PROSPECTS FOR HADRONIC PHYSICS AT BELLE II

INDIANA UNIVERSITY
Anselm Vossen
For the Belle II Collaboration

9/8/2017
OUTLINE

• Belle (I) Legacy
  • Quarkonium (like)
  • Hadronization (Fragmentation function measurements)

• SuperKEKB and Belle II
  • Upgrade
  • Status
  • Early Physics program
  • Outlook
Before there was

- KEKB: asymmetric $e^+ (3.5 \text{GeV}) e^- (8 \text{GeV})$ collider:
  - $\sqrt{s} = 10.58 \text{ GeV}$, $e^+ e^- \rightarrow Y(nS) \rightarrow B/B + \text{continuum}$
  - $\sqrt{s} = 10.52 \text{ GeV}$, $e^+ e^- \rightarrow \text{qqbar (u,d,s,c)} \text{'continuum'}$

- Ideal (at the time) detector for high precision measurements:
  - tracking acceptance $\theta [17^\circ;150^\circ]$: Azimuthally symmetric
  - particle identification (PID): dE/dx, Cherenkov, ToF, EMcal, MuID

- Available data:
  - $\sim 1 \text{ ab}^{-1}$ total
  - $\sim 1.8 \times 10^9$ events at 10.58 GeV,
  - $\sim 220 \times 10^6$ events at 10.52 GeV

(took data till 2010)
BELLE LEGACY IN HADRONIC PHYSICS – QUARKONIUM (-LIKE) PRODUCTION

- B decays
  - Charmonium only
  - All quantum numbers available
- Direct production / Initial State Radiation (ISR)
  - $E_{CM}$ or below
  - $J^{PC}=1^{--}$
- Two-photon interaction
  - $J^{PC}=0^{-+}, 0^{++}, 2^{++}$
- Double charmonium production
  - Seen for $J^{PC}=1^{--}$ ($J/\psi, \psi(2S)$) plus $J=0$ states (C=1?)
- Quarkonium transitions
  - Hadronic/radiative decays between states
QUARKONIUM STUDIES AT BELLE II BUILD ON THE SUCCESSFUL BELLE PROGRAM

• XYZ revolution kicked off by discovery of $X(3872)$ at Belle 2003
• Precision study of Charmonium: States above the DDbar threshold are a strong suit of B factories → can access energy spectrum continuously)
• Precision studies of Bottomium states and transitions

(Choi et al, PRL91 (26) 262001)
• Fragmentation Functions appear almost always when accessing partonic structure of the nucleon
• Proton Structure extracted using QCD factorization theorem
• FFs contribute to virtually all processes
• Particular important for transverse spin structure

\[
\frac{d^2\sigma(ep \rightarrow \pi X)}{dx \, dz} \propto q(x, k_T) \times FF(z, p_T)
\]
ACCESS TO FRAGMENTATION FUNCTIONS IN $e^+e^-$
ACCESS TO FRAGMENTATION FUNCTIONS IN $e^+e^-$

- Polarized FFs can be extracted from back-to-back production
B-FACTORIES: A NEW ERA FOR THE STUDY OF FRAGMENTATION FUNCTIONS
EXAMPLES OF FF ‘FIRSTS’ AT BELLE

- First observation of Collins effect in back-to-back hadrons
- First access to polarization dependent di-hadron FFs


BELLE-CONF-1611, arXiv:1611.06648

Belle preliminary

- First observation of transverse $\Lambda$ polarization in $e^+e^-$
- Learn about Baryon spin structure in hadronization
AND THERE IS MORE BELLE HADRONIC PHYSICS

• Exclusive hadronic x-sections (see talk by Griessinger on Wed. on BaBar results)
• Transition form factors
• ....
WISHLIST

• More data will help Quarkonium and Fragmentation Fct! studies!
  • Map out resonances
  • More data at/above \(Y(4S)\) → search molecular structures near open bottom thresholds
  • Experimental information of charmonium > Ddbar threshold very incomplete,
  • More data below \(Y(4S)\) → test predictions for unobserved bottomium states
  • Determine transitions and quantum numbers
  • More differential access to fragmentation functions
  • Precision back-to-back correlations of less copious hadrons (e.g. \(\Lambda\))
  • Precision should be on par with anticipated SIDIS data from JLab12

• State of the Art Detector
  • PID: increase efficiency of e.g. multi kaon final states
  • Vertexing: More efficient charm rejection for FF studies
KEKB → SUPERKEKB: DELIVER INSTANTANEOUS LUMI × 40

e^+ 4 GeV 3.6 A

e^- 7 GeV 2.6 A

(~2x KEKB)

SuperKEKB
Target: \( L = 8 \times 10^{35} / \text{cm}^2 / \text{s} \)

- New superconducting final focusing quads (QCS) near the IP
- Reinforce RF systems for higher beam current
- New positron target / capture section
- New IR

- Damping ring (new)
- To inject low emittance positrons

Redesign the lattices of HER & LER to squeeze the emittance
- TiN-coated beam pipe with antechambers
- Cu for wigglers and Al alloy for the rest
- Replace short dipoles with longer ones

To inject low emittance electrons

\[ L = \frac{Y_e}{2er_e} \left( 1 + \frac{Q_y}{2} \right) \left( \frac{I_e}{e} \right) \left( \frac{R_y}{R_e} \right) \]
**EM Calorimeter:**
CsI(Tl), waveform sampling
Pure CsI for end-caps

**Beryllium beam pipe**
2cm diameter

**Vertex Detector:**
2 layers DEPFET + 4 layers DSSD

**Central Drift Chamber**
He(50%):C₂H₆(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 layers)

**Particle Identification:**
Time-of-Propagation counter (barrel)
Prox. focusing Aerogel RICH (fwd)

**Readout (TRG, DAQ):**
Max. 30kHz L1 trigger ~100% efficient for hadronic events.
1MB(PXD)+100kB(others) per event → over 30GB/sec to record

**Offline computing:**
Distributed over the world via GRID
BELLE II DETECTOR (COMP. TO BELLE)
NEW PARTICLE ID DEVICE THAT SAMPLES CHERENKOV LIGHT DISTRIBUTION WITH PICO-SECOND TIMING

- Mainly TOP detector: goal of resolution < 40ps
- Kaon ID Efficiency >95% over large part of phase space compared with 85% at Belle
- Readout integration of installed sub-detectors and central DAQ is in progress.
- Combined data taking established in cosmic running
CURRENT STATUS AND SCHEDULE

- Phase 1 (complete)
  - Accelerator commissioning

- Phase 2 (early 2018)
  - First collisions (20±20 fb−1)
  - Partial detector
  - Background study
  - Physics possible

- Phase 3 ("Run 1", early 2019)
  - Nominal Belle II start
  - **Ultimate goal: 50 ab−1**

- **Search for New Physics via precision measurements**
  - CPV, (semi-)leptonic/penguin decays, LFV, dark sector, …
BELLE II EARLY PHYSICS PROSPECTS

- Existing B-Factories ~1.5 ab$^{-1}$: opportunity for other results in Phase 2/3?

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Scans/Off. Res. fb$^{-1}$</th>
<th>$\Upsilon(5S)$</th>
<th>$\Upsilon(4S)$</th>
<th>$\Upsilon(3S)$</th>
<th>$\Upsilon(2S)$</th>
<th>$\Upsilon(1S)$</th>
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<tbody>
<tr>
<td>CLEO</td>
<td>17.1</td>
<td>0.4 10876 MeV fb$^{-1}$ 10$^6$</td>
<td>0.1 10580 MeV fb$^{-1}$ 10$^6$</td>
<td>1.2 10355 MeV fb$^{-1}$ 10$^6$</td>
<td>5 10023 MeV fb$^{-1}$ 10$^6$</td>
<td>21 9460 MeV fb$^{-1}$ 10$^6$</td>
</tr>
<tr>
<td>BaBar</td>
<td>54</td>
<td>$R_b$ scan 433 471</td>
<td>30 122 14 99</td>
<td>–</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Belle</td>
<td>100</td>
<td>121 711 772</td>
<td>3 12 25 158</td>
<td>6 102</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Potential impact with $O(10^{-100})$ fb$^{-1}$

- Phase 2: Above $\Upsilon(4S)$
  - Study of $\Upsilon(nS)$ states in (hadronic) transitions
  - Study of exotic four-quark states (e.g. $Z_b$ at $\Upsilon(6S)$)
    → Study possible with limited tracking resolution
BELLE II EARLY PHYSICS PROSPECTS

• Existing B-Factories ~1.5 ab⁻¹: **opportunity for other results in Phase 2/3**?

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<tr>
<th>Experiment</th>
<th>Scans/Off. Res. fb⁻¹</th>
<th>( \Upsilon(5S) )</th>
<th>( \Upsilon(4S) )</th>
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<td>0.4</td>
<td>0.1</td>
<td>16</td>
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<td>1.2</td>
</tr>
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<td>BaBar</td>
<td>54</td>
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<td>433</td>
<td>471</td>
<td>30</td>
<td>122</td>
</tr>
<tr>
<td>Belle</td>
<td>100</td>
<td>121</td>
<td>36</td>
<td>711</td>
<td>772</td>
<td>3</td>
</tr>
</tbody>
</table>

Potential impact with \( \mathcal{O}(10-100) \) fb⁻¹

• Phase 2: Above \( \Upsilon(4S) \)
  • Study of exotic four-quark states (e.g. Zb at \( \Upsilon(6S) \))
    → Study possible with limited tracking resolution
  • BB** threshold? : \( R_b \) dip versus \( \pi \pi \Upsilon \) rise
  • <6fb⁻¹ accumulated by Belle at \( E_{CM} = \Upsilon(6S) \)
  • Currently energies up to \( \Lambda_b \Lambda_b \) threshold (11.24GeV) possible

• Early phase 3: Below \( \Upsilon(4S) \)
  • \( \Upsilon(2S,3S) \) access to bottomonium
  • Scan for direct production of \( \Upsilon(1^3D_j) \) triplet, \( \eta_b(1S,2S) \) studies

PRD 82, 091106 (2010). 0810.3829. (Belle)
Precise Knowledge of Fragmentation Functions Necessary for Successful SIDIS Program at JLab12

- JLab12 SIDIS program will have unprecedented precision
- \( \rightarrow \) Need similar precision for Fragmentation functions
- Example: Precise measurement of \( p_T \) dependent Collins effect at SOLID
  - Needs precise measurement of Collins and spin averaged \( p_T \) dependent fragmentation functions!
- More advantages of Belle II for FF measurements:
  - Better Vertex resolution, increased MC statistics \( \rightarrow \) lower systematics from charm contribution
  - Better PID: Multi-kaon final states
SUMMARY & OUTLOOK

• Belle II will integrate 50x Belle luminosity (= 50 ab$^{-1}$) over ~6 years
• State of the art detector
• Precision studies of Quarkonia, hadronization
• Physics program with first data focusing on $E_{CM} > Y(4S)$ already promising!
• Precision hadronization studies crucial for JLab12 SIDIS program
BACKUP
ABOVE $\Upsilon(4S) / \Upsilon(6S)$ RUNNING

- $\Upsilon(6S)$ expectation from $\Upsilon(5S)$ and $\Upsilon_c(4XXX)$
- Bottomonium: $\pi\pi h_b(1,2,3?P), \pi\pi \Upsilon(1,2,3S), \eta \Upsilon(1,2D)?$
- Resolve charged/four-quark intermediate states
- Search for $X_b(“3872”)$?
- $\Upsilon(6S) / BB$ threshold energy region behavior

- Phase 2 considerations
  - Low $p_T$ track reconstruction
  - Rest of detector nominal
  - Existing Belle data $<$6fb$^{-1}$
- **Sufficient for $Z_b$ study**

- Phase 3: 100 fb$^{-1}$ sample?
CONCLUSIONS

- The B-Factories discovered dozens of new, exotic hadrons (XYZ)
- Strong evidence of four-quark composition
- Many questions about their nature
  - Di-meson molecules? Tetraquarks? Something else?
  - Analogies between cc and bb (and light quark?) systems
- Belle-II is the next generation B-Factory
  - Collect 50x as much data over 2018-2025
  - Best chance to study and understand many of these
  - Plans for dedicated operations to study the XYZ states
\( \Upsilon(3S) \) ON-RESONANCE: BOTTOMONIUM PHYSICS

- 200 fb\(^{-1}\) ~7x BaBar (Phase 3+)

- Focus on conventional bb physics
  - \( \Upsilon(1^3D_j) \) triplet
    - \( J=1,3 \) yet to be discovered
  - \( \eta_b(1S,2S) \)
    - Confirm \( m(\eta_b(1S,2S)) \)
  - Hadronic (\( \pi^\circ, \pi^+, \pi^-, \eta, \omega \)) decays
  - Radiative transitions
  - \( Z_b^+ \) exotic states?
<table>
<thead>
<tr>
<th>Calendar Year</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
<th>2019</th>
</tr>
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<tbody>
<tr>
<td>Japanese FY</td>
<td>JFY2016</td>
<td>JFY2017</td>
<td>JFY2018</td>
<td>JFY2019</td>
</tr>
<tr>
<td></td>
<td>Summer shutdown (power saving)</td>
<td>Summer shutdown (power saving)</td>
<td>Power saving after mid July 2018</td>
<td>Summer shutdown (power saving)</td>
</tr>
</tbody>
</table>

- **phase 1**
  - w/o QCS
  - w/o Belle II
- **Installation of final focusing quads and Belle II, and other renovation of accelerator**
- **Damping Ring installation & startup**

- **phase 2**
  - Main Ring
  - (mid Feb. – mid Jul. 2018)
  - w/ Final focusing quads
  - w/ Belle II (no Vertex Detector)
- **HER start**
- **LER start**

- **phase 3**
  - w/ full Belle II
- **phase 3 operation**
  - 9 months / year
- **Damping Ring commissioning**
- **Shutdown for Vertex Detector installation**

- **Now**
OTHER PERKS

- More statistics and better vertexing will help with charm corrections
- Systematics will also be reduced since the main sources are dependent on MC statistics
- Better PID will help with multi-kaon final states

PID performance

Transverse polarization
Dependent di-hadron
Asymmetries in $e^+e^-$ from Belle

Belle II MC preliminary

Charm vs uds in $b\bar{b}$ kaon production (likesign)

$\sim 45\%$ uds
Only initial (low) performance, w/o Vertex Detector, but still there are interesting physics topics to do during phase 2.

<table>
<thead>
<tr>
<th>WG</th>
<th>Mode</th>
<th>Description</th>
<th>Benchmark study or Unique measurement?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Semileptonic</td>
<td>$B\to X \ell v$</td>
<td>Benchmark analysis in $Y(4S)$</td>
<td>Benchmark</td>
</tr>
<tr>
<td>Semileptonic</td>
<td>$B(s)\to X \ell v$ in $Y(6S)$, Di-leptons</td>
<td>$B$ and $B_s$ counting in $Y(6S)$</td>
<td>Unique</td>
</tr>
<tr>
<td>EWP</td>
<td>$B\to K^+\gamma$</td>
<td>Benchmark analysis in $Y(4S)$</td>
<td>Benchmark</td>
</tr>
<tr>
<td>BioCharm</td>
<td>$B \to D^0\ell$, $D^+\ell$, $D\to Nh, Kg X$</td>
<td>Benchmark analysis in $Y(4S)$</td>
<td>Benchmark</td>
</tr>
<tr>
<td>Bottomonium</td>
<td>$Y(6S)\to \pi\pi' + Y(nS)+h_b$</td>
<td>Zb substructure</td>
<td>Unique</td>
</tr>
<tr>
<td>Bottomonium</td>
<td>$Y(6S)$ cross section, $R_b$</td>
<td>Cross section measurement and $R_b$ decomposition at $Y(6S)$</td>
<td>Unique</td>
</tr>
<tr>
<td>Bottomonium</td>
<td>$\pi\pi Y(pS)$</td>
<td>$ECM \ 10.75 \ GeV$ decay $\to \pi\pi Y(pS)$</td>
<td>Unique</td>
</tr>
<tr>
<td>Low-multiplicity</td>
<td>$ee\to A', A'\to missing$</td>
<td>Dark matter via dark photon</td>
<td>Unique</td>
</tr>
<tr>
<td>Low-multiplicity</td>
<td>$ee\to \gamma A\to \gamma A$</td>
<td>Axion like dark sector for large $A$ masses (tri-photon final state)</td>
<td>Unique</td>
</tr>
</tbody>
</table>
Wire stringing in a clean room

- thousands of wires,
- 1 year of work...
CDC EVENT DISPLAYS
(WITH FULLY INSTRUMENTED READOUT)

Single cosmic ray track

Multiple tracks
(showering cosmic ray event)

→ talk by N. Taniguchi
THE KLM ("$K_L$–MUON DETECTOR")

- **Barrel KLM** (US-responsibility) consists of 15 active interleaved with the iron plates of the 1.5T solenoid’s flux return yoke.
- 13 outer layers: legacy Resistive Plate Chambers (RPCs)
- 2 inner layers: Scintillator (NEW)
  - Robust wrt neutron flux from beam background/shields subsequent RPC layers
BELLE II DETECTOR – VERTEX REGION

Beryllium beam pipe
2cm diameter

Vertex Detector
2 layers pixel (DEPFET)
+ 4 layers DSSD

<table>
<thead>
<tr>
<th>Beam Pipe</th>
<th>r = 10mm</th>
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<tbody>
<tr>
<td>DEPFET</td>
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<tr>
<td>Layer 1</td>
<td>r = 14mm</td>
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<tr>
<td>Layer 2</td>
<td>r = 22mm</td>
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<tr>
<td>DSSD</td>
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<td>Layer 3</td>
<td>r = 39mm</td>
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<td>Layer 4</td>
<td>r = 80mm</td>
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<tr>
<td>Layer 5</td>
<td>r = 115mm</td>
</tr>
<tr>
<td>Layer 6</td>
<td>r = 140mm</td>
</tr>
</tbody>
</table>
Mechanical mockup of the pixel detector

First laser light observed with the full size sensor

DEPFET sensor: developed at MPI Munich, produced at HLL

http://aldebaran.hll.mpg.de/twiki/bin/view/DEPFET/WebHome

talk K. Lautenbach
SVD: FOUR LAYERS OF SILICON MICROSTRIP DETECTORS.

A truly worldwide effort...
INSTALLATION OF SUB-DETECTORS
**SUPERKEKB NANOBEAMS**

To get 40x luminosity of Belle

Reduce beam size to a few 100 atomic layers!

---

### Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>KEKB</th>
<th>SuperKEKB</th>
<th>units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>KEKB</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LER</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>HER</td>
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<tr>
<td><strong>SuperKEKB</strong></td>
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<td></td>
</tr>
<tr>
<td>LER</td>
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<td></td>
</tr>
<tr>
<td>HER</td>
<td></td>
<td></td>
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</tr>
<tr>
<td><strong>Units</strong></td>
<td></td>
<td></td>
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<tr>
<td>beam energy E_b</td>
<td>3.5</td>
<td>4</td>
<td>GeV</td>
</tr>
<tr>
<td>CM boost βγ</td>
<td>0.425</td>
<td>0.28</td>
<td></td>
</tr>
<tr>
<td>half crossing angle φ</td>
<td>11</td>
<td>41.5</td>
<td>mrad</td>
</tr>
<tr>
<td>horizontal emittance εx</td>
<td>18</td>
<td>3.2</td>
<td>nm</td>
</tr>
<tr>
<td>beta-function at IP β_x*/β_y*</td>
<td>1200/5.9</td>
<td>32/0.27</td>
<td>mm</td>
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<tr>
<td>beam currents I_b</td>
<td>1.64</td>
<td>3.6</td>
<td>A</td>
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<td>beam-beam parameter ξ_y</td>
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<td>0.0881</td>
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<tr>
<td>beam size at IP σ_x*/σ_y*</td>
<td>100/2</td>
<td>10/0.059</td>
<td>μm</td>
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<tr>
<td>Luminosity L</td>
<td>2.1 x 10^{34}</td>
<td>8 x 10^{35}</td>
<td>cm^{-2}s^{-1}</td>
</tr>
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</table>

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![Diagram](https://via.placeholder.com/150)