Flavour Symmetry Breaking on CP Violation in D-Meson Decays

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Outline

- Introduction: LHCb and Charm Physics
- LHCb measurement:Direct CPV in $D^0 \to P^+P^-$
- U-spin and D-meson decays
- Results
- Conclusions

LHCb and Charm Physics

- The LHCb experiment:
  - precision studies of CP violation and rare phenomena in b-hadron decays $\Rightarrow$ Ideal platform for precision charm physics programe
  - Dedicated $D^* \to D^0(hh)\pi$ trigger $\Rightarrow$ Provide a rich and high statistics charm sample $\Rightarrow$ useful for mixing and direct CP violation (DCPV) searches
  - Search for $D^0 \to 4h$ and rare decay $D^0 \to \mu\mu$
- LHCb has the sensitivity to reach the SM expectation
- Precision measurements in charm offer windows for New Physics (NP)

Measurement: ΔA_{CP}

The time-integrated CP asymmetry $A_{\rm CP}(f)$:

$$A_{\rm CP}(f) = \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} = A^{dir}_{\rm CP} + A^{ind}_{\rm mix}$$

$$A^{ind}_{\rm mix} = -\frac{2\,|R_f|}{(1+|R_f|^2)^2\,|R_m|}\left(x \sin\phi(1 + |R_f|^2|R_m|^2) + y\cos\phi(1 - |R_f|^2|R_m|^2)\right)$$

$\Rightarrow$ No interfering amplitudes of comparable size i.e $|R_f| \approx 1$ and $Arg(R_f) \approx 0$

$\rightarrow$ $A^{\rm mix}_{CP}$ independent of the final state f !!

- In SM: For final states K^+K^- and $\pi^+\pi^-$, $A^{ind}_{\rm mix}$ is universal
- $\Delta A_{CP} = A^{dir}_{CP}(K^+K^-) - A^{dir}_{CP}(K^+K^-)$ = -$(0.82 \pm 0.21 \pm 0.11)$%
  $\Rightarrow$ 3.5σ away from zero.. [LHCb Collaboration (2011)]
- $\Delta A_{CP} = (-0.645 \pm 0.180)\%$ HFAG
  - Renewed the interest in CP violation in Charm !!
    - Poorly known SM dynamics ??
      - Difficult to estimate the size of the different amplitudes !!
    - BSM physics playing a role ??

Various explanations

Explanations of the LHCb result in SM, and in NP models:

- Isidori et.al. arxiv:1103.5785 $\Rightarrow$ NP explanation in a model independent way
- Brod et.al. arxiv:1111.4987 $\Rightarrow$ Large $1/m_c$ suppressed amplitude
- Rozanov et.al. arxiv:1111.5000 $\Rightarrow$ Large penguin in sequential 4th generation model
- Pirtskhalava et.al. arxiv:1112.5451 $\Rightarrow$ Badly broken $SU(3)_F$ symmetry
- Cheng et.al. arxiv:1201.0785 $\Rightarrow$ Large weak penguin annihilation contribution
- Bhattacharya et.al. arxiv:1201.2351 $\Rightarrow$ CP conserving NP in penguin
- Giudice et.al arxiv:1201.6204 $\Rightarrow$ Left-right flavour mixing via chromomagnetic operator
- Altmannshofer et.al. arxiv:1202.2866 $\Rightarrow$ Chirally enhanced chromomagnetic penguins
- Brod et.al. arxiv:1203.6659 $\Rightarrow$ In SM via s- and d-quark penguin contraction

  ....many more

Hopefully many more to come....

$D^0 \to P^+P^-$: $\mathcal{H}_{\rm eff}$ and U-spin

The Hamiltonian for $c \to u q \bar{q}$ decays:

$$H_{eff} = \frac{G_F}{\sqrt{2}} \left\{ (V_{cs}V_{us}^* - V_{cd}V_{ud}^*) \sum_{i=1,2} C_i \frac{(Q_i^{cu\bar{s}s} - Q_i^{cu\bar{d}d})}{2} \right.$$
$$\left. + (V_{cs}V_{us}^* + V_{cd}V_{ud}^*) \left[\sum_{i=1,2} C_i \frac{(Q_i^{cu\bar{s}s} + Q_i^{cu\bar{d}d})}{2} + \sum_{i=3}^{6} C_i\, Q_i + C_{8g} Q_{8g} + h.c \right] \right\}$$

$H_{eff}(c \to us\bar{d}) = \frac{G_F}{\sqrt{2}} V_{cs}V_{ud}^* \sum_{i=1,2} C_i Q_i^{cus\bar{d}} + h.c. \Rightarrow$ CA

$H_{eff}(c \to ud\bar{s}) = \frac{G_F}{\sqrt{2}} V_{cd}V_{us}^* \sum_{i=1,2} C_i Q_i^{cud\bar{s}} + h.c. \Rightarrow$ DCS

U-spin is the SU(2) subgroup of the full $SU(3)_F \Rightarrow$ symmetry between $s \Leftrightarrow d$

U-spin triplet states: $\bar{s}d = |1,+1\rangle$, $(\bar{s}s - \bar{d}d) \simeq |1,0\rangle$, $\bar{d}s = -|1,-1\rangle$

U-spin singlet state: $(\bar{s}s + \bar{d}d) \equiv |0,0\rangle$

The final state mesons: $|\pi^- K^+\rangle = |1,+1\rangle$, $(|K^+K^-\rangle - |\pi^+\pi^-\rangle) \simeq |1,0\rangle$,

$$|\pi^+ K^-\rangle = -|1,-1\rangle, \qquad (K^+K^- + \pi^+\pi^-) \simeq |0,0\rangle$$

$D^0 \to P^+P^-$: U-spin Decomposition

$\Rightarrow D^0 \to P^+P^-$ decays in U-spin limit:

$\mathcal{A}[D^0 \to K^-\pi^+] = 2\,V_{cs}^* V_{ud}\,B_{U=1}$ $\Rightarrow$ Cabibbo Allowed (CA)

$\mathcal{A}[D^0 \to \pi^+\pi^-] = (\lambda_d + \lambda_s)\,A_{U=0} + (\lambda_d - \lambda_s)\,B_{U=1}$

$\mathcal{A}[D^0 \to K^+K^-] = (\lambda_d + \lambda_s)\,A_{U=0} - (\lambda_d - \lambda_s)\,B_{U=1}$

$\mathcal{A}[D^0 \to K^+\pi^-] = 2\,V_{cd}^* V_{us}\,B_{U=1}$ $\Rightarrow$ Double Cabibbo Suppressed (DCS)

- Operators: $A_{U=0} \to$ (tree + penguin), $B_{U=1} \to$ only tree
- $(\lambda_d + \lambda_s) \sim \mathcal{O}(\lambda^5)$ and $(\lambda_d - \lambda_s) \sim \mathcal{O}(\lambda)$
- Expectations: if $\frac{A_{U=0}}{B_{U=1}} \approx \mathcal{O}(1)$ then $\Delta A_{CP} \approx -2\,\lambda^4\,\sin\delta$

$BR(D^0 \to P^+ P^-)$

$\Rightarrow$Additional Phenomenological Information:

Observables	Expectation (Exact U-spin)	Data
$R_1 = \frac{\mathrm{BR}[D^0 \to K^+ K^-]/\lvert\vec{p}_K\rvert}{\mathrm{BR}[D^0 \to \pi^+ \pi^-]/\lvert\vec{p}_\pi\rvert}$	≈ 1	$\simeq 3.22 \pm 0.09$
$R_2 = \frac{\mathrm{Br}[D^0 \to K^- \pi^+]/\lvert\vec{p}_{\pi K}\rvert}{\mathrm{Br}[D^0 \to K^+ K^-]/\lvert\vec{p}_K\rvert} \lambda^2$	≈ 1	$\simeq 0.47 \pm 0.01$
$R_3 = \frac{\mathrm{Br}[D^0 \to K^+ \pi^-]}{\mathrm{Br}[D^0 \to K^- \pi^+]} \lambda^{-4}$	≈ 1	$\simeq 1.28 \pm 0.03$

- Due to U-spin violation ($m_s \neq m_d$) ??
- or due to drastic enhancement in $A_{U=0}$??

.. We take into account the U-spin breaking effects $\Rightarrow$

We have not made any assumption on the size of individual contributions!!

U-spin violation

U-spin is broken $\mathcal{O}\left(\frac{m_s}{\Lambda_{QCD}}, \frac{f_k}{f_\pi} - 1\right) \Rightarrow \mathcal{H}_{break} \to$ Tensor operator $\mathcal{O}^{U=1}_{U_3=0}$

$\Rightarrow D^0 \to P^+ P^-$ decays including 1st order U-spin breaking:

$$\mathcal{A}[D^0 \to K^-\pi^+] = 2\, V^*_{cs} V_{ud}\, B_{U=1}\left[1 - r'_1\, e^{i\,\phi'_1}\right]$$
$$\mathcal{A}[D^0 \to \pi^+\pi^-] = B_{U=1}\left[(\lambda_d + \lambda_s)\, \left(r\, e^{i\,\phi} + r_1\, e^{i\,\phi_1}\right) + (\lambda_d - \lambda_s)\, \left(1 + r_0\, e^{i\,\phi_0}\right)\right]$$
$$\mathcal{A}[D^0 \to K^+K^-] = B_{U=1}\left[(\lambda_d + \lambda_s)\, \left(r\, e^{i\,\phi} - r_1\, e^{i\,\phi_1}\right) - (\lambda_d - \lambda_s)\, \left(1 - r_0\, e^{i\,\phi_0}\right)\right]$$
$$\mathcal{A}[D^0 \to K^+\pi^-] = 2\, V^*_{cd} V_{us}\, B_{U=1}\left[1 + r'_1\, e^{i\,\phi'_1}\right]$$

$\Rightarrow$ Amplitude Ratios: $r_0 = \left|\frac{\Delta A_{U=0}}{B_{U=1}}\right|$, $r_1 = \left|\frac{\Delta B_{U=1}}{B_{U=1}}\right|$, $r'_1 = \left|\frac{\Delta B'_{U=1}}{B_{U=1}}\right|$, $r = \left|\frac{\Delta A_{U=0}}{B_{U=1}}\right|$

$\Rightarrow D^0 \to K^\pm\pi^\mp$: No direct CP violation $\Rightarrow$ Only mixing-induced CP violation !!

$\Rightarrow$ Parameters need to fit: r_0, r'_1, r_1, r, ϕ_0, ϕ'_1, ϕ_1 and ϕ

$\Rightarrow$ Available data: R_1, R_2, R_3, ΔA_{CP}, $Arg\left(\frac{\mathcal{A}[D^0 \to K^-\pi^+]}{\mathcal{A}[D^0 \to K^+\pi^-]}\right) \approx \Delta\phi = 22.4^{\circ}{}^{+\ 9.7^\circ}_{-11.0^\circ}$

$\Rightarrow$ No priority to a single amplitude ratio !!

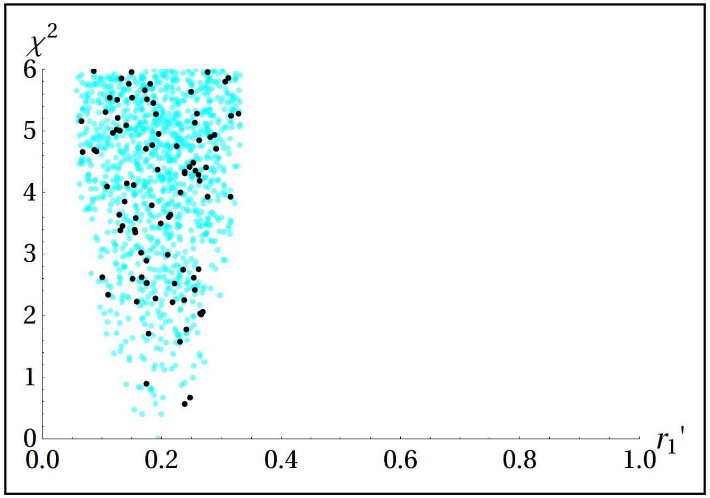
$\Rightarrow$ The individual values of r and r_1 can not be fixed from data !!

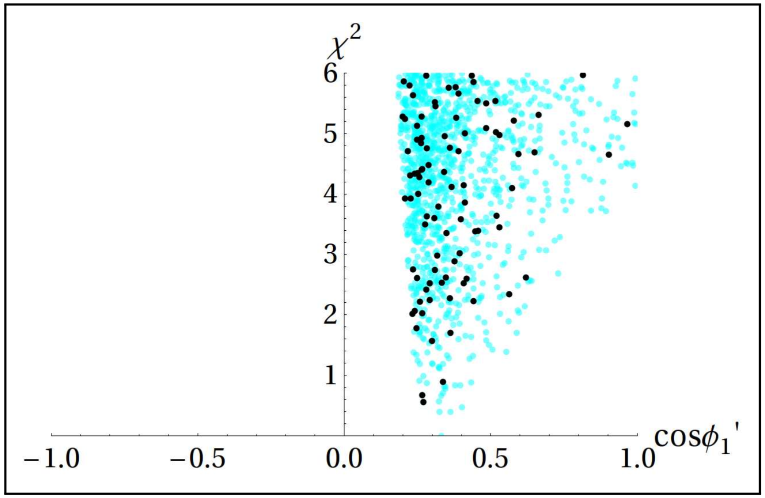
$\Rightarrow$ Hence, we define $\bar{r} = \sqrt{r^2/2 + r_1^2/2} \Rightarrow$ Sensitive to ΔA_{CP} !!

Fit results: r_1' and ϕ_1'

Feldmann, Nandi and Soni arXiv:1202.3795

r_1' and ϕ_1' are sensitive to CA and DCS decays



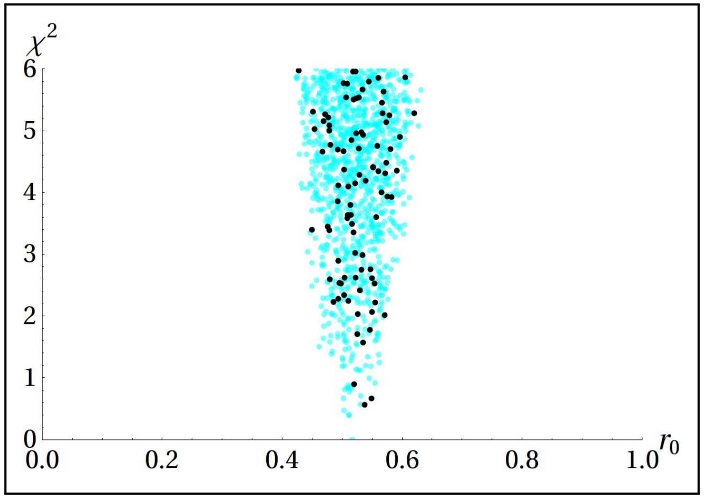


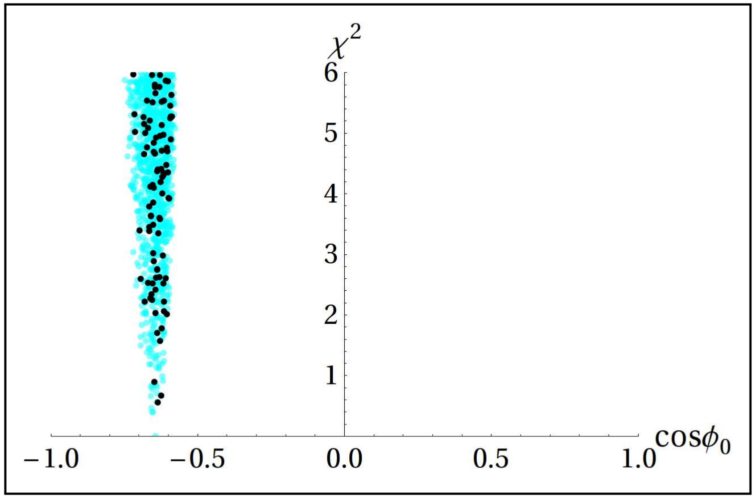
- Experimental constraints at 2σ level $\Rightarrow$ Blue regions
- $r_1' = \left|\frac{\Delta B'_{U=1}}{B_{U=1}}\right| \simeq 0.19$ and $\cos\phi_1' \gtrsim 0.18 \Rightarrow$ Reasonably constrained
- Black Points: Simplified assumptions $(\phi - \phi_0) = \{0, \pi\}$ and $\phi_1 = \{0, \pi\}$

Fit results: r_0 and ϕ_0

Feldmann, Nandi and Soni arXiv:1202.3795

r_0 and ϕ_0 are sensitive to $D \to K^+K^-(\pi^+\pi^-)$ decays

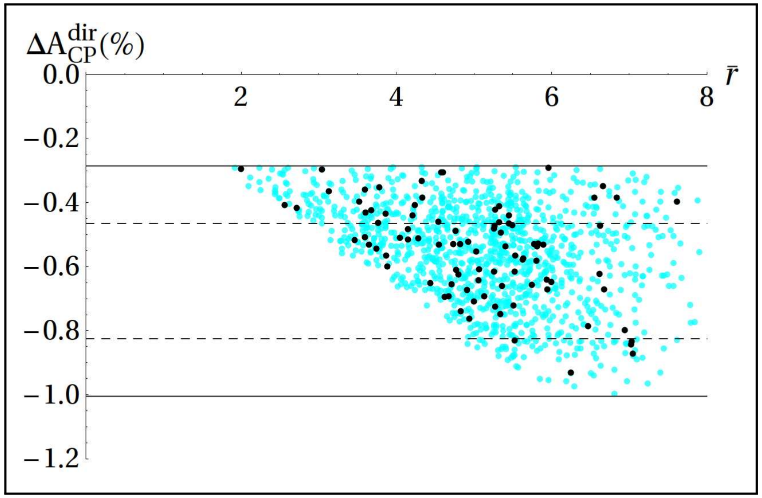




- $r_0 = \left|\frac{\Delta A_{U=0}}{B_{U=1}}\right| \simeq 0.52$ and $\cos\phi_0 \gtrsim -0.64 \Rightarrow$ Tightly constrained
- r_0 is large compared to $r_1' \Rightarrow$ Partly understood in naive factorisation :
  - $D^0 \to K^\pm\pi^\mp$: U-spin breaking in form factors and decay constants tends to compensate each other
  - $D^0 \to K^\pm K^\mp(\pi^\pm\pi^\mp)$: The two effects tend to add up

Results: ΔA_{CP} and $A_{CP}^{\rm dir}(P^+P^-)$

Feldmann, Nandi and Soni arXiv:1202.3795



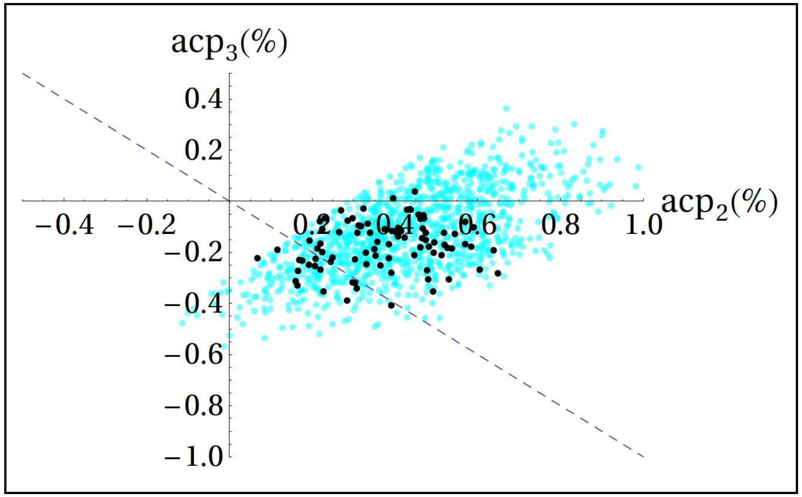
$\Delta A_{CP}^{exp} \Rightarrow$ Solid line : 2σ, Dashed line: 1σ ranges

$\Rightarrow$ Clear correlation between ΔA_{CP} and $\bar{r}$

$\Rightarrow$ $\Delta A_{CP} \approx -0.3\%$ for $\bar{r} = 2$,

2σ HFAG lower (magnitude) limit!!

$\Rightarrow$ Strong phase difference between $U = 1$ (or $U = 0$) does not play an essential role in ΔA_{CP} !!



$\Rightarrow$ $\mathrm{acp}_2 = A_{\rm CP}^{\rm dir}(D^0 \to \pi^+\pi^-)$

$\Rightarrow$ $\mathrm{acp}_3 = A_{\rm CP}^{\rm dir}(D^0 \to K^+K^-)$

$\Rightarrow$ Dashed line: Naive U-spin limit

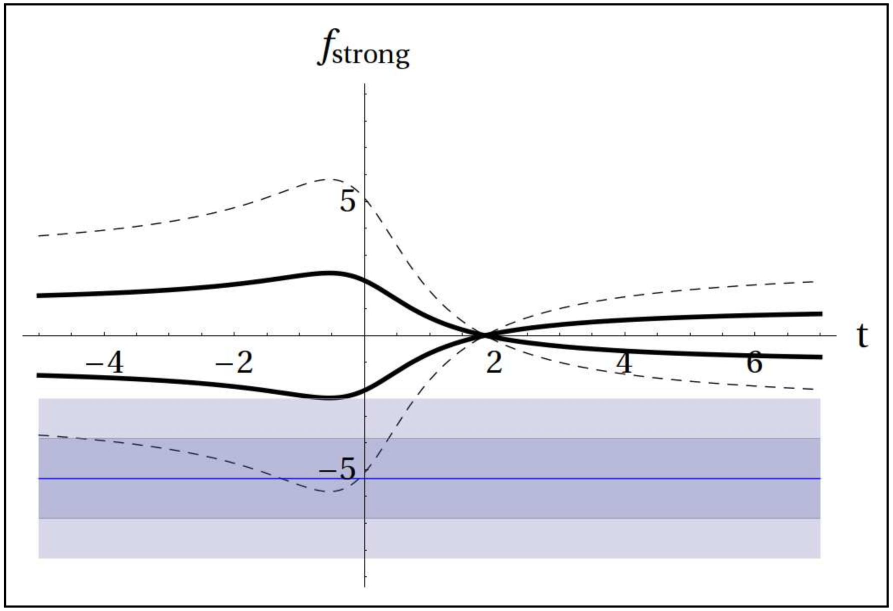
$\Rightarrow$ U-spin breaking:

$\Rightarrow$ Individual $A_{\rm CP}^{\rm dir}$: A few per mille (with opposite sign)

Simplified analysis

Simplified Assumptions: $(\phi - \phi_0) = \{0, \pi\}$ and $\phi_1 = \{0, \pi\}$

$\Rightarrow \bar{r} = 2 \rightarrow$ Solid Line $\Rightarrow \bar{r} = 5 \rightarrow$ Dashed Line



$\Rightarrow$ Wolfenstein expansion: $\Delta A_{CP} = f_{\mathrm{weak}}\, f_{\Delta \mathrm{U}}\, f_{strong}$

$\Rightarrow f_{\mathrm{weak}} \simeq 2A^2\lambda^4\eta \approx 0.11\%$

$\Rightarrow f_{\Delta \mathrm{U}}(r_0, \phi_0) \simeq 1.1$

$\Rightarrow f_{\mathrm{strong}} = -r \sin\phi + r_0 r_1 \sin\phi_0 \cos\phi_1$

$\Rightarrow t \equiv \frac{r_1 \sin\phi_0 \cos\phi_1}{r \sin\phi} = \pm\frac{r_1}{r}$

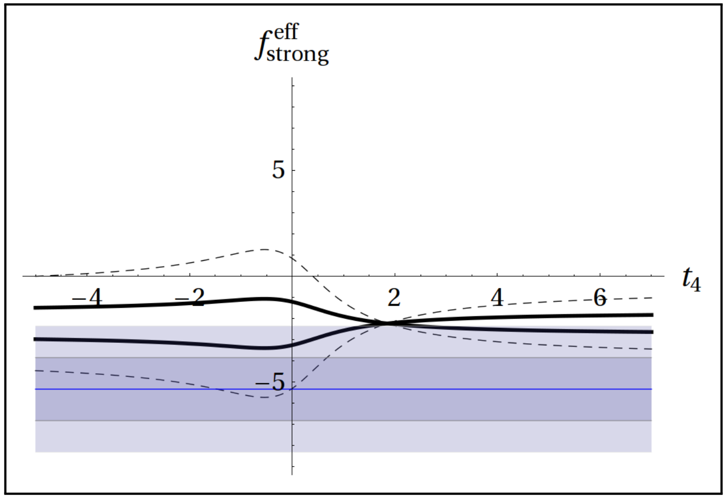
4G and ΔA_{CP}

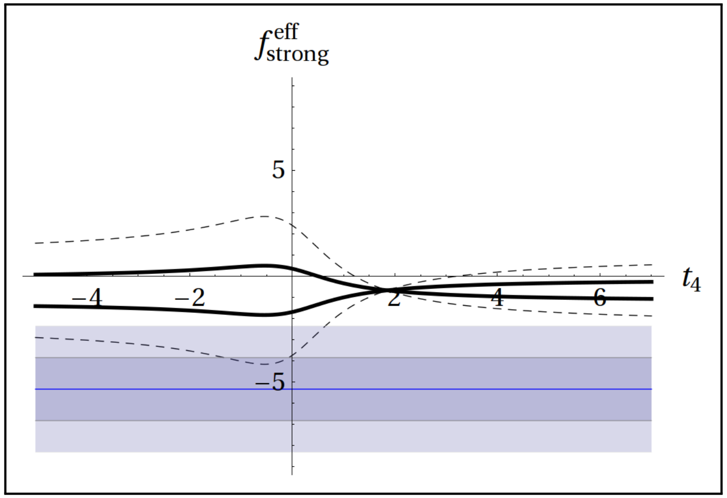
4G: As an example for generic NP model with constrained flavour sector

- Wolfenstein expansion::
  $\Delta A_{CP} \simeq f_{\Delta U} \cdot \left\{ f_{\text{weak}} \cdot f_{\text{strong}} + f_{\text{weak}}^{4\text{G}} \cdot f_{\text{strong}}^{4\text{G}} \right\}$
- $\mathcal{O}_{NP}$ with $U = 0$ and $U = 1$ can contribute
- $f_{\text{weak}}^{4\text{G}} = 4\,\text{Im}\left[\frac{\lambda_{b'}}{\lambda_d - \lambda_s}\right]$
  - Flavour data: Large values of $|\lambda_b'|$ corresponds to $\phi_b' \approx 0$
- For illustrating, let's take $f_{\text{weak}}^{4\text{G}} = f_{\text{weak}}$ and $r = \bar{r} = 2$

4G and ΔA_{CP}

4G: As an example for generic NP model with constrained flavour sector





⇒ Left plot (right plot): Constructive (destructive) interference between r_1 and r

⇒ $f^{4G}_{\text{strong}} = -r_4 \sin\phi_4 + r_0 r'_4 \sin\phi_0 \cos\phi'_4$

⇒ $\bar{r}_4 \equiv \sqrt{\frac{r_4^2 + (r'_4)^2}{2}}$ and $t_4 \equiv \frac{r'_4 \sin\phi_0 \cos\phi'_4}{r_4 \sin\phi_4}$

⇒ $\bar{r}_4 = 1 \rightarrow$ Solid Line, $\bar{r}_4 = 3 \rightarrow$ Dashed Line

⇒ Additional penguin operators can lead to an enhancement ⇒ Hard to predict !!

Future Possibilities

- We need $\bar{r} = \sqrt{r^2/2 + r_1^2/2}$ of $\mathcal{O}(2)$ to explain ΔA_{CP}
  - At this point, it is not clear which one of r and r_1 has the dominant contribution $\Rightarrow$ We need more information !!
- U-spin violation: SEVERAL amplitudes interfere
  - While the effects may be constructive in ΔA_{CP}, they can be destructive in other modes
  - Study other decay modes as well !
- $A_{CP}^{\rm dir}$ in tree-decays $\Rightarrow$ Clear NP interpretation
- All charm decays with penguins provide similar (large) $A_{CP}^{\rm dir}$ $\Rightarrow$ NP interpretation more probable
- Some $A_{CP}^{\rm dir}$ are large, some $A_{CP}^{\rm dir}$ are small (despite same H_{eff}) $\Rightarrow$ SM interpretation more probable

.....$D^0 \to PV$ decays may play an important role for our understanding of CP violation in Charm

Few More Examples

- D^+ and D_s meson may also offer many interesting and experimentally distinctive channels, with the same quark level operator, for direct CP violation studies (No assumptions on $A_{CP}^{\rm mix}$ is needed):
  - CA $D^+ \to K_s \pi^+$: In SM $A_{CP}^{\rm dir}$ is $\mathcal{O}(\lambda^6)$ $\Rightarrow$ Future LHCb 5σ reach 10^{-3}
  - More D^+ decay channels $\Rightarrow$ SCS modes:
    $D^+ \to K^+ \bar{K}^{*0}, K^{*+}\bar{K}^0, \bar{K}^0\pi^+, \pi^+\bar{K}^{*0}, \phi\pi^+, \rho^0\pi^+, \pi^+\pi^0(\eta')$
    $\Rightarrow$ CA modes: $D^+ \to \bar{K}^0(\bar{K}^{*0})\pi^+$
  - CA $D_s \to \eta'\pi^+$: Pure tree with vanishing $A_{CP}^{\rm dir}$ $\Rightarrow$ Future LHCb 5σ reach 4×10^{-3}
  - More D_s decay channels $\Rightarrow$ SCS modes: $D_s \to K^+\phi(\eta'), K^0(K^{*0})\pi^+$,
    $D_s \to K_S\pi^+$ $\Rightarrow$ CA modes: $D_s \to \phi\pi^+(K^+)$
- All such D^+ and D_s decay modes are induced by the same operators in $\mathcal{H}_{eff}$ as $D^0 \to P^+P^-$ $\Rightarrow$ Expected to yield $A_{CP}^{\rm dir}$ of similar magnitude
- SCS modes with penguin should allow CP searches to the level of a few per mille
  $\Rightarrow$ For CA modes without penguin we could get to about 0.2%

Conclusions

- The ratios of BRs in $D^0 \to \pi^+\pi^-, K^+K^-, K^\pm\pi^\mp$ require $r_0 = \left|\frac{\Delta A_{U=0}}{B_{U=1}}\right| \approx 0.5$
  "large U-spin violation effects?" $\Rightarrow$ The required magnitude can be understood from long-distance strong-interaction effects
- Relative strong phase difference between U-spin symmetric and U-spin violating contribution has to be large $\Rightarrow$ Non-perturbative rescattering effects
- A SM interpretation of the present data on ΔA_{CP} in $D^0 \to P^+P^-$ can not be ruled out
  $\Rightarrow$ Hadronic matrix element of the subleading (Cabibbo-suppressed) term should be enhanced by a factor of 3-5 with respect to the leading contribution in order to yield the observed central value $\Rightarrow$ Such a moderate enhancement does not appear unreasonable
- NP models with constrained flavour sector can contribute with a similar magnitude
- It should be worth looking into the other non-leptonic D-meson decay modes (esp. charged D, D_s) accessible to LHCb and Super-B factories

Thank you !