Charmonium and charmonium-like resonances from lattice QCD

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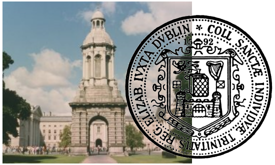

EMMI, 14th October 2015

MY CHARMING COLLABORATORS...

Graham Moir, Mike Peardon, Christopher Thomas

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Outline

- Introduction and motivation
- Some lattice technicalities
    - A toolbox for resonance calculations on the lattice
- Selected results
    - precision low-lying and excited state spectrum
    - pioneering results above threshold: the XYZ states
- Summary: conclusions and perspectives

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Many results and details omitted for time (and clarity!) constraints - APOLOGIES!

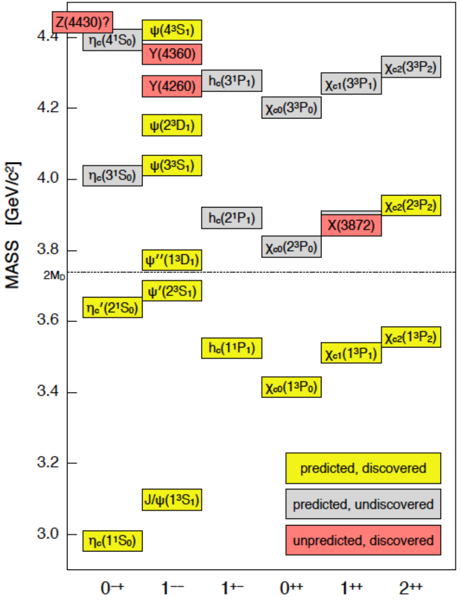
A CHARM REVOLUTION: CCBAR

X,Y,Z states: narrow charmonium-like structures above the open charm threshold. Not all in $^{2S+1}L_J$ pattern - what is the nature of these states?

States below open charm threshold: $\eta_c(1S, 2S), J/\Psi(1S, 2S)$ $\chi_{c(0,1,2)}(1P), h_c(1P)$.

- X(3872): close to $D\bar{D}^*$ threshold - a molecular meson?
- X(4260): 1^{--} hybrid meson?
- X(4430)$^\pm$: charged - not $c\bar{c}$: tetraquark?
- No clear picture has emerged.

from talk by R. Mitchell ⟶



Anatomy of charmonium on the lattice

CHARM QUARKS AND LATTICE QCD

For heavy quarks $\mathcal{O}(am_q)$ can be large [a is the lattice spacing] and must be controlled. There are now well-established methods:

- NRQCD
- Brute force - make a “small enough” ... expensive but doable now!
- Fermilab - an effective theory that interpolates smoothly between heavy and light
- Anisotropic lattices: $a_t m_c < 1$ to control discretistation.

Charm is not light but not (really) heavy either. NRQCD not really suitable.

A RECIPE FOR (MESON) SPECTROSCOPY

- Construct a basis of local and non-local operators $\bar{\Psi}(x)\Gamma D_i D_j \ldots \Psi(x)$ from *distilled* fields [PRD80 (2009) 054506].
- Build a correlation matrix of two-point functions

$$C_{ij} = \langle 0|\mathcal{O}_i \mathcal{O}_j^\dagger|0\rangle = \sum_n \frac{Z_i^n Z_j^{n\dagger}}{2E_n} e^{-E_n t}$$

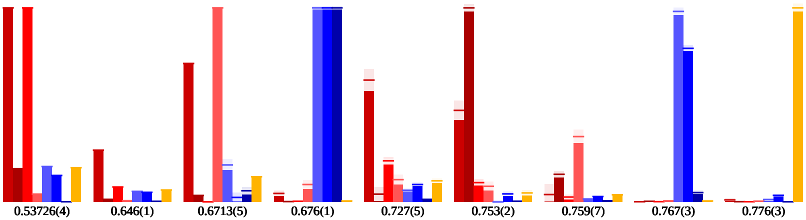
- Ground state mass from fits to e^{-Ent}
- Beyond ground state: Solve generalised eigenvalue problem $C_{ij}(t)v_j^{(n)} = \lambda^{(n)}(t)C_{ij}(t_0)v_j^{(n)}$

- eigenvalues: $\lambda^{(n)}(t) \sim e^{-E_n t}\left[1 + O(e^{-\Delta E t})\right]$ - principal correlator
- eigenvectors: related to overlaps $Z_i^{(n)} = \sqrt{2E_n} e^{E_n t_0/2} v_j^{(n)\dagger} C_{ji}(t_0)$

- operators of definite J^{PC} constructed in step 1 are subduced into the relevant irrep
- a subduced irrep carries a "memory" of continuum spin J from which it was subdduced - it **overlaps** predominantly with states of this J.

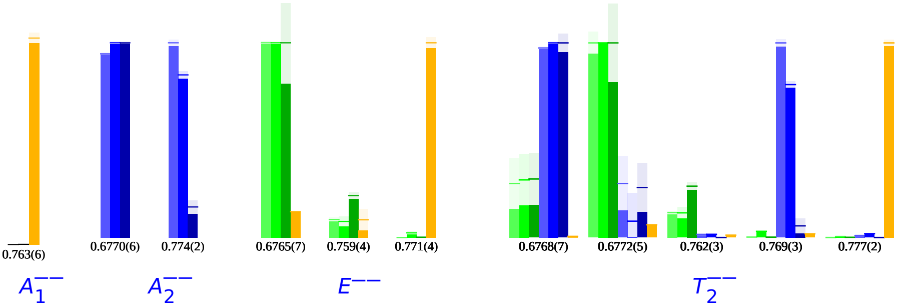
J	**0**	**1**	**2**	**3**	**4**
A_1	1	0	0	0	1
A_2	0	0	0	1	0
E	0	0	1	0	1
T_1	0	1	0	1	1
T_2	0	0	1	1	1

- Using $Z = \langle 0|\Phi|k\rangle$, helps to identify continuum spins
- For high spins, can look for agreement between irreps
- Data below for T_1^{--} irrep, colour-coding is **Spin 1**, **Spin 3** and **Spin 4**.



... THE REST OF THE SPIN-4 STATE

- All polarisations of the spin-4 state are seen
- Spin labelling: **Spin 2**, **Spin 3** and **Spin 4**.

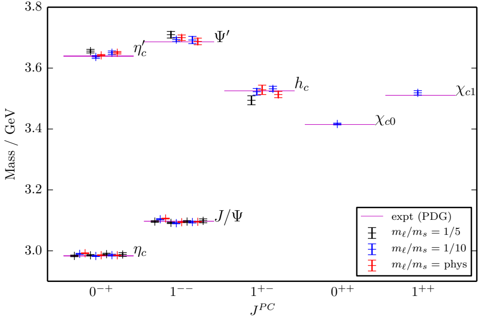


Precision Spectroscopy:
states below strong decay thresholds

Single hadron states: below threshold

- Methods: tested, validated.
- High statistics and improved actions for precise results.
- Different actions in agreement.
- Simulation at m_q^{phys} or extrapolation $m_q \to m_q^{\text{phys}}$.
- Discretisation errors $\mathcal{O}(am_c)$ and $\mathcal{O}(am_b)$ under control,

Charmonium, HPQCD 1411.1318



Continuum limit, physical quark masses

No disconnected diagrams in $c\bar{c}$ spectrum: OZI suppressed - assumed to be small
$\Rightarrow$ mixing with lighter states not included

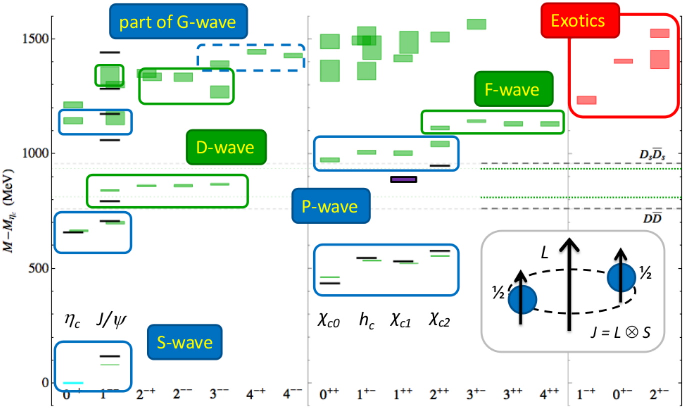
Precision Spectroscopy:
single hadron states near/above thresholds

Single hadron states: above threshold

Precision calculation of high spin ($J \geq 2$) and exotic states is relatively new

Caveat Emptor

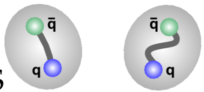
- Physics of multi-hadron states appears to need relevant operators
- No continuum extrapolation
- Relatively heavy pions ← already changing

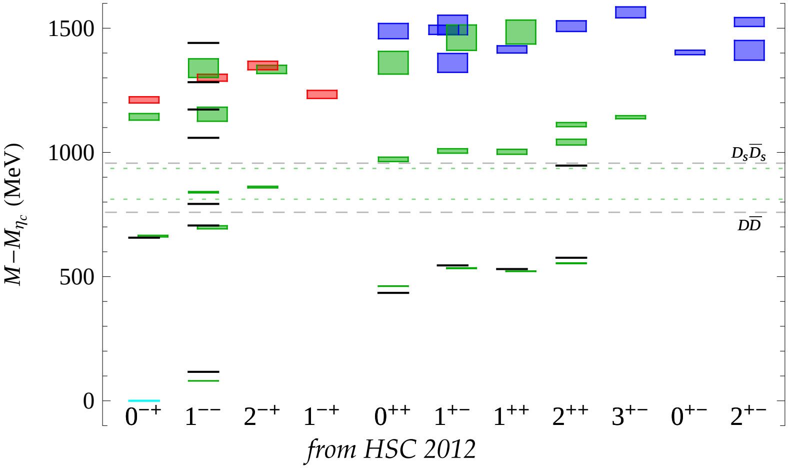


from HSC 2012

→ Expect improvements now methods established

HYBRIDS





Lightest hybrid supermultiplet and excited hybrid supermultiplet same pattern and scale as in charmonium and light[HadSpec:1106.5515] sectors.

LAST COMMENT ON SINGLE-HADRON SPECTRUM

Disconnected diagrams a remaining uncertainty in most $c\bar{c}$ calculations.
Distillation allows precision determination. BUT it's a can of worms!

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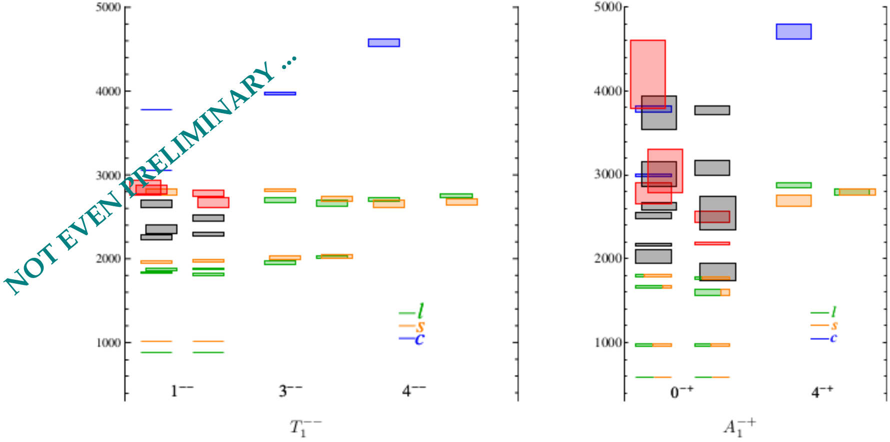


$\Delta(1^{--}) = -17(16)\mathrm{MeV}$

from HadSpec

Charmonium-like Resonances in Lattice QCD

- Pioneering calculations by Lang, Prelovsek and collaborators
- New ideas developed and tested for light mesons will be applied to charmonium

SCATTERING IN A EUCLIDEAN THEORY

Lose direct access to scattering in (Euclidean) lattice calculations

Lüscher found a way to extract scattering information in the elastic region from LQCD . [NPB354, 531-578 (1991)]

- related lattice energy levels in a finite volume to a decomposition of the scattering amplitude in partial waves in infinite volume

$$\det\left[\cot\delta(E_n^*) + \cot\phi(E_n,\ vecP, L)\right] = 0$$

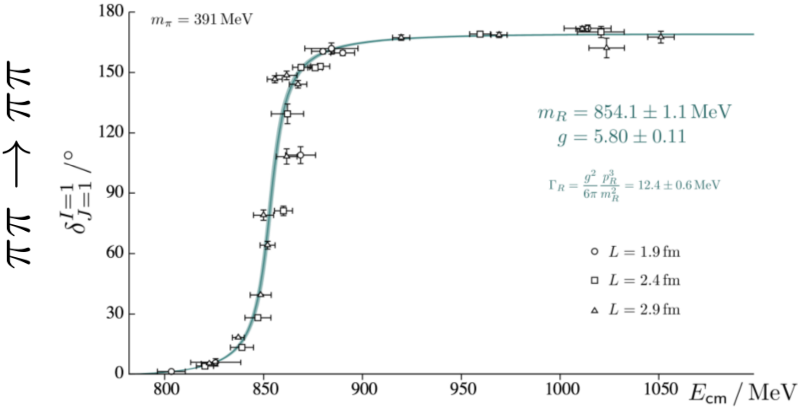
and $\cot\phi$ a known function (containing a generalised zeta function).

- To use this idea need energy levels at extraordinary precision. This is why it has taken a while ...

A different approach from HALQCD via energy-independent potentials was discussed by Oka.

USING LÜSCHER'S IDEA

Now in use to determine resonance parameters



$$m_\pi = 391 \text{ MeV}$$

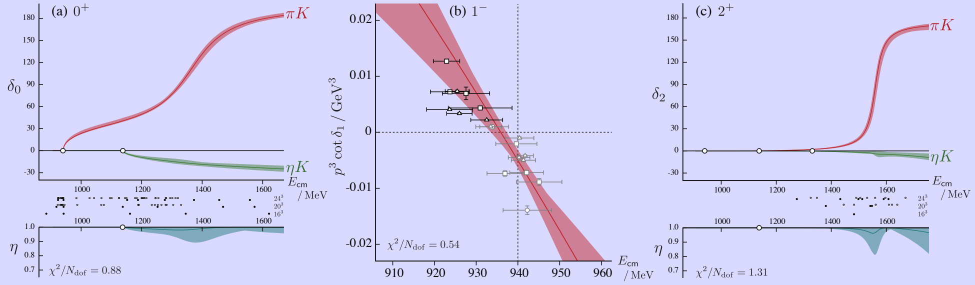
from Dudek, Edwards, Thomas in *Phys.Rev.* D87 (2013) 034505

Many talks at Lattice 2015

RECENT PROGRESS

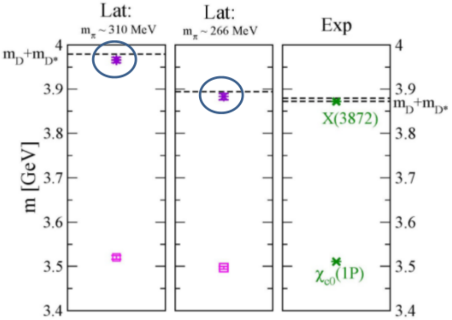
- Generalised for: moving frames; non-identical particles; multiple two-particle channels, particles with spin, by many authors.
- The precision and robustness of some numerical implementations is now very impressive. *[See talks at Lattice 2015]*
- First coupled-channel resonance in a lattice calculation

$\pi K \to \eta K$ by D. Wilson et al 1406.4158 and 1507.02599

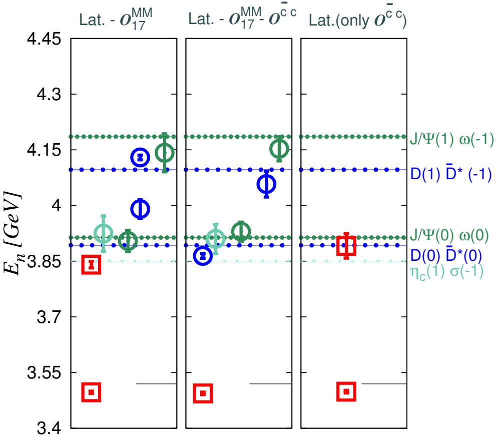


X(3872)

Prelovsek & Leskovec 1307.5172



Padmanath, Lang, Prelovsek 1503.03257



ground state: $\chi_{c1}(1P)$
$D\bar{D}^*$ scattering mx: pole just below thr.
Threshold $\sim m_{u,d}$ *and* m_c *discretisation?*

X(3872) not found if $c\bar{c}$ not in basis.

Also results from Lee et al 1411.1389
State is within 1MeV of $D^0\bar{D}^0{}^*$ and 8MeV of D^+D^* thresholds: isospin breaking effects important?

Z_c^+

An “exotic” hadron i.e. does not fit in the quark model picture.

There are a number of exploratory calculations on the lattice.

Challenges:

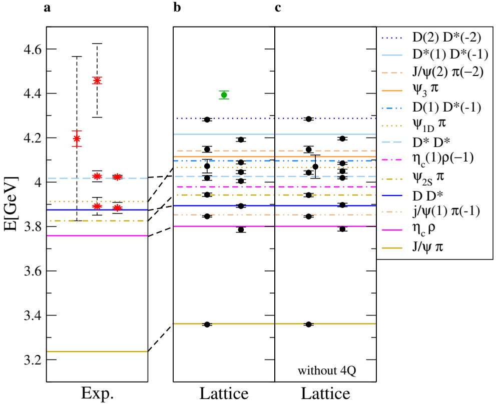
- The Z_c^+ (and most of the XYZ states) lies above several thresholds and so decay to several two-meson final states
- requires a coupled-channel analysis for a rigorous treatment
- on a lattice the number of relevant coupled-channels is large for high energies.

State of the art in coupled-channel analysis:

- Lüscher: $K\pi, K\eta$ [HSC 2014,2015]
- HALQCD: Z_c [preliminary results - see Oka's talk yesterday]

First look on the lattice

Prelovsek, Lang, Leskovec, Mohler: 1405.7615



- 13 expected 2-meson e'states found (black)
- no additional state below 4.2GeV
- no Z_c^+ candidate below 4.2GeV

Similar conclusion from Lee et al [1411.1389] and Chen et al [1403.1318]

Why no eigenstate for Zc? Is Z_c^+ a coupled channel effect? What can HALQCD say? Work needed!

MANY OTHER STATES BEING INVESTIGATED

Tetraquarks:

- Double charm tetraquarks ($J^P = 1^+, I = 0$) by HALQCD [PLB712 (2012)]
  - attractive potential, no bound tetraquark state
- Charm tetraquarks: variational method with DD^*, D^*D^* and tetraquark operators finds no candidate.

Y(4140)

- Ozaki and Sasaki [1211.5512] - no resonant Y(4140) structure found
- Padmanath, Lang, Prelovsek [1503.03257] considered operators: $c\bar{c}, (\bar{c}s)(\bar{s}c), (\bar{c}c)(\bar{s}s), [\bar{c}\bar{s}][cs]$ in $J^P = 1^+$. Expected 2-particle states found and $\chi_{c1}, X(3872)$ **not** Y(4140).

⋮

See Prelovsek @ Charm2015 for more

CHALLENGES ...

There have been many successes in charmonia in the last 5 years including

- determination of the spectrum of single-hadron states
- application of Luscher method and HALQCD's approach to study states near/above decay thresholds

Many challenges remain

- A determination of states including disconnected diagrams and mixing with light states
- Improvements to existing calculations - understanding the effect of lighter light quarks on thresholds etc, simulations at multiple and larger volumes
- Handling the large number of coupled-channels that emerged on larger volumes
- Doing a coupled channel analyses of charmonium and charmonium-like states
- A general framework for coupled channels for scattering involving more than 2 hadrons. Some progress [M. Hansen @ Lattice 2015]
- Understanding the physics!

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Thanks for listening!