Baryon-Strangeness Correlations

- Introduction
- BS and other correlations
- Some speculations

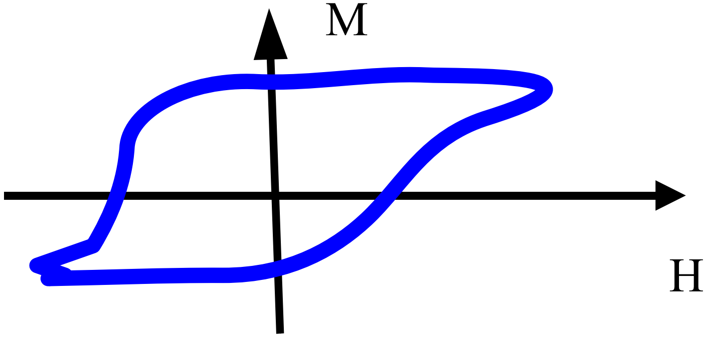
Work in collaboration with: A. Majumder and J. Randrup

Susceptibilities

$$E = E_0 + mH + \mu Q$$

$$\langle m \rangle = \frac{dF}{dH}$$

$$\langle Q \rangle = \frac{dF}{d\mu}$$



Susceptibilities

$$\chi_m = \frac{d^2 F}{dH^2}$$

$$\chi_Q = \frac{d^2 F}{d\mu^2}$$

$$\langle \delta m \rangle = \chi_m \delta H$$

$$\langle \delta Q \rangle = \chi_Q \delta \mu$$

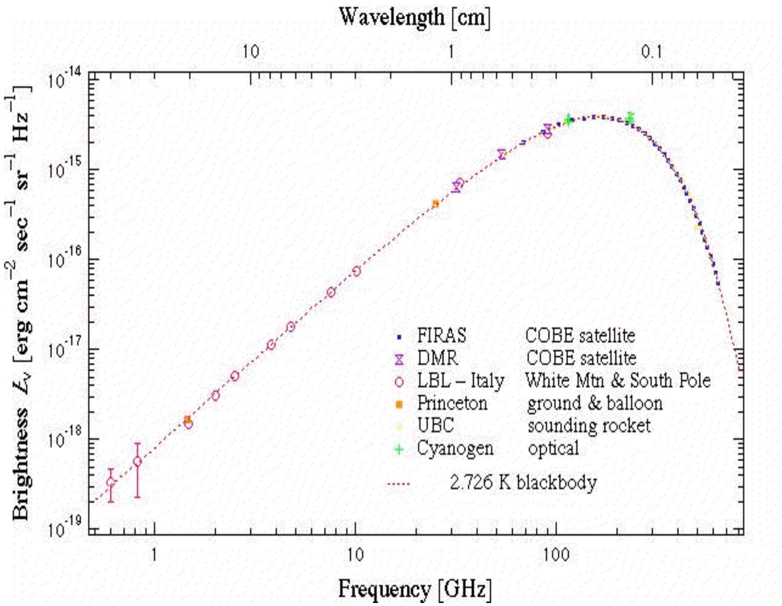
Linear response

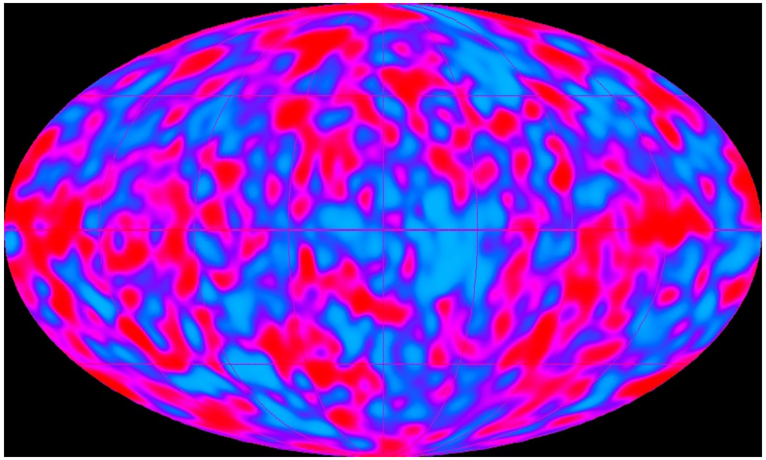
$$\langle (\delta m)^2 \rangle = \chi_m$$

$$\langle (\delta Q)^2 \rangle = \chi_Q$$

Fluctuations

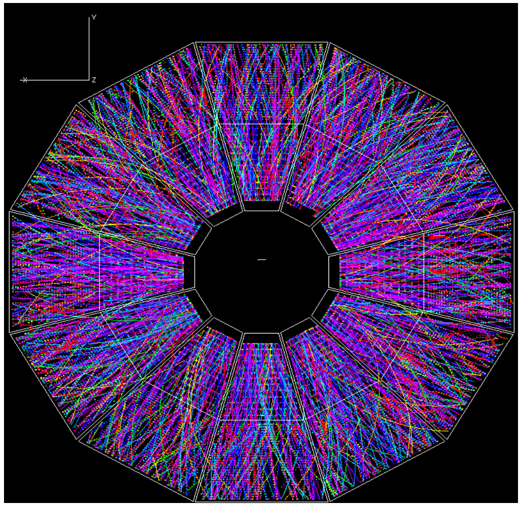
The mother of all thermal spectra and fluctuations

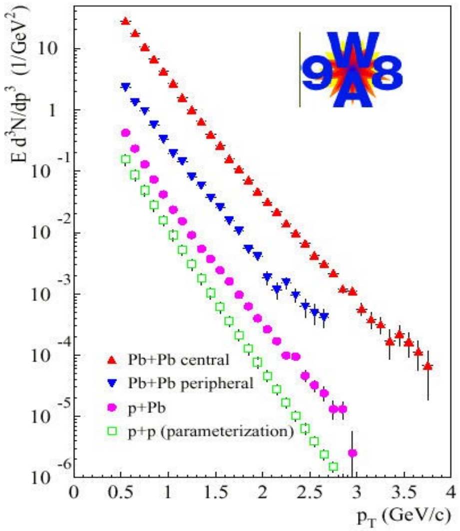




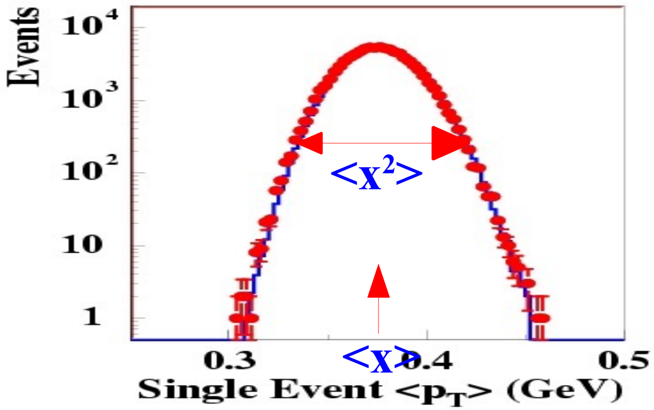
Fluctuations at the level of 10^{-5} !!!

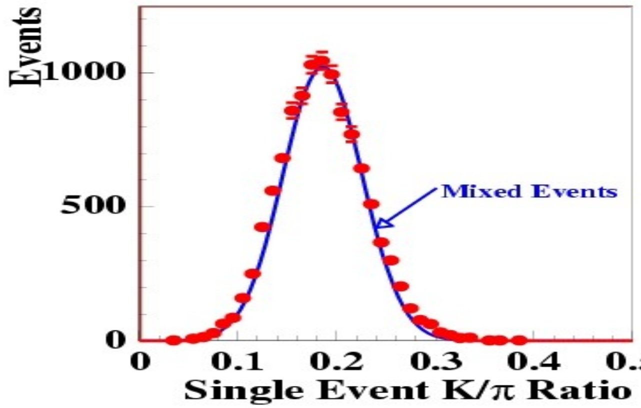
Heavy Ions: Event-by-Event





NA49 Pb+Pb Event-by-Event Fluctuations





The physics is in the width

E-by-E measures
2-particle correlations

Fluctuations in thermal system

e.g. Lattice QCD

$$Z = Tr\left[\exp\left(-\beta\left(H - \mu_Q Q - \mu_B B - \mu_S S\right)\right)\right]$$

Mean : $\langle X \rangle = T \frac{\partial}{\partial \mu_X} \log(Z) = -\frac{\partial}{\partial \mu_X} F$ $\quad X = Q, B, S$

Variance: $\langle (\delta X)^2 \rangle = T^2 \frac{\partial^2}{\partial \mu_X^2} \log(Z) = -T \frac{\partial^2}{\partial \mu_X^2} F$

Co-Variance: $\langle (\delta X)(\delta Y) \rangle = T^2 \frac{\partial^2}{\partial \mu_X \partial \mu_Y} \log(Z) = -T \frac{\partial^2}{\partial \mu_X \partial \mu_Y} F$

Susceptibility: $\chi_{XY} = -\frac{1}{V} \frac{\partial^2}{\partial \mu_X \partial \mu_Y} F = -\frac{1}{V} \frac{\partial}{\partial \mu_X} \langle Y \rangle$

Simple Observation

Or how can we test the sQGP

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 by partonic bound states

→ Baryon Number and Strangeness should be uncorrelated

<BS> and the Bound State QGP

Define: $$C_{BS} \equiv -3 \frac{\langle(\delta B)(\delta S)\rangle}{\langle(\delta S)^2\rangle} = -3 \frac{\langle\left(B-\langle B\rangle\right)\left(S-\langle S\rangle\right)\rangle}{\langle\left(S-\langle S\rangle\right)^2\rangle} = -3 \frac{\langle BS\rangle}{\langle S^2\rangle} = -3 \frac{X_{BS}}{X_{SS}}$$

(-3) compensates baryon-number and strangenes of quarks

In Experiment $$C_{BS} = -3 \frac{\frac{1}{N_{eve.}}\sum_i B_i S_i - \frac{1}{N_{eve.}^2}\sum_i B_i \sum_j S_j}{\frac{1}{N_{eve.}}\sum_i S_i^2 - \frac{1}{N_{eve.}^2}\sum_i S_i \sum_j S_j}$$

Uncorrelated particles: $$C_{BS} = -3 \frac{\sum_i \langle N_i\rangle S_i B_i}{\sum_i \langle N_i\rangle S_i^2}$$

Simple estimates

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

In a QGP phase

$$-3\langle BS\rangle = \langle n_s\rangle + \langle n_{\bar{s}}\rangle$$

$$\langle S^2\rangle = \langle n_s\rangle + \langle n_{\bar{s}}\rangle$$

At *all* T and μ

$C_{BS} = 1$

In hadron gas phase

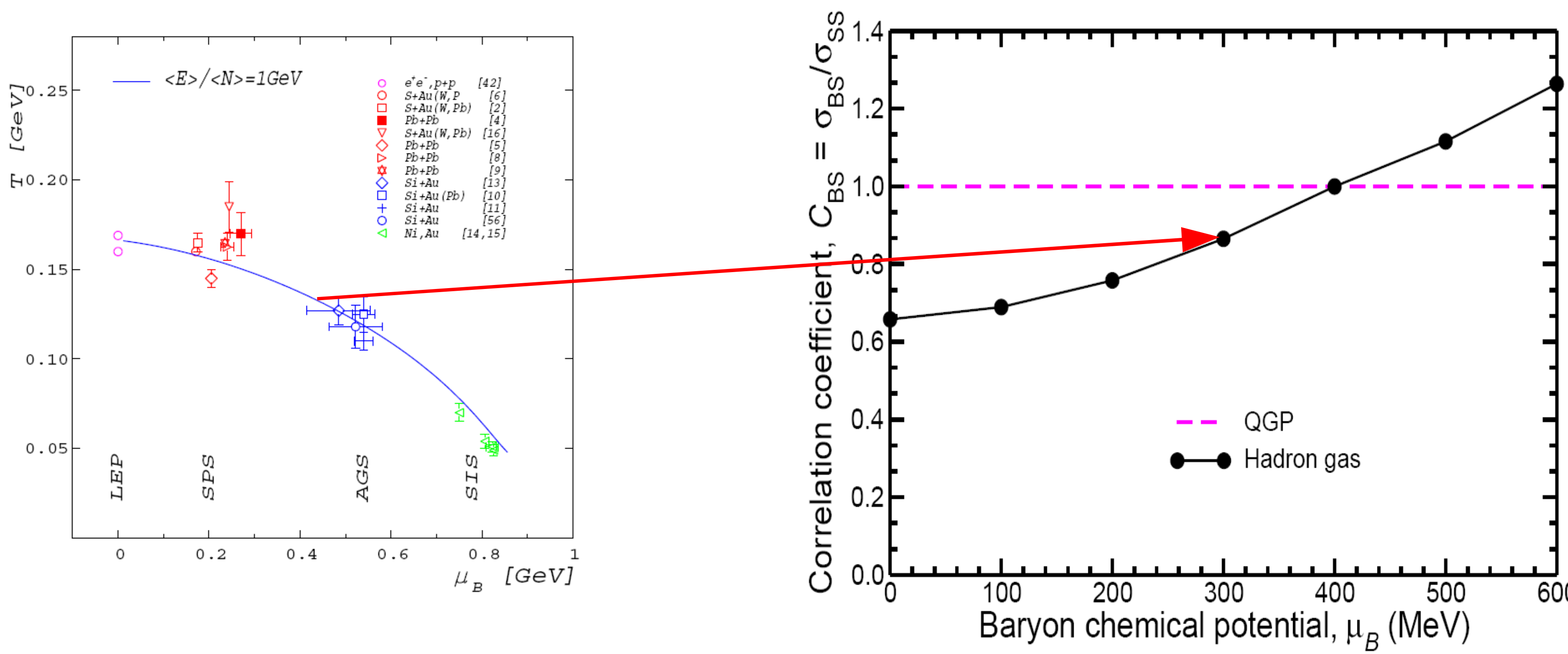
$$-3\langle BS\rangle = 3[\Lambda + \bar{\Lambda} + \Sigma + \bar{\Sigma} + \ldots] + 6[\Xi + \bar{\Xi} + \ldots] + 9[\Omega + \ldots]$$

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

At T=170MeV, μ=0

$C_{BS} = 0.66$

Hadron gas



At large μ: N(K⁺) = N(Λ+ Σ)

$$C_{BS} = 3\frac{\Lambda+\Sigma}{K^{+}+\Lambda+\Sigma} = \frac{3}{2} \quad \text{at large } \mu$$

The Bound State QGP

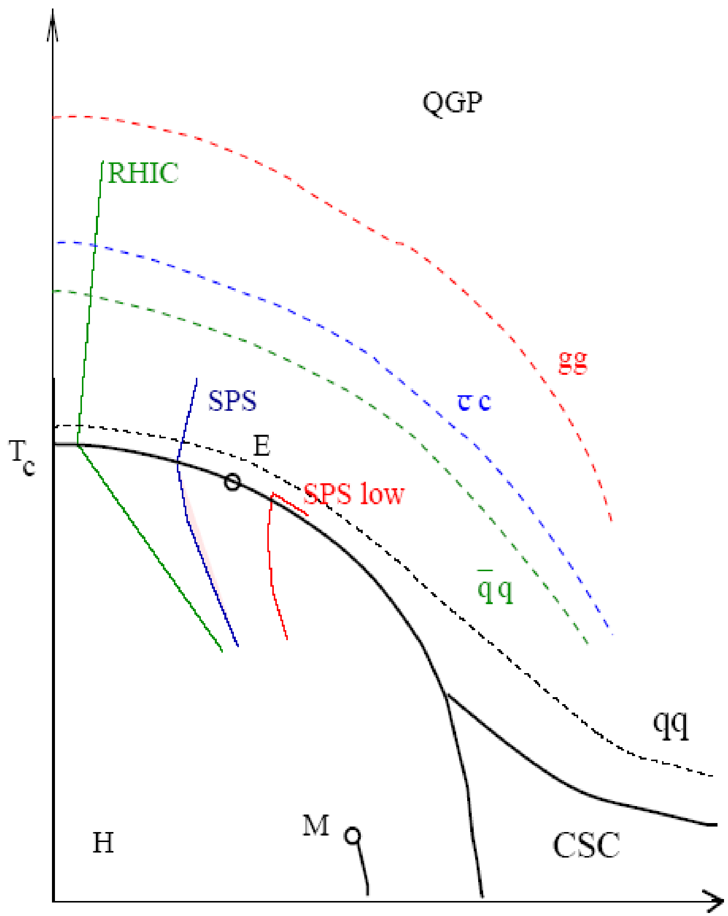


TABLE I. Binary attractive channels discussed in this work, the subscripts s, c, and f mean spin, color, and flavor; $N_f = 3$ is the number of relevant flavors.

Channel	Representation	Charge factor	No. of states
gg	1	9/4	9_s
gg	8	9/8	$9_s * 16$
$qg + \bar{q}g$	3	9/8	$3_c * 6_s * 2 * N_f$
$qg + \bar{q}g$	6	3/8	$6_c * 6_s * 2 * N_f$
$\bar{q}q$	1	1	$8_s * N_f^2$
$qq + \bar{q}\,\bar{q}$	3	1/2	$4_s * 3_c * 2 * N_f^2$

Gluon-Gluon states do not contribute!

C_{BS} in bound state QGP

- Heavy quark, antiquark quasiparticles: $C_{BS} = 1$
- Quark gluon states (color triplet, 36 states): $C_{BS} = 1$
- Quark-antiquark states: 8 π like, 24 ρ like: $\mathbf{C_{BS} = 0}$

T=1.5Tc, $C_{BS} = 0.61$

Similar to Hadron gas estimate…

Estimates from the Lattice

$$\langle BS \rangle = \frac{T}{V} \frac{\partial}{\partial \mu_B} \frac{\partial}{\partial \mu_S} \log(Z)_{\mu_B=0} = X_{BS}$$

$$C_{BS} = -3 \frac{\langle BS \rangle}{\langle S^2 \rangle} = -3 \frac{\left\langle \frac{1}{3}(u+d+s)(-s) \right\rangle}{\langle S^2 \rangle} = \frac{X_{ss} + X_{us} + X_{ds}}{X_{ss}} = 1 + \frac{X_{us} + X_{ds}}{X_{ss}}$$

Calculated by (quenched): R.V. Gavai, S. Gupta, Phys.Rev.D66:094510,2002

At T = 1.5 Tc $\quad X_{us} \approx X_{ds} \ll X_{ss}$

C_{BS} = 1+ 0.00(3)/0.53(1)

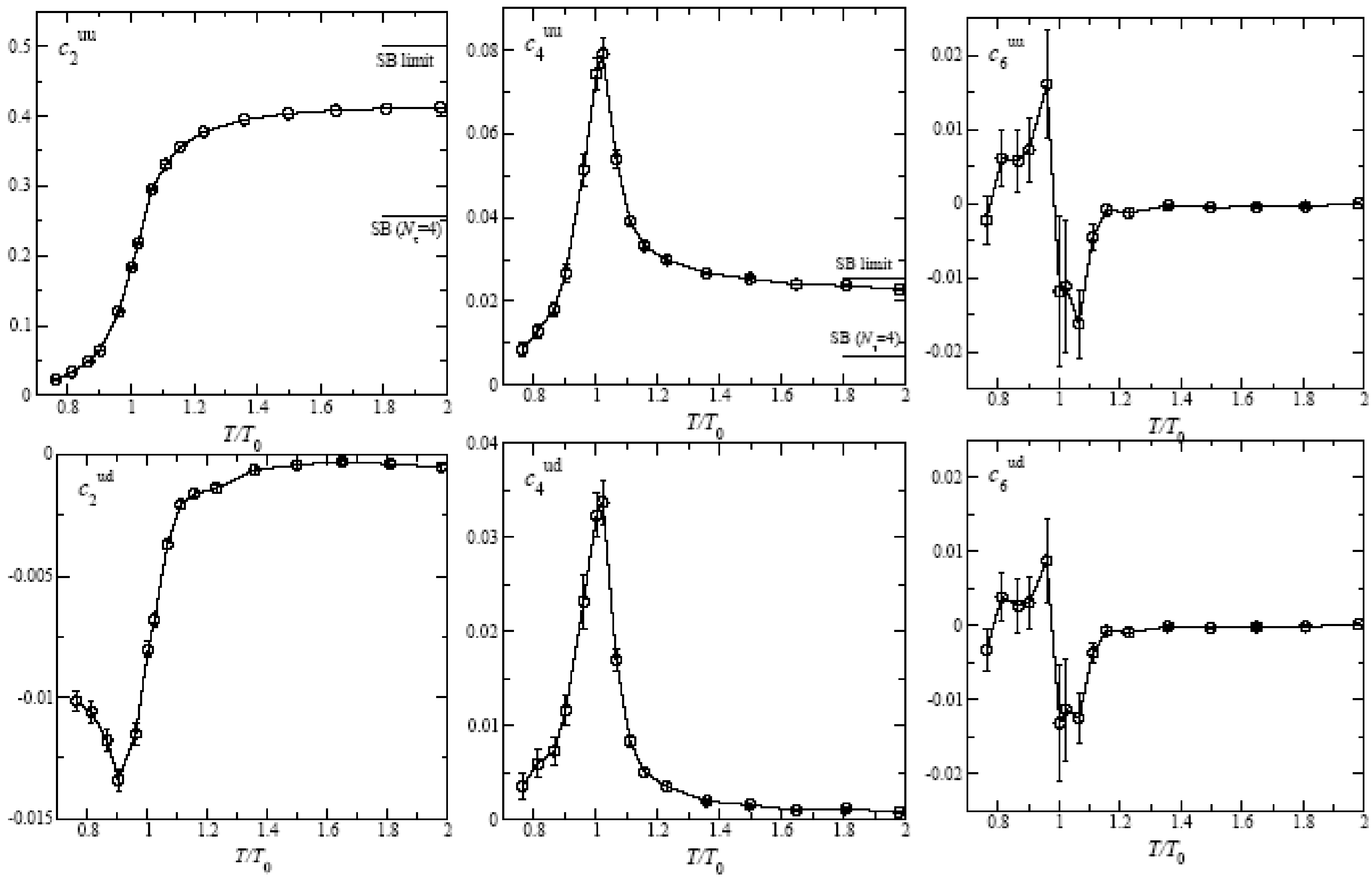
Essential result: off-diagonal susceptibilities << diagonal susceptibilities

Results

- Hadron Gas $\mathbf{C_{BS} = 0.66}$
- Bound State QGP $\mathbf{C_{BS} = 0.62}$
- Independent quarks $\mathbf{C_{BS} = 1}$
- Lattice QCD $\mathbf{C_{BS} = 1}$

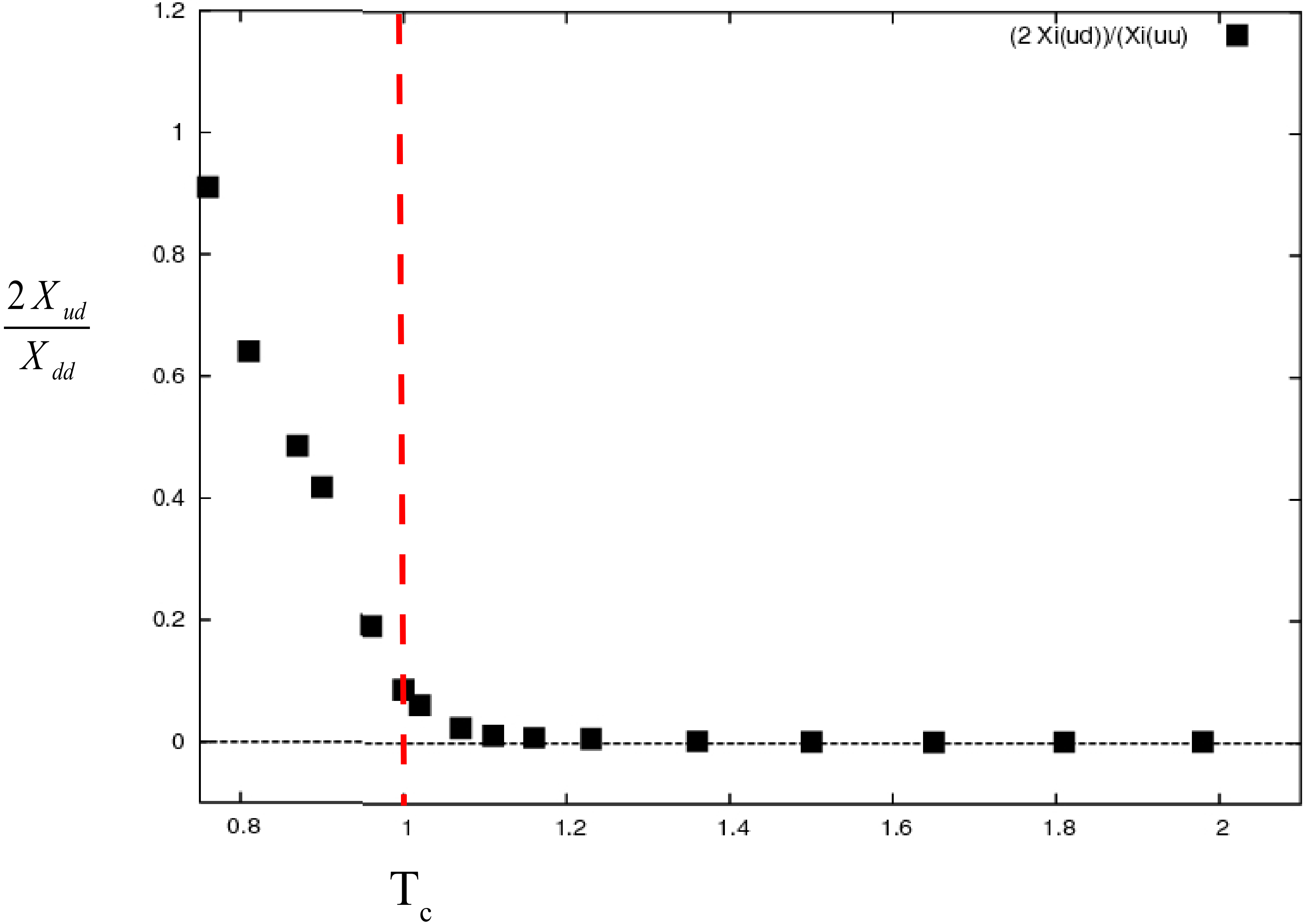
Full QCD, but with 2 flavors, gives similar insight!

$$\frac{X(T,\mu_q)}{T^2} = 2c_2 + 12c_4\left(\frac{\mu_q}{T}\right)^2 + 30c_6\left(\frac{\mu_q}{T}\right)^4 + \dots$$



From C.R. Alton et. al. Phys.Rev.D71:054508,2005

Ratio of Susceptibilities



Correlations and Lattice

(quenched) Lattice QCD:

$$X_{ud} = X_{us} = X_{ds} \approx 0$$

NO cross correlations among quark flavors!

quark – anti-quark bound states ? 

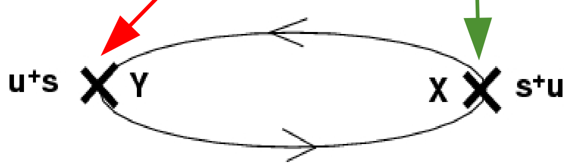
Strongly interacting QGP??? Why are there no correlations? 

Quarks appear to be independent Quasi-Particles

Bound states and off-diagonal Susceptibilities

Correlator:

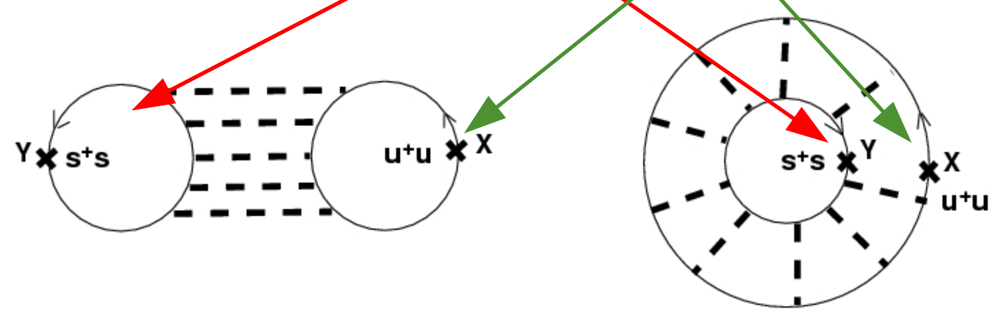
$$C(x,y)=tr\left[\rho(u^+(y)s(y))\,(s^+(x)u(x))\right]$$



Measure for mass, correlation length of bound state

Susceptibility (χ_{us})

$$\chi_{us}=\int dx\,dy'\,tr\left[(s^+(y)s(y))(u^+(x)u(x))\right]$$



"Simply" counts number of bound states

Some issues

- No statement about gluon bound states
- No statement about quark gluon bound states
- No statement about the heavy states (> 1.5 GeV) seen in correlation functions (Hatsuda et al, Karsch et al.)
  - Susceptibilities only measure the bulk!
  - Possibly collective modes ????? (G. Brown, QM 04)

Ways out...

•As many quark-quark states as quark-antiquark states

- Not consistent with Shuryak model
- Problem with higher order susceptibilities
  (Ejiri et al. hep-ph/0509051

•Large width of bound states

- ~1 % correction is allowed by lattice
- What is a bound state with large width?

Measuring C_{BS}

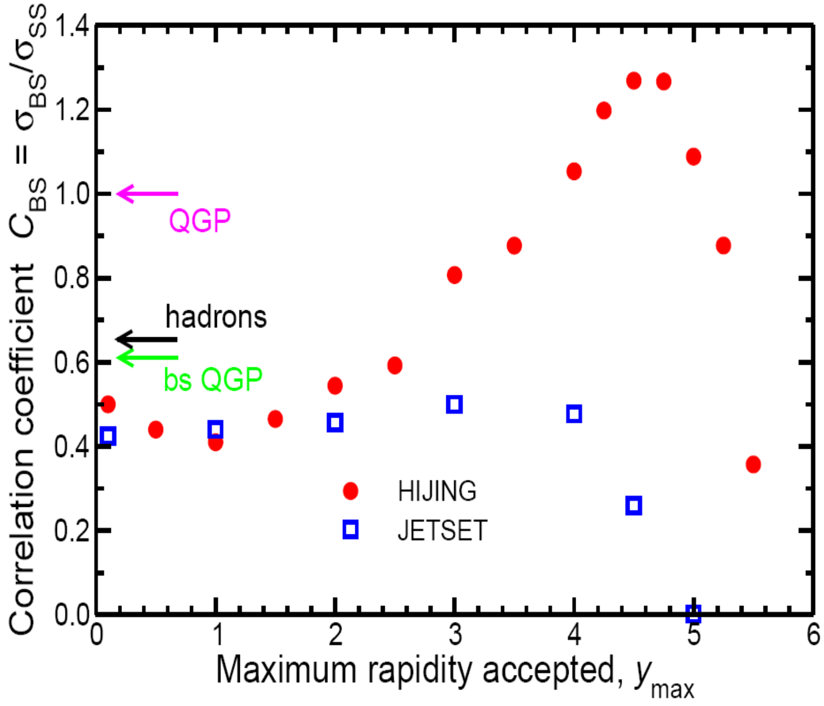
C_{BS} can be measured in principle

Advantages:

- Conserved quantities
- “Heavy” particles
  - Less uncertainty due to hadronization

Issues:

- Baryon number (neutrons)
- Weak decay corrections for strangeness



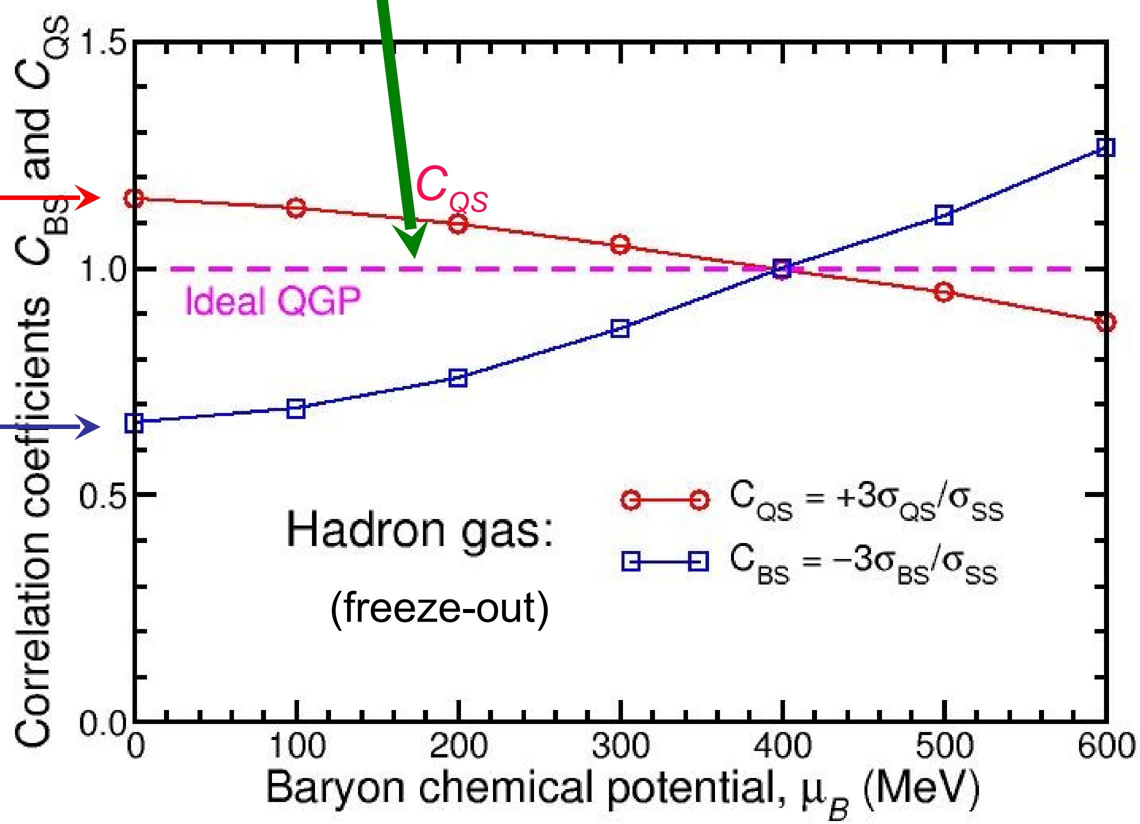
Alternative: C_{QS}

Ideal QGP: $C_{BS} = C_{QS} = 1$

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

$C_{QS}(\mu=0) = 1.15$

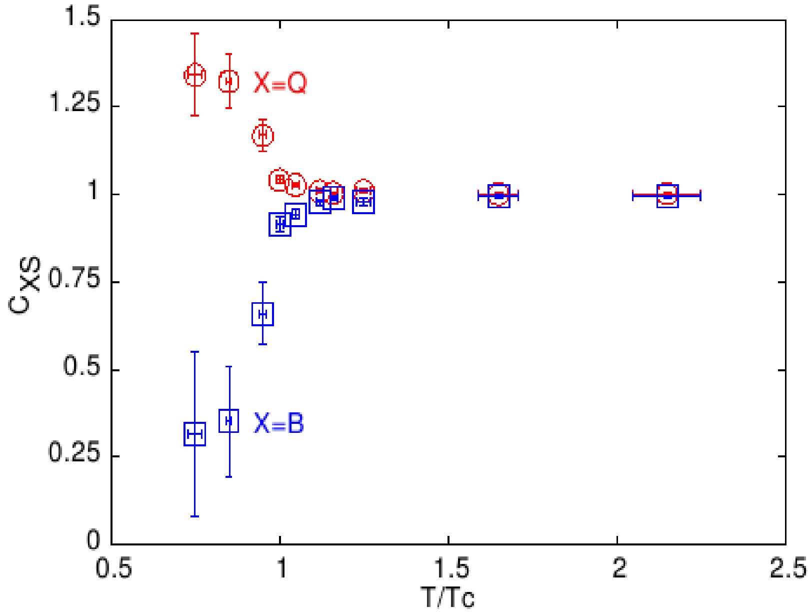
$C_{BS}(\mu=0) = 0.66$

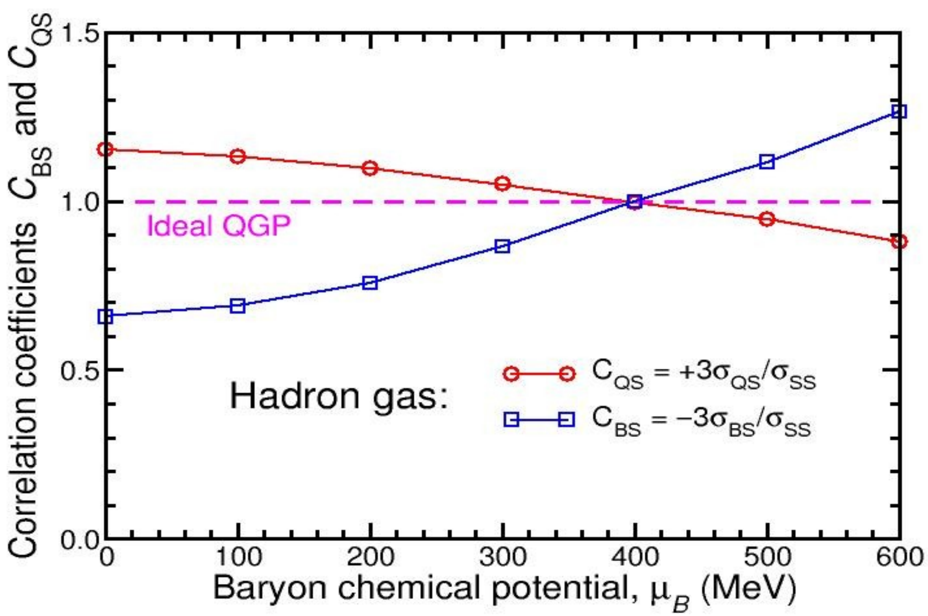


J. Randrup
Panic '05

C_{QS} continued

Hadron Gas

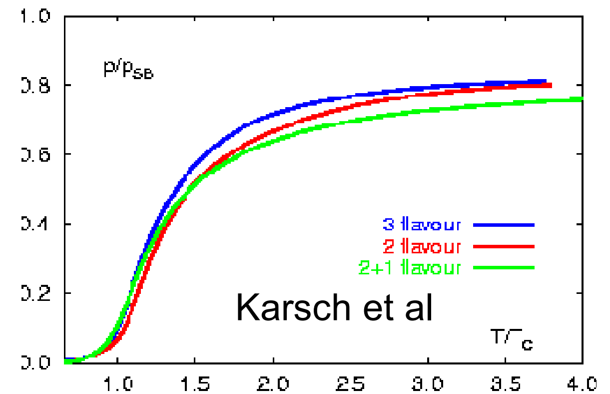




Gavai,Gupta, hep-lat/0510044

Speculations!

- Pressure in LQCD < ideal gas
- Lattice suggests a quasi-particle picture for QGP
- Lattice EOS requires **massive** quasi-particle
- This suggests a **repulsive** mean field (~500 MeV!!!)
- A repulsive mean field generates **flow**!
- RHIC data possibly consistent with **large** viscosity



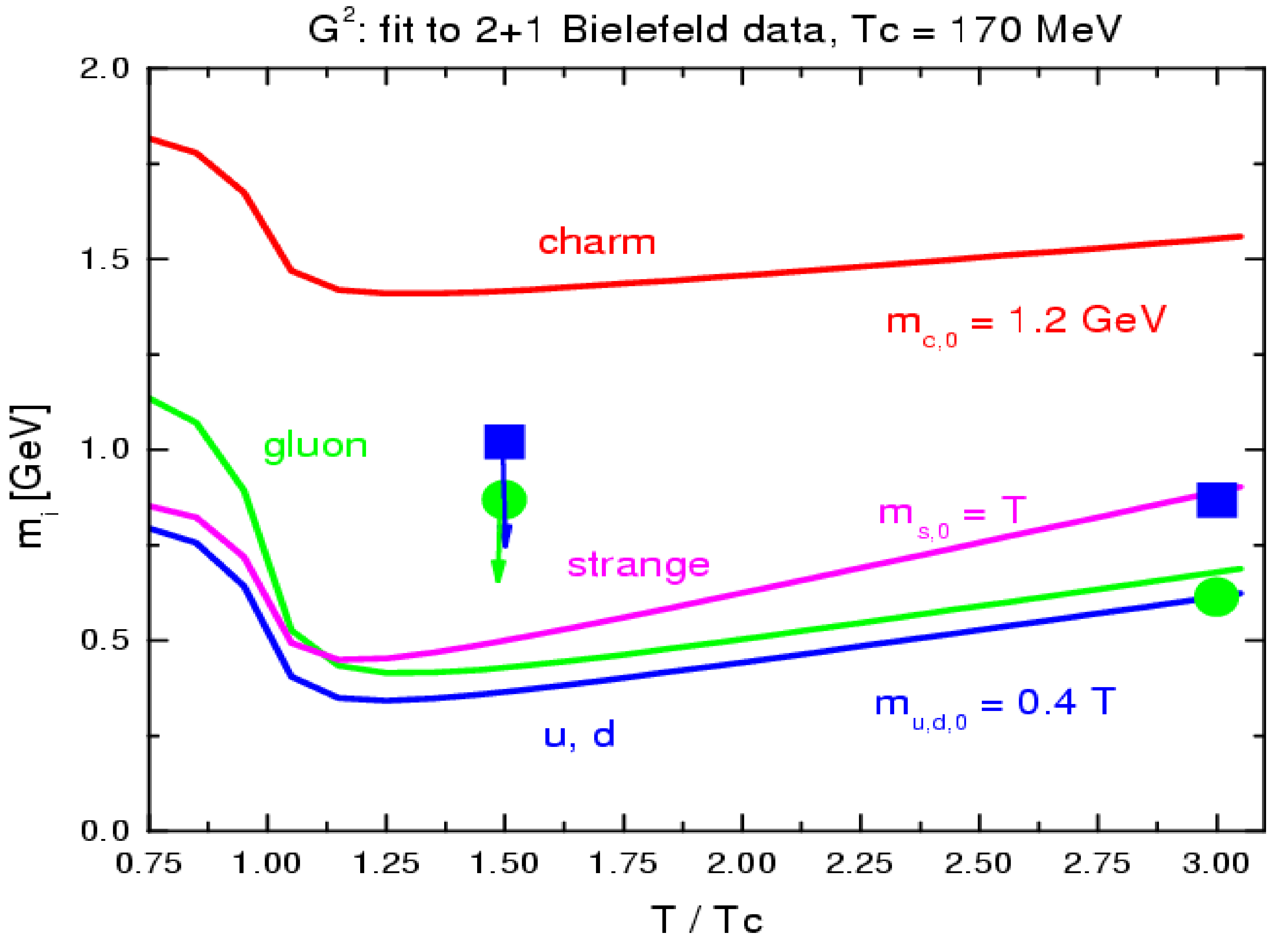
- Alternative:
  - Glue has low viscosity and quarks tag along

A. Peshier, B. Kampfer and G. Soff, Phys.Rev. D66:094003,2002.

J. P. Blaizot, E. Iancu and A. Rebhan, Phys.Rev. D63:065003,2001.

Summary

- BS correlation valuable diagnostic for structure of matter
- BS correlations impose strong limit on existence of bound states in the QCP
- Lattice QCD consistent with quasi-particle quarks
- Higher order “susceptibilities” need to be analyzed as well
- Mean field? Flow? High Viscosity? ?????

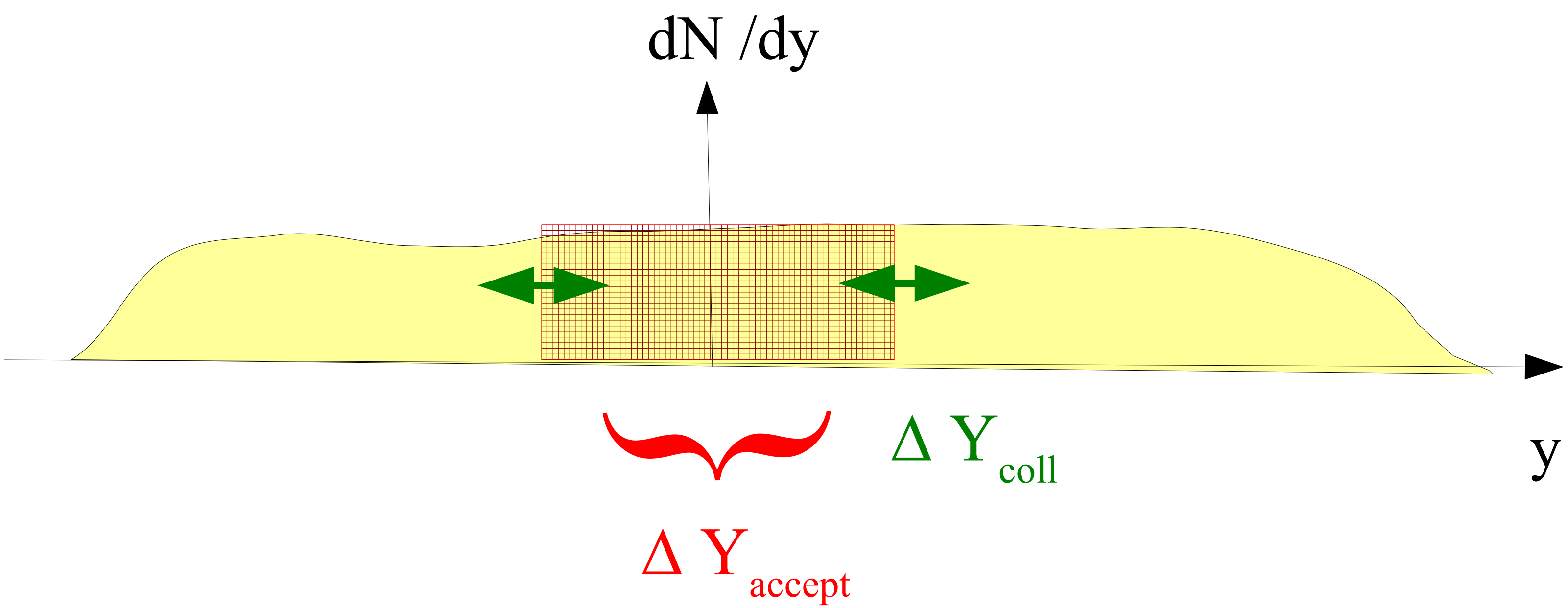


B. Kaempfer, SQM 2004

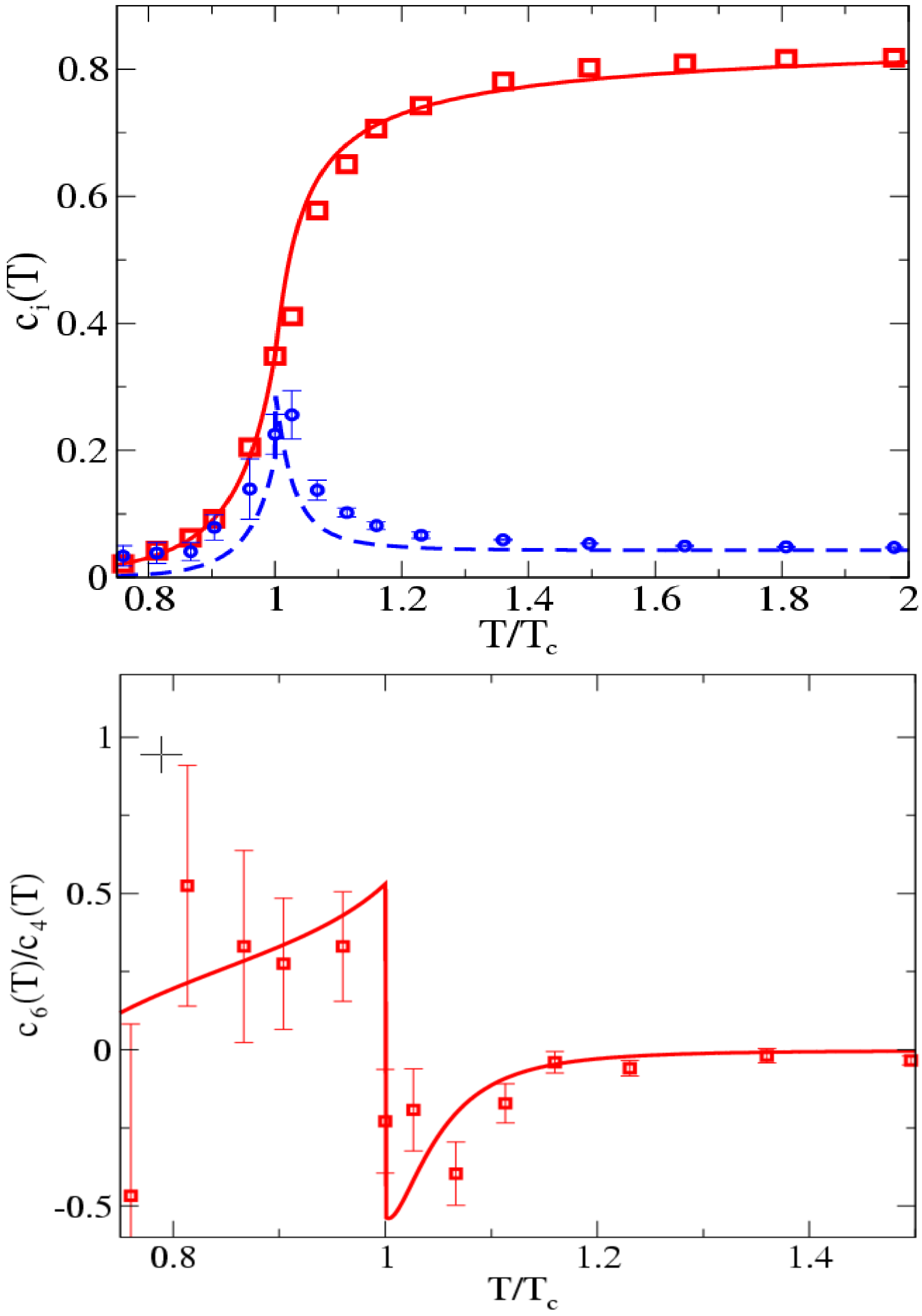
Fluctuations of conserved quantities

Quantum numbers conserved in Heavy ion collisions:

- Baryon number B (exactly)
- Charge Q (exactly)
- Strangeness S (almost!)
- Combinations are also conserved : BS, QS, BQ etc.



Condition for charge fluctuations: $\Delta Y_{total} >> \Delta Y_{accept} >> \Delta Y_{coll}$

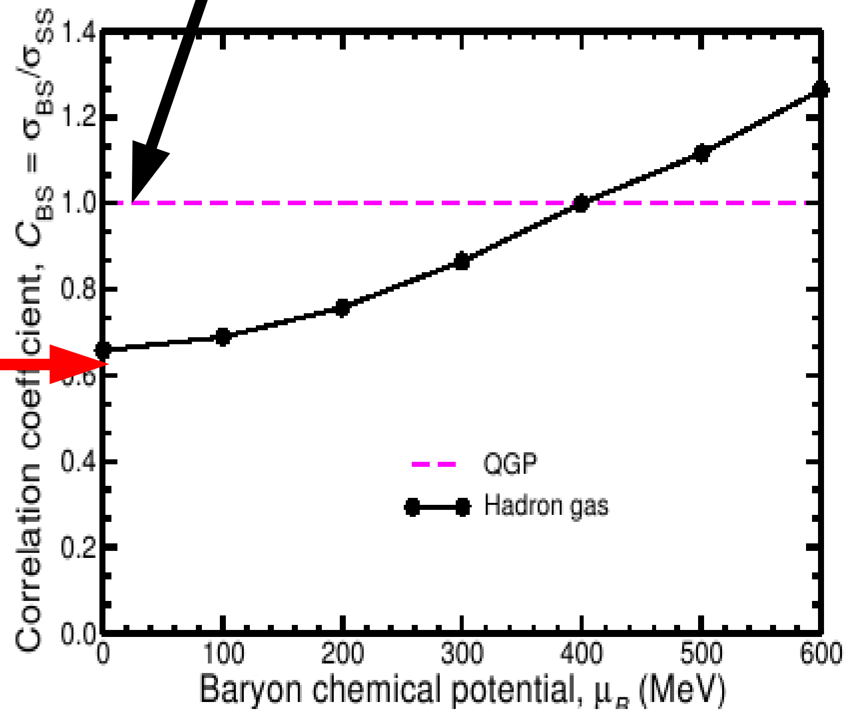


Quasi-particle model by
Bluhm et al, hep-ph/0411106

<BS> continued

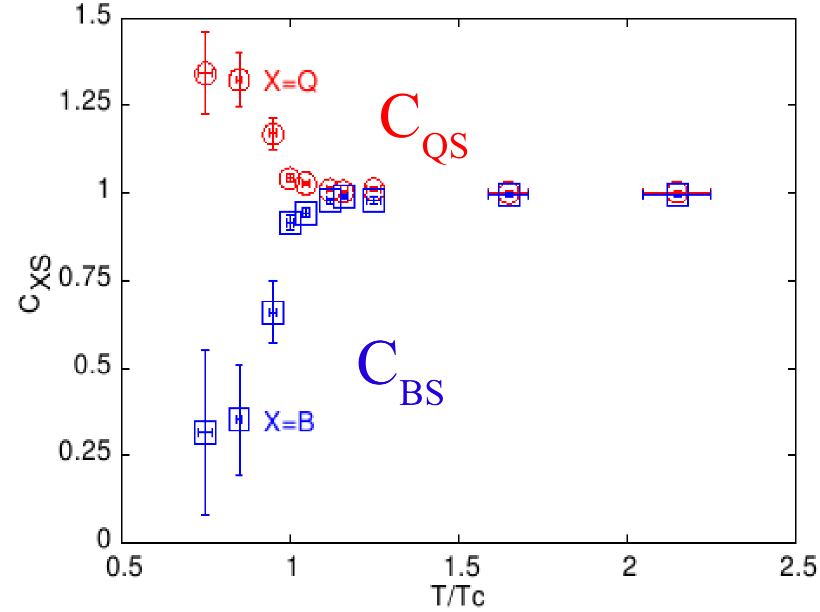
Independent quarks and
LATTICE QCD for T>1.1T_c

Bound state QGP



V.K, Majumder, Randrup PRL95:182301,2005

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

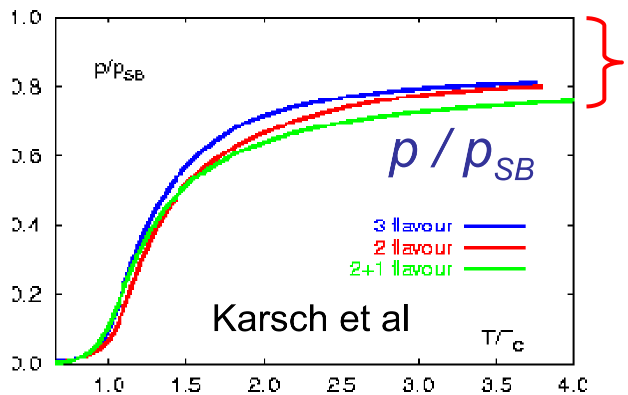


Gavai,Gupta, hep-lat/0510044

Speculation / conjecture

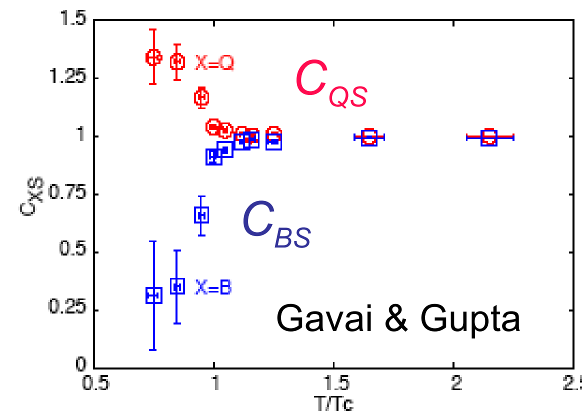
Lattice gauge calculations show that ..

.. the QGP is *not* an ideal quark-gluon gas:



$p < p_{SB}$

.. the quarks and antiquarks in QGP behave as *independent* particles:



$$\frac{C_{XS}\text{ (lattice QCD)}}{C_{XS}\text{ (}q\text{-}qbar\text{ gas)}} = 1 \qquad (X = B, Q)$$

This apparent inconsistency might be resolved in a *mean-field* picture:

The quark acquires an *effective mass* by the medium: $m\uparrow \Rightarrow p\downarrow$

The associated repulsive interaction may contribute to the *flow*