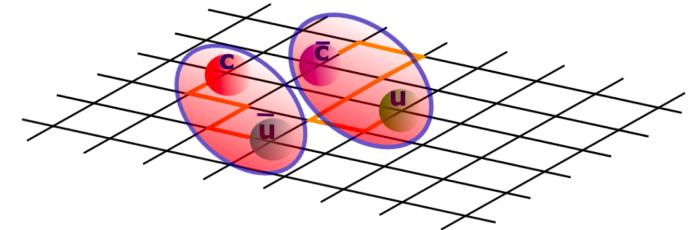


Lattice studies of charmonia and exotics



Sasa Prelovsek

Jefferson Lab, Virginia, USA

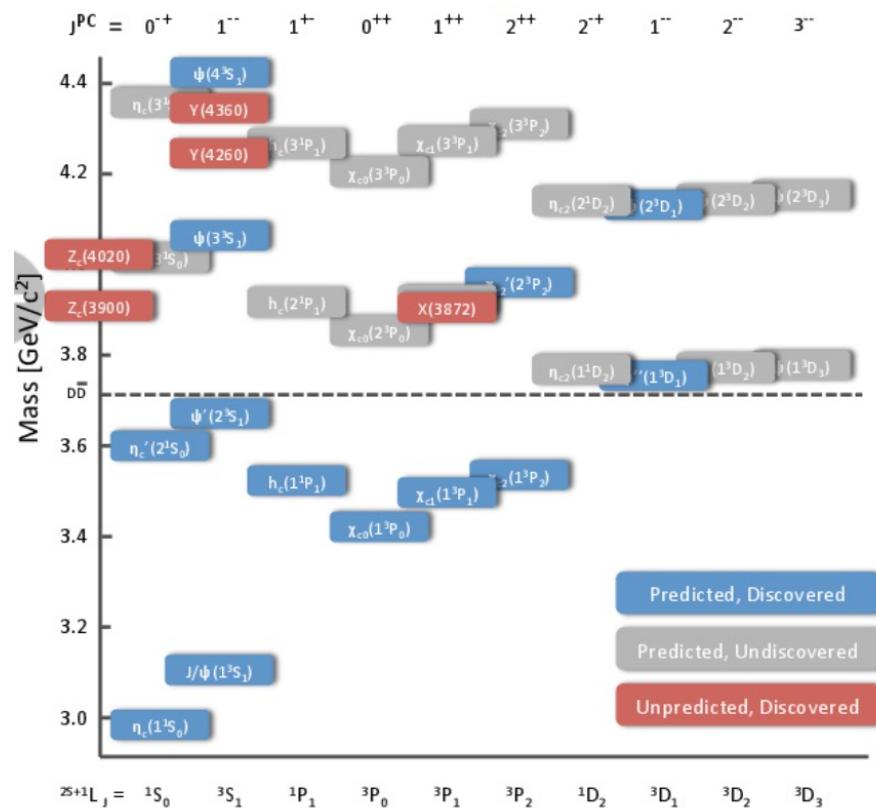
University of Ljubljana & Jozef Stefan Institute, Slovenia

CHARM 2015, 18th-22nd May 2015,
Wayne State University, Detroit, USA

Outline

Spectroscopy of charmonium and charmonium-like states:

- well below open-charm threshold
- near or above open-charm threshold:
 - ❖ single-meson approximation
 - ❖ “rigorous” treatment
 - “conventional” charmonia near th.
 - $X(3872)$ with $I=0$
 - Z_c^+
 - charged $X(3872)$
 - $Y(4140)$
 - bound states of charmonia and nuclei
- $V(r)$ between c and \underline{c} at finite temperature



J. Bannet, talk @ APS 2015

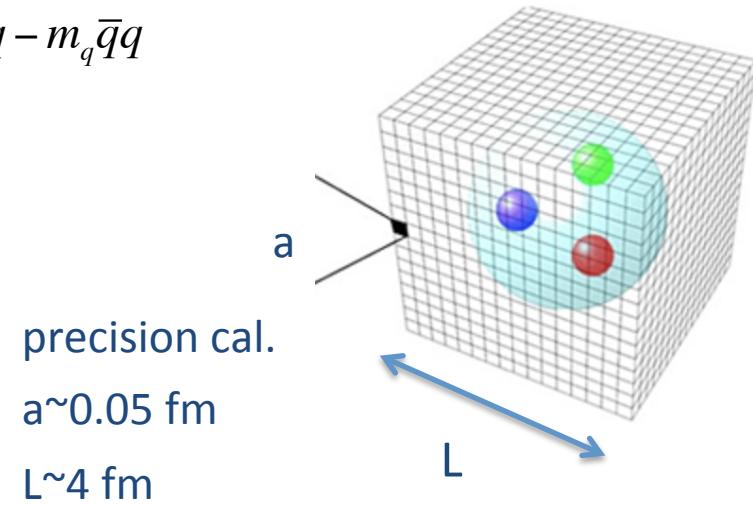
Non-perturbative method: QCD on lattice

$$L_{QCD} = -\frac{1}{4} G_{\mu\nu}^a G_a^{\mu\nu} + \sum_{q=u,d,s,c,b,t} \bar{q} i \gamma_\mu (\partial^\mu + ig_s G_a^\mu T^a) q - m_q \bar{q} q$$

input: g_s , m_q

output: hadron properties

hadron interactions (if we are lucky)



Evaluation of Feynman path integrals in discretized space-time

quantum mechanics

$$\int Dx e^{i S/\hbar}$$

$$S = \int dt L[x(t)]$$

quantum field theory in Euclidian space-time

$$\int DG Dq D\bar{q} e^{-S_{QCD}/\hbar}$$

$$S_{QCD} = \int d^4x L_{QCD}[G(x), q(x), \bar{q}(x)]$$

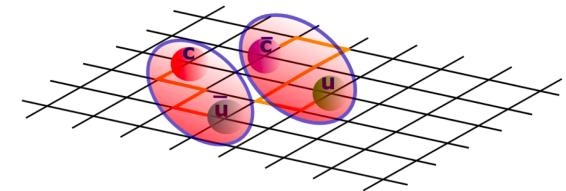
x, t (Minkovsky) \rightarrow $x, i t$ (Euclidean)

Lattice gives discrete energies of eigenstates: E_n

Meson(like) system with given J^{PC} is created by a number of interpolating fields

$$J^{PC} \quad \mathcal{O} = \bar{q}\Gamma q, \quad (\bar{q}\Gamma_1 q)_{\vec{p}_1} (\bar{q}\Gamma_2 q)_{\vec{p}_2}, \quad [\bar{q}\Gamma_3 \bar{q}][q\Gamma_4 q], \dots$$

$$X(3872), 1^{++} : \quad \bar{c}c, \quad (\bar{c}u)(\bar{u}c) = D\bar{D}^*, \quad [\bar{c}u][cu]$$



$$C_{ij}(t) = \langle 0 | \mathcal{Q}_i(t) \mathcal{Q}_j^+(0) | 0 \rangle = \sum_n Z_i^n Z_j^{n^*} e^{-E_n t}, \quad Z_i^n = \langle 0 | \mathcal{Q}_i | n \rangle$$

All physical states with given J^{PC} appear as E_n in principle (example: charmonium with 1^{++})

- single meson states $\chi_{c1} \quad m_{\chi_{c1}} = E_1 \quad \text{for } P=0 \text{ (after extrapolations)}$
 $X(3872)$
- two-meson states $D\bar{D}^*, \dots \quad E_n$ rigorously render two-hadron scattering matrix
(for example $D\bar{D}^*$ scattering matrix)

Approximation for all closed charm hadrons on the lattice (presented in this talk)

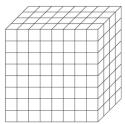
Wick contractions with **charm annihilation** are omitted

- OZI: one expects very small influence from charm annihilation on energies of eigenstates of interest: but this needs to be verified in the future
- very challenging to go beyond this approximation on the lattice due to a number of light single and multi-hadron states with the same quantum numbers



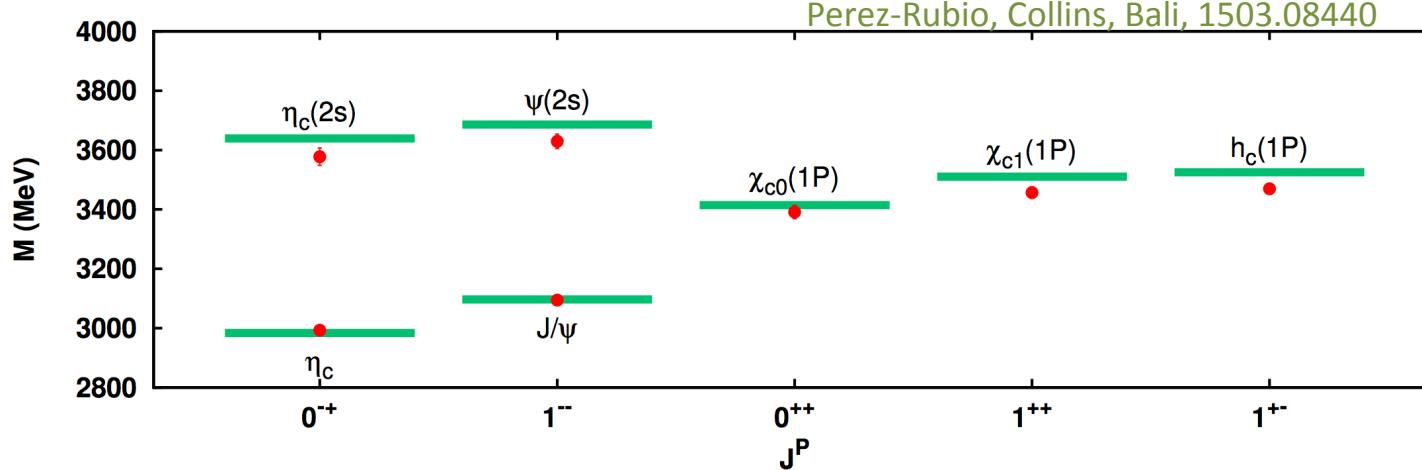
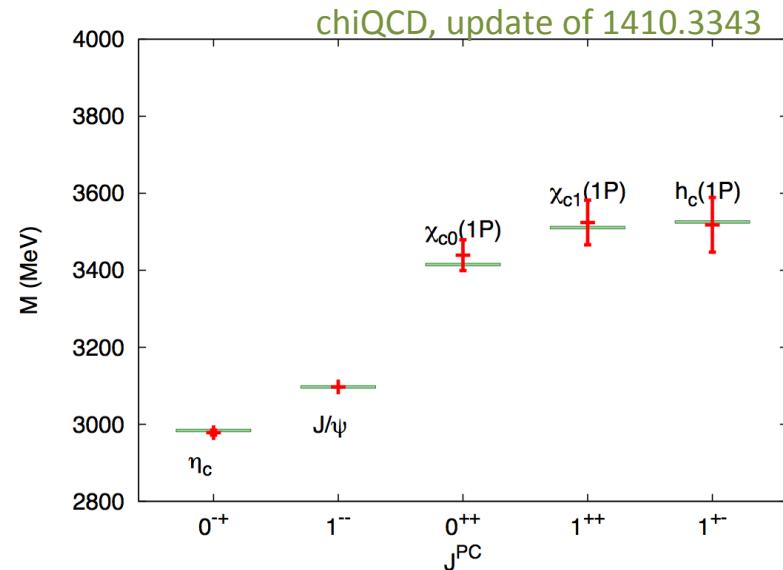
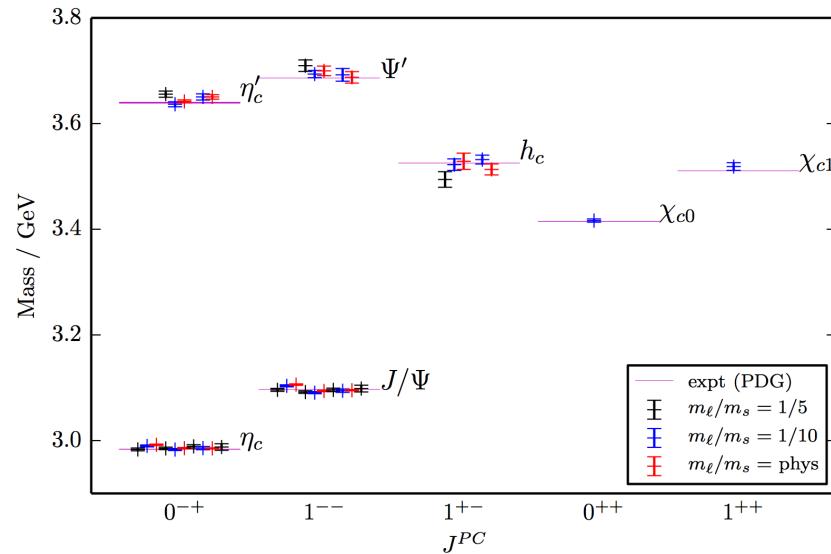
Analogous Wick contractions for u,d,s quarks are NOT omitted, unless explicitly specified

Charmonia well below DD: recent precision results



$m=E$ ($P=0$): $a\rightarrow 0$, $L\rightarrow\infty$, $m_q\rightarrow m_q^{\text{phy}}$

HPQCD, 1411.1318



see also:

FNAL/MILC,

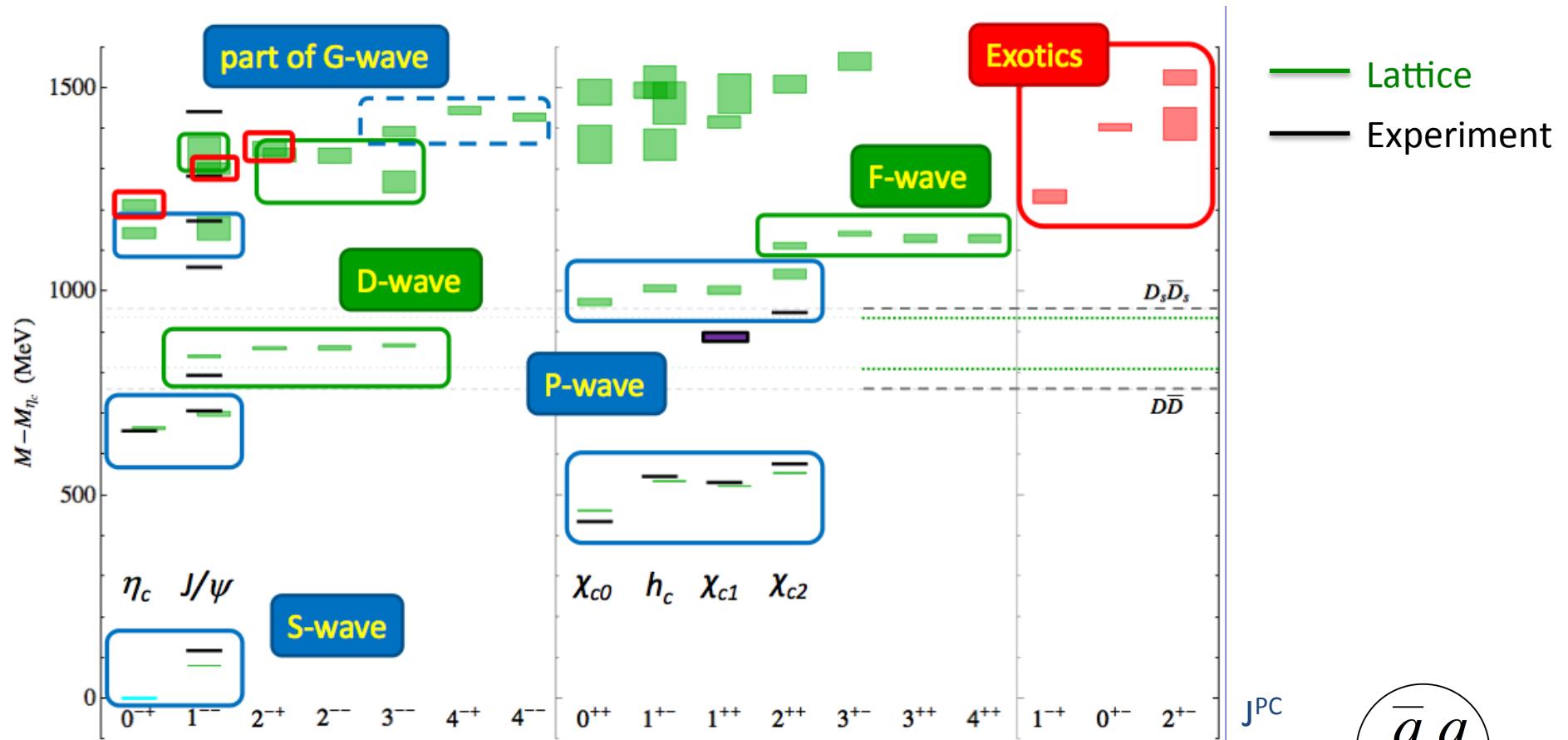
1412.1057

The omission of
charm annihilation
is the main remaining
uncertainty

Charmonia near or above DD threshold: single-meson approximation

- only interpolating fields $\mathcal{O} \approx \bar{c} c$
 - assumptions: all energy levels correspond to "one-meson" states
no two-meson state is seen
- $m=E$ (for $P=0$)
these are strong assumptions ...
but results still present valuable reference point

Charmonia: single-meson approximation



[HSC , L. Liu et al: 1204.5425, JHEP]

- $m_\pi \approx 400$ MeV, $L \approx 2.9$ fm, $N_f = 2+1$
- identification with $n^{2S+1}L_J$ multiplets using $\langle O | n \rangle$
- green: lat, black: exp

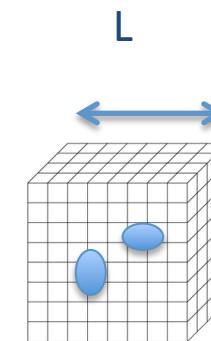
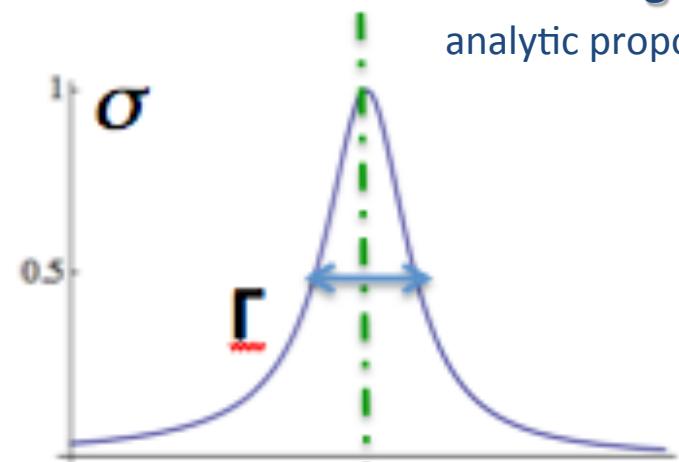
Hybrids:

some of them have exotic J^{PC}
large overlap with $O = \underline{q} F_{ij} q$

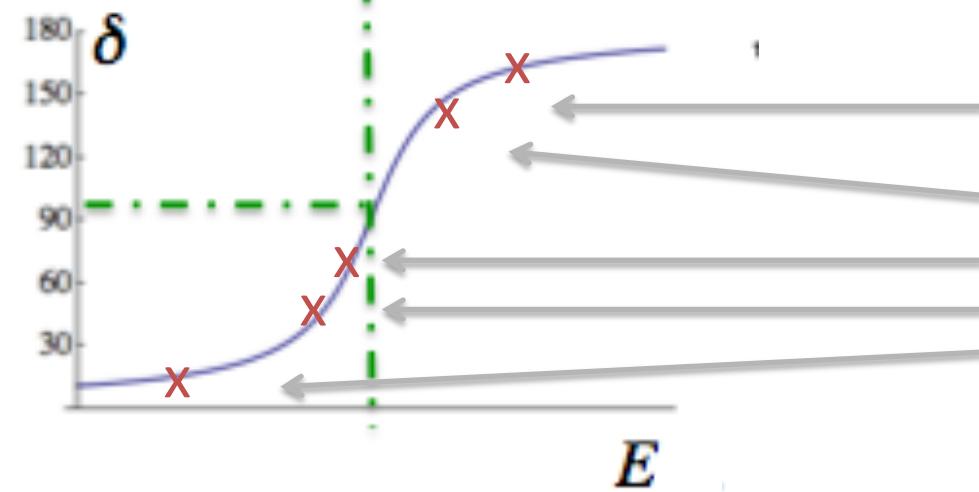
Rigorous treatment of hadrons near or above threshold:

scattering of two mesons

analytic proposal: Luscher 1991



$E(L)$



scattering phase shifts
at infinite volume

$\delta(E)$

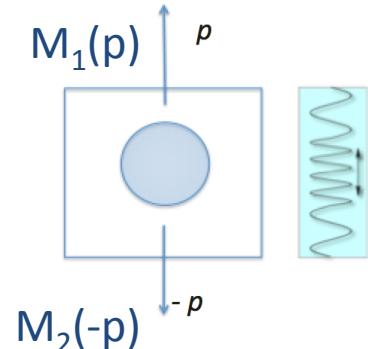
$E(L)$

energies from lattice
with spatial extent L

Scattering of two mesons

elastic scattering with total momentum $P=0$: $E=E_{\text{cm}}$

$$E_n(L) \xrightarrow{\text{Luscher's eq.}} \delta(E)$$



Scattering matrix for partial wave l :

$$S(E) = e^{2i\delta(E)}, \quad S(E) = 1 + 2iT(E), \quad T(E) = \frac{1}{\cot \delta(E) - i}$$

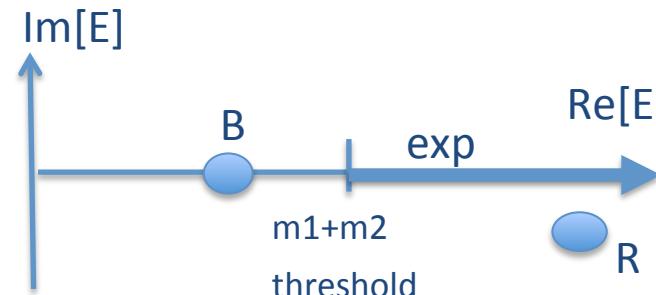
Bound state (B):

$$\cot[\delta(E_B)] = i, \quad E_B < m_1 + m_2$$

Resonance (R) (of Breit-Wigner type):

$$T(E) = \frac{-E \Gamma}{E^2 - m_R^2 + i E \Gamma}, \quad \Gamma(E) = g^2 \frac{p^{2l+1}}{E^2}$$

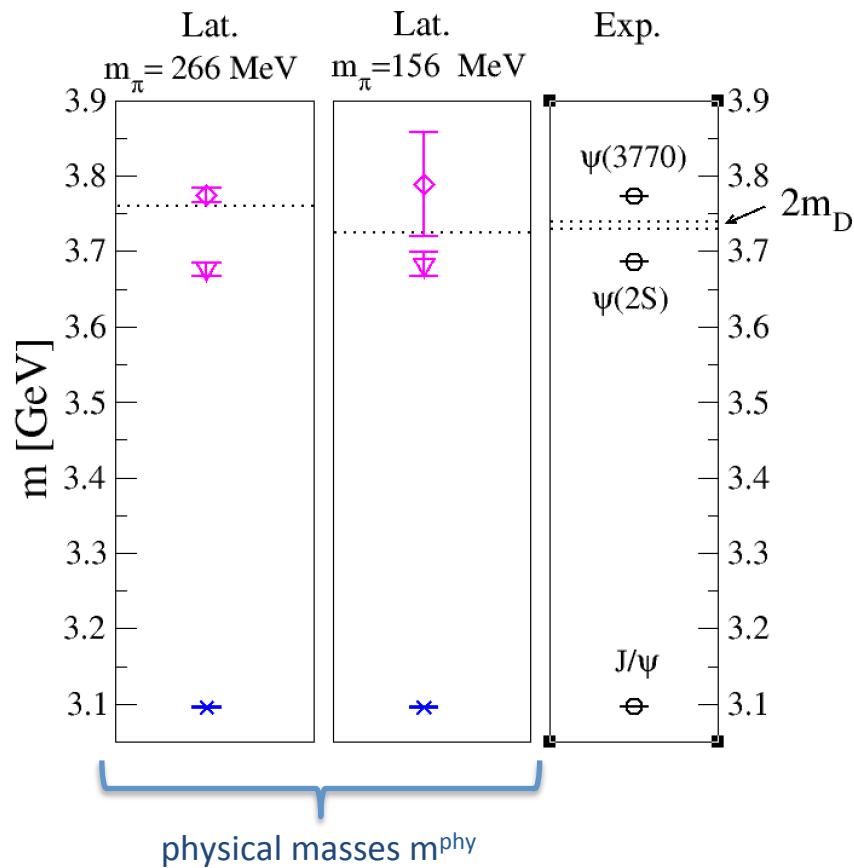
Locations of poles of $T(E)$
for res. and bound st.



Two types of plots will be shown:

- $E(L)$ energies of lat. eigenstates
- $m^{\text{phy}} = m_R, m_B$ extracted from $E(L)$

Resonance $\Psi(3770)$ and bound st. $\Psi(2S)$ from $D\bar{D}$ scattering in p-wave



$\Psi(3770)$	Mass [MeV]	g (no unit)
Lat ($m_\pi=266 \text{ MeV}$)	$3774 \pm 6 \pm 10$	19.7 ± 1.4
Lat ($m_\pi=156 \text{ MeV}$)	$3789 \pm 68 \pm 10$	28 ± 21
Exp.	3773.15 ± 0.33	18.7 ± 1.4

S. Prelovsek, CHARM 2015

$\mathcal{O}: \bar{c} c, D\bar{D}, J^{PC} = 1^{--}$

$D\bar{D}$ scat. in p-wave is simulated

T-matrix is determined from E_n

Fit of T-matrix gives:

BW resonance $\Psi(3770)$:

m_R (magenta diamonds)

Γ (given below)

Bound state $\Psi(2S)$ from pole in T:

m_B (magetna triangles)

$$\Gamma = \frac{g^2}{6\pi} \frac{p^3}{s}$$

- $\eta_c(1S)$
- $J/\psi(1S)$
- $\chi_{c0}(1P)$
- $\chi_{c1}(1P)$
- $h_c(1P)$
- $\chi_{c2}(1P)$
- $\eta_c(2S)$
- $\psi(2S)$
- $2m_D$
- $\psi(3770)$
- $X(3872)$
- $\chi_{c0}(2P)_{\text{wa}}$
- $\chi_{c2}(2P)$
- $X(3940)$
- $\psi(4040)$
- $X(4050)^{\pm}$
- $X(4140)$
- $\psi(4160)$
- $X(4160)$
- $X(4250)^{\pm}$

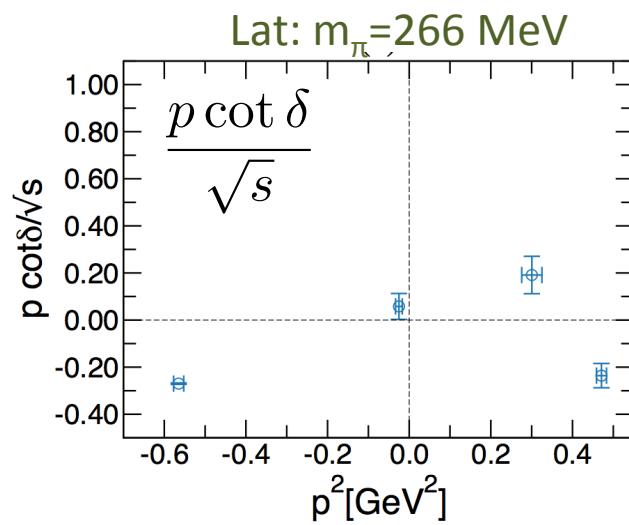
Lang, Leskovec, Mohler, S.P.,
1503.05363

Scalar charmonia from DD scattering in s-wave, $J^{PC}=0^{++}$

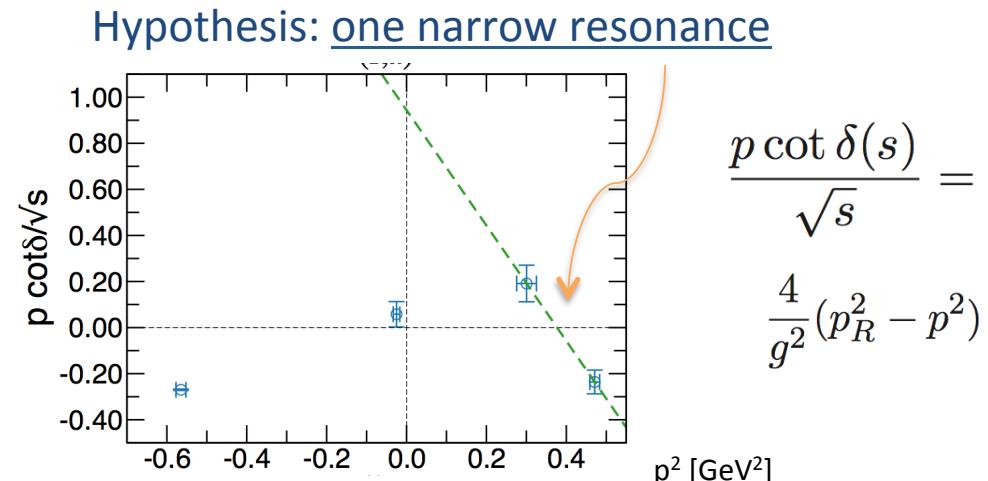
Puzzle remains in exp and on lattice, more work needed !

- PDG assigned X(3915) to be $\chi_{c0}(2P)$
- Meissner & Guo [1208.1134], Olsen [1410.6534]: arguments against this assignment
- It is still not commonly accepted which exp state corresponds to $\chi_{c0}(2P)$
- DD scattering in s-wave simulated on lattice: comparison to several hypothesis made

$$\mathcal{O}: \bar{c} c, D\bar{D}$$



Lang, Leskovec, Mohler, S.P.,
1503.05363, $m_\pi=266$, 156 MeV



$m_R=3.966(20)$ GeV $\Gamma^{\text{predict}}=67(18)$ MeV

such narrow res. not (yet) found in exp DD inv. mass
does not describe our results near threshold

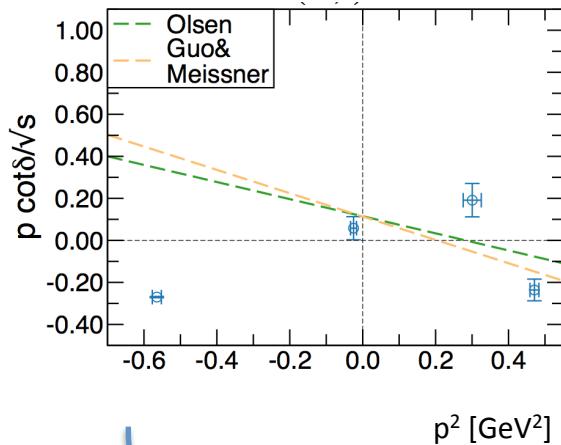
Scalar charmonia from DD scattering in s-wave, $J^{PC}=0^{++}$

$\mathcal{O}: \bar{c} c, D\bar{D}$

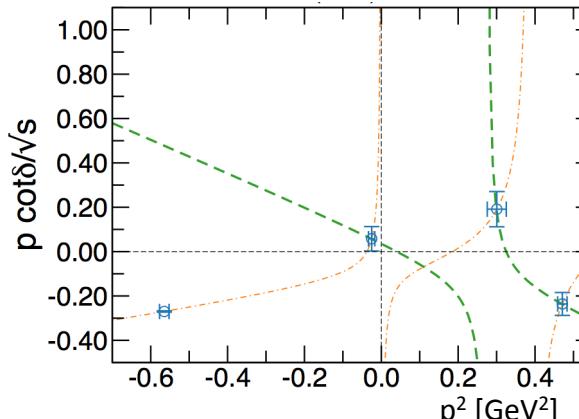
various hypothesis versus lattice results

more detailed DD lineshape needed from lattice and exp

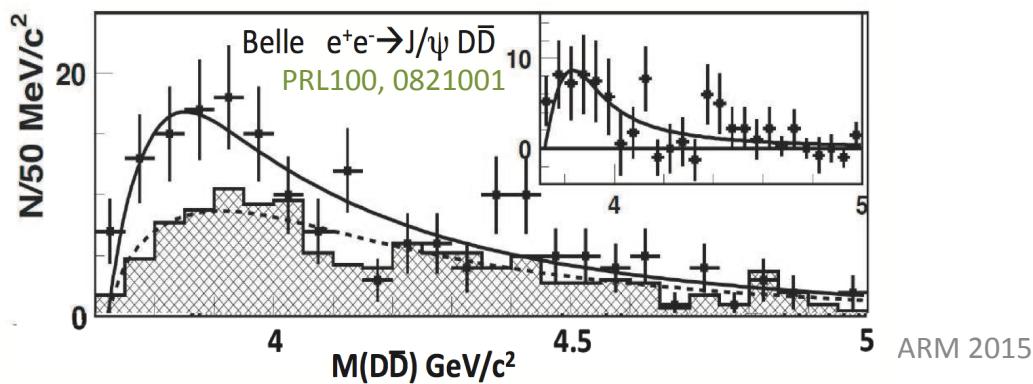
Hypothesis:
one broad BW resonance



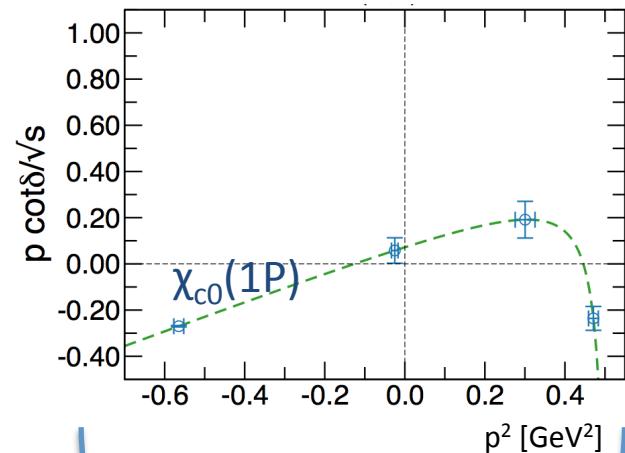
Hypothesis:
two BW resonances



not supported by lat. data near and above th.



Hypothesis:
one narrow resonance & bound state pole at $\chi_{c0}(1P)$

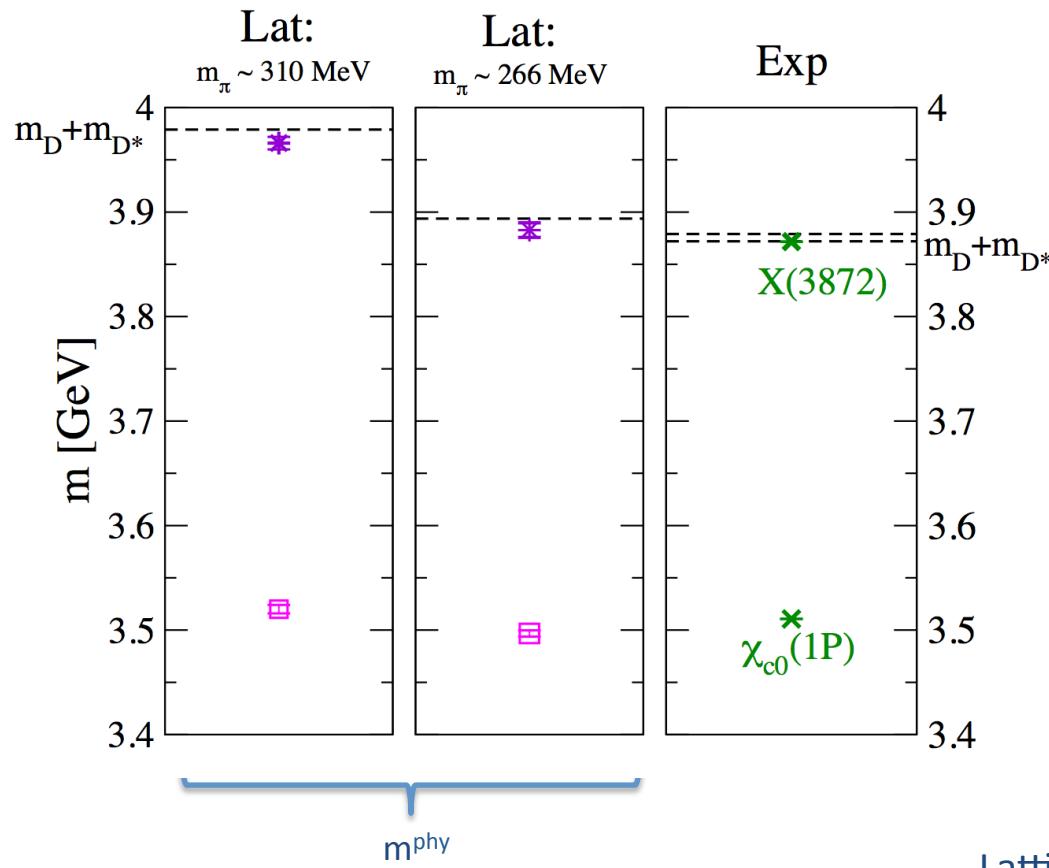


supported by lat.

narrow resonance in DD:
 $m_R = 4.002(24) \text{ GeV}$
 $\Gamma^{\text{predict}} = 32(48) \text{ MeV}$

Lang, Leskovec, Mohler, S.P.,
1503.05363

X(3872) as bound state from $\underline{D}\underline{D}^*$ scattering, $J^{PC}=1^{++}$, $I=0$



$\mathcal{O}: \bar{c} c, D\bar{D}^*$

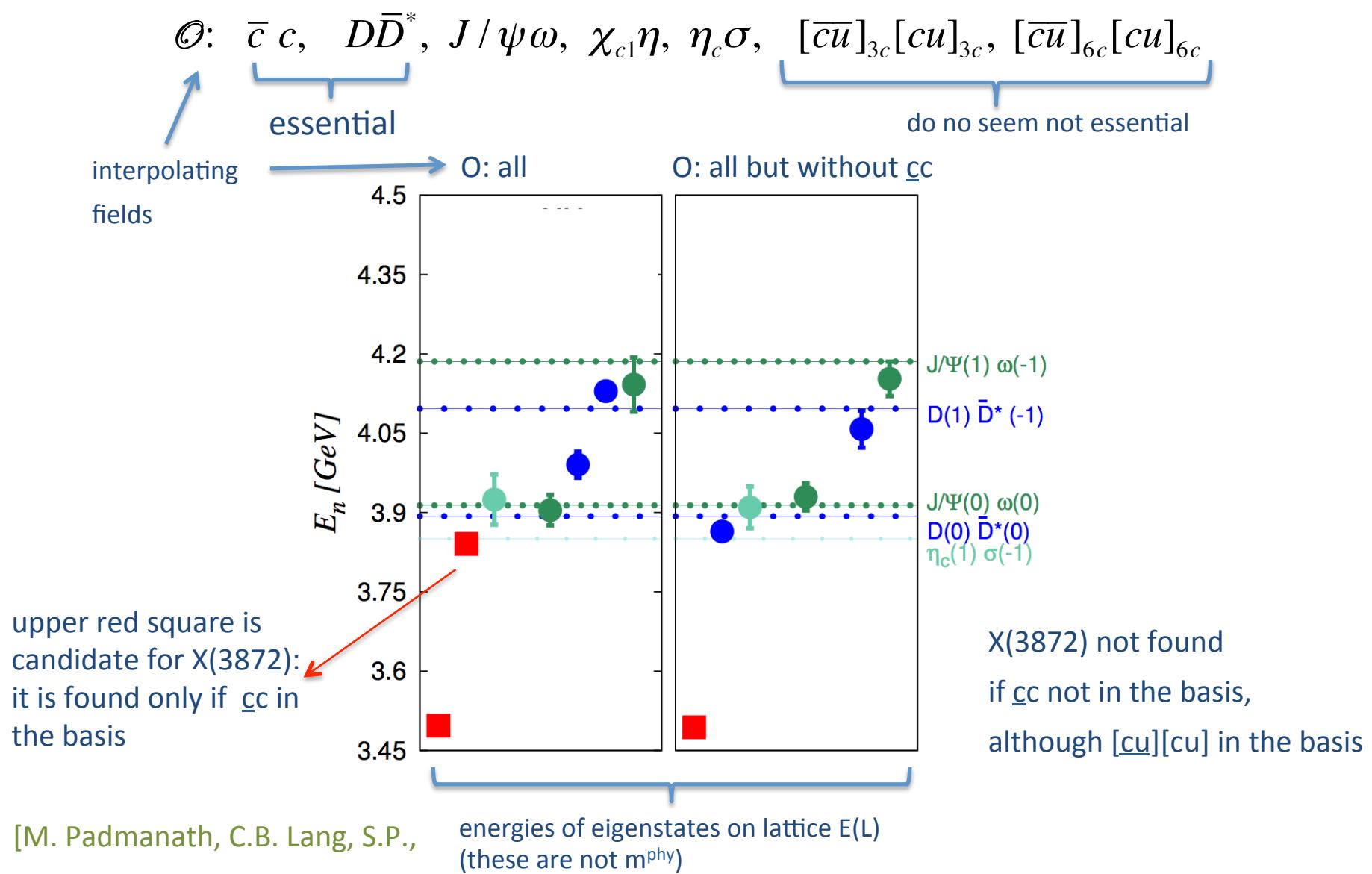
- ground state: $\chi_{c1}(1P)$
- $\underline{D}\underline{D}^*$ scattering matrix near th. determined
- A pole of $T \propto \frac{1}{\cot \delta - i}$ found just below th. (violet star)
- The pole attributed to X(3872), which is a shallow bound state in both simulations
- Position of DD* threshold depends on $m_{u/d}$, and may be affected by discretization effects related to charm quark

Lattice evidence for X(3872):

- $m_\pi \approx 266$ MeV, $a=0.124$ fm, $L=2$ fm
[S.P. and Leskovec: 1307.5172, PRL 2013]
- $m_\pi \approx 310$ MeV, $a=0.15$ fm, $L=2.4$ fm , HISQ
[Lee, DeTar, Na, Mohler , update of proc 1411.1389]

X(3872)	$m - (m_{D0} + m_{D0^*})$
lat ($m_\pi=310$ MeV)	- 13 \pm 6 MeV
lat ($m_\pi=266$ MeV)	- 11 \pm 7 MeV
exp	- 0.14 \pm 0.22 MeV

Which Fock components are essential for X(3872) with $I=0$?



Searches for hadrons with exotic flavor

“XYZ”: Z_c^+ , charged X(3872), Y(4140)



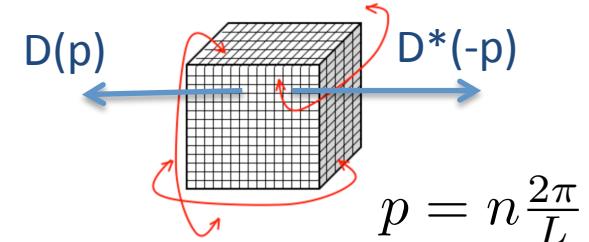
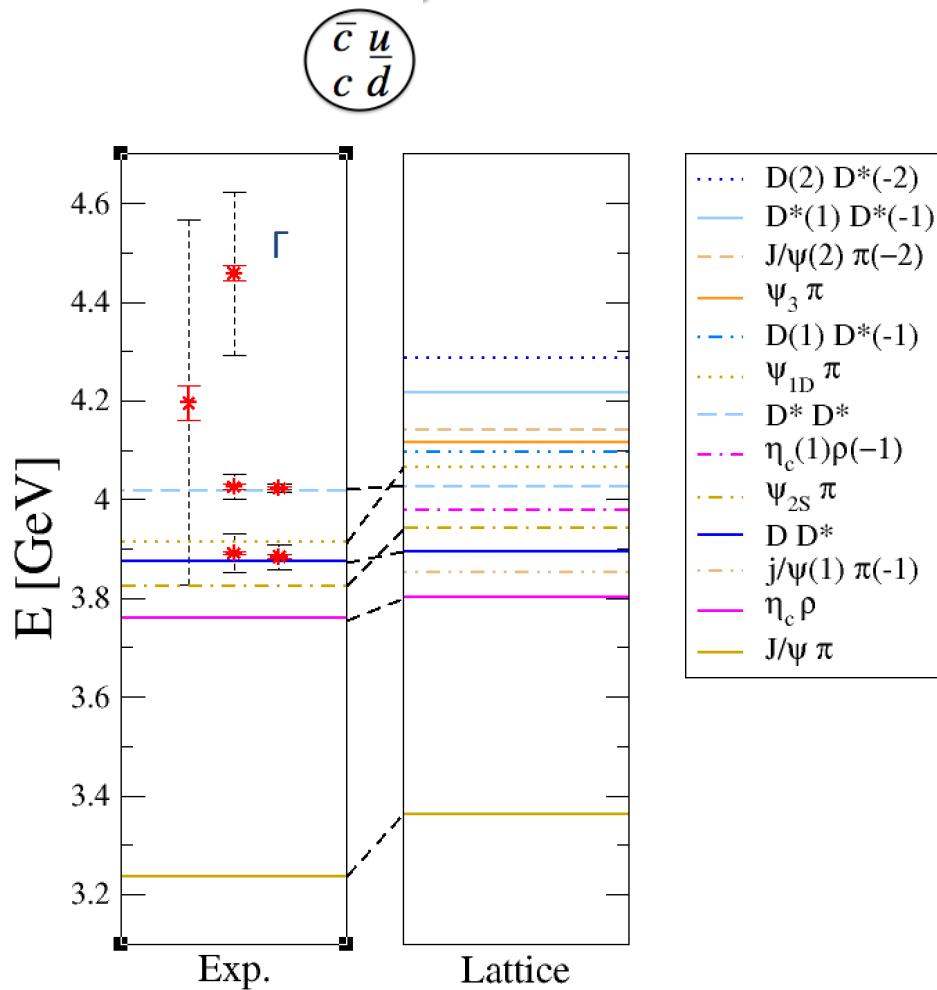
Even more challenging since most of experimental exotic “XYZ” states

- are above several thresholds and decay to several two-meson final states
- require simulation of coupled-channels

Scattering matrix for coupled-channels extracted on lattice so far only in

- a-la Luscher: $K\pi$, $K\eta$ system [Willson, Dudek, Edward, Thomas, HSC, PRL 2014, PRD 2015]
- a-la HALQCD: Z_c channel [HALQCD, preliminary results]

Search for Z_c^+ channel ($I^G=1^+$, $J^{PC}=1^{+-}$): the challenge



Lattice:

Horizontal lines represent
energies of 13 two-meson states
in non-interacting case

$$E = E[M_1(p_1)] + E[M_2(p_2)]$$

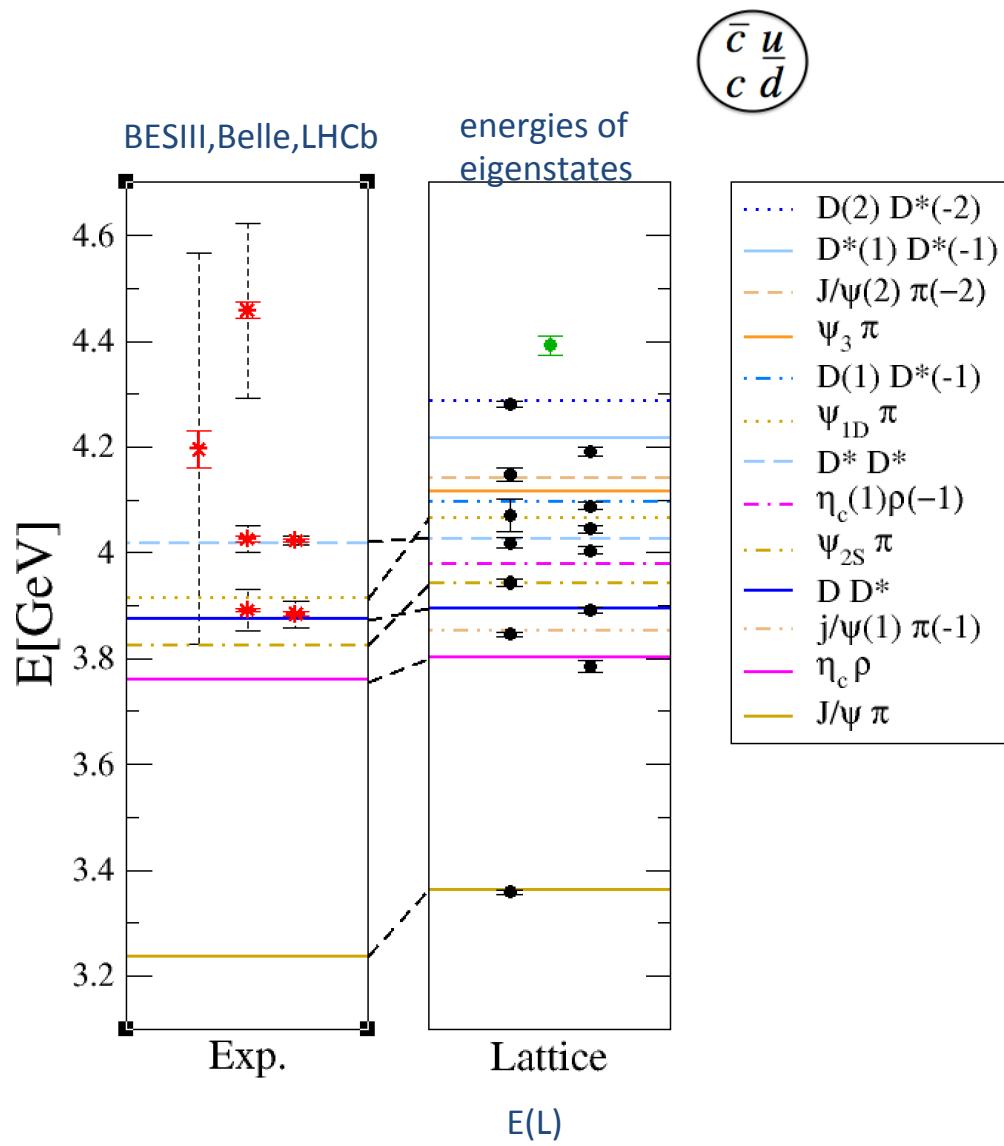
Extracting 13 two-meson states
is a huge challenge!

$$\mathcal{O} : (\bar{c}u)(\bar{d}c), (\bar{c}c)(\bar{d}u), [\bar{c}\bar{d}][cu]$$

[S.P., Lang, Leskovec, Mohler, 1405.7612, PRD 2015]

Ensemble (2), $m_\pi \approx 266$ MeV, $L \approx 2$ fm, $N_f = 2$

Search for Z_c^+ ($|G=1^+$, $J^{PC}=1^{+-}$)



Lattice results:

- 13 expected two-meson eigenstates found as expected (black circles)
- no additional eigenstate below 4.2 GeV
- **no candidate for Z_c^+ below 4.2 GeV**

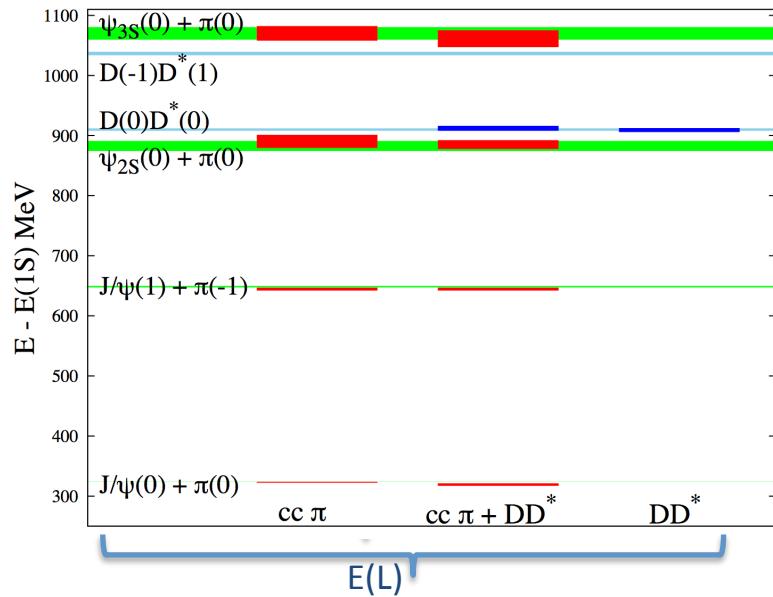
Experience from conventional channels:

- we found an additional eigenstate for each conventional resonance ρ , $\psi(3770)$, K^* , a_1 , b_1 , D_0 , D_1^* and each bound state $X(3872)$, $D_{s0}(2317)$, $D_{s1}(4260)$, $\psi(2S)$

[S.P., Lang, Leskovec, Mohler, 1405.7612, PRD 2015]

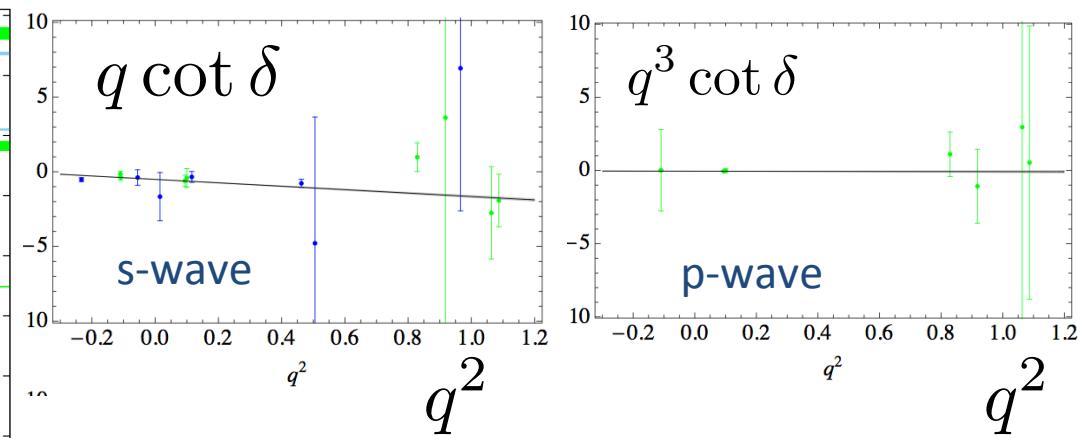
Search for $Z_c^+ (I^G=1^+, J^{PC}=1^{+-})$

$\mathcal{O} : D\bar{D}^*, \psi\pi$



- HISQ quarks, $m_\pi \sim 310$ MeV
 - only expected two-meson states
 - **no candidate for Z_c^+**
- [Lee, DeTar, Na, Mohler, update of 1411.1389]

$\mathcal{O} : D\bar{D}^*, J/\psi\pi$

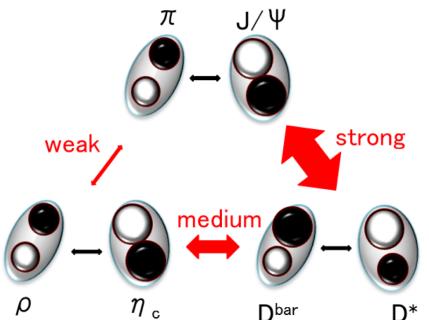
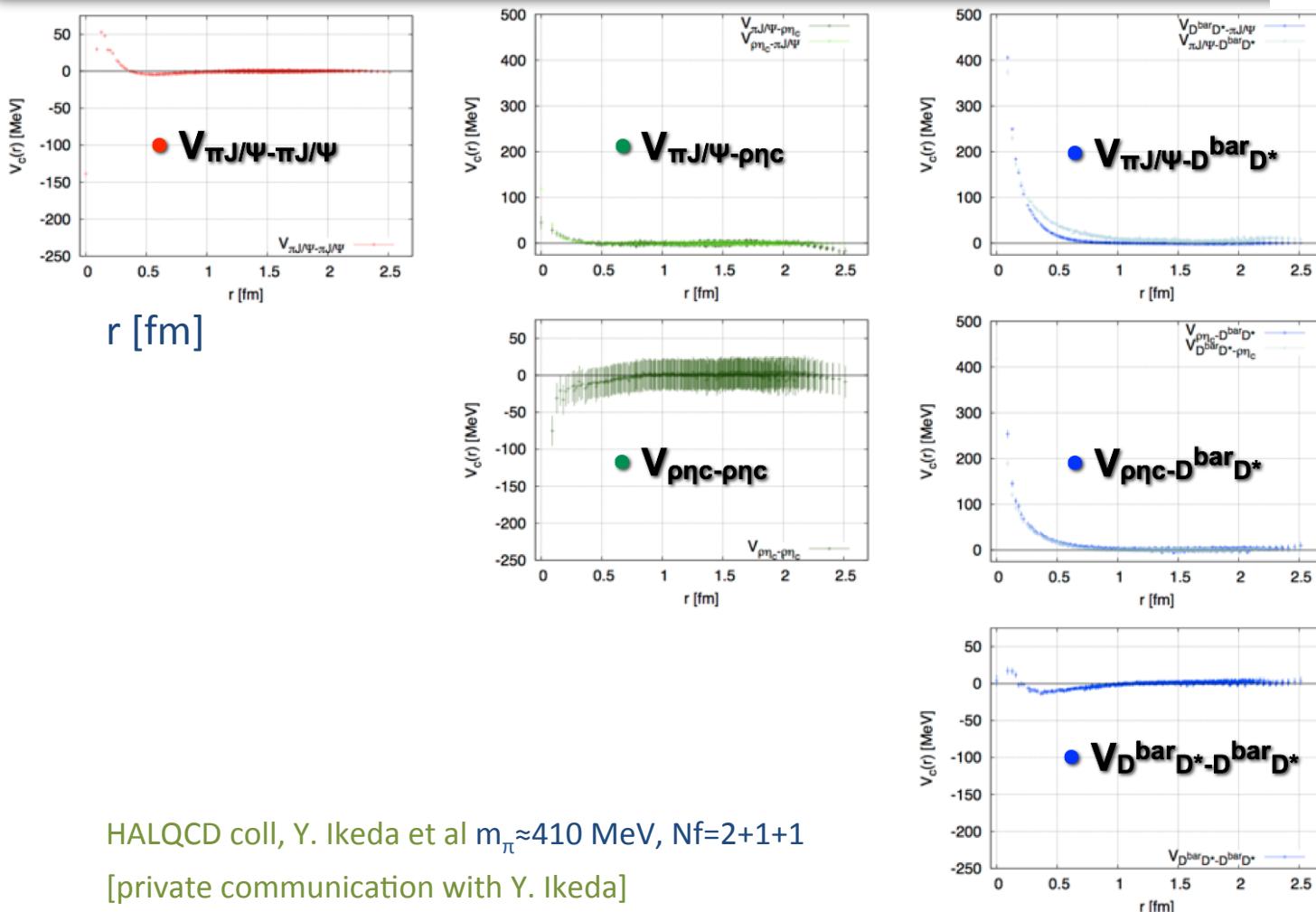


- twisted mass quarks, $m_\pi = 300, 420, 485$ MeV
- phase shift for $D\bar{D}^*$ scattering extracted near th.
- caveat: $J/\psi\pi$ channel omitted although this represents the ground state of the system
- **no candidate for Z_c^+ candidate** is found near $D\bar{D}^*$ th.
[Y. Chen et al, 1403.1318, CLQCD coll, PRD]

- Why no eigenstate for $Z_c(3900)$? It would be naively expected if $Z_c(3900)$ related to a resonance pole.
- Is $Z_c(3900)$ of a different origin? Perhaps a coupled channel effect? More work needed !

Z_c^+ channel : $|G=1^+, J^{PC}=1^{+-}|$

- HALQCD method [application on H-dibaryon: HALQCD, 1504.01717]
- application to three coupled channels that are relevant at energies of $Z_c(3900)$

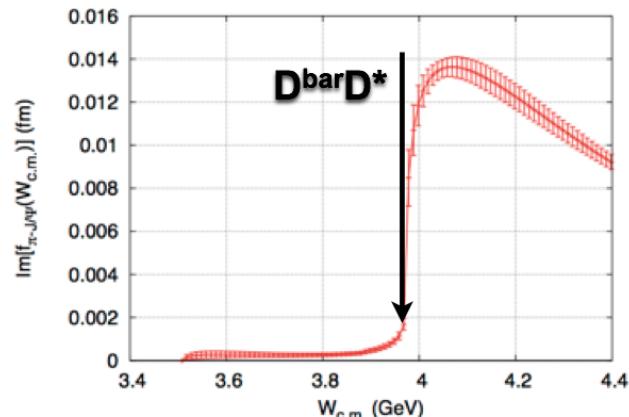


indication for
coupled channel eff.

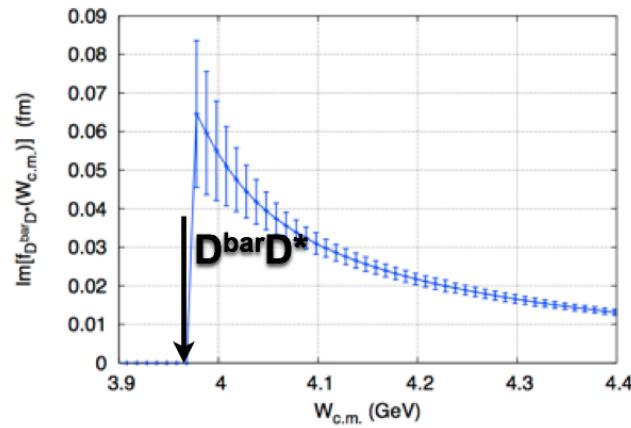
Z_c^+ channel: $|G=1^+, J^{PC}=1^{+-}$

Lattice quantity related to cross-section

- **$\pi J/\Psi$ invariant mass ($m_\pi=410\text{MeV}$)**

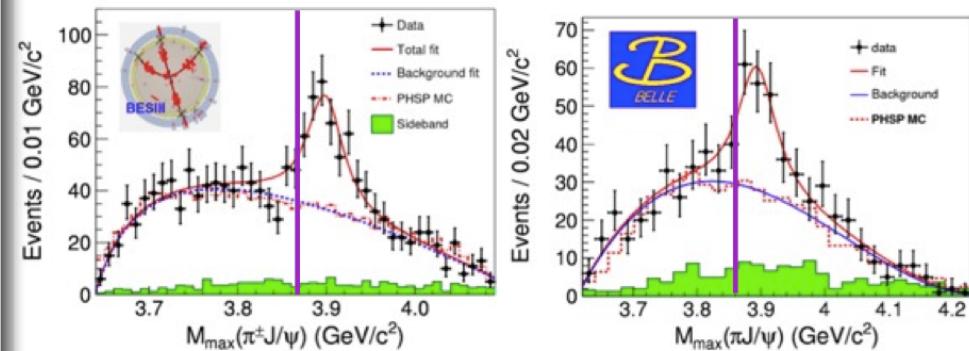


- **$D\bar{D}^*$ invariant mass ($m_\pi=410\text{MeV}$)**

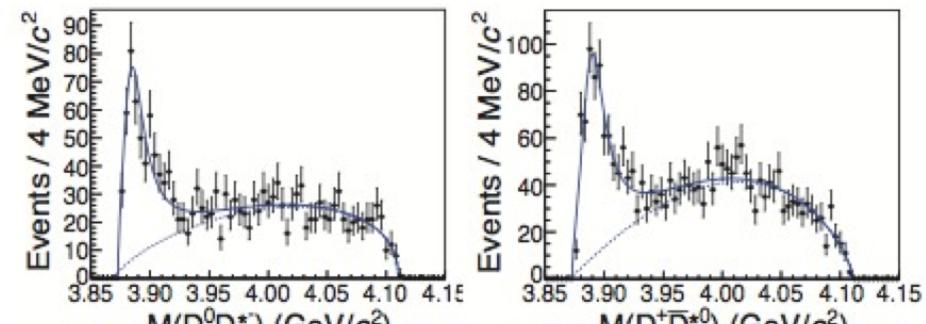


Experimental cross-section related to $Z_c^+(3900)$

- **$e^+e^- \rightarrow \pi(\pi J/\Psi) @ 4.26\text{GeV}$**



- **$e^+e^- \rightarrow \pi^{+-} (D\bar{D}^*)^{-+}$**



HALQCD coll, Ikeda et al $m_\pi \approx 410$ MeV, Nf=2+1+1
[private communication with Y. Ikeda]

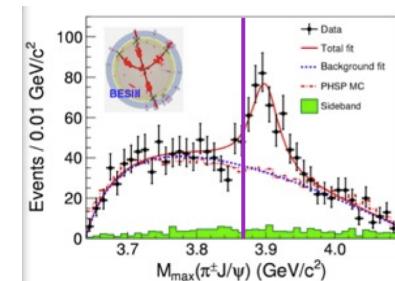
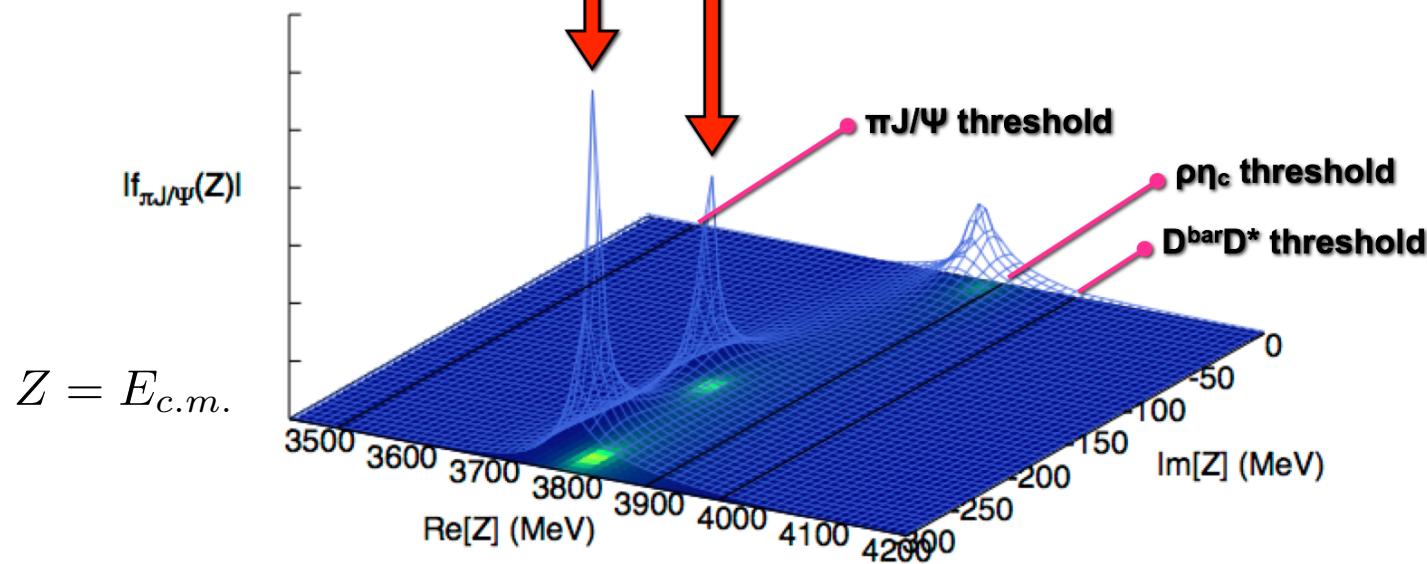
S. Prelovsek, CHARM 2015

Lineshapes resemble
experimental $Z_c(3900)$.

DD*

Z_c^+ channel : $|G=1^+, J^{PC}=1^{+-}|$

Poles of S-matrix

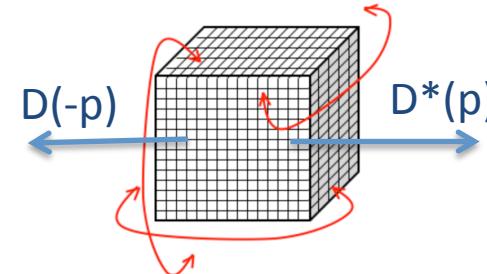
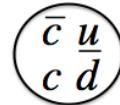
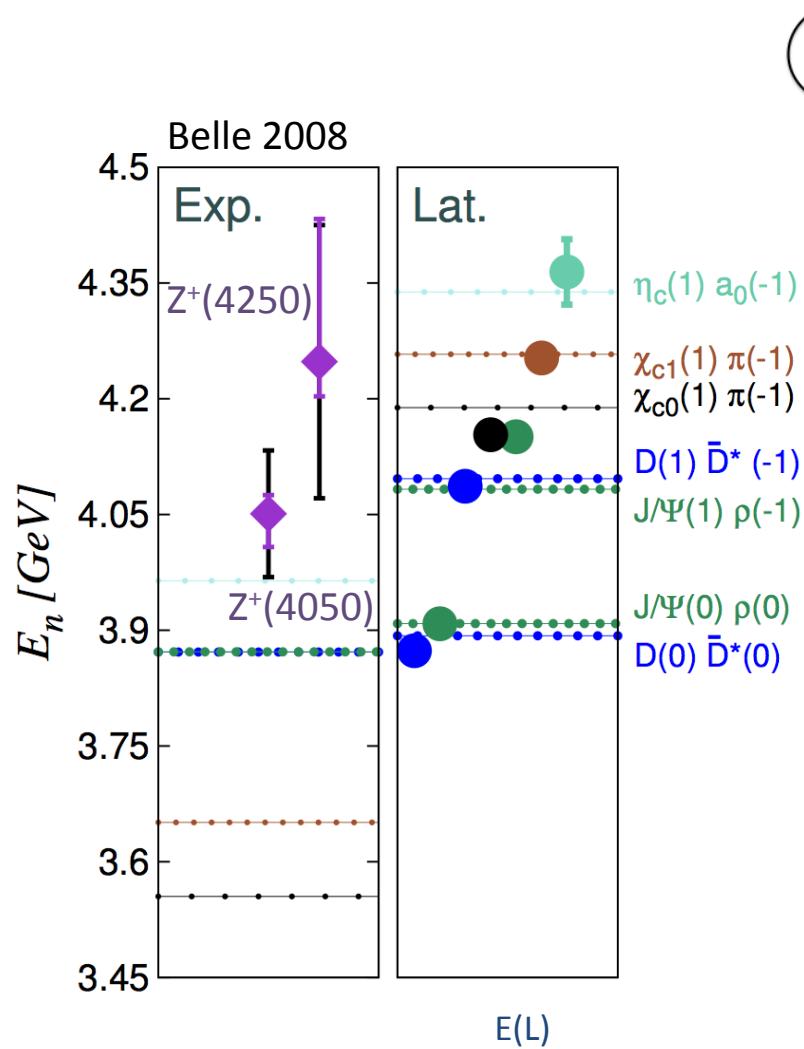


- exp: $Z_c^+(3900)$ peak appears above DD* th.
- HALQCD: poles found BELOW DD* th.
pole NOT interpreted as a resonance (such a pole would be expected above DD*)
- Remains to be seen if HALQCD result is consistent with absence of Z_c eigenstate in [S.P. et al 1405.7612] and [Lee et al. 1411.1389]

HALQCD coll, Ikeda et al $m_\pi \approx 410$ MeV, Nf=2+1+1

[private communication with Y. Ikeda]

Search for charged partner of X(3872); channel $I^G=1^-$, $J^{PC}=1^{++}$, $\bar{c}cd\bar{u}$



$$p = n \frac{2\pi}{L}$$

$$\mathcal{O} : (\bar{c}u)(\bar{d}c), (\bar{c}c)(\bar{d}u), [\bar{c}\bar{d}][cu]$$

- Horizontal lines: energies of expected two-meson states in limit of no interaction:
 $E = E[M_1(p_1)] + E[M_2(p_2)]$
- Circles: energies of eigenstates from latt
- Only expected two-meson states observed.
- **No lattice candidate for charged X(3872).**
 In agreement with absence of such state in exp.
- **No lattice candidate for other charged state below 4.3 GeV.**
- Two Belle 2008 states are exp. unconfirmed.

[M. Padmanath, C.B. Lang, S.P., 1503.03257]

$\Upsilon(4140)$, $J^{PC}=?^?+?$, ccss

Experiment:

peak in $J/\psi \Phi$ just above $J/\psi \Phi$ threshold

found: CDF 2009, CMS 2012, D0 2013, Babar 2015

not found: Belle 2010, LHCb 2012

Lattice:

- S. Ozaki and S. Sasaki, 1211.5512, PRD
caveat: strange quark annihilation neglected
no resonant $\Upsilon(4140)$ structure found

- M. Padmanath, C.B. Lang, S.P., 1503.03257

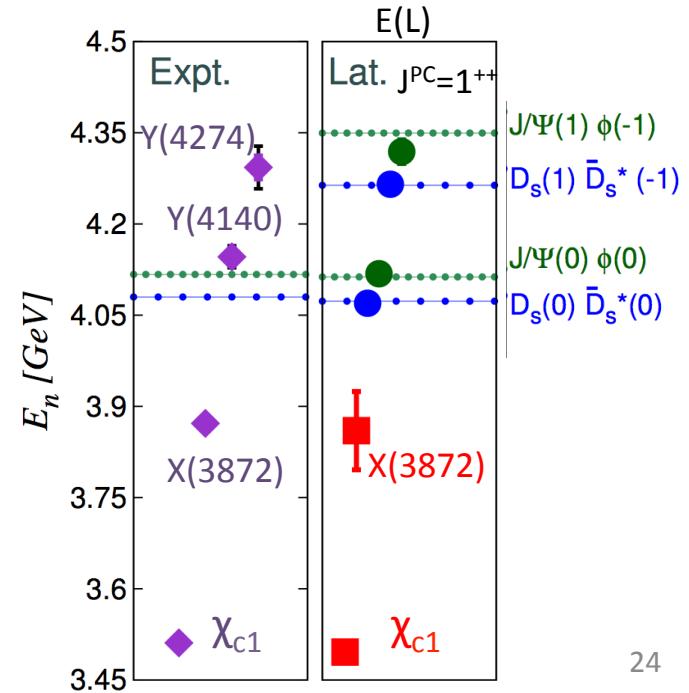
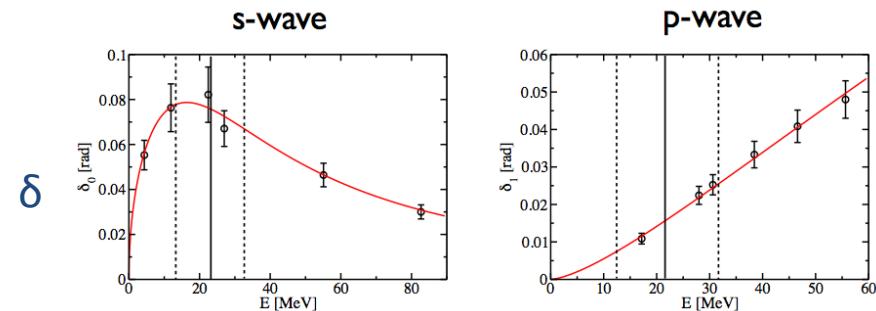
$$\mathcal{O} : \bar{c}c, (\bar{c}s)(\bar{s}c), (\bar{c}c)(\bar{s}s), [\bar{c}\bar{s}][cs]$$

channel $J^P=1^+$ considered only: expected two-particle eigenstates found and χ_{c1} , $X(3872)$ but **not $\Upsilon(4140)$**

$$Y(4140) \rightarrow J/\psi \phi$$

$$\bar{c}c \quad \bar{s}s$$

$J/\psi \Phi$ scattering phase shift [rad]

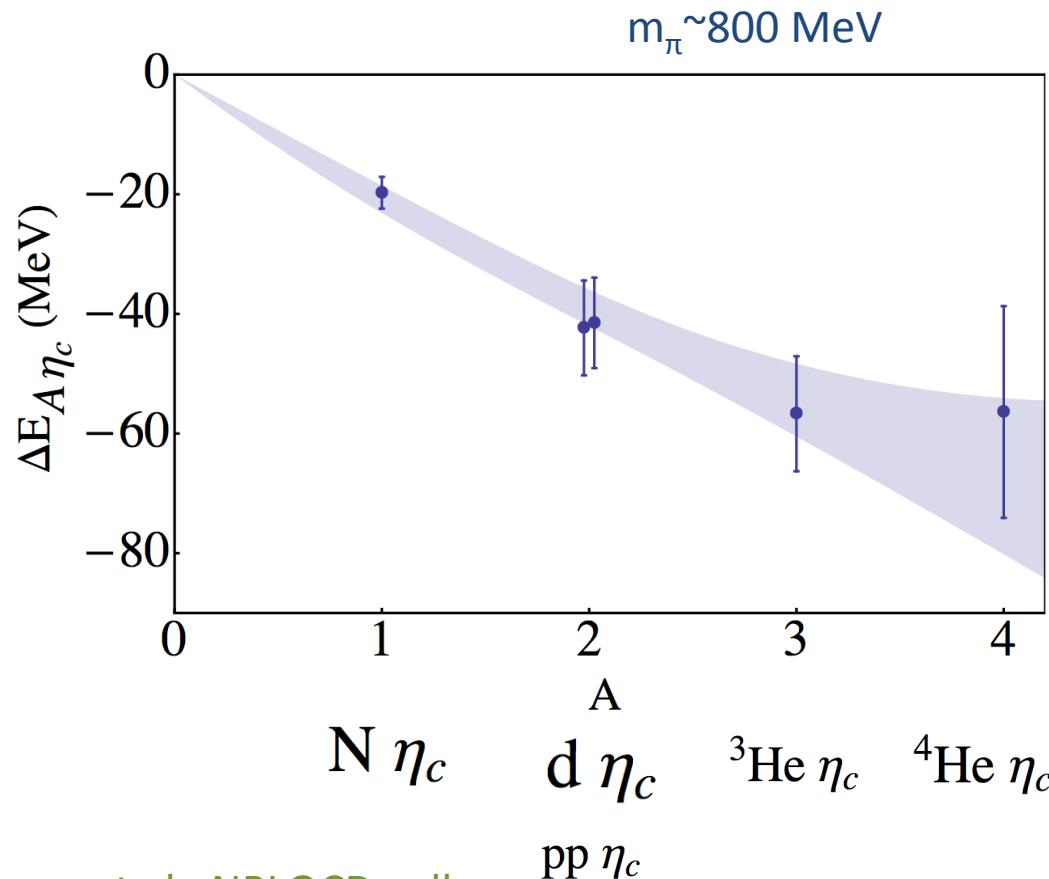


Bound states of a charmonium and a nucleus

Exp: no reliable candidates for such states yet

Lat: SU(3) symmetric point, $m_u=m_d=m_s$, $m_\pi \sim 800$ MeV, $L=3.4, 4.5, 6.7$ fm

Bound states found at this m_π . Not known yet whether these bound states survive at m_π^{phys}



Binding energies
for a system composed of
 $\eta_c + \text{nucleus } (A)$

number of nucleons
in nucleus

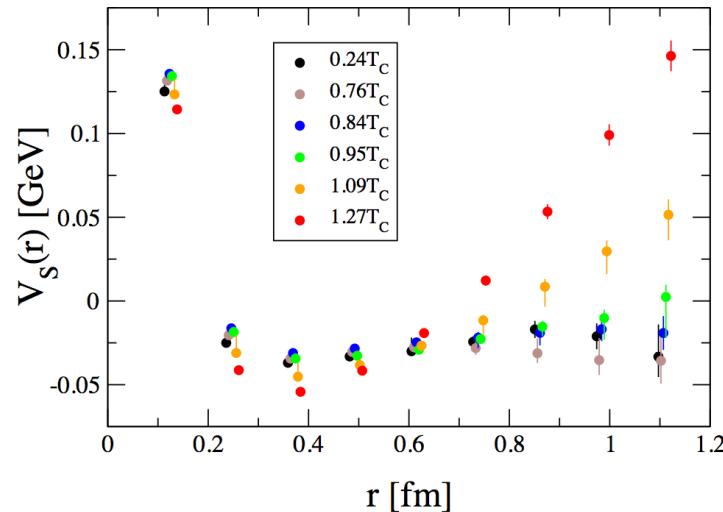
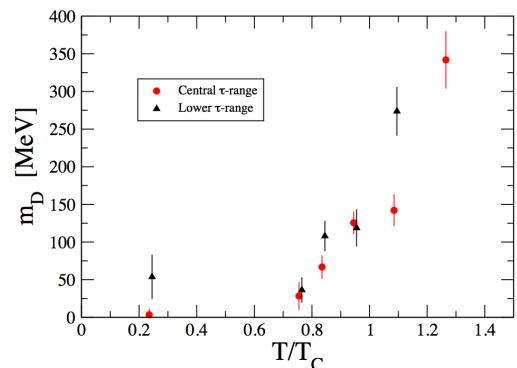
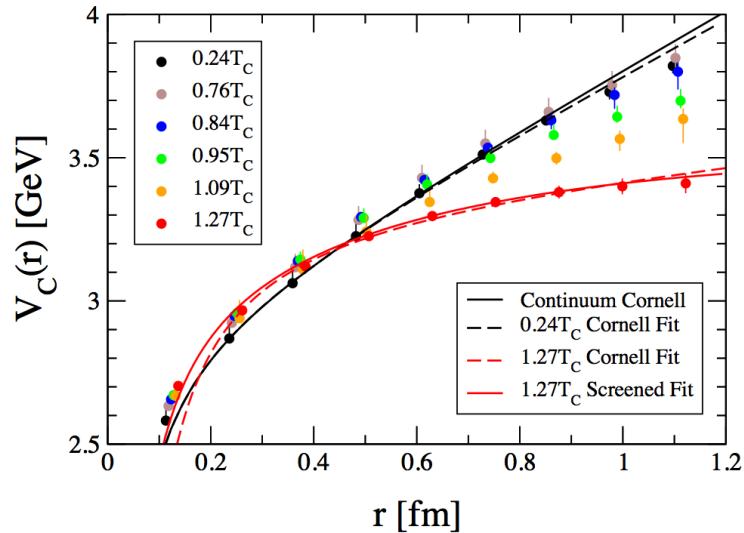
[Beane et al., NPLQCD coll. ,

1410.7069]

S. Prelovsek, CHARM 2015

$V(r)$ between c and \bar{c} at finite temperature

- HALQCD time-dependent method [HALQCD, PLB712, 437] to extract $V(r)$ for non-static c quark
- $m_\pi \sim 400$ MeV, Nf=2+1 [Allton et al, FASTSUM, private com.]



$$V_\Gamma(\mathbf{r}) = V_C(\mathbf{r}) + V_S(\mathbf{r}) s_1 \cdot s_2$$

Two fits for $V_C(r)$: Cornell fit (upper), screening fit (lower)

$$V(r, T) = -\frac{\alpha_c(T)}{r} + \sigma(T)r + C,$$

$$V(r, T) = -\frac{\alpha_s(T)}{r} e^{-m_D(T)r} + \frac{\sigma(T=0)}{m_D(T)} \left(1 - e^{-m_D(T)r}\right) + C,$$

Conclusions

Status of charmonium and charmonium-like spectrum from lattice QCD:

- Recent years have seen huge progress in lattice treatment of states near and above threshold by simulating scattering of two mesons and determining the scattering-matrix

- Evidence found for states with non-exotic flavor:

- states well below th. : all charmonia in good agreement with exp
- shallow bound states : $X(3872)$ with $I=0$,
- resonances via BW : $\Psi(3770)$, puzzles remain for excited scalar charmonia

All these (and other conventional hadrons) manifest themselves via an additional energy eigenstate !

- No reliable evidence for manifestly exotic states $cc\bar{u}\bar{d}$ yet (at least by searching an additional eigenstate in $E(L)$)

- $Z_c^+ = c\bar{c}u\bar{d}$, $J^{PC}=1^{+-}$ (HALQCD result possibly explains exp enhancement related to $Z_c(3900)$)
- $X^+(3872) = c\bar{c}u\bar{d}$, $J^{PC}=1^{++}$ (not present in exp either)
- $Y(4140) = c\bar{c}s\bar{s}$, $J^{PC}=1^{++}$

- Indication for **bound states of charmonium + nucleus** at SU(3) symmetric point with $m_\pi \sim 800$ MeV

- Further simulations and necessary analytical work ongoing!

Backup slides

Z_c^+ channel : $|G=1^+, J^{PC}=1^{+-}|$

18 two-meson
(MM)

Aiming at 9 two-meson states listed in previous slide

Interpolating fields

$$\mathcal{O}_1^{\psi(0)\pi(0)} = \bar{c}\gamma_i c(0) \bar{d}\gamma_5 u(0),$$

$$\mathcal{O}^{\psi(1)\pi(-1)} = \sum_{e_k=\pm e_x,y,z} \bar{c}\gamma_i c(e_k) \bar{d}\gamma_5 u(-e_k),$$

$$\mathcal{O}^{\eta_c(0)\rho(0)} = \bar{c}\gamma_5 c(0) \bar{d}\gamma_i u(0),$$

$$\mathcal{O}_1^{D(0)D^*(0)} = \bar{c}\gamma_5 u(0) \bar{d}\gamma_i c(0) + \{\gamma_5 \leftrightarrow \gamma_i\},$$

$$\mathcal{O}^{D^*(0)D^*(0)} = \epsilon_{ijk} \bar{c}\gamma_j u(0) \bar{d}\gamma_k c(0),$$

and 13 others ..

4 diquark-antidiquark (4Q)

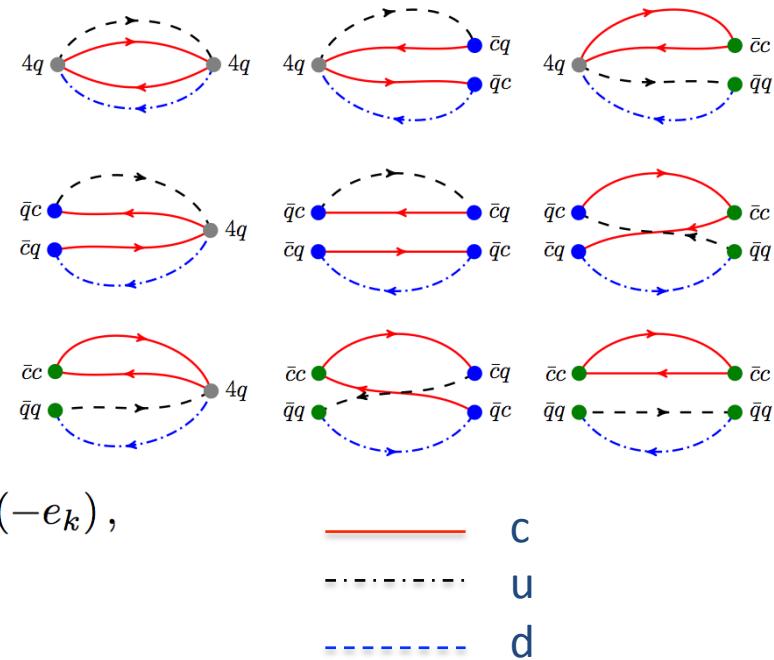
Aiming to find additional state related to exotic Z_c^+

$$\mathcal{O}_1^{4q} \approx [\bar{c} C \gamma_5 \bar{d}]_{3_c} [c \gamma_i C u]_{\bar{3}_c}$$

$$\mathcal{O}_2^{4q} \approx [\bar{c} C \bar{d}]_{3_c} [c \gamma_i \gamma_5 C u]_{\bar{3}_c}$$

and 2 others ..

[S.P., Lang, Leskovec, Mohler,
1405.7612, PRD 2015]

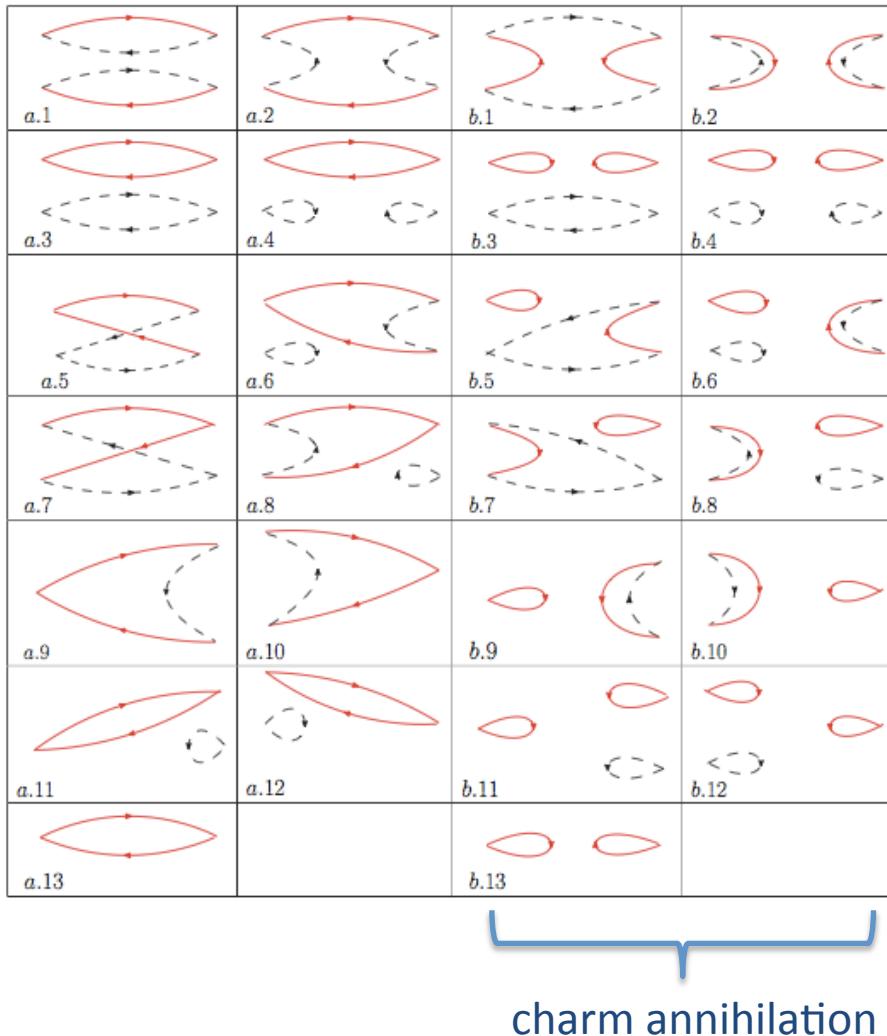


Wick contractions

$$C_{ij}(t) = \langle 0 | \mathcal{Q}_i(t) \mathcal{Q}_j^\dagger(0) | 0 \rangle$$

X(3872), 1⁺⁺, I=0

$$\mathcal{O}: \bar{c} c, \quad D\bar{D}^* = (\bar{c}u)(\bar{u}c) + (\bar{c}d)(\bar{d}c), \quad J/\psi\omega = (\bar{c}c)(\bar{u}u + \bar{d}d)$$



- all Wick contractions calculated using distillation method [Peardon et al. 2009]

- charm annihilation contractions not used in analysis

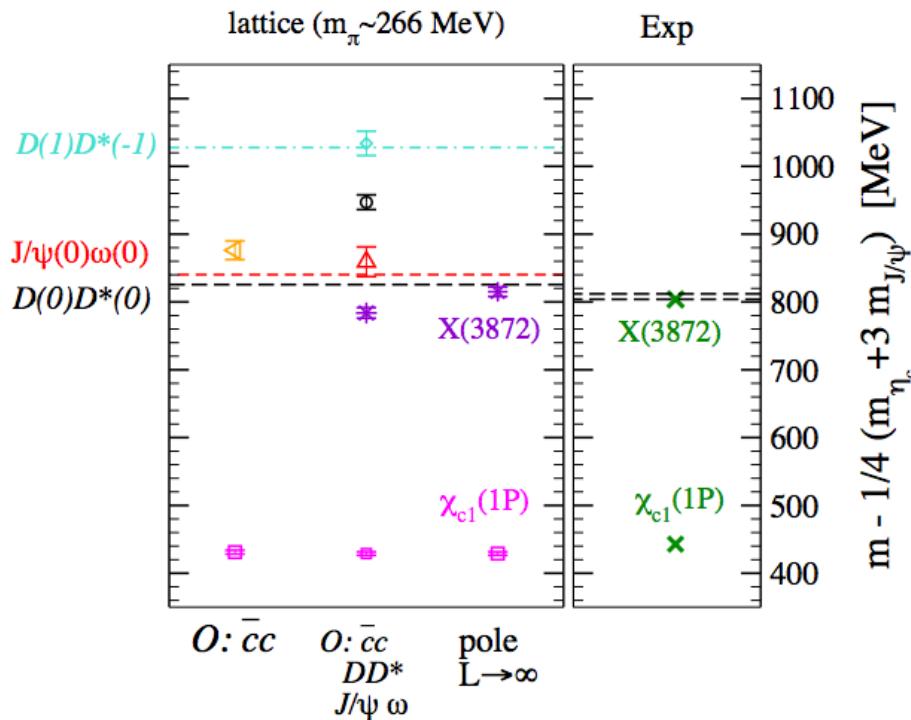
c quark
 u,d quarks

[S.P. and L. Leskovec,
Phys.Rev.Lett. 2013]

X(3872) : $J^{PC}=1^{++}$, I=0: finite volume spectrum E(L)

$\mathcal{O} : \bar{c} c, DD^*, J/\psi \omega$

$\mathcal{O} : \bar{c} c, DD^*$



S. P. and L. Leskovec : 1307.5172, PRL 2013

$$p \cot \delta(p) = \frac{1}{a_0} + \frac{1}{2} r_0 p^2$$

$$a_0 = -1.7 \pm 0.4 \text{ fm}$$

$$r_0 = 0.5 \pm 0.1 \text{ fm}$$

[Lee, DeTar, Na, Mohler ,
update of proc 1411.1389]