Hadronic B decays and charm at Belle II

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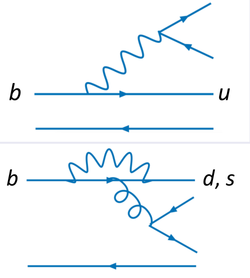
Hadronic B and D decays

Flavor physics: fundamental to test SM and its extensions

- Cabibbo-suppressed (CS) $b \to u$ trees and $b \to d, s$ penguins
  $\to$ Highly sensitive to non-SM loops
- CKM angle ϕ_3/γ: principal SM gauge for *CP* violation, very reliably predicted
- $c \to s$, and CS $c \to d$, and $c \to u$ penguin decays are important to search for new physics



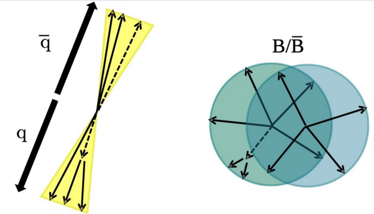
Today's focus

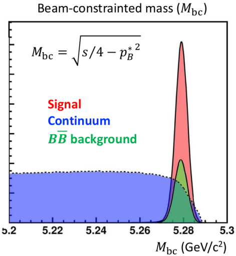
- Test SM using isospin sum rules
- Toward $\phi_2/\alpha = arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$ angle
- Determination of ϕ_3/γ
- Novel charm flavor tagger

Signal extraction

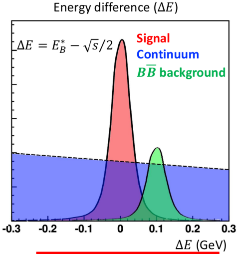
Suppress $10^5\times$ larger $q\bar{q}$ (continuum) background

- Combine several topological variables in multivariate techniques
- $q\bar{q}$ background rejection: $\approx$ 99%, signal retention: $\approx$ 80%





Separate $B\bar{B}$ events from $q\bar{q}$ background



Separate signal events from $B\bar{B}$, $q\bar{q}$ background

Isospin sum rule: $B \to K^+\pi^-, K^+\pi^0, K^0\pi^+$

New for Moriond

- Isospin sum-rule relation for $B \to K\pi$ provides a stringent SM test

$$I_{K\pi} = \mathcal{A}_{K^+\pi^-} + \mathcal{A}_{K^0\pi^+}\frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B0}}{\tau_{B+}} - 2\mathcal{A}_{K^+\pi^0}\frac{\mathcal{B}(K^+\pi^0)}{\mathcal{B}(K^+\pi^-)}\frac{\tau_{B0}}{\tau_{B+}} - 2\mathcal{A}_{K^0\pi^0}\frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} = 0$$

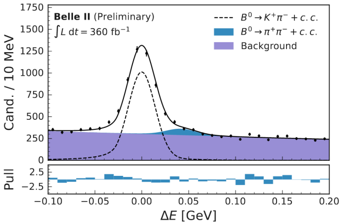
(Phys.Lett. B627 (2005) 82-8)

- Precision limited by $K^0\pi^0$ inputs — unique to Belle II

Signal yield $= 3868 \pm 71$

$\mathscr{B}(B^0 \to K^+\pi^-) = [20.7 \pm 0.4(stat) \pm 0.6(syst)] \times 10^{-6}$

$A_{CP}(B^0 \to K^+\pi^-) = -0.07 \pm 0.02(stat) \pm 0.01(syst)$



Signal yield $= 1547 \pm 45$

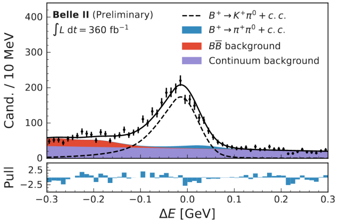
$\mathscr{B}(B^+ \to K^0\pi^+) = [24.4 \pm 0.7(stat) \pm 0.9(syst)] \times 10^{-6}$

$A_{CP}(B^+ \to K^0\pi^+) = 0.05 \pm 0.03(stat) \pm 0.01(syst)$

Signal yield $= 2070 \pm 57$

$\mathscr{B}(B^+ \to K^+\pi^0) = [14.2 \pm 0.4(stat) \pm 0.9(syst)] \times 10^{-6}$

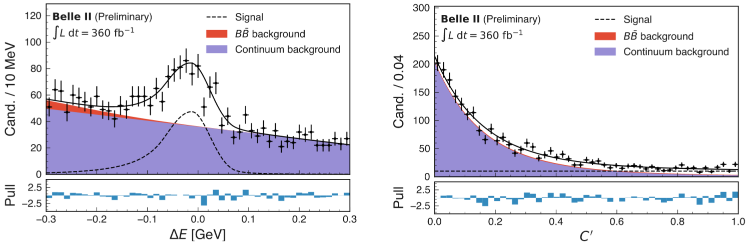
$A_{CP}(B^+ \to K^+\pi^0) = 0.01 \pm 0.03(stat) \pm 0.01(syst)$



Isospin sum rule: $K^0\pi^0$ time-integrated asymmetry

- Complementary measurement of $A_{K^0\pi^0}$ using time-integrated analysis
- Requires flavor tagging to tag $B^0/\bar{B}^0$, $\epsilon_{tag} = 30.0 \pm 1.2\%$
- $P_{sig}(q) = \frac{1}{2}.(1 + q.(1-2w_r).(1-2.\chi_d).A_{K^0\pi^0})$, where q : flavor of the B meson, w_r : wrong-tag fraction and χ_d : B^0 mixing parameter

New for Moriond



Signal yield$=502 \pm 32$

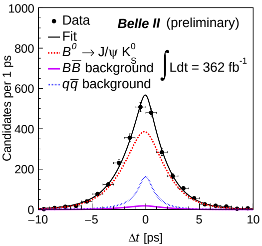
$$\mathscr{B}(B^0 \to K^0\pi^0) = [10.2 \pm 0.6(stat) \pm 0.6(syst)] \times 10^{-6}$$

$$A_{K^0\pi^0} = -0.06 \pm 0.15(stat) \pm 0.05(syst)$$

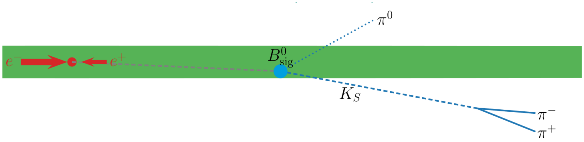
Isospin sum rule: $K^0\pi^0$ time-dependent asymmetry

New for Moriond

- Probing the effective value of $\Delta S_{CP} \equiv S_{CP} - \sin 2\phi_1$
- Challenge: No primary charged particles to vertex, poor decay time resolution, need good performance with neutrals
- Fit signal-extraction variables ΔE and M_{bc}, decay time, and continuum background discriminator output in bins of quality of flavor-identification
- Validate on $B^0 \to J/\psi K_S^0$ with K_S^0 only vertex

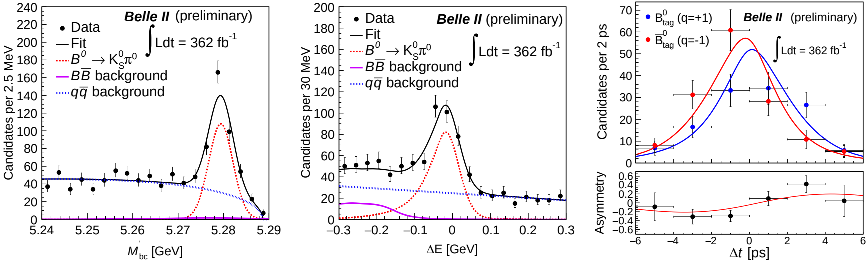


$\tau_{B^0} = 1.46 \pm 0.05$ ps



Isospin sum rule: $K^0\pi^0$ time-dependent asymmetry

New for Moriond



Signal yield $= 415 \pm 25$

$A_{CP} = 0.04 \pm 0.15(stat) \pm 0.05(syst)$, $S_{CP} = 0.75^{+0.20}_{-0.23}(stat) \pm 0.04(syst)$

- Improved neutrals reconstruction, continuum suppression and event-by-event resolution of proper times
- Achieve precision comparable with world's best result even with smaller sample!

$K\pi$ isospin sum rule: results

New for Moriond

- Combine time-integrated with time-dependent results to enhance sensitivity:

$$A_{K^0\pi^0} = -0.01 \pm 0.12(stat) \pm 0.05(syst)$$
$$\mathscr{B}(B^0 \to K^0\pi^0) = [10.5 \pm 0.6(stat) \pm 0.7(syst)] \times 10^{-6}$$

- Putting all together, we obtain an overall Belle II isospin test:

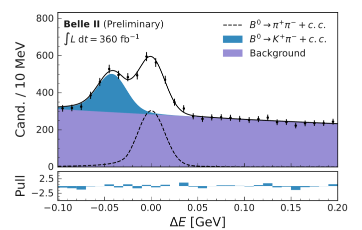
$$I_{K\pi} = -0.03 \pm 0.13(stat) \pm 0.05(syst)$$

- Consistent with SM prediction
- Comparable with world-best result (-0.13 ± 0.11) even with smaller sample

Toward α/ϕ_2 : $B \to \pi^+\pi^-, \pi^+\pi^0$

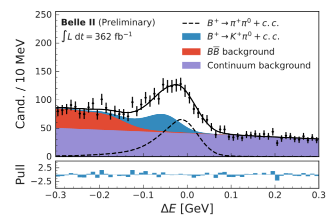
New for Moriond

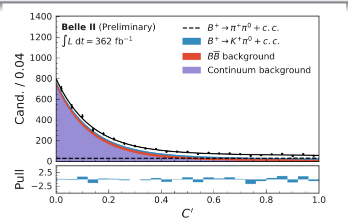
- $\alpha/\phi_2 = arg\left(-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right)$ as complementary test
- Unique Belle II capability to study all the $B \to \pi\pi$ decays to determine the CKM angle α



Signal yield$=1187 \pm 43$

$\mathcal{B}(B^0 \to \pi^+\pi^-) = 5.83 \pm 0.22(stat) \pm 0.17(syst)$





Signal yield$=786 \pm 44$, $\mathcal{B}(B^+ \to \pi^+\pi^0) = [5.02 \pm 0.28(stat) \pm 0.32(syst)] \times 10^{-6}$,

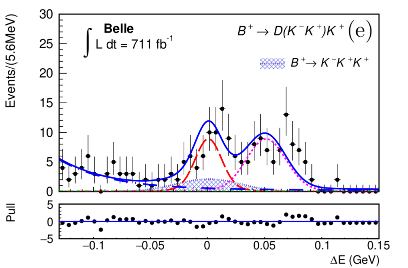
$A_{CP}(B^+ \to \pi^+\pi^0) = -0.08 \pm 0.05(stat) \pm 0.01(syst)$

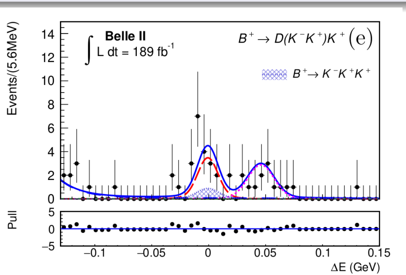
Determinations of ϕ_3/γ : $B^{\pm} \to D_{CP\pm}K^{\pm}$

- ϕ_3 is the phase beween $b \to u$ and $b \to c$ transitions

GLW method (Belle + Belle II) **New for Moriond**

- CP eigenstates such as K^+K^- (CP even) or $K_S^0\pi^0$(CP odd)





Results

Signal yield=476(Belle) + 107(Belle II)
$\mathcal{A}_{CP+} = (12.5 \pm 5.8 \pm 1.4)\%$
$\mathcal{R}_{CP+} = (1.16 \pm 0.08 \pm 0.04)$

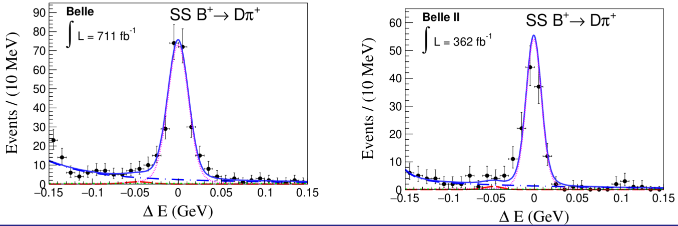
Signal yield=541(Belle) + 145(Belle II)
$\mathcal{A}_{CP-} = (-16.7 \pm 5.7 \pm 0.6)\%$
$\mathcal{R}_{CP-} = (1.15 \pm 0.07 \pm 0.02)$

- Results are not competitive

Determinations of ϕ_3/γ : $B^\pm \to Dh^\pm$

GLS method (Belle + Belle II) **New for Moriond**

- Cabibbo-suppressed channels $B^\pm \to D(\to K_S^0 K^\pm \pi^\mp) h^\pm$ (same sign); $B^\mp \to D(\to K_S^0 K^\pm \pi^\mp) h^\mp$ (opposite sign)



Results

$\mathcal{A}_{SS}^{DK} = -0.089 \pm 0.091 \pm 0.011$
$\mathcal{A}_{OS}^{DK} = 0.109 \pm 0.133 \pm 0.013$
$\mathcal{A}_{SS}^{D\pi} = 0.018 \pm 0.026 \pm 0.009$
$\mathcal{A}_{OS}^{D\pi} = -0.028 \pm 0.031 \pm 0.009$

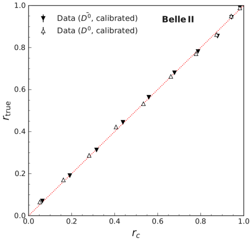
Signal yield=2209(Belle) + 1210(Belle II)
$\mathcal{R}_{SS}^{DK/D\pi} = 0.122 \pm 0.012 \pm 0.004$
$\mathcal{R}_{OS}^{DK/D\pi} = 0.093 \pm 0.013 \pm 0.003$
$\mathcal{R}_{SS/OS}^{D\pi} = 1.428 \pm 0.057 \pm 0.002$

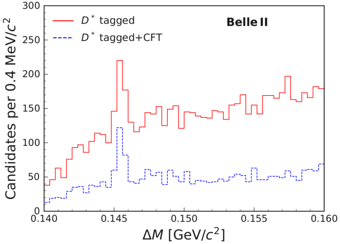
- Results are not competitive, but sensitivity greatly improved over Belle

The charm flavor tagger

- Identifying D^0 or $\bar{D}^0$ plays a crucial role in charm CPV/mixing
- Typically use D^* tag: high purity but reduced sample size
- BDT to recover additional flavor info from extra charged particles

$\epsilon_{tag}^{eff} = (47.91 \pm 0.07(stat.) \pm 0.51(syst.))\%$ **New for Moriond**





- Calibrated dilution shows good agreement with the true dilution
- Effectively double sample size for CPV/mixing measurements and improve purity of D^* tagged signals

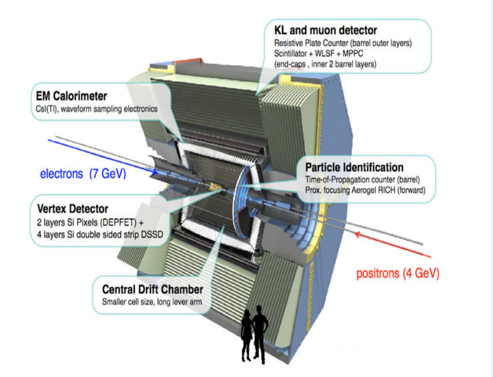
Summary

- Hadronic B decays and charm physics play an important role in sharpening flavor picture
- Belle II has unique access to channels that offer key tests of the SM
- Five results new for this conference:
  $\rightarrow$ CP violation in $B^0 \rightarrow K^0\pi^0$ that probes isospin sum rule with world leading precision
  $\rightarrow$ Precise measurements of various two body decays relative for α
  $\rightarrow$ Joining forces with Belle sample to offer most up-to date information on γ from GLW and GLS analyses
  $\rightarrow$ Novel neutral charm tagger that nearly doubles the tagged sample size

Thank You

SuperKEKB and Belle II Detector

- Asymmetric collider: e^- to 7 GeV and e^+ to 4 GeV
  $\rightarrow$ clean experimental environment
- World record peak luminosity: $4.7 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- New tracking system and improved vertexing
- Improved particle identification



Currently:

- 424 fb^{-1} data (partly energy scan) are collected

Long-shutdown activity and plans

Belle II stopped taking data in Summer 2022 for a long shutdown

- replacement of beam-pipe
- replacement of photomultipliers of the central PID detector (TOP)
- installation of 2-layered pixel vertex detector
- improved data-quality monitoring and alarm system
- completed transition to new DAQ boards (PCIe40)
- accelerator improvements: injection, non-linear collimators, monitoring
- replacement of aging components
- additional shielding and increased resilience against beam bckg

Currently working on pixel detector installation:
==> shipping to KEK in ~mid March
==> final tests at KEK scheduled in April

On track to resume data taking next winter with new pixel detector 1

GLW

We measure CP asymmetries,

$$\mathcal{A}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) - \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}, \tag{1.1}$$

and the branching ratios for decays with D decaying to the CP-eigenstate K^+K^- for D_{CP+} and $K_S^0\pi^0$ for D_{CP-}. We measure the latter relative to the branching ratio for decays with the D decaying to a flavor-specific final state $K^-\pi^+$,

$$\mathcal{R}_{CP\pm} \equiv \frac{\mathcal{B}(B^- \to D_{CP\pm}K^-) + \mathcal{B}(B^+ \to D_{CP\pm}K^+)}{\mathcal{B}(B^- \to D_{\rm flav}K^-) + \mathcal{B}(B^+ \to D_{\rm flav}K^+)} \approx \frac{R_{CP\pm}}{R_{\rm flav}}, \tag{1.2}$$

where

$$R_X \equiv \frac{\mathcal{B}(B^- \to D_X K^-) + \mathcal{B}(B^+ \to D_X K^+)}{\mathcal{B}(B^- \to D_X \pi^-) + \mathcal{B}(B^+ \to D_X \pi^+)}. \tag{1.3}$$

[1] ϕ_3 is also called γ.

$$\mathcal{R}_{CP\pm} = 1 + r_B^2 \pm 2r_B \cos\delta_B \cos\phi_3,$$
$$\mathcal{A}_{CP\pm} = \pm 2r_B \sin\delta_B \sin\phi_3 \,/\, \mathcal{R}_{CP\pm}.$$

GLW

Table 1. Systematic and statistical uncertainties.

	$\mathcal{R}_{CP+}$	$\mathcal{R}_{CP-}$	$\mathcal{A}_{CP+}$	$\mathcal{A}_{CP-}$
PDF parameters	0.012	0.014	0.002	0.002
PID parameters	0.009	0.010	0.003	0.005
$B\overline{B}$-background yields	0.033	0.002	0.013	—
Efficiency ratio	0.001	0.001	0.000	0.000
commonality of ΔE modes	−0.005	−0.006	0.000	0.000
Total systematic uncertainty	0.036	0.019	0.014	0.006
Statistical uncertainty	0.081	0.074	0.058	0.057

Parameters of Interests (4 Acp and 3 Ratios)

- 2 Acp for DK: (plus 2 similar Acp for Dpi)

$$A_{SS}^{DK} \equiv \frac{N_{SS}^{-} - N_{SS}^{+}}{N_{SS}^{-} + N_{SS}^{+}}, \qquad A_{OS}^{DK} \equiv \frac{N_{OS}^{-} - N_{OS}^{+}}{N_{OS}^{-} + N_{OS}^{+}},$$

Physics meanings

$$A_{SS}^{DK} = \frac{2r_B r_D \kappa \sin(\delta_B - \delta_D)\sin\phi_3}{1 + r_B^2 r_D^2 + 2r_B r_D \kappa \cos(\delta_B - \delta_D)\cos\phi_3},$$

$$A_{OS}^{DK} = \frac{2r_B r_D \kappa \sin(\delta_B + \delta_D)\sin\phi_3}{r_B^2 + r_D^2 + 2r_B r_D \kappa \cos(\delta_B + \delta_D)\cos\phi_3},$$

- 3 Ratios:

$$R_{SS}^{DK/D\pi} \equiv \frac{N_{SS}^{-} + N_{SS}^{+}}{N_{SS}^{\prime -} + N_{SS}^{\prime +}}, \qquad R_{OS}^{DK/D\pi} \equiv \frac{N_{OS}^{-} + N_{OS}^{+}}{N_{OS}^{\prime -} + N_{OS}^{\prime +}}, \qquad R_{SS/OS}^{D\pi} \equiv \frac{N_{SS}^{\prime -} + N_{SS}^{\prime +}}{N_{OS}^{\prime -} + N_{OS}^{\prime +}},$$

Physics meanings

$$R_{SS}^{DK/D\pi} = R\frac{1 + r_B^2 r_D^2 + 2r_B r_D \kappa \cos(\delta_B - \delta_D)\cos\phi_3}{1 + r_B^{\prime 2} r_D^2 + 2r_B^{\prime} r_D \kappa \cos(\delta_B^{\prime} - \delta_D)\cos\phi_3},$$

$$R_{OS}^{DK/D\pi} = R\frac{r_B^2 + r_D^2 + 2r_B r_D \kappa \cos(\delta_B + \delta_D)\cos\phi_3}{r_B^{\prime 2} + r_D^2 + 2r_B^{\prime} r_D \kappa \cos(\delta_B^{\prime} + \delta_D)\cos\phi_3},$$

$$R_{SS/OS}^{D\pi} = \frac{1 + r_B^{\prime 2} r_D^2 + 2r_B^{\prime} r_D \kappa \cos(\delta_B^{\prime} - \delta_D)\cos\phi_3}{r_B^{\prime 2} + r_D^2 + 2r_B^{\prime} r_D \kappa \cos(\delta_B^{\prime} + \delta_D)\cos\phi_3},$$

GLS

Table 2. Systematic and statistical uncertainties in percent.

	A_{SS}^{DK}	A_{OS}^{DK}	$A_{SS}^{D\pi}$	$A_{OS}^{D\pi}$	$R_{SS}^{DK/D\pi}$	$R_{OS}^{DK/D\pi}$	$R_{SS/OS}^{D\pi}$
full D phase space							
PID	0.38	0.56	0.19	0.14	0.05	0.06	0.09
$\epsilon_{DK}/\epsilon_{D\pi}$	0.00	0.03	0.00	0.00	0.04	0.03	0.02
Model	0.62	0.78	0.02	0.02	0.30	0.22	0.07
$\epsilon_{K_S^0 K^- \pi^+}/\epsilon_{K_S^0 K^+ \pi^-}$	0.82	0.83	0.82	0.83	0.01	0.01	0.02
Total syst. unc.	1.10	1.30	0.90	0.90	0.40	0.30	0.20
Stat. unc.	9.10	13.30	2.60	3.10	1.20	1.30	5.70
K^* region							
PID	0.37	0.61	0.17	0.15	0.03	0.08	0.13
$\epsilon_{DK}/\epsilon_{D\pi}$	0.02	0.02	0.01	0.01	0.03	0.04	0.04
Model	1.04	0.97	0.20	0.03	0.46	0.49	0.61
$\epsilon_{K_S^0 K^- \pi^+}/\epsilon_{K_S^0 K^+ \pi^-}$	1.60	0.80	1.60	0.80	0.10	0.10	1.70
Total syst. unc.	2.00	1.40	1.60	0.90	0.50	0.60	1.90
Stat. unc.	11.90	18.40	2.90	4.60	1.20	2.00	13.20

$K\pi$

TABLE III. Summary of the fractional systematic uncertainties (%) on the branching ratios.

Source	$B^0 \to K^+\pi^-$	$B^0 \to \pi^+\pi^-$	$B^+ \to K^+\pi^0$	$B^+ \to \pi^+\pi^0$	$B^+ \to K_S^0\pi^+$	$B^0 \to K_S^0\pi^0$
Tracking	0.5	0.5	0.2	0.2	0.7	0.5
$N_{B\bar{B}}$	1.5	1.5	1.5	1.5	1.5	1.5
f^{+0}	2.5	2.5	2.4	2.4	2.4	2.5
π^0 efficiency	-	-	5.0	5.0	-	5.0
K_S^0 efficiency	-	-	-	-	2.0	2.0
CS efficiency	0.2	0.2	0.7	0.7	0.5	1.7
PID correction	0.1	0.1	0.1	0.2	-	-
ΔE shift and scale	0.1	0.2	1.2	2.0	0.3	0.2
$K\pi$ signal model	0.1	0.2	0.1	<0.1	<0.1	0.1
$\pi\pi$ signal model	<0.1	0.1	<0.1	<0.1	-	-
$K\pi$ CF model	<0.1	0.1	<0.1	0.1	-	-
$\pi\pi$ CF model	0.1	0.2	<0.1	0.1	-	-
$K_S^0K^+$ model	-	-	-	-	0.1	-
$B\overline{B}$ model	-	-	0.3	0.5	<0.1	0.3
Multiple candidates	<0.1	<0.1	1.0	0.3	0.1	0.3
Total	3.0	3.0	6.0	6.2	3.6	6.4

$K\pi$

TABLE IV. Summary of the absolute systematic uncertainties on the CP asymmetry.

Source	$B^+ \to K^+\pi^-$	$B^+ \to K^+\pi^0$	$B^+ \to \pi^+\pi^0$	$B^+ \to K^0_S\pi^+$	$B^0 \to K^0_S\pi^0$
ΔE shift and scale	<0.001	0.001	0.002	0.001	0.003
$K^0_S K^+$ model	-	-	-	0.001	-
$B\overline{B}$ background asymmetry	-	-	-	-	0.046
$q\bar{q}$ background asymmetry	-	-	-	-	0.024
Fitting bias	-	-	0.007	0.006	-
Instrumental asymmetry	0.007	0.005	0.004	0.004	-
Total	0.007	0.005	0.008	0.007	0.052

$K_S^0 \pi^0$

Source	$\delta\mathcal{A}_{CP}$	$\delta\mathcal{S}_{CP}$
Flavor tagging	0.013	0.011
Resolution function	0.014	0.022
$B\overline{B}$ background asymmetry	0.030	0.018
$q\overline{q}$ background asymmetry	0.028	< 0.001
Signal modelling	0.004	0.003
Background modelling	0.006	0.018
Fit bias	0.005	0.011
Best candidate selection	0.005	0.010
τ_{B^0} and Δm_d	< 0.001	< 0.001
Tag-side interference	0.006	0.011
VXD misalignment	0.004	0.005
Total	0.047	0.040