X(3872) and Y(4140) using diquark-antidiquark operators with lattice QCD

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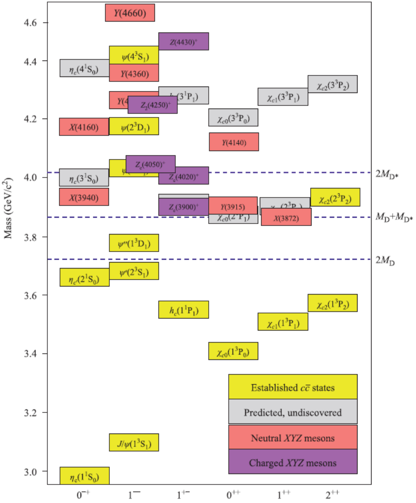
- PRD XX XXXXXX, arXiv:1503.03257

Charmonium spectrum to be explored

- Established states
  Predicted, undiscovered
  Neutral XYZ mesons
  Charged XYZ mesons
- Single hadron treatment : reliable for states well below threshold. Levels near and above the open charm thresholds questionable.
- Require rigorous multi-channel calculations considering possibility of strong decay.
- Aim : The importance of tetraquark Fock components in established lattice candidate for X(3872), and search signals for other XYZ with $J^{PC} = 1^{++}$.

S. L. Olsen, arXiv:1411.7738v1 [hep-ex]



XYZs near open flavor threshold

N. Brambilla, *et al.*, arXiv:1404.3723v2

TABLE 10: Quarkonium-like states at the open flavor thresholds. For charged states, the C-parity is given for the neutral members of the corresponding isotriplets.

State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [810, 1030] (>10), BaBar [1031] (8.6)	2003	Ok
				$p\bar{p} \to (\pi^+\pi^- J/\psi)\ldots$	CDF [1032, 1033] (11.6), D0 [1034] (5.2)	2003	Ok
				$pp \to (\pi^+\pi^- J/\psi)\ldots$	LHCb [1035, 1036] (np)	2012	Ok
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	Belle [1037] (4.3), BaBar [1038] (4.0)	2005	Ok
				$B \to K(\gamma\, J/\psi)$	Belle [1039] (5.5), BaBar [1040] (3.5)	2005	Ok
					LHCb [1041] (> 10)		
				$B \to K(\gamma\, \psi(2S))$	BaBar [1040] (3.6), Belle [1039] (0.2)	2008	NC!
					LHCb [1041] (4.4)		
				$B \to K(D\bar{D}^*)$	Belle [1042] (6.4), BaBar [1043] (4.9)	2006	Ok
$Z_c(3885)^+$	3883.9 ± 4.5	25 ± 12	1^{+-}	$Y(4260) \to \pi^-(DD^*)^+$	BES III [1044] (np)	2013	NC!
$Z_c(3900)^+$	3891.2 ± 3.3	40 ± 8	$?^{?-}$	$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BES III [1045] (8), Belle [1046] (5.2)	2013	Ok
					T. Xiao *et al.* [CLEO data] [1047] (>5)		
$Z_c(4020)^+$	4022.9 ± 2.8	7.9 ± 3.7	$?^{?-}$	$Y(4260, 4360) \to \pi^-(\pi^+ h_c)$	BES III [1048] (8.9)	2013	NC!
$Z_c(4025)^+$	4026.3 ± 4.5	24.8 ± 9.5	$?^{?-}$	$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BES III [1049] (10)	2013	NC!
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(10860) \to \pi(\pi\Upsilon(1S, 2S, 3S))$	Belle [1050–1052] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [1051] (16)	2011	Ok
				$\Upsilon(10860) \to \pi^-(B\bar{B}^*)^+$	Belle [1053] (8)	2012	NC!
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(10860) \to \pi^-(\pi^+\Upsilon(1S, 2S, 3S))$	Belle [1050, 1051] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [1051] (16)	2011	Ok
				$\Upsilon(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle [1053] (6.8)	2012	NC!

XYZs above open charm threshold

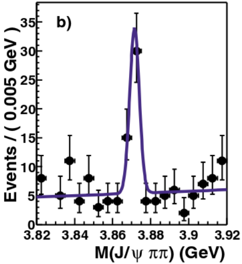
N. Brambilla, *et al.*, arXiv:1404.3723v2

TABLE 12: Quarkonium-like states above the corresponding open flavor thresholds. For charged states, the C-parity is given for the neutral members of the corresponding isotriplets.

State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$Y(3915)$	3918.4 ± 1.9	20 ± 5	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [1088] (8), BaBar [1038, 1089] (19)	2004	Ok
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [1090] (7.7), BaBar [1091] (7.6)	2009	Ok
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [1092] (5.3), BaBar [1093] (5.8)	2005	Ok
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle [1086, 1087] (6)	2005	NC!
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle [1046, 1094] (7.4)	2007	NC!
$\psi(4040)$	4039 ± 1	80 ± 10	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)}(\pi))$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1095] (6.0)	2013	NC!
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1096] (5.0), BaBar [1097] (1.1)	2008	NC!
$Y(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1098] (5.0), Belle [1099] (1.9), LHCb [1100] (1.4), CMS [1101] (>5) D0 [1102] (3.1)	2009	NC!
$\psi(4160)$	4153 ± 3	103 ± 8	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)})$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1095] (6.5)	2013	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle [1087] (5.5)	2007	NC!
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1103] (7.2)	2014	NC!
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1096] (5.0), BaBar [1097] (2.0)	2008	NC!
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \to (\pi\pi J/\psi)$	BaBar [1104, 1105] (8), CLEO [1106, 1107] (11) Belle [1046, 1094] (15), BES III [1045] (np)	2005	Ok
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar [1105] (np), Belle [1046] (np)	2012	Ok
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BES III [1045] (8), Belle [1046] (5.2)	2013	Ok
				$e^+e^- \to (\gamma X(3872))$	BES III [1108] (5.3)	2013	NC!
$Y(4274)$	4293 ± 20	35 ± 16	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1098] (3.1), LHCb [1100] (1.0), CMS [1101] (>3), D0 [1102] (np)	2011	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [1109] (3.2)	2009	NC!

Experimental facts : X(3872)

- first observed in Belle 2003 (Belle : PRL 96, 262001.)
- Quantum numbers, $J^{PC} = 1^{++}$: (LHCb : PRL 110, 222001.)
- Appears within 1 MeV below $D^0 \bar{D}^{*0}$ threshold.



- Preferred strong decay modes $D^0 \bar{D}^{*0}$, $J/\psi\ \omega$ and $J/\psi\ \rho$
- The isospin still uncertain
  - * nearly equal branching fraction to $J/\psi\ \omega$ and $J/\psi\ \rho$ decays.
  - * No charge partner candidates observed.

Experimental facts : Y(4140)

- first observed in $B^+ \to K^+ \phi J/\psi$ decays (CDF : PRL 102, 242002)
- LHCb did not observe such peaks in these decays.
  (LHCb : Aaij, et al., PRD 85, 091103).
- CMS confirmed the observation of the peak
  (Chatrchyan, et al., PLB 734, 261).
- Results from BaBar have much less statistical significance
  (Lees, et al., 91, 012003).
- Quantum numbers not determined except for $C = +$.
- Appears $\sim$30 MeV above $D_s \bar{D}_s^*$ threshold.
- Preferred strong decay mode $J/\psi\ \phi$.
  Not observed in $D^0 \bar{D}^{*0}$ or $J/\psi\ \omega$.

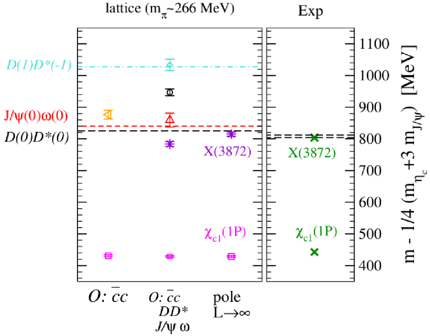
Lattice we use

Lattice size	N_f	N_{cfgs}	m_π [MeV]	a [fm]	L [fm]
$16^3 \times 32$	2	280	266(3)(3)	0.1239(13)	1.98

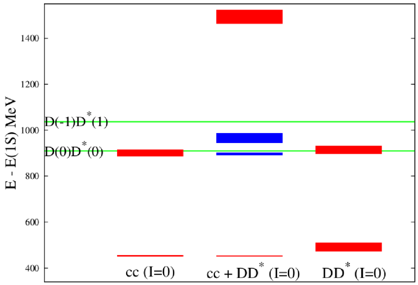
Hasenfratz et al. PRD 78, 054511 (2008), PRD 78, 014515 (2008)

- dynamical u, d and valence u, d, s : clover Fermions
- Fermilab treatment for charm quarks.
- m_s set using $[M(\phi)]_{lat} = [M(\phi)]_{exp}$.
- m_c set using $[M_2(\eta_c) + 3M_2(J/\psi)]_{lat} = [M_2(\eta_c) + 3M_2(J/\psi)]_{lat}$.
- "Distilled" quark sources for all flavors.
- Advantages of small lattice extension :
  Full distillation,
  relatively less number of scattering levels.

An X(3872) candidate from lattice



Prelovsek, Leskovec, PRL 111, 192001



Lee, DeTar, Mohler, Na, arXiv:1411.1389

- Studies with two-meson operators : First hint for a candidate
- Both calculations neglects charm annihilation
- Observed only when both $\bar{c}c$ and $\bar{D}^*D$ are used.
- Vastly different systematics, yet results are similar.

Interpolators we use

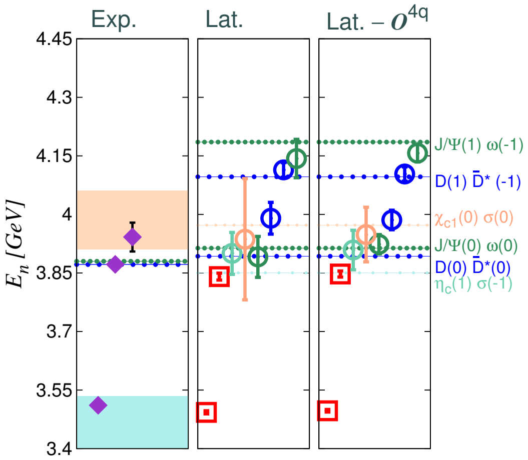
N	$I=0$	$I=1$
$O^{\bar{c}c}_{1-8}$	$\bar{c}\ \hat{\Gamma}\ c$	does not couple
O^{MM}_{9}	$D(0)\bar{D}^*(0)$	$D(0)\bar{D}^*(0)$
O^{MM}_{10}	$J/\psi(0)\omega(0)$	$J/\psi(0)\rho(0)$
O^{MM}_{11}	$D(1)\bar{D}^*(-1)$	$D(1)\bar{D}^*(-1)$
O^{MM}_{12}	$D(0)\bar{D}^*(0)$	$D(0)\bar{D}^*(0)$
O^{MM}_{13}	$J/\psi(0)\omega(0)$	$J/\psi(0)\rho(0)$
O^{MM}_{14}	$J/\psi(1)\omega(-1)$	$J/\psi(1)\rho(-1)$
O^{MM}_{15}	$\eta_c(1)\sigma(-1)$	$\eta_c(1)a_0(-1)$
O^{MM}_{16}	$\chi_{c1}(1)\eta(-1)$	$\chi_{c1}(1)\pi(-1)$
O^{MM}_{17}	$\chi_{c1}(0)\sigma(0)$	$\chi_{c1}(0)a_0(0)$
O^{MM}_{18}	$\chi_{c0}(1)\eta(-1)$	$\chi_{c0}(1)\pi(-1)$
O^{4q}_{19-20}	$[\bar{c}\bar{q}]_{3_c}[cq]_{\bar{3}_c}$	$[\bar{c}\bar{u}]_{3_c}[cd]_{\bar{3}_c}$
O^{4q}_{21-22}	$[\bar{c}\bar{q}]_{\bar{6}_c}[cq]_{6_c}$	$[\bar{c}\bar{u}]_{\bar{6}_c}[cd]_{6_c}$

Two meson scattering levels $\lesssim$ 4.2 GeV

- $I=0$; $\bar{c}c(\bar{u}u+\bar{d}d)$
  $D(0)\bar{D}^*(0)$, $J/\psi(0)\omega(0)$,
  $D(1)\bar{D}^*(-1)$, $J/\psi(1)\omega(-1)$,
  $\eta_c(1)\sigma(-1)$, $\chi_{c1}(0)\sigma(0)$.
- $I=1$; $\bar{c}c\bar{u}d$
  $D(0)\bar{D}^*(0)$, $J/\psi(0)\rho(0)$,
  $D(1)\bar{D}^*(-1)$, $J/\psi(1)\rho(-1)$,
  $\chi_{c1}(1)\pi(-1)$, $\chi_{c0}(1)\pi(-1)$.
- $I=0$; $\bar{c}c\bar{s}s$
  $D_s(0)\bar{D}_s^*(0)$, $J/\psi(0)\phi(0)$,
  $D_s(1)\bar{D}_s^*(-1)$, $J/\psi(1)\phi(-1)$,

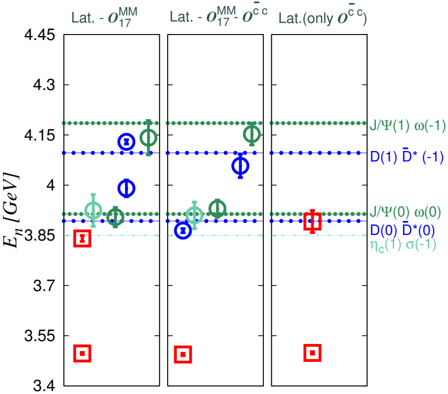
- $\bar{c}\ \hat{\Gamma}\ c$: as listed in table X of Mohler et al., PRD 87, 034501, arXiv:1208.4059.
- Assumption : Interpolators of $I=0$; $\bar{c}c\bar{s}s$ have negligible coupling with two-meson levels in $I=0$; $\bar{c}c(\bar{u}u+\bar{d}d)$
- charm annihilation not considered : OZI suppression.

$I = 0 : \bar{c}c(\bar{u}u + \bar{d}d)$



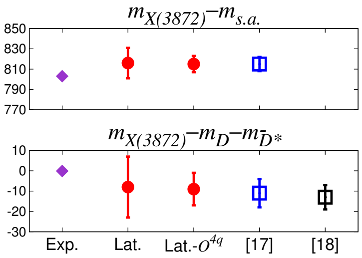
- No significant effects in the low lying spectrum by the inclusion of diquark-antidiquark operators.
- $[\bar{c}\bar{u}]_{\bar{\mathcal{G}}}[cu]_{\mathcal{G}}$ operators related to two-meson operators by Fierz relations.
- Makes the interpretation as a pure tetraquark unlikely.
- Simulation still unphysical in many ways. Sizable lattice artifacts.
- However, gives a qualitative picture.

X(3872) candidate



- O^{MM}_{17} : $\chi_{c1}(0)\sigma(0)$
- Without $\bar{c}c$ interpolators, signal doesn't appear.
- Both $\bar{c}c$ combinedly determine the position of the signal for the candidate.
- No significant effects on the levels identified as $J/\psi\omega$ or $\eta_c(1)\sigma(-1)$.

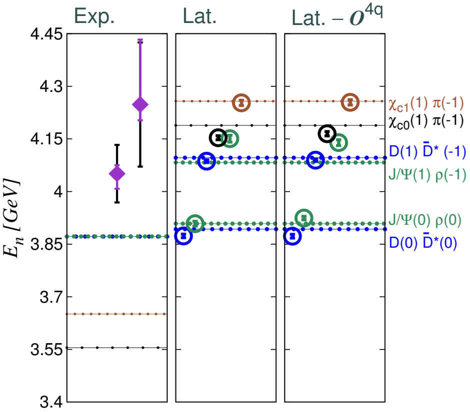
X(3872) candidate



Lat. & Lat. - O^{4q} : This work
[17]: Prelovsek and Leskovec, PRL 111, 192001
[18]: Lee, et al., arXiv:1411.1389

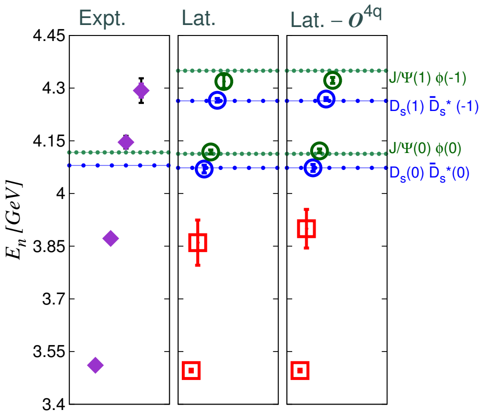
- δ for levels 2 and 5 using Lüscher's formulae :
  $p.cot(\delta(p)) = \frac{2\ Z_{00}(1;q^2)}{\sqrt{\pi}L}$
- Phase shift near threshold interpolated using effective range approximation
  $p.cot(\delta(p)) = \frac{1}{a_0} + \frac{1}{2} r_0 p^2$.
- Large negative scattering length, $a_0 = -1.7(4) fm$, agrees with a shallow bound state.
  Sasaki and Yamazaki, PRD 74, 114507
- Infinite volume bound state position from pole in the resulting scattering matrix.
- No significant effects from O^{4q}.

$I = 1 : \bar{c}c\bar{u}d$



- All levels identified with various scattering levels.
- No additional candidate observed.
- No charge partner for X(3872) observed.
- Simulation assumes $m_u = m_d$. Popular interpretations based on isospin breaking. Simulations with $m_u \neq m_d$ required for confirmation.

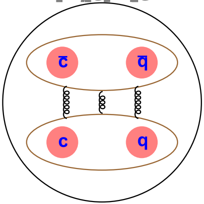
$I = 0 : \bar{c}c\bar{s}s$



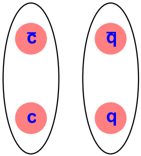
- All levels identified with various scattering levels.
- Candidates for χ_{c1} and X(3872) observed. No additional candidate observed.
- No effect observed with the inclusion of diquark-antidiquark operators.
- No candidate for Y(4140) in 1^{++}. (J^P is not known for Y(4140))

Fierz relations

$[\bar{c}\bar{q}]_G[cq]_G$



Mesons



- $[\bar{c}\bar{q}]_{\bar{\mathcal{G}}}[cq]_{\mathcal{G}}$ and two-meson operators are linearly related.

$$O^{4q}(x) = \sum F_i \; M_1^i(x) \; M_2^i(x)$$

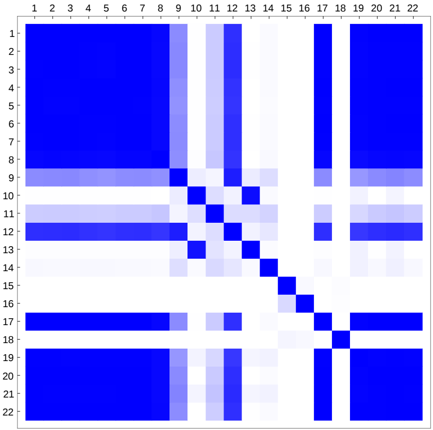
- After appropriate Fierz rearrangement

$$\begin{aligned} O^{4q} &= [\bar{c}\ C\gamma_5\ \bar{u}]_{\mathcal{G}}[c\ \gamma_i C\ u]_{\mathcal{G}} + [\bar{c}\ C\gamma_i\ \bar{u}]_{\mathcal{G}}[c\ \gamma_5 C\ u]_{\mathcal{G}} \\ &= \mp\frac{(-1)^i}{2}\{\ (\bar{c}\ \gamma_5\ u)(\bar{u}\ \gamma_i\ c) -\ (\bar{c}\ \gamma_i u)(\bar{u}\ \gamma_5\ c) \\ &\quad + (\bar{c}\ \gamma^\nu\gamma_5\ u)(\bar{u}\ \gamma_i\gamma_\nu\ c)|_{i\neq\nu}\ -\ (\bar{c}\ \gamma_i\gamma_\nu\ u)(\bar{u}\ \gamma^\nu\gamma_5\ c)|_{i\neq\nu}\} \\ &\quad + \frac{(-1)^i}{2}\{\ (\bar{c}\ c)(\bar{u}\ \gamma_i\gamma_5\ u) +\ (\bar{c}\ \gamma_i\gamma_5\ c)(\bar{u}\ u) \\ &\quad - (\bar{c}\ \gamma^\nu c)(\bar{u}\ \gamma_i\gamma_\nu\gamma_5\ u)|_{i\neq\nu}\ -\ (\bar{c}\ \sigma^{\alpha\beta}\ c)(\bar{u}\ \sigma_{\alpha\beta}\gamma_i\gamma_5\ u)|_{i\neq(\alpha<\beta)}\} \end{aligned}$$

where $\mathcal{G}$ could be 3_c or 6_c.

- Any gauge-covariant quark smearing preserves this relation.

Fierz relations



- The time averaged normalized ensemble averaged correlation matrix.

$$\tilde{\mathcal{C}}_{ij} = \frac{1}{9}\sum_{t=2}^{10} \frac{\bar{\mathcal{C}}_{ij}(t)}{\sqrt{\bar{\mathcal{C}}_{ii}(t)\bar{\mathcal{C}}_{jj}(t)}}$$

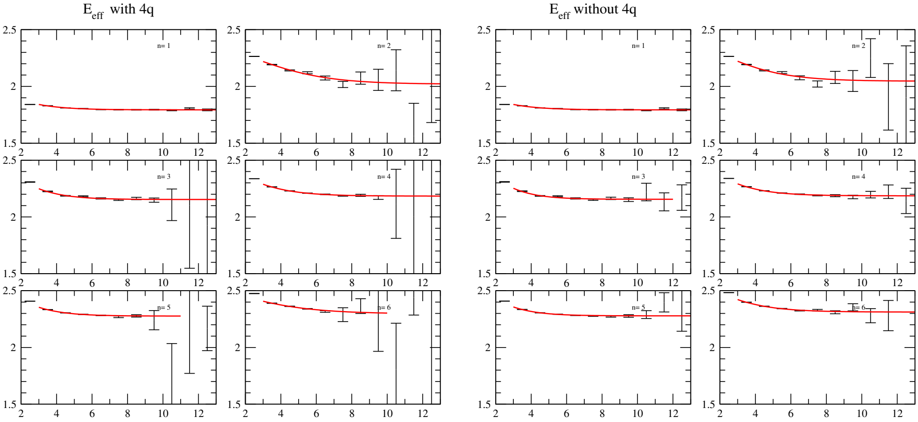
- Strong correlations with two-meson operators and $\bar{c}c$ operators.

- $O_{1-8} \sim \bar{c}c$
  $O_{9,11,12} \sim \bar{D}^* D$
  $O_{10,13-18} \sim HL$
  $O_{19-22} \sim [\bar{c}\bar{q}]_{\bar{\mathcal{G}}}[cq]_{\mathcal{G}}$

Conclusions

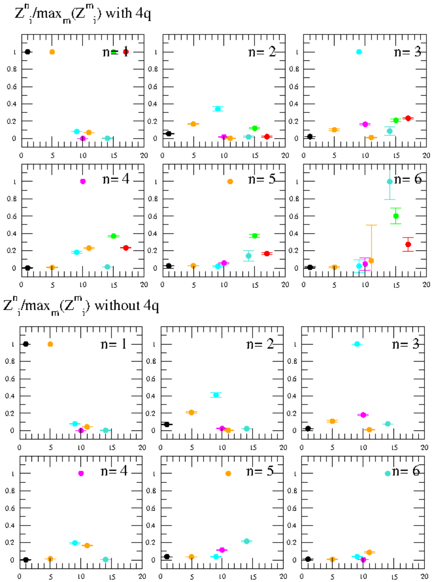
- A first dynamical study of 1^{++} channel with diquark-antidiquark operators looking for possible exotic candidates has been made.
- Diquark-antidiquark operators are found to have no significant effects on the low lying spectrum.
- A candidate for X(3872) found below the lattice $\bar{D}^* D$ non-interacting level. The infinite volume bound state position from an amplitude analysis shows no effect from the diquark-antidiquark operators.
- No additional candidates observed hinting an exotic signal or a charge partner for X(3872).
- $I = 0$, $\bar{c}c\bar{s}s$: All energy levels identified with various scattering levels. No candidate for Y(4140) observed.
- Outlook : Better O^{4q} interpolators to be invented.
  Rigorous calculations involving coupled channel effects :
  Extraction of coupled channel S-matrix.
  Calculations on lattices with better systematics.
  Simulations with $m_u \neq m_d$ for isospin breaking effects.

Level counting : E_{eff}



Compare effective masses to see correspondence between the basis.

Level counting : the overlaps



- Identify the dominant overlaps from Z_i^ns and ratios of Z_i^ns.
- Ratio of Z_i^ns are defined such that the overlap ratio for the state with largest overlap to a given operator is unity.