CP violation in two-body charm decays at LHCb

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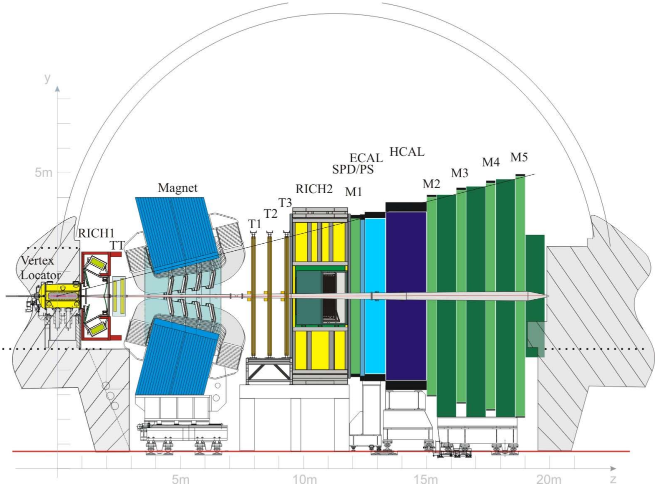
Introduction to LHCb

The LHCb detector

Physics at LHCb

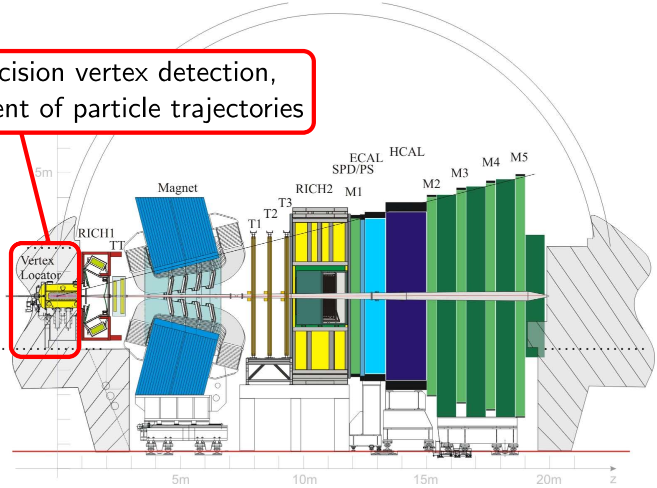
- LHCb designed for heavy flavour (b, c) physics:
  - Indirect searches for new physics in loop diagrams,
  - Precision measurements of CP violation parameters,
  - Rare decays,
  - Electroweak and soft QCD.
- Huge $b\bar{b}$ and $c\bar{c}$ cross sections:
  - Open charm cross section (6.10 ± 0.93) mb,
  - $B^{\pm}$ cross section $(41.4 \pm 1.5 \pm 3.1)$ μb.
- Large forward boost.
- LHCb designed to exploit these features:
  - Precision vertexing capabilities,
  - Good time resolution,
  - Excellent PID.

The LHCb detector

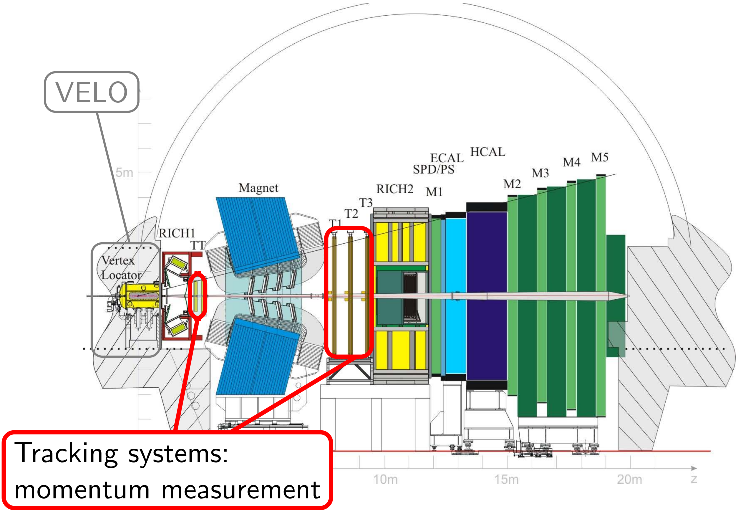


The LHCb detector

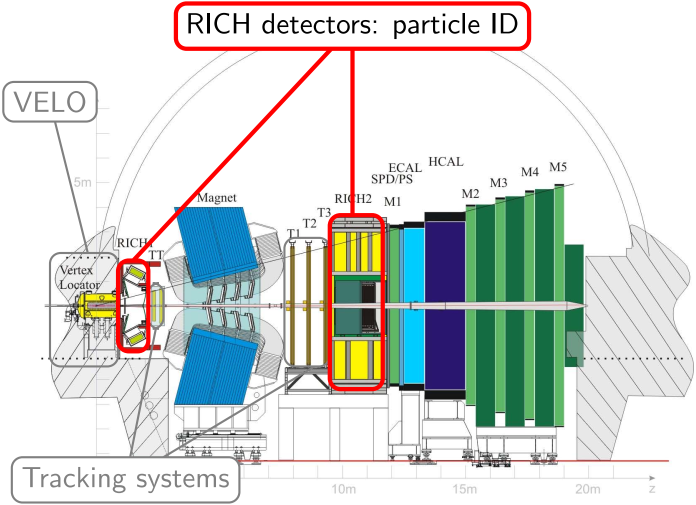
VELO: precision vertex detection, measurement of particle trajectories



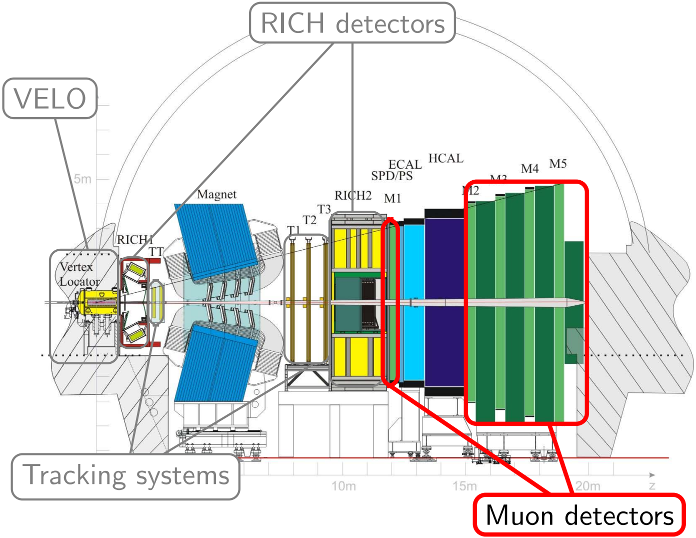
The LHCb detector



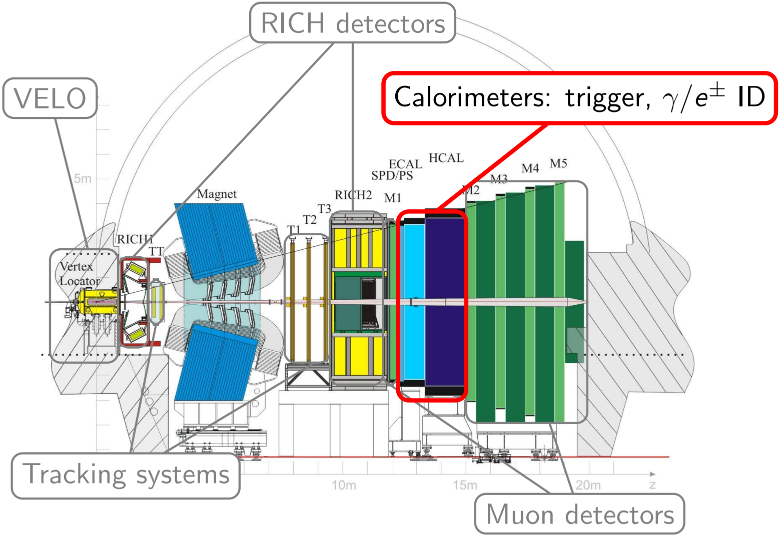
The LHCb detector



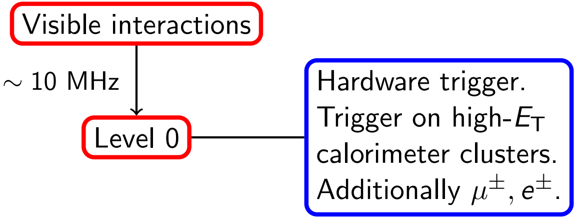
The LHCb detector



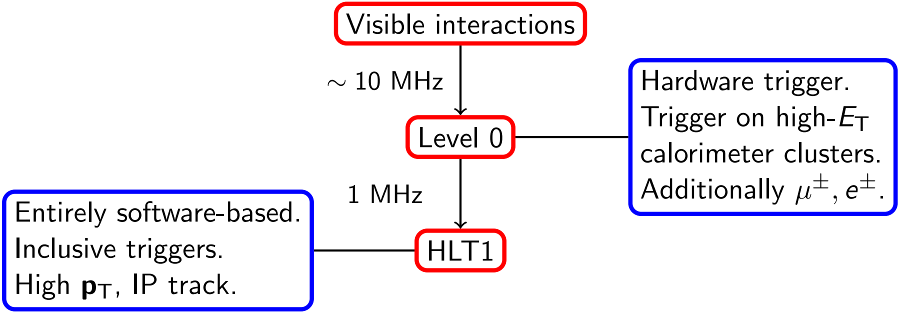
The LHCb detector



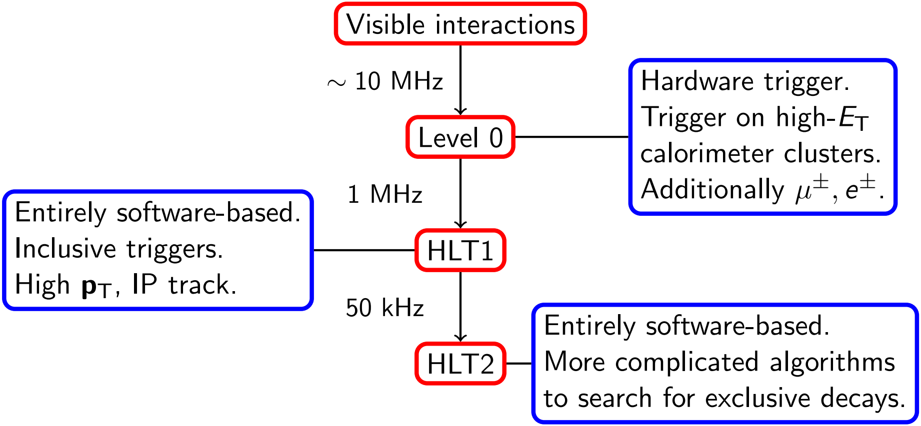
Triggering at LHCb



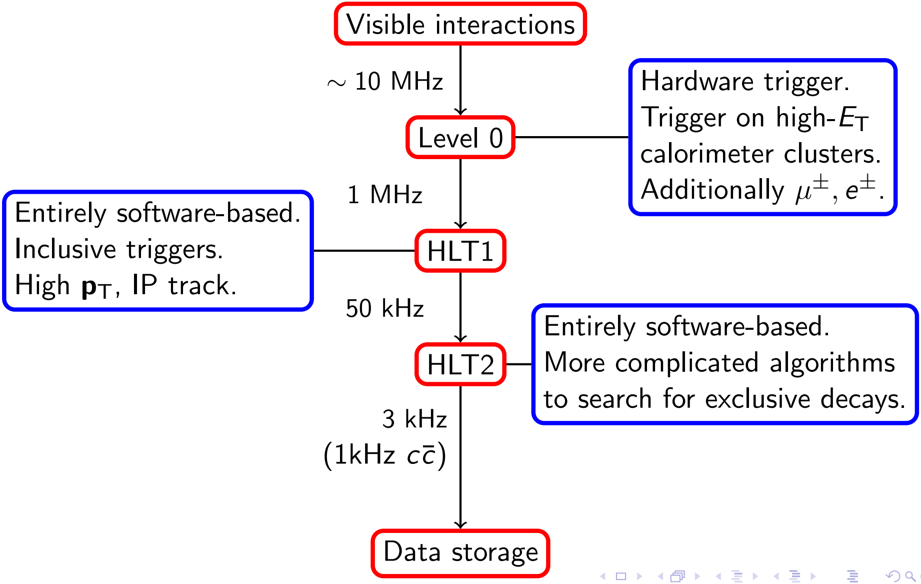
Triggering at LHCb



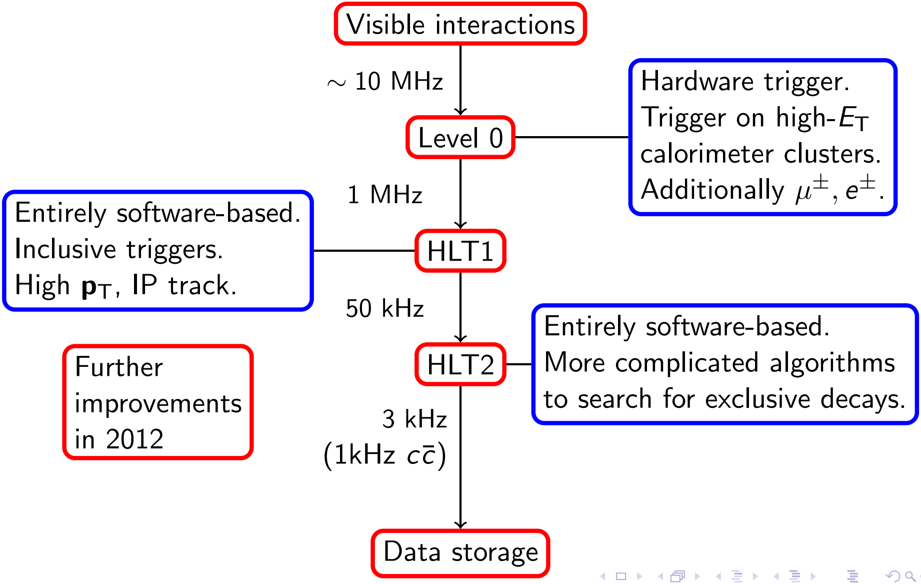
Triggering at LHCb



Triggering at LHCb



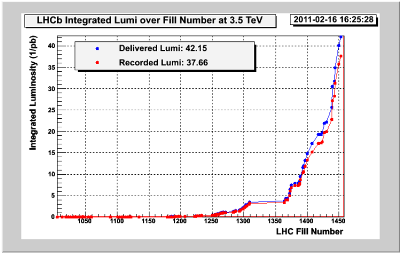
Triggering at LHCb

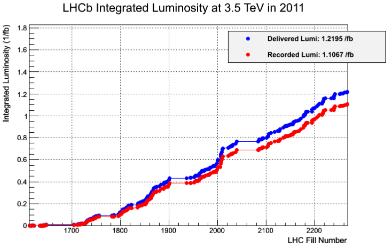


Data recorded in 2010 and 2011

2010: 38 pb^{-1}

2011: 1.1 fb^{-1}



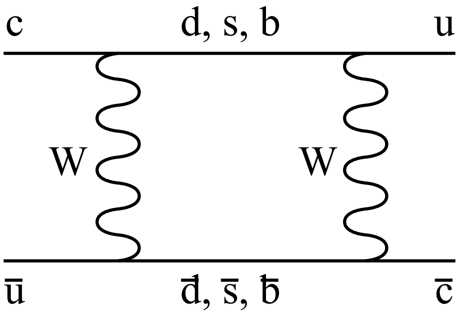


Luminosity levelling used to control pileup. Adjust beam deflection over fill to achieve constant luminsity.

Charm mixing and *CP* violation

Charm mixing

Mixing in the charm sector is unique in the SM because it occurs between up-type quarks. One possible mechanism is the box diagram:



Small effect compared to well-established K and B systems.
Mixing connected intimately with CP violation.

Time evolution of neutral mesons

Physical (mass) states are related to flavour states as follows:

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

where $|p|^2 + |q|^2 = 1$.
Time evolution of this system:

$$|D_1(t)\rangle = |D_1\rangle e^{-i(m_1 - i\Gamma_1/2)t},$$
$$|D_2(t)\rangle = |D_2\rangle e^{-i(m_2 - i\Gamma_2/2)t}.$$

where $m_{1,2}$ and $\Gamma_{1,2}$ are respectively the masses and widths of $|D_{1,2}\rangle$.
Invert this to obtain evolution of flavour eigenstates:

$$|D^0(t)\rangle = \frac{1}{2p}\Big[e^{-i(m_1 - i\Gamma_1/2)t}(p|D^0\rangle + q|\bar{D}^0\rangle) + e^{-i(m_2 - i\Gamma_2/2)t}(p|D^0\rangle - q|\bar{D}^0\rangle)\Big].$$

CP violation in mesons

CP violation arises when a decay can proceed via two different amplitudes with different strong and weak phases. Three types of CPV are possible in neutral meson systems. For the final state f:

- Decay: A_f, the rate of $D^0 \to f$, is not equal to $\bar{A}_{\bar{f}}$, the rate of $\bar{D}^0 \to \bar{f}$. Direct CPV.
- Mixing: the rate of $D^0 \to \bar{D}^0$ transitions is not equal to the rate of $\bar{D}^0 \to D^0$; $|q/p| \neq 1$. Indirect CPV.
- Interference between decay and mixing, e.g. between $D^0 \to f$ and $D^0 \to \bar{D}^0 \to f$; $Im(q\bar{A}_{\bar{f}}/pA_f) \neq 0$.

In charged meson systems only direct CPV is possible.
New physics could significantly enhance both direct and indirect CPV.

Mixing and CPV parameters

Mixing is conventionally quantified using the parameters:

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

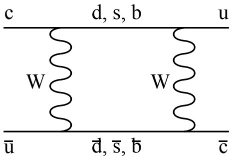
where $\Gamma \equiv (\Gamma_1 + \Gamma_2)/2$.
CP violation is expressed using:

$$\left|\frac{q}{p}\right|, \qquad \phi \equiv \arg\left(\frac{q}{p}\right).$$

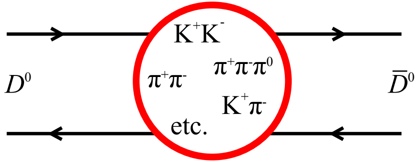
Charm mixing

Charm mixing is small in the Standard Model. Contributions from:

- Short range box diagrams: contribute mostly to x. Intermediate b are CKM suppressed; intermediate d, s are GIM suppressed. $x \sim 10^{-5}$.

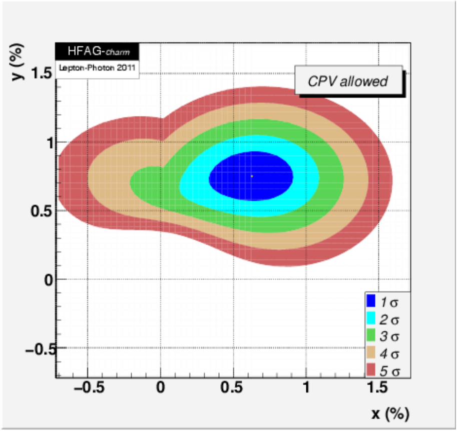


- Long range hadronic intermediate states (e.g. $D^0 \to K^+K^- \to \bar{D}^0$). Non perturbative, hard to predict SM contribution. $|x|, |y| < 0.01$.



Current values of x and y

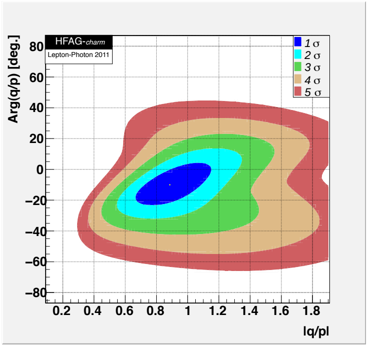
Current state of x and y allowing for CPV (HFAG):



Excludes no-mixing hypothesis by 10σ.

Current values of q and p

Current state of q and p (HFAG):



CP asymmetries are very small ($\mathcal{O}(10^{-4})$), e.g.:

$$2A_\Gamma = (|q/p| - |p/q|)y\cos(\phi) - (|q/p| + |p/q|)x\sin(\phi)$$

Terms in red $\ll 1$.

Mixing and indirect *CP* violation with $D^0 \to K^+K^-, \pi^+\pi^-$

Mixing and CPV in two-body D decays

Measurement of two key parameters: y_{CP} and A_Γ.
Analysis of 2010 data recently submitted to JHEP (hep-ex/1112.4698).
y_{CP} is a ratio of lifetimes between CP even and mixed CP final states:

$$y_{CP} \equiv \frac{\tau(D^0 \to K^-\pi^+)}{\tau(D^0 \to K^+K^-)} - 1$$
$$\simeq y\cos(\phi)\left(1 + \frac{1}{8}A_m^2\right) - \frac{1}{2}A_m x \sin(\phi)$$

where $|q/p|^{\pm 2} \approx 1 \pm A_m$, $\phi = \arg(q\bar{A}_f / pA_f)$.
In absence of CPV, $y_{CP} = y$.

Mixing and CPV in two-body D decays

A_Γ is the indirect CP asymmetry in flavour-tagged decays to CP eigenstates:

$$A_\Gamma \equiv \frac{\Gamma(D^0 \to K^+K^-) - \Gamma(\bar{D}^0 \to K^+K^-)}{\Gamma(D^0 \to K^+K^-) + \Gamma(\bar{D}^0 \to K^+K^-)} \simeq \frac{1}{2}(A_m + A_d) y \cos(\phi)$$

where $|\bar{A}_f / A_f|^{\pm 2} \approx 1 \pm A_d$.
This quantity is non-zero if CP violation is present. Both direct and indirect CPV can play a role in this.
The absolute lifetime distribution is measured for each final state and used to determine y_{CP} and A_Γ.

Experimental considerations

Main challenges:

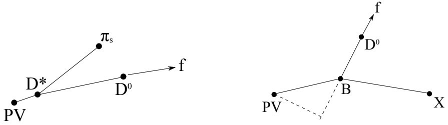
- Background from secondary charm ($b \to c$),
- Lifetime-biasing trigger and selection.

LHCb has several nice features for this analysis, including:

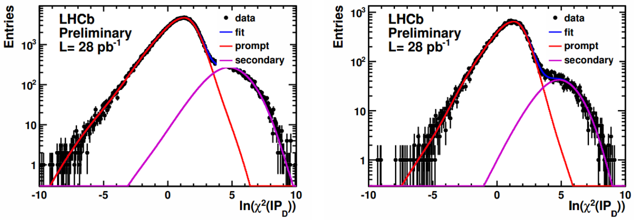
- Large boost means resolution less than lifetime,
- Large production cross section.

Prompt and secondary decays

Flavour tagging at production using $D^{*\pm} \to D\pi_s^\pm$ decays.
Prompt (left) and secondary (right) decays:

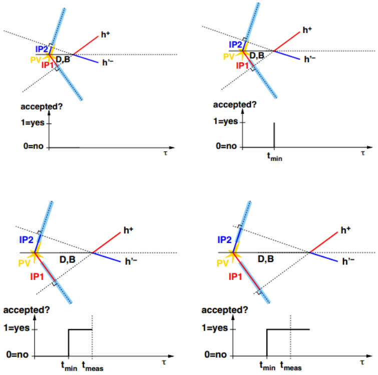


Prompt/secondary discrimination using ln(IPχ^2). Distribution for $D^0 \to K^\pm\pi^\mp$ decays:



Dealing with lifetime acceptance

Swimming used in order to determine event-by-event lifetime acceptances. Suited to LHCb because can reproduce trigger exactly in software. Use data instead of MC.

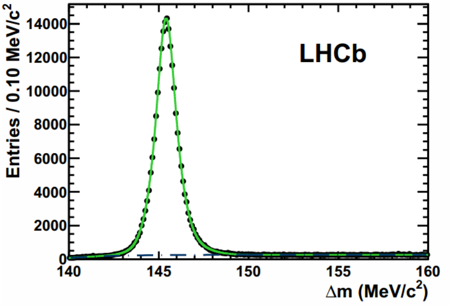


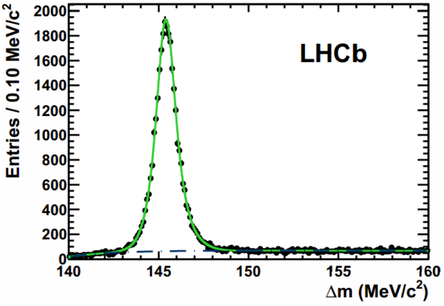
Ideally would shift D^0 decay vertex, but very challenging. Have to move all VELO hits, for example.

Instead, move primary vertices in the opposite direction. Almost the same; systematic uncertainty for difference.

Mass fits

Select 286k $D \to K^{\pm}\pi^{\mp}$ events, 39k $D \to K^+K^-$ (2010 data).
Fits on $\Delta M \equiv m_{D^*} - m_D$ for $D \to K^{\pm}\pi^{\mp}$ (left), $D \to K^+K^-$ (right):





Results

Lifetimes:

$$\tau(D^0 \to K^{\pm}\pi^{\pm}) = (410.2 \pm 0.9(\text{stat}))\ \text{fs},$$
$$\tau(D^0 \to K^+K^-) = (408.0 \pm 2.4(\text{stat}))\ \text{fs}.$$

CP violation parameters:

$$y_{CP} = (5.5 \pm 6.3(\text{stat}) \pm 4.1(\text{syst})) \times 10^{-3},$$
$$A_{\Gamma} = (-5.9 \pm 5.9(\text{stat}) \pm 2.1(\text{syst}))^{-3}.$$

Both results consistent with world averages ($y_{CP} = (1.107 \pm 0.217)\%$, $A_{\Gamma} = (0.123 \pm 0.248)\%$). Largest systematic uncertainties due to estimation of combinatoric and secondary backgrounds.
Significant improvement in precision expected when analysing entire 2011 dataset; better treatment of combinatoric background and secondaries.

Time-integrated CP asymmetries in $D^0 \to K^+K^-, \pi^+\pi^-$

Time-integrated CP violation

CP asymmetry in D decays to CP eigenstate h^+h^- $(h = \pi, K)$:

$$A_{CP}(h^+h^-) \equiv \frac{\Gamma(D^0 \to h^+h^-) - \Gamma(\bar{D}^0 \to h^+h^-)}{\Gamma(D^0 \to h^+h^-) + \Gamma(\bar{D}^0 \to h^+h^-)}.$$

Can measure separate quantities for K^+K^- and $\pi^+\pi^-$, but measuring the difference between the two is an effective way to separate physics asymmetries from other sources of asymmetry.
Submitted to Phys Rev Lett (hep-ex/1112.0938).

D^0 to K^+K^- and $\pi^+\pi^-$ measurements

CP asymmetries for K^+K^- (top) and $\pi^+\pi^-$ (bottom):

Year	Experiment	CP Asymmetry in the decay mode D0 to K+K-	[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]
2011	CDF	A. Di Canto (CDF Collab.), Preprint (BEAUTY 2011).	-0.0024 ± 0.0022 ± 0.0010
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett. B 670, 190 (2008).	-0.0043 ± 0.0030 ± 0.0011
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	+0.0000 ± 0.0034 ± 0.0013
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.000 ± 0.022 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	-0.001 ± 0.022 ± 0.015
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.010 ± 0.049 ± 0.012
1995	CLEO	J.E. Bartelt et al. (CLEO Collab.), Phys. Rev. D 52, 4860 (1995).	+0.080 ± 0.061
1994	E687	P.L. Frabetti et al. (E687 Collab.), Phys. Rev. D 50, 2953 (1994).	+0.024 ± 0.084
.	.	COMBOS average	-0.0023 ± 0.0017

Year	Experiment	CP Asymmetry in the decay mode D0 to π+π-	[Γ(D0)-Γ(D0bar)]/[Γ(D0)+Γ(D0bar)]
2010	CDF	M.J. Morello (CDF Collab.), Preprint (CHARM 2010).	+0.0022 ± 0.0024 ± 0.0011
2008	BELLE	M. Staric et al. (BELLE Collab.), Phys. Lett. B 670, 190 2008).	+0.0043 ± 0.0052 ± 0.0012
2008	BABAR	B. Aubert et al. (BABAR Collab.), Phys. Rev. Lett. 100, 061803 (2008).	-0.0024 ± 0.0052 ± 0.0022
2002	CLEO	S.E. Csorna et al. (CLEO Collab.), Phys. Rev. D 65, 092001 (2002).	+0.019 ± 0.032 ± 0.008
2000	FOCUS	J.M. Link et al. (FOCUS Collab.), Phys. Lett. B 491, 232 (2000).	+0.048 ± 0.039 ± 0.025
1998	E791	E.M. Aitala et al. (E791 Collab.), Phys. Lett. B 421, 405 (1998).	-0.049 ± 0.078 ± 0.030
.	.	COMBOS average	+0.0020 ± 0.0022

K^+K^- and $\pi^+\pi^-$ consistent but opposite sign.

Asymmetries

Use $D^\pm \to D\pi_s^\pm$ decays in which the D decays to f.
Raw (measured) asymmetry is:

$$A_{\text{raw}}(f) = A_{CP}(f) + A_{\text{det}}(f) + A_{\text{det}}(\pi_s) + A_{\text{prod}}(D^{*\pm}),$$

where A_{det} is detector asymmetry, A_{prod} is production asymmetry. This expansion is valid because all asymmetries are small.
Measure difference between raw asymmetries of D decays to K^+K^- and $\pi^+\pi^-$. Expect:

- A_{prod} and $A_{\text{det}}(\pi_s)$ cancel in the difference,
- $A_{\text{det}}(f)$ will be zero for D^0 decays to h^+h^-.

i.e. all D^*-related production and detection effects cancel.
All that remains is:

$$\Delta A_{CP} \equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-).$$

Direct and indirect CP asymmetry

CP asymmetry is decomposed into direct (A_{CP}^{dir}) and indirect (A_{CP}^{ind}) contributions.

$$A_{CP}(f) = A_{CP}^{\text{dir}}(f) + \frac{\langle t \rangle}{\tau} A_{CP}^{\text{ind}},$$

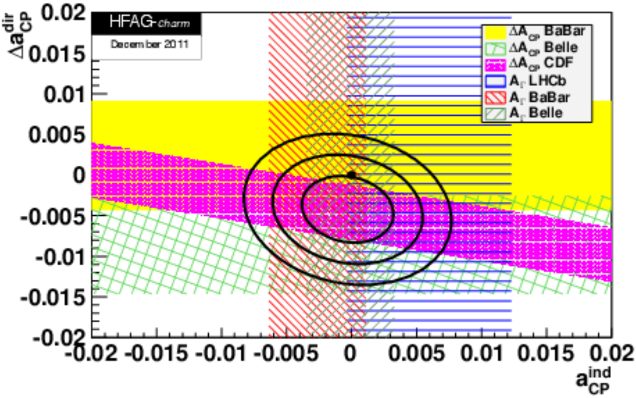
where $\langle t \rangle$ is average decay time in sample, τ is D^0 lifetime.
A_{CP}^{ind} thought to be universal between D decays to different CP eigenstates. Therefore:

$$\begin{aligned} \Delta A_{CP} &\equiv A_{CP}(K^+K^-) - A_{CP}(\pi^+\pi^-) \\ &= [A_{CP}^{\text{dir}}(K^+K^-) - A_{CP}^{\text{dir}}(\pi^+\pi^-)] + \frac{\Delta\langle t \rangle}{\tau} A_{CP}^{\text{ind}} \end{aligned}$$

where $\Delta\langle t \rangle$ is difference between the values of $\langle t \rangle$ obtained for K^+K^- and $\pi^+\pi^-$. This difference is zero if equal proper time acceptance for both (BaBar, Belle). Define $\Delta A_{CP}^{\text{dir}} \equiv A_{CP}^{\text{dir}}(K^+K^-) - A_{CP}^{\text{dir}}(\pi^+\pi^-)$.

Previous measurements

HFAG world-average plot of direct and indirect contributions *without* including the measurement shown today:



Best-fit A_{CP}^{ind} is $(-0.03 \pm 0.23)\%$; $\Delta A_{CP}^{\text{dir}}$ is $(-0.42 \pm 0.27)\%$. Consistency with no-CPV hypothesis is 28%.

LHCb analysis

Analysis of 580 pb^{-1}, 2011 data only. About 1.44M in K^+K^- sample, 0.38M in $\pi^+\pi^-$.

Kinematic and geometrical selection criteria:

- Track fit quality for all three tracks,
- D and D^* vertex fit quality,
- D $\mathbf{p}_\mathrm{T} > 2$ GeV/c,
- D $c\tau > 100$ μm,
- D cos(helicity angle) < 0.9,
- D IP $\chi^2 < 9$,
- Lower limits on D daughters' IP χ^2,
- Kaon DLL$(K-\pi) > 5$, pion DLL$(\pi - K) > 5$,

D candidate must be fire relevant HLT line.

D mass between 1844 and 1884 MeV/c^2.

Second-order effects

Double difference is robust against systematics.
However, kinematics of the final states K^+K^- and $\pi^+\pi^-$ differ slightly.
Likely that A_{prod} and/or A_{det} do not cancel exactly due to second-order effects that can fake an asymmetry.

- A_{prod} and/or A_{det} could vary with $\mathbf{p}_{\text{T}}$ or η; so could $K^+K^-/\pi^+\pi^-$ detection efficiency. Would cause a correlated variation of A_{prod} and A_{det} with kinematics (p_T, η).
- Asymmetric peaking background different between K^+K^- and $\pi^+\pi^-$. Peaking background caused by misreconstructed $D^{*\pm} \to D\pi_s$ decays. Estimate that this effect is $\mathcal{O}(10^{-4})$. Small due to excellent LHCb hadron ID.

Binning

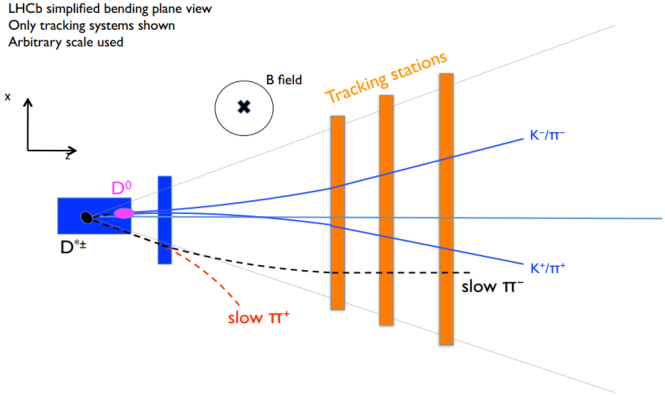
To mitigate second-order effects, divide data into kinematic bins such that conditions are similar in each bin:

- $(3 \times 3 \times 3)$ bins in D^* $\mathbf{p}_\mathrm{T}$, D^* η, and π_s $|\mathbf{p}|$,
- Left/right detector hemispheres,
- Magnet polarity,
- Before/after technical stop,
- Fit K^+K^- and $\pi^+\pi^-$ separately.

432 bins in total.

Left/right differences

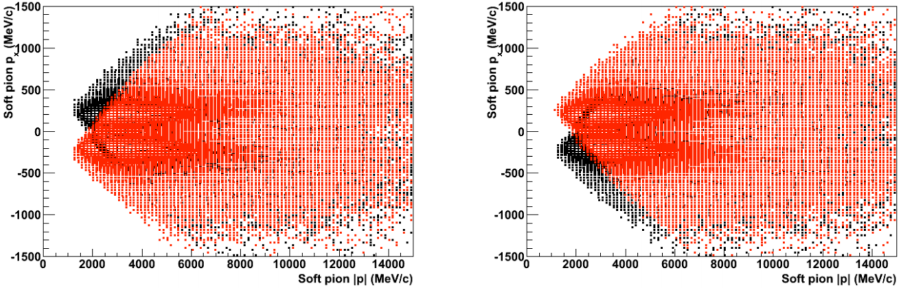
Magnetic field curves trajectory of slow pion. Causes differences in D^{*+}, D^{*-} reconstruction in different halves of the detector:



Large raw asymmetries could induce second-order effects.

Acceptance at edges of detector

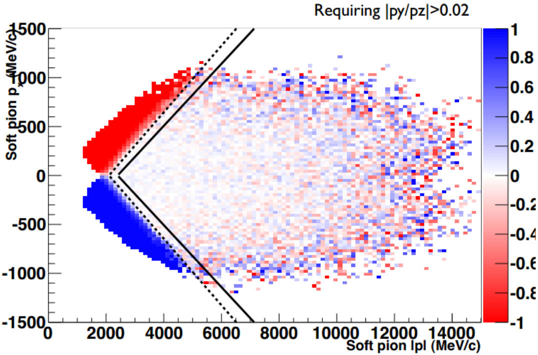
Small regions of phase space in which only D^{*+} or D^{*-} are possible:



Large raw asymmetries. Could have second order effects if raw asymmetry changes rapidly and ratio of efficiencies of K^+K^- and $\pi^+\pi^-$ changes. Minimal information on ΔA_{CP} in these regions, so exclude them.

Acceptance at edges of detector

Edge regions are excluded with fiducial cuts.
Raw asymmetry in $(p_x, |p|)$ plane of tagged slow pion:

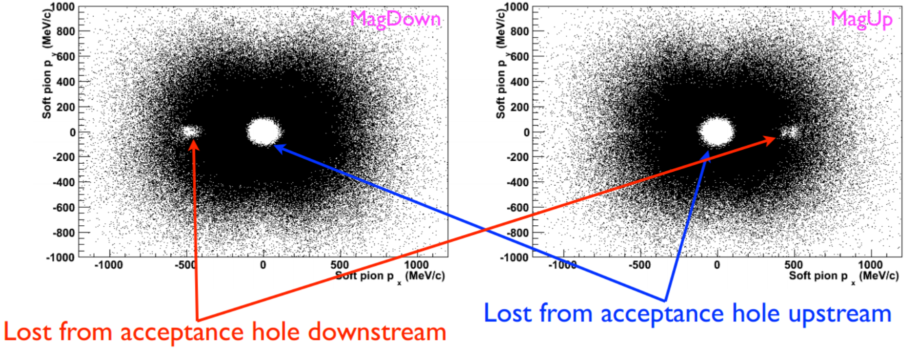


Solid line shows cuts applied; dotted line is looser cuts used for cross check.

Beampipe downstream of magnet

Small region in which one charge of π_s is more likely to be deflected into beampipe: reduced efficiency.

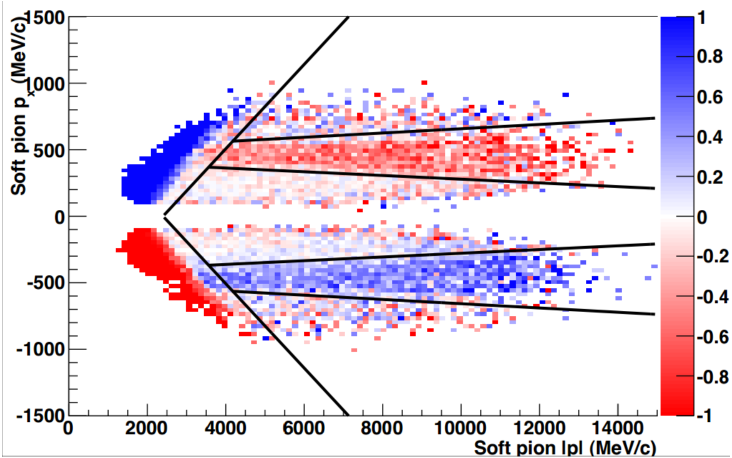
Slow pion p_y vs p_x:



Upstream acceptance charge-independent; downstream has L/R asymmetry.

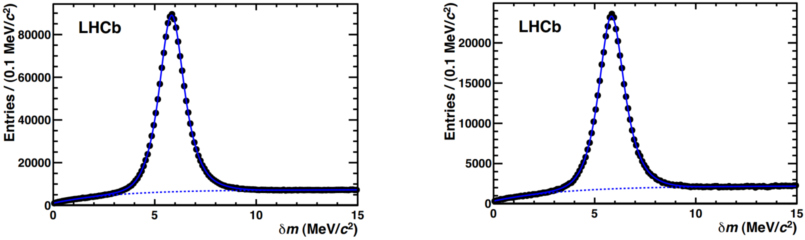
Beampipe downstream of magnet

Apply further fiducial cuts to account for asymmetries in beampipe. Only applied when $|\mathbf{p}_y/\mathbf{p}_z| < 0.02$.



Mass fits

Fits to $\delta m \equiv m_{D^*} - m_D - m_{\pi_s}$ distributions (left: K^+K^-, right: $\pi^+\pi^-$):



Signal model is double Gaussian convolved with asymmetric tail:

$$g(\delta m) = [\Theta(\delta m' - \mu)A(\delta m' - \mu)^s] \otimes G_2(\delta m - \delta m'; f_{core}, \sigma_{core}, \sigma_{tail})$$

Background model is empirical parameterisation of combinatoric shape:

$$h(\delta m) = B\left[1 - \exp\left(\frac{-\delta m - \delta m_0}{c}\right)\right]$$

δm_0 fixed from fit to high-statistics $K^\pm\pi^\mp$ channel.

Systematic uncertainties

- Kinematic binning: 0.02%
  - Change in ΔA_{CP} between default binning and one giant bin.
- Fit procedure: 0.08%
  - Change in ΔA_{CP} between baseline and no fitting, just sideband subtraction.
- Peaking background: 0.04%
  - Toy studies; inject a peaking background with a size and asymmetry set according to D^0 mass sidebands.
- Multiple candidates: 0.06%
  - Mean change in ΔA_{CP} when removing multiple candidates, keeping one per event chosen at random.
- Fiducial cuts: 0.01%
  - Change in ΔA_{CP} when significantly loosening the cuts.

Sum in quadrature: 0.11%.

Results

$$\Delta A_{CP} = (-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{syst}))\%.$$

3.5σ deviation from zero.

First evidence for CPV in the charm sector.

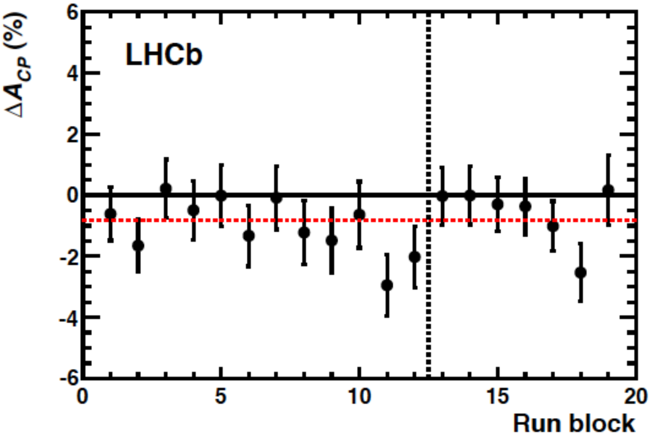
Cross checks

Numerous cross checks performed:

- Electron and muon vetos on soft pion and D daughters,
- Different kinematic binnings,
- Stability over time,
- Toy MC studies,
- Tightening PID cuts,
- Stability with kinematic variables,
- Variation with event track multiplicity,
- Use of other signal and bkg lineshapes,
- Alternative offline processing (skimming/stripping),
- Internal consistency between subsamples of data.

All variation is within appropriate statistical/systematic uncertainties.

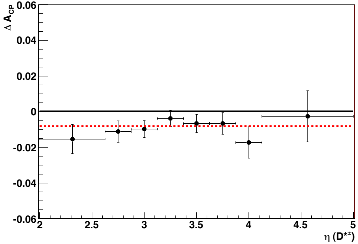
Stability over time

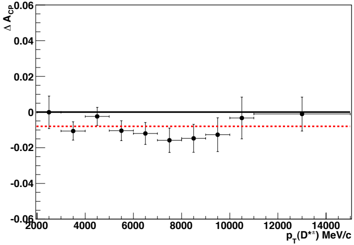


Red line: average value of ΔA_{CP}. Black line: technical stop

Stability against kinematic variables

Determine ΔA_{CP} in bins of kinematic variables:





No evidence of dependence on relevant kinematic variables.

Consistency among subsamples

Subsample	ΔA_{CP}	χ^2/ndf
Pre-TS, field up, left	$(-1.22 \pm 0.59)\%$	$13/26(98\%)$
Pre-TS, field up, right	$(-1.43 \pm 0.59)\%$	$27/26(39\%)$
Pre-TS, field down, left	$(-0.59 \pm 0.52)\%$	$19/26(84\%)$
Pre-TS, field down, right	$(-0.51 \pm 0.52)\%$	$29/26(30\%)$
Post-TS, field up, left	$(-0.79 \pm 0.90)\%$	$26/26(44\%)$
Post-TS, field up, right	$(+0.42 \pm 0.93)\%$	$21/26(77\%)$
Post-TS, field down, left	$(-0.24 \pm 0.56)\%$	$34/26(15\%)$
Post-TS, field down, right	$(-1.59 \pm 0.57)\%$	$35/26(12\%)$
All data	$(-0.82 \pm 0.21)\%$	$211/215(56\%)$

Split by:

- Before/after technical stop (60% before);
- Magnetic field polarity;
- Charge of slow pion.

Consistency among subsamples: $\chi^2/\text{dof} = 6.7/7$ (45%)

Lifetime acceptance

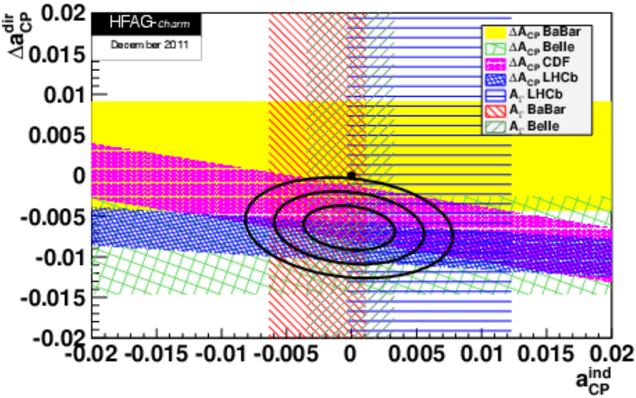
Lifetime acceptance is different between K^+K^- and $\pi^+\pi^-$.

- Smaller opening angle for K^+K^-. Short-lived $D \to K^+K^-$ more likely than $D \to \pi^+\pi^-$ to fail the cut requiring daughters NOT to point to the primary vertex.

Determine influence of this on indirect CP asymmetry. To recap:
$\Delta A_{CP} \equiv \Delta A_{CP}^{\text{dir}} + \frac{\Delta\langle t\rangle}{\tau} A_{CP}^{\text{ind}}$.
Fit to background-subtracted samples passing full selection, correcting for $\sim 3\%$ secondary charm.
Measure $\Delta\langle t\rangle/\tau$ as $(9.8 \pm 0.9)\%$.
Consequence: indirect contribution to CP violation mostly cancels.

Updated world average

Newest HFAG world average:



Best-fit A_{CP}^{ind} is $(-0.02 \pm 0.23)\%$; $\Delta A_{CP}^{\text{dir}}$ is $(-0.65 \pm 0.18)\%$.
Consistency with no CPV is 0.15% (cf 28% before).

The future

- Update with full 1.1 fb^{-1},
- LHCb will collect another 1-2 fb^{-1} before long shutdown,
- CDF result on full dataset imminent,
- Determine ΔA_{CP} with independent methods, e.g. semileptonic $B^\pm$ decays,
- Search for both direct and indirect CP violation in other modes, e.g. $D^\pm \to h^\pm h^+ h^-$.

Conclusions

- Results presented for CP violation searches in two-body charm decays:
  - Time-dependent indirect CP violation: y_{CP} and A_Γ (2010 data),
  - Difference in time-integrated asymmetries for K^+K^- and $\pi^+\pi^-$: ΔA_{CP} (2011 data).
- $\Delta A_{CP} = (-0.82 \pm 0.21(\text{stat}) \pm 0.11(\text{syst}))\%$. 3.5σ significance.
- First observation of CP violation in charm.
- Indirect CP violation suppressed by term $\Delta\langle t\rangle/\tau = (9.8 \pm 0.3)\%$.
- ΔA_{CP} measured here is consistent with HFAG average.
  - Larger than SM expectation, but hard to pin down theoretically.
- More data available to study.