D^{**} spectroscopy

2+1+1 Setup

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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: First steps focussing on tuning valence s and c quark masses and computing low-lying D mesons.

Wilson twisted mass action

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

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

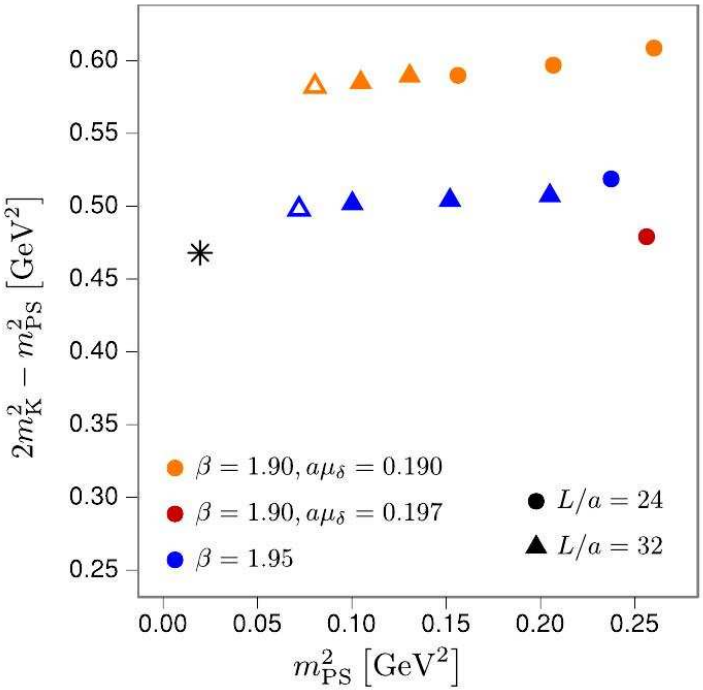
$$\chi_l = \begin{pmatrix} \chi_u \\ \chi_d \end{pmatrix}, \quad \chi_h = \begin{pmatrix} \chi_s \\ \chi_c \end{pmatrix} \qquad \tau^1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \tau^3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

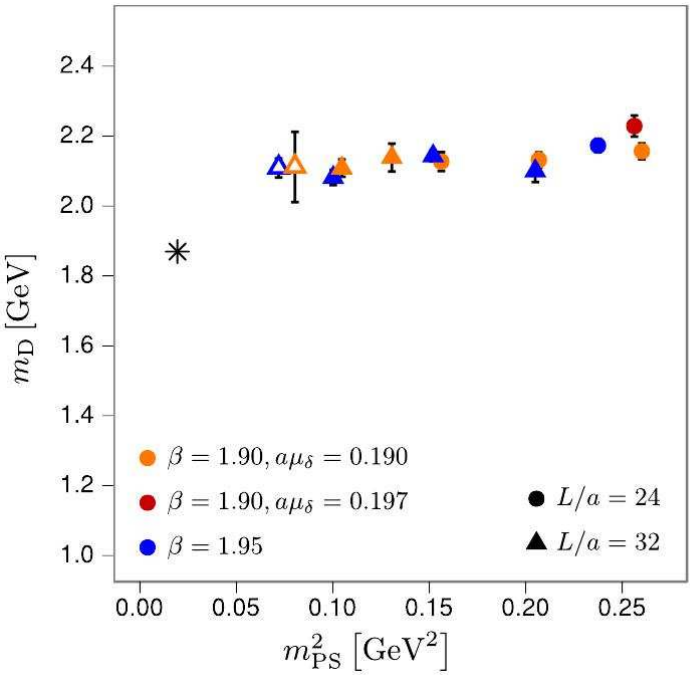
$$\psi_h^{phys} = e^{\frac{\mathrm{i}}{2}\omega_h \gamma_5 \tau_1} \chi_h, \qquad \bar{\psi}_h^{phys} = e^{\frac{\mathrm{i}}{2}\omega_h \gamma_5 \tau_1} \bar{\chi}_h. \quad \text{diff. masses}$$

$$\psi_l^{phys} = e^{\frac{\mathrm{i}}{2}\omega_l \gamma_5 \tau_3} \chi_l, \qquad \bar{\psi}_l^{phys} = e^{\frac{\mathrm{i}}{2}\omega_l \gamma_5 \tau_3} \bar{\chi}_l \quad \text{mass degenerated}$$

- Tuned to 'maximal' twist:
  $m_{0,l} = m_{0,h} \to m_{crit} \Rightarrow \omega_h = \omega_l \to \frac{\pi}{2}$
- $\Rightarrow$ automatic $\mathcal{O}(a)$ improvement for physical observables.

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.

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

Switching the basis assuming maximal twist

- Mass degenerated doublets $\begin{pmatrix}\psi_{up}\\ \psi_{dn}\end{pmatrix}, \begin{pmatrix}\psi_{s1}\\ \psi_{s2}\end{pmatrix}, \begin{pmatrix}\psi_{c1}\\ \psi_{c2}\end{pmatrix}$
- Twisted basis $\begin{pmatrix}\chi_{up+}\\ \chi_{dn-}\end{pmatrix}, \begin{pmatrix}\chi_{s+}\\ \chi_{s-}\end{pmatrix}, \begin{pmatrix}\chi_{c+}\\ \chi_{c-}\end{pmatrix}$
- $\psi = exp(i\gamma_5\tau_3\omega/2)\chi, \quad \bar{\psi} = \bar{\chi}exp(i\gamma_5\tau_3\omega/2)$
- $\bar{\psi}\Gamma\psi = \bar{\chi}(\mathbb{1} + i\gamma_5\tau_3)\Gamma(\mathbb{1} + i\gamma_5\tau_3)\chi \propto \bar{\chi}\Gamma_{twm}\chi$

Γ_{phys}	Γ_{twm}
γ_i	γ_i
$\gamma_i\gamma_j$	$\gamma_5\gamma_i\gamma_j$
γ_5	$\mathbb{1}$
$\mathbb{1}$	γ_5

$\bar{\psi}_u\Gamma\psi_u$

Γ_{phys}	Γ_{twm}
γ_i	$\gamma_5\gamma_i$
$\gamma_i\gamma_j$	$\gamma_i\gamma_j$
γ_5	γ_5
$\mathbb{1}$	$\mathbb{1}$

$\bar{\psi}_u\Gamma\psi_d$

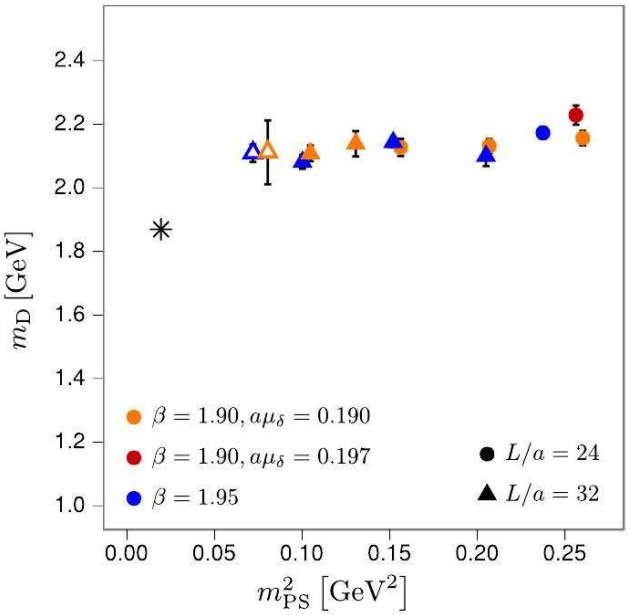
- Example: D - meson

$$\bar{\psi}_{up}\gamma_5\psi_{c1} \to \bar{\chi}_{up}\chi_{c+}, \quad \bar{\psi}_{up}\gamma_5\psi_{c2} \to \bar{\chi}_{up}\gamma_5\chi_{c-}$$

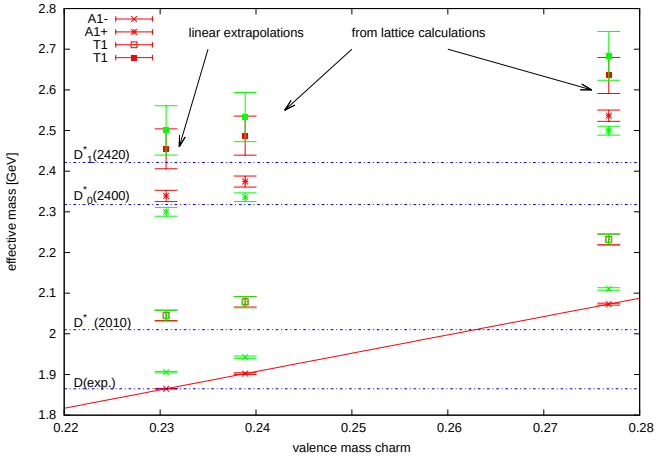
- Two numbers for every mass.

Introduction of strange and charm valence quarks

unitary setup



valence quark setup



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

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

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

Example operators

Irrep	Continuum J^P	Operators
$A1^-$	$0^-, 4^-, \ldots$	$\bar{q}\gamma_5 q$
		$\bar{q}\gamma_5\gamma_i q_{D_i}$
$A1^+$	$0^+, 4^+, \ldots$	$\bar{q}q$
		$\bar{q}\gamma_i q_{D_i}$
$T1^-$	$1^-, 3^-, \ldots$	$\bar{q}\gamma_i q$
		$\bar{q}q_{D_i}$
		$\bar{q}\epsilon_{ijk}\gamma_j q_{D_k}$
$T1^+$	$1^+, 3^+, \ldots$	$\bar{q}\gamma_5\gamma_i q$
		$\bar{q}\gamma_5 q_{D_i}$
		$\bar{q}\gamma_5\epsilon_{ijk}\gamma_j q_{D_k}$

q_{D_i} means a derivative source in direction i. All operators $q\Gamma q_D$ stay in the same irrep when Γ is multiplied by γ_0.

Setup

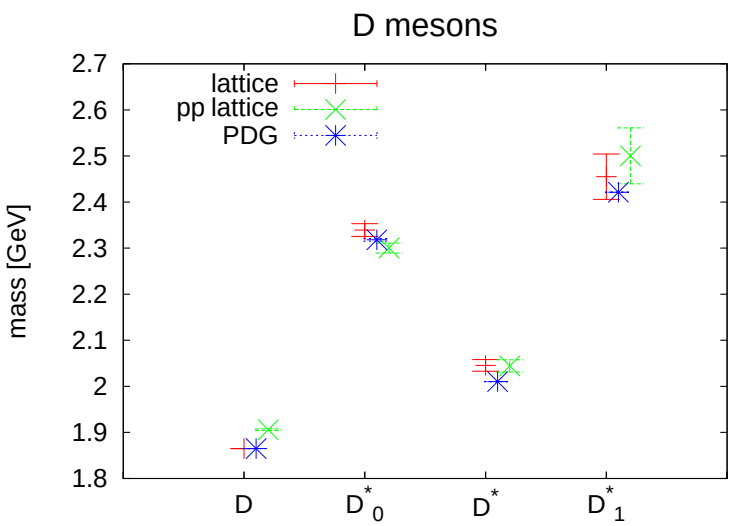
- Gauge link configurations with $2+1+1$ dynamical quark flavors (ETMC).
  - Tuning charm valence quark mass to reproduce physical m_D mass.
  - Tuning strange valence quark mass to reproduce physical value of $2m_K^2 - m_\pi^2$ mass. Weak dependence on the pion mass.
- Mixed action setup to avoid mixing 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 ensemble:

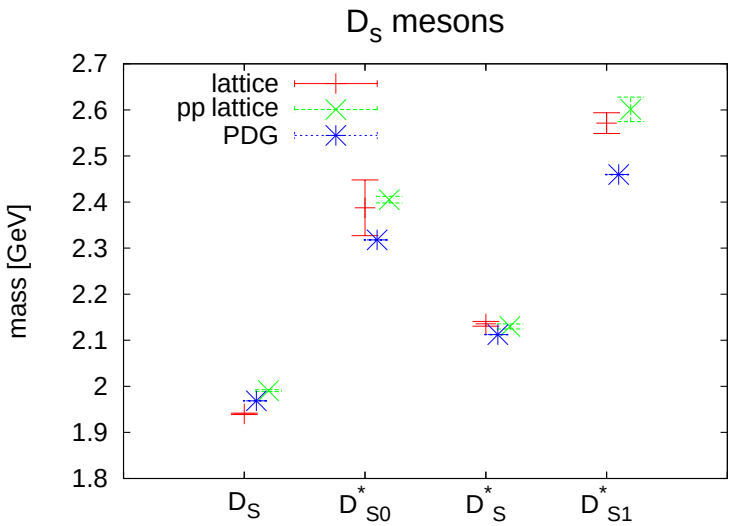
$$(L/a)^3 \times (T/a) = 32^3 \times 64,$$

$$\beta = 1.9, \quad \mu = 0.004, \quad \mu_\delta = 0.19, \quad \mu_\sigma = 0.15,$$

$$a = 0.0859(5)\text{fm}, \quad m_\pi \approx 325\text{MeV}$$

Desults D D_s

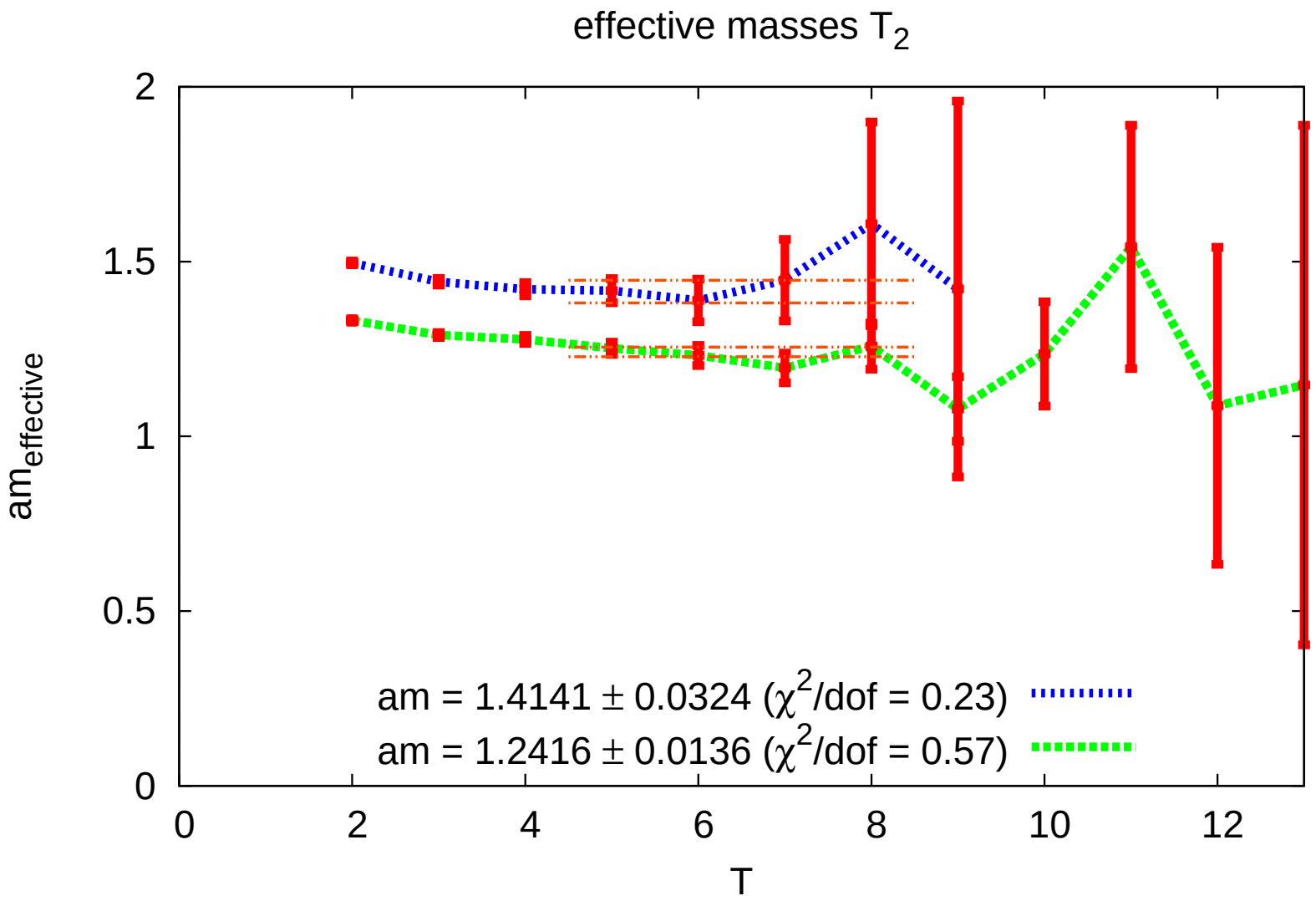




Results for a single ensemble at the pion mass $m_\pi \approx 325$MeV. Rather good agreement with experiment, even without chiral and continuum extrapolation.

Discrepancies for D^*_{s0} and D^*_{s1}. Similar findings in other lattice studies and phenomenological model calculations.

quality of the $T_2(J = 2, 3, 4, ...)$ channel



- Thank you for your attention.