Charm physics: past, present and future

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Disclaimer:

"It's Hard To Make Predictions, Especially About the Future"

Yogi Berra, Niels Bohr or Mark Twain

Disclaimer:

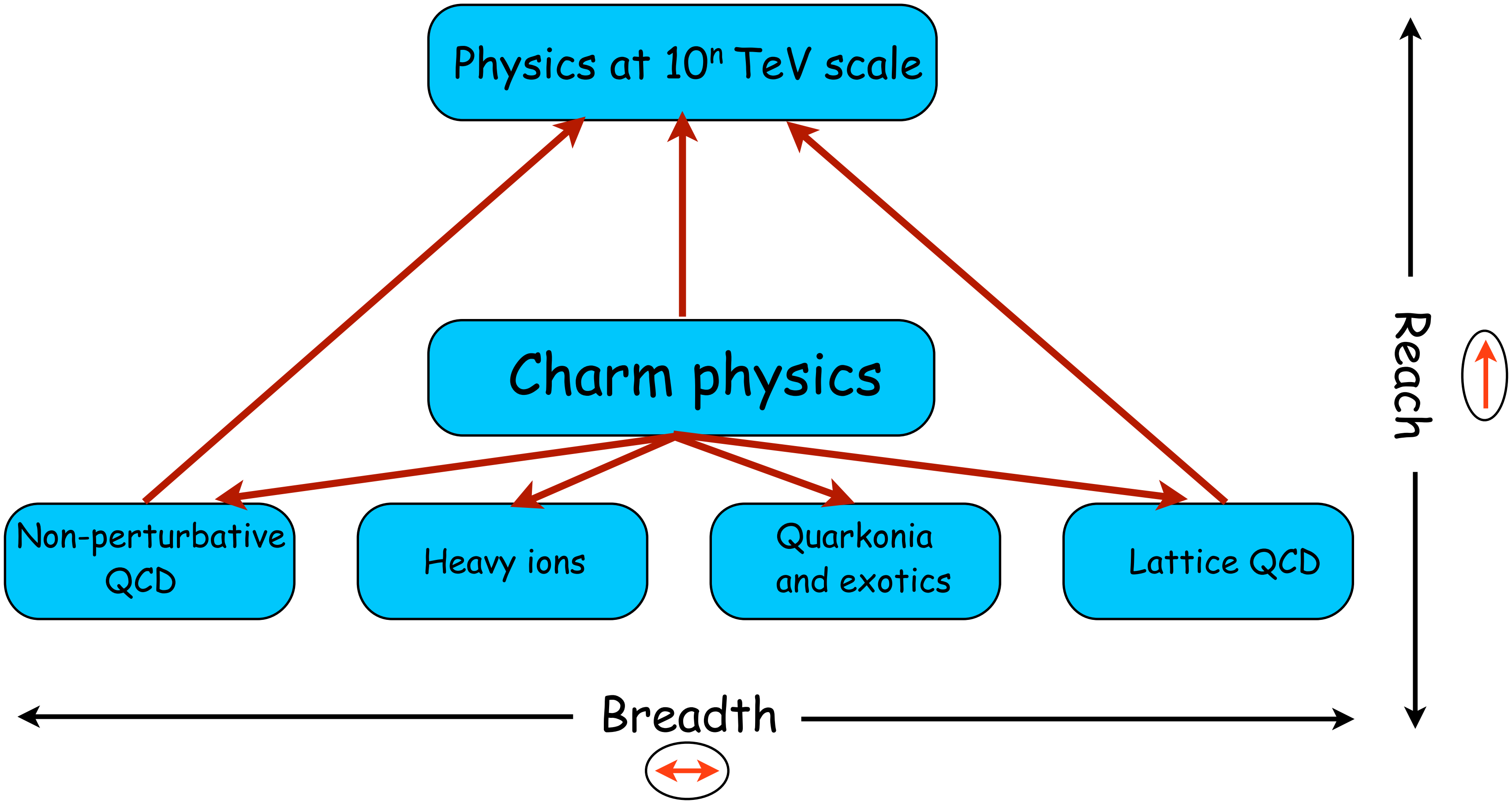
"It Is Always Wise To Look Ahead, But Difficult To Look Further Than You Can See."

Winston Churchill

Introduction: charm

★ Charm physics provides incredible opportunities to study both QCD and NP!

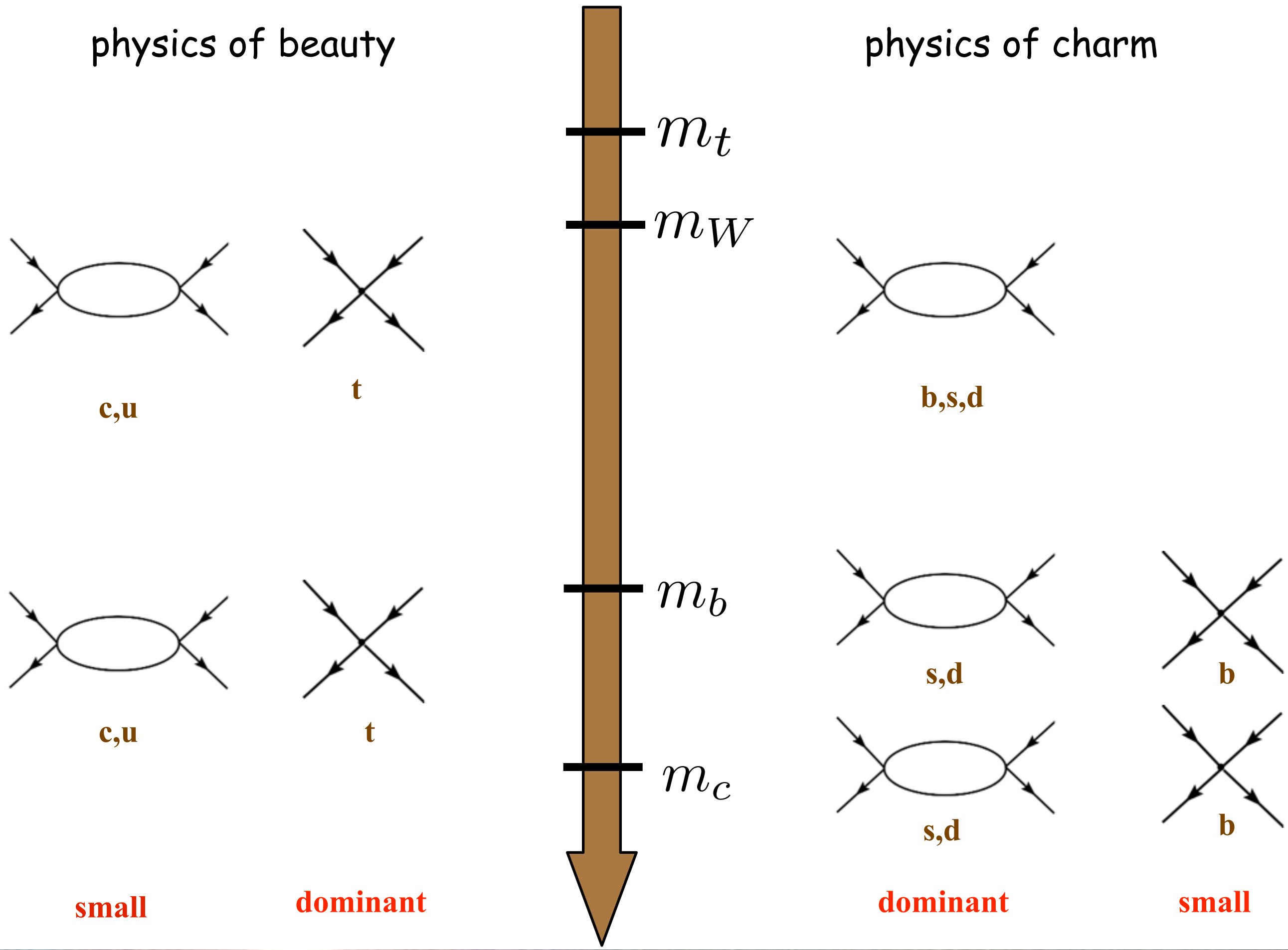
★ Most studies of New Physics involve flavor changing neutral current transitions



Δc = 2 example: mixing

★ Main goal of the exercise: understand physics at the most fundamental scale

★ It is important to understand relevant energy scales for the problem at hand



Mixing: short vs long distance

★ How can one tell that a process is dominated by long-distance or short-distance?

★ To start thing off, mass and lifetime differences of mass eigenstates...

$$x_D = \frac{M_2 - M_1}{\Gamma_D}, \; y_D = \frac{\Gamma_2 - \Gamma_1}{2\Gamma_D}$$

★ ...can be calculated as real and imaginary parts of a correlation function

$$y_{\mathrm{D}} = \frac{1}{2M_{\mathrm{D}}\Gamma_{\mathrm{D}}} \operatorname{Im} \langle \overline{D^0} | \, i \int \mathrm{d}^4 x \, T \left\{ \mathcal{H}_w^{|\Delta C|=1}(x) \, \mathcal{H}_w^{|\Delta C|=1}(0) \right\} | D^0 \rangle$$

bi-local time-ordered product

$$x_{\mathrm{D}} = \frac{1}{2M_{\mathrm{D}}\Gamma_{\mathrm{D}}} \operatorname{Re} \left[2\langle \overline{D^0} | H^{|\Delta C|=2} | D^0 \rangle + \langle \overline{D^0} | \, i \int \mathrm{d}^4 x \, T \left\{ \mathcal{H}_w^{|\Delta C|=1}(x) \, \mathcal{H}_w^{|\Delta C|=1}(0) \right\} | D^0 \rangle \right]$$

local operator
(b-quark, NP): small?

bi-local time-ordered product

★ So, the big question is if the integrals are dominated by $x \to 0$???

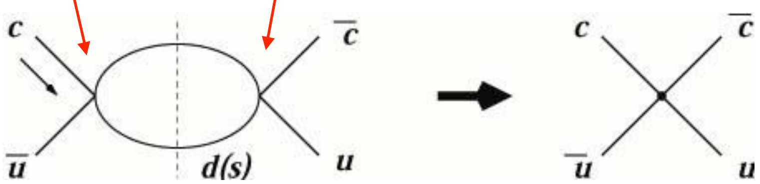
Mixing: short vs long distance

★ How can one tell that a process is dominated by long-distance or short-distance?

★ It is important to remember that the expansion parameter is $1/E_{released}$

$$y_{\mathrm{D}} = \frac{1}{2M_{\mathrm{D}}\Gamma_{\mathrm{D}}} \mathrm{Im}\, \langle \overline{D^0} | \, i \int \mathrm{d}^4x\, T\left\{ \mathcal{H}_w^{|\Delta C|=1}(x)\, \mathcal{H}_w^{|\Delta C|=1}(0) \right\} | D^0 \rangle$$

OPE-leading contribution:



★ In the heavy-quark limit $m_c \to \infty$ we have $m_c \gg \sum m_{intermediate\ quarks}$, so $E_{released} \sim m_c$

- the situation is similar to B-physics, where it is "short-distance" dominated
- one can consistently compute pQCD and 1/m corrections

★ But wait, m_c is NOT infinitely large! What happens for finite m_c???

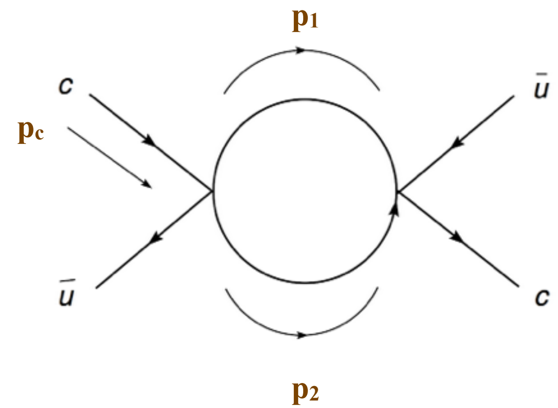
- how is large momentum routed in the diagrams?
- are there important hadronization (threshold) effects?

Threshold (and related) effects in OPE

★ How can one tell that a process is dominated by long-distance or short-distance?

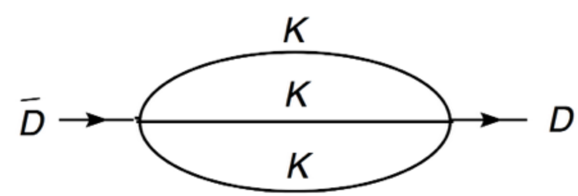
★ Let's look how the momentum is routed in a leading-order diagram

- injected momentum is $p_c \sim m_c$, so
- thus, $p_1 \sim p_2 \sim m_c/2 \sim O(\Lambda_{QCD})$?



★ For a particular example of the lifetime difference, have hadronic intermediate states

- let's use an example of KKK intermediate state
- in this example, $E_{released} \sim m_D - 3\ m_K \sim O(\Lambda_{QCD})$

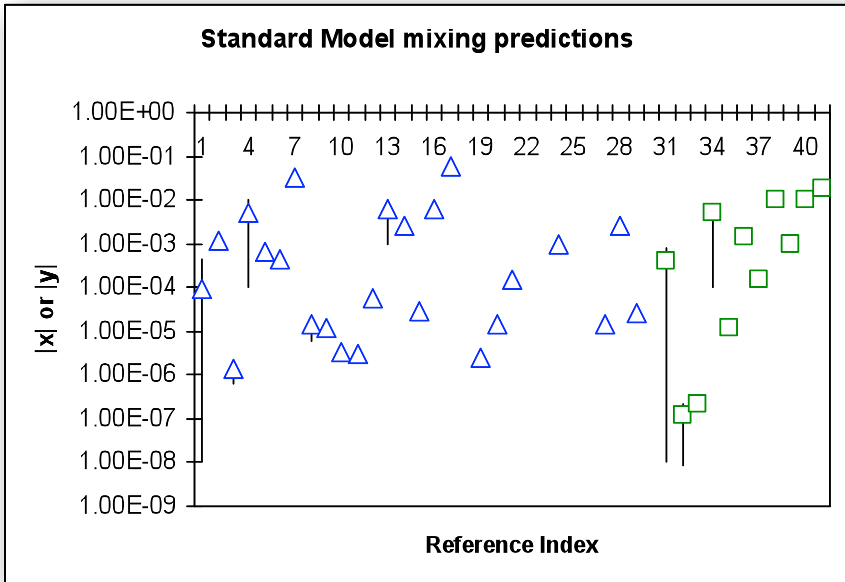


★ Similar threshold effects exist in B-mixing calculations

- but $m_b \gg \sum m_{intermediate\ quarks}$, so $E_{released} \sim m_b$ (almost) always
- quark-hadron duality takes care of the rest!

Maybe a better approach would be to work with hadronic DOF directly?

Mixing: Standard Model predictions



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* 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, $1/m_c^6$!
  - -threshold effects?

H. Georgi; T. Ohl, …
I. Bigi, N. Uraltsev;

M. Bobrowski et al

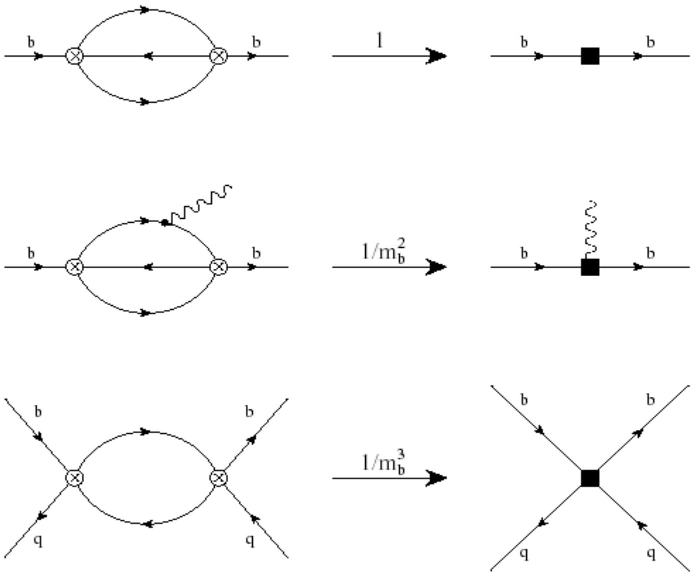
★ Long distance:
- -assume m_c is NOT large
  - -sum of large numbers with alternating signs, SU(3) forces zero!
  - -multiparticle intermediate states dominate

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

Test: inclusive decays and lifetimes

1. Nice test of our understanding of non-perturbative QCD effects in charm
2. One of the few unambiguous theoretical predictions that are easy to test experimentally
3. Theoretical uncertainty can be estimated: precision studies



$$\Gamma(H_b) = \frac{1}{2M_b}\langle H_b | T | H_b \rangle = \frac{1}{2M_b}\langle H_b | \mathrm{Im}\, i \int d^4x\, T\left\{ H_{eff}^{\Delta B=1}(x) H_{eff}^{\Delta B=1}(0) \right\} | H_b \rangle$$

$$\Gamma(H_b) = \frac{G_F^2 m_Q^5}{192\pi^3}\left[A_0 + \frac{A_2}{m_Q^2} + \frac{A_2}{m_Q^3} + \ldots \right]$$

HQ expansion is converging reasonably well

Generic restrictions on NP from $D\bar{D}$-mixing

★ 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

Experiment	R_D ($\times 10^{-3}$)	y' ($\times 10^{-3}$)	x'^2 ($\times 10^{-3}$)	Excl. No-Mix Significance	R_B ($\times 10^{-3}$)
Belle (2006)	3.64 ± 0.17	0.6 ± 4.0	0.18 ± 0.22	2.0	3.77 ± 0.09
BaBar (2007)	3.03 ± 0.19	9.7 ± 5.4	-0.22 ± 0.37	3.9	3.53 ± 0.09
LHCb	3.52 ± 0.15	7.2 ± 2.4	-0.09 ± 0.13	9.1	4.25 ± 0.04
CDF (9.6/fb)	3.51 ± 0.35	4.27 ± 4.30	0.08 ± 0.18	6.1	4.30 ± 0.06

M. Mattson, 2013

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

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

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

or has highly suppressed couplings to charm!

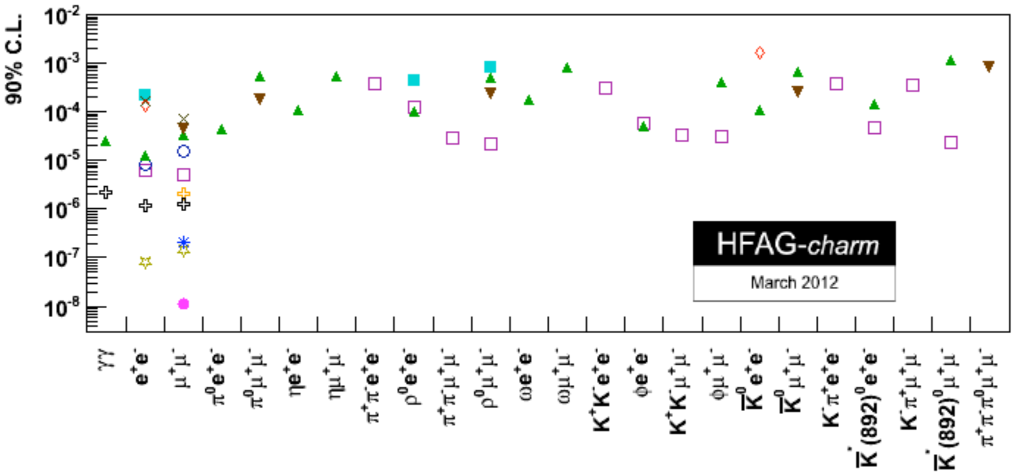
Gedalia, Grossman, Nir, Perez
Phys.Rev.D80, 055024, 2009

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

★ Constraints on particular NP models also available!

$\Delta c = 1$ example: radiative and rare decays

★ There are some improvements in measurements of rare decays



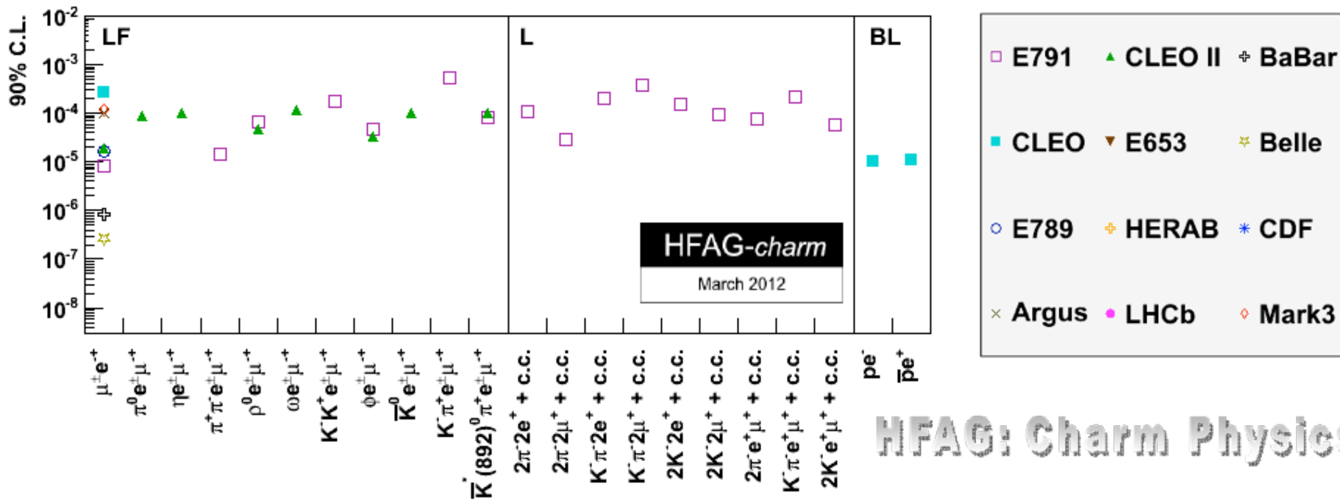
★ FCNC transitions "directly" probe NP

★ SM calculable contributions are usually small

★ ... but long-distance effects dominate

★ can use we rare and radiative charm decays to rule out NP models...

★ ... and help with sorting out surprises?



HFAG: Charm Physics Parameters

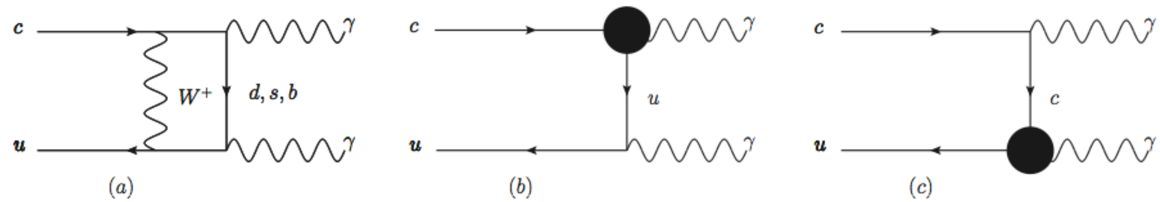
Rare radiative decays of charm

★ Standard Model contribution to D → γγ

$$A(D \to \gamma\gamma) = \epsilon_{1\mu}\epsilon_{2\nu}\left[A_{PC}\epsilon^{\mu\nu\alpha\beta}k_{1\alpha}k_{2\beta} + iA_{PV}\left(g^{\mu\nu} - \frac{k_2^\mu k_1^\nu}{k1 \cdot k_2}\right)\right]$$

$$\Gamma(D \to \gamma\gamma) = \frac{m_D^3}{64\pi}\left[\left|A_{PC}\right|^2 + \frac{4}{m_D^4}\left|A_{PV}\right|^2\right]$$

★ Short distance analysis $\mathcal{L} = -\frac{G_f}{\sqrt{2}}V_{us}V_{cs}^* C_{7\gamma}^{eff}\frac{e}{4\pi^2}F_{\mu\nu}m_c\left(\bar{u}\sigma^{\mu\nu}\frac{1}{2}(1+\gamma_5)c\right)$



Paul, Bigi, Recksiegel (2011)

- only one operator contributes
- including QCD corrections, SD effects amount to Br = $(3.6\text{-}8.1)\times10^{-12}$

★ Long distance analysis

- long distance effects amount to Br = $(1\text{-}3)\times10^{-8}$

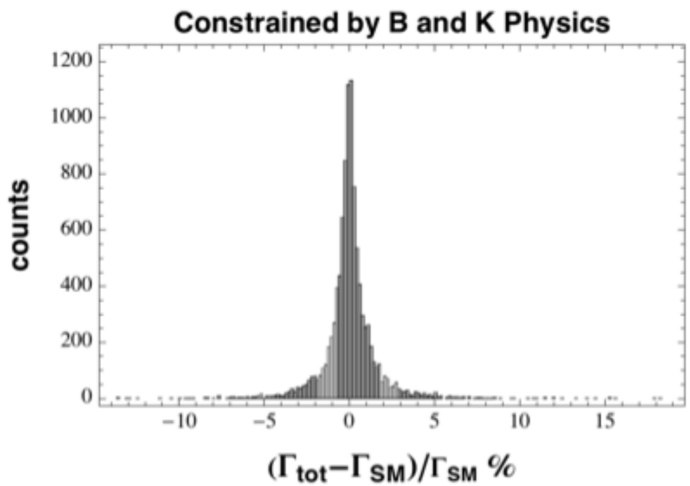
Burdman, Golowich, Hewett, Pakvasa (02);
Fajfer, Singer, Zupan (01)

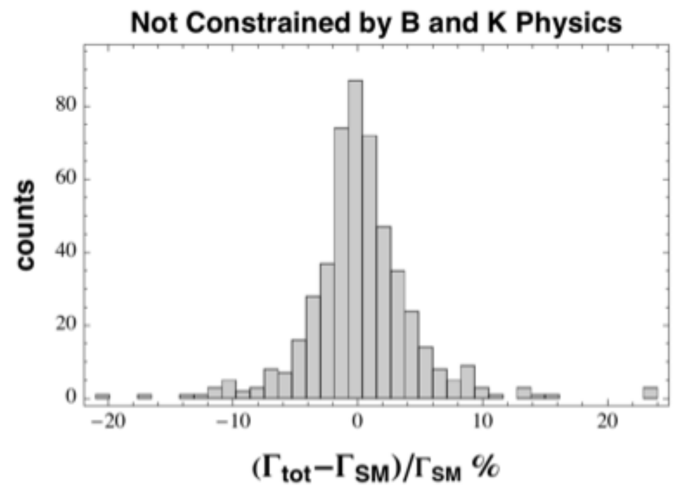
New physics and radiative D-decays

★ New constraints on NP models from $D \to \gamma\gamma$ since 2010

★ Some popular "LHC models" can be tested with $D \to \gamma\gamma$

- consider an example of Littlest Higgs model with T-parity — Paul, Bigi, Recksiegel (2011)
- new particles: partner of top, mirror fermions and gauge bosons, triplet and singlet Higgs bosons: possible effect!





★ No observable effect in $D \to \gamma\gamma$! But could affect D-mixing: anti-correlation!

Rare leptonic decays of charm

★ Standard Model contribution to D → $\mu^+\mu^-$.

★ Short distance analysis

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

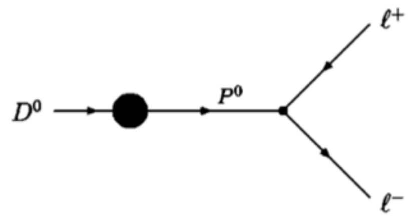
$$B^{(\text{s.d.})}_{D^0 \ell^+ \ell^-} \simeq \frac{G_F^2 M_W^2 f_D m_\ell}{\pi^2} F\,,$$

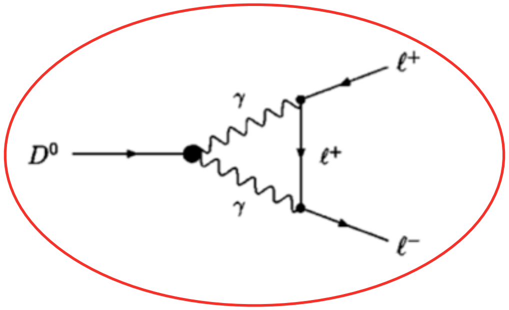
$$F = \sum_{i=d,s,b} V_{ui} V_{ci}^* \left[\frac{x_i}{2} + \frac{\alpha_s}{4\pi} x_i \cdot \left(\ln^2 x_i + \frac{4+\pi^2}{3} \right) \right]$$

- only Q_{10} contribute, SD effects amount to Br ~ 10^{-18}
- single non-perturbative parameter (decay constant)

UKQCD, HPQCD; Jamin, Lange; Penin, Steinhauser; Khodjamirian

★ Long distance analysis





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

Update soon: Healey, AAP

$$B^{(\text{mix})}_{D^0 \ell^+ \ell^-} = \sum_{P_n} \langle P_n | \mathcal{H}^{(\text{p.c.})}_{wk} | D^0 \rangle \frac{1}{M_D^2 - M_{P_n^2}} B_{P_n \ell^+ \ell^-}$$

$$\mathcal{I}m\, \mathcal{M}_{D^0 \to \ell^+ \ell^-} = \frac{1}{2!} \sum_{\lambda_1, \lambda_2} \int \frac{d^3 q_1}{2\omega_1 (2\pi)^3} \frac{d^3 q_2}{2\omega_2 (2\pi)^3} \times \mathcal{M}_{D \to \gamma\gamma} \mathcal{M}^*_{\gamma\gamma \to \ell^+ \ell^-} (2\pi)^4 \delta^{(4)}(p - q_1 - q_2)$$

- LD effects amount to Br ~ 10^{-13}
- could be used to study NP effects in correlation with D-mixing

Generic NP contribution to $D \to \mu^+\mu^-$

★ Most general effective Hamiltonian:

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

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

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

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

plus $L \leftrightarrow R$

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

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

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

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

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

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

Mixing vs rare decays: a particular model

★ Recent experimental constraints

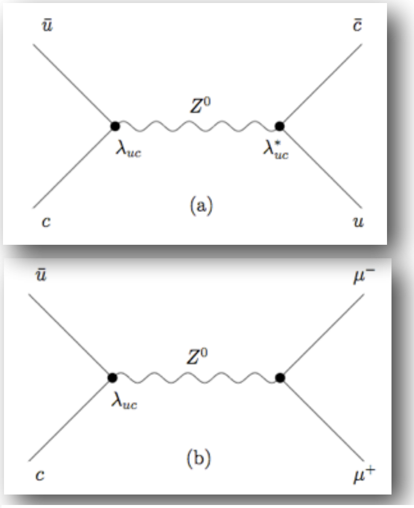
$$\mathcal{B}_{D^0\to\mu^+\mu^-} \le 1.3\times 10^{-6}, \qquad \mathcal{B}_{D^0\to e^+e^-} \le 1.2\times 10^{-6},$$

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

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.



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

Mixing:

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

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

Rare decay:

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

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

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. (09)

★ Consider 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	$1.7 \times 10^{-9}\ (500\ \text{GeV}/m_{\tilde{d}_k})^2$

Obtained upper limits on rare decay branching ratios.

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

Blum, Grossman, Nir, Perez (09)

Rare semileptonic decays of charm

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

★ Rare decays D → M $e^+e^-/\mu^+\mu^-$ just like D → $e^+e^-/\mu^+\mu^-$ are mediated by c→u ll

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

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

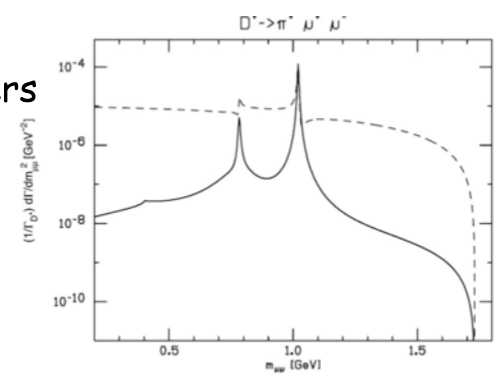
- SM contribution is dominated by LD effects
- could be used to study NP effects

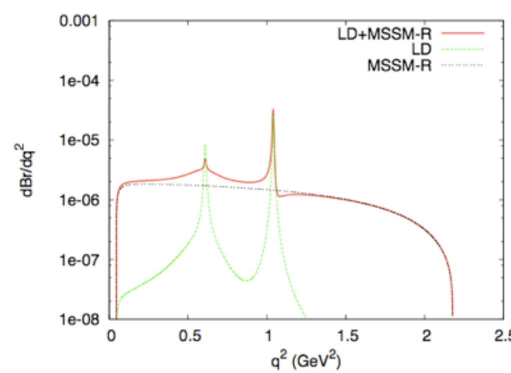
Burdman, Golowich, Hewett, Pakvasa;
Fajfer, Prelovsek, Singer

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}	

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

Fajfer, Kosnik, Prelovsek





CP-violation in charmed mesons (general)

★ Fundamental problem: observation of CP-violation in up-quark sector!

★ Possible sources of CP violation in charm transitions:

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

$$\Gamma(D \to f) \neq \Gamma(CP[D] \to CP[f])$$

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

$$\left|D_{1,2}\right\rangle = p\left|D^0\right\rangle \pm q\left|\overline{D^0}\right\rangle \Rightarrow |D_{CP\pm}\rangle = \frac{1}{\sqrt{2}}\left(\left|D^0\right\rangle \pm \left|\overline{D}^0\right\rangle\right)$$

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

★ 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 I: indirect

★ Indirect CP-violation manifests itself in $D\bar{D}$-oscillations

- see time development of a D-system:

$$i\frac{d}{dt}|D(t)\rangle = \left(M - \frac{i}{2}\Gamma\right)|D(t)\rangle$$

$$\langle D^0|\mathcal{H}|\overline{D^0}\rangle = M_{12} - \frac{i}{2}\Gamma_{12} \qquad \langle \overline{D^0}|\mathcal{H}|D^0\rangle = M_{12}^* - \frac{i}{2}\Gamma_{12}^*$$

★ Define mixing parameters

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

Note: can be calculated in a given model

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

- 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

CP-violation I: 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: $\Lambda_{NP} \geq (4-10) \times 10^3\ \mathrm{TeV}$

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

or have highly suppressed couplings to charm!

Gedalia, Grossman, Nir, Perez
Phys.Rev.D80, 055024, 2009

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

★ Constraints on particular NP models possible as well

CP-violation I: indirect

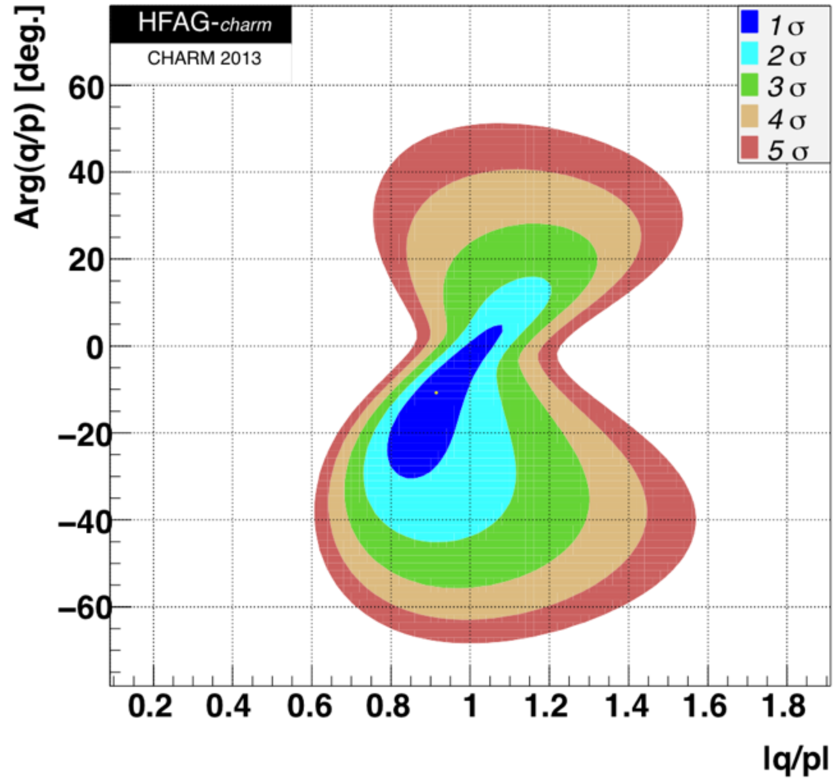
★ Relation; data from HFAG's compilation

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

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

- aside: if $|M_{12}| < |\Gamma_{12}|$:

$$\begin{aligned} x/y &= 2\,|M_{12}/\Gamma_{12}|\cos\phi_{12}, \\ A_m &= 4\,|M_{12}/\Gamma_{12}|\sin\phi_{12}, \\ \phi &= -2\,|M_{12}/\Gamma_{12}|^2\sin 2\phi_{12}. \end{aligned}$$



Note: CPV is suppressed even if M_{12} is all NP!!!

Bergmann, Grossman, Ligeti, Nir, AAP
PL B486 (2000) 418

★ With available experimental constraints on x, y, and q/p, one can bound WCs of a generic NP Lagrangian -- bound any high-scale model of NP

CP-violation II: direct

★ IDEA: consider the DIFFERENCE of decay rate asymmetries: D →ππ vs D → KK!
For each final state the asymmetry

D^0: no neutrals in the final state!

$$a_f = \frac{\Gamma(D \to f) - \Gamma(\overline{D} \to \overline{f})}{\Gamma(D \to f) + \Gamma(\overline{D} \to \overline{f})} \quad \Rightarrow \quad a_f = \underbrace{a_f^d}_{\text{direct}} + \underbrace{a_f^m}_{\text{mixing}} + \underbrace{a_f^i}_{\text{interference}}$$

★ A reason: $a^m_{KK}=a^m_{\pi\pi}$ and $a^i_{KK}=a^i_{\pi\pi}$ (for CP-eigenstate final states), so, ideally, mixing asymmetries cancel!

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

★ ... and the resulting DCPV asymmetry is $\Delta a_{CP} = a^d_{KK} - a^d_{\pi\pi} \approx 2a^d_{KK}$ (double!)

$$A_{KK} = \frac{G_F}{\sqrt{2}}\lambda\left[(T+E+P_{sd}) + a\lambda^4 e^{-i\gamma}P_{bd}\right]$$

$$A_{\pi\pi} = \frac{G_F}{\sqrt{2}}\lambda\left[(-(T+E)+P_{sd}) + a\lambda^4 e^{-i\gamma}P_{bd}\right]$$

★ ... so it is doubled in the limit of $SU(3)_F$ symmetry

SU(3) is badly broken in D-decays
e.g. Br(D → KK) ~ 3 Br(D →ππ)

Experiment?

★ Experiment: the difference of CP-asymmetries: $\Delta a_{CP} = a_{CP,KK} - a_{CP,\pi\pi}$

★ Earlier results (before 2013):

Experiment	ΔA_{CP}
LHCb	$(-0.82 \pm 0.21 \pm 0.11)\%$
CDF	$(-0.62 \pm 0.21 \pm 0.10)\%$
Belle	$(-0.87 \pm 0.41 \pm 0.06)\%$
BaBar	$(+0.24 \pm 0.62 \pm 0.26)\%$

Looks like CP is broken in charm transitions! Now what?

★ Recent results (after 2013):

D^{*+} tag (this analysis): $\Delta A_{CP} = (-0.34 \pm 0.15\,(\text{stat.}) \pm 0.10\,(\text{syst.}))\,\%$
Semileptonic analysis: $\Delta A_{CP} = (+0.49 \pm 0.30\,(\text{stat.}) \pm 0.14\,(\text{syst.}))\,\%$
Combination: $\Delta A_{CP} = (-0.15 \pm 0.16)\,\%$

LHCb-CONF-2013-003

Not so sure anymore…

Is it Standard Model or New Physics??

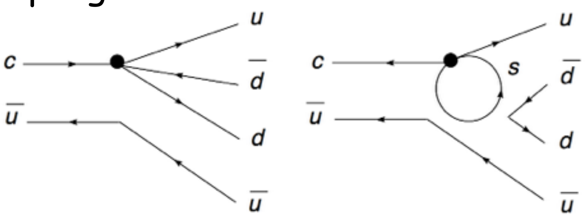
★ Is it Standard Model or New Physics? Theorists used to say...

Naively, 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

...what do you say now?

★ assuming SU(3) symmetry, $a_{CP}(\pi\pi) \sim a_{CP}(KK) \sim 0.15\%$. Looks more or less 0.1%...
★ let us try Standard Model

- need to estimate size of penguin/penguin contractions vs. tree



- unknown penguin enhancement (similar to $\Delta I = 1/2$)
  - SU(3) analysis: some ME are enhanced

    Golden & Grinstein PLB 222 (1989) 501;Pirtshalava & Uttayarat 1112.5451

  - unusually large $1/m_c$ corrections

    Isidori et al PLB 711 (2012) 46; Brod et al 1111.5000

  - no assumptions, flavor-flow diagrams

    Broad et al 1203.6659; Bhattacharya et al PRD 85 (2012) 054014; Cheng & Chiang 1205.0580

New Physics: operator analysis

★ Factorizing decay amplitudes, e.g.

$$\mathcal{H}^{\mathrm{eff-NP}}_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_{i=1,2,5,6} \sum_{q} (C_i^q Q_i^q + C_i^{q\prime} Q_i^{q\prime}) + \frac{G_F}{\sqrt{2}} \sum_{i=7,8} (C_i Q_i + C_i' Q_i') + \mathrm{H.c.}$$

$$Q_1^q = (\bar{u} q)_{V-A} \, (\bar{q} c)_{V-A}$$

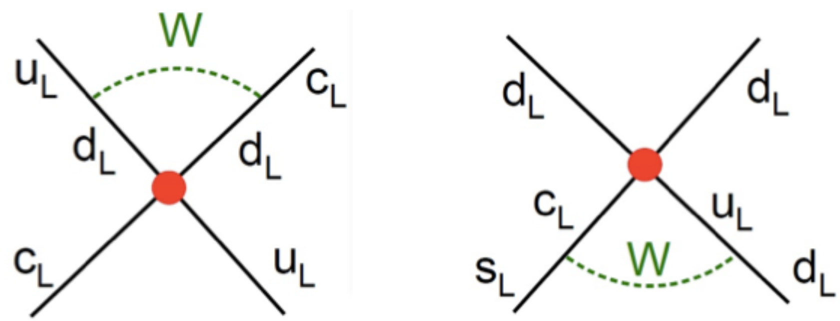
$$Q_2^q = (\bar{u}_\alpha q_\beta)_{V-A} \, (\bar{q}_\beta c_\alpha)_{V-A}$$

$$Q_5^q = (\bar{u} c)_{V-A} \, (\bar{q} q)_{V+A}$$

$$Q_6^q = (\bar{u}_\alpha c_\beta)_{V-A} \, (\bar{q}_\beta q_\alpha)_{V+A}$$

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

$$Q_8 = -\frac{g_s}{8\pi^2} m_c \, \bar{u} \sigma_{\mu\nu} (1+\gamma_5) T^a G_a^{\mu\nu} c$$



Z. Ligeti, CHARM-2012

★ one can fit to ε′/ε and mass difference in D-anti-D-mixing

Gedalia, et al, arXiv:1202.5038

- LL are ruled out
- LR are borderline
- RR and dipoles are possible

Allowed	Ajar	Disfavored
$Q_{7,8}$, $Q'_{7,8}$, $\forall f\ Q^{f\prime}_{1,2}$, $Q^{(c-u,b,0)\prime}_{5,6}$	$Q^{(c-u,8d,b,0)}_{1,2}$, $Q^{(0)}_{5,6}$, $Q^{(8d)\prime}_{5,6}$	$Q^{s-d}_{1,2}$, $Q^{(s-d)\prime}_{5,6}$, $Q^{s-d,c-u,8d,b}_{5,6}$

Constraints from particular models also available

Future: lattice to the rescue*?

★ There are methods to compute decays on the lattice (Lellouch-Lüscher)
- calculation of scattering of final state particles in a finite box
- matching resulting discrete energy levels to decaying particle
- reasonably well developed for a single-channel problems (e.g. kaon decays)

★ Can these methods be generalized to D-decays?
- make D-meson slightly lighter, $m_D < 4\ m_\pi$
- assume G-parity and consider scattering of two pions and two kaons in a box with SM scattering energy

Hansen, Sharpe
PRD86, 016007 (2012)

$$2m_\pi < 2m_K < E^* < 4m_\pi$$

- only four possible scattering events: $\pi\pi\to\pi\pi$, $\pi\pi\to KK$, $KK\to\pi\pi$, $KK\to KK$
- couple the two by adding weak part to the strong Hamiltonian $\mathcal{H}(x) \to \mathcal{H}(x) + \lambda\mathcal{H}_W(x)$

★ Application of this approach to calculate lifetime difference is not trivial!!!
- need to consider other members of SU(3) octet
- need to consider 4π states that mix with $\pi\pi$ + others
- need to consider 3-body and excited light-quark states

* See "**panacea**": In Greek mythology, **Panacea** (Greek *Πανάκεια*, **Panakeia**) was a goddess of Universal remedy.

Future: CP-violation in charmed baryons

- Other observables can be constructed for baryons, e.g.

$$A(\Lambda_c \to N\pi) = \bar{u}_N(p,s)\left[A_S + A_P\gamma_5\right]u_{\Lambda_c}(p_\Lambda, s_\Lambda)$$

These amplitudes can be related to "asymmetry parameter" $\alpha_{\Lambda_c} = \dfrac{2\,\mathrm{Re}\left(A_S^* A_P\right)}{|A_S|^2 + |A_P|^2}$

... which can be extracted from $\dfrac{dW}{d\cos\vartheta} = \dfrac{1}{2}\left(1 + P\alpha_{\Lambda_c}\cos\vartheta\right)$

Same is true for $\overline{\Lambda}_c$-decay

If CP is conserved $\alpha_{\Lambda_c} \overset{CP}{\Rightarrow} -\overline{\alpha}_{\Lambda_c}$, thus CP-violating observable is

$$A_f = \frac{\alpha_{\Lambda_c} + \overline{\alpha}_{\Lambda_c}}{\alpha_{\Lambda_c} - \overline{\alpha}_{\Lambda_c}}$$

FOCUS[2006]: $A_{\Lambda\pi} = -0.07 \pm 0.19 \pm 0.24$

Transitions forbidden w/out CP-violation

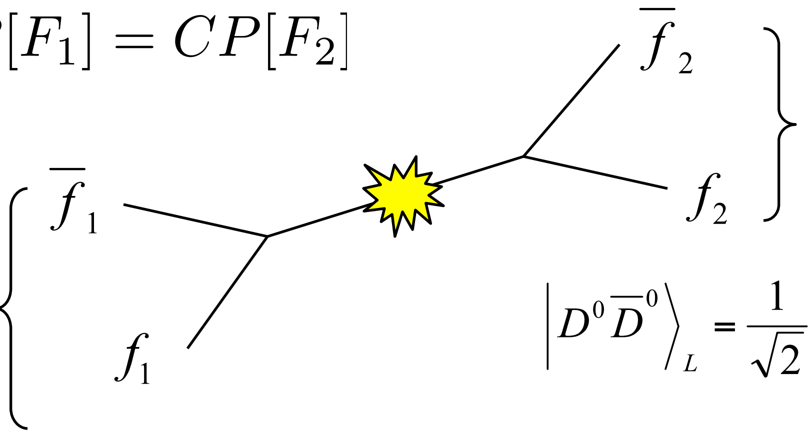
τ-charm factory

★ 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

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

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

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

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

★ Cleanest measurement of CP-violation!

AAP, Nucl. Phys. PS 142 (2005) 333 hep-ph/0409130

Better observables: untagged asymmetries?

A.A.P., PRD69, 111901(R), 2004

★ Look for CPV signals that are
- first order in CPV parameters
- do not require flavor tagging (for D^0)

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

$$A_{CP}^U(f) = \frac{\Sigma_f - \Sigma_{\bar f}}{\Sigma_f + \Sigma_{\bar f}} \quad \text{where} \quad \Sigma_f = \Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to f)$$

★ For a CF/DCS final state $K\pi$, the time-integrated asymmetry is simple

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

(<10^{-4} for NP)

★ For a SCS final state $\rho\pi$, neglecting direct CPV contribution,

$$\boxed{A_{CP}^U\left(\rho^+\pi^-\right) = -y \sin\delta_{\rho\pi} \sin\phi \sqrt{R_{\rho\pi}}}$$

(<10^{-2} for NP)

Note: a "theory-free" relation!

"I'm looking for a lot of men who have an infinite capacity to not know what can't be done."

Henry Ford

Things to take home

- Computation of charm mixing amplitudes is a difficult task
  - no dominant heavy dof, as in beauty decays
  - light dofs give no contribution in the flavor SU(3) limit
  - D-mixing is a second order effect in SU(3) breaking ($x,y \sim 1\%$ in the SM)
- Charm quark is neither heavy nor light enough for a clean application of well-established techniques
  - "heavy-quark" techniques miss threshold effects
  - "heavy-quark" techniques give numerically leading contribution that is parametrically suppressed by $1/m^6$
  - "hadronic" techniques need to sum over large number of intermediate states, AND cannot use current experimental data on D-decays
  - "hadronic" techniques currently neglect some sources of SU(3) breaking
- Calculations of New Physics contributions to mixing are in better shape
  - contributions of NP in $\Delta c=2$ operators are local and well-behaved
  - $\Delta\Gamma_D$ can have large (even dominant) contribution from NP
- Lattice calculations can, in principle, provide a result for exclusive y_D!


The Evening Herald
EXTRA!

Experimental analyses of mixing

★ In principle, can extract mixing (x,y) and CP-violating parameters (A_m, φ)

See talk by S. Stone

★ In particular, time-dependent $D^0(t) \to K^+\pi^-$ analysis

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

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

LHCb: $x'^2 = (-0.9 \pm 1.3) \times 10^{-4}$, $y' = (7.2 \pm 2.4) \times 10^{-3}$

★ The expansion can be continued to see how well it converges for large t

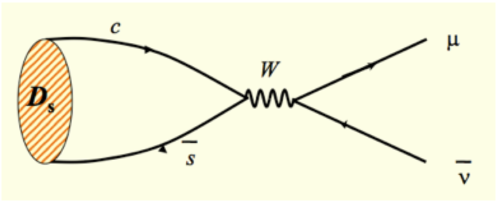
$$\begin{aligned}\Gamma[D^0(t) \to K^+\pi^-] \left|A_{K_\pi}\right|^{-2} e^{\Gamma t} = R &- \sqrt{R} R_m \left(x \sin(\delta+\phi) - y \cos(\delta+\phi)\right)(\Gamma t) \\ &+ \frac{1}{4}\left(\left(R_m - R\right) x^2 + \left(R + R_m\right) y^2\right)(\Gamma t)^2 \\ &+ \frac{1}{6}\sqrt{R} R_m \left(x^3 \sin(\delta+\phi) + y^3 \cos(\delta+\phi)\right)(\Gamma t)^3 \\ &- \frac{1}{48} R_m \left(x^4 - y^4\right)(\Gamma t)^4\end{aligned}$$

2b. Leptonic decays of D^+ and D_s

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

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

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

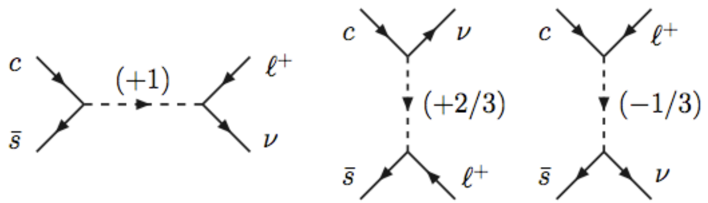


... so theory can be compared to experiment by comparing $|f_{Dq} V_{cq}|$

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

- possible heavy NP mediators

Akeryod; Hou; Hewett
Dobrescu, Kronfeld

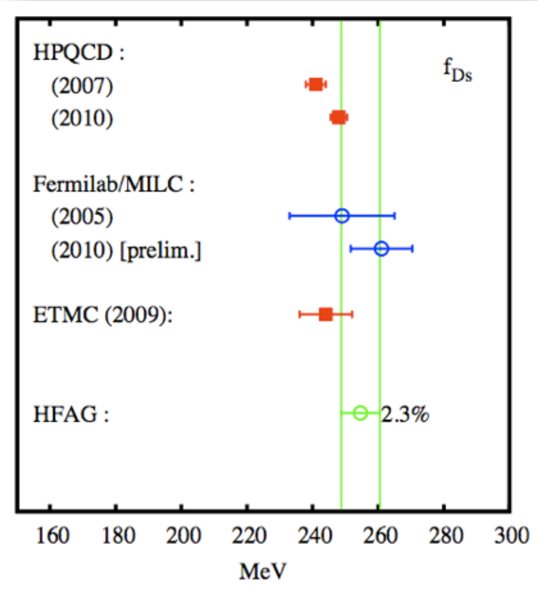


see Dorsner, Fajfer, Kamenik and Kosnik
Aditya, Healey, AAP

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

No helicity suppression !!!

see Artuso, Meadows, AAP



J. Shigemitsu, CKM-2010

No discrepancy between theory and experiment

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

★ 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

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

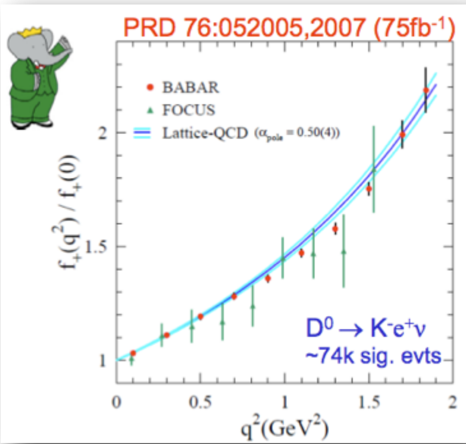
Lunghi, Pirjol, Wyler
Korchemsky, Prjol, Yan

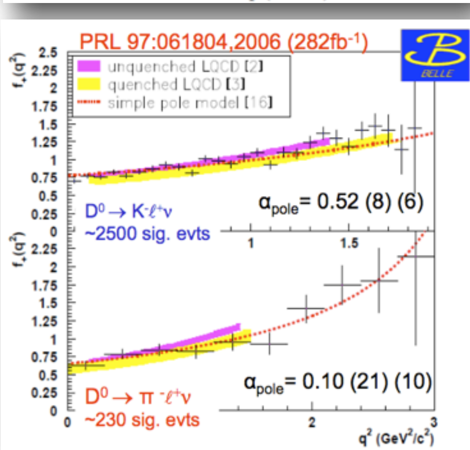
★ Is lattice prediction for $D \to \mu\nu\gamma$ possible?
- charmonium radiative decays — **Dudek, Edwards; Dudek, Edwards, Roberts**
- photon structure functions, pion form-factor, etc. — **X. Ji, C. Jung**

2c. 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

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

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

★ 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

Quarkonia and exotics

★ Rich physics opportunities for studies of QCD in different regimes

- effective theories for charmonium states
- charmonium exotics
- lattice QCD: exclusive transitions

Charm in heavy ion collisions

★ Rich physics opportunities for studies of QCD in different regimes

- charmonium suppression
- do charm quarks flow?
- how do charm quarks loose energy while propagating through a QGP (radiative vs. collisional energy loss)?
- how do charm quarks hadronize in a decaying QGP (recombination vs. fragmentation)?
- what are the charm quark transport coefficients (e.g. diffusion constant)?
- what QGP properties are charm quarks most sensitive to?

Rare radiative decays of charm

★ Can radiative charm decays help with Δa_{CP}?

★ In many NP models, there is a link between chromomagnetic and electric-dipole operators

Isidori, Kamenik (12)

$$Q_8 = \frac{m_c}{4\pi^2}\bar{u}_L \sigma_{\mu\nu} T^a g_s G_a^{\mu\nu} c_R$$

$$Q_7 = \frac{m_c}{4\pi^2}\bar{u}_L \sigma_{\mu\nu} Q_u e F^{\mu\nu} c_R$$

Same is true for operators of opposite chirality as well

★ There are many operators that can generate Δa_{CP}

Giudice, Isidori, Paradisi (12)

- one possibility is that NP affects Q_8 the most; the asymmetry then

$$|\Delta a_{CP}^{\rm NP}| \approx -1.8 |{\rm Im}[C_8^{\rm NP}(m_c)]|$$

- e.g. in SUSY, gluino-mediated amplitude satisfies $C_7^{\rm SUSY}(m_{\rm SUSY}) = (4/15) C_8^{\rm SUSY}(m_{\rm SUSY})$
- then at the charm scale,

$$|{\rm Im}[C_7^{\rm NP}(m_c)]| = (0.2 - 0.8)\times 10^{-2}$$

$$|C_7^{\rm SM-eff}(m_c)| = (0.5 \pm 0.1)\times 10^{-2}$$

What about LD effects?

CP-violation in radiative decays of charm

★ Probing a_{CP} in radiative D-decays can probe Im C_7 → Im C_8 → Δa_{CP}

- problem is, radiative decays are dominated by LD effects

Isidori, Kamenik (12)

$$\Gamma(D \to V\gamma) = \frac{m_D^3}{32\pi}\left(1 - \frac{m_V^2}{m_D^2}\right)^3 \left[|A_{PV}|^2 + |A_{PC}|^2\right]$$

★ CP-violating asymmetry in radiative transitions would be

$$|a_{(\rho,\omega)\gamma}|^{\max} = 0.04(1)\left|\frac{\mathrm{Im}[C_7(m_c)]}{0.4\times 10^{-2}}\right| \times \\ \times \left[\frac{10^{-5}}{\mathcal{B}(D\to(\rho,\omega)\gamma)}\right]^{1/2} \lesssim 10\% \, .$$

★ Better go off-resonance (consider $K^+K^-\gamma$) or even $h^+h^-\mu^+\mu^-$ final states

- the LD effects would be smaller, but the rate goes down as well

Isidori, Kamenik (12)
Cappiello, Cata, D'Ambrosio (12)

Do we need full SU(3)?

★ Since m_s provides the dominant source for SU(3) breaking, try U-spin

- U-spin interchanges s- and d-quarks
- ... thus, has the same source of breaking
- ... but the formulas could be simpler

Gronau, Rosner
PRD86, 114029 (2012)

$$H_W^{\Delta C=-1} = H_{-1} + H_0 + H_{+1}$$

$$H_{-1} = \frac{G_F C^2}{\sqrt{2}} (\bar{s}c)(\bar{u}d), \quad H_0 = \frac{G_F CS}{\sqrt{2}} [(\bar{s}c)(\bar{u}s) - (\bar{d}c)(\bar{u}d)], \quad H_{+1} = -\frac{G_F S^2}{\sqrt{2}} (\bar{d}c)(\bar{u}s)$$

-the Hamiltonian has three parts corresponding to three components of U-spin vector

U-spin triplets

$$\Delta\Gamma = \sum_{S=\mp 1,0} \sum_{f_S^D} \rho(f_S^D) \langle \bar{D}^0 | H_{-S} | f_S^D \rangle \langle f_S^D | H_S | D^0 \rangle + c.c.$$

U-spin singlets

★ One can follow the same logic as with full SU(3), but tracking U-spin only

- get several sum rules in the U-spin limit
- GR used experimental data to see how much sum rules are violated
- those contributions (esp 4-body) add up to the physical value of y_D~1%

CAUTION