Plans for exotic bottomonium-like states at Belle II

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INFN - Sezione di Torino
Part I. Accelerator and Detector
**Belle II: the detector**

- **EM Calorimeter:** CsI(Tl), waveform sampling (barrel) workflow sampling (end-caps)

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

- **Beryllium beam pipe:** 2cm diameter

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

- **Central Drift Chamber:** He(50%):C_{2}H_{6}(50%), Small cells, long lever arm, fast electronics

- **KL and muon detector:** Resistive Plate Counter (barrel) Scintillator + WLSF + MPPC (end-caps)

- **Electron (7 GeV)**

- **Positron (4 GeV)**

Translated into performances for $\pi\pi$ transitions...

<table>
<thead>
<tr>
<th>Channel</th>
<th>BaBar</th>
<th>BelleII</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(2S)$</td>
<td>$\approx 4 \text{ MeV}/c^2$</td>
<td>$2.5 \text{ MeV}/c^2$</td>
</tr>
<tr>
<td>$\Upsilon(3S) \rightarrow \pi^+\pi^- \Upsilon(1S)$</td>
<td>$\leq 4 \text{ MeV}/c^2$</td>
<td>$1.8 \text{ MeV}/c^2$</td>
</tr>
</tbody>
</table>


*BelleII: preliminary MC*
Super-KEKB aims for $8 \times 10^{35} \text{ cm}^2 \text{ s}^{-1}$

Super-KEKB will try to make the smallest $\beta_y^*$ in the world!

KEKB head-on (crab crossing)

Nano-Beam Scheme SuperKEKB

Interaction region = bunch length

Interaction region $\ll$ bunch length

$\phi_{\text{pwiniski}} \sim 20$

Half crossing angle: $\phi$

$\sigma_x^{*} = 100-150 \mu m$

$\sigma_z = 6-7 \text{ mm}$

$d = \frac{\sigma_x^{*}}{\phi}$

$\sigma_z = 5-6 \text{ mm}$

$\sigma_x^{*} = 10-12 \mu m$

$2 \phi = 83 \text{ mrad}$

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Super-KEKB aims for \(8 \times 10^{35} \text{ cm}^2 \text{s}^{-1}\)

A reasonable non-Y(4S) request:
- 1 ab\(^{-1}\) @ Y(5S)
- 100 fb\(^{-1}\) @ Y(6S)
- 300 fb\(^{-1}\) @ Y(3S) (1.2 Billions)
- 400 fb\(^{-1}\) scan (?)
Super-KEKB: energy and limitations

Super-KEKB is technically an accumulation ring
→ All the acceleration phase is carried out in the LINAC
→ RF cavities in the ring only to sustain the beams
→ Continuous injection

Present max $E_{cm} \approx 11.02$ GeV, a bit above $Y(6S)$
Possible max $E_{cm} \approx 11.24$ GeV, at $\Lambda_b \bar{\Lambda}_b$ threshold
Part II. Bottomonium physics

→ Hadronic transitions
→ Scan opportunities
Bottomonia: what we’ve learned

An “light quark” effect can enhance a transition and lead to the discovery of a conventional state

→ Constraint on the initial state ($J^{PC} = 1^-$)

→ All the bottomonium studies are studies of transitions

Predictions on the exotics production modes and rates are as important as the ones on the decays
Discoveries: missing transitions

Transitions to/from known states

Missing Y(3S) transitions (300 fb⁻¹):

BF [Y(3S) → η Y(1S)] > 2 x 10⁻⁵
BF [Y(3S) → ππ h_b (1P)] > 5 x 10⁻⁵

Missing Y(5S) transitions (1 ab⁻¹):

BF [Y(5S) → η h_b (1P, 2P)] > 3 x 10⁻³

Other opportunities

A Very large set of h_b(nP) will be available using Y(4S, 5S) → ππ/η h_b (1P, 2P).
→ Predictions/ideas on transitions from the h_b(nP)?
→ h_b (2P) → η Y(1S)?
Most of the discovery of new states requires to run at the largest possible $E_{cm}$

No sensitivity predictions yet... stay tuned!
Most of the discovery of new states requires to run at the largest possible $E_{\text{cm}}$

- **Thresholds**:
  - Lowest $W_b + \text{hadron}$
  - SuperKEKB max
  - SuperKEKB present limit

- **Production Rates**:

<table>
<thead>
<tr>
<th>$J^G(P)$</th>
<th>Name</th>
<th>Composition</th>
<th>Co-produced particles [Threshold, GeV/$c^2$]</th>
<th>Decay channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1$^+$$(1^+)$</td>
<td>$Z_b$</td>
<td>$B\bar{B}^*$</td>
<td>$\pi$ [10.75]</td>
<td>$\Upsilon(nS)\pi, \eta_b(nP)\pi, \eta_b(nS)\rho$</td>
</tr>
<tr>
<td>1$^+$$(1^+)$</td>
<td>$Z'_b$</td>
<td>$B^*\bar{B}$</td>
<td>$\pi$ [10.79]</td>
<td>$\Upsilon(nS)\pi, \eta_b(nP)\pi, \eta_b(nS)\rho$</td>
</tr>
<tr>
<td>1$^-$$(0^+)$</td>
<td>$W_{b0}$</td>
<td>$BB$</td>
<td>$\rho$ [11.34] $\gamma$ [10.56]</td>
<td>$\Upsilon(nS)\rho, \eta_b(nS)\pi$</td>
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<td>1$^-$$(0^+)$</td>
<td>$W'_{b0}$</td>
<td>$B^*\bar{B}$</td>
<td>$\rho$ [11.43] $\gamma$ [10.65]</td>
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<tr>
<td>1$^-$$(1^+)$</td>
<td>$W_{b1}$</td>
<td>$BB^*$</td>
<td>$\rho$ [11.38] $\gamma$ [10.61]</td>
<td>$\Upsilon(nS)\rho$</td>
</tr>
<tr>
<td>1$^-$$(2^+)$</td>
<td>$W_{b2}$</td>
<td>$B^<em>\bar{B}^</em>$</td>
<td>$\rho$ [11.43] $\gamma$ [10.65]</td>
<td>$\Upsilon(nS)\rho$</td>
</tr>
<tr>
<td>0$^-(1^-)$</td>
<td>$X_{b1}$</td>
<td>$BB^*$</td>
<td>$\eta$ [11.15]</td>
<td>$\Upsilon(nS)\eta, \eta_b(nS)\omega$</td>
</tr>
<tr>
<td>0$^-$(1$^-$)</td>
<td>$X'_{b1}$</td>
<td>$B^<em>\bar{B}^</em>$</td>
<td>$\eta$ [11.20]</td>
<td>$\Upsilon(nS)\eta, \eta_b(nS)\omega$</td>
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<td>0$^+$(0$^+$)</td>
<td>$X_{b0}$</td>
<td>$BB$</td>
<td>$\varepsilon$ [11.34] $\gamma$ [10.56]</td>
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Predictions on the production rates?
Precision studies: \( Y(5S-6S) \) scans

\[
\begin{align*}
\text{Phys. Rev. D 93, 011101 (2016)} & \quad e^+e^- \rightarrow \pi^+\pi^- Y(1S) \\
\text{BESIII scan: Phys. Rev. Lett. 118, 092001} & \quad e^+e^- \rightarrow \pi^+\pi^- Y(2S) \\
\text{Belle II prospects} & \quad e^+e^- \rightarrow \pi^+\pi^- Y(3S) \\
\end{align*}
\]

... with an eye on what happens in charmonia...

\[
\begin{align*}
\text{BESIII scan: Phys. Rev. Lett. 118, 092001} & \quad e^+e^- \rightarrow \pi\pi J/\psi \\
\end{align*}
\]

\[
\begin{align*}
\text{Belle II prospects} & \quad \rightarrow \text{Beam energy spread} \ 5 \ \text{MeV} \\
& \quad \rightarrow \ 10 \ \text{fb}^{-1} \ \text{per point}, \ 10 \ \text{MeV} \ \text{steps} \ (10x \ \text{Belle}) \\
& \quad \rightarrow \ \text{Almost} \ 0.5 \ \text{ab}^{-1}: \ \text{needs strong theoretical motivation}
\end{align*}
\]
Precision studies: Di-pion transitions

Belle Y(5S) → ππ Y(1S)

A QCDME diagram (purely as example)

Heavy vertex
(HF tetraquarks, molecules, hybrids)
Precision studies: Di-pion transitions

Belle Y(5S) → ππ Y(1S)

A QCDME diagram (purely as example)

Light vertex
( LF tetraquarks, molecules, hybrids...)

Heavy vertex
( HF tetraquarks, molecules, hybrids)

Belle Y(4S) → ππ Y(1S) (Elisa Guido’s talk)

Study of scalar mesons using di-pion transitions is not a new idea, but we lacked of statistics
H.W. Ke et al, PRD 76 (2007) 074035

Actually, also Zb’s can contribute to Y(3S) → ππ Y(1S)!

Belle prospects

→ High-statistic full PWA of the di-pion transitions
→ Confirm Exotica as contributors to transitions below threshold!
→ Hunt for CP = ++ contributions: σ, f₂...
→ ππ scattering length from Y(3S) → ππ Y(2S)

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Part III. Beyond bottomonia

→ Light meson effects in transitions
→ Bottomonium annihilations
Lots of observation of exotica, but quite few completely independent confirmations
→ Usually structures in one (or few...) Dalitz plot with limited Q.
→ Only X(3872) has been seen in prompt production (in pp and pp collisions)
→ Production is debated A. Pilloni’s talk on Wednesday (look for the backup slides...)
Charmonia: pp and $e^+e^-$ compared

A tentative comparison between Belle and CMS.

→ 3-5 x sensitivity in inclusive production from Y(3S)
→ 10-15 x sensitivity in double charmonium
→ Theoretical predictions, at least for X(3872)?

→ Directly from this conference: DD* correlation in Y(3S) → DD* + hadrons
Deuteron production: bottomonium for DM

$\bar{d}$ detection in cosmic rays is considered since long a probe for low or intermediate mass WIMPs

Original idea:

Recent review:

Production at B-factories highlights:
→ No in-medium and extended source corrections
→ Complete access to the rest of event
→ Belle II is made for PID...

\[
\frac{dN_{\bar{d}}}{dT_{\bar{d}}} = \frac{\lambda_0^3}{6} \frac{m_{\bar{d}}}{m_{\bar{n}} m_{\bar{p}}} \frac{1}{\sqrt{T_{\bar{d}}^2 + 2m_{\bar{d}}T_{\bar{d}}}^2} \frac{dN_{\bar{n}}}{dT_{\bar{n}}} \frac{dN_{\bar{p}}}{dT_{\bar{p}}}
\]

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Deuteron from Y(3S)

With no dedicated PID or tracking, BaBar and CLEO measured the $\bar{d}$ spectrum. 

$\text{Phys.Rev. D89} (2014) \text{ no.11, 111102}$

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<th>Process</th>
<th>Rate</th>
</tr>
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<tbody>
<tr>
<td>$B(Y(3S) \rightarrow \bar{d}X)$</td>
<td>$(2.33 \pm 0.15^{+0.31}_{-0.28}) \times 10^{-5}$</td>
</tr>
<tr>
<td>$B(Y(2S) \rightarrow \bar{d}X)$</td>
<td>$(2.64 \pm 0.11^{+0.26}_{-0.21}) \times 10^{-5}$</td>
</tr>
<tr>
<td>$B(Y(1S) \rightarrow \bar{d}X)$</td>
<td>$(2.81 \pm 0.49^{+0.29}_{-0.24}) \times 10^{-5}$</td>
</tr>
<tr>
<td>$\sigma(e^+e^- \rightarrow \bar{d}X)$ [$\sqrt{s} \approx 10.58 \text{ GeV}$]</td>
<td>$(9.63 \pm 0.41^{+1.17}_{-1.01}) \text{ fb}$</td>
</tr>
<tr>
<td>$\frac{\sigma(e^+e^- \rightarrow \bar{d}X)}{\sigma(e^+e^- \rightarrow \text{Hadrons})}$</td>
<td>$(3.01 \pm 0.13^{+0.37}_{-0.31}) \times 10^{-6}$</td>
</tr>
</tbody>
</table>

**Belle II prospects**

- Collect $\sim$30000 $\bar{d}$, with dedicated tracking and PID
- Get the world best estimate of the coalescence parameter
- Simultaneous fit of the proton spectrum
- $d\bar{d}$ associated production
- Search for excited nucleons: $d^* \rightarrow d\pi\pi$

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**Probing the ΛΛ interaction**

Belle left two main results on ΛΛ pairs (More to come!)

Near-threshold enhancement in exclusive Y annihilations

No sign of weakly bound H-dibaryon

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**Belle prospects**

→ Rough extrapolation for 1.2 B Y(3S)
  ~60 Million events with one Λ or Λ̅  ~3 Million events with one ΛΛ pair
→ High statistics study near threshold enhancement
→ search for Η di-baryon in missing mass from Y(3S) → Η ΛΛ + hadrons
→ Extract the ΛΛ potential from correlation functions (no in-medium corrections!)
Wrapping it up

Belle II offers:
→ Improved tracking (efficiency and resolution)
→ Improved hermeticity (smaller boost)
→ 8-10x Belle statistics
→ 10 MeV-wide cross section scans

Belle II could take
→ O(ab-1) at Y(5S)
→ Fine-grained scan around Y(5S) and Y(6S)
→ O(1 B) Y(3S)

Unfortunately, nothing comes for free
→ BelleII is mainly focused on BSM physics in the weak sector
→ Most of the data taking will take place at Y(4S) for B physics: max 30% of data off-Y(4S), including continuum
→ Competition with LHCb is pressing

Support and inputs from all the QCD communities are welcome!
Backup
Light mesons: the $\pi$ scattering length

At low energy the $\pi\pi$ interaction is described by two scattering lengths who vanish in the chiral limit:

$$a_0^0 = \frac{7M_\pi^2}{32\pi F_\pi^2} + \mathcal{O}(m_q^2) \quad a_0^2 = -\frac{M_\pi^2}{16\pi F_\pi^2} + \mathcal{O}(m_q^2)$$

Weinberg, PRL17,616(1966)

Using ChPT, theory predicts:

$$a_0^0 - a_0^2 = 0.265 \pm 0.004$$


Q-value for $Y(3S) \rightarrow \pi\pi$

$Y(2S)$ is only 50 MeV

Liu et al, EPJC73, 2284 (2013)
Rare decays as BSM probes

$\chi_b(2P) \rightarrow \tau\tau$ is sensitive to the presence of a CP-even light Higgs (as $B \rightarrow \tau\tau$, $B \rightarrow \tau\mu$...)

$$\begin{align*}
BR^H(\chi_b(1P) \rightarrow \tau\tau) &= 3.1 \times 10^{-13} \\
BR^H(\chi_b(2P) \rightarrow \tau\tau) &= (1.9 \pm 0.5) \times 10^{-12} \\
\end{align*}$$

$$\left( 1 + \frac{M_{H_{125}}^2 \tan^2 \beta}{M_{\text{new}}^2 - M_{\chi_b}^2} \right)^2$$

Will only need $(M_{H_{125}}/M_{\text{new}}) \tan \beta \sim 30$ for $\mathcal{O}(100)$ signal events in Y(3S) → $\gamma\chi_b(2P) \rightarrow \gamma\tau\tau$

Results: Y(3S)

- DELPHI $e^+e^- \rightarrow \chi_b(\rightarrow b\bar{b})$
- CMS $\not\!p\not\!p \rightarrow \tau\tau$
- ATLAS $\not\!p\not\!p \rightarrow \gamma\gamma$

BellII prospects:

→ Collect 300fb$^{-1}$ at Y(3S) only, and run both fully inclusive and fully exclusive analysis
→ Challenging background from QED $ee \rightarrow \gamma\tau\tau$

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