Fasi della QCD, modelli di teoria dei campi e teoria del trasporto: un approccio sistematico alla fenomenologia degli ioni pesanti all'LHC

Partecipanti al progetto

6 - Risorse umane da impegnare nelle attività dell'Unità di Ricerca

6.1 - Personale a tempo indeterminato (A.1.1) e/o determinato (A.1.2)
Personale dipendente dell'Istituzione, sede dell'Unità di ricerca

n°	Cognome	Nome	Dipartimento/Istituto/ Divisione/Settore	Qualifica	Tipologia	Mesi/ uomo	Costo
1.	*BARBARO*	*Maria Benedetta*	*FISICA TEORICA*	*Professore Associato non confermato*	*Tempo Indeterminato*	*16*	*80.000*
	TOTALE					**16**	**80.000**

Personale docente esterno alla sede dell'Unità di ricerca

n°	Cognome	Nome	Ente / Istituzione / Impresa	Dipartimento/Istituto/ Divisione/Settore	Qualifica	Tipologia	Mesi/ uomo	Costo
	TOTALE						**0**	**0**

Personale di Enti/Istituzioni/Imprese esterno alla sede dell'Unità di ricerca

n°	Cognome	Nome	Ente / Istituzione / Impresa	Dipartimento/Istituto/ Divisione/Settore	Qualifica	Tipologia	Mesi/ uomo	Costo
1.	*MONTENO*	*Marco*	*Istituto Nazionale di Fisica Nucleare*		*Primo ricercatore*	*Tempo Indeterminato*	*24*	*80.000*
2.	*DE PACE*	*Arturo*	*Istituto Nazionale di Fisica Nucleare*		*Primo ricercatore*	*Tempo Indeterminato*	*12*	*40.000*
3.	*NARDI*	*Marzia*	*Istituto Nazionale di Fisica Nucleare*		*Ricercatore a tempo det.*	*Tempo Determinato*	*24*	*0*
	TOTALE						**60**	**120.000**

6.2 -Assegnisti, dottorandi, post-doc e borsisti (A.2) - Già acquisiti con altri fondi e saltuariamente impiegato nel Progetto di Ricerca

n°	Cognome	Nome	Università	Dipartimento/Istituto	Qualifica	Mesi/ uomo
1.	*BERAUDO*	*Andrea*	*Università degli Studi di TORINO*	*FISICA TEORICA*	*Assegnista*	*26*
2.	*ORTONA*	*Giacomo*	*Università degli Studi di TORINO*		*Dottorando*	*24*

Purposes of the project (I)

- study the microscopic origin of the “nearly perfect fluid” behavior of QGP
- study the impact of a finite shear viscosity on various observables
- understand if the plasma to be created at LHC energies belongs to a new phase, with respect to the highly non-perturbative one created at RHIC
- two research units: University of Catania and Torino
  - more theoretical point of view (Torino)
  - more phenomenological point of view (Catania)

Purposes of the project (II)

- in particular:
  - development of field-theoretical microscopic models under the guidance of the numerical lattice QCD results
  - identify the relevant degrees of freedom in the different temperature/density regimes
  - provide a theoretical ground on which a transport theory incorporating the field interactions can be constructed
- verify the effects that the new proposed theoretical ideas have on the experimental observations at RHIC and at the upcoming LHC
- the study will be extended to heavy flavors
  - relevant at the LHC energies

Specific tasks of the Torino research unit

- Development of phenomenological models for QCD thermodynamics
  - capture the main features of QCD in a certain regime
  - reach regions of the phase diagram where lattice QCD cannot go
  - give an interpretation of lattice data in terms of effective degrees of freedom
- quarkonia correlators in a thermal medium
- effects of the color glass condensate on the dynamical evolution of the system

What happens below T_c?

- At low T and $\mu = 0$, QCD thermodynamics is dominated by pions
- The interaction between pions is suppressed
  - chiral perturbation theory: pion contribution to the thermodynamic potential
  - the energy density of pions from 3-loop ChPT differs only less than 15% from the ideal gas value

    P. Gerber and H. Leutwyler (1989)
- as T increases, heavier hadrons start to contribute
- for $T \geq 140$ MeV heavy states dominate the energy density

Why HRG?

- In the virial expansion, the partition function can be split into a non-interacting piece and a piece which includes all interactions
- virial expansion and experimental information on scattering phase shift

  Prakash and Venugopalan (1992)

  ➠ interplay between attractive and repulsive interaction

Interacting hadronic matter

can be well approximated by

a non-interacting gas of resonances

Features of HRG model

- An increase of energy in the system has three consequences:
  - a fixed temperature limit $T \to T_H$;
  - the momenta of the constituents do not continue to increase;
  - more and more species of heavier particles appear

New, non-kinetic way to use energy:

increasing the number of species

not the momentum per particle

- $T_H \simeq 150 - 200$ MeV: critical temperature for transition to quark matter

  Hagedorn and Rafelsky (1981); Blanchard, Fortunato and Satz (2004).

Partition function of HRG model

- The pressure can be written as

$$p^{HRG}/T^4 = \frac{1}{VT^3} \sum_{i \in \, mesons} \ln \mathcal{Z}^M_{m_i}(T, V, \mu_{X^a}) + \frac{1}{VT^3} \sum_{i \in \, baryons} \ln \mathcal{Z}^B_{m_i}(T, V, \mu_{X^a}) \; ,$$

where

$$\ln \mathcal{Z}^{M/B}_{m_i} = \mp \frac{V d_i}{2\pi^2} \int_0^\infty dk k^2 \ln(1 \mp z_i e^{-\varepsilon_i/T}) \quad ,$$

with energies $\varepsilon_i = \sqrt{k^2 + m_i^2}$, degeneracy factors d_i and fugacities

$$z_i = \exp\left((\sum_a X_i^a \mu_{X^a})/T \right) \; .$$

X^a: all possible conserved charges, including the baryon number B, electric charge Q, strangeness S.

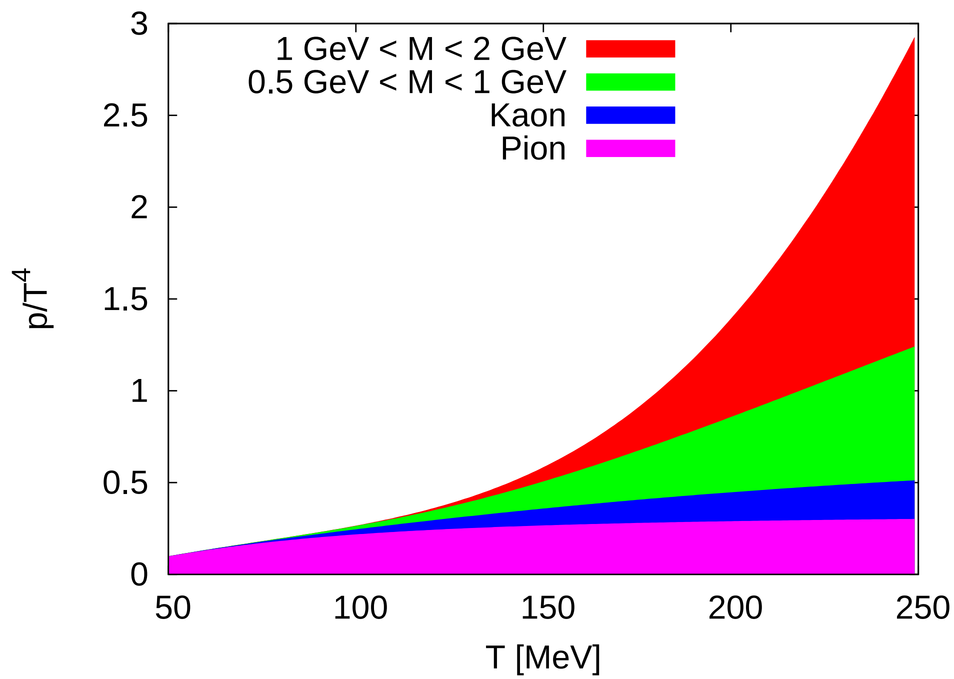
F. Karsch, A. Tawfik, K. Redlich; S. Ejiri, F. Karsch, K. Redlich

Hadronic species from the Particle Data Book

hadron	m_i (GeV)	d_i	B_i	S_i	I_i	hadron	m_i (GeV)	d_i	B_i	S_i	I_i
π	0.140	3	0	0	1	N (1535)	1.530	4	1	0	1/2
K	0.496	2	0	1	1/2	π_1 (1600)	1.596	9	0	0	1
$\overline{K}$	0.496	2	0	-1	1/2	Δ (1600)	1.600	16	1	0	3/2
η	0.543	1	0	0	0	Λ (1600)	1.600	2	1	-1	0
ρ	0.776	9	0	0	1	Δ (1620)	1.630	8	1	0	3/2
ω	0.782	3	0	0	0	η_2 (1645)	1.617	5	0	0	0
K^*	0.892	6	0	1	1/2	N (1650)	1.655	4	1	0	1/2
$\overline{K}^*$	0.892	6	0	-1	1/2	ω (1650)	1.670	3	0	0	0
N	0.939	4	1	0	1/2	Σ (1660)	1.660	6	1	-1	1
η'	0.958	1	0	0	0	Λ (1670)	1.670	2	1	-1	0
f_0	0.980	1	0	0	0	Σ (1670)	1.670	2	1	-1	1
a_0	0.980	3	0	0	1	ω_3 (1670)	1.667	7	0	0	0
ϕ	1.020	3	0	0	0	π_2 (1670)	1.672	15	0	0	1
Λ	1.116	2	1	-1	0	Ω^-	1.672	4	1	-3	0
h_1	1.170	3	0	0	1	N (1675)	1.675	12	1	0	1/2
Σ	1.189	6	1	-1	1	ϕ (1680)	1.680	3	0	0	0
a_1	1.230	9	0	0	1	K^* (1680)	1.717	6	0	1	1/2
b_1	1.230	9	0	0	1	$\overline{K}^*$ (1680)	1.717	6	0	-1	1/2
Δ	1.232	16	1	0	3/2	N (1680)	1.685	12	1	0	1/2
f_2	1.270	5	0	0	0	ρ_3 (1690)	1.688	21	0	0	1
K_1	1.273	6	0	1	1/2	Λ (1690)	1.690	4	1	-1	0
$\overline{K}_1$	1.273	6	0	-1	1/2	Ξ (1690)	1.690	8	1	-2	1/2
f_1	1.285	3	0	0	1	ρ (1700)	1.720	9	0	0	1
η (1295)	1.295	1	0	0	0	N (1700)	1.700	8	1	0	1/2
π (1300)	1.300	3	0	0	1	$\Delta(1700)$	1.700	16	1	0	3/2

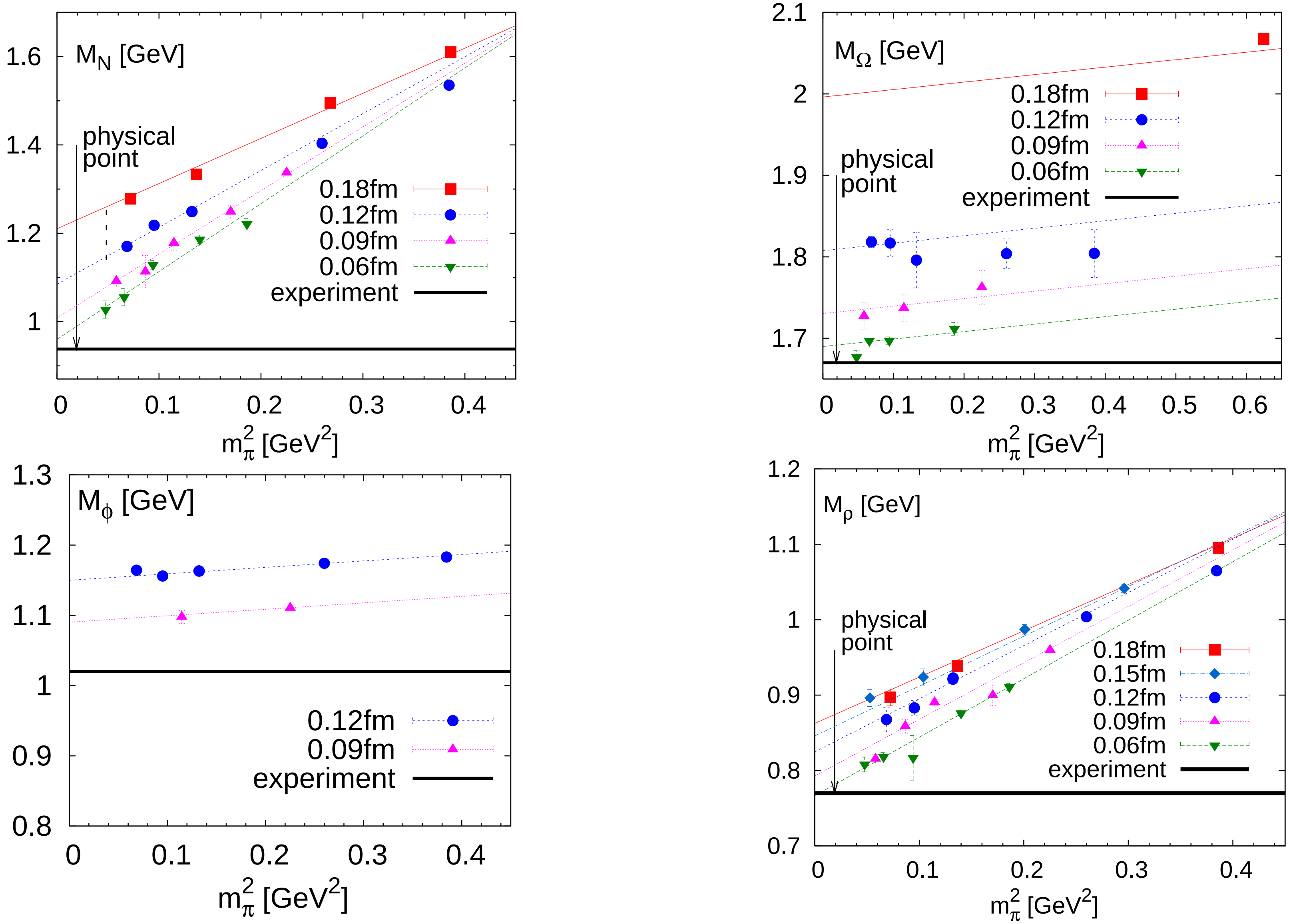
How many resonances do we include?

- With different mass cutoffs we can separate the contributions of different particles



- No visible difference between cuts at 2 GeV and 2.5 GeV in our temperature regime
- We include all resonances with $M \leq$ 2.5 GeV
  - $\simeq 170$ different masses $\leftrightarrow$ 1500 resonances

Discretization effects



C. W. Bernard *et al.*, PRD (2001), C. Aubin *et al.*, PRD (2004), A. Bazavov *et al.*, 0903.3598.

Hadron masses

- Non-strange baryons and mesons:

$$r_1 m = r_1 m_0 + \frac{a_1 (r_1 m_\pi)^2}{1 + a_2 x} + \frac{b_1 x}{1 + b_2 x}, \qquad x = (\frac{a}{r_1})^2$$

- Strange baryons and mesons:

$$r_1 \cdot m_\Lambda(a, m_\pi) = r_1 m_\Lambda^{phys} + \frac{2}{3}\frac{a_1 (r_1 m_\pi)^2}{1+a_2 x} + \frac{b_1 x}{1+b_2 x} + \frac{r_1 \cdot (m_\Lambda^{phys} - m_p^{phys})}{1+a_2 x}\left(\frac{m_s}{m_s^{phys}}\right),$$

$$r_1 \cdot m_\Sigma(a, m_\pi) = r_1 m_\Sigma^{phys} + \frac{1}{3}\frac{a_1 (r_1 m_\pi)^2}{1 + a_2 x} + \frac{b_1 x}{1 + b_2 x} + \frac{r_1 \cdot (m_\Sigma^{phys} - m_p^{phys})}{1 + a_2 x}\left(\frac{m_s}{m_s^{phys}}\right),$$

$$r_1 \cdot m_\Xi(a, m_\pi) = m_\Xi^{phys} + \frac{1}{3}\frac{a_1 (r_1 m_\pi)^2}{1 + a_2 x} + \frac{b_1 x}{1 + b_2 x} + \frac{r_1 \cdot (m_\Xi^{phys} - m_p^{phys})}{1 + a_2 x}\left(\frac{m_s}{m_s^{phys}}\right)$$

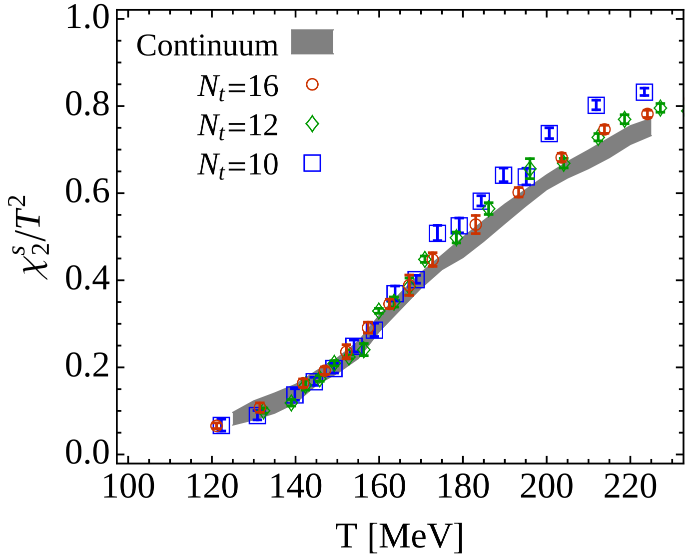
$$r_1 m_\Omega(a, m_\pi) = r_1 m_\Omega^{phys} + a_1 (r_1 m_\pi)^2 - a_1 (r_1 m_\pi^{phys})^2 + b_1 x + (m_\Omega^{phys} - m_\Delta^{phys}) \cdot 1.02 x$$

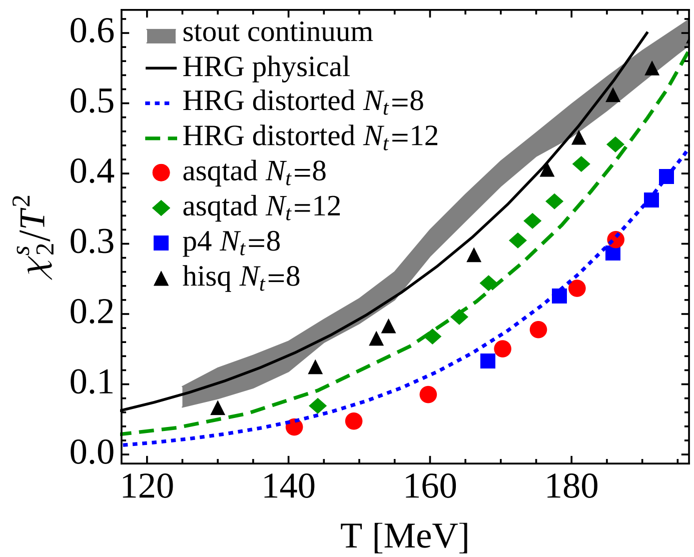
- Distorted spectrum implemented in the HRG model
- Assumption: all resonances behave as their fundamental states

P. Huovinen and P. Petreczky (2009).

Results: strangeness susceptibilities

$$\chi_n^S = T^n \frac{\partial^n p(T,\mu_B,\mu_S,\mu_I)}{\partial \mu_S^n}\Big|_{\mu_X=0}$$



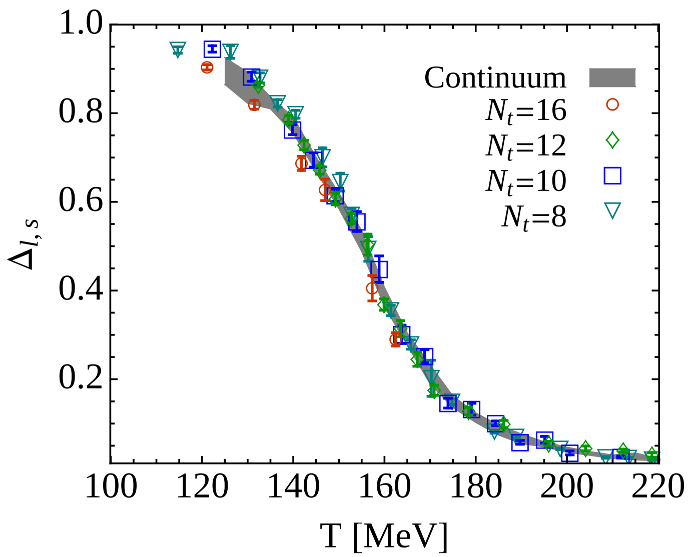


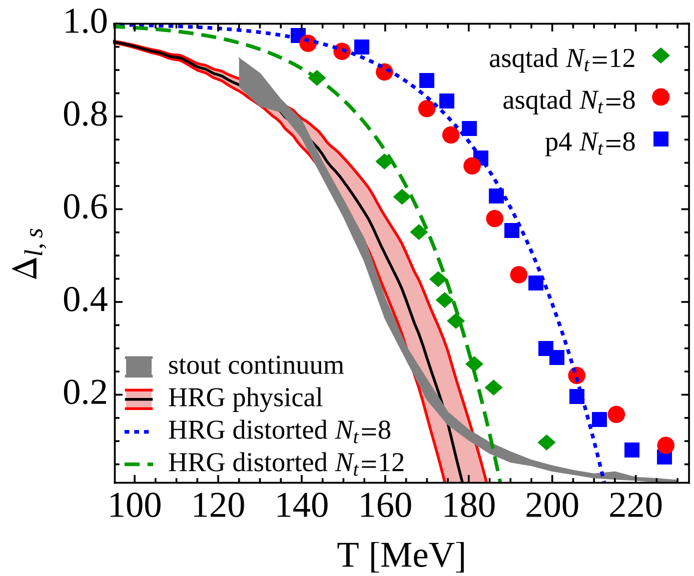
- HRG results in good agreement with stout action
- asqtad and p4 results show similar shape but shift in temperature
  - ➡ HRG results with corresponding distorted spectrum reproduce asqtad and p4 results

S. Borsanyi *et al.*, JHEP1009 (2010)

Results: subtracted chiral condensate

$$\Delta_{l,s} = \frac{\langle\bar\psi\psi\rangle_{l,T} - \frac{m_l}{m_s}\langle\bar\psi\psi\rangle_{s,T}}{\langle\bar\psi\psi\rangle_{l,0} - \frac{m_l}{m_s}\langle\bar\psi\psi\rangle_{s,0}}$$



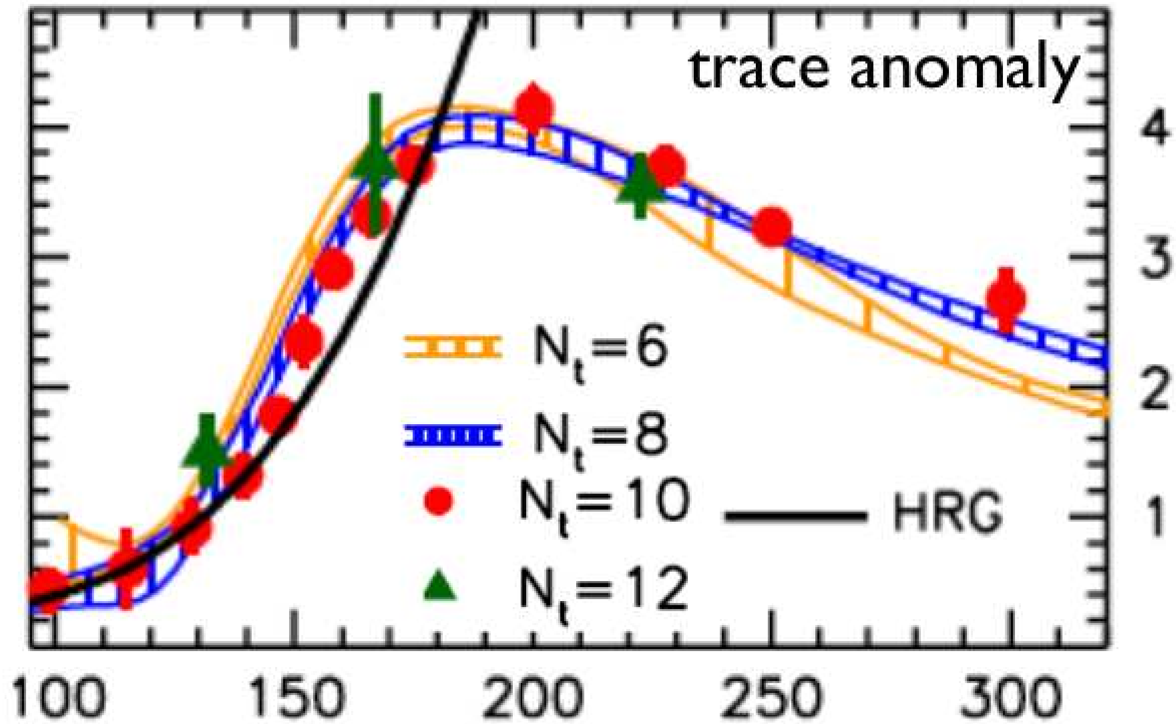


$$\langle\bar\psi\psi\rangle_s = \langle\bar\psi\psi\rangle_{s,0} + \langle\bar\psi\psi\rangle_K + \sum_{i\in mesons}\frac{\partial\ln Z^M_{m_i}}{\partial m_i}\frac{\partial m_i}{\partial m_s} + \sum_{i\in baryons}\frac{\partial\ln Z^B_{m_i}}{\partial m_i}\frac{\partial m_i}{\partial m_s}.$$

- $\frac{\partial m_i}{\partial m_s}$ from fit to lattice data Camalich, Geng and Vacas (2010)

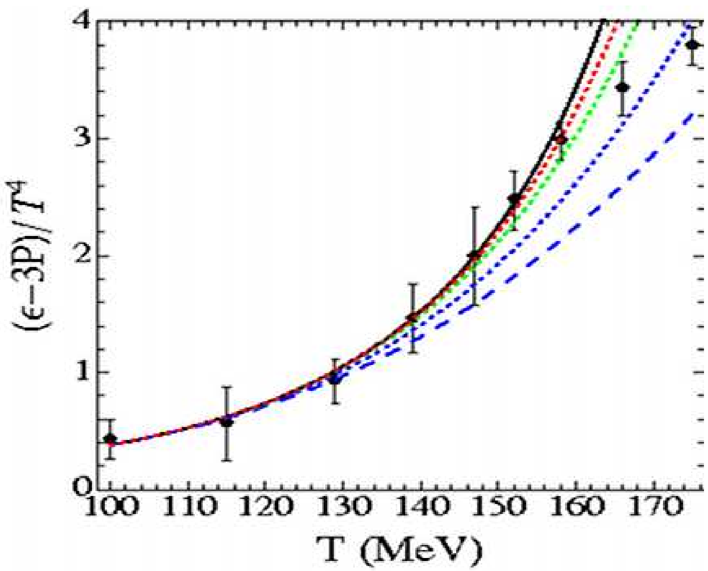
S. Borsanyi *et al.*, JHEP1009 (2010)

Results: trace anomaly



- Very good agreement between HRG and lattice results

Inclusion of exponential spectrum in HRG model



- For large masses few states are known experimentally
- Inclusion of exponentially growing hadron mass spectrum

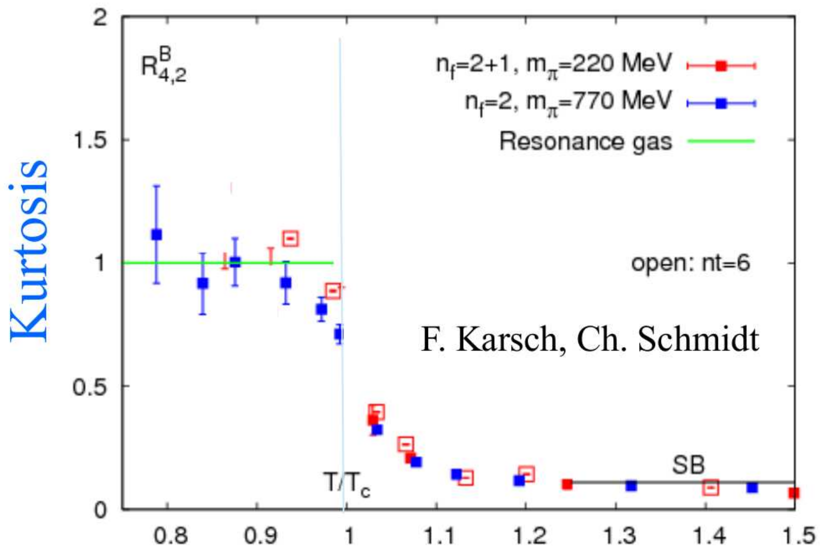
  J. Noronha-Hostler, C. Greiner, I. Shovkovy (2008); J. Noronha-Hostler, M. Beitel, C. Greiner, I. Shovkovy (2010)

- Agreement between lattice and HRG improved up to $T \sim 155$ MeV

  (A. Majumder, B. Müller: 1008.1747)

Open questions

- Up to which temperature should we describe the system in terms of the HRG model?
- $T_c \simeq 155$ MeV, transition is a crossover
  - ➡ one should expect deviations from HRG already below T_c



$$R^B_{4,2} = \frac{C^B_4}{C^B_2}, \qquad C^B_n = \frac{\partial^n p}{\partial \mu^n_B}$$