MFD Models
3-Fluid Models
3FD
Phys. Input
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So far
Directed Flow
Elliptic Flow
Summary

Relativistic Heavy-Ion Collisions within Alternative Scenarios: Directed and Elliptic Flow

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Seminar "THEORY OF HADRONIC MATTER UNDER EXTREME CONDITIONS" at BLTF JINR 03.06.2015

Outline

1. **Multi-Fluid Models:**
   - 3-Fluid Models
   - 3-Fluid Dynamics (3FD), present version
2. Physical Input of the Model
3. Results
   - So far
   - **Directed Flow**
   - **Elliptic Flow**
4. **Summary**

Exploring Nuclear Phase Diagram

3FD model

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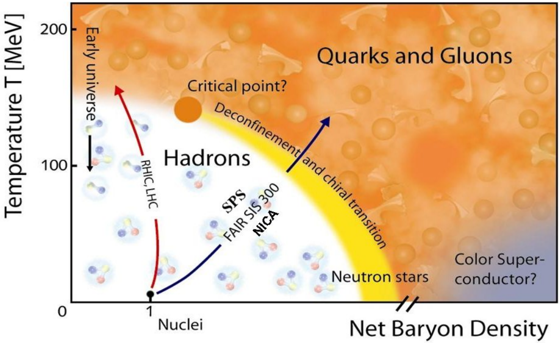

At which incident energy an onset of deconfinement happen?
What is the order of the deconfinement transition at high baryon densities?

Is there a critical end point in the phase diagram?

Facilities (chronologically):

- **AGS** in Brookhaven (heavy ions 1991-1999) - now injector for RHIC **3** $\geq \sqrt{s_{NN}} \geq$ **5 GeV**
- **SPS** at CERN - now mostly injector for LHC **6.4** $\geq \sqrt{s_{NN}} \geq$ **17.3 GeV**
- **RHIC** in Brookhaven (since 2000) - beam-energy-scan program **7.7** $\geq \sqrt{s_{NN}} \geq$ **200 GeV**
- **LHC** at CERN (since 2009) $\sqrt{s_{NN}}$ **= 2.76 - 5.6 TeV**
- **NICA** in Dubna - under construction **3** $\geq \sqrt{s_{NN}} \geq$ **9 GeV**
- **FAIR** in Darmstadt - under construction **3** $\geq \sqrt{s_{NN}} \geq$ **5 GeV**

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**

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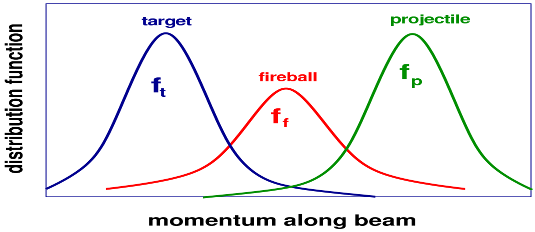
3-Fluid Models

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

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

- Produced particles populate mid-rapidity ⇒ **fireball fluid**



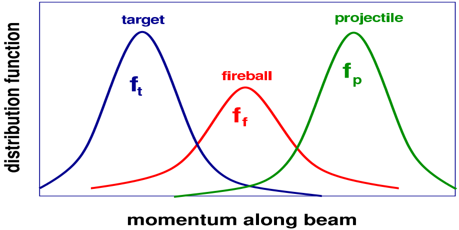
This a minimal extension of hydrodynamics required by heavy-ion dynamics

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
  Ivanov, 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 — 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 — Source term — 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:

$J^{\mu}_{\alpha} = n_{\alpha} u^{\mu}_{\alpha}$

n_{α} = baryon density of α-fluid

u^{μ}_{α} = 4-velocity of α-fluid

Energy-momentum tensor:

$T^{\mu\nu}_{\alpha} = (\varepsilon_{\alpha} + P_{\alpha}) u^{\mu}_{\alpha} u^{\nu}_{\alpha} - g_{\mu\nu} P_{\alpha}$

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

In-plain evolution of energy density

3FD model

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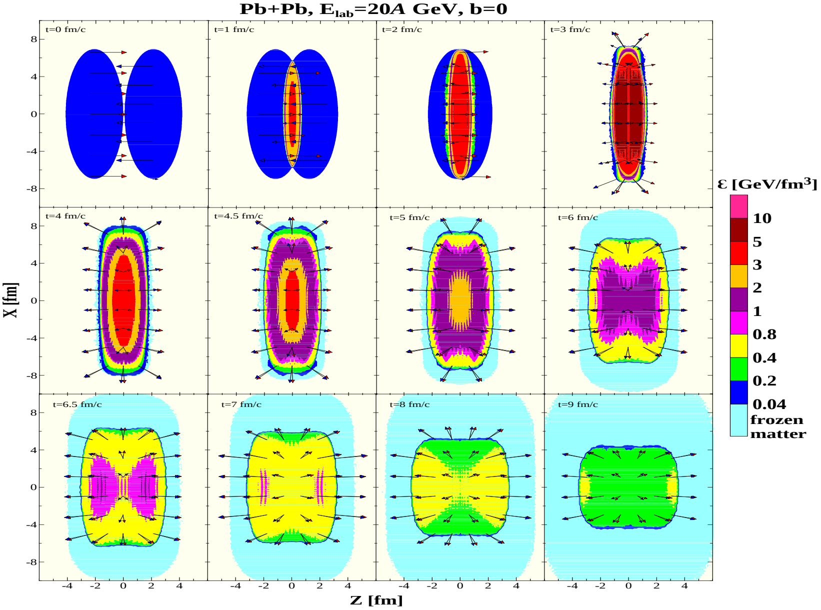
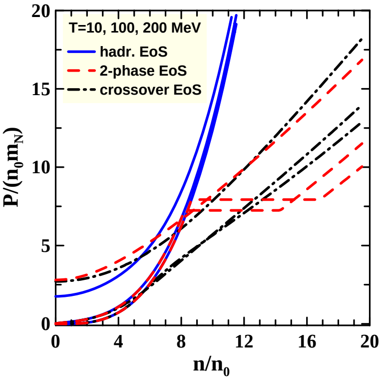


Physical Input I

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 and III

II. Friction was fitted to reproduce the baryon stopping

- **Hadronic EoS**

  Friction in hadronic phase was estimated by Satarov (SJNP 1990)

  This friction had to be enhanced.

- **2-phase EoS and crossover EoS**

  Phenomenological friction in QGP phase.

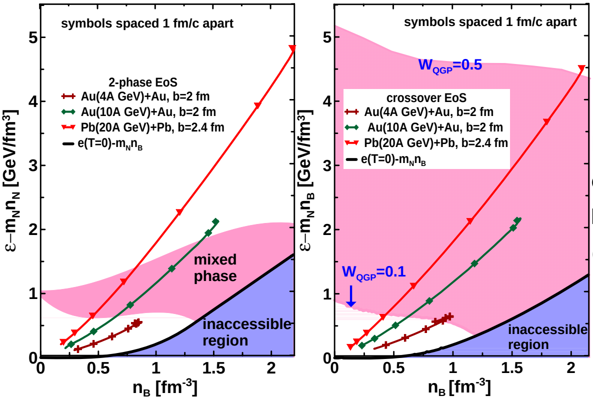
  Advantage of deconfinement scenarios:
  Satarov’s friction in hadronic phase needs no modification

III. Freeze-out

When system becomes dilute, hydro has to be stopped

Freeze-out energy density ε_{frz} = 0.4 GeV/fm^3

Phase Evolution



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

Crossover transition by ***Khvorostukhin et al.*** **is too smooth**

Lattice QCD predicts a fast crossover.

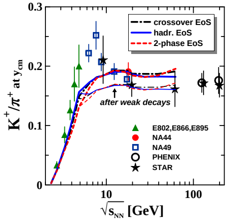
Therefore, a true EoS is somewhere in between the *"Khvorostukhin et al."*-crossover and *"Khvorostukhin et al."*-2-phase EoS's.

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

Results analysed so far

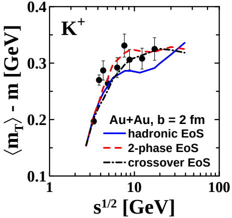
- **Particle Production: hadronic scenario fails at high energies**
- **Hadron Ratios:**

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



- **Transverse-Momentum Spectra:**
  hadronic scenario fails for antiprotons
- **Inverse Slopes and Mean Transverse Masses:**

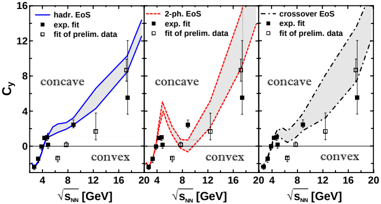
"Step" is not a signal of deconfinement



Results analysed so far

- **Baryon Stopping, i.e. proton rapidity distributions:**

C_y = reduced curvature of net-proton rapidity distribution at midrapidity



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

a wiggle irregularity of C_y at midrapidity

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

Except for the baryon stopping, predictions of the crossover and first-order-transition scenarios looked very similar so far.
Only a slight preference could be given to the crossover EoS.

Flow

Fourier expansion of a particle distribution, $d^2N/dy\,d\phi$, in azimuthal angle ϕ with respect to the reaction plane

$$\frac{d^2N}{dy\,d\phi} = \frac{dN}{dy}\left(1 + \sum_{n=1}^{\infty} 2\,v_n(y)\cos(n\phi)\right)$$

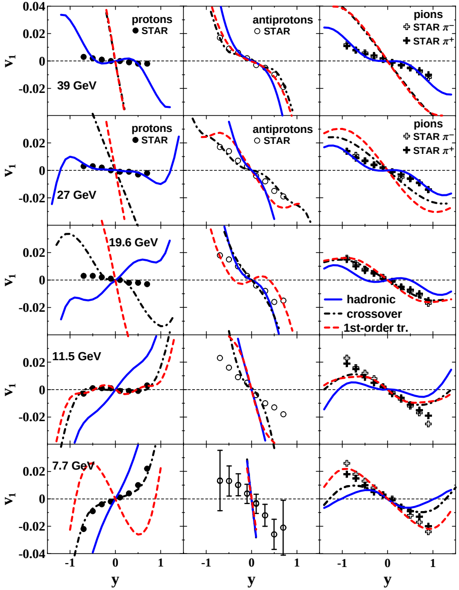
where y is the longitudinal rapidity of a particle.

$v_1(y)$ = **directed flow**

$v_2(y)$ = **elliptic flow**

$v_3(y)$ = **triangular flow**

Directed Flow at RHIC



STAR data: L. Adamczyk *et al.*, Phys. Rev. Lett. 112, 162301 (2014)

High sensitivity of the proton directed flow to the EoS.

The crossover EoS is preferable in the energy range of 7.7 $\lesssim \sqrt{s_{NN}} \lesssim$ 20 GeV.

The deconfinement EoS's in the QGP sector should be stiffer at high baryon densities.

V. P. Konchakovski, W. Cassing, Y. B. Ivanov and V. D. Toneev, Phys. Rev. C 90, no. 1, 014903 (2014)

Y. B. Ivanov and A. A. Soldatov, Phys. Rev. C 91, no. 2, 024915 (2015)

Directed Flow at RHIC

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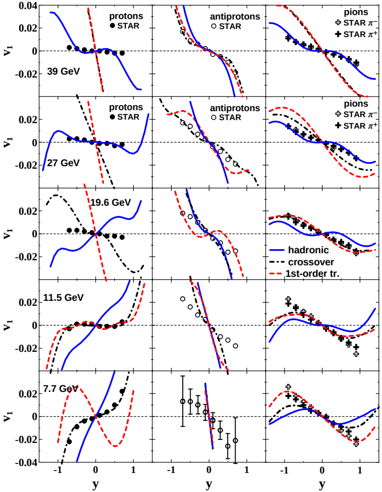
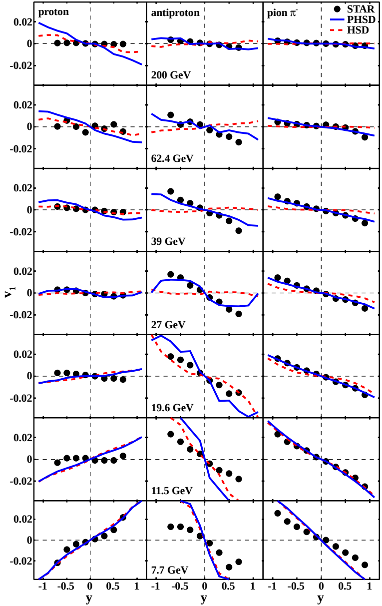


Parton-Hadron String Dynamics (PHSD)



V. P. Konchakovski, W. Cassing, Y. B. Ivanov and V. D. Toneev, Phys. Rev. C 90, no. 1, 014903 (2014)

Directed Flow at SPS and AGS

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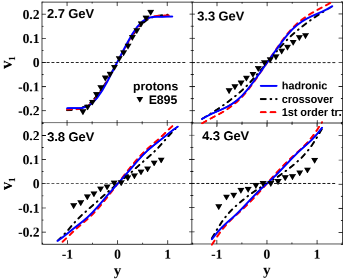
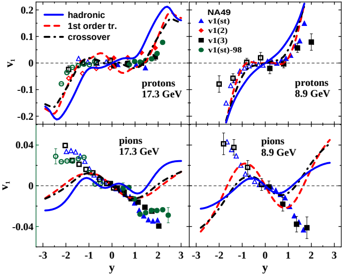
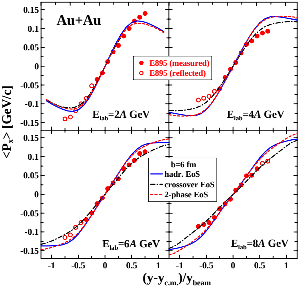






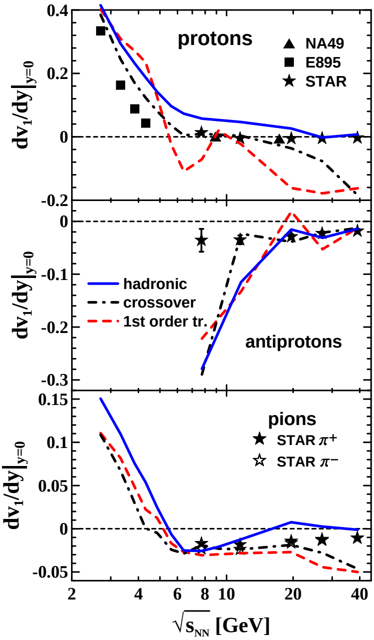
$$\langle P_x \rangle(y) = \frac{\int d^2p_T \, p_x \, E \, dN/d^3p}{\int d^2p_T \, E \, dN/d^3p},$$

where p_x is the transverse momentum of in the reaction plane.

Agreement of $\langle P_x \rangle(y)$ with the data is much better than that in terms of $v_1(y)$.

The crossover $\langle P_x \rangle(y)$ almost perfectly reproduces the data.

Midrapidity slopes of Directed Flow



High sensitivity of the proton directed flow to the EoS.

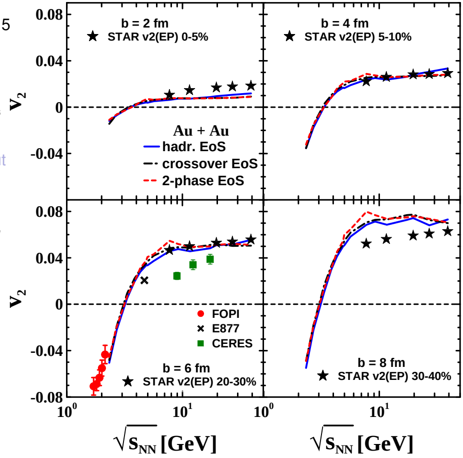
v_1 indicates the crossover deconfinement transition in a wide range of energies 4 $\lesssim \sqrt{s_{NN}} \lesssim$ 20 GeV.

The crossover EoS is preferable in this energy range.

The deconfinement EoS's in the QGP sector should be stiffer at high baryon densities.

The latter is in agreement with that discussed in astrophysics.

Elliptic Flow Charged particles



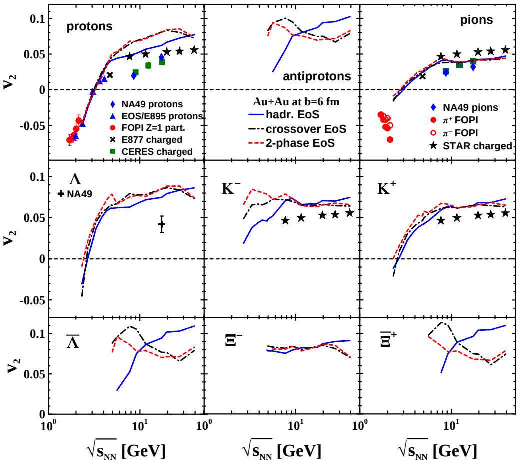
Y. B. Ivanov and A. A. Soldatov, Phys. Rev. C 91, no. 2, 024914 (2015)

Low sensitivity of v2(charged) to the EoS.

Reproduction of change of sign at $\sqrt{s_{NN}} \approx 3.5$ GeV.

No non-monotonicity of v_2 predicted by Kolb, Sollfrank and Heinz, PRC 62, 054909 (2000).

Elliptic Flow Identified Hadrons



Y. B. Ivanov and A. A. Soldatov, Phys. Rev. C 91, no. 2, 024914 (2015)

A stronger EoS dependence: antibaryons and K^-.

Reproduction of sign change at $\sqrt{s_{NN}} \approx 3.5$ GeV.

Non-monotonicity of anti-baryon v_2 within the deconfinement scenarios (Kolb, et al. (2000)). However, low multiplicities of anti-baryons at $\sqrt{s_{NN}} \leq 10$ GeV $\Rightarrow$ large fluctuations may wash out this non-monotonicity.

Summary

Deconfinement scenarios look preferable at $\sqrt{s_{NN}} > 4$ GeV

Except for the baryon stopping, predictions of the crossover and first-order-transition scenarios looked very similar so far.

So far only a slight preference could be given to the crossover EoS.

- baryon stopping, i.e. net-proton rapidity distributions:
  Irregularity signals deconfinement onset (no reliable data yet)
- **directed flow:**
  - **High sensitivity of the proton directed flow to the EoS**
  - **v_1 indicates the crossover deconfinement transition in a wide range of energies $4 \lesssim \sqrt{s_{NN}} \lesssim 20$ GeV.**
  - **QGP EoS's in the high-baryon-density sector should be stiffer**

    Similar constraint from astrophysics
- **elliptic flow:**
  - **Low sensitivity to the EoS.**
  - **A stronger EoS dependence for antibaryons and K^-**
  - **No qualitative signals of deconfinement**
- Analysis is still in progress