Study of newly found charmonium-like resonances using lattice QCD

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Free Meson Seminar, DTP, TIFR
18^{th} Aug. 2016

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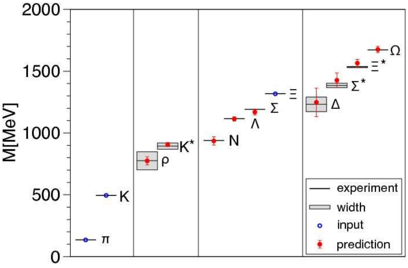
Outline

Outline

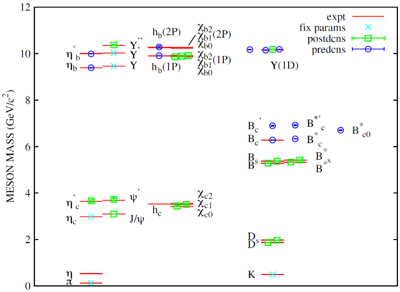
Low lying hadron spectrum

Ground states from lattice QCD : fully controlled systematics



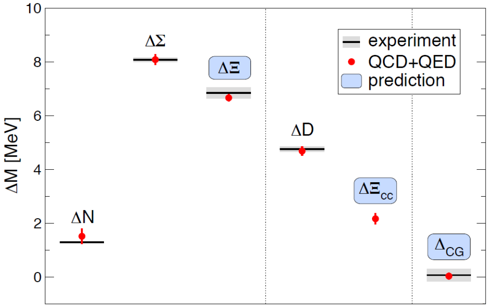
Dürr, et. al. Science 21 Vol. 322 no. 5905 pp. 1224-1227

'Gold-plated' channels : studies at physical point



Dowdall, *et al.*, PRD, **86**, 094510, 2012

Isospin spliting

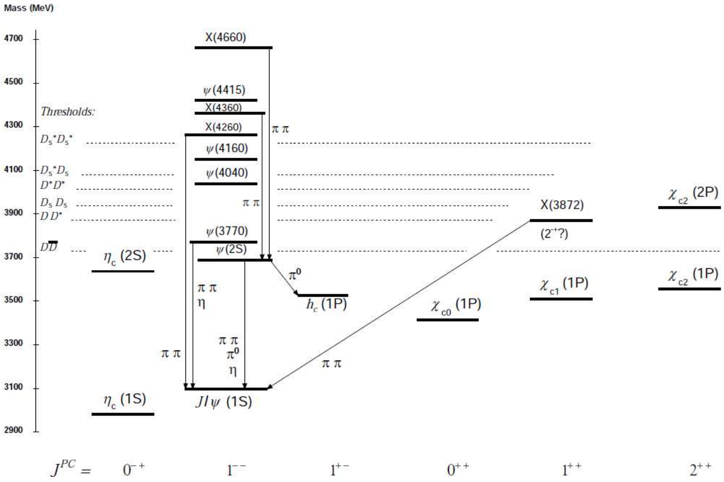


- Fully controlled ab initio calculation
- 1+1+1+1 flavor QCD+QED with clover improved Wilson quarks.
- Accuracy of low energy description is down to per mil level.

- Coleman-Glashow relation : $\Delta_{CG} = \Delta M_N - \Delta M_\Sigma + \Delta M_\Xi$.

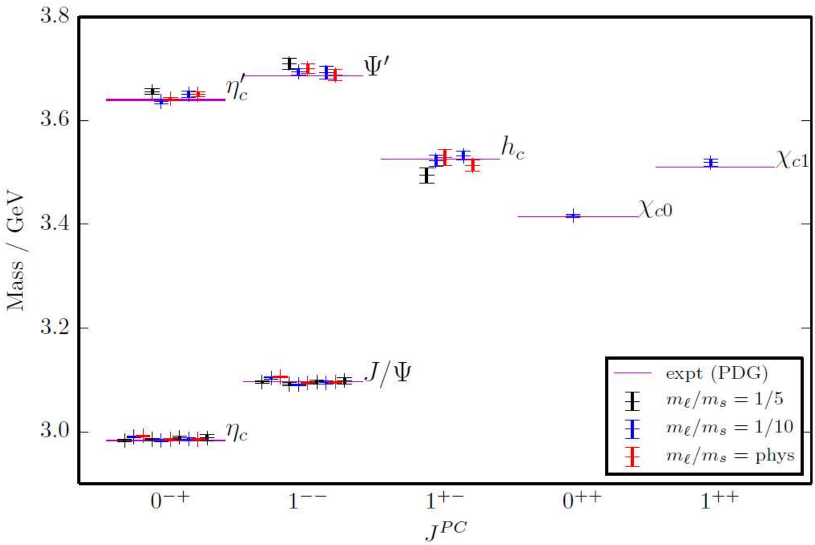
Borsanyi, *et al.*, Science, **347**, 1452-1455, 2015

Established $\bar{c}c$ hadrons



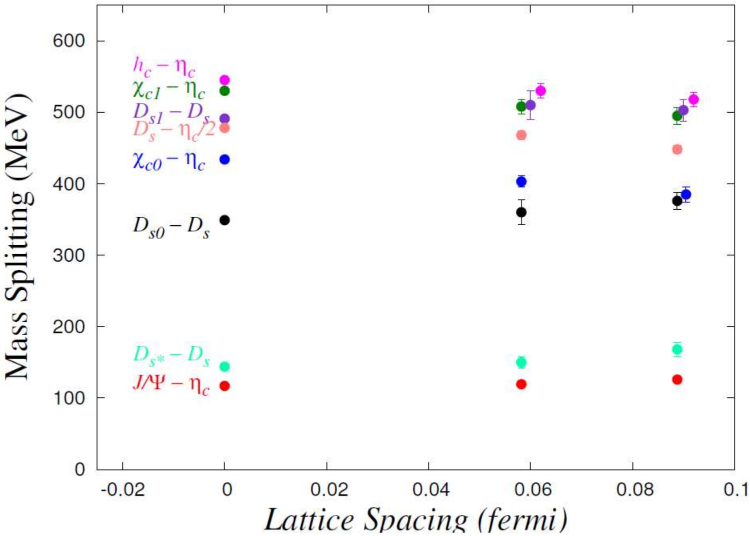
PDG, (2015)

Low lying charmonium spectra from LQCD



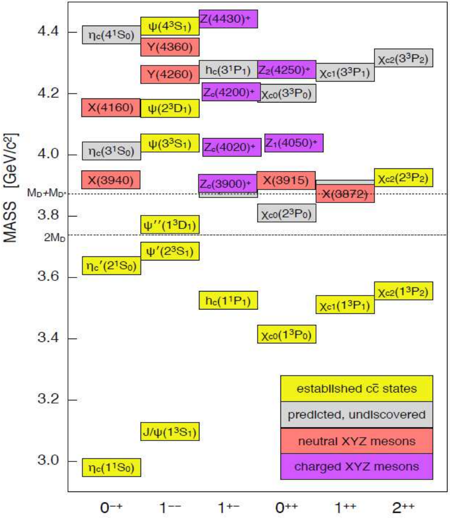
HPQCD, arXiv : 1411:1318

Low lying charmonium spectra from LQCD



ILGTI, arXiv : 1312:3050

‘Non-precision’ spectrum to be explored



S. L. Olsen, (arXiv : 1511.01589v1[hep-ex])

The XYZ's

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) LHCb [1041] (> 10)	2005	Ok
				$B \to K(\gamma\, \psi(2S))$	BaBar [1040] (3.6), Belle [1039] (0.2) LHCb [1041] (4.4)	2008	NC!
				$B \to K(D\bar{D}^*)$	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) T. Xiao *et al.* [CLEO data] [1047] (>5)	2013	Ok
$Z_c(4020)^+$	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!

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

The XYZ's

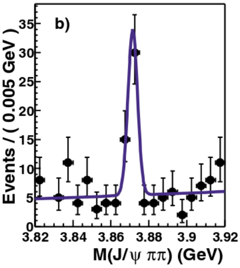
N. Brambilla, *et al.*, arXiv:1404.3723v2

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!
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1110] (8), BaBar [1111] (np)	2007	Ok

Experimental facts : X(3872)

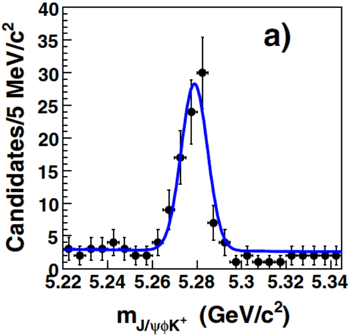
- first observed in Belle 2003 (Belle PRL 2003)
  D0 @ TIFR and Belle @ TIFR.
- Quantum numbers, $J^{PC} = 1^{++}$: (LHCb, 2013)
- Appears within 1 MeV below $D^0 \bar{D}^{*0}$ threshold.



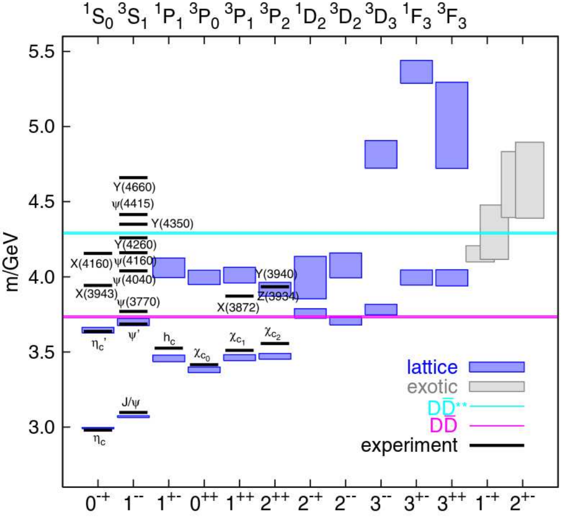
- Preferred strong decay modes $D^0 \bar{D}^{*0}$, $J/\psi\ \omega$ and $J/\psi\ \rho$
- The isospin still uncertain
  * nearly equal branching fraction to $J/\psi\ \omega$ and $J/\psi\ \rho$ decays.
  * No charge partner candidates observed.

Experimental facts : Y(4140)

- first observed in $B^+ \to K^+ \phi J/\psi$ decays (CDF : PRL 102, 242002)
- Quantum numbers, $J^{PC} = 1^{++}$: (LHCb, 2016 [QWG2016])
- 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).
- Appears ∼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 $J/\psi\ \omega$.

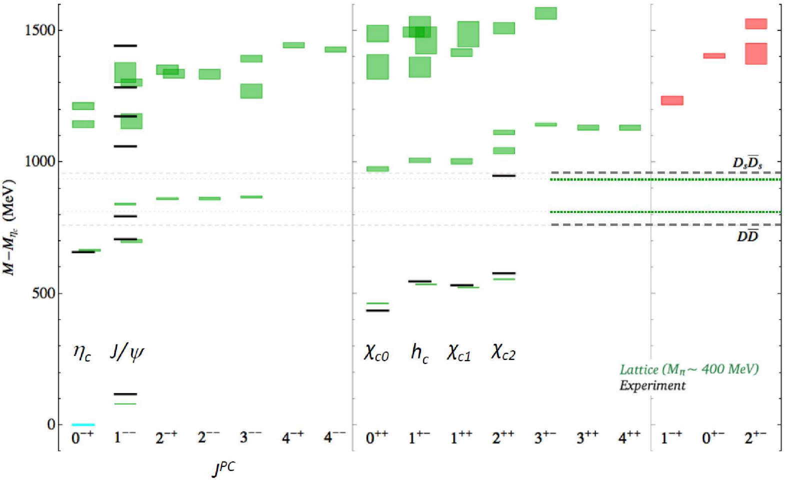


The charmonium spectra I



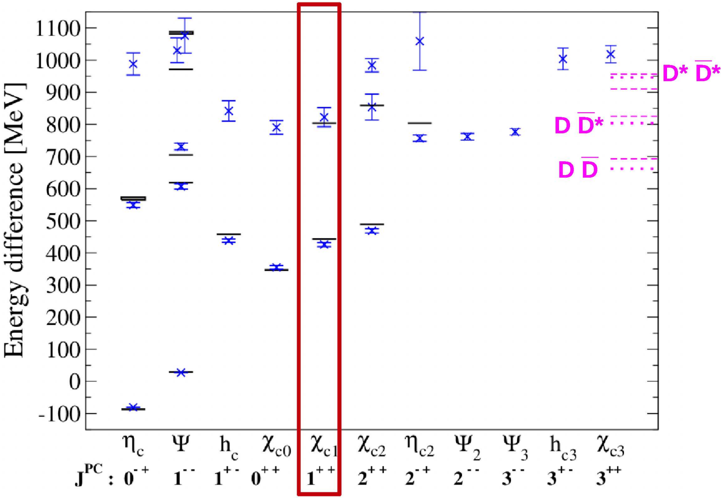
Bali, *et al.*, PRD 84, 094506, 2011

The charmonium spectra I



L. Liu, *et al.*, JHEP 2012

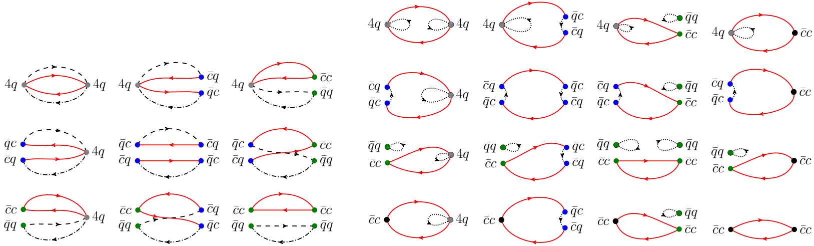
The charmonium spectra I



Mohler, Prelovsek, Woloshyn, PRD, 87, 034501 (2013)

The charmonium spectra II

- Charmonia well below open-charm threshold : “straightforward” on lattice
- Above open charm threshold :
  All physical states with given J^{PC} can appear as E_n.
  Single meson states, two-meson states, etc.
- Necessitates the inclusion of multi-hadron operators
- $\mathcal{O} = \bar{Q}\Gamma Q, \quad (\bar{Q}\Gamma_1 q)_{1_c}(\bar{q}\Gamma_2 Q)_{1_c}, \quad (\bar{Q}\Gamma_1 Q)_{1_c}(\bar{q}\Gamma_2 q)_{1_c}, \quad [\bar{Q}\Gamma_1\bar{q}]_{d_c}[Q\Gamma_2 q]_{d_c}.$
- Wick contractions



- Wick contractions with disconnected charm lines are assumed to be negligible : OZI rule

Take home message

- Dynamical study of 1^{++} channel with diquark-antidiquark operators.
- $I = 0$: The low lying spectrum remains unaffected with tetraquark operators.
- A candidate for X(3872) found below the lattice $\bar{D}^* D$ non-interacting level.
- Tetraquark operators are found to have very little effect on this candidate.
- $I = 1$: All energy levels identified with various scattering levels.
  No additional candidates for X(3872) charge partner observed.

Outline

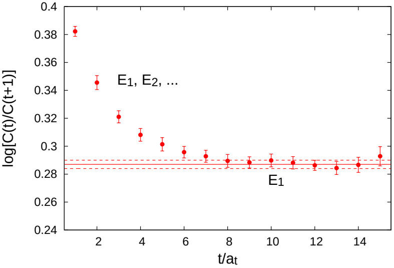
QCD spectrum from Lattice QCD

- Aim : to extract the physical states of QCD.
- Euclidean two point current-current correlation functions

$$C_{ji}(t_f - t_i) = \langle 0|O_j(t_f)\bar{O}_i(t_i)|0\rangle = \sum_n \frac{Z_i^{n*} Z_j^n}{2m_n} e^{-m_n(t_f - t_i)}$$

where $O_j(t_f)$ and $\bar{O}_i(t_i)$ are the desired interpolating operators and $Z_j^n = \langle 0|O_j|n\rangle$.

- Effective mass defined as $\log[\frac{C(t)}{C(t+1)}]$
- Excited states appear as sub-leading exponentials

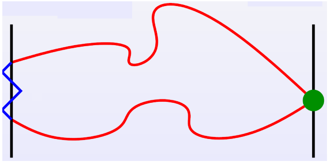


- The ground states : from the exponential fall off at large times.
  Non-linear fitting techniques.
- Multi-exponential fit : Numerically unstable

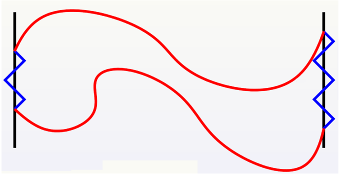
Interpolating operators

- Need interpolating operators that create states with desired quantum numbers
  → Example operators for $J^{PC} = 1^{++}$: $O_i^j = \bar{q}\gamma_5\gamma_i q, \; \bar{q}\overleftarrow{\Delta}\gamma_5\gamma_i\vec{\Delta}q$
- In practice many different constructions possible.
- All those operators with correct quantum numbers should be OK : Overlaps (Z_j^n)?
- With multiple interpolators → a tower of states
- Cost of computation of correlation matrices (C_{ij}) very large.
- Particularly with non-local operators as well as disconnected diagrams.

Local and extended operators : "Distillation"



Meson two point correlators using local source operators



Meson two point correlators using extended source operators

M. Peardon *et al.*, PRD **80**, 054506, 2009

Local and extended operators : "Distillation"

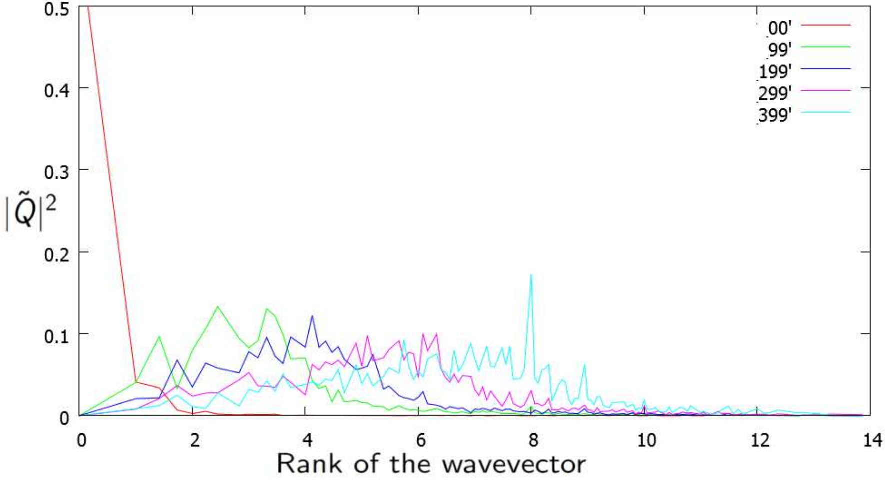
- Idea : Quark smearing using low modes of the 3D lattice Laplacian ($\xi_x^{(k)}(t)$)
- Smearing operator defined by

$$\Box_{xy}(t) = V_{xz}(t)V_{zy}^{\dagger}(t) = \sum_{k=1}^{N} \xi_x^{(k)}(t)\xi_y^{(k)\dagger}(t)$$

- Advantages :
  - * all-to-all propagators
  - * correlation matrix for large basis of interpolators
  - * momentum projection at source and sink
- Disadvantages : expensive; unfavorable volume scaling
- Stochastic approach improves the scaling.

M. Peardon *et al.*, PRD **80**, 054506, 2009

Local and extended operators : “Distillation”



Courtesy (plots) : Abhijit

Local and extended operators : "Distillation"

- Consider an isovector meson two-point function:

$$C_M(t_1 - t_0) = \langle \bar{u}(t_1) \quad \Gamma_{t_1} \quad d(t_1)\bar{d}(t_0) \quad \Gamma_{t_0} \quad u(t_0)\rangle$$

Local and extended operators : "Distillation"

- Consider an isovector meson two-point function:

$$C_M(t_1 - t_0) = \langle \bar{u}(t_1)\Box_{t_1}\Gamma_{t_1}\Box_{t_1} d(t_1)\bar{d}(t_0)\Box_{t_0}\Gamma_{t_0}\Box_{t_0} u(t_0)\rangle$$

Integrating over the quark fields one gets

$$C_M(t_1 - t_0) = Tr_{(\sigma,s,c)}(\Box_{t_1}\Gamma_{t_1}\Box_{t_1} M^{-1}(t_1,t_0)\Box_{t_0}\Gamma_{t_0}\Box_{t_0} M^{-1}(t_0,t_1))$$

Substituting the definition of $\Box$ and redefining the quantities, the trace reduces to a smaller space.

$$C_M(t_1 - t_0) = Tr_{(\sigma,\mathcal{D})}(\phi(t_1)\tau(t_1,t_0)\phi(t_0)\tau(t_0,t_1))$$

$\phi^{ab}_{\alpha\beta}$ and $\tau^{ab}_{\alpha\beta}$ are $(4N_{\mathcal{D}}) \times (4N_{\mathcal{D}})$ matrices.

$$\phi(t) = V^\dagger(t)\Gamma_t V(t) \text{ and } \tau(t,t') = V^\dagger(t)M^{-1}(t,t')V(t')$$

(perambulator)

Generalized eigenvalue problem

Solving the generalized eigenvalue problem for $C_{ij}(t)$.

$$C_{ij}(t)v_j^{(n)}(t,t_0) = \lambda^{(n)}(t,t_0)C_{ij}(t_0)v_j^{(n)}(t,t_0)$$

Solve for several t_0's.
Choice of t_0's crucial $\Rightarrow$ Determine quality of extractions.

- Principal correlators given by eigenvalues

$$\lambda_n(t,t_0) \propto \exp^{-E_n(t-t_0)}(1+\mathcal{O}(\exp^{-\Delta E_n(t-t_0)}))$$

Extraction of a tower of states.

- Eigenvectors related to the overlap factors

$$Z_i^{(n)} = \langle 0|\mathcal{O}_i|n\rangle = \sqrt{2E_n}\exp^{E_n t_0/2} v_j^{(n)\dagger} C_{ji}(t_0)$$

C. Michael, Nucl. Phys. B 259, 58, (1985)

M. Lüscher and U. Wolff, Nucl. Phys. B 339, 222 (1990)

Resonant scattering

- Most hadrons are resonances under the strong interaction
- Width and the branching fractions often known poorly
- Experimental data is analyzed with a partial wave analysis
- Elastic scattering : amplitudes T_l and phase shifts δ_l:

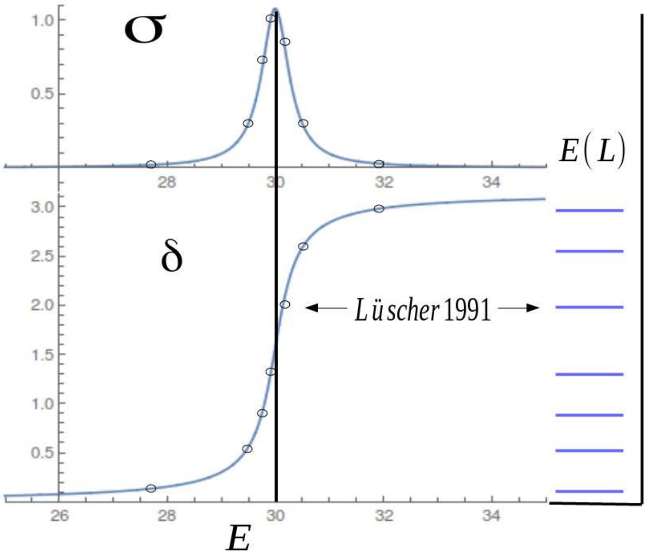
$$T_l = sin(\delta_l)e^{i\delta_l} = \frac{e^{2i\delta_l} - 1}{2i}$$

- A bound state : $\cot[\delta_l] = i$
- An isolated narrow resonance peak : a relativistic Breit-Wigner shaped resonance

$$T_l = \frac{-\sqrt{s}\Gamma(s)}{s - s_R + i\sqrt{s}\Gamma(s)}$$

with the resonance position $s_R = m_R^2$ and decay width $\Gamma(s_R)$

Discrete energy levels : Lüscher's formulae



Discrete energy levels : Lüscher's formulae

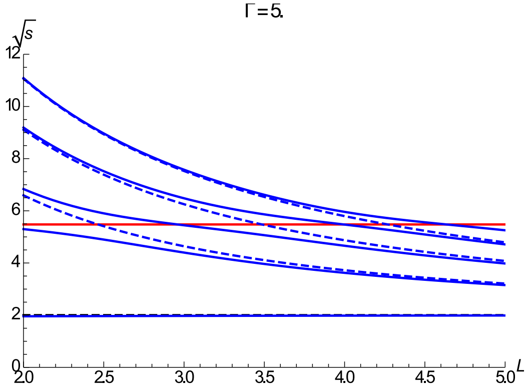
- Energy levels represent states with the desired J^{PC}.
- Non-interacting two-meson levels are given by

$$E(L) = \sqrt{m_1^2 + \vec{p}_1^{\,2}} + \sqrt{m_2^2 + \vec{p}_2^{\,2}}$$

  where $\vec{p}_{1,2} = \frac{2\pi}{L}(n_x, n_y, n_z)$.
- Switching on the interaction makes $\vec{p}_{1,2} \neq \frac{2\pi}{L}(n_x, n_y, n_z)$.
  The interactions induce a phase shift in the momentum,
  e.g. in 1D $\quad \vec{p}_{1,2} = \frac{2\pi}{L} n + \frac{2}{L}\delta(k)$.
- Lüscher's formula relates these level shifts to the infinite volume phase shifts, $\delta_l(k)$.
- For S-wave,

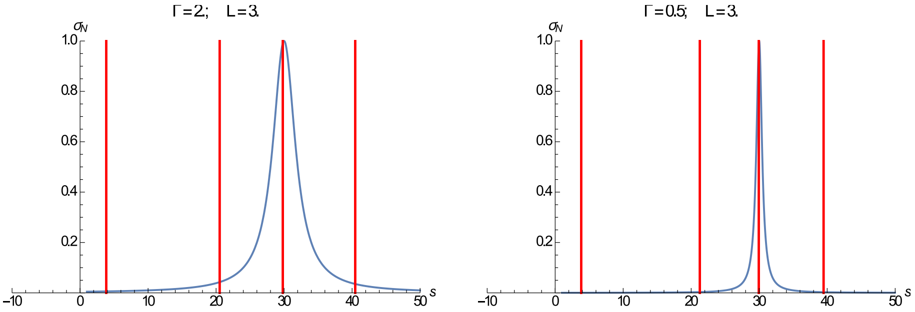
$$tan\delta(p) = \frac{\pi^{3/2} q}{Z_{00}(1; q^2)}; \quad Z_{00}(1; q^2) = \sum_{\vec{n} \in N^3} \frac{1}{\vec{n}^2 - q^2}; \quad q = \frac{L}{2\pi} p$$

Discrete energy levels : Lüscher's formulae



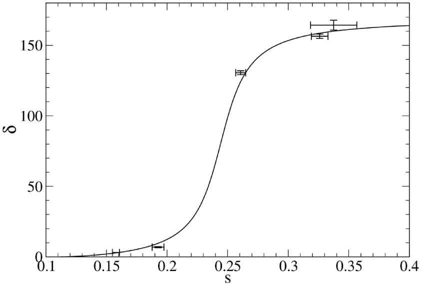
- Resonance : Avoided level crossings
- Narrower the resonance, smaller the level shifts
- Lüscher's formulae relates these level shifts to the infinite volume phase shifts.

Discrete energy levels : Lüscher's formulae



- Narrower the resonance, smaller the level shifts
- Lüscher's formulae relates these level shifts to the infinite volume phase shifts.

ρ resonance : an old benchmark calculation



Lang, Mohler, Prelovsek, Vidmar, PRD 2011

- Results from a calculation with $m_\pi = 266(3)(3) MeV$

$$g_{\rho\pi\pi} = 5.13(20); \quad m_\rho = 792(7)(8) MeV$$

- $g_{\rho\pi\pi}$ coupling defined as

$$\Gamma(s) = \frac{p^{*3}}{s} g^2_{\rho\pi\pi}$$

Outline

Interpolators

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

- $I = 0$;
  $D(0)\bar{D}^*(0)$, $J/\psi(0)\omega(0)$, $D(1)\bar{D}^*(-1)$, $J/\psi(1)\omega(-1)$, $\eta_c(1)\sigma(-1)$, $\chi_{c1}(0)\sigma(0)$.
- $I = 1$;
  $D(0)\bar{D}^*(0)$, $J/\psi(0)\rho(0)$, $D(1)\bar{D}^*(-1)$, $J/\psi(1)\rho(-1)$, $\chi_{c1}(1)\pi(-1)$, $\chi_{c0}(1)\pi(-1)$.

Lattice we use

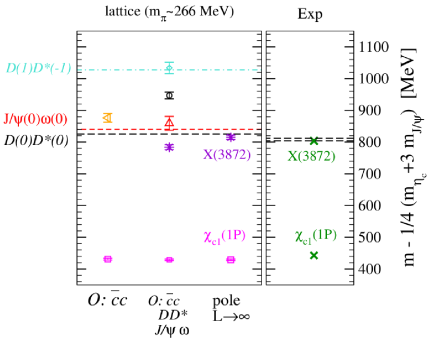
Lattice size	N_f	$N_{\rm cfgs}$	m_π [MeV]	a [fm]	L [fm]
$16^3 \times 32$	2	280	266(3)(3)	0.1239(13)	1.98

Hasenfratz et al. PRD 78 054511 (2008)

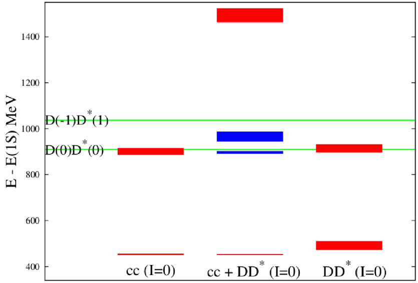
Hasenfratz et al. PRD 78 014515 (2008)

- 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.

An X(3872) candidate from lattice



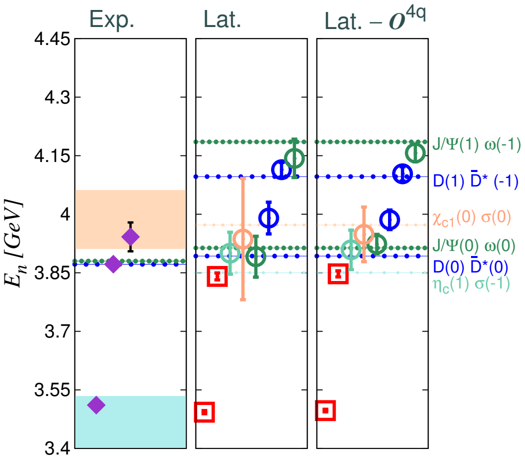
Prelovsek, Leskovec, PRL 2013



Lee, DeTar, Mohler, Na, arXiv:1411.1389

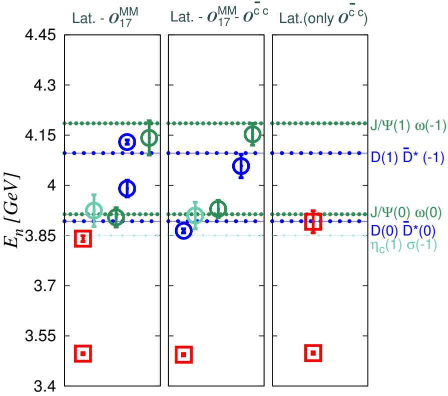
- Studies with two-meson operators : First hint for a candidate
- Both calculations neglects charm annihilation
- Observed only when both $\bar{c}c$ and $\bar{D}^*D$ are used.
- Vastly different systematics, yet results are similar.

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



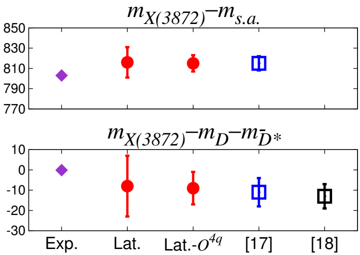
- No significant effects in the low lying spectrum by the inclusion of diquark-antidiquark operators.
- $[\bar{c}\bar{u}]_{\bar{\mathcal{G}}}[cu]_{\mathcal{G}}$ operators related to two-meson operators by Fierz relations.
- Makes the interpretation as a pure tetraquark unlikely.
- Simulation still unphysical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

X(3872) candidate



- O_{17}^{MM} : $\chi_{c1}(0)\sigma(0)$
- 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 $\eta_c(1)\sigma(-1)$.

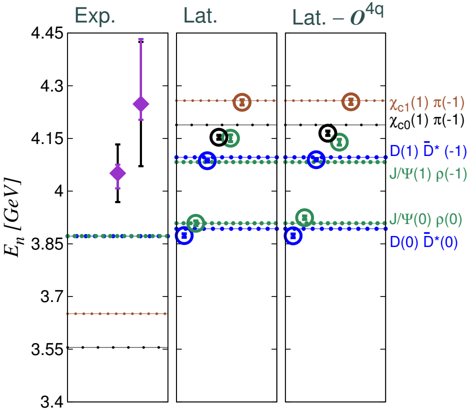
X(3872) candidate



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

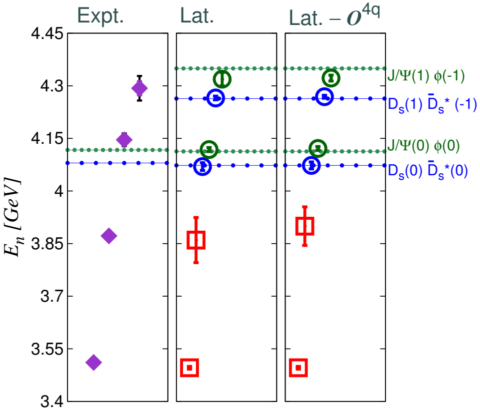
- δ for levels 2 and 5 using Lüscher's formulae : $p.cot(\delta(p)) = \frac{2\ Z_{00}(1;q^2)}{\sqrt{\pi}L}$
- Phase shift near threshold interpolated using effective range approximation $p.cot(\delta(p)) = \frac{1}{a_0} + \frac{1}{2}r_0p^2$.
- Large negative scattering length, $a_0 = -1.7(4)fm$, agrees with a shallow bound state.
- Infinite volume bound state position from pole in the resulting scattering matrix.
- No significant effects from O^{4q}.

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



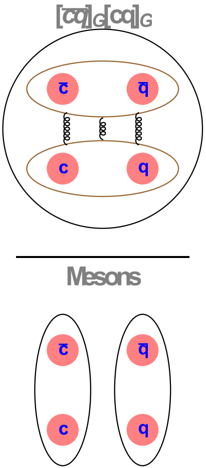
- All levels identified with various scattering levels.
- No additional candidate observed.
- No charge partner for X(3872) observed.
- Simulation assumes $m_u = m_d$. Popular interpretations based on isospin breaking. Simulations with $m_u \neq m_d$ required for confirmation.

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



- 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^{++}.

Fierz relations



- $[\bar{c}\bar{q}]_{\bar{\mathcal{G}}}[cq]_{\mathcal{G}}$ 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.
- Large N : S. Weinberg

Outline

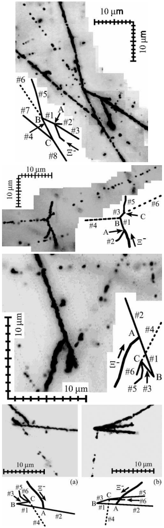
1. Introduction
2. Methodology
3. Results
4. Conclusions

Conclusions

- Dynamical study of 1^{++} channel with diquark-antidiquark operators looking for possible exotic candidates.
- Diquark-antidiquark operators are found to have negligible significant effects on the low lying spectrum (for all three channels).
- A candidate for X(3872) found below the lattice $\bar{D}^*D$ non-interacting level.
- Amplitude analysis within elastic approximation for $\bar{D}^*D$ scattering; a bound state immediately below the $\bar{D}^*D$ threshold.
- No additional candidates observed hinting an exotic signal.
- Outlook : Rigorous calculations involving coupled channel effects.
- Outlook : Calculations on larger lattice volumes.
- Outlook : Simulations with $m_u \neq m_d$ for isospin breaking effects.

H dibaryon

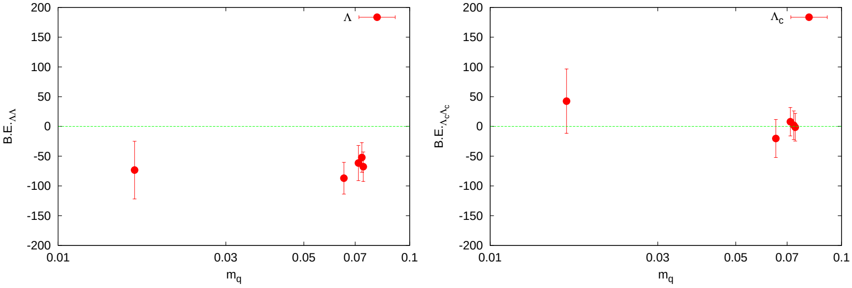
- Bound six quark system with $S = -2$, $I = 0$, $J^P = 0^+$: R. L. Jaffe, PRL 38, (1977) 195.
- K. Nakazawa *et al.*, KEK-E176 & E373 Collaboration
  Nagara Event, Mikage event, Demachiyanagi event, Hida event.
- C. J. Yoon *et al.*, KEK-PS E522 Collaboration
- Plethora of theoretical studies, no conclusions yet.
- NPLQCD (PRL 2011) : $B.E. = 16\text{MeV}$.
  HALQCD (PRL 2011) : $B.E. = 30 - 40\text{MeV}$.
  Unphysical quark masses.
- Recent calculations at physical quark masses
  See Lattice 2016 talks by HALQCD.



Technical details

- MILC lattices with $N_f = 2 + 1 + 1$ dynamical HISQ fermions.
  Three ensembles : 24^3, 32^3 and 48^3.
- Physical volume ~ 2.9fm.
- Overlap formulation, with wall sources, for valence quarks.
- Light quark masses as low as physical light quark masses.
- Tuned strange and charm quark masses.
- $\Lambda \; = \; s(u\Gamma d)$ and $O_{\Lambda-\Lambda} = \Lambda^T C\gamma_5\Lambda$.

Very preliminary



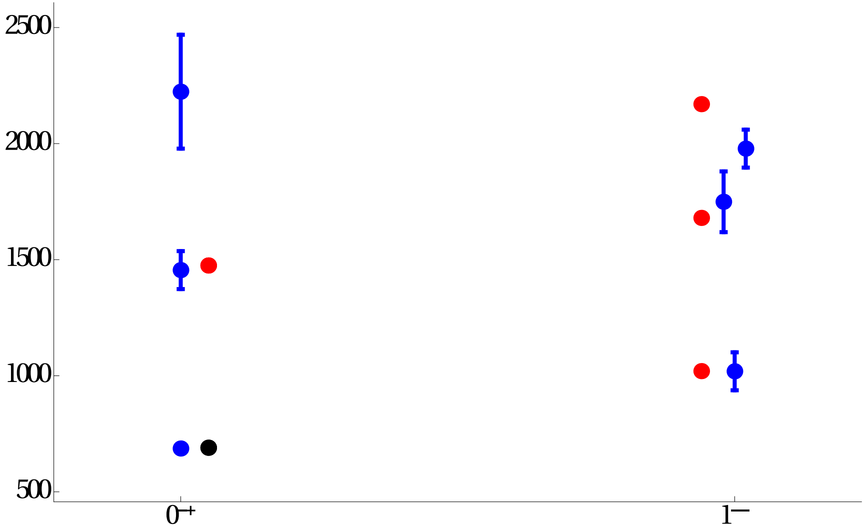
N. Mathur, M. P. and S. Pavaskar

Distillation on MILC lattices : preliminary

$n\,^{2s+1}\ell_J$ $\quad J^{PC}$	$\mathrm{I}=0$ $c\bar{c}$	$\mathrm{I}=0$ $b\bar{b}$	$\mathrm{I}=\frac{1}{2}$ $c\bar{u}$, $c\bar{d}$; $\bar{c}u$, $\bar{c}d$	$\mathrm{I}=0$ $c\bar{s}$; $\bar{c}s$	$\mathrm{I}=\frac{1}{2}$ $b\bar{u}$, $b\bar{d}$; $\bar{b}u$, $\bar{b}d$	$\mathrm{I}=0$ $b\bar{s}$; $\bar{b}s$	$\mathrm{I}=0$ $b\bar{c}$; $\bar{b}c$
$1\,^1S_0$ $\quad 0^{-+}$	$\eta_c(1S)$	$\eta_b(1S)$	D	$D_s^{\pm}$	B	B_s^0	$B_c^{\pm}$
$1\,^3S_1$ $\quad 1^{--}$	$J/\psi(1S)$	$\Upsilon(1S)$	D^*	$D_s^{*\pm}$	B^*	B_s^*	
$1\,^1P_1$ $\quad 1^{+-}$	$h_c(1P)$	$h_b(1P)$	$D_1(2420)$	$D_{s1}(2536)^{\pm}$	$B_1(5721)$	$B_{s1}(5830)^0$	
$1\,^3P_0$ $\quad 0^{++}$	$\chi_{c0}(1P)$	$\chi_{b0}(1P)$	$D_0^*(2400)$	$D_{s0}^*(2317)^{\pm\dagger}$			
$1\,^3P_1$ $\quad 1^{++}$	$\chi_{c1}(1P)$	$\chi_{b1}(1P)$	$D_1(2430)$	$D_{s1}(2460)^{\pm\dagger}$			
$1\,^3P_2$ $\quad 2^{++}$	$\chi_{c2}(1P)$	$\chi_{b2}(1P)$	$D_2^*(2460)$	$D_{s2}^*(2573)^{\pm}$	$B_2^*(5747)$	$B_{s2}^*(5840)^0$	
$1\,^3D_1$ $\quad 1^{--}$	$\psi(3770)$			$D_{s1}^*(2860)^{\pm\ddagger}$			
$1\,^3D_3$ $\quad 3^{--}$				$D_{s3}^*(2860)^{\pm}$			
$2\,^1S_0$ $\quad 0^{-+}$	$\eta_c(2S)$	$\eta_b(2S)$	$D(2550)$				
$2\,^3S_1$ $\quad 1^{--}$	$\psi(2S)$	$\Upsilon(2S)$		$D_{s1}^*(2700)^{\pm\ddagger}$			
$2\,^1P_1$ $\quad 1^{+-}$		$h_b(2P)$					
$2\,^3P_{0,1,2}$ $\quad 0^{++},1^{++},2^{++}$	$\chi_{c0,2}(2P)$	$\chi_{b0,1,2}(2P)$					
$3\,^3P_{0,1,2}$ $\quad 0^{++},1^{++},2^{++}$		$\chi_b(3P)$					

PDG

Distillation on MILC lattices : preliminary



ρ meson by HSC