

Baryons, chiral symmetry and in-medium effects: Results from lattice QCD

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FASTSUM Collaboration

Quark Matter 2018, Venezia

Mesons in a medium

Mesons in a medium very well studied

- ▶ hadronic phase: thermal broadening, mass shift
- ▶ QGP: deconfinement/dissolution/melting
- ▶ quarkonia survival as thermometer
- ▶ transport: conductivity/dileptons from vector current
- ▶ chiral symmetry restoration

Relatively easy on the lattice

- ▶ high-precision correlators

What about baryons?

Baryons in a medium

Lattice studies of baryons at finite temperature very limited

- ▶ screening masses De Tar and Kogut 1987
- ▶ ... with a small chemical potential QCD-TARO: Pushkina, de Forcrand, Kim, Nakamura, Stamatescu et al 2005
- ▶ temporal correlators Datta, Gupta, Mathur et al 2013

Not much more ...

- ▶ effective models, mostly at $T \sim 0$ and nuclear density
⇒ parity doubling models De Tar & Kunihiro 89
Mukherjee, Schramm, Steinheimer & Dexheimer,
Sasaki 17

Baryons in a medium

But understanding of in-medium effects highly relevant for

- ▶ hadron resonance gas descriptions in confined phase
- ▶ benchmarking models for dense QCD
- ▶ extensions into QCD phase diagram
- ▶ ...

Outline

Baryons across the deconfinement transition:

- ▶ baryon correlators
- ▶ FASTSUM collaboration
- ▶ in-medium effects below T_c
- ▶ parity doubling above T_c
- ▶ spectral functions

FASTSUM: PRD 92 (2015) 014503 [arXiv:1502.03603]

+ JHEP 06 (2017) 034 [arXiv:1703.09246]

+ EPJ WoC 171 (2018) 14005 [arXiv:1710.00566]

+ in preparation

Baryons

- ▶ correlators $G^{\alpha\alpha'}(x) = \langle O^\alpha(x) \bar{O}^{\alpha'}(0) \rangle$
- ▶ examples: N, Δ, Ω baryons

$$O_N^\alpha(x) = \epsilon_{abc} u_a^\alpha(x) \left(d_b^T(x) C \gamma_5 u_c(x) \right)$$

$$O_{\Delta,i}^\alpha(x) = \epsilon_{abc} \left[2u_a^\alpha(x) \left(d_b^T(x) C \gamma_i u_c(x) \right) + d_a^\alpha(x) \left(u_b^T(x) C \gamma_i u_c(x) \right) \right]$$

$$O_{\Omega,i}^\alpha(x) = \epsilon_{abc} s_a^\alpha(x) \left(s_b^T(x) C \gamma_i s_c(x) \right)$$

- ▶ essential difference with mesons: role of parity

$$\mathcal{P} O(\tau, \mathbf{x}) \mathcal{P}^{-1} = \gamma_4 O(\tau, -\mathbf{x})$$

- ▶ positive/negative parity operators

$$O_\pm(x) = P_\pm O(x) \quad P_\pm = \frac{1}{2}(1 \pm \gamma_4)$$

Baryons

- ▶ positive/negative parity operators

$$O_{\pm}(x) = P_{\pm} O(x) \quad P_{\pm} = \frac{1}{2}(1 \pm \gamma_4)$$

- ▶ no parity doubling in Nature: nucleon ground state

positive parity: $m_+ = m_N = 0.939 \text{ GeV}$

negative parity: $m_- = m_{N^*} = 1.535 \text{ GeV}$

- ▶ thread: what happens as temperature increases?

How are \pm parity states encoded in correlators?

$$G_{\pm}(x-x') = \langle \text{tr} P_{\pm} O(x) \overline{O}(x') \rangle \quad \rho_{\pm}(x-x') = \langle \text{tr} P_{\pm} \{ O(x), \overline{O}(x') \} \rangle$$

Charge conjugation

Charge conjugation symmetry (at vanishing density):

$$G_{\pm}(\tau, \mathbf{p}) = -G_{\mp}(1/T - \tau, \mathbf{p}) \quad \rho_{\pm}(-\omega, \mathbf{p}) = -\rho_{\mp}(\omega, \mathbf{p})$$

- ▶ relates \pm parity channels

Using $G_+(\tau, \mathbf{p})$ and $\rho_+(\omega, \mathbf{p})$

- ▶ positive- (negative-) parity states propagate forward (backward) in euclidean time
- ▶ negative part of spectrum of ρ_+ \leftrightarrow positive part of ρ_-

example: single state

$$G_+(\tau) = A_+ e^{-m_+ \tau} + A_- e^{-m_- (1/T - \tau)}$$

$$\rho_+(\omega)/(2\pi) = A_+ \delta(\omega - m_+) + A_- \delta(\omega + m_-)$$

Chiral symmetry

- ▶ propagator

$$G(x) = \sum_{\mu} \gamma_{\mu} G_{\mu}(x) + \mathbb{1} G_m(x)$$

- ▶ chiral symmetry $\{\gamma_5, G\} = 0 \Rightarrow G_m = 0$
- ▶ hence

$$G_+(\tau, \mathbf{p}) = -G_-(\tau, \mathbf{p}) = G_+(1/T - \tau, \mathbf{p}) = 2G_4(\tau, \mathbf{p})$$

Degeneracy of \pm parity channels

$$\rho_+(p) = -\rho_-(p) = \rho_+(-p) = 2\rho_4(p)$$

- ▶ parity doubling
- ▶ in Nature at $T = 0$: no chiral symmetry/parity doubling

Parity and chiral symmetry

However, if chiral symmetry is unbroken ($m_q = 0$ and no SSB)

- ▶ degeneracy between \pm parity channels already at the level of the correlators

What happens at the confinement/deconfinement transition?

- ▶ $SU(2)_A$ chiral symmetry restored
- ▶ expect degeneracies to emerge
- ▶ how does this affect mass spectrum?
- ▶ role of $m_s > m_{u,d}$?

FASTSUM

- ▶ Anisotropic $N_f = 2 + 1$ Wilson-clover ensembles

FASTSUM collaboration

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This work

Gert Aarts, CA, Simon Hands, Kristi Praki, Jonivar Skullerud

Davide de Boni, Benjamin Jäger

PRD 92 (2015) 014503, [arXiv:1502.03603]

JHEP 06 (2017) 034, [arXiv:1703.09246]

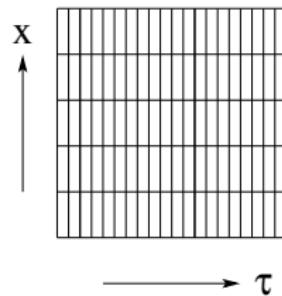
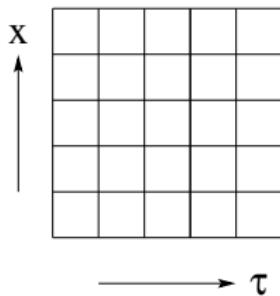
EPJ WoC 171 (2018) 14005 [arXiv:1710.00566]

in preparation

FASTSUM set up

- ▶ $N_f = 2 + 1$ dynamical quark flavours
- ▶ $M_\pi = 384(4)$ MeV
- ▶ anisotropic lattices $a_\tau < a_s$
 - ▶ allowing better resolution, particularly at finite temperatures

since
$$T = \frac{1}{L_\tau} = \frac{1}{N_\tau a_\tau}$$



- ▶ moving towards continuum, infinite volume, realistic light quark masses

Physics/lattice parameters

2nd Generation

2+1 flavours

larger volume: $(3\text{fm})^3 - (4\text{fm})^3$

finer lattices: $a_s = 0.123 \text{ fm}$

quark mass: $M_\pi = 384(4) \text{ MeV}$

temporal cut-off: $a_s \sim 3.5 a_\tau \text{ GeV}$

Gauge Action:

Symanzik-improved, tree-level tadpole

Fermion Action:

clover, stout-links, tree-level tadpole

N_s	N_τ	$T(\text{MeV})$	T/T_c
24, 32	16	352	1.90
24	20	281	1.52
24, 32	24	235	1.27
24, 32	28	201	1.09
24, 32	32	176	0.95
24	36	156	0.84
24	40	141	0.76
32	48	117	0.63
16	128	44	0.24

(Hadron Spectrum Collaboration)

Baryon correlators

	$S = 0:$	N	Δ
computed all octet and decuplet baryon correlators	$S = -1:$	Λ	Σ
	$S = -2:$	Ξ	Ξ^*
	$S = -3:$		Ω

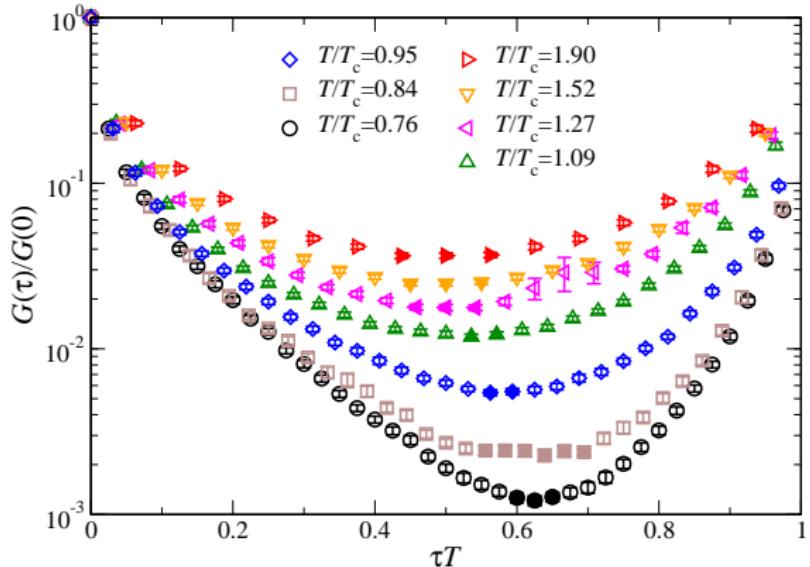
For each baryon: positive and negative parity channels

Technical remarks

- ▶ studied various interpolation operators
- ▶ Gaussian smearing for multiple sources and sinks
- ▶ same smearing parameters at all temperatures

Lattice correlators: Nucleon

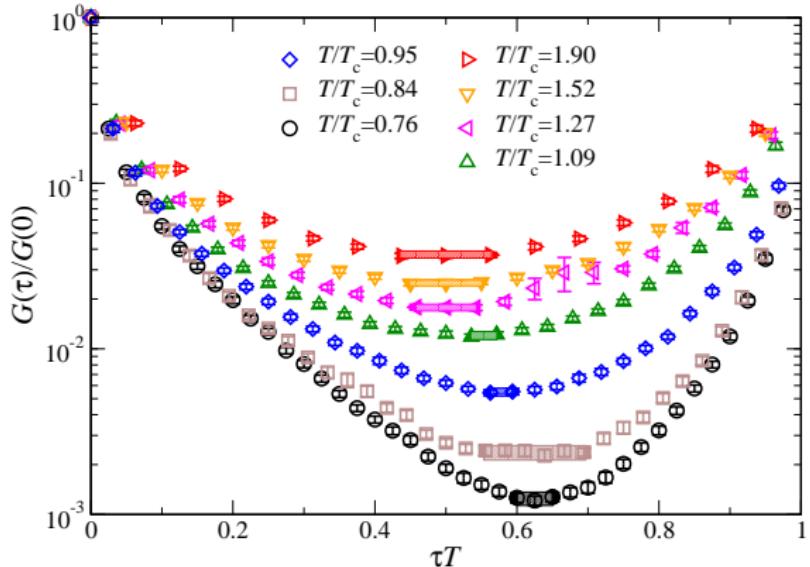
- ▶ euclidean correlator $G_+(\tau)$



- ▶ not symmetric around $\tau = 1/2T$ below T_c
- ▶ more symmetric as temperature increases

Lattice correlators: Nucleon

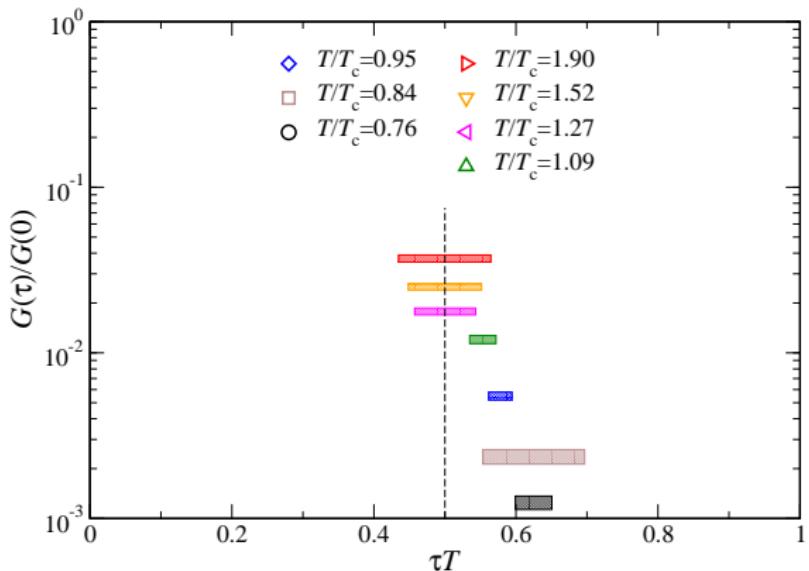
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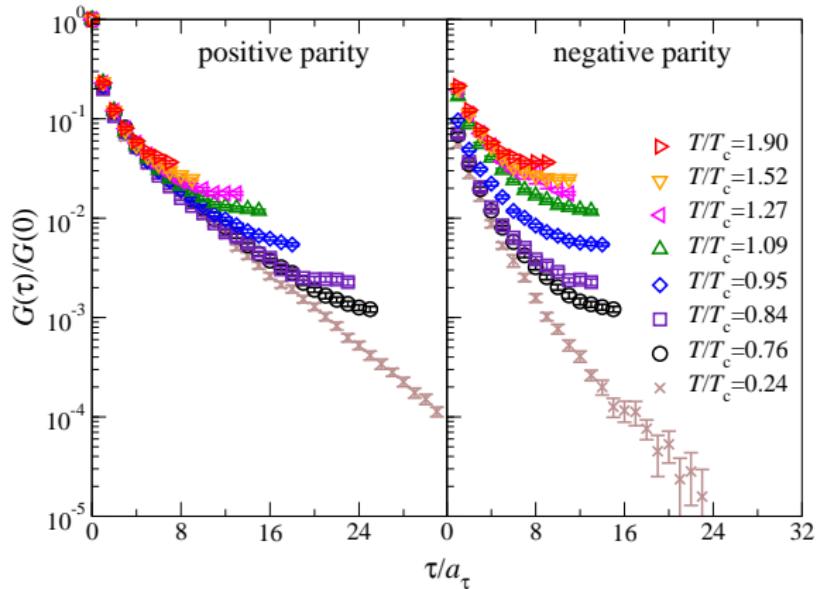
Lattice correlators: Nucleon

- ▶ euclidean correlator $G_+(\tau)$



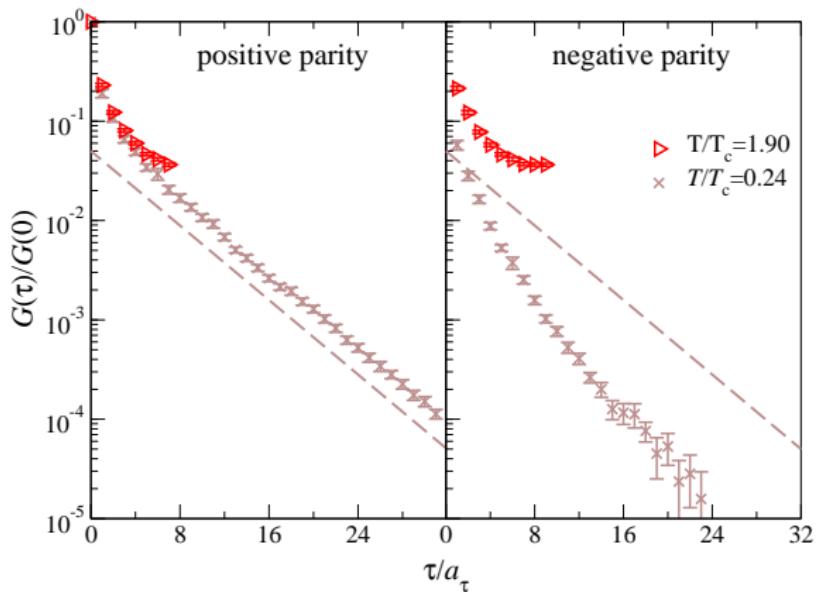
- ▶ not symmetric around $\tau = 1/2T$ below T_c
- ▶ more symmetric as temperature increases

Lattice correlators: Nucleon



- \pm parity channels nondegenerate
- more T dependence in negative-parity channel

Lattice correlators: Nucleon

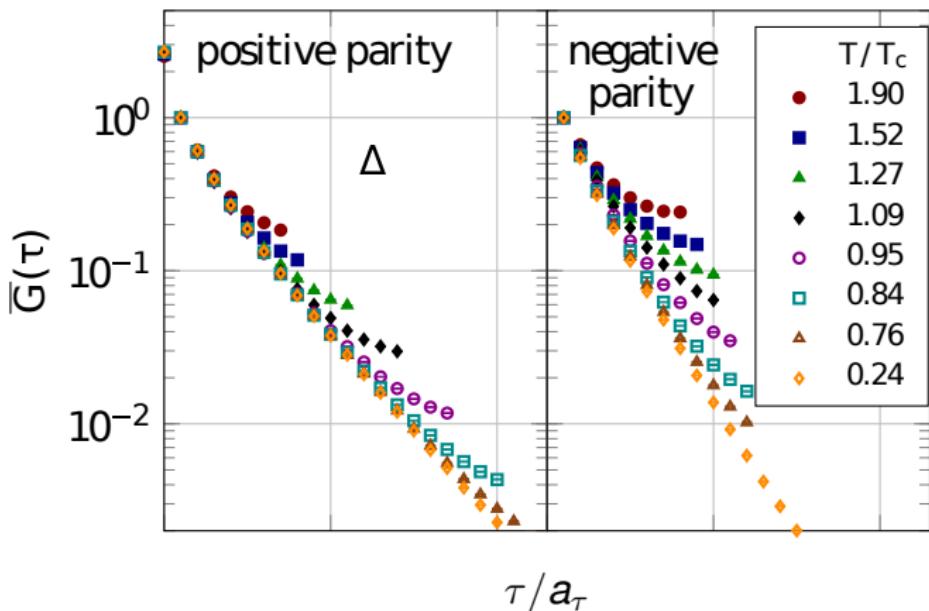


Experiment:

+ve parity: $M_N = 939 \text{ MeV}$

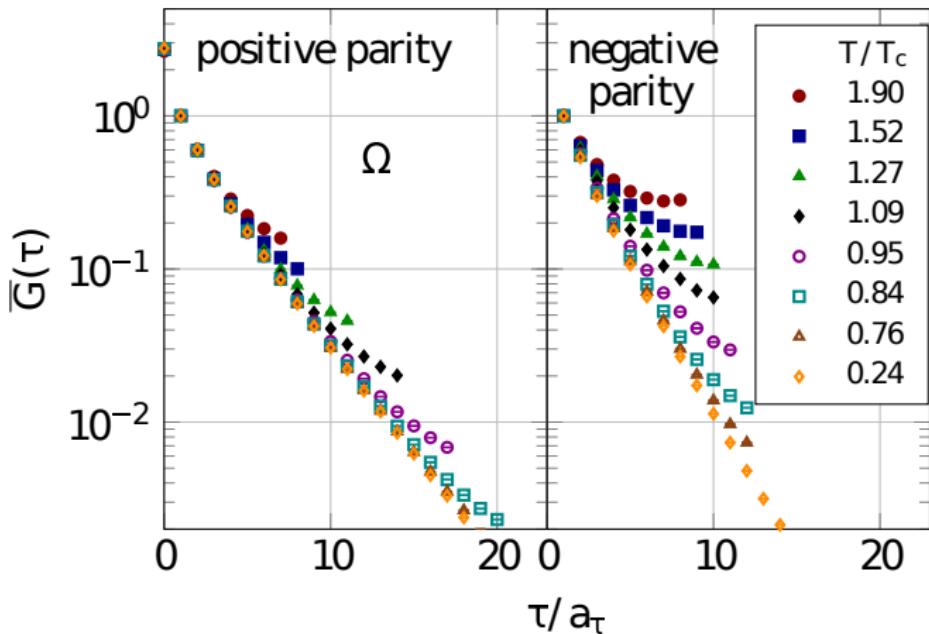
-ve parity: $M_{N*} = 1535 \text{ MeV}$

Lattice correlators: Δ



- ▶ at low $T \pm$ parity channels nondegenerate
- ▶ more T dependence in negative-parity channel

Lattice correlators: Ω



- ▶ at low $T \pm$ parity channels nondegenerate
- ▶ more T dependence in negative-parity channel

Baryons in the hadronic phase

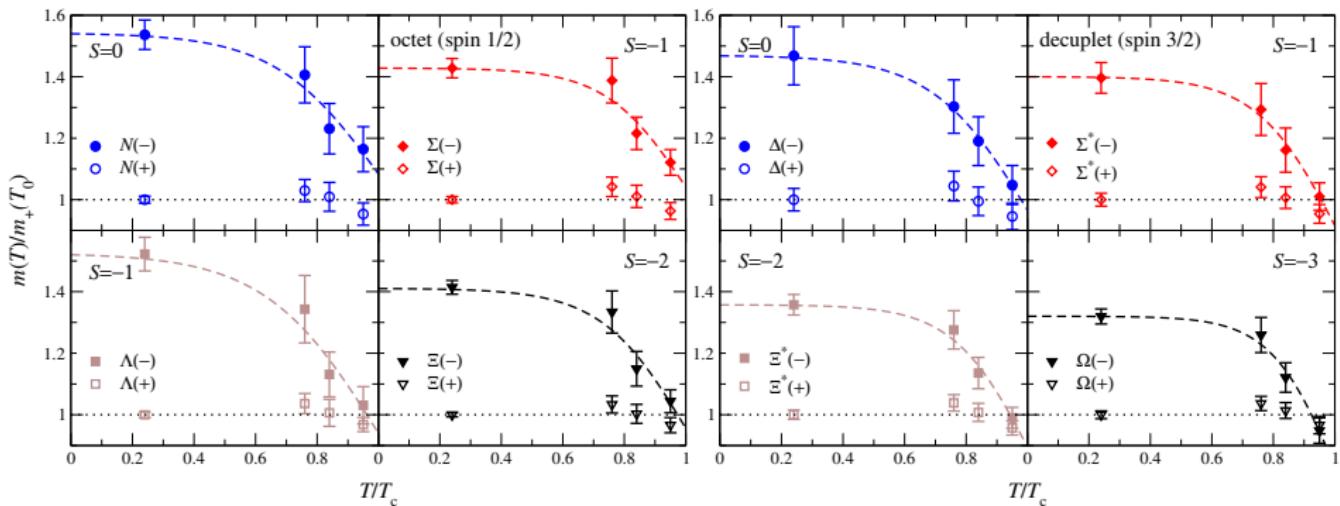
- ▶ determine masses of \pm parity groundstates
- ▶ in-medium effects

Masses of \pm parity groundstates (in MeV)

S	T/T_c	0.24	0.76	0.84	0.95	PDG ($T = 0$)
0	m_+^N	1158(13)	1192(39)	1169(53)	1104(40)	939
	m_-^N	1779(52)	1628(104)	1425(94)	1348(83)	1535
	m_+^Δ	1456(53)	1521(43)	1449(42)	1377(37)	1232
	m_-^Δ	2138(114)	1898(106)	1734(97)	1526(74)	1700
-1	m_+^Σ	1277(13)	1330(38)	1290(44)	1230(33)	1193
	m_-^Σ	1823(35)	1772(91)	1552(65)	1431(51)	1750
	m_+^Λ	1248(12)	1293(39)	1256(54)	1208(26)	1116
	m_-^Λ	1899(66)	1676(136)	1411(90)	1286(75)	1405–1670
	$m_+^{\Sigma^*}$	1526(32)	1588(40)	1536(43)	1455(35)	1385
	$m_-^{\Sigma^*}$	2131(62)	1974(122)	1772(103)	1542(60)	1670–1940
-2	m_+^{Ξ}	1355(9)	1401(36)	1359(41)	1310(32)	1318
	m_-^{Ξ}	1917(27)	1808(92)	1558(76)	1415(50)	1690–1950
	$m_+^{\Xi^*}$	1594(24)	1656(35)	1606(40)	1526(29)	1530
	$m_-^{\Xi^*}$	2164(42)	2034(95)	1810(77)	1578(48)	1820
-3	m_+^Ω	1661(21)	1723(32)	1685(37)	1606(43)	1672
	m_-^Ω	2193(30)	2092(91)	1863(76)	1576(66)	2250

Baryons in the hadronic phase

Masses $m_{\pm}(T)$, normalised with m_+ at lowest temperature



In each channel:

- ▶ emerging degeneracy around T_c
- ▶ negative-parity masses reduced as T increases
- ▶ positive-parity masses nearly T independent

Baryons in the hadronic phase

Findings:

- ▶ positive-parity masses nearly T independent
- ▶ negative-parity masses reduced as T increases
- ▶ characteristic behaviour, *modelled by*:

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

with one-parameter transition function

$$w(T, \gamma) = \tanh[(1 - T/T_c)/\gamma]/\tanh(1/\gamma)$$

- ▶ small (large) $\gamma \Leftrightarrow$ narrow (broad) transition region

Fits in each
channel

- ▶ $0.22 \lesssim \gamma \lesssim 0.35$, mean $\gamma = 0.27(1)$
- ▶ $0.85 \lesssim m_-(T_c)/m_+(0) \lesssim 1.1$

Baryons and parity partners

- ▶ distinct temperature dependence in hadronic phase
- ▶ understand further using
 - ▶ effective parity doublet models?
Mukherjee, Schramm, Steinheimer & Dexheimer, Sasaki [2017]
 - ▶ holography?
- ▶ relevant for heavy-ion phenomenology?

Application to HRG

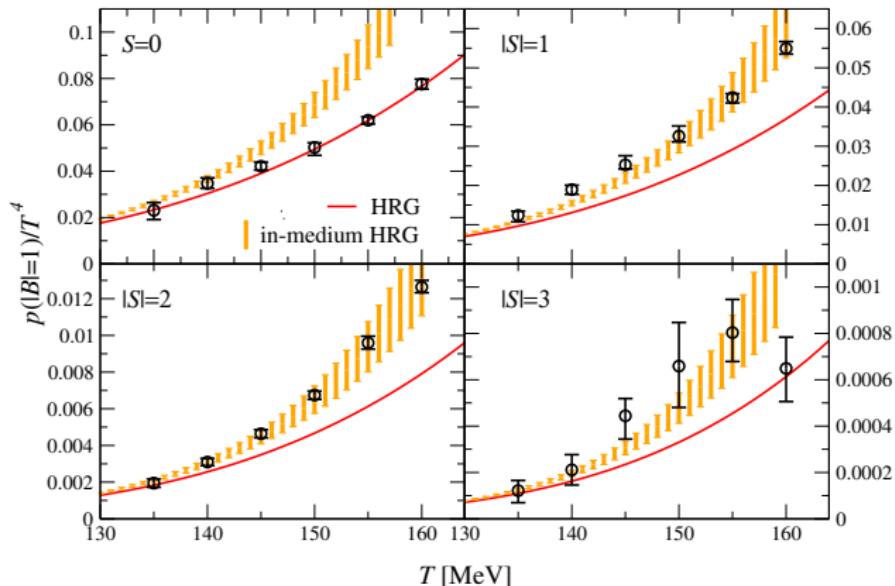
- ▶ use states in PDG (not QM)
- ▶ T -dependent groundstates in neg parity channels

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

with $\gamma = 0.3$ and $1 < m_-(T_c)/m_+(0) < 1.1$

In-medium HRG: Pressure

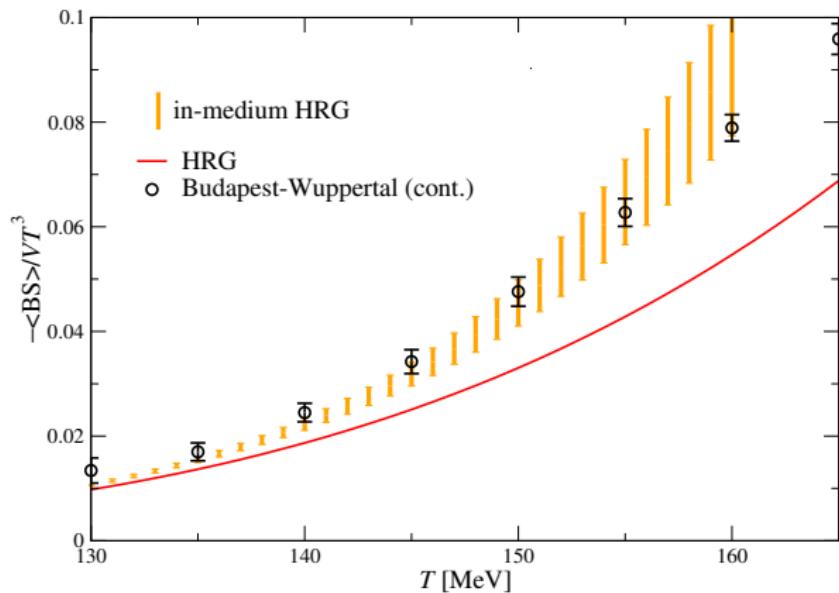
Contributions to pressure from baryons with strangeness



Compare with lattice data from Alba, Ratti et al,
1702.01113

In-medium HRG: Strangeness

Fluctuations of strange baryons $\langle BS \rangle$



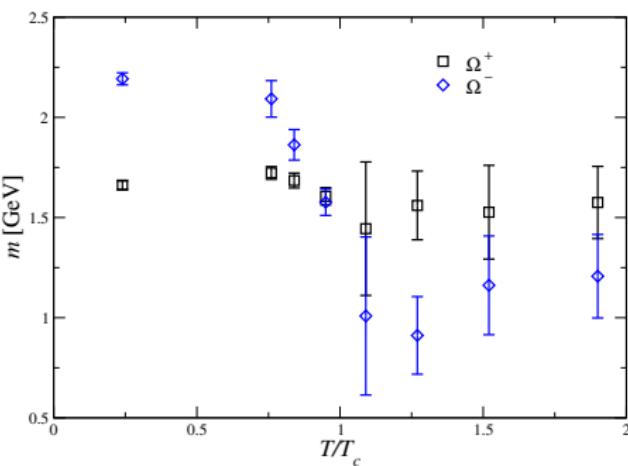
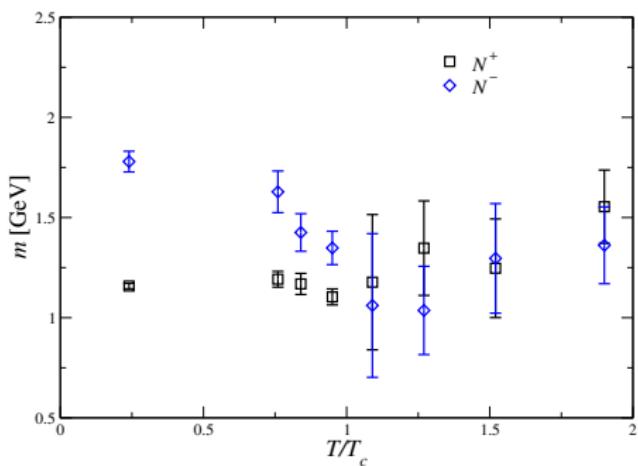
Compare with lattice data from Budapest-Wuppertal

QGP: fate of light baryons

Consider now the quark-gluon plasma

- ▶ no clearly identifiable groundstates: baryons dissolved

Example: use conventional exponential fits



No clearly defined groundstates above T_c

QGP: fate of light baryons

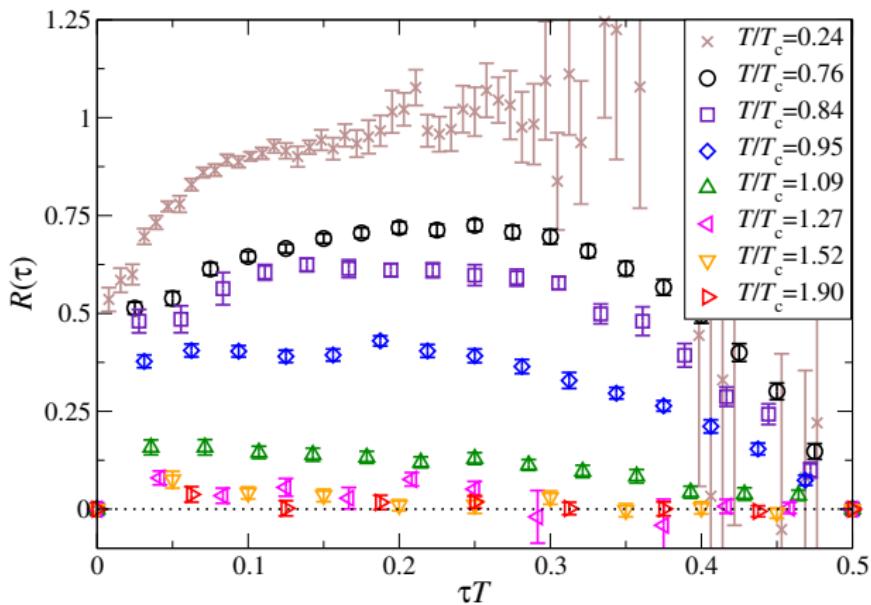
- ▶ no clearly identifiable groundstates: baryons dissolved
- ▶ chiral symmetry restoration \Leftrightarrow parity doubling
- ▶ study correlator ratio [Datta, Gupta, Mathur et al 2013](#)

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

- ▶ no parity doubling and $m_- \gg m_+$: $R(\tau) = 1$
- ▶ parity doubling: $R(\tau) = 0$

by construction: $R(1/T - \tau) = -R(\tau)$ and $R(1/2T) = 0$

Nucleon channel



- ▶ ratio close to 1 below T_c , decreasing uniformly
- ▶ ratio close to 0 above T_c , parity doubling

Quasi-order parameter

Integrate the $R(\tau)$ ratio

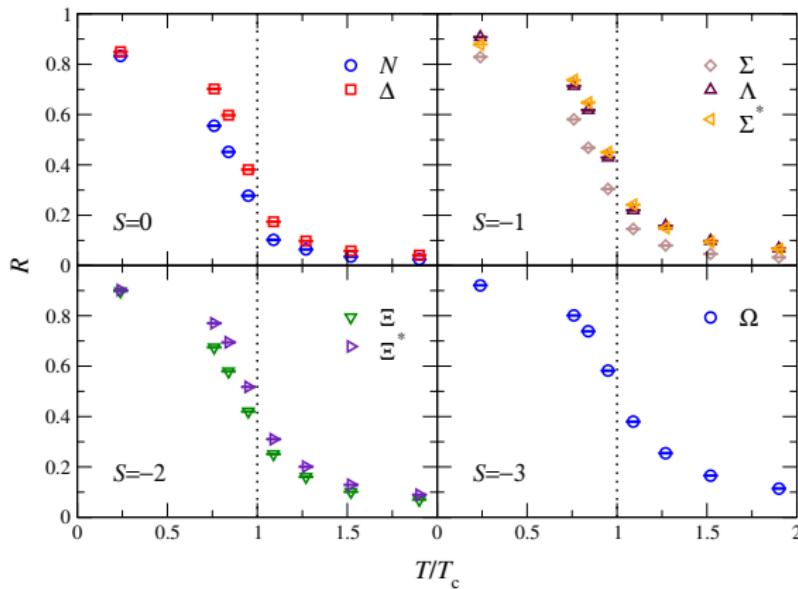
$$R(\tau) = \frac{G_+(\tau) - G_-(\tau)}{G_+(\tau) + G_-(\tau)}$$

⇒ quasi-order parameter

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

Quasi-order parameter

parity doubling in the QGP: $R \sim 1 \rightarrow 0$



- ▶ crossover behaviour, tied with deconfinement transition and hence chiral transition – note: $m_q \neq 0$
- ▶ effect of heavier s quark visible

Parity doubling

- ▶ clear signal for parity doubling even with finite quark masses
- ▶ crossover behaviour, coinciding with transition to QGP
- ▶ visible effect of heavier s quark

Spectral properties: fermions

$$G^{\alpha\alpha'}(\tau, \mathbf{p}) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} K(\tau, \omega) \rho^{\alpha\alpha'}(\omega, \mathbf{p})$$

- ▶ fermionic Matsubara frequencies

$$K(\tau, \omega) = T \sum_n \frac{e^{-i\omega_n \tau}}{\omega - i\omega_n} = \frac{e^{-\omega \tau}}{1 + e^{-\omega/T}} = e^{-\omega \tau} [1 - n_F(\omega)]$$

- ▶ kernel not symmetric, instead

$$K(1/T - \tau, \omega) = K(\tau, -\omega)$$

- ▶ positivity: $\rho_4(p), \pm\rho_{\pm}(p) \geq 0$ for all ω
- ▶ $\rho_m(p) = [\rho_+(p) + \rho_-(p)]/4$ not sign definite

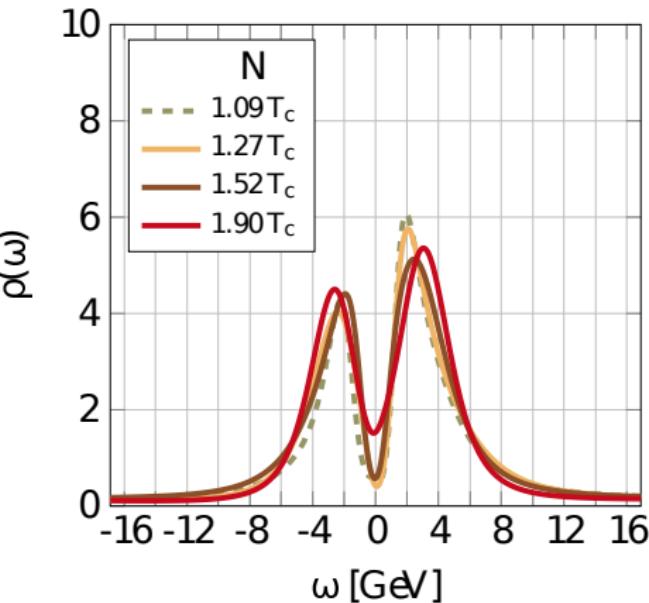
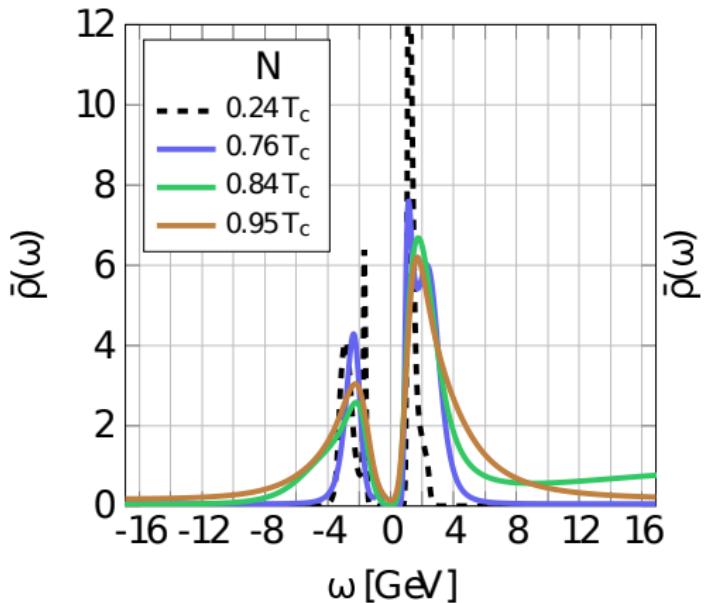
Spectral functions

Extract same information from spectral functions

$$G_{\pm}(\tau) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} K(\tau, \omega) \rho_{\pm}(\omega) \quad K(\tau, \omega) = \frac{e^{-\omega\tau}}{1 + e^{-\omega/T}}$$

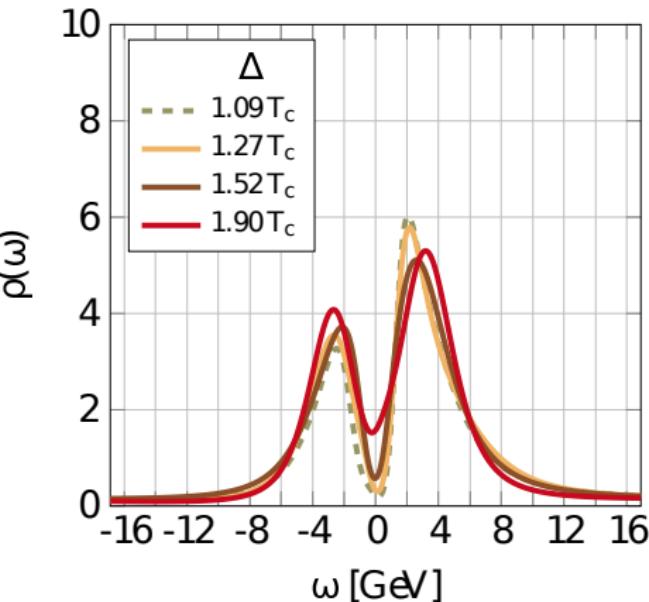
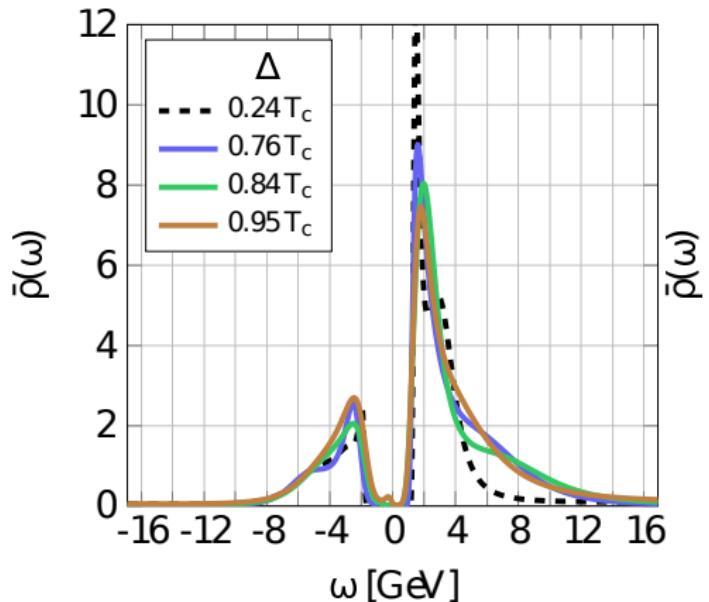
- ▶ *ill-posed* inversion problem
- ▶ use Maximum Entropy Method (MEM)
- ▶ featureless default model
- ▶ construct $\rho_+(\omega) \geq 0$ for all ω
- ▶ $\rho_-(\omega) = -\rho_+(-\omega)$

Baryon spectral functions: Nucleon



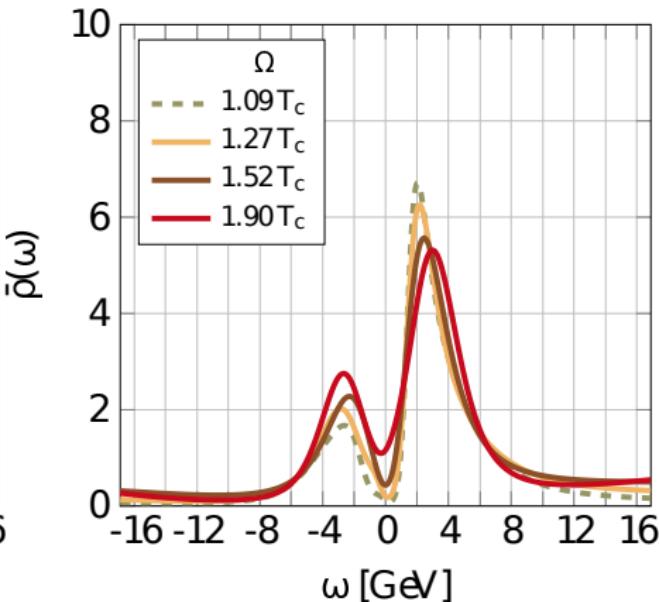
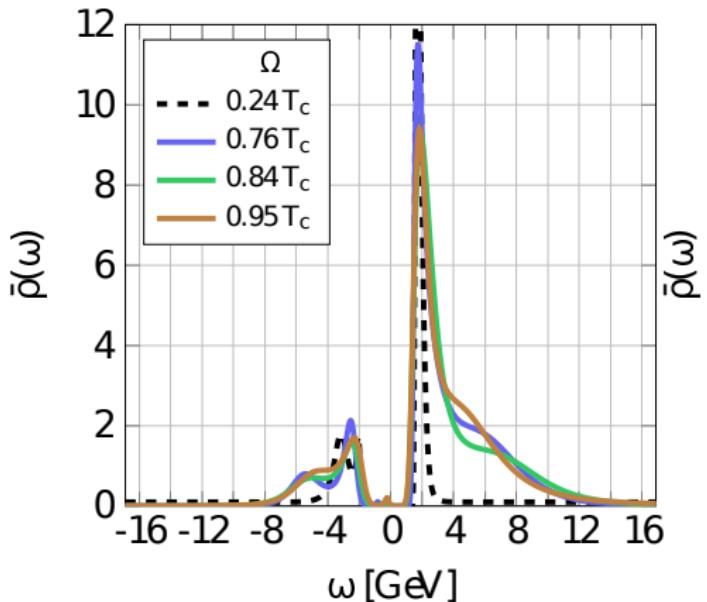
- ▶ groundstates below T_c
- ▶ degeneracy emerging above T_c

Baryon spectral functions: Δ



- ▶ groundstates below T_c
- ▶ degeneracy emerging above T_c

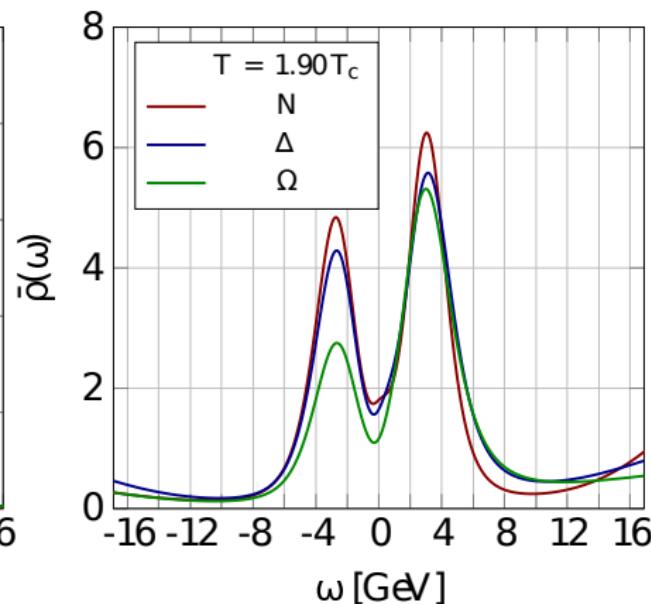
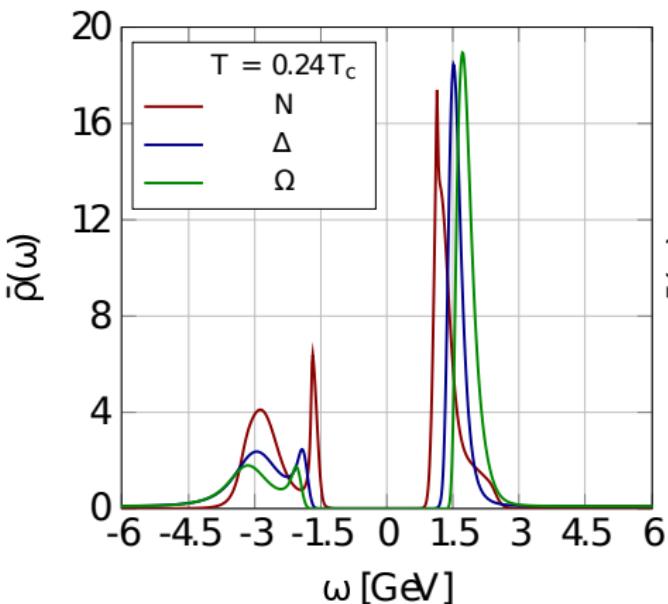
Baryon spectral functions: Ω



- ▶ groundstates below T_c
- ▶ degeneracy emerging above T_c , finite m_s

Baryon spectral functions

- ▶ all channels: low and high temperature



- ▶ groundstates below T_c
- ▶ degeneracy emerging above T_c

Baryon spectral functions

- ▶ results consistent with correlator analysis
- ▶ effect of heavier s quark visible

Summary

In hadronic phase

- ▶ +ve parity groundstates mostly T independent
- ▶ characteristic T dependence in -ve parity groundstates
reduction in mass, near degeneracy close to T_c

Application

- ▶ heavy-ion phenomenology: in-medium HRG

In quark-gluon plasma

- ▶ \pm parity channels degenerate: parity doubling
- ▶ linked to deconfinement transition and chiral symmetry restoration
- ▶ effect of heavier s quark noticeable