Higher order fluctuations of strangeness and flavour hierarchy

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in collaboration with

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Outline

Strangeness in Heavy Ion Collisions (HIC)

- What information could we learn on Quark Gluon Plasma formation (QGP) and on properties of matter at hadronization

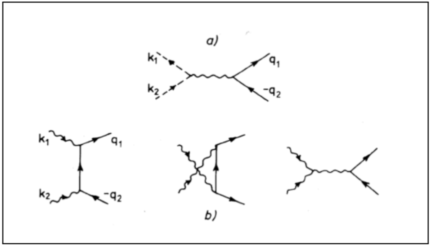
Chemical freeze-out and strangeness within a Hadron Resonance Gas model

- reproduce strange particle ratios at STAR → a higher T_{ch} is needed to reproduce the data?
- extract freeze-out parameters from the analysis of cumulants → sensitivity of fluctuations to freeze-out conditions and preliminary results of kaons at STAR
- link between LQCD and HRG
  - study of ratios of higher order cumulants for strange particles as experimental observables in HIC
  - flavour hierarchy in the chemical freeze-out process

- Conclusions & Outlook

Strangeness in HICs

- signal of QGP formation:
  $g + g \leftrightarrow s + \overline{s}$, $q + \overline{q} \leftrightarrow s + \overline{s}$
- $Q \approx 2m_s \approx 200$ MeV near T_c

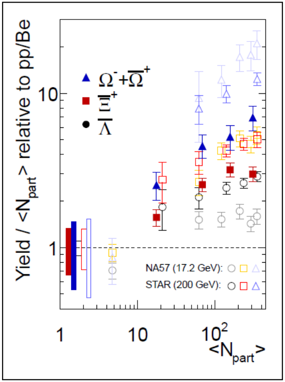


J.Rafelski and B.Müller Phys.Rev.Lett. 48 (1082) 1066

STRANGENESS IS EASY TO PRODUCE
ONCE A QGP STATE HAS BEEN FORMED

Strangeness in HICs

- experimental observation of an enhancement in $A-A$ collisions with respect to pp both at RHIC and LHC
- enhancement reduces with increasing collision energy



Abelev et al. Phys.Lett. B728 (2014) 216 – 227

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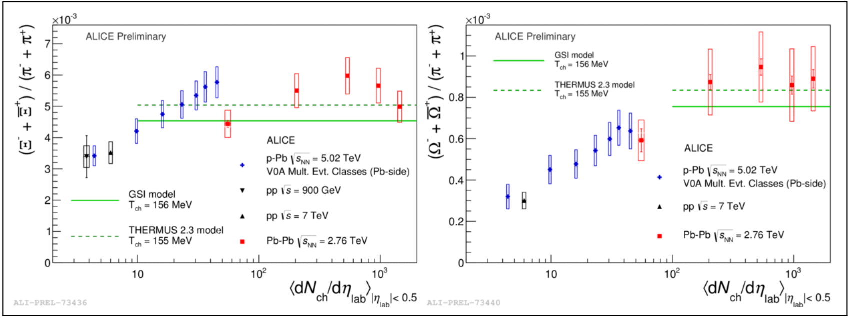
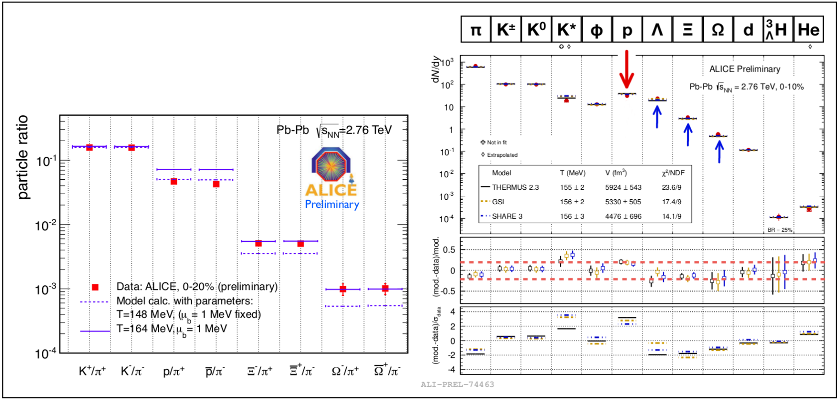


J.F. Grosse-Oetringhaus, Alice overview QM2014

Strangeness in HICs

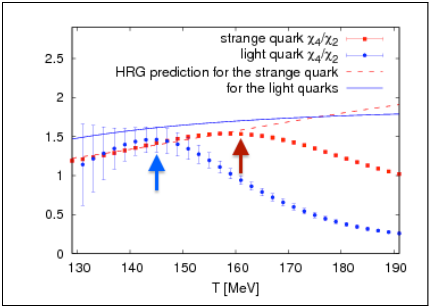
- fits to yields and ratios of strange particles indicate a higher temperature with respect to particles containing only light quarks



Preghenella Acta Phys.Pol. B (2012) 18 — 24, M.Floris, Quark Matter 2014

Strangeness in HICs

- indications of flavour hierarchy in the deconfinement transition from LQCD

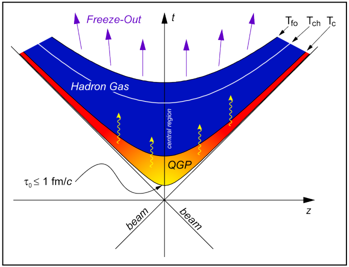


Bellwied, Ratti et al. Phys.Rev.Lett. 111 (2013) 202302

FLAVOUR HIERARCHY AT CHEMICAL FREEZE-OUT?

HIC evolution: chemical freeze-out

- inelastic scattering among particles ceases → particle yields and ratios are fixed → T_{ch} and $\mu_{B,ch}$



- description of hadronic matter at freeze-out obtained through a HRG model:
  - partial chemical equilibrium → feed-down from resonances up to 2 GeV
  - inclusion of acceptance and kinematics cuts for particle distribution

HIC evolution: chemical freeze-out

- inelastic scattering among particles cease $\rightarrow$ particle yields and ratios are fixed $\rightarrow$ T_{ch} and $\mu_{B,ch}$
- description of hadronic matter at freeze-out obtained through an HRG model:
  - partial chemical equilibrium $\rightarrow$ feed-down from resonances up to 2 GeV
  - inclusion of acceptance and kinematics cuts of particle distribution
- chemical freeze-out for strange particles (kaons and hyperons) might occur earlier with respect to pions and nucleons

HOW COULD WE EXTRACT THE FREEZE-OUT PARAMETERS FOR STRANGE PARTICLES?

Fluctuations of conserved charges

In a grand canonical ensemble approach the fluctuations for a specific conserved charge are defined as:

$$\chi_{lmn}^{BSQ} = \frac{\partial^{l+m+n} p/T^4}{\partial(\mu_B/T)^l \partial(\mu_S/T)^m \partial(\mu_Q/T)^n}.$$

They are related to the moments of multiplicity distributions available experimentally:

$$M = VT^3\chi_1, \quad \sigma^2 = VT^3\chi_2$$

$$S = \frac{VT^3\chi_3}{(VT^3\chi_2)^{3/2}}, \quad \kappa = \frac{VT^3\chi_4}{(VT^3\chi_2)^2}$$

and to volume-independent ratios:

$$S\sigma = \frac{\chi_3}{\chi_2}, \quad \kappa\sigma^2 = \frac{\chi_4}{\chi_2}$$

$$\frac{M}{\sigma^2} = \frac{\chi_1}{\chi_2}, \quad \frac{S\sigma^3}{M} = \frac{\chi_3}{\chi_1}$$

Fluctuations of conserved charges

The chemical potentials are not independent:

$$\rho_S = 0\,,\ \rho_Q = \frac{Z}{A}\rho_B \quad \frac{Z}{A} = 0.4$$

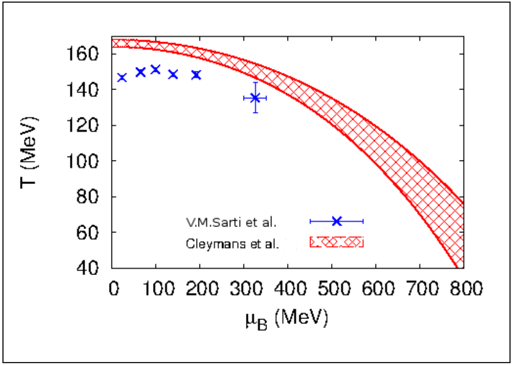
The comparison to experimental data of the ratios of moments for a specific charge, evaluated in the HRG model including:

- acceptance and kinematics cuts;
- feed-down from resonances

allows to extract temperature T_{ch} and baryochemical potential μ_B at freeze-out as function of the center of mass energy $\sqrt{s_{NN}}$

Freeze-out parametrization from net-proton and net-charge fluctuations at RHIC

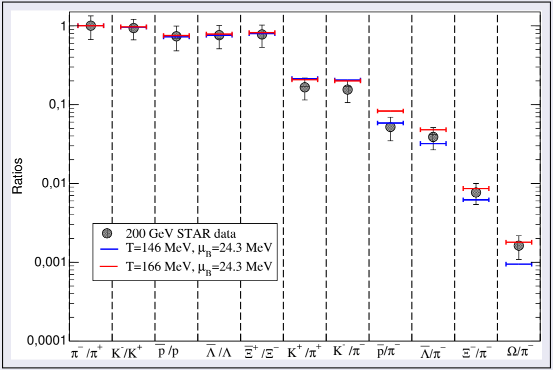
- Fit of χ_2/χ_1 for the net-electric charge and net-proton data at STAR
(for more details see P.Alba's talk and arXiv:1403.4903)



- at $\sqrt{s_{NN}} = 200$ GeV: $T = 146.8 \pm 1.2$ MeV, $\mu_B = 24.3 \pm 0.6$ MeV

Freeze-out parametrization from net-proton and net-charge fluctuations at RHIC

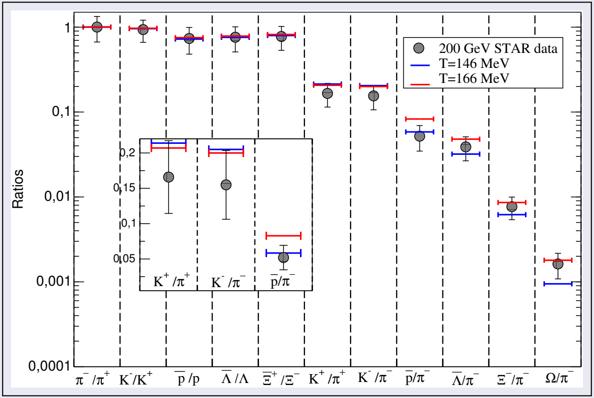
How well do we reproduce strange particle ratios with this parametrization?



Data from Andronic et al. NPA 904 – 905 (2013) 535*c*

Hyperon to pion ratios need a higher T_{ch} in order to reproduce data

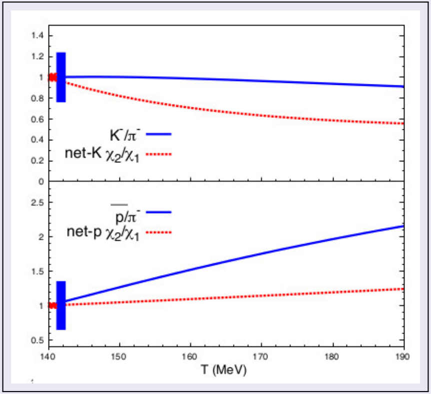
Focus on kaon and proton ratios: are they good thermometers?



- the kaon to pion ratios shows a less sensitive result to T_{ch} $\rightarrow$ we reproduce data within error bars both for $T_{ch} = 146$ and $T_{ch} = 166$ MeV
- the proton to pion ratio seems to have more sensitivity to T_{ch}

Freeze-out parametrization from net-proton and net-charge fluctuations at RHIC

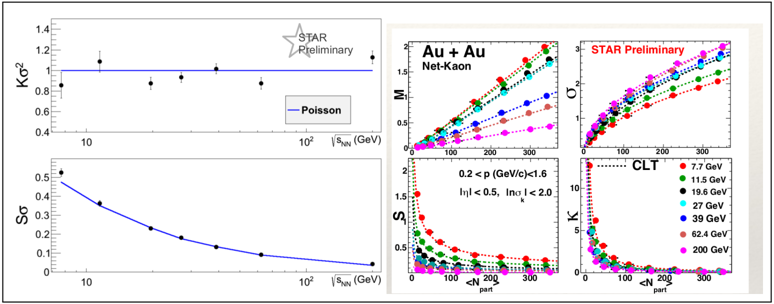
Sensitivity to temperature: fluctuations and ratios



lower moments for kaons ⇔ proton to pion ratio
smaller errors for fluctuations

Freeze-out parametrization from lower moments of net-kaons

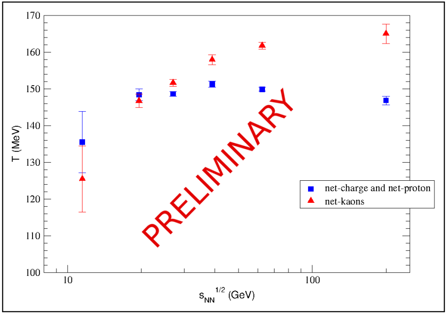
- the same analysis performed on protons and pions has been used with *NOT EFFICIENCY CORRECTED* data on net-kaons from the STAR collaboration
- at the moment the analysis has been done only on kaons, more data on hyperons are needed in order to obtain stronger constraints on the strange sector



D.McDonald, Quark Matter 2012 — A.Sarkar, Quark Matter 2014

Freeze-out parametrization from lower moments of net-kaons

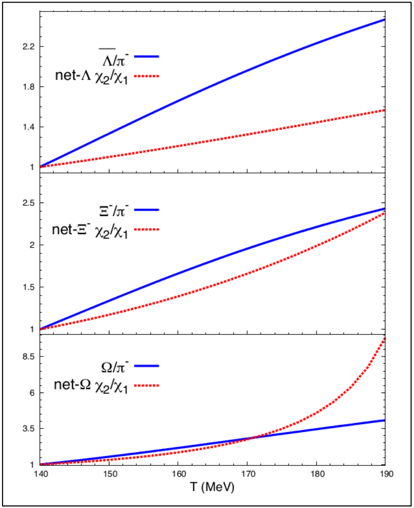
- fit of χ_2/χ_1 for net-kaons $\rightarrow$ μ_B fixed from net-proton (connected to $\sqrt{s_{NN}}$) $\rightarrow$ T_{ch}
- decoupling of T_{ch} at higher energies $\rightarrow$ $T_{ch}(200\ GeV) \approx$ 164 MeV



V.Mantovani Sarti et al. (preliminary)

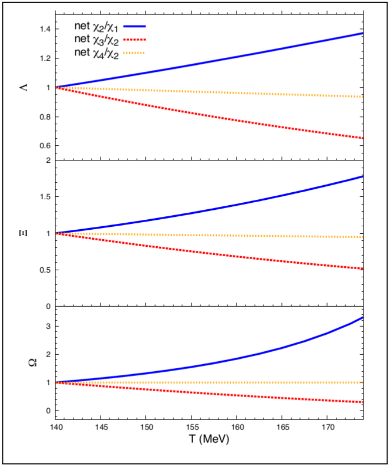
The analysis can be extended to hyperons:

- ratios of hyperons seems to be a useful tool to constrain the temperature → WHAT ABOUT HIGHER ORDER FLUCTUATIONS?
- experimental data are needed to compare the error bars of the two quantities



V.Mantovani Sarti et al. (to be published)

Sensitivity of fluctuations to freeze-out conditions in HICs

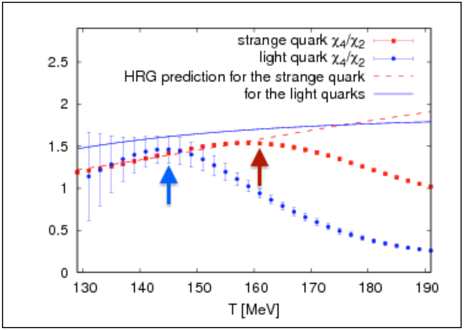


V.Mantovani Sarti et al. (to be published)

- LOWER MOMENTS→ most sensitive to the temperature, along with ratios could narrow the range of T_{ch} but at the moment there are no experimental data available
- HIGHER MOMENTS→ data from Lattice

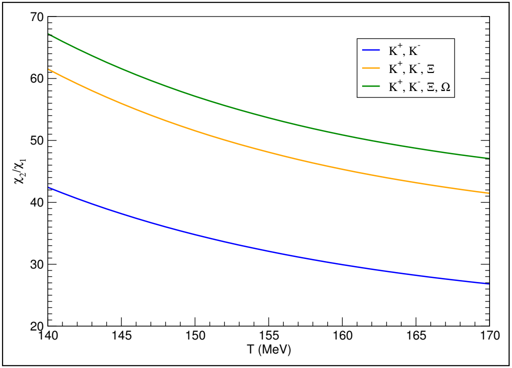
- Presently only uncorrected data for moments of the strangeness multiplicity have been published and it is not possible to evaluate χ_2/χ_1 on the lattice.
- in order to connect to LQCD, we need to go to higher moments of strangeness, such as χ_4/χ_2

- agreement with full HRG at low T, potential sensitivity to flavour hierarchy $\rightarrow$ THERMOMETER



Bellwied, Ratti et al. Phys.Rev.Lett. 111 (2013) 202302

- χ_2/χ_1 in HRG is very sensitive to T_{ch} for kaons alone
- addition of strange baryons changes the magnitude but not sensitivity



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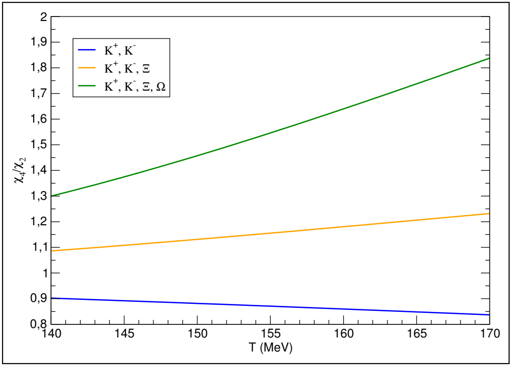
χ_2/χ_1 cannot be related to LQCD but EVEN ratios can

- χ_4/χ_2 requires a significant contribution from multi-strange baryons in order to be sensitive to T $\rightarrow$ the curve gets steeper as the content of strangeness increases
- inclusion of hyperons $\rightarrow$ major challenge for experiment!



V.Mantovani Sarti et al. (to be published)

Conclusions

- the study of strangeness production could provide information and insights on properties of QGP and of hadronic matter at freeze-out
- fluctuations of conserved charges at HICs prove to be a useful tool to determine T and μ_B at freeze-out $\rightarrow$ freeze-out parametrization from net-proton and net-charge fluctuations with $T_{ch} = 146.8 \pm 1.2$ MeV and $\mu_B = 24.3 \pm 0.6$ MeV at 200 GeV
- the analysis of particle ratios at STAR for these FO conditions shows hints of a higher temperature for strange particles with respect to protons and pions
- preliminary results on lower moments of uncorrected data for kaons at STAR shows a stronger sensitivity to the temperature and indicate a $T_{ch} \approx 164$ at 200 GeV $\rightarrow$ flavour hierarchy at chemical freeze-out?
- in order to connect to LQCD calculations, a study on higher moments, such as χ_4/χ_2, for combinations of strange particles is in progress, experimental data are needed as soon as possible.

Outlook

THe FAIR program will cover a lower range of energy:

- extend this analysis to low values of $\sqrt{s_{NN}}$ to check if the decoupling of T_{ch} for strange and non-strange particles occurs
- search for critical behaviour in higher-order fluctuations $\rightarrow$ critical point
- coupling of HRG model to a model for the deconfined phase in order to evaluate physical quantities (such as K^+/π^+) sensitive to the deconfinement process