Future of Hadron Spectroscopy at Belle II

Jake Bennett
The University of Mississippi
Snowmass CSS - July 20, 2022

- Belle/KEKB (KEK) and BaBar/PEP-II (SLAC)
  - Very successful physics programs with a total recorded sample over $1.5 \text{ ab}^{-1}$ ($1.25 \times 10^9$ $B\bar{B}$ pairs)
  - Flavor physics (CKM/UT, CPV), NP in rare processes, new particle discoveries


Even >10 years after data taking, still producing new results in hadron spectroscopy

>350 papers published since shutdown!
Belle II capabilities

• Belle II is the next generation B-factory
  - Upgraded detector and accelerator
  - ~1000 members (~100 US @ 18 institutions)
  - ~15-year program ongoing since 2019

• Advantages for quarkonium physics program
  - World record instantaneous luminosity
    (aiming for 50x Belle integrated luminosity)
  - High resolution, hermetic detector, good PID capability
  - Efficient reconstruction of neutrals ($\pi^0$, $\eta$, …)
  - Reconstruct single resonance to explore recoiling system
    (e.g. $e^+e^- \rightarrow J/\psi X$)
  - Using tagged events (i.e. with a fully reconstructed partner B)
    to measure absolute branching fractions
  - Variety of production mechanisms accessible

Belle II potential - B decays

- High-statistics continuation from B-factories
- Competition and complementarity with LHCb (advantages for modes with neutrals)
  - Confirm $Z_c$ states and search for neutral partners
  - Absolute branching fractions $B \rightarrow X(3872,3915) K$
  - Confirmation of $X(3872)$ width measurement with $D^0\bar{D}^0\pi^0$
  - Revamp $B \rightarrow$ baryons, search for pentaquarks!

- $Z_c^+(4050)$
- $Z_c^+(4250)$

[Graphs and tables]

PRD 78, 072004 (2008)
PRD 97, 012005 (2018)
H. Hirata (KMI/Nagoya), MSc Thesis (2019)
Belle II potential - initial state radiation

- Study Y states complementary to BESIII direct $E_{CM}$ scans

- Belle II advantages
  - Comparable sample sizes
  - Continuous mass ranges
  - Access $E > 4.6$ GeV

- Potential contributions
  - Improved $\sigma(e^+e^- \rightarrow \gamma_{ISR}(c\bar{c})(x))$
  - Higher masses/channels (e.g. $\gamma_{ISR}\sum_c\sum_{\bar{c}}$)
  - Confirm $Z_c$ states (e.g. $e^+e^- \rightarrow h_c\pi\pi$)
Belle II potential - double charmonium and two-photon processes

- Unique production modes at Belle II
  - Double-$c\bar{c}$
    - $e^+e^- \rightarrow (c\bar{c})_{J=1}(c\bar{c})_{J=0}$ production rule
    - Discovery of $X(3940, 4160)$
    - Expand to other $c\bar{c}$, search for new states
  - Two-photon
    - $J^{PC}$ of $X(3915)$
    - Confirm $\phi J/\psi$ state?
    - $D^{(*)}\bar{D}^{(*)}$ final states
    - Search for $T_{c\bar{c}c\bar{c}}$

Belle II potential - above $\Upsilon(4S)$

- Aside from $\Upsilon(5S)$, B-factories collected limited data above $\Upsilon(4S)$
  - $\Upsilon(6S) = 11$ GeV, $L_{eff} = \sim 3$ fb$^{-1}$
    - Study nature of $Z_b$ and $\Upsilon(6S)$
    - Higher energy: pathway to other states?
  - $"Y_b(10750)"$, $L = \sim 1$ fb$^{-1}$
    - Far from threshold, no direct conventional match
    - Further study needed - dedicated Belle II data

Unique potential for SuperKEKB/Belle II

References:
- JHEP 10 (2019) 220
- PRL 117, 142001 (2016)
- MPLA 32, 1750025 (2017)
Unique Belle II dataset - dedicated run at 10.750 GeV

- Scan data near $\sqrt{s} = 10.75$ GeV at Belle II - unique opportunity
  - First results quickly after data taking in Fall 2021!

- NEW! $Y(10753) \rightarrow \omega \chi_{bJ}$ observed for the first time
  - $\sigma^B(e^+e^-[@10.745] \rightarrow \omega \chi_{b_1}) = 3.6^{+0.7}_{-0.7} \pm 0.4$ pb
  - $\sigma^B(e^+e^-[@10.745] \rightarrow \omega \chi_{b_2}) = 1.8^{+1.2}_{-1.0} \pm 0.5$ pb

- No significant $X_b$ signal around 10.6 GeV
  - Upper limits are set

- Additional searches ongoing
  - Precise measurements of mass and width
  - Search for additional decay modes
  - Study hadronic transitions (test NRQCD)
Many recent results in charm baryon spectroscopy!

- Production via quark fragmentation, B decays
- Search for new states, measure properties

Recent Belle results
- \( \Lambda_c^+ \to p\omega \), PRD 104, 072008 (2021)
- \( \Lambda_c^+ \to p\eta, p\pi^0 \) PRD 103, 072004 (2021)
- \( \Lambda_c^+ \to \eta\Lambda\pi^+, \eta\Sigma^0\pi^+, \Lambda(1670)\pi^+, \eta\Sigma(1385)^+ \) PRD 103, 052005 (2021)
- \( \Xi_c^0 \to \Lambda K^0_S, \Sigma^0 K^0_S, \Sigma^+ K^- \) arXiv:2111.08981
- \( \Xi_c^0 \to \Xi^0 K^+ K^- \) PRD 103, 112002 (2021)
- \( \Xi_c^0 \to \Lambda\bar{K}^*\Xi_0, \Xi_c^0 \to \Sigma^0\bar{K}^*\Xi_0, \Xi_c^0 \to \Sigma^+ K^- \) JHEP06 160 (2021)
- \( \Xi_c^0 \to \Xi^-\ell^+\nu\ell, \) asymmetry par. of \( \Xi_c^0 \to \Xi^-\pi^+ \) PRL 127, 121803 (2021)
- Spin and parity of \( \Xi_c(2970)^+ \) PRD 103, L111101 (2021)
- Masses and Widths of \( \Sigma_c(2455)^+, \Sigma_c(2520)^+ \) PRD 104, 052003 (2021)
- Evidence for \( \Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(\bar{K}\Xi)^- \) PRD 104, 052005 (2021)

**Belle II is already in the game!**
World’s most precise measurement of the \( \Lambda_c^+ \) lifetime

![Graph showing Belle II Preliminary results with fits and data points](image)

Confirmation that the \( \Omega_c \) is not the shortest-lived charm baryon

arXiv:2206.15227

[ICHEP presentation]
Summary

• Belle II: next generation B-factory building upon success of Belle
• Wide-ranging physics program including study of new XYZ states
• Many opportunities in unique production and decay modes