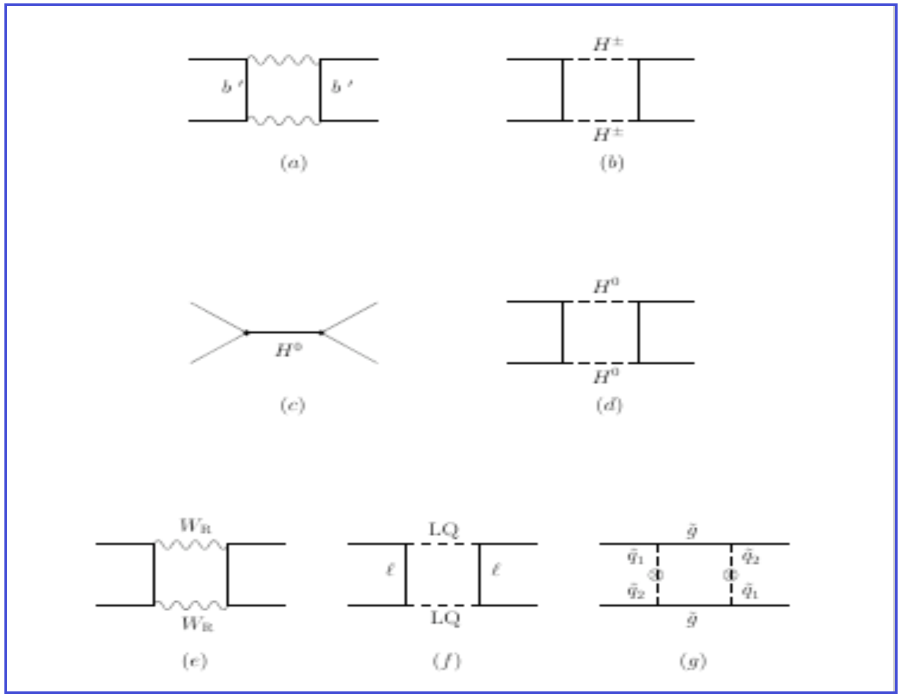

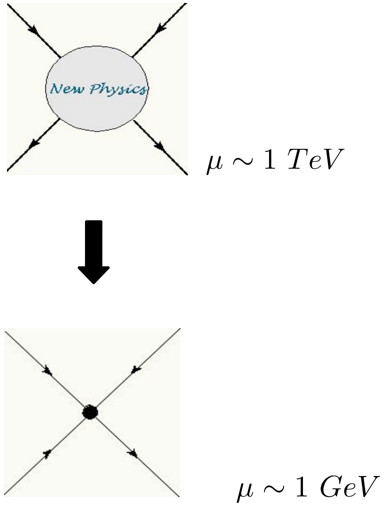

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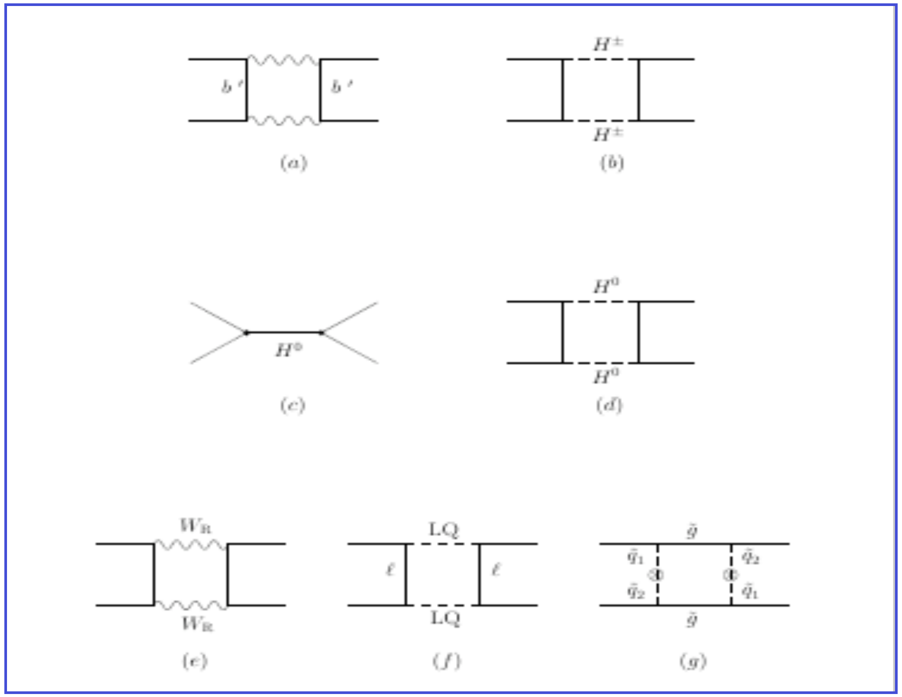
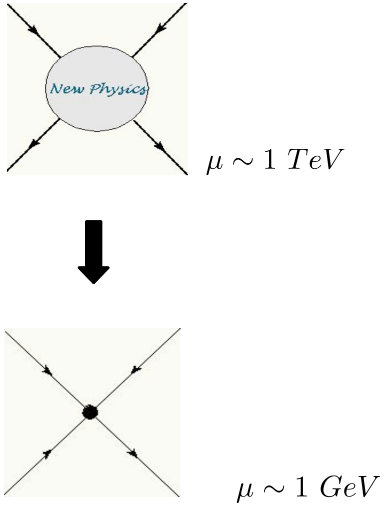


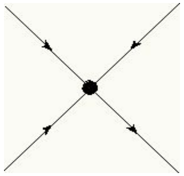


Global Analysis of New Physics: ΔC=2

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

★ Let's write the most general ΔC=2 Hamiltonian

$$\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} C_i(\mu) Q_i$$



$\mu \le 1\,TeV$

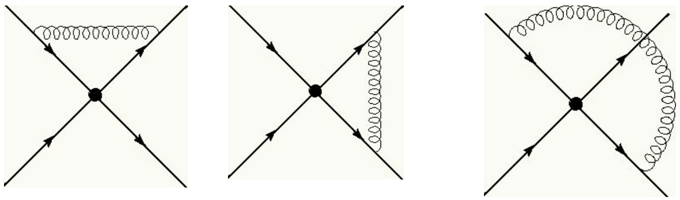
... with the following set of 8 independent operators...

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

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

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

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



μ : $1\,GeV$

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 $C_i(\Lambda_{NP})$

Generic restrictions on NP

★ Comparing to experimental value of x, obtain constraints on NP models
- assume x is dominated by the New Physics model
- assume no accidental strong cancellations b/w SM and NP

$$\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} z_i(\mu) Q'_i$$

$$\begin{aligned} Q_1^{cu} &= \bar{u}_L^\alpha \gamma_\mu c_L^\alpha \bar{u}_L^\beta \gamma^\mu c_L^\beta, \\ Q_2^{cu} &= \bar{u}_R^\alpha c_L^\alpha \bar{u}_R^\beta c_L^\beta, \\ Q_3^{cu} &= \bar{u}_R^\alpha c_L^\beta \bar{u}_R^\beta c_L^\alpha, \end{aligned} + \left\{ \begin{matrix} L \\ \updownarrow \\ R \end{matrix} \right\} + \begin{aligned} Q_4^{cu} &= \bar{u}_R^\alpha c_L^\alpha \bar{u}_L^\beta c_R^\beta, \\ Q_5^{cu} &= \bar{u}_R^\alpha c_L^\beta \bar{u}_L^\beta c_R^\alpha, \end{aligned}$$

★ ... which are

$$|z_1| \lesssim 5.7 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$

$$|z_2| \lesssim 1.6 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$

$$|z_3| \lesssim 5.8 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$

$$|z_4| \lesssim 5.6 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2,$$

$$|z_5| \lesssim 1.6 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\ TeV}\right)^2.$$

New Physics is either at a very high scales

tree level: $\Lambda_{NP} \geq (4-10) \times 10^3\ \mathrm{TeV}$

loop level: $\Lambda_{NP} \geq (1-3) \times 10^2\ \mathrm{TeV}$

or have highly suppressed couplings to charm!

Gedalia, Grossman, Nir, Perez
arXiv:0906.1879 [hep-ph]

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

★ Constraints on particular NP models available

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.

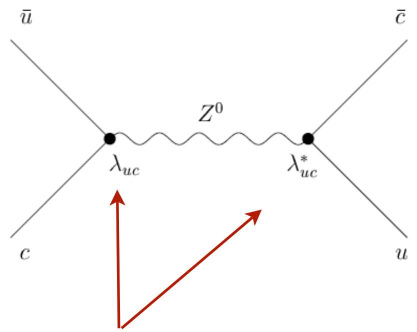
- ★ Extra gauge bosons
  - Left-right models, horizontal symmetries, etc.
- ★ Extra scalars
  - Two-Higgs doublet models, leptoquarks, Higgsless, etc.
- ★ Extra fermions
  - 4^{th} generation, vector-like quarks, little Higgs, etc.
- ★ Extra dimensions
  - Universal extra dimensions, split fermions,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

Total: 21 models considered

Example of a model of New Physics

★ 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

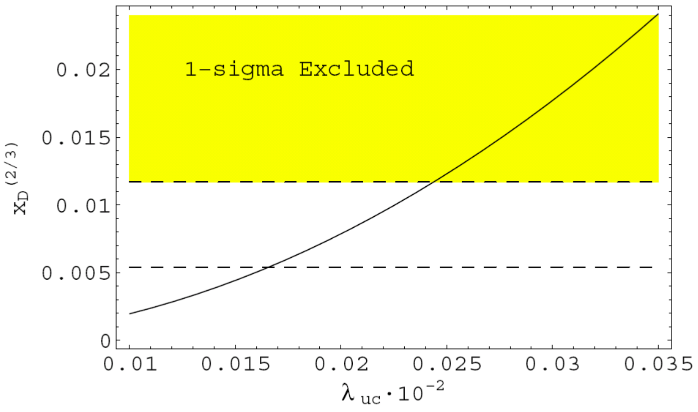
$$\mathcal{H}_{2/3} = \frac{g^2}{8\cos^2\theta_w M_Z^2}\left(\lambda_{uc}\right)^2 \bar{u}_L\gamma_\mu c_L \bar{u}_L\gamma^\mu c_L$$

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

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

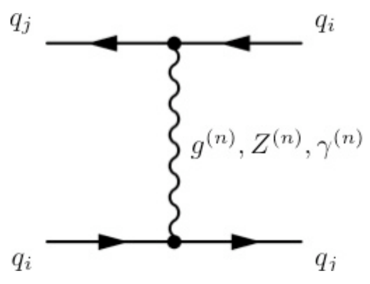


4. Assume no SM - get an upper bound on NP model parameters (coupling)

Example of a model of New Physics - II

➢ Consider another example: warped extra dimensions

FCNC couplings via KK gluons



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

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

M(TeV)	$r_1(m_c, M)$	$r_2(m_c, M)$	$r_3(m_c, M)$	$r_4(m_c, M)$	$r_5(m_c, M)$
1	0.72	0.85	3.7	0.41	2.2
2	0.71	0.84	4.0	0.39	2.3

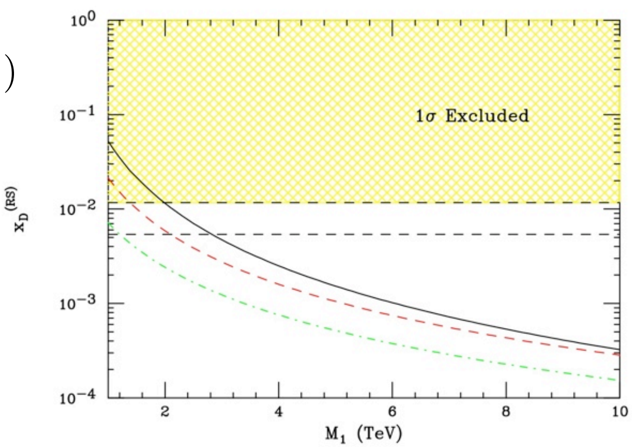
TABLE I: Dependence of the RG factors on the heavy mass scale M.

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

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



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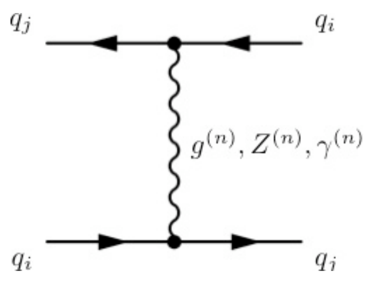

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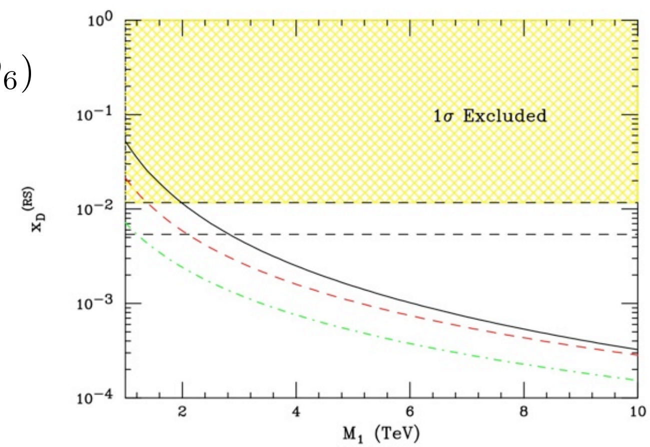
3. Compute relevant matrix elements and x_D

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



Implies: M_{1KKg} > 2.5 TeV!

Summary: New Physics in mixing

	Model	Approximate Constraint
Extra fermions	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
Extra gauge bosons	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}
Extra scalars	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
Extra dimensions	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
SUSY	Minimal Supersymmetric Standard (Fig. 23)	$\|(\delta^u_{12})_{LR,RL}\| < 3.5 \cdot 10^{-2}$ for $\tilde{m} \sim 1$ TeV
		$\|(\delta^u_{12})_{LL,RR}\| < .25$ 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 on your favorite model!

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

Gedalia, Grossman, Nir, Perez
arXiv:0906.1879 [hep-ph]

Bigi, Blanke, Buras, Recksiegel,
JHEP 0907:097, 2009

Mixing vs rare decays

★ Recent experimental constraints

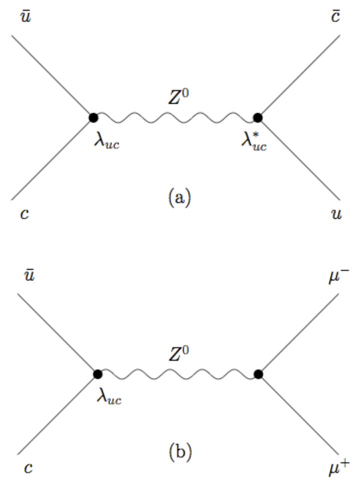
$$\mathcal{B}_{D^0\to\mu^+\mu^-} \le 1.3\times 10^{-6}, \qquad \mathcal{B}_{D^0\to e^+e^-} \le 1.2\times 10^{-6},$$

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

E.Golowich, J. Hewett, S. Pakvasa and A.A.P.
PRD79, 114030 (2009)

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

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

Note: a NP 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. PRD79, 114030 (2009)

★ 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]

A word on CP-violation in charmed mesons

- Possible sources of CP violation in charm transitions:

  - ★ CPV in $\Delta c = 1$ decay amplitudes ("direct" CPV)

$$A\left(D \to f\right) \equiv A_f = \left|A_1\right| e^{i\delta_1} e^{i\phi_1} + \left|A_2\right| e^{i\delta_2} e^{i\phi_2}, \quad \Delta\delta \neq 0, \Delta\phi \neq 0$$

  - ★ CPV in $D^0 - \overline{D^0}$ mixing matrix ($\Delta c = 2$)

$$R_m^2 = |q/p|^2 = \left|\frac{2M_{12}^* - i\Gamma_{12}^*}{\Delta m - (i/2)\Delta\Gamma}\right|^2 = 1 + A_m \neq 1$$

  - ★ CPV in the interference of decays with and without mixing

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

- One can separate various sources of CPV by customizing observables

CP-violation: indirect

★ Assume that direct CP-violation is absent $(\mathrm{Im}\,(\Gamma_{12}^* \bar{A}_f/A_f) = 0, \quad |\bar{A}_f/A_f| = 1)$

- can relate x, y, ϕ, $|q/p|$ to x_{12}, y_{12} and ϕ_{12}

$$xy = x_{12}y_{12}\cos\phi_{12}, \qquad x^2 - y^2 = x_{12}^2 - y_{12}^2,$$

$$(x^2 + y^2)|q/p|^2 = x_{12}^2 + y_{12}^2 + 2x_{12}y_{12}\sin\phi_{12},$$

$$x^2\cos^2\phi - y^2\sin^2\phi = x_{12}^2\cos^2\phi_{12}.$$

★ Four "experimental" parameters related to three "theoretical" ones

- a "constraint" equation is possible

$$\boxed{\frac{x}{y} = \frac{1-|q/p|}{\tan\phi} = -\frac{1}{2}\frac{A_m}{\tan\phi}}$$

Note: a "theory-free" relation!

★ Measurements of mixing parameters say something about CP-violation

- $y/x \approx 0.8 \pm 0.3$ ➠ $A_m \sim \tan\phi$
- CPV in mixing is comparable to CPV in the interference of decays with and w/out mixing

Grossman, Nir, Perez
PRL 103, 071602 (2009)
Kagan, Sokoloff
arXiv: 0907.3917 [hep-ph]

CP-violation: indirect

★ Assume that direct CP-violation is absent $(\mathrm{Im}\,(\Gamma_{12}^* \bar{A}_f/A_f) = 0, \;\; |\bar{A}_f/A_f| = 1)$
- experimental constraints on x, y, φ, |q/p| exist
- can obtain generic constraints on Im parts of Wilson coefficients

$$\mathcal{H}_{NP}^{\Delta C=2} = \frac{1}{\Lambda_{NP}^2} \sum_{i=1}^{8} z_i(\mu) Q_i'$$

★ In particular, from $x_{12}^{\rm NP} \sin\phi_{12}^{\rm NP} \lesssim 0.0022$

$$\mathcal{I}m(z_1) \lesssim 1.1 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\; TeV}\right)^2,$$
$$\mathcal{I}m(z_2) \lesssim 2.9 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\; TeV}\right)^2,$$
$$\mathcal{I}m(z_3) \lesssim 1.1 \times 10^{-7} \left(\frac{\Lambda_{\rm NP}}{1\; TeV}\right)^2,$$
$$\mathcal{I}m(z_4) \lesssim 1.1 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\; TeV}\right)^2,$$
$$\mathcal{I}m(z_5) \lesssim 3.0 \times 10^{-8} \left(\frac{\Lambda_{\rm NP}}{1\; TeV}\right)^2.$$

New Physics is either at a very high scales

tree level: $\Lambda_{NP} \geq (4-10) \times 10^3$ TeV

loop level: $\Lambda_{NP} \geq (1-3) \times 10^2$ TeV

or have highly suppressed couplings to charm!

Gedalia, Grossman, Nir, Perez
arXiv:0906.1879 [hep-ph]

Bigi, Blanke, Buras, Recksiegel,
JHEP 0907:097, 2009

★ Constraints on particular NP models possible

Mixing

Wishes for the lattice:

i) calculation of all D-mixing matrix elements!

Wish List

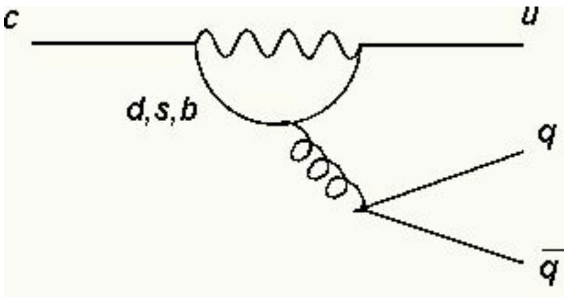
i) confirm SM numbers for leptonic decays
ii) use them to constrain NP
iii) can one compute $D \to \mu\nu\gamma$ on the lattice?
iv) compute form factors for $D \to \eta(\eta')\mu\nu$
v) compute form factor for $\Lambda_c \to \Lambda\mu\nu$
vi) can one calculate WA in $D \to \gamma V$ (without dipole)?
vii) calculate $B \to \gamma D^*$ as a test
viii) calculate all D-mixing matrix elements!

Extra slides

A comment on the size of CPV

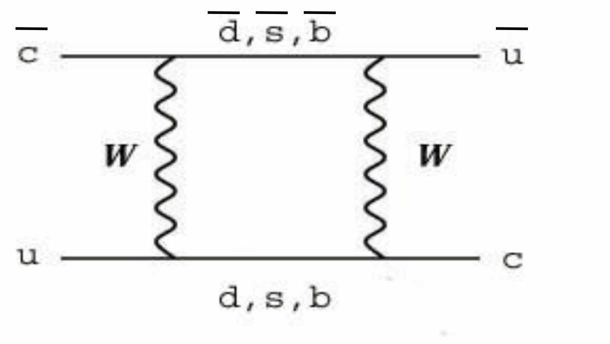
- Generic expectation is that CP-violating observables in the SM are small

Δc = 1 amplitudes



Penguin amplitude

Δc = 2 amplitudes



D-$\bar{D}$ mixing

- The Unitarity Triangle for charm:

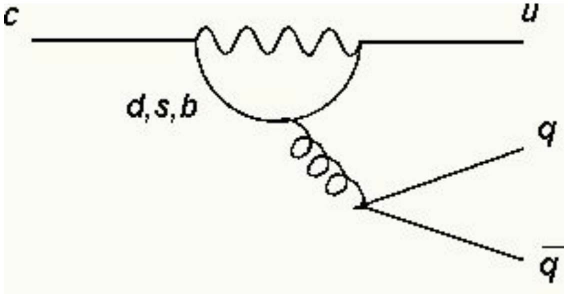
$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$

$$\sim\lambda \qquad \sim\lambda \qquad \sim\lambda^5$$

A comment on the size of CPV

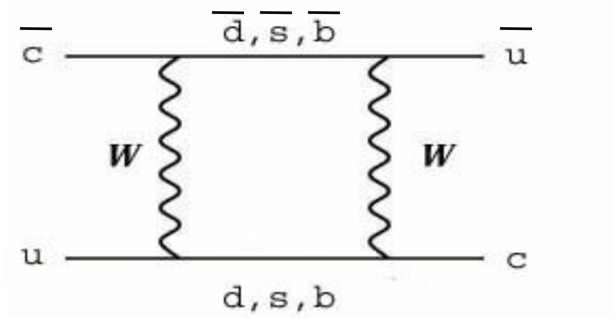
- Generic expectation is that CP-violating observables in the SM are small

Δc = 1 amplitudes



Penguin amplitude

Δc = 2 amplitudes



D-$\bar{D}$ mixing

- The Unitarity Triangle for charm:

$$V_{ud}V_{cd}^* + V_{us}V_{cs}^* + V_{ub}V_{cb}^* = 0$$

$$\sim\lambda \qquad \sim\lambda \qquad \sim\lambda^5$$

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

Any CP-violating signal in the SM will be small, at most $O(V_{ub}V_{cb}^*/V_{us}V_{cs}^*) \sim 10^{-3}$
Thus, O(1%) CP-violating signal can provide a "smoking gun" signature of New Physics

CP-violating decay rates

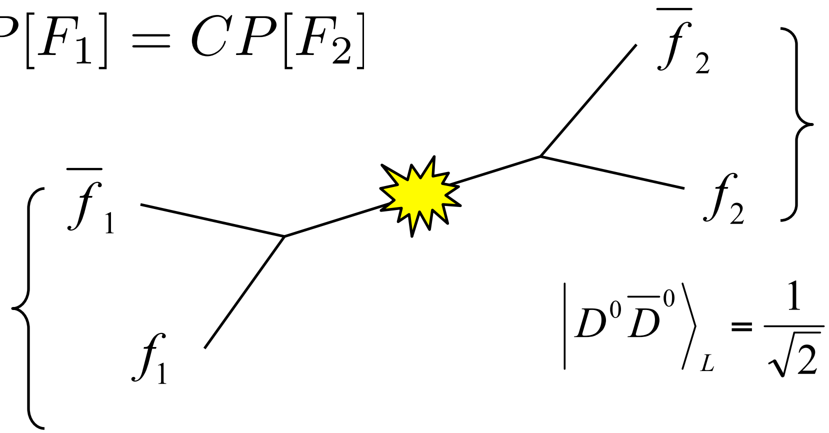
τ-charm factory

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

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

I. Bigi, A. Sanda; H. Yamamoto; Z.Z. Xing; D. Atwood, AAP

$$CP[F_1] = CP[F_2]$$



CP eigenstate F_2

CP eigenstate F_1

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

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

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

★ CP-violation in the **rate** → of the second order in CP-violating parameters.

★ Cleanest measurement of CP-violation!

CP-violation II: direct

★ What about direct CP-violation? Consider asymmetries

$$a_f = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})} \quad \text{and} \quad a_{\overline{f}} = \frac{\Gamma(D \to \overline{f}) - \Gamma(\overline{D} \to f)}{\Gamma(D \to \overline{f}) + \Gamma(\overline{D} \to f)}$$

★ Each of those asymmetries can be expanded as

$$a_f = \underbrace{a_f^d}_{\text{direct}} + \underbrace{a_f^m}_{\text{mixing}} + \underbrace{a_f^i}_{\text{interference}}$$

$$a_f^d = 2 r_f \sin\phi_f \sin\delta_f$$

$$a_f^m = -R_f \frac{y'_f}{2}\left(R_m - R_m^{-1}\right)\cos\phi$$

$$a_f^i = R_f \frac{x'_f}{2}\left(R_m + R_m^{-1}\right)\sin\phi$$

Y. Grossman, A. Kagan, Y. Nir, Phys Rev D 75, 036008, 2007

1. similar formulas available for $\overline{f}$
2. for CP-eigenstates: $f=\overline{f}$ and $y_f' \to y$

Those observables are of the <u>first</u> order in CPV parameters

What to expect for direct CPV?

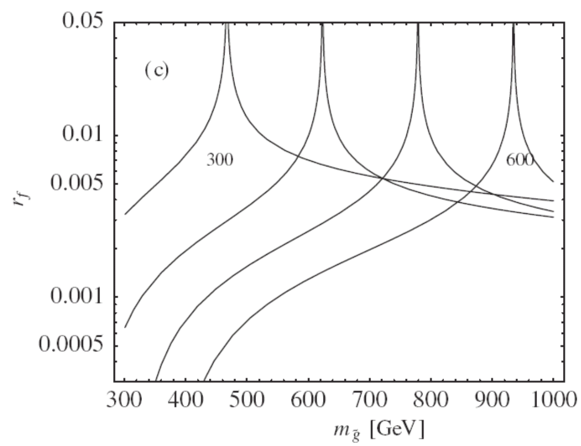
★ Standard Model asymmetries (in 10^{-3}):

Final state	$\pi^+\eta$	$\pi^+\eta'$	$K^+\overline{K^0}$	$\pi^+\rho^0$	$\pi^0\rho^+$	$K^{*+}\overline{K^0}$	$K^+\overline{K^{*0}}$
a_f, $\cos\delta > 0$	-1.5±0.4	0.04±0.01	1.0±0.3	-2.3±0.6	2.9±0.8	-0.9±0.3	2.8±0.8
a_f, $\cos\delta < 0$	-0.7±0.4	0.02±0.01	0.5±0.3	-1.2±0.6	1.5±0.8	-0.5±0.3	1.4±0.7

F. Buccella et al, Phys. Lett. B302, 319, 1993

★ New Physics (in new tree-level interaction and new loop effects):

Model	r_f
Extra quarks in vector-like rep	$< 10^{-3}$
RPV SUSY	$< 1.5\times10^{-4}$
Two-Higgs doublet	$< 4\times10^{-4}$



Y. Grossman, A. Kagan, Y. Nir, Phys Rev D 75, 036008, 2007

Experimental constraints (HFAG)

➢ HFAG provides the following averages from BaBar, Belle, CDF, E687, E791, FOCUS, CLEO collaborations

Decay mode	CP-asymmetry
$D^0 \to \pi^+\pi^-$	0.0022 $\pm$ 0.0037
$D^0 \to \pi^0\pi^0$	0.001 $\pm$ 0.048
$D^0 \to K_S^0 K_S^0$	-0.23 $\pm$ 0.19
$D^0 \to K^+K^-$	-0.0016 $\pm$ 0.0023
$D^+ \to K_S^0 K^+$	-0.0009 $\pm$ 0.0063

Most measurements are at the (sub)percent sensitivity

HFAG-charm
http://www.slac.stanford.edu/xorg/hfag/charm/index.html