Excited and exotic Charmonium, $D_s$ and $D$ meson spectra for two light quark masses

David Tims, Trinity College Dublin

Gavin K. C. Cheung, Cian O’Hara, Graham Moir, Michael Peardon, Sinéad M. Ryan, Christopher E. Thomas

Southampton, 28th July, 2016
Outline of talk

- Why charmed mesons?
- Method and Lattice Details
- Results from $M_\pi \sim 240$ MeV
- Comparison with $M_\pi \sim 400$ MeV
Why mesons with charm quarks?

- Open-charm mesons and Charmonium contain a number of experimentally well-established states.
- However, there are a plethora of unexpected charmonium-like states discovered (X, Y, Z’s) and they are subject to many theoretical interpretations.
- Possibilities: hybrid states, tetra-quarks, molecular mesons, hadro-quarkonium.

- Measured masses and widths of the low-lying $D_{s0}^*(2317)^\pm$ and $D_{s1}(2460)^\pm$ states are significantly lighter and narrower than expected from phenomenological models. [arXiv:hep-ph/0505206v2]

- Complete understanding of these states can in principle be achieved using lattice QCD.

Figure: BaBar $B^+ \rightarrow J/\psi \omega K$, $B^0 J/\psi \omega K_S^0$ decays [arXiv:1012.0074]
Goal: Determine spectrum of open and hidden charmed meson states, including excitations and any states with an intrinsic gluonic component at pion mass $M_{\pi} \sim 240\,\text{MeV}$. Compare with previous study with $M_{\pi} \sim 400\,\text{MeV}$. [arXiv:1301.7670]

We use the setup of the Hadron Spectrum Collaboration; dynamical 2+1 anisotropic lattices [arXiv:1004.4930v1]

We use distillation to compute correlation functions for a large basis of interpolating operators

Employing this we solve a GEVP:

$$C_{ij}(t)v_{j}^{n} = \lambda(t, t_0)^{n}C_{ij}(t_0)v_{j}^{n}$$

$$\lambda \propto e^{-E_{n}(t-t_0)}$$, $v_{j}^{n}$ related to $Z_{i}^{n} = \langle n |O_{i}^{\dagger}|0\rangle$

| Lattice Volume | $M_{\pi}$ (MeV) | $N_{\text{cfgs}}$ | $N_{\text{tsrcs}}$ for $c\bar{c}$, $c\bar{s}$, $c\bar{l}$ | $N_{\text{vecs}}$
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$24^3 \times 128$</td>
<td>391</td>
<td>553</td>
<td>32, 16, 16</td>
<td>162</td>
</tr>
<tr>
<td>$32^3 \times 256$</td>
<td>236</td>
<td>484</td>
<td>1, 1, 2</td>
<td>384</td>
</tr>
</tbody>
</table>
Operator Overlaps

$M_\pi \sim 240\,\text{MeV}$

$M_\pi \sim 400\,\text{MeV}$

Figure: **Top row**: principal correlators for a selection of low-lying charmonium states in the $T_1^{--}$ irrep. **Middle row**: the operator-state overlaps, $Z$, for the state above. **Bottom row**: overlaps for the corresponding state on the $M_\pi \sim 400\,\text{MeV}$ ensemble.
Charmonium Spectrum $M_\pi \sim 240\,\text{MeV}$

Figure: Charmonium spectrum up to around 4.5 GeV.
Charmonium Spectrum $M_\pi \sim 240\text{MeV}$

- States labeled by $J^{PC}$
- Masses presented with $M_{\eta_c}$ subtracted
- Most states follow $n^{2S+1}L_J$ pattern, grouped into S,P,D,F,G wave multiplets using $Z_i$
- Red + Blue 'hybrids', some states with exotic quantum numbers $1^{--},0^{+-},2^{+-}$
- Group hybrids into multiplets, pattern consistent with $q\bar{q}$ coupled to $1^{+-}$ gluonic excitation
$D_s$ spectrum $M_\pi \sim 240\text{MeV}$

Figure: $D_s$ meson spectrum.
$D_s$ spectrum $M_\pi \sim 240\text{MeV}$

- Identify complete S,P,D and F wave multiplets
- Four states highlighted in red that do not fit $n^{2S+1}L_J$ pattern
- Again: Identified as lightest hybrid meson multiplet, consistent with $q\bar{q}$ (in S-wave) coupled to $1^{+-}$ gluonic excitation
- Not able to identify first excited hybrid multiplet
D spectrum $M_\pi \sim 240\,\text{MeV}$

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure}
\caption{D meson spectrum.}
\end{figure}
Figure: Charmonium spectrum, with $M_\pi \sim 240$ MeV (left column for each $J^{PC}$) compared to the spectrum with $M_\pi \sim 400$ MeV (right column for each $J^{PC}$).
Charmonium comparison

- Light quark dep. enters through sea quarks
- Mild light quark dependence, **no change in overall pattern of states**
- $J/\psi$: statistically significant increase in mass
  $\sim 80\text{MeV} \rightarrow \sim 87\text{MeV}$
- Checked for possible systematic effects arising from scale setting, no effects found!
$D_s$ comparison

**Figure:** $D_s$ meson spectrum labelled by $J^P$. 

\[ M - M_{\eta_c}/2 \text{ (MeV)} \]

- $0^-$
- $1^-$
- $2^-$
- $3^-$
- $4^-$

- $0^+$
- $1^+$
- $2^+$
- $3^+$
- $4^+$

$M_\pi$ / MeV
- 240
- 400

Red (240)
Light red (400)
$D_s$ comparison

- Again, mild light quark dependence, **no change in overall pattern of states**
- Largest change: $0^+$ corresponding to $D_{s0}^*(2317)$, expected influence by $DK$ threshold
- Tendency for hybrids to increase in mass as $M_\pi$ is reduced (however pattern unchanged)
$D$ comparison

**Figure:** $D$ meson spectrum labelled by $J^P$. 

$M - M_{\eta_c}/2$ (MeV) vs. $J^P$. 

- $D_{\pi}$
- $D^*_{\pi}$

Legend:
- $M_{\pi}$ / MeV
- 240
- 400
- $D_{\pi}$
- $D^*_{\pi}$
**$D$ comparison**

- $D$ mesons contain light quarks
- Again, we see mild light quark dependence

- Largest change: Lowest $0^+$ and $1^+$ states, possibly due to coupling to $D\pi$ and $D^*\pi$
Distillation and variational method allow us to extract highly excited spectra and robustly identify the continuum $J^{P(C)}$ of states up to $J = 4$

States with intrinsic gluonic excitations and states with exotic quantum numbers identified

Many states follow the $n^{2S+1}L_J$ pattern, also find states which we identify as hybrid mesons that fall into hybrid supermultiplets, pattern consistent with a quark-antiquark combination coupled to a $1^{+-}$ gluonic excitation

Only mild differences between the spectra calculated on an ensemble where $M_\pi \sim 240$ MeV to our previously determined spectra on an ensemble with $M_\pi \sim 400$ MeV

Even in the case of the $D$ meson we find only minor quantitative changes

At least between $240$ MeV $\lesssim M_\pi \lesssim 400$ MeV, the mass of the light quarks play very little role in the overall pattern of structure of our hidden and open-charm spectra
Thank You for listening!