Measurements of $B \rightarrow D(*)h$ and charmless $B$-decays at Belle II

Benedikt Wach on behalf of the Belle II collaboration

*Max-Planck-Institute for Physics, Munich*

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Charmed and Charmless B-decays

$B \to D(*)h$
- mediated through favoured $b \to c$ tree transition with high branching fractions of $\sim 0.5$
  $\to$ serve as important control modes
- $B \to D(*)K$ modes are theoretically clean modes to precisely determine $\gamma/\varphi_3$

Charmless decays:
- mediated through Cabibbo-suppressed $b \to u$ and/or loop-suppressed $b \to d/s$ transitions
- highly sensitive to non-SM loop contributions
- probe SM and non-SM dynamics in all three CKM angles (today: $\alpha/\varphi_2$)

Challenges:
- low BFs of order $\leq 10^{-5}$
- $e^+e^- \to q\bar{q}$ background dominated
SuperKEKB and Belle II Detector

- SuperKEKB: energy-asymmetric $e^+ e^-$ collider running at $\Upsilon(4S)$ resonance (10.58 GeV)
- clean experimental environment

- world record peak luminosity: $3.1 \times 10^{34}$ cm$^{-2}$ s$^{-1}$
- Goal: 50 ab$^{-1}$ by mid 2030s
- so far 213 fb$^{-1}$ of data collected

- unique reach on final states with multiple neutrinos and $\pi^0$/photons

- Today: results on $\sim 63$ fb$^{-1}$
Analysis Overview

1. **Reconstruction**
   - combine candidates in kinematic fits to fill list of B-meson candidates from low-level observables

2. **Selection**
   - mostly loose baseline selection cuts followed by optimized continuum suppression and particle identification cuts

3. **Modelling**
   - extract models from simulated data (+ calibrate on data)
   - determine selection efficiencies for BR calculations

4. **Fit to data & calculate physics quantities**
   - fit using usually one to three fit variables (ΔE, \( M_{bc} \) and **continuum suppression** variable)

5. **Systematic Uncertainties**
   - toy studies and control mode analyses

momenta distribution in CMS frame
$B \to D^0 h^-$

- important observable: ratio of decay rates

$$R^0 = \frac{\Gamma(B^- \to D^0 K^-)}{\Gamma(B^- \to D^0 \pi^-)}$$

- allows for cancellation of many systematic uncertainties

→ clean approach to test theory predictions of factorization and SU(3) symmetry breaking in QCD

- simultaneous 2D-fit in $\Delta E$ and CS classifier of kaon/pion-enhanced samples

Results compatible with world average values!

https://arxiv.org/pdf/2104.03628

<table>
<thead>
<tr>
<th></th>
<th>$B^- \to D^0(K^-\pi^+)h^-$</th>
<th>$B^- \to D^0(K^0_{S}\pi^+\pi^-)h^-$</th>
<th>$\bar{B}^0 \to D^+ h^-$</th>
<th>$B^- \to D^{*0}h^-$</th>
<th>$\bar{B}^0 \to D^{**}h^-$</th>
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<tbody>
<tr>
<td>Belle II $R^{+/0}$ ($\times 10^{-2}$)</td>
<td>7.66 ± 0.55 ^{+0.11}_{-0.08}</td>
<td>6.32 ± 0.81 ^{+0.09}_{-0.11}</td>
<td>9.22 ± 0.58 ± 0.09</td>
<td>6.80 ± 1.01 ± 0.07</td>
<td>5.99 ± 0.82 ^{+0.17}_{-0.08}</td>
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<tr>
<td>LHCb $R^{+/0}$ ($\times 10^{-2}$)</td>
<td>7.77 ± 0.04 ± 0.07 [24]</td>
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<td>8.22 ± 0.11 ± 0.25</td>
<td>7.93 ± 0.11 ± 0.56 [24]</td>
<td>7.76 ± 0.34 ± 0.26</td>
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</table>
\[ B^0 \rightarrow \pi^0 \pi^0 \]

• unique Belle II capability to study all \( B \rightarrow \pi\pi \) channels in consistent manner to extract \( \alpha/\varphi_2 \)

• most challenging mode:
  • two \( \pi^0 \)'s in final state (i.e. photons only)
  • low \( \mathcal{B} \) \( (10^{-6}) \)

• optimized \( \pi^0 \) selection: combine 20 ECL variables using multivariate technique to suppress background photons

• 3D-fit in \( \Delta E, M_{bc} \) and transformed continuum suppression variable \( T_c \)

First measurement in Belle II data!

\[ N_{\text{fit}}(B^0 \rightarrow \pi^0 \pi^0) = 14^{+6.8}_{-5.6} \text{ with } 3.4\sigma \]

\[ \mathcal{B}_{\text{fit}}(B^0 \rightarrow \pi^0 \pi^0) = [1.09^{+0.50}_{-0.41} \text{ (stat)} \pm 0.27 \text{ (sys)}] \times 10^{-6} \]

\[ B^+ \rightarrow \rho^+ \rho^0 \]

- pion-only final state and broad \( \rho \)-peak \( \rightarrow \) large backgrounds
- Spin-0 \( \rightarrow \) Spin+1 + Spin-1 \( \rightarrow \) angular analysis
- 6D-fit including \( \Delta E \), \( T_c \), and \( \rho \) masses to extract signal; and helicity angles to measure fraction \( f_L \) of decays with longitudinal polarization
- syst. uncertainty dominated by data driven \( \pi^0 \) efficiency \( \rightarrow \) will decrease with time

\[ N_{\text{fit}} = 104 \pm 16 \]

\[ \mathcal{B}_{\text{fit}} = [20.6 \pm 3.2 \text{(stat)} \pm 4.0 \text{(sys)}] \times 10^{-6} \]

\[ f_L = 0.936^{+0.049}_{-0.041} \text{(stat)} \pm 0.021 \text{(sys)} \]

First reconstruction in Belle II data, surpassing early Belle performance!
(20% better precision than Belle using 78 fb-1)
(PRL 91, 221801 (2003))
\[ B^0 \to K_S^0 \pi^0 \]

\[ I_{K\pi} = A_{K^+\pi^-} + A_{K^0\pi^+} \frac{B(K^0\pi^+)}{B(K^+\pi^-)} \tau_B^0 - 2A_{K^+\pi^0} \frac{B(K^+\pi^0)}{B(K^+\pi^-)} \tau_B^0 - 2A_{K^0\pi^0} \frac{B(K^0\pi^0)}{B(K^+\pi^-)} \tau_B^0 \]

**Isospin sum rule:** stringent null test of SM, sensitive to presence of non-SM dynamics in Belle II: unique, consistent access to all channels

**BF:** challenging as it requires \( K_S^0 \) and \( \pi^0 \) reconstruction

**\( A_{CP} \):** requires flavor tagging: fit of \( \Delta E - M_{bc} \)-flavor of the \( B \)-meson (\( q \)) (see Stephan Duell’s talk this morning)

\[ N_{\text{fit}}(B^0 \to K_S^0 \pi^0) = 45^{+9}_{-8} \]
\[ B_{\text{fit}}(B^0 \to K^0\pi^0) = [8.5^{+1.7}_{-1.6} \text{ (stat)}] \pm 1.2 \text{ (sys)} \times 10^{-6} \]
\[ A_{\text{CP}}(B^0 \to K^0\pi^0) = 0.40^{+0.46}_{-0.44} \text{ (stat)} \pm 0.04 \text{ (sys)} \]

First measurement in Belle II data and last missing piece to sum rule!
Isospin sum rule – uncertainty projection

• extrapolate the uncertainty on $I_{K\pi}$ into next decade (assuming stat. ≈ syst.)
• future projections with Belle II and LHCb expected luminosities
• dominant uncertainty coming from $\mathcal{A}_{K\pi\pi}$ → Belle II will play crucial role in pinning down $I_{K\pi}$

https://arxiv.org/abs/2104.14871
Summary

• Belle II train has picked up pace for a leading role in testing isospin sum rule and precise determinations of $\alpha$ and $\gamma$

• First/improved measurements of charmless decays in 63 fb$^{-1}$ of early data and a number of vital control modes

• First Belle II measurement of $\mathcal{A}_{K\pi\pi}$ completes the ingredients for the isospin sum rule

• All results agree with known values within uncertainties, still dominated by small sample size

• but already 213 fb$^{-1}$ on tape, ready to be analysed!

A lot of done and ongoing work not presented today: expect many more new/updated results in the future!

B$\to$ D(*)h : https://arxiv.org/abs/2104.03628
B$\to$ K$^*$π, K$^0\pi$, π$^0$π$^0$ : https://arxiv.org/abs/2106.03766
B$\to$ K$^*$π$^0$, π$^0$π$^0$ : https://arxiv.org/abs/2105.04111
B$\to$ K$^0\pi^0$ : https://arxiv.org/abs/2104.14871
B$\to$ π$^0$π$^0$ : https://arxiv.org/pdf/2107.02373.pdf
Backup
Continuum Suppression

- continuum background strongly dominating
- exploit kinematic, topological differences between $B\bar{B}$ and $q\bar{q}$
- employ binary boosted decision tree (FastBDT) to create classifier variable from up to $\sim 40$ variables
- cut and/or fit this CS classifier
\[ B \to D h^- \]

- simultaneous 1D-fit of pion- and kaon-enriched samples in \( \Delta E \) \(^{(1)}\) to determine \( R \)

- kaon(pion)-enriched sample: \( \mathcal{L}(K/\pi) > (<) 0.6 \)

\[
\begin{array}{|c|c|c|}
\hline
\text{Belle II } R_{+0}^{+0} \times 10^{-2} & 7.66 \pm 0.55 & +0.11 -0.08 \\
\text{LHCb } R_{+0}^{+0} \times 10^{-2} & 7.77 \pm 0.04 \pm 0.07 & 7.77 \pm 0.04 \pm 0.07 & 8.22 \pm 0.11 \pm 0.25 \ \\
\hline
\end{array}
\]

Results compatible with world average values!

\(^{(1)}\) : 2D-fit in \( \Delta E \) and CS classifier for \( B^- \to D^0(K^-\pi^+)h^- \)

July 26th, 2021
Results compatible with world average values!
CPV in multibody decays
First step towards search of local CPV in Dalitz plots: investigates relative contributions of tree and penguins, and probes non-SM physics.

First reconstruction in Belle II data!

\[ \mathcal{B}(B^+ \to K^+K^-K^+) = [35.8 \pm 1.6\text{(stat)} \pm 1.4\text{(syst)}] \times 10^{-6} \]

\[ A_{CP}(B^+ \to K^+K^-K^+) = -0.103 \pm 0.042\text{(stat)} \pm 0.020\text{(syst)} \]

\[ \mathcal{B}(B^+ \to K^+\pi^-\pi^+) = [67.0 \pm 3.3\text{(stat)} \pm 2.3\text{(syst)}] \times 10^{-6} \]

\[ A_{CP}(B^+ \to K^+\pi^-\pi^+) = -0.010 \pm 0.050\text{(stat)} \pm 0.021\text{(syst)} \]

\[ \mathcal{B}(B^0 \to K^+\pi^-\pi^0) = [38.1 \pm 3.5\text{(stat)} \pm 3.9\text{(syst)}] \times 10^{-6} \]

\[ A_{CP}(B^0 \to K^+\pi^-\pi^0) = 0.207 \pm 0.088\text{(stat)} \pm 0.011\text{(syst)} \]

Belle II accesses consistently all channels

stolen from Sebastiano Raiz’s talk at PHENO21
Two-body: $B^{+,0} \rightarrow h^+\pi^-, h^+\pi^0, K_S^0\pi^+$

Unique Belle II capability to study all the $B \rightarrow K\pi$ decays to investigate isospin sum-rules.

Probe of tracking and PID performances.

$\mathcal{B} \left[ 10^{-6} \right]$: $18.0 \pm 0.9$ (stat) $\pm 0.9$ (syst)

$N(B^0 \rightarrow K^+\pi^-)$: 568 $^{+29}_{-28}$

$N(B^0 \rightarrow \pi^+\pi^-)$: 115 $^{+14}_{-13}$

Benchmark of $K_S^0$ reconstruction

$N(B^+ \rightarrow K_S^0\pi^+)$: 103 $^{+11}_{-10}$

$21.4^{+2.3}_{-2.2}$ (stat) $\pm 1.6$ (syst)

Challenge of $\pi^0$ reconstruction performances, require good PID.

$\mathcal{B} \left[ 10^{-6} \right]$: 11.9$^{+1.1}_{-1.0}$ (stat) $\pm 1.6$ (syst)

$N(B^+ \rightarrow K^+\pi^0)$: 211 $^{+18.8}_{-18}$

$N(B^+ \rightarrow \pi^+\pi^0)$: 83.9 $^{+14.7}_{-13.9}$

5.5$^{+1.0}_{-0.9}$ (stat) $\pm 0.7$ (syst)
CP asymmetries in two-body decays

\[ A_{CP}(B^0 \rightarrow K^+\pi^-) = -0.16 \pm 0.05({\text{stat}}) \pm 0.01({\text{syst}}) \]

\[ A_{CP}(B^+ \rightarrow K^0\pi^+) = -0.01 \pm 0.08({\text{stat}}) \pm 0.05({\text{syst}}) \]

\[ A_{CP}(B^+ \rightarrow K^+\pi^0) = -0.09 \pm 0.09({\text{stat}}) \pm 0.03({\text{syst}}) \]

\[ A_{CP}(B^+ \rightarrow \pi^+\pi^0) = -0.04 \pm 0.17({\text{stat}}) \pm 0.06({\text{syst}}) \]
syst. uncertainties: 1) branching ratios

- **Tracking efficiency**: 0.91% per charged track as suggested by TG
- **K_s rec. efficiency**: 1% per cm average flight length
- **PID/CS efficiency**: stat. uncert. of selection efficiency using control channel \( B^- \rightarrow D^0 (\rightarrow K^+\pi^-)\pi^- \)
- **N_{BB}**: combination of uncertainties in \( \mathcal{L}, \sigma(\Upsilon(4S)), f_{00}(f_{+-}) \) and beam energy spread \( \rightarrow 2.7 \% \)
- **Signal modeling:**
  - **shape**: fit with 2 Gaussians instead, difference as systematic
  - **nCDCHits mismodeling**: require > 4 hits in CDC for each track, difference as systematic
- **Background modeling**: fit with first order poly. instead, difference as systematic
- **Peaking background**: fix peak. bkg. ratio instead of floating, difference as systematic
Instrumental asymmetries

Observed charge-dependent signal yields depend on CP violation but also on charge-dependent instrumental reconstruction asymmetries ($K_{S}/K_{L}$ ecc) that need be corrected for CP violation measurements

\[ \mathcal{A} = \mathcal{A}_{CP} + \mathcal{A}_{det} \]

Tree-dominated hadronic D decays $D^{+} \rightarrow K_{S} \pi^{+}$ and $D^{0} \rightarrow K \pi \pi$ restricted to charmless-like kinematics to determine instrumental asymmetries on data. CPV in charm tree decays assumed inexistent or irrelevant.

\[
\begin{align*}
\mathcal{A}_{det}(K^{+}\pi^{-}) & = -0.010 \pm 0.001 \\
\mathcal{A}_{det}(K_{S}^{0}\pi^{+}) & = +0.026 \pm 0.019 \\
\mathcal{A}_{det}(K^{+}) & = +0.017 \pm 0.019 \\
\mathcal{A}_{det}(\pi^{+}) & = +0.026 \pm 0.019
\end{align*}
\]