Recent results from Belle and Belle II
Jens Sören Lange (Justus-Liebig-Universität Giessen)
International Workshop on Heavy Quark Physics
Islamabad, 23.-26.11.2021
Outline

• Belle II
  • Status and plan of data taking
  • $D$ meson lifetime
  • $B \to K\nu\bar{\nu}$
  • $X(3872)$
• Belle
  • $X(3872)$
  • New high mass XYZ state in ISR
  • Search for $R^{++}$
  • Search for $D$-wave charmonium
  • Charmed baryons
  • $Y_b$ scan

Emphasis on spectroscopy
Belle II

EM Calorimeter (ECL): 
CsI(Tl), waveform sampling

$K_L$ and muon detector (KLM): 
RPC (barrel outer layers), 
Scintillator + WLSF + SiPM 
(end-caps, inner 2 barrel layers)

Beryllium beam pipe: 
2 cm diameter

electrons 7 GeV

Belle II

$z$ vertex resolution factor $\simeq 2$ better than Belle 
($\geq 15 \mu m$)

Vertix detector (VXD): 
2 layers DEPFET pixels, 
4 layers double-sided silicon strip detectors

1.5 T superconductive solenoid

charged tracks $\simeq 20\%$ longer than Belle

Central Drift Chamber (CDC) 
$He(50\%): C_2 H_6 (50\%)$, small cells, long 
lever arm, fast electronics

Particle Identification: 
Prox. focusing Aerogel RICH

$\simeq 7 \times 7 \times 7 \text{ m}^3$
Nano-Beam Scheme

Belle → Belle II
Peak luminosity x 30

Resulting in slightly smaller boost
\[ \beta' = 0.43 \text{ (Belle)} \]
\[ \beta' = 0.29 \text{ (Belle II)} \]

originally proposed for SuperB by P. Raimondi (INFN)
Status and plan of Belle II data taking

- Belle II collected data 215 fb\(^{-1}\) (~20% of Belle, ~50% of BaBar data)
- 1 fb\(^{-1}\) is about 1.1 Mill. \(B\bar{B}\) pairs
- Peak luminosity reached 3.12 \(\times 10^{34}\) cm\(^{-2}\) s\(^{-1}\)
- 50% higher than previous world record by KEKB
- factor 3 higher than KEKB design luminosity
- 89.5% data taking efficiency during the pandemic situation (remote shifts & heroic local effort)
- Plan: long shutdown in 2023 (2\(^{nd}\) layer of PXD, TOP upgrade)
- Plan: 50 ab\(^{-1}\) in \(\geq 2031\)
$D^0$ and $D^+$ meson lifetime at Belle II

- Belle II Vertex Detector
  - 2-layer all-silicon pixel detector (PXD)
    - 1st layer of PXD fully installed (4 M pixels)
    - Innermost PXD layer is only 1.4 cm from the IP (factor 2 nearer than Belle)
    - Very low material budget (0.21% $X_0$/layer)
  - 4-layer double-sided silicon strip detector (SVD)
  - Factor 2 improvement in the impact parameter resolution vs. Belle
$D^0$ and $D^+$ meson lifetime at Belle II

- $D^*$ tagging
- Unbinned fit to $(t, \sigma_t)$
- Resolution $\sim 60-70$ fs
- Largest systematic error: alignment
  0.72 fs ($D^0$), 1.70 fs ($D^+$)

Improvement in resolution visible at $t<0$

Background permille level (no red line)
$D^0$ and $D^+$ meson lifetime at Belle II

Phys Rev. Lett. 127 (2021) 211801

$\tau(D^0) = 410.5 \pm 1.1 \pm 0.8 \, fs$

$\tau(D^+) = 1030.4 \pm 4.7 \pm 3.1 \, fs$

• Consistent with current world averages
  $410.1\pm1.5 \, fs \, (D^0)$ and $1040\pm7 \, fs \, (D^+)$

• World’s most precise measurements
  accuracies:
  3.5 permille ($D^0$) and 5.4 permille ($D^+$)
\[ B^+ \rightarrow K^+ \nu \bar{\nu} \]
Radiative penguin

Wilson coefficients
$C_7$, $C_9$, $C_{10}$

For definition of Wilson coefficients, see talks by Ahmed Ali and Cai-Dian Lu.
$B^+ \rightarrow K^+ \nu \bar{\nu}$ at Belle

- Complementary to $b \rightarrow s l^+ l^-$ (tensions with the SM observed)
- SM prediction
  \[ \mathcal{B}(B \rightarrow K \nu \bar{\nu})_{SM} = (4.6 \pm 0.5) \times 10^{-6} \]
  T. Blake et al., Prog. Part. Nucl. Phys. 92 (2017) 50
- Previous analyses
  - Advantage for $e^+ e^-$ collisions, $\sqrt{s}$ is fixed
    Signature: missing energy (peaking at zero)
  - $B$ meson tagging
    (full reconstruction on the opposite side)
    hadronic tagging $\varepsilon_{\text{sig}} \cdot \varepsilon_{\text{tag}} \approx 0.04\%$
    semileptonic tagging $\varepsilon_{\text{sig}} \cdot \varepsilon_{\text{tag}} \approx 0.20\%$
- New approach:
  "inclusive tagging"
  Belle II data (only), 63 fb$^{-1}$
\( B^+ \rightarrow K^+ \nu \bar{\nu} \) at Belle II

- Signal reconstructed as the highest \( p_T \) track
- Inclusive reconstruction of the rest–of–event (ROE)
- New technique: two boosted decision trees (BDT)
  51 input parameters for background suppression
  (BDT\(_2\) is trained with preselected events BDT\(_1\)>0.9)
- Background: e.g. \( K^+ \) from \( D \) decays
- No signal yet: upper limit determined
  \( \mathcal{B}(B \rightarrow K\nu\bar{\nu}) \leq 4.1 \times 10^{-5} \) (90% CL)

\[ \frac{p_T(K^+)}{GeV/c} \]
**XYZ states**

- Unexplained, narrow states in charmonium/bottomonium mass region
- Some of them charged (Z states) minimum quark content \([QQqq']\)
- Historically first candidate: \(X(3872)\)
  - observed by 7 experiments
  - very narrow (\(\leq 1\) MeV)
  - isopin violating decays

**TETRAQUARK**

\[
\begin{array}{c}
Q \\
q \\
\bar{q} \\
\bar{Q}
\end{array}
\in [qQ][qQ][qQ][qQ]
\]

Diquarks are colored

**MOLECULE**

\[
\begin{array}{c}
\bar{D} \\
\pi \\
D^*
\end{array}
\]

**HADRO-CHARMONIUM**

Maiani, Riquer, Piccinini, Polosa, Burns; Ebert, Faustov, Galkin; Chiu, Hsieh; Ali, Hambrock, Wang (b quarks)

Tornqvist; Swanson; Braaten, Kusonoki, Wong; Voloshin; Close, Page Guo, Hanhart, Meißner, Wang, Zhao, Zou

Voloshin, Dubysnkiy Wang, Cleven, Guo, Hanhart, Meißner, Wu, Zhao; Ferretti
X(3872) at Belle II (new 2021)

Unbinned maximum likelihood fit with triple Gaussian and 1st order Chebyshev polynomial

By now, already factor 3 more data on tape

Efficiency 22.9%

Efficiency 17.5%
X(3872) in neutral and charged $B$ meson decays

- Ratio is sensitive to the nature of the $X(3872)$
- If $X(3872)$ is a $D\bar{D}^*$ molecule, ratio should be small ($<0.1$)
  
  $B^0, K^0$ contain $d$ quarks --- $B^+, K^+, D^0, \bar{D}^{*0}$ contain $u$ quarks


- If $X(3872)$ is charmonium, hybrid, glueball, ratio should be large ($=1$)

- Exotic nature of $X(3872)$ is already seen in present Belle II data but caution: simultaneous fit of $B^0$ and $B^+$, and ratio was fixed to 0.5

\[
\frac{\mathcal{B}(B^0 \to K_s^0 \psi(2S))}{\mathcal{B}(B^+ \to K^+ \psi(2S))} = \frac{(5.8 \pm 0.5) \times 10^{-4}}{(6.24 \pm 0.20) \times 10^{-4}} \simeq 0.93
\]

PDG 2021

\[
\frac{\mathcal{B}(B^0 \to K_s^0 X(3872))}{\mathcal{B}(B^+ \to K^+ X(3872))} = \frac{(1.1 \pm 0.4) \times 10^{-4}}{(2.1 \pm 0.7) \times 10^{-4}} \simeq 0.52
\]
Belle results

Belle collected data $\sim 1 \text{ ab}^{-1}$
$(711 \text{ fb}^{-1} \text{ on } \Upsilon(4S), 121 \text{ fb}^{-1} \text{ on } \Upsilon(5S))$
Evidence for $\gamma\gamma \rightarrow X(3872)$

- $X(3872)$ has $J^{PC}=1^{++}$
- Landau–Yang theorem: coupling of $J=1$ particle to two real photons is forbidden
- Here: at least one of the photon is virtual
  \[ \Gamma_{\gamma\gamma} B(X \rightarrow J/\psi \pi^+\pi^-) = 5.5^{+4.1}_{-3.8} \text{(stat.)} \pm 0.7 \text{(syst.)} \text{ eV} \]
- Upper limit from BESIII  
  \[ \Gamma_{ee} B(X \rightarrow J/\psi \pi^+\pi^-) < 0.13 \text{ eV} \]

(Belle result is measurement, not upper limit, with QED vertex factor relates to 0.50 eV)

Reference signal ($J^{PC}=1^{--}$)

Significance $3.2\sigma$

(background $0.11\pm0.10$ events)
XYZ States decaying into $D^{(*)}D^{(*)}$

- Many states observed
  - $X(3872)$ decays, $J^P=1^+$, $[D \text{ anti-}D^{(*)}]$
  - $Z$ states, $J^P=1^+$, $[D \text{ anti-}D^{(*)}]$ and $[D^{(*)} \text{ anti-}D^{(*)}]$
  - States in double charmonium production $J^P=0^+, 2^+, ...$
    - Belle, Phys. Rev. Lett. 100 (2008) 202001, 693 fb$^{-1}$
  - All of them above threshold, order few MeV $\rightarrow$ not bound
- $T_{cc}^+, [DD^{*+}]$ state
  - [meson meson], not [meson anti-meson]
  - in tetraquark picture: a baryon (QQq) with $q$ replaced by $qq$ pair (color-equivalent in QCD)
- Below threshold! And very narrow!
- What can Belle (II) do? $\rightarrow J^P=1^-$ states
New XYZ state in ISR (Initial State Radiation)

- Only observable in $e^+e^-$ collisions, not at hadron colliders
- Quantum numbers fixed $J^{PC} = 1- -$

Belle, Phys. Rev. D100 (2019) 111103, 922 fb$^{-1}$

$\begin{align*}
\text{Belle, Phys. Rev. D 101 (2020) 091101, 922 fb}^{-1}
\end{align*}$
**XYZ states with high mass (above 4.6 GeV)**

Only XYZ state so far decaying into baryons, possible hexaquark \([uuuddcc]\)

- **Belle**
  - Y(4660)
  - New, \(~200\,\text{pb (peak)}\)
  - \(m(D_s^+D_s^{*-}(2536)) / \text{GeV}\)

- **BaBar**
  - Y(4660)
  - \(~30\,\text{pb (peak)}\)

- **X(4630)**
  - \(~600\,\text{pb (peak)}\)
  - \(m(\Lambda_c^+\Lambda_c^-) / \text{GeV}\)

- **New, \(~200\,\text{pb (peak)}\)**
  - \(m(D_s^+D_s^{*-}(2573)) / \text{GeV}\)

Diagram:
- \(Q\) needs 2 gluons
- \(\bar{Q}\) needs 2 gluons
$\text{XYZ states with high mass (above 4.6 GeV)}$

<table>
<thead>
<tr>
<th></th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Source</th>
<th>Cross Section (fb$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle</td>
<td>$\Lambda_c^+ \Lambda_c^-$</td>
<td>$4634^{+8+5}_{-7-8}$</td>
<td>$92^{+40+10}_{-24-21}$</td>
<td>Phys. Rev. Lett. 101(2008)172001</td>
</tr>
<tr>
<td>Belle</td>
<td>$\psi(2S)\pi^+\pi^-$</td>
<td>$4652 \pm 10 \pm 8$</td>
<td>$68 \pm 11 \pm 1$</td>
<td>Phys. Rev. D91(2015)112007</td>
</tr>
<tr>
<td>BaBar</td>
<td>$\psi(2S)\pi^+\pi^-$</td>
<td>$4669 \pm 21 \pm 3$</td>
<td>$104 \pm 48 \pm 10$</td>
<td>Phys. Rev. D98(2014)111103</td>
</tr>
<tr>
<td>Belle</td>
<td>$D_s^+ D_{s1}^- (2536)$</td>
<td>$4626^{+7}_{-7} \pm 1$</td>
<td>$49.8^{+14}_{-12} \pm 10$</td>
<td>Phys. Rev. D100(2019)111103</td>
</tr>
<tr>
<td>Belle</td>
<td>$D_s^+ D_{s2}^- (2573)$</td>
<td>$4620^{+9}_{-8} \pm 3$</td>
<td>$47.0^{+32}_{-15} \pm 5$</td>
<td>Phys. Rev. D101(2020)091101</td>
</tr>
</tbody>
</table>

Compatible in mass and width
All of them $J^{PC}=1^{--}$
Search for $R^{++}$

- Remember $T_{cc}^+$, as $[D^0D^{*+}]$ state at LHCb
- $[D^+D_{s0}^{*+}(2317)]$ predicted [DDK] molecular state by kaon exchange
  5-15 MeV binding energy
  mass 4.13–4.17 GeV

- $D_{s0}^{*+}(2317)$ decay to $DK$ kinematically forbidden, but decay to $[D^+D_s^{*+}]$ possible by triangle diagram

- Needs two charm quarks, thus also two anti-charm quarks
  $\Upsilon(nS) \rightarrow ccccX$

- $\rightarrow$ take $\Upsilon(1S)$ and $\Upsilon(2S)$ decays and inclusive production in $e^+e^-$ at three energies (continuum, $\Upsilon(4S)$ and $\Upsilon(5S)$)
  Belle, Phys. Rev. D 102 (2020) 112001
Search for $R^{++}$

Fit examples for fixed mass 4.14 GeV/c$^2$ and fixed width 2 MeV

No signal observed. Upper limits on cross sections are small (order of few fb)
Search for $\eta_{c2} \left( ^1D_2 \right)$

- D-wave state ($L=2$)
- Last missing charmonium state below $D\bar{D}^*$ threshold!
- One of the $X(3872)$ interpretations before determination of quantum numbers
  
- Predicted width very narrow $\Gamma = 0.46$ MeV
  
  $D\bar{D}^*$ and $D^*\bar{D}^*$ decays kinematically forbidden
  
  $D\bar{D}$ decay forbidden by parity
  
- Search in $e^+e^-$ direct production
  
  $\sigma(e^+e^- \to \gamma\eta_{c2}(1D))B(\eta_{c2}(1D) \to \gamma h_c(1P)) < 4.9$ fb
  
  Belle, Phys. Rev. D104 (2021) 012012
- Search in B decays
  
  $B(B^+ \to \eta_{c2}(1D)K^+) \times B(\eta_{c2}(1D) \to h_c\gamma) < 3.7 \times 10^{-5}$
  
  Belle, JHEP 2005 (2020) 034

$$\eta_{c2} \to \gamma h_c, h_c \to \gamma \eta_c$$

$\eta_c$ reconstructed in 10 decay channels
CHARMED BARYONS
Introduction to charmed baryons $\Xi_c^0 (dsc), \Xi_c^+ (usc)$

- After decades of searches, double charmed baryon discovered by LHCb
  $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^-$

- Confirmed in $\Xi_{cc}^{++} \rightarrow \Xi_c^+ \pi^+, \Xi_c^+ \rightarrow pK^- \pi^+$

- Isospin partner ($ccu$ instead of $ccd$) still missing would decay $\Xi_{cc}^+ \rightarrow \Xi_c^+ \pi^- \pi^+$
  experimentally difficult, lifetime predicted factor 2-4 smaller

- Important input for predictions of stable tetraquarks ($ccqq$) e.g. $T_{cc}^+$

- Three new states discovered $\Xi_c^0 (2923), \Xi_c^0 (2939), \Xi_c^0 (2965)$, orbital excitations?
$\Xi_c$ decay channels at Belle

All decays are Cabibbo allowed ($V_{cs}$ transition).

Belle, Phys. Rev. D 94 (2016) 052011
New $\Xi_c$ branching fractions in 2021

$\Xi_c^0 \rightarrow \Lambda K^{*0}, \Sigma_0 K^{*0}, \Sigma^+ K^{*-}$

Belle, JHEP 2106 (2021) 160, 980 fb$^{-1}$

$\Xi_c^0 \rightarrow \Xi^0 K^+ K^-$

Belle, Phys. Rev. D103 (2021) 112002, 980 fb$^{-1}$

$\Xi_c^0 \rightarrow \Xi^- l^+ \nu_l$

Belle, Phys. Rev. Lett. 127 (2021) 121803, 800 fb$^{-1}$

Parity violation (hyperon polarization)

W exchange

Semileptonic decay
Absolute branching fraction of $\Xi_c^+$

- $\bar{B}^0 \rightarrow \bar{\Lambda}_c^- \Xi_c^+$
- Reconstruct $\bar{\Lambda}_c^- \rightarrow \bar{p}K^+\pi^-$
- Measure $\Xi_c^+$ exclusive decays
- Recoil mass of $\bar{\Lambda}_c^-$ w/o reconstructing $\Xi_c^+$ subdecay (normalization of 100% branching fraction)
- Tag $B^0$ (on the opposite side, normalization of absolute yield)

$$B(\Xi_c^+ \rightarrow \Xi^-\pi^+\pi^+) = (2.86 \pm 1.21 \pm 0.38)\%$$

$$B(\Xi_c^+ \rightarrow pK^-\pi^+) = (0.45 \pm 0.21 \pm 0.07)\%$$

Belle, Phys. Rev. D 100 (2019) 031101, 711 fb$^{-1}$

Both decays are Cabibbo suppressed ($V_{cd}$ transition)

→ Conclusion: Only 24.4% of $\Xi_c^+$ branching fractions known (PDG2021)
Radiative decays of orbitally $\Xi_c$ excited states

- Strong decays dominant in charmed baryons
- EM decays
  - only observed in rare cases, e.g. if pion transition forbidden by kinematics (e.g. $\Xi_c^{'} \rightarrow \Xi_c \gamma$)
  - allowed, if parity flip possible ($L=1$ transition)
- first observation of an EM decay of an orbitally-excited charmed baryon (significance 8.6 $\sigma$)

Belle, Phys. Rev. D 102 (2020) 071103, 980 fb$^{-1}$
Radiative decays of orbitally excited $\Xi_c$ states

Orbital $\lambda$ excitation $L=1$ with spin-1 diquark

Orbital $\lambda$ excitation $L=1$ with spin-0 diquark

Decay of orbitally excited charged $\Xi_c^+$ not observed, $\left[ + - \right]$ vs. $\left[ ++ \right]$ diquark $\rightarrow \rho$ excitation disfavored
$Y_b$ SCAN
BOTTOMONIUM

- $\Upsilon(5S)$ never observed at LHC
- Branching of $\Upsilon(5S)\rightarrow\Upsilon(nS)\pi\pi$ is factor $\approx 1000$ larger than $\Upsilon(4S)\rightarrow\Upsilon(nS)\pi\pi$ $\rightarrow\Upsilon(5S)$ exotic itself?
- Charged $Z_b$ states observed in $\Upsilon(5S)$ decays
  Belle, Phys. Rev. D91 (2015) 072003
  peculiar properties:
  - spin flip in decays not suppressed
- New state observed: $Y_b(10750)$

- $Z_b(10610)\pm$ $m=10607.2\pm2.0$ MeV
  2.6 MeV above $B\bar{B}^*$ threshold
- $Z_b'(10650)\pm$ $m=10652.2\pm1.5$ MeV
  2.0 MeV above $B^*\bar{B}^*$ threshold
  confirmed in 5 decay modes

**Y_b(10750)**

- Seven scan points below \( \Upsilon(5S) \) at Belle, each \( \approx 1 \text{ fb}^{-1} \)
- New structure observed in \( \Upsilon(nS)\pi\pi \)

Further evidence in destructive interference

Refit of BaBar and Belle scan data

Dong et al., Chin. Phys. C 44 (2020) 8, 083001

<table>
<thead>
<tr>
<th>Parameter</th>
<th>( \Upsilon(10860) )</th>
<th>( \Upsilon(11020) )</th>
<th>New structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass/(MeV/c^2)</td>
<td>10885.3 ( \pm 1.5^{+2.2}_{-0.9} )</td>
<td>11000.0 (^{+4.0}<em>{-4.5}^{+1.0}</em>{-1.3} )</td>
<td>10752.7 (^{+0.7}_{-1.1} )</td>
</tr>
<tr>
<td>Width/MeV</td>
<td>36.6 (^{+4.5}<em>{-3.9}^{+0.5}</em>{-1.1} )</td>
<td>23.8 (^{+8.0}<em>{-6.8}^{+0.7}</em>{-1.8} )</td>
<td>35.5 (^{+17.6}<em>{-11.3}^{+3.9}</em>{-3.3} )</td>
</tr>
</tbody>
</table>

JHEP 10 (2019) 220
New $Y_b$ Scan at Belle II (ongoing)

- Accelerator energies are changed
- Scan started 11.11.2021
- Prediction for $Y_b(10750) \rightarrow \Upsilon(1S)\pi\pi$


- $\Upsilon(5S)$ decay is dominated by $Z_b$ states but $Y_b$ decay to $Z_b$ suppressed/forbidden
- $\pi\pi$ Mass distribution: tetraquark should have strong contribution from scalar $f_0$ states

<table>
<thead>
<tr>
<th>Energy</th>
<th>Int. Luminosity</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.751 GeV</td>
<td>$\approx 10 \text{ } fb^{-1}$</td>
</tr>
<tr>
<td>10.657</td>
<td>$\approx 1 \text{ } fb^{-1}$</td>
</tr>
<tr>
<td>10.706</td>
<td>$\approx 1 \text{ } fb^{-1}$</td>
</tr>
<tr>
<td>10.810</td>
<td>$\approx 1 \text{ } fb^{-1}$</td>
</tr>
</tbody>
</table>

Plan
New $Y_b$ Scan at Belle II (ongoing) – $B\bar{B}$ decomposition

$q\bar{q}$ pair is present in the system

$q\bar{q}$ pair is created from vacuum

$^{3}_P_{0}$ model

<table>
<thead>
<tr>
<th>Mode</th>
<th>$B(4q)$ (%)</th>
<th>$B(bb)$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B\bar{B}$</td>
<td>39.3 $^{+38.7}_{-22.9}$</td>
<td>21.3</td>
</tr>
<tr>
<td>$B\bar{B}^*$</td>
<td>~0.2</td>
<td>14.3</td>
</tr>
<tr>
<td>$B^<em>\bar{B}^</em>$</td>
<td>52.3 $^{+54.9}_{-31.7}$</td>
<td>64.1</td>
</tr>
<tr>
<td>$B_s\bar{B}_s$</td>
<td>-</td>
<td>0.3</td>
</tr>
</tbody>
</table>


Belle, JHEP 2106 (2021) 137

$e^+e^- \rightarrow B\bar{B}$

$e^+e^- \rightarrow B\bar{B}^*$

$e^+e^- \rightarrow B^*\bar{B}^*$
Conclusion

- New analysis results from Belle still appearing
- Data taking at Belle II progressing
- First Belle II publications, new techniques enabling competitive measurements (not shown today: dark sector, τ mass, CKM angles, ...)
- Belle II upgrade planned for 2023