Hadronic spectrum calculations in the quark-gluon plasma

Aleksandra Rylund Glesaaen

July 27th 2018

Swansea University
In collaboration with G. Aarts, C. Allton, S. Hands, B. Jäger, J. Skullerud

Talk overview

1. Introduction
2. Method
3. Results
4. Future work
5. openQCD-FASTSUM

Introduction

Baryons at finite temperature

Although mesons have been thoroughly studied at finite temperatures, baryons have not been given nearly the same attention

- They have definite parity: $P_{\pm}\mathcal{O}_B(x) = \mathcal{O}_B(x)$
- Experimentally accessible results
- Important for model builders
  - Quark models, e.g. hadron resonance gas
  - Verification of thermodynamic models

More broken symmetries...

In nature baryon parity is a broken symmetry

$$m_{\{uud\}^{1/2+}} \equiv m_N = 0.939 \text{ GeV}$$
$$m_{\{uud\}^{1/2-}} \equiv m_{N*} = 1.535 \text{ GeV}$$

Similar to other broken symmetries, what happens to this one as we increase temperature and enter the deconfined phase?

More broken symmetries...

In nature baryon parity is a broken symmetry

$$m_{\{uud\}^{1/2+}} \equiv m_N = 0.939\ \mathrm{GeV}$$
$$m_{\{uud\}^{1/2-}} \equiv m_{N*} = 1.535\ \mathrm{GeV}$$

Similar to other broken symmetries, what happens to this one as we increase temperature and enter the deconfined phase?

Previous studies by FASTSUM:

1502.03603, 1703.09246, 1710.00566, ...

Open questions

- Does parity restoration happen at T_c?
- How does hadron content effect parity restoration?
- Is there a flavour hierarchy in the deconfinement transition?
- How does m_π affect parity restoration?

Method

Lattice setup - Gen2l ensembles

Results produced with the FASTSUM "Gen2l" ensembles (lattice parameters by the HadSpec collaboration)

- $N_f = 2 + 1$ dynamical quarks, Wilson-Clover action
- Anisotropic action: $a_s = 0.1227(8)\,\mathrm{fm},\ a_s/a_t = 3.5$
- $m_\pi = 236$ MeV, $m_s = \mathit{physical}$

N_t	256	48	40	36	32	28	24	20	16
T/T_c	0.12	0.63	0.76	0.84	0.95	1.09	1.27	1.52	1.90
N_{cfg}	750	500	500	500	500	1000	1000	1000	1000

Lattice setup - Gen2l ensembles

Results produced with the FASTSUM ”Gen2l” ensembles (lattice parameters by the HadSpec collaboration)

- $N_f = 2 + 1$ dynamical quarks, Wilson-Clover action
- Anisotropic action: $a_s = 0.1227(8)\,\text{fm},\ a_s/a_t = 3.5$
- $m_\pi = 236$ MeV, $m_s = \textit{physical}$

N_t	256	48	40	36	32	28	24	20	16
T/T_c	0.12	0.63	0.76	0.84	0.95	1.09	1.27	1.52	1.90
N_{cfg}	750	500	500	500	500	1000	1000	1000	1000

Have to be checked, numbers from Gen2 ensembles

Lattice setup - Gen2l ensembles

Results produced with the FASTSUM ”Gen2l” ensembles (lattice parameters by the HadSpec collaboration)

- $N_f = 2 + 1$ dynamical quarks, Wilson-Clover action
- Anisotropic action: $a_s = 0.1227(8)\,\text{fm},\ a_s/a_t = 3.5$
- $m_\pi = 236$ MeV, $m_s = \textit{physical}$

N_t	256	48	40	36	32	28	24	20	16
T/T_c	0.12	0.63	0.76	0.84	0.95	1.09	1.27	1.52	1.90
N_{cfg}	750	500	500	500	500	1000	1000	1000	1000

By the HadSpec collaboration

Lattice setup - Gen2l ensembles

Results produced with the FASTSUM "Gen2l" ensembles (lattice parameters by the HadSpec collaboration)

- $N_f = 2 + 1$ dynamical quarks, Wilson-Clover action
- Anisotropic action: $a_s = 0.1227(8)\,\text{fm},\ a_s/a_t = 3.5$
- $m_\pi = 236$ MeV, $m_s = \textit{physical}$

N_t	256	48	40	36	32	28	24	20	16
T/T_c	0.12	0.63	0.76	0.84	0.95	1.09	1.27	1.52	1.90
N_{cfg}	750	500	500	500	500	1000	1000	1000	1000

Still generating

Lattice setup - baryon correlation functions

Use the following baryon interpolation functions:

$$
\begin{aligned}
\chi_{N,\gamma} &= \epsilon^{abc} u^a_\gamma (u^b_\alpha (C\gamma_5)_{\alpha\beta} d^c_\beta) \\
\chi_{\Delta^+,\gamma,\mu} &= \epsilon^{abc} \big(2u^a_\gamma (u^b_\alpha (C\gamma_\mu)_{\alpha\beta} d^c_\beta) + d^a_\gamma (u^b_\alpha (C\gamma_\mu)_{\alpha\beta} u^c_\beta)\big) \\
\chi_{\Delta^{++},\gamma,\mu} &= \epsilon^{abc} u^a_\gamma (u^b_\alpha (C\gamma_\mu)_{\alpha\beta} u^c_\beta)
\end{aligned}
$$

for all baryons that can be constructed with from them having flavour content using $\{u, d, s, c\}$

- N, $\Delta_{s/c}$, $\Sigma_{s/c}$, $\Sigma^*_{s/c}$, $\Xi_{s/c}$, $\Omega_{s/c}$

Sinks and sources smeared with Gaussian smearing to extract ground states

Results

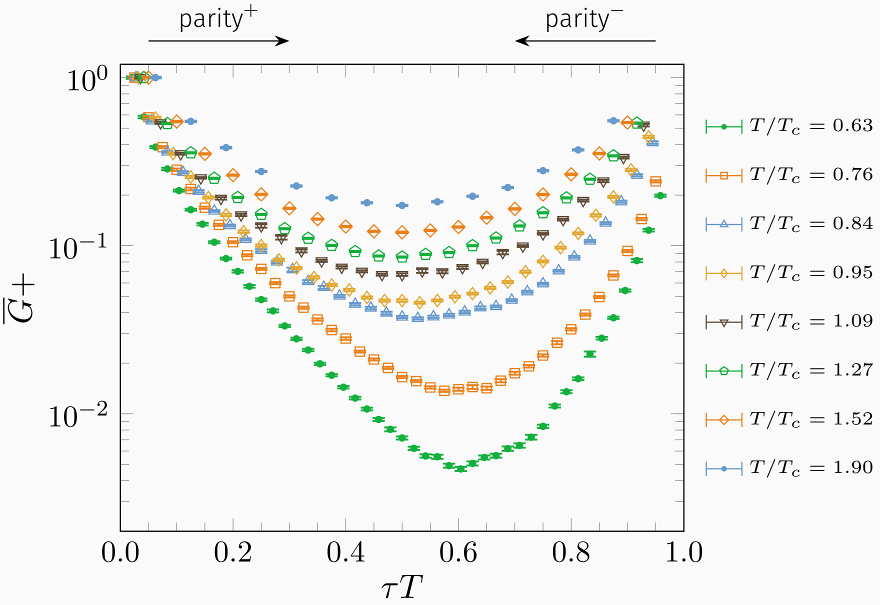
Parity and correlation functions

Due to charge conjugation symmetry (at $\mu = 0$)

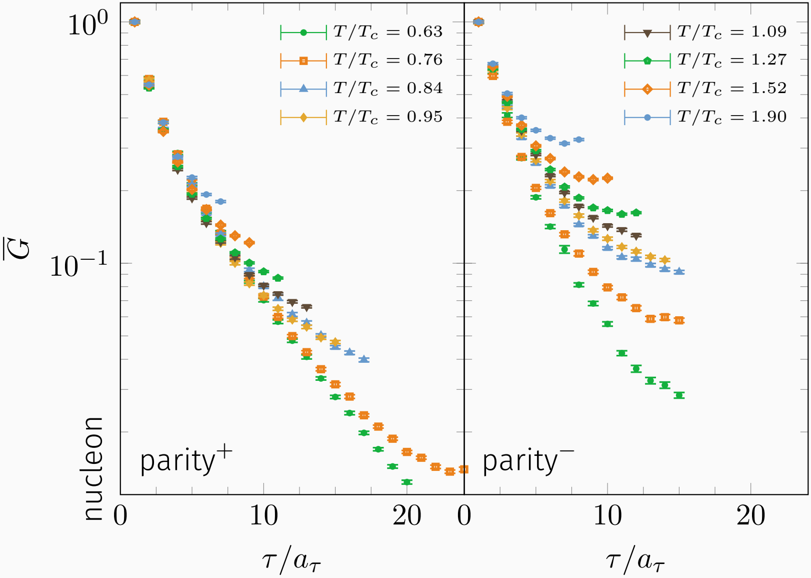
$$G_{\pm}(\tau, \mathrm{p}) = -G_{\mp}(1/T - \tau, \mathrm{p})$$

Thus the correlation function is a sum of forward moving parity^{+} states and backwards moving parity^{-} states

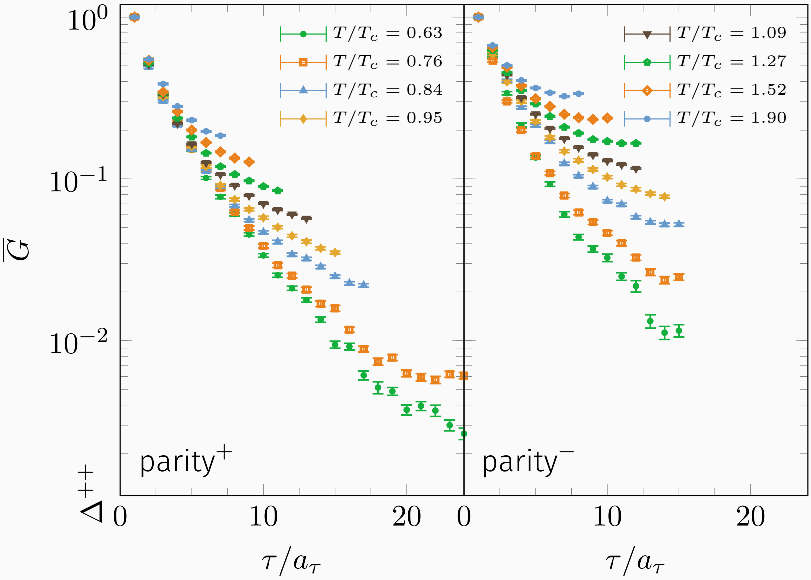
Correlation functions



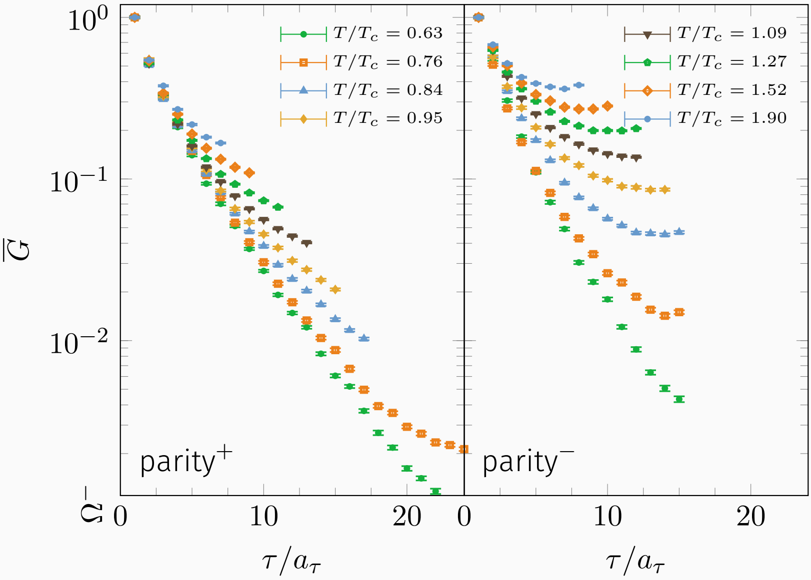
Parity channels - nucleon



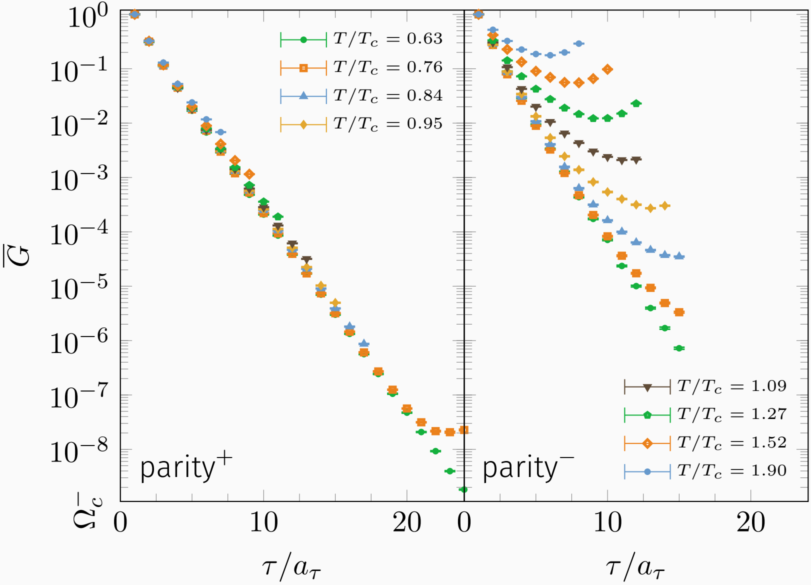
Parity channels - Δ^+ particle



Parity channels - Ω particle



Parity channels - Ω_c particle



Symmetry restoration parameter - the R parameter

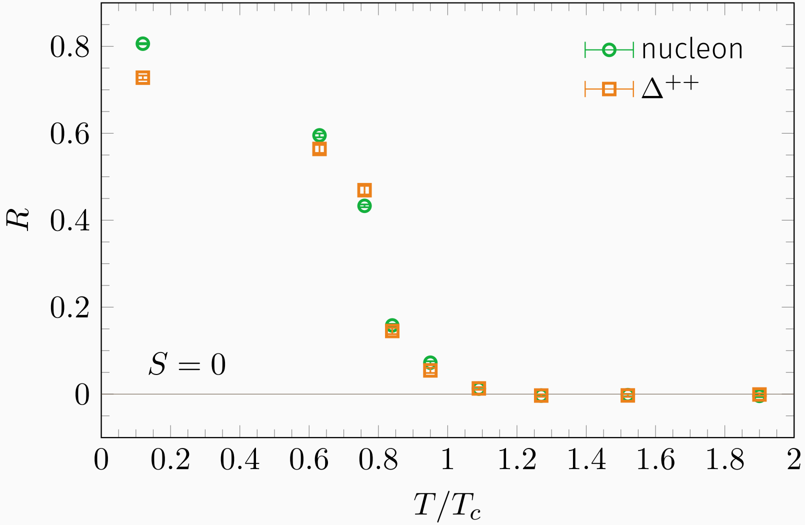
$$R(\tau) = \frac{G_+(\tau) - G_+(1/T - \tau)}{G_+(\tau) + G_+(1/T - \tau)}$$

- $R(\tau) \neq 0 \Leftrightarrow$ no parity doubling
- $R(\tau) = 0 \Leftrightarrow$ parity doubling

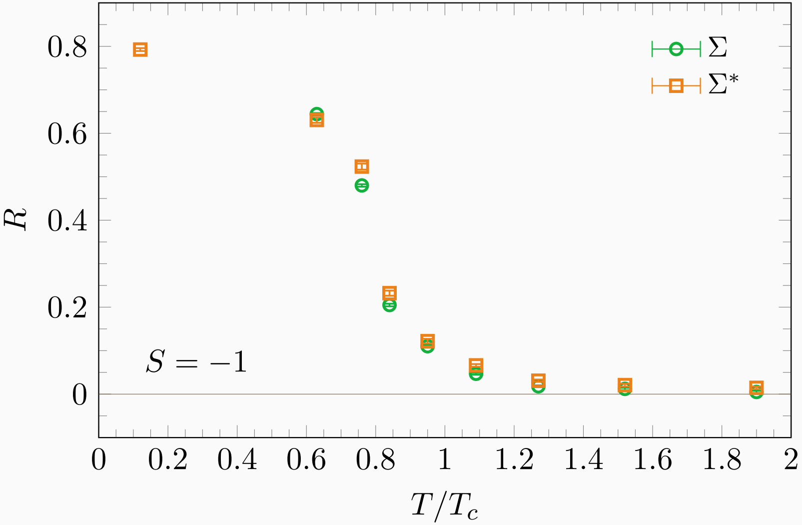
The summed ratio is a quasi-order parameter (as we will see)

$$R = \frac{\sum_n R(\tau_n)/\sigma^2(\tau_n)}{\sum_n 1/\sigma^2(\tau_n)}$$

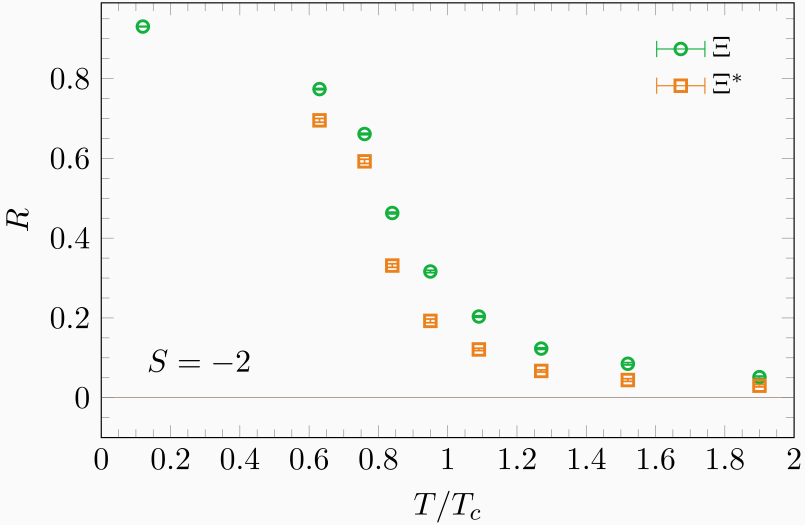
The R-factor - $S = 0$



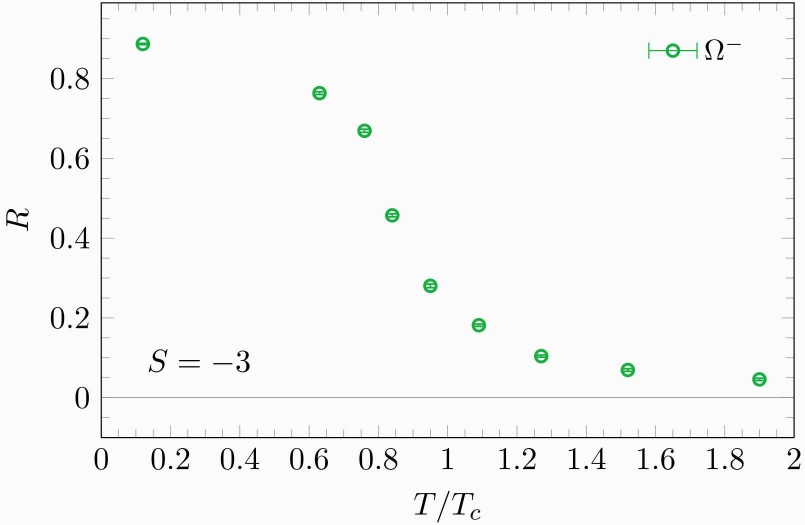
The R-factor - $S = -1$



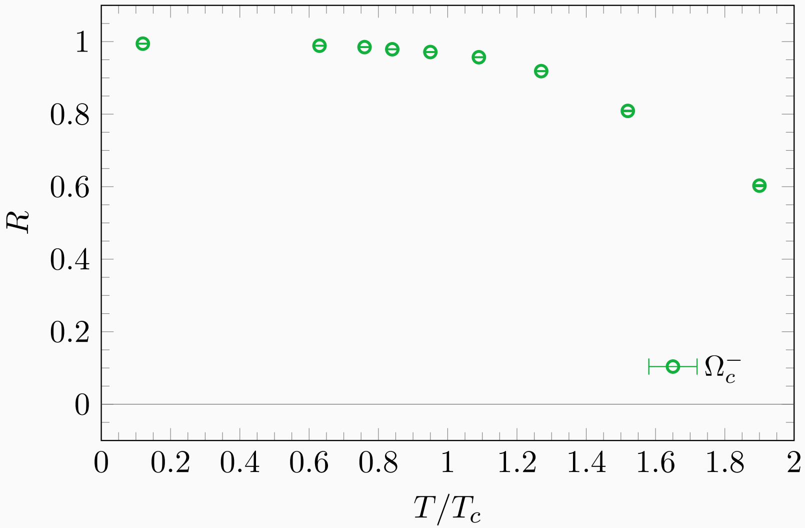
The R-factor - $S = -2$



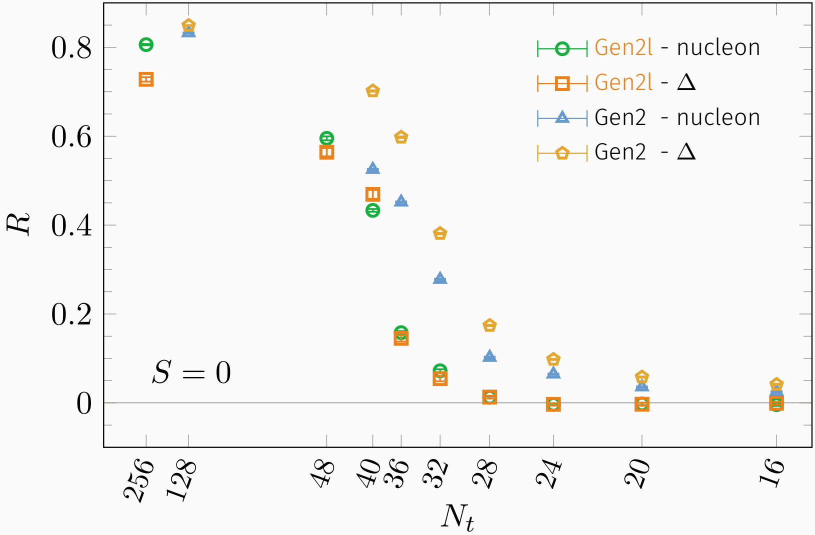
The R-factor - $S = -3$



The R-factor - Ω_c particle



The R-factor - comparison with previous ensemble



Future work

Still a lot more to be done

Study just getting started

- More thorough look at the masses and correlators
- Spectral reconstruction analysis
- Susceptibility calculations

Planned future ensembles

- Generation 2P
- Generation 3

Still a lot more to be done

Study just getting started

- More thorough look at the masses and correlators
- Spectral reconstruction analysis
- Susceptibility calculations

Planned future ensembles

- Generation 2P (physical quark masses)
- Generation 3

Still a lot more to be done

Study just getting started

- More thorough look at the masses and correlators
- Spectral reconstruction analysis
- Susceptibility calculations

Planned future ensembles

- Generation 2P (physical quark masses)
- Generation 3 (higher anisotropy)

openQCD-FASTSUM

Two major features

- Anisotropic lattice actions
- Stout link smearing

+ AVX512 optimisations courtesy of the SA2C

openQCD-FASTSUM

Two major features

- Anisotropic lattice actions
- Stout link smearing

+ AVX512 optimisations courtesy of the SA2C

Future development plans

- Library/back-end interface
- Unit testing and CI

`https://fastsum.gitlab.io`

Questions?