Hadronic $B$ decays at Belle II

Sebastiano Raiz (University and INFN Trieste) on behalf of the Belle II collaboration

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Hadronic $B$ decays

**Charmed decays:** Cabibbo-favoured $b \rightarrow c$ tree transitions 
($B \rightarrow D(\ast)K$, $B \rightarrow D(\ast)\pi \ldots$).

**Charmless decays:** Cabibbo-suppressed $b \rightarrow u$ trees and $b \rightarrow d, s$ penguins 
($B \rightarrow K\pi$, $B \rightarrow \rho\rho \ldots$).

Probe SM dynamics in all three CKM angles
- $\gamma$ with theoretically clean modes $B \rightarrow DK$
- $\alpha$ with $B \rightarrow \rho\rho$, $B \rightarrow \rho\pi$, $B \rightarrow \pi\pi$ isospin analyses
- $\beta$ with $B^0 \rightarrow J/\psi K_S^0$, $B^0 \rightarrow \eta'K_S^0$, $B^0 \rightarrow \phi K_S^0$

and by testing isospin sum rules, chiral structure, ...

Charmed: competitive on channels with neutrals (e.g. $B \rightarrow D(K_S^0\pi^0)h$)
→ challenging reconstruction. Key control channels for other analyses.

Charmless: highly sensitive to new physics but

pheno challenges: predictions limited by complicated calculations of non-perturbative QCD,

exp. challenges: rare, $BF \sim O(10^{-5})$, same final states of the dominant background ("continuum" $e^+e^- \rightarrow q\bar{q}$ at Belle II).

Today: $\gamma$ direct determination, $B^+ \rightarrow \rho^+\rho^0$ towards $\alpha$, time-dependent measurements.
The Belle II detector

- SuperKEKB: 7-on-4 GeV $e^- e^+$ collider at 10.58 GeV;
- Aim at 700 $B \bar{B}$ pairs/second in low-bkg environment;
- 400 fb$^{-1}$ (440 x10$^6$ $B \bar{B}$ pairs) of data collected;
- Record peak luminosity: 4.1x10$^{34}$ cm$^{-2}$ s$^{-1}$

- EM Calorimeter (ECL)
  Energy resolution: 4%-1.6%

- Central Drift Chamber
  Spatial resolution: 100 μm
  $dE/dx$ resolution: 5%
  $p_T$ resolution: 0.4%

- Vertex Detector
  Vertex resolution: 15 μm

- Particle identification
  K eff. 90%, fake π rate 5%

Main Belle II strength: unique reach on final states with multiple neutrinos and $\pi^0$/photons.
Analysis workflow

-1/5 of hadronic events from $e^+e^-$ are $B\bar{B}$.

**Typical $B$ hadronic event:** 10 tracks/clusters — easy to trigger on unbiasing variables (e.g. number of tracks) — isotropically distributed in space.

**Main backgrounds:** $e^+e^- \rightarrow q\bar{q}$ (collimated jets, very different event shape), other misidentified $B$ events.

**Reconstruction**
- combine final state particles ($K$, $\pi$, ...) in kinematic fits to form the $B$ decay

**Selection**
- optimize event-shape multivariate classifier (CS) and particle ID criteria

**Fit**
- extract models from simulation (calibrate on data), fit in to data and calculate physics quantities

**Systematic uncertainties**
- with control modes and simulations
Measurement of $\gamma$
**γ from $B \rightarrow DK$ decays**

$\gamma$: phase between $b \rightarrow u$ and $b \rightarrow c$ transitions. Accessible via tree-level decays: no direct new physics $\rightarrow$ strong constraints on SM.

Current WA dominated by LHCb:

$$\gamma[^{\circ}] = 65.9 \pm 3.3 \pm 3.5 \quad \text{HFLAV}$$

Use $D \rightarrow K_S^0 h^+ h^-$ decays and model-independent method: divide Dalitz plot in bins (less information, but no amplitude-model systematics):

$$N_i^\pm = h_B^\pm \left[ F_i + r_B^2 \bar{F}_i + 2 \sqrt{F_i \bar{F}_i} (c_i x^\pm + s_i y^\pm) \right]$$

$$(x^\pm, y^\pm) = r_B \left( \cos(\gamma + \delta_B), \sin(\gamma + \delta_B) \right)$$

$c_i, s_i$: $D^0-\bar{D}^0$ strong phase differences (inputs from BES III/CLEO)

$F_i$: fraction of $D$ decays to $i$-th bin

**Results limited by sample size (small branching fractions).**
Signal yield determination

128 fb\(^{-1}\) Belle II + 711 fb\(^{-1}\) Belle.

Improvements wrt previous Belle:
- \(K_S^0\) selection
- background suppression
- signal determination
- include \(D^0 \rightarrow K_S^0 KK\)
- new inputs from BESIII

Simultaneous fit of \(B \rightarrow DK\) and \(B \rightarrow D\pi\): \(K/\pi\) misID rate is extracted from data.

**Signal yields**

Belle:
- \(K_S^0 \pi\pi\): 1467 ± 53
- \(K_S^0 \pi\pi\): 280 ± 21
- \(K_S^0 KK\): 194 ± 17
- \(K_S^0 KK\): 34 ± 7

Belle II:
- \(K_S^0 \pi\pi\): 280 ± 21
- \(K_S^0 \pi\pi\): 34 ± 7

\[D^0 \rightarrow K_S^0 \pi^+\pi^-\]

\[D^0 \rightarrow K_S^0 K^+K^-\]
Determination of CPV parameters

Simultaneous fit in Dalitz bins to extract CP observables \((x_\pm, y_\pm)\). MisID fixed from previous fit.

Extract \(F_i\) directly in data to cancel associated systematics and reduce reliance on simulation.

\[
\begin{align*}
\delta_B[^\circ] &= 124.8 \pm 12.9 \text{ (stat)} \pm 0.5 \text{ (syst)} \pm 1.7 \text{ (ext)} \\
r_B^{DK} &= 0.129 \pm 0.024 \text{ (stat)} \pm 0.001 \text{ (syst)} \pm 0.002 \text{ (ext)} \\
\gamma[^\circ] &= 78.4 \pm 11.4 \text{ (stat)} \pm 0.5 \text{ (syst)} \pm 1.0 \text{ (ext)}
\end{align*}
\]

Still not competitive with LHCb, but most precise result from a \(B\)-factory.

Latest inputs on strong-phase from BESIII highly reduce systematics.

Expect < 3° uncertainty with 10 \(ab^{-1}\), including also more \(D\) final states.

Uncertainty dominated by the data sample size.
Towards CKM angle $\alpha$
\( \alpha \) and \( B^+ \to \rho^+ \rho^0 \) analysis

\[ \alpha = \arg \left[ -V_{td} V_{tb}^*/V_{ud} V_{ub}^* \right] \] less precisely known angle, may limit the global testing power of CKM fits.

Determined using \( B \to \rho \rho \), \( B \to \rho \pi \), and \( B \to \pi \pi \) isospin analyses (to reduce impact of hadronic uncertainties — non-perturbative QCD).

Unique Belle II capability to study in consistent way all channels. \( B \to \rho \rho \) best probes.

Current best \( B^+ \to \rho^+ \rho^0 \) measurement is from BaBar (424 fb\(^{-1}\)).

Goal: measure \( B^+ \to \rho^+ \rho^0 \) branching fraction, \( A_{CP} \), and fraction of longitudinal polarised decays \( f_L \).

\[ \alpha[^\circ] = 85.2 \pm 4.8 \pm 4.3 \text{ (HFLAV)} \]
$\mathcal{B}^+ \to \rho^+\rho^0$ challenges

Pion-only final state $(\pi^+\pi^0)(\pi^+\pi^-)$ and broad $\rho$ peak $\to$ large background.

Intermediate $\rho$ states have spin $= 1$ $\to$ need to fit also angular distributions to determine fraction of longitudinal polarization.

6D fit with multidimensional shapes to take correlations into account.

Shapes calibrated using BtoCharm control mode.

$A_{CP}$ is corrected for instrumental asymmetries (use $D^+ \to K_S^0\pi^+$).
$B^+ \rightarrow \rho^+\rho^0$ results

\[ B = [23.2^{+2.2}_{-2.1}(\text{stat}) \pm 2.7(\text{syst})] \times 10^{-6} \]

\[ A_{CP} = -0.069 \pm 0.068(\text{stat}) \pm 0.060(\text{syst}) \]

\[ f_L = 0.943^{+0.035}_{-0.033}(\text{stat}) \pm 0.027(\text{syst}) \]

First $A_{CP}(B^+ \rightarrow \rho^+\rho^0)$ measurement in Belle II data.
$B^0$ lifetime and $B^0 - \bar{B}^0$ mixing
Analyses of time evolution

Lifetime ($\tau_B$) and oscillation frequency ($\Delta m_d$) measurement: fundamental validation for time-dependent CP-violation analyses.

Must-have elements:
- good vertex resolution
- high tagging efficiency (flavour-tagger)

Belle II

$\epsilon_{\text{tag}} = (30.0 \pm 1.3)\%$

*Belle II* *Eur. Phys. J. C* 82, 283 (2022)
Use $B^0 \to D^{(*)-}\pi^+/K^+$ modes (~40k total events).

**Strategy:**

- 2D fit to $\Delta E$ and CS;
- subtract background (sWeights) to obtain background-free signal sample;
- fit background-subtracted $\Delta t$ distribution.

**Main challenge:**

- complicated likelihood taking into account wrong-tag fraction, finite vertex resolution.
Lifetime and mixing results

\[ \tau_{B^0} = 1.499 \pm 0.013 \text{(stat)} \pm 0.008 \text{(syst)} \text{ ps} \]

\[ \Delta m_d = 0.516 \pm 0.008 \text{(stat)} \pm 0.005 \text{(syst)} \text{ ps}^{-1} \]

Not yet competitive with global best results, but systematic uncertainties already on par with best Belle/Babar results.

Milestone in Belle II program: we are fully ready for time-dependent analyses (e.g. \( \sin 2\beta \)).

Next step: improve precision by using also \( B^0 \rightarrow D^*-l^+\nu \) modes.
Time evolution of $B^0 \rightarrow K_{S}^{0}\pi^{0}$
Isospin sum rule and $B^0 \rightarrow K_S^0 \pi^0$

Stringent null test of SM, sensitive to presence of non-SM dynamics. Inconsistency between current measurements: “$K\pi$ puzzle” (anomalously enhanced amplitudes or new physics):

$$I_{K\pi} = A_{CP}^{K^+\pi^-} + A_{CP}^{K^0\pi^+} \frac{\mathcal{B}(K^0\pi^+)}{\mathcal{B}(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{CP}^{K^0\pi^0} \frac{\mathcal{B}(K^+\pi^-)}{\mathcal{B}(K^+\pi^-)} \frac{\tau_{B^0}}{\tau_{B^+}} - 2A_{CP}^{K^0\pi^0} \frac{\mathcal{B}(K^0\pi^0)}{\mathcal{B}(K^+\pi^-)} \approx 0$$

Belle II: unique access to $B^0 \rightarrow K^0\pi^0$ (major limitation in $I_{K\pi}$). Need time-dependent $A_{CP}$.

Challenges:
Requires $K_S^0$ and $\pi^0$ reconstruction.
Vertexing with $K_S^0$ decay products only.

Strategy:
Perform 4D fit ($\Delta E$, $M_{bc}$, $\Delta t$, and CS).
Use $B^0 \rightarrow J/\psi K_S^0$ to calibrate $\Delta t$ shapes.
Constrain $\tau_{B_{sig}}$, $\Delta m_d$, and $S_{CP}$ from WA.
$B^0 \rightarrow K^0_S \pi^0$ results

$$\mathcal{B}(B^0 \rightarrow K^0 \pi^0) = [11.0 \pm 1.2(\text{stat}) \pm 1.0(\text{syst})] \times 10^{-6}$$

$$A_{CP}(B^0 \rightarrow K^0 \pi^0) = -0.41^{+0.30}_{-0.32}(\text{stat}) \pm 0.09(\text{syst})$$

Extrapolate uncertainty on $I_{K\pi}$ (capability of measuring a deviation from its SM value) using also LHCb prospects:

dominant uncertainty coming from $A_{K^0\pi^0}$.

Fundamental role of Belle II in improvement of precision.
Hadronic decays important element in Belle II $B$ physics program.

- Most precise CKM $\gamma$ determination from $B$-factories (combine Belle and Belle II data to be impactful with early data).

- Angular $CP$-violation analysis with $B^+ \to \rho^+\rho^0$: key element in $B \to \rho\rho$ analysis.

- Precision lifetime and $B^0$ oscillation frequency measurement, important validation for time-dependent analyses.

- Time-dependent $B^0 \to K^0_S\pi^0$: unique to Belle II (multiple neutrals).

Competitive physics results even with initial data sets
Backup
Projections of integrated luminosity delivered by SuperKEKB to Belle II

Target scenario: extrapolation from 2021 run including expected improvements.

Base scenario: conservative extrapolation of SuperKEKB parameters from 2021 run.

- We start long shutdown I (LS I) from summer 2022 for 15 months to replace VXD. There will be other maintenance/improvements works of machine and detector.
- We resume physics running from Fall 2023.
- A SuperKEKB International Taskforce (aiming to conclude in summer 2022) is discussing additional improvements.
- An LS2 for machine improvements could happen on the time frame of 2026-2027.
Fit of Belle data

\[ D^0 \rightarrow K_S^0 \pi^+ \pi^- \]

\[ D^0 \rightarrow K_S^0 K^+ K^- \]
Greatly improved time resolution compared to previous $B$-factories.

Flavor tagging efficiency comparable to Belle.

Strong charged particle identification. Good momentum resolution. High $\gamma$ efficiency.