Belle II Physics Results

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On behalf of the Belle II Collaboration

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The Belle II Experiment

Belle II is a B factory experiment at the SuperKEKB $e^+e^-$ asymmetric-energy collider

- Design instantaneous luminosity of $6 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$ with record of $4.7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ already achieved
- Target data sample of 50 ab$^{-1}$
  ~30x combined data set of previous experiments
  - ~100 billion B mesons

Optimized for tracking and B vertex reconstruction, K - $\pi$ particle identification, and precision calorimetry

- **Clean** environment with large solid-angle detector coverage and good missing energy reconstruction
- **Inclusive trigger** ($N_{\text{tracks}}>3$) as well as dedicated low-multiplicity triggers
Belle II experiment

Belle II data set now approaching the integrated luminosity of previous generation of B Factory experiments (BABAR and Belle)

- Current results based on < 1% of target data sample

Physics data taking began in 2019

- Total integrated luminosity of 362 fb\(^{-1}\) at the \(\Upsilon(4S)\) resonance
- 42 fb\(^{-1}\) recorded 60 MeV below \(\Upsilon(4S)\) ("offpeak")
- 19 fb\(^{-1}\) at 10.8 GeV for exotic hadron studies (\(\Upsilon(5S)\) and \(\Upsilon(6S)\) region)
Belle II physics program

Broad physics program for precision tests of SM predictions in B meson decays

- CKM matrix elements and CP-violation in the B meson sector
- Tree and loop-level (e.g. FCNC) processes probed to test for evidence of beyond Standard Model contributions

<table>
<thead>
<tr>
<th>Process</th>
<th>$\sigma$ (nb)</th>
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<tbody>
<tr>
<td>$b\bar{b}$</td>
<td>1.1</td>
</tr>
<tr>
<td>$c\bar{c}$</td>
<td>1.3</td>
</tr>
<tr>
<td>Light quark $q\bar{q}$</td>
<td>~2.1</td>
</tr>
<tr>
<td>$\tau^+\tau^-$</td>
<td>0.9</td>
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<tr>
<td>$e^+e^-$</td>
<td>~40</td>
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Very extensive program of non-B physics as well:

- Quarkonium and “exotic states”
- Light Higgs, Z', ALPs, dark sector etc.
- Tau, charm precision measurements and rare decay searches
Outline

- Belle II introduction
- \( \tau \) lepton mass
- Charmed hadron lifetimes
- Lepton flavour universality and \( R(X), R(D^*) \)
- Search for \( B^+ \rightarrow K^+ \nu \bar{\nu} \)
- Prospects
Mass of the $\tau$ lepton is a fundamental SM parameter

- Use kinematic edge of $M_{\text{min}}$ distribution in $\tau\rightarrow 3\pi\nu$ decays

Pseudomass endpoint method:

$$M_{\text{min}} = \sqrt{M_{3\pi}^2 + 2(\sqrt{s}/2 - E_{3\pi})^2} \leq m_{\tau}$$

- Assumes neutrino is collinear with $3\pi$ direction, and utilizes beam energy constraint

$\tau^+\tau^-$ pairs are produced at Belle II in $e^+e^- \rightarrow \tau^+\tau^-$ with relatively high boost

- “Jetty” topology, with the decay daughters from the two taus cleanly separated into two “hemispheres”
- “Tag and probe” to cleanly and inclusively select $\tau$ signal candidate sample
τ lepton mass

Critical to control beam energy and track momentum scale calibrations

- Beam energy calibrated using B meson hadronic decays
- Momentum scale sensitive to magnetic field imperfections, detector material etc.
  Extract scale factors for K and π using $D^{*+} \to D^0 \to K^-\pi^+\pi^+$ from data
Mass determined from unbinned maximum likelihood fit to an empirical endpoint function:

\[ m_\tau = 1777.09 \pm 0.08 \pm 0.11 \text{ MeV}/c^2 \]

- **Most precise experimental determination to date!**

**Source**

**Uncertainty (MeV/c^2)**

- Knowledge of the colliding beams:
  - Beam-energy correction: 0.07
  - Boost vector: < 0.01
- Reconstruction of charged particles:
  - Charged-particle momentum correction: 0.06
  - Detector misalignment: 0.03
- Fit model:
  - Estimator bias: 0.03
  - Choice of the fit function: 0.02
  - Mass dependence of the bias: < 0.01
- Imperfections of the simulation:
  - Detector material density: 0.03
  - Modeling of ISR, FSR and \( \tau \) decay: 0.02
  - Neutral particle reconstruction efficiency: \( \leq 0.01 \)
  - Momentum resolution: < 0.01
  - Tracking efficiency correction: < 0.01
  - Trigger efficiency: < 0.01
  - Background processes: < 0.01
- Total: 0.11

Charmed hadron lifetimes

Charmed hadrons have lifetimes of order 0.1 - 1 ps, resulting in decay distances of typically 100 – 500 μm at B factories

- $D^0$, $D^+$, $D_s^+$, $\Lambda_c^+$ and $\Omega_c^0$
- Decay time determined from flight distance between production and decay vertex
- Momentum vector constraint (from tracking) and hadron mass (from decay daughters)

Substantially improved vertex resolution and reduced beam spot size compared with Belle

Luminous region is $\{10,0.2,250\}$ μm $\{x,y,z\}$ (compared to $\{100,1,6000\}$ μm for Belle)
Charmed hadron lifetimes

Consider only high purity, large branching fraction decay modes

- Charm from B decays vetoed (to avoid lifetime bias)
- Backgrounds modelled using invariant mass sideband regions
- Very small background-related systematics

\[ D^{*+} \to D^0 (\to K^- \pi^+) \pi^+ \]
\(~171k \text{ with } 99.8\% \text{ purity}\)

\[ D^{*+} \to D^+(\to K^- \pi^+ \pi^+) \pi^0 \]
\(~59k \text{ with } 91\% \text{ purity}\)

\[ \Lambda_c^+ \to p K^+ \pi^+ \]
\(~116k \text{ with } 93\% \text{ purity}\)

\[ D_s^+ \to \phi (\to K^- K^+) \pi^+ \]
\(~116k \text{ with } 92\% \text{ purity}\)

\[ \Omega_c^0 \to \Omega^- \pi^+ \]
\[ \Omega \to \Lambda_c^0 (\to p \pi^-) K^- \]
\(~90 \text{ events with } 67\% \text{ purity}\)
Charmed hadron lifetimes

Lifetimes are extracted using an unbinned maximum-likelihood fit to the decay time ($t$) and decay-time uncertainty ($\sigma_t$)

- Signal distributions are convolutions of an exponential with a resolution function
- Simultaneous fit to signal and sideband regions with all shape parameters free
- Possible backgrounds from long-lived particles taken into consideration (e.g. $\Xi_c \rightarrow \Lambda_c^+ \pi$)

$L$-dependence of lifetimes

$$
\tau(D^0) = 410.5 \pm 1.1 \text{(stat.)} \pm 0.8 \text{(syst.)} \text{fs} \\
\tau(D^+) = 1030.4 \pm 4.7 \text{(stat.)} \pm 3.1 \text{(syst.)} \text{fs}
$$

Systematics at level of 0.2%

PRL 127 (2021) 21801
arXiv:2306.00365
PRL 130 (2023) 071802
PRD 107 (2023) L031103
Charmed hadron lifetimes

Not previously measured by BABAR or Belle!

- Most precise $D^0$, $D^+$, $D_s^+$ and $\Lambda_c^+$ lifetime measurements to date

Confirmation of unexpectedly long lifetime of $\Omega_c^0$ by LHCb
- not the shortest-lived weakly decaying charm baryon

Clear demonstration of the performance of the Belle II tracking and vertexing system

- Precise detector alignment, calibration and understanding at a level not previously achieved at B factories
Semileptonic $B$ decays occur via tree-level processes mediated by weak interaction

- Potentially provide experimentally clean and high-rate measurements of CKM matrix elements $V_{ub}$ and $V_{cb}$
- Lepton flavour universality (LFU) tests provide theoretically clean SM probes in semileptonic decays
- Long-standing “anomaly” in LFU related to 3$^{rd}$ generation leptons:

Test LFU in ratio of $b \rightarrow c l \nu$ decays to 3$^{rd}$ generation $\tau$ relative to light 1$^{st}$ and 2$^{nd}$ generation $e$ and $\mu$

$$R(D^*) = \frac{\mathcal{B}(B \rightarrow D^* \tau \nu_\tau)}{\mathcal{B}(B \rightarrow D^* l \nu_\ell)}$$

- Alternatively, can study the inclusive ratio of branching fractions:

$$R(X) = \frac{\mathcal{B}(B \rightarrow X \tau \nu_\tau)}{\mathcal{B}(B \rightarrow X l \nu_\ell)}$$
B → Xτν signal events contain multiple neutrinos in the final state

- Significant missing energy and limited kinematic constraints

Reconstruct the accompanying “tag B” in one of a large number of hadronic decay modes; referred to as “Full Event Interpretation” (FEI)

- Search for the signal B decay in the remainder of the event
- Signal electron or muon from
  \[ \tau \rightarrow e\nu\bar{\nu}, \quad \tau \rightarrow \mu\nu\bar{\nu} \]
  \[ p_{T,\text{lab}}(e) > 0.3/0.5 \text{ GeV}, \quad p_{T,\text{lab}}(\mu) > 0.4/0.7 \text{ GeV} \]
- Remaining reconstructed particles in the event comprise the hadronic system “X”

Primary experimental challenge is modelling and characterizing backgrounds, which arise from:

- B → Xlν \((l = e, \mu)\) decays
- generic B\(\bar{B}\) events with mis-reconstruction
- “continuum” q\(\bar{q}\) events
Data-driven $X\ell\nu$ modelling using $M_X$ distribution in $p_B^\ell > 1.4$ GeV sideband region

Signal determined from 2D distribution of $p_B^\ell$ vs $M_{2\text{miss}}^2$

- Total of 34 bins in $(p_B^\ell, M_{2\text{miss}}^2)$ plane
- Four fit components in each of $e, \mu$ modes:
  - signal $B\rightarrow X\tau\nu$
  - $B\rightarrow X\ell\nu$ background
  - other $BB$ background
  - continuum background
- Systematics dominated by data-driven corrections to background and signal modelling
Results consistent with SM expectation, and previous measurements (from LEP):

$$ R(X) = \frac{\mathcal{B}(B \rightarrow X \tau \nu_\tau)}{\mathcal{B}(B \rightarrow X \ell \nu_\ell)} $$

- Systematics dominated measurement, even with this “small” data set

Combined:

$$ R(X) = 0.228 \pm 0.016 (\text{stat}) \pm 0.036 (\text{syst}) $$

SM expectation: $0.223 \pm 0.006$
Alternative approach:

Exclusively reconstruct the hadronic “X” system in addition to the tag $B$

- Three $D^*$ signal modes are considered:
  - $D^{*+} \rightarrow D^0\pi^+$ and $D^+\pi^0$
  - $D^{*0} \rightarrow D^0\pi^0$

- Identify electron or muon from
  - $\tau \rightarrow e\nu\bar{\nu}$, $\tau \rightarrow \mu\nu\bar{\nu}$

- Require that there are no additional charged tracks or $\pi^0$ candidates left over

- Residual calorimeter energy $E_{ECL}$ and $M_{miss}^2 = (p_{e^+e^-} - p_B - p_{D^*} - p_l)^2$ used to extract signal

Primary experimental challenge is to understand the significant (and poorly known) backgrounds from $B \rightarrow D^{**}l\nu$
Very detailed data-driven validation of background and signal modelling based on studies of sideband regions

- Sideband regions enhanced in specific backgrounds:
  - \( B \rightarrow D^* l \nu \) sideband
  - \( q^2 < 3.5 \text{ GeV} \) (below \( m_\tau^2 \) threshold)
  - \( B \rightarrow D^{**} l \nu \) enhanced sideband
  - (i.e. requiring an additional \( \pi^0 \)) unknown rate and can mimic signal
  - \( D^* \) mass sideband
  - \( (\Delta m_{D^*} = m_{D^*} - m_D) \) constrain fake \( D^* \) yields

- Excellent agreement between data and simulation after sideband-based corrections applied
$R(D^*)$ = \(0.267^{+0.041}_{-0.039}\) (stat) \(+0.028\) (syst)

First $R(D^*)$ experimental result from Belle II

- Consistent with SM and previous experimental results, but still fairly large statistical uncertainties
\( B^+ \rightarrow K^+ \nu \bar{\nu} \)

\( B^+ \rightarrow K^+ \nu \bar{\nu} \) is a rare decay in the SM occurring via a one-loop electroweak FCNC process

- Precise SM prediction:
  \[
  B(B^+ \rightarrow K^+ \nu \bar{\nu}) = (5.6 \pm 0.4) \times 10^{-6}
  \]
  (arXiv:2207.13371)

- Complementary to similar FCNC \( B \) decay such as \( B \rightarrow X_s \gamma \) and \( B \rightarrow K \ell^+ \ell^- \)

- Can be enhanced by BSM contributions, and signature of “\( K + E_{\text{miss}} \)” potentially sensitive to other non-SM models (e.g. dark sector)

Very challenging experimentally due to lack of kinematic constraints for background discrimination

- Previous searches by \( B \) factories have relied on exclusive reconstruction of the accompanying “tag \( B \)” in hadronic or semileptonic decay modes

New Belle II analysis utilizes an “inclusive” search strategy

- Large statistical advantage (~8\% compared with ~0.4\% for hadronic tagging), but challenging backgrounds

- Conventional “hadronic \( B \) tag” method as an auxiliary measurement
B$^+ \rightarrow K^+\nu\bar{\nu}$

Select signal candidate as charged kaon which yields the minimal mass of the di-neutrino $q^2$ (computed as the recoil from the kaon)

- Utilize event topology, the signal kaon, and information about additional particles in the event

Three step selection process:

- Event preselection
  
  $4 \leq N_{\text{tracks}} \leq 10$, $E_{\text{total}} > 4$ GeV and $17^\circ < \theta_{\text{miss}} < 160^\circ$

- BDT1 - Event shape variables (12 inputs)

- BDT2 - Kinematic and “rest-of-event” quantities (35 inputs)

Precise understanding of the background is critical:

- Use multiple control channels to validate all aspects of the analysis performance

- Background mainly from B decays, with $B^+ \rightarrow K^+K^0\bar{K}^0$, $B^+ \rightarrow K^+\pi\pi$, $B \rightarrow Xc(\rightarrow K_L^0 + X)$, and pion mis-identification being problematic
Backgrounds containing $K_L^0$ are potentially a significant issue

- $K_L^0$ detector performance verified directly in data using radiative $\phi \rightarrow K_L^0 K_s^0$
- $B^+ \rightarrow K^+ K^0 \bar{K}^0$ branching fraction is poorly constrained. Use $B^+ \rightarrow K^+ K_s^0 \bar{K}_s^0$ to estimate $B^+ \rightarrow K^+ K_L^0 \bar{K}_L^0$

Pion and lepton enriched samples to study $B \rightarrow X_c (\rightarrow K_L^0 + X)$
- scaling MC predictions leads to excellent agreement with data
$B^+ \rightarrow K^+ \nu \bar{\nu}$

Signal extracted from binned maximum likelihood fit to $q^2$ and classifier output:

- $3.6\sigma$ evidence for $B^+ \rightarrow K^+ \nu \bar{\nu}$ occurring at a rate somewhat above SM expectation
  \[ \mu = 5.6 \pm 1.1\text{(stat)}^{+1.0}_{-0.9}\text{(syst)} \]

- Hadronic tag analysis consistent with no signal, and SM prediction
  \[ \mu = 2.2 \pm 2.3\text{(stat)}^{+1.6}_{-0.7}\text{(syst)} \]

$B_{\text{incl}} = (2.8 \pm 0.5 \text{ (stat)} \pm 0.5 \text{ (syst))} \times 10^{-5}$

$B_{\text{had}} = (1.1^{+0.9}_{-0.8} \text{ (stat)}^{+0.8}_{-0.5} \text{ (syst))} \times 10^{-5}$
Prospects

Belle II is now approaching an integrated luminosity which is directly competitive with the previous generation of B factories

- Improvements in detector, trigger, and analysis strategies have enabled precision measurements and new physics with early Belle II data, and demonstrated the capabilities of the upgraded detector

- Very active ongoing program of research with many new results across a very broad range of physics topics

Data collection and physics program is just beginning!

- Stay tuned for new results with world's largest B Factory data set

![Graph showing peak luminosity and integrated luminosity over time with labels for LS1 and LS2 periods and recorded luminosity of 424 fb⁻¹.]
Additional material
Charmed hadron lifetimes

Factor of 2 improvement in impact parameter resolution compared with BABAR or Belle
Signal:

\[ M^2_{\text{miss}} = (p_{e^+e^-} - p_B - p_{D^*} - p_l)^2 \]

\[ E_{\text{ECL}} = \sum E_{\text{clus}} \]

where \( E_{\text{clus}} \) are clusters that were not used in tag B or D* reconstruction
\[ B^+ \rightarrow K^+ \nu \bar{\nu} \]

Very detailed signal validation:

- Kaon identification performance corrected using \( D^{*+} \rightarrow D^0 (\rightarrow K^- \pi^+) \pi^+ \) control samples, and validated using \( B^+ \rightarrow D^0 (\rightarrow K^+ \pi^-) h^+ \) (\( h = K, \pi \))
- Veto \( D^0 \) daughters to mimic signal signature

\[ B^+ \rightarrow J/\psi K^+ \text{ with } J/\psi \text{ daughters removed to validate MC modelling of extra neutrals} \]