Heavy Flavor Hadron Physics at Belle and Belle II

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Outline

• A big picture (in my personal point of view)
  – Identify effective degree of freedom → spectroscopy
  – Generalized parton distribution (GPD)

• Intensity frontier $e^+e^-$ experiments : Belle & Belle II
  – Variety of recorded reactions, access various final states.

• Hadron spectroscopy
  – XYZ states and charm baryons

• Importance of low multiplicity events
  – Two photon events and GPD.

• Summary
Running of $\alpha_s$ and established.

Two issues are identified.
- Effective degree of freedom.
  - Hadron spectroscopy
- Generalized parton distribution.
  - Hadron tomography

M. Tanabashi et al. (PDG)
PRD 98, 030001 (2018)
Legacy of B-factories

High luminosity, asymmetric-energy $e^+e^-$ colliding beam experiments were desired to study CP violation.

KEKB&Belle 8 GeV × 3.5 GeV (Run 1999-2010)

PEP II&BaBar 9 GeV × 3.1 GeV (Run 1999-2008)
In total, more than 1.5 \text{ ab}^{-1} including 1G BB pairs are recorded at B-factories.
SuperKEKB collider

- Nano-beam
- Increase currents

Peak luminosity: $2.1 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \Rightarrow 8.0 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

Beam energy: $3.5 / 8.0 \text{ GeV} \Rightarrow 4.0 / 7.0 \text{ GeV}$

Boost factor $\approx 2/3$
Belle II detector

**ECL:** CsI (TI), waveform sampling

**VXD:**

**PXD:** DEPFET (pixel)

**SVD:** Silicon strip

**CDC:** drift chamber

**KLM:** "KL and muon" RPC (barrel) + SiPM (end-cap, inner barrel)

**PID:** Cherenkov ring image

**TOP** (barrel): Quarts

**ARICH** (endcap): Aerogel

1.5T solenoid coil

**Technical choice**

- Finer segmentation, waveform sampling.
- Material change
- Larger angular coverage (CDC, SVD)
- Closer to the IP (PXD) 3 -> 2cm
- Particle ID improve \((K/\pi)\) (TOP, ARICH)

**Issues to overcome**

- Beam background
- High rate capability
- Boost \(\sim 2/3\)

\(e^- (7\text{GeV})\)

\(e^+ (4\text{GeV})\)
Originally in order for time-dependent CPV

\[ \Delta z = \beta \gamma c \Delta t, \]
\[ \beta \gamma = 0.425 \text{(KEKB)}, \]
\[ 0.56 \text{(PEP-II)}, \]
\[ 0.28 \text{(SuperKEKB)} \]

\[ A_{CP}(\Delta t) = \frac{\Gamma(\overline{B^0}(\Delta t) \rightarrow f_{CP}) - \Gamma( B^0(\Delta t) \rightarrow f_{CP})}{\Gamma(\overline{B^0}(\Delta t) \rightarrow f_{CP}) + \Gamma( B^0(\Delta t) \rightarrow f_{CP})} = S_{f_{CP}} \sin(\Delta m \Delta t) + A_{f_{CP}} \cos(\Delta m \Delta t) \]

This is very demanding measurement, requires sophisticated detector and analysis methodology!
All these are great benefit

4π general purpose spectrometer with

- High momentum resolution, $\sigma_p/p = 0.3\% @ 1\text{GeV/c}$.
- Ability to detect $\gamma$ down to 30 MeV.
- Good $\gamma$ energy resolution, $\sigma_M = 5$ MeV for $\pi^0 \rightarrow \gamma\gamma$.
- Lepton identification capability, $\varepsilon > 0.9$, fake $< 0.01$.
- $K/\pi/p$ separation capability, $\varepsilon \sim 0.9$, fake $< 0.1$.
- Excellent B decay vertex reconstruction, $\sigma_{\Delta z} = 80 \mu\text{m}$.

- World highest luminosity
Exploiting the advantages

In terms of physics reach to study strong interaction,

• Variety of the recorded reactions
  – Each process has preference of the quantum numbers.
  – Interplay among several approaches is effective.

• Possibility to access various final state particles
  – Variety of recorded reactions results in variety of final states.
  – To explain an exotic state, each hypothesis has predictions for other decay modes and partner states.
Variety of recorded reactions

- **B decays**
  - $J^{PC}=0^{-+}, 1^{--}, 1^{++}$

- **Initial state radiation**
  - $J^{PC}=1^{--}$
  - $e^+ e^- \rightarrow \gamma c \bar{c}$

- **Double $c\bar{c}$**
  - $C=+1$

- **$\gamma\gamma$ collisions**
  - $J^{PC}=0^{\pm\pm}, 2^{\pm\pm}, 3^{\pm\pm}$

Allowed/favored quantum numbers are different depending on production processes.
Belle’s the most famous discovery

X(3872) → J/ψ γ, C=+1

J^{PC}=1^{++} (Belle, BaBar, CDF, LHCb) from J/ψ π⁺π⁻ angular distribution.
(PRL110, 222001(2013) and cited papers)

Br(X(3872)→D^0\bar{D}^{*0}) is about Br(X(3872)→J/ψ π⁺π⁻) × 10.
Admixture: most plausible interpretation for X(3872)

Meson-meson molecule

E. J. Eichiten et al. Phys. Rev. D 73, 014014 (2006);
A. M. Badalin et al. Phys. Rev.D 85, 031103 (2012);

$D\bar{D}^*$ component is coupled with the same $J^{PC}$ $c\bar{c}$, $\chi_{c1}(2P)$ (unseen).
$
\rightarrow$ can explain $\text{Br}(X\rightarrow D^0D^{*0})/\text{Br}(X\rightarrow J/\psi \pi^+\pi^-)$ is about 10.
$
\rightarrow D^+D^{*-}$ component can explain $J/\psi \pi^+\pi^-$ and $J/\psi \pi^+\pi^-\pi^0$ coexist.
$
\rightarrow$ pure molecule; too fragile to have prompt produced in Tevatron/LHC.
$
\rightarrow$ another $\chi_{c1}(2P)$ dominant state would become broad.
New observation for charmonium

\[ B^+ \rightarrow h_c K^+, \ h_c \rightarrow \gamma \ \eta_c. \]
\[ \eta_c \text{ is reconstructed in 11 modes.} \]
\[ (K_S K^+ \pi^-, K^+ K^- \pi^0, K_S K_S \pi^0, K^+ K^- K^+ K^-, K^+ K^- K^+ K^-, \eta' \pi^+ \pi^-, pp, pp\pi^0, pp\pi^+ \pi^-, \Lambda \Lambda) \]

A multivariable analysis technique is introduced to overcome factorization suppression (i.e. low S/N).

PRD100,012001(2019)

The first evidence of \( h_c \) production in B decays.
The radiative decays into \( \gamma \ \eta_c \) or \( \gamma \ \eta_c(2S) \) are important to look for \( X(3872) \)'s C-odd partner, this Belle analysis shows that we have passed the first milestone toward such a direction.
\[ \overline{b}b \pi^\pm \text{ system at } \Upsilon(10860) \]

10610 MeV~\( M(\overline{B}B^*) \)
10650 MeV~\( M(B^*\overline{B}^*) \)

\[ \Upsilon(1S)\pi^\pm \quad \Upsilon(2S)\pi^\pm \quad \Upsilon(3S)\pi^\pm \]

\[ Z_{b1} \quad Z_{b2} \quad Z_{b3} \]

Z\(_b\)'s decay to B\(^*(\ast)\)B\(^*\) found to be dominant.

Belle PRL108,122001(2012)
Belle PRL116,212001(2016)
Decays to $\Upsilon$ and $h_b$ can co-exist. Decay into $B^*B^*$ found to be dominant. $J^P=1^+$ is supported by Dalitz analysis.

Theoretical predictions given for relevant partner states. Search for them is likely to require Belle II statistics.
Charm baryon to check “di-quark”

- Thought to be a good place to check if “di-quarks” is behaving as a good degree of freedom to form hadrons.
- One of the constituent quark is heavy, correlation between the remaining light quarks would become clear.
- $L_1: \rho$ mode, $L_2: \lambda$ mode.
To which mode, how much br.? 

PRD89,052003(2014) 

PRD94,032002(2016) 

“charm baryon + light hadron” or “charm meson + baryon”? Very important info., just started to be got in our hand.

For J\(^P\) determination, higher statistics needed.
$B^- \rightarrow \Lambda_c^- \Xi_c^0$ with missing mass technique and absolute $\Xi_c^0$ Br.

$\text{Br}(B^- \rightarrow \Lambda_c^- \Xi_c^0) = (9.51 \pm 2.10 \pm 0.88) \times 10^{-4}$
$\text{Br}(\Xi_c^0 \rightarrow \Xi^- \pi^+) = (1.80 \pm 0.50 \pm 0.14)\%$
$\text{Br}(\Xi_c^0 \rightarrow \Lambda K^- \pi^+) = (1.17 \pm 0.37 \pm 0.09)\%$
$\text{Br}(\Xi_c^0 \rightarrow p K^+ K^- \pi^+) = (0.58 \pm 0.23 \pm 0.05)\%$

PRL122,082001(2019)
Higher statistics physics reach
(an example at LHCb)

In 2015, 3/fb (\(\sqrt{s}=7 \text{ and } 8 \text{ TeV}\))
26k \(\Lambda_b \rightarrow J/\psi K^- p\) events
Two \(P_c^+\) states claimed.

In 2019, 3/fb + 6/fb (\(\sqrt{s}=13 \text{ TeV}\))
246k \(\Lambda_b \rightarrow J/\psi K^- p\) events
Three \(P_c^+\) states appeared.
• The vertex detector system has been installed 2018 autumn, now Belle II is fully equipped (except for partial 2\textsuperscript{nd} layer vertex pixel detectors).
• Beam operation resumed 2019 Mar. 11\textsuperscript{th}.
Fully reconstructed B mesons

\[ \Delta E = \left( \frac{E_{CM}}{2} \right) - E_{\text{rec}} \]

\[ M_{bc} = \sqrt{\left( \frac{E_{CM}}{2} \right)^2 - P_{\text{rec}}^2} \]

We got 22k fully reconstructed B decay events from ~ half of 2019 Mar.-Jun. run data : 2.6/fb.
Not only charged Kaons and pions but also neutrals and \( K_S \) are efficiently reconstructed.
For GPDs and GPAs

Nowadays, Generalized Parton Distribution (GPD) and Generalized Parton Amplitude (GPA) are intensively discussed. (Parton distribution as a func. of $x$: 1D, here 3D dist. considered.)

S. Kumano et al., PRD97, 014020(2018)

\[ \gamma^* \rightarrow \pi^0 \pi^0 \]

Data: PRD86, 092007(2012), PRD93, 032003(2016)
Low multiplicity events are properly taken

Search for $e^+e^- \rightarrow \mu^+\mu^-Z'$, $Z'\rightarrow$invisible

Compatible with backgrounds so far.

Trigger logic to accept low multiplicity events is properly functioning. Improvement in $\gamma\gamma^* \rightarrow hh$ at Belle II is promising.
Next runs and prospects

Note: Physics cases are based on some assumptions..

All the details are in
“The Belle II Physics Book”
E. Kou, P. Urquijo et al.,

https://inspirehep.net/record/1692393/
Summary

• At intensity frontier e^+e^- experiments, variety of recorded reactions and accessibility for various decay modes continue to be exploited.

• For quarkonium(-like) XYZ states
  – Other decay modes and Partner searches need more data.
  – Production of h_c in B decay confirmed.

• Charmed baryons to test “di-quark” picture.
  – J^P determination need more data.
  – Ξ_c absolute branching fractions have been measured.

• Low multiplicity events are also properly taken.

• SuperKEKB/Belle II next beam run starts soon, Oct.