Measurement of the CP Asymmetry of $D^0 \rightarrow K_s K_s$ decay (Belle + Belle II)

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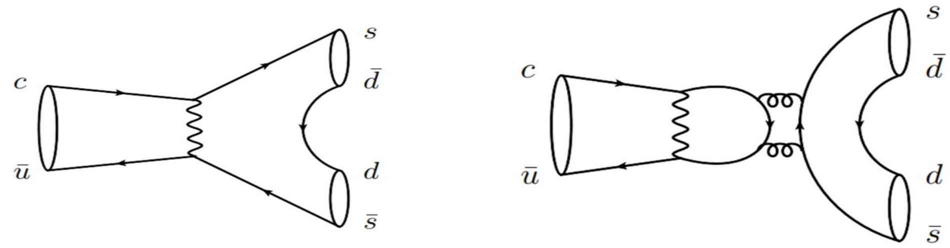
Physics Motivation

- $D^0 \rightarrow K_s K_s$ is a Singly Cabibbo Suppressed (SCS) decay, which involves the interference of $c\bar{u} \rightarrow s\bar{s}$ and $c\bar{u} \rightarrow d\bar{d}$ transitions.



- Due to this interference, the CP Asymmetry (A_{CP}) may be enhanced to an observable level within the Standard Model.

- The world-average determination of $A_{CP}(D^0 \rightarrow K_s K_s)$: $(-1.9 \pm 1.0)\%$, is limited by the statistical precision.

- The world average is dominated by measurements from **Belle** and **LHCb**:
  - Using 921fb^{-1} and $D^0 \rightarrow K_s \pi^0$ as the control mode, Belle measured $A_{CP}(D^0 \rightarrow K_s K_s) = (-0.02 \pm 1.53\ (\text{stat.}) \pm 0.02 (\text{syst.}) \pm 0.17\ (\text{control mode}))\ \%$ **[Phys. Rev. Lett. 119 171801]**
  - A more precise result of A_{CP} is obtained by LHCb with $D^0 \rightarrow K^+K^-$ as the control mode : $A_{CP}(D^0 \rightarrow K_s K_s) = (-3.1 \pm 1.2\ (\text{stat.}) \pm 0.4\ (\text{syst.}) \pm 0.2\ (\text{control mode}))\%$ **[Phys. Rev. D 104, L031102]**

- The measurement of $A_{CP}(D^0 \rightarrow K^+K^-)$ has been recently improved by LHCb bringing the corresponding uncertainty below the 0.1% level **[Phys. Rev. Lett. 131, 091802]**

➡**Goal of this analysis is to measure the time integrated Asymmetry (A_{CP}) in $D^0 \rightarrow K_s K_s$ decays using $D^0 \rightarrow K^+K^-$ as the control mode, with Belle and Belle II data.**

Time Integrated CP Asymmetry (A_{cp})

- Time integrated A_{CP} is defined as: $A_{CP} \equiv \frac{\Gamma(D^0 \to K_S^0 K_S^0) - \Gamma(\overline{D}^0 \to K_S^0 K_S^0)}{\Gamma(D^0 \to K_S^0 K_S^0) + \Gamma(\overline{D}^0 \to K_S^0 K_S^0)}$ *Γ = partial decay width*

- Experimentally we measure the quantity of raw asymmetry (A_{raw}), defined as:

$$A_{raw} \equiv \frac{N(D^0) - N(\overline{D}^0)}{N(D^0) + N(\overline{D}^0)}$$

$N(D^0)$ = measured yield of $D^{*+} \to D^0\pi^+$, $D^0 \to K_S K_S$ decays
$N(\overline{D}^0)$ = measured yield of $D^{*-} \to \overline{D}^0\pi^-$, $\overline{D}^0 \to K_S K_S$ decays

$$A_{raw} \approx A_{FB}^{D^{*+}} + A_{CP} + A_{\varepsilon}^{\pi_s}$$

$A_{\varepsilon}^{\pi_s}$ = *asymmetry of the detection efficiency of the slow pion*

A_{FB} = *forward backward asymmetry*

$$A_{CP}^{K_s K_s} = (A_{raw}^{K_s K_s} - A_{raw}^{KK}) + A_{CP}^{KK}$$

Assuming that the distributions of cosθ and momenta for D^{*+} and π_s are in agreement, due to which, corresponding A_{FB} and A_ε cancel.

$$A_{CP}(D^0 \to K^+K^-) = A_{CP}^{dir}(D^0 \to K^+K^-) + \Delta Y = (6.7 \pm 5.4) \times 10^{-4}$$

direct CP Asymmetry
Phys. Rev. Lett. 131 (2023) 091802

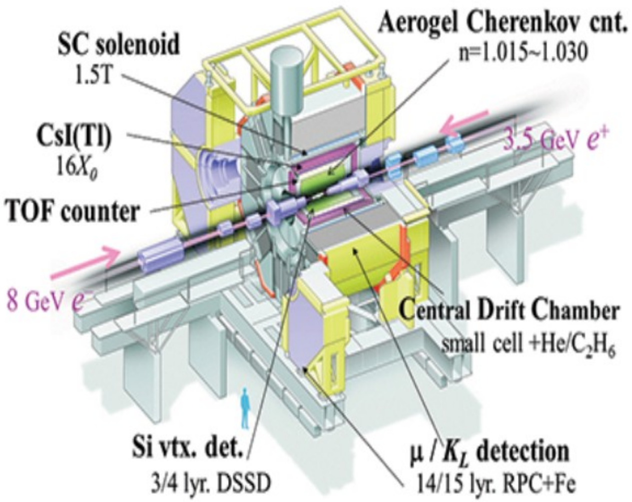
asymmetry from CP violation in mixing and in the interference between mixing and decay
Phys. Rev. D104 (2021) 072010

Experimental facility Belle and Belle II @ KEK, Japan

Instantaneous luminosity: 2.11 x 10^{34} $cm^{-2}s^{-1}$ (June 2009, world record)

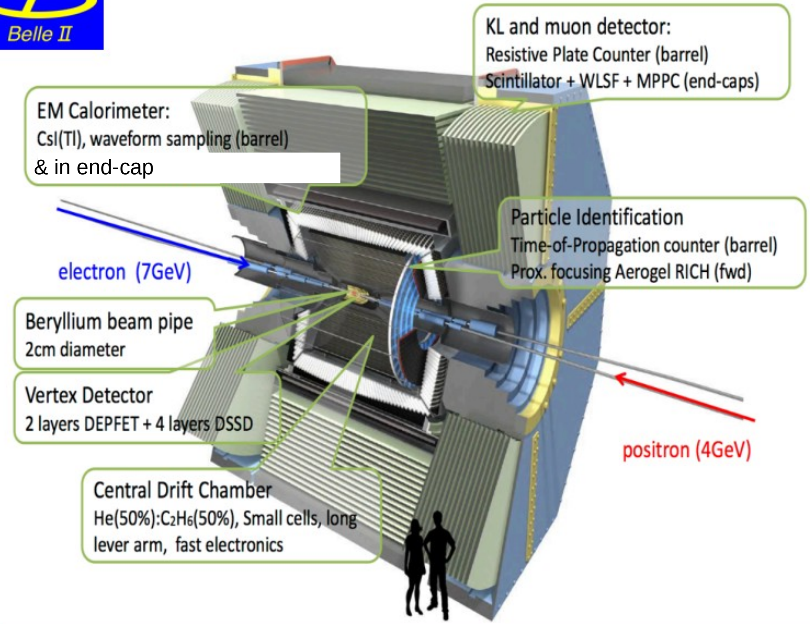
Dataset: 1ab^{-1}

Nucl. Instrum. Methods Phys. Res, Sect. A 479, 117 (2002)



Used full data sample collected by Belle of 980 fb^{-1} for $D^0 \rightarrow K_s K_s$ analysis.

Prog. Theor. Exp. Phys. 2019, 123C01



Target dataset: 50 ab^{-1}

Collected till date: 428 fb^{-1}

Instantaneous luminosity: 4.7 x 10^{34} $cm^{-2}s^{-1}$ (June 2022, current world record)

Used data sample collected at 927 fb^{-1} by Belle II (before LS1)

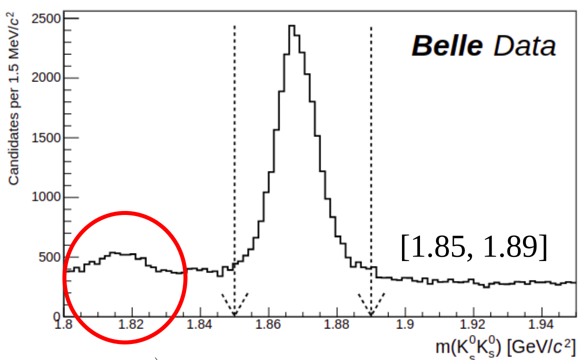
Measurement of the integrated luminosity of data samples collected during 2019-2022 by Belle II experiment arXiv:2407.00965 (hep-ex)

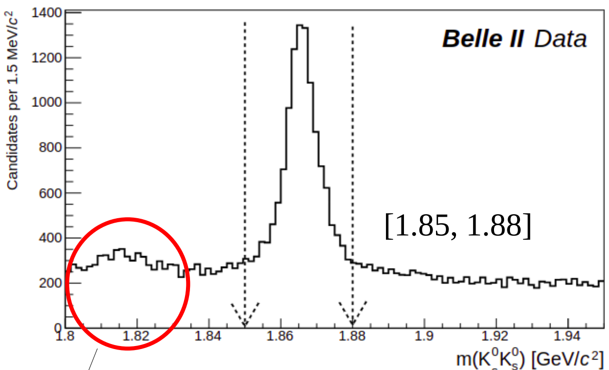
$D^0 \rightarrow K_s K_s$

Selection Criteria

Variable	Criteria	
$\lvert d_r(\pi_s)\rvert$	< 0.5 cm	(Selection criteria on Impact parameters)
$\lvert d_z(\pi_s)\rvert$	< 2 cm	
$\theta(\pi_s)$	$[17, 150]^\circ$	
$m(\pi^+\pi^-)$	$[0.45, 0.55]$ GeV/c^2	
$m(K_S^0 K_S^0)$	$[1.85, 1.89]$ GeV/c^2 (Belle) or $[1.85, 1.88]$ GeV/c^2 (Belle II)	
Δm = (m(D^{*+}) - m(D^0))	< 0.16 GeV/c^2	
$p_{\mathrm{cms}}(D^{*+})$	> 2.5 GeV/c	➡ (To reduce the events where D^{*+} coming from B meson)
`TreeFitter` probability	> 0.001	
Best-candidate selection	D^{*+} candidate with largest `TreeFitter` probability	

Treefitter is used with K_s mass constraint and IP constraint

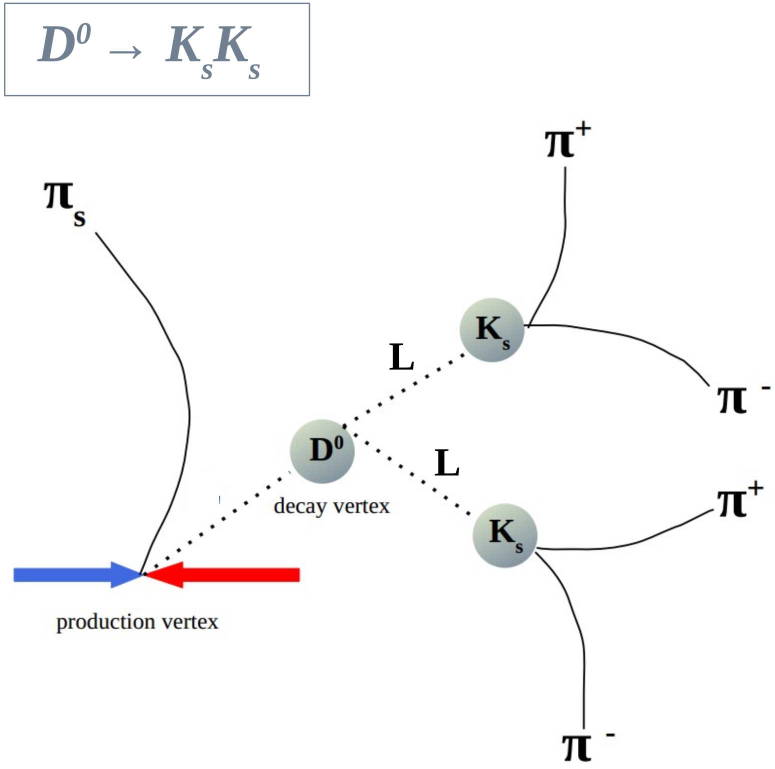


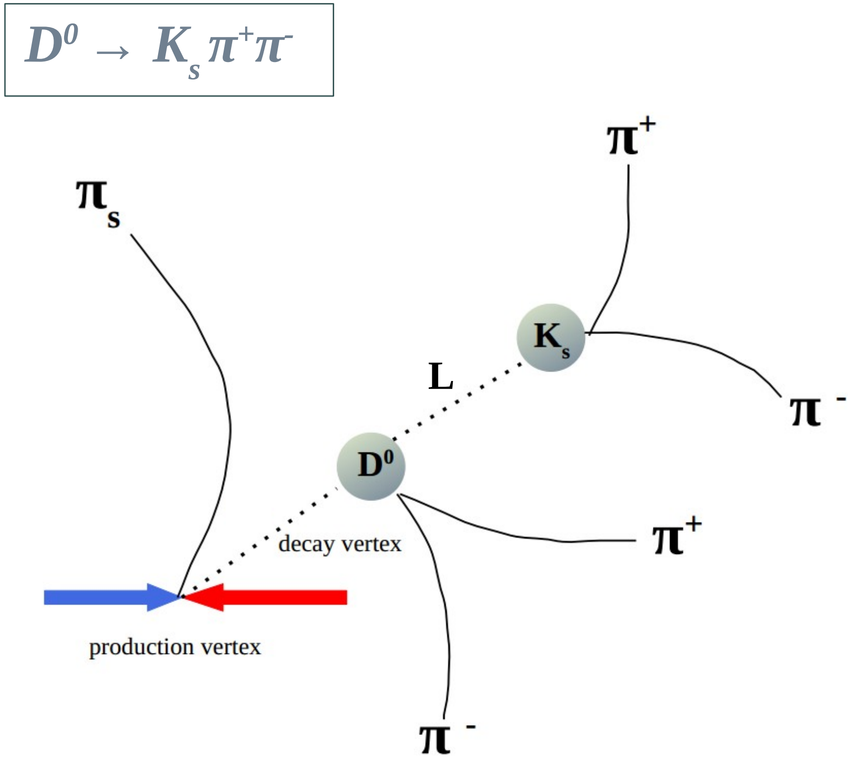


$D_s \rightarrow K_s K_s \pi^+$ ($\mathcal{B} = 7.7\times10^{-3}$), in which the charged pion acts as soft pion candidate.

$D^0 \rightarrow 2\pi^+ 2\pi^-$ is negligible and the only remaining physics background is $D^0 \rightarrow K_S \pi^+ \pi^-$

The background rejection variable S_{min}





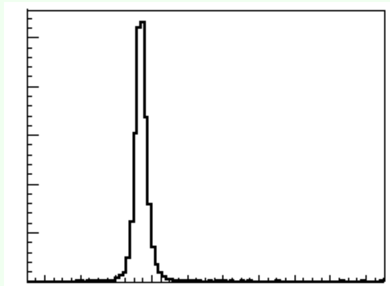
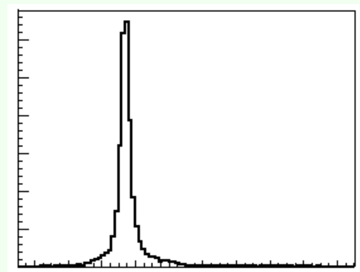
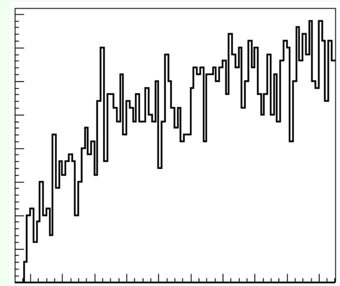
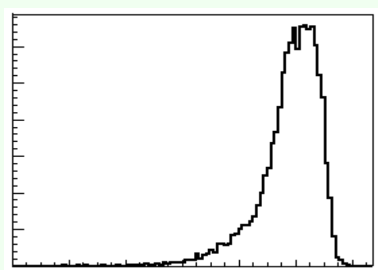
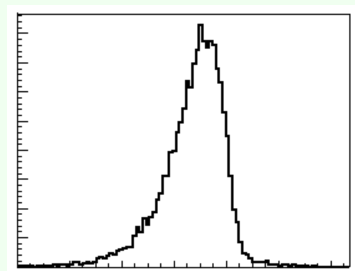
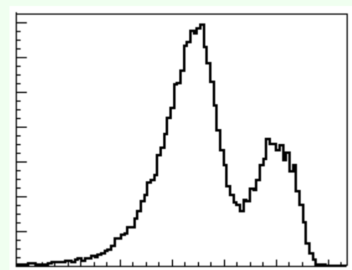
The flight distance of the K_s (with respect to the D^0 vertex) is exploited to provide separation of the peaking background ($D^0 \to K_s\pi^+\pi^-$) from the signal ($D^0 \to K_sK_s$).

S_{min} is used in the fit (no cut on S_{min} is applied).

$$S_{min} = \log(\min (L_i/\sigma_i))$$

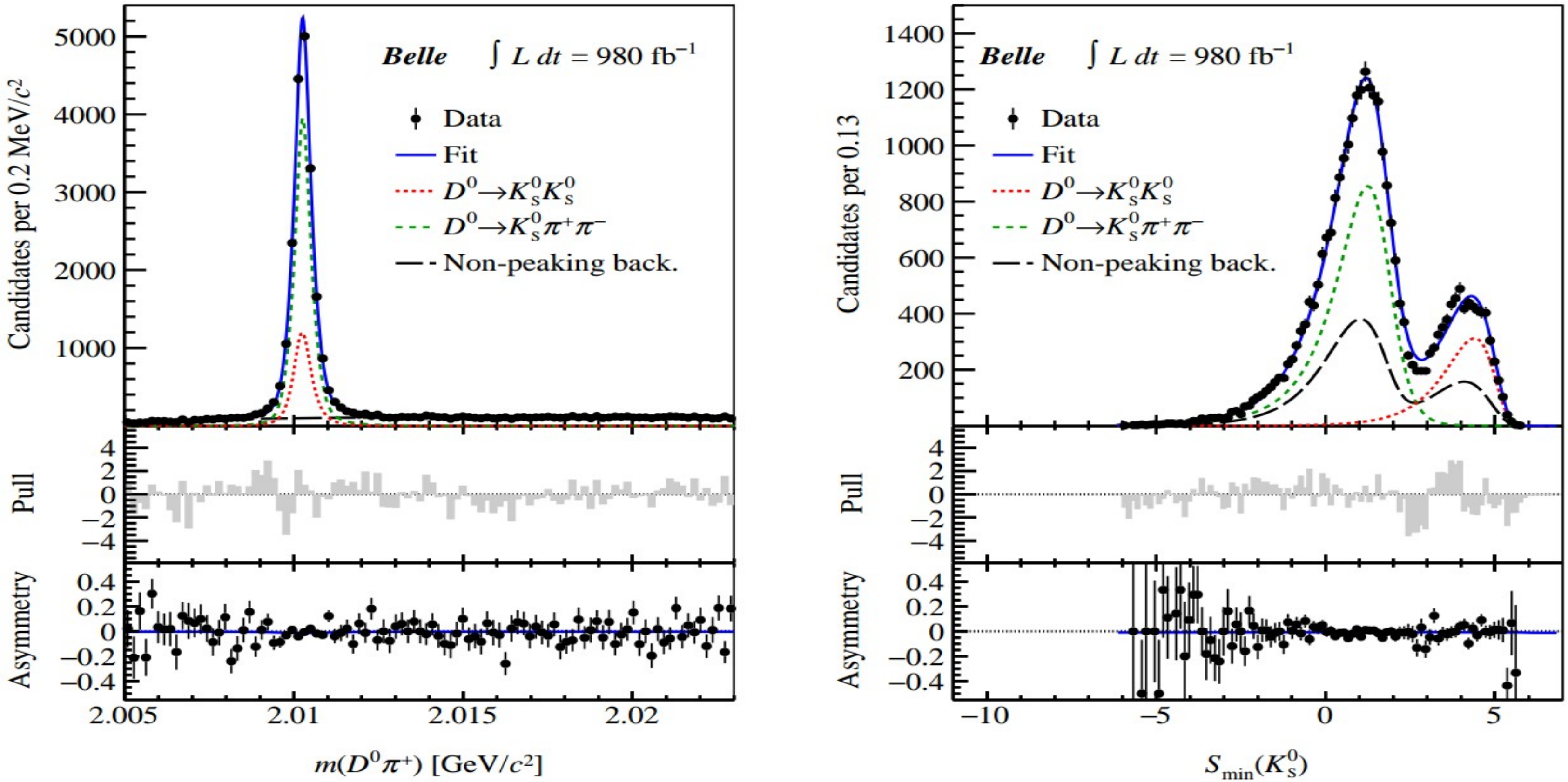
where, i runs over the K_s candidates.

Sample Composition ($D^0 \rightarrow K_s K_s$)

Variables	Signal	Peaking Background	Non-peaking Background
$m(D^0\pi^+)$			
S_{min}			

- Asymmetry determined from unbinned fit to (m, S_{min}) distributions of D^0 and $\overline{D}^0$ candidates.
- Shapes determined from either simulation or sideband data, assumed to be the same for D^0 and $\overline{D}^0$ decays.

Fit projections for Belle Data

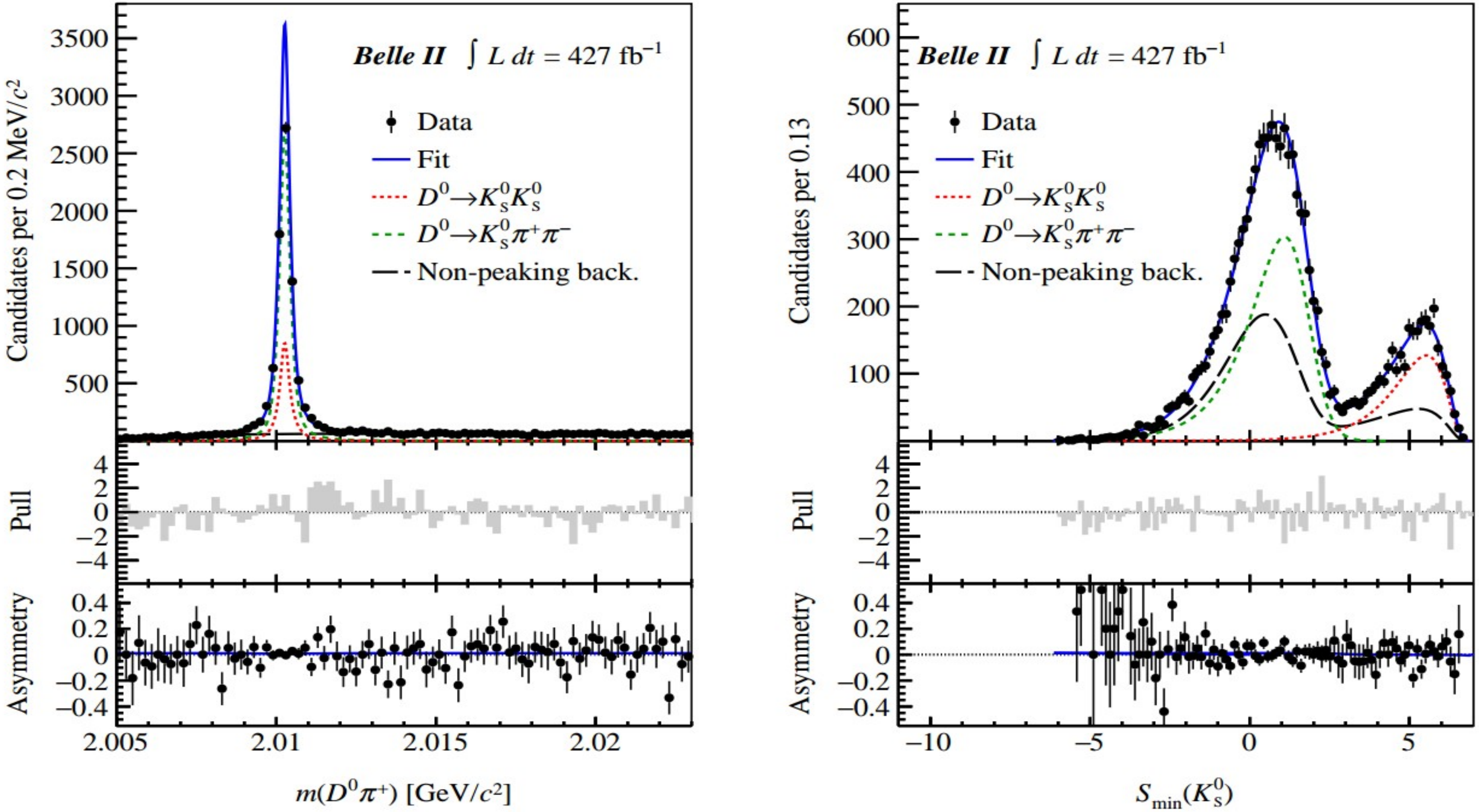


The fit model describes the data well in Belle, except in the region around $S_{min}(K^0_S)$ = 3.5.

Fit to data:

- N ($D^0 \rightarrow K_s K_s$) = 4864 ± 78
- A_{raw} ($D^0 \rightarrow K_s K_s$) = (-1.0 ± 1.6)%

Fit projections for Belle II Data



The fit model describes the data well in Belle II

- N ($D^0 \to K_s K_s$) = 2214 ± 51
- A_{raw} ($D^0 \to K_s K_s$) = (-0.6 ± 2.3)%

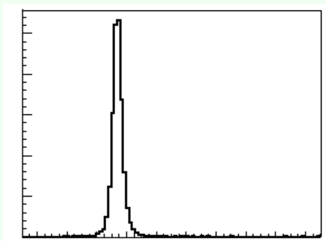
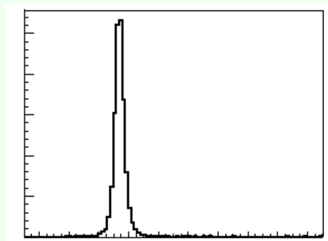
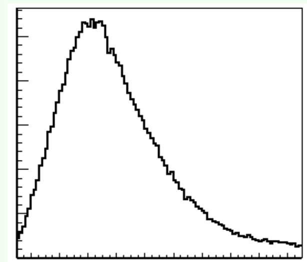
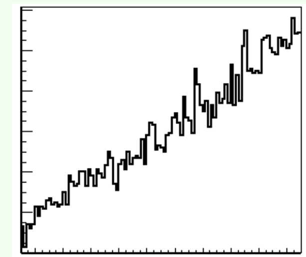
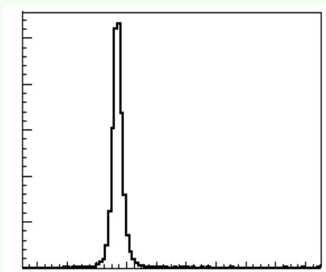
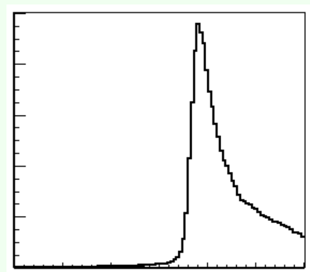
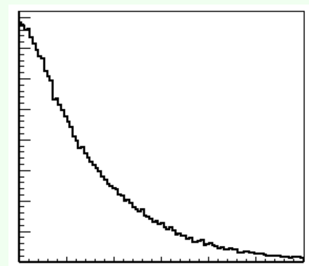
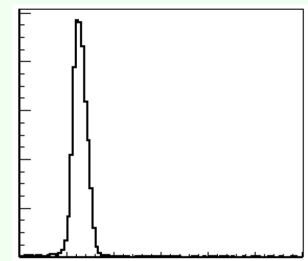
$D^0 \to K^+K^-$ decay

Selection Criteria

Variable	Criteria	
$\lvert d_r \rvert(\pi_s^+, K^\pm)$	$< 0.5\,\mathrm{cm}$	(Selection criteria on Impact parameters)
$\lvert d_z \rvert(\pi_s^+, K^\pm)$	$< 2\,\mathrm{cm}$	
$\theta(\pi_s^+, K^\pm)$ (Belle II only)	$[17, 150]^\circ$	
# CDC hits $(K^\pm)$	> 20	
# SVD hits $(K^\pm)$	> 0	
$\mathcal{L}_K/(\mathcal{L}_K + \mathcal{L}_{\pi/e})(K^\pm)$	$0.6/0.1$	➡ (Identification of charged kaon from pion/electron)
Δm = (m(D^{*+}) - m(D^0))	$< 0.16\,\mathrm{GeV}/c^2$	
$p_{\mathrm{cms}}(D^{*+})$	$> 2.5\,\mathrm{GeV}/c$	➡ (To reduce the events where D^{*+} coming from B meson)
TreeFitter probability	> 0.001	
Best-candidate selection	D^{*+} candidate with largest TreeFitter probability	

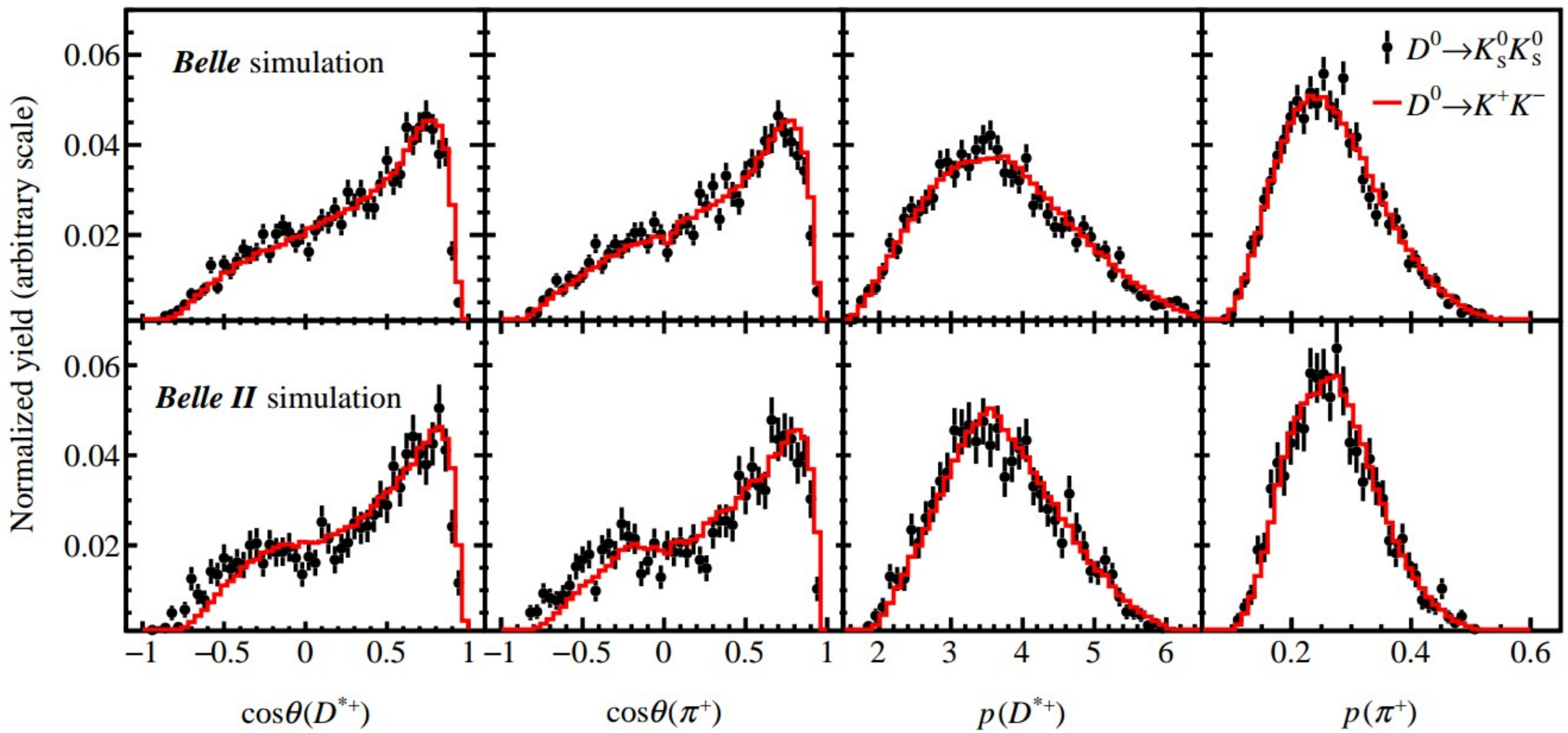
Treefitter is used with IP constraint.

Sample Composition ($D^0 \to K^+K^-$)

Variables	Signal	$D^0 \to K\pi$	$D^0 \to$ multibody (semi-leptonic, $K\pi\pi^0$)	$D_s \to KK\pi$
$m(D^0\pi^+)$				
$m(K^+K^-)$				

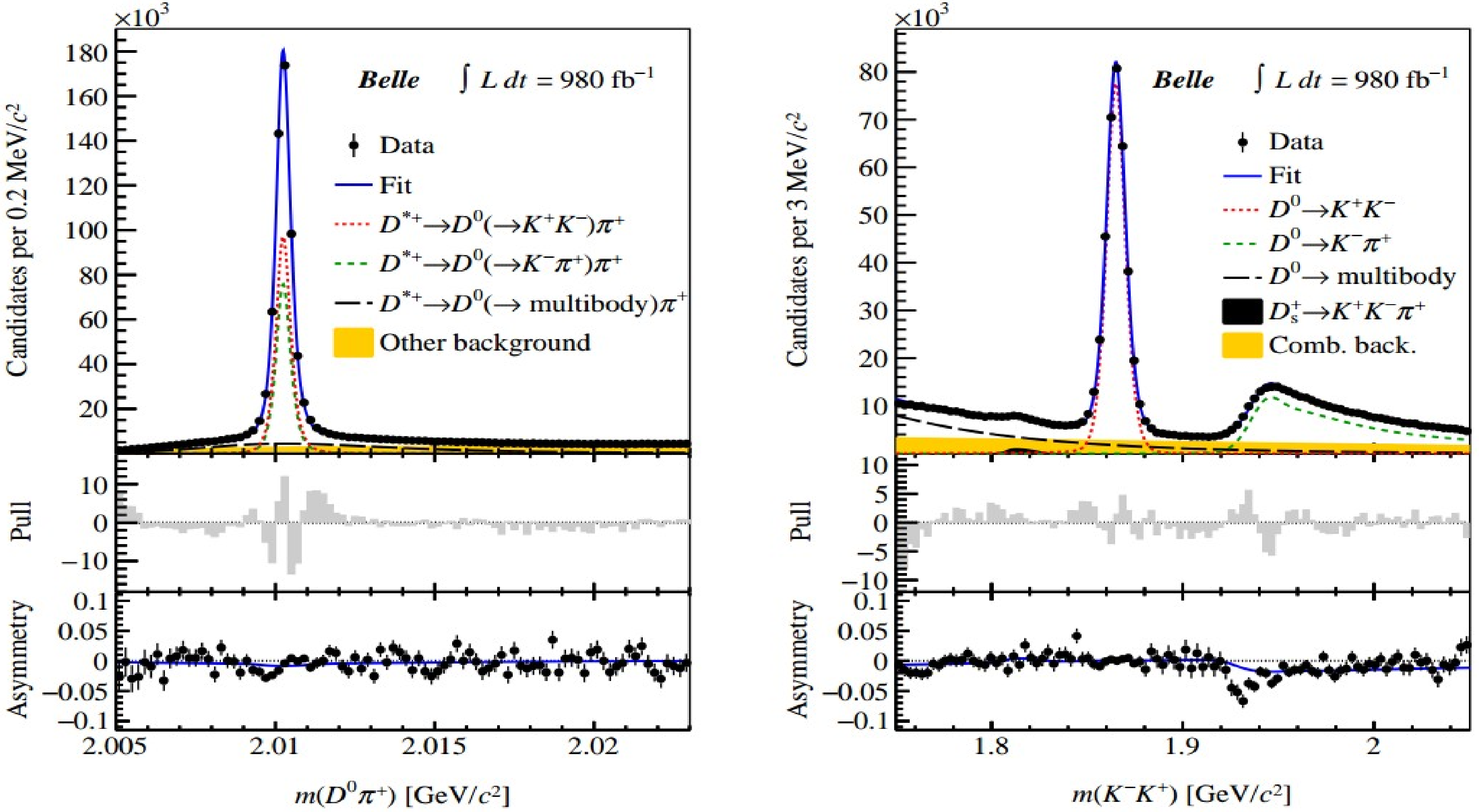
- Asymmetry determined from unbinned fit to ($m(D^0\pi^+)$, $m(K^+K^-)$) distributions of D^0 and $\overline{D}^0$ candidates.
- Shapes determined from either simulation or sideband data, assumed to be the same for D^0 and $\overline{D}^0$ decays.

Distributions of momentum and cosθ for D^{*+} and π_s



- The kinematic difference between signal and control modes in Belle II.
- Exclusively determined by the PID requirement on the charged kaons in the control mode, which imposes a reduced acceptance in the backward region due to the limited acceptance from the TOP.
- In Belle this effect is essentially absent because the PID requirement and detector acceptance are different (also due to the fact that the boost in the forward direction is larger than in Belle II).

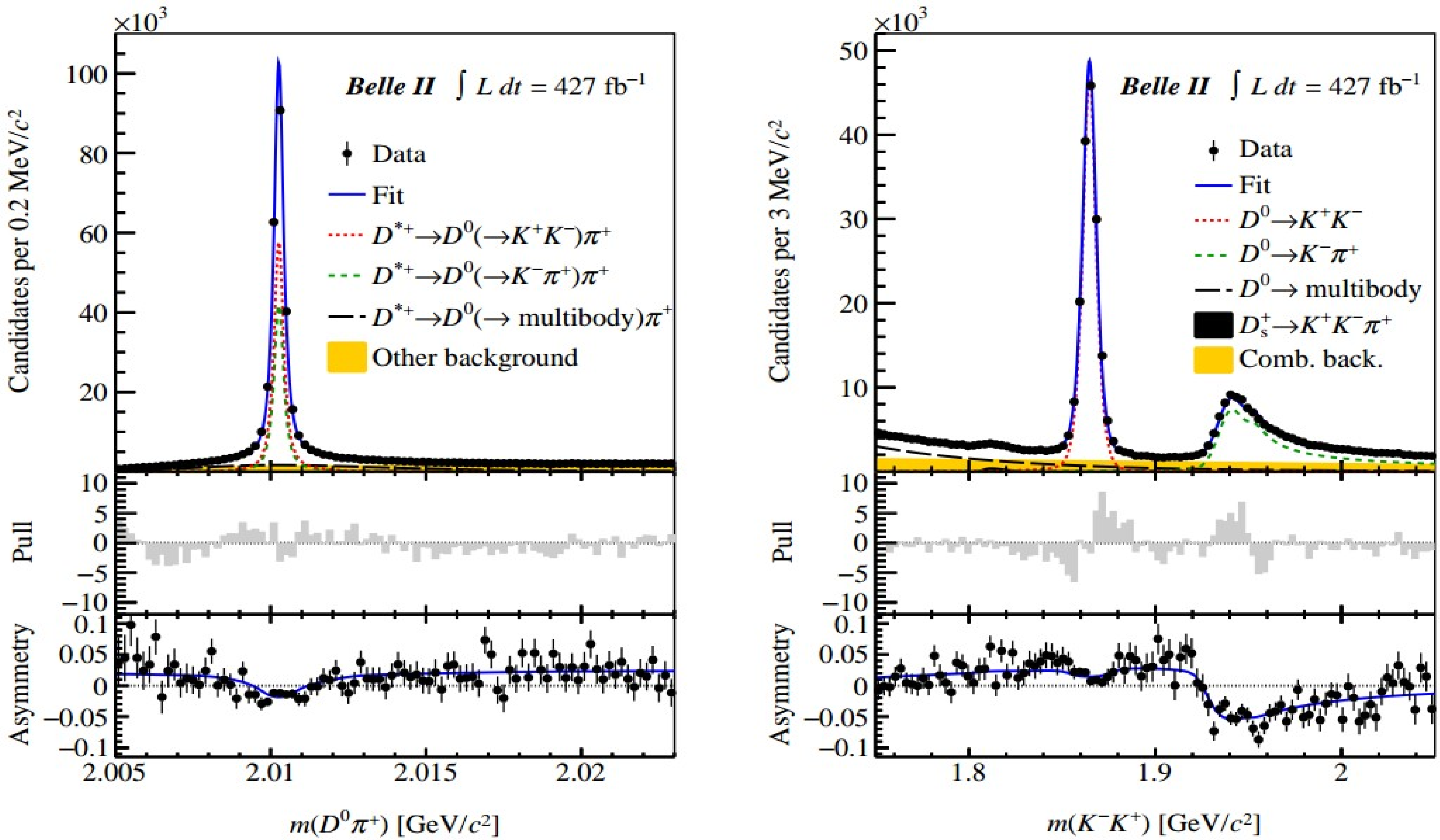
Fit projections for $D^0 \rightarrow K^+K^-$ (Belle)



$N(D^0 \rightarrow K^+K^-) = 308760 \pm 570$

$A_{raw}(D^0 \rightarrow K^+K^-) = (0.17 \pm 0.19)\%$

Fit projections for $D^0 \to K^+K^-$ (Belle II)



$N(D^0 \to K^+K^-) = 145520 \pm 400$

$A_{raw}(D^0 \to K^+K^-) = (1.61 \pm 0.27)\%$

Sources of systematic uncertainties in $A_{CP}(D^0 \to K_s K_s)$

- **PDF shape:**
  - Different signal and background models are tried, while the D^0 and $\overline{D}^0$ shapes are same.
  - Same PDFs as that of the default fit model are used, but asymmetries are introduced in the shape parameters.
- **Re-Weighting:**
  - Distributions of cosθ and momenta for D^{*+} and π_s are not in perfect agreement for the signal and control modes.
  - The difference between the weighted and unweighted fits are incorporated as a systematic.
- **A_{CP} $(D^0 \to K^+K^-)$:** External input

Source	Uncertainty (%) Belle	Belle II
Modeling in the $D^0 \to K_S^0 K_S^0$ fit	0.04	0.05
Modeling in the $D^0 \to K^+K^-$ fit	0.02	< 0.01
Kinematic equalization	0.06	0.07
Input $A_{CP}(D^0 \to K^+K^-)$	0.05	0.05
Total systematic	0.09	0.10
Statistical	1.60	2.30

Results

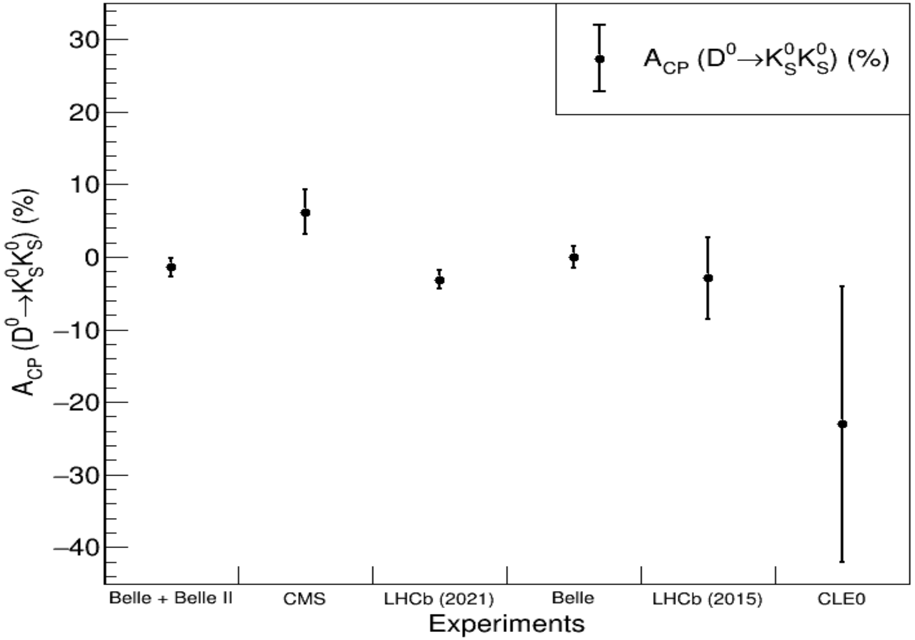
$A_{CP}(D^0 \to K_s K_s)$ in Belle: (-1.1 ± 1.6 ± 0.1) %

$A_{CP}(D^0 \to K_s K_s)$ in Belle II: (-2.2± 2.3 ± 0.1) %

$A_{CP}(D^0 \to K_s K_s)$ (Belle + Belle II) = (-1.4 ± 1.3 ± 0.1) %

In $A_{CP}(D^0 \to K_s K_s)$, the first uncertainty is statistical and the second is systematic.

Comparison of A_{cp} *with previous Measurements*



The combined results has comparable precision to the world-best measurement from LHCb.

Summary

- Measured the A_{CP} in $D^0 \rightarrow K_s K_s$ with (Belle + Belle II) dataset.

  $A_{CP}(D^0 \rightarrow K_s K_s)$ in Belle: $(-1.1 \pm 1.6 \pm 0.1)$ %

  $A_{CP}(D^0 \rightarrow K_s K_s)$ in Belle II: $(-2.2 \pm 2.3 \pm 0.1)$ %

  $A_{CP}(D^0 \rightarrow K_s K_s)$ (Belle + Belle II) = $(-1.4 \pm 1.3 \pm 0.1)$ %

- It has a factor-two better systematic uncertainty compared to the previous Belle published results, thanks to the usage of the $D^0 \rightarrow K^+K^-$ control mode, which provides a more precise A_{CP} external input compared to the $D^0 \rightarrow K_S^0\pi^0$ control mode used in previous study. **Phys. Rev. Lett. 119 (2017) 171801**

- The combined results has comparable precision to the world-best measurement from LHCb.