Prospects for searches for a stable double strange hexaquark at Belle II

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Double strange hexaquark

**udsuds (H)**, long-standing saga (R. L. Jaffe, 1977)

- Double strange six-quark state, same quark content as two Λ hyperons
- Privileged 6-quark combination, the spatial wave function can be totally symmetric

**Extremely fascinating object**

- H would improve our understanding of the strength of Λ-Λ interactions
- Hyperon interactions are of fundamental interest in nuclear physics and nuclear astrophysics
- A direct hyperon-hyperon scattering experiment is not feasible in a laboratory

Many theoretical calculations and experimental searches in the years

- At present no conclusion about its existence
Double strange hexaquark

$H$ received revived interest in the last years
- Recent LQCD results
- Renewed theoretical effort

G. R. Farrar, 2017: stable $H$ is potentially an excellent dark matter (DM) candidate
- DM candidate within QCD
- Could have eluded all searches to date

Whether the $H$ is stable enough to be a DM candidate depends on its mass/binding energy
- Deep binding is facilitated by the unique symmetry structure of the $H$
Deeply bound udsuds hexaquark

\[
2(m_p - m_\pi) \quad m_p - m_\pi + m_\pi = 2(m_\pi + m_\pi) \\
2m_p 
\]

Stable

(ABSOLUTELY STABLE)

(meta-stable)

not stable

Free

DM candidate

Original proposal

\[ M_H [\text{GeV/c}^2] \]

1.00 1.25 1.50 1.75 2.00 2.25 2.50 2.75

mass

binding energy (B_H)
Y(1,2,3) ideal to look for states with nonzero strangeness

- Decay primarily in three gluons
- $s\bar{s}$ quark pairs produced with ~ same probability as $u\bar{u}$ and $d\bar{d}$

Deeply bound udsuds hexaquark

Original proposal

DM candidate

mass

binding energy ($B_H$)

PRL 122 (2019) 7, 072002

PRL 110, 222002 (2013)
Possible discovery strategy for stable $H$

\begin{itemize}
  \item Searches @ BFactories: $e^+e^- \rightarrow Y(1,2,3S) \rightarrow H \Lambda \Lambda \eta \eta$
\end{itemize}

Requirements

\begin{itemize}
  \item High luminosity
  \item Good reconstruction capabilities of charged tracks
\end{itemize}

In the near future, Belle II@SuperKEKB can play a major role!
E_{cm} \sim 10 \text{ GeV}

e^{-} (7 \text{ GeV}) \quad e^{+} (4 \text{ GeV})

boost FW direction

Spectrum of bottomonium (b\bar{b})

Y(nS)

\begin{array}{c|c|c|c|c}
\hline
\text{Y(1S)} & \text{Y(2S)} & \text{Y(3S)} & \text{Y(4S)} & \text{Y(5S)} & \text{Y(6S)} \\
\hline
9.25 & 9.50 & 9.75 & 10.00 & 10.25 & 10.50 & 11.00 \\
\hline
\end{array}

\begin{array}{c|c|c|c|c}
\hline
\eta_{b}(1P) & \eta_{b}(2S) & \eta_{b}(2P) \\
\hline
\hline
X_{0}(2P) & X_{1}(2P) & X_{0}(3P) \\
\hline
X_{0}(1P) & X_{1}(1P) & X_{0}(2P) \\
\hline
\end{array}

\text{B}^{+}\text{B}^{-}
**SuperKEKB**

**Belle II dataset**

- **$E_{cm} \sim 10$ GeV**
  - $e^-$ (7 GeV)
  - $e^+$ (4 GeV)
- Boost FW direction

<table>
<thead>
<tr>
<th>Decay</th>
<th>Integrated Luminosity [fb$^{-1}$]</th>
</tr>
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<tbody>
<tr>
<td>$Y(3S)$</td>
<td>300 fb$^{-1}$</td>
</tr>
<tr>
<td>$Y(4S)$</td>
<td>420 fb$^{-1}$</td>
</tr>
<tr>
<td>$Y(5S)$</td>
<td>1 ab$^{-1}$</td>
</tr>
<tr>
<td>$Y(6S)$</td>
<td>100 fb$^{-1}$</td>
</tr>
</tbody>
</table>

- Belle II, planned: 50 ab$^{-1}$
- Belle II, current dataset:
Belle II

Tracking detectors

- VerteX Detector (VXD)
- PiXel Detector (PXD, 2 layers)
- Silicon Vertex Detector (SVD, 4 layers)
- Central Drift Chamber (CDC)

Particle identification subsystems

- Time Of Propagation (TOP) counter (central region)
- Aerogel Ring-Imaging CHERENkov (ARICH, forward region)

Outermost structures

- Electromagnetic CaLorimeter (ECL)
- Superconductive solenoid (1.5 T)
- $K_L$ and Muon detector (KLM)

arXiv:1011.0352, 2010
Tracking detectors

- VXD: PXD (2 layers) + SVD (4 layers)
- CDC

Particle identification subsystems (CDC)
- TOP (central region)
- ARICH (FW region)

Outermost structures
- ECL
- KLM

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University of Mainz

VXD: PXD (2 layers) + SVD (4 layers)
- 6 layers
  - \( r_{in} \) (L1) = 1.4 cm
  - \( r_{out} \) (L6) = 13.5 cm

- 56 layers
  - over 14K sense wires
  - \( r_{out} \) = 113 cm

arXiv:1011.0352, 2010
Deeply bound uuddss hexaquark @ Belle II

$Y(3S) \rightarrow H \Lambda \Lambda (+ 2n \pi)$: analysis procedure

➤ Signal / background MC generation

➤ Signal events selection
  ➤ Particle-related optimization
  ➤ Best candidate selection
  ➤ Rest of event

➤ Upper limit (UL) sensitivity estimation w/ MC

➤ Signal observation / UL derivation in data
Deeply bound uuddss hexaquark @ Belle II

\[ Y(3S) \rightarrow H \Lambda \Lambda (\pm 2n \pi) : \text{analysis procedure} \]

- Signal / background MC generation
- Signal events selection
  - Particle-related optimization
  - Best candidate selection
  - Rest of event
- Upper limit (UL) sensitivity estimation w/ MC
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Inputs from analysis
- Signal efficiency \( \varepsilon_S \)
- Number of background events \( F \)
- CI = 90%
- \( N_{Y(3S)} \) depends on the luminosity

Assumptions:
- Poisson counting experiment, \( \lambda = F \)
- H0: no signal, all observed events (n) are background (n = F)

\[ UL(M_S) = \frac{S_{up}(F(M_S), CI)}{N_{Y(3S)}} \varepsilon_S(M_S) \]
Deeply bound uuddss hexaquark @ Belle II

\( \text{Y}(3S) \to H \Lambda \Lambda (\pm 2n \pi) \): analysis procedure

- Signal / background MC generation
- Signal events selection
- Particle-related optimization
- Best candidate selection
- Rest of event
- Upper limit (UL) sensitivity estimation w/ MC
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\[
UL(M_S) = \frac{S_{\text{up}}(F(M_S), CI)}{N_{Y(3S)} \epsilon_S(M_S)}
\]

\( \text{Belle II simulation} \)

\[
\int C \, dt = 300 \text{ fb}^{-1}
\]
Deeply bound uuddss hexaquark @ Belle II

Belle II enters the game

\( Y(3S) \rightarrow H \Lambda \Lambda \)

\( M_H = 1.179 \text{ GeV}/c^2 \)

Projected 90% UL estimation

\[ \times 10^{-7} \]

\( \int \mathcal{L} \, dt [\text{fb}^{-1}] \)

Belle II enters the game
Deeply bound uuddss hexaquark @ Belle II

Y(3S) → H Λ Λ 2π

\[ M_H = 1.179 \text{ GeV/c}^2 \]

Projected 90% UL estimation

Y(3S) → H Λ Λ 4π

\[ M_H = 1.179 \text{ GeV/c}^2 \]

Projected 90% UL estimation

Y(3S) → H Λ Λ 6π

\[ M_H = 1.179 \text{ GeV/c}^2 \]

Projected 90% UL estimation

Y(3S) → H Λ Λ 8π

\[ M_H = 1.179 \text{ GeV/c}^2 \]

Projected 90% UL estimation

No existing limits from BaBar

Novel measurement!
**Outlook**

Double strange hexaquark @ B Factories: **why/how**
- Similarities between hadronic collisions and narrow bottomonia annihilations
- Good place to look for strange (exotic) baryons

Double strange hexaquark @ B Factories: **where are we**
- *Belle*: *PRL* 110, 222002 (2013)
- *BaBar*: *PRL* 122 (2019) 7, 072002

Double strange hexaquark @ B Factories: **future plans @ Belle II**
- Cover whole $H$ mass range (both stable and not-stable regime)
- Study more possible decay channels (additional $\pi$, $\gamma$, ..)
- Improve UL estimation (more data)
Exciting years ahead with the Belle II experiment

Many intriguing perspectives for baryon and exotics physics (see also John Yelton’s talk on Wednesday)

Among others, the search for a stable $H$ @ Belle II in the decay of $Y(3S)$ is part of the program

With a relatively modest amount of data Belle II will make a world-leading measurement
Conclusions

- Exciting years ahead with the Belle II experiment

- Many intriguing perspectives for baryon and exotics physics (see also John Yelton’s talk on Wednesday)

- Among others, the search for a stable $H$ @ Belle II in the decay of $Y(3S)$ is part of the program

- With a relatively modest amount of data Belle II will make a world-leading measurement

Thank you for your attention!
Additional material
Belle II, luminosity projection
\[ \mathcal{L} = \frac{\gamma^+}{2e r_e} \left( 1 + \frac{\sigma_y^+}{\sigma_x^+} \right) \left( \frac{I^x}{\xi_y^x} \right) \left( \frac{R}{R_{\xi y}} \right) \]

**SuperKEKB**

<table>
<thead>
<tr>
<th>KEKB</th>
<th>SuperKEKB</th>
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</thead>
<tbody>
<tr>
<td>LER (e⁺) / HER (e⁻)</td>
<td>LER (e⁺) / HER (e⁻)</td>
</tr>
<tr>
<td>E [GeV]</td>
<td>3.5 / 8.0</td>
</tr>
<tr>
<td>2\phi [mrad]</td>
<td>22</td>
</tr>
<tr>
<td>(\xi_x)</td>
<td>0.127 / 0.102</td>
</tr>
<tr>
<td>(\xi_y)</td>
<td>0.129 / 0.090</td>
</tr>
<tr>
<td>(\beta_y^*)</td>
<td>5.9 / 5.9</td>
</tr>
<tr>
<td>I [A]</td>
<td>1.64 / 1.19</td>
</tr>
<tr>
<td>(\sigma_z^* [\mu m])</td>
<td>147 / 170</td>
</tr>
<tr>
<td>(\sigma_y^* [nm])</td>
<td>940 / 940</td>
</tr>
<tr>
<td>(\mathcal{L} [10^{36} \text{ cm}^{-2} \text{ s}^{-1}])</td>
<td>0.211</td>
</tr>
<tr>
<td>(\int \mathcal{L} , dt [\text{ab}^{-1}])</td>
<td>1</td>
</tr>
</tbody>
</table>