Charmed states on the lattice

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We calculate

- the charmonium spectrum under $D^0\overline{D}^{0*}$ threshold,
- the energies of D mesons,
- the energies of the tetraquark and molecule states.

Our goal:

- To investigate the physical properties and parameters of charmed hadrons including exotic states in lattice QCD

Several exotic states:

- X(3872) state near $D^0\overline{D}^{0*}$ threshold, $J^{PC} = 1^{++}$, $X(3872) \to J/\psi\omega$ (I=0), $J/\psi\rho$ (I=1), $D^0\overline{D}^{0*}$, etc. The state was found by Belle collaboration.
- X(3900), $J^{PC} = 1^{+-}$, possible quark structure is $\bar{c}c\bar{d}u$. It was discovered in $J/\psi\pi^{\pm}$ inv.mass by BESII and confirmed by Belle and CLEOc.
- X(4140) with $J^{PC} = 1^{++}$ was found in $J/\psi\phi$ inv.mass by CDF, CMS and D0.
- X(3915) with C=+1 and many other X,Y,Z states.

Possible candidates for describing the nature of exotic states

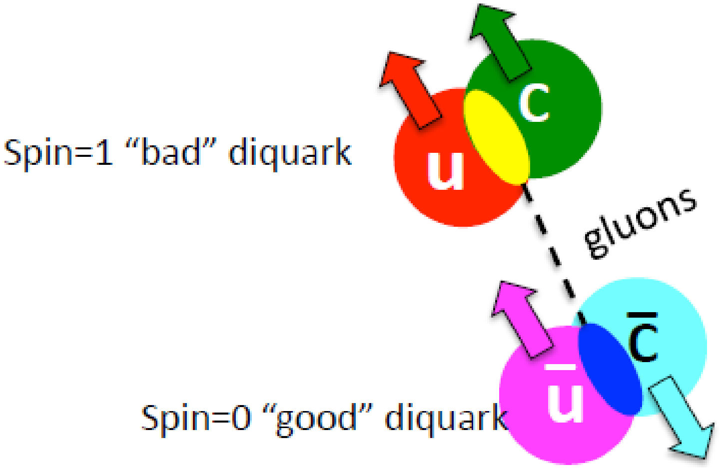
- $\mathrm{D\overline{D}^*}$ molecules composed of a charmed meson D and antimeson $\mathrm{\overline{D}^*}$.
- Tetraquark states consisting of diquark-antidiquark pairs bound by QCD forces.
- $\bar{c}c\mathrm{g}$ hybrid states consisting of charm-anticharm quark pair and additional gluons.
- A compact $\mathrm{\bar{c}c}$ core bound inside a light meson called hadrocharmonium.
- Superposition of the molecule and tetraquark states, molecule and hadrocharmonium, etc.

Two popular models for X(3872) state with $J^{PC} = 1^{++}$

- Tetraquark

The model assumes the existence of charged partners of the X(3872), which have not been observed yet. But they are not excluded.

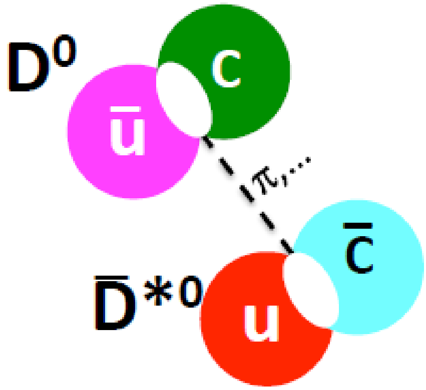
A careful analysis of the decays $B \to KD\bar{D}^*$ and $B \to KD^*\bar{D}^*$ is needed.



- $D\bar{D}^*$ molecule

Arguments against this:

the branching ratio of X(3872) → $\gamma\psi'$ is sufficiently large, it is difficult to form such a fragile object in high-energy collisions.



Constructing of the correlation matrix for the X(3872) state

- The correlation function corresponding to the tetraquark state

$$\left\langle \bar{c}(x)\gamma_\mu c(x)\bar{q}(x)\gamma_\mu q(x)\bar{c}(y)\gamma_\mu c(y)\bar{q}(y)\gamma_\mu q(y) \right\rangle_A \cong$$

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

- The correlation function corresponding to the molecule state

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

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

Details of our configurations

Configurations of the QCDSF collaboration with $N_f = 2 + 1$ dynamical quarks

Ensemble	β	V	a, fm	κ_l	$M_\pi L$	L, fm	N_{conf}
E_l	5.65	$32^3 \times 64$	0.068	0.122005	4.67	2.19	174

m_c is fixed by 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])

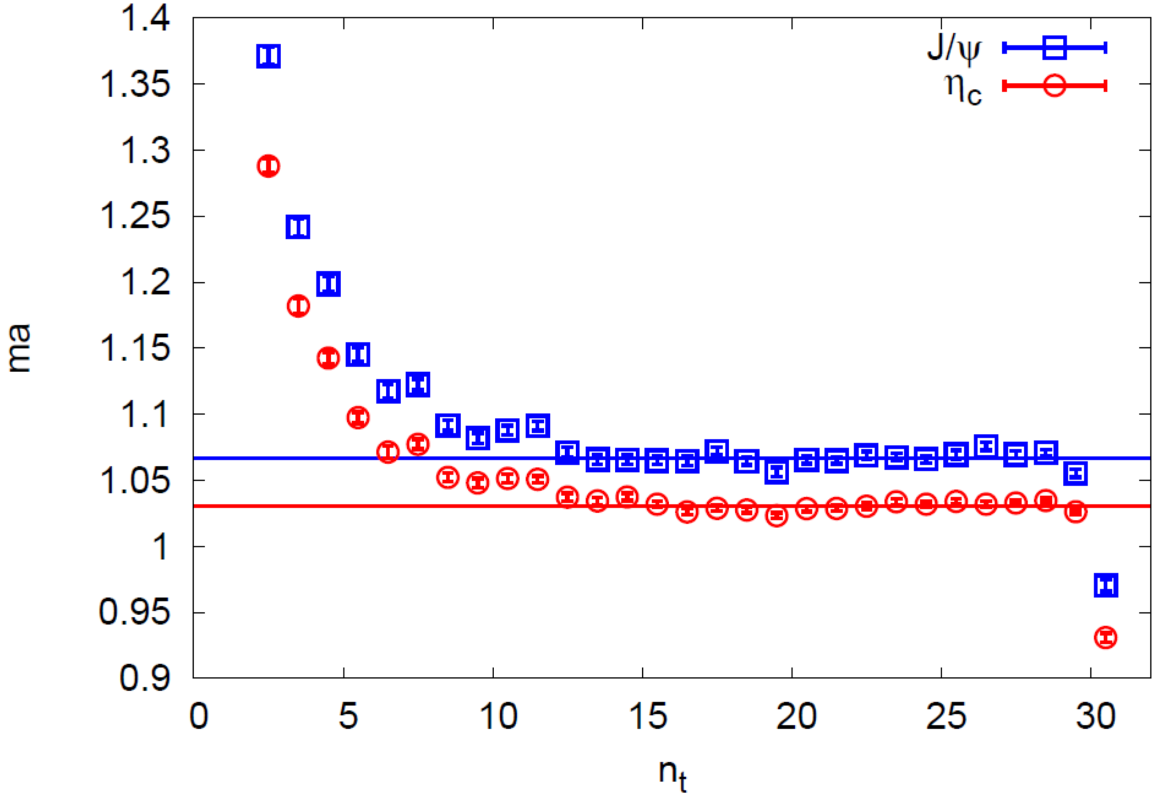
Tuning of the c-quark mass on the lattice

Experiment: $\frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$ =3068 $\pm$ 2 MeV,

$m_{J/\psi} = 3096{,}9 \pm 0.006\ MeV$, $m_{\eta_c}(1S) = 2983{,}4 \pm 0{,}5$ MeV.

Our results: $\frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$ =3064 $\pm$ 3 MeV,

$m_{J/\psi} = 3091 \pm 3\ MeV$, $m_{\eta_c}(1S) = 2985 \pm 3$ MeV at a = 0.068 fm.



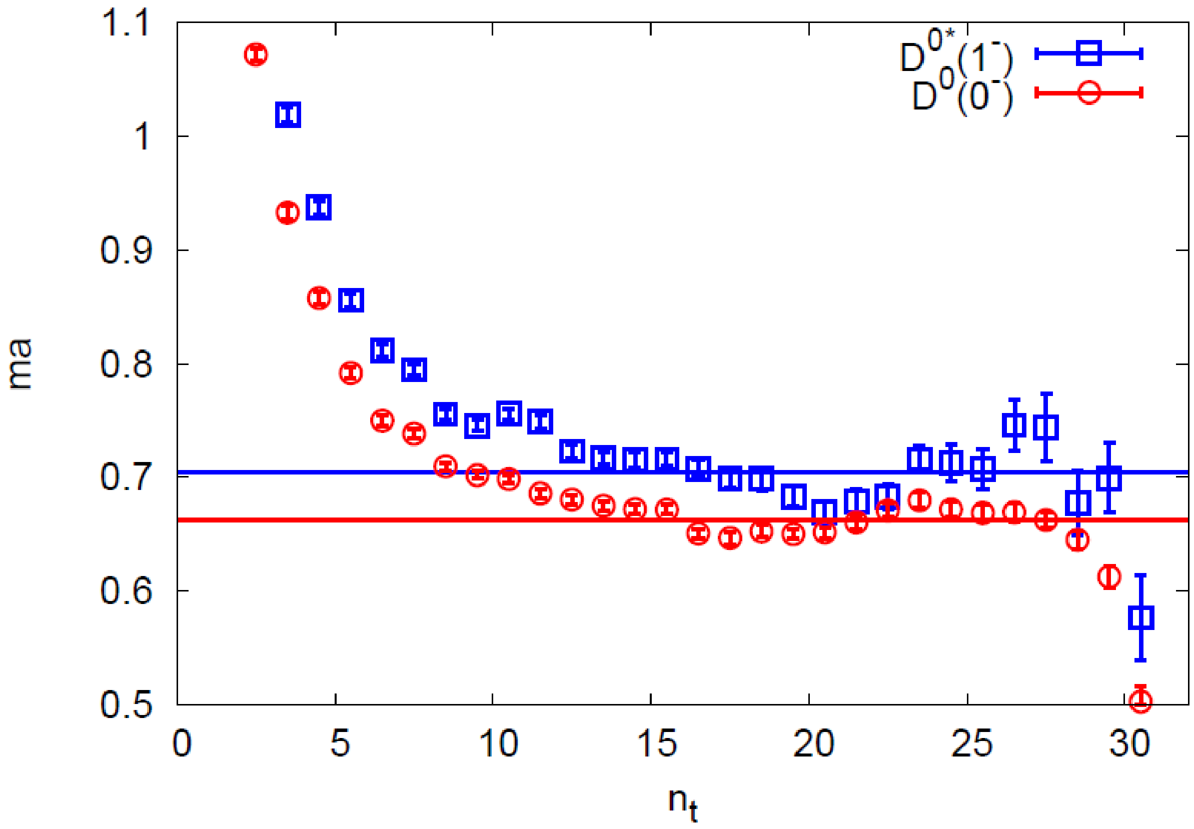
D and D* mesons

Experiment: $m_{D^{0*}} = 2006{,}85 \pm 0.05$ MeV,$m_{D^0} = 1864{,}83 \pm 0{,}05$ MeV.

$m_{D^{0*}} + m_{D^0} = 3871{,}68 \pm 0{,}05$ MeV.

Our results: $m_{D^{0*}} = 2040 \pm 10$ MeV, $m_{D^0} = 1920 \pm 10$ MeV,

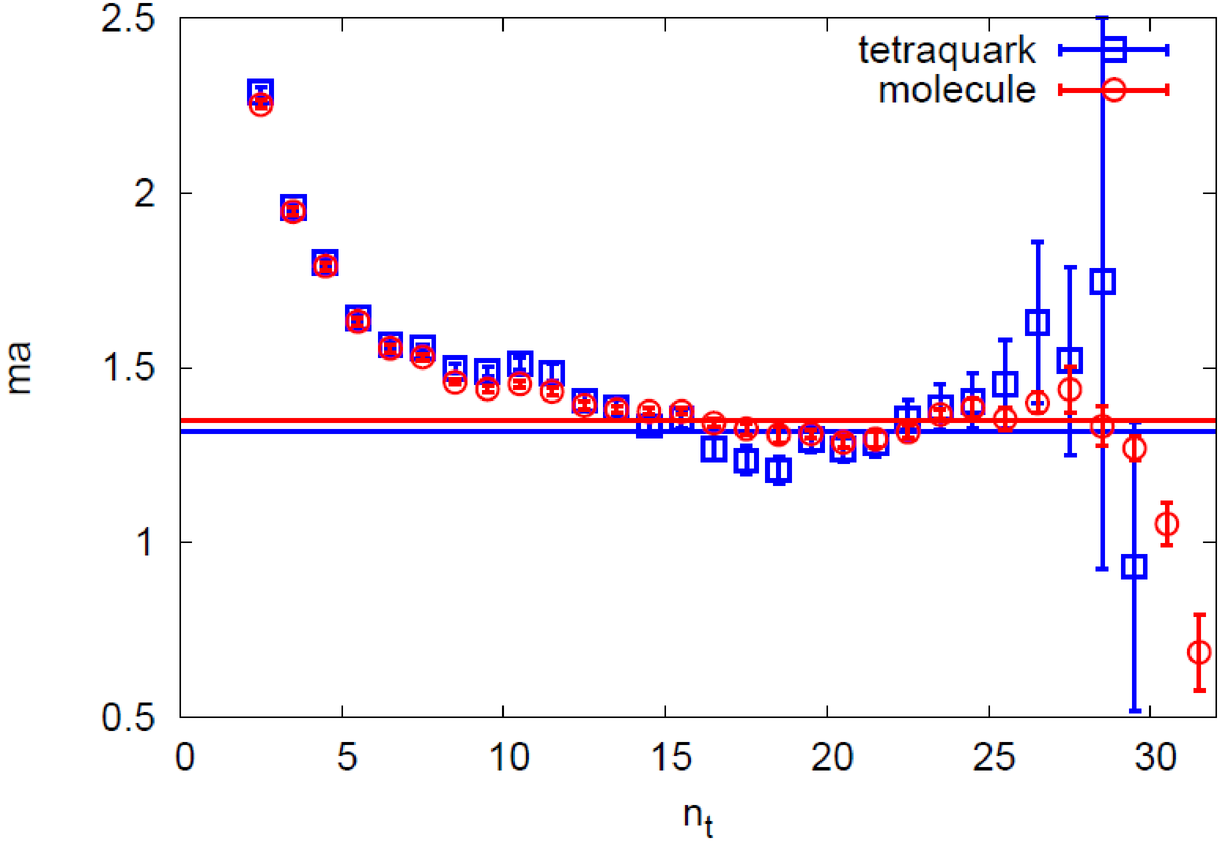
$m_{D^{0*}} + m_{D^0} = 3960 \pm 20$ MeV at $m_\pi = 420$ MeV.



Energies of the tetraquark and molecule

$\mathrm{E_{tetr}} = 3820 \pm 50\ \mathrm{MeV}$ for the fit range $n_t = 22 \div 28$, the state lies below the $\mathrm{D^0}\ \mathrm{D^{0*}}$ threshold. It requires much more statistics.

$\mathrm{E_{mol}} = 3920 \pm 30\ \mathrm{MeV}$, the exploration of finite volume effects is needed.



‘Single-meson treatment of the excited states’

- Using only quark-antiquark interpolating fields $O \sim q\bar{q}$ for mesons;
- Assuming that all energy levels corresponding to one-particle states;
- The mass of the state equals the measured energy level m=E.

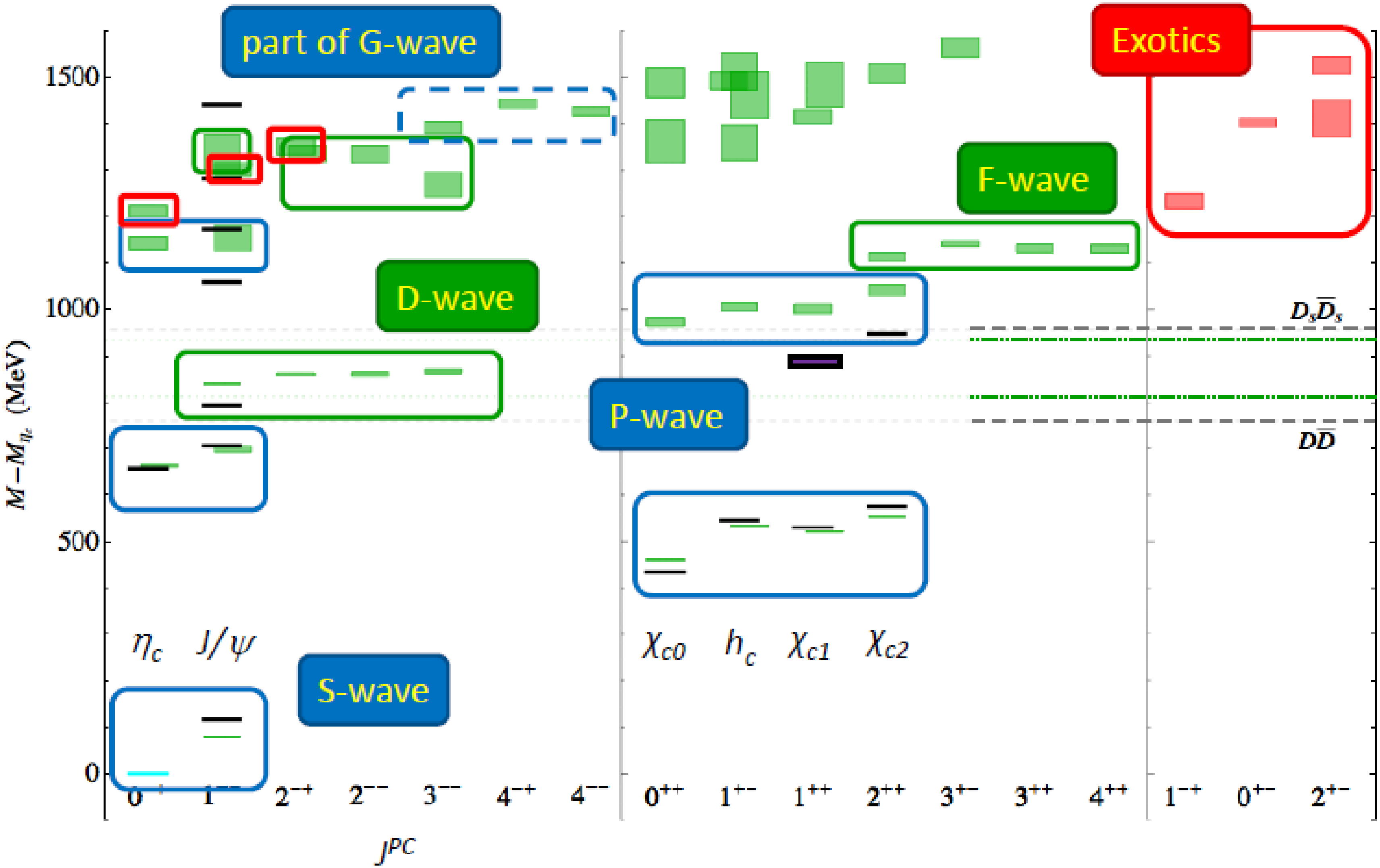
These assumptions are too strong for the resonances, which are not asymptotic states. This approach also ignores the effect of the threshold and near-threshold states.

For the states below open charm threshold

$$m = \sqrt{E^2 - P^2}$$

Perform extrapolations: $L \to \infty, a \to 0, m \to m_{phys}$.

$\overline{c}c$ spectrum by the HSC, G.Moir et.al. arXiv:1301.7670



Rigorous treatment of near-threshold states X(3872)

$$X(3872) \to J/\psi\omega,\ J/\psi\rho$$

Consider also discrete scattering levels DD* and $J/\psi V$, where V=ω for I=0 and $V = \rho$ for I=1.

The eigenstates are also the s-wave scaterring states $D(\vec{p})D^*(-\vec{p})$ and J/ψ($\vec{p}$)V(− $\vec{p}$) with discrete momenta $\vec{p}$.

All states carrying the same quantum numbers, including the single-particle and multi-particle states, in principle contribute to the eigenstates of Hamiltonian.

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

9 new interpolators have been added into consideration

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

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

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

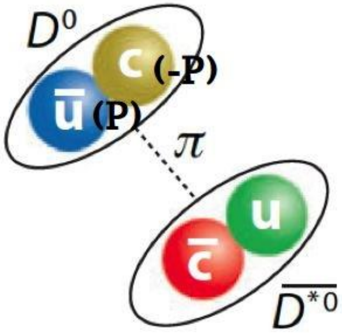
Phys. Rev. D 92, 034501 (2015),arXiv:1503.03257 [hep-lat] , M. Padmanath,C. B. Lang, Sasa Prelovsek

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

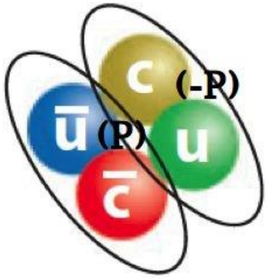
arXiv:1411.1389 [hep-lat] , S.Lee et al (Fermilab Lattice and MILC)

Tetraquark or molecule

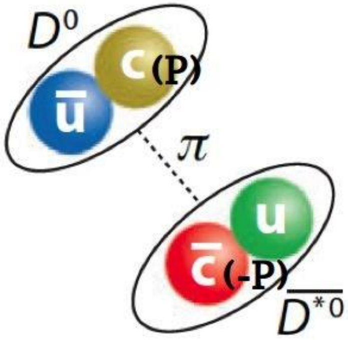
We also plan to compare the correlators behavior at finite momentum



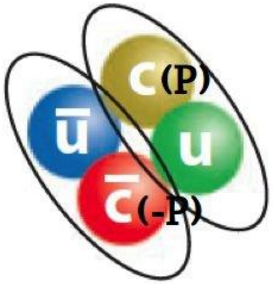
D^0–$\overline{D}^{*0}$ "molecule"



Diquark–diantiquark



D^0–$\overline{D}^{*0}$ "molecule"



Diquark–diantiquark

Conclusions:

- The energies of the ground charmonia states in a good agreement with the experimen/.
- The energies of the tetraquark and molecule states were calculated.
- The tetraquark state lies under the DD* threshold.
- The molecule state is close to the DD* threshold.

Future plans:

- Take into account mixing between the tetraquark and molecule state.
- Increase statistics.
- Add another interpolation operators into the correlation matrix.
- Go to physical pion masses and consider decays.

Thank you for your attention!