

CP violation in charm decays: Standard Model and Beyond

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BASED ON FELDMANN , NANDI+AS (arXiv1202.3795) JHEP

MOST IMPORTANT
A NEW FRONTIER FOR TESTING OUR
UNDERSTANDING OF CP HAS BEEN
OPENED !

THANKS TO LHCb !

Outline

- **Introduction: Experimental Info**
- **U-spin breaking important**
- **Large hadronic uncertainties**
- **Rough Estimates**
- **Conclusion & outlook**

Recent results from LHCb, CDF

LHCb

$$\hookrightarrow \Delta A_{CP}^{\text{dir}} \equiv A_{CP}^{\text{dir}}(K^+K^-) - A_{CP}^{\text{dir}}(\pi^+\pi^-) = -(0.82 \pm 0.21 \pm 0.11)\%$$

using Spin $\Rightarrow A_{CP}^{\text{dir}}(K^+K^-) \simeq -A_{CP}^{\text{dir}}(\pi^+\pi^-)$

$$A_{CP}(K^+K^-) = (-0.24 \pm 0.22 \pm 0.09)\% \quad) \quad \text{CDF}$$
$$A_{CP}(\pi^+\pi^-) = (+0.22 \pm 0.24 \pm 0.11)\%$$

LHCb+CDF $\Rightarrow \Delta A_{CP}^{\text{dir}} = (-0.645 \pm 0.180)\%$ HFA6

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

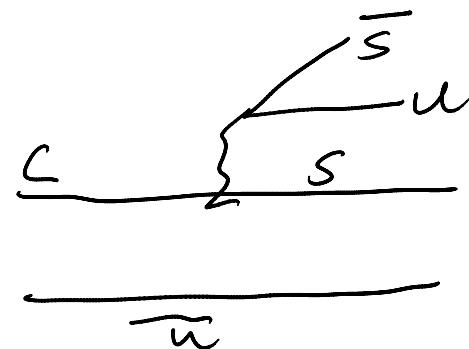
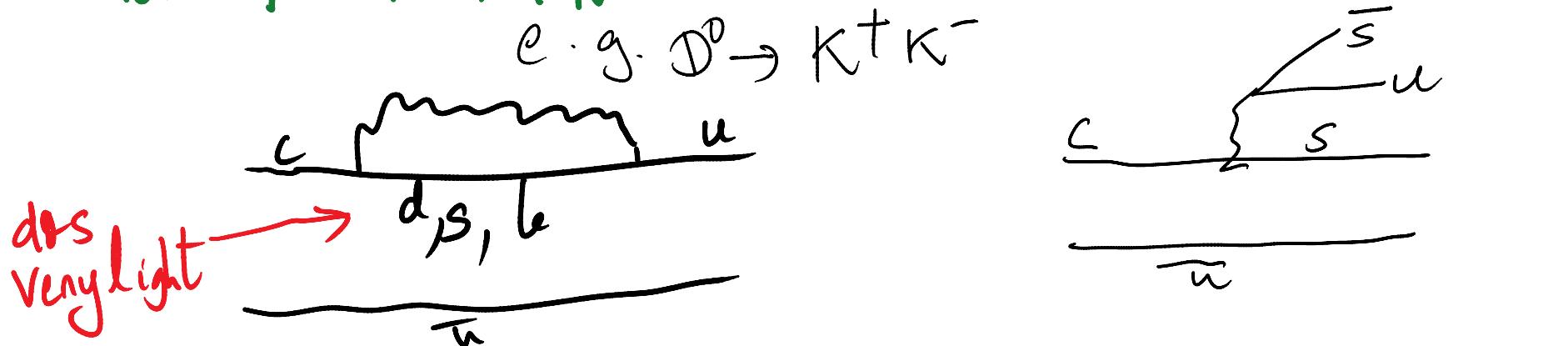
Hopefully many more to come....

Franco, Mihama , Silverstein' 1213.3131

Gist of talk

- SM explanation cannot be ruled out and is plausible
- Huge hadronic uncertainties make precise predictions virtually impossible
- More experimental input (other modes) may be useful
- Potentially charm CP very sensitive to new phase(s): warped models; 4 G' ; LR.....

BACK of a NAPKIN



$$\Delta A_{CP} \sim 4 \left(\frac{P}{T}\right) \frac{V_{ub} V_{cb}^*}{V_{cs}^* V_{us}} \Rightarrow 4 A^2 \lambda^4 m \sin \delta_{ST} \left(\frac{P}{T}\right)$$

$\sim 2 \times 10^{-3}$ *HIGHLY
Nonperturbative*

$\Delta A_{CP} \Rightarrow 0$ EXACT Uspim

Nanely $\frac{P}{T} \sim \alpha_s(m_c)/\pi \sim 0.3$ MISLEADING

Peek @ PDG: old results

$$\text{BR}[D^0 \rightarrow K^-\pi^+] = (3.949 \pm 0.023 \pm 0.040 \pm 0.025)\%,$$

$$\text{BR}[D^0 \rightarrow \pi^+\pi^-] = (0.1425 \pm 0.0019 \pm 0.0018 \pm 0.0014)\%,$$

$$\text{BR}[D^0 \rightarrow K^+K^-] = (0.3941 \pm 0.0038 \pm 0.0050 \pm 0.0024)\%,$$

$$\frac{\text{BR}[D^0 \rightarrow K^+\pi^-]}{\text{BR}[D^0 \rightarrow K^-\pi^+]} = (0.331 \pm 0.008)\%,$$

$$\text{obs}_1 \equiv \frac{\text{BR}[D^0 \rightarrow K^+K^-]/|\vec{p}_K|}{\text{BR}[D^0 \rightarrow \pi^+\pi^-]/|\vec{p}_\pi|} \simeq 3.22 \pm 0.09$$

$$\text{obs}_2 \equiv \frac{\text{Br}[D^0 \rightarrow K^-\pi^+]/|\vec{p}_{\pi K}|}{\text{Br}[D^0 \rightarrow K^+K^-]/|\vec{p}_K|} \lambda^2 \simeq 0.47 \pm 0.01,$$

$$\text{obs}_3 \equiv \frac{\text{Br}[D^0 \rightarrow K^+\pi^-]}{\text{Br}[D^0 \rightarrow K^-\pi^+]} \lambda^{-4} \simeq 1.28 \pm 0.03,$$

↗ +1

⇒ USpin Badly Broken

EXACT U-SPIN LIMIT

$$H_{\text{eff}}(c \rightarrow us\bar{d}) = - (V_{cs}^* V_{ud}) H_{U=1}^{(U_3=-1)},$$

$$H_{\text{eff}}(c \rightarrow uq\bar{q}) = \left(\frac{V_{cd}^* V_{ud} - V_{cs}^* V_{us}}{\sqrt{2}} \right) H_{U=1}^{(U_3=0)} + (V_{cd}^* V_{ud} + V_{cs}^* V_{us}) H_{U=0},$$

$$H_{\text{eff}}(c \rightarrow ud\bar{s}) = (V_{cd}^* V_{us}) H_{U=1}^{(U_3=+1)}.$$

$$\mathcal{A}[D^0 \rightarrow K^- \pi^+] = 2 V_{cs}^* V_{ud} B_{U=1},$$

$\lambda_q = V_{cq}^* V_{uq}$ $q = d, s$
 $\xrightarrow{\mathcal{O}(\mathcal{N})}$

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

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

$$\mathcal{A}[D^0 \rightarrow K^+ \pi^-] = 2 V_{cd}^* V_{us} B_{U=1},$$

$\xrightarrow{\mathcal{O}(\lambda)}$

Taking U-spin breaking into a/c

$$\mathcal{A}[D^0 \rightarrow K^- \pi^+] \equiv 2 V_{cs}^* V_{ud} (B_{U=1} - \Delta B'_{U=1}) = 2 V_{cs}^* V_{ud} B_{U=1} \left[1 - r'_1 e^{i\phi'_1} \right],$$

$$\begin{aligned} \mathcal{A}[D^0 \rightarrow \pi^+ \pi^-] &= (\lambda_d + \lambda_s) (A_{U=0} + \Delta B_{U=1}) + (\lambda_d - \lambda_s) (B_{U=1} + \Delta A_{U=0}) \\ &= B_{U=1} \left[(\lambda_d + \lambda_s) \left(r e^{i\phi} + r_1 e^{i\phi_1} \right) + (\lambda_d - \lambda_s) \left(1 + r_0 e^{i\phi_0} \right) \right], \end{aligned}$$

$$\begin{aligned} \mathcal{A}[D^0 \rightarrow K^+ K^-] &= (\lambda_d + \lambda_s) (A_{U=0} - \Delta B_{U=1}) - (\lambda_d - \lambda_s) (B_{U=1} - \Delta A_{U=0}) \\ &= B_{U=1} \left[(\lambda_d + \lambda_s) \left(r e^{i\phi} - r_1 e^{i\phi_1} \right) - (\lambda_d - \lambda_s) \left(1 - r_0 e^{i\phi_0} \right) \right], \end{aligned}$$

$$\mathcal{A}[D^0 \rightarrow K^+ \pi^-] = 2 V_{cd}^* V_{us} (B_{U=1} + \Delta B'_{U=1}) = 2 V_{cd}^* V_{us} B_{U=1} \left[1 + r'_1 e^{i\phi'_1} \right].$$

SOURCE OF U-SPIN BREAKING: $m_s \neq m_d$

U-spin violation

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

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

$$\mathcal{A}[D^0 \rightarrow K^-\pi^+] = 2V_{cs}^* V_{ud} B_{U=1} \left[1 - r'_1 e^{i\phi'_1} \right]$$

$$\mathcal{A}[D^0 \rightarrow \pi^+\pi^-] = B_{U=1} \left[(\lambda_d + \lambda_s) (r e^{i\phi} + r_1 e^{i\phi_1}) + (\lambda_d - \lambda_s) (1 + r_0 e^{i\phi_0}) \right]$$

$$\mathcal{A}[D^0 \rightarrow K^+K^-] = B_{U=1} \left[(\lambda_d + \lambda_s) (r e^{i\phi} - r_1 e^{i\phi_1}) - (\lambda_d - \lambda_s) (1 - r_0 e^{i\phi_0}) \right]$$

$$\mathcal{A}[D^0 \rightarrow K^+\pi^-] = 2V_{cd}^* V_{us} B_{U=1} \left[1 + r'_1 e^{i\phi'_1} \right]$$

$$\Rightarrow \text{Amplitude Ratios: } r_0 = \left| \frac{\Delta A_{U=0}}{B_{U=1}} \right|, \quad r_1 = \left| \frac{\Delta B_{U=1}}{B_{U=1}} \right|, \quad r = \left| \frac{\Delta A_{U=0}}{B_{U=1}} \right|$$

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

\Rightarrow Parameters need to fit: $r_0, r'_1, r_1, r, \phi_0, \phi'_1, \phi_1$ and ϕ

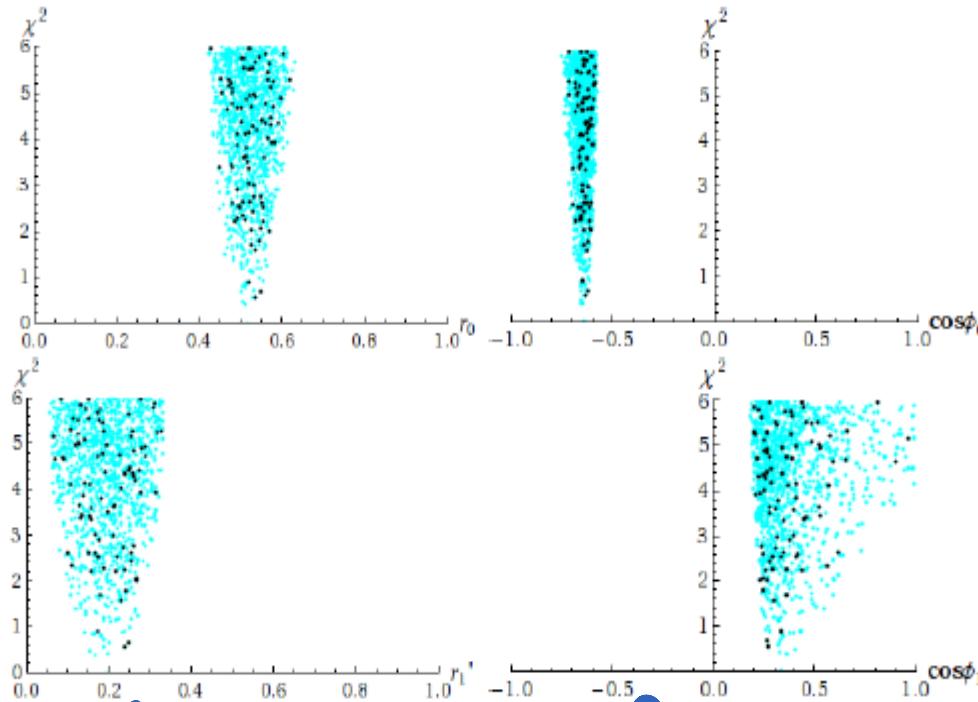
$$\Rightarrow \text{Available data: } R_1, R_2, R_3, \Delta A_{CP}, \text{Arg} \left(\frac{\mathcal{A}[D^0 \rightarrow K^-\pi^+]}{\mathcal{A}[D^0 \rightarrow K^+\pi^-]} \right) \approx \Delta\phi = 22.4^\circ \pm 9.7^\circ$$

\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} !!

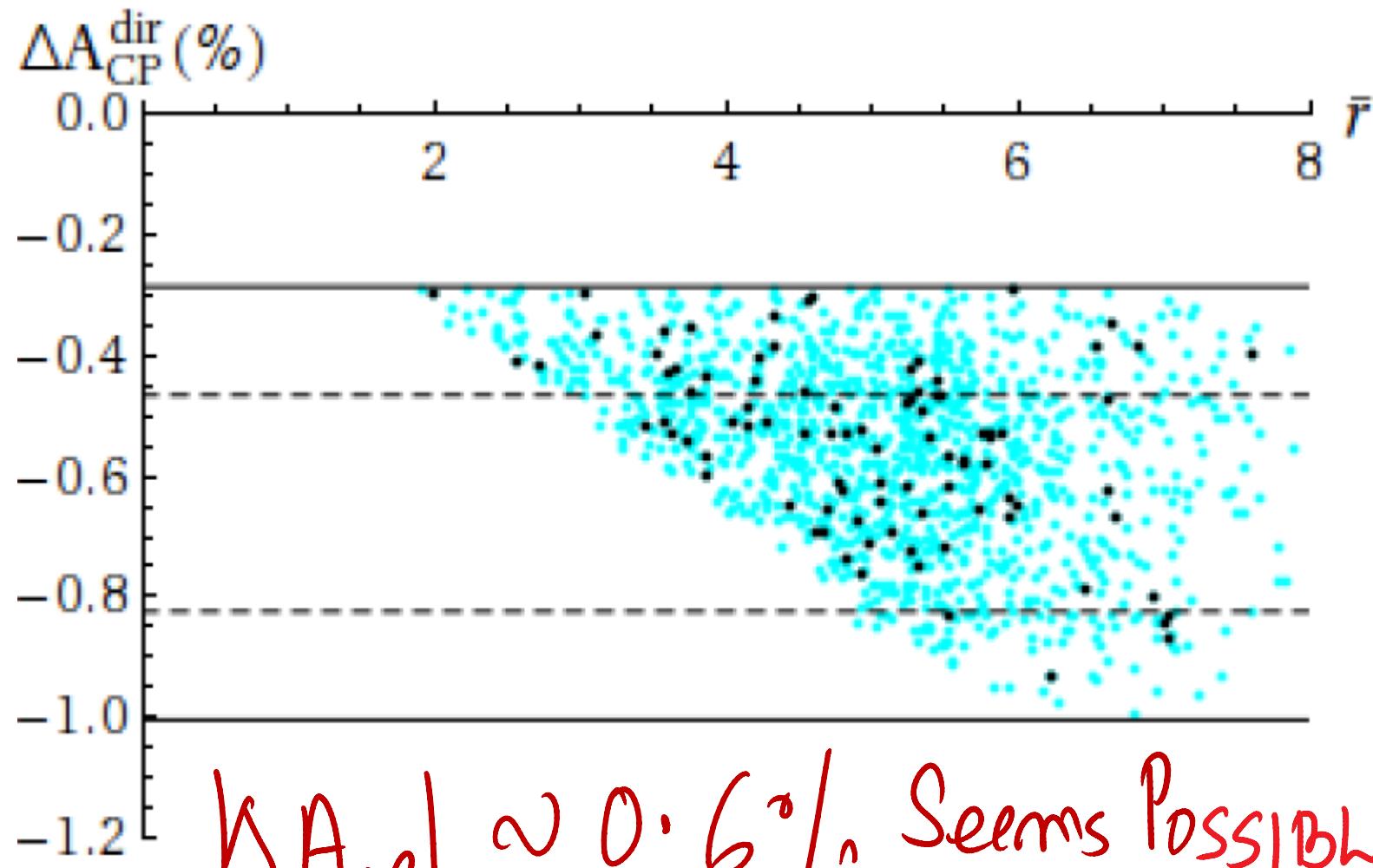
FIT to BR _{$D^0 \rightarrow P^+ P^-$} to Constaain U-Spin Breaking



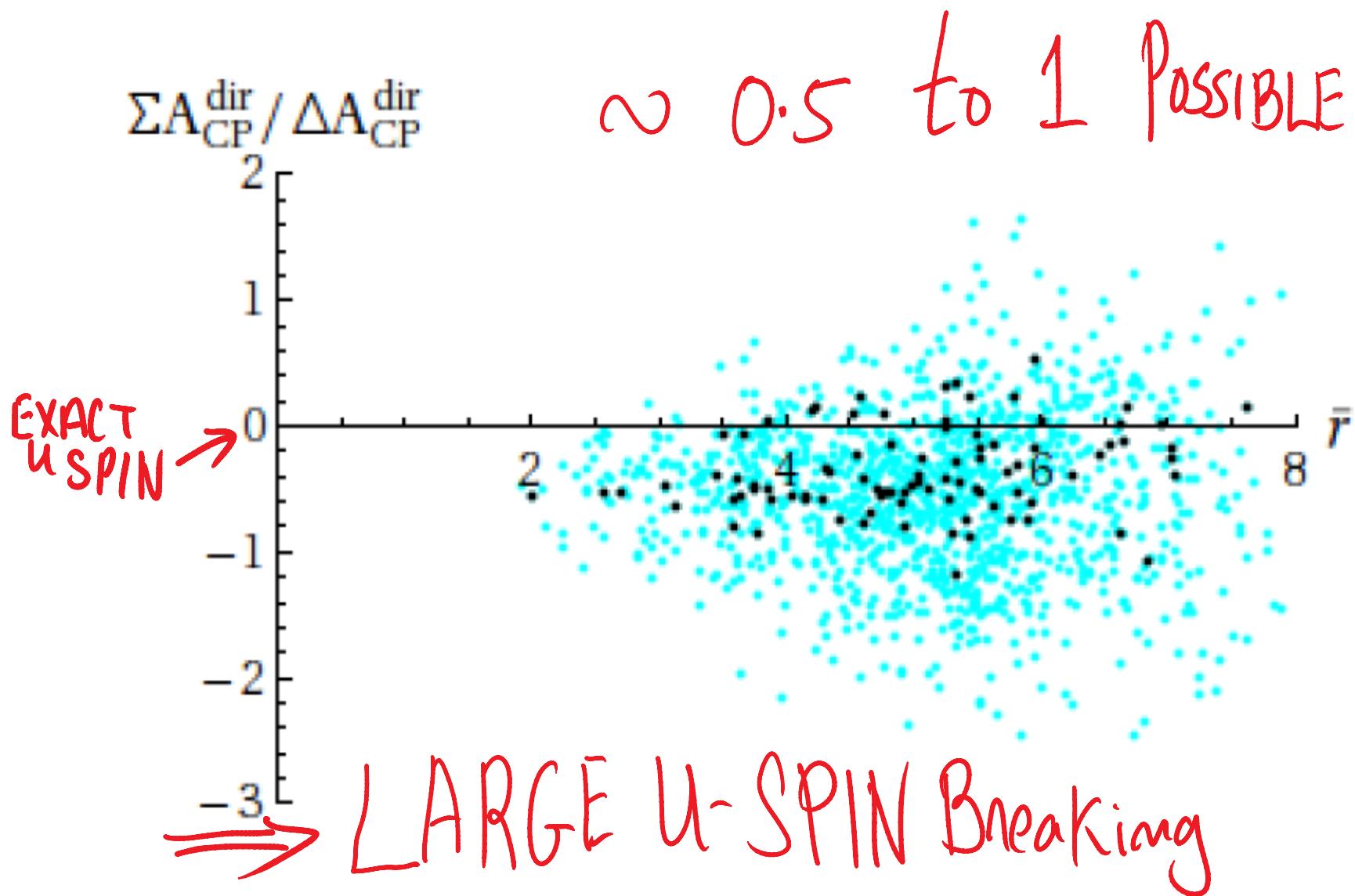
Amplitude Ratios

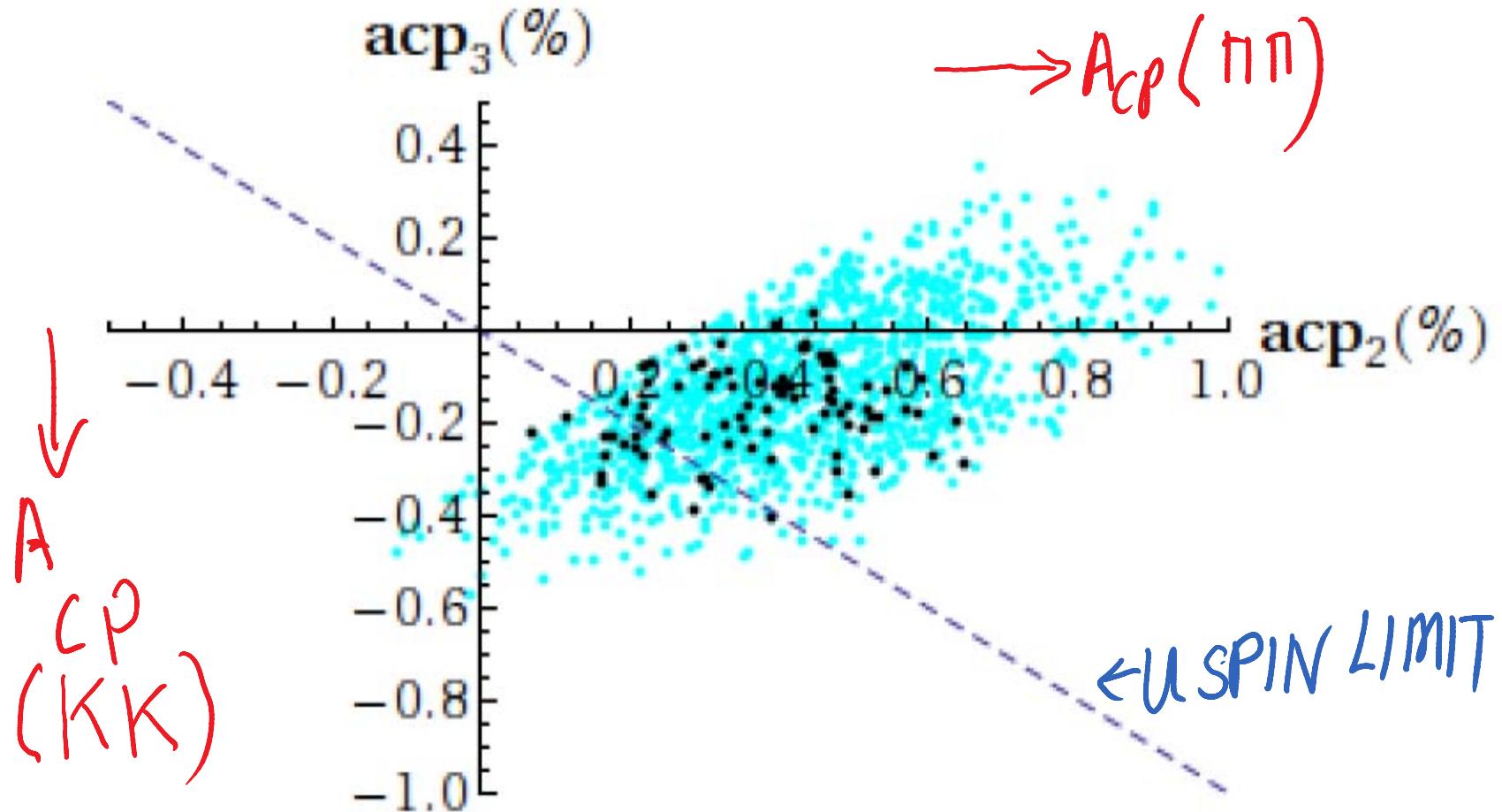
STRONG PHASES

Figure 1. Fit result for the amplitude parameters r_0 and $\cos\phi_0$ (upper row) and r'_1 and $\cos\phi'_1$ (lower row), determining the amount of U-spin breaking in $D^0 \rightarrow P^+ P^-$ BRs. The generic points shown in light blue are consistent with the experimental constraints at the 2σ -level and obey $\chi^2 \leq 6$. The black points denote a subset of points where the strong phase differences between $A_{U=0}$ and $\Delta A_{U=0}$, as well as between $B_{U=1}$ and $\Delta B_{U=1}$ are assumed to be equal within a few percent, $(\phi - \phi_0) = \{0, \pi\}$ and $\phi_1 = \{0, \pi\}$.



$|\Delta A_{CP}| \approx 0.6\%$, Seems POSSIBLE
 $> 1\%$ HIGHLY UNLIKELY





MORE EXPERIMENTAL INPUT COULD BE VERY USEFUL (PDG + HFA6 would $A_{\phi} \neq 0$)

Mode	BR	A_{CP} in %	5σ Reach
$D^+ \rightarrow K_S \pi^+$	1.47×10^{-2}	-0.52 ± 0.14 [32]	1×10^{-3}
$D_s \rightarrow \eta' \pi^+$	3.94×10^{-2}	-6.1 ± 3.0 [63]	0.7×10^{-3}
		$-5.5 \pm 3.7 \pm 1.2$ [32]	
$D_s \rightarrow K_S \pi^+$	1.21×10^{-3}	6.6 ± 3.3 [63]	4×10^{-3}
		6.53 ± 2.46 [32]	

THESE Need classification.

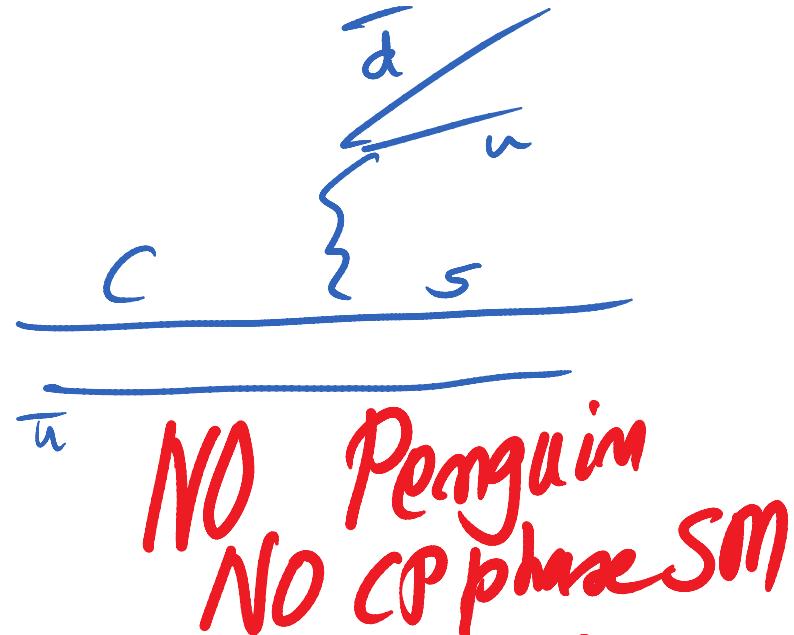
AT ISSUE IS DIRECT CP \Rightarrow USE D^\pm , D_s
 MANY INTERESTING MODES e.g. $D^0 \rightarrow K^{*\pm} K^\mp, \rho^\pm \pi^\mp$
 $D^+ \rightarrow K^{*0} \pi^+, \phi \pi^+$
 $D_s \rightarrow \phi \pi^+, \eta' \pi^+, \bar{K}^{(\mp)0} \pi^\pm, \phi K^\pm$

Important to measure CP in pure trees

Example

$D^0 \rightarrow K^- \pi^+$

[NICE FINAL STATE]



NO Penguin

NO CP phase SM

ESPECIALLY IMPORTANT To Search CP
since Extractions ASSUME No CP in D^0

Conclusion on Recent D-CP results

- *SM explanation cannot be ruled out and is quite plausible; however, a compelling case for SM explanation can also not be made.*
- *Unless true result is , for sure, 1% or more , not a compelling sign of new physics*
- *theory estimates plagued by large hadronic (non-perturbative) uncertainties; NO RIGOUROUS METHOD IN SIGHT; LONG-TERM WORRY => Ghost of ε'/ε . However, unlike K-> pi pi, lattice methods appear exceedingly difficult*
- *More exptal input (many other modes) crucial & could change interpretation...*

EXTRA

Natural Explanation from SM Penguin Enhancement?

[Brod, Grossman, Kagan, Zupan 2012]

- Re-parametrize:

$$r_0/r'_1 = \frac{\epsilon |2s_1|}{\epsilon |t_1|} \gg 1, \quad (\leftarrow \text{BRs})$$
$$r_1 = \frac{\epsilon |p_1|}{|t_0|} \sim 1, \quad r = \frac{2p_0}{t_0} \gg 1 \quad (\rightarrow \Delta A_{CP})$$

- assign enhancement to penguin contractions of tree operators
- U-spin breaking (ϵ) of “nominal size”

FROM T. Feldmann