Flavor hierarchy in the confinement transition of QCD

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in collaboration with
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Motivation

- confinement/deconfinement transition of QCD at $\mu_B = 0$ is an analytic crossover
- $T_c = (154 \pm 9)$ MeV A. Bazavov et al., Phys. Rev. D 85 (2012) 054503
  $T_c = (147 \pm 5)$ - (155 ± 6) MeV S. Borsányi et al., JHEP 1009 (2010) 073
  from a rapid change in different order parameters

- fluctuations of conserved charges (in heavy-ion collisions *B*, *Q* and *S*) are sensitive to the microscopic structure of the matter
- a rapid change in these observables provides a signal for a phase transition
- measurable experimentally and calculable (as susceptibilities) in lattice QCD

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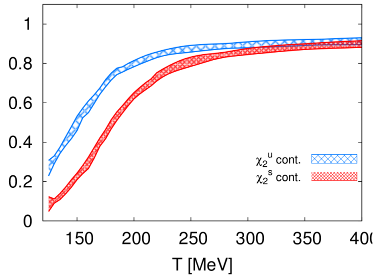
- diagonal susceptibilities measure the impact of an infinitessimal chemical potential change on the conserved charge density

$$\chi_2^X = \frac{\partial^2 (p/T^4)}{\partial(\mu_X/T)^2} = \frac{\partial(n_X/T^3)}{\partial(\mu_X/T)}$$

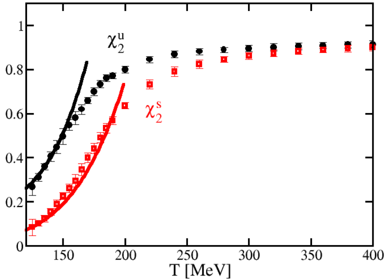
- non-diagonal susceptibilities measure correlations between different conserved charges

$$\chi_{11}^{XY} = \frac{\partial^2 (p/T^4)}{\partial(\mu_X/T)\partial(\mu_Y/T)}$$



S. Borsányi et al., JHEP 1201 (2012) 138

Motivation



data taken from S. Borsányi et al., JHEP 1201 (2012) 138

diagonal quark number susceptibilities for light and strange quark flavors:

- fairly well described by Hadron Resonance Gas (HRG) model for lower *T*

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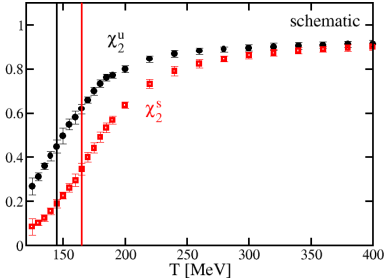


data taken from S. Borsányi et al., JHEP 1201 (2012) 138

- quantitatively similar observation from the combination of (B, Q, S)-susceptibilities in

  A. Bazavov et al., Phys. Rev. D 86 (2012) 034509

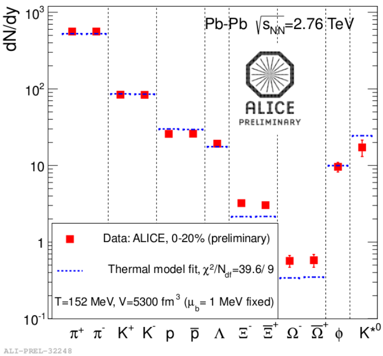
diagonal quark number susceptibilities for light and strange quark flavors:

- clear difference between different quark flavors: rapid change happens for strange quarks at a larger T than for light quarks (about $(15 - 20)$ MeV difference), i.e. fluctuations of strange quark number density cease at a larger T
- might be an indication for a flavor hierarchy in the confinement transition

Experimental indications: Charged hadron production

- integrated yields provide higher flavor-sensitivity than e.g. hadron/pion ratios

feed-down corrected dN/dy at midrapidity in central (0-20%) Pb-Pb



L. Milano (for ALICE), arXiv:1302.6624 [hep-ex] and QM2012

- standard Statistical Hadronization Model (SHM) fit with $T_{ch} = 164$ MeV gives poor overall description
- global fit: $T_{ch} = (152 \pm 3)$ MeV but yields of (multi)strange baryons underestimated
- fit to individual yields would be better if T_{ch} for strange hadrons was higher than for non-strange hadrons (sequential progression)

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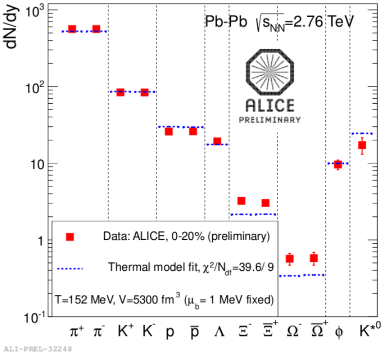
feed-down corrected *dN / dy* at midrapidity in central (0-20%) Pb-Pb



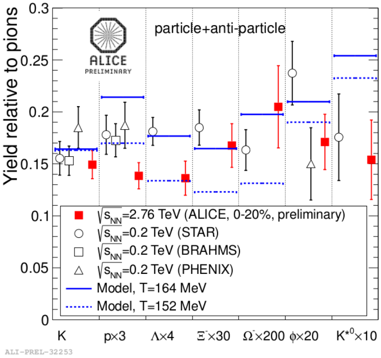
L. Milano (for ALICE), arXiv:1302.6624 [hep-ex] and QM2012

- possible explanation: flavor hierarchy in the chemical freeze-out
- caveat: for SHM-fits of yields knowledge of a (T-dependent) volume V is needed

Experimental indications: Charged hadron production

- particle-yield ratios

yields relative to pions



L. Milano (for ALICE), arXiv:1302.6624 [hep-ex] and QM2012

cf. R. Preghenella (for ALICE), Acta Phys. Polon. B43 (2012) 555

- similar observations can be made in particle/pion ratios
- caveat: (multi)strange baryon/pion ratios mix quark-flavor sectors (less flavor-specific)

Possible alternative explanations

- anti-baryon–baryon annihilation in the hadronic phase:
  - non-equilibrium, final state effect as consequence of in-medium enhanced annihilation cross section

    F. Becattini et al., Phys. Rev. C 85 (2012) 044921; arXiv:1212.2431 [nucl-th];

    J. Steinheimer et al., Phys. Rev. Lett. 110 (2013) 042501; Y. Karpenko et al., Phys. Rev. C 87 (2013) 024914
  - regeneration processes important

    Y. Pan and S. Pratt, arXiv:1210.1577 [nucl-th]
  - effect more pronounced in central than in peripheral collisions

cf. talks by J. Steinheimer, R. Stock

- viscous-hydro approach with species-dependent (dynamically generated) T_{ch}

  P. Bozek and I. Wyskiel-Piekarska, Phys. Rev. C 85 (2012) 064915
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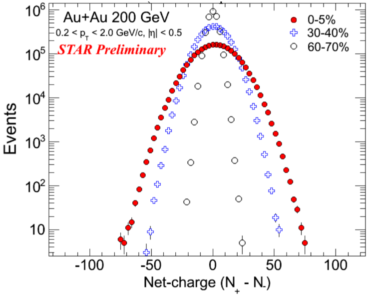
Idea: fingerprint of a flavor hierarchy measurable in higher moments of multiplicity distributions?

Statistical moments of multiplicity distributions

- measurement of fluctuations in conserved charges



from D. McDonald, talk at QM2012

observable X: net electric charge

statistical moments:

- mean $\langle X \rangle$
- deviation $\langle \delta X \rangle = \langle X - \langle X \rangle \rangle$
- variance (width) $\sigma_X^2 = \langle (\delta X)^2 \rangle$
- skewness (∼asymmetry) $S_X = \langle (\delta X)^3 \rangle / \sigma_X^3$
- kurtosis (∼center peakedness) $\kappa_X = \langle (\delta X)^4 \rangle / \sigma_X^4 - 3$
- etc.

Relation to susceptibility ratios

- conserved charge susceptibility ratios can be directly related to the statistical moments: e.g.

$$\kappa_Q \sigma_Q^2 = \frac{\chi_4^Q(T, \mu_B)}{\chi_2^Q(T, \mu_B)} = \frac{\chi_4^Q(T)}{\chi_2^Q(T)} + \mathcal{O}(\mu_B^2)$$

- provide a model-independent measure of freeze-out conditions from lattice QCD F. Karsch, Central Eur. J. Phys. 10 (2012) 1234

cf. talk by S. Mukherjee

- advantage of ratios: V-dependence cancels out

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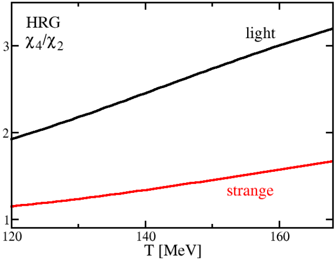
Goal: define a measurement of flavor-specific fluctuation observables

$\Rightarrow$ ongoing project

Flavor-specific observables

- quark number susceptibilities ratios:
  2 (light) and 1 (strange) dynamical quark flavors



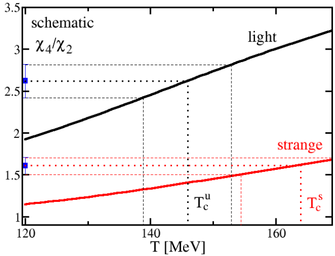
$$\chi_2^u = \chi_2^B + 2\chi_{11}^{BQ} + \chi_2^Q$$
$$\chi_4^u = \chi_4^B + 4\chi_{31}^{BQ} + 6\chi_{22}^{BQ} + 4\chi_{13}^{BQ} + \chi_4^Q$$
$$\chi_2^s = \chi_2^S$$
$$\chi_4^s = \chi_4^S$$

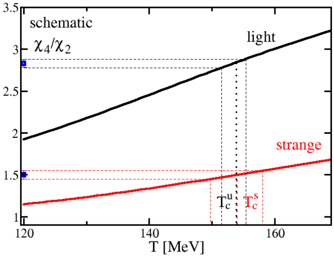
as the chemical potentials are related via

$$\mu_u = \frac{1}{3}\mu_B + \frac{2}{3}\mu_Q$$
$$\mu_d = \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q$$
$$\mu_s = \frac{1}{3}\mu_B - \frac{1}{3}\mu_Q - \mu_S$$

How to relate measurement and model?

- non-trivial issue, cf. talks by V. Skokov, A. Bzdak
- ALICE has measurements of π, p; K, Λ, Ξ, Ω
- have to be sensitive to the flavor-composition of the individual hadrons ($\rightarrow$ optimal measurement: p vs. Ω)
- possible scenarios:





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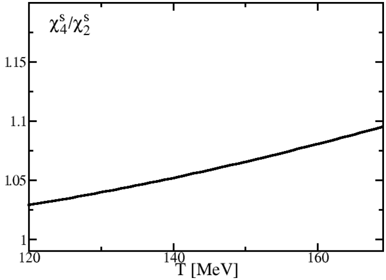
- ALICE has measurements of $\pi, p; K, \Lambda, \Xi, \Omega$
- have to be sensitive to the flavor-composition of the individual hadrons ($\rightarrow$ optimal measurement: p vs. Ω)
- most promising measurement proposal: measure all strange ground states and all light ground states (feed-down corrected for weak decays) separately

$$\begin{aligned}
\kappa_s \sigma_s^2 &= \kappa\sigma^2(K, K^0, \Lambda, \Xi, \Omega \text{ incl. } K^*, \Lambda^*, \Sigma, \Xi^*) \\
\kappa_u \sigma_u^2 &= \kappa\sigma^2(\pi, p \text{ incl. } \rho, \omega, \Delta, N^*)
\end{aligned}$$

- highlights the importance of taking resonance decays into account in the model

Example: $K^+ - K^-$ measurement

- net-Kaon multiplicity distribution measures net-strangeness distribution in the (K^+, K^-)–subsystem
- $\kappa\sigma^2(N_{K^+} - N_{K^-}) = \chi_4^s / \chi_2^s$



- HRG model result

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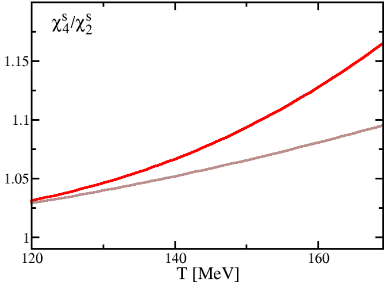

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- influence of resonance decays is sizeable

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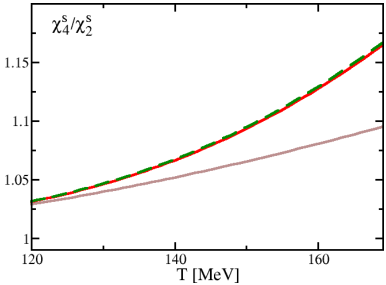

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- exhibits little chemical potential dependence for small μ_X ($\mu_B = 20$ MeV, $\mu_S = 4$ MeV)

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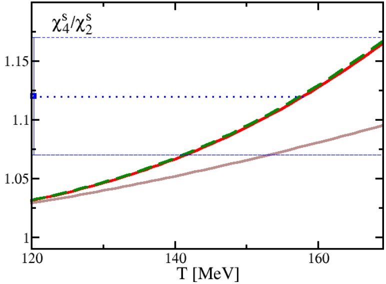

data from D. McDonald (for STAR), arXiv:1210.7023 [nucl-ex]

$\kappa\sigma^2$ of net-Kaons, $0-5\%$ centrality, Au+Au at $\sqrt{s} = 200$ GeV

- HRG model result
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- influence of resonance decays is sizeable
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Conclusions

- continuum-extrapolated lattice QCD quark number susceptibility results show a clear separation between different quark flavors in the crossover region
- might be a signature for a hierarchy in the hadronization process
  - should be reflected in the integrated yields of strange vs. non-strange hadrons (indications at ALICE)
- proposal: look for evidences in higher moments of multiplicity distributions (ongoing work)
- non-trivial to relate experimental measurement to model calculation
  - highlighted importance of resonance decays