The effect of charmed sea quarks on charmonium finestructure

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- Motivation to study charm loop effects
- Impact on charmonium spectrum
- Conclusions

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Part I

Motivation

Do we need to simulate a dynamical charm quark?

Simulations of lattice QCD with N_f sea (dynamical) quarks

$N_\mathrm{f} = 2 + 1$ (u, d, s) vs $N_\mathrm{f} = 2 + 1 + 1$ (u, d, s, c)

$N_\mathrm{f} = 2 + 1$ QCD is cheaper to simulate (CLS, Hadron Spectrum, ...)

- adding a dynamical charm requires fine lattices and
- complicates the tuning of the parameters
- decoupling applies at low energies $E \ll M_\mathrm{c} \equiv M_\mathrm{charm}$

Hadrons with charm quarks

Charm physics is increasingly interesting because of the discovery of charmoniumlike states (exotic XYZ states) [S. L. Olsen, CHARM 2018, 1812.10947] and other candidates like pentaquarks by Belle, BaBar, LHCb, BESIII. How reliable is quenching of the charm quark?

Charmed sea quark (loop) effects

QCD with quarks $q^i, i = \{u, d, s, c\}$ and Dirac operators D_i

$$\langle O[q^i, U] \rangle = \frac{1}{Z} \int \mathcal{D}[U] \underbrace{\left(\prod_{j=u,d,s} \det D_j \right) \det D_c}_{\text{quark loops}} \tilde{O}[D_i^{-1}, U] \, \mathrm{e}^{-S[U]}$$

$$\equiv \left\langle \tilde{O}[D_i^{-1}, U] \right\rangle^{\text{gauge}}$$

Quenching the charm: set $\det D_c = 1 \Rightarrow$ no charm loops

How good is this approximation? Distinguish

1. low energy quantity: O does not depend on q^c
   effective theory of decoupling
2. valence charm: $O = (\bar{q}^c \Gamma q^c)(t) \, (\bar{q}^c \Gamma q^c)^\dagger(0)$
   this talk

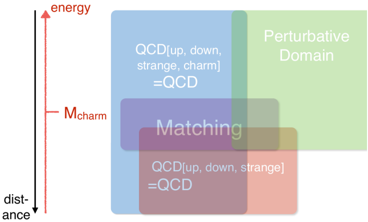
Effective theory of decoupling

Effective theory for energies $E \ll M$ (M is the mass of the heavy quark)

[Weinberg, Phys. Lett. B91, 51 (1980)]

$$\mathcal{L}_{\mathrm{QCD}}^{(N_\mathrm{f})} = \mathcal{L}_{\mathrm{QCD}}^{(N_\mathrm{f}-1)}(\psi_{\mathrm{light}}, \bar{\psi}_{\mathrm{light}}, A_\mu; g_{N_\mathrm{f}-1}(M), m_{\mathrm{light}}(M)) + \frac{1}{M^2}\mathcal{L}_6 + \ldots$$

$$\mathcal{L}_6 = \bar{\psi}_{\mathrm{light}}\sigma_{\mu\nu}F_{\mu\nu}m_{\mathrm{light}}\psi_{\mathrm{light}} + \mathrm{tr}\,\{D_\mu F_{\nu\rho} D_\mu F_{\nu\rho}\} + \ldots$$



Effective theory couplings $g_{N_\mathrm{f}-1}(M)$, $m_{\mathrm{light}}(M)$ depend on M through matching $\leftrightarrow$ decoupling relations. Heavy quarks contribute only through loops.

Model study of charm loops

Non-perturbative model study on the lattice

- To avoid a multi-scale problem in comparing QCD_4 and QCD_3, we study a model, QCD_2 with $N_\mathrm{f} = 2$ degenerate quarks of mass $1.2\,M_\mathrm{c} \gtrsim M \gtrsim M_\mathrm{c}/8$
- Effective theory for $E \ll M$ is a Yang–Mills (YM) theory ($N_\mathrm{l} = 0$) at leading order

$$\mathscr{L}_\mathrm{QCD}^{(N_\mathrm{f}=2)} = \mathscr{L}_\mathrm{YM}(A_\mu; g_\mathrm{YM}(M)) + \frac{1}{M^2}\mathscr{L}_6 + \ldots$$

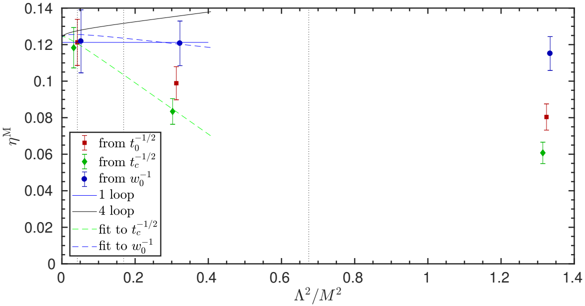
  where $\mathscr{L}_6$ is a complete set of fields in the YM theory of dimension 6
- We can afford very small lattice spacings down to $a = 0.023\,\mathrm{fm}$ and volumes comparable to YM theory, and control the continuum limit

Mass dependence function: decoupling

$\mathcal{S}$ is a low energy scale of mass dimension one. The mass-scaling function is

$$\eta^{\mathrm{M}} = \frac{\partial \log \mathcal{S}}{\partial \log M}$$

η^{M} is universal up to non-perturbative $1/M^2$ corrections $\Delta\eta^{\mathrm{M}}_{\mathrm{NP}}$



$\Delta\eta^{\mathrm{M}}_{\mathrm{NP}} < 0.014$ for the charm quark *in QCD* [A. Athenodorou, J. Finkenrath, FK, T. Korzec, B. Leder, M. Krstić Marinković, R. Sommer, Nucl. Phys. B943, 114612 (2019)]

Part II

Impact on charmonium spectrum

Strategy

Comparison of $N_\mathrm{f} = 0$ QCD and QCD with $N_\mathrm{f} = 2$ degenerate charm quarks

[S. Cali, FK, T. Korzec, `1811.05285` and in preparation]

1. Matching: pick a low energy scale $\mathcal{S}$ and apply decoupling

$$[\mathcal{S}(M_\mathrm{c})]^{N_\mathrm{f}=2} = [\mathcal{S}]^{N_\mathrm{f}=0}$$

The charm-quark mass M_c is then fixed by requiring

$$\frac{m_{\eta_c}}{\mathcal{S}} \equiv 1.8075 \qquad \text{with } \mathcal{S} = t_0^{-1/2}$$ [M. Lüscher, JHEP 08, 071 (2010)]

This corresponds to $M_\mathrm{c}/\Lambda_{\overline{\mathrm{MS}}} = 4.87$ on $N_\mathrm{f} = 2$ at $a = 0.023\,\mathrm{fm}$

2. Differences like

$$\left[\frac{m_{J/\psi}}{\mathcal{S}(M_\mathrm{c})}\right]^{N_\mathrm{f}=2} - \left[\frac{m_{J/\psi}}{\mathcal{S}}\right]^{N_\mathrm{f}=0}$$

are then due to charm loop effects

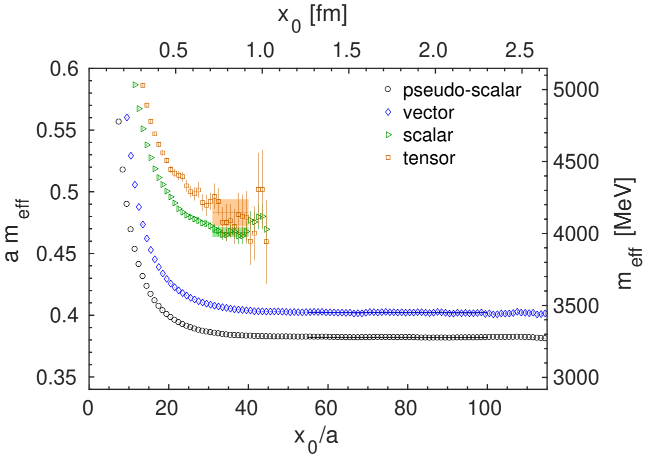
Ensembles

Lattice discretizations

- $N_f = 2$ clover improved twisted-mass Wilson fermions at maximal twist
- Wilson's plaquette gauge action
- open boundary conditions in time
- simulated mass set through $M_c/\Lambda_{\overline{MS}} = 4.87$ (PDG for M_c and $\Lambda_{\overline{MS}} = 310(20)$ MeV [P. Fritzsch et al., Nucl. Phys. B865, 397 (2012)])
- conservative error estimates include effects of slow modes $\tau_{exp} = 20\, t_0/a^2$
- lattice spacing is set through $N_f = 2$ scale L_1 and decoupling for $N_f = 0$

N_f	$\frac{T}{a} \times \left(\frac{L}{a}\right)^3$	β	a[fm]	κ	$a\mu$	$\sqrt{t_0} m_{\eta c}$	t_0/a^2	MDUs
2	96×24^3	5.300	0.066	0.135943	0.36151	1.79321(53)	1.23950(85)	8000
	120×32^3	5.500	0.049	0.136638	0.165997	1.8049(16)	4.4730(95)	8000
	192×48^3	5.600	0.042	0.136710	0.130949	1.7655(15)	6.609(15)	8000
	120×32^3	5.700	0.036	0.136698	0.113200	1.7931(28)	9.104(36)	17184
	192×48^3	5.880	0.028	0.136509	0.087626	1.8129(29)	15.622(62)	23088
	192×48^3	6.000	0.023	0.136335	0.072557	1.8075(42)	22.39(12)	22400
0	120×32^3	6.100	0.049	–	–	–	4.4329(32)	64000
	120×32^3	6.340	0.036	–	–	–	9.034(29)	20080
	192×48^3	6.672	0.023	–	–	–	21.924(81)	73920
	192×64^3	6.900	0.017	–	–	–	39.41(15)	160200

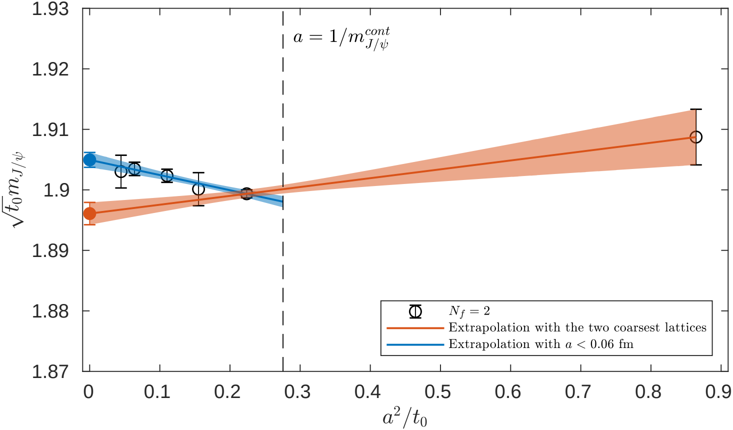
Effective masses: example $N_\mathrm{f} = 2$, $\beta = 6.0$



$$G(x_0, y_0) = \sum_{\boldsymbol{x},\boldsymbol{y}} \left\langle \bar{c}_1(x)\Gamma_A c_2(x)\ \bar{c}_2(y)\bar{\Gamma}_B c_1(y) \right\rangle = -\sum_{\boldsymbol{x},\boldsymbol{y}} \left\langle \mathrm{tr}\left[\Gamma_A S_2(x,y)\bar{\Gamma}_B S_1(y,x)\right] \right\rangle^{\mathrm{gauge}}$$

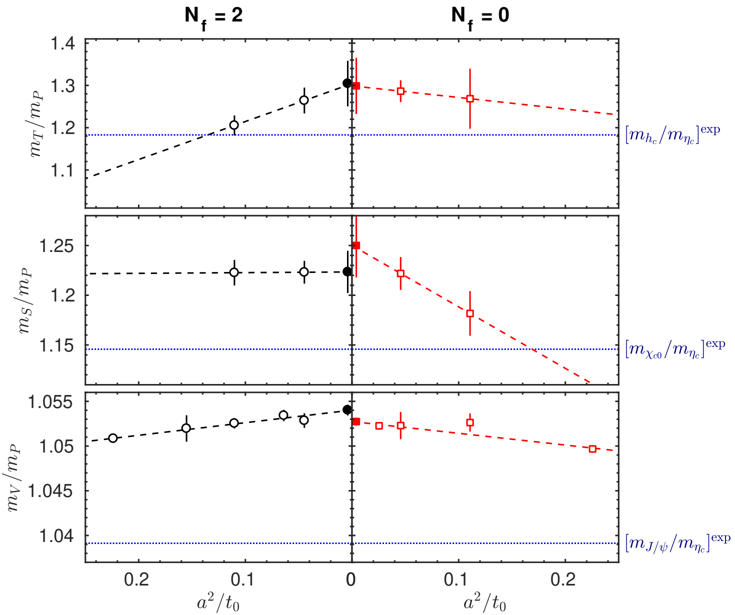
We use 16 U(1) time-diluted stochastic sources to evaluate the expression

Continuum extrapolation



Reliable continuum extrapolations only for $am_{J/\psi} < 1$ or $a \lesssim 0.06$ fm

Fine- and hyperfine structure



Fine- and hyperfine structure contd

Continuum extrapolations of m_X/m_P

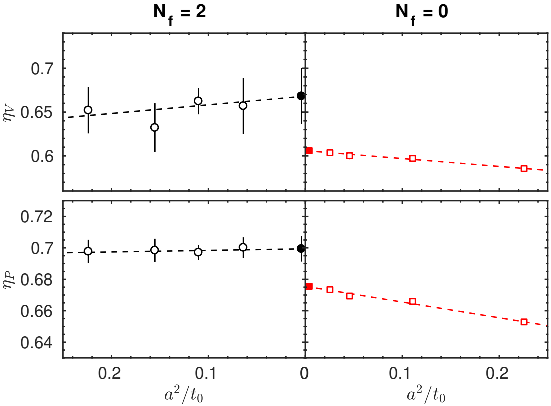
X (particle)	$N_\mathrm{f} = 2$	$N_\mathrm{f} = 0$
Vector (J/ψ)	1.05402(60)	1.05274(46)
Scalar (χ_{c0})	1.223(21)	1.250(32)
Tensor (h_c)	1.304(54)	1.299(66)

- relative charm loop effects in the hyperfine splitting $\Delta_V = m_V/m_P - 1$ are $1 - [\Delta_V]^{N_\mathrm{f}=0} / [\Delta_V]^{N_\mathrm{f}=2} = 0.024(14)$
- Discrepancies with the experimental values are probably due to neglected effects of light sea quarks, disconnected contributions and electromagnetism

Mass-scaling function $\eta_{P,V}$

Mass-scaling function of meson masses $\eta_X = \partial \log m_X / \partial \log M$, $X = P, V$

$$\frac{\mathrm{d}\langle \tilde{O} \rangle^{\text{gauge}}}{\mathrm{d}\mu} = \underbrace{- \left\langle \frac{\mathrm{d}S}{\mathrm{d}\mu} \tilde{O} \right\rangle^{\text{gauge}} + \left\langle \frac{\mathrm{d}S}{\mathrm{d}\mu} \right\rangle^{\text{gauge}} \langle \tilde{O} \rangle^{\text{gauge}}}_{\text{charm loops}} + \underbrace{\left\langle \frac{\mathrm{d}\tilde{O}}{\mathrm{d}\mu} \right\rangle^{\text{gauge}}}_{\text{valence charm}}$$



Part III

Conclusions

Conclusions

Charmonium

- We have simulated a model, QCD with $N_\mathrm{f} = 2$ charm quarks
- By comparing to $N_\mathrm{f} = 0$ we compute the impact of charm quark loops
- Their effect is below 2% for the hyperfine splitting
- Good news for lattice QCD computations of charmonium with $N_\mathrm{f} = 2 + 1$
- $am_{\bar{c}\Gamma c} < 1$ is needed for continuum extrapolations with O(a) improved Wilson quarks

Outlook

- charm loops in decay constants and finestructure of B_c mesons
- disconnected contributions, mixing with glueballs