# Correlations and fluctuations from lattice QCD

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(Wuppertal-Budapest collaboration)

# Motivation

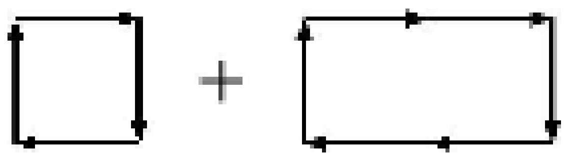
- The deconfined phase of QCD can be reached in the laboratory
- Need for unambiguous observables to identify the phase transition
  - fluctuations of conserved charges (baryon number, electric charge, strangeness)
    S. Jeon and V. Koch (2000), M. Asakawa, U. Heinz, B. Müller (2000)
- A rapid change 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

# Choice of the action

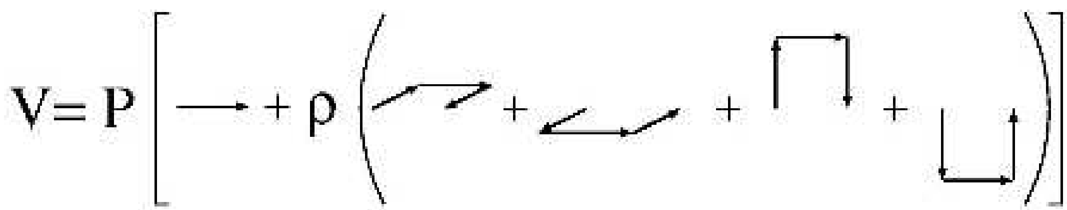
- no consensus: which action offers the most cost effective approach

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

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



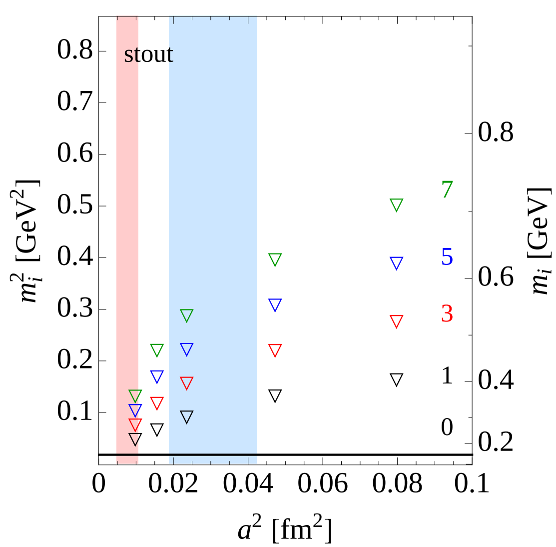
2-level (stout) smeared improved staggered fermions

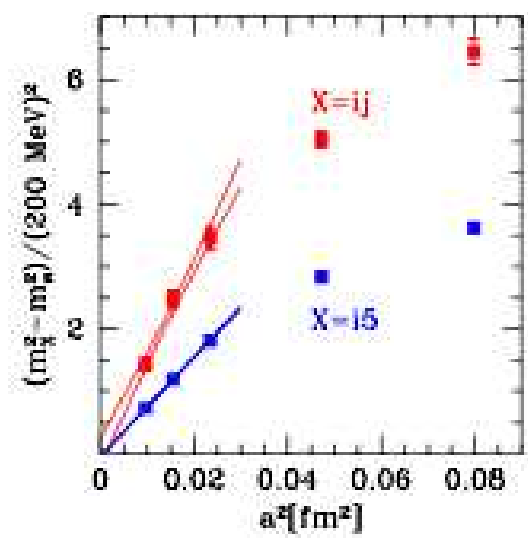



one of best known ways to improve on taste symmetry violation

# 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 $N_t \geq 8$.

diagonal and non-diagonal

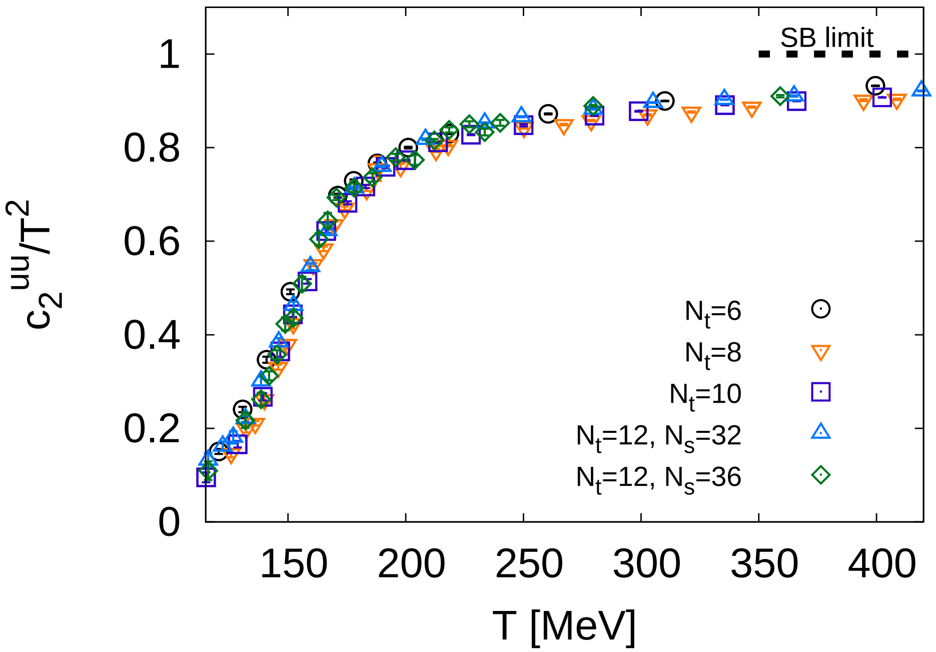
quark number susceptibilities

$N_f = 2 + 1$ dynamical quark flavors

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

# Results: light quark susceptibilities

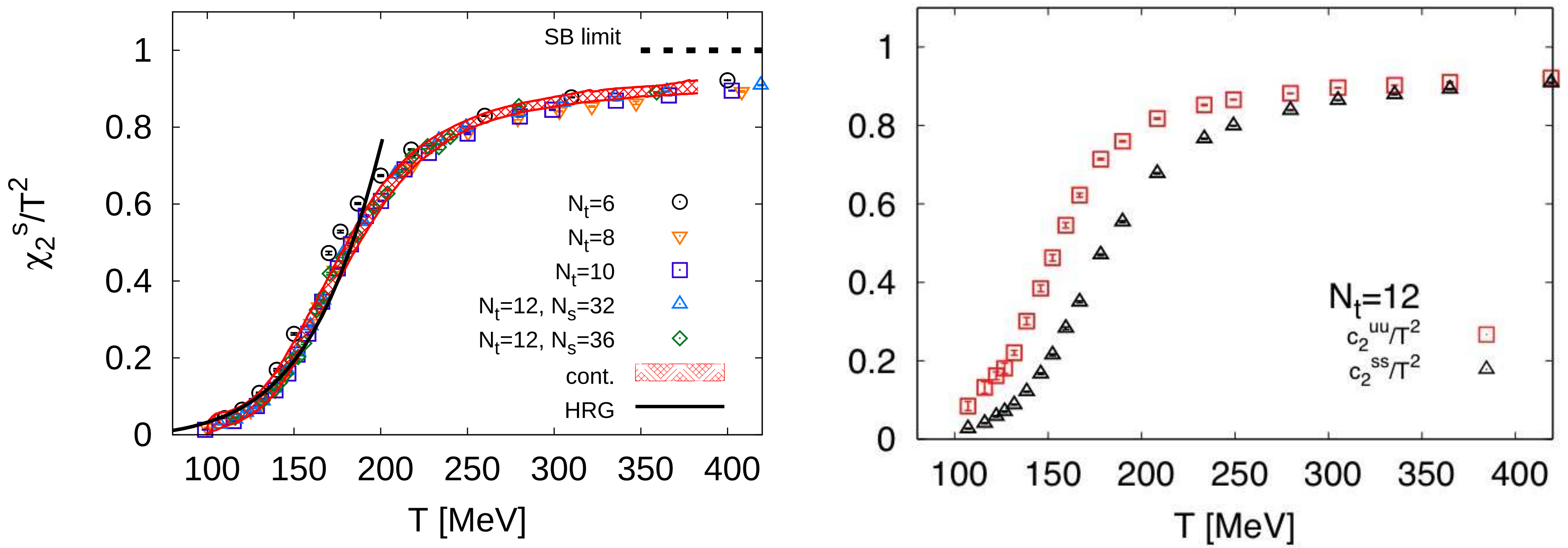
$$c_2^{uu} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial\mu_u\partial\mu_u}\Bigg|_{\mu_i=0}$$




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

# Results: strange quark susceptibilities

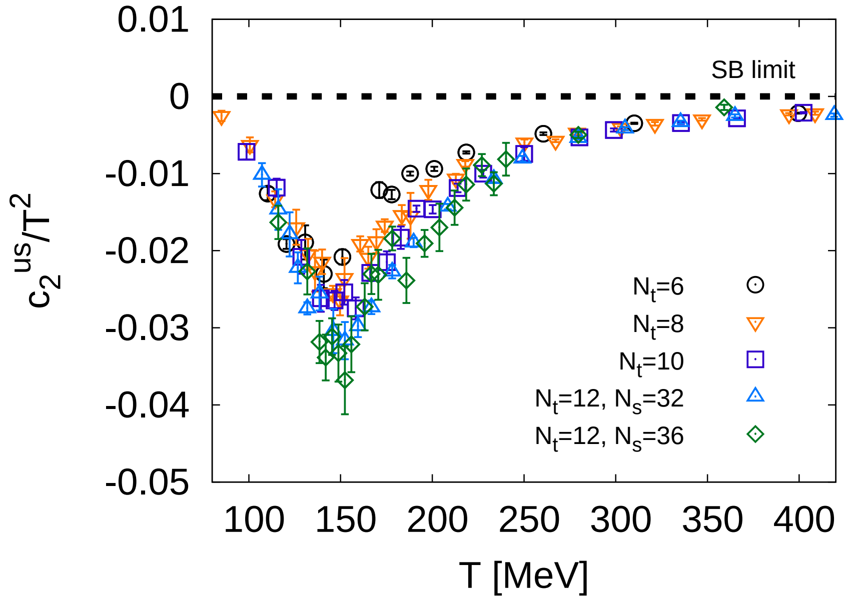
$$c_2^{ss} = \chi_2^s = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial \mu_s^2}\bigg|_{\mu_i=0}$$




- strange quark susceptibilities rise more slowly as functions of $T$
  - ➠ strange quarks are liberated at larger temperatures

# Results: nondiagonal susceptibilities

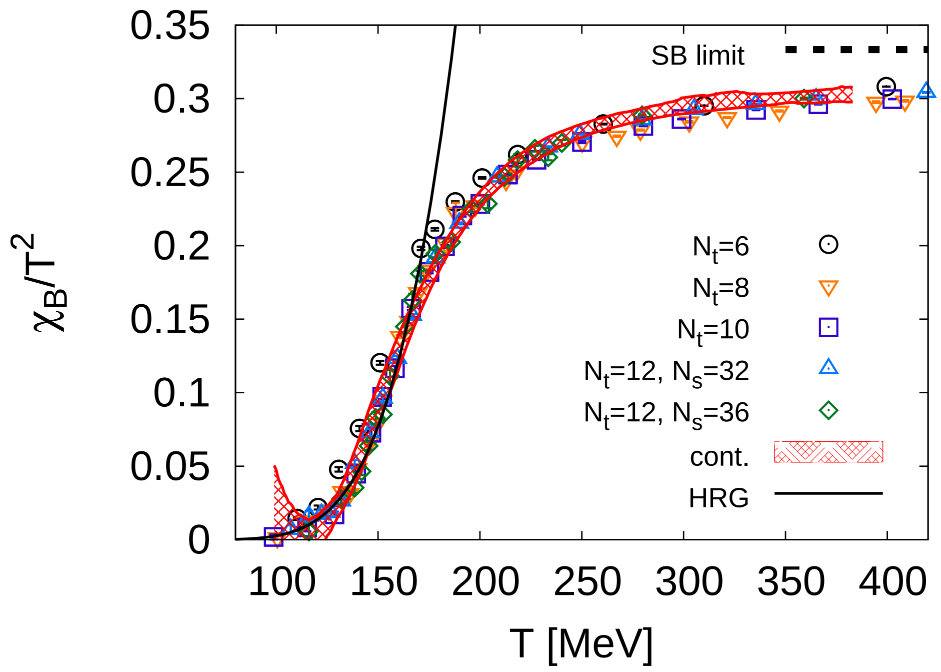
$$c_2^{us} = c_2^{ds} = \frac{T}{V} \frac{\partial^2 \ln Z}{\partial \mu_u \partial \mu_s} \Big|_{\mu_i=0}$$




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

# 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

# Testing 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 $\mu$**

  $$C_{BS} = 1$$

## In hadron gas phase:

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

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

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

  $$C_{BS} = 0.66$$

## In bound state QGP:

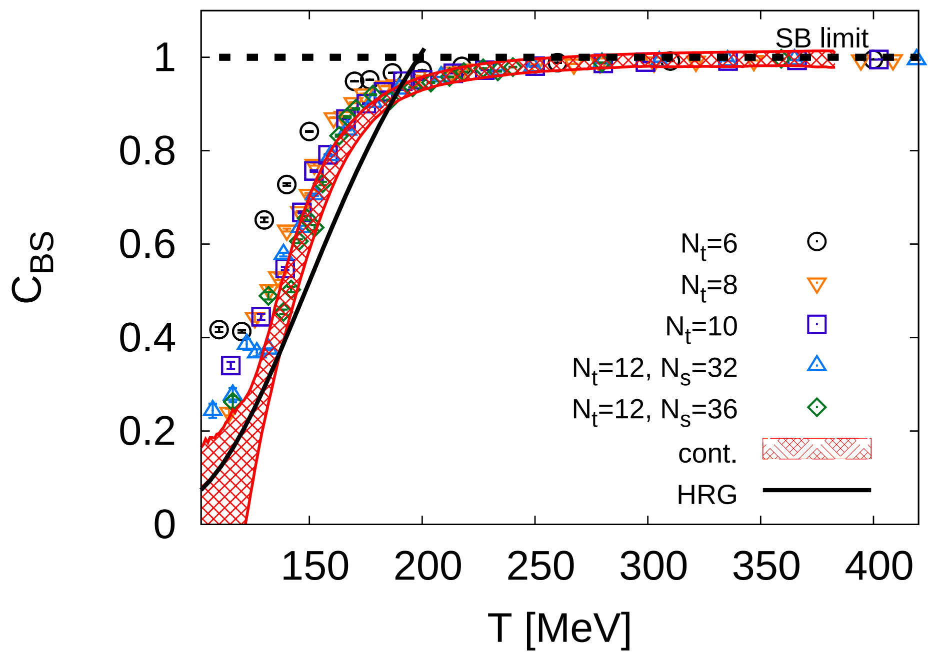
- heavy quark, antiquark quasiparticle contribute both to $\langle BS\rangle$ and to $\langle S^2\rangle$
- bound states of the form $sg$ or $\bar{s}g$ contribute both to $\langle BS\rangle$ and to $\langle S^2\rangle$
- bound states of the form $s\bar{q}$ or $\bar{s}q$ contribute only to $\langle S^2\rangle$

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

  $$C_{BS} = 0.62$$

# Results: baryon-strangeness correlator

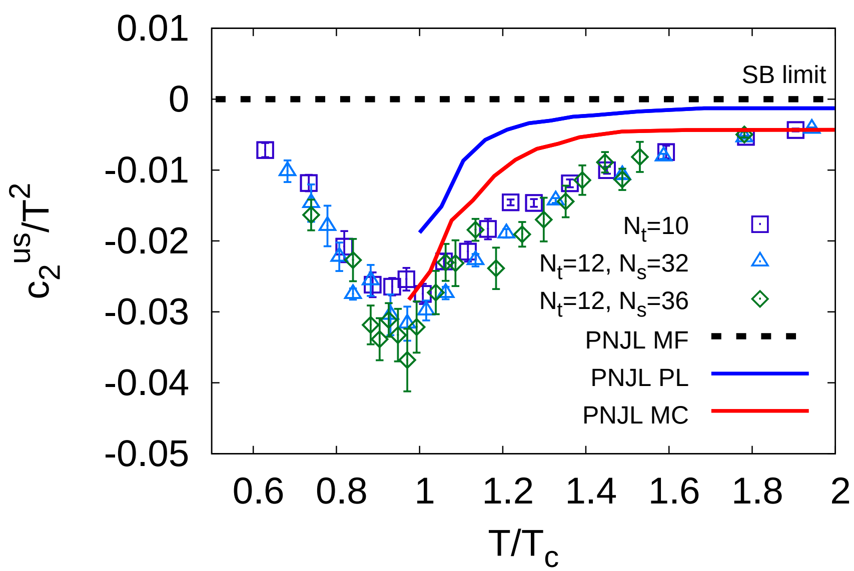
$$C_{BS} = 1 + \frac{c_2^{us} + c_2^{ds}}{\chi_2^s}$$




- $C_{BS}$ 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 $C_{BS} < 1$

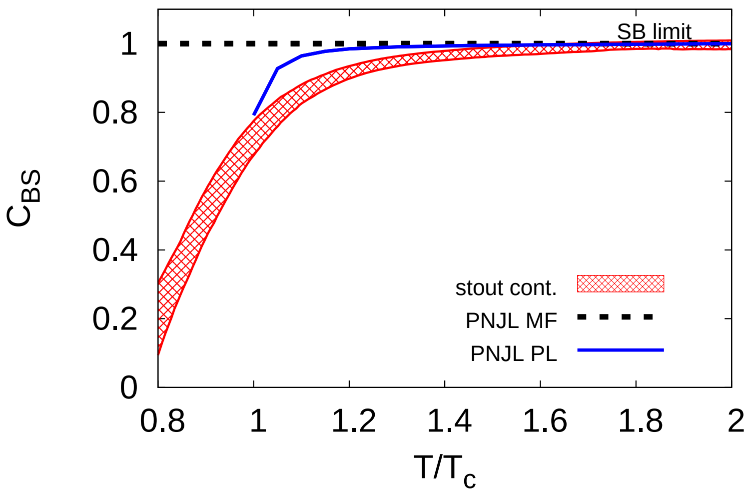
# Recent work: are there bound states in the QGP?

- Comparison of lattice to PNJL (C.R., R. Bellwied, M. Cristoforetti, M. Barbaro, arXiv:1109.6243)

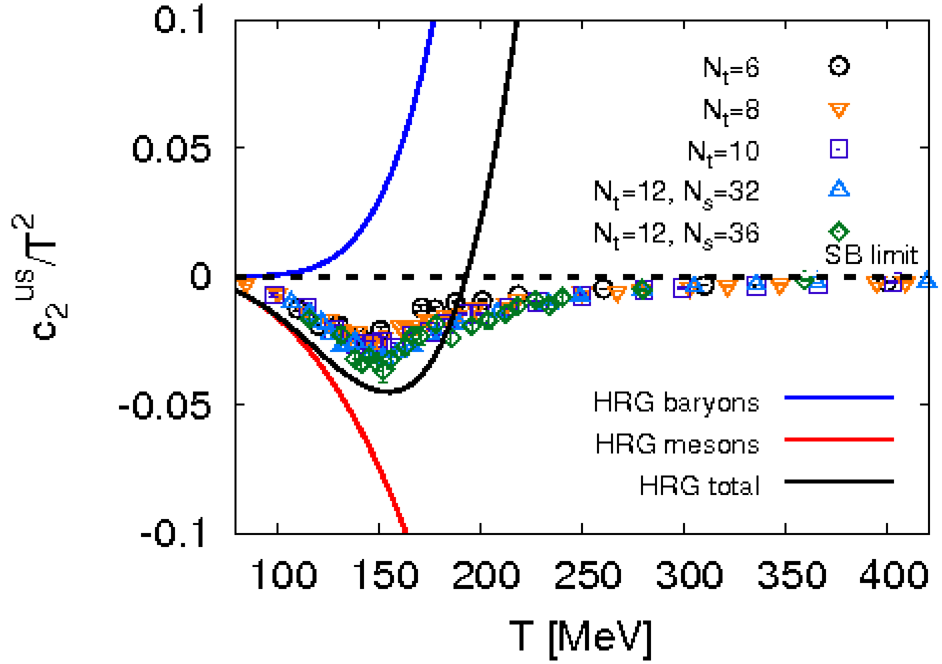



- PNJL MF: pure mean field calculation
- PNJL PL: mean field plus Polyakov loop fluctuations
- PNJL MC: full Monte Carlo result with all fluctuations taken into account
- the red curve falls on the blue for $V \to \infty$

- Even the inclusion of fluctuations is not enough to describe lattice data above $T_c$
- There has to be a contribution from bound states



# Baryon-meson dependence in correlator




- Baryons dominate in HRG at $T > 190 MeV$
- The lattice correlator never turns positive
  - ➡ bound states above $T_c$ are predominantly of mesonic nature
- The upswing in the lattice data shows that baryon contribution increases with $T$

C.R., R. Bellwied, M. Cristoforetti, M. Barbaro, arXiv:1109.6243 charm quark susceptibilities

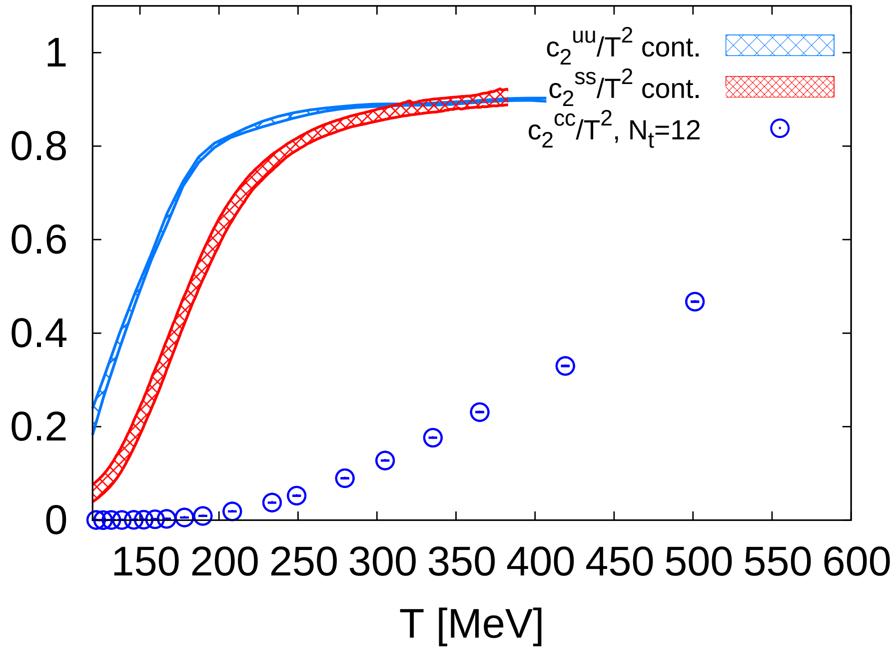
$$N_f = 2 + 1 + 1$$

with partial quenched charm

$$m_c/m_s = 11.85$$

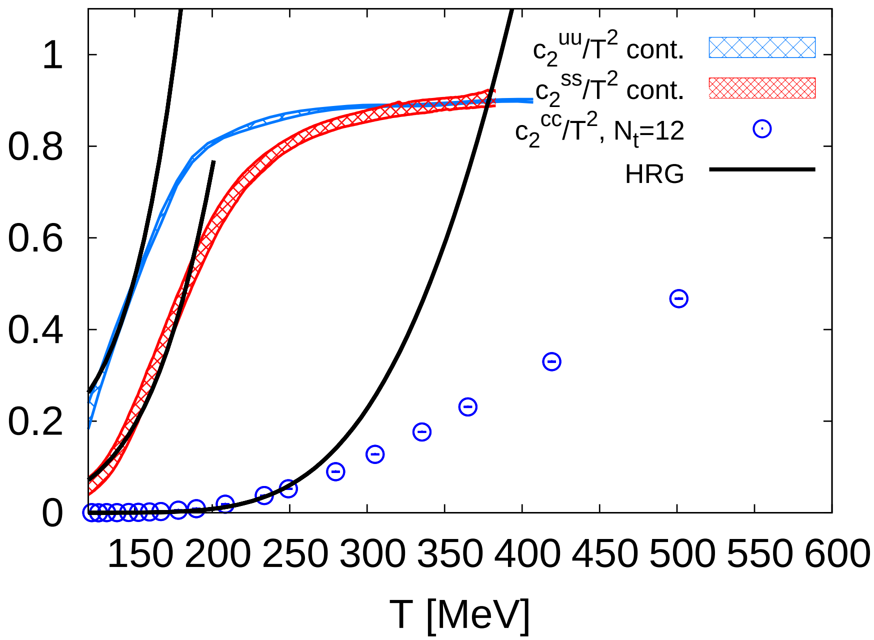
# Charm quark number susceptibilities

$$c_2^{cc} = \frac{T}{V}\frac{\partial^2 \ln Z}{\partial\mu_c\partial\mu_c}\bigg|_{\mu_i=0}$$



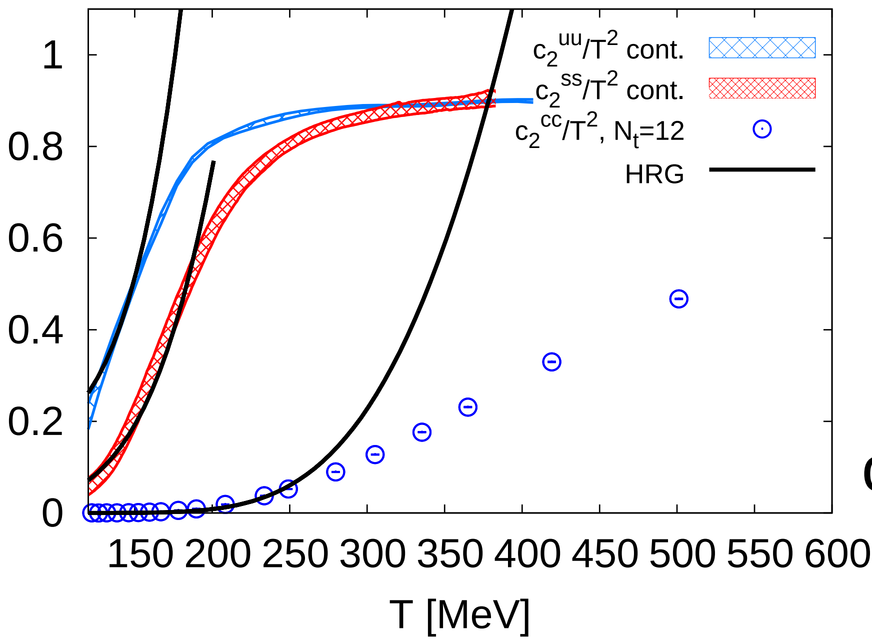

- charm susceptibilities rise at much larger temperatures compared to the light quark ones
- their rise with temperature is much slower

# Possible interpretations

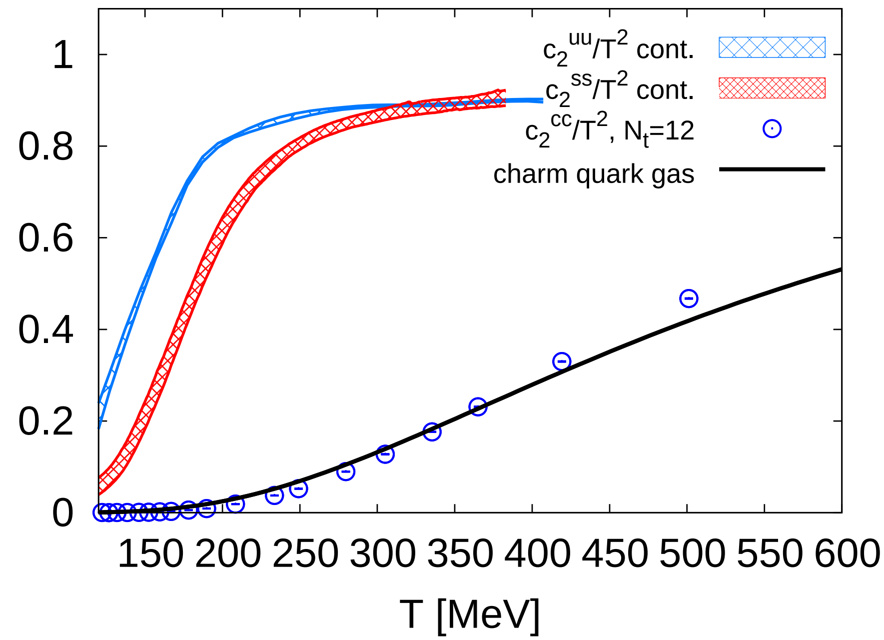



- survival of open charm hadrons up to $T \simeq 2T_c$?
- HRG results agree with the lattice up to the inflection point in the data

# 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

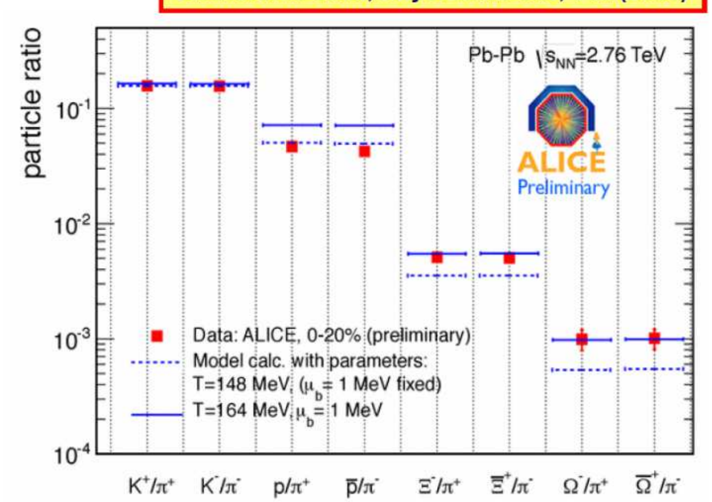
# There are evidences for deviations from statistical model predictions at the LHC
## - baryon production -

R. Preghenella, ALICE Collaboration, SQM 2011:

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

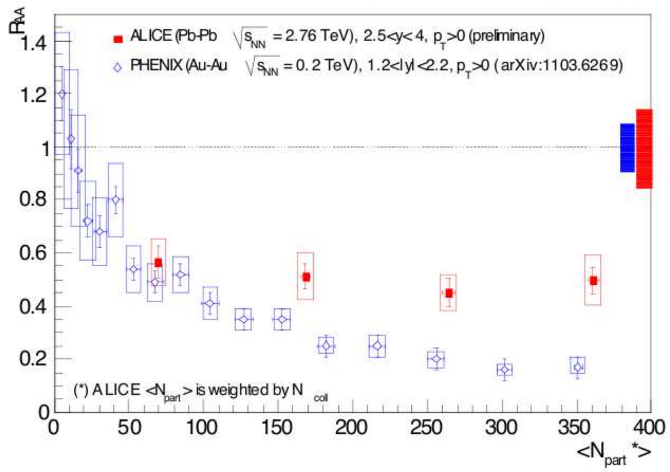



Conclusion:
possibly no common freeze-out surface for all particle species ?

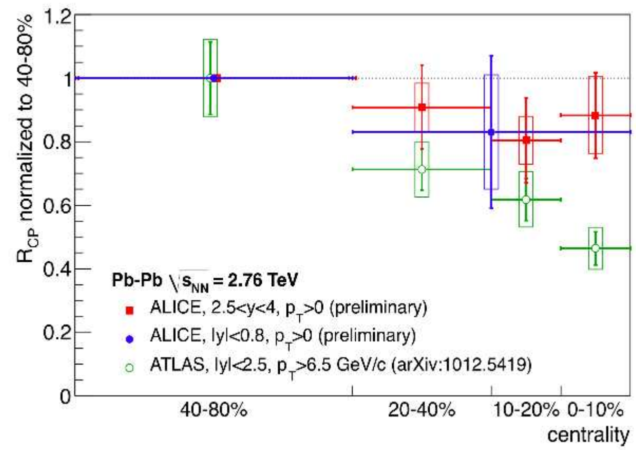
# There are evidences for deviations from statistical model predictions at the LHC

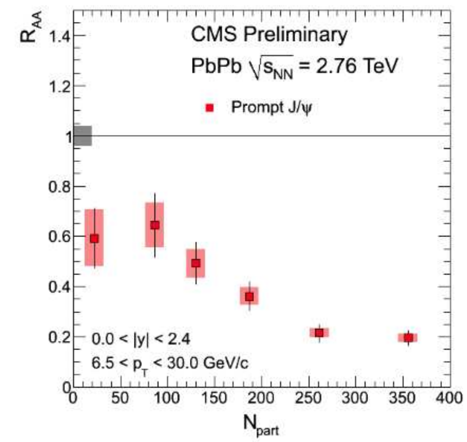
## - $J/\psi$ production -

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

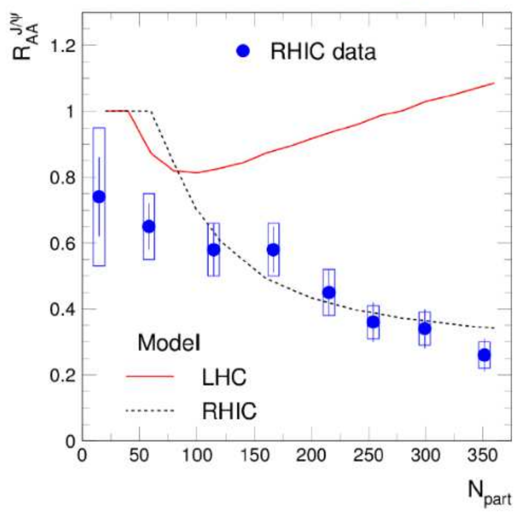



Data: ALICE / ATLAS / CMS (mid rapidity) - QM 2011



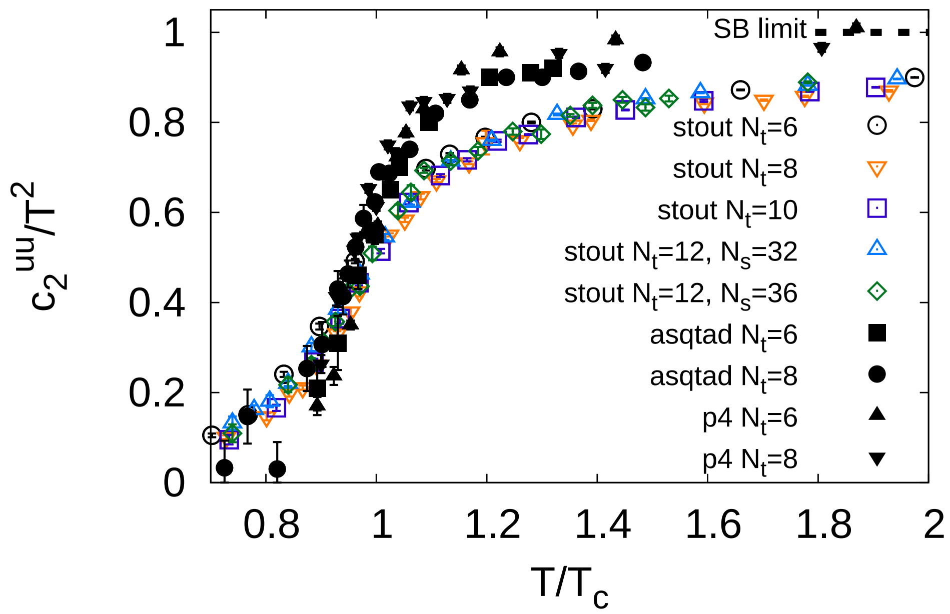

Prediction: Braun-Munzinger, Stachel arXiv:0901.2500




Conclusion:
All datasets (forward and mid-rapidity, low and high pT) show significant $J/\psi$ 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

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




- 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