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

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BOLOGNA

Aman Sangal

(on behalf of Belle collaboration)

University of CINCINNATI

BELLE

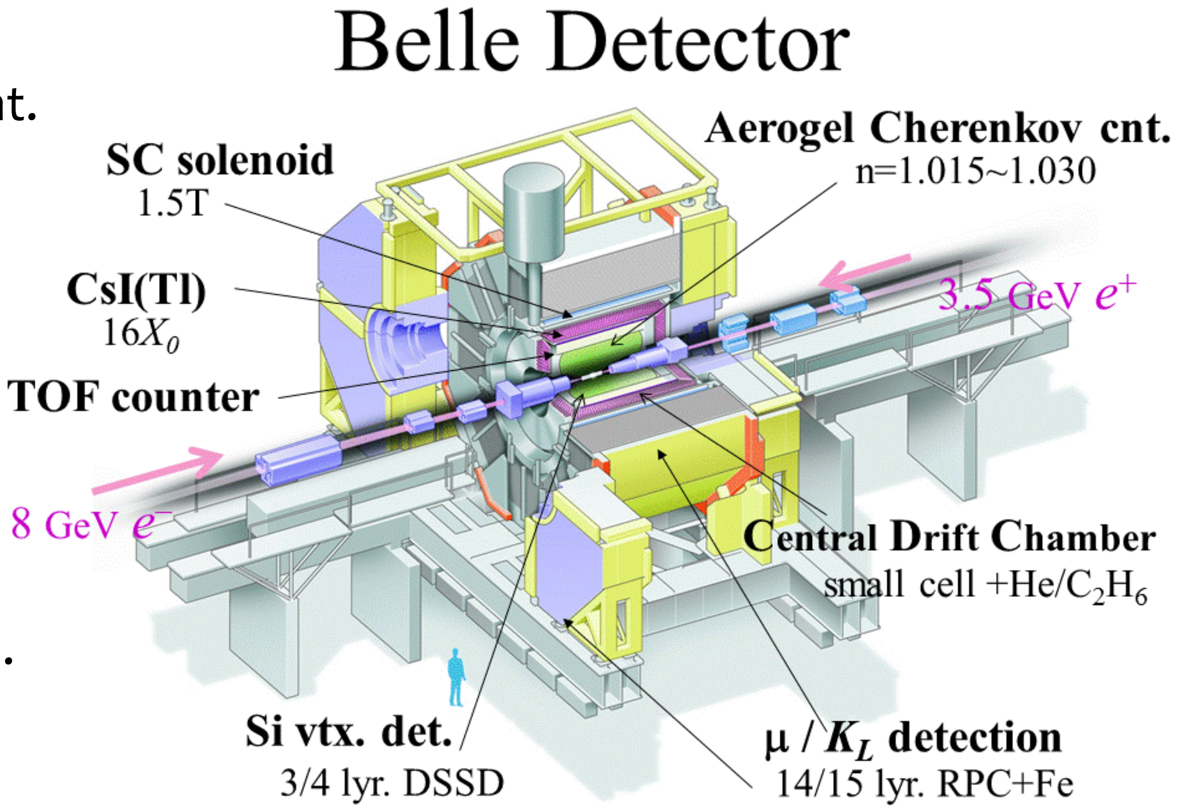
Belle experiment at KEKB e^+e^- collider:

- KEKB: Asymmetric e^+e^- collider operating at and near 10.58 GeV [$\Upsilon(4S)$ mass peak]

- Belle detector was situated around e^+e^- interaction point.

- Belle experiment collected total $\sim 1\ \mathrm{ab}^{-1}$ data including
  - $1.3 \times 10^9\ c\bar{c}$ *(charm factory)*

- Belle experiment ran successful physics program with very good particle identification and vertexing performance.



Motivation:

- Standard Model framework: Very small, $\mathcal{O}(10^{-3})$ or smaller *CP* violation in charm meson decays [1].
- *CP* violation measurement significantly deviating from SM expectation would probe new physics contributions.
- **Singly Cabibbo suppressed (SCS) charm meson decay,** uniquely sensitive to new physics effects [1].
- Only CP violation observed in charm was in SCS decays [2].
- This talk present recent results from Belle experiment on:
  - **Precision measurement of decay rates** for **Cabibbo suppressed charm meson decays**
  - Search for **CP violation in Cabibbo suppressed charm meson decays**

[1] (Y. grossman, et al. Phys.Rev.D 75 (2007), 036008)
[2] LHCb Collaboration Phys.Rev.Lett. 122 (2019) 21, 211803

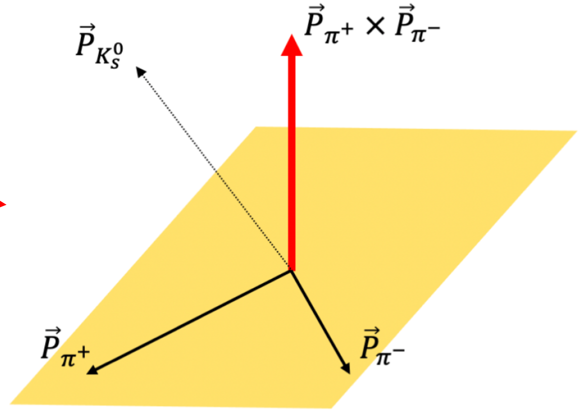
Measurement of Branching Fraction and search for CP violation in $D^0 \rightarrow K_s^0 K_s^0 \pi^+ \pi^-$

(Preliminary, paper to be submitted)

CP violating observable a_{CP}^{T} :

- Search for CP violation using T-odd triple product (TP) asymmetries.
- Define scalar triple product C_T as:
  - $C_T = \vec{p}_{K_S^0} \cdot (\vec{p}_{\pi^+} \times \vec{p}_{\pi^-})$ (K_S^0 with higher momentum is used)
  - For D^0 decays, T-odd triple product asymmetry A_T is defined as :
    - $A_T = \frac{N_1\,(C_T>0) - N_2\,(C_T<0)}{N_1\,(C_T>0) + N_2\,(C_T<0)}$
  - For $\overline{D}^0$ decays, CP conjugate observables: $A_T \xrightarrow{CP} \bar{A}_T$, $C_T \xrightarrow{C} \bar{C}_T \xrightarrow{P} -\bar{C}_T$
    - $\bar{A}_T = \frac{N_3\,(-\bar{C}_T>0) - N_4(-\bar{C}_T<0)}{N_3\,(-\bar{C}_T>0) + N_4(-\bar{C}_T<0)}$

- I. I. Y. Bigi. *Charm physics: Like Botticelli in the Sistine Chapel.*
- *Michael Gronau et.al PRD,495 84(9), Nov 2011.*



- The difference $a_{CP}^{\mathrm{T}} = \frac{1}{2}(A_T - \bar{A}_T)$ is a CP violating observable.
- $\boldsymbol{a_{CP}^{T}}$:
  - Independent of effects from strong phases.
  - By construction, unaffected by D^0 versus $\overline{D}^0$ production and detection related asymmetries.

- *Michael Gronau et.al PRD,495 84(9), Nov 2011.*

CP violation measurement using A_{CP} :

- We can also search for CP violation using observable A_{CP} defined as:

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

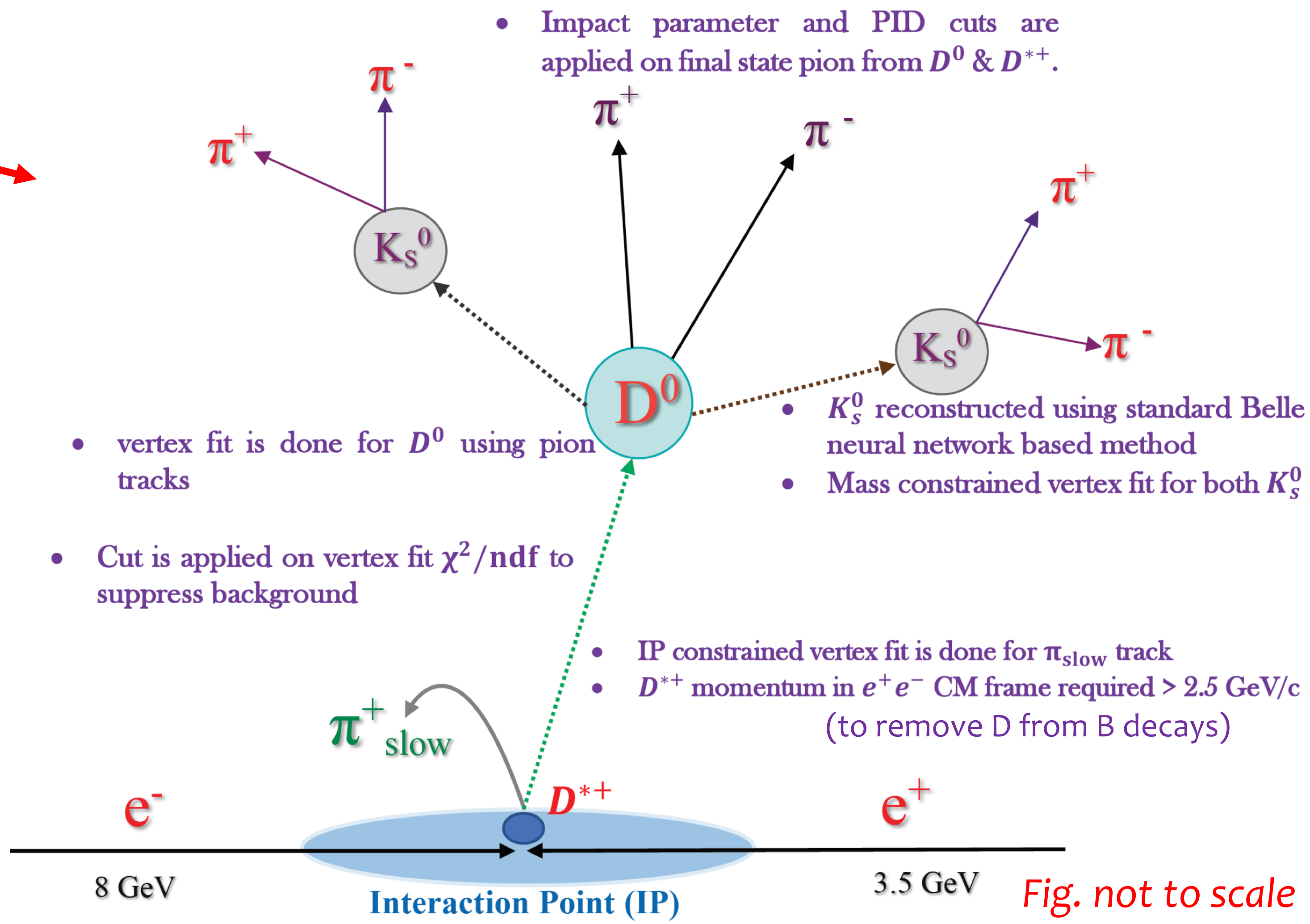
  - It is the difference in number of D^0 and $\bar{D}^0$ decays to the CP conjugate final states f and $\bar{f}$.

- Measurement of both A_{CP} and a_{CP}^T are complementary to each other:
  - The observable $\boldsymbol{A_{CP}} \propto \boldsymbol{sin(\phi)\, sin(\delta)}$, where (ϕ) is weak and (δ) is strong phase difference between the contributing amplitudes.
  - The observable $\boldsymbol{a_{CP}^T} \propto \boldsymbol{sin(\phi)\, cos(\delta)}$
    - Non zero A_{CP} : strong phase difference (δ) must be non zero,
    - a_{CP}^T is largest when the strong phase difference (δ) is zero.

- A. Datta et.al, Int.J.Mod.Phys.A 19 (2004), 2505-2544

Reconstruction of decay at Belle detector

- Reconstructed decay chain and the corresponding selection criteria
- Multiple candidate events:
  - choose a single candidate with lowest value for $\sum \chi^2/\mathrm{ndf}$ of D^*, D^0 and K_S^0 vertex fit.
- Same set of selection criteria for normalization channel $D^0 \to K_S^0\pi^+\pi^-$
- Reconstruction efficiency:
  - 6.92% for $D^0 \to K_S^0 K_S^0 \pi^+\pi^-$
  - 14.97% for $D^0 \to K_S^0\pi^+\pi^-$



Branching fraction measurement:

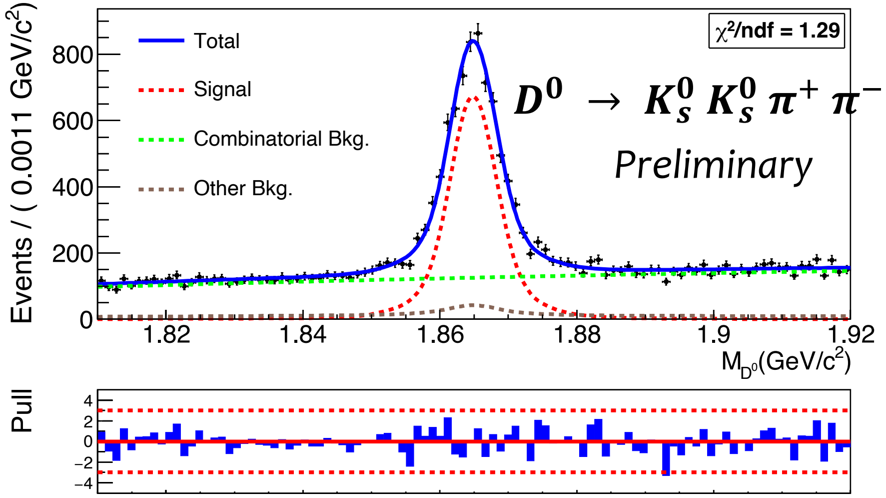
- Extracted signal events using 2d fit in variables:
  - $M_{D^0}[M(K_S^0 K_S^0 \pi^+\pi^-)]$ and $\Delta M\ [M(K_S^0 K_S^0 \pi^+\pi^-\pi^+_{slow}) - M(K_S^0 K_S^0 \pi^+\pi^-)]$
- $\sim$921 fb^{-1} Belle data, → $\sim\mathbf{6.1k}\ D^0 \rightarrow K_S^0\ K_S^0\ \pi^+\ \pi^-$ and $\sim\mathbf{1M}\ \ D^0 \rightarrow K_S^0\pi^+\pi^-$

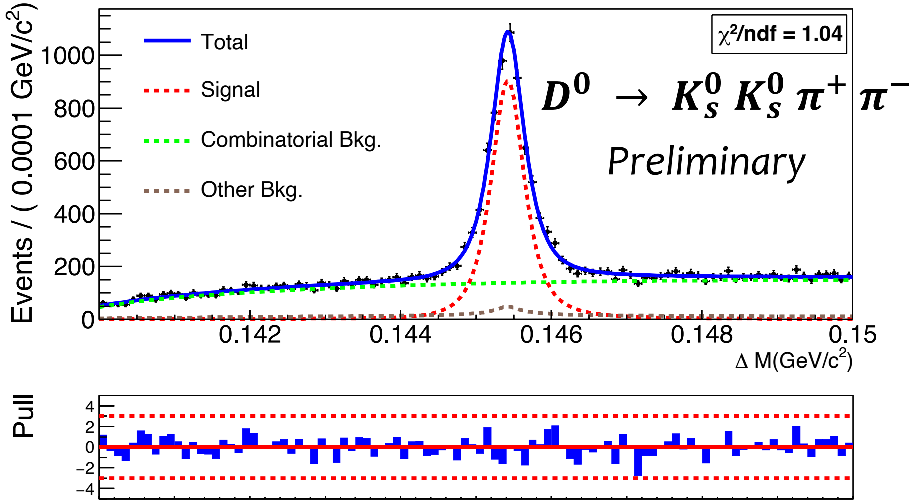
- **BF(** $\boldsymbol{D^0 \rightarrow K_S^0\ K_S^0\ \pi^+\ \pi^-)/BF(\ D^0 \rightarrow K_S^0\ \pi^+\ \pi^-)}$ = [1.72 ± 0.03 (stat.) ± 0.04 (syst.)] %

- **BF(** $\boldsymbol{D^0 \rightarrow K_S^0\ K_S^0\ \pi^+\ \pi^-)} = [4.82\ \pm 0.08\ (\text{stat.})\ {}^{+0.10}_{-0.11}\ (\text{syst.})\ \pm 0.31\ (\text{norm.})] \times 10^{-4}$

World's most precise measurement, *compare to previous result* $(5.30\ \pm \mathbf{0.90}\ (\textit{stat.}) \pm 0.30\ (\textit{syst.})] \times 10^{-4})$

Fit Projections



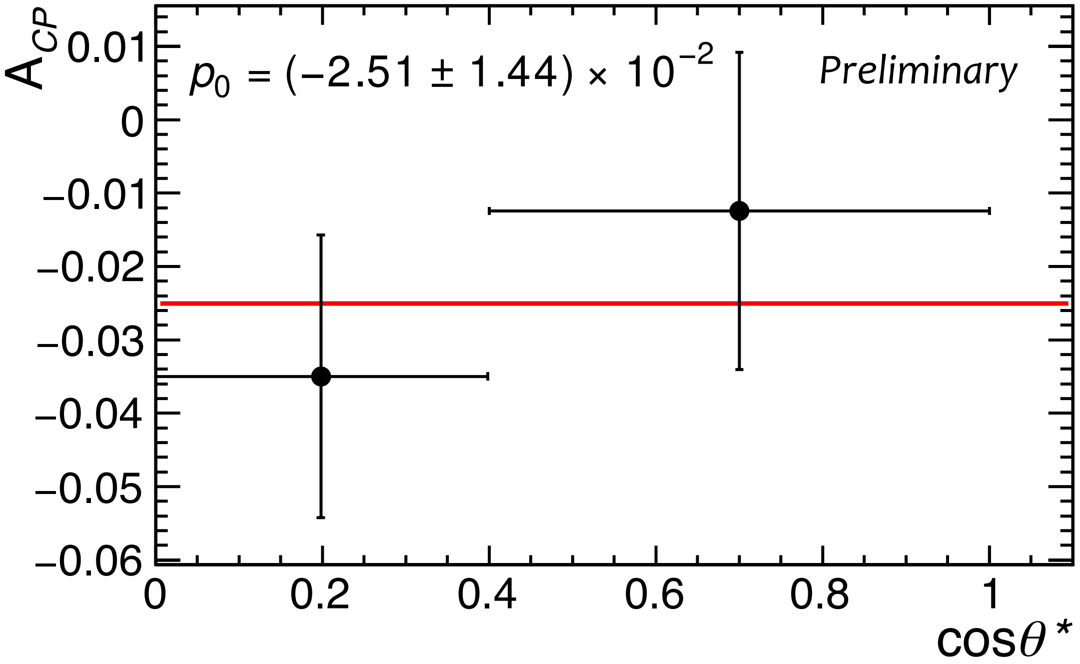


A_{CP} measurement:

- The A_{CP} value obtained using below equation includes contribution from non CP violating production and reconstruction asymmetries:
$$A_{CP}^{\text{det}} = \frac{N(D^0 \to f) - N(\overline{D}^0 \to \overline{f})}{N(D^0 \to f) + N(\overline{D}^0 \to \overline{f})}$$
- $$A_{CP}^{\text{det}} = A_{CP} + A_{FB} + A_{\epsilon}^{\pi_s}$$
Asymmetry due to difference in reconstruction efficiency between π_s^+ and π_s^-
Forward backward asymmetry
CP violating asymmetry
- To account for $A_{\varepsilon}^{\pi_s}$, we weight the D^0 and $\overline{D}^0$ events as :
$$w_{D^0} = 1 - A_{\epsilon}^{\pi_s}(p_T, \cos\theta_{\pi_s})$$
$$w_{\overline{D}^0} = 1 + A_{\epsilon}^{\pi_s}(p_T, \cos\theta_{\pi_s})$$
- Resulting A_{CP} now includes $A_{CP}^{\text{cor}} = A_{CP} + A_{FB}$.
- The forward backward asymmetry is odd function of cos(θ^*), where θ^* is D* polar angle in COM frame.
- For a given cos(θ^*) bin, we obtain true CP violating asymmetry $A_{CP} = \frac{A_{CP}^{\text{cor}}(\cos\theta^*) + A_{CP}^{\text{cor}}(-\cos\theta^*)}{2}$
- The average of all positive cos(θ^*) bins will be quoted as final A_{CP} asymmetry.

A_{CP} measurement

A_{CP} values as function of $\cos(\theta^*)$:



- The red line is a straight line fit to A_{CP} values

- Final A_{CP} result is :
  $$A_{CP} = \left[-2.51 \pm 1.44\,(\text{stat.})\,^{+0.35}_{-0.52}\,(\text{syst.})\right] \times 10^{-2}$$

- **First CPV search for this decay**
- **Consistent with zero CP Violation.**

Simultaneous fit for a_{CP}^{T} measurement:

- To measure a_{CP}^{T}, data sample is divided into four categories:

Charge of π_s is used to tag the flavor of neutral D meson

D^0 decays | $\bar{D}^0$decays

$C_T > 0$ (N_1) | $C_T < 0$ (N_2) | $-\bar{C}_T > 0$ (N_3) | $-\bar{C}_T < 0$ (N_4) → Signal yields

- To obtain a_{CP}^{T} , we perform a 2d fit simultaneously to these four datasets.

- $\mathrm{a}_{CP}^{\mathrm{T}} = [-1.95 \pm 1.42\,(\mathrm{stat.})\,^{+0.14}_{-0.12}\,(\mathrm{syst.})]\%$
- **First search for CPV using T-odd observable in this decay**
- **Result Consistent with zero CP Violation.**

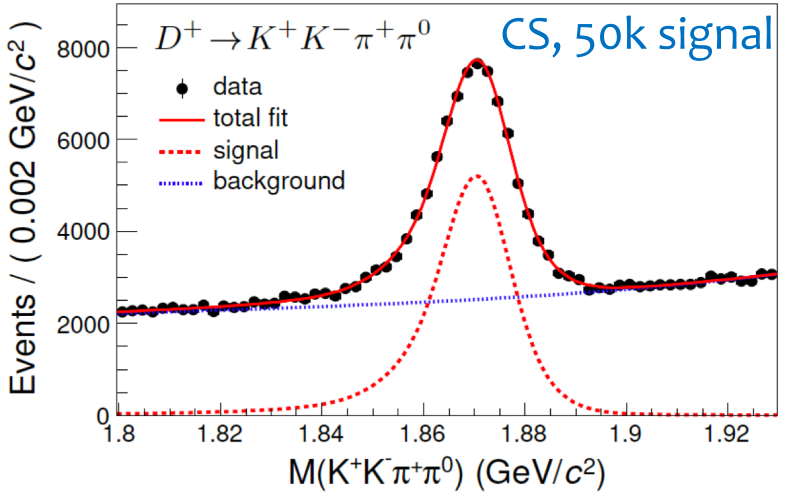
Branching fraction measurement for $D^+ \to K^+K^-\pi^+\pi^0$, $D_{(s)}^+ \to K^+\pi^-\pi^+\pi^0$

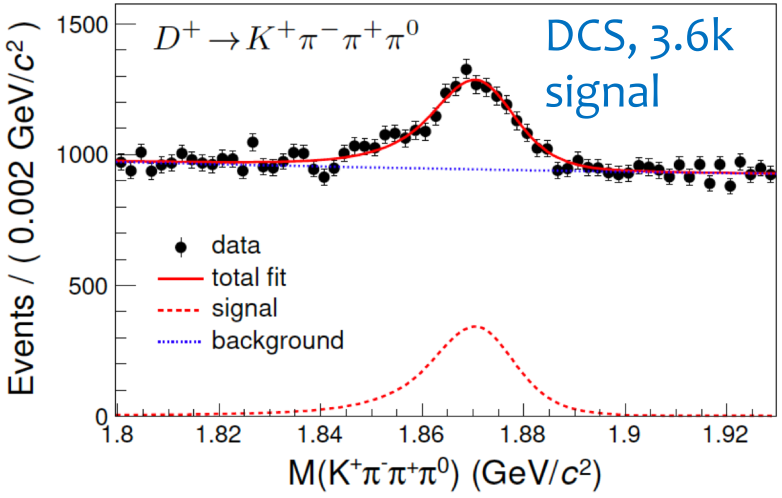
arXiv:2205.02018 **[hep-ex]**

$D^+ \rightarrow K^+K^-\pi^+\pi^0$, $D^+_{(s)} \rightarrow K^+\pi^-\pi^+\pi^0$

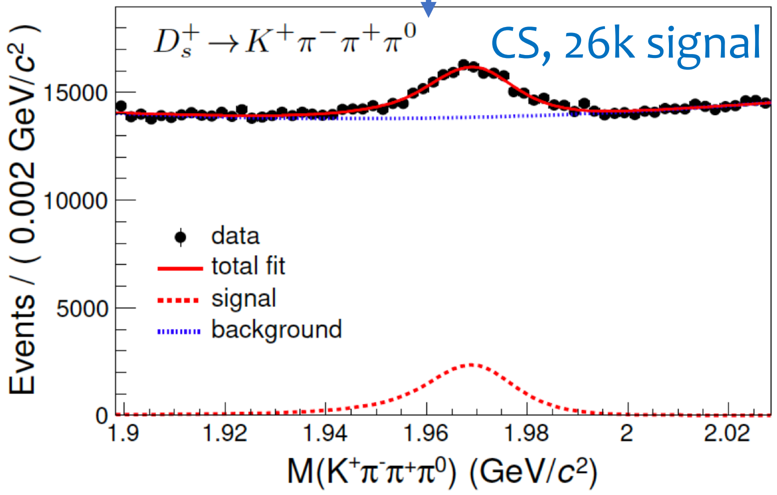
- Measured $D^+ \rightarrow K^+K^-\pi^+\pi^0$, $D^+_{(s)} \rightarrow K^+\pi^-\pi^+\pi^0$ branching fractions
  - Used 988 fb^{-1} of data
  - Measurement done relative to normalization modes: $D^+ \rightarrow K^-\pi^+\pi^+\pi^0$, $D_s^+ \rightarrow K^+K^-\pi^+\pi^0$

- Signal yields are extracted using fit to M($D^+_{(s)}$)





First observation



Results:

arXiv:2205.02018 **[hep-ex]**

- **Measured branching fraction ratios are:**

$$\frac{\mathcal{B}(D^+\to K^+K^-\pi^+\pi^0)}{\mathcal{B}(D^+\to K^-\pi^+\pi^+\pi^0)} = (11.32\pm0.11\pm0.26)\%$$

$$\boxed{\frac{\mathcal{B}(D^+\to K^+\pi^-\pi^+\pi^0)}{\mathcal{B}(D^+\to K^-\pi^+\pi^+\pi^0)} = (1.68\pm0.08\pm0.03)\%}$$

$$\frac{\mathcal{B}(D_s^+\to K^+\pi^-\pi^+\pi^0)}{\mathcal{B}(D_s^+\to K^+K^-\pi^+\pi^0)} = (17.13\pm0.46\pm0.51)\%\,,$$

- ***Ratio of DCS/CF decay = $(5.83 \pm 0.30) \times tan^4\theta_c$***
- *Significantly larger than $(0.21 - 0.58)$ %, measured for other DCS decays*
- *Consistent with previous result $(6.28 \pm 0.52) \times tan^4\theta_c$*
- *Possible explanation is* ***presence of massive isospin symmetry violation in the decay*** *(Phys. Rev. D* ***104****, 072005)*

- **Measured branching fractions are:**

$$\mathcal{B}(D^+\to K^+K^-\pi^+\pi^0) = (7.08\pm0.07\pm0.16\pm0.20)\times10^{-3}$$

$$\mathcal{B}(D^+\to K^+\pi^-\pi^+\pi^0) = (1.05\pm0.05\pm0.02\pm0.03)\times10^{-3}$$

Improved precision from latest measurements

$B(D^+ \to K^+K^-\pi^+\pi^0) = (6.62 \pm 0.20 \pm 0.25)\times10^{-3}$

$B(D^+ \to K^+\pi^-\pi^+\pi^0) = (1.21 \pm 0.08 \pm 0.03)\times10^{-3}$

$$\mathcal{B}(D_s^+\to K^+\pi^-\pi^+\pi^0) = (9.44\pm0.25\pm0.28\pm0.32)\times10^{-3}$$

First observation

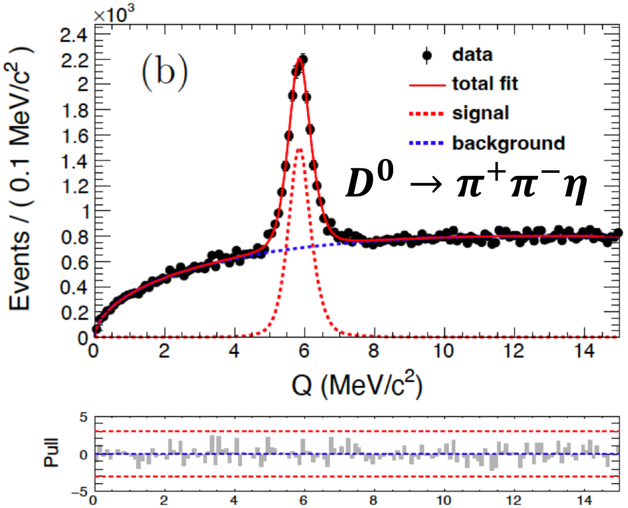
Branching fraction and A_{CP} measurement for $D^0 \to \pi^+\pi^-\eta$, $K^+K^-\eta$, and $\phi\eta$

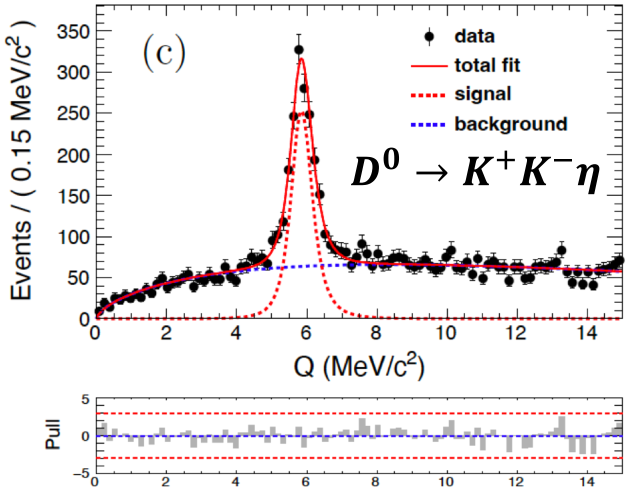
[JHEP09(2021)075]

Branching fraction:

[JHEP09(2021)075]

- Measured $D^0 \to \pi^+\pi^-\eta$, $K^+K^-\eta$, and $\phi\eta$ branching fractions
  - Using 988 fb^{-1} of data, relative to normalization modes: $D^0 \to K^-\pi^+\eta$
  - Signal yields are extracted using fit to Q = M[$K^+K^-\eta\,\pi^+_{slow}$] − M[$K^+K^-\eta$] − M[π^+_{slow}]

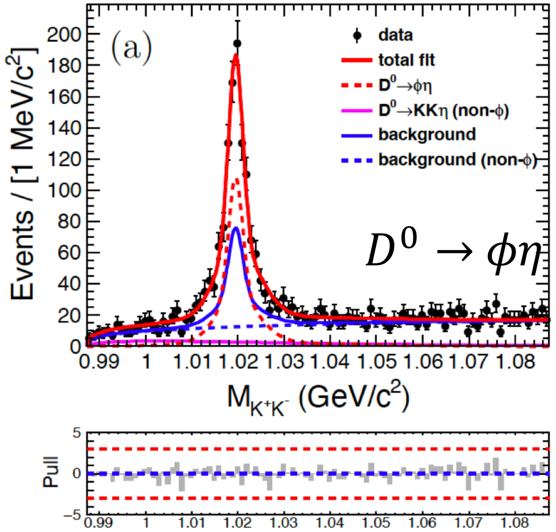


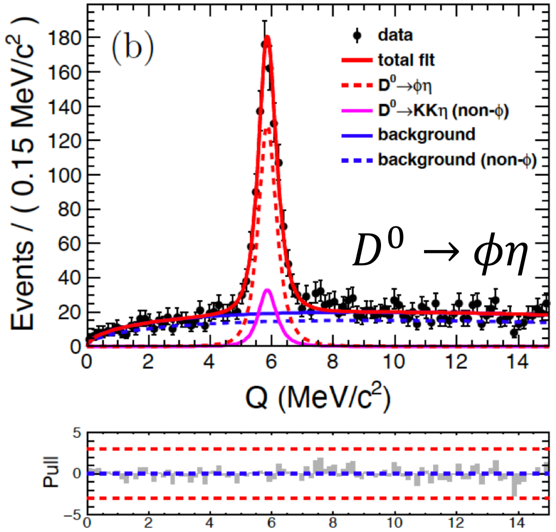


B($D^0 \to \pi^+\pi^-\eta$)= [$1.22 \pm 0.02\ \pm 0.02\ \pm 0.03$]$\times 10^{-3}$
(world's best precision)

B($D^0 \to K^+K^-\eta$)= [$1.80^{+0.07}_{-0.06} \pm 0.04\ \pm 0.05$]$\times 10^{-4}$
(first measurement)

- 2d fit used for $D^0 \to \phi\eta$: Q , M[K^+K^-]



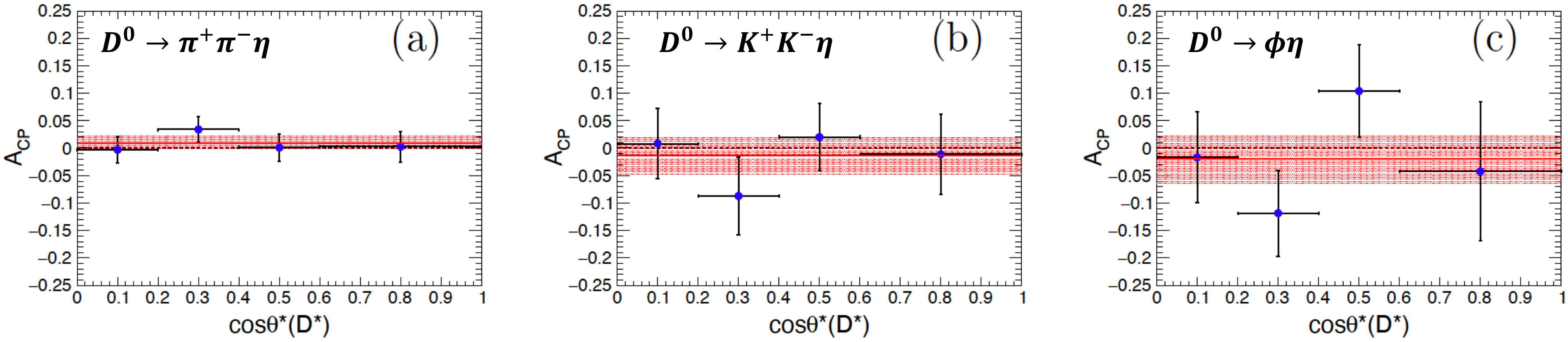


- **B($D^0 \to \phi\,\eta$)= [$1.84 \pm 0.09 \pm 0.06\ \pm 0.05$]$\times 10^{-4}$**
  - ***Improvement to PDG world average [1.8 ± 0.5]*** $\times 10^{-4}$

A_{CP} measurement:

[JHEP09(2021)075]

- Simultaneous fit for D^0 and $\overline{D}^0$, Q distributions in bins of $\cos(\theta^*)$



- $A_{CP}\,(D^0 \to \pi^+\pi^-\eta) = [0.9\ \pm 1.2\ (\text{stat.}) \pm 0.4\ (\text{syst.})]\%$
- $A_{CP}\,(D^0 \to K^+K^-\eta) = [-1.4\ \pm 3.3\ (\text{stat.}) \pm 1.0\ (\text{syst.})]\%$
- $A_{CP}\,(D^0 \to \phi\,\eta) = [-1.9\ \pm 4.4\ (\text{stat.}) \pm 0.6\ (\text{syst.})]\%$

Significant improvement over previous best measurement
$A_{CP}\ = [-9.6 \pm 5.4 \pm 1.8\,]\%$

First search for CPV in these decays
All results consistent with zero CPV

Search for $D^+ \to K^- K_S^0 \pi^+ \pi^+ \pi^0$ at Belle

(Preliminary, paper to be submitted)

Search for $D^+ \to K^- K_S^0 \pi^+ \pi^+ \pi^0$

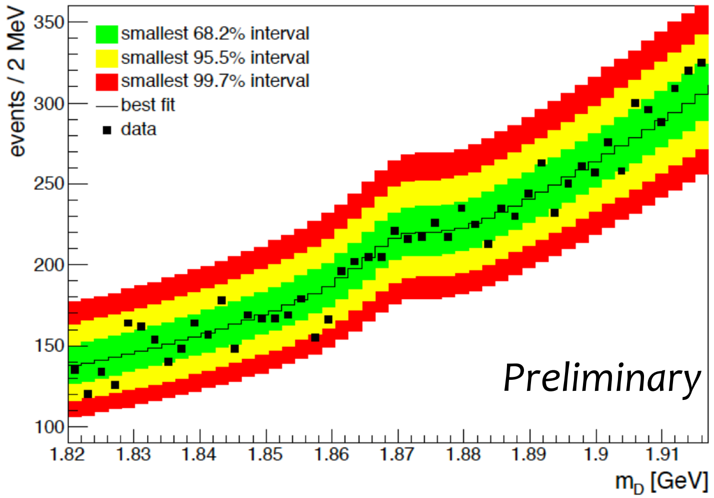
- SM CP violation is highly suppressed, $\mathcal{O}(10^{-4})$ in the $\Delta I = 3/2$ transitions.

- Calculate asymmetry in $\Delta I = 3/2$ transition
  - Use five particle final state common to $D^+ \to K^* \overline{K}^* \pi$ charge configurations i.e. $D^+ \to K^- K_S^0 \pi^+ \pi^+ \pi^0$ to measure the following amplitude sum

$$\mathcal{A}(K^{*+}K^{*-}\pi^+) + \mathcal{A}(K^{*0}\overline{K}^{*0}\pi^+) + \sqrt{2}\mathcal{A}(K^{*+}\overline{K}^{*0}\pi^0)$$

- Results:
  - $\mathrm{B}(D^+ \to K^- K_S^0 \pi^+ \pi^+ \pi^0) = 6.4^{+3.9}_{-3.8} \times 10^{-5}$ with an **upper limit at 95% credibility of 1.4×10^{-4}** **(Bayesian)**
  - $B(D^+ \to \overline{K}^* \eta \pi^+ + D^+ \to \overline{K}^* \omega \pi^+) = 6.0^{+6.3}_{-5.8} \times 10^{-5}$ with an upper limit at **95% credibility of 1.8×10^{-4}**

Invariant mass distribution for $D^+ \to K^- K_S^0 \pi^+ \pi^+ \pi^0$



Summary:

Charm mesons BF measurements:

- $B(D^0 \to K_S^0 K_S^0 \pi^+ \pi^-) = [4.82 \pm 0.08\,(\text{stat.})\,^{+0.10}_{-0.11}\,(\text{syst.}) \pm 0.31\,(\text{norm.})] \times 10^{-4}$

- $B(D^0 \to \pi^+\pi^-\eta) = [1.22 \pm 0.02 \pm 0.02 \pm 0.03] \times 10^{-3}$
- $B(D^0 \to K^+K^-\eta) = [1.80^{+0.07}_{-0.06} \pm 0.04 \pm 0.05] \times 10^{-4}$
- $B(D^0 \to \phi\,\eta) = [1.84 \pm 0.09 \pm 0.06 \pm 0.05] \times 10^{-4}$

- $B(D^+ \to K^+ K^- \pi^+ \pi^0) = [7.08 \pm 0.07 \pm 0.16 \pm 0.20] \times 10^{-3}$
- $B(D^+ \to K^+ \pi^- \pi^+ \pi^0) = [1.05 \pm 0.05 \pm 0.02 \pm 0.03] \times 10^{-3}$
- $B(D_s^+ \to K^+ \pi^- \pi^+ \pi^0) = [9.44 \pm 0.25 \pm 0.28 \pm 0.32] \times 10^{-3}$

- $B(D^+ \to K^- K_S^0 \pi^+ \pi^+ \pi^0)$, **upper limit at 95% credibility of $\mathbf{1.4 \times 10^{-4}}$**

All reported BF measurements provides either world's best precision or first observation

CP violation measurements:

- A_{CP}, a_{CP}^T for SCS decay $D^0 \to K_S^0 K_S^0 \pi^+ \pi^-$
  - $A_{CP} = [-2.51 \pm 1.44\,(\text{stat.})\,^{+0.35}_{-0.52}\,(\text{syst.})] \times 10^{-2}$
  - $a_{CP}^T = [-1.95 \pm 1.42\,(\text{stat.})\,^{+0.14}_{-0.12}\,(\text{syst.})]\%$

- $A_{CP}\,(\boldsymbol{D^0 \to \pi^+\pi^-\eta}) = [0.9 \pm 1.2\,(\text{stat.}) \pm 0.4\,(\text{syst.})]\%$
- $A_{CP}\,(\boldsymbol{D^0 \to K^+K^-\eta}) = [-1.4 \pm 3.3\,(\text{stat.}) \pm 1.0\,(\text{syst.})]\%$
- $A_{CP}\,(\boldsymbol{D^0 \to \phi\,\eta}) = [-1.9 \pm 4.4\,(\text{stat.}) \pm 0.6\,(\text{syst.})]\%$

All reported CPV measurements consistent with zero CP violation

Backup

Systematics for $D^+ \rightarrow K^+K^-\pi^+\pi^0$, $D^+_{(s)} \rightarrow K^+\pi^-\pi^+\pi^0$

TABLE II. Fractional systematic uncertainties (in %) for the following ratios of branching fractions:
(a) $\mathcal{B}(D^+ \rightarrow K^+K^-\pi^+\pi^0)/\mathcal{B}(D^+ \rightarrow K^-\pi^+\pi^+\pi^0)$;
(b) $\mathcal{B}(D^+ \rightarrow K^+\pi^-\pi^+\pi^0)/\mathcal{B}(D^+ \rightarrow K^-\pi^+\pi^+\pi^0)$; and
(c) $\mathcal{B}(D_s^+ \rightarrow K^+\pi^-\pi^+\pi^0)/\mathcal{B}(D_s^+ \rightarrow K^+K^-\pi^+\pi^0)$.

Sources	(a)	(b)	(c)
PID efficiency correction	1.7	...	1.7
Multiple-candidate selection	1.1	1.3	1.2
Signal parameterization	0.5	0.5	1.1
$M(D)$ resolution	0.5	...	1.4
Binning	0.6	0.5	0.7
Background Dalitz distribution	0.1	0.1	0.3
Efficiency correction bias	0.6	0.8	1.1
Total uncertainty	2.3	1.9	3.0

Systematics for $D^0 \to K_S^0 K_S^0 \pi^+ \pi^-$

Summary of systematic uncertainty for BF measurement:

Source	$K_S^0 K_S^0 \pi^+\pi^-$ (%)	$K_S^0 \pi^+\pi^-$ (%)
Fixed PDF parameters	0.14	0.09
$D^0 \to K_S^0 K_S^0 K_S^0$ background	0.11	–
Broken charm background	0.98	–
MC statistics	0.26	0.17
PID efficiency correction	0.80	0.74
K_S^0 reconstruction efficiency	0.83	0.36
Tracking Efficiency	0.70	
$M(\pi^+\pi^-)$ veto efficiency	$^{+0.42}_{-0.93}$	–
Fraction of mis-reconst. signal	$^{+0.02}_{-0.03}$	–
$D^0 \to K_S^0 K_S^0 \pi^+\pi^-$ decay model	0.73	
$\mathcal{B}(K_S^0 \to \pi^+\pi^-)$	0.07	–
Total for $\mathcal{B}_{K_S^0 K_S^0 \pi^+\pi^-}/\mathcal{B}_{K_S^0 \pi^+\pi^-}$	$^{+2.07}_{-2.23}$	

Summary of systematic uncertainties evaluated for a_{CP}^T:

Source	(%)
Fixed PDF parameters	0.010
$D^0 \to K_S^0 K_S^0 K_S^0$ background	$^{+0.000}_{-0.013}$
Broken charm background	$^{+0.014}_{-0.040}$
Efficiency variation with C_T, $\overline{C}_T$	$^{+0.14}_{-0.11}$
Total	$^{+0.14}_{-0.12}$

Summary of systematic uncertainties evaluated for A_{CP}

Sources	(%)
Fixed PDF parameters	± 0.01
$D^0 \to K_S^0 K_S^0 K_S^0$ background	$^{+0.02}_{-0.03}$
Broken charm background	$^{+0.09}_{-0.07}$
Binning in $\cos\theta^*$	$^{+0.33}_{-0.51}$
Reconstruction asymmetry $A_\epsilon^{\pi_s}$	± 0.01
Fixed background fractions	± 0.04
Total	$^{+0.35}_{-0.52}$

- Fina