Correlations and fluctuations from lattice QCD

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(Wuppertal-Budapest collaboration); arXiv: 1112.4416 (JHEP 2012)

Motivation

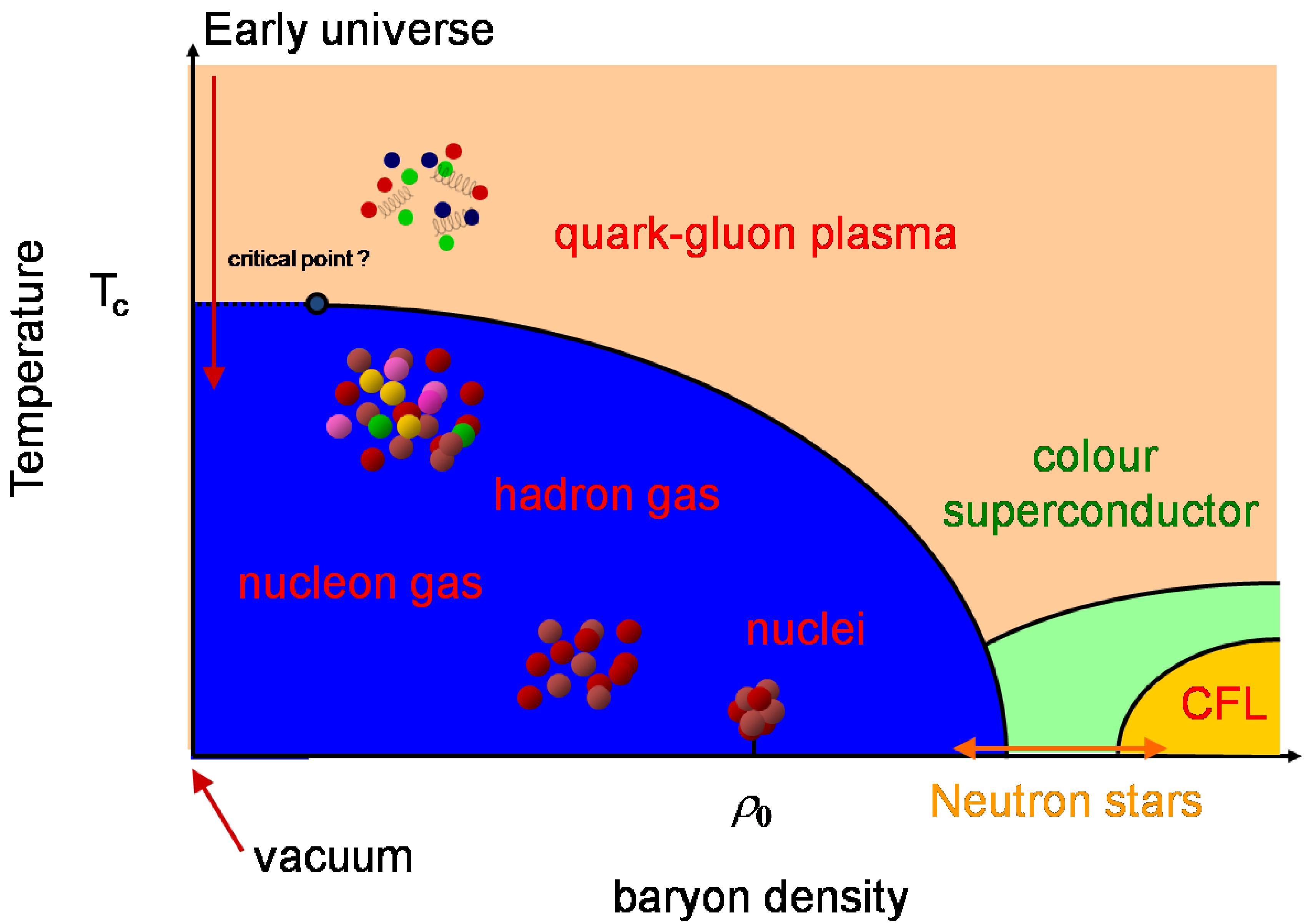
- We live in a very exciting era to understand the fundamental constituents of matter and the evolution of the Universe

- We can create the deconfined phase of QCD in the laboratory

- Lattice QCD simulations have reached unprecedented levels of accuracy
  - physical quark masses
  - several lattice spacings $\rightarrow$ continuum limit

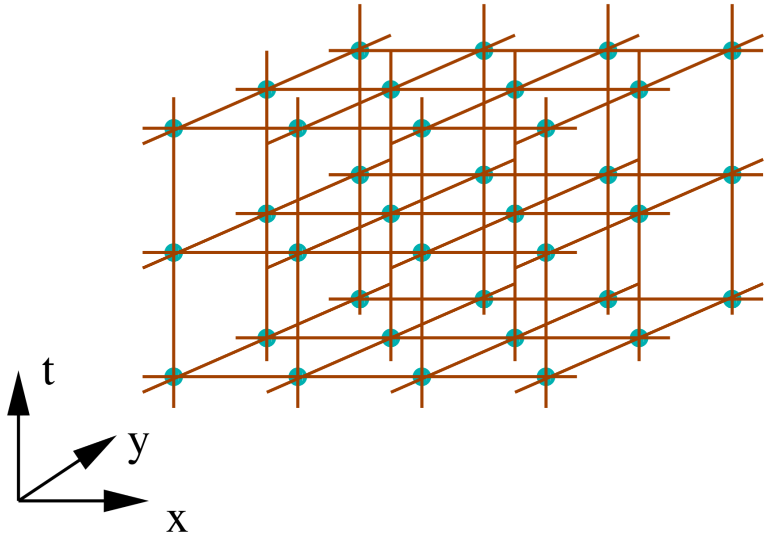
- The joint information between theory and experiment can help us to shed light on QCD

The QCD phase diagram



Discretization of space-time

- Simplest: isotropic hypercubic grid with spacing $a = a_S = a_T$ and size $N_S \times N_S \times N_S \times N_T$.



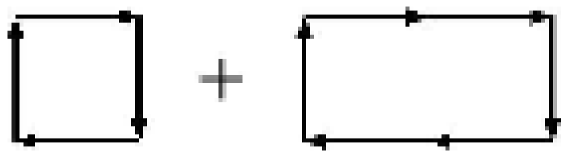
- Physical size of the lattice: $L = N_S a$
- Temperature: $T = \frac{1}{N_T a}$
- N_T large $\Rightarrow$ a small: closer to continuum limit but computationally expensive

Choice of the action

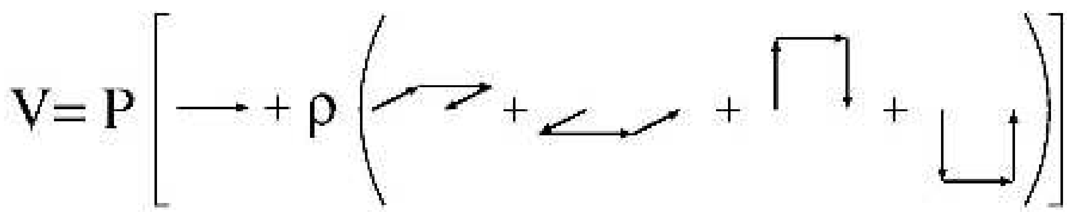
- no consensus: which action offers the most cost effective approach

  Aoki, Fodor, Katz, Szabo, JHEP 0601, 089 (2006)

- our choice tree-level $O(a^2)$-improved Symanzik gauge action



2-level (stout) smeared improved staggered fermions



Quark number susceptibilities

- The deconfined phase of QCD can be reached in the laboratory
- Need for unambiguous observables to identify the phase transition
  - susceptibilities of conserved charges (baryon number, electric charge, strangeness)
    S. Jeon and V. Koch (2000), M. Asakawa, U. Heinz, B. Müller (2000)
- A rapid change of these observables in the vicinity of T_c provides an unambiguous signal for deconfinement
- These observables are sensitive to the microscopic structure of the matter
  - ➡ non-diagonal correlators give information about presence of bound states in the QGP
- They can be measured on the lattice as combinations of quark number susceptibilities

The observables under study

- The chemical potentials are related:

$$
\begin{aligned}
\mu_u &= \frac{1}{3}\mu_B + \frac{2}{3}\mu_Q; \\
\mu_d &= \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q; \\
\mu_s &= \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q - \mu_S.
\end{aligned}
$$

- susceptibilities are defined as follows:

$$\chi_{lmn}^{BSQ} = \frac{\partial^{\,l+m+n} p/T^4}{\partial(\mu_B/T)^l \partial(\mu_S/T)^m \partial(\mu_Q/T)^n}.$$

- Here we concentrate on the quadratic susceptibilities

$$\chi_2^X = \frac{1}{VT^3}\langle N_X^2 \rangle$$

- and on the correlators between different charges

$$\chi_{11}^{XY} = \frac{1}{VT^3}\langle N_X N_Y \rangle.$$

diagonal and non-diagonal

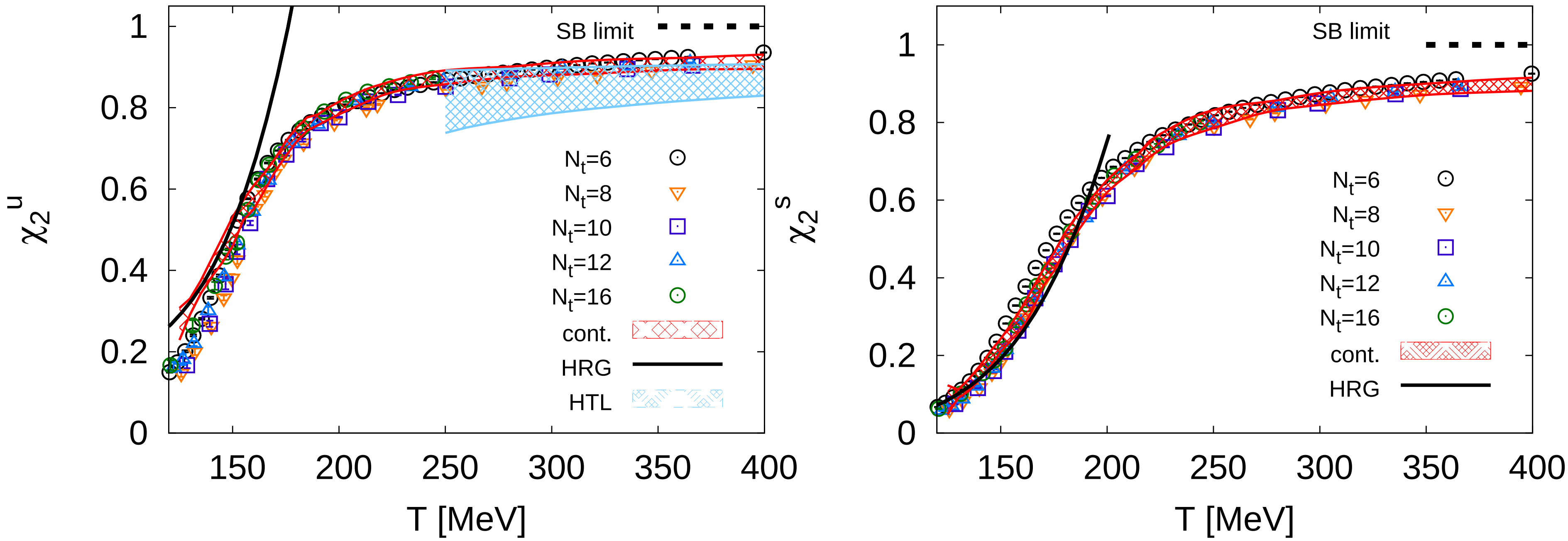
quark number susceptibilities

$N_f = 2 + 1$ dynamical quark flavors

$$m_s/m_{u,d} = 28.15$$

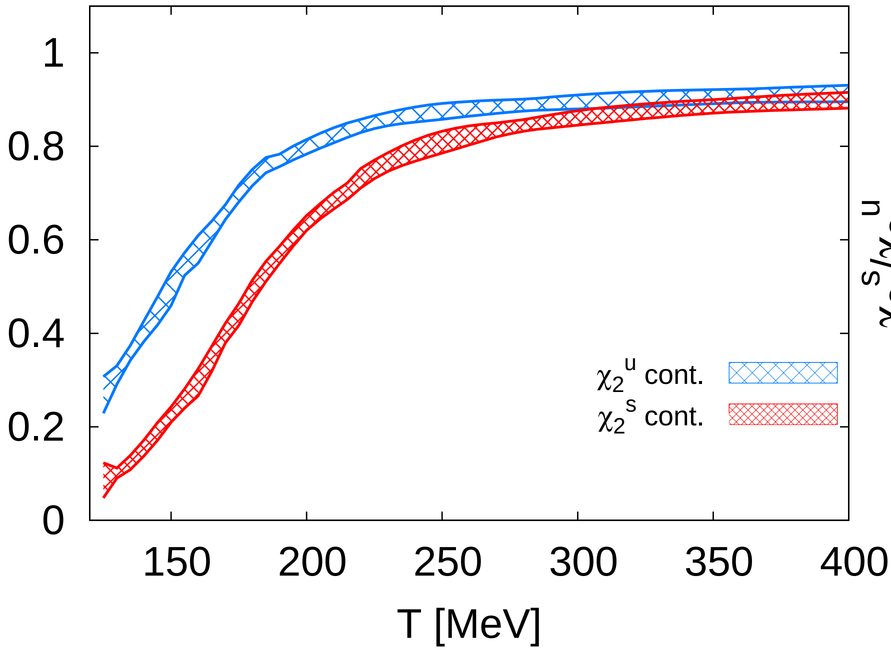
Results: light and strange quark susceptibilities

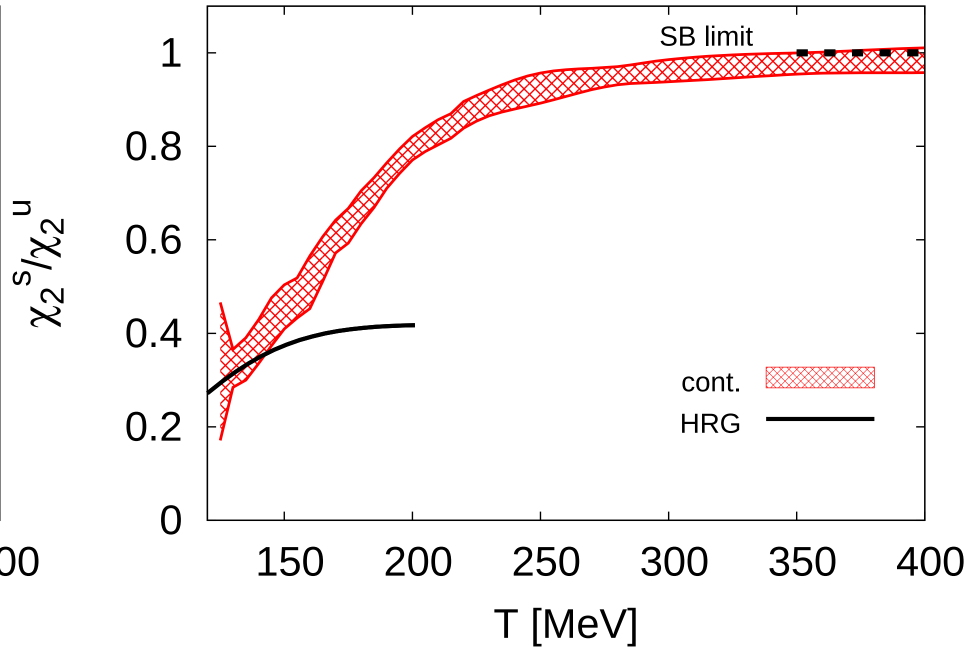
$$\chi_2^u = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial\mu_u\partial\mu_u}\Big|_{\mu_i=0} \qquad \chi_2^s = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial\mu_s^2}\Big|_{\mu_i=0}$$



- quark number susceptibilities exhibit a rapid rise close to T_c
- at large T they reach $\sim 90\%$ of the ideal gas limit

Comparison between light and strange quark susceptibilities

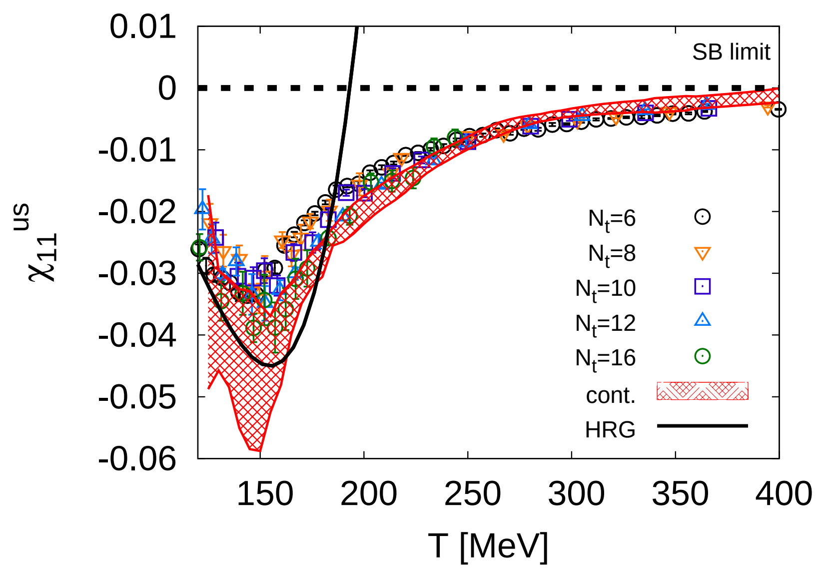




- strange quark susceptibilities have their rapid rise at larger temperatures compared to the light quark ones
- they rise more slowly as a function of T

Results: nondiagonal susceptibilities

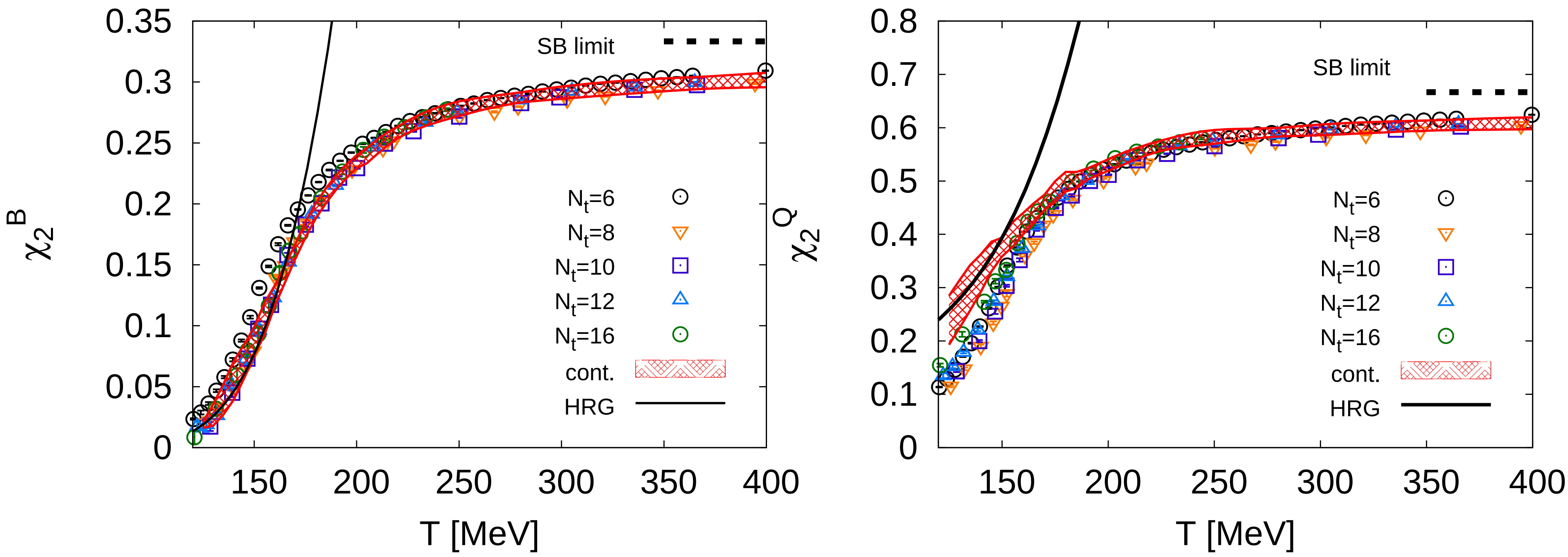
$$\chi_{11}^{us} = \chi_{11}^{ds} = \frac{T}{V} \frac{\partial^2 \ln Z}{\partial \mu_u \partial \mu_s}\Big|_{\mu_i=0}$$



- non-diagonal susceptibilities look at the linkage between different flavors
- they exhibit a strong dip in the vicinity of T_c
- they vanish in the QGP phase at large temperatures

Results: susceptibilities of baryon number and electric charge

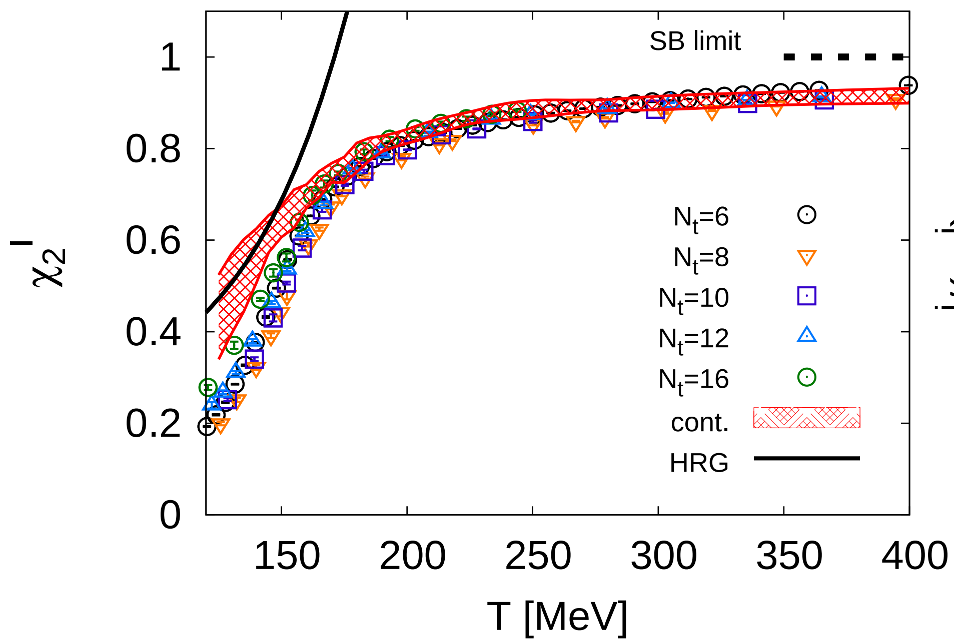
$$\chi_2^B = \frac{1}{9}\left(2\chi_2^u + \chi_2^s + 2\chi_{11}^{ud} + 4\chi_{11}^{us}\right); \quad \chi_2^Q = \frac{1}{9}\left(5\chi_2^u + \chi_2^s - 4\chi_{11}^{ud} - 2\chi_{11}^{us}\right)$$

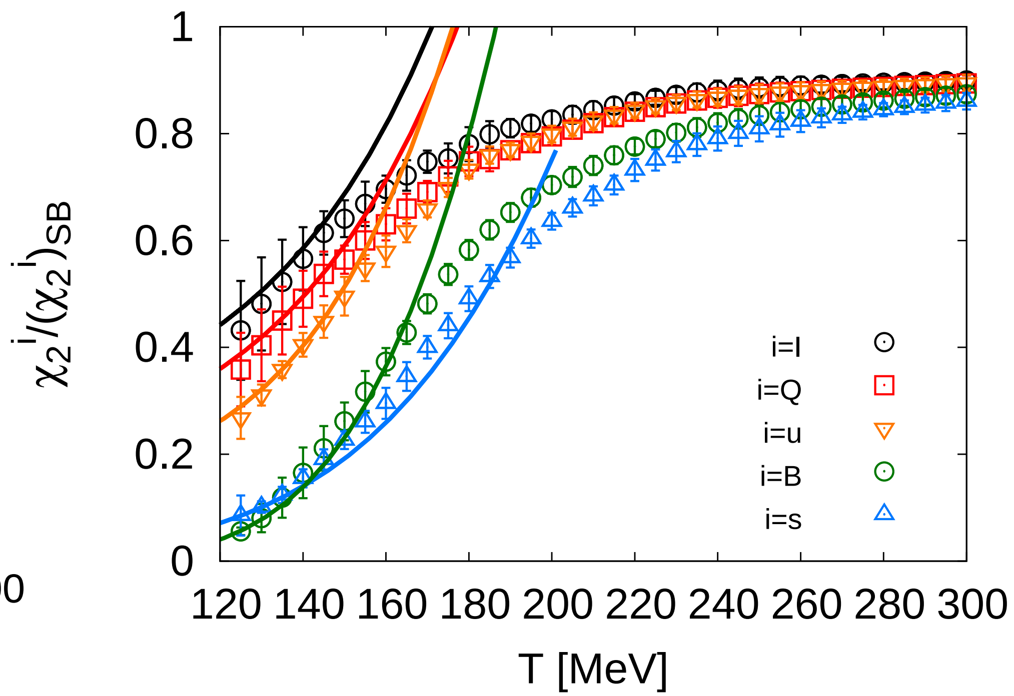


- rapid rise around T_c
- It reaches $\sim 90\%$ of ideal gas value at large temperatures

Results: isospin susceptibility

$$\chi_2^I = \frac{1}{2}\left(\chi_2^u - \chi_{11}^{ud}\right)$$





- rapid rise around T_c
- It reaches $\sim 90\%$ of ideal gas value at large temperatures

Testing the presence of bound states in the QGP

We define the following object

$$C_{BS} = -3\frac{\langle BS\rangle}{\langle S^2\rangle}$$

V. Koch, A. Majumder, J. Randrup, PRL95 (2005).

In a QGP phase:

- $-3\langle BS\rangle = \langle (n_{\bar{s}} - n_s)^2\rangle$

  $\langle S^2\rangle = \langle (n_{\bar{s}} - n_s)^2\rangle$

  at all T and μ

$$C_{BS} = 1$$

In hadron gas phase:

- $-3\langle BS\rangle = 3[\Lambda + \bar{\Lambda} + \Sigma + \bar{\Sigma} + ...] + 6[\Xi + \bar{\Xi} + ...] + 9[\Omega + \bar{\Omega} + ...]$

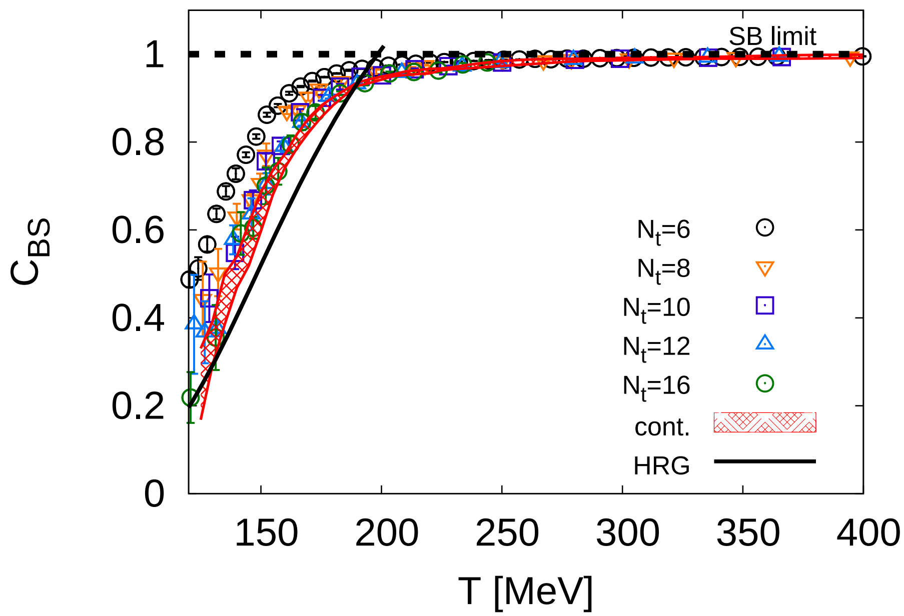
  $\langle S^2\rangle = K^+ + K^- + K^0 + \Lambda + \bar{\Lambda} + ...$

  at $T \simeq T_c$ and $\mu = 0$

$$C_{BS} = 0.66$$

Results: baryon-strangeness correlator

$$C_{BS} = 1 + \frac{\chi_{11}^{us} + \chi_{11}^{ds}}{\chi_2^s}$$



- C_{BS} indicates the possibility of bound states in a certain window above T_c
- there is a window of about 100 MeV above the transition where $C_{BS} < 1$

charm quark susceptibilities

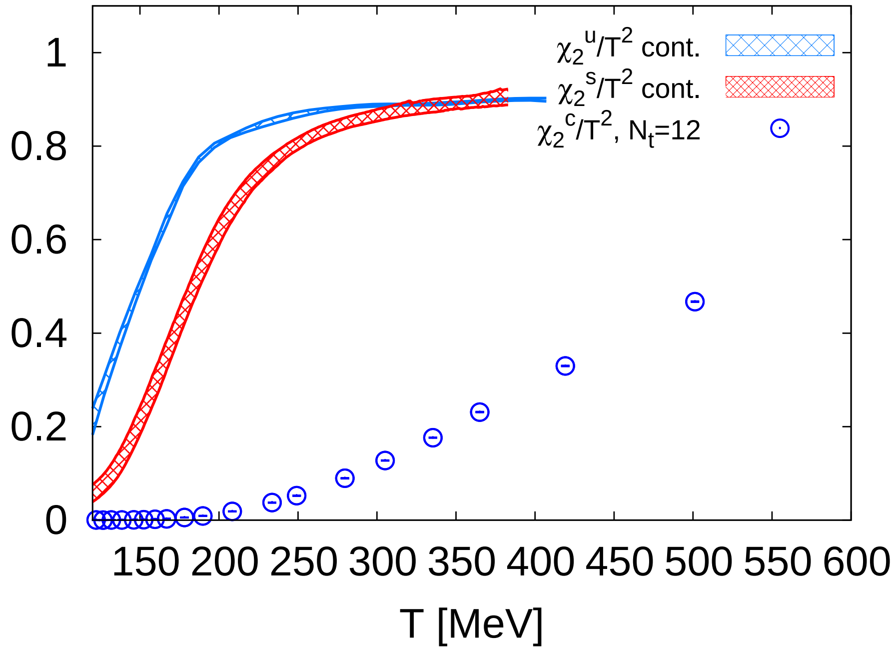
$$N_f = 2 + 1 + 1$$

with partial quenched charm

$$m_c / m_s = 11.85$$

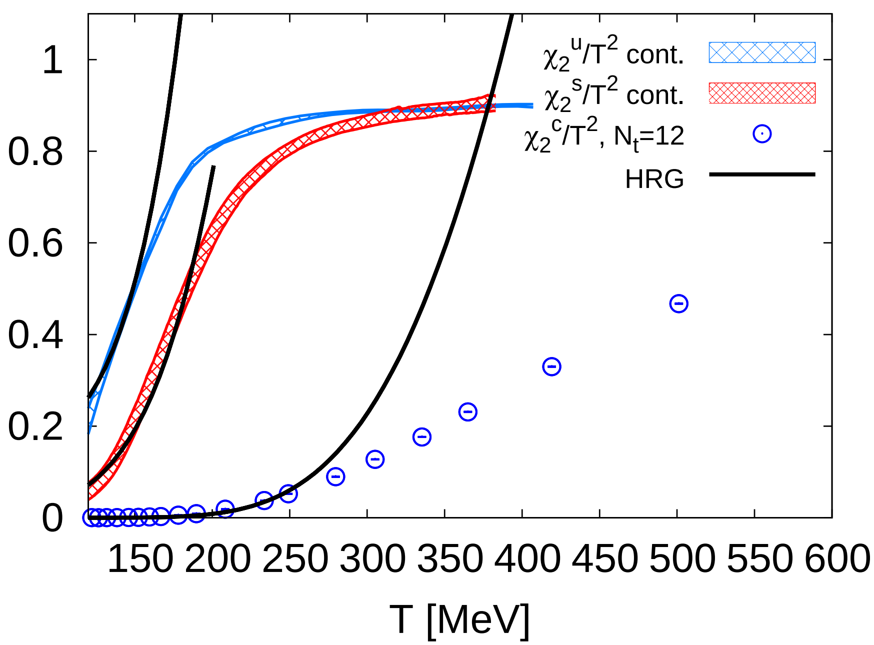
Charm quark number susceptibilities

$$\chi_2^c = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial\mu_c\partial\mu_c}\bigg|_{\mu_i=0}$$



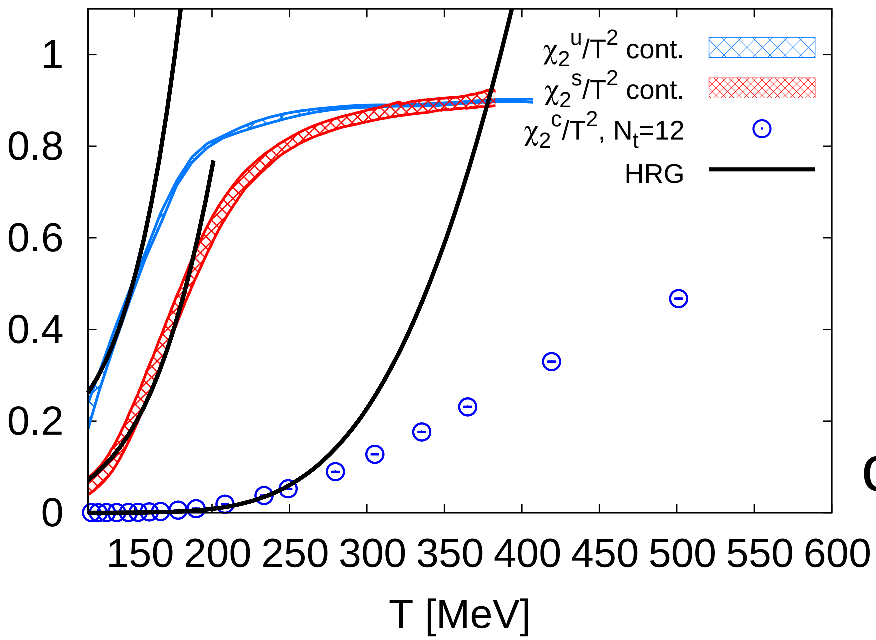
- charm susceptibilities rise at much larger temperatures compared to the light quark ones
- their rise with temperature is much slower

Possible interpretations

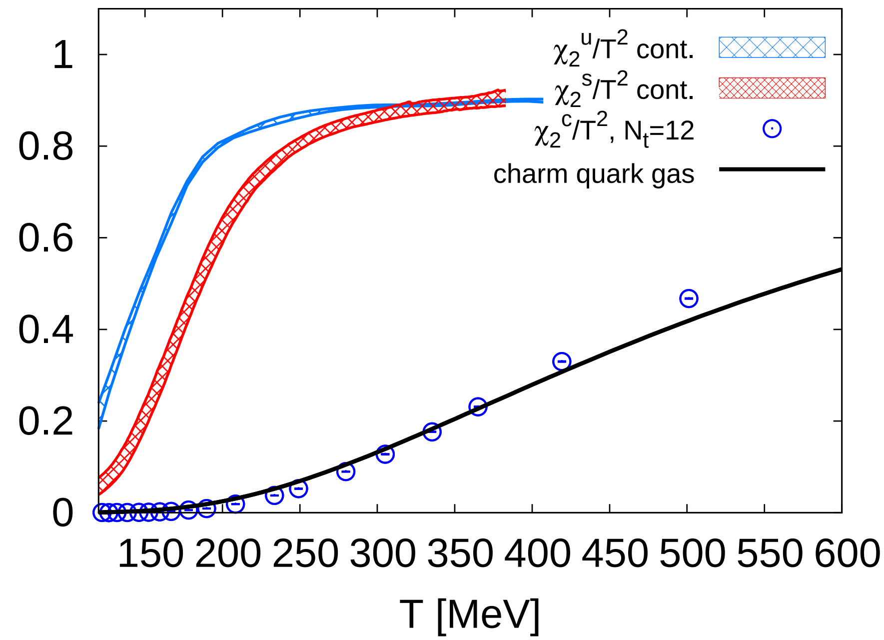


- survival of open charm hadrons up to $T \simeq 2T_c$?
- HRG results agree with the lattice up to the inflection point in the data

Possible interpretations



or



- survival of open charm hadrons up to $T \simeq 2T_c$?
- HRG results agree with the lattice up to the inflection point in the data

- thermal excitation of charm quarks takes place at larger temperatures
- ideal gas of charm quarks agrees with lattice

need for non-diagonal quark number susceptibilities

Conclusions

- study of diagonal and non-diagonal quark number susceptibilities for $N_f = 2+1$ dynamical flavors
- diagonal quark number susceptibilities: signals of QCD phase transition
  - rapid rise close to T_c
  - susceptibilities of different flavors show their rise at different T
- correlations between different flavors are large immediately above T_c
  - possibility of bound states survival in the QGP
- diagonal charm quark susceptibilities rise at much larger temperatures
- they don't allow to distinguish between HRG and free charm gas
  - need for non-diagonal correlators

Backup slides

There are evidences for deviations from statistical model predictions at the LHC

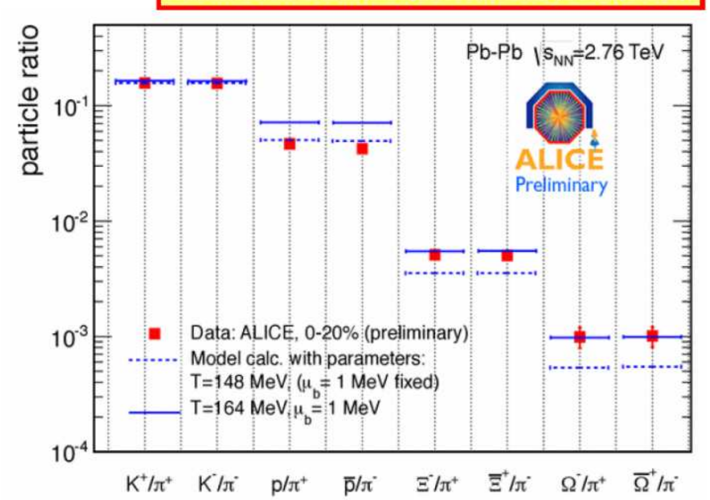
- baryon production -

R. Preghenella, ALICE Collaboration, SQM 2011:

	ALICE data Pb-Pb $\sqrt{s_{NN}}$ = 2.6 TeV these results	LHC prediction* T_{ch} = 164 MeV, μ_B =1 MeV A.Andronic et al, Phys.Lett.B 673, 142 (2009)	LHC prediction* T_{ch} = (170 ± 5) MeV, μ_B = (1 ± 4) MeV J.Cleymans et al, PRC 74, 034903 (2006)
K^+/π^+	0.156 ± 0.012	0.164	0.180 ± 0.001
K^-/π^-	0.154 ± 0.012	0.163	0.179 ± 0.001
p/π^+	0.0454 ± 0.0036	0.072	0.091 ± 0.009
$\bar{p}/\pi^-$	0.0458 ± 0.0036	0.071	0.091 ± 0.009

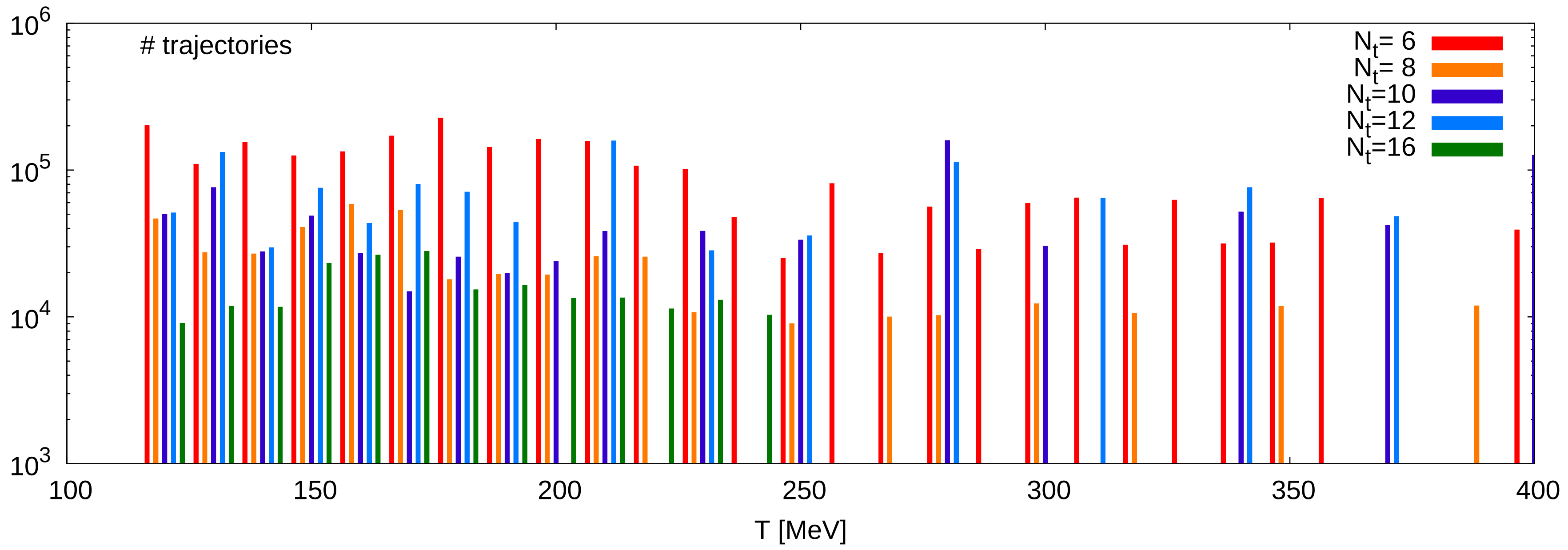
* prediction for central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 5.5 TeV

A.Andronic et al., Phys.Lett.B 673, 142 (2009)

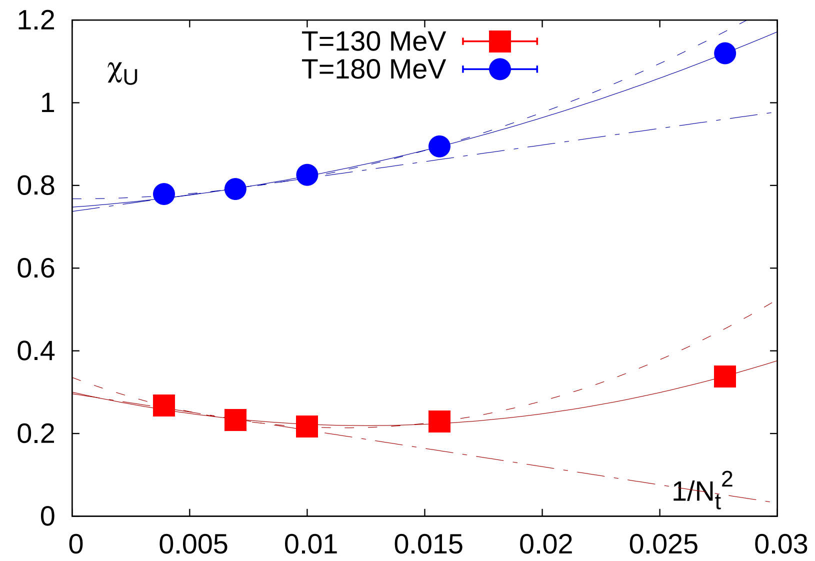


Conclusion:
possibly no common freeze-out surface for all particle species ?

Statistics and continuum extrapolation



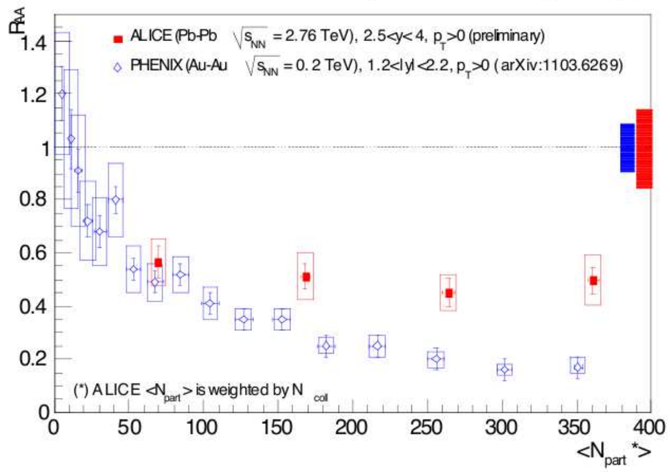
- all observables are continuum extrapolated
  - ➜ obtained by measuring them at several $a \sim 1/N_t$ and taking the limit $a \to 0$
- parabolic fit is perfomed



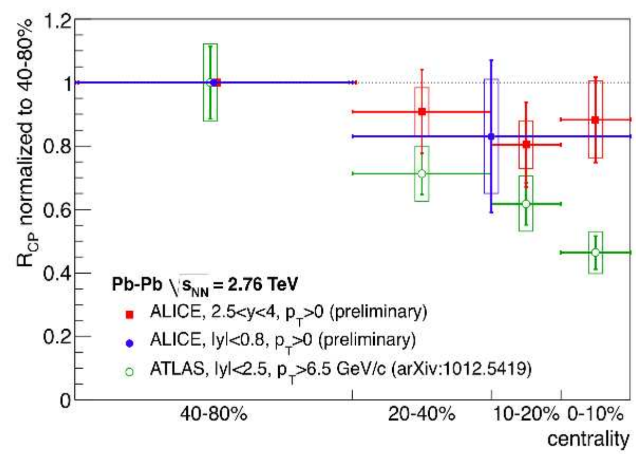
There are evidences for deviations from statistical model predictions at the LHC

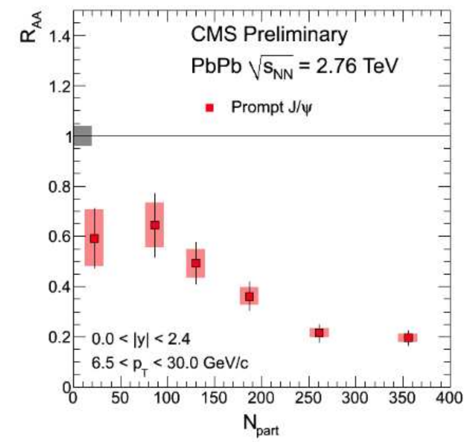
- J/ψ production -

Data: ALICE/ PHENIX (forward rapidity) - QM 2011

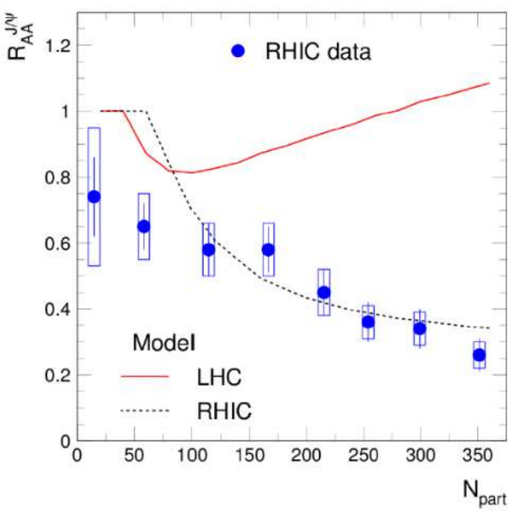


Data: ALICE / ATLAS / CMS (mid rapidity) - QM 2011





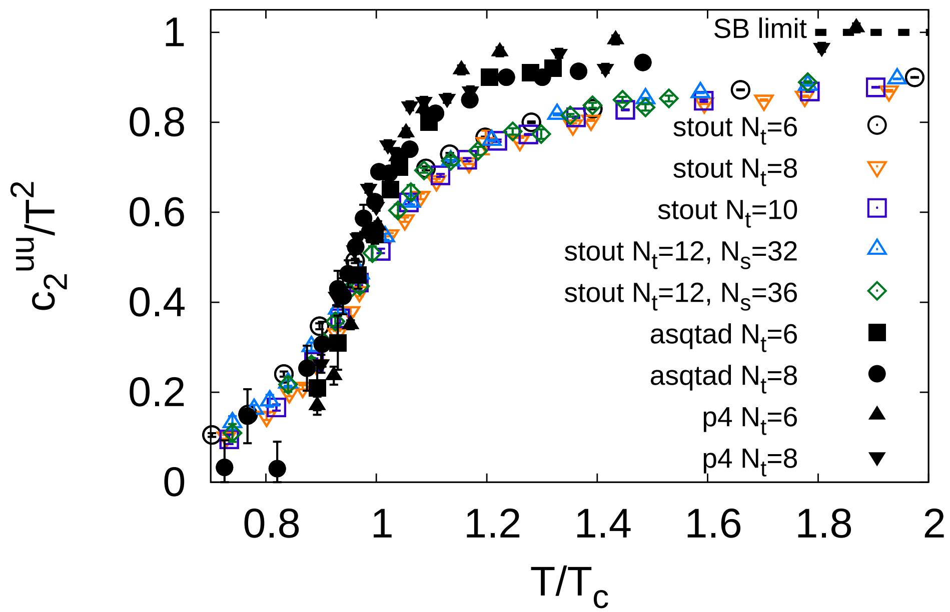
Prediction: Braun-Munzinger, Stachel arXiv:0901.2500



Conclusion:
All datasets (forward and mid-rapidity, low and high pT) show significant J/ψ suppression in central collisions in contradiction to statistical model predictions: possibly no common freeze-out surface or no strong partonic recombination ?

Comparison with previous lattice data

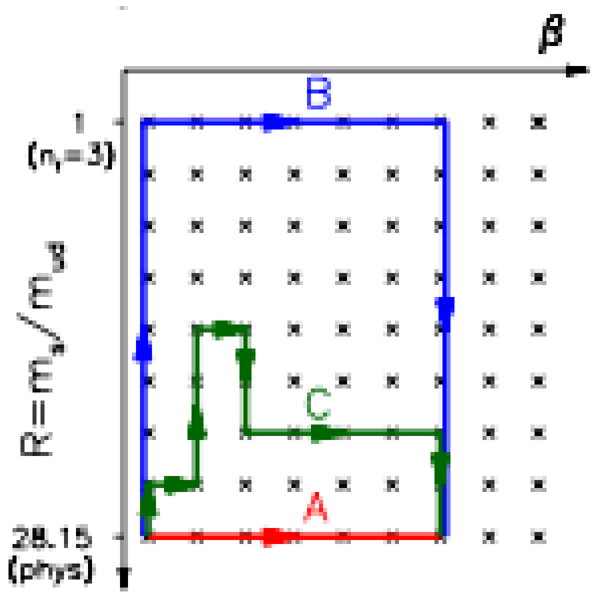
$$c_2^{uu} = \frac{T}{V} \frac{\partial^2 \ln Z}{\partial \mu_u \partial \mu_u} \Bigg|_{\mu_i = 0}$$



- physical quark masses $m_s/m_{u,d} = 28.15$
- finer lattice spacings approaching the continuum
- the phase transition turns out to be much smoother

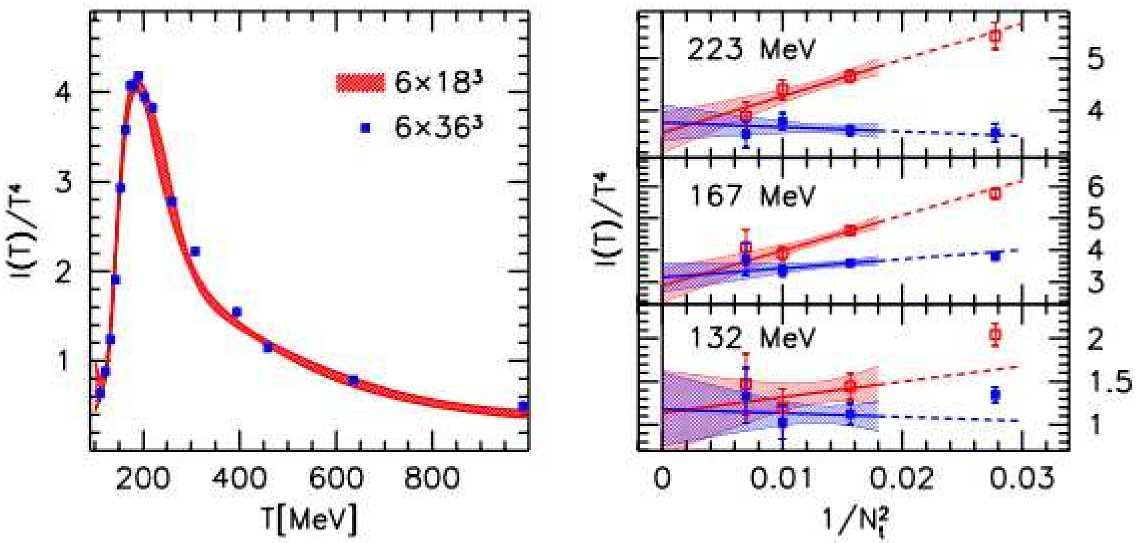
All path approach

- Our goal:
  - determine the equation of state for several pion masses
  - reduce the uncertainty related to the choice of β^0



- conventional path: A, though B, C or any other paths are possible
- generalize: take all paths into account

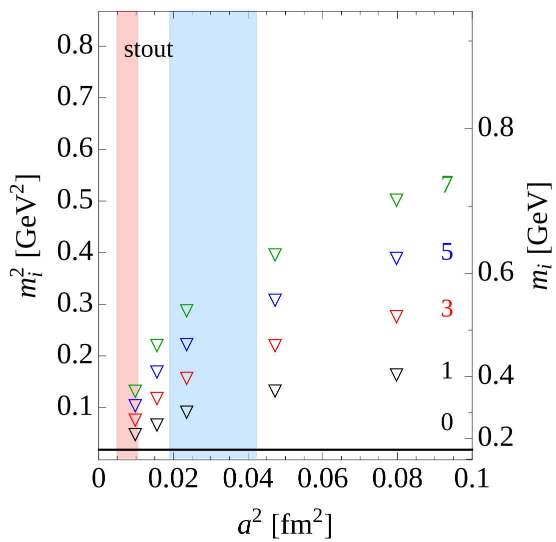
Finite volume and discretization effects

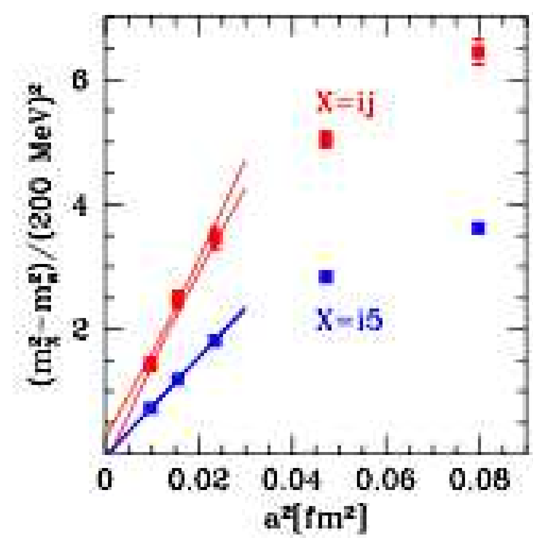


- finite V : $N_s/N_t = 3$ and 6 (8 times larger volume): no sizable difference
- finite a: improvement program of lattice QCD (action observables)
  - tree-level improvement for p (thermodynamic relations fix the others)
  - trace anomaly for three T-s: high T, transition T, low T
  - continuum limit $N_t = 6, 8, 10, 12$: same with or without improvement
- improvement strongly reduces cutoff effects: slope$\simeq 0$ ($1-2\sigma$ level)

Pseudo-scalar mesons in staggered formulation

- Staggered formulation: four degenerate quark flavors (‘tastes’) in the continuum limit
- Rooting procedure: replace fermion determinant in the partition function by its fourth root
- At finite lattice spacing the four tastes are not degenerate
  - each pion is split into 16
  - the sixteen pseudo-scalar mesons have unequal masses
  - only one of them has vanishing mass in the chiral limit





- Scaling starts for $N_t \geq 8$.