Excited $D$ and $D_s$ meson spectroscopy from lattice QCD

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(for the Hadron Spectrum Collaboration)
HadSpec plan for charm physics

- Charmed meson spectra □ [GM, M.Peardon, S.Ryan, C. Thomas, In preperation]
HadSpec plan for charm physics

- Charmed meson spectra [GM, M.Peardon, S.Ryan, C. Thomas, In preparation]
- Multi-particle spectra and Scattering
  - Phase shifts
  - Widths
Experimental motivation
Outline

- Experimental motivation
- Lattice Details (Very Briefly!)
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- Experimental motivation

- Lattice Details (Very Briefly!)

- Results:
  - $D$ and $D_s$ spectra
  - Gluonic excitations - hybrid mesons
  - $SU(4)$ breaking: $^3P_1$ and $^1P_1$ mixing
Why study the charm sector?

- Before 2003 the charm sector was believed to be well understood.

- 03’ - Hidden charm sector:
  - BELLE observes the $X(3872)$ state which is unexpectedly narrow
    [S. Choi et al. [BELLE Collaboration], arXiv:hep-ex/0312021]
  - Surplus of 'X, Y, Z' states with unknown structure emerge
Why study the charm sector?

03’ - Open charm sector

- BARBAR observes the $D_s^+(2317)$ state

- CLEO confirms the BARBAR discovery and observes a further resonance $D_s^+(2463)$
03′ - Open charm sector

- BARBAR observes the $D_s^+$ (2317) state

- CLEO confirms the BARBAR discovery and observes a further resonance $D_s^+$ (2463)

- Lighter and narrower than potential/quark model predictions
Lattice details in brief

* Calculations performed on the HadSpec anisotropic dynamical $N_f = 2 + 1$ ensembles using Wilson 'Clover' fermions

* Fully relativistic calculation

* Two volumes: $16^3 \times 128 \approx 1.9$ fm and $24^3 \times 128 \approx 2.9$ fm

* Smearing (Removes contaminating high modes):
Lattice details in brief

- Calculations preformed on the HadSpec anisotropic dynamical $N_f = 2 + 1$ ensembles using Wilson 'Clover' fermions

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- Two volumes: $16^3 \times 128 \approx 1.9 \text{ fm}$ and $24^3 \times 128 \approx 2.9 \text{ fm}$

- Smearing (Removes contaminating high modes):

Caveat: Pion mass $\approx 396 \text{ MeV}$
Recipe for extracting ground and excited states:

- Energies and matrix elements can be extracted from correlation functions of interpolating fields

- Build a correlation matrix from a carefully chosen large basis of operators:

\[
C_{ij} = \langle 0 | O_i O_j^\dagger | 0 \rangle = \sum_n \frac{e^{-E_n t}}{2E_n} \langle 0 | O_i | n \rangle \langle n | O_j^\dagger | 0 \rangle
\]  

(1)

- Solve the generalised eigenvalue problem:

\[
C_{ij}(t) \nu_j^{(n)} = \lambda^{(n)}(t) C_{ij}(t_0) \nu_j^{(n)}
\]  

(2)

Solving the generalised eigenvalue problem yields two pieces of information:

- The principal correlator:
  \[ \lambda_n = e^{-E_n(t-t_0)} \]

- The overlap factor:
  \[ Z_i^{(n)} = \langle n | O_i^\dagger | 0 \rangle \]
Spectroscopy from LQCD

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- The principal correlator:
  \[ \lambda_n = e^{-E_n(t-t_0)} \]
- The overlap factor:
  \[ Z_i^{(n)} = \langle n | O_i^\dagger | 0 \rangle \]
- Allows extraction of the mass of a state
- Allows us to identify the total angular momentum of a state

On the lattice \( SO(3) \) reduces to \( O_h \) ... \( J^p \)'s distributed across five irreps: \( A1, A2, E, T1, T2 \)
Results
Overlaps used to identify $J^P$'s and then to match states across irreps ...
$D$ meson spectrum (Preliminary)
D meson spectrum (Preliminary)

 Lets interpret via the quark model ...
Observe $S$
Observe $S, P$
Observe $S$, $P$, $D$
Observe S, P, D, F
$D$ meson - Quark model interpretation (Preliminary)

Observe S, P, D, F and part of the G wave multiplets
Observe S, P, D, F and part of the G wave multiplets

Observe an excess of states
$D_s$ meson spectrum (Preliminary)

Let's interpret via the quark model ...
Observe $S$
Observe S, \(P\)
Observe $S$, $P$, $D$
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Observe S, P, D, F and part of the G wave multiplets

Observe similar excess of states
Gluonic excitations?

Hybrid candidates have a large overlap onto operators constructed to be sensitive to gluonic excitations:

\[ O \sim [D_i, D_j] \sim F \]

In the charmonium and light meson sector a supermultiplet structure of hybrid states was found

[J. Dudek, Phys. Rev. D84 (2011) 074023]
[L. Liu et al, JHEP 07 (2012) 126]
$D$ meson spectrum - hybrid candidates (Preliminary)

Graham Moir (TCD)

Charmed Mesons
$D_s$ meson spectrum - hybrid candidates (Preliminary)
$D$ meson spectrum - $\eta_c/2$ subtracted (Preliminary)
$D_s$ meson spectrum - $\eta_c/2$ subtracted (Preliminary)
Since $m_q \neq m_{\bar{q}}$, open charm mesons are not charge conjugation eigenstates.

$J^P = 1^+$ axial vector states are coherent superpositions of quark model $^3P_1$ and $^1P_1$ states:

$$|1\rangle = \cos \theta |^3P_1\rangle - \sin \theta |^1P_1\rangle$$

$$|2\rangle = \sin \theta |^3P_1\rangle + \cos \theta |^1P_1\rangle$$

In general our operators have the form:

$$\bar{\psi} \Gamma D_i D_j \ldots \psi$$
In the non-relativistic limit:

\[ \left[ \left( \gamma_i - \gamma_0 \gamma_i \right) \times D_i \right]_{J=1} \text{ overlaps only onto } |^3P_1 \rangle \]

\[ \left[ \gamma_5 \times D_i \right]_{J=1} \text{ overlaps only onto } |^1P_1 \rangle \]

Taking ratios of the overlap factors \( Z \), of the same operator from the two different states allows a calculation of the mixing angle. We observe:

\[ 20^\circ \leq \theta \leq 30^\circ \]
Conclusions and outlook

Conclusions:

▶ Reliably calculated highly excited spectra in the charmed mesonic sector

▶ Observe hybrid candidates that seem to fit into the previously observed hybrid supermultiplet

▶ Calculation of the mixing angle between the $p$-wave axial vector states due to the breaking of $SU(4)$ symmetry

Outlook:

▶ Scattering calculations in the charm sector are underway