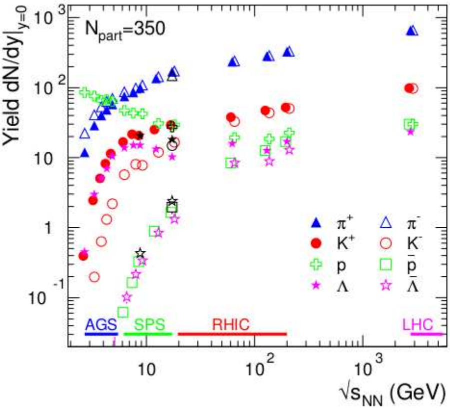
Discriminating thermal model approaches in a baryonic fireball

Sandeep Chatterjee
AGH-UST, Krakow

Phase diagram of strongly interacting matter-
From LQCD to HICs,
ECT*, Trento, 27 Nov. - 1 Dec., 2017

Hadron yields: Probes of the freezeout surface

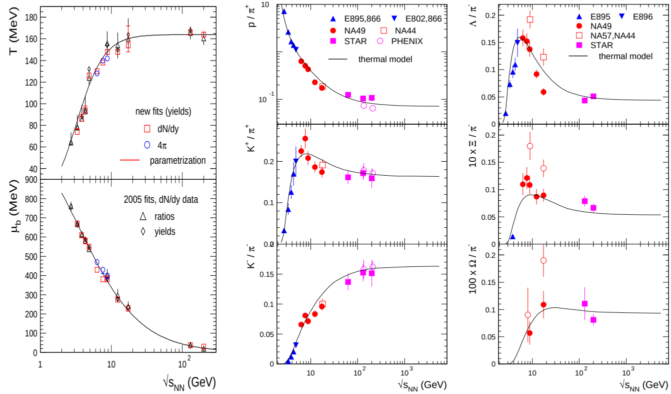


Andronic, 1407.5003

the single freezeout thermal model claim is:

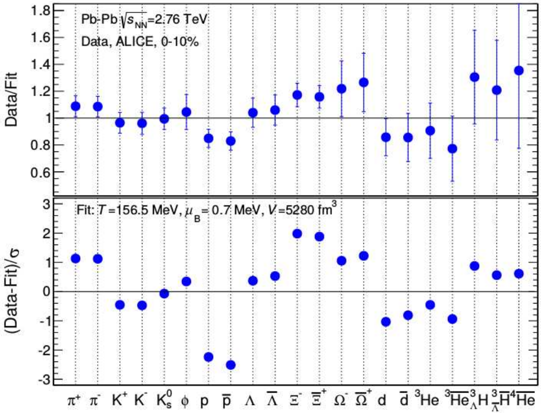
- The hadronic fireball is in complete thermal and chemical equilibrium at the time of chemical freezeout (CFO) when the hadron yields are frozen
- We have a Grand Canonical Ensemble for the hadronic fireball labelled by
  - temperature T,
  - hadron chemical potentials μ_h. Under complete chemical equilibrium, all possible forward and backward hadronic reactions rates are equal. Then all hadron chemical potentials can be expressed only in terms of three chemical potentials $\mu_{B,Q,S}$
    $$\mu_h = B_h\mu_B + Q_h\mu_Q + S_h\mu_S$$
  - To be fitted from experiments: T, μ_B, V (μ_Q and μ_S from constraints).
- thus yields that vary over several orders of magnitude and across several orders of $\sqrt{s_{\mathrm{NN}}}$ can be understood within an equilibrium thermal model framework i.e. can be parametrised by 2 parameters T and μ_B (if hadron ratios) / 3 parameters T, μ_B and V (if hadron yields)

Single freezeout results



Andronic, Munzinger, Stachel 2009

Pending issues



Andronic, Munzinger, Redlich, Stachel 2016

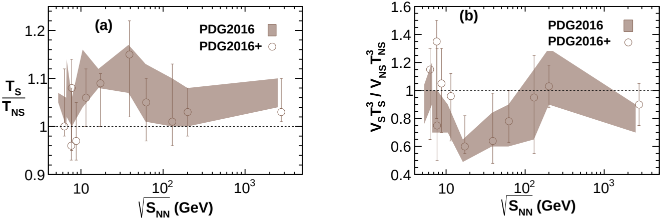
suggested variants to complete equilibrium single freezeout scenario

- deviation from complete equilibrium, introduce additional fugacity factors for light and strange flavors Petran et al 2013
- deviation from single towards multiple freezeout scenarios: simplest application- separate freezeout for non-strange and strange hadrons
  Bellwied et al, SC et al, Bugaev et al 2013; Rincon et al 2014

2CFO scheme

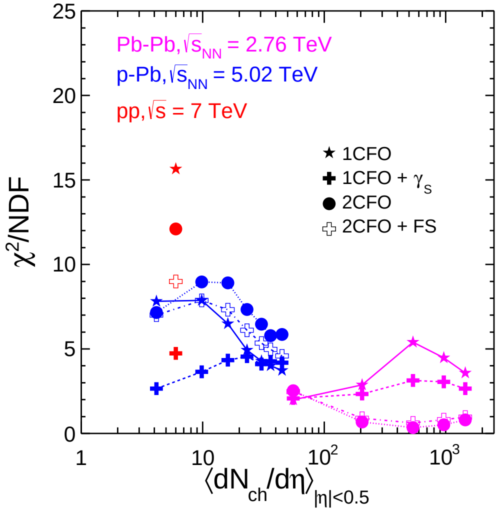
- Kaon to pion ratio $\sim e^{-\Delta m/T}$ rapidly falls as the system cools. Hence strangeness changing reactions freezeout earlier due to the depletion of the kaon bath
- Motivates to propose separate CFO for (strange+hidden strangeness) and non strange hadrons: 2CFO
- T_s, V_s, μ_{B_s} characterise the strange surface
- T_{ns}, V_{ns}, $\mu_{B_{ns}}$ characterise the non-strange surface

Flavor hierarchy: survives missing resonances contribution; peaks at $\sqrt{s_{\mathrm{NN}}} \sim 10 - 100$ GeV



SC, Mishra, Mohanty, Samanta 2017

1CFO - 2CFO: System size dependence



SC, Dash, Mohanty 2016

Ratios

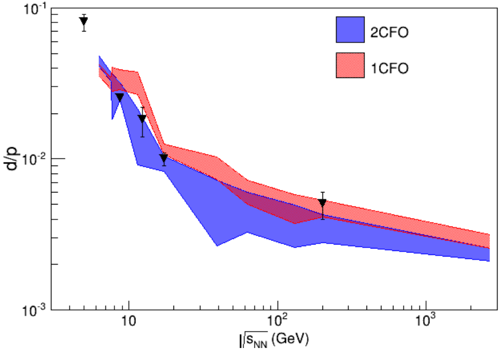
- Unlike Flavor Ratio (R^{UF}):

$$R^{\mathrm{UF}}_{\mathrm{2CFO}} \sim \left(\frac{T_s}{T_{ns}}\right)^{3/2} \left(\frac{V_s}{V_{ns}}\right) R^{\mathrm{UF}}_{\mathrm{1CFO}}$$

- Like Flavor Ratio (R^{LF}):

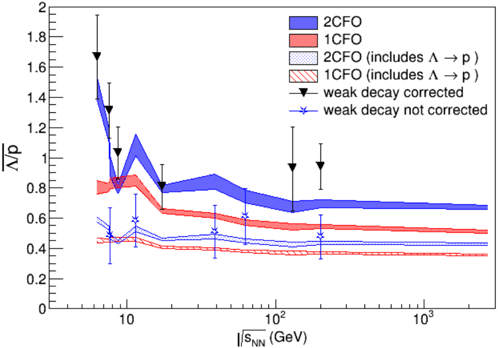
$$R^{\mathrm{LF}}_{\mathrm{2CFO}} \sim R^{\mathrm{LF}}_{\mathrm{1CFO}}$$

Like Flavor Ratio



SC, Mohanty 2014

Unlike Flavor Ratio



SC, Mohanty 2014

Nuclei

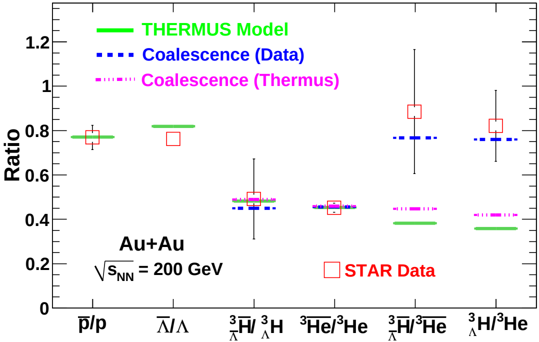
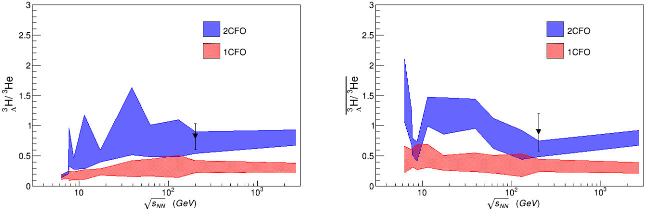


fig. from 1105.3719 Cleymans et al (similar concl. by Andronic et al 2011, Pal et al 2013)

Nuclei



SC, Mohanty 2014

1CFO vs 2CFO

- How to interpret the improvement of χ^2/N_{df} in 2CFO over 1CFO ?
- Is it really physics beyond 1CFO or interplay of parameters and χ^2 ?
- The issue lies in the fact that the particle ratios / yields are not parameter independent predictions of thermal models.
- Ask: Can we construct parameter independent predictions of the 1CFO thermal model ? If yes, that could be tested without the confusion of number of parameters vs χ^2 debate.

Parameter free prediction

- Primary yield

$$N_i^p = \left(\frac{V_i T_i g_i m_i^2}{\pi^2}\right) \sum_{l=1}^{\infty} \frac{(-a)^{l+1}}{l}\; K_2\left(\frac{l m_i}{T_i}\right) \mathrm{e}^{l(B_i \mu_{B_i} + Q_i \mu_{Q_i} + S_i \mu_{S_i})/T}$$

- Boltzmann approximation $m_i/T >> 1$ good for all except pions

$$N_i^p = \left(\frac{V_i T_i g_i m_i^2}{\pi^2}\right) K_2\left(\frac{m_i}{T_i}\right) \mathrm{e}^{(B_i \mu_{B_i} + Q_i \mu_{Q_i} + S_i \mu_{S_i})/T_i}$$

- Particle to anti-particle ratio

$$\left(N_i^{\mathrm{p}}/\overline{N_i^{\mathrm{p}}}\right) = R_i^{\mathrm{p}}\left(\hat{\mu}_{iB}, \hat{\mu}_{iQ}, \hat{\mu}_{iS}\right) = \exp\left(2\left(B_i \hat{\mu}_{iB} + Q_i \hat{\mu}_{iQ} + S_i \hat{\mu}_{iS}\right)\right)$$

- In 1CFO, only 3 independent fugacity factors corresponding to the 3 conserved charges. Hence, only 3 independent particle to anti-particle ratios. The rest are constrained.

Parameter free prediction

- We focus on the following class of parameter-free conditions

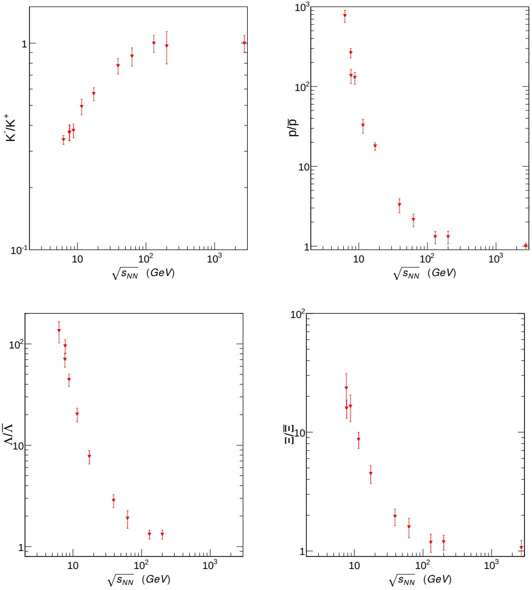
$$\mathcal{R}^{\mathrm{p}}_{\Lambda p K} = \frac{R^{\mathrm{p}}_{\Lambda}}{R^{\mathrm{p}}_{p} R^{\mathrm{p}}_{K}} \quad = \quad 1$$

$$\mathcal{R}^{\mathrm{p}}_{\Xi \Lambda K} = \frac{R^{\mathrm{p}}_{\Xi}}{R^{\mathrm{p}}_{\Lambda} R^{\mathrm{p}}_{K}} \quad = \quad 1$$

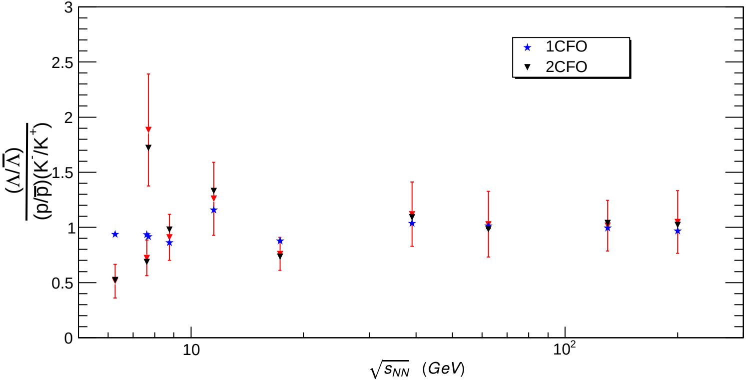
  ...... all such ratios where the quantum numbers add up to zero.

- Secondary feeddown contribution can spoil this. Feeddown can be systematically included in thermal models. Typically, their influence $< 20\%$. Hence deviations of more than 20% in data is interesting.

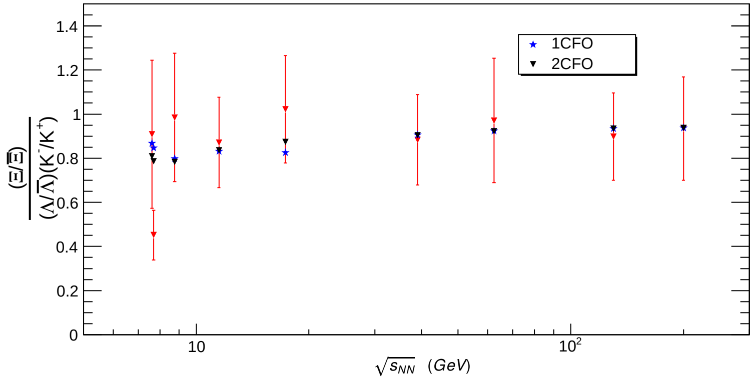
Data: Single ratios



Data - 1CFO - 2CFO: Triple ratios



Data - 1CFO - 2CFO: Triple ratios



Summarising

- The goodness of description of hadron yields in thermal models is usually based on minimization of a chisquare that measures the difference between model predictions and data of individual hadrons. Such a statistical analysis although provides a qualitative picture, it is often not possible to draw any firm conclusion on the thermal nature of the source.
- We find constraints that allow us to make robust statements on the nature of freezeout. These correlations between the multiplicities of several hadrons which are apparently being produced independently from a thermal source arise due to the conserved charges of QCD and present in a grand canonical ensemble. They provide stringent tests for the idea of a single thermal source of all the observed hadrons.

Summarising

- Hints of strong deviation in data in the baryon dominated fireball. Currently, error bars calculated by adding stat. and sys. errors in quadratures. It is desirable that the triple ratio itself is measured in experiments to take into account correlated systematic errors in particle - anti particle pairs. Presently, yields of strange baryons are not available for $\sqrt{s_{\mathrm{NN}}} < 6.27$ GeV. With the availabilty of data from FAIR / NICA, the situation will get cleaner.
- Including attractive and repulsive Van der Waals type interactions modify the fugacity factors and hence expected to modify the constraints within 1CFO itself. Thus, these triple ratio observables could also be used to constrain such interacting HRG models