The early thermalization and HBT puzzles at RHIC

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50 Cracow School of Theoretical Physics
Zakopane, June 9 - 19, 2010

RHIC at BNL

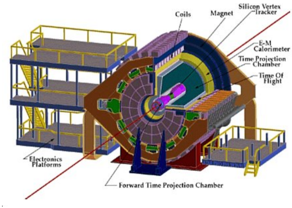
Relativistic Heavy Ion Collider at Brookhaven National Laboratory

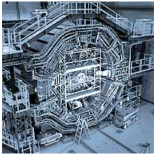
Google Maps: `http://maps.google.com/?ll=40.874649,-72.870598&spn=0.047118,0.079823&z=14`

RHIC at BNL

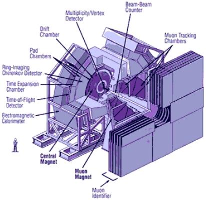
Four experiments

STAR





PHENIX



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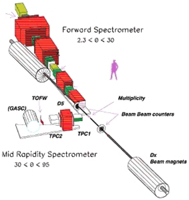

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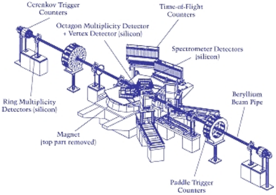


Outline

1. Successes and problems of perfect-fluid hydrodynamics at RHIC
   - very good description of one-particle soft hadronic observables: transverse-momentum spectra, elliptic flow
   - problems with two-particle observables (the so called HBT puzzle)
   - unphysical (?) very early start of hydrodynamics (later ET puzzle)
2. Resolving HBT puzzle (almost done)
   - equation of state
   - initial profiles
   - initial transverse flow
3. Resolving ET problem (not done yet)
   - very strongly interacting matter → AdS/CFT
   - Color Glass Condensate & String Models
   - this talk: Interpolation between initial weakly interacting system and later strongly interacting fluid — initial free-streaming or initial transverse-hydrodynamics followed by the perfect-fluid hydrodynamics, Landau matching conditions

Outline

4. Concept of transverse hydrodynamics
   - motivation
   - general formalism
   - description of the RHIC data
5. HBT vs. v_2 puzzle (?)
   - consequences of realistic EOS
   - quark-coalescence picture
   - inclusion of shear and bulk viscosity

6 Consequences for the early Universe

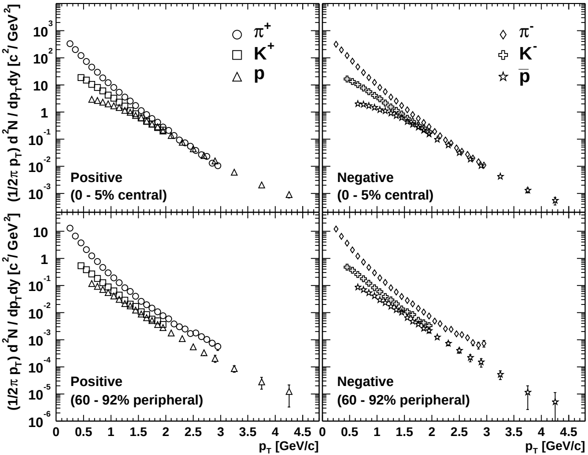
- no dramatic phenomena at the phase transition
- precise time development at times 5–100 μs

7 Conclusions

1. Soft hadronic production at RHIC — successes and problems

1.1 Experimental transverse-momentum spectra

effective inverse slopes: $T_{\rm eff} = T + \frac{1}{2} m v_{\rm hyd}^2$, different slopes → evidence for flow

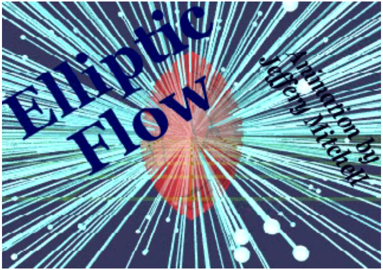


PHENIX, Phys. Rev. C69, 034909 (2004)

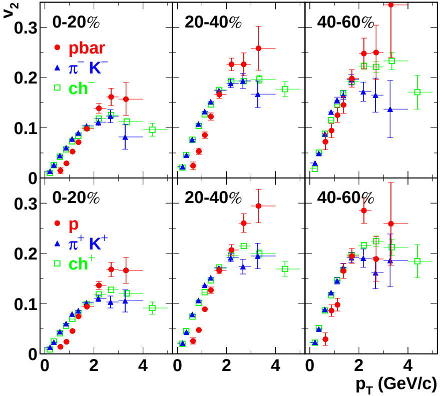
1.2 Experimental elliptic flow

$v_2^{\rm exp}$ agrees with perfect-hydro predictions!

$$\frac{dN}{dy d^2 p_\perp} = \frac{dN}{2\pi dy p_\perp dp_\perp}\left(1 + 2 v_2 \cos(2\phi_p)\right)$$



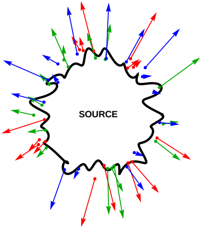
http://www.phenix.bnl.gov/WWW/software/luxor/ani/ellipticFlow/ellipticSmall1-1.mpg
Animation by Jeffery Mitchell (Brookhaven National Laboratory)



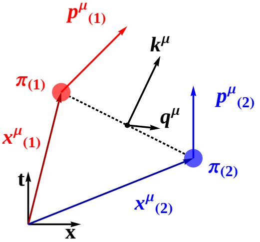
PHENIX, Phys.Rev.Lett.91,182301(2003)

1.3 HBT radii – definitions

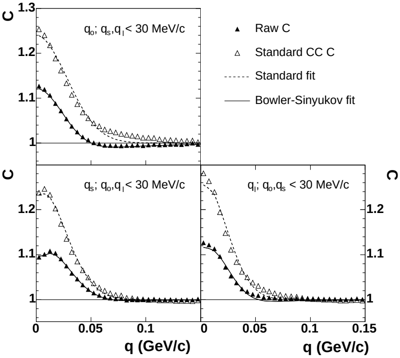
source emits identical pions, $\pi^+\pi^+$, $\pi^-\pi^-$



correlation function $\equiv$ two-particle distribution function, $C(p_1, p_2) \to C(k, q)$



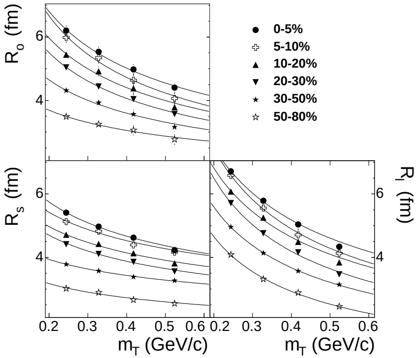
three projections of the correlation functions



STAR, Phys.Rev.C71,044906(2005)

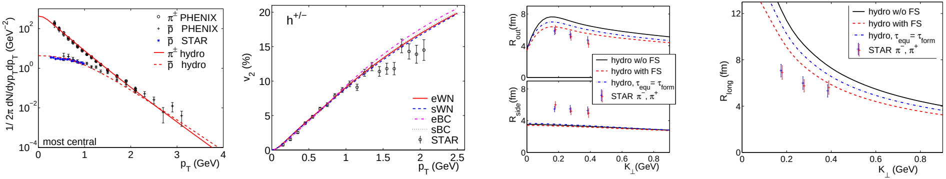
1.3 HBT radii – physical interpretation

- "Fourier transform"
- HBT radii
  - ***R_{side}*** - spatial transverse extension, $R^2_{side} = \langle \tilde{y}^2 \rangle$
  - ***R_{out}*** - spatial transverse extension + emission time, $R^2_{out} = \langle (\tilde{x} - v_\perp \tilde{t})^2 \rangle$
  - ***R_{long}*** - longitudinal extension (homogeneity length), $R^2_{long} = \langle (\tilde{z} - v_\parallel \tilde{t})^2 \rangle$
- HBT radii decrease with k_T, a signal of flow again!

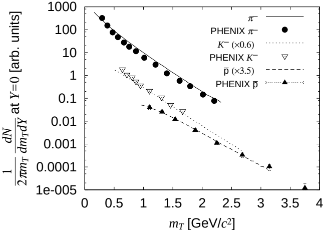


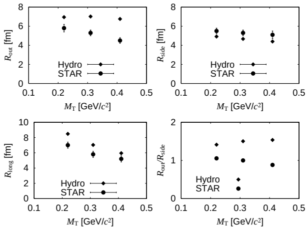
STAR, Phys.Rev.C71,044906(2005)

1.4 Experiment vs. theory / start of RHIC activity



U.Heinz and P.Kolb, Nucl. Phys. A702, 269 (2002)





T.Hirano, K.Morita, S.Muroya, and C.Nonaka, Phys. Rev. C65, 061902 (2002)

1.5 "Standard Model/Scheme" of heavy-ion collisions

main ingredients of the 2+1 models:

- initial conditions, short thermalization time, $\tau_i \leq 1$ fm
  - Glauber model, e.g., initial entropy/energy density is proportional to the linear combination of the wounded-nucleon density and binary-collision density,

$$\sigma_{\rm i}(\mathbf{x}_\perp) \text{ or } \varepsilon_{\rm i}(\mathbf{x}_\perp) \propto \rho_{\rm sr}(\mathbf{x}_\perp) = \frac{1-\kappa}{2}\,\overline{w}\,(\mathbf{x}_\perp) + \kappa\,\overline{n}\,(\mathbf{x}_\perp)$$

  - Color Glass Condensate
  - initial transverse flow, usually set equal to zero (?)
- HYDRODYNAMIC STAGE
  - v_2 data suggest that matter behaves like a perfect fluid main tool: perfect-fluid hydrodynamics (Shuryak + Teaney, Heinz + Kolb + Huovinen + Ruuskanen + Voloshin, Kolb + Rapp, Hirano + Nara, Bass + Nonaka, ...)
  - hadronization included in the equation of state
- freeze-out, Cooper-Frye formula
  - freeze-out hypersurface, thermal description of hadron production
  - transition hypersurface, change to a hadronic cascade

1.6 Perfect-fluid hydrodynamics

- energy-momentum conservation law

$$\partial_\mu T^{\mu\nu} = 0$$

- energy-momentum of the perfect fluid

$$T^{\mu\nu} = (\epsilon + P)\, u^\mu u^\nu - P g^{\mu\nu}$$

ϵ - energy density, P - pressure, u^μ - fluid four-velocity

- mid-rapidity ($|y| \leq 1$) for RHIC
  $\mu_B \approx 0$, temperature is the only independent parameter
- 2+1 codes
  boost-invariance, equations solved at $z = 0$, solutions for $z \neq 0$ obtained by Lorentz boosts
- 3+1 codes – general codes in 3 spatial dimensions

1.7 RHIC puzzles in soft hadronic sector

both the HBT and ET puzzles are related to the applications of hydrodynamics

HBT: discrapancy between the data and hydrodynamic calculations

- simple parameterizations a la Blast-Wave model very often did a very good job in describing all soft hadronic observables
- dramatic failure of kinetic models

ET: very early starting point for hydrodynamics

- τ_i identified with complete local thermalization time τ_{therm}
- Shuryak, Teaney: τ_i = 1 fm, hadronic cascade
- Heinz, Kolb: τ_i = 0.6 fm
- Cracow: τ_i = 0.25 fm
- Pratt: τ_i = 0.2 fm
- partonic cascade models by inclusion of $2 \to 3$ and back $3 \to 2$ processes make $\tau_{therm} \sim 1$ fm.

2. Resolving the HBT puzzle

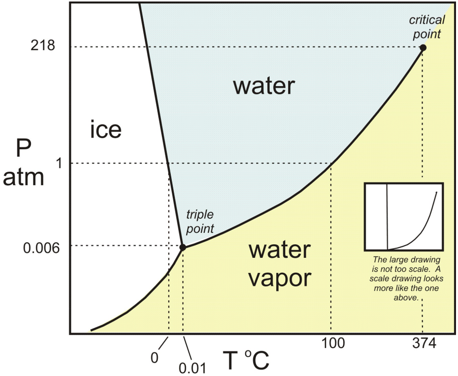
- W. Broniowski, M. Chojnacki, WF, A. Kisiel, PRL **101** (2008) 022301
- S. Pratt, PRL **102** (2009) 232301 (considerations without v_2)

  with several improvements done in the hydrodynamic models, the HBT puzzle is practically eliminated (discrapancy at the level of 10%)

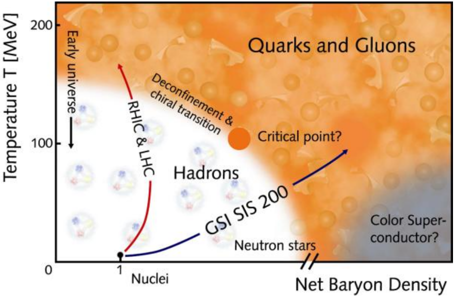
  - realistic equation of state (++)
  - early start of hydrodynamics (++)
  - modified initial conditions (+-)
  - shear viscosity included (-+)
  - fluctuations of the initial eccentricity (+-)
  - two-particle method for the correlation functions important (++)
  - Coulomb corrections not important (++)
  - fast freeze-out (+-)

2.1 phase diagrams

- phase diagram for water



- phase diagram for QCD



2.1 modeling the QCD at zero baryon chemical potential

- hadron gas model for low temparatures

  input files from **SHARE: Statistical hadronization with resonances**
  G. Torrieri, S. Steinke, W. Broniowski, W. Florkowski, J. Letessier, J. Rafelski, Comput. Phys. Commun. **167**, 229 (2005)

- lattice QCD simulations for large temperatures

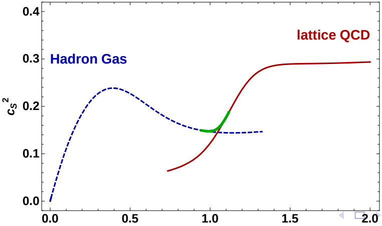
  based on: Y. Aoki, Z. Fodor, S. Katz, K. Szabo, JHEP **0601**, 089 (2006)

  simple parameterization of pressure: T. Biro, J. Zimanyi, Phys.Lett.**B650**, 193 (2007)

- cross-over phase transition, M. Chojnacki, Acta Phys. Pol. **38** (2007) 3249

  thermodynamic variables change suddenly at T_c but smoothly ,

  the sound velocity does not drop to zero



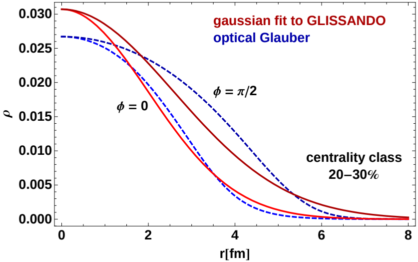
2.2 Initial conditions

Nuclear matter profiles play an important role

- most of the approaches use the Glauber model or Color Glass Condensate,
- W. Broniowski et al., PRL **101** (2008) 022301, Gaussian profiles (Gaussian approximation to Glauber)

$$\frac{dN}{dxdy} \sim \exp\left(-\frac{x^2}{2a^2} - \frac{y^2}{2b^2}\right)$$

the widths a and b determined from GLISSANDO, W. Broniowski et al., Comput. Phys. Commun. **180** (2009) 69



2.3 THERMINATOR

THERMINATOR

THERMal heavy-IoN generATOR

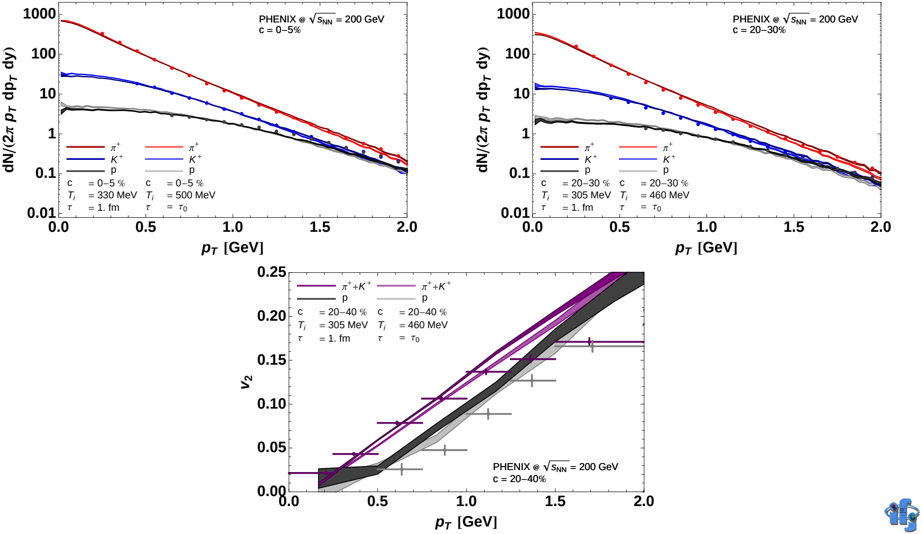
Adam Kisiel, Tomasz Tałuć, Wojciech Broniowski, Wojciech Florkowski

A.Kisiel, T.Taluc, W.Broniowski, W.Florkowski, Comput.Phys.Commun.174:669-687, 2006.

http://www.ifj.edu.pl/dept/no4/nz41/therminator/therminator.html

- Cooper-Frye formula used with the freeze-out hypersurface ($T_f = const$)
- Monte-Carlo code used for particles generation and decays
- THERMINATOR 2, M. Chojnacki, in preparation

2.4 Results for the spectra and v_2



2.4 Results for femtoscopy

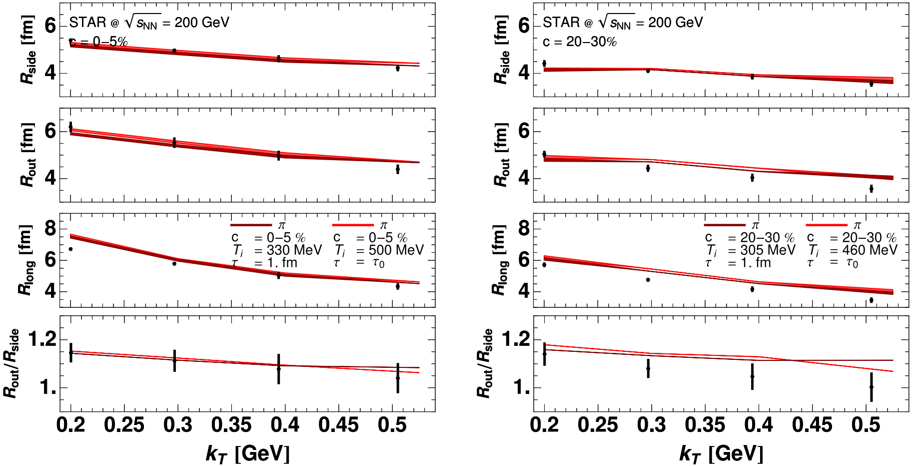
A. Kisiel, WF, and W. Broniowski, Phys. Rev. **C73**, 064902 (2006)

- two-particle method used to calculate the correlation functions (procedure mimics closely the experimental situation),
- the wave function calculated in the pair rest frame (PRF) includes Coulomb (option)
- correlation function fitted in the Bertsch-Pratt coordinates $(k_T, q_{\rm out}, q_{\rm side}, q_{\rm long})$ with Bowler-Sinyukov correction (option)

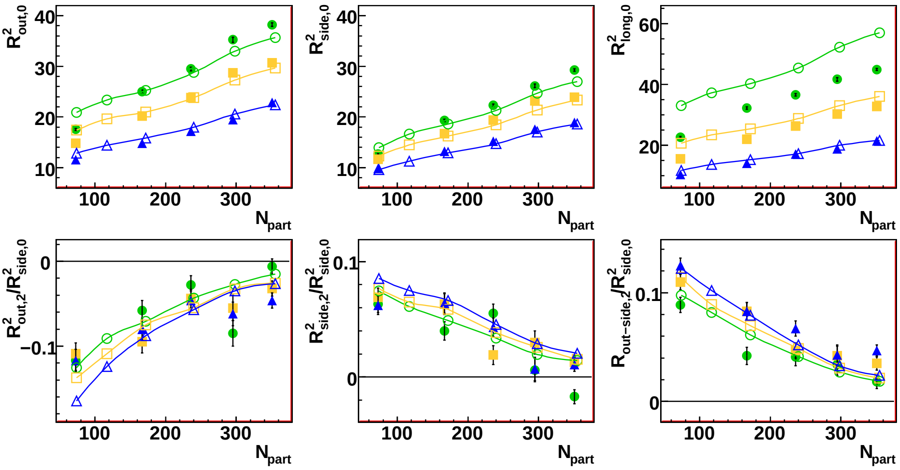
$$C(\vec{q},\vec{k}) = (1-\lambda)+\lambda K_{\rm coul}(q_{\rm inv}) \left[1 + \exp\left(-R_{\rm out}^2{}^2 q_{\rm out}^2 - R_{\rm side}^2 q_{\rm side}^2 - R_{\rm long}^2 q_{\rm long}^2\right)\right],$$

- HBT radii $(R_{\rm out}, R_{\rm side}, R_{\rm long})$ obtained from the fit and compared with data

2.4 HBT results



2.4 Oscillations of the HBT radii, Kisiel et al, PRC 79 (2009) 014902



3. Early-thermalization puzzle

2.1 Fluctuating string tension

- apparent thermalization in string models
  Bialas Phys. Lett. B466 (1999) 301
  Gaussian fluctuations of the string tension can account for "thermal" character of transverse-mass distributions

$$\frac{dn_\kappa}{d^2p_\perp} \sim e^{-\pi m_\perp^2/\kappa^2}, \quad P(\kappa) = \sqrt{\frac{2}{\pi\langle\kappa^2\rangle}} \exp\left(-\frac{\kappa^2}{2\langle\kappa^2\rangle}\right)$$

$$\int_0^\infty d\kappa P(\kappa) \frac{dn_\kappa}{d^2p_\perp} \sim \exp\left(-m_\perp\sqrt{\frac{2\pi}{\langle\kappa^2\rangle}}\right)$$

$$T = \sqrt{\frac{\langle\kappa^2\rangle}{2\pi}}, \qquad y \approx \eta, P_L \approx 0$$

- similar effects from the fluctuations of color fields in heavy-ion reactions, color-flux-tube models,
  WF, Acta Phys. Polon. B35 (2004) 799

2.1 Color glass condensate & Glasma

Larry McLerran et al.

- Kovchegov Nucl. Phys. A830, 395-402, 2009
  at early proper times $\tau \ll 1/Q_s$ the classical gluon fields lead to the following energy-momentum tensor (Lappi,Fukushima)

$$T^{\mu\nu}\Big|_{\tau \ll 1/Q_s} = \begin{pmatrix} \epsilon(\tau) & 0 & 0 & 0 \\ 0 & \epsilon(\tau) & 0 & 0 \\ 0 & 0 & \epsilon(\tau) & 0 \\ 0 & 0 & 0 & -\epsilon(\tau) \end{pmatrix}$$

  at later proper times $\tau \gg 1/Q_s$ both the analytical perturbative approaches (Kovchegov) and the full numerical simulations (Krasnitz) lead to

$$T^{\mu\nu}\Big|_{\tau \gg 1/Q_s} = \begin{pmatrix} \epsilon(\tau) & 0 & 0 & 0 \\ 0 & \epsilon(\tau)/2 & 0 & 0 \\ 0 & 0 & \epsilon(\tau)/2 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

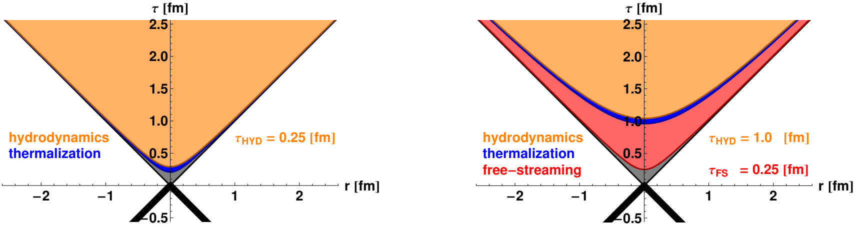
similar effects from viscosity!

$$T^{\mu\nu} = \begin{pmatrix} \varepsilon_3 & 0 & 0 & 0 \\ 0 & P_3 + \frac{2}{3}\frac{\eta}{\tau} & 0 & 0 \\ 0 & 0 & P_3 + \frac{2}{3}\frac{\eta}{\tau} & 0 \\ 0 & 0 & 0 & P_3 - \frac{4}{3}\frac{\eta}{\tau} \end{pmatrix}$$

2.2 Free-streaming, W. Broniowski et al., PRC 80 (2009) 034902

- thermalization requires some time ($\tau \approx 0.25 - 1.0$ fm)
- two scenarios

— early thermalization — free-streaming



- model for early stage dynamics
  - free streaming of particles, no interactions
  - sudden thermalization – Landau's matching conditions, $T^{\mu\nu}_{fr.\,str.} u_\nu = T^{\mu\nu}_{perf.\,hyd.} u_\nu$
- our results indicate that the two scenarios are equivalent

The early thermalization and HBT puzzles at RHIC PART II

- free-streaming = free motion, Boltzmann equation without the collision term, at large times the correlation $y = \eta$ builds in (due to pure relativistic kinematics!), $P_L = 0$, another example of the assymetric energy-momentum tensor, Yura Sinyukov et al.
- our opinion: delayed but sudden thermalization is equivalent to the gradual thermalization
- kinetic models: partonic, based on QCD (before hydro stage) & hadronic, UrQMD (after hydro stage)
- no dip in $c_s(T) \rightarrow$ no shock waves — (simple) numrical algorithms for solving hydro work, we do it with Mathematica, later ROOT

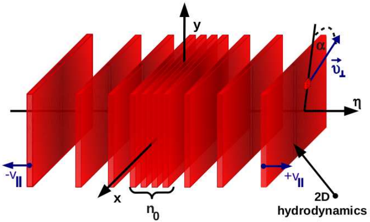
4. Transverse hydrodynamics

4.1 Transverse-hydro concept

- at early stages only the transverse degrees of freedom are thermalized and described by hydrodynamics
- an earlier formulation of this idea:
  Heinz and S.M.H. Wong Phys. Rev. **C66** (2002) 014907
  Heinz and S.M.H. Wong Nucl. Phys. **A715** (2003) 649
- the new implementation
  Bialas, Chojnacki and Florkowski Phys. Lett. **B661** (2008) 325
  correct description of the $p_\perp$ spectra and v_2
  partons identified with pions
  $\langle p_\perp \rangle$ is conserved in transverse hydro
  $\langle p_\perp \rangle \approx 2\lambda_{\rm slope} \approx T\sqrt{(1+v)/(1-v)}$
- most recent developments:
  Chojnacki and Florkowski, Acta Phys. Pol. **B39** (2008)
  Ryblewski and Florkowski, Phys. Rev. **C77** (2008) 064906

4.1 Transverse clusters

- superposition of non-interacting transverse clusters
- each cluster is formed by particles moving with the same value of rapidity
- single cluster $\Rightarrow$ 2D hydrodynamics
- $n_0(\eta)$ - density of clusters in rapidity



$$y = \frac{1}{2} \ln \frac{E + p_{||}}{E - p_{||}} \qquad \eta = \frac{1}{2} \ln \frac{t+z}{t-z}$$

- standard parameterization of the four-momentum and spacetime coordinate

$$p^\mu = (E, \vec{p}_\perp, p_{||}) = (m_\perp \cosh y, \vec{p}_\perp, m_\perp \sinh y)$$
$$x^\mu = (t, \vec{x}_\perp, z) = (\tau \cosh \eta, \vec{x}_\perp, \tau \sinh \eta)$$
$$\tau = \sqrt{t^2 - z^2} \qquad m_\perp = \sqrt{m^2 + p_x^2 + p_y^2}$$

4.1 2D thermodynamics

- non-interacting bosons

$$\Omega_2(T_2, V_2, \mu) = \nu_g T_2 V_2 \int \frac{d^2 p_\perp}{(2\pi)^2} \ln\left(1 - e^{(\mu - m_\perp)/T_2}\right)$$

- gluon dominated systems $\rightarrow \ \nu_g = 16$
- number of particles not conserved $\rightarrow \ \mu = 0$

$$n_2 = \frac{\nu_g \pi T_2^2}{12} \qquad \varepsilon_2 = \frac{\nu_g \zeta(3) T_2^3}{\pi} \qquad P_2 = \frac{\varepsilon_2}{2} \qquad \varepsilon_2 + P_2 = T\sigma_2$$

4.1 Energy-momentum tensor

- energy-momentum tensor $T_2^{\mu\nu}$, entropy current S_2^μ, particle current N_2^μ

$$T_2^{\mu\nu} = \frac{n_0}{\tau}\left[(\varepsilon_2 + P_2)\, U^\mu U^\nu - P_2\,(g^{\mu\nu} + V^\mu V^\nu)\right]$$

$$N_2^\mu = \frac{n_0}{\tau} n_2 U^\mu \quad S_2^\mu = \frac{n_0}{\tau} s_2 U^\mu$$

- four vectors U^μ and V^μ are defined by

$$U^\mu = (u_0 \cosh\eta, u_x, u_y, u_0 \sinh\eta)$$
$$V^\mu = (\sinh\eta, 0, 0, \cosh\eta)$$

- rest-frame of the fluid element (similar to CGC, glasma)

$$T_2^{\mu\nu} = \frac{n_0}{\tau}\begin{pmatrix} \varepsilon_2 & 0 & 0 & 0 \\ 0 & P_2 & 0 & 0 \\ 0 & 0 & P_2 & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$$

4.1 Transverse-hydrodynamics equations

- energy-momentum conservation law

$$\partial_\mu T_2^{\mu\nu} = 0$$

- entropy conservation

$$\partial_\mu S_2^\mu = 0$$

- three-dimensional densities of the transversally thermalized system

$$\varepsilon_3^{\rm tr} = \frac{n_0}{\tau}\varepsilon_2, \quad \sigma_3^{\rm tr} = \frac{n_0}{\tau}\sigma_2, \quad \ldots$$

- hydrodynamic equations

$$\begin{aligned} U^\mu \partial_\mu \left(T_2 U^\nu \right) &= \partial^\nu T_2 + V^\nu V^\mu \partial_\mu T_2 \\ \partial_\mu \left(\sigma_3^{\rm tr} U^\mu \right) &= 0 \end{aligned}$$

4.1 Initial transverse profiles

- $\tau = 0 \quad \rightarrow$ two nuclei pass through each other
- $\tau = \tau_i \quad \rightarrow$ transverse thermalization

initial flow

$v_i(\vec{x}_\perp) = 0$

initial profiles, NOT GAUSSIANS NOW! (mixed model)

$$\sigma_{2\mathrm{i}}(\vec{x}_\perp) = \sigma_2(\tau_\mathrm{i}, \vec{x}_\perp) \;\propto\; \rho_\mathrm{sr}(\vec{x}_\perp) = \frac{1-\kappa}{2}\,\overline{w}\,(\vec{x}_\perp) + \kappa\,\overline{n}\,(\vec{x}_\perp)$$

$$\varepsilon_{2\mathrm{i}}(\vec{x}_\perp) = \varepsilon_2(\tau_\mathrm{i}, \vec{x}_\perp) \;\propto\; \rho_\mathrm{sr}(\vec{x}_\perp) = \frac{1-\kappa}{2}\,\overline{w}\,(\vec{x}_\perp) + \kappa\,\overline{n}\,(\vec{x}_\perp)$$

initial temperature profile (2D bosons)

$$\varepsilon_2\left(\tau_\mathrm{i}, \vec{x}_\perp\right) = \frac{\nu_g \zeta(3)\, T_2^3(\tau_\mathrm{i}, \vec{x}_\perp)}{\pi} \qquad \sigma_2\left(\tau_\mathrm{i}, \vec{x}_\perp\right) = \frac{3}{2}\,\frac{\nu_g \zeta(3)\, T_2^2(\tau_\mathrm{i}, \vec{x}_\perp)}{\pi}$$

$$T_{2\,\mathrm{i}} = T_2(\tau_\mathrm{i}, 0)$$

4.2 Landau matching conditions

microscopic view: full isotropisation is expected eventually, gradual process approximated by a delayed step-like transition at τ_{tr} = const.

- Landau matching conditions

$$T_2^{\mu\nu} U_\nu = T_3^{\mu\nu} U_\nu$$

$$T_3^{\mu\nu} = (\varepsilon_3 + P_3) U^\mu U^\nu - P_3 g^{\mu\nu}$$

- equivalent condition supplemented by the requirement of the entropy growth

$$\varepsilon_3^{\rm tr} = \frac{n_0}{\tau_{\rm tr}} \varepsilon_2 = \varepsilon_3,$$

$$\sigma_3^{\rm tr} = \frac{n_0}{\tau_{\rm tr}} \sigma_2 \leq \sigma_3,$$

- microscopic approaches:
  P. Bozek, Acta Phys. Polon., **B39** (2008) 1375 - dissipative hydro, η very large in the early stage
  B. Zhang, L.-W. Chen, C. M. Ko, arXiv:0805.0587 - transport theory

4.2 Landau matching conditions

- transverse-hydrodynamics equations are scale invariant — temperature may be multiplied by an arbitrary factor without the change of the flow profile
- the following transformation does not change the 3D energy density and flow, but changes the 3D entropy density in the transverse stage

$$n_0 \to \lambda n_0, \quad T_2 \to \lambda^{-1/3} T_2$$

$$\varepsilon_3^{\rm tr} \to \varepsilon_3 \qquad \sigma_3^{\rm tr} \to \lambda^{1/3} \sigma_3^{\rm tr} \leqslant \sigma_3 \qquad v \to v$$

- $\lambda \searrow$ as we shall see, the fit to the data favors fewer and hotter clusters (small n_0)

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- $\lambda \searrow$ as we shall see, the fit to the data favors fewer and hotter clusters (small n_0)

4.3 Model parameters

Model parameters

n_0	?	overall normalization
T_{2i}	?	initial central temperature of 2D system
T_{3f}	?	freeze-out temperature
τ_i	?	initial proper time
τ_{tr}	?	the 2D $\longrightarrow$ 3D transition time
κ	?	admixture of the binary-collision density
μ_B	?	baryon chemical potential
μ_S	?	strangeness chemical potential
μ_{I_3}	?	isospin chemical potential

4.3 Model parameters

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n_0	?	overall normalization
T_{2i}	?	initial central temperature of 2D system
T_{3f}	?	freeze-out temperature
τ_i	?	initial proper time
τ_{tr}	?	the 2D $\rightarrow$ 3D transition time
κ	?	admixture of the binary-collision density
μ_B	28.5 MeV	baryon chemical potential
μ_S	6.9 MeV	strangeness chemical potential
μ_{I_3}	0.9 MeV	isospin chemical potential

chemical potentials μ_B, μ_S, μ_{I_3}, M.Michalec et al. Acta Phys. Pol. B33 (2002) 761

- $\ll T_{3f}$
- their effect on the evolution of matter is neglected
- appear **only** in the thermal distribution functions used to generate particles on the freeze-out hypersurface

4.3 Model parameters

Model parameters

n_0	?	overall normalization
T_{2i}	?	initial central temperature of 2D system
T_{3f}	145 MeV	freeze-out temperature
τ_i	?	initial proper time
τ_{tr}	?	the 2D $\rightarrow$ 3D transition time
κ	?	admixture of the binary-collision density
μ_B	28.5 MeV	baryon chemical potential
μ_S	6.9 MeV	strangeness chemical potential
μ_{I_3}	0.9 MeV	isospin chemical potential

freeze-out temperature

- typical values for freeze-out temperature used are $\sim$ 140-145 MeV
- control the slope of the spectra

4.3 Model parameters

Model parameters

n_0	?	overall normalization
T_{2i}	?	initial central temperature of 2D system
T_{3f}	145 MeV	freeze-out temperature
τ_i	0.25 fm	initial proper time
τ_{tr}	1 fm	the 2D $\rightarrow$ 3D transition time
κ	?	admixture of the binary-collision density
μ_B	28.5 MeV	baryon chemical potential
μ_S	6.9 MeV	strangeness chemical potential
μ_{I_3}	0.9 MeV	isospin chemical potential

transverse evolution time interval

- $\tau_{tr} - \tau_i \geq 0.75$ fm $\Rightarrow$ radial flow too strong

4.3 Model parameters

Model parameters

n_0	?	overall normalization
T_{2i}	?	initial central temperature of 2D system
T_{3f}	145 MeV	freeze-out temperature
τ_i	0.25 fm	initial proper time
τ_{tr}	1 fm	the 2D $\rightarrow$ 3D transition time
κ	?	admixture of the binary-collision density
μ_B	28.5 MeV	baryon chemical potential
μ_S	6.9 MeV	strangeness chemical potential
μ_{I_3}	0.9 MeV	isospin chemical potential

fitting procedure performed for n_0, T_{2i}, κ

- we find n_0, T_{2i}, κ
- rescale n_0, T_{2i} to satisfy L.M.C.

4.3 Model parameters

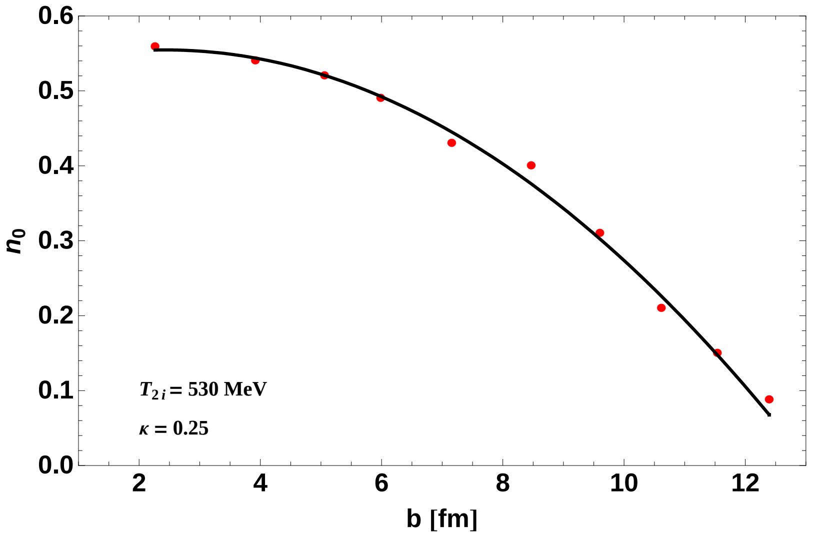
Model parameters

n_0	$n_0(b)$	overall normalization
T_{2i}	530 MeV	initial central temperature of 2D system
T_{3f}	145 MeV	freeze-out temperature
τ_i	0.25 fm	initial proper time
τ_{tr}	1 fm	the 2D $\rightarrow$ 3D transition time
κ	0.25	admixture of the binary-collision density
μ_B	28.5 MeV	baryon chemical potential
μ_S	6.9 MeV	strangeness chemical potential
μ_{I_3}	0.9 MeV	isospin chemical potential

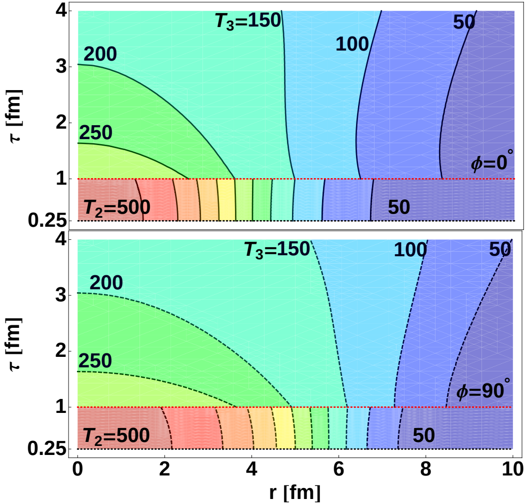
fitting procedure performed for n_0, T_{2i}, κ

- we find n_0, T_{2i}, κ
- rescale n_0, T_{2i} to satisfy L.M.C.

4.3 Centrality dependence of n_0



4.3 2D → 3D transition (c=20-30%)



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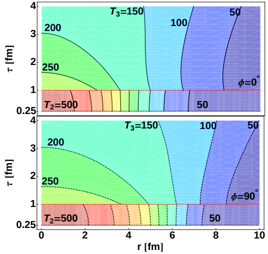
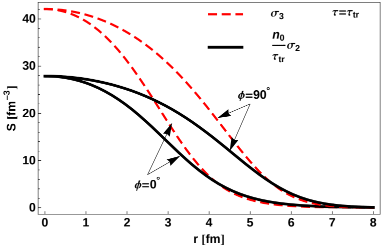
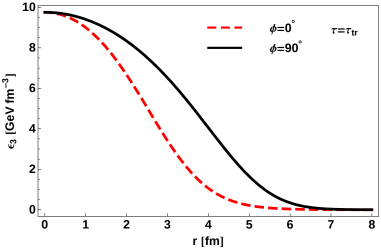
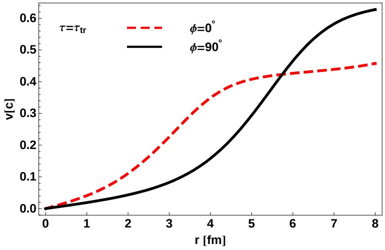
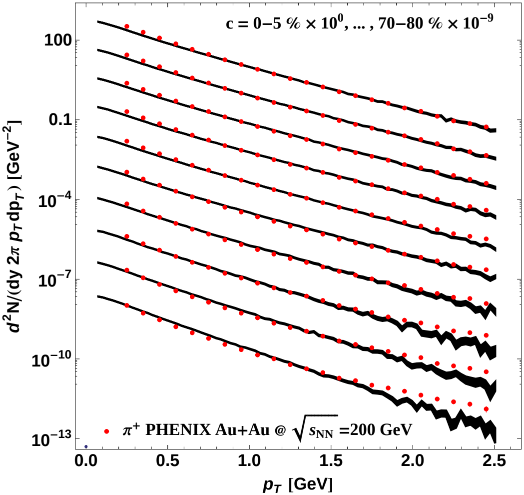




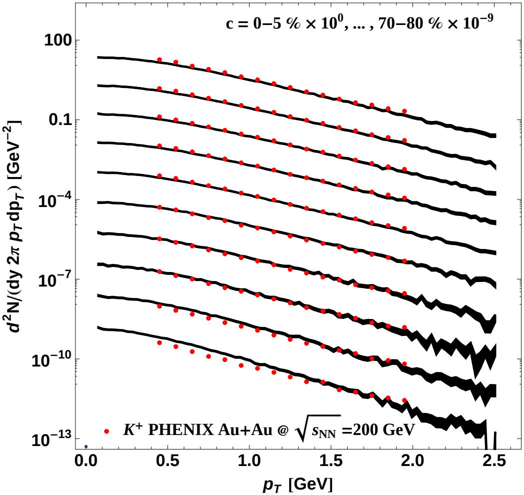




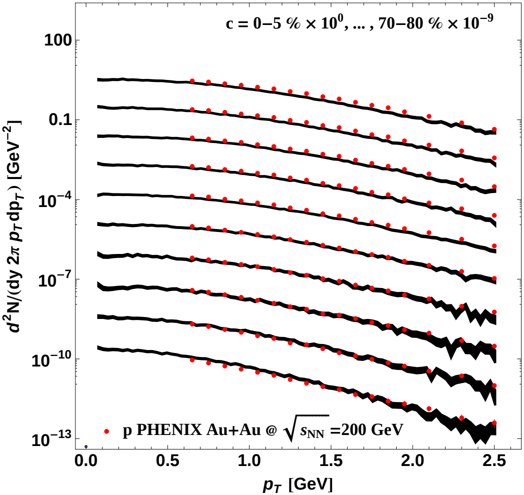
π^+ $p_\perp$-spectra



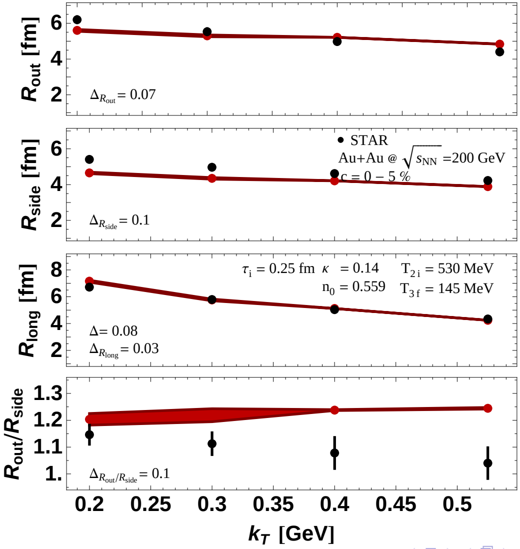
K^+ $p_\perp$-spectra



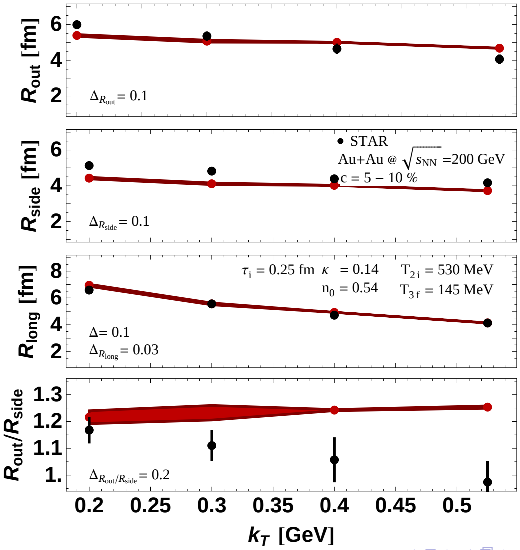
proton $p_\perp$-spectra



π HBT (c=0-5%)

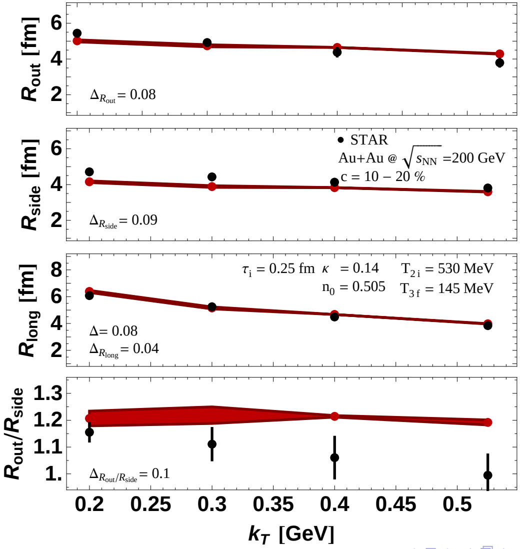

R_{out} [fm]
$\Delta_{R_{out}} = 0.07$
R_{side} [fm]
● STAR
Au+Au @ $\sqrt{s_{NN}}$ =200 GeV
c = 0 – 5 %
$\Delta_{R_{side}} = 0.1$
R_{long} [fm]
τ_i = 0.25 fm κ = 0.14
n_0 = 0.559
T_{2i} = 530 MeV
T_{3f} = 145 MeV
Δ= 0.08
$\Delta_{R_{long}} = 0.03$
R_{out}/R_{side}
$\Delta_{R_{out}/R_{side}} = 0.1$
k_T [GeV]

π HBT (c=5-10%)



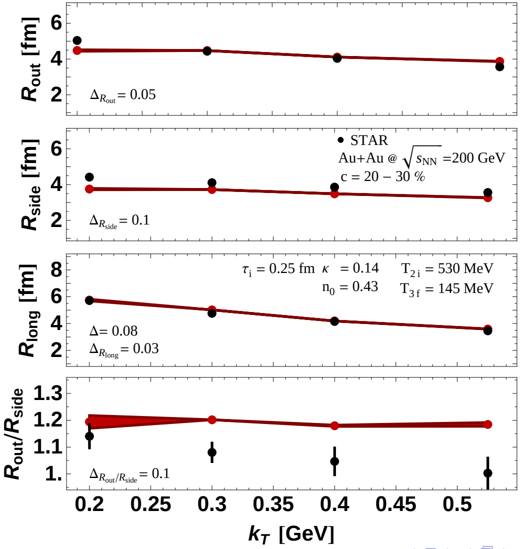
R_{out} [fm]
$\Delta_{R_{out}} = 0.1$
R_{side} [fm]
● STAR
Au+Au @ $\sqrt{s_{NN}}$ =200 GeV
c = 5 – 10 %
$\Delta_{R_{side}} = 0.1$
R_{long} [fm]
τ_i = 0.25 fm κ = 0.14 T_{2i} = 530 MeV
n_0 = 0.54 T_{3f} = 145 MeV
Δ= 0.1
$\Delta_{R_{long}} = 0.03$
R_{out}/R_{side}
$\Delta_{R_{out}/R_{side}} = 0.2$
k_T [GeV]

π HBT (c=10-20%)



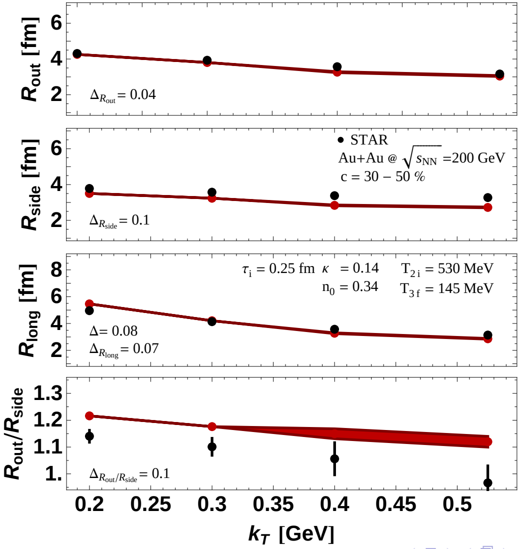
R_out [fm]
Δ_R_out = 0.08
R_side [fm]
• STAR
Au+Au @ √s_NN =200 GeV
c = 10 – 20 %
Δ_R_side = 0.09
R_long [fm]
τ_i = 0.25 fm κ = 0.14 T_2i = 530 MeV
n_0 = 0.505 T_3f = 145 MeV
Δ= 0.08
Δ_R_long = 0.04
R_out/R_side
Δ_R_out/R_side = 0.1
k_T [GeV]
0.2 0.25 0.3 0.35 0.4 0.45 0.5

π HBT (c=20-30%)

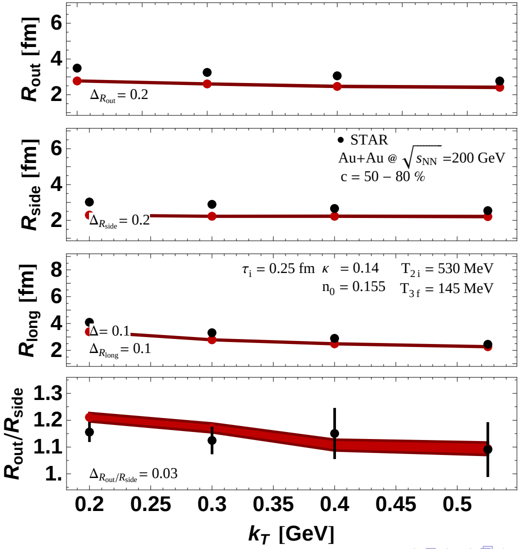


R_out [fm]
Δ_Rout = 0.05
R_side [fm]
● STAR
Au+Au @ √s_NN =200 GeV
c = 20 – 30 %
Δ_Rside = 0.1
R_long [fm]
τ_i = 0.25 fm κ = 0.14 T_2i = 530 MeV
n_0 = 0.43 T_3f = 145 MeV
Δ= 0.08
Δ_Rlong = 0.03
R_out/R_side
Δ_Rout/Rside = 0.1
0.2 0.25 0.3 0.35 0.4 0.45 0.5
k_T [GeV]

π HBT (c=30-50%)

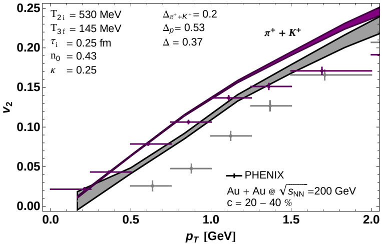

Rout [fm]
ΔRout = 0.04
Rside [fm]
• STAR
Au+Au @ √sNN =200 GeV
c = 30 – 50 %
ΔRside = 0.1
Rlong [fm]
τi = 0.25 fm κ = 0.14 T2i = 530 MeV
n0 = 0.34 T3f = 145 MeV
Δ= 0.08
ΔRlong = 0.07
Rout/Rside
ΔRout/Rside = 0.1
0.2 0.25 0.3 0.35 0.4 0.45 0.5
kT [GeV]

π HBT (c=50-80%)



R_{out} [fm]
$\Delta_{R_{out}} = 0.2$
R_{side} [fm]
• STAR
Au+Au @ $\sqrt{s_{NN}}$ =200 GeV
c = 50 – 80 %
$\Delta_{R_{side}} = 0.2$
R_{long} [fm]
τ_i = 0.25 fm κ = 0.14 T_{2i} = 530 MeV
n_0 = 0.155 T_{3f} = 145 MeV
Δ= 0.1
$\Delta_{R_{long}} = 0.1$
R_{out}/R_{side}
$\Delta_{R_{out}/R_{side}} = 0.03$
k_T [GeV]

v_2 (c=20-30%)



protons v_2 is too large by about 50%

possible reasons:

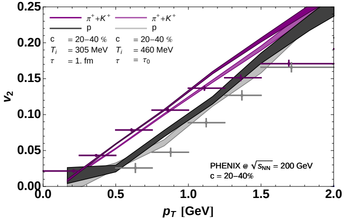
- lack of the hadronic interactions in the final state
- neglecting the viscous effects (inclusion of the bulk viscosity,

  P.Bożek Phys.Rev.C81:034909,2010)

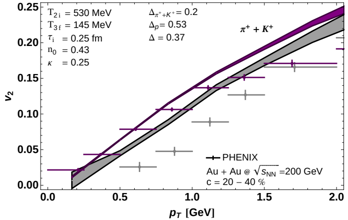
5. HBT vs v_2 puzzle?

5.1 Proton v_2 for realistic EOS is too large!

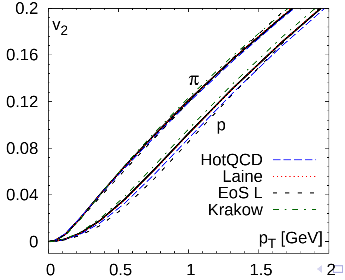
Gaussian initial conditions



transverse hydrodynamics

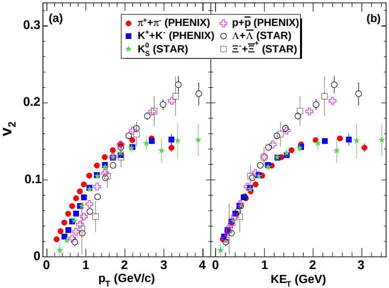


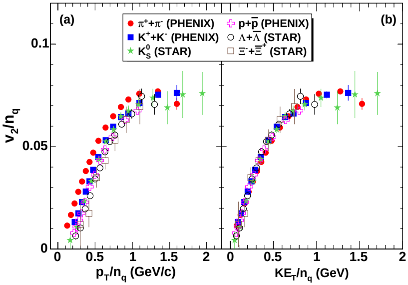
Huovinen and Petreczky, Nucl. Phys. A837 (2010) 26



5.2 v_2 scaling

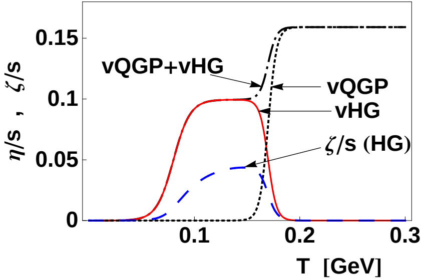
PHENIX, PRL98 (2007) 162301

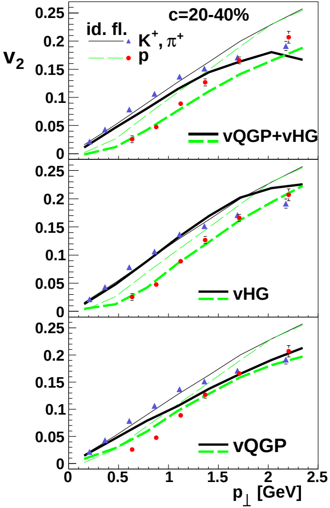




5.3 Inclusion of the shear and bulk (!) viscosity

P. Bozek, PRC81 (2010) 034909,
ζ lowers T_f to 135 MeV



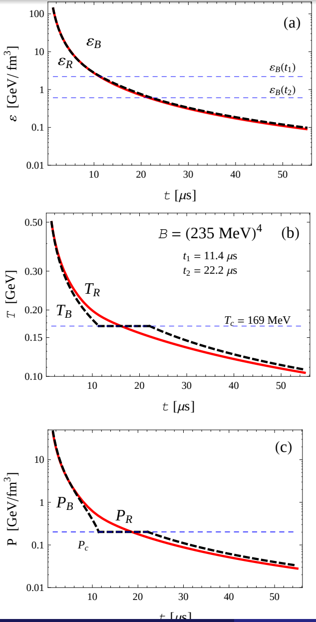


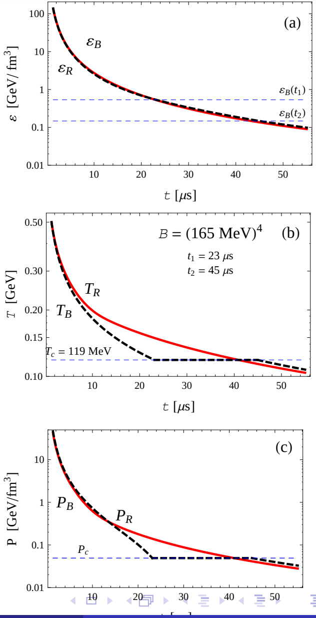
6. QCD phase transition in the early Universe

$$\frac{d\varepsilon_R}{dt} = -3\sqrt{\frac{8\pi G \varepsilon_R}{3}}(\varepsilon_R + P_R)$$

$$\left[c_s^{-2}\sigma + 3\sigma_{\rm ew}\right]\frac{dT_R}{dt} = -3\sqrt{\frac{8\pi G(\varepsilon + \varepsilon_{\rm ew})}{3}}(\varepsilon + \varepsilon_{\rm ew} + P + P_{\rm ew})$$

6.1 Energy density evolution





7. Conclusions

- the inclusion of the realistic EOS and the bulk viscosity is the most attractive solution of the HBT-v_2 puzzle
- the shear and shear viscosities are small — perfect fluid behavior confirmed
- the finite-state rescattering negligible
- the modified early dynamics helps to circumvent the early thermalization problems