$Z_c(3900)$: experiment, theory, lattice


Miguel Albaladejo (IFIC, Valencia)

In collaboration with:
P. Fernandez-Soler (Valencia)
F. K. Guo (Beijing)
C. Hidalgo-Duque (Valencia)
J. Nieves (Valencia)
Outline

1. Experiment
2. Theory
3. Lattice
4. Conclusions
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### Charmonium-like sector

- **Recent reviews (2015-2016):**
  - [Olsen, Front. Phys. 10, 121('15)]
  - [Chen et al., Phys. Rept. 639, 1('16)]
  - [Hosaka et al., PTEP 2016, 062C01('16)]

- **All the c\bar{c} states predicted by QM below D\bar{D} threshold have been found**

- **In 2003, \textbf{X(3872)} is discovered**
  - [Belle Collab., PRL, 91, 262001]
  - Very close to D^0\bar{D}^0 threshold.
  - Close to (but lower) \chi_c 1(2^3P_1).

- **Lattice QCD:**
  - [Prelovsek, Leskovec, PRL, 111, 192001]
  - Candidate for X(3872) only if c\bar{c} + D\bar{D}^* components are considered together

(Taken from: [Olsen, Front. Phys. 10, 121('15)])
Experimental information on $Z_c(3885) / Z_c(3900)$

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  [PRL,110,252001('13)][PRL,110,252002('13)]

- Later on, CLEO-c data confirmed $Z_c(3900)$ in $e^+e^- \to \psi(4160) \to J/\psi\pi^{+}\pi^-$
  
  [PL,B727,366('13)]

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- If they are the same object, **Ratio**: $\frac{\Gamma(Z_c\to D\bar{D}^*)}{\Gamma(Z_c\to J/\psi\pi)} = 6.2 \pm 2.9$
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“One of the most interesting resonances”: couples strongly to charmonium ($\sim \bar{c}c$) and yet it has charge ($\sim \bar{u}d$). Minimal quark constituent is four $[\bar{c}c\bar{u}d]$.

Many different interpretations have been given (see reviews mentioned before):

- Tetraquark
- $\bar{D}^* D$ molecular state
- Simply a kinematical effect
- Hadrocharmonium
- It has also been searched for in lattice QCD

What is still missing?

A joint study of both reactions in which the $Z_c$ structure has been seen
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What is still missing?

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**Coupling \( \bar{D}^* D \) and \( J/\psi \pi \) channels**

**Coupled channel** formalism is needed, because \( Z_c(3900) \):
- is expected to be dynamically generated in \( \bar{D}^* D \) channel (#2),
- but it is also seen in \( J/\psi \pi \) channel (#1).

\[
T = (\mathbb{I} - V \cdot G)^{-1} \cdot V,
\]
\[
V_{ij} = 4 \sqrt{m_{i1} m_{i2}} \sqrt{m_{j1} m_{j2}} e^{-q_i^2/\Lambda_i^2} e^{-q_j^2/\Lambda_j^2} C_{ij},
\]

- \( G(E) \) are loop functions (Regularized with standard gaussian regulator)
- \( J/\psi \pi \rightarrow J/\psi \pi \): known to be tiny, \( C_{11} = 0 \).
- \( \bar{D}^* D \rightarrow J/\psi \pi \): we make the simplest possible assumption, \( C_{12} \equiv \tilde{C} \) (constant)
- \( \bar{D}^* D \rightarrow \bar{D}^* D \): In a momentum expansion (HQSS), simply a constant, \( C_{22} \equiv C_{1Z} \).
- **Problem**: no resonance in the complex plane above threshold with only constant potentials (even with coupled channels).
- We introduce some energy dependence,

\[
C_{22}(E) = C_{1Z} + b(E - m_D - m_{D^*}).
\]
Amplitudes: $Y(4260) \rightarrow (J/\psi \pi^-)\pi^+, (D^*-D^0)\pi^+$

\[
|M_2(s, t)|^2 = \left| \frac{1}{t - m_{D_1}^2} + i_3(s)T_{22}(s) \right|^2 q_\pi^4(s) + |\beta (1 + T_{22}(s)G_{22}(s))|^2
\]

- $s$ (Mandelstam) $\bar{D}^*D$ invariant mass squared
- $i_3(s)$: three meson loop propagator
- $\bar{D}^*D$ rescattering enters through $T_{22}(s)$
- $q_\pi^2(s) = \lambda(M_Y^2, s, m_\pi^2)/(4M_Y^2)$
Amplitudes: \( Y(4260) \rightarrow (J/\psi \pi^-)\pi^+, (D^* - D^0)\pi^+ \)

The decay proceeds mainly through \([T_{12}(s)]\)

\[ Y \rightarrow (\bar{D}^* D)\pi \rightarrow (J/\psi \pi)\pi \]

Some direct production included through \(\alpha\)

\( s, t \) (Mandelstam) \( J/\psi \pi^-, J/\psi \pi^+ \)
invariant mass squared

\[
\left| \mathcal{M}_1(s, t) \right|^2 = |\tau(s)|^2 q^4_\pi(s) + |\tau(t)|^2 q^4_\pi(t) + \frac{3 \cos^2 \theta - 1}{4} \left( \tau(s)\tau(t)^* + \tau(s)^* \tau(t) \right) q^2_\pi(s)q^2_\pi(t),
\]

\[
\tau(s) = \sqrt{2} l_3(s) T_{12}(s) + \alpha
\]
Events distributions and Experimental data

- Events distributions $N_i$:
  
  $$N_i(s) = K_i (A_i(s) + B_i(s))$$
  
  $$A_i(s) = \int_{t_i^-}^{t_i^+} dt |\mathcal{M}_i(s, t)|^2$$

  - $K_i$ (unknown) global normalization constants
  - $B_i$ are background functions (parametrized as in the experimental analyses) ($B_2 = 0$)
  - "Branching ratio":
    
    $$R_{\text{exp}} = \frac{\Gamma (Z_c \to D\bar{D}^*)}{\Gamma (Z_c \to J/\psi\pi)} = 6.2 \pm 2.9$$

  - Theoretically estimated as the (physical) ratio of areas around $Z_c(3900)$ mass
    
    $$R_{\text{th}} = \frac{\int ds A_2(s)}{\int ds A_1(s)}$$
Results: comparison with experiment(s)

- Four different fits: \( b = \{\text{free}, 0\} \), \( \Lambda_2 = \{0.5, 1.0\} \) GeV
- Only the \( T \)-matrix parameters are shown (not shown: normalization, ...)
- All fits have \( \chi^2 / \text{dof} \approx 1 \) (\( \approx 1.4 \) for \( b = 0 \)), and are within the error band of the best one
- Reproduction of the data is excellent

<table>
<thead>
<tr>
<th>( \Lambda_2 ) (GeV)</th>
<th>( C_{1Z} ) (fm(^2))</th>
<th>( b ) (fm(^3))</th>
<th>( \tilde{C} ) (fm(^2))</th>
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<th>( R_{th} )</th>
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<tr>
<td>1.0</td>
<td>(-0.19 \pm 0.08 \pm 0.01)</td>
<td>(-2.0 \pm 0.7 \pm 0.4)</td>
<td>0.39 \pm 0.10 \pm 0.02</td>
<td>1.02</td>
<td>6.0 \pm 3.5 \pm 0.5</td>
</tr>
<tr>
<td>0.5</td>
<td>(+0.01 \pm 0.21 \pm 0.03)</td>
<td>(-7.0 \pm 0.4 \pm 1.4)</td>
<td>0.64 \pm 0.16 \pm 0.02</td>
<td>1.09</td>
<td>6.5 \pm 3.6 \pm 0.2</td>
</tr>
<tr>
<td>1.0</td>
<td>(-0.27 \pm 0.08 \pm 0.07)</td>
<td>(0 ) (fixed)</td>
<td>0.34 \pm 0.14 \pm 0.01</td>
<td>1.31</td>
<td>10.3 \pm 9.0 \pm 1.1</td>
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<tr>
<td>0.5</td>
<td>(-0.27 \pm 0.16 \pm 0.13)</td>
<td>(0 ) (fixed)</td>
<td>0.54 \pm 0.16 \pm 0.02</td>
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Reflection of threshold and $Z_c(3900)$ in $J/\psi \pi^+ \pi^-$ spectrum

When $M_{J/\psi \pi^-} \equiv \sqrt{s} \in (3.40, 3.55)$ GeV

$M_{J/\psi \pi^+} \equiv \sqrt{t}$ can be at $\sqrt{t} = 3.9$ GeV

($D\bar{D}^*$ threshold, $Z_c(3900)$ mass)

This explains the enhancement (reflection)
Results: Spectroscopy

Two different scenarios:

1. \(b \neq 0\) \(Z_c\) is a \(\bar{D}^*D\) resonance very close to threshold

   (Differences with experiments are related to Breit-Wigner parametrizations)

2. \(b = 0\) \(Z_c\) is a virtual state

In both scenarios,

- Data are very well reproduced
- A single structure (not two) \(Z_c(3885)/Z_c(3900)\) is needed
**Bound state, resonance, virtual ...**

A **virtual state** does not correspond to a real particle. (Wavefunction not localized.)

It produces effects at the threshold similar to those of a bound state or a nearby resonance.

**Well known example: NN scattering and the deuteron**

**Triplet** ($^3S_1 - ^3D_1$):
- $a_t \simeq 5$ fm.
- In this wave there is a **bound state**. The deuteron is a well known, really physical particle.

**Singlet** ($^1S_0$):
- $a_s \simeq -24$ fm.
- In this wave there is a **virtual state**.
Complex plane & poles: First scenario (resonance)

- Pole located at $3894 - 30$ MeV
- Plot: unphysical Riemann sheet connected to the physical one above $D^*\bar{D}$
- Shift of the pole towards higher energies (interference!)
Complex plane & poles: First scenario (resonance)

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**Z_c(3900) on the lattice**

- LQCD simulations on Z_c(3900) still scarce:
  - [Prelovsek et al., PR,D91,014504(’15)] \((m_\pi = 266\ \text{MeV})\) “no additional candidate”
  - [Y. Ikeda et al. [HAL QCD], arXiv:1602.03465] \((m_\pi \geq 410\ \text{MeV})\)
    Virtual poles with very low masses and deep in the complex plane.
    [see talk by Y. Ikeda on Wednesday 10:35h]
  - [Y. Chen et al., PR,D89,094506(’14)]
  - [L. Liu et al., PoS LATTICE 2014, 117(’14)]
  - [S. H. Lee et al., arXiv:1411.1389]

- Results are not conclusive (large pion masses, etc...)

- We can predict energy levels in a finite box.
  **Cooperation** between (unitary) EFTs and LQCD simulations is useful to understand the hadron spectrum.
  [M. Doring, U. G. Meissner, E. Oset and A. Rusetsky, EPJ,A47,139(’11)]

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### Formalism for finite volume


#### Periodic boundary conditions: discrete momenta

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- \( \omega_{D\bar{D}}(q) = m_D + m_{D^*} + \frac{m_D + m_{D^*}}{2m_D m_{D^*}} q^2 \) (non relativistic)
- Finite volume \( \rightarrow \) box of edge \( L \): it is an infinite square well potential (like QM)
- Energy levels: bound states in the box. Given by:
  \[ \tilde{T}^{-1}(E_m(L), L) = 0 \] (Interacting energy levels)
- In particular, if the interaction is zero (\( V(E) = 0 \)), then the energy levels are given by the poles of the \( \tilde{G} \) function:
  \[ E_m(L) = \omega_{D\bar{D}} \left( \frac{2\pi}{L} n \right) \] (Free energy levels)
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### Energy-momentum dispersion relation on the lattice

[Prelovsek et al., PR,D91,014504('15)]

$$\omega^{\text{the}}_{\bar{D}D^*}(q) = m_D + m_{D^*} + \frac{m_D + m_{D^*}}{2m_D m_{D^*}} q^2$$

$$\omega^{\text{lat}}_{\bar{D}D^*}(q) = m_{D,1} + m_{D^*,1} + \frac{m_{D,2} + m_{D^*,2}}{2m_{D,2} m_{D^*,2}} q^2 - \frac{m_{D,4}^3 + m_{D^*,4}^3}{8m_{D,4}^3 m_{D^*,4}^3} q^4.$$
Results for the discrete energy levels as a function of box size ($L$)

- **$J/\psi\pi$ channel not essential:**
  - Always a level close to a free $J/\psi\pi$ one.
  - Coupled channels case levels follow single channel case levels (except near the free $J/\psi\pi$ levels).

- Level below threshold (attractive interaction) goes to threshold for $L \to \infty$: no bound state.

- **Relevant** energy level: the one above threshold. Shift w.r.t. free levels is larger for the resonance case.

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- Our aim is to compare with an actual LQCD simulation
  [Prelovsek et al., PR,D91,014504('15) [arXiv:1405.7623]]

- Calculations done at $L = 1.98$ fm, $m_\pi = 266$ MeV.

- Three separate regions, all theoretical predictions in good agreement with LQCD

- Except for this point?

  $E_{\text{th}} = 4000^{+24}_{-13}$ MeV
  $E_{\text{lat}} = 4070 \pm 30$ MeV
  $\Delta E = 70 \pm 40$ MeV ($< 2\sigma$ dev)

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Summary: both scenarios (resonance and virtual) agree with LQCD

- R scenario (left) vs. VS scenario (right)
- Lattice energy levels: center
  - $\Lambda_2 = 0.5$ GeV: (●, ○)
  - $\Lambda_2 = 1.0$ GeV: (●, ○)
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  \[ E_{lat} = 4070 \pm 30 \text{ MeV} \]
  \[ \Delta E = 70 \pm 40 \text{ MeV (} < 2\sigma \text{ dev.)} \]
- Summary: both scenarios (resonance and virtual) agree with LQCD

- R scenario (left) vs. VS scenario (right)
- Lattice energy levels: center
  \[ \Lambda_2 = 0.5 \text{ GeV: (○, ○)} \]
  \[ \Lambda_2 = 1.0 \text{ GeV: (●, ○)} \]
Comparison with LQCD simulations: what’s next?

Both scenarios (resonance and virtual) agree with both cutoffs ($\Lambda_2 = 0.5$ GeV and 1 GeV). What to do?

One possibility is to study volume dependence (several volumes)

We compare here two predictions:

- Resonance scenario with $\Lambda_2 = 0.5$ GeV (blue bands)
- Virtual scenario with $\Lambda_2 = 1.0$ GeV (orange bands)

Both are indistinguishable around $L \simeq 2$ fm (say $1.9 \text{ fm} < L < 2.2 \text{ fm}$)

But they are clearly different at $L \simeq 2.4$ fm (say $2.3 \text{ fm} < L < 2.5 \text{ fm}$)
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### Conclusions (this work)

- $Z_c(3900)$ is a most-interesting, exotic, structure. A candidate for “tetraquark”, or a $D^*\bar{D}$ molecule...


- We have presented the first simultaneous study of the two decays $(Y(4260) \to J/\psi\pi\pi, D^*D\pi)$ in which $Z_c(3900)$ is seen.

- Data are well reproduced in all fits ($\chi^2 \approx 1$).

- Two different scenarios are found:
  1. ($b \neq 0$) $Z_c(3900)$ is a $D^*\bar{D}$ resonance
  2. ($b = 0$) $Z_c(3900)$ is a virtual state

- In any case, a single structure for $Z_c(3885)/Z_c(3900)$ is needed.

- Improved data on $J/\psi\pi$ invariant mass spectrum are necessary.


- We have used our $T$-matrix to compute energy levels in a finite volume.

- Good agreement is found for both scenarios (resonance and virtual state) with the energy levels reported in a LQCD simulation [Prelovsek et al., PR, D91, 014504(15)].

- To discriminate both scenarios, we suggest to perform LQCD simulations at several different volumes.
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Conclusions (general)

- Charmonium spectrum, well known below $D\bar{D}$ threshold.
- Since 2003, the charmonium(-like) spectrum increases continuously ($\sim 1$ state/year), but we do not fully understand: there are $c\bar{c}$, there are meson-meson molecules, there are tetraquarks, and many others.
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$Z_c(3900)$: experiment, theory, lattice


Miguel Albaladejo (IFIC, Valencia)

Thanks for your attention