

# The net-proton kurtosis in heavy-ion collisions

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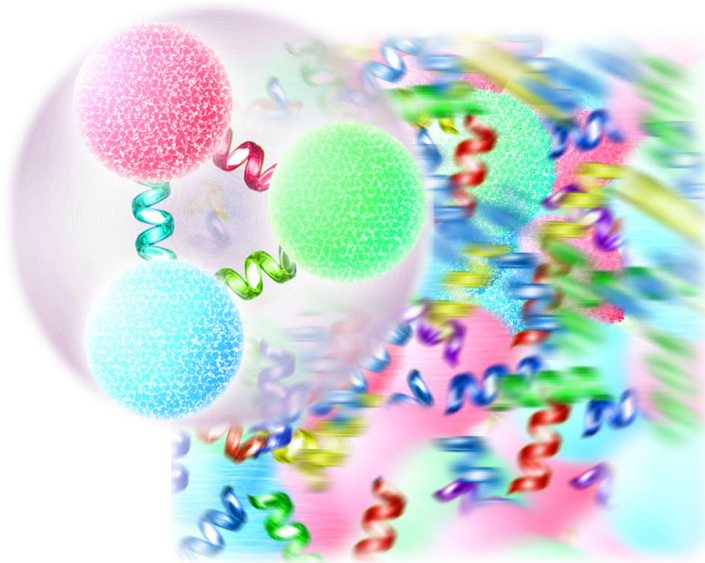
# The particle zoo

|                |  |  |  |                                      |                               |
|----------------|--|--|--|--------------------------------------|-------------------------------|
| mass →         | $\approx 2.3 \text{ MeV}/c^2$                  | $\approx 1.275 \text{ GeV}/c^2$              | $\approx 173.07 \text{ GeV}/c^2$             | 0                                    | $\approx 126 \text{ GeV}/c^2$ |
| charge →       | 2/3  | 2/3  | 2/3  | 0                                    | 0                             |
| spin →         | 1/2  | 1/2  | 1/2  | 1                                    | 0                             |
|                | <b>u</b><br>up                                 | <b>c</b><br>charm                            | <b>t</b><br>top                              | <b>g</b><br>gluon                    | <b>H</b><br>Higgs boson       |
| <b>QUARKS</b>  | $\approx 4.8 \text{ MeV}/c^2$                  | $\approx 95 \text{ MeV}/c^2$                 | $\approx 4.18 \text{ GeV}/c^2$               | 0                                    |                               |
|                | -1/3   | -1/3   | -1/3   | 0                                    |                               |
|                | 1/2  | 1/2  | 1/2  | 1                                    |                               |
|                | <b>d</b><br>down                               | <b>s</b><br>strange                          | <b>b</b><br>bottom                           | <b><math>\gamma</math></b><br>photon |                               |
| <b>LEPTONS</b> | $0.511 \text{ MeV}/c^2$                        | $105.7 \text{ MeV}/c^2$                      | $1.777 \text{ GeV}/c^2$                      | $91.2 \text{ GeV}/c^2$               |                               |
|                | -1   | -1   | -1   | 0                                    |                               |
|                | 1/2  | 1/2  | 1/2  | 1                                    |                               |
|                | <b>e</b><br>electron                           | <b><math>\mu</math></b><br>muon              | <b><math>\tau</math></b><br>tau              | <b>Z</b><br>Z boson                  |                               |
|                | $< 2.2 \text{ eV}/c^2$                         | $< 0.17 \text{ MeV}/c^2$                     | $< 15.5 \text{ MeV}/c^2$                     | $80.4 \text{ GeV}/c^2$               |                               |
|                | 0  | 0  | 0  | $\pm 1$                              |                               |
|                | 1/2  | 1/2  | 1/2  | 1                                    |                               |
|                | <b><math>\nu_e</math></b><br>electron neutrino | <b><math>\nu_\mu</math></b><br>muon neutrino | <b><math>\nu_\tau</math></b><br>tau neutrino | <b>W</b><br>W boson                  |                               |
|                |  |  |  |                                      | <b>GAUGE BOSONS</b>           |

# The particle zoo

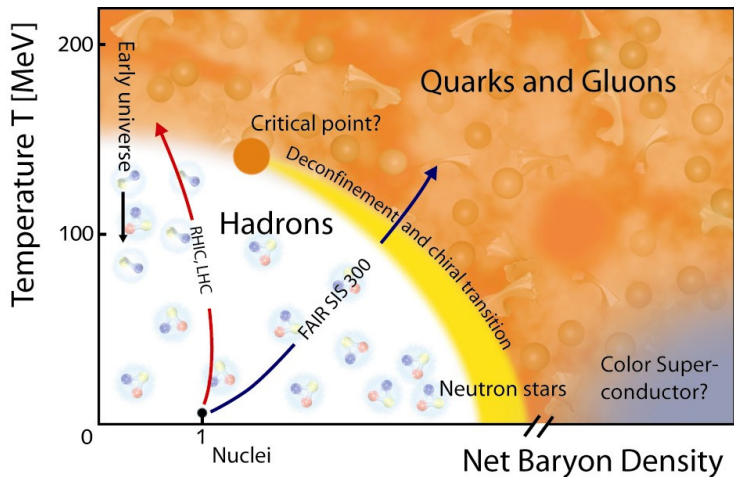
|                       |   |   |   |   |                 |
|-----------------------|---|---|---|---|-----------------|
| <b>QUARKS</b>         |  <b>UP QUARK</b><br>A teeny little point inside the proton and neutron, it is friends forever with the down quark. |  <b>CHARM QUARK</b><br>A second generation quark, it is charmed, indeed.                             |  <b>TOP QUARK</b><br>This heavyweight champion doesn't live long enough to make friends with anyone.   |   |                 |
|                       |  <b>DOWN QUARK</b><br>A tiny little point inside the proton and neutron, it is friends forever with the up quark.  |  <b>STRANGE QUARK</b><br>Why is this second generation quark so strange?                             |  <b>BOTTOM QUARK</b><br>This third generation quark is puttin' on the pounds.  |   |                 |
|                       | <b>LEPTONS</b>  |  <b>ELECTRON-NEUTRINO</b><br>These miniscule bandits like to steal away energy and escape detection. |  <b>MUON-NEUTRINO</b><br>A slightly heavier bandit than its sibling to the left.   |  <b>TAU-NEUTRINO</b><br>Wily and sneaky, this bandit is the newest particle to arrive at the Zoo.  |                 |
|                       |   |  <b>ELECTRON</b><br>A familiar friend, this negatively charged, busy f'll guy likes to bond.         |  <b>MUON</b><br>A "heavy electron" who lives fast and dies young.  |  <b>TAU</b><br>A "heavy muon" who could stand to lose a little weight.                             |                 |
|                       |   | <b>THEORETICALS</b>   |  <b>HIGGS BOSON</b><br>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> . |  <b>GRAVITON</b><br>Still unobserved, yet theoretically everywhere.                                | <b>NUCLEONS</b> |
|                       |   |   |  <b>TACHYON</b><br>Can this devious and clever particle really travel faster than light?   |  <b>DARK MATTER</b><br>The mysterious missing mass. Difficult to see because it's so <i>dark</i> . |                 |
|                       |   |   |   |  <b>NEUTRON</b><br>He insists on remaining neutral.  |                 |
| <b>FORCE CARRIERS</b> |   |   |  <b>PHOTON</b><br>The massless waveric we know and love.  | <b>W BOSON<br/>Z BOSON</b><br>As the carrier particles of the weak nuclear force, they're downright obese.  |                 |
|                       |  <b>GLUON</b><br>The "glue" of the strong nuclear force.  |   |   |   |                 |
|                       |   |   |   |   |                 |
|                       |   |   |   |   |                 |
|                       |   |   |   |   |                 |
|                       |   |   |   |   |                 |

# Hadrons and Quark-gluon-plasma





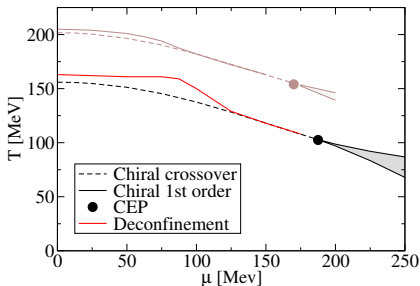
# The QCD phase diagram



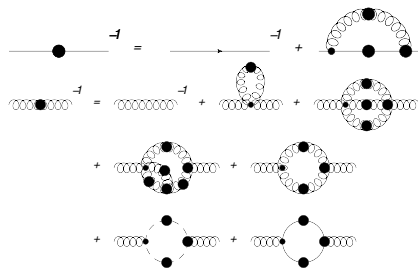
# Finding the critical point - I

## 1. From the QCD Lagrangian

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



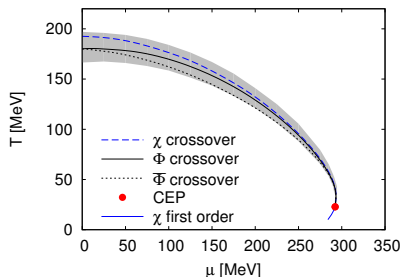
(Fischer, Luecker, Phys. Lett. B **718** (2013) 1036-1043)



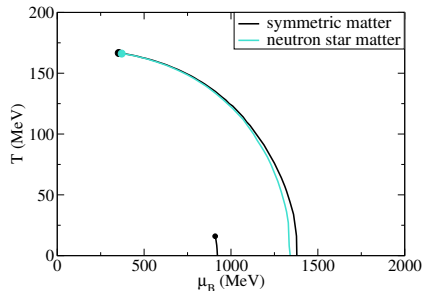
# Finding the critical point - II

## 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

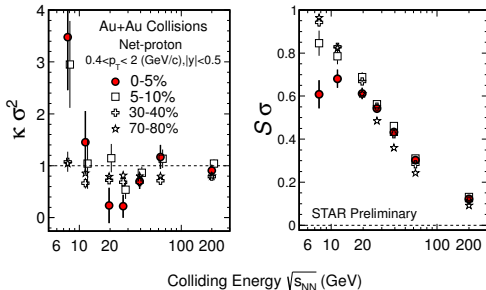
- Fluctuations sensitive to critical region ...

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

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

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

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

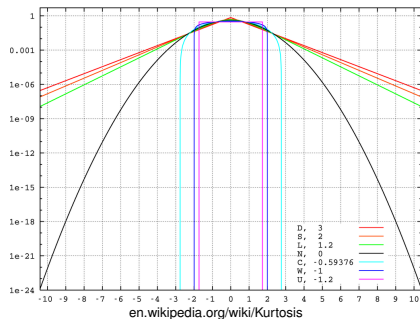
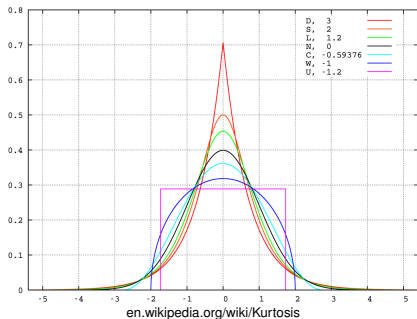


(STAR collaboration, PoS CPOD (2014) 019)

- ... and first-order phase transition?

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

# The Kurtosis, visually

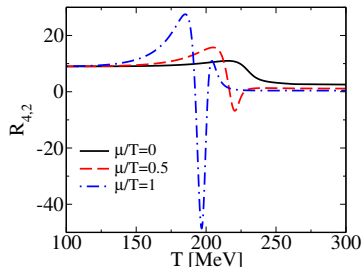


- distinguish peak, shoulders and tails
- for normal distribution 0, for Poisson 1

# The Kurtosis from effective models

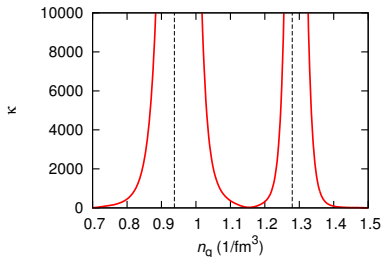
Kurtosis as calculated from effective PQM model (mean-field)

Near critical point



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

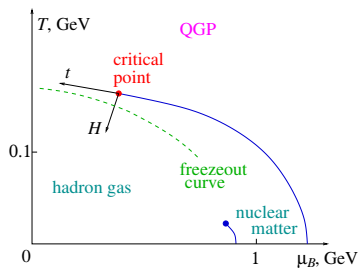
First-order phase transition



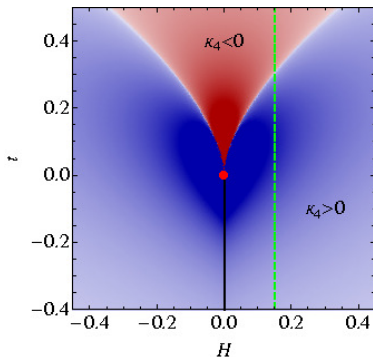
(Herold, Nahrgang, Yan, Kobdaj, J. Phys. G 41 (2014))

**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 ( $\chi$ 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  $\chi^2$ FD

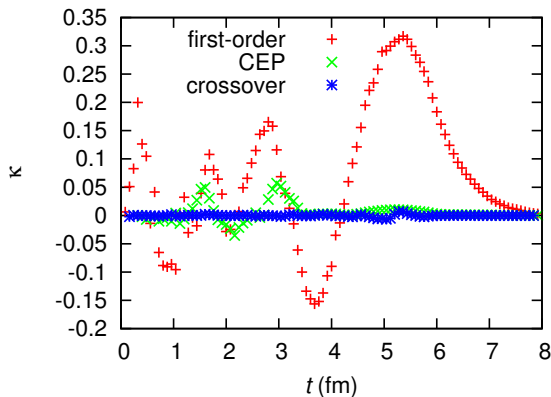
- In-medium (net-baryon)
- After freezeout (net-proton)

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 $\chi$ FD



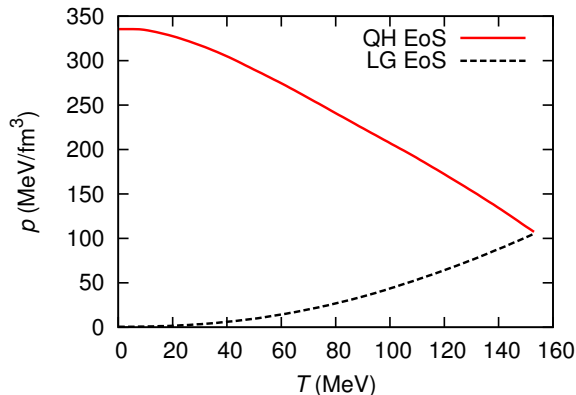
Fixed volume vs. rapidity ( $|y| < 0.5$ ) and  $p_T$  cut ( $100 \text{ MeV}/\text{fm}^3 < p_T < 500 \text{ MeV}/\text{fm}^3$ )  
Things to be considered:

- 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 $\chi$ FD after freezeout - I

We consider 2 different equations of state



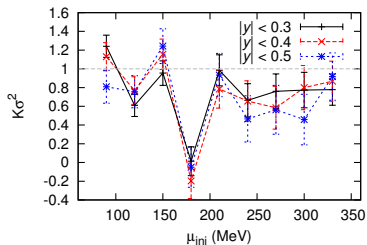
Behavior of the pressure along the phase boundary distinguishes

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

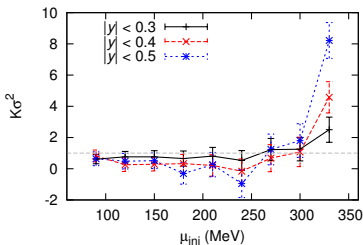


# The kurtosis in $\chi$ FD after freezeout - II

LG eos

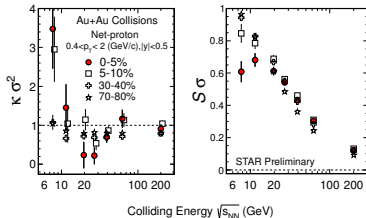


HQ eos



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

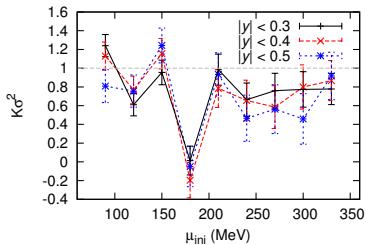
- significant enhancement for low beam energies
- dip as CP signal



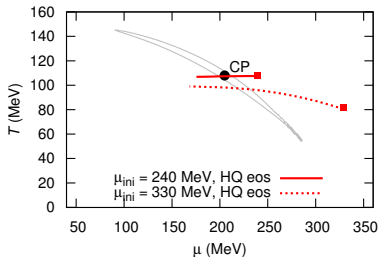
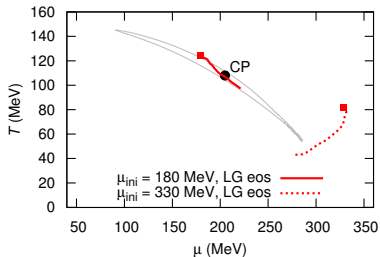
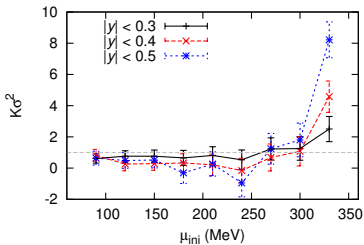
(STAR collaboration, PoS CPOD (2014) 019)

# The kurtosis in $\chi$ FD after freezeout - III

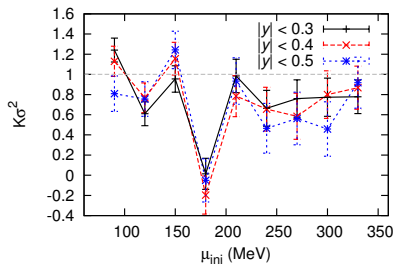
LG eos



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