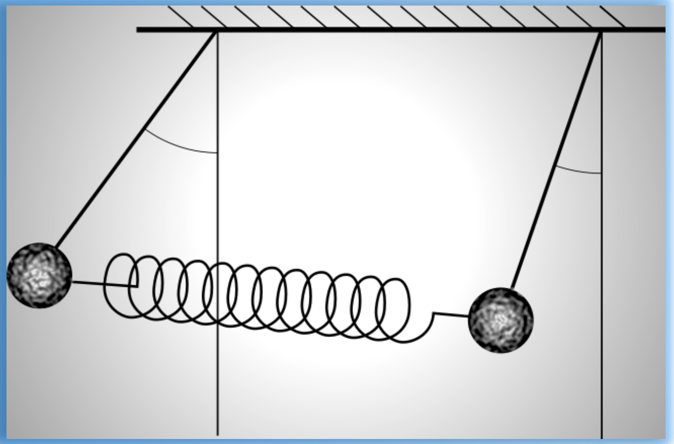
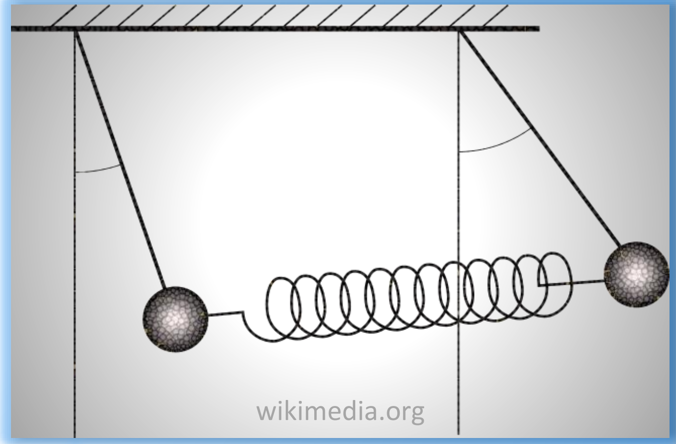
Осцилляции и $\mathcal{CP}$ нарушение в распадах D мезонов



В.С. Воробьев

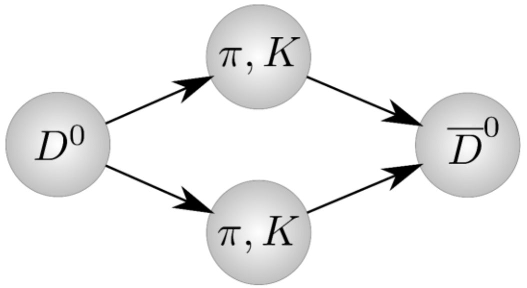
ИЯФ СО РАН

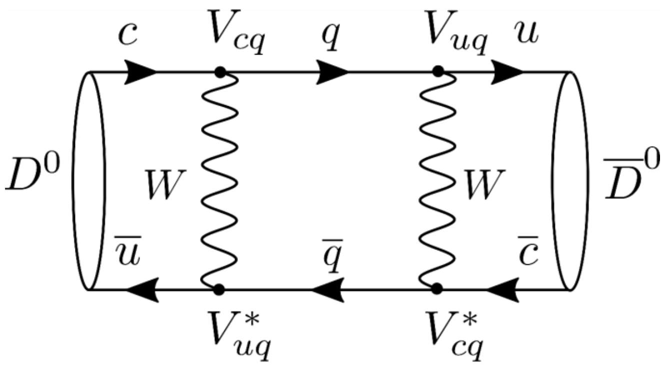


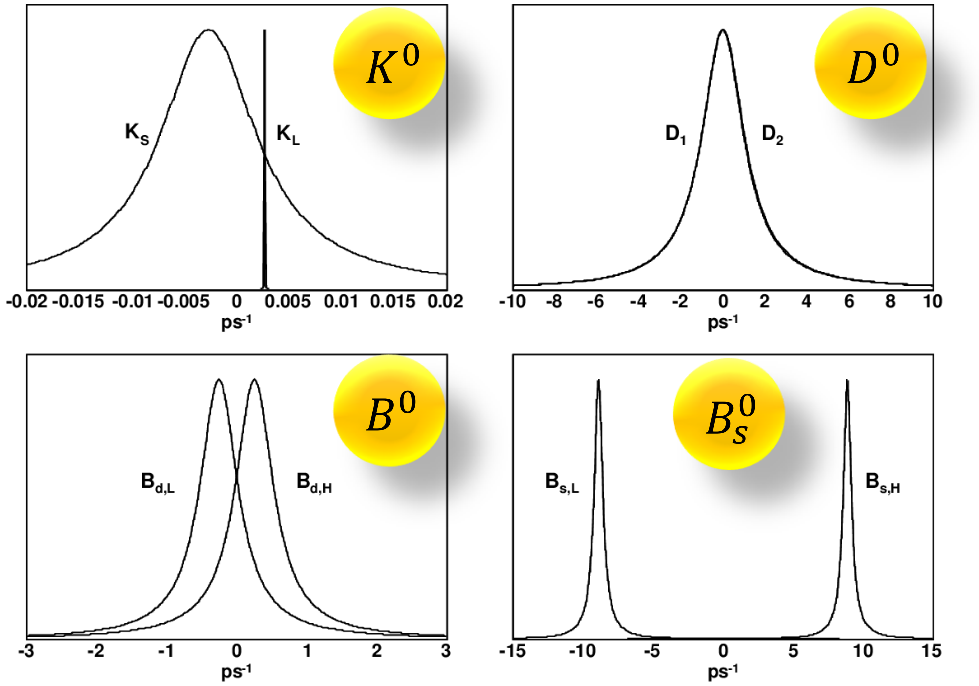
Совещание по физической программе Супер c-τ фабрики

19 декабря 2017, Новосибирск

Charm mixing formalism







M. Gersabeck, arXiv:1207.2195 [hep-ex]

The mass eigenstates

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle$$
$$|p|^2 + |q|^2 = 1$$
$$m(D_{1,2}) \equiv m_{1,2}, \Gamma\,(D_{1,2}) \equiv \Gamma_{1,2}$$

The mixing parameters

$$x \equiv \frac{m_2 - m_1}{\Gamma}, \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}$$
$$\Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2}$$

The phase convention

$$\mathcal{CP}|D^0\rangle = -|\overline{D}^0\rangle$$

The SM expectations

Short distances $x \sim y \sim 10^{-3}$
Long distances $x \sim y \sim 10^{-2}$

The first evidences

Phys. Rev. Lett. 98, 211802 (2007)
Phys. Rev. Lett. 98, 211803 (2007)

Charm forms the only neutral meson system with the heavy up quark

$\mathcal{CP}$ violation parameters

The decay amplitudes

$$\mathcal{A}_f \equiv \langle f|\mathcal{H}|D^0\rangle, \quad \bar{\mathcal{A}}_f \equiv \langle f|\mathcal{H}|\bar{D}^0\rangle$$
$$\mathcal{A}_{\bar{f}} \equiv \langle \bar{f}|\mathcal{H}|D^0\rangle, \quad \bar{\mathcal{A}}_{\bar{f}} \equiv \langle \bar{f}|\mathcal{H}|\bar{D}^0\rangle$$

The parameter λ

$$\lambda_f \equiv \frac{q}{p}\cdot\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f} \equiv \left|\frac{q}{p}\right| r_f e^{i(\varphi+\delta_f)}$$

$$r_f \equiv \left|\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}\right|$$

- For a $\mathcal{CP}$ eigenstate f

$$\lambda_f = -\eta_{CP}\left|\frac{q}{p}\right| e^{i\varphi}$$

$\mathcal{CP}$ violation

$$\left|\frac{\bar{\mathcal{A}}_{\bar{f}}}{\mathcal{A}_f}\right|^{\pm 2} \approx 1 \pm A_d$$ Direct

Indirect

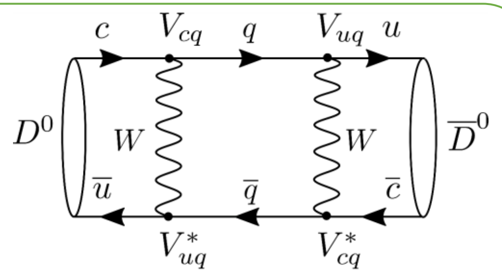
$$\left|\frac{q}{p}\right|^{\pm 2} \approx 1 \pm A_m$$ In mixing

$$\mathrm{Im}\,\lambda_f \neq 0$$ In interference between mixing and decay

Charm mixing within the Standard Model

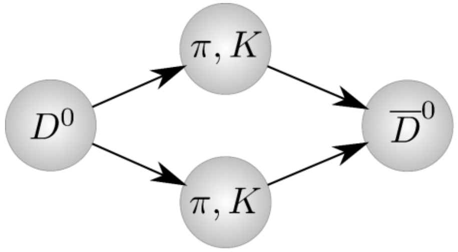
Inclusive approach

- Difficult since c is *not heavy enough*
- OPE, LQCD
- $x, y < 10^{-3}$



Exclusive approach

- Sum over intermediate hadronic states
- Cancelations between states within $SU(3)_f$
- Precise *data* on many decay rates is needed
- $x \lesssim y \sim 10^{-2}$



Conclusions

- $x \lesssim y \sim \sin^2\theta_C \times \left[SU(3)_f \text{ breaking}\right]^2$
- Clear signals of new dynamics
  - $y \ll x \sim 1\%$
  - $\mathcal{CP}$ violation $> 10^{-3}$

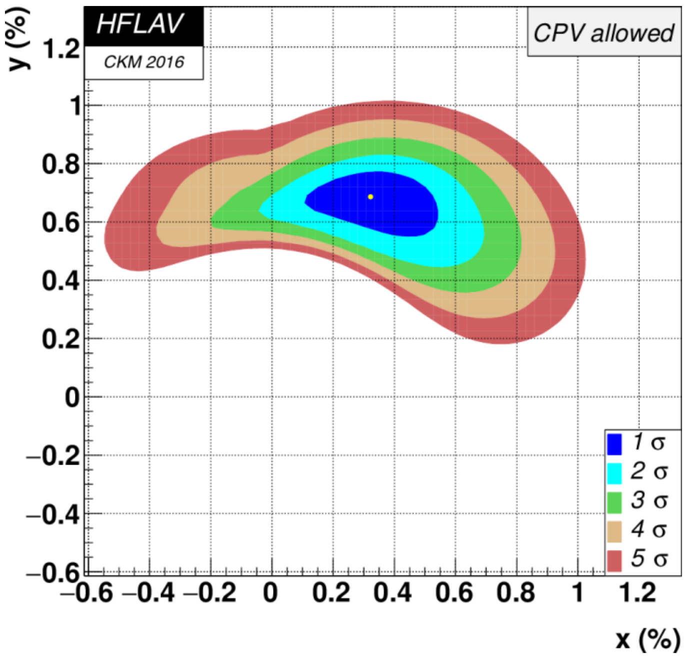
HFAG

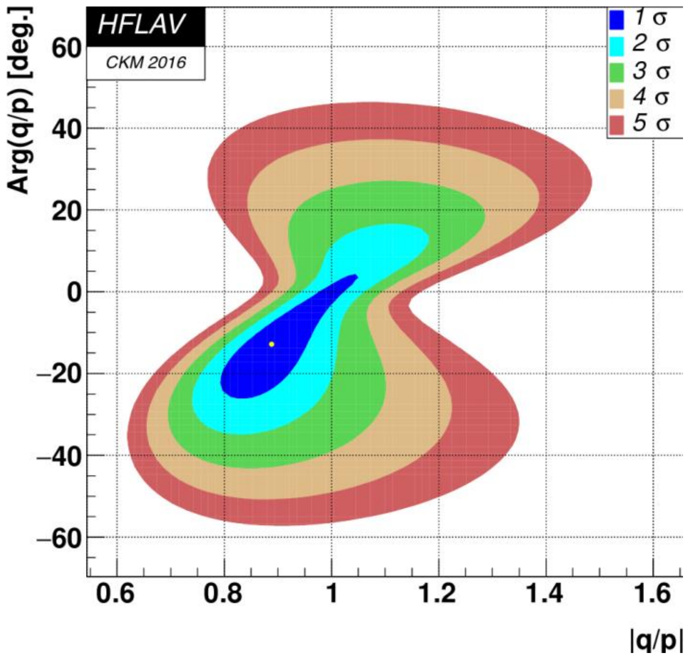
$$x = (0.32 \pm 0.14)\%$$

$$y = (0.69^{+0.06}_{-0.07})\%$$

$$|q/p| = 0.89^{+0.08}_{-0.07}$$

$$\arg(q/p) = (-12.9^{+9.9}_{-8.7})$$





Charm production

Parameter	**Belle+BaBar** ($1.5\ \mathrm{ab}^{-1}$)	**Belle II** ($50\ \mathrm{ab}^{-1}$)	**LHCb** ($5\ \mathrm{fb}^{-1}$)	**LHCb** ($50\ \mathrm{fb}^{-1}$)	**Super c-τ** ($10\ \mathrm{ab}^{-1}$)
Decay time	✓		✓✓		✗
Incoherent decays	✓		✓		✓
Coherent decays	✗		✗		✓
$N(D^0 \to K^-\pi^+)$ untagged, 10^6				40000 [1]	100
$N(D^{*+} \to D^0\pi^+, D^0 \to K^-\pi^+)$, 10^6	2.5 [2]	140 [2]	100 [1]	7000 [1]	20*
$N(D^+ \to K^-\pi^+\pi^+)$, 10^6	1.2 [4]	40	150 [1]	11000 [1]	200
$N(D_s^+ \to \varphi\pi^+)$, 10^6	0.5	17	13 [1]	1000 [1]	40

* Expected yield of $\psi(3770) \to D^0\overline{D}^0 \to (K^-\pi^+)(K^+\pi^-)$ is shown for SCTF

[1] LHCb Collaboration, Eur. Phys. J. C73, 2373 (2013) «Implications of LHCb measurements and future prospects»
[2] Physics at Super B Factory, arXiv:1002.5012 [hep-ex]
[3] CLEO Collaboration, Phys. Rev. D86, 112001 (2012)
[4] Phys. Rev. Lett. 102, 221802 (2009)

- $\sigma(pp \to D^0X)$ @ 13 TeV $\approx$ 2 mb
- $\sigma(e^+e^- \to c\bar{c})$ @ $\Upsilon(4S) \approx$ 1.3 nb
- $\sigma(e^+e^- \to c\bar{c})$ @ $\psi(3770) \approx$ 6 nb

Charm mixing

Charm mixing observables

Wrong-sign semileptonic

$$R_M \equiv \frac{x^2+y^2}{2} \approx \frac{\Gamma(D^0 \to l^- X)}{\Gamma(D^0 \to l^+ X)}$$

Phys. Rev. D76, 014018 (2007) (BaBar)
Phys. Rev. D77, 112003 (2009) (Belle)

CF and DCS D decays

$$\Gamma(D^0(t) \to f_{WS}) = e^{-\tau}\left|A_f\right|^2\left[R_f^2 + R_f y'\tau + \frac{1}{2}R_M\tau^2\right]$$

$$y' \equiv y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$$

Phys. Rev. Lett. 98, 211802 (2007) (BaBar)
Phys. Rev. Lett. 112, 111801 (2014) (Belle)
Phys. Rev. D95, 052004 (2017) (LHCb)

$x,\quad y,\quad \delta_{K\pi}$ Coherent

Phys. Rev. D86, 112001 (2012) (CLEO-c)
Phys. Lett. B 734, 277 (2014) (BESIII)
Phys. Rev. D73, 034024 (2006) (Asner, Sun)

D to $\mathcal{CP}$ eigenstate

$$y_{\mathcal{CP}} \equiv \eta_{\mathcal{CP}}\frac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\bar{D}^0 \to f)}{2\hat{\Gamma}(D^0 \to K^-\pi^+)}$$ Time dep

Phys. Rev. Lett. 98, 211803 (2007)
JHEP 04, 129 (2012) (LHCb)
Phys. Rev. D87, 012004 (2013) (BaBar)

$$y_{\mathcal{CP}} \approx \frac{1}{4}\left(\frac{\mathcal{B}(D_{\mathcal{CP}-} \to l)}{\mathcal{B}(D_{\mathcal{CP}+} \to l)} - \frac{\mathcal{B}(D_{\mathcal{CP}+} \to l)}{\mathcal{B}(D_{\mathcal{CP}-} \to l)}\right)$$ Coherent

Phys. Lett. B744, 339 (2015) (BESIII)

Dalitz analysis

Direct sensitivity to x and y

- Incoherent: model-dependent
  - Phys. Rev. Lett. 105, 081803 (2010) (BaBar)
  - Phys. Rev. D89, 091103 (2014) (Belle)
- Incoherent with external coherent input
  - JHEP 04, 033 (2016) (LHCb)
- Coherent: model-independent measurement

Dalitz analysis of $D^0 \to K_S^0 \pi^+ \pi^-$ decay

Time-dependent

The method

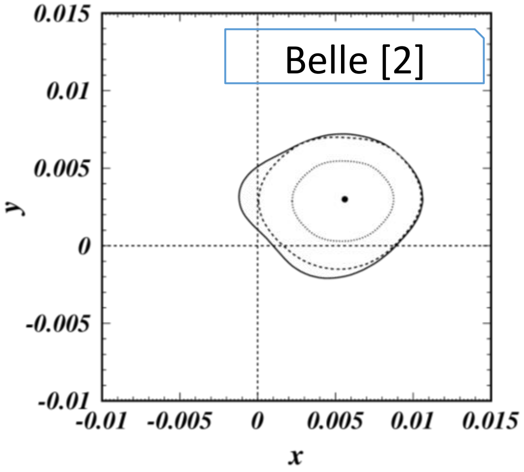
- Time-dependent Dalitz analysis
  $\mathcal{P}_D(t, m_+^2, m_-^2) \approx \Gamma e^{-\Gamma t}\left[|\mathcal{A}_D|^2 - \Gamma t \,\mathrm{Re}\left(\mathcal{A}_D^* \mathcal{A}_{\bar{D}}(y+ix)\right)\right]$
- Sensitivity due to the strong phase variation over the Dalitz plot
- $\mathcal{A}(m_+^2, m_-^2)$ from $D^0 \to K_S^0\pi^+\pi^-$ decay model

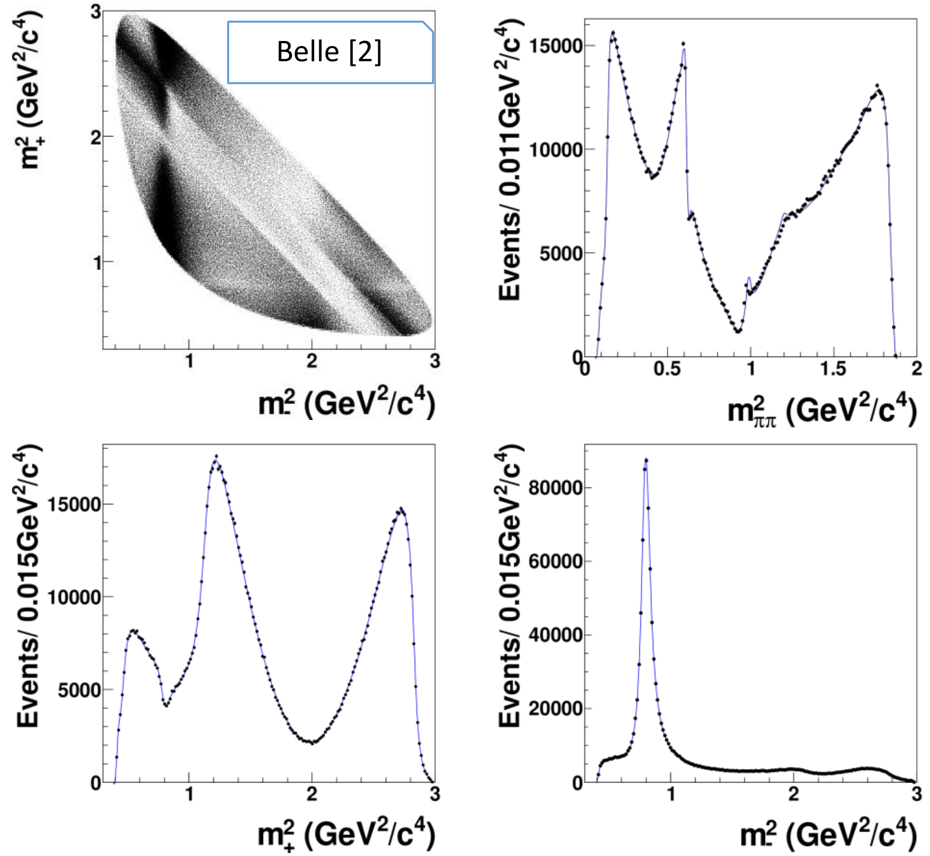
BaBar [1]

- $468.5\ \mathrm{fb}^{-1}, D^{*+} \to D^0\pi^+$
  $x = (0.16 \pm 0.23 \pm 0.12 \pm 0.08)\%$
  $y = (0.57 \pm 0.20 \pm 0.13 \pm 0.07)\%$

Belle [2]

- $921\ \mathrm{fb}^{-1}, D^{*+} \to D^0\pi^+$
  $x = (0.56 \pm 0.19 \pm 0.08 \pm 0.08)\%$
  $y = (0.30 \pm 0.15 \pm 0.05 \pm 0.07)\%$





[1] Phys. Rev. Lett. 105, 081803 (2010) (BaBar)
[2] Phys. Rev. D89, 091103 (2014) (Belle)

Model-independent Dalitz analysis

The method

- *Binned* time-dependent Dalitz analysis [1,2]

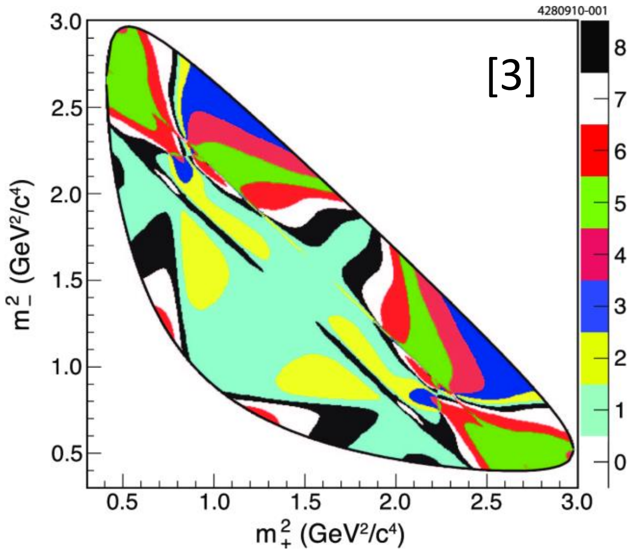
$$\mathcal{P}_D(t,i) \propto e^{-\Gamma t}\left[K_i - \Gamma t\sqrt{K_i K_{-i}}(C_i y + S_i x)\right]$$
$$\mathcal{P}_{\bar{D}}(t,i) \propto e^{-\Gamma t}\left[K_{-i} - \Gamma t\sqrt{K_i K_{-i}}(C_i y - S_i x)\right]$$

- C_i and S_i are measured in coherent $D^0\bar{D}^0$ pair decays [3]

$$Z_i = \frac{\int_{D_i} \mathcal{A}_D^* \mathcal{A}_{\bar{D}}\, \mathrm{d}m_+^2 \mathrm{d}m_-^2}{\sqrt{\int_{D_i} |\mathcal{A}_D|^2 \mathrm{d}m_+^2 \mathrm{d}m_-^2 \cdot \int_{D_i} |\mathcal{A}_{\bar{D}}|^2 \mathrm{d}m_+^2 \mathrm{d}m_-^2}}$$
$$C_i = \mathrm{Re}\, Z_i,\ \ S_i = \mathrm{Im}\, Z_i$$

LHCb [4]

- $1.0\ \mathrm{fb}^{-1} @7\ TeV, D^{*+} \to D^0\pi^+$
  $x = (-0.86 \pm 0.53 \pm 0.17)\%$
  $y = (+0.03 \pm 0.46 \pm 0.13)\%$



[1] Phys. Rev. D68, 054018 (2003)
[2] Phys. Rev. D82, 034033 (2010)
[3] Phys. Rev. D82, 112006 (2010)
[4] JHEP 04, 033 (2016)

Future precision

1. "Implications of LHCb measurements and future prospects", Eur. Phys. J. C73, 2373 (2013)
2. "Physics at Super B Factory", arXiv:1002.5012 [hep-ex]
3. A. Bondar et al., Phys. Rev. D82, 034033 (2010)

Parameter	**Belle II** @ $50\ \mathrm{ab}^{-1}$	**LHCb** @ $50\ \mathrm{fb}^{-1}$	**Super c-τ** @ $10\ \mathrm{ab}^{-1}$
WS semileptonic			
$\mathrm{R_M}$	$\sim 5\times10^{-5}$	$\mathcal{O}(5\times10^{-7})$ [1]	
CF and DCS D decays			
$y, 10^{-4}$	✗	✗	2
$y', 10^{-4}$	16 (syst.) [2]	$\mathcal{O}(1)$ [1]	—
$\cos\delta_{K\pi}$	✗	✗	2×10^{-3}
$R_D, 10^{-5}$	10	$\mathcal{O}(0.3)$	1
D to $\mathcal{CP}$ eigenstates			
$y_{\mathcal{CP}}, 10^{-4}$	10 (syst.) [2]	0.4 [1]	4
Dalitz analysis			
$x, 10^{-4}$	10 (syst.) [2]	1.7 [1]	~ 1 [3]
$y, 10^{-4}$	7 (syst.) [2]	1.9 [1]	~ 1 [3]

Quantum correlations

Measurements using quantum correlations I

Correlations with $\mathcal{C} = -1$

$$\Gamma(i,j) \propto |\langle i|D_2\rangle\langle j|D_1\rangle - \langle i|D_1\rangle\langle j|D_2\rangle|^2 + \mathcal{O}(x^2, y^2)$$

Average strong phase differences

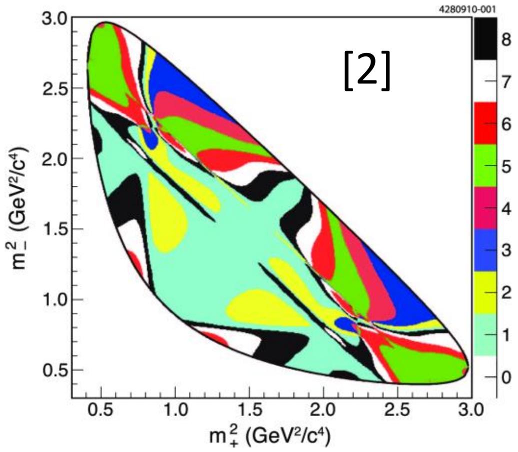
- Measurement using $D^0\overline{D}^0 \to 2(K_S^0\pi^+\pi^-)$ [1]

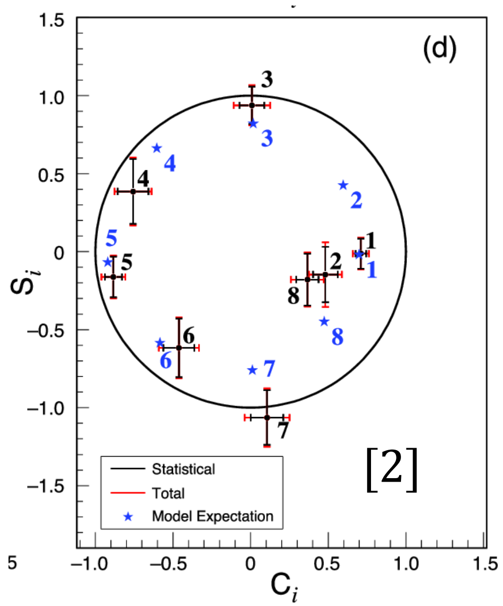
$$M_{ij} \propto K_iK_{-j} + K_{-i}K_j - 2\sqrt{K_iK_{-j}K_{-i}K_j}(C_iC_j + S_iS_j)$$

- Existing results
  - $D \to K_S^0\pi^+\pi^-$ [2]
  - $D \to \pi^+\pi^-\pi^+\pi^-$[3]
  - $D \to K_S^0\pi^-\pi^+\pi^0$[4]
- Applications
  - Charm mixing
  - CKM angle γ in $B^\pm \to DK^\pm, D \to K_S^0\pi^+\pi^-$

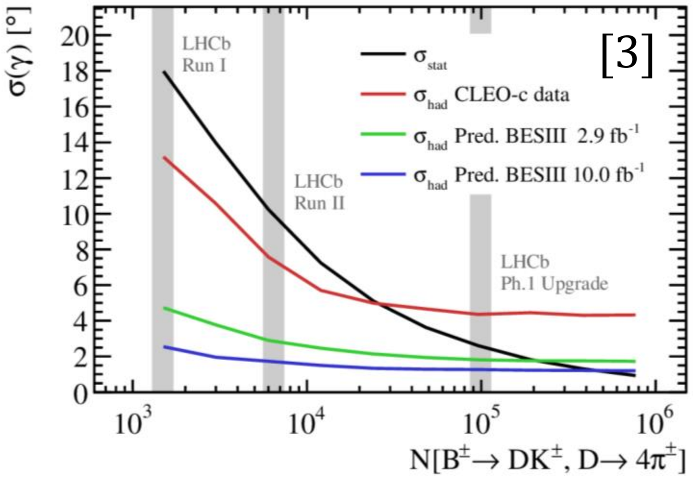
$$N_i \propto K_i + r_B^2K_{-i} + 2\sqrt{K_iK_{-i}}(x_BC_i + y_BS_i)$$

  - CKM angle β in $B^0 \to D^0h^0, D \to K_S^0\pi^+\pi^-$





Important input for future CKM measurements



[1] Phys. Rev. D68, 054018 (2003)
[2] Phys. Rev. D82, 112006 (2012)
[3] arXiv: 1709.03467 [hep-ex]
[4] arXiv: 1710.10086 [hep-ex]

Measurements using quantum correlations II

Coherence factors and average strong phase differences [1]

$$R_f e^{i\xi_f} \equiv \frac{\int \mathcal{A}_f^*(\boldsymbol{x})\bar{\mathcal{A}}_f(\boldsymbol{x})\mathrm{d}\boldsymbol{x}}{\int \left|\mathcal{A}_f(\boldsymbol{x})\right|^2 \mathrm{d}\boldsymbol{x} \cdot \int \left|\bar{\mathcal{A}}_f(\boldsymbol{x})\right|^2 \mathrm{d}\boldsymbol{x}}$$

- Measurement using $D^0\bar{D}^0 \to FG$

$$\Gamma(FG) = \Gamma_0 \left[P_F\bar{P}_G + \bar{P}_F P_G - 2R_F R_G\sqrt{P_F\bar{P}_G\bar{P}_F P_G}\cos(\xi_F - \xi_G)\right]$$

- Existing results
  - $D^0 \to K^-\pi^+$ ($R_{K\pi} = 1, \xi_{K\pi} \equiv \delta_{K\pi}$) [2,3]
  - $D^0 \to K^-\pi^+\pi^0$ [4]
  - $D^0 \to K^-\pi^+\pi^+\pi^-$ [4,5]
- CKM angle γ in $B^\pm \to DK^\pm$ (ADS-like method)

$$\Gamma\left(B^\mp \to DK^\mp\right) \propto r_B^2 + r_D^2 + 2r_B r_D R_f \cos\left(\delta_B + \xi_f \mp \gamma\right)$$

$\mathcal{CP}$ content of multibody decays

$$F_+ \equiv \frac{N^+}{N^+ + N^-}, \qquad N^\pm \equiv \frac{M^\pm}{S^\pm},$$

where $S^\pm$ is number of ST $f_{CP\pm}$ events and $M^\pm$ is number of DT ($f_{CP\mp}\, f$) events

- Existing results
  - $F_+(\pi^+\pi^-\pi^0) = 0.968 \pm 0.017 \pm 0.006$ [6]
  - $F_+(K^+K^-\pi^0) = 0.731 \pm 0.058 \pm 0.021$ [6]
  - $F_+\left(K_S^0\pi^+\pi^-\pi^0\right) = 0.238 \pm 0.012 \pm 0.012$ [7]
- CKM angle γ in $B^\pm \to DK^\pm$ (GLW-like method)

$$\Gamma\left(B^\mp \to DK^\mp\right) \propto 1 + r_B\cos(\delta_B \mp \gamma)\,(2F_+ - 1)$$

[1] Phys. Rev. D68, 033003 (2003)
[2] Phys. Rev. D86, 112001 (2012)
[3] Phys. Lett. B734, 227 (2014)
[4] Phys. Rev. D80, 031105(R) (2009)
[5] Phys. Lett. B757, 520 (2016)
[6] Phys. Lett. B740, 1 (2015)
[7] arXiv: 1710.10086 [hep-ex]

Measurements using quantum correlations III

Access to coherent $\mathcal{C} = \pm 1$ and non-coherent decays

$$e^+e^- \to \psi(4040) \to D\bar{D}^*$$

- Coherent $\mathcal{C} = -1$: $D^0\bar{D}^{*0} \to D^0\bar{D}^0\pi^0$

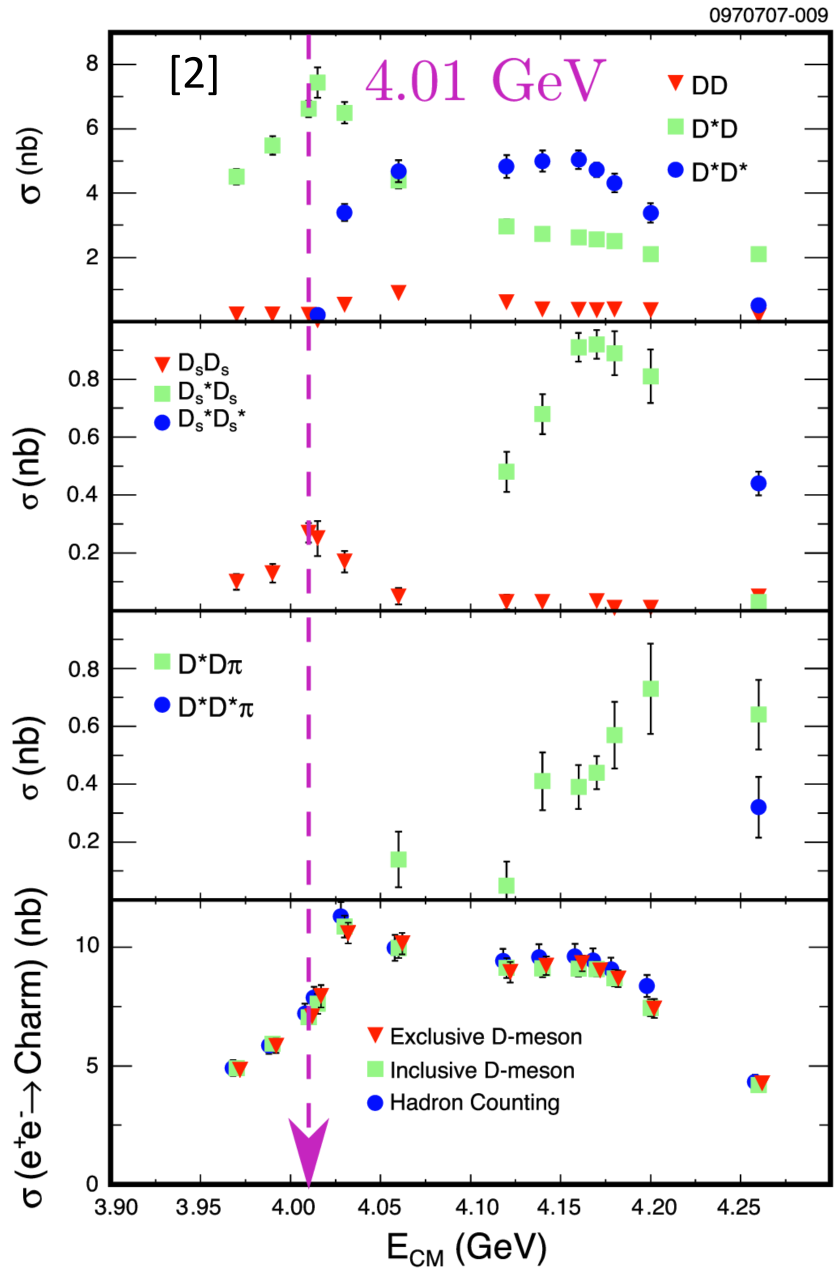
$$M_{ij}^- = K_iK_{-j} + K_{-i}K_j - 2\sqrt{K_iK_{-j}K_{-i}K_j}(C_iC_j + S_iS_j)$$

- Coherent $\mathcal{C} = +1$: $D^0\bar{D}^{*0} \to D^0\bar{D}^0\gamma$

$$M_{ij}^+ = K_iK_{-j} + K_{-i}K_j - 2\sqrt{K_iK_{-j}K_{-i}K_j}(C_iC_j + S_iS_j)$$
$$+2K_j\sqrt{K_iK_{-i}}(yC_i - xS_i) + 2K_{-j}\sqrt{K_iK_{-i}}(yC_i + xS_i)$$
$$+2K_i\sqrt{K_jK_{-j}}(yC_j - xS_j) + 2K_{-i}\sqrt{K_jK_{-j}}(yC_j + xS_j)$$

- Incoherent $D^-D^{*+} \to D^-D^0\pi^+$

$$K_i' = K_i + \sqrt{K_iK_{-i}}(yC_i + xS_i)$$



[1] Phys. Rev. D82, 034033 (2010)
[2] Phys. Rev. D80, 072001 (2009)

Measurement of the charm mixing and the phase parameters in a single experiment

$\mathcal{CP}$ violation

$\mathcal{CP}$ violation observables

$\mathcal{CP}$ violation

$$\left|\frac{\bar{\mathcal{A}}_{\bar{f}}}{\mathcal{A}_f}\right|^{\pm 2} \approx 1 \pm A_d$$ Direct

Indirect

$$\left|\frac{q}{p}\right|^{\pm 2} \approx 1 \pm A_m$$ In mixing

$$\mathrm{Im}\,\lambda_f \neq 0$$ In interference between mixing and decay

D^0 to $\mathcal{CP}$ eigenstate

- The decay rate asymmetry

$$\mathcal{A}_{CP} \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\bar{D}^0 \to f)}{\Gamma(D^0 \to f) + \Gamma(\bar{D}^0 \to f)} \approx a_{\mathcal{CP}}^{\mathrm{dir}} - A_\Gamma \frac{\langle t \rangle}{\tau},$$

where $\langle t \rangle$ is the average decay time of candidates

- The effective lifetime ratio

$$A_\Gamma = \frac{\hat{\Gamma}(D^0 \to f) - \hat{\Gamma}(\bar{D}^0 \to f)}{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\bar{D}^0 \to f)}$$

- The lifetime $\mathcal{CP}$ asymmetry

$$\Delta Y_f \equiv \frac{\hat{\Gamma}(\bar{D}^0 \to f) - \hat{\Gamma}(D^0 \to f)}{2\Gamma} = (1 + y_{CP}) A_\Gamma$$

Direct $\mathcal{CP}$ violation

$$a_{\mathcal{CP}}^{\mathrm{dir}} \equiv \frac{|\mathcal{A}_f|^2 - |\bar{\mathcal{A}}_{\bar{f}}|^2}{|\mathcal{A}_f|^2 + |\bar{\mathcal{A}}_{\bar{f}}|^2} \approx -\frac{1}{2} A_d$$

Dalitz analysis

Direct sensitivity to A_m and φ

- Incoherent: model-dependent
- Incoherent with external coherent input
- Coherent: model-independent measurement

Four-body decays

$\mathcal{T}$-odd correlations

Energy test

…

Dalitz analysis of $D^0 \to K_S^0 \pi^+ \pi^-$

Belle

- $921\ \mathrm{fb}^{-1}, D^{*+} \to D^0\pi^+, D^0 \to K_S^0\pi^+\pi^-$ [1]
  - Time-dependent Dalitz analysis

$$\left|\frac{q}{p}\right| = 0.90 \pm 0.16 \pm 0.05 \pm 0.06$$

$$\arg\left(\frac{q}{p}\right) = (-6 \pm 11 \pm 3 \pm 4)^\circ$$

Future precision

Parameter	Belle II @ $50\ \mathrm{ab}^{-1}$	Super c-τ @ $10\ \mathrm{ab}^{-1}$
$\left\|\frac{q}{p}\right\|$	0.05 [2]	~ 0.01 [3]
$\arg\left(\frac{q}{p}\right)$	3°[2]	$\sim 1^\circ$[3]

[1] Phys. Rev. D89, 091103(R) (2014) (Belle)
[2] arXiv:1002.5012 [hep-ex]
[3] A. Bondar et al., Phys. Rev. D82, 034033 (2010)

Direct $\mathcal{CP}$ violation in charm

Direct $\mathcal{CP}$ violation

(At least) two different coherent amplitudes with different weak and strong phases generates direct $\mathcal{CP}$ violation

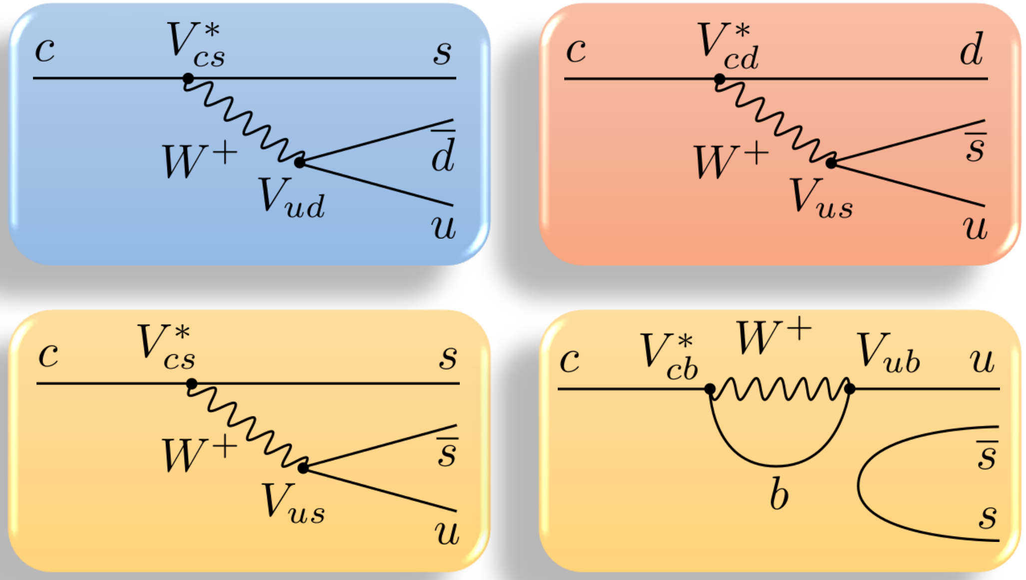
$$A(D \to f) = a_1 e^{i(\varphi_1+\delta_1)} + a_2 e^{i(\varphi_2+\delta_2)}$$

where φ_i - weak phases and δ_i - strong phases

$$\mathcal{A}_{CP} \propto \sin\Delta\varphi \sin\Delta\delta$$

A charm(ing) feature

long-distance dynamics is important in charm decays: re-scattering leads to the complex connections between the worlds of hadrons and quarks [I. Bigi]



- SM expectations
  - Zero weak phase in CF and DCS transitions
  - Very small weak phases in SCS transitions
    $\mathcal{A}_{CP} < 10^{-3}$
- It is important to probe regional asymmetries in multibody decays

Direct $\mathcal{CP}$ violation in $D^{\pm}$ decays (some examples)

$*$ the effects due to kaon system substracted

$\mathcal{A}_{\mathcal{CP}}$ (%)				
Mode	**CLEO-c**	***B* factories**	**LHCb**	**LHCb 50 fb^{-1}**
$D^+ \to K_S^0 K^+$	$-0.2 \pm 1.5 \pm 0.9$ [1]	$0.08 \pm 0.28 \pm 0.14^*$ [3]	$0.03 \pm 0.17 \pm 0.14^*$ [4]	0.01 [5]
$D^+ \to \pi^+ \pi^0$	$+2.9 \pm 2.9 \pm 0.3$ [1]			
$D^+ \to K^+ \pi^0$	$-3.5 \pm 10.7 \pm 0.9$ [1]			
$D^+ \to \pi^+ \eta$	$-2.0 \pm 2.3 \pm 0.3$ [1]	$+1.74 \pm 1.13 \pm 0.19$ [2]		
$D^+ \to \pi^+ \eta'$	$-4.0 \pm 3.4 \pm 0.3$ [1]	$-0.12 \pm 1.12 \pm 0.17$ [2]		

Belle II and Super c-τ can achieve the precision level of $10^{-3} \div 10^{-4}$

CLEO-c charge asymmetry [1]

$K^{\pm}$: $\pm 0.8\%$, $\pi^{\pm}$: $\pm 0.3\%$

[1] Phys. Rev. D81, 052013 (2010) (CLEO-c 818 pb^{-1})
[2] Phys. Rev. Lett. 107, 221801 (2011)
[3] JHEP 02, 098 (2013)
[4] JHEP 1410, 025 (2014) (LHCb 3 fb^{-1})
[5] Eur. Phys. J. C73, 2373 (2013)

Techniques for multibody decays

$\mathcal{T}$-odd asymmetries

- Consider $D^0 \to K^+K^-\pi^+\pi^-$
  $$C_T \equiv \langle \boldsymbol{p}_{K^+} \cdot (\boldsymbol{p}_{\pi^+} \times \boldsymbol{p}_{\pi^-}) \rangle$$
  - $\mathcal{T}(C_T) = -C_T$
  - FSI can generate $C_T \neq 0$
- Consider $\bar{D}^0 \to K^+K^-\pi^+\pi^-$
  $$\bar{C}_T \equiv \langle \boldsymbol{p}_{K^-} \cdot (\boldsymbol{p}_{\pi^-} \times \boldsymbol{p}_{\pi^+}) \rangle$$
  - $C_T \neq -\bar{C}_T$ establishes $\mathcal{CP}$ violation [1]
- $\mathcal{T}$-odd asymmetry [5]
  $$A_{\mathcal{T}} \equiv \frac{\Gamma(C_{\mathcal{T}} > 0) - \Gamma(C_{\mathcal{T}} < 0)}{\Gamma(C_{\mathcal{T}} > 0) + \Gamma(C_{\mathcal{T}} < 0)}$$
  $$\bar{A}_{\mathcal{T}} \equiv \frac{\Gamma(-\bar{C}_{\mathcal{T}} > 0) - \Gamma(-\bar{C}_{\mathcal{T}} < 0)}{\Gamma(-\bar{C}_{\mathcal{T}} > 0) + \Gamma(-\bar{C}_{\mathcal{T}} < 0)}$$
  $$A_{\mathcal{T}odd} \equiv \frac{A_{\mathcal{T}} - \bar{A}_{\mathcal{T}}}{2}$$

Regional phase space test

- Binned [2]
  $D^0 \to K^+K^-\pi^+\pi^-$, $D^0 \to \pi^+\pi^-\pi^+\pi^-$
- Binned and model-independent unbinned [3]
  $$D^+ \to \pi^-\pi^+\pi^+$$
- «Energy test» [4]
  $$D^0 \to \pi^-\pi^+\pi^0$$

[1] arXiv:hep-ex/0309021
[2] Phys. Lett. B726, 623 (2013) (LHCb 1 fb^{-1})
[3] Phys. Lett. B728, 585 (2014) (LHCb 1 fb^{-1})
[4] Phys. Lett. B740, 158 (2015) (LHCb 2 fb^{-1})
[5] JHEP 10, 005 (2014) (LHCb 3 fb^{-1})

Выводы

1. Супер c-τ фабрика позволит измерить
   - Параметры x и y осцилляций D мезонов с точностью $\sim 10^{-4}$
     - Эта точность находится на уровне ожидаемых результатов Belle II и LHCb
   - Прямое $\mathcal{CP}$ нарушение в распадах $D_{(s)}$ мезонов с точностью $10^{-3} \div 10^{-4}$
     - Эта точность находится на уровне ожидаемых результатов Belle II
     - LHCb может получить более точные результаты для некоторых процессов
2. Квантовые корреляции дают уникальную возможность для измерения различных адронных параметров
   - (Средние) разности фаз $\delta_{K\pi}$, $\delta_{K\pi\pi}$, …
   - Фазовые параметры C_i и S_i для модельно-независимого анализа многочастичных распадов
   - Факторы когерентности многочастичных распадов
   - $Доли$ $\mathcal{CP}$ в амплитудах многочастичных распадов
3. Эти адронные параметры необходимы для изучения физики B и D мезонов в экспериментах Belle II и LHCb
   - Модельно-независимое измерение СКМ фаз β и γ
   - Модельно-независимое изучение осцилляций D мезонов

Backup

D^0 decay rates

$$\lambda_f \equiv \frac{q}{p} \cdot \frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}$$

Incoherent

$$D^{*\pm} \to D\pi^\pm, \qquad B \to DX, \qquad e^+e^- \to c\bar{c} \to D\bar{D}X, \qquad pp \to c\bar{c}X$$

$$|\langle f|\mathcal{H}|D^0(t)\rangle|^2 = e^{-\Gamma t}\left|\mathcal{A}_f\right|^2\left[1 - \left(y\,\mathrm{Re}\lambda_f + x\,\mathrm{Im}\lambda_f\right)\Gamma t\right] + \mathcal{O}(x^2, y^2)$$

$$|\langle f|\mathcal{H}|D^0\rangle|^2 \propto \left|\mathcal{A}_f\right|^2\left(1 - y\,\mathrm{Re}\lambda_f + x\,\mathrm{Im}\lambda_f\right) + \mathcal{O}(x^2, y^2)$$

Boost

B factories: $(\gamma\beta)_D \sim 1$

LHCb: $(\gamma\beta)_D \gg 1$

Super c-τ: $(\gamma\beta)_D \ll 1$

Coherent (at rest)

$$e^+e^- \to D^{(*)0}\bar{D}^{(*)0}, \qquad \mathcal{C}+: D^0\bar{D}^0\gamma, \qquad \mathcal{C}-: D^0\bar{D}^0(\pi^0)$$

$$|\langle ij|\mathcal{H}|D^0\bar{D}^0\rangle|^2 \propto |\mathcal{A}_i|^2\left|\mathcal{A}_j\right|^2\left[|\zeta_\mathcal{C}|^2 + (1+\mathcal{C})\left(x\,\mathrm{Im}(\xi_\mathcal{C}^*\zeta_\mathcal{C}) - y\,\mathrm{Re}(\xi_\mathcal{C}^*\zeta_\mathcal{C})\right)\right] + \mathcal{O}(x^2, y^2)$$

$$\xi_\mathcal{C} \equiv \frac{p}{q}(1 + \mathcal{C}\lambda_i\lambda_j), \qquad \zeta_\mathcal{C} \equiv \frac{p}{q}(\lambda_j + \mathcal{C}\lambda_i)$$

The CKM matrix

$$V_{\text{CKM}} = \begin{pmatrix} 1-\frac{\lambda^2}{2} & \lambda & A\lambda^3\left(\rho - i\eta + \frac{i}{2}\eta\lambda^2\right) \\ -\lambda & 1-\frac{\lambda^2}{2} - i\eta A^2\lambda^4 & A\lambda^2(1+i\eta\lambda^2) \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^6)$$

$$\lambda \approx 0.225, \qquad A \approx 0.81, \qquad \bar{\rho} \approx 0.12, \qquad \bar{\eta} \approx 0.35$$

$\mathcal{CP}$ violation observables

$$A_\Gamma \approx \eta_{\mathcal{CP}}\left[\frac{1}{2}(A_m + A_d)y\cos\varphi - x\sin\varphi\right]$$

$$y_{\mathcal{CP}} \approx \eta_{\mathcal{CP}}\left[\left(1-\frac{1}{8}A_m^2\right)y\cos\varphi - \frac{1}{2}A_m x\sin\varphi\right]$$

CF and DCS D^0 decays ($D^0 \to K^{\mp}\pi^{\pm}$)

Time-integrated

CLEO-c [1]

- 0.82 fb^{-1} @ $\psi(3770)$, fit of 261 yields

$$y = (4.2 \pm 2.0 \pm 1.0)\%$$
$$R_D = (0.533 \pm 0.107 \pm 0.045)\%$$
$$\cos\delta_{K\pi} = +0.81 \pm 0.22 \pm 0.07$$
$$\sin\delta_{K\pi} = -0.01 \pm 0.41 \pm 0.04$$

BESIII [2]

- 2.92 fb^{-1} @ $\psi(3770)$
- y and R_D taken as an external input

$$\cos\delta_{K\pi} = 1.02 \pm 0.11 \pm 0.06 \pm 0.01$$

Correlations with $J^{PC} = 1^{--}$

$$\Gamma(i,j) \propto |\langle i|D_2\rangle\langle j|D_1\rangle - \langle i|D_1\rangle\langle j|D_2\rangle|^2 + \mathcal{O}(x^2, y^2)$$

Future precision

Parameter	**Belle II** @ 50 ab^{-1}	**LHCb** @ 50 fb^{-1}	**Super c-τ** @ 10 ab^{-1}
$y, 10^{-4}$	* ✗	* ✗	2
$y', 10^{-4}$	$\pm 4 \pm 16$ [4]	$\mathcal{O}(1)$ [3]	—
$\cos\delta_{K\pi}$	✗	✗	2×10^{-3}
$R_D, 10^{-5}$	10	$\mathcal{O}(0.3)$	1

*x and y can be measured in multibody decays, see below

[1] Phys. Rev. D86, 112001 (2012)
[2] Phys. Lett. B 734, 277 (2014)
[3] Eur. Phys. J. C73, 2373 (2013)
[4] arXiv:1002.5012 [hep-ex]

D^0 decays to $\mathcal{CP}$ eigenstates

Time-integrated

The observable

$$y_{\mathcal{CP}} \equiv \eta_{\mathcal{CP}} \frac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\bar{D}^0 \to f)}{2\hat{\Gamma}(D^0 \to K^-\pi^+)} - 1 \approx y \cos\varphi - \frac{1}{2} A_m x \sin\varphi$$

Future precision

Belle II @ 50 ab^{-1}: $(\pm 0.05(\mathrm{stat.}) \pm \mathbf{0.10}(\mathbf{syst.}))\%$ [2]

LHCb @ 50 fb^{-1}: 0.004% [3]

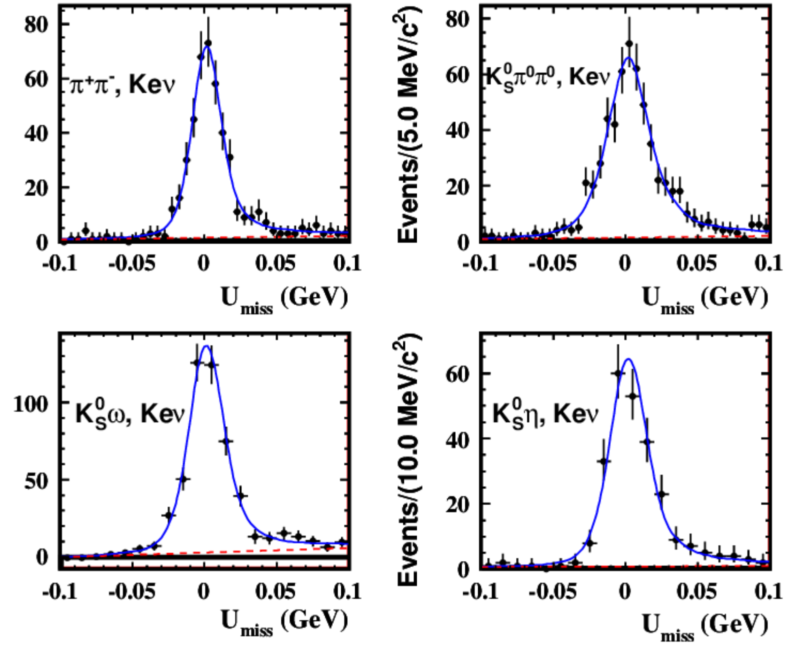
SCTF @ 10 ab^{-1}: 0.04%

BESIII [1]

- 2.92 fb^{-1} @ 3.773 GeV
- Single tag: $D \to f_{\mathcal{CP}}$
- *Quantum correlated* $D\bar{D} \to f_{\mathcal{CP}} + Kl\mu$
- Systematic uncertainty has statistical origin $y_{\mathcal{CP}} = (-2.0 \pm 1.3 \pm 0.7)\%$

$$y_{CP} \approx \frac{1}{4}\left(\frac{\mathcal{B}(D_{CP-} \to l)}{\mathcal{B}(D_{CP+} \to l)} - \frac{\mathcal{B}(D_{CP+} \to l)}{\mathcal{B}(D_{CP-} \to l)}\right)$$

$$\mathcal{B}(D_{CP\mp} \to l) = \frac{N_{CP\pm;l}}{N_{CP\pm}} \cdot \frac{\varepsilon_{CP\pm}}{\varepsilon_{CP\pm;l}}$$



[1] Phys. Lett. B744, 339 (2015)
[2] arXiv:1002.5012 [hep-ex]
[3] Eur. Phys. J. C73, 2373 (2013)

D^0 decays to $\mathcal{CP}$ eigenstates

Time-dependent

The observable

$$y_{\mathcal{CP}} \equiv \eta_{\mathcal{CP}} \frac{\hat{\Gamma}(D^0 \to f) + \hat{\Gamma}(\bar{D}^0 \to f)}{2\hat{\Gamma}(D^0 \to K^-\pi^+)} - 1 \approx y \cos\varphi - \frac{1}{2} A_m x \sin\varphi$$

LHCb [1]

- $29\ \mathrm{pb}^{-1}, D^{*+} \to D^0\pi^+$
  $y_{\mathcal{CP}} = (0.55 \pm 0.63 \pm 0.41)\%$

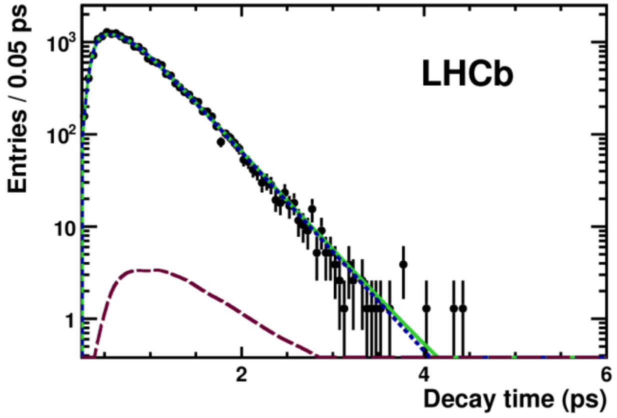
$$y_{CP} \approx \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^-K^+)} - 1$$

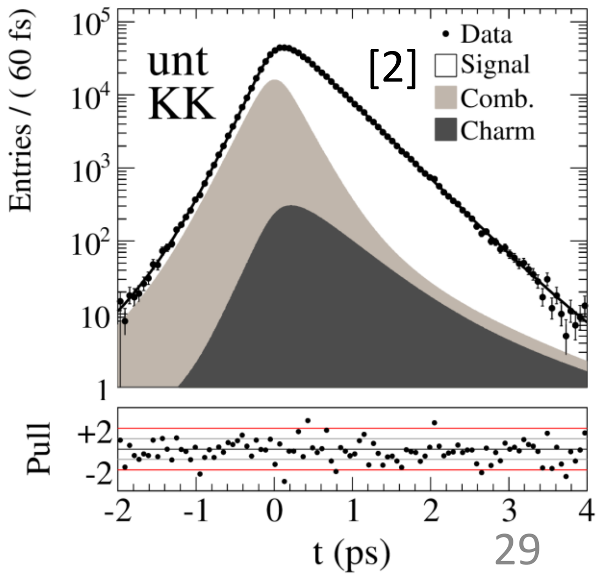
BaBar [2]

- $468\ \mathrm{fb}^{-1}, D^0 \to K^\mp\pi^\pm, K^-K^+, \pi^-\pi^+$
  $y_{\mathcal{CP}} = (0.72 \pm 0.18 \pm 0.12)\%$

Belle [3]

- $540\ \mathrm{fb}^{-1}, D^0 \to K^\mp\pi^\pm, K^-K^+, \pi^-\pi^+$
  $y_{\mathcal{CP}} = (1.31 \pm 0.32 \pm 0.25)\%$





[1] JHEP 04, 129 (2012)
[2] Phys. Rev. D87, 012004 (2013)
[3] Phys. Rev. Lett. 98, 211803 (2007)

CF and DCS D^0 decays ($D^0 \to K^{\mp}\pi^{\pm}$)

Time-dependent

BaBar [1]

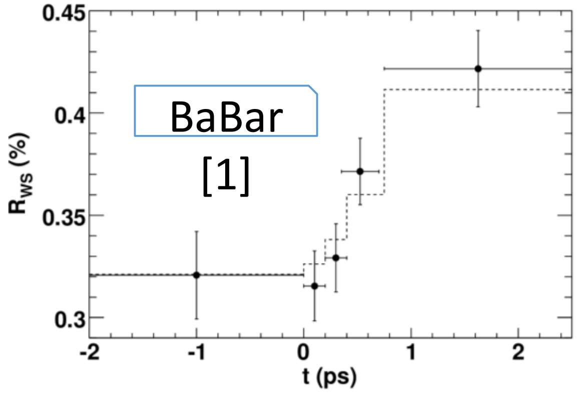
- $384\ \text{fb}^{-1}, D^{*+} \to D^0\pi^+$
  $y' = (0.97 \pm 0.44 \pm 0.31)\%$
  $R_D = (0.303 \pm 0.019)\%$

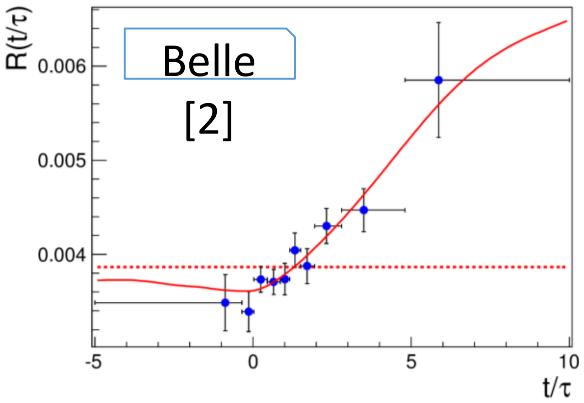
Belle [2]

- $976\ \text{fb}^{-1}, D^{*+} \to D^0\pi^+$
  $y' = (0.46 \pm 0.34)\%$
  $R_D = (0.353 \pm 0.013)\%$

LHCb [3]

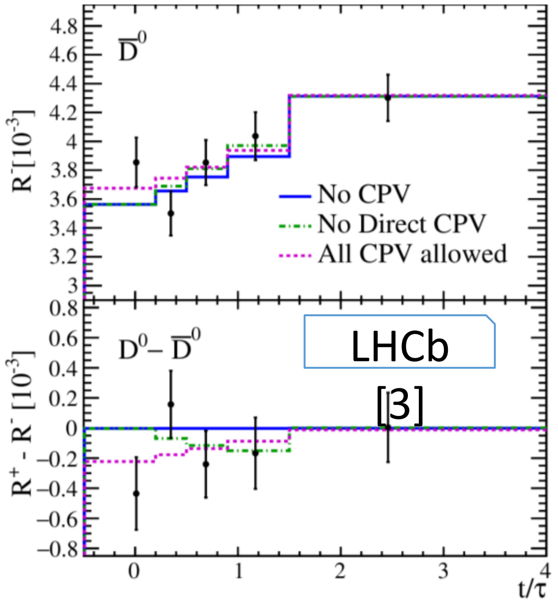
- $3\ \text{fb}^{-1}, \bar{B} \to D^{*+}\mu^- X, D^{*+} \to D^0\pi^+$
  $y' = (0.460 \pm 0.370 \pm 0.018)\%$
  $R_D = (0.348 \pm 0.010 \pm 0.001)\%$





The observable

$$x' \equiv x \cos\Delta_{K\pi} + y \sin\Delta_{K\pi}$$
$$y' \equiv y \cos\Delta_{K\pi} - x \sin\Delta_{K\pi}$$



$$\Gamma(D^0(t) \to f_{WS}) = e^{-\tau}|A_f|^2\left[R_f^2 + R_f y'\tau + \frac{1}{2}R_M\tau^2\right]$$

[1] Phys. Rev. Lett. 98, 211802 (2007)
[2] Phys. Rev. Lett. 112, 111801 (2014)
[3] Phys. Rev. D95, 052004 (2017)

$\mathcal{CP}$ violation in $D^0 \to h^+h^-$

Belle

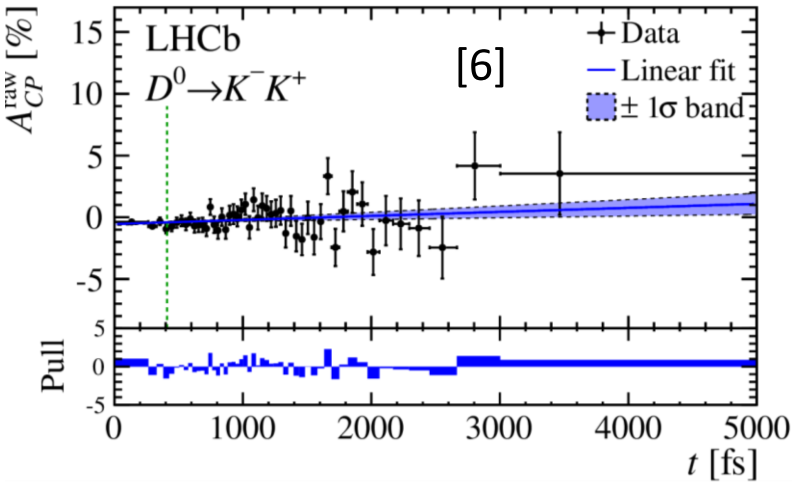
- 540 fb^{-1}, $D^{*+} \to D^0\pi^+, D^0 \to h^+h^-$ [1]
  $$A_\Gamma = \frac{\tau(\bar{D}^0 \to K^+K^-) - \tau(D^0 \to K^+K^-)}{\tau(\bar{D}^0 \to K^+K^-) - \tau(D^0 \to K^+K^-)}$$
  $= (0.01 \pm 0.30 \pm 0.15)\%$

BaBar

- 385.8 fb^{-1}, $D^{*+} \to D^0\pi^+$ [2]
  $\mathcal{A}_{CP}(K^+K^-) = (+0.00 \pm 0.34 \pm 0.13)\%$
  $\mathcal{A}_{CP}(\pi^+\pi^-) = (-0.24 \pm 0.52 \pm 0.22)\%$
- 468 fb^{-1}, $D^{*+} \to D^0\pi^+, D^0 \to h^+h^-$ [3]
  $\Delta Y = (0.09 \pm 0.26 \pm 0.06)\%$

LHCb

- 29 pb^{-1} @ 7 TeV, $D^{*+} \to D^0\pi^+$ [4]
  $A_\Gamma(K^+K^-) = (-0.59 \pm 0.59 \pm 0.21)\%$
- 3 fb^{-1}, $\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$ [5]
  $\Delta\mathcal{A}_{CP} = (+0.14 \pm 0.16 \pm 0.08)\%$
  $\mathcal{A}_{CP}(K^-K^+) = (-0.06 \pm 0.15 \pm 0.10)\%$
  $\mathcal{A}_{CP}(\pi^-\pi^+) = (-0.20 \pm 0.19 \pm 0.10)\%$
- 3 fb^{-1}, $\bar{B} \to D^0\mu^-\bar{\nu}_\mu X$ [6]
  $A_\Gamma(K^-K^+) = (-0.134 \pm 0.077^{+0.026}_{-0.034})\%$
  $A_\Gamma(\pi^-\pi^+) = (-0.092 \pm 0.145^{+0.025}_{-0.033})\%$
- 3 fb^{-1}, $D^{*+} \to D^0\pi^+$ [7]
  $\Delta\mathcal{A}_{CP} = (-0.10 \pm 0.08 \pm 0.03)\%$

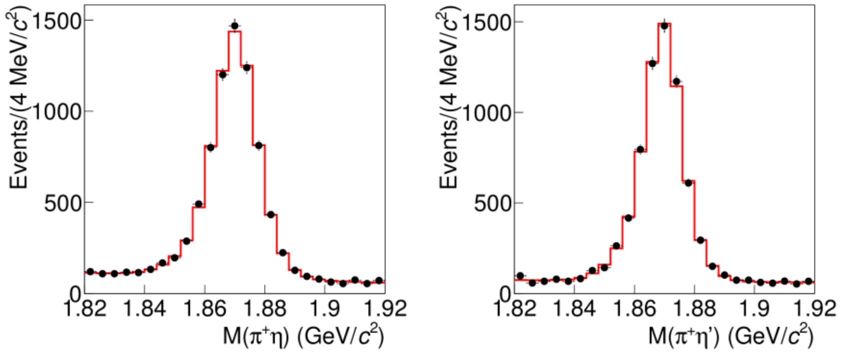


[1] Phys. Rev. Lett. 98, 211803 (2007) (Belle)
[2] Phys. Rev. Lett. 100, 061803 (2007) (BaBar)
[3] Phys. Rev. D87, 012004 (2013) (BaBar)
[4] JHEP 04, 129 (2012) (LHCb)
[5] JHEP 07, 041 (2014) (LHCb)
[6] JHEP 04, 043 (2015) (LHCb)
[7] Phys. Rev. Lett. 116, 191601 (2016) (LHCb)

An example: $D^+ \to \pi^+\eta^{(\prime)}$

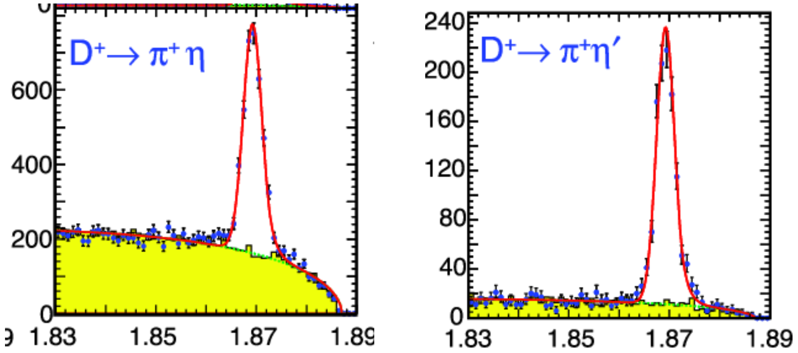
Belle PRL 107, 221801 (2011)

- $791\ \mathrm{fb}^{-1}$
- $N(\pi^+\eta) = 6476, N(\pi^+\eta') = 6023$
  $\mathcal{A}_{CP}(\pi^+\eta) = (+1.74 \pm 1.13 \pm 0.19)\%$
  $\mathcal{A}_{CP}(\pi^+\eta') = (-0.12 \pm 1.12 \pm 0.17)\%$



CLEO-c PRD 81, 052013 (2010)

- $0.818\ \mathrm{fb}^{-1}$ @ 3774 MeV, single tag
- $N(\pi^+\eta) = 2940, N(\pi^+\eta') = 1037$
  $\mathcal{A}_{CP}(\pi^+\eta) = (-2.0 \pm 2.3 \pm 0.3)\%$
  $\mathcal{A}_{CP}(\pi^+\eta') = (-4.0 \pm 3.4 \pm 0.3)\%$



Naive extrapolation:

- Belle II @ $50\ \mathrm{ab}^{-1}$: $\sigma = 0.15\ \%$
- Super c-τ @ $10\ \mathrm{ab}^{-1}$: $\sigma = 0.02\ \%$

Direct $\mathcal{CP}$ violation in D^0 decays

$\mathcal{A}_{\mathcal{CP}}$ (%)			
Mode	**CLEO-c**	***B* factories**	**LHCb**
$D^0 \to K^-\pi^+$	$+0.3 \pm 0.3 \pm 0.6$ [1]		
$D^0 \to K^-\pi^+\pi^0$	$+0.1 \pm 0.3 \pm 0.4$ [1]		
$D^0 \to K^+\pi^-\pi^0$		-0.6 ± 5.3 [3]	
$D^0 \to K^-2\pi^+\pi^-$	$+0.2 \pm 0.3 \pm 0.4$ [1]		
$D^0 \to K^+2\pi^-\pi^+$		-1.8 ± 4.4 [3]	
$D^0 \to \pi^-\pi^+\pi^0$		$+0.31 \pm 0.41 \pm 0.17$ [5]	Energy test [4]

Tracking and identification asymmetry systematics

- CLEO-c [1]:
  - $K^\pm$: $\pm 0.8\%$
  - $\pi^\pm$: $\pm 0.3\%$

[1] Phys. Rev. D81, 052013 (2010) (CLEO-c 818 pb^{-1})
[2] Phys. Rev. D89, 072002 (2014) (CLEO-c 818 pb^{-1})
[3] Phys. Rev. Lett. 95, 231801 (2005) (Belle 281 fb^{-1})
[4] Phys. Lett. B740, 158 (2015) (LHCb)
[5] Phys. Rev. D78, 051102 (2008) (BaBar 385 fb^{-1})

Direct $\mathcal{CP}$ violation in $D^{\pm}$ decays II

$\mathcal{A}_{\mathcal{CP}}$ (%)				
Mode	**CLEO-c**	***B* factories**	**LHCb**	**LHCb 50 fb**
$D^+ \to K^-\pi^+\pi^+$	$-0.3 \pm 0.2 \pm 0.4$ [1]			
$D^+ \to K^-\pi^+\pi^+\pi^0$	$-0.3 \pm 0.6 \pm 0.4$ [1]			
$D^+ \to K^-K^+\pi^+$	$-0.1 \pm 0.9 \pm 0.4$ [1]	$+0.37 \pm 0.30 \pm 0.15$ [4]		5×10^{-5}
$D^+ \to K_S^0\pi^+$	$-1.1 \pm 0.6 \pm 0.2$ [1]	$-0.36 \pm 0.09 \pm 0.07$ [3]		
$D^+ \to K_S^0\pi^+\pi^0$	$-0.1 \pm 0.7 \pm 0.2$ [1]			
$D^+ \to K_S^0\pi^+\pi^+\pi^-$	$+0.0 \pm 1.2 \pm 0.3$ [1]			
$D^+ \to \mu^+\nu_\mu$	8 ± 8 [2]			

[1] Phys. Rev. D89, 072002 (2014) (CLEO-c 818 pb^{-1})
[2] Phys. Rev. D78, 052003 (2008) (CLEO-c 818 pb^{-1})
[3] Phys. Rev. Lett. 109, 021601 (2012) (Belle 977 fb^{-1})
[4] Phys. Rev. D87, 052010 (2013) (BaBar 476 fb^{-1})

Direct $\mathcal{CP}$ violation in D_s decays I

$*$ the effects due to kaon system substracted

$\mathcal{A}_{\mathcal{CP}}$ (%)			
Mode	**CLEO-c [1]**	***B* factories**	**LHCb**
$D_s \to K_S^0 K^+$	$2.6 \pm 1.5 \pm 0.6$	$-0.28 \pm 0.23 \pm 0.24^*$ [2]	
$D_s \to K^- K^+ \pi^+$	$-0.5 \pm 0.8 \pm 0.4$ [2]		
$D_s \to K_S^0 K^+ \pi^0$	$-1.6 \pm 0.6 \pm 1.1$ [2]		
$D_s \to K_S^0 K_S^0 \pi^+$	$3.1 \pm 5.2 \pm 0.6$ [2]		
$D_s \to K^- K^+ \pi^+ \pi^0$	$0.0 \pm 2.7 \pm 1.2$ [2]		
$D_s \to K_S^0 K^+ \pi^+ \pi^-$	$-5.7 \pm 5.3 \pm 0.9$ [2]		
$D_s \to K_S^0 K^- \pi^+ \pi^+$	$4.1 \pm 2.7 \pm 0.9$ [2]		
$D_s \to \pi^+ \pi^+ \pi^+$	$-0.7 \pm 3.0 \pm 0.8$ [2]		
$D_s \to \mu\nu$	$+4.8 \pm 6.1$ [3]		

[1] Phys. Rev. D88, 032009 (2013) (CLEO-c $586\ \mathrm{pb}^{-1}$ @ $D_s^* D_s$)
[2] Phys. Rev. D87, 052012 (2013) (BaBar $469\ \mathrm{fb}^{-1}$)
[3] Phys. Rev. D79, 052001 (2009) (CLEO-c $600\ \mathrm{pb}^{-1}$ @ $D_s^* D_s$)

Direct $\mathcal{CP}$ violation in D_s decays II

$*$ the effects due to kaon system substracted

$\mathcal{A}_{\mathcal{CP}}$ (%)			
Mode	**CLEO-c**	**B factories**	**LHCb**
$D_s \to \pi^+\pi^0\eta'$	$-0.4 \pm 7.4 \pm 1.9$ [2]		
$D_s \to K^+\pi^+\pi^-$	$+4.5 \pm 4.8 \pm 0.6$ [2]		
$D_s \to K_S^0\pi^+$	$16.3 \pm 7.3 \pm 0.3$ [1]	$+0.3 \pm 2.0 \pm 0.3^*$ [3]	$+0.38 \pm 0.46 \pm 0.17$ [4]
$D_s \to K^+\pi^0$	$-26.6 \pm 23.8 \pm 0.9$ [1]		
$D_s \to K^+\eta$	$9.3 \pm 15.2 \pm 0.9$ [1]		
$D_s \to K^+\eta'$	$6.0 \pm 18.9 \pm 0.9$ [1]		
$D_s \to \pi^+\eta$	$1.1 \pm 3.0 \pm 0.6$ [2]		
$D_s \to \pi^+\eta'$	$-2.2 \pm 2.2 \pm 0.6$ [2]		

[1] Phys. Rev. D81, 052013 (2010) (CLEO-c 0.586 pb^{-1} @ $D_s^*D_s$)
[2] Phys. Rev. D88, 032009 (2013) (CLEO-c 0.586 pb^{-1} @ $D_s^*D_s$)
[3] Phys. Rev. D87, 052012 (2013) (BaBar 469 fb^{-1})
[4] JHEP 1410, 025 (2014) (LHCb 3 fb^{-1})