Les Rencontres de Physique de la Vallée d'Aoste

CPV in the Charm System

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Why CP Violation in Charm?

- CPV in charm provides a unique probe of New Physics (NP)
  - sensitive to NP in the up sector
  - SM charm physics is CP conserving to first approximation (2 generation dominance, no hard GIM breaking)
- Common lore "any signal for CPV would be NP":
  - In the SM, CPV in mixing enters at $O(V_{cb}V_{ub}/V_{cs}V_{us}) \sim 10^{-3}$
  - In the SM, direct CPV enters at $O([V_{cb}V_{ub}/V_{cs}V_{us}]\ \alpha_s/\pi) \sim 10^{-4}$ (in singly Cabibbo suppressed decays)

Experimental observables

- **CPV in Mixing** $|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle$

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

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

- Experimentally accessible mixing quantities:
  - *x,y* (CP conserving)

Cannot be estimated accurately within SM

NP contributions are predictable

  - flavor specific time-dependent CPV decay asymmetries [sensitive to q/p]

$$a_f(t) \equiv \frac{\Gamma(D^0(t) \to f) - \Gamma(\bar{D}^0(t) \to f)}{\Gamma(D^0(t) \to f) + \Gamma(\bar{D}^0(t) \to f)}\,,$$

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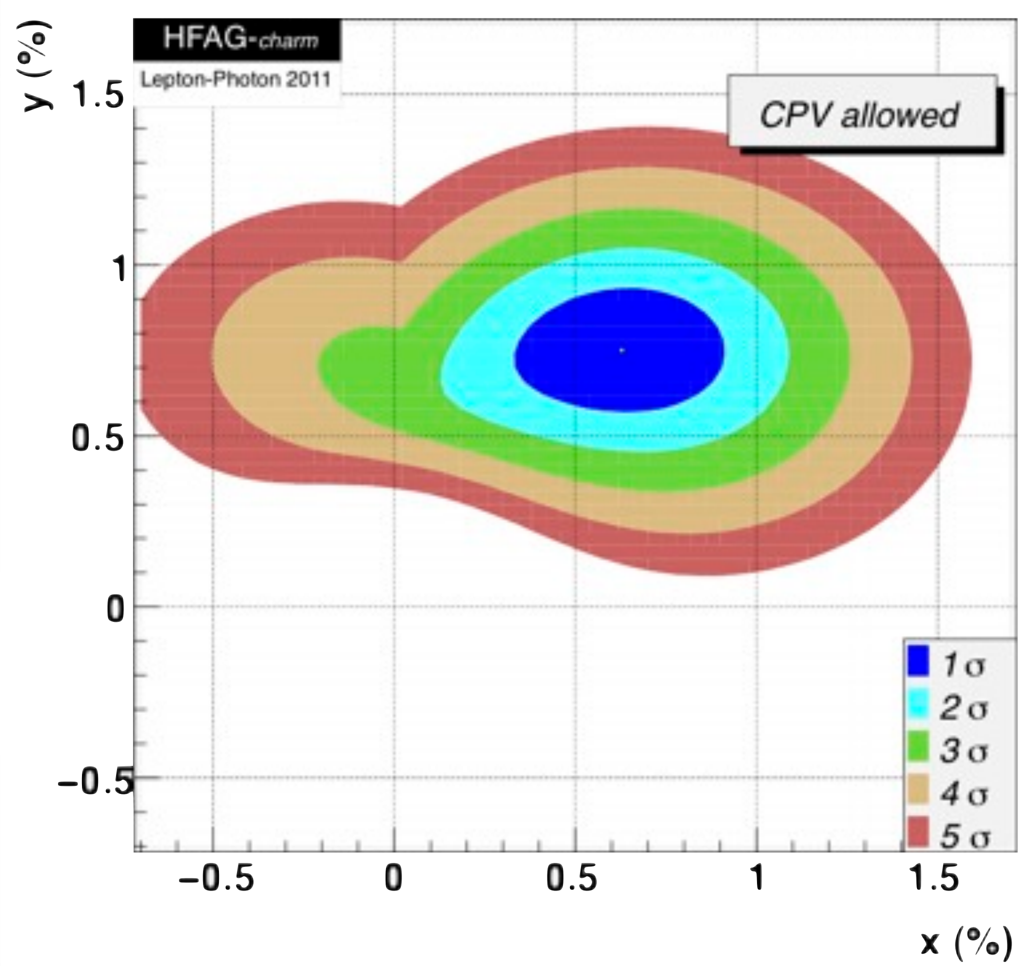

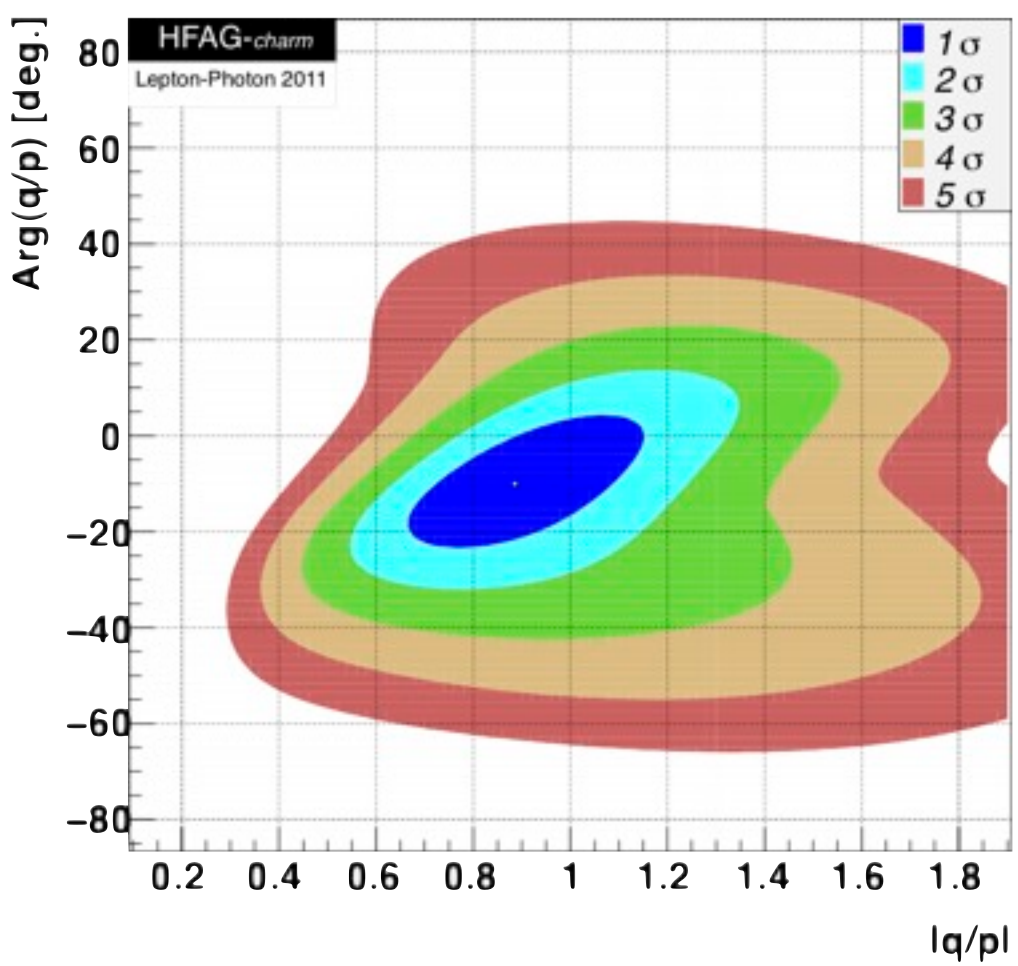

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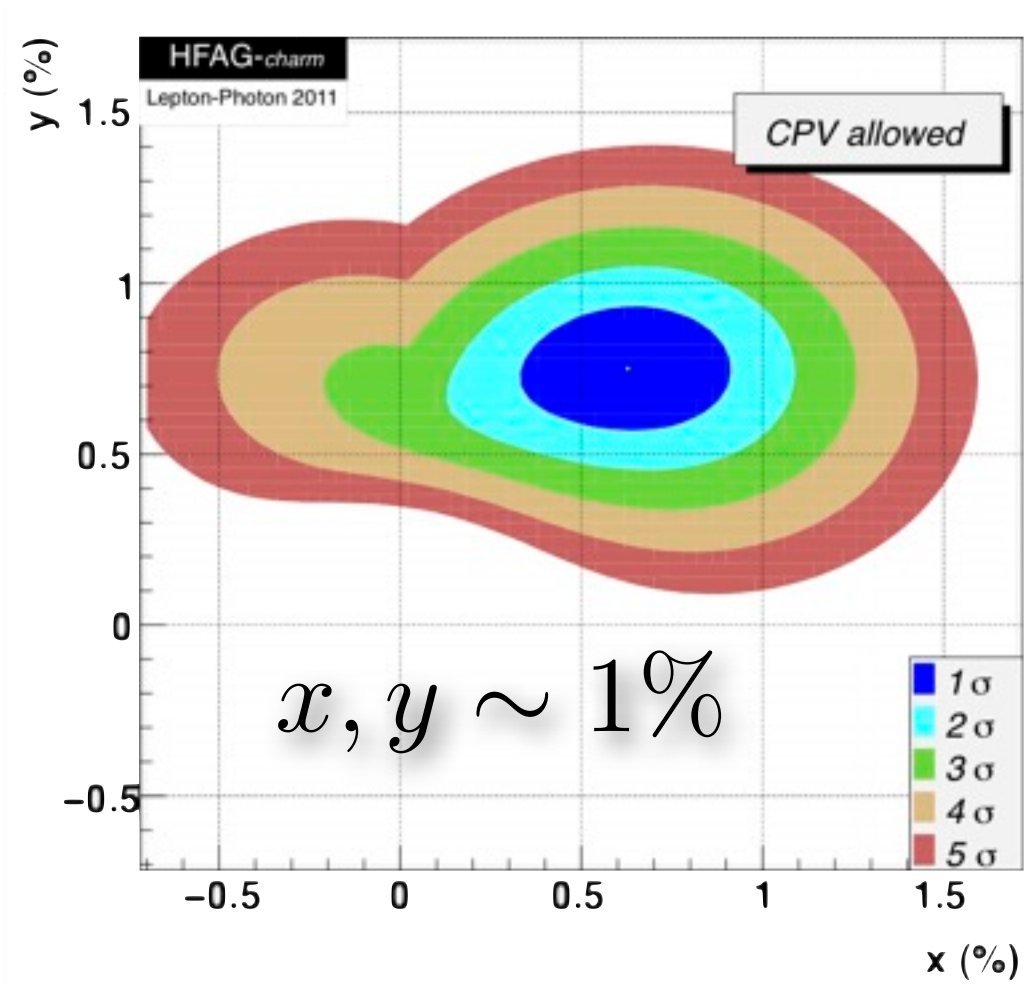

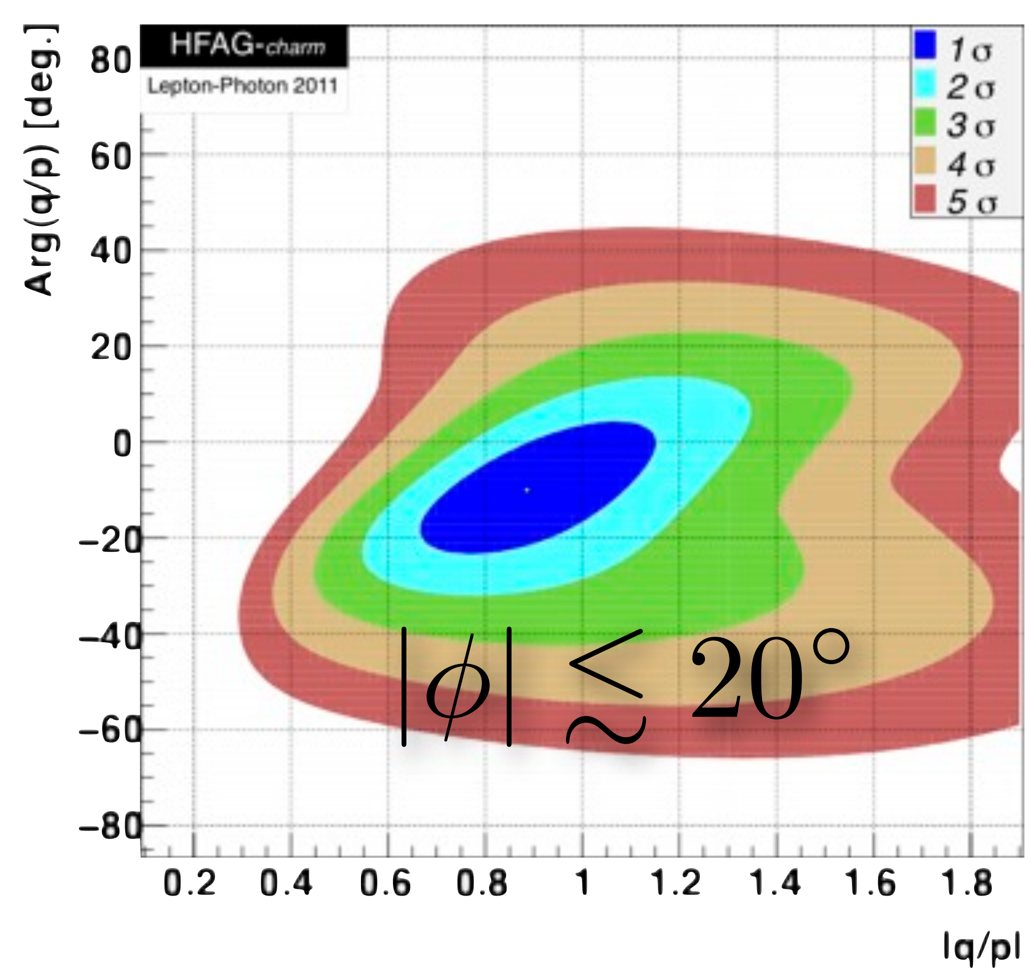

Experimental observables

- **CPV in Mixing**

Isidori, Nir & Perez 1002.0900

Operator	Bounds on Λ (TeV)		Bounds on c_{ij} ($\Lambda = 1$ TeV)		Observables
	Re	Im	Re	Im	
$(\bar{s}_L \gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	Δm_K; ε_K
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	Δm_K; ε_K
$(\bar{c}_L \gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	Δm_D; $\lvert q/p \rvert$, ϕ_D
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	Δm_D; $\lvert q/p \rvert$, ϕ_D
$(\bar{b}_L \gamma^\mu d_L)^2$	5.1×10^2	9.3×10^2	3.3×10^{-6}	1.0×10^{-6}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	1.9×10^3	3.6×10^3	5.6×10^{-7}	1.7×10^{-7}	Δm_{B_d}; $S_{B_d \to \psi K}$
$(\bar{b}_L \gamma^\mu s_L)^2$	1.1×10^2	1.1×10^2	7.6×10^{-5}	7.6×10^{-5}	Δm_{B_s}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	3.7×10^2	3.7×10^2	1.3×10^{-5}	1.3×10^{-5}	Δm_{B_s}

$$x, y \sim 1\%$$

$$|\phi| \lesssim 20^\circ$$

Imply significant constraints on CPV NP contributions, second only to kaon sector

Experimental observables

- **CPV in decays (direct CPV)**
  - Time-integrated CPV decay asymmetries to CP eigenstates

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}\,.$$

  - Focus on K^+K^- and $\pi^+\pi^-$ final states: $\Delta a_{CP} \equiv a_{K^+K^-} - a_{\pi^+\pi^-}$

$$\Delta a_{CP}^{\mathrm{World}} = -(0.67 \pm 0.16)\%$$ (~3.8σ from 0)

  - including new CDF and LHCb results (see previous talks by Maurice and Di Canto)

$\boxed{\text{presently most precise (direct) CPV observable in charm}}$

Reexamining theoretical predictions

- $D^0(\bar{D}^0)$ decay amplitudes to CP eigenstate f

$$A_f = A_f^T\, e^{i\phi_f^T}\left[1 + r_f\, e^{i(\delta_f+\phi_f)}\right],$$
$$\bar{A}_f = \eta_{CP}\, A_f^T\, e^{-i\phi_f^T}\left[1 + r_f\, e^{i(\delta_f-\phi_f)}\right],$$

$$\eta_{CP} = \pm 1$$

  - contribution to direct CPV asymmetries

$$a_f^{\mathrm{dir}} = -\frac{2r_f \sin\delta_f \sin\phi_f}{1 + 2r_f \cos\delta_f \cos\phi_f + r_f^2},$$

$$f = K, \pi$$

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- relevant Hamiltonian in the SM, $\lambda_q \equiv V_{cq}^* V_{uq}$

"tree" operator contributions (O(1) Wilson coefficients)

$$\mathcal{H}^{\mathrm{eff}}_{|\Delta c|=1} = \lambda_d \mathcal{H}^{d}_{|\Delta c|=1} + \lambda_s \mathcal{H}^{s}_{|\Delta c|=1} + \lambda_b \mathcal{H}^{\mathrm{peng}}_{|\Delta c|=1}$$

"penguin" operator contributions (tiny Wilson coefficients at $m_c < \mu < m_b$)

$$\mathcal{H}^{q}_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_{i=1,2} C_i^q Q_i^s + \mathrm{H.c.}\,,$$
$$Q_1^q = (\bar{u}q)_{V-A}\, (\bar{q}c)_{V-A}\,,$$
$$Q_2^q = (\bar{u}_\alpha q_\beta)_{V-A}\, (\bar{q}_\beta c_\alpha)_{V-A}\,,$$

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“tree” operator contributions

$$A_K = \lambda_d A_K^d + \lambda_s A_K^s + \lambda_b A_K^b$$
$$A_\pi = \lambda_d A_\pi^d + \lambda_s A_\pi^s + \lambda_b A_\pi^b$$

“penguin” operator contributions

Reexamining theoretical predictions

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- decay amplitudes in the SM, $\lambda_q \equiv V_{cq}^* V_{uq}\,, \quad \lambda_d + \lambda_s + \lambda_b = 0$

$$A_K = \lambda_s (A_K^s - A_K^d) + \lambda_b (A_K^b - A_K^d)$$
$$A_\pi = \lambda_d (A_\pi^d - A_\pi^s) + \lambda_b (A_\pi^b - A_\pi^s)$$

Reexamining theoretical predictions

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different weak phase (CKM) - ϕ_f

$$A_K = \lambda_s (A_K^s - A_K^d) + \lambda_b (A_K^b - A_K^d)$$
$$A_\pi = \lambda_d (A_\pi^d - A_\pi^s) + \lambda_b (A_\pi^b - A_\pi^s)$$

different strong phase (isospin) - δ_f

$$r_f \propto \xi = |\lambda_b/\lambda_s| \simeq |\lambda_b/\lambda_d| \approx 0.0007$$

$$\begin{aligned}\phi_K^{\mathrm{SM}} &= \arg(\lambda_b/\lambda_s)\\ &\approx -\arg(\lambda_b/\lambda_d) = -\phi_\pi^{\mathrm{SM}}\\ &\approx 70^\circ\end{aligned}$$

Reexamining theoretical predictions

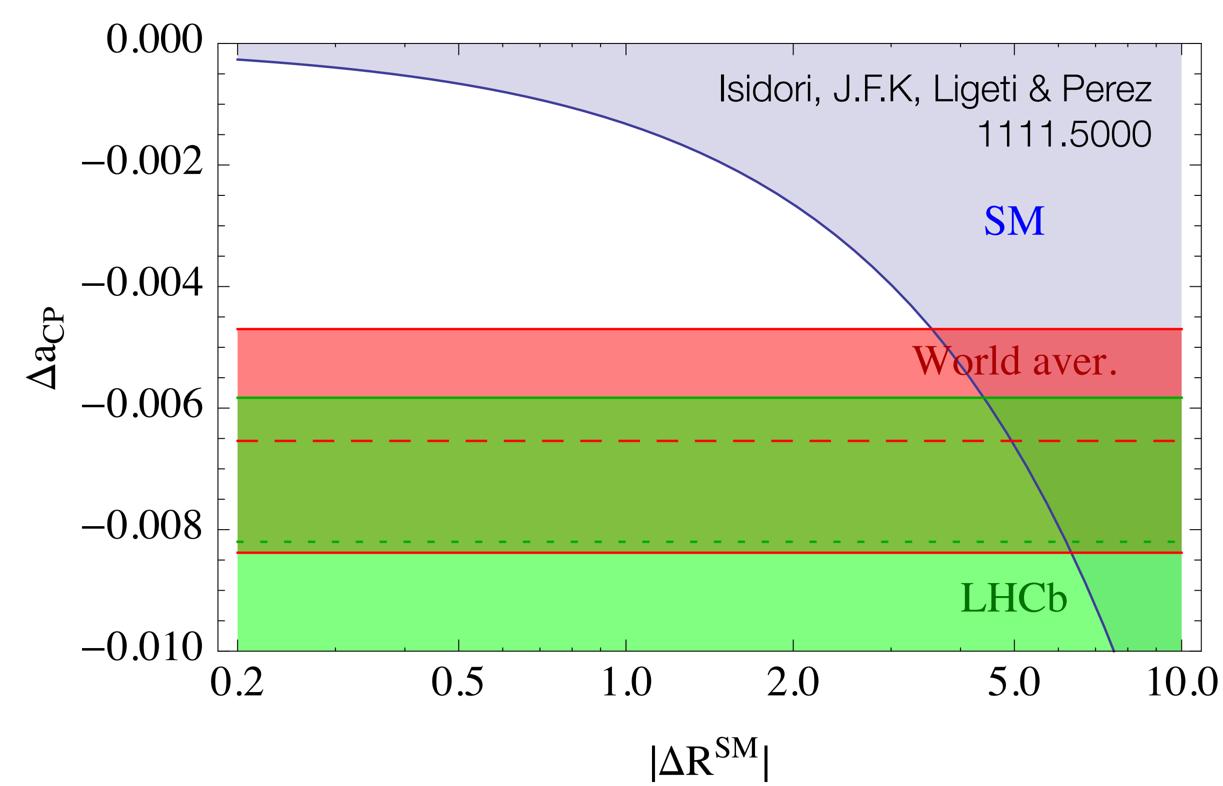
- SM expectations
  - define ratios of weak amplitudes $R_K^{\rm SM} \equiv \frac{A_K^b - A_K^d}{A_K^s - A_K^d}\,, \quad R_\pi^{\rm SM} \equiv \frac{A_\pi^b - A_\pi^s}{A_\pi^d - A_\pi^s}\,.$

$$a_K^{\rm dir,SM} \approx 2\xi\,{\rm Im}(R_K^{\rm SM})\,, \quad a_\pi^{\rm dir,SM} \approx -2\xi\,{\rm Im}(R_\pi^{\rm SM})$$

$$\Delta a_{CP} \approx (0.13\%){\rm Im}(\Delta R^{\rm SM})\,,$$

$$\Delta R^{\rm SM} \equiv R_K^{\rm SM} + R_\pi^{\rm SM}$$

(in *SU(3)* limit $R_K^{\rm SM} = R_\pi^{\rm SM}$)



O(2-5) values of $|R_{K,\pi}|$ needed

Reexamining theoretical predictions

- SM expectations
  - define ratios of weak amplitudes $R_K^{\rm SM} \equiv \frac{A_K^b - A_K^d}{A_K^s - A_K^d}\,, \quad R_\pi^{\rm SM} \equiv \frac{A_\pi^b - A_\pi^s}{A_\pi^d - A_\pi^s}\,.$
  - In the $m_c \gg \Lambda_{QCD}$ limit, computable perturbatively
    - $|A_K^d/A_K^s| \sim \alpha_s(m_c)/\pi \sim 0.1 \qquad |A^b| \lesssim |A^d|$
    - would expect $|R_{K,\pi}| \ll 1$

Grossman, Kagan & Nir
hep-ph/0609178

see also
Cheng & Chiang
1201.0785

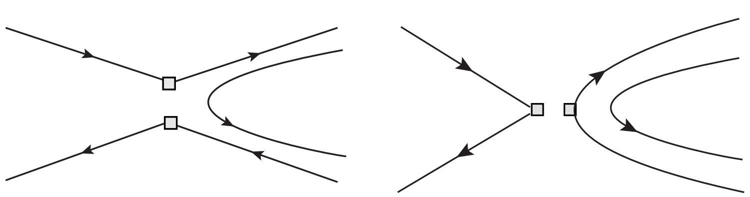
- **However:** ξ suppressed amplitudes unconstrained by rate measurements - "ΔI=1/2 rule" type enhancement possible

Golden & Grinstein Phys. Lett. B 222 (1989)

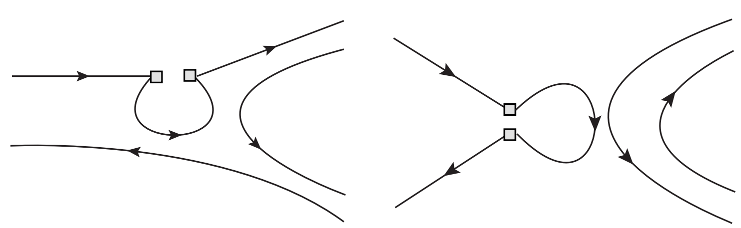
Reexamining theoretical predictions

- SM expectations
  - define ratios of weak amplitudes $R_K^{\mathrm{SM}} \equiv \frac{A_K^b - A_K^d}{A_K^s - A_K^d}\,, \quad R_\pi^{\mathrm{SM}} \equiv \frac{A_\pi^b - A_\pi^s}{A_\pi^d - A_\pi^s}\,.$
  - In the $m_c \gg \Lambda_{QCD}$ limit, computable perturbatively
    - Estimate of (large) $1/m_c$ non-perturbative corrections

Brod, Kagan & Zupan
1111.5000



"Tree topologies" - no A_K^d, A_π^s contributions



"Penguin contractions" - generate A_K^d, A_π^s

Obtain $\Delta a_{CP}^{\mathrm{SM}} \lesssim 0.4\%$ with O(1) error

Implications for New Physics

- Assume SM does not saturate the experimental value

- Parametrize NP contributions in EFT normalized to the effective SM scale

$$\mathcal{H}^{\mathrm{eff-NP}}_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_i C_i^{\mathrm{NP}} Q_i$$

$$\begin{aligned}
Q_1^q &= (\bar{u}q)_{V-A}\,(\bar{q}c)_{V-A} \\
Q_2^q &= (\bar{u}_\alpha q_\beta)_{V-A}\,(\bar{q}_\beta c_\alpha)_{V-A}\,, \\
Q_5^q &= (\bar{u}c)_{V-A}\,(\bar{q}q)_{V+A}\,, \\
Q_6^q &= (\bar{u}_\alpha c_\beta)_{V-A}\,(\bar{q}_\beta q_\alpha)_{V+A}\,, \\
Q_7 &= -\frac{e}{8\pi^2}\, m_c\, \bar{u}\sigma_{\mu\nu}(1+\gamma_5)F^{\mu\nu}\, c\,, \\
Q_8 &= -\frac{g_s}{8\pi^2}\, m_c\, \bar{u}\sigma_{\mu\nu}(1+\gamma_5)T^a G_a^{\mu\nu} c\,,
\end{aligned}$$

+ Ops. with V↔A

x 5 $q\bar{q}$ flavor structures

  - most general dim 6 Hamiltonian at $\mu < m_{W,t}$

Implications for New Physics

- Assume SM does not saturate the experimental value

- Parametrize NP contributions in EFT normalized to the effective SM scale

$$\Delta a_{CP} \approx (0.13\%)\mathrm{Im}(\Delta R^{\mathrm{SM}}) + 9\sum_i \mathrm{Im}(C_i^{\mathrm{NP}})\,\mathrm{Im}(\Delta R_i^{\mathrm{NP}}) \qquad R_{K,i}^{\mathrm{NP}} \equiv \frac{G_F \langle Q_i \rangle}{\sqrt{2}(A_K^s - A_K^d)}$$

- for $\mathrm{Im}(C_i^{\mathrm{NP}}) = \dfrac{v^2}{\Lambda^2}$: $\dfrac{(10\ \mathrm{TeV})^2}{\Lambda^2} = \dfrac{(0.61 \pm 0.17) - 0.12\,\mathrm{Im}(\Delta R^{\mathrm{SM}})}{\mathrm{Im}(\Delta R^{\mathrm{NP}})}$

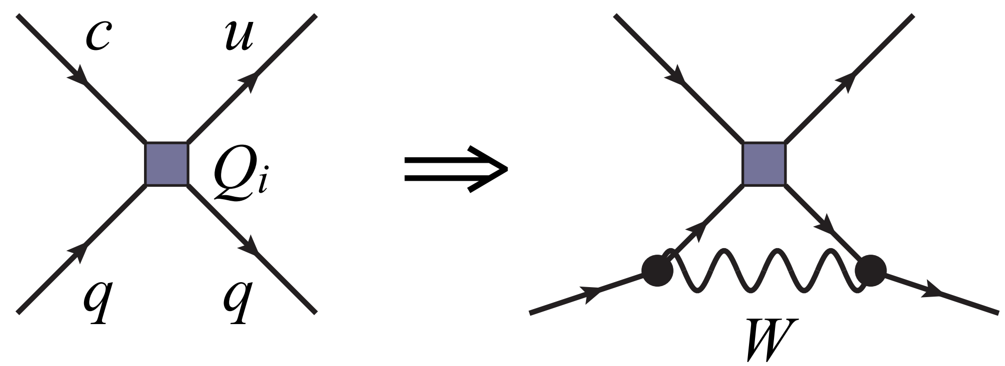
Are such contributions allowed by other flavor constraints?

Implications for New Physics

Isidori, J.F.K, Ligeti & Perez
1111.5000

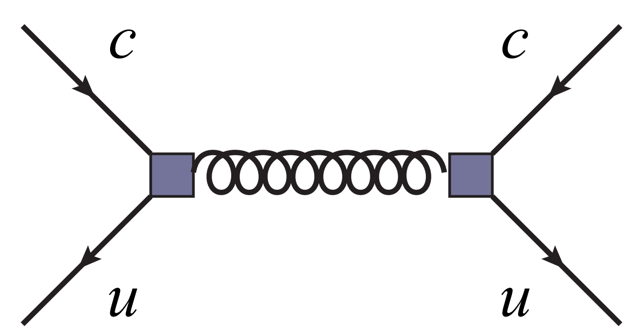
- In EFT can be estimated via “weak mixing” of operators

$$T\left\{\mathcal{H}^{\mathrm{eff-NP}}_{|\Delta c|=1}(0),\mathcal{H}^{\mathrm{SM}}(x)\right\}$$

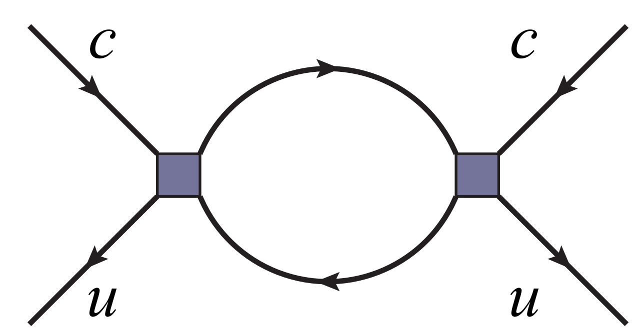


  - Important constraints expected from **D-$\bar{\mathrm{D}}$ mixing** and direct CPV in $K^0\to\pi^+\pi^-$ **(ε’/ε)**

- Quadratic NP contributions
  - either chirally suppressed...
  - ...or highly UV sensitive



$\propto \alpha\, m_c^2/v^2$



$\propto \Lambda^2$

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On Universality of CPV in |ΔF|=1 processes

- SM quark flavor symmetry $\mathcal{G}_F = \boxed{SU(3)_Q} \times SU(3)_U \times SU(3)_D$
  - two sources of breaking: $\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{\not{\text{tr}}}\,, \qquad \mathcal{A}_d \equiv (Y_d Y_d^\dagger)_{\not{\text{tr}}}$

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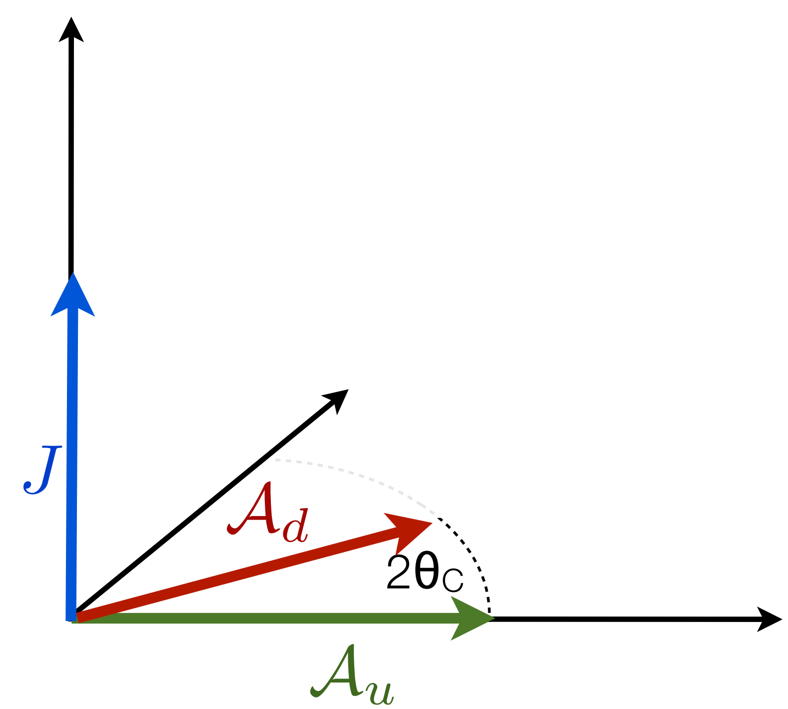
  - in the 2-gen limit single source of CPV: $J \equiv i[\mathcal{A}_u,\, \mathcal{A}_d]$ Gedalia, Mannelli & Perez 1002.0778, 1003.3869
    - invariant under SO(2) rotations between up-down mass bases



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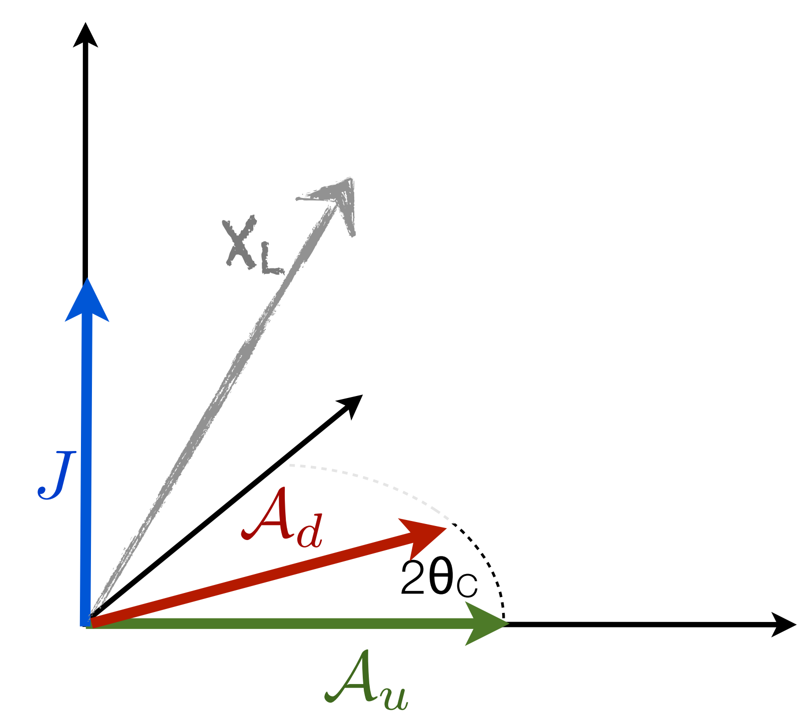
    - invariant under SO(2) rotations between up-down mass bases
- $SU(2)_Q$ breaking NP $\mathcal{O}_L = \left[(X_L)^{ij}\,\overline{Q}_i\gamma^\mu Q_j\right] L_\mu$

$$\mathrm{Im}(X_L^u)_{12} = \mathrm{Im}(X_L^d)_{12} \propto \mathrm{Tr}\,(X_L \cdot J)\ .$$



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  - SM 3-gen case characterized by SU(3)/SU(2) breaking pattern by $Y_{b,t}$

Kagan et al., 0903.1794

- 3-gen X_L can be decomposed under SU(2), constrained separately

(barring cancelations)

- SM breaking of residual $SU(2)_Q$ suppressed by m_c/m_t, m_s/m_b, θ_{13}, θ_{23}

(charm and kaon sectors dominated by 2-gen physics)

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  - two sources of breaking: $\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{\cancel{\text{tr}}}\,, \qquad \mathcal{A}_d \equiv (Y_d Y_d^\dagger)_{\cancel{\text{tr}}}$
  - **Implication:** direct correspondence between Δa_{CP} and ε'/ε

    (no weak loop suppression)
    - constraint on $SU(3)_Q$ breaking NP: $\Delta a_{CP}^{\mathrm{NP}} \lesssim 4 \times 10^{-4}$ Gedalia, J.F.K, Ligeti & Perez 1202.5038
  - Similarly for rare semileptonic decays:

$$\mathrm{Br}(K_L \to \pi^0 e^+ e^-) < 2.8 \times 10^{-10}$$ (mostly CPV process)

$$\Downarrow$$

$$a_e^D \equiv \frac{\mathrm{Br}(D^+ \to \pi^+ e^+ e^-) - \mathrm{Br}(D^- \to \pi^- e^+ e^-)}{\mathrm{Br}(D^+ \to \pi^+ e^+ e^-) + \mathrm{Br}(D^- \to \pi^- e^+ e^-)} \lesssim 0.02$$ for $SU(3)_Q$ breaking NP

}

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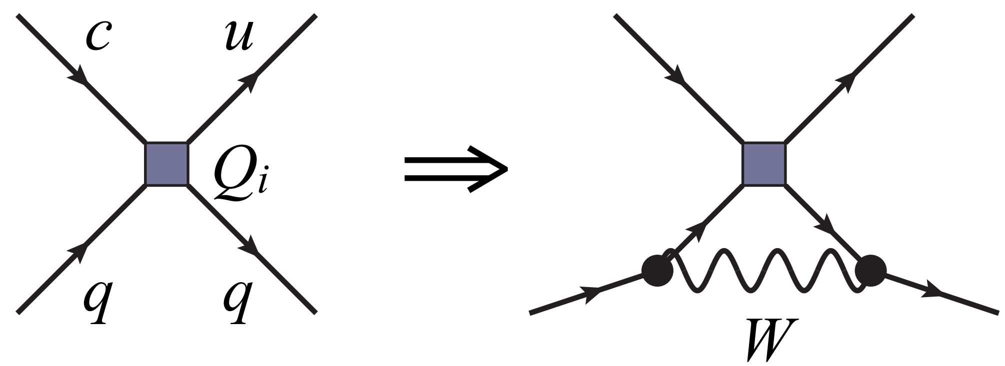


- Important constraints expected from **D-$\overline{\text{D}}$ mixing** and direct CPV in $K^0\to\pi^+\pi^-$ **(ε'/ε)**
  - **LL 4q operators:** excluded
  - **LR 4q operators:** ajar - potentially visible effects in D-$\overline{\text{D}}$ and/or ε'/ε
  - **RR 4q operators:** unconstrained in EFT - UV sensitive contributions?

Dipole operators only weakly constrained (edm's)

see also
Altmannshofer et al.
1202.2866

Implications for (enter favorite NP model name)

Before LHCb result,

DCPV in charm not on top of NP theorists expectations

Implications for (enter favorite NP model name)

Before LHCb result,

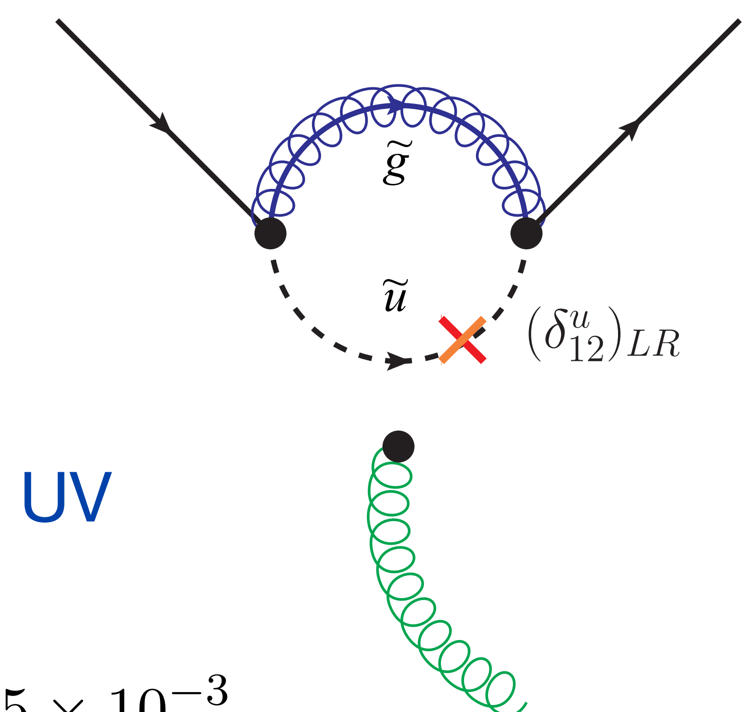
DCPV in charm not on top of NP theorists expectations

In last 2.5 months, situation has improved considerably

Implications for SUSY Models

- Left-right up-type squark mixing contributions

Grossman, Kagan & Nir, hep-ph/0609178
Giudice, Isidori & Paradisi, 1201.6204



$$\left|\Delta a_{CP}^{\rm SUSY}\right| \approx 0.6\% \left(\frac{\left|{\rm Im}\,(\delta^u_{12})_{LR}\right|}{10^{-3}}\right)\left(\frac{\rm TeV}{\tilde{m}}\right)$$

- contributions to ΔF=2 helicity suppressed

- requires large trilinear (A) terms, non-trivial flavor in UV

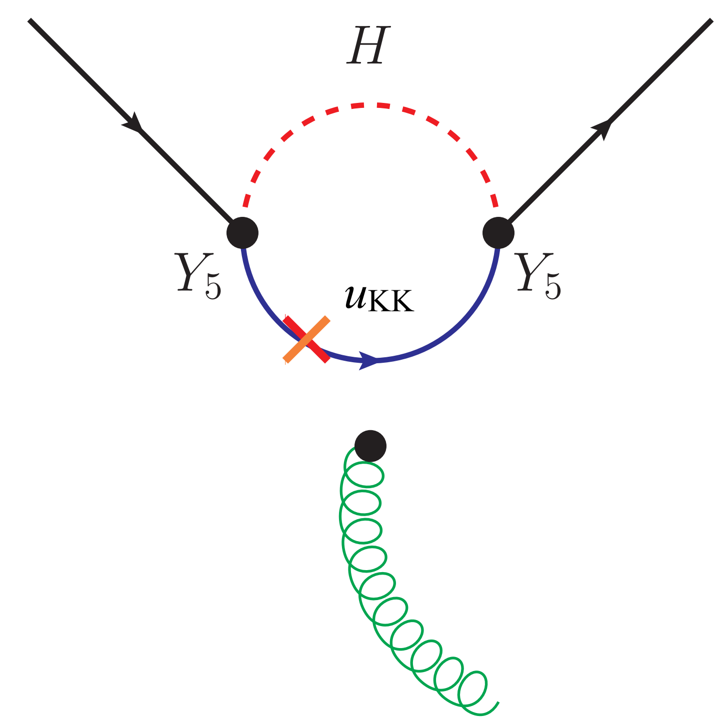
$${\rm Im}\,(\delta^u_{12})_{LR} \approx \frac{{\rm Im}(A)\ \theta_{12}\ m_c}{\tilde{m}} \approx \left(\frac{{\rm Im}(A)}{3}\right)\left(\frac{\theta_{12}}{0.3}\right)\left(\frac{\rm TeV}{\tilde{m}}\right) 0.5\times 10^{-3}$$

Implications for Warped Extra-Dim. Models

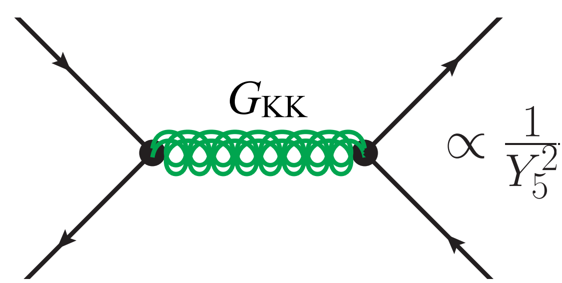
- Anarchic flavor with bulk Higgs

Delaunay, J.F.K., Perez & Randall
1203.XXXX

$$\left|\Delta a_{CP}^{\mathrm{chromo}}\right|_{\mathrm{RS}} \simeq 0.6\% \times \left(\frac{Y_5}{6}\right)^2 \left(\frac{3\,\mathrm{TeV}}{m_{\mathrm{KK}}}\right)^2$$



  - requires very large 5D Yukawas
    - helps to avoid D-$\overline{\mathrm{D}}$ mixing constraints
      Gedalia et al., 0906.1879



    - implies low UV cut-off $\frac{1}{2} \lesssim Y_5 \lesssim \frac{4\pi}{\sqrt{N_{KK}}}$

Agashe, Azatov & Zhu, 0810.1016
Csaki et al., 0907.0474

- Can be mapped to 4D partial compositness models

Implications for 4th Generation

- 3-gen CKM non-unitarity and b' penguins

Feldmann, Nandi & Soni 1202.3795

$$\Delta a_{CP} \propto \; 4\,\mathrm{Im}\left[\frac{\lambda_{b'}}{\lambda_d - \lambda_s}\right] \simeq \frac{2\,\sin\theta_{14}\sin\theta_{24}\sin(\delta_{14}-\delta_{24})}{\sin\theta_{12}}$$

  - No parametric enhancement allowed due to existing ΔF=2 CPV bounds

Nandi & Soni, 1011.6091
Buras et al., 1002.2126

    - Effects comparable to SM still allowed

- Similar conclusions for generic mixing with vector-like quarks

Grossman, Kagan & Nir hep-ph/0609178

Implications for Experiment

- NP explanations of Δa_{CP} via chromo-magnetic dipole operators
  - generically predict EM dipoles - rare radiative charm decays

$$D^0 \to X\gamma \qquad\qquad D^0 \to X e^+ e^-$$

Delaunay, J.F.K., Perez & Randall
1203.XXXX

unfortunately typically orders below SM LD contributions

  - correlations with EDM's, rare top & down-type quark processes

very model dependent

Giudice, Isidori & Paradisi, 1201.6204
Hochberg & Nir, 1112.5268
Altmannshofer et al., 1202.2866

Implications for Experiment

- Possibility to disentangle SD (NP) vs. LD (SM) contributions to Δa_{CP} ?
  - Individual asymmetries in U-spin limit: $a_{CP}^K \simeq -a_{CP}^\pi$
  - Chromo-magnetic dipole operators preserve U-spin
  - **However:** D→KK, ππ, Kπ rates imply sizable U-spin breaking - signature of LD strong interaction effects

    Feldmann, Nandi & Soni 1202.3795
    Pirtskhalava & Uttayarat 1112.5451
    - $a_{CP}^K \simeq -a_{CP}^\pi$ not necessarily expected, neither in SM nor if due to NP
- rates and DCPV in related modes, with same SD transitions

  Bhattacharya, Gronau & Rosner 1201.2351

$$D^+ \to \phi\pi^+, D_s \to \phi K^+, D^+ \to \bar{K}^{*0}\pi^+, D^0 \to K^{*\pm}K^\mp, D^0 \to \rho^\pm\pi^\mp$$

First interesting hints? Belle, PRL 108, 071801 (2012) $D^0 \to \pi^0\pi^0, D_s \to \pi^+ K^0, D_s \to \pi^0 K^+, \ldots$