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Study of Branching fraction and CP asymmetry of charm mesons at Belle

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CP violation in charm meson decays is expected to be small within the Standard Model (SM) framework, and an observation of a large CP asymmetry could indicate new physics. We report measurement of branching fractions and direct CP asymmetries A_{CP} in $D^0 \to \pi^+\pi^-\eta$, $K^+K^-\eta$, $\phi\eta$ and $D^0 \to K^0_S K^0_S \pi^+\pi^-$ decays. For the latter the T-odd asymmetry a^T_{CP} sensitive to CP violation in the decay, is also measured. This report also covers the search for CP violation in $D \to Kh\pi\pi^0$ $(h = \pi, K)$ decays. The results are based on the full data collected with the Belle detector at the KEKB asymmetric-energy e^+e^- collider.

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1. Introduction

Equal amounts of matter and antimatter existed in the early Universe [1]. For such an initial state to evolve into our current matter-dominated universe [2, 3] violation of *CP* (charge-conjugation and parity) symmetry [4] is required. The amount of *CP* violation (*CPV*) present in the Standard Model (SM) fails to account for the observed imbalance between matter and antimatter [3, 5]. Thus, it is important to search for new sources of *CPV*. In the SM framework, *CPV* is expected to be very small ($\mathcal{O}(10^{-3})$ or smaller) in the charm meson decays [6]. Any significant deviation from SM expectation will probe new physics effects beyond the SM. Singly Cabibbo suppressed (SCS) decays are expected to be especially sensitive to physics beyond the SM, as their amplitudes receive contributions from QCD "penguin" operators and also chromomagnetic dipole operators [6]. The SCS decays $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ [7] are the only decay modes in which *CPV* has been observed in the charm sector. The *CP* asymmetry measured,

$$A_{CP} \equiv \frac{\Gamma(D^0 \to f) - \Gamma(\overline{D}^0 \to \bar{f})}{\Gamma(D^0 \to f) + \Gamma(\overline{D}^0 \to \bar{f})}, \tag{1}$$

is small, at the level of 0.1%.

All the results reported in this document are obtained using full data collected by Belle detector running at KEKB asymmetric-energy e^+e^-collider operating at and near $\Upsilon(4S)$ mass peak. Belle experiment [8] ran a successful physics program with very good performance on particle identification, momentum resolution and vertexing. The Belle experiment collected a total of 1 ab^{-1} of data, which includes 1.3×10^9 $c\bar{c}$ events. In this proceeding, we report the recent charm results from the Belle experiment including; a) Measurement of the branching fraction ($\mathcal{B}$) and search for *CPV* in the SCS decay $D^0 \to K_S^0 K_S^0 \pi^+\pi^-$ [9]; b) the measurement of branching fraction and search for *CPV* in $D^0 \to \pi^+\pi^-\eta$, $D^0 \to K^+K^-\eta$, $D^0 \to \phi\eta$ [10]; and c) the measurement of branching fractions for $D \to Kh\pi\pi^0$ $(h = \pi, K)$ decays [11].

2. Measurement of the branching fraction and search for *CPV* in the SCS decay $D^0 \to K_S^0 K_S^0 \pi^+\pi^-$

In $D^0 \to K_S^0 K_S^0 \pi^+\pi^-$ analysis, we search for *CPV* in two complementary ways. We first measure the asymmetry A_{CP}; a nonzero value may result from interference between contributing decay amplitudes. The *CP*-violating interference term is proportional to $\sin(\phi)\sin(\delta)$ [12–14] where ϕ and δ are the weak and strong phase differences, respectively, between the amplitudes. Thus, to observe $A_{CP} \neq 0$, δ must be nonzero. To avoid the need for $\delta \neq 0$, we also search for *CPV* by measuring the asymmetry in the triple-product $C_T = \vec{p}_{K_S^0} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$, where $\vec{p}_{K_S^0}$, $\vec{p}_{\pi^+}$, and $\vec{p}_{\pi^-}$ are the three-momenta of the K_S^0, π^+, and π^- daughters, respectively, and defined in the D^0 rest frame. From the two K_S^0 in final state we choose the K_S^0 with the higher momentum for this calculation. The asymmetry is defined as

$$A_T \equiv \frac{N(C_T > 0) - N(C_T < 0)}{N(C_T > 0) + N(C_T < 0)}, \tag{2}$$

where $N(C_T > 0)$ and $N(C_T < 0)$ correspond to the yields of $D^0 \to K_S^0 K_S^0 \pi^+\pi^-$ decays having $C_T > 0$ and $C_T < 0$, respectively. For $\overline{D}^0$ decays, we define the *CP* conjugate quantity

$$\bar{A}_T \equiv \frac{\overline{N}(-\overline{C}_T > 0) - \overline{N}(-\overline{C}_T < 0)}{\overline{N}(-\overline{C}_T > 0) + \overline{N}(-\overline{C}_T < 0)}. \tag{3}$$

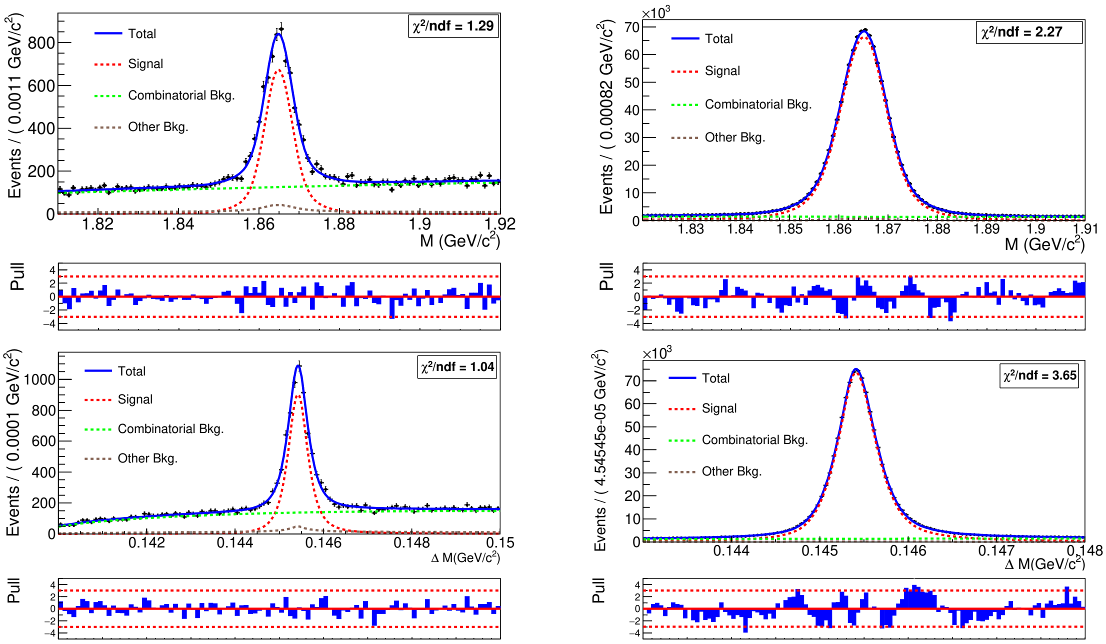
The difference is a *CP* violating observable

$$a_{CP}^T \equiv \frac{A_T - \bar{A}_T}{2} \tag{4}$$

proportional to $\sin(\phi)\cos(\delta)$, and, unlike A_{CP}, $\delta = 0$ results in the largest *CP* asymmetry. The observable a_{CP}^T is also advantageous to measure experimentally, as any production- or detection-related asymmetry cancels out.

To measure the branching fraction and search for *CP* violation, we use 922 fb^{-1} of Belle data. We reconstruct the decay chain $D^{*+} \to D^0\pi_s^+$, $D^0 \to K_S^0 K_S^0 \pi^+\pi^-$ where the charge of slow pion (π_s) is used to tag the flavor of D meson. We measure the branching fraction relative to Cabibbo favored $D^0 \to K_S^0 \pi^+\pi^-$ decays observed in the same data set. For $D^0 \to K_S^0 K_S^0 \pi^+\pi^-$, we determine the signal yield via a two-dimensional unbinned extended maximum-likelihood fit to the variables M and $\Delta M \equiv M(K_S^0 K_S^0 \pi^+\pi^-\pi_s^+) - M$. The fitted ranges are $1.810\ \mathrm{GeV}/c^2 < M < 1.920\ \mathrm{GeV}/c^2$ and $0.140\ \mathrm{GeV}/c^2 < \Delta M < 0.150\ \mathrm{GeV}/c^2$. The fit yields 6095 ± 98 signal events. Projections of the fit are shown in Fig. (1a). We determine $N_{K_S^0\pi^+\pi^-}$ from a two-dimensional binned fit (rather than unbinned, as the statistics are large) to the M and ΔM distributions. The fitted ranges are $1.820\ \mathrm{GeV}/c^2 < M < 1.910\ \mathrm{GeV}/c^2$ and $0.143\ \mathrm{GeV}/c^2 < \Delta M < 0.148\ \mathrm{GeV}/c^2$ [15]. The fit yields $1\,069\,870 \pm 1831$ $D^0 \to K_S^0 \pi^+\pi^-$ decays. Projections of the fit are shown in Fig. (1b).

We measure the *CP* asymmetry A_{CP} from the difference in signal yields for D^0 and $\overline{D}^0$ decays $A_{CP}^{\mathrm{det}} = \frac{N(D^0\to f) - N(\overline{D}^0\to \overline{f})}{N(D^0\to f) + N(\overline{D}^0\to \overline{f})}$. The observable A_{CP}^{det} includes asymmetries in production and reconstruction, $A_{CP}^{\mathrm{det}} = A_{CP} + A_{\mathrm{FB}} + A_\epsilon^{\pi_s}$ where A_{FB} is the "forward-backward" production asymmetry [16] between D^{*+} and D^{*-} due to $\gamma^* - Z^0$ interference in $e^+e^- \to c\bar{c}$; and $A_\epsilon^{\pi_s}$ is the asymmetry in reconstruction efficiencies for $\pi_s^\pm$ tracks. We correct for $A_\epsilon^{\pi_s}$ in $K_S^0 K_S^0 \pi^+\pi^-$ events by separately weighting D^0 and $\overline{D}^0$ decays. After correcting for $A_\epsilon^{\pi_s}$, we obtain $A_{CP}^{\mathrm{cor}} = A_{CP} + A_{\mathrm{FB}}$. The asymmetry A_{FB} is an odd function of $\cos\theta^*$, and A_{CP} is constant, where θ^* is the polar angle between the $D^{*\pm}$ momentum and the $+z$ axis in the CM frame. We thus extract A_{CP} and A_{FB} via $A_{CP} = \frac{A_{CP}^{\mathrm{cor}}(\cos\theta^*) + A_{CP}^{\mathrm{cor}}(-\cos\theta^*)}{2}$, $A_{\mathrm{FB}} = \frac{A_{CP}^{\mathrm{cor}}(\cos\theta^*) - A_{CP}^{\mathrm{cor}}(-\cos\theta^*)}{2}$ We calculate A_{CP}^{cor} in four bins of $\cos\theta^*$: $(-1.0, -0.4)$, $(-0.4, 0)$, $(0, 0.4)$ and $(0.4, 1.0)$. We determine A_{CP}^{cor} for each bin by simultaneously fitting for D^0 and $\overline{D}^0$ signal yields for weighted events in that bin. The results for A_{CP}^{cor} are combined to obtain A_{CP} and A_{FB}. Fitting the A_{CP} values in bins of $\cos\theta^*$ to a constant, we obtain $A_{CP} = [-2.51 \pm 1.44\,(\mathrm{stat})\,^{+0.35}_{-0.52}\,(\mathrm{syst})]\%$, where the first uncertainty is statistical and second is systematic [9]. To measure a_{CP}^T, we divide the data into four subsamples: D^0 decays with $C_T > 0$ (yield$=N_1$) and $C_T < 0$ (yield$=N_2$); and $\overline{D}^0$ decays with $-\overline{C}_T > 0$ (N_3) and $-\overline{C}_T < 0$ (N_4). Thus, $A_T = (N_1 - N_2)/(N_1 + N_2)$, $\bar{A}_T = (N_3 - N_4)/(N_3 + N_4)$, and $a_{CP}^T = (A_T - \bar{A}_T)/2$. We fit the four subsamples simultaneously and take the fitted parameters to be N_1, N_3, A_T, and a_{CP}^T. The fit gives $a_{CP}^T = [-1.95 \pm 1.42\,(\mathrm{stat})\,^{+0.14}_{-0.12}\,(\mathrm{syst})]\%$, where the first uncertainty is statistical and



(a) Projections of the fit for $D^0 \to K^0_S K^0_S \pi^+\pi^-$ on M (upper) and ΔM (lower).

(b) Projections of the fit for $D^0 \to K^0_S \pi^+\pi^-$ on M (upper) and ΔM (lower).

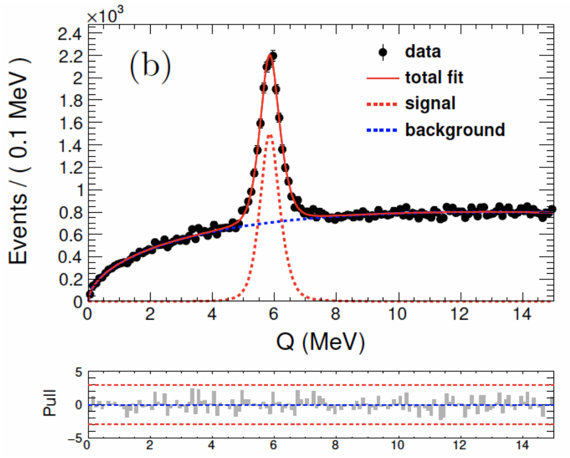
Figure 1: Fit projections in M and ΔM for $D^0 \to K^0_S K^0_S \pi^+\pi^-$ on left and $D^0 \to K^0_S \pi^+\pi^-$ on right. The corresponding pull [= (data − fit result)/(data uncertainty)] distributions are shown below each projection. The dashed red lines correspond to $\pm 3\sigma$ values.

second is systematic [9]. We report the first *CP* violation search for $D^0 \to K^0_S K^0_S \pi^+\pi^-$ decays using A_{CP} and a^T_{CP}. Both A_{CP} and a^T_{CP} measurements are consistent with zero *CP* violation.

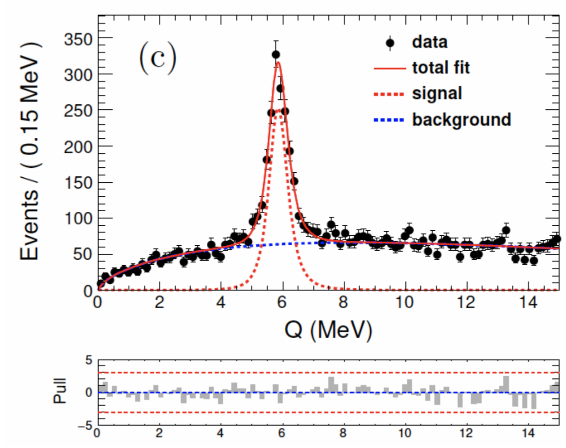
We report the world's most precise branching fraction measurement for $D^0 \to K^0_S K^0_S \pi^+\pi^-$ decays. The branching fraction, measured relative to that for $D^0 \to K^0_S \pi^+\pi^-$, is: $\mathcal{B}(D^0 \to K^0_S K^0_S \pi^+\pi^-)/\mathcal{B}(D^0 \to K^0_S \pi^+\pi^-) = [1.72 \pm 0.03\,(\text{stat}) \pm 0.04\,(\text{syst})\,] \times 10^{-2}$. Inserting the world average value $\mathcal{B}(D^0 \to K^0_S \pi^+\pi^-) = (2.80 \pm 0.18)\%$ [17] gives $\mathcal{B}(D^0 \to K^0_S K^0_S \pi^+\pi^-) = [4.82 \pm 0.08\,(\text{stat})^{+0.10}_{-0.11}\,(\text{syst}) \pm 0.31\,(\text{norm})] \times 10^{-4}$ where the last uncertainty is due to $\mathcal{B}(D^0 \to K^0_S \pi^+\pi^-)$.

3. Measurement of branching fractions and search for *CP* violation in $D^0 \to \pi^+\pi^-\eta$, $D^0 \to K^+K^-\eta$, $D^0 \to \phi\eta$ decays

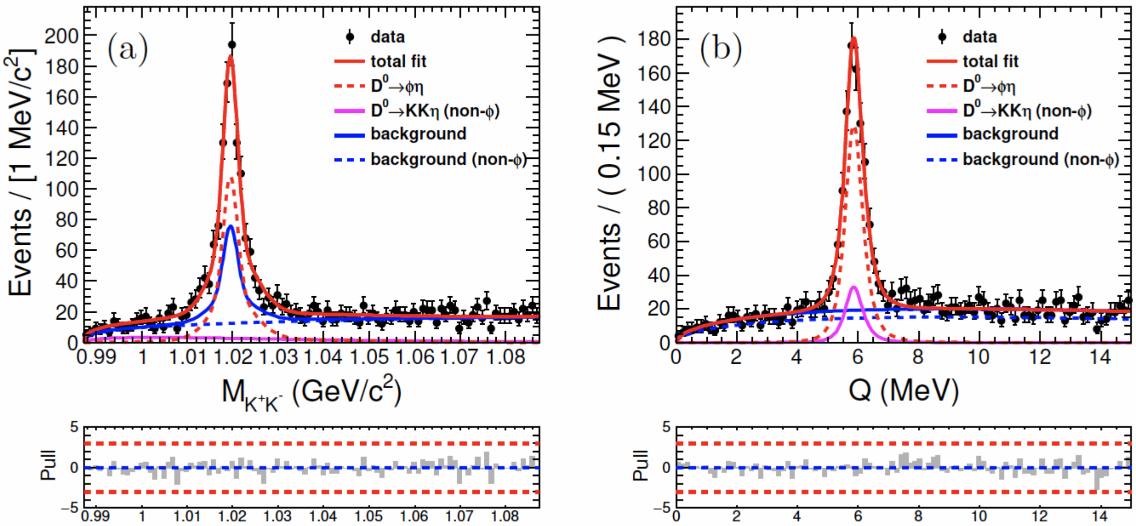
This paper [10] reports the branching fraction of Cabibbo suppressed $D^0 \to \pi^+\pi^-\eta$, $D^0 \to K^+K^-\eta$ and $D^0 \to \phi\eta$ decays relative to the normalization mode $D^0 \to K^-\pi^+\eta$ using 988 fb^{-1} of Belle data set. The signal yield is determined via a one-dimensional unbinned extended maximum-likelihood fit to the variable Q, where $Q = M[K^+K^-\eta\pi^+_s] - M[K^+K^-\eta] - M[\pi^+_s]$ for $D^0 \to \pi^+\pi^-\eta$, $D^0 \to K^+K^-\eta$ and a two-dimensional fit in variables $M[K^+K^-]$, Q for $D^0 \to \phi\eta$ decays. Fig. 2 shows the fit projections for the three modes. The measured branching fractions are $\mathcal{B}(D^0 \to \pi^+\pi^-\eta) = [1.22 \pm 0.02\,(\text{stat}) \pm 0.02\,(\text{syst}) \;\pm 0.03\,(\text{syst})\,] \times 10^{-3}$, $\mathcal{B}(D^0 \to K^+K^-\eta) = [1.80^{+0.07}_{-0.06} \;\pm 0.04 \;\pm 0.05] \times 10^{-4}$ and $\mathcal{B}(D^0 \to \phi\eta) = [1.84 \pm 0.09 \pm 0.06 \;\pm 0.05] \times 10^{-4}$. The analysis report the search for *CPV* using A_{CP} similar to $D^0 \to K^0_S K^0_S \pi^+\pi^-$ but with 8 bins in



(a) $D^0 \to \pi^+\pi^-\eta$



(b) $D^0 \to K^+ K^- \eta$



(c) $D^0 \to \phi\eta$

Figure 2: Fig. (a), (b) show the 1d fit projections for $D^0 \to \pi^+\pi^-\eta$ and $D^0 \to K^+ K^- \eta$. Fig. (c) show the 2d fit projections on $M[K^+K^-]$, Q for $D^0 \to \phi\eta$ decays.

$\cos(\theta^*)$. The measured A_{CP} values are $A_{CP}(D^0 \to \pi^+\pi^-\eta)$ = [+0.90 ± 1.20 (stat) ± 0.40(syst)]%, $A_{CP}(D^0 \to K^+ K^- \eta)$ = [−1.40 ± 3.30 ± 1.0]% and $A_{CP}(D^0 \to \phi\eta)$ = [−1.90 ± 4.40 ± 0.60]%. The result for $D^0 \to \pi^+\pi^-\eta$ is a significant improvement over the previous measurement and the other two are first *CPV* search for those decays. All results are consistent with zero *CPV*.

4. Measurement of branching fractions for Cabbibo-Suppressed $D^+ \to K^+ K^- \pi^+\pi^0$, $D^+_{(s)} \to K^+ \pi^-\pi^+\pi^0$ decays

This analysis[11] measures the branching fraction of $D^+ \to K^+ K^- \pi^+\pi^0$, $D^+_{(s)} \to K^+ \pi^-\pi^+\pi^0$ decays observed in the 988 fb^{-1} of Belle data set relative to the normalization modes $D^+ \to K^- \pi^+ \pi^+\pi^0$, $D^+_s \to K^+ K^-\pi^+\pi^0$. We extract the signal yield with a one-dimensional unbinned extended maximum-likelihood fit to $M[D^+_{(s)}]$. The fit yields 50k $D^+ \to K^+ K^- \pi^+\pi^0$, 3.6k for doubly CS $D^+ \to K^+ \pi^-\pi^+\pi^0$ and 26k for CS $D^+_s \to K^+ \pi^-\pi^+\pi^0$ which is also the first observation for this decay. The measured branching fractions are: $\mathcal{B}(D^+ \to K^+ K^- \pi^+\pi^0) = [7.08 \pm 0.07 \pm 0.16 \pm 0.20] \times 10^{-3}$, $\mathcal{B}(D^+ \to K^+ \pi^-\pi^+\pi^0) = [1.05 \pm 0.05 \pm 0.02 \pm 0.03] \times 10^{-3}$ and $\mathcal{B}(D^+_s \to K^+ \pi^-\pi^+\pi^0) = [9.44 \pm 0.25 \pm 0.28 \pm 0.32] \times 10^{-3}$.

5. Summary

We reported precision measurements of branching fraction and *CPV* using A_{CP} and a^T_{CP} in Cabibbo suppressed charm meson decays obtained using the Belle detector. All the branching fractions and *CPV* measurements are either world's most precise results or first observation. All *CPV* results are consistent with zero *CPV* asymmetry.

References

[1] R. Allahverdi et al., Open Jour. Astrophys. 4 (2021).

[2] L. Canetti, M. Drewes, and M. Shaposhnikov, New J. Phys. 14, 095012 (2012).

[3] G. R. Farrar and M. E. Shaposhnikov, Phys. Rev. D 50, 774 (1994).

[4] A. D. Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5, 32 (1967).

[5] P. Huet and E. Sather, Phys. Rev. D 51, 379 (1995).

[6] Y. Grossman, A. L. Kagan, and Y. Nir, Phys. Rev. D 75, 036008 (2007).

[7] R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 122, 211803 (2019).

[8] A. Abashian et al. (Belle Collaboration), Nucl. In- strum. Meth. A 479, 117 (2002), also see Section 2 in J. Brodzicka et al., Prog. Theor. Exp. Phys. 2012, 04D001 (2012).

[9] B. Collaboration (Belle Collaboration) (2022), arXiv:hep-ex/2207.07555

[10] L.K. Li et al. (Belle Collaboration), Measurement of branching fractions and search for CP violation in $D^0 \to \pi^+\pi^-\eta$, $D^0 \to K^+ K^- \eta$, $D^0 \to \phi\eta$ at Belle. J. High Energ. Phys. 2021, 75 (2021). https://doi.org/10.1007/JHEP09(2021)075

[11] B. Collaboration (Belle Collaboration) (2022), https://arxiv.org/abs/2205.02018

[12] G. Durieux and Y. Grossman, Phys. Rev. D 92, 076013 (2015).

[13] G. Valencia, Phys. Rev. D 39, 3339 (1989).

[14] W. Bensalem and D. London, Phys. Rev. D 64, 116003 (2001).

[15] The fitted ranges are larger for the signal mode in order to more accurately model the background level.

[16] F. Berends, K. Gaemers, and R. Gastmans, Nucl. Phys. B63, 381 (1973).

[17] P. Zyla et al. (Particle Data Group), PTEP 2020, 083C01 (2020).