Quarkonium at Belle II
History – I.

• In 1963 Gellmann proposed the quark model
  – Conventional hadrons
    • Mesons: 2 quarks
    • Baryons: 3 quarks are described
  – Additionally, also objects of 4 and 5 quarks were predicted
• Many mesons and baryons were discovered since then
• The first “exotic” object with more than 3 quarks was discovered in 2003 at Belle
History – II.

- Until 2003 no evidence for a new, „exotic“ state was found
  - First exotic state discovered in 2003 at the Belle experiment
  - From there on, many new exotic states were discovered from different experiments
  - Neutrals as well as charged states were found
  - Six theoretical models still compete for the description
  - In most cases, statistics is the limiting factor → Belle II is designed to tackle that problem


X(3872)
Belle 2003

Y(4260)
BaBar 2005

Y(4360)
BaBar 2007

Y(4660)
Belle 2007/08

X(4140)
CDF 2008

Z_c(4430)
Belle 2008

Z_b(10650)
Belle 2012

Z_c(3900)
BESIII/Belle 2013

Z_c(4020)
BESIII 2013

P_c(4312)
P_c(4440)
P_c(4457)
LHCb 2015/19

Z_cs(3985)
BESIII 2021

Z_cs(4220)
LHCb 2021

X(6900)
LHCb 2020

X_0(2900)
X_1(2900)
LHCb 2020

T_cc(3875)
LHCb 2021
Theoretical models

- Hadronic Molecules
  - Two conventional meson bound states
  - Bound by one pion exchange
  - Many new states in good agreement
  - \(X(3872)\) most likely a molecular state

- Tetraquarks
  - Internally di-quark system
  - Double-well potential
  - Decay through tunneling of light quark
  - Favors open-charm decays

- Hadro-Quarkonia

- Hybrids

- Glueballs

- Cusps (Threshold Effects)

Physics Reports 873 (2020) 1–154
Belle II is hosted at the SuperKEKB accelerator

- Asymmetric energy e⁺e⁻ (4 & 7 GeV) collider in Tsukuba, Japan
- Goal for SuperKEKB → 30x KEKB instantaneous luminosity (nano-beam-scheme) : \( \sim 6 \times 10^{-35} \text{ cm}^2 \text{ s}^{-1} \)
  - 50x integrated Belle luminosity → 50/ab
- Full event reconstruction, decays with neutral/soft particles
- Nominal CMS energy 10.58 GeV = \( M(Y(4S)), Y(5S) \) and \( Y(6S) \) also producible
- So far \( \sim 350/\text{fb} \) are collected since April 2018, instantaneous luminosity world record in December 2021
X(3872) – The most concerned particle in the charmonium sector

- Discovery paper of X(3872) was the highest cited paper of Belle
- $D^0D^{*0}$ molecular model is most favored so far, but still not confirmed
- Belle II capability
  - Branching fraction
  - Lineshape measurement
- Very narrow state, even though it is so close to the $D^0D^{*0}$ threshold
  - $M(X(3872)) = 3871.65 \pm 0.06$ MeV
  - $M(D^0D^{*0}) = 3871.69 \pm 0.11$ MeV
  - Radius > 5 fm for a molecular hypothesis

$0.04 \pm 0.12$ MeV binding energy

Belle, PRD 81, 031103 (2010)
X(3872) production

- Measuring absolute branching fraction $\mathcal{B}\left( B \rightarrow X(3872)K^+ \right)$ will help in measuring $\mathcal{B}\left( X(3872) \rightarrow \text{final State} \right)$
  - Only possible at B-factories operating at Y(4S) center of mass energy which decays to $\bar{B}B$
  - Missing mass recoiling against $K^+$,
    - Improve B-tagging efficiency compared to Belle („Results related to anomalies at Belle II“, by Martin Angelsmark Wed. 9:20)
    → Full Event Interpretation (FEI)
      - Reconstruction of ~10000 modes
      - Extensive ML use
      - Semileptonic and hadronic tag modes
      - Up to 50% increase in efficiency and comparable purity
  - Belle II might measure this value not only for $X(3872)$, but also for other states

Belle, PRD 97, 012005 (2018)
BaBar, PRL 124, 152001 (2019)
**X(3872) rediscovery @BelleII**

- **X(3872) was rediscovered @BelleII in** $B^\pm \rightarrow X(3872) \left( J / \Psi \pi^+ \pi^- \right) K^\pm$
  - $14.4 \pm 4.6 \text{ signal events} \rightarrow 4.6\sigma$
  - BELLE2-NOTE-PL-2021-002
  - Selection criteria
    - Particle identification
    - Continuum suppression
    - Kinematics criteria: $M_{bc} = \sqrt{\left(\sqrt{s}/2\right)^2 - p_B^2} \cdot \sqrt{s}/2$, $|\Delta E| = E_{\text{beam}} - E_B$

![Diagram](image)

**Selection criteria**
- Particle identification
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**Belle II Preliminary**

- Events / (0.0025 GeV/c^2)
- $\int L \, dt = 62.8 \text{ fb}^{-1}$
- $B^+ \rightarrow X(3872) K^+$
- $\sigma(B^\pm \rightarrow X(3872) K^\pm) / \sigma(B^0 \rightarrow X(3872) K_S^0) \approx 0.5$
- $M(J/\psi \pi^+ \pi^-) [\text{GeV/c}^2]$
X(3872) – upcoming lineshape study @Belle

- LHCb measures mass and width with $X(3872) \rightarrow J/\psi\pi\pi$
- Difficult to distinguish BW and Flatté distributions
  → Lineshape is more sensitive to $X(3872) \rightarrow D^0\bar{D}^{*0}$
- Revised study on this also ongoing @Belle

Belle II MC study
Upper limit @90% CL
Measurable total width 3σ
Measurable total width 5σ
Current UL
Partner state to the $X(3872)$ at the $D^*{}^0D^*{}^0$ threshold?

- If the $X(3872)$ is a hadronic molecular state, it should have a partner state at the $D^*{}^0D^*{}^0$ threshold
  
  
  - Mass prediction around $D^*{}^0D^*{}^0$ threshold at 4014 MeV
  
  - Heavy quark spin symmetry partner to $X(3872)$ (Phys. Rev. D88 (2013) 054007)
  
  - Width up to 10MeV due to D-wave decay to $D^*{}^0D^*{}^0$
  
  - First Belle II MC study performed for different scenarios for the width and the branching fraction show discovery potential above 2/ab
Search for exotics using ISR @Belle

First observation of a resonant state in $D^+D_{s1}(2536)^- + cc$ with $5.9\sigma$ in 921.9/fb

$$M = 4625 \pm 0.4 \text{ GeV} / c^2, \Gamma = 49 \pm 4.0 \text{ MeV}$$

- Explore $1^-$ states far from $e^+e^-$ collision energy
- Whole hadron spectrum visible
- Effective luminosity and detection efficiency are relatively low
- $Y(4230), Y(4660)$ and other results were achieved by the ISR technique at Belle
Preliminary ISR results @BelleII

\[ e^+ e^- \gamma_{ISR} \rightarrow J/\psi(l^+l^-) \pi^+\pi^- \]
- Nominal PID requirements
  - |M(J/\psi) – M(PDG)| < 75 MeV
- ISR photon NOT required (higher efficiency)
  - |missingM^2(\pi\pi J/\psi)| < 2 GeV^2

- Clear observation of ISR \( \Psi(2S) \) signals
  - Cross sections compatible with theoretical calculations

<table>
<thead>
<tr>
<th>Mode</th>
<th>Our measurement</th>
<th>Theoretical Prediction (Yad. Fit. 41, 733 (1985))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( J/\psi \rightarrow \mu^+\mu^- )</td>
<td>(12.0 \pm 1.2) \text{ pb}</td>
<td>(14.1 \pm 0.3) \text{ pb}</td>
</tr>
<tr>
<td>( J/\psi \rightarrow e^+e^- )</td>
<td>(13.0 \pm 1.2) \text{ pb}</td>
<td>(14.1 \pm 0.3) \text{ pb}</td>
</tr>
</tbody>
</table>

- Next \rightarrow Y(4260) rediscovery
  - Expected are ~60 events @100/fb
Other productions

- **Double charmonium production**
  - Discovery of X(3940), $\chi_{c0}(2P)$
  - Expand for other cc states
  - Search for new states

- **Two photon production**
  - $J^{PC}$ of X(3915)
  - Confirm $\phi J/\Psi$ and X(3872) states

Belle Data: $\int \mathcal{L} \, dt = 825 \text{ fb}^{-1}$
$\Rightarrow 3.2 \sigma$

References:
- PRD 98, 092001 (2007)
- PRL 104, 112004 (2010)
- PRL 126.122001 (2021)
Bottomonia - I

- Unique Study in Belle & Belle II
- Y(5S), Y(6S)
  - Study of Z branching ratios and decays
  - Search for new resonances (predicted / unpredicted)
  - Y(2,3,4S) / Y(5S) transitions are different
    - Hint for non-bb nature
  - Extra resonance around 10.75 GeV?

PRL 100, 112001 (2008)  \( \Gamma (\text{MeV}) \)

\[
\begin{array}{|c|c|}
\hline
\gamma (5S) & \gamma (1S) \pi^+ \pi^- \\
\hline
\gamma (5S) & \gamma (2S) \pi^+ \pi^- \\
\hline
\gamma (5S) & \gamma (3S) \pi^+ \pi^- \\
\hline
\gamma (2S) & \gamma (1S) \pi^+ \pi^- \\
\hline
\gamma (3S) & \gamma (1S) \pi^+ \pi^- \\
\hline
\gamma (4S) & \gamma (1S) \pi^+ \pi^- \\
\hline
\end{array}
\]

\[
\begin{array}{c}
0.59 \pm 0.04 \pm 0.09 \\
0.85 \pm 0.07 \pm 0.16 \\
0.52^{+0.20}_{-0.17} \pm 0.10 \\
0.0060 \\
0.0009 \\
0.0019 \\
\end{array}
\]

\( > 10^2 x \)

JHEP 1910, 220 (2019)
Bottomonia - II

• Scan data sample at 22 points with 1/fb at each point
  – In addition, 121/fb at $\Upsilon(10860)$ on-resonance and 60/fb continuum sample at 10.52 GeV

• In the final state of $\Upsilon(1,2,3S)^{\pi^+\pi^-}$ a resonant structure is observed with 5.2$\sigma$
  – Test this also with new Belle II data

<table>
<thead>
<tr>
<th></th>
<th>$\Upsilon(10860)$</th>
<th>$\Upsilon(11020)$</th>
<th>New structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$ (MeV/c$^2$)</td>
<td>10885.3 ± 1.5$^{+2.2}_{-0.9}$</td>
<td>11000.0$^{+4.0}<em>{-4.5}$ $^{+1.0}</em>{-1.3}$</td>
<td>10752.7 ± 5.9$^{+0.7}_{-1.1}$</td>
</tr>
<tr>
<td>$\Gamma$ (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>

• Many models on the nature of the $\Upsilon(10750)$ have emerged
  – None of them confirmed so far => more data needed
  – D-wave bottomonium (arXiv:1910.06065),
    BB dynamically generated pole (arXiv:1910.04827),
    Hybrid (arXiv:1908.05179),
    Tetraquark state (arXiv:1905.06610)
Interpretations of the $\Upsilon(10750)$

→ More data needed!!

- Belle II collected data at 4 energy points around 10.75 GeV, more is needed!

- Physics goal: understand the nature of the $\Upsilon(10750)$ energy region

- The mechanism of $\Upsilon(10750) \rightarrow \pi \pi \Upsilon(1S)$ in the tetraquark interpretation
  - $J^{PC} = 1^{-}$ state with dominant tetraquark component

Normalized resonant $M(\pi^+\pi^-)$ distribution for $e^+e^- \rightarrow \Upsilon(10750) \rightarrow \Upsilon(1S)\pi^+\pi^-$: f0(500) and f0(980) scalars component, f2(1270) component

 Accumulated luminosities around the $\Upsilon(10750)$ as of November 21

- Quarkonium spectroscopy (conventional and exotic)
- Hadronic and radiative transitions
- Annihilations in exclusive final states
- Precision study of the vector states using ISR
- New Physics in Bottomonia (rare and forbidden decay, LUV, LFV, invisible decays)
- Cross section for hyperon production
- Dynamic correlations in hyperon pair production
- Search for di-baryons and anti-nuclei production
Summary

- Belle II is at the beginning of a long-term quarkonium journey
  - Many opportunities for world leading physics
- Early measurements display the foundations we will build upon

- Expectations of great achievements in hadronic spectroscopy
  - Dedicated study of unknown XYZ states
  - Determination of the $X(3872)$ nature from the many models available
  - Search for new particles via ISR, two photon production, double charmonium production...
  - Bottomonium search through $\Upsilon(nS)$

Extrapolation from 2021 including expected improvements

Conservative extrapolation from SuperKEKB parameters of 2021
Thank You!