BEACH 2022

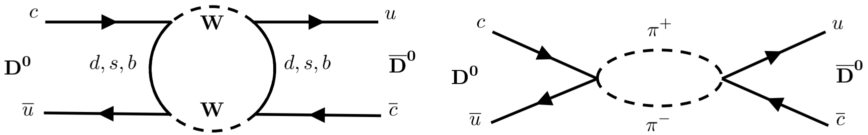
Mixing and indirect *CP* violation in charm mesons at LHCb

Edward Shields
on behalf of the LHCb collaboration
Univeristá di Milano-Bicocca & INFN
edward.brendan.shields@cern.ch

June 6, 2022

Outline

- Setting the stage
- y_{CP} in $D^0 \to h^+h^-$
  (Phys. Rev. D 105, 092013)
- Mixing and CPV parameters in $D^0 \to K^0_S\pi^+\pi^-$ with 'bin-flip'
  (Phys. Rev. Lett. 127, 111801)
- ΔY in $D^0 \to h^+h^-$
  (Phys. Rev. D 104, 072010)
- Summary



The mass eigenstates of neutral D mesons are superpositions of the flavour eigenstates,

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

Oscillations characterised by four parameters:

$$\left.\begin{aligned} x &= (m_1 - m_2)/\Gamma \\ y &= (\Gamma_1 - \Gamma_2)/2\Gamma \end{aligned}\right\}\text{Mixing}$$

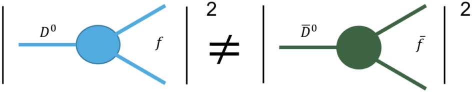
$$\left.\begin{aligned} &|q/p| \\ \phi &= \arg(q/p) \end{aligned}\right\}CP\text{ violation}$$

- Unique access to up-type quarks
- New-Physics sensitive (CPV very small $\mathcal{O}\left(10^{-3}\right)$) in SM

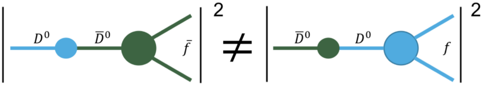
Types of CPV in Charm

Direct CPV (See Arturs talk)

- $|\bar{A}_f/A_f| \neq 1$



Indirect CPV (Focus of this talk!)

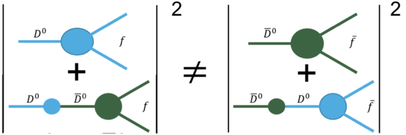


CPV in mixing

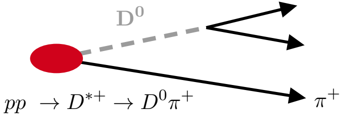
- $|q/p| \neq 1$

CPV in interference between mixing and decay

- $\phi \equiv \arg\left(\frac{q\bar{A}_f}{pA_f}\right) \neq 0$

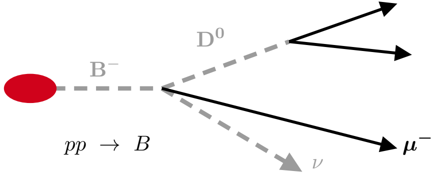


π-tagged ("prompt charm")



- Lifetime-biasing trigger
- High signal yield & purity
- (All analyses presented today use 'prompt' tagged decays)

μ-tagged ("secondary charm")



- Lifetime unbiased trigger
- Higher backgrounds, lower yields
- Important background to prompt analyses!

What do we want to measure?

$$y_{CP}^{f} = \frac{\hat{\Gamma}\left(D^0 \to f\right) + \hat{\Gamma}\left(\bar{D}^0 \to f\right)}{2\Gamma} - 1$$

In the absence of CP violation, $y_{CP} = y$.

Important input for global fits of charm mixing and CPV parameters

Use average of $K\pi$ in denominator, introduces a small shift of $\approx 0.04\%$

$$\frac{\hat{\Gamma}\left(D^0 \to f\right) + \hat{\Gamma}\left(\bar{D}^0 \to f\right)}{\hat{\Gamma}\left(D^0 \to K^-\pi^+\right) + \hat{\Gamma}\left(\bar{D}^0 \to K^+\pi^-\right)} - 1 \approx y_{CP}^{f} - y_{CP}^{K\pi}$$

Measure separately for $f = K^+K^-, \pi^+\pi^-$ final states.

$$R^f(t) = \underbrace{\frac{N\left(D^0 \to f, t\right)}{N\left(D^0 \to K^-\pi^+, t\right)}}_{\text{Measure this ratio by fitting yields in bins of decay time}} \propto e^{-(\underbrace{y_{CP}^{f} - y_{CP}^{K\pi}}_{\text{What we want}})t/\tau_{D^0}} \underbrace{\frac{\varepsilon\left(f, t\right)}{\varepsilon\left(K^-\pi^+, t\right)}}_{\text{Ratio of time-dependent efficiencies}}$$

Account for backgrounds:

- Combinatorial
- Secondary charm ($b \to c$)
- Partially reconstructed decays and misID

Control by:

- Careful event selection criteria
- Kinematic equalization procedure
- Validate with MC and real data

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

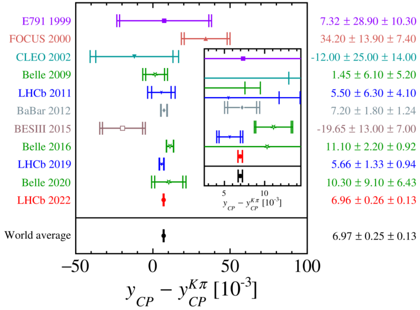
Phys. Rev. D 105, 092013

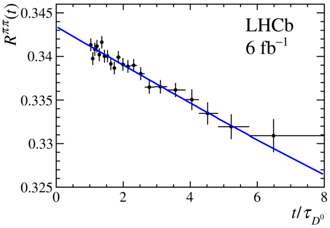
$$y_{CP}^{\pi\pi} - y_{CP}^{K\pi} = (6.57 \pm 0.53 \pm 0.16) \times 10^{-3}$$

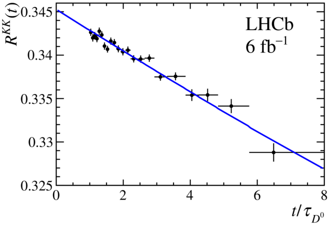
$$y_{CP}^{KK} - y_{CP}^{K\pi} = (7.08 \pm 0.30 \pm 0.14) \times 10^{-3}$$

Combining channels:

$$y_{CP} - y_{CP}^{K\pi} = (6.96 \pm 0.26 \pm 0.13) \times 10^{-3}$$

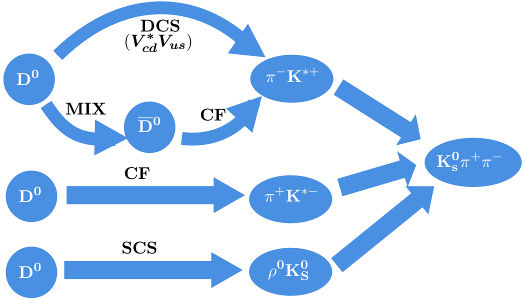


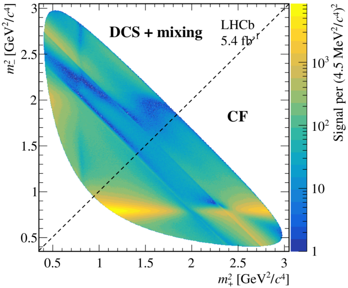




4x more precise than previous world-average

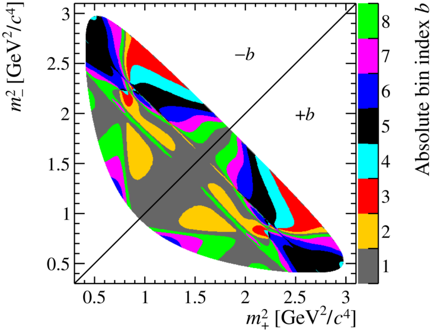
Many possible interfering amplitudes, including via $D^0 - \bar{D}^0$ oscillation.





$(m_\pm^2 = m^2 \left(K_S^0 \pi^\pm\right))$

Can directly measure all four mixing and CPV parameters, $x, y, |q/p|, \&\ \arg(q/p)$.

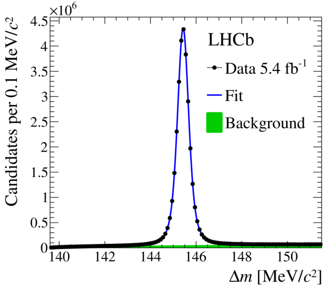


The data is partitioned into disjoint regions (bins) of the Dalitz plot, which are defined to preserve nearly constant strong-phase differences $(\Delta\delta\left(m_-^2, m_+^2\right))^a$. Two sets of eight bins are formed symmetrically about the $m_+^2 = m_-^2$ bisector.

[a] Phys. Rev. D 82, 112006

The data is further split into 13 bins of decay time, chosen such that they are approximately equally populated. For each decay-time interval the ratio of the number of decays in each bin above the bisector to below the bisector is measured.[1]

[1] Formalism in the backup



$\sim$ **31M** signal candidates coming from $D^{*+} \to D^0 \pi^+$ decays.
Fit the Δm $(m_{D^{*+}} - m_{D^0})$ distributions in bins of the Dalitz-plot and decay time to get the ratio of number of decays.

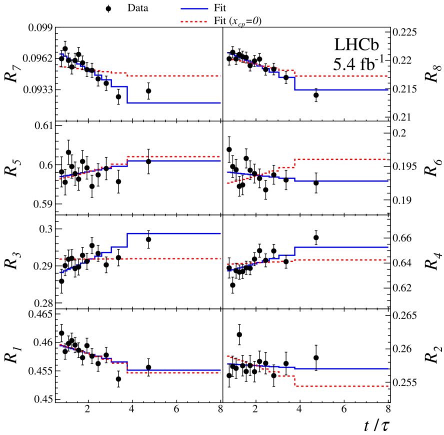
Correct for experimental effects:

1. Correlations between time and phasespace
2. Charge detection asymmetries

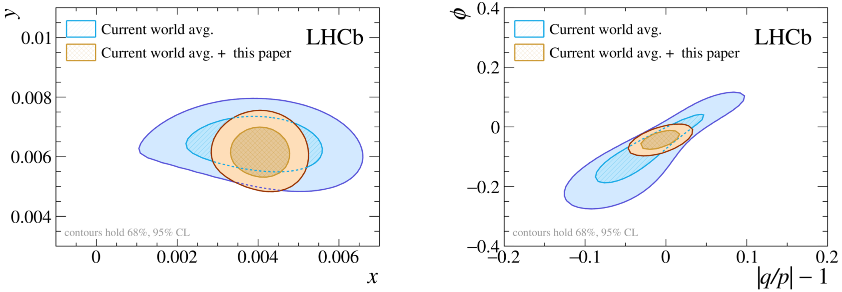
Source	x_{CP}	y_{CP}	Δx	Δy
Reconstruction and selection	0.199	0.757	0.009	0.044
Secondary charm decays	0.208	0.154	0.001	0.002
Detection asymmetry	0.000	0.001	0.004	0.102
Mass-fit model	0.045	0.361	0.003	0.009
Total systematic uncertainty	0.291	0.852	0.010	0.110
Strong phase inputs	0.23	0.66	0.02	0.04
Detection asymmetry inputs	0.00	0.00	0.04	0.08
Statistical (w/o inputs)	0.40	1.00	0.18	0.35
Total statistical uncertainty	0.46	1.20	0.18	0.36

$$x_{CP} = (3.97 \pm 0.46 \pm 0.29) \times 10^{-3}$$
$$y_{CP} = (4.59 \pm 1.20 \pm 0.85) \times 10^{-3}$$
$$\Delta x = (-0.27 \pm 0.18 \pm 0.01) \times 10^{-3}$$
$$\Delta y = (0.20 \pm 0.36 \pm 0.13) \times 10^{-3}$$

$$x = \left(3.98^{+0.56}_{-0.54}\right) \times 10^{-3}$$
$$y = \left(4.6^{+1.5}_{-1.4}\right) \times 10^{-3}$$
$$|q/p| = 0.996 \pm 0.052$$
$$\phi = 0.056^{+0.047}_{-0.051}$$



Significant improvements in World Average for both mixing and CPV parameters



First observation of non-zero mass-difference between neutral charm-meson eigenstates ($x \neq 0$)

Cabibbo-suppressed $D^0 \to f$ decays, where the final state $f = K^+K^-, \pi^+\pi^-$ is common to D^0 and $\bar{D}^0$ mesons, provide one of the most sensitive tests of the time-dependent CP violation.

$$A_{CP}(f,t) \equiv \frac{\Gamma\left(D^0 \to f,t\right) - \Gamma\left(\bar{D}^0 \to f,t\right)}{\Gamma\left(D^0 \to f,t\right) + \Gamma\left(\bar{D}^0 \to f,t\right)}$$

As mixing is expected to be small ($< 1\%$) this can be expanded as,

$$A_{CP}(f,t) \approx a_f^d + \Delta Y_f \frac{t}{\tau_{D^0}},$$

where[2]

$$\Delta Y_f \approx -x_{12} \sin\phi_f^M + y_{12} a_f^d$$

[2] $\Delta Y_f \approx -A_\Gamma^f$

The measured raw asymmetry between the number of D^0 and $\bar{D}^0$ decays into the final state f and time t,

$$A_{\text{raw}}(f,t) \equiv \frac{N\left(D^{*+} \to D^0(f,t)\,\pi^+_{\text{tag}}\right) - N\left(D^{*-} \to \bar{D}^0(f,t)\,\pi^-_{\text{tag}}\right)}{N\left(D^{*+} \to D^0(f,t)\,\pi^+_{\text{tag}}\right) + N\left(D^{*-} \to \bar{D}^0(f,t)\,\pi^-_{\text{tag}}\right)},$$

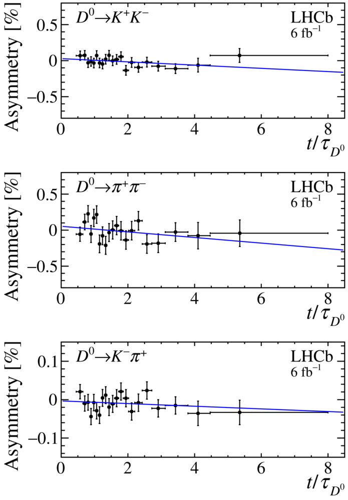
is equal to

$$A_{\text{raw}}(f,t) \approx A_{CP}(f,t) + A_{\text{det}}\left(\pi^+_{\text{tag}}\right) + A_{\text{prod}}\left(D^{*+}\right)$$

- $A_{\text{det}}\left(\pi^+_{\text{tag}}\right)$ is the detection asymmetry due to different reconstruction efficiencies of positively and negatively charged tagging pions.
- $A_{\text{prod}}\left(D^{*+}\right)$ is the production asymmetry of $D^{*\pm}$ mesons in pp collisions.

ΔY in $D^0 \to h^+h^-$

Phys. Rev. D 104, 072010



$$\Delta Y_{K^+K^-} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4}$$

$$\Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4}$$

$$\Delta Y = (-2.7 \pm 1.3 \pm 0.3) \times 10^{-4}$$

$\Delta Y_{K^-\pi^+}$ consistent with 0

Combined with previous LHCb results, gives,

$$\Delta Y_{K^+K^-} = (-0.3 \pm 1.3 \pm 0.3) \times 10^{-4}$$

$$\Delta Y_{\pi^+\pi^-} = (-3.6 \pm 2.4 \pm 0.4) \times 10^{-4}$$

$$\Delta Y = (-1.0 \pm 1.1 \pm 0.3) \times 10^{-4}$$

A factor of 2 improvement on previous world average!

No CPV observed, constrained at the 10^{-4} level

Summary

- Reaching incredible levels of precision, $\mathcal{O}\left(10^{-4}\right)$, of measurements of mixing and indirect CPV in charm.
- New channels and techniques are being exploited to get the most of the available data.
- Lot's of exciting new results to come with LHCb Run 3-4, Belle-II, BES-III, ...
- Expecting to be approaching $\mathcal{O}\left(10^{-5}\right)$ precision in Run 3 and beyond (A_Γ)!

BACKUP

Mixing in Charm

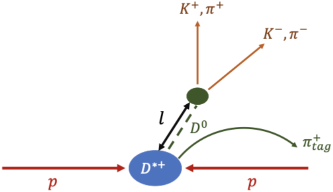
The mass eigenstates of neutral D mesons are not flavour eigenstates. But they can be written in terms of the flavour eigenstates:

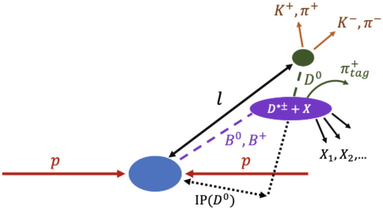
$$|D_{1,2}\rangle = p\left|D^0\right\rangle \pm q\left|\bar{D}^0\right\rangle$$

The time evolution of the flavour eigenstates is then given by

$$\left|D^0(t)\right\rangle = g_+(t)\left|D^0\right\rangle + \frac{q}{p}g_-(t)\left|\bar{D}^0\right\rangle$$
$$\left|\bar{D}^0(t)\right\rangle = \frac{p}{q}g_-(t)\left|D^0\right\rangle + g_+(t)\left|\bar{D}^0\right\rangle$$

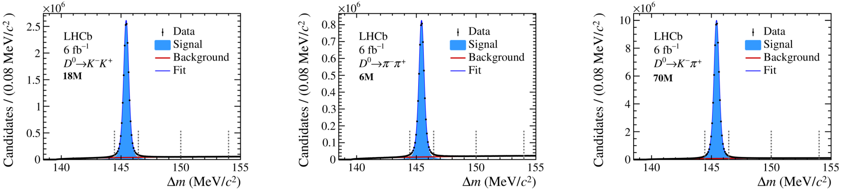
where $g_\pm(t) = e^{-iMt}e^{i\Gamma t/2}\left[{}^{\cos}_{\sin}(-i(x+iy)\Gamma t/2)\right]$.





Decay-time is calculated as,

$$t = \frac{lm}{p}$$

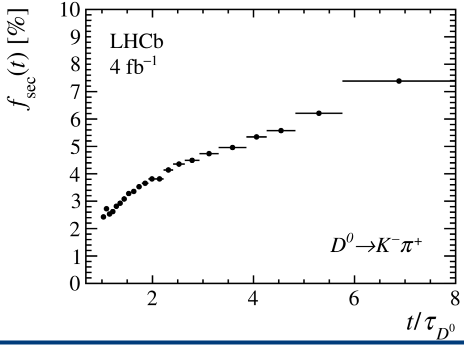

LHCb
6 fb^{-1}
$D^0 \to K^-K^+$
18M
Data
Signal
Background
Fit
Candidates / (0.08 MeV/c^2)
Δm (MeV/c^2)
LHCb
6 fb^{-1}
$D^0 \to \pi^-\pi^+$
6M
Data
Signal
Background
Fit
Candidates / (0.08 MeV/c^2)
Δm (MeV/c^2)
LHCb
6 fb^{-1}
$D^0 \to K^-\pi^+$
70M
Data
Signal
Background
Fit
Candidates / (0.08 MeV/c^2)
Δm (MeV/c^2)

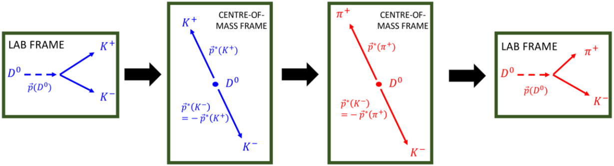
Correct for secondary contamination:

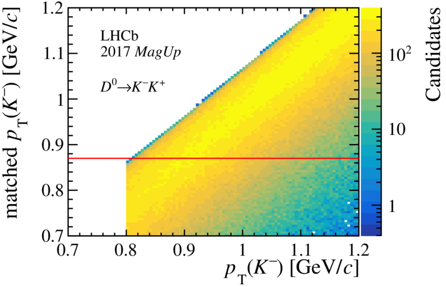
$$R^f(t) = (1 - f_{\text{sec}}(t))\, R^f_{\text{prompt}}(t) + f_{\text{sec}}(t)\, R^f_{\text{sec}}(t)\,,$$

where,

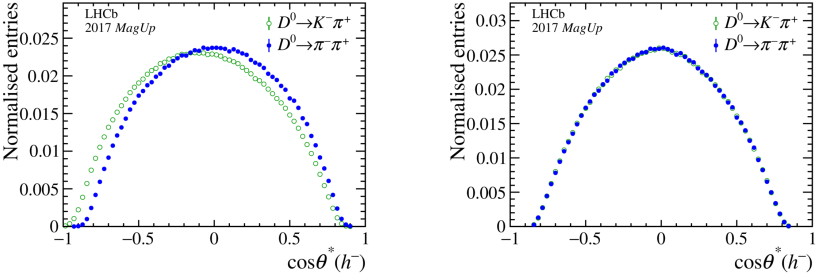
$$R^f_{\text{sec}}(t) \propto e^{-\left(y^f_{CP} - y^{K\pi}_{CP}\right)\langle t_{D^0}(t)\rangle/\tau_{D^0}}$$




LAB FRAME
K^+
D^0
$\vec{p}(D^0)$
K^-
CENTRE-OF-MASS FRAME
K^+
$\vec{p}^*(K^+)$
D^0
$\vec{p}^*(K^-) = -\vec{p}^*(K^+)$
K^-
CENTRE-OF-MASS FRAME
π^+
$\vec{p}^*(\pi^+)$
D^0
$\vec{p}^*(K^-) = -\vec{p}^*(\pi^+)$
K^-
LAB FRAME
π^+
D^0
$\vec{p}(D^0)$
K^-


LHCb
2017 MagUp
$D^0 \to K^-K^+$
matched $p_T(K^-)$ [GeV/c]
$p_T(K^-)$ [GeV/c]
Candidates
0.7
0.8
0.9
1
1.1
1.2
10^2
10
1

Example kinematic matching and reweighting results



'Bin-flip' technique

Mixing and CP violation are parametrized by z_{CP} and Δz, which is defined as,

$$z_{CP} \pm \Delta z \equiv -\left(q/p\right)^{\pm 1}\left(y + ix\right).$$

These results are expressed in terms of the CP-even mixing parameters,

$$x_{CP} \equiv -\mathrm{Im}\left(z_{CP}\right), \quad y_{CP} \equiv -\mathrm{Re}\left(z_{CP}\right),$$

and of the CP-violating differences,

$$\Delta x \equiv -\mathrm{Im}\left(\Delta z\right), \quad \Delta y \equiv -\mathrm{Re}\left(\Delta z\right)$$

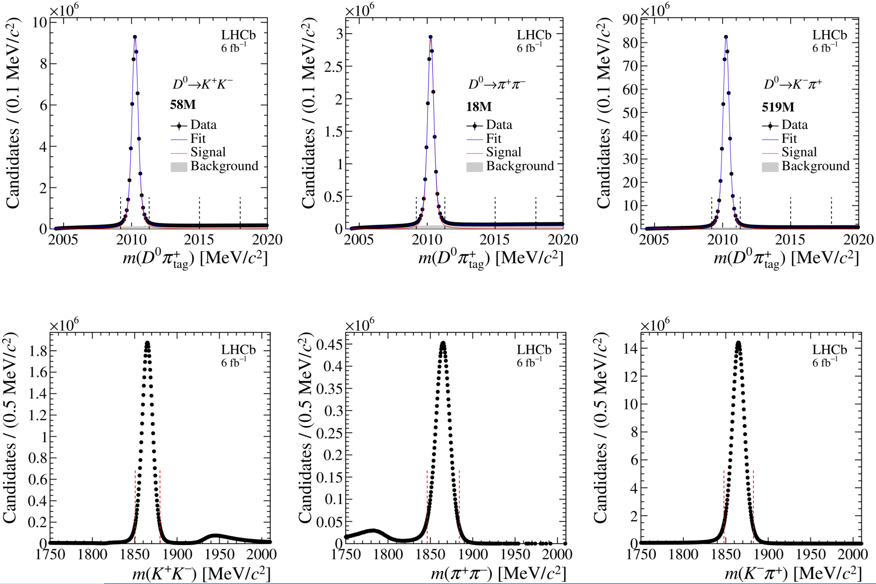
Conservation of CP symmetry implies that $x_{CP} = x$, $y_{CP} = y$, and $\Delta x = \Delta y = 0$.

Data are partitioned into disjoint regions (bins) of the Dalitz plot, which are defined to preserve nearly constant strong-phase differences, $\Delta\delta\left(m_-^2, m_+^2\right)$, between the D^0 and $\bar{D}^0$ amplitudes within each bin. Bins are labelled $-b$ above the symmetric bisector and $+b$ below. For each decay-time interval (j), the ratio of the number of decays in each negative Da;itz-plot bin $(-b)$ to its positive counterpart $(+b)$ is measured.

$$R_{bj}^{\pm} \approx \frac{r_b + r_b \frac{\langle t^2 \rangle_j}{4} \mathrm{Re}\left(z_{CP}^2 - \Delta z^2\right) + \frac{\langle t^2 \rangle_j}{4} \left|z_{CP} \pm \Delta z\right|^2 + \sqrt{r_b} \langle t \rangle_j \mathrm{Re}\left[X_b^* \left(z_{CP} \pm \Delta z\right)\right]}{1 + \frac{\langle t^2 \rangle_j}{4} \mathrm{Re}\left(z_{CP}^2 - \Delta z^2\right) + r_b \frac{\langle t^2 \rangle_j}{4} \left|z_{CP} \pm \Delta z\right|^2 + \sqrt{r_b} \langle t \rangle_j \mathrm{Re}\left[X_b^* \left(z_{CP} \pm \Delta z\right)\right]}$$

where r_b is the value of R_{bj} at $t = 0$. X_b is the amplitude-weighted strong-phase differences between opposing bins. External information on $c_b \equiv \mathrm{Re}\left(X_b\right)$ and $s_b \equiv -\mathrm{Im}\left(X_b\right)$, is used as a constraint.

ΔY in $D^0 \to h^+h^-$



ΔY definition

$$A_{CP}(f,t) \equiv \frac{\Gamma\left(D^0 \to f, t\right) - \Gamma\left(\bar{D}^0 \to f, t\right)}{\Gamma\left(D^0 \to f, t\right) + \Gamma\left(\bar{D}^0 \to f, t\right)}$$

As mixing is expected to be small ($< 1\%$) this can be expanded as,

$$A_{CP}(f,t) \approx a_f^d + \Delta Y_f \frac{t}{\tau_{D^0}}.$$

Where a_f^d is the CP asymmetry in the decay, τ_{D^0} is the lifetime of the D^0 meson, and the ΔY_f parameter is approximately equal to

$$\Delta Y_f \approx -x_{12} \sin\phi_f^M + y_{12} a_f^d$$

and $\phi_f^M \equiv \arg\left(M_{12} A_f / \bar{A}_f\right)$. At the current level of experimental precision, final-state dependent contributions to ΔY_f can safely be neglected. Under this assumption,

$$\Delta Y \approx -x_{12} \sin\phi_2^M,$$

where ϕ_2^M is the dispersive mixing phase common to all D^0 decays.

Mixing and CPV parameters in $D^0 \to K_S^0\pi^+\pi^-$

Sample (lumi $\mathcal{L}$)	Tag	Yield	$\sigma(x)$	$\sigma(y)$	$\sigma(\lvert q/p\rvert)$	$\sigma(\phi)$
Run 1–2 (9 fb^{-1})	SL	10M	0.07%	0.05%	0.07	4.6°
	Prompt	36M	0.05%	0.05%	0.04	1.8°
Run 1–3 (23 fb^{-1})	SL	33M	0.036%	0.030%	0.036	2.5°
	Prompt	200M	0.020%	0.020%	0.017	0.77°
Run 1–4 (50 fb^{-1})	SL	78M	0.024%	0.019%	0.024	1.7°
	Prompt	520M	0.012%	0.013%	0.011	0.48°
Run 1–5 (300 fb^{-1})	SL	490M	0.009%	0.008%	0.009	0.69°
	Prompt	3500M	0.005%	0.005%	0.004	0.18°

Future prospects

A_Γ in $D^0 \to h^+h^-$

Sample ($\mathcal{L}$)	Tag	Yield K^+K^-	$\sigma(A_\Gamma)$	Yield $\pi^+\pi^-$	$\sigma(A_\Gamma)$
Run 1–2 (9 fb^{-1})	Prompt	60M	0.013%	18M	0.024%
Run 1–3 (23 fb^{-1})	Prompt	310M	0.0056%	92M	0.0104 %
Run 1–4 (50 fb^{-1})	Prompt	793M	0.0035%	236M	0.0065 %
Run 1–5 (300 fb^{-1})	Prompt	5.3G	0.0014%	1.6G	0.0025 %