Charmonium resonances on the lattice

Stefano Piemonte

for the RQCD collaboration

G. Bali, S. Collins, D. Mohler, M. Padmanath, S. Prelovsek, S. Weishaeupl

Universität Regensburg

23 June 2017

Charmonium bound states and resonances

Charmonium states have been crucial for the understanding of flavor physics and strong interactions. The history of charm physics starts with the discovery of the J/ψ (1974) and continues till today with the study of the "XYZ" resonances (2000-present).

The aim of our project is the understanding of the nature of charmonium $\bar{c}c$ resonances and exotic "XYZ" states near the decay threshold from lattice numerical investigations. For the first study we focus on the 1^{--} and 0^{++} channels.

Charmonium bound states and resonances

In particular, we plan to focus our attention on the $\psi(3770)$, a vector resonance which decays into $\bar{D}D$ mesons in P-wave (93% BR), and on the determination of the properties of the scalar resonances.

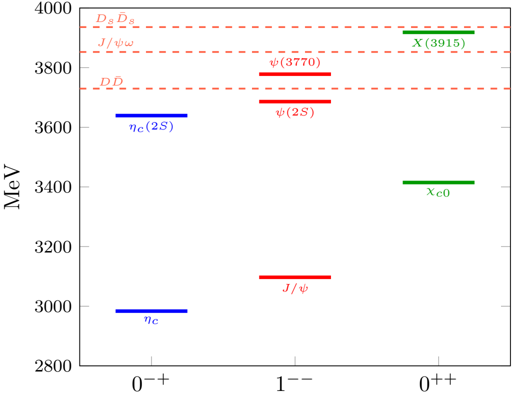

Figure: Simplified spectrum of the charmonium states in the channels 0^{-+}, 1^{--} and 0^{++}.

What is the X(3915)?

The $X(3915)$ resonance has been discovered by Belle (2004) in $J/\psi\omega$ decays, later confirmed by BaBar (2007). [Phys. Rev. Lett. 94(2005), 182002; Phys. Rev. Lett. 101 (2008) 082001; Phys. Rev. Lett. 104(2010) 092001]

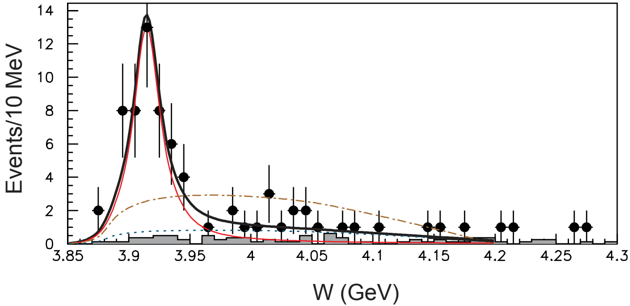

Figure: W distribution from Phys. Rev. Lett. 104(2010) 092001

PDG estimates (2016): $m = 3918.4 \pm 1.9$ MeV, $\Gamma = 20 \pm 5$ MeV.

What is the X(3915)?

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- OZI rule allows decays for an excited $\bar{c}c$ state in $\bar{D}D$ (not seen) but not in $J/\psi\omega$. [Phys. Rev. D 86 (2012), 091501, Phys. Rev. D 91(2015), 057501]
- Possible $\bar{D}_s D_s$ molecule: not seen in $\eta\eta_c$ channel. [Phys. Rev. D 91, 114014 (2015)]
- Possible $cs\bar{c}\bar{s}$ tetraquark: decays to $J/\psi\omega$ explained in terms of the $\omega - \phi$ mixing. [Eur. Phys. J. C77 (2017) 78]
- If $X(3915)$ is not the excited state of χ_{c0}, where is χ'_{c0}? $X^*(3860)$ is a possible candidate. [hep-ex/1704.01872]
- Possible alternative interpretation of experimental data as 2^{++} state [Phys. Rev. Lett. 115, 022001 (2015)]

Lattice and distillation methods

We study the charmonium spectrum on the U101 and H105 CLS ensembles, $m_\pi = 280$ MeV, $a = 0.0854$ fm and $V = 24^3 \times 128$ and $V = 32^3 \times 96$. We employ the full distillation method.

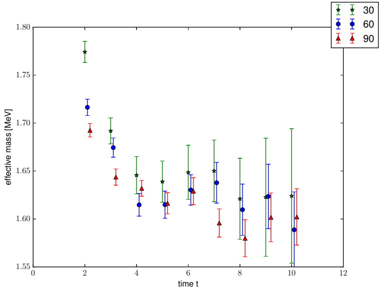
The starting point of our analysis is the determination of the charm mass:

1. The mass of the J/ψ and of the η_c is used to tune κ_c
2. There are many different alternative "trajectories" that extrapolate to the physical point
3. We use two different κ_c to control systematic errors and to understand how the physics of charmonium resonances is influenced by the precise value of the charm quark mass.

We use $\kappa_c = 0.123147$, corresponding to a D meson mass m_D equal to 1966(8) MeV, and $\kappa_c = 0.125220$ corresponding to $m_D = 1789(6)$.

Lattice and distillation methods

After the tuning of the κ_c, we compute light, strange and charm perambulators for 90 Laplacian eigenvectors for the U101. We always neglect diagrams with disconnected charm quark lines.



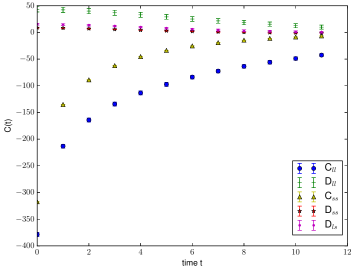


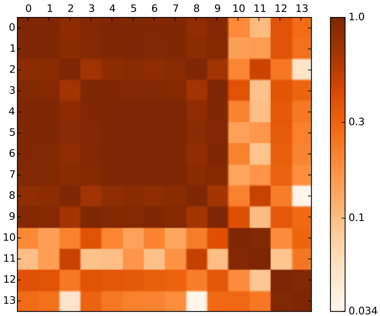
Figure left: Effective mass plots for the first excited charmonium state (0^{-+}) using 30, 60 and 90 Laplacian eigenvectors.

Figure right: Connected and disconnected pseudoscalar correlators on U101 for 120 configurations computed with full distillation.

Correlation matrix in the 1^{--} channel

We optimize the choice of the basis of operators by looking for the normalized correlation matrix $M_{ij}(t) = C_{ij}(t)/\sqrt{C_{ii}(t)C_{jj}(t)}$.

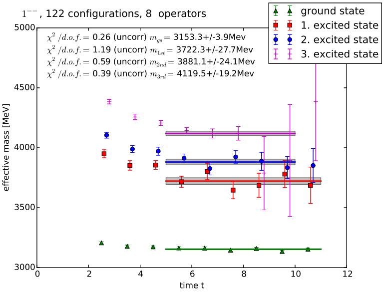
0	$\bar q\ q$
1	$\bar q\ \gamma_i\gamma_t\ q$
2	$\bar q\ \overrightarrow{\nabla}_i\ q$
3	$\bar q\ \epsilon_{ijk}\gamma_j\gamma_5\overrightarrow{\nabla}_k\ q$
4	$\bar q\ \overleftarrow{\nabla}_k\gamma_i\overrightarrow{\nabla}_k\ q$
5	$\bar q\ \overleftarrow{\nabla}_k\gamma_i\gamma_t\overrightarrow{\nabla}_k\ q$
6	$\bar q\ \overleftarrow{\Delta}\gamma_i\overrightarrow{\Delta}\ q$
7	$\bar q\ \overleftarrow{\Delta}\gamma_i\gamma_t\overrightarrow{\Delta}\ q$
8	$\bar q\ \overleftarrow{\Delta}\overrightarrow{\nabla}_i\ q$
9	$\bar q\ \overleftarrow{\Delta}\epsilon_{ijk}\gamma_j\gamma_5\overrightarrow{\nabla}_k\ q$
10	$\bar q\ \lvert\epsilon_{ijk}\rvert\gamma_j\overrightarrow{D}_k\ q$
11	$\bar q\ \lvert\epsilon_{ijk}\rvert\gamma_j\gamma_t\overrightarrow{D}_k\ q$
12	$O^{\bar D(-1)D(1)} \sim \bar c\gamma_5 l\ \bar l\gamma_5 c$
13	$O^{\bar D(-1)D(1)} \sim \bar c\gamma_5\gamma_t l\ \bar l\gamma_5\gamma_t c$



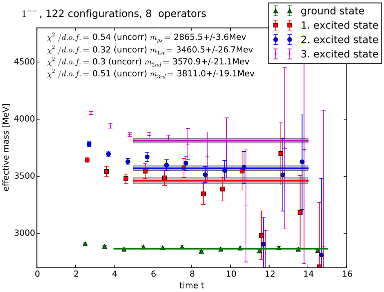
In the 1^{--} channel we see small correlations between $\bar D D$ two-particle operators and $\bar c c$ single particle operators.

Effective mass plots for the 1^{--} channel

Energy levels on the U101 ensemble in the 1^{--} channel for the two different κ_c:



(a) $\kappa_c = 0.123147$



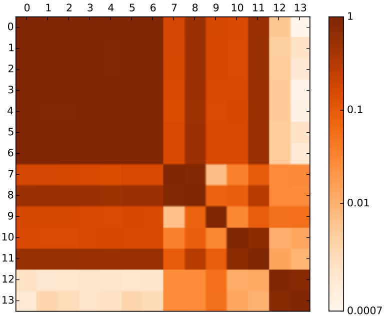
(b) $\kappa_c = 0.125220$

The energy splittings with respect to the ground states are unchanged up to the precision given by our statistics!

Correlation matrix in the 0^{++} channel

We optimize the choice of the basis of operators by looking for the normalized correlation matrix $M_{ij}(t) = C_{ij}(t)/\sqrt{C_{ii}(t)C_{jj}(t)}$.

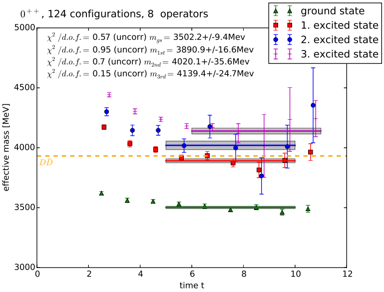
0	$\bar q\ q$
1	$\bar q\ \gamma_i \overrightarrow{\nabla}_i\ q$
2	$\bar q\ \gamma_i\gamma_t \overrightarrow{\nabla}_i\ q$
3	$\bar q\ \overleftarrow{\nabla}_i \overrightarrow{\nabla}_i\ q$
4	$\bar q\ \overleftarrow{\Delta}\ \overrightarrow{\Delta}\ q$
5	$\bar q\ \overleftarrow{\Delta}\gamma_i \overrightarrow{\nabla}_i\ q$
6	$\bar q\ \overleftarrow{\Delta}\gamma_i\gamma_t \overrightarrow{\nabla}_i\ q$
7	$O^{\bar D(0)D(0)} \sim \bar c\gamma_5 l\ \bar l\gamma_5 c$
8	$O^{\bar D(0)D(0)} \sim \bar c\gamma_5\gamma_t l\ \bar l\gamma_5\gamma_t c$
9	$O^{\bar D(p)D(-p)} \sim \bar c\gamma_5 l\ \bar l\gamma_5 c$
10	$O^{\bar D^*(0)D^*(0)} \sim \bar c\gamma_i l\ \bar l\gamma_i c$
11	$O^{\bar D^*(0)D^*(0)} \sim \bar c\gamma_i\gamma_t l\ \bar l\gamma_i\gamma_t c$
12	$O^{J/\psi(0)\omega(0)} \sim \bar c\gamma_i c\ \bar l\gamma_i l$
13	$O^{J/\psi(0)\omega(0)} \sim \bar c\gamma_i\gamma_t c\ \bar l\gamma_i\gamma_t l$



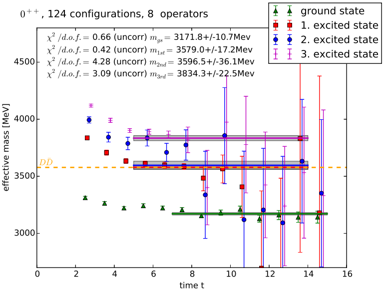
In the 0^{++} channel we see small correlations between $J/\psi\omega$ two-particle operators and $\bar c c$ single particle and $\bar D D$ two-particle operators.

Effective mass plots for the 0^{++} channel

Energy levels on the U101 ensemble in the 0^{++} channel for the two different κ_c:



(c) $\kappa_c = 0.123147$

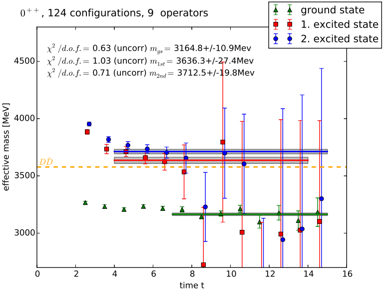


(d) $\kappa_c = 0.125220$

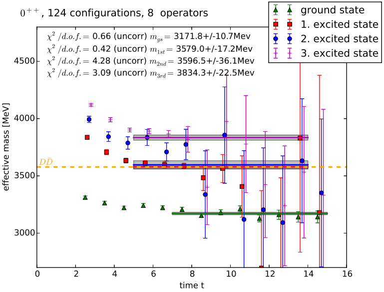
The energy splittings with respect to the ground states are unchanged up to the precision given by our statistics!

Effective mass plots for the 0^{++} channel

Energy levels on the U101 ensemble in the 0^{++} channel for $\kappa_c = 0.125220$:



(e) charm + strange quark lines



(f) charm + light quark lines

The "hidden strange" sector is relevant for the analysis of the resonances in the 0^{++} channel.

Conclusions

- Energy level splittings are not significantly affected by the value of the charm quark mass.
- Hidden strange sector and coupled channel analysis required for the study of the 0^{++} resonances.
- Our studies provide already a good signal for charmonium single and two-particle correlators $\rightarrow$ more statistics required to compute the phase shift with the Lüscher method

Thank you for your attention!