Flavor hierarchy in the confinement transition of QCD

Marcus Bluhm

University of Torino & INFN

in collaboration with
P. Alba, W. Alberico, R. Bellwied, M. Nahrgang and C. Ratti

Strangeness in Quark Matter 2013
Birmingham, UK, July 23, 2013

INFN
Istituto Nazionale
di Fisica Nucleare

Motivation

- confinement transition of $N_f = 2+1$ QCD at $\mu_B = 0$ is an analytic crossover
- pseudo-critical temperature:
  $T_c = (154 \pm 9)$ 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; in QCD net u-, d- and s-quark numbers) are sensitive to the microscopic structure of the matter

  Jeon and Koch, Phys. Rev. Lett. 85 (2000) 2076; Asakawa, Heinz and Müller, Phys. Rev. Lett. 85 (2000) 2072
- a rapid change in these observables provides a signal for a phase transition
- measurable experimentally and calculable (as susceptibilities) in lattice QCD:

$$\chi_{lmn}^{uds} = \frac{\partial^{l+m+n}(p/T^4)}{\partial(\mu_u/T)^l \, \partial(\mu_d/T)^m \, \partial(\mu_s/T)^n}$$

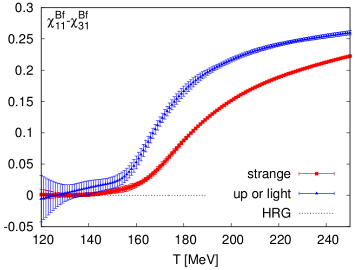
Lattice QCD results

- continuum-extrapolated lattice QCD data of χ_2^u and χ_2^s at physical u- and s-quark masses show a clear separation in the behavior between up and strange quarks
  $\rightarrow$ interpreted as an indication for a flavor hierarchy in the crossover transition C. Ratti et al., Phys. Rev. D 85 (2012) 014004
- quark mass effect

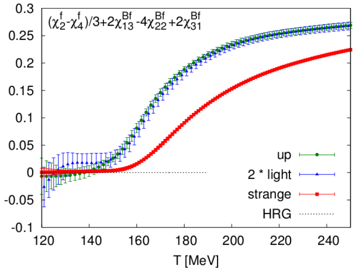
Lattice QCD results

- model-dependent approach via comparison of Hadron Resonance Gas (HRG) model with lQCD data:
  - combinations of higher-order susceptibilities suggested which are zero in the hadronic phase and become non-zero with the onset of *s*-quark liberation (deconfinement) A. Bazavov et al., arXiv:1304.7220 [hep-lat]

    $\rightarrow$ see talk by C. Schmidt (Friday)
  - generalized to any flavor in order to study a possible flavor-specific behavior R. Bellwied et al., arXiv:1305.6297 [hep-lat]



from R. Bellwied et al., arXiv:1305.6297 [hep-lat]



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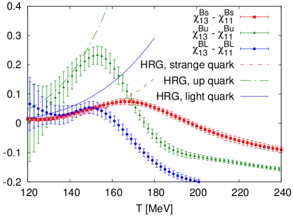
Lattice QCD results

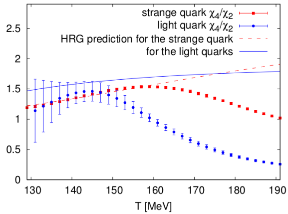
- a different susceptibility combination: in hadronic phase sensitive to baryons containing more than one quark of flavor *f*



from R. Bellwied et al., arXiv:1305.6297 [hep-lat]

→ shows a pronounced separation of flavors

- investigate fluctuations of <u>net</u> light-quark number and <u>net</u> strange-quark number χ_4^f/χ_2^f (π do not carry <u>net</u> light-quark number)



from R. Bellwied et al., arXiv:1305.6297 [hep-lat]

→ flavor-dependence of the liberation temperature (*T* at which HRG model starts to deviate from lQCD)

→ flat curves

Lattice QCD results

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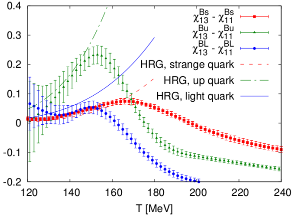

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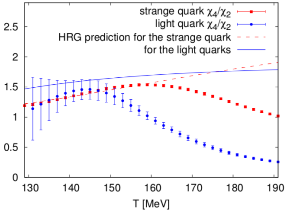
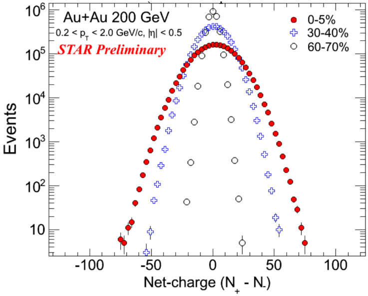


from R. Bellwied et al., arXiv:1305.6297 [hep-lat]

Idea: fingerprint of a flavor hierarchy measurable in higher-order moments of particle-identified multiplicity distributions?

Statistical moments of multiplicity distributions

- measurement of fluctuations in a conserved charge X



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 ($\sim$asymmetry) $S_X = \langle (\delta X)^3 \rangle / \sigma_X^3$
- kurtosis ($\sim$center peakedness) $\kappa_X = \langle (\delta X)^4 \rangle / \sigma_X^4 - 3$
- ...

Relation to ratios of susceptibilities

- ratios of susceptibilities of a conserved charge can be directly related to the statistical moments: e.g. net electric charge

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

- provide a model-independent measure of freeze-out conditions from lattice QCD F. Karsch, Central Eur. J. Phys. 10 (2012) 1234; A. Bazavov et al., Phys. Rev. Lett. 109 (2012) 192302; S. Borsanyi et al., arXiv:1305.5161[hep-lat]

- advantage of susceptibility ratios: volume-dependence cancels out

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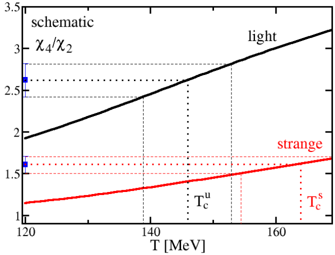
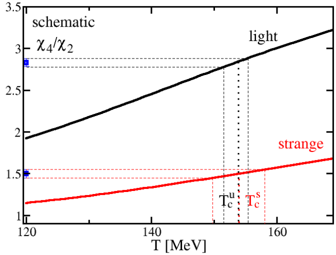
Goal: define a measurement of flavor-specific fluctuation observables being related to ratios of quark number susceptibilities

$\Rightarrow$ ongoing project

Defining a suitable measurement

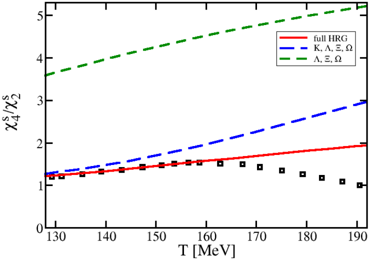
- ALICE has measurements of π, p, K, Λ, Ξ, Ω
- higher-order moment analysis of particle-identified multiplicity distributions
- have to be sensitive to the flavor-composition of the individual hadrons ($\rightarrow$ optimal measurement: p vs. Ω but flat χ_4^f/χ_2^f)
- task: find optimal final state combinations that allow a discrimination of light from strange quarks by providing steep χ_4^f/χ_2^f-curves





Defining a suitable measurement

- strange-quark number fluctuations:



lQCD data from R. Bellwied et al., arXiv:1305.6297 [hep-lat]

→ optimal final state subset: Λ^0, Ξ^- and Ω^- plus their antiparticles

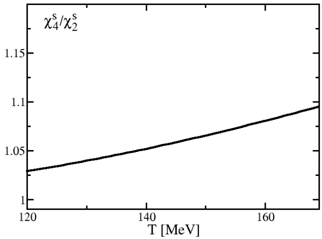
- light-quark number fluctuations: consider as subset K^+ and p plus their antiparticles (π do not contribute to the net light-quark number)

How to relate measurement with HRG model?

- non-trivial issue M. Kitazawa and M. Asakawa, Phys. Rev. C 86 (2012) 024904; A. Bzdak and V. Koch, Phys. Rev. C 86 (2012) 044904 ...
- detector acceptance:
  for identified particles express HRG model momentum-integrals in terms of transverse momentum p_T and rapidity $y \rightarrow$
  $E_i = \sqrt{p_T^2 + m_i^2} \cosh y \; ; \; d^3p = p_T \sqrt{p_T^2 + m_i^2} \cosh y \, dp_T \, dy \, d\phi$
- influence of strong resonance decays: H. Bebie et al., Nucl. Phys. B 378 (1992) 95
  - assumption: ground state excitations inherit the fluctuations of the decaying resonances
  - effective number of ground state excitation i
    $\overline{N}_i(T, \mu_i) = N_i(T, \mu_i) + \sum_r d_{r \rightarrow i} N_r(T, \mu_r)$
    is the sum of the actual number of i plus resonance decay contributions with $d_{r \rightarrow i}$ the average number of i produced from r (modulo efficiency corrections due to acceptance cuts)
- feed-down correction for weak decay contributions (experiment)

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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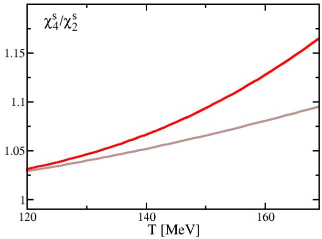

- HRG model result
- influence of resonance decays is sizeable

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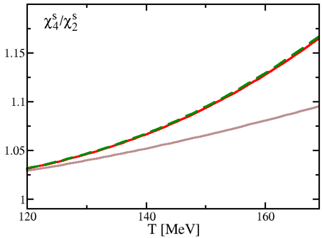

- HRG model result
- influence of resonance decays is sizeable
- exhibits negligible chemical potential dependence for small μ_X ($\mu_B = 20$ MeV, $\mu_S = 4$ MeV)

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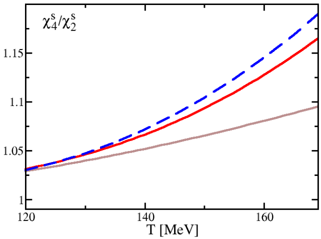

- HRG model result
- influence of resonance decays is sizeable
- acceptance cuts: $0.2 \leq p_T$ (GeV/c) ≤ 2.0, $|y| \leq 0.5$

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

- net-Kaon multiplicity distribution measures net-strangeness distribution in the (K^+, K^-) – subsystem
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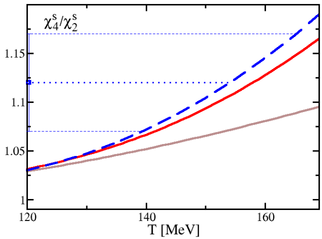


data from D. McDonald (for STAR), arXiv:1210.7023 [nucl-ex]

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

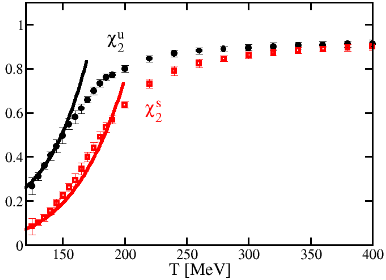
- HRG model result
- influence of resonance decays is sizeable
- acceptance cuts: $0.2 \leq p_T$ (GeV/c) ≤ 2.0, $|y| \leq 0.5$
- fluctuations in net-strangeness fixed at $T_{f.o.} \simeq 153$ MeV

Conclusions

- continuum-extrapolated lattice QCD results for suitably chosen combinations of susceptibilities of conserved charges show a clear separation in the behavior of different quark flavors in the crossover region
- might be an indication for a flavor hierarchy
- idea: look for evidences of a flavor hierarchy in higher moments of particle-identified multiplicity distributions
- proposed a possible experimental measurement and discussed how to deduce from it information about details in the transition region (in a model-dependent way)
  - highlighted importance of resonance decays and detector acceptance cuts for (K^+, K^-) subsystem

Backup-Slides

First indications for a flavor-separation

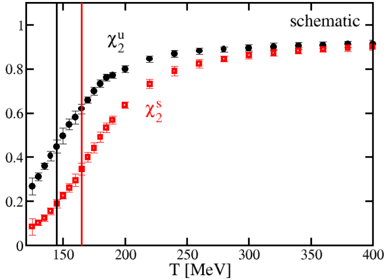


data taken from S. Borsányi et al., JHEP 1201 (2012) 138

diagonal quark number susceptibilities for up and strange quark flavors:

- fairly well described by a HRG model for lower *T*

First indications for a flavor-separation



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

- quantitatively similar observation from the combination of (B, Q, S)-susceptibilities from A. Bazavov et al., Phys. Rev. D 86 (2012) 034509

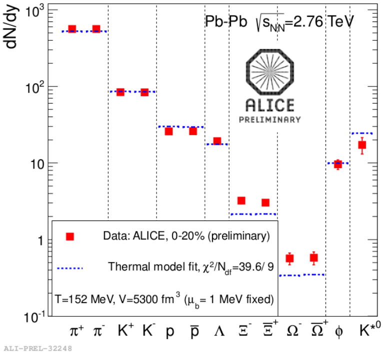
diagonal quark number susceptibilities for up and strange quark flavors:

- clear difference between light (up) and strange quarks: rapid change happens for strange quarks at a larger T than for light quarks (about $(15-20)$ MeV difference), i.e. fluctuations in strange quark number density cease at a larger T
- indication for a flavor hierarchy in the QCD crossover 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



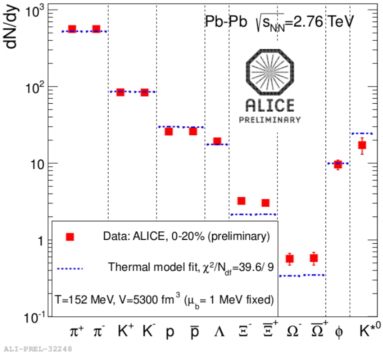
L. Milano (for ALICE), arXiv:1302.6624 [hep-ex] and QM2012

- 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)

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



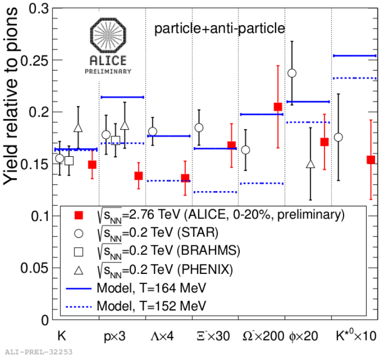
L. Milano (for ALICE), arXiv:1302.6624 [hep-ex] and QM2012

- 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

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 explanations for yield measurements

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

  P. Bozek and I. Wyskiel-Piekarska, Phys. Rev. C 85 (2012) 064915
- chemical non-equilibrium SHM

  M. Petrán et al., arXiv:1303.2098 [hep-ph]
- flavor hierarchy