D^0 oscillation and CP Violation in charm decays and at LHCb

Angelo Carbone
INFN and University of Bologna
Outline

• Introduction
• $D^0$ oscillation and CP violation
• Impact of LHCb in the charm sector
  • CP violation in the decay
  • CP violation in $D^0$ mixing and in the interference between mixing and decay
  • New for today: Observation of the mass difference between neutral charm-meson eigenstates with the $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decay
• Impact of the new $D^0$ mixing results on the world averages
• Conclusions
CP violation
A $CP$ transformation has the effect of:

- changing the sign of the phase due to weak interactions ($\theta$)
- leaving unchanged the phase due to strong interactions ($\delta$)
CP violation

\[ A_1 = \rho_1 e^{i\delta_1} e^{i\theta_1} \]

\[ \bar{A}_1 = \rho_1 e^{i\delta_1} e^{-i\theta_1} \]

\[ A_2 = \rho_2 e^{i\delta_2} e^{i\theta_2} \]

\[ \bar{A}_2 = \rho_2 e^{i\delta_2} e^{-i\theta_2} \]

\[ |\bar{A}_1 + \bar{A}_2|^2 - |A_1 + A_2|^2 = 4\rho_1\rho_2 \sin(\theta_1 - \theta_2) \sin(\delta_1 - \delta_2) \]
To observe CP violation in the decay it is necessary to have two distinct paths with amplitudes of different phases.

$$|\tilde{A}_1 + \tilde{A}_2|^2 - |A_1 + A_2|^2 = 4\rho_1\rho_2 \sin(\theta_1 - \theta_2) \sin(\delta_1 - \delta_2)$$

It differs from zero if $\delta_1 \neq \delta_2$ and $\theta_1 \neq \theta_2$.
D⁰ oscillation
D⁰ oscillation and key dates

**B⁰**: ARGUS
*Observation of B⁰ oscillations*

**D⁰**: Belle & BaBar
*Evidence of D⁰ oscillations*


**K⁰**
*Behavior of neutral particles*
e.g. Phys.Rev. 97 (1955) 1387

**B⁰**
*Observation of B⁰ oscillations*

**D⁰**: LHCb
*Observation of D⁰ oscillations*

Angelo Carbone  CHARM 2020, 31 May – 4 June
$D^0$ mixing

The $D^0$ and $\bar{D}^0$ mesons are produced as flavor eigenstates. They propagate and decay according to

$$i \frac{\partial}{\partial t} \left( \frac{D^0(t)}{\bar{D}^0(t)} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \frac{D^0(t)}{\bar{D}^0(t)} \right)$$
$D^0$ **mixing**

The $D^0$ and $\bar{D}^0$ mesons are produced as flavor eigenstates. They propagate and decay according to

$$i \frac{\partial}{\partial t} \left( \begin{array}{c} D^0(t) \\ \bar{D}^0(t) \end{array} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \begin{array}{c} D^0(t) \\ \bar{D}^0(t) \end{array} \right)$$

Mixing occurs because $D^0$ and $\bar{D}^0$ are linear combinations of mass eigenstates:

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$$
$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$$
$D^0$ mixing

The $D^0$ and $\bar{D}^0$ mesons are produced as flavor eigenstates. They propagate and decay according to

$$i \frac{\partial}{\partial t} \left( \begin{array}{c} D^0(t) \\ \bar{D}^0(t) \end{array} \right) = \left( M - \frac{i}{2} \Gamma \right) \left( \begin{array}{c} D^0(t) \\ \bar{D}^0(t) \end{array} \right)$$

Mixing occurs because $D^0$ and $\bar{D}^0$ are linear combinations of mass eigenstates

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$$
$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$$

The mass eigenstates develop in time as follow

$$|D_{1,2}(t)\rangle = e_{1,2}(t)|D_{1,2}(0)\rangle$$
$$e_{1,2}(t) \equiv \exp \left[ -i \left( M_{1,2} - \frac{i}{2} \Gamma_{1,2} \right) t \right]$$
**$D^0$ mixing**

The $D^0$ and $\bar{D}^0$ mesons are produced as flavor eigenstates. They propagate and decay according to:

$$i \frac{\partial}{\partial t} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \begin{pmatrix} M - \frac{i}{2} \Gamma \end{pmatrix} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

Mixing occurs because $D^0$ and $\bar{D}^0$ are linear combinations of mass eigenstates:

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$$
$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$$

The mass eigenstates develop in time as follow:

$$|D_{1,2}(t)\rangle = e_{1,2}(t)|D_{1,2}(0)\rangle$$
$$e_{1,2}(t) = \exp \left[-i \left(M_{1,2} - \frac{i}{2} \Gamma_{1,2} \right)t \right]$$

Two parameters characterize the $D^0$ and $\bar{D}^0$ mixing:

$$\Delta M_D = m_2 - m_1 \quad \Delta \Gamma_D = \Gamma_2 - \Gamma_1$$

$$x = \frac{\Delta M_D}{\Gamma_D}, \quad y = \frac{\Delta \Gamma_D}{2\Gamma_D}$$
$D^0$ mixing

The $D^0$ and $\bar{D}^0$ mesons are produced as flavor eigenstates. They propagate and decay according to

$$i \frac{\partial}{\partial t} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix} = \begin{pmatrix} M - i/2 \Gamma & 0 \\ 0 & M + i/2 \Gamma \end{pmatrix} \begin{pmatrix} D^0(t) \\ \bar{D}^0(t) \end{pmatrix}$$

Mixing occurs because $D^0$ and $\bar{D}^0$ are linear combinations of mass eigenstates

$$|D_1\rangle = p|D^0\rangle + q|\bar{D}^0\rangle$$
$$|D_2\rangle = p|D^0\rangle - q|\bar{D}^0\rangle$$

Two parameters characterize the $D^0$ and $\bar{D}^0$ mixing

$$\Delta M_D = m_2 - m_1 \quad \Delta \Gamma_D = \Gamma_2 - \Gamma_1$$
$$x = \frac{\Delta M_D}{\Gamma_D} \quad y = \frac{\Delta \Gamma_D}{2\Gamma_D}$$

The mass eigenstates develop in time as follow

$$|D_{1,2}(t)\rangle = e_{1,2}(t)|D_{1,2}(0)\rangle$$
$$e_{1,2}(t) = \exp \left[ -i \left( M_{1,2} - \frac{i}{2}\Gamma_{1,2} \right) t \right]$$

If either $x$ or $y$ are different from zero, mixing occurs

$$|\langle \bar{D}^0|D^0(t)\rangle|^2 = \frac{1}{2} \left| \frac{q}{p} \right|^2 e^{-\Gamma t} \left[ \cosh(y\Gamma t) - \cos(x\Gamma t) \right]$$
$$|\langle D^0|\bar{D}^0(t)\rangle|^2 = \frac{1}{2} \left| \frac{p}{q} \right|^2 e^{-\Gamma t} \left[ \cosh(y\Gamma t) - \cos(x\Gamma t) \right]$$
CP violation in $D^0$ mixing

If $|q/p| \neq 1$

CP violation occurs in $D^0$ mixing

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

CP violation occurs in the interference between decay and $D^0$ mixing

(*) definition $\phi$ is for common $D^0, \bar{D}^0$ final state where the final state dependent correction is neglected at the current level of experimental precision.
Search for CP violation
The direct CPV

CPV in decay occurs when the absolute value of the decay rate $M \to f$ differs from the decay rate involving the CP-conjugate states

$$|A(M^0 \to f)| \neq |A(\bar{M}^0 \to \bar{f})|$$

CP violation in the decay can be observed if the asymmetry

$$A_{CP}^{dir} (D^0 \to f) = \frac{|A_f|^2 - |A_{\bar{f}}|^2}{|A_f|^2 + |A_{\bar{f}}|^2}$$

is different from zero

In the Standard Model direct CP violation is naively estimated to be

$$A_{CP}^{dir} (D^0 \to hh) \sim 10^{-3} - 10^{-4}$$

Non-perturbative QCD as well as New Physics effects can contribute to enhance CPV but we already know that these effects can not be large
First observation of CP violation in charm decays [2019]

\[ \Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4} \]

5.3 standard deviations from zero
Recent LHCb results on direct CP violation

**LHCb-PAPER-2020-047**
PRD Lett.

**LHCb-PAPER-2021-001**
JHEP

CPV in $D^0 \to K_S^0 K_S^0$ decay

$A_{CP}(D^0 \to K_S^0 K_S^0) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$

compatible with no CP asymmetry at the level of 2.4 standard deviations.

CPV in $D_{(s)}^+ \to h^+ \pi^0$ $D_{(s)}^+ \to h^+ \eta$ decay

$A_{CP}(D^+ \to \pi^+ \pi^0) = (-1.3 \pm 0.9 \pm 0.6)\%$,
$A_{CP}(D^+ \to K^+ \pi^0) = (-3.2 \pm 4.7 \pm 2.1)\%$,
$A_{CP}(D^+ \to \pi^+ \eta) = (-0.2 \pm 0.8 \pm 0.4)\%$,
$A_{CP}(D^+ \to K^+ \eta) = (-6.0 \pm 10.0 \pm 4.0)\%$,
$A_{CP}(D_s^+ \to K^+ \pi^0) = (-0.8 \pm 3.9 \pm 1.2)\%$,
$A_{CP}(D_s^+ \to \pi^+ \eta) = (0.8 \pm 0.7 \pm 0.5)\%$,
$A_{CP}(D_s^+ \to K^+ \eta) = (0.9 \pm 3.7 \pm 1.1)\%$,
## Current experimental status on SCS

<table>
<thead>
<tr>
<th>Observable</th>
<th>Current precision ( \times 10^4 )</th>
<th>Experiments (ordered by precision)</th>
<th>Perspectives</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta A^{\text{dir}}<em>{CP} = A</em>{CP}(KK) - A_{CP}(\pi\pi) )</td>
<td>(-15.4 \pm 2.9)</td>
<td>LHCb, CDF, BaBar, Belle</td>
<td>Run1+Run2</td>
</tr>
<tr>
<td>( A_{CP}(D^0 \rightarrow K^-K^+) )</td>
<td>(-9 \pm 11)</td>
<td>LHCb, CDF, Cleo, Focus, BaBar, Belle</td>
<td>update expected soon full Run1+Run2</td>
</tr>
<tr>
<td>( A_{CP}(D^0 \rightarrow \pi^-\pi^+) )</td>
<td>(-1 \pm 14)</td>
<td>LHCb, CDF, Cleo, Focus, BaBar, Belle</td>
<td>update expected soon Run1+Run2</td>
</tr>
<tr>
<td>( A_{CP}(D^0 \rightarrow \pi^0\pi^0) )</td>
<td>(-3 \pm 64)</td>
<td>Cleo, Belle</td>
<td></td>
</tr>
<tr>
<td>( A_{CP}(D^0 \rightarrow K_S^0K_S^0) )</td>
<td>(-150 \pm 110)</td>
<td>LHCb, Belle, Cleo</td>
<td>recently updated Run2</td>
</tr>
<tr>
<td>( A_{CP}(D^+ \rightarrow \pi^+\pi^0) )</td>
<td>(40 \pm 80)</td>
<td>LHCb, Belle, Cleo</td>
<td>recently updated Run2</td>
</tr>
<tr>
<td>( A_{CP}(D^+ \rightarrow K_S^0K^+) )</td>
<td>(1 \pm 7)</td>
<td>LHCb, Belle, BaBar</td>
<td>missing 30% of data Run2</td>
</tr>
<tr>
<td>( A_{CP}(D^+ \rightarrow \phi\pi^+) )</td>
<td>(0.1 \pm 5)</td>
<td>LHCb, Belle, BaBar</td>
<td>missing 30% of data Run2</td>
</tr>
<tr>
<td>( A_{CP}(D_S^+ \rightarrow K_S^0\pi^+) )</td>
<td>(16 \pm 18)</td>
<td>LHCb, BaBar</td>
<td>missing 30% of data Run2</td>
</tr>
<tr>
<td>( A_{CP}(D_S^+ \rightarrow K^+\pi^0) )</td>
<td>(200 \pm 300)</td>
<td>LHCb, Belle, Cleo</td>
<td>recently updated</td>
</tr>
</tbody>
</table>
CP violation in oscillation and in the interference between $D^0$ decay and oscillation
Singly-Cabibbo-suppressed decays

- Search for time-dependent CP violation in $D^0 \rightarrow K^- K^+$ and $D^0 \rightarrow \pi^- \pi^+$ decays

\[ A_{CP}(f, t) \equiv \frac{\Gamma(D^0 \rightarrow f, t) - \Gamma(\bar{D}^0 \rightarrow f, t)}{\Gamma(D^0 \rightarrow f, t) + \Gamma(\bar{D}^0 \rightarrow f, t)} \approx a^d_f + \frac{\Delta Y_f}{\tau_{D^0}} \]

\[ \Delta Y_f \approx -x_{12} \sin \phi_2^M \]

\[ \phi_2^M \sim \arg(M_{12}) \]

$O(10^{-5} - 10^{-4})$ in the SM

current experimental precision: $2 \times 10^{-4}$

For details see Guillaume’s talk @ CHARM2020

\[ \Delta Y_{K^-K^+} = (-2.3 \pm 1.5 \pm 0.3) \times 10^{-4} \]
\[ \Delta Y_{\pi^+\pi^-} = (-4.0 \pm 2.8 \pm 0.4) \times 10^{-4} \]

Neglecting final-state dependent contributions

\[ \Delta Y = (-2.7 \pm 1.3 \pm 0.3) \times 10^{-4} \]
Observation of a nonzero mass difference between neutral charm-meson eigenstates

Run 2 [5.4 fb$^{-1}$]

LHCb-PAPER-2021-009
[soon on arXiv]
Measurement of $D^0$ Mixing Parameters

- $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ has a rich resonance structure
- The analysis is performed by means of a quasi-model independent approach (bin-flip method)
  - avoids accurate modelling of the efficiency
- $D^0 \rightarrow K_S^0 \pi^+ \pi^-$ decay receive contribution from Cabibbo-favoured and doubly-Cabibbo-suppressed decay amplitudes only
  - With good approximation CP symmetry is conserved in the decay
  - Direct access to the mixing phase independent of the final state ($\phi_2$ for detail see Kagan & Silvestrini 2020)
Analysis Strategy

• Production flavour of $D^0$ and $\bar{D}^0$ identified by the reconstruction of $D^{*+} \rightarrow D^0 \pi^+$ (apex $\rightarrow$ “±”)

• 8 bins over the Dalitz plane chosen to have almost constant strong-phase differences (subscript $\rightarrow$ “b”)

• Dalitz plane divided into two regions
  • $m_+ > m_-$ large contribution from CF decays $b = +1, \ldots, +8$
  • $m_+ < m_-$ large contribution from DCS decays $b = -1, \ldots, -8$

• Data further divided into 13 bins of decay-time (subscript $\rightarrow$ “j”)

• A total of 416 disjoint data samples

\[ m_\pm^2 \equiv \begin{cases} 
  m^2(K_s^0 \pi^\pm) & \text{for } D^0 \rightarrow K_s^0 \pi^+ \pi^- \\
  m^2(K_s^0 \pi^-) & \text{for } \bar{D}^0 \rightarrow K_s^0 \pi^+ \pi^- 
\end{cases} \]
The Formalism

For each decay-time interval \((j)\), the ratio of the number of decays in each negative Dalitz-plane bin \((-b)\) to its positive counterpart \((+b)\) is measured

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

\(r_b\) \(\rightarrow\) value of the ratio for \(t = 0\)

\(< t > (< t^2 >) \rightarrow\) average (squared) decay time

\(z = (-y + ix)\) with \(z_{CP} \pm \Delta z \equiv \left(\frac{q}{p}\right)^{\pm 1} z\)


\[
\begin{align*}
x_{CP} &= -\text{Im} \left( z_{CP} \right) = \frac{1}{2} \left[ x \cos \phi \left( \frac{q}{p} + \frac{p}{q} \right) + y \sin \phi \left( \frac{q}{p} - \frac{p}{q} \right) \right] \\
\Delta x &= -\text{Im} \left( \Delta z \right) = \frac{1}{2} \left[ x \cos \phi \left( \frac{q}{p} - \frac{p}{q} \right) + y \sin \phi \left( \frac{q}{p} + \frac{p}{q} \right) \right] \\
y_{CP} &= -\text{Re} \left( z_{CP} \right) = \frac{1}{2} \left[ y \cos \phi \left( \frac{q}{p} + \frac{p}{q} \right) - x \sin \phi \left( \frac{q}{p} - \frac{p}{q} \right) \right] \\
\Delta y &= -\text{Re} \left( \Delta z \right) = \frac{1}{2} \left[ y \cos \phi \left( \frac{q}{p} - \frac{p}{q} \right) - x \sin \phi \left( \frac{q}{p} + \frac{p}{q} \right) \right]
\end{align*}
\]

Useful parametrisation in terms of mixing parameters

\[x_{CP}, y_{CP}, \Delta x, \Delta y \rightarrow x, y, \phi, \left| \frac{q}{p} \right|\]
The Signal Selection

- $K^0_s \rightarrow \pi^- \pi^+$ reconstructed as long and downstream

- Online event selection
  - Lo-level (hardware) $\rightarrow$ based on calorimeter and muon detector information
  - High Level Trigger (software) $\rightarrow$ requirements on track and vertex quality, momenta and final-state charged-particle displacements from primary vertices, and particle identification

- Offline selection
  - Kinematical constrains the tracks to form vertices according to the decay topology
  - D mesons originating from $b$ hadrons suppressed by requiring to point back to the interaction point

LHCB-PAPER-2019-001 [soon on arXiv]
Determination of $R_{b,j}^{\pm}$

- 416 separate invariant mass fits are performed for each set of Dalitz-plot, decay-time and $D^0 - \bar{D}^0$ data samples
  - Fit model assumes same parameter for $\pm b$ data samples
  - Time-integrated fits used to fix some parameters in the fits
- Yields are then corrected for two effects that do not cancel in the ratio:
  - experimentally induced correlations between the phase space and decay time
  - charge-dependent efficiencies

Data driven approach to remove correlation between decay time and $m(\pi^+\pi^-)$

Detection efficiencies $A_{det}(\pi^-\pi^+)$ measured by means of control sample

\[
A_{meas}(D_s^+ \to \pi^+\pi^+\pi^-) = A_{det}(\pi^+\pi^-) + A_{det}(\pi^+) + A_{pred}(D_s^+) + A_{trigger}(D_s^+) \\
A_{meas}(D_s^+ \to \phi\pi^+) = A_{det}(\pi^+) + A_{pred}(D_s^+) + A_{trigger}(D_s^+)
\]
Results

The deviations from constant values are due to mixing

The deviations from constant values are due to CPV

---

Angelo Carbone  CHARM 2020, 31 May – 4 June
Systematic uncertainties

- Systematic uncertainties are assessed from ensembles of pseudoexperiments generated with different systematic effects.
- The impact on measured parameters is then evaluated.
- Reconstruction and selection (mainly affect $x_{CP}$ and $y_{CP}$)
  - Neglecting decay time and $m_{\pm}$ resolutions and efficiencies (mainly effect $x_{CP}$ and $y_{CP}$)
  - Correction to remove the correlation between decay time and $m_{\pm}$
- Approximation of constant strong phase in each Dalitz bin (mainly affect $y_{CP}$)
- Neglecting time-dependent detection asymmetries (mainly affect $\Delta y$)
- Mis-modelling in the signal yield fits (mainly affect $x_{CP}$)

<table>
<thead>
<tr>
<th>Source</th>
<th>$x_{CP}$</th>
<th>$y_{CP}$</th>
<th>$\Delta x$</th>
<th>$\Delta y$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reconstruction and selection</td>
<td>0.199</td>
<td>0.757</td>
<td>0.009</td>
<td>0.044</td>
</tr>
<tr>
<td>Secondary charm decays</td>
<td>0.208</td>
<td>0.154</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>Detection asymmetry</td>
<td>0.000</td>
<td>0.001</td>
<td>0.004</td>
<td>0.102</td>
</tr>
<tr>
<td>Mass-fit model</td>
<td>0.045</td>
<td>0.361</td>
<td>0.003</td>
<td>0.009</td>
</tr>
<tr>
<td>Total Systematic Uncertainty</td>
<td>0.291</td>
<td>0.852</td>
<td>0.010</td>
<td>0.110</td>
</tr>
</tbody>
</table>

Consistency check: analysis repeated in subsets of the data selected based on
- magnet polarity
- trigger and $K_s^0$ category
- data-taking period
- $D^{**}$ meson kinematics

Angelo Carbone
CHARM 2020, 31 May – 4 June
Results

First observation at the level of 7 standard deviations of the mass difference between $D^0$ mass eigenstates
limits on mixing-induced CP violation significantly improved

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

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>95.5% CL interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x \ [10^{-3}]$</td>
<td>$3.98^{+0.56}_{-0.45}$</td>
<td>[2.9, 5.0]</td>
</tr>
<tr>
<td>$y \ [10^{-3}]$</td>
<td>$4.6^{+1.5}_{-1.4}$</td>
<td>[2.0, 7.5]</td>
</tr>
<tr>
<td>$</td>
<td>q/p</td>
<td>$</td>
</tr>
<tr>
<td>$\phi$</td>
<td>$-0.056^{+0.047}_{-0.051}$</td>
<td>[-0.172, 0.040]</td>
</tr>
</tbody>
</table>

Angelo Carbone
CHARM 2020, 31 May – 4 June
Yet another milestone by LHCb!

$B^0$: ARGUS
Observation of $B^0$ oscillations

$D^0$: Belle & BaBar
Evidence of $D^0$ oscillations

$D^0$: LHCb
Observation of $D^0$ mass difference
LHCb-PAPER-2021-009


$K^0$
Behavior of neutral particles
e.g. Phys.Rev. 97 (1955) 1387

$B^0_s$: CDF
Observation of $B^0_s$ oscillations

$D^0$: LHCb
Observation of $D^0$ oscillations

Angelo Carbone
CHARM 2020, 31 May – 4 June
LHCb impact on world averages

The combination procedure follows closely HFLAV methods

ΔY LHCb measurement included
Conclusions

The LHCb Collaboration observes for the first time a difference between $D^0$ mass eigenstates with a significance of about 7 standard deviations.

No mixing-induced CP violation was observed, but limits have been significantly improved.

Search for CPV in pure mixing and interference of decay amplitudes with and without mixing remains an important tool for constraining New Physics.

The upcoming LHCb-upgrade precision era will have an exciting time in store for us.