Observation of the decay $B^0_{(s)} \to D_{s1}(2536)^{\mp} K^{\pm}$

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on behalf of LHCb collaboration

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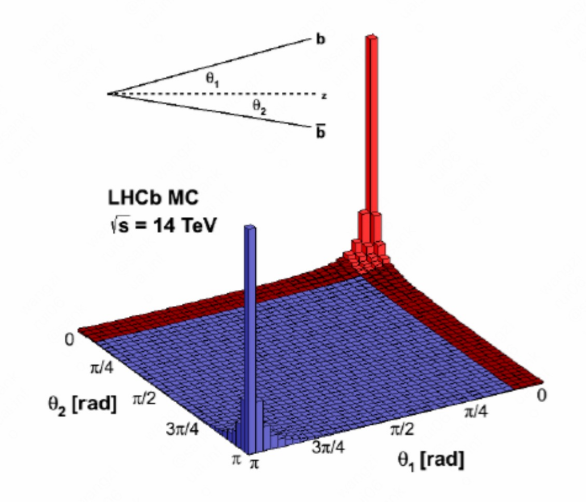
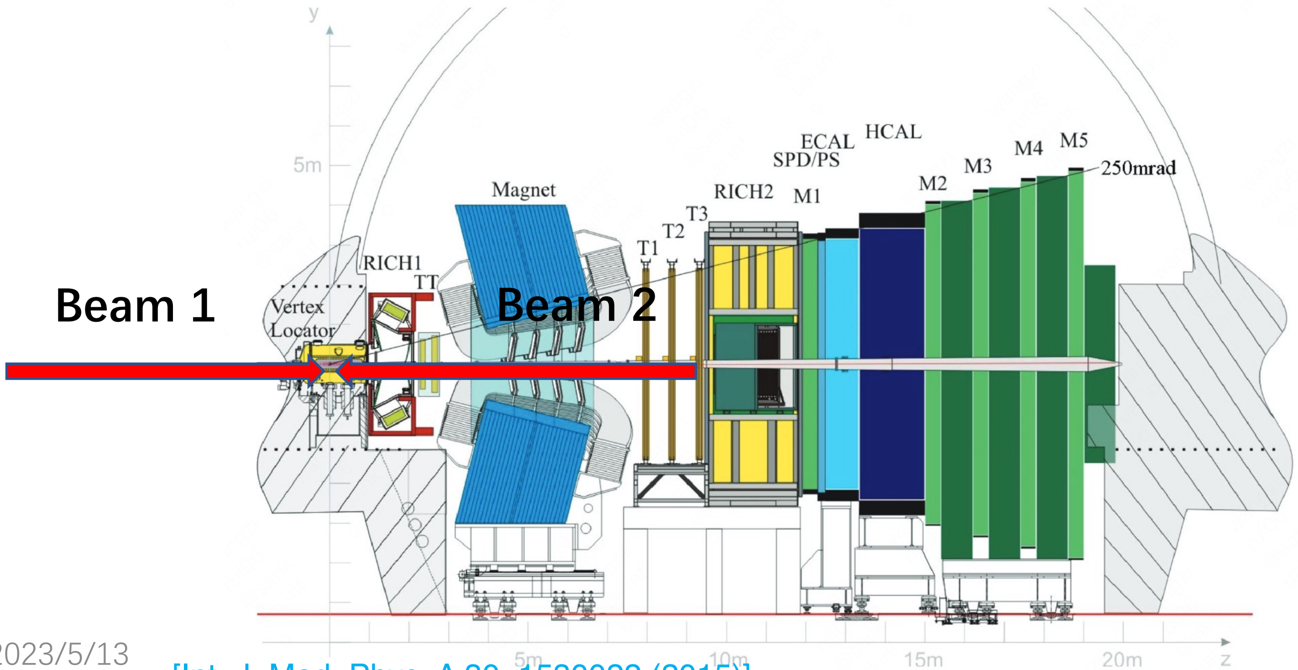
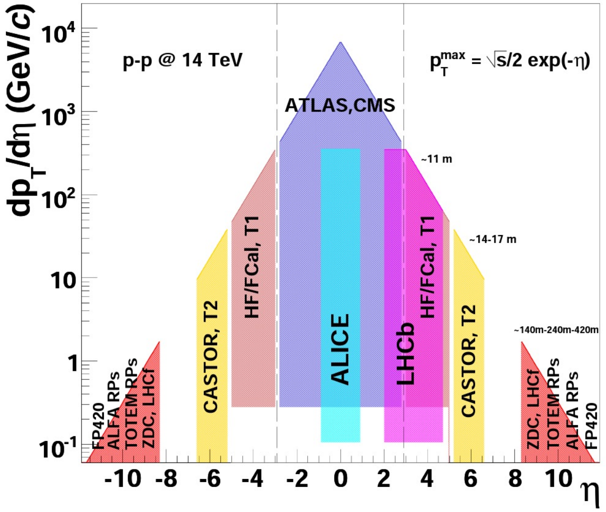
LHCb detector

- Single-arm forward spectrometer
- Designed for the study of b and c physics
- Forward region $2 < \eta < 5$
  - $\sim 4\%$ of solid angle, but $\sim 25\%$ of $b\bar{b}$ quark pairs accepted
- Data collection
  - Totally $\sim 9\text{fb}^{-1}$ pp collision data at $7, 8, 13$ TeV





[Int. J. Mod. Phys. A 30, 1530022 (2015)]



[arXiv:0708.0551]

Observation of the decay $B^0_{(s)} \rightarrow D_{s1}(2536)^{\mp}K^{\pm}$

published in JHEP, JHEP 10 (2023) 106

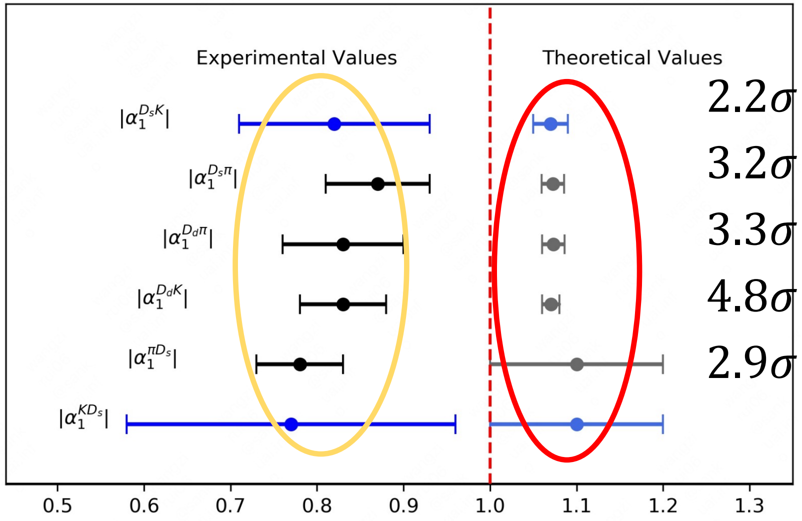
- Motivation
- Analysis strategy
- Differential decay rate
- Mass fitting
- Systematic uncertainty
- Conclusion

Motivation

- The puzzle in the decays $B^0 \to D^{(*)-}K^+$ and $B_s^0 \to D_s^{(*)-}\pi^+/K^+$:
  - their measured branching fractions are smaller than those from calculation with QCD factorization.

[Phys. Rev. D **83**, 014017 (2011)]

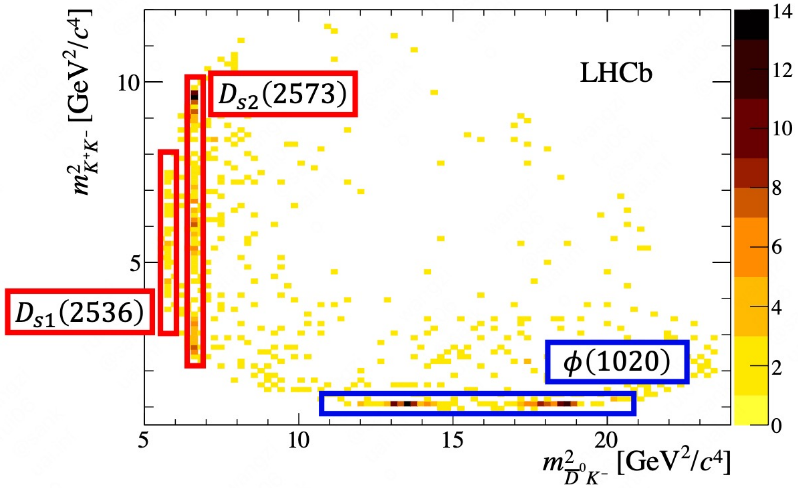
[Eur. Phys. J. C **80**, 951 (2020)]



[Phys. Rev. D **106**, 056004 (2022)]

- An extension of previous $B_{(s)}^0 \to \bar{D}^0 K^+K^-$ measurement
  - A significant peak corresponding to $D_{s1}(2536)$
  - $D_{s1}K$ decay mode not observed for $B_{(s)}^0$

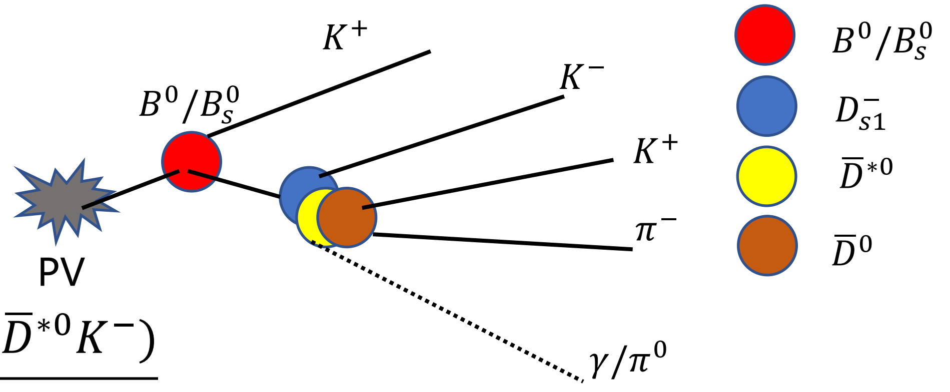
- Same quark content as $D_s^{\mp}K^{\pm}$
  - The B_s^0 mode can process via both $b \to c$ and $b \to u$ transition – sensitive to CKM angle γ
  - Probe γ from $B_s^0 - \bar{B}_s^0$ mixing and decay, time-dependent measurement
  - We focus on its branching fraction measurement in this analysis



[Phys. Rev. D98 072006 (2018)]

Analysis strategy

- Signal: $B^0_{(s)} \to D^{\mp}_{s1} K^{\pm}, D^{+}_{s1} \to D^{*0} K^{+}, D^{*0} \to D^0 \gamma/\pi^0$
  - Studied with partially reconstructed approach (γ/π^0 missing)
  - Forms a $D^0 K^+ K^-$ final state



- Control channel: $B^0 \to \overline{D}^0 K^+ K^-$

- Relative branching fraction

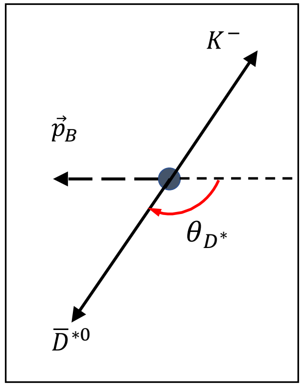
$$\mathcal{R}(B^0_{(s)} \to D^{\mp}_{s1} K^{\pm}) \equiv \frac{\mathcal{B}(B^0_{(s)} \to D^{\mp}_{s1} K^{\pm}) \times \mathcal{B}(D^{-}_{s1} \to \overline{D}^{*0} K^{-})}{\mathcal{B}_{B^0 \to \overline{D}^0 K^+ K^-}}$$

$$= \frac{N_{\boldsymbol{B^0_{(s)} \to D^{\mp}_{s1} K^{\pm}, D^{-}_{s1} \to \overline{D}^{*0} K^{-}}}}{N_{B^0 \to \overline{D}^0 K^+ K^-}} \times \frac{\epsilon_{B^0 \to \overline{D}^0 K^+ K^-}}{\epsilon_{B^0_{(s)} \to D^{\mp}_{s1} K^{\pm}}} \left(\times \frac{1}{f_s/f_d} \right)$$

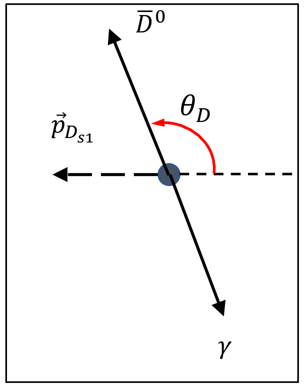
Differential decay rate of signal

- Due to the non-zero spin of D_{s1} and D^{*0}, the decay amplitude of signal process $B^0_{(s)} \to D_{s1}K$ contains multiple processes
- Using helicity formalism, the differential decay rate of the decay can be expressed as a function of
  - θ_{D^*}: the angle between $\bar{D}^{*0}$ and the direction opposite the B momentum vector in the D_{s1} rest frame
  - θ_D: : the angle between $\bar{D}^0$ and the direction opposite the D_{s1} momentum vector in the D^* rest frame
  - χ: the angle between two decay planes defined in the B rest frame

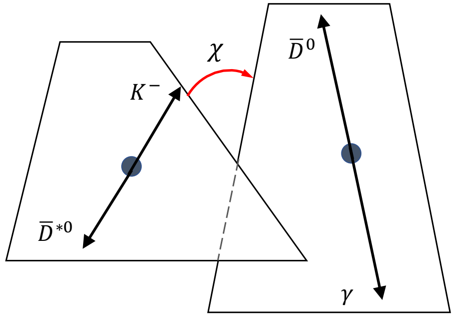
	D_{s1}	$\to$	D^{*0}	K
J^P	1^+		1^-	0^-
λ	0		$0, \pm 1$	0



$D_{s1}(2536)^-$ rest frame



$\bar{D}^{*0}$ rest frame



B rest frame

Differential decay rate of signal (cont.)

- The differential decay rate:

Here containing the condition that $H_+ = H_-$,
due to parity conversation on the process, $D_{s1}^- \to \bar{D}^{*0} K^-$

$$\frac{d\Gamma}{d\cos\theta_{D^*} d\cos\theta_D d\chi} \propto \omega_{\mathrm{long}}(\theta_{D^*}, \theta_D) H_0^2 + \omega_{\mathrm{tran}}(\chi, \theta_{D^*}, \theta_D) H_+^2 + \omega_{\mathrm{int}}(\chi, \theta_{D^*}, \theta_D) \mathcal{R}e(H_0, H_+)$$

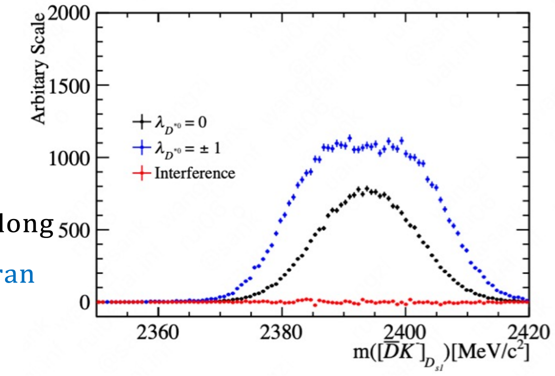
  - $H_+/H_0 = ke^{i\phi}$ is the ratio of the two amplitudes.

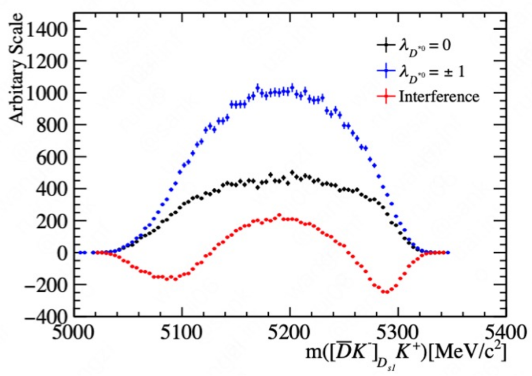
- The signal channel is split into γ chain (where $D^{*0} \to D^0\gamma$) and π^0 chain (where $D^{*0} \to D^0\pi^0$).
  - $\omega_{\mathrm{long/tran/int}}$ and $H_{+/0}$ are different for γ and π^0 chains, but H_+/H_0 is same for both of them.

	γ chain	π^0 chain
$\omega_{\mathrm{long}}(\theta_{D^*}, \theta_D)$	$\cos^2\theta_{D^*}\sin^2\theta_D$	$\cos^2\theta_{D^*}\cos^2\theta_D$
$\omega_{\mathrm{tran}}(\chi, \theta_{D^*}, \theta_D)$	$\sin^2\theta_{D^*}(\sin^2\chi + \cos^2\chi\cos^2\theta_D)$	$\cos^2\chi\sin^2\theta_{D^*}\sin^2\theta_D$
$\omega_{\mathrm{int}}(\chi, \theta_{D^*}, \theta_D)$	$2\cos\chi\sin\theta_{D^*}\cos\theta_{D^*}\sin\theta_D\cos\theta_D$	$-2\cos\chi\sin\theta_{D^*}\cos\theta_{D^*}\sin\theta_D\cos\theta_D$

Toy samples generated for γ chain, plotting invariant mass
ω_{int} has no contribution on $m(\bar{D}^0 K^-)$

black: ω_{long}
blue: ω_{tran}
red: ω_{int}

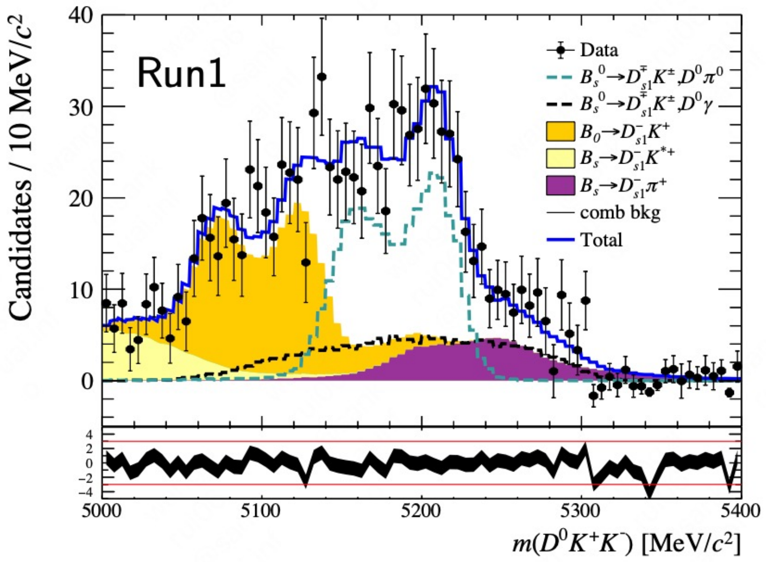


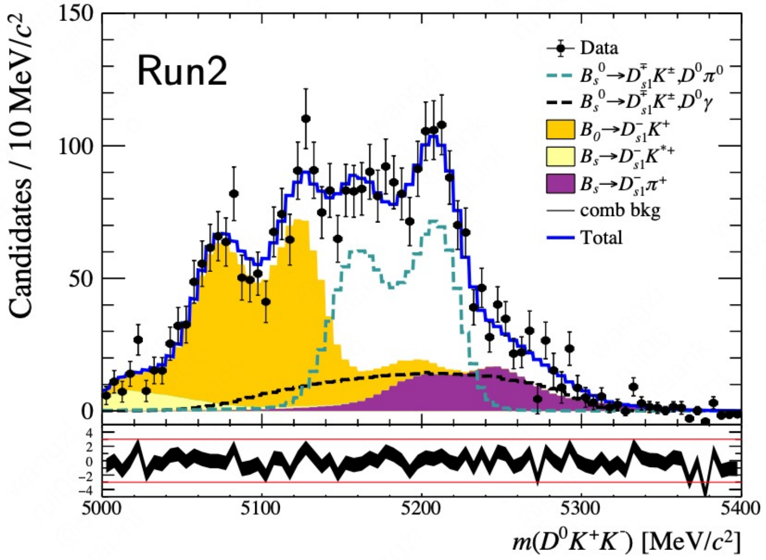


Fit for signal channel

- Signal: $B_s^0 \to D_{s1}K$ and $B^0 \to D_{s1}K$
- Background: $B_s^0 \to D_{s1}\pi$ and $B_s^0 \to D_{s1}K^*$
- Mass shapes:
  - Shapes of $D_{s1}K$ and $D_{s1}\pi$ channels are obtained from PHSP MC weighted by ω_{long}, ω_{tran} and ω_{int}, the ratio of which is $1: k^2: k\cos\phi$
  - Shapes of $D_{s1}K^*$ is obtained from PHSP MC, as only the tail of the decay enters the mass range
- Yield setup
  - Yields between γ and π^0 chains are fixed by branching fractions for all decay channels

$$\frac{N_\gamma(X)/\epsilon_\gamma(X)}{N_{\pi^0}(X)/\epsilon_{\pi^0}(X)} = \frac{\mathcal{B}_{D^{*0}\to D^0\gamma}}{\mathcal{B}_{D^{*0}\to D^0\pi^0}}$$



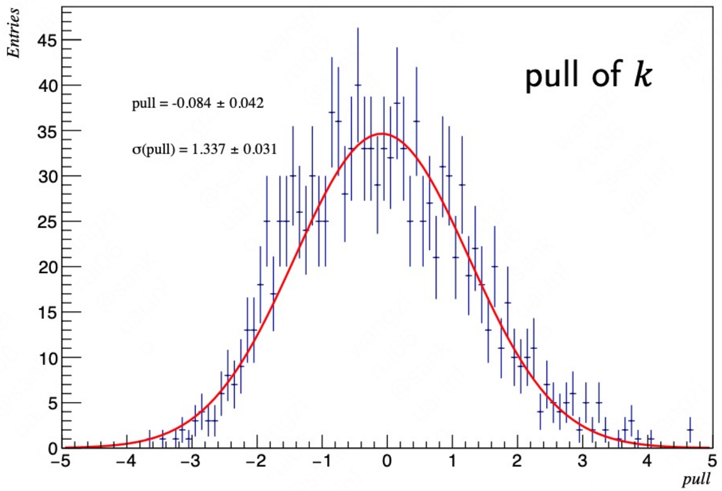


Fit to sweighted $\mathrm{m}(\bar{\mathrm{D}}^0\mathrm{K}^+\mathrm{K}^-)$: toy studies

- Generate 2D ($m(\bar{D}^0K^-)\times m(\bar{D}^0K^+K^-)$) distributions for
  - non-D_{s1} background: assume no correlation between two masses
  - $B^0_{(s)} \to D_{s1}K, B^0_s \to D_{s1}\pi, B^0_s \to D_{s1}K^*$: from weighted MC samples
- Perform mass fits to toy samples and obtain pulls for
  - yields of $B^0_{(s)} \to D_{s1}K$
  - amplitude ratio k and phase difference $|\phi|$
- Pull means are mostly consistent with 0 in 3σ, pull widths are significantly larger than 1. Correction applied to fit results $x_m \pm \sigma_{x_m}$

$$x_c = x_m - \mu^x_{\mathrm{pull}} \times \sigma_{x_m}$$

$$\sigma_{x_c} = \sigma^x_{\mathrm{pull}} \times \sigma_{x_m}$$

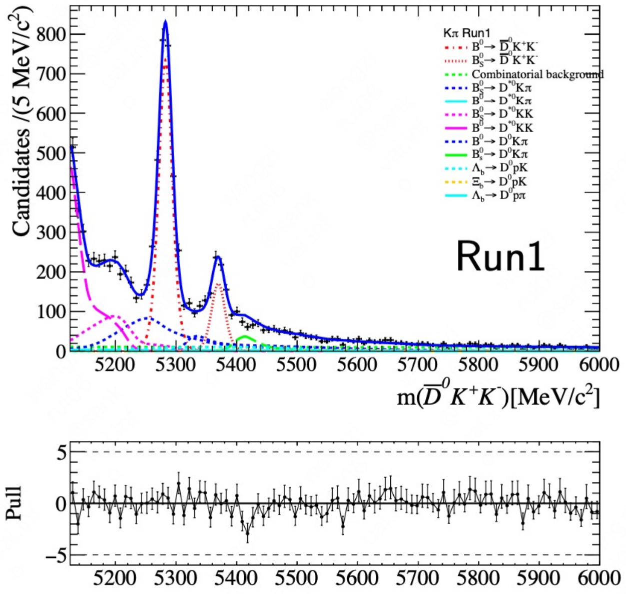


corrected fit results

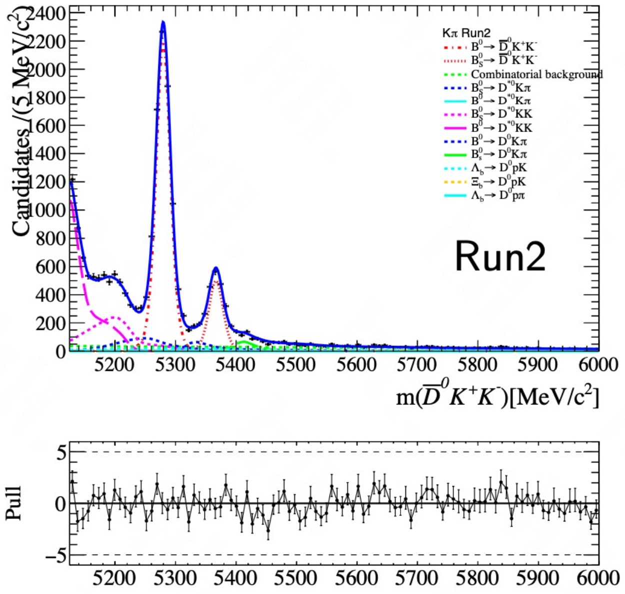
Parameter		Run1	Run2
$B^0_s \to D_{s1}K$	$D^0\gamma$ yield	154 ± 13	493 ± 25
	$D^0\pi^0$ yield	335 ± 28	1071 ± 55
$B^0 \to D_{s1}K$	$D^0\gamma$ yield	95 ± 8	374 ± 15
	$D^0\pi^0$ yield	226 ± 20	856 ± 35
k		1.89 ± 0.24	
$\lvert\phi\rvert$ [rad]		1.81 ± 0.20	

Fit for control channel

- Signal: $B^0_{(s)} \to \bar{D}^0 K^+ K^-$ described by Two crystal balls, parameters from MC
- Combinatorial background: exponential
- Physical background: shapes from MC and weighted by Dalitz models, yields of some channel ($\Lambda_b^0/\Xi_b^0 \to D^0 pK/\pi$) constrained



$N_{B^0\to\bar{D}^0KK} = 2518 \pm 79$



$N_{B^0\to\bar{D}^0KK} = 7855 \pm 124$

Systematic uncertainty

- Efficiency-related systematic
  - generator-level efficiency: small difference between Gauss and RapidSim
  - simulated sample size: studied by toys based on uncertainties of efficiencies
  - PID efficiency: studied by toys from PIDCalib efficiency tables and alternative binning schema
  - L0 efficiency: use alternative method to compute L0 efficiency for signal
- Mass fit-related systematic
  - modeling of signal channel
  - modeling of control channel
  - branching fraction ratio $\mathcal{B}(D^{*0} \to D^0\pi^0)/\mathcal{B}(D^{*0} \to D^0\gamma)$
  - correlation between $m(D^0K^+)$ and $m(D^0K^+K^-)$
- External inputs
  - f_s/f_d

Results: branching fractions

[Phys. Rev. D98 072006 (2018)]

- The branching fraction of $B^0 \to \bar{D}^0 K^+ K^-$, $\mathcal{B}(B^0 \to \bar{D}^0 K^+ K^-) = (6.1 \pm 0.4 \pm 0.3 \pm 0.3)\times 10^{-5}$

$$\mathcal{B}\left(B^0 \to D_{s1}(2536)^{\mp} K^{\pm}\right)\times\mathcal{B}(D_{s1}^- \to \bar{D}^{*0}K^-) = \begin{cases} (0.53 \pm \boxed{0.05} \pm \boxed{0.10} \pm \boxed{0.05})\times 10^{-5} \text{ (Run 1)} \\ (0.506 \pm \boxed{0.023} \pm \boxed{0.031} \pm \boxed{0.050})\times 10^{-5} \text{ (Run 2)} \end{cases}$$

stat. syst. norm.

$$\mathcal{B}\left(B_s^0 \to D_{s1}(2536)^{\mp} K^{\pm}\right) \mathcal{B}(D_{s1}^- \to \bar{D}^{*0}K^-) = \begin{cases} (3.27 \pm \boxed{0.28} \pm \boxed{0.20} \pm \boxed{0.32} \pm \boxed{0.10})\times 10^{-5} \text{ (Run 1)} \\ (2.34 \pm \boxed{0.12} \pm \boxed{0.12} \pm \boxed{0.23} \pm \boxed{0.07})\times 10^{-5} \text{ (Run 2)} \end{cases}$$

stat. syst. norm. f_s/f_d

- Combine the Run 1&2 results according to the statistical uncertainties. As for systematic uncertainties, each source are combined first by correlation factor between Run 1&2, and then the different sources of systematic uncertainty are considered to be independent.

$$\mathcal{B}\left(B^0 \to D_{s1}(2536)^{\mp} K^{\pm}\right)\times\mathcal{B}(D_{s1}^- \to \bar{D}^{*0}K^-) = (0.510 \pm 0.021 \pm 0.040 \pm 0.050)\times 10^{-5}$$

stat. syst. norm.

$$\mathcal{B}\left(B_s^0 \to D_{s1}(2536)^{\mp} K^{\pm}\right)\times\mathcal{B}(D_{s1}^- \to \bar{D}^{*0}K^-) = (2.49 \pm 0.11 \pm 0.13 \pm 0.25 \pm 0.06)\times 10^{-5}$$

stat. syst. norm. f_s/f_d

Results: amplitude ratios

- The helicity coupling ratio of H_+ to H_0, $ke^{i\phi}$, is measured to be

$$\begin{aligned} k &= 1.89 \pm \underbrace{\boxed{0.24}}_{\text{stat.}} \pm \underbrace{\boxed{0.06}}_{\text{syst.}} \\ |\phi| &= 1.81 \pm \boxed{0.20} \pm \boxed{0.11}\ \mathrm{rad} \end{aligned}$$

- Converting to LS coupling, the ratio of S-wave over D-wave amplitudes, Ae^{iB}, is measured to be

$$\begin{aligned} A &= 1.11 \pm \underbrace{\boxed{0.15}}_{\text{stat.}} \pm \underbrace{\boxed{0.06}}_{\text{syst.}} \\ |B| &= 0.70 \pm \boxed{0.09} \pm \boxed{0.04}\ \mathrm{rad} \end{aligned}$$

- The fraction of S-wave component in $D_{s1}(2536)^+ \to D^{*0}K^+$ is $(55 \pm 7 \pm 3)\%$, consistent with its isospin partner $D_{s1}(2536)^+ \to D^{*+}K^0$, in which the S-wave fraction is $(72 \pm 5 \pm 1)\%$

[Phys. Rev. D77 032001 (2008)]

Summary

- First observation of $B^0_{(s)} \to D_{s1}K$ and measurement of their branching fraction

- First measured the helicity coupling ratio of D^{*0} in $D_{s1} \to D^{*0}K$ decay

- Prospect: more data will be collected after Run 3 and 4, time-dependent analysis would be possible then and γ angle can be measured via this $B^0_s \to D_{s1}K$ decay

Thank you!

Backup

Efficiency

$$\epsilon = \underbrace{\epsilon^{\text{geom}}}_{\text{geometrical acceptance}} \times \overbrace{\epsilon^{\text{RecSel|geom}}}^{\text{reconstruction\&selection efficiency}} \times \underbrace{\epsilon^{\text{PID|RecSel\&geom}}}_{\text{PID efficiency}} \times \overbrace{\epsilon^{\text{trig|PID\&RecSel\&geom}}}^{\text{trigger efficiency}}$$

- Efficiencies determined from angular weighted ($\omega_{010,100,\text{int}}$) MC, and calibrated by data
- Efficiencies from different years combined by the production cross-section of B mesons and integrated luminosities, Run1/2 separated

$$\epsilon_{\text{avg}} = \frac{\sum_i \mathcal{L}_i \sigma_i}{\sum_i \mathcal{L}_i \sigma_i / \epsilon_i}$$

Efficiency correction (cont.)

- Geometrical acceptance
  - acceptance requirements are applied to missing γ and π^0 in full simulation which introduces large bias
  - computed from RapidSim to save computational time: proved to be consistent with Gauss simulation, a small systematic has been assigned
- Reconstruction&selection efficiency
  - computed from MC samples after Stripping, initial cuts and MVA selections
- PID efficiency
  - computed from PIDCalib tool
- Trigger efficiency
  - from MC samples, and L0 TOS efficiencies are corrected by calibration data

Total efficiency

Total efficiency in 10^{-4}

	Run1	Run2
$B^0 \to D_{s1}K$, γ chain	17.17 ± 0.25	25.80 ± 0.20
$B^0 \to D_{s1}K$, π^0 chain	22.09 ± 0.30	32.21 ± 0.22
$B_s^0 \to D_{s1}K$, γ chain	18.70 ± 0.27	28.90 ± 0.21
$B_s^0 \to D_{s1}K$, π^0 chain	22.25 ± 0.30	34.37 ± 0.26
$B^0 \to \bar{D}^0 KK$	13.87 ± 0.07	15.81 ± 0.09