Decipering deconfinement in correlations of conserved charges: C_{BS},C_{QS} and related susceptibilities

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What are the degrees of freedom of matter @ RHIC

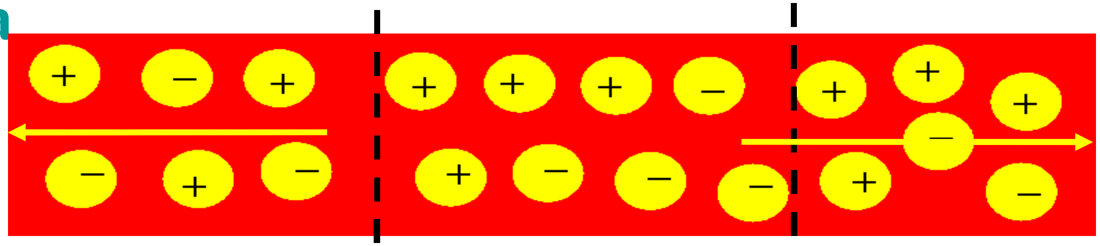
- Quasi-particle quarks & gluons
- Bound states of quarks and gluons
- Hadron gas
- Strings ...

Devise the same diagnostic and measure on the lattice, RHIC and in models

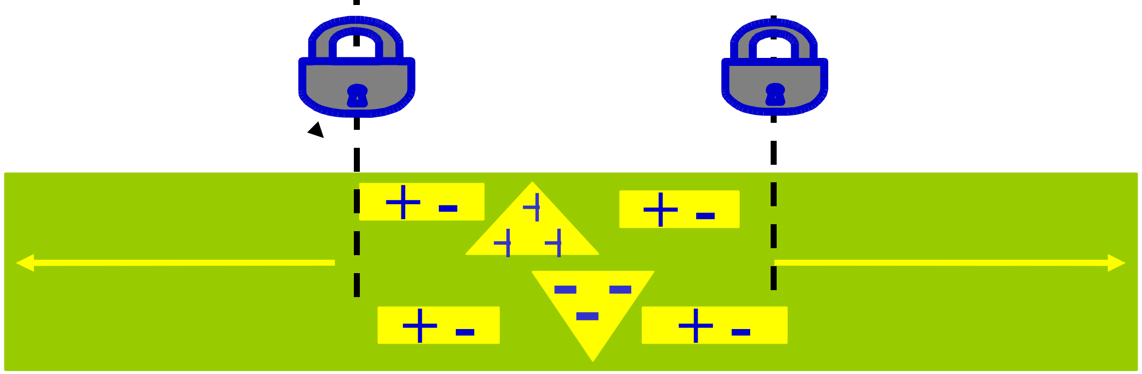
Fluctuations of conserved quantities

- Charge Q, Baryon Number B, Strangeness S.
- $u = n_u - n_{\bar{u}}$, $d = n_d - n_{\bar{d}}$, $s = n_s - n_{\bar{s}}$
- Combinations are also conserved : BS, QS, BQ etc.

Imagine a conserved charge carried by a particle in the plasma



Net charge conserved in a chosen rapidity interval



If nothing drastic happens during hadronization

Different degrees of freedom introduce different correlations between conserved charges

e.g., (Baryon number) * (strangeness)

Canonical QGP vs. Hadron gas

- **BS is carried by s, $\bar{s}$**
- **Strangeness carriers s, $\bar{s}$**

- BS carried by Λ,Σ,Ξ,Ω...
- Strangeness carried by K,Λ,Σ,...

B and S locked together in a QGP,
But not in a hadron gas,

$$\frac{\text{Correlation in B \& S}}{\text{Fluctuations of S}}$$

x(-3) as quarks have B=1/3, and S=-1

Calculating on the Lattice

$$\langle BS\rangle - \langle B\rangle\langle S\rangle = T^2\left[\frac{\partial}{\partial\mu_B}\frac{\partial}{\partial\mu_S}\log(Z(T,\mu))\right]_{\mu=0} = TV\chi_{BS}$$

$$C_{BS} \simeq -3\frac{\langle BS\rangle}{\langle S^2\rangle} = -3\frac{\frac{1}{3}\langle(u+d+s)(-s)\rangle}{\langle s^2\rangle}$$

$$= \frac{\chi_{us}+\chi_{ds}+\chi_s}{\chi_s} = 1 + \frac{\chi_{us}+\chi_{ds}}{\chi_s}$$

At T > Tc Off-Diagonal susceptibilities are very small compared to diagonal susceptibilities,
Demonstrated in multiple lattice calculations

Need off-diagonal susceptibilities in unquenched QCD with $SU(3)_f$

Simple model estimates

assume independent massive flavors & variance = mean

$$-3\frac{\langle B\,S\rangle}{\langle S^2\rangle}=1+\frac{\langle us\rangle+\langle ds\rangle}{\langle s^2\rangle}$$

$$\langle us\rangle=\sum_i^{events}\sum_f n_i^f u_f s_f$$

- In ideal QGP : no flavor has upness & strangeness

$$\langle us\rangle=\langle ds\rangle=0$$

C_{BS} = 1

- In hadron gas: kaons have

$$\langle us\rangle=-\sum_i^{events} n_i^{K^+}+n_i^{K^-}<0$$

Baryons have

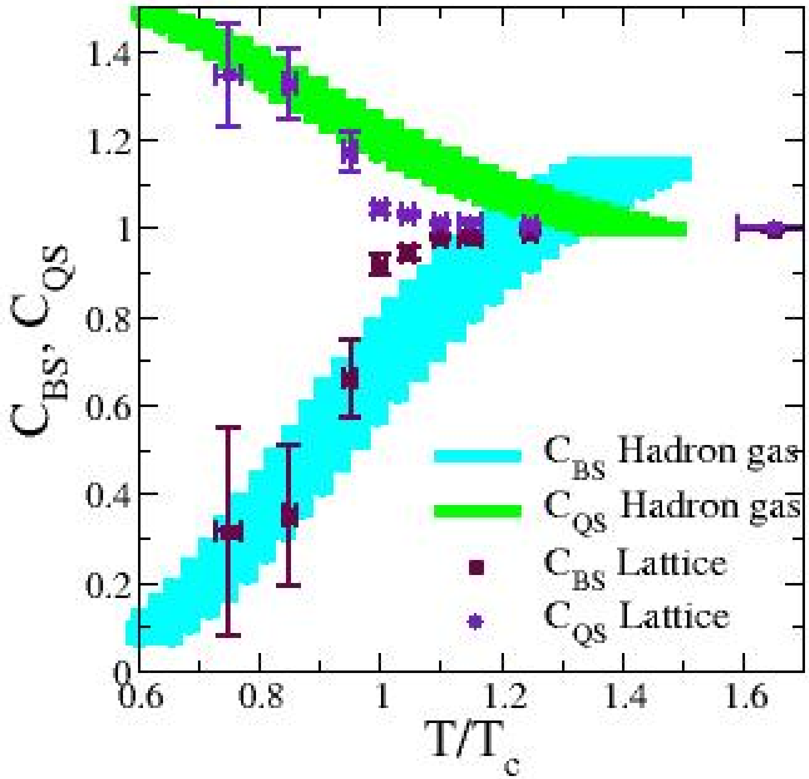
$$\langle us\rangle=\sum_i^{events} n_i^{\Lambda}+2n_i^{\Sigma^+}+\ldots>0$$

At T=170MeV, μ=0, More mesons than baryons, C_{BS} = 0.66

C_{BS} and C_{QS} from quenched lattice

Hadron gas has spectrum upto Ω.

Tc assumed to be 160 -180 MeV



Lattice data from: Gavai & Gupta, PRD 73, 14006, 2006.

Quenched calculations!

At T=Tc both C_{BS} and C_{QS} jump from the hadron gas value to 1, for an ideal quasiparticle QGP

Basically, at T = Tc , the correlation between flavors $\chi_{us} = 0$

Estimates from a Bound-State-QGP!

E. Shuryak, I. Zahed, PRC70:021901,2004; PRD70:054507,2004.

QGP is strongly coupled Large scattering cross-sections
Multitude of binary bound states

- **Heavy quark, antiquark quasiparticle have <us>= <ds> =0**

- **Quark-antiquark states: 8 π like, 24 ρ like**
  $u\bar{s} + d\bar{s} + s\bar{u} + s\bar{d}$, These lead to <us> < 0, <ds> < 0

Quark gluon bound states, have <us> = <ds> = 0

All together at T=1.5Tc, <us> < 0, <ds> < 0, C_{BS} = 0.61
Similar to Hadron gas estimate

How to get C_{BS} = 1, make <us> = 0, introduce baryons

J.Liao, E. Shuryak, PRD73, 014509, 2006

Artifically enhancing the baryon population to get <ud> **-->** 0
as baryons give positive <ud> correlation.

What will this do to the derivatives of <ud> ?

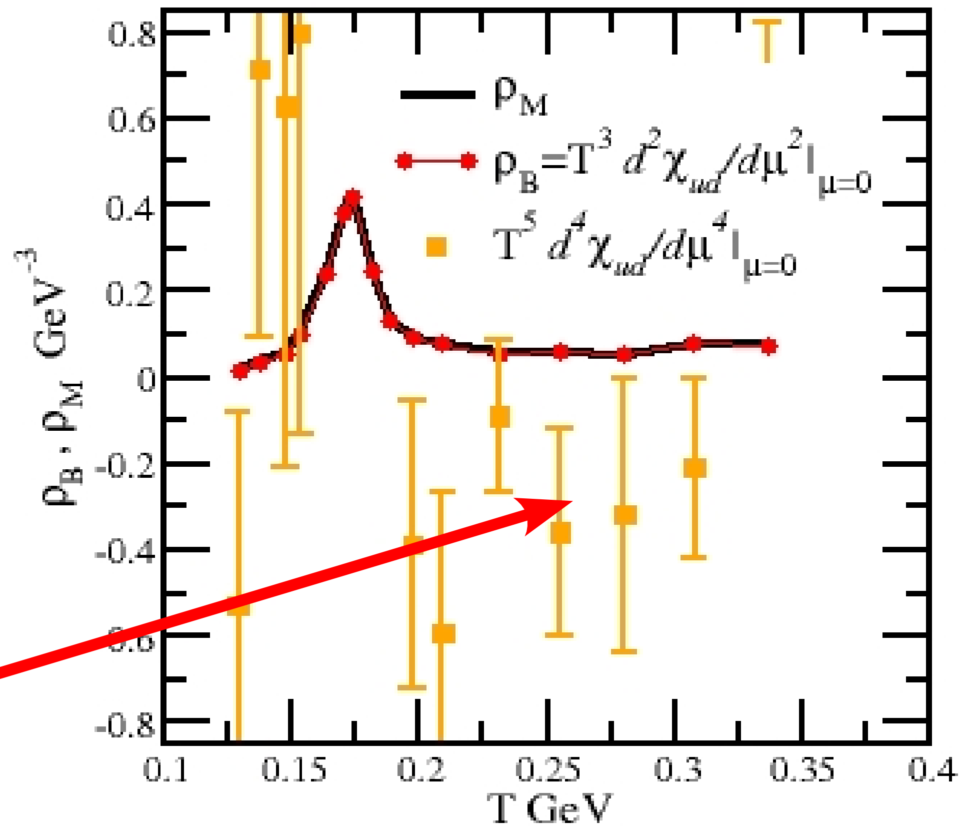
$$T\chi_{ud}(T,\mu)=\left[2\rho^0_{ud}(T)+4\rho^0_{uud}(T)+4\rho^0_{udd}(T)\right]\cosh(\mu/T)-2\rho^0_{u\bar{d}}$$
$$=\rho_B\cosh(\mu/T)-\rho_M$$

$$T^3\frac{\partial^2\chi_{ud}}{\partial\mu^2}\Big|_{\mu=0}=\rho_B$$

$$T^5\frac{\partial^2\chi_{ud}}{\partial\mu^4}\Big|_{\mu=0}=\rho_B$$

$$\chi_{ud}(T)|_{\mu=0},\ \frac{\partial^2\chi_{ud}(T)}{\partial\mu^2}\Big|_{\mu=0},\ \frac{\partial^4\chi_{ud}(T)}{\partial\mu^4}\Big|_{\mu=0}$$

Calculated in Allton et. al. PRD71, 054408, 2005



4th derivative < 0

Isospin symmetry and Experimental observable!

All phases of QCD exhibit isospin symmetry,
changing I3 leaves mass unchanged

$$m_u \simeq m_d, m_{\pi^+} \simeq m_{\pi^-}, m_{K^+} \simeq m_{K^0}, m_p \simeq m_n, etc.$$

Gell-Mann-Okubo formula

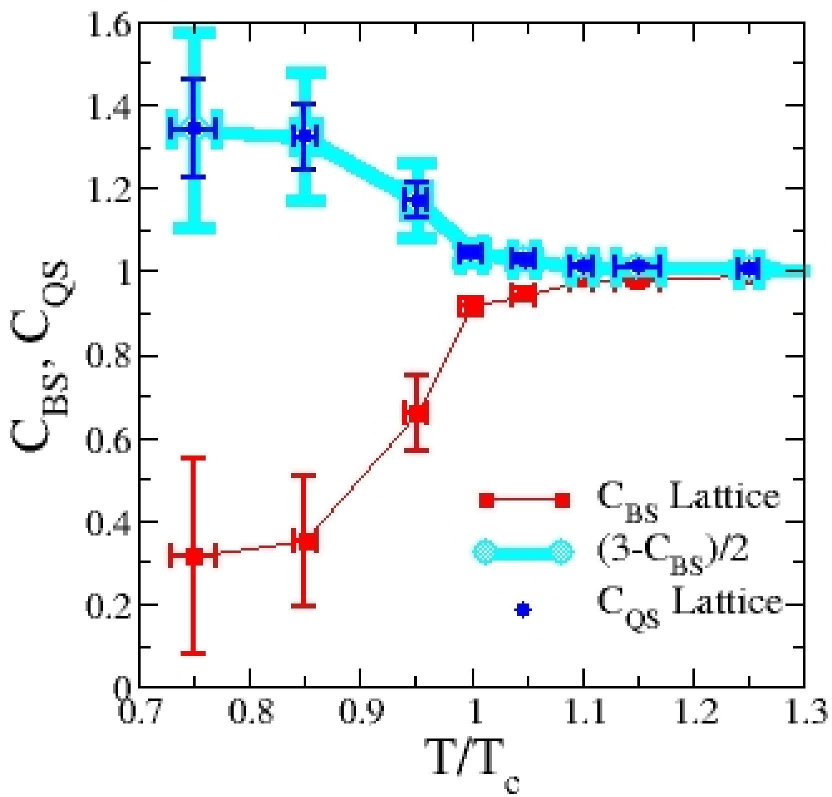
$$Q = I_3 + \frac{B+S}{2} \Rightarrow QS = I_3 S + \frac{BS+S^2}{2}$$

Fluctuates to zero

$$\sigma_{QS} = \sigma_{I_3 S} + \frac{\sigma_{BS} + \sigma_S}{2} \simeq \frac{\sigma_{BS} + \sigma_S}{2}$$

$$\Rightarrow C_{QS} = \frac{3 - C_{BS}}{2}$$

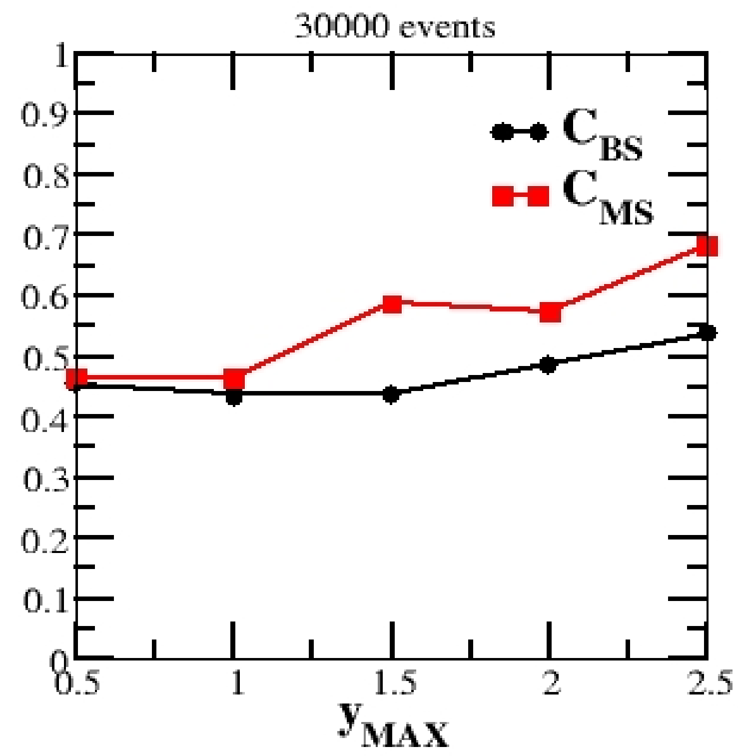
Lattice data from:
Gavai & Gupta, PRD
73, 14006, 2006.



Experimentally hard to measure C_{BS}

Neutrons carry baryon number and cannot be detected!

Invent a quantum number $M=B + 2I_3$



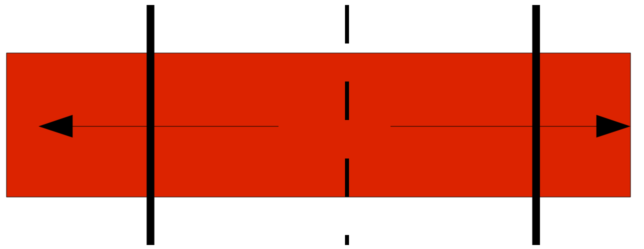
$$\sigma_{MS}=\sigma_{BS}+\sigma_{I_3 S}\simeq\sigma_{BS}$$
$$\Rightarrow C_{MS}\simeq C_{BS}$$

If isospin sym. holds...

Neutrons have M=0

C_{MS} can be measured in expt.

Hijing simulation with acceptance in y



$-|y_{max}| < y < |y_{max}|$

Conclusions & expt. problems

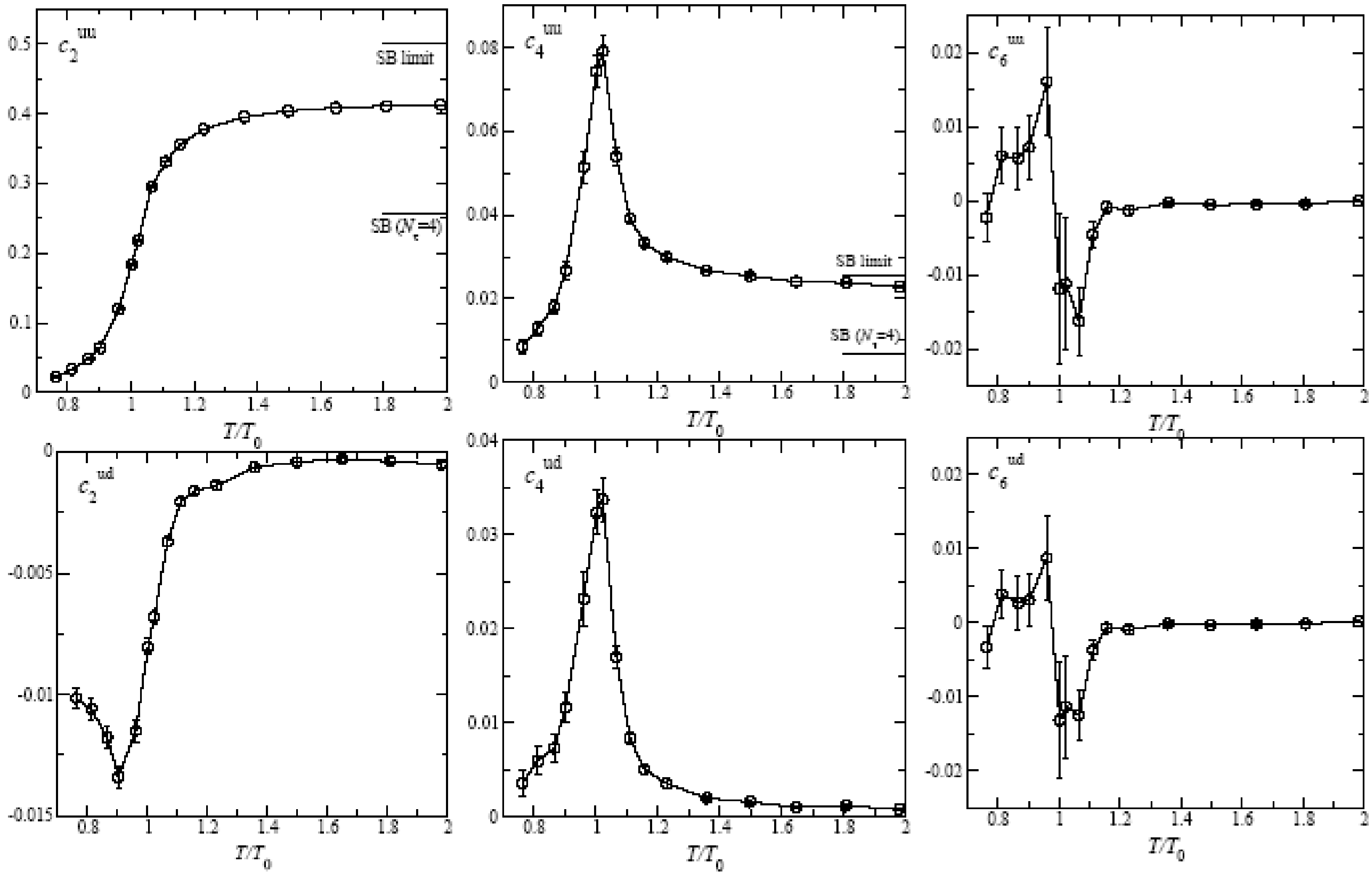
- Bulk fluctuations of conserved charges can determine the degrees of freedom
- Same observable on lattice, RHIC & models!
- Flavor degrees of freedom are quasi-particulate
- Bound states not allowed by behavior of <ud> and its derivatives
- E-by-E measurement of $C_{BS} = C_{MS}$ can give insight into the primordial matter.
- Phase transition causes reshuffling of B & S
- Contamination by weak decays from heavier states

Back up!

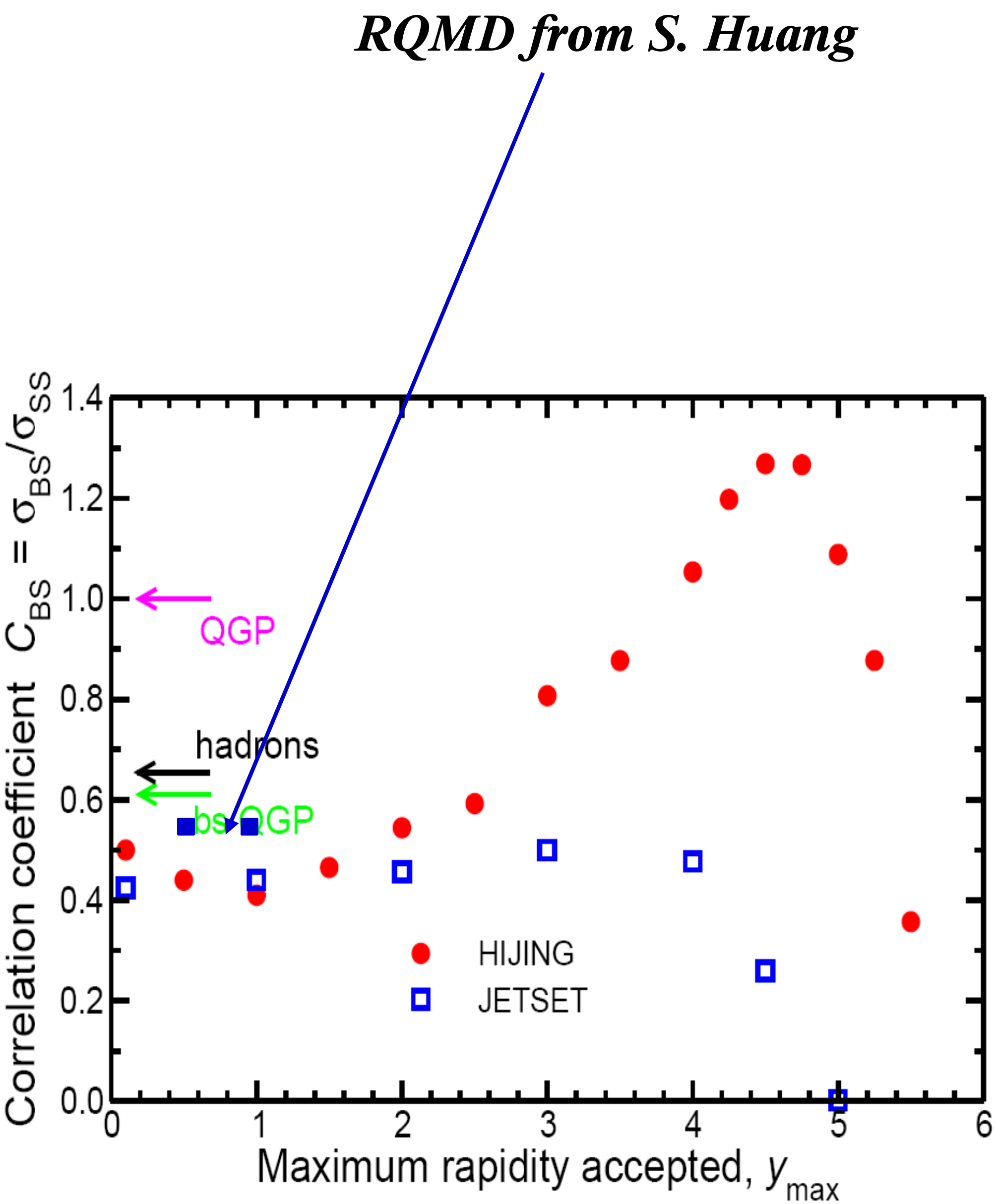
Full QCD, but with 2 flavors, gives similar insight!

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

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



Final results, from 4 approaches !



At $y_{max}<y<y_{min}$ C = 0

All events have δB=0

C_{BS} rises and stabilizes at Smaller range of y

Still much smaller than Hadron gas estimate

Hadron gas, SZ plasma smaller than naïve QGP or Lattice estimate

C_{BS}: discerning experimental observable

Speculations!

A) Its still hydro-dynamic

i) The dynamics is driven by gluons

ii) Quark quasi-particles go along for the ride

iii) Need alternative means to determine the existence of bound states!

B) Its not hydro-dynamic

i) Everything is quasi-particulate,

ii) Submerged in a repulsive mean field,

iii) Expansion driven by mean field !! ??

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.