Local thermal equilibrium of dense hadronic matter at FAIR

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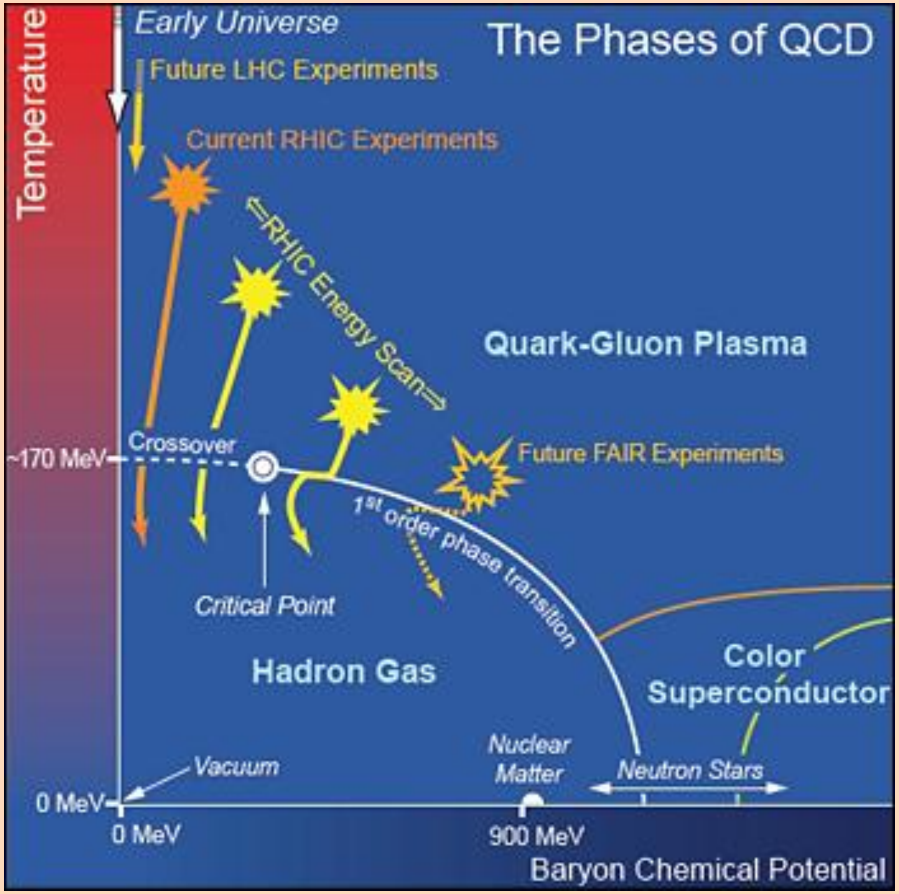
Outline of the talk:

- Introduction
- Brief description of UrQMD model and methodology
- Time evolution of physical observables
- Comparison with statistical thermal model
- Summary

Motivation

➢ The quest of exploring the state matter at extreme temperature ~10^{11} -10^{12} Kelvin and/or density~ 10^{14} – 10^{15} g/cm^3. Such ambient conditions may have existed few micro-seconds after Big-Bang, core of neutron star.



New Journal of Phys. 13 (2011) 065031

OR

➢Can be achieved at laboratory by colliding two heavy nuclei at relativistic energies.

➢ The Compressed Baryonic Matter (CBM) experiment at FAIR/ GSI is aimed to explore the QCD phase diagram at high baryon density and moderate temperature, complementary to the heavy ion studies performed at RHIC and LHC experiment.

❑The Compressed Baryonic Matter (CBM) experiment at FAIR / GSI

■The experiment is being designed to collide stable (and exotic) nuclei at fixed target mode at laboratory energies 5--45 GeV/ nucleon with reaction rates ~ 10^5--10^7 / sec. (H. R. Schmidt (CBM Coll.), PoS (Bromino 2013) 061)

■ The existence of first order quark-hadron phase transition and restoration of chiral symmetry at large baryo-chemical potential are expected to be found from the CBM energy scan program.

■ Rare probes like; Charmed hadrons (D, Λ_C), Multi-strange Hyperons, Hyper-nuclei are copiously produced even at such low energies due to high beam luminosity.

■Precise measurement of dilepton invariant mass spectrum in the region ($M_{inv.} \leq 1$ GeV) provides valuable information about in-medium mass modification of vector mesons.

Ref: P. Senger, Prog. Part. Nucl. Phys., 62 (2009)

■Dynamic evolution of intensive properties of the system or the final state particle yield is described by various microscopic (AMPT, UrQMD) or macroscopic (Hydrodynamics, Statistical Thermal Model) models.

■Macroscopic models rely upon the assumption of local thermodynamic equilibrium of the system, however the microscopic Monte-Carlo models do not require such assumption.

■**Our goal in the present study** is to investigate the time scale of local thermal equilibration of the hadronic matter created in such collisions; specially the baryons (non-strange and strange).

■We have used UrQMD-3.3p2 model to simulate central (b=2fm) **Au+Au** collisions at the laboratory energies 10, 20, 30, 40 GeV/ nucleon.

Brief tour to UrQMD model

❖The Ultra Relativistic Quantum Molecular Dynamics (UrQMD) is a N-body transport model extensively used for describing heavy ion collisions of c.m. energy ranging from a few GeV/ nucleon to a few TeV/ nucleon. It includes 55 baryon species (up to mass 2.25 GeV) and 32 meson species (up to mass 1.9 GeV) and their isospin projected states and corresponding anti-particles.

Ref: S. A. Bass et al., Prog. Nucl. Part. Phys. 41, 225 (1998)

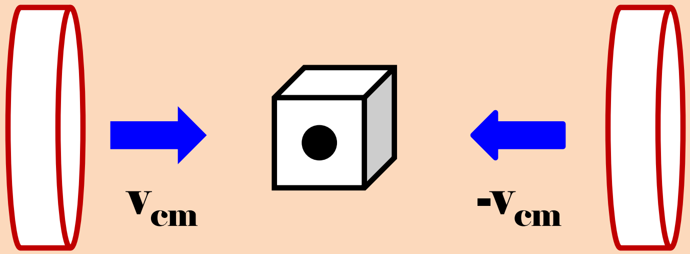
❖***Initialization***: the projectile and target nuclei are modeled in the spirit of Fermi gas model. The nucleons are described by Gaussian density distributions and the wavefunction of the nucleus is defined as product of single nucleon wavefunction. The distance between the target and projectile is set 0.0 fm and Lorentz contraction has been taken into account.

❖For $E_{lab} > 4$ GeV/ nucleon, the hadron-hadron collisions are performed stochastically in the spirit of Cascade model. UrQMD only considers binary elastic and inelastic collisions. The total cross-sections are fitted through experimental p-p or p- π scattering data and iso-spin symmetry is used to reduce the number of available cross-sections. Hyperon-Baryon collisions are scaled to n-n collisions with Additive Quark Model.

❖Particles are generated in UrQMD via s-channel collisions, decay of resonances and string decays (similar to Lund string fragmentation at high energies). The inelastic collisions and decays are the only source for changing chemical composition of the system while the elastic collisions changes the momentum distribution of hadrons.

Choice of volume in phase space

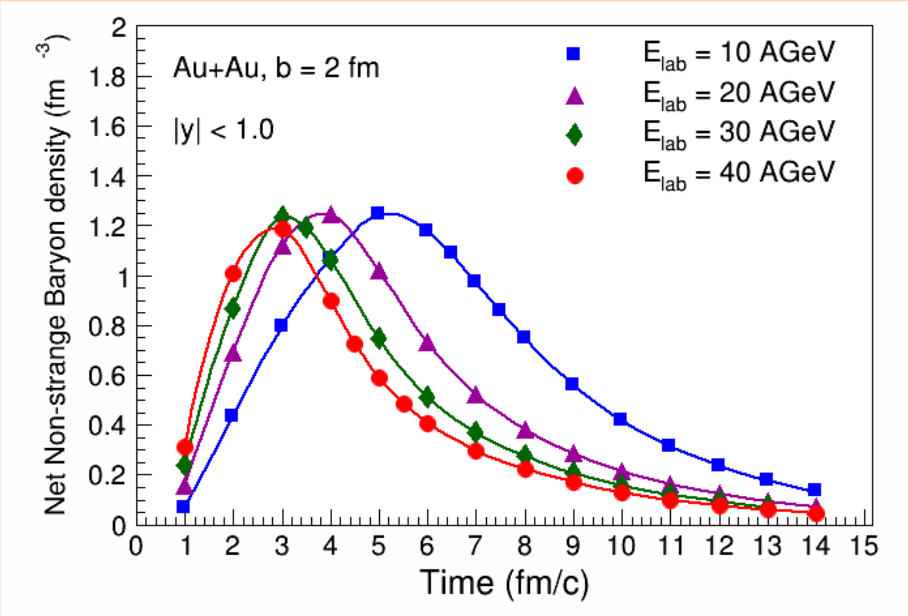
- We have considered a cell ($2\times2\times2$ fm^3) centered around the origin in the c.m. frame of Au+Au system in order to minimize the effect of collective flow. In addition, we are only interested in the rapidity window $|\mathbf{y}_{cm}| < 1.0$.

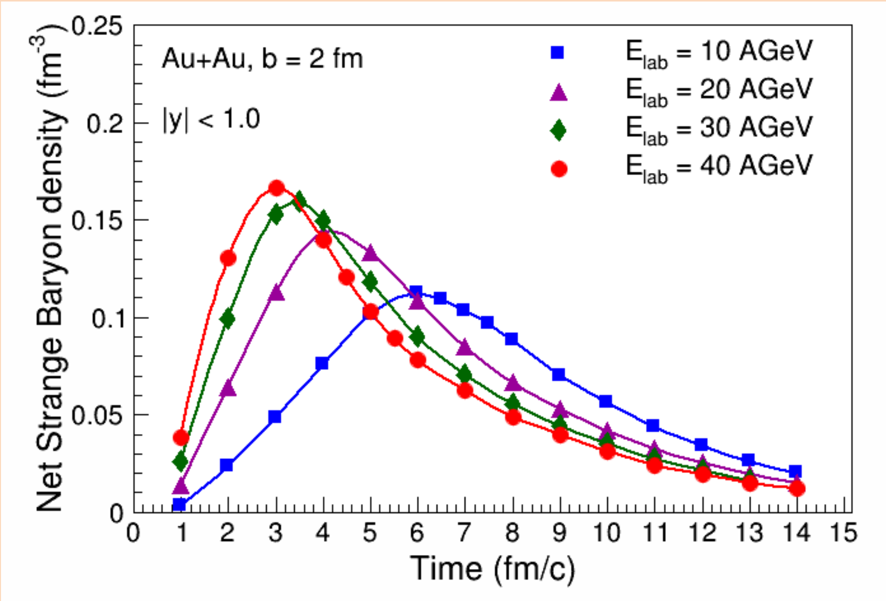


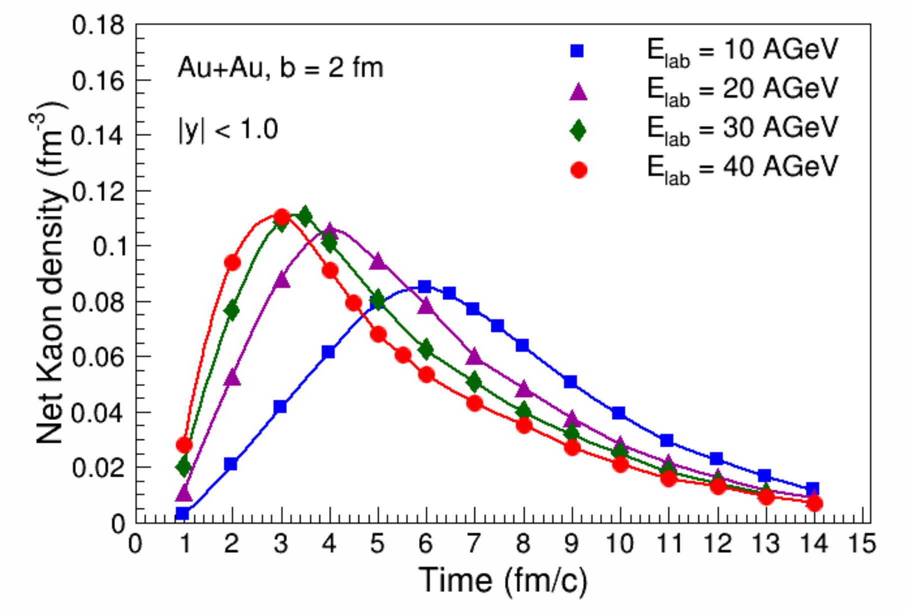
- We have studied time evolution of Net particle density, Longitudinal-to-Transverse pressure anisotropy ratio, Inverse slope parameter of the energy spectra for Non-strange baryon (p,n), Strange baryon (Λ, Σ, Ξ, Ω) and Kaons (K^+, K^0). All higher mass resonances are allowed to decay.

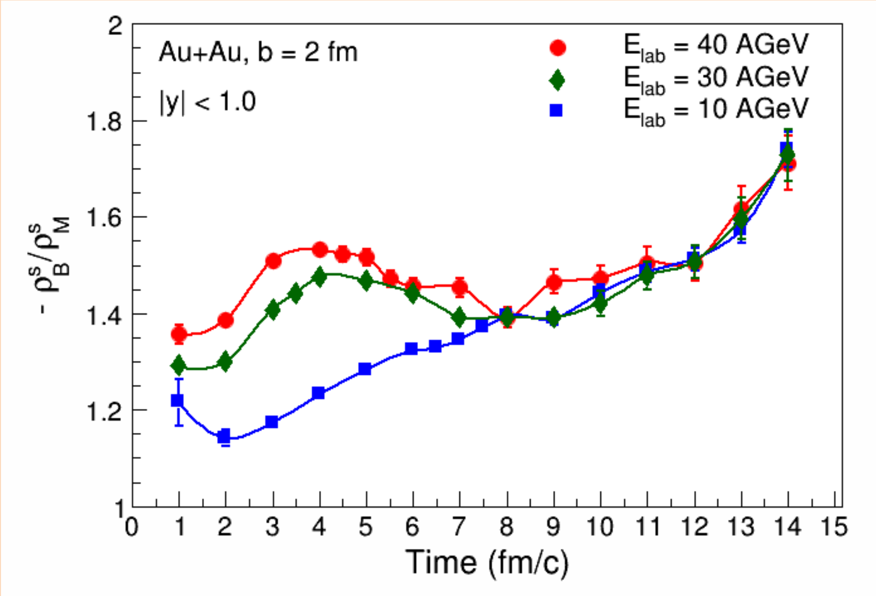
- The above physical quantities are statistically averaged over **60K** events for each time step.

Evolution of particle densities









Isotropization of pressure components:

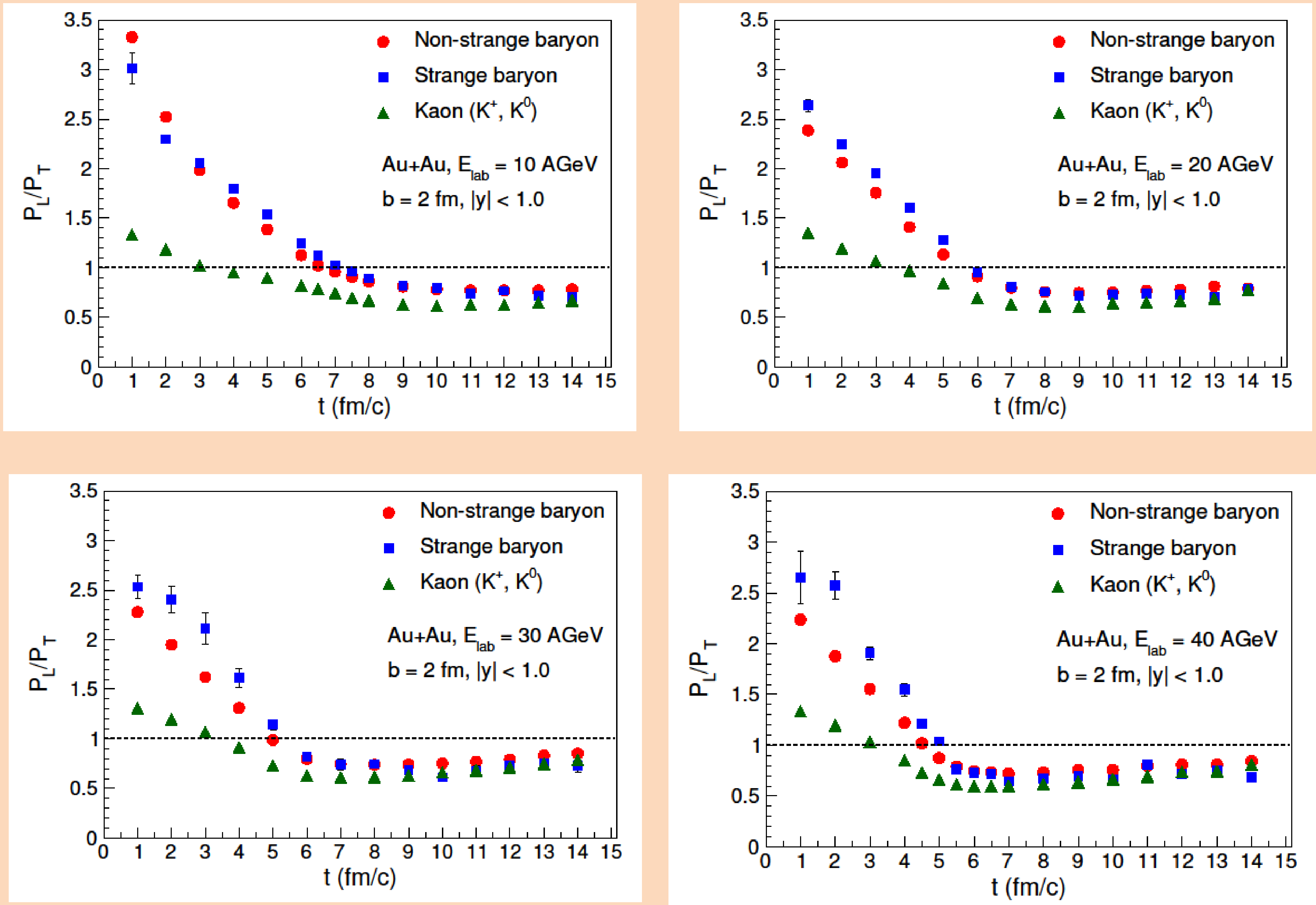
- Consider an ideal gas of relativistic particles, different components of microscopic pressure of hadrons are calculated in **UrQMD** as:

$$P_{\{x,y,z\}} = \sum_i \frac{p^2_{i\{x,y,z\}}}{3V(p_i^2 + m_i^2)^{1/2}}$$

$$P_L = \langle P_z \rangle \qquad P_T = \frac{1}{2}(\langle P_x \rangle + \langle P_y \rangle)$$

- Thermal equilibrium is established inside the cell when microscopic pressure components have become nearly isotropic.

- We have studied the time evolution of longitudinal-to-transverse pressure ratio (**P_L / P_T**) at the four laboratory energies.



Non-strange baryon
Strange baryon
Kaon (K^+, K^0)
Au+Au, E_{lab} = 10 AGeV
b = 2 fm, |y| < 1.0
Au+Au, E_{lab} = 20 AGeV
b = 2 fm, |y| < 1.0
Au+Au, E_{lab} = 30 AGeV
b = 2 fm, |y| < 1.0
Au+Au, E_{lab} = 40 AGeV
b = 2 fm, |y| < 1.0
P_L/P_T
t (fm/c)

❑*Key points of observation*

- The pressure anisotropy (**P_L / P_T**) of non-strange and strange baryons becomes almost constant ~0.8-0.7 for t≥ 9fm/c , 8 fm/c, 7 fm/c and 6 fm/c at E_{lab} = 10A GeV, 20A GeV, 30A GeV and 40A GeV respectively.

- The (**P_L / P_T**) ratio of kaons has found to saturate at~ 0.6-0.7 at the similar time scales as the baryons.

- A small difference (Δt~0.5 fm/c) between the pressure isotropization time of non-strange barons and strange baryons can be noticed.

- Earlier studies for Au+Au collisions at AGS energies (10.7A GeV) by Bravina et al. [PLB, 434 (1998)], has found the thermal equilibrium of hadronic matter for t≥ 10 fm/c.

Thermalization of energy spectrum:

- We have parameterized the baryon energy spectra inside the cell as:

$$E\frac{dN}{d^3p} = C(1+(q-1)E/T)^{\frac{-1}{q-1}}$$

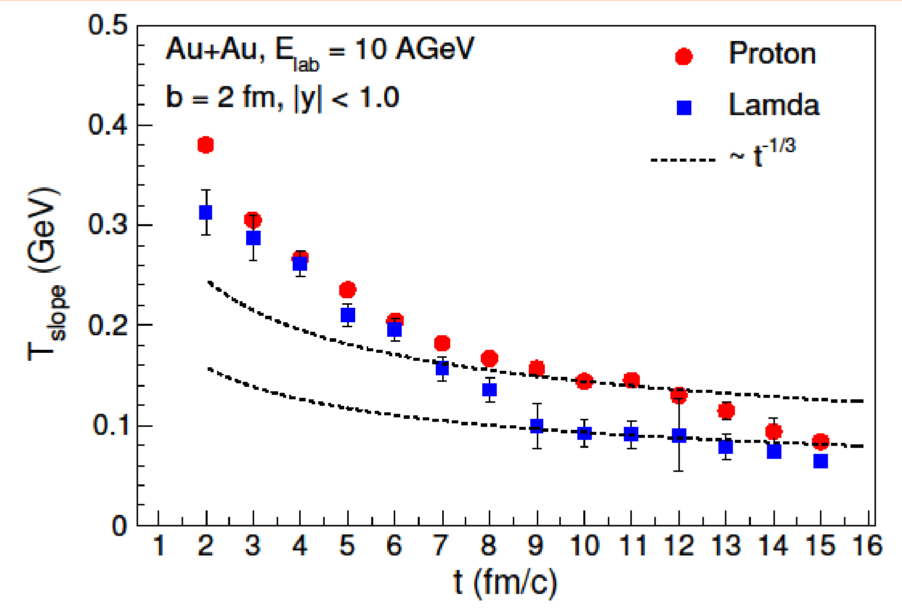
Tsallis distribution

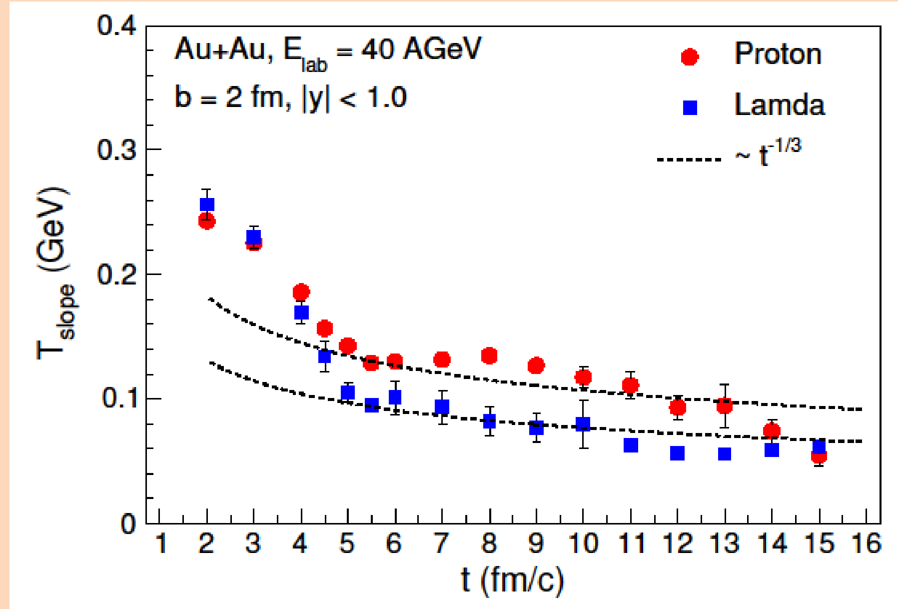
Ref.: C. Tsallis et al., Phys. Lett. A, 310 (2003) 372.

- Inverse slope parameter (T_{slope}) : T + (q-1) E

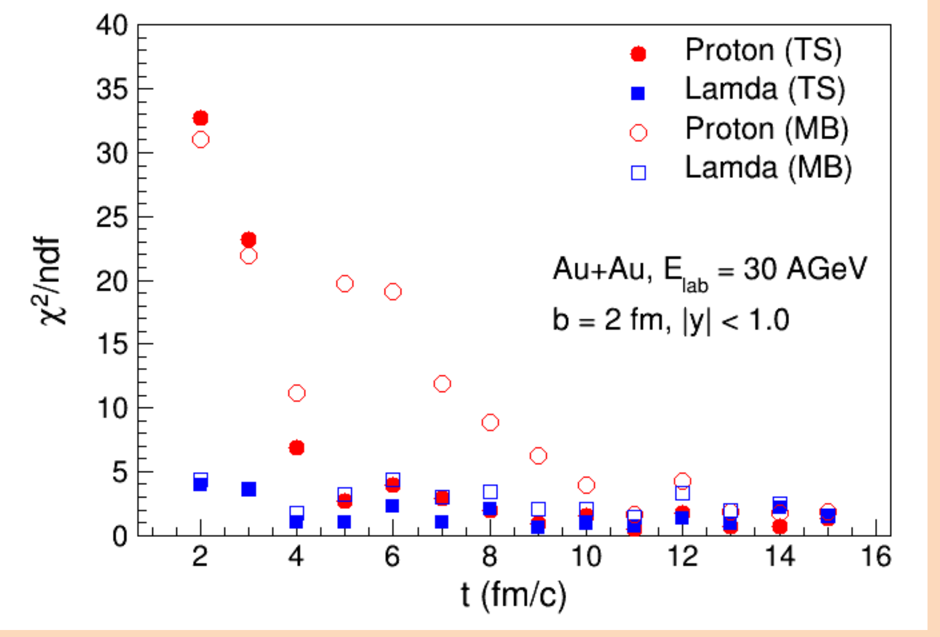
- In the asymptotic limit (E$\rightarrow$ 0); T_{slope} corresponds to thermodynamic temperature of the system. Ref. : Biro and Purcsel, Phys. Lett. A, 372(2008)

- We have studied the time evolution of T_{slope} (at E = 0.1 GeV) of Lamda and Proton energy spectra at four collision energies.

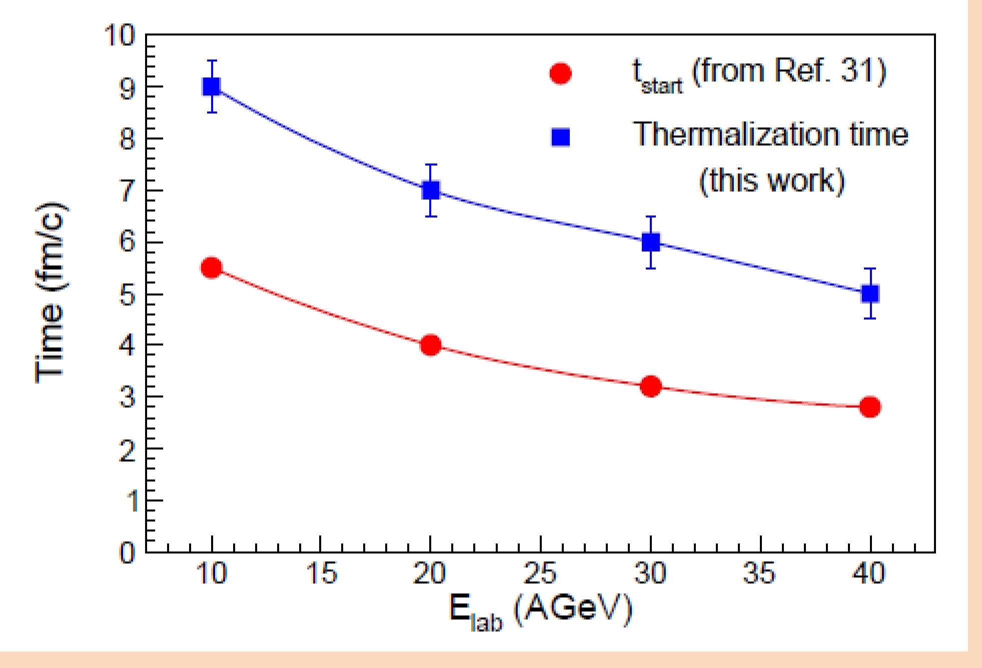




- We found T_{slope} approximately scales as **~ $t^{-1/3}$** for $t \geq 9$ fm/c at 10A GeV and for $t \geq 5.5$ fm/c at 40A GeV laboratory energy.
- Thus T_{slope} (~ local temperature) is seen to follow the Bjorken scaling solution of ideal realativistic hydrodynamics.
- We consider the time as the local thermal equilibration time for the central cell.



Chi- square fit for Tsallis and Maxwell-Boltzmann distributions



Comparison of time scales:

This work and hydro start time from PRC 78, 044901 (2008)

Comparison with Statistical Thermal Model:

- We have extracted the equilibrium thermodynamic properties like; Temperature, Chemical potential of the hadronic matter during subsequent evolution.

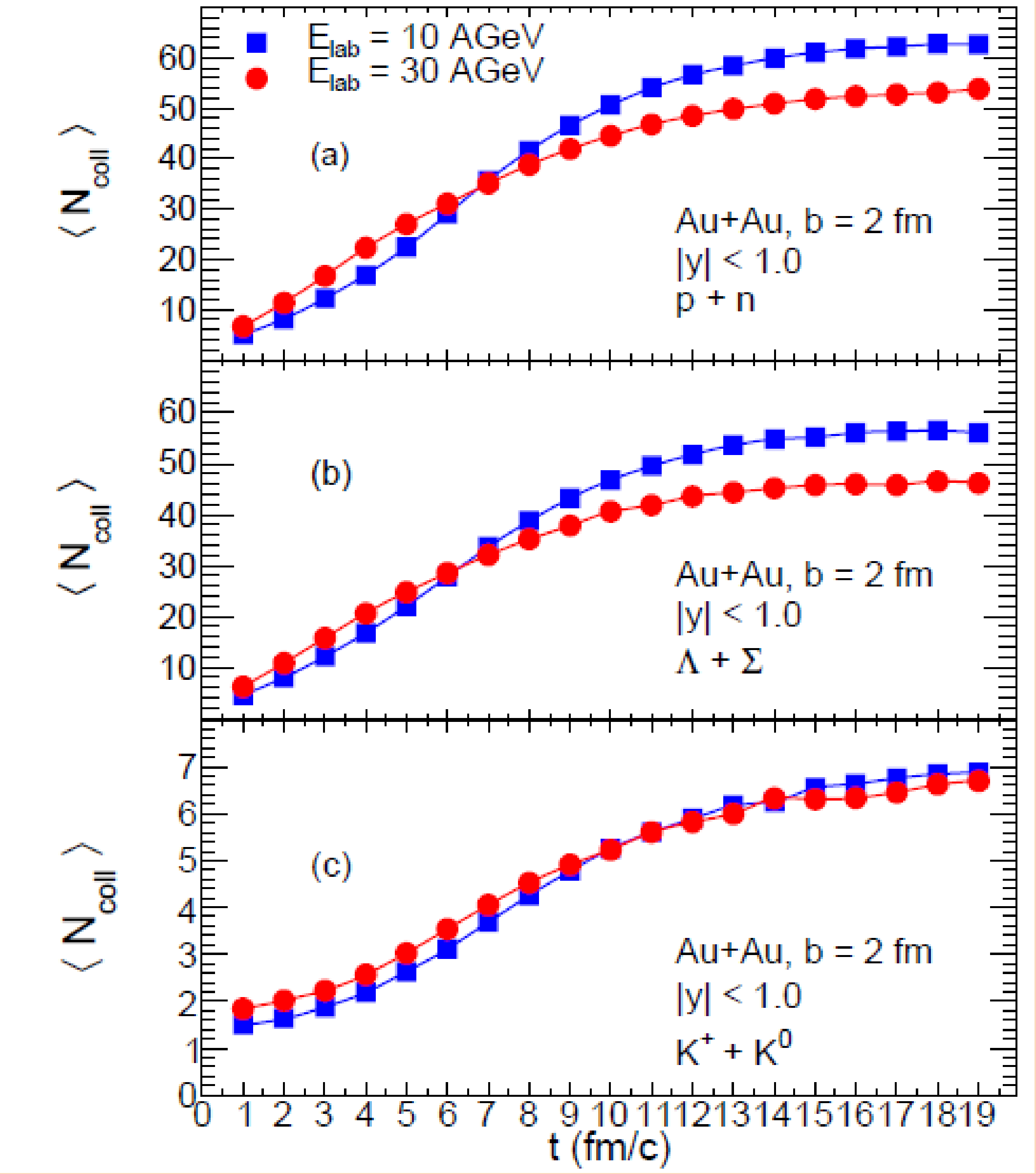
$$n_i = \frac{g}{(2\pi)^3} \int 4\pi p^2 dp\, f_i(T, \mu_i) \rightarrow Number\, density$$

$$\varepsilon_i = \frac{g}{(2\pi)^3} \int 4\pi p^2 dp\, (p^2 + m^2)^{\frac{1}{2}}\, f_i(T, \mu_i) \rightarrow Energy\, density$$

The hadronic chemical potential: $\mu_i = b_i \mu_B + s_i \mu_s$

- A comparison of UrQMD and statistical model is made till thermal freeze-out of the system i.e. mean free path is larger than typical system size.

Time dependence of av. number of collisions:



Thermal model contd..

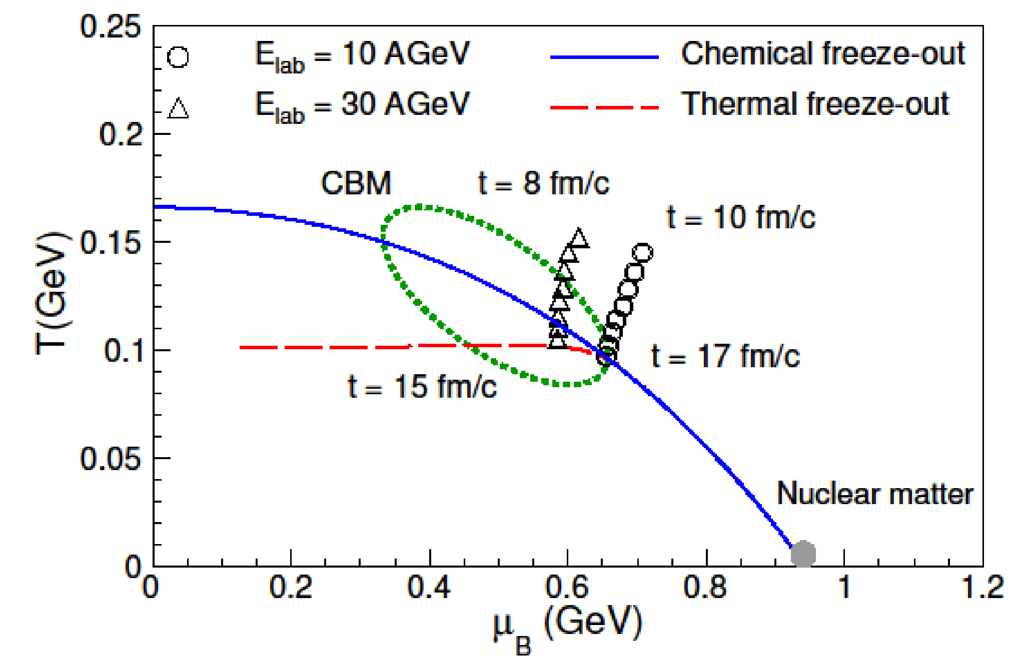
- We have chosen the time interval 10 fm/c $\leq$ t $\leq$ 17 fm/c at E_{lab} =10 A GeV and 8 fm/c $\leq$ t $\leq$ 15 fm/c at E_{lab} =30A GeV.

- T, μ_B, μ_s are extracted from the following set of equations:

$$\varepsilon_B = \sum_i^{baryon} \varepsilon_i, \; n_B = \sum_i^{baryon} b_i n_i, \; n_s = \sum_i^{baryon, meson} s_i n_i$$

- The quantities in L.H.S are obtained from the UrQMD evolution in the central cell of dimension (2×2×2) fm^3 for Au+Au collisions (b=2 fm) at E_{lab} = 10A and 30A GeV.

E_{lab} = 10A GeV				E_{lab} = 30A GeV			
t fm/c	T GeV	μ_B GeV	μ_s GeV	t fm/c	T GeV	μ_B GeV	μ_s GeV
10	0.145	0.708	0.174	8	0.152	0.616	0.123
11	0.136	0.697	0.148	9	0.145	0.601	0.100
12	0.128	0.687	0.125	10	0.137	0.595	0.081
13	0.120	0.680	0.102	11	0.129	0.593	0.067
14	0.114	0.670	0.082	12	0.123	0.587	0.047
15	0.108	0.664	0.070	13	0.115	0.586	0.031
16	0.102	0.659	0.049	14	0.110	0.586	0.019
17	0.097	0.656	0.041	15	0.105	0.585	0.011



Chem. Freeze-out: J. Cleymans PRC 73 034905 (2006).
Thermal Freeze-out: U. Heinz, arXiv:0901.4355

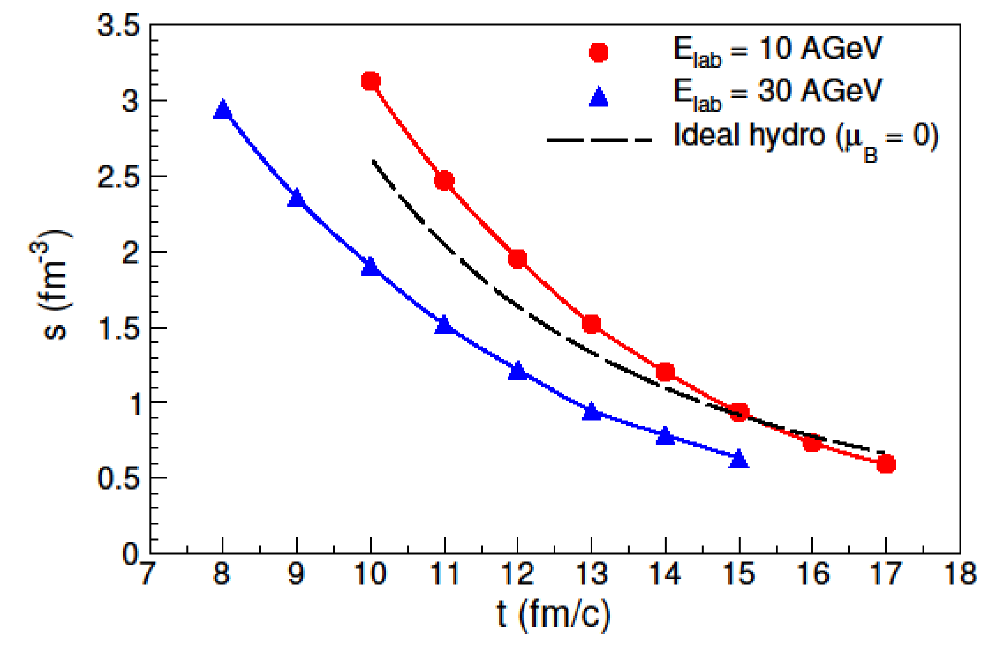
Entropy Evolution:

❖We have also calculated entropy density of baryon matter using the relation:

$$Ts = \varepsilon_B + P - \mu_i(n_B + n_B^s)$$

❖A recent study of S. Jeon, C. Gale *et al*. (PRC 88 (2013)) has conclude:

"We find that a hadron resonance gas with large baryon number density is closer to the ideal fluid limit than the corresponding gas with zero baryon number."



Ideal hydrodynamics result is taken from AZHYDRO simulation. (Ref. nucl-th/0305084)

The baryonic matter produced at 10A GeV is more ideal than the same at 30A GeV beam energies.

Summary and Outlook:

❖We have studied the local thermal equilibrium of baryon rich hadronic matter for central Au-Au collisions at proposed CBM energies.

❖We find the density of particles becomes maximum during the nuclear passage time at the c.m. frame, as expected. Total strangeness content of the created matter is found to be dominated by baryons for all energies.

❖From the analysis of longitudinal-to-transverse pressure anisotropy, we conclude that baryons (strange and non-strange) achieve thermal equilibrium for $t \geq 9$ fm/c at 10A GeV and for $t \geq 6$fm/c at 40A GeV collision energies.

❖An alternative analysis of time evolution of inverse slope parameter of energy spectra of baryons supports the earlier conclusion.

❖ We have found the post-equilibrium evolution of temperature and chemical potential of the system with statistical thermal model.

❖ Time evolution of entropy densities at FAIR energies closely resembles with ideal hydrodynamic evolution at the top RHIC energy.

Thank you