Baryons in the plasma: in-medium effects and parity doubling

Gert Aarts

Swansea University
Prifysgol Abertawe

Introduction

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

lattice QCD: relatively easy

- 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

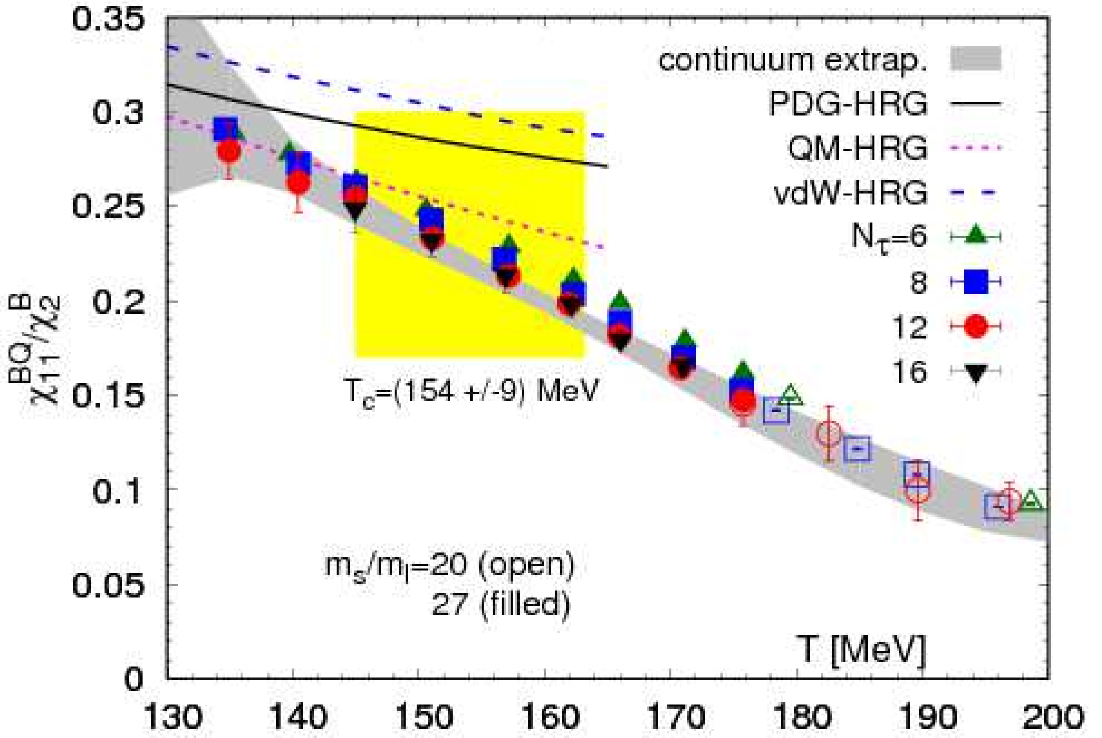
not much more ...

- effective models, mostly at $T \sim 0$ and nuclear density $\Rightarrow$ parity doubling models De Tar and Kunihiro 1989

but understanding highly relevant for e.g. hadron resonance gas (HRG) descriptions in confined phase

Baryons and HRG

ratio of fluctuations: $\langle BQ \rangle / \langle BB \rangle$
fluctuations of charged baryons / fluctuations of all baryons



Karsch (HotQCD)
arXiv:1706.01620

standard HRG is somewhat off

- what is the source of this discrepancy?
- more states? residual interactions? in-medium effects?

Outline

baryons across the deconfinement transition:

- lattice QCD – FASTSUM collaboration
- baryon correlators
- in-medium effects below T_c
- implications for HRG
- parity doubling above T_c

FASTSUM

- anisotropic $N_f = 2 + 1$ Wilson-clover ensembles

FASTSUM collaboration

GA (Swansea)
Chris Allton (Swansea)
Simon Hands (Swansea)
Seyong Kim (Sejong University)
Maria-Paola Lombardo (Frascati)
Sinead Ryan (Trinity College Dublin)
Don Sinclair (Argonne)
Jonivar Skullerud (Maynooth)

Ale Amato (Swansea->Helsinki->)
Davide de Boni (Swansea)
Wynne Evans (Swansea->Bern->)
Pietro Giudice (Swansea->Münster->)
Tim Harris (TCD->Mainz->Milan)
Benjamin Jäger (Swansea->ETH)
Aoife Kelly (Maynooth)
Bugra Oktay (Utah->)
Kristi Praki (Swansea)

This work

GA, Chris Allton, Simon Hands, Kristi Praki, Jonivar Skullerud

Davide de Boni, Benjamin Jäger

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

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

in preparation

FASTSUM ensembles

- $N_f = 2 + 1$ dynamical quark flavours, Wilson-clover
- many temperatures, below and above T_c
- anisotropic lattice, $a_s/a_\tau = 3.5$, many time slices
- strange quark: physical value
- two light flavours: somewhat heavy $m_\pi = 384(4)$ MeV

N_s	24	24	24	24	24	24	24	24
N_τ	128	40	36	32	28	24	20	16
T/T_c	0.24	0.76	0.84	0.95	1.09	1.27	1.52	1.90
$N_{\rm cfg}$	139	501	501	1000	1001	1001	1000	1000
$N_{\rm src}$	16	4	4	2	2	2	2	2

- tuning and $N_\tau = 128$ data from HadSpec collaboration

Baryon correlators

computed all octet and decuplet baryon correlators

$S = 0$:	N	Δ	
$S = -1$:	Λ	Σ	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

Parity and baryons

example: nucleon

- operator $O^\alpha = \epsilon_{abc} u_a^\alpha \left(d_b^T C\gamma_5 u_c \right)$
- role of parity:

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

- pos/neg parity operators:

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

- no parity doubling in Nature: nucleon ground state

positive parity: $m_+ = m_N = 0.939$ GeV

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

Parity and chiral symmetry

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

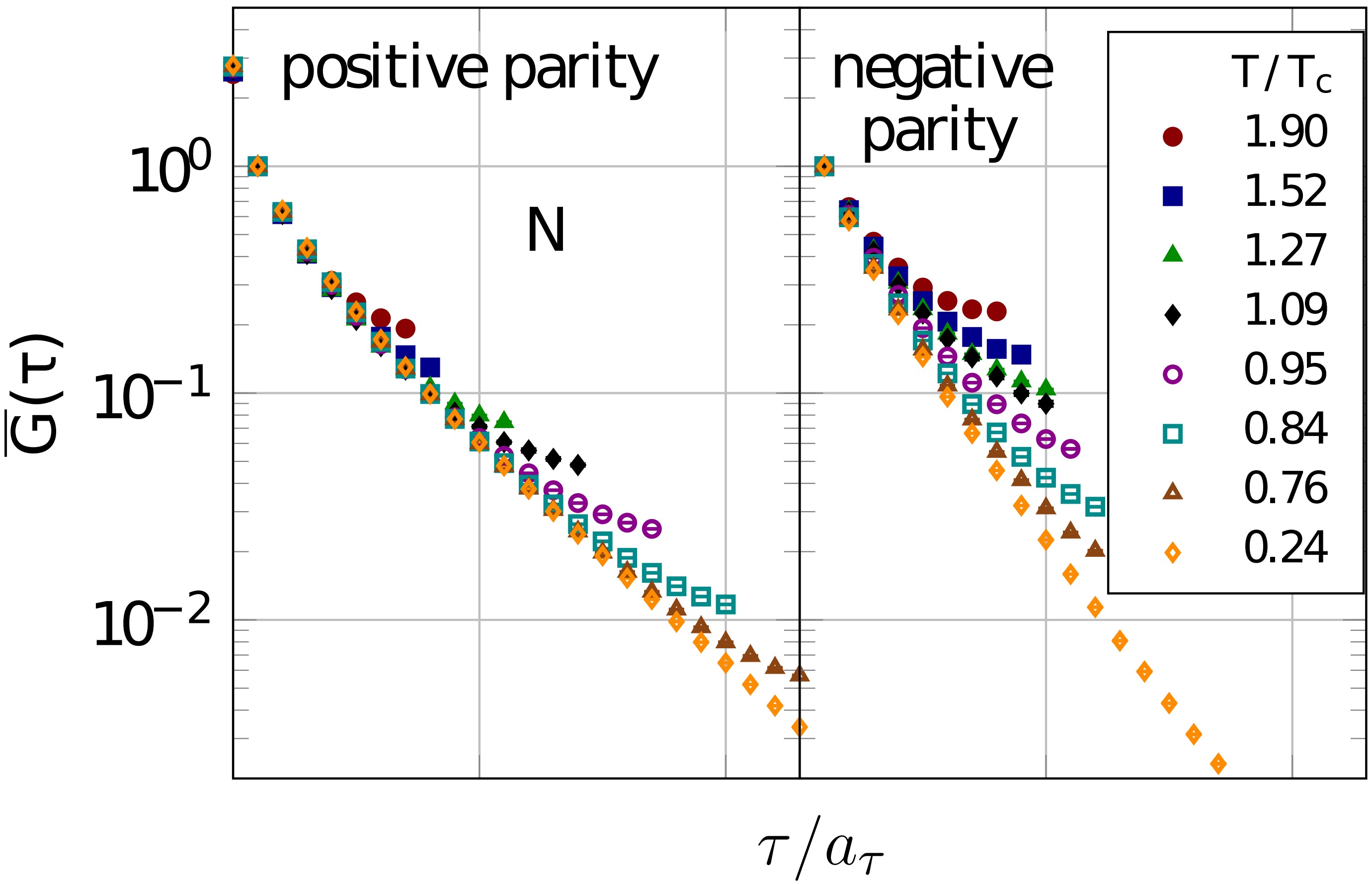
- degeneracy between pos/neg parity channels already at the level of the correlators

what happens at the confinement/deconfinement transition?

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

Lattice correlators

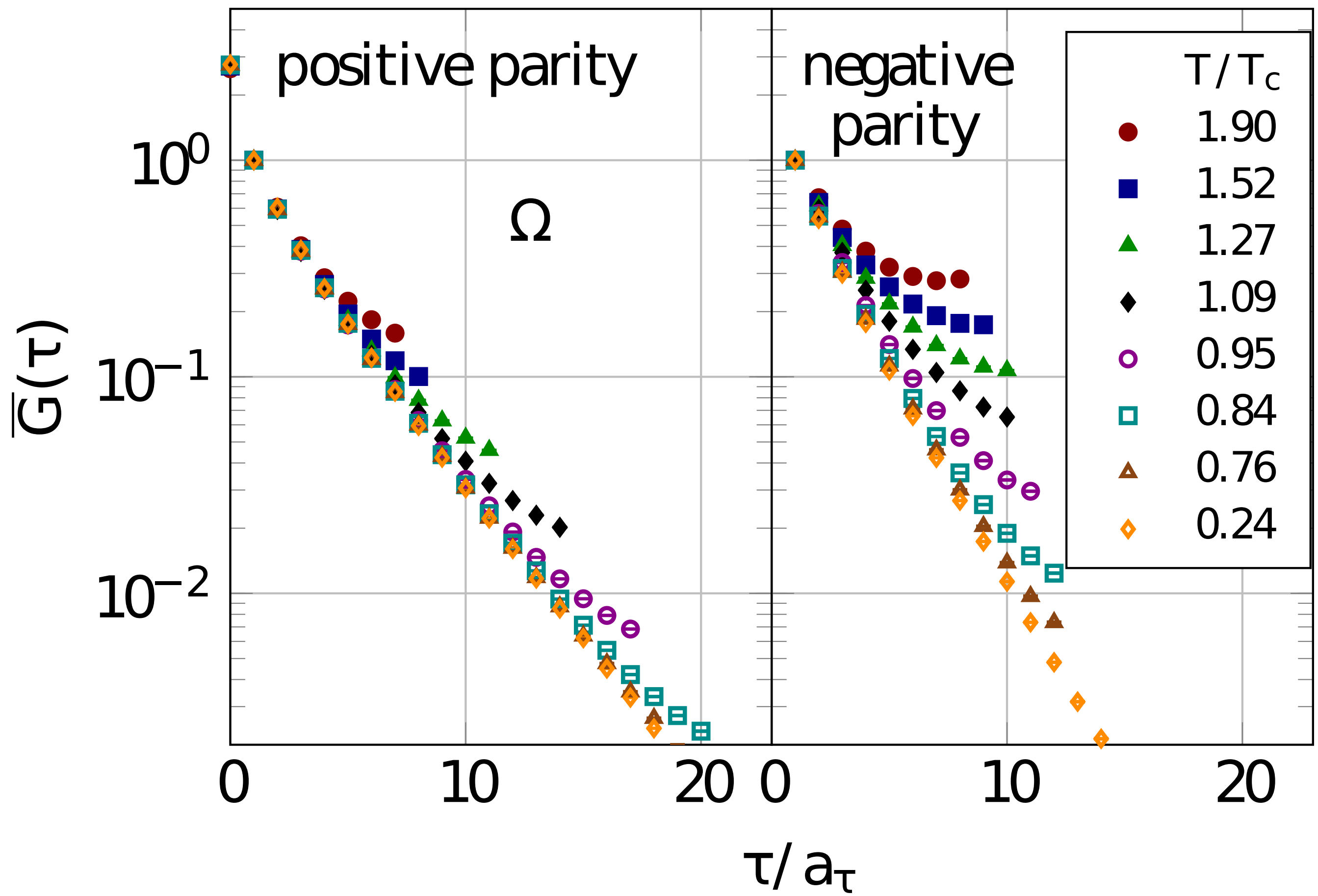
- nucleon



- at low T pos/neg parity channels nondegenerate
- more T dependence in negative-parity channel

Lattice correlators

- Ω



- at low T pos/neg parity channels nondegenerate
- more T dependence in negative-parity channel

Baryons in the hadronic phase

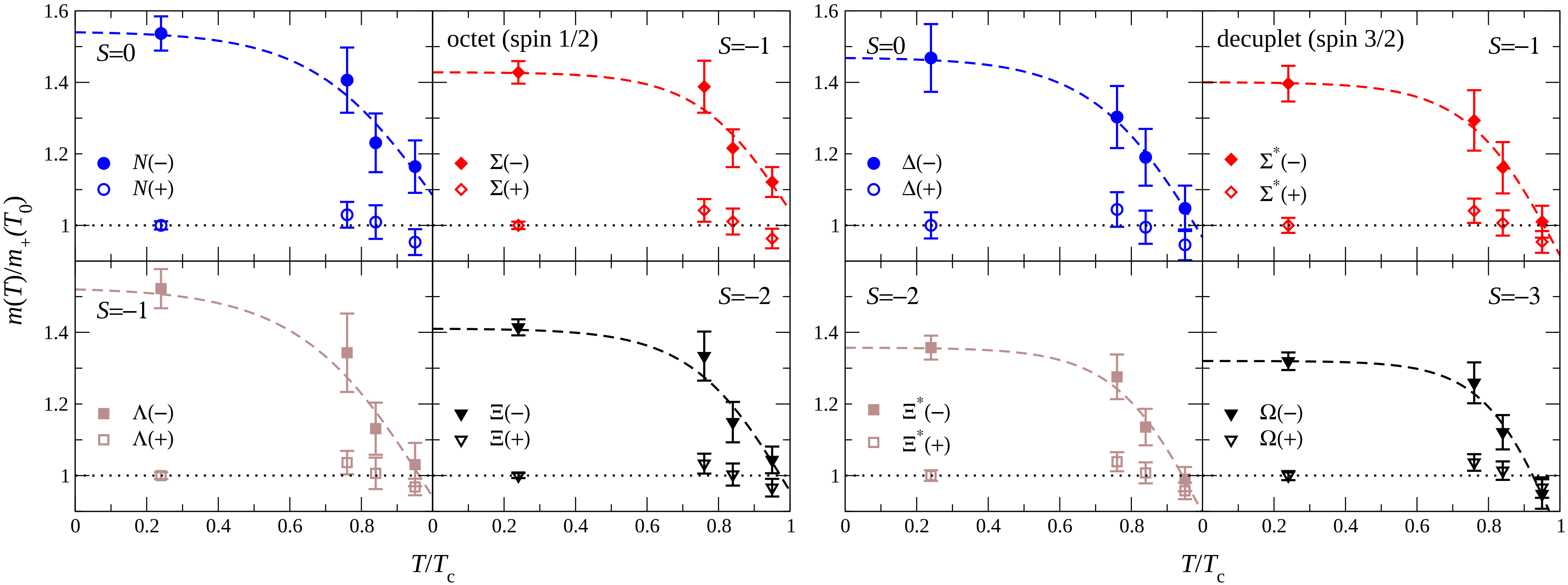
- determine masses of pos/neg parity groundstates
- in-medium effects
- implications for HRG

Masses of pos/neg 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

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

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
- relevant for heavy-ion phenomenology?

implement in HRG: in-medium baryon masses

Baryons and parity partners

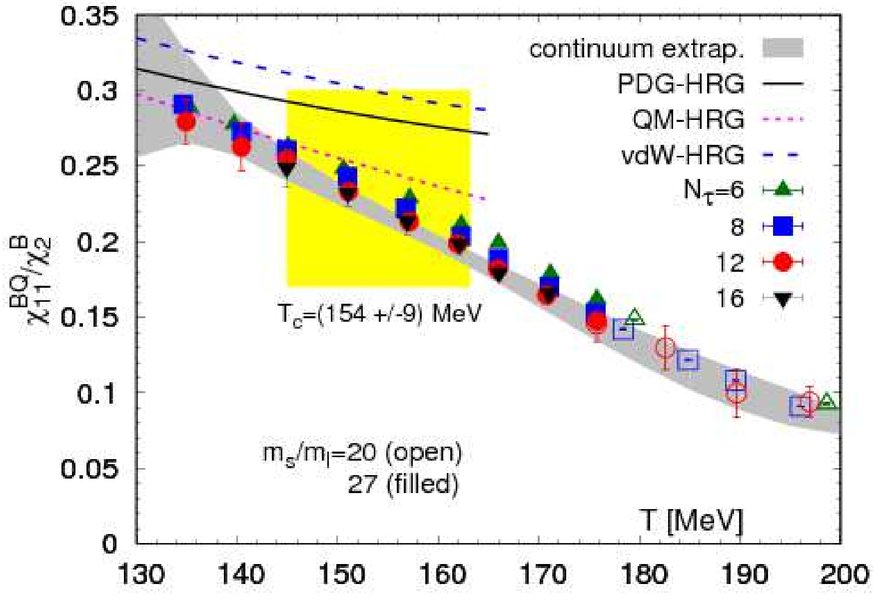
- distinct temperature dependence in hadronic phase
- relevant for heavy-ion phenomenology?

implement in HRG: in-medium baryon masses

- keep pos parity masses fixed
- reduce neg parity groundstate masses according to

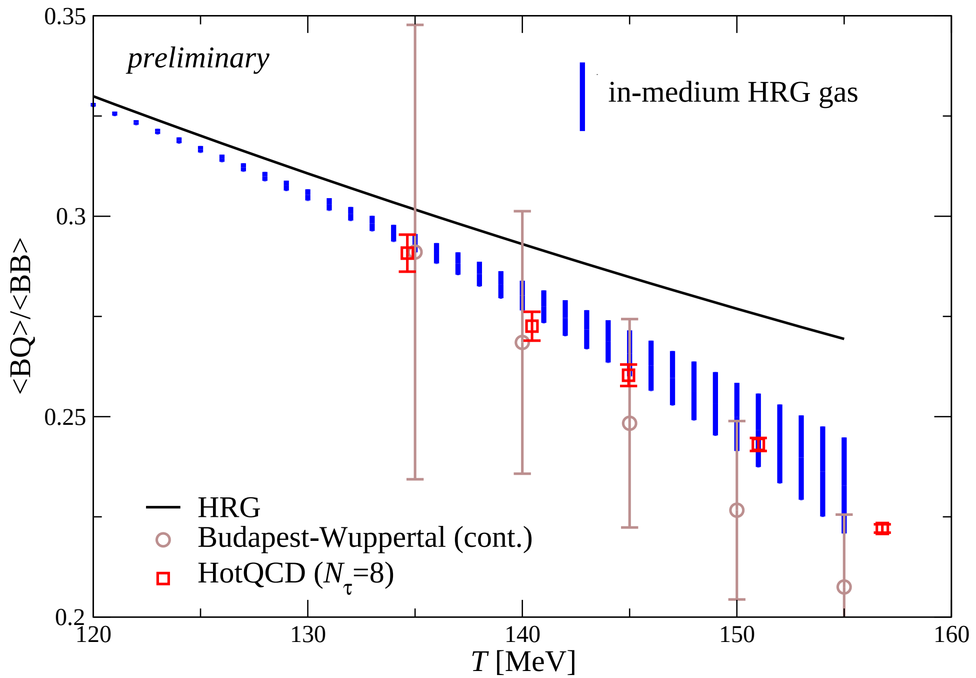
$$m_-(T) = w(T,\gamma)m_-(0) + [1 - w(T,\gamma)]m_-(T_c)$$

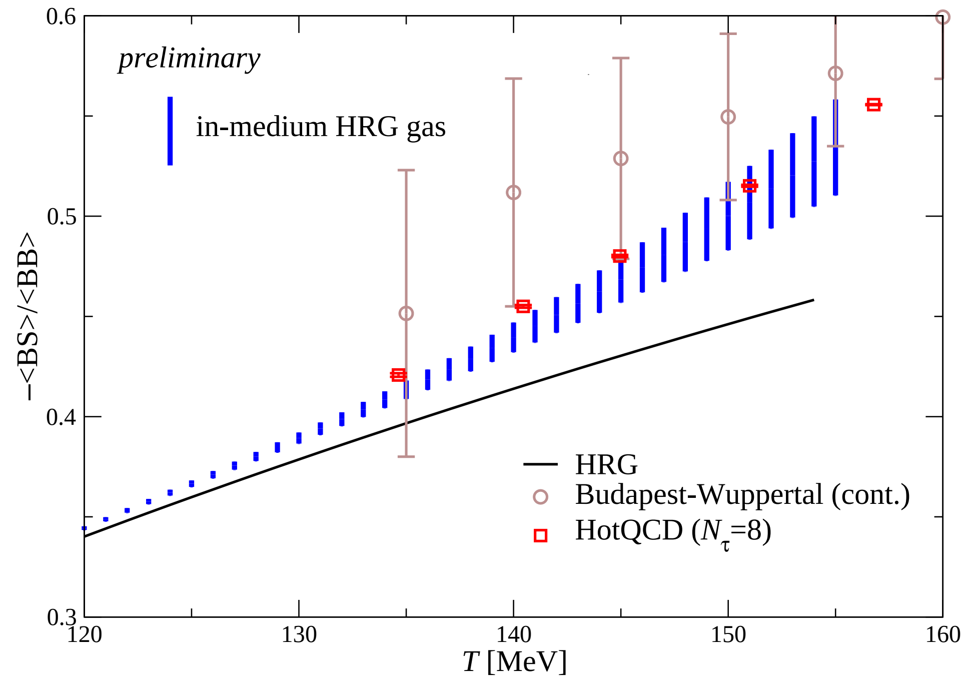
- use PDG masses at $T = 0$
- strength of crossover: vary γ
- biggest uncertainty: $m_-(T_c)$



$\langle BQ\rangle/\langle BB\rangle$

In-medium hadron resonance gas



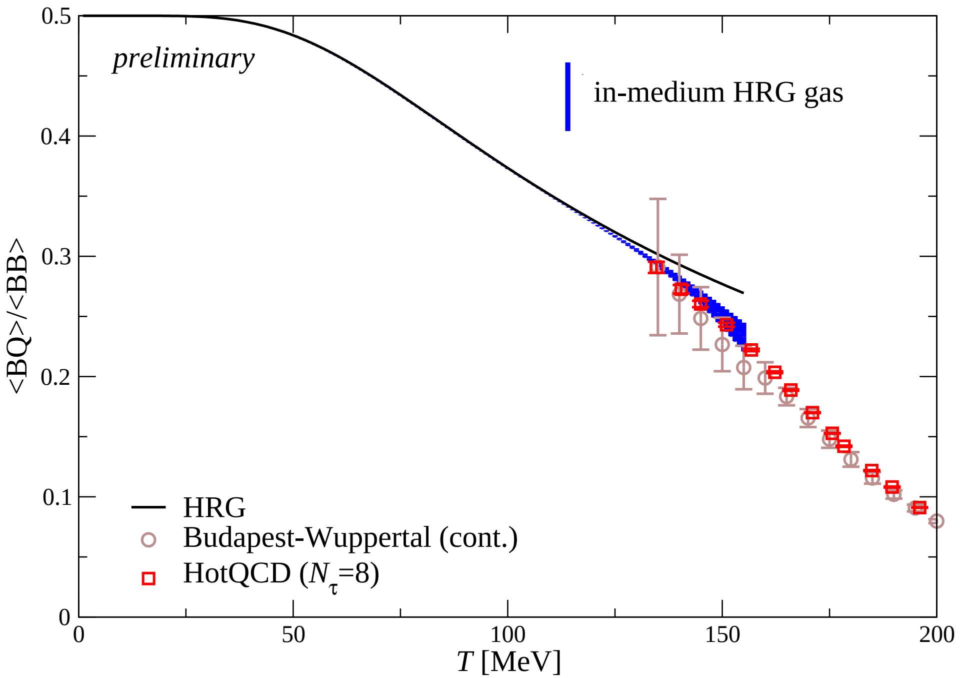


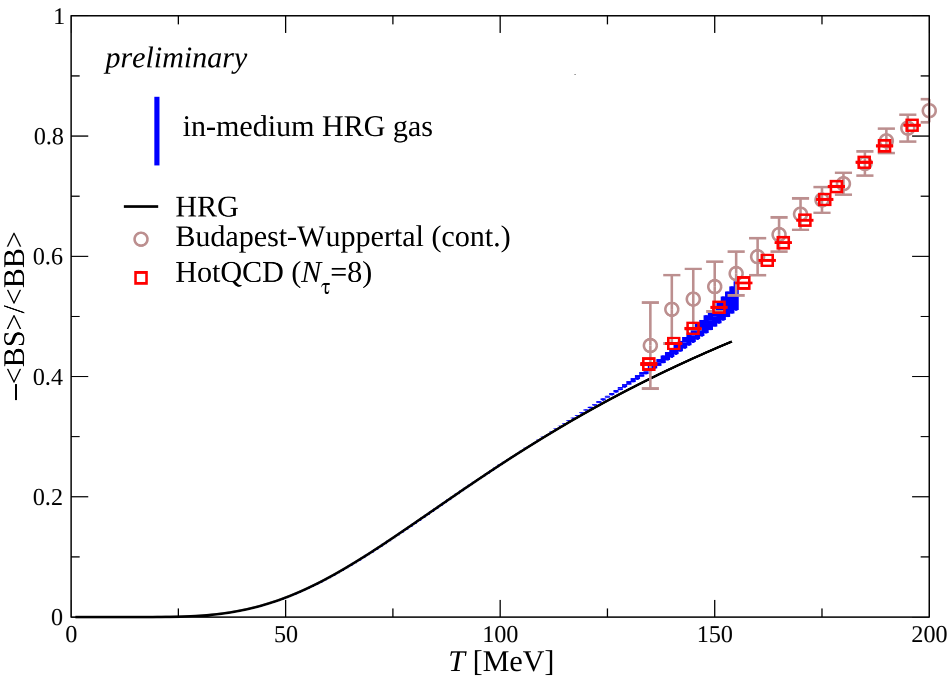
$\langle BQ\rangle / \langle BB\rangle$ $\quad$ $-\langle BS\rangle / \langle BB\rangle$

- comparison with convential HRG and lattice data
- bands indicate uncertainty in width of transition γ (minor effect) and $m_-(T_c)$

thanks to Szabolcs Borsanyi and Frithjof Karsch for lattice data

In-medium hadron resonance gas





$$\langle BQ\rangle/\langle BB\rangle \qquad -\langle BS\rangle/\langle BB\rangle$$

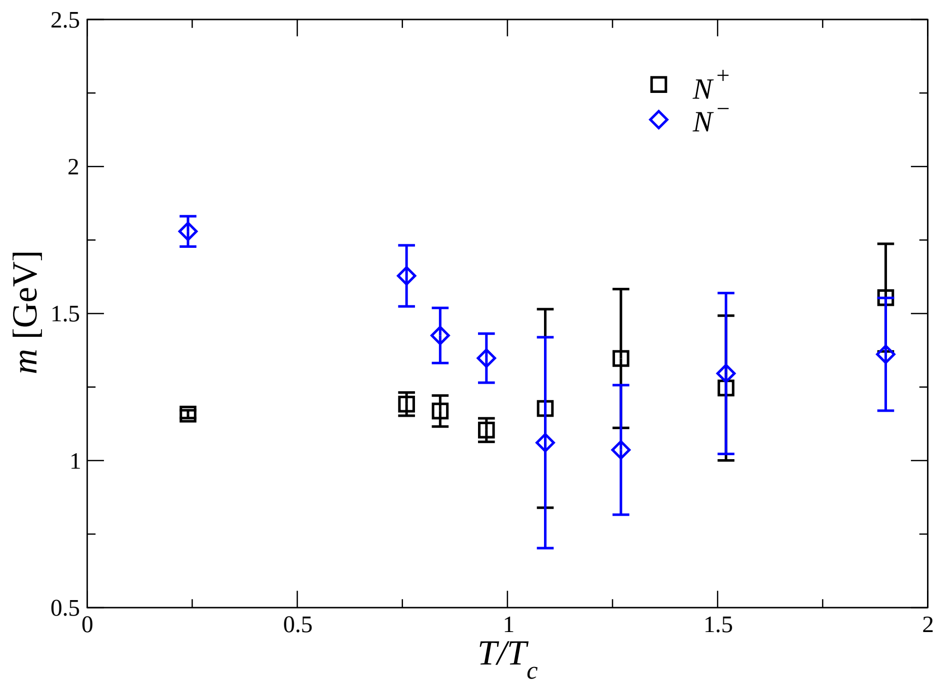
- entire temperature range: striking effect
- improvement on conventional HRG
- combine with other suggestions (quark model states)?

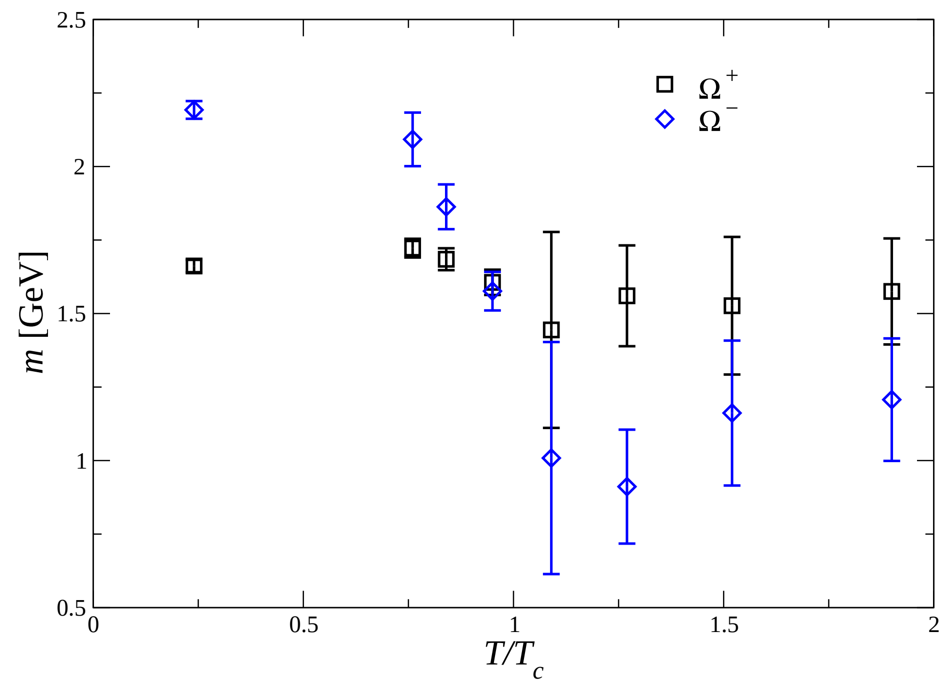
QGP: fate of light baryons

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 $R(1/2T) = 0$

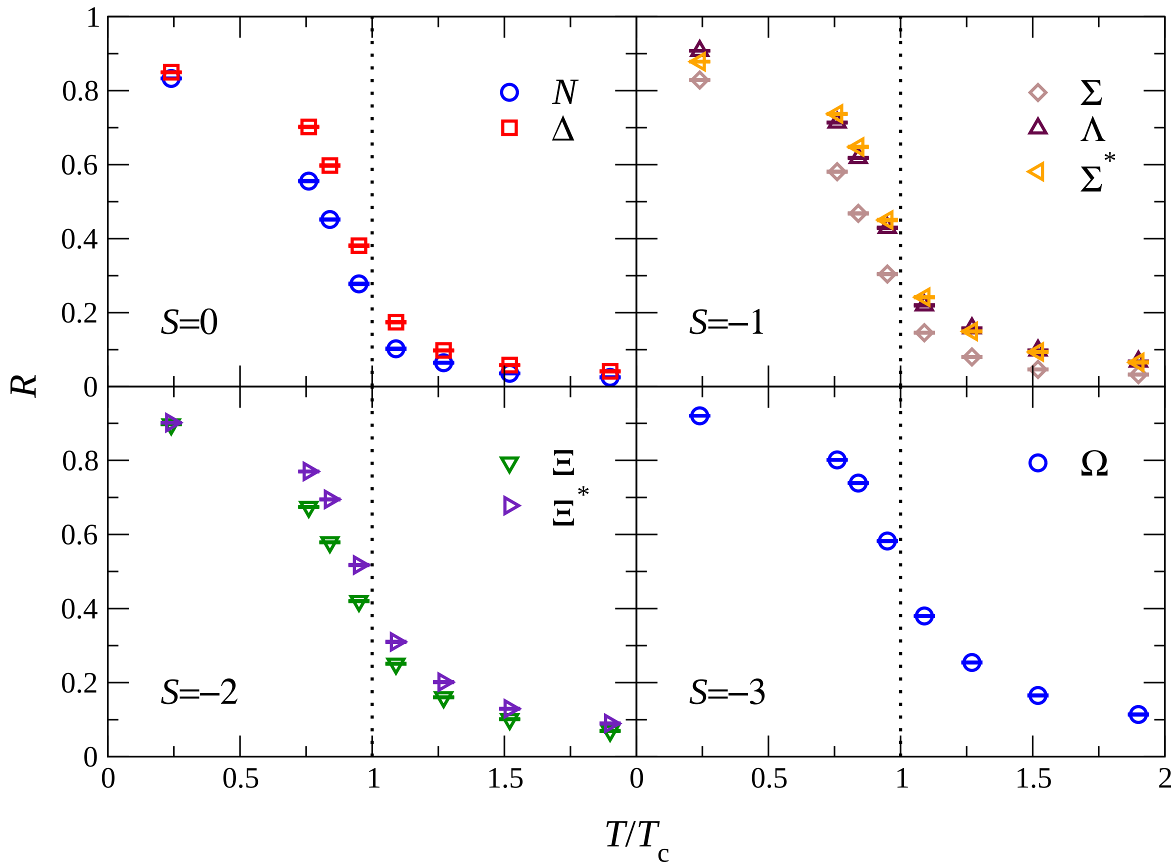
- integrated ratio

$\Rightarrow$ 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: $R \sim 1 \to 0$



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

Summary: baryons in medium

in hadronic phase

- pos parity groundstates mostly T independent
- T dependence in neg-parity groundstates
  reduction in mass, near degeneracy close to T_c
- relevant for heavy-ion phenomenology?
- application: in-medium HRG

in quark-gluon plasma

- pos/neg parity channels degenerate: parity doubling
- linked to deconfinement and chiral symmetry
- effect of heavier s quark noticeable

Outlook

in hadronic phase

- further implications for heavy-ion phenomenology
- strangeness dependence

lattice

- dependence on lighter quark masses/pions
- strength of crossover: transition region
- chiral properties important: use chiral fermions?

model approaches

- holography
- parity doubling models