Flavor hierarchy in freezeout

Sandeep Chatterjee (sandeepc@vecc.gov.in)
VECC, Kolkata, India

Strangeness in Quark Matter, Dubna, Russia
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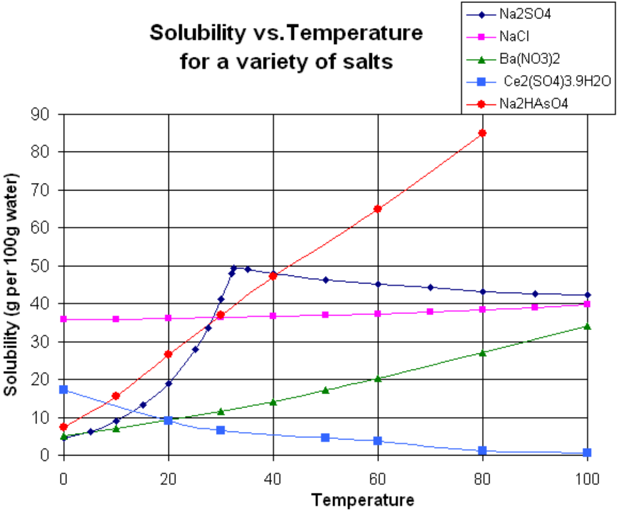
Multiple Freezeout on your table top: Salt mixture in water



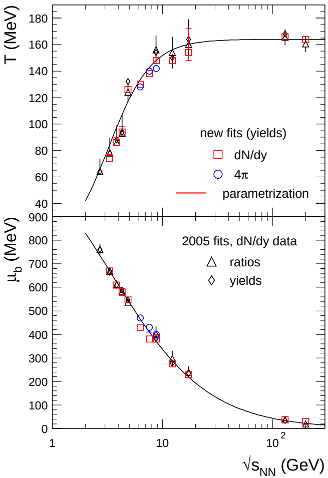
Freezeout in HIC

- Freezeout is a result of competition between 2 effects: constituent interactions and fireball expansion- Cross section vs Dilution
- In the late stage of a heavy ion collision (HIC), the rate of collisions between the constituents can no longer cope with the expansion rate. As a result, hadrons start freezing out.
- Simple assumption: All strong interaction rates are same. Hence single chemical freezeout (1CFO).

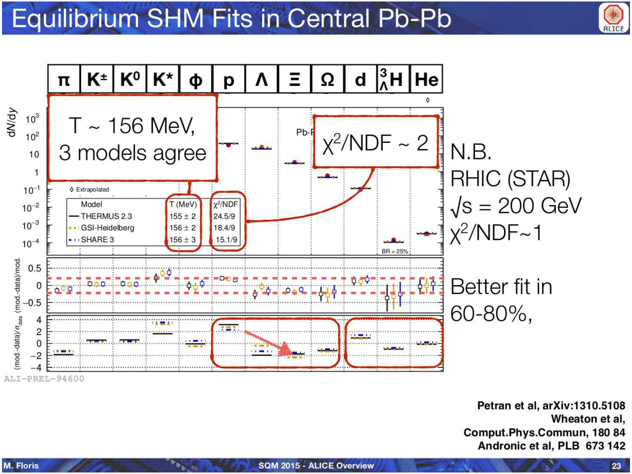
Single Chemical Freezeout: 1CFO

Standard practice:
All the hadrons CFO at the same (T, μ_B) surface.
This provides an overall good qualitative picture of CFO at $\sqrt{s_{\rm NN}} \sim 2 - 200$ GeV with ~ 4 params.

Andronic et al: 0812. 1186



1CFO at LHC

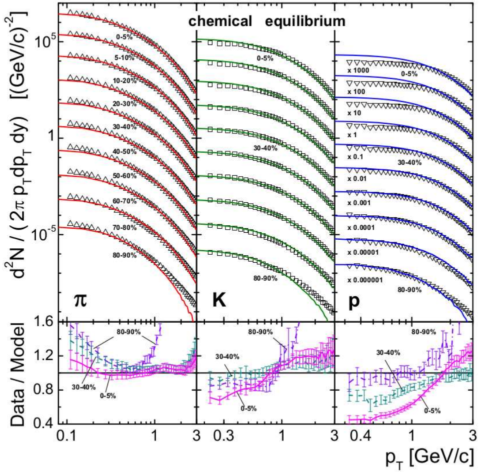


N.B.
RHIC (STAR)
$\sqrt{s}$ = 200 GeV
χ^2/NDF~1

Better fit in
60-80%,

Floris: SQM 2015

1CFO at LHC



Begun et al: 1405.7252

Revisitng our 1CFO assumption: When does chemistry freeze out?

Basic observables are the spectra of identified particles; from this one gets yields. Relative yields of hadrons is the outcome of "chemistry".

At early times, fireball is a reactive fluid. Reaction rates depend on local densities as well as rates of mixing.

When does isospin freeze out?

- The rates for processes $p + \pi^- \leftrightarrow n + \pi^0$, remain high at $\simeq 150$ MeV, because $m_n - m_p$ is small and the yield of pions is large. So the chemical freezeout of baryon isospin can be delayed. The $p \leftrightarrow n$ reaction may proceed without suppression right up to kinetic freezeout
  Asakawa, Kitazawa, 2011

Can the K and π freeze separately?

- Indirect transmutations of K and π involve strange baryons in reactions such as $\Omega^- + K^+ \leftrightarrow \Xi^0 + \pi^0$. These have very high activation thresholds. There is no physics forcing K and π to freezeout together. But K and ϕ are resonantly coupled, so freeze out together.
  SC, Godbole, Gupta, 2013

Double Chemical Freezeout: 2CFO

- 'Isospin changing' reactions are last to freezeout ($p + \pi^0 \leftrightarrow n + \pi^+$) (Asakawa, Kitazawa 2011)
  - low activation energy
  - high pion density
- 'Strangeness changing' reactions can freezeout earlier ($\Omega^- + K^+ \leftrightarrow \Xi^0 + \pi^0$)(SC, Godbole, Gupta, 2013)
  - High activation energy
  - Ω and K densities much less compared to that of π; $\Omega^- + K^+$ reactions much suppressed
- 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
- Using conservation of baryon number and entropy, 4 parameter fit is sufficient (Bugaev et al, 2013)

Hadron Yields in Thermal Model

- The ideal hadron resonance gas (HRG) partition function Z in the grand canonical ensemble at the time of CFO at a particular beam energy $\sqrt{s_{\mathrm{NN}}}$ is given as

$$\log\left[Z\left(\sqrt{s_{\mathrm{NN}}}\right)\right] = \sum_i \log\left[Z_i\left(T_i\left(\sqrt{s_{\mathrm{NN}}}\right), \mu_i\left(\sqrt{s_{\mathrm{NN}}}\right), V_i\left(\sqrt{s_{\mathrm{NN}}}\right)\right)\right]$$

-

$$\begin{aligned} N_i^{\mathrm{p}} &= \frac{\partial}{\partial\left(\frac{\mu_i}{T_i}\right)} \log\left[Z\right] \\ &= \frac{V_i T_i}{\pi^2} g_i m_i^2 \sum_{l=1}^{\infty} (-a)^{l+1} l^{-1} K_2\left(l m_i / T_i\right) \times \\ &\quad \exp\left(l\left(B_i \mu_{B\,i} + Q_i \mu_{Q\,i} + S_i \mu_{S\,i}\right) / T_i\right) \end{aligned}$$

Ratios

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

$$\begin{aligned}\left(N_s^{\mathrm{t}}/N_{ns}^{\mathrm{t}}\right)^{\mathrm{th}} &= \exp\left(S\mu_S/T_s\right)\frac{g_s V_s}{g_{ns} V_{ns}}\left(\frac{T_s m_s}{T_{ns} m_{ns}}\right)^{3/2} \times \\ &\exp\left(m_{ns}/T_{ns} - m_s/T_s\right) \times \\ &\exp\left(\mu_{B\,s}/T_s - \mu_{B\,ns}/T_{ns}\right)\end{aligned}$$

- Hence,

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

Ratios

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

$$N_i^t / N_j^t = \left(\frac{g_i}{g_j}\right)\left(\frac{m_i}{m_j}\right)^{3/2} \times \exp\left(\left(\left(m_j - m_i\right) + \left(B_i - B_j\right)\mu_B\right)/T\right)$$

- Hence,

$$R_{\mathrm{2CFO}}^{\mathrm{LF}} \sim R_{\mathrm{1CFO}}^{\mathrm{LF}}$$

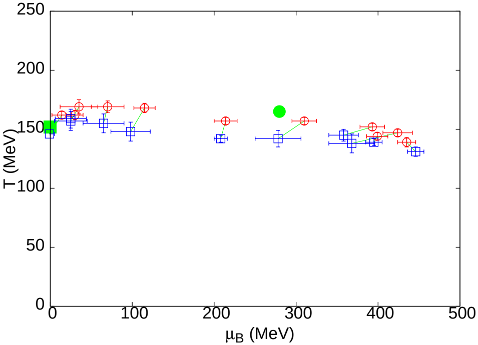
- Anti-particle to particle ratios simplifies even further.

$$\left(\overline{N_i^t}/N_i^t\right)^{\mathrm{th}} = \exp\left(-2\left(B_i {\mu_B}_i + Q_i {\mu_Q}_i + S_i {\mu_S}_i\right)/T\right)$$

- Hence,

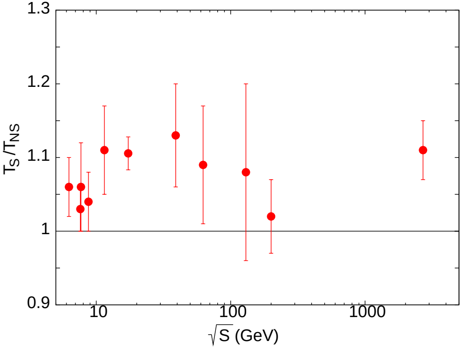
$$R_{\mathrm{2CFO}}^{\mathrm{AP/P}} \sim R_{\mathrm{1CFO}}^{\mathrm{AP/P}}$$

2CFO Freezeout Parameters



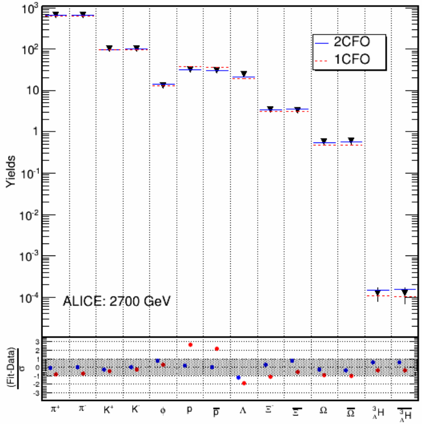
SC, Godbole, Gupta: 1306.2006

2CFO Freezeout Parameters



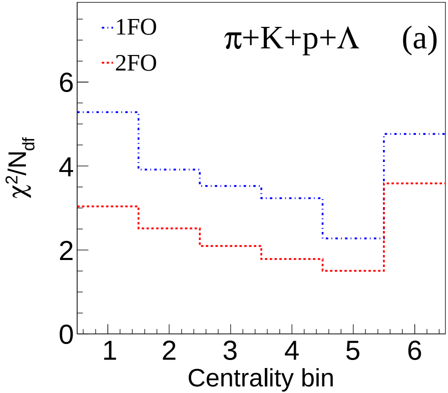
SC, Godbole, Gupta: 1306.2006

2CFO at LHC: yields



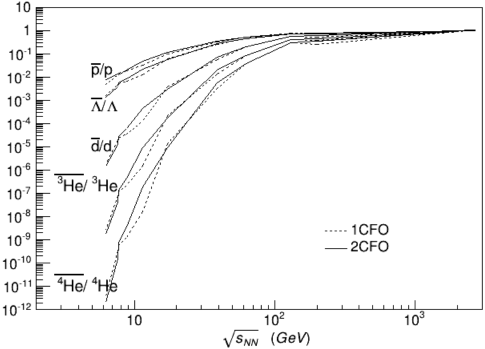
SC, Mohanty: 1405.2632

2CFO at LHC: spectra



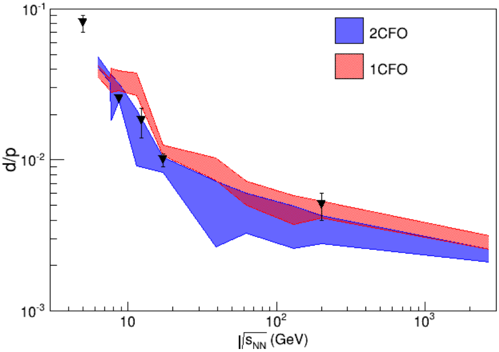
SC, Mohanty, Singh: 1411.1718

Antiparticle to Particle Ratio



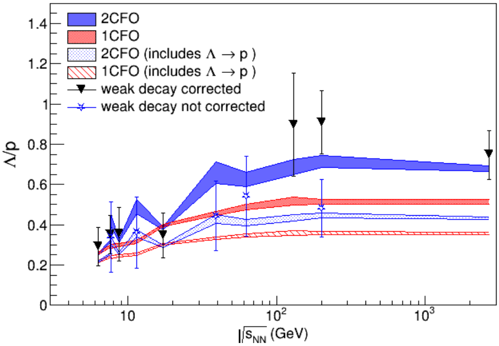
SC, Mohanty: 1405.2632

Like Flavor Ratio



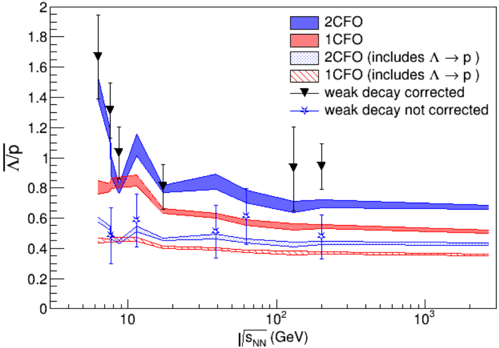
SC, Mohanty: 1405.2632

Unlike Flavor Ratio



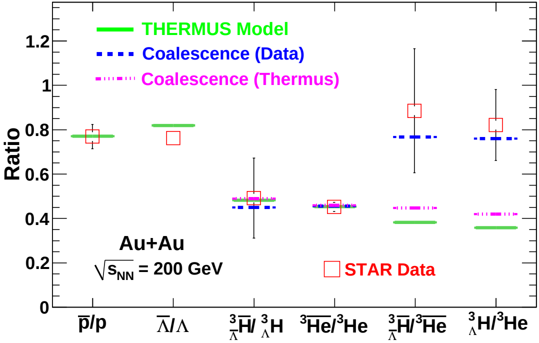
SC, Mohanty: 1405.2632

Unlike Flavor Ratio



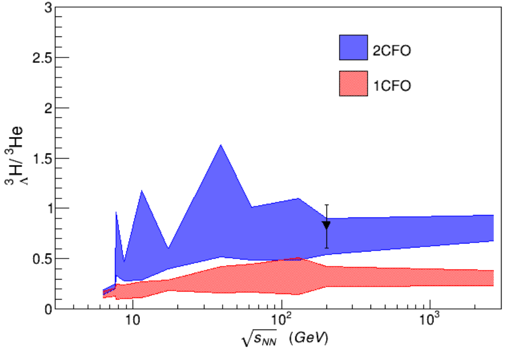
SC, Mohanty: 1405.2632

Unlike Flavor Ratio: Nuclei



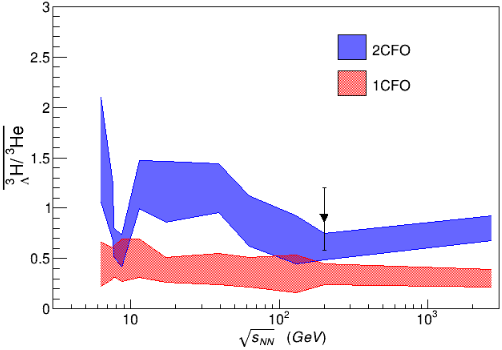
Andronic et al 2011, Cleymans et al 2011, Pal et al 2013

Unlike Flavor Ratio



SC, Mohanty: 1405.2632

Unlike Flavor Ratio



SC, Mohanty: 1405.2632

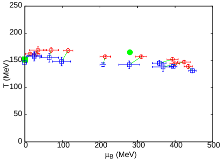
Other schemes

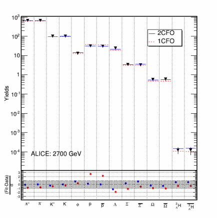
- Flavor dependence in hadronization- Bellwied et al, 2013; Torres-Rincon et al, 2015
- Post 1CFO employ hadronic afterburner: Microscopic Transport Approach (UrQMD Model). Baryon-antibaryon annihilation main source of correction- Steinheimer et al, 2013
- Introduce additional light and strange chemical non-equilibrium fugacity factors- Petran et al, 2013
- Incomplete hadron spectrum- Bazavov et al, 2014

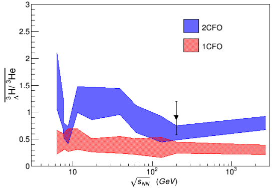
Summarising..

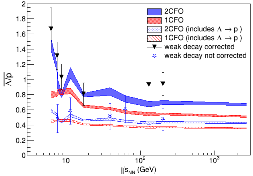
- Multiple freezeout is a common occurence in nature: from a cooling salt mixture in water to the cooling early universe. A multi-component system naturally freezes over a range in the relevant parameter space.
- Freezeout in the cooling fireball in HIC- Is the freezeout gradual enough to leave an imprint on the data ?
- 1CFO provides an overall good description of the hadrons(nuclei) yields across a wide range of $\sqrt{s_{\rm NN}}$
- Does closer/careful inspection of the data reveal details in freezeout ? Which observables are most sensitive?
- Strange to non strange hadron/nuclei ratios are most sensitive to flavor dynamics at freezeout
- Anomaly with data of Λ/p at LHC, ${}^3_\Lambda\mathrm{H}/{}^3\mathrm{He}$ at top RHIC have a common origin: flavor dynamics at freezeout
- Influence of additional resonances ?- they will affect the above strange to non strange ratios. On including them, can the above anomalies with data be addressed within 1CFO ? Require input on their branching ratios. Data from the low $\sqrt{s_{\rm NN}}$ (where these heavy resonances do not play a role) FAIR, BES-II can throw more light

Take home


T (MeV)
μ_B (MeV)


Yields
2CFO
1CFO
ALICE: 2700 GeV
(Fit-Data)/σ


2CFO
1CFO
$^{3}_{\Lambda}H/^{3}He$
$\sqrt{s_{NN}}$ (GeV)


2CFO
1CFO
2CFO (includes $\Lambda \to p$)
1CFO (includes $\Lambda \to p$)
weak decay corrected
weak decay not corrected
$\overline{\Lambda}/\overline{p}$
$\sqrt{s_{NN}}$ (GeV)