The evolution of the net-proton kurtosis in the QCD critical region

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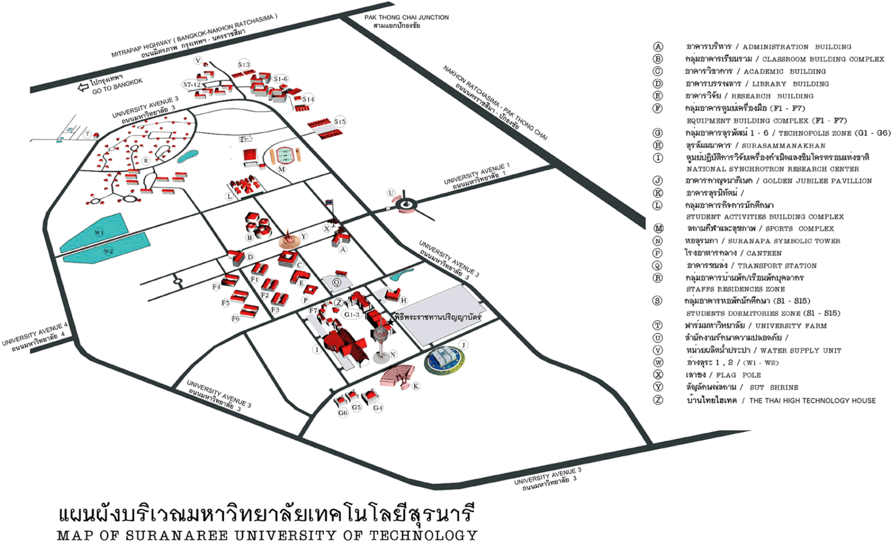
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NAKHON RATCHASIMA - PAK THONG CHAI
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X เสาธง / FLAG POLE
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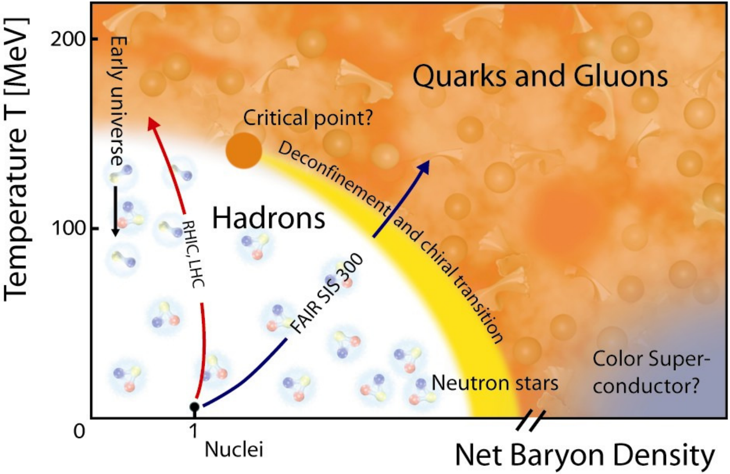
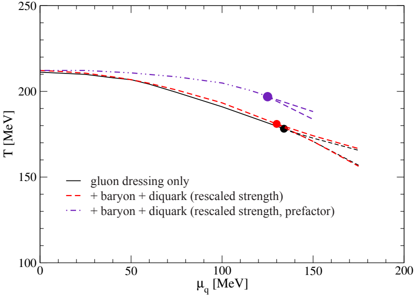
The QCD phase diagram

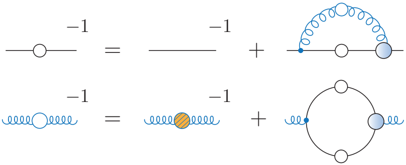


Finding the critical point - I

1. From the QCD Lagrangian

- Solve partition function $\mathcal{Z}$ on a lattice (sign problem for finite μ)
- Solve Dyson-Schwinger equations



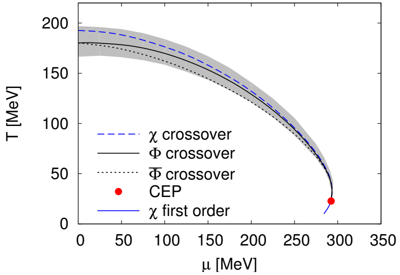


(Eichmann, Fischer, Welzbacher, Phys. Rev. D **93** (2016))

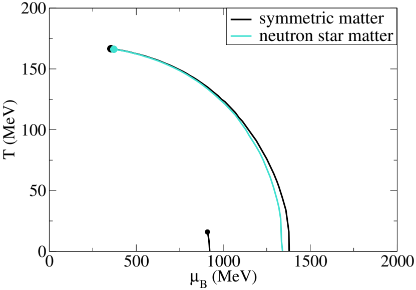
Finding the critical point - II

2. From effective models

- Respect chiral symmetry (Sigma model, NJL model, ...)
- Existence/location of CP not universal!



(Herbst, Pawlowski, Schaefer, Phys. Lett. B **696** (2011) 58-67)



(Dexheimer, Schramm, Phys. Rev. C **81** (2010) 045201)

Finding the critical point - III

3. From experiment

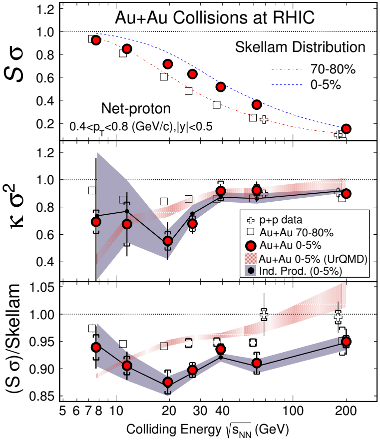
- Fluctuations sensitive to critical region

$$\sigma^2 = \langle \delta N^2 \rangle \sim \xi^2$$

$$S\sigma = \frac{\langle \delta N^3 \rangle}{\langle \delta N^2 \rangle} \sim \xi^{2.5}$$

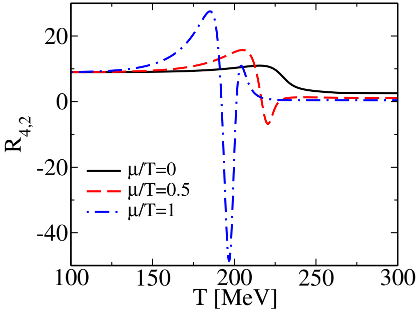
$$\kappa\sigma^2 = \frac{\langle \delta N^4 \rangle}{\langle \delta N^2 \rangle} - 3\langle \delta N^2 \rangle \sim \xi^5$$

(Stephanov, Phys. Rev. Lett. **102** (2009))



(STAR collaboration, Phys. Rev. Lett. **112** (2014))

From Susceptibilities to cumulants I - Baryon number



(Skokov, Friman, Redlich, Phys. Rev. C. **83** (2011))

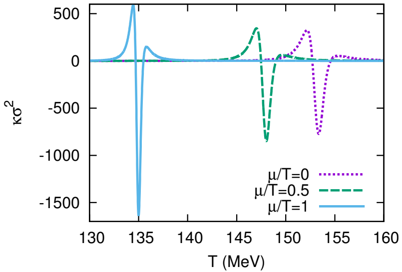
- Generalized quark number susceptibilities:

$$c_2 = \frac{\partial^2 (p/T^4)}{\partial(\mu/T)^2} = \frac{1}{VT^3}\langle \delta N^2 \rangle$$

$$c_4 = \frac{\partial^4 (p/T^4)}{\partial(\mu/T)^4} = \frac{1}{VT^3}\left[\langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2\right]$$

$$\kappa\sigma^2 = c_4/c_2 = \frac{\langle \delta N^4 \rangle}{\langle \delta N^2 \rangle} - 3\langle \delta N^2 \rangle$$

From Susceptibilities to cumulants II - Sigma field



- Generalized sigma susceptibilities ($\tilde{\sigma} = \sigma/T$):

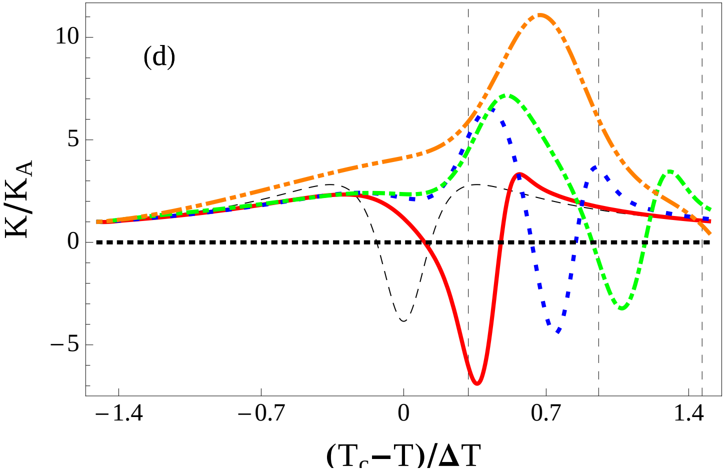
$$c_2 = \left(\frac{\delta^2\Gamma}{\delta\tilde{\sigma}^2}\right)^{-1}$$

$$c_4 = -\frac{\delta^4\Gamma}{\delta\tilde{\sigma}^4}\left(\frac{\delta^2\Gamma}{\delta\tilde{\sigma}^2}\right)^{-1} + 3\left(\frac{\delta^3\Gamma}{\delta\tilde{\sigma}^3}\right)^2\left(\frac{\delta^4\Gamma}{\delta\tilde{\sigma}^4}\right)^{-5}$$

(CH, Nahrgang, *in preparation*)

$$\kappa\sigma^2 = c_4/c_2 = \frac{\langle\delta\tilde{\sigma}^4\rangle}{\langle\delta\tilde{\sigma}^2\rangle} - 3\langle\delta\tilde{\sigma}^2\rangle$$

The kurtosis in heavy-ion collisions II



(Mukherjee, Venugopalan, Yin, Phys. Rev. C **92**, (2015))

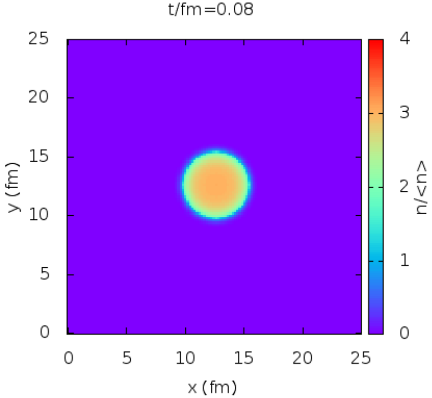
The NχFD model - I

Ingredients for **NχFD** model

- Fluctuations (chiral fields)
- Fluid (quarks)

$$\frac{\partial^2\sigma}{\partial t^2} - \nabla^2\sigma + \eta\frac{\partial\sigma}{\partial t} + \frac{\delta\Omega}{\delta\sigma} = \xi$$
$$\partial_\mu T_{\mathrm{q}}^{\mu\nu} = S_\sigma^\nu$$

(Nahrgang, Leupold, CH, Bleicher, Phys. Rev. C 84 (2011))



- Potential Ω and equation of state from effective QCD models
- Successfully describes: critical fluctuations, spinodal decomposition

The NχFD model - II

Effective Lagrangian from quark-meson model
(plus possible extensions, e.g. Polyakov loop ℓ, dilaton field χ)

$$\mathcal{L} = \bar{q}\left(i\gamma^\mu\partial_\mu - g\sigma\right) + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - U(\sigma)$$
$$U(\sigma) = \frac{\lambda}{4}\left(\sigma^2 - \nu^2\right) - h\sigma - U_0$$

One-loop thermodynamic potential reads

$$\Omega(T,\mu;\sigma) = U(\sigma) - d_q T\int\frac{\mathrm{d}^3 p}{(2\pi)^3}\ln\left(1 + \mathrm{e}^{-\frac{E\pm\mu}{T}}\right)$$

Pressure, energy density are given by

$$p(T,\mu;\sigma) = -\Omega(T,\mu;\sigma)$$
$$e(T,\mu;\sigma) = Ts - p + \mu n$$

The NχFD model - III

Two possible evolutions:

- Mean-field, local thermal equilibrium without fluctuations

$$\left.\frac{\partial\Omega(T,\mu;\sigma)}{\partial\sigma}\right|_{\sigma=\sigma_{\mathrm{eq}}} = 0$$

$$p(T,\mu;\sigma) = -\Omega(T,\mu;\sigma)\ , \quad \partial_\mu T^{\mu\nu} = 0$$

- Full nonequilibrium dynamics with damping and stochastic fluctuations

$$\frac{\partial^2\sigma}{\partial t^2} - \nabla^2\sigma + \eta\frac{\partial\sigma}{\partial t} + \frac{\delta\Omega}{\delta\sigma} = \xi$$

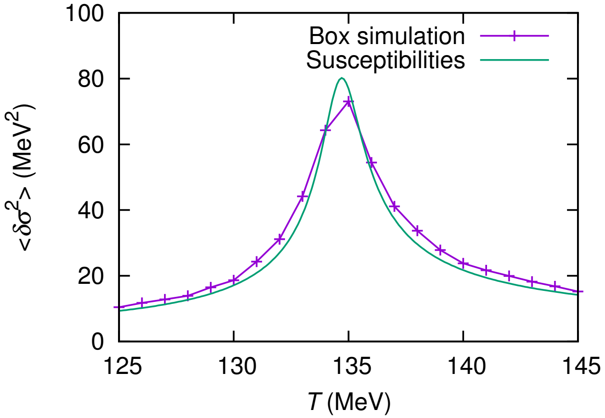
$$p(T,\mu;\sigma) = -\Omega_{\bar{\mathrm{q}}\mathrm{q}}(T,\mu;\sigma)\ , \quad \partial_\mu T^{\mu\nu} = S^\nu$$

In both cases quark densities are propagated via

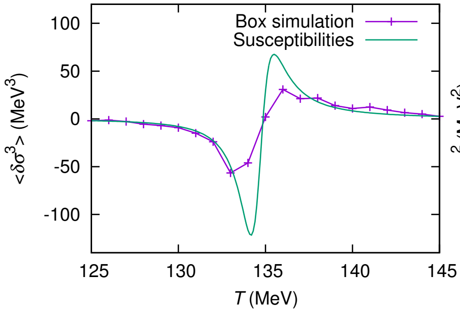
$$\partial_\mu n^\mu = 0$$

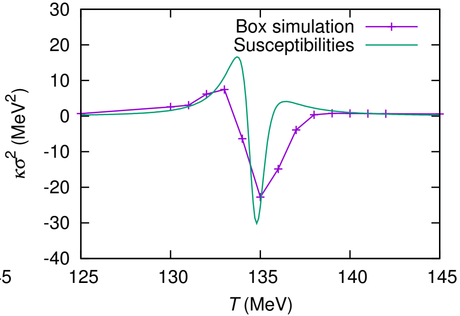
Moments of dynamical fluctuations in a box - I

- Isothermal box with periodic boundary conditions
- Evolution of the sigma field with coarse-grained noise, $\xi_{\mathrm{corr}} = 1/m_\sigma$



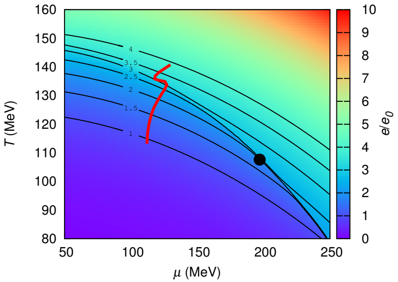
Moments of dynamical fluctuations in a box - II



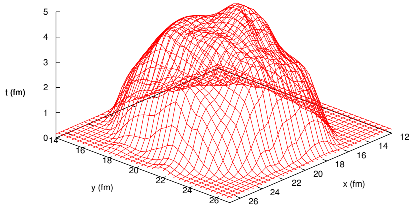


- Higher moments follow trend of susceptibilities
- Is the same true for fluctuations of n_q? (work in progress)

The kurtosis on different freeze-out surfaces

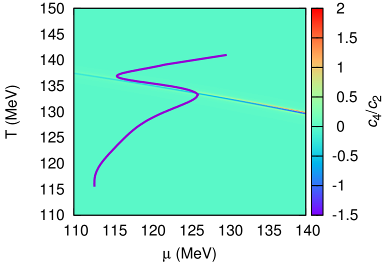


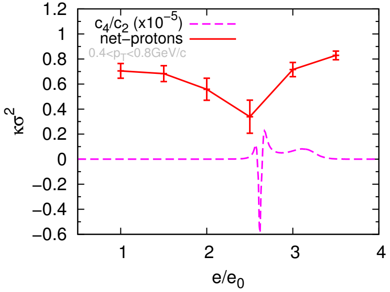
(CH, Nahrgang, Yan, Kobdaj, PRC 93 (2016))



- Study crossover evolution left of CP
- Determine net-proton kurtosis on energy hypersurfaces
- Smooth hypersurfaces at crossover

The kurtosis - net-proton vs. susceptibilities





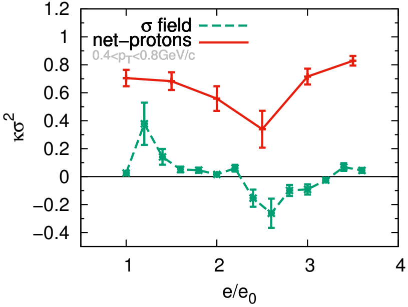
(CH, Nahrgang, Yan, Kobdaj, PRC 93 (2016))

- Comparison of net-proton kurtosis to equilibrium fluctuations
- Characteristic dip imprints signal on net-proton kurtosis

The kurtosis - net-proton vs. sigma

- Net-proton kurtosis follows kurtosis of sigma field

(CH, Nahrgang, Yan, Kobdaj, PRC 93 (2016))



- Net-proton number

$$\kappa\sigma^2 = \frac{\langle \delta N^4 \rangle}{\langle \delta N^2 \rangle} - 3\langle \delta N^2 \rangle$$

- Sigma field

$$\kappa\sigma^2 = \frac{\langle \delta \sigma^4 \rangle}{\langle \delta \sigma^2 \rangle} - 3\langle \delta \sigma^2 \rangle$$

The kurtosis - net-proton dynamical vs. mean-field

- Net-proton kurtosis follows kurtosis of sigma field
- In contrast: Mean-field kurtosis remains flat
- In mean-field (hydro/eos): critical fluctuations do not build up

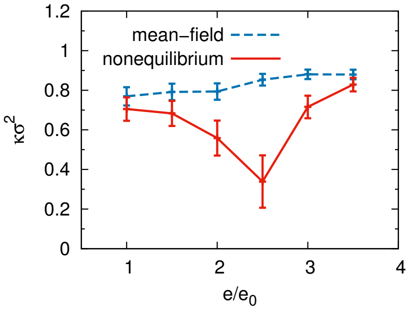
(CH, Nahrgang, Yan, Kobdaj, PRC **93** (2016))

- Mean-field

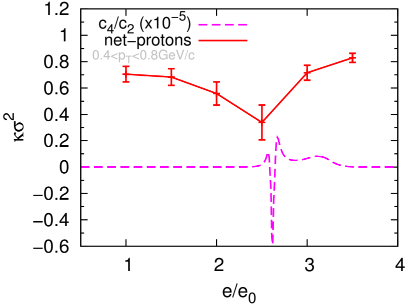
$$\left.\frac{\partial \Omega}{\partial \sigma}\right|_{\sigma=\langle\sigma\rangle} = 0$$

- Nonequilibrium

$$\frac{\partial^2 \sigma}{\partial t^2} - \nabla^2 \sigma + \eta \frac{\partial \sigma}{\partial t} + \frac{\delta \Omega}{\delta \sigma} = \xi$$



Summary



- Modeling phase transitions in HICs with **NχFD**
- Criticality visible in nonmonotonic net-proton kurtosis
- Hydro plus eos not sufficient

Outlook

- Compare net-proton with net-baryon, acceptance range
- Study beam energy dependence of kurtosis
- Include baryonic degrees of freedom