



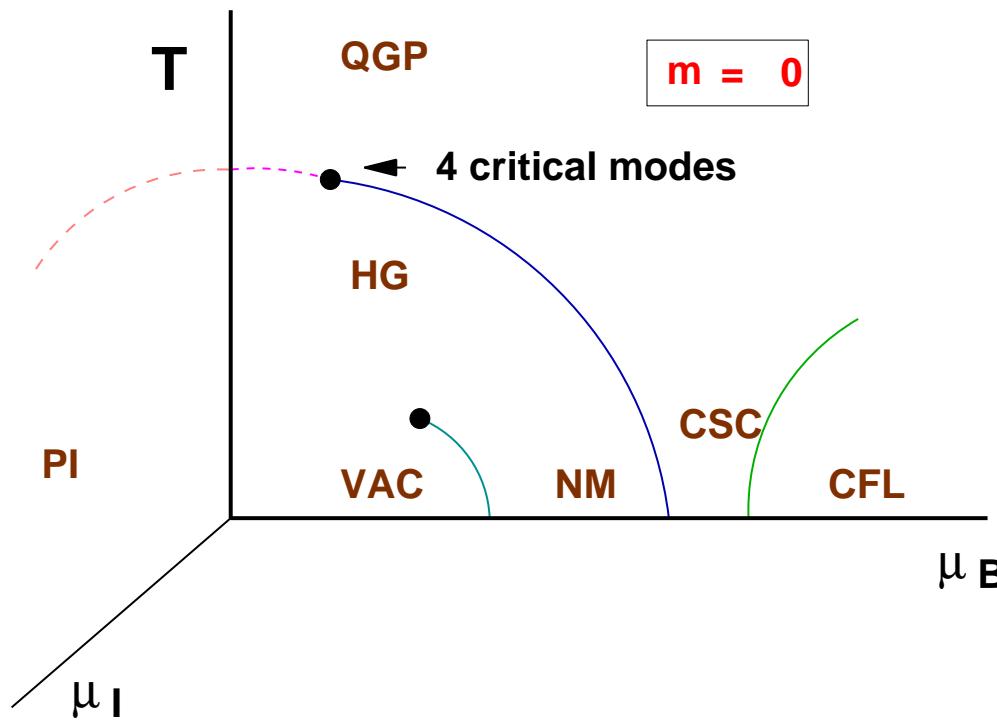
Chemical Equilibrium in Strong Interactions

Rajarshi Ray

Bose Institute, Kolkata

QCD with Electron-Ion Collider, IITB, 2020

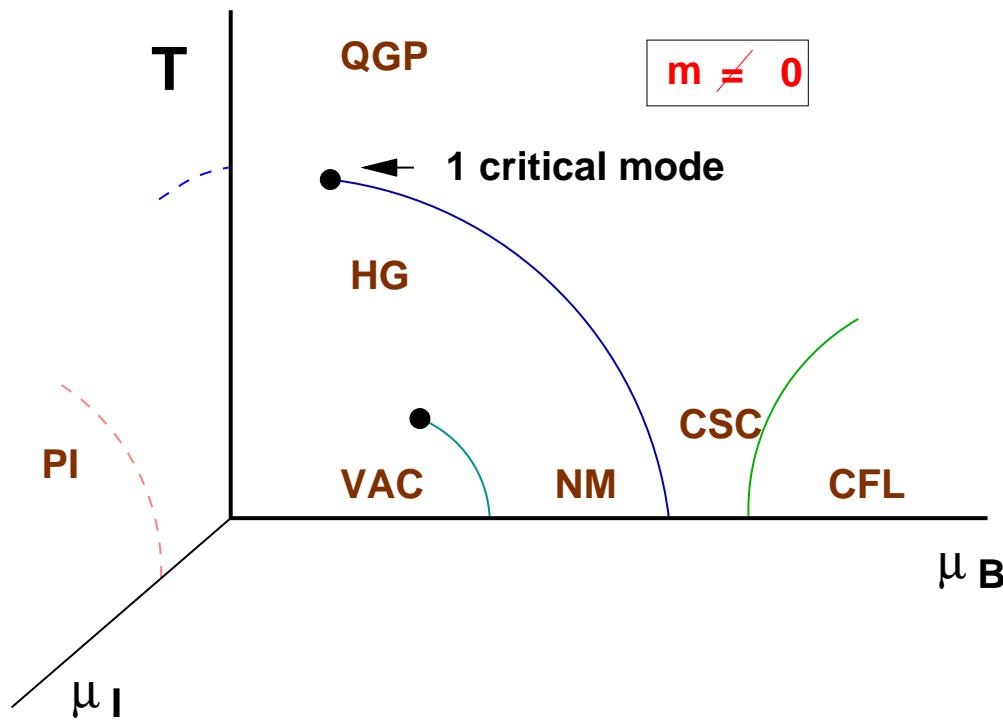
Phase Diagram



$$\mu_B = \frac{1}{3} \left(\frac{\mu_u + \mu_d}{2} \right) \quad ; \quad \mu_I = \left(\frac{\mu_u - \mu_d}{2} \right)$$

Rajagopal, Wilczek : The Condensed Matter Physics of QCD
Ch. 35, 'Handbook of QCD', M. Shifman, ed., (World Scientific) (hep-ph/0011333).

Phase Diagram

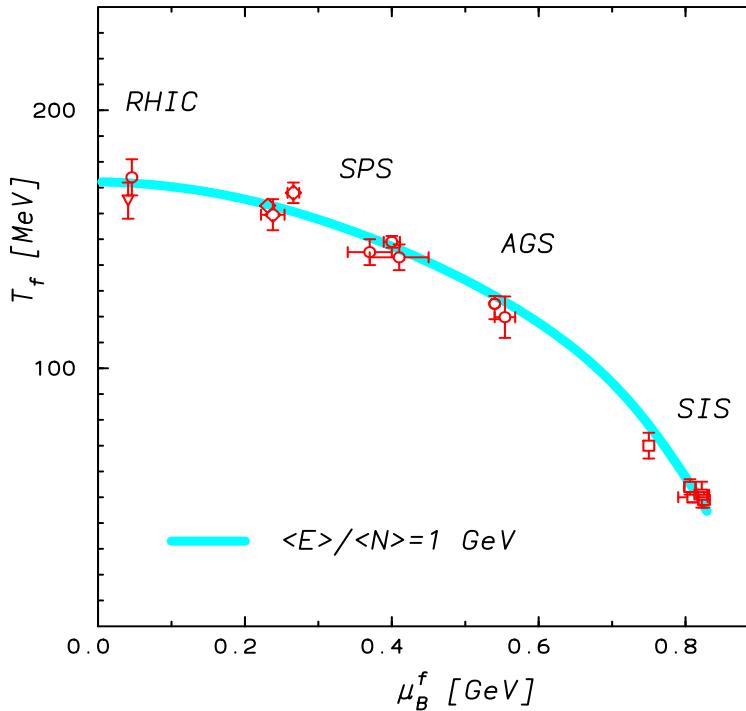
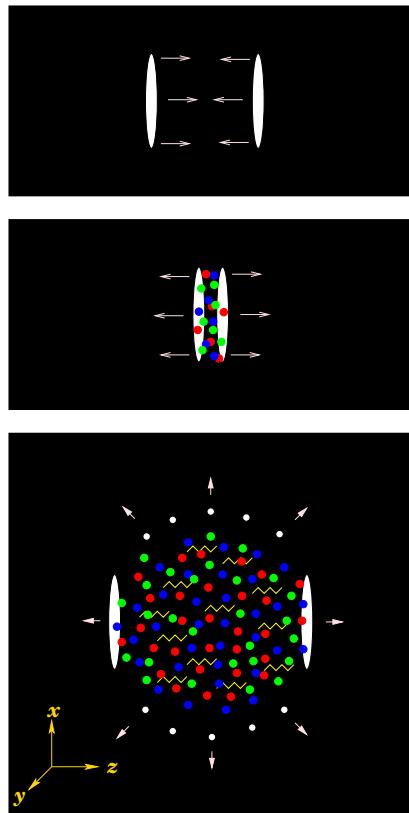


$$\mu_B = \frac{1}{3} \left(\frac{\mu_u + \mu_d}{2} \right) \quad ; \quad \mu_I = \left(\frac{\mu_u - \mu_d}{2} \right)$$

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Thermalization in HIC



Thermal model:

$$Z(T, \mu_B, \mu_I, \mu_S) = \sum_i Z_i(T, \mu_B, \mu_I, \mu_S) \Rightarrow n_i(T, \mu_B, \mu_I, \mu_S)$$

J. Cleymans and K. Redlich: Phys. Rev. Lett 81 (1998) 5284

P. Braun-Munzinger, K. Redlich and J. Stachel:

Quark Gluon Plasma 3, R.C. Hwa and X.-N. Wang, ed., (World Scientific) (nucl-th/0304013)

Chemical Freezeout:

- Thermal density of i 'th Hadron is given as,

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

- $\mu_i = B_i \mu_B + S_i \mu_S + Q_i \mu_Q$ is total chemical potential, g_i is the degeneracy factor.
- In [chemical equilibrium](#), detected i 'th hadron's rapidity density,

$$\frac{dN_i}{dy} = \frac{dV}{dy} n_i(T, \mu_Q, \mu_B, \mu_S) + \text{feed down} + \text{decay} \Rightarrow$$

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

- Add external constraints,

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

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



Chemical Freezeout:

- Thermal density of i 'th Hadron is given as,

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

- $\mu_i = B_i \mu_B + S_i \mu_S + Q_i \mu_Q$ is total chemical potential, g_i is the degeneracy factor.

- In **chemical equilibrium**,

$$\text{Minimize } \chi^2 \text{ w.r.t. } T \text{ and } \mu_B \text{ constructed from } \left(\frac{dN_i/dy}{dN_j/dy} - \frac{n_i^T}{n_j^T} \right)$$

- Add external constraints,

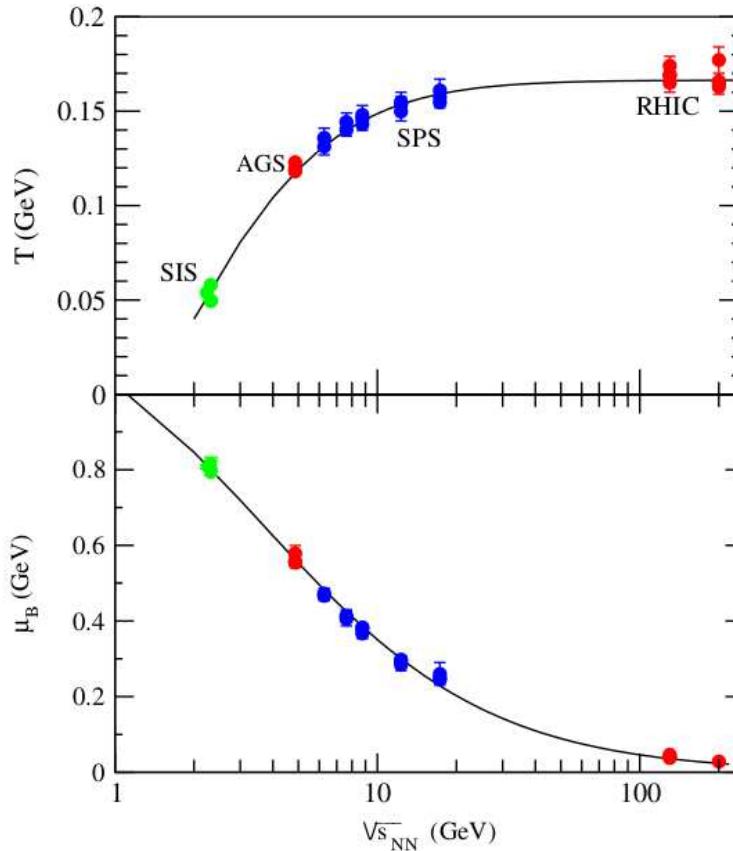
$$\frac{\sum_i n_i(T, \mu_B, \mu_S, \mu_Q) Q_i}{\sum_i n_i(T, \mu_B, \mu_S, \mu_Q) B_i} = r$$

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



HRG at Freezeout I

From hadron multiplicity data:

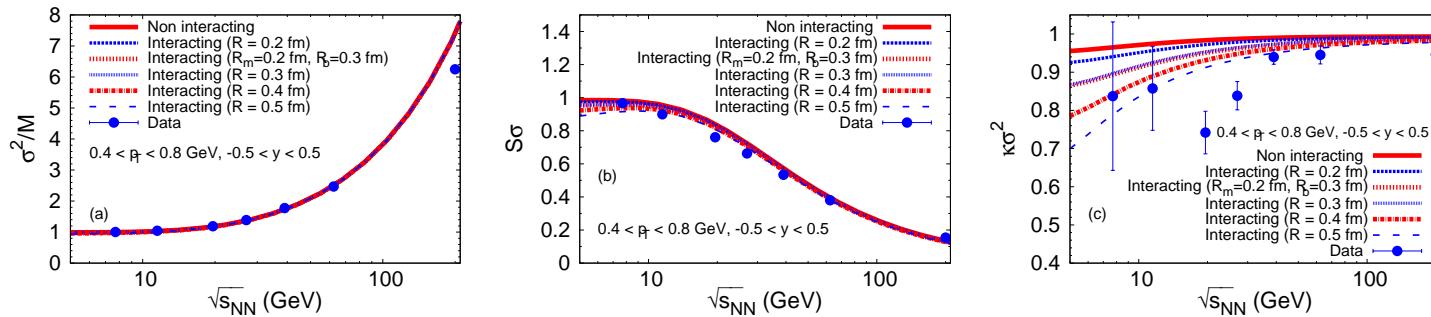


J. Cleymans *et al.*, PRC 73, 034905 (2006)

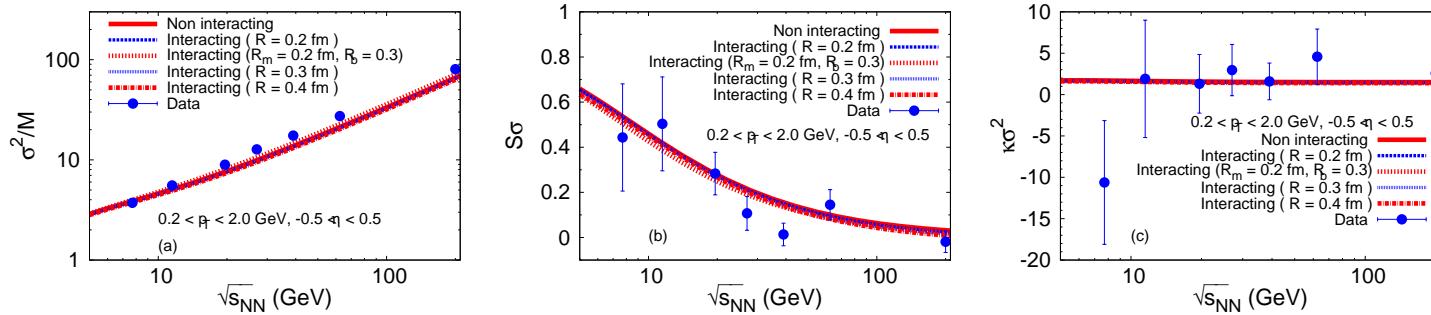
What happens for ratios of fluctuations with the freezeout data ??



HRG at Freezeout II



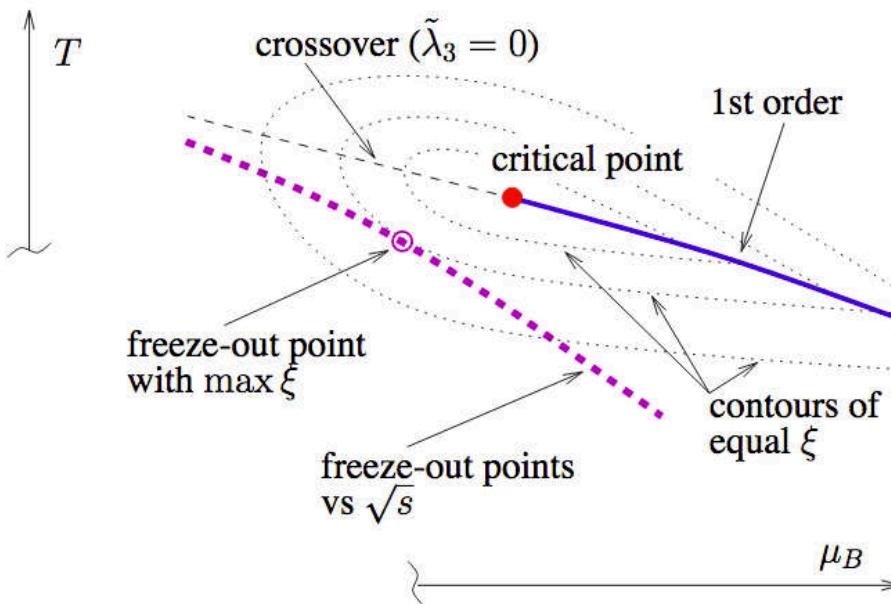
Net-proton data: X. Luo (for the STAR collaboration), Nucl. Phys. A 904-905, 911c (2013)



Net-charge data: L. Adamczyk et al. (STAR), Phys. Rev. Lett. 113, 092301 (2014)

- HRG Results: RR *et al.*, PRC 90 034909 '14.

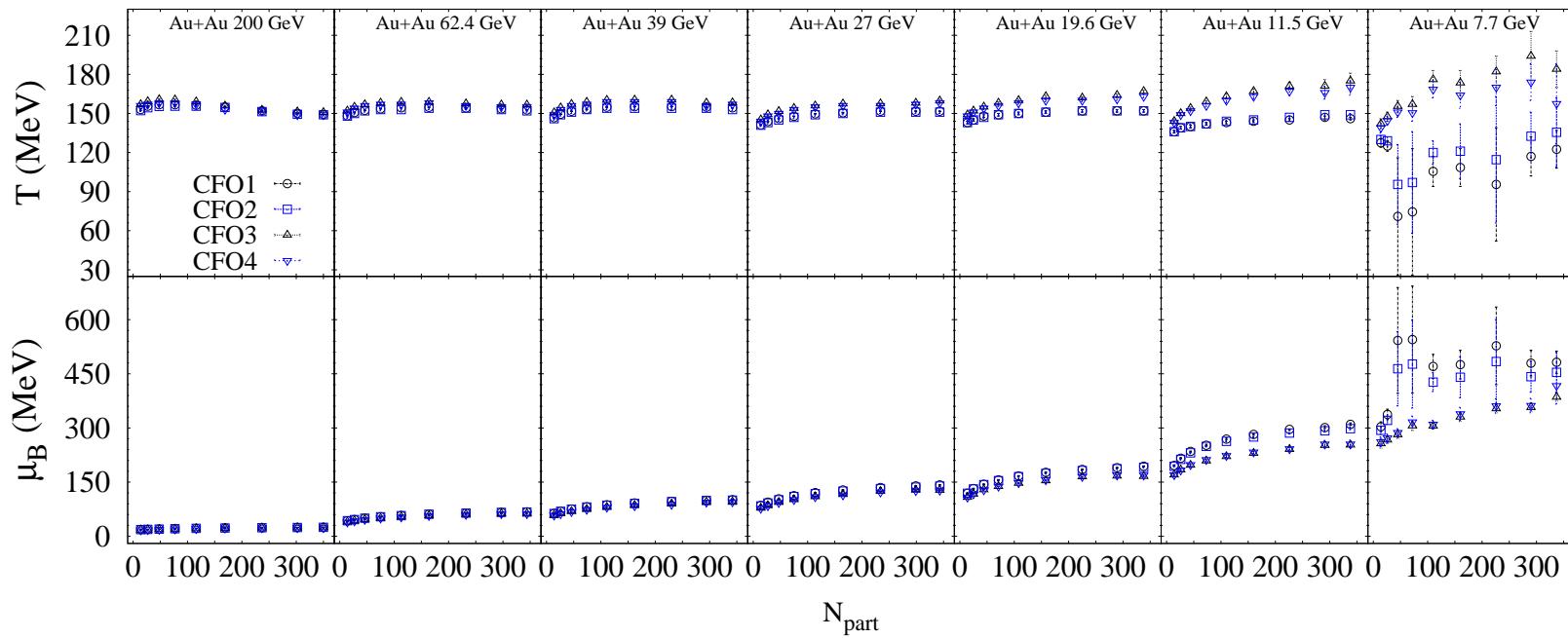
Scales and dynamics



- Separation of scale: $\langle (\delta N)^k \rangle \sim \xi^{f(k)}$
M. Stephanov, PRL 102, 032301, (2009)
- Critical slow down may induce differential imprints on moments



Freezeout of fluctuations



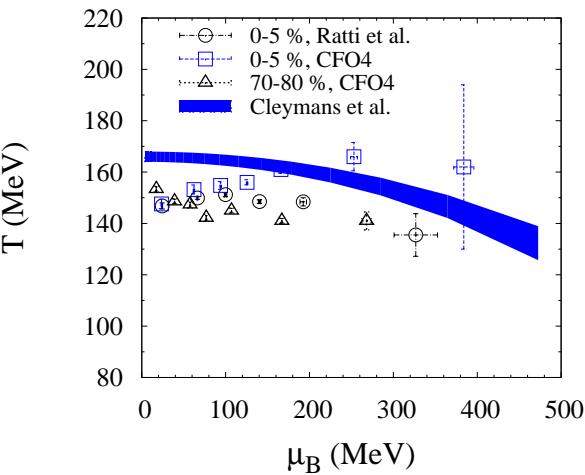
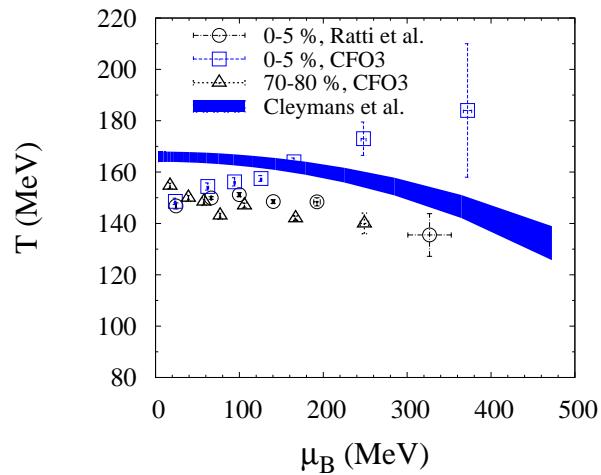
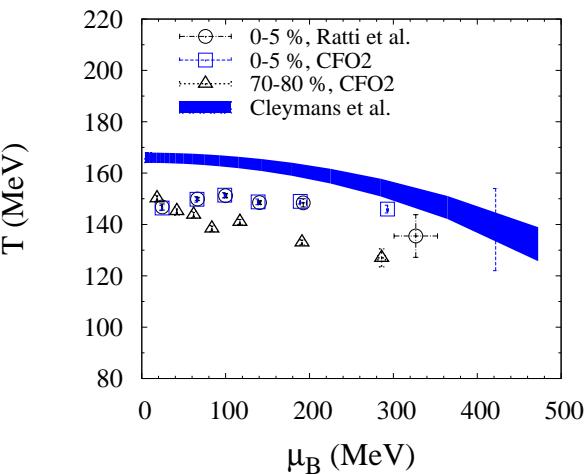
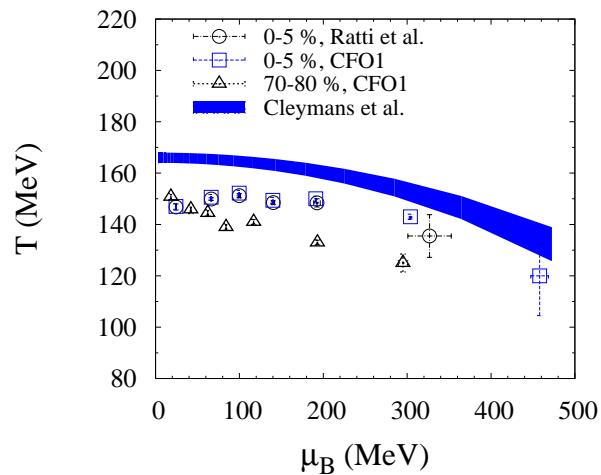
Sets of parameters	Experimental data used	Model used
CFO1	$(\sigma^2/M)_{np}, (\sigma^2/M)_{nc}$	HRG
CFO2	$(\sigma^2/M)_{np}, (\sigma^2/M)_{nc}$	EVHRG
CFO3	$(\sigma^2/M)_{nc}, (S\sigma)_{np}, (S\sigma)_{nc}$	HRG
CFO4	$(\sigma^2/M)_{nc}, (S\sigma)_{np}, (S\sigma)_{nc}$	EVHRG

RR *et. al.*, PRC 96 014902 '17.

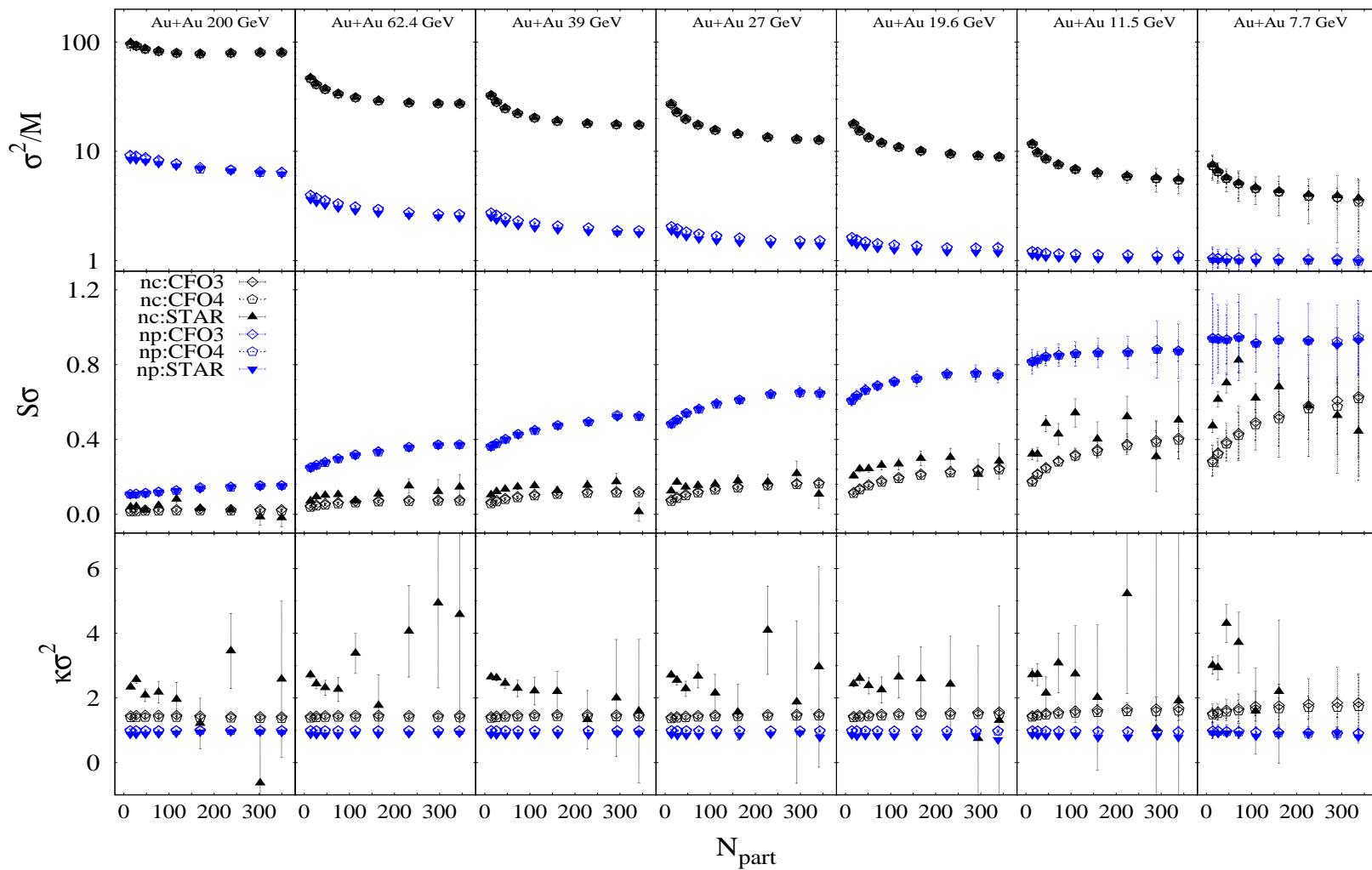
Data from STAR: PRL 112, 032302 (2014); PRL 113, 092301 (2014)



Freezeout surface



Partial HRG at Freezeout II



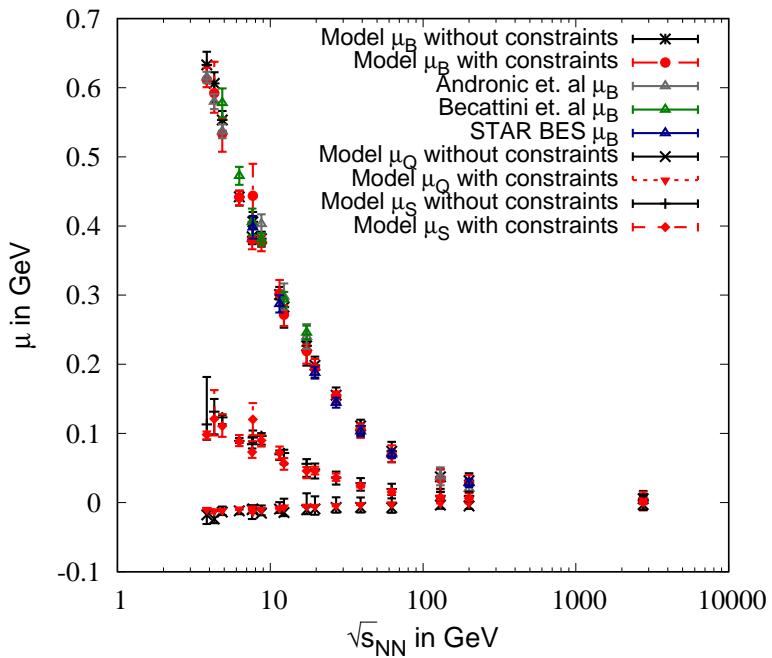
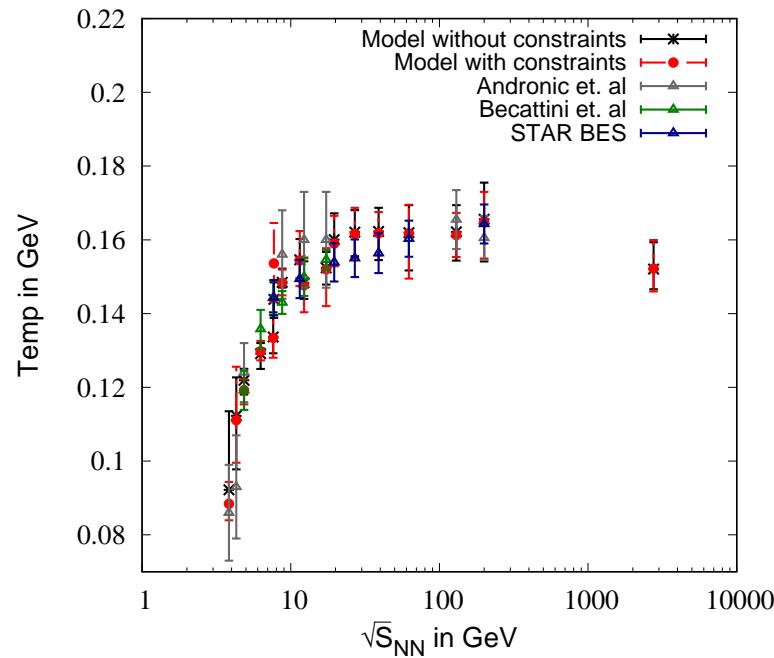
Choice of ratios:

Set 1	$\frac{\pi^-}{\pi^+}, \frac{k^+}{\pi^+}, \frac{k^-}{\pi^+}, \frac{p}{\pi^+}, \frac{\bar{p}}{\pi^+}, \frac{\Lambda}{\pi^+}, \frac{\bar{\Lambda}}{\pi^+}, \frac{\Xi^-}{\pi^+}, \frac{\Xi^+}{\pi^+}$
Set 2	$\frac{\pi^-}{\pi^+}, \frac{k^+}{\pi^-}, \frac{k^-}{\pi^-}, \frac{p}{\pi^-}, \frac{\bar{p}}{\pi^-}, \frac{\Lambda}{\pi^-}, \frac{\bar{\Lambda}}{\pi^-}, \frac{\Xi^-}{\pi^-}, \frac{\Xi^+}{\pi^-}$
Set 3	$\frac{\pi^-}{\pi^+}, \frac{k^+}{\pi^-}, \frac{k^-}{k^+}, \frac{p}{k^+}, \frac{\bar{p}}{k^+}, \frac{\Lambda}{k^+}, \frac{\bar{\Lambda}}{k^+}, \frac{\Xi^-}{k^+}, \frac{\Xi^+}{k^+}$
Set 4	$\frac{\pi^-}{\pi^+}, \frac{k^+}{\pi^-}, \frac{k^-}{k^+}, \frac{p}{k^-}, \frac{\bar{p}}{k^-}, \frac{\Lambda}{k^-}, \frac{\bar{\Lambda}}{k^-}, \frac{\Xi^-}{k^-}, \frac{\Xi^+}{k^-}$
Set 5	$\frac{\pi^-}{\pi^+}, \frac{k^+}{\pi^-}, \frac{k^-}{k^+}, \frac{p}{k^-}, \frac{\bar{p}}{p}, \frac{\Lambda}{p}, \frac{\bar{\Lambda}}{p}, \frac{\Xi^-}{p}, \frac{\Xi^+}{p}$
Set 6	$\frac{\pi^-}{\pi^+}, \frac{k^+}{\pi^-}, \frac{k^-}{k^+}, \frac{p}{k^-}, \frac{\bar{p}}{p}, \frac{\Lambda}{\bar{p}}, \frac{\bar{\Lambda}}{\bar{p}}, \frac{\Xi^-}{\bar{p}}, \frac{\Xi^+}{\bar{p}}$
Set 7	$\frac{\pi^-}{\pi^+}, \frac{k^+}{\pi^-}, \frac{k^-}{k^+}, \frac{p}{k^-}, \frac{\bar{p}}{p}, \frac{\Lambda}{\bar{p}}, \frac{\bar{\Lambda}}{\Lambda}, \frac{\Xi^-}{\Lambda}, \frac{\Xi^+}{\Lambda}$
Set 8	$\frac{\pi^-}{\pi^+}, \frac{k^+}{\pi^-}, \frac{k^-}{k^+}, \frac{p}{k^-}, \frac{\bar{p}}{p}, \frac{\Lambda}{\bar{p}}, \frac{\bar{\Lambda}}{\bar{\Lambda}}, \frac{\Xi^-}{\bar{\Lambda}}, \frac{\Xi^+}{\bar{\Lambda}}$
Set 9	$\frac{\pi^-}{\pi^+}, \frac{k^+}{\pi^-}, \frac{k^-}{k^+}, \frac{p}{k^-}, \frac{\bar{p}}{p}, \frac{\Lambda}{\bar{p}}, \frac{\bar{\Lambda}}{\Lambda}, \frac{\Xi^-}{\bar{\Lambda}}, \frac{\Xi^+}{\Xi^-}$

- A sample of various possible independent ratios



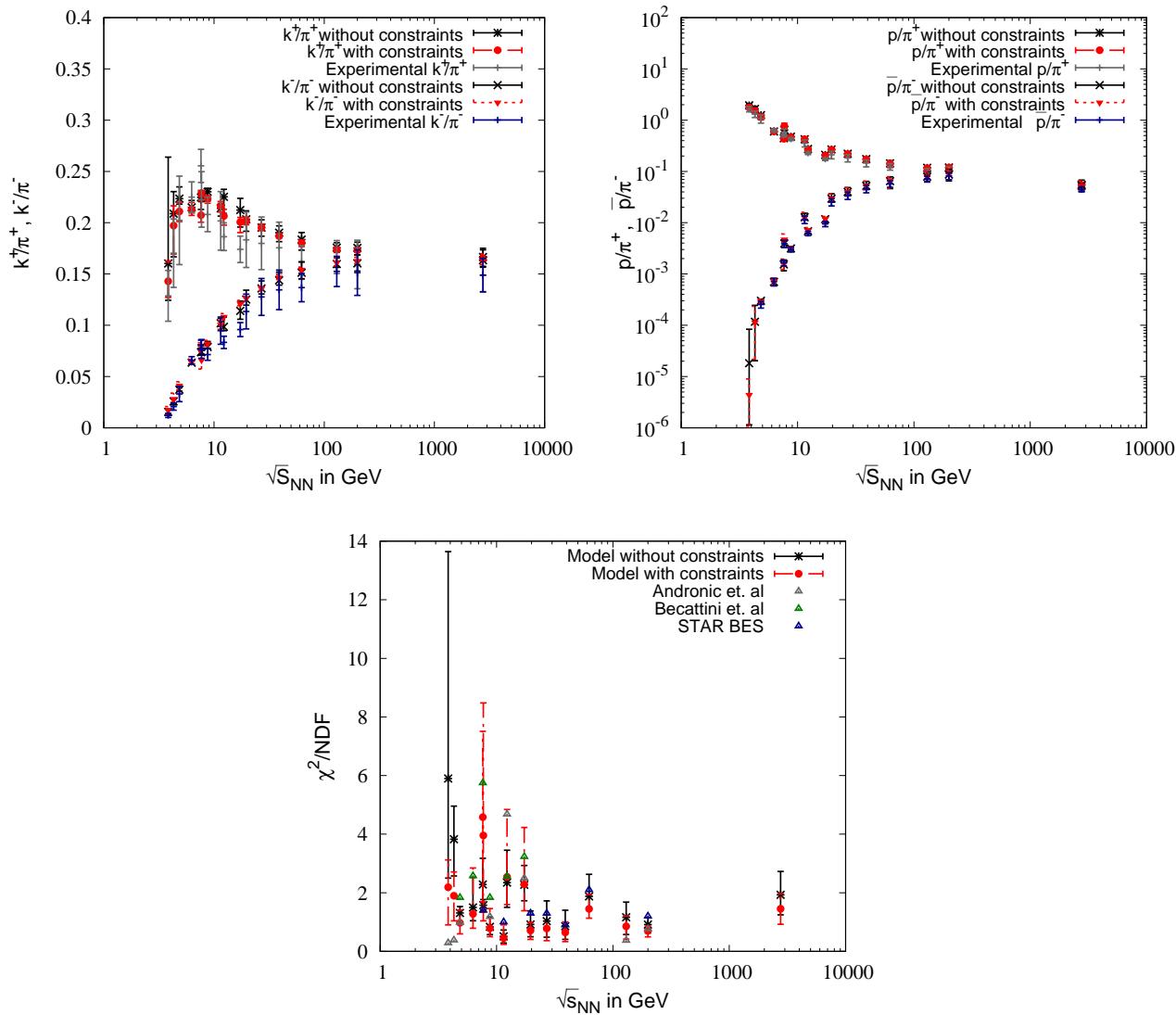
Freezeout parameters:



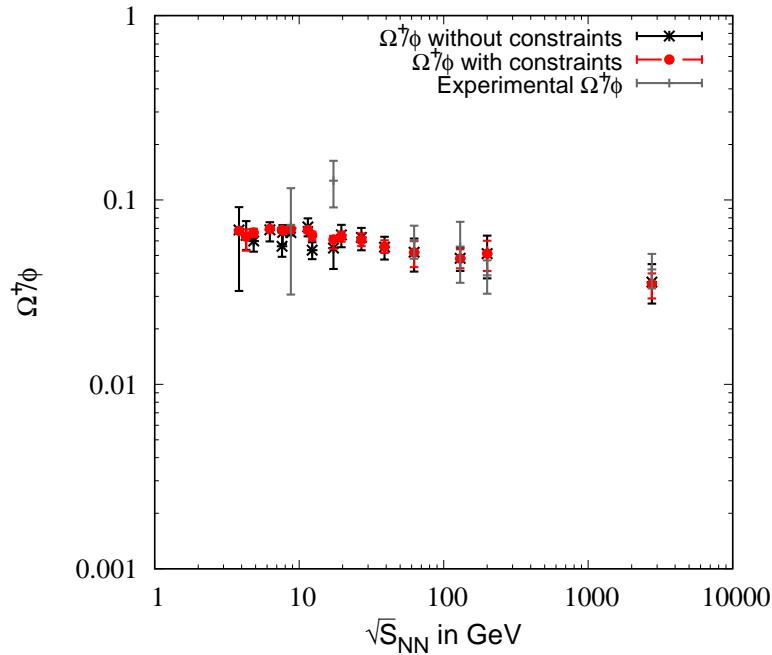
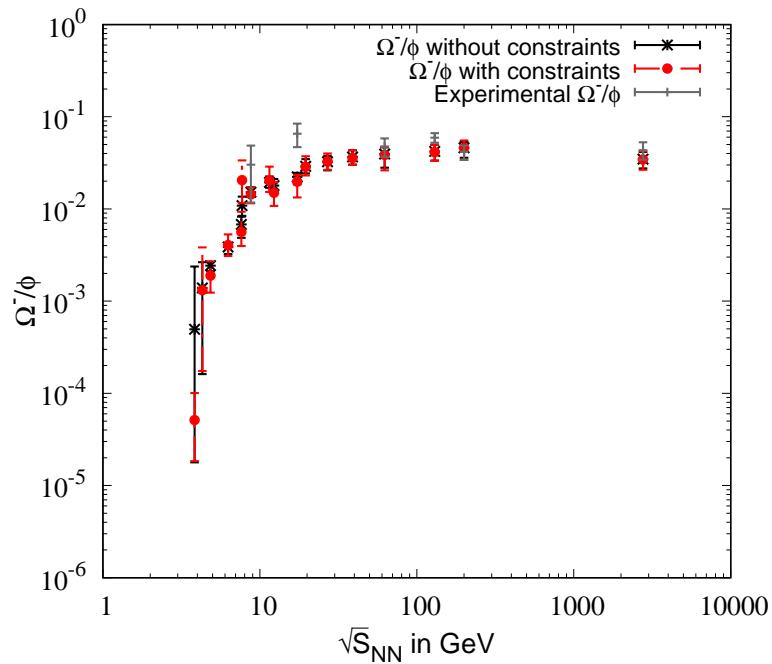
- AGS, SPS, RHIC and LHC (2.76 TeV) data have been used.
- Study has been performed for mid-rapidity data of most central collision of these \sqrt{s} .
- Yield of $(\pi^\pm, k^\pm$ and $p, \bar{p}, \Lambda, \bar{\Lambda}, \Xi^\pm)$ were used for fitting.
- We have not used Ω^\pm yield as it is not available for most of the \sqrt{s} .

RR et. al. arXiv: 1911.04828

Hadron ratios – reproduced:



Hadron ratios – predicted:



- Experimental data for these hadrons were not part of the fitting

Chemical Freezeout: Alternative approach

- Thermal density of i 'th Hadron is given as,

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

- $\mu_i = B_i \mu_B + S_i \mu_S + Q_i \mu_Q$ is total chemical potential, g_i is the degeneracy factor.

- In **chemical equilibrium**,

$$\frac{\sum_i B_i n_i}{\sum_i |B_i| n_i} = \frac{\sum_i B_i \frac{dN_i}{dY}}{\sum_i |B_i| \frac{dN_i}{dY}}$$

and

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

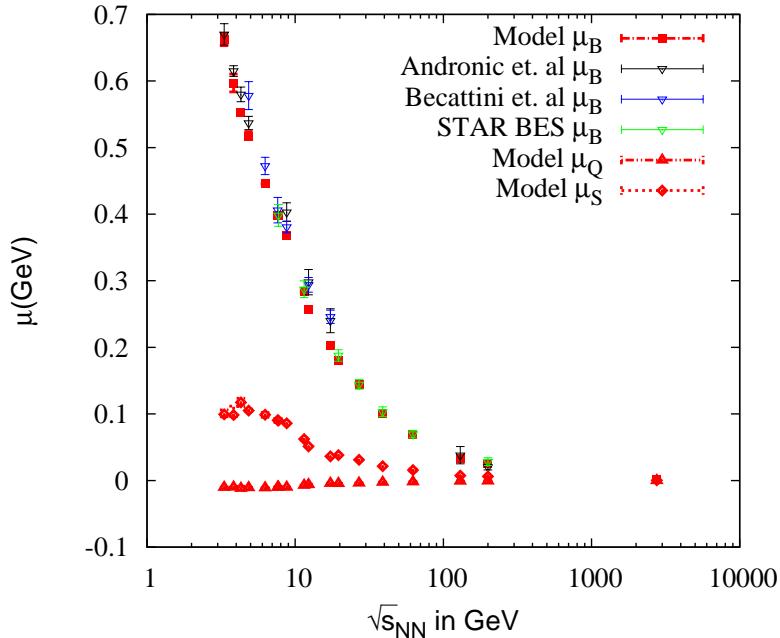
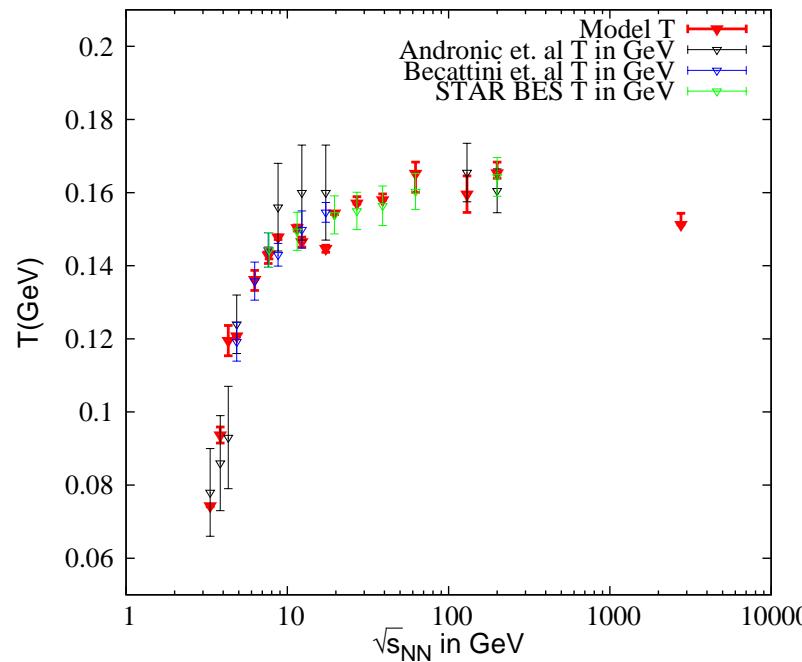
- Add external constraints,

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

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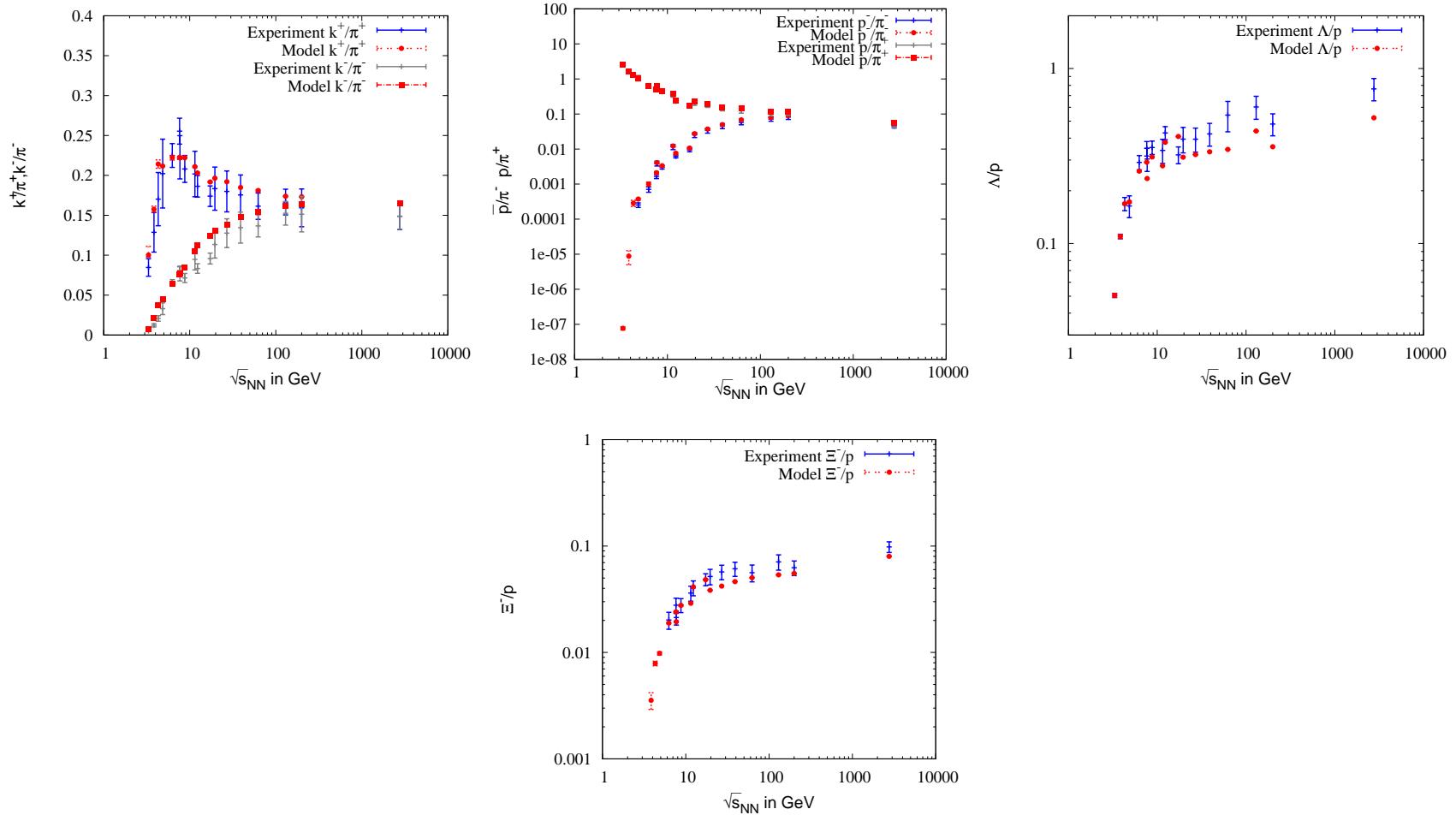
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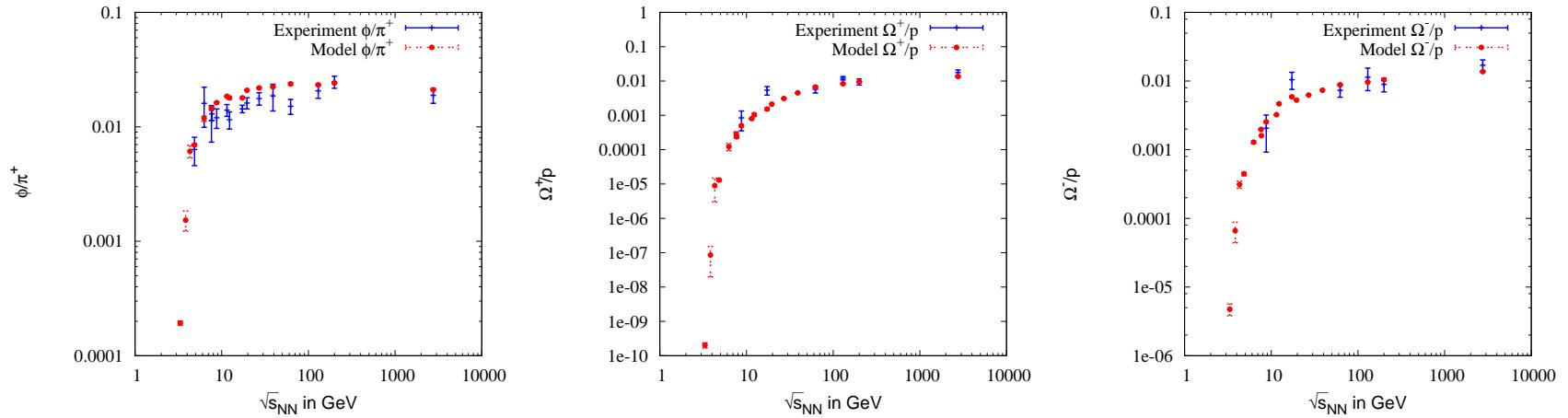
RR et. al. PRD 100 054037 '19.

Chemical Freezeout: Alternative approach



- Predictions for hadron yield ratios (hadrons used in analysis)
RR et. al. PRD 100 054037 '19.

Chemical Freezeout: Alternative approach



- Predictions for hadron yield ratios (hadrons not used in analysis)
RR et. al. PRD 100 054037 '19.

Multiplicity Ratio \Rightarrow chemical equilibrium

Fluctuation Ratio \Rightarrow chemical equilibrium for low \sqrt{s} ??

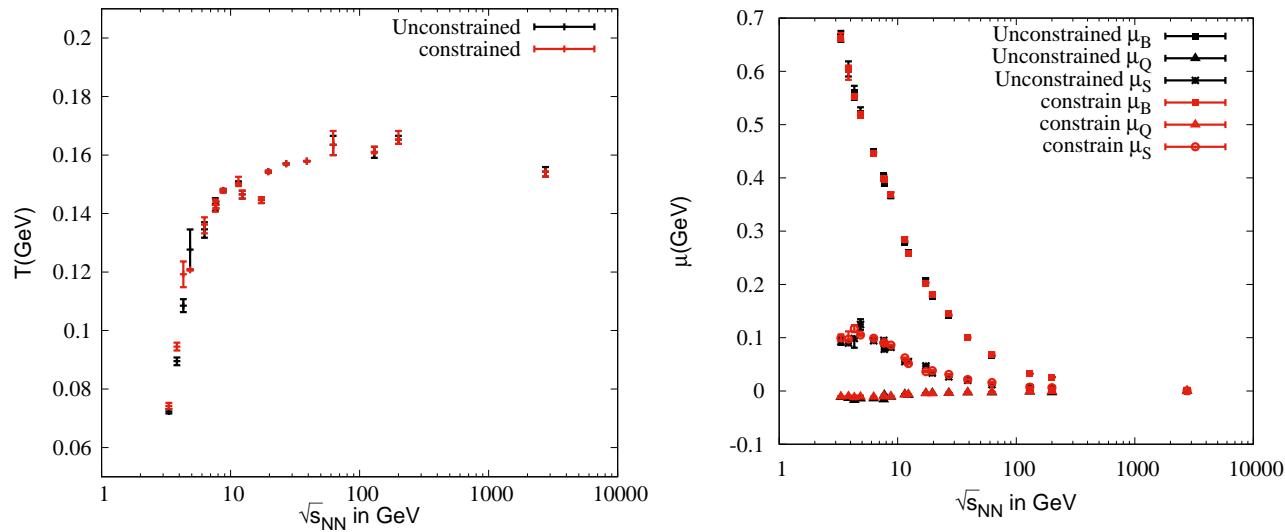


Discussion:

- In heavy-ion collision chemical equilibrium seems to be approximately valid
- There is a possibility to learn about the phase diagram of QCD
- But why equilibrium appears is unclear



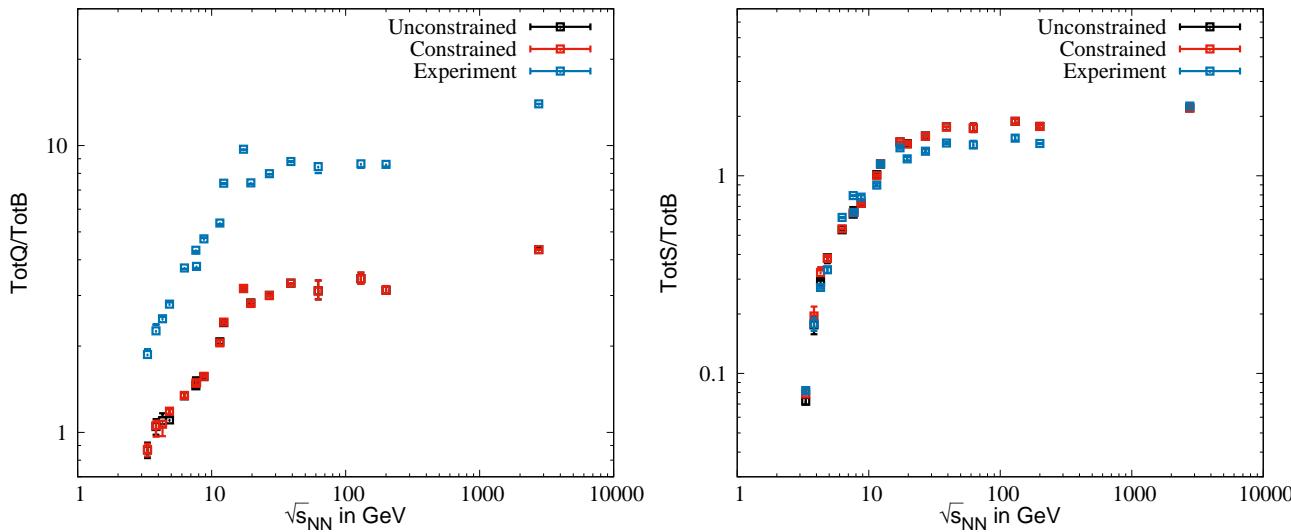
Freezeout parameters: relook



- Parameters without the external constraints have similar variation
- Numerical differences significant for the lower energies



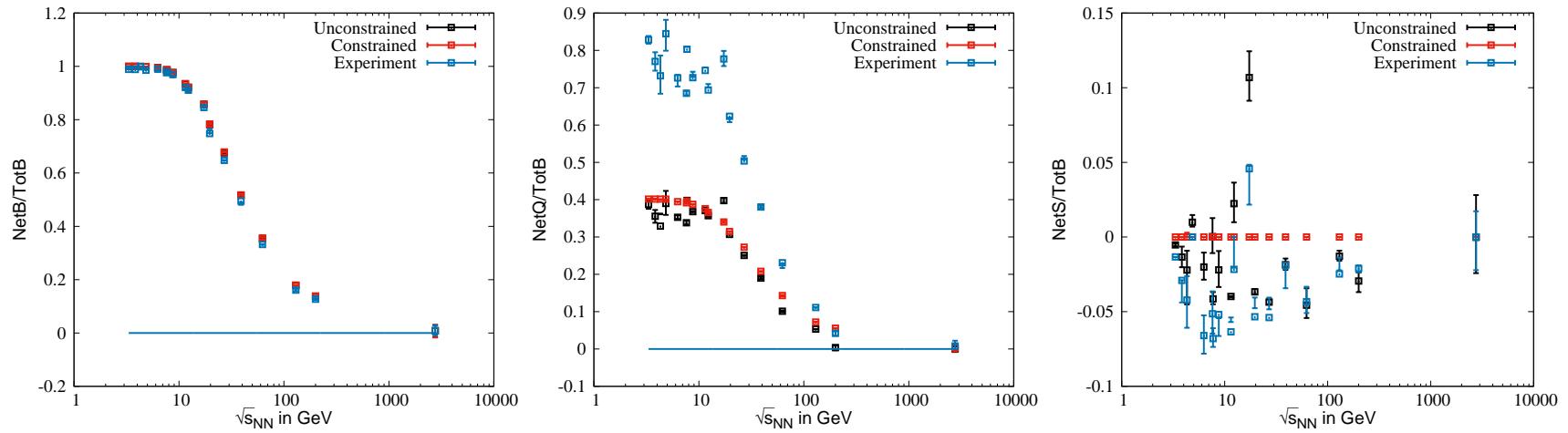
Total charge ratios:



- A view of charge and strangeness enhancement with respect to baryon number
- There is almost no dependence on the constraints

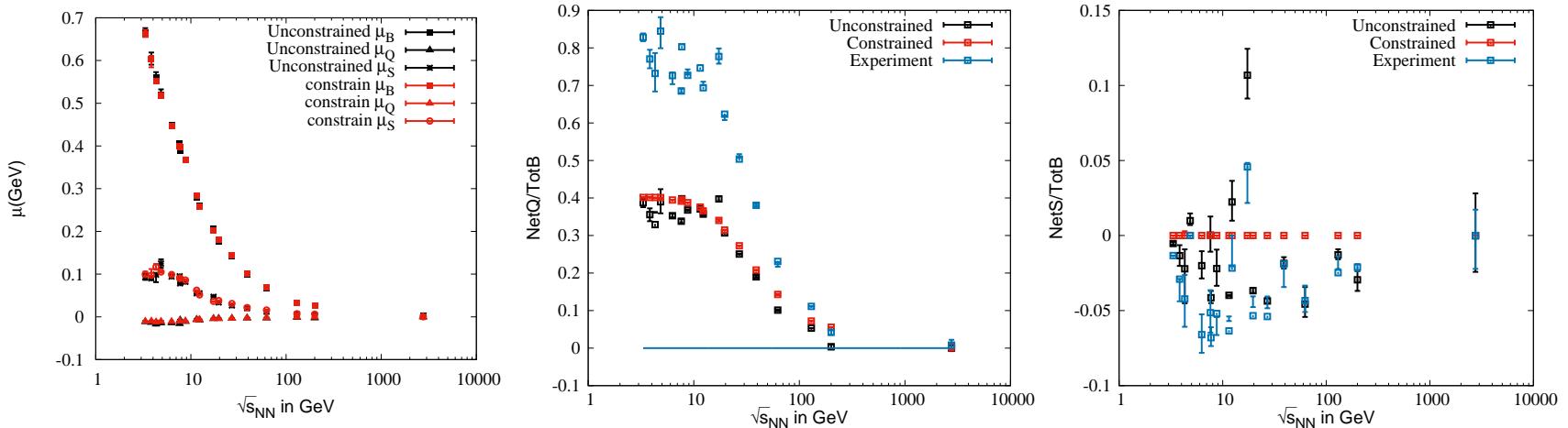


Net charges:



Constraints affect net charge and net strangeness significantly

Net charges:



- Sign of the net charge and net strangeness opposite to μ_Q and μ_S
 - Q is dummy for I – equilibration a partonic effect?
Observation: $\pi^- > \pi^+$
 - Baryon density is a major driving force – generate strange baryons
Counter balanced by kaons: $k+ > k-$
 μ_S a frustrated remnant

Equilibration \Rightarrow initial/intermediate state effect ??

Redistribution of charges \Rightarrow final state effect ??

Conclusion:

- Signatures of chemical equilibration in HIC experiments from multiplicities of identified hadrons observed
- Limited data for proton and charged particle fluctuations indicate equilibration is incomplete
- A scheme with independent conserved charges discussed
- Are these charges truly independent ?



Collaborators

Abhijit Bhattacharyya

Ramaprasad Adak

Sumana Bhattacharyya

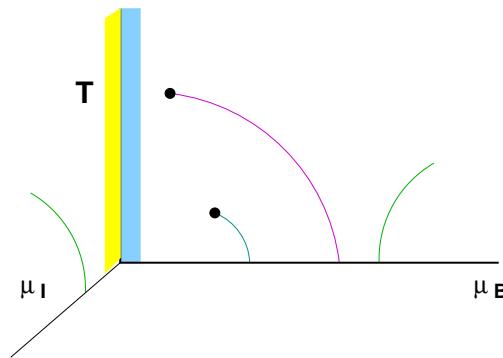
Deeptak Biswas

Supriya Das

Sanjay K. Ghosh

Subhasis Samanta

Pracheta Singha



Backup:

