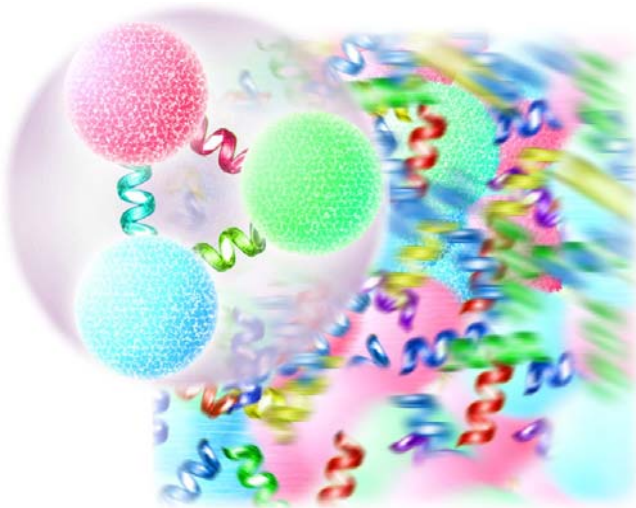
Talk @ INT Program "Frontiers in QCD" Seattle, NOV.3rd, 2011

Fermion Fluctuations & Correlations in sQGP: Quasi-Particles, or Bound-States, or Holography?



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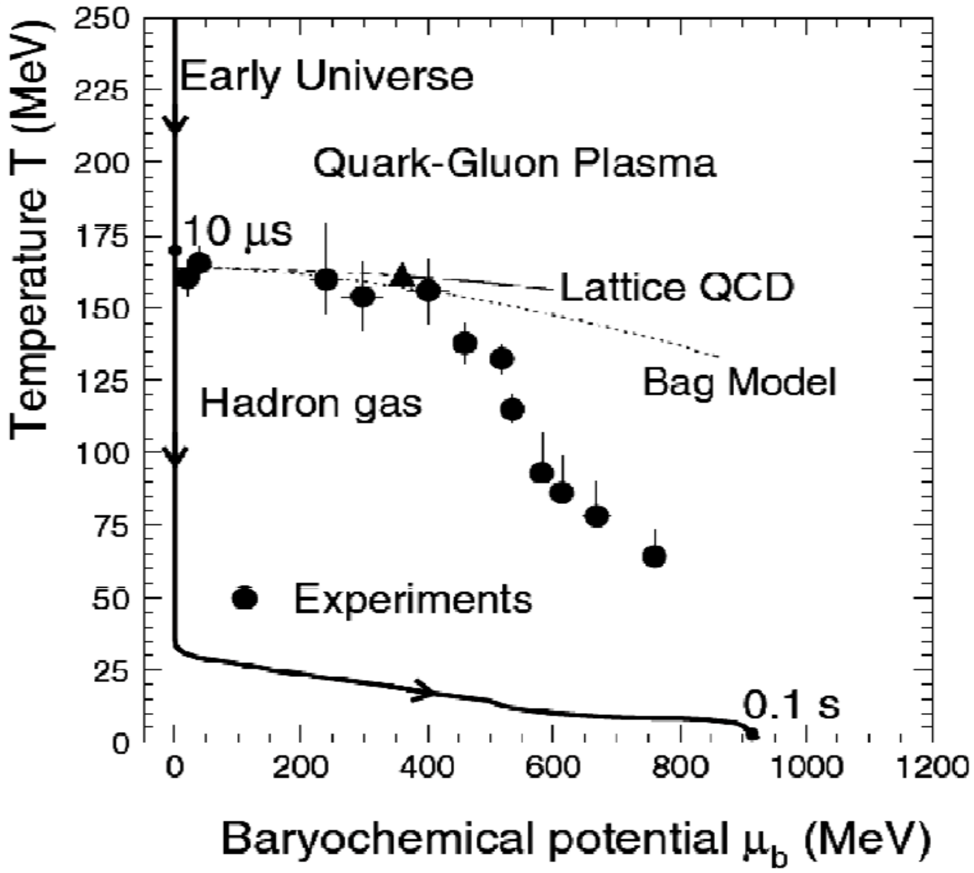
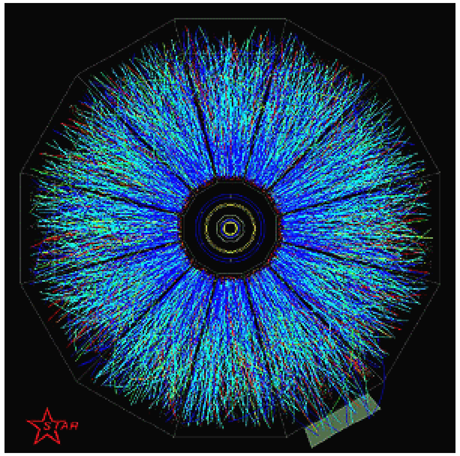
Outline

- Fermion fluctuations & correlations: introduction
- Susceptibilities in QCD: quasi-particles? bound states?
- Strongly interacting quarks: results from holography
- Discussions & Summary

References:
JL & Shuryak, Phy. Rev. D 73(2006)014509;
Kim & JL, Nucl. Phys. B 822(2009)201.

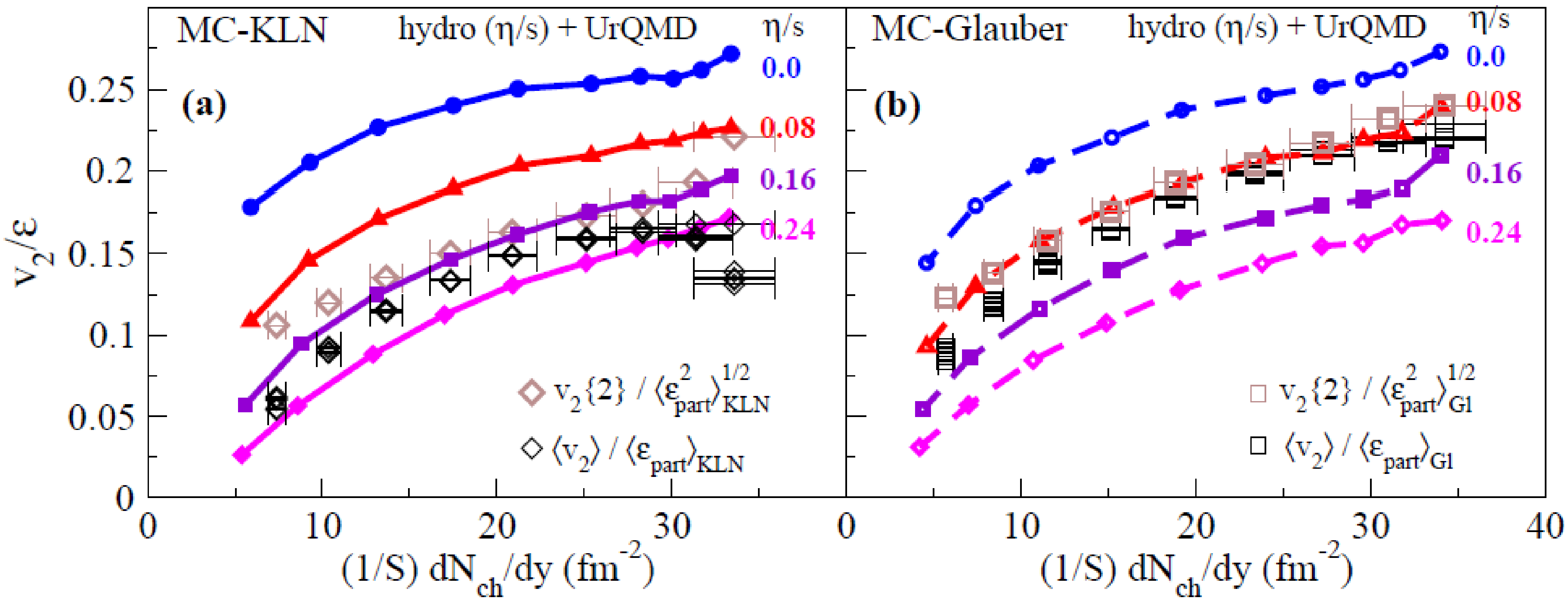
Quest for the Phases of QCD





Remarkable progresses in the last 10 years:
RHIC experiments; lattice QCD.
Now LHC Era

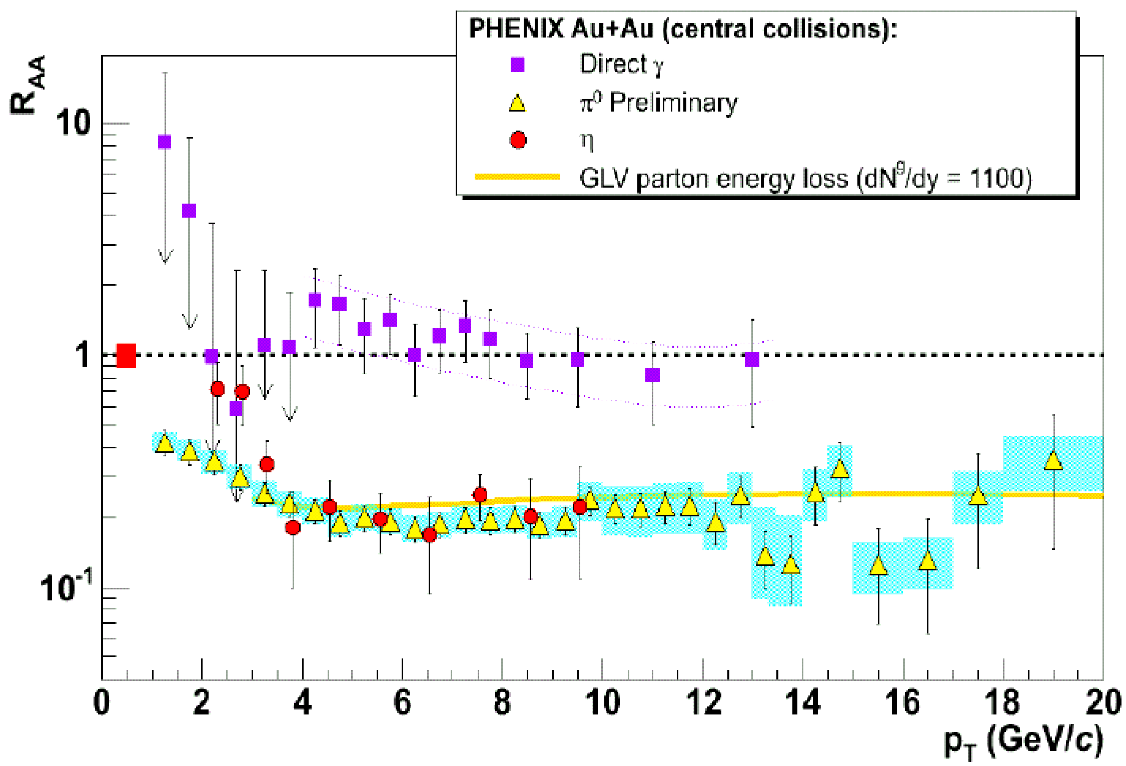
RHIC: Nearly Perfect Fluid

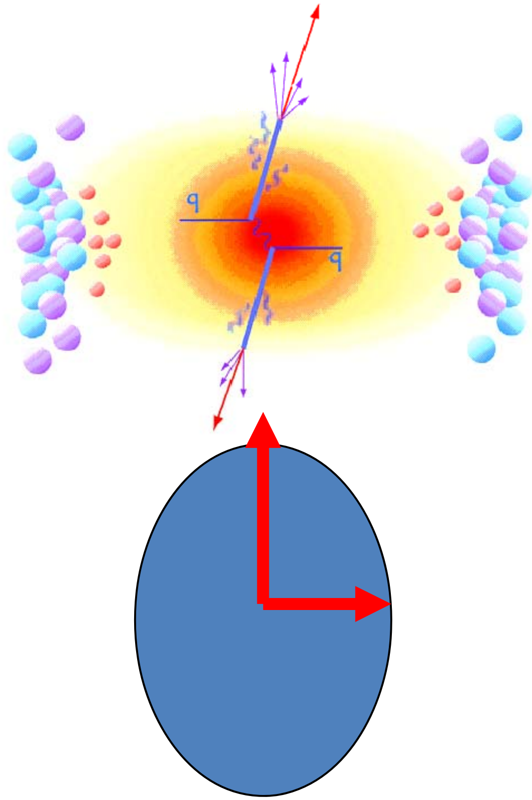


Song, Bass, Heinz, Hirano, Shen, 2010

Created matter's explosion appears nearly ideal → strongly coupled

RHIC: Strong Jet Quenching





Jet-medium interaction is very strong→ color-opaque matter!

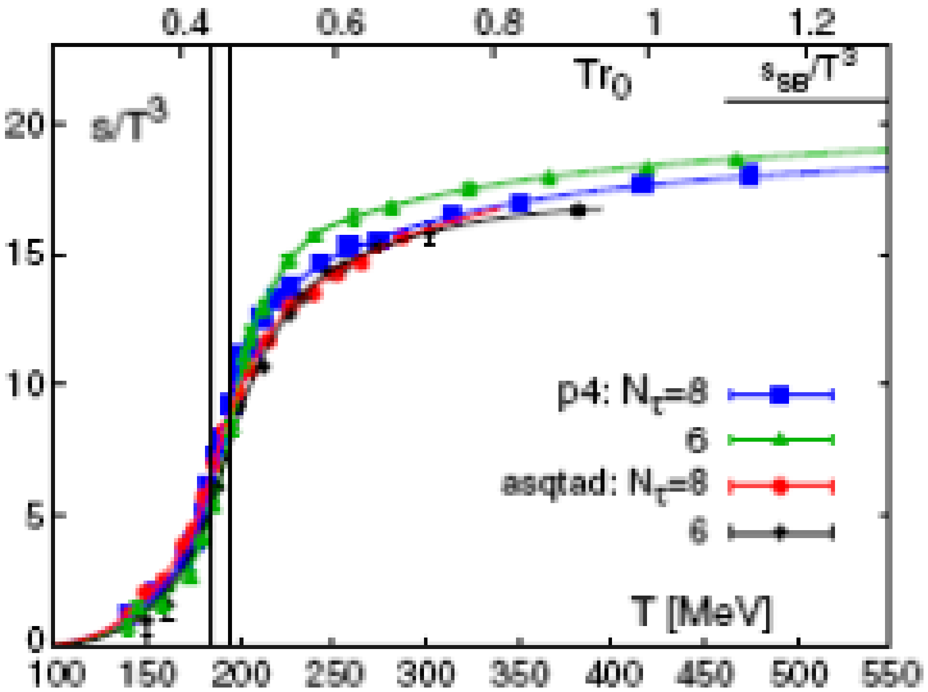
Physics beyond pQCD needed for full account of data

sQGP: how strongly coupled?

Coupling scale a la thermodynamics e.g. entropy

Infinity ——— **0**

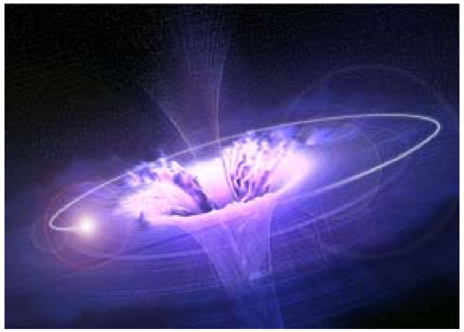
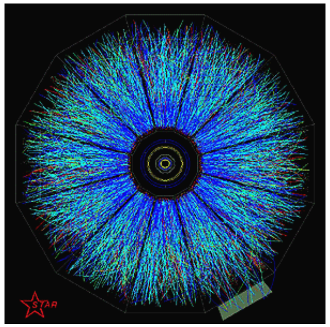
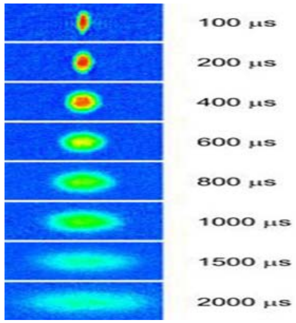
(3/4 * SB) **(Stefan-Boltzmann)**



sQGP: How strongly coupled?

Coupling scale a la transport e.g. shear viscosity

Infinity (eta/s=1/4pi) (quantum limit?) —— **0 (infinitely viscous)**

$$\frac{\eta}{s}[\text{AdS BH}] \lesssim \frac{\eta}{s}[\text{sQGP , cold atom}] \ll \frac{\eta}{s}[\text{water}]$$

Caveat: eta/s may NOT be a good fluidity measure everywhere !

See: JL & Koch , PRC,10

Fermions in sQGP

Strongly coupled quark-gluon plasma:

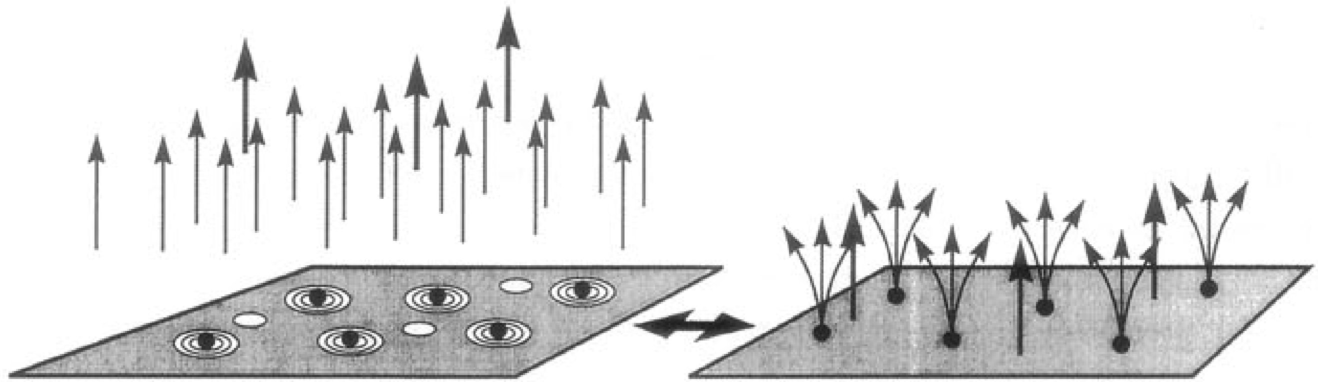
What would be the pattern for fluctuations & correlations of fermions that carry conserved charges ?

Study of these fluctuations & correlations are important:

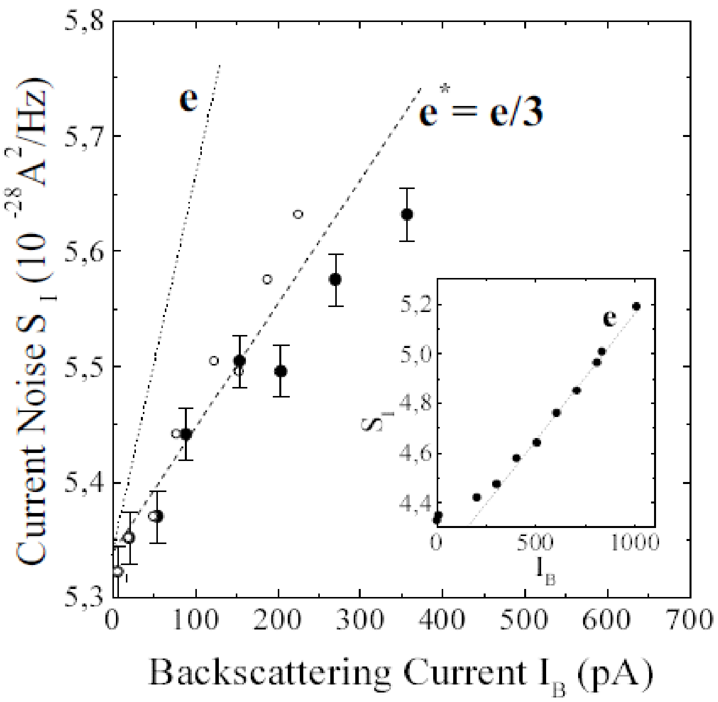
**--- it may tell new degrees of freedom: new unit of conserved charge fluctuations,
i.e. is the system partonic or hadronic?**

--- it may indicate specific phenomenon like a critical point

In Search of Fractional Charge



Fractional Quantum Hall State: quasi-particle with charge (1/3) of electron's



New state of matter

→→

New degrees of freedom

& conserved charge carrier

→→

New basic UNIT for transmission

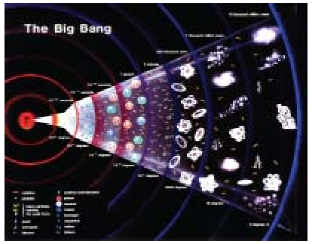
of conserved charge

→→

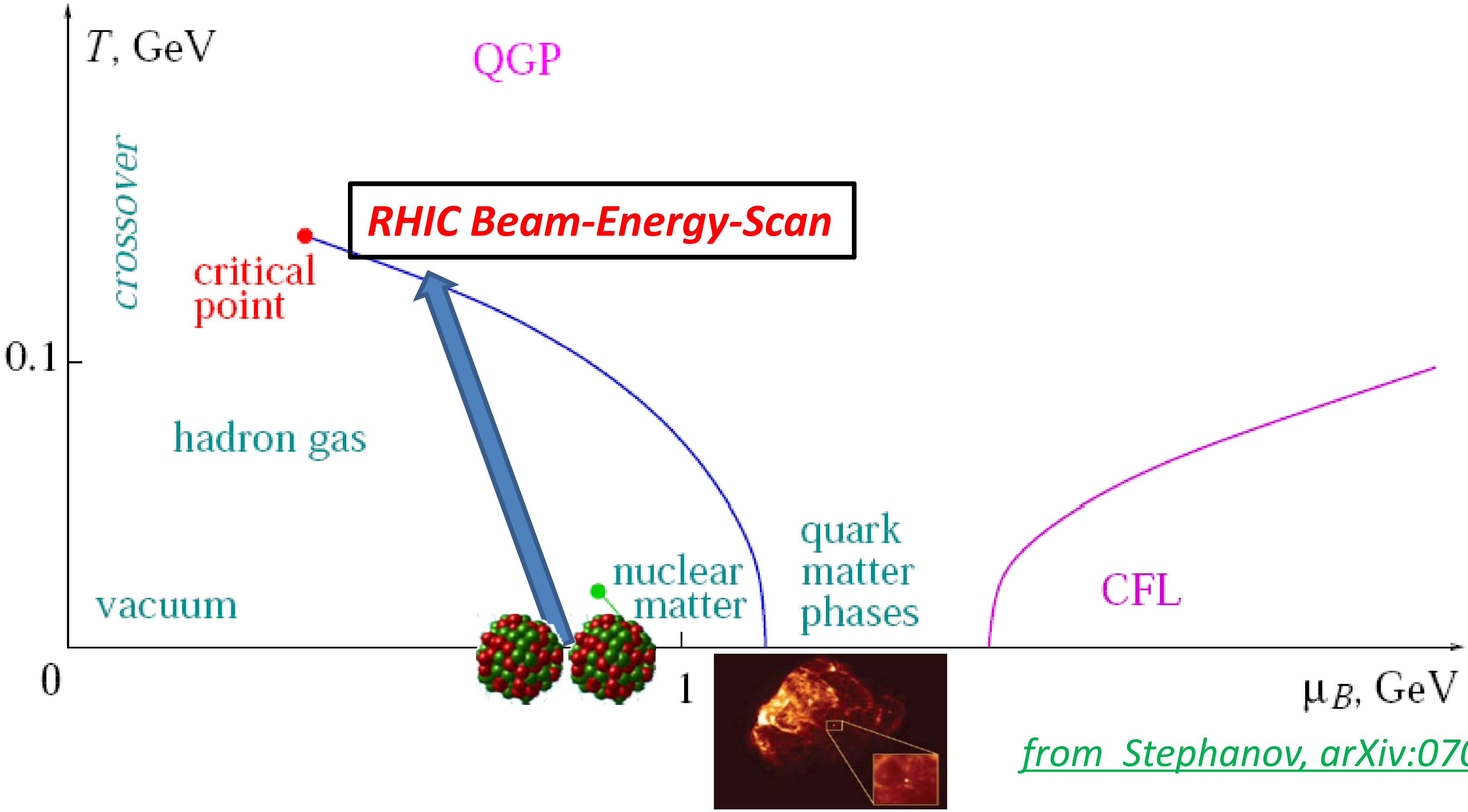
New behavior of fluctuation & correlation

Is the baryon number to be transmitted in its broken fraction, 1/3, in QGP?

Phases of QCD



Looking for distinctive patterns of fluctuations & correlations:
Can we spot the critical fluctuations?

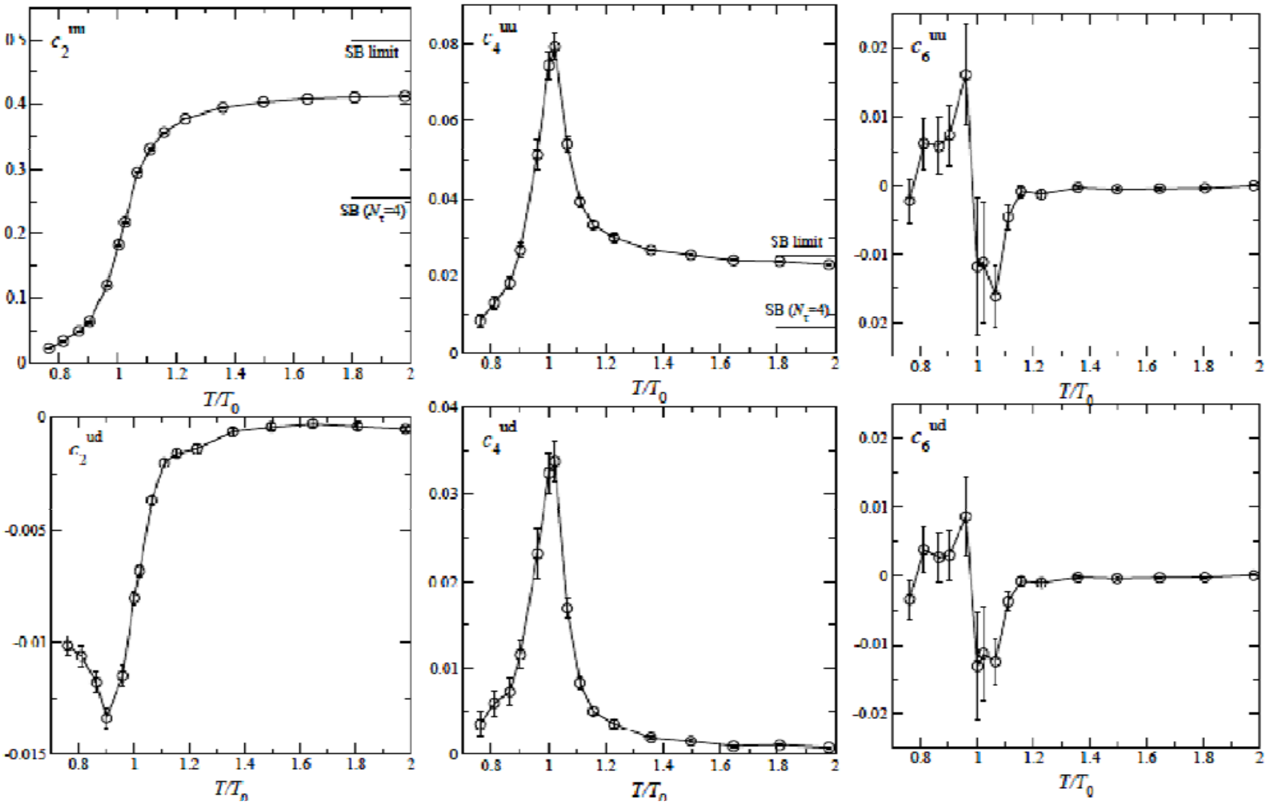


from Stephanov, arXiv:0701002

Susceptibilities

$$\chi^{(n_i,n_j,n_k)} \equiv \frac{1}{VT}\frac{\partial^{n_i}}{\partial(\mu_i/T)^{n_i}}\frac{\partial^{n_j}}{\partial(\mu_j/T)^{n_j}}\frac{\partial^{n_k}}{\partial(\mu_k/T)^{n_k}}\log Z.$$

Can be defined for various conserved charges & their mixture (non-diagonal).



Susceptibilities: Taylor coefficients for expanding the pressure in terms of chemical potentials

See reviews in e.g. V. Koch, arXiv:0701002

Susceptibilities connected with Data

$$\chi_q^{(1)} = \frac{1}{VT^3}\langle \delta N_q \rangle$$

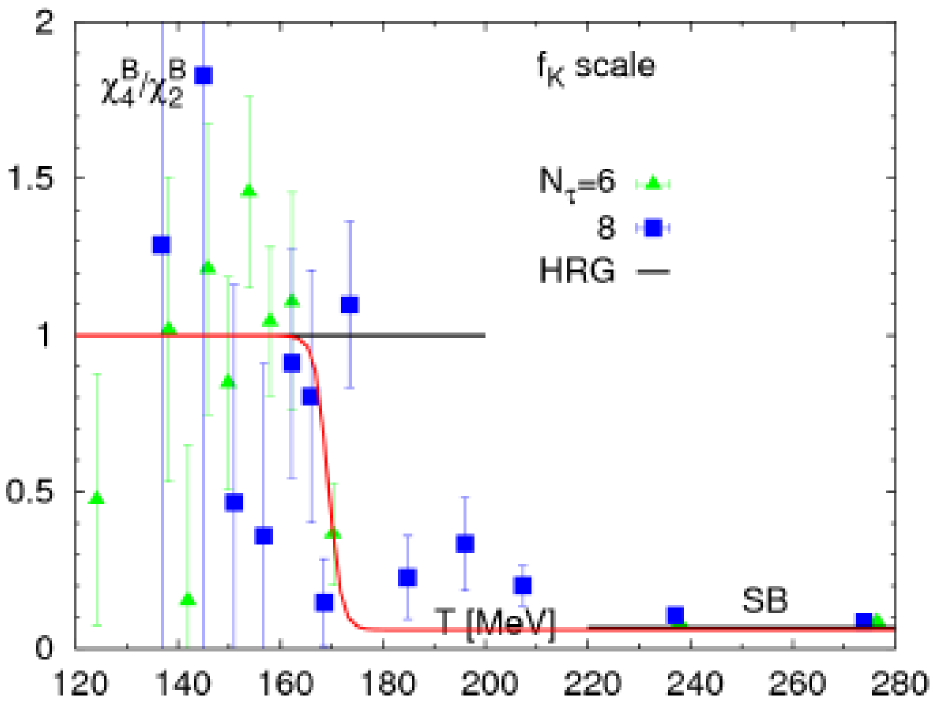
$$\chi_q^{(2)} = \frac{1}{VT^3}\left\langle \left(\delta N_q\right)^2 \right\rangle$$

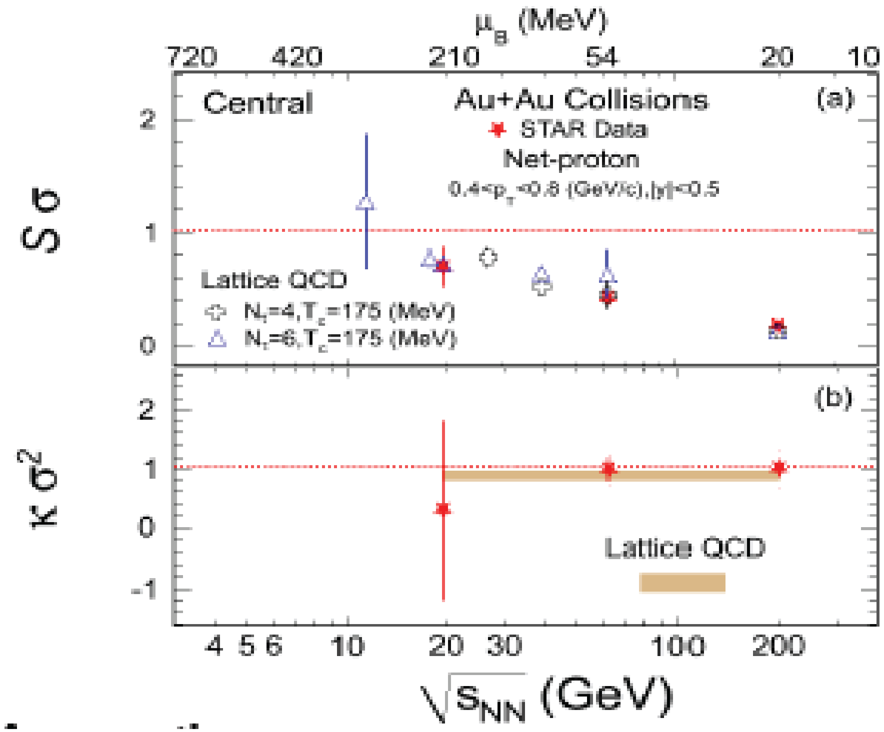
$$\chi_q^{(3)} = \frac{1}{VT^3}\left\langle \left(\delta N_q\right)^3 \right\rangle$$

$$\chi_q^{(4)} = \frac{1}{VT^3}\left(\left\langle \left(\delta N_q\right)^4 \right\rangle - 3\left\langle \left(\delta N_q\right)^2 \right\rangle^2\right)$$

$$\frac{T^2\chi_q^{(4)}}{\chi_q^{(2)}} = \kappa\sigma^2$$

$$\frac{T\chi_q^{(3)}}{\chi_q^{(2)}} = S\sigma$$





Susceptibilities: Benchmark I

$$P(T,\mu) = T^4 \sum_{n=0}^{\infty} \frac{d_n(T)}{n!} \left(\frac{\mu}{T}\right)^n$$

Consider a free gas of heavy particles (non-relativistic, N.R.), with baryon number B, and mass M>>T:

$$d_n^{\text{free}}\Big|_{\text{NR}} = N_i \left(\frac{M}{2\pi T}\right)^{\frac{3}{2}} e^{-\frac{M}{T}} \times 2B^n \equiv \mathcal{F}\left[\frac{M}{T}\right] B^n.$$

- Same T-dependence for all orders
- d_n is positive, proportional to B^n
- at any order the ratio d_(n+2)/d_n = B^2

Susceptibilities: Benchmark II

$$P(T,\mu) = T^4 \sum_{n=0}^{\infty} \frac{d_n(T)}{n!} \left(\frac{\mu}{T}\right)^n$$

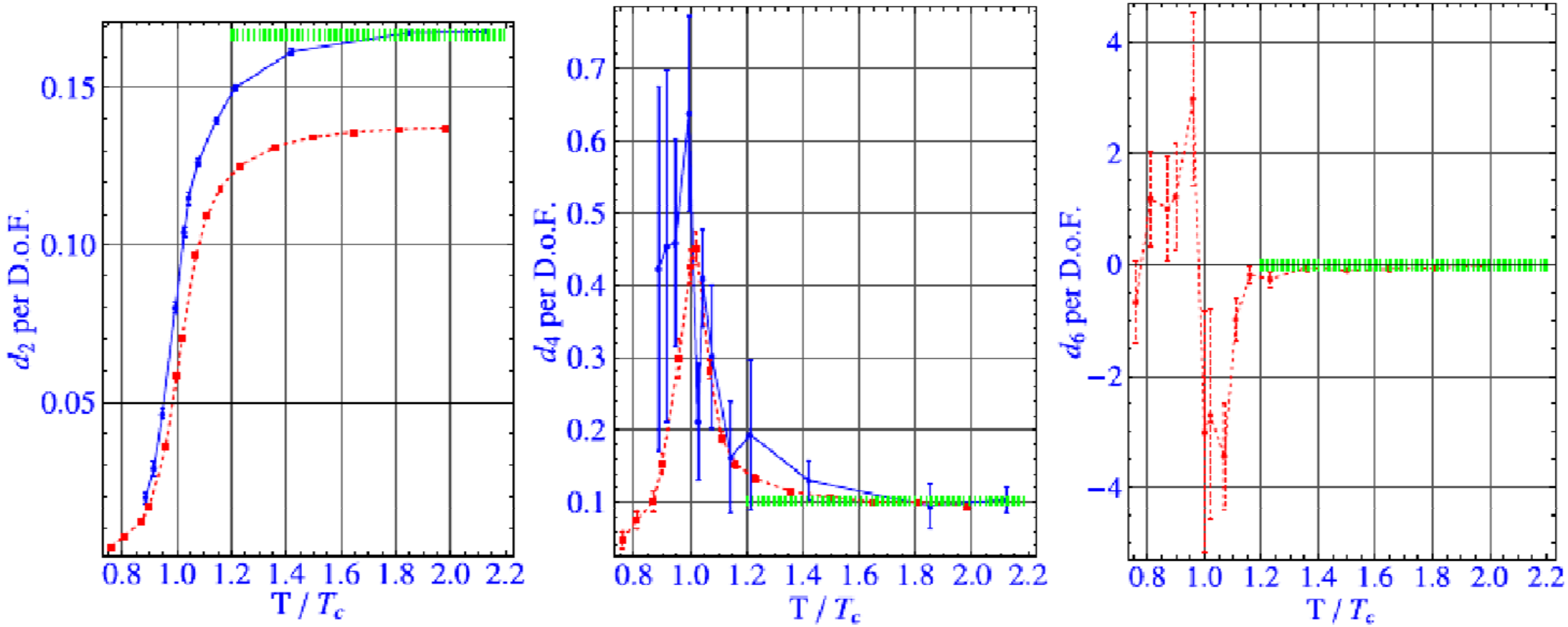
Consider a free gas of massless particles (Stefan-Boltzmann, S.B.), with baryon number B, and mass M=0:

$$d_2^{\text{free}}\big|_{\text{UR}} = N_i \frac{B^2}{6}, \qquad d_4^{\text{free}}\big|_{\text{UR}} = N_i \frac{B^4}{\pi^2}, \qquad d_{n>4}^{\text{free}}\big|_{\text{UR}} = 0.$$

- No T-dependence, up to n=4
- d_n is positive, proportional to B^n
- d_4/d_2 ~ B^2

Susceptibilities from Lattice QCD

LQCD data: Bielefeld-BNL 2005 2-flavor with heavy pion; 2009 “almost physical” pion mass



Below Tc: behavior close to the N.R.-benchmark , ratios~B=1

i.e. hadronic(baryonic) resonance gas (verified by many)

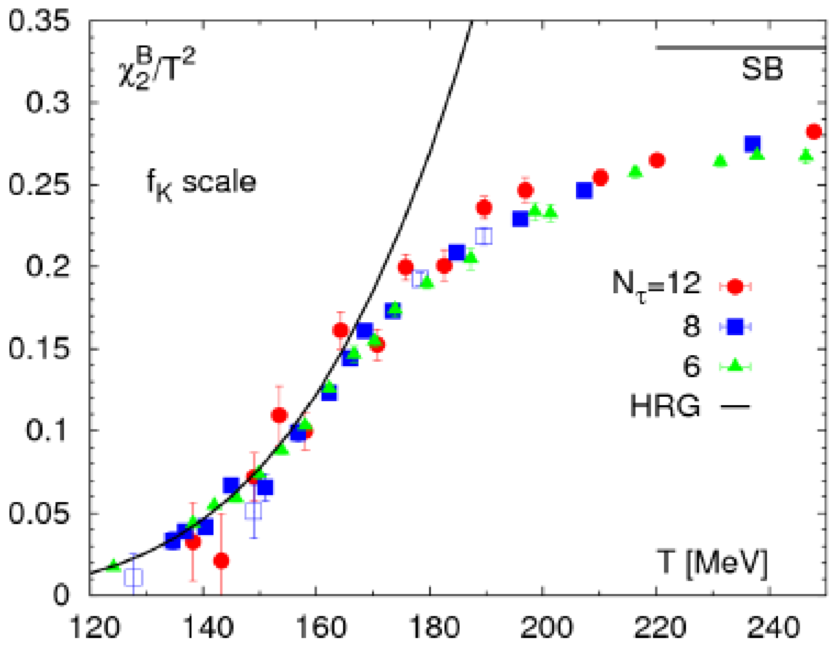
Well above Tc (at least 1.5Tc up): behavior close to S.B., ratios~B=1/3

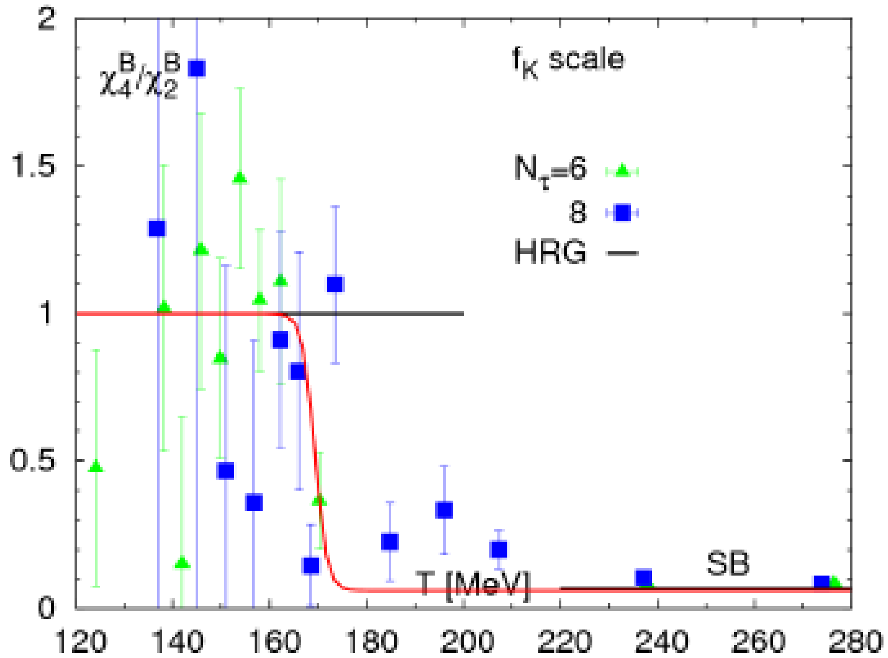
i.e. seemingly (quasi-)quarks that are VERY light ! ?

[caution: stay tuned till conclusive and agreed data from varied groups]

Susceptibilities from Lattice QCD

Newest HotQCD data





Yet, a few nontrivial questions to be answered:

- **what about the near-Tc plasma? The behavior there resembles neither!**
- **what are those nontrivial structures --- peaks and wiggles ---- due to?**
- **is the nearly S.B. behavior at higher T in accord with our integrated picture of QGP in this T-region?**

Different models have varied answers --- let's examine them.

Quasi-particle Models

Free gas of quark quasi-particles with medium generated mass: M(T , \mu)

$$d_2 = \frac{\partial (n_B/T^3)}{\partial \tilde{\mu}}\Big|_{\mu=0} = -\frac{2g}{2\pi^2}\int dx x^2 n^2 F^{(1)}(\epsilon_0),$$

$$d_4 = \frac{\partial^3 (n_B/T^3)}{\partial \tilde{\mu}^3}\Big|_{\mu=0}$$
$$= -\frac{2g}{2\pi^2}\int dx x^2\Big[n^4 F^{(3)}(\epsilon_0) + 3n^2 F^{(2)}(\epsilon_0)\frac{\tilde{m}_0}{\epsilon_0} \times\Big(\frac{\partial^2 \tilde{m}}{\partial \tilde{\mu}^2}\Big|_{\mu=0}\Big)\Big],$$

$$d_6 = \frac{\partial^5 (n_B/T^3)}{\partial \tilde{\mu}^5}\Big|_{\mu=0}$$
$$= -\frac{2g}{2\pi^2}\int dx x^2\Big[n^6 F^{(5)}(\epsilon_0) + 10n^4 F^{(4)}(\epsilon_0)\frac{\tilde{m}_0}{\epsilon_0} \times\Big(\frac{\partial^2 \tilde{m}}{\partial \tilde{\mu}^2}\Big|_{\mu=0}\Big) + 15n^2 F^{(3)}(\epsilon_0)\frac{\tilde{m}_0^2}{\epsilon_0^2}\Big(\frac{\partial^2 \tilde{m}}{\partial \tilde{\mu}^2}\Big|_{\mu=0}\Big)^2 + 5n^2 F^{(2)}(\epsilon_0)\Big(\frac{\tilde{m}_0}{\epsilon_0}\Big(\frac{\partial^4 \tilde{m}}{\partial \tilde{\mu}^4}\Big|_{\mu=0}\Big) + \frac{3x^2}{x^2+\tilde{m}_0{}^2}\Big(\frac{\partial^2 \tilde{m}}{\partial \tilde{\mu}^2}\Big|_{\mu=0}\Big)^2\Big)\Big].$$

The main message:

$d_2(T) \rightarrow \{M\}_{T,\mu=0}$

$d_4(T) \rightarrow \left\{M, \frac{d^2 M}{d\mu^2}\right\}_{T,\mu=0}$

$d_4(T) \rightarrow \left\{M, \frac{d^2 M}{d\mu^2}, \frac{d^4 M}{d\mu^4}\right\}_{T,\mu=0}$

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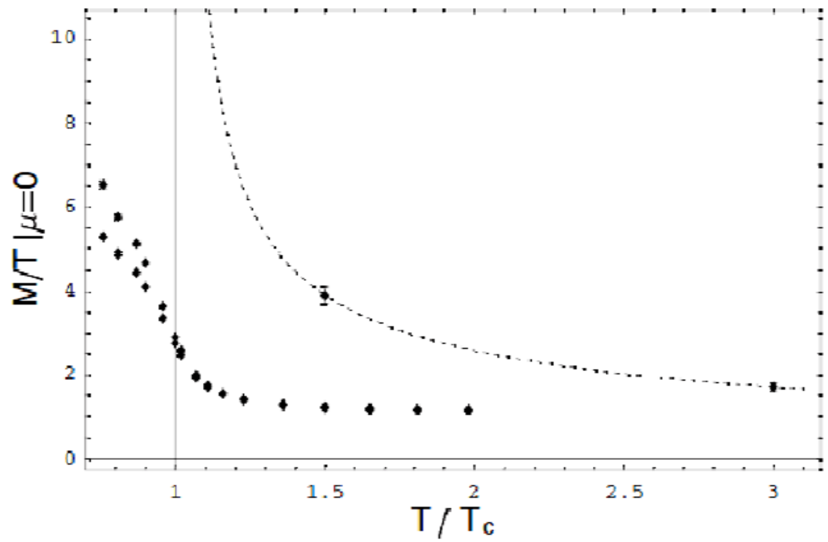
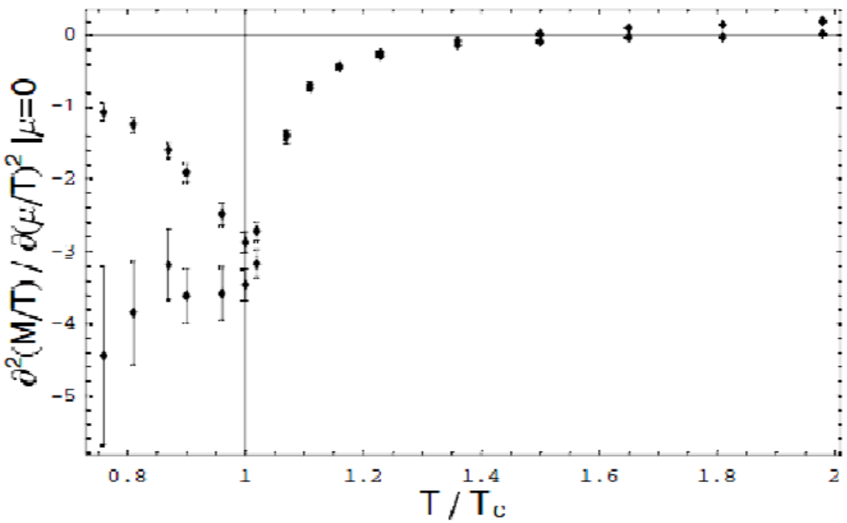
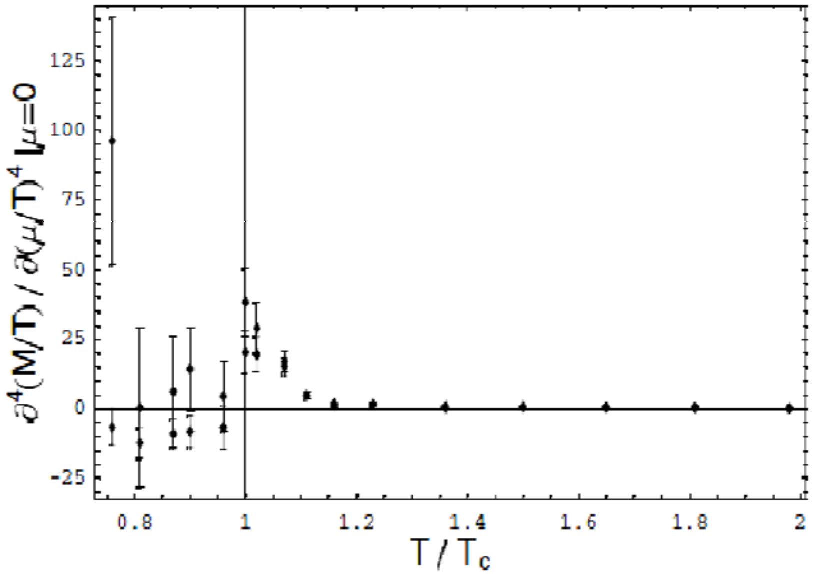
JL & Shuryak, Phy. Rev. D 73(2006)014509.

Quasi-particle Models

Free gas of quark quasi-particles with medium generated mass: M(T , \mu)





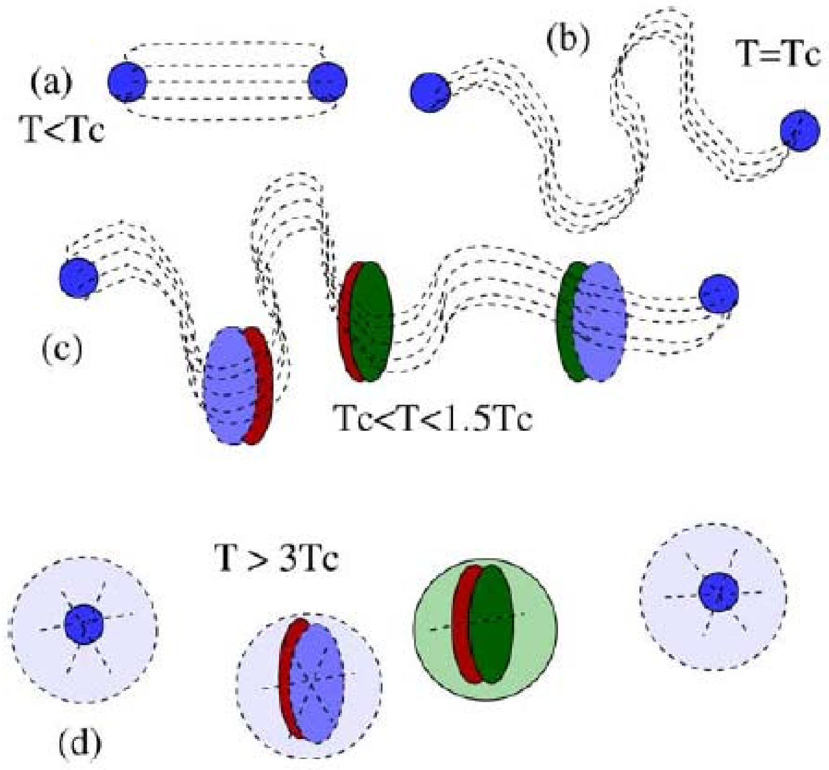


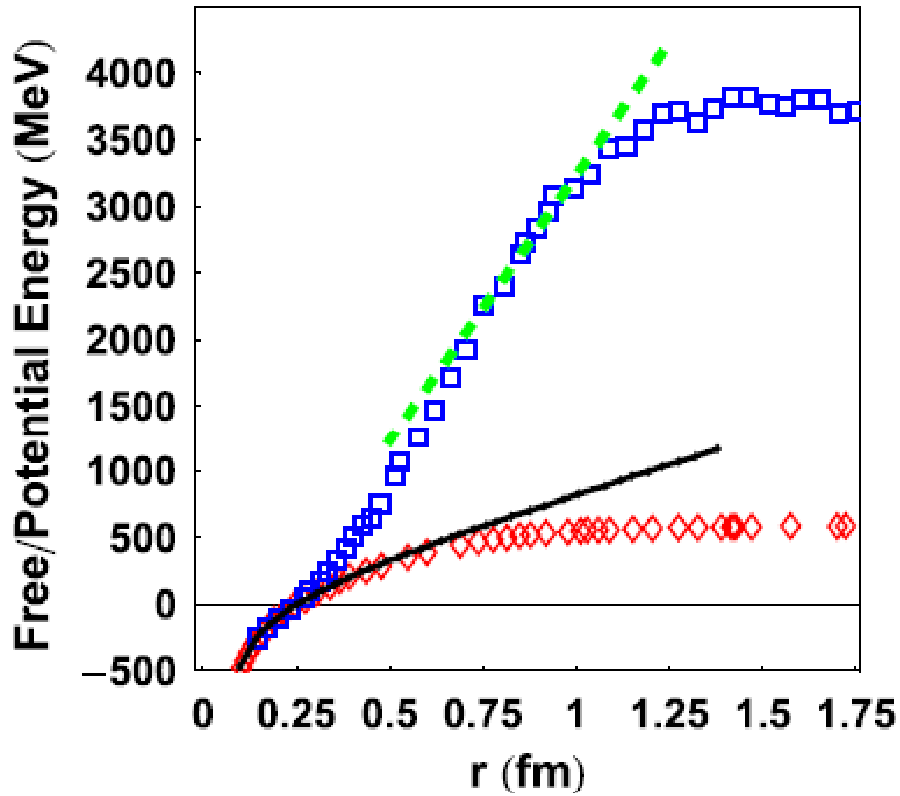
There are problems with quasi-particle models:

- dynamical explanation of such dependence?
  e.g. HTL not generating these…
- masses compared with direct lattice results?
  e.g. M_g/q ~ 1-3 T (Petreczky…; Karsch…)
- Polyakov loop suppression ?!
- what about the “perfect fluid” and quenching?
  → susceptibilities of quarks at strong coupling?

Back to Baryons: Dead or Alive in sQGP?

- RHIC phenomenology → collective flow, jet quenching,… → strongly coupled!
- Lattice QCD → strong screening kicks in late; Polyakov line restores late;
  VERY strong potential between color charges!





JL&Shuryak,
Nucl. Phys. A 775(2006)224.

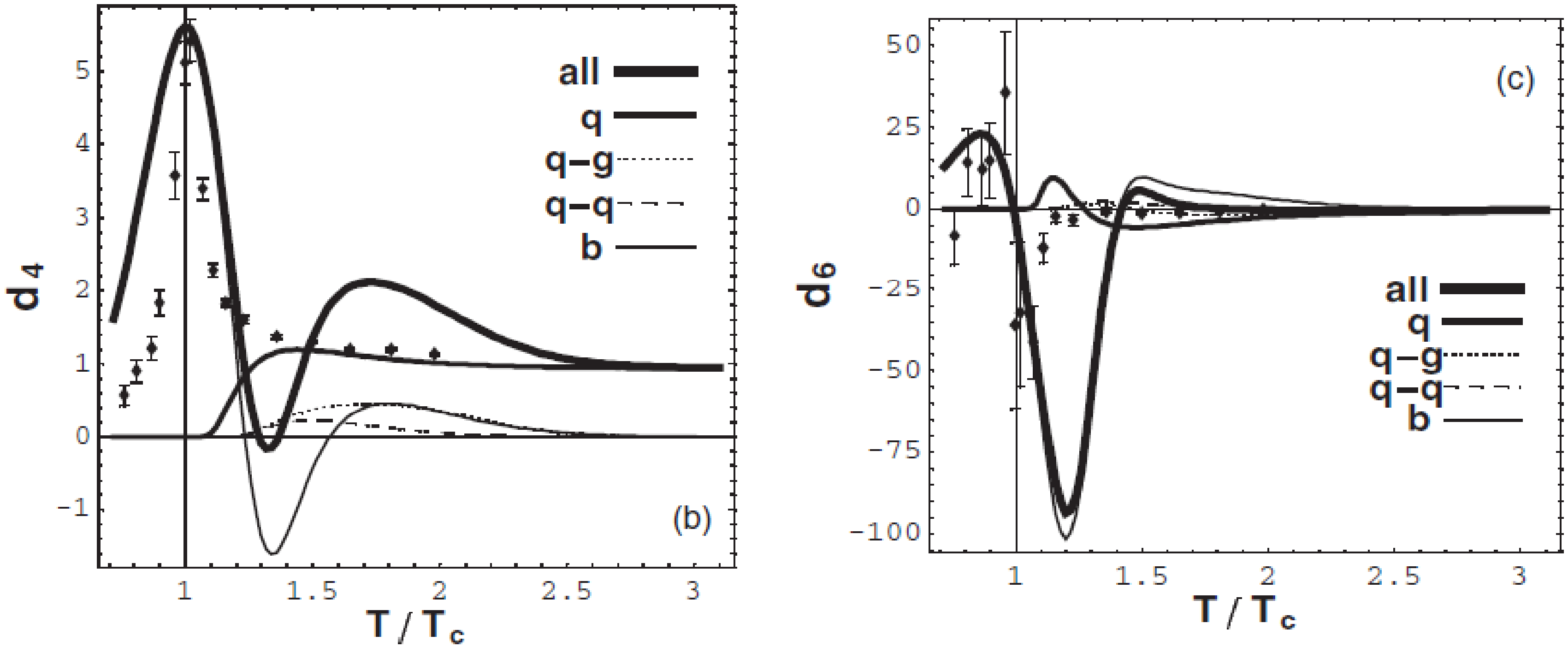
JL&Shuryak,
Phy. Rev. D 82(2010)094007.

Susceptibilities: Baryons v.s. Quarks

Thermal factor : $e^{-M_q/T}$ v.s. $e^{-M_B/T}$

Charge factor : $\left(B_q = \frac{1}{3}\right)^n$ v.s. $\left(B_B = \frac{1}{3}\right)^n$

Baryons, or baryonic correlations, can contribute much more prominently in higher order susceptibilities, particularly the *<u>4-th and 6-th orders</u>*!

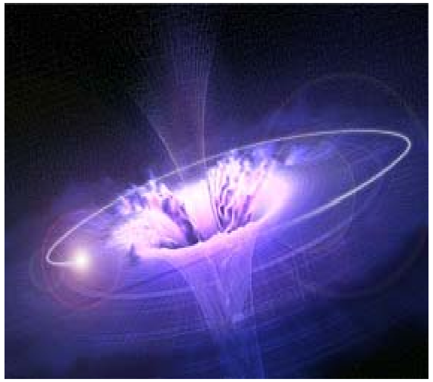


Baryons dominate the near Tc peaks and wiggles in the 4-th and 6-th order.

<u>JL & Shuryak, Phy. Rev. D 73(2006)014509.</u>

Susceptibilities from Holography

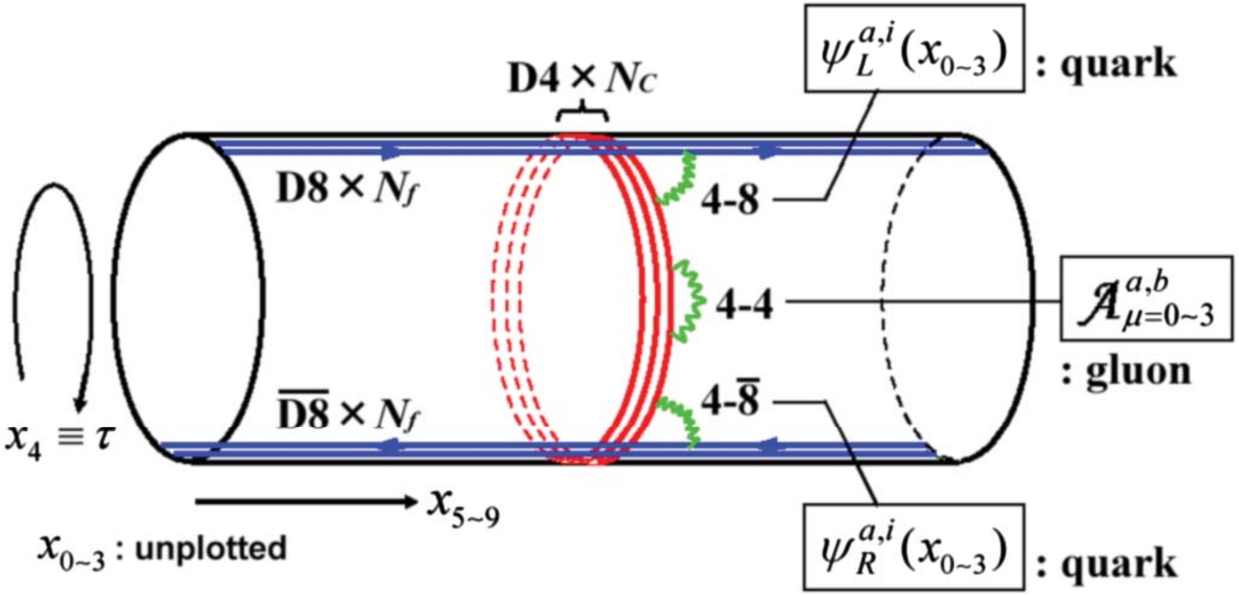
RHIC produces the sQGP: we need benchmarks of susceptibilities at strong coupling!
May holography provide a useful benchmark as in the case of e.g. shear viscosity?



$$s(\lambda \to \infty) / s(\lambda = 0) = 3/4$$

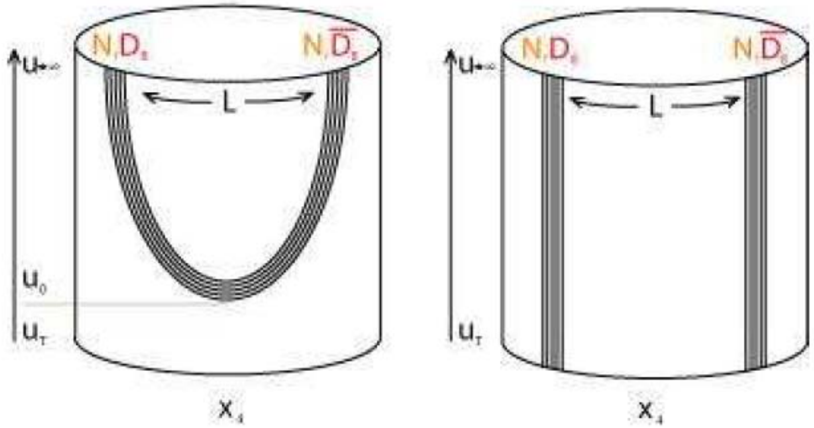
$$\eta / s \geq 1/(4\pi)$$

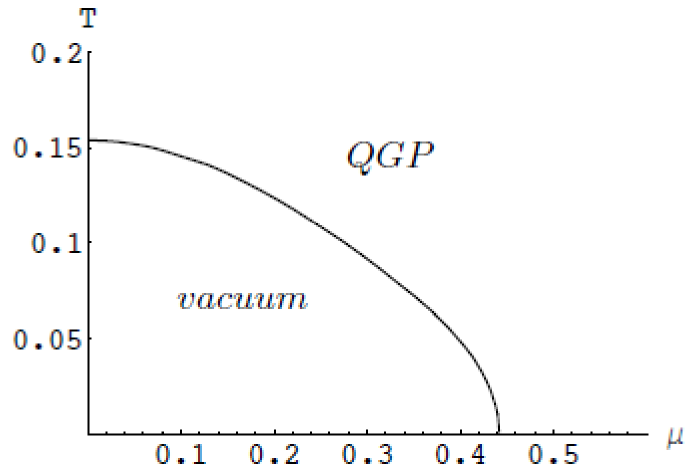
For baryonic susceptibilities: we Sakai-Sugimoto model (D4/D8 branes)



Thermodynamics in Sakai-Sugimoto

There are different phases ---- we focus on the **high-T and low-density phase**, QGP phase





Thermodynamics of QGP phase in Sakai-Sugimoto Model with nonzero baryonic density:

$$P_{\rm QGP}[T,d(T,\mu)]=\left[\frac{2}{7}\Gamma_A d^{\frac{7}{5}}+\frac{2}{7}u_T(d^2+u_T^5)^{\frac{1}{2}}-\frac{2}{7}u_T d\,{}_2\mathrm{F}_1\left(\frac{1}{5},\frac{1}{2};\frac{6}{5};-\frac{u_T^5}{d^2}\right)\right],$$

$$\Gamma_A d^{\frac{2}{5}}-u_T\,{}_2\mathrm{F}_1\left(\frac{1}{5},\frac{1}{2};\frac{6}{5};-\frac{u_T^5}{d^2}\right)-\mu=0,\qquad \Gamma_A=\frac{\Gamma(\frac{3}{10})\Gamma(\frac{6}{5})}{\sqrt{\pi}}.$$

Susceptibilities from Holography

Results for susceptibilities in QGP phase from such a holographic model of QCD:

$$d_n = \xi_n N_s N_c N_f \left(\frac{1}{\lambda \tilde{T}}\right)^{n-3}$$

$\lambda = g^2 N_c$

$\tilde{T} = T / T_c$

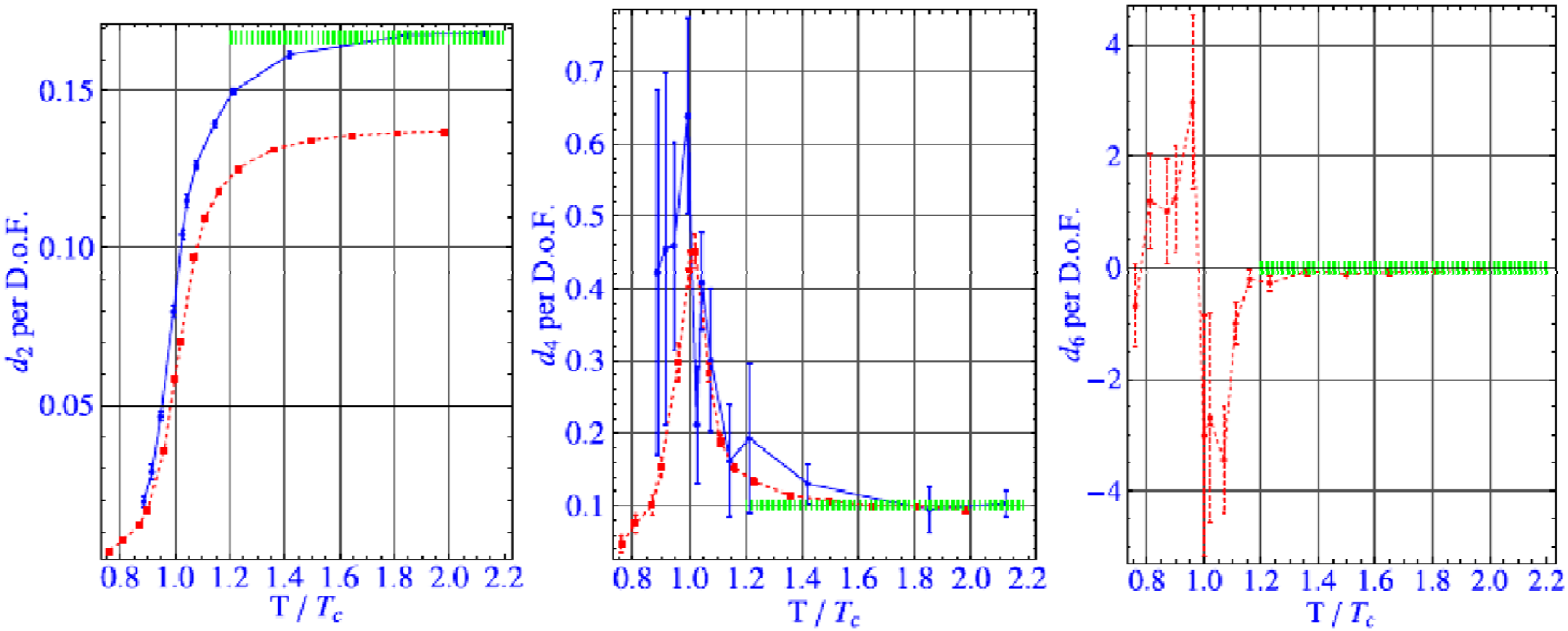
$$\frac{d_2}{N_s N_f N_c} \approx 0.012 \cdot \lambda \tilde{T}, \qquad \frac{d_4}{N_s N_f N_c} \approx \frac{0.37}{\lambda \tilde{T}}, \qquad \frac{d_6}{N_s N_f N_c} \approx -\frac{26}{\lambda^3 \tilde{T}^3}.$$

Very interesting dynamical feature:

- **alternating signs (beyond 6-th order as we checked)**
- **strong coupling suppressing higher fluctuations while enhancing leading order**
- **temperature dependence is unusual as well**

Kim & JL, Nucl. Phys. B 822(2009)201.

A Quick Comparison



$$\frac{d_2}{N_s N_f N_c} \approx 0.012 \cdot \lambda \tilde{T}, \qquad \frac{d_4}{N_s N_f N_c} \approx \frac{0.37}{\lambda \tilde{T}}, \qquad \frac{d_6}{N_s N_f N_c} \approx -\frac{26}{\lambda^3 \tilde{T}^3}.$$

- **qualitatively similar near Tc, but not quantitatively, and need further understanding… (as in all holographic calculations)**
- **a useful (but only a) benchmark for how quarks might contribute to susceptibilities at strong coupling**

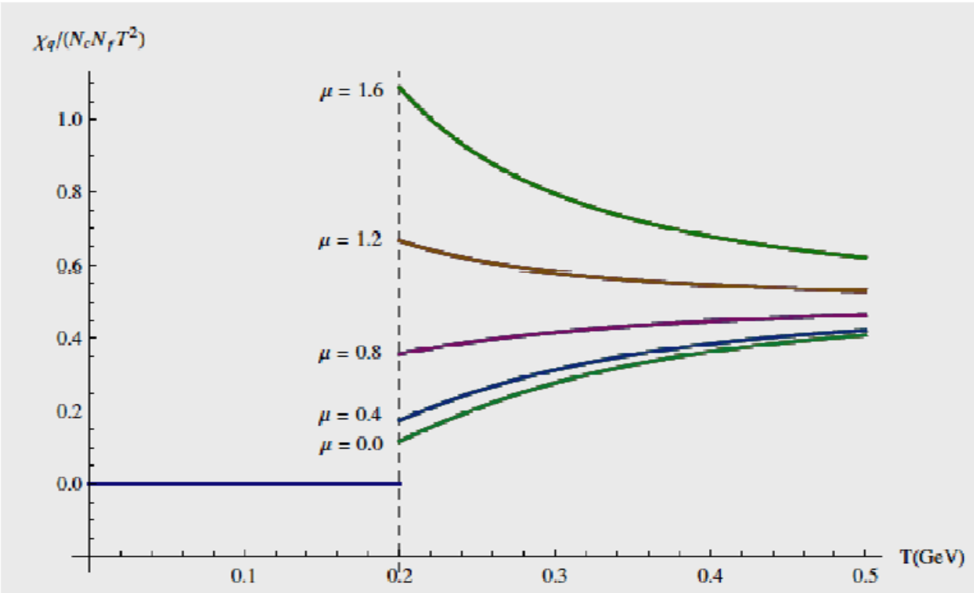
Different Holographic Results

Our D4-D8 setup results: $d_n = \xi_n N_s N_c N_f \left(\frac{1}{\lambda \tilde{T}}\right)^{n-3}$

$$\frac{d_2}{N_s N_f N_c} \approx 0.012 \cdot \lambda \tilde{T}, \qquad \frac{d_4}{N_s N_f N_c} \approx \frac{0.37}{\lambda \tilde{T}}, \qquad \frac{d_6}{N_s N_f N_c} \approx -\frac{26}{\lambda^3 \tilde{T}^3}.$$

A D3-D7 setup result (for the second susceptibility only) :
Kim-Matsuo-Sim-Takeuchi-Tsukioka, JHEP05(2010)038.

$$\chi_q(T) = \frac{2\pi^2 T^2}{g_5^2}\left(\frac{c}{e^c - 1}\right)$$



$$\chi_q \sim T^2, \qquad \text{D3/D7},$$
$$\chi_q \sim T^3, \qquad \text{D4/D8}.$$

Cross-Flavor Susceptibilities

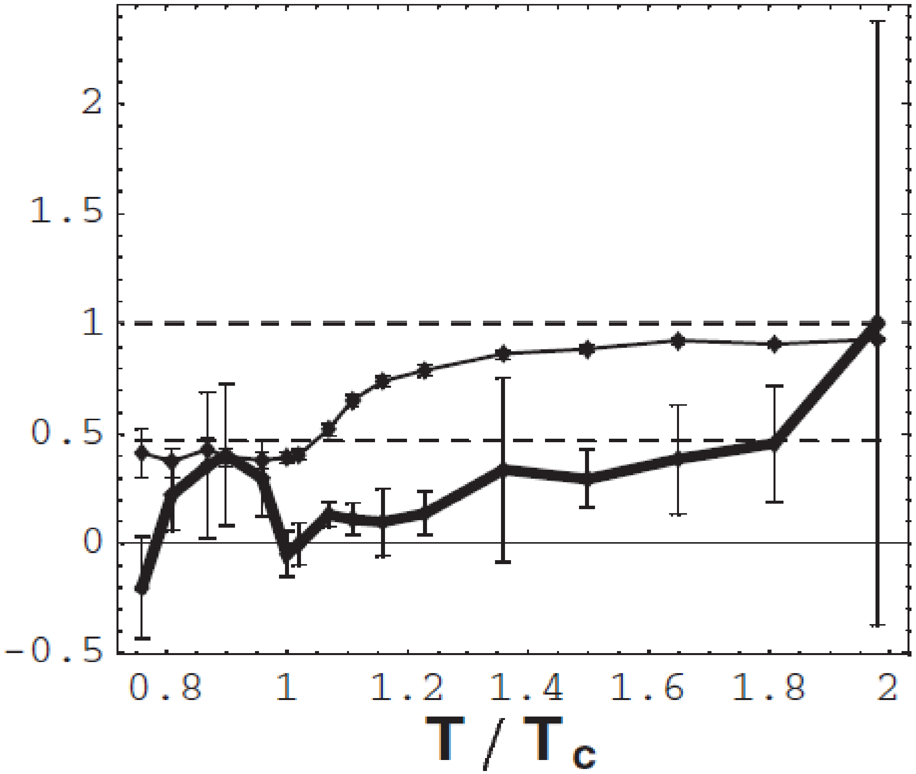
There are more conserved charges (within QCD): Baryon , Isospin , Strangeness
→ Provides additional probes of charge carriers

N : I = 1 / 2 , B = 1

Δ : I = 3 / 2 , B = 1

Q (u, d) :

I = 1 / 2, B = 1 / 3



An example of mixed-susceptibilities

$$\frac{d_4^{\,I}}{d_4} \sim \frac{I^2}{B^2} \qquad \frac{d_6^{\,I}}{d_6} \sim \frac{I^2}{B^2}$$

QUARKs

BARYONs

What could be said about these non-diagonal susceptibilities from holography?

Need to turn on new external probe flux …

Other example: B-S correlations by Koch, et al.

SUMMARY

- Susceptibilities of conserved charges provide sensitive probe to the ***new D.o.F in new phases of matter***, as well as ***possible critical point.***
- Three models are examined***: quasi-particles, bound states, & holography***.
- The ***near-Tc structure is intriguing*** --- need more accurate lattice data as well as theoretical calculations (e.g. holography) in ***higher order susceptibilities*** and in ***cross-flavor non-diagonal susceptibilities***;
- Holographic models to calculate critical fluctuations and correlations that might be related to the measurements from RHIC Low Energy Scan??

Thank you!