On freezeout

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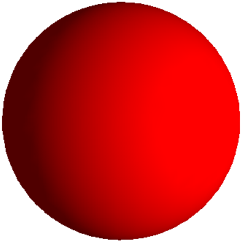
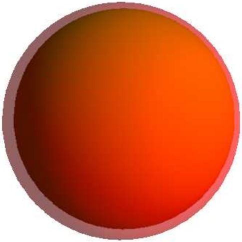
Outline

Standard model of heavy-ion collisions



All hadrons freeze out together: fireball is completely opaque until freeze out.

Standard model of heavy-ion collisions



All hadrons freeze out together: fireball is completely opaque until freeze out. Probably an over simplification.

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: requires coupling of hydrodynamics with diffusion and flavour chemistry. Reaction rates depend on local densities as well as rates of mixing. Mixing controlled by advection (stirring) and diffusion. Need to understand the relative importance of the two effects.

Cooper-Frye treatment of freezeout in hydrodynamics is over-simplified by necessity. Actual kinetic equations are more complicated. Need to understand model kinetic equations and average behaviour first; then thermal fluctuations.

A well-stirred fireball

If the fireball is constantly stirred then it is enough to examine chemical rate equations. A (not very) toy model is:

$$\begin{aligned}
\dot{p} &= -\gamma(p\pi^0 - n\pi^+) - \gamma'(p\pi^- - n\pi^0), \\
\dot{n} &= \gamma(p\pi^0 - n\pi^+) + \gamma'(p\pi^- - n\pi^0), \\
\dot{\pi}^0 &= -\gamma(p\pi^0 - n\pi^+) + \gamma'(p\pi^- - n\pi^0), \\
\dot{\pi}^+ &= \gamma(p\pi^0 - n\pi^+), \\
\dot{\pi}^- &= -\gamma'(p\pi^- - n\pi^0).
\end{aligned}$$

QCD determines only the rate constants γ and γ'. The equilibrium concentrations are given by

$$\frac{p}{n} = \frac{\pi^+}{\pi^0} = \frac{\pi^0}{\pi^-} \quad (= \zeta).$$

ζ is the isospin fugacity. Since $\pi^+/\pi^- = \zeta^2$, we know that $\zeta \simeq 1$ at RHIC. So $\mu_I = T \log \zeta \simeq 0$.

Shaken or stirred?

Flavour chemistry changes due to reactions controlled by densities and diffusion or mixing. Which is more important is controlled by Peclet's number

$$\mathrm{Pe} = \frac{Lv}{D} = \frac{Lv}{\xi c_s} = \left(\frac{L}{\xi}\right) M.$$

When $\mathrm{Pe} \ll 1$ diffusion dominates; when $\mathrm{Pe} \gg 1$ it is mixing.
Crossover regime when $\mathrm{Pe} \simeq 1$.
New length scale: defines when advection becomes comparable to diffusion—

$$L \simeq \frac{\xi}{M}.$$

Since longitudinal flow has $M \le \sqrt{3}$, for baryons, $L \simeq 0.3$ fm and for strange particles, $L \simeq 0.5$ fm. So over most of the history of the fireball chemistry is governed by diffusion, but initial advection may be important.

Bhalerao and SG, 2009

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When does isospin freeze out?

The rates for processes $p + \pi^- \leftrightarrow n + \pi^0$, remain high at $\simeq 100$ 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.

In the warm fireball, pion densities are $\rho_\pi \simeq (m_\pi T)^{3/2}$. The nucleon density is $\rho_N \simeq (m_N T)^{3/2} \exp(-m_N/T)$. The ratio is

$$\frac{\rho_N}{\rho_\pi} \simeq \left(\frac{m_N}{m_\pi}\right)^3 \exp\left(-\frac{m_N}{m_\pi}\right) \simeq 0.06$$

So the nucleons exist in a isospin bath of pions.

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.

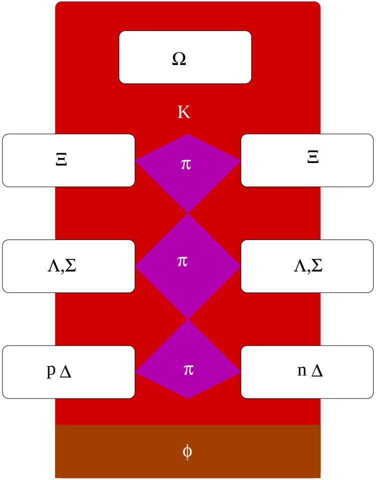
Direct transmutations can proceed through the strong interactions such as $K^+ + K^- \leftrightarrow \pi^+ + \pi^-$. These are OZI violating reactions; slower than generic strong-interaction cross sections.

Direct transmutations through weak interactions are not of relevance in the context of heavy-ion collisions.

There is no physics forcing K and π to freezeout together. But K and ϕ are resonantly coupled, so freeze out together.

Chatterjee, Godbole, SG, 2013

Keeping in touch



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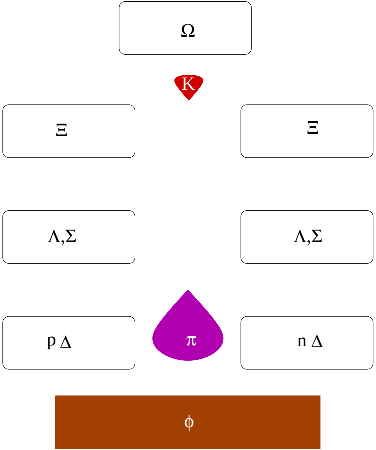
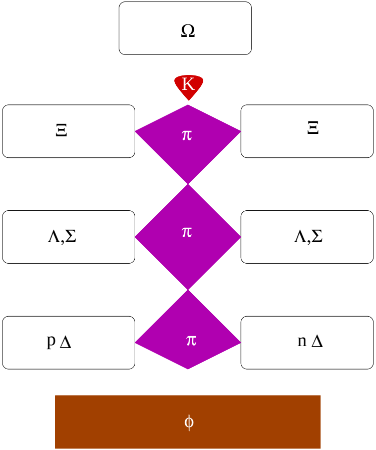


T, μ, V, γ_S

Keeping in touch



$$T_S,\ \mu_S,\ V_S,\ T_{NS},\ \mu_{NS},\ V_{NS}$$

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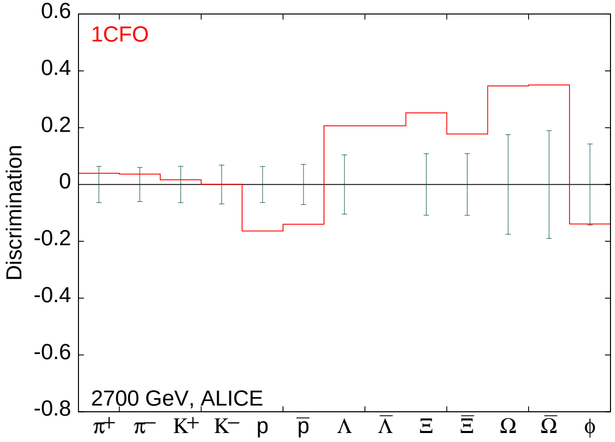
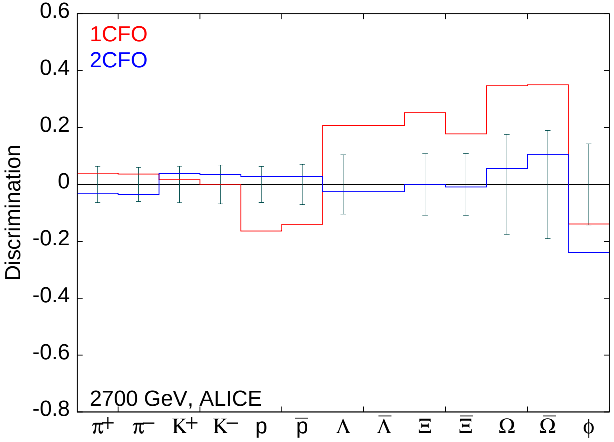
LHC lowest energy



Large non-thermal fluctuations? **Bleicher et al, Becattini et al**

LHC lowest energy



Large non-thermal fluctuations? **Bleicher et al, Becattini et al**

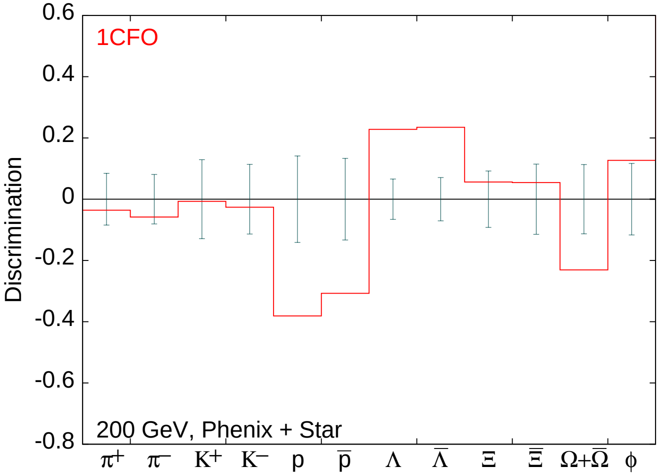
Or normal late-stage kinetics?

RHIC highest energy data corpus

STAR	2004		0–5%	ϕ
	2005	10^6	0–5%	Λ, $\overline{\Lambda}$, Ξ^+, Ξ^-, $\Omega+\overline{\Omega}$
	2009	2×10^6	0–5%	$\pi^\pm$, $K^\pm$, p, $\overline{p}$
PHENIX	2004	2×10^7	0–5%	$\pi^\pm$, $K^\pm$, p, $\overline{p}$
	2005	2×10^7	0–10%	ϕ
BRAHMS	2005		0–10%	$\pi^\pm$, $K^\pm$, p, $\overline{p}$

PHENIX 2004 corrects for feed down. Cross checked that the fit STAR 2004, 2005 + PHENIX 2004 nearly agrees with all-STAR data; small tension. BRAHMS data notionally in tension with STAR, but probably because of different centrality binning.

RHIC highest energy results



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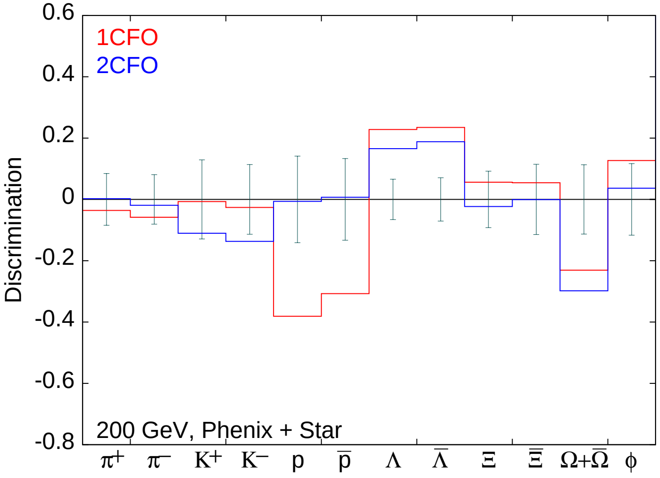

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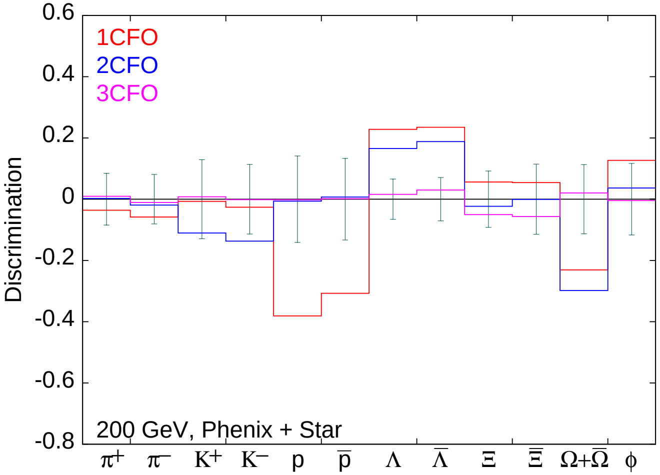
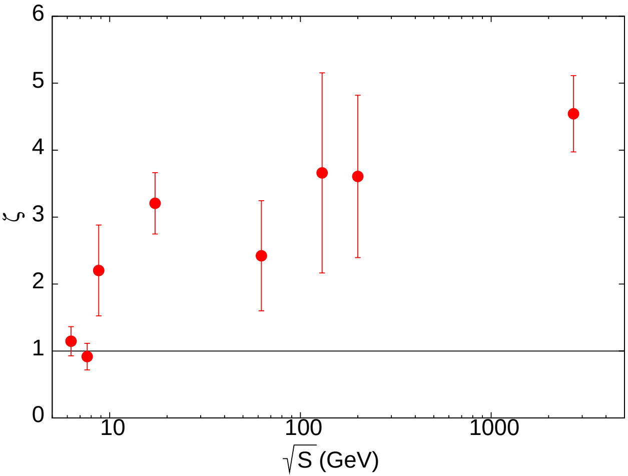
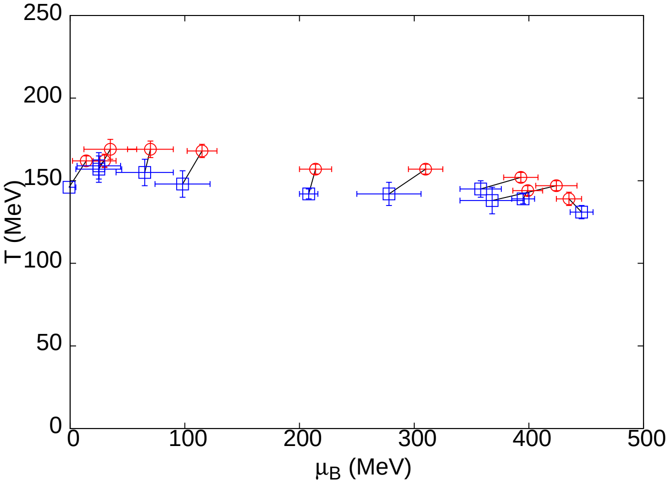


Are the volumes sensible?



Comparison of V_{NS} and pion correlation volume deduced from HBT radii. Increase due to collective flow. **Pratt, Lisa**

The freezeout curves



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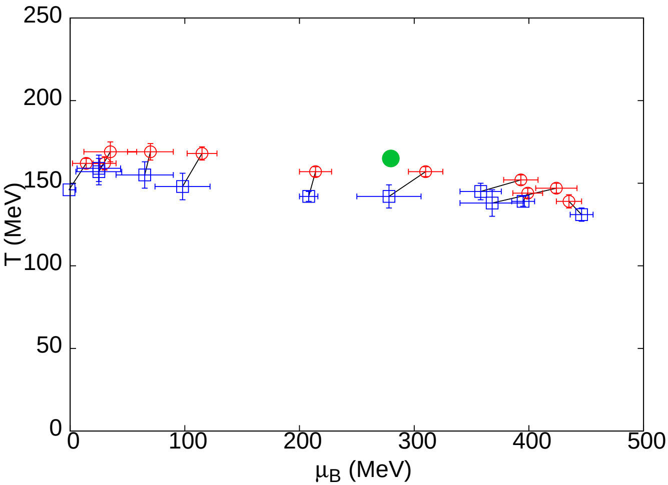

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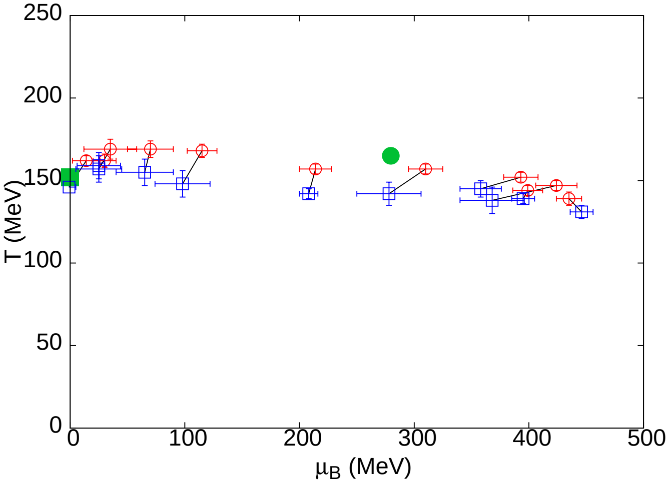
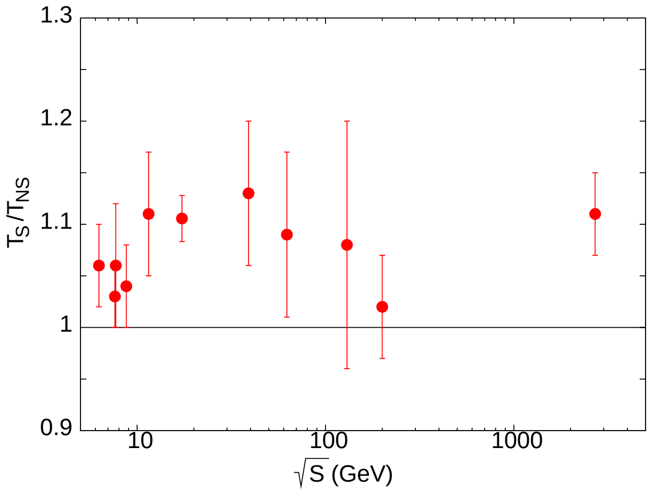


How transparent is the fireball?



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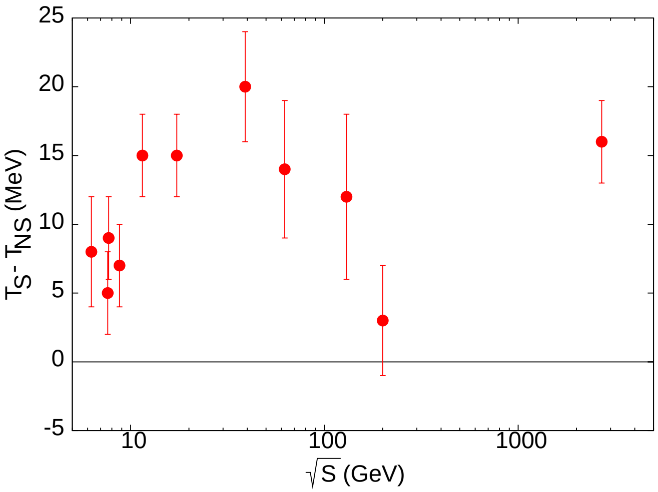

Outline

Questions and conjectures

- The final state at freezeout contributes most of the observables in heavy-ion experiments. Flavour and hadron physics dominates observables: many scales, finely graded physics. Requires detailed study of kinetics.
- First step beyond the standard picture: a two freezeout phenomenological model. Well-constrained and predictive: 6 parameters and typically 14 yields.
- Multiple freezeout points mean that the fireball is not perfectly opaque before the freezeout. So some information on the hydrodynamic trajectory becomes available: potentially useful.
- Would be useful for BES to collect very much larger statistics in the range $10\ \mathrm{GeV}\ \leq \sqrt{S} \leq 40$ GeV. Aim for 5% errors on yields of strange baryons.