QCD factorization tests with $\bar{B}^0 \rightarrow D^+h^-(K/\pi)$ and $B \to \bar{D}^0 \pi$ decays at Belle

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JAPAN SOCIETY FOR THE PROMOTION OF SCIENCE

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Test of Factorization in B decays

- Non-leptonic weak decays of B mesons play an excellent role to explore flavor physics and strong interactions.
- Factorization \rightarrow estimate matrix element of four-quark operators through the product of the matrix elements of corresponding quark currents.
- Factorization works well in $\overline{B}^0 \to D^{(*)+}K^-$ decays
 - Contributions from color-allowed (tree level) topologies as $\bar{B}^0 \to D^{(*)+}\pi^-$.
- $\bar{B}^0 \to D^{(*)+}\pi^-$ amplitude can be probed in three ways
 - Comparing the hadronic branching fractions to the semi-leptonic decay rates \rightarrow calculating $|a_1|$ (Results from Belle coming soon)
 - Ratios of branching fractions governed by the color-allowed and colorsuppressed amplitudes \rightarrow calculating Ratio = $\frac{\mathcal{B}(B^0 \rightarrow D^{(*)} - K^+)}{\mathcal{B}(B^0 - B^{(*)})}$
 - probing decays amplitude directly through the branching fractions of decays.





Study of $\bar{B}^0 \to D^+h^-(h = K/\pi)$

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

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

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





 θ_c is Cabibbo angle, and f_K and f_{π} are meson decay constants.



The Belle Experiment

1999 – 2010: Belle B factory at KEK

KEKB double ring e⁺e⁻ collider

e⁺e⁻ → Y(4S) → BB

Belle detector

- 3.5 GeV positrons on 8 GeV electrons
- E_{cm} = 10.58 GeV,





The Belle Detector

- K/π identification is carried out by the information from independent measurement from
 - dE/dx measurement by CDC
 - TOF measurement
 - Measurement of number of photo electrons in ACC









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

- Analysis with full Belle data set of 711fb⁻¹
- Decay Chain: $B^0 \to D^-(\to K^+\pi^-\pi^-)K^+$ and $B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+$
- Both modes are topologically very similar therefore same event selection criteria is applied \rightarrow minimize efficiency differences between the modes.
- High momentum particle identification capability of the Belle detector enables us to extract signals for $B^0 \to D^- K^+$ that are well separated from the more abundant, Cabibbo favored $B^0 \to D^- \pi^+$ processes.

Variable
Prompt K^+
Prompt π^+
$D^-(\to K^+\pi^-\pi^-)$ mass
$M_{\rm bc} = \sqrt{E_{beam}^2 - p_B^*}$
$\Delta E = E_B^* - E_{beam}$
p_D^*
Fox–Wolfram Moment R_2









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meg the reconstruction quality of poor to ex-For charge lidates. We retain Bragicandidates that show assignment tral chersy derate a (that Ositions and all charged particles with momentant le refat Malssfownsattansed planse and the theo alter for carrenter for tata of the Geralsconsentents in company mass squared, pain Weam-effergy allows decays toppology flavor 2 bightum of the B_{tailed} dates are required to have a mass \overline{w} ndificates to have at least a beam-constrained which have at least a beam-constrained which have at least a beam-constrained $\approx m_{\nu}^2 \approx 0 \,\mathrm{GeV}^2$. correctly reconstructed semileptonic $B \rightarrow$ $B_2 \rightarrow X_c \mathcal{P}^{\sharp}_{(s)} \mathcal{V}_{\mathcal{R}}^{\mathfrak{g}} decays in Free Pateronic mass of the$ (11)bc $E_{\text{prime}} = 10^{-35}$ $E_{\text{prime}} = 1$ decays from $\frac{1}{2}$ and $\frac{1}{2}$ and other remaining back-be pions. With the X system reconstructed, vork we can also reconstruct the missing mass squared, enoting the moment Prostille Backage inhote etterof-mass frame of \underline{a}_{2060} he colliding e^+e^- -pair. the prect probability, /2 ettonotag half the set ofythe the colliding e^+e^- -pair. The energy dif In addition, we the four promentum trained tion correctly squared, q^2 , as e re-500 ormula is used in the full reconstruction agon this described in the next $B \to X_c$ in to calculate the signal probability for Q odes with low purity so that the tem is fraction had to be increased for the network transing. p_X used in the input layer of the neural network, decays, t etfinanst Reconst the inconstantion in the Bry B graunds, 1.845.1.85 1.855 1.86 1.865 1.87 1.87 e care of the thousands of exclusive decay. channels individually, Instead for a construction approach was chosen. We divide the reconstruction and 4 stages, where a physical approach are the reconstruction and 4 stages, where a divide the reconstruction and 4 stages, where a divide the reconstruction are 0.47 C 1.6 →D ev → D^{**} →

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$$B_{\text{tag}}$$
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Prelimin
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ged lep Kstrions. The fraurenconsistency calculated
Charged Tracks Neutral Clusters
(14), $(2\sqrt{5}\pi_{\odot}^{2}f^{+}tHe_{i}t^{2}te_{i}the_{i}te_{j})$, (E_{j}, \mathbf{k}_{j}) , (13)
it hin $(2\sqrt{5}\pi_{\odot}^{2}f^{+}tHe_{i}t^{2}te_{i}the_{i}te_{j})$ and (E_{j}, \mathbf{k}_{j}) , (13)
for

(15)
$$M_{\text{miss}}^2 = \left(p_{\text{sig}} - p_X \overline{Mass}\right)^2 \text{resolution is}^{(14)} \text{MeV}$$

Again peak at zero, $M_{\text{miss}}^2 \approx m_{\nu}^2 \approx 0 \text{ GeV}^2$, for
v reconstructed semileptonic $B \to X_u \ell^+ \nu_\ell$ and
 $\ell^+ \nu_\ell \text{ decays}$. The hadronic mass of the X sys-
ategy used to discriminate $B \to X_u \ell^+ \nu_\ell$ signal
 $\mu_\ell \oplus K_{\ell^+} \oplus K_{\ell^+} \to \ell^+$ and other remaining back-
 $M_{\ell^+} = 0$ and other remaining back-
 $M_{\ell^+} = 0$ and $M_{\ell^+} = 0$ (15)
 $M_{\ell^+} = 0$ for $M_{\ell^+} =$



CIUS_III_COMDILIATION PAS The hadronic X system is reconstructed the center of mass frament based on these two outputs in beam of the contract of the contract beam of the contract of the cont Ppart id suthand gral/side and demai Bruman $and and a ferminate [1].05, 3\pi 15] (PeV, Pi$ as energy of the comains e^-e^- -pair. The energy of the constrained in the energy of the decay constituents inscorption estimation is which are should be also be the energy of the decay constituents inscorption estimation is which are should be also b nd four-momentum of the B_{tEg} candid \mathfrak{A}_{eon} We Bethind as the structure of the s and and and the input layer of the neilealt network ates deverse from Band Roand Roand Band Book and the signal side ained The hike like like the many structure of the stand notes the spergy of the Bill preside the second of the sec mass flame an she was the provide the providence of the providenc sing let Betag departing the in the new ofd heads and different the contract of the contract o hich should peak at zero, $M_{\rm r}$ Borthermorall $E_{\text{Facks}} = and s$ cluster stability of the construction of the signal stability of the next $B \to X_c \overline{\ell} + \mathcal{U}_{\ell}$ decays. The had mass of gnal fraction had to be increased for the network transport of the state of the first of the network transport of enanceide. is already used in the final stage of the reconstruction of the neural one transfer of the frequency of the stage of the reconstruction of the first of the firs lenotes the nerzy) of the <u>B</u> Kandida Citer of the property of the structure of the structu $M_{\text{mass}} = (p_{\text{sign}} + p_{\text{sign}} +$ rendrate via All tracks and clusters not dised in the re-onstruction of the B_{tag} candidate are used to define the section to calculate and section to calculate and share the part of the part of the part of the part $B \xrightarrow{0.8}$ $X_c \ell^+ \nu_\ell$ decays. The has side. signal fraction had tosbeling see for the Idneore one inesolution is determines later used to discrimin

 $m_{D}^{2} + |\mathbf{n}_{\perp}|^{2} |\mathbf{n}_{\perp}|^{2}$



Fit Strategy to Extract Ratio $\equiv R^D = \frac{\bar{B}^0 \to D^+ K^-}{\bar{B}^0 \to D^+ \pi^-}$

- Significant background from $\bar{B}^0 \to D^+\pi^-$ decays in \bar{B} due to the misidentification of pion as a kaon.
- A simultaneous fit is performed to samples enhance prompt tracks that are either **pions** [$\mathscr{L}(K/\pi) < 0.6$] o $[\mathscr{L}(K/\pi) > 0.6]$
- Cross-feed from both decay modes is also determin the simultaneous fit.
- Due to the low yield of $\bar{B}^0 \to D^+ K^-$ cross feed to the 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 $\Delta E = E_R^* - E_{beam}$ distribution simultaneously in $\bar{B}^0 \to D^+\pi^-$ and $\bar{B}^0 \to D^+K^-$ samples.



$\bar{B}^0 \to D^+ K^-$	$N_{\text{pion enhanced}}^{D^+\pi^-} = (1 - \kappa) N_{\text{total}}^{D^+\pi^-}$
	$N_{\text{pion enhanced}}^{D^+K^-} = (1 - \epsilon_K) R^D \Lambda$
ed in or kaons	$N_{\text{kaon enhanced}}^{D^+K^-} = \epsilon_K R^D N_{\text{total}}^{D^+\pi^-}$
	$N_{\text{kaon enhanced}}^{D^+\pi^-} = \kappa N_{\text{total}}^{D^+\pi^-}$
led from	Fix in fit
	Floating in fit
e pion-	• $N_{\text{total}}^{D^+\pi^-}$ is the total yield in both decays.

- $\bullet \epsilon_K$ is kaon identification efficiency
- $\star \kappa$ is pion misidentification rate/pion fake rate
- \bullet R^D is the ratio

From Belle official PID system



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he Benergen didates to have at least a beam-constrained $M_{\rm miss}^2 \approx m_{\nu}^2 \approx 0 \,{\rm GeV}^2$, for correctly regainstructed semileptonic Belle (preliminar Vall charge hans har in sed endinence to be pions. With the Bransvetensore con the inence backwork decays from B Andre V structure alsolation structure in the structure of the st idate inheheen the colliding e^+e^- -pair. patrighten beam and the propa of the other half the centor of ed $acos field for even the colliding <math>e_2^+e^+$ -pair. Back for the result of the colliding $e_2^+e^+$ -pair. Back for the result of the colliding $e_2^+e^+$ -pair. Back for the result of the colliding $e_2^+e^+$ -pair. Back for the result of the colliding $e_2^+e^+$ -pair. Back for the result of the colliding $e_2^+e^+$ -pair. Back for the result of the colliding $e_2^+e^+$ -pair. Back for the result of the colliding $e_2^+e^+$ -pair. Back for the colliding $e_2^+e^+$ -pair. Bac Rentingenansistertioneak at zerofion nive reconstruct the four not compared if the operative date is the property $\overline{P_t(B)} \times X_u \ell^+ \nu_\ell$ and e used to vertice formula is used in the full account in algorithm descrived in the full account of the section tem is later fused to be criminate the network that in 2/ psignal Ascalysationsel in the input and other heenairing back - Analymets 31 felse for an structure for a construction ridber Edrag B ter stepotes1 the energy sobot their BEigeneersd interview is the presence t eadfof-massafile (are of the thousands of exclusive decay. channels individed in the instead for the second of the second of the thousands of exclusive decay. channels individed in the second of the 47's singlight the middle Bugher Berered according to the 0.47'G tion, which is a gombination of 0.8 B and the X reconstruction. The RMS



Calculation of Systematics Uncertainties

- Kinematics of $\bar{B}^0 \to D^+\pi^-$ and $\bar{B}^0 \to D^+K^$ processes are quite similar, most of the systematic effects cancel in the ratio of the branching fractions.
- The main source of systematic error that do not cancel is the uncertainty in K/π identification efficiency.
- All the sources of systematic uncertainty are assumed to be independent.
- Total systematic uncertainty is the sum in quadrature of the contributions from individual sources.



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Source	R^D	$\mathcal{B}(\overline{B}^0 \to D^+ \pi^-)$	${\cal B}(\overline B^0$ –
$\mathcal{B}(D^+ \to K^- \pi^+ \pi^+)$		1.71%	1.7
Multiplicative uncertainties	5		
Tracking	_	1.40%	1.40
MC statistics	_	0.04%	0.0^{2}
$\Delta N_{B\bar{B}}$	_	1.37%	1.3'
f_{00}	_	1.23%	1.23
PID efficiency of K/π (stat.)	0.01%	0.00%	0.3
PID efficiency of K/π (syst.)	0.01%	0.04%	0.6^{2}
Total multiplicative	0.01%	2.31%	2.42
Additive uncertainties			
PDF parameterisation	0.199×10^{-2}	0.040×10^{-3}	0.028 :
D^+ mass selection window	0.002×10^{-2}	0.058×10^{-3}	0.047 :
J/ψ veto selection	0.003×10^{-2}	0.001×10^{-3}	0.000 >
Fit bias		0.030×10^{-3}	0.020 :
Total additive	0.199×10^{-2}	0.077×10^{-3}	0.058 >











Results

• The ratio of $B^0 \to D^- K^+$ and $B^0 \to D^- \pi^+$ branching fraction

$$R^{D} \equiv \frac{\mathscr{B}(\bar{B}^{0} \to D^{+}K^{-})}{\mathscr{B}(\bar{B}^{0} \to D^{+}\pi^{-})} = (8.20 \pm 0.20(\text{stat}) \pm 0.20(\text{syst}))$$

• Measurement of branching fraction for $B^0 \to D^- \pi^+$ $\mathscr{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+] = \frac{N_{D\pi}^{\text{HOIAI}}}{2 \times f_{00} \times N_{R\bar{R}} \times \epsilon_{D\pi} \times \mathscr{B}(D^- \to K^+\pi^-\pi^-)}$

$$\mathscr{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+] = [2.50 \pm 0.01_{\text{stat}} \pm 0.10_{\text{syst}} \pm 0.04_{\mathscr{B}(D^- \to K^+\pi^-\pi^-)}] \times 10^{-3}$$

• Measurement of branching fraction for $B^0 \rightarrow D^- K^+$ $\mathscr{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)K^+] = \mathscr{B}(B^0 \to D^-\pi^+) \times R^D$

 $\mathscr{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)K^+] = [2.05 \pm 0.05_{\text{stat}} \pm 0.08_{\text{syst}} \pm 0.04_{\mathscr{B}(D^- \to K^+\pi^-\pi^-)}] \times 10^{-4}$



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LHCb: J. High Energ. Phys. 2013, 1 (2013) Ratio = $8.22 \pm 0.11(\text{stat}) \pm 0.25(\text{syst})$

BaBar: Phys.Rev.D 75 (2007) 031101 $\mathscr{B}[B^0 \to D^- \pi^+] = [2.55 \pm 0.05_{\text{stat}} \pm 0.16_{\text{syst}}] \times 10^{-3}$ CLEO2: Phys.Rev.D 66 (2002) 031101 $\mathscr{B}[B^0 \to D^- \pi^+] = [2.68 \pm 0.12_{\text{stat}} \pm 0.24_{\text{syst}}] \times 10^{-3}$

LHCb: Phys.Rev.Lett. 107 (2011) 211801 $\mathscr{B}[B^0 \to D^- K^+] = [1.89 \pm 0.19_{\text{stat}} \pm 0.10_{\text{syst}}] \times 10^{-4}$

Belle: Phys.Rev.Lett. 87 (2001) 111801 $\mathscr{B}[B^0 \to D^- K^+] = [1.7 \pm 0.4_{\text{stat}} \pm 0.1_{\text{syst}}] \times 10^{-4}$







Study of $B \to \bar{D}^0 \pi$

- $b \rightarrow c\bar{u}d$ transition does not have simple penguin amplitude.
- No penguin diagram possible as final state quark different flavour
- Branching fraction of color suppressed $B^0 \to \overline{D}^0 \pi^0$ has been measured using "naive" factorization model.
- Both are commonly used control mode in many analysis \rightarrow allow for high-precision validations of techniques.
 - Important for Belle II precision frontier.













Analysis Strategy of $B \to \overline{D}^0 \pi$

- Analysis performed with full Belle data set of 711fb⁻¹
- Decay Chain: $B \to \overline{D}^0 (\to K^+ \pi^-) \pi^0$ and $B \to \overline{D}^0 (\to K^+ \pi^- \pi^0) \pi^0$; $\pi^0 \to \gamma \gamma$
- Signal reconstruction
 - Charged particles reconstructed from hadron ID and tracking
 - Neutral particles from $\pi^0 \rightarrow \gamma \gamma$ pairs in ECL
- Kinematic variables used for fitting $\Delta E = E_R^* E_{beam}$ and $M_{\rm bc} = \sqrt{E_{\rm beam}^2 - p_B^2}$
- Continuum Suppression using R_2 and variables in NN \rightarrow transformation to fit as

•
$$C'_{NN} = log\left(\frac{C_{NN} - C_{NN}^{min}}{C_{NN}^{max} - C_{NN}}\right)$$

- Unbinned maximum likelihood fit in $M_{\rm bc}$ and ΔE and C'_{NN}
 - Simultaneous fit over four datasets divided by D^0 decay and kaon charge.







Results $B^+ \to \bar{D}^0 \pi^+$

$$\begin{split} M_{\rm bc}(\bar{D}^0\to K^+\pi^-) & \Delta E(\bar{D}^0\to K^+\pi^-) \\ & \Delta E(\bar{D}^0\to K^+\pi^-\pi^0) \\ & \Delta E(\bar$$





$$\mathscr{B}(B^+ \to \bar{D}^0 \pi^+) = (4.53 \pm 0.02 \pm 0.14)$$

Most precise measurement in this channel







Results $B^0 \to \bar{D}^0 \pi^0$

 $M_{\rm bc}(\bar{D}^0 \to K^+ \pi^-)$ $\Delta E(\bar{D}^0 \to K^+ \pi^-)$ 450 Belle 400 Belle 500 350 Preliminary Preliminary ි ලී 300 250 8)/200 € 300 ± 200 ⊨ ອຼັ້ 150 100 E 100 E 0 -0.2 -0.15 -0.1 -0.05 0 ΔE [GeV] 5.26 5.265 5.27 5.275 5.28 5.285 M_{ec} [GeV] 0.05 0.1 0.15 0.2 5.255 $M_{\rm bc}(\bar{D}^0 \to K^+ \pi^- \pi^0)$ $\Delta E(\bar{D}^0 \to K^+ \pi^- \pi^0)$ Belle Belle 400 E 350 300 Preliminary Preliminary (10₅06) (10,200) (10,200) 250 150 E . ੈੱ 200 – 100 50 E 5.27 5.275 5.28 5.285 M_{ec} [GeV] 5.265 5.255 5.26 $\mathbf{I}^{\mathbf{I}} \mathbf{I}^{\mathbf{I}} \mathbf{I}$

 \mathcal{B} BELLE

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$$C_{NN}^{'}(\bar{D}^{0}\rightarrow K^{+}\pi^{-})$$



Total Signal $B\overline{B}$ bkg $q \overline{q}$ bkg Rare bkg

 $\mathscr{B}(B^0 \to \bar{D}^0 \pi^0) = (2.69 \pm 0.06 \pm 0.09) \times 10^{-4}$



Most precise measurement in this channel





Summary

- Measurements performed with full Belle data.
- Preliminary results for $\bar{B}^0 \to D^+h^-(h = K/\pi)$ are

 $\mathscr{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)\pi^+] = [2.50 \pm 0.01_{\text{stat}} \pm 0.10_{\text{syst}} \pm 0.04_{\mathscr{B}(D^- \to K^+\pi^-\pi^-)}] \times 10^{-3}$ $\mathscr{B}[B^0 \to D^-(\to K^+\pi^-\pi^-)K^+] = [2.05 \pm 0.05_{\text{stat}} \pm 0.08_{\text{syst}} \pm 0.04_{\mathscr{B}(D^- \to K^+\pi^-\pi^-)}] \times 10^{-4}$ $R^D = 0.082 \pm 0.002(\text{stat}) \pm 0.002(\text{syst})$

- Most precise measurement till date and the values agrees with world averages.
- $\bar{B}^0 \to D^{*+}h^-(h = K/\pi)$ results from Belle coming soon
- Preliminary results for $\bar{B} \to \bar{D}^0 \pi$ are $\mathscr{B}(B^+ \to \bar{D}^0 \pi^+) = (4.53 \pm 0.02_{\text{stat}} \pm 0.14_{\text{syst}}) \times 10^{-3}$ $\mathscr{B}(B^0 \to D^0 \pi^0) = (2.69 \pm 0.06_{\text{stat}} \pm 0.09_{\text{syst}}) \times 10^{-4}$
 - Precision is improved in both decay channels.



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