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

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Outline

- Motivation and Analysis strategy
- Dataset and selection
- 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

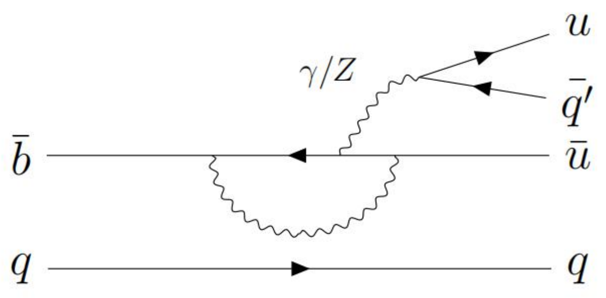
Theoretical predictions $\to$ Strong model dependence

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

- 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



P'_{EW}

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 → 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

Motivation

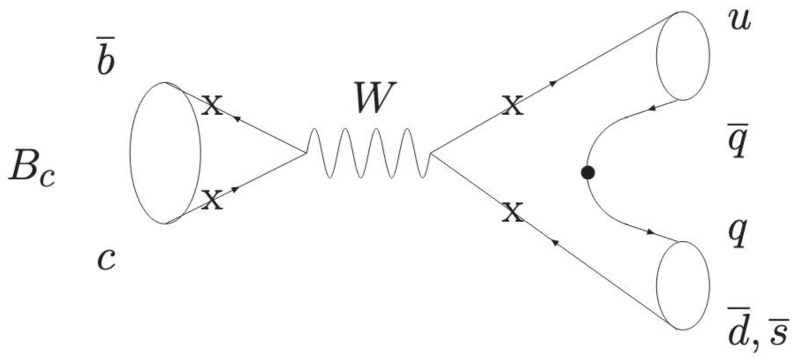
At tree level, only annihilation diagrams contribute to $\boldsymbol{B_c^+ \to K_s^0 K^+}$

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]

Motivation

Previous measurements:

➢ LHCb 2011+2012 ($3fb^{-1}$)   only Long-Long

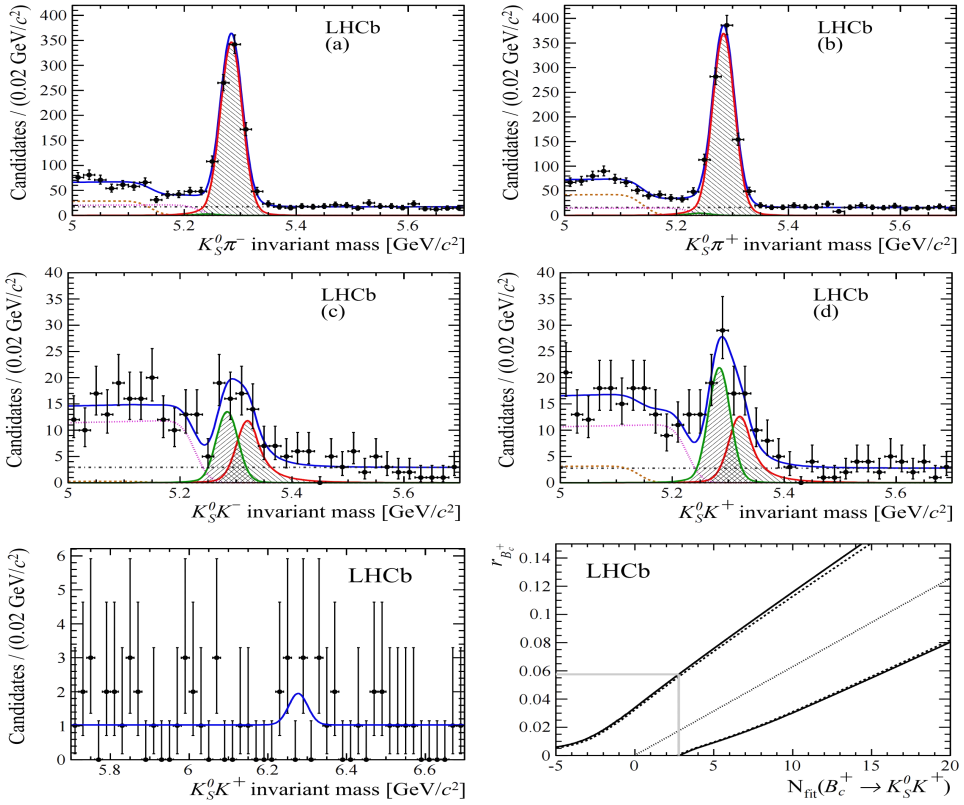
- $\mathcal{R} = \frac{\mathcal{B}(B^+ \to K_S^0 K^+)}{\mathcal{B}(B^+ \to K_S^0 \pi^+)} = 0.0640 \pm 0.0038 \pm 0.0101$
- $\mathcal{A}^{CP}(B^+ \to K_S^0 K^+) =- 0.21 \pm 0.14 \pm 0.01$
- $\mathcal{A}^{CP}(B^+ \to K_S^0 \pi^+) =- 0.024 \pm 0.025 \pm 0.010$
- $\mathcal{R}' = \frac{f_c}{f_u} \cdot \frac{\mathcal{B}(B_c^+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

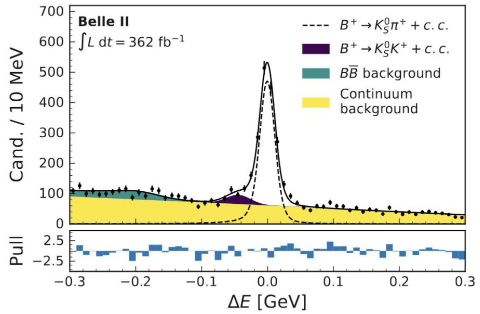
LHCb-PAPER-2013-034
ArXiv:1308.1277

➢ 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:

  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

Selection

- StrippingBu2KShLLLine
- 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	$(z(K^0_S) - z(B))/\sqrt{\sigma^2_z(K^0_S) + \sigma^2_z(B)}$	> 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	$\lvert p_x\rvert > 0.267 \times \lvert p - 1400\rvert$ $-0.00285 \times p + 818 < \lvert p_x\rvert < 0.01034 \times p + 818$

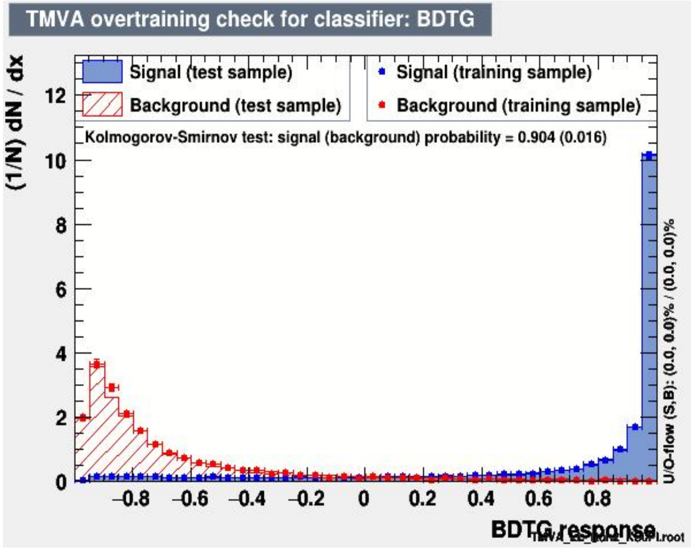
MVA

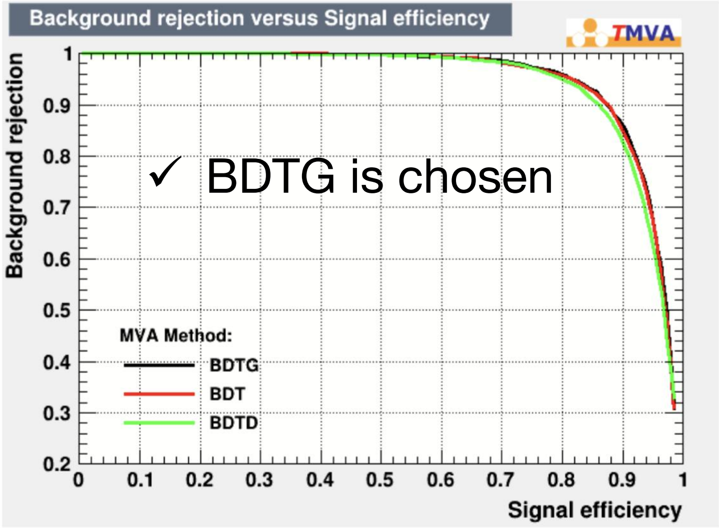
- **Training samples** ($B^+ \to K_s^0\pi^+$and $B^+ \to K_s^0 K^+$are trained separately)
- Signal: $B^+ \to K_s^0\mathrm{h}^+$ full simulated sample (reweighted)
- Background: candidates in high sideband m($K_s^0\mathrm{h}^+$)∈(5600,6000)MeV

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}	$(z(K^0_{\mathrm{S}}) - z(B))/\sqrt{\sigma^2_z(K^0_{\mathrm{S}}) + \sigma^2_z(B)}$
B	DIRA
B	DecayTreeFitter (DTF) χ^2/ndf
B	$c\tau$

Algorithms





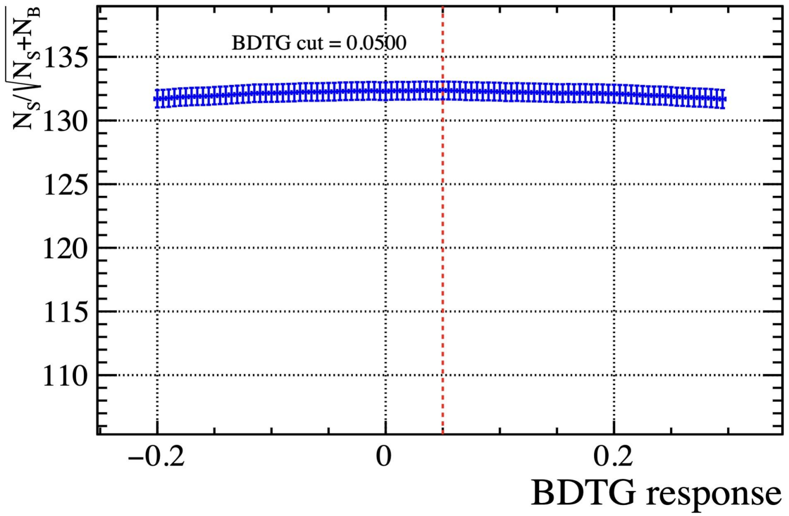
✓ BDTG is chosen

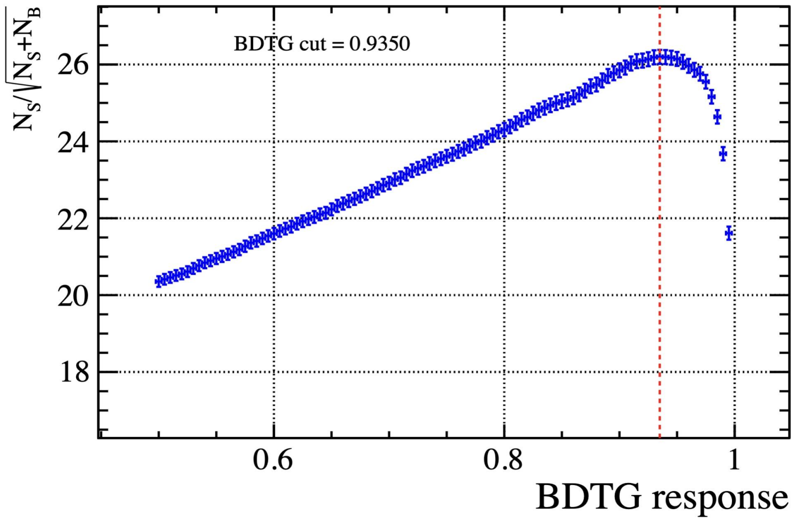
PID&MVA optimization

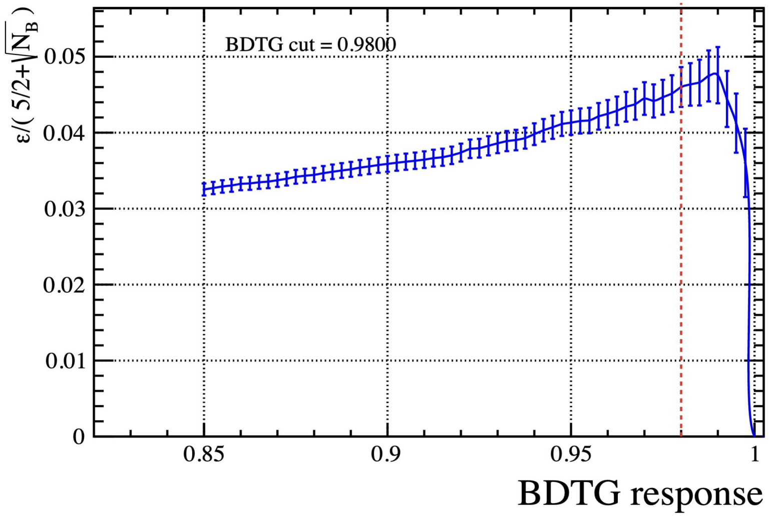
- PID requriements follow the same strategy as Run 1 → pion: PIDK < 3; kaon: PIDK >3
- Optimal BDTG output requirement
  - $B^+ \to K_s^0 h^+$: maximize signal significance

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

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

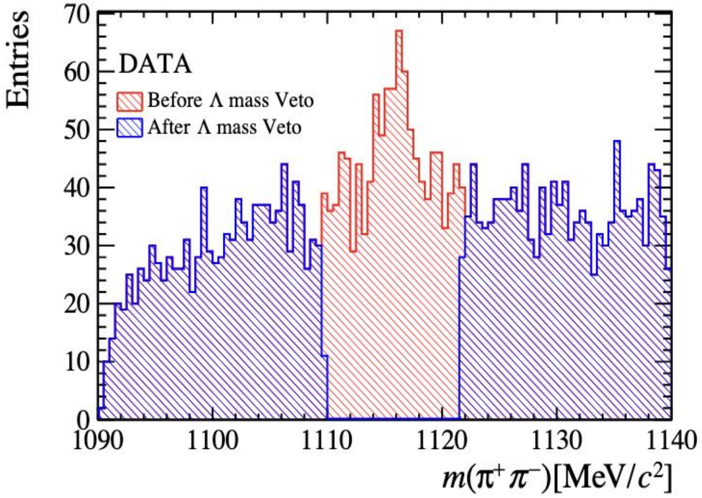




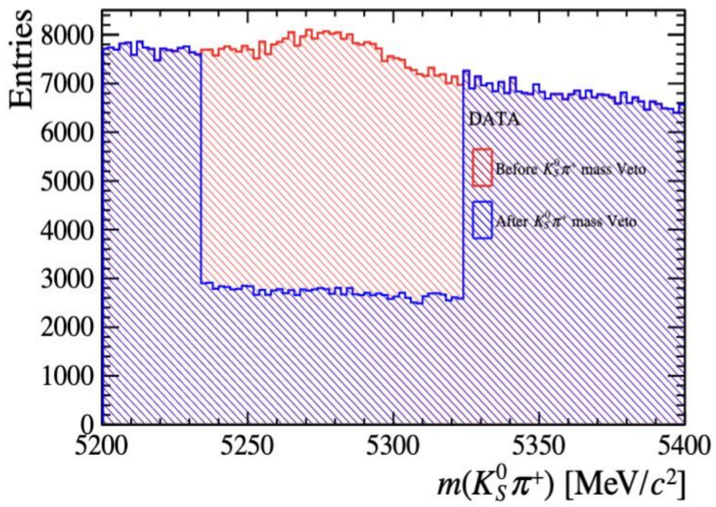


Veto Peaking background

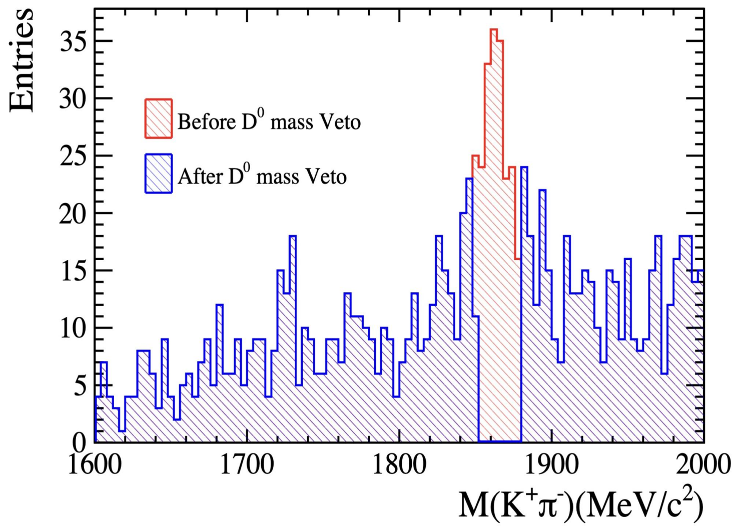
- For the $B^+ \to K_s^0\pi^+$ mode
  - Peaking background from $\Lambda \to p\pi^-$ misidentified as $K_s^0 \to \pi^+\pi^-$ ($p \to \pi$ mis-ID) (left plot)
- For the $B^+ \to K_s^0 K^+$ mode
  - Cross-feed from $B^+ \to K_s^0\pi^+$ decays (middle plot)
  - The $B^+ \to D^0\pi^+$ process, with $D^0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



(a) Λ mass veto

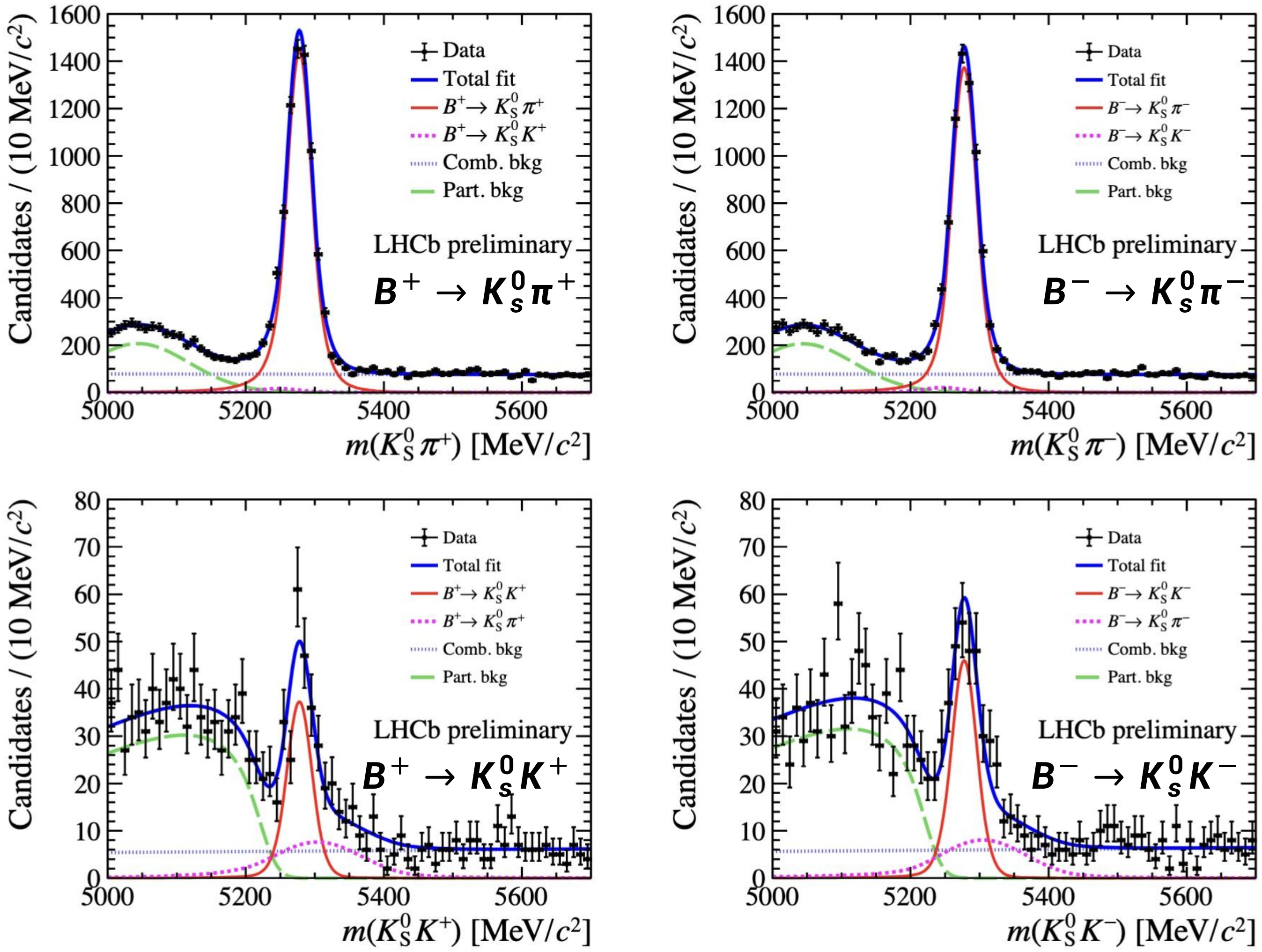


(b) $K_s^0\pi^+$ mass veto



(c) D^0 mass veto

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



- **Combinatorial background**: a first-order polynomial function
- **Partially Reconstructed Backgrounds:** Argus function ⊗ Gauss resolution
- **Misidentified Backgrounds**: a DSCB 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

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

- Raw asymmetry $\mathcal{A}^{raw} = \frac{N(B^-)-N(B^+)}{N(B^-)+N(B^+)}$
- Production and detection asymmetry

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

  - $\mathcal{A}^{det+prod}_{B^+\to K_S^0K^+} = \mathcal{A}^{det+prod}_{B^+\to J/\psi K^+} = \mathcal{A}^{raw}_{B^+\to J/\psi K^+} - \underline{\mathcal{A}^{CP}(B^+ \to J/\psi K^+)}$ from PDG Phys. Rev. D110372 (2024) 030001
  - $\mathcal{A}^{det+prod}_{B^+\to K_S^0\pi^+} = \mathcal{A}^{det+prod}_{B^+\to K_S^0K^+} - \mathcal{A}^{K^+\pi^-} = \mathcal{A}^{det+prod}_{B^+\to K_S^0K^+} - \underline{(\mathcal{A}^{K^+\pi^-} + \mathcal{A}^{K^0})} + \mathcal{A}^{K^0}$

LHCb-PUB-2018-004

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

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

arXiv:1110.3790

Phys. Rev. D84 (2011)

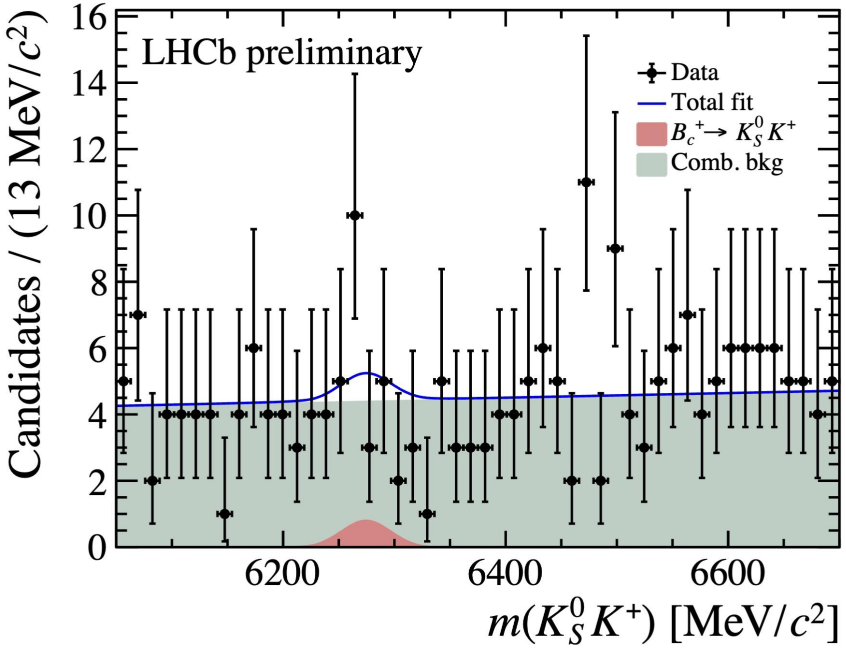
Systematic Uncertainties

	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 asymmetry	0.01	0.01	-
PID efficiency	-	–	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	–
L0 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	$\boxed{0.89}$	$\boxed{3.11}$	$\boxed{3.97}$

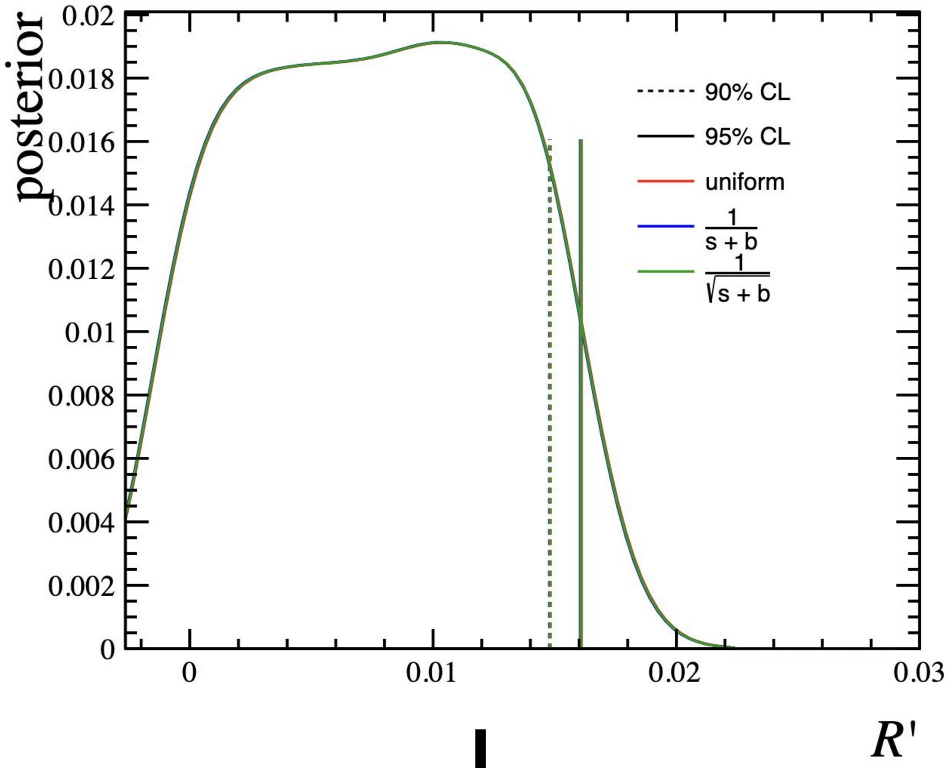
Absolute uncertainties for $\mathcal{A}^{CP}$, relative uncertainties for $\mathcal{R} = \frac{\mathcal{B}(B^+ \to K^0_S K^+)}{\mathcal{B}(B^+ \to K^0_S \pi^+)}$

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

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

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

Efficiency(mc)

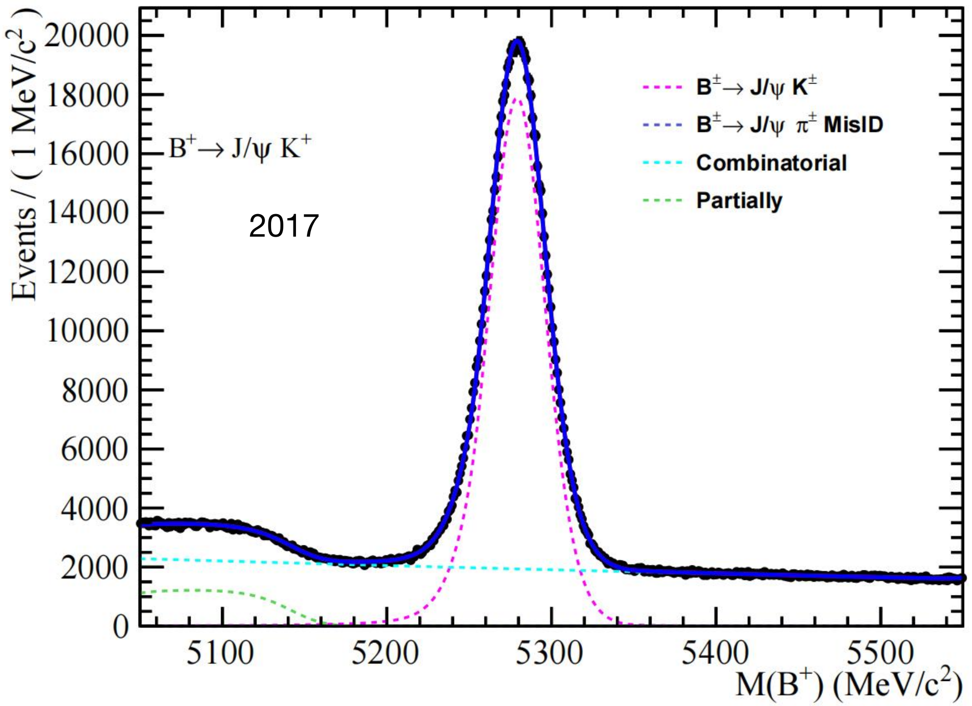
Selection	$B^+ \to K^0_S \pi^+$	$B^+ \to K^0_S K^+$	$B_c^+ \to K^0_S K^+$
Acceptance(%)	25.98 ± 0.05	18.48 ± 0.03	24.81 ± 0.04
MC Match(%)	96.70 ± 0.14	96.97 ± 0.15	99.80 ± 0.08
Preselection(%)	1.15 ± 0.01	1.58 ± 0.01	1.03 ± 0.01
Trigger(%)	44.00 ± 0.23	42.25 ± 0.20	32.07 ± 0.23
LooseSelection(%)	97.46 ± 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})	$\boxed{10.27 \pm 0.10}$	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 ± 0.11
2	5 - 10	-1.15 ± 0.05
3	10 - 15	-0.97 ± 0.04
4	15 - 20	-0.79 ± 0.06
5	20 - 25	-0.68 ± 0.07
6	25 - 40	-0.64 ± 0.07
7	40 - 60	-0.46 ± 0.14
8	60 - 80	-0.37 ± 0.17

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

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

LHCb-PUB-2018-004

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

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

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

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

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

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

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