Understanding the QCD spectrum: progress and prospects from Lattice QCD

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Colloquium @ GSI 10th May 2016

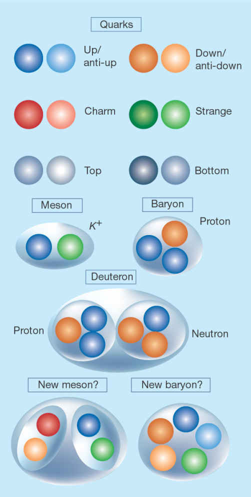
Plan

- The QCD spectrum
  - Quark models and QCD.
  - New discoveries and further puzzles.
- A consumers guide to Lattice QCD
  - compromises and consequences
- Discussion and selected results (mostly charm/charmonium)
  - parallel tracks for progress
  - old challenges and new results
  - new challenges and exploratory results
    - **precision spectroscopy of single hadron states including excited and exotic states**
    - **spectroscopy of scattering states - progress and challenges**
- Summary

Why Hadron Spectroscopy?

- Many recently discovered hadrons have unexpected properties.
- Understand the hadron spectra to separate EW physics from strong-interaction effects
- Techniques for non-perturbative physics useful for physics at LHC energies.
- Understanding EW symmetry breaking may require nonperturbative techniques at TeV scales, similar to spectroscopy at GeV.
- Better techniques may help understand the nature of masses and transitions

Objects of interest



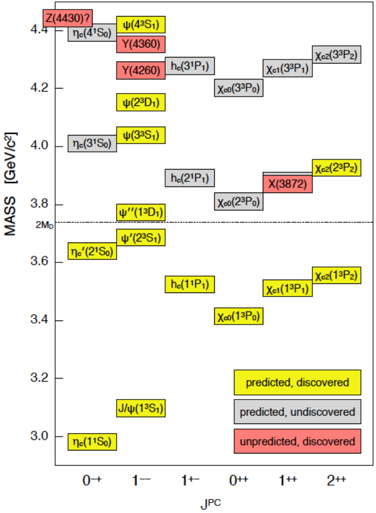
- Built from fundamental objects: quarks and gluons
- Fields of Lagrangian in colorless combinations: confinement

quark model object	structure
meson	$3 \otimes \bar{3} = 1 \oplus 8$
baryon	$3 \otimes 3 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 10$
hybrid	$\bar{3} \otimes 8 \otimes 3 = 1 \oplus 8 \oplus 8 \oplus 8 \oplus 10 \oplus 10$
glueball	$8 \otimes 8 = 1 \oplus 8 \oplus 8 \oplus 10 \oplus 10$
$\vdots$	$\vdots$

- This is a model. QCD does not always respect this constituent picture! There can be strong mixing.

Hadron states: questions and puzzles not resolved by models

- States classified by $J^{P(C)}$ multiplets (representations of the poincare symmetry).
- In quark models, mesons with $P = (-1)^J$ and $CP = -1$ forbidden. Some J^{PC} combinations don't appear: $0^{+-}, 0^{--}, 1^{-+}, 2^{+-}, \ldots$ These *exotics* (not just a $q\bar{q}$ pair) allowed in **QCD** .
- Many more baryon states predicted than observed - the missing resonance problem.
- Where are the other states **QCD** allows - hybrids, glueballs, ... ?



from D. Bettoni CIPANP2015

Why Lattice QCD ?

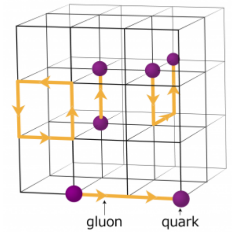
- A systematically-improvable non-perturbative formulation of QCD
  - Well-defined theory with the lattice a UV regulator
- Arbitrary precision is in principle possible
  - of course algorithmic and field-theoretic “wrinkles” can make this challenging!
- Starts from first principles - i.e. from the QCD Lagrangian
  - inputs are quark mass(es) and the coupling - can explore mass dependence and coupling dependence but getting to physical values can be hard!

A lattice QCD primer

Start from the QCD Lagrangian:

$$\mathcal{L} = \bar{\Psi}\left(i\gamma^{\mu}D_{\mu} - m\right)\Psi - \frac{1}{4}G^{a}_{\mu\nu}G^{\mu\nu}_{a}$$

Gluon fields on links of a hypercube;
Quark fields on sites: approaches to fermion discretisation - Wilson, Staggered, Overlap.;
Derivatives $\longrightarrow$ finite differences.



Solve the QCD path integral on a finite lattice with spacing $a \neq 0$ estimated stochastically by Monte Carlo. Can only be done effectively in a Euclidean space-time metric (no useful importance sampling weight for the theory in Minkowski space).

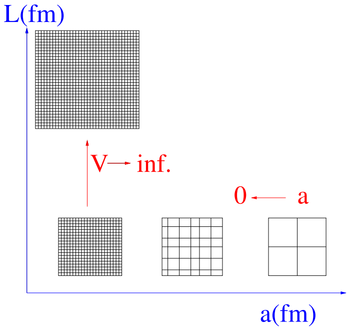
Observables determined from (Euclidean) path integrals of the QCD action

$$\langle \mathcal{O} \rangle = 1/Z \int \mathcal{D}U\mathcal{D}\bar{\Psi}\mathcal{D}\Psi\ \mathcal{O}[U,\bar{\Psi},\Psi]e^{-S[U,\bar{\Psi},\Psi]}$$

Compromises and the Consequences

1. Working in a finite box at finite grid spacing

- Identify a "scaling window" where physics doesn't change with a or V. Recover continuum **QCD** by extrapolation.



A costly procedure but a regular feature in lattice calculations now

2. Simulating at physical quark masses

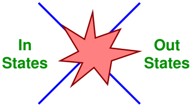
- Computational cost grows rapidly with decreasing quark mass $\longrightarrow m_q = m_{u,d}$ costly. Care needed vis location of decay thresholds and identification of resonances.
- c-quark can be handled relativistically. b-quark with: NRQCD, FNAL etc.

Better algorithms for physical light quarks and/or chiral extrapolation. Relativistic m_b in reach

2. Breaking symmetry

- Lorentz symmetry broken at $a \neq 0$ so $SO(4)$ rotation group broken to discrete rotation group of a hypercube.
  Classify states by irreps of O_h and relate by subduction to J values of O_3. Lots of degeneracies in subduction for $J \geq 2$ and physical near-degeneracies. Complicates spin identification.

Spin identification at finite lattice spacing: 0707.4162, 1204.5425



3. Working in Euclidean time.

- Scattering matrix elements not directly accessible from Euclidean QFT [*Maiani-Testa theorem*]. Scattering matrix elements: asymptotic $|\mathrm{in}\rangle$, $|\mathrm{out}\rangle$ states:
  $\langle\mathrm{out}|e^{i\hat{H}t}|\mathrm{in}\rangle \rightarrow \langle\mathrm{out}|e^{-\hat{H}t}|\mathrm{in}\rangle$. Euclidean metric: project onto ground state. Analytic continuation of numerical correlators an ill-posed problem.

Lüscher and generalisations of: method for indirect access.

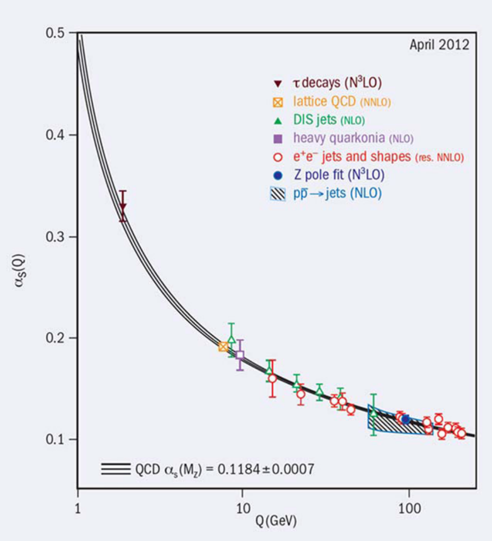
4. Quenching

No longer an issue: Simulations done with $N_f = 2, 2+1, 2+1+1$.

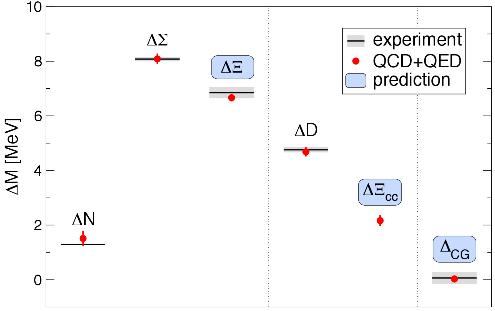
Validation:
can we reproduce known results and make verified predictions?

Validation

The running coupling, α_s



Baryon electromagnetic mass splittings

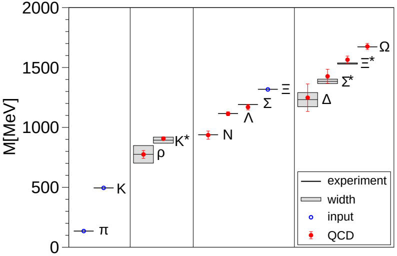


QED + QCD

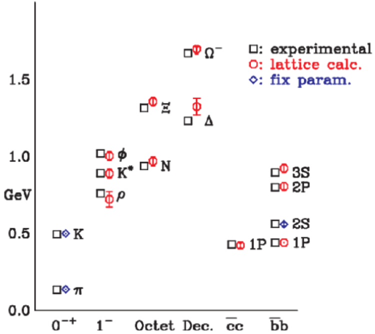
BMW Collab. Science 347 (2015) 1452

Convergence through universality

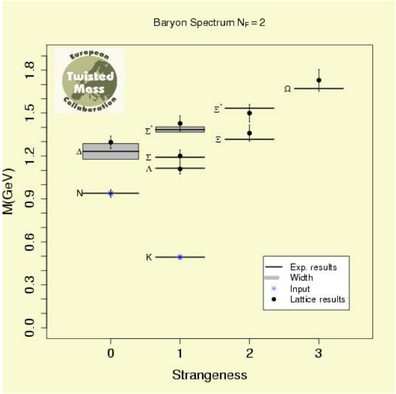
BMW Collaboration



MILC Collaboration



ETMC Collaboration



BMW: SW-Wilson [Science 322:1224-1227,2008.]

ETMC: Twisted Mass [arXiv:0910.2419,0803.3190]

MILC: Staggered [arXiv:0903.3598]

Two strategies for progress

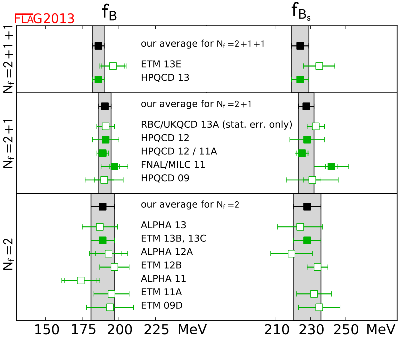
Gold-plated quantities

- e.g. single hadron states, or decays below thresholds
- phenomenologically relevant
- incremental progress
- robust/well-tested methods
- careful error budgeting

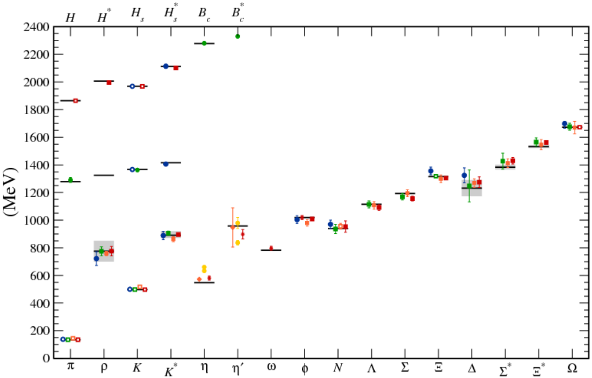
New directions

- new ideas - theoretical and algorithmic that open new avenues
- recent examples are scattering states, g-2, ...
- also improves gold-plated
- pioneering, error budgets not yet “robust”

Strategies for progress: gold plated quantities - a selection



FLAG 2013 itpwiki.unibe.ch/flag/



A. Kronfeld, Ann.Rev.Nucl.Part.Sci. 62 (2012)

- Stable single-hadron states, below thresholds
- Including continuum extrapolation, realistic quark masses, renormalisation etc

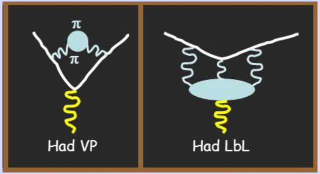
Strategies for progress: new directions - a selection

New ideas in hadron spectroscopy

- **Distillation** for quark propagation enabled isoscalars, precision spectroscopy, efficient calculation and motivated ...
- **Scattering and Coupled channels** new theoretical ideas to tackle scattering states and study (X,Y,Z), resonance parameters in eg πK, $\pi\eta$ ...

New ideas for g-2

- Dominant uncertainty is in hadronic contributions - HVP and HLbL



- lots more!

Lattice Hadron Spectroscopy
precision & pioneering results

(i) Precision spectroscopy of single-hadron states
(ii) Exploratory studies of "exotic" and scattering states

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 - the key enabling idea!** [PRD80 (2009) 054506].
- Build a correlation matrix of two-point functions

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

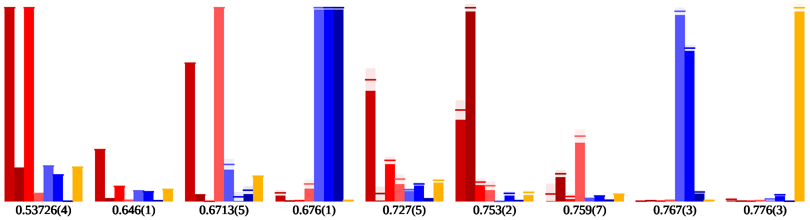
- Ground state mass from fits to $e^{-E_n t}$
- Beyond ground state: Solve generalised eigenvalue problem $C_{ij}(t)v_j^{(n)} = \lambda^{(n)}(t)C_{ij}(t_0)v_j^{(n)}$

- 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 subddduced - it **overlaps** predominantly with states of this J.

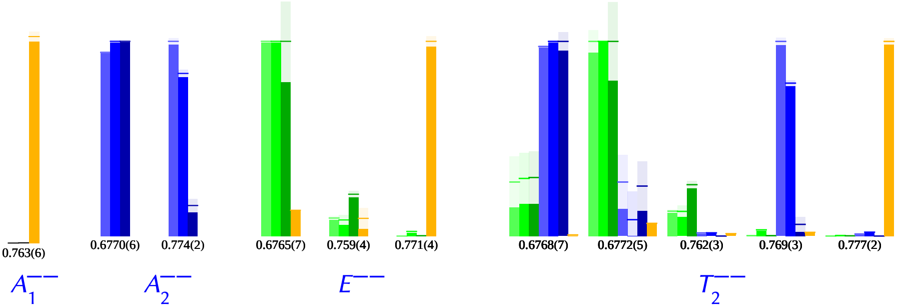
J	0	1	2	3	4
A_1	1	0	0	0	1
A_2	0	0	0	1	0
E	0	0	1	0	1
T_1	0	1	0	1	1
T_2	0	0	1	1	1

- 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**.

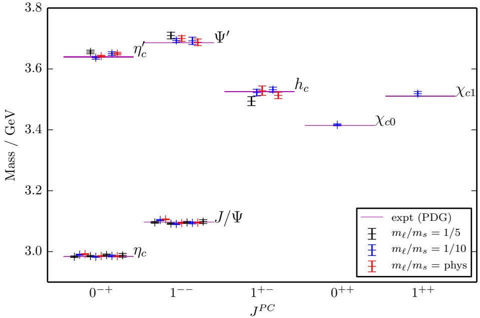


Precision Spectroscopy:
states below strong decay thresholds

Single hadron states: below threshold - "gold-plated"

- Methods: tested, validated.
- High statistics and improved actions for precise results.
- Different actions in agreement.
- Simulation at m_q^{phys} or extrapolation $m_q \longrightarrow m_q^{\text{phys}}$.
- 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

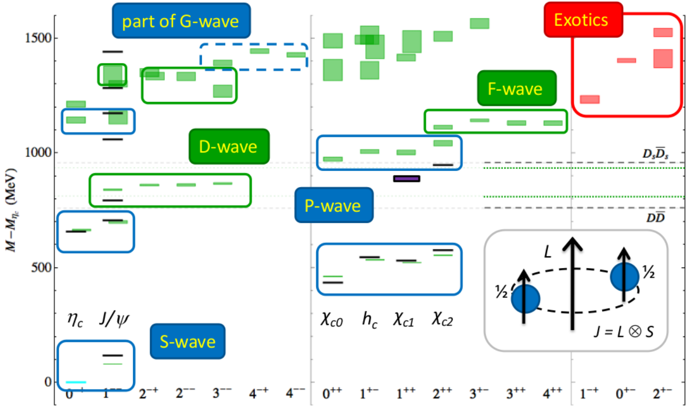
Single hadron states: above threshold

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

Charmonium

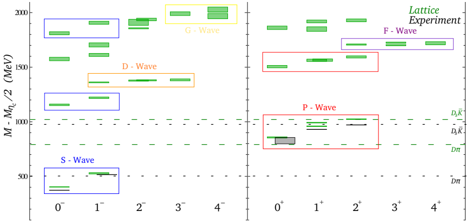
Caveat Emptor

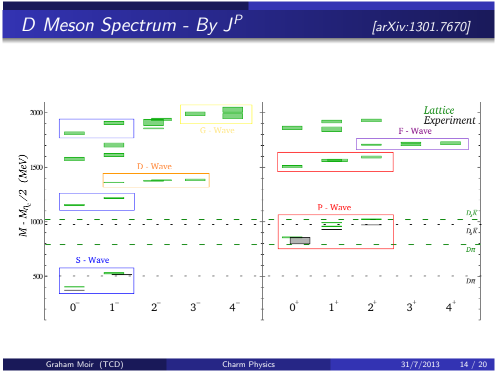
- Only single-hadron operators
- Physics of multi-hadron states appears to need relevant operators
- No continuum extrapolation
- Relatively heavy pions ← already changing

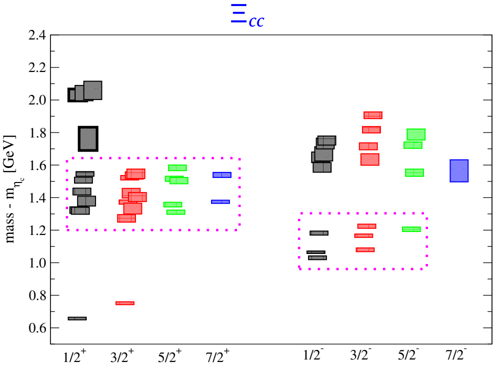


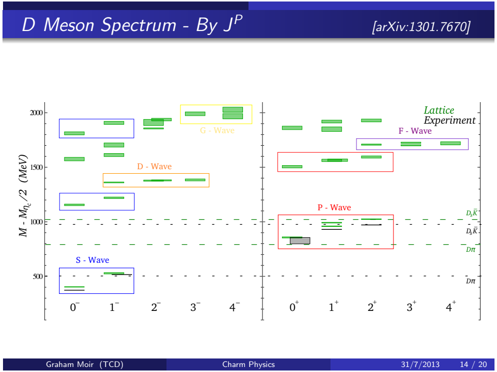
from HSC 2012

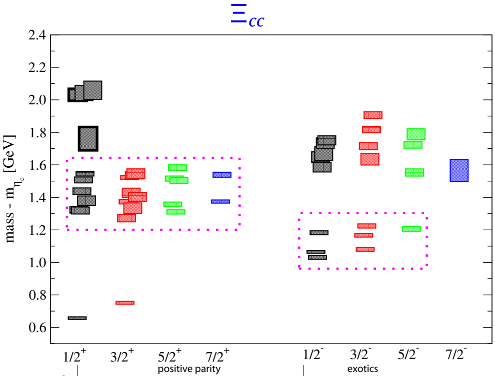
→ Expect improvements now methods established


Lattice
Experiment
G - Wave
F - Wave
D - Wave
P - Wave
S - Wave
$D_s\bar{K}$
$D\pi$
2000
1500
1000
500
M - M_{η_c}/2 (MeV)
0^- 1^- 2^- 3^- 4^-
0^+ 1^+ 2^+ 3^+ 4^+

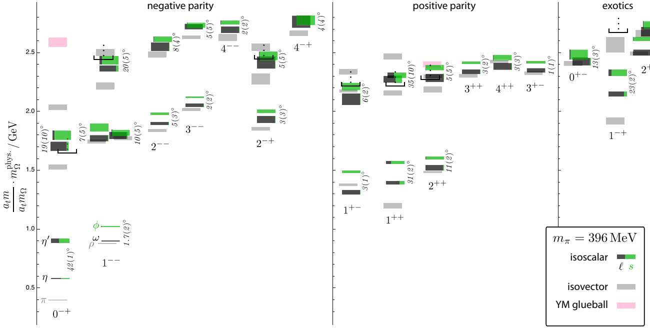

D Meson Spectrum - By J^P
[arXiv:1301.7670]
Lattice
Experiment
G - Wave
F - Wave
D - Wave
P - Wave
S - Wave
$M - M_{\eta_c}/2$ (MeV)
2000
1500
1000
500
$D_s\bar{K}$
$D_s\bar{K}$
$D\pi$
$D\pi$
0^- 1^- 2^- 3^- 4^-
0^+ 1^+ 2^+ 3^+ 4^+
Graham Moir (TCD)
Charm Physics
31/7/2013
14 / 20


Ξ_{cc}
mass - m_{η_c} [GeV]
2.4
2.2
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
$1/2^+$ $3/2^+$ $5/2^+$ $7/2^+$
$1/2^-$ $3/2^-$ $5/2^-$ $7/2^-$



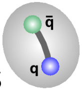


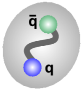
HadSpec results

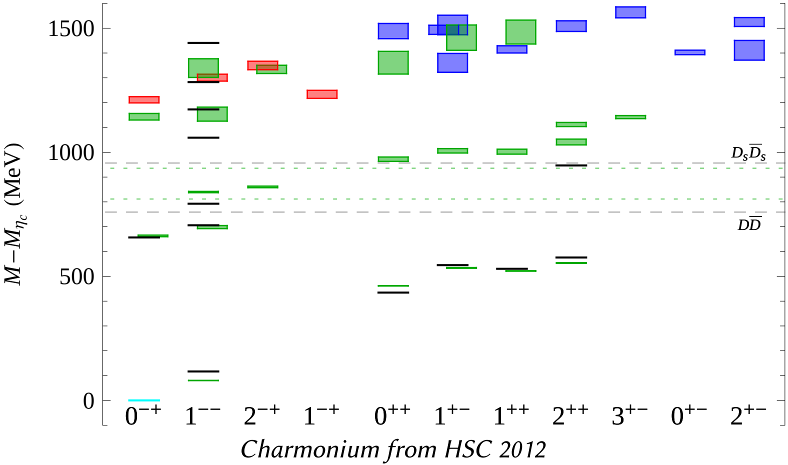


light mesons

Hybrids







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

Exploratory studies of scattering states

Characterised by

- New methods (developed/applied in last 5 years)
    - algorithmic: distillation allows access to all elements of propagators *and* construction of sophisticated basis of operators.
    - theoretical: spin-identification; construction of multi-hadron operators and mesons in flight; scattering below inelastic thresholds; coupled-channels (new in ’14).
- Generally high statistics, improved actions etc - results can be very precise.
- Systematic errors not all controlled in exploratory studies: e.g. no continuum extrapolation, relatively heavy pions ...

Rapid progress in the last 5 years!

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

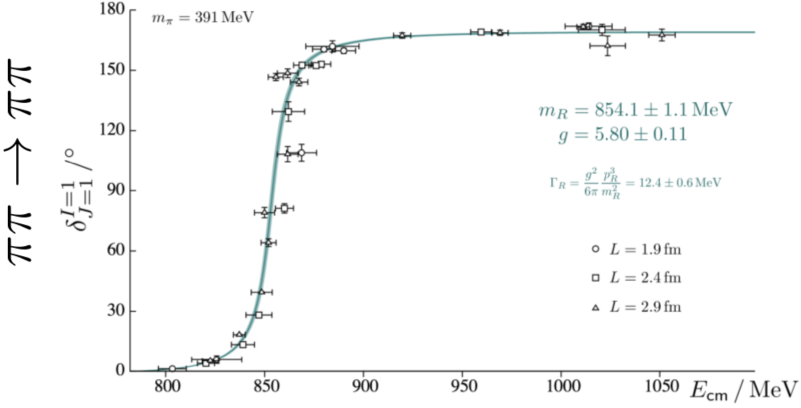
$$\det\left[\cot\delta(E_n^*) + \cot\phi(E_n, \vec{P}, L)\right] = 0$$

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

- The idea dates from the quenched era. To use it in a dynamical simulation need energy levels at extraordinary precision. This is why it has taken a while ...

Using Lüscher's idea

Now in use to determine resonance parameters



$m_\pi = 391$ MeV

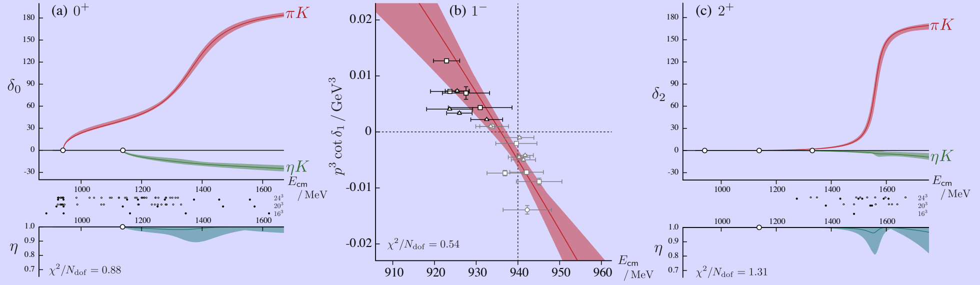
from Dudek, Edwards, Thomas in *Phys.Rev.* D87 (2013) 034505

Many talks at Lattice 2015 & 2016

Even more recent progress

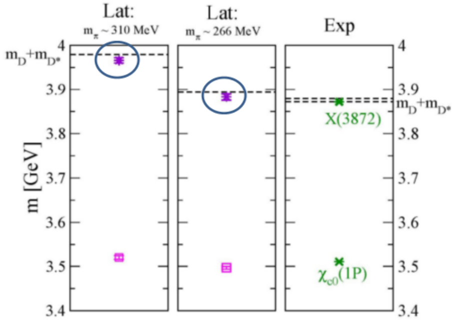
- Generalised for: moving frames; non-identical particles; multiple two-particle channels, particles with spin, by many authors.
- The precision and robustness of some numerical implementations is now very impressive. *[See talks at Lattice 2015 & 2016]*
- First coupled-channel resonance in a lattice calculation

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

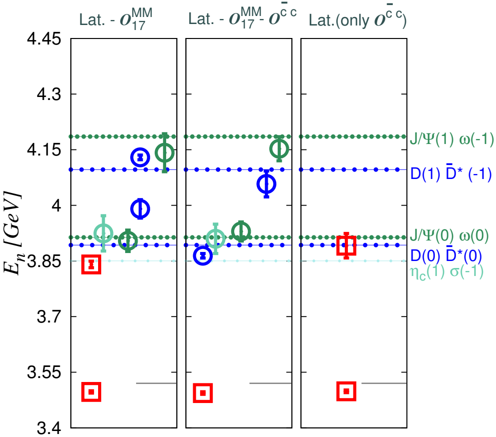


X(3872) - a first look

Prelovsek & Leskovec 1307.5172



Padmanath, Lang, Prelovsek 1503.03257



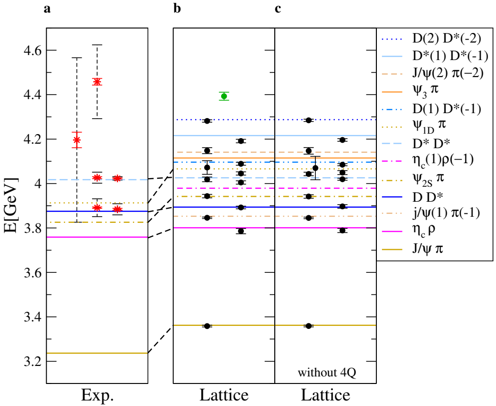
ground state: $\chi_{c1}(1P)$
$D\bar{D}^*$ scattering mx: pole just below thr.
Threshold $\sim m_{u,d}$ *and* m_c *discretisation?*

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^+ - 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 other groups say? Work needed!

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]

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 χ_{c1}, $X(3872)$ **not** Y(4140).

⋮

See Prelovsek @ Charm2015 for more

Form factors and Resonances: new in 2016

a_0 resonance in $\pi\eta$, $K\bar{K}$

- First calculation of coupled channel meson-meson scattering in I=1, G-parity negative sector from lattice QCD
- $a_0(980)$-like resonance strongly coupled to both $\pi\eta$ and $K\bar{K}$ identified as a pole in the complex energy plane. Hadron Spectrum Collaboration, Dudek et al, 1602.05122

Transition amplitudes

- $\pi\pi \rightarrow \pi\gamma^*$ and the resonant $\rho \rightarrow \pi\gamma^*$ transition. Hadron Spectrum Collaboration 1604.03530
- First lattice calculation of the form factor of an unstable hadron, albeit at unphysical pion mass (400MeV).
- Extensions to nucleon resonances, heavy flavour decays and an extension to the coupled channel case, will allow calculations of radiative transitions with exotic hybrid mesons.

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Expect many new results at Lattice 2016!

Challenges

There have been many successes in lattice spectroscopy in the last 5 years including

- "Gold-plated" quantities increasingly well-determined
- New ideas have led to rapid progress in spectroscopy - precision excited and exotic states and scattering analyses

Many challenges remain

- ♦ Improving 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 emerge on larger volumes
- ♦♦ A general framework for coupled channels for scattering involving more than 2 hadrons. Some progress [M. Hansen @ Lattice 2015]
- Haven't discussed the many other open problems including finite density, BSM, ... !

Challenges

There have been many successes in lattice spectroscopy in the last 5 years including

- "Gold-plated" quantities increasingly well-determined
- New ideas have led to rapid progress in spectroscopy - precision excited and exotic states and scattering analyses

Many challenges remain

- ♦ Improving 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 emerge on larger volumes
- ♦♦ A general framework for coupled channels for scattering involving more than 2 hadrons. Some progress [M. Hansen @ Lattice 2015]
- Haven't discussed the many other open problems including finite density, BSM, ... !

Thanks for listening!

Backup Slides

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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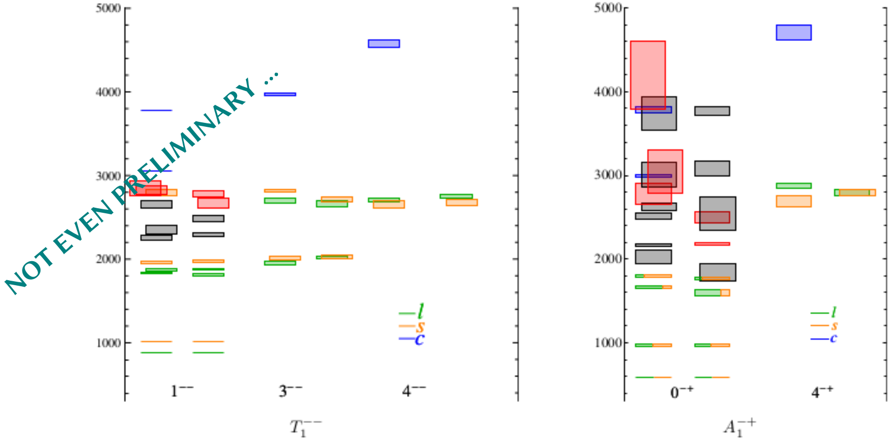
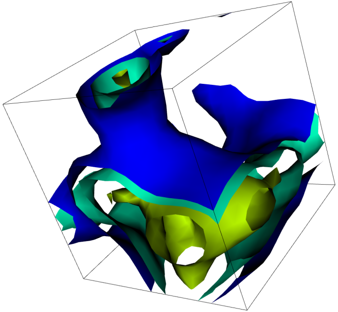


$\Delta(1^{--}) = -17(16)\text{MeV}$

from HadSpec

What's the plot?



Distillation

- A new approach to quark propagation by redefining smearing as a projection operator
- Basis vectors of the distillation operator (lattice laplacian) look like confining blobs