Hadroquarkonium from Lattice QCD

Gunnar Bali

with Maurizio Alberti, Sara Collins, Francesco Knechtli, Graham Moir, Wolfgang Söldner

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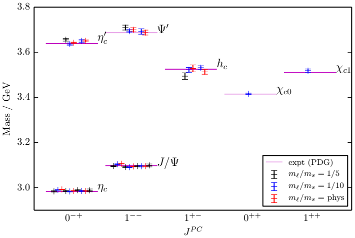
Outline

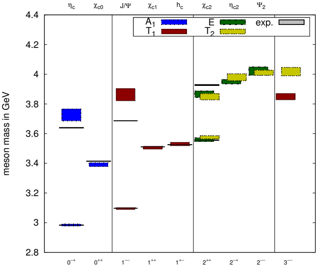
- Motivation
- Hadroquarkonium
- Lattice simulation
- Summary

Recent charmonium spectrum results

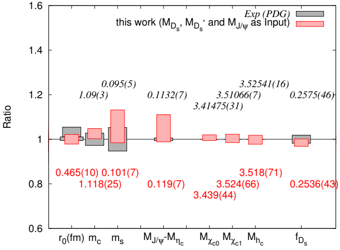
HPQCD [arXiv:1411.1318]



ETMC [arXiv:1510.07862]



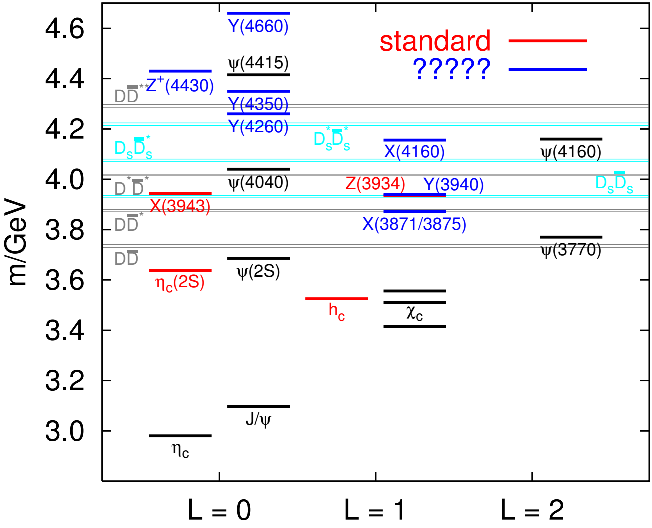
χQCD [arXiv:1410.3343]



However ∃ many states near thresholds

1974 – 1977: 10 $c\bar{c}$ resonances,   1978 – 2001: 0 $c\bar{c}$'s

2002 – 13: $\leq$ 12 new $c\bar{c}$'s found by BaBar, Belle, CLEO-c, CDF, D0



- new detectors
- higher luminosity
- new channels:
- *B* decays
- $\gamma\gamma$
- $\psi\psi$-production
- *gg* in *pp* collisions.
- Will there be $p\bar{p}$?
- Discoveries at LHC!
- $c\bar{q}q\bar{c}$?
- $cg\bar{c}$ hybrids ?

Near threshold states and resonances

Multihadron channels need to be included!

Recent studies, open charm:

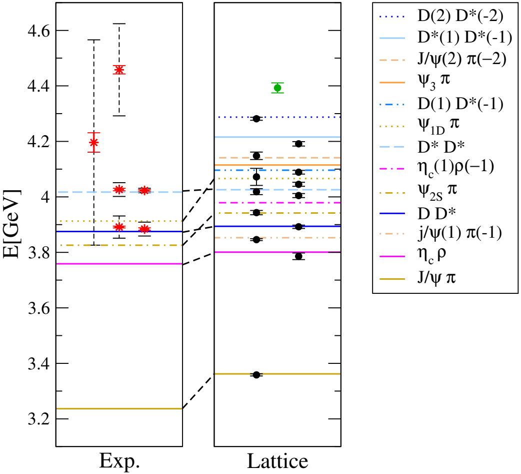
- $D_{s0}^*(2317)$ $[DK]$ $J^P = 0^+$, $D_{s1}(2460)$ $[D^*K]$ $J^P = 1^+$ Lang et al. [1403.8103]
- $D_0^*(2400)$ $[\bar{D}\pi]$ $J^P = 0^+$, $D_1(2430)$ $[\bar{D}^*\pi]$ $J^P = 1^+$, Mohler et al. [1208.4059]

Hidden charm:

- $\psi(3770)$ $J^{PC} = 1^{--}$, $\chi_{c0}(2P)$ $J^{PC} = 0^{++}$ $[\bar{D}D]$ Lang et al. [1503.05363].
- $X(3872)$ $I = 0$ $[D\bar{D}^*, J/\psi\omega]$ $J^{PC} = 1^{++}$, Prelovsek et al. [1307.5172], DeTar et al. [1411.1389], update in [1508.07322].
- $X(3872)$ $I = 1$ $[D\bar{D}^*, J/\psi\rho, (\bar{c}\bar{d})(cu)]$ $J^{PC} = 1^{++}$ Padmanath et al. [1503.03257], no candidate found.
- $Y(4140)$ $[J/\psi\phi, D_s\bar{D}_s^*, (\bar{c}\bar{s})(cs)]$ $J^{PC} = 1^{++}$ channel Padmanath et al. [1503.03257], s- and p-wave scattering Ozaki et al. [1211.5512], no candidate found.
- $Z_c(3900)^+$ $[J/\psi\pi, D\bar{D}^*, \eta_c\rho, \ldots]$ $I^G(J^P) = 1^+(1^+)$, Prelovsek et al. [1405.7623], Lee et al. [1411.1389], no candidate found.

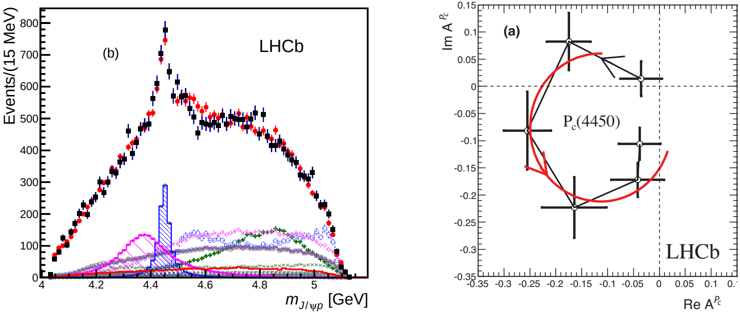
$Z_c(3900)^+$, $I^G(J^P) = 1^+(1^+)$

Prelovsek et al. [1405.7623]



Even in this "simple" case where the minimal configuration consists of four quarks and mixing with standard charmonia can be excluded, a huge number of channels needs to be considered!

Basis of 22 operators: no candidate for a Z_c^+ found below 4.2 GeV.



$P_c^+(4380)$ ($J^P = \frac{3}{2}^-$) and $P_c^+(4450)$ ($J^P = \frac{5}{2}^+$) from $\Lambda_b \to J/\psi pK$ [LHCb: R. Aaij et al, 1507.03414].

Conjecture of attractive forces between charmonium and *pp* systems: [S. Brodsky, I. Schmidt, G. de Teramond, PRL64 (90) 1011].

Many interpretations, pre- and post-dictions (190 citations).

5 quark (4 q, 1 $\bar{q}$) systems are very difficult to study directly on the lattice, in particular if many decay channels are possible.

What about testing a particular model instead?

Hadroquarkonia: [S. Dubynskiy, M. Voloshin 0803.2224]: Quarkonia bound **within** ordinary hadrons.

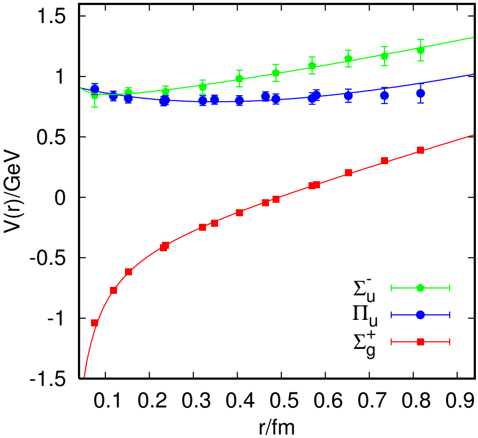
Many combinations of baryon plus charmonium are close-by. Examples:

$J^P = \frac{3}{2}^-$: $m(\Delta) + m(J/\psi) \approx 4329\,\mathrm{MeV}$ vs. $4380\,\mathrm{MeV}$ (width $200\,\mathrm{MeV}$).

$J^P = \frac{5}{2}^+$: $m(N) + m(\chi_{c2}) \approx 4496\,\mathrm{MeV}$ vs. $4450\,\mathrm{MeV}$ (width $40\,\mathrm{MeV}$).

$m_Q, m_Q v \gg \Lambda_{\rm QCD}$, $v \ll 1 \longrightarrow$ Non-relativistic approach (pNRQCD):

$$H\psi_{nlm} = E_{nl}\psi_{nlm} \quad , \quad H = 2(m_Q - \delta m_Q) + \frac{p^2}{m_Q} + V_0(r) + \cdots$$



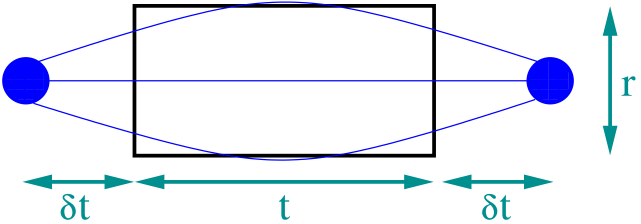
$V_0(r)$ can be computed on the lattice.
(also $1/m_Q$ and $1/m_Q^2$ corrections)

Does this apply to charmonia?
Is $v \lesssim 0.5 \ll 1$?
Is $m_c v \approx 600\,\mathrm{MeV} \gg \Lambda_{\rm QCD}$?

Nevertheless, we can say something about bottomonia and provide guidance for charmonia.

Hadroquarkonia in the static limit

This particular picture can be tested in the static limit.
Does the static potential $V_0(r)$ become more or less attractive in the background of a light hadron?



Create a zero-momentum projected hadronic state $|H\rangle$ at the time 0.
Let it propagate to δt, create a quark-antiquark "string".
Destroy this at $t + \delta t$ and the light hadron at $t + 2\delta t$.

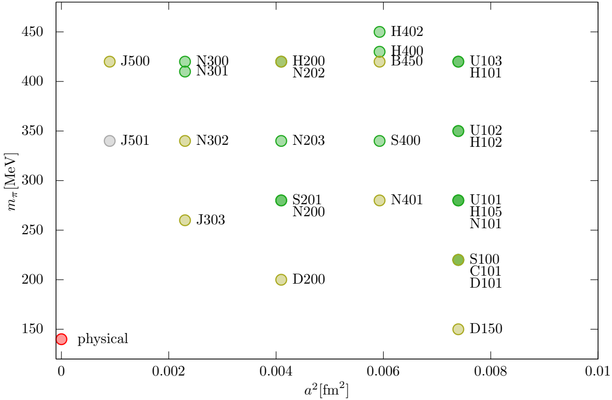
In the limit $t \to \infty$ compute

$$\Delta V_H(r, \delta t) = V_H(r, \delta t) - V_0(r)$$

and extrapolate $\delta t \to \infty$.

CLS Ensembles

$N_f = 2+1$ CLS ensembles with $2m_\ell + m_s = \text{const.}$
($\exists$ additional sets with $\tilde{m}_s = \text{const}$ and $m_\ell = m_s$)



U: 128×24^3
B: 64×32^3
H: 96×32^3
S: 128×32^3
C: 96×48^3
N: 128×48^3
D: 128×64^3
J: 192×64^3

CLS: HU Berlin, TC Dublin, UA Madrid, Mainz, Milano Bicocca, Regensburg, Roma I, Roma II, Wuppertal, DESY Zeuthen

Lattice details

We want a large volume that comfortably accommodates the hadron.

We wish to go to realistically light quark masses but not too light since then correlation functions can become noisy and statistically less meaningful.

$N_f = 2 + 1$ **CLS** ensemble C101 (96×48^3 sites):

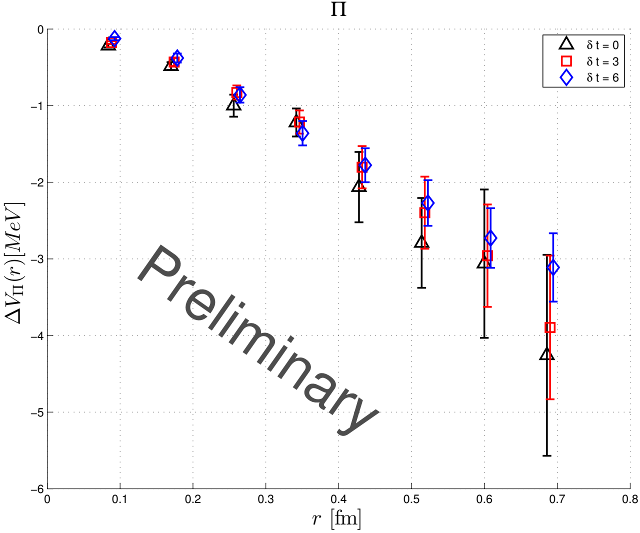
$M_\pi = 220\,\text{MeV}$, $M_K = 470\,\text{MeV}$, $LM_\pi \approx 4.6$, $L \approx 4.1\,\text{fm}$, $a \approx 0.086\,\text{fm}$.

High statistics: 1552 configs, separated by 4 MDUs, times 12 hadron sources (1 forward, 1 backward, 10 forward and backward propagating $\Rightarrow$ 22 2-point functions). Wilson loops at all positions and in all directions.

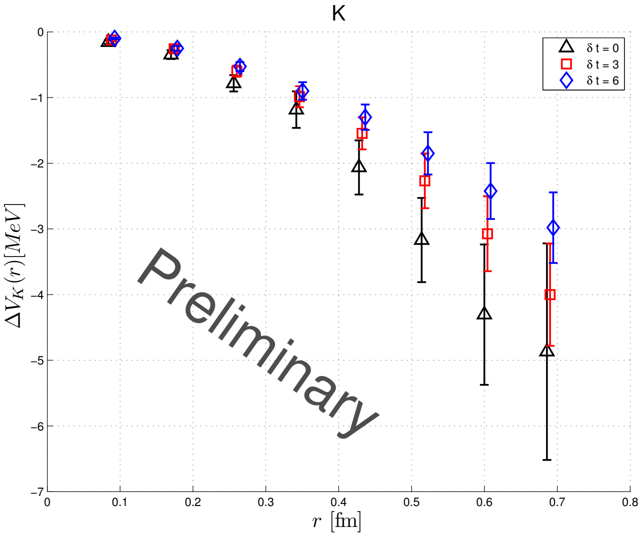
Wilson loops are optimized using four smearing levels and ground state overlap of the hadronic two-point function is optimized too.

$\overline{Q}Q$ binding energy shift "within" a pion

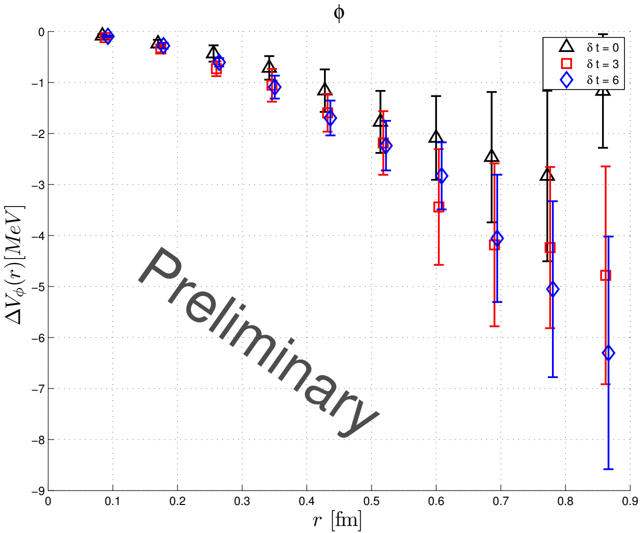
[M. Alberti et al, PRELIMINARY]



Within a kaon

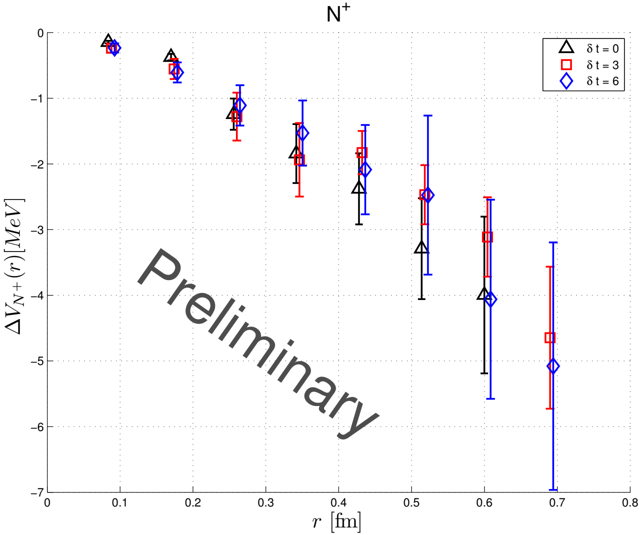


Within a ϕ

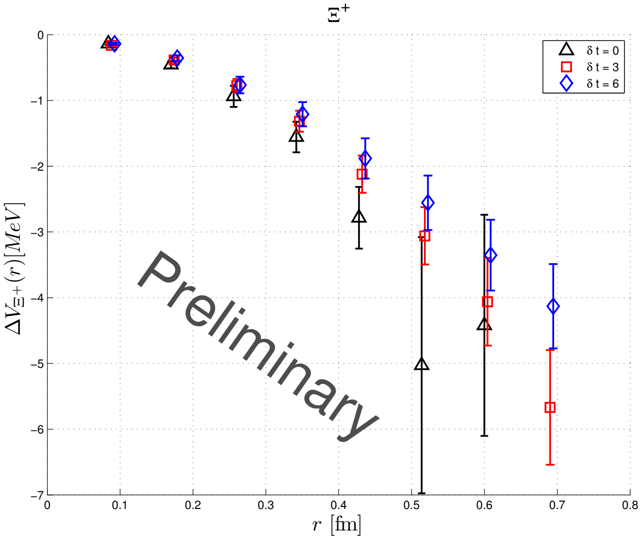


Here we have to be careful with polarizations!

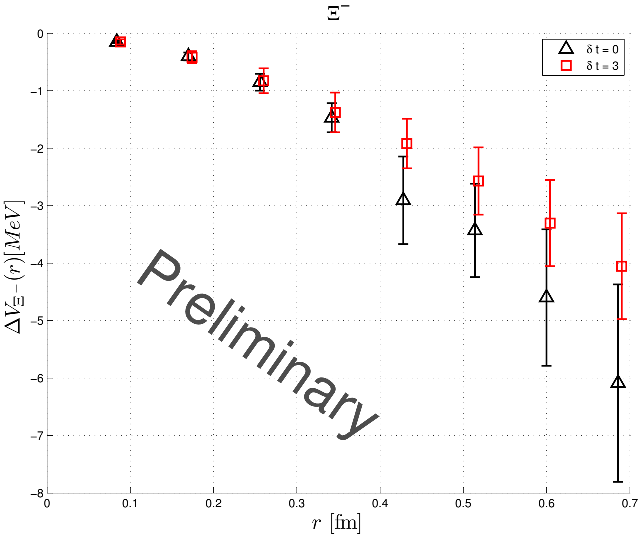
$\overline{Q}Q$ binding energy shift "within" a nucleon



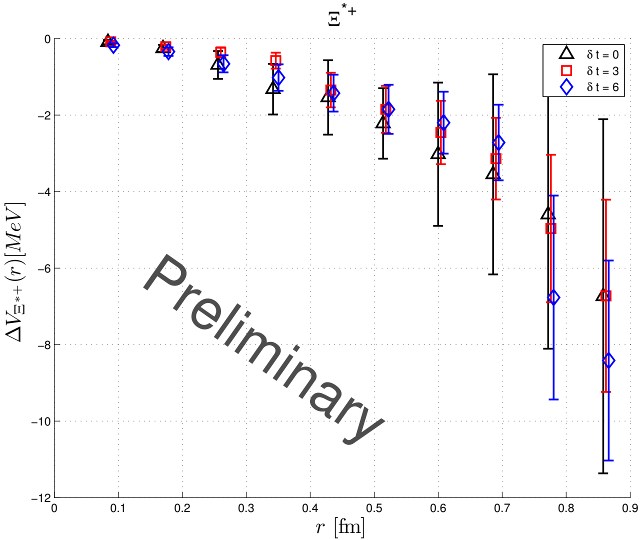
Within a cascade



... and negative parity



Within a decuplet cascade



Again we have to be careful with the helicity!

What does this mean?

In the absence of a light hadron the slope of V_0 is $\approx 1\,\mathrm{GeV/\,fm}$.
Within V_H this is reduced by $\approx 3\,\mathrm{MeV}/(0.5\,\mathrm{fm}) \approx 6‰$.
The heavy quarks are a bit weaker bound but is there any energy gain?

Virial theorem for a purely linear potential $V(r) = \sigma r$:

$$2\langle T\rangle = \left\langle r\frac{dV}{dr}\right\rangle = \sigma\langle r\rangle = 2E - 2\langle V\rangle = 2E - 2\sigma\langle r\rangle$$

This means $\langle r\rangle = 2E/(3\sigma)$. Feynman-Hellmann:

$$\frac{\partial E}{\partial\sigma} = \left\langle\frac{\partial H}{\partial\sigma}\right\rangle = \langle r\rangle = \frac{2E}{3\sigma}$$

$$\Longrightarrow \qquad E(\sigma_H) = E(\sigma_0) + (\sigma_H - \sigma)\left.\frac{\partial E}{\partial\sigma}\right|_{\sigma=\sigma_0} = \left(1 + 2\frac{\sigma_H}{\sigma_0}\right)\frac{E(\sigma_0)}{3}$$

A 6‰ smaller σ gives a 4‰ smaller energy (adding to $2m_Q$). The real world effect is smaller as the potential also contains a Coulomb term. So this amounts to $|\Delta E| = 1$–$2\,\mathrm{MeV}$.

Summary and Outlook

- Heavy quark states are narrower and cleaner than many light quark resonances. Theoretically, the heavy quark limit provides guidance. This is a prime arena for addressing "exotic" spectroscopy.
- Threshold states with hidden charm or bottom are a huge challenge, however, some aspects can be addressed within approximations and/or model assumptions.
- Pentaquarks are back! For how long?
- Modifications of the static potential in the presence of light hadrons appear tiny (similarly small as in the deuteron). Is this the end of hadro-quarkonia?
- Interestingly, there appears to be similar attraction in all of the channels investigated so far.