Measurements of charmless $B$ decays at Belle II

May 18, 2021

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Charmless B decay

Hadronic $B$ decays not mediated by $b \rightarrow c$. Cabibbo-suppressed $b \rightarrow u$ trees and $b \rightarrow d, s$ penguins.

- Highly sensitive to non-SM loops.
- Probe non-SM dynamics in all the three CKM angles.

Account for ~15% of experimental flavor physics papers.

Pheno challenges: predictions limited by complicated calculation of hadronic matrix elements.

Exp. challenges: $O(10^{-5} - 10^{-6})$ branching fractions means highly limited by statistics, same final states of the dominant background (“continuum” $e^+e^- \rightarrow q\bar{q}$ at Belle II)

Belle II goals
- Improve precision on $\phi_2/\alpha$ angle
- Test SM using isospin sum rules
- Investigate localized CP asymmetries in Dalitz plot of three-body decays

Today: charmless B decay results on 62.8 fb$^{-1}$

In-depth validation of detector early operation and analysis tools.
**Goal:** blind measurements of branching fractions, CP asymmetries and polarizations for various charmless B decays using 62.8 fb\(^{-1}\)

**Selection**
Continuum suppression, optimize on simulation and data.

**Signal extraction**
\[ \Delta E = E_B^* - E_{\text{beam}}^* \]
\[ M_{bc} = \sqrt{E_{\text{beam}}^*}^2 - p_B^*^2 \]
Models from simulation, adjusted on control modes.

**Efficiencies and corrections**
Efficiencies from simulation, validated on data. Instrumental asymmetries from data.

**Flavor Tagger**
Multivariate methods determines flavor of the not reconstruct \( B^0 \)

**Systematic uncertainties**
Toy studies or control modes in data.

**Validation**
Validation of the full analysis on more abundant control modes.

**Unblinding**
Apply full analysis to data.
Continuum suppression: exploit topological differences, combine 30+ kinematic, decay-time and topological variables in multivariate techniques. E.g. $B^0 \rightarrow \pi^0\pi^0$: 0.62 signal/fb$^{-1}$ and 245 continuum/fb$^{-1}$ $q\bar{q}$ background rejection: $\sim$99 %

Peaking backgrounds: study vetoes from simulation to exclude them and add fit components to account for survivors.
Results
$K\pi$ isospin sum-rule

Stringent null test of SM, sensitive to presence of non-SM dynamics.

$$I_{K\pi} = A^{K^+\pi^-}_{\text{CP}} + A^{K^0\pi^+}_{\text{CP}} \frac{B(K^0\pi^+)}{B(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2A^{K^+\pi^0}_{\text{CP}} \frac{B(K^+\pi^0)}{B(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2A^{K^0\pi^0}_{\text{CP}} \frac{B(K^0\pi^0)}{B(K^+\pi^-)} = 0$$

$B(B^0 \rightarrow K^+\pi^-)$

$= [18.0 \pm 0.9\,(\text{stat}) \pm 0.9\,(\text{syst})] \times 10^{-6}$

$A_{\text{CP}}(B^0 \rightarrow K^+\pi^-)$

$= -0.16 \pm 0.05\,(\text{stat}) \pm 0.01\,(\text{syst})$

$B(B^+ \rightarrow K^0\pi^+)$

$= [21.4^{+2.3}_{-2.2}\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-6}$

$A_{\text{CP}}(B^+ \rightarrow K^0\pi^+)$

$= -0.01 \pm 0.08\,(\text{stat}) \pm 0.05\,(\text{syst})$

$B(B^+ \rightarrow K^+\pi^0)$

$= [11.9^{+1.1}_{-1.0}\,(\text{stat}) \pm 1.6\,(\text{syst})] \times 10^{-6}$

$A_{\text{CP}}(B^+ \rightarrow K^+\pi^0)$

$= -0.09 \pm 0.09\,(\text{stat}) \pm 0.03\,(\text{syst})$

Belle II is the only experiment capable to analysing all modes in a consistent way.

Isospin sum rule: needs $K^0\pi^0$

$BF$: challenging as it requires $K_S^0$ and $\pi^0$ reconstruction.
$A_{CP}$: requires also flavor tagging. Fit of $\Delta E\text{-}M_{bc}$ of the $B$ meson ($q$), simultaneously in 7 ranges of wrong-tag fraction (output from flavor tagger).

$$P_{\text{sig}}(q) = \frac{1}{2} \left( 1 + q \cdot \left( 1 - 2w_r \right) \cdot \left( 1 - 2\chi_d \right) \cdot A_{CP}(K^0\pi^0) \right)$$

$B^0 \to K^0\pi^0$

$\mathcal{B}(B^0 \to K^0\pi^0) = [8.5^{+1.7}_{-1.6}(\text{stat}) \pm 1.2(\text{syst})] \times 10^{-6}$

$A_{CP}(B^0 \to K^0\pi^0) = -0.40^{+0.46}_{-0.44}(\text{stat}) \pm 0.04(\text{syst})$

First measurement in Belle II data!
CPV in multibody

First step towards search of local CPV in Dalitz plots: investigates relative contributions of tree and penguins, and probes non-SM physics.

\[ B^+ \rightarrow K^+K^-K^+ \]
\[ B^+ \rightarrow K^+\pi^-\pi^+ \]

Rich Dalitz structure poses the additional challenge of many peaking backgrounds.

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

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

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

\[ A_{CP}(B^+ \rightarrow K^+\pi^-\pi^+) = -0.010 \pm 0.050(stat) \pm 0.021(syst) \]
Determination of $\alpha/\phi_2$

Unique Belle II capability to study all the $B \rightarrow \pi\pi, \rho\rho$ decays to determine the CKM angle $\alpha = arg[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}]$, known to 6% precision.

Isospin relation can be used to disentangle penguins and trees contribution to determine $\alpha$.

Requires all BF and CP violation parameters for $B \rightarrow \pi\pi$.

$$B(0 \rightarrow \pi^+\pi^-) = [5.8 \pm 0.7(stat) \pm 0.3(syst)] \times 10^{-6}$$

$$B(B^+ \rightarrow \pi^+\pi^0) = [5.5^{+1.0}_{-0.9}(stat) \pm 0.7(syst)] \times 10^{-6}$$

$$A_{CP}(B^+ \rightarrow \pi^+\pi^0) = -0.04 \pm 0.17(stat) \pm 0.06(syst)$$

Benchmarks PID and $\Delta E$ resolution.

Probes $\pi^0$ reconstruction and PID.

https://doi.org/10.1103/PhysRevLett.65.3381
Determination of $\alpha/\phi_2$: $B^0 \rightarrow \pi^0\pi^0$

Challenging with two $\pi^0$: high continuum, low BF ($1.26 \times 10^{-6}$), higher beam background relative to Belle, lowest signal-to-background ratio in current Belle II charmless studies.

$B^0 \rightarrow \pi^0\pi^0$ has the largest branching fraction and $A_{CP}$ uncertainties of all three $B \rightarrow \pi\pi$ modes, i.e. 16% on BF for $B^0 \rightarrow \pi^0\pi^0$ vs 4% for $B^0 \rightarrow \pi^+\pi^-$ and is currently posing the greatest limitation to the determination of $\alpha$ from $B \rightarrow \pi\pi$.

Belle II is currently the only experiment that can improve the current world average.

Analysis validated on $B^0 \rightarrow D^0 (\rightarrow K^+\pi^-\pi^0)\pi^0$ in data.

$N_{\text{sig}} = 295 \pm 31$
Determination of $\alpha/\phi_2$: $B^0 \rightarrow \pi^0\pi^0$

Fit to $\Delta E$, $M_{bc}$ and the continuum suppression output $T_c$ simultaneously in 8 ranges of flavour tagger output (q.r).

Candidates with higher flavour tagger output are more likely to be genuine $B^0 \rightarrow \pi^0\pi^0$

$B^0 \rightarrow \pi^0\pi^0$

$\mathcal{B}(B^0 \rightarrow \pi^0\pi^0) = [0.98^{+0.48}_{-0.39}(\text{stat}) \pm 0.27(\text{syst})] \times 10^{-6}$

First reconstruction in Belle II data!
Evidence (3.4 $\sigma$) at 62.8 fb$^{-1}$ a performance comparable with Belle with 140 fb$^{-1}$
$B^+ \to \rho^+\rho^0$ results

Unique Belle II capability to determine $\alpha/\phi_2 = \arg[-V_{td}V_{tb}^{*}/V_{ud}V_{ub}^{*}]$ using $B \to \rho\rho$ decays

Challenges:
• pion-only $(\pi^+\pi^0)(\pi^+\pi^-)$ final state and broad $\rho$ peak $\Rightarrow$ large bckg
• Spin-0 $\rightarrow$ spin1 + spin-1 $\Rightarrow$ angular analysis.

6D fit including $\Delta E$, CS, and $\rho$ masses to extract signal, and helicity angles to measure fraction $f_L$ of decays with longitudinal polarization.

$N = 104 \pm 16$

$\mathcal{B} = [20.6 \pm 3.2(stat) \pm 4.0(syst)] \times 10^{-6}$

$f_L = 0.936^{+0.049}_{-0.041}(stat) \pm 0.021(syst)$

20% better precision than Belle on 78 fb$^{-1}$
(PRL 91, 221801 (2003)):

$N = 59 \pm 13$

$\mathcal{B} = [31.7 \pm 7.1(stat)^{+3.8}_{-6.7}(syst)] \times 10^{-6}$

$f_L = 0.948 \pm 0.106(stat) \pm 0.021(syst)$

First reconstruction in Belle II data!
Surpass early Belle’s performance.
Charmless $B$ physics plays an important role in sharpening our flavor picture.

Era of precision physics! Belle II will play a leading role in: $\alpha/\phi_2$, local CPVs, isospin sum rules.

First/improved measurements of charmless decays in 62.8 fb$^{-1}$ of early data compatible with known values within $\sim$6% to $\sim$25% precision, dominated by small sample size

First Belle II measurement of $A_{\text{CP}}(K^0\pi^0)$ completes the ingredients for the isospin sum rule; $\rho\rho$ and $\pi\pi\pi$ analysis surpasses early Belle’s.

Performance comparable/better than at Belle demonstrates advanced understanding of detector/analysis tools.
Backup
Charmless physics at Belle II

Goals

๏ Improve precision on $\phi_2/\alpha$ angle;
๏ Test SM using isospin sum rules;
๏ Investigate localized CP asymmetries in three-body $B$ decays;
๏ Study time-dependent CP violations.

Belle II

๏ ~700 BB pairs/second in low-bkg environment;
๏ 140 fb$^{-1}$ of data collected;
๏ World record peak luminosity in June 2020: $2.4\times10^{34}$ cm$^{-2}$ s$^{-1}$
๏ Complementary to LHCb (final states with neutrals and V0s).
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.

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

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

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

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

$5.8 \pm 0.7(stat) \pm 0.3(syst)$

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

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

Probe of tracking and PID performances.

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

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

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

$5.5^{+1.0}_{-0.9}(stat) \pm 0.7(syst)$

Benchmark of $K_S^0$ reconstruction.
CP asymmetries in two-body decays

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

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

\[ A_{CP}(B^+ \to K^+\pi^0) = -0.09 \pm 0.09 \text{(stat)} \pm 0.022 \text{(syst)} \]

\[ A_{CP}(B^+ \to \pi^+\pi^0) = -0.04 \pm 0.17 \text{ (stat)} \pm 0.06 \text{(syst)} \]
$B^0 \to K^0\pi^0$: branching fraction

$N(B^0 \to K_S^0\pi^0): 45^{+9}_{-8}$

$\mathcal{B}(B^0 \to K^0\pi^0) = [8.5^{+1.7}_{-1.6}(\text{stat}) \pm 1.2(\text{syst})] \times 10^{-6}$
Multibody: branching fractions

$B^+ \to K^+ K^- K^+$

$\mathcal{B}[10^{-6}]: \quad 35.8 \pm 1.6(\text{stat}) \pm 1.4(\text{syst})$

$\mathcal{B}^+ \to K^+ \pi^- \pi^+$

$N_{\text{Sig}}: \quad 843 \pm 42$

$67.0 \pm 3.3(\text{stat}) \pm 2.3(\text{syst})$
Observed charge-dependent signal yields depend on CP violation but also on charge-dependent instrumental reconstruction asymmetries (K+/K- 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 $D^0 \rightarrow K^- \pi^+$ restricted to charmless-like kinematics to determine instrumental asymmetries on data. CPV in charm tree decays assumed inexistent or irrelevant.

- $\mathcal{A}_{det}(K^+ \pi^-) = -0.010 \pm 0.001$
- $\mathcal{A}_{det}(K^0_S \pi^+) = +0.026 \pm 0.019$
- $\mathcal{A}_{det}(K^+) = +0.017 \pm 0.019$
- $\mathcal{A}_{det}(\pi^+) = +0.026 \pm 0.019$
Validate the efficiencies by applying the same selection on data and simulation for abundant and signal-rich control channels.

Here, as example the $\pi^0$ reconstruction efficiency.

$$\varepsilon(\pi^0) = \frac{\text{Yield}(B^0 \rightarrow D^{*-}[-D^0[-K^+\pi^0\pi^-]\pi^+]\pi^+)}{\text{Yield}(B^0 \rightarrow D^{*-}[-D^0[-K^+\pi^-]\pi^-]\pi^+)} \cdot \frac{B(D^0 \rightarrow K^+\pi^-)}{B(D^0 \rightarrow K^+\pi^-) \cdot B(\pi^0 \rightarrow \gamma\gamma)}$$

Similar strategy adopted for continuum suppression and PID selections.

Results generally compatible within $O(1)\%$ uncertainties, which propagate as systematics.