Experimental investigations of relativistic hydrodynamics and the ideal fluid scenario at RHIC

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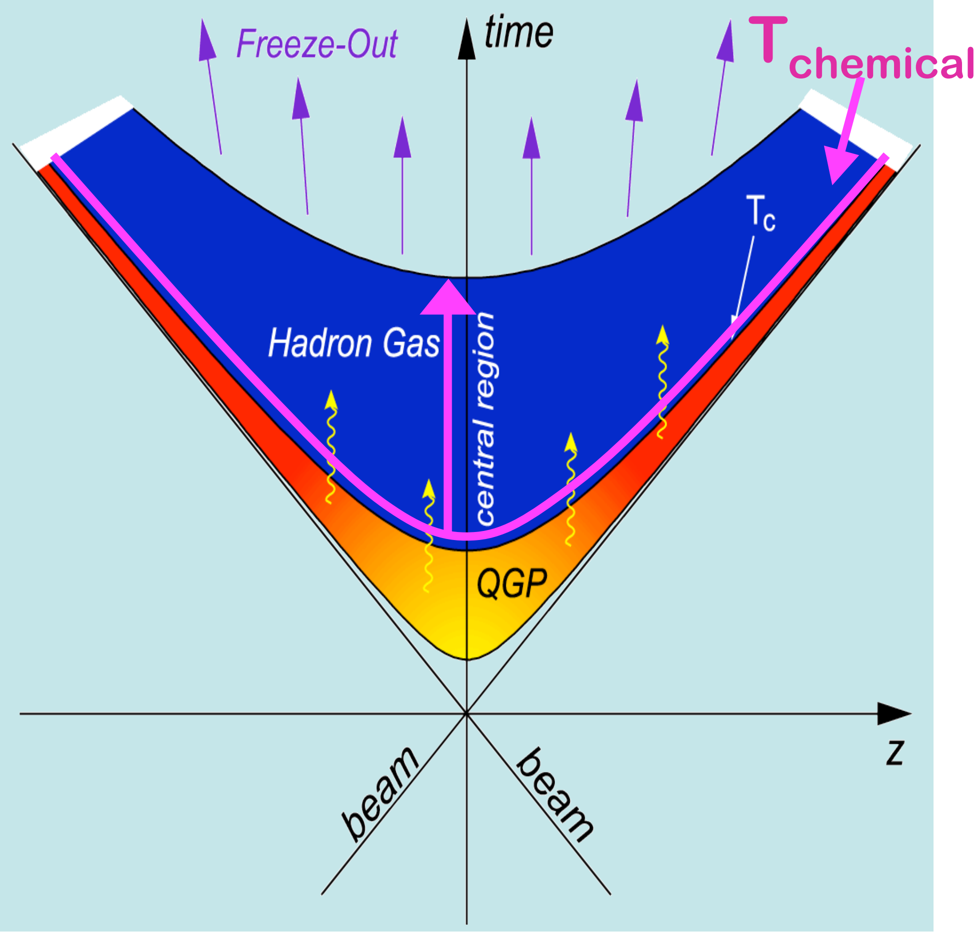
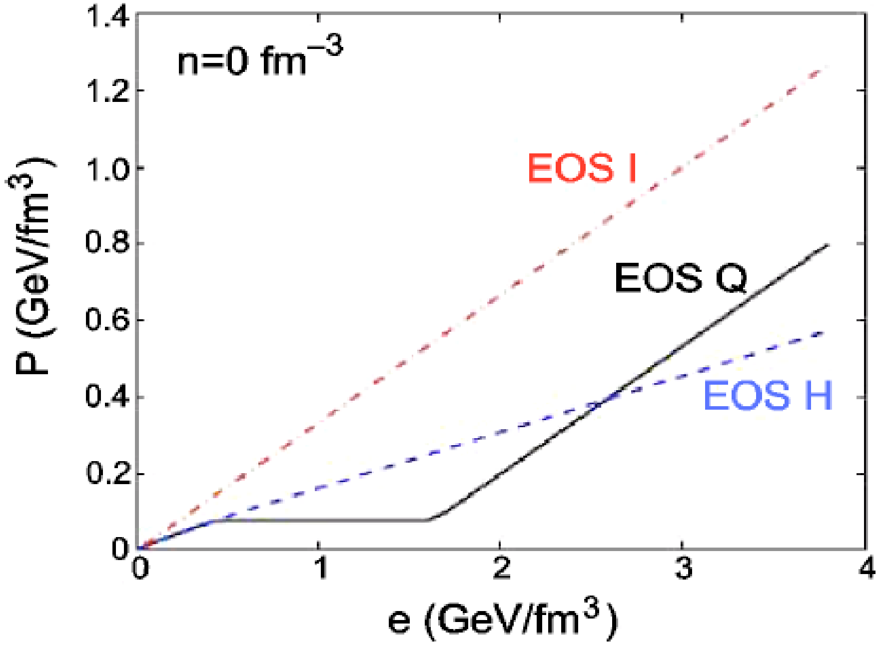
Hydrodynamic evolution



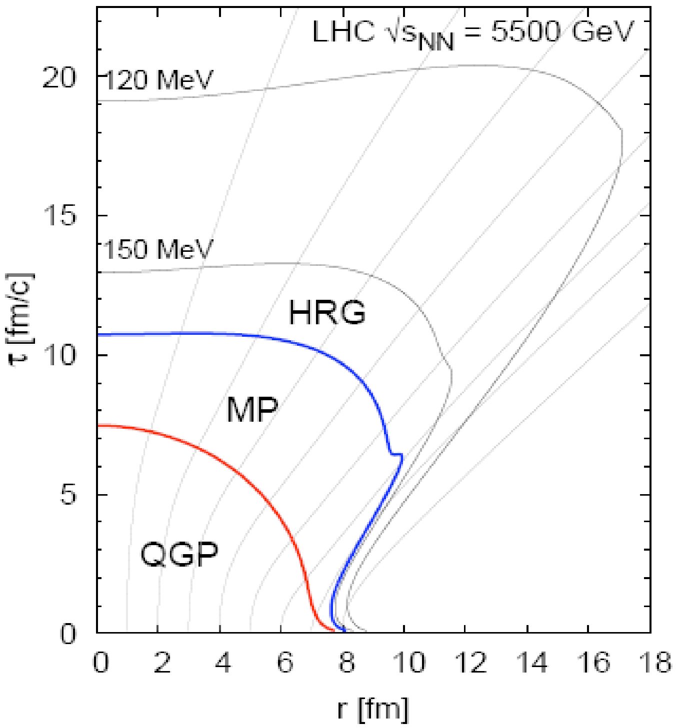
Equation of State

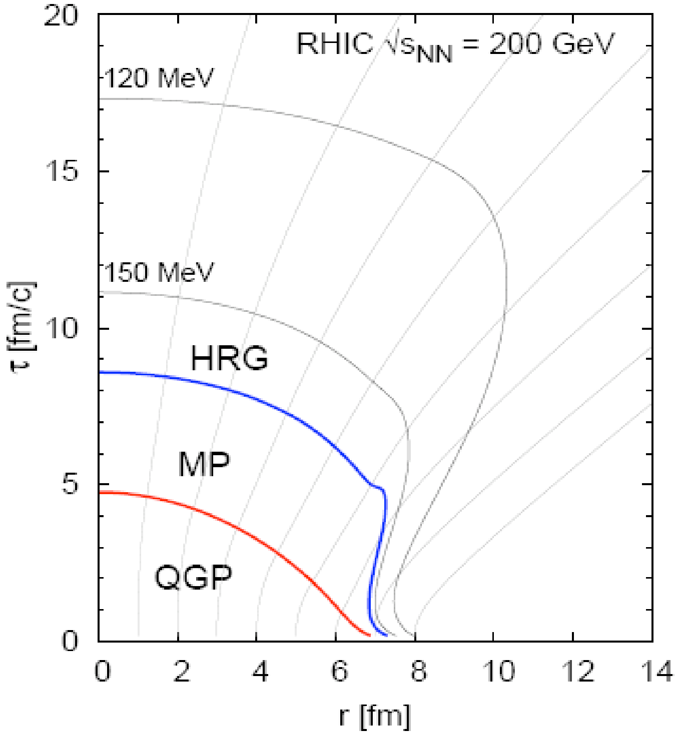
- Hagedorn resonance gas (EOS H)
- ideal gas of massless partons (EOS I)
- first-order phase transition at Tc = 164 MeV (EOS Q)



*Ref. [1]

Hydrodynamic spacetime evolution



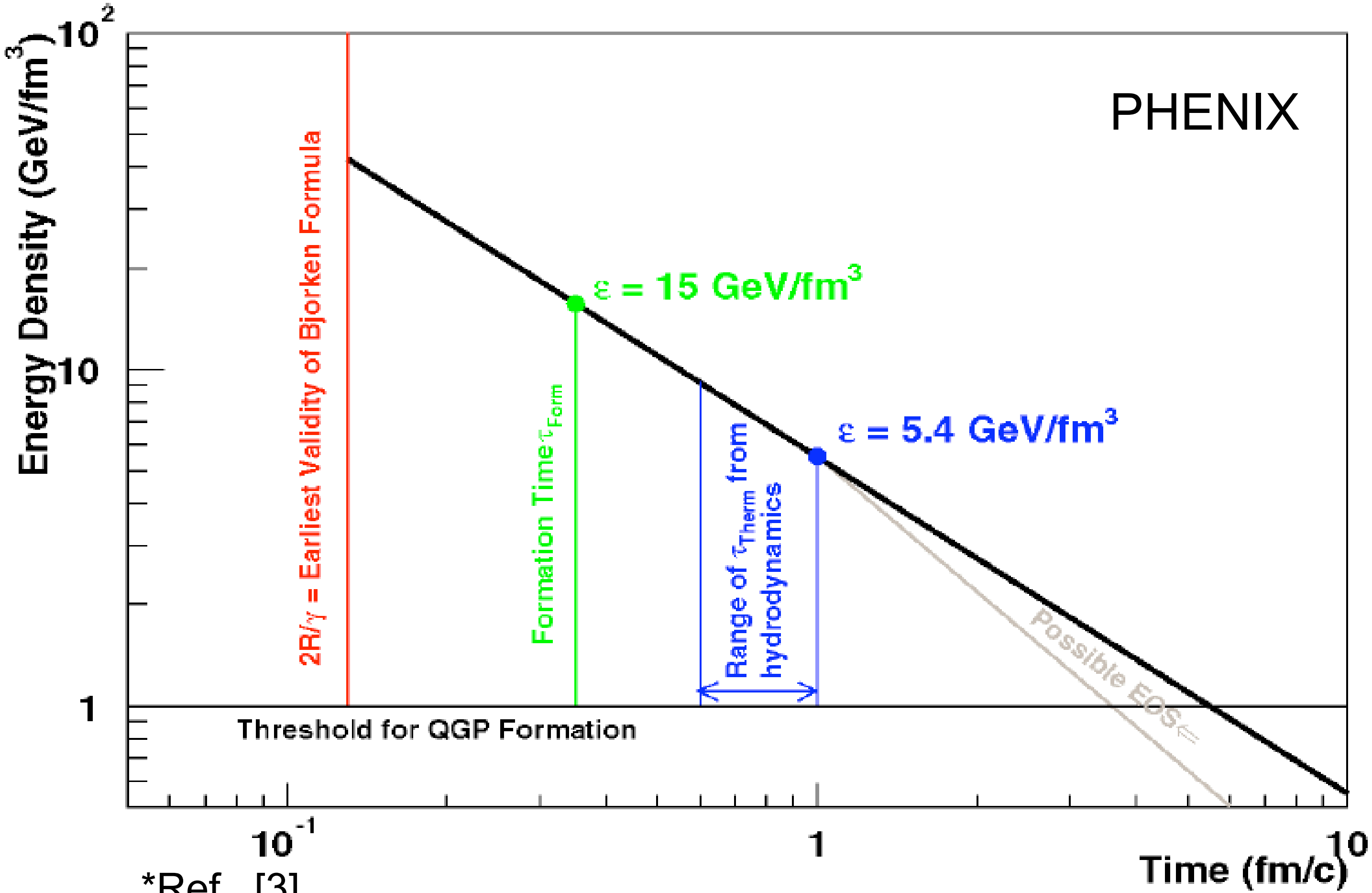


*Ref. [2]

Initial state: pQCD + saturation

Boundaries of Mixed Phase between QGP and Hadron Resonance Gas at Tc = 167 MeV are shown in colored curves

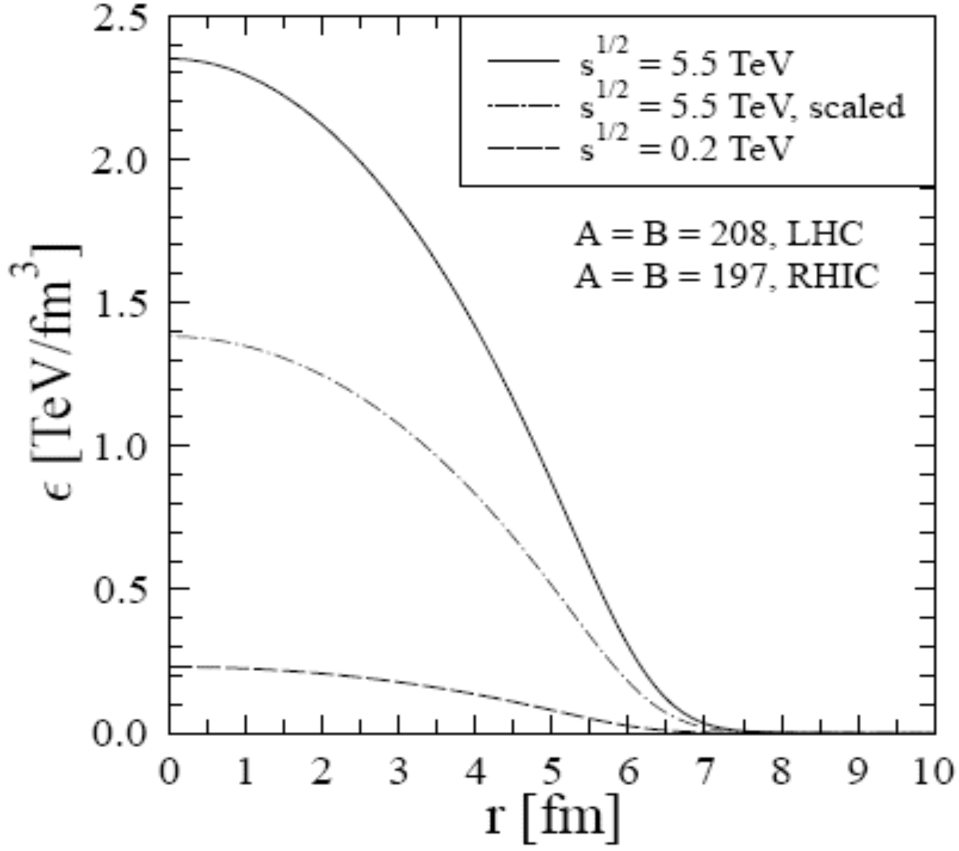
Energy density



*Ref. [3]

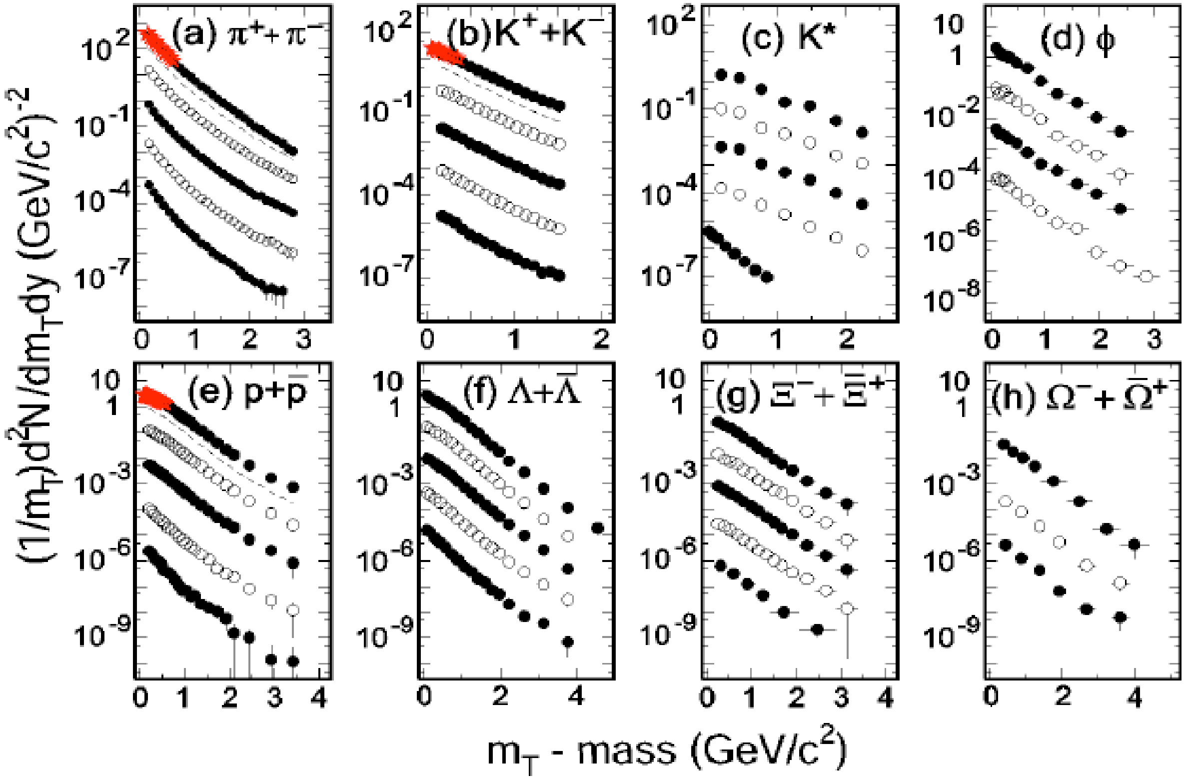
Energy density

- Initial condition:
  pQCD + final state saturation model(minijet)
- Formation time:
  0.170 fm/c(RHIC)
  0.100 fm/c(LHC)
- Saturation scale:
  1.16 GeV(RHIC)
  2.03 GeV(LHC)
- Strong dependence on initial time



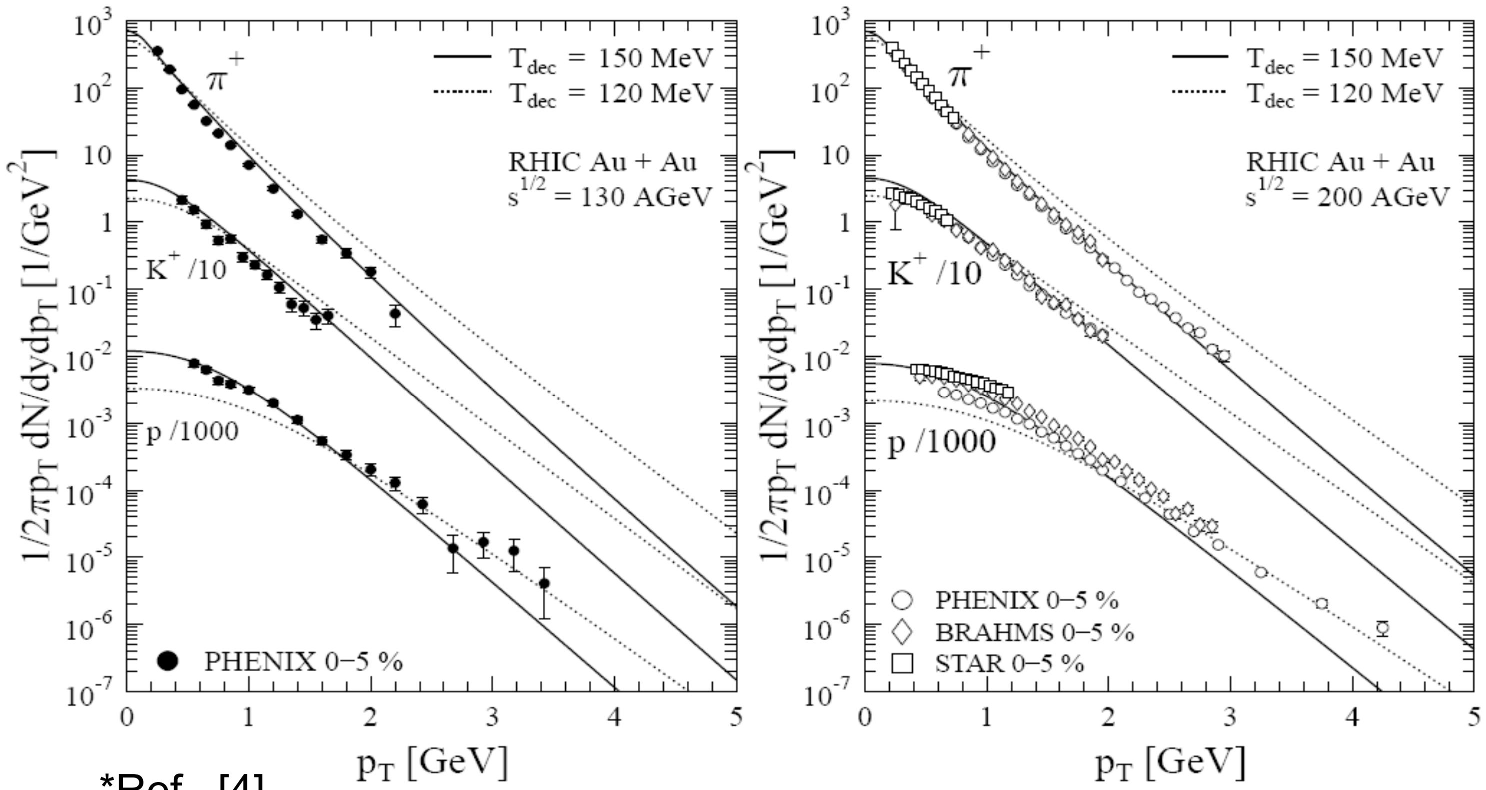
*Ref. [4]

Particle spectrum



*Ref. [1]

Particle spectrum



*Ref. [4]

kinetic freeze-out Temperature fits well with p_t<1.5 GeV/c

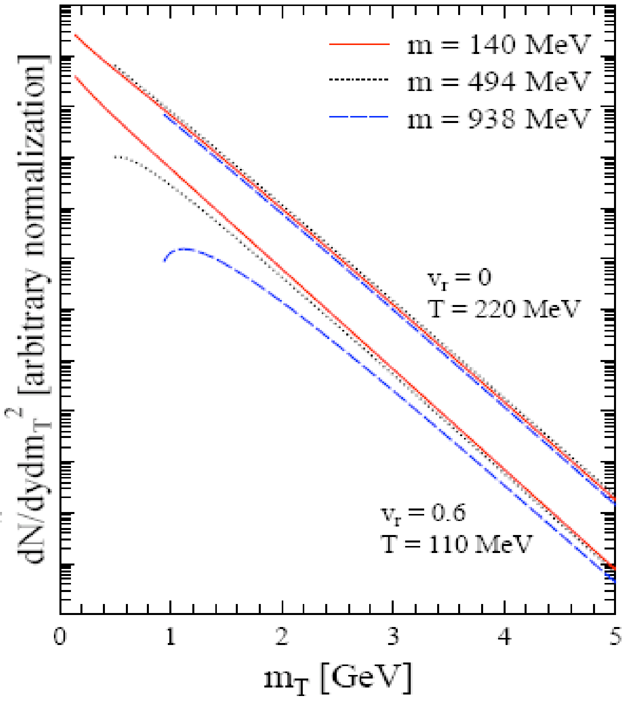
Particle spectrum

$$\frac{dN}{dy\,dm_T^2} = \frac{g}{2\pi}\tau_f m_T \sum_{n=1}^{\infty}(\pm 1)^{n+1}\int_0^R dr\; r I_0(n\gamma_r v_r \frac{p_T}{T}) K_1(n\gamma_r \frac{m_T}{T}),$$

If no transverse flow v_r=0:

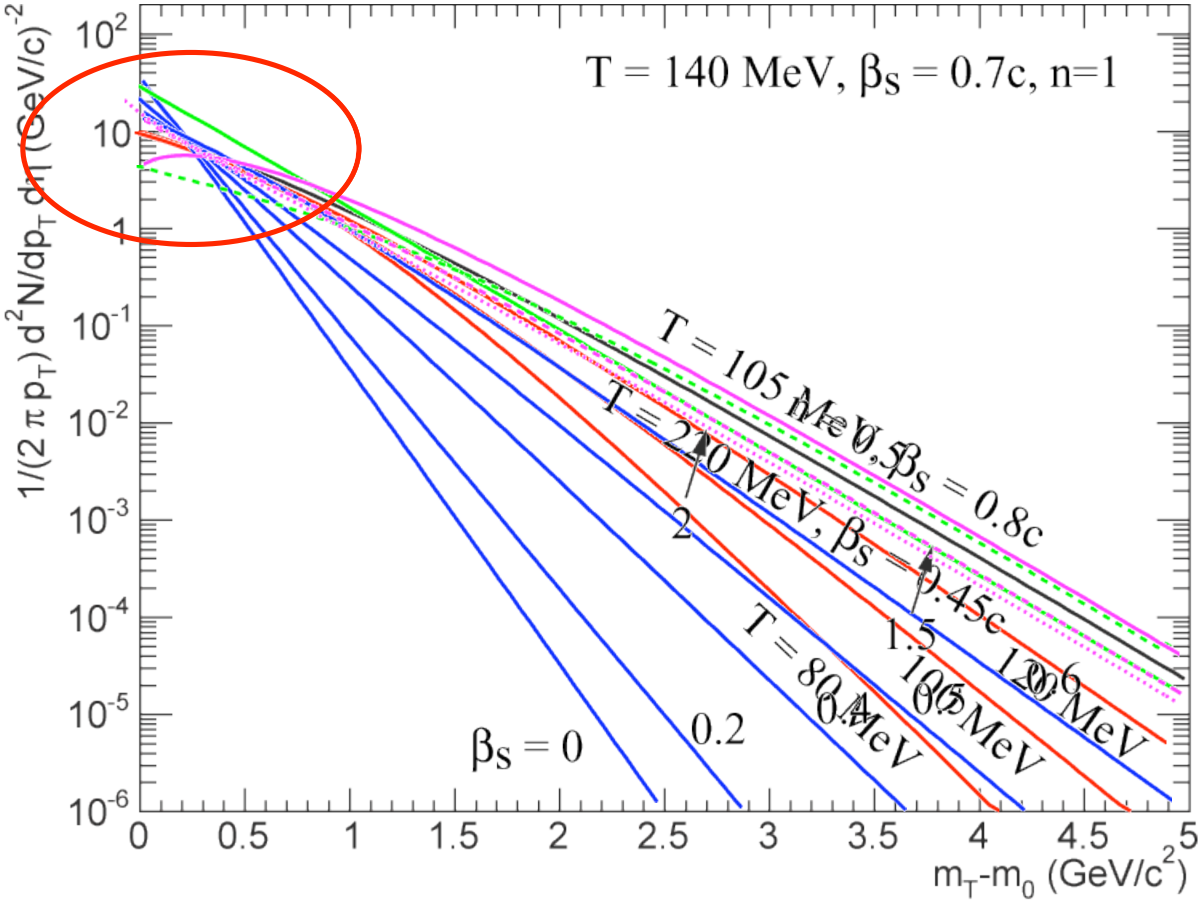
$$\frac{dN}{dy\,dm_T^2} = \frac{g}{4\pi}\tau_f R^2 m_T \sum_{n=1}^{\infty}(\pm 1)^{n+1} K_1(\frac{n m_T}{T}) \xrightarrow{m_T/T \gg 1} \frac{g}{\sqrt{32\pi}}\tau_f R^2 \sqrt{m_T T}\, e^{-m_T/T}$$

m_T scaling broken due to non-zero v_r



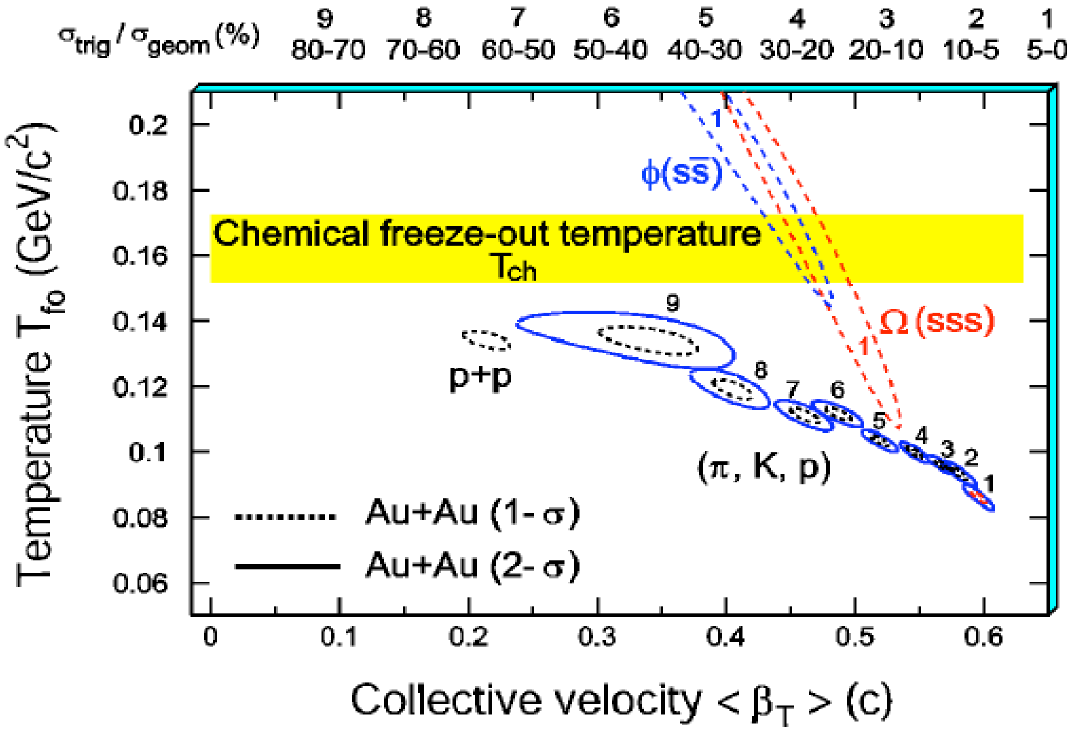
*Ref. [2]

The Blastwave Function



- Increasing T has similar effect on a spectrum as increasing β_s
- Flow profile (n) matters at lower m_T!
- Need high quality data down to low-m_T

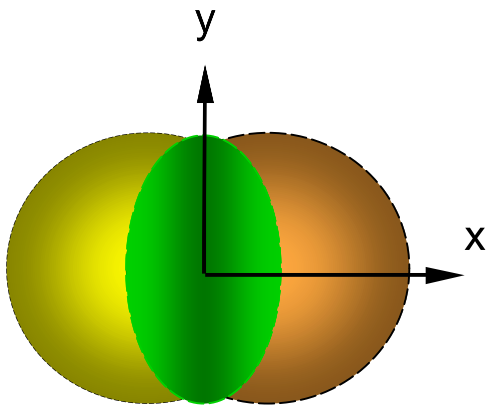
Direct Flow

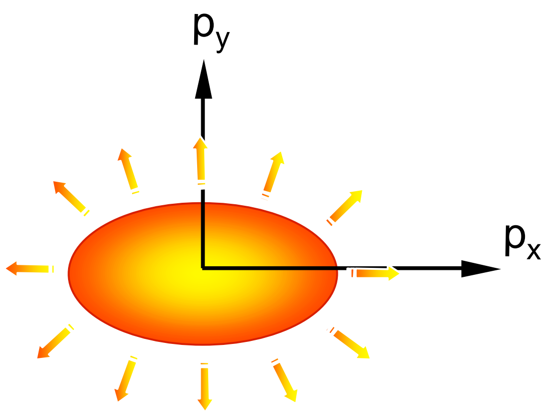


*Ref. [1]

Elliptic Flow (v2)

coordinate-space-anisotropy ➪ momentum-space-anisotropy

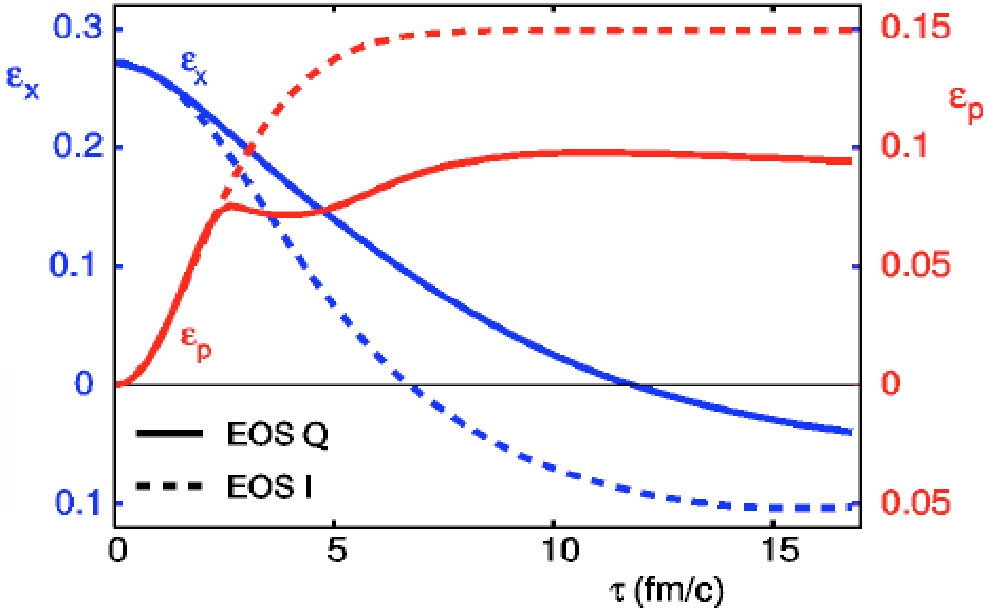




$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \qquad v_2 = \langle \cos 2\varphi \rangle, \;\; \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

Time evolution of anisotropy

- Calculation for a first-order phase transition
- Au + Au at RHIC
- 7 fm impact parameter



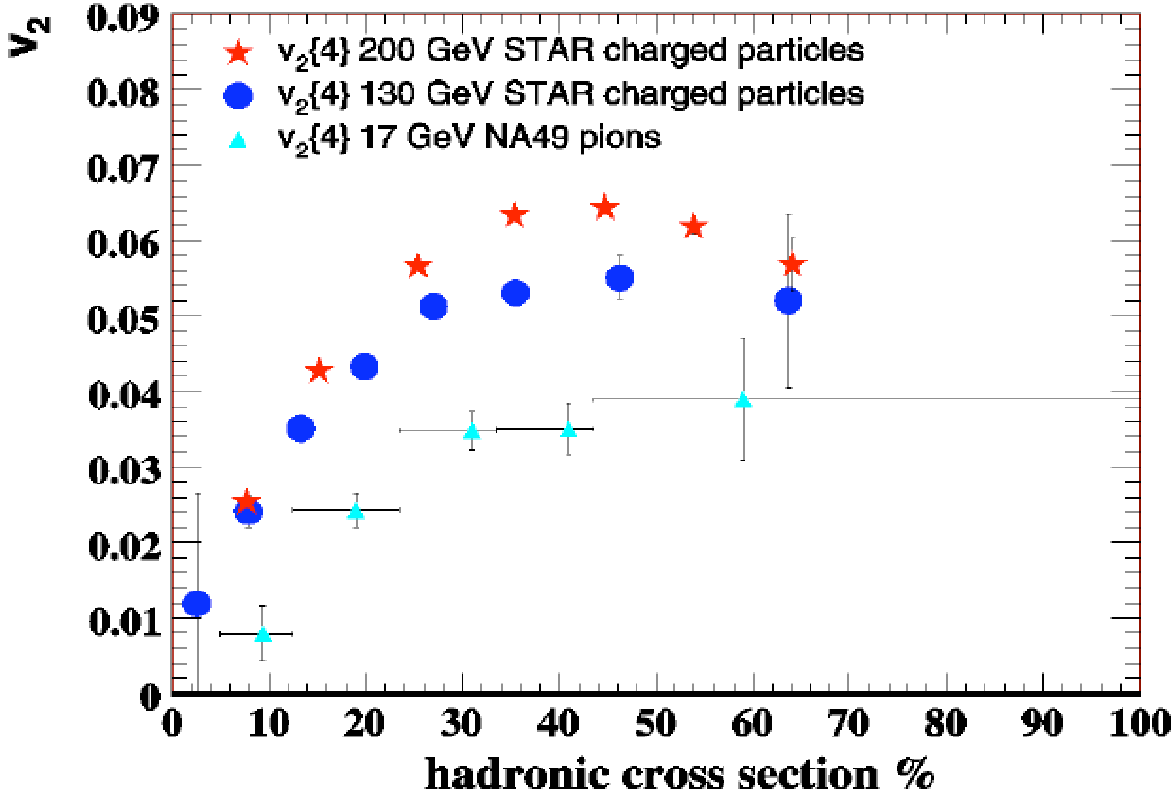
Spatial eccentricity: $\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle}$

Momentum anisotropy:

$$\epsilon_p = \delta = \frac{\langle T^{xx} - T^{yy} \rangle}{\langle T^{xx} + T^{yy} \rangle} = \frac{\int \mathrm{d}x\,\mathrm{d}y\,(T^{xx} - T^{yy})}{\int \mathrm{d}x\,\mathrm{d}y\,(T^{xx} + T^{yy})}$$

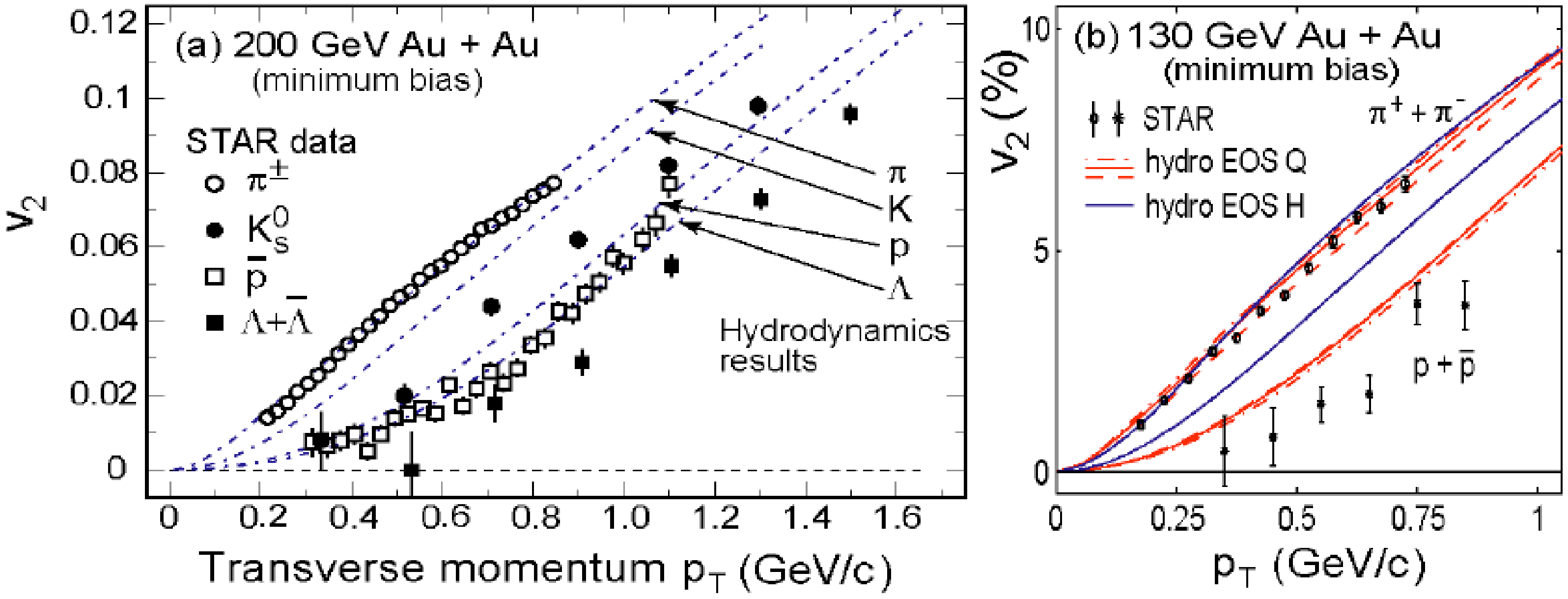
*Ref. [1]

Centrality dependence



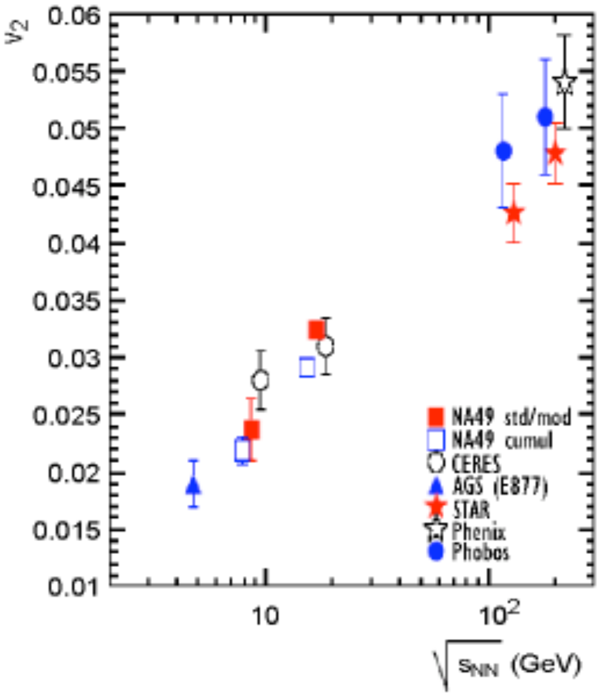
*Ref. [1]

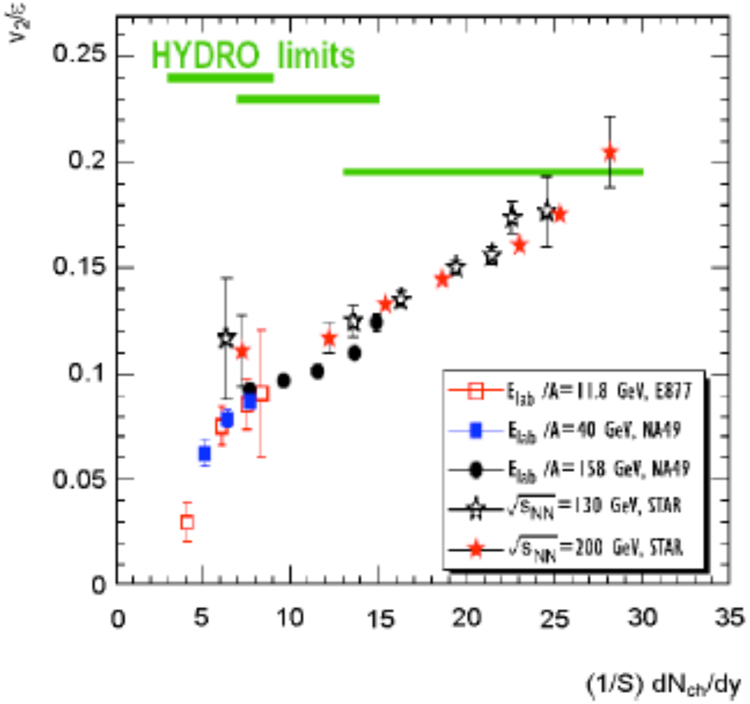
Pt dependence



*Ref. [1]

Energy dependence





*Ref. [1]

HBT effect

- Correlation function:

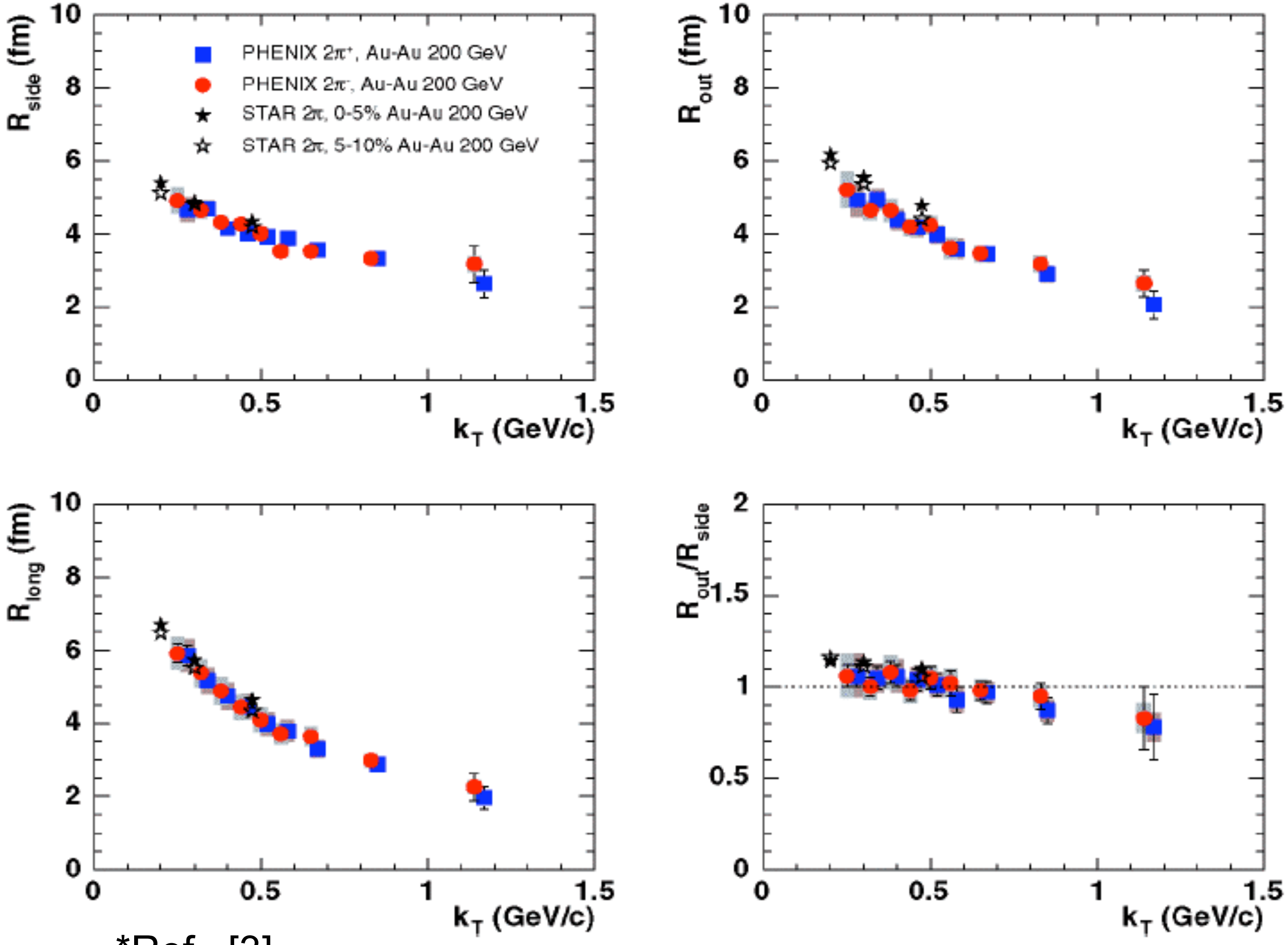
$$C(\boldsymbol{q},\boldsymbol{K}) = \frac{E_1 E_2 \frac{\mathrm{d}N}{\mathrm{d}^3\boldsymbol{p}_1 \mathrm{d}^3\boldsymbol{p}_2}}{E_1 \frac{\mathrm{d}N}{\mathrm{d}\boldsymbol{p}_1} E_2 \frac{\mathrm{d}N}{\mathrm{d}\boldsymbol{p}_2}},$$

$$C(\boldsymbol{q},\boldsymbol{K}) \approx 1 + \exp[-R_o^2(K_T)q_o^2 - R_s^2(K_T)q_s^2 - R_l^2(K_T)q_l^2].$$

where: $q = p_1 - p_2,$

$$K = \tfrac{1}{2}(p_1 + p_2).$$

Bose–Einstein correlations



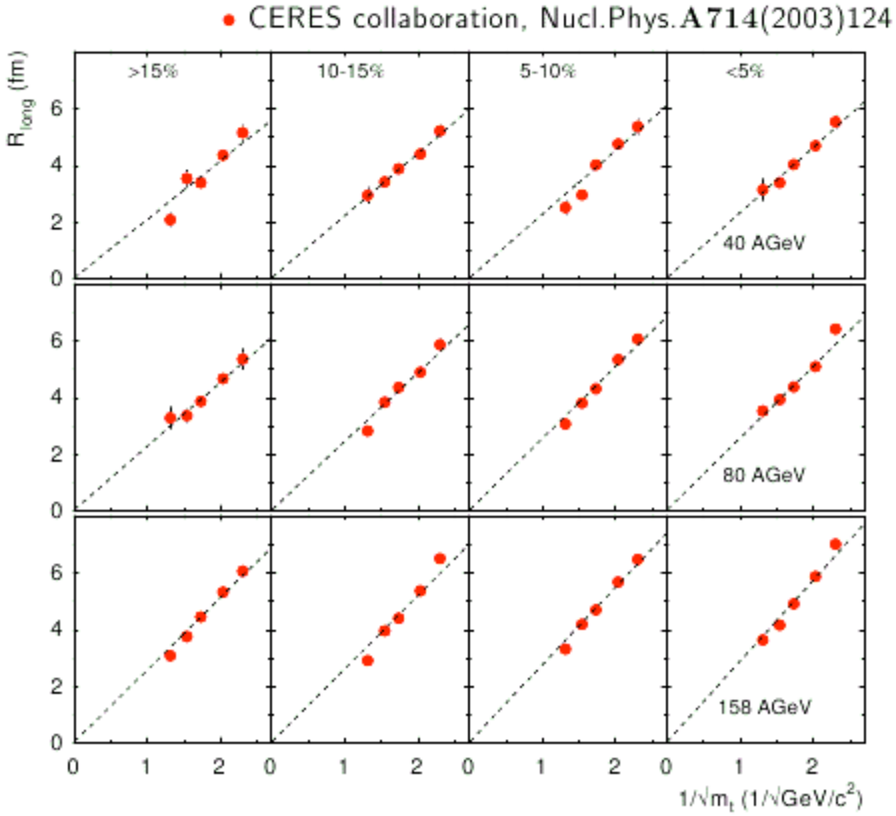
*Ref. [3]

Longitudinal expansion

Duration of expansion (lifetime) τ of the system can be estimated from the transverse momentum dependence of $R_{\rm long}$:

$$R_{\rm long} \approx \tau \cdot \sqrt{\frac{T_f}{m_t}}$$ **Y. Sinyukov**

⇒ $\tau = 6.5 - 8$ **fm/c** for $T_f = 120$ **MeV**



Transverse Expansion

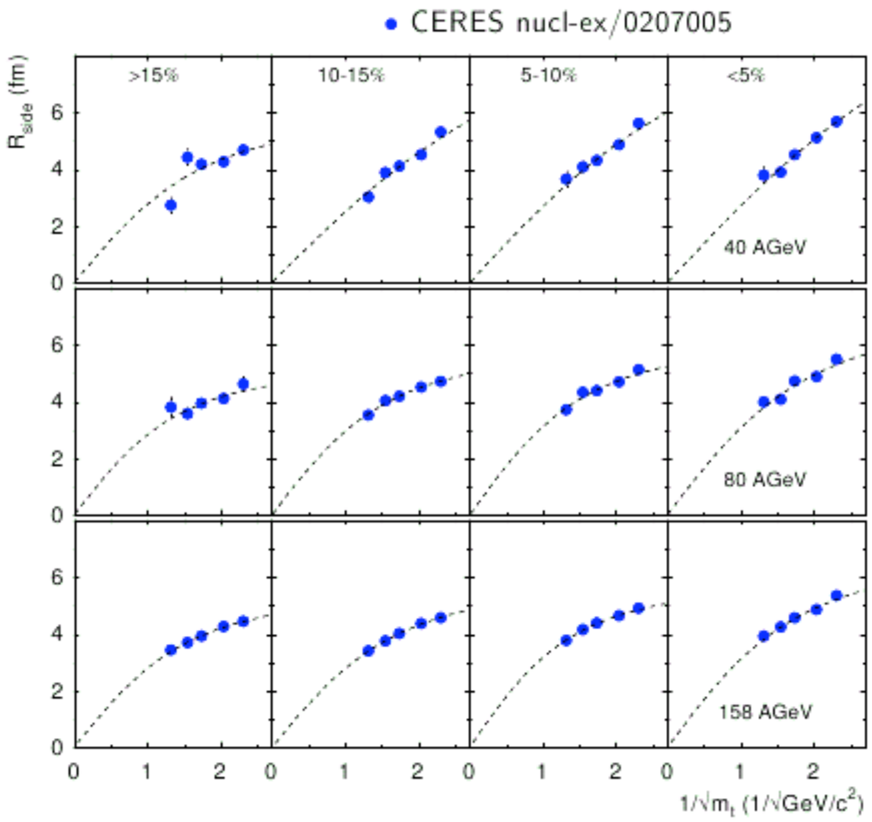
Transverse momentum dependence of R_{side} allows determination of geometric source size R_{geo} and average transverse flow velocity β_t:

$$R_{\mathrm{side}} \approx R_{\mathrm{geo}}/(1 + m_t \cdot F(T_f, \beta_t))^{\frac{1}{2}}$$

U. Heinz *et al.*

⇒

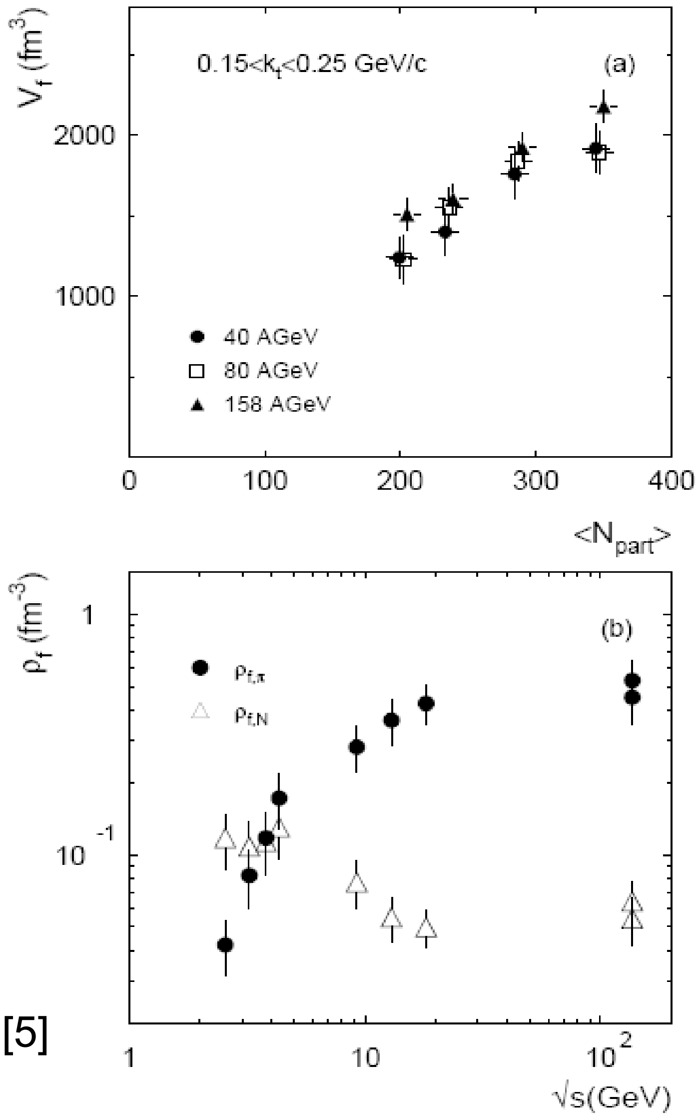
$\beta_t \approx 0.55$ for $T_f = 120$ MeV



HBT in CERES

$$\lambda_f = \frac{1}{\rho_f \cdot \sigma} = \frac{V_f}{N \cdot \sigma},$$

λ_f: mean free path
ρ_f: freeze-out density
V_f: freeze-out volumn



*Ref. [5]

viscosity

$$\eta = \begin{cases} 1.264\,\frac{\mathrm{T}}{\sigma_0} & \text{for } e < e_c \\ \frac{1}{5}\,\mathrm{s} & \text{for } e > e_c \end{cases}$$

where $e_c = 1\,\mathrm{GeV/fm^3}$ and $\sigma_0 = 10\,\mathrm{mb}$.

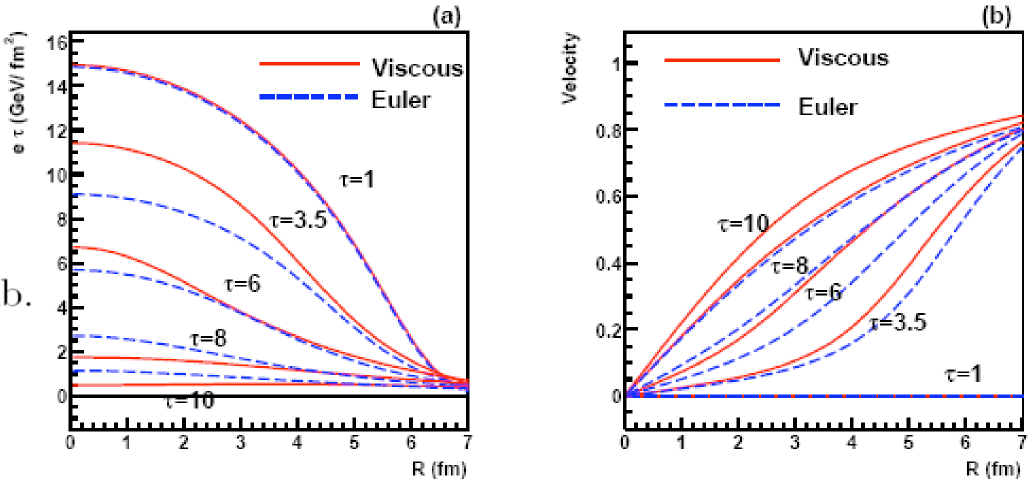


Figure 1. A comparison of the viscous and inviscid (Euler) solutions for a Bjorken expansion with radial symmetry. The initial conditions are from P. Kolb's hydrodynamic model [9]. The equation of state is $p = \frac{1}{3}e$. The viscosity is proportional to the entropy $\eta/s = \frac{1}{5}$. (a) The energy density multiplied by τ for various times (b) The fluid velocity for various times.

*Ref. [6]

In analogy

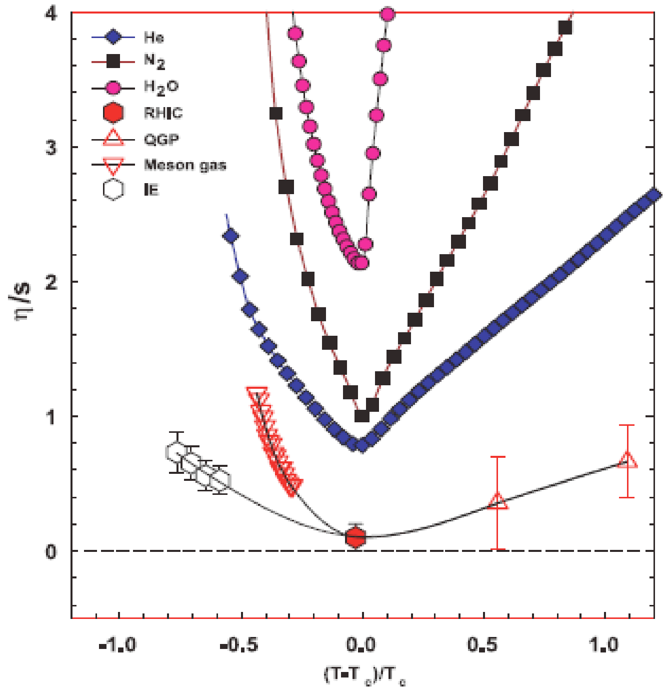


FIG. 3: (Color online) η/s vs $(T-T_c)/T_c$ for several substances as indicated. The calculated values for the meson-gas have an associated error of $\sim 50\%$ [38]. The lattice QCD value $T_c = 170$ MeV [4] is assumed for nuclear matter. The lines are drawn to guide the eye.

*Ref. [7]

summary

- Hydrodynamics model describes particle spectrum well at low p_t
- Effects like energy loss, particle correlation is applied to fit the results
- Anisotropy of the transverse spectrum is a good evidence

Reference

1) STAR White Paper, Nuclear Physics A 757 (2005) 102–183
2) RHIC-tested predictions for low-pT and high-pT hadron spectra in nearly central Pb+Pb collisions at the LHC, K. J. Eskola H. Honkanen et. al, hep-ph/0506049
3) PHENIX White Paper, Nuclear Physics A 757 (2005) 184–283
4) Hydrodynamic Models for Heavy Ion Collisions, P. Huovinen P.V. Ruuskanen, nucl-th/0605008
5) Universal Pion Freeze-out in Heavy-Ion Collisions, CERES Collaboration, nucl-ex/0207008
6) Viscosity and Thermalization, Derek A. Teaney, nucl-th/0403053
7) Recent Results of Source Function Imaging from AGS through CERN SPS to RHIC, Roy A. Lacey, Brazilian Journal of Physics, vol. 37, no. 3A, September, 2007