LHCb status and charm physics program

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LHCb is a dedicated flavor physics experiment that will observe the 14 TeV proton–proton collisions at CERN's Large Hadron Collider (LHC). Construction of the LHCb detector is near completion, commissioning of the detector is well underway, and LHCb will be fully operational and ready to take data in advance of the projected May 2008 turn-on date for the LHC. The LHCb software trigger will feature a dedicated channel for events containing D^* mesons that will dramatically enhance the statistical reach of LHCb in many charm physics measurements. The LHCb charm physics program is initially focused on mixing and CP violation measurements in two body decay modes of D^0. A much broader program is possible and will be explored as manpower allows. We intend to use both promptly produced charm and secondary charm from B meson decays in measurements. Initial studies have focused on using secondary D^{*+} mesons for mixing measurements in two body decays. Preliminary Monte Carlo studies indicate that LHCb may obtain a statistical precision of $\sigma_{\text{stat}}(x'^2) = \pm 0.064 \times 10^{-3}$ and $\sigma_{\text{stat}}(y') = \pm 0.87 \times 10^{-3}$ from a time dependent mixing analysis of wrong sign two body $D^0 \to \pi^- K^+$ decays and a statistical precision of $\sigma_{\text{stat}}(y_{\text{CP}}) = \pm 0.5 \times 10^{-3}$ from a ratio of the lifetimes of D^0 decays to the final states K^-K^+ and $K^-\pi^+$ in $10\,\text{fb}^{-1}$ of data.

1. LHCb status

As the dedicated flavor experiment at CERN's Large Hadron Collider (LHC), LHCb is designed to optimally exploit the large $b\bar{b}$ production cross–section in the LHC 14 TeV proton–proton collisions for precision measurements of b hadron properties. Figure 1 shows the layout of the LHCb detector. In high energy hadronic collisions that produce $b\bar{b}$ pairs, the b– and $\bar{b}$–hadrons are predominantly produced into the same forward cone—a fact that led to LHCb's single–arm spectrometer design [2]. The angular acceptance of the detector extends from approximately 10 mrad around the beam axis to 300 mrad in the magnetic bending plane and to 250 mrad in the non–bending plane.

Many of the features that make LHCb an excellent B physics laboratory also make LHCb well–suited for many charm physics studies at unprecedented levels of precision. The silicon Vertex Locator (VELO) will provide the excellent vertex resolutions necessary for time dependent measurements—an estimated 45 fs proper time resolution for $D^0 \to K^-\pi^+$ decays where the D^0 mesons are produced in b-hadron decays. The LHCb tracking system will supply precise momentum measurements—an estimated 6 MeV mass resolution for two body decays of D^0 mesons. The LHCb Ring Imaging Cherenkov (RICH) detectors will provide excellent K–π discrimination over a wide momentum range from 2 GeV/c to 100 GeV/c. Finally, the LHCb trigger system will have a high statistics charm stream, described in Section 2, so that the large charm production in LHC collisions can be exploited for precision measurements.

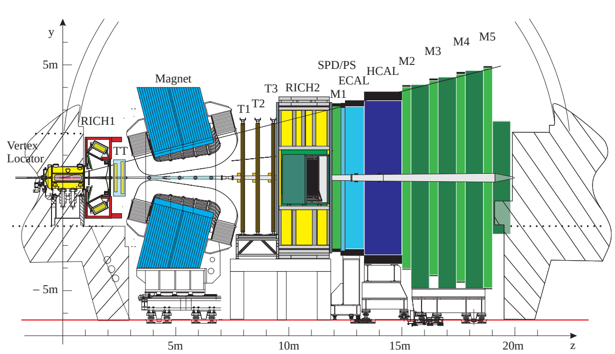


Figure 1:: LHCb detector layout, showing all of the detector components. Also shown are the direction of the y and z coordinate axes; the x axis completes the right handed coordinate system [1].

As of September 2007, construction of the LHCb detector is well advanced with commissioning activities underway for all sub–detectors. LHCb is on–schedule to be complete and ready for data taking by the projected LHC turn-on date in May 2008.

2. LHCb trigger and D^* stream

LHCb will have a two stage trigger: a fast hardware trigger called the Level 0 Trigger (L0) followed by a software High Level Trigger (HLT). Although the triggers are designed to favor $b\bar{b}$ events, the HLT will feature a dedicated D^* stream for selecting charm events at a high rate.

At design operation, LCHb will observe bunch crossings at 40 MHz with a luminosity of $2 \times 10^{32}\,\text{cm}^{-2}\,\text{s}^{-1}$. The L0 trigger is designed to reduce the 40 MHz input rate to approximately 1 MHz while efficiently favoring $b\bar{b}$ events. Using the fact that the decay products of b-hadrons typically have significant transverse momentum, the L0 trigger reads data from the calorimeters and the muon detectors to identify quickly individual candidate hadrons, electrons, photons, and muons that have a few GeV of transverse energy or momentum. The

Table I: Estimated yield of reconstructed secondary $D^{*+} \to \pi_s^+ D^0(h^- h'^+)$ candidates in $2\,\mathrm{fb}^{-1}$ of LHCb data passing the LHCb trigger sequence.

Two body D^0 mode	HLT Yield in $2\,\mathrm{fb}^{-1}$
$D^0 \to K^-\pi^+$	50×10^6
$D^0 \to K^-K^+$	5×10^6
$D^0 \to \pi^-\pi^+$	2×10^6
$D^0 \to \pi^-K^+$	0.2×10^6

L0 E_T thresholds must be tuned on real data, but, to illustrate the expected scale, current detector studies indicate a trigger threshold for hadrons of $E_T > 3.5\,\mathrm{GeV}$.

The HLT software trigger performs an event reconstruction to identify events of specific physics interest, reducing the 1 MHz L0 output/HLT input rate to approximately 2 kHz. The HLT has access to all of the detector information and uses it to reconstruct final state particle candidates and the locations of the primary proton-proton interactions. These objects are then used in several parallel channels to identify events of specific physical interest. Although the configuration of the HLT channels has yet to be finalized, the HLT will contain a high yield stream for charm events. In the current configuration, 300 Hz, 15% of the recorded 2 kHz of LHCb events, are allocated to an inclusive D^* stream. Table I shows potential yields of some key charm decays in a preliminary configuration the D^* stream. These estimates are based on the performance of the HLT on fully simulated LHCb events. LHCb will record at least 50×10^6 fully reconstructed $D^{*+} \to \pi_s^+ D^0(h^- h'^+)$ [3] candidates per $2\,\mathrm{fb}^{-1}$ (a nominal year of LHCb data at design luminosity), where the D^{*+} originates in a b-hadron decay and $h, h' \in \{K, \pi\}$. The subscript on the π_s^+ labels it as the tagging 'slow' pion. Studies indicate that this HLT configuration also yields a similar number of reconstructed prompt D^{*+} candidates in each mode.

3. D^{*+} event selection

The charm physics program at LHCb is initially focused on mixing and CP violation measurements in two body decays of D^0. LHCb note [4] details a preliminary selection of wrong sign (WS) $D^0 \to \pi^- K^+$ decays from $D^{*+} \to D^0 \pi_s^+$, where the D^{*+} originates from a B meson decay. The intent of the selection is to provide a sample of candidates suitable for a time dependent mixing analysis (see Section 4.1). The performance of the selection on fully simulated LHCb data predicts a yield of approximately $230,000$ true WS decays in $10\,\mathrm{fb}^{-1}$ of LHCb data (5 years of nominal LHCb data taking) with a background-to-signal ratio of $1.07 < B/S < 5.28$ at the 90% confidence level.

3.1. Selection backgrounds

The primary backgrounds accepted by this selection result from combinatoric coincidences and can be divided into two classes: random slow pion backgrounds where properly reconstructed right sign $D^0 \to K^-\pi^+$ decays are combined with random pions produced somewhere else in the event to mimic a $D^{*\pm}$ decay, and pure combinatoric coincidences where the candidate D^0 decay products come from different decays in the event. These backgrounds will be separated from the signal with the typical method of fitting the reconstructed D^0 mass (m_{D^0}) and D^{*+}-D^0 mass difference (Δm) distributions.

3.2. D^{*+} decay vertex

In order to perform a time dependent mixing measurement, both the creation and decay vertices of the D^0 must be precisely determined. The D^0 decay vertex can be measured from its decay products very precisely in the VELO. Table II shows the results of vertex resolution studies in fully simulated LHCb events. The coordinate system in the table is that defined in Figure 1, with the primary proton-proton collisions along the z axis. The D^0 decay vertex can be determined with a resolution of 257 μm along the beam axis. To provide some context for this value, the mean laboratory flight distance for a $60\,\mathrm{GeV/c}$ D^0 (the mean momentum of D^0 from D^{*+} from B mesons) is approximately 4 mm.

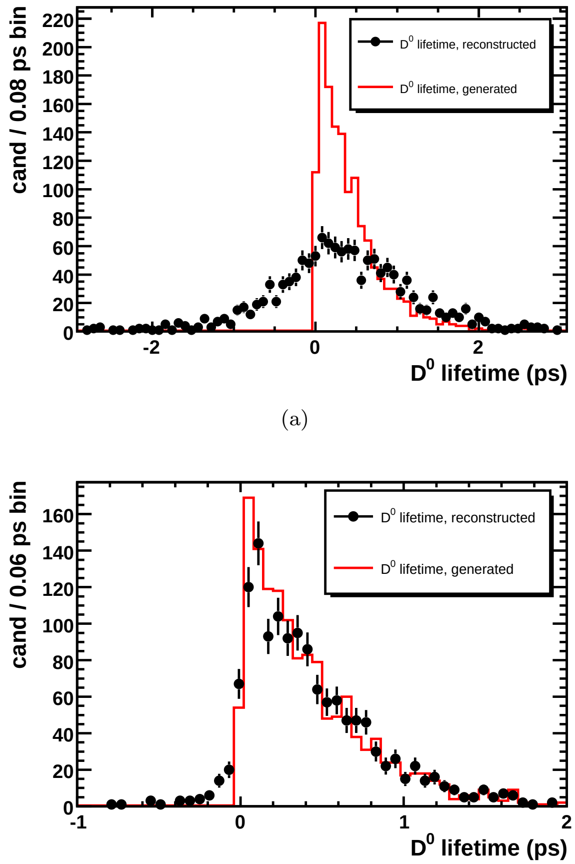
In contrast, the D^{*+} decay vertex (D^0 creation vertex) is poorly determined from its decay products. The small mass difference between the D^{*+} and its decay products leads to a narrow laboratory frame angle between the D^0 and π_s^0 momenta. The D^{*+} column in Table II shows that the resolution of the D^{*+} decay vertex estimated only from its decay products is 4232 μm, the same size as the mean laboratory flight distance of D^0 mesons. The precision of the D^{*+} vertex must be improved by including additional tracks from particles created with the D^{*+}. For D^{*+} from B decays, this means finding additional charged particles created at the B decay vertex.

In studies of fully simulated events, 63% of $B \to D^{*+}X$ decays in triggered events produce an additional reconstructed charged particle at the B meson decay vertex that can be used to improve the precision of the estimated D^0 birth vertex. As shown in the B_{part} column of Table II, using such additional tracks dramatically improves the precision of the estimated D^0 production vertex, and, consequently, the measured D^0 proper time. The subscript on B_{part} signifies that the parent B is partially reconstructed. Figure 2 shows the dramatic improvement in measured proper time obtained by using the B_{part} decay vertex as the D^0 production vertex. In these plots, the reconstructed proper time is signed to represent

Table II: Estimated resolutions of D^0, D^{*+}, and $B_{\rm part}$ vertices, and of D^0 proper time in simulated LHCb data.

	D^0	D^{*+}	$B_{\rm part}$
x	21.6 μm	187. μm	18.1 μm
y	16.9 μm	144. μm	18.4 μm
z	257. μm	4232. μm	237. μm
τ	0.465 ps		0.045 ps

whether the D^0 momentum and flight direction are aligned (positive proper time) or anti-aligned (negative proper time). When the D^{*+} decay vertex is used in calculating the D^0 proper time, its resolution dominates the exponential decay distribution as shown in Figure 2a. When the $B_{\rm part}$ decay vertex is used, as in Figure 2b, the proper time resolution is relatively narrow and the reconstructed proper time distribution closely reproduces the generated proper time. Preliminary work in [4] has demonstrated that this partial B reconstruction can be done with an 80% efficiency, and that LHCb can use D^{*+} mesons from B decays for time dependent analyses.



(a)

(b)

Figure 2:: Distributions of the proper times for simulated D^0 mesons from $B \to D^{*+}X$ decays. In each plot, the solid lines are the generated proper times and the points are the estimated D^0 proper times using (a) the poorly estimated D^{*+} decay vertex, or (b) the precisely estimated parent B decay vertex as the D^0 production vertex.

4. Charm mixing measurements at LHCb

Mixing observables are commonly expressed in terms of two dimensionless parameters: the mass difference parameter, x, and the full width difference parameter, y, defined by

$$x = \frac{2(m_1 - m_2)}{\Gamma_1 + \Gamma_2}, \qquad y = \frac{\Gamma_1 - \Gamma_2}{\Gamma_1 + \Gamma_2},$$

where the subscripts denote the mass eigenstates of the D^0-$\overline{D^0}$ system. Various measurements are sensitive to different combinations of these variables, and each of these should be explored with the highest possible precision to gain a full understanding of the charm mixing phenomenon. Preliminary work at LHCb has focused on the measurement of mixing parameters in a time dependent analysis of two body WS decays (Section 4.1 below) and in an analysis of the ratios of two body lifetimes (Section 4.2 below). However, future plans include multi-body mixing measurements (Section 6).

4.1. Time dependent WS $D^0 \to \pi^- K^+$

The time dependent analysis of WS $D^0 \to \pi^- K^+$ decays is one of the long established methods of searching for D^0-$\overline{D^0}$ mixing [5, 6, 7, 8, 9]. If D^0 and $\overline{D^0}$ mix, a meson created as a D^0 may decay to the WS final state $\pi^- K^+$ either directly, by a doubly Cabibbo suppressed (DCS) decay, or indirectly, by mixing into a $\overline{D^0}$ meson that undergoes a Cabibbo favored (CF) decay. Interference between the two processes leads to a decay time dependence that can be expanded to leading order in the small parameters x and y (in the absence of CP violation) as

$$r_{\rm WS}(t) \propto {\rm e}^{-\Gamma t}\left(R_D + \sqrt{R_D}y'(\Gamma t) + \frac{1}{2}R_M(\Gamma t)^2\right),$$

where R_D is the ratio of the DCS decay rate to the CF decay rate, $R_M = (x^2+y^2)/2 = (x'^2+y'^2)/2$ is the mixing rate, and x' and y' are rotated with respect to the parameters x and y by the relative strong phase between the CF and DCS decays, δ:

$$\begin{aligned} x' &\equiv x\cos\delta + y\sin\delta, \\ y' &\equiv y\cos\delta - x\sin\delta. \end{aligned}$$

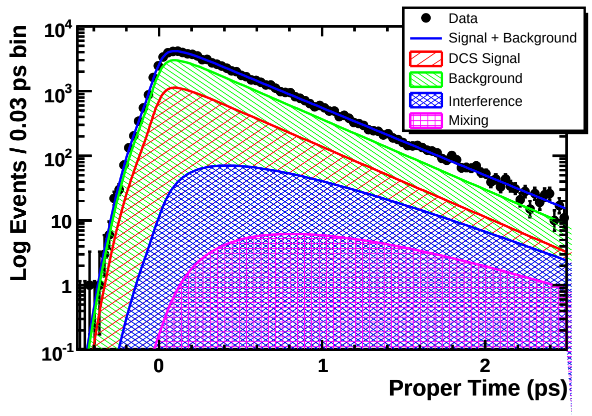


Figure 3:: An example of a Toy Monte Carlo sample from the time dependent WS analysis study.

Hence, a detailed analysis of the WS D^0 proper time distribution is sensitive to x'^2 and y'. The strong phase δ that relates these quantities to the mixing parameters x and y must be measured independently. Since x'^2 enters the decay time distribution only in $R_M = (x'^2 + y'^2)/2$, the values of x'^2 measured by this method are highly anti-correlated to the values of y'.

Because of the small values of x and y, it is only recently that this method has yielded values over 3σ from $x'^2 = 0$, $y' = 0$ [5]. The large charm statistics at LHCb should be able to improve significantly this picture. The selection described in Section 3 estimates that a time dependent WS mixing analysis on $10\,\mathrm{fb}^{-1}$ of LHCb data would incorporate approximately $230,000$ D^{*+} tagged WS decays from B decays. The $10\,\mathrm{fb}^{-1}$ signal and background yields, the proper time resolution, and the proper time acceptance of this selection were used in a toy Monte Carlo study to estimate the LHCb statistical sensitivity to x'^2 and y':

$$\sigma_{\mathrm{stat}}(x'^2) = \pm 0.064 \times 10^{-3},$$
$$\sigma_{\mathrm{stat}}(y') = \pm 0.87 \times 10^{-3}.$$

The toy study verifies the expected large negative correlation between x'^2 and y': $\mathrm{Corr}(x'^2, y') = -0.95$. Figure 3 shows a toy sample from this study [4].

4.2. Lifetime ratio

Just as it does in the K^0 and B^0 systems, the presence of mixing in the D^0 system can lead to different lifetimes for states of different CP content. These differences are related to the mixing parameters x and y. In two body D^0 decays, the ratio of the lifetime of decays to the CP-even eigenstate K^-K^+, $\tau(K^-K^+)$, and the lifetime of decays to the non-CP CF eigenstate $K^-\pi^+$, $\tau(K^-\pi^+)$, form the observable

$$y_{\mathrm{CP}} \equiv \frac{\tau(K^-\pi^+)}{\tau(K^-K^+)} - 1,$$

which is related to the mixing parameters by

$$y_{\mathrm{CP}} = y\cos\phi - \frac{1}{2}A_M x \sin\phi,$$

where ϕ is a weak phase and A_M parameterizes CP violation in D^0 mixing. Decays to the CP-even eigenstate $\pi^-\pi^+$ may also be used in place of K^-K^+ for an independent measurement of y_{CP}. The CP violating parameters A_M and ϕ must be measured independently, but in the no CP violation limit, $A_M = 0$ and $\phi = 0$, and the lifetime ratio is a direct measurement of $y_{\mathrm{CP}} = y$.

This two body lifetime ratio measurement has been carried out at several previous experiments [10, 11, 12, 13] culminating in Belle's recent 3.2σ measurement of y_{CP} in [14]. LHCb expects to use its statistical advantage over current experiments to improve the precision of the lifetime ratio measurement of y_{CP}.

The LHCb statistical sensitivity to y_{CP} has been estimated with a toy Monte Carlo study similar to the the WS mixing toy study described in Section 4.1. The selection described in Section 3, with appropriate modifications of the final state particle identification criteria, yields approximately 8×10^6 D^{*+} tagged $D^0 \to K^-K^+$ decays and 3×10^6 D^{*+} tagged $D^0 \to \pi^-\pi^+$ decays originating from b-hadron decays in $10\,\mathrm{fb}^{-1}$ of LHCb data. The signal to background ratios of the selection are $S/B = 4.8$ for the K^-K^+ mode and $S/B = 2.6$ for the $\pi^-\pi^+$ mode. Using the estimated $D^0 \to K^-K^+$ yield and signal to background ratio with proper time resolution and acceptance functions determined from fully simulated LHCb events, the estimated statistical precision of y_{CP} is $\sigma_{\mathrm{stat}}(y_{\mathrm{CP}}) = \pm 0.5^{-3}$.

5. Searches for CP violation at LHCb

The Standard Model (SM) predicts any CP violation in charm interactions to be very small. Observable CP violation at the level of 1% would be an unambiguous sign of new physics [15]. Each of the mixing measurements performed at LHCb will be analyzed in charge conjugate subsets to measure possible CP violating effects. In addition, LHCb will perform time integrated CP violation searches in as many charm decays as are possible. Initial studies have focused on searching for CP violation in two body decays of D^{*+} tagged D^0 mesons, in particular the CP eigenstate decays $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$. These singly Cabibbo suppressed decays, in which a small CP violation is predicted by the SM, are particularly sensitive to CP violation enhanced by well-motivated new physics scenarios [15]. Experimental measurements in this channel have steadily reduced the upper limit of CP violation with increasing data set sizes and improved treatments of systematic uncertainties [12, 16, 17, 18, 19]. However, CP violation at the order of 1% has not been ruled out.

With 8×10^6 tagged $D^0 \to K^-K^+$ decays and 3×10^6 tagged $D^0 \to \pi^-\pi^+$ decays (Section 4.2), LHCb will have the statistical power to search for CP asymmetries to order $\mathcal{O}(0.0004)$ or below, provided the systematic uncertainties can be controlled to this level.

Charm meson production asymmetries and final state particle detector asymmetries, particularly the detector asymmetries associated with the tagging slow pion, are expected to be the primary sources of systematic uncertainties in CP asymmetry measurements. Methods of measuring the production and detections asymmetries precisely from data are under development. Also, advantage may be gained by comparing the asymmetries of related decays. For example, the decays $D^0 \to K^-K^+$ and $D^0 \to \pi^-\pi^+$ are subject to the same production and slow pion detection asymmetries, so the difference of their measured asymmetries will have a much smaller systematic uncertainty than either asymmetry measured separately. Although this difference will be small, it is an observable that can be measured very precisely, and, if found to be significantly different from zero, can provide evidence of direct CP violation in at least one of the two decay channels.

6. Multi-body channels

LHCb will also investigate the use of D meson decays to three or more final state hadrons in mixing and CP violation measurements. However, development of multi-hadron charm analyses is less advanced than the two body D^0 program. For example, a time dependent amplitude analysis of the three body decay $D^0 \to K^0_S\pi^+\pi^-$ is directly sensitive to the mixing parameters x and y. This decay mode should be efficiently reconstructible at LHCb. Preliminary work is also under way to develop selections for D^0 decays to four hadrons, both for HLT triggering and for analysis. Further development in four body decays will investigate the feasibility of time dependent amplitude analyses for mixing measurements. The technology of four body amplitude analyses is already quite advanced [20].

In four body decays, CP violation searches will include analyses of quantities that are odd under the time reversal operation in addition to complete amplitude analyses of the decays. Although studies are still in their earliest stages, LHCb should be able to reconstruct with acceptable signal-to-background ratios

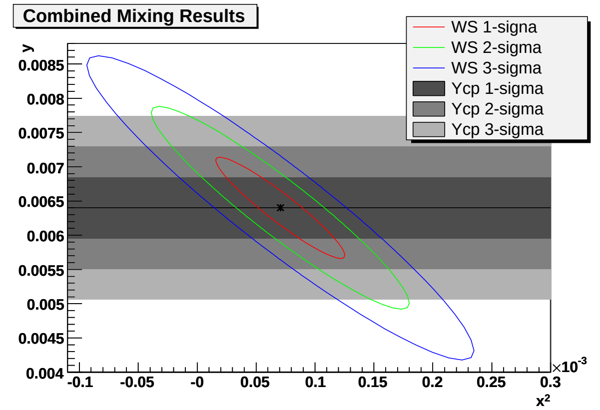


Figure 4:: Contours representing the 1σ, 2σ, and 3σ regions for the toy WS mixing study (ellipses) and for the toy lifetime ratio study (bands). The central values are $\sqrt{x^2} = 8.4 \times 10^{-3}$ and $y = 6.4 \times 10^{-3}$, the very preliminary averages of [21]. For purposes of this plot, it is assumed that $x'^2 = x^2$ and $y' = y_{\rm CP} = y$.

the decays $D^0 \to K^0_S h^+ h'^-$ and three body decays of charged D^+ containing at least one kaon. Amplitude analyses of these modes will expand the scope for CP violation searches in charm decays.

7. Conclusions

The LHCb trigger will provide LHCb with charm physics data sets of unprecedented statistics. Current analysis in charm physics has focused on mixing measurements and CP violation searches in two body decays $D^0 \to h^-h'^+$, but a broader charm physics program is envisaged. Toy Monte Carlo studies indicate that with $10\,\mathrm{fb}^{-1}$ LHCb can achieve a statistical precision of $\sigma_{\rm stat}(x'^2) = \pm 0.064 \times 10^{-3}$ and $\sigma_{\rm stat}(y') = \pm 0.87 \times 10^{-3}$ with a two body wrong sign mixing analysis, and a statistical precision of $\sigma_{\rm stat}(y_{\rm CP}) = \pm 0.5 \times 10^{-3}$ with a two body lifetime ratio measurement. Figure 4 summarizes these precisions by showing the intersection of the 1σ ellipse in (x'^2, y'), also scaled to 2σ and 3σ, and the toy lifetime ratio 1σ band in $y_{\rm CP}$, also scaled to 2σ and 3σ.

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