$CP$-violating asymmetries from the decay-time distribution of prompt $D^0 \rightarrow K^+ K^-$ and $D^0 \rightarrow \pi^+ \pi^-$ decays in the full LHCb Run 1 data sample

Measurement using unbinned, acceptance corrected decay-time

The LHCb collaboration

Abstract

A study of indirect $CP$ violation in $D^0$ mesons is presented through a measurement of the asymmetry of the effective decay widths of $D^0$ and $\bar{D}^0$ mesons to $CP$ eigenstates. This observable, known as $A_\Gamma$, is measured with the $CP$ eigenstates $K^+ K^-$ and $\pi^+ \pi^-$ using data collected in $pp$ collisions by the LHCb experiment in 2012 with an integrated luminosity of 1.9 fb$^{-1}$. The results are combined with a previously published LHCb measurement using this method for data collected in 2011 to yield average values of

\[
A_\Gamma(D^0 \rightarrow K^+ K^-) = (-0.14 \pm 0.37 \pm 0.10) \times 10^{-3},
\]
\[
A_\Gamma(D^0 \rightarrow \pi^+ \pi^-) = (0.14 \pm 0.63 \pm 0.15) \times 10^{-3},
\]

where the first quoted uncertainty is statistical, and the second systematic. The results are compatible with $CP$ conservation and with the Standard Model prediction.
1 Introduction

Violation of the symmetry under the combined parity and charge conjugation operations (CP) has yet to be observed unambiguously in charmed mesons. This system is the only one in which mesons of up-type quarks participate in matter-antimatter transitions, a loop-level process in the Standard Model (SM). The theoretical calculation of CP violation effects is challenging in the charm system. SM estimates of the asymmetry in the mixing rate or CP violation due to the interference between the mixing and decay amplitudes, collectively known as indirect CP violation, are $O(10^{-4})$ \[1,2\]. Enhancement of these CP violation effects would be an indication of physics beyond the SM.

The observable $A_\Gamma$ is defined as the asymmetry of the effective decay widths, $\hat{\Gamma}(D^0 \to f)$, in decays of $D^0$ mesons into CP-even final states denoted $f$,

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

The effective decay width is defined as the inverse of the mean decay time for an initial state identified as $D^0$ or $\bar{D}^0$, decaying to a specific CP eigenstate and is related to the time dependent decay rate by $\Gamma(t; D^0 \to f) \propto \exp(-\hat{\Gamma}(D^0 \to f)t) \equiv e^{-t/\hat{\tau}}$, where $\hat{\tau}$ is the effective lifetime determined by this measurement.

In the approximation of a negligible asymmetry in the rate of particle and antiparticle decays, known as direct CP violation, the parameter $A_\Gamma$ is given in terms of the basic parameters of the $D^0$ system by,

$$A_\Gamma = -(a_m + a_i),$$

$$a_m = -\frac{y}{2} \left( \frac{|q/p|}{|p|} - \frac{|p/q|}{|q|} \right) \cos \phi,$$

$$a_i = \frac{x}{2} \left( \frac{|q/p|}{|p|} + \frac{|p/q|}{|q|} \right) \sin \phi,$$

$$\phi = \arg \left( \frac{q \bar{A}_f}{p A_f} \right),$$

where $a_m$ represents CP violation in mixing, $a_i$ indicates CP violation in the interference of decays with and without mixing, $x$ and $y$ are the charm mixing parameters, $A_f(\bar{A}_f)$ is the amplitude of the $D^0 \to f$ ($\bar{D}^0 \to f$) decay, and $p$ and $q$ are the coefficients of linear combinations of the flavour eigenstates that define the mass eigenstates,

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

satisfying $|p|^2 + |q|^2 = 1$. Neglecting terms of order $|(V_{ub}V_{cb})/(V_{us}V_{cs})| \approx 10^{-3}$ and neglecting non tree-level contributions, $\phi$ is independent from the final state $f$ and is equal to the $D^0$ mixing phase, $\phi_D = \arg(q/p)$ \[3\].

The observable $A_\Gamma$ is primarily sensitive to indirect CP violation, as contributions from the asymmetry in the rate of particle and antiparticle decays are measured to be small compared to the current measurement precision \[4,6\]. Currently available measurements \[7,12\] of $A_\Gamma$ are in agreement with CP conservation.

\[1\]Charge conjugate states are included unless stated otherwise.
This conference report details a measurement of $A_T$ in the final states $K^+K^-$ and $\pi^+\pi^-$. The $K^-\pi^+$ decay channel is used to cross-check the analysis method. The analysis closely follows that reported in Ref. [8]. In the SM, the $K^+K^-$ and $\pi^+\pi^-$ final states are expected to yield the same result, but non-SM contributions could lead to differences. The analysis is performed with data collected by the LHCb experiment at the LHC in 2012 and uses $D^0$ mesons produced promptly at the primary $pp$ collision vertex. The data sample corresponds to an integrated luminosity of 1.9 fb$^{-1}$ of $pp$ collisions at 8 TeV centre-of-mass energy. The result is combined with a previously published LHCb result using the same method for data taken by the LHCb experiment in 2011, corresponding to an integrated luminosity of 1 fb$^{-1}$ at a centre-of-mass energy of 7 TeV, to provide a result from the full data sample recorded by the LHCb experiment during the first period of operation of the LHC, commonly known as Run 1.

The LHCb detector [13,14] is a single-arm forward spectrometer covering the pseudorapidity range $2<\eta<5$, designed for the study of particles containing $b$ or $c$ quarks. The detector elements that are particularly relevant to this analysis are: a silicon-strip vertex detector (VELO) surrounding the $pp$ interaction region that allows $c$ hadrons to be identified by their characteristically long flight distance; a tracking system that provides a measurement of momentum, $p$, of charged particles; and two ring-imaging Cherenkov detectors that are able to discriminate between different species of charged hadrons.

2 Event selection

The selection of $D^0$ events decaying to the final states $K^+K^-$, $\pi^+\pi^-$ and $K^-\pi^+$ is performed by the detector’s trigger system followed by an offline selection. The trigger [15] consists of a hardware stage, based on information from the calorimeter and muon systems, followed by a software stage, which performs a full event reconstruction. The software trigger first requires at least one track to have momentum transverse to the beamline, $p_T$, greater than $1.6 \text{ GeV}/c$ and $\chi^2_{IP} > 16$. The variable $\chi^2_{IP}$ is defined as the difference in the $\chi^2$ of a given primary interaction vertex reconstructed with and without the considered track. This $\chi^2_{IP}$ requirement introduces a preference for selecting longer-lived decays and gives rise to the largest effect on the observed decay-time distribution of any of the applied selection criteria.

The selected track is then combined with a second track to form a candidate for a $D^0$ decay into two hadrons. Selection criteria are applied to the tracks, including requiring the second track to have $p_T > 0.8 \text{ GeV}/c$ and $\chi^2_{IP} > 9$. The tracks are required to form a good quality vertex and the reconstructed $D^0$ candidate is required to point back to the primary interaction vertex. The $D^0$ invariant mass, $m(hh)$, where $hh$ represents the final state particles, has to lie within a $\pm 50 \text{ MeV}/c^2$ range of 1865 $\text{ MeV}/c^2$.

The offline selection consists of a set of criteria that are closely aligned to those applied at the trigger stage. The final state particles have to match particle identification criteria to separate kaons from pions [16] using combined information from the tracking and particle identification systems. A requirement on flight distance perpendicular to the beam line of less than $4 \text{ mm}$ is applied to the $D^0$ candidate in order to reduce the number of candidates produced by interactions with the detector material that separates the silicon strip sensors of the VELO from the primary beam vacuum of the LHC [17].

Flavour tagging is performed through the measurement of the charge of the soft pion
in the decay \( D^{*+} \to D^0 \pi^+ \). Additional criteria are applied to the track quality of the soft pion as well as to the vertex quality of the \( D^{*+} \) meson. The invariant mass difference between the \( D^{*+} \) and \( D^0 \) candidates, \( \Delta m \), is required to be less than 152 MeV/c^2.

About 13\% of the selected events have more than one candidate passing the selections, mostly due to one \( D^0 \) candidate being associated with several soft pions. One of these candidates is selected at random. The \( D^0 \) decay time is restricted to the range from 0.25 ps to 10 ps such that there are sufficient data in all decay-time regions to ensure a stable fit.

The whole dataset is split into six subsets identified by the direction of the magnetic field in the spectrometer dipole (up or down) and three separate data taking periods, to account for known differences in the detector alignment and calibration. The smallest subset contains about 11\% of the total data sample. The results of the subsets are combined in a weighted average.

3 Fits to mass spectra

The effective lifetimes are determined by fits carried out in two stages: a fit to the invariant mass, \( m(hh) \), and \( \Delta m \) to determine the relative signal yield, described here; and a fit to the decay time and \( \ln(\chi^2_{IP}) \) of the \( D^0 \) candidate to determine the effective lifetime, described in Sect. 4. Twelve independent unbinned maximum likelihood fits are carried out to the six subsets, separated also by the \( D^0 \) flavour as determined by the charge of the soft pion.

In the first stage the mass spectra fits are used to distinguish the following candidate classes by determining their relative yields: correctly tagged signal decays, which peak in both \( m(hh) \) and \( \Delta m \) variables; correctly reconstructed \( D^0 \) decays associated with a random soft pion (labelled “Rnd. \( \pi_s \)” in figures); combinatorial background; and partially reconstructed backgrounds for the \( K^+K^- \) decay channel. The \( m(hh) \) and \( \Delta m \) variables are uncorrelated and therefore treated as independent in the fit.

Signal decays include both \( D^0 \) mesons produced at the interaction point and \( D^0 \) mesons that arise from \( b \) hadron decays. These two sources of \( D^0 \) mesons can only be
Figure 2: The distributions of (left) decay time and (right) $\ln(\chi^2_{IP})$ for the $D^0 \to K^+K^-$ selected candidates in the middle run period and with magnetic field pointing down. The fit results are overlaid. Gaussian kernels are used to smooth the combinatoric and partially reconstructed backgrounds as discussed in the text.

distinguished in the second stage of the fitting procedure. The signal peak in $m(hh)$ is described by a sum of two Gaussian functions and a Crystal Ball function [18], all with the same peak positions. The power-law tail of the Crystal Ball function is used to describe radiative effects present in the distribution of $\pi^+\pi^-$ and $K^-\pi^+$ decays. A sum of three Gaussian functions is used to describe the correctly tagged signal distribution in $\Delta m$.

The $D^0$ decays associated with a random soft pion have the same model in $m(hh)$ as signal decays. They are described by a polynomial function in $\Delta m$ which goes to zero at the known pion mass [19]. The combinatorial background is described by an exponential function in $m(hh)$ and a polynomial function in $\Delta m$ which is zero at the pion mass.

Partially reconstructed decays constitute additional background sources to the $K^+K^-$ channel. The channels that give significant contributions are the decays $D^0 \to K^-\pi^+\pi^0$, with the charged pion reconstructed as a kaon and the $\pi^0$ meson not reconstructed, and $D^+_s \to K^+K^-\pi^+$, with the pion not reconstructed. The first is described by a linear function in $m(hh)$, as seen in simulated events, while the second is described by an exponential function. For both channels the shape of the $\Delta m$ distribution is taken from simulated events. Reflections from other two-body decays, due to incorrect mass assignment of the tracks, do not need to be taken into account as they fall outside the fit range. Fit projections for one data subset of the $K^+K^-$ final state are shown in Fig. 1. Projections for the $\pi^+\pi^-$ final state from the same data subset are shown in the appendix.

4 Fits to decay time

Charm mesons originating from long-lived $b$ hadrons (secondary decays) form a potentially large background that cannot be separated in the mass fit. They do not come from the interaction point and thus lead to a biased decay-time measurement. The flight distance of the $b$ hadrons causes the $D^0$ candidates into which they decay to have large $\chi^2_{IP}$ on average. This quantity is therefore used as a separating variable, along with the decay time, in the second stage of the fit.

Prompt signal decays, where the $D^{*+}$ is produced directly in the $pp$ interaction, are
modelled by an exponential function in decay time. The decay constant determines the effective lifetime, which was initially blinded using a random factor to prevent observer bias. Prompt signal decays are modelled by a modified $\chi^2$ function in $\ln(\chi^2_{IP})$, of the form

$$f(x) \equiv \begin{cases} 
C \exp \left[ \alpha(x - \mu) - \exp(\alpha(x - \mu)) \right], & x \leq \mu, \\
C \exp \left[ \beta(x - \mu) - \exp(\beta(x - \mu)) \right], & x > \mu.
\end{cases} \quad (1)$$

The parameters $\alpha$ and $\beta$ describe the left and right widths of the distribution, respectively, while $\mu$ is the peak position and $C$ is a normalisation constant. The $\mu$ and $\alpha$ parameters are allowed to have a linear variation with decay time.

Secondary decays originating from $b$ hadrons are described by the sum of a convolution of two exponential functions with a further single exponential in decay time. This is motivated by the two components of decay time, one from the $b$ hadron and one from the $D^0$, and from studies on simulated events. The $\ln(\chi^2_{IP})$ distribution of secondary decays is given by Eq. (1) where $\mu$, $\alpha$ and $\beta$ have the following time dependencies: $\mu$ is the sum of a constant and a sigmoid function, while $\alpha$ and $\beta$ are each the sum of a linear function and an exponential function. The parameterisations are motivated by studies on highly enriched samples of secondary decays in data and on simulated decays.

The prompt and secondary background from correctly reconstructed $D^0$ mesons associated to a random soft pion are described by the same parameterisations as the prompt signal decays and secondary decays, respectively, but the prompt soft pion lifetime parameter floats independently of the prompt signal in the fit.

Combinatorial backgrounds and partially reconstructed decays for the $K^+K^-$ final state are described by non-parametric functions. The shapes are obtained by applying the $sPlot$ technique [20] to the result of the $m(hh)$ and $\Delta m$ fit. Gaussian kernel density estimators [21] are used to create smooth distributions.

The detector resolution is accounted for by the convolution of a Gaussian function with the decay-time function. The Gaussian width is 50 fs, an effective value determined from studies of $B \to J/\psi X$ decays [22], which has negligible effect on the measurement.

Biases on the decay-time distribution, introduced by the selection criteria, are accounted for through per-candidate acceptance functions which are determined using a data-driven method. These acceptance functions are used to normalise the per-candidate probability density functions (PDFs) over the decay-time range in which the event would be accepted. The procedure for determination and application of these functions is described in detail in Refs. [23, 24]. The $D^0$ decay time is varied by moving the primary vertex of the $D^+ \to D^0 \pi^+$ decay along the $D^0$ momentum direction. The trigger and offline selection are run for each new vertex position to determine the decay-time acceptance due to these selections. Three additional geometric detector acceptance effects are also included in the procedure. The first accounts for an acceptance effect at large decay times due to the finite length of the VELO: the daughters of very long-lived $D^0$ candidates may not traverse the required number of VELO sensors for a track to be reconstructed. The second, discussed in Ref. [25], accounts for a preference in the track finding for reconstructing tracks coming from the beam line, thus reducing the acceptance for long-lived $D^0$ mesons. The third biasing effect occurs at large decay times due to the requirement that the $D^0$ flight distance perpendicular to the beam line be less than 4 mm.

Fit projections of decay time and $\ln(\chi^2_{IP})$ for one data subset are shown in Fig. 2 for the $K^+K^-$ final state. Projections for the $\pi^+\pi^-$ final state from the same data subset are
Figure 3: Asymmetry between $D^0$ and $\bar{D}^0$ data overlaid by the total fit and prompt signal fit component for the $K^+K^-$ final state. The data are from all subsets and the fit components are constructed from the individual fits to each subset. The residual between data and fit is shown in units of statistical standard deviation, labelled as pull.

shown in the appendix. A discrepancy between the data and the decay-time fit projection at 0.5 ps and below is partially due to correlations seen in data which are not accounted for in the fit. For example, the $D^0$ invariant mass, fitted in the first stage of the fit, and the $\chi^2_0$ fitted in the second stage are observed to be correlated. This correlation is found to be the same for the $D^0$ and $\bar{D}^0$ samples leading to a cancellation of the effect in the final asymmetry calculation. Shown in Fig. 3 is the asymmetry between the $D^0$ and $\bar{D}^0$ decay-time distributions of $K^+K^-$ candidates, overlaid by the fit results. The distribution of the normalised residual, or pull, shown below the plot is well behaved and demonstrates the similarity of the effect between the $D^0$ and $\bar{D}^0$ samples. The corresponding asymmetry for the $\pi^+\pi^-$ final state can be found in the appendix. Systematic uncertainties are assigned to account for remaining differences between the effects from the two flavours.

The yields returned by the fits indicate that the samples contain about $6.7 \times 10^6$ $D^0 \to K^+K^-$ and $2.2 \times 10^6$ $D^0 \to \pi^+\pi^-$ signal events, for which the $D^{*+}$ meson is produced directly in the $pp$ collision. The purities with respect to the total number of selected events are 85.1% and 84.3%, respectively, as measured in a region of two standard deviations around the signal peaks in $m(hh)$ and $\Delta m$, using the fractions of candidate classes returned by the two fit stages.

5 Systematic uncertainties and cross-checks

The measurement techniques for $A_\Gamma$ are applied to the Cabibbo-favoured $K^-\pi^+$ final state, where no asymmetry is expected. This dataset contains $58.0 \times 10^6$ prompt signal events, more than eight times larger than the $K^+K^-$ dataset, providing a powerful check of the method. The measured lifetime agrees to within 1% with the world average $D^0$ lifetime [19]. The analysis is applied to this channel to yield a pseudo-$A_\Gamma$ measurement. The values obtained from the six subsets have a p-value of 0.70. The weighted average of these results over all subsets is $A_\Gamma(D^0 \to K^-\pi^+, 2012) = (-0.07 \pm 0.15) \times 10^{-3}$, where
Table 1: Assigned systematic uncertainties for each final state, given as multiples of $10^{-3}$.

<table>
<thead>
<tr>
<th>Source</th>
<th>$A_T(D^0 \rightarrow K^+ K^-)$</th>
<th>$A_T(D^0 \rightarrow \pi^+ \pi^-)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Charm from $b$ decays</td>
<td>±0.08</td>
<td>±0.08</td>
</tr>
<tr>
<td>Combinatorial background</td>
<td>±0.02</td>
<td>±0.10</td>
</tr>
<tr>
<td>Random soft pion background</td>
<td>±0.02</td>
<td>±0.03</td>
</tr>
<tr>
<td>Partially reconstructed background</td>
<td>±0.01</td>
<td>—</td>
</tr>
<tr>
<td>Decay-time acceptance</td>
<td>±0.03</td>
<td>±0.02</td>
</tr>
<tr>
<td>Decay-time resolution</td>
<td>±0.01</td>
<td>±0.01</td>
</tr>
<tr>
<td>Fit model</td>
<td>±0.04</td>
<td>±0.09</td>
</tr>
<tr>
<td><strong>Total systematic uncertainty</strong></td>
<td>±0.10</td>
<td>±0.16</td>
</tr>
</tbody>
</table>

the uncertainty is only statistical. As expected, the result is consistent with zero and shows no dependence on the magnet polarity or data taking period.

A large number of pseudoexperiments, generated with both zero and non-zero values for $A_T$, are performed to confirm the validity and uncertainties of the results. Furthermore, the dependence of the measured $A_T$ values in data on $D^0$ kinematics and flight direction, on soft pions observed close to the beamline or the outer edge of the detector fiducial volume, the selection at the hardware trigger stage, and the vertex multiplicity, are found to be negligible.

Candidates originating from $b$ hadron decays are the second largest source of background, after $D^0$ candidates associated with a random soft pion. To test the sensitivity of $A_T$ to the treatment of this component, the fraction of secondary background is increased and decreased by a factor of two in simulation studies. For each study the distribution of the normalised residual between the generated and measured values of $A_T$ is formed and its mean is taken as the bias on $A_T$. The sensitivity to variations of a fixed secondary decay-time constant is also considered in the systematic uncertainty.

Potential inaccuracies in the description of the combinatorial background, which contributes more to the $\pi^+ \pi^-$ final state, are assessed through simulation studies. The fraction of this background and its models of $m(hh)$, $\Delta m$ and decay-time are varied in the simulation while leaving the rest of the fit model unchanged.

Another important background source is from $D^0$ candidates associated to random soft pions. The lifetime of this background is the fit parameter with the highest correlation with the signal lifetime and hence is considered carefully. The size of this final state dependent correlation is 26%, 28% and 24% for $K^+ K^-$, $\pi^+ \pi^-$ and $K^- \pi^+$, respectively. Alternative fit configurations are studied in which the lifetime is fitted as a multiple of the signal lifetime and where the mass distribution of this background is fitted independently of the signal.

The parameters describing the effective lifetimes of the small partially reconstructed background components in the $K^+ K^-$ final state are estimated from the data. A systematic uncertainty describing the sensitivity to the initial conditions of the fit and to varying the fractions of these backgrounds is determined.

The decay-time acceptance correction that is applied is crucial in the measurement of the lifetimes. A corresponding systematic uncertainty is assessed by testing the sensitivity of the fit to artificial biases applied to the per-event acceptance functions.

The excellent vertex detector resolution in LHCb ensures that the results have low
sensitivity to the decay-time resolution. The corresponding systematic uncertainty is assessed by varying the width of the Gaussian resolution model utilised in the analysis by a factor of two and by using an alternative model.

The fitting method does not account for all the observed correlations between the fit variables. Simulated data including these correlations, with artificial asymmetries, were generated and the fit procedure applied. Small mismodelling effects, similar to those in data, are observed in these fits. A corresponding systematic uncertainty on the fit model is assigned from the resulting bias to $A_\Gamma$. The assigned systematic uncertainties are summarised in Table 1.

6 Results and conclusions

Parameters of indirect $CP$ violation in decays of $D^0$ mesons produced promptly at the primary $pp$ collision vertex have been measured in data collected by the LHCb experiment in 2012. The results of this measurement are

$$A_\Gamma(D^0 \rightarrow K^+K^-, 2012) = (-0.03 \pm 0.46 \pm 0.10) \times 10^{-3},$$
$$A_\Gamma(D^0 \rightarrow \pi^+\pi^-, 2012) = (0.03 \pm 0.79 \pm 0.16) \times 10^{-3},$$

where the first uncertainty is statistical and the second is systematic.

These results are combined with those from the analysis of $D^0$ mesons produced promptly at the primary $pp$ collision vertex in data taken in 2011 [8] that utilised the same analysis method. The statistical uncertainties are fully independent, while the systematic uncertainties are conservatively considered to be fully correlated. The averages, calculated as the best linear unbiased estimator (BLUE) [26],

$$A_\Gamma(D^0 \rightarrow K^+K^-, 2011 - 2012) = (-0.14 \pm 0.37 \pm 0.10) \times 10^{-3},$$
$$A_\Gamma(D^0 \rightarrow \pi^+\pi^-, 2011 - 2012) = (0.14 \pm 0.63 \pm 0.15) \times 10^{-3},$$

are consistent with zero and with SM predictions. The final state difference $\Delta A_\Gamma = (0.28 \pm 0.73 \pm 0.05) \times 10^{-3}$, where the systematic uncertainties are treated as fully correlated, is also consistent with zero and with SM predictions.

Under the assumption that the true asymmetries are the same for both decay modes, as in the SM, the final state results are averaged to give,

$$A_\Gamma(2011 - 2012) = (-0.07 \pm 0.32 \pm 0.11) \times 10^{-3},$$

where the systematic uncertainties of the two final states are assumed to be fully correlated. The results are also consistent with those from an independent analysis of the same data with a different method [27], taking into account the correlation between the two measurements. The average is consistent with $CP$ conservation and gives further evidence to the small order of potential $CP$ violation in the charm system.
References


[27] LHCb collaboration, CP-violating asymmetries from the decay-time distribution of prompt $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ decays in the full LHCb Run 1 data sample; Measured using yield asymmetries in bins of decay time, LHCb-CONF-2016-009.
Appendix

Figure 4: The distributions of (left) $m(\pi^+\pi^-)$ and (right) $\Delta m$ for the $D^0 \rightarrow \pi^+\pi^-$ selected candidates in the middle run period and with magnetic field pointing down. The fit results are overlaid.

Figure 5: The distributions of (left) decay time and (right) $\ln(\chi^2_{IP})$ for the $D^0 \rightarrow \pi^+\pi^-$ selected candidates in the middle run period and with magnetic field pointing down. The fit results are overlaid. Gaussian kernels are used to smooth the combinatoric and partially reconstructed backgrounds as discussed in the text.

Figure 6: The asymmetry between $D^0$ and $\bar{D}^0$ data overlaid by the total fit and prompt signal fit component for the $\pi^+\pi^-$ final state. The data are from all subsets and the fit components are constructed from the individual fits to each subset. The residual between data and fit is shown in units of statistical standard deviation, labelled as pull.