

# **HFLAV** - charm

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for HFLAV Charm

**CHARM2021 Workshop**  
**Mexico City, June 2021**

# HFLAV Charm - group (re)structure

- **Charm CP violation and oscillations**
  - $D^0$  mixing [Marco Gersabeck, Alan Schwartz]
  - CP violation [Jolanta Brodzicka, Marco Gersabeck, Alan Schwartz]
  - T-violation [Jolanta Brodzicka]
- **Charm decays**
  - Properties of  $D^{**}$  and  $D_{sJ}$  states [Tara Nanut]
  - Excited charm baryon properties [John Yelton]
  - Semileptonic decays [Hai Bo Li, Aranza Oyanguren]
  - Decay constants [Hai Bo Li]
  - Hadronic branching fractions [Paras Naik, Lawrence Gibbons]
  - Rare decays [Marco Gersabeck]

# HFLAV 2018 Report

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THE EUROPEAN  
PHYSICAL JOURNAL C



Review

## Averages of $b$ -hadron, $c$ -hadron, and $\tau$ -lepton properties as of 2018

Heavy Flavor Averaging Group (HFLAV)

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~ 60 charm pages

• Already preparing for 2021 Report

# Inputs to global mixing fit

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Decay mode	Observables
$D^0 \rightarrow K^+ K^-, \pi^+ \pi^-$	$y_{CP}, A_\Gamma$
$D^0 \rightarrow K_S \pi^+ \pi^-$	$x, y,  q/p , \phi$
$D^0 \rightarrow K_S K^+ K^-$	$x, y$
$D^0 \rightarrow \pi^+ \pi^- \pi^0$	$x, y$
$D^0 \rightarrow K^+ \pi^- \pi^0$	$x'', y''$
$D^0 \rightarrow K^+ \pi^-$	$x'^2, y', x'^{2\pm}, y'^{\pm}$
$D^0 \rightarrow K^+ \pi^- \pi^+ \pi^-$	$R_M = (x^2 + y^2)/2$
$D^0 \rightarrow K^+ l^- \bar{\nu}_l$	$R_M$
$D^0 \rightarrow K^+ \pi^-, K^- \pi^+$	$R_D = \Gamma_{DCS}/\Gamma_{CF}, R_D^\pm, A_D$
$D^0 \rightarrow K^+ K^-, \pi^+ \pi^-$	$A_{CP}, \Delta A_{CP}$
$\psi(3770) \rightarrow D\bar{D}$	$R_M, R_D, y, \sqrt{R_D} \cos \delta$

# Observables and underlying parameters (I)

$$R_M = \frac{1}{2}(x^2 + y^2)$$

$$2 y_{CP} = (|q/p| + |p/q|) y \cos \phi - (|q/p| - |p/q|) x \sin \phi$$

$$2 A_\Gamma = (|q/p| - |p/q|) y \cos \phi - (|q/p| + |p/q|) x \sin \phi$$

$$\begin{pmatrix} x'' \\ y'' \end{pmatrix}_{K+\pi-\pi^0} = \begin{pmatrix} \cos \delta_{K\pi\pi} & \sin \delta_{K\pi\pi} \\ -\sin \delta_{K\pi\pi} & \cos \delta_{K\pi\pi} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

$$\begin{pmatrix} x' \\ y' \end{pmatrix}_{K+\pi^-} = \begin{pmatrix} \cos \delta & \sin \delta \\ -\sin \delta & \cos \delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

$$A_M = \frac{|q/p|^2 - |p/q|^2}{|q/p|^2 + |p/q|^2}$$

$$x'^{\pm} = \left( \frac{1 \pm A_M}{1 \mp A_M} \right)^{1/4} (x' \cos \phi \pm y' \sin \phi)$$

$$y'^{\pm} = \left( \frac{1 \pm A_M}{1 \mp A_M} \right)^{1/4} (y' \cos \phi \mp x' \sin \phi)$$

# Observables and underlying parameters (II)

$$\begin{aligned}
 \frac{\Gamma(D^0 \rightarrow K^+\pi^-) + \Gamma(\bar{D}^0 \rightarrow K^-\pi^+)}{\Gamma(D^0 \rightarrow K^-\pi^+) + \Gamma(\bar{D}^0 \rightarrow K^+\pi^-)} &= R_D && \Gamma_{\text{DCS}}/\Gamma_{\text{CF}} \\
 \frac{\Gamma(D^0 \rightarrow K^+\pi^-) - \Gamma(\bar{D}^0 \rightarrow K^-\pi^+)}{\Gamma(D^0 \rightarrow K^+\pi^-) + \Gamma(\bar{D}^0 \rightarrow K^-\pi^+)} &= A_D && \text{direct } A_{\text{CP}} \\
 \frac{\Gamma(D^0 \rightarrow K^+K^-) - \Gamma(\bar{D}^0 \rightarrow K^+K^-)}{\Gamma(D^0 \rightarrow K^+K^-) + \Gamma(\bar{D}^0 \rightarrow K^+K^-)} &= A_K + \frac{\langle t \rangle}{\tau_D} \mathcal{A}_{\text{CP}}^{\text{indirect}} \\
 \frac{\Gamma(D^0 \rightarrow \pi^+\pi^-) - \Gamma(\bar{D}^0 \rightarrow \pi^+\pi^-)}{\Gamma(D^0 \rightarrow \pi^+\pi^-) + \Gamma(\bar{D}^0 \rightarrow \pi^+\pi^-)} &= A_\pi + \frac{\langle t \rangle}{\tau_D} \mathcal{A}_{\text{CP}}^{\text{indirect}} \\
 2\mathcal{A}_{\text{CP}}^{\text{indirect}} &= (|q/p| + |p/q|)x \sin \phi - (|q/p| - |p/q|)y \cos \phi && -2A_\Gamma
 \end{aligned}$$

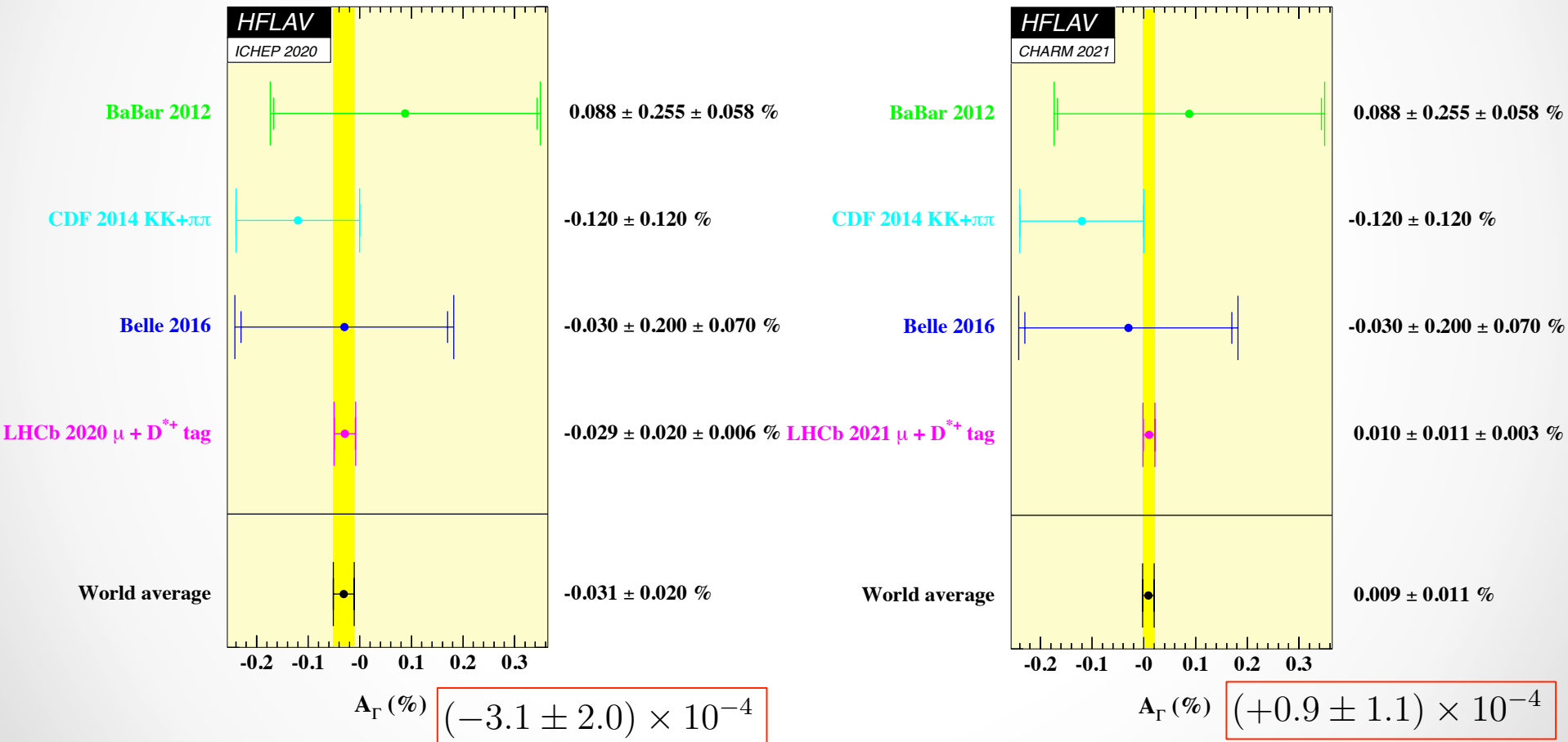
# Latest experimental additions

- $A_{\Gamma}$  from  $D^0 \rightarrow K^+K^-, \pi^+\pi^-$ , LHCb Run2,  
arXiv:2105.09889 [submitted to PRD]
- Global fits including this result shown for the first time  
[thanks to Alan Schwartz and Marco Gersabeck]
- Note: fits with new  $D^0 \rightarrow K_S \pi^+ \pi^-$  results not ready yet

# $A_\Gamma$ world average

- Average  $A_\Gamma$  used in the mixing fit
- 2020

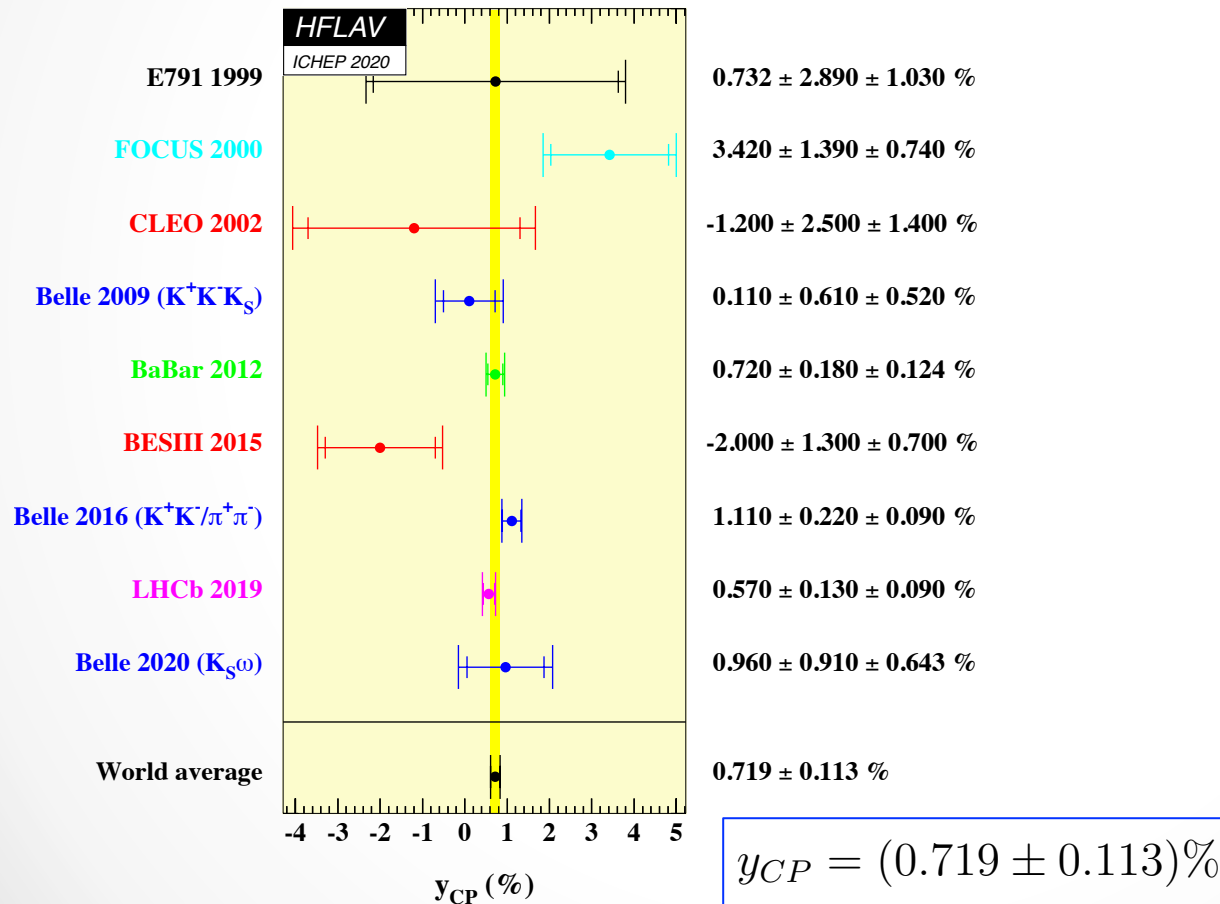
2021





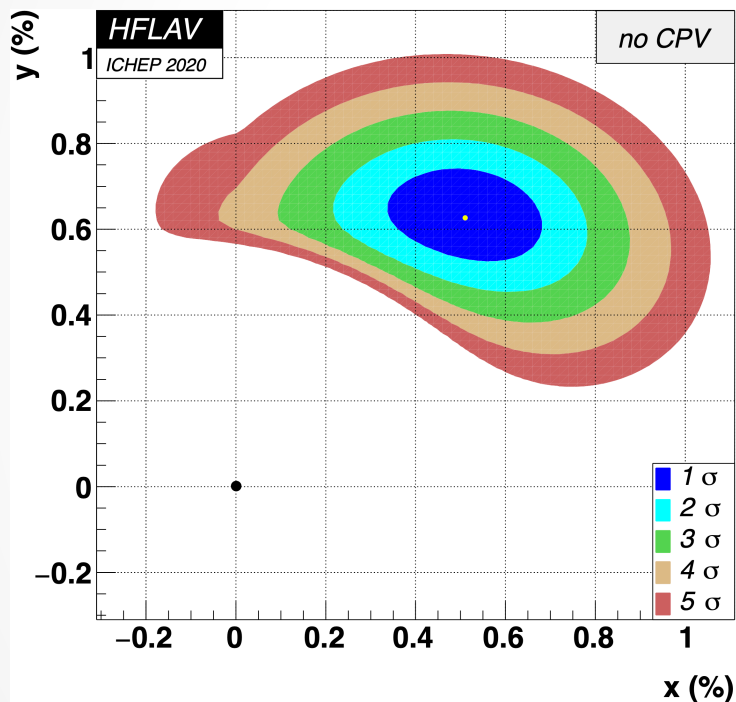
# $y_{CP}$ world average

- Average  $y_{CP}$  used in the mixing fit
- 2020



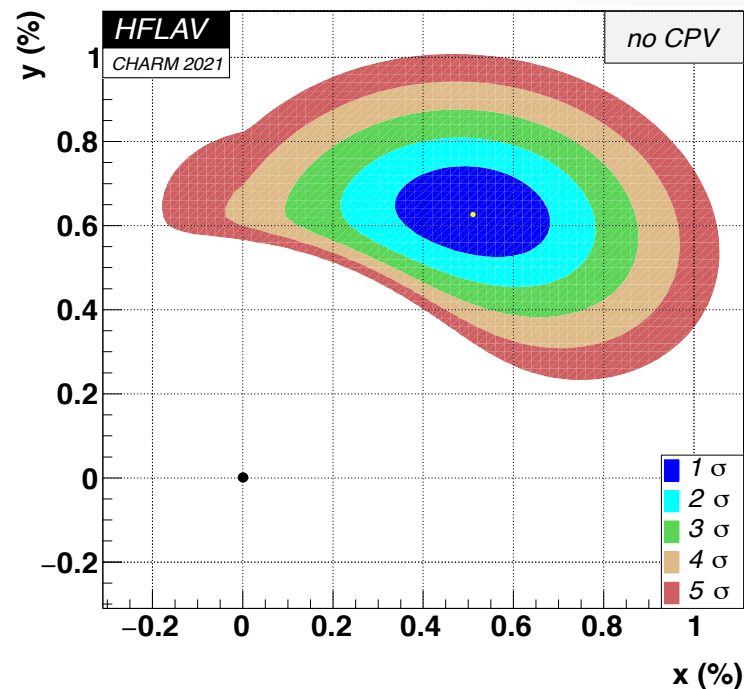
# Fit w/o CPV

- $|q/p|=1, \phi=0, A_K=0, A_\pi=0, A_D=0$
- 2020



$$x = (0.51^{+0.12}_{-0.14})\%$$
$$y = (0.63 \pm 0.07)\%$$

2021

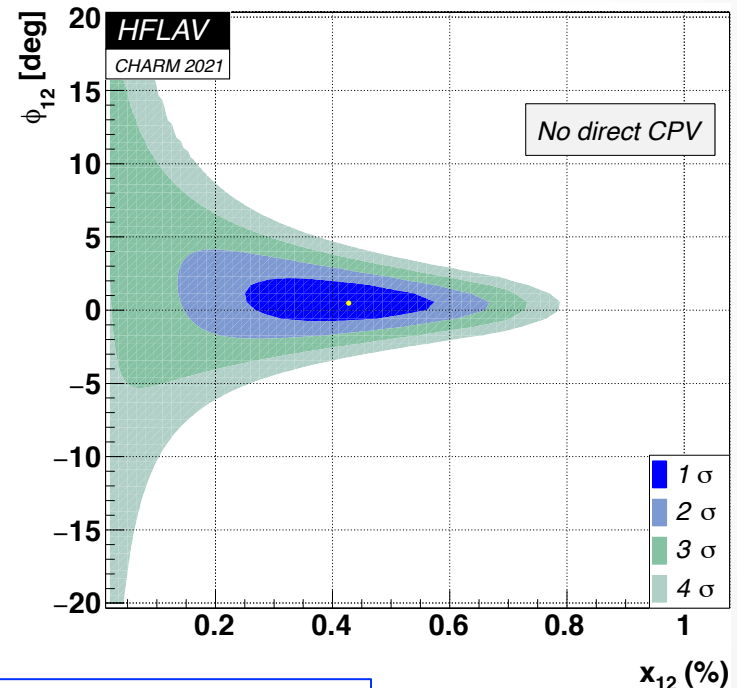
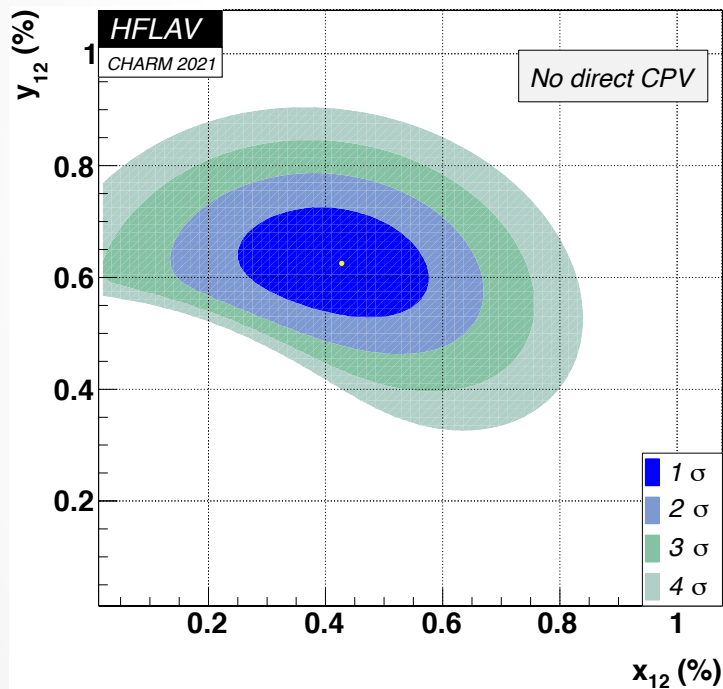


$$x = (0.51 \pm 0.13)\%$$
$$y = (0.63 \pm 0.07)\%$$

$$\chi^2/\text{ndf} = 91.4/52$$

# Fit w/o direct CPV at tree level

- No direct CPV in DCS decays ( $A_D = 0$ )
- $\tan\phi = (1 - |q/p|^2)/(1 + |q/p|^2)(x/y) \Rightarrow$  3 independent parameters
- $x_{12}, y_{12}, \phi_{12} \Rightarrow x, y, \phi$  relation in PRD 80, 076008 (2009)



$$x_{12} = (0.43 \pm 0.11)\%$$

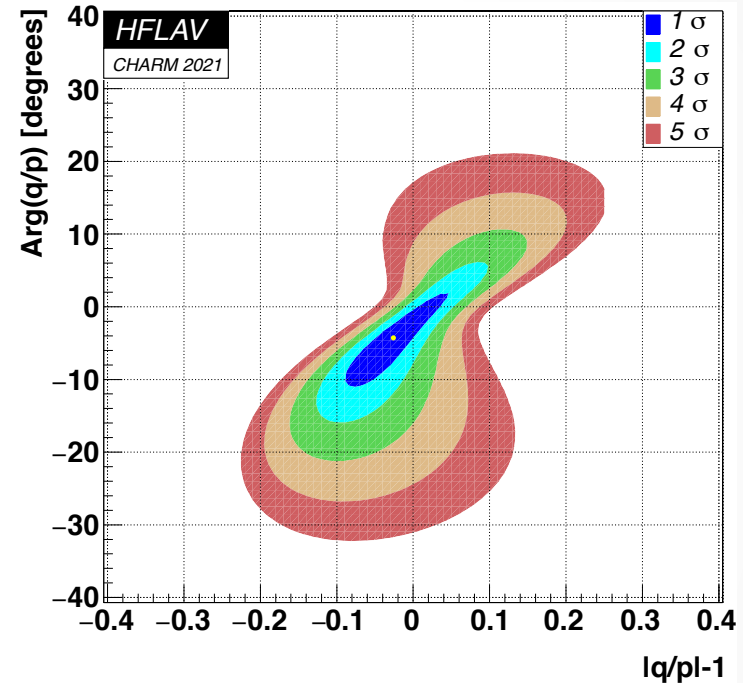
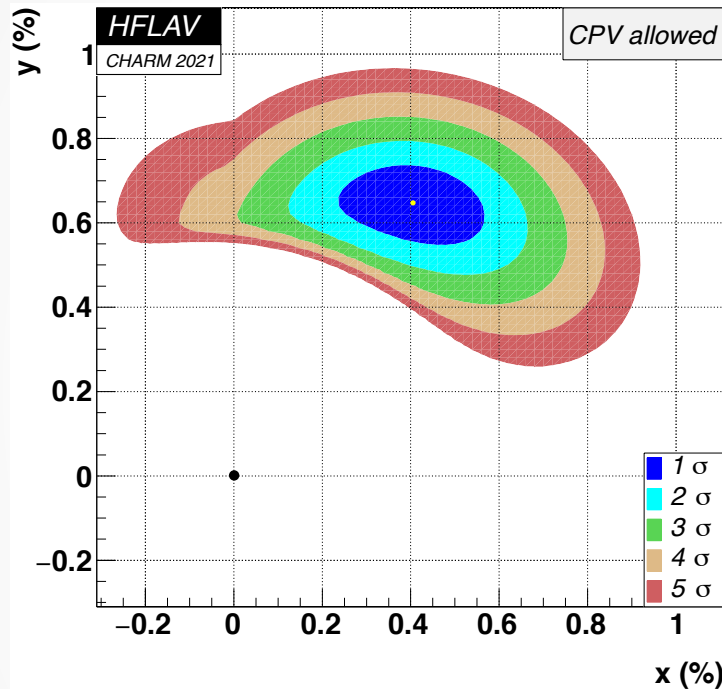
$$y_{12} = (0.62 \pm 0.06)\%$$

$$\phi_{12} = (0.48 \pm 0.88)^\circ$$

$$\chi^2/\text{ndf} = 62.6/48$$

# Fit with CPV allowed

- 2021



$$x = (0.40 \pm 0.11)\%$$

$$y = (0.65 \pm 0.06)\%$$

$$|q/p| = 0.97 \pm 0.04$$

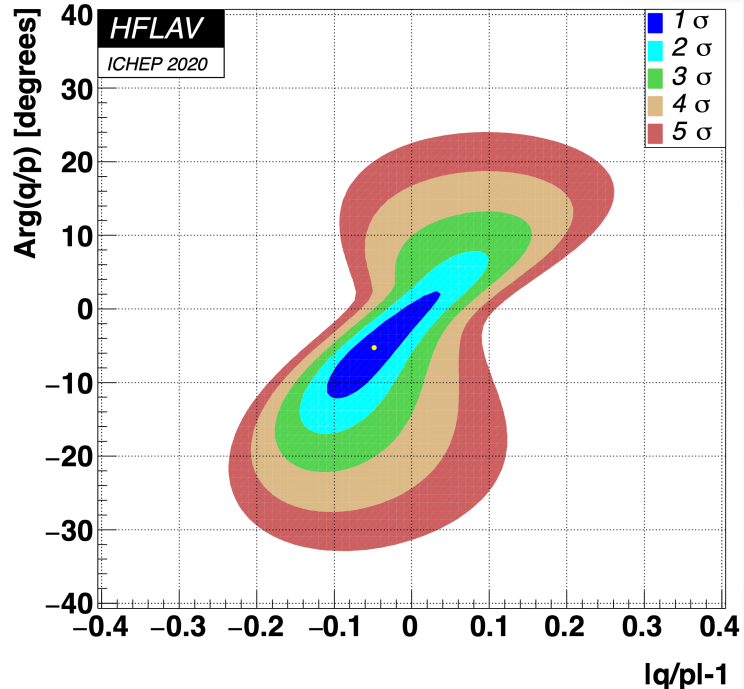
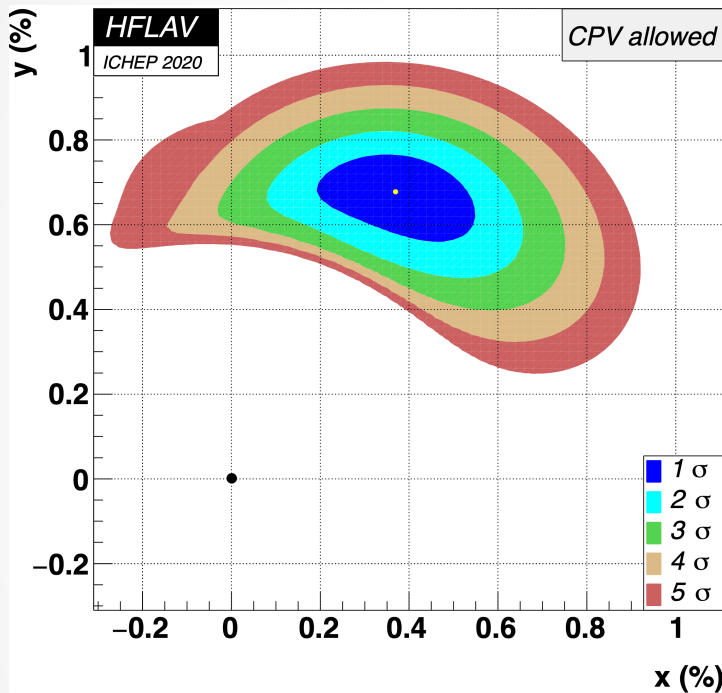
$$\phi = (-4.3 \pm 4.2)^\circ$$

$$\chi^2/\text{ndf} = 62.1/47$$

[ $\chi^2$  dropped with new  $A_\Gamma$ ]

# 2020 fit with CPV allowed

- 2020



$$x = (0.37 \pm 0.12)\%$$

$$y = (0.68_{-0.07}^{+0.06})\%$$

$$|q/p| = 0.95_{-0.04}^{+0.05}$$

$$\phi = (-5.3_{-4.5}^{+4.9})^\circ$$

$$\chi^2/\text{ndf} = 65.8/47$$

# Disentangle direct & indirect CPV

- Both contribute to asymmetries measured for  $D^0 \rightarrow K^+K^-, \pi^+\pi^-$

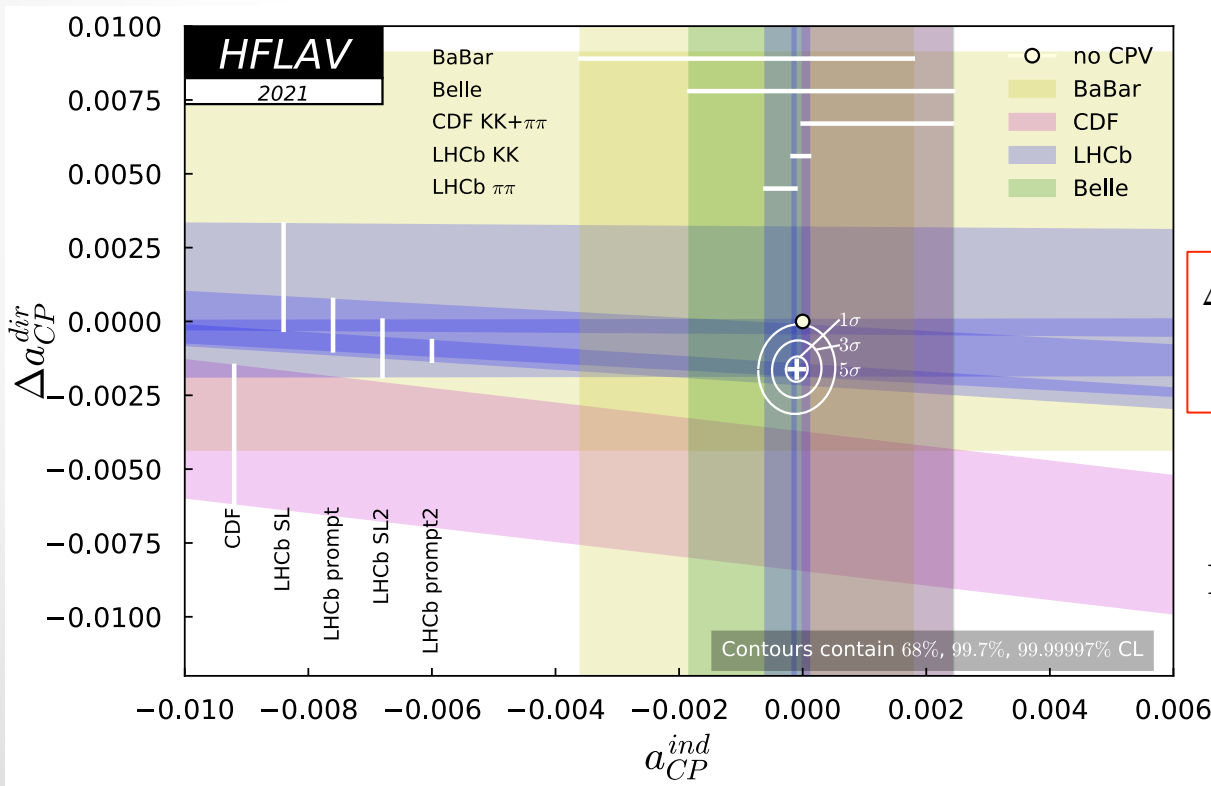
$$\Delta A_{CP} \simeq \Delta a_{CP}^{dir} \left( 1 + y_{CP} \frac{\langle \bar{t} \rangle}{\tau} \right) + a_{CP}^{ind} \frac{\Delta \langle t \rangle}{\tau}$$

$$A_{\Gamma} \simeq -a_{CP}^{ind} - a_{CP}^{dir} y_{CP}$$

- $\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) = (-15.4 \pm 2.9) \times 10^{-4} [5.3\sigma]$

LHCb combination  
PRL122 231802 (2019)

**CPV discovery**



$$\Delta a_{CP}^{dir} = (-16.1 \pm 2.8) \times 10^{-4}$$

$$a_{CP}^{ind} = (-1.0 \pm 1.2) \times 10^{-4}$$

No-CPV point excluded at  $5.4\sigma$

# Recent progress in $A_{CP}$ for SCS decays [I]

- $A_{CP}$  measured in time-independent manner
- For  $D^0$  decays includes indirect contribution [negligible at current precision]
- $D^0 \rightarrow K_S K_S$

Year	Experiment	$[\Gamma(D^0) - \Gamma(D^0\text{bar})] / [\Gamma(D^0) + \Gamma(D^0\text{bar})]$
2021	LHCb	$-0.031 \pm 0.012 \pm 0.004 \pm 0.002$
2017	Belle	$-0.0002 \pm 0.0153 \pm 0.0002 \pm 0.0017$
2015	LHCb	$-0.029 \pm 0.052 \pm 0.022$
2001	CLEO	$-0.23 \pm 0.19$
	<b>HFLAV</b>	<b>average</b> $-0.019 \pm 0.010$

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

Year	Experiment	$[\Gamma(D^+) - \Gamma(D^-)] / [\Gamma(D^+) + \Gamma(D^-)]$
2021	LHCb	$-0.013 \pm 0.009 \pm 0.006$
2018	BELLE	$+0.0231 \pm 0.0124 \pm 0.0023$
2010	CLEO	$+0.029 \pm 0.029 \pm 0.003$
	<b>HFLAV</b>	<b>average</b> $+0.004 \pm 0.008$

# Recent progress in $A_{CP}$ for SCS decays [II]

- $D^+ \rightarrow \pi^+ \eta$ 

Year	Experiment	$[\Gamma(D^+) - \Gamma(D^-)] / [\Gamma(D^+) + \Gamma(D^-)]$
2021	LHCb	$-0.002 \pm 0.008 \pm 0.004$
2011	BELLE	$+0.0174 \pm 0.0113 \pm 0.0019$
2010	CLEO	$-0.020 \pm 0.023 \pm 0.003$
	<b>HFLAV</b>	<b>average</b> $+0.003 \pm 0.007$

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

Year	Experiment	$[\Gamma(D_s^+) - \Gamma(D_s^-)] / [\Gamma(D_s^+) + \Gamma(D_s^-)]$
2021	LHCb	$-0.008 \pm 0.039 \pm 0.012$
2021	BELLE	$+0.064 \pm 0.044 \pm 0.011$
2010	CLEO	$-0.266 \pm 0.238 \pm 0.009$
	<b>HFLAV</b>	<b>average</b> $+0.020 \pm 0.030$

- $D_s^+ \rightarrow K^+ \eta$ 

Year	Experiment	$[\Gamma(D_s^+) - \Gamma(D_s^-)] / [\Gamma(D_s^+) + \Gamma(D_s^-)]$
2021	BELLE	$+0.021 \pm 0.021 \pm 0.004$
2021	LHCb	$+0.009 \pm 0.037 \pm 0.011$
2010	CLEO	$+0.093 \pm 0.152 \pm 0.009$
	<b>HFLAV</b>	<b>average</b> $+0.019 \pm 0.019$



# Testing sum rule for $D \rightarrow \pi\pi$ (I)

- Proposed by Grossman, Kagan, Zupan in PRD85 114036 (2012)
- First experimental test by Belle in PRD97 011101 (2018)
- Isospin decomposition of  $D \rightarrow \pi\pi$  decay amplitudes:

$$\begin{aligned} A_{\pi^+\pi^-} &= \sqrt{2}\mathcal{A}_3 + \sqrt{2}\mathcal{A}_1, \\ A_{\pi^0\pi^0} &= 2\mathcal{A}_3 - \mathcal{A}_1, \\ A_{\pi^+\pi^0} &= 3\mathcal{A}_3, \end{aligned}$$



$$\frac{1}{\sqrt{2}}A_{\pi^+\pi^-} + A_{\pi^0\pi^0} - A_{\pi^+\pi^0} = 0.$$

$A_1, A_3$  isospin amplitudes of  $\Delta I=1/2$  and  $3/2$  transitions

- In terms of differences between decay rates:

$$|A_{\pi^+\pi^-}|^2 - |\bar{A}_{\pi^+\pi^-}|^2 + |A_{\pi^0\pi^0}|^2 - |\bar{A}_{\pi^0\pi^0}|^2 - \frac{2}{3}(|A_{\pi^+\pi^0}|^2 - |\bar{A}_{\pi^-\pi^0}|^2) = 3(|\mathcal{A}_1|^2 - |\bar{\mathcal{A}}_1|^2).$$

- SM tests:

- if sum is non-zero  $\Rightarrow$  CPV in  $\Delta I=1/2$  (e.g. SM penguin)
- if sum is zero and individual asymmetries non-zero  $\Rightarrow$  NP in  $\Delta I=3/2$

# Testing sum rule for $D \rightarrow \pi\pi$ (II)

- $$|A_{\pi^+\pi^-}|^2 - |\bar{A}_{\pi^+\pi^-}|^2 + |A_{\pi^0\pi^0}|^2 - |\bar{A}_{\pi^0\pi^0}|^2 - \frac{2}{3}(|A_{\pi^+\pi^0}|^2 - |\bar{A}_{\pi^-\pi^0}|^2) = 3(|\mathcal{A}_1|^2 - |\bar{\mathcal{A}}_1|^2)$$

- To facilitate experimental test, left-hand side rewritten as:

$$R = \frac{A_{CP}(D^0 \rightarrow \pi^+\pi^-)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{+-}} \left( \frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{2}{3} \frac{\mathcal{B}_{+0}}{\tau_{D^+}} \right)} + \frac{A_{CP}(D^0 \rightarrow \pi^0\pi^0)}{1 + \frac{\tau_{D^0}}{\mathcal{B}_{00}} \left( \frac{\mathcal{B}_{+-}}{\tau_{D^0}} + \frac{2}{3} \frac{\mathcal{B}_{+0}}{\tau_{D^+}} \right)} - \frac{A_{CP}(D^+ \rightarrow \pi^+\pi^0)}{1 + \frac{3}{2} \frac{\tau_{D^+}}{\mathcal{B}_{+0}} \left( \frac{\mathcal{B}_{00}}{\tau_{D^0}} + \frac{\mathcal{B}_{+-}}{\tau_{D^0}} \right)},$$

- HFLAV averages of  $A_{CP}$  and PDG averages for BFs and lifetimes

$$A_{CP}(D^0 \rightarrow \pi^+\pi^-) = (+0.12 \pm 0.14) \times 10^{-2}$$

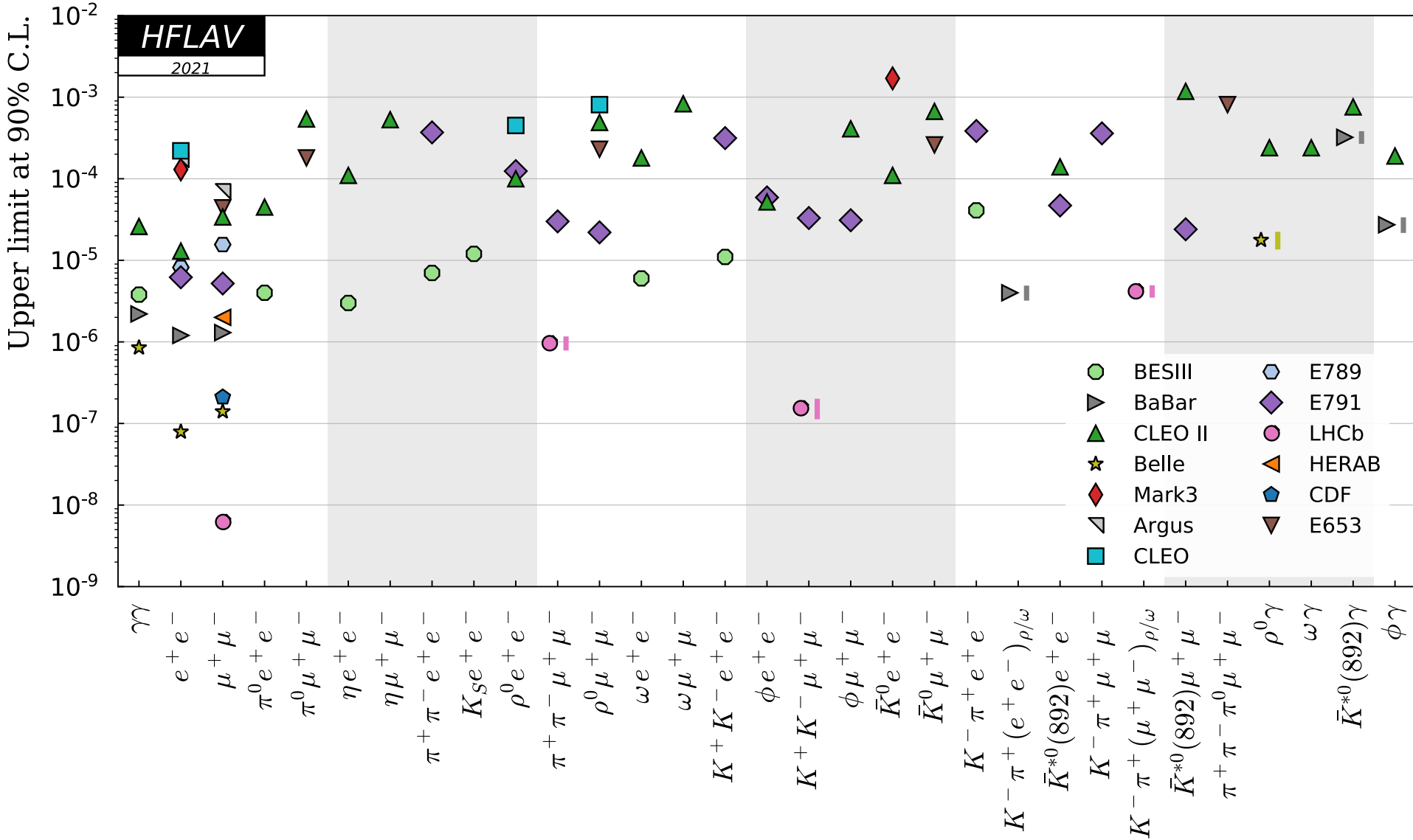
$$A_{CP}(D^0 \rightarrow \pi^0\pi^0) = (-0.03 \pm 0.64) \times 10^{-2}$$

$$A_{CP}(D^+ \rightarrow \pi^+\pi^0) = (+0.43 \pm 0.79) \times 10^{-2}$$

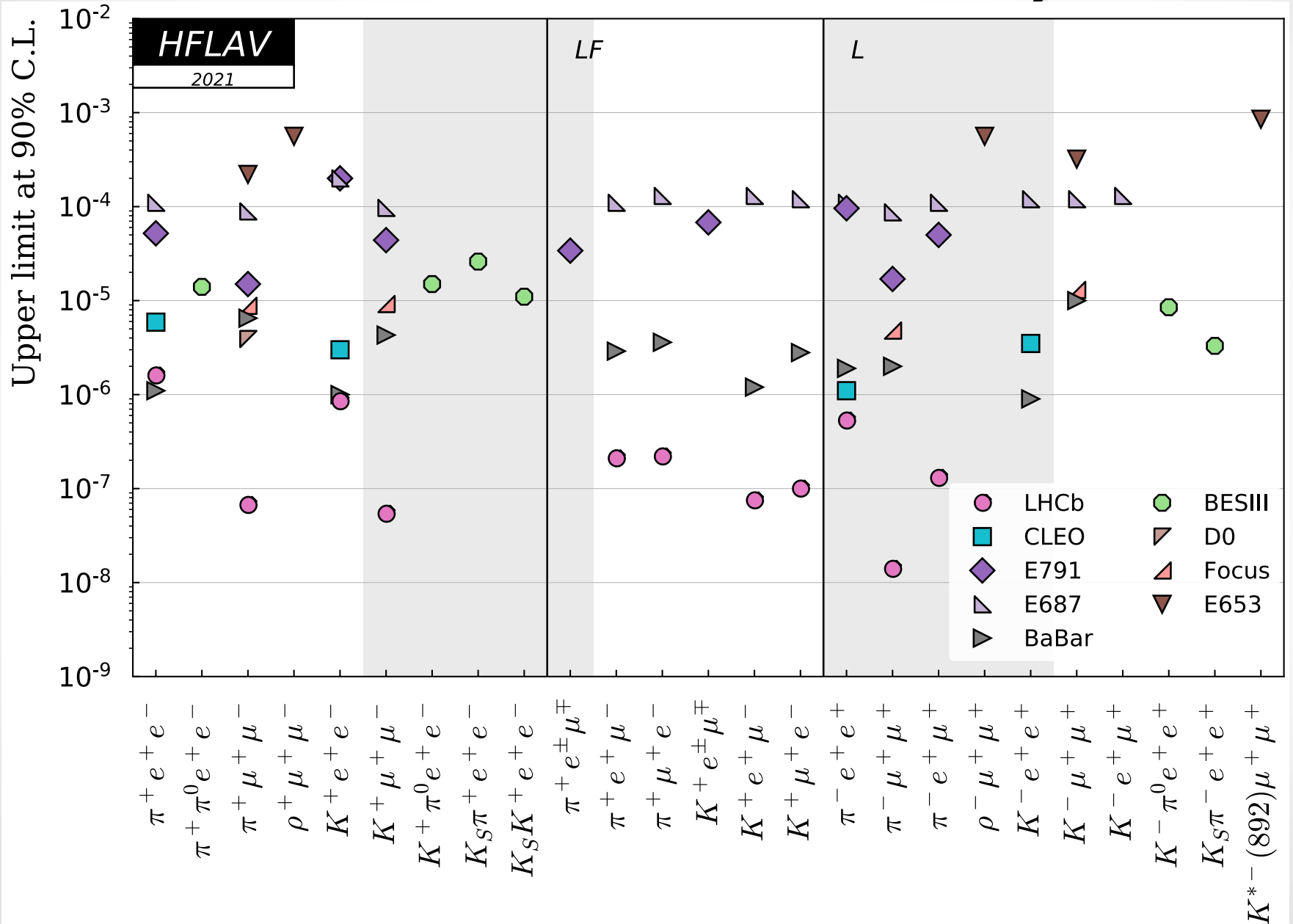
$$R = (+0.06 \pm 2.44) \times 10^{-3}$$

- other sums e.g. for  $D \rightarrow KK$  require SU(3) considerations

# Rare $D^0$ decays



# Rare and forbidden $D^+$ decays



# Summary

- More HFLAV charm on:  
<https://hflav.web.cern.ch/content/charm-cpv-and-oscillations>  
<https://hflav.web.cern.ch/content/charm-decays>
- Stay tuned for a **significant-x** mixing fit!



# Backups

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# Rare and forbidden $D_s^+$ decays

