The Experimental Search for a QCD Phase Boundary

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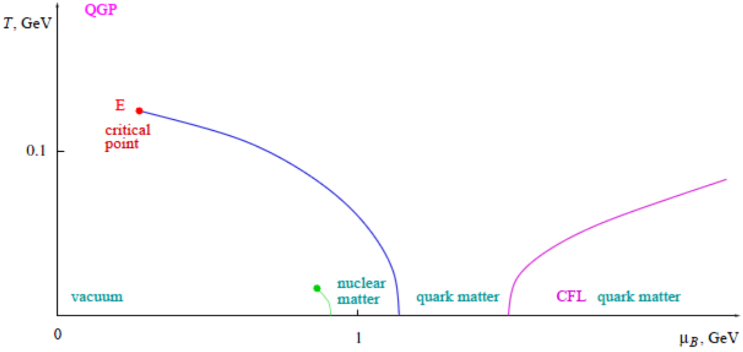
Outline

Phase Diagram of QCD



M. Stephanov hep-ph/0402115v1

- critical point separates crossover-region from first order phase transition
- critical point (CP) is of second order → universal critical behavior → critical exponents

Why should there be a critical point? -theoretical "evidences"

- temperature driven transition at $\mu_B = 0$ is crossover (lattice)
- μ driven transition at $T = 0$ is first order (model calculations)
- first order line at zero temperature cannot end at $\mu_B = 0$

Question: What indicates the phase boundary/critical point in a theoretical sense and how can we relate it to measurable observales of heavy ion collisions?

I Definition of susceptibilities

- n-th order cumulant: $\chi^{(n)}(T)$ for $\mu_B = 0$

$$\chi^{(n)}(T) = \frac{1}{VT^3} \frac{\partial^n \log \mathrm{Z}}{\partial(\mu_B/T)^n}$$

- expansion coefficients from expansion of pressure:

$$\frac{P(T,\mu_B)}{T^4} = \sum_{n=0}^{n=\infty} \frac{1}{n!} \chi^{(n)}(T) \left(\frac{\mu_B}{T}\right)^n$$

- for $\mu_B \neq 0$

$$\chi^{(n)}(T,\mu_B) = \sum_{k=0}^{k=\infty} \frac{1}{k!} \chi^{(k+n)}(T) \left(\frac{\mu_B}{T}\right)^k$$

- higher orders are increasingly sensitive to critical behavior

II variance, skewness and kurtosis

- variance σ^2

$$\sigma^2 = \chi^{(2)}$$

- skewness S

$$S = \chi^{(3)}/(\chi^{(2)})^{3/2}$$

- kurtosis κ

$$\kappa = \chi^{(4)}/(\chi^{(2)})^2$$

- the products $\kappa\sigma^2$ and $S\sigma$ can be related to measurement (without any explicit volume dependence)
- $\kappa\sigma^2$ allow to determine pseudo-critical/freeze-out temperature $T(\mu_B)$
- both should show large deviations from poisson statistic when CP is reached
- skewness S changes sign when crossing phase boundary

Xiaofeng Luo for STAR 1106.2926v1 M. Asakaswa et al PRL 103, 262301, (2009)

III Fluctuations of net baryon number

- net proton number $N = N_{p-\overline{p}} = N_p - N_{\overline{p}}$
- in experiment low p_T protons are lost due to detector efficiency
- define mean $\langle N \rangle$ ensemble average of an event-by-event distribution
- deviation of N from its mean $\delta N = N - \langle N \rangle$
- define various order cumulants of event-by-event distributions:
  $C_{1,N} = \langle N \rangle,\ C_{2,N} = \left\langle (\delta N)^2 \right\rangle,\ C_{3,N} = \left\langle (\delta N)^3 \right\rangle,\ C_{4,N} = \left\langle (\delta N)^4 \right\rangle - 3\left\langle (\delta N)^2 \right\rangle^2$
- we obtain: $\kappa\sigma^2 = \frac{C_{4,N}}{C_{2,N}},\ S\sigma = \frac{C_{3,N}}{C_{2,N}}$

Xiaofeng Luo for STAR 1106.2926v1

V Fluctuations of net charge

- charge fluctuations per entropy scale with the square of the charge
  $\rightarrow$ Quark-Gluon-Plasma with fractional charges should be distinguishable from hadron gas with unit charges
  $\rightarrow$ charge fluctuations per particle of a QGP should be smaller
- example QGP in classical approx. and non interacting pion gas:

$$\frac{\langle \delta Q_\pi^2 \rangle}{S_\pi} \approx \frac{1}{6}$$

$$\frac{\langle \delta Q_{QGP}^2 \rangle}{S_{QGP}} \approx \frac{1}{24}$$

S. Jeon, V.Koch hep-ph/0304012v1

VI Fluctuations of net charge

- measurable quantities

$$D \approx 4 \frac{\langle \delta Q^2 \rangle}{\langle N_{ch} \rangle}$$

- Q net charge, N_{ch} number of charges particles
- non-interacting pion gas $D = 4$, HRG $D \approx 3$, QGP $D \cong 1 - 1.5$
- uncertainty of QGP rises from the uncertainty relating the entropy to the number of charges particles in the final state ($\langle N_{ch} \rangle \propto S$)

ALICE 1207.6068v1 S. Jeon, V. Koch hep-ph/0003168v3

VII Fluctuations of net charge

- dynamical charge observable $\nu_{+-,dyn}$

$$\nu_{+-,dyn} = \frac{\langle N_+(N_+ - 1)\rangle}{\langle N_+\rangle^2} + \frac{\langle N_-(N_- - 1)\rangle}{\langle N_-\rangle^2} - 2\frac{\langle N_- N_+\rangle}{\langle N_+\rangle \langle N_-\rangle}$$

- $\nu_{+-,dyn}$ is robust against random detection efficiency losses
- charge conservation implies minimum value of $\nu_{+-,dyn}$
- $\langle N_{ch}\rangle \nu_{+-,dyn} \approx D - 4$
- net charge is extensive quantity
  $\rightarrow$ volume fluctuations will also contribute to the measurement
  $\rightarrow$ $\nu_{+-,dyn}$ has to be corrected due to global charge conservation

$$\nu^{corr}_{+-,dyn} = \nu_{+-,dyn} + \frac{4}{\langle N_{total}\rangle}$$

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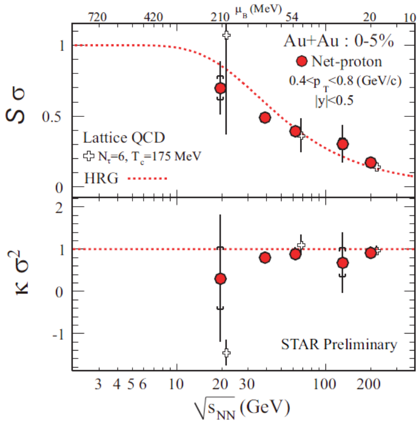
Measurement of $S\sigma$ and $\kappa\sigma^2$ I



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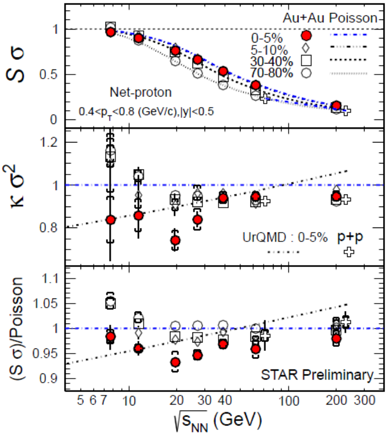
- theory: kurtosis is negative when critical point is reached but become positive again for smaller energies (lattice): e.g. R.V.Gavai, S. Gupta 1001.3796v2

Measurement of $S\sigma$ and $\kappa\sigma^2$ II



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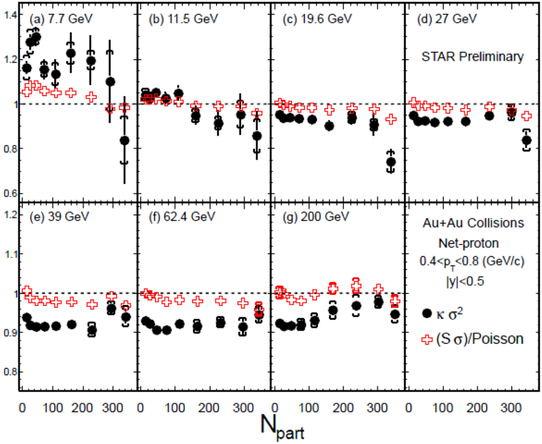
- UrQMD (microscopic transport model) doesn't incorporate CP and phase boundary
- deviations from Poisson-statistics and UrQMD are significantly visible

Measurement of $S\sigma$ and $\kappa\sigma^2$ III



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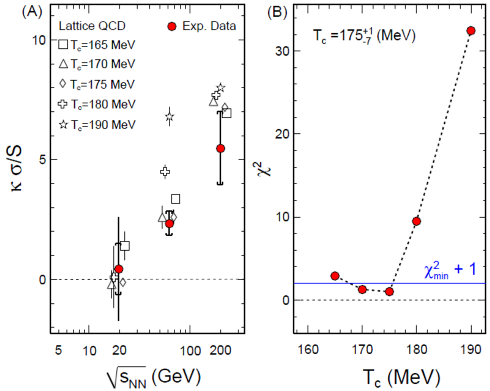
- values normalized to Poisson-statistics, at 7.7 GeV values are mostly above unity

Estimation of T_c from $S\sigma$ and $\kappa\sigma^2$

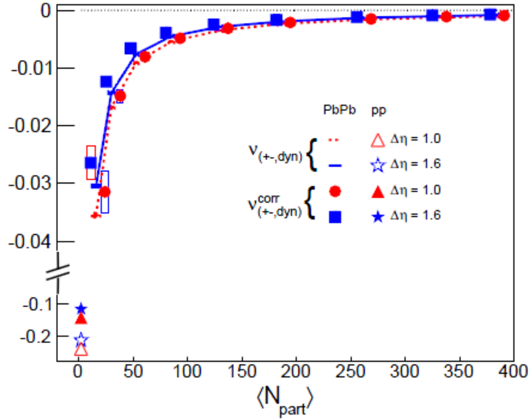


S. Gupta et al. 1105.3934v1

- T_c is regarded as free parameter → estimation via standart statistical analysis of experimental and lattice data

$$\chi^2(T_c) = \sum_{\sqrt{s_{NN}}} \frac{\left(\frac{\kappa\sigma}{S}\big|_{exp} - \frac{\kappa\sigma}{S}(T_c)\big|_{QCD}\right)^2}{Error^2_{exp} + Error^2_{QCD}}$$

Net-charge fluctuations I



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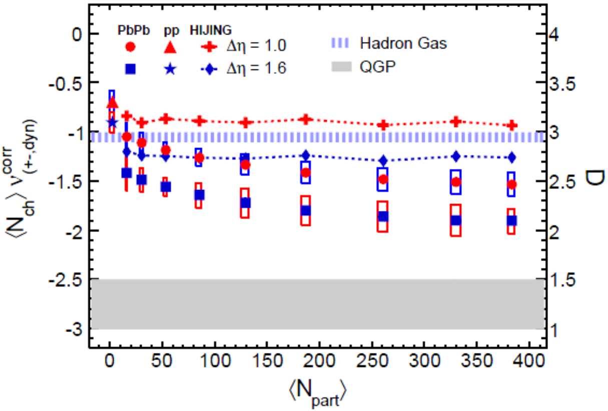
- $\sqrt{s_{NN}} = 2.76$ TeV, $0.2 \leq p_T \leq 5.0$ GeV/c
- $\nu_{+-,dyn}$ increases with increasing η window and centrality
- correlations of opposite charged particles dominate

Net-charge fluctuations II



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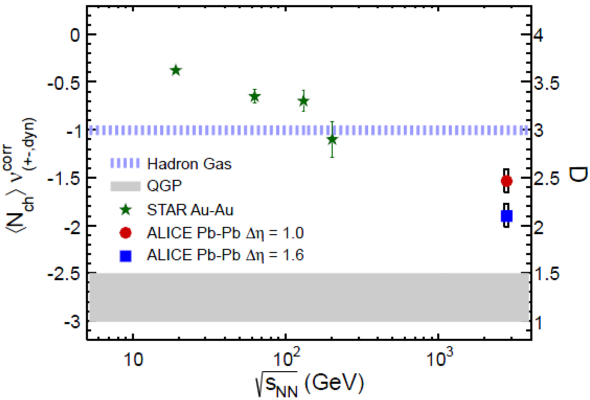
- from peripheral to central collisions: decreasing trend of fluctuations
- HIJING-model show no centrality-dependence

Net-charge fluctuations III



ALICE 1207.6068v1

- monotonic decrease of net-charge fluctuation with increasing beam energy
- for small energies STAR (with $\Delta\eta = 1.0$) results above HRG

- measured results for net proton number and charge fluctuations show deviations from calculations from hadronic models
  $\rightarrow$ conjecture that there is "more" than pure hadronic phase
- measure of charge fluctuations show a trend towards the QGP-value at LHC energies
- critical endpoint is not really found yet and also not refuted and estimation of T_c is improvable...

$\rightarrow$ more high rate and precision experiments are needed!

Thank you for your attention!!

- Xiofeng Luo for STAR: Search for the QCD Critical Point by Higher Moments of Net-proton Multiplicity Distributions at STAR, (2012), arXiv:1210.5573$v1$
- NA49: Critical fluctuations of the proton density in A+A collisions at 158A GeV, (2012), arXiv:1208.5292$v1$
- Satyajit Jena for ALICE: Charge fluctuations in Pb-Pb collusions at $\sqrt{s_{NN}} = 2.76$ TeV measured by ALICE experiment, (2012), arXiv:$1203 : 0542v1$
- F. Karsch: Determination of Freeze-out Conditions from Lattice QCD Calculations, (2012), arXiv: 1202.4173$v1$
- F.Karsch & K.Redlich: Has T_c been measured by heavy ion experiments?, (2011), arXiv:1107.1412$v1$
- Sourendu Gupta, Xiaofeng Luo, Bedangadas Mohanty, Hans-Georg Ritter, Nu Xu: Scale for the Phase Diagramm of Quantum Chromodynamics, (2011), arXiv:1105.3934$v1$
- Xiaofeng Luo for STAR: Probing the QCD Critical Point with Higher Moments of Net-proton Multiplicity Distributions, (2011), arXiv:1106.2926$v1$

- P.B.Munzinger,B.Friman,F.Karsch,K.Redlich & V.Skokov: Net-proton propability distribution in heavy ion collisions, (2011), arXiv:1107.4267v1
- R.V. Gavai, S. Gupta: Lattice QCD predictions for shapes of event distributions along the freezeout curve in heavy ion collisions, (2010), arXiv:1001.3796v2
- M. Asakawa et al: Third Moments of Conserved Charges as Probes of QCD Phase Structure, PRL 103, 262301, (2009)
- STAR: Beam-Energy and System-Size Dependence of Dynamical Net Charge Fluctuations, (2008) ,arXiv:0807.3269v1
- M.Stephanov: QCD phase diagram and the critical point, (2006), arXiv:hep-ph/0402115v1
- S.Jeon: Event by Event Fluctuations, (2003), arXiv:hep-ph/0304012v1
- S. Jeon, V. Koch Charged Particle Ratio Fluctuation as a Signal for QGP, (2000), arXiv: hep-ph/0003168v3
- M.Stephanov, K.Rajagopal, E.Shuryak: Event-by-Event Fluctuations in Heavy-Ion-Collisions and the QCD Critical Point, (1999), arXiv:hep-ph/9903292v2

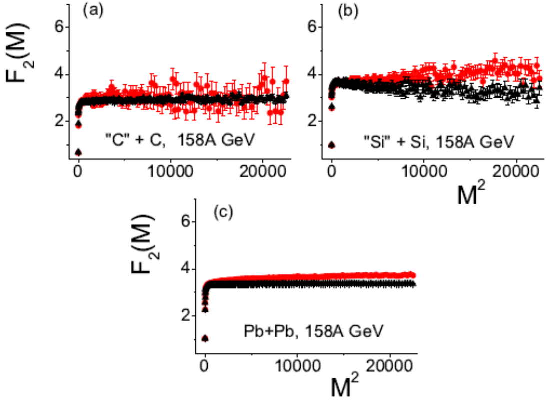
Appendix: Fluctuation of proton density

- second factorial moment of proton density:

$$F_2(M) = \left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i(n_i - 1) \right\rangle / \left\langle \frac{1}{M^2} \sum_{i=1}^{M^2} n_i^2 \right\rangle$$

- n_i proton number, M number of subdivisions
- $F_2(M)$ scales with critical exponent $\Phi_{2,cr}$ near the chiral critical point
- theoretical value: $\Phi_{2,cr} = \frac{5}{6}$

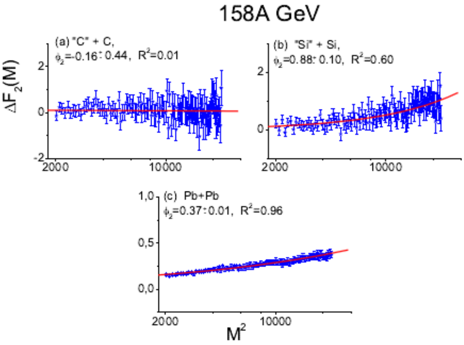
Appendix: Critical fluctuation of proton density I



NA49 1208.5292v1

- midrapidity: $-0.75 < \eta < 0.75$, $\sqrt{s_{NN}} = 17.3$ GeV
- black: "mixed events": include uncorrelated proton from, e.g. hyperon decay and particles misidentified as protons

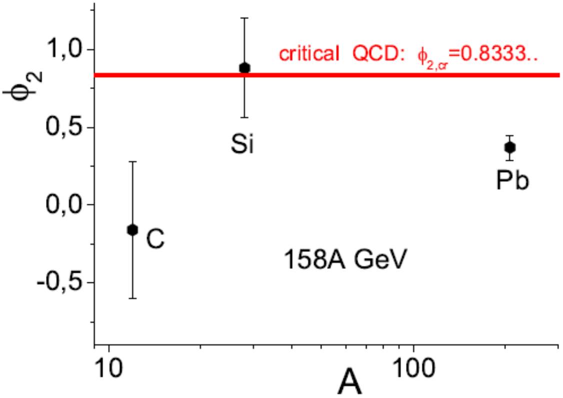
Appendix: Critical fluctuation of proton density II



NA49 1208.5292v1

- corrected correlators, without "background" : $\Delta F_2(M) = F_2^{(d)}(M) - F_2^{(m)}(M)$

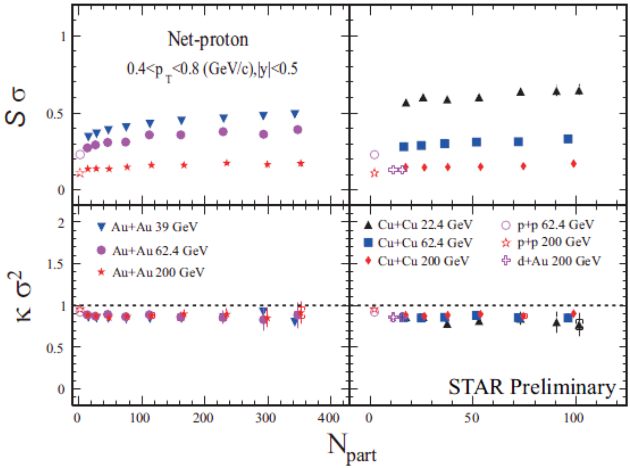
Appendix: Critical fluctuation of proton density III



NA49 1208.5292v1

- results (exept C) show that measured freeze-out states are in the neighbourhood of the chiral critical point

Appendix: Measurement of $S\sigma$ and $\kappa\sigma^2$ IV



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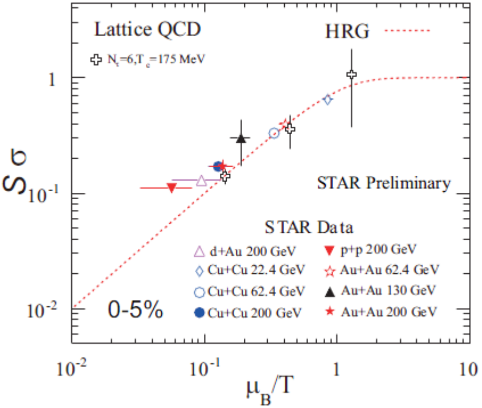
- $S\sigma$ increases weakly with centrality, $\kappa\sigma^2$ remains constant
- $\kappa\sigma^2$ on slide 13 show centrality dependence

Appendix: Measurement of $S\sigma$ and $\kappa\sigma^2$ V



STAR 1106.2926v1

- data points for most central collisions are consistent with LQCD and HRG: evidence for thermalization
  $\rightarrow$ this (older) result contradict slide 12!