

Medium effects and parity doubling of hyperons across the deconfinement phase transition

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For N , Δ and Ω baryons: [JHEP06\(2017\)034, 1703.09246](#)

Motivation

$m_q = 0 \Rightarrow$ **chiral symmetry** $SU(N_f)_V \times SU(N_f)_A$ of QCD action

$$\Lambda_A : \quad \psi' = e^{i\theta^i \gamma_5 T_i} \psi, \quad \bar{\psi}' = \bar{\psi} e^{i\theta^i \gamma_5 T_i}$$

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

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Positive and negative parity baryonic correlators (zero momentum)

$$G_{\pm}(\tau) = \int d\mathbf{x} \langle \text{tr} O(\mathbf{x}, \tau) P_{\pm} \bar{O}(\mathbf{0}, 0) \rangle, \quad P_{\pm} = \frac{1}{2}(\mathbb{1} \pm \gamma_4)$$

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$$G_{\pm}(\tau) \approx A_{\pm} e^{-m_{\pm}\tau} + A_{\mp} e^{-m_{\mp}(a_{\tau}N_{\tau}-\tau)}$$

Chiral symmetry $\Rightarrow G_+ = -G_- \Rightarrow m_+ = m_-$ (parity doubling)

Motivation

In Nature ($T = 0$) $m_{B^*} - m_B \approx 500 - 600$ MeV

$m_{u,d} \approx 5$ MeV $m_s \approx 95$ MeV

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

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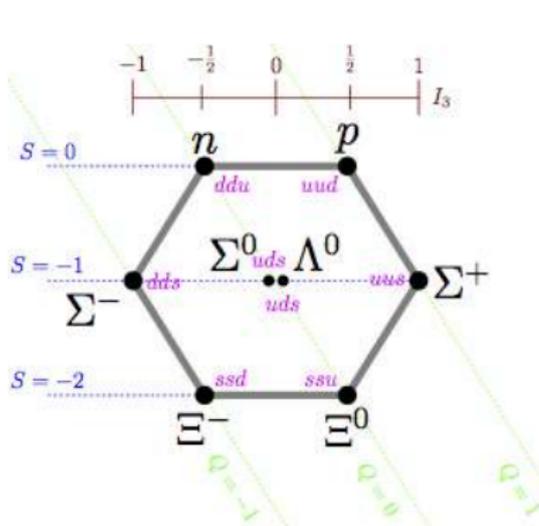
$$SU(N_f)_V \times SU(N_f)_A \rightarrow SU(N_f)_V$$

What happens at high temperature?

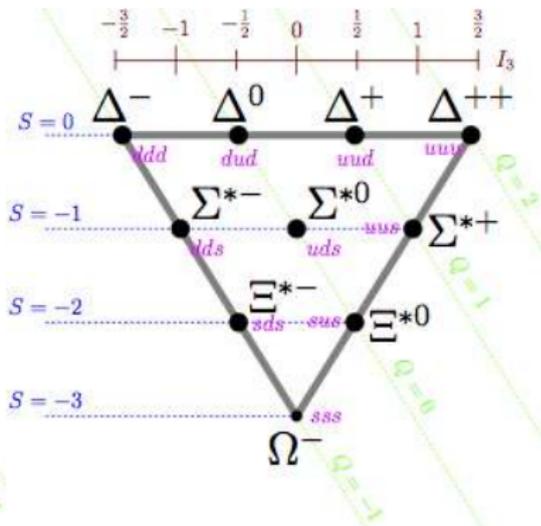
- Parity doubling for N and Δ baryons around T_c [1703.09246]
- Signal of parity doubling for hyperons around T_c

Name	N	Δ	Λ	Σ, Σ^*	Ξ, Ξ^*	Ω
Isospin	1/2	3/2	0	1	1/2	0
Strangeness		0		-1	-2	-3

Spin 1/2 octet



Spin 3/2 decuplet



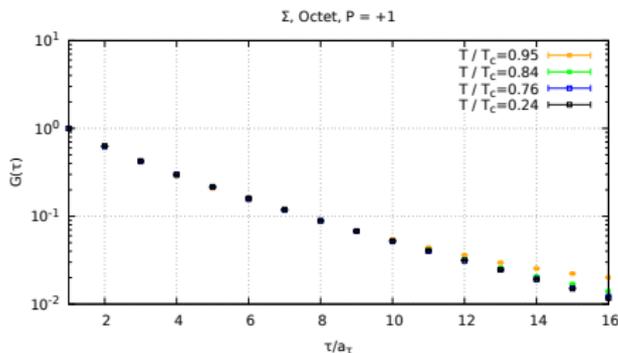
Lattice setup

FASTSUM ensembles and tuning by HadSpec collaboration

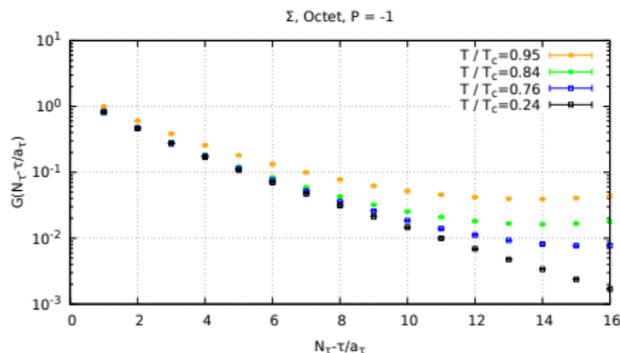
- $N_f = 2 + 1$ non-perturbatively improved Wilson fermions
- Anisotropic lattice: $a_s/a_\tau = 3.5$, $a_\tau^{-1} \approx 5.6$ GeV
- $T = \frac{1}{a_\tau N_\tau}$ varies by changing N_τ from 128 to 16
- Large volume of the box $\sim (3 \text{ fm})^3$, $N_s = 24$
- Degenerate u and d quarks, heavier 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

Correlator of Σ (Octet, $S = -1$)

Positive parity



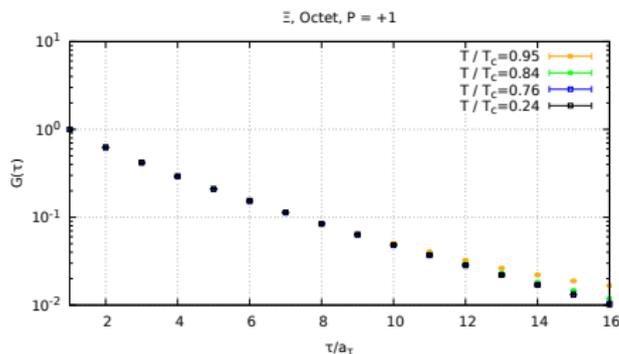
Negative parity



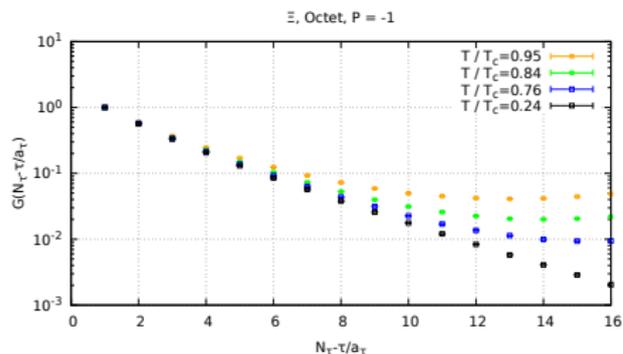
- Positive-parity ground state largely independent of temperature
- Negative-parity partner much more sensitive to temperature
- Slope of the curves gives the groundstate masses m_\pm

Correlator of Ξ (Octet, $S = -2$)

Positive parity



Negative parity



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R factor for measuring parity doubling

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

[Datta, Mathur et al. (2013)]

- 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 $R(1/(2T)) = 0$

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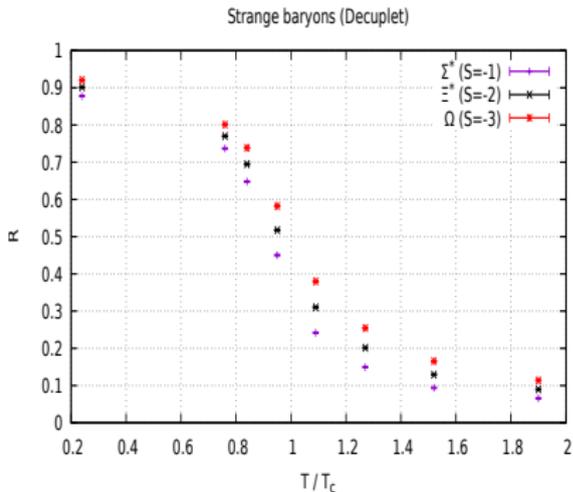
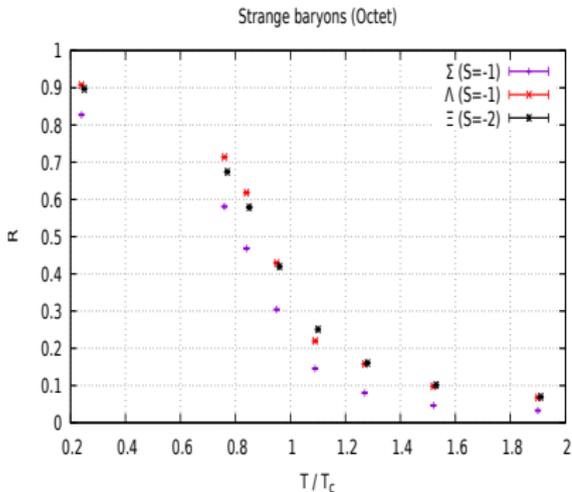
We consider the weighted average

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

[1502.03603]

Technical note: Smearing essential to have a clear ground state

R factor and parity doubling

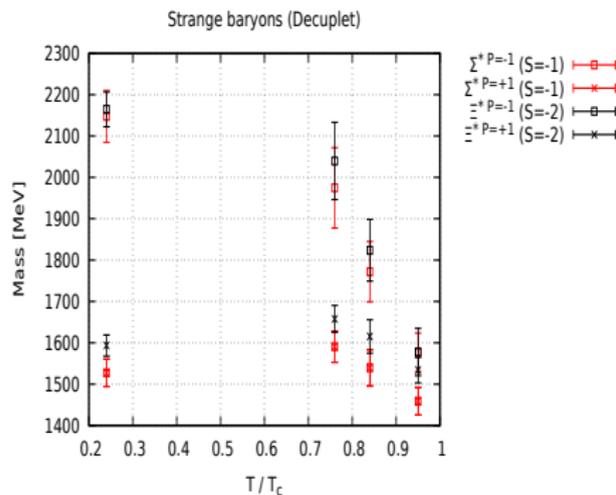
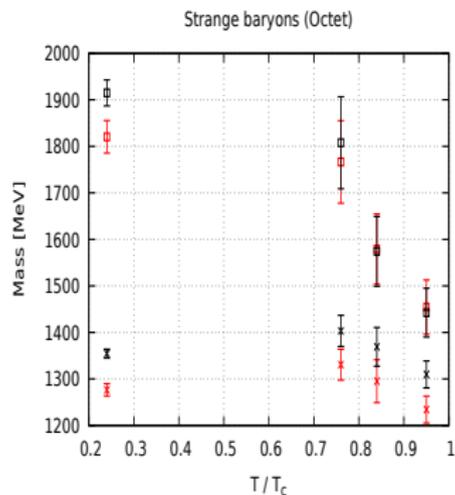


Strong signal of chiral symmetry restoration around T_c

T-dependence of negative-parity masses

$$m_+(T) = \text{constant}$$

$$m_-(T) \rightarrow m_+ \text{ as } T \rightarrow T_c$$

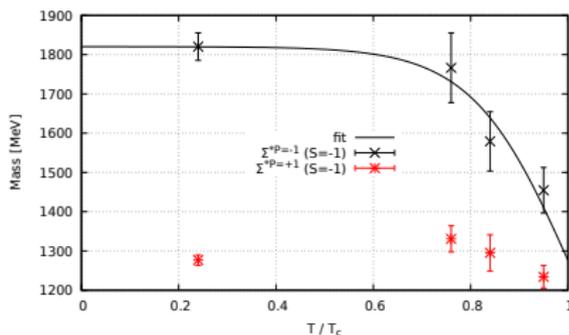
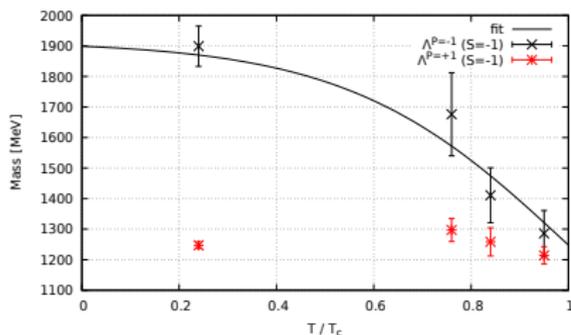


For the Ω particle look at [1703.09246](#)

Fit: $m_-(T) = \omega(T, \gamma)m_-(0) + [1 - \omega(T, \gamma)] m_-(T_c)$

$$\omega(T, \gamma) = \frac{\tanh [(1 - T/T_c)/\gamma]}{\tanh [1/\gamma]}, \quad \omega(0, \gamma) = 1, \quad \omega(T_c, \gamma) = 0$$

$$m_-(T_c) \sim m_+(T_c) \sim m_+(0) \quad \gamma \ll 1 \leftrightarrow \text{narrow transition}$$



$\gamma \sim 0.25 - 0.35$ for hyperons

Summary of the lattice results

- Around T_c we have seen a clear signal of parity doubling of hyperons, which is related to chiral symmetry restoration

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- Around T_c we have seen a clear signal of parity doubling of hyperons, which is related to chiral symmetry restoration
- The approach to parity doubling happens via a drop of the mass of the negative-parity ground state (m_-) towards $m_+(T=0)$
- The mass of the positive-parity ground state does not change with T
- We apply these last two results to the [Hadron Resonance Gas](#) model and study the implications

Application: Hadron Resonance Gas (HRG)

- To model QCD at $T < T_c$ (confined phase)
- Non-interacting mesonic and baryonic resonances
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- Hadrons with $m \gg T$ are Boltzmann suppressed

$$\ln Z_i = \pm V g_i \int \frac{d\mathbf{p}}{(2\pi)^3} \ln \left(1 \pm e^{-\sqrt{\mathbf{p}^2 + m_i^2}/T} \right)$$

$$\ln Z = \sum_i \ln Z_i \quad e^{-\frac{m_i}{T}} \ll 1 \quad \approx \frac{VT}{2\pi^2} \sum_i g_i m_i^2 K_2(m_i/T), \quad i \in \text{hadrons}$$

g_i = degeneracy, $T = 0$ masses in the standard HRG

Fluctuations of conserved charges

$$\chi_2^X = \frac{1}{VT^3} \left. \frac{\partial^2 \ln Z}{\partial \mu_X^2} \right|_{\mu=0} = \left. \frac{\partial^2 (P/T^4)}{\partial \mu_X^2} \right|_{\mu=0} = \frac{\langle (\delta N_X)^2 \rangle_{\mu=0}}{VT^3}$$

$$X = B, Q, S, \quad \delta N_X = N_X - N_{\bar{X}}$$

Fluctuations in conserved charges (B,Q,S)

- are measured in experiments
- help towards understanding the phase transition from HRG to QGP
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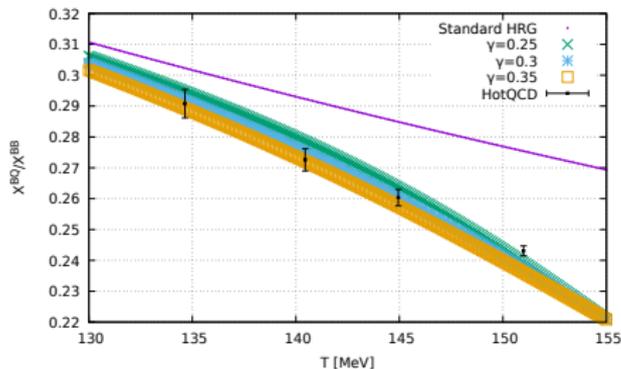
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Here we focus only on baryonic fluctuations, in particular on the ratios $\frac{\chi^{BQ}}{\chi^{BB}}$ and $\frac{\chi^{BS}}{\chi^{BB}}$

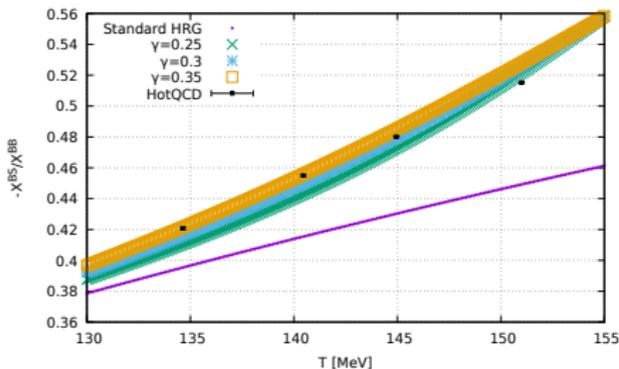
[Extensive lattice studies of those fluctuations have been performed by the Wuppertal-Budapest and HotQCD collaborations]

Baryonic fluctuations

$$\frac{\chi^{BQ}}{\chi^{BB}} = \frac{\sum_i Q_i P_i}{\sum_i P_i}$$



$$-\frac{\chi^{BS}}{\chi^{BB}} = -\frac{\sum_i S_i P_i}{\sum_i P_i}$$



- Models including additional strange baryon resonances (QM-HRG) over-predict these ratios
- Models with attractive/repulsive van der Waals interactions (vdW-HRG) do not do a better job

HotQCD results from [1701.04325](#), [1706.01620](#)

Conclusions and perspectives

Summary

- Signal of parity doubling for hyperons around T_C
Even if chiral symmetry is explicitly broken by $m_{u,d,s}$ and lattice artefacts Wilson fermions \rightarrow No chiral symmetry at short distances
- Negative-parity masses decrease when approaching T_C
- Positive parity masses do not vary with temperature
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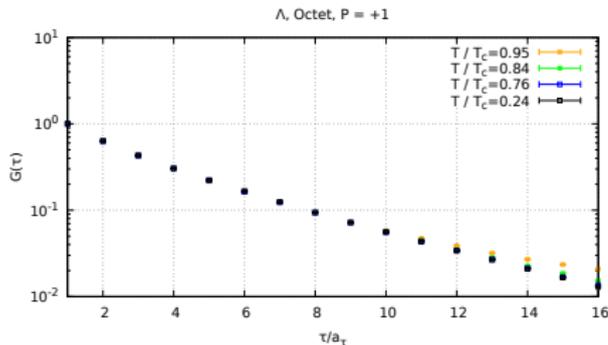
Outlook

- To study in-medium effects for mesons
- To use chiral (overlap) fermions
- Finer lattice spacing

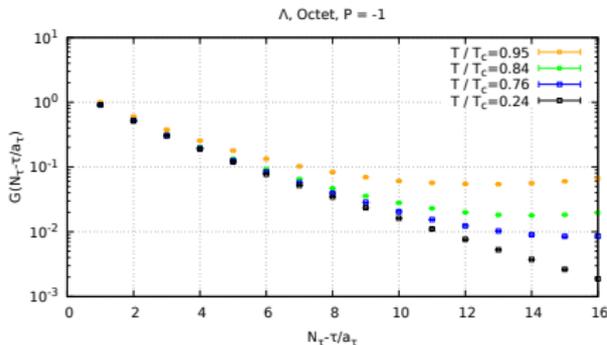
Backup Slides

Correlator of Λ (Octet, $S = -1$)

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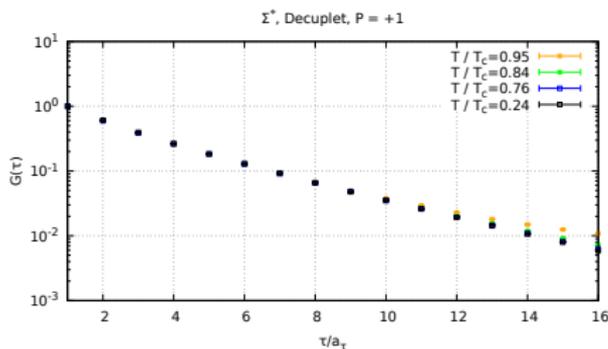
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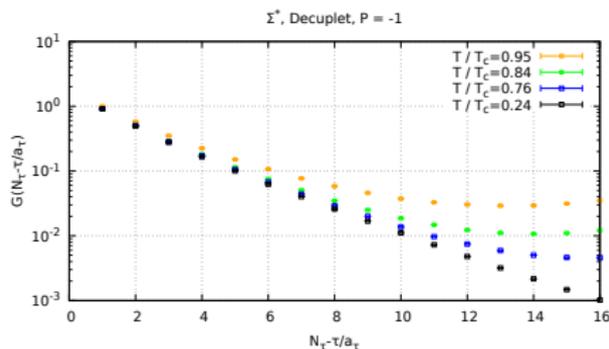
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Correlator of Σ^* (Decuplet, $S = -1$)

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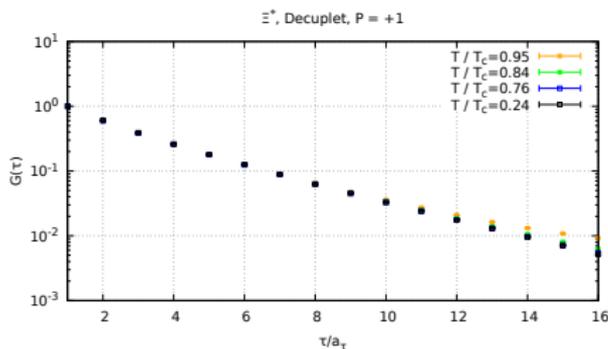
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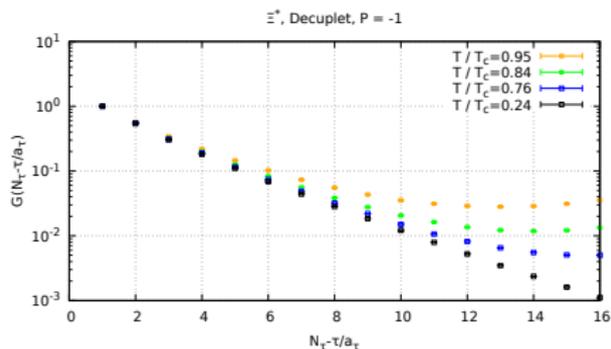
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Correlator of Ξ^* (Decuplet, $S = -2$)

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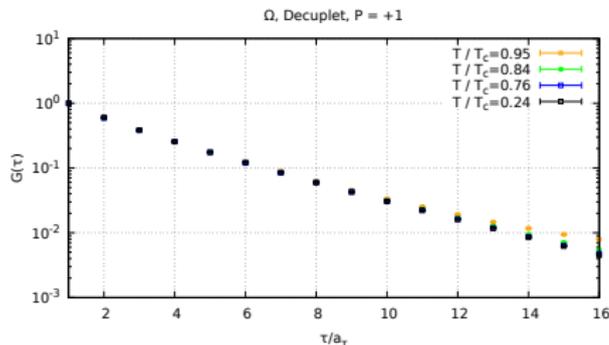
Negative parity



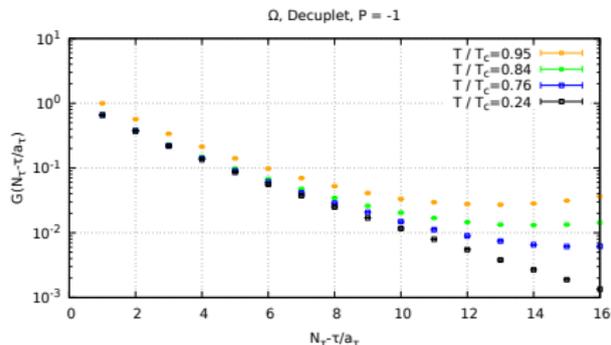
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Correlator of Ω (Decuplet, $S = -3$)

Positive parity



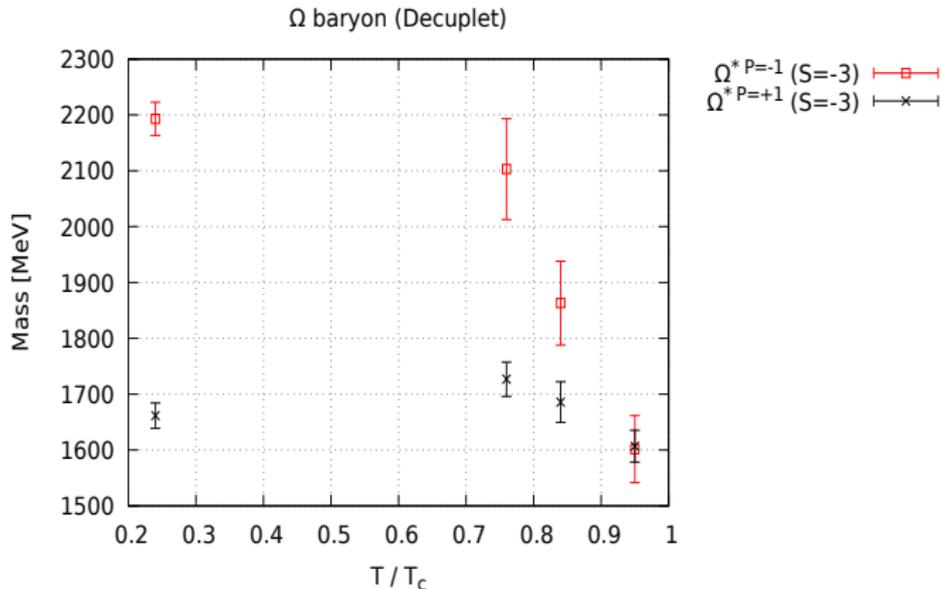
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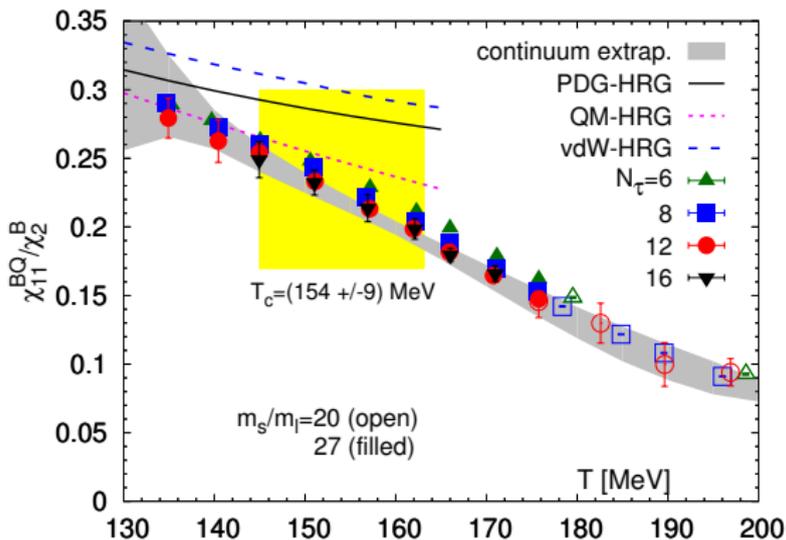
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Baryonic fluctuations

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What about mesons?

$$\Lambda_A: \quad \pi^\alpha (P = -1) \rightarrow f_0 (P = +1),$$
$$\rho_\mu^\alpha (P = -1) \rightarrow (a_1)_\mu^\alpha (P = +1)$$

