Implications of LHCb measurements and future prospects

NP interpretations of Δa_{CP}

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Outline

- 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

Experimental observables

see talk by Mat Charles

- **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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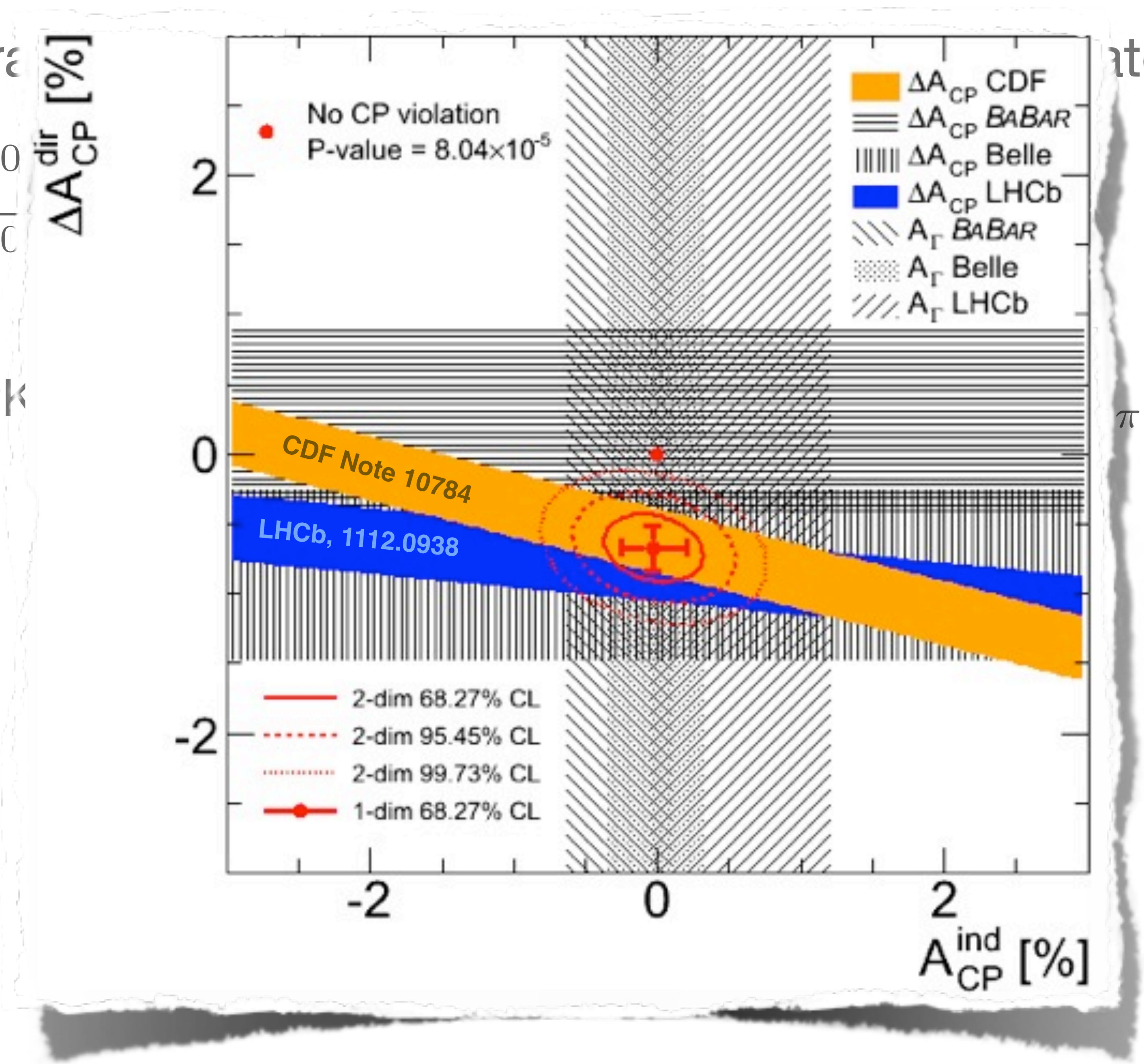

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$$\boxed{\Delta a_{CP}^{\mathrm{World}} = -(0.67 \pm 0.16)\% \qquad \text{(\textasciitilde 3.8}\sigma\text{ from 0)}}$$

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$$\boxed{\Delta a_{CP}^{\mathrm{World}} = -(0.67 \pm 0.16)\% \qquad (\sim 3.8\sigma \text{ from } 0)}$$

    - ...beyond natural expectation within the SM $\mathcal{O}([V_{cb}V_{ub}/V_{cs}V_{us}]\ \alpha_s/\pi) \sim 10^{-4}$

Grossman et al., hep-ph/0609178

    - but not possible to prove from first principles, and SM-like explanation cannot be excluded

see talks by Joachim Brod & Soumitra Nandi

Golden & Grinstein Phys. Lett. B 222 (1989)
Brod, Kagan & Zupan 1111.5000
Brod, Grossman, Kagan & Zupan 1203.6659
Feldmann, Nandi & Soni 1202.3795

Quantifying theoretical predictions

- SM expectations for $a_f^{\mathrm{dir.}} \simeq 2r_f \sin\phi_f \sin\delta_f \qquad f = K, \pi$

absolute ratio of interf.
decay amplitudes

CPV & strong phase differences

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CPV & strong phase differences

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

$$A_K = \lambda_s A_K^{(1)} + \lambda_b A_K^{(2)}$$
$$A_\pi = \lambda_d A_\pi^{(1)} + \lambda_b A_\pi^{(2)}$$

- naive expectation $A_f^{(2)}/A_f^{(1)} \sim \dfrac{\alpha_s(m_c)}{\pi}$

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

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

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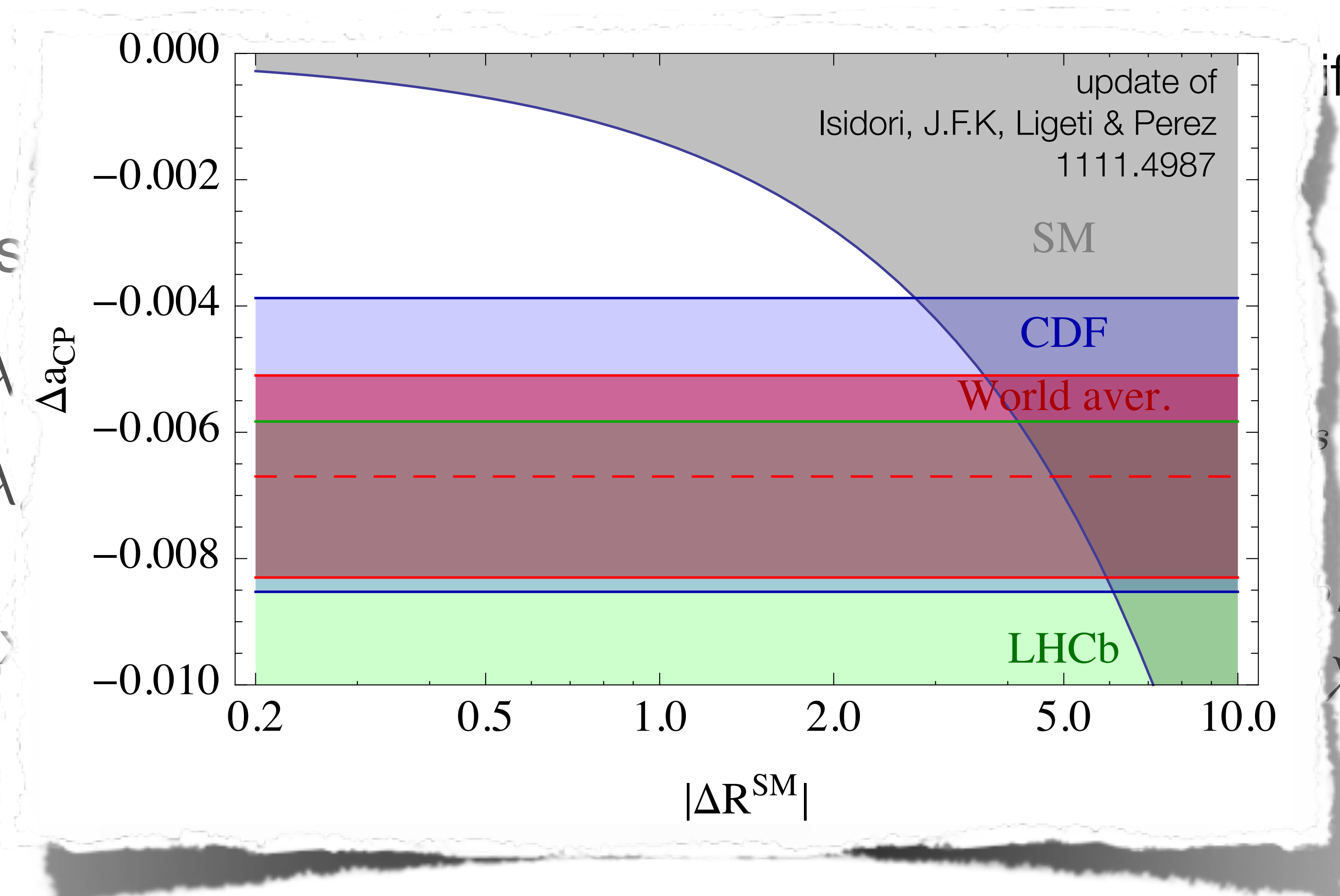

ifferences

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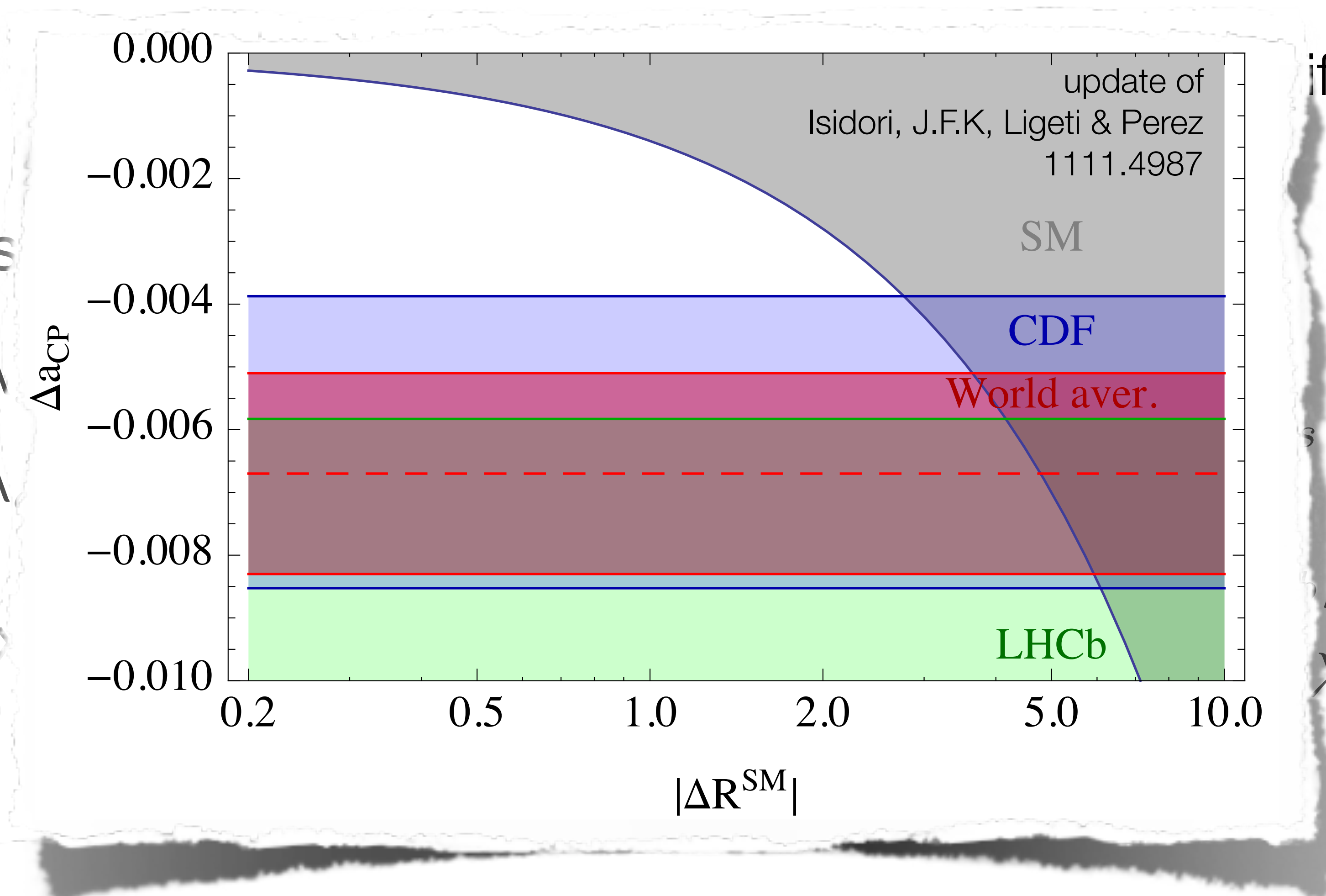

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O(4-6) values of $|\Delta R^{SM}|$ needed

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

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$$\Delta a_{CP} \approx (0.13\%)\mathrm{Im}(\Delta R^{\mathrm{SM}}) + 9\sum_i \mathrm{Im}(C_i^{\mathrm{NP}})\,\mathrm{Im}(\Delta R_i^{\mathrm{NP}}) \qquad \Delta R_i^{\mathrm{NP}} \equiv \frac{G_F}{\sqrt{2}} \sum_{f=\pi,K} \frac{\langle Q_i \rangle_f}{A_f^{(1)}}$$

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

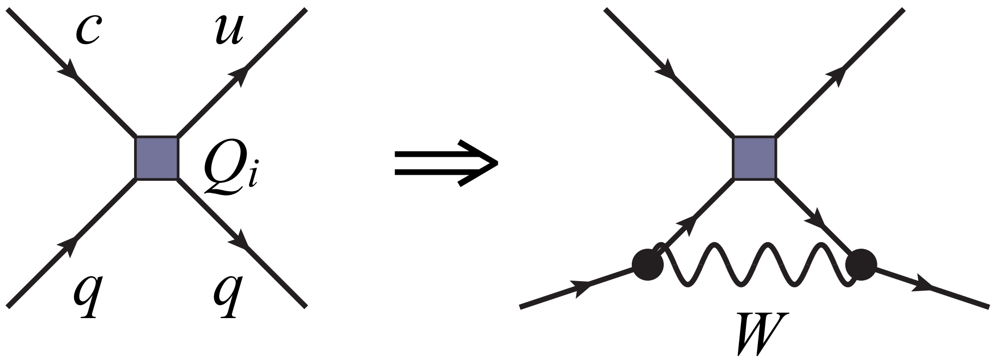
Are such contributions allowed by other flavor constraints?

Δa_{CP} and New Physics

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

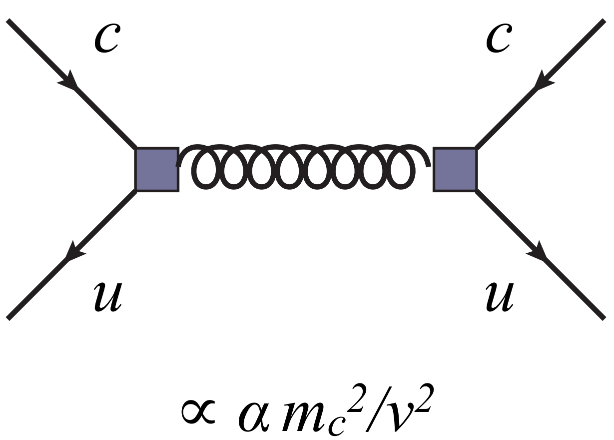
- In EFT can be estimated via "weak mixing" of operators

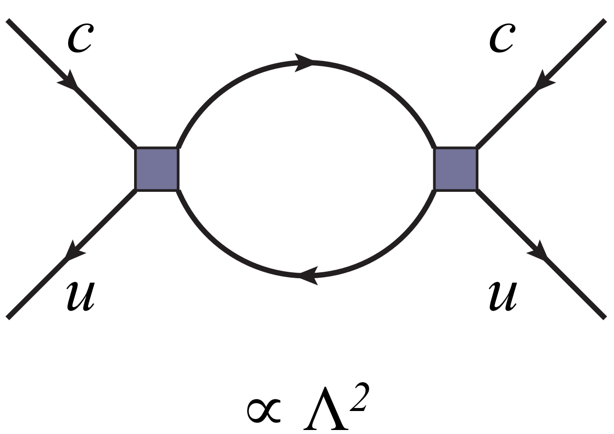
$$T\left\{\mathcal{H}^{\mathrm{eff-NP}}_{|\Delta c|=1}(0),\mathcal{H}^{\mathrm{SM}}(x)\right\}$$



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

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





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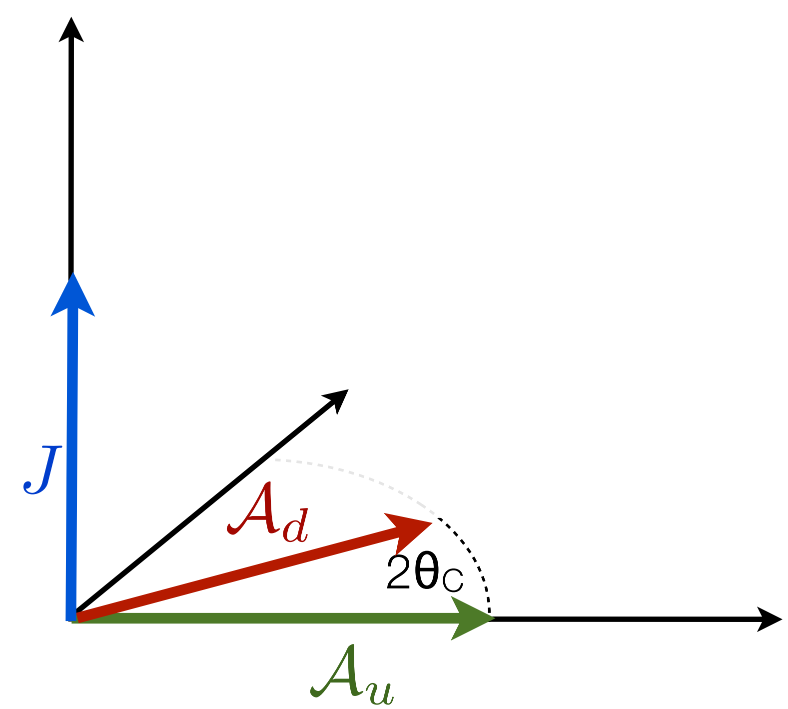
  - in the 2-gen limit single source of CPV: $J \equiv i[\mathcal{A}_u,\, \mathcal{A}_d]$ Gedalia, Mannelli & Perez 1002.0778, 1003.3869
    - invariant under SO(2) rotations between up-down mass bases



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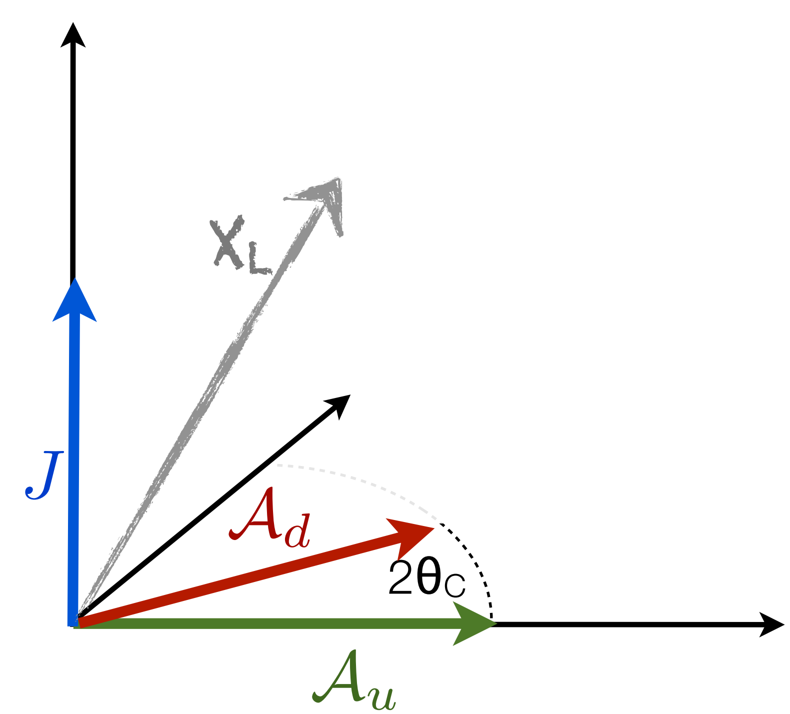
    - invariant under SO(2) rotations between up-down mass bases
- $SU(2)_Q$ breaking NP $\mathcal{O}_L = \left[(X_L)^{ij}\, \overline{Q}_i \gamma^\mu Q_j\right] L_\mu$

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



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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)

On Universality of CPV in |ΔF|=1 processes

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  - **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

}

Δa_{CP} and New Physics

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

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

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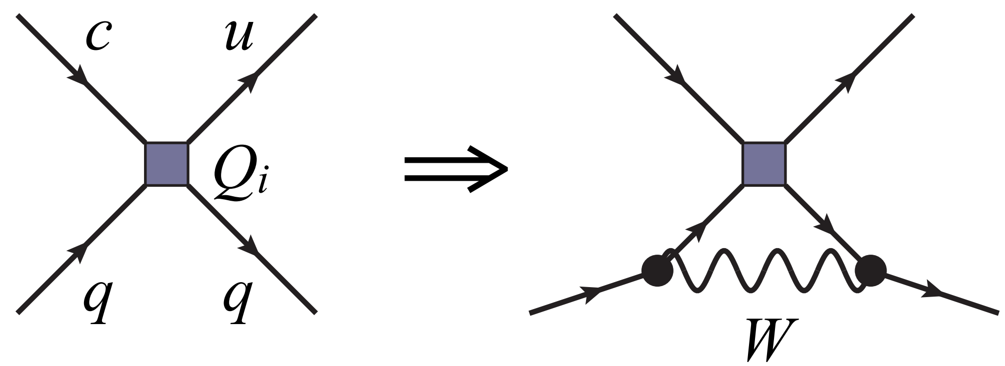

- Important constraints expected from **D-D̄ mixing** and direct CPV in $K^0 \to \pi^+\pi^-$ **(ε’/ε)**
  - **LL 4q operators:** excluded
  - **LR 4q operators:** ajar - potentially visible effects in D-D̄ and/or ε’/ε

Model example:
Hochberg, Nir, 1112.5268

see talk by Yossi Nir

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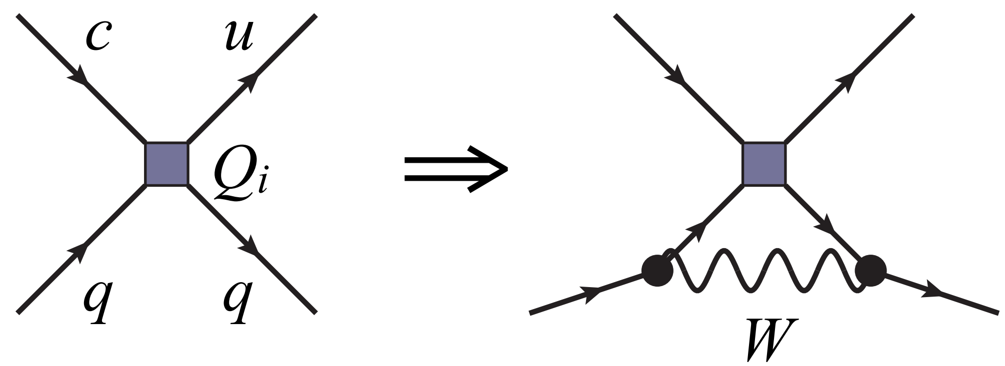

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    - **LL 4q operators:** excluded
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    - **RR 4q operators:** unconstrained in EFT - UV sensitive contributions?

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

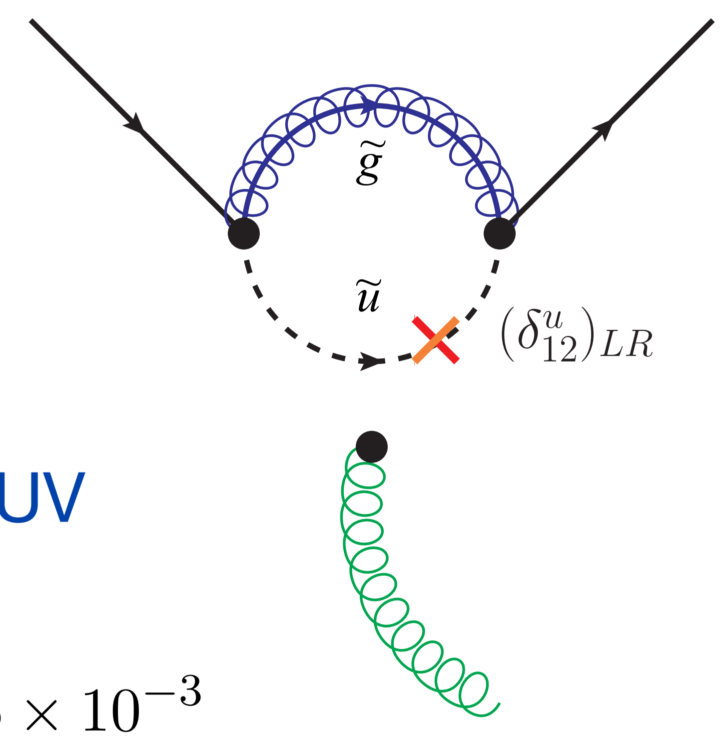
In last 5 months, situation has improved considerably

Δa_{CP} in SUSY Models

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

- Left-right up-type squark mixing contributions

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



- contributions to ΔF=2 helicity suppressed

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

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

see talks by Yossi Nir, Gino Isidori

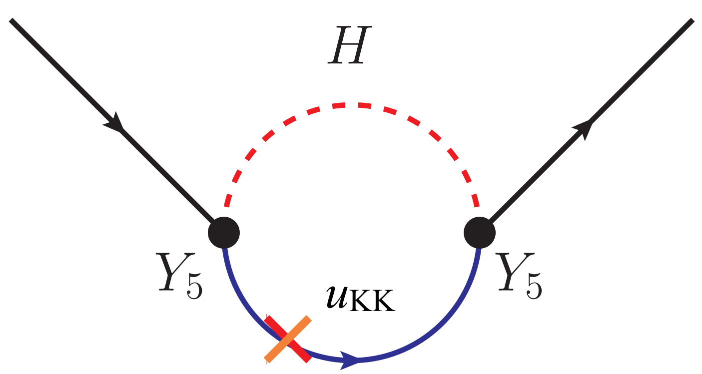
Δa_{CP} in Warped Extra-Dim. Models

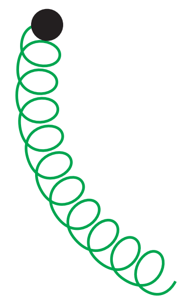
see talk by Cedric Delaunay

- Anarchic flavor with bulk Higgs

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

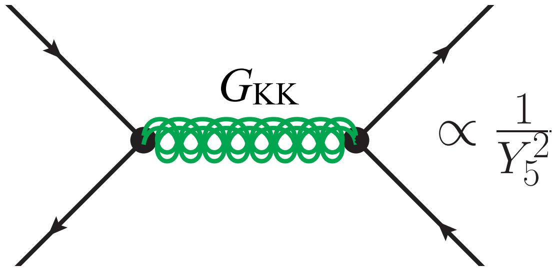
$$\left|\Delta a_{CP}^{\rm chromo}\right|_{\rm RS} \simeq 0.6\% \times \left(\frac{Y_5}{6}\right)^2 \left(\frac{3\,{\rm TeV}}{m_{\rm KK}}\right)^2$$





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

see talk by Riccardo Rattazzi

Δa_{CP} and 4th Generation

see talk by Soumitra Nandi

- 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

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

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

Expected NP rates few orders below SM LD contributions

- possibility to access CPV observables

see talk by Gino Isidori

- 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

Generic Implications for Experiment

- NP explanations of Δa_{CP} via $\underline{\Delta I{=}3/2}$ contributions — Grossman, Kagan & Zupan, 1204.3557
  - SM contributions to $A_f^{(2)}$ purely $\Delta I{=}1/2$

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 $\Delta I{=}3/2$ NP contributions
  - decay amplitude sum-rules even in presence isospin breaking

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