Twisted mass lattice computation of charmed mesons with focus on $D^{**}_{(s)}$

2+1+1 Setup

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in collaboration with Marc Wagner

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Aims

- Long term project to compute spectra of mesons with strange and charm quark content using lattice QCD methods.
- Extrapolation to the physical pion mass and the continuum limit.

Here

- Tuning valence s and c quark masses and computing low-lying D, D_s mesons and charmonium states.
- First three points for the continuum extrapolation (light quark mass extrapolation).
- Establish contact to the "(1/2,3/2) limit" for $D^{**}_{(s)} = \{D^*_{(s)0}, D_{(s)1}, D_{(s)1}, D^*_{s2}\}$

Wilson twisted mass action

Action

$$S_l = a^4 \sum_x \bar{\chi}_l(x) \left[D_W[U] + m_{0,l} + \mathrm{i}\mu_l \gamma_5 \tau^3 \right] \chi_l(x)$$

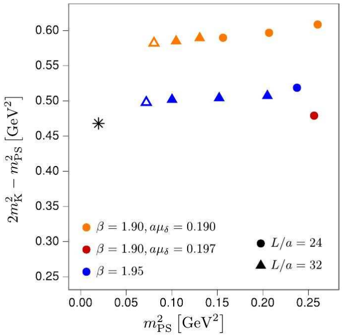
$$S_h = a^4 \sum_x \bar{\chi}_h(x) \left[D_W[U] + m_{0,h} + \mathrm{i}\mu_\sigma \gamma_5 \tau^1 + \mu_\delta \tau^3 \right] \chi_h(x)$$

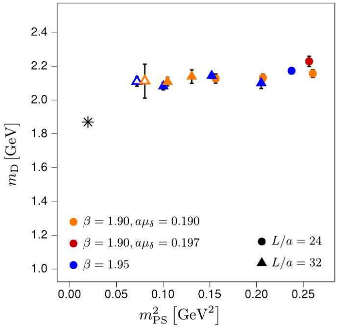
$$\begin{pmatrix} st \\ ch \end{pmatrix} = \psi_h^{phys} = e^{\frac{\mathrm{i}}{2}\omega_h \gamma_5 \tau_1} \chi_h \quad , \quad \begin{pmatrix} up \\ dn \end{pmatrix} = \psi_l^{phys} = e^{\frac{\mathrm{i}}{2}\omega_1 \gamma_5 \tau_3} \chi_l$$

$$\chi_l = \begin{pmatrix} \chi_u \\ \chi_d \end{pmatrix}, \quad \chi_h = \begin{pmatrix} \chi_s \\ \chi_c \end{pmatrix} \qquad \tau^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \tau^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

- $tan\omega_1 = \frac{\mu_l}{m_{0,l}}$
- Tuned to 'maximal' twist:
  $m_{0,l} = m_{0,h} \rightarrow m_{crit} \Rightarrow (\omega_1)_{ren.} = (\omega_2)_{ren.} \rightarrow \frac{\pi}{2}$
- $\Rightarrow$ automatic $\mathcal{O}(a)$ improvement for physical observables.
- Broken Parity.

ETMC $2+1+1$ ensembles



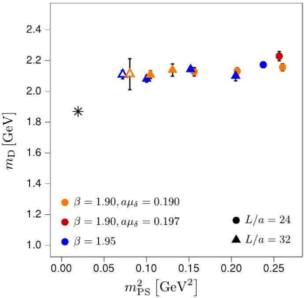


- Available $2+1+1$ configurations.
- Mismatch of strange and charm mass.
- Idea: different valence action for s and c quarks.

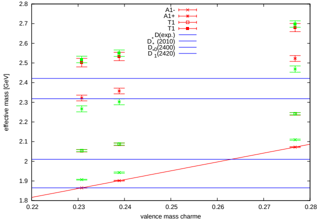
$$\chi_c := \begin{pmatrix} \chi_{c+} \\ \chi_{c-} \end{pmatrix}, \quad D_W + m_{crit} \pm \mathrm{i}\mu_c\gamma_5$$

Introduction of strange and charm valence quarks

unitary setup



valence quark setup



- Introduction of mass degenerated doublets for charm and strange quarks(valence sector).

$$\chi_c := \begin{pmatrix} \chi_{c+} \\ \chi_{c-} \end{pmatrix}, \quad D_W + m_{crit} \pm i\mu_c\gamma_5$$

- Calculation at different bare masses and extrapolation/interpolation to the 'physical' point (c: m_D, s: $2m_K^2 - m_{PS}^2$)

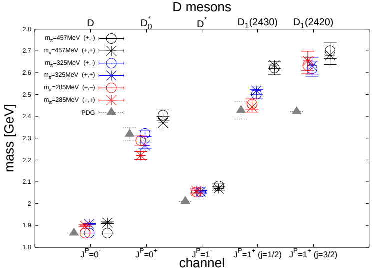
Setup

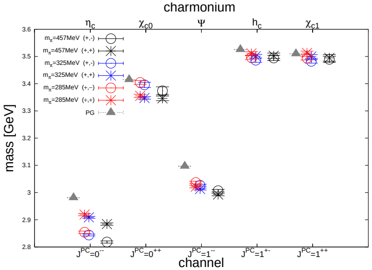
- Gauge link configurations with $2+1+1$ dynamical quark flavors (ETMC).
  - Tuning charm valence quark mass to reproduce physical m_D mass.
  - Tuning strange valence quark mass to reproduce physical value of $2m_K^2 - m_\pi^2$ mass. Weak dependence on the pion mass.
- Mixed action setup to avoid mixing of strange and charm flavor and repair mismatch in the sea.
- Gaussian distributed spin diluted timeslice sources with APE smeared gauge links.
- Parameters of the ensembles:

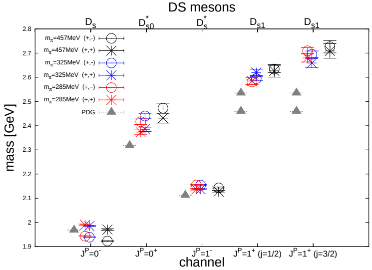
$$\beta = 1.9, \quad a = 0.0859(5)\mathrm{fm}$$

  - $(L/a)^3 \times (T/a) = 32^3 \times 64, \quad \mu = 0.003, \quad m_\pi \approx 285\mathrm{MeV}$
  - $(L/a)^3 \times (T/a) = 32^3 \times 64, \quad \mu = 0.004, \quad m_\pi \approx 325\mathrm{MeV}$
  - $(L/a)^3 \times (T/a) = 24^3 \times 48, \quad \mu = 0.008, \quad m_\pi \approx 457\mathrm{MeV}$

Results and chiral 'extrapolation'







Motivation heavy quark limit

- Consider semileptonic decays of B mesons (B, $B^\star$) into orbitally excited P wave D mesons ($D^{\star\star}$):

$$B^{(\star)} \rightarrow D^{\star\star} \mathrm{l}\nu.$$

  - Talk by Mariam Atoui: $B_s \rightarrow D_s l \nu_l$ near zero recoil from tmQCD (Fri, 16:50 Parallels 10D)
- Precise knowledge of the corresponding branching fractions important, e.g. to reduce the systematic uncertainty in the measurements of the CKM matrix element $|Vcb|$.
- There is a persistent conflict ($1/2$ versus $3/2$ puzzle) between theory and experiment:
  - Experiment favors the decay into $1/2P$ wave $D^{\star\star}$ s.
  - Theory favors the decay into $3/2P$ wave $D^{\star\star}$s.
  - Lattice calculations can help to resolve this conflict.

Heavy quark limit operators

Generators

$$
\begin{aligned}
L_x &= \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -\mathrm{i} \\ 0 & \mathrm{i} & 0 \end{pmatrix}, L_y = \begin{pmatrix} 0 & 0 & \mathrm{i} \\ 0 & 0 & 0 \\ -\mathrm{i} & 0 & 0 \end{pmatrix}, L_z = \begin{pmatrix} 0 & -\mathrm{i} & 0 \\ \mathrm{i} & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \\
S_x &= i\gamma_2\gamma_3/2, S_y = i\gamma_3\gamma_1/2, S_z = i\gamma_1\gamma_2/2
\end{aligned}
$$

$$[L_x, L_y] = -iL_z, [L_i, L_j] = -iL_k\epsilon_{ijk}, \quad [S_x, S_y] = -iS_z, [S_i, S_j] = -iS_k\epsilon_{ijk}$$

Spin addition

$$J^2 = L^2 + S^2 + 2LS = L^2 + s_h^2 + s_l^2 + 2Ls_l + 2Ls_h + 2s_l s_h$$

Heavy quark limit

$$
\begin{aligned}
j^2 &= L^2 + s_l^2 + 2Ls_l \\
s_l : &\quad \bar{Q}\Gamma q \to \bar{Q}\Gamma s_l q
\end{aligned}
$$

Possible spin couplings for $J = 1$

- Possible combinations for total angular momentum 1:

	S	L	j
1.	1	0	1/2
2.	1	1	1/2,3/2
3.	1	2	3/2

- We see two nearby states with positive parity.
- So far we consider only the first and the second case.
- But, if in our basis the $3/2$ dominates for one of the two states
  $\rightarrow$ dominance in the whole basis

Our basis for the first and second case

$$\begin{aligned} & & q(x)\,(\Gamma\, Y(x - x_0))\, Q(x_0) \\ \{\vec{x} \times \vec{\gamma} + \vec{x}\gamma_1\gamma_2\gamma_3, \quad \gamma_i\}, & & J = 1, j = 1/2 \\ \{\vec{x} \times \vec{\gamma} - 2\vec{x}\gamma_1\gamma_2\gamma_3\}, & & J = 1, j = 3/2 \end{aligned}$$

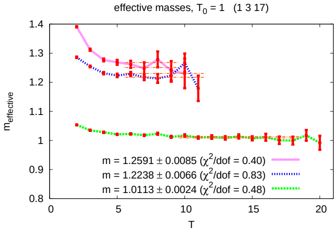
Number of operators

Our basis with well defined heavy quark limit

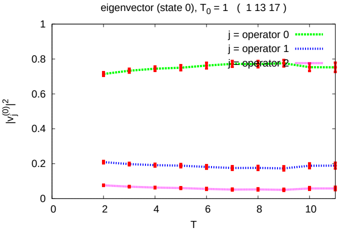
$$
\begin{array}{rr}
 & q(x)\,(\Gamma Y(x-x_0))\,Q(x_0) \\
\{\vec{x}\times\vec{\gamma}+\vec{x}\gamma_1\gamma_2\gamma_3, \quad \gamma_i\}, & J=1, j=1/2 \\
\{\vec{x}\times\vec{\gamma}-2\vec{x}\gamma_1\gamma_2\gamma_3\}, & J=1, j=3/2
\end{array}
$$

- Parity breaking action $\Rightarrow$ we have to include also operators from above times γ_5 to resolve the opposite parity states.
- Same quantum numbers after multiplication with γ_4
- $\Rightarrow$ We have to consider 12 states.

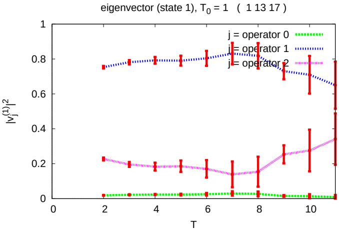
Eigenvector components for the D_1



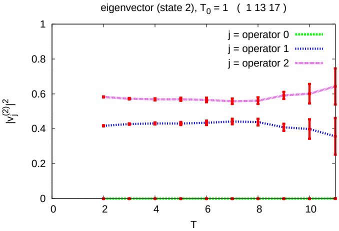
Effective mass plot



Eigenvector components: ground state P=-



Eigenvector components: first state P=+



Eigenvector components: second state P=+

- Operator 0: γ_i
- Operator 1: $j = 1/2$ with spherical excitation
- Operator 2: $j = 3/2$

Summary

- We presented calculations for some low lying D, D_s and charmonium states treated as quark-antiquark states for three pion masses at a single lattice spacing.
- We found discrepancies in some charmonium masses and the PDG values this might be caused by lattice artefacts.
- We found discrepancies in the 1^+ channel in the D_s and D meson spectrum. These states might require more advanced technique (tetraquarks, resonances,...)
- We showed some indications for a dominance of a "3/2 heavy quark limit structure" in the heavier D_1 state.
- Thank you for your attention!