Perfect-fluid hydrodynamics for RHIC – successes and problems

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HIRSCHEGG 2010: Strongly Interacting Matter under Extreme Conditions
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RHIC at BNL

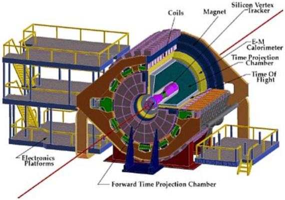
Relativistic Heavy Ion Collider at Brookhaven National Laboratory

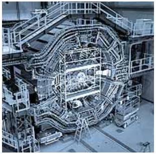
Google Maps: http://maps.google.com/?ll=40.874649,-72.870598&spn=0.047118,0.079823&z=14

RHIC at BNL

Four experiments

STAR





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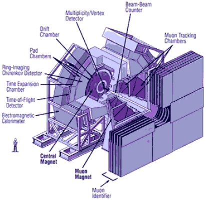
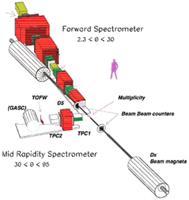
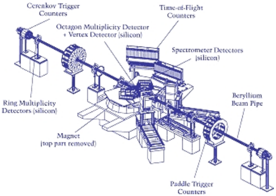


BRAHMS

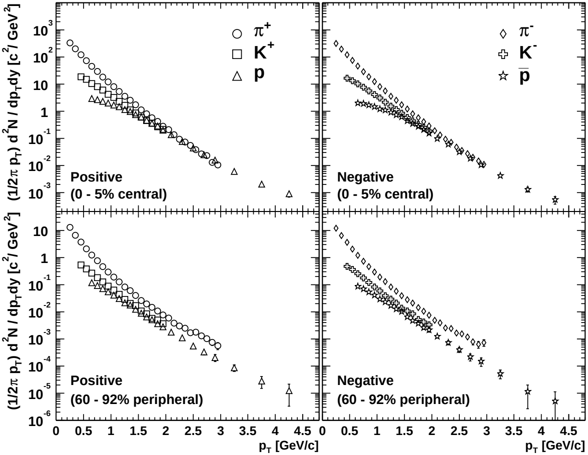


PHOBOS



Experimental data (soft hadronic sector)

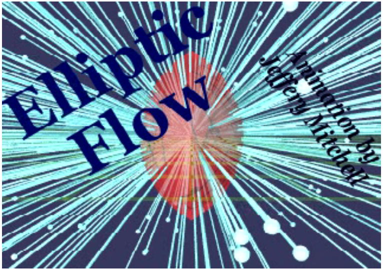
1) transverse-momentum spectra, p_T distributions



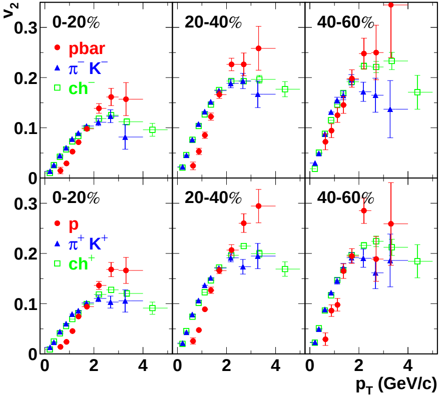
PHENIX, Phys. Rev. C69, 034909 (2004)

Experimental 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)

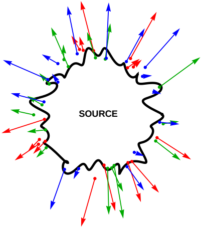


PHENIX, Phys.Rev.Lett.91,182301(2003)

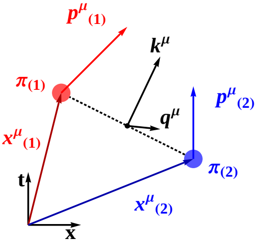
Experimental data

3) correlations of identical particles (Hanbury-Brown, Twiss)

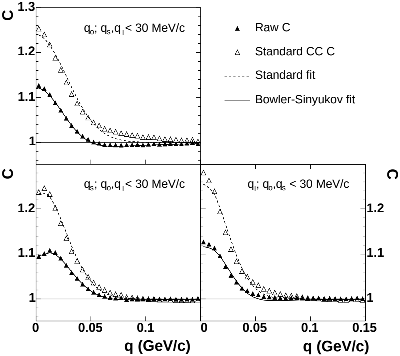
source emitting particles



two identical pions, $\pi^+\pi^+$, $\pi^-\pi^-$



three projections of the correlation functions



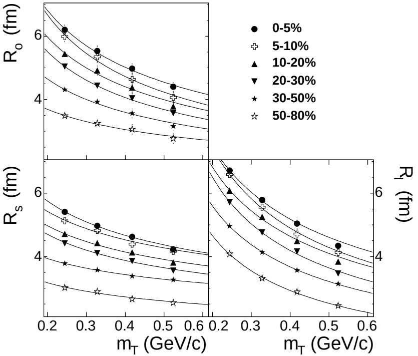
STAR, Phys.Rev.C71,044906(2005)

Experimental data

3) source sizes (HBT radii)

HBT radii depend on k_T

- "Fourier transform"
- HBT radii
  - R_{side} - spatial transverse extension
  - R_{out} - spatial transverse extension + emission time
  - R_{long} - longitudinal extension



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

"Standard Model/Scheme" of heavy-ion collisions

main ingredients of the 2+1 models:

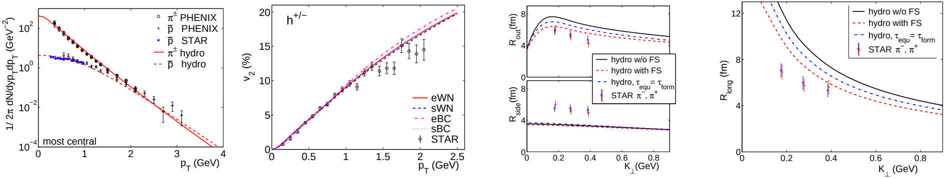
- initial conditions, short thermalization time, $\tau_i \leq 1$ fm
  - Glauber model, e.g., initial entropy/energy density is proportional to the linear combination of the wounded-nucleon density and binary-collision density,

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

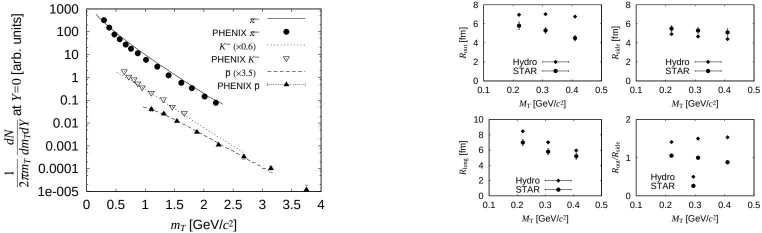
  - Color Glass Condensate
  - initial transverse flow, usually set equal to zero (?)
- HYDRODYNAMIC STAGE
  - v_2 data suggest that matter behaves like a perfect fluid main tool: perfect-fluid hydrodynamics (Shuryak, Heinz, ...)
  - hadronization included in the equation of state
- freeze-out, Cooper-Frye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

Motivation for our research

an attempt to obtain a uniform description of soft observables (resolution of the HBT puzzle)



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



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

2+1 Cracow hydrodynamic model

- initial conditions, short thermalization time, $\tau_i \leq 1$ fm
  - Glauber and Gaussian initial conditions (including fluctuations)
  - option: initial transverse flow obtained from free-streaming (Yu. Sinyukov)
- HYDRODYNAMIC STAGE
  - perfect-fluid hydrodynamics — implemented in the code LHYQUID (M. Chojnacki)
  - hadronization included in the modern equation of state
- freeze-out, Cooper-Frye formula
  - freeze-out hypersurface, thermal description of hadron production — THERMINATOR (A. Kisiel et al.), complete set of resonances, single-freeze-out scenario assumed, two-particle method, with or without Coulomb, used to calculate the HBT radii: R_{side}, R_{out}, R_{long}, R_{out}/R_{side}

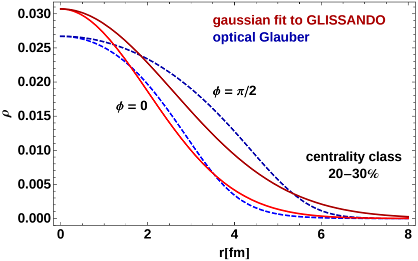
Initial conditions

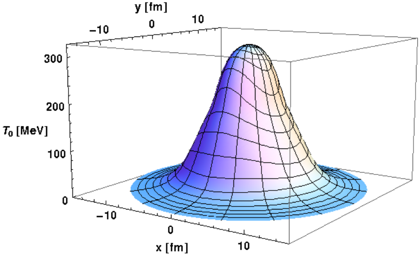
Nuclear matter profiles play an important role, Phys. Rev. Lett. **101** (2008) 022301

- most of the approaches use the Glauber model or Color Glass Condensate,
- we assume the Gaussian profile (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[1]





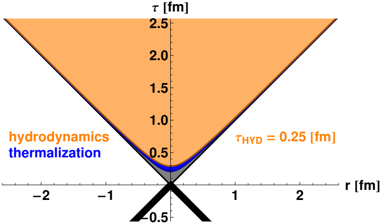
[1] W. Broniowski, M. Rybczyński, P. Bożek arXiv:0710.5731[nucl-th]

Initial conditions

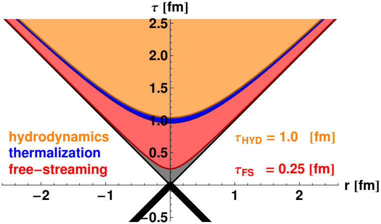
Free-streaming

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

— early thermalization



— free-streaming

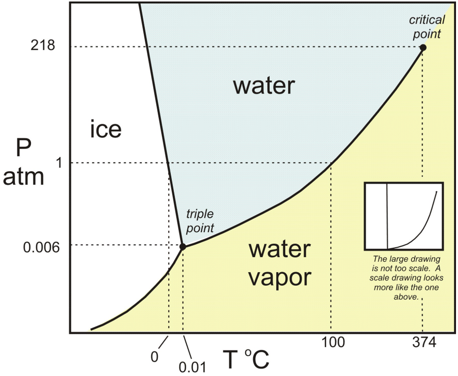


- model for early stage dynamics
  - free streaming of particles, no interactions
  - sudden hermalization – Landau's matching conditions.
- our results indicate that the two scenarios are equivalent

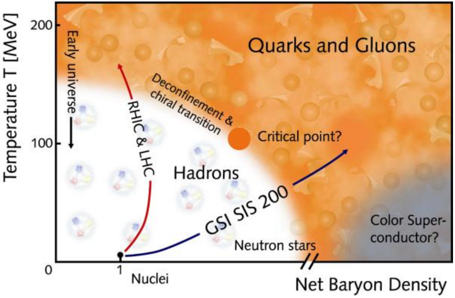
Thermodynamics

phase diagrams

- phase diagram for water



- phase diagram for QCD



Thermodynamics

modeling of the QCD EOS

- hadron gas model for low temparatures

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

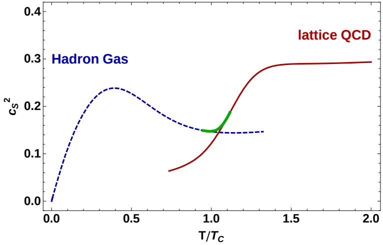
- lattice QCD simulations for large temperatures

  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
  thermodynamic variables change suddenly at T_c but smoothly ,

  the sound velocity does not drop to zero



Hydrodynamics

- energy-momentum conservation law

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

- energy-momentum of the perfect fluid

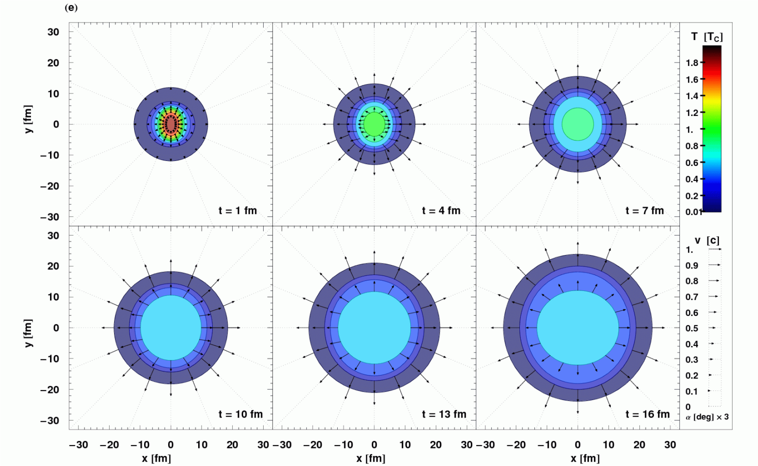
$$T^{\mu\nu} = (\epsilon + P)\, u^\mu u^\nu - P g^{\mu\nu}$$

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
- boost-invariance
  equations solved at $z = 0$, solutions for $z \neq 0$ obtained by Lorentz boosts
- EOS encoded in c_s — Baym, Friman, Blaizot, Soyeur, Czyz, Hydrodynamics of Ultrarelativistic Heavy Ion Collisions, Nucl. Phys. A407 (1983) 541

results from LHYQUID

reLativistic HYdrodynamics of QUark-gluon fluID

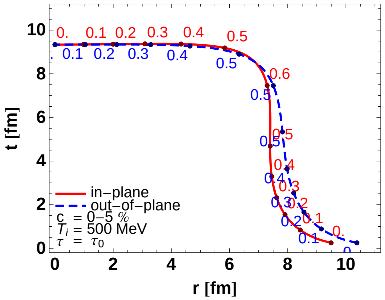


Hydrodynamics

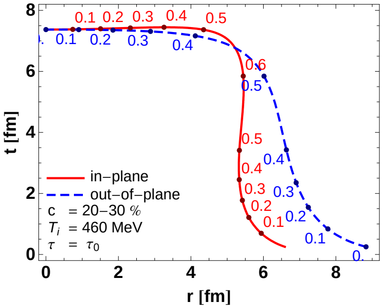
freeze-out hypersurfaces

- freeze-out temperature T_f = 145 MeV

- central collisions



- peripheral collisions



- because of the strong transverse flow, hadron do not reenter the medium
- space-like and time-like emission is similar

THERMINATOR[2]

THERMal heavy-IoN generATOR

- primordial particles are emitted according to the Cooper-Frye formula

$$\frac{dN}{dy\, d^2p_T} = \int d\Sigma^\mu p_\mu f_{\rm eq}\,(p \cdot u)\,,$$

$d\Sigma^\mu$ - element of the freeze-out hypersurface – obtained from hydro
u^μ - four-velocity of the fluid

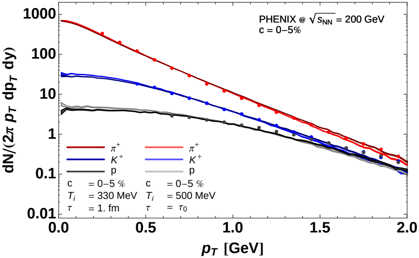
- all resonances included
- elliptic flow coefficient v_2

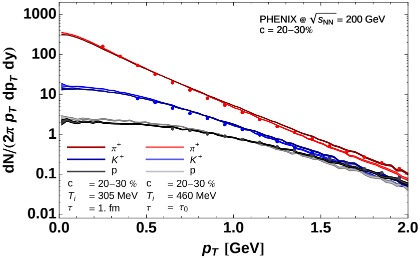
$$\frac{dN}{dy\, d^2p_T} = \frac{dN}{dy\, 2\pi p_T\, dp_T}\left(1 + 2v_2(p_T)\cos(2\phi_p) + \ldots\right)$$

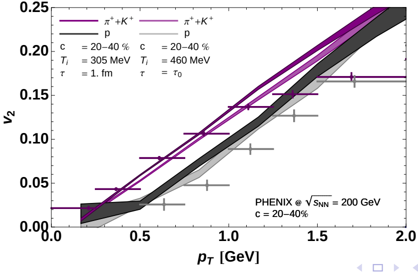
[2] A. Kisiel, T. Tałuć, W. Broniowski and W. Florkowski Comput. Phys. Commun. **174**, 669 (2006)

THERMINATOR

results for the spectra and v_2







THERMINATOR

femtoscopy [3]

- 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)

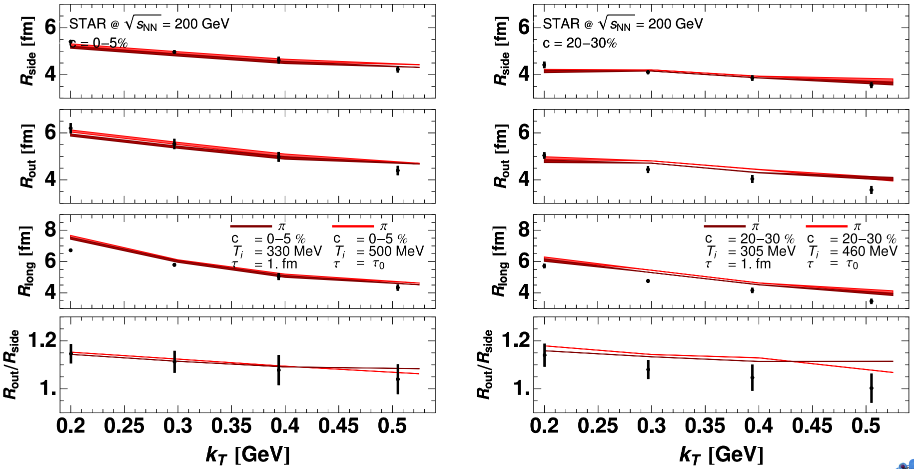
$$C(\vec{q},\vec{k}) = (1-\lambda)+\lambda K_{\rm coul}(q_{\rm inv}) \left[1 + \exp\left(-R_{\rm out}^2{}^2 q_{\rm out}^2 - R_{\rm side}^2 q_{\rm side}^2 - R_{\rm long}^2 q_{\rm long}^2\right)\right],$$

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

[3] A. Kisiel, W. Florkowski and W. Broniowski Phys. Rev. **C73**, 064902 (2006)

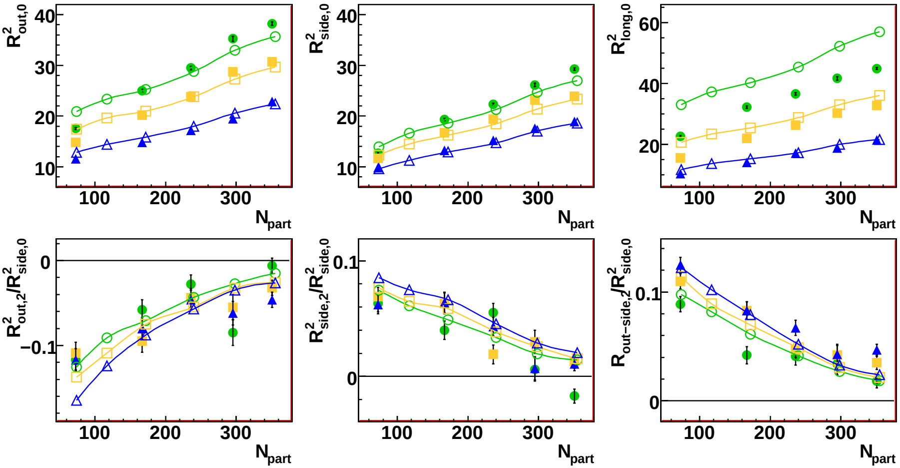
THERMINATOR

HBT results



THERMINATOR

oscillations of the HBT radii, PRC 79 (2009) 014902



Conclusions

- 2+1 Cracow hydrodynamical model correctly describes the soft-hadronic data, in our opinion, this is the first successful attempt to solve the RHIC HBT puzzle.
- the things which matter
  - realistic equation of state (no soft point!)
  - initial profile – Gaussian approximation to Glauber, fluctuations of the eccentricity
  - all resonances included
  - two-particle algorithm for femtoscopy