Susceptibilities from a Black Hole Engineered EoS with a Critical Point

Israel Portillo

UNIVERSITY of HOUSTON

Collaborators:

University of Houston: Claudia Ratti, Jacquelyn Noronha-Hostler, Paolo Parotto

University of Sao Paulo: Jorge Noronha, Romulo Rougemont, Stefano Finazzo, Renato Critelli

Exploring QCD Phase Diagram

Lattice QCD

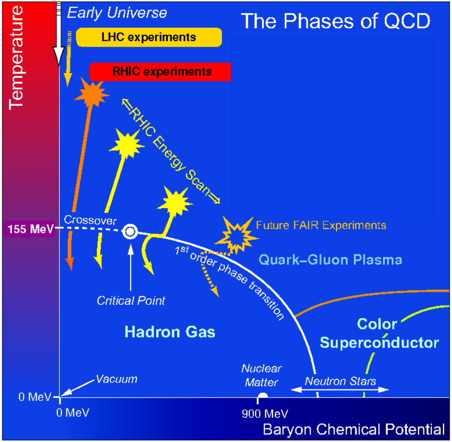
Perform calculations at $\mu_B = 0$, and extrapolate via Taylor expansion to finite μ_B

Black Hole Engineering

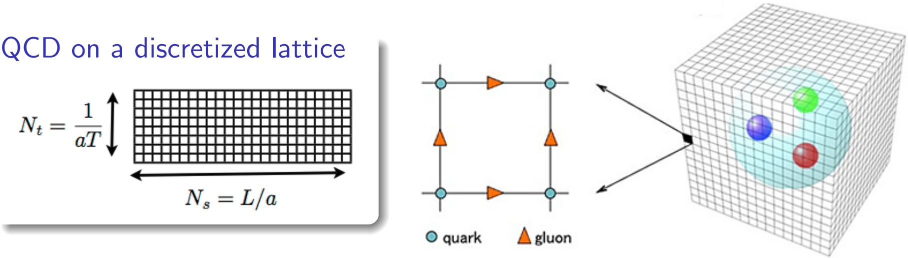
Based on Lattice data at $\mu_B = 0$, allows us to calculate observable at finite density.

Fluctuations of conserved Charges

Provide essential information about the effective degrees of freedom of a system.



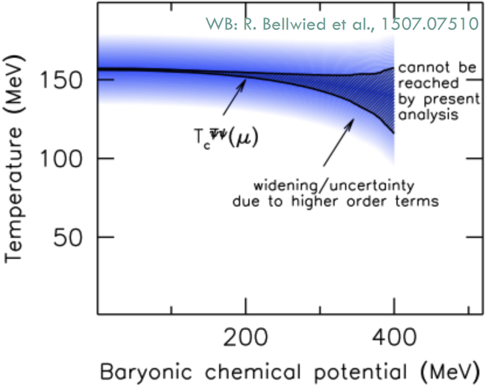
Lattice QCD



- Study QCD from first principles in the non-perturbative region.
- Calculates equilibrium properties at $\mu_B = 0$ or at imaginary-μ_B (sign problem!)
- It has technical difficulties to compute transport properties
- Critical behavior of the CEP can be lost when extrapolate calculations at finite μ

Lattice at Finite μ_B

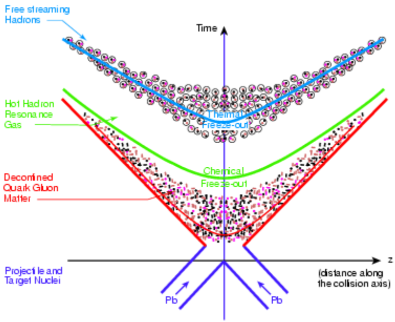
Phase diagram bases on the μ-dependent T_c from the chiral condensate (analytically continued from the imaginary-μ_B)



[WB:] R. Bellwied *et. al.*, Phys. Lett. B **751** (2015) 053

Evolution of a heavy ion collision

- Chemical freeze-out: all inelastic interactions cease. The chemical composition of the system is fixed
- Kinetic freeze-out: all elastic interactions cease: the spectra of the particles are fixed



- We want to study the chemical freeze-out
- Observable: fluctuations of conserved charges
  - They are fixed at the freeze-out
  - They can be measured and calculated
  - They are sensitive to the critical point

Susceptibilities

A system in thermal equilibrium is characterized by

$$Z = \mathrm{Tr}\left[-\frac{H - \sum_i \mu_i Q_i}{T}\right]$$
$$P = \frac{T}{V}\ln Z$$

$$\mu_u = \frac{1}{3}\mu_B + \frac{2}{3}\mu_Q$$
$$\mu_d = \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q$$
$$\mu_s = \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q - \mu_S$$

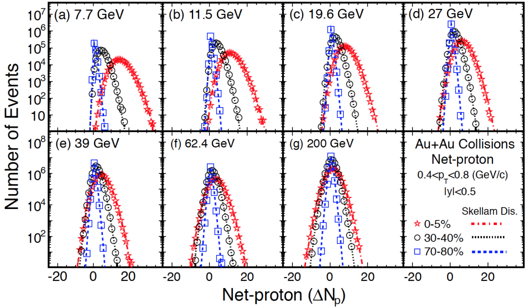
The Susceptibilities χ_{lmn}^{BSQ} are defined as

$$\chi_{lmn}^{BSQ} = \frac{\partial^l}{\partial(\mu_B/T)^l}\frac{\partial^m}{\partial(\mu_S/T)^m}\frac{\partial^n}{\partial(\mu_Q/T)^n}\left(\frac{P}{T^4}\right)$$

Fluctuations of Conserved Charges

- The susceptibilities $\chi_i = \chi_i^B(T, \mu_B)$ are related directly to the moments of the distribution.
- The volume-independent ratios are useful quantities to compare to experimental data.

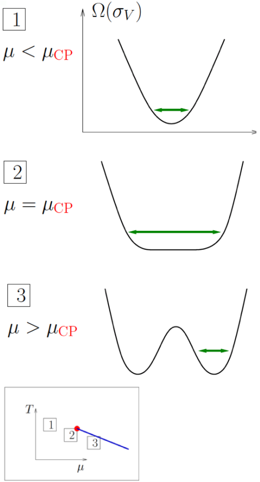
$$
\begin{aligned}
\text{mean}: \quad & M = \chi_1 \\
\text{variance}: \quad & \sigma^2 = \chi_2 \\
\text{skewness}: \quad & S = \chi_3/\chi_2^{3/2} \\
\text{kurtosis}: \quad & \kappa = \chi_4/\chi_2^2
\end{aligned}
$$



$$
\begin{aligned}
M/\sigma^2 &= \chi_1/\chi_2 \\
S\sigma &= \chi_3/\chi_2 \\
\kappa\sigma^2 &= \chi_4/\chi_2 \\
S\sigma^3/M &= \chi_3/\chi_1
\end{aligned}
$$

[STAR] Phys. Rev. Lett. **112** (2014) 032302 Karsch Central Eur.J.Phys. 10 (2012) 1234

Fluctuations at the Critical End Point



The probability distribution for the order parameter

$$P[\sigma] \sim \exp\{-\Omega[\sigma]/T\}$$

$$\Omega = \int \mathrm{d}^3x \left[\frac{1}{2}(\nabla\sigma)^2 + \frac{m_\sigma^2}{2}\sigma_2 + \frac{\lambda_3}{3}\sigma^3 + \cdots\right]$$

The correlation length ($\xi = m_\sigma^{-1}$)

$$\xi \sim |T - T_c|^{-\nu} \text{ where } \nu > 0$$

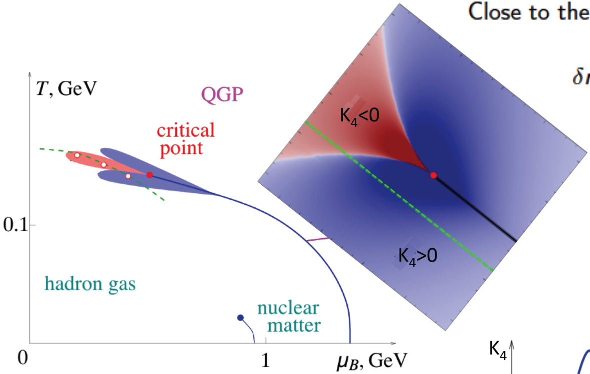
$$\chi_2 = VT\xi^2$$

$$\chi_3 = 2VT^{3/2}\hat{\lambda}_3\xi^{9/2}$$

$$\chi_4 = 6VT^2[2\hat{\lambda}_3^2 - \hat{\lambda}_4]\xi^7$$

M. A. Stephanov, Phys. Rev. Lett. **102** (2009) 032301

Kurtosis at the Critical End Point

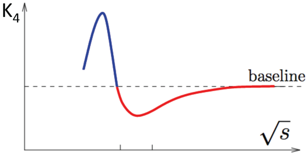


Close to the critical point

$$\delta n_p = \underbrace{\delta n_p^0}_{stat.} + \underbrace{\frac{\partial \bar{n}_p}{\partial m} g \delta \sigma}_{critical}$$

The fluctuation of an observable

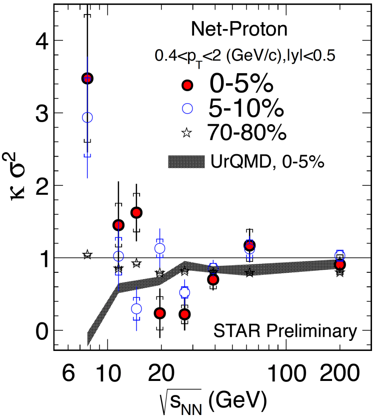
$$\delta N = \sum_p \delta n_p$$



M. A. Stephanov, Phys. Rev. Lett. **107** (2011) 052301

Net-Proton Fluctuations from STAR

- Preliminary STAR data for net-proton fluctuations $(\kappa\sigma^2 = \chi_4/\chi_2)$
- Non-monotonic behavior at low energies
- Is it due to the critical point?
- If so, how close to the critical point does the Non-monotonic behavior show up?



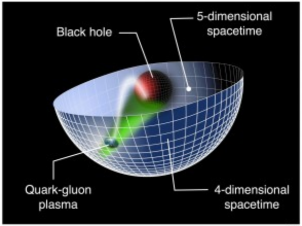
[STAR] Xiaofeng Luo, Quark Matter 2015

Black Hole Engineering

Holography (gauge/string duality at Strong Coupling)

Quantum Field Theory in 4- dimension $\Longleftrightarrow$ Classical Gravity in at least 5-dimension

- Coupling $>>1$ in QFT $\rightarrow$ vanishing string coupling
- (T, μ) in QFT $\rightarrow$ black hole solution
- Holography $\rightarrow$ Near Perfect fluidity



J M Maldacena 1999 Int. J. Theor. Phys. (**38**) 1113

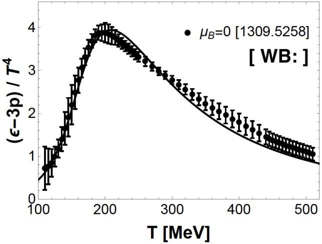
Holographic model

Lagrangian of non-conformal General Relativity in 5 dimensions

$$\mathcal{S} = \frac{1}{16\pi G_5}\int \mathrm{d}x^5\sqrt{-g}\left[\mathcal{R} - \frac{1}{2}(\partial_M\phi)^2 - \underbrace{V(\phi)}_{\text{nonconformal}} - \frac{1}{4}\underbrace{f(\phi)F^2_{MN}}_{\mu_B\neq 0}\right]$$

- ϕ scalar field
- A_M abelian vector field

- G_5 gravitational constant
- $V(\Phi)$ dilaton potential
- $f(\phi)$ Maxwell-dilaton coupling



O DeWolfe, S S Gubser, and C Rosen, Phys. Rev. D **83**, (2011) 086005

R Rougemont, A Ficnar, S Finazzo and J Noronha, High Energ. Phys. (2016) **102**.

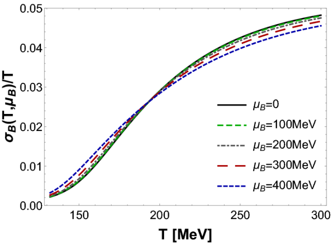
Black Hole Engineering

Black Hole Model

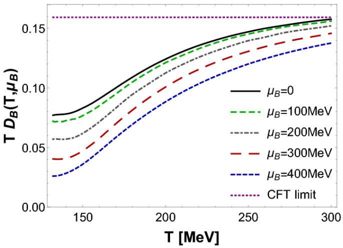
- Input parameter are fixed by Lattice data at $(T, \mu_B = 0)$
- Non-conformal Equation of State
  - at finite T and finite μ_B
  - with a critical end point
  - agrees with lattice data at small μ_B
  - allows to extract freeze-out parameters
- Near perfect fluidity
  - Ability to compute transport coefficients near the crossover and at large μ_B

Baryon Transport Coefficients

Baryon dc conductivity

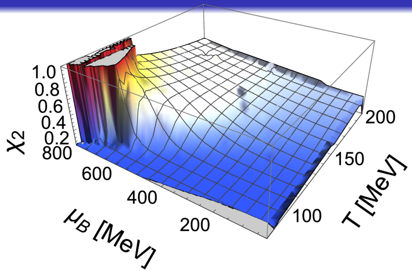


Baryon diffusion constant



R Rougemont, J Noronha, and J Noronha-Hostler Phys.Rev.Lett. **115** (2015) 202301

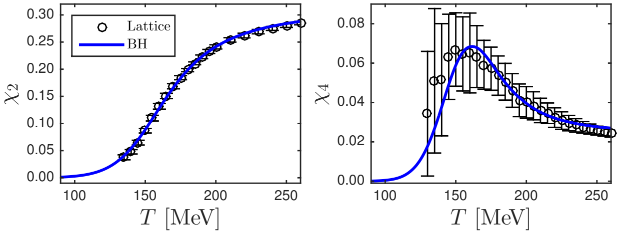
Model Predictions



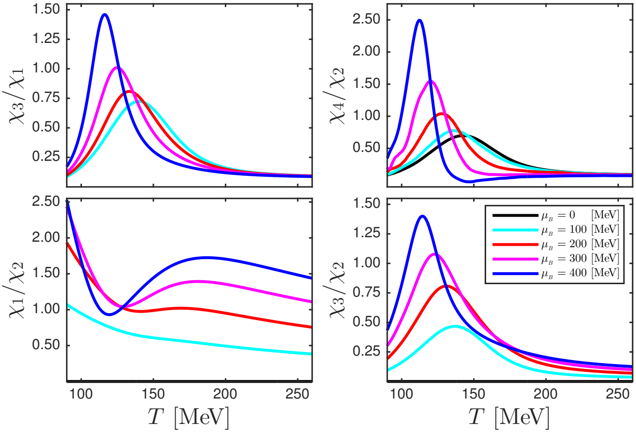
Critical end point

$$\mu_B = 705\ \mathrm{MeV}$$
$$T = 80\ \mathrm{MeV}$$

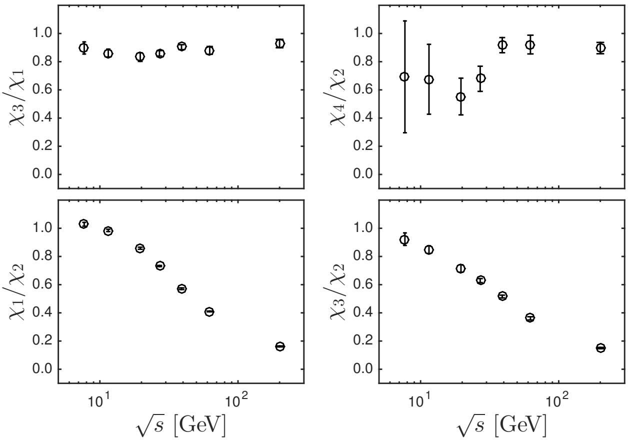
χ_2 and χ_4 agree with lattice points



Black Hole Susceptibility Ratios



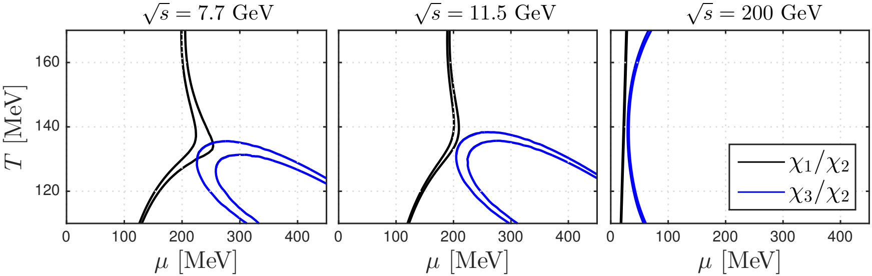
[STAR] Net Proton Fluctuation Susceptibility Ratios



[STAR] Phys. Rev. Lett. **112** (2014) 032302

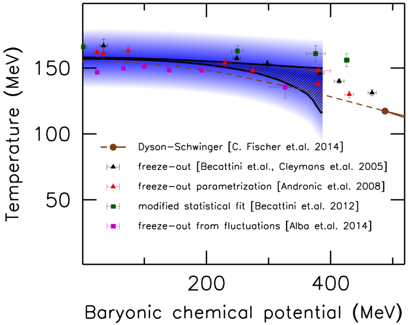
Freeze out: Extracted from χ_1/χ_2 and χ_3/χ_2

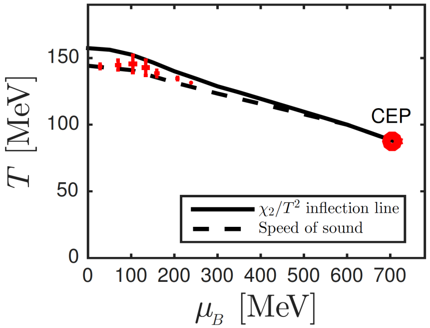
Trajectory in the $[T - \mu]$ plane that satisfy the experimental values



- Freeze out points $[T - \mu_B]$ are extracted from the line made by the closer points between χ_1/χ_2 and χ_3/χ_2

Freeze-out Line





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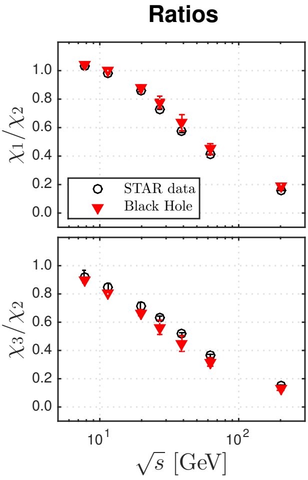
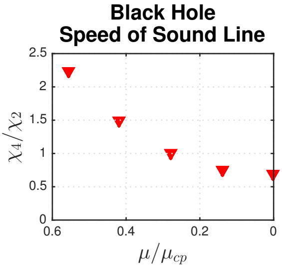
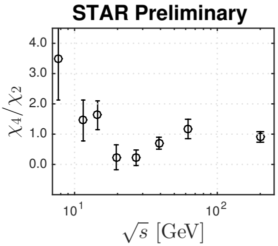
Black Hole Model

Model Predictions







Conclusions

We study a Black Hole Model that up to a $\mu_B = 400$MeV and found that

- Reproduces lattice data at $\mu_B = 0$
- Contains a critical end point at $\mu_B = 705$MeV and $T = 80$MeV
- The freeze-out points we found are very close to the points obtained by HRG, and they are far from our critical end point
- When we extrapolate to points close to the CEP we found a monotonic behavior of χ_4/χ_2.

Outlooks

- Explore susceptibilities for μ_B closer to the critical end point
- Study sensitivity of the location of the critical point to initial parameters
- Determine the universality class of the critical end point in the black hole model