

The net-proton kurtosis from nonequilibrium fluid dynamics

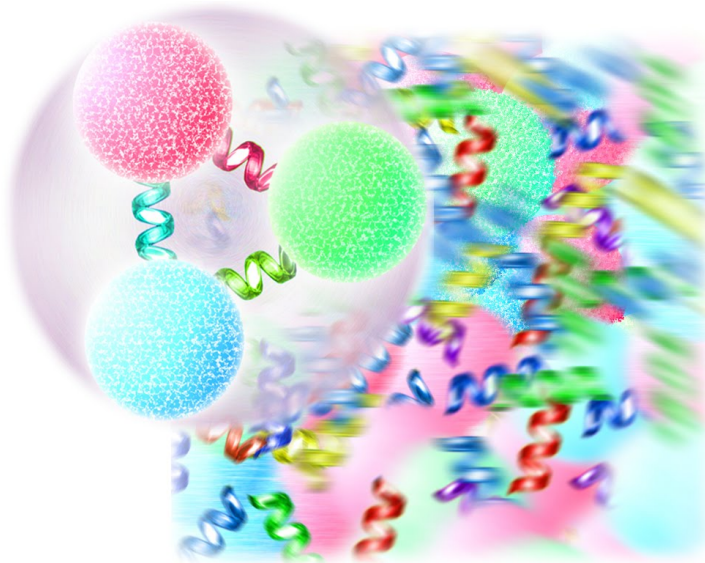
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Rencontres du Vietnam, July 2015

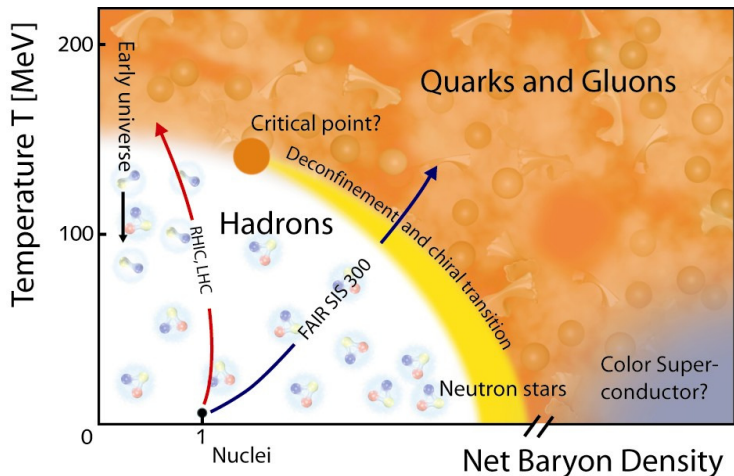
Hadrons and Quark-gluon-plasma



The particle zoo

QUARKS	 UP QUARK A teeny little point inside the proton and neutron, it is friends forever with the down quark.	 CHARM QUARK A second generation quark, it is charmed, indeed.	 TOP QUARK This heavyweight champion doesn't live long enough to make friends with anyone.	FORCE CARRIERS	 PHOTON The massless waveric we know and love.
	 DOWN QUARK A tiny little point inside the proton and neutron, it is friends forever with the up quark.	 STRANGE QUARK Why is this second generation quark so strange?	 BOTTOM QUARK This third generation quark is puttin' on the pounds.		 GLUON The "glue" of the strong nuclear force.
	 ELECTRON-NEUTRINO These miniscule bandits like to steal away energy and escape detection.	 MUON-NEUTRINO A slightly heavier bandit than its sibling to the left.	 TAU-NEUTRINO Wily and sneaky, this bandit is the newest particle to arrive at the Zoo.		 W BOSON
	 ELECTRON A familiar friend, this negatively charged, bossy I'll guy likes to bond.	 MUON A "heavy electron" who lives fast and dies young.	 TAU A "heavy muon" who could stand to lose a little weight.		 Z BOSON As the carrier particles of the weak nuclear force, they're downright obese.
	 HIGGS BOSON It's the one everyone wants to meet, but for now it's playing hard to get. You'd be smiling too if everyone was looking to interview <i>you</i> .	 GRAVITON Still unobserved, yet theoretically everywhere.	 TACHYON Can this devious and clever particle really travel faster than light?		 PROTON We would not be here without her positivity.
	 DARK MATTER The mysterious missing mass. Difficult to see because it's so <i>dark</i> .	 NEUTRON He insists on remaining neutral.	 NUCLEONS		

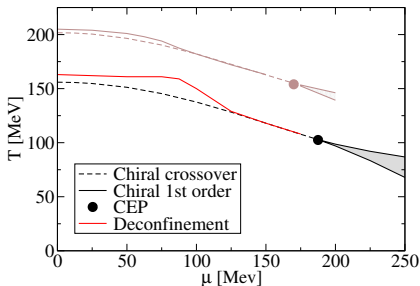
The QCD phase diagram



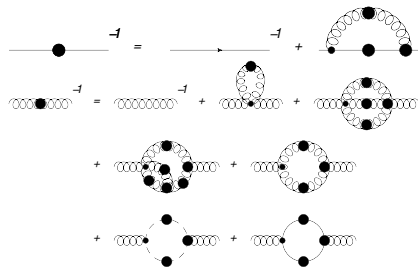
Finding the critical point - I

1. From the QCD Lagrangian

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



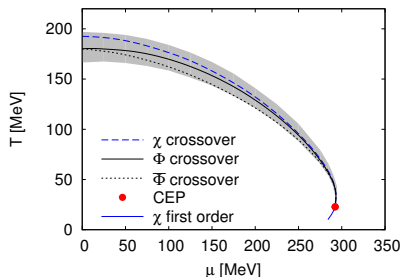
(Fischer, Luecker, Phys. Lett. B **718** (2013) 1036-1043)



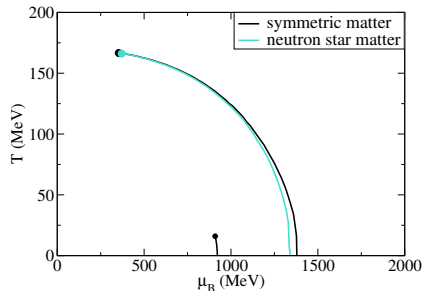
Finding the critical point - II

2. From effective models

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



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



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

Finding the critical point - III

3. From experiment

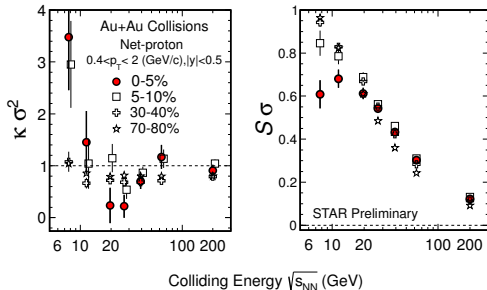
- Fluctuations sensitive to critical region ...

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

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

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

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

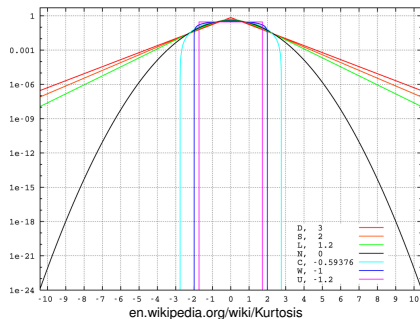
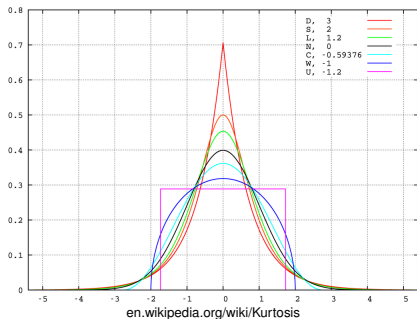


(STAR collaboration, PoS CPOD (2014) 019)

- ... and first-order phase transition?

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

The Kurtosis, visually

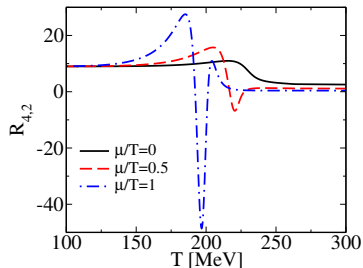


- distinguish peak, shoulders and tails
- for normal distribution 0, for Poisson 1

The Kurtosis from effective models

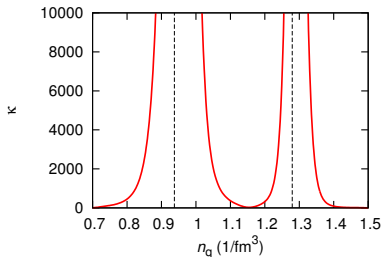
Kurtosis as calculated from effective PQM model (mean-field)

Near critical point



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

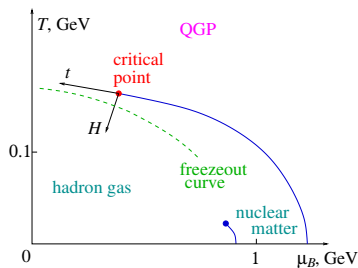
First-order phase transition



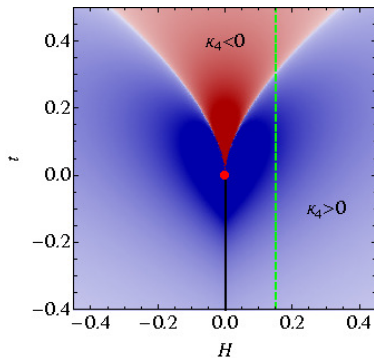
(Herold, Nahrgang, Yan, Kobdaj, J. Phys. G 41 (2014))

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 (χ FD)

$$-\frac{\delta S_{\text{cl}}}{\delta \sigma} - D = \xi, \quad \partial_\mu T_q^{\mu\nu} = S_\sigma^\nu$$

(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 χ^2 FD

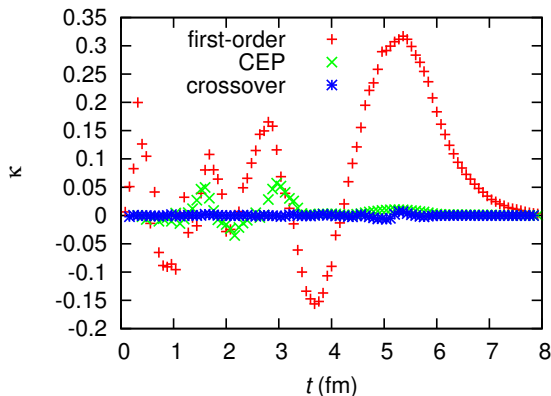
- In-medium (net-baryon)
- After freezeout (net-proton)

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 χ FD



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

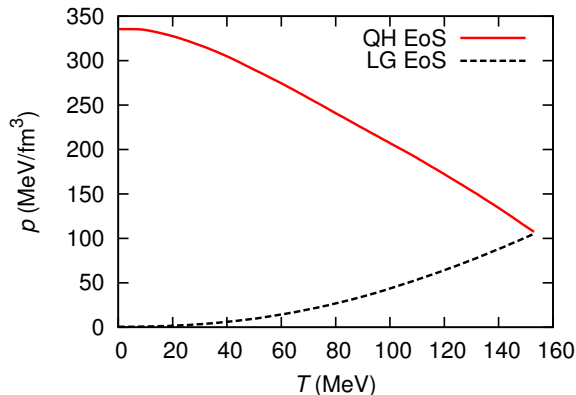
Things to be considered:

- 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 χ FD after freezeout - I

We consider 2 different equations of state

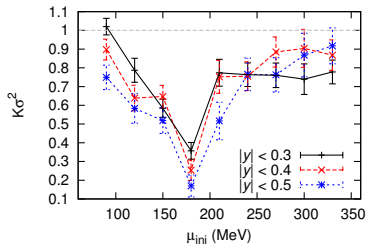


Behavior of the pressure along the phase boundary distinguishes

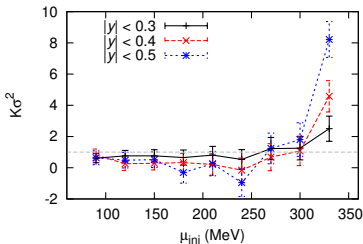
- Hadron-quark (HQ): from dilute hadron gas to dense QGP
- Liquid-gas (LG): from dense liquid to dilute gas

The kurtosis in χ FD after freezeout - II

LG eos

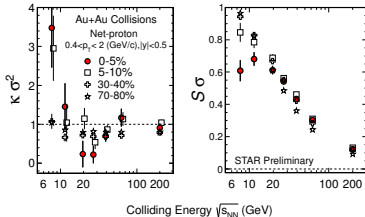


HQ eos



p_T cut ($0.4 \text{ GeV}^3 < p_T < 2.0 \text{ GeV}$)

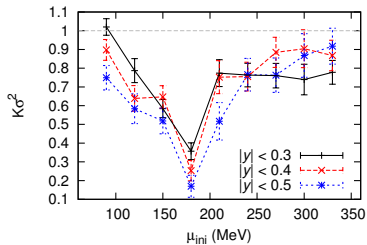
- significant enhancement for low beam energies
- dip as CP signal



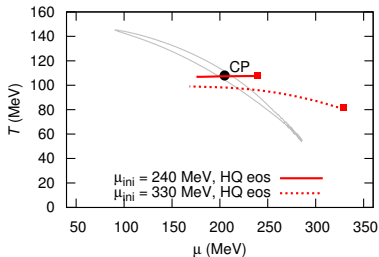
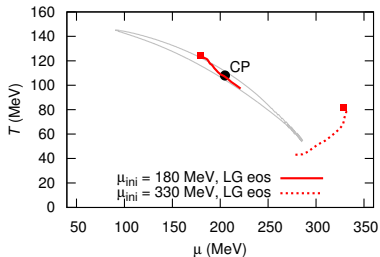
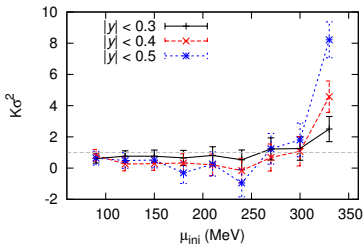
(STAR collaboration, PoS CPOD (2014) 019)

The kurtosis in χ FD after freezeout - III

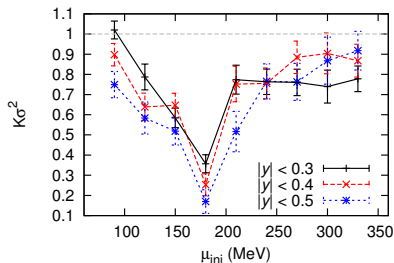
LG eos



HQ eos



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