Mixing and CP Violation with $D^0 \to K_S^0 \pi^+ \pi^-$

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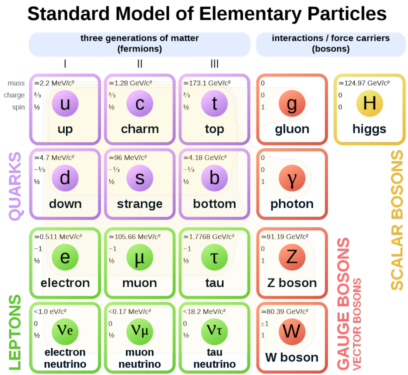
Overview

- Motivation and background
- Observation of CP violation in charm decays
- Bin-flip Observation of the non-zero mass difference in neutral charm mesons
- Model-dependent amplitude analysis
- Future prospects

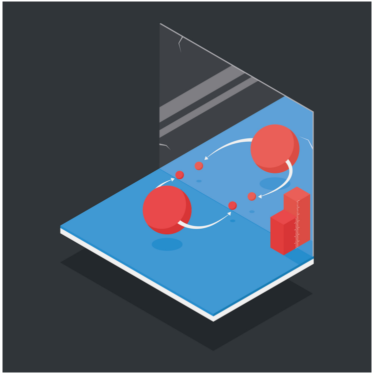
The Standard Model is incomplete



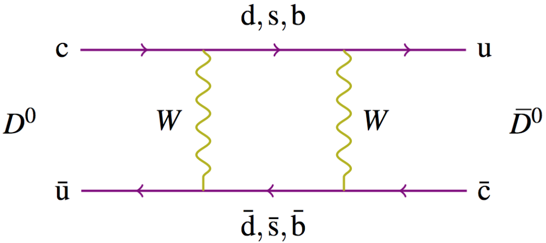
- Experimentally verified
  - Very successful at predicting behaviour at small scales / low energies
- Does not explain large scale behaviour of the universe
  - No dark matter candidate
  - Does not explain the matter-antimatter asymmetry in the universe
- Does not incorporate enough **CP violation**
  - Need contributions from new particles or interactions which violate CP symmetry and are associated with large mass scales

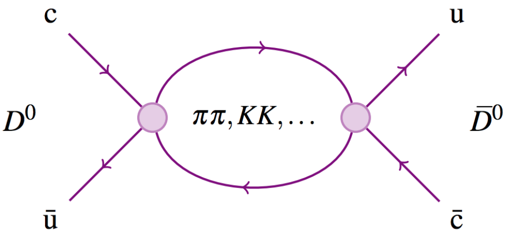
CP Violation

- CP violation discovered in charm in 2019 at LHCb
- CPV in charm is predicted to be small in the Standard Model ($\sim \mathbf{10^{-4} - 10^{-3}}$)
    - CKM suppression
    - GIM mechanism
- Theoretical prediction has large uncertainties due to strong interactions
- CPV searches in charm complementary to those in kaons and B mesons, unique probe to new CP violating processes in the up-type sector



D^0 Mixing





Mass Eigenstates:

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

Mixing parameters:

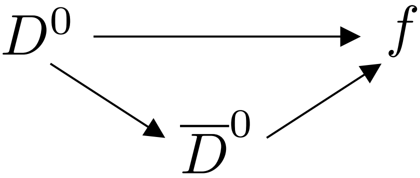
$$x \equiv \frac{(m_1 - m_2)}{\Gamma} \qquad y \equiv \frac{(\Gamma_1 - \Gamma_2)}{2\Gamma}$$

Types of CP Violation

To observe CP violation we need two amplitudes to the same final state with different strong (CP-conserving) phases and different weak (CP-violating) phases.

Direct CP Violation:

$$\Gamma(D^0 \to f) \neq \Gamma(\bar{D}^0 \to \bar{f}) \text{ or } |A_f| \neq |\bar{A}_{\bar{f}}|$$



CP Violation in Mixing:

$$\Gamma(D^0 \to \bar{D}^0, t) \neq \Gamma(\bar{D}^0 \to D^0, t) \text{ or } |q| \neq |p|$$

CP Violation in interference in mixing and decay:

$$\Gamma(D^0(\to \bar{D}^0) \to f, t) \neq \Gamma(\bar{D}^0(\to D^0) \to f, t) \text{ or } \phi = arg\left(\frac{q\bar{A}_f}{pA_f}\right) \neq 0$$

1955
Neutral meson mixing prediction *Gell-Mann and Pais*

1957
Strange particles: Mixing in Kaons *Lederman et al.*

1964
Strange particles: CP violation in K meson decays *J. W. Cronin, V. L. Fitch et al.*

1987
Beauty particles: Mixing in neutral B meson decays *ARGUS collaboration*

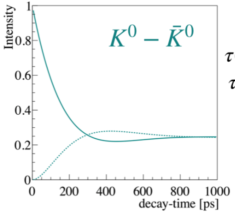
2001
Beauty particles: CP violation in B meson decays *BaBar and Belle collaborations*

2007
Charm particles: First evidence of D meson mixing *BaBar and Belle collaborations*

2019
Charm particles: CP violation in D meson decays *LHCb collaboration*

2021
Observation of the non-zero mass difference in neutral charm mesons *LHCb collaboration*

2022
Run 3 and beyond *LHCb collaboration*

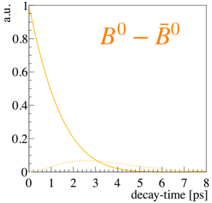


Very different lifetime:

$\tau(K_S^0) \sim 0.9 \times 10^{-10}$

$\tau(K_L^0) \sim 0.5 \times 10^{-7}$

the oscillation period longer than the K_S lifetime, but K_L^0 exceptionally long



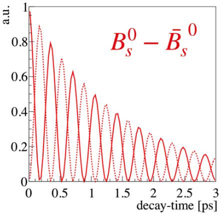
Oscillations

$\Delta m \sim 0.5\ ps^{-1}$

Lifetime

$\tau(B^0) \sim 1.5\ ps$

The same order of magnitudes

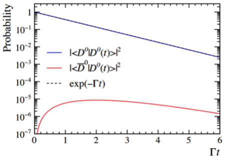


Very fast oscillations

$\Delta m_s > 15\ ps^{-1}$

$\tau(B_s^0) \sim 1.5\ ps$

Non-zero $\Delta\Gamma_s$



$D^0 - \bar{D}^0$

Very slow oscillations

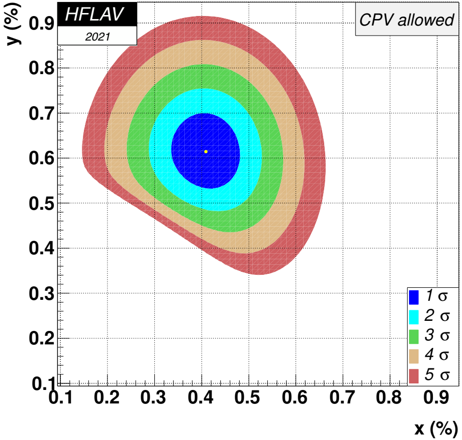
$\Delta m \sim 10^{-3}\ ps^{-1}$

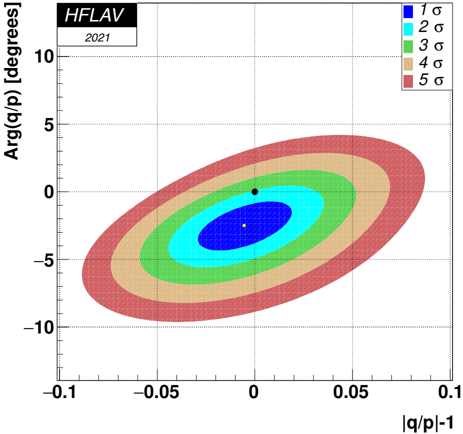
Very short lifetime

$\tau(D^0) \sim 0.4\ ps$

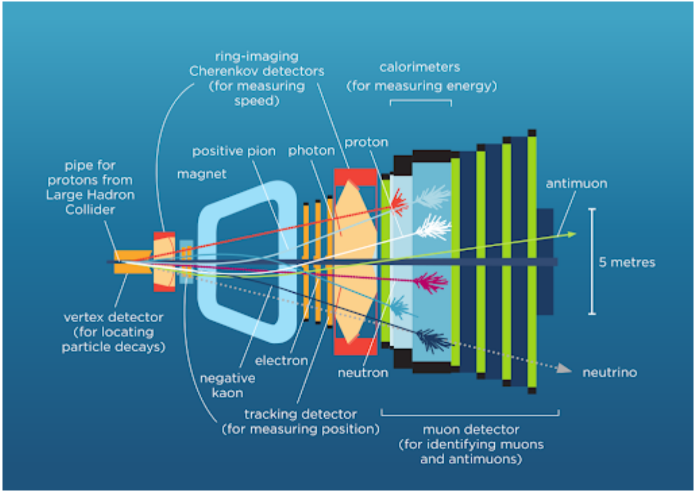
D^0 decays before has a chance to oscillate

World Averages





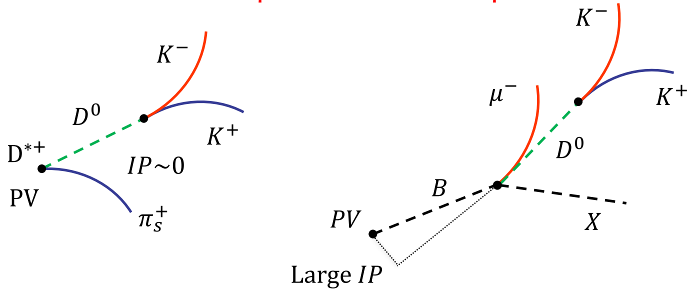
World averages of the mixing and CP-violation parameters 2021, from HFLAV.



- Production cross section of charm 20 times larger than that of beauty
- Excellent decay-time resolution, particle identification and impact parameter resolution

Two mechanisms of D^0 production

Independent data sample



Prompt sample tagged by the charge of the soft pion.
Semi-leptonic sample tagged by the charge of the muon.

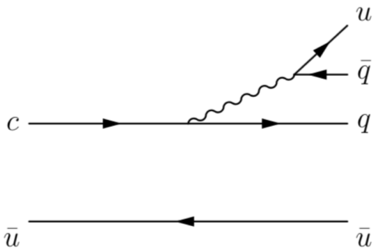
Observation of CP violation in charm

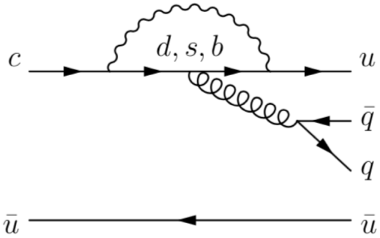
ΔA_{CP}: Time-integrated CP Asymmetry

CP asymmetry:

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

where $f = K^- K^+$ and $f = \pi^- \pi^+$





Raw asymmetry:

$$A_{raw}(f) = \frac{N(D^0 \rightarrow f) - N(\bar{D}^0 \rightarrow f)}{N(D^0 \rightarrow f) + N(\bar{D}^0 \rightarrow f)}$$

where N is the number of reconstructed signal decays

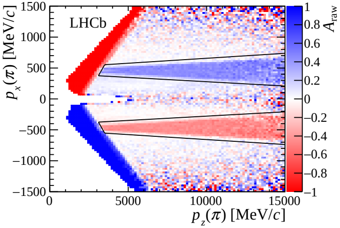
$$A_{raw} = A_{CP}(f) + A_D(\pi_s^+) + A_P(D^{*+})$$

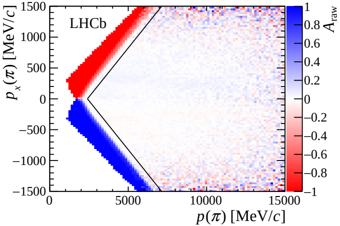
$$\Delta A_{CP} \equiv A_{CP}(D^0 \rightarrow K^- K^+) - A_{CP}(D^0 \rightarrow \pi^- \pi^+)$$

The initial flavour of the neutral D meson is tagged by the charge of the slow pion from $D^{*\pm} \rightarrow D^0 \pi^+$ decays or the muon from semi-leptonic B decays: $B \rightarrow D^0 \mu^- X$.

$$\Delta A_{CP} = \left[a_{CP}^{dir}(K^+K^-) - a_{CP}^{dir}(\pi^+\pi^-)\right] + \frac{\Delta \langle t \rangle}{\tau} a_{CP}^{ind}$$

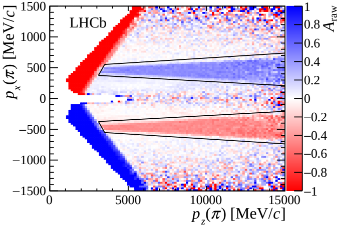
where $\Delta \langle t \rangle$ is the difference in proper time between $D^0 \rightarrow \pi^+\pi^-$ and $D^0 \rightarrow K^+K^-$

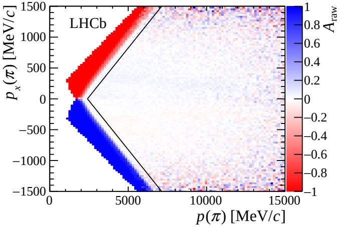




Fiducial selection:

- For regions of phase space the soft pion is kicked out of the detector acceptance by the magnetic field
- This breaks the assumption that the raw asymmetries are small



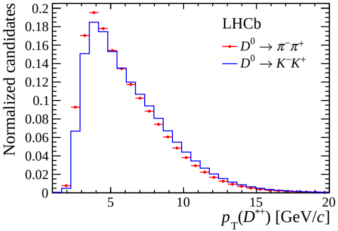


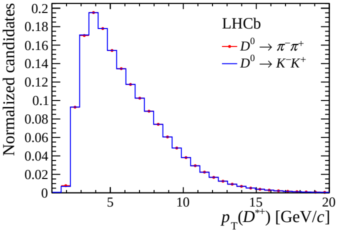
Fiducial selection:

- For regions of phase space the soft pion is kicked out of the detector acceptance by the magnetic field
- This breaks the assumption that the raw asymmetries are small

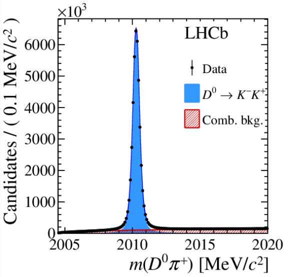
Kinematic reweighting:

- Detection and production asymmetries are dependent on the kinematics of the reconstructed particles
- The K^+K^- sample is corrected to match the $\pi^+\pi^-$ sample by a reweighting procedure

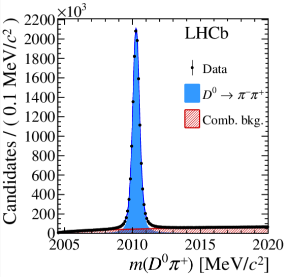




Results

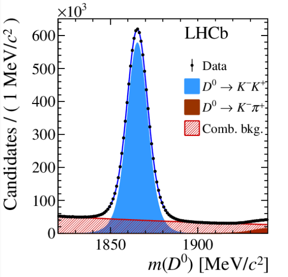


44M

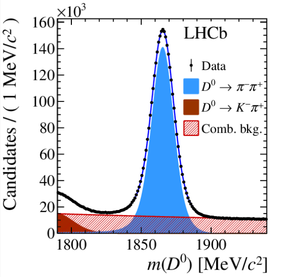


14M

Prompt dataset



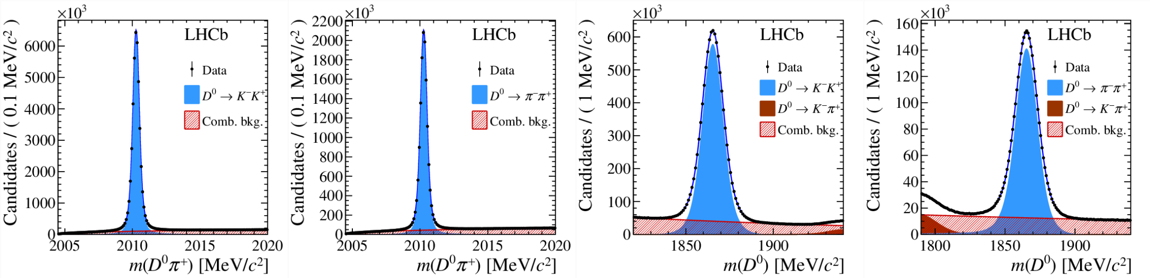
9M



3M

Semi-leptonic dataset

Results



44M **14M** **9M** **3M**

Prompt dataset — Semi-leptonic dataset

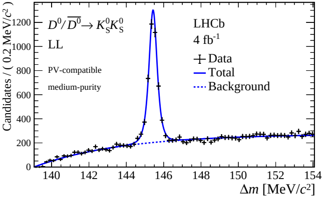
$$\Delta A_{CP} = (-15.4 \pm 2.9) \times 10^{-4}$$

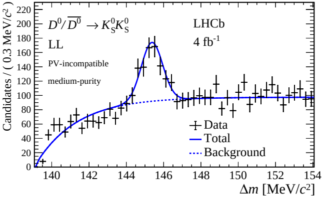
CP violation observed in charm decays at $\mathbf{5.3\sigma}$

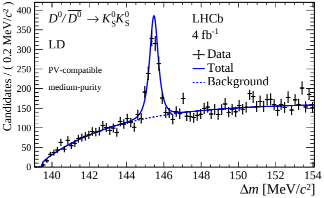
What next?

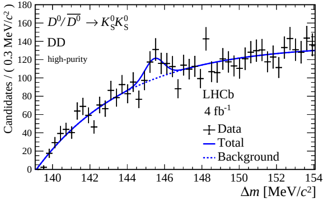
- Can this be explained by the Standard Model?
  - No clear consensus since theoretical predictions of A_{CP} are challenging
- More precise measurements of CP violation in decay including new channels
  - See next slide.
- Time dependent CP violation (see later in this talk)

What next? A_{CP} K_S^0 K_S^0







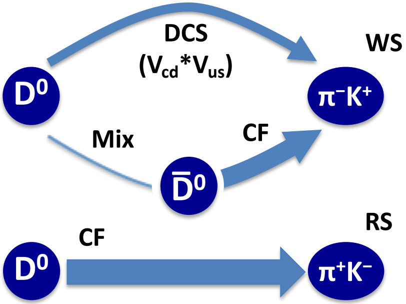


$$A_{CP}(D^0 \to K_S^0K_S^0) = (-3.1 \pm 1.2 \pm 0.4 \pm 0.2)\%$$

Most precise single measurement.

CP violation in mixing

To probe CP violation need flavour specific final state. Measure ratio of **'wrong-sign'** and **'right-sign'** decays



Remember from previous slide:

CP Violation in Mixing:

$$\Gamma(D^0 \to \bar{D}^0) \neq \Gamma(\bar{D}^0 \to D^0)$$

CP Violation in interference in mixing and decay:

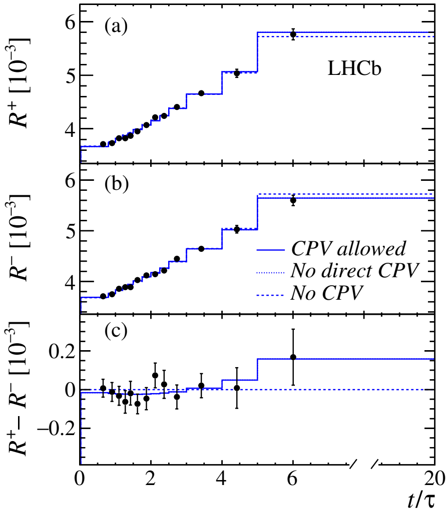
$$\Gamma(D^0 \to \bar{D}^0 \to f, t) \neq \Gamma(\bar{D}^0 \to D^0 \to f, t)$$

$$R(t) = R_D + \sqrt{R_D} y' \left(\frac{t}{\tau}\right) + \frac{x'^2 + y'^2}{4} \left(\frac{t}{\tau}\right)^2$$

Measure rotated mixing parameters:

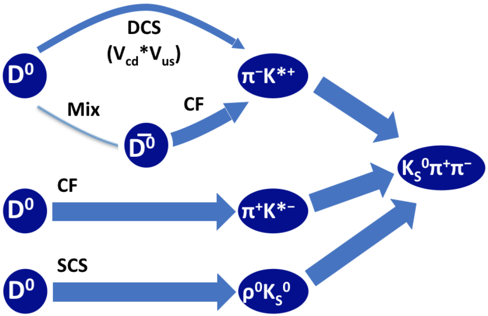
$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos\delta & \sin\delta \\ -\sin\delta & \cos\delta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$

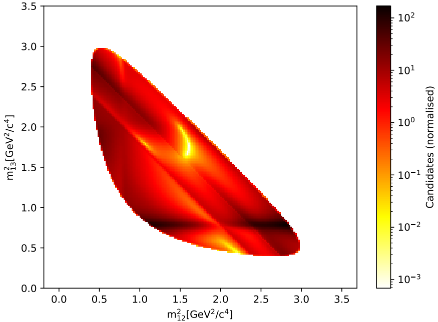
where $\boldsymbol{\delta}$ is the phase between the CF and DCS amplitudes



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

- 'Right-sign' (CF) and 'wrong-sign' (DCS or mixed) decay into **same final state**



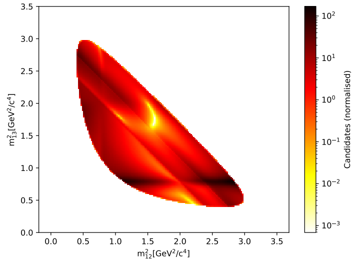


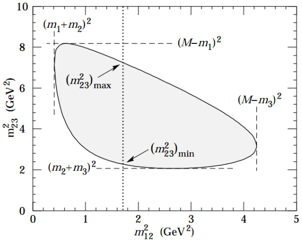
- Offers **direct** access to mixing and CPV parameters x, y, $|q/p|$, ϕ
- Requires **time and phase-space** dependent analysis

Multi-body charm

N-body decay = phase-spce wth **3N - 7** dimensions e.g.
3-body decay = 2D (Dalitz)
Intermediate resonances, amplitude varies over phase-space
e.g. $K^0_S\pi^+\pi^-$ has $K^*(892)^+\pi^-$, $\rho(770)^0 K^0_S$

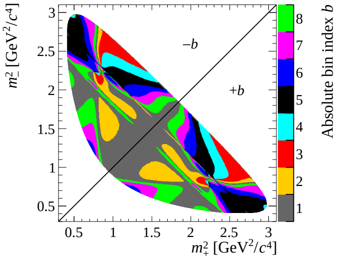
- Decay rate varies over phase-space
- Strong phase varies over phase-space
- Asymmetry in component amplitudes can be observed locally

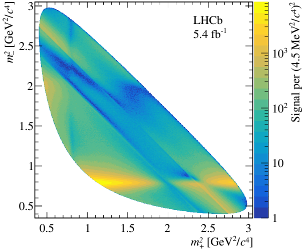




Bin-flip Model-independent analysis

- Data is binned in Dalitz coordinates where the binning scheme is chosen to have approximately constant strong-phase differences
- Measure the yield ratio $R_{bj}^{\pm}$ between $-b$ and b in bins of decay time
- $R_{bj}^{\pm}$ is the ratio of D^0 and $\bar{D}^0$ in each decay-time (j) and Dalitz $(b^{\pm})$ bin
- Fit the time-dependent ratios R_b^+/R_b^- and $R_b^+ - R_b^-$
- Fit parameters are x, y, Δx and Δy can be translated into $\left|q/p\right|$ and ϕ





Ratio of signal decays in upper ($+b$) and lower ($-b$) Dalitz bins, and decay-time bin j is given by:

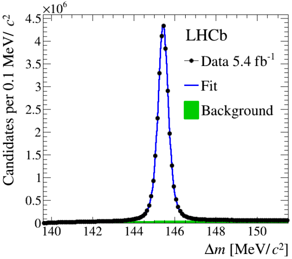
$$R_{bj}^{\pm} \approx \frac{r_b + \frac{1}{4} r_b \left\langle t^2 \right\rangle_j Re(\boldsymbol{z_{CP}^2} - \boldsymbol{\Delta z^2}) + \frac{1}{4} \left\langle t^2 \right\rangle_j |\boldsymbol{z_{CP}} \pm \boldsymbol{\Delta z}|^2 + \sqrt{r_b} \left\langle t \right\rangle_j Re[X_b^*(\boldsymbol{z_{CP}}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

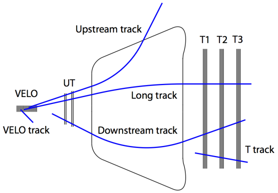
- $\langle t \rangle_j$: Average decay time of unmixed decays in bin j
- r_b: Ratio of signal yields in symmetric Dalitz bins $\pm b$ at $t = 0$
- X_b: Average strong phase difference in each bin
  - Use external constraints from quantum correlated charm production (CLEO, BESIII)
- z_{CP} and Δz: Obtained from a fit to $R_{bj}^{\pm}$ ratios in decay time

$$\boldsymbol{x_{CP} \equiv -\mathrm{Im}(z_{CP})} \qquad \boldsymbol{y_{CP} \equiv -\mathrm{Re}(z_{CP})}$$
$$\boldsymbol{\Delta x \equiv -\mathrm{Im}(\Delta z)} \qquad \boldsymbol{\Delta y \equiv -\mathrm{Re}(\Delta z)}$$

and in the limit of CP symmetry $\boldsymbol{x_{CP} = x}$, $\boldsymbol{y_{CP} = y}$ and $\boldsymbol{\Delta x = \Delta y = 0}$

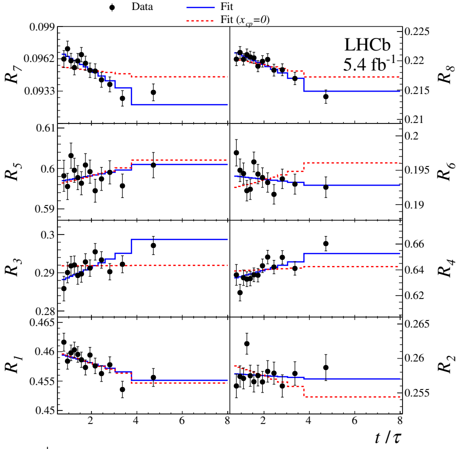
Analysis overview





- **31M** signal candidates, 10 times larger yield than Run 1 data. **Prompt** dataset
- Remains statistically limited including strong phase inputs
- Fit Δm distributions in bins of Dalitz plane and decay-time to get R_{bj} values
- Correct for experimental effects
  - Correlations between decay-time and phase space acceptance
  - Charge detection asymmetries

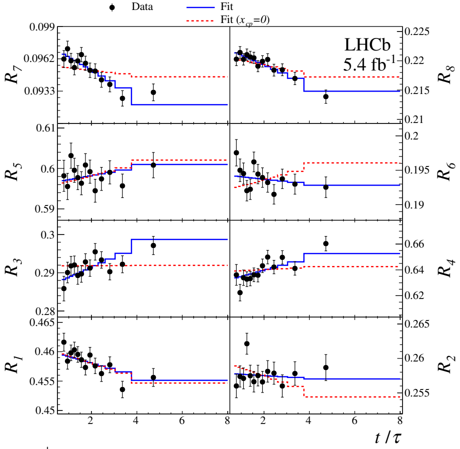
Bin-flip Results

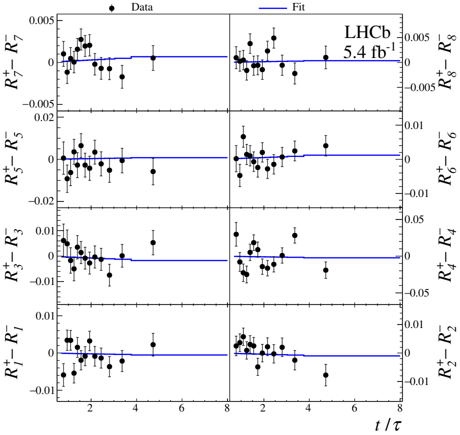


Ratios R_b^+/R_b^-, the slope shows a sign of mixing, red line is $x = 0$ hypothesis.

Clear time-dependence shows mixing. Oscillation period is $\sim$**630 ps** compared to the D^0 lifetime of **0.41 ps**

Bin-flip Results





Ratios R_b^+/R_b^-, the slope shows a sign of mixing, red line is $x = 0$ hypothesis.

$R_b^+ - R_b^-$ any slope shows sign of CP-violation (none seen).

Results

Parameter	Value $[10^{-3}]$	Stat. correlations y_{CP}	Stat. correlations Δx	Stat. correlations Δy	Syst. correlations y_{CP}	Syst. correlations Δx	Syst. correlations Δy
x_{CP}	$3.97 \pm 0.46 \pm 0.29$	0.11	−0.02	−0.01	0.13	0.01	0.01
y_{CP}	$4.59 \pm 1.20 \pm 0.85$		−0.01	−0.05		−0.02	0.01
Δx	$-0.27 \pm 0.18 \pm 0.01$			0.08			0.31
Δy	$0.20 \pm 0.36 \pm 0.13$						

Parameter	Value	95.5% CL interval
x $[10^{-3}]$	$3.98\,^{+0.56}_{-0.54}$	$[2.9, 5.0]$
y $[10^{-3}]$	$4.6\,^{+1.5}_{-1.4}$	$[2.0, 7.5]$
$\lvert q/p \rvert$	0.996 ± 0.052	$[\ 0.890, 1.110]$
ϕ	$-0.056\,^{+0.047}_{-0.051}$	$[-0.172, 0.040]$

First observation of a non-zero mass difference ($x > 0$) in neutral charm mesons.

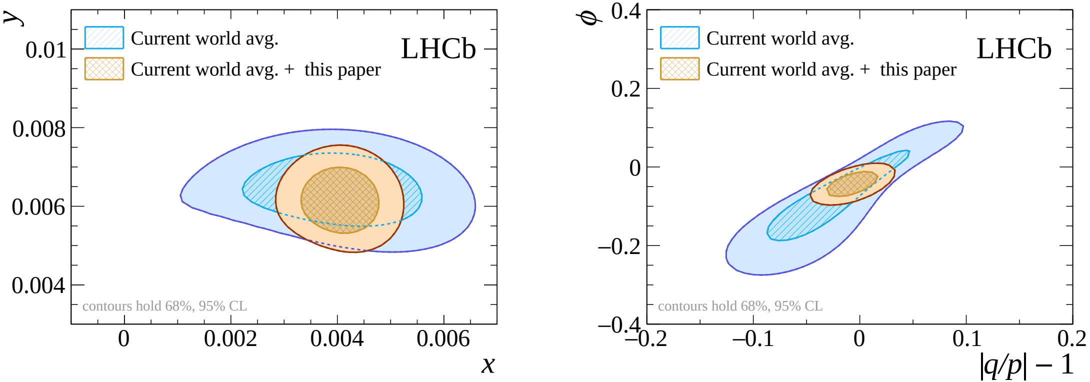
Systematic uncertainties

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

Uncertainties are in units of 10^{-3}.

World Averages



World averages of the mixing and CPV parameters showing the impact of this result. Pre-2021 WA in blue and including this result in orange.

Paper: PhysRevLett.127.111801

What next?

- Measure x and y using a different method
  - Time-dependent amplitude analysis
- A full amplitude analysis gives the best possible precision on time-dependent mixing and CP violation
- Does not rely on external measurements of strong-phase differences

Amplitude formalism

The square of the time-dependent amplitude of the process $D^0 \to K_S^0\pi^+\pi^-$ is given by:

$$| \mathcal{A}_f(t) |^2 = \frac{1}{2} e^{-\Gamma t} \left[\left(| A |^2 - | \frac{q}{p} B |^2 \right) \cos(x\Gamma t) - 2\,\mathrm{Im} \left(AB^* \left[\frac{q}{p} \right]^* \right) \sin(x\Gamma t) \right.$$
$$\left. + \left(| A |^2 + | \frac{q}{p} B |^2 \right) \cosh(y\Gamma t) - 2\,\mathrm{Re} \left(AB^* \left[\frac{q}{p} \right]^* \right) \sinh(y\Gamma t) \right]$$

as well as a similar equation for $\left|\bar{\mathcal{A}}_f(t)\right|^2$ ($\bar{D}^0 \to K_S^0\pi^+\pi^-$).

$A = \mathcal{A}_f$ and $B = \bar{\mathcal{A}}_f$ are the amplitudes of $D^0(\bar{D}^0) \to f$ and depend on the phase-space defined by the Dalitz variables $m^2(K_s^0\pi^+)$ and $m^2(K_s^0\pi^-)$.

CP Violation

Include CP-violation in the fit by allowing x and y to be different for D^0 and $\bar{D}^0$:
$x = x_{CP} \pm \Delta x$ and $y = y_{CP} \pm \Delta y$ (Bin-flip paper)

$$x_{CP} = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

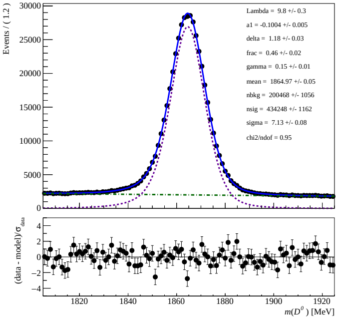
$$\Delta x = \frac{1}{2}\left[x\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) + y\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

$$y_{CP} = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right)\right]$$

$$\Delta y = \frac{1}{2}\left[y\cos\phi\left(\left|\frac{q}{p}\right| - \left|\frac{p}{q}\right|\right) - x\sin\phi\left(\left|\frac{q}{p}\right| + \left|\frac{p}{q}\right|\right)\right]$$

$$\mathcal{P}(t, m_+^2, m_-^2, p_{sig}, tag, \vec{\alpha}) = \boldsymbol{p_{sig}} \Big[(1 - \omega_{muontag})\mathcal{P}_{sig}(t, m_+^2, m_-^2, tag, \vec{\alpha}) + \omega_{muontag}\mathcal{P}_{mt}(t, m_+^2, m_-^2, tag, \vec{\alpha})\Big] + (1 - p_{sig})\mathcal{P}_{bkg}(t, m_+^2, m_-^2)$$

- $\boldsymbol{p_{sig}}$ is the signal probability and is a per-event quantity



$$\mathcal{P}(t, m_+^2, m_-^2, p_{sig}, tag, \vec{\alpha}) = p_{sig}\Big[(1-\boldsymbol{\omega_{muontag}})\mathcal{P}_{sig}(t, m_+^2, m_-^2, tag, \vec{\alpha}) + \omega_{muontag}\mathcal{P}_{mt}(t, m_+^2, m_-^2, tag, \vec{\alpha})\Big] + (1-p_{sig})\mathcal{P}_{bkg}(t, m_+^2, m_-^2)$$

- $\boldsymbol{p_{sig}}$ is the signal probability and is a per-event quantity
- $\boldsymbol{\omega_{muontag}}$ is the mistag component derived from a $D^0 \to K\pi$ sample

$$\begin{aligned}\mathcal{P}(t, m_+^2, m_-^2, p_{sig}, tag, \vec{\alpha}) = p_{sig} \Big[(1 - \omega_{muontag})\mathcal{P}_{sig}(t, m_+^2, m_-^2, tag, \vec{\alpha}) \\ + \omega_{muontag}\boldsymbol{\mathcal{P}_{mt}(t, m_+^2, m_-^2, tag, \vec{\alpha})}\Big] \\ + (1 - p_{sig})\mathcal{P}_{bkg}(t, m_+^2, m_-^2)\end{aligned}$$

- $\boldsymbol{p_{sig}}$ is the signal probability and is a per-event quantity
- $\boldsymbol{\omega_{muontag}}$ is the mistag component derived from a $D^0 \to K\pi$ sample
- $\boldsymbol{\mathcal{P}_{mt}(t, m_+^2, m_-^2, tag, \vec{\alpha})}$ is the mistag PDF

$$\mathcal{P}(t, m_+^2, m_-^2, p_{sig}, tag, \vec{\alpha}) = p_{sig}\Big[(1-\omega_{muontag})\mathcal{P}_{sig}(t, m_+^2, m_-^2, tag, \vec{\alpha}) + \omega_{muontag}\mathcal{P}_{mt}(t, m_+^2, m_-^2, tag, \vec{\alpha})\Big] + (1-p_{sig})\boldsymbol{\mathcal{P}_{bkg}(t, m_+^2, m_-^2)}$$

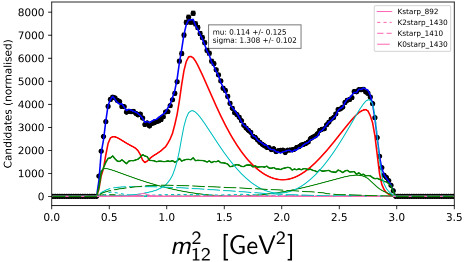
- $\boldsymbol{p_{sig}}$ is the signal probability and is a per-event quantity
- $\boldsymbol{\omega_{muontag}}$ is the mistag component derived from a $D^0 \to K\pi$ sample
- $\boldsymbol{\mathcal{P}_{mt}(t, m_+^2, m_-^2, tag, \vec{\alpha})}$ is the mistag PDF
- $\boldsymbol{\mathcal{P}_{bkg}(t, m_+^2, m_-^2)}$ is the background PDF

$$
\begin{aligned}
\mathcal{P}(t, m_+^2, m_-^2, p_{sig}, tag, \vec{\alpha}) = p_{sig} \Big[&(1 - \omega_{muontag}) \boldsymbol{\mathcal{P}_{sig}(t, m_+^2, m_-^2, tag, \vec{\alpha})} \\
&+ \omega_{muontag} \mathcal{P}_{mt}(t, m_+^2, m_-^2, tag, \vec{\alpha}) \Big] \\
&+ (1 - p_{sig}) \mathcal{P}_{bkg}(t, m_+^2, m_-^2)
\end{aligned}
$$

- $\boldsymbol{p_{sig}}$ is the signal probability and is a per-event quantity
- $\boldsymbol{\omega_{muontag}}$ is the mistag component derived from a $D^0 \to K\pi$ sample
- $\boldsymbol{\mathcal{P}_{mt}(t, m_+^2, m_-^2, tag, \vec{\alpha})}$ is the mistag PDF
- $\boldsymbol{\mathcal{P}_{bkg}(t, m_+^2, m_-^2)}$ is the background PDF
- $\boldsymbol{\mathcal{P}_{sig}(t, m_+^2, m_-^2, tag, \vec{\alpha})}$ is the signal PDF

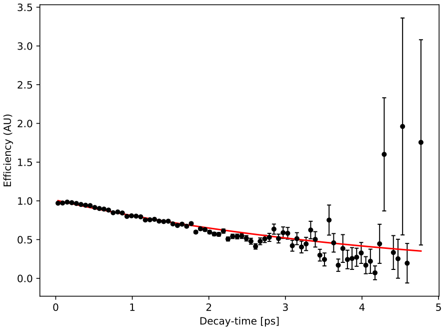
$$\mathcal{P}_{sig}(t, m_+^2, m_-^2, tag, \vec{\alpha}) = \left[\left(| \mathcal{A}_f(t', m_+^2, m_-^2) |^2 \epsilon(t') \right) \otimes R(t, t', \mu_t, \sigma_t) \right] \epsilon(m_+^2, m_-^2)$$

- $\mathcal{A}_f(t', m_+^2, m_-^2)$ is the amplitude model



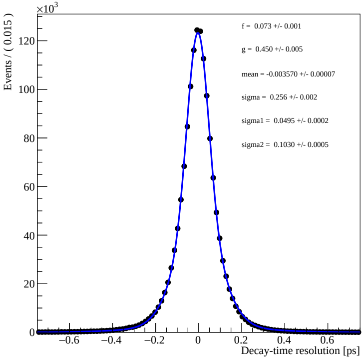
$$\mathcal{P}_{sig}(t, m_+^2, m_-^2, tag, \vec{\alpha}) = \left[\left(|\ \mathcal{A}_f(t', m_+^2, m_-^2)\ |^2\ \boldsymbol{\epsilon(t')}\right) \otimes R(t, t', \mu_t, \sigma_t)\right] \epsilon(m_+^2, m_-^2)$$

- $\boldsymbol{\mathcal{A}_f(t', m_+^2, m_-^2)}$ is the amplitude model
- $\boldsymbol{\epsilon(t')}$ is the decay-time acceptance



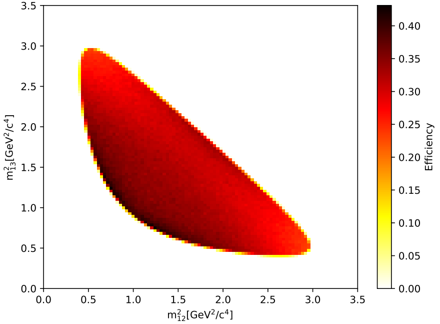
$$\mathcal{P}_{sig}(t, m_+^2, m_-^2, tag, \vec{\alpha}) = \left[\left(|\mathcal{A}_f(t', m_+^2, m_-^2)|^2\, \epsilon(t')\right) \otimes \boldsymbol{R(t, t', \mu_t, \sigma_t)}\right] \epsilon(m_+^2, m_-^2)$$

- $\boldsymbol{\mathcal{A}_f(t', m_+^2, m_-^2)}$ is the amplitude model
- $\boldsymbol{\epsilon(t')}$ is the decay-time acceptance
- $\boldsymbol{R(t, t', \mu_t, \sigma_t)}$ is the decay-time resolution

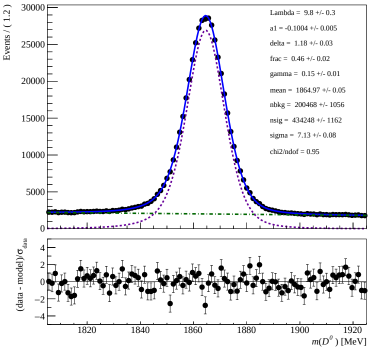


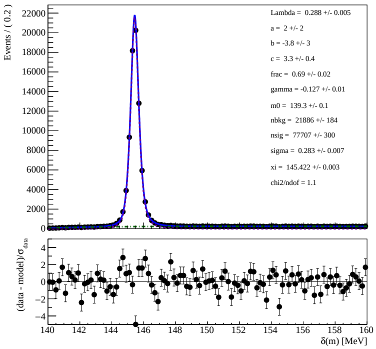
$$\mathcal{P}_{sig}(t, m_+^2, m_-^2, tag, \vec{\alpha}) = \left[\left(\mid \mathcal{A}_f(t', m_+^2, m_-^2) \mid^2 \epsilon(t')\right) \otimes R(t, t', \mu_t, \sigma_t)\right] \boldsymbol{\epsilon(m_+^2, m_-^2)}$$

- $\mathcal{A}_f(t', m_+^2, m_-^2)$ is the amplitude model
- $\epsilon(t')$ is the decay-time acceptance
- $R(t, t', \mu_t, \sigma_t)$ is the decay-time resolution
- $\epsilon(m_+^2, m_-^2)$ is the phase-space acceptance



Data Selection





- Turbo trigger, offline pre-selection and data-trained MVA.
- 1.36M (2.80M) single-tagged LL (DD) signal candidates, and 0.22M (0.48M) double-tagged LL (DD) signal candidates, summing to $\sim$ 4.9M signal candidates in total.

Amplitude formalism

- The amplitude for $D \to abc$ through an intermediate resonance $r \to ab$ is given by:

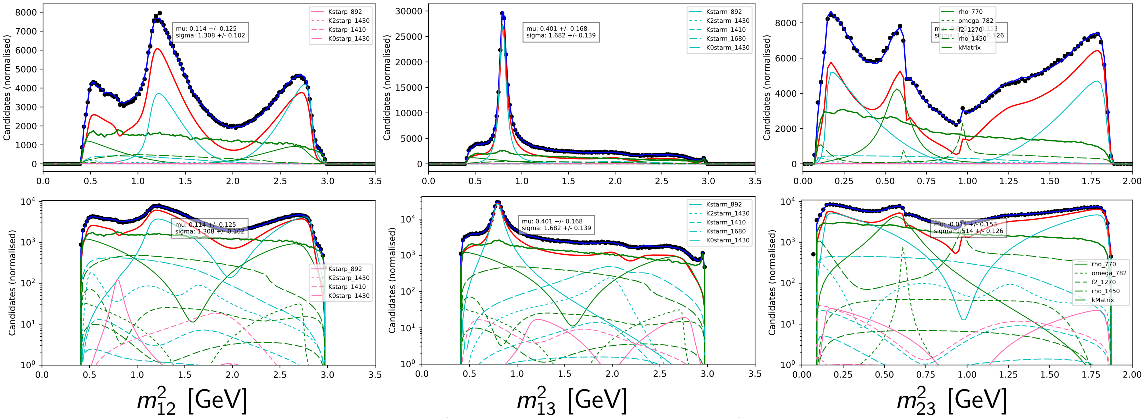
$$A_r(m_+^2, m_-^2) = F_D^{(L)}(q, q_0) \times F_r^{(L)}(p, p_0) \times Z_L(\Omega) \times \mathcal{T}_r(m) \tag{1}$$

- where the form factors $F_D^{(L)}$ and $F_r^{(L)}$ describe the decay $D \to rc$ and $r \to ab$,
- L is the orbital angular momentum between a and c,
- p and q are the momenta of c and a in the resonance rest frame,
- $Z_L(\Omega)$ describes the angular distribution of the final state particles,
- $\mathcal{T}_r$ is the dynamical function describing the resonance r

$$\mathcal{T}(D^0 \to K_S^0\pi^+\pi^-) = c_K\mathcal{T}_{\pi\pi} + c_L\mathcal{T}_{K\pi} + \sum_r c_r\mathcal{T}_r \tag{2}$$

- $\pi\pi$ S-wave described by K-matrix ($\mathcal{T}_{\pi\pi}$), $K\pi$ S-wave by LASS ($\mathcal{T}_{K\pi}$)

Time-integrated Fit

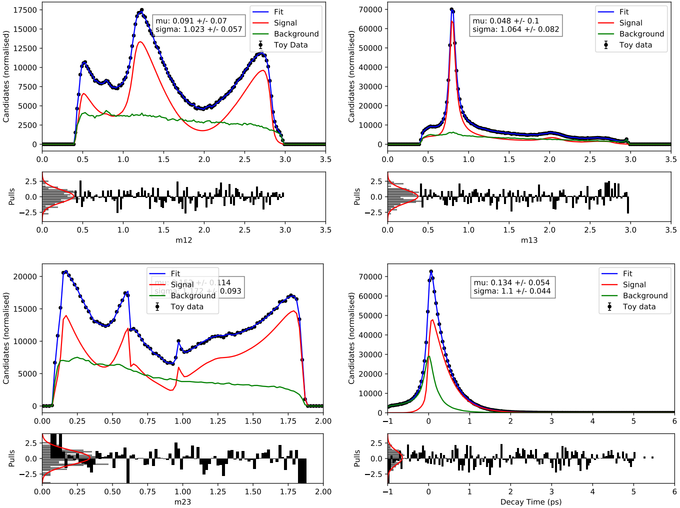


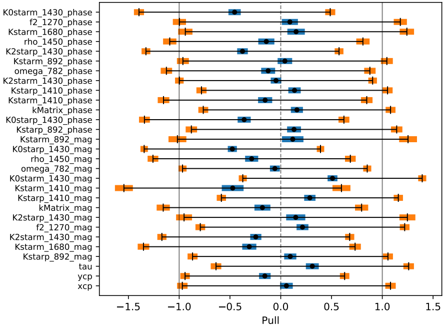
Fit projections. Single-tagged K_S^0 (LL) 2016 sample. Fit $\chi^2/\text{ndof} = 1.18$ for 6763 ndof.

Toy studies

- Toy psuedoexperiments are used to validate the fitter, assess potential biases and estimate statistical precision.
- Amplitude model taken from initial time-integrated fit
- Realistic background and detector effects are included
- Decay-time is generated using the PDG value of D^0 lifetime
- Toys are generated with world average values of x and y $\pm 1\sigma$

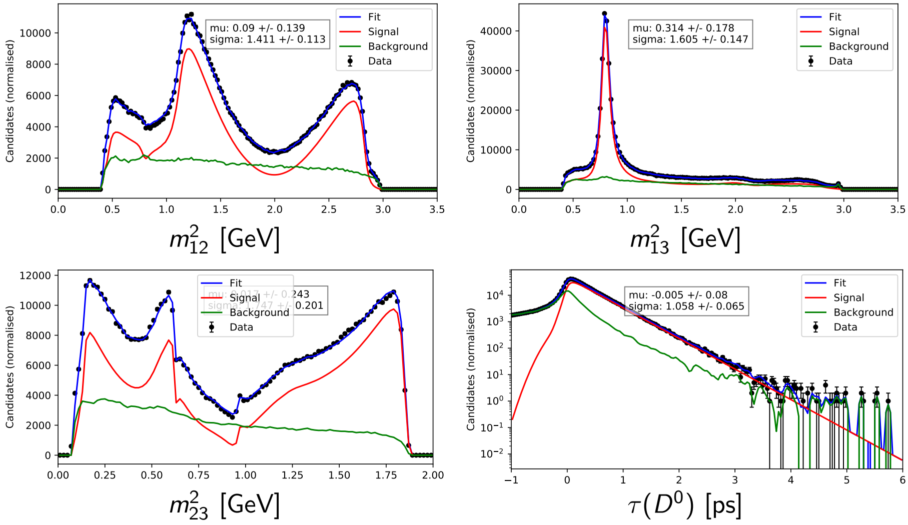
Toy Studies





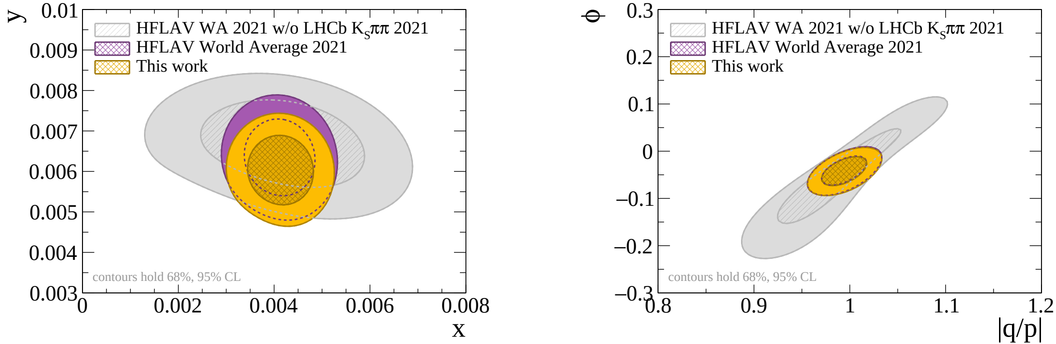
Mean and width of pulls of fit parameters (above). Fit projections for one toy (left).

Time-dependent Fit (Single-tagged K_S^0 (LL) 2016)



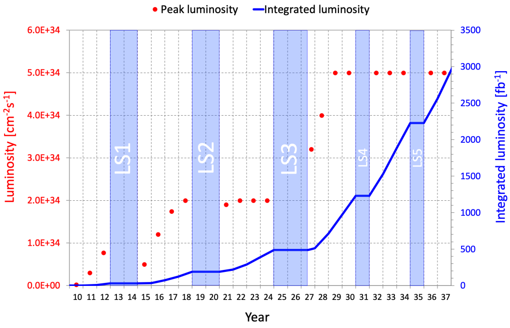
Systematic Uncertainties

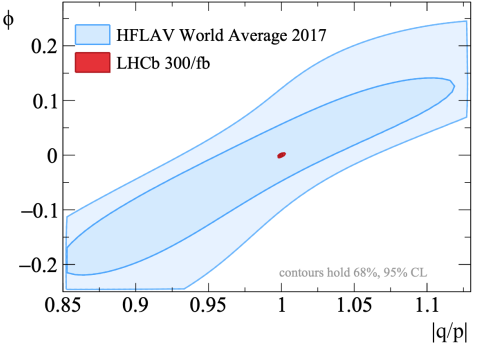
- Model-dependent systematic uncertainties are related to the choice of amplitude model
- Largest experimental systematic uncertainty is due to the background PDF
- Systematics are evaluated by resampling and rerunning fit to data or with toys
- Numbers are preliminary, some need to be updated with the simultaneous fit
- So far they are under control and comparable but below the statistical uncertainty



This figure shows world average not including the bin-flip result (grey), current world averages on the mixing and CP-violation parameters (purple) including the bin-flip result, and this work (yellow)*.

* This work refers to the model-dependent amplitude analysis which is currently WIP and blind, here central values assumed are those of the bin-flip result.





Charm CP-violation still statistically limited. With the LHCb upgrade, the statistical precision will improve.

Summary

- CP violation in charm discovery ΔA_{CP}
- CP violation in charm is a potential probe of new physics and CP violating processes in the up-type sector
- First observation of the non-zero mass measurement in neutral charm mesons
- Motivates precision measurements in mixing and the CP violation in mixing in charm
- New results in progress and more data in Run 3 make LHCb charm physics an exciting program!

Back Up