XL International Meeting on Fundamental Physics

CPV in the Charm System

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26/05/2012, Benasque

Outline

- Significance of CPV in Charm within and beyond SM
- Quantify (parametrize) theory expectations of direct CPV in charm decays
  - Δa_{CP} implications for weak scale NP
    - EFT & models

      (new insights into NP CPV in $\Delta F=1$)
  - Consequences of NP Δa_{CP} explanations
    - Discriminate among NP, NP vs. SM

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 $\mathcal{O}(V_{cb}V_{ub}/V_{cs}V_{us}) \sim 10^{-3}$
  - In the SM, direct CPV enters at $\mathcal{O}([V_{cb}V_{ub}/V_{cs}V_{us}]\ \alpha_s/\pi) \sim 10^{-4}$ (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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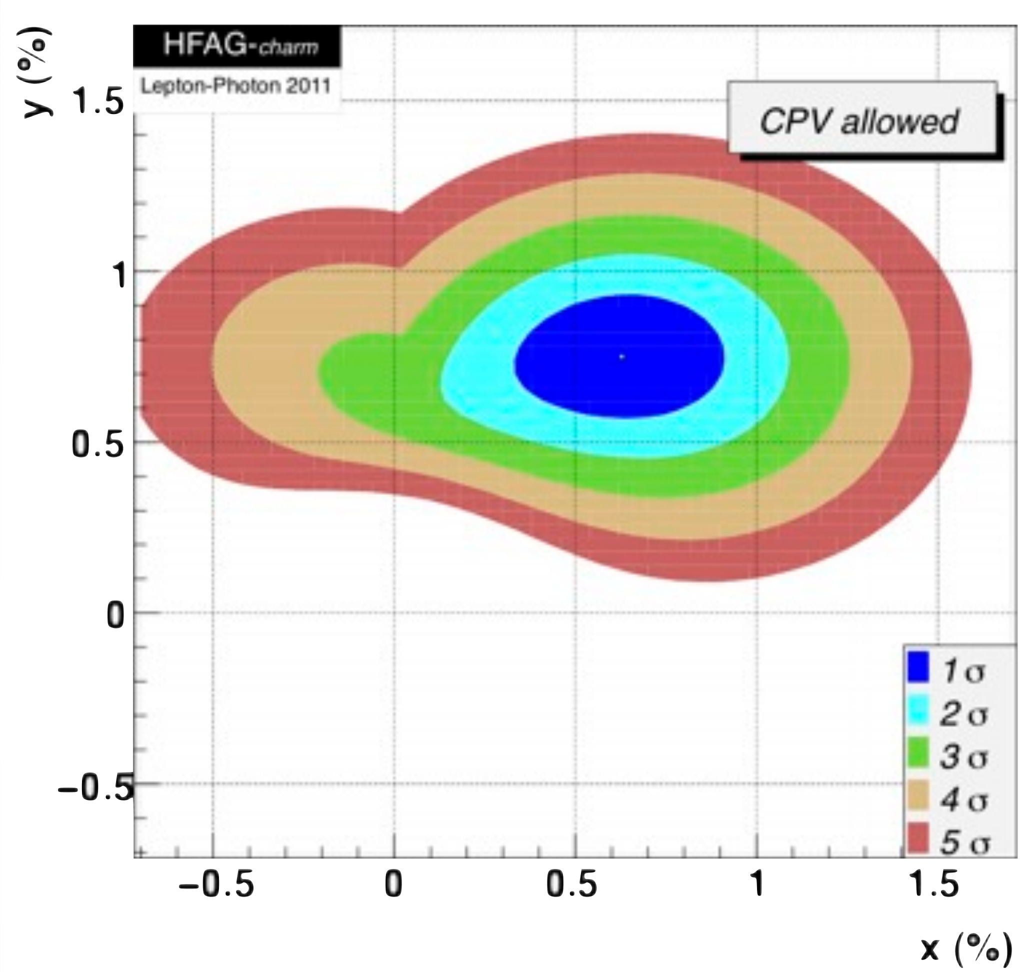

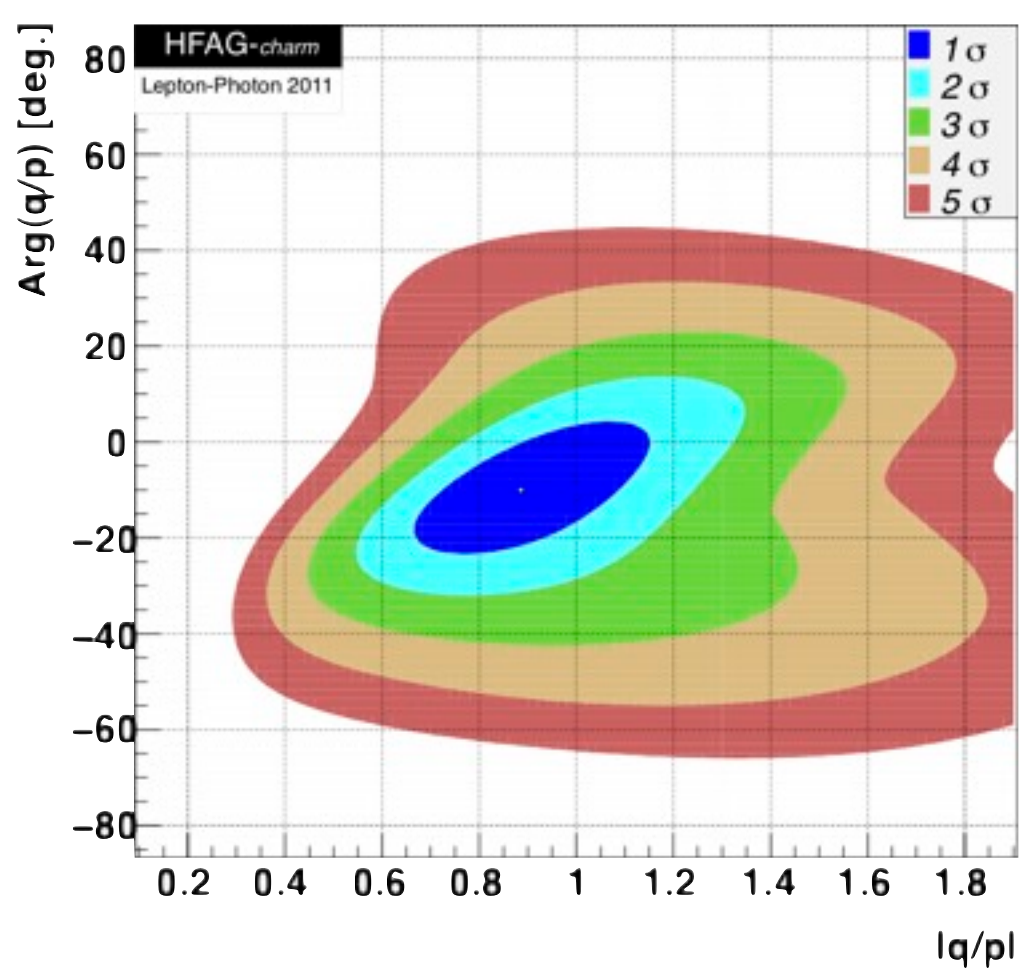

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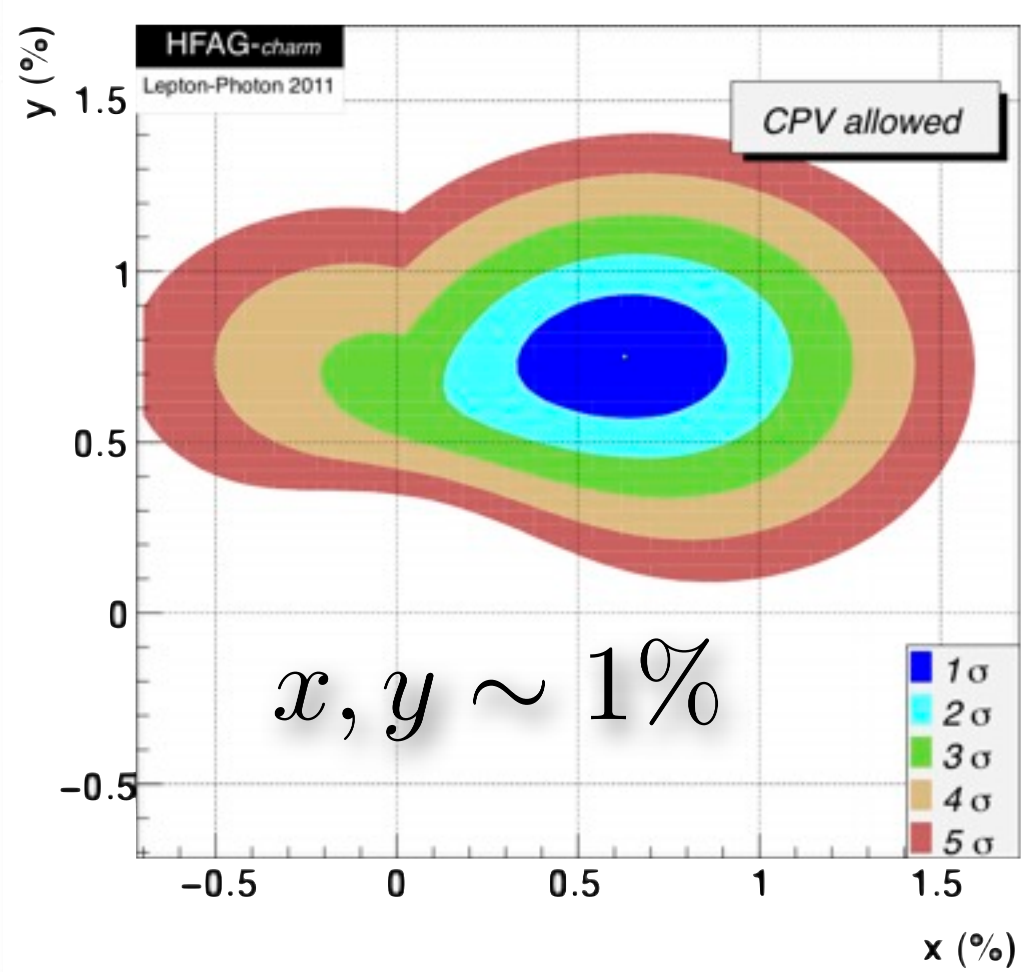

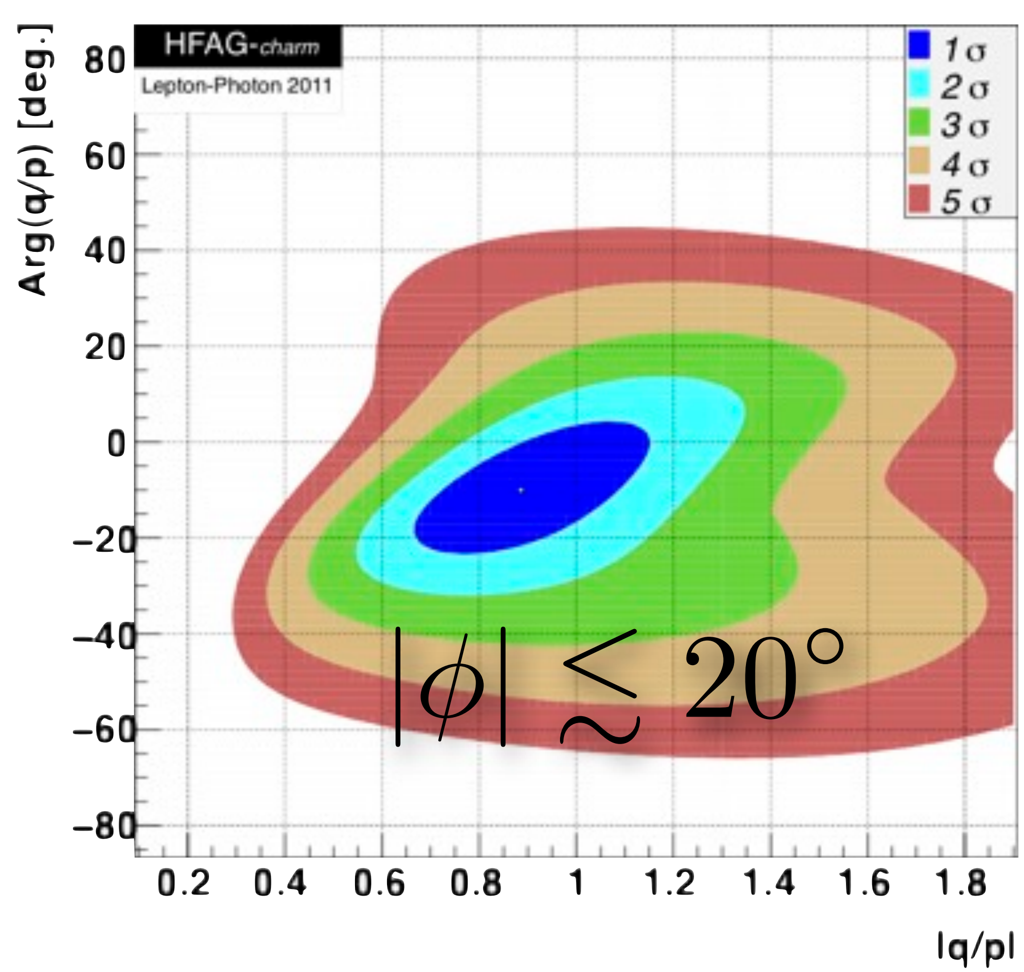

Experimental observables

- **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}

$x, y \sim 1\%$ $\qquad$ $|\phi| \lesssim 20^\circ$

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

$$a_f \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)}\,. \qquad a_f = a_f^{\mathrm{dir.}} + \frac{\langle \tau \rangle}{\tau_D} a_{CP}^{\mathrm{indir.}}$$

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

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  - Time-integra … ates

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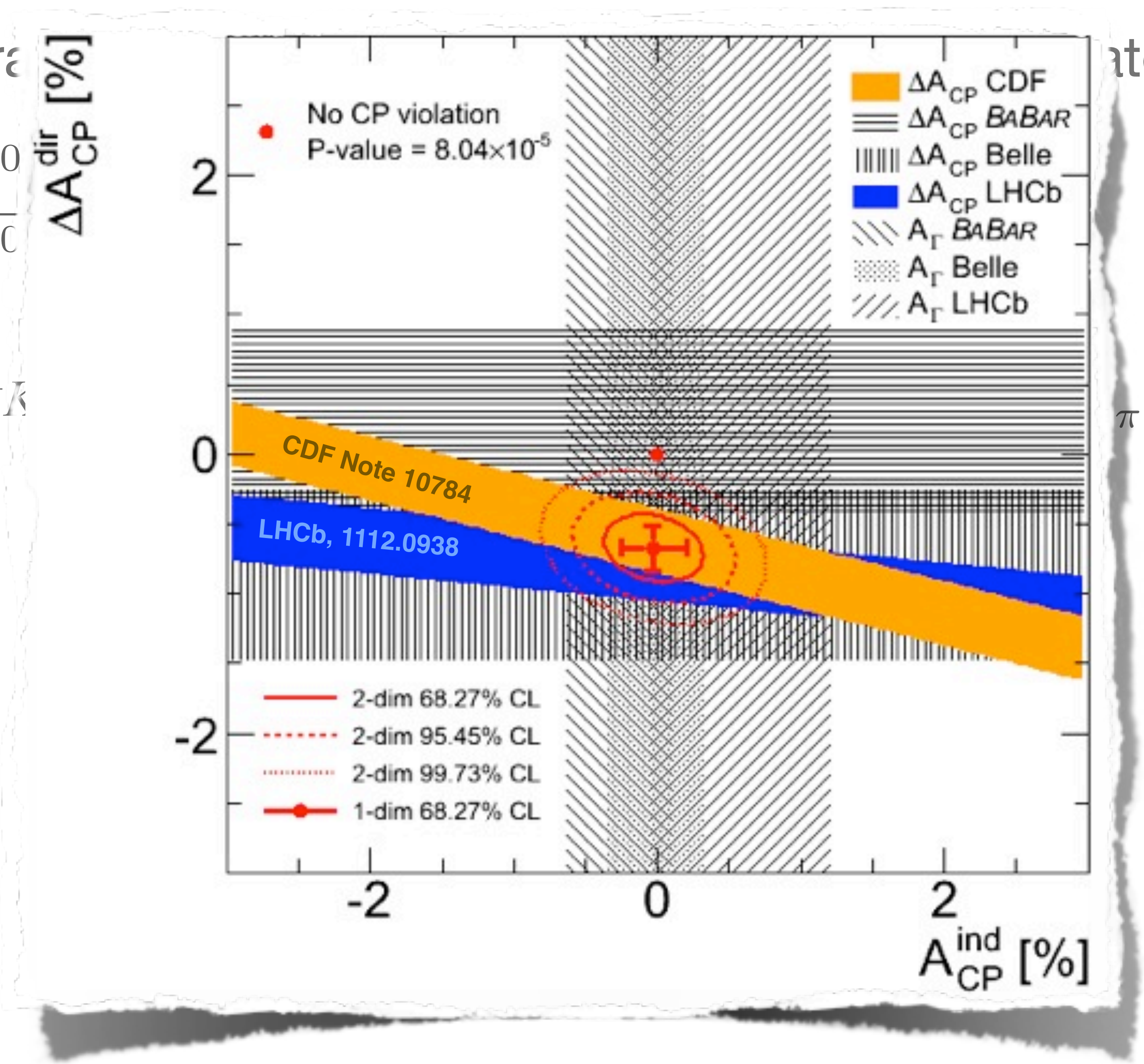
  - Focus on K^+K … π^-



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$$\Delta a_{CP}^{\mathrm{World}} = -(0.67 \pm 0.16)\%$$ (~4σ from 0)

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

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

$$f = K, \pi$$

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

"tree" operator contributions ($\mathcal{O}(1)$ Wilson coefficients)

$$\mathcal{H}^{\rm eff}_{|\Delta c|=1} = \lambda_d \mathcal{H}^d_{|\Delta c|=1} + \lambda_s \mathcal{H}^s_{|\Delta c|=1} + \lambda_b \mathcal{H}^{\rm peng}_{|\Delta c|=1}$$

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

$$\mathcal{H}^q_{|\Delta c|=1} = \frac{G_F}{\sqrt{2}} \sum_{i=1,2} C_i^q Q_i^s + \text{H.c.}\,,$$
$$Q_1^q = (\bar{u}q)_{V-A}\,(\bar{q}c)_{V-A}\,,$$
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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, $\lambda_q \equiv V_{cq}^* V_{uq}\,, \quad \lambda_d + \lambda_s + \lambda_b = 0$

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

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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

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

$$\phi_K^{\rm SM} = \arg(\lambda_b/\lambda_s)$$
$$\approx -\arg(\lambda_b/\lambda_d) = -\phi_\pi^{\rm SM}$$
$$\approx 70^\circ$$

Reexamining theoretical predictions

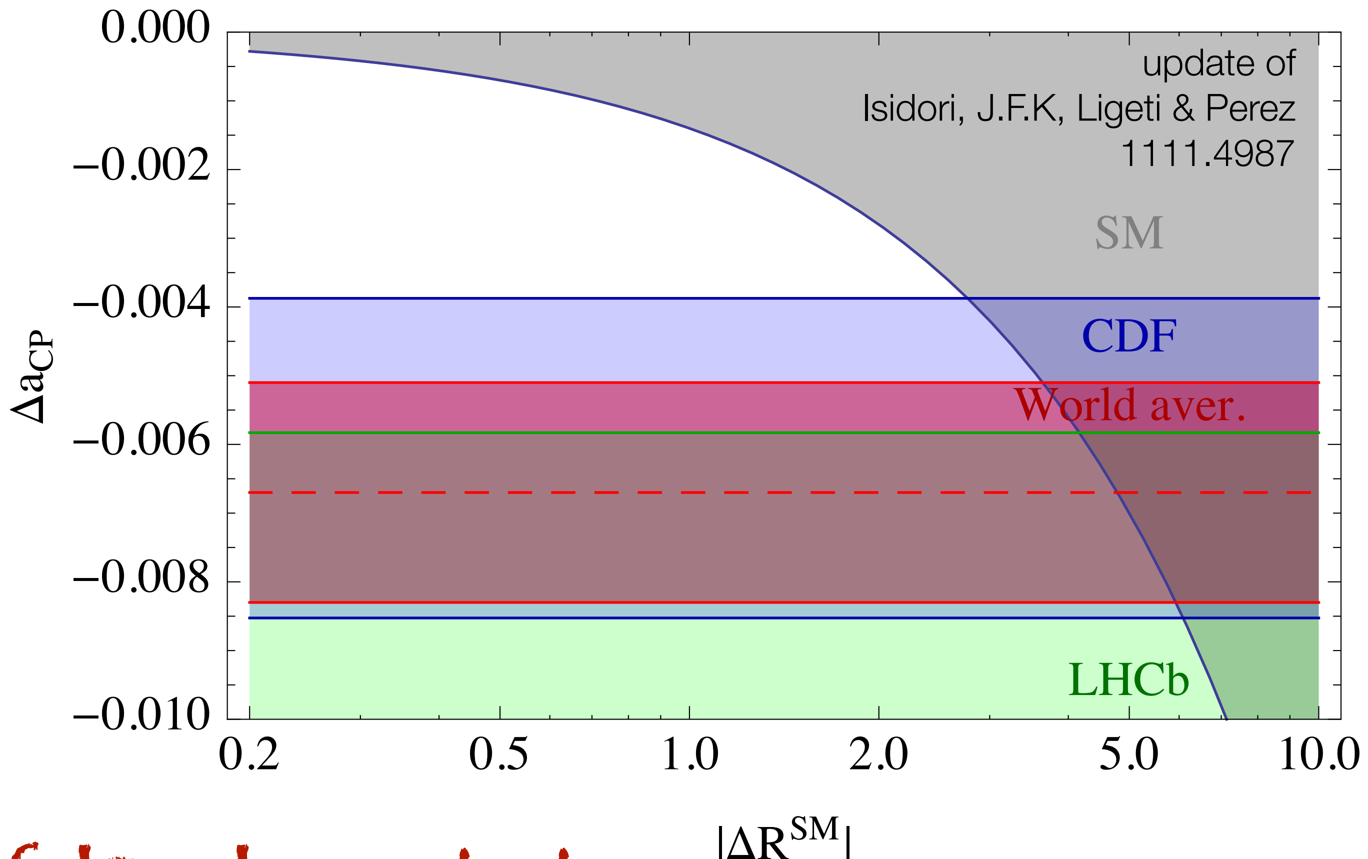
- SM expectations
  - define ratios of weak amplitudes $R_K^{\rm SM} \equiv \dfrac{A_K^b - A_K^d}{A_K^s - A_K^d}\,, \quad R_\pi^{\rm SM} \equiv \dfrac{A_\pi^b - A_\pi^s}{A_\pi^d - A_\pi^s}\,.$

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

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

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

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



O(2-3) values of $|R_{K,\pi}|$ needed

Reexamining theoretical predictions

- SM expectations
  - define ratios of weak amplitudes $R_K^{\rm SM} \equiv \dfrac{A_K^b - A_K^d}{A_K^s - A_K^d}\,, \quad R_\pi^{\rm SM} \equiv \dfrac{A_\pi^b - A_\pi^s}{A_\pi^d - A_\pi^s}\,.$
  - In the $m_c >> \Lambda_{\rm QCD}$ 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 - "$\Delta I = 1/2$ rule" type enhancement possible

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

Reexamining theoretical predictions

- SM expectations
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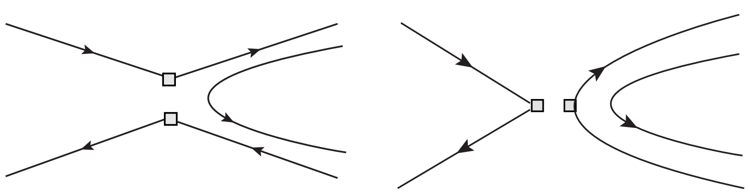
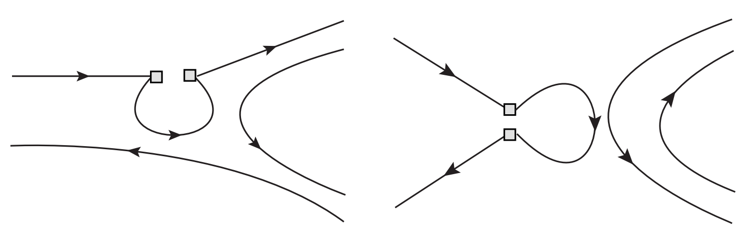
  - In the $m_c >> \Lambda_{\rm QCD}$ limit, computable perturbatively
    - Estimate of (large) $1/m_c$ non-perturbative corrections

Brod, Kagan & Zupan
1111.5000



"Tree topologies" - no $A_K^d,\, A_\pi^s$ contributions



"Penguin contractions" - generate $A_K^d,\, A_\pi^s$

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

see also
Brod, Grossman, Kagan & Zupan
1203.6659
Feldmann, Nandi & Soni
1202.3795

Δa_{CP} and 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 $\mu < m_{W,t}$

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

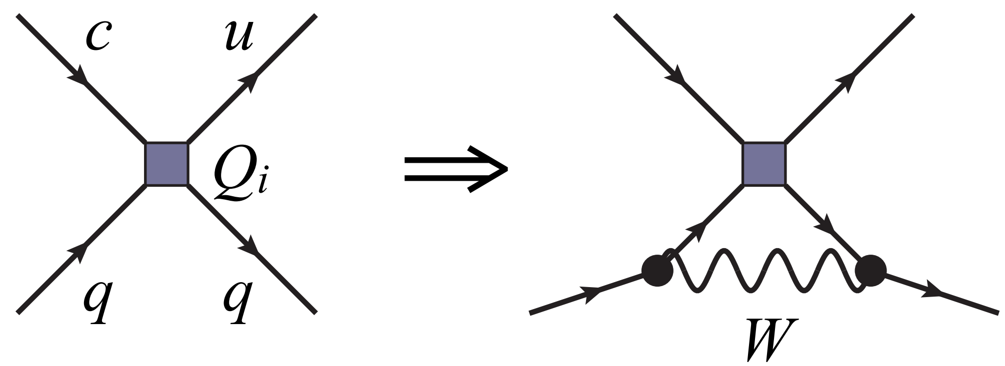
Are such contributions allowed by other flavor constraints?

Δa_{CP} and New Physics

Isidori, J.F.K, Ligeti & Perez
1111.4987

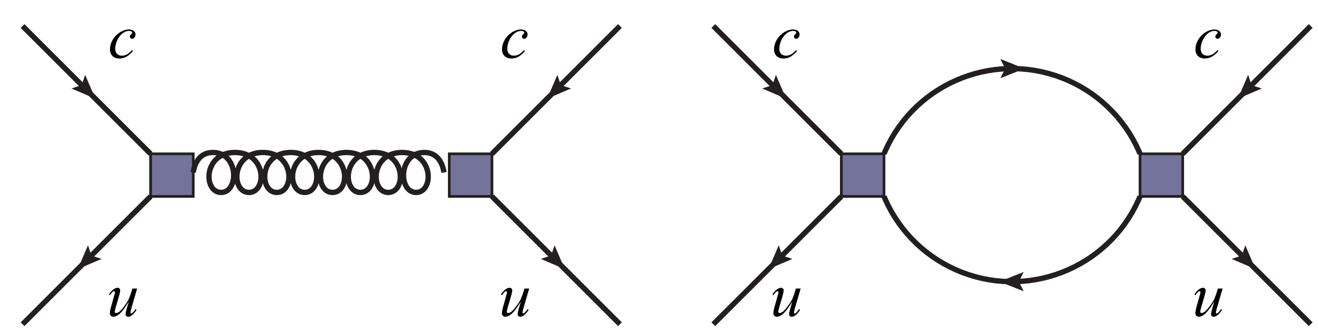
- In EFT can be estimated via “weak mixing” of operators

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



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

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



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

{

On Universality of CPV in |ΔF|=1 processes

- SM quark flavor symmetry $\mathcal{G}_F = SU(3)_Q \times SU(3)_U \times SU(3)_D$
  - 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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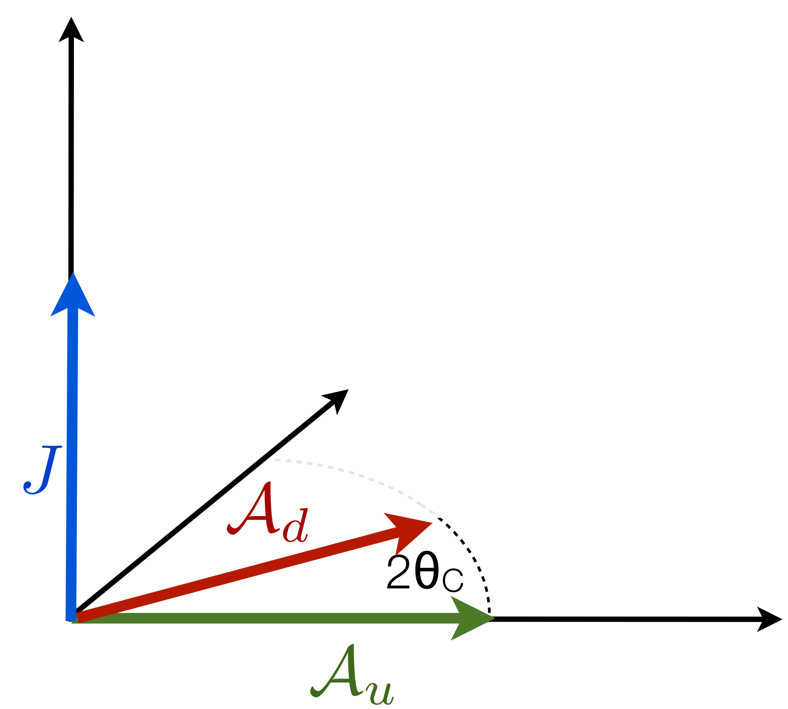
  - in the 2-gen limit single source of CPV: $J \equiv i[\mathcal{A}_u, \mathcal{A}_d]$ Gedalia, Mannelli & Perez 1002.0778, 1003.3869
    - invariant under SO(2) rotations between up-down mass bases



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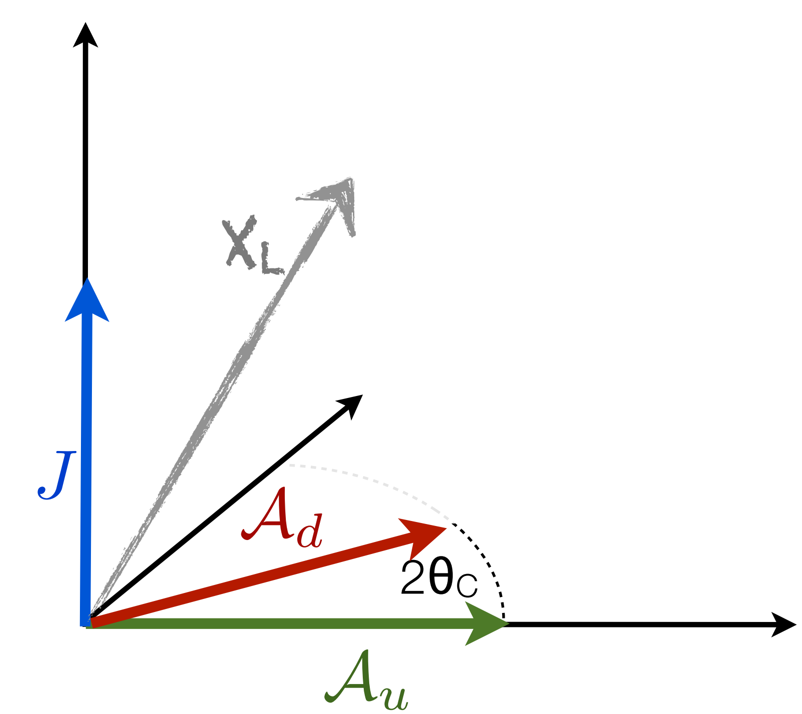
    - invariant under SO(2) rotations between up-down mass bases
- $SU(2)_Q$ breaking NP $\mathcal{O}_L = \left[(X_L)^{ij}\,\overline{Q}_i \gamma^\mu Q_j\right] L_\mu$

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



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  - two sources of breaking: $\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{\not{\rm tr}}\,, \qquad \mathcal{A}_d \equiv (Y_d Y_d^\dagger)_{\not{\rm tr}}$
  - 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)

On Universality of CPV in |ΔF|=1 processes

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  - two sources of breaking: $\mathcal{A}_u \equiv (Y_u Y_u^\dagger)_{\not{\text{tr}}}$, $\mathcal{A}_d \equiv (Y_d Y_d^\dagger)_{\not{\text{tr}}}$
  - **Implication:** direct correspondence between Δa_{CP} and ε'/ε (no weak loop suppression)
    - constraint on $SU(3)_Q$ breaking NP: $\Delta a_{CP}^{\rm NP} \lesssim 4 \times 10^{-4}$ 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

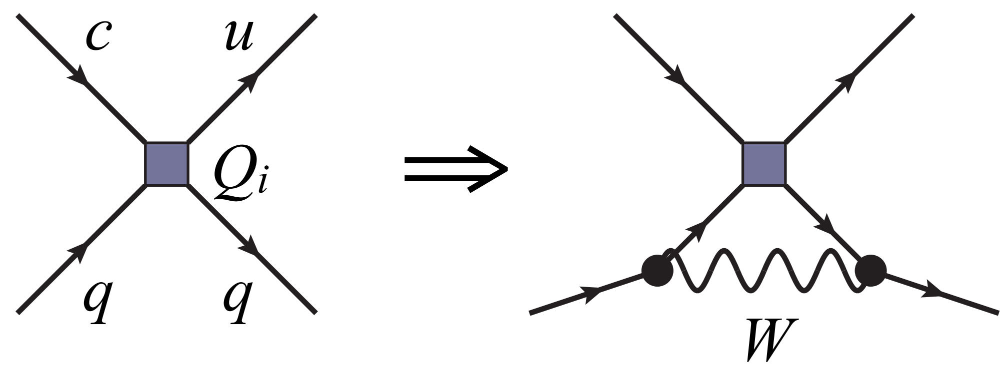
}

Δa_{CP} and New Physics

Isidori, J.F.K, Ligeti & Perez
1111.4987

- In EFT can be estimated via "weak mixing" of operators

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



- Important constraints expected from **D-D̅ 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-D̅ and/or ε'/ε

Model example:
Hochberg, Nir, 1112.5268

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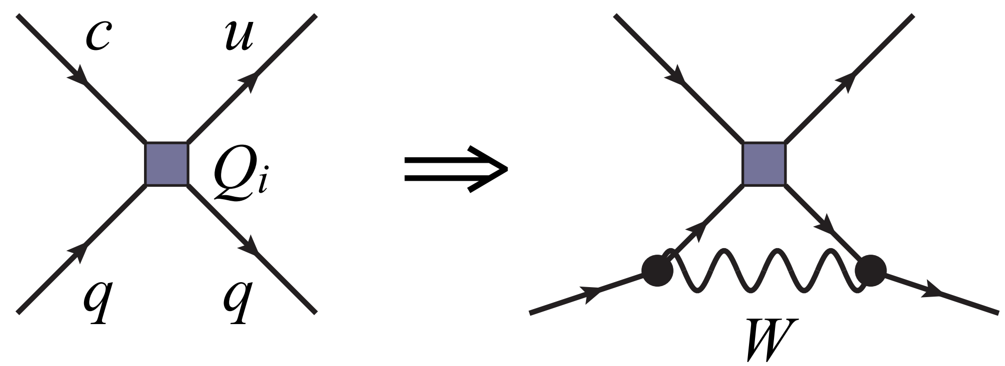

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  - **RR 4q operators:** unconstrained in EFT - UV sensitive contributions?

Dipole operators only weakly constrained (edm's)

Δa_{CP} in (enter favorite NP model name) __

Before LHCb result,

DCPV in charm not on top of NP theorists expectations

Δa_{CP} in (enter favorite NP model name)

Before LHCb result,

DCPV in charm not on top of NP theorists expectations

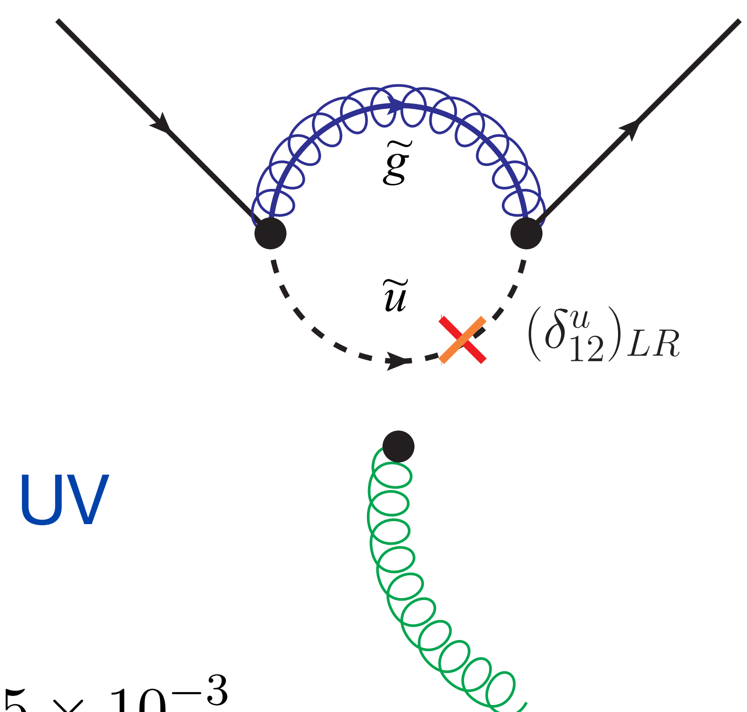
In last 6 months, situation has improved considerably

Δa_{CP} in SUSY Models

- Left-right up-type squark mixing contributions

Grossman, Kagan & Nir, hep-ph/0609178
Giudice, Isidori & Paradisi, 1201.6204
Hiller, Hochberg, Nir, 1204.1046

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



- contributions to ΔF=2 helicity suppressed

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

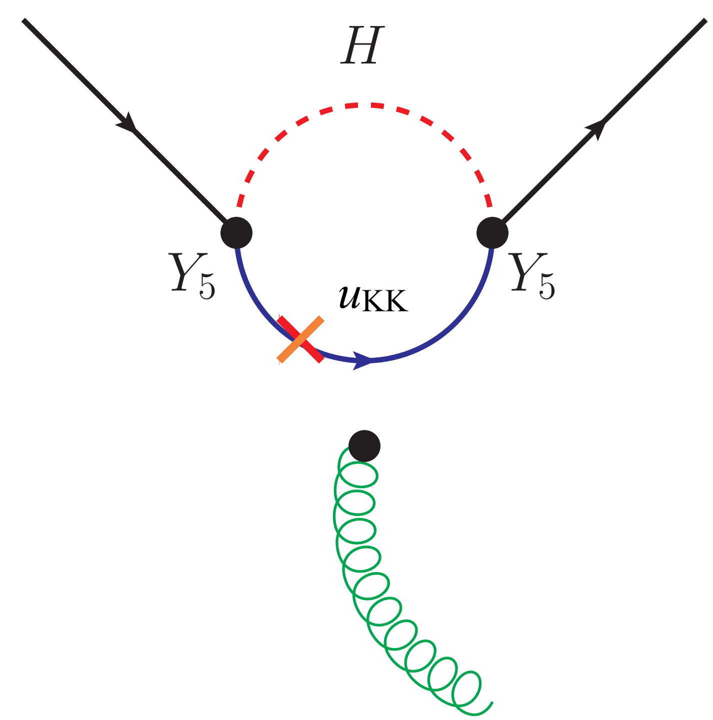
$${\rm Im}\,(\delta^u_{12})_{LR} \approx \frac{{\rm Im}(A)\ \theta_{12}\ m_c}{\tilde m} \approx \left(\frac{{\rm Im}(A)}{3}\right)\left(\frac{\theta_{12}}{0.3}\right)\left(\frac{\rm TeV}{\tilde m}\right) 0.5\times 10^{-3}$$

Δa_{CP} in Warped Extra-Dim. Models

- Anarchic flavor with bulk Higgs

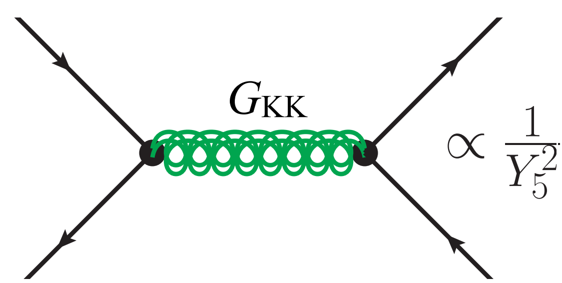
Delaunay, J.F.K., Perez & Randall
in progress

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



  - requires very large 5D Yukawas
    - helps to avoid D-$\overline{\text{D}}$ 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

Δa_{CP} and 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

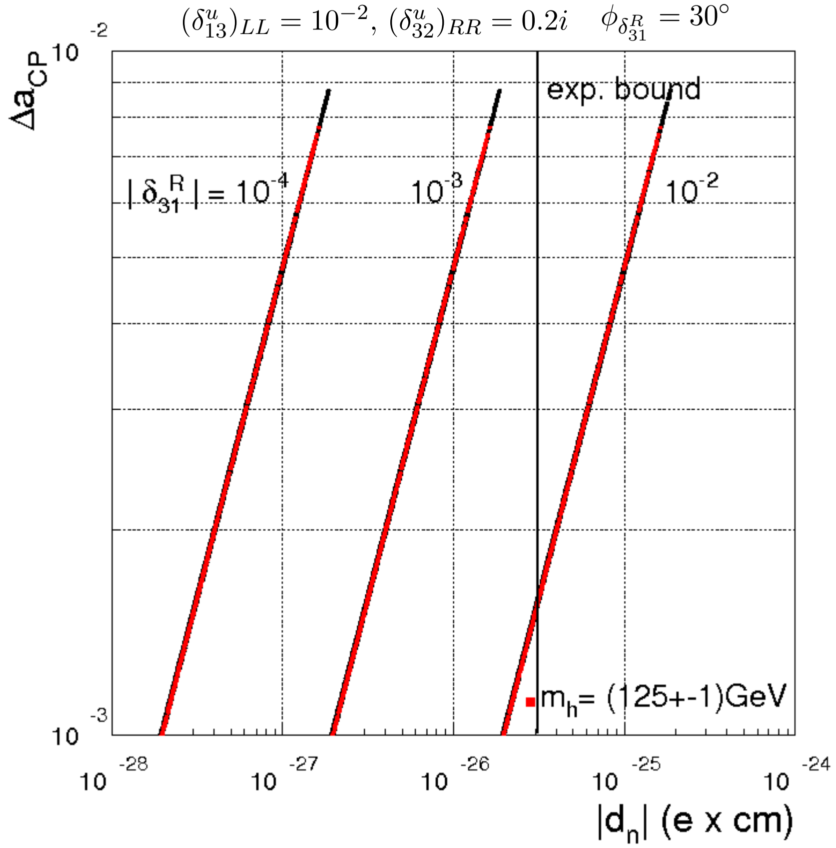
  - Effects comparable to SM still allowed

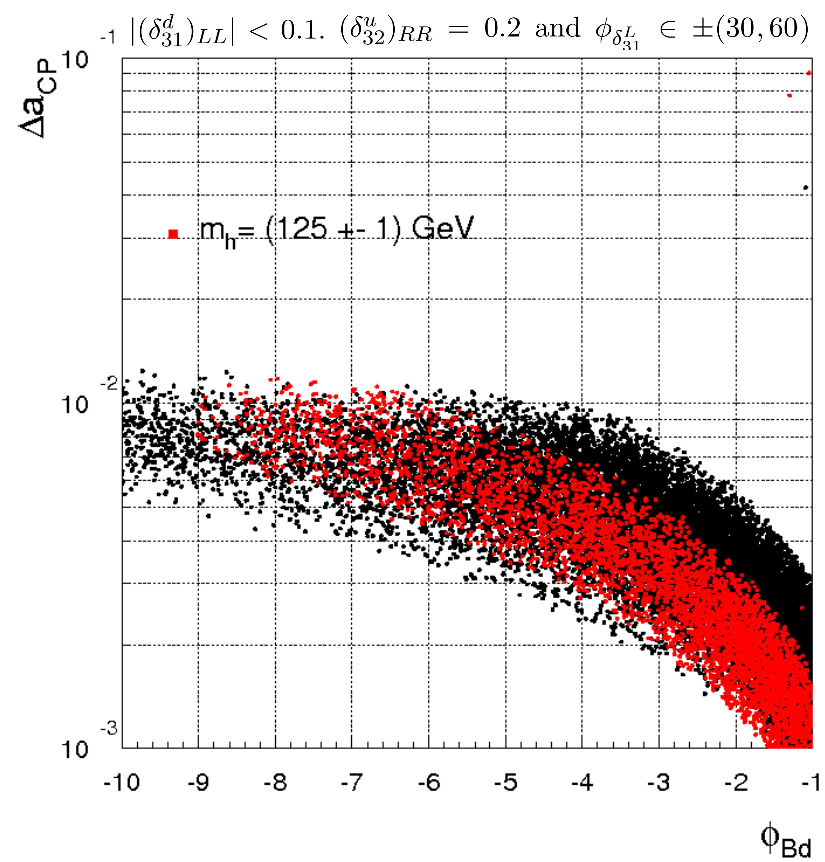
- Similar conclusions for generic mixing with vector-like quarks

Grossman, Kagan & Nir
hep-ph/0609178
Altmannshofer et al.
1202.2866

Generic Implications for Experiment

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





Example: MSSM

$$0.5\ \text{TeV} \leq \tilde{m}, \tilde{m}_g \leq 2\ \text{TeV},$$

$$|A| \leq 3,\ \tan\beta = 10.$$

Giudice, Isidori & Paradisi, 1201.6204

Hochberg & Nir, 1112.5268

Altmannshofer et al., 1202.2866

very model dependent

Generic Implications for Experiment

- NP explanations of Δa_{CP} via chromo-magnetic dipole operators

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

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

(estimate of matrix element in QCD fact.)

  - generically predict EM dipoles

$$|{\rm Im}[C_7^{\rm NP}(m_c)]| \approx |{\rm Im}[C_8^{\rm NP}(m_c)]| \approx 0.4 \times 10^{-2} \ .$$

(QCD RGE evolution with TeV NP)

Isidori & J.F.K., 1205.3164

    - rare radiative charm decays $D^0 \to X\gamma$ $D^0 \to X e^+ e^-$

Expected NP rates few orders below SM LD contributions

Delaunay, J.F.K., Perez & Randall
in progress

Generic Implications for Experiment

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(QCD RGE evolution with TeV NP) Isidori & J.F.K., 1205.3164

    - possibility to access CPV observables in $D^0 \to \pi\pi\gamma, KK\gamma$
      - in SM CPV expected similar as in $D^0 \to \pi\pi, KK$
      - large strong phases natural for LD SM contributions

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

(smaller effects also in $D^0 \to KK\gamma$ *with* m_{KK} around Φ mass)

Generic Implications for Experiment

- NP explanations of Δa_{CP} via ΔI=3/2 contributions

Grossman, Kagan & Zupan, 1204.3557

- SM contributions to $A_K^{(d)}$, $A_\pi^{(s)}$ purely ΔI=1/2

No CPV expected in pure ΔI=3/2 decays

$$\Gamma(D^+ \to \pi^+\pi^0) - \Gamma(D^- \to \pi^-\pi^0) = 0$$

(up to small isospin breaking)

- nonzero difference would point towards CPV ΔI=3/2 NP contributions

- decay amplitude sum-rules even in presence isospin breaking

$$\frac{1}{\sqrt{2}}\left|A_{\pi^+\pi^-} - \bar{A}_{\pi^-\pi^+}\right| \neq \left|A_{\pi^0\pi^0} - \bar{A}_{\pi^0\pi^0}\right|,$$

→ signal of ΔI=3/2 CPV NP

  - experimentally accessible with time-dependent measurements

  (also Dalitz plot analyses in $D\to 3\pi$, $D\to KK\pi$)

Conclusions

- The observed size of CPV is borderline...
    - larger than naive SM expectations
    - however, SM explanation cannot be excluded from first principles
- If NP, points towards new flavor structures in u_R sector at the TeV scale
- More experimental observables could clarify the picture
    - (CPV in) rare radiative charm decays - sensitive to NP in dipole ops.
    - CPV in isospin related 2-, 3-body modes - can test $\Delta I=3/2$ NP