The use of weak reactions to learn about hadron interactions at Belle II

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B factories

- Belle/KEKB (KEK) and BaBar/PEP-II (SLAC)
  - Very successful physics programs with a total recorded sample over $1.5 \text{ ab}^{-1} \times 1.25 \times 10^9$ $B\bar{B}$ 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!
SuperKEKB and Belle II: 2nd generation “Super B Factory”

$c\bar{c}$, $u\bar{u}$, $d\bar{d}$, $\ell^+\ell^-$ $\leftrightarrow$ $e^+e^-$ $\rightarrow \Upsilon(nS) \rightarrow B^{(*)}\bar{B}^{(*)}$

**Key Components:**
- **New final focus**
- **New positron damping ring**
- **~1 km**
- **4 GeV $e^+$**
- **7 GeV $e^-$**
- **EM Calorimeter:** CsI(Tl), waveform sampling
- **Beryllium beam pipe:** 2 cm diameter
- **Vertex detector:** 2 layers DEPFET + 4 DSSD
- **Central Drift Chamber:** He(50%):C$_2$H$_6$(50%), small cells, long lever arm, fast electronics
- **K_L and muon detector:** Resistive Plate Counter (barrel outer layers) Scintillator + WLSF + MPPC (end-caps, inner 2 barrel)
- **Particle Identification:** Time-of-Propagation counter Prox. Focusing Aerogel RICH
- **Readout (TRG, DAQ):** Max. 30kHz L1 trigger ~100% efficient for hadronic events 1MB (PXD) + 100kB per event - over 30GB/sec to record
- **Offline computing:** Distributed over the world via the GRID
Weak decays and hadronic interactions

- Searches for BSM physics rely on accurate theory **descriptions of strong interactions at low energy**
  - Often rely on predictive models like the Heavy Quark Expansion (HQE)
    - A standard tool for theoretical description of inclusive decays of heavy hadrons
    - Decay widths calculated with expansion in terms of heavy quark mass
CKM metrology

- Measure $|V_{ub}|$ and $|V_{cb}|$ to overconstrain unitarity condition → potent test of Standard Model
- Long-standing discrepancy between inclusive and exclusive measurements
- We need new experimental and theoretical results that challenge existing knowledge
$|V_{cb}|$ from exclusive $B \rightarrow X_c \ell \nu$ decays

- Decay rate depends on product of CKM element and hadronic form factor
  - Global fit for CKM element, extract form factors (test theory predictions)
  - Theory prediction for form factor, extract CKM elements

- Exclusive measurement of $|V_{cb}|$
  - Now have LQCD predictions beyond zero recoil
  - LHCb measurements with $B_s \rightarrow D_s^{(*)} \mu \bar{\nu}_\mu$ [Phys. Rev. D 101, 072004]
  - Preliminary results for $|V_{cb}|$ in $B^0 \rightarrow D^{*-} \ell^+ \nu_\ell$ at Belle II

Short-distance radiative corrections

$$\frac{d\Gamma}{dw} \propto F(w) \ |V_{cb}|^2 \eta_{EW}^2$$
\[ |V_{cb}| \text{ from inclusive } B \rightarrow X_c \ell \nu \text{ decays} \]

Operator Product Expansion

\[ \Gamma = \frac{G_F^2 m_b^5}{192 \pi^3} |V_{cb}|^2 \left( 1 + \frac{c_5(\mu) O_5(\mu)}{m_b^2} + \frac{c_6(\mu) O_6(\mu)}{m_b^3} + \mathcal{O}\left( \frac{1}{m_b^4}\right) \right) \]

- **Traditional approach**: Use hadronic mass moments, lepton energy moments, etc. to determine non-perturbative matrix elements of OPE and extract \( |V_{cb}| \)
  - Allows model-independent extraction of HQE parameters up to \( \mathcal{O}(1/m_b^3) \)
  - Extraction of higher order terms complicated by proliferation of hadronic parameters - rely on modeling

- **Alternative approach** \([\text{JHEP 02 (2019) 177}]\) (M. Fael, T. Mannel, K. Vos): exploit relations between HQE parameters due to reparameterization invariance to reduce the number of independent parameters
  - Not true for every observable (e.g. not for \( \langle M_X \rangle \)), but holds for \( \langle q^2 \rangle \)
  - At \( 1/m_b^4 \) the number of matrix elements reduces from 13 to 8
$q^2$ moments from $B \to X_c \ell \nu$ decays

Improved Hadronic Tagging technique using Belle II algorithm (approximately twice better efficiency than Belle)

$$q^2 = (p_{\text{sig}} - p_{X_c})^2$$

$$M_X = \sqrt{(p_{X_c})_\mu (p_{X_c})^\mu}$$

Belle II - arXiv:2205.06372 (Submitted to PRD)
moments from $B \rightarrow X_c \ell \nu$ decays

Belle II already reaches similar precision to Belle and can reach lower $q^2$ threshold
First extraction of inclusive $|V_{cb}|$ from $q^2$ moments

- Good agreement with the most precise previous measurement, $|V_{cb}| = 42.16(51) \times 10^{-3}$ [hep-ph/2107.00604]
- Provides strong evidence that inclusive $|V_{cb}|$ can be reliably obtained using the HQE
  - Uncertainties well under control

\begin{table}
\begin{tabular}{lcccccccccc}
  |$V_{cb}$| $\times 10^3$ & $m_b^{\text{kin}}$ & $\bar{m}_c$ & $\rho_{G}^{2}$ & $\mu_{m}^{2}$ & $\rho_{P}^{3}$ & $\gamma_{G}^{A}$ & $\gamma_{P}^{B} \times 10^3$ & $\rho_{\text{cut}}$ & $\rho_{\text{norm}}$
\hline
  Value & 41.69 & 4.56 & 1.09 & 0.37 & 0.43 & 0.12 & -0.21 & 0.02 & 0.05 & 0.09
  Uncertainty & 0.59 & 0.02 & 0.01 & 0.07 & 0.24 & 0.20 & 0.69 & 0.34 & +0.03 & +0.10
\end{tabular}
\end{table}
Other tests of theory predictions for hadronic interactions

- Particle lifetimes sensitive to higher order terms in HQE
  - Charm hadrons complicated by poor performance of HQE to describe non-perturbative effects
  - Recent charm lifetime measurements break established charm baryon lifetime hierarchy

\[ \tau(\Xi_c^+) > \tau(\Lambda_c^+) > \tau(\Xi_c^0) > \tau(\Omega_c^0) \]
Charmed baryon lifetimes

- **Charm hadrons in particular provide excellent tests**
  - Charm quark mass is much less than that of the beauty quark
  - Higher order corrections and spectator effects more significant
  - Charmed baryons are most difficult to describe due to model-dependent spectator effects like weak W-annihilation and Pauli interference
  - Provide stringent tests of theory predictions that can be used to inform models used for BSM searches
Charmed hadron lifetimes: experimental status

- $D^0$ and $D^+$ dominated by
  - FOCUS: photon beam experiment
  - SELEX: hyperon beam experiment
  - CLEO: the only $e^+e^-$ measurements

- Other charmed hadrons dominated by LHCb
  - All relative measurements with respect to $D^+$

$$\tau_{\Lambda_c^+} = 203.5 \pm 1.0 \text{ (stat)} \pm 1.3 \text{ (syst)} \pm 1.4 \text{ (}\tau_{D^+}\text{) fs}$$

LHCb - PRD 100 (2019) 032001
Precise lifetime measurements by Belle II

- Lifetimes calculated from distance between production and decay vertices
  - Decay times become negative due to resolution (tool to understand resolution)
  - High precision measurements probe beam spot and alignment calibration

\[
  t = \frac{m_D}{p} \left( \vec{d} \cdot \hat{p} \right)
\]

- Belle II can make precision, absolute lifetime measurements
  - Large samples of exclusive charm decays without lifetime-biasing triggers and selections
  - Precise calibration of final state particle momenta
  - Excellent vertex detector alignment
  - Very good vertex resolution, small beam size
Precise lifetime measurements by Belle II

- High instantaneous luminosity via the “nano-beam” scheme
  - Small beam size better constrains event kinematics
  - Improved flight time resolution
- Beam spot calibrated continuously
  - Using $e^+e^- \rightarrow \mu^+\mu^-$ events

Integrated luminosity goal: 50 $ab^{-1}$
Target luminosity: $6.5 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
June 22, 2022: $4.71 \times 10^{34} \text{ cm}^{-1} \text{ s}^{-1}$

World record!
$D^0$ and $D^+$ measurements by Belle II

- Lifetime measured from an unbinned 2D fit to the ($t$, $\sigma_t$) distribution
  - Simultaneous fit to signal and sidebands
  - Background constrained from mass fit

Belle II - PRL 127 211801 (2021)

Belle II

$\int L dt = 72$ fb$^{-1}$

$D^0$

- Data
- Fit
- Background

$D^+$

- Data
- Fit
- Background

~70 ps resolution

~60 ps resolution

Background neglected

9% backgrounds
D^0 and D^+ measurements by Belle II

\[ \tau(D^0) = 410.5 \pm 1.1 \pm 0.8 \text{ fs} \]
\[ \tau(D^+) = 1030.4 \pm 4.7 \pm 3.1 \text{ fs} \]

<table>
<thead>
<tr>
<th>Source</th>
<th>( \tau(D^0) ) [fs]</th>
<th>( \tau(D^+) ) [fs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resolution model</td>
<td>0.16</td>
<td>0.39</td>
</tr>
<tr>
<td>Backgrounds</td>
<td>0.24</td>
<td>2.52</td>
</tr>
<tr>
<td>Detector alignment</td>
<td>0.72</td>
<td>1.70</td>
</tr>
<tr>
<td>Momentum scale</td>
<td>0.19</td>
<td>0.48</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.80</strong></td>
<td><strong>3.10</strong></td>
</tr>
</tbody>
</table>

- **World’s best measurements of the** \( D^0 \) **and** \( D^+ \) **lifetimes**
  - Consistent with current world averages
  - Sub-1% accuracy establishes excellent detector performance
  - Paves the way for additional lifetime measurements
$\Lambda_c^+$ lifetime measurement at Belle II

- Relatively clean sample of $\Lambda_c^+ \rightarrow pK^-\pi^+$ events
  - Lifetime measured from a fit to the $(t, \sigma_t)$ distribution
  - Reprocessing includes improved alignment calibration
  - Potential bias due to $\Xi_c^0 \rightarrow \Lambda_c^+\pi^-$ and $\Xi_c^+ \rightarrow \Lambda_c^+\pi^0$

Belle II

$\int L \, dt = 207.2 \, fb^{-1}$

Candidates per 0.4 MeV/c$^2$

- Data
- Total fit
- Signal
- Background

$\sim 90 \, ps$

Resolution

Belle II - hep-ex/2206.15227, accepted at PRL
$\Xi_c$ contamination

- Potentially problematic background from $\Xi_c^0 \rightarrow \Lambda_c^+\pi^-$ and $\Xi_c^+ \rightarrow \Lambda_c^+\pi^0$
  - Not accounted in previous $\Lambda_c$ lifetime measurements
  - $\text{BR}(\Xi_c^0 \rightarrow \Lambda_c^+\pi^-) = 0.55 \pm 0.20\%$ (LHCb: PhysRevD.102.071101)
  - $\text{BR}(\Xi_c^+ \rightarrow \Lambda_c^+\pi^0) = 1.11\%$ (https://arxiv.org/pdf/2111.14111.pdf)

- Reduce backgrounds with veto and correct for remaining
  - Reject events with $M(\Lambda_c^+\pi^0) - M(\Lambda_c^+)$ within $2\sigma$ of expected value
  - Conservative estimate determined from fit to impact parameter for $\Lambda_c^+$
  - Mix signal events with generic MC to test potential remaining bias
  - Take half the shift as correction and systematic uncertainty

Lifetimes

\[
\begin{align*}
\tau(\Xi_c^0) &= 153 \pm 6\text{ fs} \\
\tau(\Xi_c^+) &= 456 \pm 5\text{ fs}
\end{align*}
\]

No BF measurement (theory prediction made after LHCb measurement for $\Xi_c^0 \rightarrow \Lambda_c^+\pi^-$)

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty [fs]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Xi_c$ contamination</td>
<td>0.34</td>
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<tr>
<td>Resolution model</td>
<td>0.46</td>
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<tr>
<td>Non-$\Xi_c$ backgrounds</td>
<td>0.20</td>
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<tr>
<td>Detector alignment</td>
<td>0.46</td>
</tr>
<tr>
<td>Momentum scale</td>
<td>0.09</td>
</tr>
<tr>
<td>Total</td>
<td>0.77</td>
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</table>
$\Lambda_c^+$ lifetime measurement at Belle II

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Lifetime (fs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This measurement</td>
<td>$203.20 \pm 0.89 \pm 0.77$</td>
</tr>
<tr>
<td>LHCb (2019)</td>
<td>$203.5 \pm 1.0 \pm 1.3 \pm 1.4$</td>
</tr>
<tr>
<td>FOCUS (2002)</td>
<td>$204.6 \pm 3.4 \pm 2.5$</td>
</tr>
<tr>
<td>SELEX (2001)</td>
<td>$198.1 \pm 7.0 \pm 5.6$</td>
</tr>
<tr>
<td>CLEO (2001)</td>
<td>$179.6 \pm 6.9 \pm 4.4$</td>
</tr>
</tbody>
</table>

- **World’s best measurements of the $\Lambda_c^+$ lifetime**
  - Consistent with current world averages
  - Slight tension with CLEO measurement remains
  - Benchmark for future baryon lifetime measurements
Measurement of the $\Omega_c$ lifetime at Belle II

Belle II - hep-ex/2208.08573, accepted at PRD(L)

Belle II result:
\[
\tau(\Omega_c^0) = 243 \pm 48 \text{(stat)} \pm 11 \text{(syst)} \text{ fs}
\]

Consistent with LHCb average of 274.5 ± 12.4 fs

- Inconsistent at 3.4σ with the pre-LHCb world average, 69 ± 12 fs
  - Confirmation that the $\Omega_c^0$ is NOT the shortest lived charm baryon
Summary

• Major upgrade at KEK for the next generation B-factory
  - Many detector components and electronics replaced, software and analysis tools also improved!
  - Rich physics program, complementary to existing experiments and the energy frontier program
  - Even with early data, excellent performance and good understanding of the Belle II detector

• First high-precision results are here!
  • $q^2$ moments in $B \rightarrow X_c\ell\nu$ with comparable precision to Belle, but much smaller sample
  - World’s best D lifetimes, establishes excellent vertexing
  - World’s best $\Lambda_c$ lifetime, benchmark for future baryon lifetimes
  - Confirmation that the $\Omega_c^0$ is NOT the shortest lived charm baryon

• Only 0.5% of target integrated luminosity collected so far - much more to come!
Belle II capabilities

- 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

Precise lifetime measurements by Belle II

- Upgraded vertex detector
  - More robust tracking
  - Better vertex resolution

- Precise alignment crucial for precision measurements
  - Includes all 14336 wires in central drift chamber (60,000 parameters)