The net-proton kurtosis from nonequilibrium fluid dynamics

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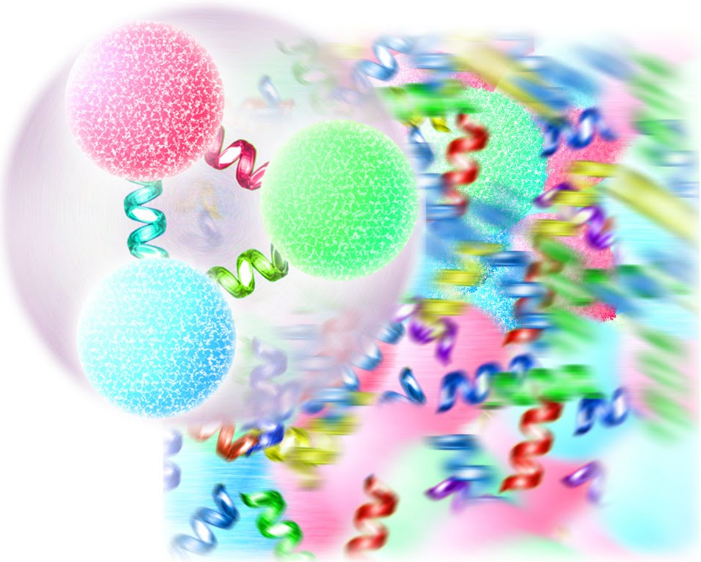
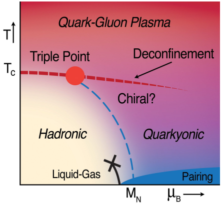
Hadrons and Quark-gluon-plasma

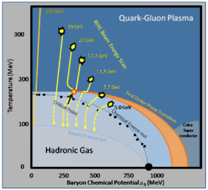


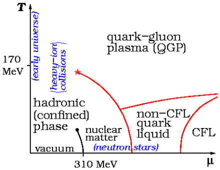
The particle zoo

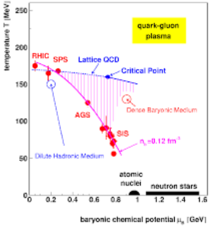
www.particlezoo.net

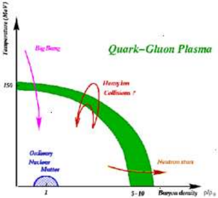
The phase diagram zoo

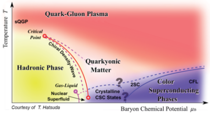


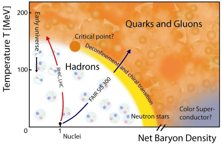


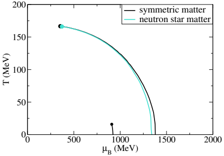


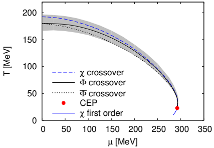




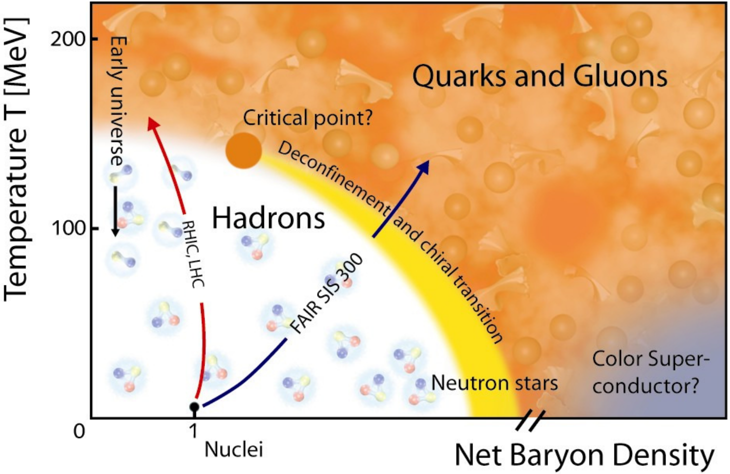








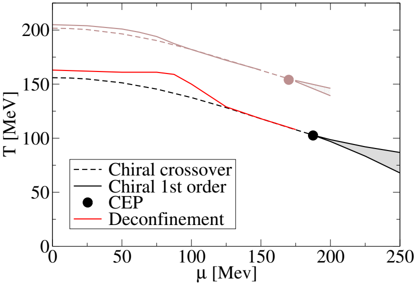
The QCD phase diagram

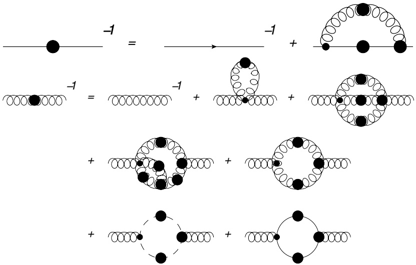


Finding the critical point - I

1. From the QCD Lagrangian

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



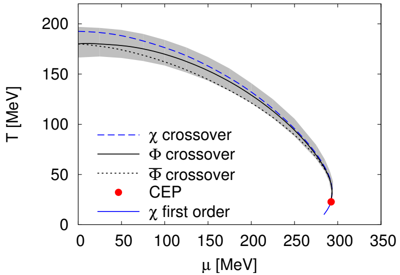


(Fischer, Luecker, Phys. Lett. B **718** (2013) 1036-1043)

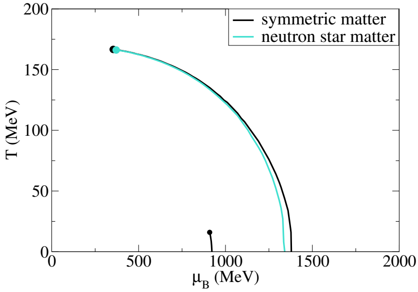
Finding the critical point - II

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

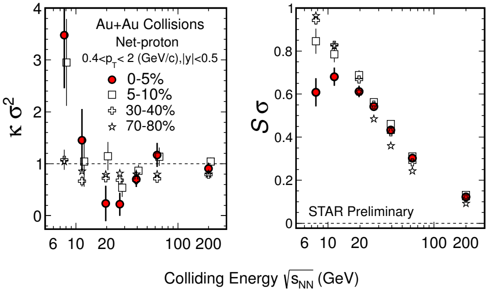
- Fluctuations sensitive to critical region ...

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

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

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

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

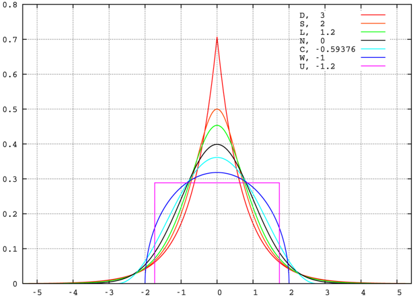


(STAR collaboration, PoS CPOD (2014) 019)

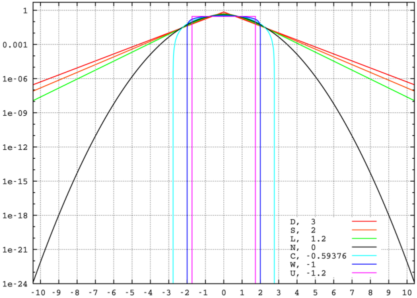
- ... and first-order phase transition?

$\kappa\sigma^2$ **(Kurtosis) interesting, sensitive to** ξ **and volume independent**

The Kurtosis, visually



en.wikipedia.org/wiki/Kurtosis



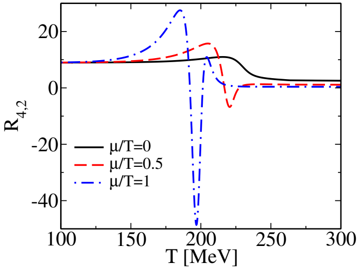
en.wikipedia.org/wiki/Kurtosis

- distinguish peak, shoulders and tails
- for normal distribution 0, for Poisson 1

The Kurtosis from effective models

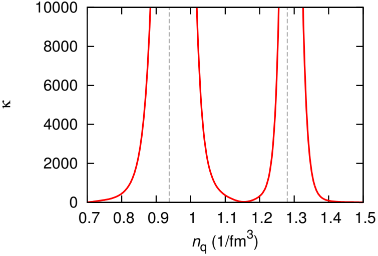
Kurtosis as calculated from effective PQM model (mean-field)

Near critical point



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

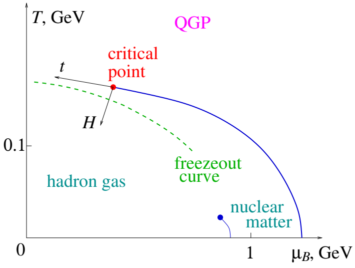
First-order phase transition



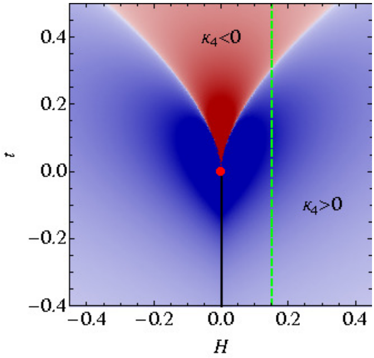
(Herold, Nahrgang, Yan, Kobdaj, J. Phys. G 41 (2014))

Something is going on, but how do we measure that?

The Kurtosis in heavy-ion collisions



(Stephanov, Phys. Rev. Lett. **107** (2011))



$$\langle \delta N^4 \rangle = \langle N \rangle + \kappa_4 \left(\frac{gd}{T} \int_p \frac{n_p}{\gamma_p} \right)^4 + \dots$$

Non-statistical behavior from fluctuations in order parameter

Modeling Heavy-Ion Collisions - I

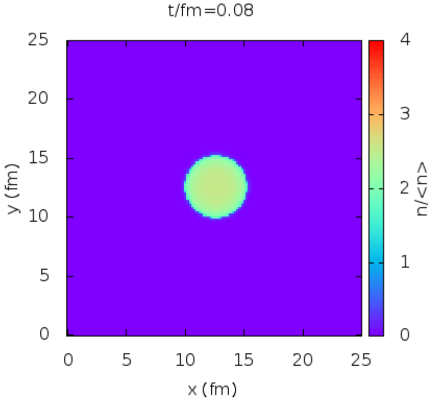
Ingredients for fully dynamical model:

- Fluid (quarks)
- Fluctuations (chiral fields)

Chiral fluid dynamics (χFD)

$$-\frac{\delta S_{\rm cl}}{\delta\sigma} - D = \xi\ ,\quad \partial_\mu T_{\rm q}^{\mu\nu} = S_\sigma^\nu$$

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



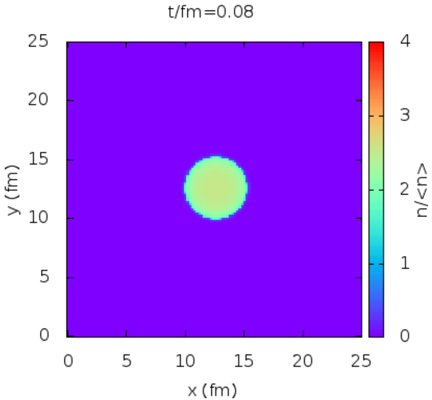
- Potential and equation of state from effective QCD models
- Successfully describes: critical fluctuations, spinodal decomposition

Modeling Heavy-Ion Collisions - II

How to study kurtosis in χFD

- In-medium (net-baryon)
- After freezeout (net-proton)

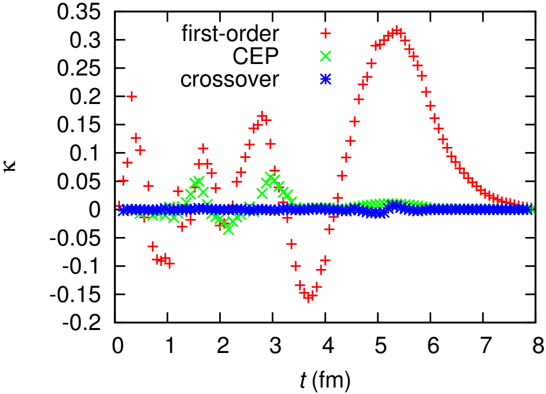
Comparison with STAR data



What we want to understand

- **Impact of CP and phase transition on kurtosis**
- **Impact of the equation of state**

The kurtosis in χFD



Fixed volume vs. rapidity ($|y| < 0.5$) and p_T cut (100 MeV/fm$^3 < p_T <$ 500 MeV/fm^3)

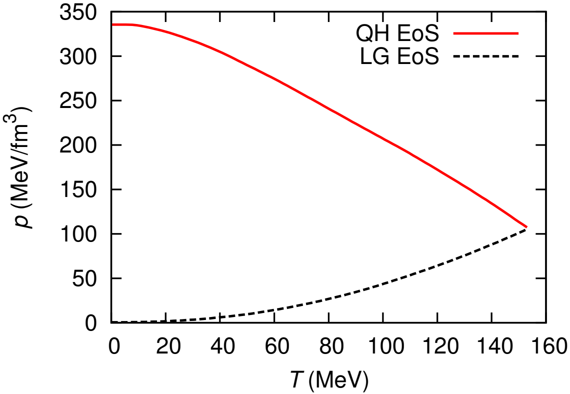
Things to be considered:

- baryon number conservation
- Ratios of cumulants depend on fraction of measured to total baryons

(Herold, Nahrgang, Yan, Kobdaj, J. Phys. G 41 (2014))

The kurtosis in χFD after freezeout - I

We consider 2 different equations of state

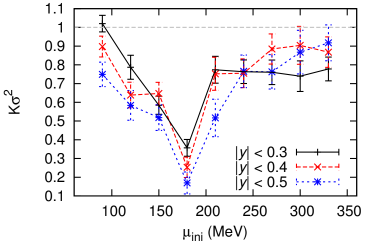


Behavior of the pressure along the phase boundary distinguishes

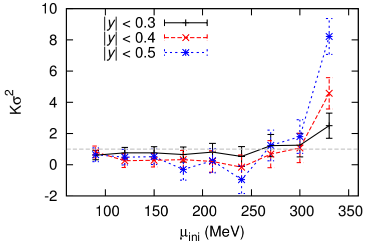
- Hadron-quark (HQ): from dilute hadron gas to dense QGP
- Liquid-gas (LG): from dense liquid to dilute gas

The kurtosis in χFD after freezeout - II

LG eos

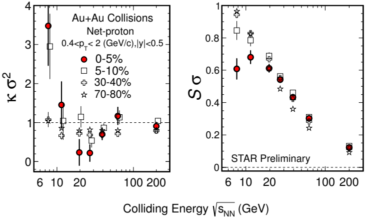


HQ eos



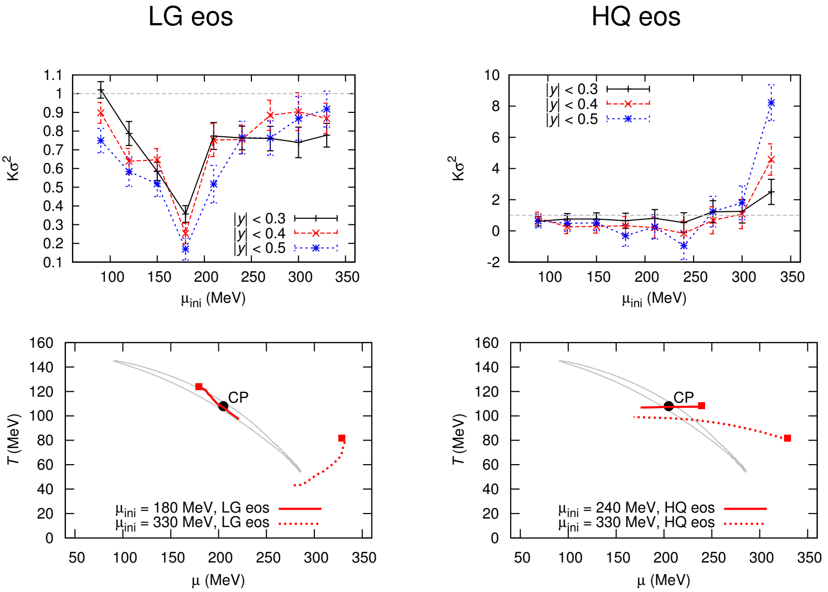
p_T cut (0.4 GeV$^3 < p_T <$ 2.0 GeV)

- significant enhancement for low beam energies
- dip as CP signal

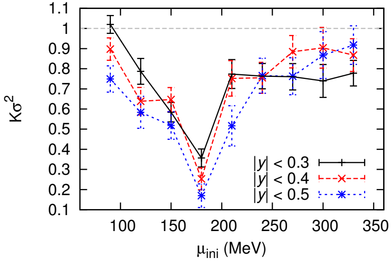


(STAR collaboration, PoS CPOD (2014) 019)

The kurtosis in χFD after freezeout - III



Summary and Conclusions



- Modeling phase transitions in HICs
- Fluid + chiral dynamics
- Study kurtosis as signal for CP and phase transition

- Enhancement at low beam energies possible with right EoS
- Time inside critical region influences strength of CP signal