Evidence for the charged charmonium-like state Z_c^+ from lattice QCD

based on arXiv:1405.7623

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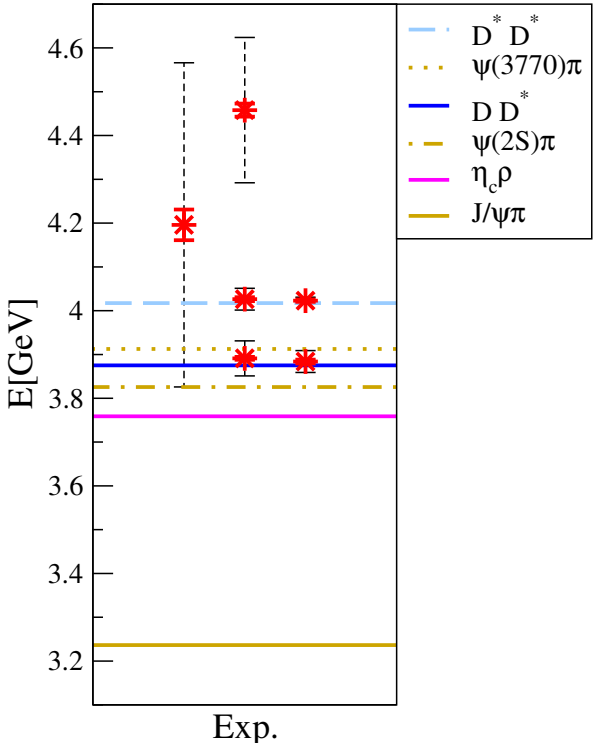
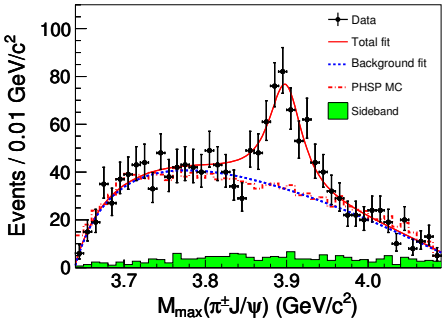
- $\bar{q}q$ mesons?
- experiments: **two c's and charge**
- Z_c^+ not found in first principle studies (yet)
- can such a state exist within QCD?

[Brambilla et al., 1404.3723]

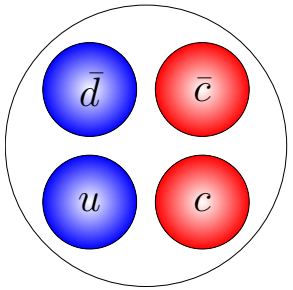
particle	C	J^P	decay	collab.
$Z^+(4430)$	-1	1^+	$\psi(2S)\pi^+$	Belle[08], LHCb[14]
$Z_c^+(3900)$	-1	$?^?$	$J/\psi\pi^+$	BESIII[13], Belle[13], CLEO-c[13]
$Z_c^+(3885)$	-1	1^+	$(DD^*)^+$	BESIII[13]
$Z_c^+(4020)$	-1	$?^?$	$h_c(1P)\pi^+$	BESIII[13]
$Z_c^+(4025)$	-1	$?^?$	$(D^*D^*)^+$	BESIII[13]
$Z^+(4200)$	-1	1^+	$J/\psi\pi^+$	Belle[14] @ Moriond14

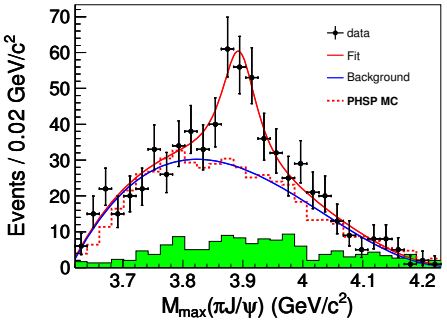


$$Z_c^+ \to J/\psi \ \ \pi^+$$



BESIII, 1303.5949 PRL, $Z_c^+(3900)$





Belle, 1304.0121 PRL, $Z_c^+(3900)$

Introduction
outline

- gauge ensemble and methods
- the expected spectrum in $I^G(J^{PC}) = 1^+(1^{+-})$
- interpolators
- wick contractions
- results
- conclusion

Previous studies of Z_c^+

no candidate so far...

[Prelovsek, LL, 1308.2097 PLB]:

- focused on region below 4GeV
- no additional state
- no considerable energy shifts

[Y. Chen et al.,1403.1318 PRD]:

- DD^* scattering in $J^{PC} = 1^{+-}$
- extracted near threshold parameters
- they claim no candidate found
- see previous talk by L.Liu

- poster by c. DeTar @Poster Session

Gauge ensemble
...and a bit about the methods

ensemble provided by A. Hasenfratz (Thank you)
[Hasenfratz et al., 0805.2369 PRD, 0806.4586 PRD]

- $N_f = 2$ clover-wilson quarks
- $m_\pi = 266(4) MeV$
- $a = 0.1239(13) fm$
- $16^3 \times 32$
- $L \approx 2fm$ (advantage!)

Distillation method
[Peardon et al., 0905.2160 PRD]:

- smeared sources (64 or 32 laplacian eigenvectors)
- all-to-all method (not really needed)
- propagators $\rightarrow$ perambulators
- additionally ϕ matrices (contains all interpolator structure)

Fermilab method for charm quarks
[El-Khadra et al., hep-lat/9604004 PRD]:

- $m_{s.a.} = \frac{1}{4}(m_{\eta_c} + 3m_{J/\psi})$
- discretization errors suppressed in $E_n - m_{s.a.}$
- use $E_n - m_{s.a.}^{latt} + m_{s.a.}^{phys}$

Simulate $I^G(J^{PC}) = 1^+(1^{+-})$ *channel to study* Z_c^+.

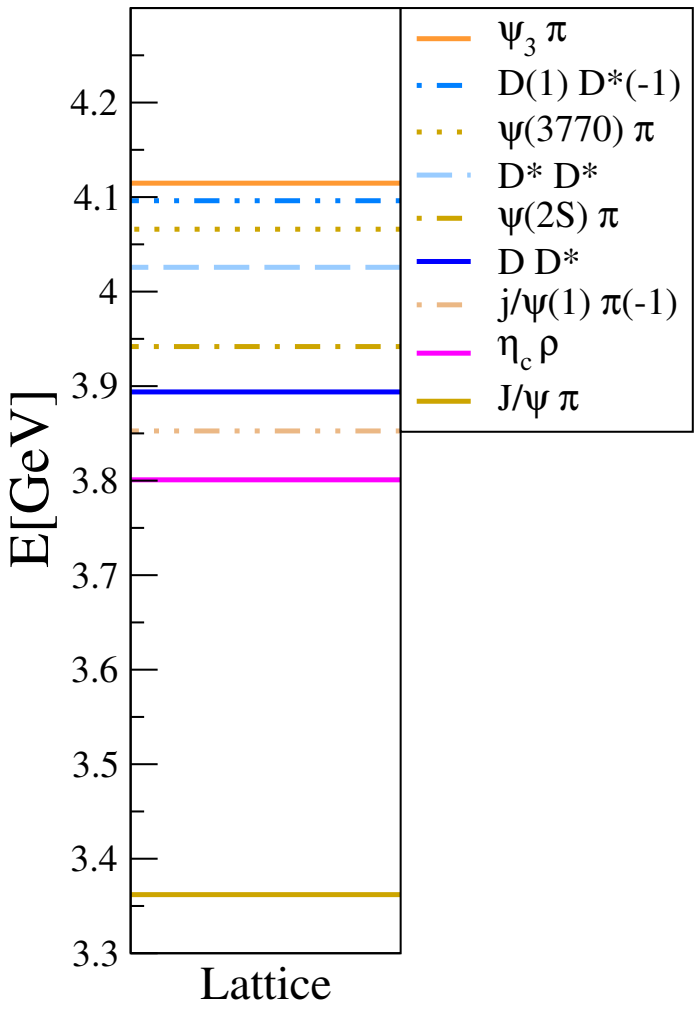
- all states with given quantum numbers appear
- various two meson states appear
- resonances/bound states appear as additional states

- Z_c^+ should appear near its physical mass
- scattering states appear near

$$E_{ni} = E_1(\tfrac{2\pi}{L}\,\vec{n}) + E_2(\tfrac{2\pi}{L}\,\vec{n})$$

Focus on specific energy region and simulate all states within.

Energy eigenstates
$I^G(J^{PC}) = 1^+(1^{+-})$ channel



!many states!

Many open channels and many relevant scattering states in FV below 4.3 GeV:

- $J/\psi\pi$ like:
  - $J/\psi[0]\pi[0]$
  - $J/\psi[1]\pi[-1]$
  - $\psi(2S)[0]\pi[0]$
  - $\psi(3770)[0]\pi[0]$
  - $\psi_{3^{--}}[0]\pi[0]$
- $\eta_c\rho$
- DD^*:
  - $D[0]D^*[0]$
  - $D[1]D^*[-1]$
- D^*D^*

3^{--} state appears in the T_1^{--} irrep (no PDG $J = 3$ charmonium)

Interpolators
scattering interpolators

$$
\left.
\begin{aligned}
\mathcal{O}_1 &= \bar{c}\gamma_i c[0]\ \bar{d}\gamma_5 u[0] \\
\mathcal{O}_2 &= \bar{c}\gamma_i\gamma_t c[0]\ \bar{d}\gamma_5 u[0] \\
\mathcal{O}_3 &= \bar{c}\overleftarrow{\nabla}_j\gamma_i\overrightarrow{\nabla}_j c[0]\ \bar{d}\gamma_5 u[0] \\
\mathcal{O}_4 &= \bar{c}\overleftarrow{\nabla}_j\gamma_i\gamma_t\overrightarrow{\nabla}_j c[0]\ \bar{d}\gamma_5 u[0] \\
\mathcal{O}_5 &= |\epsilon_{ijk}||\epsilon_{klm}|\ \bar{c}\gamma_j\overleftarrow{\nabla}_l\overrightarrow{\nabla}_m c[0]\ \bar{d}\gamma_5 u[0] \\
\mathcal{O}_6 &= |\epsilon_{ijk}||\epsilon_{klm}|\ \bar{c}\gamma_t\gamma_j\overleftarrow{\nabla}_l\overrightarrow{\nabla}_m c[0]\ \bar{d}\gamma_5 u[0] \\
\mathcal{O}_7 &= R_{ijk}Q_{klm}\ \bar{c}\gamma_j\overleftarrow{\nabla}_l\overrightarrow{\nabla}_m c[0]\ \bar{d}\gamma_5 u[0] \\
\mathcal{O}_8 &= R_{ijk}Q_{klm}\ \bar{c}\gamma_t\gamma_j\overleftarrow{\nabla}_l\overrightarrow{\nabla}_m c[0]\ \bar{d}\gamma_5 u[0] \\
\mathcal{O}_9 &= \sum_{e_k=\pm e_{x,y,z}} \bar{c}\gamma_i c[e_k]\ \bar{d}\gamma_5 u[-e_k]
\end{aligned}
\right\}\ [\bar{c}\Gamma_1 c]_{1_c}\ [\bar{d}\Gamma_2 u]_{1_c}\quad J/\psi\pi\text{-like}
$$

$$
\mathcal{O}_{10} = \bar{c}\gamma_5 c[0]\ \bar{d}\gamma_i u[0]\quad\Big\}\ [\bar{c}\Gamma_1 c]_{1_c}\ [\bar{d}\Gamma_2 u]_{1_c}\quad \eta_c\rho
$$

$$
\left.
\begin{aligned}
\mathcal{O}_{11} &= \bar{c}\gamma_5 u[0]\ \bar{d}\gamma_i c[0] \\
\mathcal{O}_{12} &= \bar{c}\gamma_5\gamma_t u[0]\ \bar{d}\gamma_i\gamma_t c[0] \\
\mathcal{O}_{13} &= \bar{c}\gamma_5 u[1]\ \bar{d}\gamma_i c[-1]
\end{aligned}
\right\}\ [\bar{c}\Gamma_1 u]_{1_c}\ [\bar{d}\Gamma_2 c]_{1_c}\quad DD^*
$$

$$
\mathcal{O}_{14} = \epsilon_{ijk}\bar{c}\gamma_j u[0]\ \bar{d}\gamma_k c[0]\quad\Big\}\ [\bar{c}\Gamma_1 u]_{1_c}\ [\bar{d}\Gamma_2 c]_{1_c}\quad D^*D^*
$$

Interpolators
diquark interpolators

$$\mathcal{O}_{15} = N_L^3\ \epsilon_{abc}\epsilon_{ab'c'}(\bar{c}_b C\gamma_5 \bar{d}_c\ c_{b'}\gamma_i C u_{c'} - \bar{c}_b C\gamma_i \bar{d}_c\ c_{b'}\gamma_5 C u_{c'}) \quad \}\ [\bar{c}\Gamma_1\bar{d}]_{3_c}\ [c\Gamma_2 u]_{\bar{3}_c}$$

$$\mathcal{O}_{16} = N_L^3\ \epsilon_{abc}\epsilon_{ab'c'}(\bar{c}_b C\bar{d}_c\ c_{b'}\gamma_i\gamma_5 C u_{c'} - \bar{c}_b C\gamma_i\gamma_5 \bar{d}_c\ c_{b'} C u_{c'}) \quad \}\ [\bar{c}\Gamma_1\bar{d}]_{3_c}\ [c\Gamma_2 u]_{\bar{3}_c}$$

$$\left.\begin{aligned}\mathcal{O}_{17} &= \mathcal{O}_{15}\\ \mathcal{O}_{18} &= \mathcal{O}_{16}\end{aligned}\right\} Nv = 32$$

Note: operators implement well within the distillation method.

4q interpolators are very different than scattering interpolators
[Jaffe, hep-ph/0409065 PR]

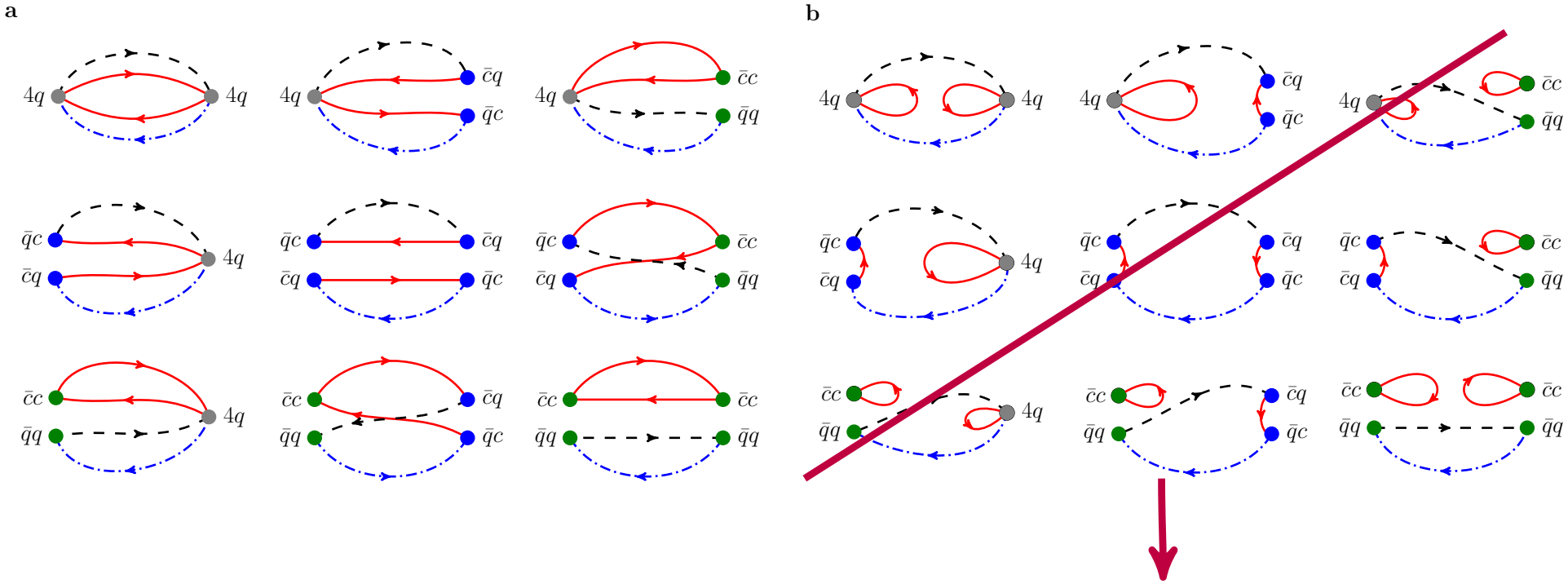
- $\mathcal{O}_{15}$ is combination of "good" and "bad" positive parity diquarks
- $\epsilon_{abc}\bar{c}_b C\gamma_5 \bar{d}_c$ has $J^P = 0^+$
- $\epsilon_{abc}\bar{c}_b C\gamma_i \bar{d}_c$ has $J^P = 1^+$
- symmetrize to get good $\mathcal{C}$!

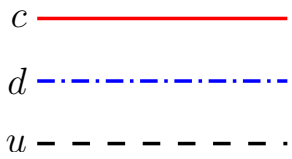
- $\mathcal{O}_{16}$ is combination of negative parity diquarks
- $\epsilon_{abc}\bar{c}_b C\bar{d}_c$ has $J^P = 0^-$
- $\epsilon_{abc}\bar{c}_b C\gamma_i\gamma_5 \bar{d}_c$ has $J^P = 1^-$
- symmetrize to get good $\mathcal{C}$!

Note: π has γ_5 and negative parity. Similar diquark with γ_5 has positive parity!

Wick contractions
3×3 flavor structure matrix

All possible wick contractions for Z_c^+:





- (Okuba-Zweig-Iizuka) suppressed
- couples to light states

Analysis

- create correlator matrix:

$$C_{ij}(t) = \langle \Omega | \mathcal{O}_i(t_{src}) \mathcal{O}_j(t_{src} + t) | \Omega \rangle$$
$$C_{ij}(t) = \sum_n Z_i^n Z_j^{*n} e^{-E_n t}$$

  - E_n is the discrete energy of the n-th state
  - if resonance, E_n is approximate mass
  - Z_i^n tells us composition of n-th state

- solve the GEVP:

$$C(t)\vec{u}(t) = \lambda(t) C(t_0) \vec{u}(t)$$

- and determine E_n from eigenvalues

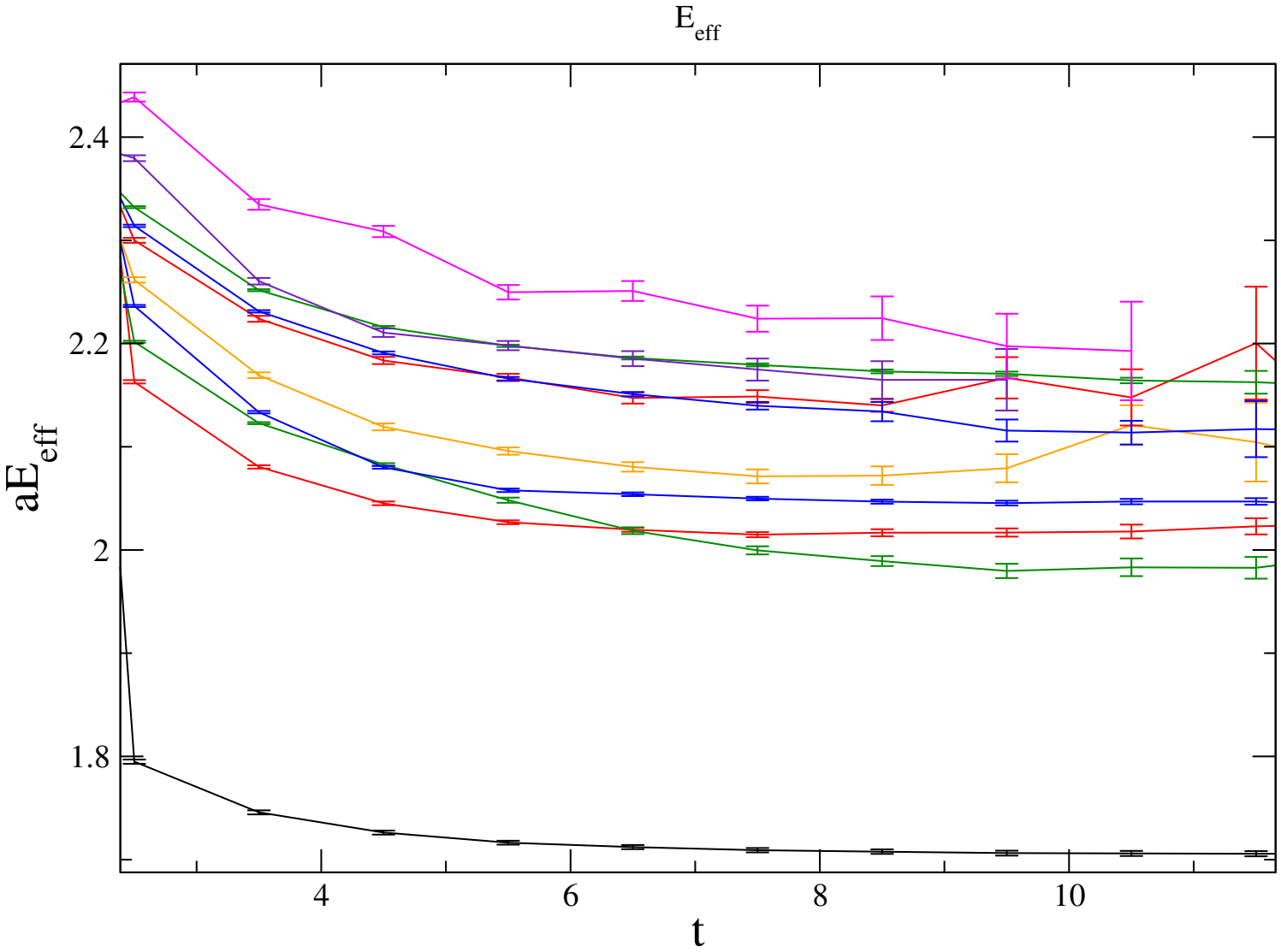
$$\lambda(t) \propto e^{-E_n t}$$

- observe the spectrum and identify with variation of basis
- determine Z_i^n

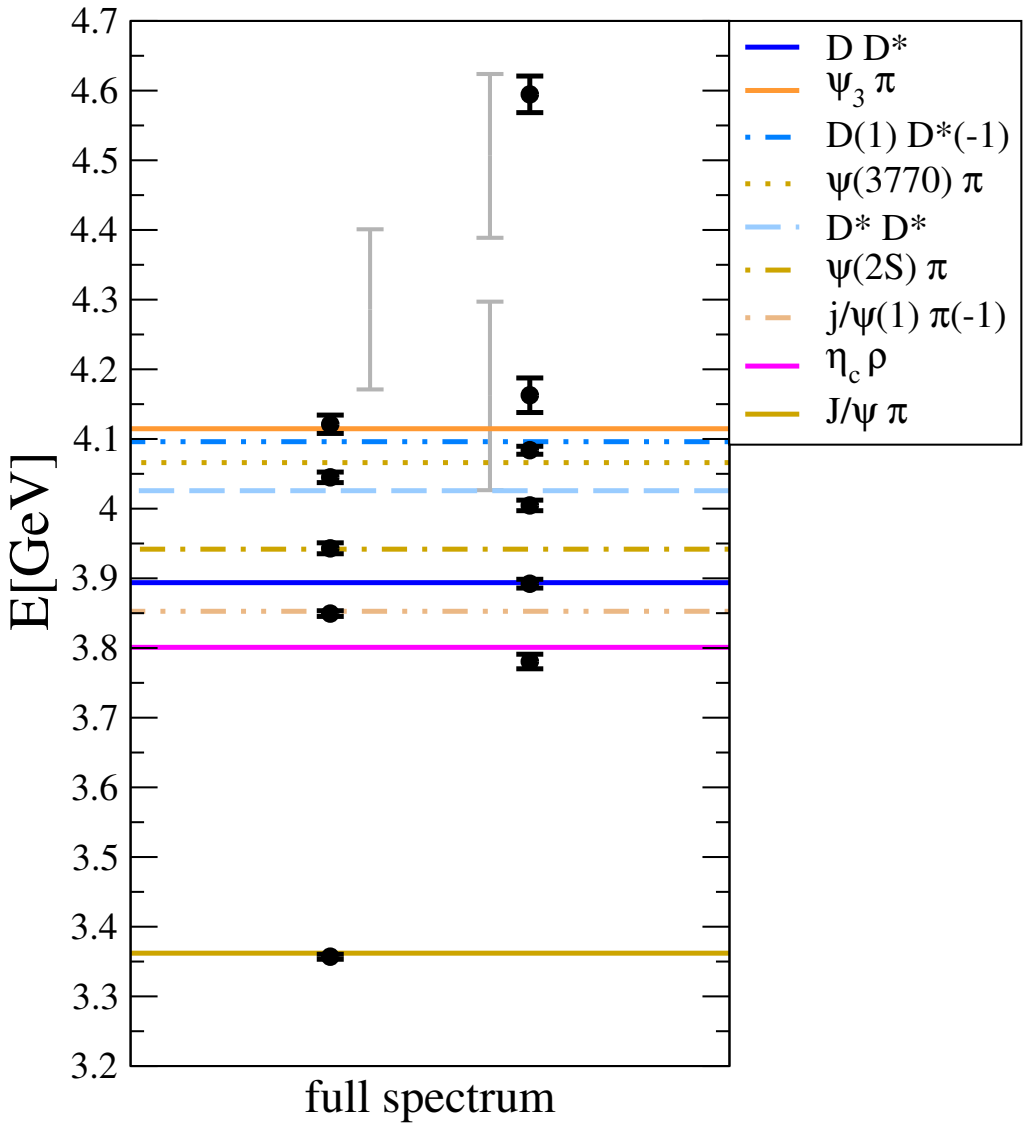
$$Z_i^n(t) = e^{E_n t/2} \frac{|C_{ij}(t) \vec{u}_j{}^n(t)|}{|C^{1/2}(t) \vec{u}^{\,n}(t)|}$$

- Z_i^n gives overlap of i-th operator to the n-th state
- confirm or improve identification
- determine state composition

Results
effective masses

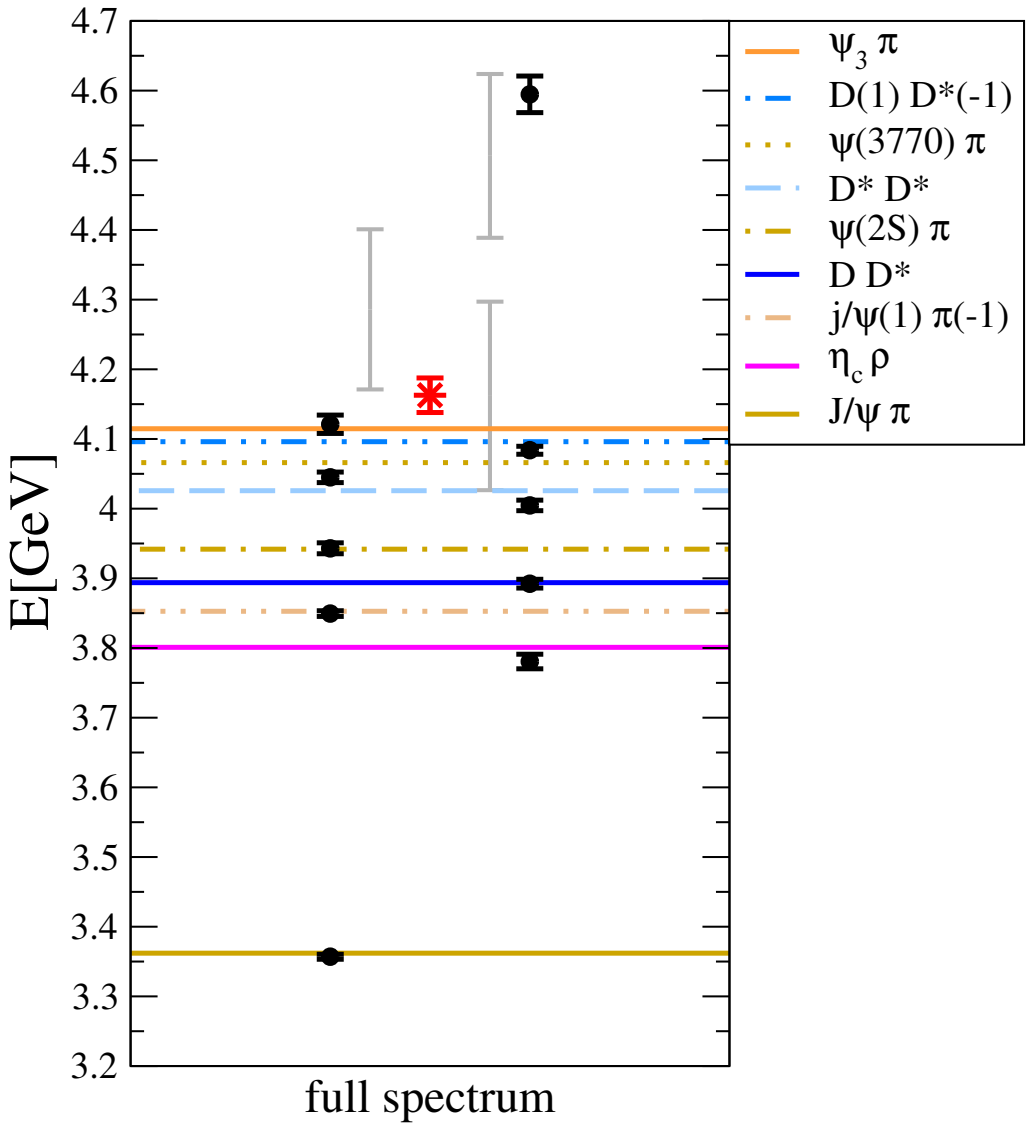


Results
the full result - spectrum



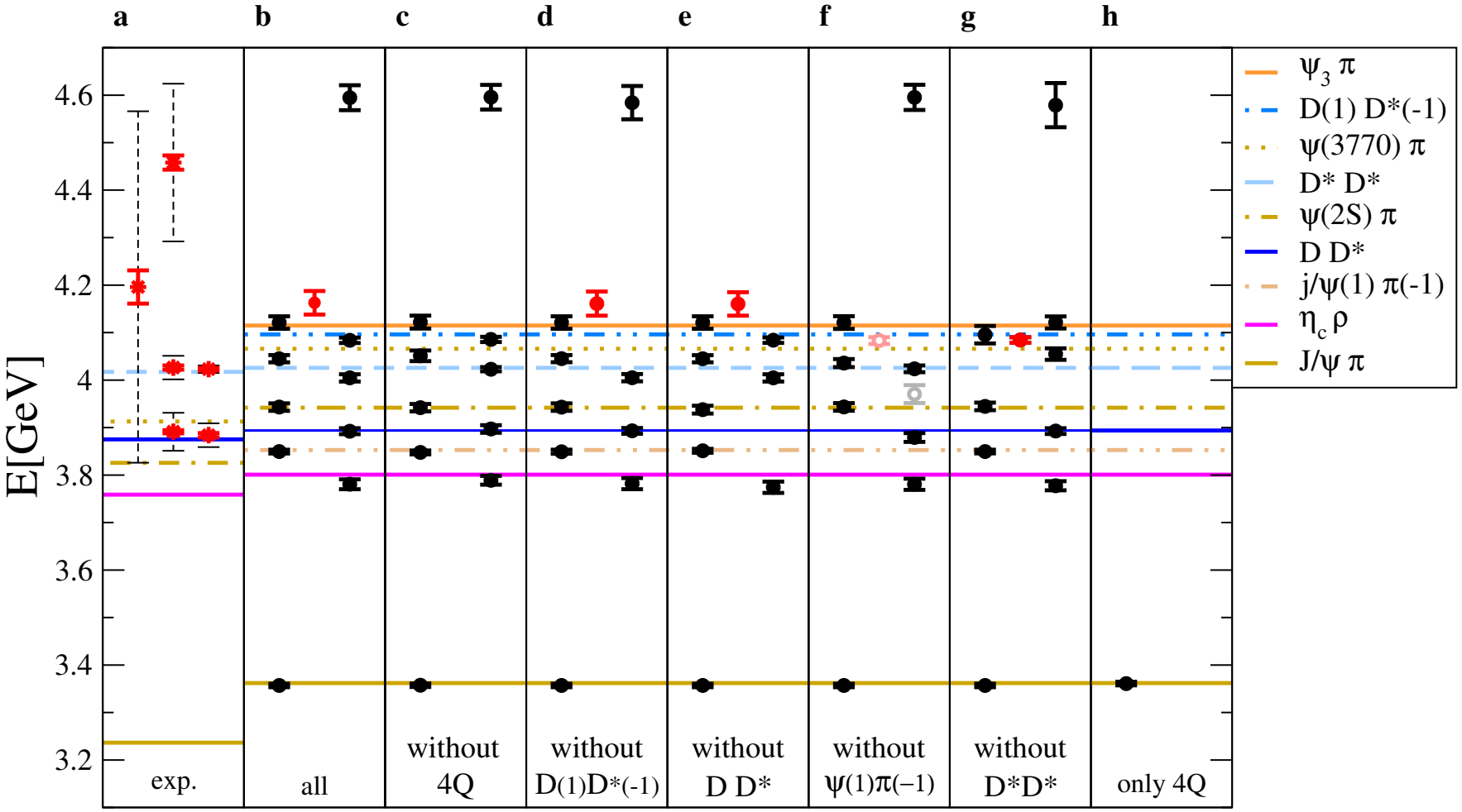
- 18×18 correlator matrix spectrum
- some states less reliable than others
- black dots: fits from simulation
- lines: non-interacting levels
- expected: 9 energy levels below 4.3GeV
- seen: more!
- candidates for additional state

Results
the full result - a candidate

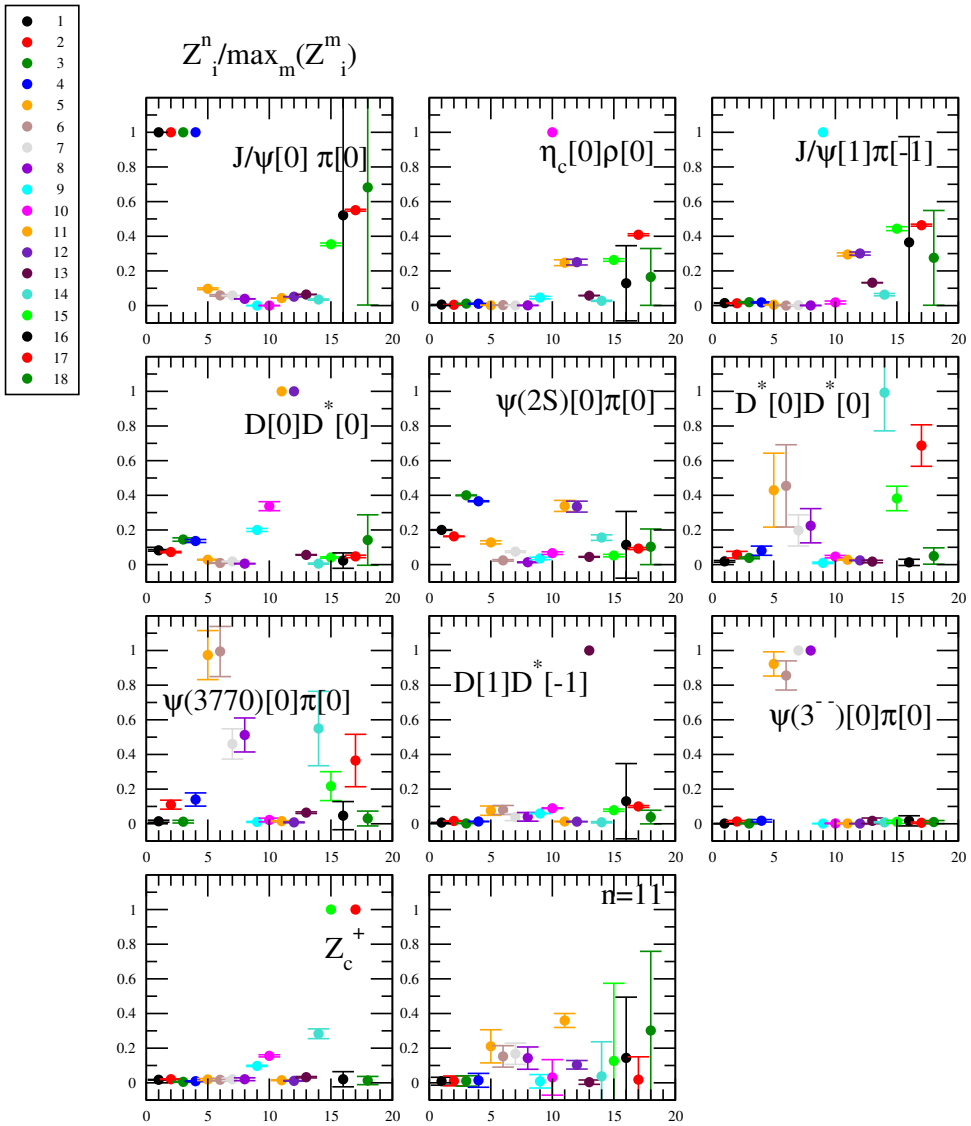


- scattering states
- additional state!
- red star: Z_c^+
- arguments: basis variation + Zfcators

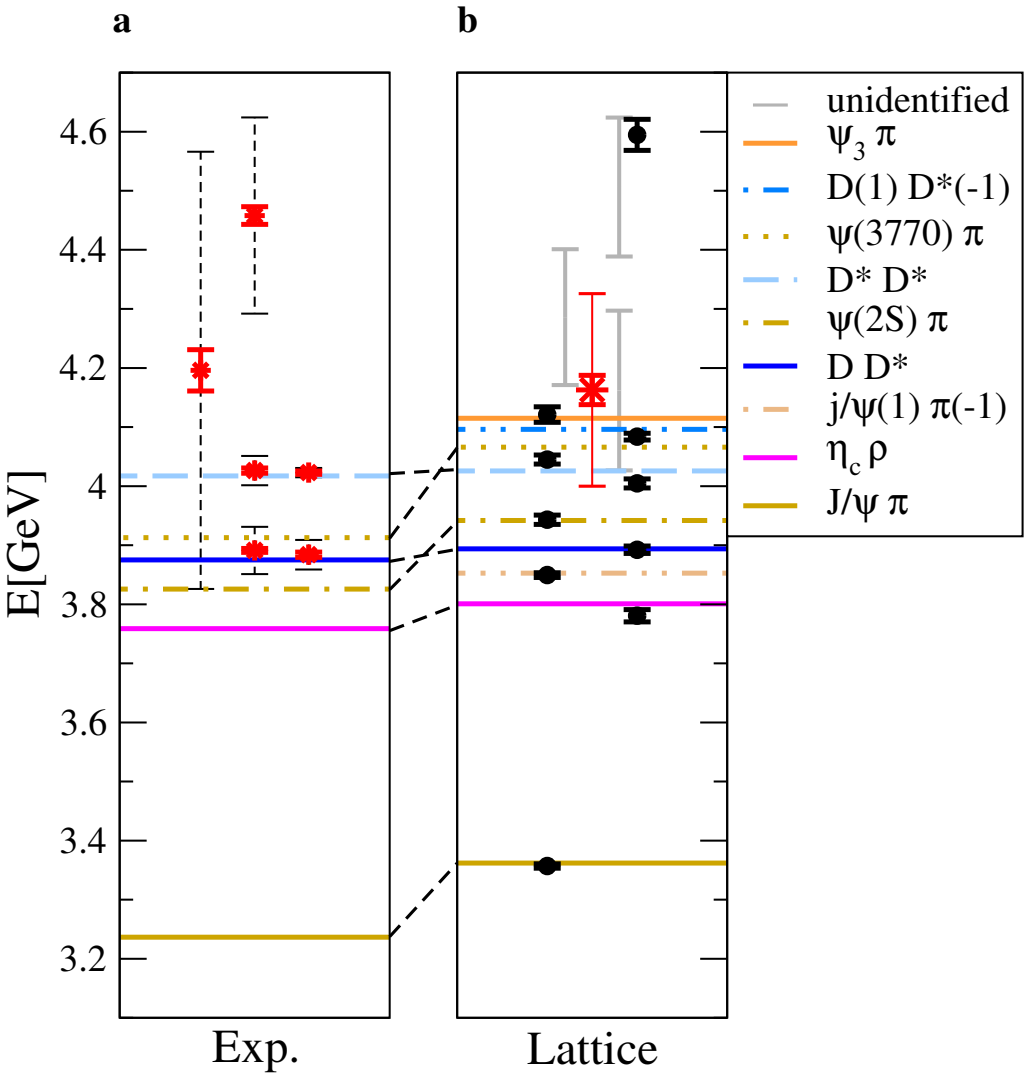
Results
identification of states - basis variation

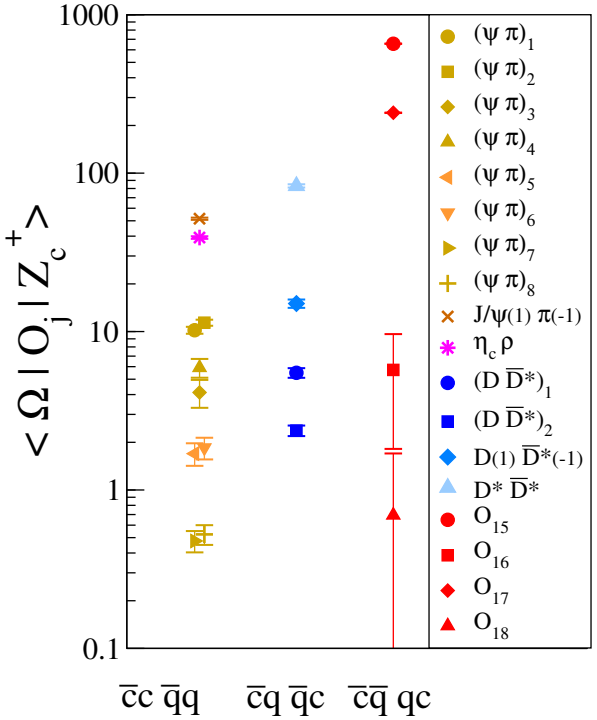


Results
identification of states - Zfactor composition



- this work [S. Prelovsek, C.B. Lang, LL, D. Mohler, 1405.7623]
- overlaps of states to operators
- confirmed identification
- Z_c^+ has dominant contributions from $\mathcal{O}_{15}$ and $\mathcal{O}_{17}$





- $E_n = 4.16 \pm 0.03 \pm 0.16 \pm \mathcal{O}(\Gamma_{Z_c^+})$ GeV

$Z_c(4020)$ $\Gamma = 7.9 \pm 3.7$ *MeV*, *[BESIII 2013]*
$Z_c(4025)$ $\Gamma = 24.8 \pm 9.5$ *MeV*, *[BESIII 2013]*
$Z_c(4200)$ $\Gamma = 370 \pm 110$ *MeV*, *[Belle @ Moriond 2014]*

Results
Rigorous treatment - difficult

- inelastic scattering
- extremely difficult to extract scattering parameters
- Lüscher-type analysis requires multiple volumes
- large volumes ($L = 2\text{fm}+$) have very dense scattering levels ($p = \frac{2\pi}{L}$)
- rigorous treatment predicts additional state!

Conclusion
...something to take away

- when simulating: include "exotic" interpolators!
- Z_c^+ is exotic
- Z_c^+ exists within QCD
- $m_{Z_c^+} = 4.16 \pm 0.16 \pm \mathcal{O}(\Gamma_{Z_c^+})$ GeV

THE END

Thank you for your attention :)