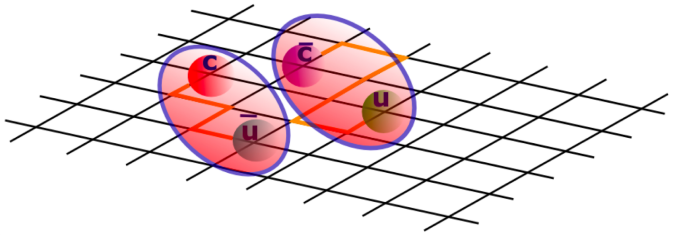
Conventional and exotic charmonia and bottomonia from lattice QCD



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26th-29th October 2015

KEK, Tsukuba, Japan

KEK meeting & B2TiP

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

Outline

- charmonia and bottomonia below DD/BB thresholds

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

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

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

- Lattice QCD study of three channels with $J^{PC}=1^{++}$

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

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

- Pentaquarks with charm form lattice QCD

$$\eta p \ \ \text{bound state}$$

[NPLQCD, 1410.7069, PRD 2015]

- Conclusions & Outlook: what is feasible and what is challenging for lattice
- not covered: search for Zc [see my talk at KEK 2014, Sasaki's talk at this meeting]

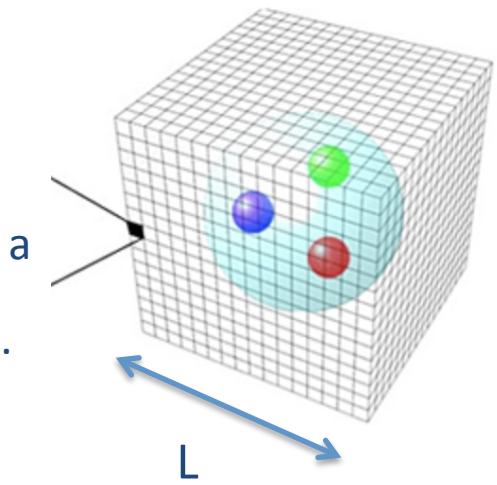
Non-perturbative method: QCD on lattice

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

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

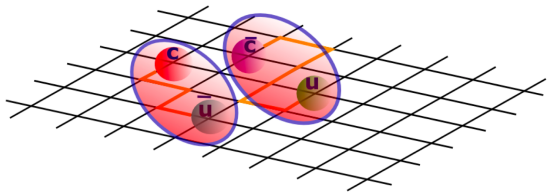
  - distillation (Ensemble 1) [Peardon et. al., HSC, 2009]
  - stochastic distillation (Ensemble 2) [Morningstar et al., 2011]

Lattice gives discrete energies of eigenstates: E_n

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

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

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



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

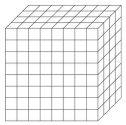
All physical states with given J^{PC} appear as E_n in principle (example: charmonium with 1^{++})

- "single-meson" states χ_{c1} $\qquad m_{\chi_{c1}} = E_1$ for P=0 (after extrapolations)

  $X(3872)$

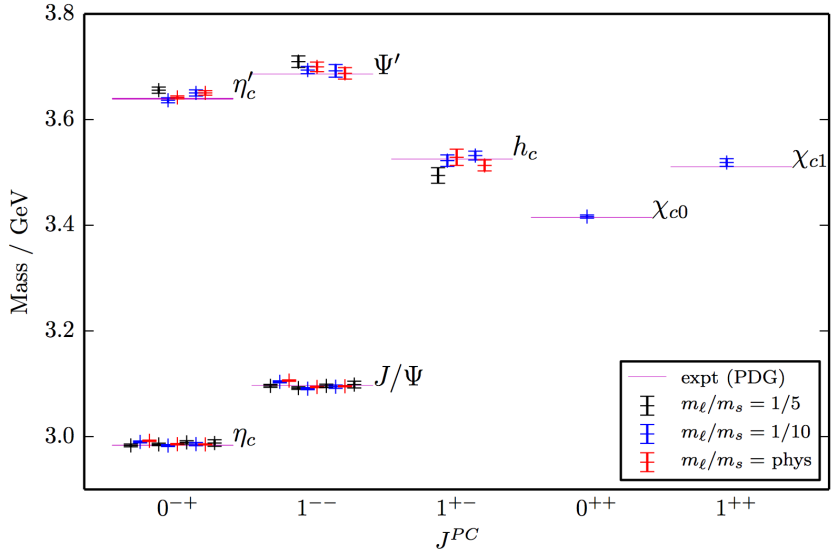
- "two-meson" states $D\bar{D}^*,\ldots$ $\qquad$ E_n rigorously render two-hadron scattering matrix (for example $D\bar{D}^*$ scattering matrix)

Charmonia well below DD: recent precision results

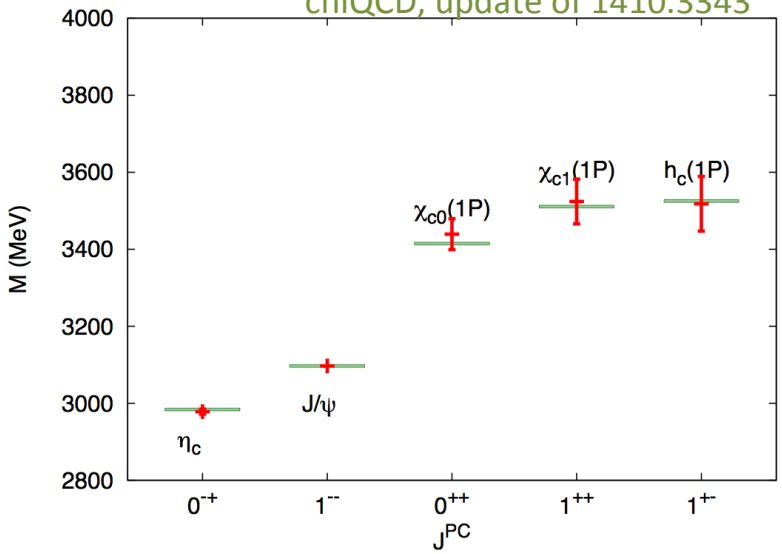


$m=E$ (P=0): $a\to 0$, $L\to\infty$, $m_q\to m_q^{phy}$

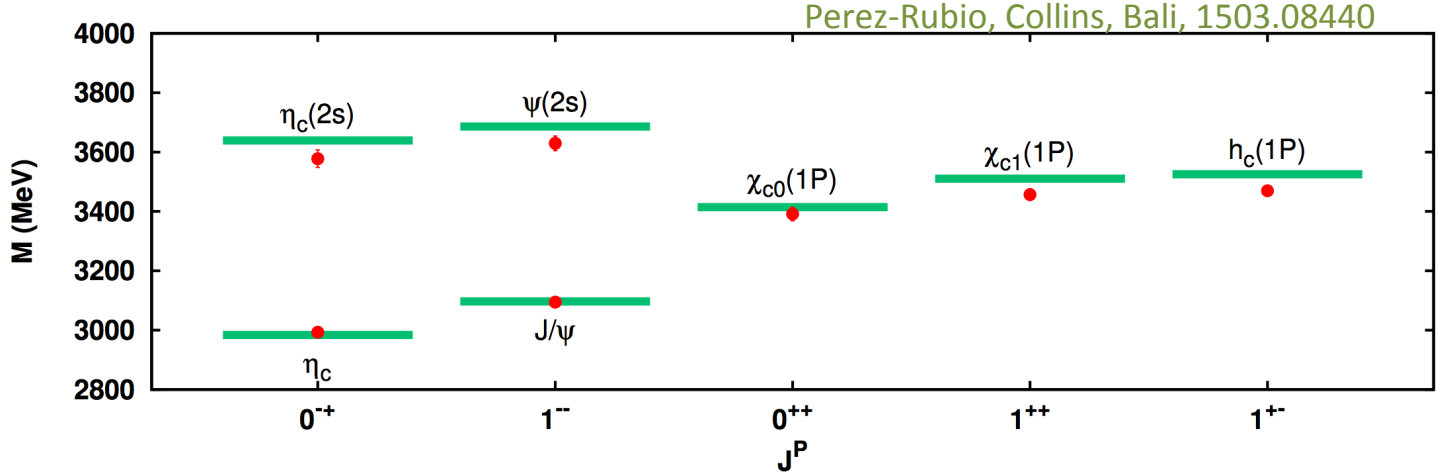
HPQCD, 1411.1318



chiQCD, update of 1410.3343



Perez-Rubio, Collins, Bali, 1503.08440



see also:

FNAL/MILC, 1412.1057

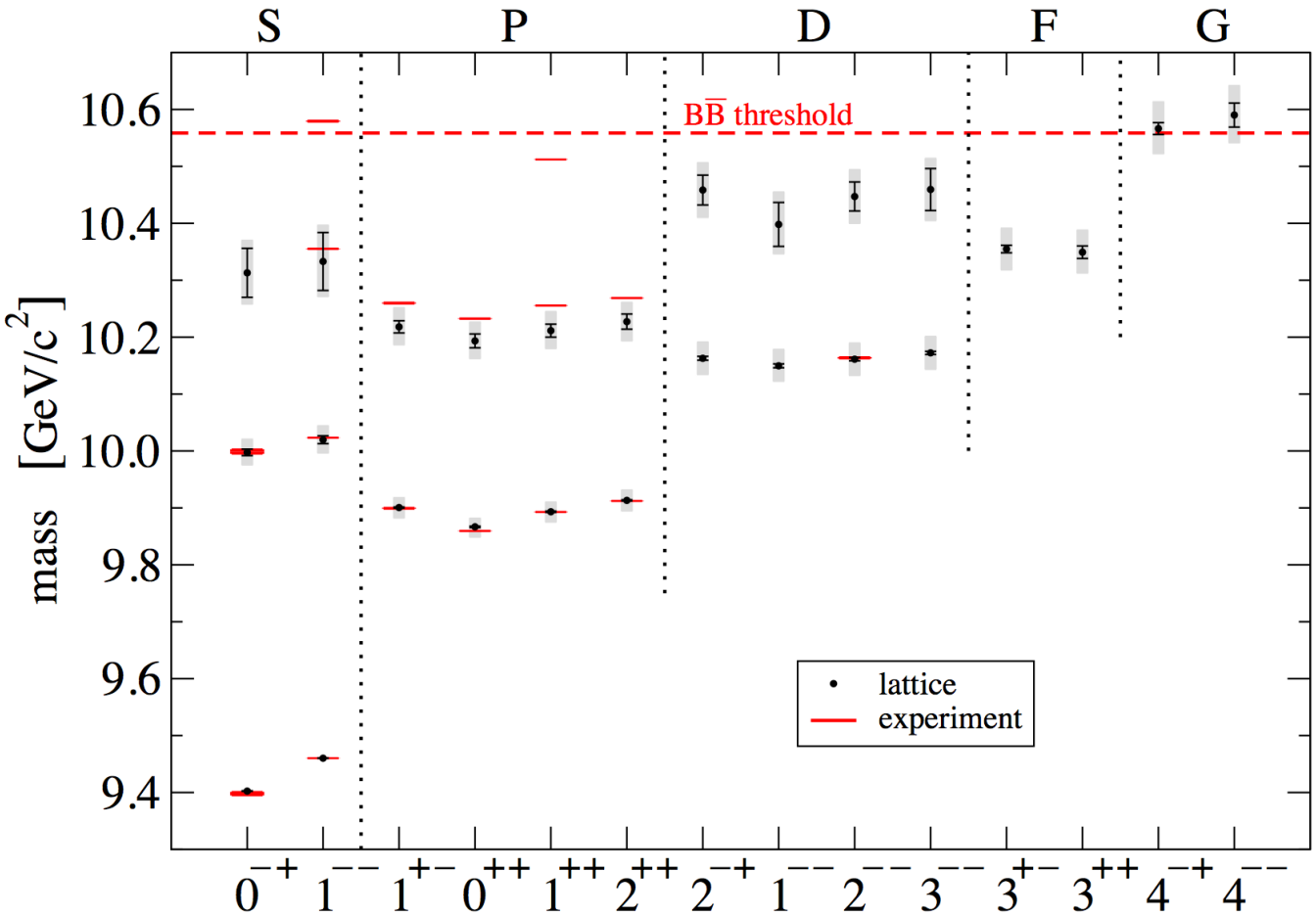
The omission of charm annihilation is the main remaining uncertainty

Bottomonium spectrum below threshold

... is richer than the charmonium one

The most complete spectrum has been recently published:

[Wurtz, Lewis, Woloshyn, 0505.04410, PRD 2015] (see talk of Lewis at KEK 2014 meeting)



Valuable and reliable predictions for 1D and 2D states that have not been observed in exp yet !!

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

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

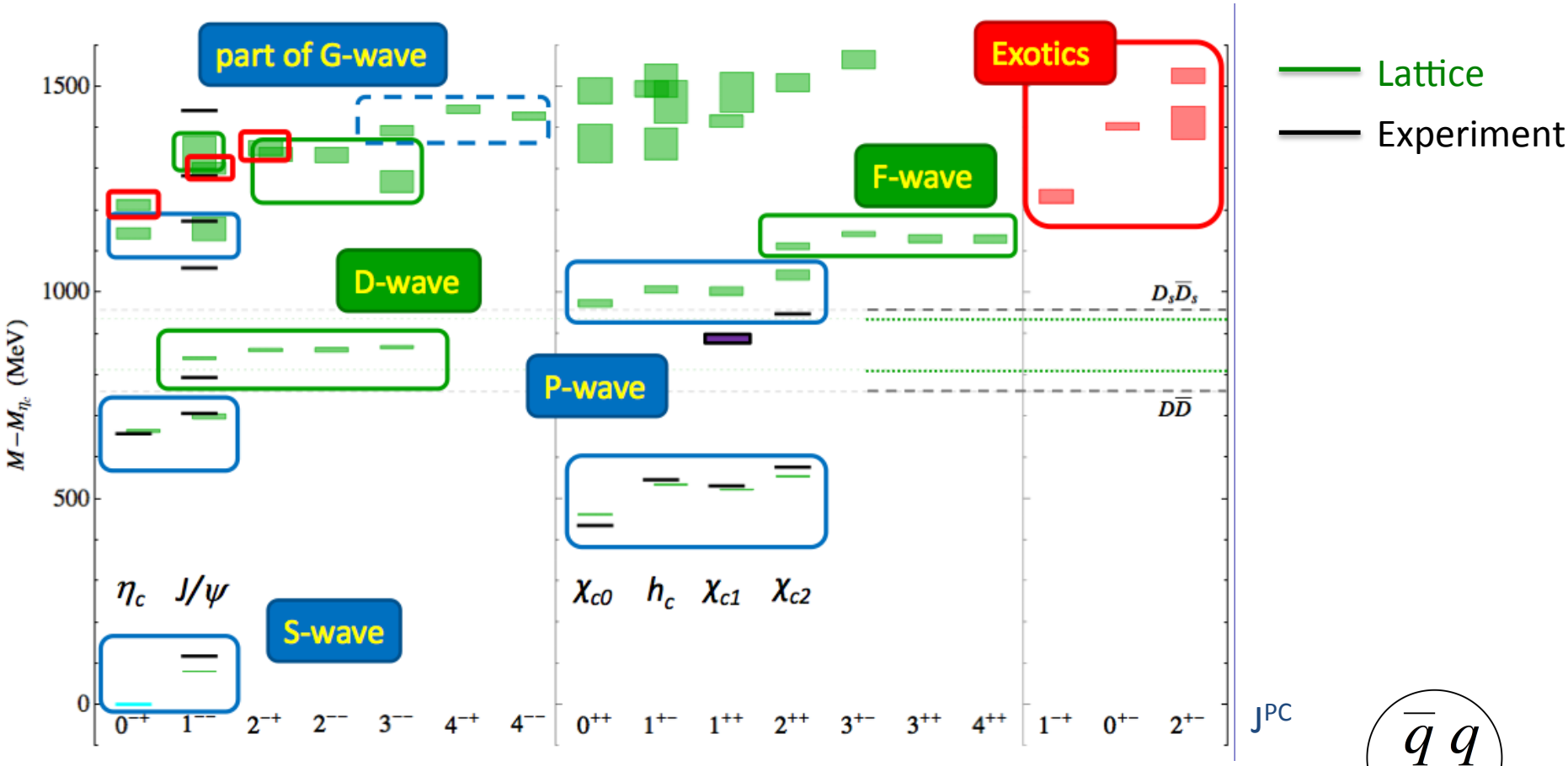
  effects of thresholds on near-threshold states ignored

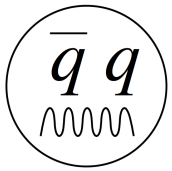
  m=E (for P=0)

  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, $L \approx 2.9$ fm, Nf=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}

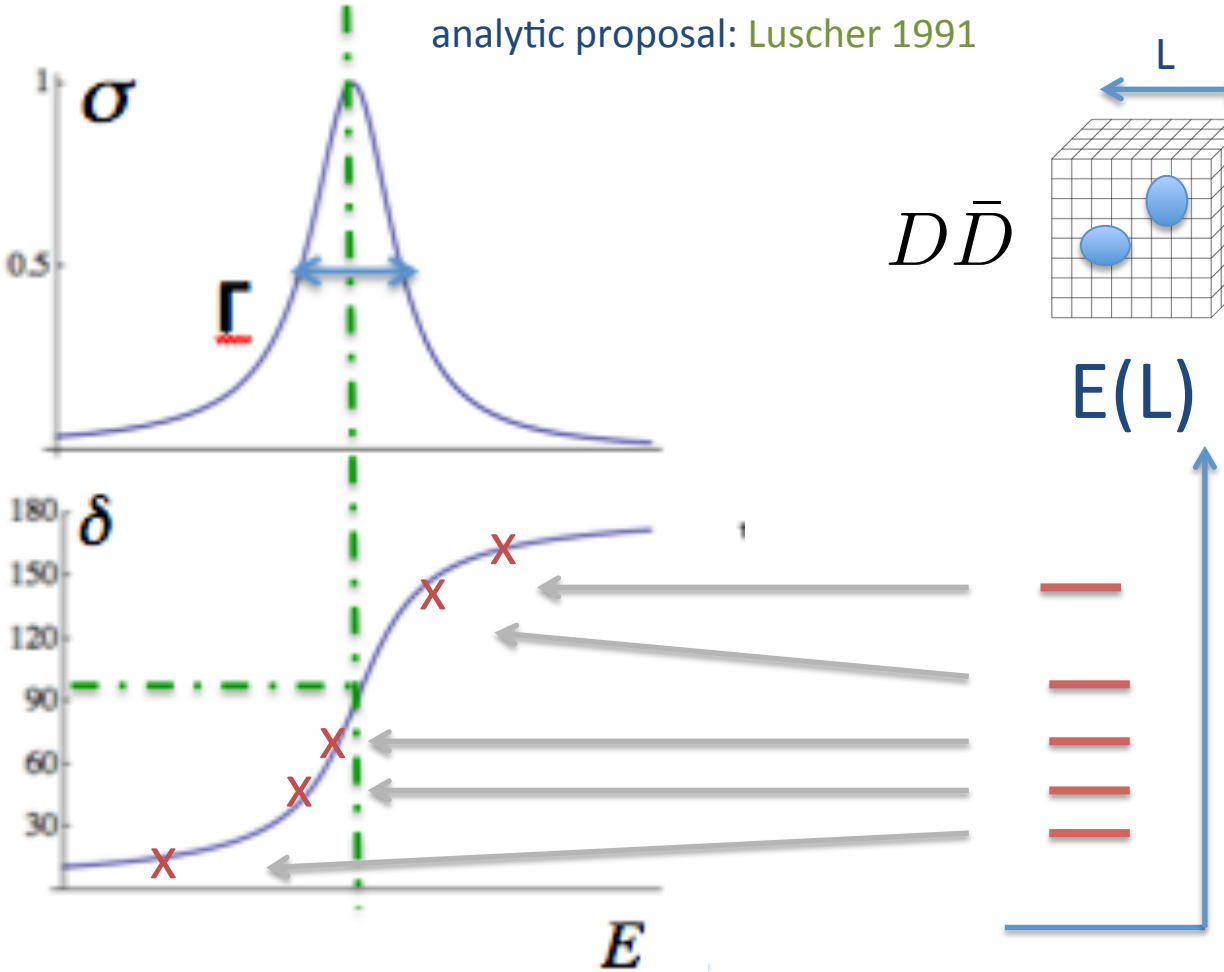
large overlap with $O = \underline{q}\, F_{ij}\, q$

Rigorous treatment of hadrons near or above threshold:

scattering of two mesons $D\bar{D} \to \psi(3770) \to D\bar{D}$

example

analytic proposal: Luscher 1991



two mesons in a lattice box

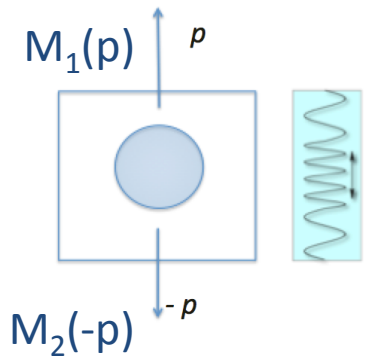
E(L)

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

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

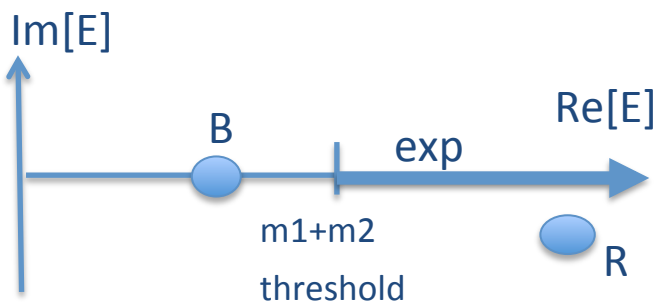
Bound state (B):

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

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.



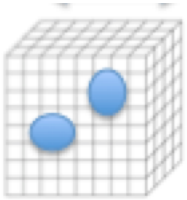
Two types of plots will be shown:

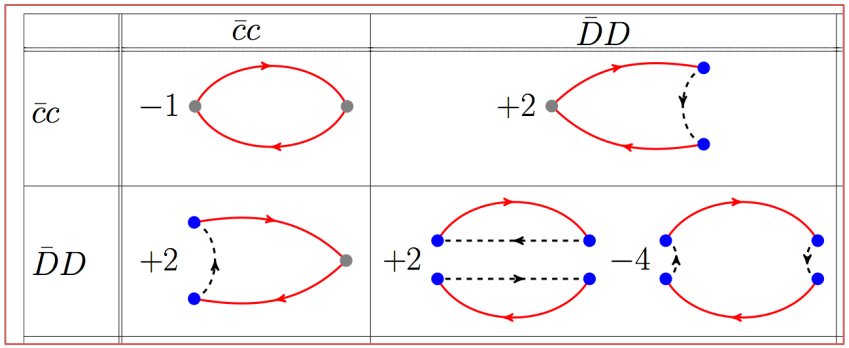
- E(L) energies of lat. eigenstates
- $m^{phy} = m_R$, m_B extracted from E(L)

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

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

$D\bar{D}$





c quark

u,d quarks

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

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

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

$$E_n \;\to\; \delta(E_n)$$

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 DD scattering in p-wave

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

This quantity presented as it is approx. linear near simple BW resonance:

- BW fit (i):

$$T_l(s) = \frac{\sqrt{s}\,\Gamma(s)}{m_R^2 - s - i\sqrt{s}\,\Gamma(s)} = \frac{1}{\cot\delta_l(s) - i}$$

$$\Gamma(s) = \frac{g^2}{6\pi}\frac{p^3}{s} \qquad \frac{p^3\cot\delta(s)}{\sqrt{s}} = \frac{6\pi}{g^2}4(p_R^2 - p^2)$$

- fit (ii): captures also bound st.:

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

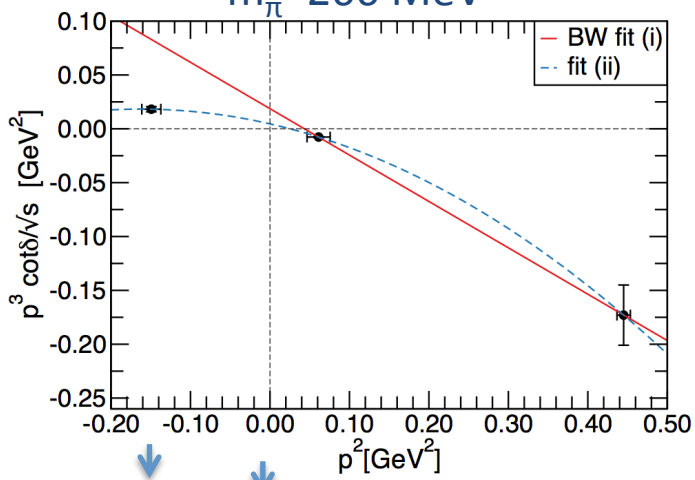
R : m_R: zero, Γ_R : slope near zero

B: cot δ = i

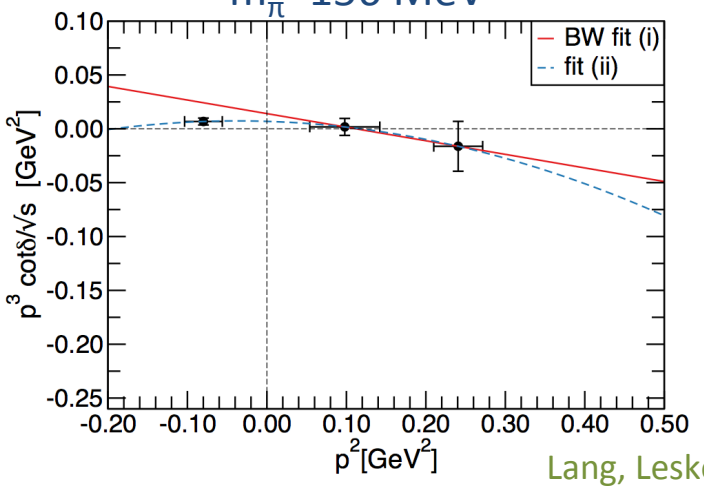
$$p = i|p| \;\rightarrow\; p^3 cot\delta = (i|p|)^3 i = |p|^3 > 0$$

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

m_π=266 MeV



m_π=156 MeV

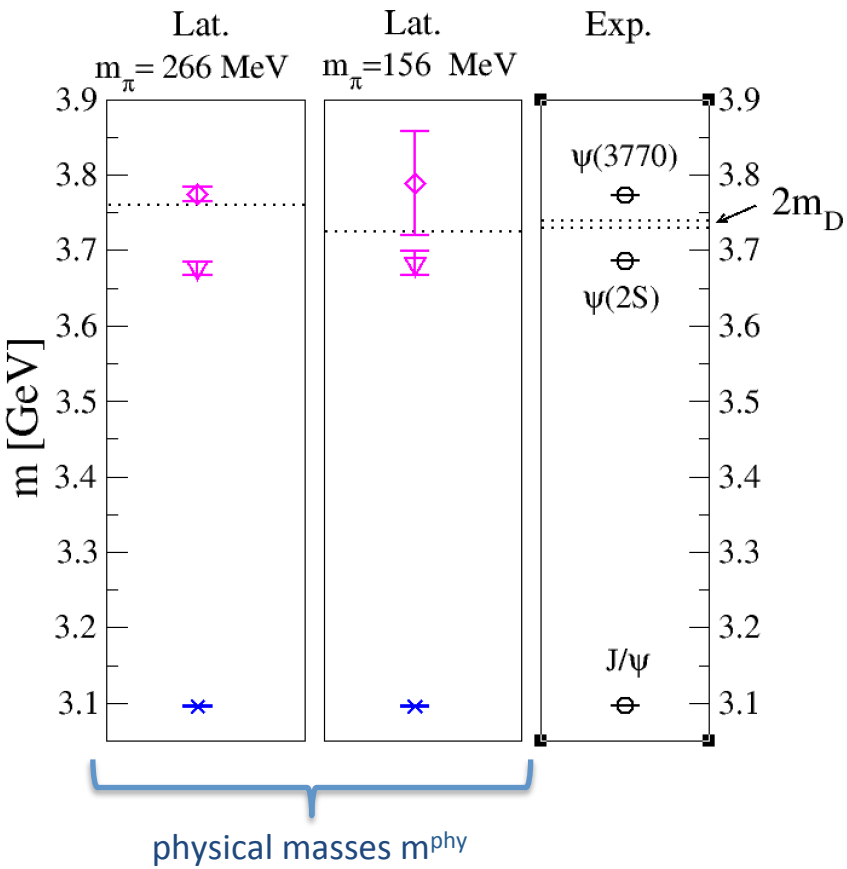


$$\frac{p^3\cot\delta}{\sqrt{s}}$$

$\psi(2S)$ DD threshold

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

T-matrix is determined from E_n

Fit of T-matrix gives:

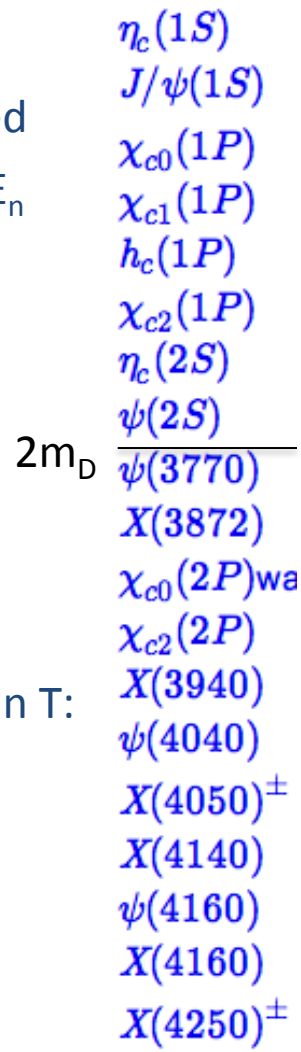
BW resonance ψ(3770):

m_R (magenta diamonds)

Γ (given below)

Bound state ψ(2S) from pole in T:

m_B (magetna triangles)



ψ(3770) , fit (ii)	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

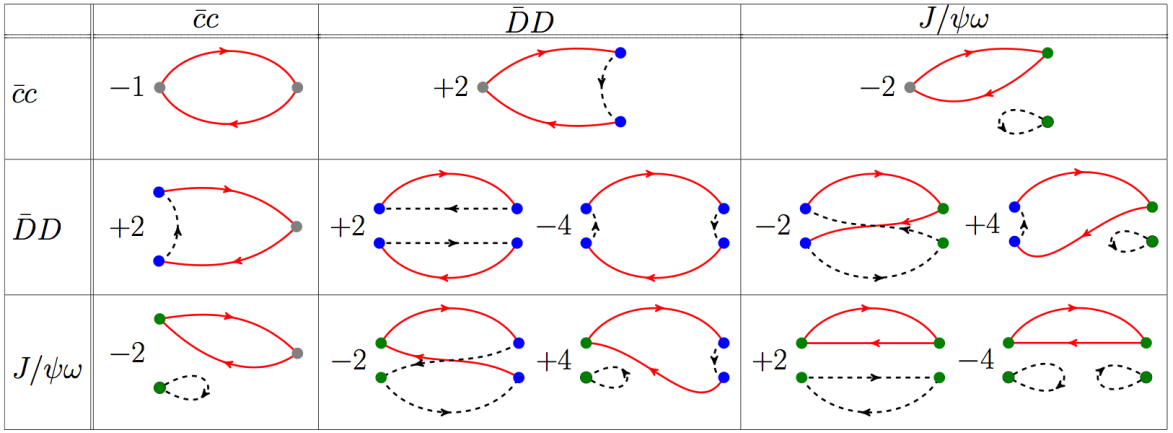
$$\Gamma = \frac{g^2}{6\pi}\frac{p^3}{s}$$

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

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

- χ_{c0}(1P): the only settled state; χ_{c0}(2P) : PDG assigned it with X(3915)
- Meissner & Guo [1208.1134] , Olsen [1410.6534]: arguments against this assignment
- Zhou et al [1501.00879, PRL 2015] : experimental X(3915) could be compatible with $J^{PC}=2^{++}$

  talk at the meeting
- It is still not commonly accepted which exp state corresponds to χ_{c0}(2P)
- D$\underline{D}$ 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$\underline{D}$ 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, $J^{PC}=0^{++}$

D$\underline{D}$ scattering phase shift

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

real also below threshold

Near simple BW resonance:

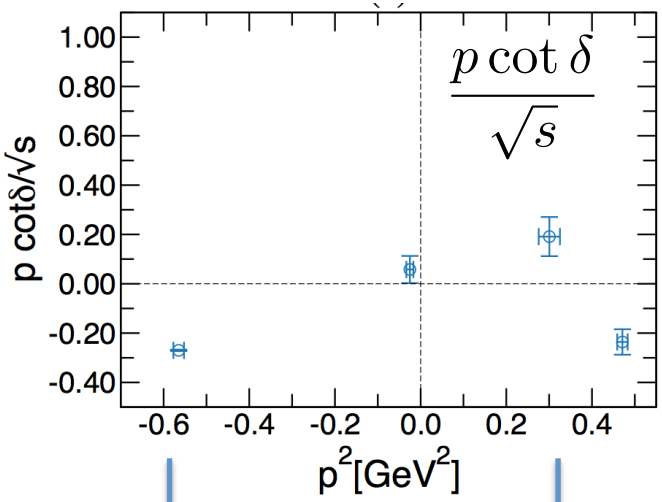
$$\frac{p\cot\delta(s)}{\sqrt{s}} = \frac{4}{g^2}(p_R^2 - p^2)\ , \quad \Gamma(s) = g^2\frac{p}{s}$$

At the bound state pole:

$$p = i|p| \to p\cot\delta = (i|p|)i = -|p| < 0$$

This curious shape seems to suggest narrow resonance and influence from the bound state pole at $\chi_{c0}(1P)$

Lat: m_π=266 MeV



E=3.4 GeV $\chi_{c0}(1P)$ | $2m_D$ | E=3.96 GeV

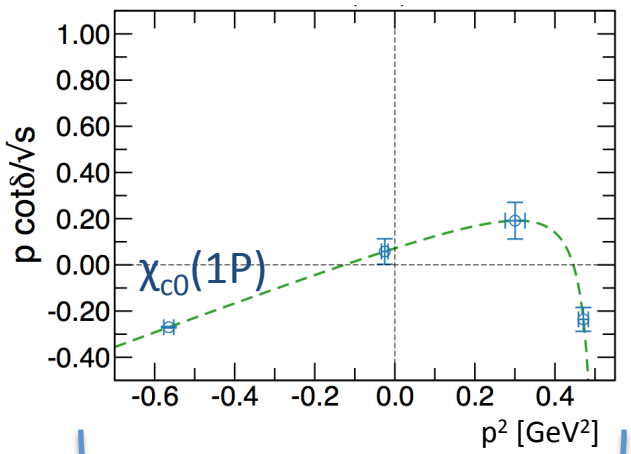
Scalar charmonia from DD scattering in s-wave, $J^{PC}=0^+$

DD scattering in s-wave simulated on lattice: comparison to several hypothesis made

Hypothesis:

one narrow resononance &

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



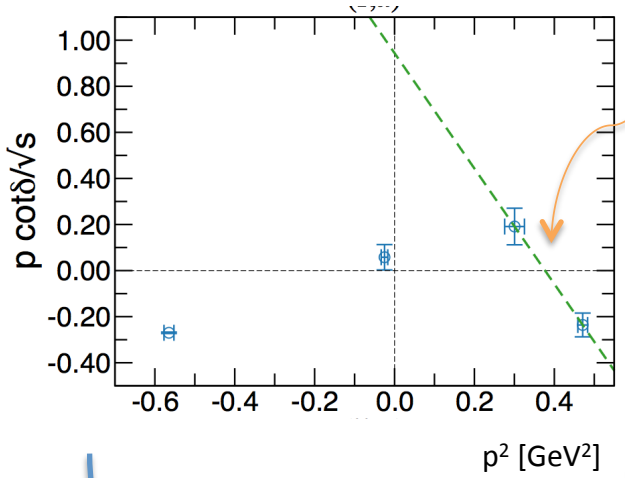
supported by lat.

narrow resonance in DD:
m_R=4.002(24) GeV

$\Gamma^{predict}$=32(48) 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 DD inv. mass

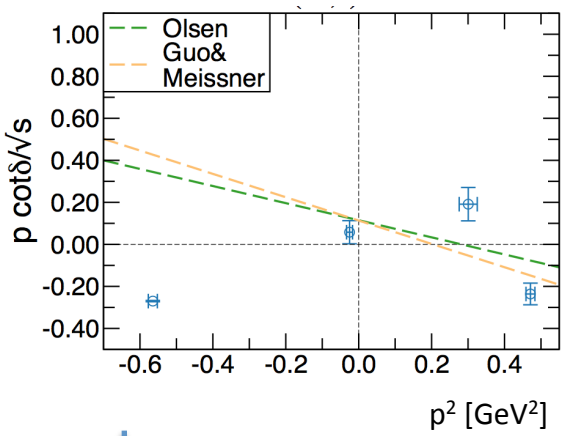
does not describe our results near threshold

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

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

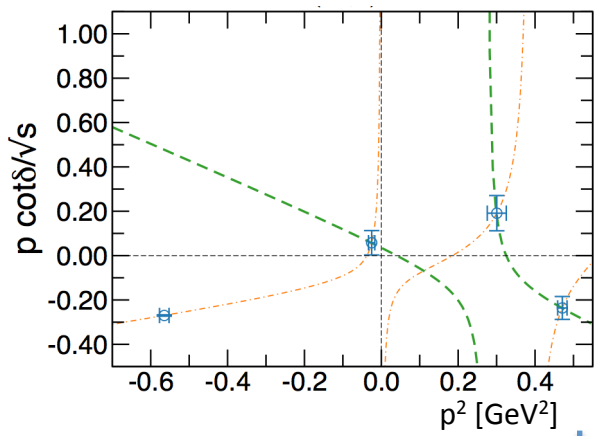
Hypothesis:

one broad BW resonance



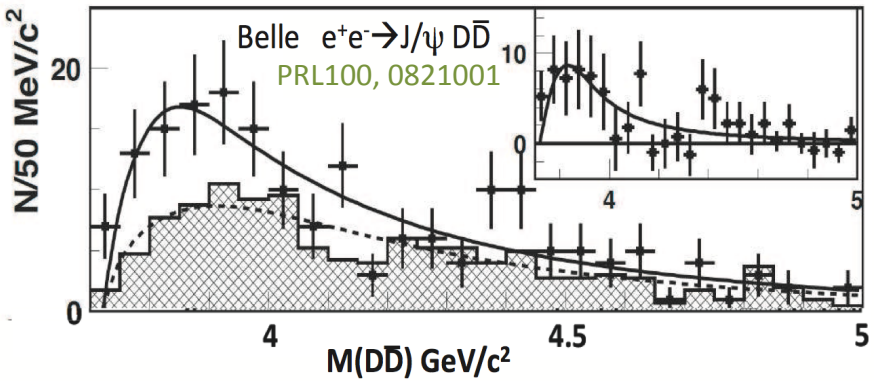
Hypothesis:

two BW resonances



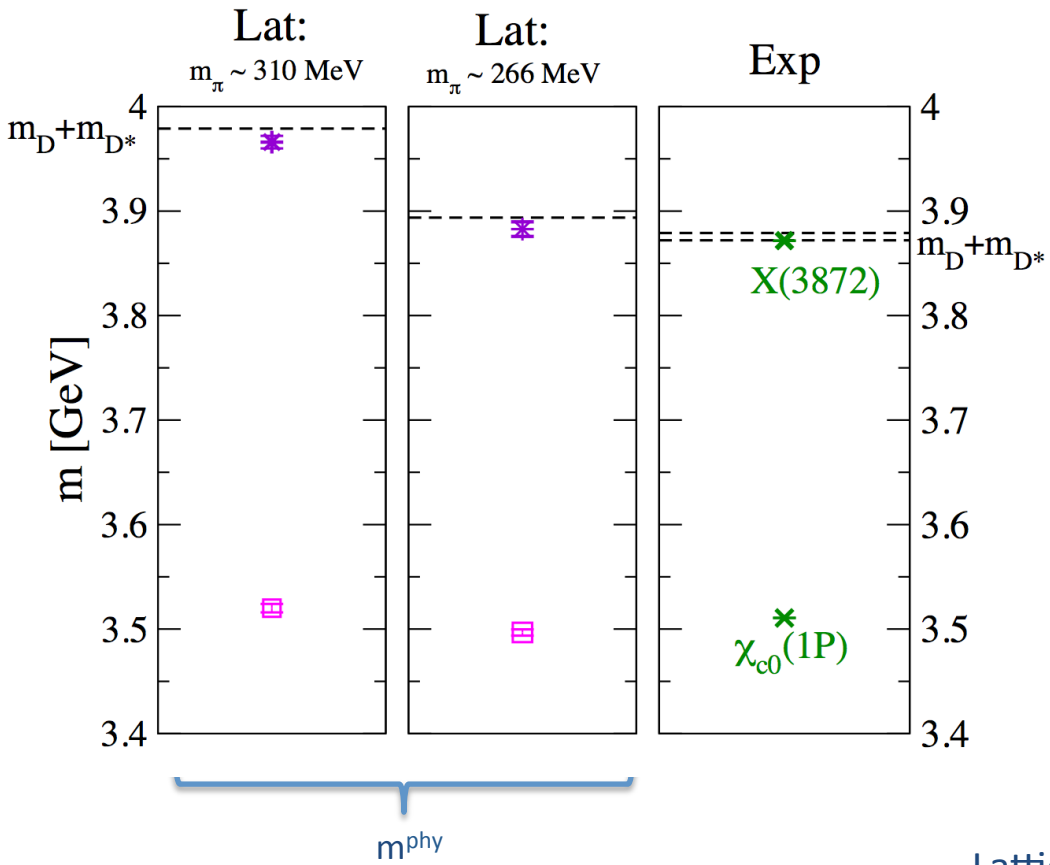
This hypothesis leads to additional energy eigenstate (at the crossing of green and orange lines) which is not observed in simulation

not supported by lat. data near and above th.



more detailed D$\underline{D}$ and J/Ψ ω lineshapes needed from lattice and exp

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



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

- ground state: $\chi_{c1}(1P)$
- D$\underline{D}$* scattering matrix near th. determined
- A pole of $T \propto \frac{1}{\cot\delta - i} = \infty$ 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

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

Lattice evidence for X(3872):

- m_π≈266 MeV, a=0.124 fm, L= 2 fm

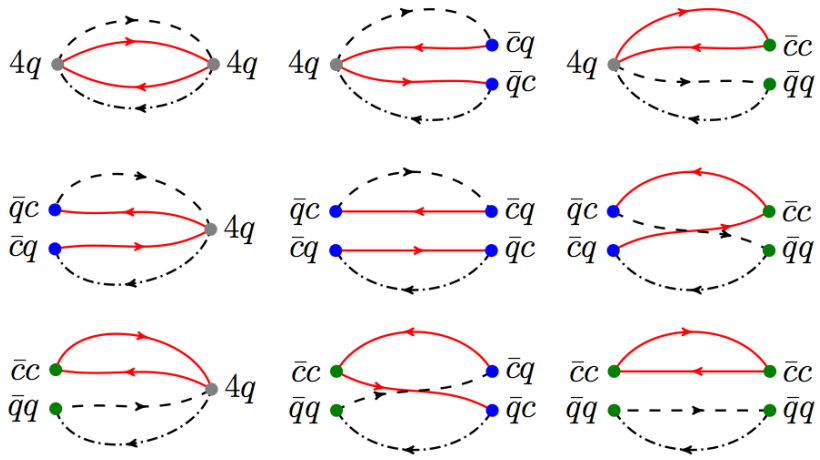
[S.P. and Leskovec: 1307.5172, PRL 2013]

- m_π≈310 MeV, a=0.15 fm, L=2.4 fm , HISQ

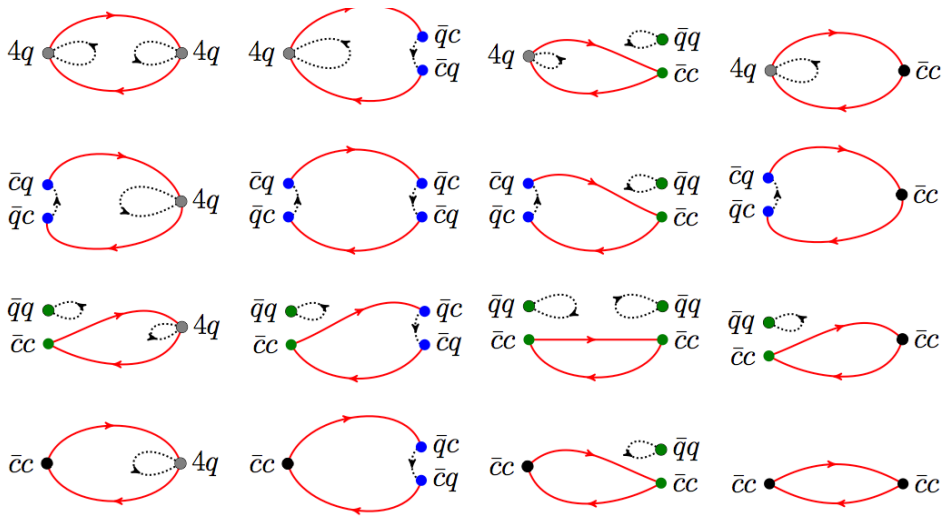
[Lee, DeTar, Na, Mohler , update of proc 1411.1389]

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

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



(a)



(b)

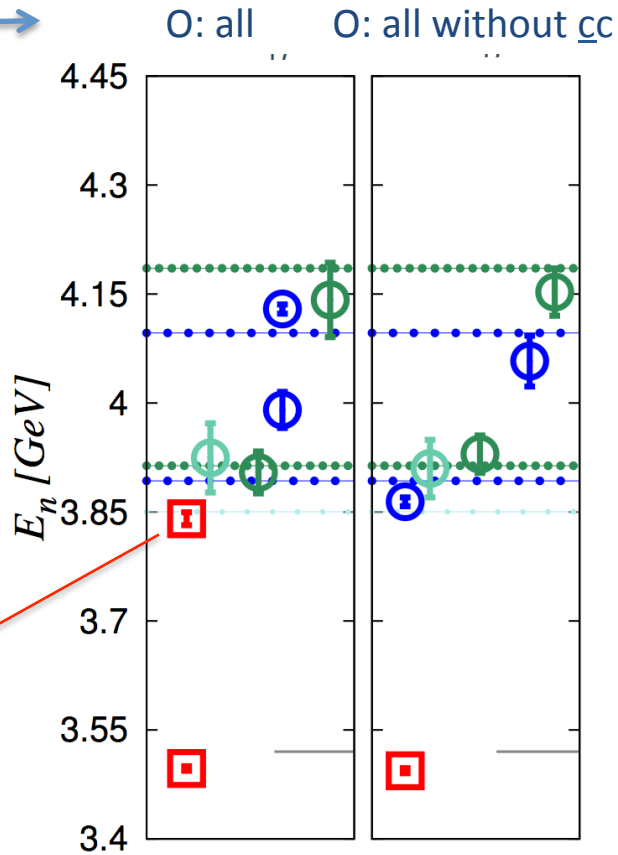
Which Fock components are essential for X(3872) with I=0 ?

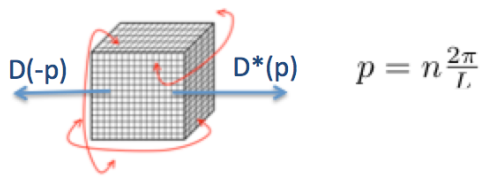
localaized diquark antidiquark

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

interpolating fields

$m_\pi \approx 266$ MeV





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

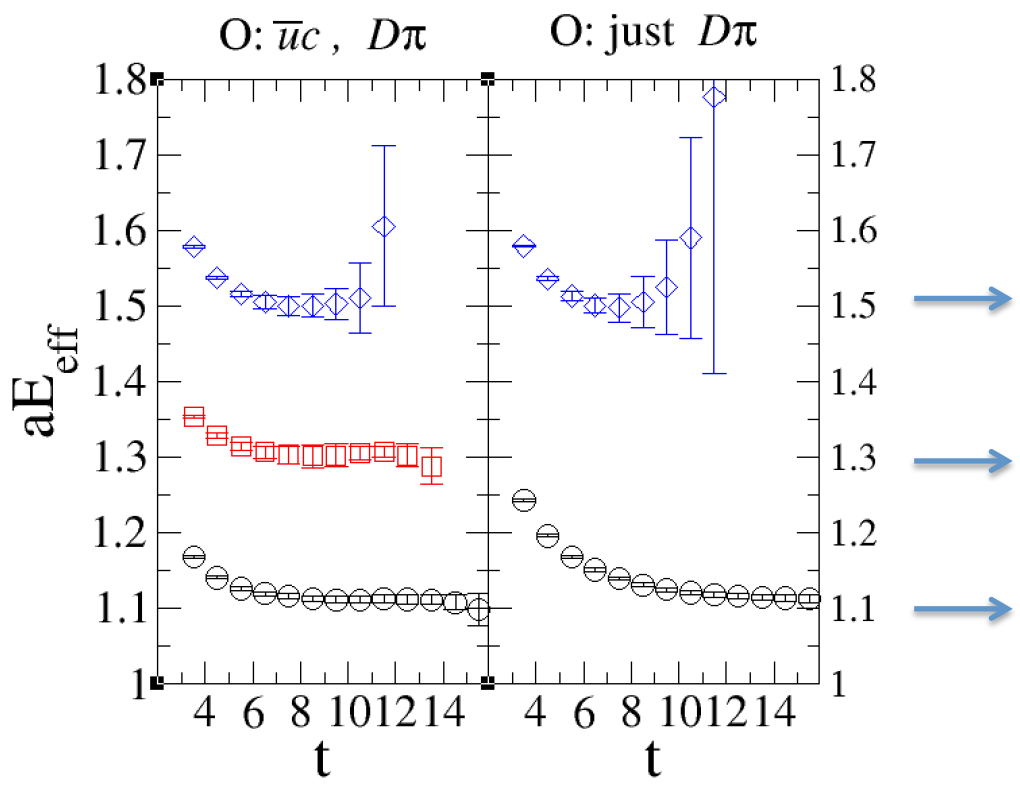
X(3872) not found if cc not in the basis, although [cu][cu] in the basis

[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

Effective energies: $E_n(t) \to E_n$ in plateau region



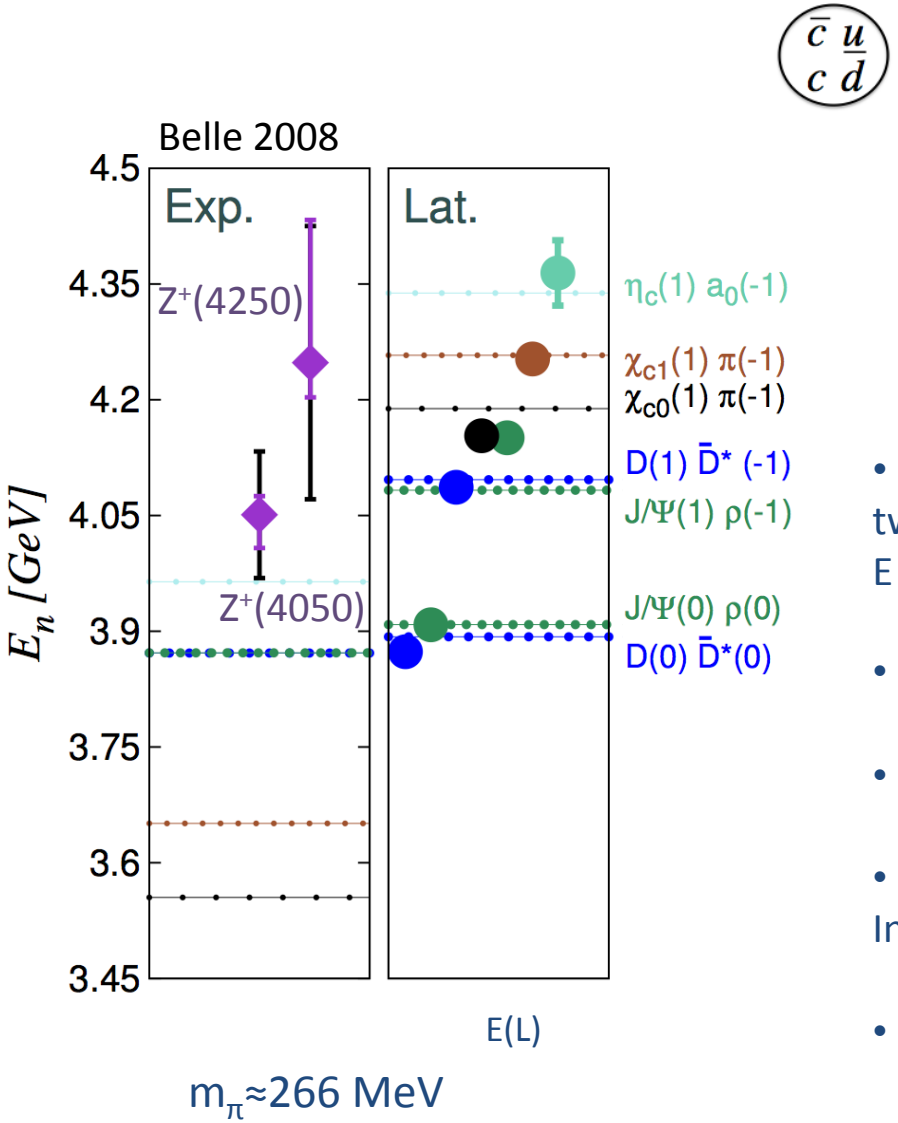
$D(1)\pi(-1)$

$D_0^*(2400)$ scalar $\bar{u}c$ resonance

$D(0)\pi(0)$

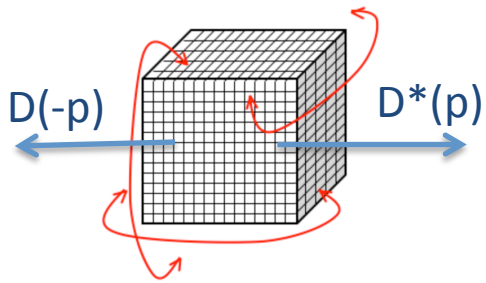
[Mohler, S.P., Woloshyn, PRD 87 (2013) 034501]

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



$m_\pi \approx 266$ MeV

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



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

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

- 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.

Y(4140), $J^{PC}=?^{?+}$, $\underline{c}c\underline{s}s$

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

Experiment:

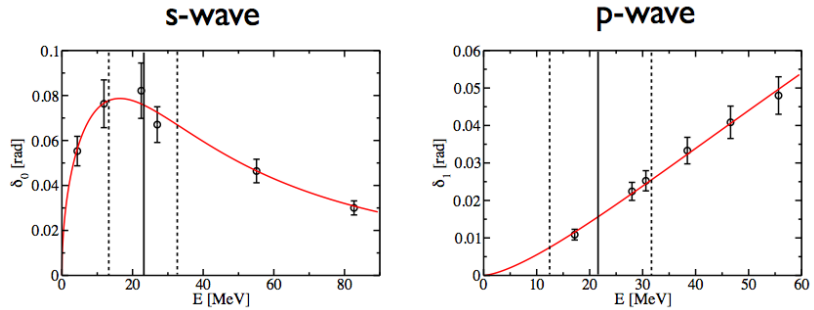
peak in J/ψ Φ just above J/ψ Φ threshold

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

not found: Belle 2010, LHCb 2012

J/Ψ Φ scattering phase shift [rad]

δ



Lattice:

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

  caveat: strange quark annihilation neglected

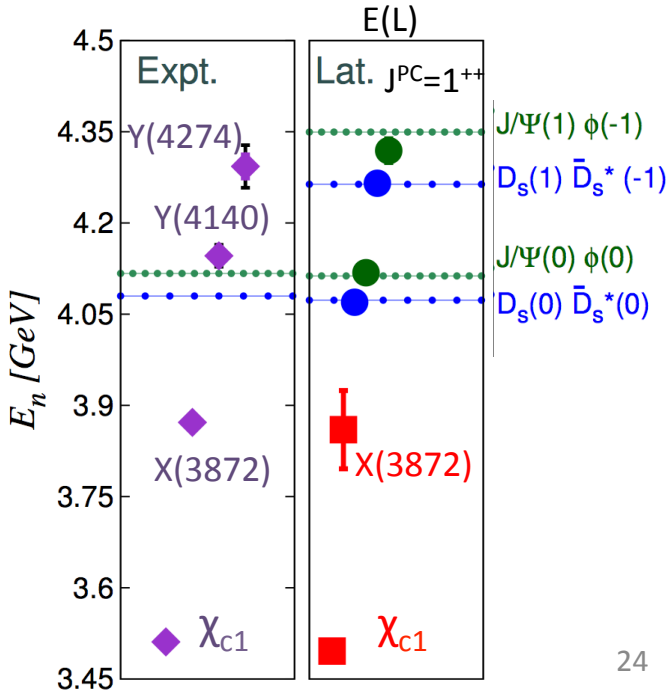
  no resonant Y(4140) structure found

- 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



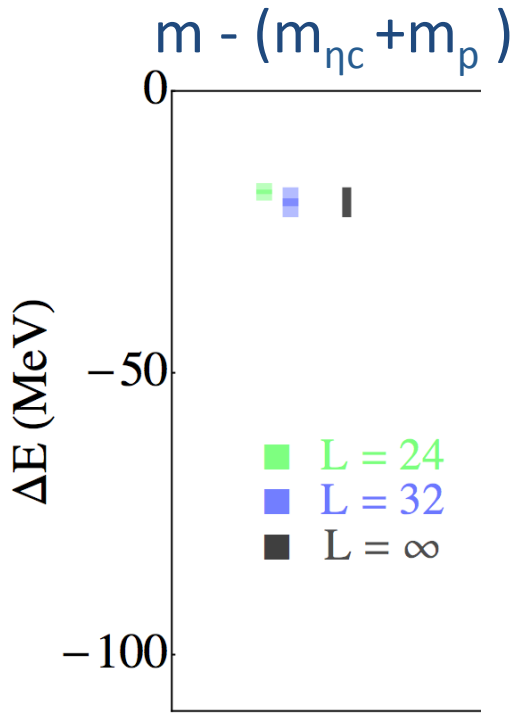
Bound state of a η_c and p from lattice

[NPLQCD, 1410.7069, PRD, m_π~800 MeV]

$\eta_c \; p$

$\bar{c}c \; uud$

~ 20 MeV below th. $m_{\eta c}+m_p$



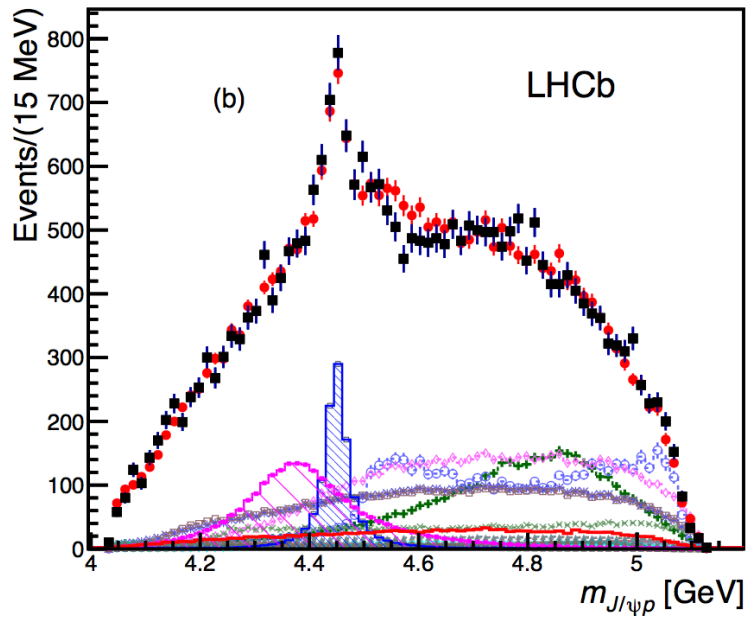
Two pentaquark resonances in J/ψ and p from exp

LHCb: 1507.03414

$J/\psi \; p$

$\bar{c}c \; uud$

~ 400 MeV above th. $m_{J/\psi}+m_p$



no lattice results for these Pc yet:

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

Conclusions & Outlook

- states well below strong decay threshold: easy, under control

  First extensive results on bottomonium spectrum

- resonances and shallow bound states where one channel dominates:

  first rigorous results obtained during past two years:

  - first simulation of charmonium resonance $D\bar{D} \to \psi(3770) \to D\bar{D}$
  - first evidence for shallow bound state $D\bar{D}^* \to \psi(3872) \to D\bar{D}^*$

  Improved lattice results for these and other channels expected

- States that can decay to two or three channels:

  - S for two-coupled channels from Luscher approach

    Kπ, Kη system [Willson, Dudek, Edward, Thomas, HSC, PRL 2014]

    Very challenging! But feasible. There are efforts in this direction. More results expected.

  - S for three-coupled channels with HALQCD approach: Zc(3900) [Sasaki, talk at this meeting]

Conclusions & Outlook, continued

- Some of very interesting states can decay to more than three channels
  - Z_b^+ by Belle in 5 decay modes $Y(1S,2S,3S)\pi^+,\ h_c(1S,2S)\pi^+$
  - $Z^+(4430)$

Rigorous results on 5-coupled channels nor realistic soon ...

Simplifying assumptions will be necessary.

Analytic efforts necessary to understand which simplifying assumptions could be relied on ...