# Hadronic observables in hydrokinetic picture of A+A collisions at RHIC and LHC

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**Based on Iu. Karpenko, Yu.S., K. Werner**

**arXiv:1204.5351**

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# The main ingredients of the HydroKinetic Model (HKM)

- Initial conditions:
- Glauber model
- Fluctuating MC-Glauber IC via GLISSANDO code by W. Broniowski, M. Rybczynski, P. Bozek
- Fluctuating MC-KLN (CGC) IC via mckln-3.43 code by Y. Nara

- Hydrodynamics:
- Evolution of QGP with crossover transition between quark-gluon and hadron phases
- Evolution of chemically equilibrated hadron gas

- Hydrokinetics:
- Evolution of the partially equilibrated hadron matter at the decaying stage

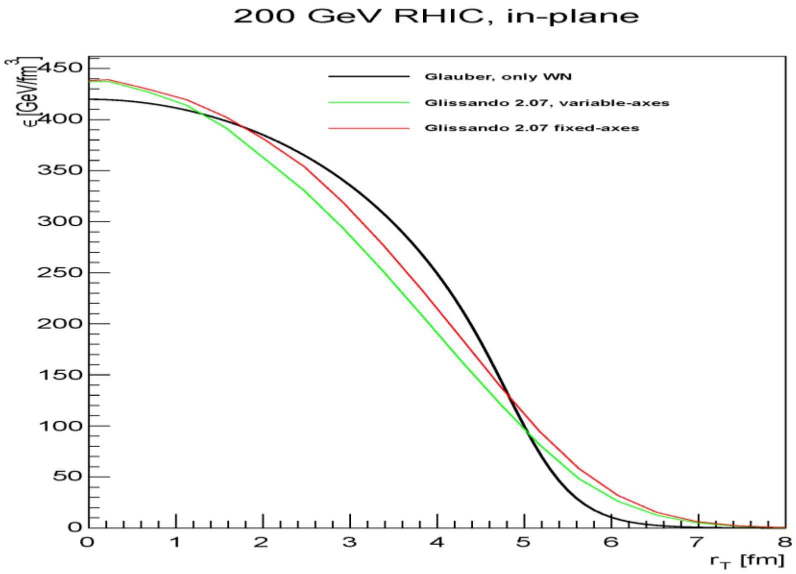
- Hadronic cascade:
- Nonequilibrium UrQMD-evolution of hadron-resonance gas
- Momentum spectra formation

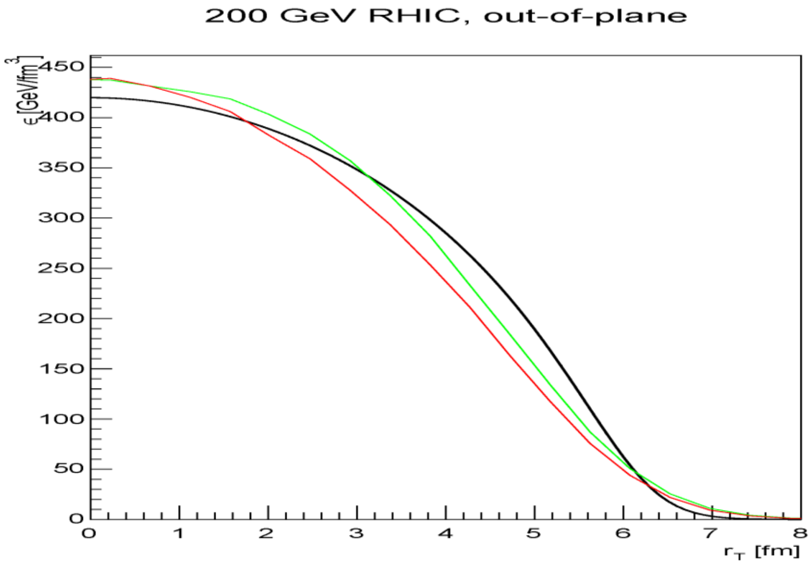
# Initial conditions (IC)

Glauber IC (entropy profile ~ the overlapping of *average* profiles of the colliding nuclei)

$$s(x_T) = C\left(\frac{1-\delta}{2}\frac{dN_{\mathtt{W}}}{d^2x_T} + \delta\frac{dN_{\mathtt{bin}}}{d^2x_T}\right)$$

MC Glauber IC (entropy profile ~ the overlapping of *fluctuating* profiles of the colliding nuclei)


200 GeV RHIC, in-plane

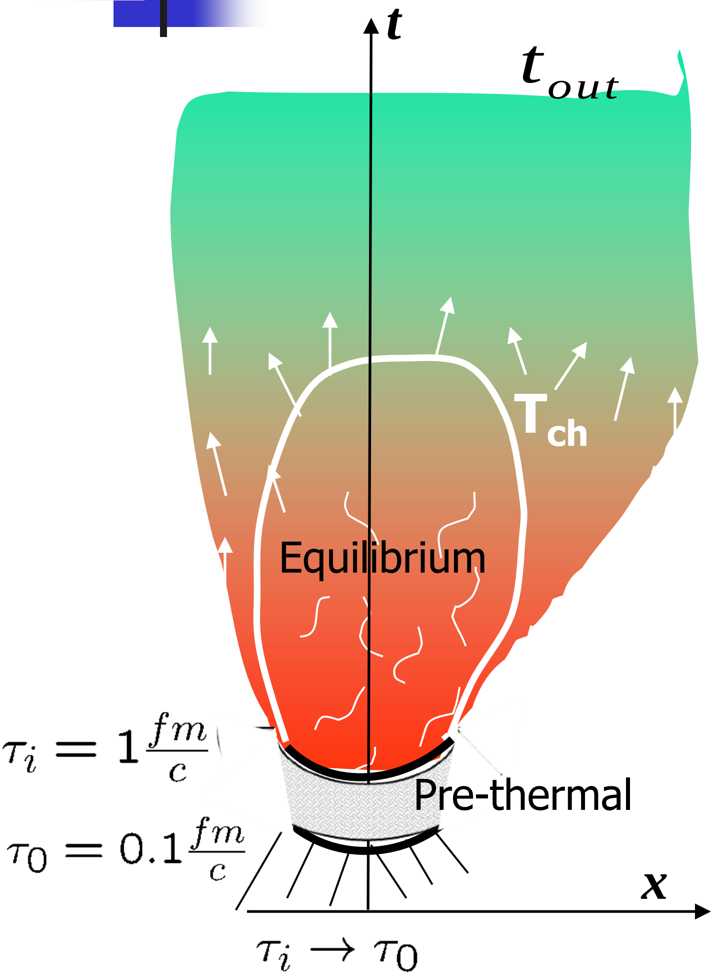

200 GeV RHIC, out-of-plane

MC KLN IC (entropy profile ~ the distribution of gluons in transverse plane of reaction)

$$s_0(x_T) = C \cdot 3.6\frac{dN_g}{\tau_0 d^2x_T d\eta_s}\Big|_{y=\eta_s=0}$$

# Matter evolution in chemically equilibrated space-time zone

# Locally (thermally & chemically) equilibrated evolution and initial conditions



To estimate pre-thermal flow at thermalization time $\tau_i$ the hydro is started at $\tau_0$ with the modified EoS

(see, Yu.S. Act. Phys. Pol. 2006)

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

EoS $p = p(\epsilon, \{Q_{\alpha}\})$ from lattice QCD

$$\begin{cases} \partial_{\nu} T^{\mu\nu} = 0 \\ \partial_{\nu}(Q_{\alpha} u^{\nu}) = 0 \qquad \alpha = B, S, E \end{cases}$$

**Initial transv. entropy profiles:**

$s(\mathbf{x}_T) = s_0 F^{(i)}_{prof}(\mathbf{x}_T)$, *i= Glauber, MC Glauber, MC KLN*

$s_0$ is fixed by the multiplicity

**Initial transv. rapidity profiles in φ - direction:**

$y_T = \alpha \frac{r_T}{R_T^2(\phi)}$ where $R_T = \sqrt{< r_T^2 >}$

$y_L = \eta = \frac{1}{2} \ln[(t+z)/(t-z)]$ boost-invariance

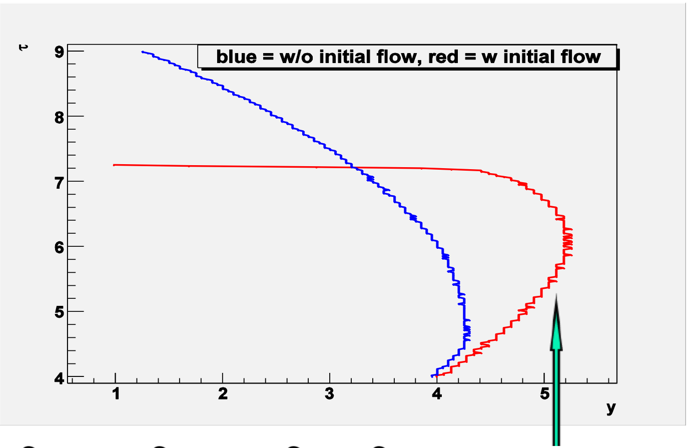
**$s_0$ and $\alpha$ are only fitting parameters in HKM**

# The role of the pre-thermal flows

- Transverse pre-thermal flow and its anisotropy appear due the transv. finiteness of the system:

Yu.S. Acta Phys.Polon. B37 (2006) 3343**;** Gyulassy, Yu.S., Karpenko, Nazarenko Braz.J.Phys. 37 (2007) 1031. Yu.S., Nazarenko, Karpenko: Acta Phys.Polon. B40 1109 (2009).

- They reduce Rout/Rside ratio:



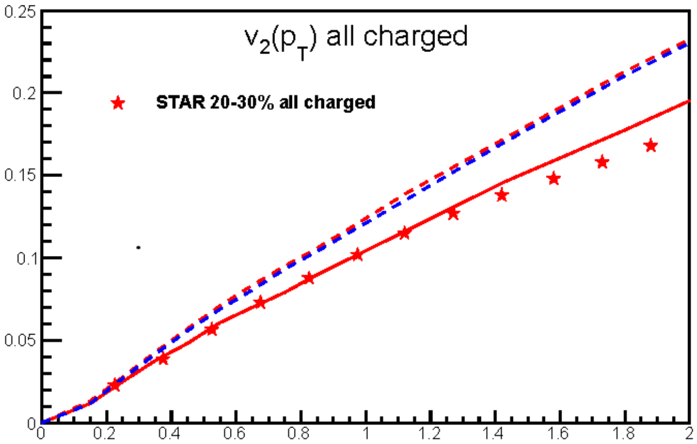
Borysova, Yu.S. , Akkelin, Erazmus, Karpenko. Phys. Rev C **73**, 024903 (2006)

- Result in stronger final radial flow.

$$R^2_{out} \approx R^2_{side} + v^2\langle\triangle t^2\rangle_p - 2v\langle\triangle x_{out}\triangle t\rangle_p, v = \frac{p_T}{p^0}$$

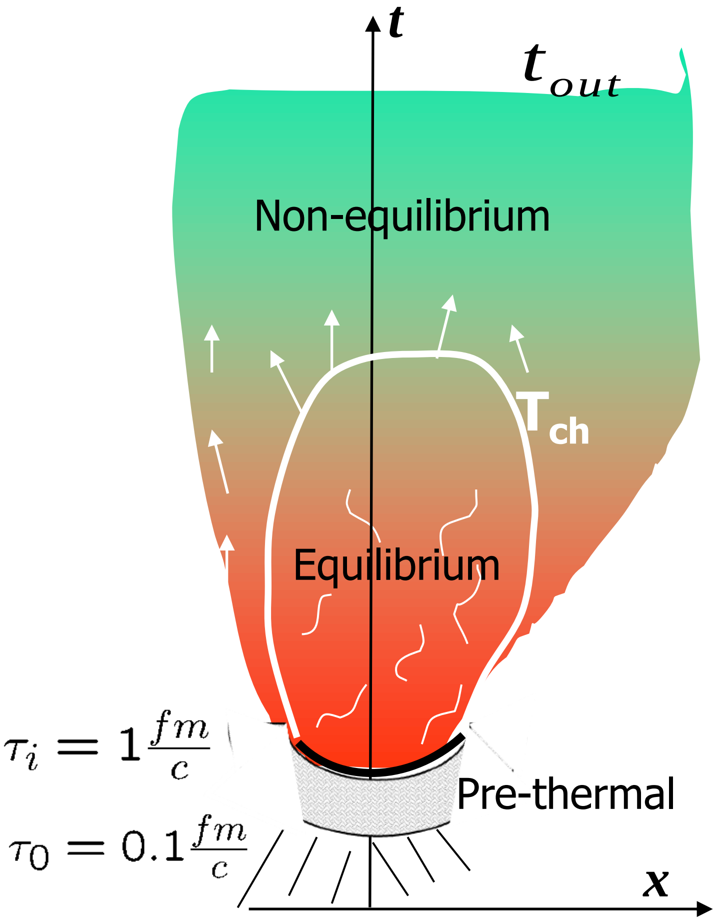
- Reduce elliptic flows.

The similar effects appear due to shear viscosity, namely: a redaction of elliptic flow and an increase of radial one:



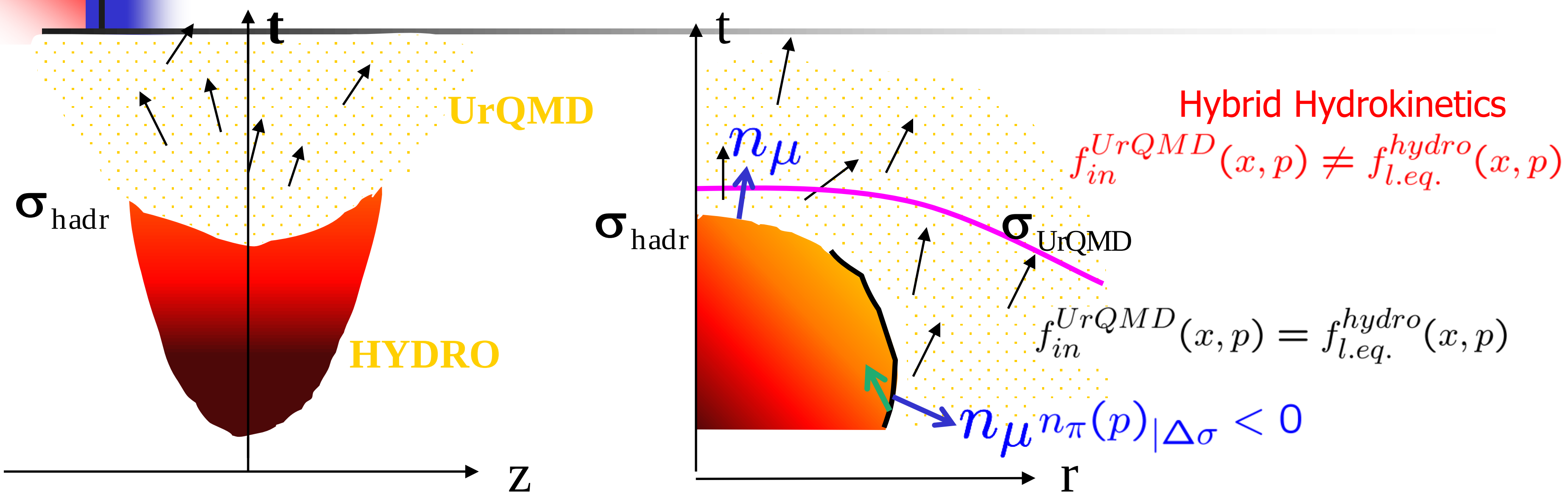
Dashed lines: no transverse flow at initial time $\tau_0 = 0.1$ fm/c with lattice QCD and modified hard EoS. Solid line – small initial flow <v_T> = 0.02 are inputted

# II. Evolution of the hadronic matter in non-equlibrated zone.



**Decay of the system**
**and**
**spectra formation**

# Hybrid models: HYDRO + UrQMD (**Bass, Dumitru (2000)**)



$\sigma_{\text{hadr}} : \tau \equiv \sqrt{t^2 - z^2} = const$

at $r = const$

$\sigma_{\text{hadr}} : \tau(r)$ at $z = 0$

## The problems:

- the system just after hadronization is not so dilute to apply hadronic cascade models;
- hadronization hypersurface $\tau(r)$ contains non-space-like sectors (causality problem: Bugaev, PRL 90, 252301, 2003);
- An opacity for the particles moving inside the system is ignored.
- At *r*-periphery of space-like hypsurf. the system is far from l.eq.

**The initial conditions for hadronic cascade models should be based on non-local equilibrium distributions**

# Hydro-kinetic approach

**Yu.S., Akkelin, Hama: PRL 89 , 052301 (2002);**
**+ Karpenko: PRC 78, 034906 (2008); Karpenko, Yu.S. 81, 054903 (2010)**

MODEL

- is based on relaxation time approximation for emission function of relativistic finite expanding system;

- provides evaluation of emission function based on escape probabilities with account of deviations (even strong) of distribution functions [DF] from local equilibrium;

○ accounts for conservation laws: back reaction of the particle emission to the hydro-evolution at the particle emission;

} UrQMD

Complete algorithm includes:

- solution of equations of ideal hydro;
- calculation of non-equilibrium DF and emission function in first approximation;

○ solution of equations for ideal hydro with non-zero left-hand-side that accounts for conservation laws for non-equilibrium process of the system which radiated free particles during expansion;
○ Calculation of "exact" DF and emission function;
○ Evaluation of spectra and correlations.

} UrQMD

# Boltzmann equations and probabilities of particle free propagation

**Boltzmann eqs (differential form)**

$$\frac{p^\mu}{p^0}\frac{\partial f_i(x,p)}{\partial x^\mu} = G_i(x,p) - L_i(x,p)$$

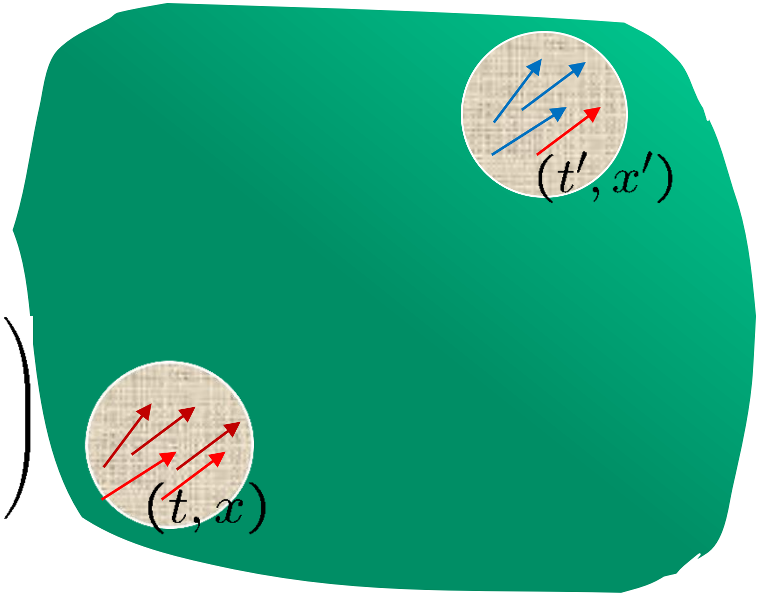
$G_i(x,p)$ and $L_i(x,p) = J_i(x,p) f_i(x,p)$ are G(ain), L(oss) terms for $i$ p. species

**Probability of particle free propagation (for each component $i$ )**

$$x = (t, \mathbf{x})$$

$$\overline{x}_{t\to s} = (s, \mathbf{x} + \frac{\mathbf{p}}{p^0}(s-t))$$

$$\mathcal{P}_{t\to t'}(x,p) = \exp\left( -\int_t^{t'} ds J(\overline{x}_{t\to s}, p) \right)$$



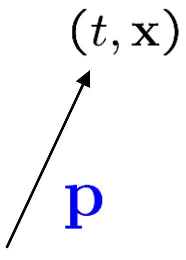
# Basic equations in HKM

**Boltzmann eqs (integral form)**

$$f(t,\mathbf{x},p) = f(\overline{x}_{t\to t_0},p)\mathcal{P}_{t_0\to t}(\overline{x}_{t\to t_0},p) + \int_{t_0}^{t} G(\overline{x}_{t\to s},p)\mathcal{P}_{s\to t}(\overline{x}_{t\to s},p)ds$$

$\mathcal{P}_{s\to t}[J]$

$(s,\mathbf{x}-\frac{\mathbf{p}}{p^0}(t-s))$



**Relax. time approximation for emission function (Yu.S. , Akkelin, Hama PRL, 2002)**

$$J(x,p) \approx R_{l.eq.}(x,p) + J^{decay}(x,p),$$
$$G(x,p) \approx R_{l.eq.}(x,p)f_{l.eq.}(x,p) + G^{decay}(x,p)$$

**Hydro equations** **(4 eqs)**

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

**Equations for decays of resonances into fluid** **(359 eqs)**

$$\partial_\mu(n_i(x)u^\mu(x)) = -\Gamma_i n_i + \sum_j b_{ij}\Gamma_j n_j(x)$$

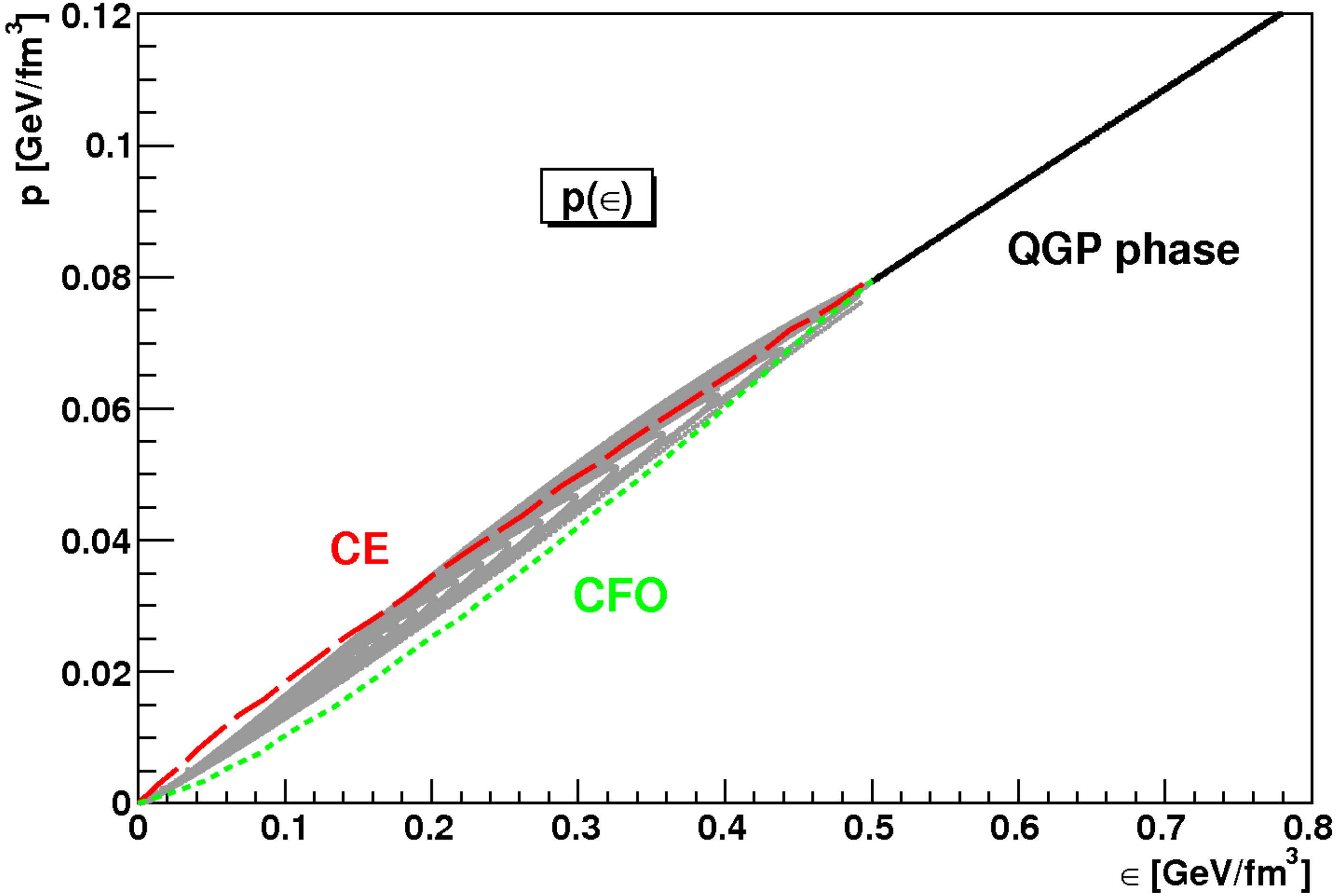
where $b_{ij} = \sum_k \Gamma_{j\to ik}/\Gamma_j$

**EoS for** $T < T_{ch} = 165$

$$p = p(\epsilon,\{n_i\})$$

where $i = 1,...,N = 359 \ (m_i < 2.6 \text{ GeV})$

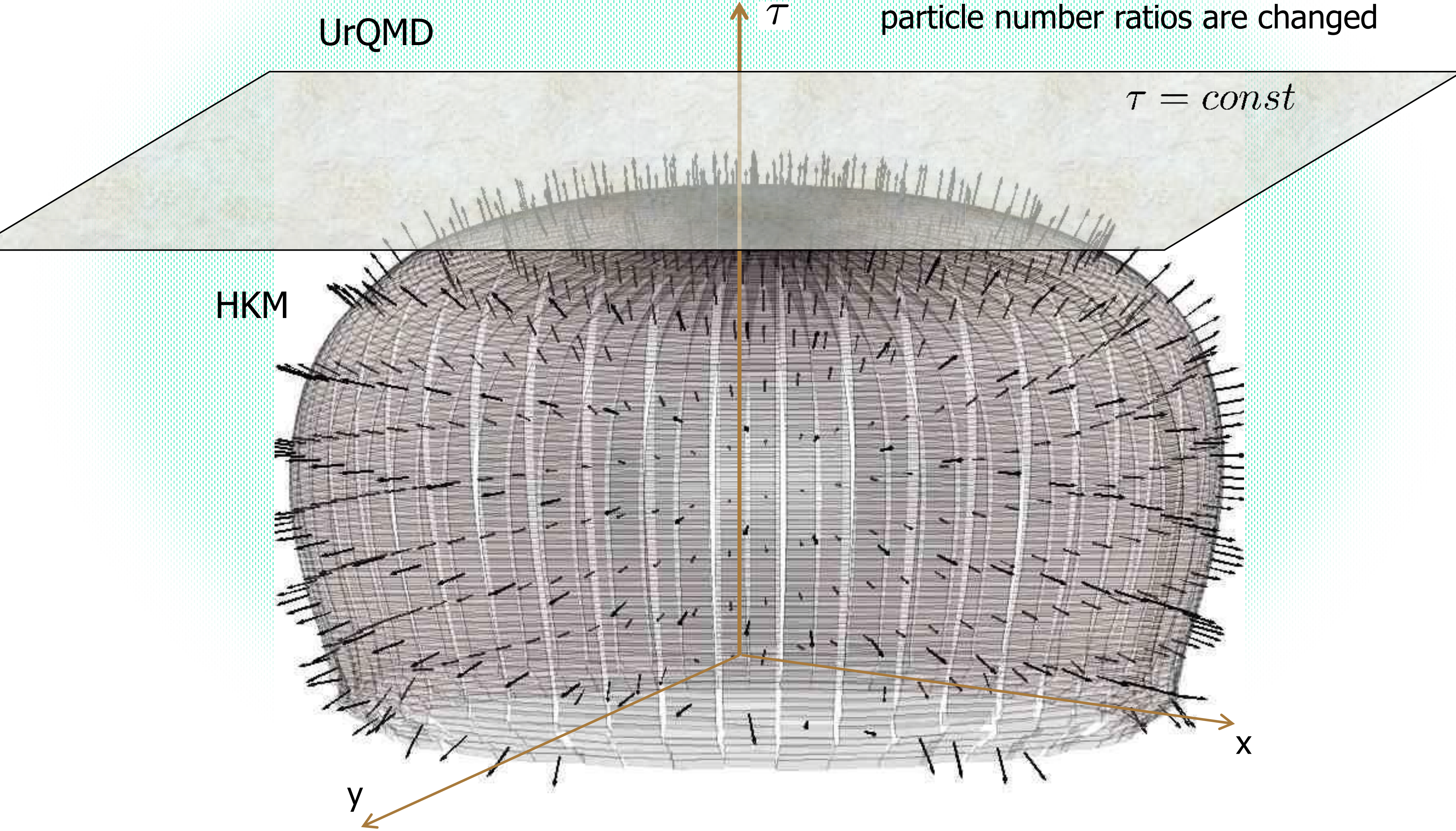
# EoS used in HKM calculations for the top RHIC energy



**The gray region consists of the set of the points corresponding to the different hadron gas compositions at each $\epsilon$ occurring during the late nonequilibrium stage of the evolution.**

# Hybrid HKM (hHKM):

matching of HKM and UrQMD at the space-like hypersurface $\tau = \tau(x = y = 0, T = T_{ch})$



particle number ratios are changed

A dissipation in the systems is responsible for formation of the HBT radii:
Yu.S. et al **PRL 89 , 052301 (2002)**

# The RESULTS for RHIC TOP ENERGY

# Parameters for the RHIC top energy

## Fitting parameters

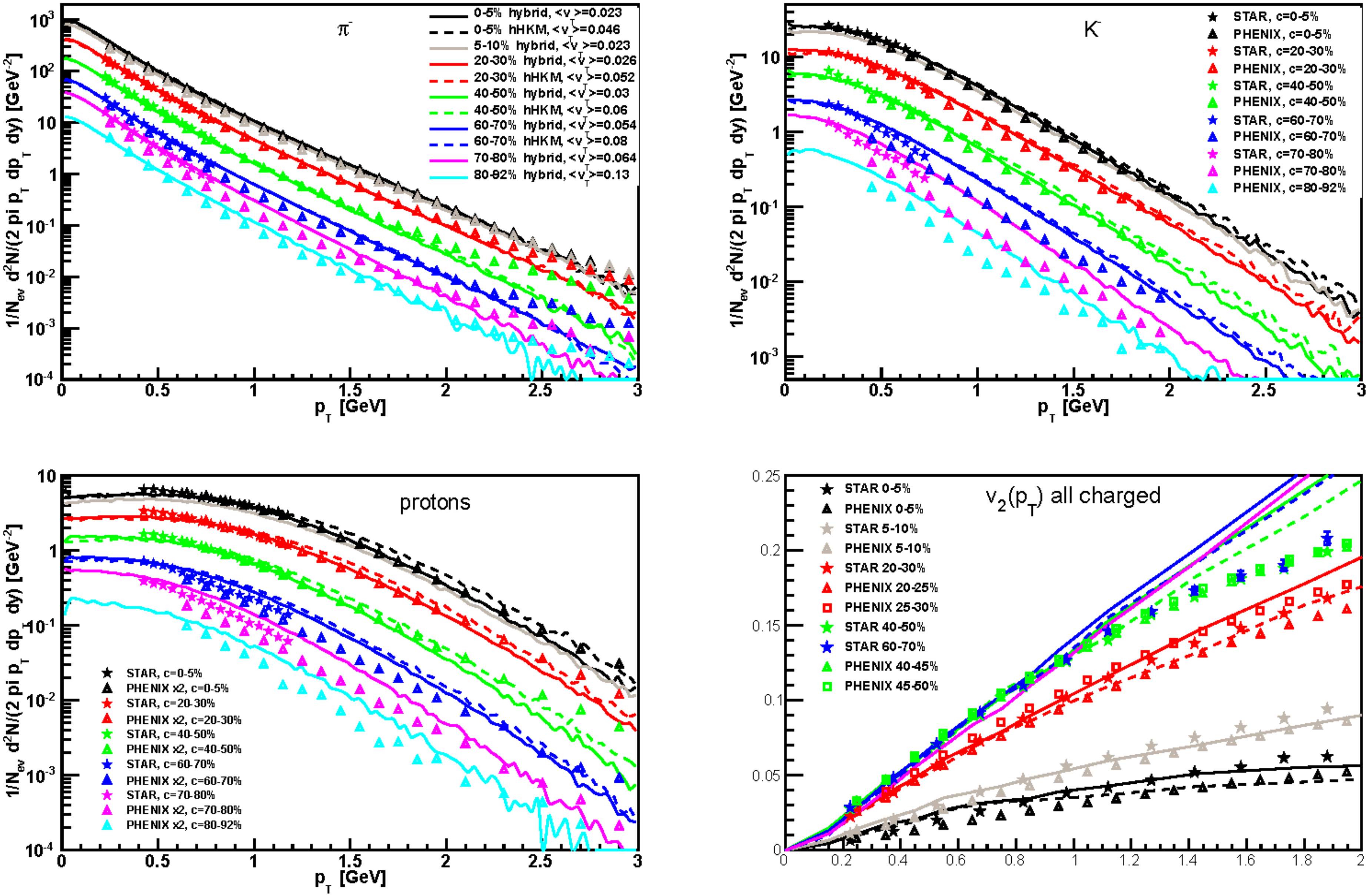
| | **Initial time** $\tau_0$ | **Initial transverse flows** $\langle v_T \rangle$ |
|---|---|---|
| MC Glauber IC | 0.1 fm/c | 0.023- 0.026 |
| CGC IC (MC KLN) | 0.6 fm/c | 0.063 – 0.079 |

**The parameter $s_0$ serves as the normalization factor to the number of charged particles.**

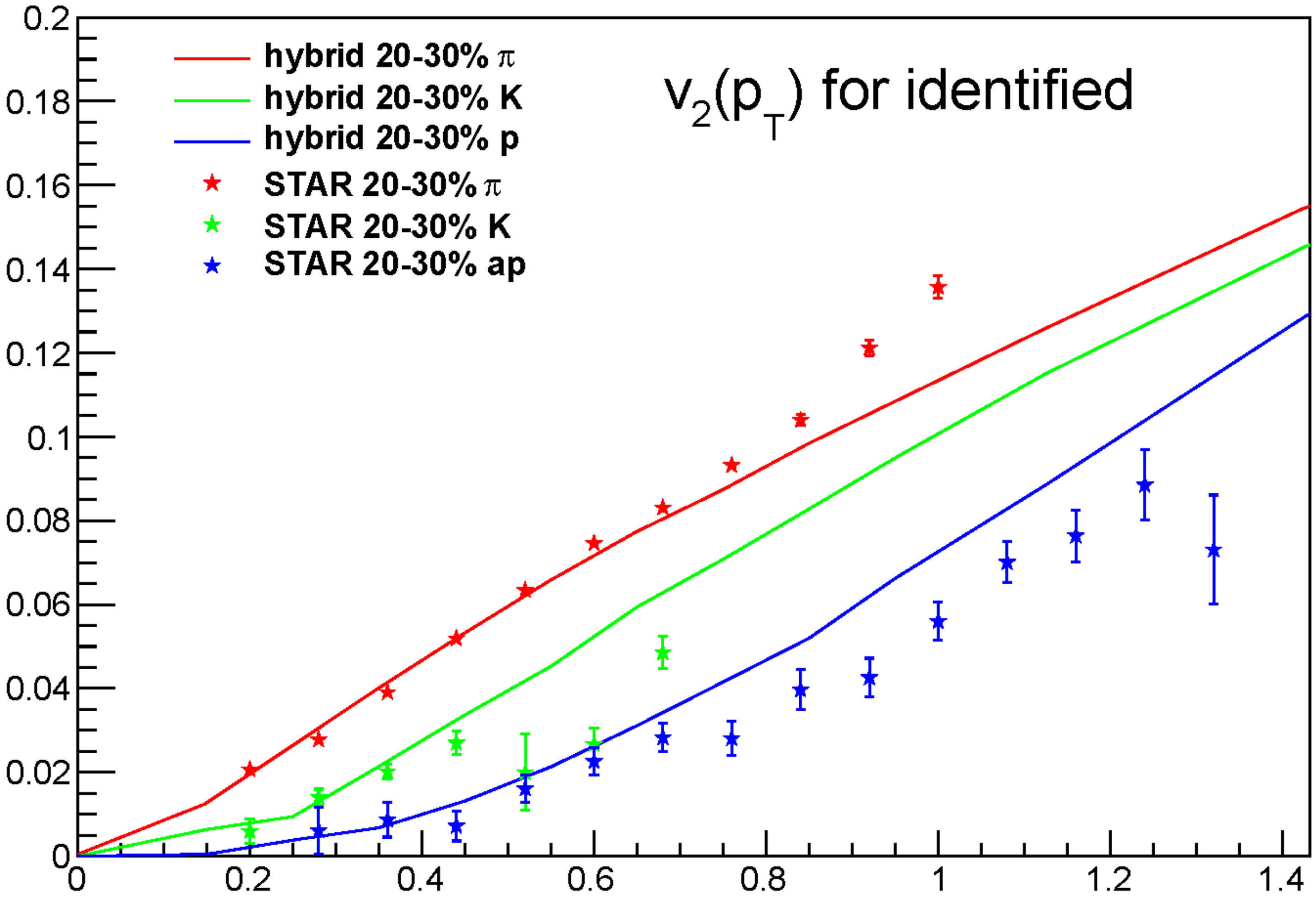
- For MC Glauber IC the parameter $\langle v_T \rangle$ imitates the input of shear viscosity into hydrodynamics of QGP.
- For MC KLN IC the initial transverse velocity $\langle v_T \rangle$ "absorbs" unknown portion of the pre-thermal
- flows as well as the viscosity effects in QGP.
- The "effective" initial transverse flow increases $T_{eff}$ of the inclusive transv momentum spectra

  and reduces the anisotropy of the flow, v_2 –coefficient.

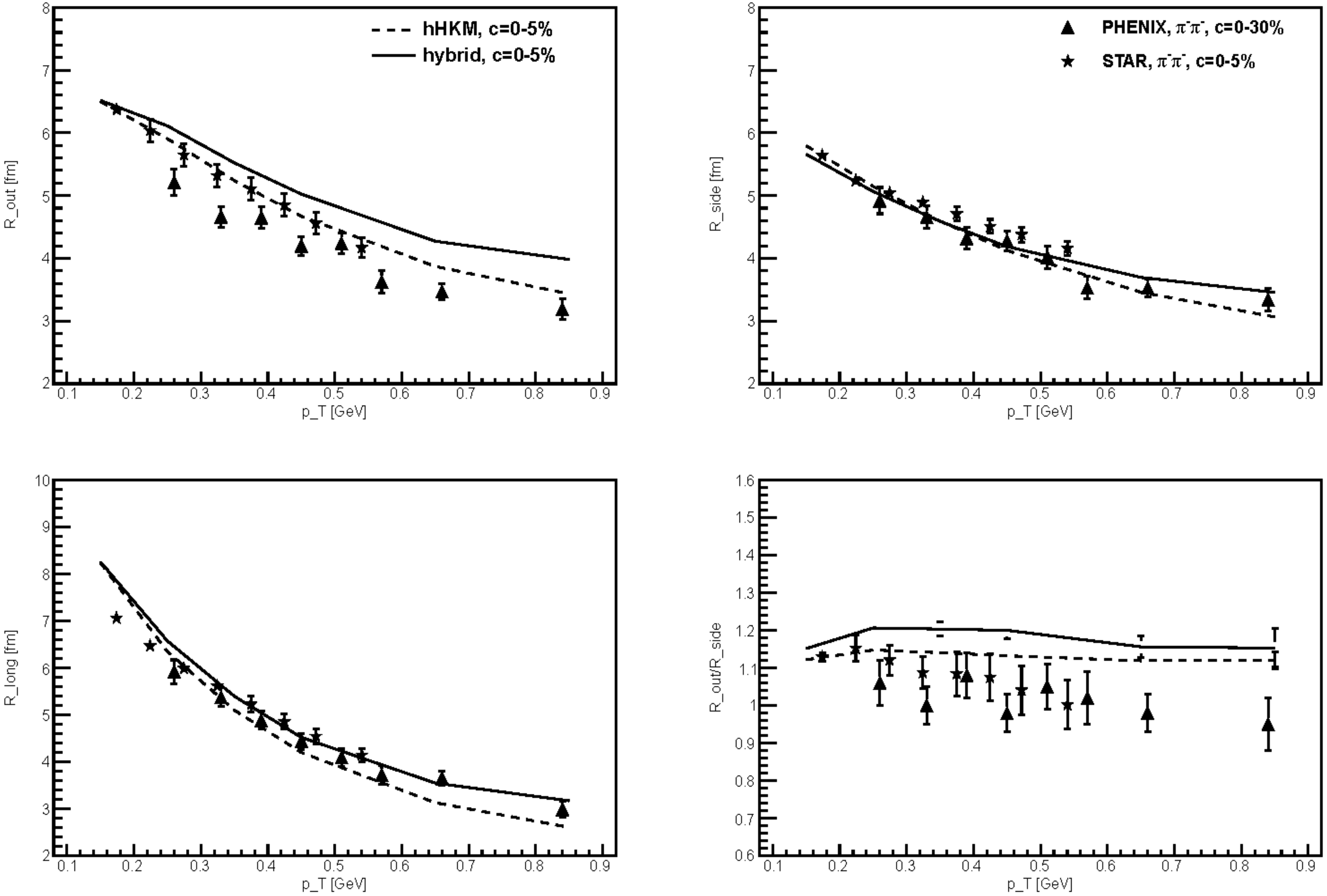
# Transverse spectra for p, K, P and v2 for all charged particles at different centralities at the top RHIC energy in HKM with MC Glauber IC



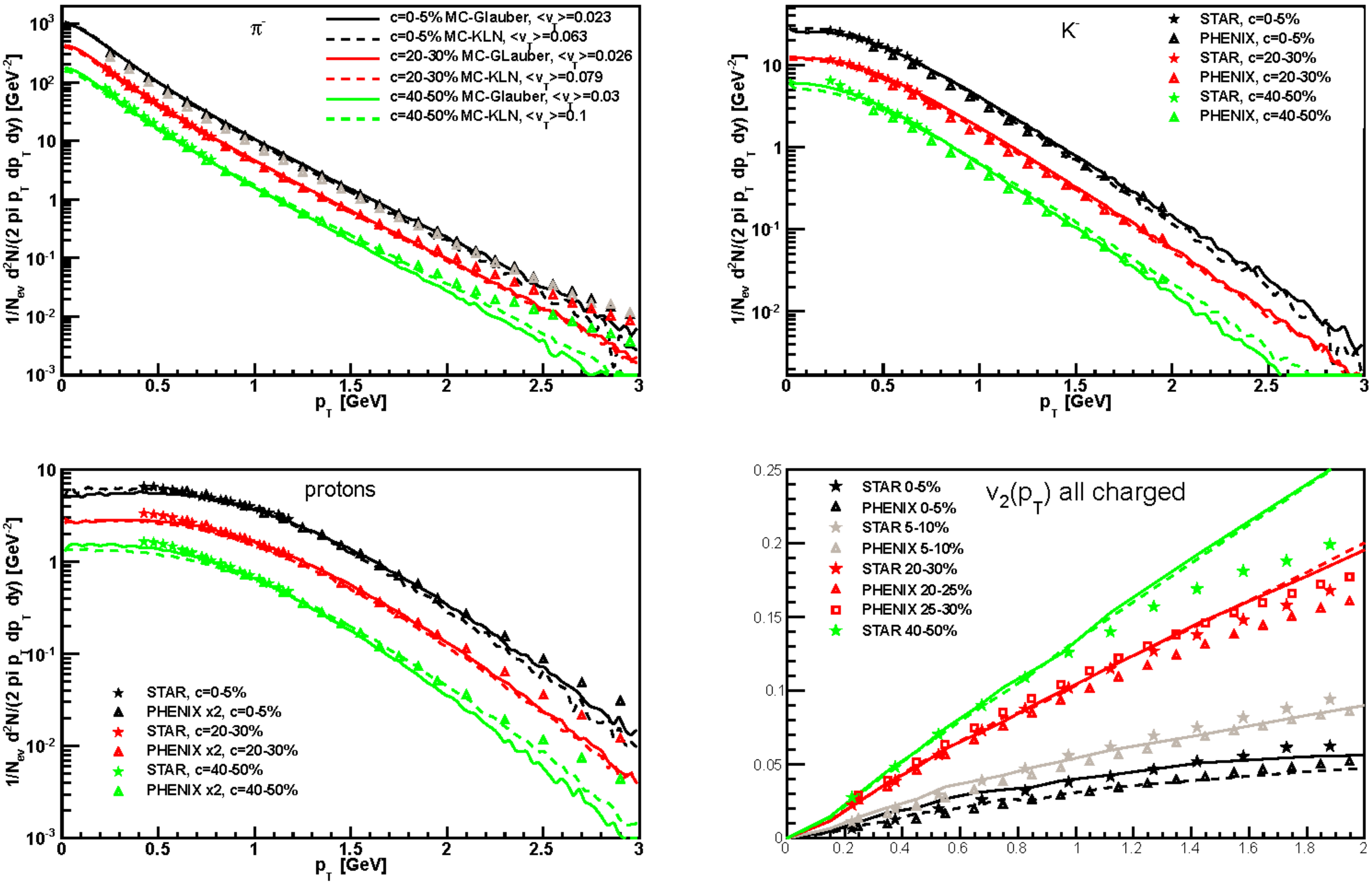
# v2 for the identified particles at RHIC in HKM with MC Glauber IC



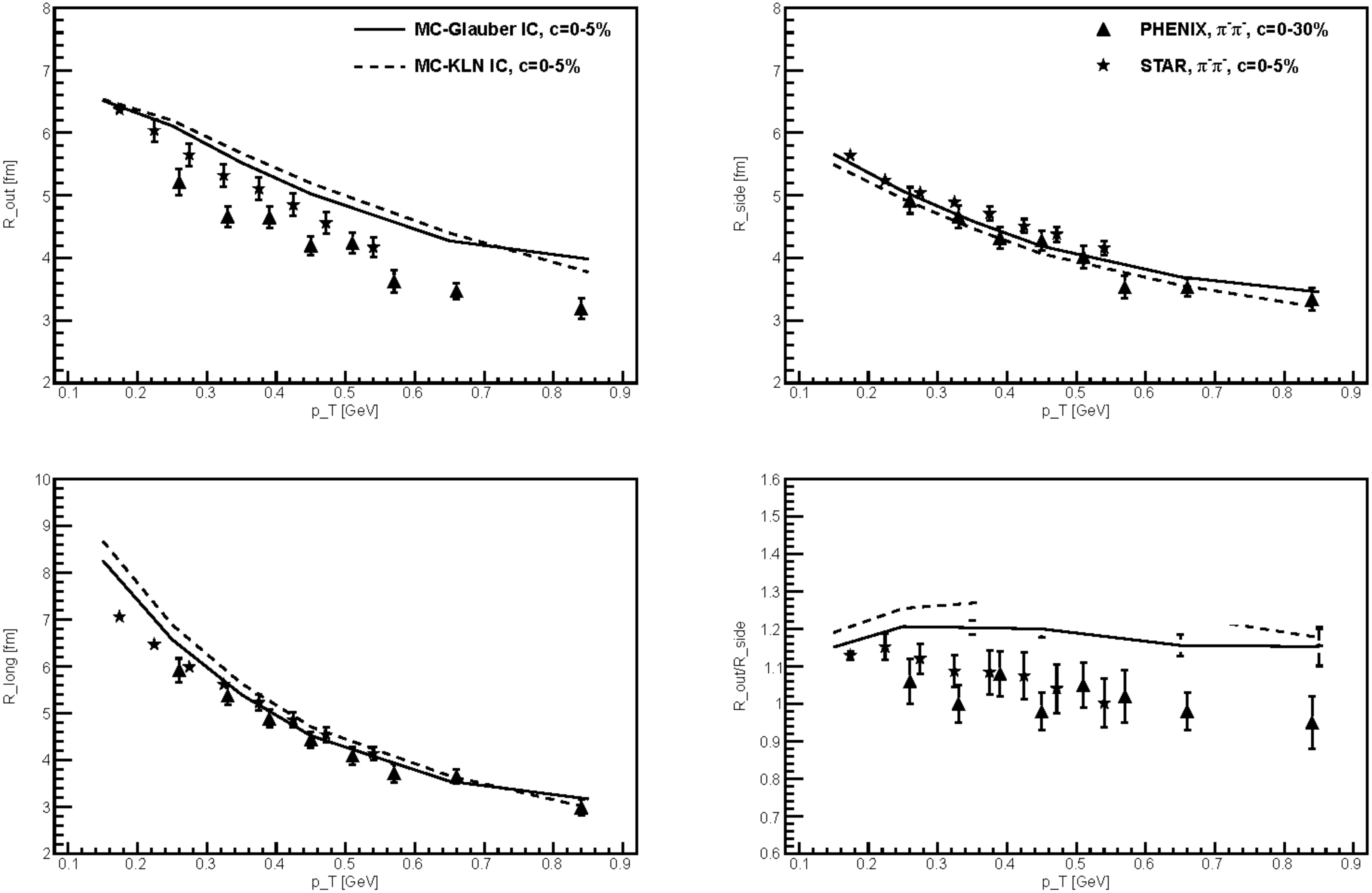
# Interfereometry radii at the top RHIC energies (MC Glauber IC)



# Comparison of the results on the spectra and v2 for MC KLN IC with that for MC Glauber IC

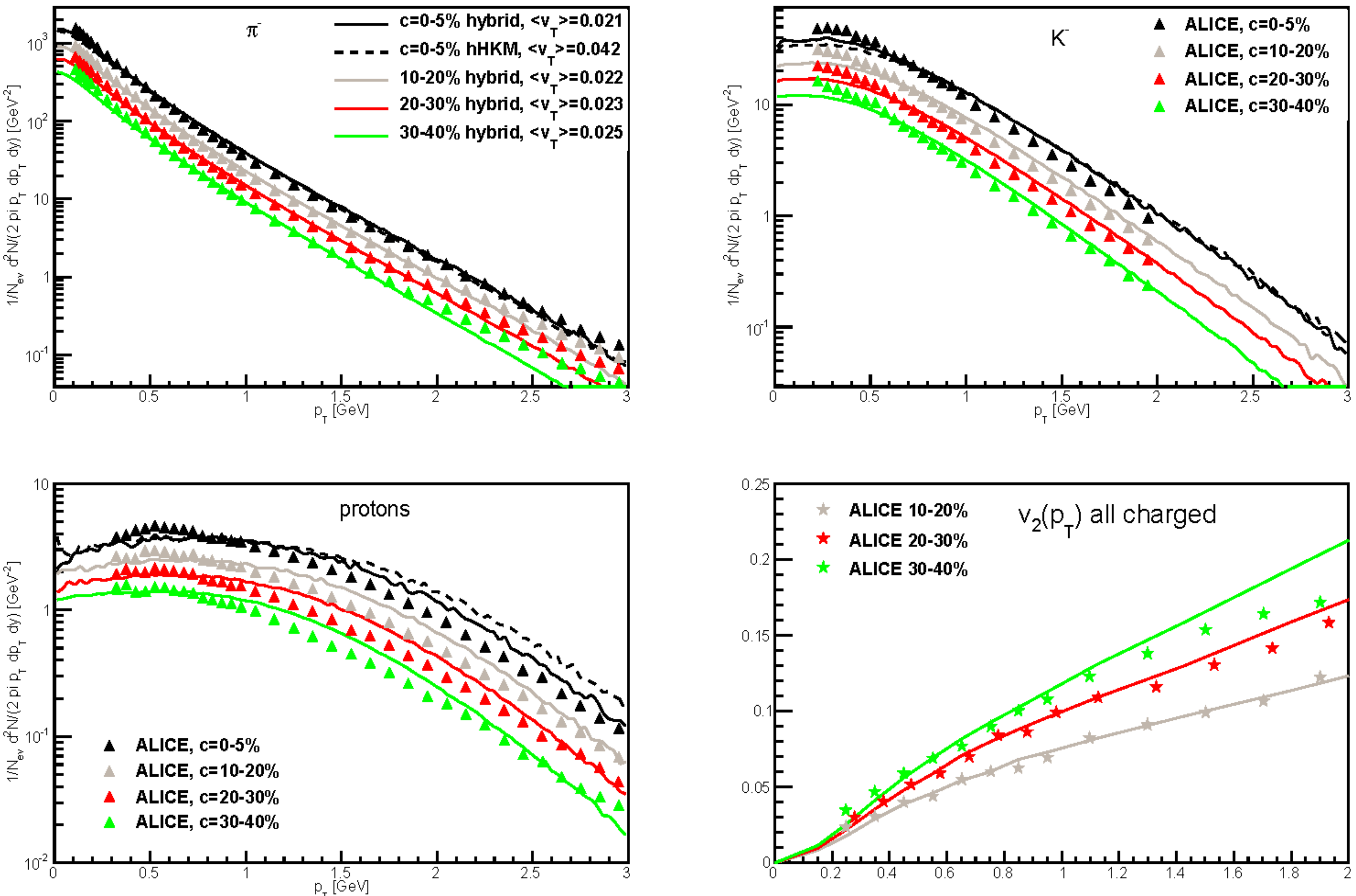


# Comparison of the results on the femtoscopy for MC KLN IC with that for MC Glauber IC

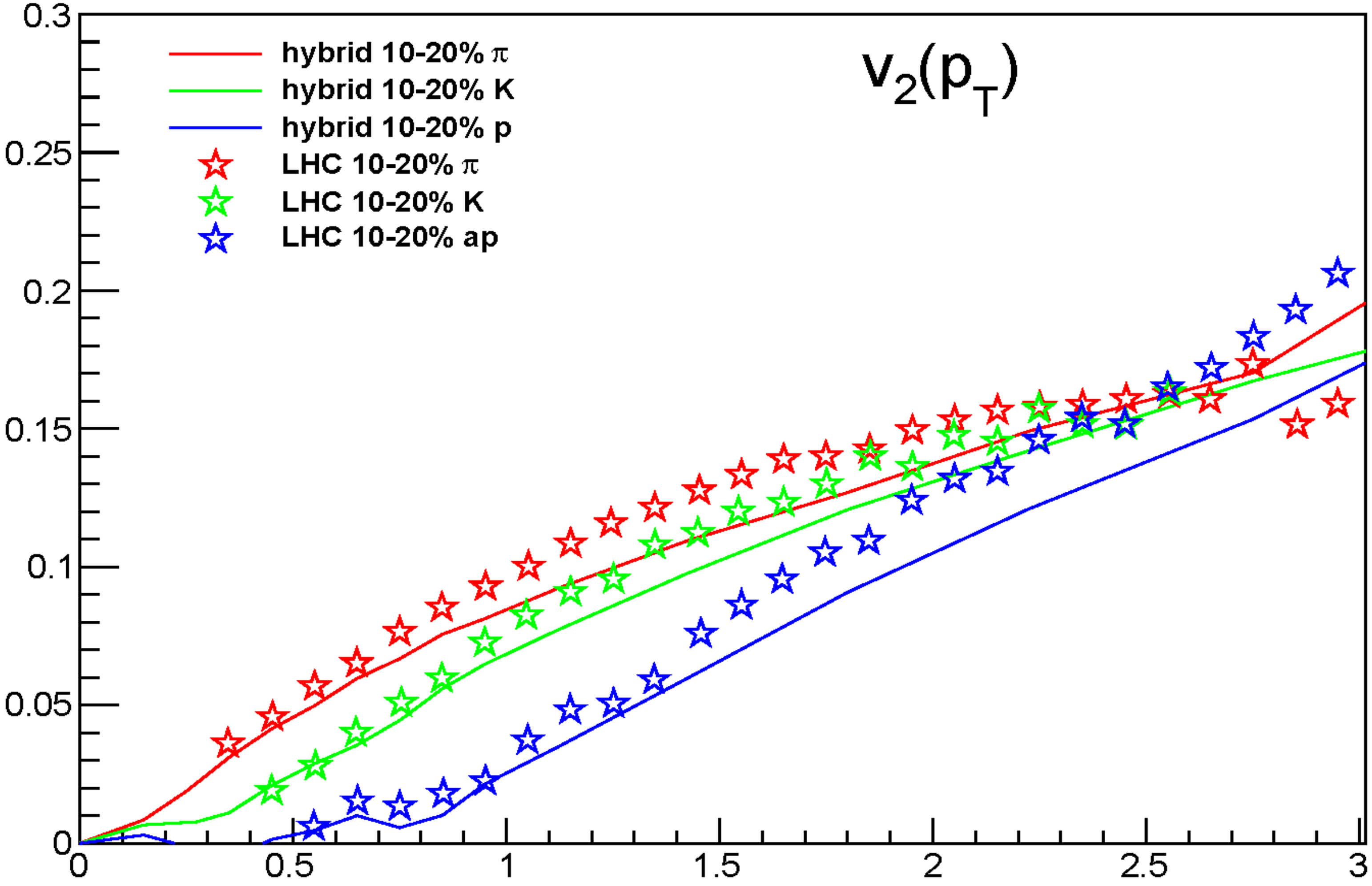


# The RESULTS for LHC ENERGY

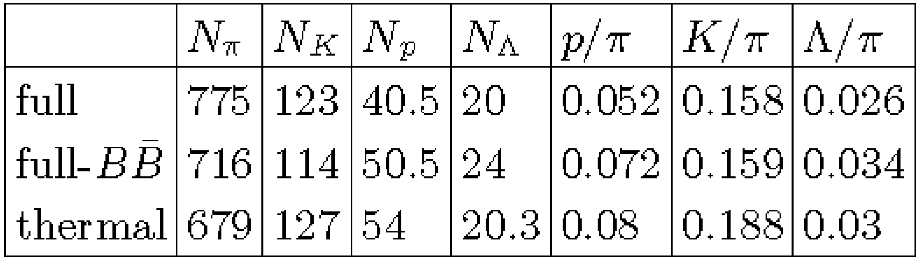
# Transverse spectra for p, K, P and v2 for all charged particles at different centralities at the LHC energy in HKM with MC Glauber IC



# v2 for the identified particles at LHC in HKM with MC Glauber IC



# The modification of the particle number ratios and multiplicities caused, in particular, by the particle annihilations at the afterburn (UrQMD) stage



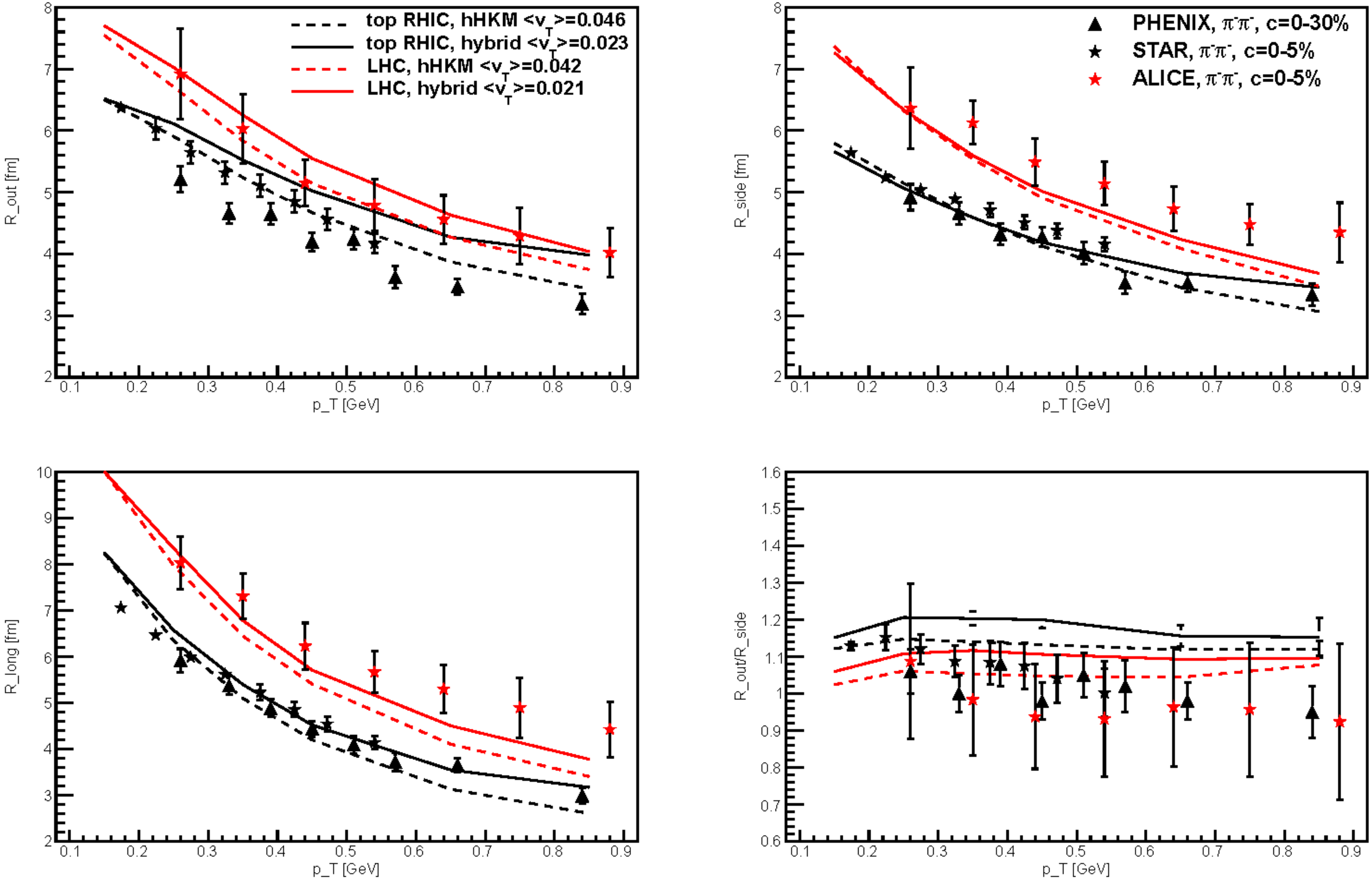
|  | $N_\pi$ | $N_K$ | $N_p$ | $N_\Lambda$ | $p/\pi$ | $K/\pi$ | $\Lambda/\pi$ |
|---|---|---|---|---|---|---|---|
| full | 775 | 123 | 40.5 | 20 | 0.052 | 0.158 | 0.026 |
| full-$B\bar{B}$ | 716 | 114 | 50.5 | 24 | 0.072 | 0.159 | 0.034 |
| thermal | 679 | 127 | 54 | 20.3 | 0.08 | 0.188 | 0.03 |

These values are close to that in ALICE, R. Preghenella Acta Phys Polon. B 43 (2012) 555

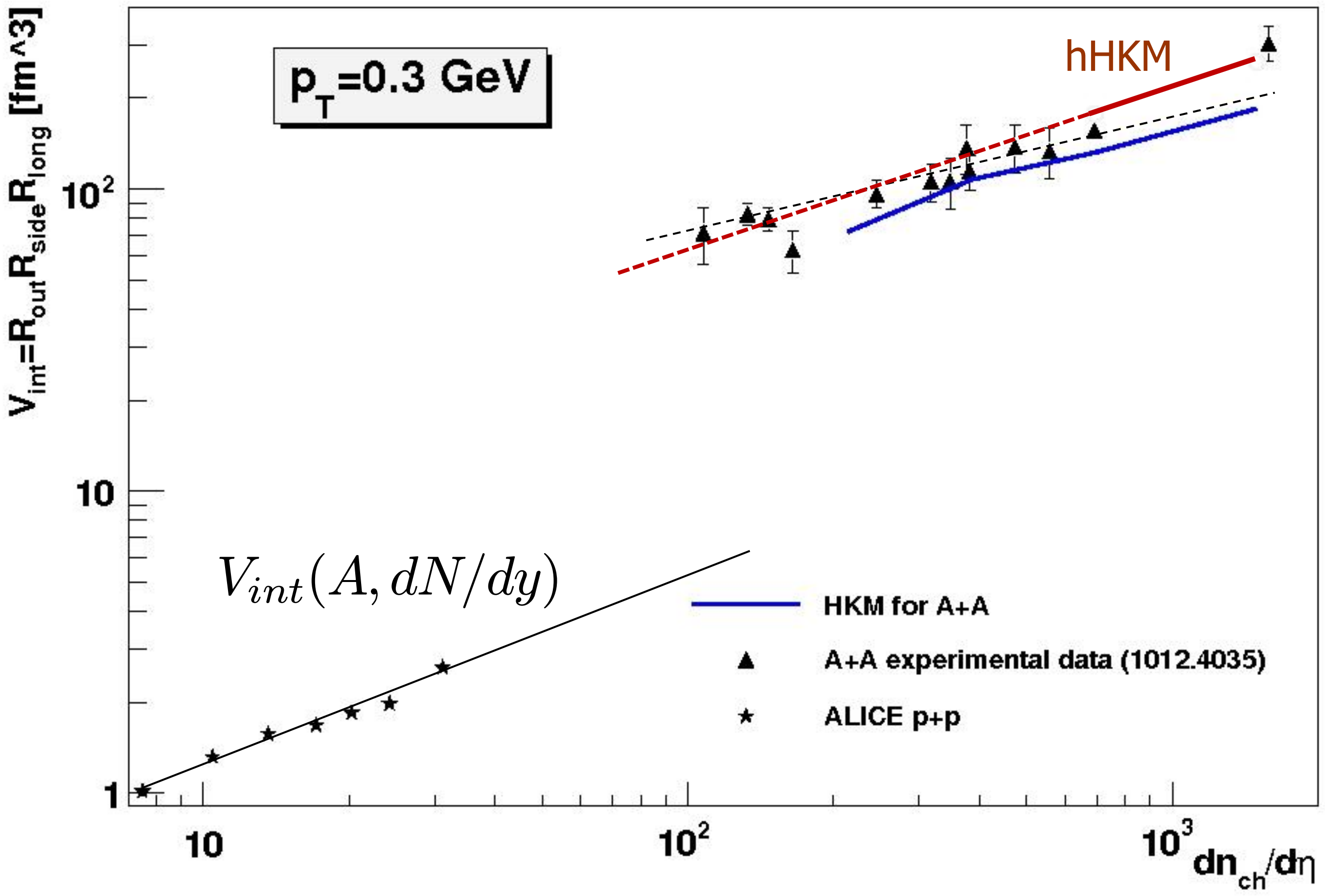
Particle multiplicities and particle number ratios, calculated within hHKM model for most central (0-5%) PbPb collisions with $\sqrt{s} = 2.76$ TeV in differen scenarios of particle production: full scenario (hydro+UrQMD), full-$B\bar{B}$ (baryon-antibaryon annihilator switched off in UrQMD), and thermal model (kinetic phase with resonance decays only).

The value of the effect depends on the dynamics of the fireball that defines a duration of the afterburn stage and so can differ at RHIC and LHC energies.

# Interfereometry radii at the LHC energies (MC Glauber IC)



# Role of non-dissipative stage in formation of large Vint at LHC



# Conclusions

- A successful simultaneous description of hadronic yields, pion, kaon and proton spectra, elliptic flows and femtoscopy scales in the hydrokinetic model of A+A collisions is presented at different centralities for the top RHIC and LHC energies.
The only changed parameter at different collision energies and centralities is the normalization of initial entropy to the multiplicity at the corresponding energies and centralities.

- The pre-thermal flow also imitate the viscosity effects in QGP that help to describe elliptic flows.
- The pre-thermal flow as well as the collision energy increase lead to a magnification of the positive correlations $r-\tau$ between space and time positions of emitted pions, and so reduce $R_{out}/R_{side}$ ratios which tend to unity at LHC.

- The afterburn (UrQMD) evolution stage enhances the overall value of the radii and "interferometry volume" . This effect is most expressed at the LHC energies.

- The hHKM better describes the femtoscopy scales, in particular, $R_{out}/R_{side}$ ratio, than pure hybrid model.

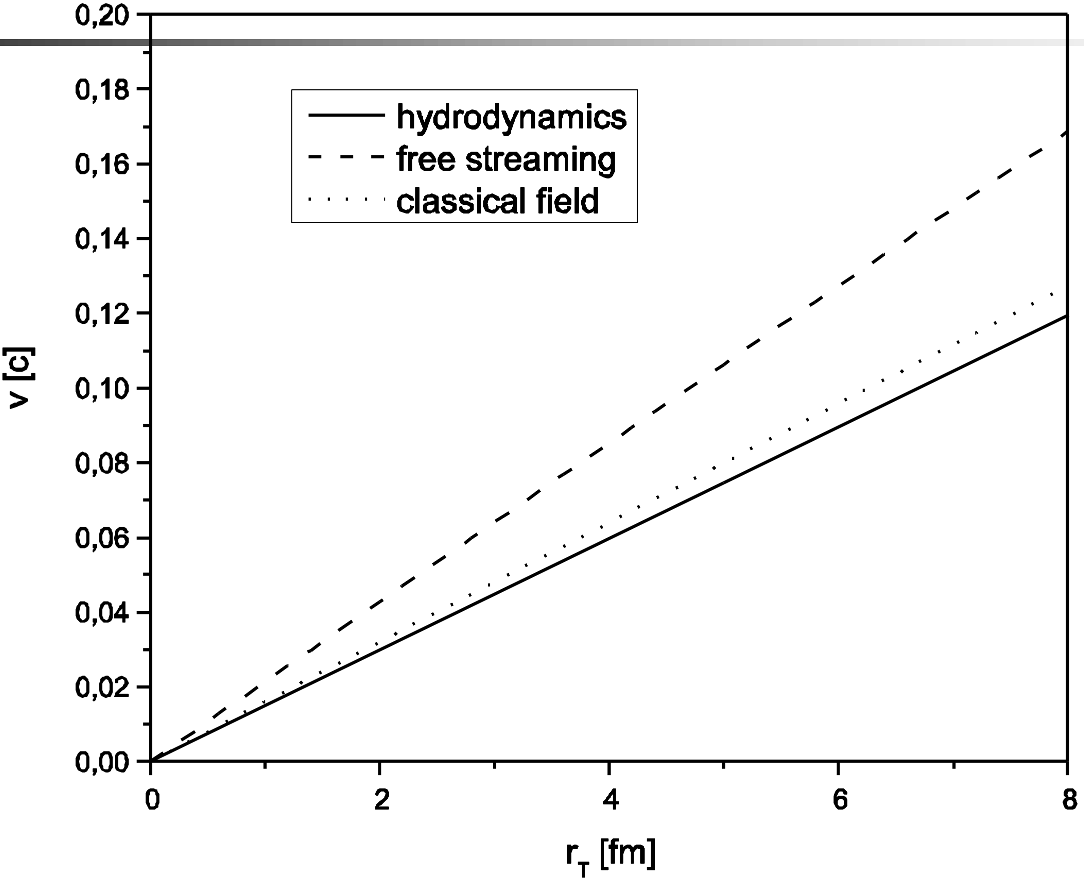
- The afterburn UrQMD stage corrects well the particle number ratios approaching them to experimental values at RHIC and LHC energies.

- It seems that the observables, especially the femtoscopy data, prefer the MC Glauber initial conditions comparing to MC KLN one.

THANK YOU !

- BACK UP SLIDES

# Collective velocities developed between $\tau_0$ =0.3 and $\tau$ =1.0 fm/c

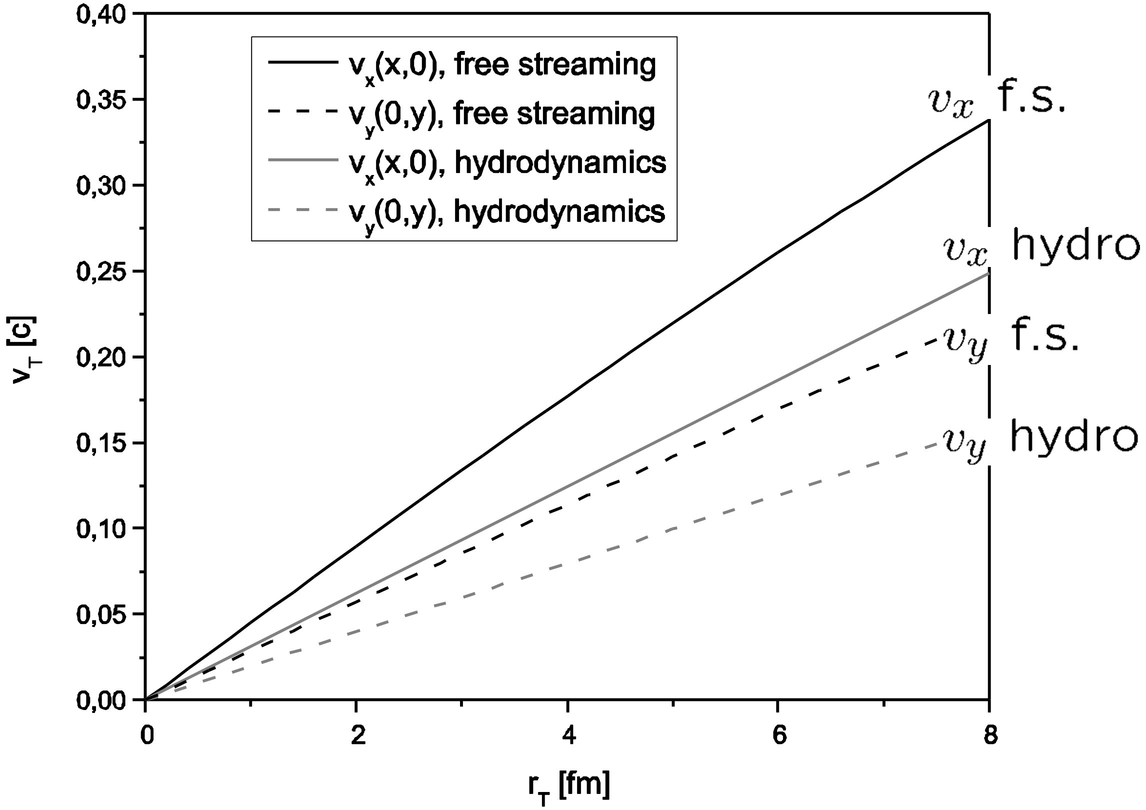


**Central collisions**

**Collective velocity developed at pre-thermal stage from proper time tau_0 =0.3 fm/c by supposed thermalization time tau_th = 1 fm/c for scenarios of partonic free streaming and free expansion of classical field. The results are compared with the hydrodynamic evolution of perfect fluid with hard equation of state p = 1/3 epsilon started at $\tau_0$ . Impact parameter b=0.**

Yu.S. Acta Phys.Polon. B37 (2006) 3343**;** Gyulassy, Yu.S., Karpenko, Nazarenko Braz.J.Phys. 37 (2007) 1031. Yu.S., Nazarenko, Karpenko: Acta Phys.Polon. B40 1109 (2009) .

# Collective velocities and their anisotropy developed between $\tau_0$=0.3 and $\tau$=1.0 fm/c



**Non-central collisions**
**b=6.3 fm**

**Collective velocity developed at pre-thermal stage from proper time $\tau_0$=0.3 fm/c by supposed thermalization time tau_i = 1 fm/c for scenarios of partonic free streaming. The results are compared with the hydrodynamic evolution of perfect fluid with hard equation of state p = ε/3 started at $\tau_0$ . To reach the same flow in hydro scenario one needs EoS p=0.45 ε. The anisotropy of flows**

$$y_T \propto rt/R^2(\phi)$$

# Back to initial conditions for hydro

Initial conditions at $\tau_0$ "Effective" initial distribution, bringing average hydro results for EbE case.

- Glauber model
  $\varepsilon(\mathbf{b},\mathbf{r}_\mathrm{T}) = \varepsilon_0 \frac{\rho(\mathbf{b},\mathbf{r}_\mathrm{T})}{\rho_0}$ (like we did before) or $s(\mathbf{b},\mathbf{r}_\mathrm{T}) = \mathbf{s}_0 \frac{\rho(\mathbf{b},\mathbf{r}_\mathrm{T})}{\rho_0}$ (like in VISHNU)

  $$\rho(\mathbf{b},\mathbf{r}_\mathrm{T}) = T(\mathbf{r}_\mathrm{T} - \mathbf{b}/2)S(\mathbf{r}_\mathrm{T} + \mathbf{b}/2) + T(\mathbf{r}_\mathrm{T} + \mathbf{b}/2)S(\mathbf{r}_\mathrm{T} - \mathbf{b}/2)$$

  Centrality = cuts on impact parameter **b**.

- MC-Glauber model, GLISSANDO
  Monte-Carlo procedure: nucleons in nuclei are distributed randomly, according to the nuclear density profile.
  $\rho(r_T) =$ distribution of wounded nucleons, averaged over many MC events.
  - fixed-axes determined by the reaction plane
  - variable-axes analysis, accounting for EbE fluctuation of center of mass and the direction of the principal axes of the distribution.

  Centrality = cuts on $N_\mathrm{part}$

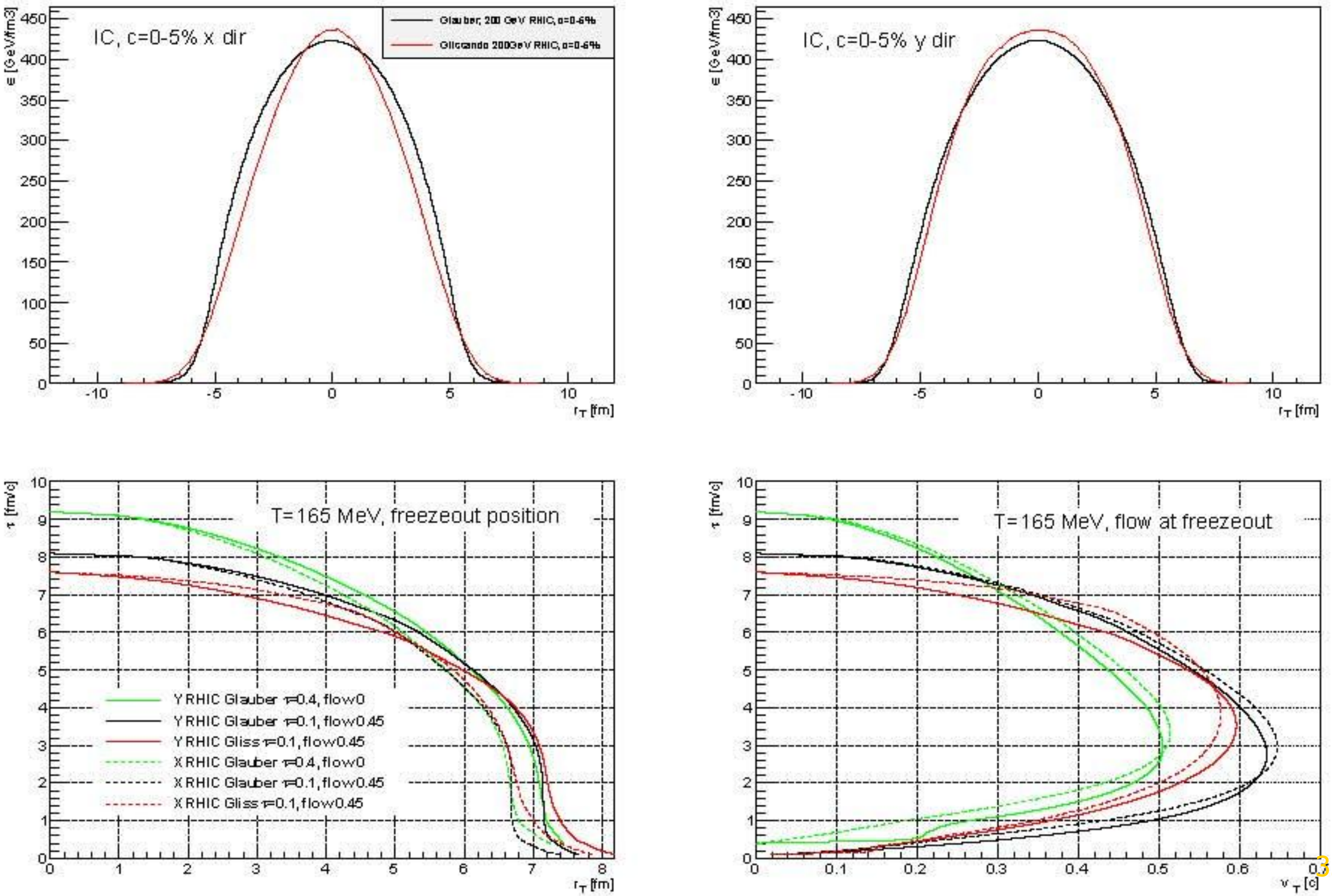
  | c [%] | 0-5 | 5-10 | 10-20 | 20-30 | 30-40 | ... |
  |---|---|---|---|---|---|---|
  | $N_\mathrm{part}$ | >324 | 324-273 | 273-191 | 191-131 | 131-89 | ... |

  for MC-Glauber case, initial energy density/entropy is composed from "soft+hard parts": $s(r_T)/s_0 \propto (1-\alpha)\rho(r_T) + \alpha_\mathrm{bin}\rho_\mathrm{bin}(r_T)$, where $\rho_\mathrm{bin}(r_T)$ is the density of binary scatterings and $\alpha_\mathrm{bin} = 0.14$ is fixed for top RHIC energy from $dN_{ch}/d\eta$(centrality) fit by PHOBOS collaboration.

- MC-KLN model, via `mckln-3.43` code
  H. J. Drescher and Y. Nara, Phys. Rev. C 75, 034905 (2007).

# Different initial shapes ⇒ different chemical freeze-outs

Both Glauber⇒MC-Glauber and $\alpha_{\text{bin}}$ “squeeze” energy density profile



# Emission functions for top SPS, RHIC and LHC energies