Precision measurement of CP violation and branching fractions in $B^\pm \to K^0_S h^\pm$ ($h = \pi, K$) decays, and a search for the rare decay $B^\pm_c \to K^0_S K^\pm$

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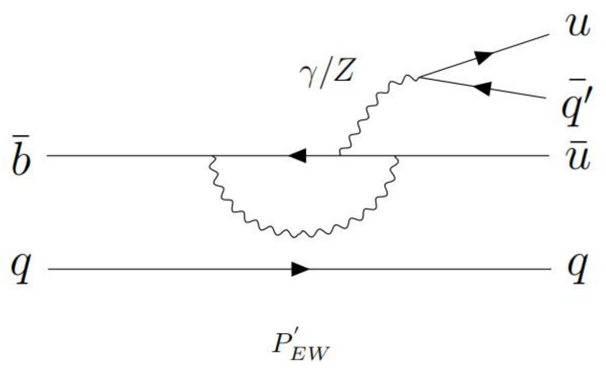
Outline

- Motivation and Previous measurements
- Analysis strategy
- Corrections to the asymmetry
- Systematic uncertainties
- Search for Bc decay
- Summary

Motivation

$B^+ \to K_s^0 h^+$ $(h^+ = \pi^+, K^+)$

- Dominated by gluonic penguin contributions
- Color-suppressed electroweak P'_{EW} and annihilation amplitudes are expected to be small



Theoretical predictions $\longrightarrow$ Strong model dependence

$A_{CP}(B^{\pm} \to K_S^0 K^{\pm})$:

- pQCD predicts: $(1.83^{+1.94}_{-1.88})\%$ [Chin. Phys. C 46 (2022) 123103]
- QCDF predicts: $(-6.4^{+2.0}_{-1.9})\%$ [Phys. Rev. D 80, 114008] [Phys. Rev. D 91, 014011]

$A_{CP}(B^{\pm} \to K_S^0 \pi^{\pm})$:

Both predict ~ 0, with < 0.1% uncertainty

The sign flip between models for $K_S^0 K^{\pm}$ implies competing contributions:

- Penguin annihilation vs. NLO QCD effects
- Needs experimental clarification

Motivation

A long-standing anomaly associated with the significant differences between direct CP-violating asymmetries observed in $B^+ \to K^+\pi^0$ and $B_d^0 \to K^+\pi^-$ decays.

Mode	BR[10^{-6}]	A_{CP}
$B^+ \to K^+\pi^0$	12.94 ± 0.52	0.040 ± 0.021
$B_d^0 \to K^+\pi^-$	19.57 ± 0.53	−0.082 ± 0.006

[JHEP 01 (2018) 074]

$\boldsymbol{B \to \pi K}$ Puzzle

The isospin sum rule observable $I_{K\pi}$: [Phys. Rev. D 59 (1999) 113002]

$I_{K\pi} = A_{K^+\pi^-} + A_{K^0\pi^+} \cdot \frac{B(K^0\pi^+)}{B(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{K^+\pi^0} \cdot \frac{B(K^+\pi^0)}{B(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{K^0\pi^0} \cdot \frac{B(K^0\pi^0)}{B(K^+\pi^-)} \approx 0$ (SM predicts, with ~1% uncertainty)

- in the limit of isospin symmetry
- assuming no electroweak penguin contributions

$\rightarrow$ a good test of the SM

$\boldsymbol{B^+ \to K_s^0\pi^+}$ is sensitive to hadronic effects

- ➢ Useful for testing the isospin sum rule $I_{K\pi}$
- ➢ Probes EW penguin and annihilation contributions

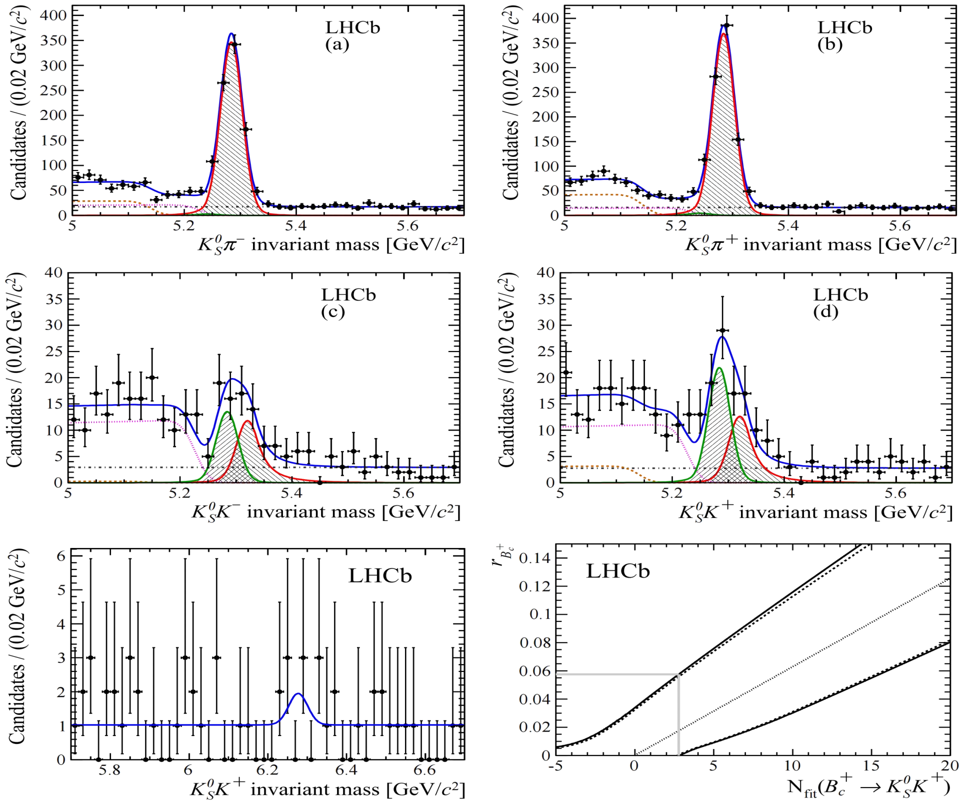
Previous measurements

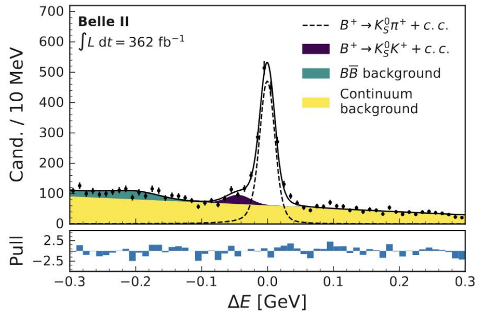
- LHCb 2011+2012 $(3fb^{-1})$
  - $\mathcal{R} = \frac{\mathcal{B}(B^+ \to K_S^0 K^+)}{\mathcal{B}(B^+ \to K_S^0 \pi^+)} = 0.0640 \pm 0.0038 \pm 0.0101$
  - $\mathcal{A}^{CP}(B^+ \to K_S^0 K^+) = -0.21 \pm 0.14 \pm 0.01$
  - $\mathcal{A}^{CP}(B^+ \to K_S^0 \pi^+) = -0.024 \pm 0.025 \pm 0.010$
  - $\mathcal{R}' = \frac{f_c}{f_u} \cdot \frac{\mathcal{B}(B_c^+ \to K_S^0 K^+)}{\mathcal{B}(B^+ \to K_S^0 \pi^+)} < 5.8 \times 10^{-2}$ at 90% confidence level

LHCb-PAPER-2013-034
ArXiv:1308.1277

- Belle II $(362fb^{-1})$
  - $\mathcal{B}(B^+ \to K^0 \pi^+) = [24.37 \pm 0.71 \pm 0.86] \times 10^{-6}$
  - $\mathcal{A}^{CP}(B^+ \to K_S^0 \pi^+) = 0.046 \pm 0.029 \pm 0.007$

Belle II
arXiv:2310.06381(2024)
Phys. Rev. D 109, 012001 (2024)





Analysis strategy

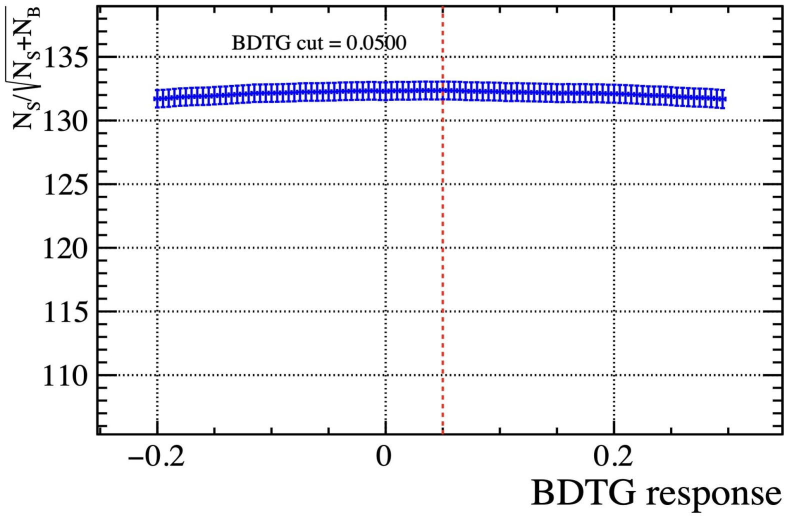
- Samples: $\boldsymbol{B^+ \to K_S^0 \pi^+}$, $\boldsymbol{B_{(c)}^+ \to K_S^0 K^+}$ data/MC Run 2$(16/17/18, 5.4 fb^{-1}$, 13TeV$)$
- Event Selection:
  - StrippingBu2KShLLLine
  - Offline selection, Simulated samples corrections, Multivariate selection, Mass Veto
- Mass fits: $B^+ \to K_S^0 \pi^+$and $B^+ \to K_S^0 K^+$ are fitted simultaneously
- Corrections to the asymmetry measurement
- Systematics uncertainties
- Search for $B_c^+ \to K_S^0 K^+$ decay

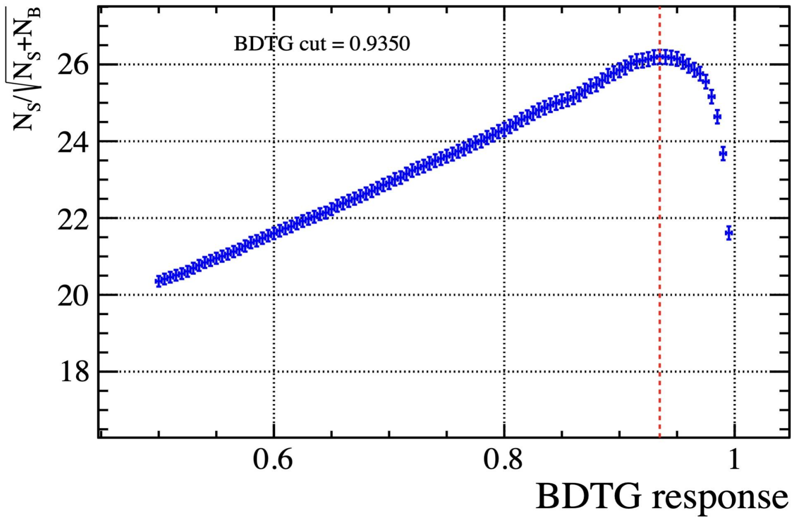
PID&MVA optimization

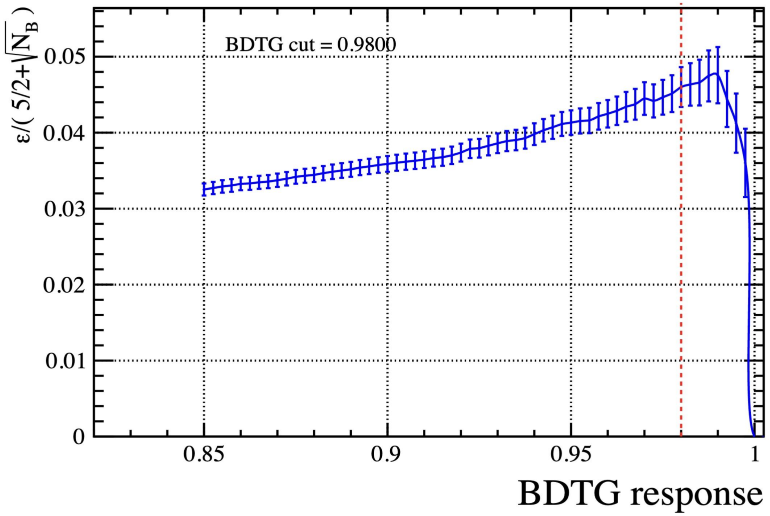
- PID requriements follow the same strategy as Run 1 → pion: PIDK < 3; kaon: PIDK >3
- Optimal BDTG output requirement
  - $B^+ \to K^0_s h^+$: maximize signal significance

    $FoM = \frac{N_S}{\sqrt{N_S + N_B}}$, $N_S(N_B)$: expected signal (background) yield
  - $B_c^+ \to K^0_s K^+$: Punzi FoM

    $FoM = \frac{\varepsilon}{\frac{a}{2}+\sqrt{N_B}}$, $a = 5$, ε: signal efficiency

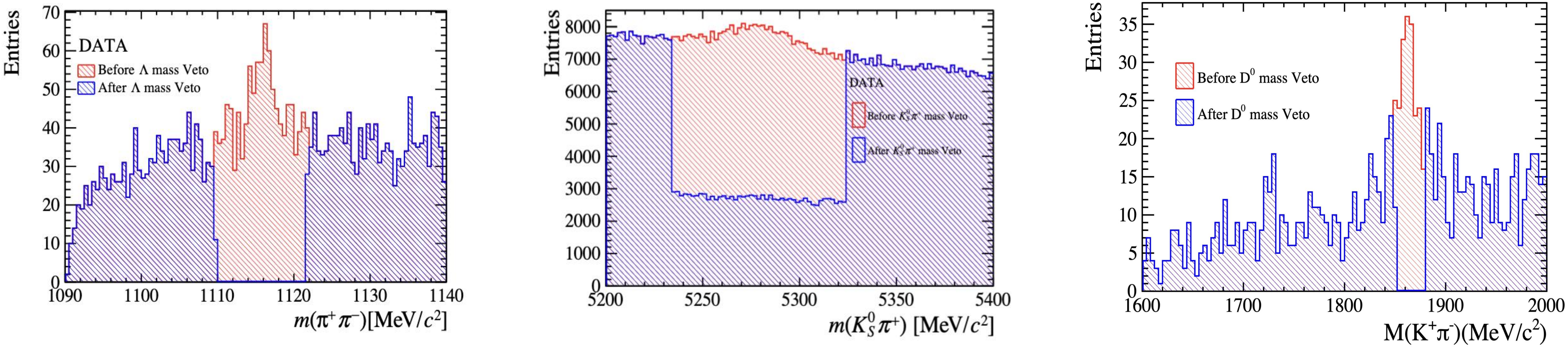






Veto Peaking background

- For the $B^+ \to K_s^0\pi^+$ mode
  - Peaking background from $\Lambda \to p\pi^-$ misidentified as $K_s^0 \to \pi^+\pi^-$ ($p \to \pi$ mis-ID) (left plot)
- For the $B^+ \to K_s^0 K^+$ mode
  - The same Λ mass veto as in the $B^+ \to K_s^0\pi^+$ mode is applied
  - Cross-feed from $B^+ \to K_s^0\pi^+$ decays (middle plot)
  - The $B^+ \to D^0\pi^+$ process, with $D^0 \to K^+\pi^-$ decays (the bachelor kaon and an oppositely charged pion from K_S^0) (right plot)

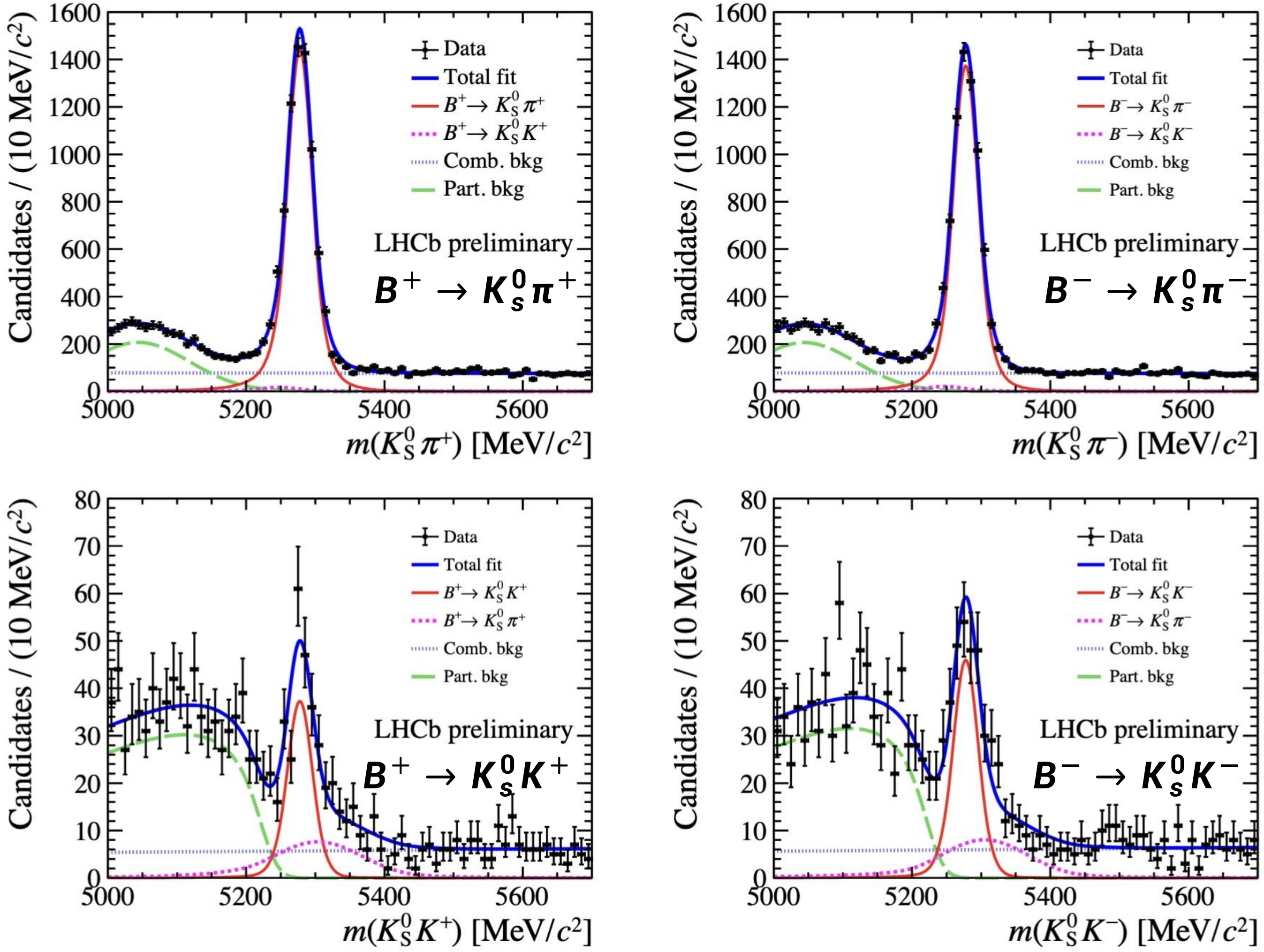


(a) Λ mass veto

(b) $K_s^0\pi^+$ mass veto

(c) D^0 mass veto

Simultaneous fit of $K_s^0\pi^+$ and $K_s^0K^+$



- **Partially Reconstructed Backgrounds**
  - B^0, B^+ and B_s^0 decays -> open-charm final states
  - smaller ones from charmless 3-body decays
  - Model: Argus function ⊗ Gauss resolution
- **Misidentified Backgrounds**
  - a DSCB function
  - constrained to expected signal yields
- Combinatorial background: a first-order polynomial function
- **Signal mode** $B^+ \to K_S^0\pi^+/B^+ \to K_S^0K^+$: a DSCB function + a Gaussian function

	$B^\pm \to K_s^0\pi^\pm$ Run 2	$B^\pm \to K_s^0K^\pm$ Run 2
N_{signal}	14482 ± 156	393 ± 28

Corrections to the CP asymmetry

- $\mathcal{A}^{CP}(B^+ \to K^0_S\pi^+) = \mathcal{A}^{raw}_{B^+\to K^0_S\pi^+} - \mathcal{A}^{det+prod}_{B^+\to K^0_S\pi^+} + \mathcal{A}^{K^0_S}_{B^+\to K^0_S\pi^+}$
- $\mathcal{A}^{CP}(B^+ \to K^0_S K^+) = \mathcal{A}^{raw}_{B^+\to K^0_S K^+} - \mathcal{A}^{det+prod}_{B^+\to K^0_S K^+} - \mathcal{A}^{K^0_S}_{B^+\to K^0_S K^+}$

- Raw asymmetry $\mathcal{A}^{raw} = \frac{N(B^-)-N(B^+)}{N(B^-)+N(B^+)}$
- Production and detection asymmetry   Control channel: $B^+ \to J/\psi K^+$
  - $\mathcal{A}^{det+prod}_{B^+\to K^0_S K^+} = \mathcal{A}^{det+prod}_{B^+\to J/\psi K^+} = \mathcal{A}^{raw}_{B^+\to J/\psi K^+} - \underline{\mathcal{A}^{CP}(B^+ \to J/\psi K^+)}$ from PDG Phys. Rev. D110372 (2024) 030001
  - $\mathcal{A}^{det+prod}_{B^+\to K^0_S\pi^+} = \mathcal{A}^{det+prod}_{B^+\to K^0_S K^+} - \mathcal{A}^{K^+\pi^-} = \mathcal{A}^{det+prod}_{B^+\to K^0_S K^+} - \underline{(\mathcal{A}^{K^+\pi^-} + \mathcal{A}^{K^0})} + \mathcal{A}^{K^0}$

LHCb-PUB-2018-004

- Neutral kaon asymmetry $\mathcal{A}^{K^0}$

CP violation in the decay $K^0_S \to \pi^+\pi^-$ and interaction of the K^0 with the detector material

arXiv:1110.3790

Phys. Rev. D84 (2011)

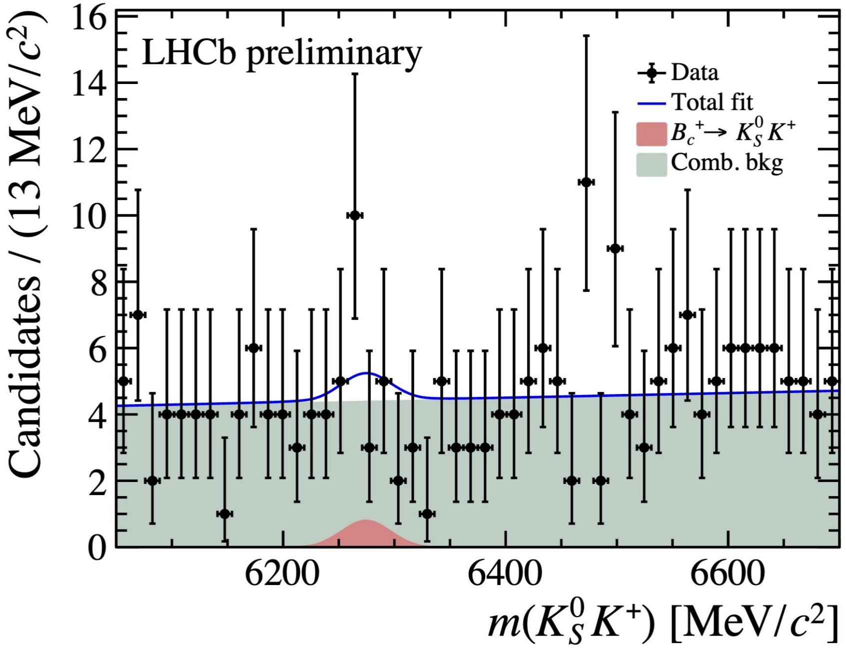
Systematic Uncertainties

	CP asymmetry (%)		$\mathcal{R}$ (%)
	$B^+ \to K^0_S \pi^+$	$B^+ \to K^0_S K^+$	
Fit model	0.15	1.29	1.92
PID weighting	0.01	0.01	0.44
$\mathcal{A}^{\text{det+prod}}$	0.32	0.32	–
$(\mathcal{A}^{K^+\pi^-} + \mathcal{A}^{K^0})$	–	0.01	–
$\mathcal{A}^{K^0}$	0.01	0.01	–
Trigger	0.70	0.74	0.23
Tracking efficiency	–	–	0.01
K/π interaction	–	–	0.30
BDTG selection	0.41	2.56	–
Mass veto selection	0.10	0.88	3.31
Simulation sample size	–	–	0.87
Total	$\boxed{0.89}$	$\boxed{3.11}$	$\boxed{3.97}$

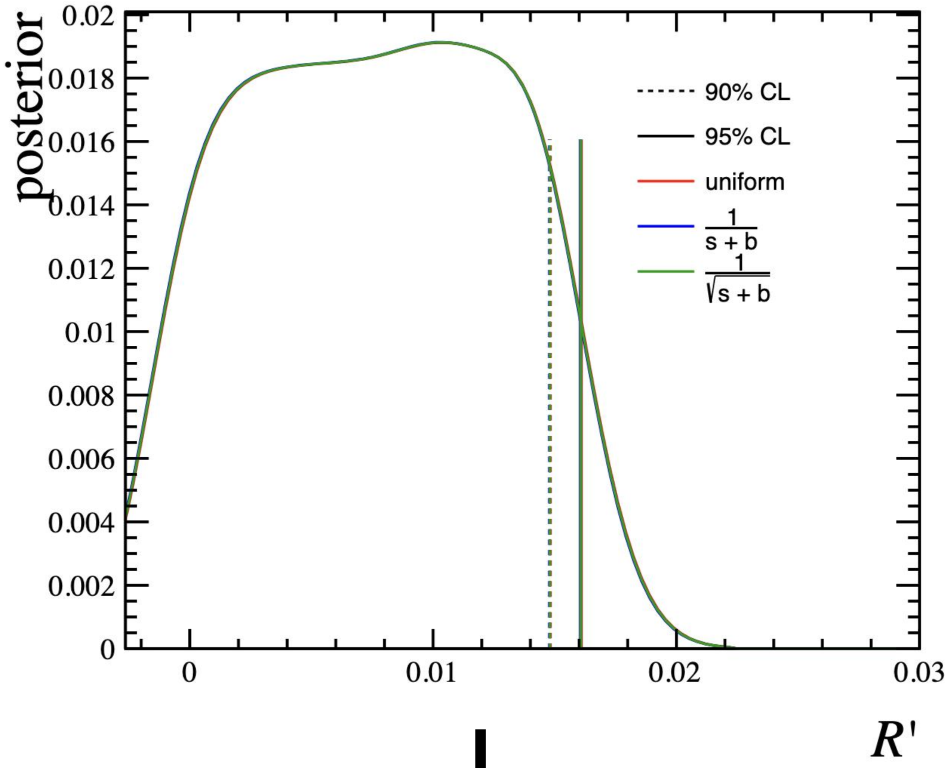
Absolute uncertainties for $\mathcal{A}^{CP}$, relative uncertainties for $\mathcal{R} = \frac{\mathcal{B}(B^+ \to K^0_S K^+)}{\mathcal{B}(B^+ \to K^0_S \pi^+)}$

Search for $B_c^+ \to K_S^0 K^+$ decay

- **Combinatorial background:** a first-order polynomial function
- **Signal model:** a DSCB function, tail parameters and σ fixed from MC, μ fixed from PDG.



- Smeared profile likelihood curve



$$\mathcal{R}' = \frac{f_c}{f_u} \times \frac{\mathcal{B}(B_c^+ \to K_S^0 K^+)}{\mathcal{B}(B^+ \to K_S^0 \pi^+)} < 0.015(0.016) \text{ at } 90\%(95\%) \text{ CL}$$

Summary

➢ Results

- $\mathcal{A}^{CP}(B^+ \to K_S^0 \pi^+) = -0.028 \pm 0.009(\text{stat}) \pm 0.009(\text{syst})$
- $\mathcal{A}^{CP}(B^+ \to K_S^0 K^+) = 0.118 \pm 0.062(\text{stat}) \pm 0.031(\text{syst})$
- $\mathcal{R} = \frac{\mathcal{B}(B^+ \to K_S^0 K^+)}{\mathcal{B}(B^+ \to K_S^0 \pi^+)} = 0.055 \pm 0.004(\text{stat}) \pm 0.002(\text{syst})$

  $\to$ All results are statistically dominated.
- $\mathcal{R}' = \frac{f_c}{f_u} \times \frac{\mathcal{B}(B_c^+ \to K_S^0 K^+)}{\mathcal{B}(B^+ \to K_S^0 \pi^+)} < 0.015(0.016)$ at 90%(95%) CL

➢ Conclusion and Outlook

- Improved precision compared to previous LHCb measurement
- All measurements are consistent with SM predictions, while offering improved constraints for flavor physics and searches for physics beyond the SM
- With the increased statistics from LHCb Run 3, future analyses will further enhance the sensitivity to potential deviations from the SM

Thanks for listening!

Back up

Motivation

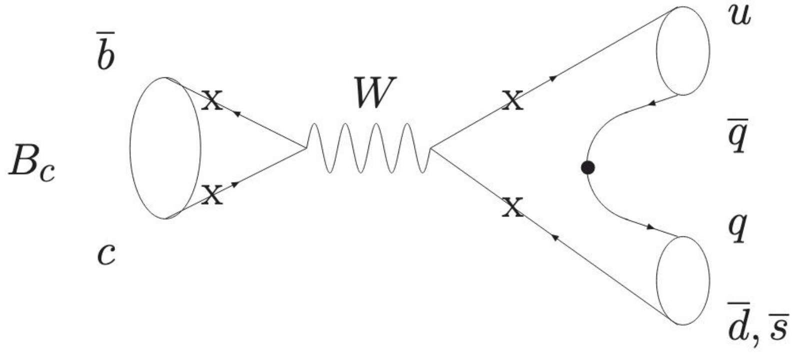
At tree level, only annihilation diagrams contribute to $\boldsymbol{B_c^+ \to K_s^0 K^+}$

Offers clean test of QCD annihilation via $b - c$ annihilation mediated by W^+ boson.

Theoretical prediction:

- Branching fraction → 10^{-6} to 9×10^{-8} [Phys. Rev. D 80 (2009) 114031]

If observed, this decay would offer a unique test ground for annihilation dynamics in heavy meson decays



Generic diagram for the non-leptonic charmless B_c decays [arXiv:0907.2256v1]

Selection

- Trigger
  - L0: Hadron TOS || DiMuon TIS || Muon TIS || Electron TIS || MuonEW TIS || Hadron TIS || JetElectron TIS || JetPhysics TIS
  - HLT1: TrackMVA TOS || TwoTrackMVA TOS
  - HLT2: Topo(2,3)Body(Simple) TOS
- Further offline selection

Particle	Variable	Cut
K^0_S	$(z(K^0_S)-z(B))/\sqrt{\sigma_z^2(K^0_S)+\sigma_z^2(B)}$	>2
Bachelor h	χ^2_{IP}	>16
Bachelor h	p	<300 GeV
Bachelor h	`hasRich`	`true`
track	`hasMuon && isMuon`	`false`
B	χ^2 of the B^+ vertex fit	<20
Fiducial cut	n / a	$\lvert p_x\rvert > 0.267\times\lvert p-1400\rvert$ $-0.00285\times p+818<\lvert p_x\rvert<0.01034\times p+818$

MVA

- **Training samples** ($B^+ \to K_s^0\pi^+$ and $B^+ \to K_s^0K^+$ are trained separately)

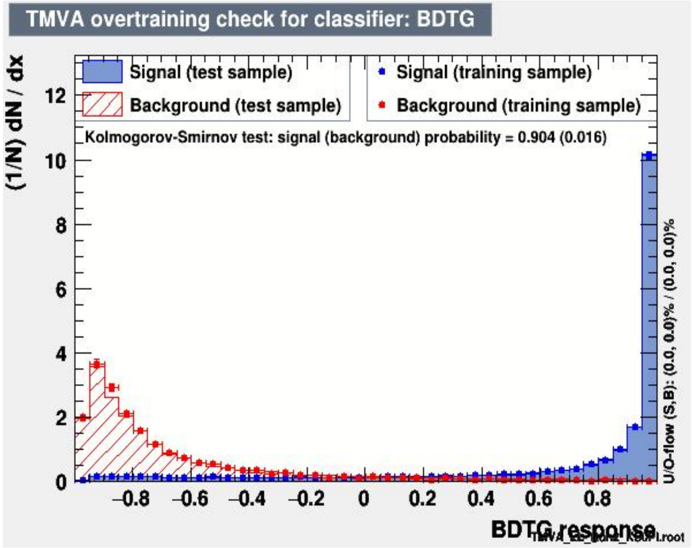
- Signal: $B^+ \to K_s^0 \mathrm{h}^+$ full simulated sample (reweighted)

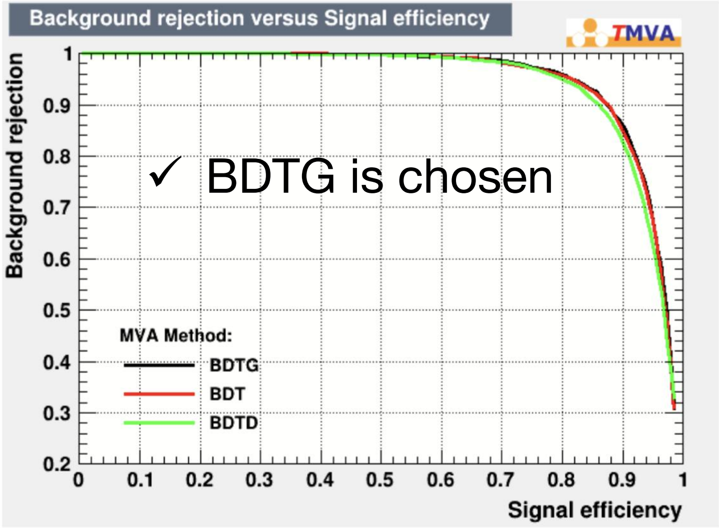
- Background: candidates in high sideband m($K_s^0\mathrm{h}^+$)∈(5600,6000)MeV

- **Training variables**

Particle	Variable
B	p_{T} asymmetry in a cone of 1 rad
B	p_{T}
B	χ^2_{IP}
B	$\chi^2_{\mathrm{vtx}}/\mathrm{ndf}$
bachelor π	χ^2_{IP}
K^0_{S}	χ^2_{IP}
K^0_{S}	$(z(K^0_{\mathrm{S}}) - z(B))/\sqrt{\sigma_z^2(K^0_{\mathrm{S}}) + \sigma_z^2(B)}$
B	DIRA
B	DecayTreeFitter (DTF) χ^2/ndf
B	$c\tau$

- **Algorithms**





✓ BDTG is chosen

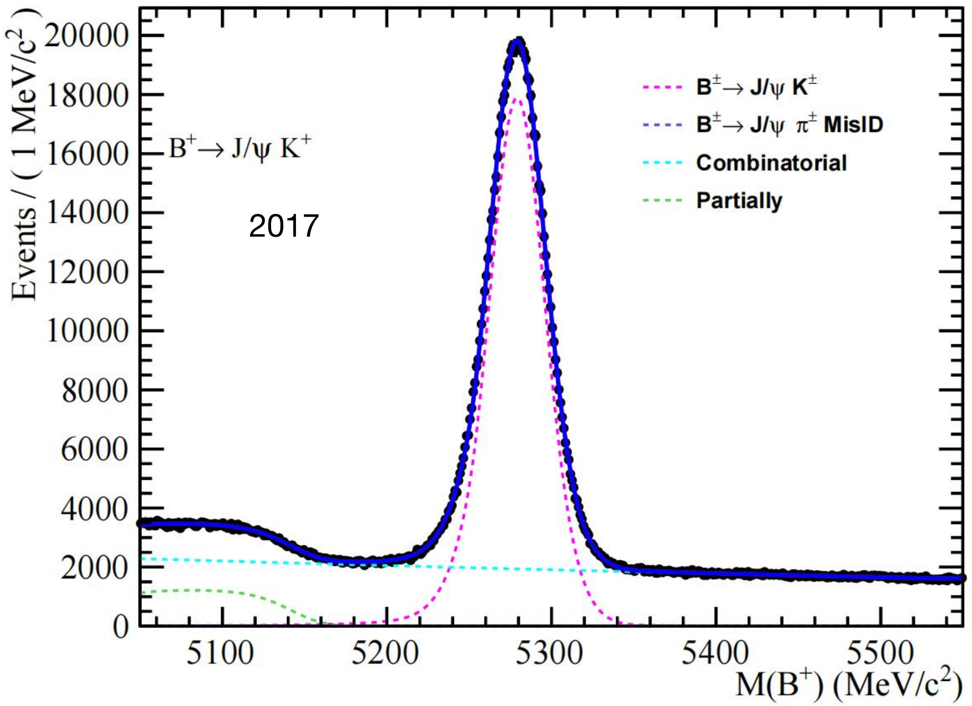
Efficiency(mc)

Selection	$B^+ \to K^0_S \pi^+$	$B^+ \to K^0_S K^+$	$B_c^+ \to K^0_S K^+$
Acceptance(%)	25.98 ± 0.05	18.48 ± 0.03	24.81 ± 0.04
MC Match(%)	96.70 ± 0.14	96.97 ± 0.15	99.80 ± 0.08
Preselection(%)	1.15 ± 0.01	1.58 ± 0.01	1.03 ± 0.01
Trigger(%)	44.00 ± 0.23	42.25 ± 0.20	32.07 ± 0.23
LooseSelection(%)	97.46 ± 0.11	-	-
Veto(%)	95.48 ± 0.20	76.35 ± 0.36	-
PID(%)	97.46 ± 0.14	78.11 ± 0.30	75.96 ± 0.37
BDTG(%)	85.64 ± 0.31	71.08 ± 0.37	39.61 ± 0.49
Track(%)	99.88 ± 0.00	99.87 ± 0.00	99.64 ± 0.00
Total(10^{-4})	10.27 ± 0.10	5.41 ± 0.06	2.45 ± 0.04

Production and detection asymmetry($\mathcal{A}^{det+prod}_{B^+\to K^0_S K^+}$)

Control channel: $B^+ \to J/\psi K^+$
Stripping line: FullDSTDimuonJpsi2MuMuDetachedLine

Particle	Variable	Cut
J/ψ	invariant mass	[3048, 3139]
	χ^2_{vtx}/ndf	< 10
K	p_T	> 1000.0 MeV
	momentum	< 300000 MeV
	χ^2_{track}/ndf	< 16
	PID	> 3
fiducial cut	n / a	$\lvert h_{PX}\rvert > 0.267\lvert h_P - 1400\rvert$
		$-0.00385 h_P + 818 < \lvert h_{PX}\rvert < 0.01034 h_P + 818$
trigger	L0	L0Muon TOS | | L0DiMuon TOS
trigger	HLT1	Hlt1TrackMuon TOS | | Hlt1DiMuonHighMass TOS
trigger	HLT2	Topo(2,3)Body(Simple) TOS



First Second

$$\mathcal{A}^{det+prod}_{B^+\to K^0_S K^+} = \mathcal{A}^{det+prod}_{B^+\to J/\psi K^+} = \boxed{\mathcal{A}^{raw}_{B^+\to J/\psi K^+}} - \boxed{\mathcal{A}^{CP}(B^+\to J/\psi K^+)}$$

$$\mathcal{A}^{raw}_{B^+\to J/\psi K^+} = \frac{N^{B^-\to J/\psi K^-} - N^{B^+\to J/\psi K^+}}{N^{B^-\to J/\psi K^-} + N^{B^+\to J/\psi K^+}}$$

$(0.18 \pm 0.30)\%$ From PDG 2025

Production and detection asymmetry($\mathcal{A}^{det+prod}_{B^+\to K^0_S\pi^+}$)

$$\mathcal{A}^{det+prod}_{B^+\to K^0_S\pi^+} = \mathcal{A}^{det+prod}_{B^+\to K^0_S K^+} - \mathcal{A}^{K^+\pi^-} = \mathcal{A}^{det+prod}_{B^+\to K^0_S K^+} - \boxed{(\mathcal{A}^{K^+\pi^-} + \mathcal{A}^{K^0})} + \mathcal{A}^{K^0}$$

depends on momentum(P)

Bin	p(K^-) GeV/c	$\mathcal{A}^{det}(K^-\pi^+) + \mathcal{A}(K^0)$[%]
1	3 - 5	-1.81 $\pm$ 0.11
2	5 - 10	-1.15 $\pm$ 0.05
3	10 - 15	-0.97 $\pm$ 0.04
4	15 - 20	-0.79 $\pm$ 0.06
5	20 - 25	-0.68 $\pm$ 0.07
6	25 - 40	-0.64 $\pm$ 0.07
7	40 - 60	-0.46 $\pm$ 0.14
8	60 - 80	-0.37 $\pm$ 0.17

$$\longrightarrow \quad N_{eff} = \frac{(\Sigma_{j=1}^{N} w_i)^2}{\Sigma_{j=1}^{N} w_i^2}$$

$$\mathcal{A}^{K^+\pi^-} + \mathcal{A}^{K^0} = (-0.64 \pm 0.01)\%$$

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Systematic Uncertainties

1. Mass fit
2. PID efficiency and PID asymmetry
   - Binning scheme of PID efficiencies →the PID efficiency maps
   - Statistics of PID calibration sample
   - Kernel density PDFs used in the PID efficiency study
   - Statistics of signal simulation sample
3. L0 Trigger efficiency and L0 Trigger asymmetry $\varepsilon_{L0trigger}^{weighted} = \frac{\sum_{i=1} w_{GB,i}}{\sum_{i=1} w_{GB,i}/\varepsilon_i}$ → L0 hadron efficiency tables
4. Selection efficiency
   - MVA selection efficiency
   - Veto selection efficiency
5. Other uncertainties

   Asymmetry: Det+Prod asymmetry, $A^{K^+\pi^-} + A^{K^0}$, neutral kaon asymmetry

   Branching-fraction ratio:

   - Tracking efficiency correction→based on the momentum (p) and pseudorapidity (η)
   - K/π interaction→Limitations in the description of the detector material → Tracking systematics for hadrons
   - MC Sample statistics

CP asymmetry and Branch fraction ratio

- $\mathcal{A}^{raw}_{B^+\to K^0_S\pi^+} = -0.030 \pm 0.009(\text{stat})$ $\mathcal{A}^{raw}_{B^+\to K^0_S K^+} = -0.109 \pm 0.062(\text{stat})$
- $\mathcal{A}^{det+prod}_{B^+\to K^0_S K^+} = (-1.02 \pm 0.32)\%$ $\mathcal{A}^{det+prod}_{B^+\to K^0_S\pi^+} = (-0.31 \pm 0.32)\%$
- $\mathcal{A}^{K^+\pi^-} + \mathcal{A}^{K^0} = (-0.64 \pm 0.01)\%$ $\mathcal{A}^{K^0_S}_{B^+\to K^0_S h^+} = (-0.07 \pm 0.01)\%$

➢ $\mathcal{A}^{CP}(B^+ \to K^0_S\pi^+) = -0.030 \pm 0.009(\text{stat}) \pm 0.009(\text{syst})$

➢ $\mathcal{A}^{CP}(B^+ \to K^0_S K^+) = 0.118 \pm 0.062(\text{stat}) \pm 0.031(\text{syst})$

➢ $\mathcal{R} = \frac{\mathcal{B}(B^+\to K^0_S K^+)}{\mathcal{B}(B^+\to K^0_S\pi^+)} = \frac{N(B^+\to K^0_S K^+)}{N(B^+\to K^0_S\pi^+)} \times \frac{\varepsilon(B^+\to K^0_S\pi^+)}{\varepsilon(B^+\to K^0_S K^+)} = 0.055 \pm 0.004(\text{stat}) \pm 0.002(\text{syst})$

Search for $B_c^+ \to K_s^0 K^+$

Upper limit

- The method of profile likelihood $L(x|R', \theta)$ scan is employed to calculate the upper limit on the branching fraction of $B_c^+ \to K_s^0 K^+$

  profile likelihood ratio λ(R'):

$$\lambda_0(\mathcal{R}') = \frac{L(x|\mathcal{R}', \hat{\hat{\theta}})}{L(x|\hat{\mathcal{R}}', \hat{\theta})}$$

- Toy MC samples are generated under the "background" only hypothesis.
- The high-mass sideband region (6400-6700 MeV) is fitted using a first-order polynomial function.

Signal Estimation:

- Signal yield is extrapolated from the mass sideband to the search region (6050-6700 MeV).
- Toy MC samples are randomly generated with the assumption of a first-order polynomial slope and a given yield.

- Assuming a flat prior PDF for R' from 0 to 100%, the Bayesian upper limit on R' is calculated at 90%(95%) confidence level

$$\int_0^{\mathcal{R}'_{up}} \lambda(\mathcal{R}')d\mathcal{R}' = 90\%(95\%) \times \int_0^1 \lambda(\mathcal{R}')d\mathcal{R}'$$