Doubly charm tetraquark using meson-meson and diquark-antidiquark interpolators

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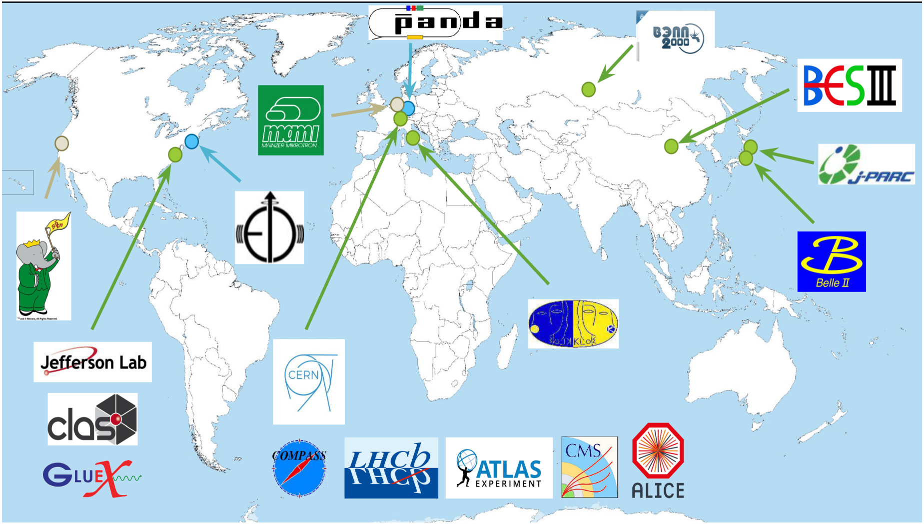
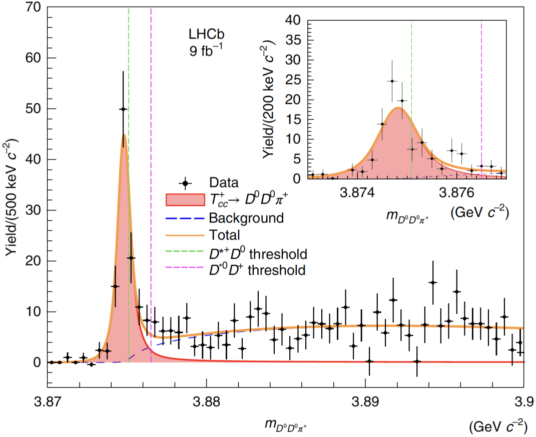


LHCb : Double-charm tetraquark T_{cc}^{+} $[\,cc\bar{u}\bar{d}\,]$

2021: Signal in $D^0D^0\pi^+$ just 0.4 MeV below D^0D^{*+} threshold. [1] [2]



$\Gamma = 410 \pm 165$ keV.

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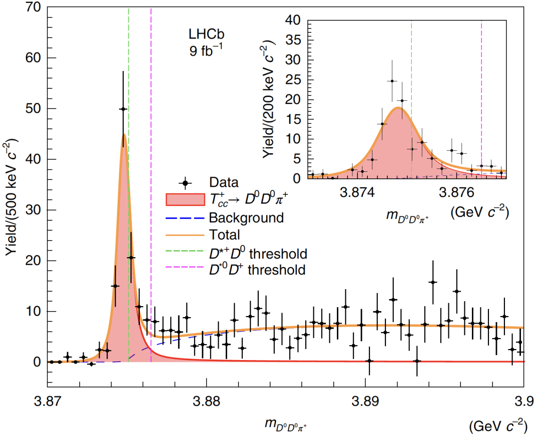

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From different models expected:

$I(J^P) = 0(1^+)$

Does this state exist in QCD?

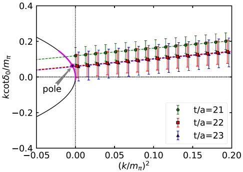
- What is its mass?
- Quantum numbers?

[1] R. Aaij *et al.* (LHCb Collaboration), Nature Physics **18**, 751 (2022). arXiv:2109.01038v4.

[2] R. Aaij *et al.* (LHCb Collaboration), Nature Communications **13**, 3351 (2022). arXiv:2109.01056v4.

Available lattice studies on T_{cc}^+, $J^P = 1^+$

HALQCD, 2302.04505, $m_\pi = 146$ **MeV**



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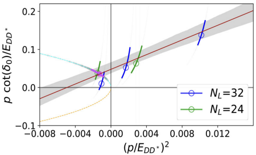

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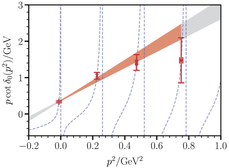

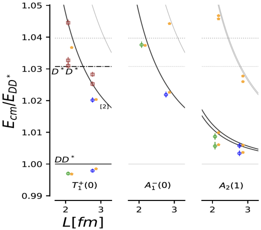

E_n obtained with $D(\vec{p}_1)D^*(\vec{p}_2)$ interpolators.
Scattering amplitude extracted via Lüsher eq.

$\Longleftarrow$

Adittional works [a] [b] [c]

[a] Hadspec et al. J. High Energ. Phys. 2017, 33 (2017).

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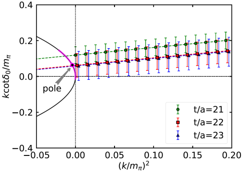

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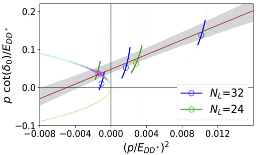

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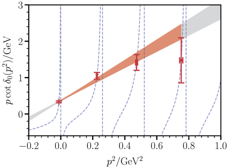

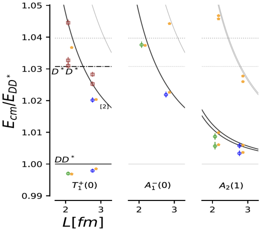

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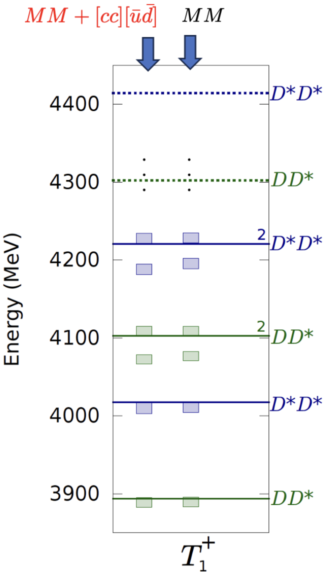
Is the T_{cc}^{+} basis with two-mesons sufficient?

Study of T_{cc}^{+} with $M(\vec{p}_1)M(\vec{p}_2) + [cc][\bar{u}\bar{d}]$

Hadspec collaboration[a]**:**

- $m_\pi = 391$ MeV, distillation.
- resulting spectrum found to be insensitive to addition of the $[cc][\bar{u}\bar{d}]$.
- Only total momentum $\vec{P} = 0$ employed.
- Energy shift of the ground state not resolved
- Scattering amplitude not extracted.



[a] Cheung, G.K.C., Thomas, C.E., Dudek, J.J. et al. J. High Energ. Phys. 2017, 33 (2017).

Present work

This work is a follow up of the study of T_{cc}^{+} with $M(\vec{p}_1)M(\vec{p}_2)$ interpolators [M. Padmanath, Prelovsek: 2202.10110, PRL], now adding also $[cc]_{\bar{3}_c}[\bar{u}\bar{d}]_{3_c}$ interpolators.

Simulation details:

- $N_f = 2+1$ CLS ensambles.
- $m_\pi \simeq 280\ MeV$
- Spatial lattice extent $N_L = 24, 32$
- a $\simeq 0.086$ fm

We employ two heavy quark masses m_Q for the system $QQ\bar{u}\bar{d}$ with $J^P = 1^+$, $I = 0$:

m$_Q \simeq m_c : m_D \simeq 1.931\, GeV \quad m_{D^*} \simeq 2.051\, GeV$

m$_Q \simeq m_{``b"} : m_{``B"} \simeq 4.042\, GeV \quad m_{``B^*"} \simeq 4.075\, GeV$

The heavier the quark mass is close the b quark mass.

$M(\vec{p}_1)M(\vec{p}_2)$ and $[cc]_{\bar{3}_c}[\bar{u}\bar{d}]_{3_c}$ interpolators within distillation

- Total momenta : $P = 0$ (irrep T_1^+), $P = 1$ (irrep A_2)
- Color singlet Meson-Meson interpolators $[\bar{u}c]_{1_c}[\bar{d}c]_{1_c}$

$$O^{D^{(*)}D^*}(\vec{p}_1, \vec{p}_2) = D^{(*)}(\vec{p}_1)D^*(\vec{p}_2) = \sum_{\vec{x}_1} \bar{u}^a_A(\Gamma_1)_{AB} e^{i\vec{p}_1\vec{x}_1} c^a_B \quad \sum_{\vec{x}_2} \bar{d}^b_C(\Gamma_2)_{CD} e^{i\vec{p}_2\vec{x}_2} c^b_D - \{u \leftrightarrow d\}, \qquad \mathbf{N_v^{MM} = 60}$$

Several operators

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- **Diquark-antidiquark interpolators** $[cc]_{\bar{3}_c}[\bar{u}\bar{d}]_{3_c}$

$$O^{4q}(\vec{P})=\sum_{\vec{x}}\epsilon_{abc}c^b_A(\vec{x})(C\gamma_i)_{AB}c^c_B(\vec{x}) \;\; \epsilon_{ade}\bar{u}^d_C(\vec{x})(C\gamma_5)_{CD}\bar{d}^e_D(\vec{x})e^{i\vec{P}\vec{x}}, \qquad \mathbf{N_v^{4q}=45}$$

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- Distillation method - all quarks fields are smeared $\longrightarrow$ spectral decomposition

$$q^b_A(\vec{x}) = \sum_{i=1}^{N_v} v_b^{(i)}(\vec{x})v_{\bar{b}}^{(i)\dagger}(\vec{y})q^{\bar{b}}_A(\vec{y}),$$

N_v is the **number of eigenvectors**

$M(\vec{p}_1)M(\vec{p}_2)$ and $[cc]_{\bar{3}_c}[\bar{u}\bar{d}]_{3_c}$ interpolators within distillation

Tensors (in distillation space) needed to compute correlators:

- MM : single meson kernel

$$\phi^{ij}(\vec{p}) = \sum_{\vec{x}} \sum_{c} v_c^{(i)}(\vec{x}) v_c^{(j)}(\vec{x}) e^{i\vec{p}\vec{x}}.$$

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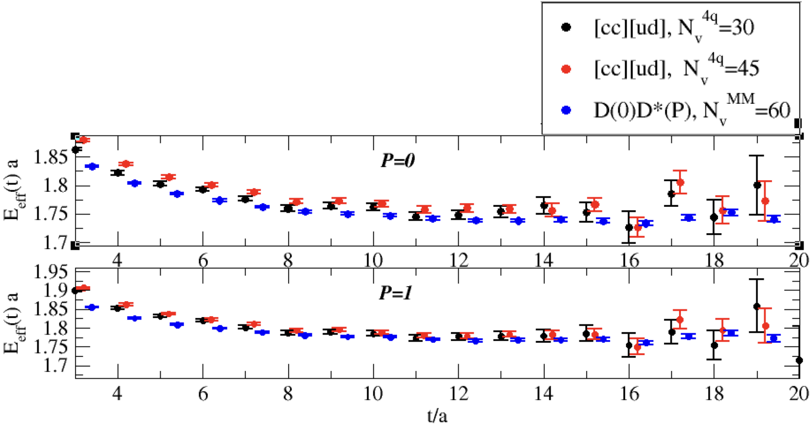
- $4q$: kernel for compact tetraquark $[cc]_{\bar{3}_c}[\bar{u}\bar{d}]_{3_c}$

$$\phi^{jklm}(\vec{p}) = \sum_{\vec{x}} \sum_{abcde} \epsilon_{abc}\epsilon_{ade} v_c^{(j)}(\vec{x}) v_c^{(k)}(\vec{x}) v_c^{(l)}(\vec{x})^\dagger v_c^{(m)}(\vec{x})^\dagger e^{i\vec{p}\vec{x}}.$$

- Costly summation over distillation indices for $4q \Longrightarrow$ we employ $N_v^{4q} < N_v^{MM}$.

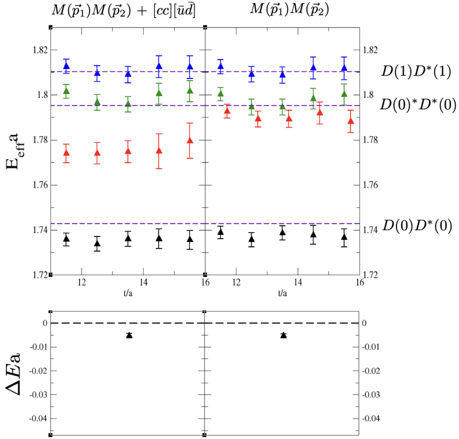
Effective masses of the diagonal correlators, dependence on N_v



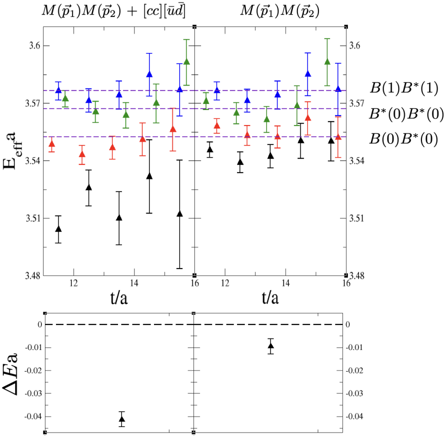
Effective energies for $\vec{P}=0$ (irrep T_1^+)

$O^{4q}: [cc]_{\bar{3}_c}[\bar{u}\bar{d}]_{3_c}$ $\quad$ $O^{MM}: D(0)D^*(0)$
$D(1)D^*(-1)|_{l=0}$
$D(1)D^*(-1)|_{l=2}$
$D^*(0)D^*(0)$

$c-$quark



"b" $-$ quark $\quad$ "B"



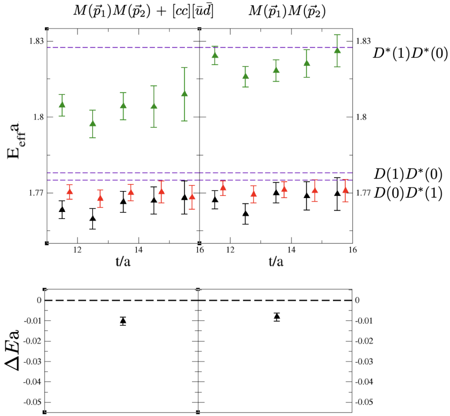
Effective energies for $\vec{P} = 1$ (irrep A_2)

$O^{4q} : [cc]_{\bar{3}_c}[\bar{u}\bar{d}]_{3_c}$ $\quad O^{MM} : D(0)D^*(1)$

$D(1)D^*(0)$

$D^*(1)D^*(0)$

$c -$ quark



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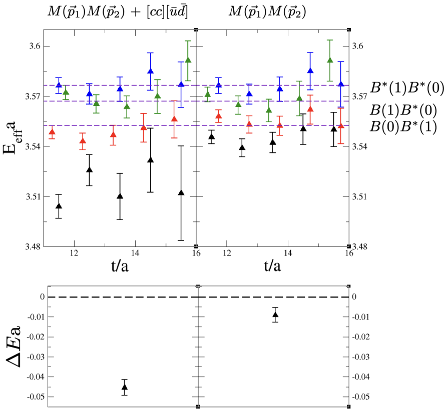

Conclusions

- Obtaining the scattering amplitude from correlators based on the $M(\vec{p}_1)M(\vec{p}_2) + [cc][\bar{u}\bar{d}]$ interpolators. Studying the dependence of the spectrum as well as the scattering amplitude and pole position on different heavy quark masses m_Q.
- In both studied irreps, with $\vec{P} = 0$ and $\vec{P} = 1$, the ground state does not move significantly when diquark-anti-diquark interpolators are included for charm quarks.
- However, for a heavy quark mass close to the bottom sector, there is a significant energy shift of approximately $90\ MeV$ in favor of the basis with diquark-antidiquark, as expected for the b quark sector.
- Computational cost of the diquark-anti-diquark operators increases significantly with N_v. Smaller N_v chosen for O^{4q} compared to O^{MM}.
- Analyze the contribution of the left hand cuts from the one pion exchange on the pole extraction of the doubly charm tetraquark.

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