Charmonia above and at open thresholds from lattice QCD

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in collaboration with C.B. Lang, L. Leskovec, D. Mohler and M. Padmanath

Outline

- charmonia well below DD thresholds : “straightforward” on the lattice

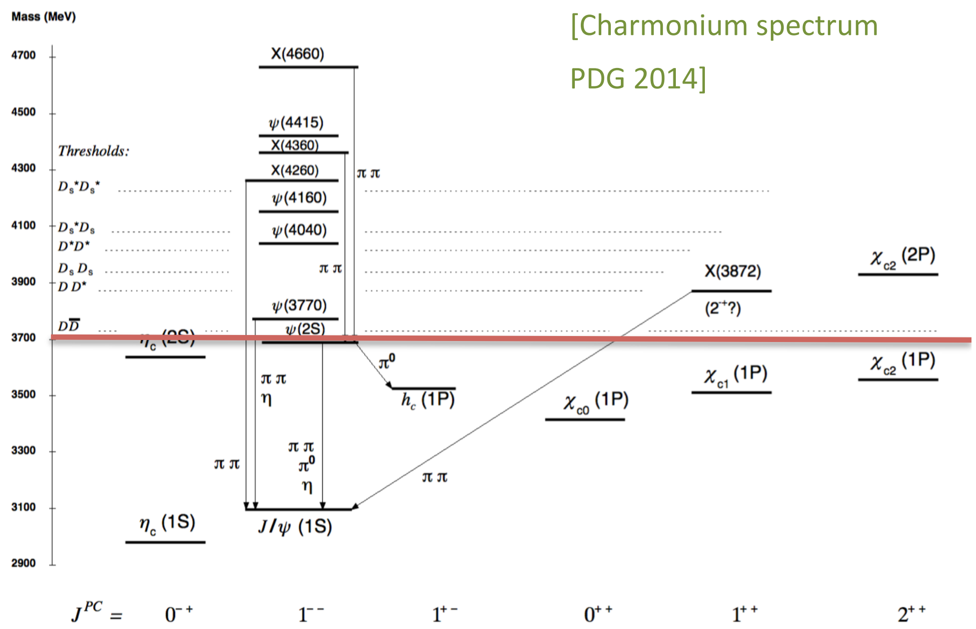
- First lattice QCD study of “conventional” charmonium resonances above open-charm threshold taking into account strong decay

  [Lang, Leskovec, Mohler, S.P., 1503.05363, JHEP 2015]

$$J^{PC} = 1^{--}: \ \psi(3770) \to D\bar{D}$$
$$J^{PC} = 0^{++}: \ \chi_{c0}(2P) \to D\bar{D}$$

  not clear which exp state corresponds to χ_{c0}(2P)

  -> happy to discuss this puzzling channel after the talk in person



[Charmonium spectrum PDG 2014]

- Three channels with $J^{PC}=1^{++}$

  [M. Padmanath, C.B. Lang, S.P., 1503.03257, PRD 2015]

$$\bar{c}c(\bar{u}u+\bar{d}d), \ I=0, \ X(3872)$$
$$\bar{c}c\bar{u}d, \ I=1, \ \text{charged } X(3872) \ ?$$
$$\bar{c}c\bar{s}s, \ I=0, \ Y(4140) \ ?$$

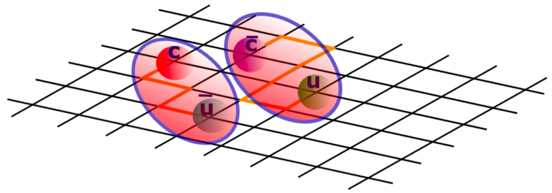
- Zc^+(3900) with HALQCD method, [HALQCD, Ikeda et al, 1602.03465]

Lattice gives discrete energies of eigenstates: E_n

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

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

$$1{-}{-}: \qquad \bar{c}c\,, \quad (\bar{c}u)(\bar{u}c) = D\bar{D}\,, \qquad [\overline{cu}][cu]$$



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

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

- "single-meson" states **J/Ψ** — $m=E_1$ for P=0 (after extrapolations)

  Ψ(2S)

- "two-meson" states $D\bar{D}, \ldots$ — E_n rigorously render two-hadron scattering matrix (for example D$\underline{\text{D}}$ 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

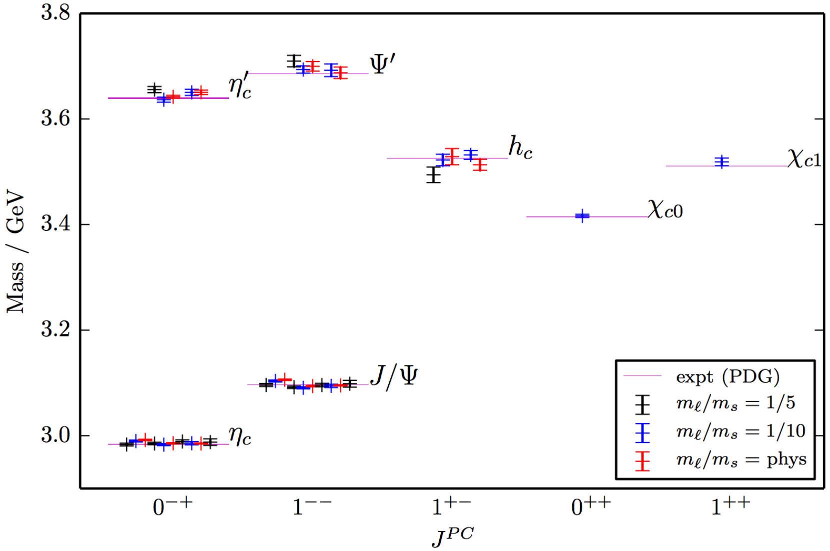
$\bar{c}c$

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

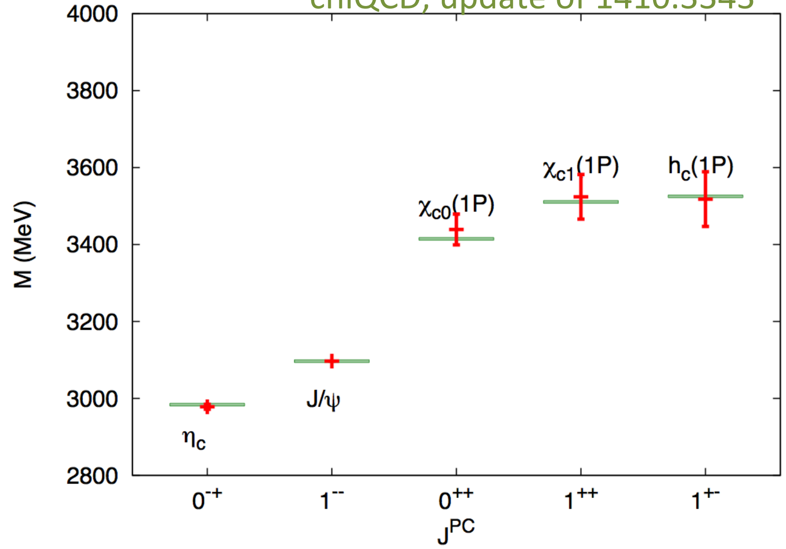
Charmonia well below DD: recent precision results

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

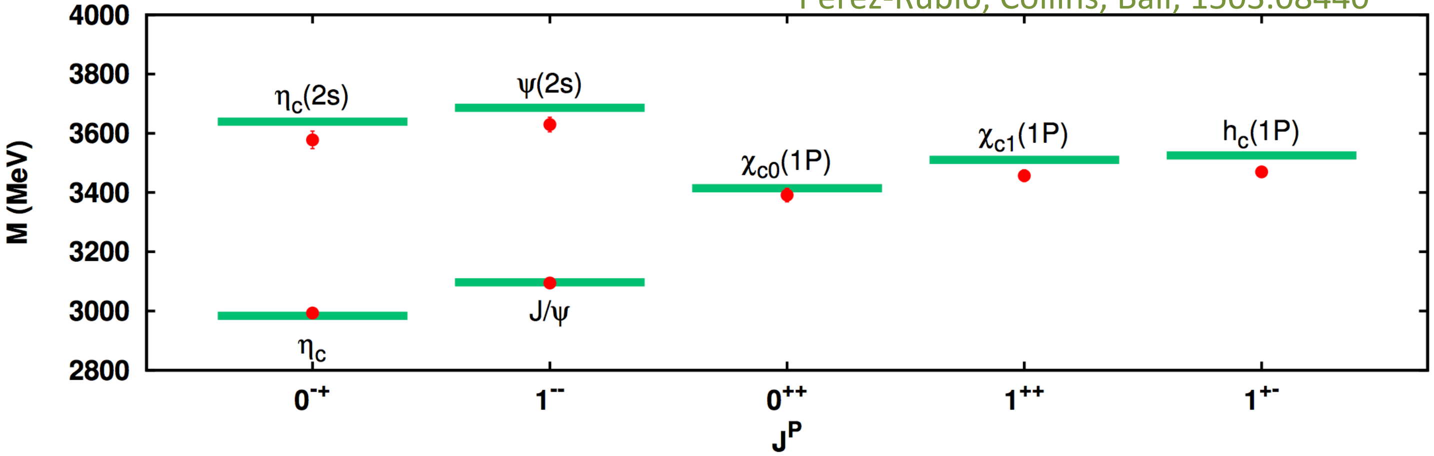
HPQCD, 1411.1318



chiQCD, update of 1410.3343



Perez-Rubio, Collins, Bali, 1503.08440



see also:

FNAL/MILC, 1412.1057

The omission of charm annihilation is the main remaining uncertainty

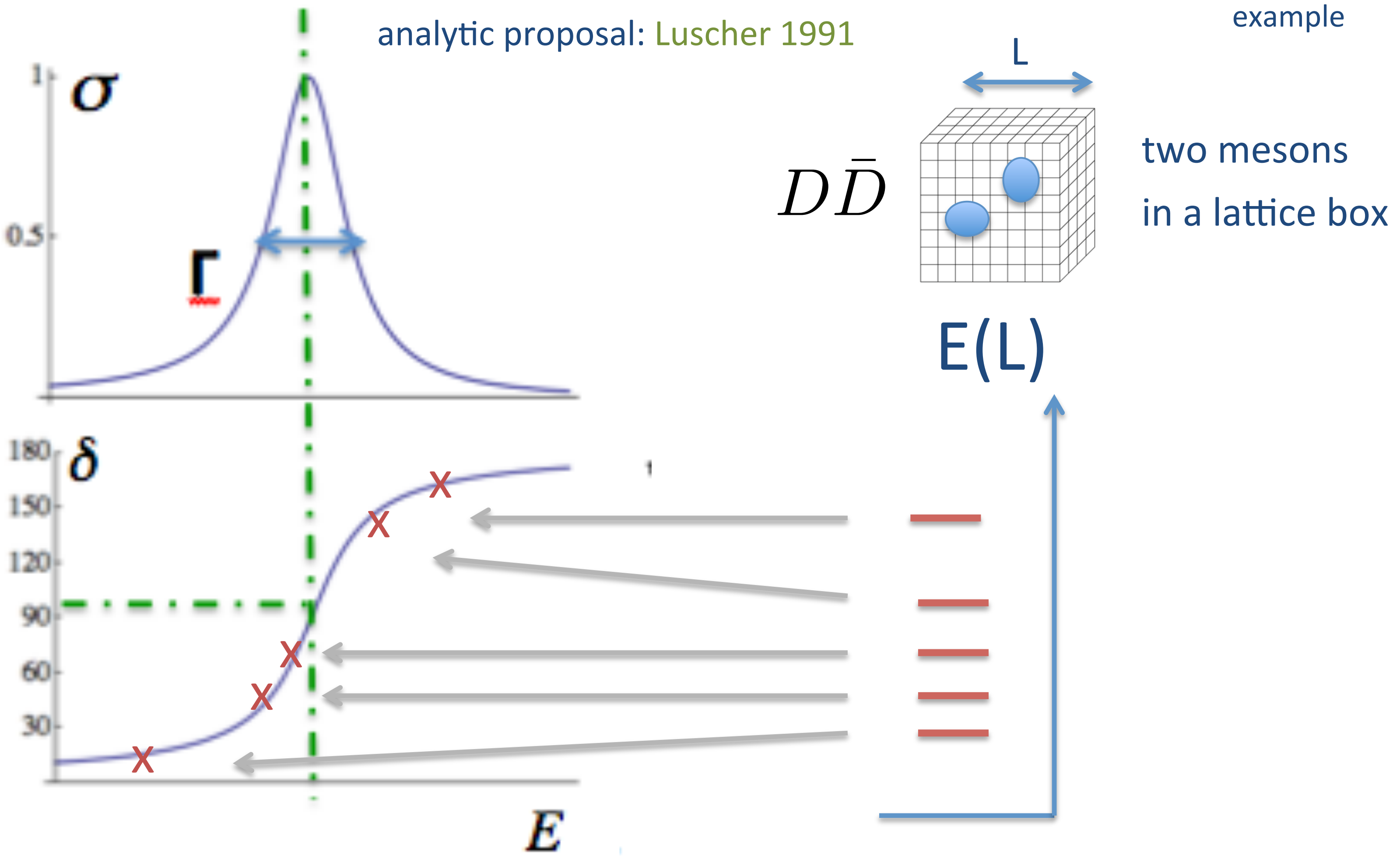
Rigorous treatment of hadrons near or above threshold:

scattering of two mesons in elastic channel

$$D\bar{D} \to \psi(3770) \to D\bar{D}$$

example

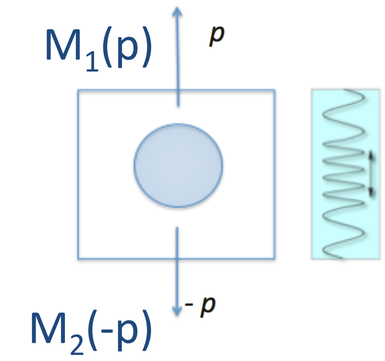
analytic proposal: Luscher 1991



scattering phase shifts at infinite volume δ(E) ← E(L) energies from lattice with spatial extent L

Scattering of two mesons

one-channel (elastic) scattering with total momentum P=0: $E=E_{cm}$



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

Scattering matrix for partial wave l

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

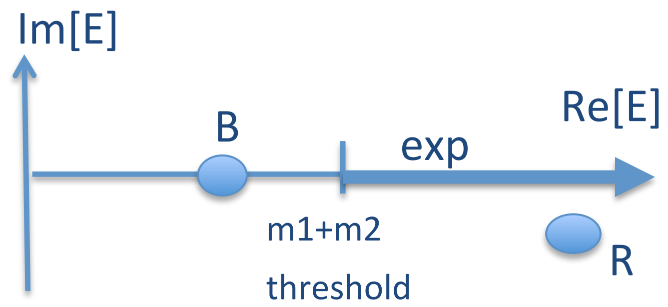
Bound state (B):

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

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.



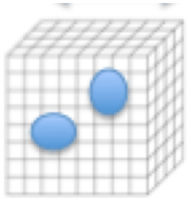
Two types of plots will be shown:

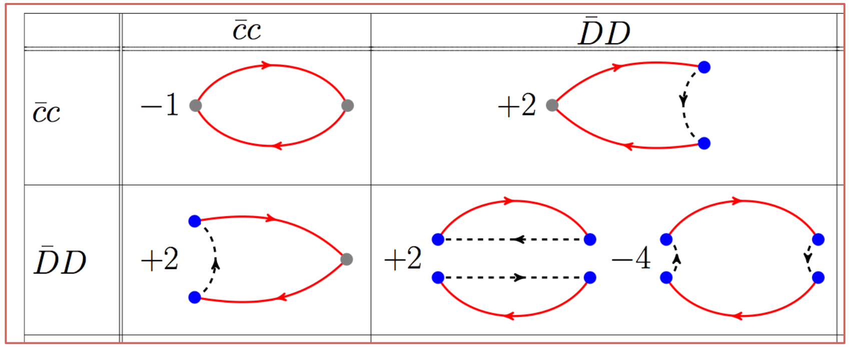
- E(L) energies of lat. eigenstates
- $m^{phy} = m_R$, m_B extracted from E(L)

Resonance ψ(3770) and bound st. ψ(2S) from DD scattering in p-wave

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

$D\bar{D}$





c quark

u,d quarks

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

$$D\bar{D} \to \psi(3770) \to D\bar{D}$$

Charm annihilation Wick contractions omitted
(like in all charmonium-like lattice simulations)

$$E_n \quad \to \quad \delta(E_n)$$

First lattice simulation of a charmonium resonance above open-charm threshold taking into account its strong decay $\psi(3770) \to D\bar{D}$

Lang, Leskovec, Mohler, S.P., 1503.05363, JHEP 2015

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

$$E_n \;\to\; \delta(E_n) \;\to\; p^3 \cot\delta(p)/\sqrt{s}$$

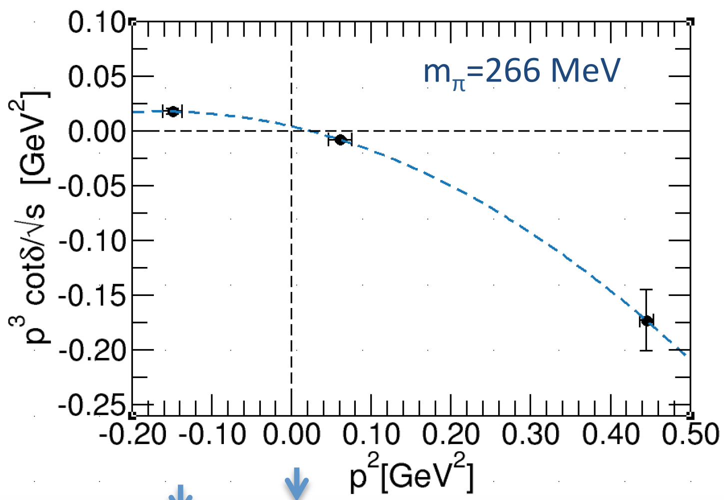
Fitting the resulting phase shift

$$\frac{p^3}{\sqrt{s}} \cot\delta_1(s) = A + Bp^2 + Cp^4$$

Bound state: cot δ(p_B) = i

$$T \propto \frac{1}{\cot\delta - i}$$

Resonance : m_R: δ=90°, cot δ=0, Γ_R : slope near zero



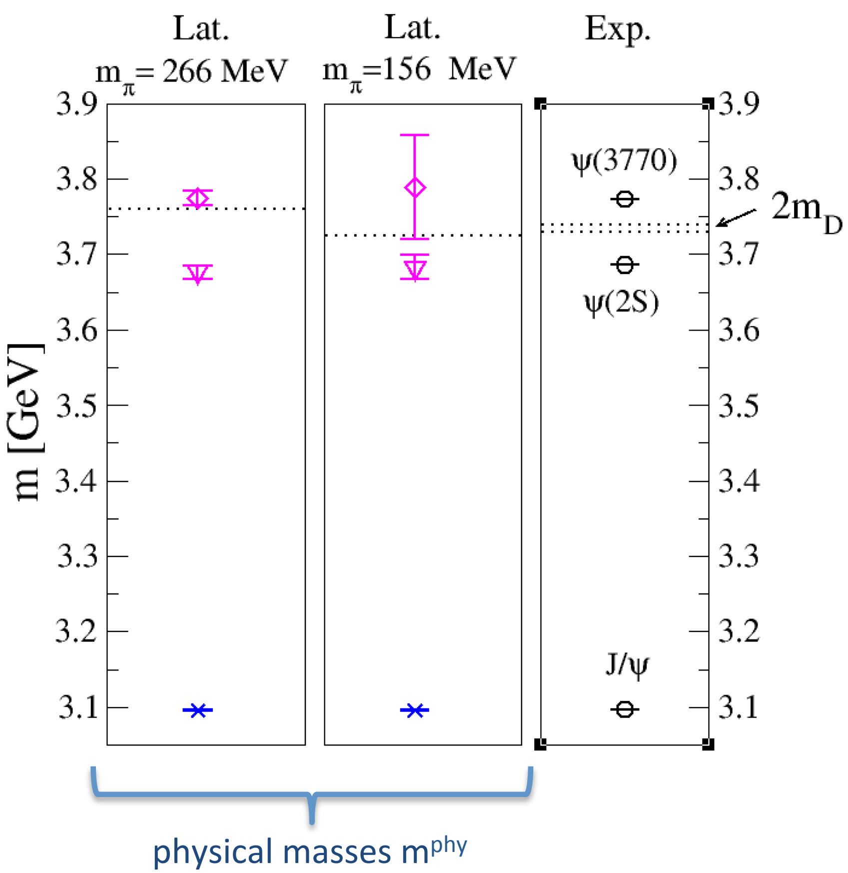
$$\frac{p^3 \cot\delta}{\sqrt{s}}$$

$\psi(2S)$ DD threshold

$\eta_c(1S)$
$J/\psi(1S)$
$\chi_{c0}(1P)$
$\chi_{c1}(1P)$
$h_c(1P)$
$\chi_{c2}(1P)$
$\eta_c(2S)$
$\psi(2S)$
$2m_D$
$\psi(3770)$
$X(3872)$
$\chi_{c0}(2P)$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, JHEP 2015

Resonance ψ(3770) and bound st. ψ(2S) from DD scattering in p-wave



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

DD scat. in p-wave is simulated

$$E_n \rightarrow \delta(E_n)$$

T-matrix is determined from E_n

and interpolated near threshold:

Bound state ψ(2S) from pole in T:

cot $\delta(p_B)$ = i

m_B (triangles)

$$T \propto \frac{1}{\cot\delta - i}$$

Resonance ψ(3770): $\delta(m_R)=90^o$

m_R (diamonds), Γ (given below)

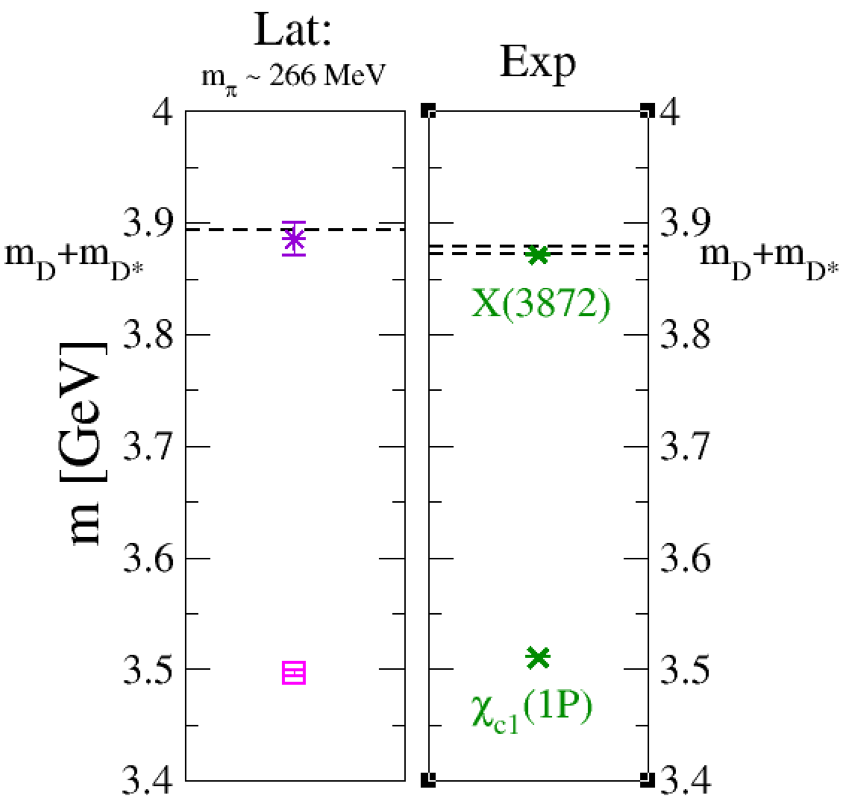
$\eta_c(1S)$
$J/\psi(1S)$
$\chi_{c0}(1P)$
$\chi_{c1}(1P)$
$h_c(1P)$
$\chi_{c2}(1P)$
$\eta_c(2S)$
$\psi(2S)$
$2m_D$
$\psi(3770)$
$X(3872)$
$\chi_{c0}(2P)$wa
$\chi_{c2}(2P)$
$X(3940)$
$\psi(4040)$
$X(4050)^\pm$
$X(4140)$
$\psi(4160)$
$X(4160)$
$X(4250)^\pm$

ψ(3770)	Mass [MeV]	g (no unit)
Lat (m_π=266 MeV)	3774 ±6±10	19.7 ±1.4
Lat (m_π=156 MeV)	3789 ±68±10	28 ± 21
Exp.	3773.15± 0.33	18.7 ± 1.4

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

Lang, Leskovec, Mohler, S.P., 1503.05363, JHEP 2015]

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



physical masses m^{phy}

$$\mathcal{O}:\quad \bar{c}\,c,\quad D\bar{D}^*,\ [\overline{cu}]_{3c}[cu]_{3c},\ [\overline{cu}]_{6c}[cu]_{6c}$$

- ground state: χ_{c1}(1P)
- D$\underline{\text{D}}$* scattering matrix near th. determined

$$p\cot\delta(p)=\frac{1}{a_0}+\frac{1}{2}r_0p^2,\qquad a_0<0$$

$$T\propto\frac{1}{\cot\delta-i}=\infty$$

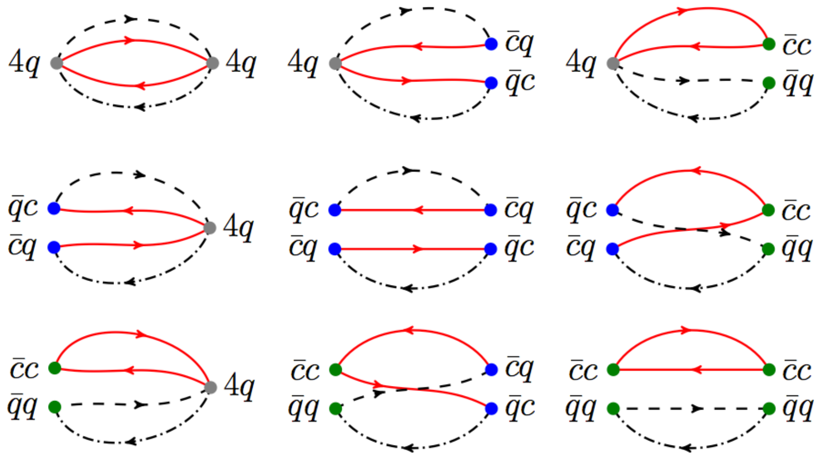
- A pole of found just below th. (violet star)
- The pole attributed to X(3872), which is a shallow bound state

[M. Padmanath, C.B. Lang, S.P., 1503.03257, PRD 2015]

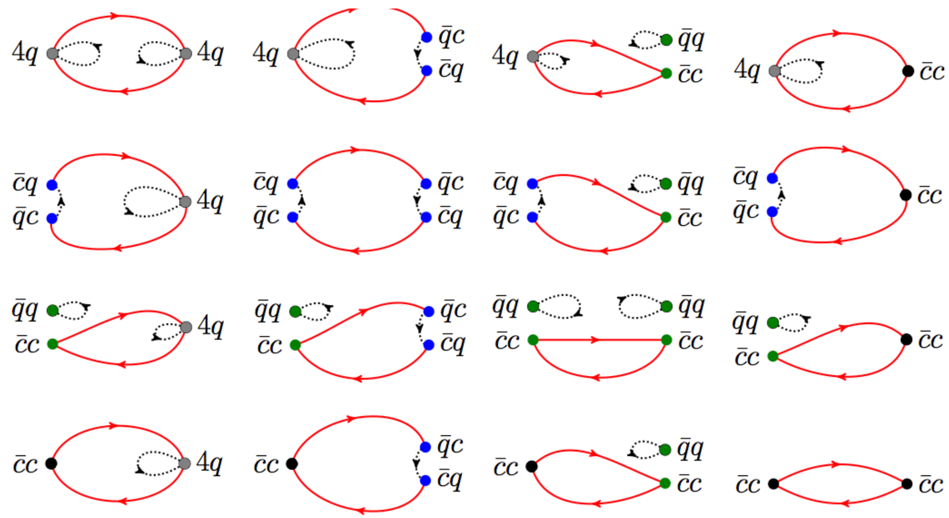
m_π≈266 MeV, a=0.124 fm, L= 2 fm

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

$J^{PC}=1^{++}$ $\quad \mathcal{O}:\ \bar{c}\,c,\ \ \underbrace{D\bar{D}^*,\ J/\psi\omega,\ \chi_{c1}\sigma,\ \eta_c\sigma,}_{(\bar{c}q)_{1_c}(c\bar{q})_{1_c},\ (\bar{c}c)_{1_c}(\bar{q}q)_{1_c}}\ \ [\overline{cu}]_{3c}[cu]_{3c},\ [\overline{cu}]_{6c}[cu]_{6c}$



(a)



(b)

[M. Padmanath, C.B. Lang, S.P., 1503.03257, PRD 2015]

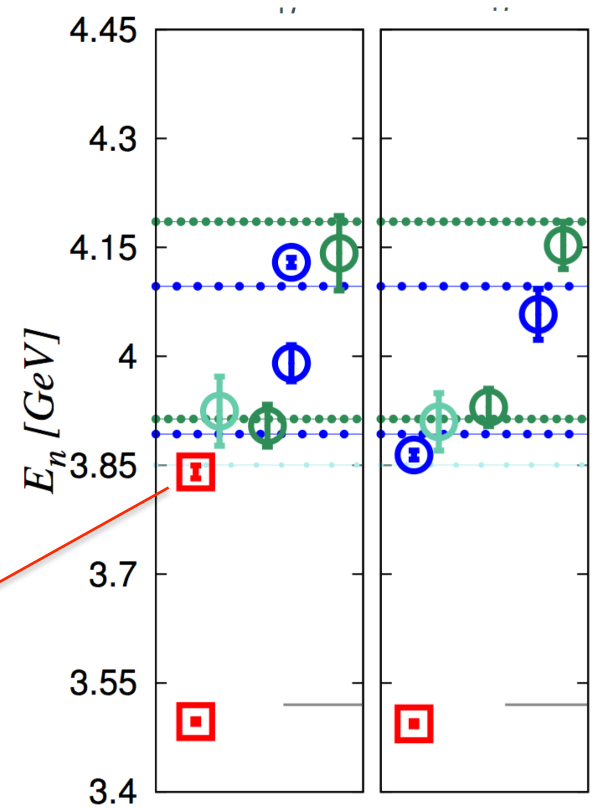
Which Fock components are essential for X(3872) with I=0 ?

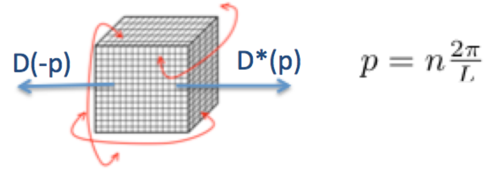
localaized diquark antidiquark

$$\mathcal{O}:\ \underbrace{\bar{c}\,c,\quad D\bar{D}^*}_{\text{essential}},\ J/\psi\omega,\ \chi_{c1}\sigma,\ \eta_c\sigma,\ \underbrace{[\overline{cu}]_{3c}[cu]_{3c},\ [\overline{cu}]_{6c}[cu]_{6c}}_{\text{do no seem not essential}}$$

interpolating fields

O: all O: all without cc





m_π≈266 MeV

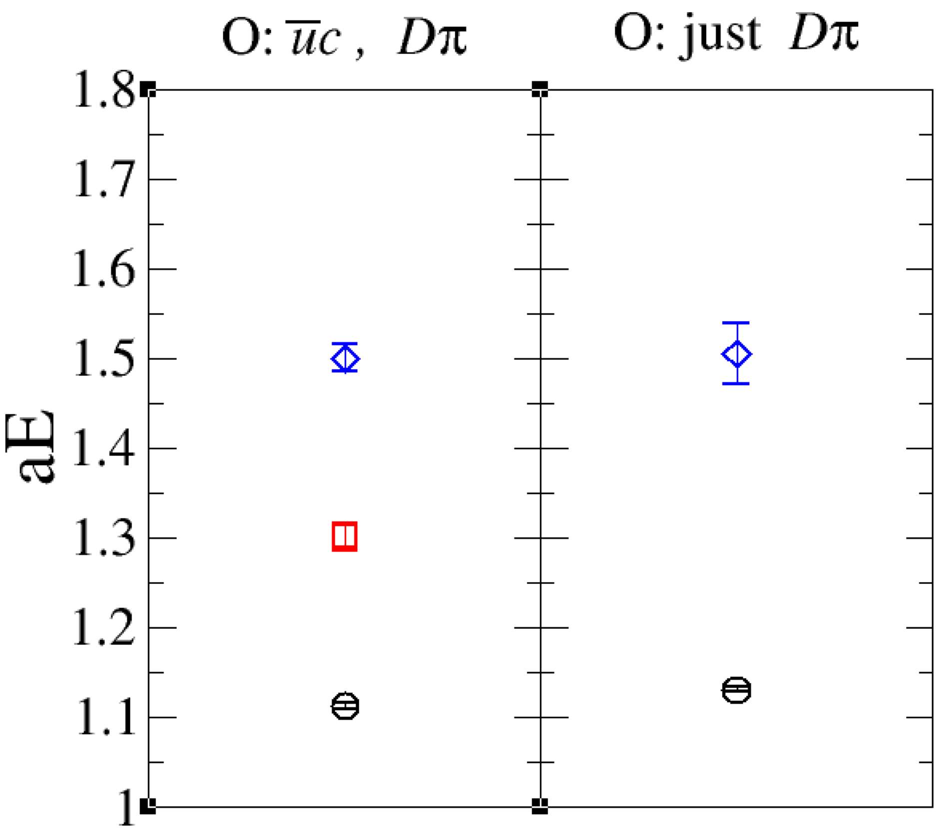
upper red square is candidate for X(3872): it is found only if cc in the basis

X(3872) not found if cc not in the basis, although [cu][cu] in the basis

[M. Padmanath, C.B. Lang, S.P., 1503.03257, PRD 2015]

energies of eigenstates on lattice E(L) (these are not m^{phy})

Illustration how eigenstate $D_0^*(2400)$ dominated by "$\bar{q}q$" dissapears when $\bar{q}q$ interpolators omitted



→ D(1)π(-1)

→ $D_0^*(2400)$ $\quad \bar{u}c \quad J^{PC} = 0^{++}$

→ D(0)π(0)

Effective energies at t=8 plotted.

[Mohler, S.P., Woloshyn, PRD 87 (2013) 034501]

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

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

$\bar{c}\ u$
$c\ \bar{d}$

- Simulation is done in the isospin limit: $m_u=m_d$
- **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**

Search for Y(4140) in channel $J^{PC}=1^{++}$, $\underline{c}c\underline{s}s$

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

- **No lattice candidate for Y(4140) or other candidate below 4.3 GeV found**
- Note: experimentaly J^{PC} of Y(4140) is unknown; 1^{++} is not favored by phenomenology anyway.

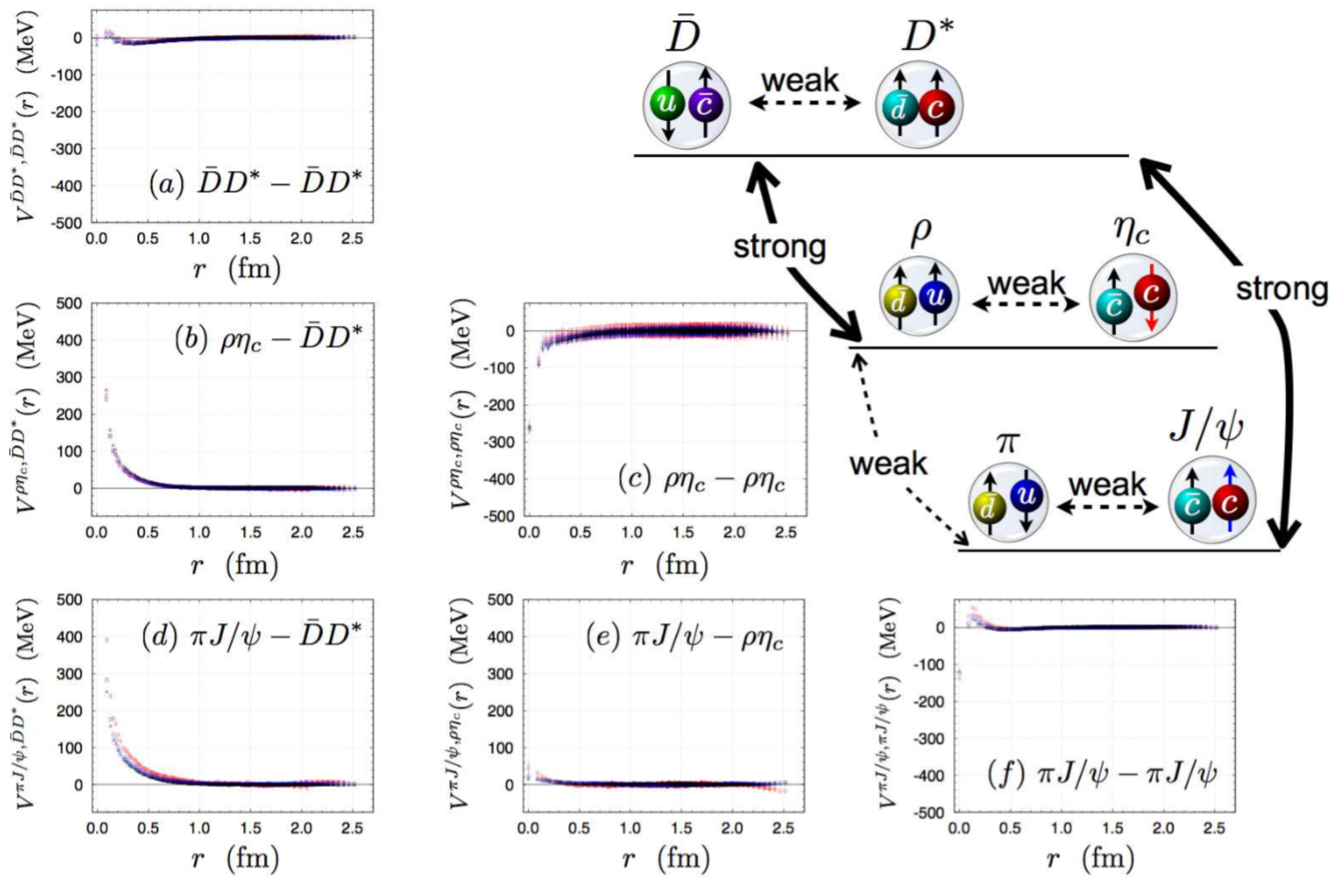
[M. Padmanath, C.B. Lang, S.P., PRD 2015, 1503.03257]

[HALQCD, Ikeda et al, 1602.03465]

$Z_c^+(3900)$ channel : $I^G=1^+$, $J^{PC}=1^{+-}$ HALQCD method V(r)

HALQCD is another method to extract scattering matrix from lattice

(considered to be less rigorous than the Luscher's method for coupled channels)

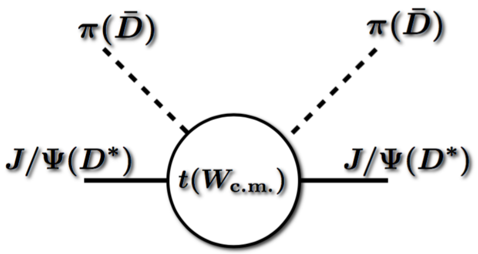


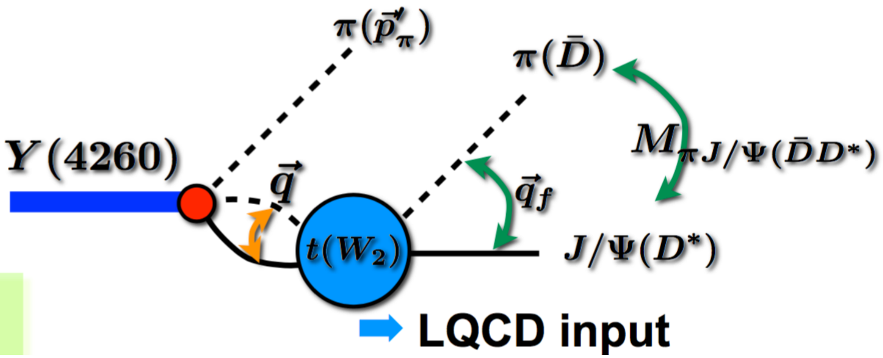
$$C^{\alpha\beta}(\vec{r},t) \equiv \sum_{\vec{x}} \langle 0|\, \phi_1^\alpha(\vec{x}+\vec{r},t)\phi_2^\alpha(\vec{x},t)\overline{\mathcal{J}}^\beta \,|0\rangle \,/\sqrt{Z_1^\alpha Z_2^\alpha},$$

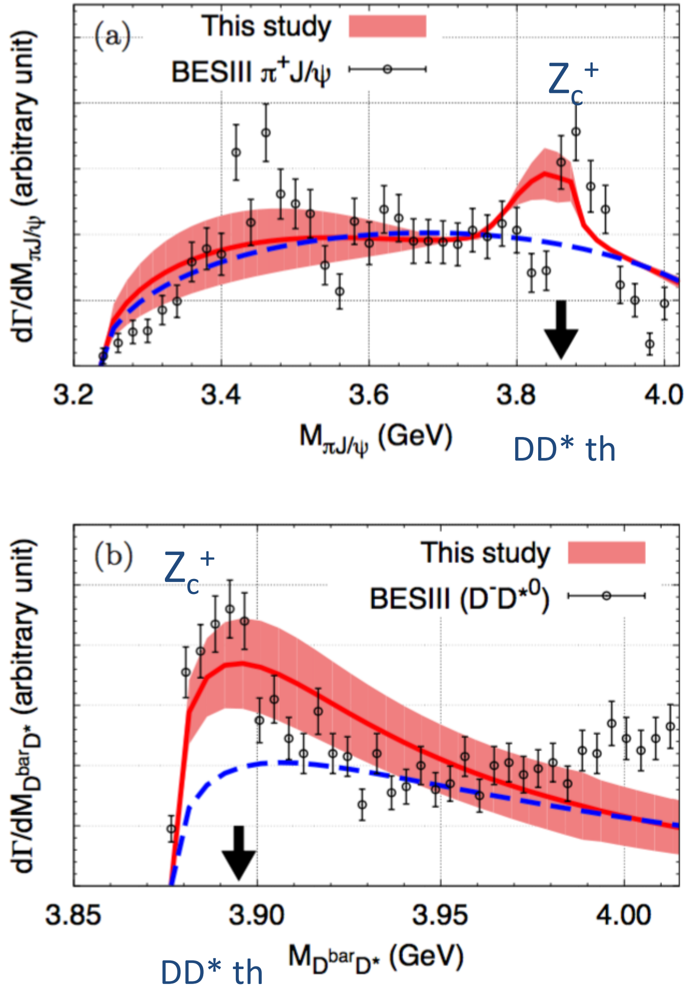
$$R^{\alpha\beta}(\vec{r},t) \equiv C^{\alpha\beta}(\vec{r},t)e^{(m_1^\alpha+m_2^\alpha)t}$$

$$\left(-\frac{\partial}{\partial t} - H_0^\alpha\right)R^{\alpha\beta}(\vec{r},t) \simeq \sum_\gamma \Delta^{\alpha\gamma}\int d\vec{r}'\, U^{\alpha\gamma}(\vec{r},\vec{r}')R^{\gamma\beta}(\vec{r}',t)$$

Z_c^+ channel , three-body Y(4260) decay: lattice & exp

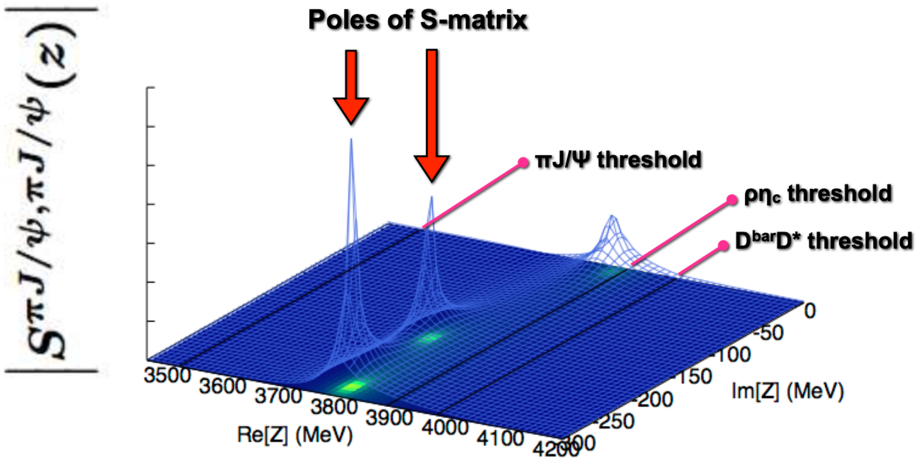




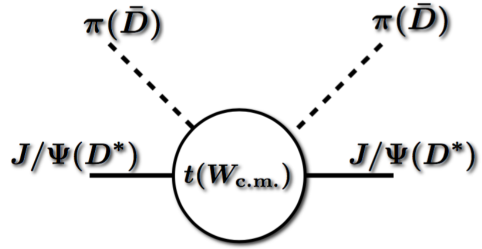


[HALQCD, Ikeda et al, 1602.03465]

Z_c^+ channel : HALQCD method , poles of S in complex plane



Second Riemann sheet for all three channels shown.



[HALQCD, Ikeda et al, 1602.03465]

Remarks:

- HALQCD method not considered as rigorous as the Luscher's method for coupled channels
- 3x3 matrix S in Zc channel has not been determined by Luscher method yet
- HALQCD method has not verified any of the conventional resonances yet (to my knowledge)
- Luscher's method has been verified on conventional res. like ρ, K*, ψ(3770), D_0(2400) ...

Conclusions & Outlook

- quarkonia <u>well below strong decay threshold</u>: easy, under control

- resonances and shallow bound states where <u>one channel dominates</u>:

  first rigorous results for chamonium-like state obtained during past few years:

  - first simulation of charmonium resonance $D\bar{D} \to \psi(3770) \to D\bar{D}$

    [Lang, Leskovec, Mohler, S.P., 1503.05363, JHEP 2015]

  - first evidence for shallow bound state $D\bar{D}^* \to \psi(3872) \to D\bar{D}^*$

    [S.P. and Leskovec: PRL 2013; Lee et al. proceedings 1411.1389; Padmanath, Lang, S.P., PRD 2015]

  Improved lattice results for these and other channels expected

- States that can decay to two or three channels:

  - S for three-coupled channels with HALQCD approach: Zc(3900)

    [HALQCD, Ikeda et al, 1602.03465]

- Lots of interesting open problems to solve ... and I am looking forward.

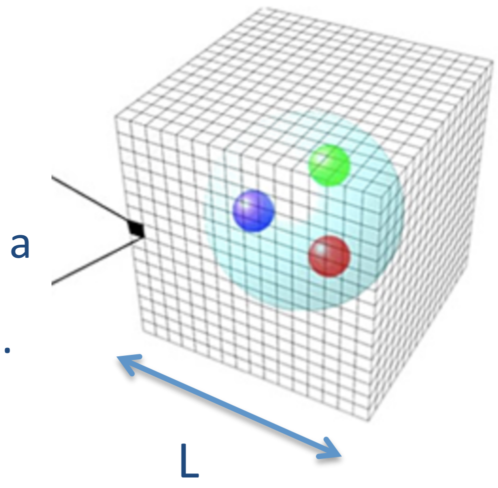
Non-perturbative method: QCD on lattice

$$L_{QCD} = -\tfrac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a + \sum_{q=u,d,s,c,b,t} \bar{q} i\gamma_\mu (\partial^\mu + i g_s G^\mu_a T^a) q - m_q \bar{q} q$$

input: g_s , m_q

output: hadron properties

hadron interactions (if we are lucky)



precision cal.

a~0.05 fm

L~4 fm

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) → x, i t (Euclidean)

Lattice setup

PACS-CS

	Ensemble (1)	Ensemble (2)
$N_L^3 \times N_T$	$16^3 \times 32$	$32^3 \times 64$
N_f	2	2+1
a [fm]	0.1239(13)	0.0907(13)
L [fm]	1.98(2)	2.90(4)
m_π [MeV]	266(3)(3)	156(7)(2)

- Wilon-clover quarks
- Fermilab method for c and b : [El Khadra, Kronfeld et al, 1997]

  Rest hadron energies have sizable discretization errors but these largely cancel in splittings.

  Only splittings with respect to a chosen reference mass are compared to experiment.

- evaluating Wick contractions to simulate scattering on the lattice is challenging and computationally intensive – that is part of the reason why a small number of studies have been made. We apply two methods

  - distillation (Ensemble 1) [Peardon et. al., HSC, 2009]
  - stochastic distillation (Ensemble 2) [Morningstar et al., 2011]

Charmonia near or above D$\underline{D}$ threshold: single-meson approximation

- only interpolating fields $\mathcal{O} \approx \bar{c}\, c$
- assumptions: strong decays of resonances above threshold ignored

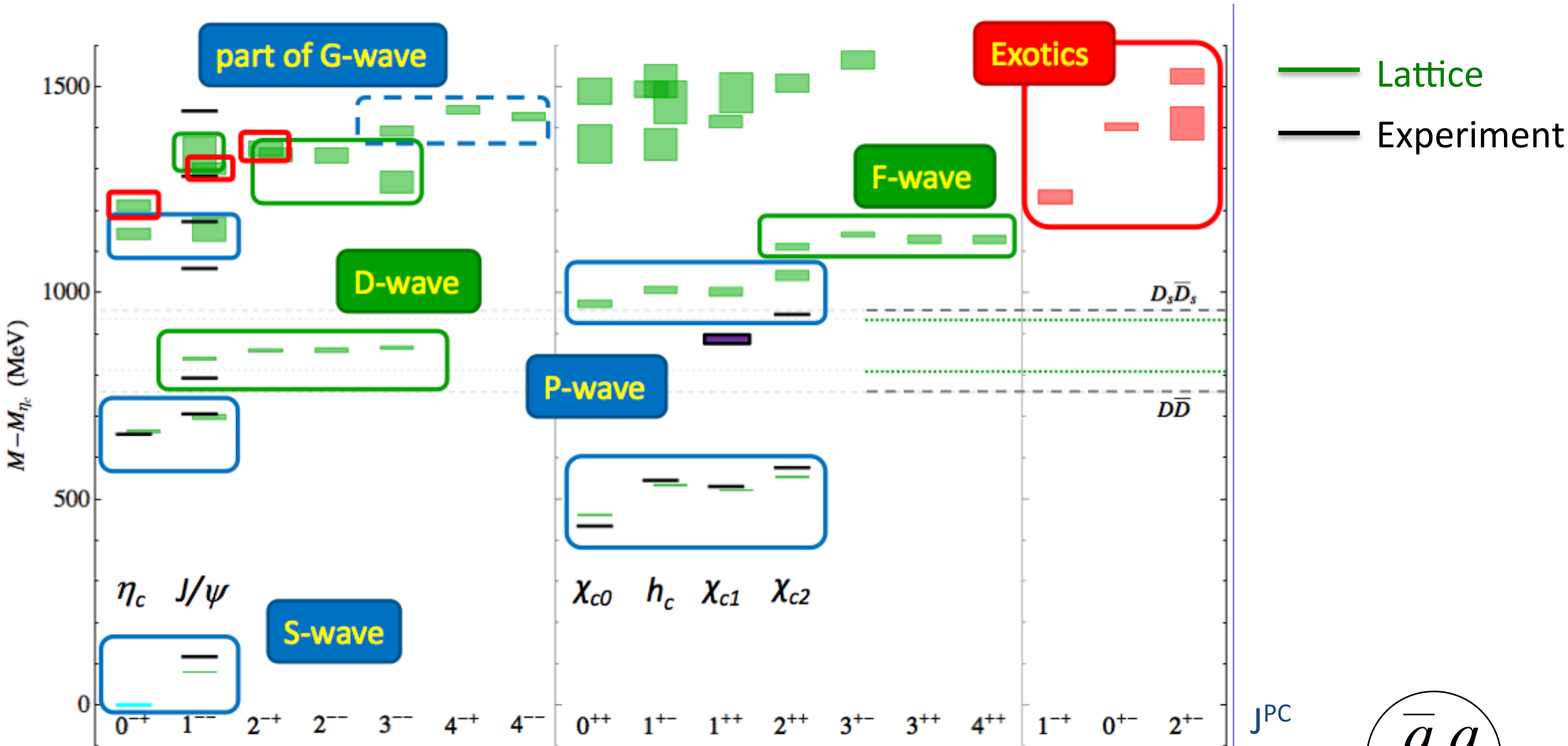
  effects of thresholds on near-threshold states ignored

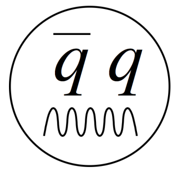
m=E (for P=0)

these are strong assumptions ...

but results still present valuable reference point

Charmonia: single-meson approximation $\mathcal{O} : \bar{c}c$





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

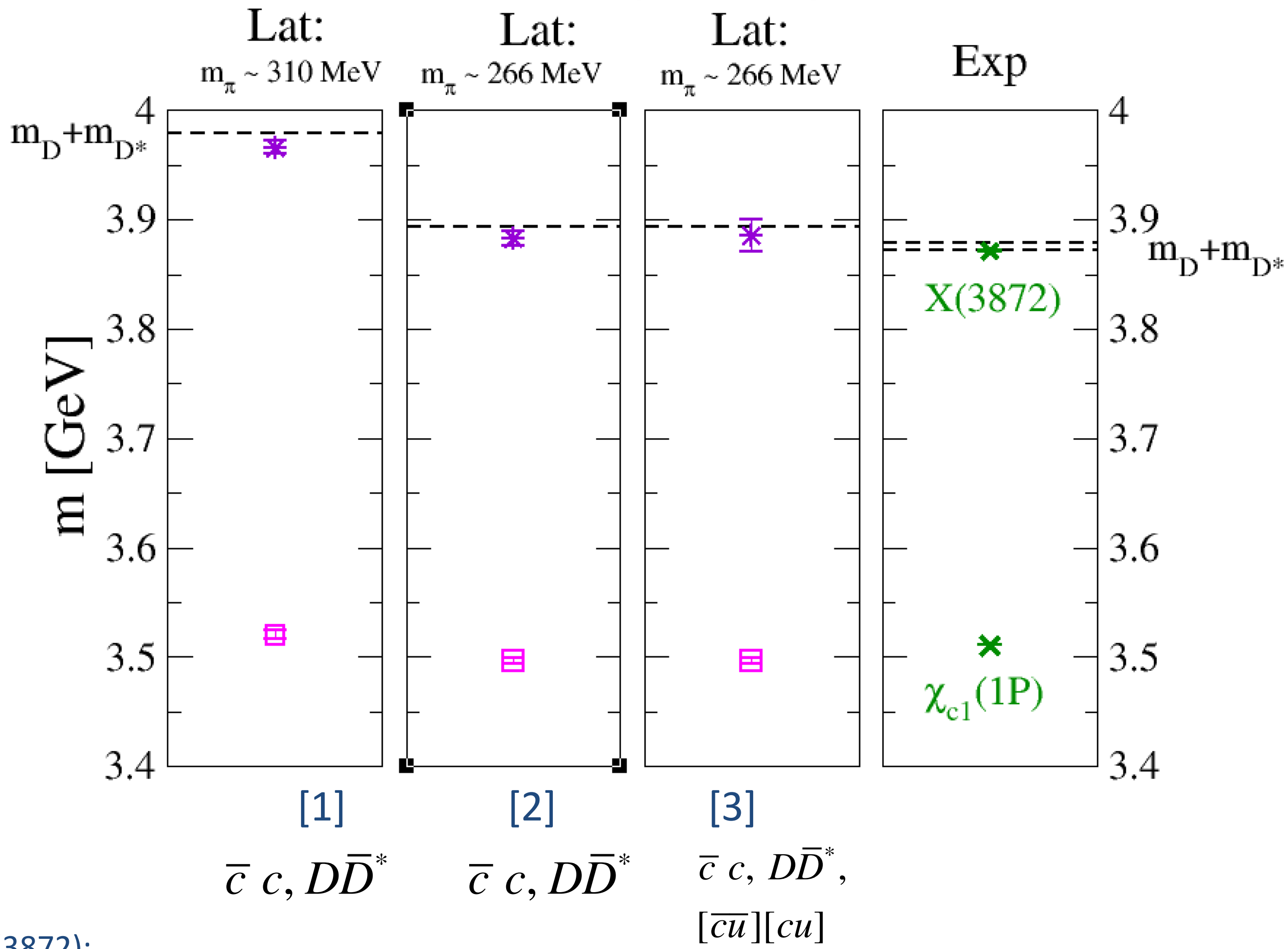
- $m_\pi \approx 400$ MeV, L≈2.9 fm, Nf=2+1
- identification with n $^{2S+1}L_J$ multiplets using <O|n>
- green: lat, black: exp

Hybrids:

some of them have exotic J^{PC}

large overlap with $O = \underline{q}\, F_{ij}\, q$

Comparing lattice results for X(3872), $J^{PC}=1^{++}$, I=0

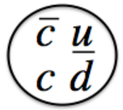


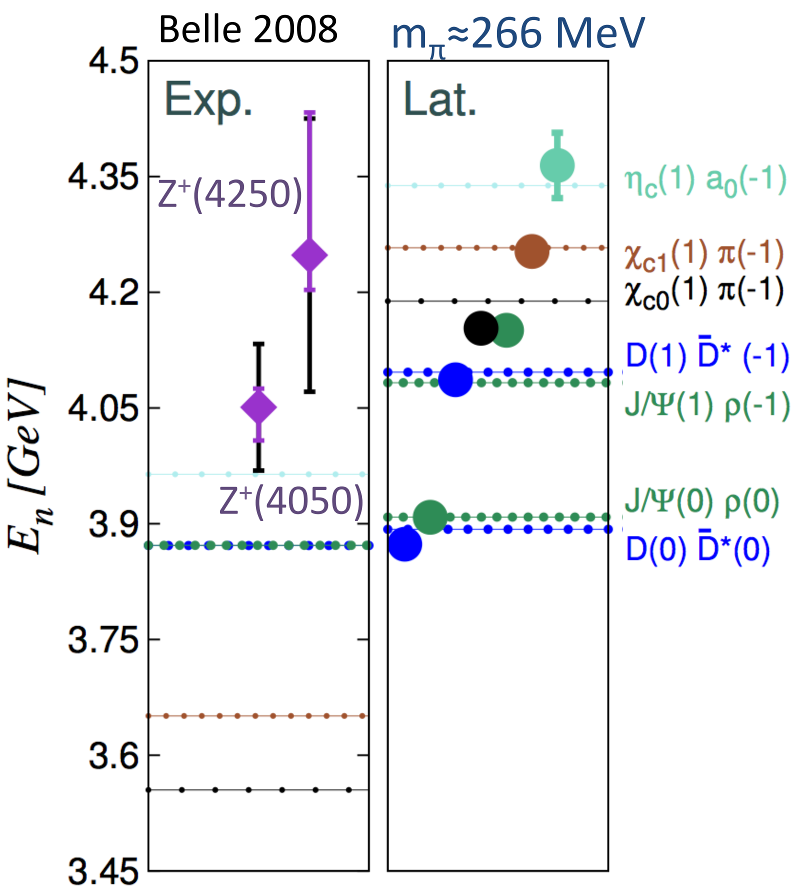
Lattice evidence for X(3872):

- [1] [Lee, DeTar, Na, Mohler , update of proc 1411.1389] $m_\pi \approx 310$ MeV, a=0.15 fm, L=2.4 fm , HISQ
- [2] [S.P. and Leskovec: 1307.5172, PRL 2013]
- [3] [M. Padmanath, C.B. Lang, S.P., 1503.03257, PRD 2015]

  ([2] and [3]:) $m_\pi \approx 266$ MeV, a=0.124 fm, L= 2 fm
- Position of DD* threshold depends on $m_{u/d}$, and may be affected by discretization effects related to charm quark

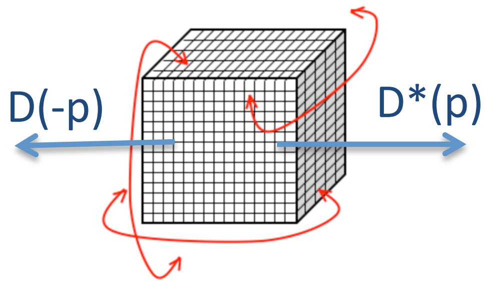
Search for charged partner of X(3872); channel $I^G=1^-$, $J^{PC}=1^{++}$, $c\bar{c}\bar{d}u$





eigen-energies E(L)

(not m^{phy})



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

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

- 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., PRD 2015, 1503.03257]

Y(4140), J^{PC}=??+, <u>ccss</u>

$$Y(4140) \to \underset{\bar{c}c}{J/\psi}\ \underset{\bar{s}s}{\phi}$$

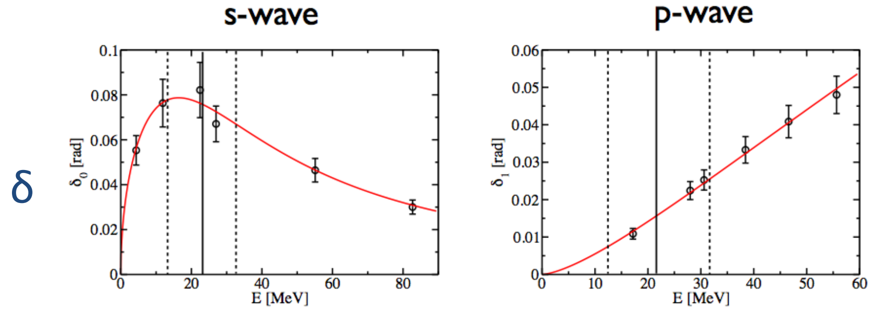
Experiment:

peak in J/ψ Φ just above J/ψ Φ threshold

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

not found: Belle 2010, LHCb 2012

J/Ψ Φ scattering phase shift [rad]



Lattice:

- S. Ozaki and S. Sasaki, 1211.5512, PRD

  caveat: strange quark annihilation neglected

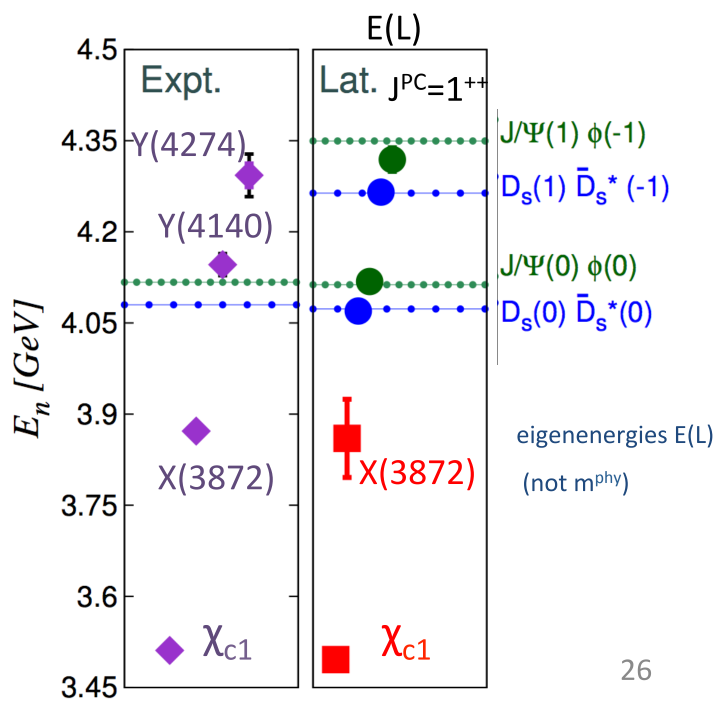
  no resonant Y(4140) structure found

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

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

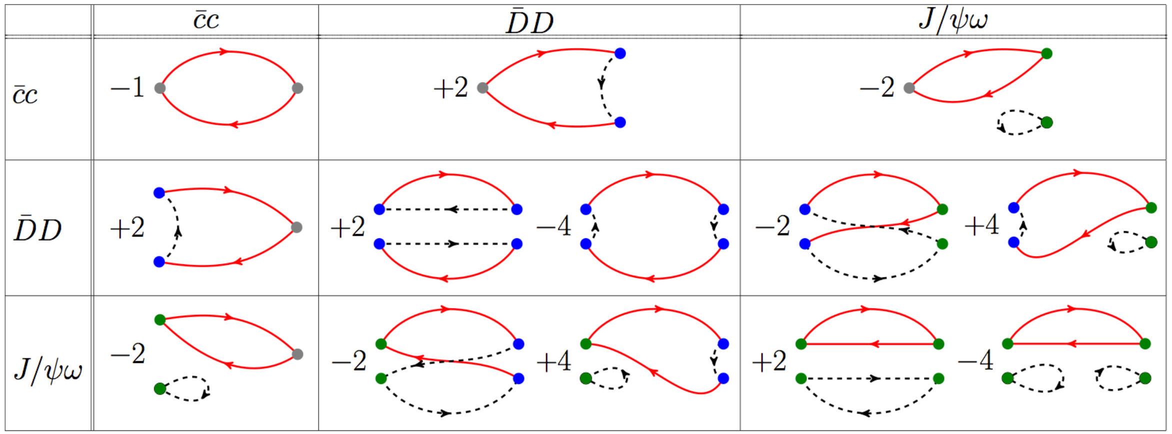
  channel $J^P=1^+$ considered only: expected two-particle eigenstates found and χ_{c1} , X(3872) but **not Y(4140)**

  $m_\pi \approx 266$ MeV



Scalar charmonia from D$\underline{\text{D}}$ scattering in s-wave, $J^{PC}=0^{++}$

- $\chi_{c0}(1P)$: the only settled state
- It is still not commonly accepted which exp state corresponds to $\chi_{c0}(2P)$
- D$\underline{\text{D}}$ and J/Ψ ω scattering in s-wave simulated on lattice:



$\mathcal{O}$: $\bar{c}\, c, D\bar{D},\ J/\psi\omega$

c quark

u,d quarks

Assumption for extracting D$\underline{\text{D}}$ phase shifts: J/Ψ ω channel approximately decoupled

Verified in lattice data (when J/Ψ ω interpolator removed all other E_n and Z remain unaffected)

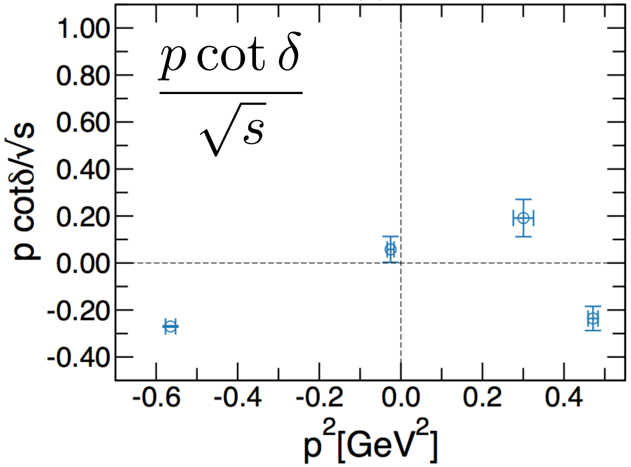
Scalar charmonia from D$\underline{D}$ scattering in s-wave, $J^{PC}=0^{++}$

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

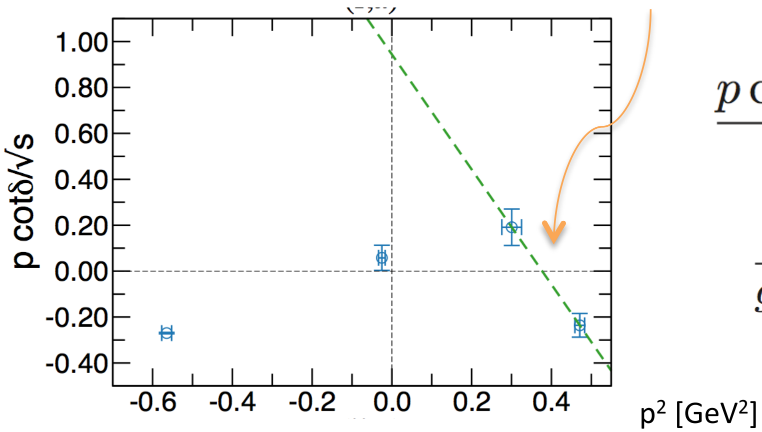
- PDG assigned X(3915) to be $\chi_{c0}(2P)$
- Meissner & Guo [1208.1134] , Olsen [1410.6534]: arguments against this assignment
- It is still not commonly accepted which exp state corresponds to $\chi_{c0}(2P)$
- D$\underline{D}$ scattering in s-wave simulated on lattice: comparison to several hypothesis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

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

Lat: m_π=266 MeV



Hypothesis: one narrow resonance



$$\frac{p\cot\delta(s)}{\sqrt{s}} = \frac{4}{g^2}(p_R^2 - p^2)$$

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

such narrow res. not (yet) found in exp D$\underline{D}$ inv. mass

does not describe our results near threshold

Lang, Leskovec, Mohler, S.P.,
1503.05363, m_π=266, 156 MeV

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

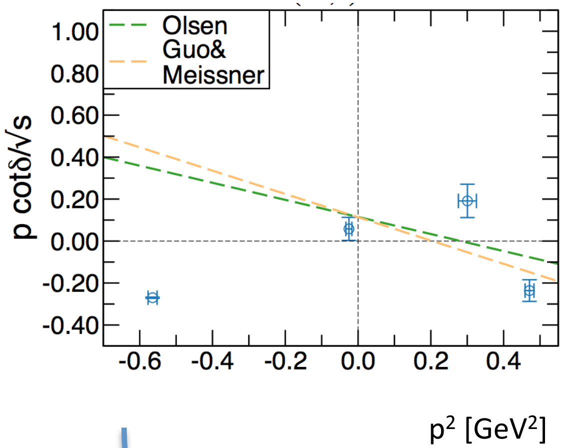
$\mathcal{O}: \bar{c}\, c, D\bar{D}$

various hypothesis versus lattice results

more detailed DD lineshape needed from lattice and exp

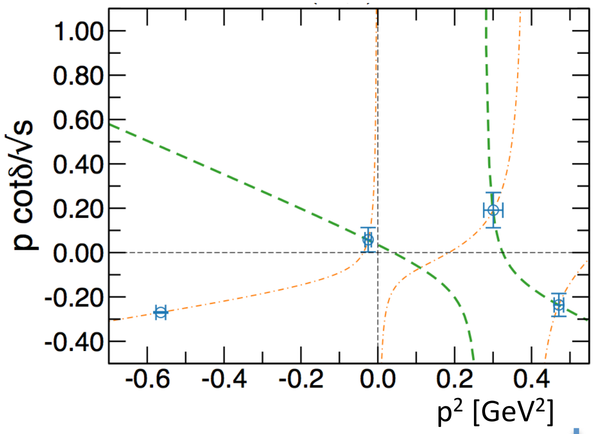
Hypothesis:

one broad BW resonance



Hypothesis:

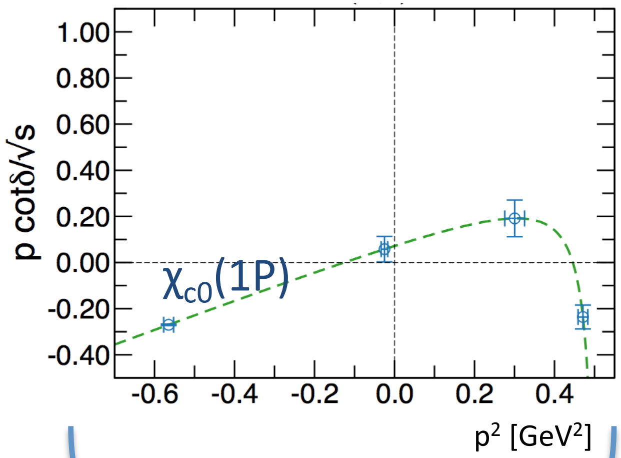
two BW resonances



Hypothesis:

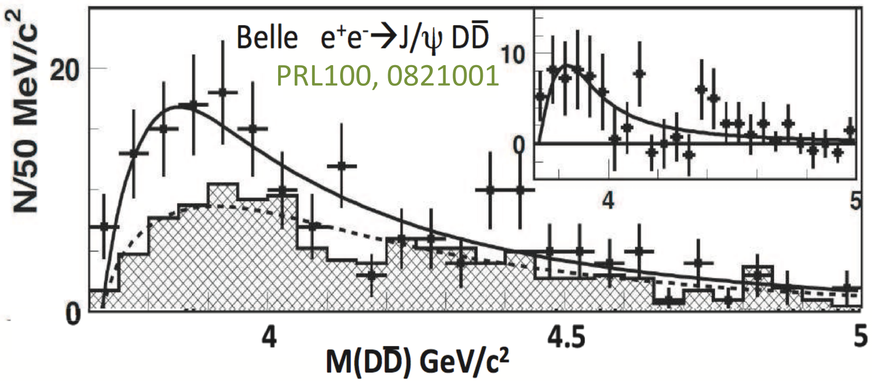
one narrow resononance &

bound state pole at $\chi_{c0}(1P)$



not supported by lat. data near and above th.

supported by lat.



narrow resonance in DD:

m_R=4.002(24) GeV

$\Gamma^{predict}$=32(48) MeV

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

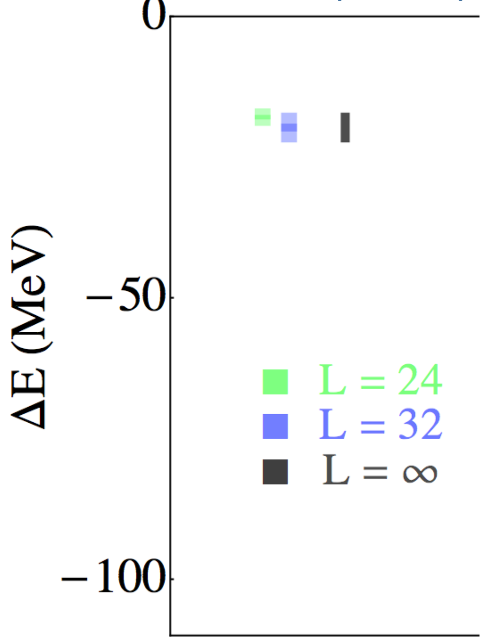
Bound state of a η_c and p from lattice

[NPLQCD, 1410.7069, PRD, m_π~800 MeV]

$\eta_c \; p$ ~ 20 MeV below

$\bar{c}c \; uud$ th. $m_{\eta c} + m_p$

$m - (m_{\eta c} + m_p)$

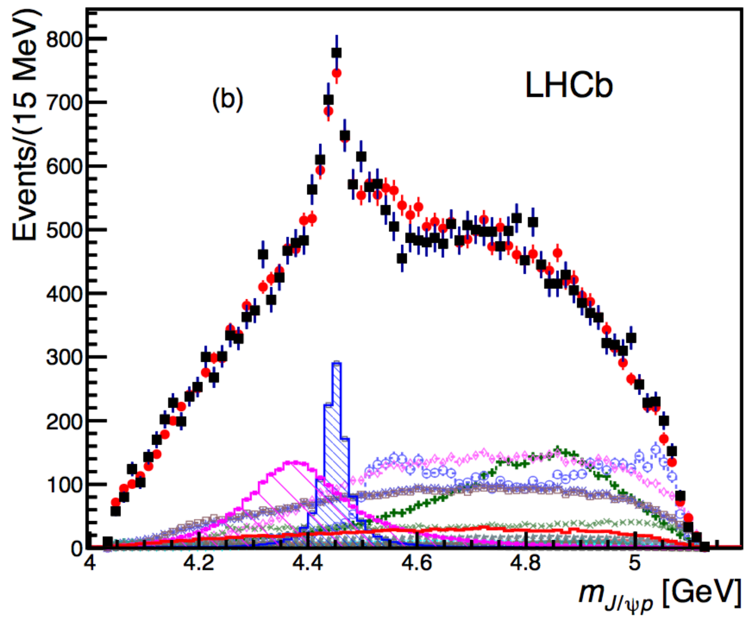


Two pentaquark resonances in J/ψ and p from exp

LHCb: 1507.03414

$J/\psi \; p$ ~ 400 MeV above

$\bar{c}c \; uud$ th. $m_{J/\psi} + m_p$



no lattice results for these Pc yet:

challenging as it can in principle decay to several decay ch.