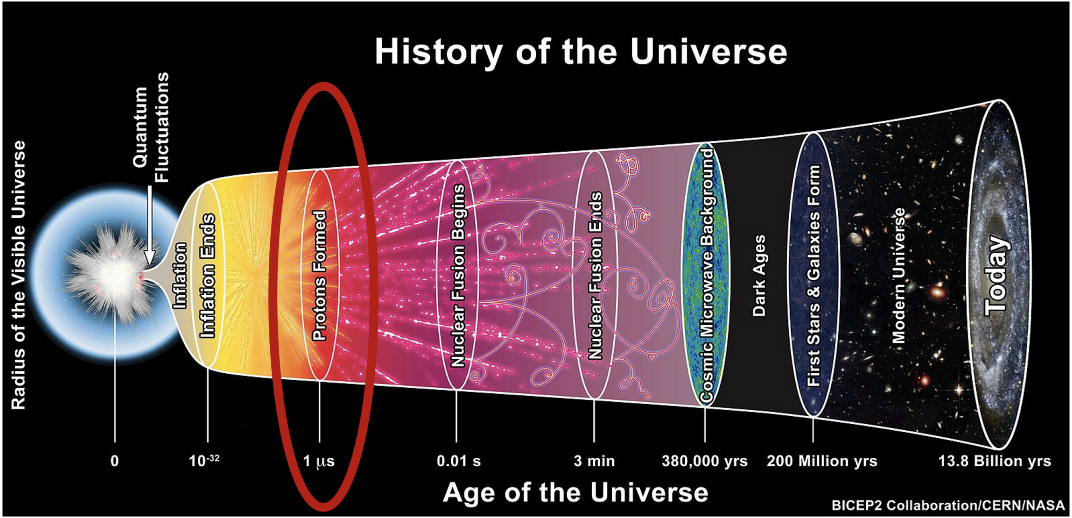
Conservation laws in net-particle fluctuation measurements:

the effect on LQCD predictions of the QCD phase transition

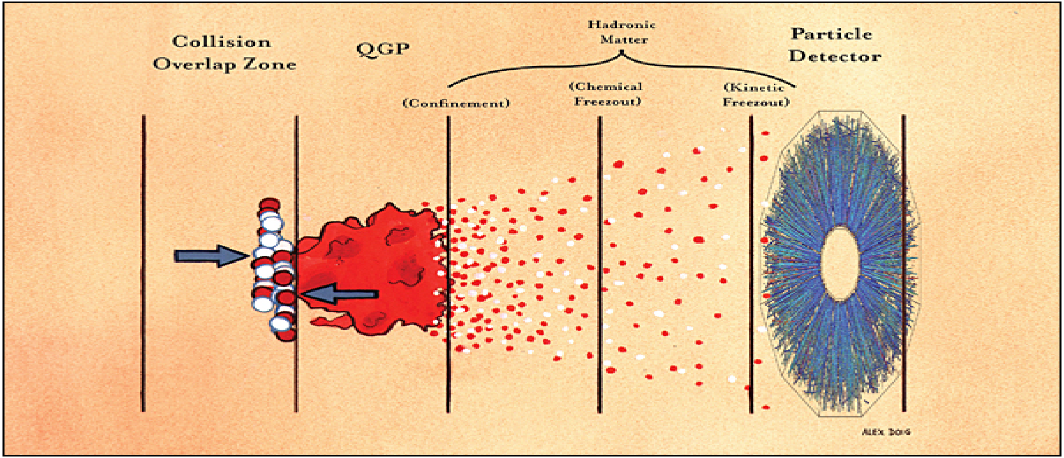
Ejiro Umaka (ISU) • P-3 Seminar @ LANL • August 18, 2021

The quark-hadron transition



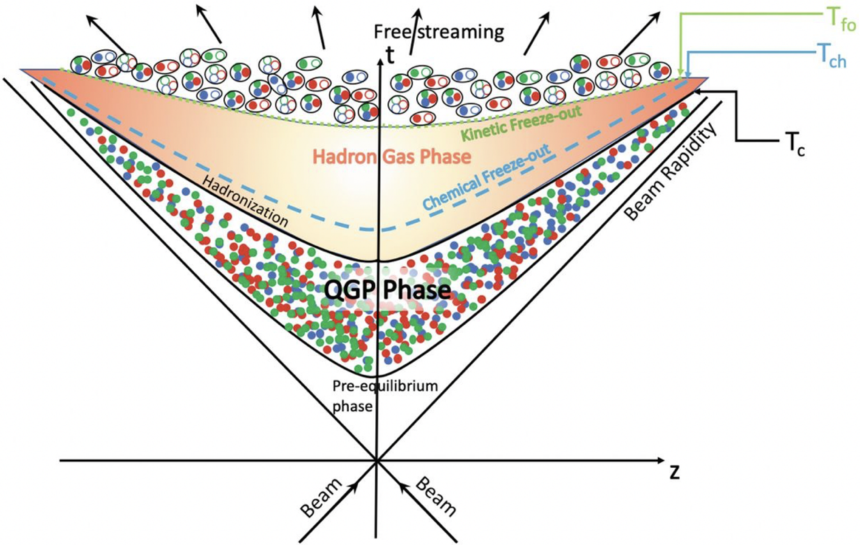
- 1 μs after the Big Bang de-confined quarks and gluons transitioned into confined hadrons
- A key goal of HI collisions is to map out this transition

Recreating the Big Bang with heavy-ion collisions

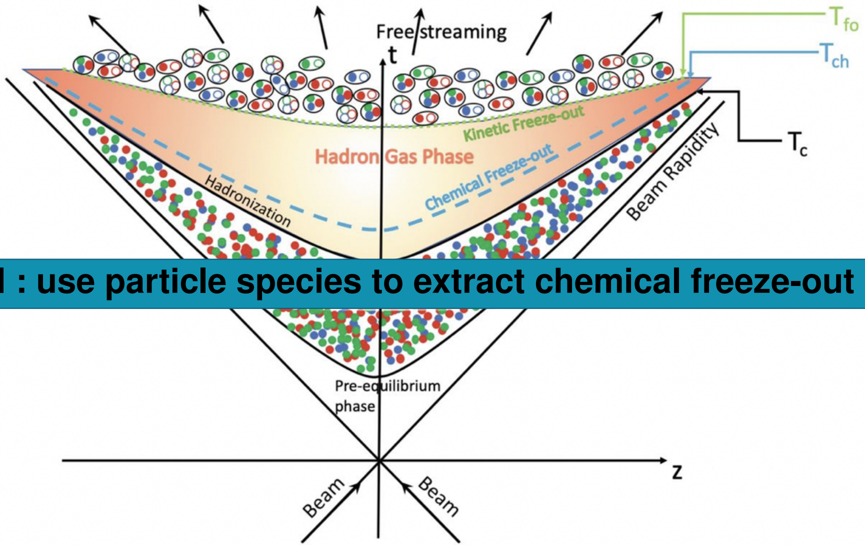


- **Chemical freeze-out :** all inelastic collisions between particle species cease
- **Kinetic freeze-out :** all elastic collisions between hadrons cease

Time evolution of heavy-ion collision

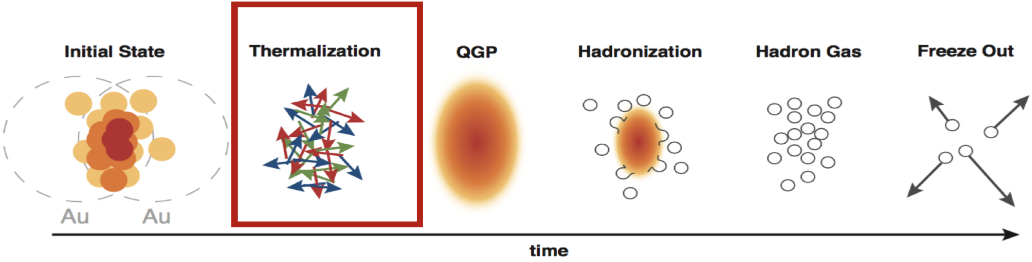


Time evolution of heavy-ion collision



Goal : use particle species to extract chemical freeze-out line

Insight from theory



- There is the assumption that the system in HI collisions reaches thermalization
- Conserved quantities, Q_i : **net-charge, net-strangeness, and net-baryon number**
- Described by GCE with partition function :

$$\mathrm{Z} = \mathrm{Tr}[\, exp(-\frac{H - \sum_i \mu_i Q_i}{T})\,] \tag{1}$$

- Fluctuations of conserved quantities are described with susceptibilities :

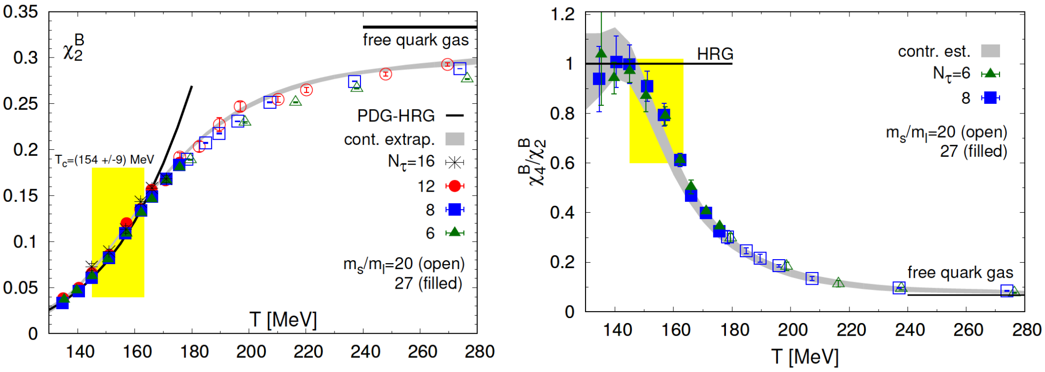
$$\chi^{B,S,Q}_{n_B,n_S,n_Q} \equiv \frac{1}{VT^3} \frac{\partial^{n_B}}{\partial(\mu_B/T)^{n_B}} \frac{\partial^{n_S}}{\partial(\mu_S/T)^{n_S}} \frac{\partial^{n_Q}}{\partial(\mu_Q/T)^{n_Q}} \ln Z \tag{2}$$

- Susceptibilities measure the response of the system to infinitesimal change in chemical potential

$\Longrightarrow$ 'Knobs' of the system to extract T and μ_B

Theory in action

BNL-Bielefeld-CCNU



- Test of LQCD at $\mu_B \approx 0$
- Smaller than in HRG for T $>$ 150 MeV (right figure)
- Yellow boxes indicate the transition region, $T_c \approx 154 \pm 9$ MeV

What we know so far

Crossover temperature from LQCD : $T_c \approx 154 \pm 9$ **MeV**

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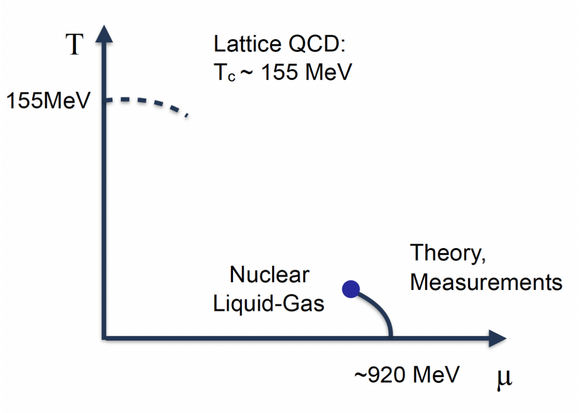

Can use experiment to map out the QCD phase transition !

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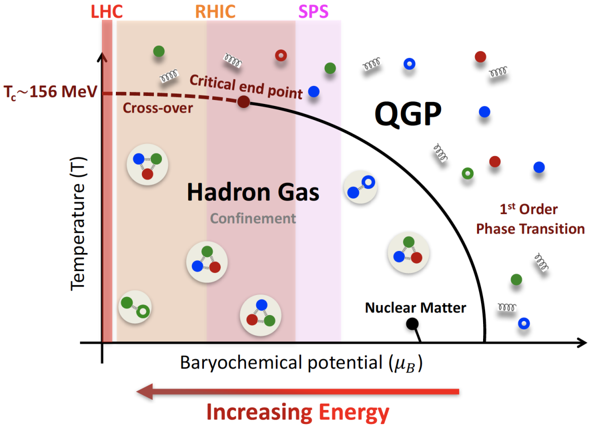
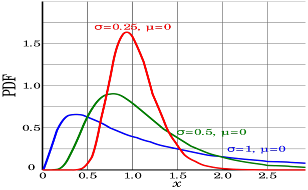
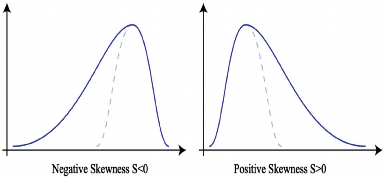
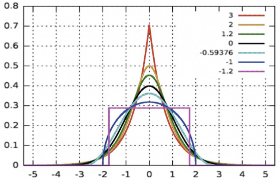


Can use experiment to map out the QCD phase transition !

Fluctuations of conserved quantities in experiment







- Event-by-event particle multiplicity fluctuations are characterized by the cumulants of the event-by-event multiplicity distributions
- N is the net-particle number, i.e., particle *minus* antiparticle, $\delta N = N - \langle N \rangle$, cumulants are :

$$C_1 = \langle N \rangle \tag{3}$$

$$C_2 = \langle (\delta N)^2 \rangle \tag{4}$$

$$C_3 = \langle (\delta N)^3 \rangle \tag{5}$$

$$C_4 = \langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2 \tag{6}$$

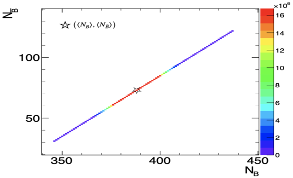
- The skewness, S, and kurtosis, κ, can be extracted as follows :

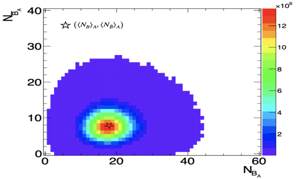
$$S = \frac{C_3}{(C_2)^{\frac{3}{2}}} \tag{7}$$

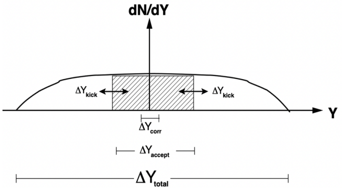
$$\kappa = \frac{C_4}{(C_2)^2} \tag{8}$$

Generating fluctuations in experiment

P. Braun-Munzinger et al   V. Koch







- Fluctuations of net-baryons appear only inside finite acceptance
- The fluctuations can be considered as meaningfully observables if the following is true (GCE) :

$$\Delta Y_{accept} \gg \Delta Y_{corr} \tag{9}$$

$$\Delta Y_{total} \gg \Delta Y_{accept} \gg \Delta Y_{kick} \tag{10}$$

- ΔY_{accept} : acceptance of measurement
- ΔY_{total} : full phase space
- ΔY_{corr} : rapidity correlation length
- ΔY_{kick} : rapidity shift due to hadronization

Connecting theory to experiment

- The cumulants of the conserved charges are related to the susceptibilities :

$$C_{ijk}^{BQS} = VT^3 \chi_{ijk}^{BQS}(T, \mu_B, \mu_Q, \mu_S) \tag{11}$$

- Since the volume is unknown in experiment, take ratios, e.g. :

$$\frac{C_2}{C_1} = \frac{\sigma^2}{M} = \frac{\chi_2}{\chi_1} \tag{12}$$

$$\frac{C_3}{C_2} = S\sigma = \frac{\chi_3}{\chi_2} \tag{13}$$

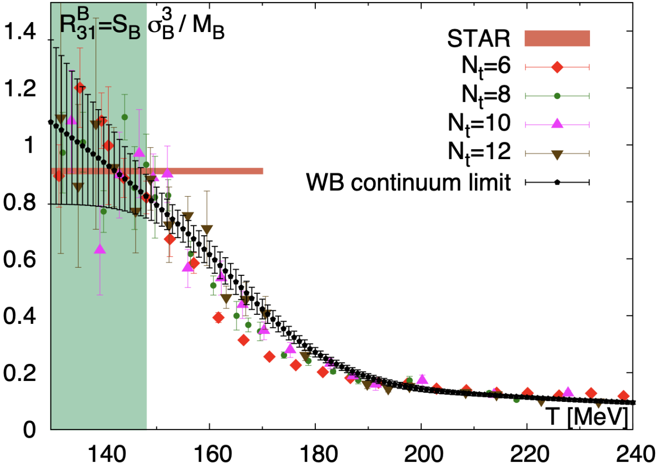
$$\frac{C_4}{C_2} = \kappa\sigma^2 = \frac{\chi_4}{\chi_2} \tag{14}$$

$$\frac{C_4}{C_3} = \frac{\kappa\sigma}{S} = \frac{\chi_4}{\chi_3} \tag{15}$$

- Focus of this talk will be on the highlighted ratio

Theory and experiment in action

S. Borsanyi et al   STAR collab.



- Dark orange band is STAR net-proton data
- The green-shaded area shows the valid temperature range

Limitations with connecting theory to experiment

- **Some assumptions and approximations :** The net-particle multiplicity distribution from experiment follows a Poisson PD
  $\Longrightarrow$ Skellam baseline : $C_n = \langle N_B \rangle + (-1)^n \langle N_{\bar{B}} \rangle$
  $\Longrightarrow$ Proxies : e.g. net-proton $\approx$ net-baryon
- **Global charge conservation :** experiment mimics GCE by analyzing a subset of the particles in the final state
  $\Longrightarrow$ acceptance cuts can lead to global conservation laws

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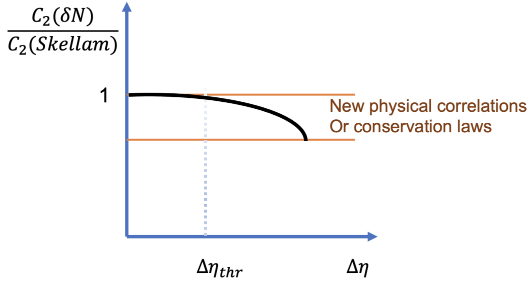
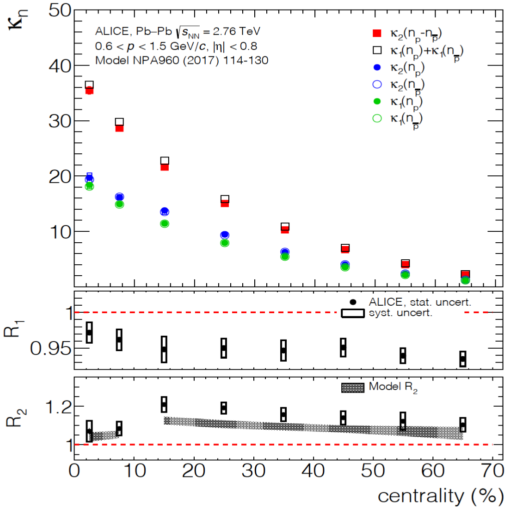


Net-proton fluctuation measurement from ALICE

First and second cumulants of net-protons

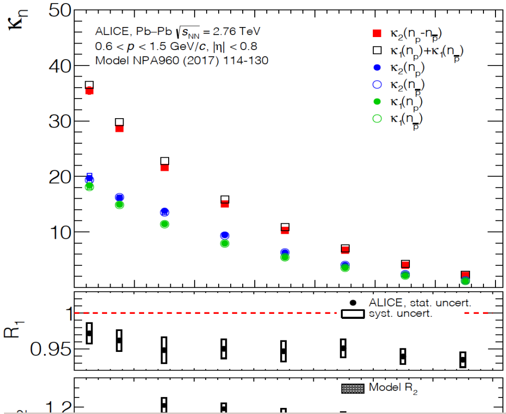
ALICE collab.



$$R_1 = \kappa_2(n_p - n_{\bar{p}})/\langle n_p + n_{\bar{p}} \rangle \qquad R_2 = \kappa_2(n_p)/\langle n_p \rangle$$

First and second cumulants of net-protons

ALICE collab.



Measured second cumulants of net-proton deviates from Skellam baseline ($R_1 \neq 1$)

R_1

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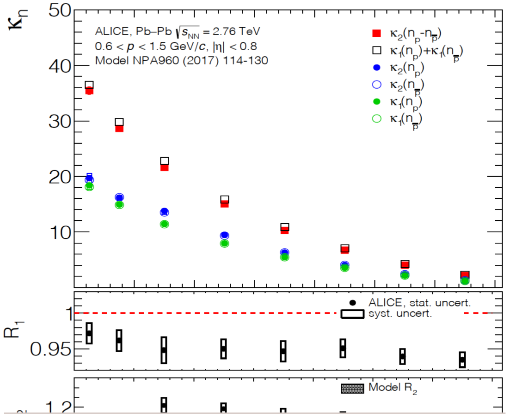
ALICE collab.



Measured second cumulants of net-proton deviates from Skellam baseline ($R_1 \neq 1$)

$\Longrightarrow$ New physical correlations ?

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First and second cumulants of net-protons

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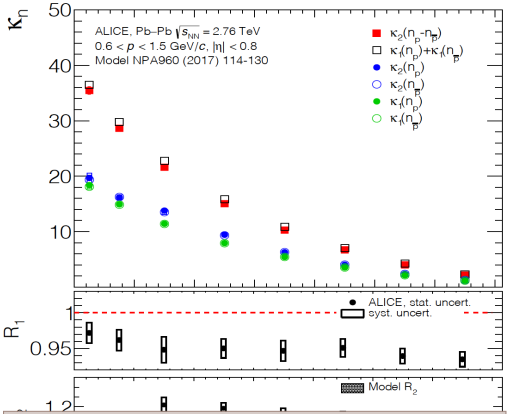


Measured second cumulants of net-proton deviates from Skellam baseline ($R_1 \neq 1$)

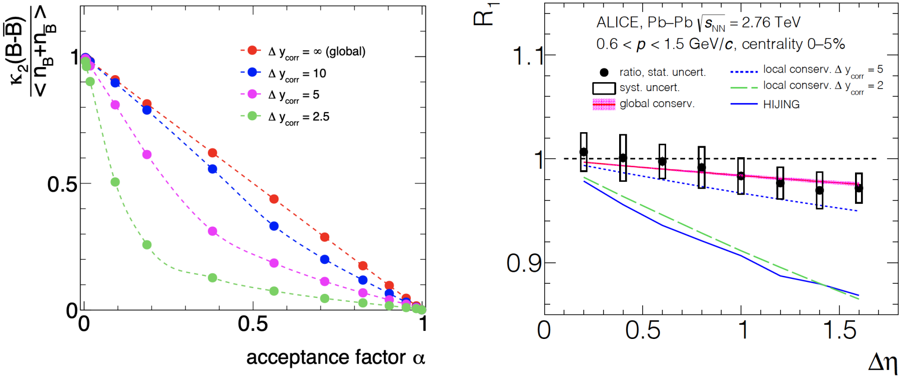
$\Longrightarrow$ New physical correlations ?

$\Longrightarrow$ Conservation laws ?

R_1

Baryon number conservation in fluctuation measurements

P. Braun-Munzinger et al ALICE collab.

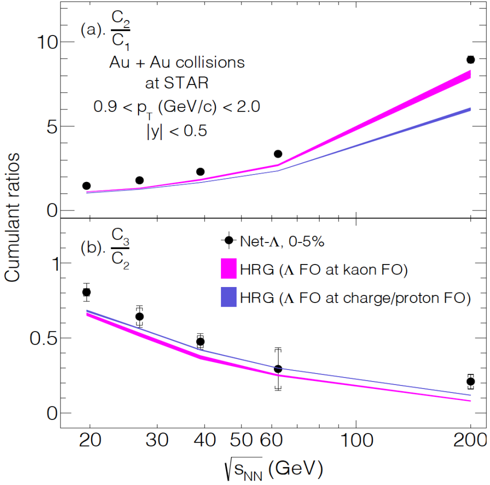


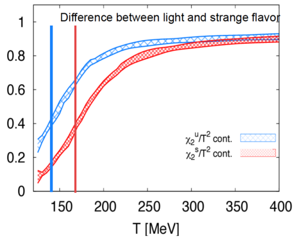
- $\alpha = \langle n_p \rangle / \langle n_B^{4\pi} \rangle \qquad R_1 = 1 - \alpha$
- The data is best described with the assumption of global baryon number conservation
  ✓Consistent with LQCD prediction of a Skellam behavior for κ_2 of net-baryons after accounting for baryon number conservation

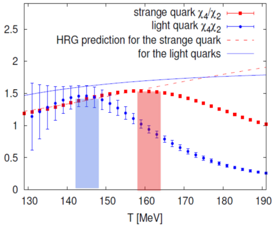
Net-Λ fluctuation measurement from STAR

Beam energy dependence of net-Λ fluctuations

STAR collab. R. Bellwied et al







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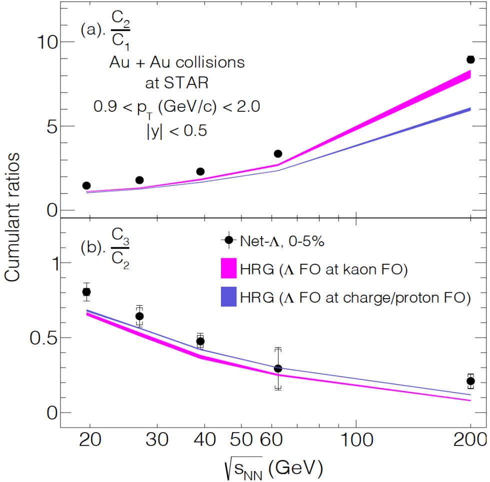
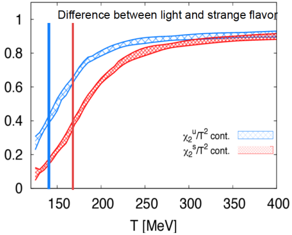
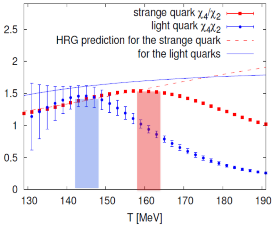
STAR collab. R. Bellwied et al





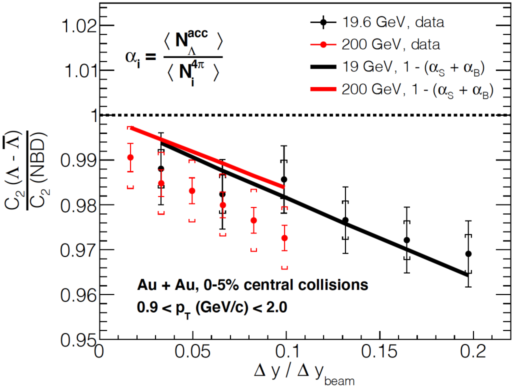


Λ carries strangeness :
test for presence of quark flavor dependent freeze out

Need higher order cumulants to distinguish FO

Rapidity dependence of net-Λ cumulants

STAR collab.



- Acceptance factor α includes strangeness
- $\approx$ works for 19.6 GeV data
- Coupling of strangeness and baryon number conservation is unclear

Summary

- Susceptibilities from lattice QCD calculations are directed linked to net-particle fluctuation measurements from experiment

  $\Longrightarrow$ Net-proton fluctuation measurement of the second cumulant from ALICE is consistent with LQCD predictions after accounting for baryon number conservation

  $\Longrightarrow$ Coupling between strangeness and baryon number requires more studies

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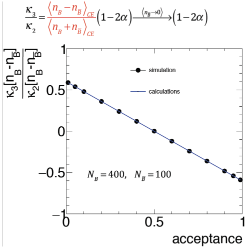
- Higher order cumulants of net-proton at LHC and of net-Λ at RHIC will take advantage of higher statistics in upcoming runs



Third order cumulant dependence on acceptance in simulation

P. Braun-Munzinger, A. Rustamov, J. Stachel