Correlations and fluctuations from lattice QCD

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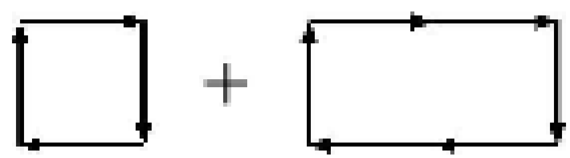
S.Borsanyi,Z.Fodor,S.Katz, S.Krieg, C.R. and K.Szabó, forthcoming

Choice of the action

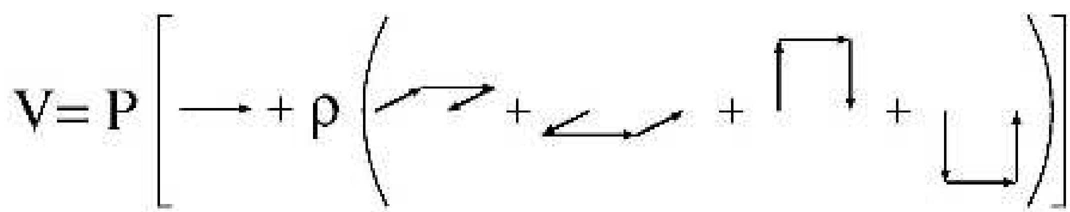
- no consensus: which action offers the most cost effective approach

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

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



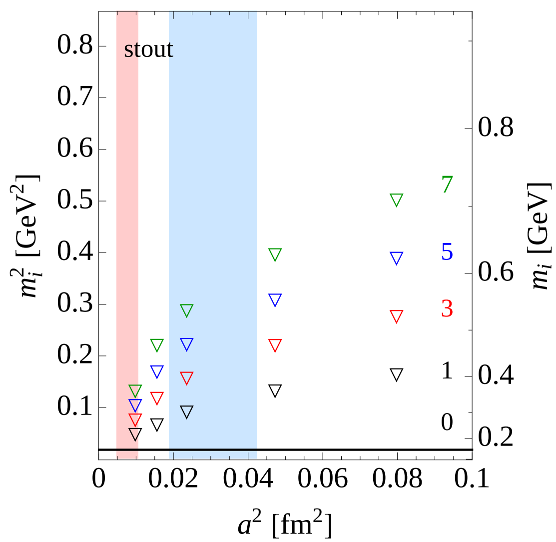
2-level (stout) smeared improved staggered fermions

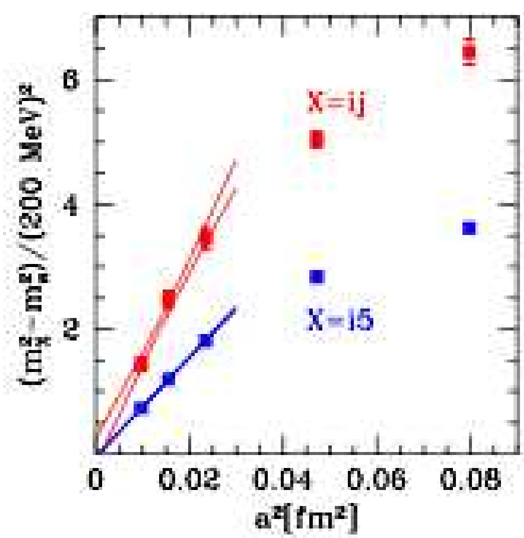


one of best known ways to improve on taste symmetry violation

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 $N_t \geq 8$.

$N_f = 2 + 1$ susceptibilities

with physical quark masses

and $N_t = 6,\ 8,\ 10,\ 12$

Motivation

- The deconfined phase of QCD can be reached in the laboratory

- Need for unambiguous observables to identify the phase transition

  - fluctuations of conserved charges (baryon number, electric charge, strangeness)
    S. Jeon and V. Koch (2000), M. Asakawa, U. Heinz, B. Müller (2000)

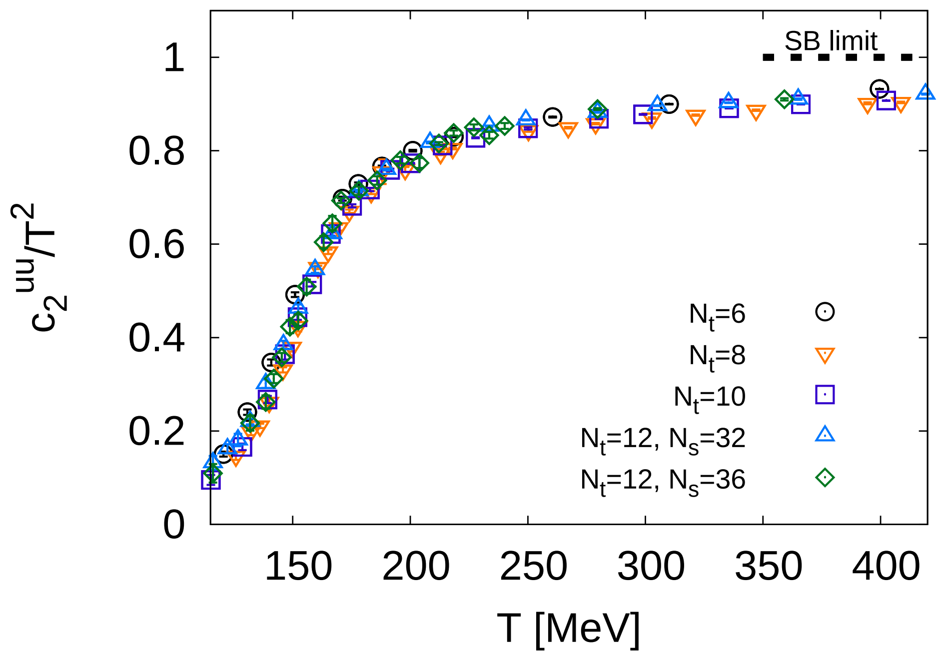
- These observables are sensitive to the microscopic structure of the matter

- A rapid change of these observables in the vicinity of T_c provides an unambiguous signal for deconfinement

- They can be measured on the lattice as combinations of quark number susceptibilities

Results: light quark susceptibilities

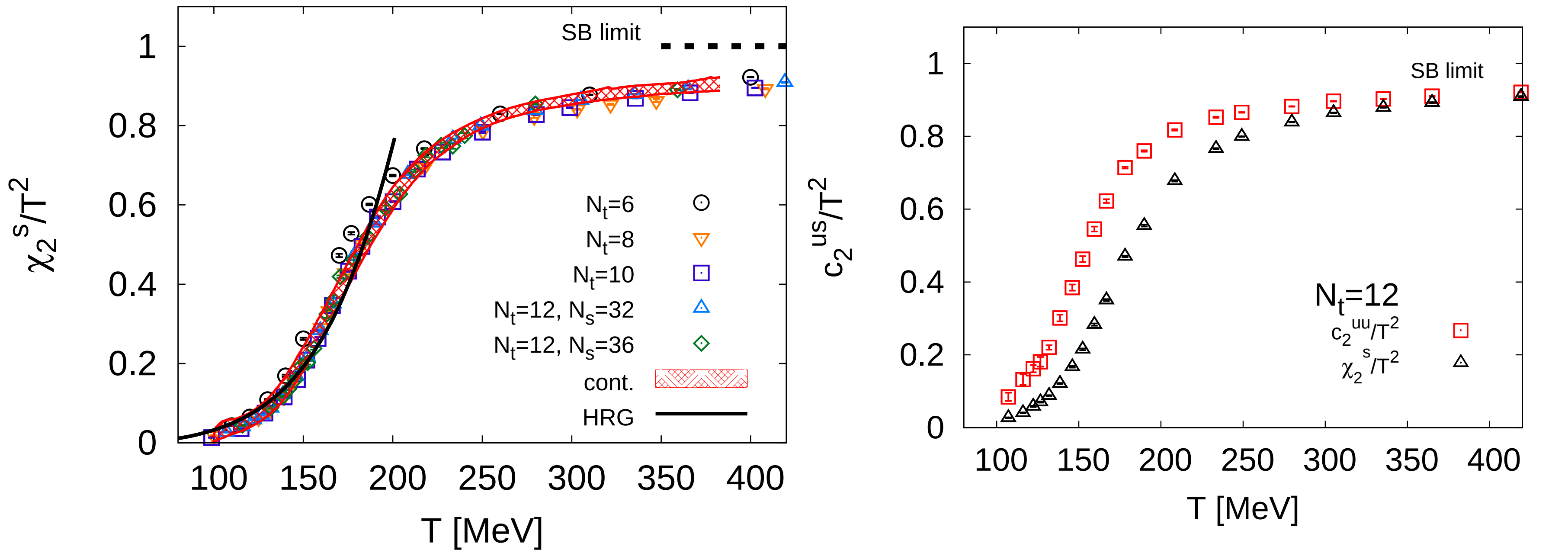
$$c_2^{uu} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial\mu_u\partial\mu_u}\Big|_{\mu_i=0}$$



- c_2^{uu} measures how easy it is to create an excess of u quarks by a finite chemical potential
- quark number susceptibilities exhibit a rapid rise close to T_c
- at large T they reach $\sim 90\%$ of the ideal gas limit

Results: strange quark susceptibilities

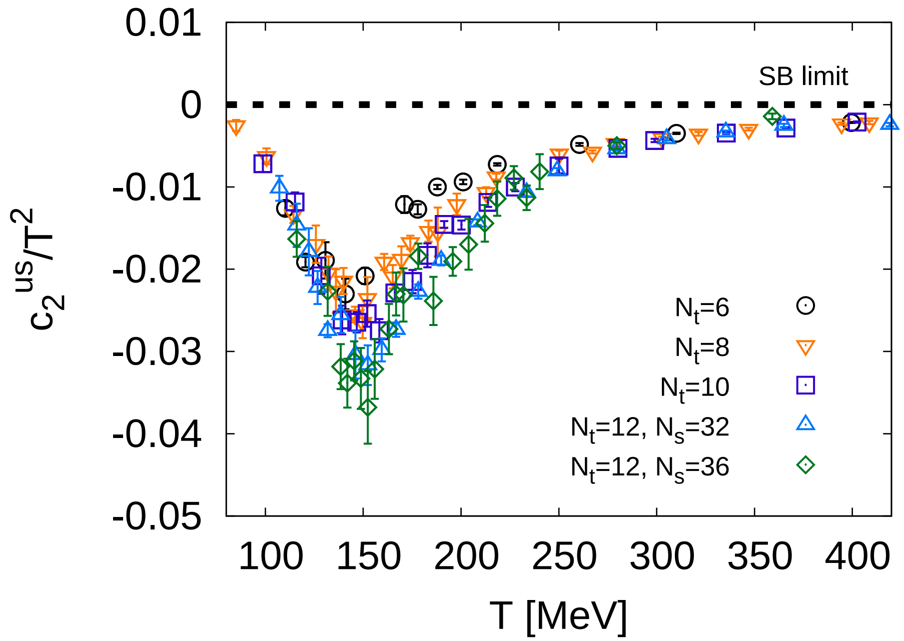
$$\chi_2^s = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial \mu_s^2}\bigg|_{\mu_i=0}$$



- strange quark susceptibilities rise more slowly as functions of T

Results: nondiagonal susceptibilities

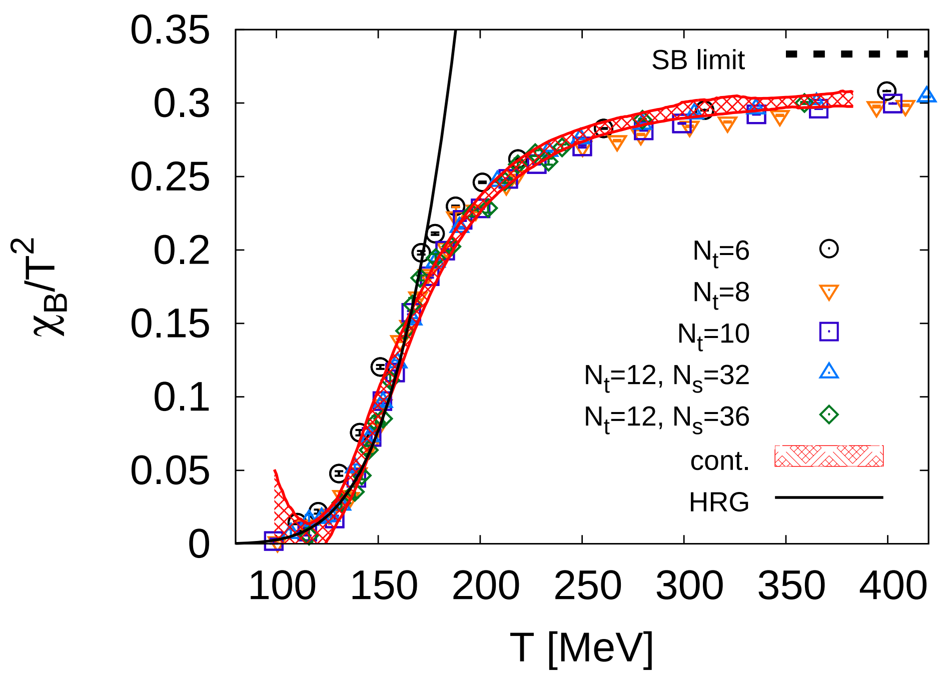
$$c_2^{us} = c_2^{ds} = \frac{1}{2}\frac{T}{V}\frac{\partial^2 \ln Z}{\partial\mu_u\partial\mu_s}\bigg|_{\mu_i=0}$$



- non-diagonal susceptibilities look at the linkage between different flavors
- in the hadronic phase they are non-zero due to mesons
- they vanish in the QGP phase at large temperatures
  - ➡ a particle carrying a flavor does not exhibit quantum numbers of another flavor

Results: fluctuations of baryon number

$$\chi_B = \frac{1}{9}\left(2c_2^{uu} + \chi_2^s + 2c_2^{ud} + 4c_2^{us}\right)$$



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

How can we test the presence of bound states in the QGP?

- Simple QGP: strangeness is carried by strange quarks
  - → Baryon number and strangeness are correlated
- Hadron gas: strangeness is carried mostly by mesons
  - → Baryon number and strangeness are uncorrelated
- Bound state QGP: strangeness is carried mostly by partonic bound states
  - → Baryon number and strangeness are uncorrelated

We define the following object

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

V. Koch, A. Majumder, J. Randrup, PRL95 (2005). E. Shuryak, I. Zahed, PRD70 (2004).

Simple estimates

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 $\mu = 0$

  $$C_{BS} = 0.66$$

In bound state QGP:

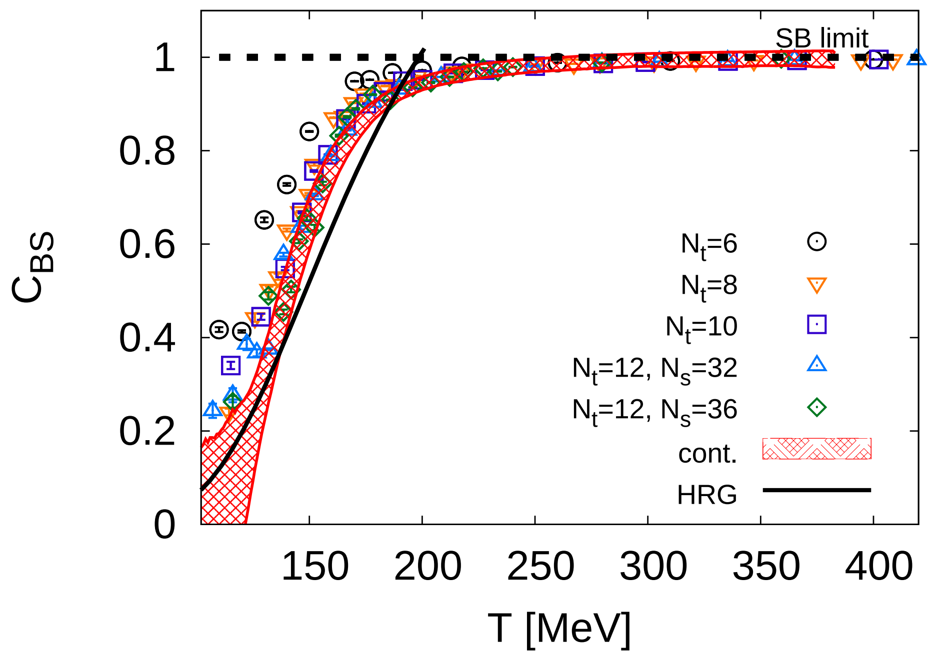
- heavy quark, antiquark quasiparticle contribute both to $\langle BS\rangle$ and to $\langle S^2\rangle$
- bound states of the form sg or $\bar{s}g$ contribute both to $\langle BS\rangle$ and to $\langle S^2\rangle$
- bound states of the form $s\bar{q}$ or $\bar{s}q$ contribute only to $\langle S^2\rangle$

  at $T = 1.5\, T_c$ MeV and $\mu = 0$

  $$C_{BS} = 0.62$$

Results: baryon-strangeness correlator

$$C_{BS} = 1 + \frac{c_2^{us} + c_2^{ds}}{\chi_2^s}$$



- C_{BS} rules out the possibility of bound states soon above T_c
- there is a window immediately above the transition where $C_{BS} < 1$
- the presence of pure gluon clusters cannot be ruled out

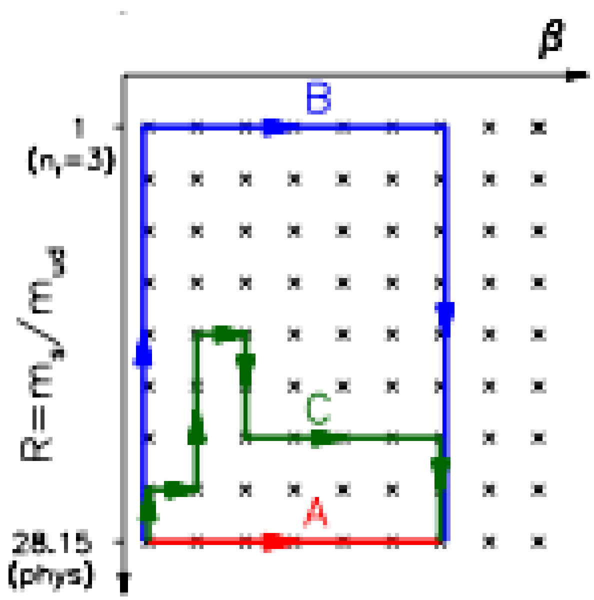
Conclusions

- diagonal and non-diagonal susceptibilities for $N_f = 2+1$ dynamical flavors
- baryon number fluctuations: signals of QCD phase transition
  - rapid rise close to T_c
- correlations between different flavors vanish soon above T_c
  - there is a window above T_c where they are non-zero
  - bound states melt in the QGP
  - the possibility of pure gluon clusters cannot be ruled out

Backup slides

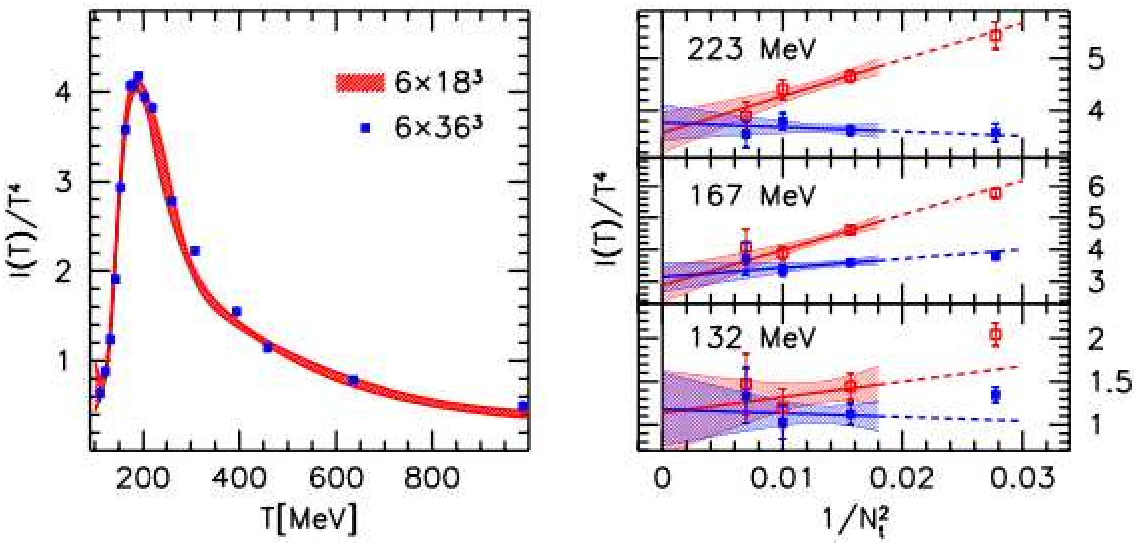
All path approach

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



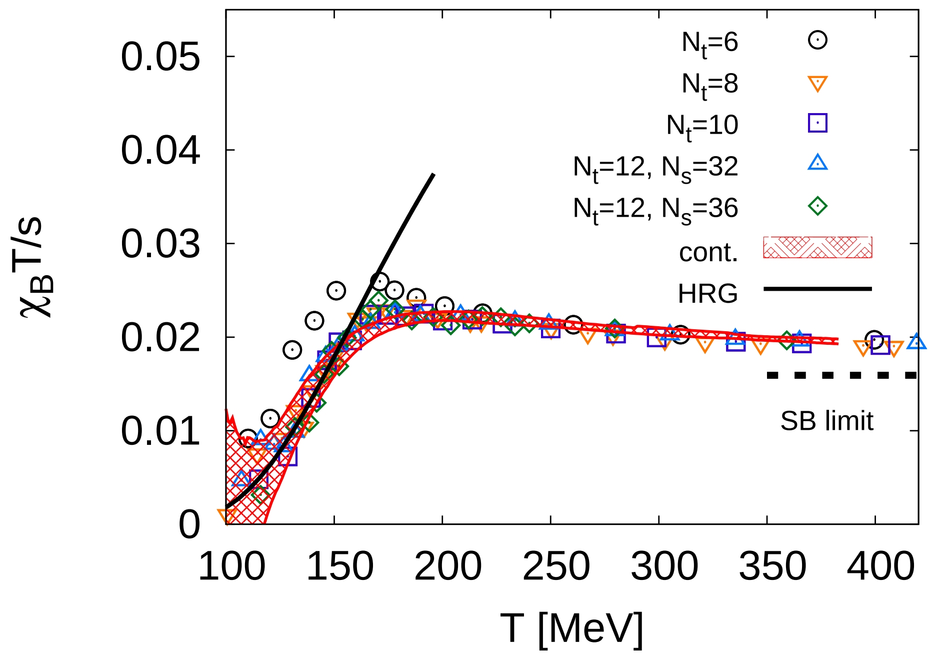
- conventional path: A, though B, C or any other paths are possible
- generalize: take all paths into account

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)

Results: fluctuations of baryon number over entropy



- it is supposed to be different in hadronic and QGP phases
- it can be measured experimentally
- it is a good signal for QGP formation