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

Davide De Boni

with G. Aarts, C. Allton, S. Hands, B. Jäger, J.-I. Skullerud

Granada, 20 June 2017

Swansea University
Prifysgol Abertawe

Contents

For N, Δ and Ω baryons: JHEP06(2017)034, 1703.09246

Swansea University
Prifysgol Abertawe

Motivation

$m_q = 0 \Rightarrow$ **chiral symmetry** $\mathrm{SU}(N_f)_{\mathrm{V}} \times \mathrm{SU}(N_f)_{\mathrm{A}}$ of QCD action

$$\Lambda_{\mathrm{A}} : \quad \psi' = \mathrm{e}^{\mathrm{i}\theta^i \gamma_5 T_i}\, \psi\,, \qquad \bar{\psi}' = \bar{\psi}\, \mathrm{e}^{\mathrm{i}\theta^i \gamma_5 T_i}$$

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

Swansea University
Prifysgol Abertawe

Motivation

$m_q = 0 \Rightarrow$ **chiral symmetry** $\mathrm{SU}(N_f)_\mathrm{V} \times \mathrm{SU}(N_f)_\mathrm{A}$ of QCD action

$$\Lambda_\mathrm{A}: \quad \psi' = \mathrm{e}^{\mathrm{i}\theta^i \gamma_5 T_i}\, \psi\,, \qquad \bar{\psi}' = \bar{\psi}\, \mathrm{e}^{\mathrm{i}\theta^i \gamma_5 T_i}$$

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

Positive and negative parity baryonic correlators (zero momentum)

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

Swansea University
Prifysgol Abertawe

Motivation

$m_q = 0 \Rightarrow$ **chiral symmetry** $\mathrm{SU}(N_f)_\mathrm{V} \times \mathrm{SU}(N_f)_\mathrm{A}$ of QCD action

$$\Lambda_\mathrm{A}: \quad \psi' = \mathrm{e}^{\mathrm{i}\theta^i \gamma_5 T_i}\,\psi\,, \qquad \bar{\psi}' = \bar{\psi}\,\mathrm{e}^{\mathrm{i}\theta^i \gamma_5 T_i}$$

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

Positive and negative parity baryonic correlators (zero momentum)

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

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

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

Swansea University
Prifysgol Abertawe

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

Swansea University
Prifysgol Abertawe

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

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

$$\mathrm{SU}(N_f)_\mathrm{V} \times \mathrm{SU}(N_f)_\mathrm{A} \to \mathrm{SU}(N_f)_\mathrm{V}$$

Swansea University
Prifysgol Abertawe

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

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

$$\mathrm{SU}(N_f)_{\mathrm{V}} \times \mathrm{SU}(N_f)_{\mathrm{A}} \rightarrow \mathrm{SU}(N_f)_{\mathrm{V}}$$

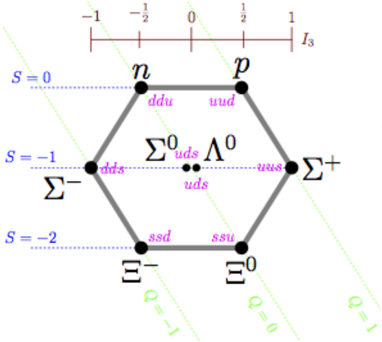
What happens at high temperature?

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

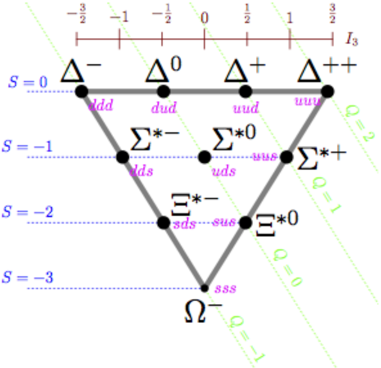
Swansea University
Prifysgol Abertawe

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

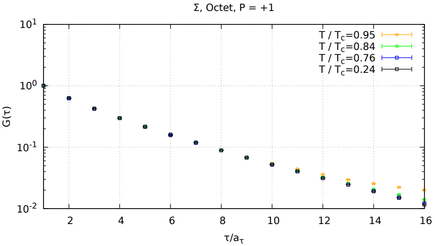
FASTSUM ensembles and tuning by HadSpec collaboration

- $N_f = 2 + 1$ non-perturbatively improved Wilson fermions
- Anistropic 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 $\sim (3\,\mathrm{fm})^3$, $N_s = 24$
- 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

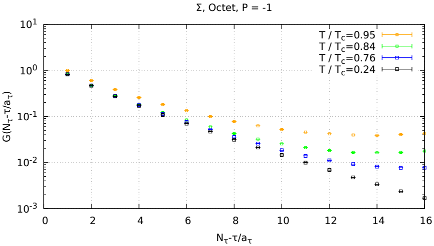
Swansea University
Prifysgol Abertawe

Correlator of Σ (Octet, $S = -1$)

Positive parity



Negative parity

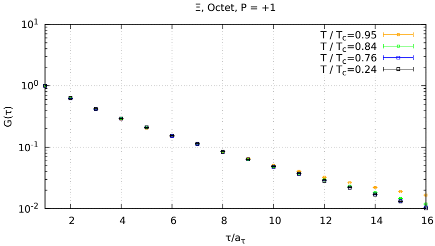


- Posite-parity ground state largely independent of temperature
- Negative-parity partner much more sensitive to temperature
- Slope of the curves gives the groundstate masses $m_{\pm}$

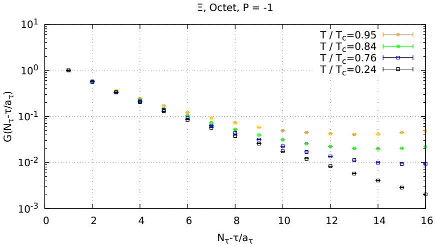
Swansea University
Prifysgol Abertawe

Correlator of Ξ (Octet, $S = -2$)

Positive parity



Negative parity



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

Swansea University
Prifysgol Abertawe

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

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 $m_- \gg m_+ \Rightarrow R(\tau) = 1$, $0 \le \tau < 1/(2T)$
- Parity doubling $\Rightarrow R(\tau) = 0$
- Note that $R(1/T - \tau) = -R(\tau)$ and $R(1/(2T)) = 0$

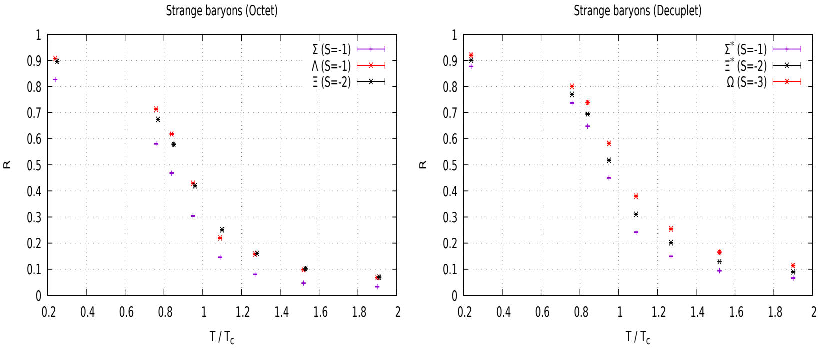
We consider the weighted average

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

[1502.03603]

Technical note: Smearing essential to have a clear ground state

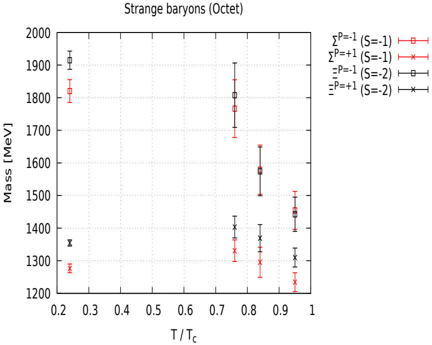
R factor and parity doubling

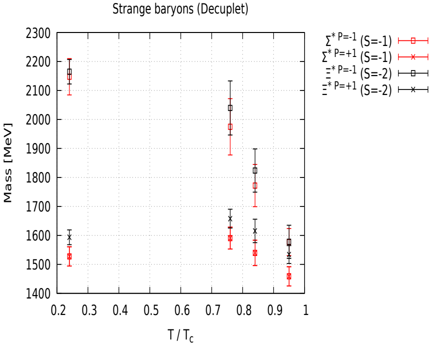


Strong signal of chiral symmetry restoration around T_c

T-dependence of negative-parity masses

$$m_+(T) = \text{constant} \qquad m_-(T) \to m_+ \text{ as } T \to T_c$$





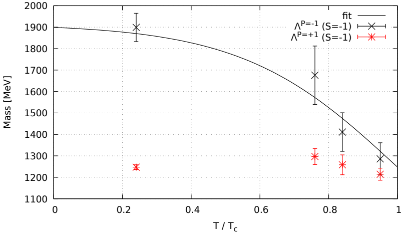
For the Ω particle look at 1703.09246

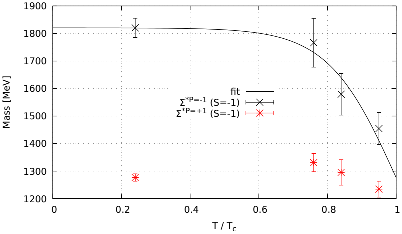
Swansea University
Prifysgol Abertawe

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

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

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





$\gamma \sim 0.25 - 0.35$ for hyperons

Swansea University
Prifysgol Abertawe

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

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
- 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

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
- 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

Swansea University
Prifysgol Abertawe

Application: Hadron Resonance Gas (HRG)

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

Application: Hadron Resonance Gas (HRG)

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

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

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

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

Swansea University
Prifysgol Abertawe

Fluctuations of conserved charges

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

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

Fluctuations in conserved charges (B,Q,S)

- are measured in experiments
- help towards understanding the phase transition from HRG to QGP
- are expected to be larger at higher temperatures

Fluctuations of conserved charges

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

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

Fluctuations in conserved charges (B,Q,S)

- are measured in experiments
- help towards understanding the phase transition from HRG to QGP
- are expected to be larger at higher temperatures

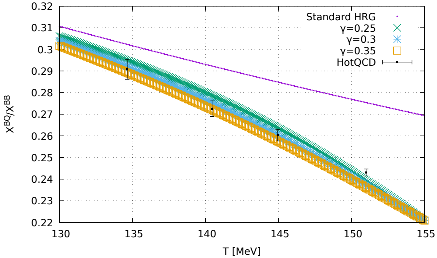
Here we focus only on baryonic fluctuations, in particular on the ratios $\frac{\chi^{\mathrm{BQ}}}{\chi^{BB}}$ and $\frac{\chi^{\mathrm{BS}}}{\chi^{BB}}$

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

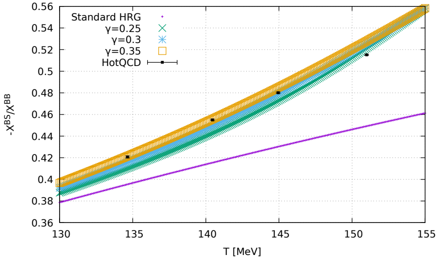
Swansea University
Prifysgol Abertawe

Baryonic fluctuations

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



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



- 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
- Phenomenological implications for fluctuations of conserved charges and HRG

Swansea University
Prifysgol Abertawe

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
- Phenomenological implications for fluctuations of conserved charges and HRG

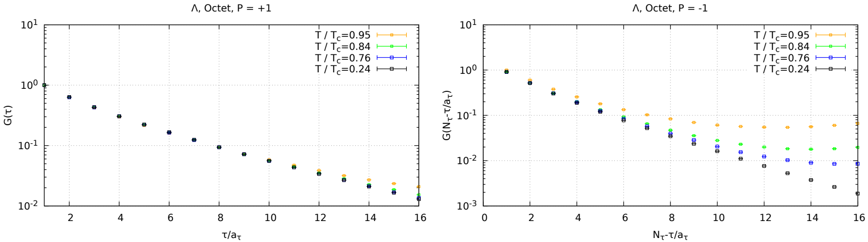
Outlook

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

Backup Slides

Correlator of Λ (Octet, $S = -1$)

Positive parity | Negative parity

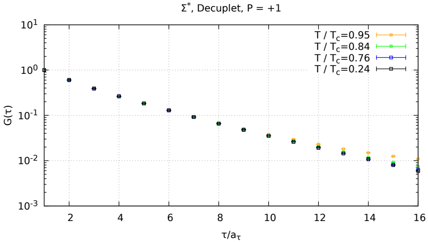


- Posite-parity ground state largely independent of temperature
- Negative-parity partner much more sensitive to temperature
- Slope (mass) of negative-parity curve decreases when T increases

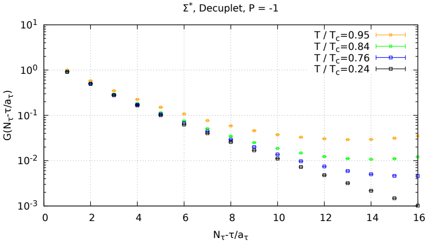
Swansea University
Prifysgol Abertawe

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

Positive parity



Negative parity

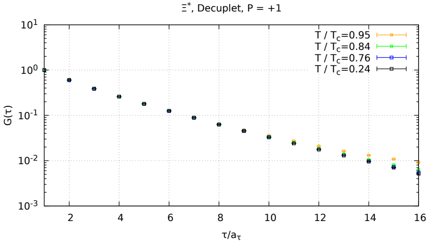


- Posite-parity ground state largely independent of temperature
- Negative-parity partner much more sensitive to temperature
- Slope (mass) of negative-parity curve decreases when T increases

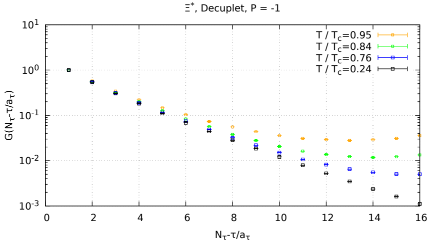
Swansea University
Prifysgol Abertawe

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

Positive parity



Negative parity

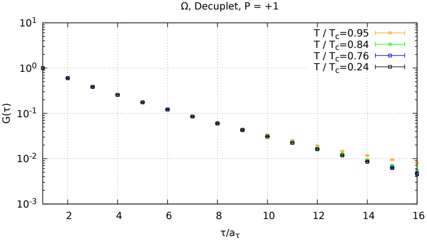


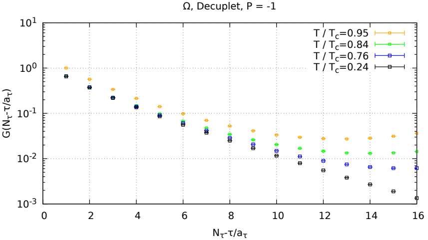
- Posite-parity ground state largely independent of temperature
- Negative-parity partner much more sensitive to temperature
- Slope (mass) of negative-parity curve decreases when T increases

Correlator of Ω (Decuplet, $S = -3$)

Positive parity

Negative parity

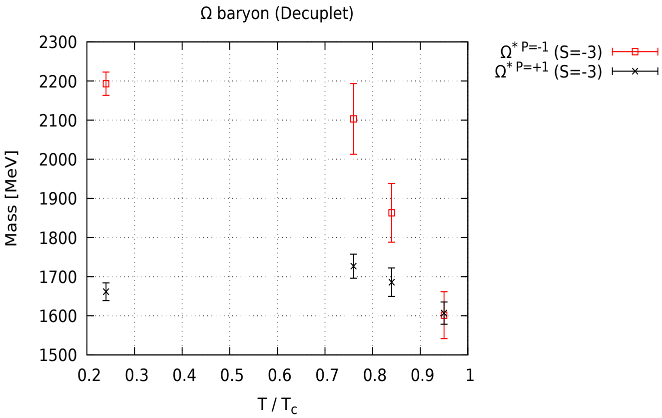




- Posite-parity ground state largely independent of temperature
- Negative-parity partner much more sensitive to temperature
- Slope (mass) of negative-parity curve decreases when T increases

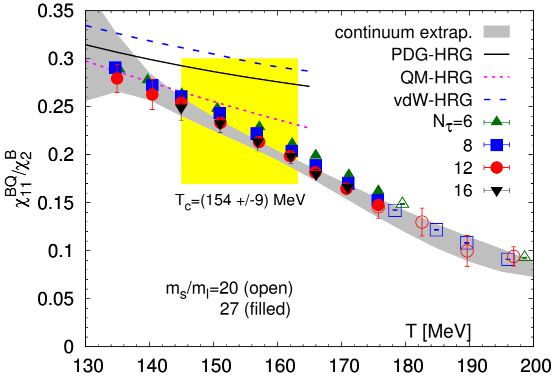
T-dependence of negative-parity masses

$m_+(T) = \text{constant} \qquad m_-(T) \to m_+ \text{ as } T \to T_c$



Baryonic fluctuations

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



HotQCD results from 1701.04325, 1706.01620

Swansea University
Prifysgol Abertawe

What about mesons?

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