(Exotic) charm spectroscopy

Gunnar Bali

Universität Regensburg

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The advent of unreason in India: corrected ground energies!

Outline

- Introduction
- Hard things first: hidden charm
- Some more introduction
- Easier: threshold states with open charm
- The return of the pentaquark
- Baryons with one and two charms
- Summary

Apologies: no flavour physics, no CP violation.

Even more apologies: the choice of results covered is very subjective.

No time for bottom.

Spectroscopy: why bother?

- Only out of utmost desperation would one search for BSM physics in hadron masses.
- But BSM searches are limited by theoretical control of QCD.
- The hadron spectrum is
  - a benchmark for QCD calculations,
  - experimentally challenging,
  - non-trivial.

What has been discovered at the LHC? Example: LHCb papers.

The LHCb Detector at the LHC (08) 2463 cites.

Test of lepton universality using $\overline{B}^+ \to K^+\ell^+\ell^-$ decays (14) 612 cites.

Observation of $J/\psi p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays (15) **592** cites.

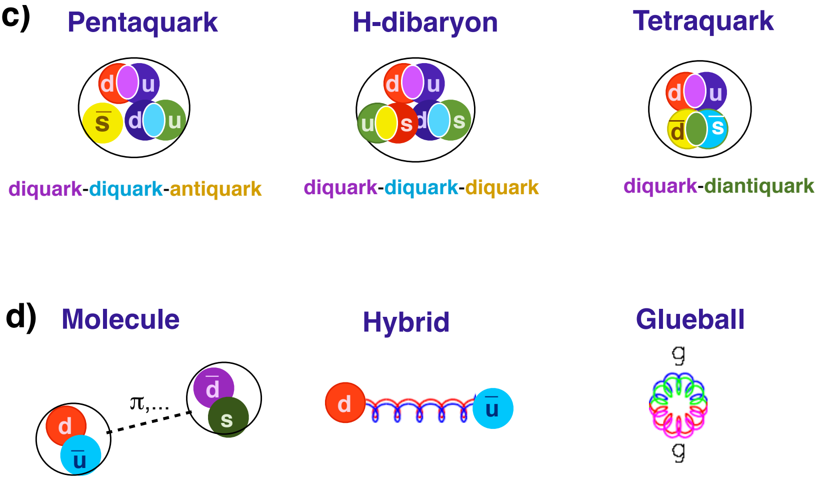
LHC: Many states with c, cc and $\bar{c}c$ but "just" one Higgs (1126 cites).

Belle: $X(3872)$ (03) **1495** cites, CP violation in B (01) 916 cites.

$\exists$ little correlation between fundamentality of discovery and cite count!

What are exotics?

From [S Olsen 1511.01589]



How can we tell?

- What is the difference between a tetraquark and a molecule?
- Glueballs, mesons, hybrids, tetraquarks have baryon number $B = 0$.
- Baryons, pentaquarks have $B = \pm 1$.
- If there is no net flavour number like $S = 2$: what is the difference?

Such questions are model-dependent and cannot be answered by experiment and neither by QCD (i.e. lattice simulation).

Positions of S matrix resonances are (ideally) model independent.

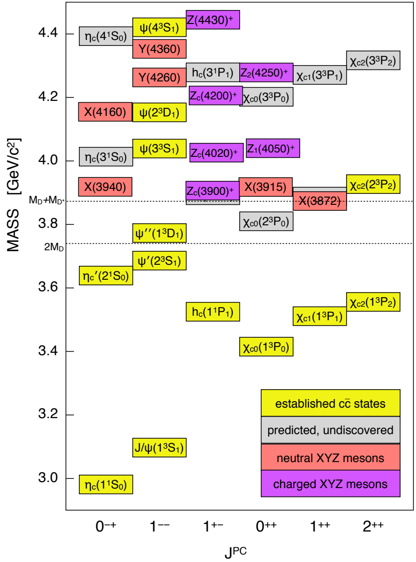
One cannot compute everything from first principles. So models are needed but they should be validated against QCD calculations.

In experiment there is only one world. In lattice simulations one can change quark masses etc.

Challenge after spectrum. Structure calculations of resonances: decay constants, distribution amplitudes, (transition) formfactors etc.

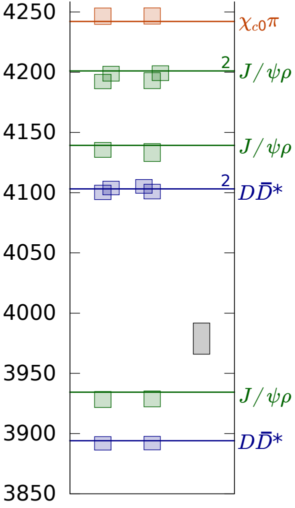
Many new $c\bar{c}$ states, some certainly not $c\bar{c}$

From [S Olsen 1511.01589]



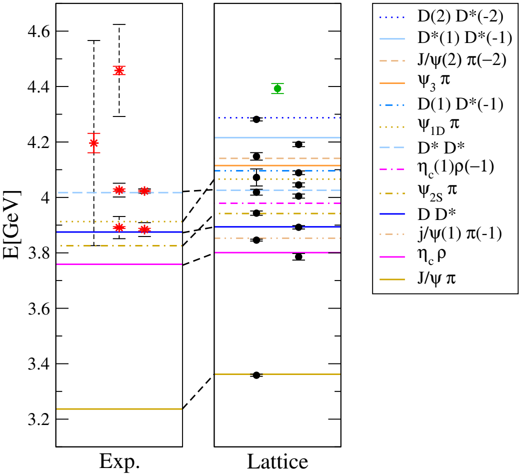
$I = 1\ 1^{+-}\ c\bar{c}q\bar{q}$ at $M_\pi = 391$ MeV

[G Cheung et al 1709.01417]



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

[S Prelovsek et al 1405.7623] $M_\pi = 266\,\text{MeV}$

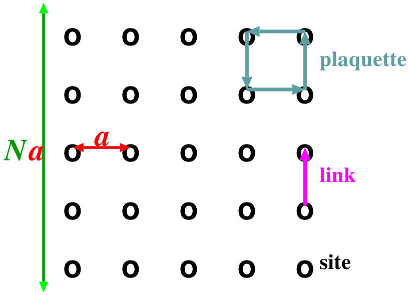


The minimal configuration cannot mix with standard charmonia!

However, even in this "simple" case a huge number of channels needs to be considered!

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

What the hell is lattice QCD?



typical values:

$a^{-1} = 2$–5 GeV, $Na = 2$–7 fm

continuum limit: $a \to 0$, Na fixed

infinite volume: $Na \to \infty$

$$\langle O \rangle = \frac{1}{Z} \int [dU]\, [d\psi][d\bar{\psi}]\, O[U] e^{-S[U,\psi,\bar{\psi}]}$$

Trick: Euclidian time $\tau = -it$.

"Measurement": average over a representative ensemble of gluon configurations $\{U_i\}$ with probability $P(U_i) \propto \int [d\psi][d\bar{\psi}] e^{-S[U,\psi,\bar{\psi}]}$

$$\langle O \rangle = \frac{1}{n} \sum_{i=1}^{n} O(U_i) + \Delta O \qquad \Delta O \propto \frac{1}{\sqrt{n}} \xrightarrow{n\to\infty} 0$$

Input: discretized $\mathscr{L}_{QCD} = \frac{1}{16\pi\alpha_s(a)} FF + \sum_f \bar{q}_f(\not{D} + m_f(a))q_f$

$$m_{\Xi}^{\text{latt}} = m_{\Xi}^{\text{phys}} \quad \longrightarrow \quad a$$
$$M_\pi^{\text{latt}}/m_{\Xi}^{\text{latt}} = M_\pi^{\text{phys}}/m_{\Xi}^{\text{phys}} \quad \longrightarrow \quad m_u(a) \approx m_d(a)$$
$$\ldots$$

Output: hadron masses, matrix elements, decay constants, etc...

Required:

1. $L = Na \to \infty$: FSE suppressed with $\exp(-LM_\pi) \Rightarrow LM_\pi \gtrsim 4$.
2. $m_q^{\text{latt}} \to m_q^{\text{phys}}$: chiral perturbation theory (χPT) helps for m_{ud} but m_{ud}^{latt} must be sufficiently small to start with ($M_\pi \lesssim 200\,\text{MeV}$?).
3. $a \to 0$: functional form known: $\mathcal{O}(a^2), \mathcal{O}(\alpha_s a) \Rightarrow \approx 4$ lattice spacings.

Only in very few calculations (almost) all of the above is done as yet, e.g., light hadron spectrum, meson decay constants, α_s, $m_{u,d,s,c}$.

Computational challenges

Cost of simulation is proportional to

- number of points: $\sim N^4 = (L/a)^4$
- condition number of linear system: $1/M_\pi^2$
- $L^{1/2}/M_\pi$ in (Omelyan) time integration within hybrid Monte Carlo
- $1/a^{\geq 2}$ critical slowing down (autocorrelations)

Adjusting $L \propto 1/M_\pi$ this means:

$$\mathrm{cost} \propto \frac{1}{a^{\geq 6}\, M_\pi^{7.5}}$$

For many observables at small M_π $\exists$ additional noise/signal problems.

State of the art: 192×96^3 sites, corresponding to $\approx (2 \times 10^{10})^2$ (sparse) complex matrices.

Tremendous progress in Hybrid Monte Carlo, solver, noise reduction.

Less improvement recently in compute power.

Scattering theory

- Elastic scattering: resonances are poles in "unphysical" Riemann sheets. Usually $\mathrm{Im}\, s_R < 0$.
- Scattering amplitude iT can be decomposed into partial waves with phase shifts δ_ℓ:

$$iT_\ell = \frac{1}{2}\left(e^{2i\delta_\ell} - 1\right) = i \sin \delta_\ell \, e^{i\delta_\ell}$$

- Breit-Wigner approximation near poles:

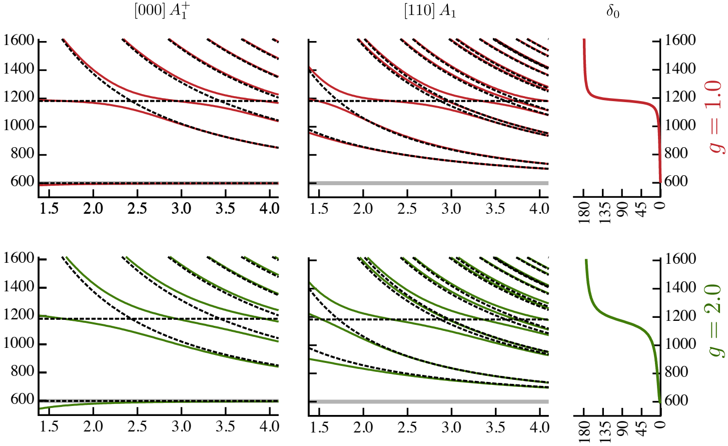
$$T_\ell \propto \frac{1}{s - s_R + i\sqrt{s}\Gamma(s)} + \text{ non singular.}$$

  Pole at $\sqrt{s} \approx \sqrt{s_R} - i\Gamma_R/2$.
- In a finite box the spectrum is discrete.
- There is no scattering in Euclidean spacetime.
- Lüscher: The shifts that occur in a finite box of energy levels of interacting particles (relative to their non-interacting counterparts) are related to scattering phase shifts in an infinite volume.

Finite volume levels in a toy model

Review [R Briceño et al, 1706.06223]

Spectrum depends on the linear box size. One channel $2 \to 2$ scattering.



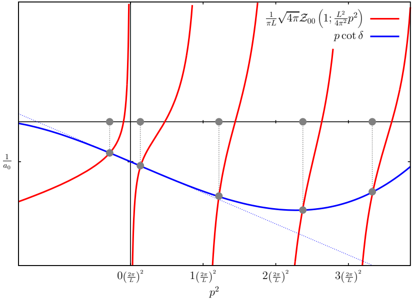
dashed: non-interacting, solid: interacting.

Resonance: avoided level crossing. Total momentum can be varied too.

Volume dependence of s-wave (pseudo)scalar^2 scattering

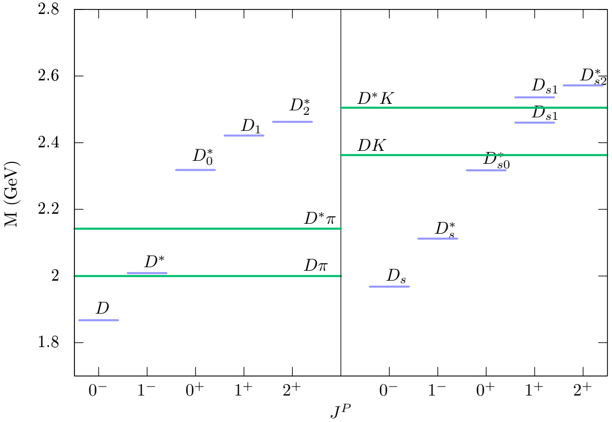
$$E_n = \sqrt{m_A^2 + k_n^2} + \sqrt{m_B^2 + k_n^2} + \Delta E_n \qquad \boldsymbol{k_n} = \frac{2\pi}{L}\boldsymbol{n}$$

$$= \sqrt{m_A^2 + p_n^2} + \sqrt{m_B^2 + p_n^2} \qquad \boldsymbol{p_n} = \frac{2\pi}{L}\boldsymbol{q_n}$$



- Lüscher relation:
$$p\cot\delta(p) = \frac{1}{\pi L}\sqrt{4\pi}\mathcal{Z}_{00}\left(1;\frac{L^2}{4\pi^2}p^2\right)$$
- Effective range approximation:
$$p\cot\delta(p) \approx a_0^{-1} + \frac{1}{2}r_0 p^2$$
- ∞ volume bound state pole condition:
$$p\cot\delta(p) = ip$$
- Volume dependence of scattering state energy:
$$\Delta E(L) = -\frac{2\pi a_0}{\mu L^3}\left(1 + c_1\frac{a_0}{L} + \dots\right)$$

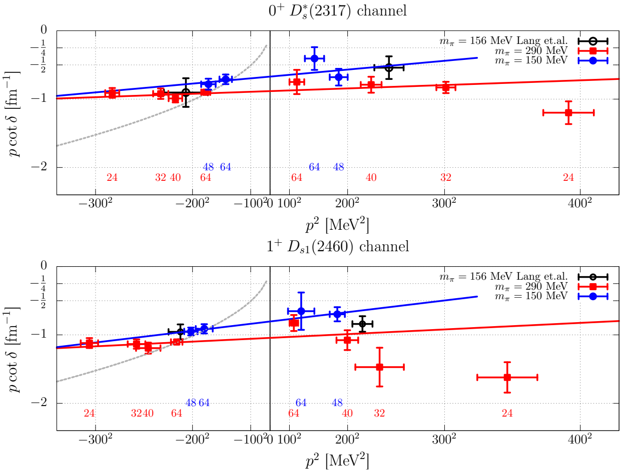
D and D_s meson masses



$D_{s0}^*(2317)$, $J^P = 0^+$, $D_{s1}(2460)$, $J^P = 1^+$:
narrow states just below (s-wave) DK and D^*K thresholds.

Before the discovery, models suggested broad resonances above thresholds.

Elastic KD^* and KD scattering



Decay constants:

$f_V^{0^+} = 114(11)$MeV

$f_A^{1^+} = 194(12)$MeV

(incl. syst. errors)

Not unusually small for P-wave mesons.

$f_V^{0^+}/f_A^{1^+}$ smaller than expectations.

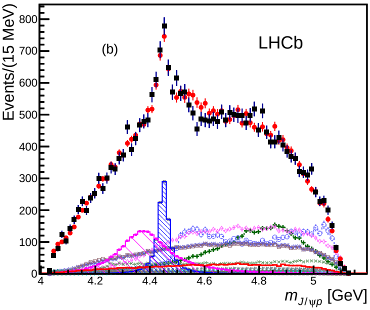
[GB, S Collins, A Cox, 1706.01247]

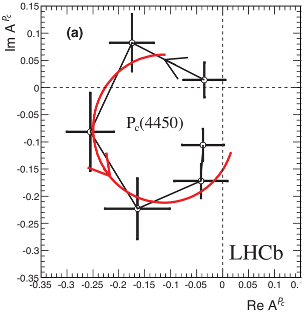
Volume dependence of D_{s1} energy weaker than for D_{s0}^*.

Splitting between D_{s1} and D_{s0}^* underestimated

(as is splitting between D_s^* and D_s): lattice spacing and $N_f = 2$ effects?

Pentaquarks are still/again with us





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

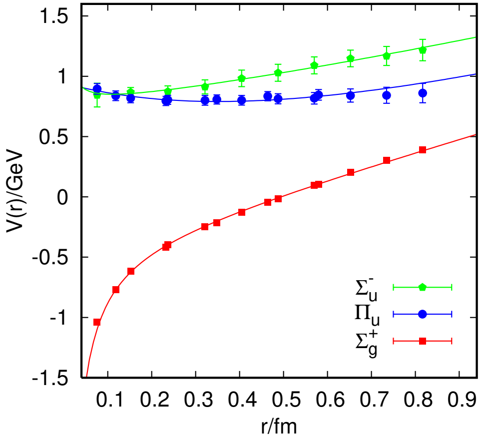
Conjecture of attractive forces between charmonium and *pp* systems:
[S Brodsky, I Schmidt, G de Teramond, PRL64 (90) 1011].

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.

Quarkonia and potentials

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

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



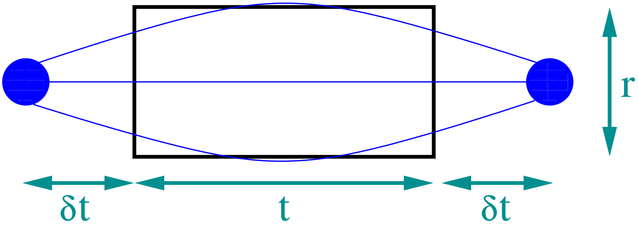
$V_0(r)$ can be computed on the lattice.
(also $1/m_Q$ and $1/m_Q^2$ corrections)

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

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

Hadroquarkonia 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

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

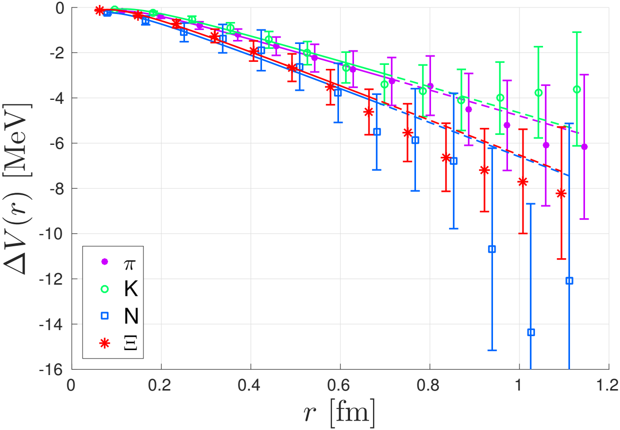
and extrapolate $\delta t \to \infty$.

$\overline{Q}Q$ binding energy shift "within" light hadrons

Many combinations are close-by:

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

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



Schrödinger eqn.:

ΔE of -1 to -5 MeV.

Robust against FSE and momentum!

Consequences?

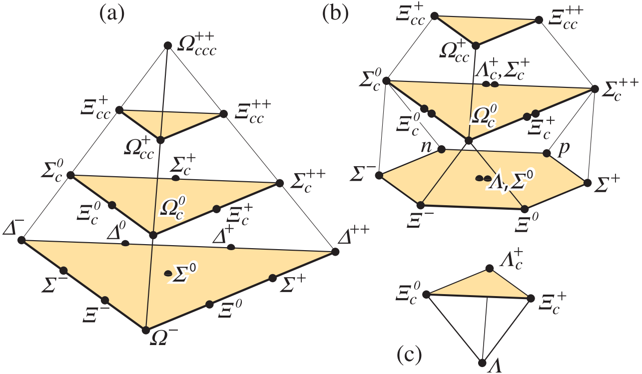
$1/m_c$ corrections?

isospin breaking?

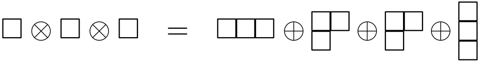
$M_\pi < 200\,\text{MeV}$?

[M Alberti et al, hep-lat/1608.06537]

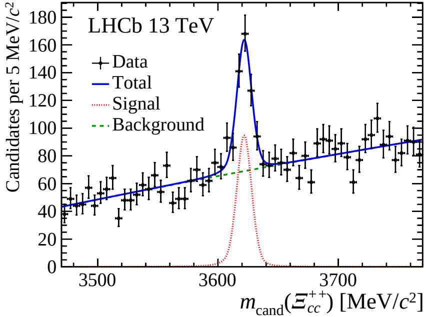
- SU(4) representations

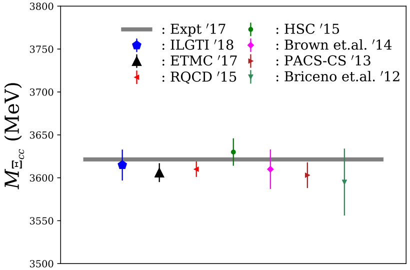


- Flavour symmetry is not respected but
- simplest way to see which baryons should exist.
- SU(4): $4 \otimes 4 \otimes 4 \quad = \quad 20 \oplus 20 \oplus 20 \oplus \overline{4}$



Doubly charmed baryon Ξ_{cc}^{++}



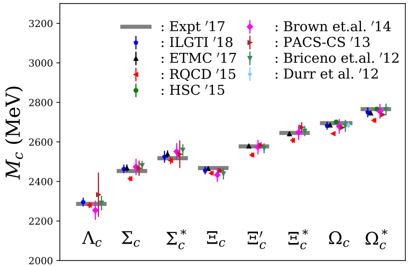


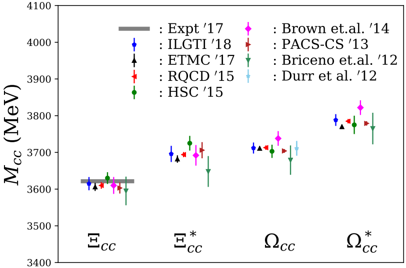
[R Briceño et al, 1207.3536]
[PACS-CS: Y Namekawa et al, 1301.4703]
[Z Brown et al, 1409.0497]
[RQCD: P Peréz Rubio et al, 1503.08440]

[HSC: M Padmanath et al, 1502.01845]
[ETMC: C Alexandrou, C Kallidonis, 1704.02647]
[LHCb: R Aaij et al, 1707.01621]
[ILGTI: N Mathur, M Padmanathar, 1807.00174]

Most lattice results were pre- and not post-dictions and all are different from 3519 MeV
[SELEX, M Mattson et al, hep-ex/020801]

Singly and doubly charmed baryons





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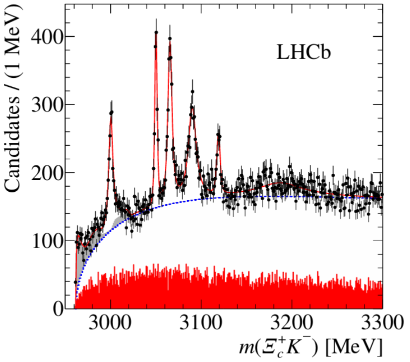
[ILGTI: N Mathur, M Padmanathar, 1807.00174]
Experiment: PDG average.

Ξ_{cc} isospin splitting 2.16(11)(17) MeV [BMW: Sz Borsanyi et al, 1406.4088]

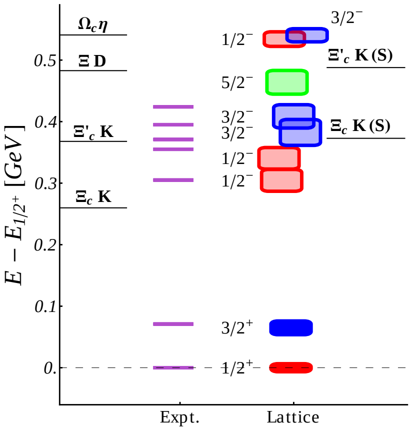
Figures provided by M Padmanath.

Many Ω_c found.

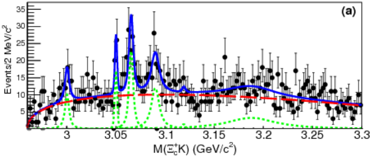
[LHCb: R Aaij et al, 1703.04639]



[M Padmanath, N Mathur, 1704.00259]



[Belle: J Yelton et al, 1711.07927]



Continuum limit taken, but at $M_\pi = 391$ MeV.

Summary and Outlook

- Hidden and open charm states are narrower and cleaner than most light quark resonances. Theoretically, the heavy quark limit provides guidance. This is a prime arena for addressing "exotic" spectroscopy.
- Charmonium masses below $\overline{D}D$ threshold can be reproduced within Lattice QCD including finestructure splittings. Still some work to do regarding annihilation diagrams and the continuum limit.
- A lot of progress regarding threshold states with open charm! Also the structure of these states should be studied.
- Threshold states with hidden charm are a huge challenge, however, can be addressed within approximations and/or model assumptions.
- Pentaquarks are back.
- A first baryonic sister of charmonium has been discovered! Do doubly charmed baryons resemble $(cc)u, (cc)s$ D, D_s "heavy mesons" — or $c(cu), c(cs)$ "charmonia"?
- Now that there is ccu, what about $cc\bar{u}\bar{u}$?