Exotic Onia-like Spectroscopy

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Are there exotics beyond meson (qq̅) / baryon (qqq) ?

QCD just require hadrons to be colorless, and allow exotics. Such exotic states exist?
Existence of such exotics have long been discussed since the birth of the quark model.

A schematic model of baryons and mesons *

M. Gell-Mann

California Institute of Technology, Pasadena, California

Received 4 January 1964

A simpler and more elegant scheme can be constructed if we allow non-integral values for the charges. We can dispense entirely with the basic baryon b if we assign to the triplet t the following properties: spin $\frac{1}{2}$, $z = -\frac{1}{2}$, and baryon number $\frac{1}{2}$. We then refer to the members u$^1$, d$^1$, and s$^1$ of the triplet as "quarks" 6) q and the members of the anti-triplet as anti-quarks $\bar{q}$. Baryons can now be constructed from quarks by using the combinations (qqq), (qqqq), etc., while mesons are made out of (q$\bar{q}$), (qq$\bar{q}$), etc. It is assuming that the lowest baryon configuration (qqq) gives just the representations 1, 8, and 10 that have been observed, while the lowest meson configuration (q$\bar{q}$) similarly gives just 1 and 8.

A formal mathematical model based on field theory can be built up for the quarks exactly as for p, n, $\Lambda$ in the old Sakata model, for example 3) with all strong interactions ascribed to a neutral vector meson field interacting symmetrically with the three particles. Within such a framework, the
Heavy quarkonium is an ideal tool to study “mesons”.

- Below $D\bar{D}$ threshold;
  - All charmonium states have been observed.
  - Spectra are in good agreement with naïve quark model

$$V_{QCD} = -\frac{4}{3} \frac{\alpha_s}{r} + kr$$

However,

- Above $D\bar{D}$ threshold;
  - Observed states DO NOT fit to the predicted spectrum.

Charged states cannot be $Z^+(4430)$,
$Z^+(4050)$, $Z^+(4250)$

We do not understood yet how hadrons are formed from QCD.
High luminosity $e^+e^-$ collider and high performance $4\pi$ detectors are essential for the “bonus” discoveries.

Data taking not only on $Y(4S)$ but also on $Y(nS)$ [$n=1,2,3,5$] and continuum.

- Good acceptance
- Good tracking
- Good Particle ID ($e,\mu,\pi,K,p$)
- Minimum-bias triggers
B factories can produce charmonium (-like) states in four ways.

1. \( B \) decay
2. Double charmonium production
3. \( 2\gamma \) production
4. Initial State Radiation (ISR)
### XYZ at B Factories

<table>
<thead>
<tr>
<th>State</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Decay</th>
<th>Production</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ys(2175)</td>
<td>2175±8</td>
<td>58±26</td>
<td>$\phi_0$</td>
<td>ISR</td>
</tr>
<tr>
<td>X(3872)</td>
<td>3871.84±0.33</td>
<td>&lt;0.95</td>
<td>$J/\psi \pi\pi$, $J/\psi\gamma$</td>
<td>B decay</td>
</tr>
<tr>
<td>X(3872)</td>
<td>3872.8±0.7/-0.6</td>
<td>3.9±2.8/-1.8</td>
<td>$D^*_0D^0$, $J/\psi\omega$</td>
<td>B decay</td>
</tr>
<tr>
<td>Y(3915)</td>
<td>3915±4</td>
<td>17±10</td>
<td>$J/\psi\rho$</td>
<td>$\gamma\gamma$</td>
</tr>
<tr>
<td>Z(3940)</td>
<td>3929±5</td>
<td>29±10</td>
<td>DD</td>
<td>$\gamma\gamma$</td>
</tr>
<tr>
<td>X(3940)</td>
<td>3942±9</td>
<td>37±17</td>
<td>DD*</td>
<td>Double-charm</td>
</tr>
<tr>
<td>Y(3940)</td>
<td>3942±17</td>
<td>87±34</td>
<td>$J/\psi\rho$</td>
<td>B decay</td>
</tr>
<tr>
<td>Y(4008)</td>
<td>4008±82/-49</td>
<td>226±97/-80</td>
<td>$J/\psi\pi\pi$</td>
<td>ISR</td>
</tr>
<tr>
<td>Z(4051)$^*$</td>
<td>4051±24/-43</td>
<td>82±51/-28</td>
<td>$\pi\chi_{c1}$</td>
<td>B decay</td>
</tr>
<tr>
<td>X(4160)</td>
<td>4156±29</td>
<td>139±113/-65</td>
<td>$D^<em>D^</em>$</td>
<td>Double-charm</td>
</tr>
<tr>
<td>Z(4248)$^*$</td>
<td>4248±185/-45</td>
<td>177±320/-72</td>
<td>$\pi\chi_{c1}$</td>
<td>B decay</td>
</tr>
<tr>
<td>Y(4260)</td>
<td>4264±12</td>
<td>83±22</td>
<td>$J/\psi\pi\pi$</td>
<td>ISR</td>
</tr>
<tr>
<td>X(4350)</td>
<td>4350±4.7/-5.1</td>
<td>13±18/-14</td>
<td>$J/\psi\phi$</td>
<td>$\gamma\gamma$</td>
</tr>
<tr>
<td>Y(4350)</td>
<td>4361±13</td>
<td>74±18</td>
<td>$\psi'\pi\pi$</td>
<td>ISR</td>
</tr>
<tr>
<td>Z(4430)$^*$</td>
<td>4433±5</td>
<td>45±35/-18</td>
<td>$\psi'\pi$</td>
<td>B decay</td>
</tr>
<tr>
<td>Y(4660)</td>
<td>4664±12</td>
<td>48±15</td>
<td>$\psi'\pi\pi$</td>
<td>ISR</td>
</tr>
<tr>
<td>Y_{c}(10890)</td>
<td>10889.6±2.3</td>
<td>54.7±8.9/-7.6</td>
<td>$\pi\pi Y (nS)$</td>
<td>$e^+e^ -$ annihilation</td>
</tr>
<tr>
<td>Z_{c}(10610)</td>
<td>10608.4±2.0</td>
<td>15.6±2.5</td>
<td>($Y (nS)$ or $h_b$) $\pi$</td>
<td>$Y (5S) / Y_0$ decay</td>
</tr>
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<td>Z_{c}(10650)</td>
<td>10653.2±1.5</td>
<td>14.4±3.2</td>
<td>($Y (nS)$ or $h_b$) $\pi$</td>
<td>$Y (5S) / Y_0$ decay</td>
</tr>
</tbody>
</table>

#### Tetraquark
- **Di-quark**

#### Hybrid

- $D(*)D(*)$ Molecule
Charmonium-like exotics
Discovery by Belle in 2003, followed by D0, CDF, BaBar.

More recently, also by LHCb, CMS.
Properties of $X(3872)$

- $C = +1$, $X(3872) \rightarrow J/\psi \gamma, J/\psi \rho$ seen
- $J^{PC} = 1^{++}$ or $2^{-+}$, Angular distribution
- $I = 0$, No charged partner found so far
- Possible interpretation
  - Conventional $c\bar{c}$: $\chi_{c1}(2^{3}P_{1})$ for $1^{++}$, $\eta_{c2}(1^{1}D_{2})$ for $2^{-+}$
  - Exotics:
    - $D^*0 \bar{D}^0$ molecule: $[c\bar{q}][\bar{c}q]$
    - Tetra-quark: $[cq][\bar{c}\bar{q}]$

Mass just around $D^*D^0$

\[
\begin{align*}
M_X - M_{D^*0} - M_{D^0} &= -0.12 \pm 0.35 \text{ MeV} \\
M_X - M_{D^{*+}} - M_{D^-} &= -7.74 \pm 0.35 \text{ MeV}
\end{align*}
\]
All $J^P_C$ values other than $1^{++}$ or $2^{-+}$ are ruled out with high confidence.

Need more statistics to distinguish $1^{++}$ vs $2^{-+}$. 
**X(3872) in $B^+ \text{ vs } B^0$ decays**

**Prediction by a tetra-quark model; $\Delta M \sim 8$ MeV**

Maiani et al PRD71, 014028

By combining:

$$M_{X(3872)} = [3871.85 \pm 0.27 \pm 0.19] \text{ MeV}$$

$$\Gamma_{X(3872)} < 1.2 \text{ MeV (90% C.L.)}$$
$X(3872)$ at LHC

CMS (40 pb$^{-1}$, $\sqrt{s} = 7$ TeV)

\[ R \equiv \frac{\sigma(pp \rightarrow X(3872) + K) \times Br(X(3872) \rightarrow J/\psi \pi^+ \pi^-)}{\sigma(pp \rightarrow \psi(2S) + K) \times Br(\psi(2S) \rightarrow J/\psi \pi^+ \pi^-)} \]

\[ = 0.087 \pm 0.017 \pm 0.009 \]

LHCb (34.7 pb$^{-1}$, $\sqrt{s} = 7$ TeV)

arXiv: 1112.5310

\[ \sigma(pp \rightarrow X(3872) + K) \times Br(X(3872) \rightarrow J/\psi \pi^+ \pi^-) \]

\[ = [4.7 \pm 1.1 \pm 0.7] \text{ nb} \]

\[ M_{X(3872)} = [3871.95 \pm 0.48 \pm 0.12] \text{ MeV} \]

Looking forward to results with $>1$ fb$^{-1}$ data.
BaBar found Y(4260) in ISR $e^+e^- \rightarrow J/\psi \pi^+\pi^-$ (2005)
CLEO-c/CLEO III/Belle confirmed, and Belle found also enhancement near 4005 MeV.

New BaBar result
- Mass/width
  $M = 4244 \pm 5 \pm 4$ MeV
  $\Gamma = 114^{+16}_{-15} \pm 7$ MeV
- but, does not confirm Y(4005).

Belle (548fb$^{-1}$)

Stay tuned for Belle result with the full data set.
BaBar found $Y(4360)$ in ISR $e^+e^- \rightarrow \psi(2S) \pi^+\pi^-$ (2005)

Belle confirmed $Y(4360)$ and found another peak $Y(4660)$

New BaBar results confirms $Y(4660)$ [QNP2012/Charm2012]

BaBar 520 fb$^{-1}$, preliminary

Belle 673 fb$^{-1}$

<table>
<thead>
<tr>
<th>(unit: MeV)</th>
<th>$M$ ($Y(4360)$)</th>
<th>$\Gamma$ ($Y(4360)$)</th>
<th>$M$ ($Y(4660)$)</th>
<th>$\Gamma$ ($Y(4660)$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Belle (673 fb$^{-1}$)</td>
<td>4361 ± 9 ± 9</td>
<td>74 ± 15 ± 10</td>
<td>4664 ± 11 ± 5</td>
<td>48 ± 15 ± 3</td>
</tr>
<tr>
<td>BaBar (520 fb$^{-1}$)</td>
<td>4340 ± 16 ± 9</td>
<td>94 ± 32 ± 13</td>
<td>4669 ± 21 ± 3</td>
<td>104 ± 48 ± 10</td>
</tr>
</tbody>
</table>

PRL99, 142002 (2007)
Belle found $Z(4430)^+$ in $B \rightarrow K \pi^+ \psi'$ decays.

- One-dimensional fit on $\psi'\pi^+$ distribution after $K^*(890)/K^*(1430)$ vetos. PRD80, 031104(2009)
- Confirmed by analysis with a full Dalitz plot. PRD80, 031104(2009)

\[
M = (4443^{+15}_{-12}^{+19}_{-13}) \text{MeV} / c^2
\]
\[
\Gamma = (107^{+86}_{-43}^{+74}_{-56}) \text{MeV}
\]

Belle found also another two states, $Z(4050)^+$ & $Z(4250)^+$, in $B \rightarrow K \pi^+ \chi_{c1}$ decays.

\[
M_1 = (4051 \pm 14^{+20}_{-41}) \text{MeV} / c^2
\]
\[
\Gamma_1 = (82^{+21}_{-17}^{+47}_{-22}) \text{MeV}
\]
\[
M_2 = (4248^{+44}_{-29}^{+180}_{-35}) \text{MeV} / c^2
\]
\[
\Gamma_2 = (177^{+54}_{-39}^{+316}_{-61}) \text{MeV}
\]

Their minimum quark content must be exotic: $c\bar{c}u\bar{d}$
Z⁺ (cont’d)

• BaBar does not confirm Z⁺’s
  – Z(4430)⁺ search in B → Kπ⁺ψ’
  – Z(4050)⁺/Z(4250)⁺ search in B → Kπ⁺χc₁
  – Excess is < 2σ w.r.t. Kπ reflection.

• But, do not rule out Belle’s results.
  – UL is statistically compatible with Belle results

\[
Br(\bar{B}^0 \rightarrow Z^+ K^-) \times Br(Z^+ \rightarrow \pi^+ \psi' / \chi_{c1})
\]

<table>
<thead>
<tr>
<th></th>
<th>BaBar U.L.</th>
<th>Belle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z(4430)⁺</td>
<td>&lt; 3.1 (95%CL)</td>
<td>4.1 ± 1.0 ± 1.4</td>
</tr>
<tr>
<td>Z(4050)⁺</td>
<td>&lt; 1.8 (90%CL)</td>
<td>3.0 ±1.5 ± 3.7 ±0.8 ±1.6</td>
</tr>
<tr>
<td>Z(4250)⁺</td>
<td>&lt; 4.0 (90%CL)</td>
<td>4.0 ±2.3 ±19.7 ±0.9 ±0.5</td>
</tr>
</tbody>
</table>

Note: In the BaBar analyses, Z⁺ amplitudes are added incoherently, therefore, interference effects are not included. They are included in the Belle analyses (see S.Olsen’s summary talk at CHARM2012, and also backup).

• Looking forward to the results from LHCb w/ full 2011 data set
  !Better statistics than Belle + BaBar ? (ref. A.A.Alves Jr. @ CHARM2012)
Bottomonium-like exotics
Nature of \( \Upsilon(5S) \)

- Unexpectedly large rate for \( \Upsilon(5S) \to \Upsilon(nS)\pi^+\pi^- \) (n=1,2,3).

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

\[\Gamma(\text{MeV}) = 0.59 \pm 0.04 \pm 0.09, 0.85 \pm 0.07 \pm 0.16, 0.52^{+0.20}_{-0.17} \pm 0.10, 0.0060, 0.0009, 0.0019\]

- \( \Upsilon(4260) \) with anomalous \( \Gamma(\Upsilon(4260) \to J/\psi\pi^+\pi^-) \)

Exotic \( Y_b \) just nearby \( \Upsilon(5S) \)?

- CLEO observed \( e^+e^- \to h_c \pi^+\pi^- \) near \( \Upsilon(4260) \).

\[e^+e^- \to h_b \pi^+\pi^- \text{ near } Y_b ?\]

- Line shape of \( Y_b \) near \( \Upsilon(4260) \).

\[Y\pi^+\pi^- \text{ peak shifted by } 2\sigma \text{ w.r.t. } \Upsilon(5S) \]
Search for $h_b$

- Use the missing mass in the reaction;
  $e^+e^- \rightarrow "Y(5S)" \rightarrow X \pi^+\pi^-$

\[
M_{\text{miss}}^2 = P_{Y(5S)}^2 - P_{\pi^+\pi^-}^2
\]

After background subtraction

Mass;  
$M [h_b(1P)] = 9898.2^{+1.1}_{-1.0}^{+1.0}_{-1.2} \text{ MeV} / c^2$  
$M [h_b(2P)] = 10259.8 \pm 0.6^{+1.4}_{-1.0} \text{ MeV} / c^2$

P-wave Hyperfine splittings;  
$\Delta M_{HF} [\chi_{bJ}(1P) - h_b(1P)] = (+1.7 \pm 1.5) \text{ MeV} / c^2$  
$\Delta M_{HF} [\chi_{bJ}(2P) - h_b(2P)] = (+0.5^{+1.6}_{-1.2}) \text{ MeV} / c^2$
Exotic Production Mechanism

Unusually large production rate!

\[
\frac{\Gamma [Y(5S) \rightarrow h_b(nP)\pi^+\pi^-]}{\Gamma [Y(5S) \rightarrow Y(2S)\pi^+\pi^-]} = \begin{cases} 
0.46 \pm 0.08^{+0.07}_{-0.12} & \text{for } h_b(1P) \\
0.77 \pm 0.08^{+0.22}_{-0.17} & \text{for } h_b(2P)
\end{cases}
\]

“\(\Upsilon(5S)\) → \(\Upsilon(nS)\pi^+\pi^-\)”

Intermediate resonance?

“\(\Upsilon(5S)\) → \(h_b(nP)\pi^+\pi^-\)”

Charged Bottomonium-like?

cf) Charm: \(B \rightarrow \psi' \pi^+ K^-\) \(Z^+(4430)\)

\(B \rightarrow \chi_{c1} \pi^+ K^-\) \(Z^+(4050), Z^+(4250)\)
Charged Bottomonium-like $Z_b^+$ in $\Upsilon(nS)\pi^+$

Two peaks at the same positions in the 3 modes.

Two resonances: $Z_b^+(10510), \ Z_b^+(10560)$

<table>
<thead>
<tr>
<th>Final state</th>
<th>$\Upsilon(1S)\pi^+\pi^-$</th>
<th>$\Upsilon(2S)\pi^+\pi^-$</th>
<th>$\Upsilon(3S)\pi^+\pi^-$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M[Z_b(10610)]$ (MeV/c²)</td>
<td>10611 ± 4 ± 3</td>
<td>10609 ± 2 ± 3</td>
<td>10608 ± 2 ± 3</td>
</tr>
<tr>
<td>$\Gamma[Z_b(10610)]$ (MeV)</td>
<td>22.3 ± 7.7^{+3.0}_{-4.0}</td>
<td>24.2 ± 3.1^{+2.0}_{-3.0}</td>
<td>17.6 ± 3.0 ± 3.0</td>
</tr>
<tr>
<td>$M[Z_b(10650)]$ (MeV/c²)</td>
<td>10657 ± 6 ± 3</td>
<td>10651 ± 2 ± 3</td>
<td>10652 ± 1 ± 2</td>
</tr>
<tr>
<td>$\Gamma[Z_b(10650)]$ (MeV)</td>
<td>16.3 ± 9.8^{+6.0}_{-2.0}</td>
<td>13.3 ± 3.3^{+4.0}_{-3.0}</td>
<td>8.4 ± 2.0 ± 2.0</td>
</tr>
<tr>
<td>Relative normalization</td>
<td>0.57 ± 0.21^{+0.19}_{-0.04}</td>
<td>0.86 ± 0.11^{+0.04}_{-0.10}</td>
<td>0.96 ± 0.14^{+0.08}_{-0.05}</td>
</tr>
<tr>
<td>Relative phase (deg)</td>
<td>58 ± 43^{+3}_{-9}</td>
<td>−13 ± 13^{+17}_{-18}</td>
<td>−9 ± 19^{+11}_{-26}</td>
</tr>
</tbody>
</table>
$h_b(1P, 2P) \pi^+ \pi^-$

$M_{\text{miss}}(\pi)$ to look at $h_b \pi^+$

Fit with $A(Z_{b1}^+) + A(Z_{b2}^+) + A(NR)$

Two peaks at the positions same as $\Upsilon(nS)\pi^+\pi^-$
$Z_b(10610)$ & $Z_b(10650)$

$\sim B\bar{B}^*$ threshold

$Z_b(10610)$

$Y(1S)\pi^+\pi^-$

$Y(2S)\pi^+\pi^-$

$Y(3S)\pi^+\pi^-$

$h_b(1P)\pi^+\pi^-$

$h_b(2P)\pi^+\pi^-$

Average

$\Delta M, \text{MeV}$

$\Delta \Gamma, \text{MeV}$

$M=10608.4 \pm 2.0 \text{ MeV}$

$\Gamma=15.6 \pm 2.5 \text{ MeV}$

$Z_b(10650)$

$\sim B^*\bar{B}^*$ threshold

$M=10653.2 \pm 1.5 \text{ MeV}$

$\Gamma=14.4 \pm 3.2 \text{ MeV}$
**Nature of $Z_{b}^{+}$**

**$B^{*}\bar{B}$ and $B^{*}\bar{B}^{*}$ molecule interpretation**

$Z_{b}^{+}(10510)$

- Masses just above $B^{*}\bar{B}$ and $B^{*}\bar{B}^{*}$
- Similar production rate for $Z_{b1}$ and $Z_{b2}$
- Similar decay width $\Gamma(Z_{b1})\sim\Gamma(Z_{b2})$
- Why $Y(5S)\rightarrow h_{b}\pi^{+}\pi^{-}$ is not suppressed
- Relative phase: $\sim0^\circ$ for $Y\pi$ and $\sim180^\circ$ for $h_{b}\pi$
- $J^P=1^+$ assignment ($0^\pm$ forbidden, $1^-$, $2^\pm$ disfavored at $\sim3\sigma$)

**Other interpretation**

- Coupled channel resonance: Daniklin et al. (arxiv:1106.1552)
- Cusp: Bugg (arXiv: 1105.5492)
Exotics in light flavors?

• $e^+e^-$ ISR:
  $Y(4260) \rightarrow \pi^+ \pi^- J/\psi$; $Y(4360) \rightarrow \pi^+ \pi^- \psi'$
  $\rightarrow Y(2175) \rightarrow \pi^+ \pi^- \phi (f_0 \phi)$
  seen by BaBar, Belle, BES III

• $\gamma\gamma$ (two-photon)
  $X(3915) \rightarrow \omega J/\psi$; $X(4350) \rightarrow \phi J/\psi$
  $\rightarrow$ What about $\omega \phi$, $\phi \phi$?
• 870 fb\(^{-1}\) near \(Y(nS)[n=1,\ldots,5]\)

• 4 charged tracks + \(\pi^0\);
  \(\phi \rightarrow K^+ K^-, \omega \rightarrow \pi^+ \pi^- \pi^0\)

• Signals are extracted by fitting distribution for each \(M(VV)\) bin.

• Obvious structures in low \(M(VV)\) region.
  – \(J^P\) of the structure is extracted from angular distributions.

• High luminosity e⁺e⁻ B factories have brought discoveries of many “exotic” hadrons (unexpected bonus of the B factories).
• Need more statistics to elucidate their properties (spin, parity, decay modes etc.)
  – Super-KEKB/Belle II and INFN SuperB will improve our knowledge.
    • Possibility to increase c.m.s energy to cover the bottom flavor region.
  – Looking forward to results from LHC experiments as well.

*This is also the area where (super) B factories and LHC communities can work together!*
Charmonium(-like)

- Belle: Evidence of $1^3D_2 = \psi_2$ in $\chi_{c1}\gamma$
- Belle: Search for $C=-1$ state in $J/\psi \, \eta$
- Belle: Search for $X(3872)$ and $\psi_2$ in $\chi_{c2}\gamma$
- Belle: Search for $Z_c^+$ in $B \rightarrow J/\psi \, \pi K$
- BaBar: Search for $\gamma \gamma \rightarrow h_c \pi^+\pi^-$
- BaBar: Confirmation of $X(3915)$ by $\gamma \gamma \rightarrow J/\psi \, \omega$

Bottomonium(-like)

- ATLAS/D0: Observation of $3^3P_j = \chi_b(3P)$
- Dobbs et al (CLEO data), excess in radiative decay of $Y(2S)$
- BaBar: Search for $Y(3S) \rightarrow h_b \, \pi^+\pi^-$
- Belle: Evidence of $2^1S_0 = \eta_b(2S)$ by $h_b(2P) \rightarrow \eta_b(2S)\gamma$
- Belle: Confirmation of $\eta_b(1S)$ by $h_b(1P) \rightarrow \eta_b(1S)\gamma$
- Belle: Confirmation of $1^3D_j = Y(1D)$
- Belle: Search for $Y(2S) \rightarrow \eta Y(1S), \ Y(2S) \rightarrow \pi^0 Y(1S)$
- Belle: Search for $Y(5S) \rightarrow \eta Y(1S,2S), \ Y(5S) \rightarrow \eta' Y(1S)$

- Belle: Search for $Y(2S) \rightarrow \chi_{cJ}/\eta_c/X/Y + \gamma$
- Belle: Search for $\chi_{bj} \rightarrow J/\psi J/\psi, J/\psi \psi', \psi \bar{\psi} \bar{\psi}$
- Belle: Observation of $Y(1S), Y(2S)$ decay into light hadrons
- LHCb: Search for $X(4140)$ and $X(4274)$

Apology if I miss any...
Apology for missing reference.

First meas. of the width
The best precise mass meas.
Backup
Search for $h_b$

- Use the missing mass in the reaction; $e^+e^- \rightarrow \text{"Y(5S)" } \rightarrow X \pi^+\pi^-$

\[ M_{\text{miss}}^2 = P_{\text{Y(5S)}}^2 - P_{\pi^+\pi^-}^2 \]

Accurate background subtraction using high statistics data!
\[ M^2(Y(ns)\pi^+) \max \text{ GeV}^2/c^4 \]

PRL 108, 122001 (2012)

- Two horizontal bands in \( Y(nS) \pi^+ \)
  - Charged!
- Dalitz plot amplitude analysis; fitted with
  \[
  A = A(Z_{b1}^+) + A(Z_{b2}^+) + A(f_0(980)) + A(f_2(1275)) + A(NR)
  \]
Belle (711 fb⁻¹)

\[ B^0 \rightarrow K^- \pi^+ \pi^0 J/\psi \]

\[ B^+ \rightarrow K^0 \pi^+ \pi^0 J/\psi \]

\[ Br(B \rightarrow KX^+) \times Br(X^+ \rightarrow \rho^+ J/\psi) \]
\[ < 4.2 \times 10^{-6} \text{ for } K = K^+ \]
\[ < 6.1 \times 10^{-6} \text{ for } K = K^0 \]

for 3850 – 3890 MeV (90% C.L.)

\[ Br(B^+ \rightarrow K^+ X(3872)) \times Br(X(3872) \rightarrow \pi^+ \pi^- J/\psi) \]
\[ = [8.63 \pm 0.82 \pm 0.52] \times 10^{-6} \]
Evidence of $1^3D_2 = \psi_2$

- Belle 711 fb$^{-1}$ preliminary
- $\psi' \rightarrow \chi_{c1}\gamma$
- $\psi' \rightarrow \chi_{c1}\gamma$

- 4.2σ peak in $\chi_{c1}\gamma$ in $B^+ \rightarrow (\chi_{c1}\gamma)K^+$
  - $M = 3823.5 \pm 2.8$ MeV, $\Gamma$ consistent with zero

- Consistent with missing $\psi_2(1^3D_2)$ E1 transition to $\chi_{c1}$
  - expected ($1^3D_1$ state is $\psi(3770)$, $1^3D_3$ state is still missing)

- No hint for $X(3872) \rightarrow \chi_{c1}\gamma$
Charged $Z^+$ in $\pi^+\chi_{c1}$ system?

BaBar (Gradl)

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