Parity doubling of nucleons, Δ and Ω baryons across the deconfinement phase transition

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Motivation

$m_q = 0 \Rightarrow$ **chiral symmetry** of QCD action

$$\psi' = \mathrm{e}^{\mathrm{i}\alpha\gamma_5 T_i}\,\psi\,, \qquad \bar{\psi}' = \bar{\psi}\,\mathrm{e}^{\mathrm{i}\alpha\gamma_5 T_i}$$

T_i generators of SU(N_f), $i = 1, \ldots, N_f^2 - 1$

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Positive and negative parity baryonic correlators (zero momentum)

$$C_\pm(\tau) = \int \mathrm{d}\mathbf{x}\,\langle \mathrm{tr}\, O(\mathbf{x},\tau) P_\pm \overline{O}(\mathbf{0},0)\rangle\,, \qquad P_\pm = \frac{1}{2}(\mathbb{1} \pm \gamma_4)$$

For nucleon $\quad O(\mathbf{x},\tau) = \epsilon_{abc} u_a(\mathbf{x},\tau)\left(u_b^{\mathrm{T}}(\mathbf{x},\tau) C\gamma_5\, d_c(\mathbf{x},\tau)\right)$

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$$C_\pm(\tau) \approx A_\pm\,\mathrm{e}^{-M_\pm \tau} + A_\mp\,\mathrm{e}^{-M_\mp (a_\tau N_\tau - \tau)}$$

Chiral symmetry $\Rightarrow C_+ = -C_- \Rightarrow M_+ = M_-$

Motivation

In Nature ($T = 0$) $M_{N^*} - M_N \approx 600$ MeV $\gg m_{u,d} \approx 5$ MeV

- Explicit chiral symmetry breaking ($m_{u,d} \neq 0$) is not enough to account for this big difference

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$\Rightarrow$ Chiral symmetry is spontaneously broken at $T = 0$

- What happens at high temperature?
- Parity restoration above T_c for N and Δ baryons

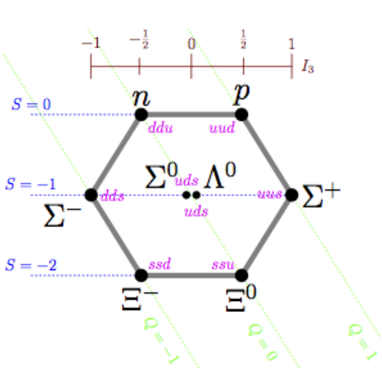
  Even if chiral symmetry is slightly explicitly broken by $m_{u,d}$ and lattice artefacts

  Wilson fermions $\rightarrow$ No chiral symmetry at short distances
- Signal of parity restoration for Ω around T_c

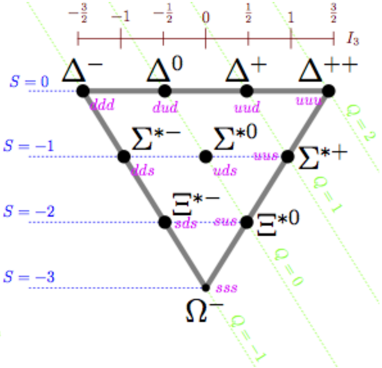
  Chiral symmetry is strongly explicitly broken by $m_s \approx 100$ MeV

Name	N	Δ	Λ	Σ	Ξ	Ω
Isospin	1/2	3/2	0	1	1/2	0
Strangenes	0		-1		-2	-3
Number of s-quarks	0		1		2	3

Spin $1/2$ octet



Spin $3/2$ decuplet



Lattice setup

FASTSUM ensembles and tuning by HadSpec collaboration

- $N_f = 2 + 1$ non-perturbatively improved Wilson fermions
- Anistropic lattice: $a_s/a_\tau = 3.5$, $a_\tau^{-1} \approx 5.6$ GeV
  $\rightarrow$ Important for constructing spectral functions
- $T = \frac{1}{a_\tau N_\tau}$ varies by changing N_τ from 128 to 16
- Large volume of the box $\sim (3\,\mathrm{fm})^3$, $N_s = 24$
- Degenerate u and d quarks, heavier than physical ones
  ($m_\pi = 384(4)$ MeV, $m_\pi/m_\rho = 0.466(3)$)
- Physical strange quark mass
- Gaussian smearing on both source and sink to enhance ground state signal

R factor for measuring parity doubling

$$R(\tau) \equiv \frac{C(\tau) - C(1/T - \tau)}{C(\tau) + C(1/T - \tau)}$$

- No parity doubling and $M_- \gg M_+ \Rightarrow R(\tau) = 1$, $0 \leq \tau < 1/(2T)$
- Parity doubling $\Rightarrow R(\tau) = 0$
- Note that $R(1/T - \tau) = -R(\tau)$ and $R(1/(2T)) = 0$

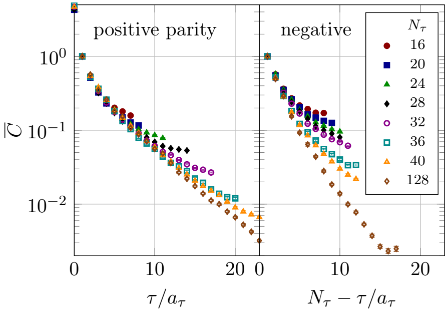
We consider the weighted average

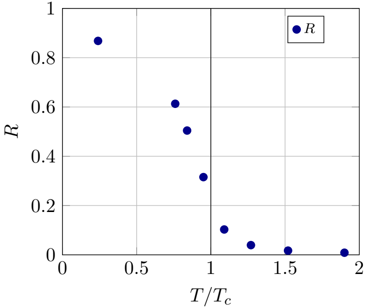
[Datta, Mathur et al. (2013)]

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

Technical note: Smearing essential to have a clear ground state

Nucleon (spin 1/2)





- Nucleon ground state largely independent of temperature
- Negative parity partner much more sensitive to temperature
- Strong signal of parity restoration around T_c

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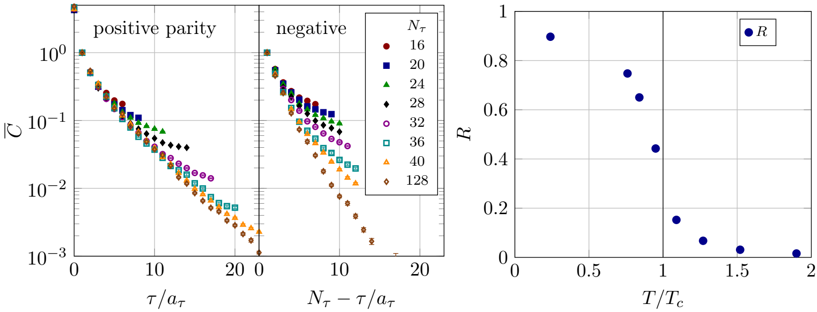
Δ-baryon (spin 3/2)



- Δ baryon ground state largely independent of temperature
- Negative parity partner much more sensitive to temperature
- Strong signal of parity restoration around deconfinement transition (tied to restoration of chiral symmetry)

Spectral functions

For baryons:

$$C_\pm(\tau,\mathbf{p}) = \int_{-\infty}^{+\infty} \frac{\mathrm{d}\omega}{2\pi}\,\rho_\pm(\omega,\mathbf{p})\,\frac{\mathrm{e}^{-\omega\tau}}{1+\mathrm{e}^{-\omega/T}}\,, \qquad \rho_\pm = \mathrm{tr}[P_\pm\rho]$$

- *Ill-posed problem*: To extract $\sim 10^3$ points for $\rho_\pm(\omega,\mathbf{p}=\mathbf{0})$ given ~ 50 noisy data for $C_\pm(\tau,\mathbf{p}=\mathbf{0})$
- The Maximum Entropy Method (MEM) is an unbiased method to get a unique solution for $\rho_\pm$ [Asakawa et al. hep:lat/0011040v2]

Important property for MEM: $\rho_+(\omega,\mathbf{p}) \geq 0 \quad \forall\omega\,,\mathbf{p}$
$(\rho_\pm(-\omega,-\mathbf{p}) = -\rho_\mp(\omega,\mathbf{p}))$

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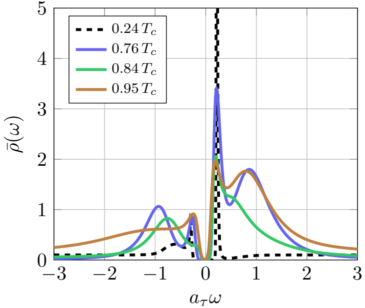
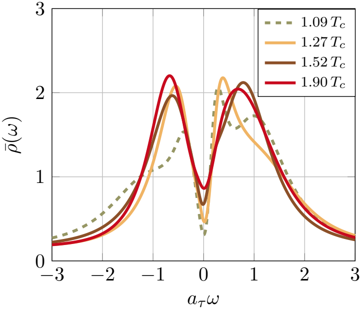
Nucleon (spin 1/2)

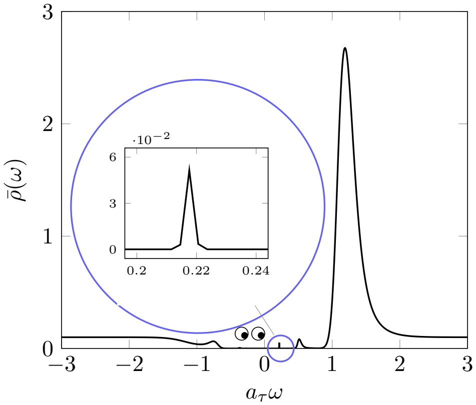
$$\bar{\rho}(\omega) \equiv \frac{1}{a_\tau} \frac{\rho(\omega)}{\langle C(\tau=0) \rangle_{\text{cfg}}}$$





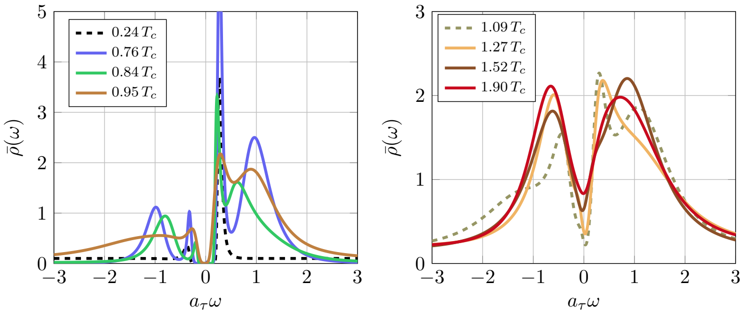
- $\omega > 0$ (+ parity): Very stable ground state below T_c
- $\omega < 0$ (- parity): Ground state moves inwards as $T \to T_c$
- Very symmetric spectral functions above T_c

Nucleon ground state without smearing ($T = 0.24T_c$)



The ground state is at the right place but we need smearing to enhance its signal

Δ-baryon (spin 3/2)



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- $\omega < 0$ (- parity): Ground state moves inwards as $T \to T_c$
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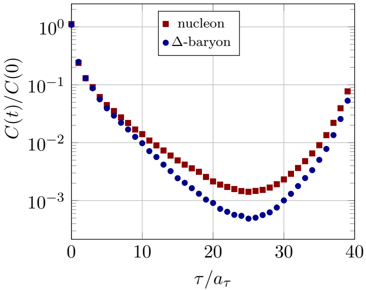
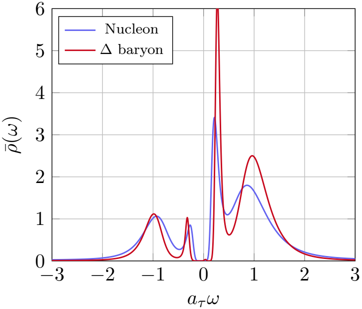
N and Δ below T_c

For ground-states ($l = 0$): $M_\Delta - M_N = \Delta M_{ss} = \frac{8}{3}\left(\frac{\hbar}{c}\right)^3 \frac{\pi \alpha_s}{m_{u,d}^2} |\psi(0)|^2$

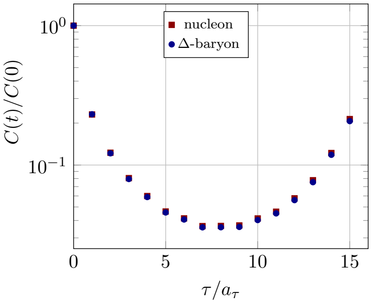
$$\Delta M_{ss}^{+\text{parity}} = \begin{cases} (293 \pm 2)\text{MeV} & \text{Nature}\,(m_\pi = 140\,\text{MeV}\,,\ T = 0) \\ (274 \pm 96)\text{MeV} & \text{Lattice}\,(m_\pi = 384\,\text{MeV}\,,\ T = 44\,\text{MeV}) \end{cases}$$

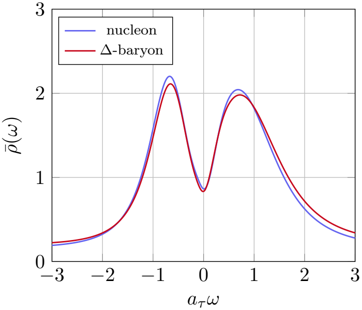




Asymmetric correlators and spectral functions

N and Δ above T_c





- Symmetric correlators and spectral functions (Parity restoration)
- Same correlators and spectral functions for N and Δ (GS melted)

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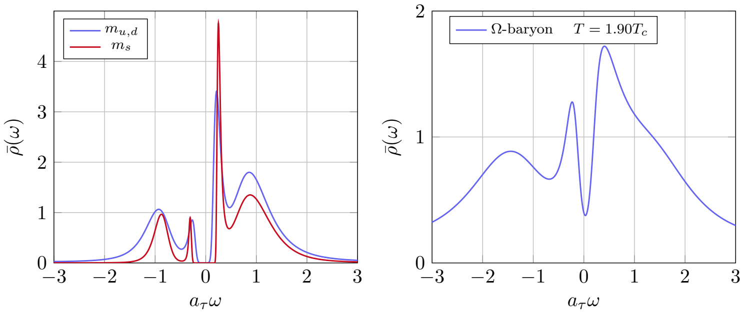
N and Ω

below T_c — above $T_c \rightarrow$ Parity not yet restored



T/T_c	m^+ [MeV]	m^- [MeV]	
0	1672.4(0.3)	2250? 2380? 2470?	PDG
0.24	1703(159)	2232(380)	

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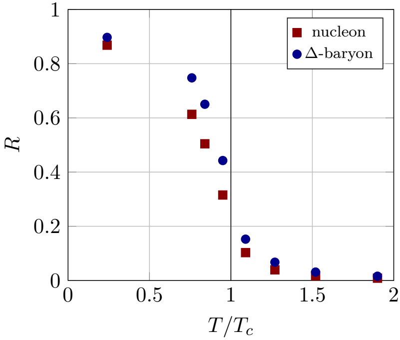
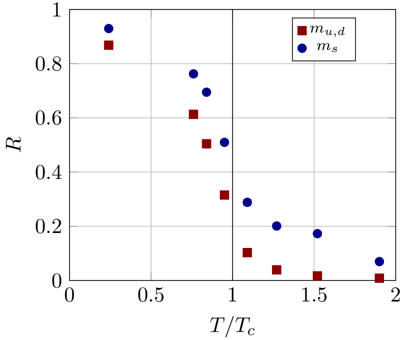
[See also HadSpec Collaboration, 0810.3588v1]

Nucleon vs Δ



Nucleon vs Ω



Parity restoration

Signal of parity doubling

Both signals occur around T_c

Conclusions and perspectives

Summary

- Negative parity channel more affected by temperature than positive parity channel
- Parity restoration above T_c for N and Δ baryons
- Signal of parity doubling for Ω at T_c
- Chiral symmetry is strongly explicitly broken by m_s

Outlook

- To use chiral (overlap) fermions
- Finer lattice spacing