Charmonium resonances on the lattice

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for the RQCD collaboration

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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.

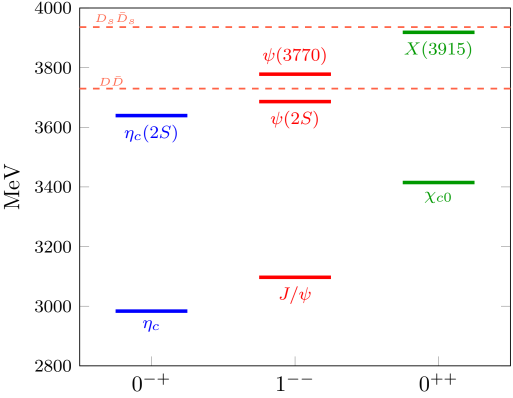

Figure: Simplified spectrum of the charmonium states in the channels 0^{-+}, 1^{--} and 0^{++}.

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]

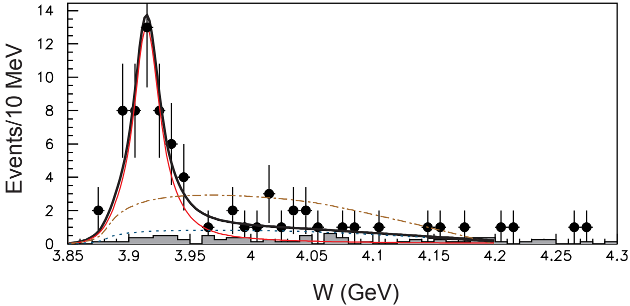

Figure: W distribution from Phys. Rev. Lett. 104(2010) 092001

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

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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.

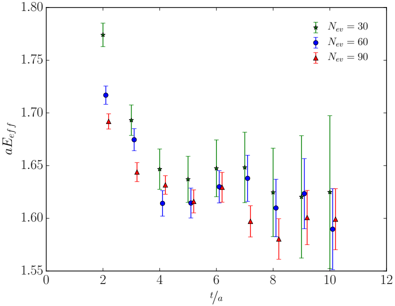
The starting point of our analysis is the determination of the charm mass:

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.



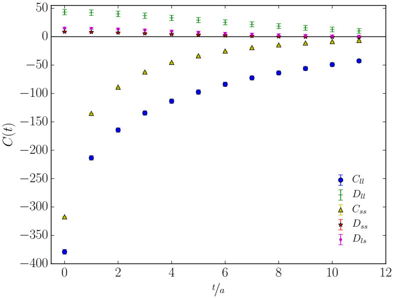


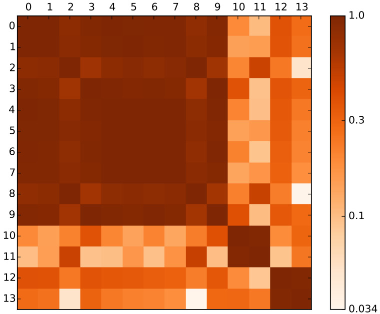
Figure left: Effective mass plots for the first excited charmonium state (0^{-+}) using 30, 60 and 90 Laplacian eigenvectors.

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 $M_{ij}(t) = C_{ij}(t)/\sqrt{C_{ii}(t)C_{jj}(t)}$.

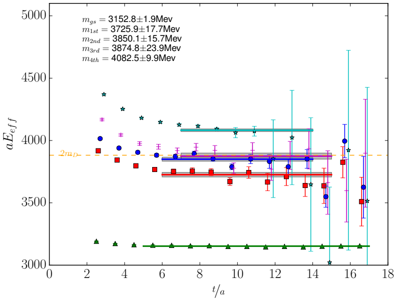
0	$\bar{q}\ q$
1	$\bar{q}\ \gamma_i\gamma_t\ q$
2	$\bar{q}\ \overrightarrow{\nabla}_i\ q$
3	$\bar{q}\ \epsilon_{ijk}\gamma_j\gamma_5\overrightarrow{\nabla}_k\ q$
4	$\bar{q}\ \overleftarrow{\nabla}_k\gamma_i\overrightarrow{\nabla}_k\ q$
5	$\bar{q}\ \overleftarrow{\nabla}_k\gamma_i\gamma_t\overrightarrow{\nabla}_k\ q$
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	$O^{\bar{D}(-1)D(1)} \sim \bar{c}\gamma_5\gamma_t l\ \bar{l}\gamma_5\gamma_t c$



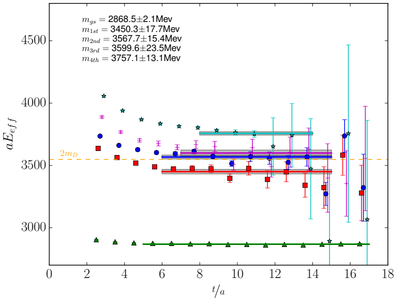
In the 1^{--} channel we see small correlations between $\bar{D}D$ two-particle operators and $\bar{c}c$ single particle operators.

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

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



(a) $\kappa_c = 0.123147$



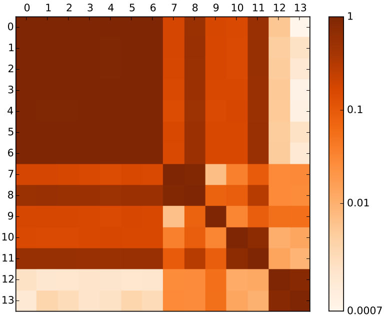
(b) $\kappa_c = 0.125220$

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 $M_{ij}(t) = C_{ij}(t)/\sqrt{C_{ii}(t)C_{jj}(t)}$.

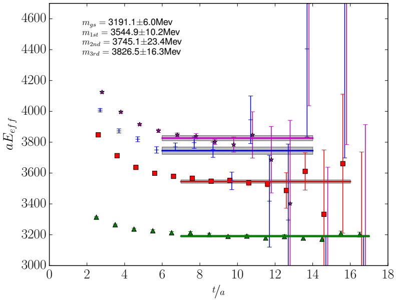
0	$\bar{q}\ q$
1	$\bar{q}\ \gamma_i \overrightarrow{\nabla}_i\ q$
2	$\bar{q}\ \gamma_i \gamma_t \overrightarrow{\nabla}_i\ q$
3	$\bar{q}\ \overleftarrow{\nabla}_i \overrightarrow{\nabla}_i\ q$
4	$\bar{q}\ \overleftarrow{\Delta}\ \overrightarrow{\Delta}\ q$
5	$\bar{q}\ \overleftarrow{\Delta} \gamma_i \overrightarrow{\nabla}_i\ q$
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	$O^{J/\psi(0)\omega(0)} \sim \bar{c}\gamma_i\gamma_t c\ \bar{l}\gamma_i\gamma_t l$



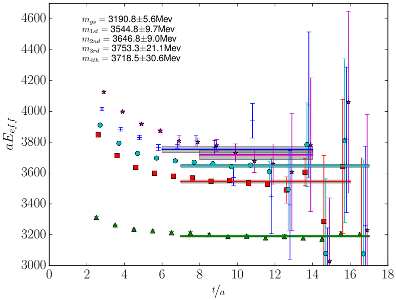
In the 0^{++} channel we see small correlations between $J/\psi\omega$ two-particle operators and $\bar{c}c$ single particle and $\bar{D}D$ two-particle operators.

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

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



(c) charm + light quark lines



(d) charm + light + strange 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!