The progress and prospect on charm mixing

Vitaly Vorobyev

Budker Institute of Nuclear Physics

and

Novosibirsk State University

On behalf of Belle & Belle II Collaborations

2nd international workshop on High Intensity Electron-Positron Accelerator
19th March 2018, UCAS, Beijing

The charm mixing parameters

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

- Mass eigenstates

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\bar{D}^0\rangle, \qquad |p|^2 + |q|^2 = 1$$

- The charm mixing parameters

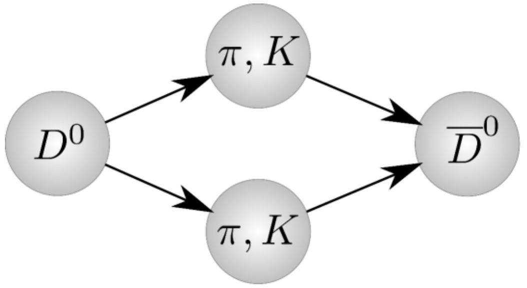
$$x \equiv \frac{m_2 - m_1}{\Gamma}, \qquad y \equiv \frac{\Gamma_2 - \Gamma_1}{2\Gamma}, \qquad \Gamma \equiv \frac{\Gamma_1 + \Gamma_2}{2}$$

- The observable parameter

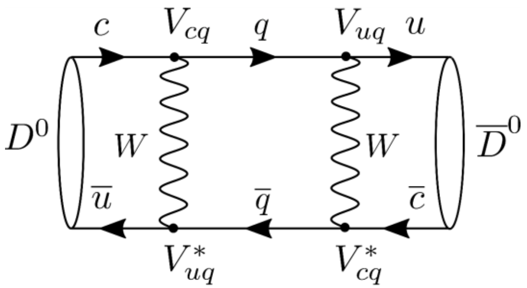
$$\lambda_f \equiv \frac{q}{p}\frac{\bar{\mathcal{A}}_f}{\mathcal{A}_f}, \qquad \mathcal{A}_f \equiv \langle f|\mathcal{H}|D^0\rangle, \qquad \bar{\mathcal{A}}_f \equiv \langle f|\mathcal{H}|\bar{D}^0\rangle$$

- $\mathcal{CP}$ violation
  - Direct: $|\langle f|\mathcal{H}|D^0\rangle| \neq |\langle \mathcal{CP}(f)|\mathcal{H}|\bar{D}^0\rangle|$
  - In mixing: $|q/p| \neq 1$
  - In interference between mixing and decay: $\mathrm{Im}\,\lambda_f \neq 0$

Long distances (dominant)



Short distances



- The Standard Model expectation

$$x \lesssim y \sim \sin^2\theta_C \times [SU(3)_f \text{ breaking}]^2$$

- Clear signals of new dynamics:
  - $y \ll x \sim 1\%$
  - $\mathcal{CP}$ violation $> 10^{-3}$

Experimental status

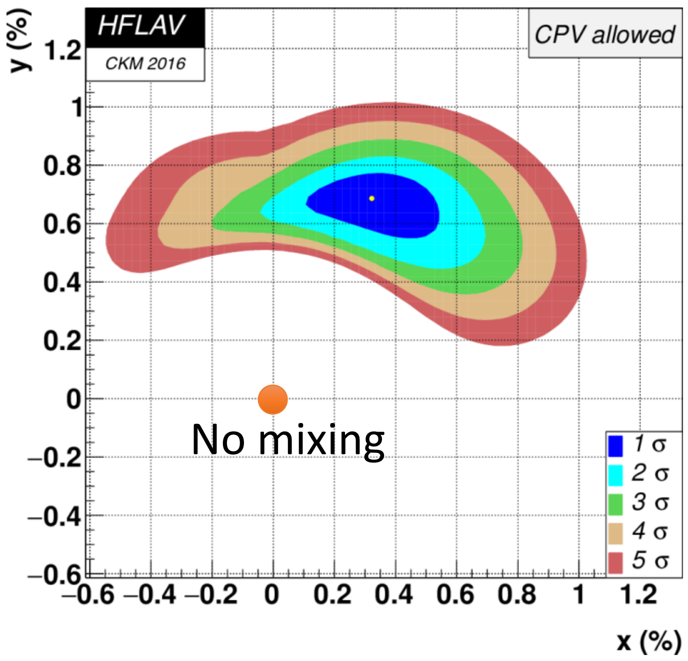
arXiv:1612.07233

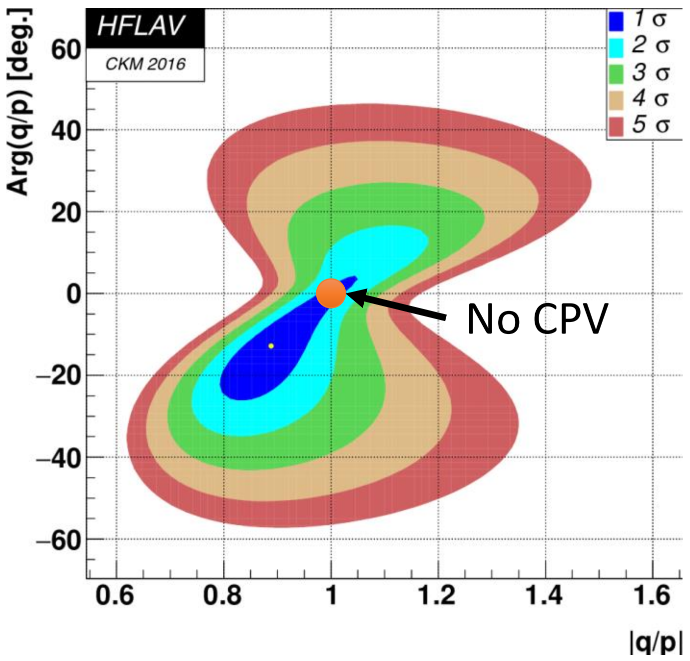
$$x = (0.32 \pm 0.14)\%$$

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

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

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

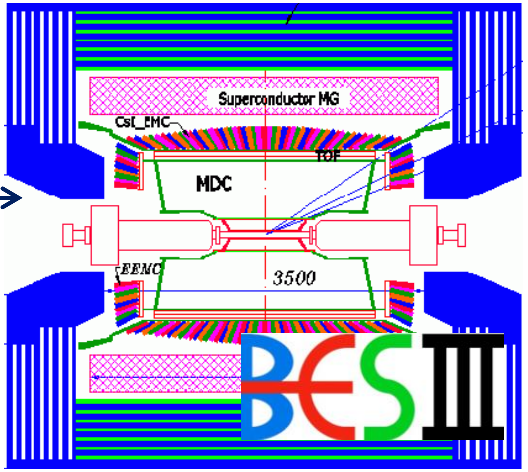




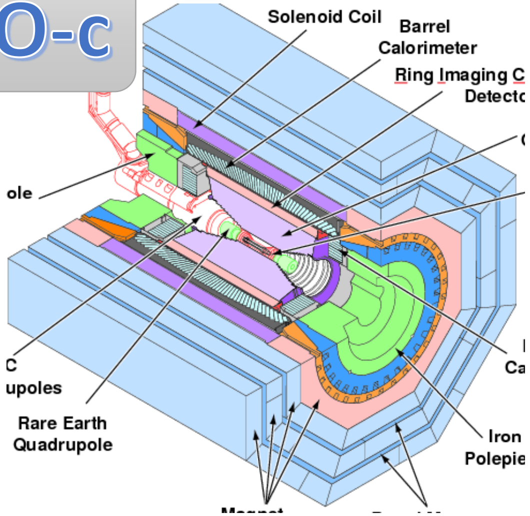
- The first evidence by Belle and BaBar
  - Phys. Rev. Lett. 98, 211802 (2007)
  - Phys. Rev. Lett. 98, 211803 (2007)
- Charm mixing is well established
- No $\mathcal{CP}$ violation observed in charm yet

Experimental landscape

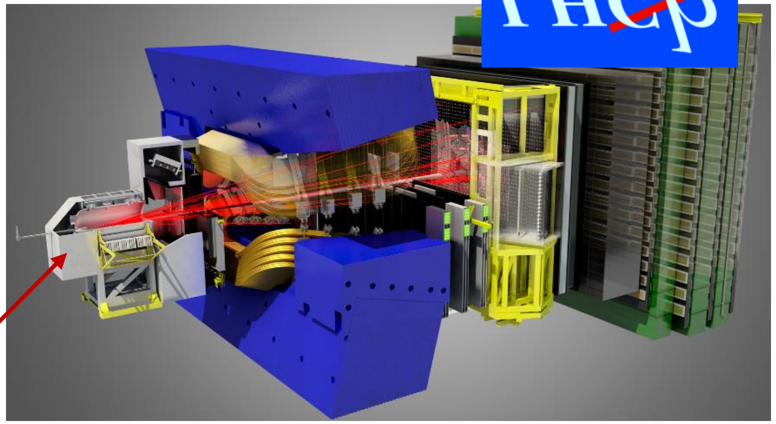
$D\bar{D}$ threshold



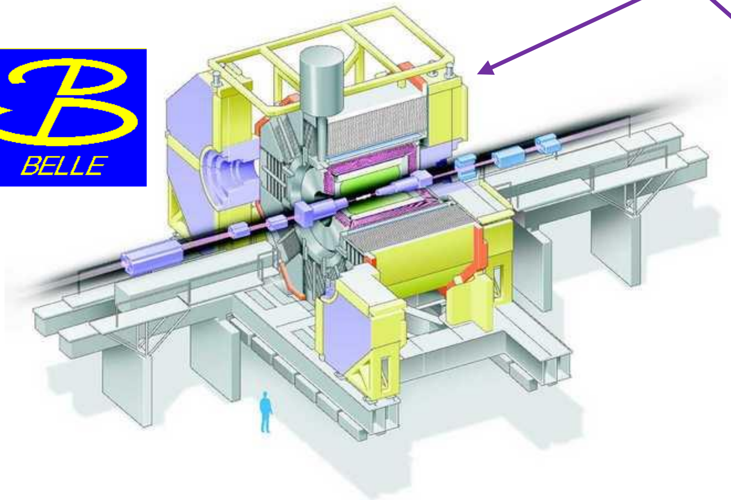
CLEO-c

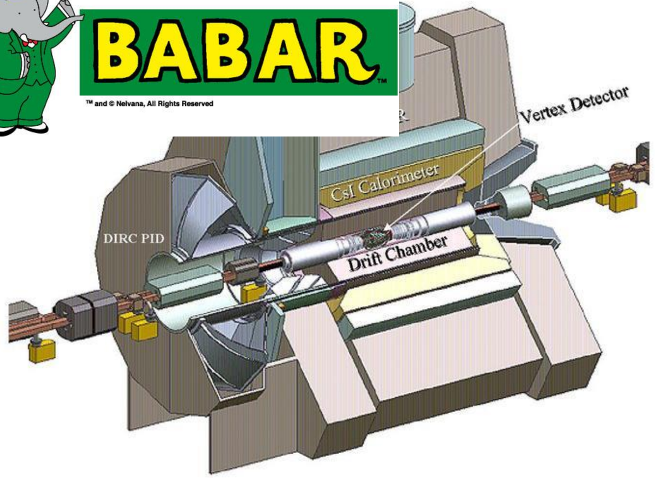


pp collisions



Asymmetric e^+e^- @ $\Upsilon(4S)$





Charm mixing observables and facilities

Classes of observables (I. Bigi)

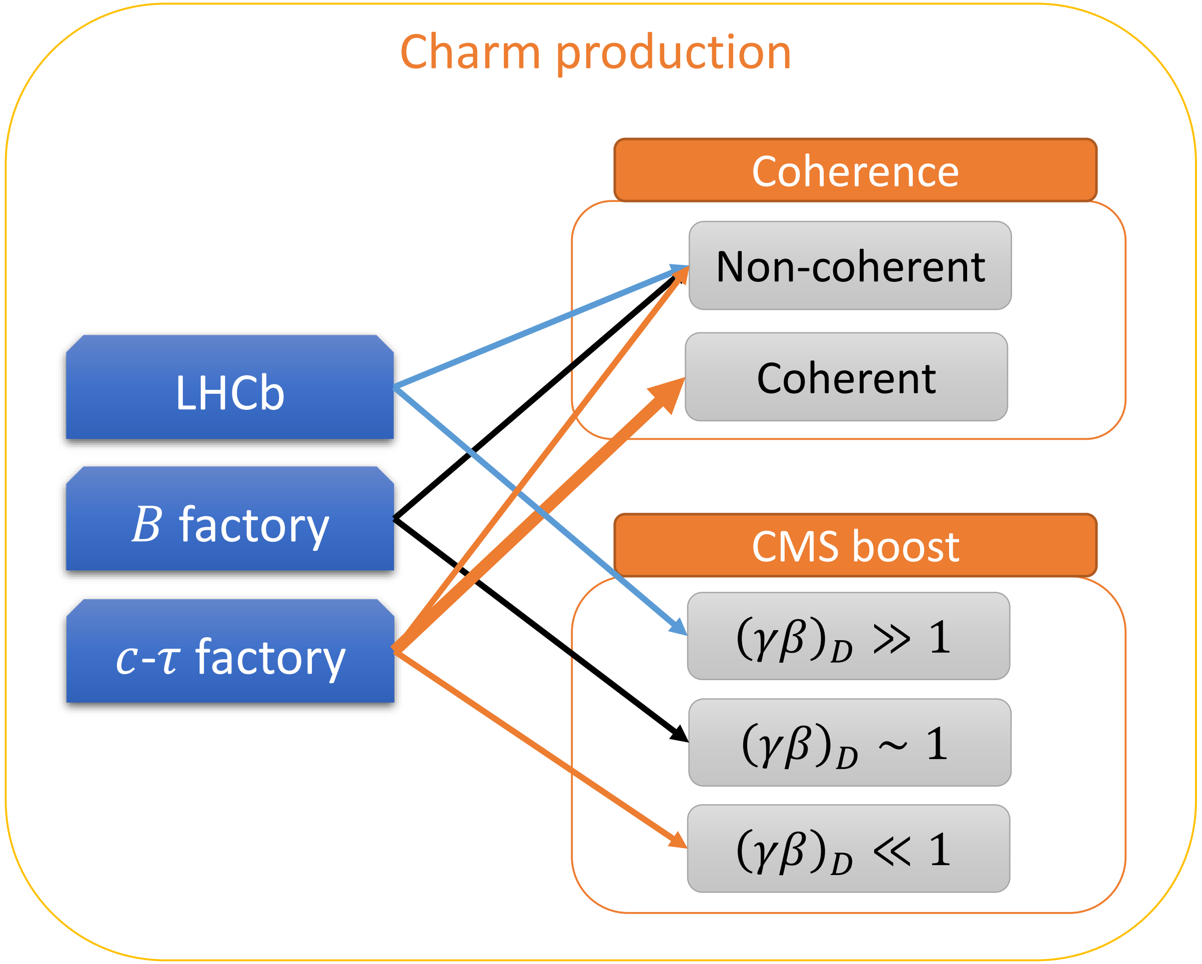
'Wrong-sign' D^0 decays

- Semileptonic
- Hadronic ($D^0 \to K^+\pi^-$ time ind.)

Non-exponential D^0 decay rate evolutions ($D^0 \to K^+\pi^-$ time dep.)

Different D^0 lifetimes in different channels ($D^0 \to h^+h^-$)

D^0 and $\overline{D}^0$ produced in $e^+e^- \to D^0\overline{D}^0$ decaying into two seemingly identical final states



Charm decay rates

Time-dependent

Incoherent

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

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

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

Time-integrated

Boost

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

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

c-τ factory: $(\gamma\beta)_D \ll 1$

Coherent (at rest)

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

$$\langle ij|\mathcal{H}|D^0\bar{D}^0\rangle \propto \langle i|\mathcal{H}|D^0\rangle\langle j|\mathcal{H}|\bar{D}^0\rangle + \mathcal{C}\langle i|\mathcal{H}|\bar{D}^0\rangle\langle j|\mathcal{H}|D^0\rangle$$

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

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

The progress

Selected experimental results

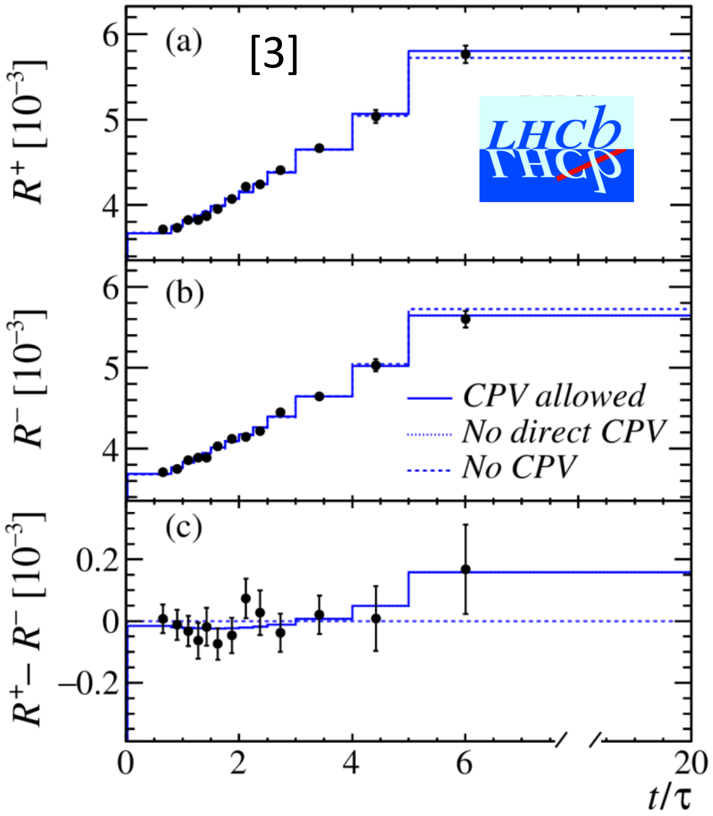
$D^0 \to K\pi$ time-dependent WS

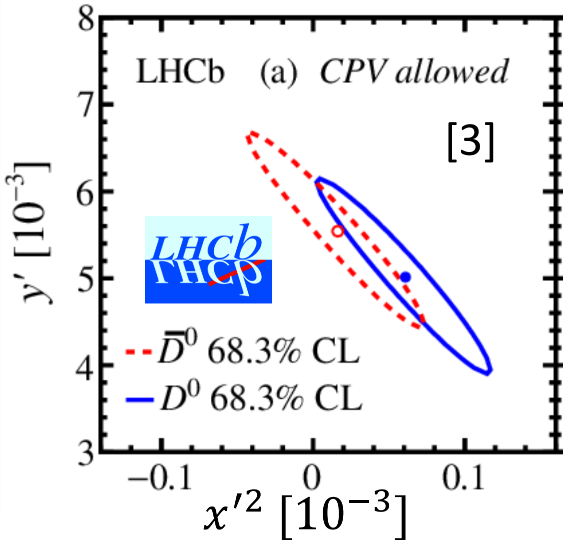
$$\Gamma(D^0(t) \to f_{WS}) = e^{-\frac{t}{\tau}}|A_f|^2\left[R_D + \sqrt{R_D}y'\frac{t}{\tau} + \frac{1}{2}R_M\left(\frac{t}{\tau}\right)^2\right]$$

$$x' \equiv x\cos\delta_{K\pi} + y\sin\delta_{K\pi}$$
$$y' \equiv y\cos\delta_{K\pi} - x\sin\delta_{K\pi}$$
$$R_M \equiv (x^2+y^2)/2$$

$$R_D^{(+)} \equiv \frac{Br(D^0 \to K^+\pi^-)}{Br(D^0 \to K^-\pi^+)}$$
$$A_D \equiv \frac{(R_D^+ - R_D^-)}{(R_D^+ + R_D^-)}$$

- BaBar [1]: 384 fb^{-1}, $D^{*+} \to D^0\pi^+$
  $y' = (9.7 \pm 4.4 \pm 3.1) \times 10^{-3}$
  $R_D = (3.03 \pm 0.19) \times 10^{-3}$
- Belle [2]: 976 fb^{-1}, $D^{*+} \to D^0\pi^+$
  $y' = (4.6 \pm 3.4) \times 10^{-3}$
  $R_D = (3.53 \pm 0.13) \times 10^{-3}$
- LHCb [3]: 5 fb^{-1}, $D^{*+} \to D^0\pi^+$
  $y' = (5.28 \pm 0.45 \pm 0.27) \times 10^{-3}$
  $x'^2 = (0.039 \pm 0.023 \pm 0.014) \times 10^{-3}$
  $R_D = (3.454 \pm 0.028 \pm 0.014) \times 10^{-3}$
  $A_D = (-0.1 \pm 9.1) \times 10^{-3}$
  $1.00 < |p/q| < 1.35$ @ 68.3% CL





[1] Phys. Rev. Lett. 98, 211802 (2007) (BaBar)
[2] Phys. Rev. Lett. 112, 111801 (2014) (Belle)
[3] Phys. Rev. D97, 031101(R) (2018) (LHCb)

Measurements with quantum correlations

Time-integrated

The method exploits the difference between correlated (double tagged) and uncorrelated (single tagged) decay rates

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

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

$\mathcal{C} = -1$ correlations

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

TABLE III. D final states reconstructed in this analysis. [1]

Type	Reconstruction	Final states
f	Full	$K^-\pi^+$, $Y_0 - Y_7$
$\bar{f}$	Full	$K^+\pi^-$, $\bar{Y}_0 - \bar{Y}_7$
S_+	Full	K^+K^-, $\pi^+\pi^-$, $K^0_S\pi^0\pi^0$
S_+	Partial	$K^0_L\pi^0$, $K^0_L\eta$, $K^0_L\omega$
S_-	Full	$K^0_S\pi^0$, $K^0_S\eta$, $K^0_S\omega$
S_-	Partial	$K^0_L\pi^0\pi^0$
ℓ^+	Partial	$K^-e^+\nu_e$, $K^-\mu^+\nu_\mu$
ℓ^-	Partial	$K^+e^-\bar{\nu}_e$, $K^+\mu^-\bar{\nu}_\mu$

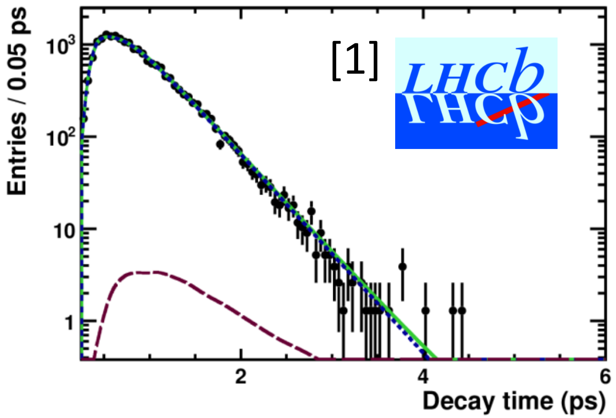
[1] Phys. Rev. D86, 112001 (2012) (CLEO-c)
[2] Phys. Lett. B 734, 277 (2014) (BESIII)

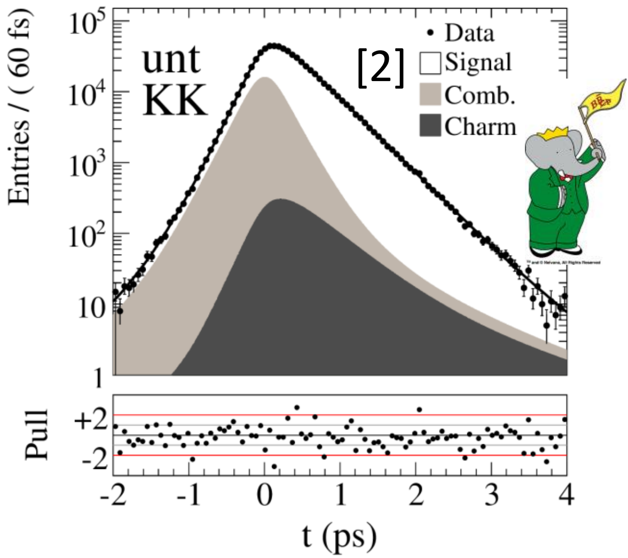
Time-dependent $D^0 \to h^+h^-$

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

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

- LHCb [1]*: 29 pb^{-1}, $D^{*+} \to D^0\pi^+$
  $y_{\mathcal{CP}} = (0.55 \pm 0.63 \pm 0.41)\%$
- BaBar [2]: 468 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 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) (LHCb)
[2] Phys. Rev. D87, 012004 (2013) (BaBar)
[3] Phys. Rev. Lett. 98, 211803 (2007) (Belle)

*There are many other LHCb publications on $\mathcal{CP}$ violation in the $D^0 \to h^+h^-$ modes

$D^0 \to f_{\mathcal{CP}}$ with quantum correlations

$$y_{CP} \approx \frac{1}{4}\left(\frac{\mathcal{B}(D_{\mathcal{CP}-} \to l)}{\mathcal{B}(D_{\mathcal{CP}+} \to l)} - \frac{\mathcal{B}(D_{\mathcal{CP}+} \to l)}{\mathcal{B}(D_{\mathcal{CP}-} \to l)}\right), \qquad \mathcal{B}(D_{\mathcal{CP}\mp} \to l) = \frac{N_{CP\pm;l}}{N_{CP\pm}} \cdot \frac{\varepsilon_{CP\pm}}{\varepsilon_{CP\pm;l}}$$

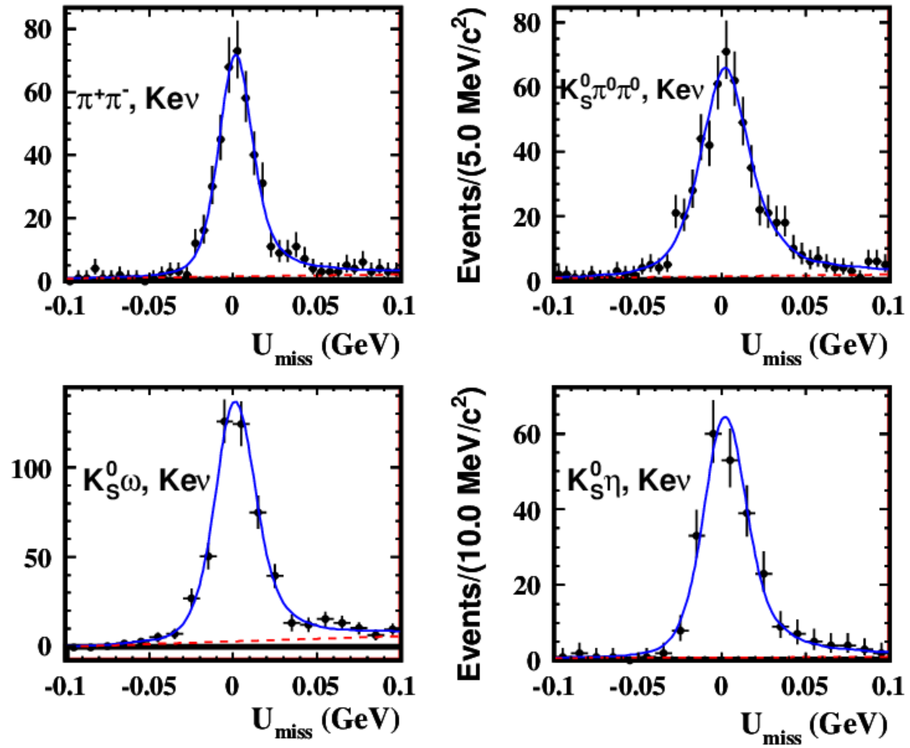
- BESIII [1]: 2.92 fb^{-1} @ 3.773 GeV

$$y_{\mathcal{CP}} = (-2.0 \pm 1.3 \pm 0.7)\%$$

  - Single tag: $D \to f_{\mathcal{CP}}$
  - Quantum correlated

$$D\bar{D} \to f_{\mathcal{CP}} + Kl\mu$$

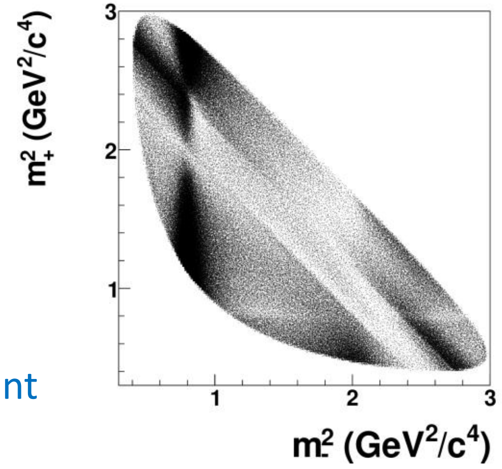
  - Systematic uncertainty has statistical origin



[1] Phys. Lett. B744, 339 (2015)

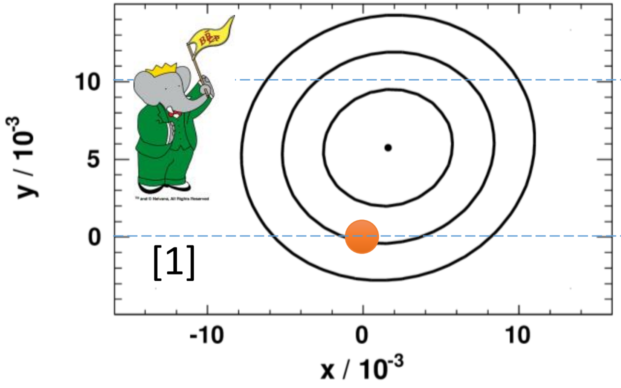
$D^0 \to K_S^0 \pi^+ \pi^-$ Dalitz plot analysis

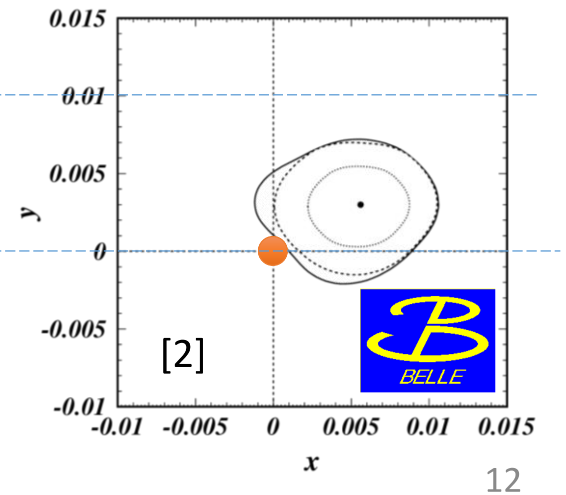
- Time-dependent Dalitz plot analysis
  $$\mathcal{P}_D(t, m_+^2, m_-^2) \approx \Gamma e^{-\Gamma t}\left[|\mathcal{A}_D|^2 - \Gamma t \,\mathrm{Re}\left(\mathcal{A}_D^* \mathcal{A}_{\bar{D}}(y + ix)\right)\right]$$
- Sensitivity to the charm mixing parameters due to the strong phase variation over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



- BaBar [1]: 468.5 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 fb^{-1}, $D^{*+} \to D^0 \pi^+$
  $$x = (0.56 \pm 0.19 \pm 0.08 \pm 0.08)\%$$
  $$y = (0.30 \pm 0.15 \pm 0.05 \pm 0.07)\%$$
  $$|q/p| = 0.90 \pm 0.16 \pm 0.05 \pm 0.06$$
  $$\arg(q/p) = (-6 \pm 11 \pm 3 \pm 4)^\circ$$

The most precise single measurement of the charm mixing parameters





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

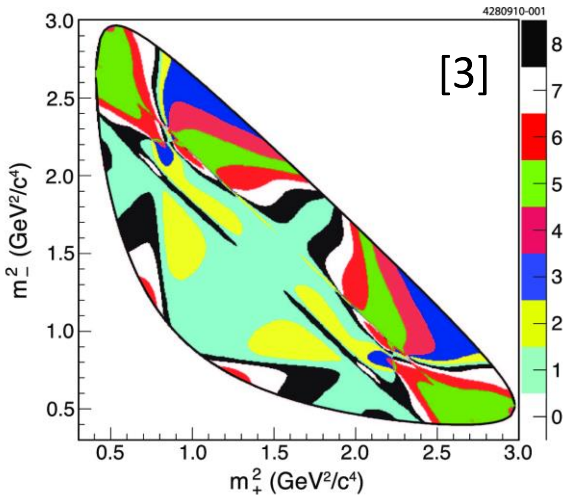
Model-independent Dalitz plot analysis

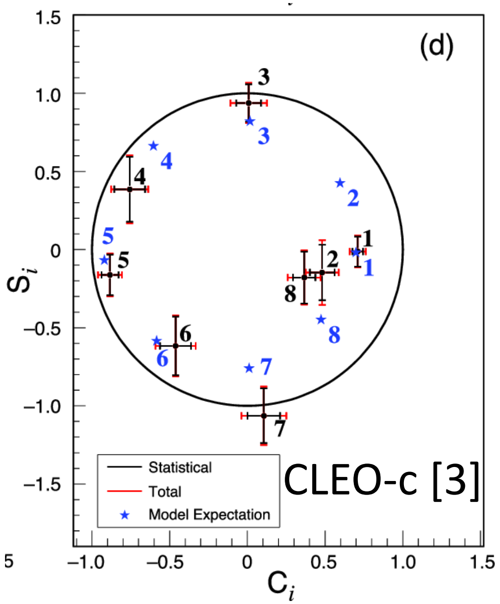
A way to eliminate (difficult to control) model dependency of a multibody decay analysis

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

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

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





- LHCb [4]: 1.0 fb^{-1} @ 7 TeV, $D^{*+} \to D^0\pi^+$

$$x = (-0.86 \pm 0.53 \pm 0.17)\%$$
$$y = (+0.03 \pm 0.46 \pm 0.13)\%$$

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

The first model-independent measurement of the charm mixing parameters

[1] Phys. Rev. D68, 054018 (2003)
[2] Phys. Rev. D82, 034033 (2010) (Bondar et al.)
[3] Phys. Rev. D82, 112006 (2010) (CLEO-c)
[4] JHEP 04, 033 (2016) (LHCb)

$D^0 \to K_S^0 \pi^+ \pi^-$ with quantum correlations

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

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

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

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

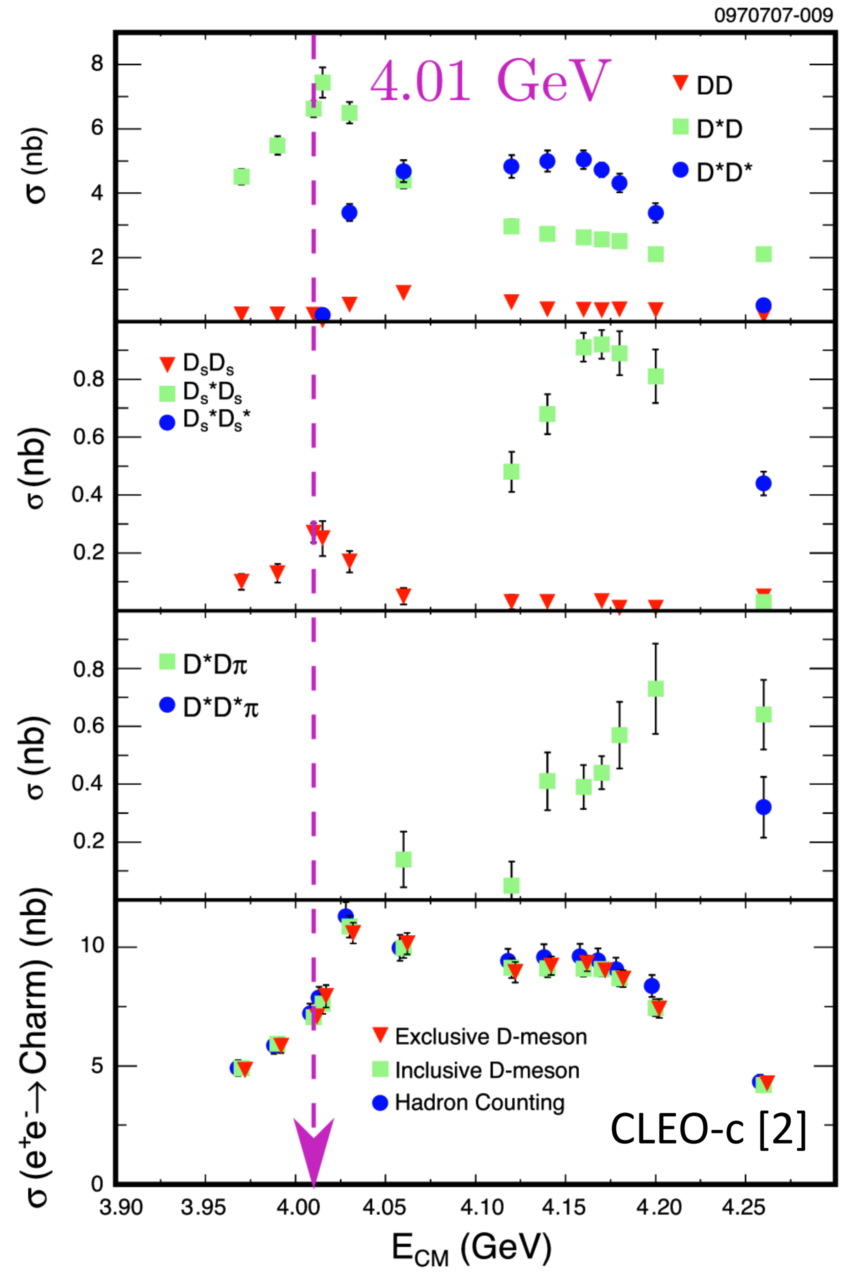
- Coherent $\mathcal{C} = +1$: $D^0\bar{D}^{*0} \to D^0\bar{D}^0\gamma$

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

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

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

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

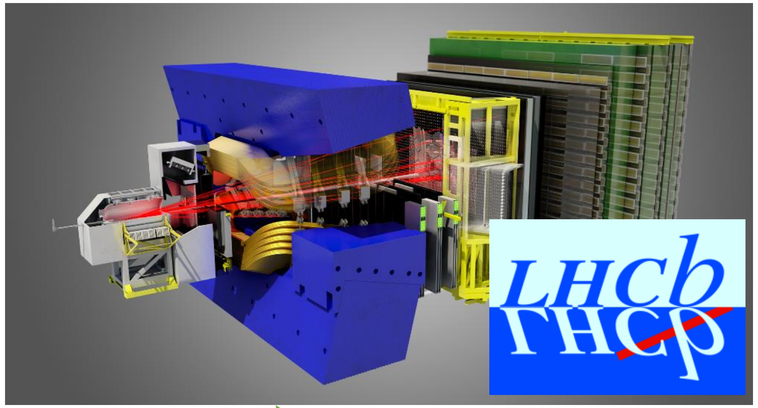


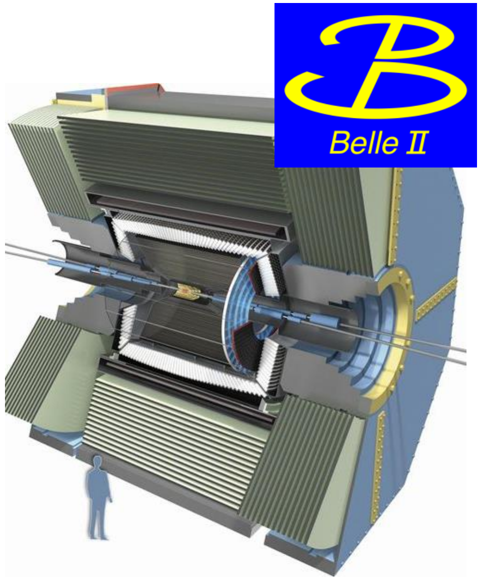
[1] Phys. Rev. D82, 034033 (2010)
[2] Phys. Rev. D80, 072001 (2009) (CLEO-c)

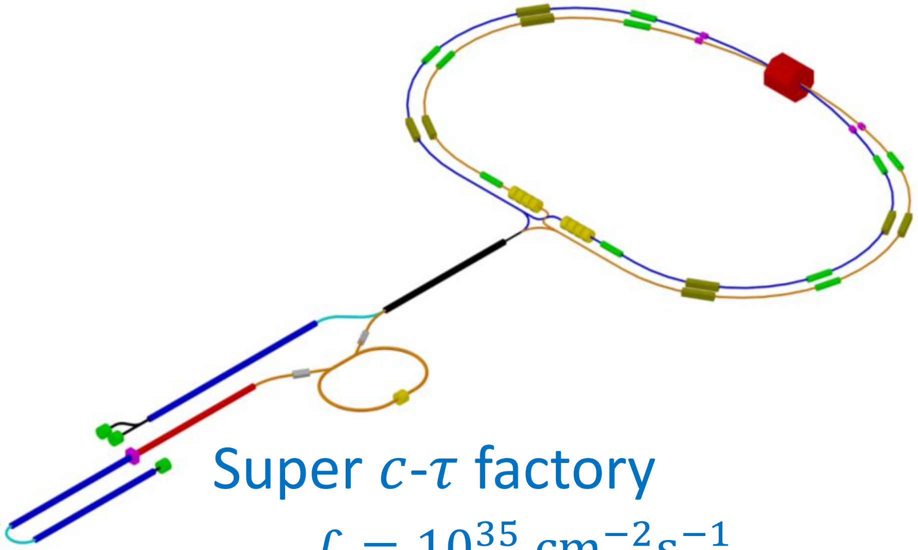
The prospects

Estimates and expectations

Future landscape







Super c-τ factory

$\mathcal{L} = 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$

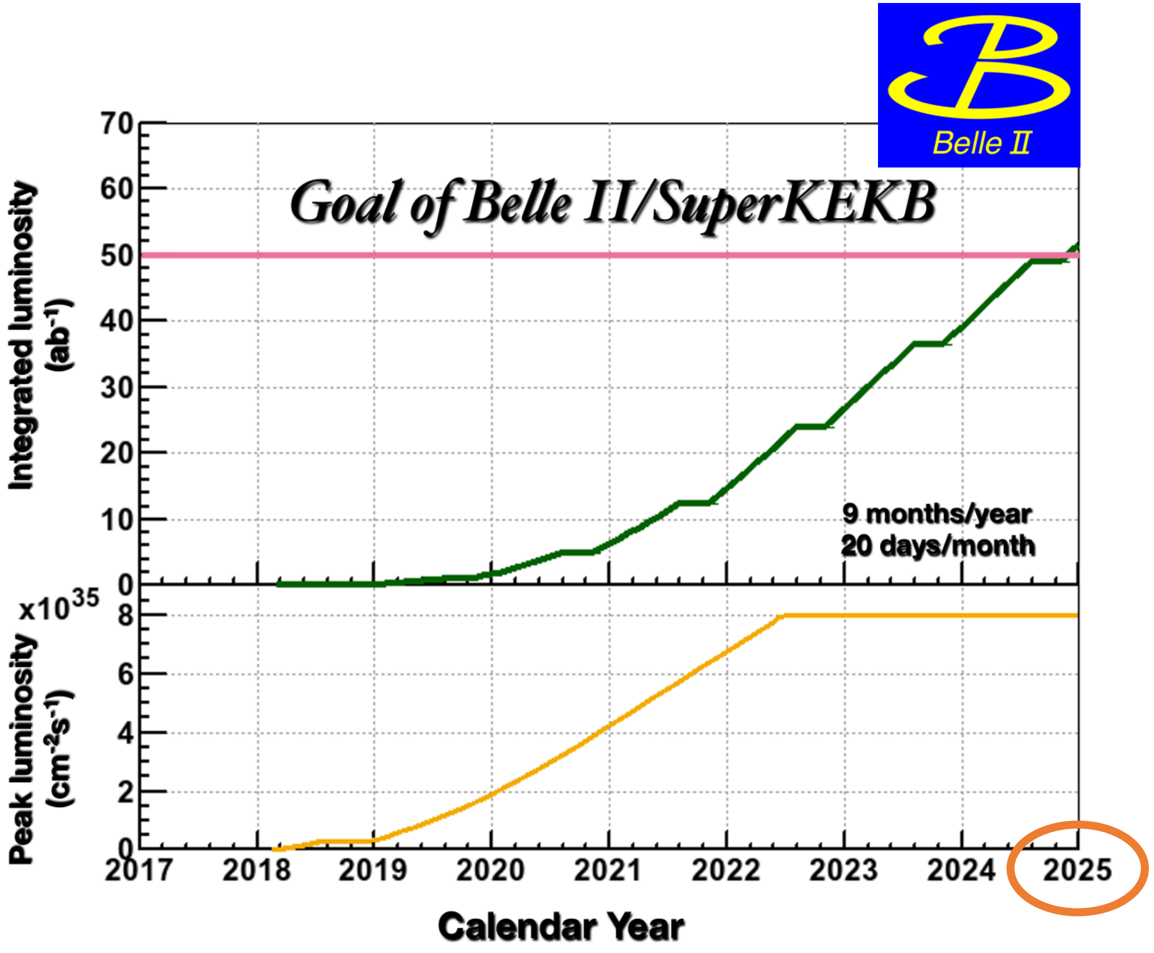
- Detector upgrade
- Trigger improvements
- Operation at higher luminosity (tens of pp interactions per event)

- Increased hermeticity and K_S^0 efficiency
- Improved IP and D vertex resolution, K/π separation and π^0 reconstruction
- Added PID and μ ID in end caps

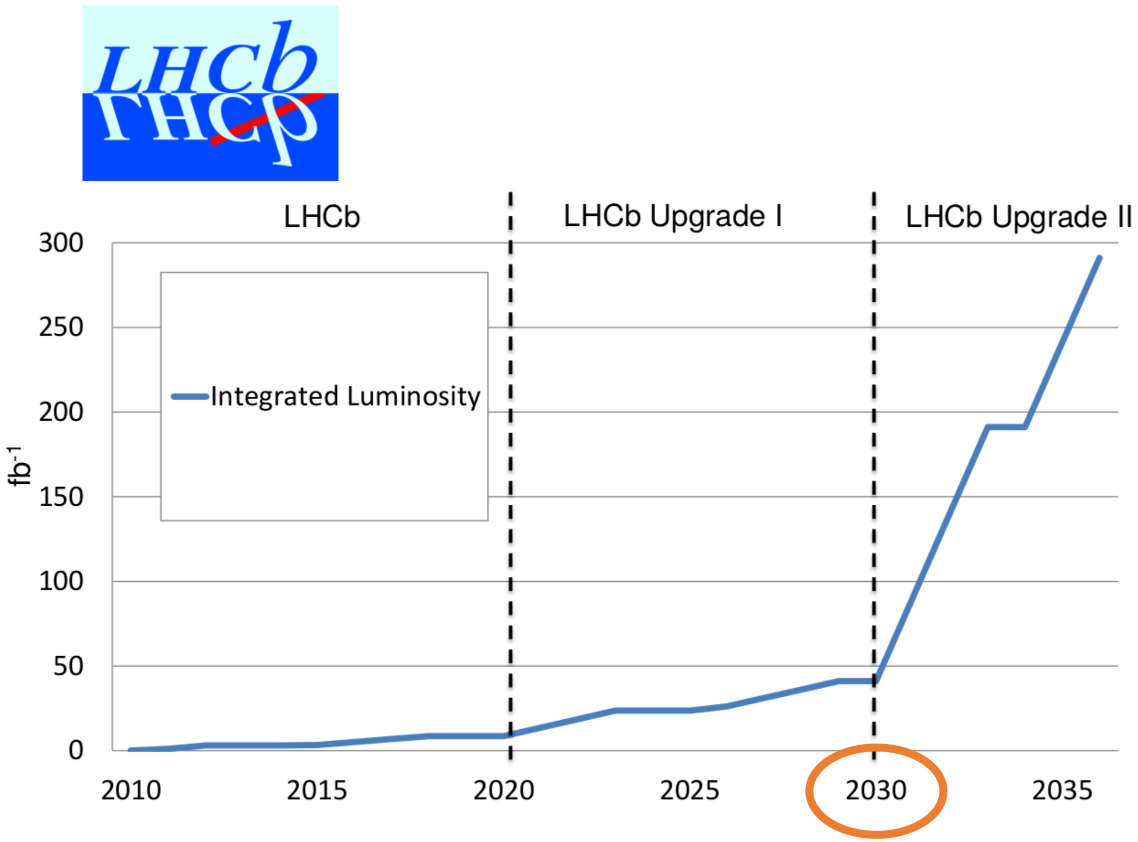
w.r.t. Belle

- HIEPA
- BINP Super c-τ factory

Timescale



Belle II
Goal of Belle II/SuperKEKB
Integrated luminosity (ab^{-1})
70
60
50
40
30
20
10
0
9 months/year
20 days/month
Peak luminosity (cm^{-2}s^{-1})
x10^{35}
8
6
4
2
0
2017
2018
2019
2020
2021
2022
2023
2024
2025
Calendar Year



LHCb
LHCb
LHCb Upgrade I
LHCb Upgrade II
fb^{-1}
300
250
200
150
100
50
0
Integrated Luminosity
2010
2015
2020
2025
2030
2035

Charm production

- $\sigma(pp \to D^0 X)$ @ 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

Parameter	**Belle+BaBar** (1.5 ab^{-1})	**Belle II** (50 ab^{-1})	**LHCb** (5 fb^{-1})	**LHCb** (50 fb^{-1})	**Super** c-τ (10 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 [3]	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 $\psi(3770) \to D^0\bar{D}^0 \to (K^-\pi^+)(K^+\pi^-)$ is shown for a Super c-τ factory

[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] Phys. Rev. Lett. 102, 221802 (2009)

Future precision

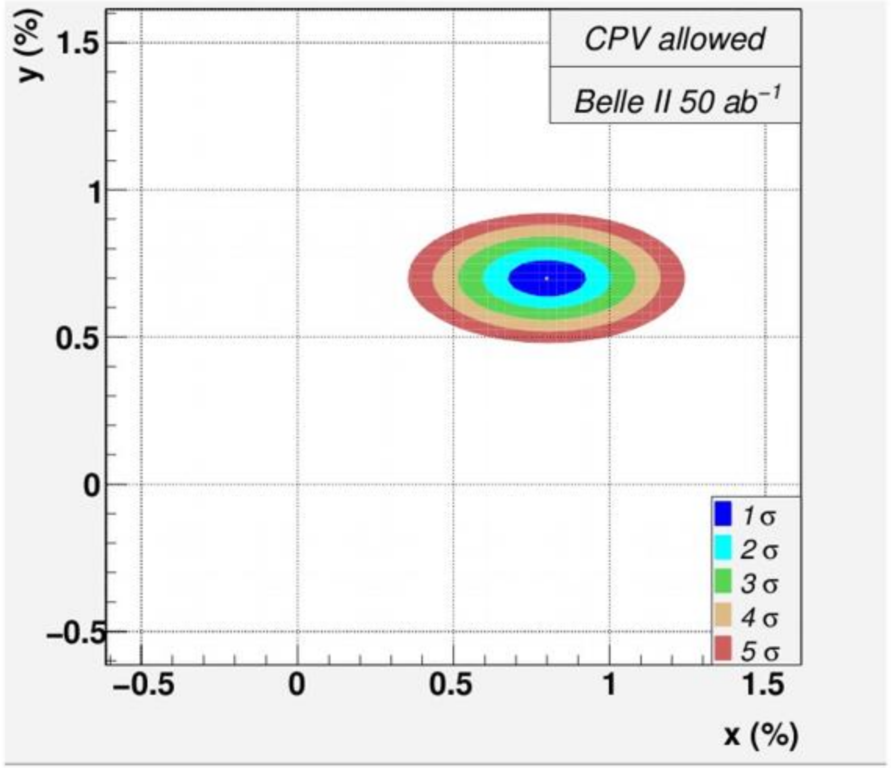
- An order of magnitude precision improvement can be achieved in the next decade
- The numbers shown are very approximate. Analysis of systematic uncertainties is needed

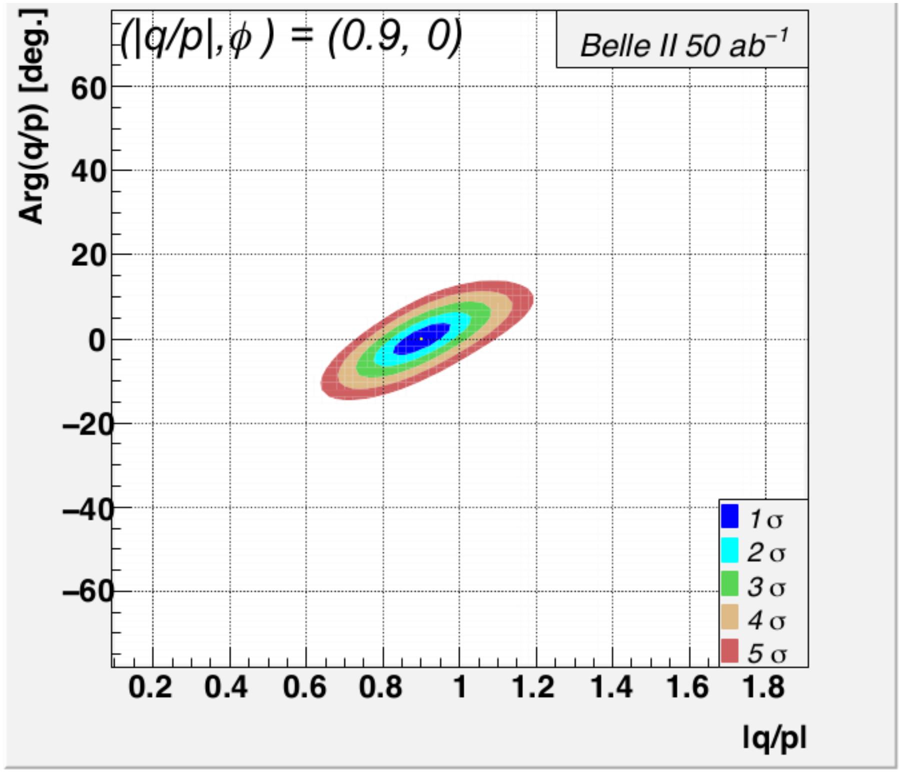
Parameter	Belle II [1] @ 50 ab^{-1}	LHCb [2] @ 50 fb^{-1}	Super c-τ @ 10 ab^{-1}
WS semileptonic			
R_M	$\mathcal{O}(5\times10^{-5})$	$\mathcal{O}(5\times10^{-7})$	?
$D\to K\pi$ WS decays			
$y, 10^{-4}$			5
$y', 10^{-4}$	4	2	
$\cos\delta_{K\pi}$			5×10^{-3}
$R_D, 10^{-5}$	10	0.2	1
$A_D, 10^{-4}$	3	?	?
$D\to h^+h^-$ ($\mathcal{CP}$ eigenstates)			
$y_{\mathcal{CP}}, 10^{-4}$	4	0.4	4
$A_\Gamma, 10^{-4}$	3	$\mathcal{O}(0.1)$	?
$D^0\to K_S^0\pi^+\pi^-$ Dalitz plot analysis			
$x, 10^{-4}$	8	1.7	$\mathcal{O}(1)$ [3]
$y, 10^{-4}$	5	1.9	$\mathcal{O}(1)$ [3]
$\lvert q/p\rvert$	0.06	0.04	$\mathcal{O}(0.01)$ [3]
$\arg(q/p)$	4°	3°	$\mathcal{O}(1°)$ [3]

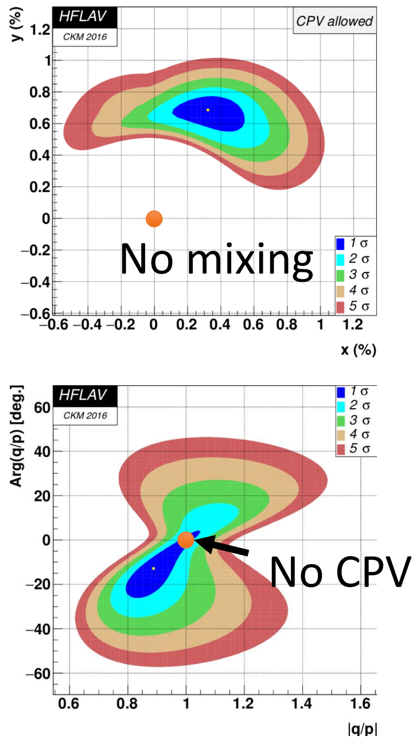
[1] "Physics at Super B Factory", arXiv:1002.5012 [hep-ex], talk by M. Staric @ KEK FF 2014
[2] "Implications of LHCb measurements and future prospects", Eur. Phys. J. C73, 2373 (2013)
[3] A. Bondar et al., Phys. Rev. D82, 034033 (2010)

Global fit for Belle II @ $50\ \mathrm{ab}^{-1}$

Alan Schwartz, IXth CKM UT Workshop (Dec. 1, 2016)





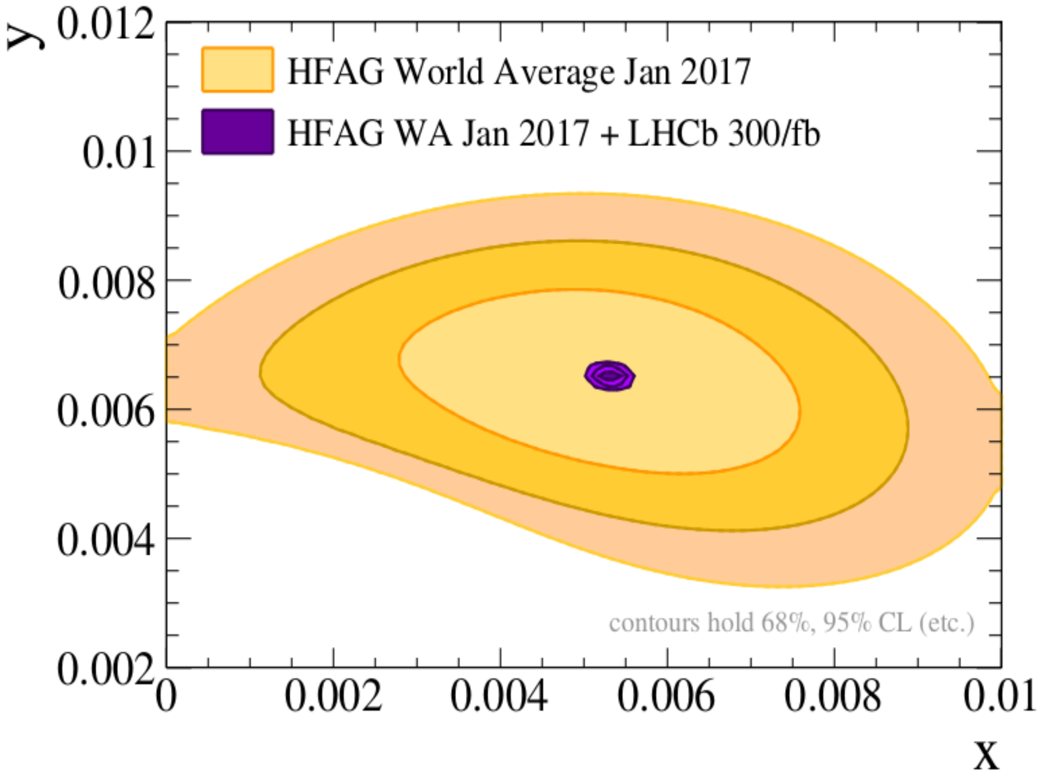


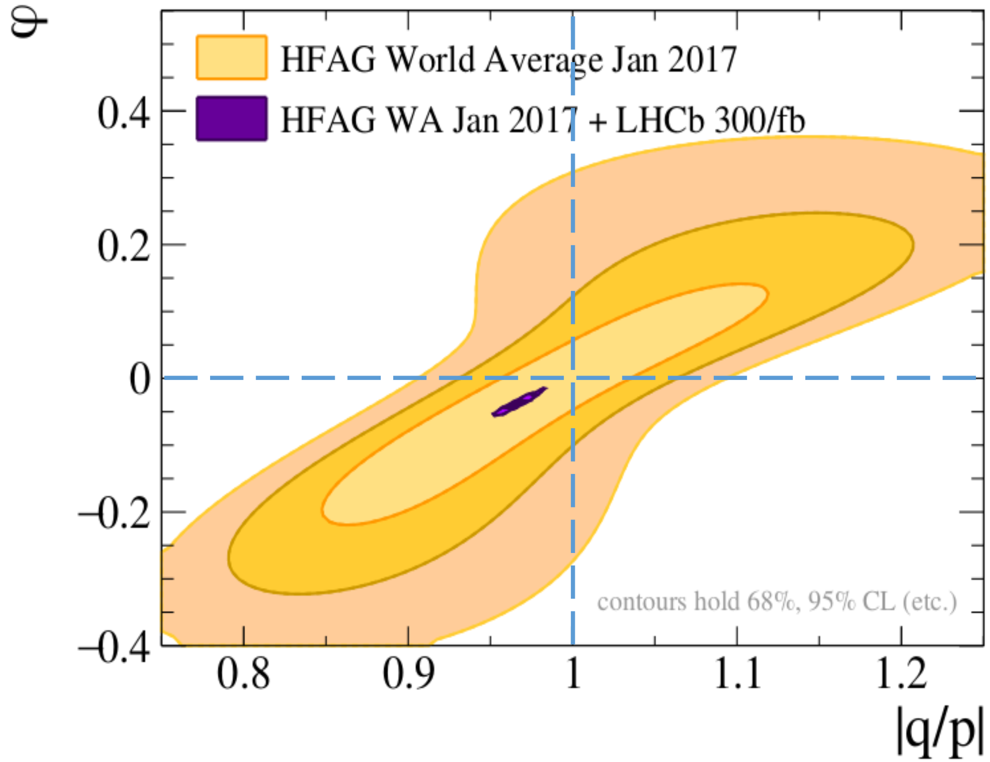
Current fit

Year 2025

Global fit for LHCb Upgr. Phase II @ $300\ \mathrm{fb}^{-1}$

CERN-LHCC-2017-003 (Feb. 8, 2017)





Year 2035+

Conclusions

1. Precise measurement of the charm mixing is a fundamental test of the SM
2. The existing measurements are consistent with the SM expectations
3. LHCb and Belle II are going to
   - measure the charm mixing parameters at the precision level of $\mathcal{O}(10^{-4})$
   - access $\mathcal{CP}$ violation in charm at the SM values ($A_\Gamma \sim 10^{-5}$)
4. A Super c-τ factory with $\mathcal{L} = 10^{35}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ is competitive for the charm mixing measurement
5. Measurements with quantum correlations will play an important role for the future charm mixing measurements