CP violation in Charm: From Rags to Riches

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A story of Charm

I know she invented Fire, but what has she done recently? – Ikaros I. Bigi

Flavour Physics at the GeV scale

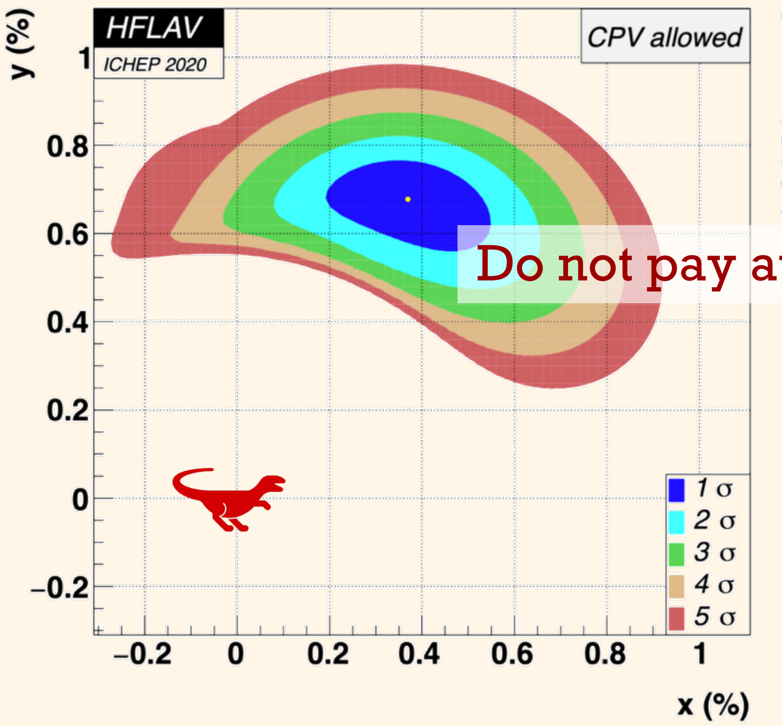
branching fractions	differential distributions	CP asymmetries
◉ Measured first since they are the easiest to measure. ◉ It has the least information of the dynamics since it is kinematically integrated. ◉ Theory uncertainties can be large due to significant non-perturbative contributions. ◉ Ratios of branching fractions can be used to reduce theory uncertainties. ◉ Limited sensitivities to new dynamics primarily through rare decays	◉ Gives increasing numbers of experimental handles for higher multiplicity final states. ◉ Various kinematic configurations can be probed. ◉ A lot more sensitive to new dynamics that can appear in distributions more distinctly than in total rates. ◉ Important for studies of resonances and strong phases. ◉ Experimentally more challenging because higher statistics is necessary.	◉ A unique probe of the weak phase coming from the CKM matrix ◉ Very challenging measurements since asymmetries are usually small with a few exceptions. ◉ Very sensitive to new dynamics at higher scales through the generations of new **CP** violating phases ◉ **CP** asymmetries have been measured in strange, charm and beauty decays

the charm sector

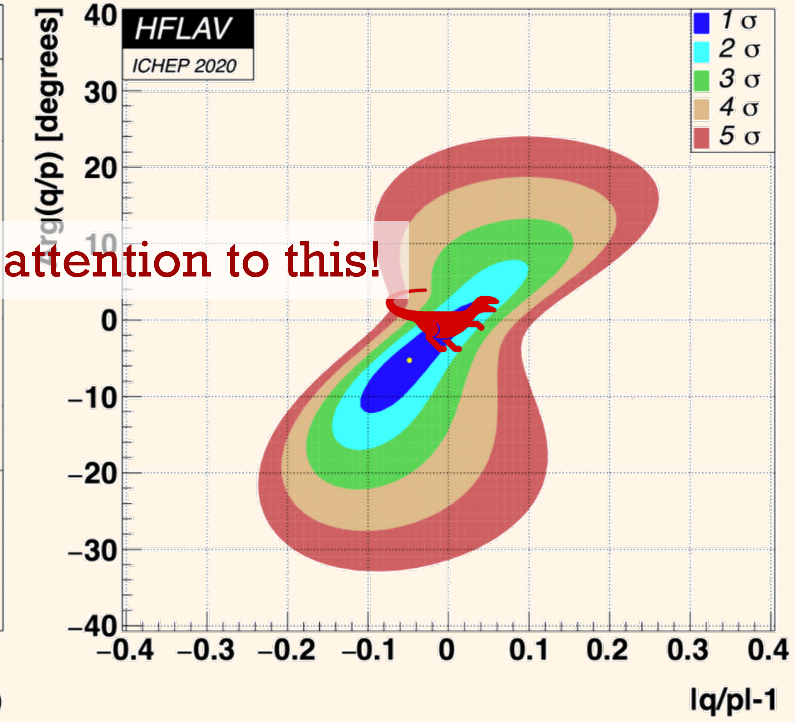
- the *ONLY* quark in the up quark sector that partakes in oscillations
- the *ONLY* neutral meson system where *direct* **CPV** can possibly overcome *indirect* **CPV**
- the *ONLY* quark that does not distinctly lie in the non-perturbative or the perturbative regime
- the *ONLY* quark dynamics that SM has chosen to leave tiny signatures in

$\Bigg\}$ **uniqueness of charm**

mixing



Indirect CP violation



Do not pay attention to this!

$$x = \frac{\Delta m}{\Gamma} = 0.43^{+0.10}_{-0.11}$$

$$y = \frac{\Delta\Gamma}{2\Gamma} = 0.62 \pm 0.06$$

$$\left|\frac{q}{p}\right| = 0.997 \pm 0.008$$

$$\phi = \arg\left(\frac{q}{p}\right) = 0.14 \pm 0.32$$

Do not pay attention to this!

no CPV in DCS

the charm sector

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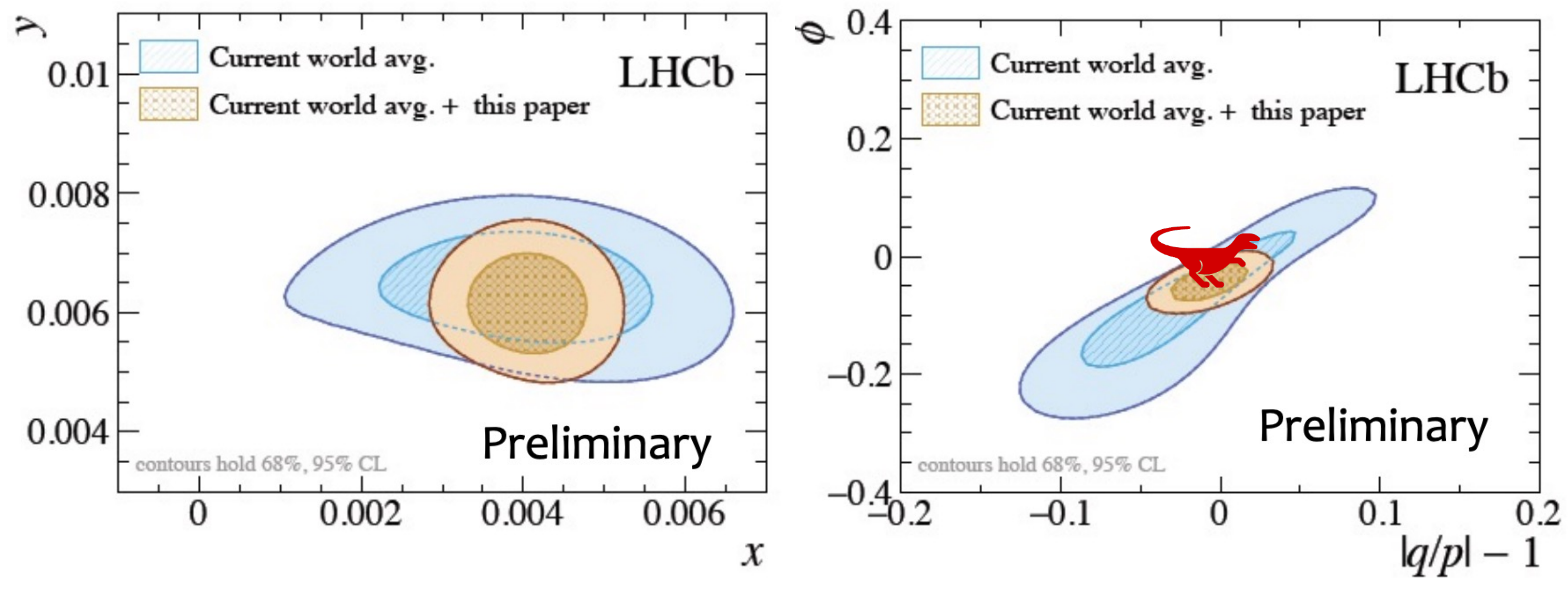
Indirect CP violation



Parameter	Value
$x\ [10^{-3}]$	$3.98\,^{+0.56}_{-0.54}$
$y\ [10^{-3}]$	$4.6\,^{+1.5}_{-1.4}$
$\lvert q/p \rvert$	0.996 ± 0.052
ϕ	$-0.056\,^{+0.047}_{-0.051}$

For details see Angelo's talk at the beginning of the session

CPV in $D \to PP$ $(P = K, \pi)$

the new big measurement of CP asymmetry

PHYSICAL REVIEW LETTERS **122,** 211803 (2019)

Editors' Suggestion | Featured in Physics

Observation of *CP* Violation in Charm Decays

R. Aaij *et al.*[*]
(LHCb Collaboration)

(Received 21 March 2019; revised manuscript received 2 May 2019; published 29 May 2019)

defined to cancel out production and detection asymmetries

$$\Delta A_{CP} \equiv A_{CP}(K^-K^+) - A_{CP}(\pi^-\pi^+)$$
$$\approx \Delta a_{CP}^{\mathrm{dir}} - \frac{\Delta\langle t\rangle}{\tau(D^0)} A_\Gamma,$$

- *The first* measurement of **CP** asymmetry in the charm sector.
- The *only* measurement of **CP** asymmetry in the up quark sector.
- The Standard Model prediction for this asymmetry is only to an order of magnitude: $\mathcal{O}(10^{-3}) - \mathcal{O}(10^{-4})$.
- While the measurement is compatible with the Standard Model, there have been suggestions that it is larger than expectation.

2012 LHCb	$\Delta A_{CP} = [-0.82 \pm 0.21(\mathrm{stat}) \pm 0.11(\mathrm{syst})]\%$
2012 CDF	$\Delta A_{CP} = [-0.62 \pm 0.21(\mathrm{stat}) \pm 0.10(\mathrm{syst})]\%$
2012 Belle	$\Delta A_{CP}^{hh} = (-0.87 \pm 0.41 \pm 0.06)\%$
2014 LHCb	$\Delta A_{CP} = (+0.14 \pm 0.16\,(\mathrm{stat}) \pm 0.08\,(\mathrm{syst}))\%$
2016 LHCb	$\Delta A_{CP} = [-0.10 \pm 0.08(\mathrm{stat}) \pm 0.03(\mathrm{syst})]\%$
2019 LHCb	$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$

the parameterization

Buccella et. al.
arxiv:1902.05564

the weak Hamiltonian:

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

the operator basis:

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

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

Buccella et. al.
arxiv:1902.05564

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

$$\frac{\langle f||6_{I=1/2}||i\rangle}{\langle f||6_{I=0}||i\rangle} = \frac{V_{cd}^*V_{ud} - V_{cs}^*V_{us}}{\sqrt{2}V_{cd}^*V_{us}}\ , \quad \frac{\langle f||6_{I=1}||i\rangle}{\langle f||6_{I=0}||i\rangle} = -\frac{V_{cs}^*V_{ud}}{V_{cd}^*V_{us}}$$
$$\frac{\langle f||15_{I=3/2}||i\rangle}{\langle f||15_{I=1/2}||i\rangle} = -\frac{2\sqrt{2}V_{cd}^*V_{ud}}{V_{cd}^*V_{ud} - 3V_{cs}^*V_{us}}\ , \quad \frac{\langle f||15_{I=3/2}||i\rangle}{\langle f||15_{I=1}||i\rangle} = \sqrt{\frac{2}{3}}\frac{V_{cd}^*V_{ud}}{V_{cs}^*V_{ud} + V_{cd}^*V_{us}}$$

- ✓ 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:

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

CA and DCS

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

SCS

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

parameterization of the $\Delta U = 1$ part

Buccella et. al.
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once $SU(3)_F$ 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

27 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

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^+

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 $\Delta U = 0$ part

Buccella et. al.
arxiv:1902.05564

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

$$B(D^0 \to K^+ K^-) = P + T + \Delta_3,$$

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 $\Delta U = 0$ part are determined by the $\Delta U = 1$ part and extracted from the branching fractions

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

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

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

the parameterization

Buccella et. al.
arxiv:1902.05564

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

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

$\varphi \to$ singlet-octet mixing angle
$\delta_0 \to$ the FSI phase of the singlet in $I = 0$ amplitude
$\delta_0' \to$ the FSI phase of the octet in $I = 0$ amplitude
$\delta_{\frac{1}{2}} \to$ the FSI phase of the singlet in $I = \frac{1}{2}$ amplitude
$\delta_1 \to$ the FSI phase of the singlet in $I = 1$ amplitude
$\epsilon_\delta \to$ the splitting in the $I = 0$ phases for D_s^+ and $D^{0,+}$

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

K and K' $\to$ non-conservation of strangeness changing neutral and charged currents

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

κ and κ' $\to SU(3)_F$ breaking in the 27 matrix element.

the U-spin components:

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

CP *conserving*

CP *violating*

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

$$B(D^0 \to K^+K^-) = P + T + \Delta_3 \equiv \mathcal{P}$$
$$B(D^0 \to K^0\bar{K}^0) = \Delta_4.$$

$\Delta_4 \to$ OZI suppressed

fit results

	$(\mu \pm \sigma)$		$(\mu \pm \sigma)$	
T	0.424 ± 0.003	δ_0	-2.373 ± 0.062	2.373 ± 0.062
C	-0.211 ± 0.003	δ_0'	-0.840 ± 0.046	0.840 ± 0.046
κ	-0.036 ± 0.004	$\delta_{\frac{1}{2}}$	-1.632 ± 0.020	1.632 ± 0.020
κ'	-0.063 ± 0.088	δ_1	-1.085 ± 0.038	1.085 ± 0.039
K	0.100 ± 0.012			
K'	-0.153 ± 0.072			
Δ	-0.026 ± 0.019			
ϕ	0.435 ± 0.025	$(P + \Delta_3)/T$	-1.897 ± 0.211	-0.465 ± 0.211
ϵ_δ	0.067 ± 0.061			

- We get both +ve and –ve solutions for the FSI phases.
- The –ve phases follow the correct Gell-Mann Ne'eman Okubo ordering of phases.
- The size of the penguin amplitude ($\mathcal{P}$) depends of the sign of the FSI phases.
- The negative solution of the phases gives $\mathcal{P}/T \sim 0.9$, i.e., the size of the penguin amplitude is comparable to the tree.

predictions

$$R(D_s^+, K^+) = -0.0103 \pm 0.0074$$

$$\delta_{K\pi} = \delta_{K^-\pi^+} - \delta_{K^+\pi^-} = 3.14^\circ \pm 5.69^\circ$$

branching fraction data

Channel	Fit ($\times 10^{-3}$)	PDG ($\times 10^{-3}$)	BESIII ($\times 10^{-3}$)
SCS			
$D^0 \to \pi^+\pi^-$	1.448 ± 0.019	1.407 ± 0.025	1.508 ± 0.028
$D_0^+ \to \pi^0\pi^0$	0.816 ± 0.025	0.822 ± 0.025	–
$D^+ \to \pi^+\pi^0$	1.235 ± 0.033	1.17 ± 0.06	1.259 ± 0.040
$D^0 \to K^+K^-$	4.064 ± 0.044	3.97 ± 0.07	4.233 ± 0.067
$D^0 \to K_S K_S$	0.168 ± 0.012	0.17 ± 0.012	–
$D^+ \to K^+ K_S$	3.164 ± 0.056	2.83 ± 0.16	3.183 ± 0.067
$D^+ \to K^+ K_L$	3.164 ± 0.056	–	3.21 ± 0.16
$D_s^+ \to \pi^0 K^+$	1.41 ± 0.15	0.63 ± 0.21	–
$D_s^+ \to \pi^+ K_S$	1.24 ± 0.06	1.22 ± 0.06	–
CA & DCS			
$D^+ \to \pi^+ K_S$	15.80 ± 0.29	14.7 ± 0.8	15.91 ± 0.31
$D^+ \to \pi^+ K_L$	14.37 ± 0.52	14.6 ± 0.5	–
$D^0 \to \pi^+ K^-$	38.96 ± 0.32	38.9 ± 0.4	–
$D^0 \to \pi^0 K_S$	12.29 ± 0.21	11.9 ± 0.4	12.39 ± 0.28
$D^0 \to \pi^0 K_L$	9.73 ± 0.21	10.0 ± 0.7	–
$D_s^+ \to K^+ K_S$	14.67 ± 0.41	15.0 ± 0.5	–
$D^+ \to \pi^0 K^+$	0.151 ± 0.013	0.181 ± 0.027	0.231 ± 0.022
$D^0 \to \pi^- K^+$	0.141 ± 0.003	0.1385 ± 0.0027	–
$D^0 \to \pi^\pm K^\mp$	39.1 ± 0.32	–	38.98 ± 0.52

\+

2019 LHCb $\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$

The choice of phase

fit results

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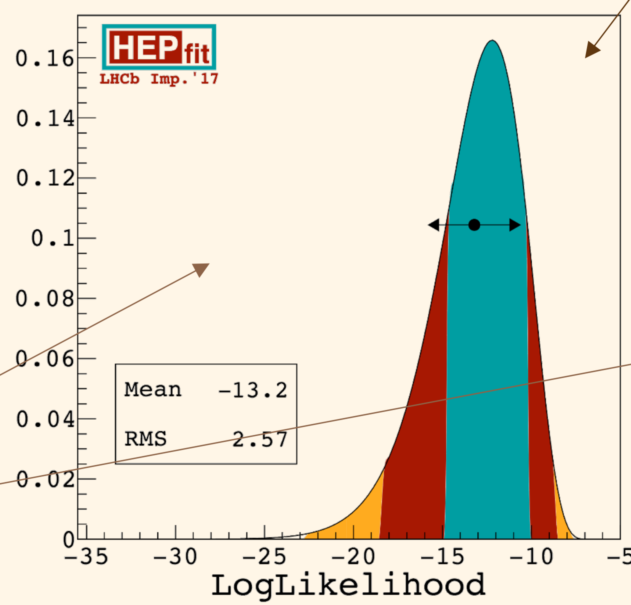
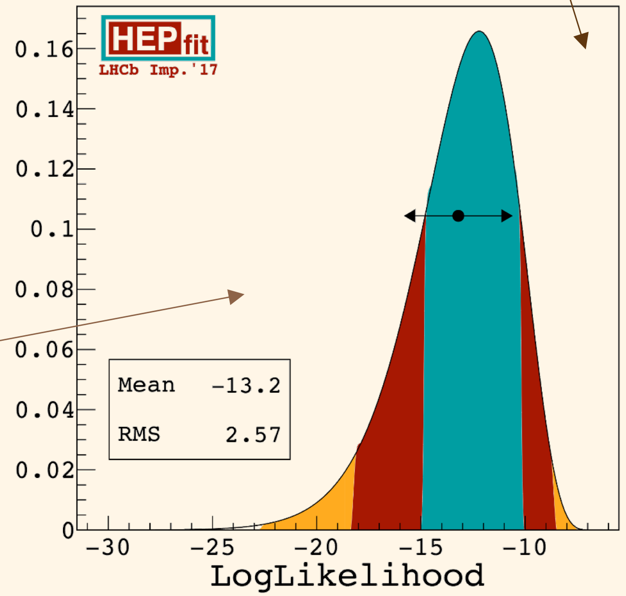
K'	-0.153 ± 0.072			
Δ	-0.026 ± 0.019			
ϕ	0.435 ± 0.025	$(P + \Delta_3)/T$	-1.897 ± 0.211	-0.465 ± 0.211
ϵ_δ	0.067 ± 0.061			

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





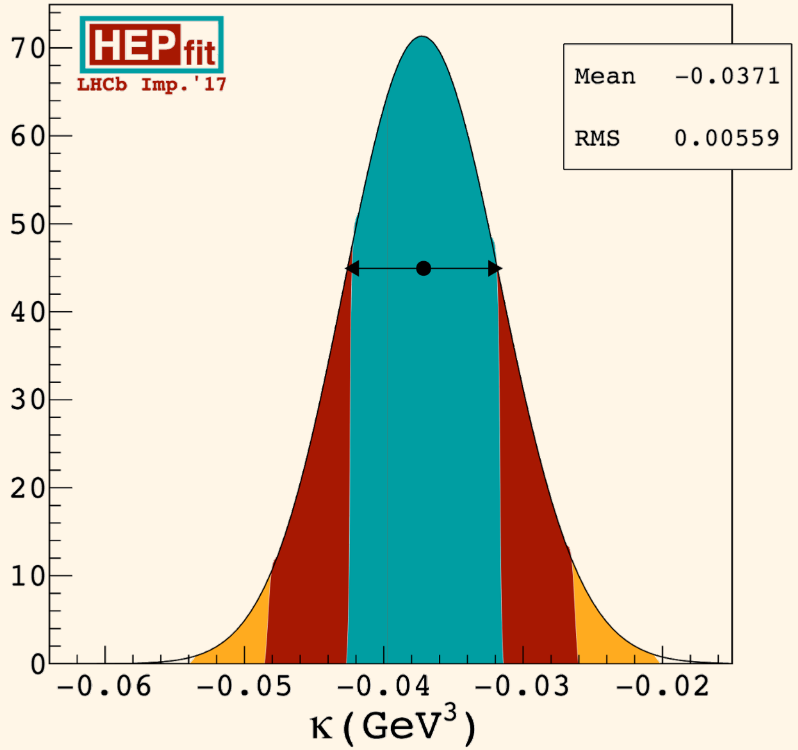
NOT measures of goodness of fit!

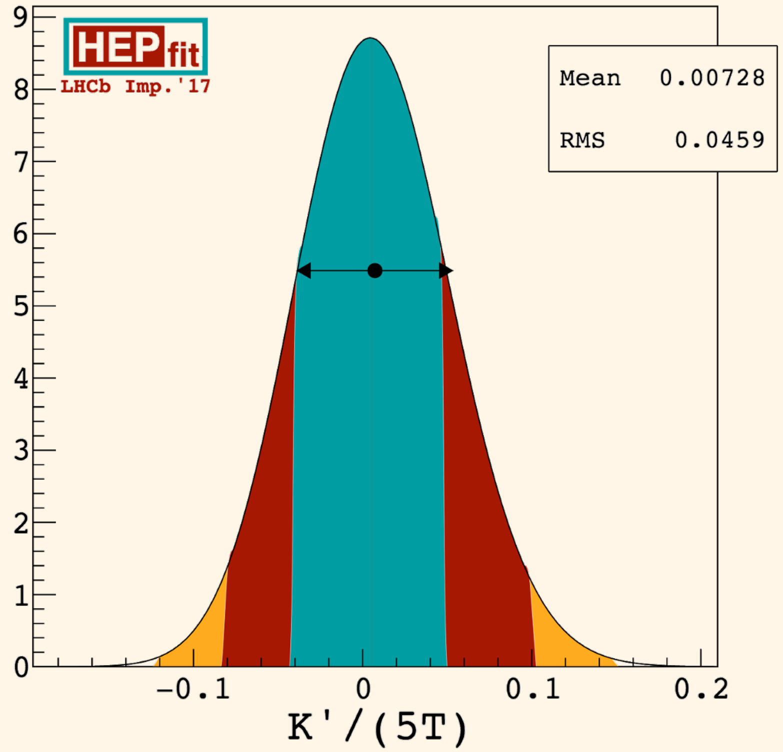
an estimate of $SU(3)_F$ breaking

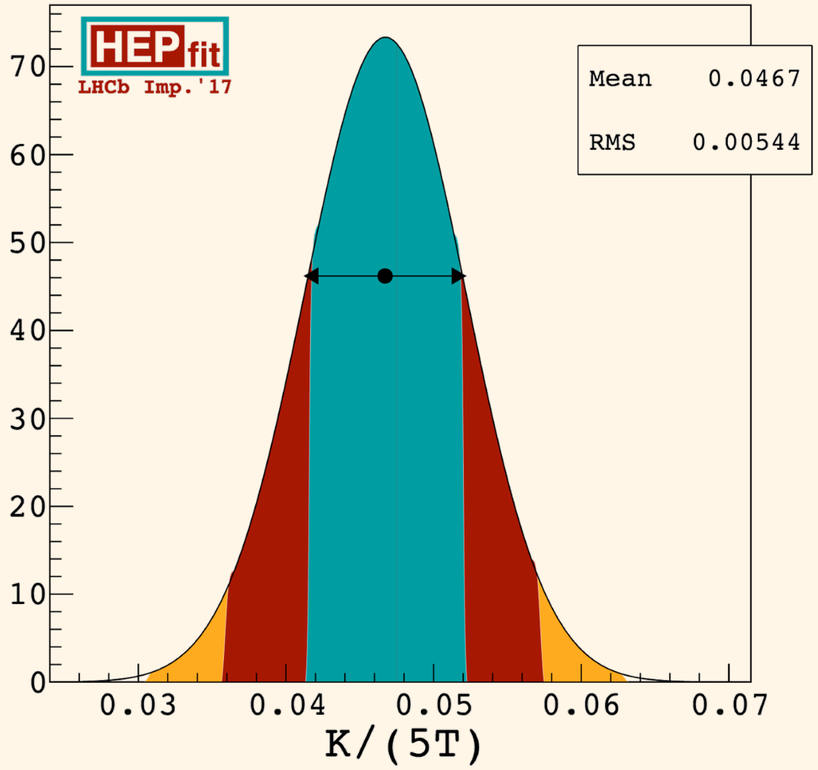
Buccella et. al.
arxiv:1902.05564

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*).







$\delta_{K\pi}$

Buccella et. al.
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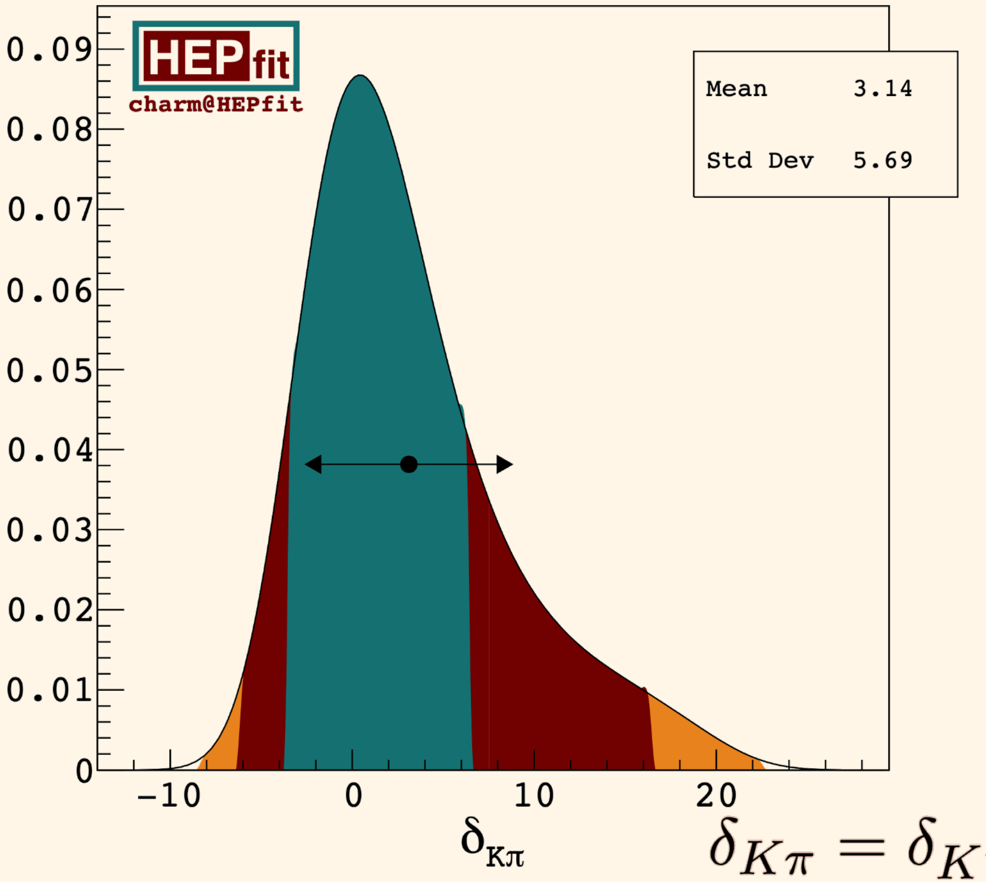
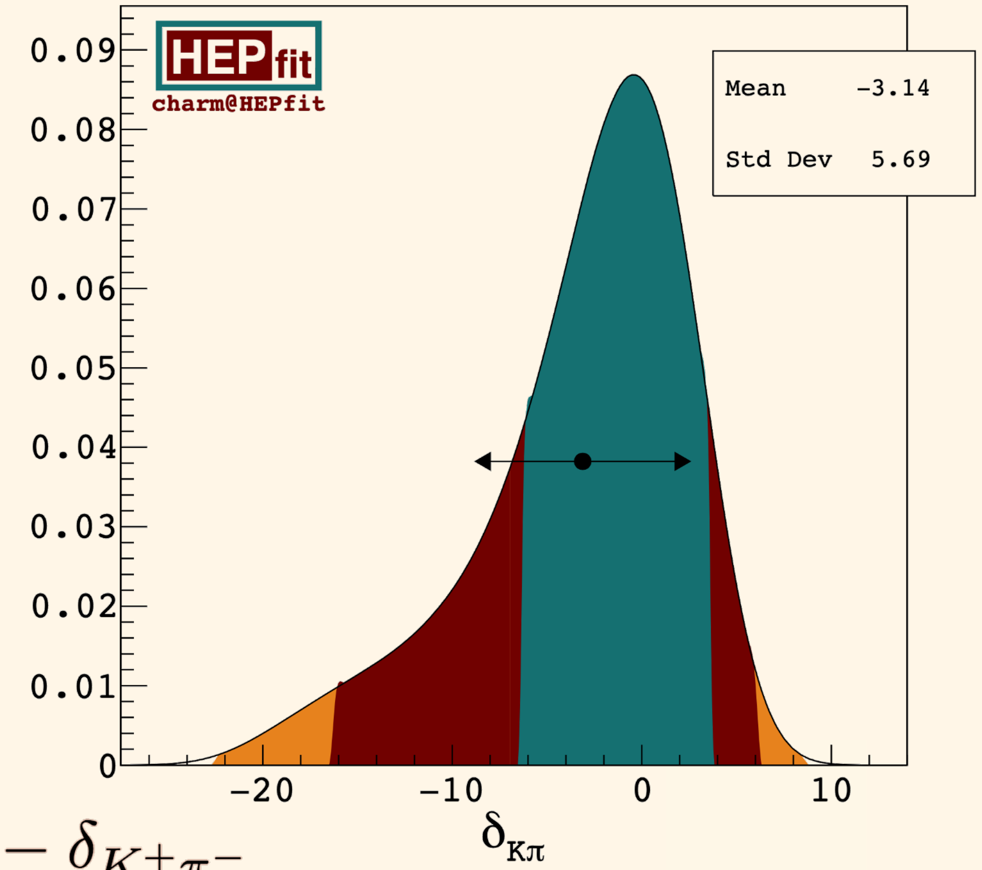
negative phases



positive phases



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

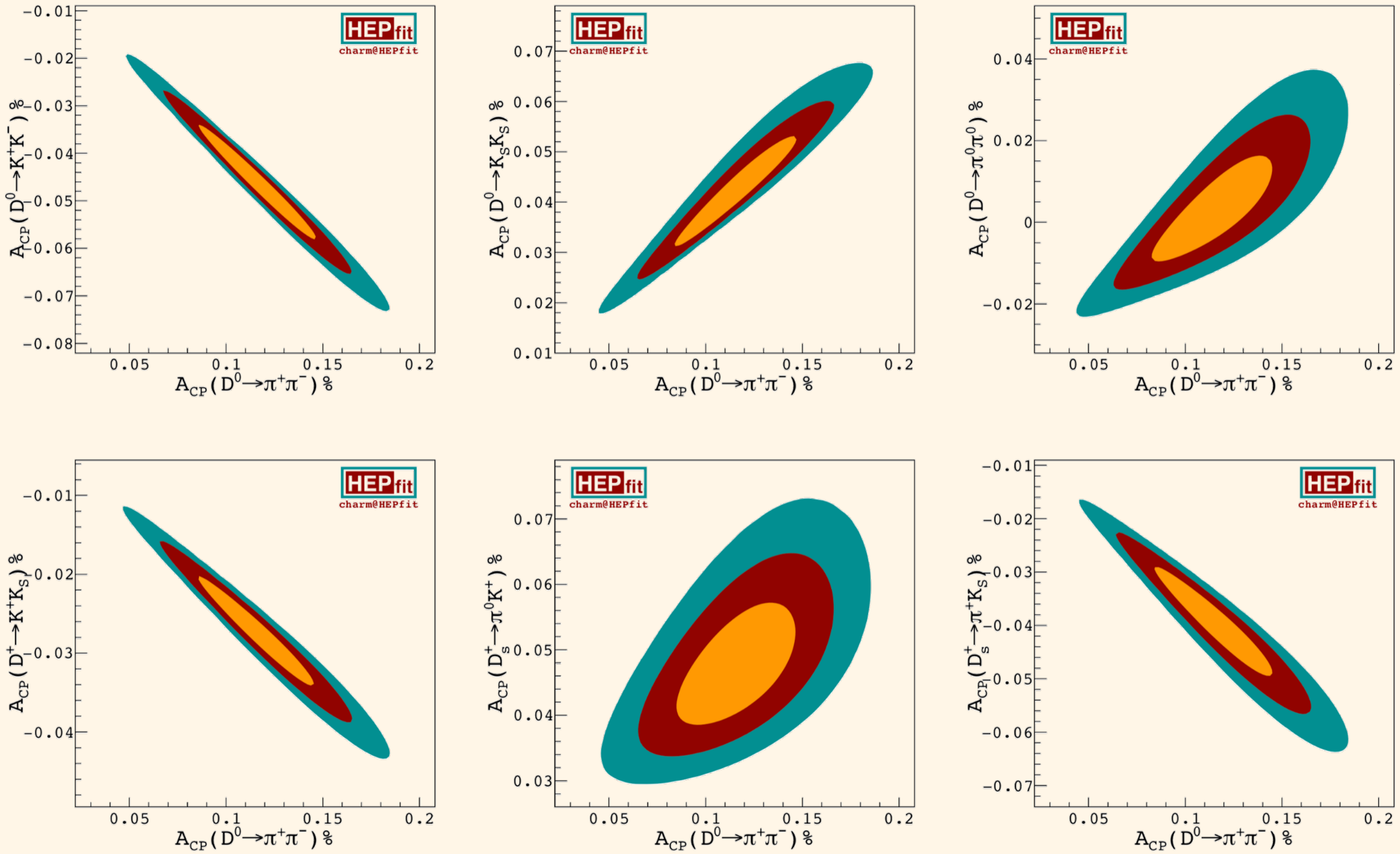
$8.9^{+8.6}_{-9.7}$ HFLAV: assuming no CPV in DCS decays. Belle II will measure it to a few degrees.

predictions

the **CP** asymmetries depend on the sign of the FSI phases

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
$D^0 \to \pi^+\pi^-$	0.117 ± 0.020	0.118 ± 0.020	$D^+ \to K^+K_S$	-0.028 ± 0.005	-0.026 ± 0.005
$D^0 \to \pi^0\pi^0$	0.004 ± 0.009	0.079 ± 0.010	$D_s^+ \to \pi^+K_S$	-0.040 ± 0.007	-0.036 ± 0.007
$D^0 \to K^+K^-$	-0.047 ± 0.008	-0.046 ± 0.008	$D_s^+ \to \pi^0K^+$	0.048 ± 0.006	-0.003 ± 0.004
$D^0 \to K_SK_S$	0.043 ± 0.007	0.038 ± 0.007			

several **CP** asymmetries can be predicted from the measurement of ΔA_{CP}



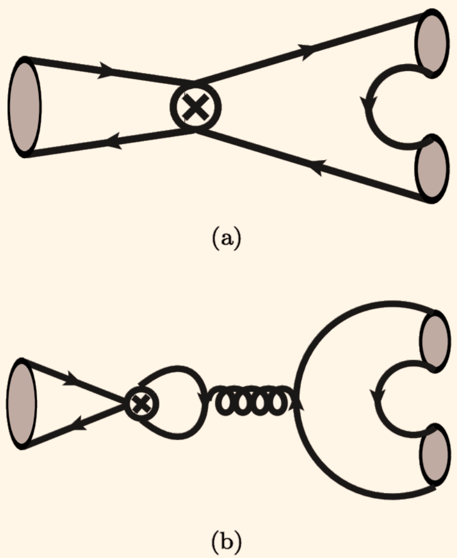
the **CP** asymmetries are parametrically correlated through the penguin amplitude

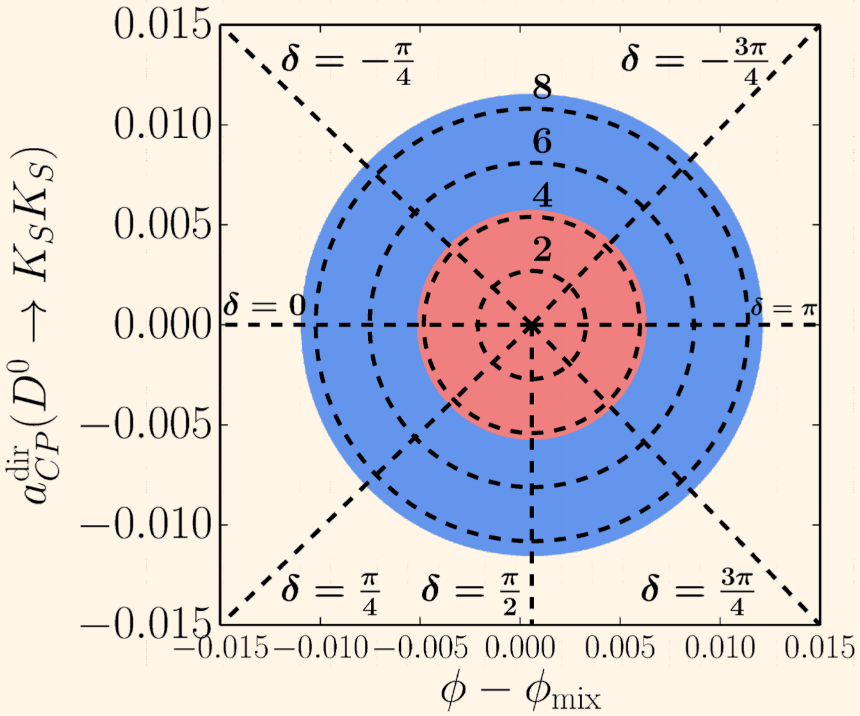
A_{CP}(channel)	mode (%)	RMS (%)		
		Current Fit	Belle II 50 ab^{-1} [137]	LHCb 50 fb^{-1} [138]
$D^0 \to \pi^+\pi^-$	0.1174	0.020	0.05	–
$D^0 \to \pi^0\pi^0$	-0.0034	0.009	0.09	–
$D^0 \to K^+K^-$	-0.0465	0.008	0.03	–
$D^0 \to K_SK_S$	0.0431	0.007	0.17	–
$D^+ \to K^+K_S$	-0.0276	0.005	0.05	–
$D_s^+ \to \pi^+K_S$	-0.0403	0.007	0.29	–
ΔA_{CP}	-0.164			0.01

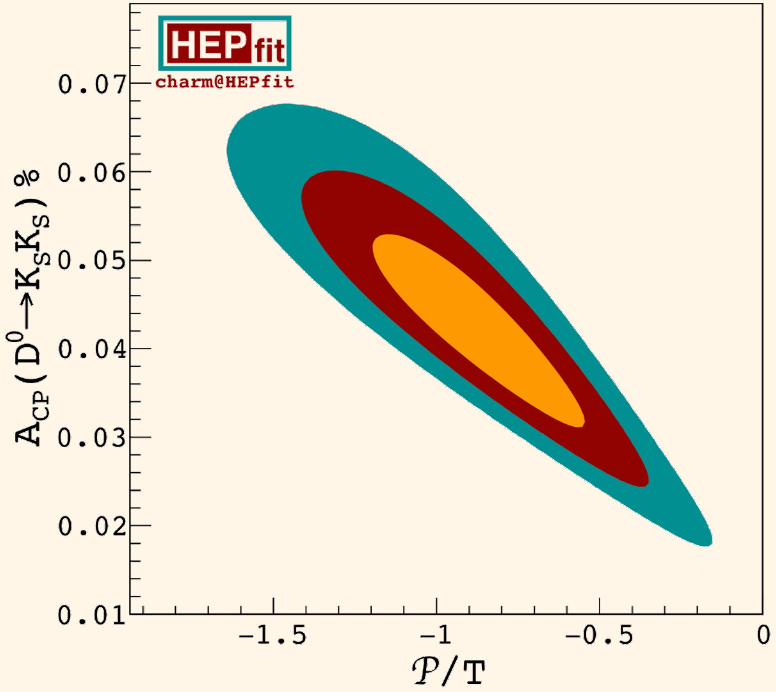
current precision of predictions of **CP** asymmetries from ΔA_{CP} already exceeds the Belle II expected precision

CPV in $D^0 \to K_S K_S$

CPV in $D^0 \to K_S K_S$







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 suppressed) is generated by rescattering in our work and is treated as an independent contribution in Nierste et. al.

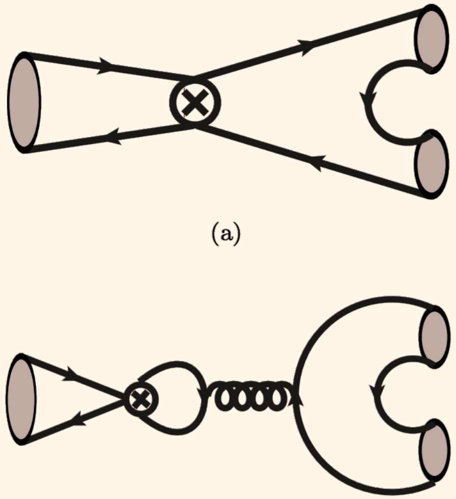
$$|a_{CP}^{\mathrm{dir}}(D^0 \to K_S K_S)| \lesssim \frac{2|V_{cb}V_{ub}|}{\varepsilon|V_{cs}V_{us}|} \sim 0.6\%$$

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].

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

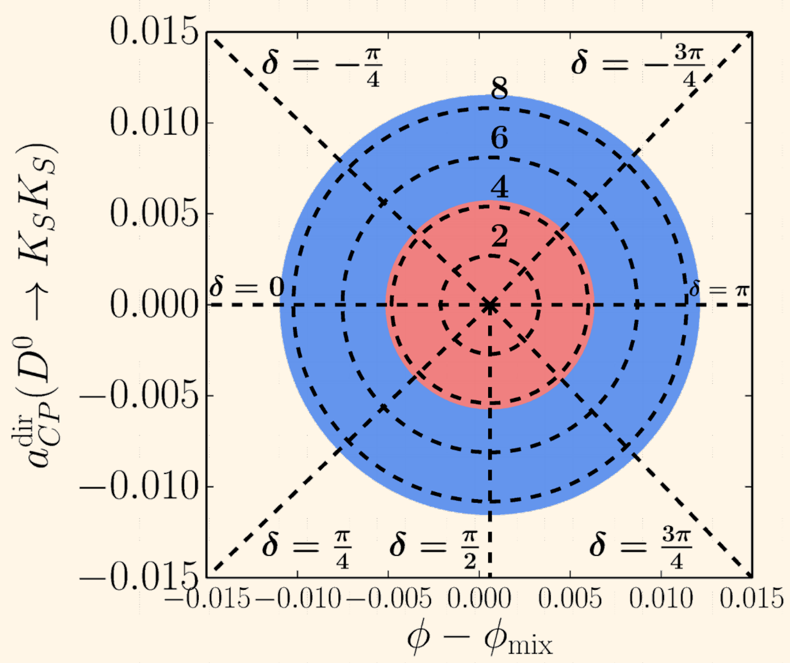
G. Hiller, M. Jung and S. Schacht, *SU(3)-flavor anatomy of nonleptonic charm decays*, *Phys. Rev.* **D87** (2013) 014024, [1211.3734].

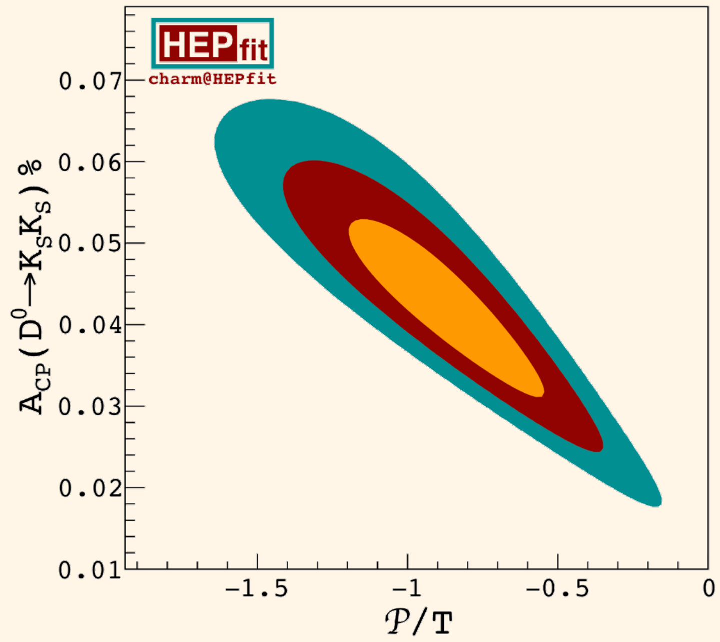
CPV in $D^0 \to K_S K_S$

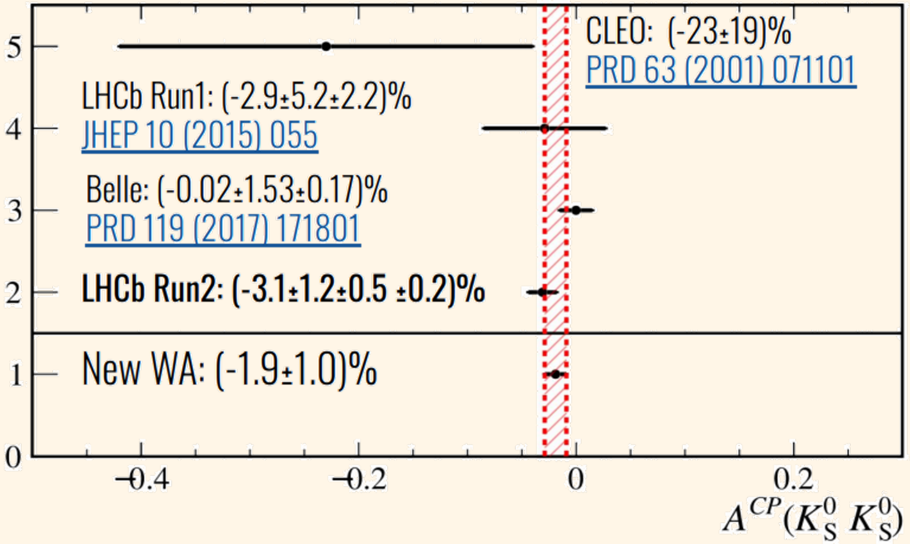


(a)

(b)







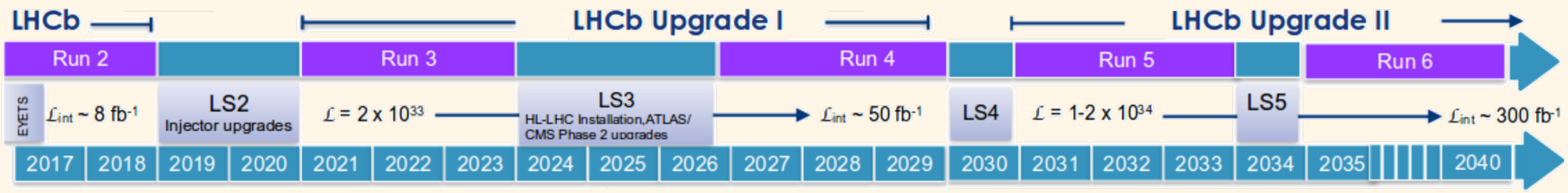
Current experimental status

LHCb Run2 from arXiv:2105.01565

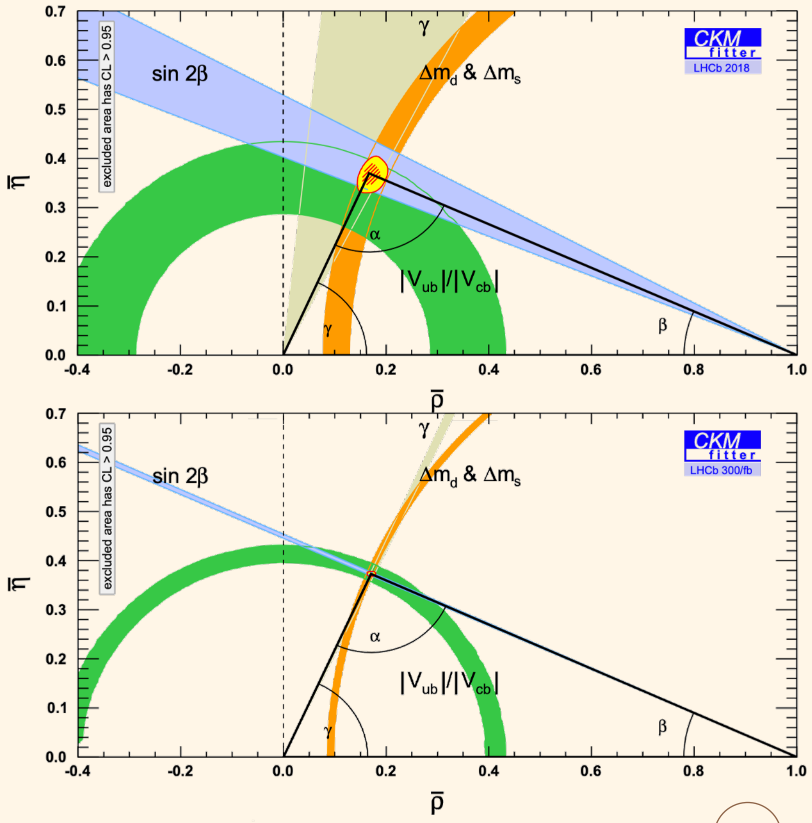
For details see Lorenzo's talk on 03/06

Future Progress

Belle II, LHCb and its upgrades



Observable	Current LHCb	LHCb 2025	Belle II	Upgrade II	ATLAS & CMS
EW Penguins					
R_K $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [274]	0.025	0.036	0.007	–
R_{K^*} $(1 < q^2 < 6\,\mathrm{GeV}^2c^4)$	0.1 [275]	0.031	0.032	0.008	–
R_ϕ, R_{pK}, R_π	–	0.08, 0.06, 0.18	–	0.02, 0.02, 0.05	–
CKM tests					
γ, with $B_s^0 \to D_s^+ K^-$	$(^{+17}_{-22})^\circ$ [136]	4°	–	1°	–
γ, all modes	$(^{+5.0}_{-5.8})^\circ$ [167]	1.5°	1.5°	0.35°	–
$\sin 2\beta$, with $B^0 \to J/\psi K^0_S$	0.04 [609]	0.011	0.005	0.003	–
ϕ_s, with $B_s^0 \to J/\psi \phi$	49 mrad [44]	14 mrad	–	4 mrad	22 mrad [610]
ϕ_s, with $B_s^0 \to D_s^+ D_s^-$	170 mrad [49]	35 mrad	–	9 mrad	–
$\phi_s^{s\bar{s}s}$, with $B_s^0 \to \phi\phi$	154 mrad [94]	39 mrad	–	11 mrad	Under study [611]
a_{sl}^s	33×10^{-4} [211]	10×10^{-4}	–	3×10^{-4}	–
$\lvert V_{ub}\rvert/\lvert V_{cb}\rvert$	6% [201]	3%	1%	1%	–
$B_s^0, B^0 \to \mu^+\mu^-$					
$\mathcal{B}(B^0 \to \mu^+\mu^-)/\mathcal{B}(B_s^0 \to \mu^+\mu^-)$	90% [264]	34%	–	10%	21% [612]
$\tau_{B_s^0 \to \mu^+\mu^-}$	22% [264]	8%	–	2%	–
$S_{\mu\mu}$	–	–	–	0.2	–
$b \to c\ell^-\bar{\nu}_l$ LUV studies					
$R(D^*)$	0.026 [215, 217]	0.0072	0.005	0.002	–
$R(J/\psi)$	0.24 [220]	0.071	–	0.02	–
Charm					
$\Delta A_{CP}(KK - \pi\pi)$	8.5×10^{-4} [613]	1.7×10^{-4}	5.4×10^{-4}	3.0×10^{-5}	–
A_Γ $(\approx x \sin\phi)$	2.8×10^{-4} [240]	4.3×10^{-5}	3.5×10^{-4}	1.0×10^{-5}	–
$x \sin\phi$ from $D^0 \to K^+\pi^-$	13×10^{-4} [228]	3.2×10^{-4}	4.6×10^{-4}	8.0×10^{-5}	–
$x \sin\phi$ from multibody decays	–	$(K3\pi)$ 4.0×10^{-5}	$(K^0_S\pi\pi)$ 1.2×10^{-4}	$(K3\pi)$ 8.0×10^{-6}	–



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

$T \to$ colour connected
$C \to$ colour suppressed
$\Delta \to$ SU(3)

$\varphi \to$ singl
$\delta_0 \to$ the F
$\delta_0' \to$ the F
$\delta_{\frac{1}{2}} \to$ the I
$\epsilon_\delta \to$ the splitting in the $I = 0$ phases for D_s^+ and $D^{0,+}$

+ additional sources of SU(3)$_F$ breaking
$+ \eta - \eta' + D \to PV + D \to VV + \ \ldots$

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

K and K' $\to$ non-conservation of strangeness changing neutral and charged currents

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

κ and κ' $\to$ SU(3)$_F$ breaking in the 27 matrix element.

the U-spin components:

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

CP violating

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

$B(D^0 \to K^+K^-) = P + T + \Delta_3 \equiv \mathcal{P}$
$B(D^0 \to K^0\bar{K}^0) = \Delta_4.$

$\Delta_4 \to$ OZI suppressed

Summary

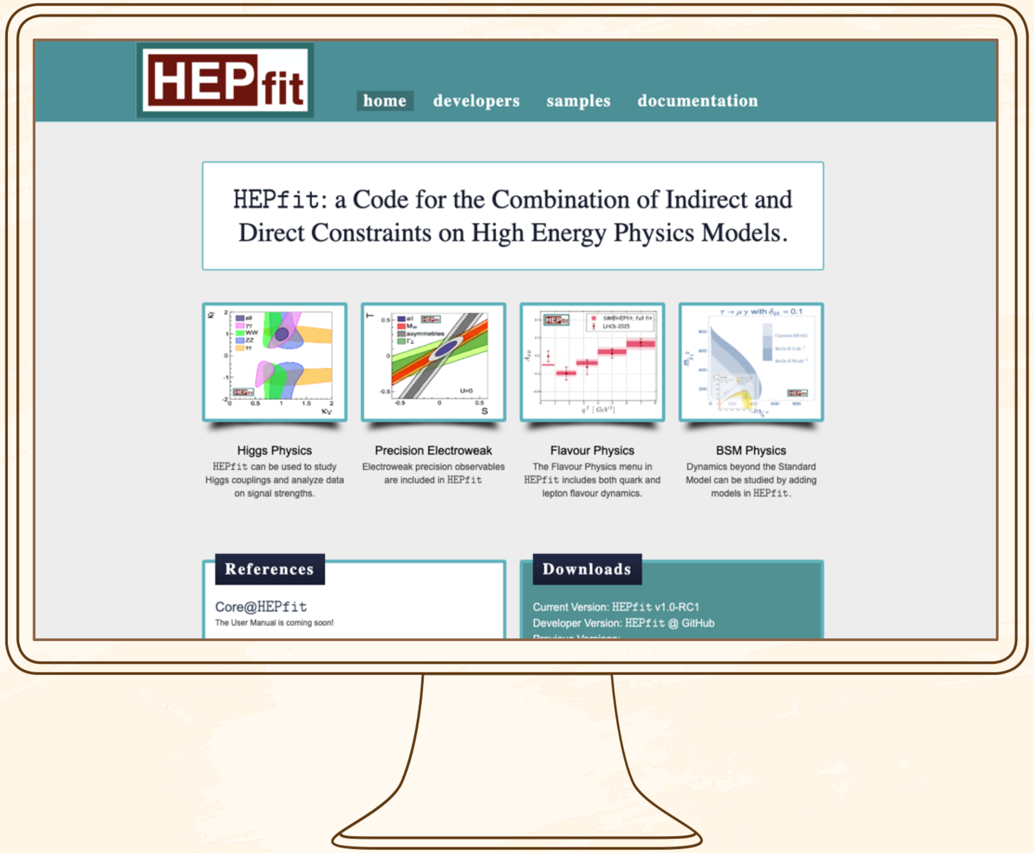
- ✓ We are reasonably successful in fitting the branching fraction of multiple decay modes applying $SU(3)_F$ breaking through large Final State Interactions and small shifts in the amplitudes.
- ✓ Since all CP asymmetries in the SCS sector, depend on one combination of parameters, they can be predicted 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.

bottom line: {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

HEPfit: a MCMC based Bayesian analysis framework

HEPfit website:

http://hepfit.roma1.infn.it



BAT website:

https://bat.mpp.mpg.de/

Epilogue: long distance effects from rescattering

One can split the effective Hamiltonian into the CP-even and CP-odd part

$$T_{fi} = \langle f|H|i\rangle = \langle f|H_R + iH_I|i\rangle = T^R_{fi} + i\,T^I_{fi}\,.$$

Scattering matrix

$$S = \left(\begin{array}{c|ccc} D\to D & D\to\pi\pi & D\to KK & \cdots \\ \hline \pi\pi\to D & \pi\pi\to\pi\pi & \pi\pi\to KK & \cdots \\ KK\to D & KK\to\pi\pi & KK\to KK & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{array}\right) \equiv \begin{pmatrix} 1 & -i(T)^T \\ -i\,\mathrm{CP}(T) & S_S \end{pmatrix}$$

strong interaction rescattering matrix rotates the two parts

$$T^R = S_S(T^R)^*, \qquad T^I = S_S(T^I)^*,$$

since S_S is symmetric it can be diagonalized

$$O\,S\,O^T = S_S^{\rm diag} \equiv {\rm diag}(e^{2i\delta_1}, e^{2i\delta_2}, \ldots, e^{2i\delta_N})\,,$$

in the diagonal basis we recover Watson's theorem

$$(OT) = S_S^{\rm diag}(OT)^* \qquad \Rightarrow \qquad (OT)_i = |(OT)|_i e^{i(\delta_i + n_i\pi)}\,.$$

in terms of the weak decay matrix elements W_k

$$T_i = O_{ji}e^{i(\delta_j+n_j\pi)}O_{jk}W_k \equiv R_{ik}(\vec{\boldsymbol{n}})W_k\,,$$

we arrive at the rescattering matrix

$$R_{ik}(\vec{\boldsymbol{n}}) = O_{ji}e^{i(\delta_j+n_j\pi)}O_{jk}\,.$$

Isospin amplitudes

$$A(D^+\to\pi^+\pi^0) = \frac{\sqrt{3}}{2\sqrt{2}}\mathcal{A}_2^\pi\,,$$

$$A(D^0\to\pi^+\pi^-) = \frac{\mathcal{A}_2^\pi + \sqrt{2}\mathcal{A}_0^\pi}{2\sqrt{3}}\,,$$

$$A(D^0\to\pi^0\pi^0) = \frac{\sqrt{2}\mathcal{A}_2^\pi - \mathcal{A}_0^\pi}{\sqrt{6}}\,,$$

$$A(D^+\to K^+\bar{K}^0) = \frac{-\mathcal{A}_{13}^K}{2} + \mathcal{A}_{11}^K\,,$$

$$A(D^0\to K^+K^-) = \frac{\mathcal{A}_{13}^K + \mathcal{A}_{11}^K + \mathcal{A}_0^K}{2}\,,$$

$$A(D^0\to K^0\bar{K}^0) = \frac{-\mathcal{A}_{13}^K - \mathcal{A}_{11}^K + \mathcal{A}_0^K}{2}\,.$$

\+ rescattering matrix from ππ rescattering

$$S_{I=0} = \begin{array}{c} \begin{pmatrix} 0.97\,e^{-i\,58^\circ} & 0.21\,e^{-i\,136^\circ} & 0.04\,e^{i\,71^\circ} & 0.05\,e^{i\,152^\circ} & 0.10\,e^{-i\,142^\circ} \\ 0.21\,e^{-i\,136^\circ} & 0.80\,e^{-i\,27^\circ} & 0.41\,e^{-i\,174^\circ} & 0.32\,e^{-i\,120^\circ} & 0.21\,e^{-i\,109^\circ} \\ 0.04\,e^{i\,71^\circ} & 0.41\,e^{-i\,174^\circ} & 0.87\,e^{-i\,144^\circ} & 0.10\,e^{i\,165^\circ} & 0.25\,e^{i\,25^\circ} \\ 0.05\,e^{i\,152^\circ} & 0.32\,e^{-i\,120^\circ} & 0.10\,e^{i\,165^\circ} & 0.92\,e^{-i\,14^\circ} & 0.21\,e^{-i\,111^\circ} \\ 0.10\,e^{-i\,142^\circ} & 0.21\,e^{-i\,109^\circ} & 0.25\,e^{i\,25^\circ} & 0.21\,e^{-i\,111^\circ} & 0.91\,e^{-i\,14^\circ} \end{pmatrix} \\ \begin{array}{ccccc} \mathcal{A}_0^\pi\,, & \mathcal{A}_0^K\,, & \mathcal{A}_0^{4\pi}\,, & \mathcal{A}^{\eta\eta}\,, & \mathcal{A}^{\eta\eta'} \end{array} \end{array}$$

let there be CP violation!

THANK YOU!

Ayan Paul

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http://www.desy.de/~apaul

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.