Chemical equilibration in heavy-ion collision

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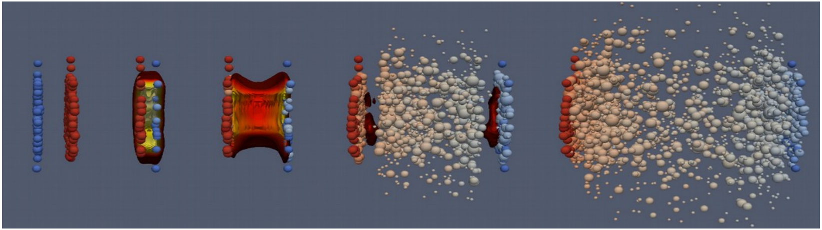
Workshop on QCD in the Nonperturbative Regime

- Nuclei are collided to create "soup of quarks and gluons".
- High pressure gradient $\Rightarrow \epsilon \downarrow$ and $T \downarrow$.
- At the piont of $T < T_c \Rightarrow$ Hadronization occurs.



- Expansion leads to dilution and inelastic collision stops (*CFO*).
- Chemical composition becomes fixed.
- Is there equilibrium at *CFO* boundary?

- Strongly interacting system in equilibrium can be described by T, μ_Q, μ_B, μ_S.
- *CFO* parameters can be extracted by fitting yield data.
- Measured T vs μ_B for various experiments is expected to carry information about the phase diagram.

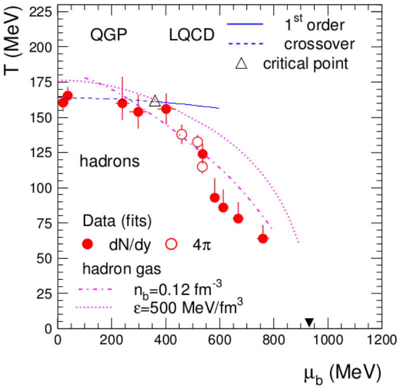


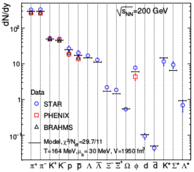
Figure: T vs μ_B[1]

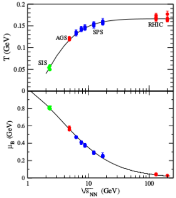
[1] Andronic et. al Nucl.Phys.A772:167-199:2006;

Statistical hadronization model

The Freezeout Curve

- Hadron yields well described using Statistical Hadronization Models, leading to the freezeout curve in the T-μ_B plane. (Andronic, Braun-Munzinger & Stachel, PLB 2009 ; Oeschler, Cleymans, Redlich & Wheaton, 2009)





- Plotting these results in the T-μ_B plane, one has the freezeout curve, which was shown to correspond the $\langle E\rangle/\langle N\rangle \simeq 1$. (Cleymans and Redlich, PRL 1998)

Slides from Prof. Gavai's Lecture, ICTS April-2019

Parameters and model for equilibrium

- One can model HRG like picture with T and μ's to understand CFO surface.
- Thermal density of i'th Hadron can be given as,

$$\boxed{n_i = \frac{g_i}{(2\pi)^3} \int \frac{d^3p}{\exp[(E_i - \mu_i)/T] \pm 1}.}$$

- $\mu_i = B_i\mu_B + S_i\mu_S + Q_i\mu_Q$ is total chemical potential, g_i is the degeneracy factor.
- Decay of parents to daughter particles has been included via,

$$\begin{aligned} n_i^{Tot} &= n_i(T, \mu_B, \mu_Q, \mu_S) + \\ \sum_j & n_j(T, \mu_B, \mu_Q, \mu_S) \times Branching\ Ratio(j \rightarrow i) \end{aligned}$$

Connection with observable

- We observe dN/dy in experiments.
- One can write $dN = ndV$
- Detected i'th primary hadron's rapidity density near mid-rapidity,

$$\boxed{\frac{dN_i}{dy} = \frac{dV}{dy} n_i(T, \mu_Q, \mu_B, \mu_S)}$$

- Information of the volume can be avoided by constructing ratios out of yields i.e

$$\boxed{\frac{dN_i/dy}{dN_j/dy} = \frac{n_i}{n_j}}$$

Extracting Parameter From Data

- We need four independent equations to extract these four thermal parameters.
- μ_Q and μ_S can be determined by imposing the constraints,

$$\boxed{\frac{\sum_i n_i(T, \mu_B, \mu_S, \mu_Q) B_i}{\sum_i n_i(T, \mu_B, \mu_S, \mu_Q) Q_i} = r}$$

$$\boxed{\sum_i n_i(T, \mu_B, \mu_S, \mu_Q) S_i = 0}$$

- Above equations contain information of the incident nuclei. For Au-Au and Pb-Pb, $r \sim 2.50$.

Extracting Parameter From Data

- To fit temperature T and the baryon chemical potential μ_B one can perform contemporary χ^2 minimization method with multiple ratios.
- Several standard codes are available *THERMUS*, *THERMINATOR*, *SHARE*.
- We tried to fit constructed ratios numerically by root finding.
- We observed that extracted parameters were dependent on the ratios we choose and systematics of the analysis. *arxiv-1911.04828*
- Is there an alternate way to extract thermodynamic parameters?

Let the conserved charges guide us

- Strong interaction conserves B, S and Q.
- Net charges are conserved, *not the individual yields*.
- So we tried to construct ratio of Net baryon charges to total baryon number with all these detected hadrons data.
- In this way one can maximally utilize yield data of all baryons.
-

$$\boxed{\frac{\sum_i B_i n_i}{\sum_i \mid B_i \mid n_i} = \frac{\sum_i B_i \frac{dN_i}{dY}}{\sum_i \mid B_i \mid \frac{dN_i}{dY}}}$$

continuing...

- We need one more equation to close our system of equations.
- To extract T, we look at the net baryon to total particles ratio.

$$\boxed{\frac{\sum_i B_i \frac{dN_i}{dY}}{\sum_i \frac{dN_i}{dY}} = \frac{\sum_i B_i n_i^{Tot}}{\sum_i n_i^{Tot}}}$$

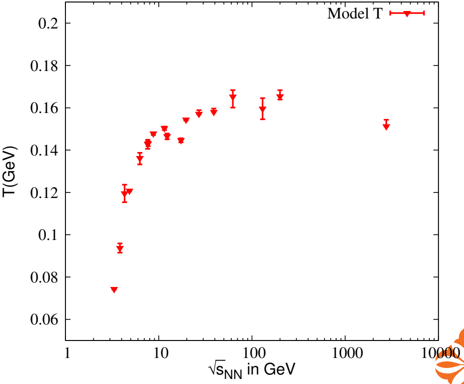
- These two equations have been constructed only out of detected hadrons. *PhysRevD 100 (5), 054037*
- To solve $\Longrightarrow$ Two new equations + Two constraints.

Dataset Used

- AGS, SPS, RHIC and LHC (2.76 TeV) data have been used.
- Study has been performed for mid-rapidity data of most central collision of these $\sqrt{s}$.
- We have used yield of all available mesons and baryons ($\pi^{\pm}, k^{\pm}$ and $p, \bar{p}, \Lambda, \bar{\Lambda}, \Xi^{\pm}$) for fitting.
- We have not used $\Omega^{\pm}$ yield, it is not available for most of the $\sqrt{s}$.
- *Feed-down corrections* are taken care of, according to the corresponding experiment.

Variation of T with $\sqrt{s}$

- There is trend of saturation after $\sqrt{s}$ 19.6$AGeV$.
- It approaches the flat region of the proposed phase diagram of hadron to QGP transition near $\mu_B = 0$.



Variation of T with $\sqrt{s}$

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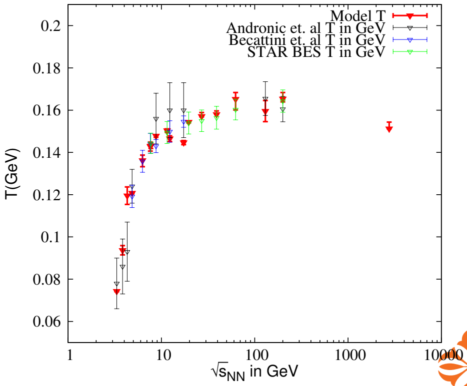
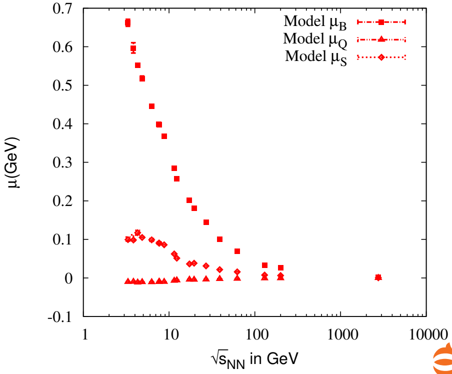
- It approaches the flat region of the proposed phase diagram of hadron to QGP transition near $\mu_B = 0$.
- We have compared our extracted T with *Andronic et.al* and BES.



Variation of μ with $\sqrt{s}$

- μ_B increases due to higher rate of baryon stopping in lower collision energy.
- The difference between μ's decrease with increasing $\sqrt{s}$ and converges to zero at very high $\sqrt{s}$.
- At low $\sqrt{s}$, μ_Q becomes negative though both μ_B and μ_S remain positive for all the values of $\sqrt{s}$.



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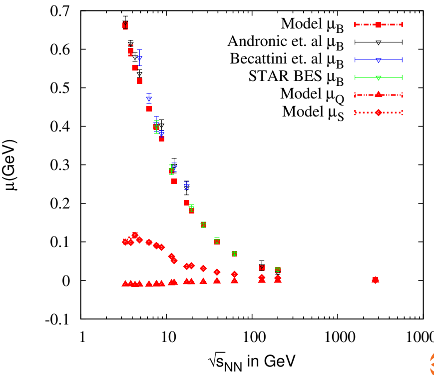


Pion, kaon to pion ratio and proton to pion

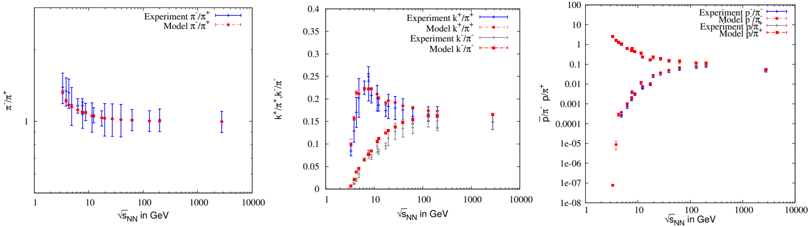


Figure: π^-/π^+, $k^\pm/\pi^\pm$ and p/π

Strange baryon to non-strange baryon ratio

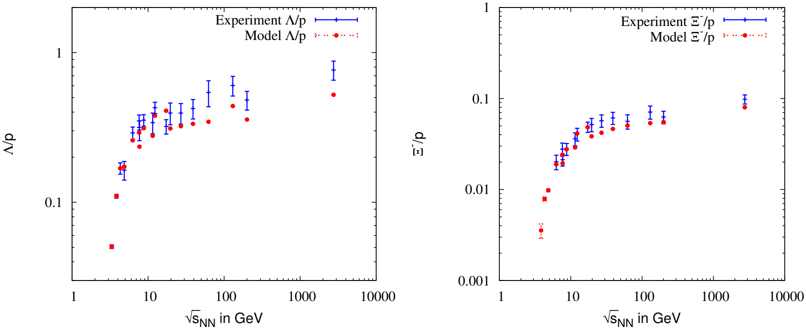


Figure: Variation of Λ/p and Ξ^-/p with $\sqrt{s}$

Predicted ratios

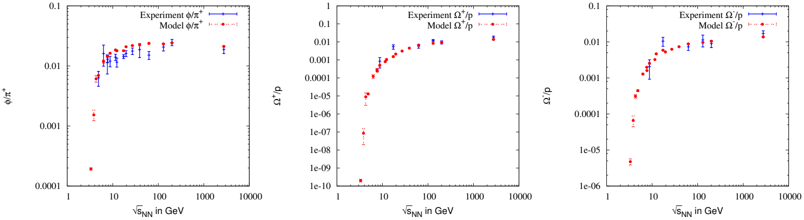
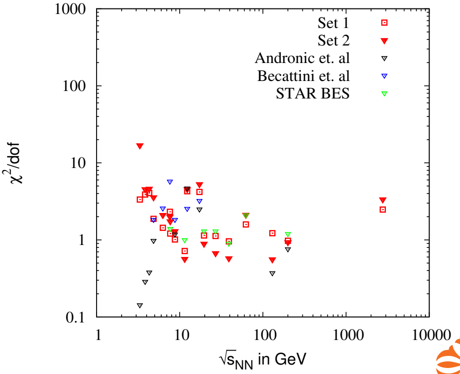


Figure: Variation of ϕ/π^+, Ω^-/p and Ω^+/p

Do we have a better χ^2 per degrees of freedom ?

- $\chi^2/d.o.f$ are better at RHIC and BES and worse at *AGS* energy range.
- Lack of hyperon data at these $\sqrt{S}$ plays a significant role. Only Λ data are available.
- Though there is good agreements between data and model predictions, $\chi^2/d.o.f$ is quite large.



Summary

- A new mechanism for freeze out parameter extraction has been proposed rather than the standard χ^2 method.
- The extracted parameters have suitably reproduced various ratios.
- Chemical equilibrium at freeze-out under the umbrella of various charges.
- Parameters value are in good agreement with that of standard literature.
- Ratios are quite independent prediction as our process does not involve any individual particle ratios like one uses in case of χ^2 minimization.
- Precise data at lower $\sqrt{S}$ can improve our prediction.

Collaborators

Sumana Bhattacharyya
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Rajarshi Ray
Pracheta Singha


THANK YOU
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