Higher order fluctuations of strangeness and flavour hierarchy

Valentina Mantovani Sarti\textsuperscript{1}, in collaboration with
P.Alba\textsuperscript{1}, W.Alberico\textsuperscript{1}, R.Bellwied\textsuperscript{2}, M.Bluhm\textsuperscript{3}, M.Nahrgang\textsuperscript{4,5}, C.Ratti\textsuperscript{1}

\textsuperscript{1} University of Torino and INFN Torino, \textsuperscript{2} University of Houston, \textsuperscript{3} North Carolina State University, \textsuperscript{4} Duke University, \textsuperscript{5} FIAS

III International Symposium on Non-equilibrium Dynamics & IV TURIC Network Workshop
Crete 9-14 June 2014
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 → 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
Strangeness in HICs

- signal of QGP formation:
  \[ g + g \leftrightarrow s + \bar{s}, \quad q + \bar{q} \leftrightarrow s + \bar{s} \]
- \[ Q \approx 2m_s \approx 200 \text{ MeV} \text{ near } T_c \]

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

Strangeness in HICs

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

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.
Strangeness in HICs

- indications of flavour hierarchy in the deconfinement transition from LQCD


FLAVOUR HIERARCHY AT CHEMICAL FREEZE-OUT?
HIC evolution: chemical freeze-out

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

- description of hadronic matter at freeze-out obtained through a HRG model:
  - partial chemical equilibrium $\rightarrow$ 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 → particle yields and ratios are fixed → $T_{ch}$ and $\mu_{B,ch}$
- description of hadronic matter at freeze-out obtained through an HRG model:
  - partial chemical equilibrium → 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:

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

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:

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

\[
\frac{M}{\sigma^2} = \frac{\chi_1}{\chi_2}, \quad \frac{S\sigma^3}{M} = \frac{\chi_3}{\chi_1}
\]
The chemical potentials are not independent:

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

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 \( \mu_B \) 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 $\chi_2/\chi_1$ for the net-electric charge and net-proton data at STAR
  (for more details see P.Alba’s talk and arXiv:1403.4903)
How well do we reproduce strange particle ratios with this parametrization?

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 show a less sensitive result to $T_{ch} \rightarrow$ we reproduce data within error bars both for $T_{ch} = 148$ 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

\[ \frac{K^+}{\pi^+} \quad \frac{K^-}{\pi^-} \quad \chi_2/\chi_1 \text{ for net kaons} \]

\[ \frac{p}{\pi^+} \quad \frac{\bar{p}}{\pi^-} \quad \chi_2/\chi_1 \text{ for net protons} \]

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

lower moments for kaons ⇔ proton to pion ratio
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 $\chi_2/\chi_1$ for net-kaons $\rightarrow \mu_B$ fixed from net-proton (connected to $\sqrt{s_{NN}}$) $\rightarrow T_{ch}$
- Decoupling of $T_{ch}$ at higher energies $\rightarrow T_{ch}(200 \text{ GeV}) \approx 164 \text{ MeV}$
Presently only uncorrected data for moments of the strangeness multiplicity have been published and it is not possible to evaluate $\chi_2/\chi_1$ on the lattice.

In order to connect to LQCD, we need to go to higher moments of strangeness, such as $\chi_4/\chi_2$.

Agreement with full HRG at low $T$, potential sensitivity to flavour hierarchy → THERMOMETER

Chemical freeze-out from first principles: higher moments of strangeness and LQCD

- $\chi_2/\chi_1$ in HRG is very sensitive to $T_{ch}$ for kaons alone
- Addition of strange baryons changes the magnitude but not sensitivity

$\chi_2/\chi_1$ cannot be related to LQCD but EVEN ratios can
\( \chi_4/\chi_2 \) 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!
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 $\mu_B$ at freeze-out → 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 → flavour hierarchy at chemical freeze-out?

- in order to connect to LQCD calculations, a study on higher moments, such as $\chi_4/\chi_2$, for combinations of strange particles is in progress, experimental data are needed as soon as possible.