



Lattice2017

Tetraquark and molecule charmonium states on the lattice

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Introduction

Some problems:

- What is the structure X,Y,Z states?
- How can we construct correlation functions for various interpretations of these states?

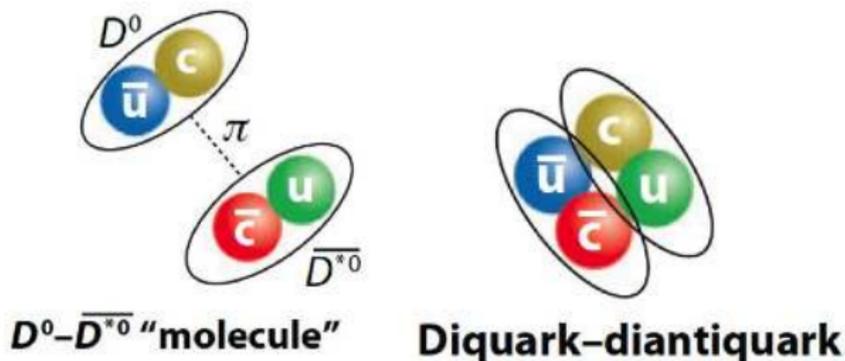
Charmonium spectroscopy (XYZ mesons)

Several exotic states:

- 1 $X(3872)$ near DD^* threshold, $J^{PC} = 1^{++}$
 $X(3872) \rightarrow J/\psi\rho, J/\psi\omega, D\bar{D}^*$ etc.;
- 2 $X(3900)$, $J^{PC} = 1^{+-}$. It was discovered in $J/\psi\pi^\pm$ inv. mass by BESII and confirmed by Belle and CLEOc, possible quark structure is $\bar{c}c\bar{d}u$;
- 3 $X(4140)$, $J^{PC} = 1^{++}$ was found in J/ϕ inv. mass by CDF and by CMS and D0.
- 4 and many more XYZ mesons

- 1 $D^{(*)}\bar{D}$ molecules, composed of a charmed meson $D^{(*)}$ and an antimeson \bar{D} ,
- 2 tetraquark states consisting of diquark-antidiquark pairs, bound by QCD forces,
- 3 $\bar{c}cg$ hybrid states consisting of charm-anticharm quark pair and additional gluons, and
- 4 a compact $\bar{c}c$ core, bound inside a light meson, hadro-charmonium.

We consider 2 popular interpretations for $X(3872)$ or $X(\dots)$ with $J^{PC} = 1^{++}$:
 tetraquark and $D^{(*)}\bar{D}$ molecules



The correlation function corresponding to the **tetraquark state**

$$\langle \bar{c}(x)\gamma_\mu c(x)\bar{q}(x)\gamma_\mu q(x)\bar{c}(y)\gamma_\mu c(y)\bar{q}(y)\gamma_\mu q(y) \rangle_A \simeq$$

$$\text{Tr} \left(\frac{1}{D+m_c}(x, y)\gamma_\mu \frac{1}{D+m_c}(x, y)\gamma_\mu \right) \cdot \text{Tr} \left(\frac{1}{D+m_q}(x, y)\gamma_\mu \frac{1}{D+m_q}(x, y)\gamma_\mu \right) \cdot$$

The correlation function corresponding to the **molecule state**

$$\langle \bar{c}(x)\gamma_\mu q(x)\bar{c}(x)\gamma_\mu q(x)\bar{c}(y)\gamma_5 q(y)\bar{c}(y)\gamma_5 q(y) \rangle_A \simeq$$

$$\text{Tr} \left(\frac{1}{D+m_c}(x, y)\gamma_\mu \frac{1}{D+m_q}(x, y)\gamma_\mu \right) \cdot \text{Tr} \left(\frac{1}{D+m_c}(x, y)\gamma_5 \frac{1}{D+m_q}(x, y)\gamma_5 \right)$$

Details of the configurations

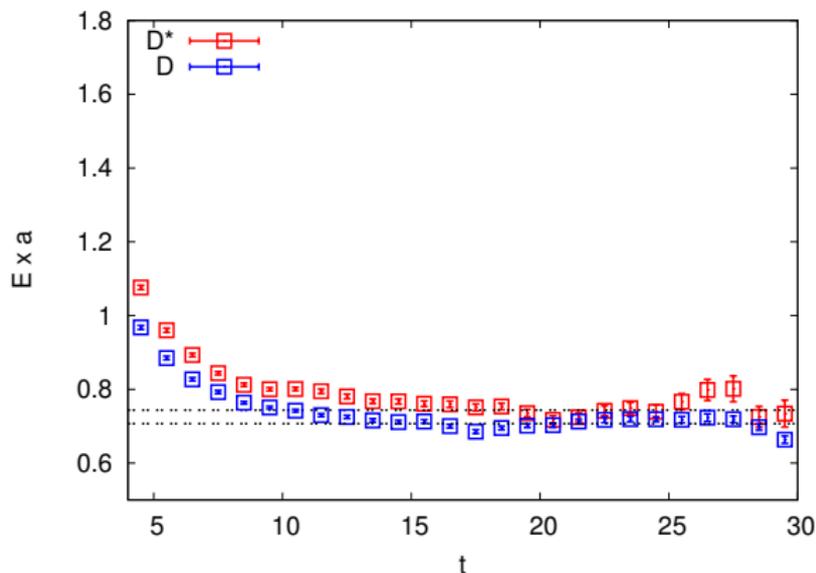
Configurations of the QCDSF collaboration

| Ensemble | β | V | a, fm | κ_0 | $M_\pi L$ | L, fm |
|----------|---------|------------------|---------|------------|-----------|---------|
| E_I | 5.65 | $32^3 \times 64$ | 0.068 | 0.122005 | 4.67 | 2.19 |

m_c is fixed by tuning the spin-averaged kinetic mass $\frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$ to its physical value (D. Mohler, S. Prelovsek and R. Woloshyn, Phys.Rev. **D87**, 034501 (2013), [arXiv:1208.4059].) (We are in progress...)

Preliminary! D and D^* mesons

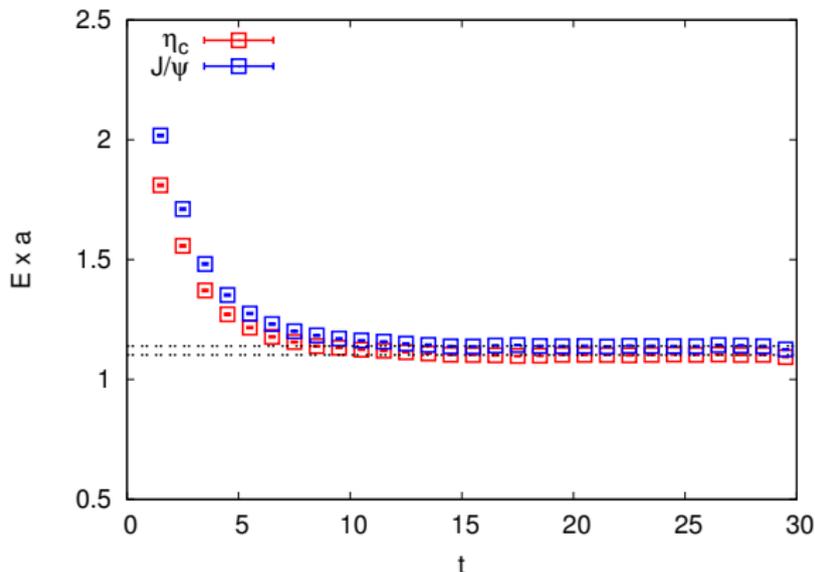
$$a = 0.068 \text{ fm} = 0.345 \frac{1}{\text{GeV}}$$



$$E_D + E_{D^*} = (4192 \pm 24) \text{ MeV}$$

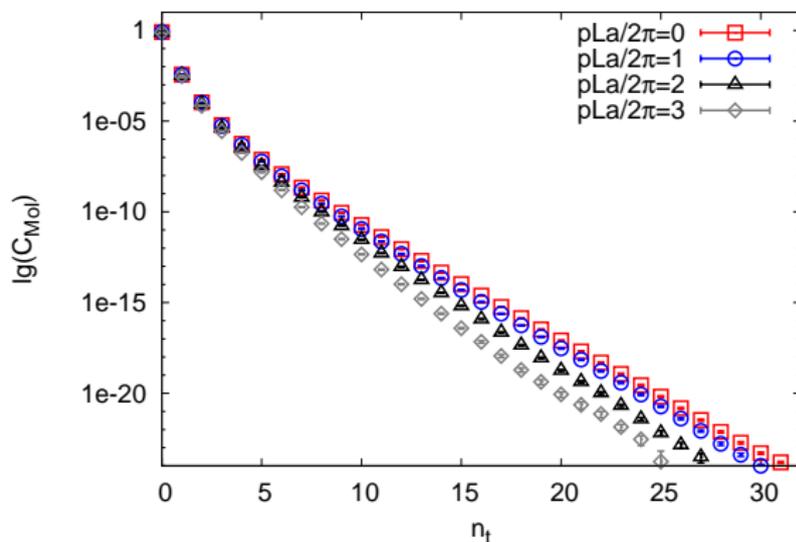
Preliminary! η_c and J/ψ

$$a = 0.068 \text{ fm} = 0.345 \text{ 1/GeV}$$



$$\text{spin-averaged kinetic mass } \frac{1}{4}(m_{\eta_c} + 3m_{J/\psi}) = (3274 \pm 2) \text{ MeV}$$

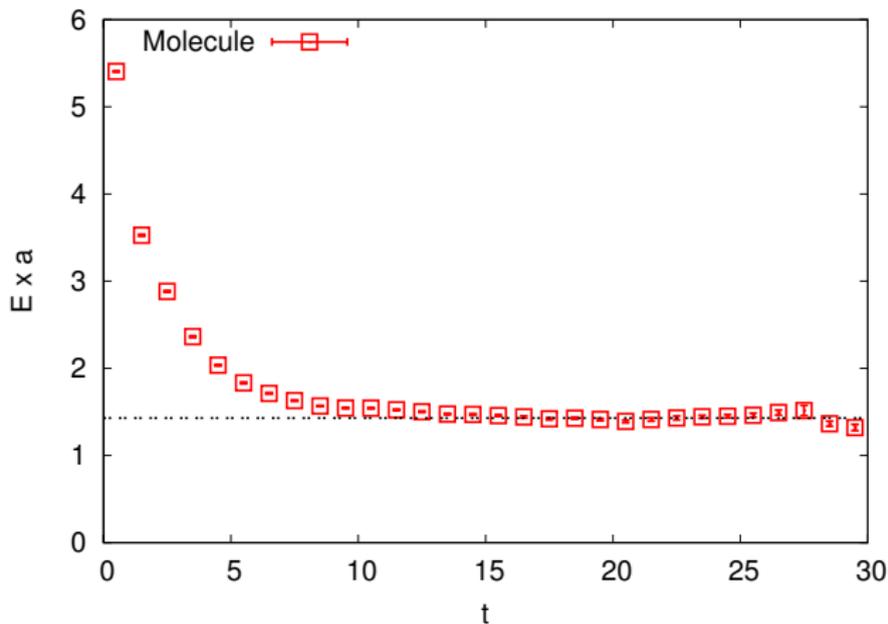
Correlation function of the molecule



Lattice $V = 32^3 \times 64$, $a = 0.068$ fm, $N_f = 2 + 1$ dynamical quarks, 256 lattice configurations

Preliminary! Energy of the molecule

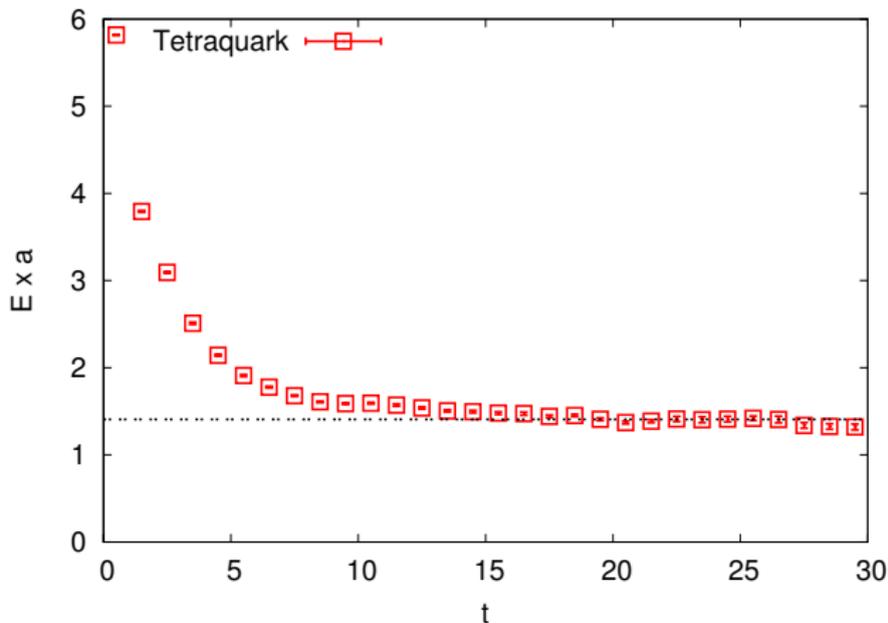
$$\text{Tr} \left(\frac{1}{D+m_c}(x, y) \gamma_\mu \frac{1}{D+m_q}(x, y) \gamma_\mu \right) \cdot \text{Tr} \left(\frac{1}{D+m_c}(x, y) \gamma_5 \frac{1}{D+m_q}(x, y) \gamma_5 \right)$$



$$E_{\text{eff}}^{t_0} = a^{-1} \ln \frac{C(t, t_0)}{C(t+a, t_0)}, \quad E_{\text{Mol}} = (4140 \pm 19) \text{ MeV}$$

Preliminary! Energy of the tetraquark

$$\text{Tr} \left(\frac{1}{D+m_c}(x, y) \gamma_\mu \frac{1}{D+m_c}(x, y) \gamma_\mu \right) \cdot \text{Tr} \left(\frac{1}{D+m_q}(x, y) \gamma_\mu \frac{1}{D+m_q}(x, y) \gamma_\mu \right).$$



$$E_{Tetr} = (4080 \pm 25) \text{ MeV}, \quad E_{D\bar{D}} = (3878 \pm 48) \text{ MeV}$$

Preliminary! Comparison lattice data and experimental value (PDG 2017) for X(3872)

| $X(3872)$ | $m_X - \frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$ | $m_X - (m_{D^0} + m_{D^{0*}})$ | $m_X - m_{J/\psi}$ |
|------------------|---|--------------------------------|--------------------|
| latt. molecule | 868 ± 17 MeV | -50 ± 5 MeV | 778 ± 23 MeV |
| latt. tetraquark | 806 ± 23 MeV | -112 ± 1 MeV | 840 ± 17 MeV |
| experiment | 803 ± 1 MeV | -0.14 ± 0.22 MeV | 775 ± 4 MeV |

$X(3872)$ from DD^* scattering on the lattice

9 new interpolators have been added into consideration

$$m(X(3872)) - (m_D + m_{D^*}) = -8 \pm (15) \text{ MeV}$$

The part of them corresponds to the tetraquark structure $[\bar{c}\bar{q}]_g[cq]_g$

$$m(X(3872)) - (m_D + m_{D^*}) = -9 \pm (8) \text{ MeV}$$

arXiv:1503.03257 [hep-lat], S.Prelovsek, L. Leskovec

$$m(X(3872)) - (m_D + m_{D^*}) = -13 \pm (6) \text{ MeV}$$

simulations with $N_f = 2 + 1 + 1$ dynamical quarks

arXiv:1411.1389 [hep-lat], S.Lee et al (Fermilab Lattice and MILC)

Conclusions

- 1 We have calculated the energies of the tetraquark and molecular states
- 2 We have obtained values of $m_X - \frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$, $m_X - m_{J/\psi}$ roughly close to the physical values .
- 3 Obtained states may be interpreted as the candidate for the X(3872) state (preliminary) (we should tune m_c).

Acknowledgments

We are grateful to the QCDSF and J. M. Zanotti for providing the gauge configurations and discussions.

Thank you for your attention!