Charm baryons at finite temperature on anisotropic lattices

R. Bignell[1], G. Aarts[1], C. Allton[1], M.N. Anwar[1], T. Burns[1], B. Jäger[2], J. Skullerud[3]

[1] Swansea University

[2] University of Southern Denmark

[3] National University of Ireland Maynooth

Exotic Hadron Spectroscopy 2023
April 19 - 21, 2023

Motivation

- Charm hadrons are important probes of quark-gluon plasma
- More experimentally accessible than bottom hadrons
- Pheno. models and heavy-quark effective field theories are viable
-
  -

Motivation

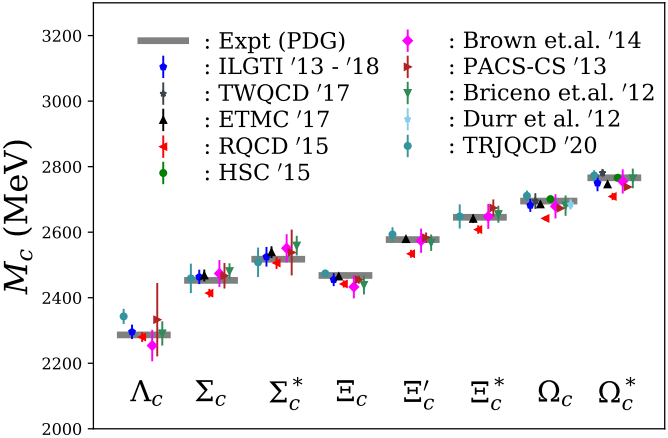


Figure: Summary of lattice QCD results for single charmed baryon masses. Lines are experimental masses. Figure from Padmanath **2109.04748**.

Motivation

- Charm hadrons are important probes of quark-gluon plasma
- More experimentally accessible than bottom hadrons
- Pheno. models and heavy-quark effective field theories are viable
- Few lattice studies on charm baryons at non-zero temperature
  - Extend our previous work on light baryons and hyperons

What are we going to do?

- Calculate charm baryon correlators at a range of temperatures
- Investigate change in correlator as temperature changes
- Determine positive and negative parity masses for each channel as a function of temperature
- Examine the parity doubling effect
  - A signature of chiral symmetry restoration

How

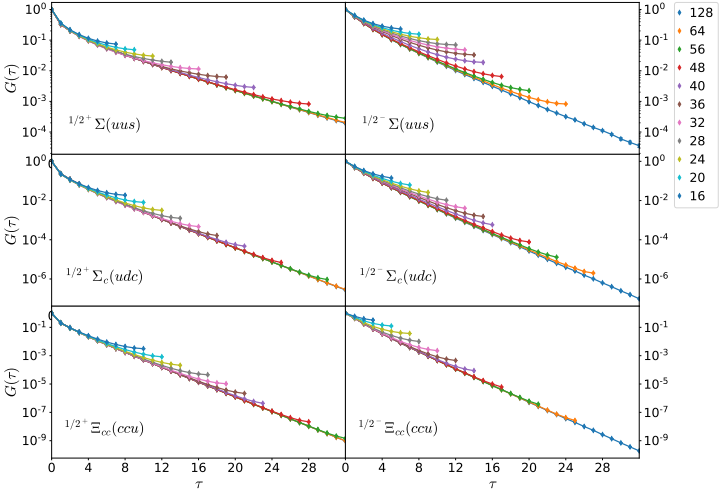
N_τ	128	64	56	48	40	36	32	28
T (MeV)	47	95	109	127	152	169	190	217
$T/T_c \sim$	0.285	0.570	0.651	0.760	0.912	1.013	1.139	1.302

- FASTSUM Generation 2L $N_f = 2 + 1$ anisotropic ensembles
  - $m_\pi \sim 230$ MeV, $\xi \sim 3.5$, $T_c \sim 167$ MeV, $N_{meas} \sim 8000$
- Standard baryon operators $[q\, C\, \gamma_5\, q]\; q$ (mostly), i.e.

$$\mathcal{O}^{\alpha}_{1/2}\left(\Omega_{ccs}\right) = \epsilon_{abc} c\alpha^a \left(c\gamma^b \left[C\gamma_5\right]_{\gamma\beta} s\beta^c\right)$$

- Calculations performed using openQCD-FASTSUM
  - https://gitlab.com/fastsum, https://doi.org/10.5281/zenodo.2217027
  - stout-link and source/sink smearing

Correlator Temperature Dependence



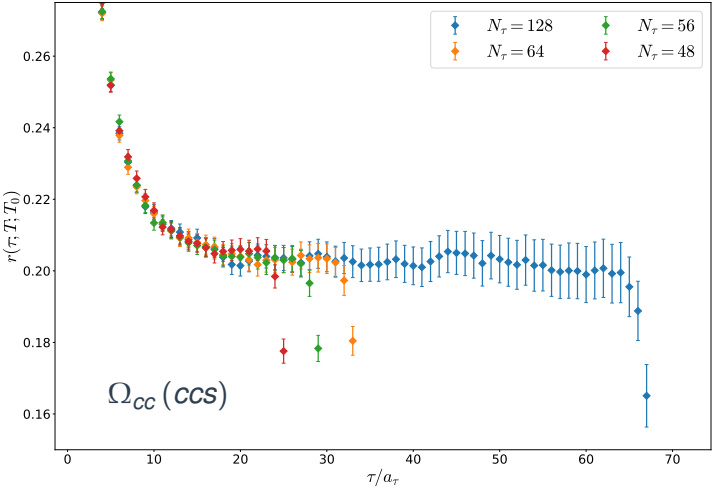
Single Ratio

- Consider model correlator only ground state G_F
- Use zero-temperature ($N_\tau = 128$) correlator to inform mass
- This accounts for the finite-size of the higher temperatures
- Take ratio of lattice correlator $G(\tau; T)$ to model correlator G_F

$$r(\tau; T, T_0) = G(\tau; T)/G_F(\tau; T, T_0).$$

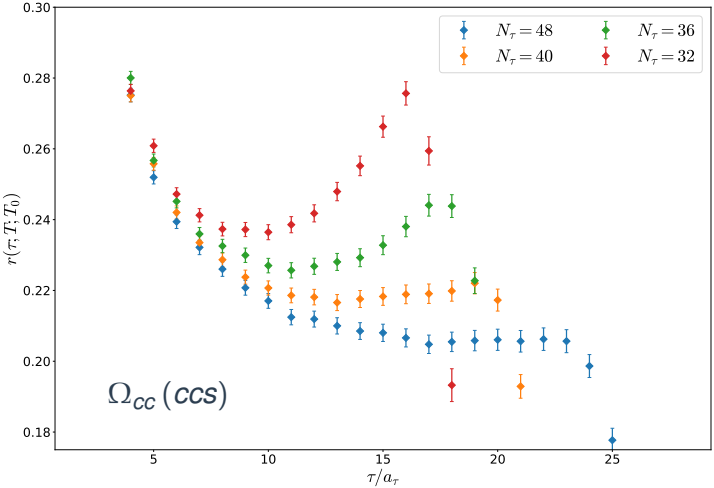
Single Ratio

$r(\tau; T, T_0) = G(\tau; T)/G_F(\tau; T, T_0)$



Single Ratio

$r(\tau; T, T_0) = G(\tau; T)/G_F(\tau; T, T_0)$



Double Ratio

- Construct double ratio of different temperatures
  - Removes excited state effects
  - Differences from **one** show difference in correlator

$$R(\tau; T, T_0) = \frac{r(\tau; T, T_0)}{r(\tau; T_0, T_0)}$$
$$= \frac{G(\tau; T)}{G_F(\tau; T, T_0)} \Big/ \frac{G(\tau; T_0)}{G_F(\tau; T_0, T_0)}.$$

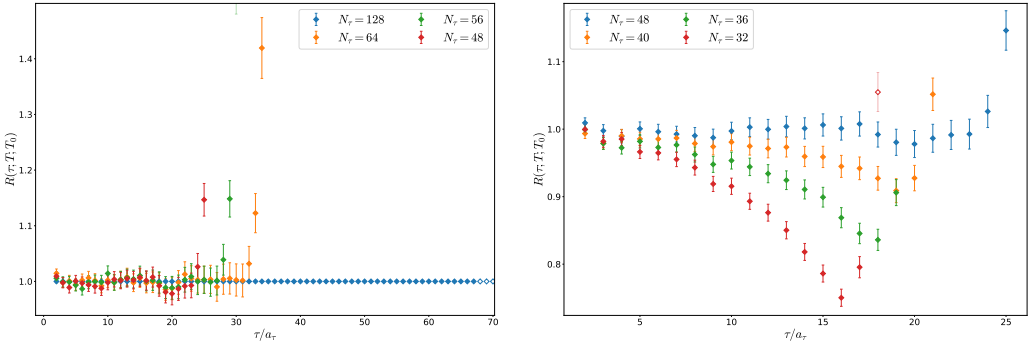


Figure: Double Ratio for Ω_{ccs} positive parity

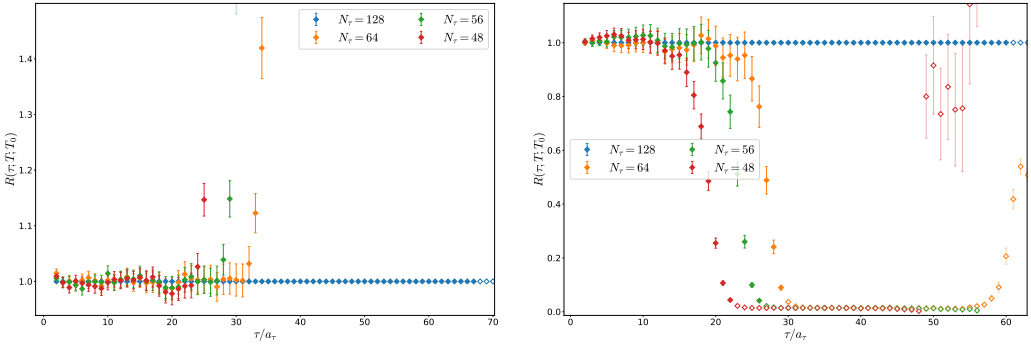


Figure: Double Ratio for Ω_{ccs} positive and negative parity

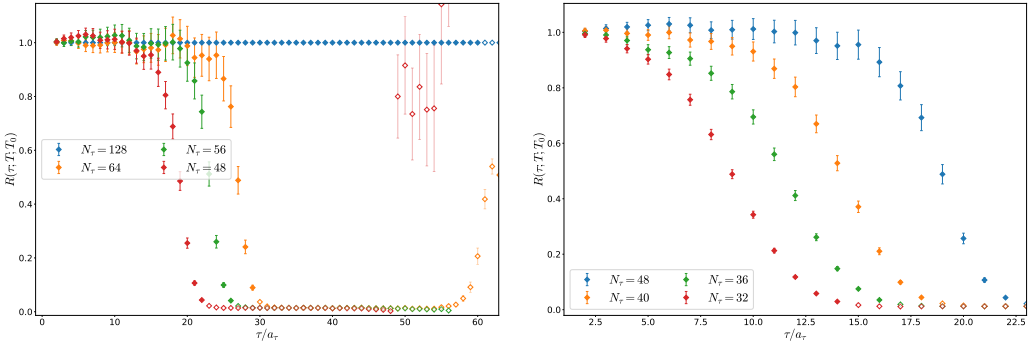


Figure: Double Ratio for Ω_{ccs} Negative Parity

Ratio Summary

- Use the double ratio examine change of correlator with temperature
- Set bounds on when to use exponential fits to extract masses
- Ratios show strong evidence of change *before* the pseudocritical temperature $T_c \sim 167$ MeV

Fit Window Dependence

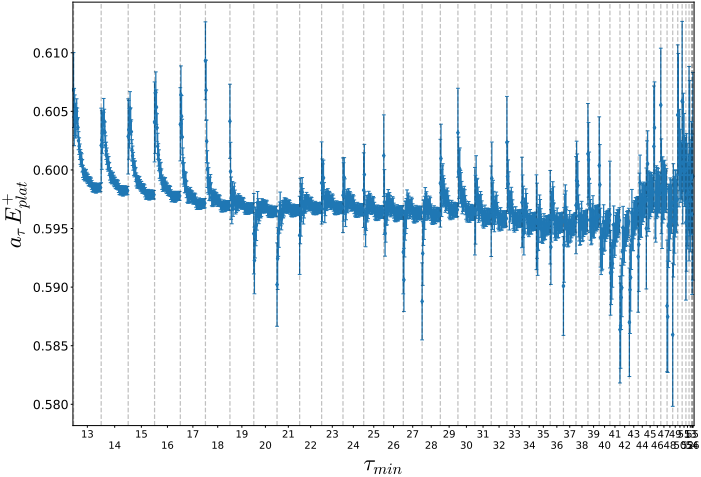


Figure: Constant plateau fits as a function of fit window for Ω_{cc} (*ccs*) $N_\tau = 128$

Fit Window Dependence

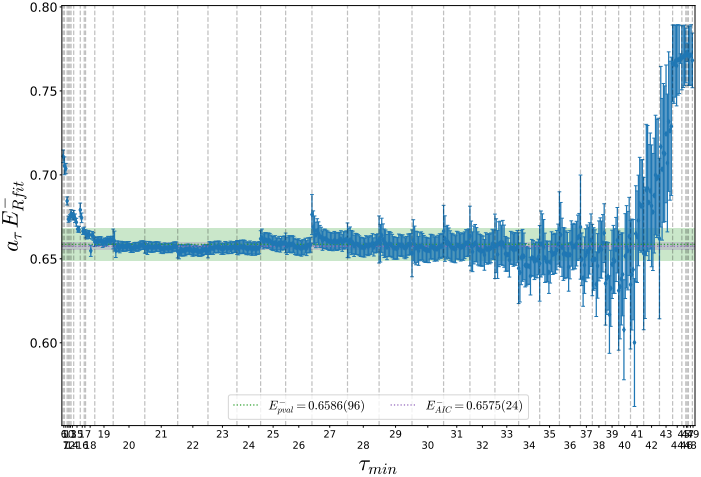


Figure: Multi-exponential fits as a function of fit window for Ω_{cc} (*ccs*) $N_\tau = 128$

Model Averaging Methods

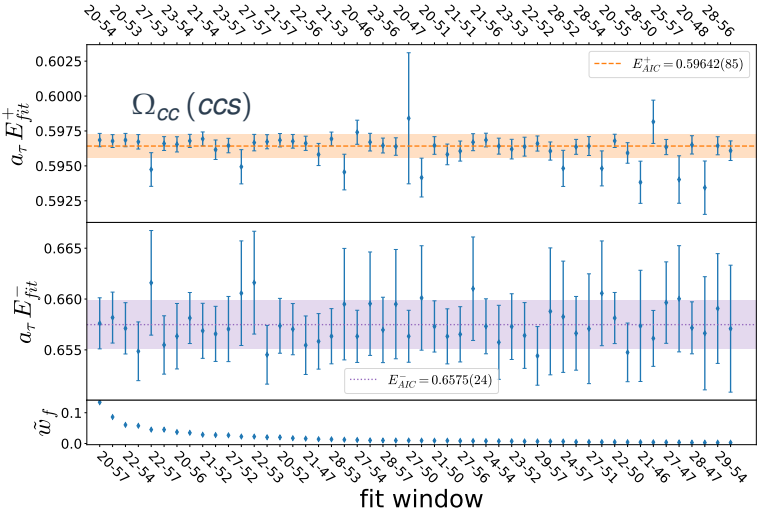
- Systematic approach to selection of “fit window”
- Weighted average over all possible fit windows
- Two different methods used to increase confidence in the result
  - First method uses modified Akaike information criterion W. Jay, E. Neil: **2008.01069**

$$\tilde{w}^f = pr(M_f|D) = \exp\left(-\frac{1}{2}\left(\chi^2_{aug}\left(E^f\right) + 2\,k + 2\,N_{\text{cut}}\right)\right),$$

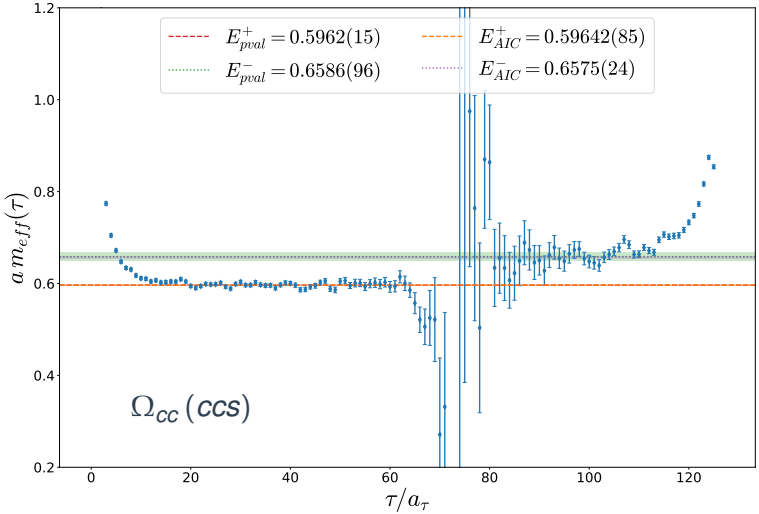
  - Second method weights proportionally to statistical error and *p*-value E. Rinaldi, *et al.*: **1901.07519**

$$\tilde{w}^f = \frac{p_f\left(\delta E^f\right)^{-2}}{\sum\limits_{f'=1}^{N} p_{f'}\left(\delta E^{f'}\right)^{-2}},$$

Model Averaging Results

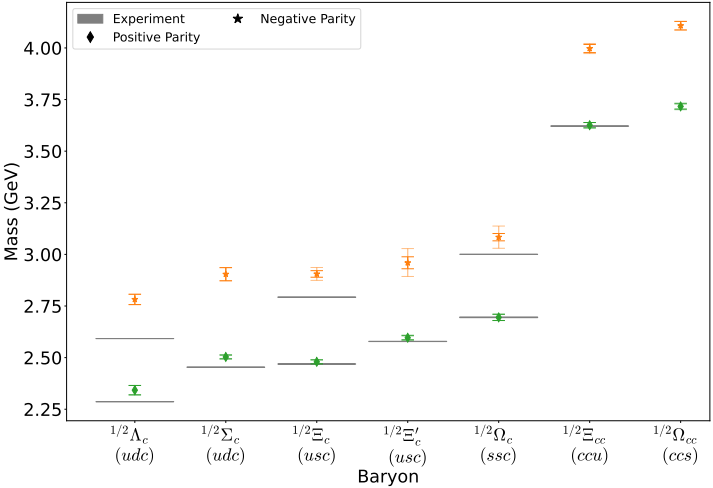


Effective mass comparison



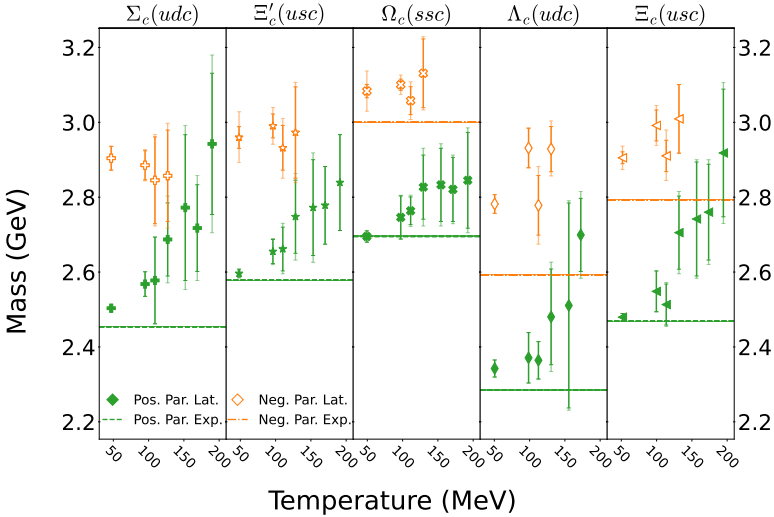
Zero-temperature spectrum $J = 1/2$

2212.09371



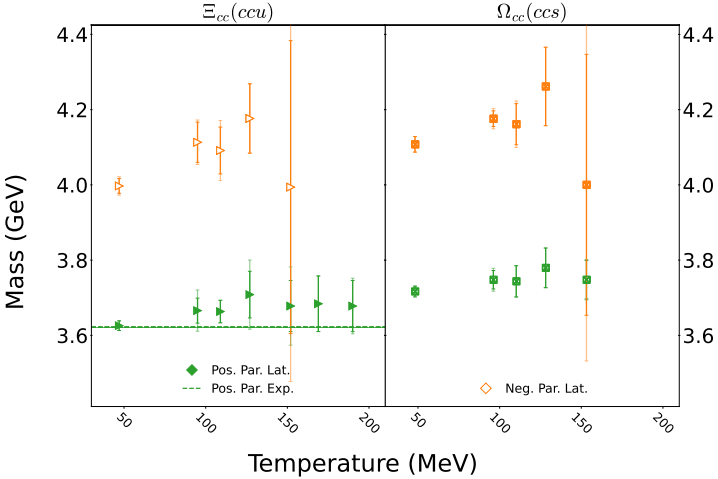
All temperature Spectrum $J = 1/2$

$C = 1$



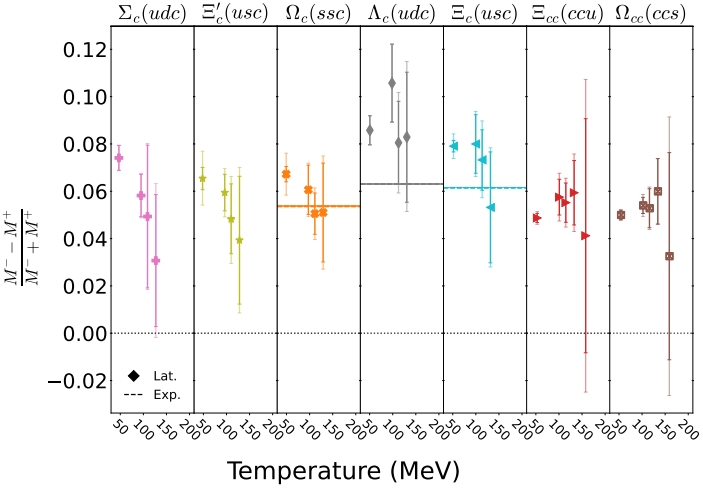
All temperature Spectrum $J = 1/2$

$C = 2$



All temperature Spectrum $J = 1/2$

Normalised mass difference



Mass Summary

- Model averaging methods used to determine mass from correlator fits
  - of positive and negative parity states
  - at multiple temperatures
- Uncertainty increases as temperature does
  - Likely signifies increasingly incorrect fit ansatz

Parity Doubling

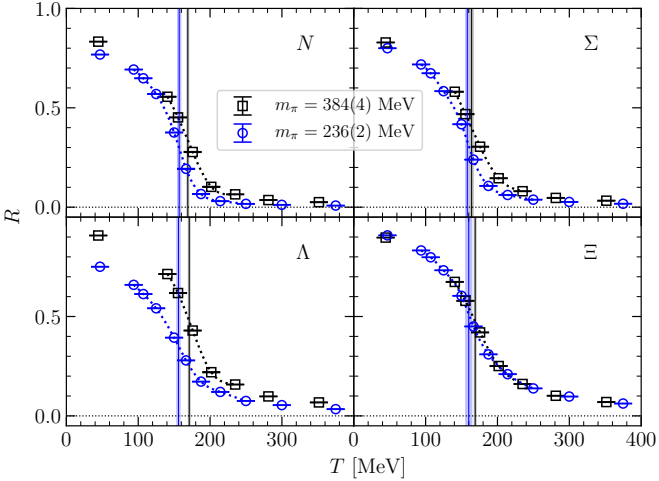
- Examine emergence of parity doubling in baryonic correlators
  - Signal of chiral symmetry restoration
- Construct from positive ($G^{+}(\tau)$) and negative ($G^{-}(\tau) = G^{+}(1/T - \tau)$) correlators

$$\mathcal{R}(\tau) = \frac{G^{+}(\tau) - G^{-}(\tau)}{G^{+}(\tau) + G^{-}(\tau)},$$

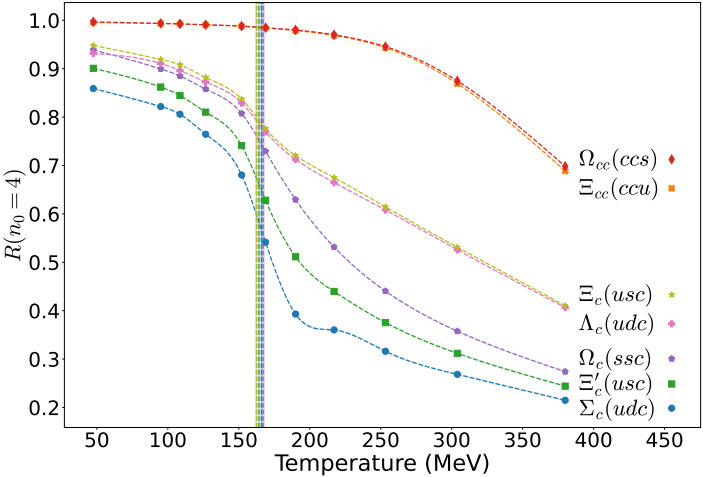
$$R(\tau_n) = \frac{\sum_{n}^{\frac{1}{2}N_\tau - 1} \mathcal{R}(\tau_n)/\sigma^2_{\mathcal{R}}(\tau_n)}{\sum_{n}^{\frac{1}{2}N_\tau - 1} 1/\sigma^2_{\mathcal{R}}(\tau_n)}.$$

Parity doubling ratio R, $J = 1/2$

Previous studies on same ensembles: Aarts *et al.* **2007.04188**



Parity doubling ratio R, $J = 1/2$



Inflection Points $\sim T_c$

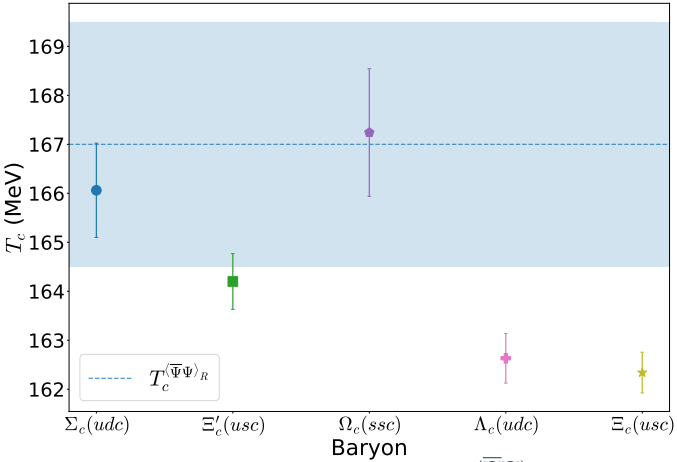


Figure: Inflection points of parity doubling ratio splines. $T_c^{\langle\overline{\Psi}\Psi\rangle_R}$ from Aarts *et al.* **1912.09827**

Summary

- Parity doubling effect decreases as quark mass increases
  - Quark mass explicitly breaks chiral symmetry
  - As does Wilson-Clover action
- Can still find inflection points for most baryons here
  - Even where parity doubling is not very evident!
  - Inflection points are close to T_c from the renormalised chiral condensate
- Exponential mass fits grow unreliable at higher temperatures
- Model averaging methods aids mass determination from many fits

FASTSUM Collaboration

- Employs anisotropic lattice QCD to study finite temperature systems
  - Anisotropy allows fine temperature and is conceptually clear $N_\tau \propto 1/T$
- Have studied wire variety of properties
  - charmonium, open-charm, bottomonium, light and strange baryons
  - electrical conductivity of QCD matter, properties of the chiral transition
- A recent summary: Skullerud *et al.* **2211.13717**, Allton *et al.* **2301.10282**
- D-mesons: Aarts *et al.* **2211.13717**
- Bottomonium spectral functions: Spriggs *et al.* **2112.04201**, Page *et al.* **2112.02075**
- Inter-quark (bottomonium) potential, Quark/Gluon propagator & more

BONUS SLIDES

Model Correlator

- Single 'forward' positive ground state with mass m^+
- Single 'backward' negative ground state with mass m^-

$$G_F(\tau; N) = \frac{e^{-m^+\tau}}{1 + e^{-Nm^+}} + \frac{e^{m^-\tau}}{1 + e^{Nm^-}}.$$

- Accounts for periodicity of finite $N_\tau = N$ lattice
- Uses masses $m^\pm$ determined at $N_\tau = N_0$, i.e. at T_0

BONUS SLIDES

Reconstructed Correlator

- Consider spectral relation of fermion correlators

$$G(\tau) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} K_F(\tau, \omega)\ \rho(\omega),$$

- Allows correlator at N_τ to be written as a sum over the correlator at $N_0 < N_\tau$
- i.e. Account for shorter lattice time

$$G_{F,\text{rec}}(\tau; N_\tau, N_0) = \sum_{n=0}^{m-1} (-1)^n\ G_F(\tau + nN_\tau; N_0).$$

BONUS SLIDES

Reconstructed Ratio Ω_{cc} (*ccs*)