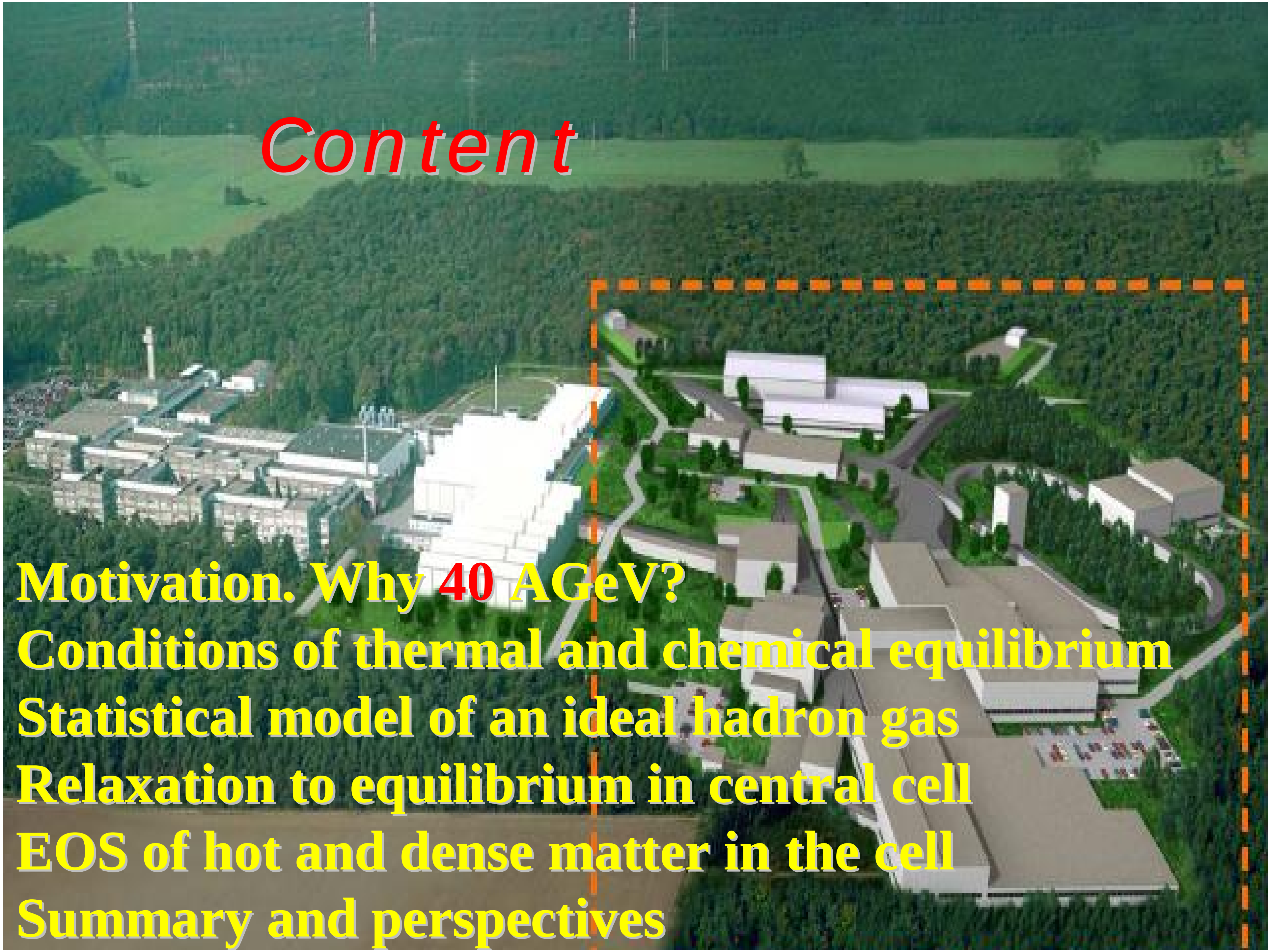
Equilibration of Matter Near QCD Critical Point

Eugene Zabrodin, University of Oslo

Content

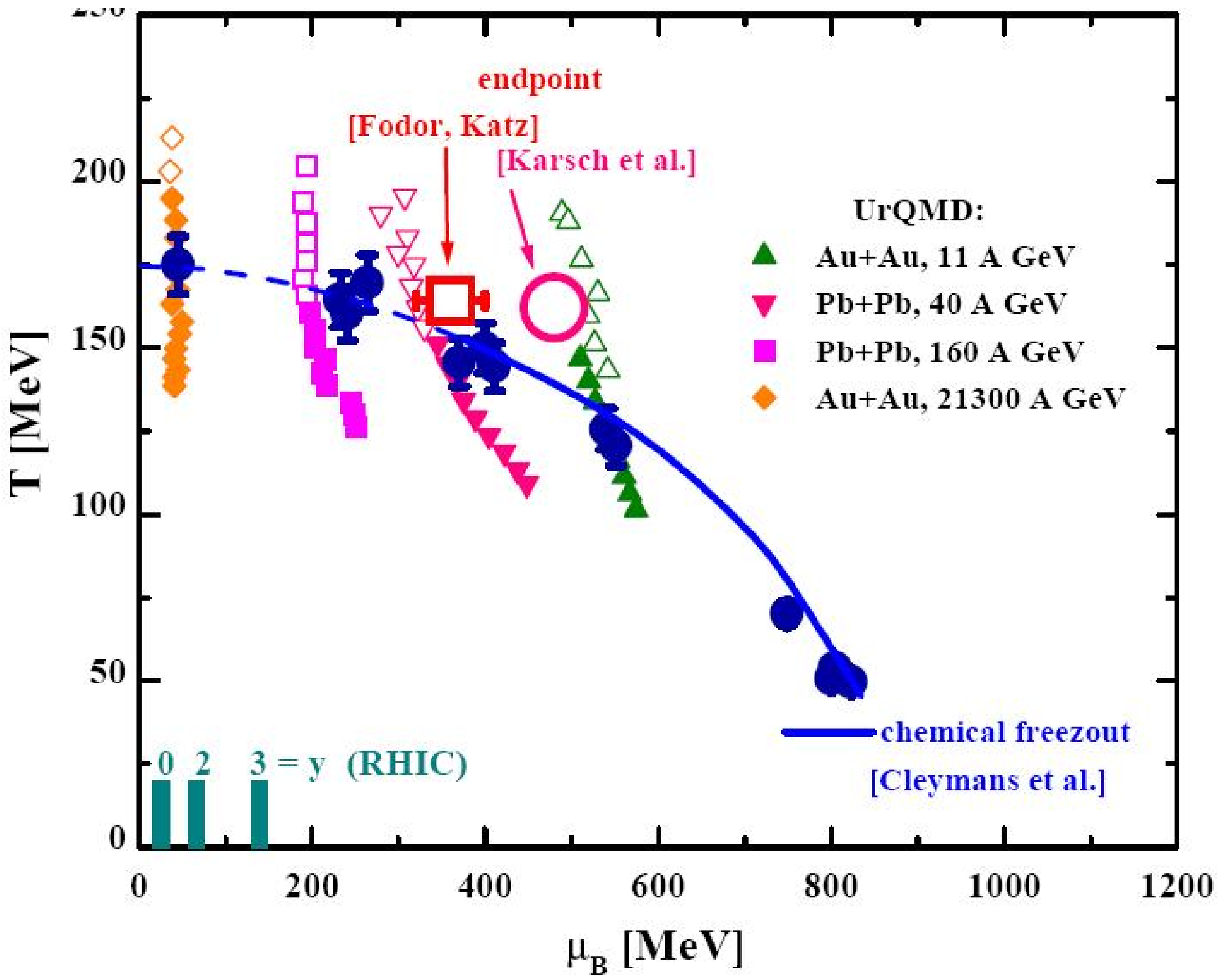


- Motivation. Why 40 AGeV?
- Conditions of thermal and chemical equilibrium
- Statistical model of an ideal hadron gas
- Relaxation to equilibrium in central cell
- EOS of hot and dense matter in the cell
- Summary and perspectives

Motivation

Why 40 AGeV?

Equation of State



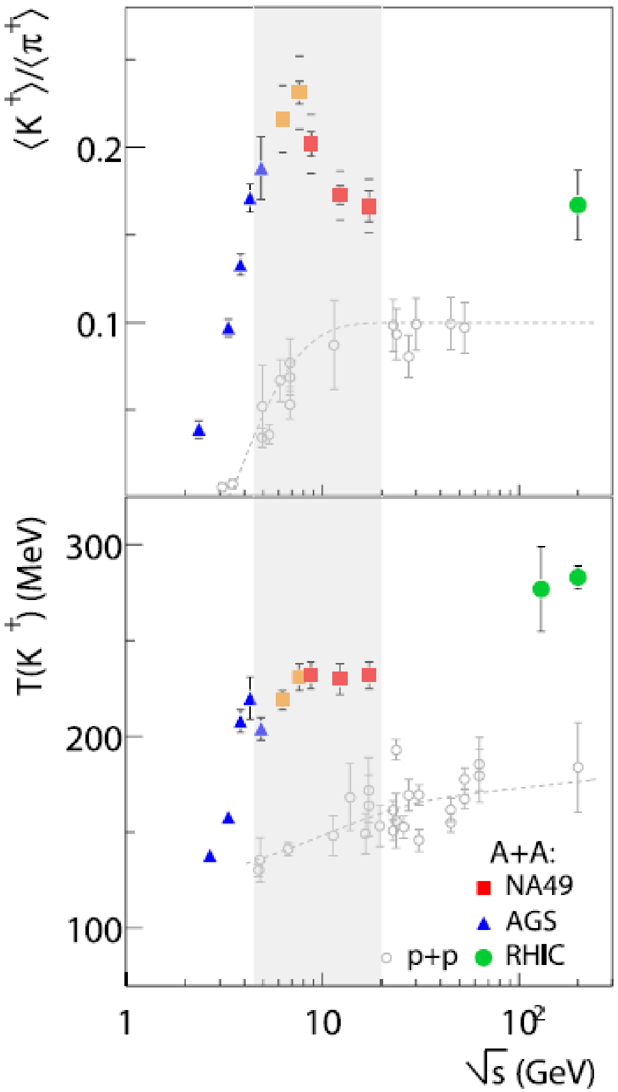
H. Stoecker, nucl-th/0506013
L. Bravina et al., PRC 60 (1999) 024904; 63 (2001) 064902

Tricritical point is located around 10-40 GeV (LQCD)

We have to explore this energy range to study the possible phase transition

QGP can be formed already at low energies

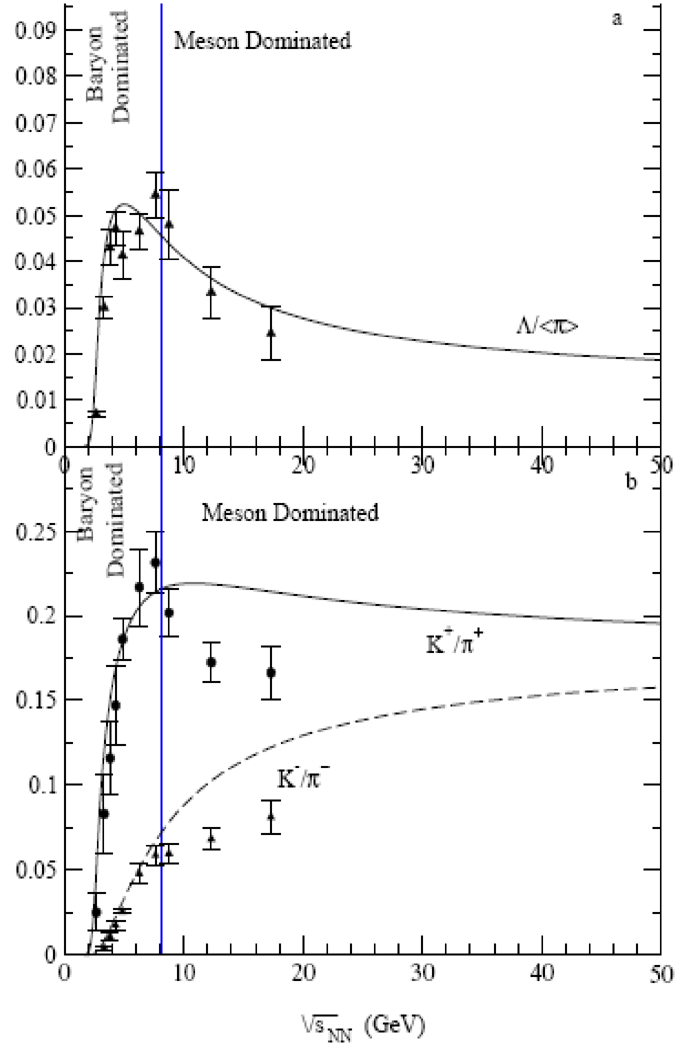
Experimental Indications



Onset of deconfinement

or

transition from baryon to meson dominated matter?



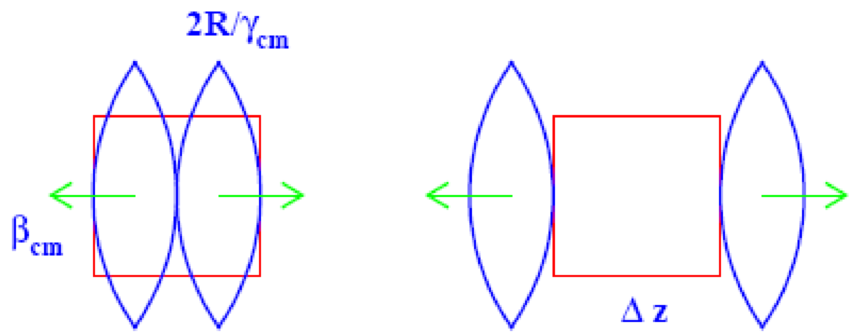
M. Gazdzicki, nucl-th/0512034

J. Cleymans et al., hep-ph/0510283

Central cell:

Relaxation to equilibrium

Equilibration in the Central Cell



$t^{cross} = 2R/(\gamma_{cm}\,\beta_{cm})$

$t^{eq} \geq t^{cross} + \Delta z/(2\beta_{cm})$

Kinetic equilibrium:

Isotropy of velocity distributions

Isotropy of pressure

Thermal equilibrium:

Energy spectra of particles are described by Boltzmann distribution

$$\frac{dN_i}{4\pi p E dE} = \frac{V g_i}{(2\pi\hbar)^3} \exp\left(\frac{\mu_i}{T}\right) \exp\left(-\frac{E_i}{T}\right)$$

Chemical equlibrium:

Particle yields are reproduced by SM with the same values of $(T,\ \mu_B,\ \mu_S)$:

$$N_i = \frac{V g_i}{2\pi^2\hbar^3} \int_0^\infty p^2 dp \exp\left(\frac{\mu_i}{T}\right) \exp\left(-\frac{E_i}{T}\right)$$

Statistical model of ideal hadron gas

input values — output values

$$
\begin{aligned}
\varepsilon^{\rm mic} &= \frac{1}{V}\sum_i E_i^{\rm SM}(T,\mu_{\rm B},\mu_{\rm S}),\\
\rho_{\rm B}^{\rm mic} &= \frac{1}{V}\sum_i B_i \cdot N_i^{\rm SM}(T,\mu_{\rm B},\mu_{\rm S}),\\
\rho_{\rm S}^{\rm mic} &= \frac{1}{V}\sum_i S_i \cdot N_i^{\rm SM}(T,\mu_{\rm B},\mu_{\rm S}).
\end{aligned}
$$

Multiplicity

Energy

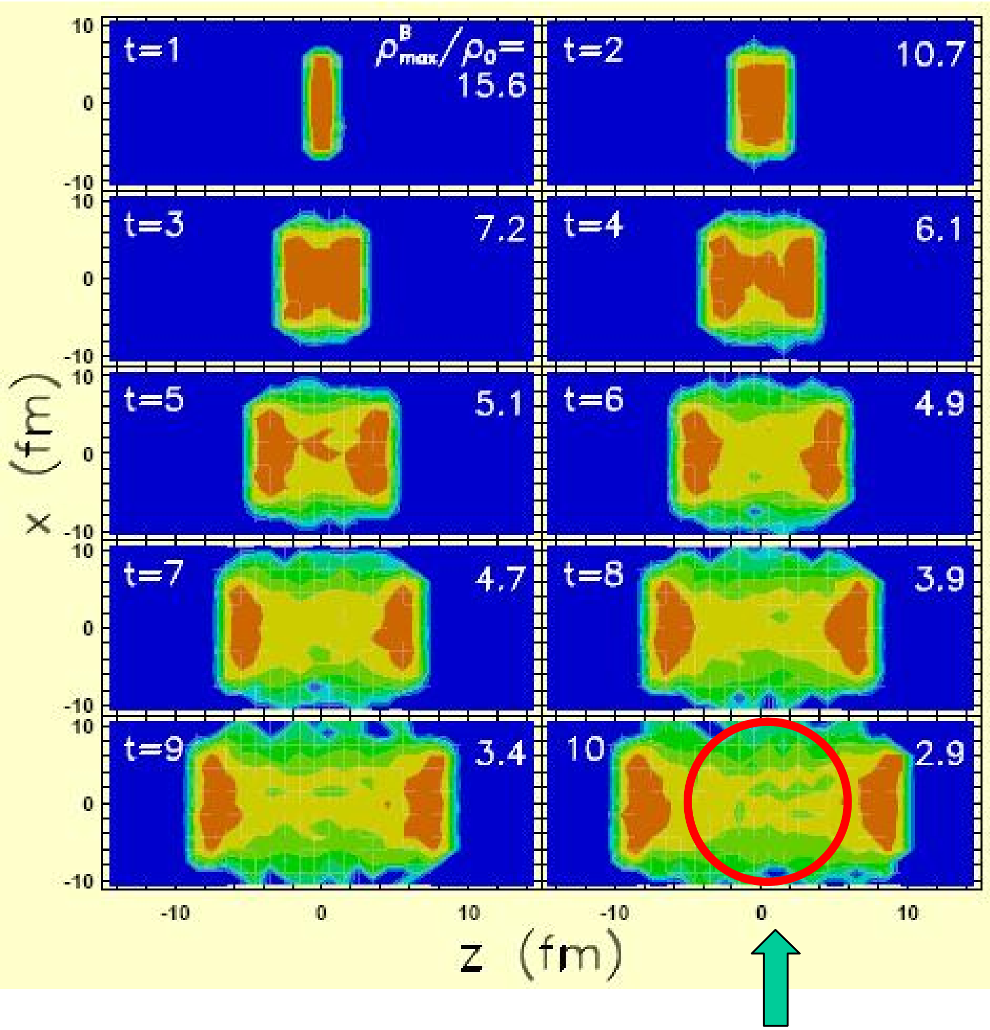
Pressure

Entropy density

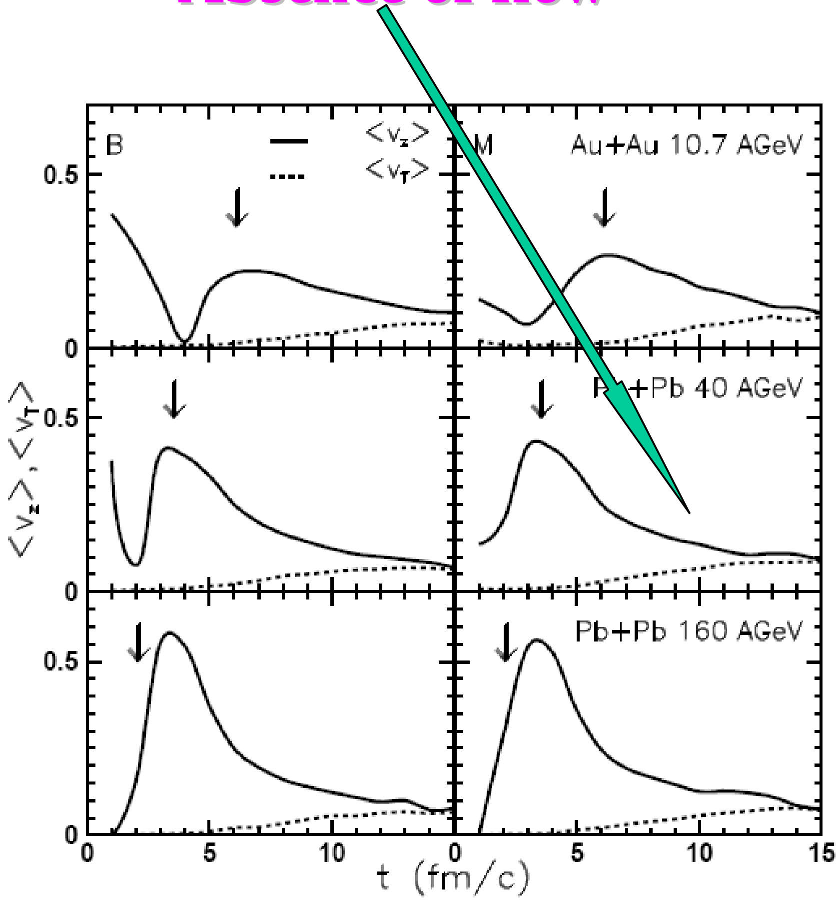
$$
\begin{aligned}
N_i^{\rm SM} &= \frac{V g_i}{2\pi^2\hbar^3}\int_0^\infty p^2 f(p,m_i)dp,\\
E_i^{\rm SM} &= \frac{V g_i}{2\pi^2\hbar^3}\int_0^\infty p^2 \sqrt{p^2+m_i^2}\, f(p,m_i)dp\\
P^{\rm SM} &= \sum_i \frac{g_i}{2\pi^2\hbar^3}\int_0^\infty p^2 \frac{p^2}{3(p^2+m_i^2)^{1/2}}\, f(p,m_i)dp\\
s^{\rm SM} &= -\sum_i \frac{g_i}{2\pi^2\hbar^3}\int_0^\infty f(p,m_i)\ [\ln f(p,m_i)-1]\ p^2 dp
\end{aligned}
$$

Pre-equilibrium Stage

Homogeneity of baryon matter



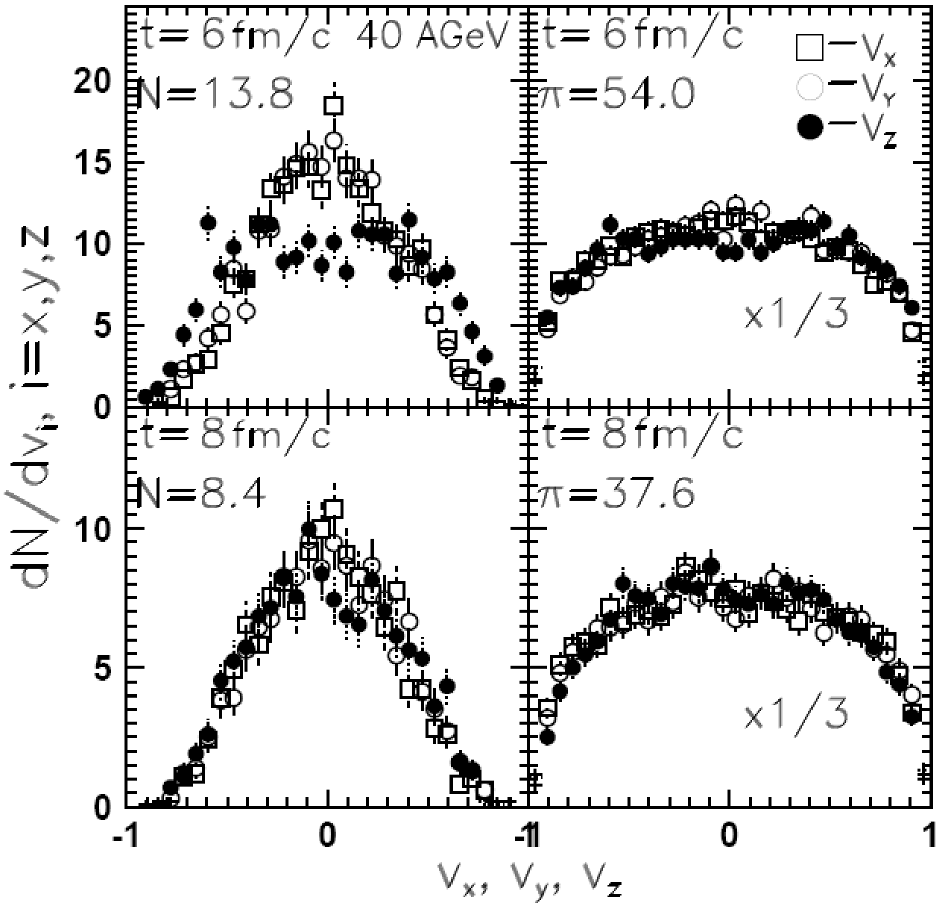
Absence of flow



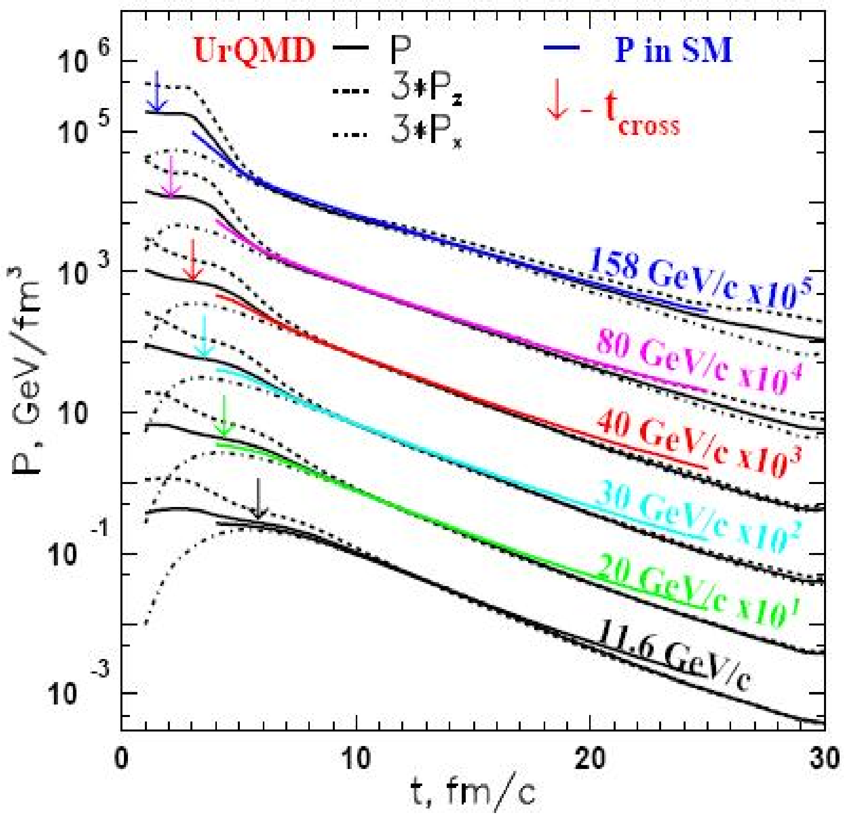
The local equilibrium in the central zone is quite possible

Kinetic Equilibrium

Isotropy of velocity distributions



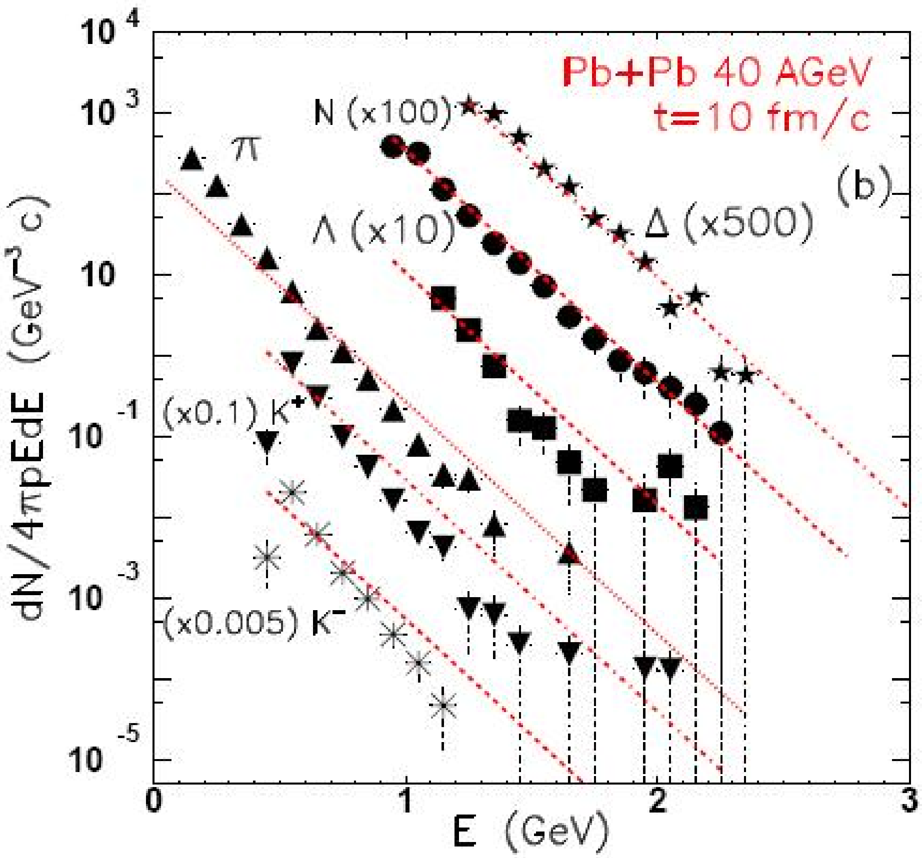
Isotropy of pressure



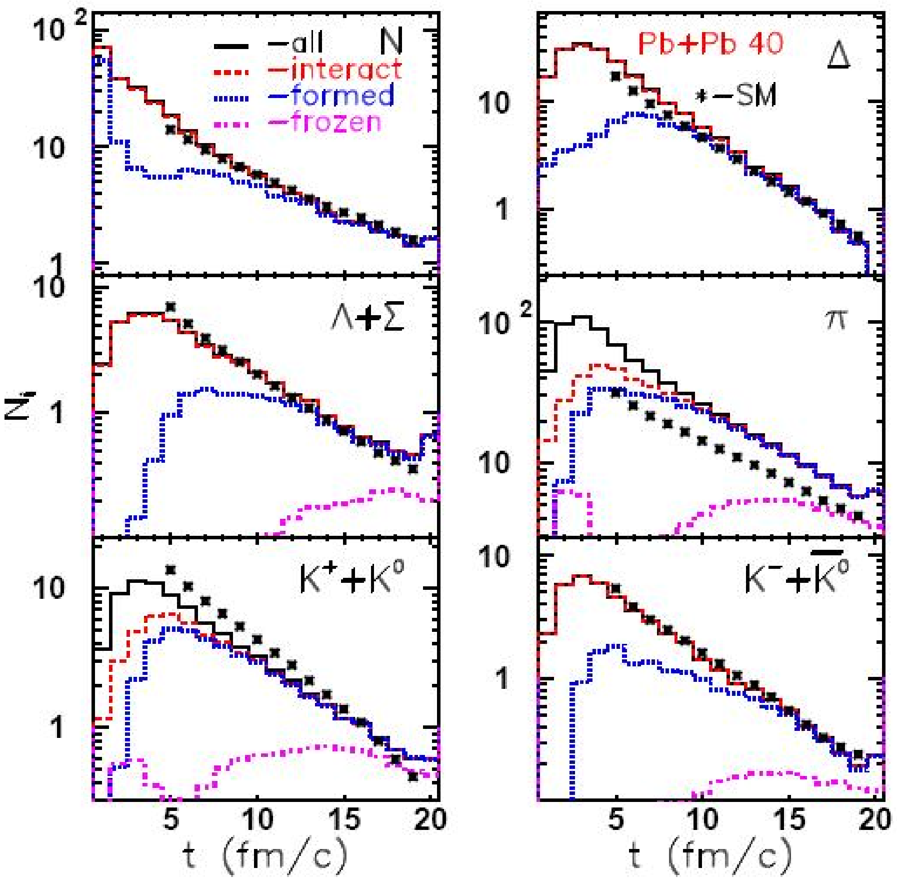
Velocity distributions and pressure become isotropic at t=9 fm/c (for 40 AGeV)

Thermal and Chemical Equilibrium

Energy spectra

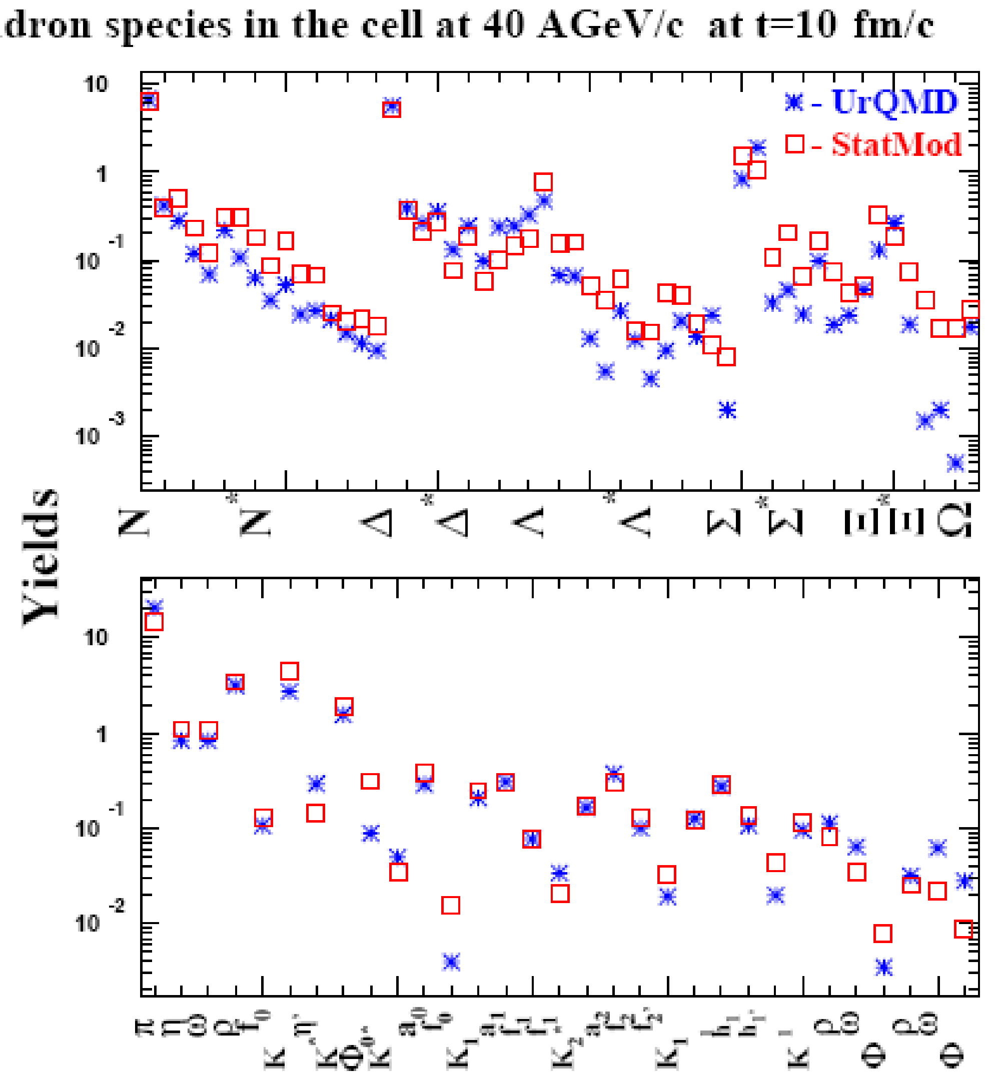


Evolution of yields



Thermal and chemical equilibrium seems to be reached

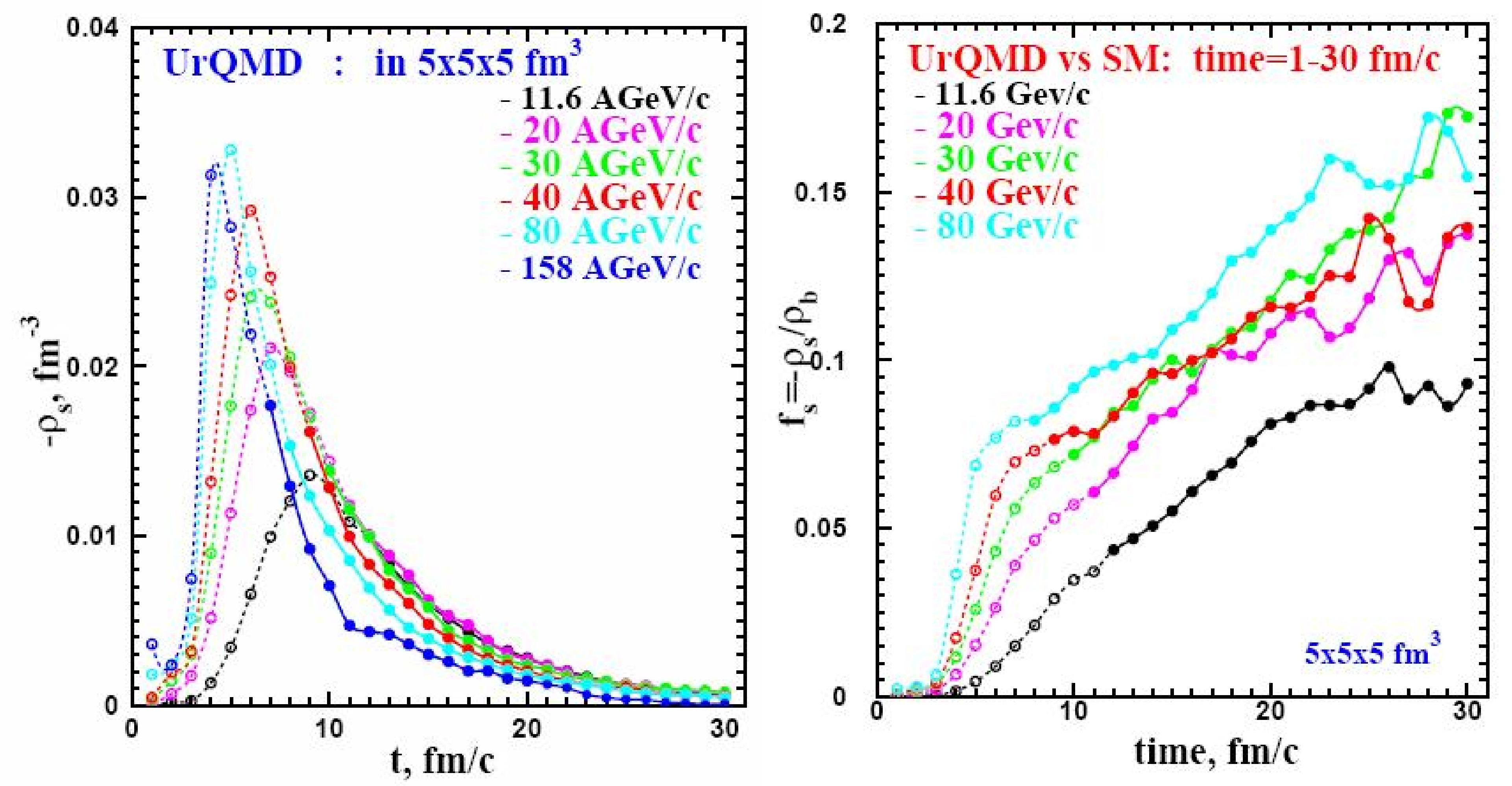
Total yields of hadrons in the cell



The system is very close to chemical equilibrium

Negative net strangeness density

Net strangeness density in the central cell at 11 to 80 AGeV



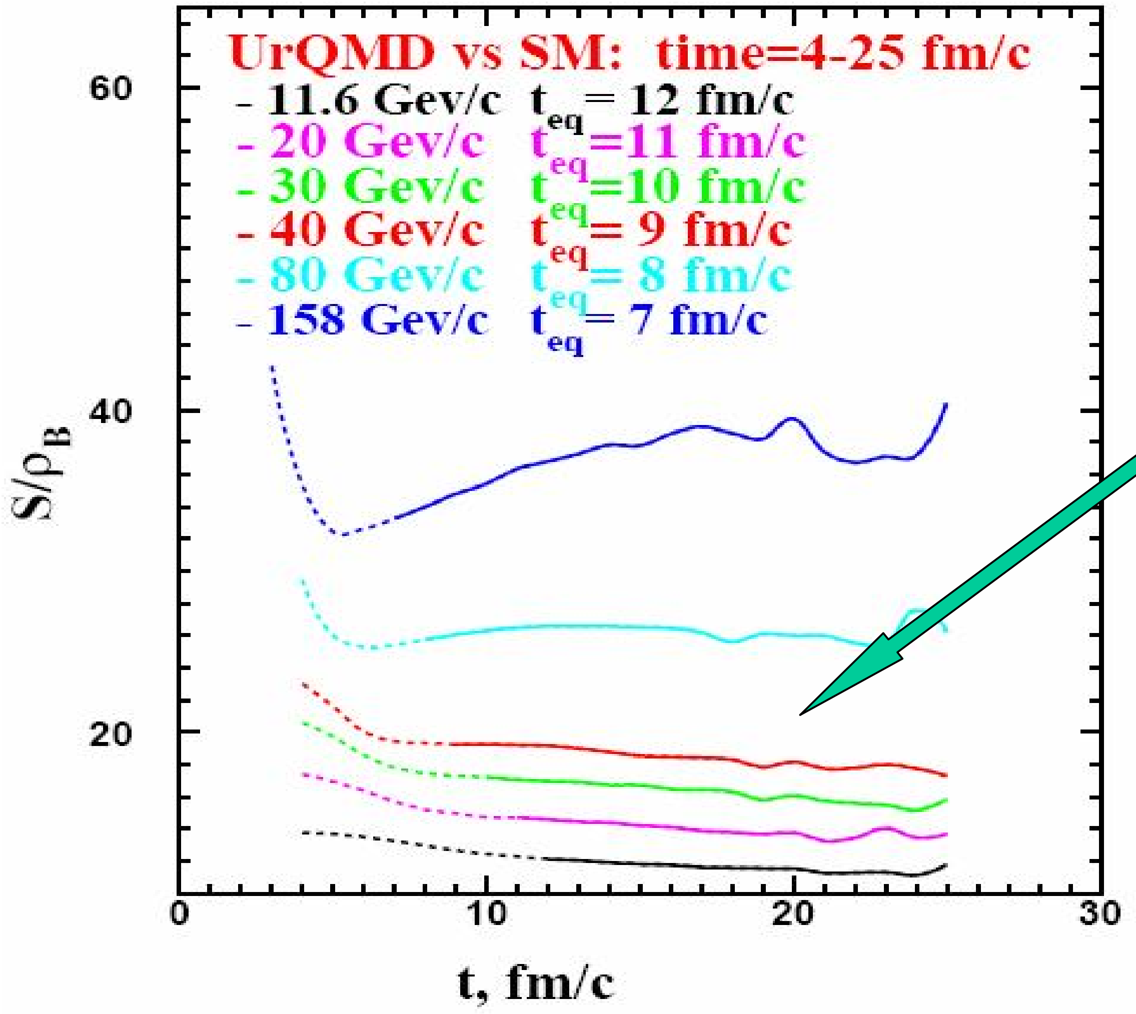
Net strangeness in the cell is negative because of different interaction cross sections for Kaons and antiKaons with Baryons

Equation of State

T vs. energy,

etc

Isentropic expansion

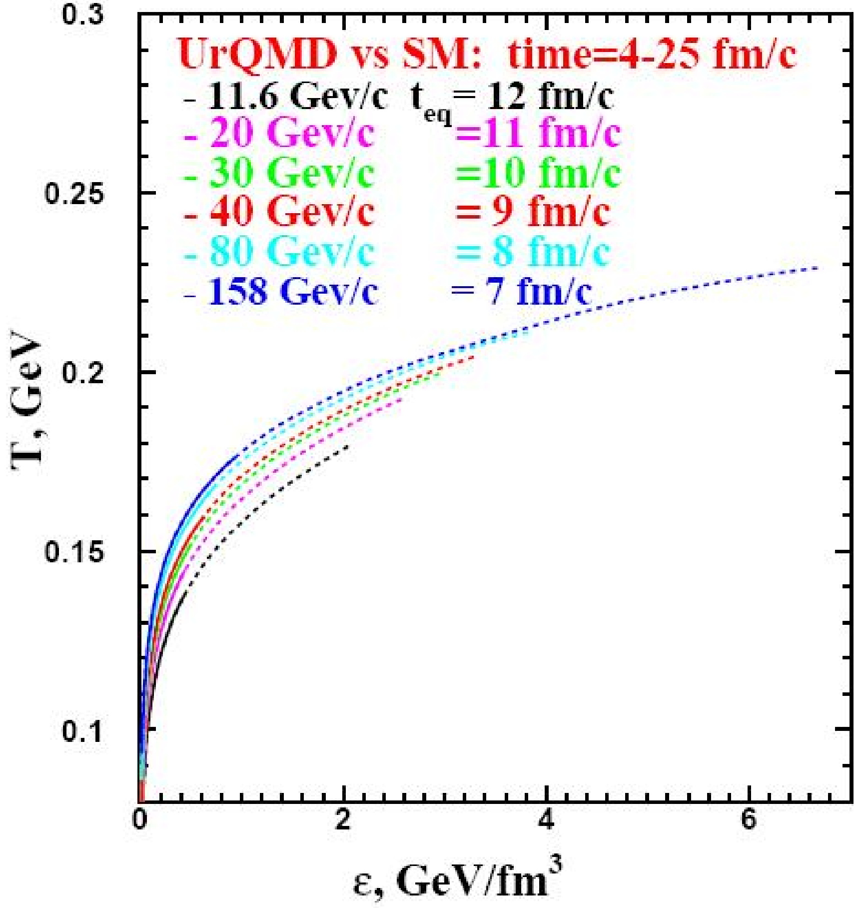


Expansion proceeds isentropically (with constant entropy per baryon). This result supports application of hydrodynamics

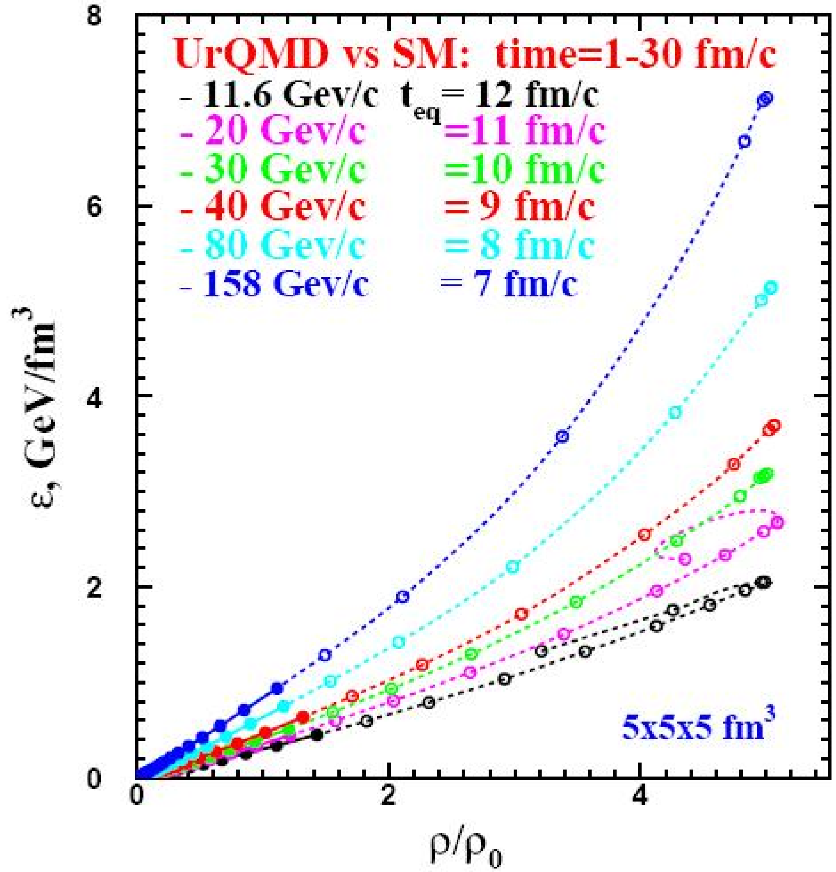
$$s/\rho_B = \text{const} = 12(\text{AGS}),\ 20(40),\ 38(\text{SPS})$$

EOS in the cell

temperature vs. energy



energy vs. baryon density

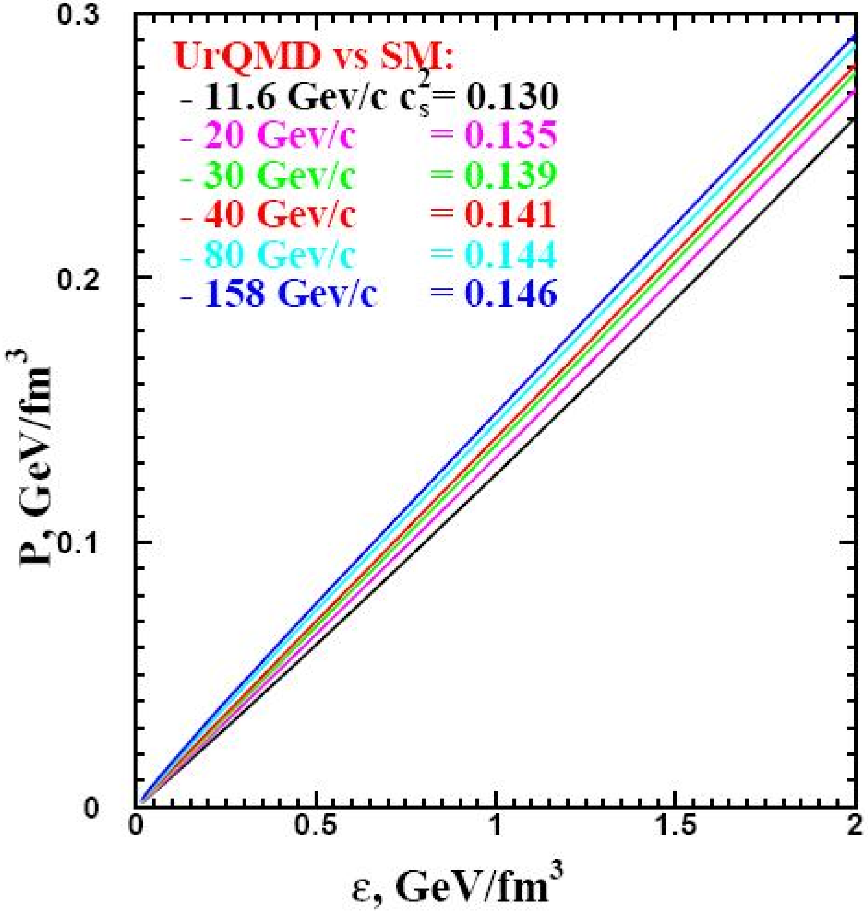


Beginning of temperature "saturation"

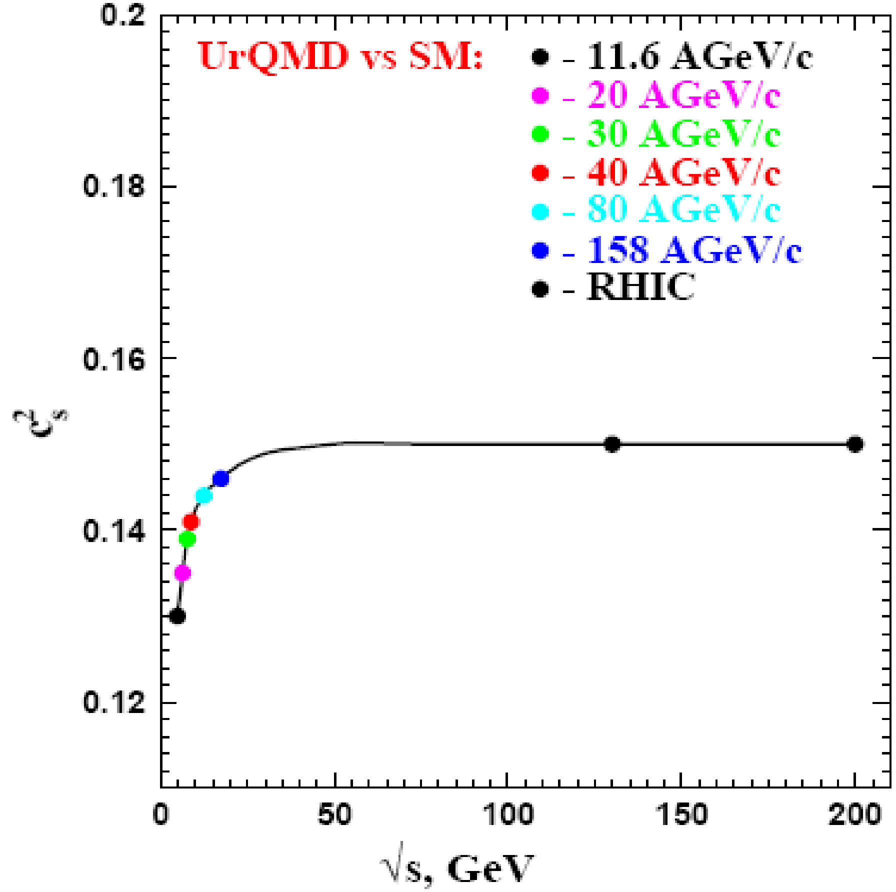
Dense and hot equilibrated matter is formed

EOS in the cell

pressure vs. energy



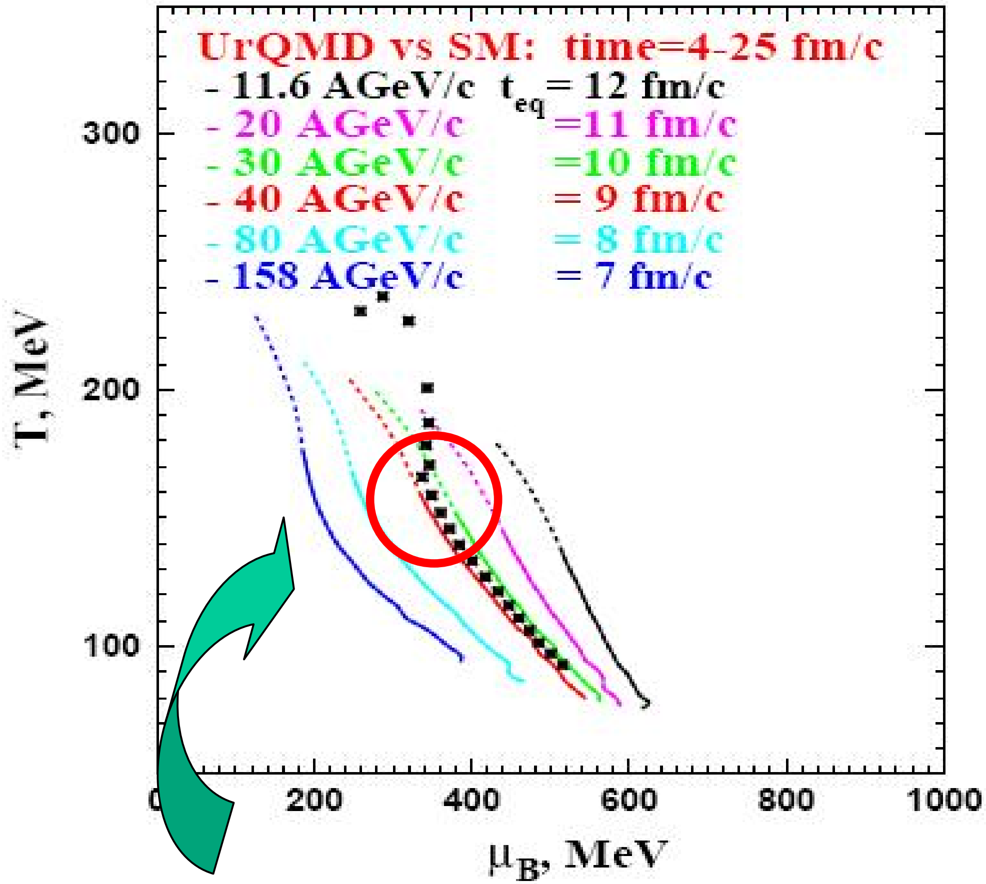
sound velocity



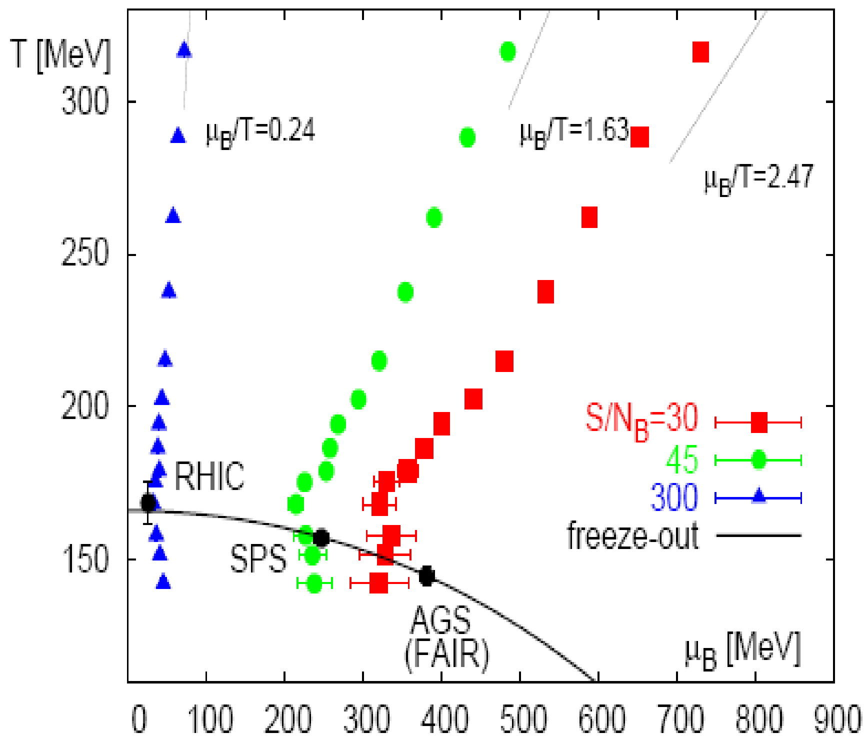
$$P/\varepsilon = 0.13(\mathrm{AGS}),\ 0.14(40),\ 0.146(\mathrm{SPS}),\ 0.15(\mathrm{RHIC})$$

EOS in the cell

temperature vs. baryo-chemical potential



S. Ejiri et al., PRD 73 (2006) 054506



The "knee" is similar to that in 2-flavor lattice QCD

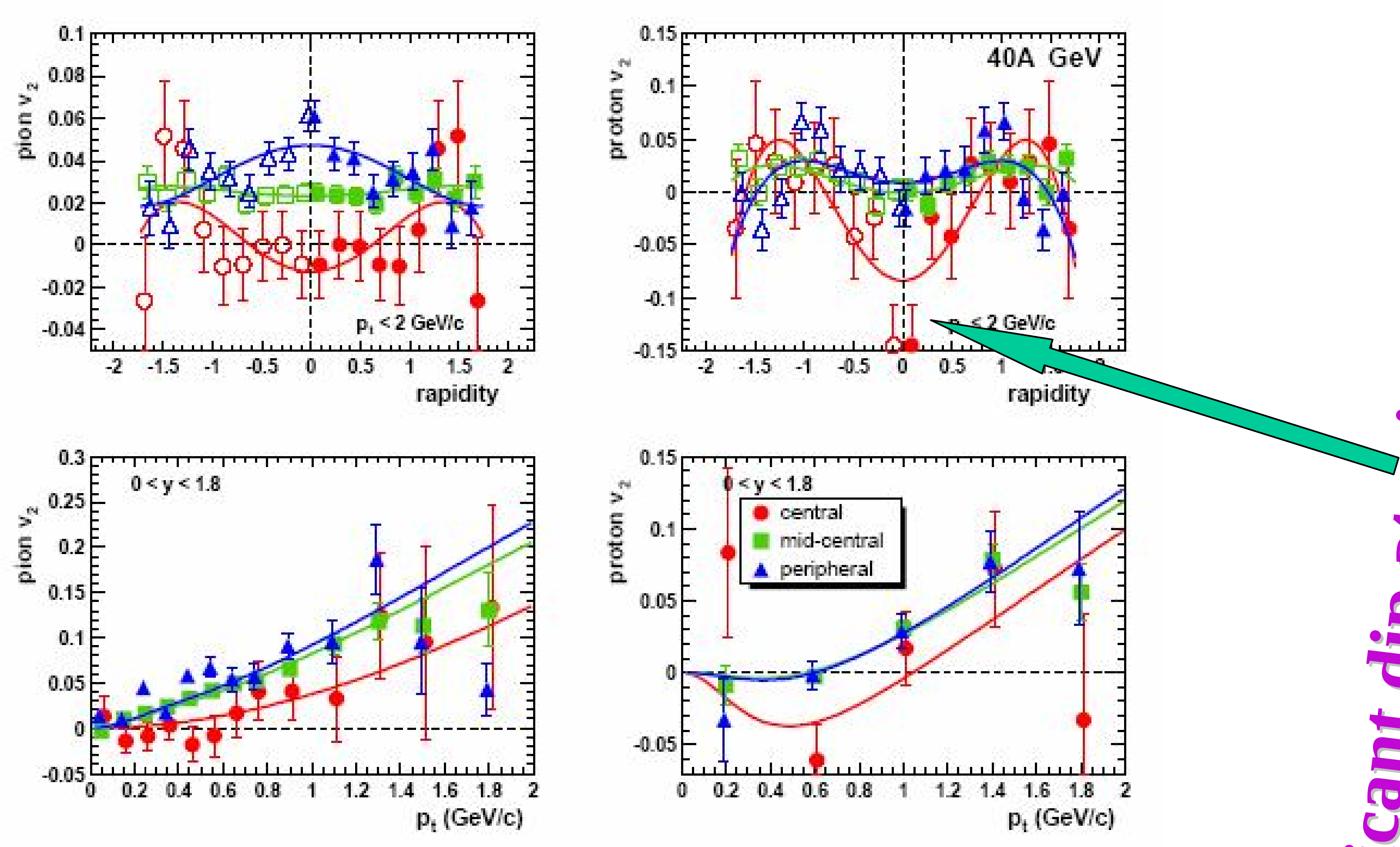
Conclusions

Summary and perspectives

- *There is a kinetic equilibrium stage of hadron-string matter in the central cell at $t > 8$ fm/c*
- *The ratio P/e is approximately constant and equals 0.12 (AGS), 0.14 (40 AGeV), and 0.15 (SPS & RHIC) => onset of saturation*
- *Entropy per baryon ratio remains constant during the time interval 8 fm/c $< t <$ 20 fm/c. This supports application of hydrodynamics*
- *Temperature vs. chemical potential: the knee structure which appears at the onset of equilibrium should be studied further*

Anisotropic flow

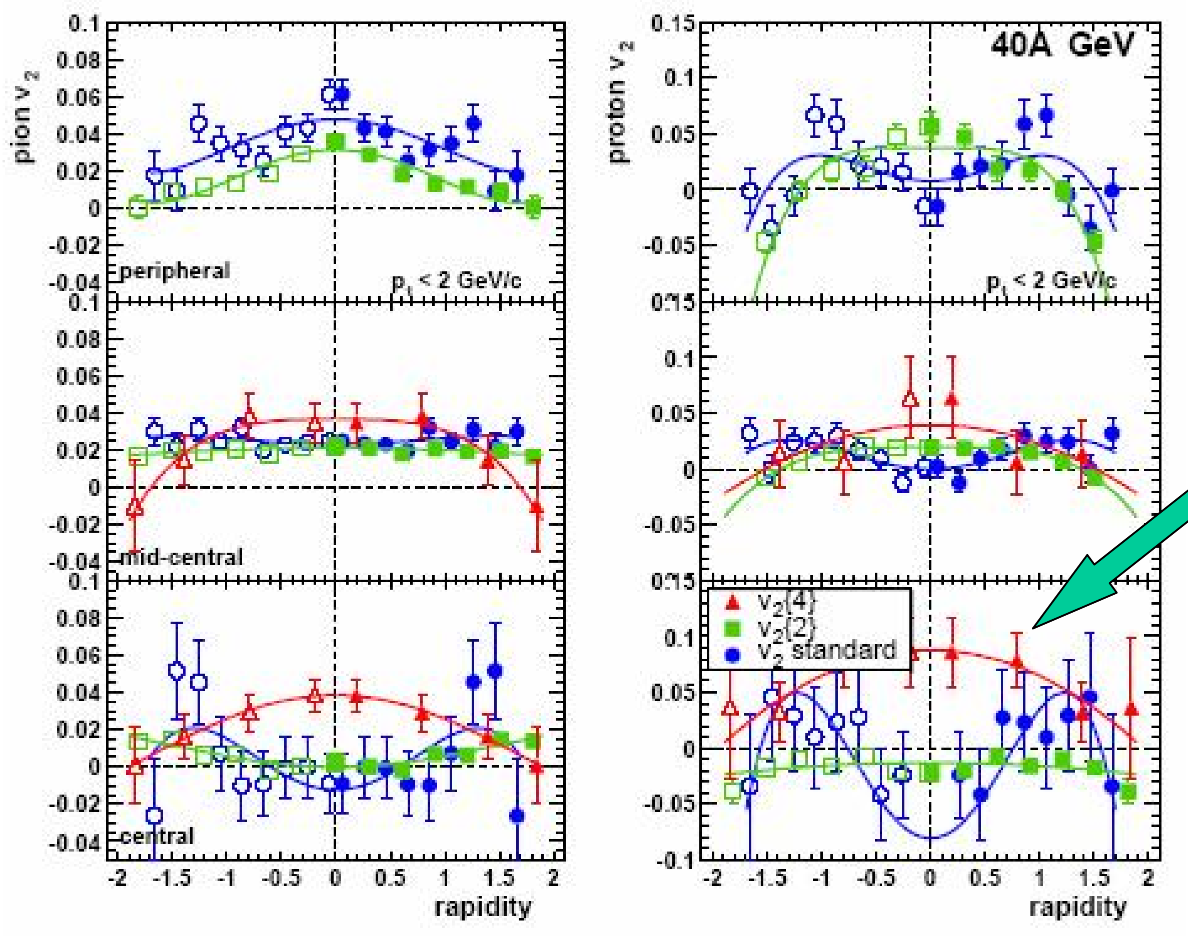
Elliptic flow of pions and protons at 40 AGeV



Significant dip at midrapidity for proton flow in central events

C. Alt et al. (NA49), PRC 68 (2003) 034903

Elliptic flow of pions and protons at 40 AGeV



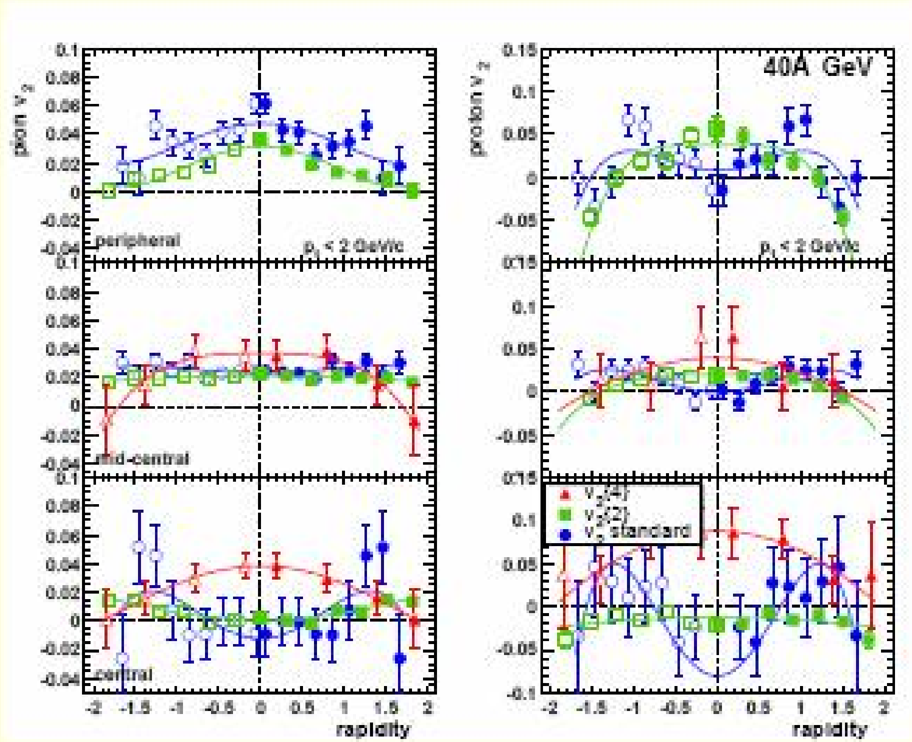
However, the dip at midrapidity disappears if one uses the {2} or {4} cumulant method

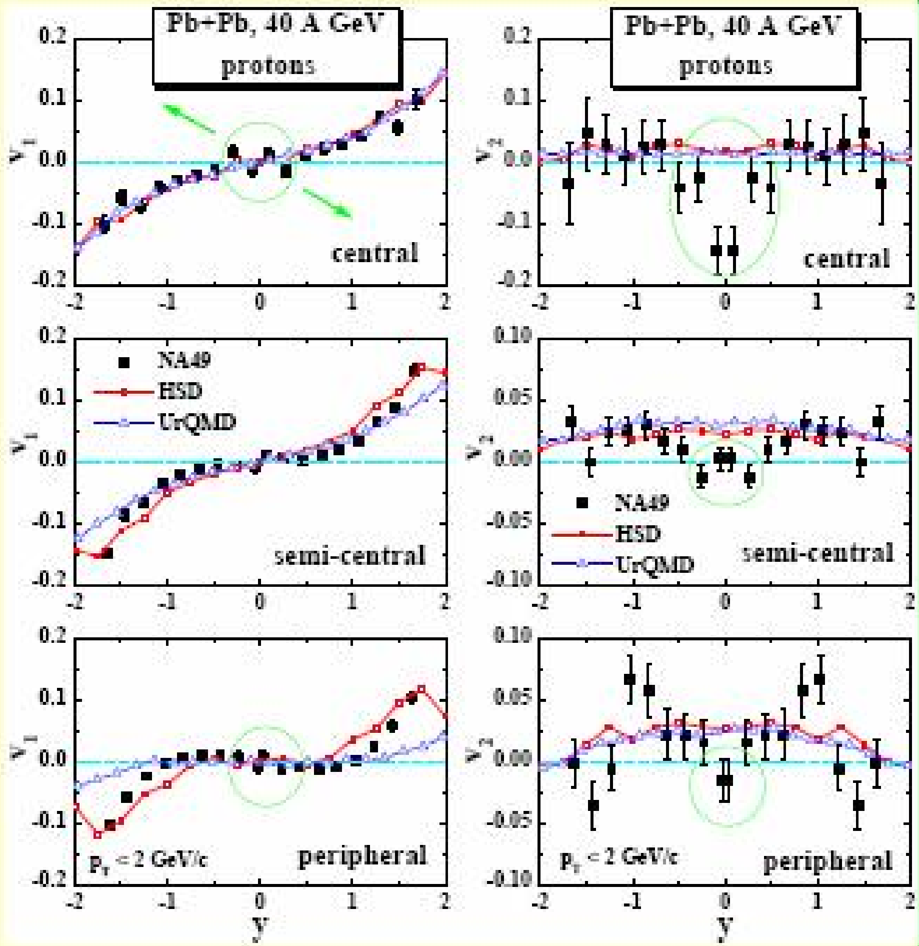
C. Alt et al. (NA49), PRC 68 (2003) 034903

Elliptic flow of pions and protons at 40 AGeV

H. Stöcker *et al.*, nucl-th/0412022

C. Alt *et al.* (NA49 Collab.), PRC 68 (2003) 034903





Collapse of proton elliptic flow:

evidence for a first order phase transition

or for non-flow two-particle correlations?