Charmonium and Bottomonium Spectroscopy at Belle II

02.09.2019 | Elisabetta Prencipe on behalf of the Belle II Collaboration

International Workshop on Partial Wave Analyses and Advanced Tools for Hadron Spectroscopy
PWA11/ATHOS6, Rio de Janeiro
Outline

- Introduction
- Motivation
  - how can we improve the B-factories achievements?
  - open questions
  - new and unique opportunities at Belle II
- The Belle II experiment
- Perspectives in search for exotics at Belle II
  - Charmonium
  - Bottomonium
  - “re-discovery” channels with Phase 3 data
- Summary
Introduction

- Gell-Mann Zweig idea: **Constituent Quark Model**
  Still valid for half century → it classifies all known hadrons

- QCD-motivated models predict the existence of hadrons with more complex structures than simple $qq$ (mesons) or $qqq$ (baryons) → the so-called XYZ “charmonium”-like states

- **Lot of experimental effort to prove the existence of XYZ!**

- No unambiguous evidence for hadrons with *non-CQM-like* structures has been found

- New possibilities, started with the observation of the X(3872):
  - tetraquarks
  - hybrids
  - molecular states
  - hadrocharmonium
  - pentaquarks
  - hexaquarks
  - glueballs
  - cusps…

- Evidence that there is more than *mesons* and *baryons!*

Substantial contribution from B-factories (1999-2010) into the field
Quark Bound States

- **Meson**
  - Lifetime: $< 10^{-8}$ s

- **Baryon**
  - Lifetime: $> 10^{30}$ y (proton)
  - Lifetime: $~ 10$ min (neutron)
  - Lifetime: $< 10^{-10}$ s (others)

- **Tetraquark**
  - Lifetime: $< 10^{-23}$ s

- **Di-baryon**

- **Pentaquark**

- **Hybrid meson**

- **Glueball**
  - Lifetime: $< 10^{-23}$ s

...and superposition of different states: $c_1 |\bar{q}q> + c_2 |\bar{q}qqq> + ...$
- Onia (conventional and exotics)

- States described by potential models, NRQCD, ..., before B-factories era
-Onia (conventional and exotics)

- States described by potential models, NRQCD,…, after B-factories era

![Graph showing particle states and masses]
- Onia (conventional and exotics)

- States described by potential models, NRQCD, ..., after B-factories era
Nomenclature

X, such as the $X(3872)$
- consistent with $D^0\bar{D}^{*0}$ molecular state
- found in B decays, large production also in pp
- no partners found

Y, such as the $Y(4260)$, $Y(4330)$, $Y(4660)$
- produced in initial state radiation and $E_{c.m.}$ scan
- $J^{PC} = 1--$
- overpopulated for charmonium

Z, such as the $Z_c(3900)$ and the $Z_b(10610)$
- seen in decays of $q\bar{q}$ and B decays
- charged states: cannot be charmonia
- b- and c- onia: similarities
Nomenclature

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Two different classes of Z states?

- Belle II is in a **unique** position to look for both Z types:
  - through B decays (LHCb, no BES III)
  - threshold state (BES III, no LHCb)
BaBar + Belle:

>1.5 ab\(^{-1}\) integrated luminosity - triumph in the history of B-factories!

- Not only B-factory, but \(c\bar{c}\)-factory with so high luminosity
- Still statistics limitation in spectroscopy for rare processes (BR<10\(^{-5}\))
- Upgrade needed!
Belle II detector
26 countries, 952 physicists

Tsukuba
Tokyo

02- September 2019
From Belle to Belle II

What has been changed?

- **PXD**, **vertex resolution** in z direction (beam direction) will be factor 2 better than before: 50 μm (Belle) → 25 μm (Belle II)
- **TOP**: no TOF (time-of-flight) detector anymore, but TOP (time-of-propagation) will do the timing of the Cerenkov light. Time resolution ~50 ps. TOP detector surface is polished to nanometer precision for total reflection of Cerenkov light
- **KLM**: inner 2 layers of barrel + all layers in the endcap replaced by scintillators, because of large background
- **ECL** readout electronics exchanged, fast **FADC** sampling for identify pile-up of pulses
- Huge gain in **luminosity** in Belle II compared to Belle: factor x40. How?
  - factor 2 by beam current: 1.64/1.19 A (Belle) → 3.6/2.6 A for e⁺(e⁻) beam in Belle II
  - factor 20 by "nano-beam" principle (collision point in vertical direction will be only 59 nm)

\[ \beta_y(z) = \beta_y^*(1 + \frac{(z - Z_0)^2}{\beta_y^{*2}}) \]
\[ \sigma_y(z) \propto \sqrt{\beta_y^2(z)} \]

\[ \beta_y^* \text{ function: } 5.9 \text{ mm (Belle), } 0.27 \text{ mm (Belle II)} \]
Luminosity and long term perspectives

- **Phase 2**, concluded on 17.07.2018: $L = 504.9 \text{ pb}^{-1}$
- **Phase 3**, concluded on 01.07.2019: $L = 6.5 \text{ fb}^{-1}$
- **Summer 2020**, expected up to $200 \text{ fb}^{-1}$
- **By 2026**, expected up to $50 \text{ ab}^{-1}$
Belle II is performing well!
**X(3872) total width**

- Known upper limit: $\Gamma < 1.2$ MeV (estimated from $X(3872) \rightarrow J/\psi \pi^+ \pi^-$), on full Belle data sample.

- Very promising: $X(3872) \rightarrow D^0 \bar{D}^{0*}$.

<table>
<thead>
<tr>
<th>mode</th>
<th>Q value [MeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$J/\psi \pi^+ \pi^-$</td>
<td>$495.65 \pm 0.17$</td>
</tr>
<tr>
<td>$D^0 \bar{D}^{0,0}_{\pi^0}$</td>
<td>$7.05 \pm 0.18$</td>
</tr>
<tr>
<td>$D^0 \bar{D}^{0,*}$</td>
<td>$0.01 \pm 0.18$</td>
</tr>
</tbody>
</table>

- Due to very low Q value, the mass resolution is extremely good → expected great improvement in the width measurement with 50 ab$^{-1}$.
XYZ Expectations at Belle II

- Yield of $X(3872) \rightarrow J/\psi \pi^+\pi^-$ in 2021 will be about Belle yield of $\psi' \rightarrow J/\psi \pi^+\pi^-$
- Radiative decay $X(3872) \rightarrow J/\psi \gamma$: expected yield $N \approx 350$ in 2021
- The width of the $X(3872)$ could be measured with a systematic error of $\pm 0.11$ MeV in radiative $X$ decay
  -monoenergetic photon provides 4-constraint fit ($\Delta E/E \sim 2\%$)
  -systematic error on width may be $\sim 110$ keV
- Search for exotics at $D^*D^*$ threshold (better slow pion detection at Belle II)
  -slow pions reconstruction efficiency $> 60\%$ (L. Koch, Master Thesis 2016)

<table>
<thead>
<tr>
<th>State</th>
<th>Production and Decay</th>
<th>$N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X(3872)$</td>
<td>$B \rightarrow KX(3872), X(3872) \rightarrow J/\psi \pi^+\pi^-$</td>
<td>$\approx 14400$</td>
</tr>
<tr>
<td>$Y(4260)$</td>
<td>ISR, $Y(4260) \rightarrow J/\psi \pi^+\pi^-$</td>
<td>$\approx 29600$</td>
</tr>
<tr>
<td>$Z(4430)$</td>
<td>$B \rightarrow K^+Z(4430), Z(4430) \rightarrow J/\psi \pi^\pm$</td>
<td>$\approx 10200$</td>
</tr>
</tbody>
</table>

Expectation with 50ab$^{-1}$ data at Belle II
Charmonium in ISR: Perspectives

- Line shape of the $Y(4260)$
- Strange partner of $Z(3900)$ in KKJ/$\psi$
- Cross sections of exclusive $(\bar{c}c)$ + hadrons

<table>
<thead>
<tr>
<th>Golden Channels</th>
<th>$E_{c.m.}$ (GeV)</th>
<th>Statistical error (%)</th>
<th>Related XYZ states</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^+ \pi^- J/\psi$</td>
<td>4.23</td>
<td>7.5 (3.0)</td>
<td>$Y(4008), Y(4260), Z_c(3900)$</td>
</tr>
<tr>
<td>$\pi^+ \pi^- \psi(2S)$</td>
<td>4.36</td>
<td>12 (5.0)</td>
<td>$Y(4260), Y(4360), Y(4660), Z_c(4050)$</td>
</tr>
<tr>
<td>$K^+ K^- J/\psi$</td>
<td>4.53</td>
<td>15 (6.5)</td>
<td>$Z_{c8}$</td>
</tr>
<tr>
<td>$\pi^+ \pi^- h_c$</td>
<td>4.23</td>
<td>15 (6.5)</td>
<td>$Y(4220), Y(4390), Z_c(4020), Z_c(4025)$</td>
</tr>
<tr>
<td>$\omega \chi_{c0}$</td>
<td>4.23</td>
<td>35 (15)</td>
<td>$Y(4220)$</td>
</tr>
</tbody>
</table>

50 ab$^{-1}$

10 ab$^{-1}$
Why Bottomonium at Belle II?

- Bottomonium spectrum is significantly different from charmonium spectrum
  - n=3 state \( (^3P) \) is below the threshold
  - L=2 state \( (^1D) \) is below the threshold
- \( Z_b \) states were only found so far in \( \Upsilon(5S) \) decays
- SuperKEKB can reach \( E_{c.m.} \approx 11 \text{ GeV} \)
  \( \Rightarrow \Upsilon(6S) \) running possible – unique possibility!
- With the high luminosity, for the 1\textsuperscript{st} time study radiative transitions between bottomonia states possible (suppressed by 1/137). Marginal statistics so far at Belle, big advantage at Belle II
Expectations on $Z_b$ states at Belle II

- If $Z_b$ is a loosely-bound state, several new molecular states should appear

$\Upsilon(6S)$ and $\Upsilon(5S)$: conventional state search
- Belle II goals:
  - search for new, predicted, resonances
  - use both, single transitions and double cascade
  - fill the remaining spectrum to measure the effect of the coupled channel contribution

$\Upsilon(6S)$ and $\Upsilon(5S)$: new exotics search
- Belle II goals:
  - $\Upsilon(6S)$: $100 \text{ fb}^{-1}$ exploratory run
  - $\Upsilon(5S)$: $1 \text{ ab}^{-1}$ high statistics run

$\Upsilon(6S)$ and $\Upsilon(5S)$: scan
- Belle II goals:
  - $\Upsilon(6S)$ and $\Upsilon(5S)$ behave differently in $\pi \pi \Upsilon$ and $\pi \pi \eta$
    $\rightarrow$ hint of a non-$bb$ nature of $\Upsilon(5S)$?
  - investigate an extra resonance around 10.750 MeV/c$^2$

Settle the nature of $\Upsilon(5S)$
ϒ(3S): Opportunities at Belle II

- Exotic states contribute to the hadronic and radiative transitions from narrow quarkonia
  → complementary approach to the direct search from ϒ(5S) and ϒ(6S)

ϒ(3S): exotics in transitions

Belle II goals:
- ϒ(3S) → ππϒ(1S, 2S) still limited by statistics
- perform full amplitude analysis
- search for missing ππ/η transitions to constraint further theoretical models
- study hindered radiative transitions

ϒ(3S): charmonia in production

Belle II goals with 300 fb⁻¹:
- up to 5x sensitivity in inclusive production from ϒ(3S)
- up to 15x in double charmonium
- inclusive rate of X(3872)
- D̅D̅* correlation in ϒ(3S) → D̅D̅* + hadron to test the nature of the X(3872)

ϒ(3S): rare χ_b decays

ϒ(3S): deuteron production mechanism
“Re-discovery” with Phase 3 Data

$J/\psi$

![Graphs showing $M(e^+e^-)$ and $M(\mu^+\mu^-)$ distributions with pull plots for $J/\psi$ candidates.](image)
“Re-discovery” with Phase 3 Data

ψ(2S)

- Inclusive $\mu^+\mu^-$ search
- Isolate $\psi(2S) \rightarrow J/\psi \pi^+\pi^-$ from ISR production
“Re-discovery” with Phase 3 Data

D⁰ meson
“Re-discovery” with Phase 3 Data

Fully hadronic B event reconstruction

Belle II
2019 (preliminary)

Candidates per 6 MeV

\[ \int L \, dt = 2.62 \text{ fb}^{-1} \]

\[ \Delta E \text{ (GeV)} \]

B \rightarrow DK^-

Belle II
2019 (preliminary)

Candidates per 0.15 GeV

\[ \int L \, dt = 2.62 \text{ fb}^{-1} \]

\[ \Delta E \text{ (GeV)} \]

N(D K) = 38 ± 8, fit gives 6σ

\[ M_{bc} = \sqrt{(E_{cm} / 2)^2 - P_{recon}^2} \]

\[ \Delta E = E_{cm} / 2 - E_{recon} \]

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“Re-discovery” with Phase 3 Data

\( \Upsilon(1S, 2S, 3S) \)

ISR process: \( \Upsilon(2S, 3S) \rightarrow \Upsilon(1S)\pi^+\pi^- \)
Summary

- Great achievements with Belle (~ 1 ab\(^{-1}\)) in spectroscopy, but still opportunities for unique physics with the new upgrade Belle II!
- In SuperKEKB e\(^{+}\)e\(^{-}\) collisions will reach unprecedented instantaneous luminosity: \(8 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}\).
- Improved tracking and PID in Belle II
- Phase 2 and 3 in Belle II completed!
- Expected by summer 2020: 200 fb\(^{-1}\)
- Expected 50 ab\(^{-1}\) integrated luminosity at Belle II in 7 years
- With x50 more data than Belle, expected in Belle II great achievements in hadron spectroscopy:
  - ISR analysis as unique case
  - favorite Bottomonium search through \(\Upsilon(6S)\) compared to Belle
  - good slow pion reconstruction to search for D\(^{*}\overline{D}^{(*)}\) threshold exotic states
Thank you for your kind attention!

e.prencipe@fz-juelich.de
Backup slides
How can Belle II perform these challenging measurements?

- most powerful e+e- collider in the world
- x40 more luminosity than Belle
- high vertex resolution
- excellent tracking performance
- improved slow pion detection
Vertex Pixel Detector (PXD)

VXD consists of 2 layers of DEPFET (Pixel Detector) and 4 layers of double-sided silicon microstrip sensors (Silicon Vertex Detector), assembled over carbon fiber ribs.

One of the 40 sensor modules which are being installed in the pixel-vertex detector.
Central Drift Chamber (CDC)

VXD + CDC hits in EventDisplay

Jan 16, 2019:
First global SVD cosmic run

Exp. 5, Run 690, Evt. 14110
(Jan 27, 2019)

02- September 2019
Cerenkov detector, laser in TOP module

Particle Identification

(Time–of-propagation, \( t \leq 50 \text{ ps} \))

Photo: K. Inami (Nagoya)

L~ 2.5m, 16 barrels
Main Achievements in Bottomonium at Belle

$e^+e^- \rightarrow \pi^+\pi^-\gamma(nS)$

$e^+e^- \rightarrow \pi^+\pi^-h_b(nP)$

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

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

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

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

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

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

fit to $|A_{5S} + e^{i\phi}A_{6S}|^2$

PRD 93, 011101(R) (2016)

PRL117, 142001 (2016)
# Main Achievements in Bottomonium at Belle

**Z\(_b\)** in \(Y(5S) \rightarrow \pi^+ \pi^- \gamma(nS)\)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>(\Upsilon(1S)\pi^+\pi^-)</th>
<th>(\Upsilon(2S)\pi^+\pi^-)</th>
<th>(\Upsilon(3S)\pi^+\pi^-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(f_{Z^\pm_b(10610)\pi^\pm}, %)</td>
<td>(4.8 \pm 1.2^{+1.5}_{-0.3})</td>
<td>(18.1 \pm 3.1^{+4.2}_{-0.3})</td>
<td>(30.0 \pm 6.3^{+5.4}_{-7.1})</td>
</tr>
<tr>
<td>(Z_b(10610)) mass, MeV/c(^2)</td>
<td>(10608.5 \pm 3.4^{+3.7}_{-1.4})</td>
<td>(10608.1 \pm 1.2^{+1.5}_{-0.2})</td>
<td>(10607.4 \pm 1.5^{+0.8}_{-0.2})</td>
</tr>
<tr>
<td>(Z_b(10610)) width, MeV/c(^2)</td>
<td>(18.5 \pm 5.3^{+6.1}_{-2.3})</td>
<td>(20.8 \pm 2.5^{+0.3}_{-2.1})</td>
<td>(18.7 \pm 3.4^{+2.5}_{-1.3})</td>
</tr>
<tr>
<td>(f_{Z^\pm_b(10650)\pi^\pm}, %)</td>
<td>(0.87 \pm 0.32^{+0.16}_{-0.12})</td>
<td>(4.05 \pm 1.2^{+0.95}_{-0.15})</td>
<td>(13.3 \pm 3.6^{+2.6}_{-1.4})</td>
</tr>
<tr>
<td>(Z_b(10650)) mass, MeV/c(^2)</td>
<td>(10656.7 \pm 5.0^{+1.1}_{-3.1})</td>
<td>(10650.7 \pm 1.5^{+0.5}_{-0.2})</td>
<td>(10651.2 \pm 1.0^{+0.4}_{-0.3})</td>
</tr>
<tr>
<td>(Z_b(10650)) width, MeV/c(^2)</td>
<td>(12.1^{+11.3}<em>{-4.8}^{+2.7}</em>{-0.6})</td>
<td>(14.2 \pm 3.7^{+0.9}_{-0.4})</td>
<td>(9.3 \pm 2.2^{+0.3}_{-0.5})</td>
</tr>
<tr>
<td>(\phi_Z), degrees</td>
<td>(67 \pm 36^{+24}_{-52})</td>
<td>(-10 \pm 13^{+12}_{-34})</td>
<td>(-5 \pm 22^{+13}_{-33})</td>
</tr>
<tr>
<td>(c_{Z_b(10650)}/c_{Z_b(10610)})</td>
<td>(0.40 \pm 0.12^{+0.05}_{-0.11})</td>
<td>(0.53 \pm 0.07^{+0.32}_{-0.11})</td>
<td>(0.69 \pm 0.09^{+0.18}_{-0.07})</td>
</tr>
<tr>
<td>(f_{\Upsilon(nS)}f_2(1270), %)</td>
<td>(14.6 \pm 1.5^{+6.3}_{-0.7})</td>
<td>(4.09 \pm 1.0^{+6.5}_{-1.0})</td>
<td>(-)</td>
</tr>
<tr>
<td>(f_{\Upsilon(nS)}(\pi^+\pi^-)_S, %)</td>
<td>(86.5 \pm 3.2^{+3.3}_{-4.9})</td>
<td>(101.0 \pm 4.2^{+6.5}_{-3.5})</td>
<td>(44.0 \pm 6.2^{+1.8}_{-4.3})</td>
</tr>
<tr>
<td>(f_{\Upsilon(nS)}f_0(980), %)</td>
<td>(6.9 \pm 1.6^{+0.8}_{-2.8})</td>
<td>(-)</td>
<td>(-)</td>
</tr>
</tbody>
</table>

\[
\sigma_{Z^\pm_b(10610)\pi^\pm} \times B_{\Upsilon(1S)\pi^\mp} = 109 \pm 27^{+35}_{-10} \text{ fb}
\]
\[
\sigma_{Z^\pm_b(10610)\pi^\pm} \times B_{\Upsilon(2S)\pi^\mp} = 737 \pm 126^{+188}_{-85} \text{ fb}
\]
\[
\sigma_{Z^\pm_b(10610)\pi^\pm} \times B_{\Upsilon(3S)\pi^\mp} = 438 \pm 92^{+92}_{-114} \text{ fb}
\]

\[
\sigma_{Z^\pm_b(10650)\pi^\pm} \times B_{\Upsilon(1S)\pi^\mp} = 20 \pm 7^{+4}_{-3} \text{ fb}
\]
\[
\sigma_{Z^\pm_b(10650)\pi^\pm} \times B_{\Upsilon(2S)\pi^\mp} = 165 \pm 49^{+43}_{-20} \text{ fb}
\]
\[
\sigma_{Z^\pm_b(10650)\pi^\pm} \times B_{\Upsilon(3S)\pi^\mp} = 194 \pm 53^{+43}_{-25} \text{ fb}
\]
Nano-Beam Scheme

SuperKEKB

present KEKB (without crain)

SuperKEKB

83 mrad crossing angle

1 μm

5mm

100μm

~50nm

22 mrad crossing angle

1 μm

5mm

100μm

originally proposed for SuperB by P. Raimondi (INFN)

graphics E. Paoloni (Pisa)
X(3872): ACHIEVEMENTS AND INTERPRETATION AT BELLE

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

\[ B(B^+ \rightarrow K^+ X(3872)) \times B(X(3872) \rightarrow \pi^+ \pi^- J/\psi) = (8.63 \pm 0.82 \text{ (stat)} \pm 0.52 \text{ (syst)}) \times 10^{-6} \]

\[ B(B^0 \rightarrow K^0 X(3872)) / B(B^+ \rightarrow K^+ X(3872)) = 0.50 \pm 0.14 \text{ (stat)} \pm 0.04 \text{ (syst)} \]

\[ \Delta M_{X[B^0,B^+]} = (-0.71 \pm 0.96 \text{ (stat)} \pm 0.19 \text{ (syst)}) \text{ MeV}. \]

- X(3872) observed in different decay modes, and different production mechanisms
- At DD\(^*\) threshold \( E_B = 160 \pm 330 \) keV, but no threshold effect
- \( \Gamma \leq 1.2 \) MeV → too narrow!  
  Bugg, JPHG35 (2008) 075005
- The DD\(^*\) decay of the X(3872) is dominant ~ x10 than other X(3872) decay modes → a molecule?
- Isospin-violating decay: \( B(X(3872) \rightarrow J/\psi \rho) \), \( \sim 10^2 \) too large
**X(3872): ACHIEVEMENTS AND INTERPRETATION AT BELLE**

- Correlation function from MC
  \[ \Gamma_{\text{output}} = f(\Gamma_{\text{input}}) \]

- 3-dim fits validated with \( \psi' \) width
  \[ \Gamma_{\psi'} = 0.52 \pm 0.11 \text{ MeV} \]
  (PDG: 0.304 \( \pm \) 0.009 MeV)
  \( \rightarrow \) bias 0.23 \( \pm \) 0.11 MeV

- procedure for upper limit:
  width in 3-dim fit fixed
  \( n_{\text{signal}} \) and \( n_{\text{BG}} \) floating
  \( \rightarrow \) calculate likelihood

- \( \Gamma_{X(3872)} < 0.95 \text{ MeV} + \text{bias} \)

Reference channel: \( B \rightarrow \psi(2s)\pi^+\pi^- \)
X(3872): ACHIEVEMENTS AND INTERPRETATION AT BELLE

- Isospin-violating decay: $B(X(3872)\to J/\psi p)$, factor $10^2$ too large
- $J^{PC} = 1^{++}$, predicted nearby $\chi_{c1}'$
- Barnes et al, PRD72 (2005) 054026
- Mass $\geq 50$ MeV higher
- Width $\geq 100$ larger

What can be done better to disclose the nature of the X(3872)?
X(3872)

Belle
B decays

m(J/ψπ+π−) - m(J/ψ) / MeV

BaBar
B decays

m(J/ψπ+π−) / GeV

LHCb
ψ′
B decays

X(3872)

m(J/ψπ+π−) / MeV

CDF-II
ψ′
X(3872)

m(J/ψπ+π−) / GeV

D0
inclusive
ψ′
X(3872)

m(J/ψπ+π−) - m(μ+μ−) / GeV

CMS
ψ′
inclusive

X(3872)

m(J/ψπ+π−) / GeV
Photoproduction of $X(3872)$

Muon data 2003-2010

$N_{\psi(2S)} = 16.1 \pm 5.2$

$N_{X(3872)} = 13.9 \pm 4.9$

$\sigma_M = 20.6 \pm 6.1$ MeV


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Is the $X(3872)$ exotic?

**TETRAQUARK**

$[qQ]_8[qQ]_8$

Diquarks are colored

Maiani, Riquer, Piccinini, Polosa, Burns;
Ebert, Faustov, Galkin; Chiu, Hsieh;
Ali, Hambrock, Wang

**MOLECULE**

Intriguing Analogon

$1.8 \text{ GeV}$ $2 \text{ GeV}$

Tornqvist; Swanson; Braaten, Kusonoki,
Wong; Voloshin; Close, Page
Guo, Hanhart, Meissner

**THRESHOLD CUSP**

$X(3872)$

$D$ $J/\psi$

$D^*$ $\pi \pi$

Bugg; Swanson
courtesy of J.S. Lange, HIRSCHEGG2018
Y STATES

Left:
- Belle
- Y(4008)
- Y(4260)

Right:
- Belle
- Y(4350)
- Y(4660)

Bottom:
- BaBar
- Y(4260)

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02- September 2019

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Mitglied der Helmholtz-Gemeinschaft
Forschungszentrum
Cornell–Potential

- Coulomb-Potential
  + Confinement-Term
  \[
  V(r) = -\frac{4}{3} \frac{\alpha_s}{r} + kr
  \]
  spin-spin
  \[+
  \frac{32\pi\alpha_s}{9m_c^2} \delta_r \vec{S}_v \vec{S}_c
  \]
  spin-orbit
  \[+
  \frac{1}{m_c^2} \left( \frac{2\alpha_s}{r^3} - \frac{k}{2r} \right) \vec{L} \vec{S}
  \]
  tensor
  \[+
  \frac{4\alpha_s}{m_c^2} \frac{3\vec{S}_c \vec{r} \cdot \vec{S}_c \vec{r}'}{r^2} - \vec{S}_c \vec{S}_c
  \]

- solve Schrödinger equation
  (quark mass heavy → on-relativistic)
  \[\rightarrow\text{states}\]
  \[
  \Psi(r, \theta, \phi) = R_{nl}(r) Y_{lm}(\theta, \phi)
  \]
  \[
  \left[ -\frac{1}{m_q} \left( \frac{\partial^2}{\partial r^2} + \frac{2}{r} \frac{\partial}{\partial r} + \frac{l(l+1)}{m_q r^2} + V(r) \right) \right] R_{nl}(r) = E_{nl} R_{nl}(r)
  \]

Notation
\[n^{2S+1}L_J\]
JPC
Cornell potential:
Wronski-Determinant must be zero at turning point

\[ r_{\text{turning point}} = \frac{E - 2m}{2\sigma} + \sqrt{\frac{4m^2 - 4mE + E^2}{4\sigma^2} + \frac{4\alpha_s}{3\sigma}} \]

- \[ m = 4.660 \text{ GeV} \rightarrow \text{turning point of wave function is 2.2 fm!} \]
- large fraction of wave function in string breaking regime \( r > 1.4 \text{ fm} \)

courtesy of J.S. Lange, HIRSCHEGG2018
Charmonium vs. Positronium

Decays to light quarks suppressed
→ narrow widths

Dissociation → DD

Dissociation → $e^+ e^-$

differences for higher states

courtesy of J.S. Lange, HIRSCHHEGG2018
Z STATES AT BESIII

$D^*D^*$ threshold

$e^+e^- \rightarrow \pi^+ \pi^- J/\Psi$

$e^+e^- \rightarrow \pi^0 \pi^0 J/\Psi$

$e^+e^- \rightarrow \pi^+ \pi^- h_c$

$e^+e^- \rightarrow \pi^0 \pi^0 h_c$

$e^+e^- \rightarrow \pi^+ (D\bar{D}^*)^-$

$e^+e^- \rightarrow \pi^0 (D\bar{D}^*)^0$

$e^+e^- \rightarrow \pi^+ (D^*\bar{D}^*)^-$

$e^+e^- \rightarrow \pi^0 (D^*\bar{D}^*)^0$

charged  neutral  charged  neutral

Recent hot topic: neutral partners $\rightarrow$ isospin triplets
All of them 1+, whereever tested.
Z states and „confinement“?
All measured $Z_c^+$ masses are **above** $D(\ast)\overline{D(\ast)}$ thresholds

<table>
<thead>
<tr>
<th>State</th>
<th>$m$ (MeV)</th>
<th>Threshold</th>
<th>$\Delta m$ (MeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z_c(3900)$</td>
<td>3899.0±3.6±4.9</td>
<td>$D^+\overline{D}^{0\ast}$</td>
<td>+22.4</td>
</tr>
<tr>
<td>$Z_c(3900)$</td>
<td>3899.0±3.6±4.9</td>
<td>$D^0\overline{D}^{+\ast}$</td>
<td>+23.9</td>
</tr>
<tr>
<td>$Z_c(3900)$</td>
<td>3894.5±6.6±4.5</td>
<td>$D^+\overline{D}^{0\ast}$</td>
<td>+17.9</td>
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<tr>
<td>$Z_c(3900)$</td>
<td>3894.5±6.6±4.5</td>
<td>$D^0\overline{D}^{+\ast}$</td>
<td>+19.4</td>
</tr>
<tr>
<td>$Z_c(3900)$</td>
<td>3885±5±1</td>
<td>$D^+\overline{D}^{0\ast}$</td>
<td>+8.4</td>
</tr>
<tr>
<td>$Z_c(3900)$</td>
<td>3885±5±1 MeV</td>
<td>$D^0\overline{D}^{+\ast}$</td>
<td>+9.9</td>
</tr>
<tr>
<td>$Z_c(3885)$</td>
<td>3883.9±1.5±4.2</td>
<td>$D^+\overline{D}^{0\ast}$</td>
<td>+7.4</td>
</tr>
<tr>
<td>$Z_c(3885)$</td>
<td>3883.9±1.5±4.2</td>
<td>$D^0\overline{D}^{+\ast}$</td>
<td>+8.8</td>
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<tr>
<td>$Z_c(4020)$</td>
<td>4022.9±0.8±2.7</td>
<td>$D^{0\ast}\overline{D}^{±\ast}$</td>
<td>+5.6</td>
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<tr>
<td>$Z_c(4025)$</td>
<td>4026.3±2.6±3.7</td>
<td>$D^{0\ast}\overline{D}^{±\ast}$</td>
<td>+9.0</td>
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<tr>
<td>$Z_c(4032)^+$</td>
<td>$\approx$ 4032.1±2.4</td>
<td>$D^{0\ast}\overline{D}^{±\ast}$</td>
<td>+15.0</td>
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<tr>
<th>possible?</th>
</tr>
</thead>
<tbody>
<tr>
<td>threshold CUSP</td>
</tr>
<tr>
<td>tetraquark</td>
</tr>
<tr>
<td>molecules</td>
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</table>