Heavy-Ion Collisions within Multi-Fluid Simulations: Scenarios with and without Deconfinement Transition

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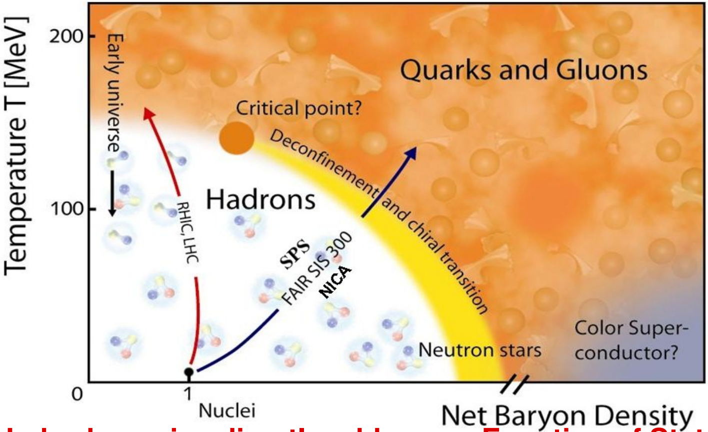
Outline

Exploring Nuclear Phase Diagram



Hydrodynamics directly addresses Equation of State

However, nonequilibrium prevents direct application of Hydrodynamics

Hydrodynamics versus Kinetics

Why we are not satisfied with kinetics?

- In practice, kinetics $\Rightarrow$ only binary collisions
  mean free path $\lambda \approx 1/(n_B\sigma)$
  if $\sigma \approx 4$ fm^2 and $n_B \approx 5n_0 \Rightarrow \lambda \approx 0.3$ fm $\sim$ nucleon core
  ($n_0 = 0.15$ fm^{-3} = normal nuclear density)

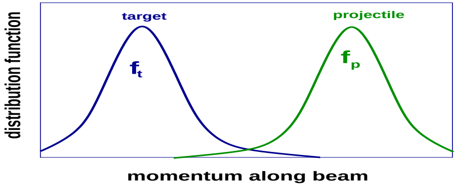
  Approximation of binary collisions is bad!
- Phase transition into QGP is inaccessible in kinetics as a rule

  Two exceptions based on simple combinatorics of quarks:
  A Multi-Phase Transport (AMPT) model [Lin, Ko and Pal, PRL 89, 152301 (2002)]
  Parton-Hadron-String Dynamics [Cassing, Bratkovskaya, arXiv:0907.5331 (2009)]

Hydrodynamics

- takes into account any multi-particle interactions
- directly addresses **Equation of State (EoS)**!
- Phase transition in QGP is accessible through EoS
- However, there are certain **problems**

2-Fluid Models



- Distributions are separated in momentum space
  ⇒ **different fluids**
- Leading particles carry baryon charge
  ⇒ **2 baryon-rich fluids: projectile-like and target-like**

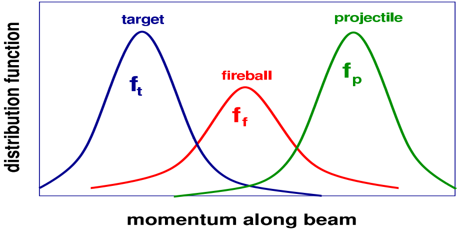
- Los Alamos 1978–1986: **Amsden, Harlow, Nix, Clare, Strottman**
  2-fluid hydrodynamics
- Kurchatov Inst. 1988–1991: **Mishustin, Russkikh, and Satarov**
  2-fluid hydro with free-streaming radiation of pions
- GSI 1991–1997: **Iv., Russkikh, Nörenberg**
  2-fluid mean-field hydro with hadrochemistry for SIS energies

From 2 Fluids to 3 Fluids

- Distributions are separated in momentum space
  $\Rightarrow$ different fluids
- Leading particles carry baryon charge
  $\Rightarrow$ 2 baryon-rich fluids: projectile-like and target-like

At high incident energies ($E_{lab} \gtrsim 10A$ GeV)

- **Produced particles populate mid-rapidity**
  $\Rightarrow$ **fireball fluid**

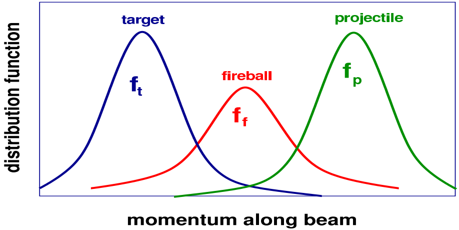


3-Fluid Models

- Kurchatov Inst. 1988–1991:
  2-fluid hydro with free-streaming radiation of pions
  Mishustin, Russkikh, and Satarov
- Frankfurt University 1993–2000:
  3-fluid hydrodynamics with instant formation of fireball
  Brachmann, Katscher, Dumitru, Rischke, Maruhn, Stöcker, Greiner, Mishustin, Satarov, *et al.*
- GSI 2003–now:
  3-fluid hydrodynamics with delayed formation of fireball
  Iv., Russkikh, Toneev

3-Fluid Dynamics, present version

Produced particles populate mid-rapidity
$\Rightarrow$ fireball fluid



Target-like fluid: $\partial_\mu J_t^\mu = 0$ $\quad \partial_\mu T_t^{\mu\nu} = -F_{tp}^\nu + F_{ft}^\nu$

Leading particles carry bar. charge $\quad$ exchange/emission

Projectile-like fluid: $\partial_\mu J_p^\mu = 0$, $\quad \partial_\mu T_p^{\mu\nu} = -F_{pt}^\nu + F_{fp}^\nu$

Fireball fluid: $J_f^\mu = 0$, $\quad \partial_\mu T_f^{\mu\nu} = F_{pt}^\nu + F_{tp}^\nu - F_{fp}^\nu - F_{ft}^\nu$

Baryon-free fluid $\quad$ Source term $\quad$ Exchange

The source term is delayed due to a formation time τ

Total energy-momentum conservation:

$$\partial_\mu (T_p^{\mu\nu} + T_t^{\mu\nu} + T_f^{\mu\nu}) = 0$$

Hydrodymanic densities

Baryon current:

$$J_\alpha^\mu = n_\alpha u_\alpha^\mu$$

n_α = baryon density of α-fluid

u_α^μ = 4-velocity of α-fluid

Energy-momentum tensor:

$$T_\alpha^{\mu\nu} = (\varepsilon_\alpha + P_\alpha) u_\alpha^\mu u_\alpha^\nu - g_{\mu\nu} P_\alpha$$

ε_α = energy density

P_α = pressure

+ Equation of state:

$$P = P(n, \varepsilon)$$

Final Aim: To find a proper EoS, which reproduces all data

Friction

$$F^{\nu}_{\alpha} = \rho^{\xi}_{\mathrm{p}} \rho^{\xi}_{\mathrm{t}} \left[\left(u^{\nu}_{\alpha} - u^{\nu}_{\bar{\alpha}} \right) D_P + \left(u^{\nu}_{\mathrm{p}} + u^{\nu}_{\mathrm{t}} \right) D_E \right],$$

$s_{\mathrm{pt}} = m_N^2 \left(u^{\nu}_{\mathrm{p}} + u^{\nu}_{\mathrm{t}} \right)^2$, $\alpha =$p or t, $\bar{\mathrm{p}} =$t and $\bar{\mathrm{t}} =$p, and ρ^{ξ}_{α} is

$$\rho^{\xi}_{\alpha}(s_{pt}) = \left(\rho^{bar.}_{\alpha} + \frac{2}{3} \rho^{mes.}_{\alpha} \right) \xi_h(s_{pt}) + \frac{1}{3} \left(\rho^{q}_{\alpha} + \rho^{g}_{\alpha} \right) \xi_q(s_{pt}),$$

$\rho^{bar.}_{\alpha}$, $\rho^{mes.}_{\alpha}$, ρ^{q}_{α} and ρ^{g}_{α} are scalar densities of all baryons, all mesons, quarks and gluons, respectively,

$$\rho^{a}_{\alpha}(x) = m_a \int \frac{d^3p}{p_0} f^{a}_{\alpha}(x,p)$$

in terms of where equilibrium distribution function f^{a}_{α}.
Factors like 2/3 and 1/3 are from naive valence-quark count.

D_P **and** D_E **were estimated based on proton-proton cross sections [Satarov, 1990]**

In view of uncertainties of the estimated friction, tuning factors are introduced for hadronic and quark-gluon phases: ξ_h **and** ξ_q**, respectively.**

Freeze-out

When system becomes dilute, we have to stop hydro

Freeze-out

Spectra of observed particles

$$E\frac{dN}{d^3p} = \sum_\alpha \int dV\,(u_\alpha^\mu p^\mu)\,\frac{\text{degeneracy factor}}{\exp[(u_\alpha^\mu p^\mu - \mu_\alpha)\,T_\alpha] \pm 1}$$

where $u_\alpha^\mu, \mu_\alpha, T_\alpha$ are taken at freeze-out instant

In-plain evolution of energy density

3FD model

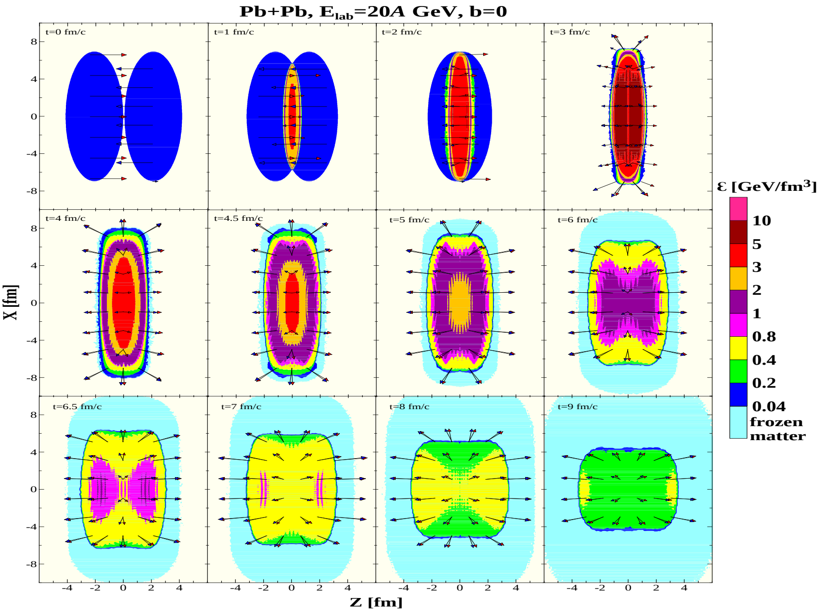
JINR,
20.02.13

MFD Models
- 2-Fluid Models
- 3-Fluid Models
- 3FD
- Friction
- Freeze-out

Phys. Input

Results
- Baryon Stopping
- Part. Production
- Hadron Ratios
- pt spectra
- Flow

Summary

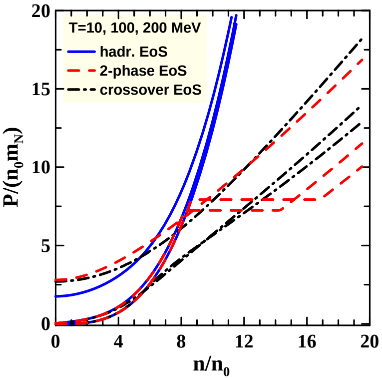


Physical Input I

I. Equation of State

- **Hadronic EoS**
  Galitsky&Mishustin (1979)
- 1st-order transition to QGP
  (2-phase EoS*)
- **crossover EoS***

*[Khvorostukhin, Skokov, Redlich, Toneev, (2006)]



Phase transition $\Longrightarrow$ EoS softening

Physical Input II

II. Friction was fitted to reproduce the baryon stopping

- **Hadronic EoS**

$$\xi_h^2(s) = 1 + \left[\ln\left(\frac{s^{1/2}}{2m_N}\right)\right]^{1/4}, \quad \tau = 2 \text{ fm/c}, \quad \varepsilon_{\text{frz}} = 0.4 \text{ GeV/fm}^3.$$

Friction is enhanced to reproduce the baryon stopping at $\sqrt{s_{NN}} > 5$ GeV.
Though the enhancement looks too high: $\xi_h^2 = 2.2$ at $\sqrt{s_{NN}} = 17.3$ GeV.

- **2-phase EoS**

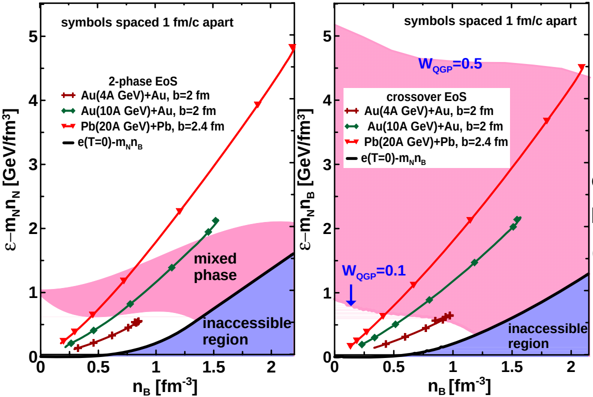
$$\xi_h^2(s) = 1, \quad \xi_q^2(s) = 60\,\frac{4m_N^2}{s}, \quad \tau = 0.17 \text{ fm/c}, \quad \varepsilon_{\text{frz}} = 0.4 \text{ GeV/fm}^3.$$

- **crossover EoS**

$$\xi_h^2(s) = 1, \quad \xi_q^2(s) = 200\,\frac{4m_N^2}{s}, \quad \tau = 0.17 \text{ fm/c}, \quad \varepsilon_{\text{frz}} = 0.4 \text{ GeV/fm}^3.$$

$\xi_h^2(s) = 1$ **is advantage of deconfinement scenarios**

Phase Evolution



Dynamical trajectories of matter in the central box of colliding nuclei ($4\text{fm}\times 4\text{fm}\times \gamma_{cm}$ 4fm)

Crossover transition by Toneev et al. is too smooth

Lattice QCD predicts a fast crossover.

Therefore, a true EoS is somewhere in between the ”Toneev”-crossover and ”Toneev”-2-phase EoS’s.

Onset of deconfinement happens at top-AGS–low-SPS energies.

Net-Proton Rapidity distributions

3FD model

JINR,
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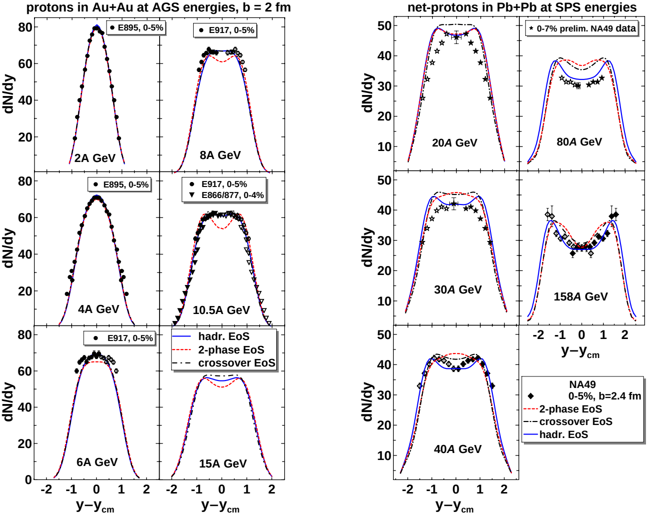


- Predictions of different scenarios differ to the largest extent in the energy region 8A GeV $\leq E_{lab} \leq$ 40A GeV.

"peak-dip-peak-dip" irregularity at midrapidity

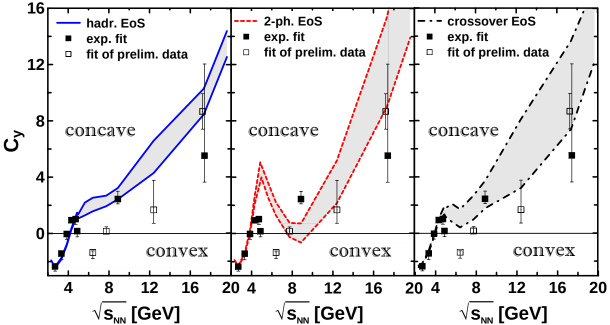
Reduced Curvature at Midrapidity

To quantify the "peak-dip-peak-dip" irregularity, net-proton rapidity distributions are fitted by (a, y_s and w_s are parameters of the fit)

$$\frac{dN}{dy} = a\left(\exp\{-(1/w_s)\cosh(y - y_{cm} - y_s)\} + \exp\{-(1/w_s)\cosh(y - y_{cm} + y_s)\}\right)$$

A reduced curvature of the spectrum at midrapidity

$$C_y = \left(y_{cm}^3 \frac{d^3N}{dy^3} \right)_{y=y_{cm}} \Big/ \left(y_{cm} \frac{dN}{dy} \right)_{y=y_{cm}} = (y_{cm}/w_s)^2 \left(\sinh^2 y_s - w_s \cosh y_s \right).$$



Updated experimental results at energies 20A and 30A GeV are badly needed

Physical Origin of the Irregularity

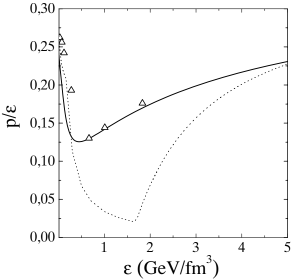
The irregularity is a combined effect of

- **softest point** of a EoS
  (a minimum of the sound speed)

  spherical fireball
  ⇒ essentially 3D expansion
  ⇒ **a peak at midrapidity**

  strongly deformed fireball
  ⇒ approximately 1D expansion
  ⇒ **a dip at midrapidity**

  the more softer matter
  ⇒ the more deformed fireball
  ⇒ **a dip at midrapidity**



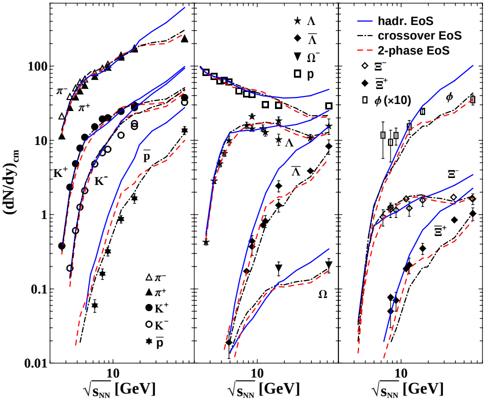
from E. G. Nikonov, A. A. Shanenko and V. D. Toneev, Heavy Ion Phys. 8, 89 (1998)

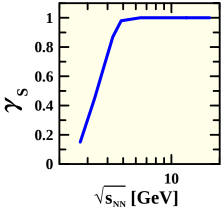
- **a change in the nonequilibrium regime** from hadronic to partonic one

  a change in cross sections ⇒ an irregularity in baryon stopping

This irregularity is a signal from hot and dense stage of nuclear collision

Particle Production





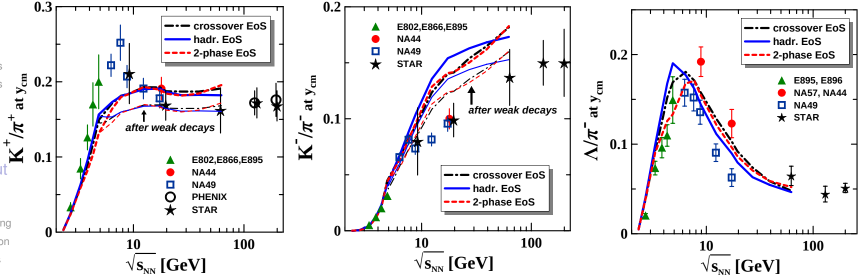
γ_S = strangeness suppression factor

- Hadr. scenario considerably overestimates experimental antibaryons already at lower SPS energies, i.e. ≈20A GeV.
- At $\sqrt{s_{NN}} > 17.4$ GeV, hadronic scenario overestimates available RHIC data on all species.
- Problem with ϕ-meson yields at lower SPS energies

hadronic scenario fails at high incident energies

Hadron Ratios

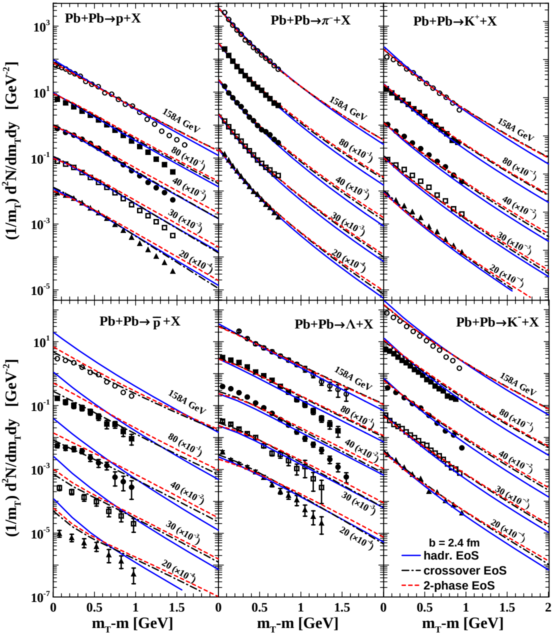
Ratios of midrapidity yield of various hadrons



- “Horn” anomaly in the K^+/π^+ ratio is not reproduced in any scenario.

?????????

Pt Spectra



hadronic scenario again fails for antiprotons

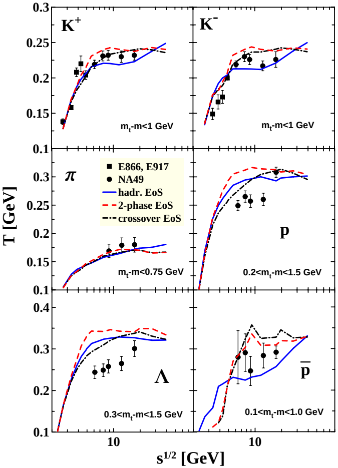
Inverse Slopes and Mean Transverse Masses

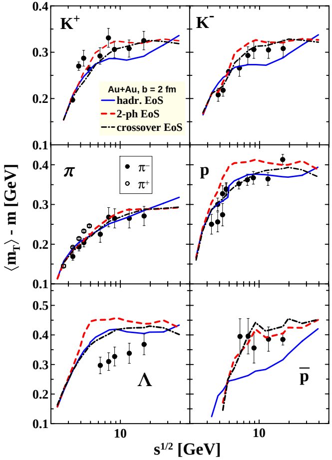
3FD model

JINR,
20.02.13

$$\frac{d^2N}{m_T\, dm_T\, dy} \propto \exp\left(-\frac{m_T}{T}\right),$$

$$\langle m_T\rangle = \frac{\int d^2p_T\; m_T \left(\frac{d^2N}{m_T\, dm_T\, dy}\right)}{\int d^2p_T \left(\frac{d^2N}{m_T\, dm_T\, dy}\right)}$$





"Step" is not a signal of deconfinement

Directed Flow

3FD model

JINR,
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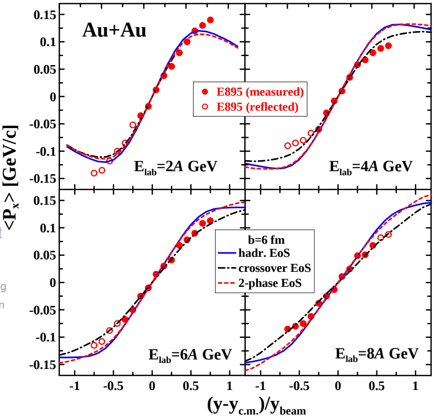

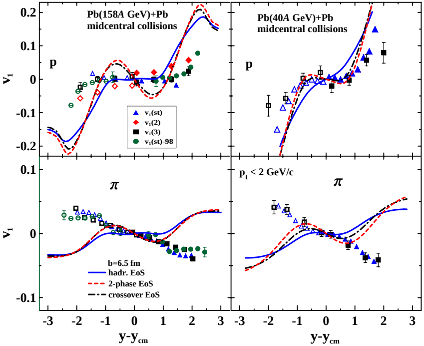

Deconfinement scenarios look preferable everywhere except for protons at 158A GeV

No comments as yet

Elliptic Flow

3FD model

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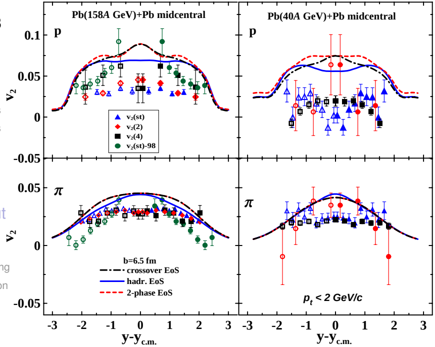

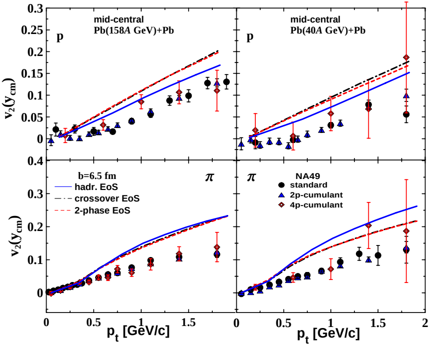

Afterburner (Hirano, et al., nucl-th/0701075) or viscosity reduces v_2 achieved at hydro stage.

Therefore, v_2 at 158A GeV is reasonable.

However, v_2 at 40A GeV is too high.

Critical point? E.Shuryak, arXiv:hep-ph/0504048

Summary

Deconfinement scenarios look preferable at $\sqrt{s_{NN}} > 5$ GeV

- net-proton rapidity distributions:
  Irregularity signaling deconfinement onset (not yet seen)
- particle production: hadronic scenario overestimates

  exp. antibaryons yields already at $\sqrt{s_{NN}} > 5$ GeV,
  and at $\sqrt{s_{NN}} > 17.4$ GeV – yields of all species
- m_T-spectra: “Step” is not a signal of deconfinement
- Directed and elliptic flow:
  reasonably well reproduced so far, analysis is still in progress
- **(i)** Disappearance of v_2 at 40A GeV (semicentral collisions) and
  (ii) maximum in K^+/π^+ ratio at 20A – 30A GeV (central collisions)
  cannot be reproduced by any scenario
- Analysis is still in progress