Effects of the equation of state on hadron spectra and elliptic flow

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Introduction

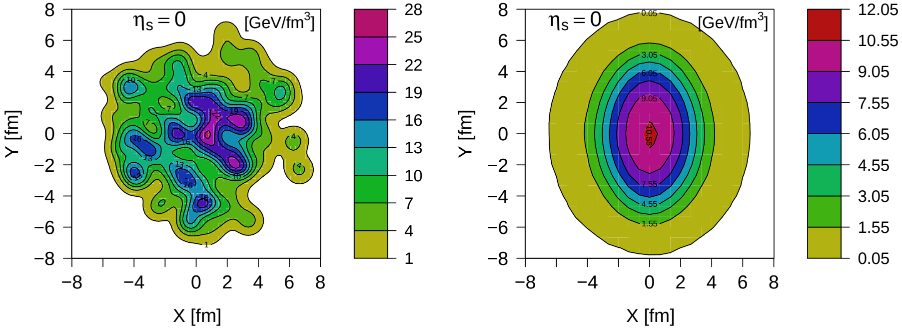
Objective

Test the sensitivity of physical observables to different equation of state with NexSPheRIO in Au+Au collisions at RHIC energies.

Tools:

- Hydrodynamic model without viscosity (SPheRIO).
    - Initial conditions (IC): NEXUS [Phys.Rev.C 65, 054902, (2002)].
    - Hydrodynamic evolution: SPheRIO [Braz.J.Phys. 35, 24, (2005)].
    - Equation of State (EoS) → important role for investigating the hydrodynamical evolution → affects particle spectra, collective flow and other experimental observables.
    - Decoupling criteria: Cooper-Frye [Phys.Rev.D 10, 196, (1974)].

IC: generated by NEXUS → two different approaches:



- Random fluctuating events (left).
- Smoothed IC by averaging over a big number of events (right).

Smoothed Particle Hydrodynamics

- Parametrize the matter flow in terms of discrete Lagrangian coordinates (namely, SPH particles).
- Entropy and baryon number $\rightarrow$ assigned to the SPH particles as a conserved quantity.
- Equation of Motion (EoM) $\rightarrow$ derived by variational principle in terms of SPH particle degrees of freedom.

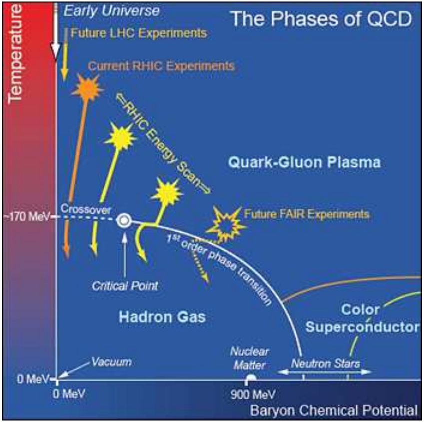


Fig. from bnl.gov

- First order phase transition with strangeness (FOS) → ideal gas (QGP phase) and resonance gas model (H phase).
- Lattice QCD (strongly interacting QGP) → smooth transition:
  - Lattice fit (LQCD) [arXiv:0912.2541].
  - Lattice inspired EoS (CEP) (with phenomenological critical end point) [arxiv:hep-ph/0510096].

Cooper-Frye prescription

$$E\frac{dN}{d^3k} = \int_\Sigma d\sigma_\mu k^\mu f(x,k)$$

$f(x,k) \rightarrow$ thermal distribution, $\Sigma \rightarrow$ hypersurface of constant temperature.
Decoupling in SPH:

$$E\frac{dN}{d^3k} = \sum_j \frac{\nu_j}{s_j} \frac{k^\mu (n_\mu)_j}{|(n_\mu)_j (u^\mu)_j|} f(T_{fo}, \mu_j, k^\nu (n_\nu)_j)$$

Particle Spectra and Elliptic Flow

Particle Spectra

Transverse momentum distribution of charged hadron measured in certain η or y range.

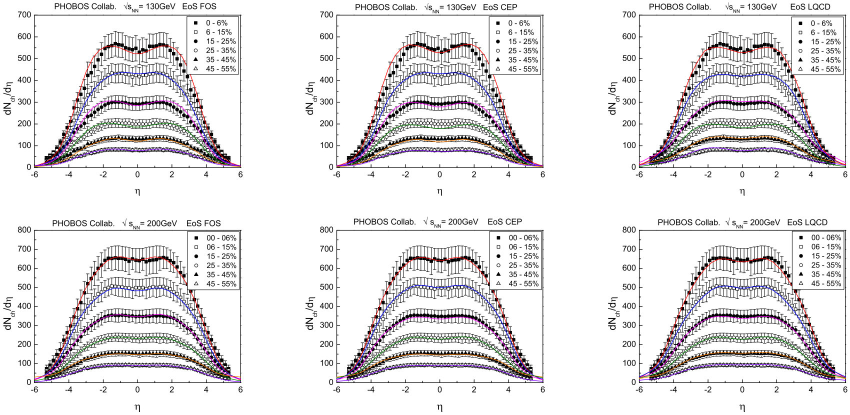
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi p_T}\frac{d^2N}{dydp_T} = \frac{1}{2\pi p_T}\sqrt{\frac{p_T^2\cosh\eta^2}{p_T^2\cosh\eta^2 + m^2}}\frac{d^2N}{d\eta dp_T}$$

Elliptic Flow

Elliptic flow $\rightarrow$ second Fourier coefficient of the azimuthal distribution:

$$\begin{aligned} E\frac{d^3N}{d^3p} &= \frac{1}{2\pi p_T}\frac{d^2N}{dydp_T}[1 + 2v_1\cos(\phi - \psi_1) + 2v_2\cos[2(\phi - \psi_2)] + ...] \\ v_n &= \langle\cos[n(\phi - \psi_n)]\rangle \quad n = 1, 2, 3, ... \end{aligned}$$

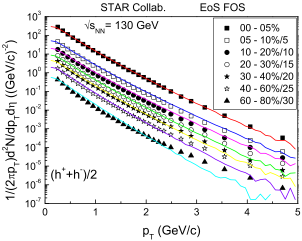
Results: Pseudo-rapidity distribution

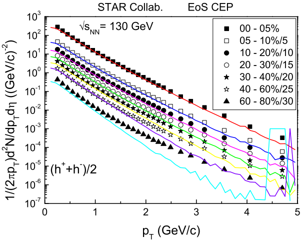


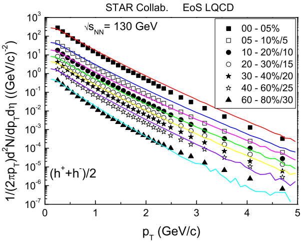
PHOBOS data: B.B. Back et al. Phys.Rev.Lett. 87, 102303 (2001) and B.B. Back et al. Braz.J.Phys. 34, 829 (2004).

Results: Particle Spectra $\sqrt{s_{NN}} = 130$ GeV

$-0.5 < \eta < 1$



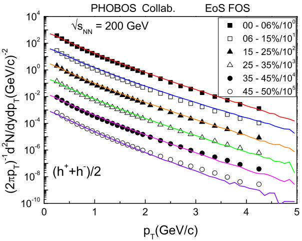


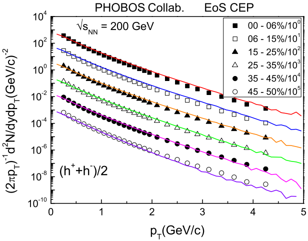


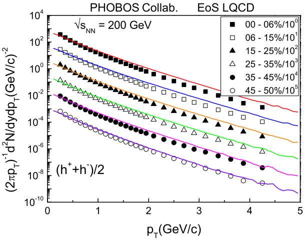
STAR data: C. Adler et al. Phys.Rev.Lett. 89, 202301 (2002).

Results: Particle Spectra $\sqrt{s_{NN}} = 200$ GeV

$0.2 < y < 1.4$







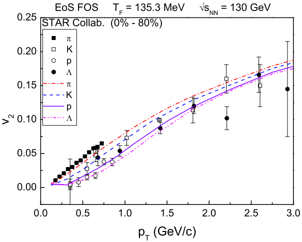
PHOBOS data: B.B. Back et al. Phys.Rev.B 578, 297 (2004).

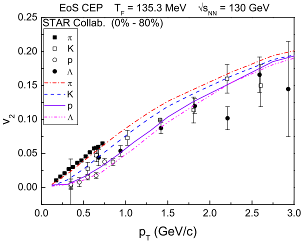
Pseudo-rapidity distribution and spectra

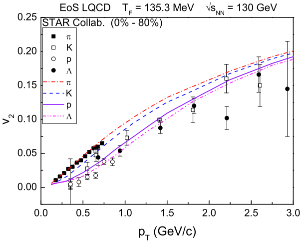
- Pseudo-rapidity distribution $\rightarrow$ used to normalized the energy density profile from Nexus to exp. data;
- p_T spectra of all charged particles $\rightarrow$ used to fix the freeze-out temperature;
- Both (normalization and T_F) are functions of the centrality window.

Results: Elliptic Flow - $\sqrt{s_{NN}} = 130$ GeV

Elliptic flow - π, K, p, Λ.

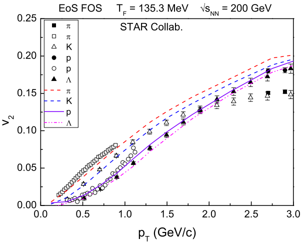


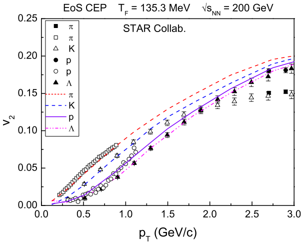


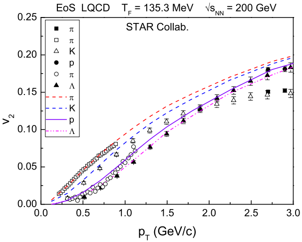


STAR data: C. Adler et al. Phys.Rev.Lett. 87, 182301 (2001) and C. Adler et al. Phys.Rev.Lett. 89, 132301 (2002).

Elliptic flow - π, K, p, Λ.



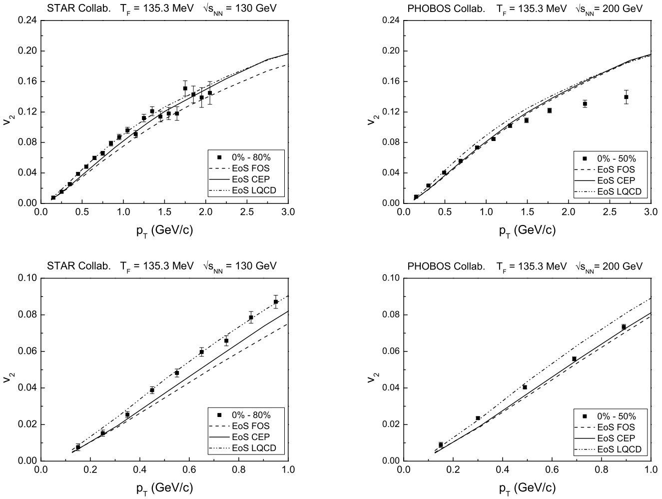




STAR data: B.I. Abelev et al. Phys.Rev.C 77, 054901, (2008).

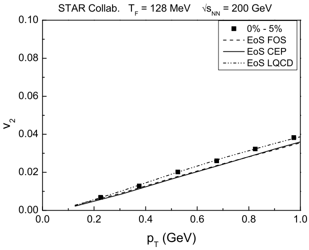
Results: Elliptic Flow - all charged hadron

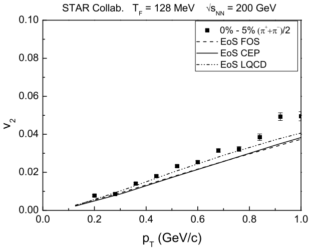
$\sqrt{s_{NN}} = 130$ GeV $\rightarrow |\eta| < 1.3$ STAR data: K.H. Ackermann et al. Phys.Rev.Lett. 86, 402 (2001)
$\sqrt{s_{NN}} = 200$ GeV $\rightarrow 0 < \eta < 1.5$ PHOBOS data: B.B. Back et al. Phys.Rev.C 72, 051901 (2005)



Results: Elliptic Flow

Small centrality regions (0% - 5%): all charged hadrons and π





STAR data: J. Adams et. al. Phys.Rev.C 72, 014904 (2005).

Conclusions

- Hadron spectra and elliptic flow $\rightarrow$ low sensitivity to the EoS: at least for small p_T, all the EoS describe the data reasonably well.
- These results are interesting $\rightarrow$ it was expected that different EoS would produce different final results, because each EoS has its own time of evolution.

In the future:

- Investigate the effects of EoS on other physical observables, for example HBT.

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Temperature table - STAR

	Centr. Window (%)	Decoupling Temp. (MeV)
1	0 - 5	128
2	5 - 10	129.63
3	10 - 20	132.07
4	20 - 30	135.33
5	30 - 40	138.59
6	40 - 60	143.48
7	60 - 80	128

Tabela: Centrality window(%) vs. decoupling temperature (MeV).

Temperature table - PHOBOS

	Centr. Window(%)	Decoupling Temp. (MeV)
1	0 - 6	128.16
2	6 - 15	130.44
3	15 - 25	133.70
4	25 - 35	136.96
5	35 - 45	140.22
6	45 - 55	143.48

Tabela: Centrality window(%) vs. decoupling temperature (MeV).

Smooth Particle Hydrodynamic (SPH)

Used for solving the equation of motion of a fluid - variational principle.
Action

$$I = -\int \epsilon(n_B, s)\sqrt{-g}\, d^4x$$

Constraint equations

$$\begin{aligned}
(n_B u^\nu)_{;\nu} &\equiv 1/\sqrt{-g}\,\partial_\nu(\sqrt{-g}\, n_B u^\nu) = 0 \\
(s u^\nu)_{;\nu} &\equiv 1/\sqrt{-g}\,\partial_\nu(\sqrt{-g}\, s u^\nu) = 0 \\
u^\nu u_\nu &= 1
\end{aligned}$$

Main idea of the method - parametrization of extensive quantities:

$$a^*(\vec{x}, \tau) = \Sigma_j \alpha_j W(\vec{x} - \vec{x}_j(\tau); h)$$

j - fluid element, then

$$n_B^*(\vec{x}, \tau) = \sum_j \beta_j W(\vec{x} - \vec{x}_j(\tau); h) \quad \beta_j \text{ portion of } n_B$$

$$s^*(\vec{x}, \tau) = \sum_j \nu_j W(\vec{x} - \vec{x}_j(\tau); h) \quad \nu_j \text{ portion of } s$$

Equation of State

- Pasi:
  Adopts a parameterization of the lattice QCD data for high temperature region while uses hadronic gas model for the low temperature region. The EoS only considers zero baryon density.
- Critical end Point:
  Use the following phenomenological parametrization in the place of Gibbs conditions for phase transition:

$$(P - P^{QGP})(P - P^{QGP}) = \delta(\mu_B) \text{ where } \delta(\mu_B) = \delta_0 exp\{-\mu_B/\mu_c\}$$

When :
$\delta_0 = 0 \rightarrow$ First order phase transition, or $\delta_0 \neq 0 \rightarrow$ critical end point. all thermodynamical relations are derived from this pressure! Here is considered finite baryon density.

Equation of State

- First order phase transition with strangeness:
  Introduces an additional condition, namely, strangeness neutrality.

  $$\delta_s = 0$$

  Strangeness chemical potential, μ_s , is introduced in the EoS, but due to $\delta_s = 0$ it does not act as an independent degree of freedom. The introduction of μ_s merely increase the dimension of the binodal surface of the phase transition. It modifies the phase structure as discussed.