CP violation in charm: from Rags to Riches

Ayan Paul

DESY, Hamburg

Institut für Physik, Humboldt-Universität zu Berlin

HUMBOLDT-UNIVERSITÄT ZU BERLIN

Geneva. November 9th 2017.

I know she invented fire,
but what has she done recently?

Ikaros I. Bigi

what are we looking at?

D^0, D^+ and D_s^+ with π, K in the final states

SCS			CA & DCS		
Channel	Fit ($\times 10^{-3}$)	Exp. ($\times 10^{-3}$)	Channel	Fit ($\times 10^{-3}$)	Exp. ($\times 10^{-3}$)
$D^0 \to \pi^+\pi^-$	1.42 ± 0.03	1.421 ± 0.025	$D^+ \to \pi^+ K_S$	15.71 ± 0.41	15.3 ± 0.6
$D_0^+ \to \pi^0\pi^0$	0.82 ± 0.04	0.826 ± 0.035	$D^+ \to \pi^+ K_L$	14.25 ± 0.38	14.6 ± 0.5
$D^+ \to \pi^+\pi^0$	1.25 ± 0.06	1.24 ± 0.06	$D^0 \to \pi^+ K^-$	39.40 ± 0.40	39.3 ± 0.4
$D^0 \to K^+K^-$	3.95 ± 0.06	4.01 ± 0.07	$D^0 \to \pi^0 K_S$	12.14 ± 0.33	12.0 ± 0.4
$D^0 \to K_S K_S$	0.17 ± 0.04	0.18 ± 0.04	$D^0 \to \pi^0 K_L$	9.57 ± 0.27	10.0 ± 0.7
$D^+ \to K^+ K_S$	3.06 ± 0.13	2.95 ± 0.15	$D_s^+ \to K^+ K_S$	14.80 ± 0.49	15.0 ± 0.5
$D_s^+ \to \pi^0 K^+$	1.05 ± 0.16	0.63 ± 0.21	$D^+ \to \pi^0 K^+$	0.128 ± 0.012	0.189 ± 0.025
$D_s^+ \to \pi^+ K_S$	1.22 ± 0.06	1.22 ± 0.06	$D^0 \to \pi^- K^+$	0.141 ± 0.003	0.139 ± 0.0027

A_{CP} (D^0)	($\mu \pm \sigma$) (%)		A_{CP} ($D^+_{(s)}$)	($\mu \pm \sigma$) (%)	
	$\delta_i \to$ -ve	$\delta_i \to$ +ve		$\delta_i \to$ -ve	$\delta_i \to$ +ve
$D^0 \to \pi^+\pi^-$	0.043 ± 0.054	0.045 ± 0.055	$D^+ \to K^+ K_S$	-0.012 ± 0.014	-0.010 ± 0.014
$D^0 \to \pi^0\pi^0$	-0.019 ± 0.026	0.056 ± 0.030	$D_s^+ \to \pi^+ K_S$	0.015 ± 0.018	0.013 ± 0.018
$D^0 \to K^+K^-$	-0.018 ± 0.022	-0.016 ± 0.022	$D_s^+ \to \pi^0 K^+$	-0.045 ± 0.017	0.021 ± 0.018
$D^0 \to K_S K_S$	0.019 ± 0.021	0.012 ± 0.024			

FIT

PREDICTION

hence we need a parameterization…

the weak Hamiltonian:

$$\mathcal{H}_{\rm w} = \frac{G_F}{\sqrt{2}} V_{ud}\, V_{cd}^* \left[C_1 Q_1^d + C_2 Q_2^d\right] + \frac{G_F}{\sqrt{2}} V_{us}\, V_{cs}^* \left[C_1 Q_1^s + C_2 Q_2^s\right] - \frac{G_F}{\sqrt{2}} V_{ub}\, V_{cb}^* \sum_{i=3}^{6} C_i Q_i + h.c.$$

the operator basis:

$$Q_1^d = \bar{u}^\alpha\, \gamma_\mu (1-\gamma_5) d_\beta\, \bar{d}^\beta\, \gamma^\mu (1-\gamma_5)\, c_\alpha\ ,$$
$$Q_2^d = \bar{u}^\alpha\, \gamma_\mu (1-\gamma_5) d_\alpha\, \bar{d}^\beta\, \gamma^\mu (1-\gamma_5)\, c_\beta\ ,$$
$$Q_3 = \bar{u}^\alpha\, \gamma_\mu (1-\gamma_5)\, c_\alpha \sum_q \bar{q}^\beta \gamma^\mu (1-\gamma_5)\, q_\beta ,$$
$$Q_4 = \bar{u}^\alpha\, \gamma_\mu (1-\gamma_5)\, c_\beta \sum_q \bar{q}^\beta \gamma^\mu (1-\gamma_5)\, q_\alpha ,$$
$$Q_5 = \bar{u}^\alpha\, \gamma_\mu (1-\gamma_5)\, c_\alpha \sum_q \bar{q}^\beta \gamma^\mu (1+\gamma_5)\, q_\beta .$$
$$Q_6 = \bar{u}^\alpha\, \gamma_\mu (1-\gamma_5)\, c_\beta \sum_q \bar{q}^\beta \gamma^\mu (1+\gamma_5)\, q_\alpha .$$

the *U*-spin components:

$$\begin{aligned} H_{\Delta U=1} &= \frac{G_F}{2\sqrt{2}} (V_{us}\, V_{cs}^* - V_{ud}\, V_{cd}^*) [C_1 (Q_1^s - Q_1^d) + C_2 (Q_2^s - Q_2^d)] \\ &\simeq \frac{G_F}{\sqrt{2}} \sin\theta_C \cos\theta_C [C_1 (Q_1^s - Q_1^d) + C_2 (Q_2^s - Q_2^d)]. \end{aligned}$$

CP conserving

CP violating

$$H_{\Delta U=0} = -\frac{G_F}{\sqrt{2}} V_{ub}\, V_{cb}^* \left\{ \sum_{i=3}^{6} C_i Q_i + \frac{1}{2} [C_1 (Q_1^s + Q_1^d) + C_2 (Q_2^s + Q_2^d)] \right\}$$

weak amplitude + rescattering + small $SU(3)_f$ breaking amplitudes

parameterization of the ΔU = 1 part

$$H_{\Delta U=1} = \frac{G_F}{2\sqrt{2}}(V_{us}\,V_{cs}^* - V_{ud}\,V_{cd}^*)[C_1(Q_1^s - Q_1^d) + C_2(Q_2^s - Q_2^d)]$$
$$\simeq \frac{G_F}{\sqrt{2}}\sin\theta_C\cos\theta_C[C_1(Q_1^s - Q_1^d) + C_2(Q_2^s - Q_2^d)].$$

$$\frac{\langle f||6_{I=1/2}||i\rangle}{\langle f||6_{I=0}||i\rangle} = \frac{V_{cd}^* V_{ud} - V_{cs}^* V_{us}}{\sqrt{2}V_{cd}^* V_{us}}\,, \quad \frac{\langle f||6_{I=1}||i\rangle}{\langle f||6_{I=0}||i\rangle} = -\frac{V_{cs}^* V_{ud}}{V_{cd}^* V_{us}}$$

$$\frac{\langle f||15_{I=3/2}||i\rangle}{\langle f||15_{I=1/2}||i\rangle} = -\frac{2\sqrt{2}V_{cd}^* V_{ud}}{V_{cd}^* V_{ud} - 3V_{cs}^* V_{us}}\,, \quad \frac{\langle f||15_{I=3/2}||i\rangle}{\langle f||15_{I=1}||i\rangle} = \sqrt{\frac{2}{3}}\frac{V_{cd}^* V_{ud}}{V_{cs}^* V_{ud} + V_{cd}^* V_{us}}$$

- ✓ we would like to introduce the minimal $SU(3)_f$ breaking through FSI but enough to give a coherent picture of the branching fractions. In the $SU(3)_f$ limit the only reduced matrix elements are:

$$R^6_{8,1} \to \frac{1}{\sqrt{30}}(5T - 5C + \Delta)\,e^{i\delta_0},\ R^{15}_{8,1} \to -\frac{1}{\sqrt{30}}(T + C - \Delta)\,e^{i\delta_0},\ R^{15}_{27,1} \to \frac{3}{\sqrt{5}}(T + C)$$
$$R^6_{8,0} \to -\frac{1}{\sqrt{30}}(5T - 5C + \Delta)\,e^{i\delta_0}$$

CA and DCS

$$R^6_{8,1/2} \to -\sqrt{\frac{5}{3}}(T - C + \Delta)e^{i\delta_0},\ R^{15}_{8,1/2} \to \frac{1}{3}\sqrt{\frac{2}{5}}(T + C - \Delta)\,e^{i\delta_0},\ R^{15}_{8,3/2} \to -\frac{1}{3\sqrt{5}}(T + C - \Delta)\,e^{i\delta_0},$$
$$R^{15}_{27,1/2} \to -2\sqrt{\frac{3}{5}}(T + C),\ R^{15}_{27,3/2} \to \sqrt{\frac{6}{5}}(T + C)$$

SCS

$T \to$ colour connected, $C \to$ colour suppressed, $\Delta \to SU(3)_f$ conserving contribution from annihilation

parameterization of the ΔU = 1 part

once SU(3) is broken:

$$R^{6}_{8,1} \to \sqrt{\frac{1}{30}}\left[(2T-3C+\Delta)\,e^{i\delta'_1} + (3T-2C-K)\,e^{i\delta_{\frac{1}{2}}}\right]$$

$$R^{15}_{8,1} \to \sqrt{\frac{1}{30}}\left[(2T-3C+\Delta)\,e^{i\delta'_1} - (3T-2C-K)\,e^{i\delta_{\frac{1}{2}}}\right]$$

$$R^{15}_{27,1} \to \frac{3}{\sqrt{5}}\,(T+C+\kappa)$$

CA

K and *K'* are $SU(3)_f$ violating contributions to annihilation

$$\boxed{\frac{\mathrm{BR}(D^0\to K^+\pi^-)}{\mathrm{BR}(D^0\to K^-\pi^+)} \neq \tan^4\theta_C}$$

$$R^{6}_{8,0} \to -\sqrt{\frac{1}{30}}\,(5T-5C+\Delta+K-K')\,e^{i\delta_{\frac{1}{2}}}$$

$$R^{15}_{8,1} \to -\sqrt{\frac{1}{30}}\,(T+C-\Delta+K+K')\,e^{i\delta_{\frac{1}{2}}}$$

$$R^{15}_{27,1} \to \frac{3}{\sqrt{5}}\,(T+C+\kappa')$$

DCS

$$\boxed{\delta'_1 = \delta_1(1-\epsilon_\delta) \text{ and } \delta'_{\frac{1}{2}} = \delta_{\frac{1}{2}}(1-\epsilon_\delta)}$$

phases for the D_s^+

24 and 42 transitions are not generated by $SU(3)_f$ breaking

$$\boxed{\tan\theta_C A(D^+\to \bar{K}^0\pi^+) \neq \sqrt{2}A(D^+\to\pi^0\pi^+)}$$

R^{15}_{27}: should be different in CA and DCS so κ is introduced.

No exotic resonances in 27: FSI phase small and set to 0

singlet-octet mixing

$$R^{3}_{1,1/2} \to -\frac{3}{2\sqrt{10}}\left(T-\frac{2}{3}C\right)\left(e^{i\delta_0}-e^{i\delta'_0}\right)\sin 2\phi$$

$$R^{3}_{8,1/2} \to -\frac{3}{8\sqrt{10}}\left(T-\frac{2}{3}C\right)\left(\left(e^{i\delta_0}+e^{i\delta'_0}\right)-\cos 2\phi\left(e^{i\delta_0}-e^{i\delta'_0}\right)\right)+\frac{1}{4\sqrt{10}}\,(7T-8C+2\Delta)\,e^{i\delta_1}$$
$$-\frac{1}{2\sqrt{10}}\,(2T-3C+\Delta-K')\,e^{i\delta'_{\frac{1}{2}}}$$

$$R^{6}_{8,1/2} \to -\frac{3}{8}\sqrt{\frac{3}{5}}\left(T-\frac{2}{3}C\right)\left(\left(e^{i\delta_0}+e^{i\delta'_0}\right)-\cos 2\phi\left(e^{i\delta_0}-e^{i\delta'_0}\right)\right)-\frac{1}{4\sqrt{15}}\,(7T-8C+2\Delta)\,e^{i\delta_1}$$
$$-\frac{1}{2\sqrt{15}}\,(2T-3C+\Delta-K')\,e^{i\delta'_{\frac{1}{2}}}$$

$$R^{15}_{8,1/2} \to \frac{9}{8\sqrt{10}}\left(T-\frac{2}{3}C\right)\left(\left(e^{i\delta_0}+e^{i\delta'_0}\right)-\cos 2\phi\left(e^{i\delta_0}-e^{i\delta'_0}\right)\right)-\frac{1}{12\sqrt{10}}\,(7T-8C+2\Delta)\,e^{i\delta_1}$$
$$-\frac{1}{2\sqrt{10}}\,(2T-3C+\Delta-K')\,e^{i\delta'_{\frac{1}{2}}}$$

$$R^{15}_{8,3/2} \to -\frac{1}{3\sqrt{5}}\,(T+C-\Delta)\,e^{i\delta_1}$$

SCS

parameterization of the ΔU = 0 part

$$H_{\Delta U=0} = -\frac{G_F}{\sqrt{2}} V_{ub} V_{cb}^* \left\{ \sum_{i=3}^{6} C_i Q_i + \frac{1}{2}[C_1(Q_1^s + Q_1^d) + C_2(Q_2^s + Q_2^d)] \right\}$$

$$\boxed{\mathcal{P} = (P + T + \Delta_3)}$$

$$B(D^0 \to K^+ K^-) = P + T + \Delta_3,$$ P and Δ_3 cannot be disentangled

$$B(D^0 \to K^0 \bar{K}^0) = \Delta_4.$$

vanishingly small since it requires the simultaneous creation of strange and down quarks pair. Suppression similar to OZI suppression but stronger.

All phases in the ΔU = 0 part are determined by the ΔU = 1 part and extracted from the branching fractions

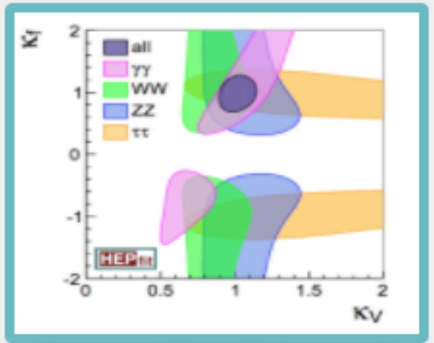
$$\begin{aligned} B(D^0 \to \pi^+\pi^-) = {} & \mathcal{P}\left(\frac{1}{2}\left(e^{i\delta_0'} + e^{i\delta_0}\right) + \left(e^{i\delta_0'} - e^{i\delta_0}\right)\left(-\frac{1}{6}\cos(2\phi) - \frac{7}{4\sqrt{10}}\sin(2\phi)\right)\right) \\ & + (T+C)\left(-\frac{3}{20}\left(e^{i\delta_0'} + e^{i\delta_0}\right) + \frac{3}{10} + \left(\frac{1}{60}\cos(2\phi) + \frac{1}{2\sqrt{10.}}\sin(2\phi)\right)\left(e^{i\delta_0'} - e^{i\delta_0}\right)\right) \\ & + \Delta_4\left(e^{i\delta_0'} - e^{i\delta_0}\right)\left(-\frac{1}{3}\cos(2\phi) - \frac{1}{4\sqrt{10}}\sin(2\phi)\right), \end{aligned}$$

$$\begin{aligned} B(D^0 \to K^+K^-) = {} & \mathcal{P}\left(\frac{1}{4}\left(e^{i\delta_0'} + e^{i\delta_0}\right) + \left(e^{i\delta_0'} - e^{i\delta_0}\right)\left(-\frac{5}{12}\cos(2\phi) + \frac{1}{4\sqrt{10}}\sin(2\phi)\right) + \frac{1}{2}e^{i\delta_1}\right) \\ & + (T+C)\left(-\frac{1}{20}\left(e^{i\delta_0'} + e^{i\delta_0}\right) + \frac{3}{10} + \frac{7}{60}\cos(2\phi)\left(e^{i\delta_0'} - e^{i\delta_0}\right) - \frac{1}{5}e^{i\delta_1}\right) \\ & + \Delta_4\left(\frac{1}{4}\left(e^{i\delta_0'} + e^{i\delta_0}\right) + \left(e^{i\delta_0'} - e^{i\delta_0}\right)\left(-\frac{1}{12}\sin(2\phi) + \frac{3}{4\sqrt{10}}\sin(2\phi)\right) - \frac{1}{2}e^{i\delta_1}\right) \end{aligned}$$

HEPfit

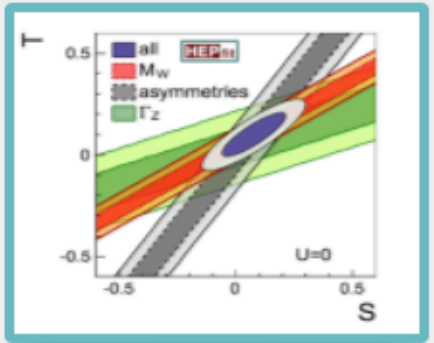
home developers samples documentation

HEPfit: a Code for the Combination of Indirect and Direct Constraints on High Energy Physics Models.



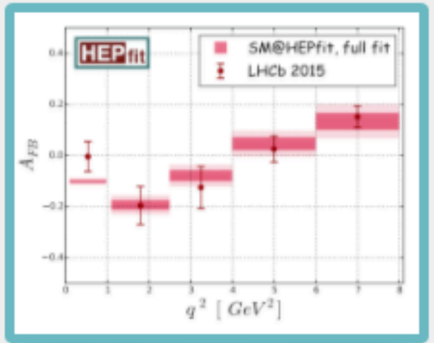
Higgs Physics

HEPfit can be used to study Higgs couplings and analyze data on signal strengths.



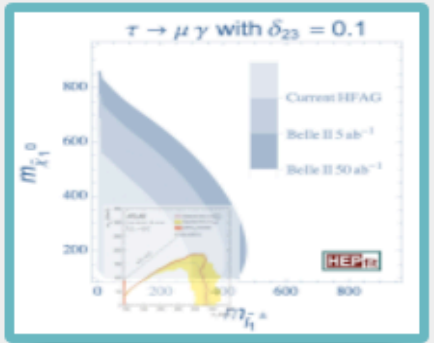
Precision Electroweak

Electroweak precision observables are included in HEPfit



Flavour Physics

The Flavour Physics menu in HEPfit includes both quark and lepton flavour dynamics.



BSM Physics

Dynamics beyond the Standard Model can be studied by adding models in HEPfit.

the solutions

LhCb Imp '17: Cooked specially for this workshop since it did not rain in Rome.

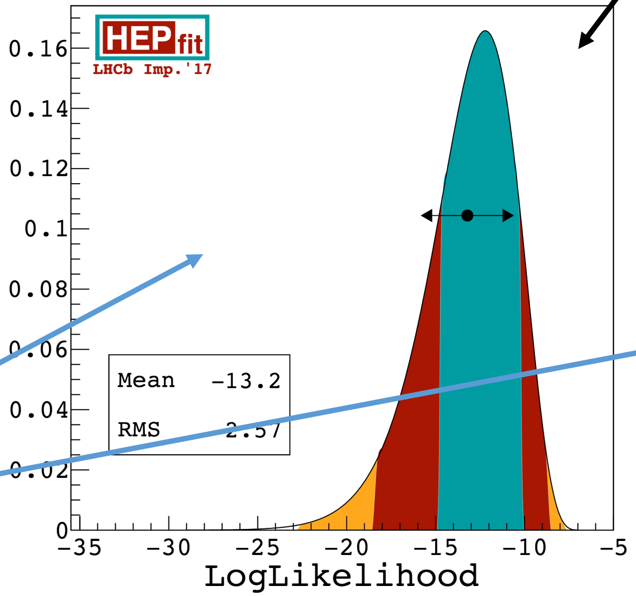
The Gell-Mann-Ne'eman-Okubo mass formula sets a direction for the choice of the sign of the phases based on the hierarchy of the phases since they correspond to resonances of particular isospin

The negative solution is favoured if we accept that the phases are generated by FSI due to a nonet of scalar resonances

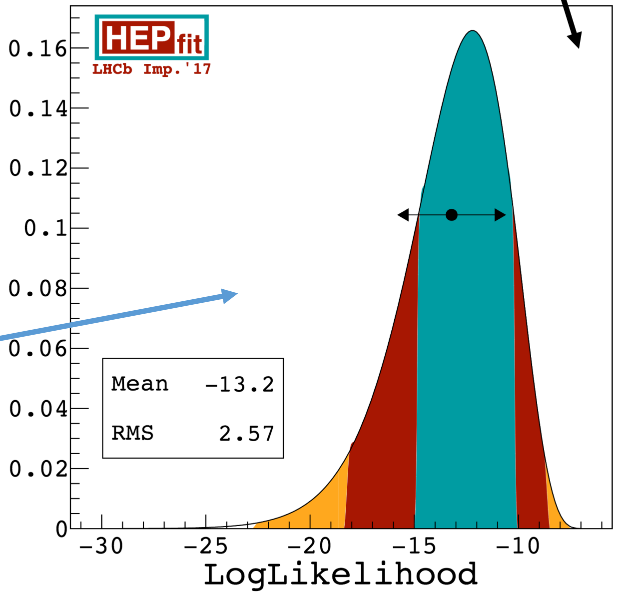
NOT measures of goodness of fit!

	$(\mu \pm \sigma)$		$(\mu \pm \sigma)$	
T	0.424 ± 0.003	δ_0	-2.518 ± 0.150	2.518 ± 0.150
C	-0.210 ± 0.004	δ_0'	-0.938 ± 0.098	0.938 ± 0.098
κ	-0.037 ± 0.006	$\delta_{\frac{1}{2}}$	-1.607 ± 0.030	1.607 ± 0.030
K	0.099 ± 0.012	δ_1	-1.191 ± 0.060	1.191 ± 0.060
K'	0.019 ± 0.098			
Δ	-0.005 ± 0.035			
ϕ	0.394 ± 0.049	$(P + \Delta_3)/T$	-1.140 ± 0.534	-0.284 ± 0.534
ϵ_δ	0.053 ± 0.080			

negative phases



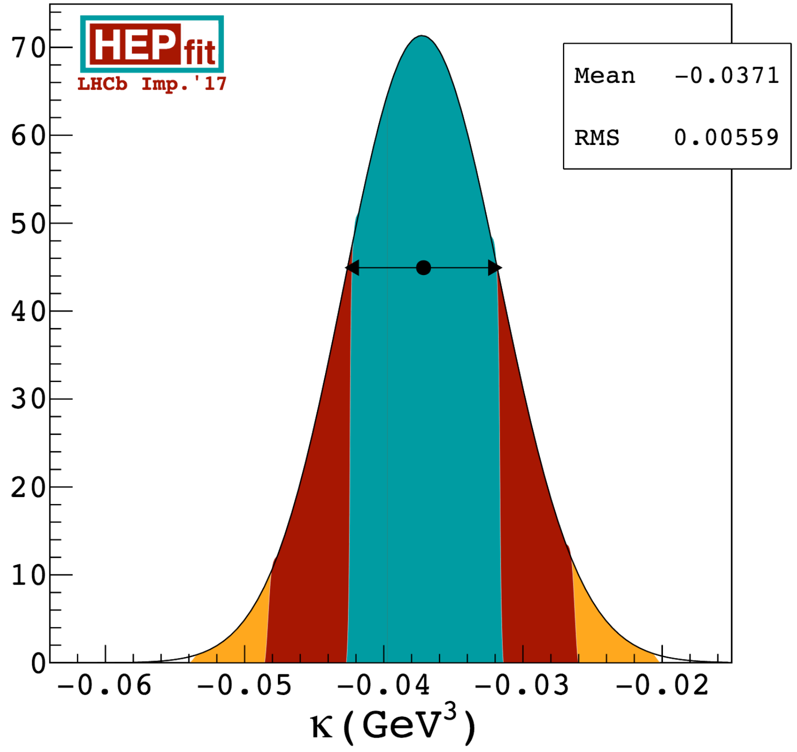
positive phases

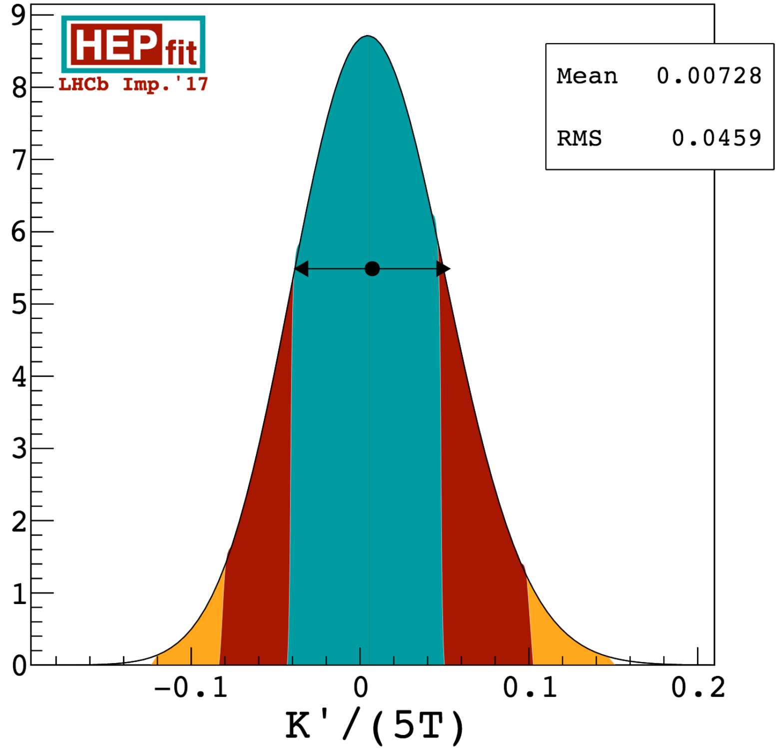


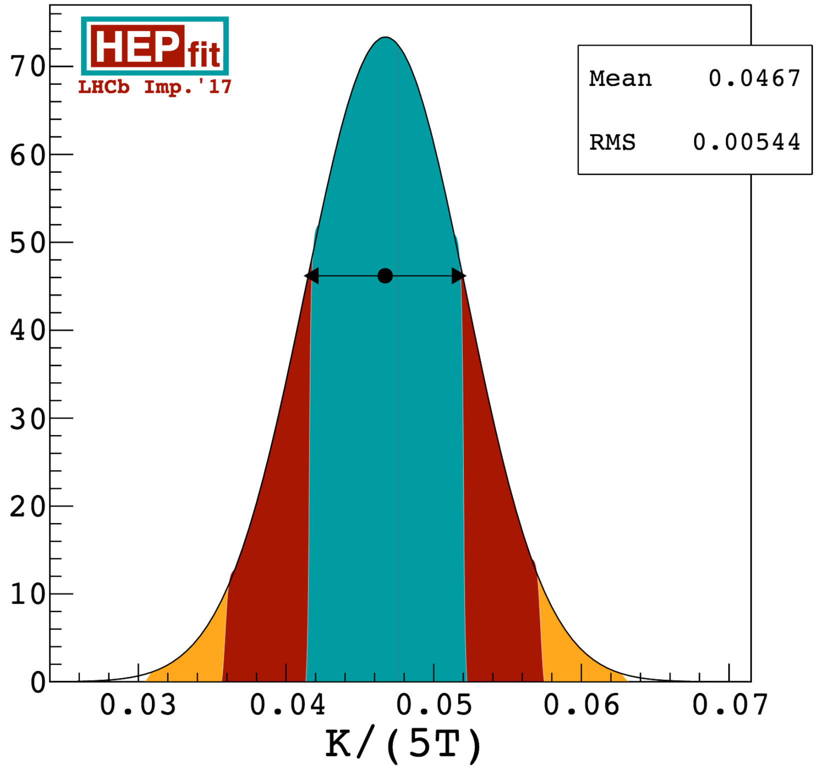
an estimate of $SU(3)_f$ breaking

Note: All $SU(3)_f$ breaking amplitudes are small in consistency with the hypothesis that the breaking of the symmetry is brought about by the strong phases from FSI.

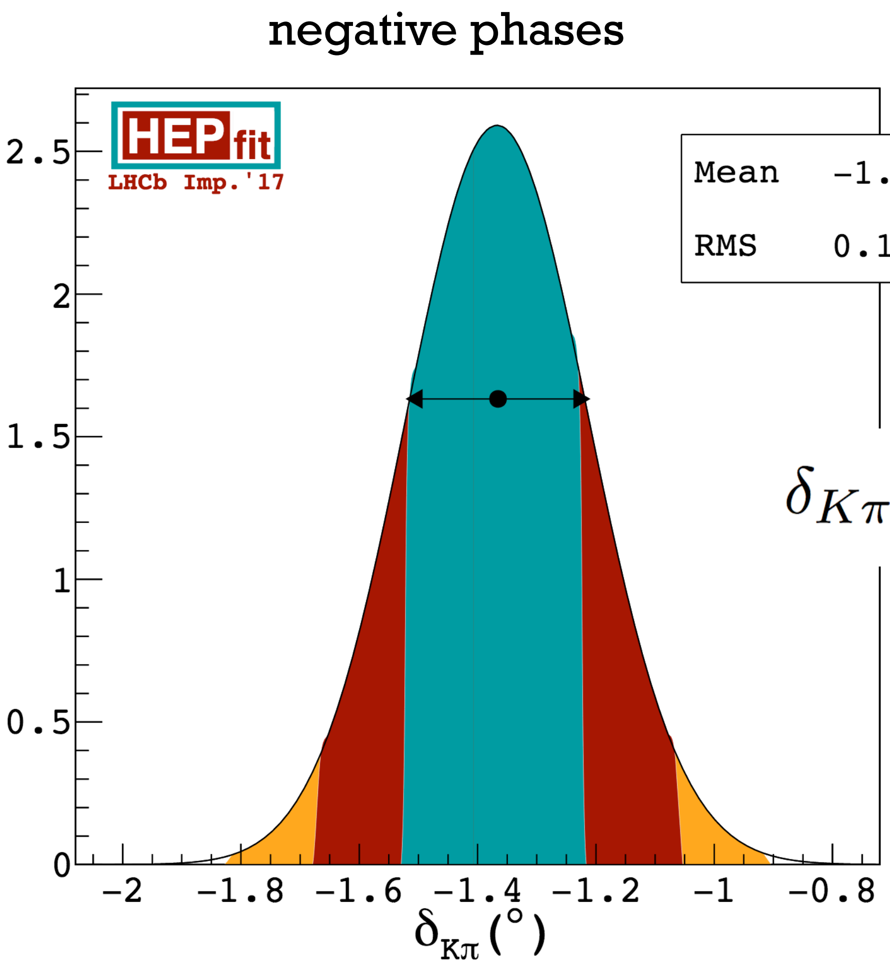
These parameters encapsulate annihilation contributions which can be expected to be much smaller than the tree contributions (T and C).



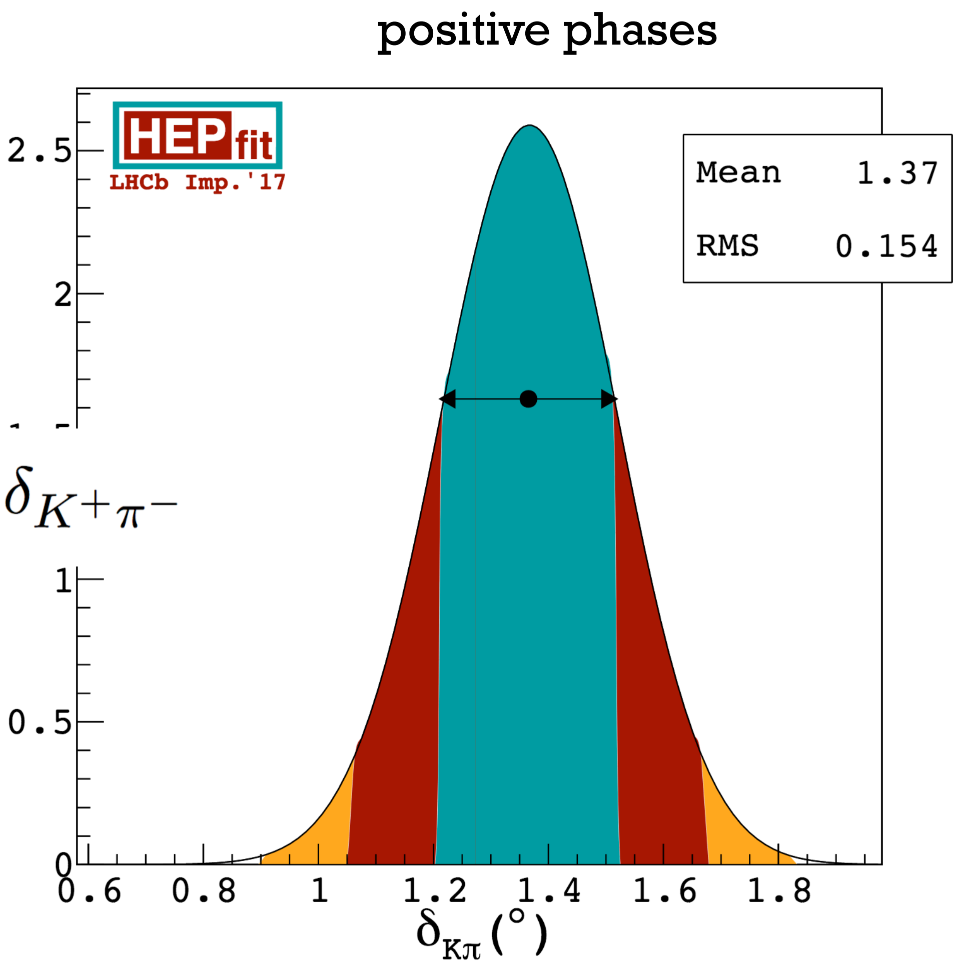




$\delta_{K\pi}$



$$\delta_{K\pi} = \delta_{K^-\pi^+} - \delta_{K^+\pi^-}$$



$4.8^{+10.4}_{-12.3}$ HFLAV: assuming no CPV in DCS decays. Belle II will measure it to a few degrees.

rate asymmetries

$$R(D^0,\pi^0) \equiv \frac{\Gamma(D^0\to K_S\pi^0) - \Gamma(D^0\to K_L\pi^0)}{\Gamma(D^0\to K_S\pi^0) + \Gamma(D^0\to K_L\pi^0)}$$

$$R(D^0,\pi^0)^{\text{CLEO}} = 0.108 \pm 0.025 \pm 0.024$$

$R(D^+,\pi^+)$ $\quad D^0 \to D^+$ and $\pi^0 \to \pi^+$

$$R(D^+,\pi^+)^{\text{CLEO}} = 0.022 \pm 0.016 \pm 0.018$$

$R(D_s^+,K^+)$ $\quad D^0 \to D_s^+$ and $\pi^0 \to K^+$

no measurement as yet

however… from Belle (used in the fit): $\text{BR}(D_s^+ \to K^+K_S) + \text{BR}(D_s^+ \to K^+K_L) = (29.5 \pm 1.1 \pm 0.9) \times 10^{-3}$

$$\boxed{\begin{array}{c} \text{BR}(D_s^+ \to K^+K_L) = (15.23 \pm 0.48) \times 10^{-3} \\ R(D_s^+,K^+) = -0.0145 \pm 0.0062 \end{array}}$$

$-0.003^{+0.019}_{-0.017}$ B. Bhattacharya and J. L. Rosner, *Flavor symmetry and decays of charmed mesons to pairs of light pseudoscalars*, *Phys. Rev.* **D77** (2008) 114020, [0803.2385].

-0.0022 ± 0.0087 B. Bhattacharya and J. L. Rosner, *Charmed meson decays to two pseudoscalars*, *Phys. Rev.* **D81** (2010) 014026, [0911.2812].

-0.008 ± 0.007 D.-N. Gao, *Asymmetries from the interference between Cabibbo-favored and doubly-Cabibbo-suppressed D meson decays*, *Phys. Rev.* **D91** (2015) 014019, [1411.0768].

H.-Y. Cheng and C.-W. Chiang, *Two-body hadronic charmed meson decays*, *Phys. Rev.* **D81** (2010) 074021, [1001.0987].

$0.11^{+0.04}_{-0.14}$ S. Müller, U. Nierste and S. Schacht, *Topological amplitudes in D decays to two pseudoscalars: A global analysis with linear $SU(3)_F$ breaking*, *Phys. Rev.* **D92** (2015) 014004, [1503.06759].

0.012 ± 0.006 D. Wang, F.-S. Yu, P.-F. Guo and H.-Y. Jiang, *$K_S^0 - K_L^0$ asymmetries in D-meson decays*, *Phys. Rev.* **D95** (2017) 073007, [1701.07173].

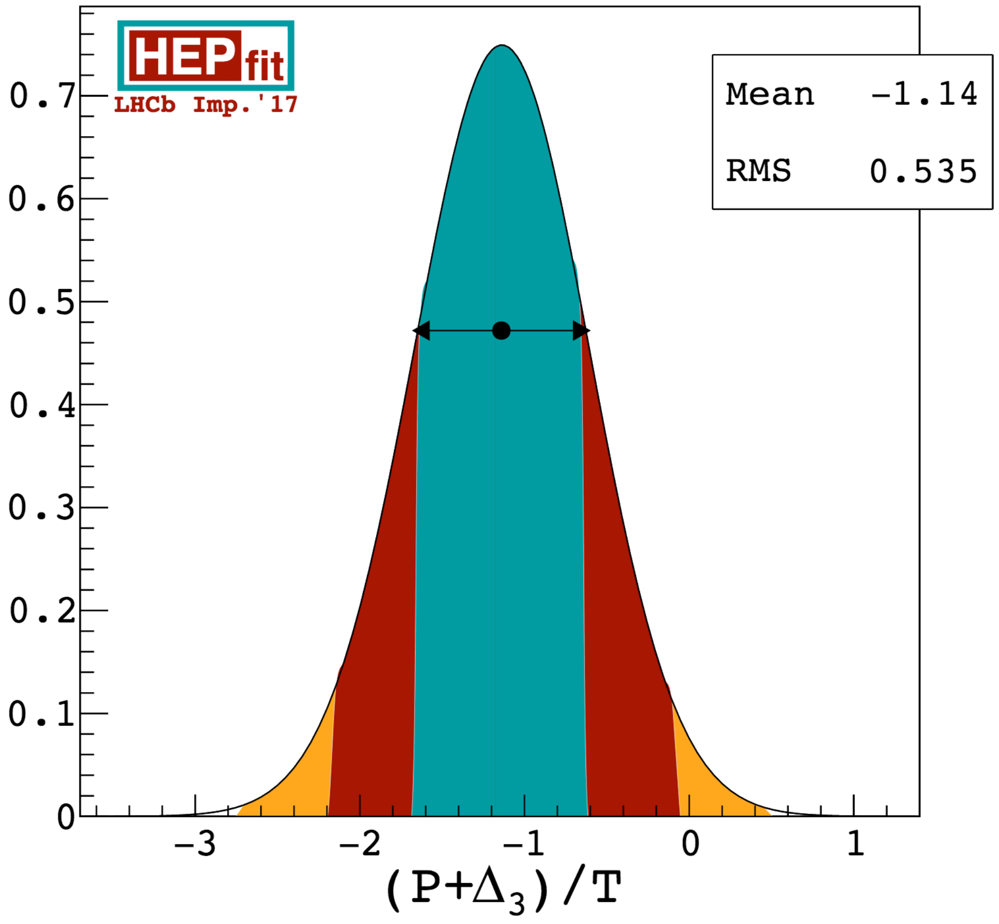
CP Violation

channel	mean ± rms	ref.
$D^0 \to K^+K^-$	$(0.04 \pm 0.12 \pm 0.10)\%$	LHCb
$D^0 \to \pi^+\pi^-$	$(0.07 \pm 0.14 \pm 0.11)\%$	LHCb
$D^0 \to K^+K^-$	$(-0.16 \pm 0.12)\%$	HFLAV
$D^0 \to \pi^+\pi^-$	$(0.00 \pm 0.15)\%$	HFLAV
$D^0 \to \pi^0\pi^0$	$(-0.03 \pm 0.64)\%$	HFLAV
$D^+ \to K^+K_S$	$(-0.11 \pm 0.25)\%$	HFLAV
$D_s^+ \to K_S\pi^+$	$(0.38 \pm 0.48)\%$	HFLAV
$D_s^+ \to K^+\pi^0$	$(-0.266 \pm 0.238 \pm 0.009)\%$	CLEO
$D^0 \to K_SK_S$	$(-2.9 \pm 5.2 \pm 2.2)\%$	LHCb
$D^0 \to K_SK_S$	$(-0.2 \pm 1.53 \pm 0.17)\%$	Belle

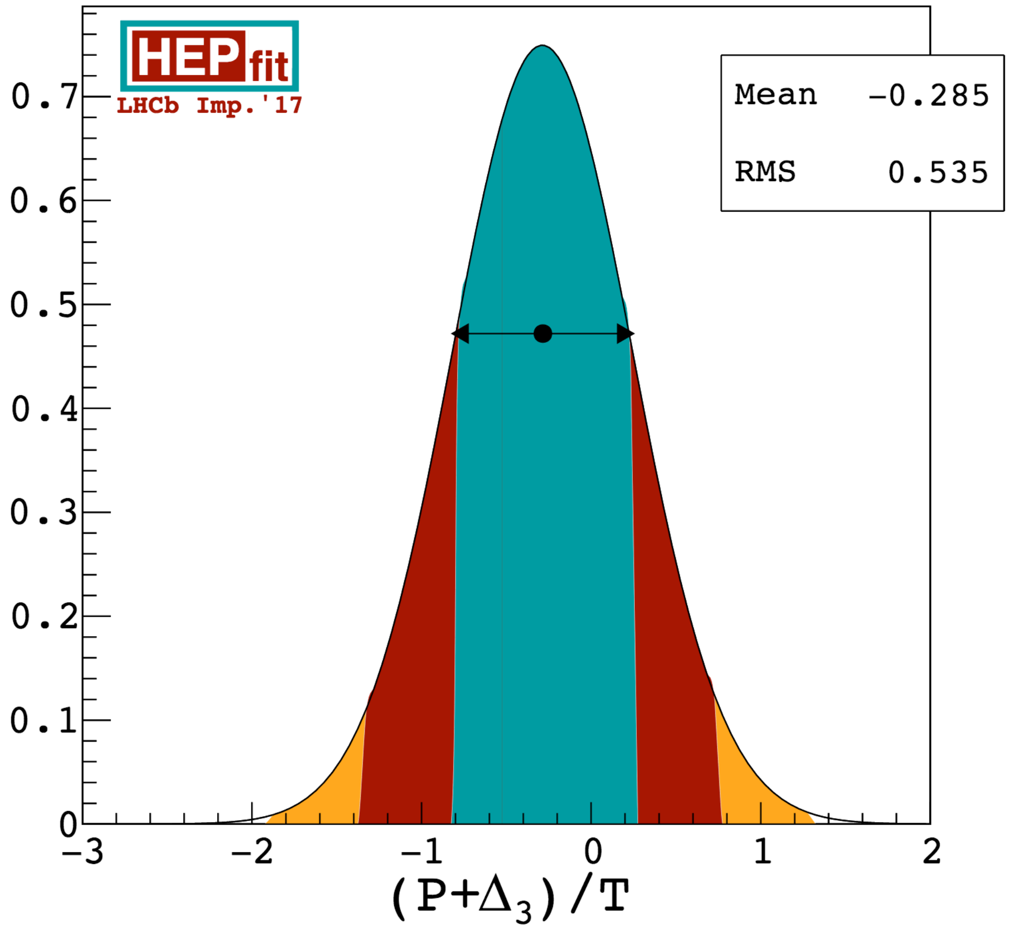
fit to ΔA_{CP} (LHCb)

$$\Delta A_{CP}^{dir} = (-0.061 \pm 0.076)\%$$

negative phases



positive phases

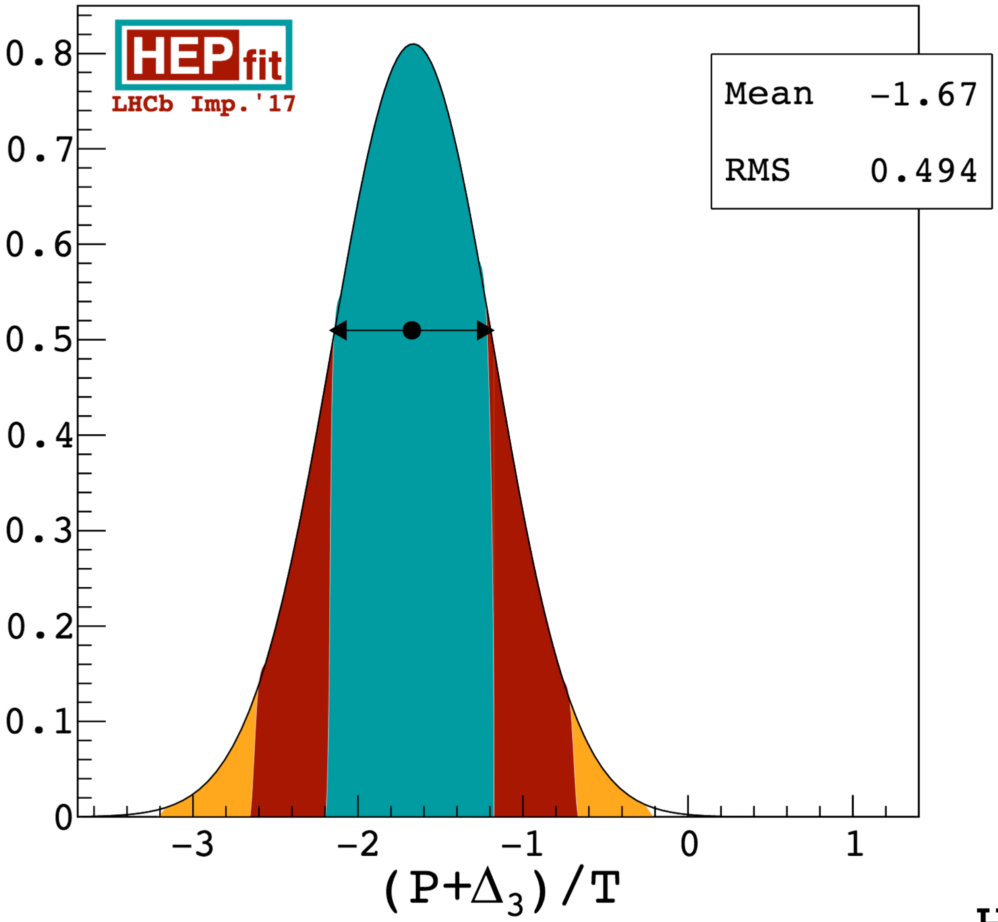


LHCb: PRL 116 (2016) 191601 [arXiV:1602:03160]

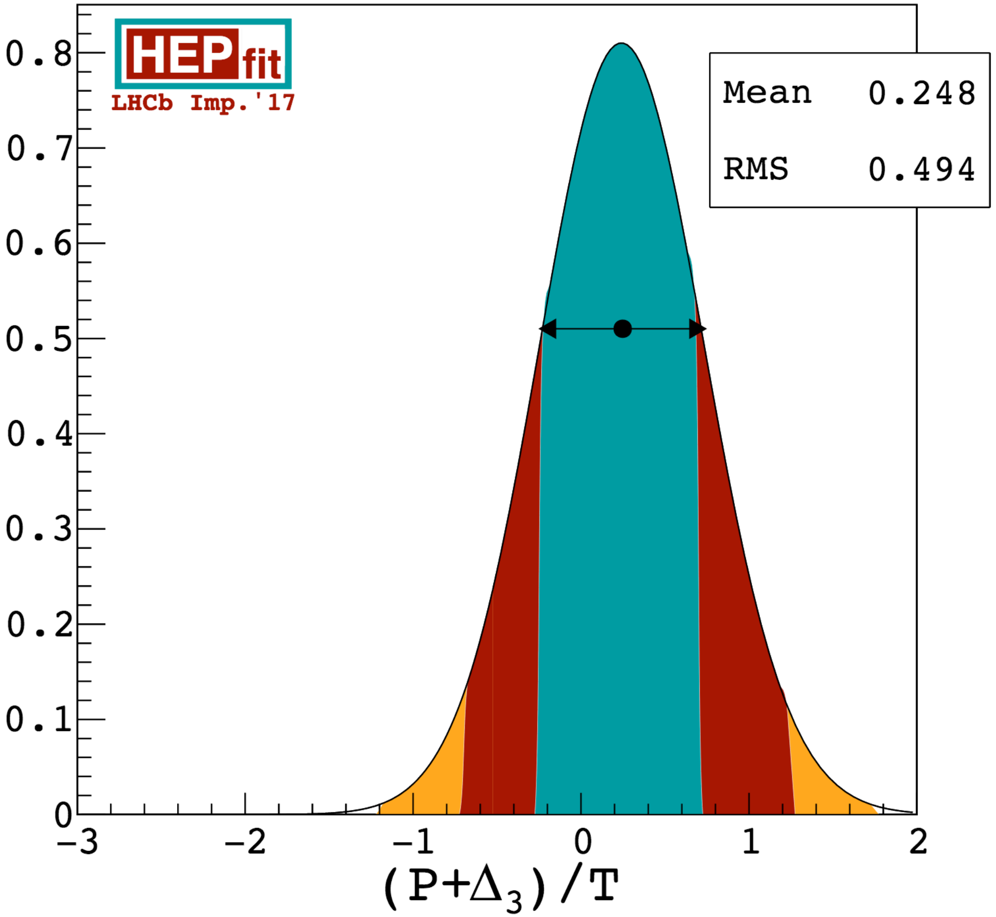
fit to ΔA_{CP} (HFLAV)

$$\Delta A_{CP}^{dir} = (-1.34 \pm 0.070)\%$$

negative phases



positive phases



HFLAV

predictions for CP asymmetries

$\Delta A_{CP}^{dir} = (-0.061 \pm 0.076)\%$ LHCb: PRL 116 (2016) 191601 [arXiV:1602:03160]

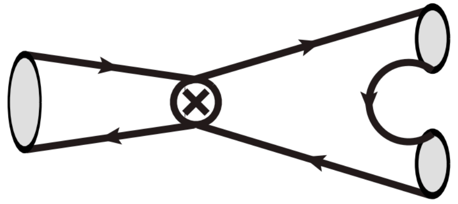
A_{CP} (D^0)	$(\mu \pm \sigma)$ (%)		A_{CP} $(D^+_{(s)})$	$(\mu \pm \sigma)$ (%)	
	$\delta_i \to$ -ve	$\delta_i \to$ +ve		$\delta_i \to$ -ve	$\delta_i \to$ +ve
$D^0 \to \pi^+\pi^-$	0.043 $\pm$ 0.054	0.045 $\pm$ 0.055	$D^+ \to K^+K_S$	-0.012 $\pm$ 0.014	-0.010 $\pm$ 0.014
$D^0 \to \pi^0\pi^0$	-0.019 $\pm$ 0.026	0.056 $\pm$ 0.030	$D_s^+ \to \pi^+K_S$	0.015 $\pm$ 0.018	0.013 $\pm$ 0.018
$D^0 \to K^+K^-$	-0.018 $\pm$ 0.022	-0.016 $\pm$ 0.022	$D_s^+ \to \pi^0K^+$	-0.045 $\pm$ 0.017	0.021 $\pm$ 0.018
$D^0 \to K_SK_S$	0.019 $\pm$ 0.021	0.012 $\pm$ 0.024			

$\Delta A_{CP}^{dir} = (-1.34 \pm 0.070)\%$ HFLAV

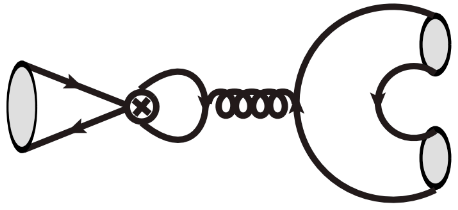
A_{CP} (D^0)	$(\mu \pm \sigma)$ (%)		A_{CP} $(D^+_{(s)})$	$(\mu \pm \sigma)$ (%)	
	$\delta_i \to$ -ve	$\delta_i \to$ +ve		$\delta_i \to$ -ve	$\delta_i \to$ +ve
$D^0 \to \pi^+\pi^-$	0.095 $\pm$ 0.050	0.096 $\pm$ 0.050	$D^+ \to K^+K_S$	-0.025 $\pm$ 0.013	-0.023 $\pm$ 0.013
$D^0 \to \pi^0\pi^0$	0.003 $\pm$ 0.026	0.081 $\pm$ 0.030	$D_s^+ \to \pi^+K_S$	0.032 $\pm$ 0.016	0.031 $\pm$ 0.017
$D^0 \to K^+K^-$	-0.039 $\pm$ 0.020	-0.038 $\pm$ 0.020	$D_s^+ \to \pi^0K^+$	-0.060 $\pm$ 0.017	0.005 $\pm$ 0.015
$D^0 \to K_SK_S$	0.039 $\pm$ 0.022	0.031 $\pm$ 0.026			

errors in the prediction are comparable, the predicted values depend on the sign of the phase in a few cases

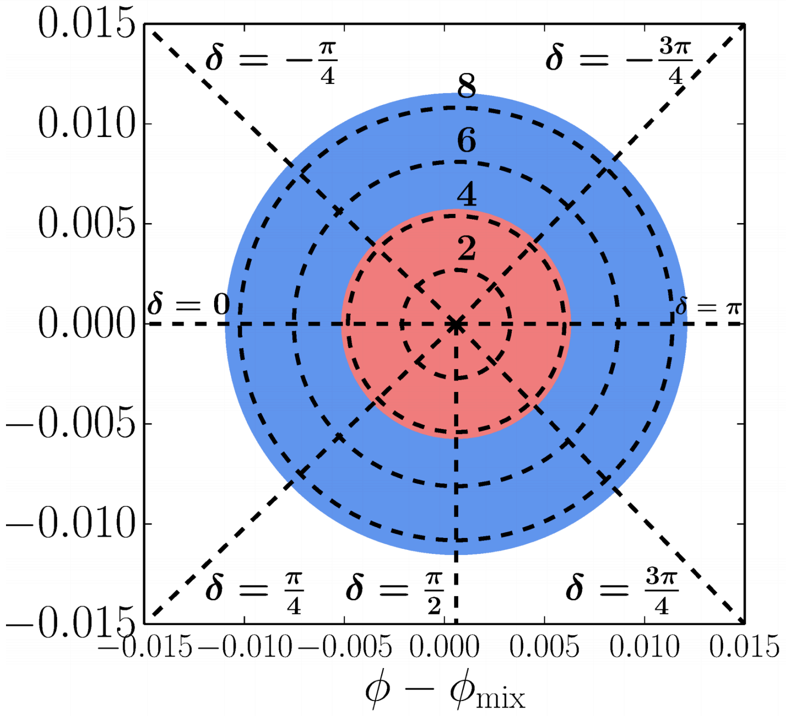
the case for CPV in $K_S K_S$

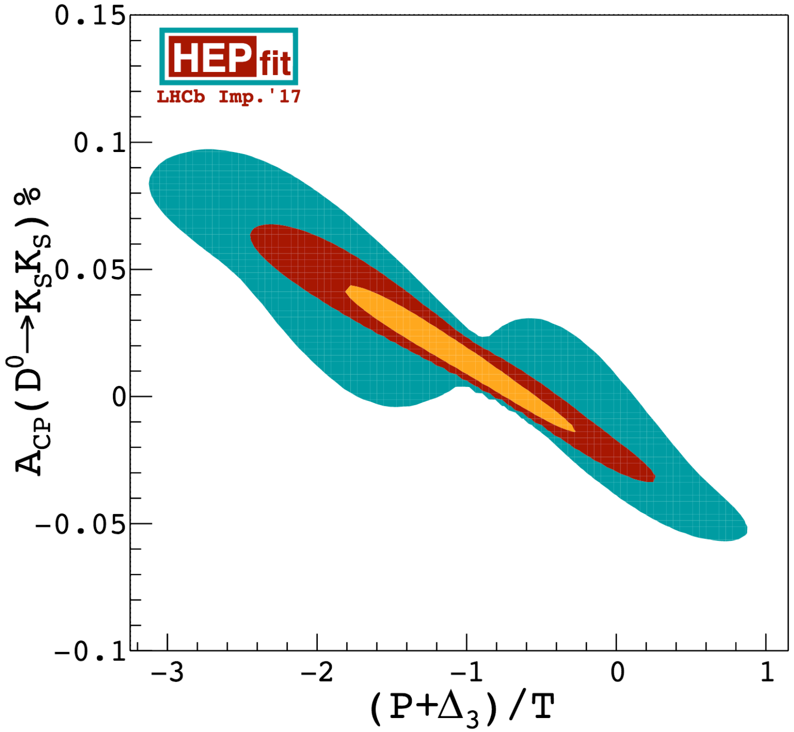


(a)



(b)





U. Nierste and S. Schacht, *CP Violation in $D^0 \to K_S K_S$*, *Phys. Rev.* **D92** (2015) 054036, [1508.00074].

The difference stems from the fact that the exchange contribution (which is not OZI supressed) is generated by rescattering in our work and is treated as an independent contribution in Nierste et. al.

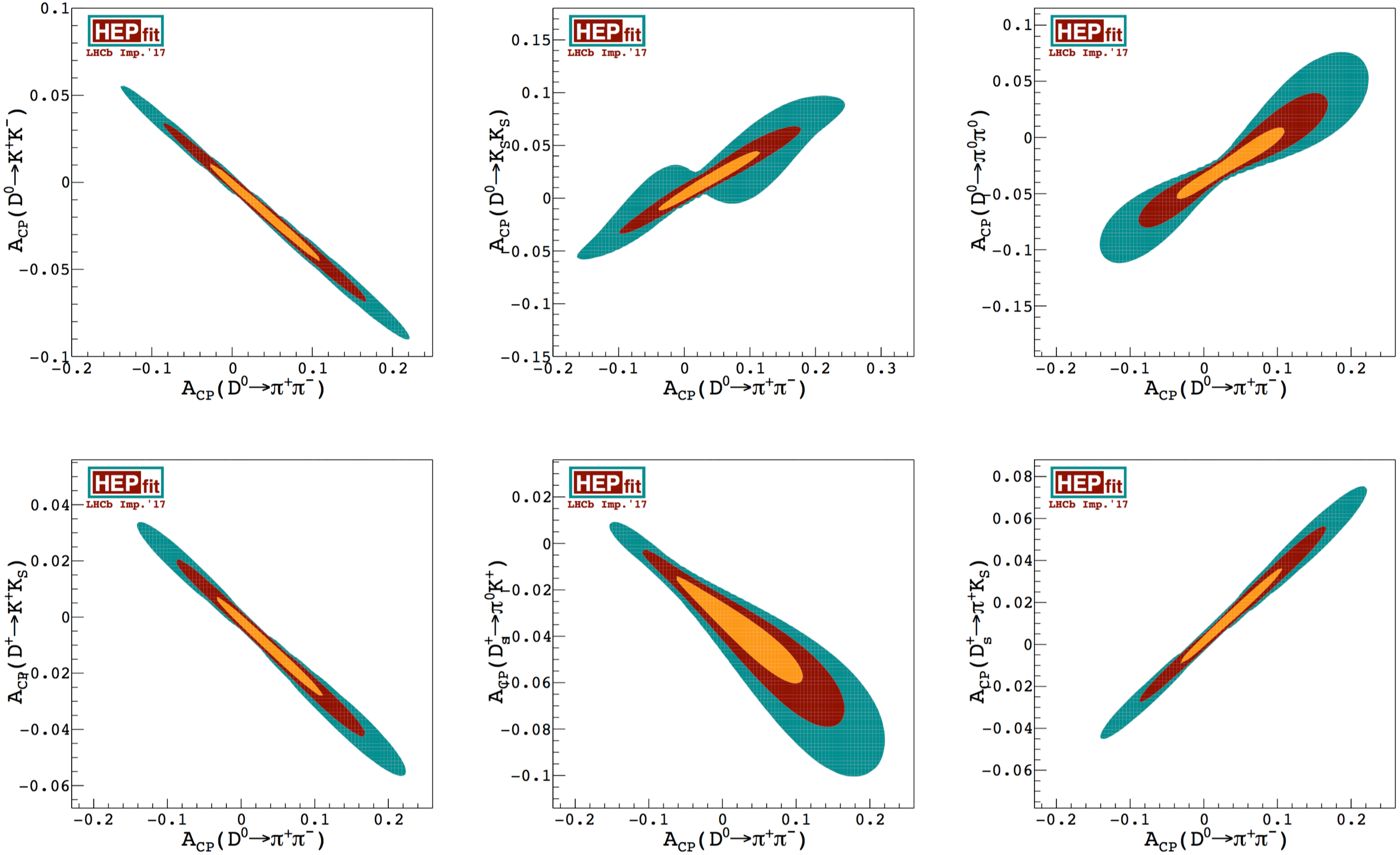
$$|a_{CP}^{\rm dir}(D^0 \to K_S K_S)| \lesssim \frac{2|V_{cb}V_{ub}|}{\varepsilon |V_{cs}V_{us}|} \sim 0.6\%$$

J. Brod, A. L. Kagan and J. Zupan, *Size of direct CP violation in singly Cabibbo-suppressed D decays*, *Phys. Rev.* **D86** (2012) 014023, [1111.5000].

$$|a_{CP}^{\rm dir}| \lesssim \frac{3}{2} \times \Delta a_{CP}^{\rm dir} = 0.4\%$$

G. Hiller, M. Jung and S. Schacht, *SU(3)-flavor anatomy of nonleptonic charm decays*, *Phys. Rev.* **D87** (2013) 014024, [1211.3734].

correlations amongst CP asymmetries



future prospects

A_{CP}(channel)	mode (%)	RMS (%)			
		Current Fit	Belle II 50 ab^{-1}	LHCb 5 fb^{-1}	LHCb 50 fb^{-1}
$D^0 \to \pi^+\pi^-$	0.043	0.054	0.05	–	–
$D^0 \to \pi^0\pi^0$	-0.020	0.026	0.09	–	–
$D^0 \to K^+K^-$	-0.018	0.022	0.03	–	–
$D^0 \to K_S K_S$	0.019	0.021	0.17	–	–
$D^+ \to K^+ K_S$	-0.011	0.014	0.05	–	–
$D_s^+ \to \pi^+ K_S$	0.014	0.018	0.29	–	–
ΔA_{CP}	-0.061	–	–	0.05	0.01

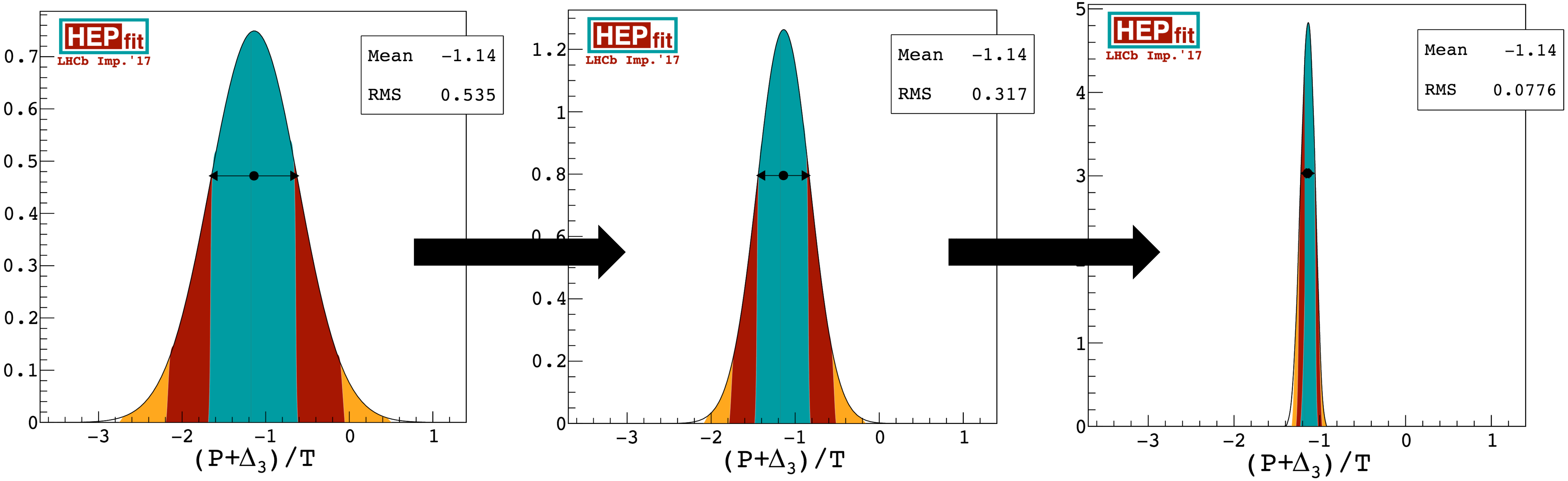
-- fit predictions from ΔA_{CP} have comparable or smaller errors than what Belle II will probe with 50 ab^{-1}

-- predicted errors do not depend on the sign of the phases

-- hence predicted errors do not depend on the size of $(P+\Delta_3)/T$ but only on the precision with which it can be determined.

Measurement of $(P+\Delta_3)/T$

assuming the phases are negative



$\Delta A_{CP}^{\mathrm{LHCb}}$ (current)

$\text{Belle II } 50\ \mathrm{ab}^{-1} + \Delta A_{CP}^{\mathrm{LHCb}}$

$\text{Belle II } 50\ \mathrm{ab}^{-1} + \text{LHCb } 50\ \mathrm{fb}^{-1}$

summary

- ✓ We are reasonably successful in fitting the branching fraction of multiple decay modes applying $SU(3)_f$ breaking through large Final State Interactions and small shifts in the amplitudes.
- ✓ Since all CP asymmetries in the SCS sector, depend on one combination of parameters, they can be predicted from current ΔA_{CP} measurement.
- ✓ The fits to the branching fractions offer both positive and negative values of the phases leading to some differences in the predictions of the CP asymmetries.
- ✓ The precision with which the CP asymmetries can be predicted from the current ΔA_{CP} measurement is equal to or smaller than what can be probed by Belle with 50 ab^{-1}.
- ✓ The sign ambiguity in the phases leads to an ambiguity in the prediction of the penguin contribution which can only be resolved by extremely precise CP asymmetry measurements.

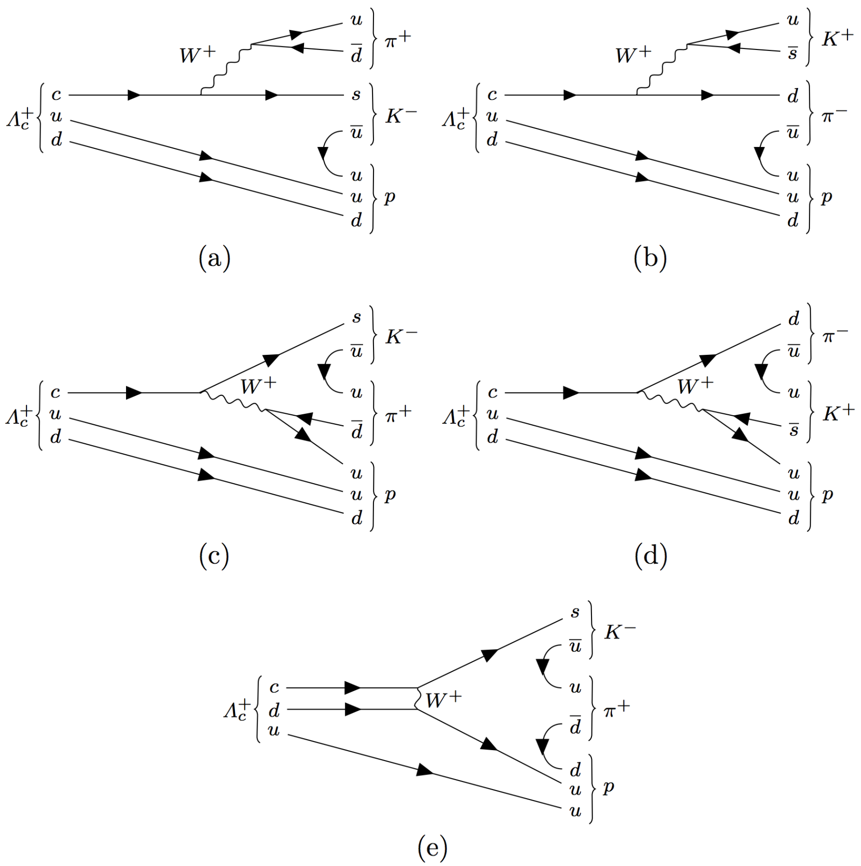
bottomline: {weak amplitudes + rescattering + small $SU(3)_f$ breaking amplitudes} gives a good description of the $D \to PP$ system and allows us to make predictions of CP asymmetries and strong phases

epilogue

CERN-EP-2017-247
LHCb-PAPER-2017-026
November 3, 2017

Measurements of the branching fractions of $\Lambda_c^+ \to p\pi^-\pi^+$, $\Lambda_c^+ \to pK^-K^+$, and $\Lambda_c^+ \to p\pi^-K^+$

LHCb collaboration†



$$\frac{\mathcal{B}(\Lambda_c^+ \to p\pi^-\pi^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (7.44 \pm 0.08 \pm 0.18)\,\%,$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to pK^-K^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (1.70 \pm 0.03 \pm 0.03)\,\%,$$

$$\frac{\mathcal{B}(\Lambda_c^+ \to p\pi^-K^+)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)} = (0.165 \pm 0.015 \pm 0.005)\,\%,$$

$$\mathcal{B}(\Lambda_c^+ \to p\pi^-\pi^+) = (4.72 \pm 0.05 \pm 0.11 \pm 0.25) \times 10^{-3},$$

$$\mathcal{B}(\Lambda_c^+ \to pK^-K^+) = (1.08 \pm 0.02 \pm 0.02 \pm 0.06) \times 10^{-3},$$

$$\mathcal{B}(\Lambda_c^+ \to p\pi^-K^+) = (1.04 \pm 0.09 \pm 0.03 \pm 0.05) \times 10^{-4},$$

a word on asymmetries in charmed baryons

I. Bigi, *Probing CP asymmetries in charm baryons decays*, arXiv:1206.4554.

- ✓ Three body decays are richer than two body decays since they provide more handles to be probed.
- ✓ Local asymmetries can be probed in amplitude analyses in cases where the global asymmetries might be washed out.
- ✓ In the DCS channels SM no 'background' in the CP asymmetries, leaving the playground open for new dynamics.
- ✓ In the SCS channels SM leaves an effect, so one must be more careful here.
- ✓ One can compare DCS and CA decays to study the impact of FSI.
- ✓ Very little theoretical work has been done. (possible?)

Thank you…!!

To my Mother and Father, who showed me what I could do,

and to Ikaros, who showed me what I could not.

"To know what no one else does, what a pleasure it can be!"

– adopted from the words of

Eugene Wigner.