Branching fractions and CP asymmetries in B decays through $b \to c$ processes at Belle

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(On behalf of the Belle Collaboration)

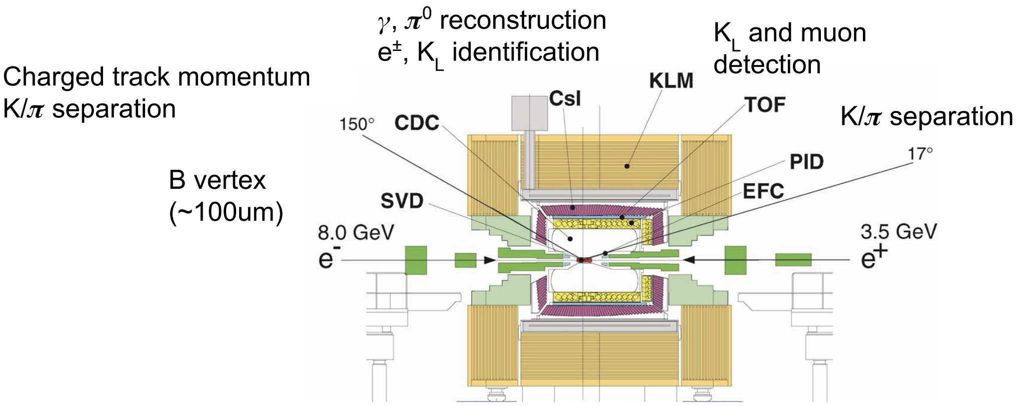
7th July, 2022

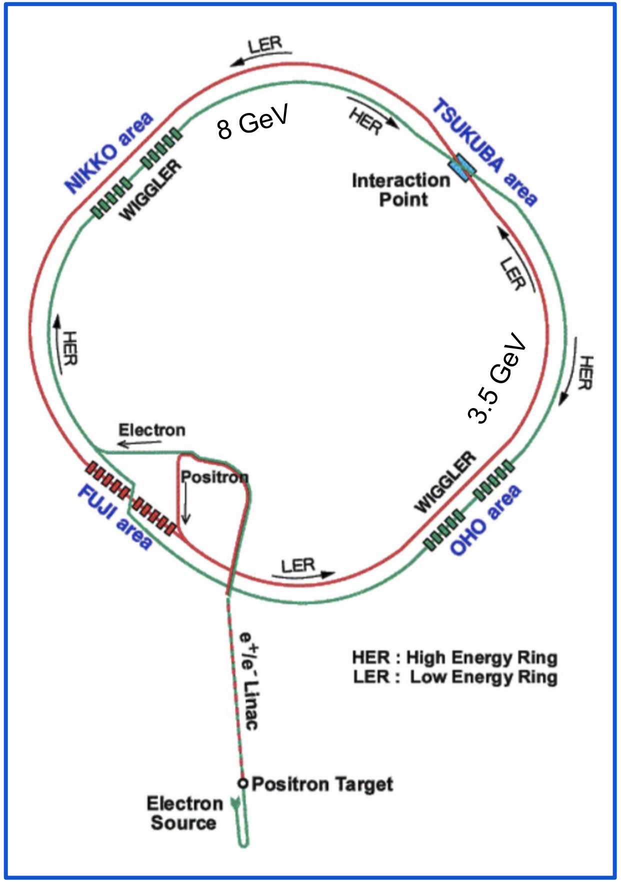
41st International Conference on High Energy Physics

The University of Melbourne

KEKB + Belle Detector

- Asymmetric e^+e^- collider, B factory, Tsukuba, Japan (1999-2010)
- 8 GeV electrons, 3.5 GeV positrons, CoM energy 10.58 GeV Y(4S) resonance
- Even split between B^+ and B^0 (1.058 ± 0.024, charged:neutral)
- Energy asymmetry leads to separation in B decay vertex
  - Allows for time dependent analyses
- Peak luminosity $2.1\times10^{34}\text{cm}^{-2}\text{s}^{-1}$, 711fb^{-1} of 772×10^6 B pairs

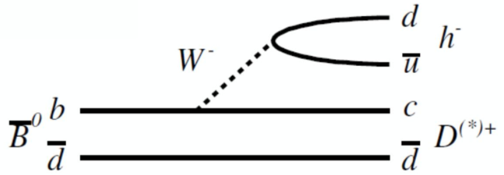




NON-LEPTONIC $b \longrightarrow c$ DECAYS

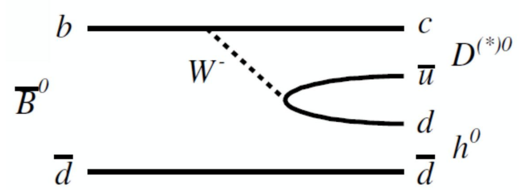
Two kinds of non-leptonic B^0 decays mediated by $b \to c$ transitions

Color-allowed



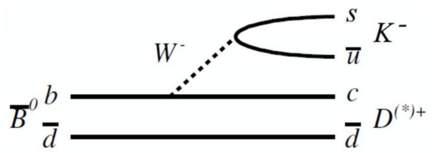
QCD factorization applicable

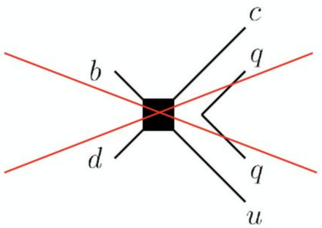
Color-suppressed



QCD factorizable **not** applicable

- Decays with four quark flavors are the simplest and cleanest non-leptonic $B_{(s)}$
  - No penguin or annihilation processes can contribute
- Focus on $B_s^0 \to D_s^{(*)-}\pi^+$ and $B^0 \to D^{(*)-}K^+$ to test QCD factorization





QCD factorization: systematic method to compute amplitudes in non-leptonic B decays in the heavy quark limit (leading power in Λ_{QCD}/m_b)

$$\mathcal{A}(\bar{B}^0 \to D^+K^-) \propto f_K F_0^{B\to D}(M_K^2)a_1(D^+K^-) + \mathcal{O}\left(\frac{\Lambda_{QCD}}{m_b}\right)$$

Improve theoretical predictions for $B_s^0 \to D_s^{*-}\pi^+$ and $B^0 \to D^{*-}K^+$ branching fractions

Discrepancy Between Measurement and Theory

source	PDG (x10^-3)	QCDF prediction	
$\mathcal{B}(\bar{B}_s^0 \to D_s^+ \pi^-)$	3.00 ± 0.23	4.42 ± 0.21	$\to 4\sigma$
$\mathcal{B}(\bar{B}^0 \to D^+ K^-)$	0.186 ± 0.020	0.326 ± 0.015	$\to 5\sigma$
$\mathcal{B}(\bar{B}_s^0 \to D_s^{*+} \pi^-)$	2.0 ± 0.5	$4.3^{+0.9}_{-0.8}$	$\to 2\sigma$
$\mathcal{B}(\bar{B}^0 \to D^{*+} K^-)$	0.212 ± 0.015	$0.327^{+0.039}_{-0.034}$	$\to 3\sigma$

- Large nonfactorizable contributions of *O*(15 - 20%) in the amplitude
  - Excluded by our estimate at 4.4σ level
- Experimental issues
  - Would imply problems in several (consistent) measurements (CLEO, BaBar, LHCb, Belle)
- Shift in the inputs (e.g. V_{ud}, V_{us}, V_{cb})
  - Probably violates unitarity of CKM matrix
- BSM physics only explanation left
- A combination of the above

$B^0 \to D^{*-}h^+ (h=K/\pi)$: Motivation

- $b \to cud$ and $b \to cus$ quark transition amplitudes (a_1) are calculated with NNLO QCD
- High precision QCD and SU(3) symmetry tests
- Prior measurements of $R_{K/\pi}$ agree with theory but have large statistical uncertainties
- Decay widths of $B \to D^*h$ can be estimated from their semileptonic counterpart

$$\Gamma(\bar{B}^0 \to D^{*+}h^-) = 6\pi^2 \tau_B |V_{uq}|^2 f_h^2 X_h |a_1(q^2)|^2 \times d\Gamma(\bar{B}^0 \to D^{*+}\ell^-\bar{\nu})/dq^2|_{q^2=m_h^2}$$

- Performing this study within a single experiment would cancel many systematic uncertainties

Previous results

Variable	Result	Collaboration	Year
$\mathcal{R}_{K/\pi}$	(7.76 ± 0.34 ± 0.26) x 10^{-2}	LHCb	2013
$\mathcal{B}[B^0 \to D^{*-}\pi^+]$	(2.79 ± 0.08 ± 0.17) x 10^{-3}	BaBar	2007
$\mathcal{B}[B^0 \to D^{*-}K^+]$	(2.13 ± 0.12 ± 0.10) x 10^{-4}	BaBar	2006

$B^0 \to D^{*-}h^+ (h=K/\pi)$: Analysis Strategy

- Full Belle dataset (772M B pairs)
- Only $D^{*-} \to D^0\pi^+$ is considered (channels with π^0 has large systematics)
- $D^0 \to K^-\pi^+$ and $D^0 \to K^-2\pi^+\pi^-$

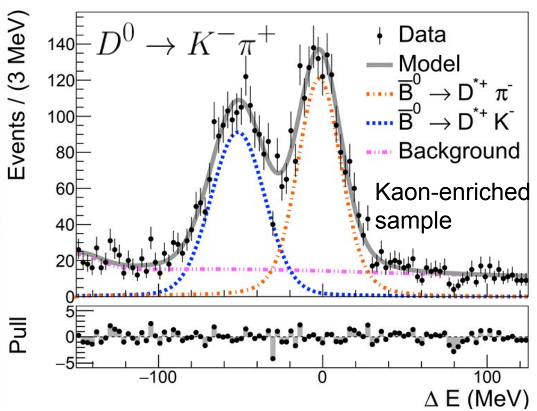
<u>Selection criteria:</u>

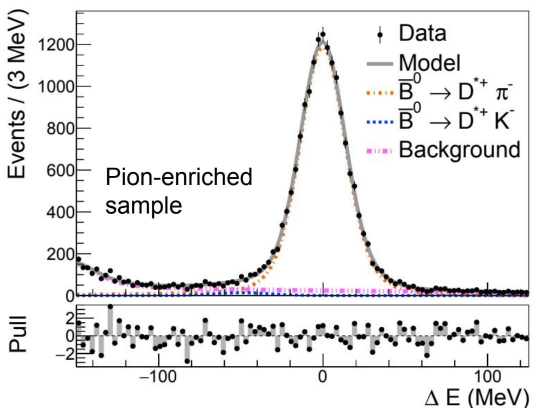
- $5.27 < M_{bc}(\mathrm{GeV}/c^2) < 5.29$
- $|\Delta E\ (\mathrm{GeV})| < 0.13$ (pion enhanced)
- $|\Delta E\ (\mathrm{GeV})| < 0.15$ (kaon enhanced)

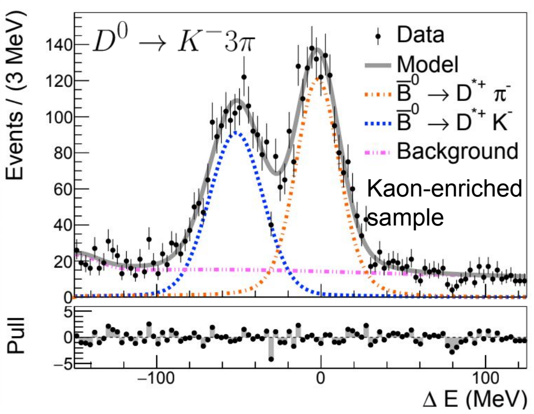
$$\Delta E = E_B - E_{\mathrm{beam}}$$
E_B = energy of B in CM frame
E_{beam} = half of beam energy
$$M_{bc} = \sqrt{E_{\mathrm{beam}}^2 - p_B^2}$$
p_B = momentum of B in CM frame

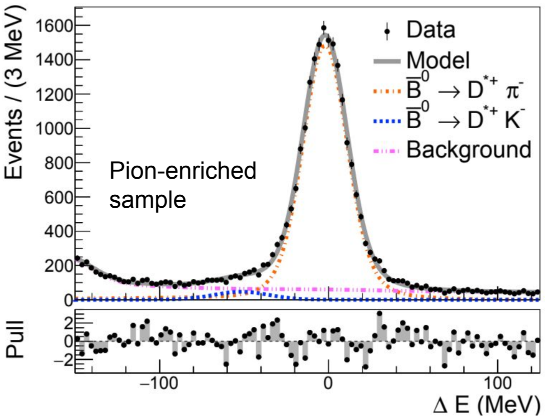
- Simultaneous UML fits to pion and kaon components in ΔE

π signal PDF = 2xGaussian + Crystal Ball
K signal PDF = Gaussian + Crystal Ball

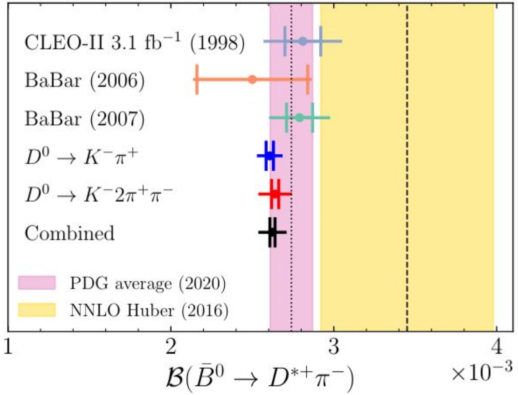


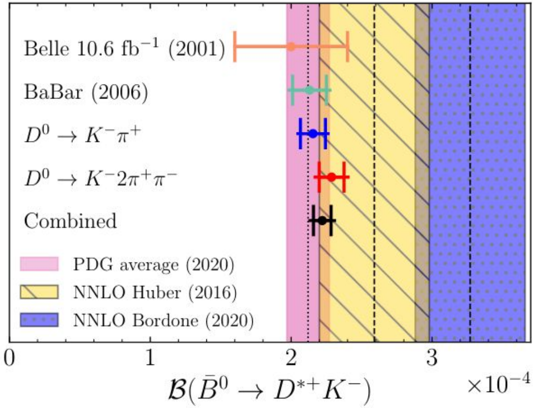


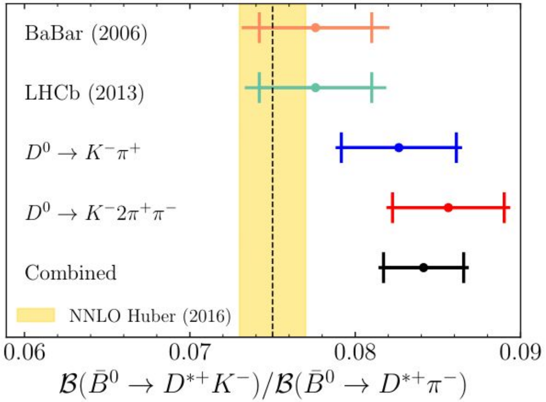




$B^0 \to D^{*-}h^+(h=K/\pi)$: Results







type	$\bar{B} \to D^{*+}\pi^-$	$\bar{B} \to D^{*+}K^-$
π-ID stat.	0.75% 0.58%†	0.32%
π-ID sys.	0.49% 0.41%†	0.19%
K-ID stat.	0.74%	1.04% 0.64%†
K-ID sys.	0.55%	0.89% 0.55%†
K-ID run dep. sys.	0.30%	0.30%
π_{slow} stat.	0.79%	0.79%
π_{slow} sys.	0.01%	0.01%
π_{slow} corr.	1.33%	1.33%
Tracking sys.	1.26%	1.26%
Fixed yields bkg. PDF	0.07%†	0.07%†
Fixed shapes bkg. PDF	0.07%†	0.07%†
Fit bias	0.09%†	0.37%†
$N_{\bar{B}^0 B^0}$	1.84%	1.84%
$\mathcal{B}(D^{*+} \to D^0\pi^+)$	0.74%	0.74%
$\mathcal{B}(D^0)$	0.94%	0.94%
MC stat.	0.26%†	0.99%†
Total sys. ($\mathcal{B}$)	3.26%	3.47%
Total sys. (ratio)	1.50%	1.50%
Total stat. err.	0.57%	2.74%

Table of uncertainties for B.F. values with † are propagated to R^D, otherwise cancelled

$\mathcal{B}(\bar{B}^0 \to D^{*+}\pi^-)$	Result	$n\sigma$ meas.−theo.
$D^0 \to K^-\pi^+$	$(2.607 \pm 0.023 \pm 0.083) \times 10^{-3}$	1.8
$D^0 \to K^-2\pi^+\pi^-$	$(2.640 \pm 0.022 \pm 0.101) \times 10^{-3}$	1.7
Combined	$(2.623 \pm 0.016 \pm 0.086) \times 10^{-3}$	1.7
$\mathcal{B}(\bar{B}^0 \to D^{*+}K^-)$		
$D^0 \to K^-\pi^+$	$(2.154 \pm 0.089 \pm 0.078) \times 10^{-4}$	1.1
$D^0 \to K^-2\pi^+\pi^-$	$(2.287 \pm 0.088 \pm 0.092) \times 10^{-4}$	0.7
Combined	$(2.221 \pm 0.063 \pm 0.077) \times 10^{-4}$	0.9
$\mathcal{R}_{K/\pi}$		
$D^0 \to K^-\pi^+$	$(8.26 \pm 0.35 \pm 0.16) \times 10^{-2}$	1.8
$D^0 \to K^-2\pi^+\pi^-$	$(8.56 \pm 0.34 \pm 0.16) \times 10^{-2}$	2.5
Combined	$(8.41 \pm 0.24 \pm 0.13) \times 10^{-2}$	2.7

BFs consistent with prior measurements. $R_{K/\pi}$ in tension with all prior values.

Additional QCDF test results found here
https://arxiv.org/abs/2207.00134

$B^0 \to D^- h^+ (h = K/\pi)$: Motivation

- Both modes are important → signal or control channels for measurements related to ϕ_3 angle
- $B^0 \to D^- K^+$ provide great opportunities to test hadronic B-meson decay theory → clean and dominant hadronic decay channel
- Improved measurements of the color-favored hadronic two-body decay of the B meson → better understanding of the QCD effects
- Branching fraction for the Cabibbo suppressed $B^0 \to D^- K^+$ is related to $B^0 \to D^- \pi^+$ by

Cabibbo angle

$$R^D \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^+ K^-)}{\mathcal{B}(\bar{B}^0 \to D^+ \pi^-)} \simeq \tan^2 \theta_C \left(\frac{f_K}{f_\pi}\right)^2 = 0.077 \pm 0.002$$

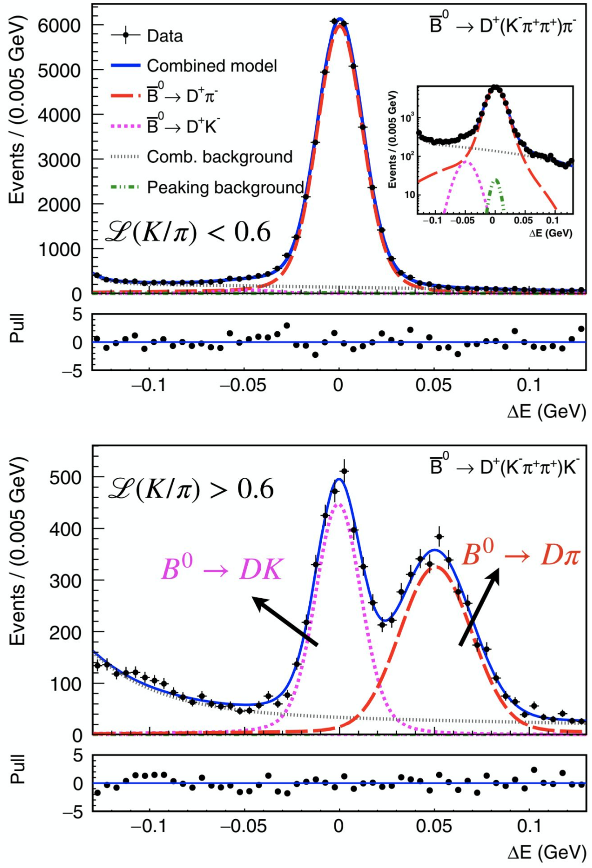
meson decay constants

J. High Energ. Phys. 2016, 112 (2016)

- Ratio of branching fraction measured systematic cancel out → important for the decays which are systematic limited
- Both decays have not been measured with full Belle data set

$B^0 \to D^- h^+ (h = K/\pi)$: Analysis Strategy

- Significant background from the $B^0 \to D^- \pi^+$ decays in $B^0 \to D^- K^+$ due to misidentification of pions as kaons
- A **simultaneous fit** is performed to samples enhanced in prompt tracks that are either **pions** [$\mathscr{L}(K/\pi) < 0.6$] or **kaons** [$\mathscr{L}(K/\pi) > 0.6$]
- Selection criteria are similar to $B^0 \to D^{*-} h^+$ except with a D mass window of ~13MeV/c^2
- Cross-feed from both decay modes is also determined from the simultaneous fit
- Due to the low yield of $B^0 \to D^- K^+$ cross-feed to the pion-enhanced sample, the kaon identification efficiency ϵ_K is fixed
- Un-binned maximum likelihood fit is performed to extract the signal yield by fitting the ΔE distribution simultaneously in $B^0 \to D^- \pi^+$ and $B^0 \to D^- K^+$ samples



$B^0 \to D^- h^+ (h = K/\pi)$: Results

Phys. Rev. D105, 012003

$$R^D \equiv \frac{\mathcal{B}(\bar{B}^0 \to D^+ K^-)}{\mathcal{B}(\bar{B}^0 \to D^+ \pi^-)} = [8.19 \pm 0.20(\text{stat}) \pm 0.23(\text{syst})] \times 10^{-2}$$

$$\mathcal{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+] = [2.48 \pm 0.01_{\text{stat}} \pm 0.09_{\text{syst}} \pm 0.04_{\mathcal{B}(D^- \to K^+\pi^-\pi^-)}] \times 10^{-3}$$

$$\mathcal{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)K^+] = [2.03 \pm 0.05_{\text{stat}} \pm 0.07_{\text{syst}} \pm 0.03_{\mathcal{B}(D^- \to K^+\pi^-\pi^-)}] \times 10^{-4}$$

Source	R^D	$\mathcal{B}(\overline{B}^0 \to D^+\pi^-)$	$\mathcal{B}(\overline{B}^0 \to D^+K^-)$
$\mathcal{B}(D^+ \to K^-\pi^+\pi^+)$	–	1.71%	1.71%
Tracking	–	1.40%	1.40%
$N_{B\overline{B}}$	–	1.37%	1.37%
f^{00}/f^{+-}	–	1.92%	1.92%
$D^+ \to K^-\pi^+\pi^+$ model	–	0.69%	0.69%
PDF parametrization	2.71%	1.63%	1.79%
PID efficiency of K/π	0.88%	0.68%	0.73%
D^+ mass selection window	0.05%	0.56%	0.64%
J/ψ veto selection	0.12%	0.004%	0.15%
Peaking background yield	0.07%	0.04%	0.00%
MC statistics	< 0.01	0.04%	0.04%
Fit bias	–	0.58%	0.61%
Total	2.85%	3.43%	3.54%

Main source of uncancelled uncertainty is in K/π identification efficiency

Results consistent with previous measurements
Remains in tension with theory

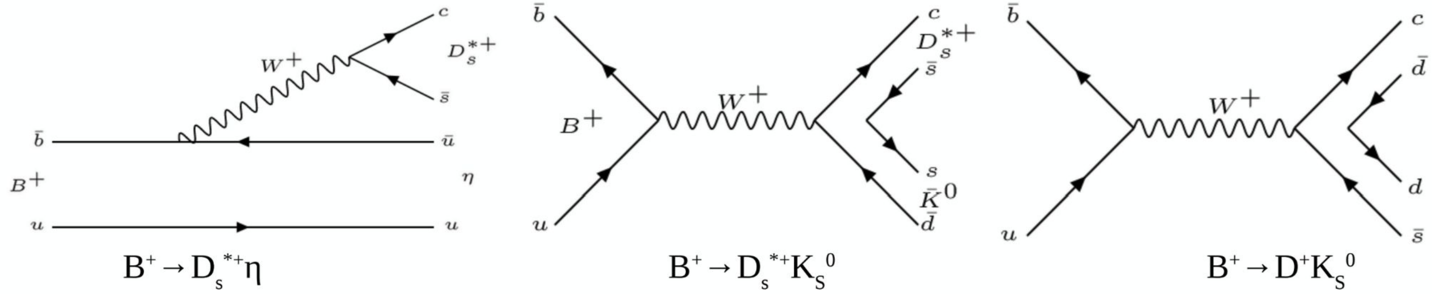
Previous results

Variable	Result	Collaboration	Year
$\mathcal{R}^D$	(8.22 ± 0.11 ± 0.25) x 10^{-2}	LHCb	2013
$\mathcal{B}[B^0 \to D^-\pi^+]$	(2.55 ± 0.05 ± 0.16) x 10^{-3}	BaBar	2007
$\mathcal{B}[B^0 \to D^-K^+]$	(1.89 ± 0.19 ± 0.10) x 10^{-4}	LHCb	2011

$B^+ \to D^+ (K_S^0/\eta), D_s^{*+} (K_S^0/\eta)$: Physics Motivation

First presentation of results

- Study of rare *B* decays probes CKM matrix unitarity conditions in search of NP
- Studies of $b \to u$ quark level transition improve understanding of internal dynamics of *B* mesons
- Charged *B* decays are expected to be dominated by weak-annihilation diagrams
- These decay modes are poorly measured



Decay Mode	BF(x10^{-4})	Collaboration	Reference
$B^+ \to D_s^{(*)+} K_S^0$	< 9	CLEO	Alexander, Phys. Lett. B319 (1993)
$B^+ \to D_s^{(*)+} \eta$	< 6	CLEO	Alexander, Phys. Lett. B319 (1993)
$B^+ \to D^+ K_S^0$	< 0.05	BaBar	Aubert, Phys. Rev. D72 (2005) 011102
$B^+ \to D^+ \eta$	-	-	-

$B^+ \to D^+ (K_S^0/\eta), D_s^{*+} (K_S^0/\eta)$: Analysis Strategy

- 1D UML fit in ΔE to extract yields

Reconstructed D channels:

$$D_s^{*+} \to D_s^+ \gamma$$

$$D_s^+ \to \phi\pi^+, \bar{K}^{*0}K^+, K_S^0 K^+$$

$$D^+ \to K^-\pi^+\pi^+, K_S^0\pi^+$$

Selection criteria:

- M_{bc} > 5.20 GeV/c^2
- $|\Delta E$ (GeV)$| < 0.18$
- Vertex fit (KFitter)

Control mode for η modes:

$$\bar{B}^0 \to D^0 \eta$$

Control mode for K_S modes:

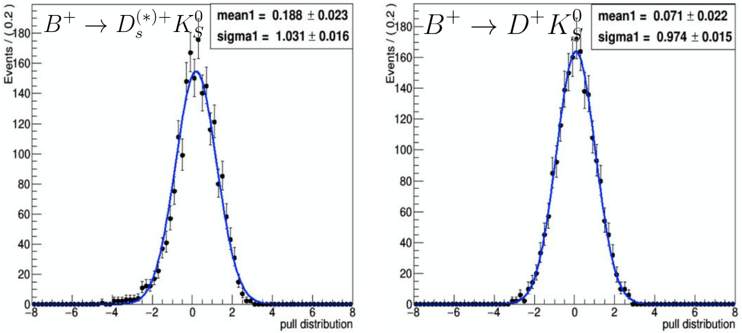
$$\bar{B}^0 \to D^0 K_S^0$$

- Best candidate minimises the following:

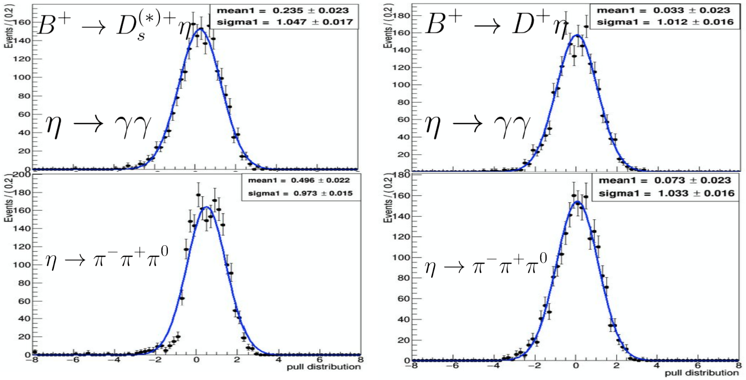
$$\chi^2 = \left(\frac{M_{D_s} - m_{D_s}^{PDG}}{\sigma_{D_s}}\right)^2 + \left(\frac{M_{bc} - m_B^{PDG}}{\sigma_{M_{bc}}}\right)^2$$

- Continuum suppression done with a trained FastBDT using 7 distinguishing variables

Signal Pulls



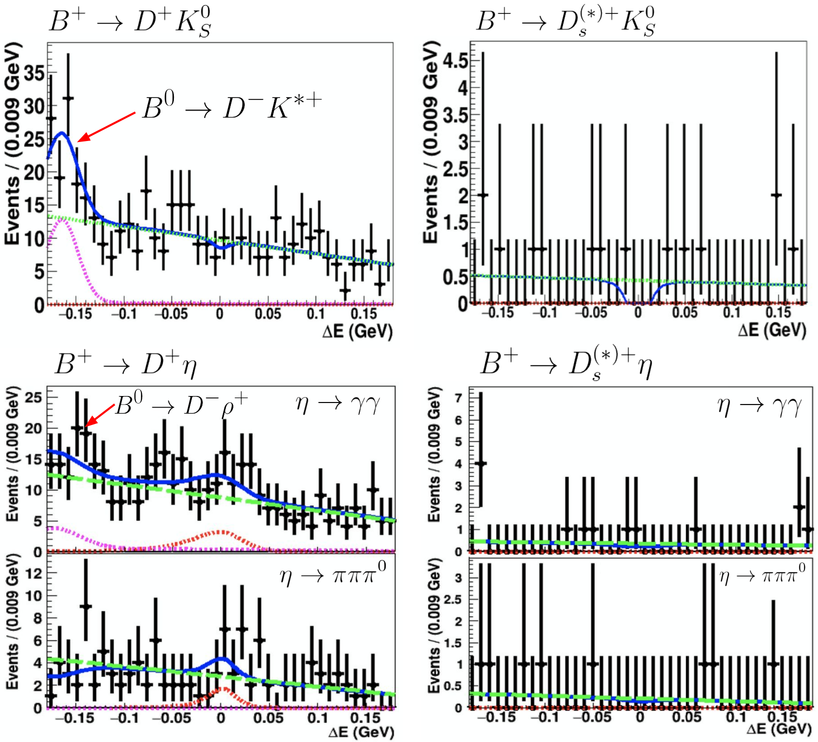
Simultaneous fit to $\eta \to \gamma\gamma$ and $\eta \to \pi\pi\pi$ for decays involving η



$B^+ \to D^+ (K_S^0/\eta), D_s^{*+} (K_S^0/\eta)$: Results

Decay Mode	Yield @ 90% CL	BF(x10^{-5}) @ 90% CL
$B^+ \to D_s^{(*)+} K_S^0$	1.8	0.6
$B^+ \to D_s^{(*)+} \eta$	5.5	1.7
$B^+ \to D^+ K_S^0$	8	0.2
$B^+ \to D^+ \eta$	42	1.2

Source	$B^+ \to D_s^{(*)+} K_S^0$	$B^+ \to D_s^{(*)+} \eta$	$B^+ \to D^+ K_S^0$	$B^+ \to D^+ \eta$
π ID	0.8%	1.4%	0.7%	1.2%
K ID	1.3%	2.0%	0.4%	0.6%
Tracking	1.8%	1.2%	1.8%	1.2%
$N_{B\bar{B}}$	1.4%	1.4%	1.4%	1.4%
K_s^0 reconstruction	0.5%	0.4%	0.5%	0.3%
η detection	-	2.1%	-	2.1%
Secondary BF	2.1%	2.2%	1.5%	1.6%
ΔE fit	-	-	-	9.7%, 12.1%
Total sys.	3.5%	4.3%	2.9%	10.3%, 12.6%



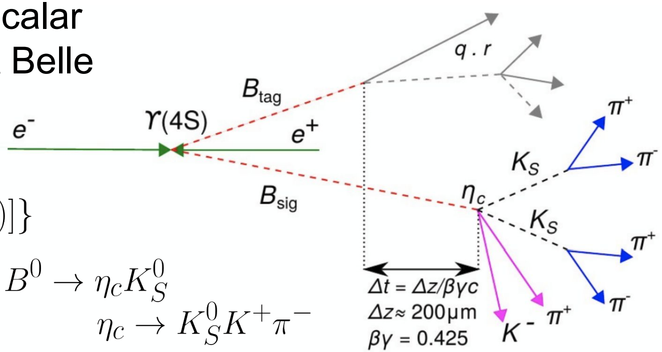
BF upper limit at 90% CL are 20x tighter than previous result

Time-Dependent CPV in $B^0 \to \eta_c K_S$: Physics Motivation

First presentation of results

- Color-suppressed ***CP***-odd final state: like the *golden channel* $B^0 \to J/\Psi\, K_S$, but η_c is a pseudoscalar
- Time-dependent ***CP***-violation at Belle

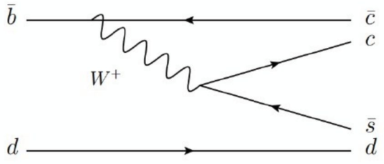
$$\mathcal{P}(\Delta t, q) = \frac{e^{-|\Delta t|/\tau_{B^0}}}{4\tau_{B^0}} \times \{1 + q \times [\mathcal{S}\sin(\Delta m_d \Delta t) + \mathcal{A}\cos(\Delta m_d \Delta t)]\}$$



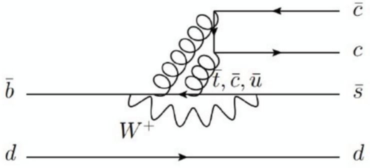
$$B^0 \to \eta_c K_S^0$$
$$\eta_c \to K_S^0 K^+ \pi^-$$
$$K_S^0 \to \pi^+ \pi^-$$

- SM predicts for all charmonia

S = sin 2φ_1
A = 0



tree-dominated



penguin pollution negligible

WA: $\sin 2\phi_1 = 0.699 \pm 0.017$

Previous measurements for $B^0 \to \eta_c K_S$

Belle (151M *B* pairs):

$$\mathcal{S}_{\eta_c K_S^0} = 1.126^{+0.27}_{-0.39} \pm 0.06_{\rm syst}$$

BaBar (465M *B* pairs) [2]:

$$\mathcal{S}_{\eta_c K_S^0} = 0.925^{+0.160}_{-0.160} \pm 0.057_{\rm syst}$$
$$\mathcal{A}_{\eta_c K_S^0} = -0.080^{+0.124}_{-0.124} \pm 0.029_{\rm syst}$$

Belle (772M *B* pairs): ???

- Inconsistency of *S* among vector and pseudoscalar (or axial vector) charmonia can be sign of NP [1]
- No Belle measurement at full integrated luminosity

[1] D. Atwood and G. Hiller (2003), hep-ph/0307251
[2] B. Aubert *et al.* [BaBar], Phys. Rev. D**79**, 072009 (2009)

$B^0 \to \eta_c K_s$: Analysis Strategy

Multi-dimensional extended unbinned maximum likelihood fit in

r-bin (tagging quality category index)

$$\Delta E \times M \equiv M(K_S^0 K^+ \pi^-) \times \Delta t \times q \times l$$

B_{tag} flavor (±1)

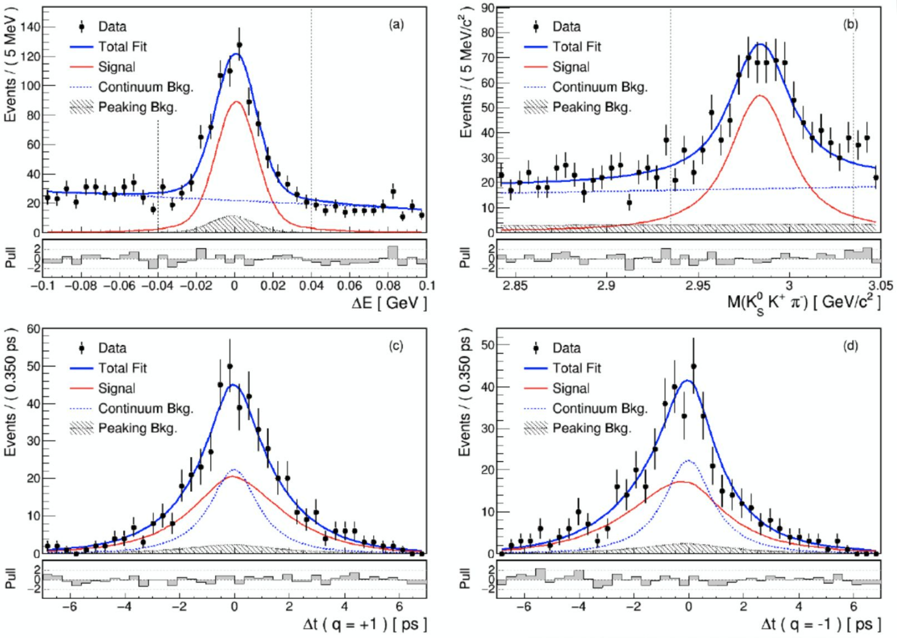
- M_{bc} for best B-candidate selection

Background parameters estimated from data (M_{bc} or M sideband)

Peaking background (~20% of signal)

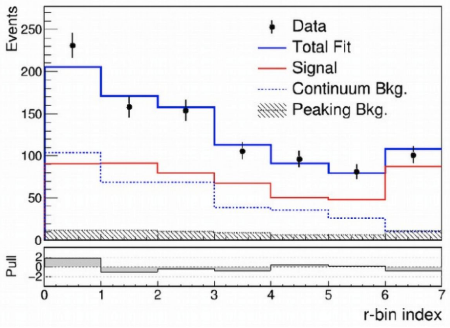
- b → c and b → s induced decays
- Includes non-resonant background → (significant) interference effects estimated in a dedicated study (ignored in data model → systematics)

Simultaneous fit for CPV parameters, signal and background yields and peaking bkg. fraction



Control and calibration mode:

$$B^{\pm} \to \eta_c K^{\pm}$$



Belle

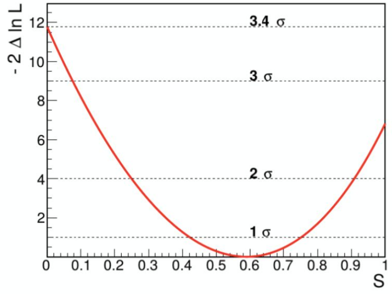
$$\boxed{\mathcal{S} = 0.59 \pm 0.17 \pm 0.07}$$

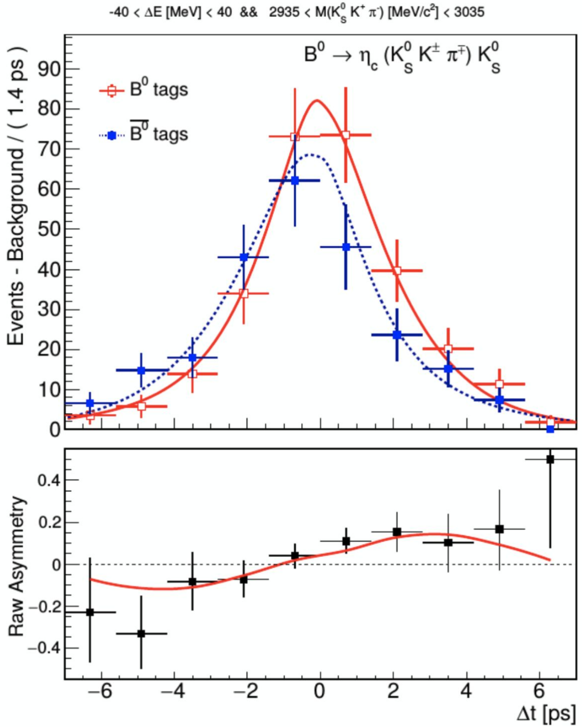
Preliminary

$$\mathcal{A} = 0.16 \pm 0.12 \pm 0.06$$

$$\mathcal{B} = (9.8 \pm 0.6 \pm 0.4 \pm 2.3_{\mathrm{int}}) \times 10^{-6}$$

$$\mathcal{B}(B^0 \to \eta_c K_S^0) \times \mathcal{B}(\eta_c \to K_S^0 K^{\pm} \pi^{\mp})$$





Systematics due to interference with non-resonant background (from interference study)

Major systematic uncertainties:

Source	$\delta\mathcal{S}$ $[10^{-2}]$	$\delta\mathcal{A}$ $[10^{-2}]$	$\delta\mathcal{B}$ [%]
Peaking bkg. *CP*-V	5.00	1.90	–
Punzi effect	2.70	1.20	0.82
η_c lineshape	2.30	0.80	–
Tag-side interference	0.70	3.30	–
$\mathcal{R}_{B\overline{B}}$	1.50	3.38	0.47
Fit model parameters	0.43	1.64	2.47

...

- Results consistent with SM and other charmonia (agreement with SM improves with BaBar+Belle)

Conclusion

Most precise measurements
$R_{K/\pi}$ is 2.7σ from theory

$$B^0 \to D^{*-}h^+ : \mathcal{B}(B^0 \to D^{*-}\pi^+) = (2.623 \pm 0.016 \pm 0.086) \times 10^{-3}$$
$$\mathcal{B}(B^0 \to D^{*-}K^+) = (2.221 \pm 0.063 \pm 0.077) \times 10^{-4}$$
$$R_{K/\pi} = (8.41 \pm 0.24 \pm 0.13) \times 10^{-2}$$

J. Krohn, D. Ferlewicz et al. (Belle) arxiv 2207.00134

Most precise measurements
Important test of Factorization
Needed for ϕ_3

$$B^0 \to D^{-}h^+ : \mathcal{B}(B^0 \to D^{-}\pi^+) = (2.48 \pm 0.01 \pm 0.09 \pm 0.04) \times 10^{-3}$$
$$\mathcal{B}(B^0 \to D^{-}K^+) = (2.03 \pm 0.05 \pm 0.07 \pm 0.03) \times 10^{-4}$$
$$R^D = (8.19 \pm 0.20 \pm 0.23 \pm 0.03) \times 10^{-2}$$

E. Waheed et al. (Belle) PRD 105, 012003 (2022)

Most precise measurements of rare BF by 20x
First measurement of $B^+ \to D^+\eta$

$$B^+ \to D_s^{*+}(K_S^0/\eta) : \mathcal{B}(B^+ \to D_s^{*+}K_S^0) < 0.6 \times 10^{-5}$$
$$\mathcal{B}(B^+ \to D_s^{*+}\eta) < 1.7 \times 10^{-5}$$
$$B^+ \to D^{+}(K_S^0/\eta) : \mathcal{B}(B^+ \to D^{+}K_S^0) < 0.2 \times 10^{-5}$$
$$\mathcal{B}(B^+ \to D^{+}\eta) < 1.2 \times 10^{-5}$$

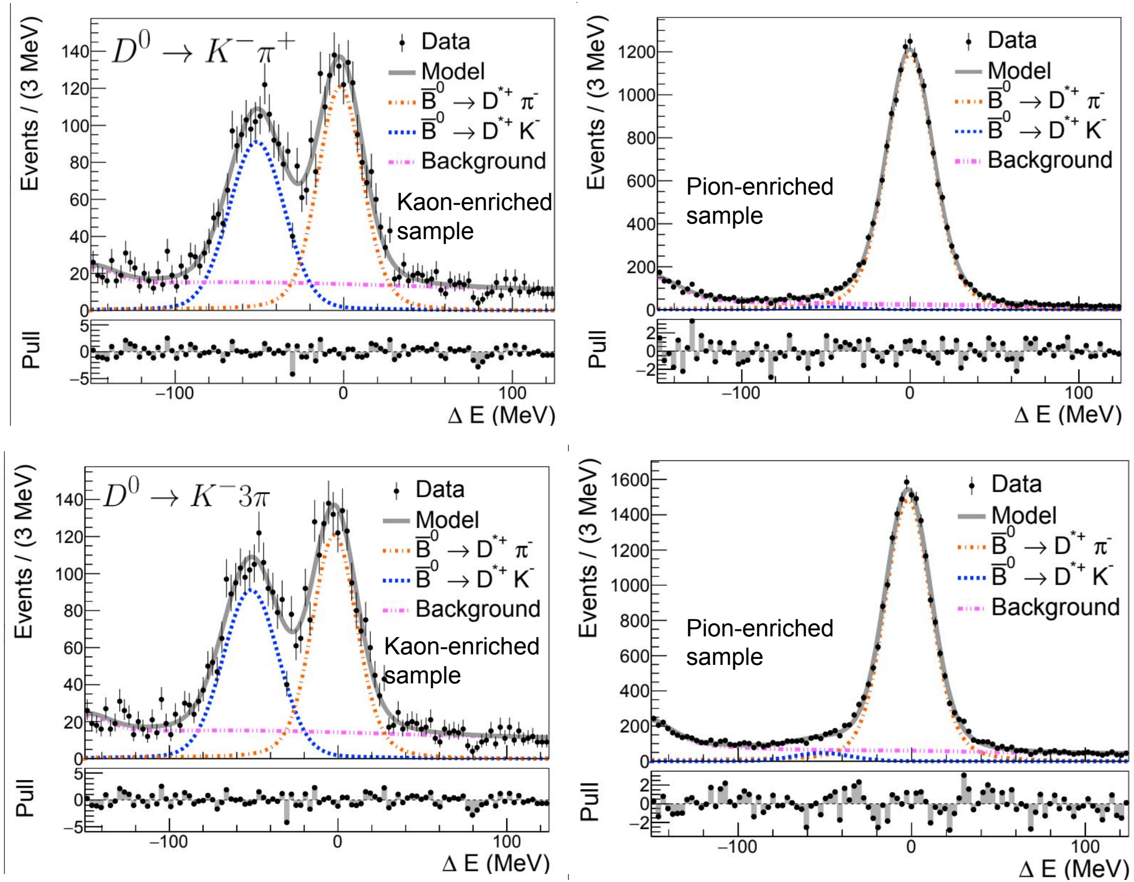
First presentation of results
Preliminary
Planned journal submission

First measurement of $\sin 2\phi_1$ with full Belle dataset

$$B^0 \to \eta_c K_S^0 : \mathcal{S} = 0.59 \pm 0.17 \pm 0.07$$
$$\mathcal{A} = 0.16 \pm 0.12 \pm 0.06$$
$$\mathcal{B} = (9.8 \pm 0.6 \pm 0.4 \pm 2.3) \times 10^{-6}$$

First presentation of results
Preliminary
Planned journal submission

Thank You!

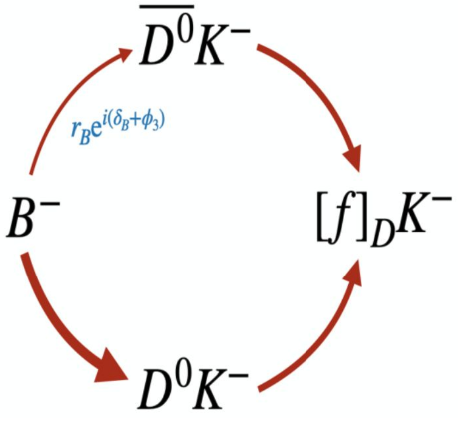


$D^0 \to K^- \pi^+$
Data
Model
$\overline{B}^0 \to D^{*+} \pi^-$
$\overline{B}^0 \to D^{*+} K^-$
Background
Kaon-enriched sample
Pion-enriched sample
$D^0 \to K^- 3\pi$
Events / (3 MeV)
Pull
Δ E (MeV)

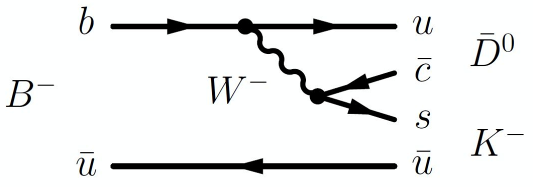
Theory Background

ϕ_3 is the phase arising from the quark transitions $b \to u$ and $b \to c$ with the theoretically cleanest being $B \to DK$

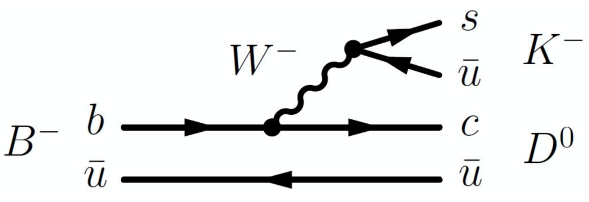
- *D* decaying to common final state → interference between both paths
- The level of interference and its exact interpretation depend on the physics of *B* and *D* decays
- Direct observation of CPV is limited by small statistics from small branching fractions



Suppressed



Favored



$$\frac{\mathcal{A}^{\text{suppr}}(B^- \to \bar{D}^0 K^-)}{\mathcal{A}^{\text{favor}}(B^- \to D^0 K^-)} = r_B e^{i(\delta_B+\phi_3)}$$

QCD Factorization

QCD factorization: systematic method to compute amplitudes in non-leptonic *B* decays in the heavy quark limit (leading power in Λ_{QCD}/m_b)

$$\mathcal{A}(\bar{B}^0 \to D^+K^-) \propto f_K F_0^{B\to D}(M_K^2) a_1(D^+K^-) + \mathcal{O}\left(\frac{\Lambda_{QCD}}{m_b}\right)$$

Improve theoretical predictions for $B_s^0 \to D_s^{*-}\pi^+$ and $B^0 \to D^{*-}K^+$ branching fractions

- Wilson coefficients a_1 computed at NNLO [Huber/Krank/Li 2016]
- Update $B \to D^*$ and $B_s \to D^*_s$ form factors [Bordone/NG/Jung/van Dyk 2019]
- Estimate Λ_{QCD}/m_b corrections for the first time [Bordone/NG/Huber/Jung/van Dyk 2020]