$SU(3)_f$ Breaking through Final State Interactions and CP Asymmetries in $D \to PP$ Decays

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ERC Ideas: NPFlavour

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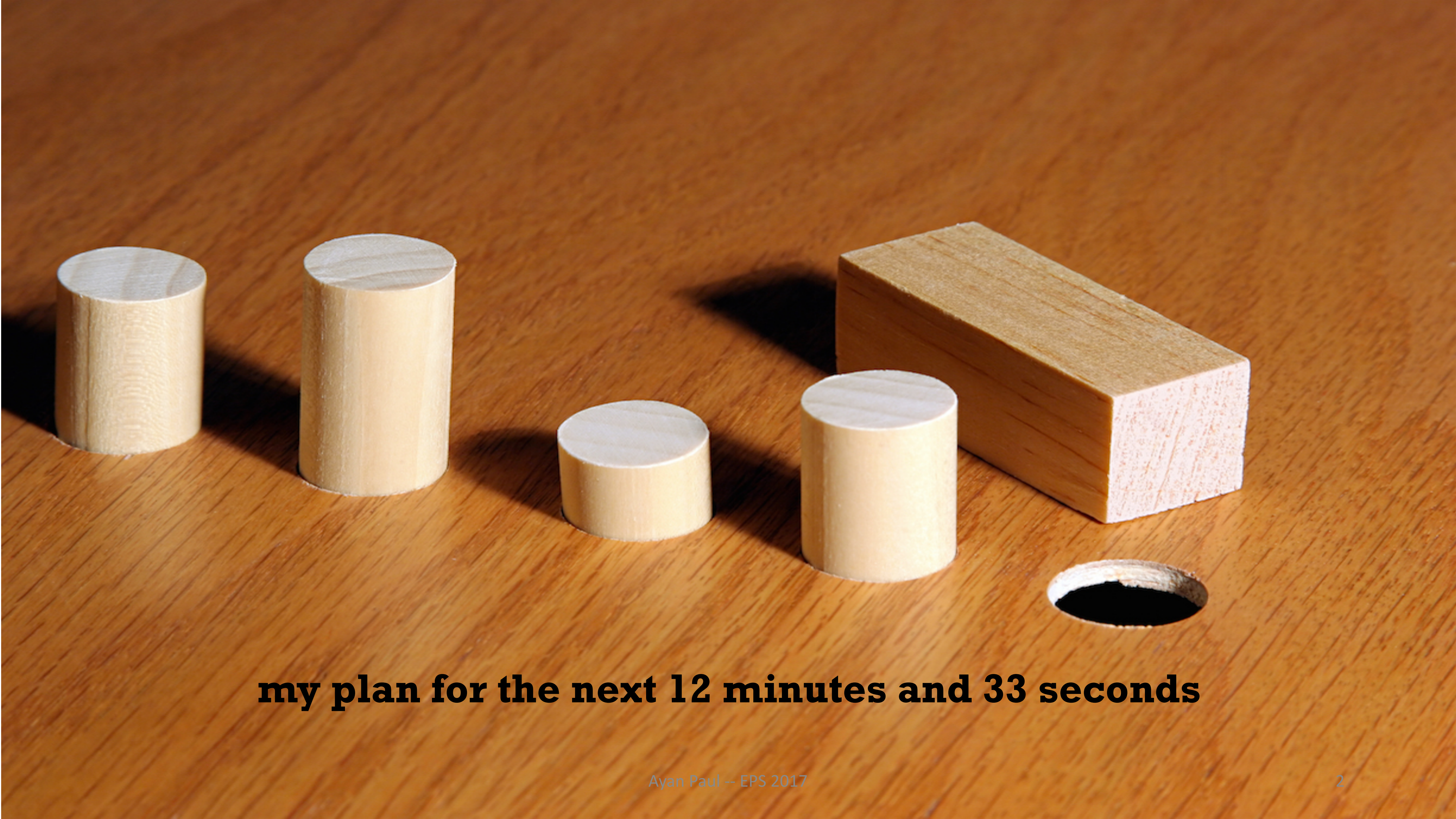


my plan for the next 12 minutes and 33 seconds

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	$D^+ \to \pi^+ K_S$	15.68 ± 0.41	15.3 ± 0.6
$D_0^+ \to \pi^0\pi^0$	0.82 ± 0.04	0.826 ± 0.035	$D^+ \to \pi^+ K_L$	14.27 ± 0.38	14.6 ± 0.5
$D^+ \to \pi^+\pi^0$	1.24 ± 0.06	1.24 ± 0.06	$D^0 \to \pi^+ K^-$	39.37 ± 0.40	39.3 ± 0.4
$D^0 \to K^+K^-$	3.98 ± 0.07	4.01 ± 0.07	$D^0 \to \pi^0 K_S$	12.02 ± 0.36	12.0 ± 0.4
$D^0 \to K_S K_S$	0.17 ± 0.04	0.18 ± 0.04	$D^0 \to \pi^0 K_L$	9.48 ± 0.29	10.0 ± 0.7
$D^+ \to K^+ K_S$	3.00 ± 0.15	2.95 ± 0.15	$D_s^+ \to K^+ K_S$	14.91 ± 0.50	15.0 ± 0.5
$D_s^+ \to \pi^0 K^+$	0.95 ± 0.18	0.63 ± 0.21	$D^+ \to \pi^0 K^+$	0.125 ± 0.015	0.189 ± 0.025
$D_s^+ \to \pi^+ K_S$	1.23 ± 0.06	1.22 ± 0.06	$D^0 \to \pi^- K^+$	0.140 ± 0.003	0.139 ± 0.0027

A_{CP} (D^0)	($\mu \pm \sigma$) (%)		A_{CP} ($D_{(s)}^+$)	($\mu \pm \sigma$) (%)	
	ND	PD		ND	PD
$D^0 \to \pi^+\pi^-$	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:

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

the operator basis:

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

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

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

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:

$$R^{6}_{8,1} \rightarrow \sqrt{\frac{1}{30}}\left[\left(2T'-3C'+\Delta\right)e^{i\delta_1'}+\left(3T'-2C'-K\right)e^{i\delta_{\frac{1}{2}}}\right]$$

$$R^{15}_{8,1} \rightarrow \sqrt{\frac{1}{30}}\left[\left(2T'-3C'+\Delta\right)e^{i\delta_1'}-\left(3T'-2C'-K\right)e^{i\delta_{\frac{1}{2}}}\right]$$

CA

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

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

DCS

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

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

$\boxed{\delta_1' = \delta_1(1-\epsilon_\delta) \text{ and } \delta_{\frac{1}{2}}' = \delta_{\frac{1}{2}}(1-\epsilon_\delta)}$ phases for the D_s^+

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

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

R^{15}_{27}: should have a different normalization so T' and C' are introduced.

No exotic resonances in 27

singlet-octet mixing

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

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

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

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

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

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

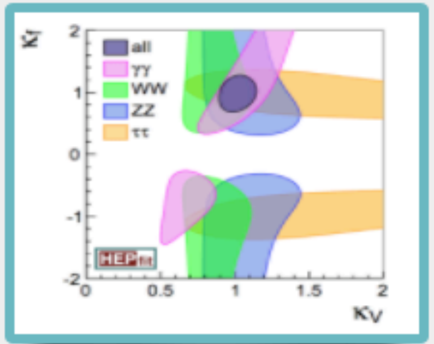
All phases in the ΔU = 0 part are determined by the ΔU = 1 part and extracted from the branching fractions

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

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

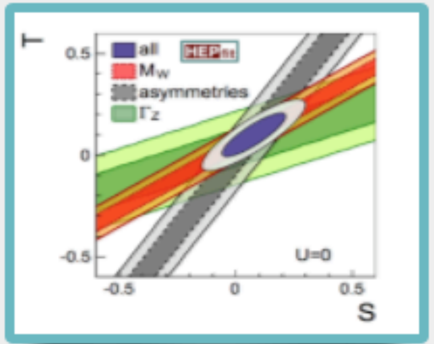
home developers samples documentation

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



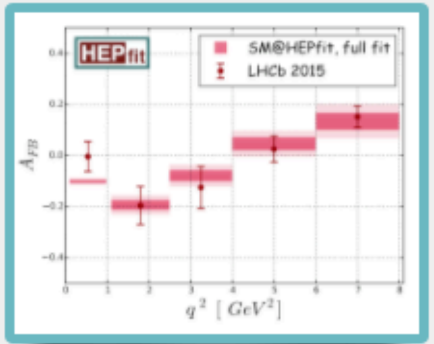
Higgs Physics

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



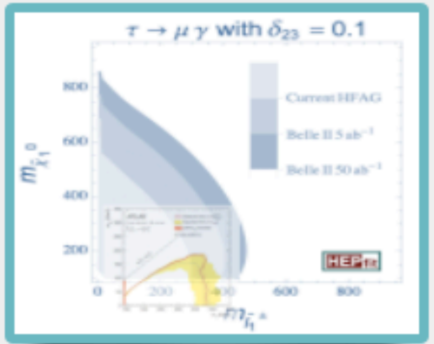
Precision Electroweak

Electroweak precision observables are included in HEPfit



Flavour Physics

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



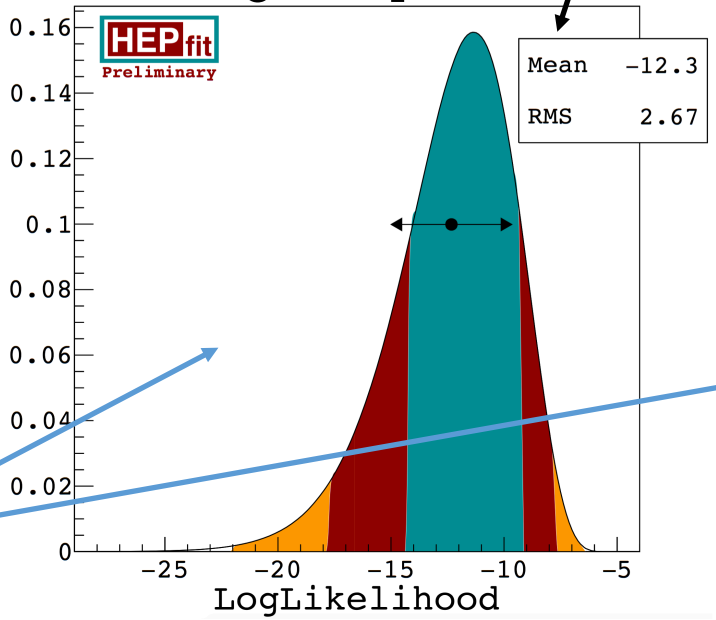
BSM Physics

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

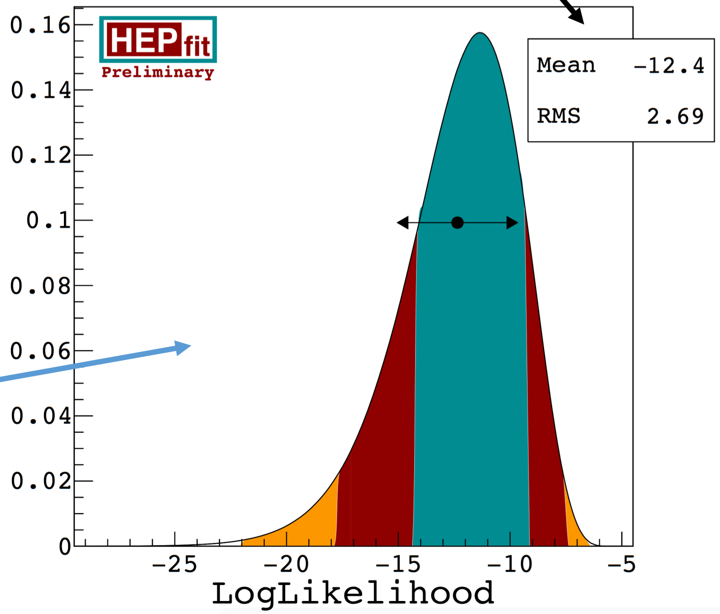
the solutions

	$(\mu \pm \sigma)$ (%)			$(\mu \pm \sigma)$ (%)	
	ND	PD		ND	PD
T	0.426 ± 0.006	0.426 ± 0.006	δ_0	-2.545 ± 0.235	2.575 ± 0.319
C	-0.212 ± 0.007	-0.212 ± 0.008	δ_0'	-0.942 ± 0.137	0.931 ± 0.153
T'	0.408 ± 0.003	0.408 ± 0.003	$\delta_{\frac{1}{2}}$	-1.598 ± 0.031	1.598 ± 0.031
C'	-0.231 ± 0.004	-0.231 ± 0.004	δ_1	-1.190 ± 0.111	1.196 ± 0.122
K	0.099 ± 0.012	0.096 ± 0.012	ϕ	0.393 ± 0.066	0.397 ± 0.073
K'	0.043 ± 0.111	0.048 ± 0.117	ϵ_δ	0.101 ± 0.092	0.105 ± 0.098
Δ	-0.033 ± 0.033	-0.032 ± 0.034			

negative phases



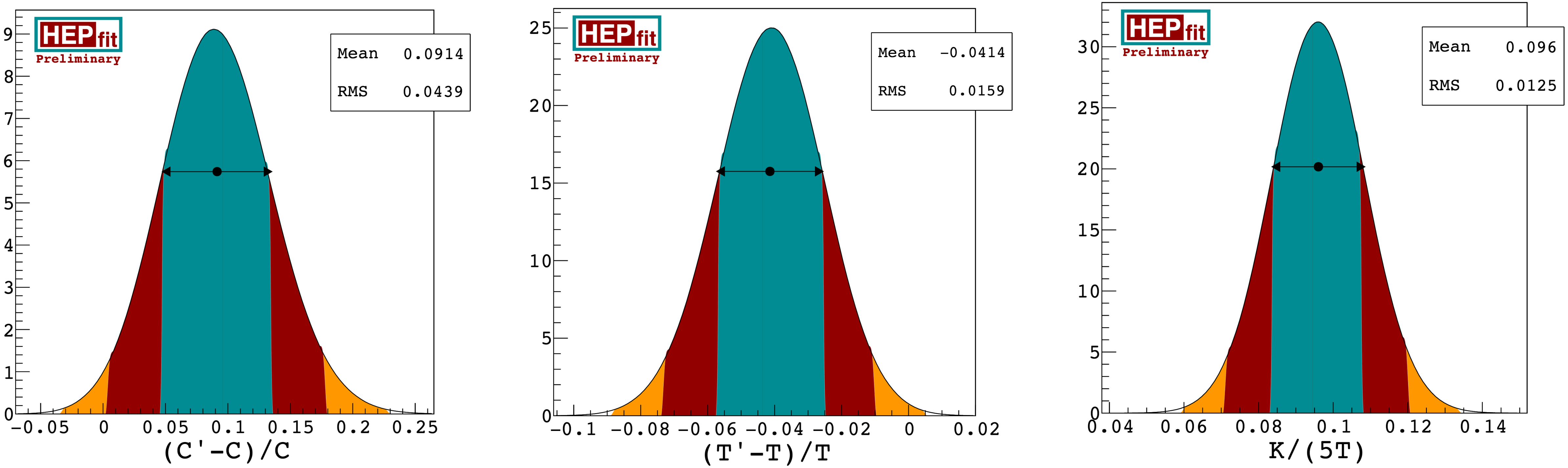
positive phases



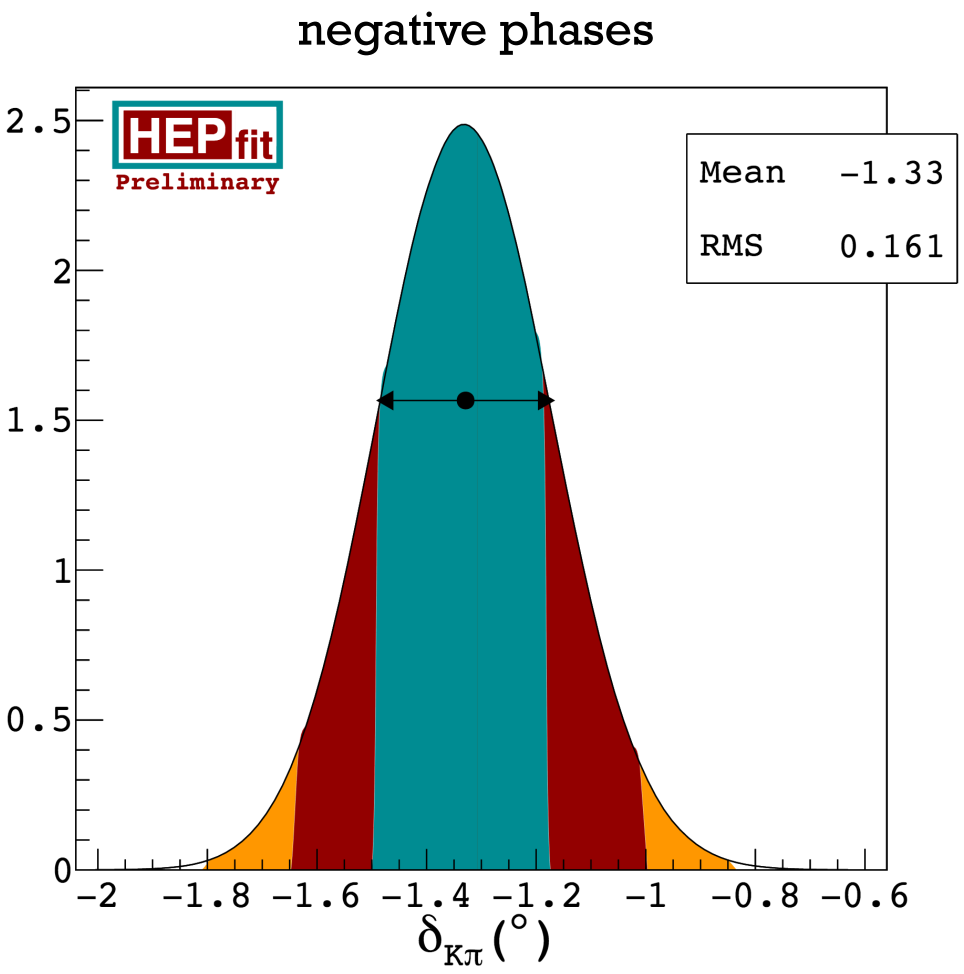
Preliminary: I am almost certain I am right but I am not sure that I can be certain.

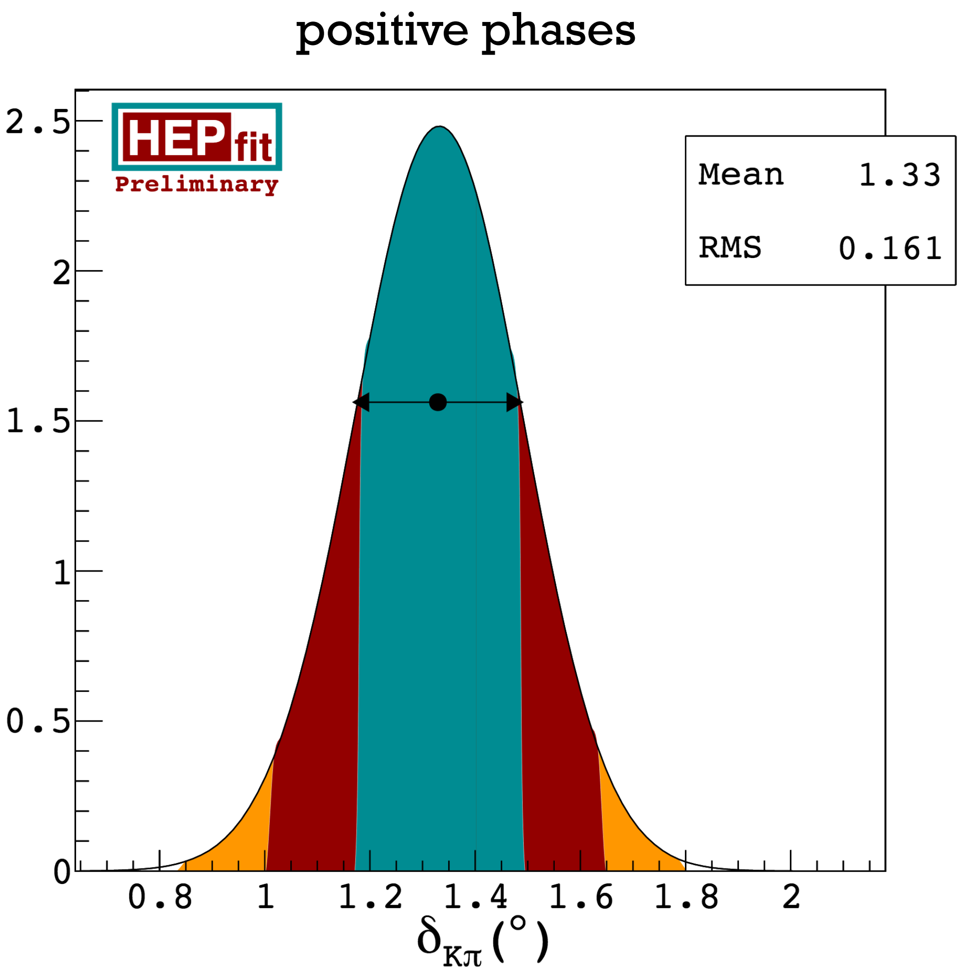
NOT measures of goodness of fit!

an estimate of $SU(3)_f$ breaking



$\delta_{K\pi}$





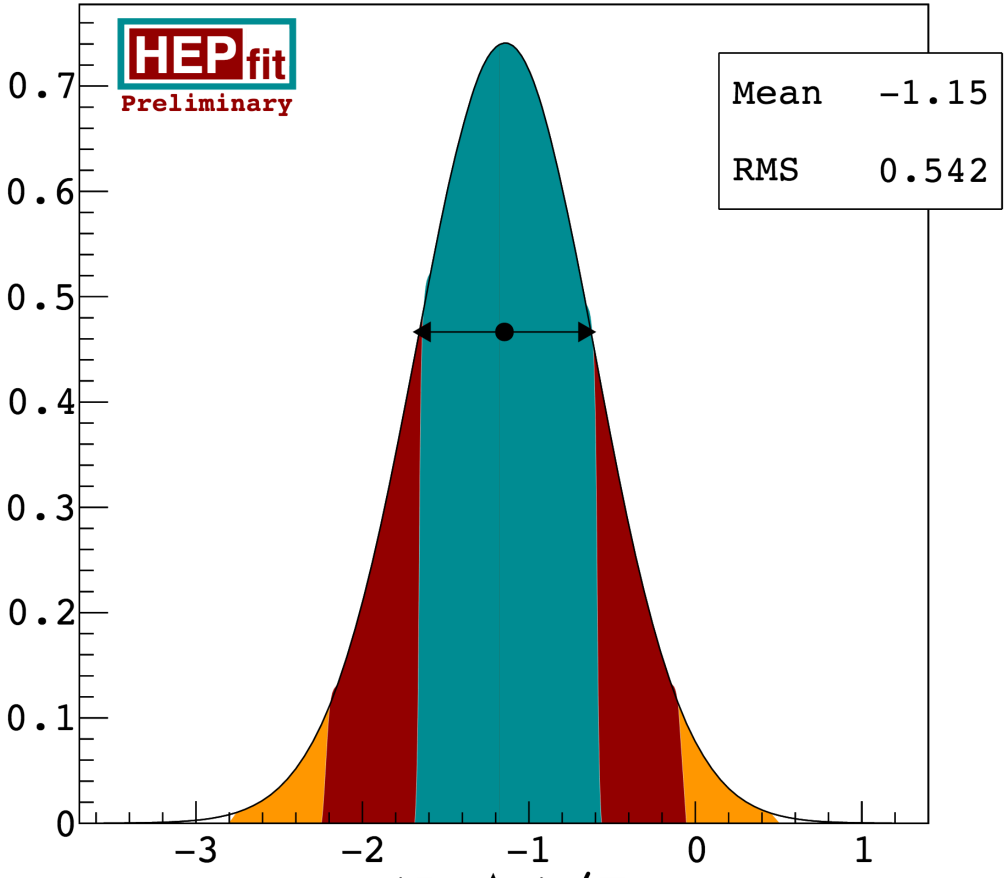
$4.8^{+10.4}_{-12.3}$ HFLAV: assuming no CPV in DCS decays. Belle II will measure it to a few degrees.

CP Violation

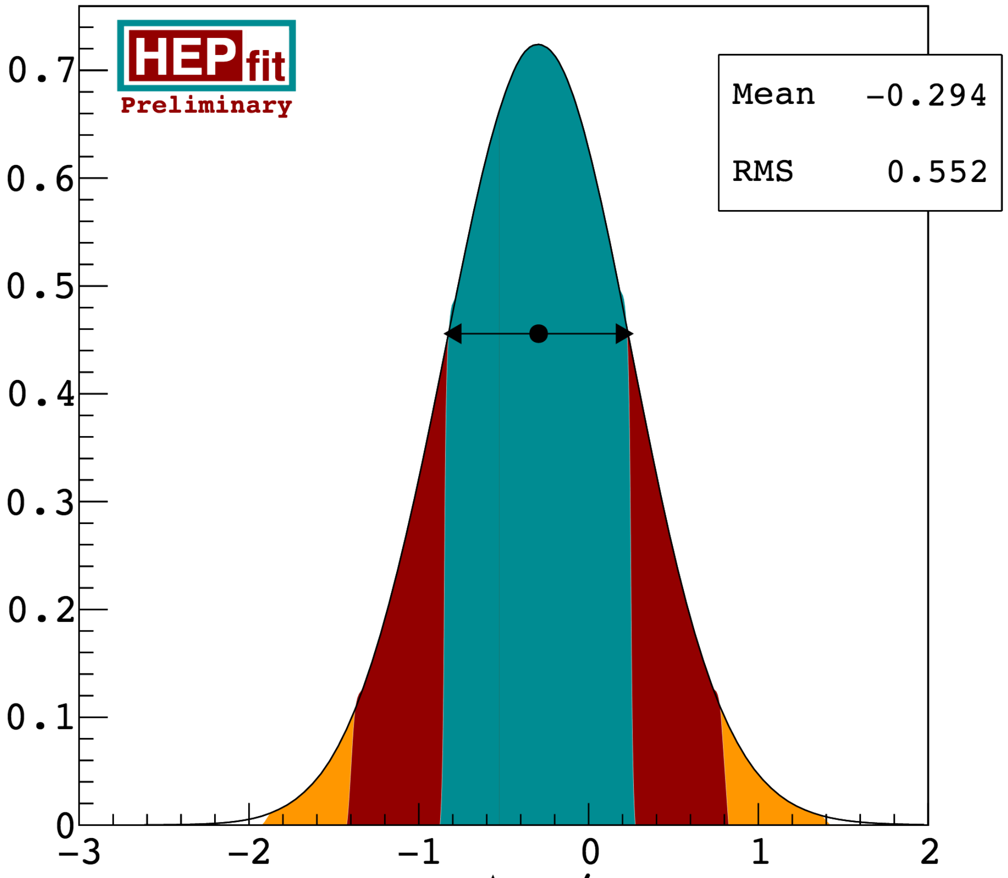
fit to ΔA_{CP} (LHCb)

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

negative phases



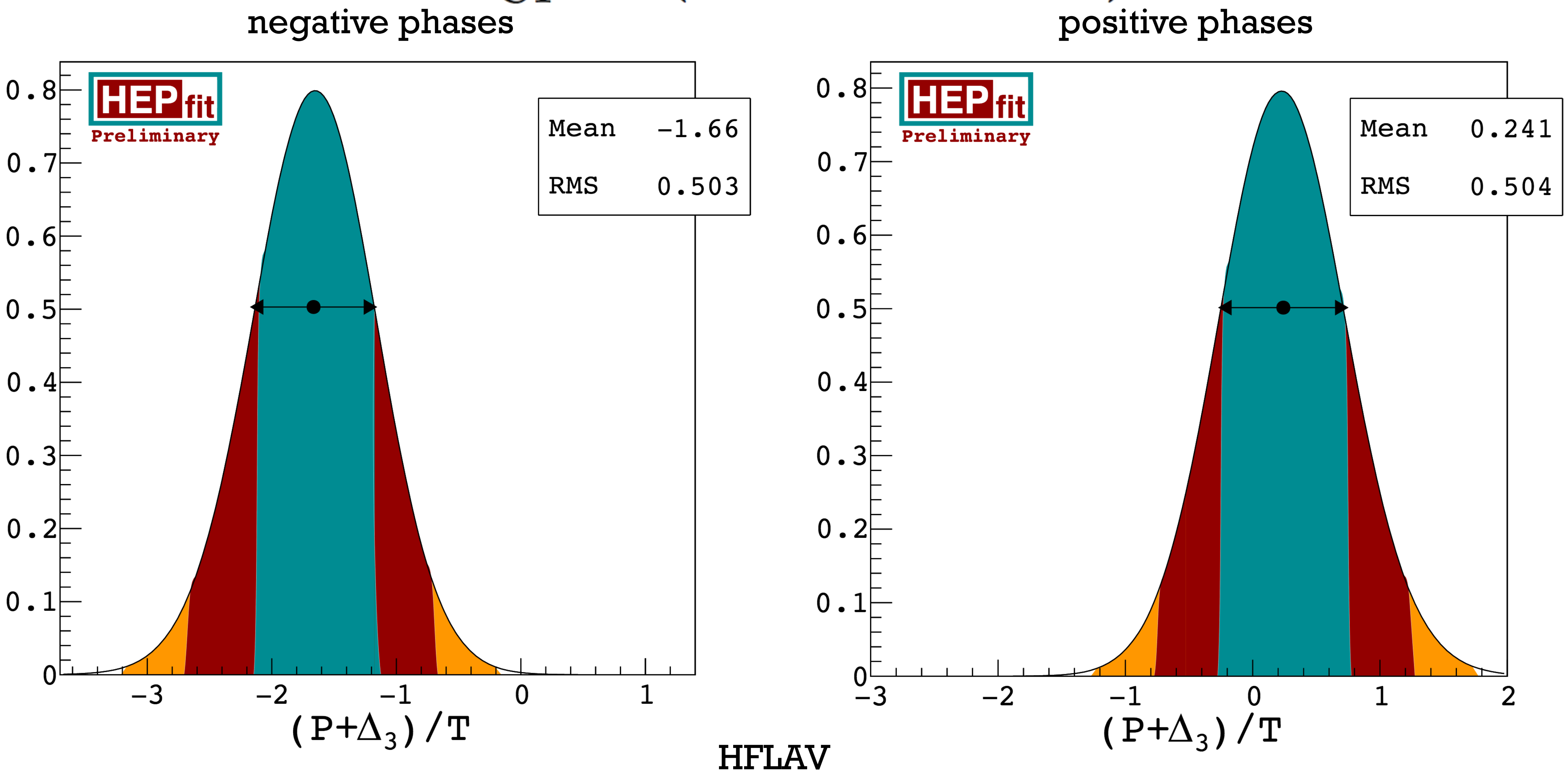
positive phases



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

fit to ΔA_{CP} (HFLAV)

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



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} $(D^+_{(s)})$	$(\mu \pm \sigma)$ (%)	
	ND	PD		ND	PD
$D^0 \to \pi^+\pi^-$	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	$D_s^+ \to \pi^0K^+$	-0.045 ± 0.017	0.021 ± 0.018
$D^0 \to K_SK_S$	0.019 ± 0.021	0.012 ± 0.024			

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

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

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

future prospects

A_{CP}(channel)	mode (%)	RMS (%)			
		Current Fit	Belle II	LHCb	
			50 ab^{-1} [107]	5 fb^{-1} [108]	50 fb^{-1} [108]
$D^0 \to \pi^+\pi^-$	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

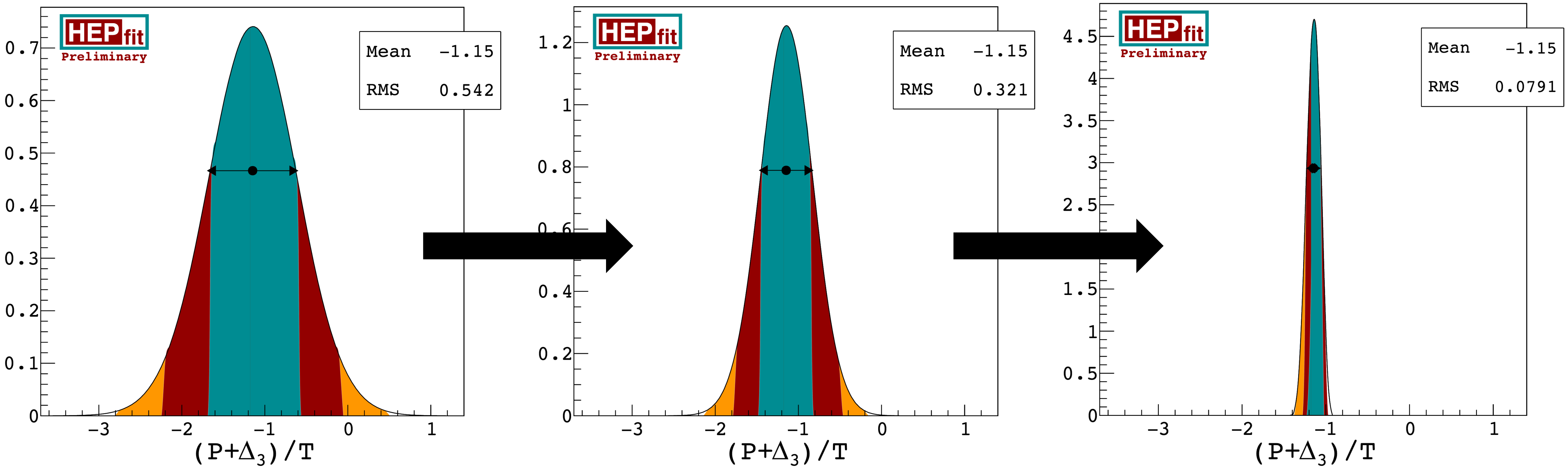
-- fit predictions from ΔA_{CP} have comparable or smaller errors than what Belle II will probe with 50 ab^{-1}

-- 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



ΔA_{CP}^{LHCb} (current) | Belle II 50 ab^{-1} + ΔA_{CP}^{LHCb} | Belle II 50 ab^{-1} + LHCb 50 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.

There is much more to this formalism with quite intriguing intricacies than I could explain in 12 mins and 33 seconds. I will leave the details for another time!

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.