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

[arXiv:1512.03638, Phys. Lett. B 755, 337 (2016)]

[arXiv:1606.03008, Eur. Phys. J. C (under review)]

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MENU 2016 KYOTO

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IFIC Institut de Física Corpuscular
Gobierno de España
Ministerio de Economía y Competitividad

Outline

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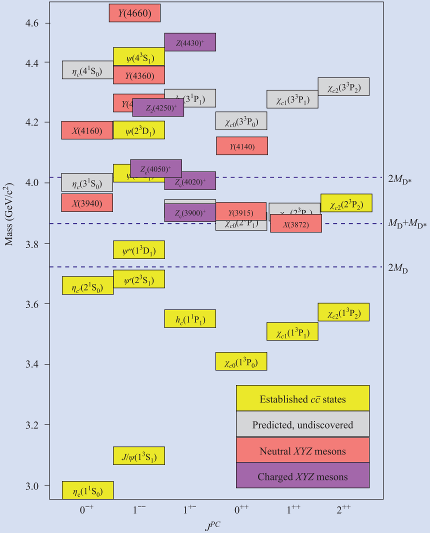
Charmonium-like sector



(Taken from: [Olsen, Front. Phys. 10, 121('15)])

- 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, ***X*(3872)** is discovered [Belle Collab., PRL,91,262001]
  - Very close to $D^0\bar{D}^0$ threshold.
  - Close to (but lower) $\chi_{c1}(2^3P_1)$.
- **Lattice QCD**: [Prelovsek, Leskovec, PRL,111,192001] candidate for $X(3872)$ only if $c\bar{c}$ + $D\bar{D}^*$ components are considered **together**

Experimental information on $Z_c(3885)/Z_c(3900)$

- **$Z_c(3900)$** first seen by **BESIII** and **Belle** Collabs. in $J/\psi\pi^\pm$ invariant mass spectrum in $e^+e^- \to Y(4260) \to J/\psi\pi^+\pi^-$
  [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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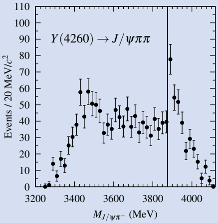
- If they are the same object, **Ratio:** $\frac{\Gamma(Z_c \to D\bar{D}^*)}{\Gamma(Z_c \to J/\psi\pi)} = 6.2 \pm 2.9$



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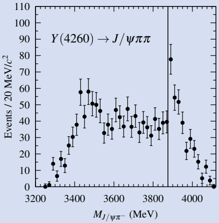

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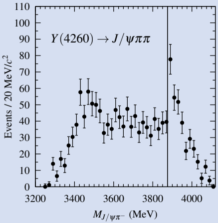

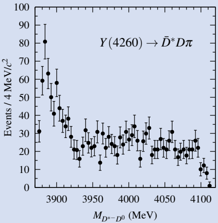

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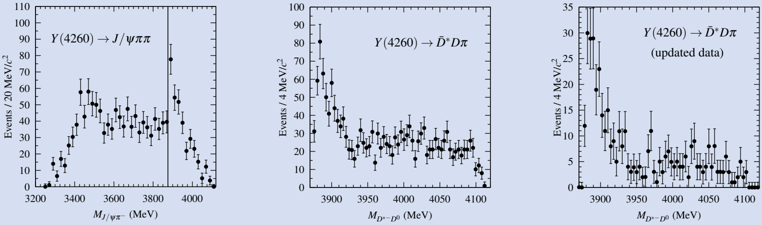

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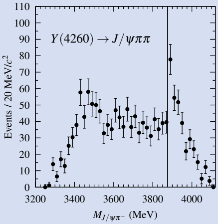
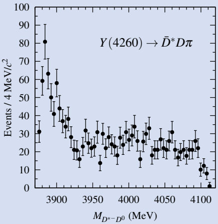
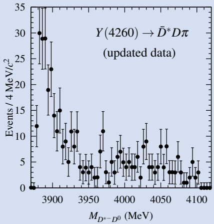
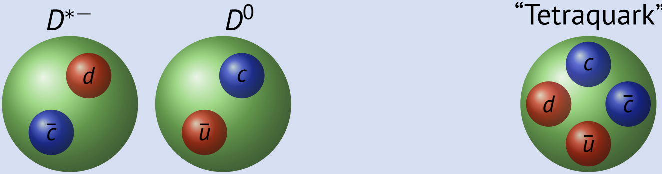






Introduction: theoretical speculation

- "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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- Many different interpretations have been given (see reviews mentioned before):
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What is still missing?

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Outline

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).

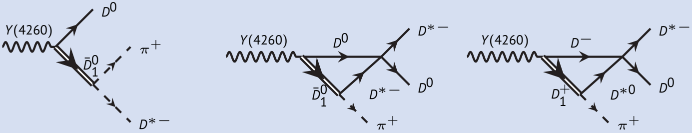
$$T = (\mathbb{I} - V \cdot G)^{-1} \cdot V \, ,$$

$$V_{ij} = 4\sqrt{m_{i1} m_{i2}}\sqrt{m_{j1} m_{j2}}\, e^{-q_i^2/\Lambda_i^2} e^{-q_j^2/\Lambda^2} C_{ij} \, ,$$

- $G(E)$ are loop functions (Regularized with standard gaussian regulator)
- **$J/\psi\pi \to J/\psi\pi$:** known to be tiny, $C_{11} = 0$.
- **$\bar{D}^* D \to J/\psi\pi$:** we make the simplest possible assumption, $C_{12} \equiv \widetilde{C}$ (constant)
- **$\bar{D}^* D \to \bar{D}^* D$:** 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: $Y(4260) \to (J/\psi\pi^-)\pi^+, (D^{*-}D^0)\pi^+$



$$\left|\overline{\mathcal{M}_2}(s,t)\right|^2 = \left|\frac{1}{t-m_{D_1}^2} + I_3(s)T_{22}(s)\right|^2 q_\pi^4(s) + \left|\beta\left(1+T_{22}(s)G_{22}(s)\right)\right|^2$$

- s (Mandelstam) $\bar{D}^*D$ invariant mass squared
- $I_3(s)$: three meson loop propagator
- $\bar{D}^*D$ rescattering enters through $T_{22}(s)$
- ${q_\pi}^2(s) = \lambda(M_Y^2, s, m_\pi^2)/(4M_Y^2)$

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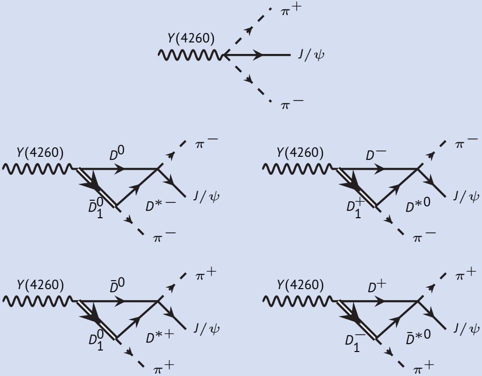


- The decay proceeds mainly through $[T_{12}(s)]$ $Y \to (\bar{D}^* D)\pi \to (J/\psi\pi)\pi$
- Some direct production included through α
- s, t (Mandelstam) $J/\psi\pi^-, J/\psi\pi^+$ invariant mass squared

$$\left|\overline{\mathcal{M}_1}(s,t)\right|^2 = |\tau(s)|^2 q_\pi^4(s) + |\tau(t)|^2 q_\pi^4(t) + \frac{3\cos^2\theta - 1}{4}\Big(\tau(s)\tau(t)^* + \tau(s)^*\tau(t)\Big) q_\pi^2(s) q_\pi^2(t)\,,$$

$$\tau(s) = \sqrt{2} I_3(s) T_{12}(s) + \alpha$$

Events distributions and Experimental data

- Events distributions $\mathcal{N}_i$:

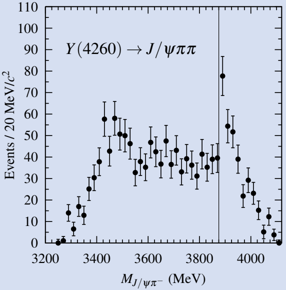
$$\mathcal{N}_i(s) = K_i\left(\mathcal{A}_i(s) + \mathcal{B}_i(s)\right)$$
$$\mathcal{A}_i(s) = \int_{t_{i,-}}^{t_{i,+}} dt \left|\overline{\mathcal{M}_i}(s,t)\right|^2$$

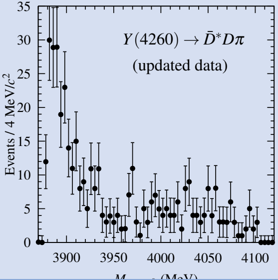
- K_i (unknown) global normalization constants
- $\mathcal{B}_i$ are background functions (parametrized as in the experimental analyses) ($\mathcal{B}_2 = 0$)
- "Branching ratio":

$$R_{\text{exp}} = \frac{\Gamma\left(Z_c \to D\bar{D}^*\right)}{\Gamma\left(Z_c \to J/\psi\pi\right)} = 6.2 \pm 2.9$$

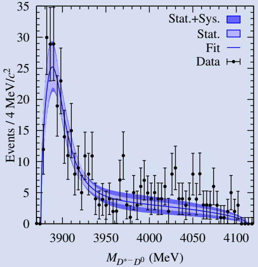
- Theoretically estimated as the (physical) ratio of areas around $Z_c(3900)$ mass

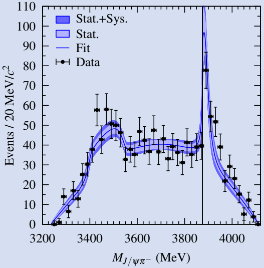
$$R_{\text{th}} = \frac{\int ds \mathcal{A}_2(s)}{\int ds \mathcal{A}_1(s)}$$





Results: comparison with experiment(s)





Λ_2 (GeV)	C_{1Z} (fm^2)	b (fm^3)	$\widetilde{C}$ (fm^2)	χ^2/dof	R_{th}
1.0	$-0.19 \pm 0.08 \pm 0.01$	$-2.0 \pm 0.7 \pm 0.4$	$0.39 \pm 0.10 \pm 0.02$	1.02	$6.0 \pm 3.5 \pm 0.5$
0.5	$+0.01 \pm 0.21 \pm 0.03$	$-7.0 \pm 0.4 \pm 1.4$	$0.64 \pm 0.16 \pm 0.02$	1.09	$6.5 \pm 3.6 \pm 0.2$
1.0	$-0.27 \pm 0.08 \pm 0.07$	0 (fixed)	$0.34 \pm 0.14 \pm 0.01$	1.31	$10.3 \pm 9.0 \pm 1.1$
0.5	$-0.27 \pm 0.16 \pm 0.13$	0 (fixed)	$0.54 \pm 0.16 \pm 0.02$	1.36	$10.9 \pm 9.0 \pm 2.5$

- 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 $\hat{\chi}^2 \simeq 1$ ($\simeq 1.4$ for $b = 0$), and are within the error band of the best one
- Reproduction of the data is **excellent**

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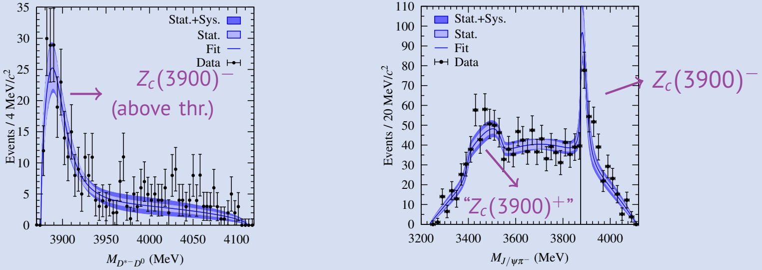

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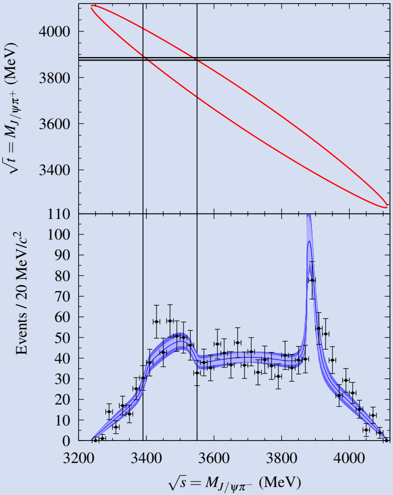
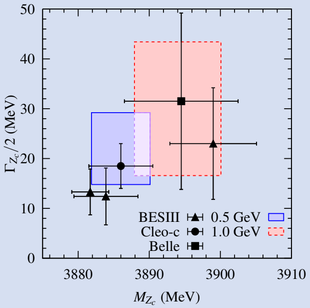
Reflection of threshold and $Z_c(3900)$ in $J/\psi\pi^+\pi^-$ spectrum



When $M_{J\psi\pi^-} \equiv \sqrt{s} \in (3.40, 3.55)$ GeV
$\Downarrow$
$M_{J\psi\pi^+} \equiv \sqrt{t}$ can be at $\sqrt{t} = 3.9$ GeV
($D\bar{D}^*$ threshold, $Z_c(3900)$ mass)

This explains the enhancement (reflection)

Results: Spectroscopy



M_{Z_c} (MeV)	$\Gamma_{Z_c}/2$ (MeV)	Ref.	Final state
3899 ± 6	23 ± 11	▲(BESIII)	$J/\psi\ \pi$
3895 ± 8	32 ± 18	■(Belle)	$J/\psi\ \pi$
3886 ± 5	19 ± 5	●(CLEO-c)	$J/\psi\ \pi$
3884 ± 5	12 ± 6	▲(BESIII)	$\bar{D}^* D$
3882 ± 3	13 ± 5	▲(BESIII)	$\bar{D}^* D$
$3894 \pm 6 \pm 1$	$30 \pm 12 \pm 6$	⬚($\Lambda = 1.0$ GeV)	both
$3886 \pm 4 \pm 1$	$22 \pm 6 \pm 4$	□($\Lambda = 0.5$ GeV)	both
$3831 \pm 26^{+7}_{-28}$	virtual state	($\Lambda = 1.0$ GeV)	both
$3844 \pm 19^{+12}_{-21}$	virtual state	($\Lambda = 0.5$ GeV)	both

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 ...

Well known example: *NN* scattering and the deuteron

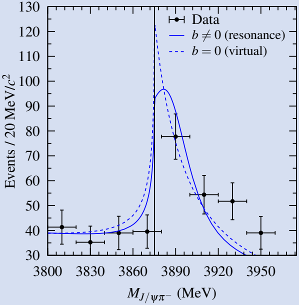
Triplet ($^3S_1$–$^3D_1$):

- $a_t \simeq 5$ fm.
- In this wave there is a **bound state**. The deuteron is a well known, really physical particle.

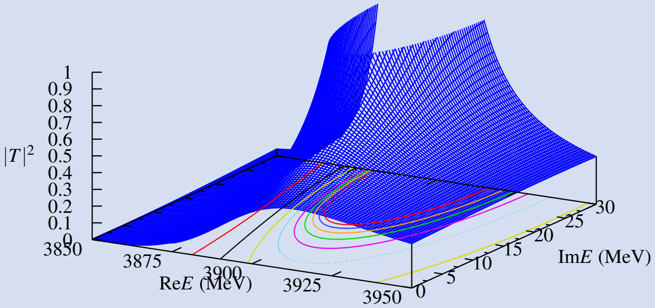
Singlet ($^1S_0$):

- $a_s \simeq -24$ fm.
- In this wave there is a **virtual state**.

- 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.



Complex plane & poles: First scenario (resonance)



- Pole located at $3894 - i30$ MeV
- Plot: unphysical Riemann sheet connected to the physical one above $D^*\bar{D}$
- Shift of the pole towards higher energies (interference!)

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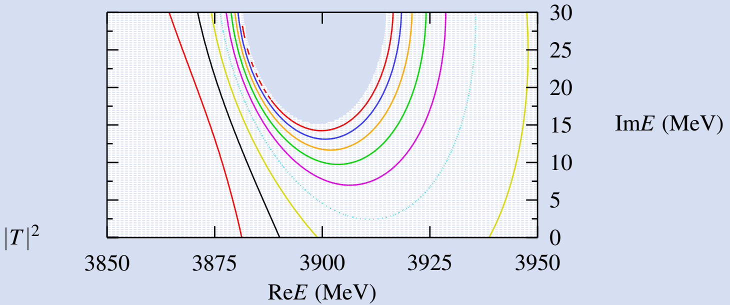

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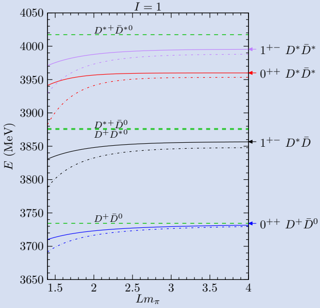
$Z_c(3900)$ on the lattice

- LQCD simulations on $Z_c(3900)$ still scarce:
  - [Prelovsek *et al.*, PR,D91,014504('15)] ($m_\pi = 266$ MeV) "no additional candidate"
  - [Y. Ikeda *et al.* [HAL QCD], arXiv:1602.03465] ($m_\pi \gtrsim 410$ 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)]



[M.A., C. Hidalgo-Duque, J. Nieves, E. Oset, PR,D88,014510('13)]

Formalism for finite volume [M.A., P. Fernández-Soler, J. Nieves, arXiv:1606.03008]

Periodic boundary conditions: discrete momenta

infinite volume	finite volume
$\vec{q}$ continuous	$\vec{q} = \frac{2\pi}{L}\vec{n}, \quad \vec{n} \in \mathbb{Z}^3$
$\int_{\mathbb{R}^3} \frac{\mathrm{d}^3 q}{(2\pi)^3} \frac{e^{-2(q^2-k_2^2)/\Lambda^2}}{E - \omega_{D\bar{D}^*}(q)}$	$\frac{1}{L^3} \sum_{\vec{n}\in\mathbb{Z}^3} \frac{e^{-2(q^2-k_2^2)/\Lambda^2}}{E - \omega_{D\bar{D}^*}(q)}$
$T^{-1}(E) = V^{-1}(E) - G(E)$	$\tilde{T}^{-1}(E,L) = V^{-1}(E) - \tilde{G}(E,L)$

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

$$\tilde{T}^{-1}(E_m(L), L) = 0 \qquad \text{(Interacting energy levels)}$$

- In particular, if the interaction is zero ($V(E) = 0$), then the energy levels are given by the poles of the $\tilde{G}$ function:

$$E_m(L) = \omega_{D\bar{D}^*}(2\pi\, n/L) \qquad \text{(Free energy levels)}$$

Formalism for finite volume [M.A., P. Fernández-Soler, J. Nieves, arXiv:1606.03008]

Periodic boundary conditions: discrete momenta

infinite volume	finite volume
$\vec{q}$ continuous	$\vec{q} = \frac{2\pi}{L}\vec{n}, \quad \vec{n} \in \mathbb{Z}^3$
$\int_{\mathbb{R}^3} \frac{d^3q}{(2\pi)^3} \frac{e^{-2(q^2-k_2^2)/\Lambda^2}}{E - \omega_{D\bar{D}^*}(q)}$	$\frac{1}{L^3} \sum_{\vec{n}\in\mathbb{Z}^3} \frac{e^{-2(q^2-k_2^2)/\Lambda^2}}{E - \omega_{D\bar{D}^*}(q)}$
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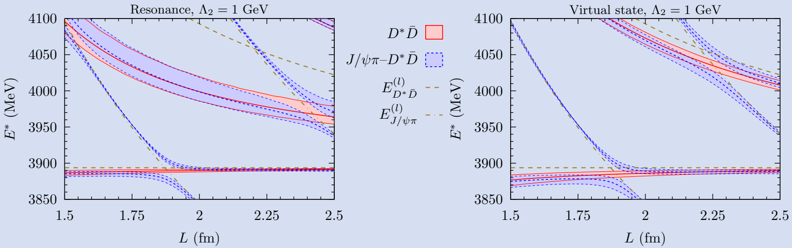
Energy-momentum dispersion relation on the lattice

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

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

$$\omega^{\rm lat}_{D\bar{D}^*}(q) = m_{D,1} + m_{D^*,1} + \frac{m_{D,2} + m_{D^*,2}}{2m_{D,2} m_{D^*,2}} q^2 - \frac{m^3_{D,4} + m^3_{D^*,4}}{8m^3_{D,4} m^3_{D^*,4}} q^4 \; .$$

Results



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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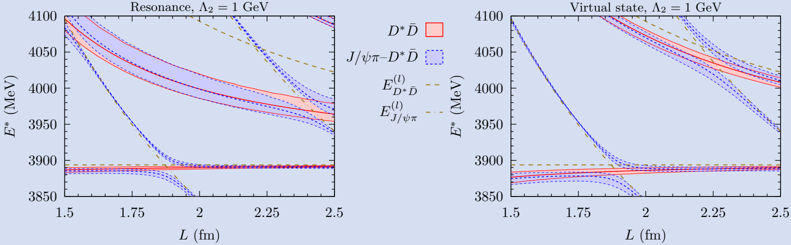

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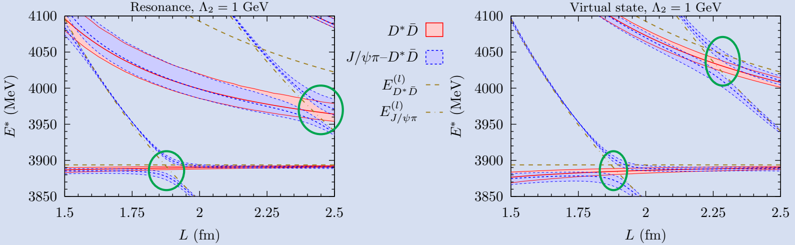

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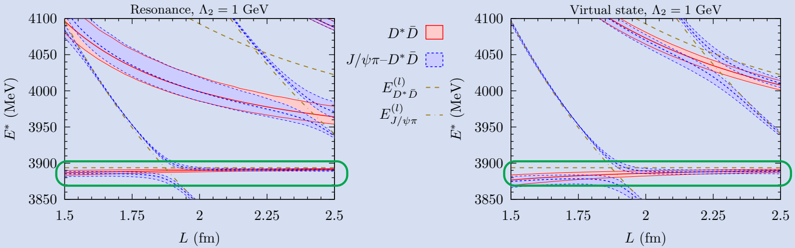

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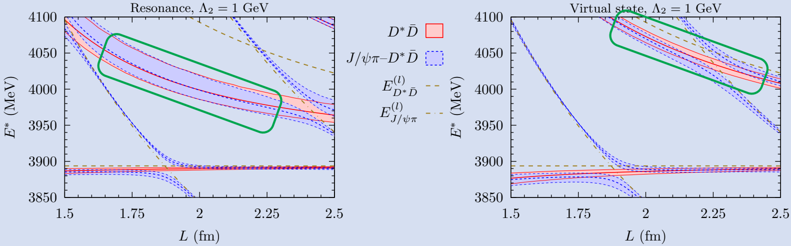

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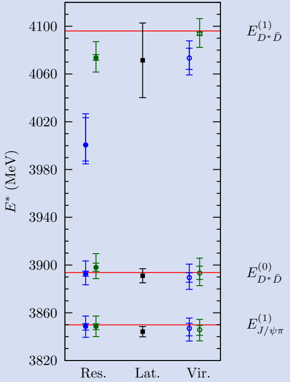
Comparison with LQCD simulations



- R scenario (left) *vs.* VS scenario (right)
- Lattice energy levels: center
- $\Lambda_2 = 0.5$ GeV: (●, ○)
- $\Lambda_2 = 1.0$ GeV: (●, ○)

- 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?

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

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

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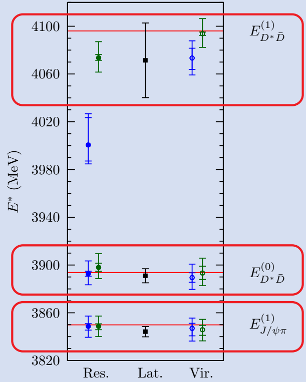

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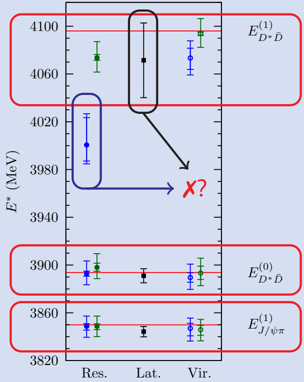

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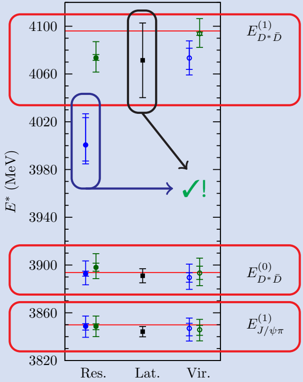

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Comparison with LQCD simulations: what's next?

- 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)
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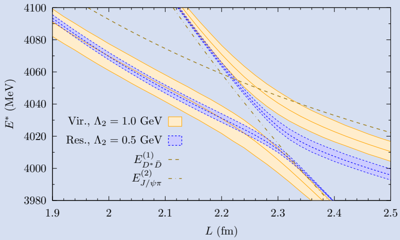

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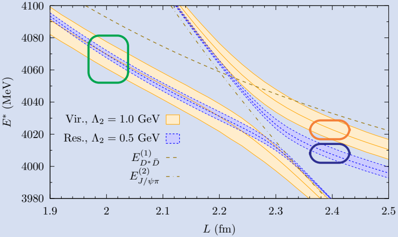

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Outline

Conclusions (this work)

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

[M. A., C. Hidalgo-Duque, F. K. Guo and J. Nieves, arXiv:1512.03638, Phys. Lett. B **755**, 337 (2016)]

- We have presented the first simultaneous study of the two decays ($Y(4260) \to J/\psi\pi\pi, \bar{D}^*D\pi$) in which $Z_c(3900)$ is seen
- Data are well reproduced in all fits ($\hat{\chi}^2 \simeq 1$)
- Two different scenarios are found:
  1. ($b \neq 0$) $Z_c(3900)$ is a $\bar{D}^*D$ 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

[M. A., P. Fernández-Soler and J. Nieves, arXiv:1606.03008, Eur. Phys. J. C (under review)]

- We have used our T-matrix to compute energy levels in a finite volume
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Conclusions (general)

- Charmonium spectrum, well known below $D\bar{D}$ threshold.
- Since 2003, the charmonium(-like) spectrum increases continuously ($\simeq 1$ 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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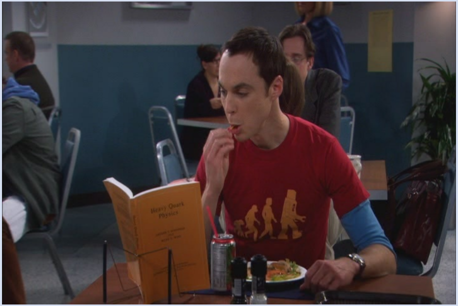

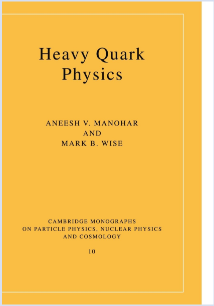

$Z_c(3900)$: experiment, theory, lattice

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Miguel Albaladejo (IFIC, Valencia)

MENU 2016

KYOTO

Thanks for your attention

CSIC
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IFIC
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Gobierno de España

Ministerio de Economía y Competitividad