Flavored tetraquark spectroscopy

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Outline

Introduction

The recent confirmation of the charged resonance $Z(4430)$ by *LHCb* strongly suggests the existence of genuine tetraquark mesons in the *QCD* spectrum

The diquark-antidiquark model in its type II version can accomodate in a unified description the puzzling spectrum of the exotics

Maiani, Piccinini, Polosa, Riquer, arXiv:1405.1551 [hep-ph]

We recently proposed a mechanism à la Feshbach to explain the experimental lack of many tetraquark states

ALG, Piccinini, Pillloni, Polosa, arXiv:1405.7929 [hep-ph]

The puzzle of the X, Z resonances

$X(3872)$, $J^{PC} = 1^{++}$

- $\Gamma_X < 1.2$MeV
- strong breaking of isospin symmetry
  $BR(X \to J/\psi\rho) \sim BR(X \to J/\psi\omega)$

$Z(3900)$, $J^{PC} = 1^{+-}$

- charged resonance discovered in $Z \to J/\psi\pi^+$
- found ~ 20MeV above the DD^* threshold

$Z(4430)$, $J^{PC} = 1^{+-}$

- charged resonance discovered in $Z \to \psi'\pi^+$
- found far from any open charm threshold
- it can be the radial excitation of the $Z(3900)$

Motivation of our lattice study

We will focus on flavored (doubly charmed) operators with flavor content

$$[cc]\,[\bar{q}_1\bar{q}_2]\;\; q_1, q_2 = u, d$$

with four valence quarks

Esposito, Papinutto, Pilloni, Polosa, Tantalo, Phys.Rev. D88 (2013) 5, 054029

In this framework we cannot have disconnected diagrams

A lattice confirmation of such exotic states could give the start to an experimental search

Good and bad tetraquark structures

Charmed diquark is fixed by symmetry

$$[cc] = \left|\bar{3}_c(A),\ \ J^P = 1^+(S)\right\rangle$$

For light antidiquark we have two choices

$$[\bar{q}_1\bar{q}_2]_G = \left|3_c(A),\, 3_f(A),\, J^P = 0^+(A)\right\rangle$$
$$[\bar{q}_1\bar{q}_2]_B = \left|3_c(A),\, \bar{6}_f(S),\, J^P = 1^+(S)\right\rangle$$

$\mathcal{T}$ states	
"Good", $J^P = 1^+$, I=0	"Bad", $J^P = 0^+, 1^+, 2^+$, I=1
$\mathcal{T}^+$ $([cc][\bar{u}\bar{d}]_A)$	$\mathcal{T}^0$ $([cc][\bar{u}\bar{u}])$
	$\mathcal{T}^{++}$ $([cc][\bar{d}\bar{d}])$
	$\mathcal{T}^+$ $([cc][\bar{u}\bar{d}]_S)$

The good state is expected to be lighter than the bad one

Phys.Rev. D88 (2013) 5, 054029

Lattice setup

We use a set of 128 CLS configurations with $V \times T = 32^3 \times 64$ non perturbatively $\mathcal{O}(a)$ improved

$\beta = 5.2$ with a corresponding lattice spacing of $a \sim 0.075\,\text{fm}$

$N_f = 2$ light sea flavors $k_{sea} = 0.13580$, $m_\pi \sim 490\,\text{MeV}$

$L \sim 2.4\,\text{fm}$ and the smallest momentum is $p = 520\,\text{MeV}$

$k_c = 0.13022$ but it's not a physical charm

Interpolating operators $I = 0$ channel

We consider a set of five operators in the $I = 0$, $J^P = 1^+$ channel

$$\mathcal{O}_1 = \varepsilon^{ijk}\varepsilon^{lmk}\bar{c}^i_c(x)\gamma^A c^j(x) \;\; (\bar{u}^l(x)\gamma^5 d^m_c(x) - \bar{d}(x)^l\gamma^5 u^m_c(x)) \qquad \text{good } \mathcal{T}^+$$

$$\mathcal{O}_2 = \bar{u}(x)\gamma^A c(x)\,\bar{d}(x)\gamma^5 c(x) - \bar{d}(x)\gamma^A c(x)\,\bar{u}(x)\gamma^5 c(x) \qquad D^0 D^{*+} - D^{*0} D^+$$

$$\mathcal{O}_3 = \bar{u}\gamma^A c\left[\vec{p} = \vec{0}\right]\,\bar{d}\gamma^5 c - \bar{d}\gamma^A c\left[\vec{p} = \vec{0}\right]\,\bar{u}\gamma^5 c \qquad D^0 D^{*+} - D^{*0} D^+$$

$$\mathcal{O}_4 = \varepsilon^{ABC}\bar{u}(x)\gamma^B c(x)\,\bar{d}(x)\gamma^C c(x) \qquad D^{*0} D^{*+}$$

$$\mathcal{O}_5 = \varepsilon^{ABC}\bar{u}\gamma^B c\left[\vec{p} = \vec{0}\right]\,\bar{d}\gamma^C c \qquad D^{*0} D^{*+}$$

All operators O_i are projected onto the states with zero total momentum

We solve separately the generalized eigenvalue problem for two sets of operators

- $\mathcal{O}_1, \mathcal{O}_2, \mathcal{O}_3$
- $\mathcal{O}_2, \mathcal{O}_3, \mathcal{O}_4, \mathcal{O}_5$

Generalized eigenvalue problem (GEP)

We construct the correlator matrix

$$\mathcal{C}_{ij}(t) = \langle 0 | \mathcal{O}_i(t) \mathcal{O}_j^\dagger(0) | 0 \rangle$$

The spectrum of the states is extracted using the GEP

$$C(t)\psi = \lambda(t, t_0) C(t_0)\psi$$

It can be shown that the ordered eigenvalues satisfy

$$\lambda_\alpha(t, t_0) \sim e^{-E_\alpha(t-t_0)}$$

Luscher, Wolff Nucl.Phys. B339(1990)

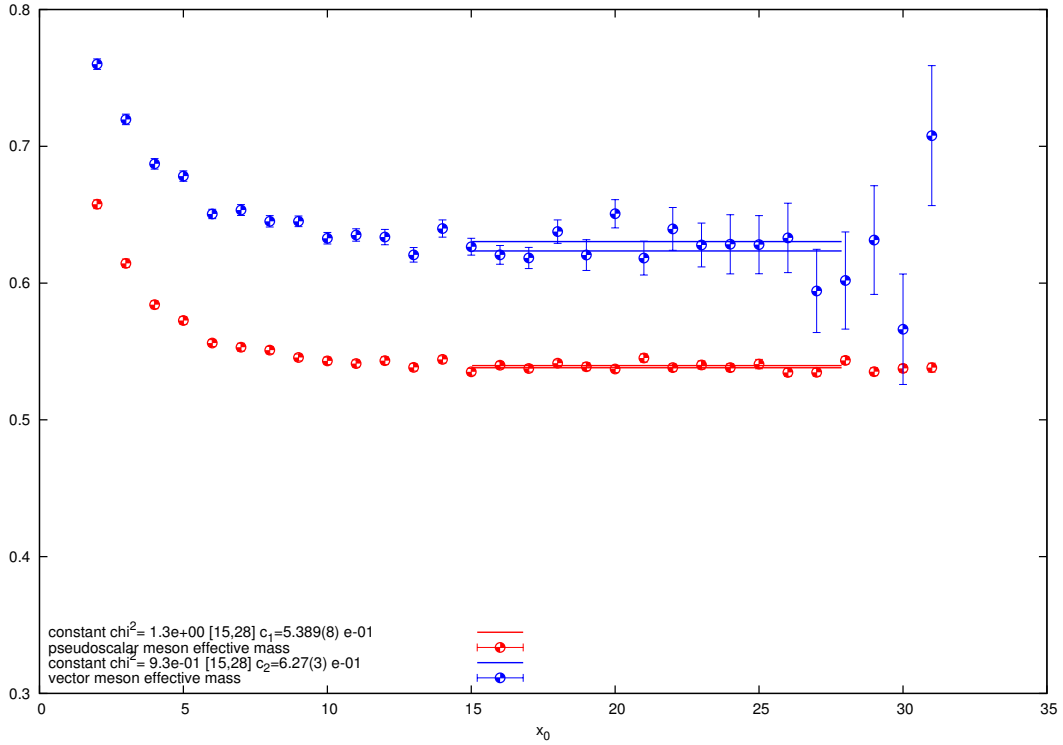
Each operator is doubled using a gaussian smearing (50 steps)

$$\frac{1+\alpha\Delta}{1+6\alpha}, \ \alpha = 0.5$$

Determination of thresholds

We solve a 2×2 GEP to determine the DD^* and D^*D^* thresholds

We use both pointlike and stochastic sources and perform the jackknife sum of the eigenvalues



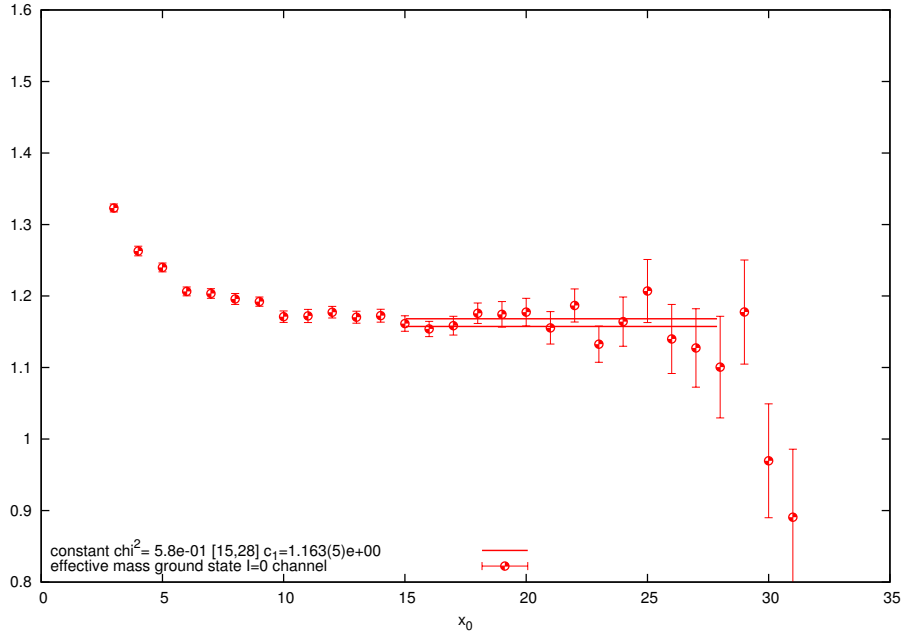
	thresholds in lattice units
DD^*	1.166(4)
$D(1)D^*(-1)$	1.230(4)
D^*D^*	1.254(7)
$D^*(1)D^*(-1)$	1.314(6)

$M(D) \sim 1420\,\text{MeV}$

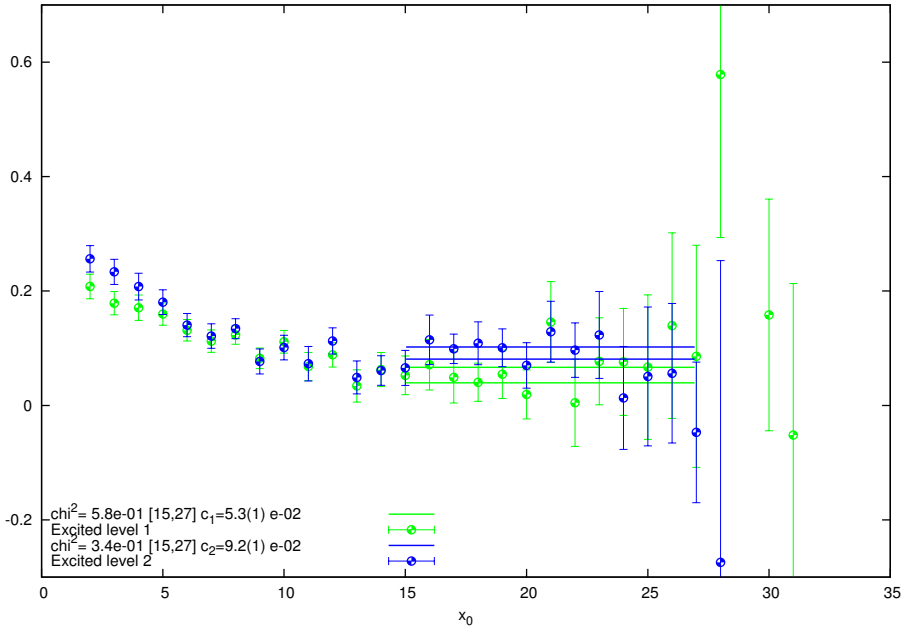
$M(D^*) \sim 1650\,\text{MeV}$

Heavy light sector with isospin $I = 0$

GEP with the operators $\mathcal{O}_1, \mathcal{O}_2, \mathcal{O}_3$



Effective mass of the ground state.

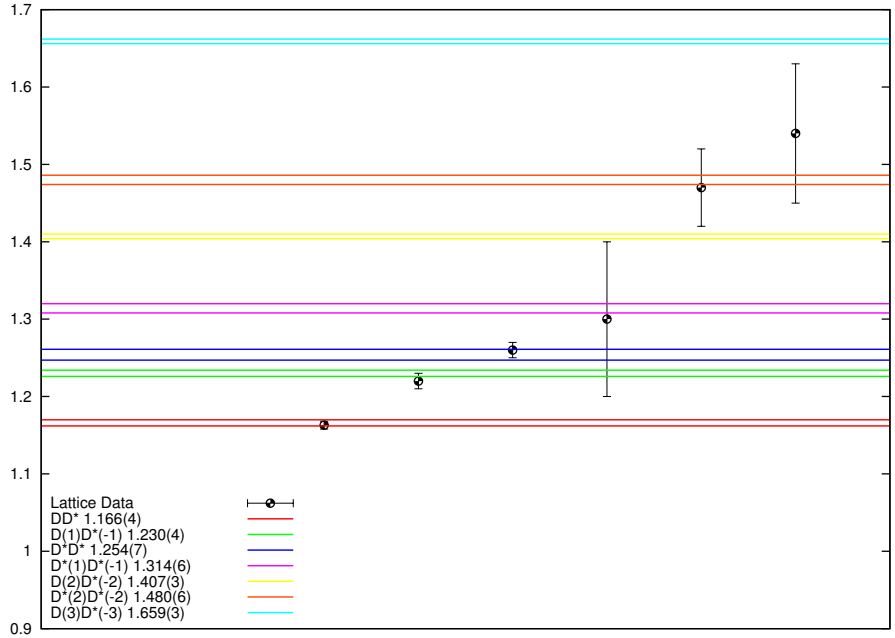


Mass splitting of the excited levels

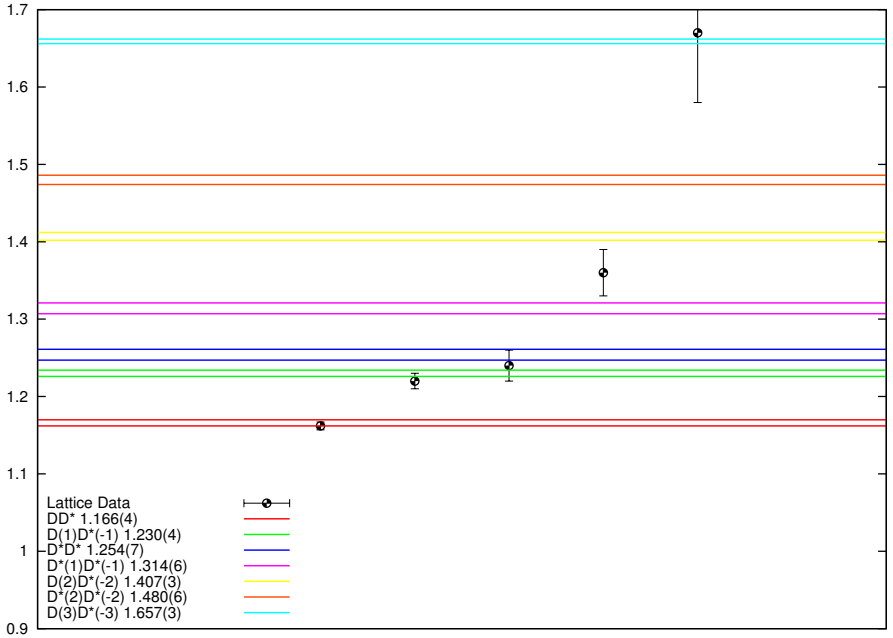
$$\Delta M_i = -\ln \frac{\lambda_i(t)\lambda_0(t-1)}{\lambda_i(t-1)\lambda_0(t)}$$

$I = 0$ spectrum

$\mathcal{O}_1, \mathcal{O}_2, \mathcal{O}_3$



$\mathcal{O}_2, \mathcal{O}_3, \mathcal{O}_4, \mathcal{O}_5$



The less accuracy in the second set of operators comes from the off diagonal elements between DD^* and D^*D^* operators

These contain a diagram which is zero at tree level

Interpolating operators I=1 channel

We consider a set of three operators in the $I = 1,\ J^P = 1^+$ channel

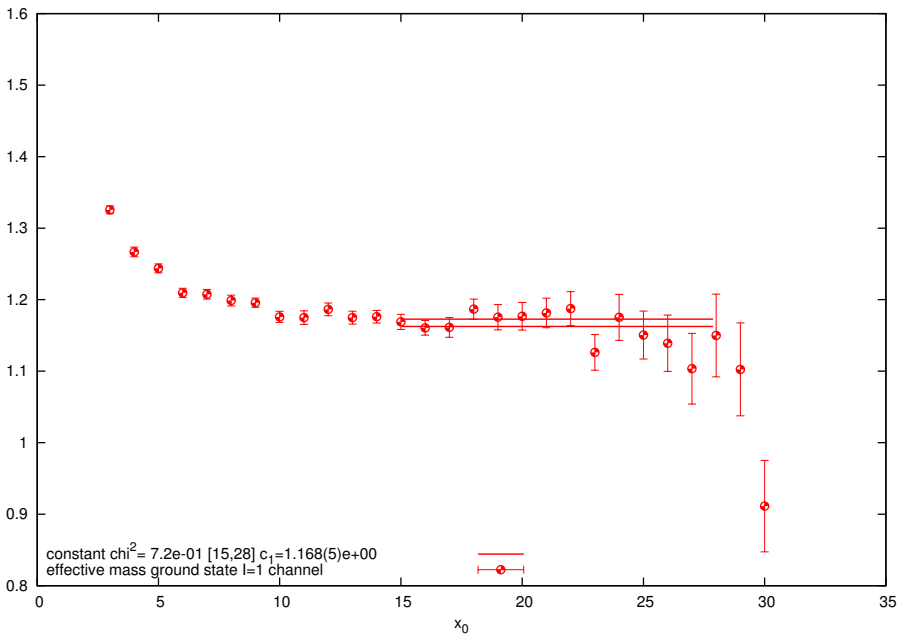
$$\mathcal{O}_1 = \varepsilon^{ijk}\varepsilon^{lmk}\bar{c}^i_c(x)\gamma^A c^j(x)\ \ (\bar{u}^l(x)\gamma^B d^m_c(x) + \bar{d}^l(x)\gamma^B u^m_c(x))\varepsilon^{ABC} \qquad \text{bad } \mathcal{T}^+$$

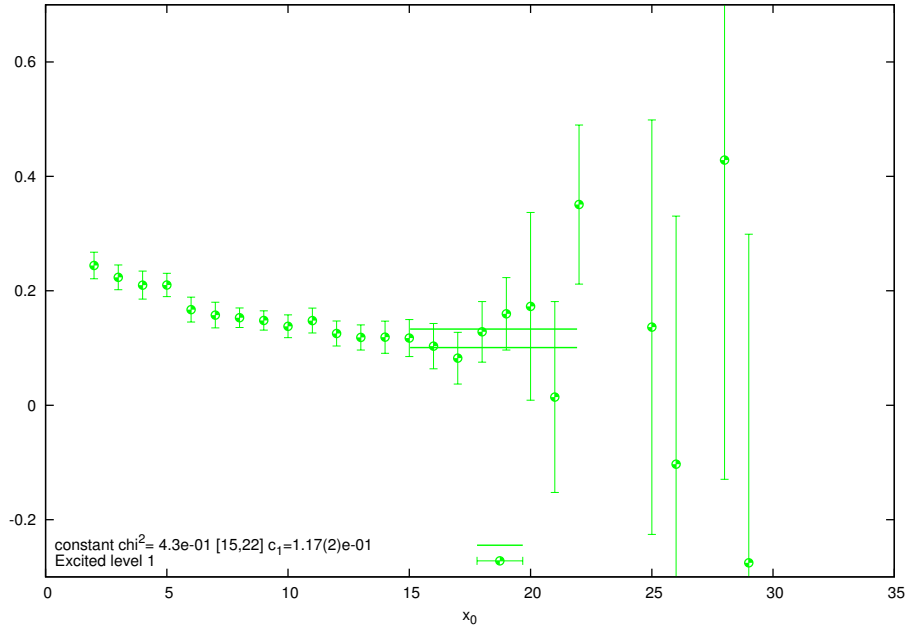
$$\mathcal{O}_2 = \bar{u}(x)\gamma^A c(x)\ \ \bar{d}(x)\gamma^5 c(x) + \bar{d}(x)\gamma^A c(x)\ \ \bar{u}(x)\gamma^5 c(x) \qquad D^0 D^{*+} + D^{*0} D^+$$

$$\mathcal{O}_3 = \bar{u}\gamma^A c\left[\vec{p} = \vec{0}\right]\ \bar{d}\gamma^5 c + \bar{d}\gamma^A c\left[\vec{p} = \vec{0}\right]\ \bar{u}\gamma^5 c \qquad D^0 D^{*+} + D^{*0} D^+$$

Heavy light sector with isospin $I = 1$

GEP with the operators $\mathcal{O}_1, \mathcal{O}_2, \mathcal{O}_3$





For a numerical comparison

$aM_{I=0} = 0.163(5)$

$aM_{I=1} = 0.168(5)$

First excited state

$aM_{exc1} = 0.128(2)$ above the D^*D^* threshold 1.254(7). In this channel we expect to see only DD^* levels

Conclusions

- We have set up a theoretical and lattice framework to study *QCD* states with four valence quarks
- We have studied the two channels $I = 0$ and $I = 1$ but no exotic states have been found
- Our analysis is incomplete and we plane to introduce operators with external momenta and to solve the *GEP* with a larger basis
- We plan to study in this framework also the channel $J^{PC} = 1^{+-}$ $I = 1$ with the $c\bar{c}$ as in Prelovsek *et al.* arXiv:1405.7623

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Thank you