The first three yoctoseconds of relativistic heavy-ion collisions

Wojciech Florkowski

IFJ PAN Kraków / UJK Kielce

Cracow Epiphany Conference on Hadronic Interactions at the Dawn of the LHC
Cracow, January 5-7, 2009

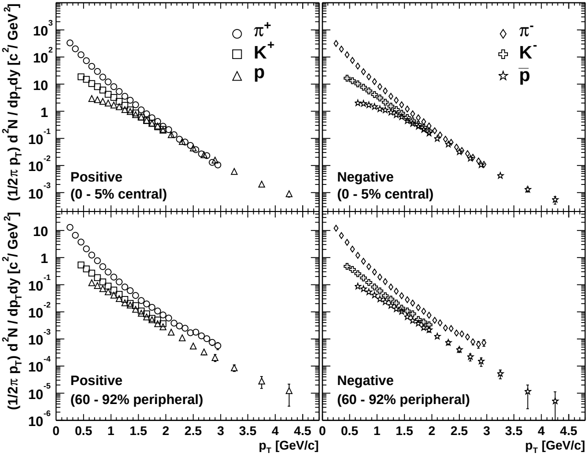
Outline of the talk

1. Soft hadronic observables in Au+Au collisions studied at RHIC
2. Hydrodynamic description – early-thermalization puzzle – discovery of sQGP?
3. RHIC HBT puzzle
4. Solution of the RHIC HBT puzzle with Gaussian initial conditions
5. Free streaming in the early stage – delayed but sudden thermalization – wQGP?
6. Our approach overcomes the two RHIC puzzles – hints for different initial conditions and/or different dynamics – extra acceleration in the initial stage of the hydrodynamic approach
7. Remaining challenge – matching between microscopic QCD description (such as Glasma) and macroscopic hydrodynamic picture within the first fm/c

$$1\,\frac{\mathrm{fm}}{\mathrm{c}} = \frac{10^{-15}\mathrm{m}}{3\cdot 10^{8}\frac{\mathrm{m}}{\mathrm{s}}} \approx 3\cdot 10^{-24}\mathrm{s} = 3\mathrm{ys}$$

1. Soft hadronic data (at midrapidity)

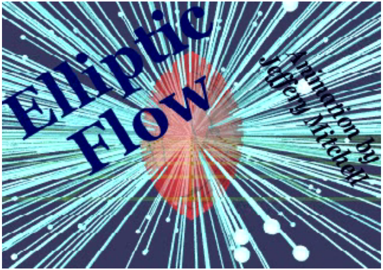
1) Transverse-momentum spectra



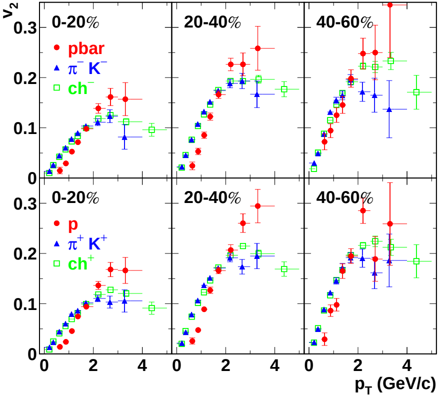
PHENIX, Phys. Rev. C69, 034909 (2004)

1. Soft hadronic data

2) Elliptic flow coefficient v_2



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



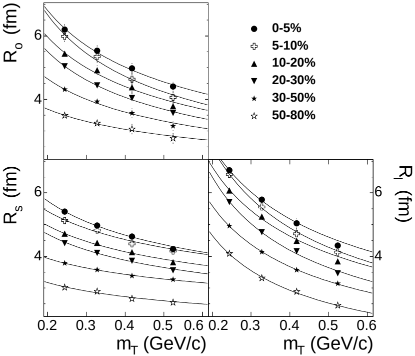
PHENIX, Phys.Rev.Lett.91,182301(2003)

1. Soft hadronic data

3) HBT radii

- two-particle observables, Bose-Einstein correlations
- Fourier transform with respect to relative momentum q, fixed average momentum of the pairs k_T
- Bertsch-Pratt parameterization
    - $\boldsymbol{R_{side}}$ - transverse size,
    - $\boldsymbol{R_{out}}$ - spatial size combined with the emission time,
    - $\boldsymbol{R_{long}}$ - longitudinal size,

HBT radii as functions of the transverse mass $\sqrt{m^2 + k_T^2}$



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

2. Hydrodynamic description

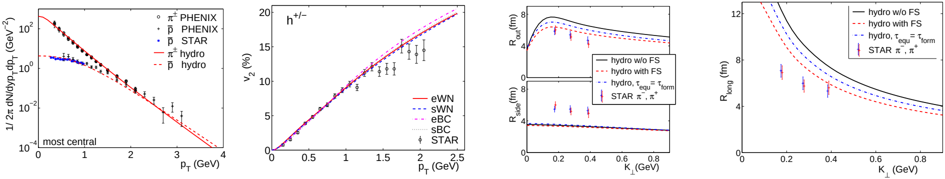
Great success of the perfect-fluid hydrodynamics in reproducing the spectra and large values of v_2 observed in the RHIC experiments (Teaney, Shuryak, Kolb, Huovinen, Heinz, Eskola, Ruuskanen, Hirano, Nara, Bass, Nonaka, Hama, Kodama, Grassi, ...), but

very early start of hydro is required, τ_0= 0.6 fm/c, sometimes τ_0= 0.1 fm/c, this implicitly assumes EARLY THERMALIZATION difficult to explain in pQCD, possible explanations:

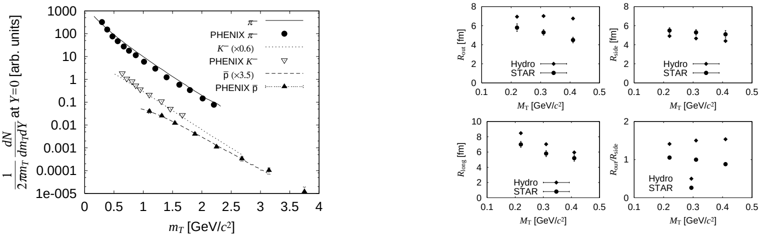
1. strongly interacting QGP [E. Shuryak, JPG30 (2004) S1221]
2. weakly interacting QGP but plasma instabilities lead to the fast isotropization that helps to achieve a thermalized state [Mrowczynski, APPB37 (2006) 427]
3. pQCD with gradual thermalization and formation of v_2 via inclusion of 3-body reactions [Xu, Greiner, and Stocker, JPG35 (2008) 104016]

3. RHIC HBT puzzle

(Great) failure of perfect-fluid hydrodynamics in reproducing the correlation functions



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



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

4. Resolving the HBT puzzle

W. Broniowski, M. Chojnacki, W. Florkowski, A.Kisiel, PRL101 (2008) 022301

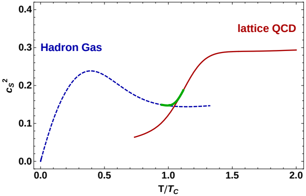
1) Equation of state ($\mu_B = 0$ at midrapidity)

$R_{\rm out}/R_{\rm side} \sim 1$ indicates very explosive scenario - faster building of the transverse flow, shorter emission times → EOS cannot be too soft, we use a semi-hard EOS

- hadron-gas model for $T < T_c$

  input from `SHARE`
  G. Torrieri, S. Steinke, W. Broniowski, W. Florkowski, J. Letessier, J. Rafelski, Comput. Phys. Commun. **167**, 229 (2005)
- lattice QCD for $T > T_c$

  Y. Aoki, Z. Fodor, S. Katz, K. Szabo, JHEP **0601**, 089 (2006)
- simple interpolation in the region $T \approx T_c = 170$ MeV, no soft point



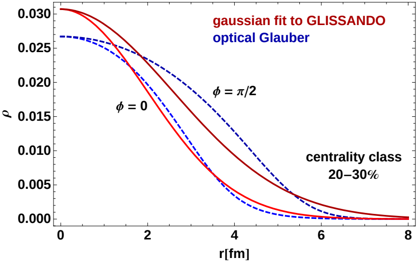
4. Resolving the HBT puzzle

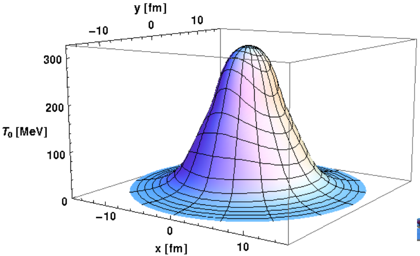
2) Initial conditions (in the transverse plane, $z = 0$, boost-invariance)

- most calculations use the Glauber optical model or Color Glass Condensate to model the initial conditions
- we use the Gaussian fit to the Monte-Carlo Glauber model
  the width parameters *a* and *b* obtained from `GLISSANDO`:

  W. Broniowski, M. Rybczynski, and P. Bozek, Comput. Phys. Commun. **180**, 69 (2009)

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





4. Resolving the HBT puzzle

3) Other important features:

- inclusion of all hadronic states in the modeling of freezeout
  `THERMINATOR` code:

  A. Kisiel, T. Taluc, W. Broniowski, W. Florkowski, Comput. Phys. Commun. **174**, 669 (2006)
- single-freeze-out assumption, freeze-out occurs at relatively high temperature

  – good approximation for pions, corrections for protons
- fluctuations of the initial eccentricity included in the initial state
- two-particle method of calculating the correlation functions
  with or without Coulomb interaction

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

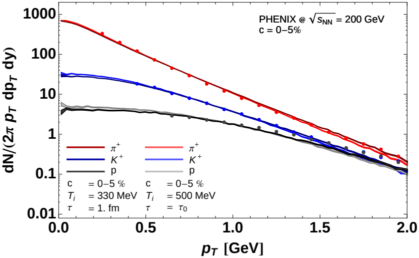
---

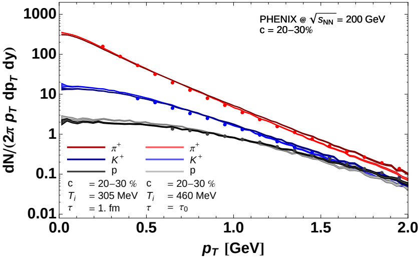
recent papers by S. Pratt, e.g., *The Long Slow Death of the HBT Puzzle*,
arXiv:0812.4714 [nucl-th],
semi-hard EOS, very early thermalization time, viscosity (again more acceleration)

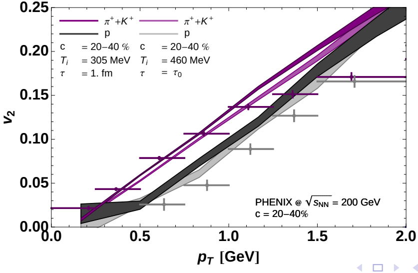
HBT right, no info about spectra and v_2

4. Resolving the HBT puzzle

4) Results for spectra and v_2

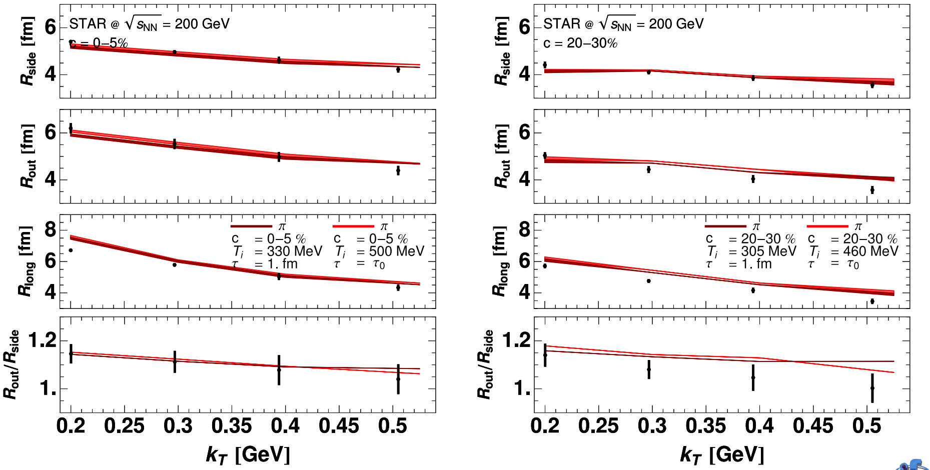






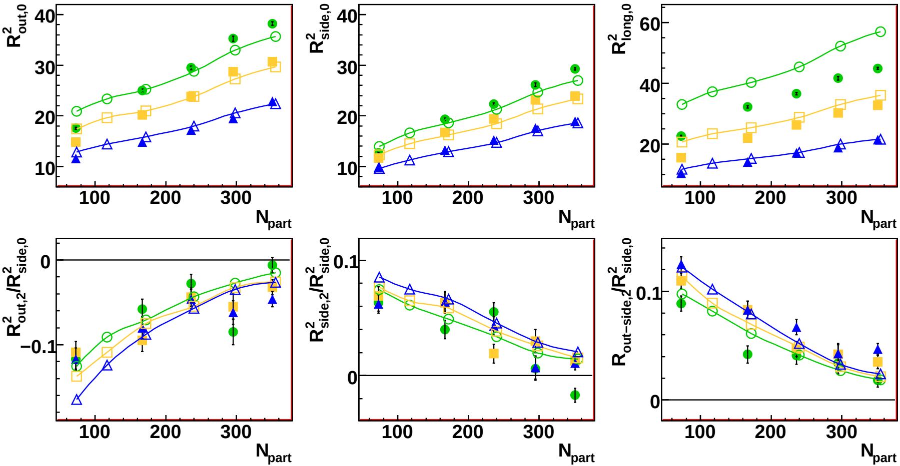
4. Resolving the HBT puzzle

5) Results for HBT



4. Resolving the HBT puzzle

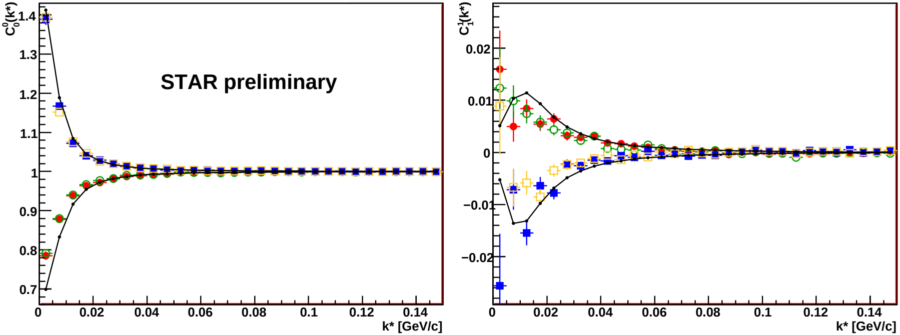
6) Results for azimuthally sensitive HBT



4. Resolving the HBT puzzle

7) Results for correlations of non-identical particles

Adam Kisiel WPCF2008



correlation functions (left) and asymmetry signal (right)

π^+K+ (filled circles), π^-K- (open circles)

π^+K- (filled squares), π^-K+ (open squares), solid line - hydro+Therminator

5. Free-streaming + sudden equilibration (FS+SE)

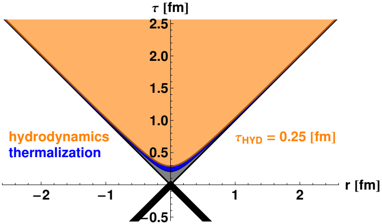
W. Broniowski, W. Florkowski, M. Chojnacki, A. Kisiel, arXiv:08123393 [nucl-th]

1) Delayed start of hydrodynamics

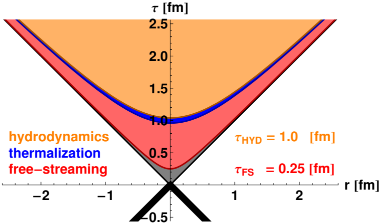
- so far, we have always started hydrodynamics at $\tau = 0.25$ fm, again early thermalization!
- a different scenario is possible

  P. Kolb, J. Sollfrank, U. Heinz, Phys. Rev. **C62**, 054909 (2000)

— early thermalization



— free-streaming + sudden equilibration



5. Free-streaming + sudden equilibration

2) Landau matching condition

- free-streaming leads to the decay of the initial spatial eccentricity which drives the formation of v_2

  P. Kolb, J. Sollfrank, U. Heinz, Phys. Rev. **C62**, 054909 (2000)

- free-streaming plus sudden equilibration induces v_2

  M. Gyulassy, Yu. Sinyukov, Iu. Karpenko, A. V. Nazarenko, Braz. J. Phys. **37**, 1031 (2007)

- Transition from the free-streaming phase to the hydrodynamic regime described in the form of Landau matching conditions

$$T^{\mu\nu}_{\mathrm{free-streaming}}\, u_\nu = T^{\mu\nu}_{\mathrm{perfect-fluid}}\, u_\nu = \varepsilon \, u^\mu$$

6. Initial extra aceleration

1) different initial conditions or different dynamics

what can be concluded so far?

1. with the modified initial conditions we have achieved the consistent description of the data including: spectra, v_2, HBT, azHBT, and non-identical correlations
simultanous description of v_2 and azHBT suggests that this is the right parameterization of the expanding fireball, $\tau > 1$ fm/c
2. early thermalization not required, perhaps the gradual thermalization and building of the flow is the right scenario
Z. Xu, C. Greiner, H. Stöcker, JPG35 (2008) 104016
3. modified initial conditions → extra initial transverse flow → extra acceleration
S. Pratt, arXiv:0811.3363 [nucl-th]
M. Lisa, S. Pratt, arXiv:0811.1352 [nucl-ex]
4. modified dynamics due to the dissipative effects such as viscosity, or completely different dynamics → transverse hydrodynamics → talk by Ryblewski

6. Initial extra aceleration

2) Transverse hydrodynamics

A. Bialas, M. Chojnacki, WF, Phys. Lett. B661 (2008) , 325

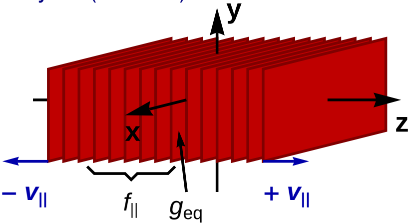
- our main assumption:

  the 3D phase-space distribution function $f(x,p)$ is factorized into the longitudinal and transverse part

$$f(x,p) \quad = \quad f_{\parallel} \;\; g_{\mathrm{eq}}$$

- $f_{\parallel}$ - non-equilibrium longitudinal part, describes essentially free-streaming
- g_{eq} - equilibrium transverse part, describes 2D hydrodynamic expansion

- useful visualization in terms of discrete independent transverse layers (clusters)

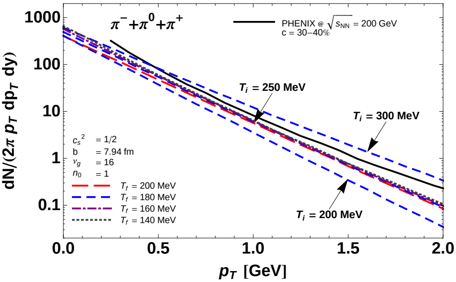


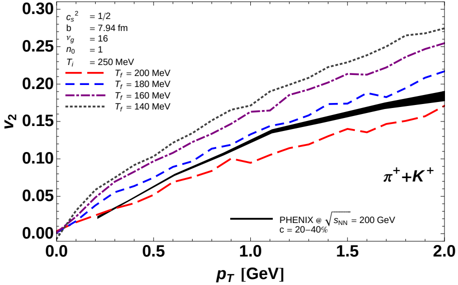
- with standard definitions of rapidity y and spacetime rapidity η

$$\begin{aligned} E &= m_\perp \cosh y, & p_\parallel &= m_\perp \sinh y \\ t &= \tau \cosh \eta, & z &= \tau \sinh \eta \\ \tau &= \sqrt{t^2 - z^2}, & m_\perp &= \sqrt{m^2 + p_\perp^2} \end{aligned}$$

6. Initial extra aceleration

3) Transverse hydrodynamics - transverse-momentum spectra and elliptic flow





- solid line: p_T spectra of π^+ (×3) by PHENIX @ $\sqrt{s_{NN}}$ = 200 GeV, centrality class 30-40%
- solid line: $v_2(p_\perp)$ of π^+ and K^+ by PHENIX @ $\sqrt{s_{NN}}$ = 200 GeV, centrality class 20-40%
- dashed and dotted lines: model spectra of gluons for $n_0 = 1$, the initial temperature T_i = 250 MeV and four final temperatures T_f = 200, 180, 160 and 140 MeV

7. Physics of the first three yoctoseconds

more conclusions

1. to achieve the consistent and uniform description of the data, the hydrodynamic expansion with extra acceleration should start somwhere in between 0.1 - 1 fm/c
2. very early dynamics is known from QCD - Glasma
3. matching QCD (Glasma) with hydro during the first 1 fm/c remains now a challenge!