Measurement of mixing and *CP*-violation in charm decays at the LHCb experiment

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Introduction

This seminar will present and discuss a technique for the measurement of the mixing parameter y_{CP} in $D^0 \to K^0_S K^+ K^-$ decays.

What will be covered today includes:

- Mixing
- *CP*-violation
- Formalism
- Dataset
- Measurement
- Systematic uncertainties
- Expected precision

Charm physics at LHCb

Charm physics is an active area of research in the LHCb collaboration with exciting results in recent years.

- First single-experiment observation of Charm mixing[1].

Observation of $D^0 - \bar{D}^0$ Oscillations

R. Aaij *et al.**
(LHCb Collaboration)
(Received 6 November 2012; published 5 March 2013)

- first observation of direct CP violation in Charm[2].

Observation of *CP* Violation in Charm Decays

R. Aaij *et al.**
(LHCb Collaboration)
(Received 21 March 2019; revised manuscript received 2 May 2019; published 29 May 2019)

To date no observation of mixing-induced CP violation in Charm has been made, providing further avenues research.

[1] 10.1103/PhysRevLett.110.101802
[2] 10.1103/PhysRevLett.122.211803

Mixing

Neutral D^0 mesons can change their flavour and turn into antimesons before they decay. This phenomenon, known as flavour oscillation or D^0-$\overline{D}^0$ mixing arises becuase the mass eigenstates of the D^0 meson which are eignestates of the Hamiltonian are a superposition of the flavour eigenstates:

$$|D_{1,2}\rangle = p|D^0\rangle \pm q|\overline{D}^0\rangle \tag{1}$$

The flavour eigenstates are then given by

$$|D^0\left(t\right)\rangle = g_+\left(t\right)|D^0\rangle + \frac{q}{p}g_-\left(t\right)|\overline{D}^0\rangle \tag{2}$$

$$|\overline{D}^0\left(t\right)\rangle = \frac{p}{q}g_-\left(t\right)|D^0\rangle + g_+\left(t\right)|\overline{D}^0\rangle \tag{3}$$

where

$$g_{\pm}\left(t\right) = e^{-iMt}e^{i\Gamma t/2}\left({}^{\cos}_{\sin}\left(-i\left(x+iy\right)\Gamma t/2\right)\right) \tag{4}$$

Mixing

p and q are complex parameters satisfying $|p|^2 + |q|^2 = 1$. In the limit of charge-parity (CP) symmetry, q equals p and the oscillations are characterised by two dimensionless parameters.

$$x \equiv (m_1 - m_2)/2\Gamma, \tag{5}$$

$$y \equiv (\Gamma_1 - \Gamma_2)/\Gamma \tag{6}$$

Here $m_{1(2)}$ and $\Gamma_{1(2)}$, are the mass and width of the mass eigenstates respectively.

In the limit of CP-symmetry the CP-eigenstates are the mass eigenstates, ${D^0}_{1(2)}$.

CP-violation

Because of D^0-$\overline{D}^0$ mixing, the effective decay width, $\Gamma_{CP+} \neq \Gamma$.
The quantity y_{CP}, is given by,

$$y_{CP} \equiv \frac{\Gamma_{CP+}}{\Gamma} - 1. \tag{7}$$

This is equal to y in the limit of CP-symmetry.
However if there is CP-violation

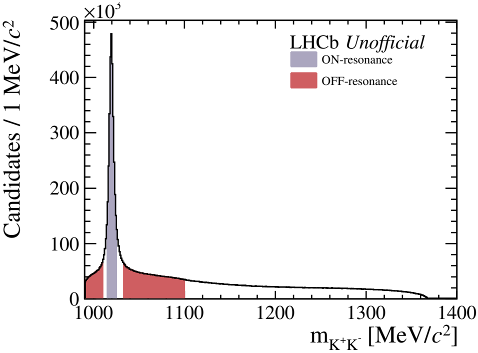
$$2y_{CP} \approx (|q/p| + |p/q|)\, y \cos\phi + (|q/p| - |p/q|)\, x \sin\phi, \tag{8}$$

thus significant discrepencies between y_{CP} and y would demonstrate CP-violation in mixing.

Formalism

Define two regions of phase-space:

- ON-resonance: $m_{K^+K^-} \in [1015, 1025]\,\mathrm{MeV}/c^2$
- OFF-resonance:
  $m_{K^+K^-} \in [2m_{K^+}, 1010] \cup [1033, 1100]\,\mathrm{MeV}/c^2$



The ON-resonance region is dominated by a CP-odd ϕK^0_S amplitude and the OFF-resonance region is dominated by a $K^0_S K^+ K^-$ S-wave amplitude.

Formalism

It can be shown that,

$$\frac{dN\left(s_0,t\right)}{dt} \propto a_1\left(s_0\right)e^{\frac{t}{\tau}(1+y)} + a_2\left(s_0\right)e^{\frac{t}{\tau}(1-y)}, \tag{9}$$

where $a_k\left(s_0,t\right) = \int_{s_+} \left|\mathcal{A}_k\left(s_0,s_+\right)\right|^2 ds_+$, and $\mathcal{A}_{1,2}\left(s_0,s_+\right)$ are the CP-even and -odd amplitudes respectively.
From this the number of events in regions of phase space can be calculated:

$$N_{\mathrm{ON}}\left(t\right) = f_{\mathrm{ON}} a_1\left(s_0\right)e^{-\frac{t}{\tau}(1+y_{CP})} + \left(1-f_{\mathrm{ON}}\right)a_2\left(s_0\right)e^{-\frac{t}{\tau}(1-y_{CP})} \tag{10}$$

$$N_{\mathrm{OFF}}\left(t\right) = f_{\mathrm{OFF}} a_1\left(s_0\right)e^{-\frac{t}{\tau}(1+y_{CP})} + \left(1-f_{\mathrm{OFF}}\right)a_2\left(s_0\right)e^{-\frac{t}{\tau}(1-y_{CP})} \tag{11}$$

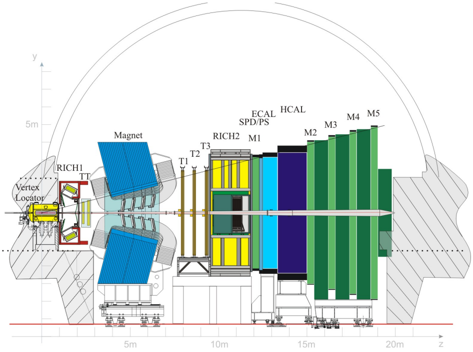
Formalism

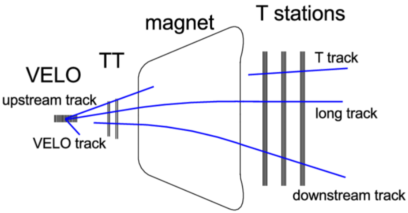
By studying the ratio of events ON- and OFF- resonance over decay time, y_{CP} can be extracted through

$$\frac{dN_{\mathrm{ON}}(t)}{dN_{\mathrm{ON}}(t)} = R_0 \left(1 - 2 \left(f_{\mathrm{ON}} - f_{\mathrm{OFF}} \right) \frac{t}{\tau} y_{CP} + \mathcal{O}\left(y_{CP}^2 \right) \right) \quad (12)$$

where R_0 absorbs any time-integrated phase-space efficiency effects.

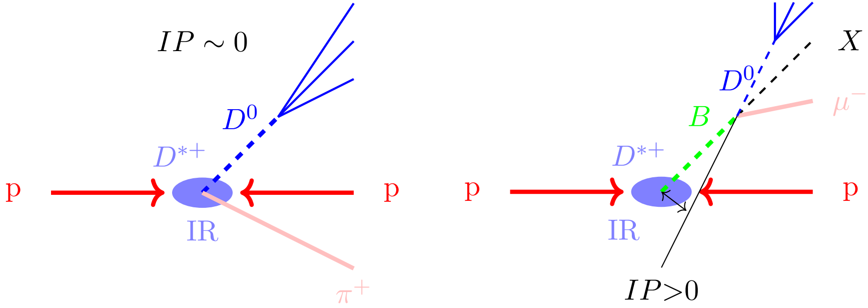
LHCb Detector





The K_S^0 decays to two pions.
In this analysis the datasample is split into events where the K_S^0 decays into two long tracks (LL), and where it decays to two downstream tracks (DD).

Charm production methods at LHCb



Prompt

Semi Leptomic (Secondary)

Lifetime unbiased (LTUNB) decays are also Prompt decays but are tiggered on independent of signal at the HLT1 level. This helps to recover decays at low decay time.

Dataset

The analysis is performed using the 5.7 fb^{-1} sample of pp collisions collected by LHCb during 2016-2018. The data is split into six sub-samples corresponding to different selection criteria.

Candidates		2016	2017	2018	Total
Total		3,489,418	4,696,346	5,461,962	13,647,726
Polarity					
Up		1,593,663	1,883,271	2,327,183	5,804,117
Down		1,895,760	1,984,754	2,211,006	6,091,520
Sample	KS type				
Prompt	LL	512,462	609,595	670,479	1,792,536
	DD	625,357	828,321	923,773	2,377,451
LTUNB	LL	768,387	1,077,508	1,261,291	3,107,186
	DD	955,426	1,517,224	1,776,737	4,249,387
SL	LL	184,430	183,785	226,203	594,418
	DD	443,356	479,913	603,479	1,526,748

Table: Total candidates after all slection has been performed.

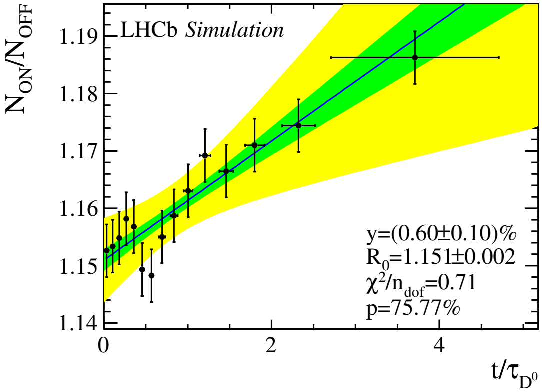
Dataset

After further background is removed by fits to the Δm $(m_{D^*} - m_{D^0})$ or m_{D^0} distribution, the final number of signal candidates is shown on the table.

Sample	KS type	Signal yield	
Prompt	LL	$845,001$	± 2108
	DD	$309,408$	± 1002
LTUNB	LL	$822,214$	± 3205
	DD	$1,270,477$	± 2893
SL	LL	$253,171$	± 964
	DD	$488,947$	± 1759
Total		$3,989,218$	

Table: Signal yields per data sub-sample after all selection.

Measurement



- Calculate $\frac{dN_{\mathrm{ON}}(t)}{dN_{\mathrm{OFF}}(t)}$
- Measure y_{CP}.

Blinding strategy

- y_{CP} will be numerically and visually blinded to prevent any user bias.
- Offset y_{CP} by a random number generated from a gaussian with width 1.5% (roughly twice world average)

Systematic uncertainties

There are three main sources of systematic uncertainity that need to be considered in this analysis:

1. Phase-space acceptance.
2. Model uncertainity.
3. Contamination of Prompt sample from Secondary decays.

The approch to measure these uncertainties will now be discussed.

Phase-space acceptance

If phase-space acceptance effects are constant as a function of decay time, they get absorbed into the R_0 term.
However if these effects are not uniform over decay time, this has the effect of introducing an efficiency term into the ratio.

$$\frac{dN_{\mathrm{ON}}}{dN_{\mathrm{OFF}}} \rightarrow \frac{\varepsilon_{\mathrm{ON}(t)} dN_{\mathrm{ON}}}{\varepsilon_{\mathrm{OFF}(t)} dN_{\mathrm{OFF}}} \tag{13}$$

Strategy

- Construct an efficiency map from MC.
- Weight on an event by event basis from the inverse of the efficiency map.

Model uncertainity

A systematic uncertainity enters the analysis from the error on the amplitude model used and how that error propogates to $f_{\mathrm{ON}} - f_{\mathrm{OFF}}$.

Three amplitude models will be considered:

1. Belle 2008.
2. Belle 2010.
3. BES III 2020.

A dedicated package has been written in C++ for the purpose of calculating the ratios[3].

[3] https://gitlab.cern.ch/eshields/amplitudemodel

Model uncertainity

Belle 2008[4]	Belle 2010[5]	BES II 2020[6]
$a_0\,(980)^0$	$a_0\,(980)^0$	$a_0\,(980)^0$
$\phi\,(1020)$	$\phi\,(1020)$	$\phi\,(1020)$
$a_0\,(1450)^+$	$a_0\,(1450)^+$	$a_0\,(980)^+$
$a_0\,(980)^+$	$a_0\,(980)^+$	$a_0\,(1450)^-$
$a_0\,(1450)^0$	$a_0\,(1450)^0$	$a_2\,(1320)^+$
$f_0\,(1370)$	$f_0\,(1370)$	$a_2\,(1320)^-$
$f_2\,(1270)$	$f_2\,(1270)$	
$a_0\,(980)^-$	$a_0\,(980)^-$	

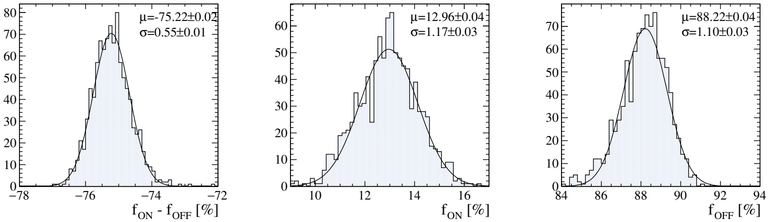
Note that although the Belle 2008 and Belle 2010 models have the same resonances, they have different amplitudes.

[4] arXiv:0804.2089v2]
[5] arXiv:1004.5053v3
[6] arXiv:2006.02800

Model uncertainity

Strategy

- Calculate the fraction $f_{\mathrm{ON}} - f_{\mathrm{OFF}}$ 1000 times using an amplitude model.
- Each time vary the parameters of the model within there errors.
- Build a distribution of $f_{\mathrm{ON}} - f_{\mathrm{OFF}}$ and take the width of this to be the uncertainty.



This error is directly propogated onto the error of y_{CP} due to it being a multiplying factor in $dN_{\mathrm{ON}}/dN_{\mathrm{OFF}}$.

Secondary contamination of Prompt sample

The D^0 decay time is defined as,

$$t = \frac{\left(m\vec{L} \cdot \vec{p}\right)}{|\vec{p}|^2} \tag{14}$$

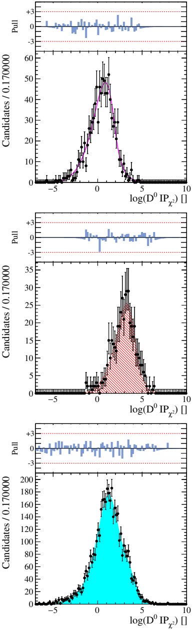
Therefore if the impact parameter is small and the detector mistakes a secondary decay for a prompt decay, the measured decay length is, $\vec{L}_{\text{measured}} = \vec{L}_{B^0} + \vec{L}_{D^0}$, this the measured decay time is higher than the true D^0 decay time. This has the effect of putting decays with a lower decay time in higher decay time bins, and thus lowers the slope and measured value of y_{CP}.

Secondary contamination of Prompt sample

Strategy

- Extract Prompt, Secondary and Background shapes from MC or data sidebands.
- Fit all the shapes together to the $\log(D^0 IP_{\chi^2})$ distribution to extract the fraction of secondary decays. Where $D^0 IP_{\chi^2}$ is the chi sqaured of the Impact Parameter fit in the D^0 vertex fit.

Secondary contamination of Prompt sample



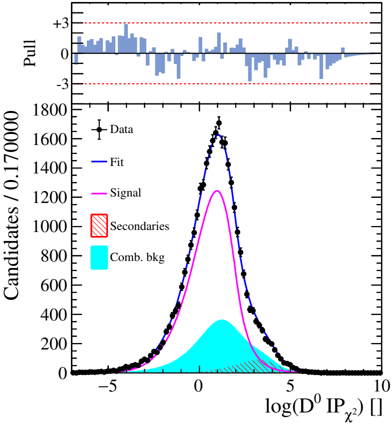
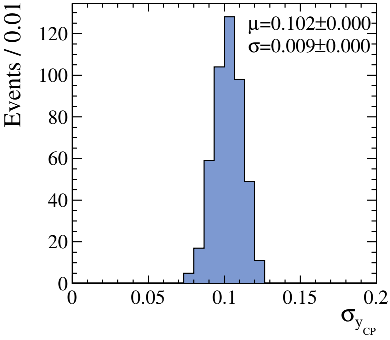
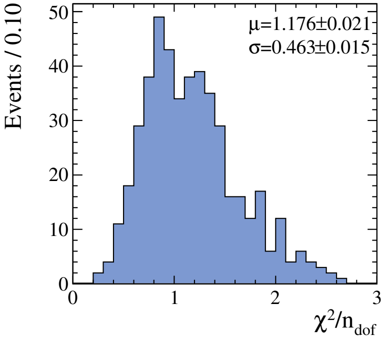


Figure: Example fit in 1st decay time bin of Prompt LL sample.

Expected precision

500 fits are performed to toy datasets to study the expected precision of this analysis.





Expected precision

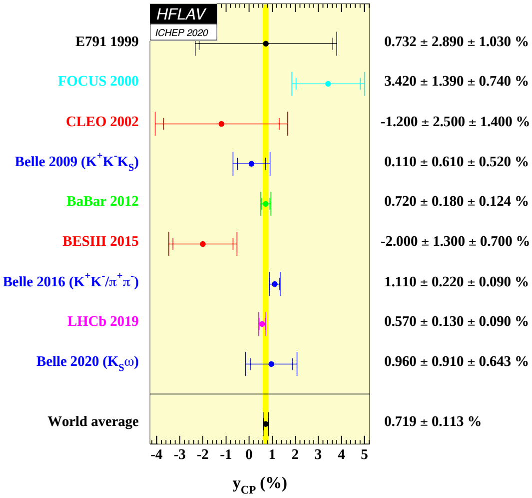


Figure: y_{CP} measurements as of 16 July 2020

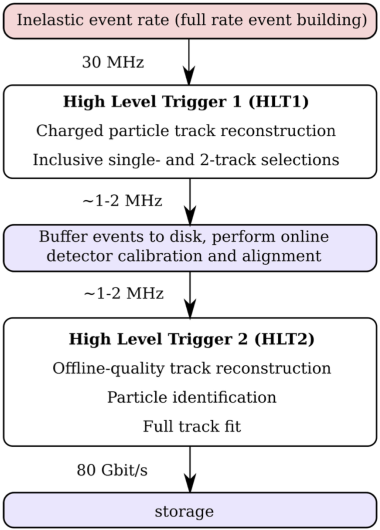
World average y_{CP} precision:

- 0.113 %

LHCb analysis expected statistical precision:

- 0.102 %

Triggering on $D^0 \to K^0_S K^+ K^-$ in the LHCb Upgrade



HLT 1

- 3/4 body vertex fitter in HLT1.
- Exclusive $D^0 \to K^0_S hh$ HLT1 line.

HLT 2

- Exclusive $D^0 \to K^0_S hh$ HLT1 lines.
- Decicated untagged $D^0 \to K^0_S K^+ K^-$ line.

Final remarks

This analysis should be competative with the world average measurement of y_{CP}.
It also allows systematics to be studied and strategies identified to limit these in order to most effectively utilise the LHCb upgrade and Run III.

BACKUP

Invariant mass fits

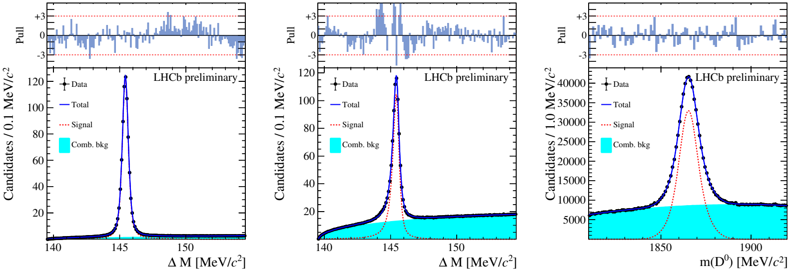


Figure: Invariant mass fits for LL sample. From left to right: Prompt, LTUNB, and Semi-Leptonic

Invariant mass fits

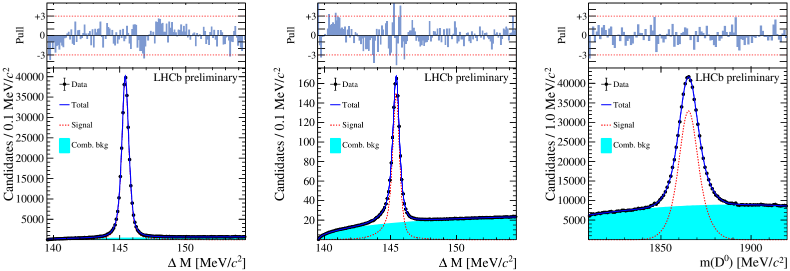


Figure: Invariant mass fits for DD sample. From left to right: Prompt, LTUNB, and Semi-Leptonic

Efficiency maps

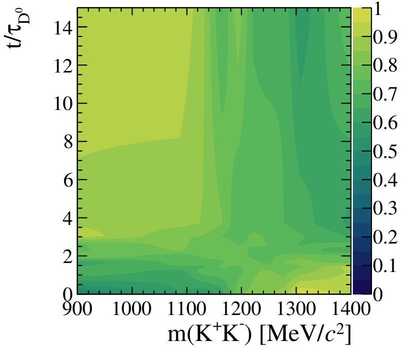


Figure: Example efficiency map for Prompt LL sample.

Secondary contamination

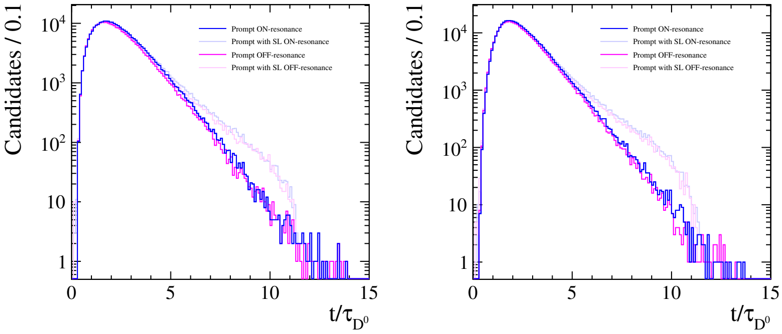
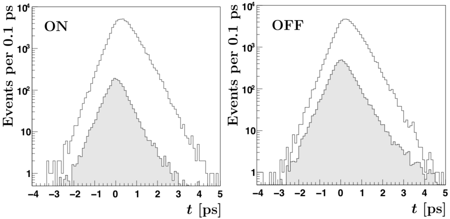


Figure: Effect on decay time distribution of secondary contamination of Prompt sample.

Measurements of y_{CP}

This analysis takes inspiration from a Belle analysis in 2009[7]



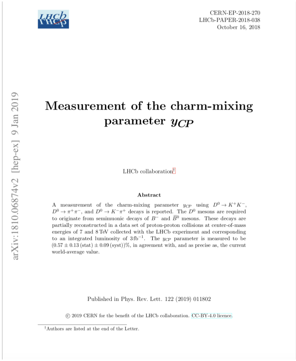
Studies the evolution of signal yields in the ON- and OFF-resonance regions of phase-space.

$$y_{CP} = (+0.11 \pm 0.61\,(\text{stat.}) \pm 0.52\,(\text{syst.}))\,\% \tag{15}$$

[7] arXiv:0905.4185v1

Measurements of y_{CP}

- Most accurate measurement of y_{CP} to date comes from LHCb in 2019 [a].
- They study the ratio of between $D^0 \to K^+K^-$ (or $D^0 \to \pi^+\pi^-$) and $D^0 \to K^+\pi^-$ as a function of decay time.



CERN-EP-2018-270
LHCb-PAPER-2018-038
October 16, 2018

arXiv:1810.06874v2 [hep-ex] 9 Jan 2019

Measurement of the charm-mixing parameter y_{CP}

LHCb collaboration[†]

Abstract

A measurement of the charm-mixing parameter y_{CP} using $D^0 \to K^+K^-$, $D^0 \to \pi^+\pi^-$, and $D^0 \to K^-\pi^+$ decays is reported. The D^0 mesons are required to originate from semimuonic decays of B^- and $\bar{B}^0$ mesons. These decays are partially reconstructed in a data set of proton-proton collisions at center-of-mass energies of 7 and 8 TeV collected with the LHCb experiment and corresponding to an integrated luminosity of $3\,\mathrm{fb}^{-1}$. The y_{CP} parameter is measured to be $(0.57 \pm 0.13\,(\mathrm{stat}) \pm 0.09\,(\mathrm{syst}))\%$, in agreement with, and as precise as, the current world-average value.

Published in Phys. Rev. Lett. 122 (2019) 011802

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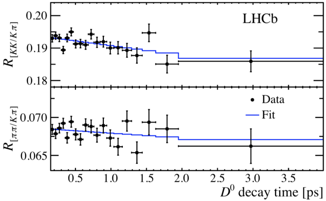
[†]Authors are listed at the end of the Letter.



[a] arXiv:1810.06874v2

$$y_{CP} = (+0.57 \pm 0.13\,(\text{stat.}) \pm 0.09\,(\text{syst.}))\,\% \qquad (16)$$