Recent quarkonium results from Belle II

16th International Conference on Heavy Quarks and Leptons

Renu
On the behalf of Belle II Collaboration
Supported by US DOE funding
28th Nov, 2023 - 2nd Dec, 2023
- **Below the $B\bar{B}$ threshold** states are well described by potential models.

- **Above $B\bar{B}$ threshold states** exhibit unexpected properties:
  - Hadronic transitions to lower bottomonia are strongly enhanced.
  - The $\eta$ transitions are not suppressed compared to $\pi^+\pi^-$ transitions. Strong violation of Heavy Quark Spin Symmetry.
  - $Z_b^+(10610)$ or $Z_b^+(10650)$: observed near the $B^{(*)}\bar{B}^*$ thresholds, properties are consistent with $B^{(*)}\bar{B}^*$ molecules.

**Exotic admixtures**: molecule, compact tetraquark, hybrid.

**Bottomonium Scheme**

- Conventional bottomonium (pure $b\bar{b}$ state)
- Bottomonium like states (mix of $b\bar{b}$ and $B\bar{B}$)
- Purely exotic states ($Z_b$)
Discovery of Υ(10753)

- Υ(10753) was observed in energy dependence of $e^+e^- \rightarrow Υ(nS)\pi^+\pi^-$ ($n = 1, 2, 3$) cross sections by Belle.
- The global significance is 5.2$\sigma$

<table>
<thead>
<tr>
<th>$Υ(10860)$</th>
<th>$Υ(11020)$</th>
<th>New structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M$ (MeV/c$^2$)</td>
<td>$10885.3 \pm 1.5^{+2.2}_{-0.9}$</td>
<td>$11000.0^{+4.0}<em>{-4.5}^{+1.0}</em>{-1.3}$</td>
</tr>
<tr>
<td>$Γ$ (MeV)</td>
<td>$36.6^{+4.5}_{-3.9}^{+0.5}$</td>
<td>$23.8^{+8.0}<em>{-6.8}^{+0.7}$ $35.5^{+17.6}</em>{-11.3}^{+3.9}$</td>
</tr>
</tbody>
</table>

- $e^+e^- \rightarrow b\bar{b}$ cross section in bottomonium energy region based on the Belle and BABAR measurement.
- A dip near 10.75 GeV likely caused by interference between BW and smooth component.

Fit function: 3 BW+smooth component
\( \Upsilon(10753) \): theoretical interpretation

Possible interpretations:

- Conventional bottomonium?
  - Phys. Rev. D 105, 114041 (2022)
  - Phys. Rev. D 106, 094013 (2022)
  - Phys. Rev. D 105, 074007 (2022)

- Hybrid state?
  - Phys. Rept. 873, 1 (2020)
  - Phys. Rev. D 104, 034019 (2021)

- Tetraquark state?
  - Phys. Rev. D 103, 074507 (2021)
  - Phys. Rev. D 107, 094515 (2023)

- Hadronic molecule with a small admixture of a bottomonium?

\[ \text{Mass does not match } \Upsilon(3D) \text{ theoretical predictions, and } D\text{-wave states are not seen in } e^+e^- \text{ collisions.} \]
\[ \Upsilon(4S) - \Upsilon(3D) \text{ mixing can be enhanced due to hadronic loops.} \]
Belle II / SuperKEKB performed an energy scan in November 2021 with a total luminosity of 19 fb$^{-1}$.

**Physics Goals:**
- The main goal was to confirm and study the $\Upsilon(10753)$.
- Improve the precision of exclusive cross-section below the $\Upsilon(5S)$.

Belle II collected data in the gaps between the Belle points.
- The point with the highest statistics (9.8 fb$^{-1}$) is near the $\Upsilon(10753)$ peak.
Study of $\Upsilon(10753) \rightarrow (\pi^+\pi^-\pi^0) \gamma \ Upsilon(1S)$
Study of $\Upsilon(10753) \rightarrow (\pi^+\pi^-\pi^0) \gamma \ Upsilon(1S)$

**Theory:**
- Mixed $4S - 3D$ model suggests $\Upsilon(10753) \rightarrow \omega \chi_{bJ}(1P)$ could be enhanced.

**Charmonium sector:**
- Similar to $\Upsilon(10753)$ in $e^+e^- \rightarrow \pi^+\pi^- \Upsilon(nS)$, $Y(4260)$ was observed in $e^+e^- \rightarrow \pi^+\pi^- J/\psi$ cross section by BESIII.
- Expect similar nature of $\Upsilon(10753)$ and $Y(4260)$.
- $Y(4260)$ was also observed in $\omega \chi_{cJ}(1P)$ and $\gamma X(3872)$ by BESIII.
- Inspired by decay modes of $Y(4260)$ charmonium state, we expect
  - $\Upsilon(10753) \rightarrow \omega \chi_{bJ}(1P)$
  - $\Upsilon(10753) \rightarrow \gamma X_b$  
    - $X_b$: bottomonium analogue of $X(3872)$

Search in $e^+e^- \rightarrow (\pi^+\pi^-\pi^0) \gamma \ Upsilon(1S)$ process
Observation of $\Upsilon(10753) \to \omega \chi_{bJ}(1P)$

The $e^+e^- \to \omega \chi_{bJ}(1P) \ (J = 1, 2)$ cross sections peak at $\Upsilon(10753)$.

Solution I: constructive interference
Solution II: destructive interference

$\frac{\sigma(e^+e^- \to \omega \chi_{b1})}{\sigma(e^+e^- \to \Upsilon(nS)\pi^+\pi^-)} \sim \begin{cases} 1.5 \text{ at } \Upsilon(10753) \text{ GeV} \\ 0.15 \text{ at } \Upsilon(5S) \text{ GeV} \end{cases}$

$\Upsilon(10753)$ and $\Upsilon(5S)$ have different internal structure?

$\frac{\sigma(e^+e^- \to \omega \chi_{b1})}{\sigma(e^+e^- \to \omega \chi_{b2})} = 1.3 \pm 0.6 \text{ at } \sqrt{s} = 10.745 \text{ GeV}$

Contradicts the expectations for a pure $D$-wave bottomonium state: 15

An observation of 1.8σ difference with the prediction for a $S - D$ mixed state: 0.2

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\sqrt{s}$ (GeV)</th>
<th>$N^{\text{sig}}$</th>
<th>$\sigma^{(\text{UL})}$ (pb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\omega \chi_{b1}$</td>
<td>10.745</td>
<td>$68.9^{+13.7}_{-13.5}$</td>
<td>$3.6^{+0.7}_{-0.7}$ ± 0.4</td>
</tr>
<tr>
<td>$\omega \chi_{b2}$</td>
<td>$27.6^{+11.6}_{-10.0}$</td>
<td>$2.8^{+1.7}_{-1.0}$ ± 0.5</td>
<td></td>
</tr>
<tr>
<td>$\omega \chi_{b1}$</td>
<td>10.805</td>
<td>$15.0^{+6.8}_{-6.2}$</td>
<td>1.6 @90% C.L.</td>
</tr>
<tr>
<td>$\omega \chi_{b2}$</td>
<td>$3.3^{+5.3}_{-3.8}$</td>
<td>1.5 @90% C.L.</td>
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</tbody>
</table>
Search for $\Upsilon(10753) \to \gamma X_b$

The $X_b$ is posited bottomonium counterpart of X(3872).

- No significant signal of $X_b$ signal is observed.
- Upper limits on cross sections are set for $M(X_b) \in (10.45 - 10.65)$ GeV

<table>
<thead>
<tr>
<th>$\sqrt{s}$ GeV</th>
<th>$\sigma_B(e^+e^- \to \gamma X_b) \times \mathcal{B}(X_b \to \omega \Upsilon(1S))$</th>
</tr>
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<tbody>
<tr>
<td>10.653</td>
<td>(0.14–0.55) pb</td>
</tr>
<tr>
<td>10.701</td>
<td>(0.25–0.84) pb</td>
</tr>
<tr>
<td>10.745</td>
<td>(0.06–0.14) pb</td>
</tr>
<tr>
<td>10.805</td>
<td>(0.08–0.37) pb</td>
</tr>
</tbody>
</table>

Recent quarkonium results from Belle II / Renu Garg / HQL 2023
Search for $\Upsilon(10753) \rightarrow \omega\chi_{b0}(1P)/\omega\eta_{b}(1S)$
Search for $\Upsilon(10753) \to \omega \chi_{b0}(1P)/\omega \eta_b(1S)$

**Motivation:**

- $\Upsilon(10753) \to \omega \eta_b(1S)$
  - Theoretically, tetraquark interpretation predicts,
    - a strong enhancement of the decay $\omega \eta_b(1S)$ compared to $\pi^+\pi^- \Upsilon(nS)$
    \[ \frac{\Gamma(\omega \eta_b)}{\Gamma(\pi^+\pi^- \Upsilon(nS))} \sim 30 \]
  - $\Upsilon(10753) \to \omega \chi_{b0}(1S)$
  - In charmonium analogy, $Y(4260) \to \omega \chi_{c0}(1P)$ transition is enhanced compared to $Y(4260) \to \omega \chi_{c1,c2}(1P)$
  - Not observed in full reconstruction analysis of $\Upsilon(10753) \to \omega \chi_{bj}(1S)$ due to small branching fraction

**Strategy**

- Partial reconstruction:
  - Reconstructed $\omega$ meson in $\pi^+\pi^-\pi^0$ and use the recoil mass of $\omega$ as signal variable
  \[
  M_{\text{recoil}}(\pi^+\pi^-\pi^0) = \sqrt{\left(\frac{\sqrt{s} - E^*}{c^2}\right)^2 - \left(\frac{p^*}{c}\right)^2}
  \]

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Recent quarkonium results from Belle II / Renu Garg / HQL 2023

CPC 43 (2019) 12, 123102

PRD 99, 091103(R) (2019)

PRL 130 091902 (2023)
Results

- No significant $\omega \chi_{b0}(1P)$ and $\omega \eta_b(1S)$ signals are observed.
- Upper limits at the 90% C.L. on the Born cross section are set.

$\omega \eta_b(1S)$:
- $\sigma(e^+e^- \rightarrow \omega \eta_b(1S)) < 2.5$ pb
- c.f. $\sigma(e^+e^- \rightarrow \Upsilon(nS)\pi^+\pi^-) \sim 2.0$ pb
- Evidence against the tetraquark model predictions.

$\omega \chi_{b0}(1P)$:
- $\sigma(e^+e^- \rightarrow \omega \chi_{b0}(1S)) < 8.7$ pb
- Supports the $S - D$ mixing model

$\omega \rightarrow \pi^+\pi^-\pi^0$ recoil mass distributions

Recent quarkonium results from Belle II / Renu Garg / HQL 2023
Search for $\Upsilon(10753) \rightarrow \pi^+\pi^-\Upsilon(nS)$
Search for $\Upsilon(10753) \rightarrow \pi^+ \pi^- \Upsilon(nS)$

- Search for $\Upsilon(nS) (\rightarrow \mu^+ \mu^-) \pi^+ \pi^-$ decay mode.
- $p^*(\mu^+ \mu^- \pi^+ \pi^-) < 100$ MeV/c to reject background.

- Clear signal for $\Upsilon(1S)\pi^+ \pi^-$ and $\Upsilon(2S)\pi^+ \pi^-$ decay mode.
- No evidence of $\Upsilon(3S)\pi^+ \pi^-$

Recent quarkonium results from Belle II / Renu Garg / HQL 2023
New measurement confirms previous Belle result: cross section is peaking near 10.75 GeV.

<table>
<thead>
<tr>
<th></th>
<th>Belle + Belle II (MeV)</th>
<th>Belle (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\Upsilon(10753)}$</td>
<td>10756.3 ± 2.7 ± 0.6</td>
<td>10752.7 ± 5.9$^{+0.7}_{-1.1}$</td>
</tr>
<tr>
<td>$\Gamma_{\Upsilon(10753)}$</td>
<td>29.7 ± 8.5 ± 1.1</td>
<td>35.5$^{+17.6+3.9}_{-11.3-3.3}$</td>
</tr>
</tbody>
</table>

Results are consistent with the Belle results.

Uncertainties are improved by a factor of two from previous Belle results.
Resonant structure in $\Upsilon(10753) \rightarrow \pi^+ \pi^- \Upsilon(nS)$

- No signal of intermediate $Z_b^+(10610)$ or $Z_b^+(10650)$ resonances are observed.
- $\pi^+ \pi^- \Upsilon(1S)$: $M(\pi^+ \pi^-)$ distribution is consistent with phase space.
- $\pi^+ \pi^- \Upsilon(2S)$: larger values of $M(\pi^+ \pi^-)$ enhanced (similar to $\Upsilon(2S) \rightarrow \pi^+ \pi^- \Upsilon(1S)$ process)

\[ \Delta M_\pi = M(\pi^+ \mu^+ \mu^-) - M(\mu^+ \mu^-) \]

$\Delta M_\pi$ is used to identify resonant structures in $\Upsilon(10753) \rightarrow \pi^+ \pi^- \Upsilon(nS)$.
Conclusion on \( Y(10753) \)

- Improved results for mass and width of \( Y(10753) \) using \( Y(10753) \to Y(nS)\pi^+\pi^- \).
- New decay modes \( Y(10753) \to \omega\chi_{b1,2}(1P) \) are observed for the first time.
- A stringent upper limit is set for the \( Y(10753) \to \omega\eta_b(1S)/\omega\chi_{b0} \) at \( \sqrt{s} = 10.745 \) GeV.
- No signal of intermediate \( Z_b^+(10610) \) or \( Z_b^+(10650) \) resonances are observed.
Energy dependence of $e^+e^- \rightarrow B^{(*)}\bar{B}^{(*)}$ cross section
Motivation:

- The open flavor final states ($B^*(\bar{B}^(*))$) make dominant contribution to $bb$ cross-section.
  - Their measurements are critical for understanding the structure of $bb$ states.
- Belle measured the energy dependencies of $\sigma(e^+e^- \rightarrow B^*(\bar{B}^(*))$ and observed an oscillatory behavior.
  - Channels $B^*(\bar{B}^(*))$ saturate the cross-section below the $B^*_s\bar{B}^*_s$ threshold.
- The measured cross sections can be used in the coupled channel analysis of all available scan data to extract the parameters of the $Y$ states.
- To improve the accuracy below $Y(5S)$ and understand the nature of $Y(10753)$, need more data: Belle II

Recent quarkonium results from Belle II / Renu Garg / HQL 2023
The obtained cross sections at four energies are consistent with the Belle results.

\( \sigma(e^+e^- \to B^*\bar{B}^*) \) increases rapidly above \( B^*B^* \) threshold.

Similar phenomenon was observed near \( D^*\bar{D}^* \) threshold.

Possible interpretation: resonance or bound state \((B^*\bar{B}^* \text{ or } b\bar{b})\) near \( B^*B^* \) threshold

Inelastic channels \([\pi^+\pi^-\Upsilon(nS) \text{ and } \eta h_b(1P)]\) could also be enhanced.

Energy dependence of \( e^+e^- \to B^*(\bar{B}^*) \) cross section

Solid curve – combined Belle + Belle II data fit
Dashed curve – Belle data fit only
Comparison of $\sigma_{b\bar{b}}$ and $\sigma_{B\bar{B}} + \sigma_{B\bar{B}^*} + \sigma_{B^*\bar{B}^*}$

- Agreement with $\sigma_{b\bar{b}}$ below the $B_s^{(*)}\bar{B}_s^{(*)}$ threshold.
- Deviation at high energy is presumably due to $B_s^{(*)}\bar{B}_s^{(*)}$, multi-body $B^{(*)}\bar{B}^{(*)}\pi(\pi)$, etc.

Black dots: Belle + BaBar
[PRL 102, 012001 (2009), PRD 93, 011101 (2016), CPC 44, 083001 (2020)]

Open blue circles: Belle
[JHEP 06, 137 (2021)]

Filled red circles: Belle II
[this work]
We are at the beginning of a long program of quarkonium physics.

The unique data sample with energy scan near $\sqrt{s} = 10.75$ GeV at Belle II provides an opportunity:

- To understand the nature of the $\Upsilon(10753)$ energy region,
- The quarkonium spectroscopy.
Introduction

Quark model: Classification scheme for hadrons in terms of valance quarks.

Hadrons are composed of mesons (q̅q, qq̅q̅, ...) and baryons (qqq, qqqq̄q̄, ...).

- $q̅q$ spectroscopy with heavy quark (mostly c or b) are best place to study quark model.
- Simple two body system, non-relativistic and narrow (with OZI suppression).
- Further, one can search for exotics with them.

M. Gell-Mann, Phys.Lett. 8, 214 (1964)

Not observed in conventional matter. However, they should be allowed.
Belle II detector

- Asymmetric $e^+e^-$ collider
- **Collected data**
  - ~ 362 fb$^{-1}$ at Y(4S)
  - 42 fb$^{-1}$ off-resonance, 60 MeV below Y(4S).
  - 19 fb$^{-1}$ energy scan between 10.6 to 10.8 GeV for exotic hadron studies.

**Features:**
- Near-hermetic detector
- Excellent vertexing and tracking
- High-efficiency detection of neutrals ($\gamma$, $\pi^0$, $\eta$, $\eta'$, ...)
- Good charged particle reconstruction.

**Record-breaking instantaneous luminosity:**

$4.7 \times 10^{34}$ cm$^{-2}$s$^{-1}$

**Central Drift Chamber**
- Spatial resolution $\approx 100\mu$m
- $\sigma(p_T)/p_T \approx 0.4\%$

**Vertex Detector**
- $\sigma_{\text{vertex}} \approx 15\mu$m

**EM Calorimeter**
- $\sigma(E)/E \approx (2 - 4)\%$

**K$_L$ & $\mu$ Detector**
- $\mu$ ID efficiency $\approx 90\%$
- $\pi$ mis-ID rate $\approx 5\%$

**Super-Conducting Solenoid**
- 1.5T B-field

**Particle Identification**
- K ID efficiency $\approx 90\%$
- $\pi$ mis-ID rate $\approx 5\%$
Coupled channel analysis

Hüsken, Mitchell, Swanson, PRD 106, 094013 (2022)

All available scan data

K-matrix: scattering via $\Upsilon(4S)$, $\Upsilon(10753)$, $\Upsilon(5S)$, $\Upsilon(6S)$ or non-resonantly.

Results: pole positions, branching fraction, energy dependence of scattering amplitudes.

Accuracy above $\Upsilon(6S)$ and near $\Upsilon(10753)$ is poor.
Energy dependence of $e^+e^- \rightarrow B^{(*)}\bar{B}^{(*)}$ cross section

Recent quarkonium results from Belle II / Renu Garg / HQL 2023

Decay modes used:

<table>
<thead>
<tr>
<th>$B^+ \rightarrow$</th>
<th>$B^0 \rightarrow$</th>
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<tbody>
<tr>
<td>$\bar{D}^0\pi^+$</td>
<td>$D^-\pi^+$</td>
</tr>
<tr>
<td>$\bar{D}^0\pi^+\pi^+\pi^-$</td>
<td>$D^-\pi^+\pi^+\pi^-$</td>
</tr>
<tr>
<td>$\bar{D}^*\pi^+$</td>
<td>$D^*\pi^-$</td>
</tr>
<tr>
<td>$\bar{D}^*\pi^+\pi^+\pi^-$</td>
<td>$D^*\pi^+\pi^+\pi^-$</td>
</tr>
<tr>
<td>$D_s^+D^0$</td>
<td>$D_s^+D^-$</td>
</tr>
<tr>
<td>$D_s^{*+}\bar{D}^0$</td>
<td>$D_s^{*+}D^-$</td>
</tr>
<tr>
<td>$D_s^+D_s^{*0}$</td>
<td>$D_s^+D_s^{*-}$</td>
</tr>
<tr>
<td>$D_s^{*+}D_s^{*0}$</td>
<td>$D_s^{<em>+}D_s^{</em>-}$</td>
</tr>
<tr>
<td>$J/\psi K^+$</td>
<td>$J/\psi K_S$</td>
</tr>
<tr>
<td>$J/\psi K_S\pi^+$</td>
<td>$J/\psi K^+\pi^-$</td>
</tr>
<tr>
<td>$J/\psi K^{+}\pi^+\pi^-$</td>
<td>$D^-\pi^+\pi^+$</td>
</tr>
<tr>
<td>$D^*\pi^-K^+K^-\pi^+$</td>
<td>$D^*-K^+K^-\pi^+$</td>
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<table>
<thead>
<tr>
<th>$D^0 \rightarrow$</th>
<th>$D^+ \rightarrow$</th>
<th>$D_s^+ \rightarrow$</th>
</tr>
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<tbody>
<tr>
<td>$K^-\pi^+$</td>
<td>$K^-\pi^+\pi^+$</td>
<td>$K^+K^-\pi^+$</td>
</tr>
<tr>
<td>$K^-\pi^+\pi^0$</td>
<td>$K^-\pi^+\pi^+\pi^0$</td>
<td>$K^+K_S$</td>
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<tr>
<td>$K^-\pi^+\pi^+\pi^-$</td>
<td>$K_S\pi^+$</td>
<td>$K^+K^-\pi^+\pi^0$</td>
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<tr>
<td>$K_S\pi^+\pi^-$</td>
<td>$K_S\pi^+\pi^0$</td>
<td>$K^+K_S\pi^+\pi^-$</td>
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<tr>
<td>$K_S\pi^+\pi^-\pi^0$</td>
<td>$K_S\pi^+\pi^-\pi^-$</td>
<td>$K^-K_S\pi^+\pi^+$</td>
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<tr>
<td>$K^+K^-\pi^-\pi^+$</td>
<td>$K^+K^+\pi^+$</td>
<td>$K^+K^-\pi^+\pi^+\pi^-$</td>
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<tr>
<td>$K^+K^-K_S$</td>
<td></td>
<td>$K^+\pi^+\pi^-$</td>
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<tr>
<td></td>
<td></td>
<td>$\pi^+\pi^+\pi^-$</td>
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</table>
**Method:**
- Reconstruct one B in full hadronic channels.
- Key variables for analysis are
  - \( M_{bc} = \sqrt{(E_{cm}/2)^2 - p_B^2} \)
  - \( \Delta E' = \Delta E - M_{bc} + M_B \), where \( \Delta E = E_B - E_{cm}/2 \)
  - \( \Delta E' \) has improved resolution and allows all desired two-body decays to be selected with a common cut
  - Populations of each can be studied by fitting the projections onto the \( M_{bc} \) axis for all energies at which data were accumulated
  - \( B^* \to B\gamma \) decays are not reconstructed.

\[ \text{Energy dependence of } e^+e^- \to B^*(\bar{B}^*) \text{ cross section} \]
Energy dependence of $e^+e^- \rightarrow B^{(*)}\bar{B}^{(*)}$ cross section

$M_{bc}$ fit at scan energies

- $M_{bc}$ fit distribution:
  - $\Delta E'$ signal region (upper)
  - $\Delta E'$ side-bands (lower)

- $e^+e^- \rightarrow B\bar{B}$, $B\bar{B}^*$, $B^*\bar{B}^*$ signals at $\sqrt{s} \sim 10.75$ GeV can be clearly observed

- Contribution of $\Upsilon(4S) \rightarrow BB$ production via ISR is visible well (black dotted histograms)

- At $\sqrt{s} = 10.653$ GeV, the sharp cut of the data at right edge is due to threshold effect
Four ways to access bottomonia:

- **Direct production** from $e^+e^-$: $J^{PC} = 1^{--}$: $\Upsilon(nS)$
- **ISR production**: $J^{PC} = 1^{--}$: $\Upsilon(nS)$
- **Hadronic transitions** from $\Upsilon(nS)$ through $\eta$, $\pi\pi$, …
  
  $J^{PC} = 0^{--}$, $1^{--}$, $1^{++}$: $\Upsilon(nS), \eta_b(nS), h_b(nS)$, …
- **Radiative transitions** from $\Upsilon(nS)$
  
  $J^{PC} = 0^{--}$, $0^{++}$, $1^{++}$, $2^{++}$: $\eta_b(nS), \chi_b(nP)$