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Susceptibilities from a black hole engineered EoS with a critical point

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Exploring The QCD Phase Diagram

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Lattice QCD

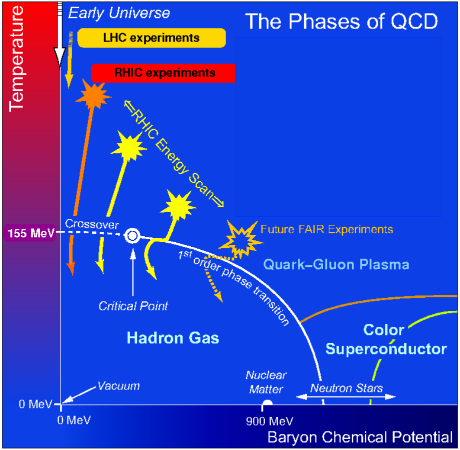
Perform calculations at $\mu_B = 0$, and extrapolate via Taylor expansion to finite μ_B

Black Hole Engineering

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

Susceptibilities of Conserved Charges

Are sensitive to the critical point and can be measured



Lattice QCD

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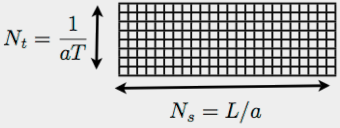
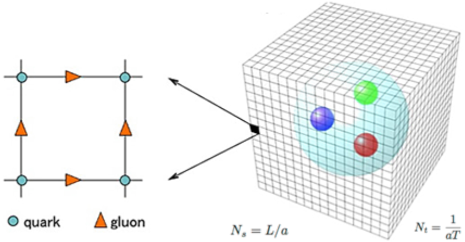
QCD on a discretized lattice





- Study QCD from first principles in the non-perturbative region (Performs path integral using Monte-Carlo technique).
- Calculate equilibrium properties at $\mu_B = 0$ or at imaginary-μ_B (sign problem!). Calculations can be extrapolated to a small regime of μ_B.
- Has technical difficulties to compute transport properties

Black Hole Engineering

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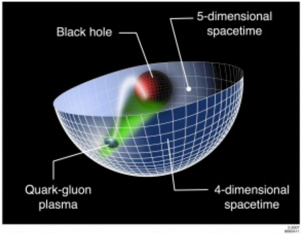
Holography (gauge/string duality at Strong Coupling)

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

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

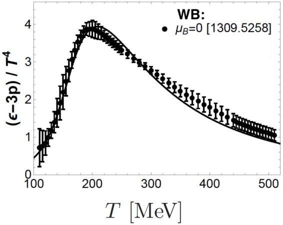


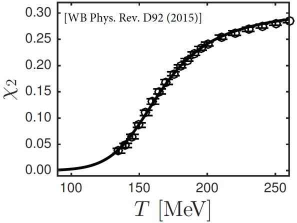
J M Maldacena 1999 Int. J. Theor. Phys. **(38)** 1113

Holographic Model

Non-conformal holographic gravity dual in 5 dimensions $\Longrightarrow$ Black Hole Solution

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





- Input parameters are fixed by lattice QCD results at $\mu_B = 0$
- Finite T and $\mu_B \rightarrow$ Predictions

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

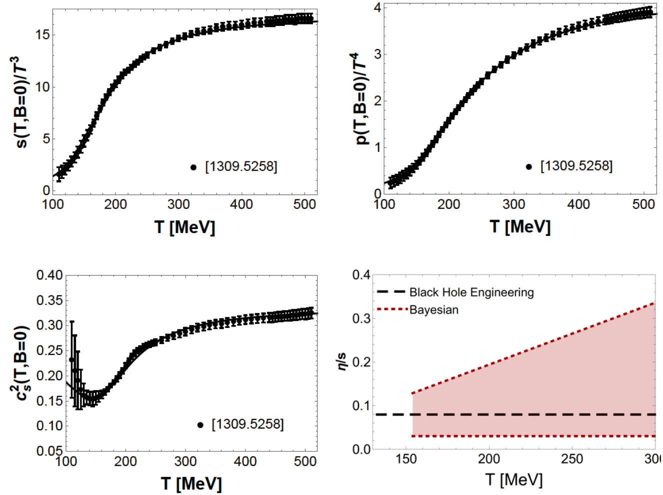
R Rougemont, A Ficnar, S Finazzo and J Noronha, JHEP (2016) **102**.

Black Hole Engineering

Black Hole Model

- Input parameters 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
- Near perfect fluidity
  - Ability to compute transport coefficients near the crossover and at large μ_B

Model Predictions at $\mu_B = 0$



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

Susceptibilities

- A system in thermal equilibrium is characterized by

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

- The Pressure

$$P = \frac{T}{V} \ln Z$$

- The Baryonic Susceptibilities χ_n^B are defined as

$$\chi_n^B(T, \mu_B) = \frac{\partial^n}{\partial(\mu_B/T)^n}\left(\frac{P}{T^4}\right)$$

Susceptibilities of Conserved Charges

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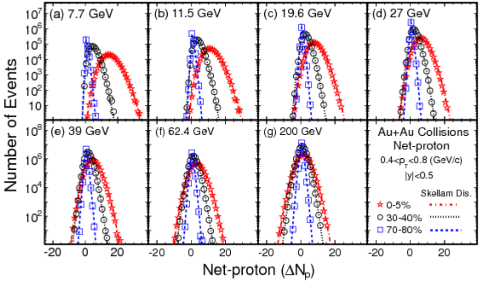
- The susceptibilities $\chi_n = \chi_n^B(T, \mu_B)$ are related directly to the moments of the distribution.
- The volume-independent ratios are useful quantities to compare to experimental data.

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

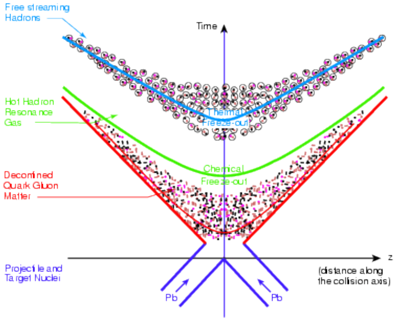


$$
\begin{aligned}
M/\sigma^2 &= \chi_1/\chi_2 \\
S\sigma &= \chi_3/\chi_2 \\
\kappa\sigma^2 &= \chi_4/\chi_2 \\
S\sigma^3/M &= \chi_3/\chi_1
\end{aligned}
$$

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

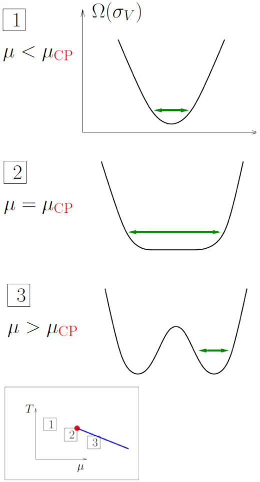
Evolution of heavy ion collisions

- 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
- Observables: susceptibilities of conserved charges
  - They are fixed at the freeze-out
  - They can be measured and calculated
  - They are sensitive to the critical point

Fluctuations at the Critical End Point



The probability distribution for the order parameter

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

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

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

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

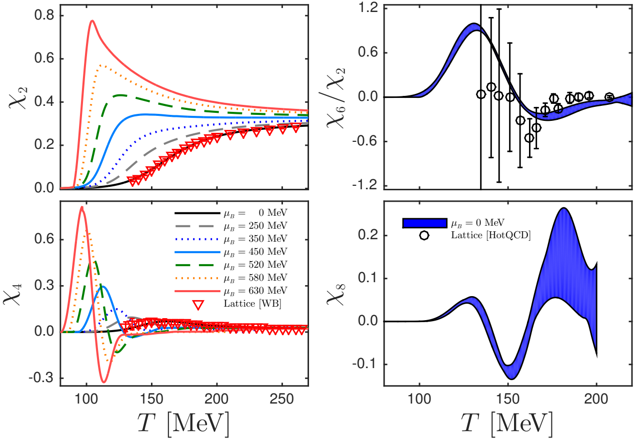
$$\chi_2 = VT\xi^2$$

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

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

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

Black Hole Susceptibilities



BH curves: R. Critelli, I. P. et al., to appear.

Lattice results: [WB] Phys. Rev. D, **92**, 114505 (2015).

[HotQCD] Phys. Rev. D, **95**, 054504 (2017).

Observables at finite μ_B

Taylor expansion of observables in terms of susceptibilities
$\chi_n = \chi_n^B(T, \mu_B = 0)$

- Pressure

$$\frac{p(T,\mu_B) - p(T,\mu_B = 0)}{T^4} = \sum_{n=1}^{\infty} \frac{\chi_{2n}}{(2n!)} \left(\frac{\mu_B}{T}\right)^{2n}$$

- Baryonic density

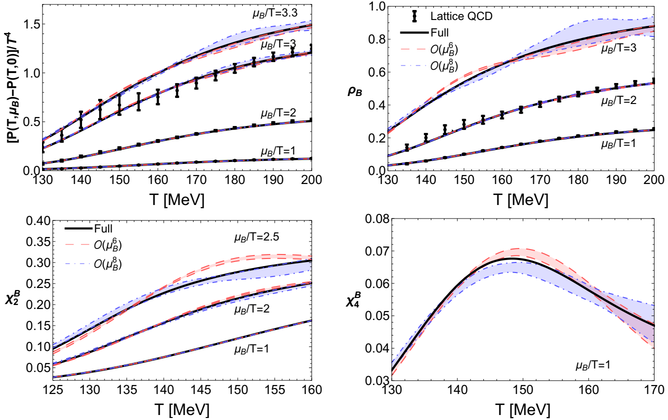
$$\frac{\rho_B(T,\mu_B)}{T^3} = \sum_{n=1}^{\infty} \frac{\chi_{2n}}{(2n-1)!} \left(\frac{\mu_B}{T}\right)^{2n-1}$$

- Susceptibilities χ_2 and χ_4

$$\chi_2(T,\mu_B) = \sum_{n=0}^{\infty} \frac{\chi_{2n+2}}{(2n!)} \left(\frac{\mu_B}{T}\right)^{2n} \qquad \chi_4(T,\mu_B) = \sum_{n=0}^{\infty} \frac{\chi_{2n+4}}{(2n!)} \left(\frac{\mu_B}{T}\right)^{2n}$$

Taylor Reconstruction up to $\mathcal{O}(\mu_B^8)$

Reconstruction of thermodynamic quantities at different values of μ_B/T via Taylor series from calculations at $\mu_B = 0$.



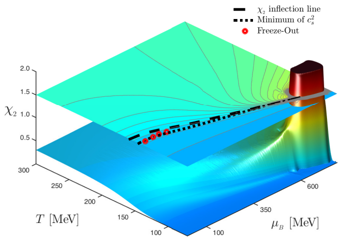
BH curves: R. Critelli, I. P. et al., to appear.

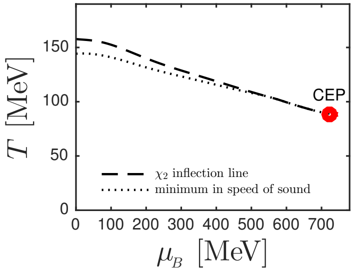
Lattice results: [HotQCD] Phys. Rev. D, **95**, 054504 (2017).

Black Hole Critical End Point

The black hole model contains a critical end point at

- $\mu_B = 723 \pm 36$ MeV
- $T = 89 \pm 11$ MeV

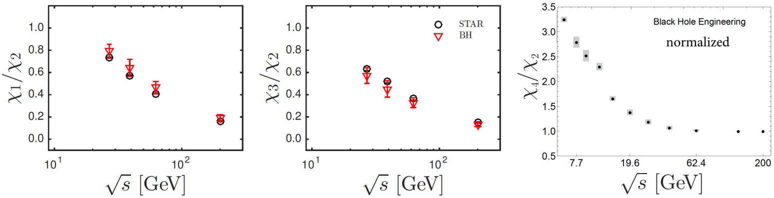




R. Critelli, I. P. et al., to appear.

Connection to Experiment

- We compare the baryonic BH susceptibilities ratios with the net-proton moments measured at STAR
- Freeze-out parameters are extracted by fitting the experimental values for χ_1/χ_2 and χ_3/χ_2
- χ_4/χ_2 predicted at the minimum in speed of sound



R. Critelli, I. P. et al., to appear. [STAR] Phys. Rev. Lett. **112** (2014)

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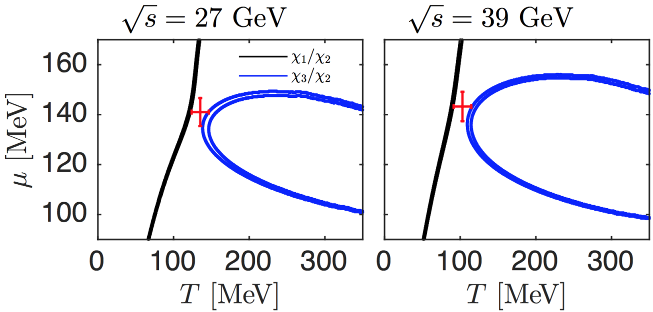
Freeze out parameters from the Black Hole model

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



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

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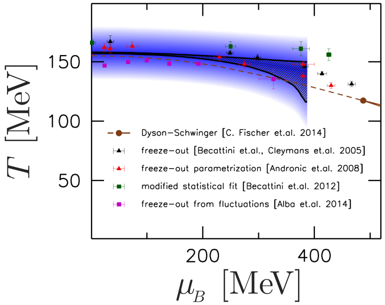
Freeze-out Line

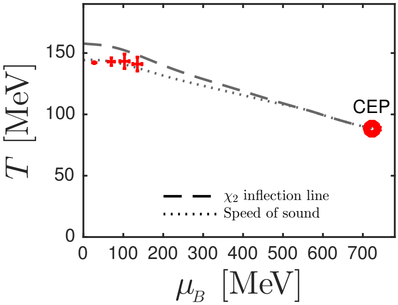
Lattice QCD



[WB:] R. Bellwied *et. al.*,

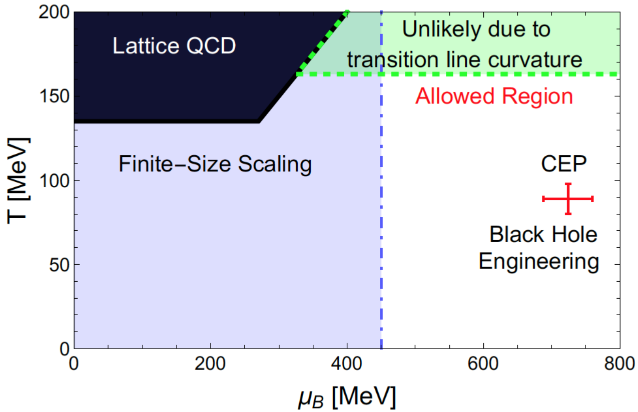
Phys. Lett. B **751** (2015) 053

BH Model



R. Critelli, I. P. et al., to appear.

Black Hole Model CEP



R. Critelli, I. P. et al., to appear.

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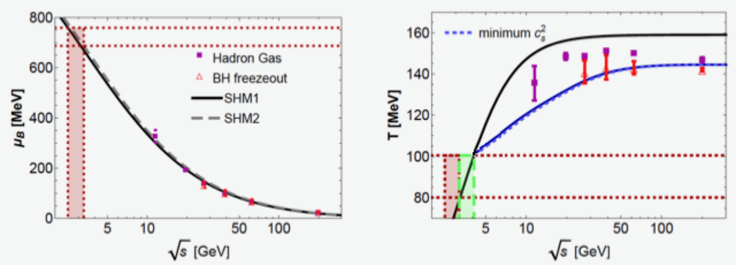
Collision Energy Estimates

We estimate a collision energy needed to hit the CEP

- $\sqrt{s} = 2.5 - 4.1$ GeV



- The collision energy is reachable by the next generation of colliders

[BH] R. Critelli, I. P. et al., to appear.
[HRG] Paolo Alba et al. Phys. Lett. B738 (2014),
[SHM1] A. Andronic et al. Phys. Lett. B673 (2009).
[SHM2] J. Cleymans et al. Phys. Rev. C73 (2006).

Conclusions

The holographic Black Hole Model

- Reproduces lattice data at $\mu_B = 0$
- Contains a critical end point at $\mu_B = 723 \pm 36$ MeV and $T = 89 \pm 11$ MeV
- Allows us to compute baryonic susceptibilities, and extract freeze-out parameters
- Estimates that the collision energy needed to hit the CEP should be $\sqrt{s} = 2.5 - 4.1$ GeV