Hydrodynamic description of relativistic heavy-ion collisions

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RHIC at BNL

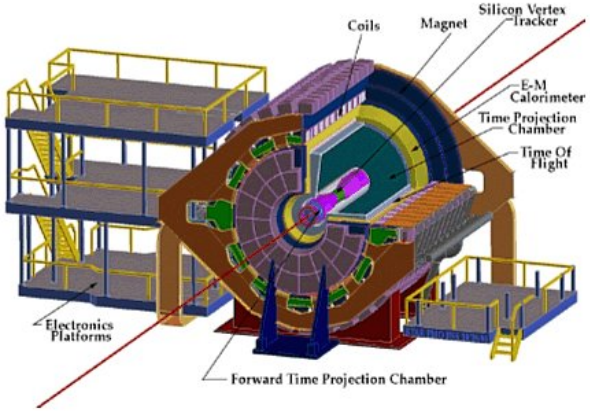
Relativistic Heavy Ion Collider at Brookhaven National Laboratory

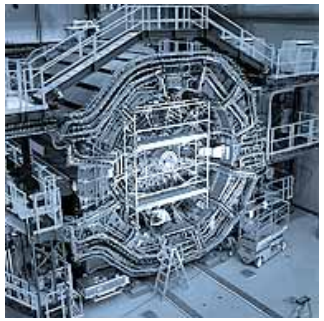
Google Maps: http://maps.google.com/?ll=40.874649,-72.870598&spn=0.047118,0.079823&z=14

RHIC at BNL

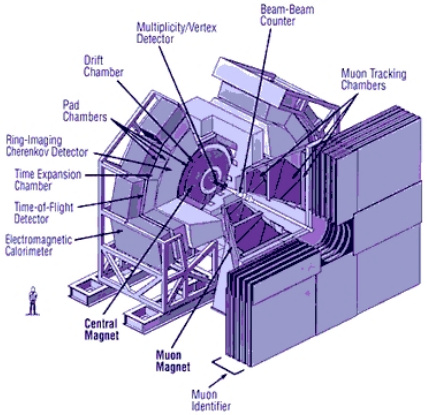
Four experiments

STAR

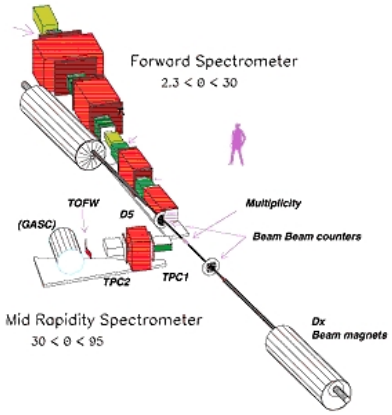




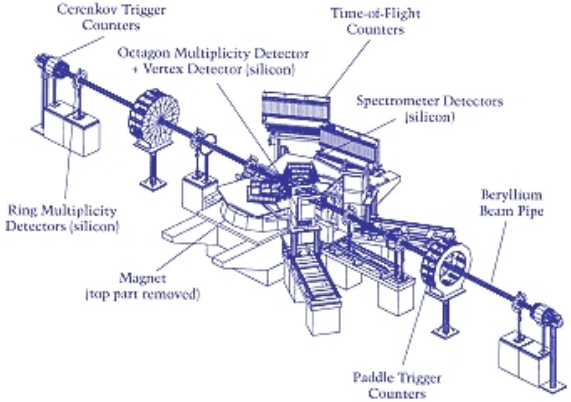
PHENIX



BRAHMS



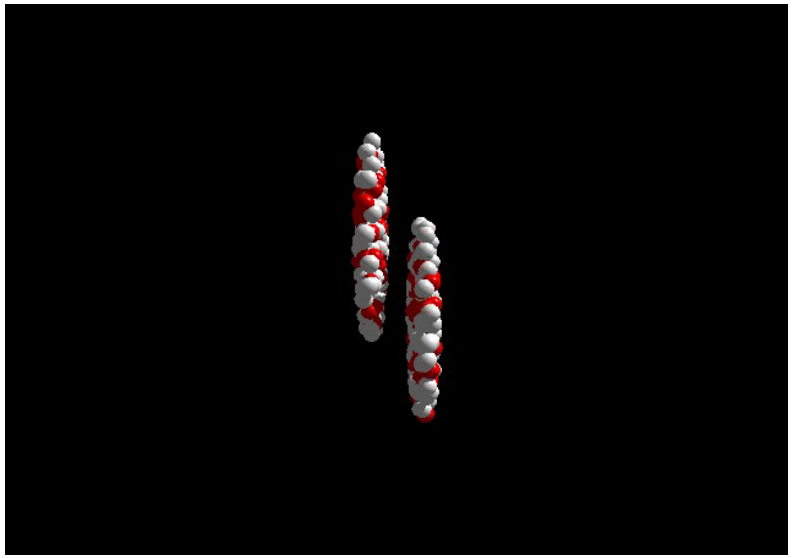
PHOBOS



Relativistic heavy-ion collisions

simulations with Ultra-relativistic Quantum Molecular Dynamics (UrQMD)

http://www.phenix.bnl.gov/WWW/software/luxor/ani/urqmdAni/urqmdForWBNL.m1v
Animation by Jeffery Mitchell (Brookhaven National Laboratory). Simulation by the UrQMD Collaboration.



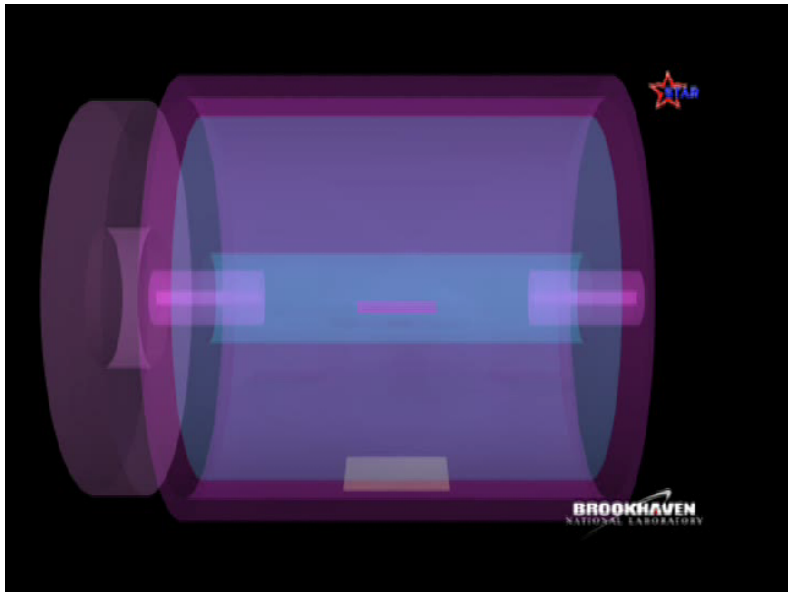
http://th.physik.uni-frankfurt.de/~weber/Movies/au200au.big.mpg
Animation by Henning Weber.
UrQMD Cascade: Au + Au; 200 GeV/u; b=5 fm

Relativistic heavy-ion collisions

Detectors

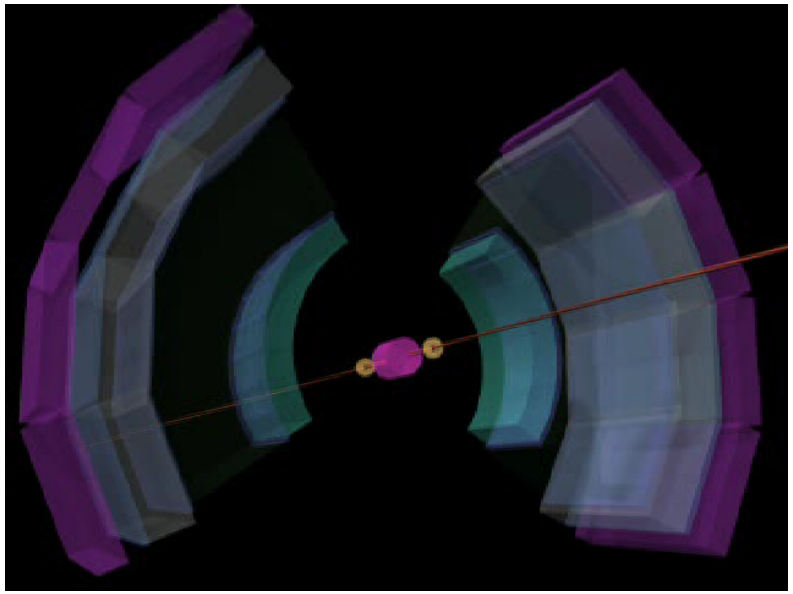
simulations in detectors

STAR



http://www.phenix.bnl.gov/WWW/software/luxor/ani/starTrails/starTrailsLargev2.mpg
Animation courtesy of Brookhaven National Laboratory

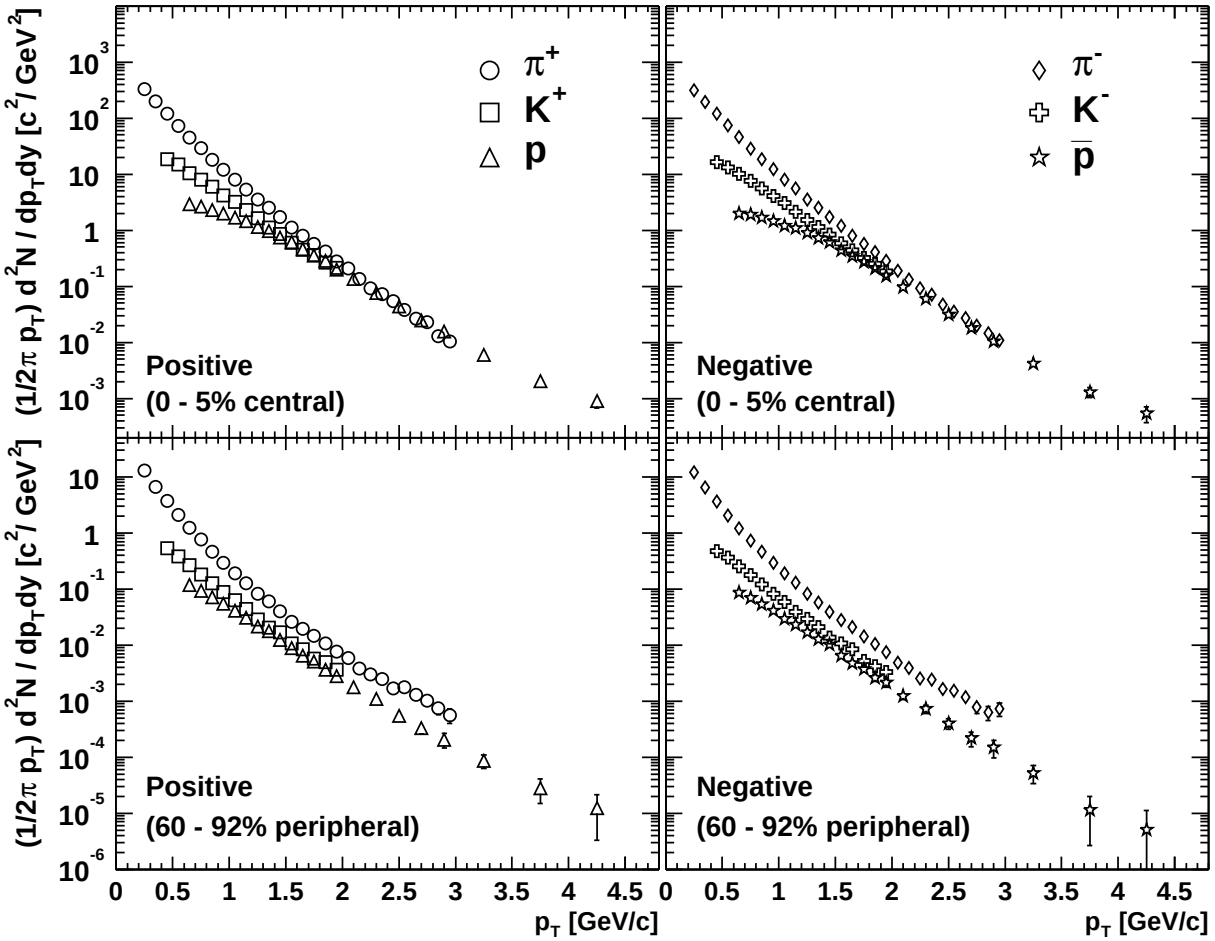
PHENIX



http://www.phenix.bnl.gov/WWW/software/luxor/ani/phxTrails/phxTrailsLarge.mpg
Animation courtesy of Brookhaven National Laboratory

Experimental data

1) transverse-momentum spectra, p_T distributions

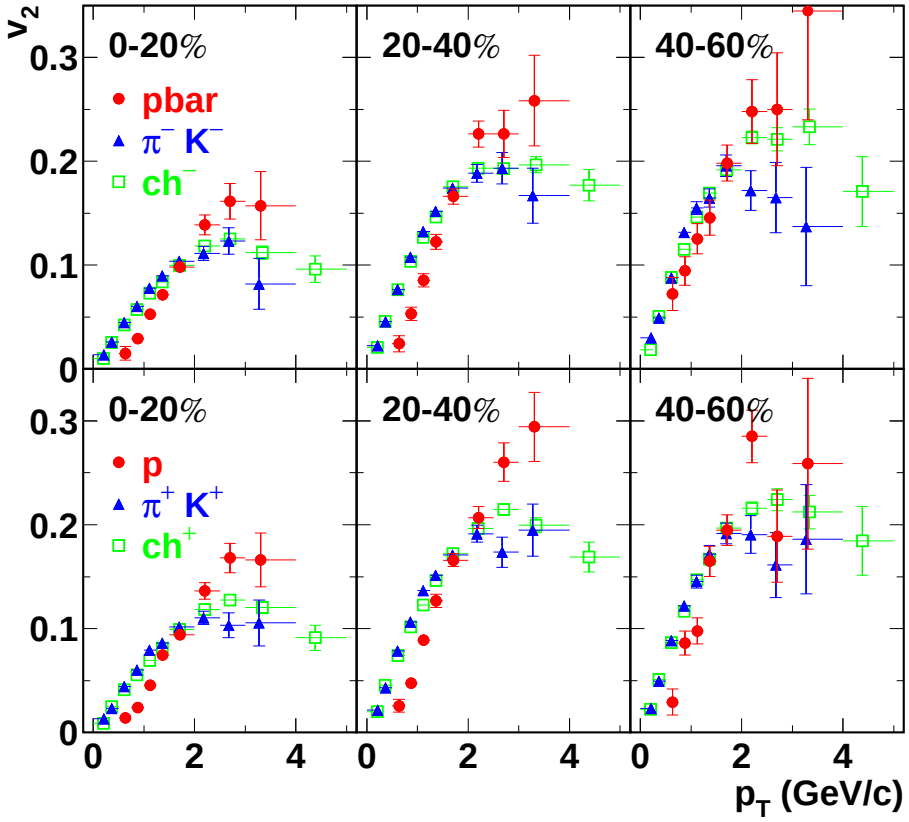


PHENIX, Phys. Rev. C69, 034909 (2004)

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)

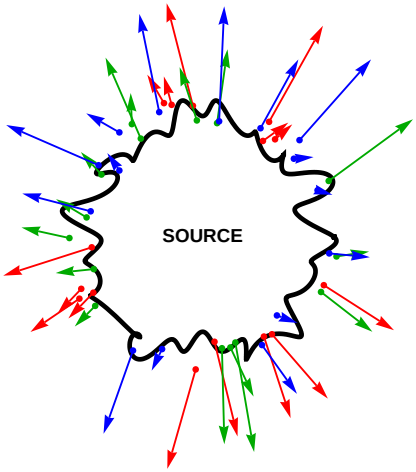


PHENIX, Phys.Rev.Lett.91,182301(2003)

Experimental data

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

source emitting particles



Experimental data

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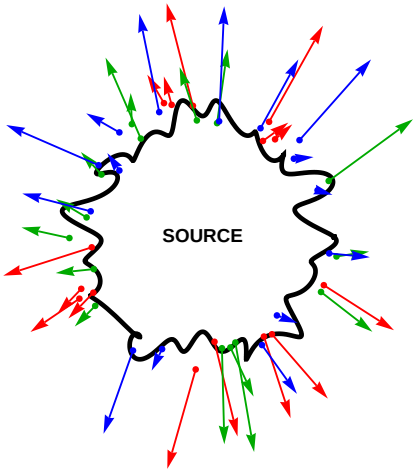
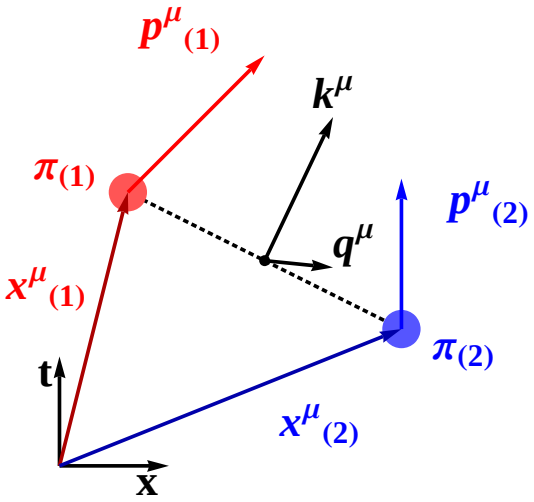
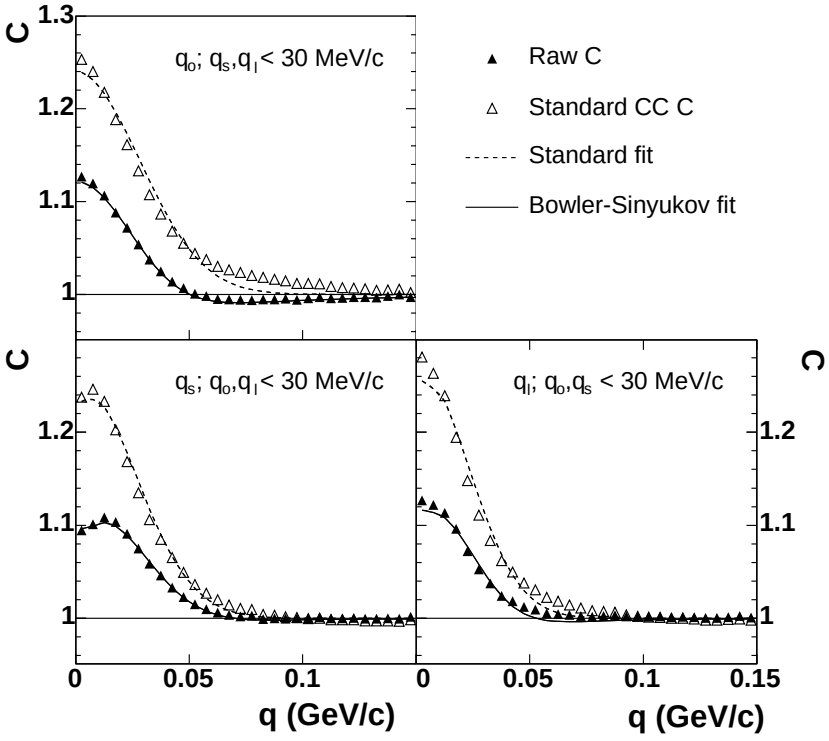


two identical pions, $\pi^+\pi^+$, $\pi^-\pi^-$



three projections of the correlation functions



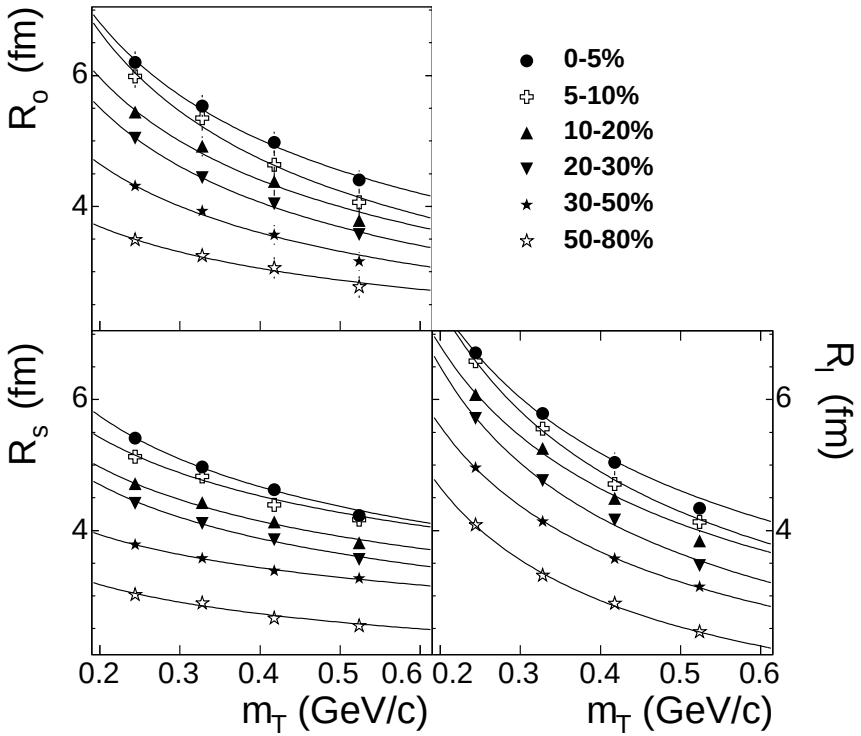
STAR, Phys.Rev.C71,044906(2005)

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)

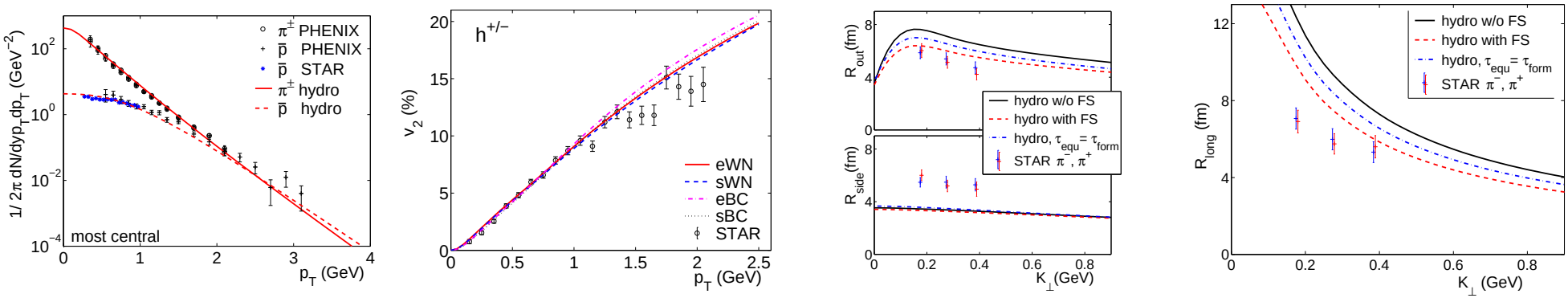
Motivation

an attempt to obtain a uniform description of soft observables
main ingredients of the models:

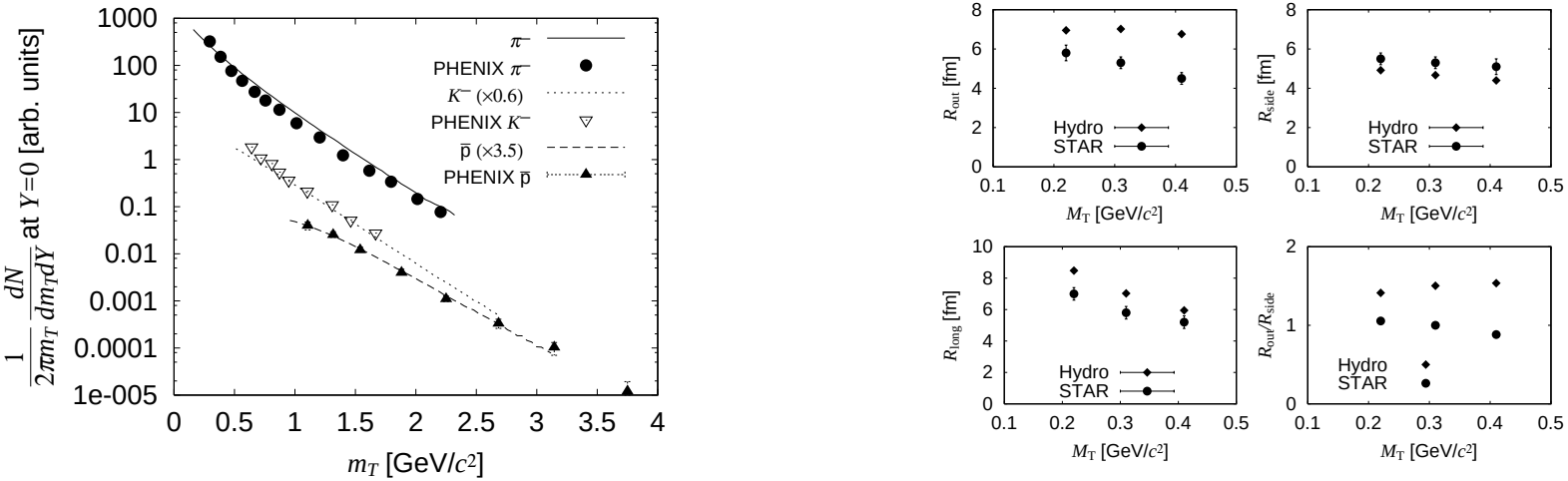
- data suggest that matter behaves like a perfect fluid
  main tool: perfect-fluid hydrodynamics (Shuryak, Heinz, ...)
- hadronization
  equation of state incorporating the phase transition
- statistical description of decoupling of hadrons
  Cooper-Frye formula

Motivation

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)

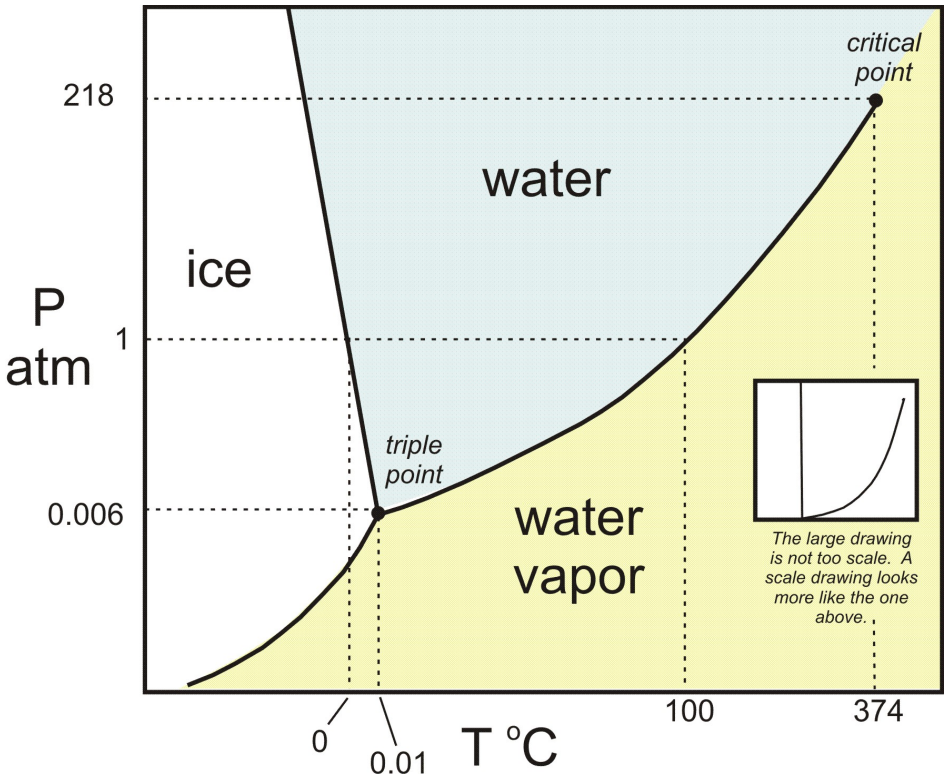
Ingredients of the hydrodynamic model

1. Thermodynamic properties described by the equation of state
2. Free-streaming (optionally precedes the hydro evolution)
3. Perfect-fluid hydrodynamics — implemented in the code LHYQUID (M. Chojnacki)
   - Equations of relativistic hydrodynamics
   - Initial conditions
   - Freeze-out hypersurface
4. Statistical model of freeze-out — THERMINATOR (A. Kisiel et al.)
   - p_T spectra
   - elliptic flow $v_2(p_T)$
   - HBT radii: $R_{side}, R_{out}, R_{long}, R_{out}/R_{side}$

Thermodynamics

phase diagrams

- phase diagram for water



Thermodynamics

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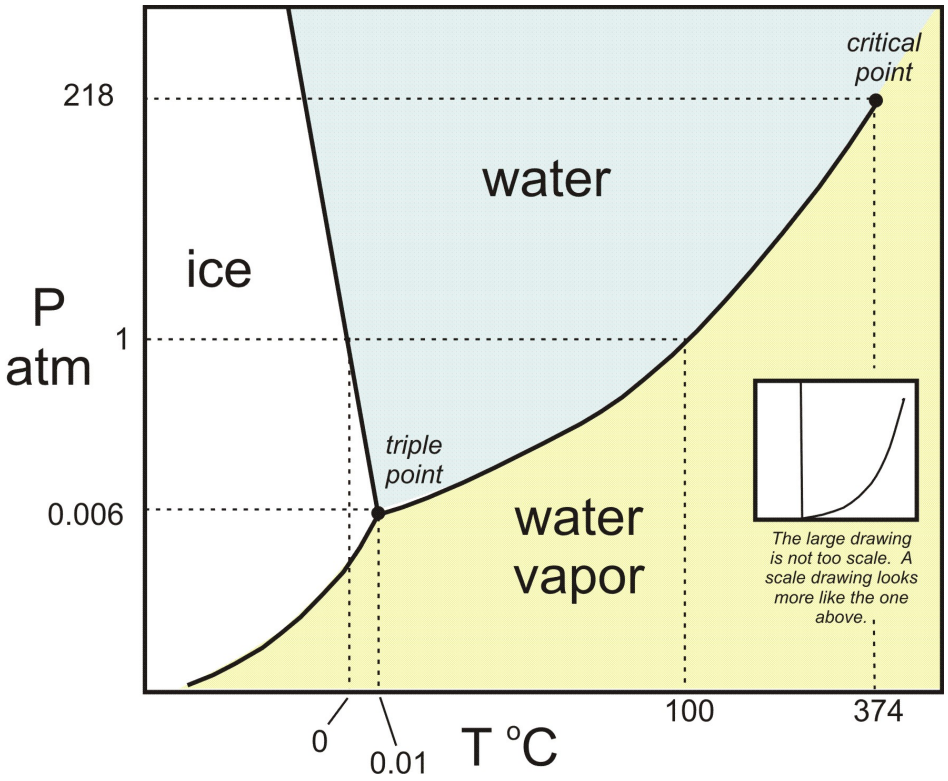
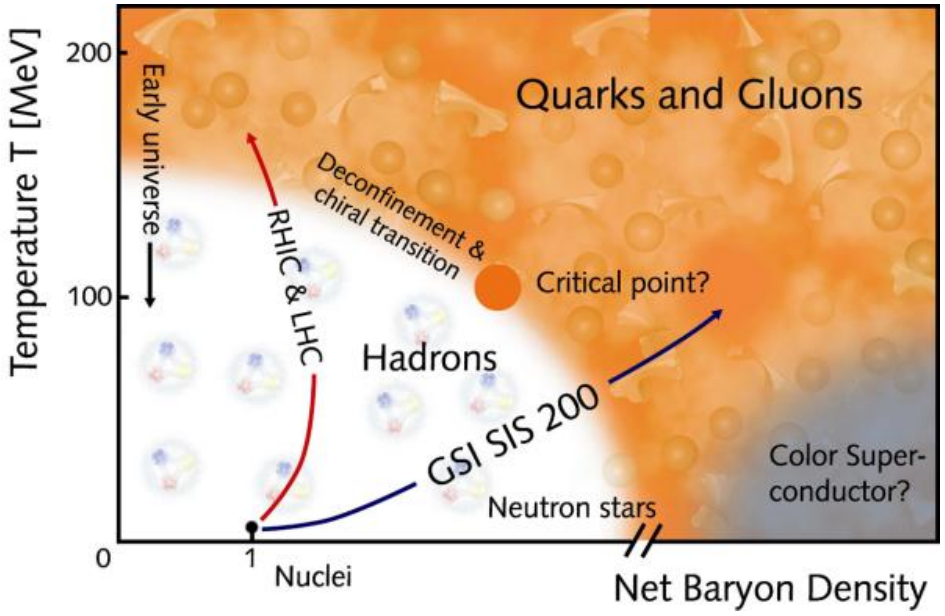


- phase diagram for QCD



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

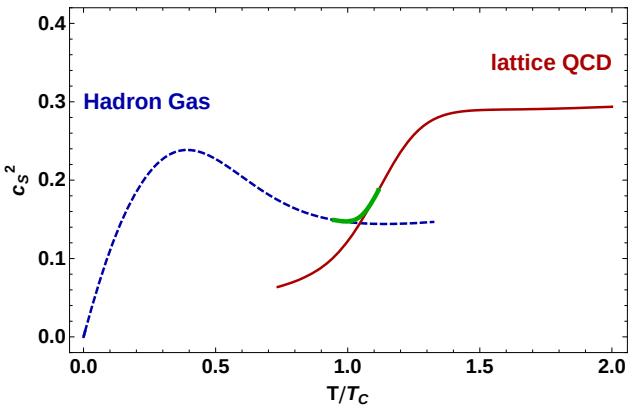
  based on: Y. Aoki, Z. Fodor, S. Katz, K. Szabo, JHEP **0601**, 089 (2006)

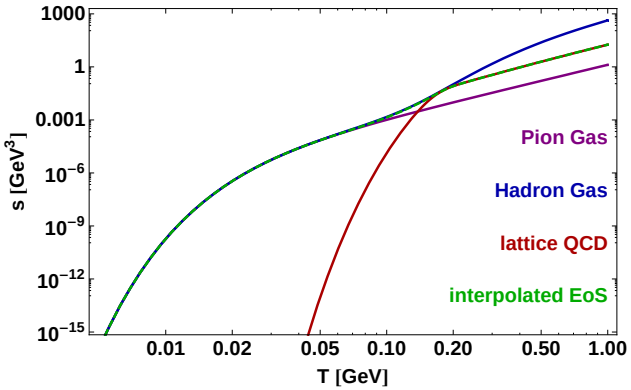
  simple parameterization of pressure: T. Biro, J. Zimanyi, Phys.Lett.**B650**, 193 (2007)

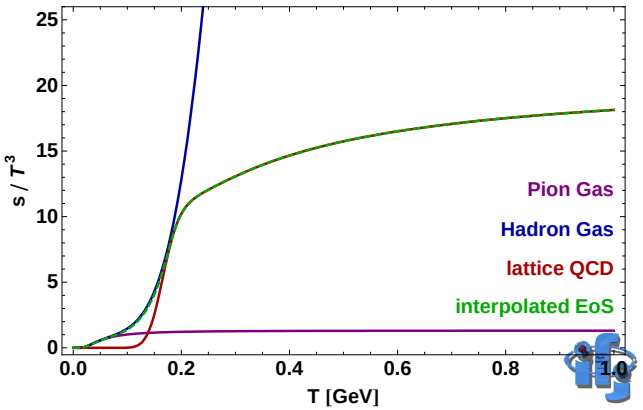
- cross-over phase transition

  thermodynamic variables change suddenly at T_c but smoothly ,

  the sound velocity does not drop to zero





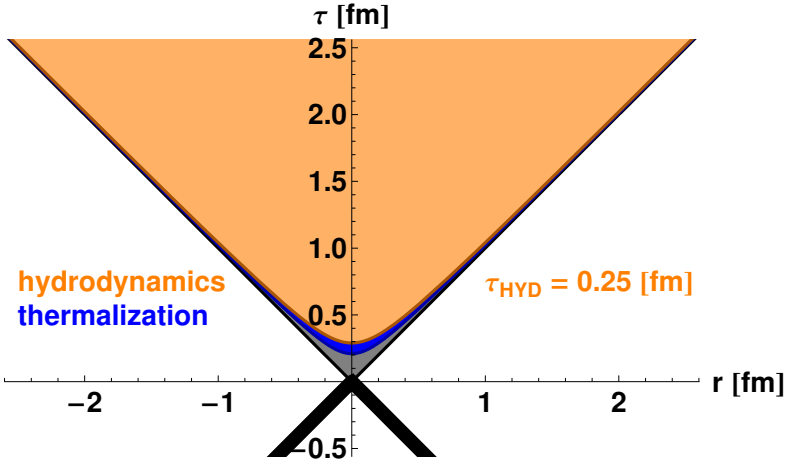


Free-streaming

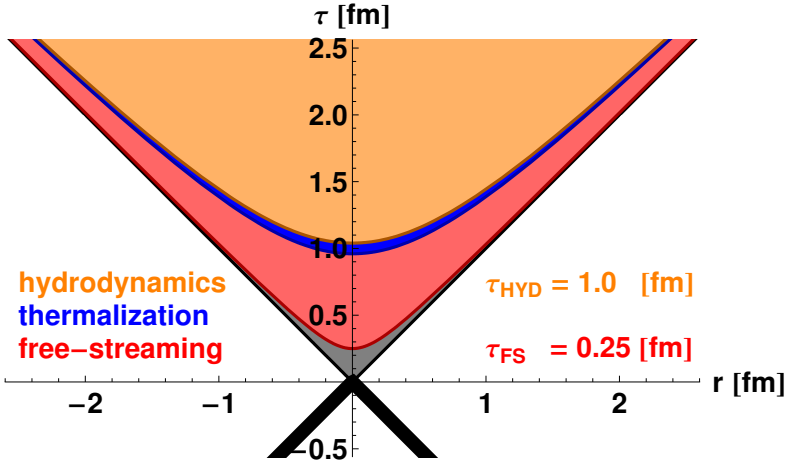
non-equilibrium process

- 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

Hydrodynamcs

conservation laws

- energy-momentum conservation law

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

Hydrodynamcs

conservation laws

- 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

Hydrodynamics

initial conditions - nuclear matter profiles

- most of the approaches use the Glauber model or Color Glass Condensate,

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

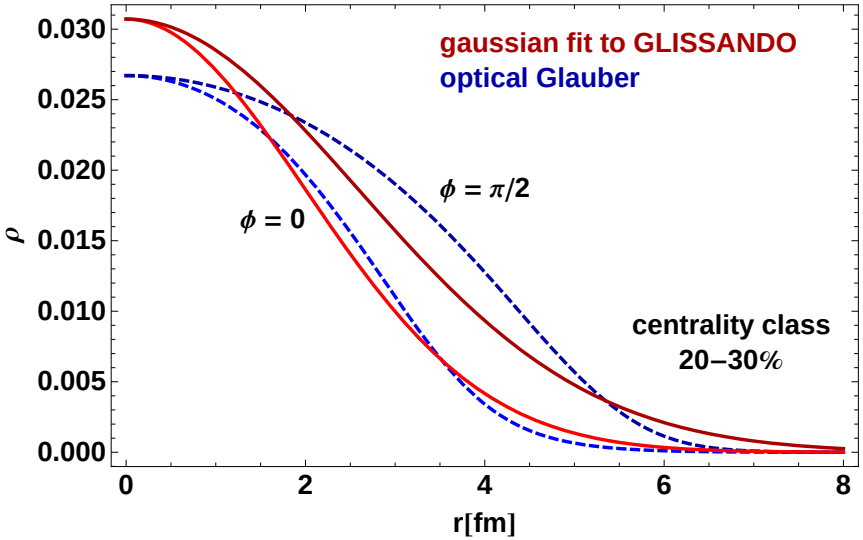
Hydrodynamics

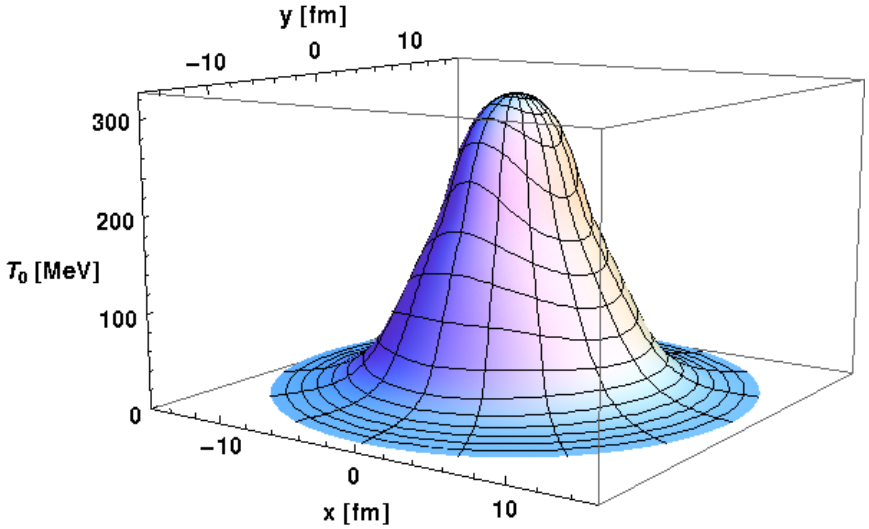
initial conditions - nuclear matter profiles

- 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]

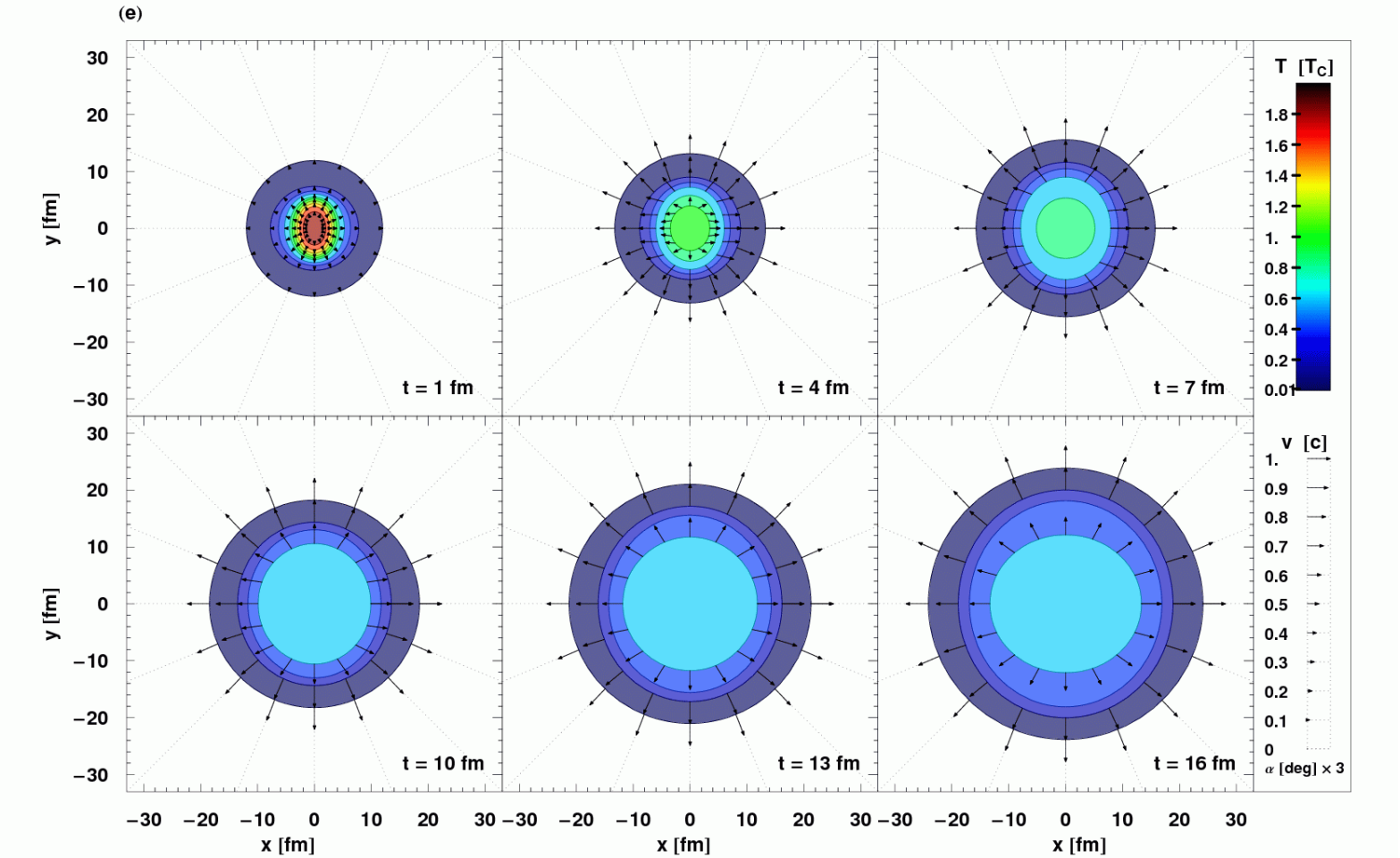




[1] W. Broniowski, M. Rybczyński, P. Bożek arXiv:0710.5731[nucl-th]

results from LHYQUID

reLativistic HYdrodynamics of QUark-gluon fluID

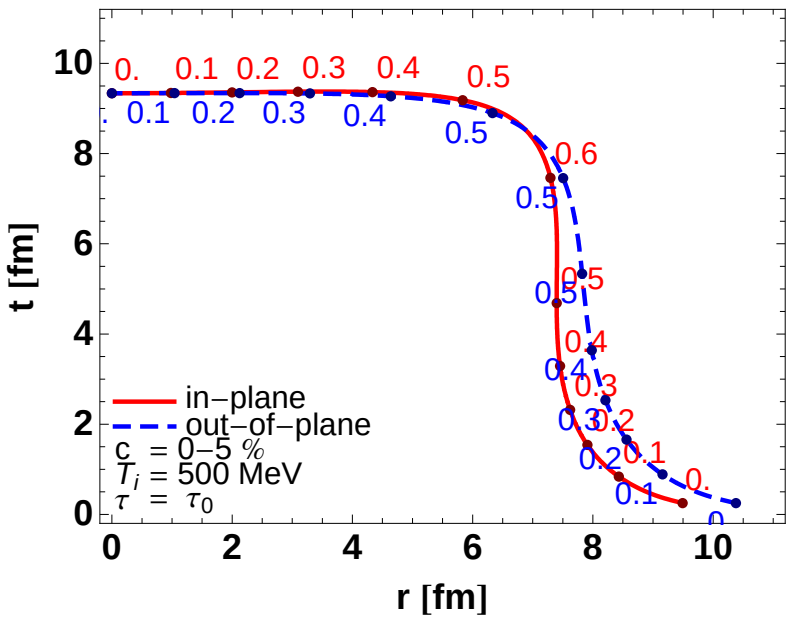


Hydrodynamics

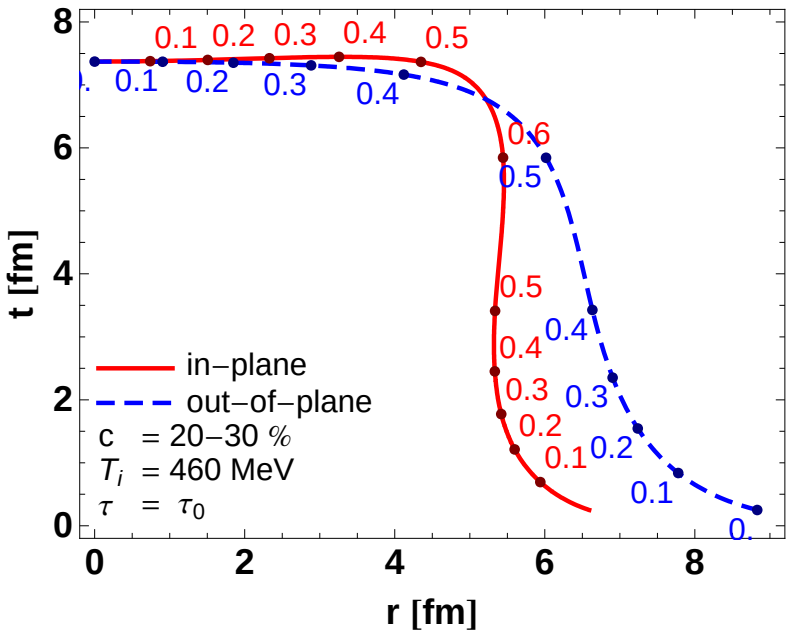
freeze-out hypersurfaces

- 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

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

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

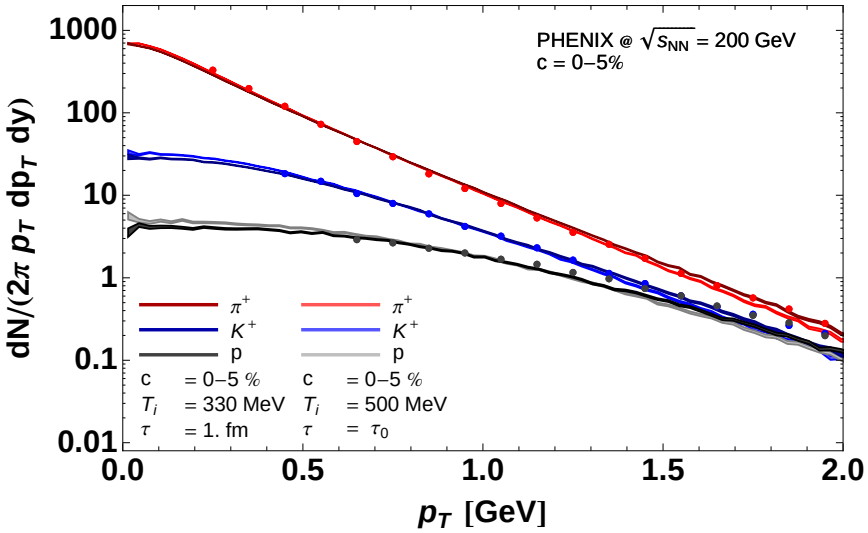
- all resonances included
- elliptic flow coefficient v_2

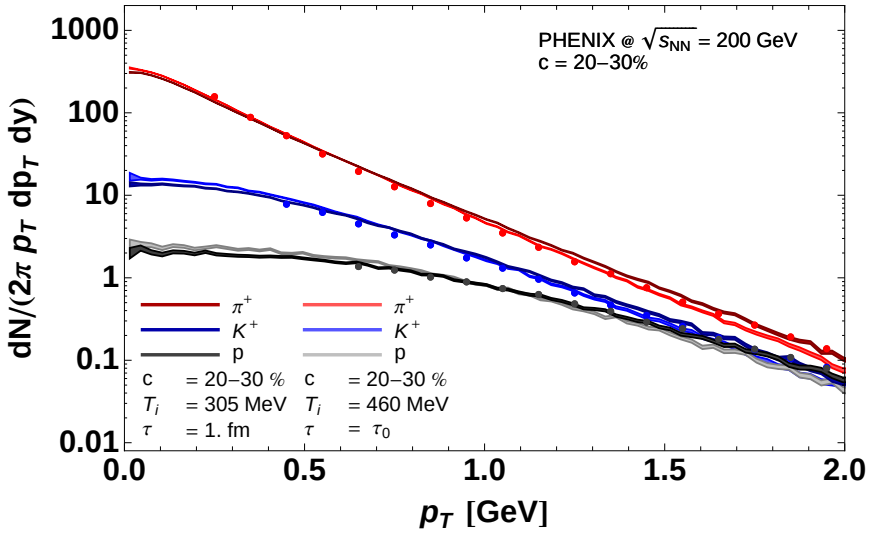
$$\frac{dN}{dy\, d^2p_T} = \frac{dN}{dy\, 2\pi p_T\, dp_T}\left(1 + 2v_2(p_T)\cos(2\phi_p) + ...\right)$$

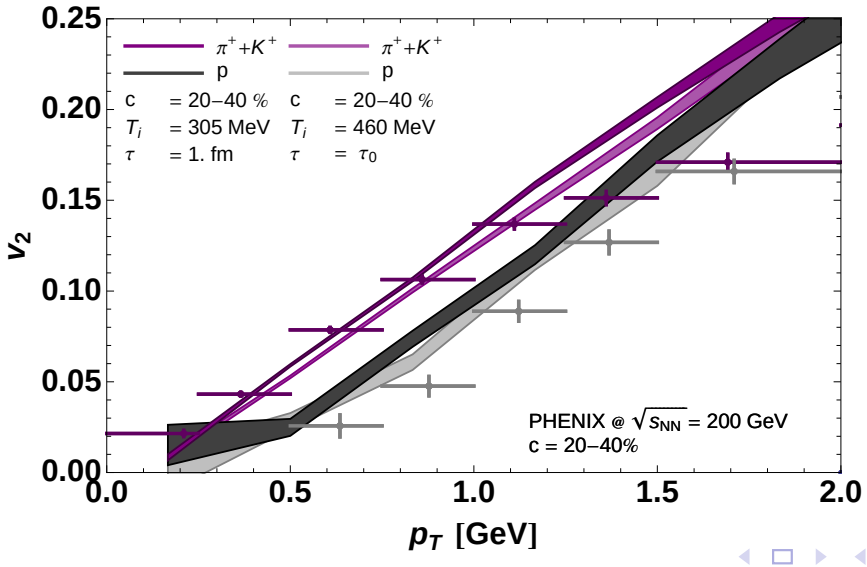
[2] A. Kisiel, T. Tałuć, W. Broniowski and W. Florkowski Comput. Phys. Commun. **174**, 669 (2006)

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)

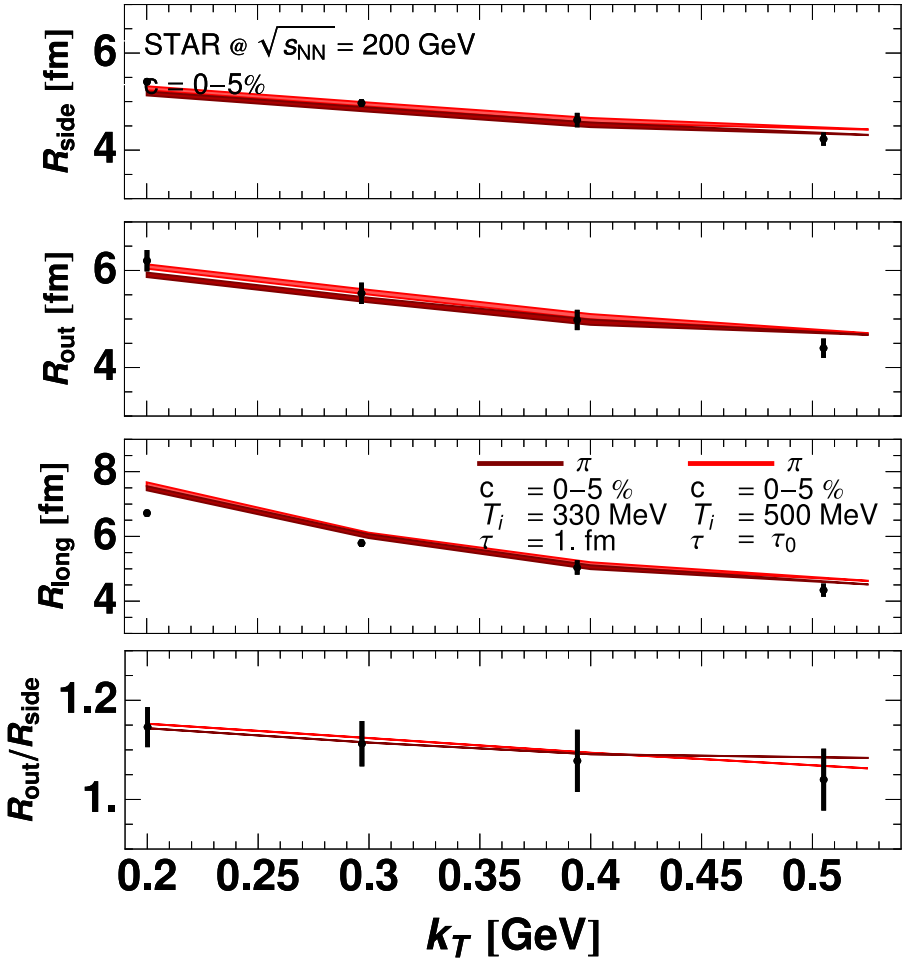
$$C(\vec{q},\vec{k}) = (1-\lambda)+\lambda K_{\rm coul}(q_{\rm inv})\left[1+\exp\left(-R_{\rm out}^2{}^2 q_{\rm out}^2 - R_{\rm side}^2 q_{\rm side}^2 - R_{\rm long}^2 q_{\rm long}^2\right)\right],$$

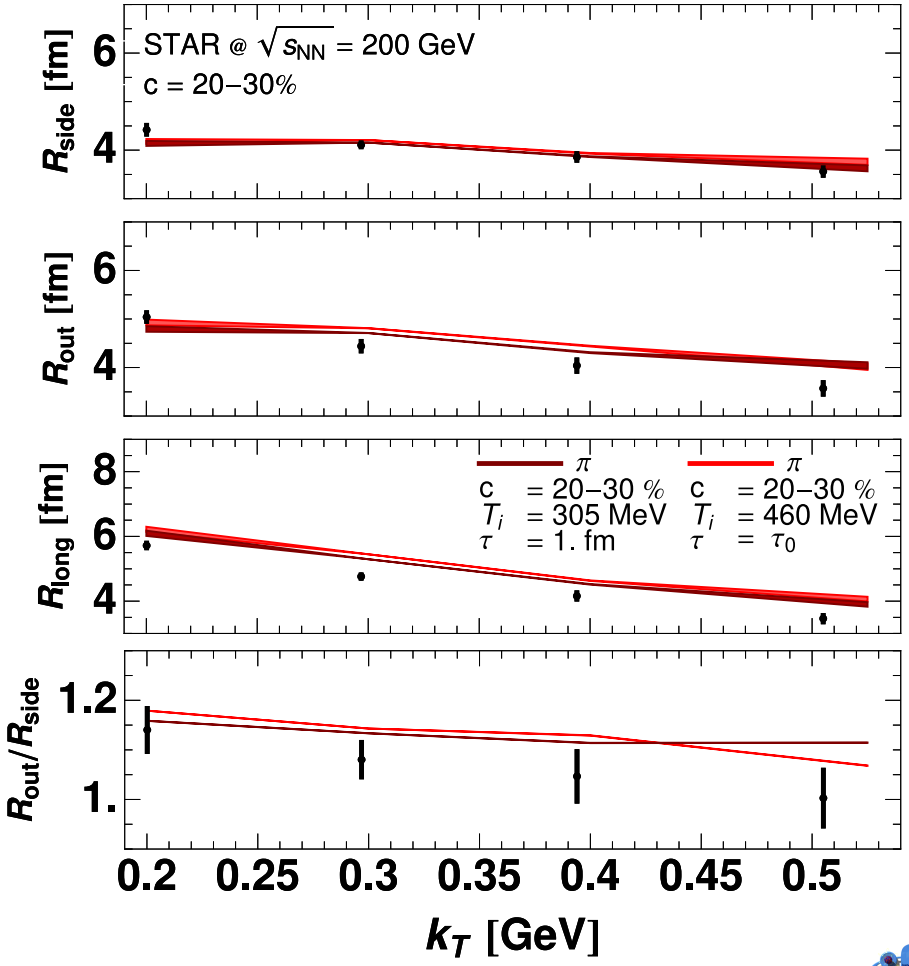
- HBT radii ($R_{\rm out}$, $R_{\rm side}$, $R_{\rm long}$) obtained from the fit and compared with data

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

THERMINATOR

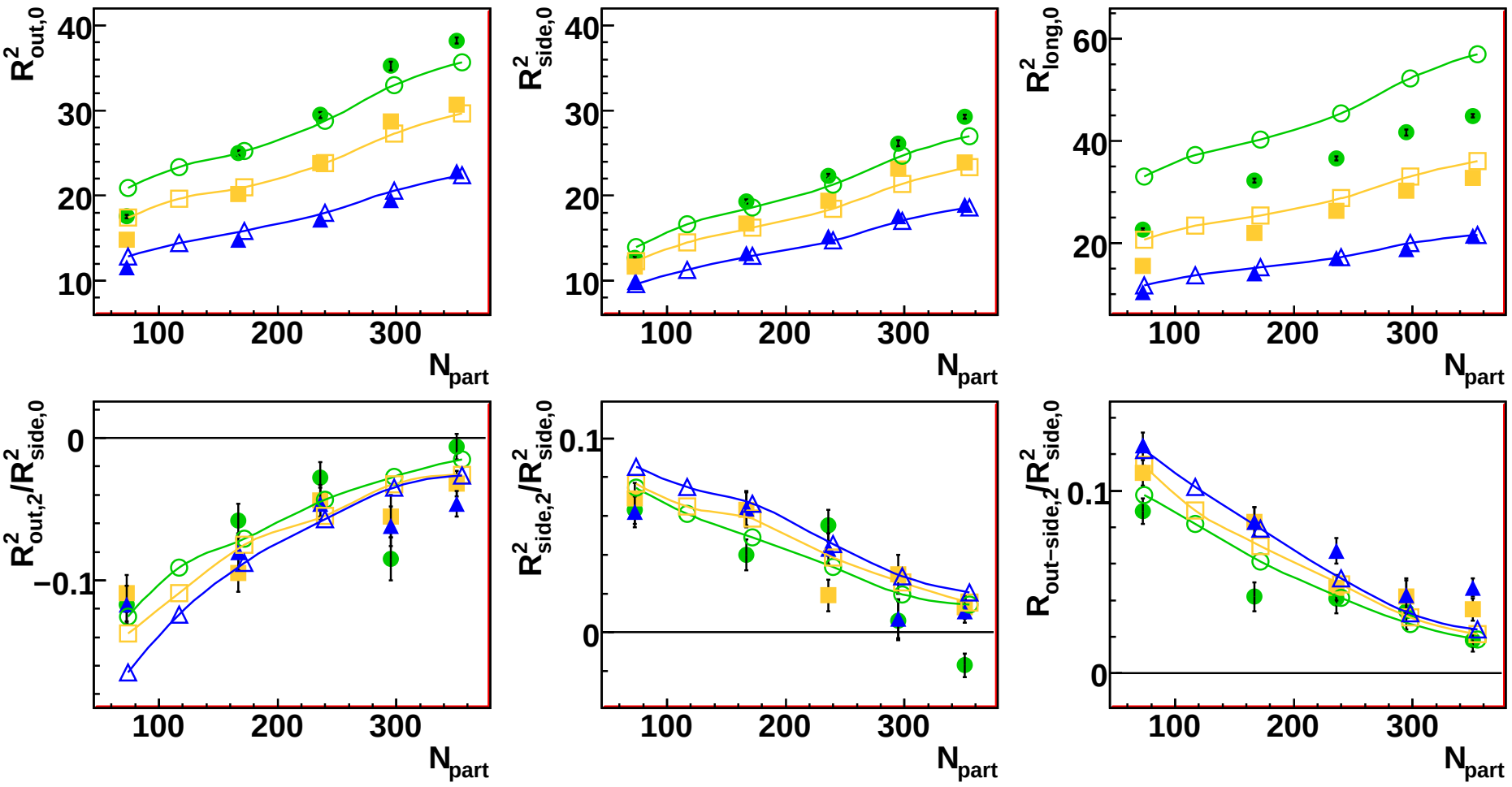
HBT results





THERMINATOR

oscillations of the HBT radii



Conclusions

- our hydrodynamical model correctly describes the soft-hadronic data first successful attempt to solve the RHIC HBT puzzle.
- the things which matter
  - realistic equation of state
  - initial profile – Gauss, fluctuations of the eccentricity
  - all resonances included
  - two-particle algorithm for femtoscopy
- future developments
  - predictions for LHC
  - full 3D evolution - Piotr Bożek
  - finite baryonic potential
  - viscosity