Recent results from hHKM model: radial, elliptic flows and HBT at RHIC and LHC

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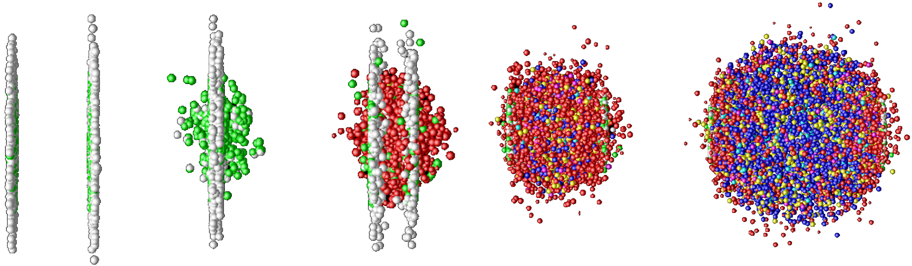
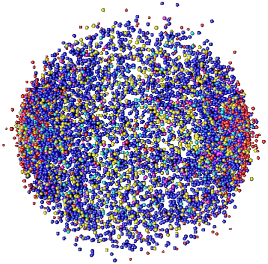
Introduction: heavy ion collision in pictures[1]



- Initial state, hard scatterings
- Thermalization
- Hydrodynamic expansion
  - Quark-gluon plasma
  - Phase transition
  - Hadron Gas
  - Chemical freeze-out
- Kinetic stage
- (kinetic) freeze-out

Typical size
10 fm $\propto 10^{-14}$m

Typical lifetime
10 fm/c $\propto 10^{-23}$s



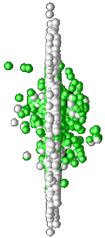
[1] taken from event generator

Hybrid Hydro-Kinetic Model

Ingredients:

- Initial conditions
  - Glauber model
  - MC-Glauber via `GLISSANDO` code by W. Broniowski, M. Rybczynski, P. Bozek
  - MC-KLN (CGC) via `mckln-3.43` by Y. Nara
- Hydrodynamic solution
  - Equation of state for hydrodynamics
- Hydro-kinetic approach: deviations from local equlibrium at decaying stage
- Boltzmann cascade (UrQMD)

Thermally and chemically equilibrated stage



Initial conditions at τ_0 "Effective" initial distribution, bringing average hydrodynamic results for EbE case. Energy density profiles:

- Glauber model
  $\epsilon(\mathbf{b},\mathbf{r_T}) = \epsilon_\mathbf{0} \frac{\rho(\mathbf{b},\mathbf{r_T})}{\rho_\mathbf{0}}$ (like we did before) or $s(\mathbf{b},\mathbf{r_T}) = \mathbf{s_0} \frac{\rho(\mathbf{b},\mathbf{r_T})}{\rho_\mathbf{0}}$ (like in VISHNU)

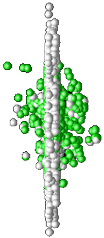
$$\rho(\mathbf{b},\mathbf{r_T}) = T(\mathbf{r_T}-\mathbf{b}/\mathbf{2})S(\mathbf{r_T}+\mathbf{b}/\mathbf{2}) + T(\mathbf{r_T}+\mathbf{b}/\mathbf{2})S(\mathbf{r_T}-\mathbf{b}/\mathbf{2})$$

  Centrality = average impact parameter $\bar{\mathbf{b}}$.
- MC-Glauber model, GLISSANDO
- MC-KLN model

Initial transverse rapidity profiles [2]: $y_T = \alpha \frac{r_T}{R_T^2}$, α[fm] (nonzero initial flow), $y_L = \eta$ (boost-inv.)
ϵ_0 /or s_0, α (and τ_0) are the fitting parameters in the model.

[2] Yu.M. Sinyukov, A.N. Nazarenko, Iu.A. Karpenko, Acta Phys.Polon.B40:1109-1118,2009

Thermally and chemically equilibrated stage



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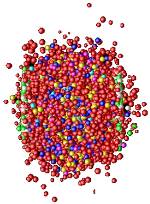


Hydrodynamic approach

ideal fluid:

$$\partial_\nu T^{\mu\nu} = 0 \qquad T^{\mu\nu} = (\varepsilon + p)u^\mu u^\nu - p \cdot g^{\mu\nu}$$

$$\partial_\mu (n_i \cdot u^\mu) = 0 \qquad \text{+equation of state } p = p(\varepsilon, \{n_i\})$$

$i = B, E, S$ in QGP phase and chemically equilibrated hadron phase

[2] Yu.M. Sinyukov, A.N. Nazarenko, Iu.A. Karpenko, Acta Phys.Polon.B40:1109-1118,2009

Hydrodynamics

- Bjorken(light-cone in z-direction) coordinates :

$$\tau = (t^2 - z^2)^{1/2}, \quad \eta = \frac{1}{2} \ln \frac{t+z}{t-z}$$

- Conservative variables:

$$\vec{Q} = \begin{pmatrix} Q_\tau \\ Q_x \\ Q_y \\ Q_\eta \\ \{Q_{n_i}\} \end{pmatrix} = \begin{pmatrix} \gamma^2(\varepsilon + p) - p \\ \gamma^2(\varepsilon + p)v_x \\ \gamma^2(\varepsilon + p)v_y \\ \gamma^2(\varepsilon + p)v_\eta \\ \{\gamma n_i\} \end{pmatrix}$$

- Velocity transformation:

$$\begin{aligned} v_x &= v_x^{lab} \cdot \frac{\cosh y_f}{\cosh(y_f - \eta)} \\ v_y &= v_y^{lab} \cdot \frac{\cosh y_f}{\cosh(y_f - \eta)} \\ v_\eta &= \tanh(y_f - \eta) \end{aligned} \qquad (1)$$

- Hydrodynamic equations:

$$\partial_\tau \underbrace{\begin{pmatrix} Q_\tau \\ Q_x \\ Q_y \\ Q_\eta \\ \{Q_{n_i}\} \end{pmatrix}}_{\text{quantities}} + \underbrace{\vec{\nabla} \cdot \begin{pmatrix} Q_\tau \\ Q_x \\ Q_y \\ Q_\eta \\ \{Q_{n_i}\} \end{pmatrix} \vec{v} + \begin{pmatrix} \vec{\nabla}(p \cdot \vec{v}) \\ \partial_x p \\ \partial_y p \\ \frac{1}{\tau}\partial_\eta p \\ 0 \end{pmatrix}}_{\text{fluxes}} + \underbrace{\begin{pmatrix} (Q_\tau + p)(1 + v_\eta^2)/\tau \\ Q_x/\tau \\ Q_y/\tau \\ 2Q_\eta/\tau \\ \{Q_{n_i}/\tau\} \end{pmatrix}}_{\text{sources}} = 0$$

where $\vec{\nabla} = \left(\partial_x, \ \partial_y, \ \frac{1}{\tau}\partial_\eta\right)$

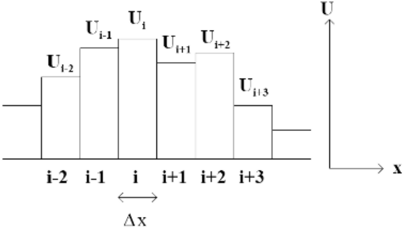
Hydrodynamics: basic method

For central A+A collisions and midrapidity: suppose longitudinal boost-ivariance and axial symmetry in transverse plane. Thus, $Q_\phi = Q_\eta = 0$, and flows $F_\phi = F_\eta = 0$.

$$\partial_\tau \underbrace{\begin{pmatrix} Q_\tau \\ Q_r \\ \{Q_{n_i}\} \end{pmatrix}}_{\text{quantities}} + \partial_r \cdot \underbrace{\begin{pmatrix} (Q_\tau + p)v_r \\ Q_r v_r + p \\ \{Q_{n_i} v_r\} \end{pmatrix}}_{\text{fluxes}} + \underbrace{\begin{pmatrix} (Q_\tau + p)(1+v_\eta^2)/\tau - (Q_\tau + p)v_r/r \\ Q_r/\tau - Q_r v_r/r \\ \{Q_{n_i}/\tau - Q_{n_i} v_r/r\} \end{pmatrix}}_{\text{sources}} = 0 \qquad (2)$$

Finite volume method:

- Divide the space into cells, Q_i in the average value of quantity inside cell



- The numerical equations:

$$Q_{ijk}^{n+1} = Q_{ijk}^n - \frac{\Delta t}{\Delta x_1}(F_{i+1/2,jk} + F_{i-1/2,jk}) - \frac{\Delta t}{\Delta x_2}(F_{i,j+1/2,k} + F_{i,j-1/2,k}) - \frac{\Delta t}{\Delta x_3}(F_{ij,k+1/2} + F_{ij,k-1/2})$$

F - time-averaged flow through the cell interface.

Hydrodynamics: numerical algorithm

- Godunov method: Flow through the cell interface depends only on the Riemann problem solution for this interface (+CFL condition)
- We use rHLLE solver for Riemann problem
- *predictor-corrector* scheme is used for the second order of accuracy in time, i.e. the numerical error is $O(dt^3)$, instead of $O(dt^2)$
- in space : in the same way, to achieve the second order scheme the *linear distributions* of quantities (conservative variables) inside cells are used.
- *Multi-dimension problem*: we use the metod, similar to operator(dimensional) splitting, but symmetric in all dimensions.
- *Grid boudaries*: we use the method of *ghost cells*, outflow boundary.
- *Vacuum treatment*: since initial grid covers both system and surrunding vacuum, we account for finite velocity of expansion into vacuum.

Equation of state

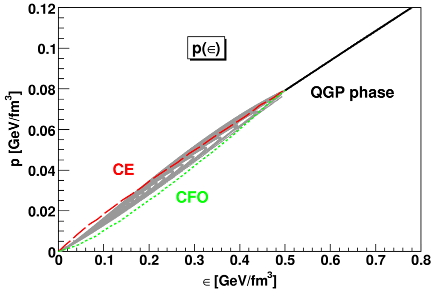
Equation of state, QGP, $T > T_c$ Realistic equation of state[3], consistent with lattice QCD results with crossover-type phase transition at $T_c = 175$ MeV, transforming into multicomponent hadron gas at $T = T_c$ ($\mu_B = 0$).

To account for chagre conservation in QGP phase → corrections for nonzero μ_B, μ_S [4]:

$$\frac{p(T,\mu_B,\mu_S)}{T^4} = \frac{p(T,0,0)}{T^4} + \frac{1}{2}\frac{\chi_B}{T^2}\left(\frac{\mu_B}{T}\right)^2 + \frac{1}{2}\frac{\chi_S}{T^2}\left(\frac{\mu_S}{T}\right)^2 + \frac{\chi_{BS}}{T^2}\frac{\mu_B}{T}\frac{\mu_S}{T} \quad (3)$$

Expansion coefficients χ_B, χ_S are baryon and strangs susceptibilies.

$$\frac{\mu_\alpha}{T} = const_\alpha, \quad \alpha = B, Q, S$$



Chemical freeze-out at $T_{ch} = 165 MeV$, (for top RHIC energy), with $\mu_B = 29 MeV$, $\mu_S = 7 MeV$, $\mu_Q = -1 MeV$ and $\gamma_S = 0.935$ suppression factor, dictated by particle number ratios analysis at 200A GeV RHIC.

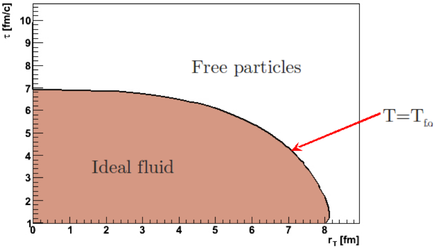
Hadron gas at $T < T_{ch}$. N=359 particle number densities are introduced, corresponding to each sort of hadrons. Equation of state $p = p(\varepsilon, \{n_i\})$. Yields from resonance decays are effectively included (massive resonance approximation):

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

Grey points: differen chemical compositions during hydro evolution

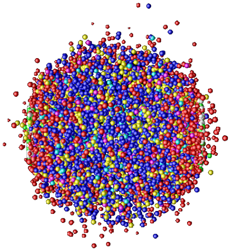
[3] M. Laine, Y. Schroder Phys. Rev. D73 (2006) 085009.

Final stage of evolution



Connecting hydrodynamic and kinetic(final) stage: Cooper-Frye prescription

Problems on non-space-like sectors of switching hypersurface...



Final stage (weakly interacting system)

- UrQMD (afterburner)
  C. Nonaka, S.A. Bass
- JAM (afterburner)
  T. Hirano, M. Gyulassy
- THERMINATOR
  W. Florkowski, W. Broniowski, M. Chojnacki, A. Kisiel
- FASTMC
  N.S. Amelin, R. Lednicky, T.A. Pocheptsov, I.P. Lokhtin, L.V. Malinina, A.M. Snigirev, Iu.A. Karpenko, Yu.M. Sinyukov

Hydro-kinetic approach

Goal: to connect hydrodynamic and final stages in a more natural way (not Cooper-Frye prescription), and account for the deviations from local equilibrium at hydrodynamic stage (remember viscosity?).

- is based on relaxation time approximation for emission function of relativistic finite expanding system
- provides evaluation of escape probabilities and deviations of distribution functions from local equilibrium
  Zero approximation is ideal hydro.

Complete algorithm:

- 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 / **input to UrQMD**

Yu.M. Sinyukov, S.V. Akkelin, Y. Hama, Phys.Rev.Lett.89:052301,2002
S.V. Akkelin, Y. Hama, Iu.A. Karpenko, Yu.M. Sinyukov, Phys.Rev.C78:034906, 2008

Hydrokinetic approach to particle emission

Particle liberation from hydrodynamically expanding system is described by the approximate method inspired by the integral form of Boltzmann equation [5]:

$$f_i(t,\vec{x},p) = f_i(\bar{x}_{t\to t_0},p)\mathscr{P}_{t_0\to t}(\bar{x}_{t\to t_0},p) + \int_{t_0}^{t} \underbrace{G_i((\bar{x}_{t\to s},p))\mathscr{P}_{s\to t}(\bar{x}_{t\to s},p)}_{S(\bar{x}_{t\to s},p)} ds, \qquad \bar{x}_{t\to s} = (s, \vec{x} + \frac{\vec{p}}{p^0}(s-t))$$

where $\frac{p^\mu}{p^0}\frac{\partial f_i(x,p)}{\partial x^\mu} = G_i(x,p) - L_i(x,p)$, $L_i(x,p) = R_i(x,p) f_i(x,p)$ and $\mathscr{P}_{t\to t'}(x,p) = \exp\left(-\int_t^{t'} d\bar{t} R_i(\bar{x}_t,p)\right)$

Relaxation time approximation for collision terms (if i=stable particle):

$$R_i(x,p) \approx R_i^{l.eq.}(x,p) = \text{collision rate}, \quad \text{and} \quad G_i \approx R_i^{l.eq.}(x,p) f_i^{l.eq.}(x,p) + G_i^{\text{decay}}(x,p)$$

$$\Downarrow$$

$$\frac{p^\mu}{p_0}\frac{\partial f_i(x,p)}{\partial x^\mu} = -\frac{f_i(x,p) - f_i^{\text{l.eq.}}(x,p)}{\tau_{\text{rel}}(x,p)} + G_i^{\text{decay}}(x,p).$$

First approximation (ideal hydro!):

$$\partial_\nu T_i^{\nu\mu}[f_i^{\text{l eq}}] = 0, \quad \partial_\nu n^\nu [f_i^{\text{l eq}}] = 0$$

The "relaxation time" $\tau_{rel} = 1/R_i^{l.eq.}$ grows with time!

For i-th coomponent of hadron gas, in Bjorken coordinates:

Emission function

$$S_i(\lambda,\theta,r_T,p) = \left[f_i^{l.eq.}(\lambda,\theta,r_T,p)\tilde{R}_i(\lambda,\theta,r_T,p) + \tilde{G}_i^{decay}(\lambda,\theta,r_T,p)\right] \exp\left(-\int_\lambda^\infty \tilde{R}_i(s,\theta^{(s)}(\lambda), r_T^{(s)}(\lambda),p)ds\right)$$

[5] for the details, see Yu.M. Sinyukov, S.V. Akkelin, Y. Hama, Phys.Rev.Lett.89:052301,2002

$$p_i^0 G_i^{decay}(x,p_i) = \sum_j \sum_k \int \frac{d^3p_j}{p_j^0} \int \frac{d^3p_k}{p_k^0} \Gamma_{j\to ik} f_j(x,p_j) \frac{m_j}{F_{j\to ik}} \delta^{(4)}(p_j - p_k - p_i)$$

Collision rate (inverse relaxation time) for i-th sort of hadrons:

$$\frac{1}{\tau_{i,\mathrm{rel}}^{\mathrm{id}*}(x,p)} = R_i^{\mathrm{id}}(x,p) = \int \frac{d^3k}{(2\pi)^3} \exp\left(-\frac{E_k - \mu_{id}(x)}{T_{id}(x)}\right) \sigma_i(s) \frac{\sqrt{s(s-4m^2)}}{2E_pE_k}.$$

where $E_p = \sqrt{\mathbf{p}^2 + m^2}$, $E_k = \sqrt{\mathbf{k}^2 + m^2}$, $s = (p+k)^2$ is squared pair energy in CMS, $\sigma(s)$ - cross-section, calculated in a way similar to URQMD. Observable quantity: particle spectrum,

$$\frac{d^3N_i}{d^3p} = n_i(p) = \int\limits_{t\to\infty} d^3x\ f_i(t,x,p)$$

Kinetics: inverse relaxation time (collision rate)

collision rate (inverse relaxation time):

$$\frac{1}{\tau_{\rm rel}^{\rm id*}(x,p)} = R^{\rm id}(x,p) = \int \frac{d^3k}{(2\pi)^3} \exp\left(-\frac{E_k - \mu_{id}(x)}{T_{id}(x)}\right) \sigma(s) \frac{\sqrt{s(s-4m^2)}}{2E_pE_k}.$$

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- meson-meson, meson-baryon:

$$\sigma_{tot}^{MB}(\sqrt{s}) = \sum_{R=\Delta,N^*} \langle j_B, m_B, j_M, m_M \| J_R, M_R \rangle \frac{2S_R+1}{(2S_B+1)(2S_M+1)} \times \frac{\pi}{p_{cm}^2} \frac{\Gamma_{R\to MB}\Gamma_{tot}}{(M_R-\sqrt{s})^2+\Gamma_{tot}^2/4} ,$$

  +5 mbarn for elastic meson-meson scattering
- $p-p$, $p-n$, $p-\bar{p}$, etc. $\rightarrow \rightarrow$ tables
- other: additive quark model:

$$\sigma_{\rm total} = 40\left(\frac{2}{3}\right)^{m_1+m_2}\left(1-0.4\frac{s_1}{3-m_1}\right)\left(1-0.4\frac{s_2}{3-m_2}\right)[\rm mb] ,$$

  $m_i = 1(0)$ for meson (baryon), s_i - number of strange quarks in particle i.

Hybrid HKM = HKM + UrQMD

Goal: initial conditions for Boltzmann cascade (UrQMD) from hydro-kinetic approach.

- switching hypersurface (e.g. $\tau =$const)
- DFs from HKM:

$$f_i(\tau,\theta,\mathbf{r}_T,\mathbf{p}_T) = f_i^{l.eq.}(x^{(\tau_0)}(\tau),\mathbf{p}_T)\exp\left(-\int\limits_{\tau_0}^{\tau}\tilde{R}_i(x^{(s)}(\tau),\mathbf{p}_T)ds\right) + \int\limits_{\tau_0}^{\tau} d\lambda \left[f_i^{l.eq.}(x^{(\lambda)}(\tau),\mathbf{p}_T)\tilde{R}_i(...)\right.$$

$$\left.+\tilde{G}_i^{decay}(x^{(\lambda)}(\tau),\mathbf{p}_T) - L_i^{decay}(x^{(\lambda)}(\tau),\mathbf{p}_T)\right]\exp\left(-\int\limits_{\lambda}^{\tau}\tilde{R}_i(x^{(s)}(\tau),\mathbf{p}_T)ds\right)$$

$$p^0\frac{d^3N}{d^3p} = \int d\sigma_\mu p^\mu f(x,p) \qquad (4)$$

- average particle multiplicities $< N_i >$ and maximum value of (4) over phase-space
- in each event, particle multiplicities are Poisson-distributed with mean $< N_i >$
- particle and coordinate generation: acceptance-rejection method based on distribution (4)

Back to initial conditions for hydro

Initial conditions at τ_0 "Effective" initial distribution, bringing average hydro results for EbE case.

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  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_{part}

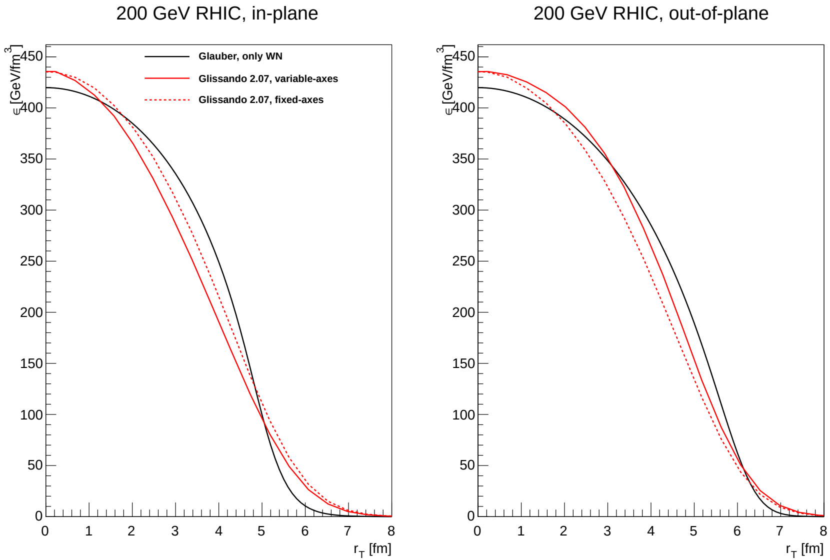
c [%]	0-5	5-10	10-20	20-30	30-40	...
N_{part}	>324	324-273	273-191	191-131	131-89	...

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

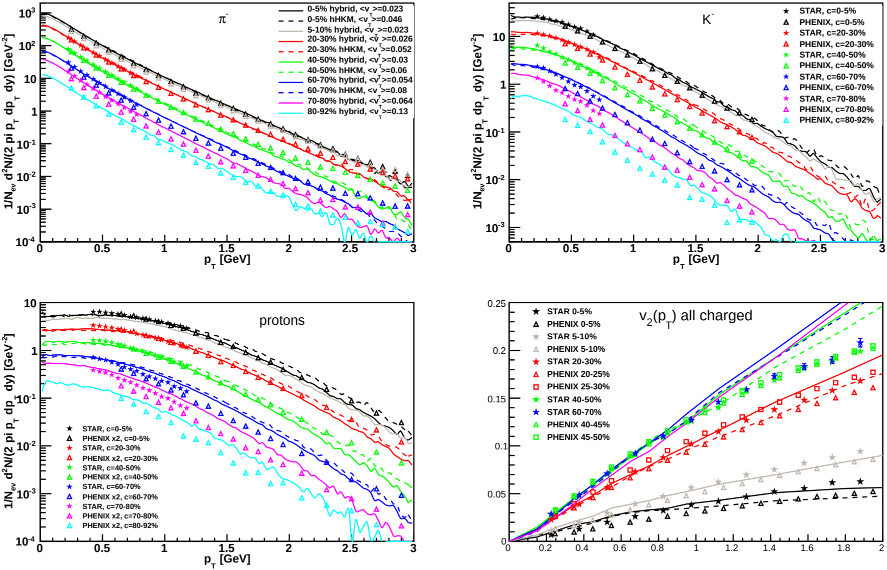
- MC-KLN model, via `mckln-3.43` code
  H. J. Drescher and Y. Nara, Phys. Rev. C 75, 034905 (2007).

Different initial shapes ⇒ different freeze-outs

Both Glauber⇒MC-Glauber and α_{bin} "squeeze" energy density profile



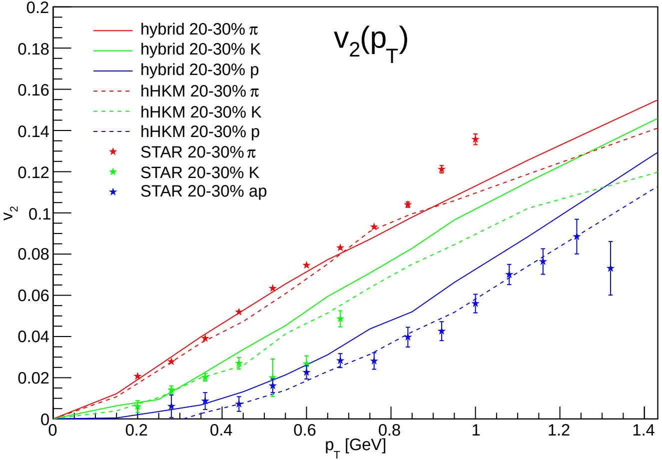
"Best choice": MC-Glauber IC, $\tau_0 = 0.1$fm/c, non-zero initial transverse flow



Different values of initial transverse flow are used for hybrid/hHKM (→ different viscosity corrections)

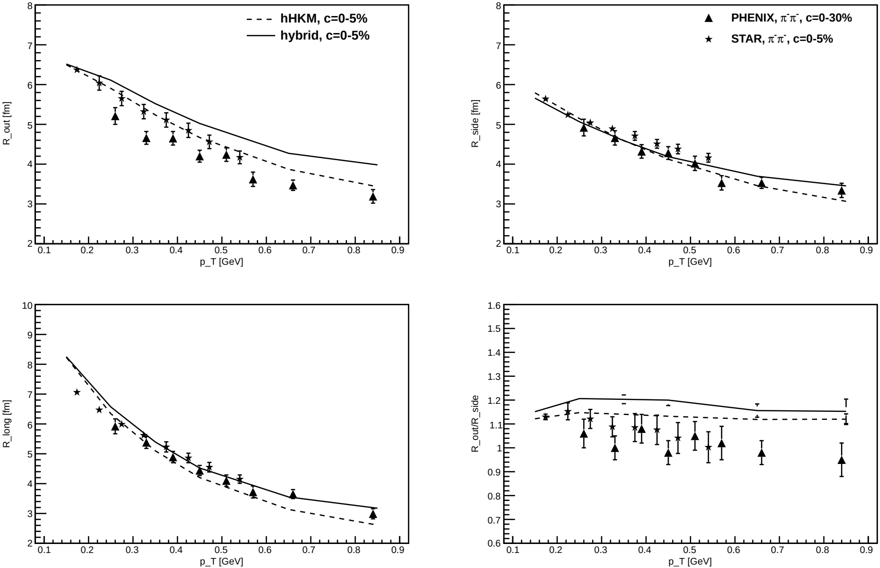
“Best choice”

v_2 for identified hadrons, STAR collaboration

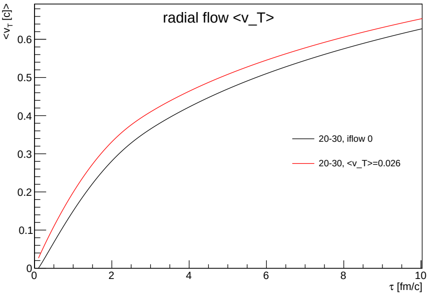


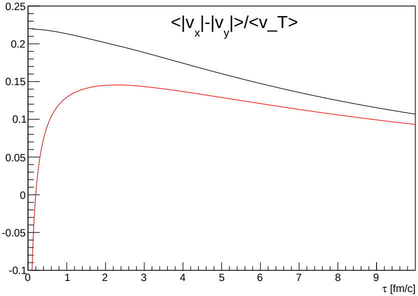
“Best choice”

femtoscopy

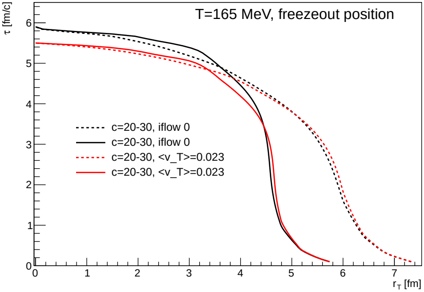


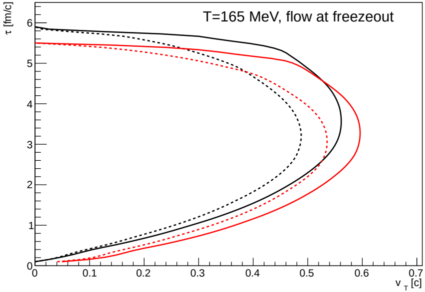
Initial transverse flow acts like viscous corrections,





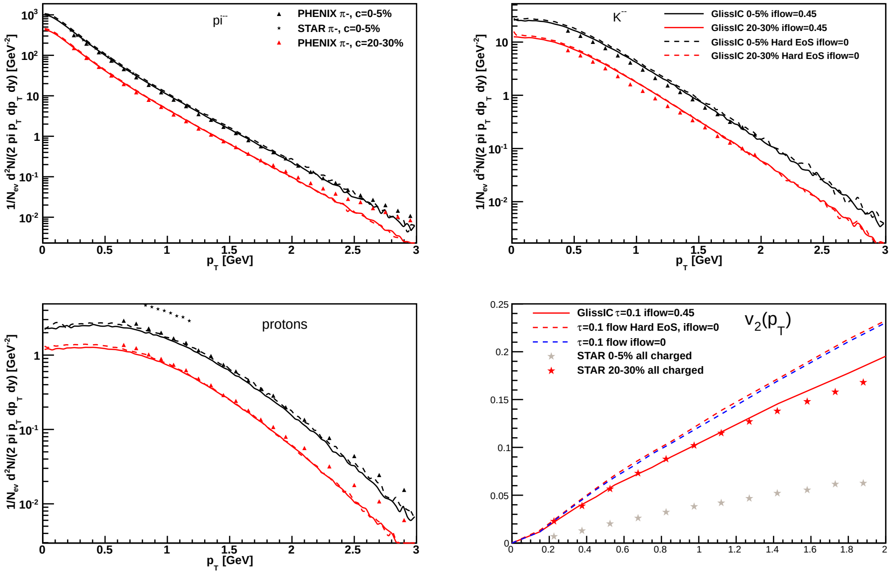
but not exactly like viscosity:





Role of initial transverse flow

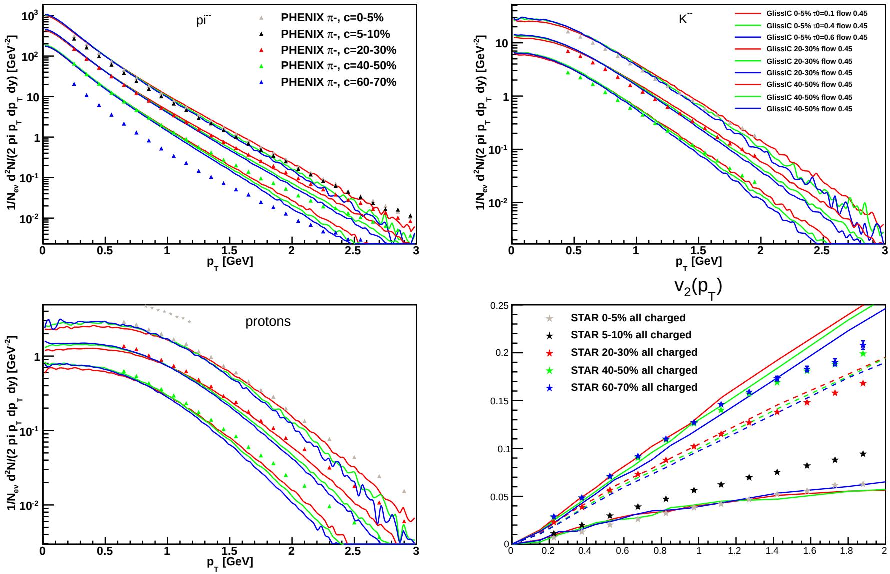
MC-Glauber ICs



initial transverse flow acts like viscous corrections!

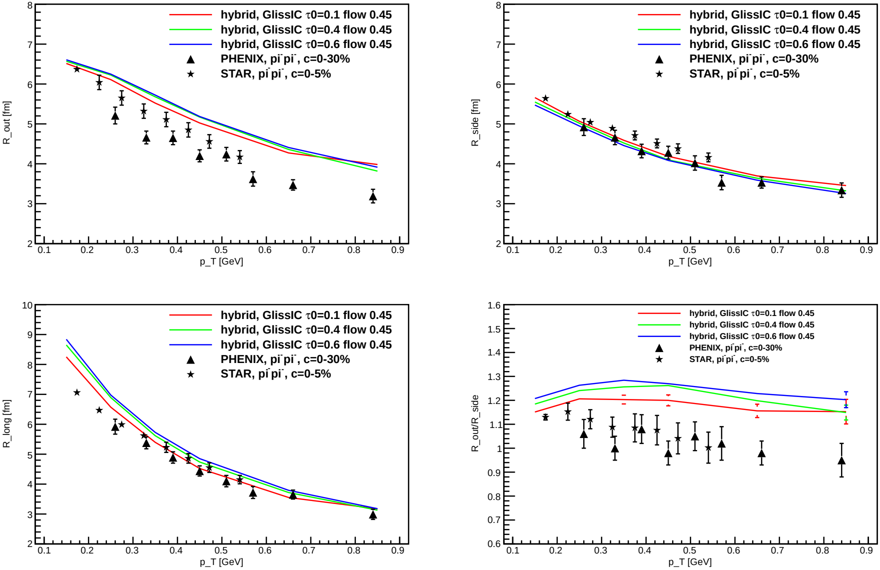
Role of “themalization” time, MC-Glauber ICs

Different choice: $\tau_0 = 0.1$ fm/c (red), 0.4 fm/c (green), 0.6 fm/c (blue); p_T-spectra and v_2 results

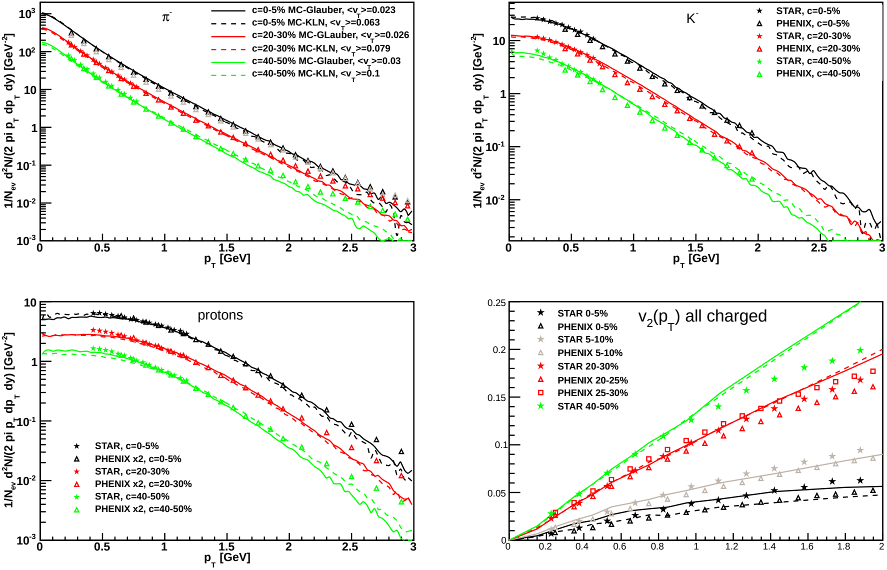


Role of “themalization” time, MC-Glauber ICs

Different choice: $\tau_0 = 0.1$ fm/c (red), 0.4 fm/c (green), 0.6 fm/c (blue)

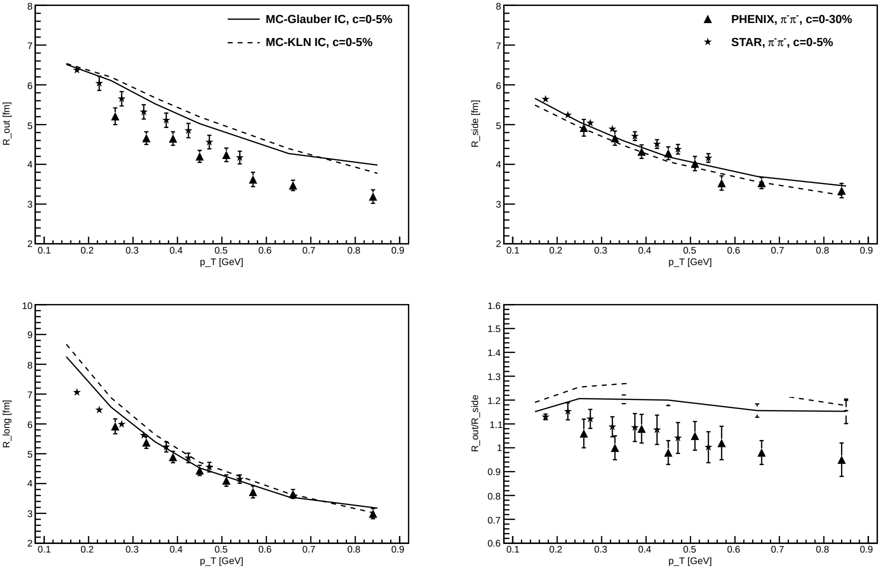


Role of IC model: MC-Glauber vs MC-KLN



MC-KLN initial conditions require “late” start of hydro ($\tau_0 = 0.6$fm/c) and bigger initial transverse flow (=bigger viscous correction)

Role of IC model: MC-Glauber vs MC-KLN



femtoscopy results favor MC-Glauber IC

Intermediate summary:
The “best choice” for top RHIC energy is hybrid HKM with:

- MC-Glauber IC for entropy density
- early start of hydrodynamics: $\tau_0 = 0.1$ fm/c
- small, but non-zero value initial transverse flow, reaching $v_T = 0.06$c at the periphery

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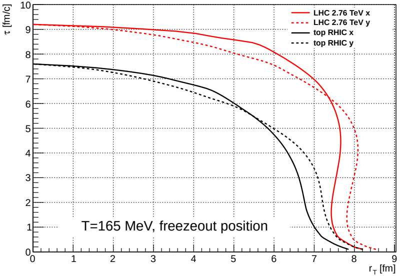
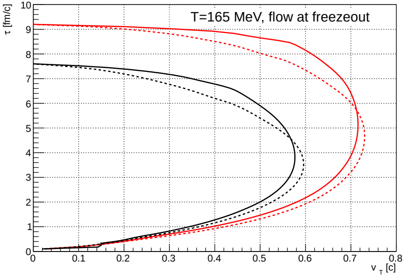
$\Downarrow$

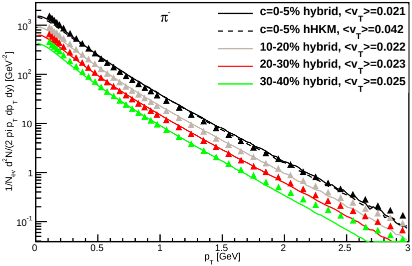
Moving to LHC energy: $\varepsilon_0 = 440$ GeV/fm^3 (top RHIC) $\rightarrow$ $\varepsilon_0 = 1170$ GeV/fm^3 (LHC 2.76 TeV)
(ε_0 is always fixed from final $dn_{ch}/d\eta$)

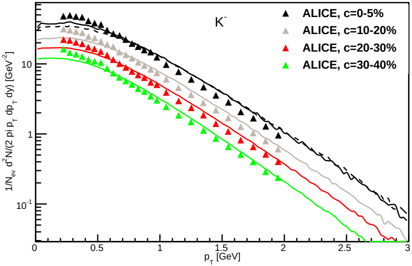


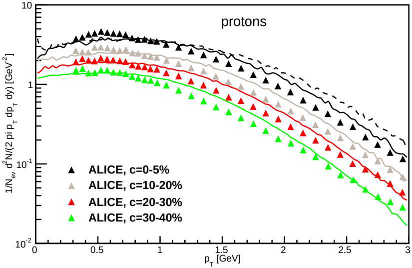


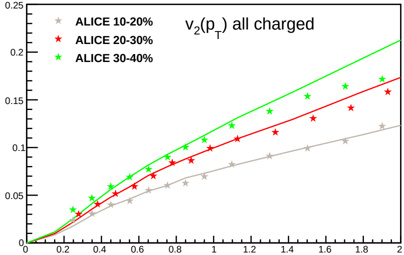
from RHIC to LHC

Identified hadron spectra: `arXiv:1111.7080`, Roberto Preghenella for the ALICE collaboration
Charged hadron v_2 from ALICE, `arXiv:1011.3914v2`





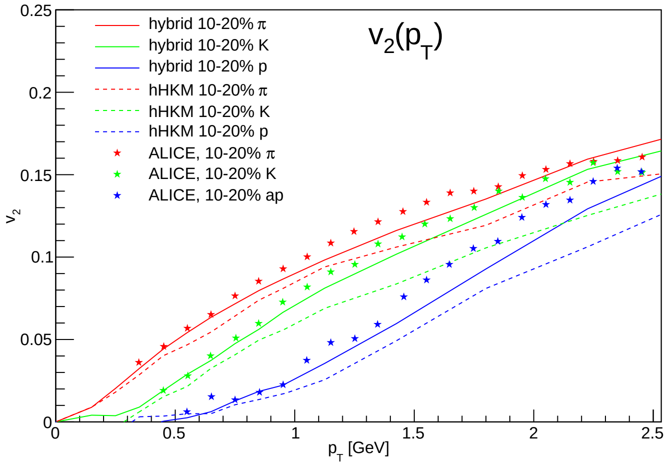




Elliptic flow at LHC

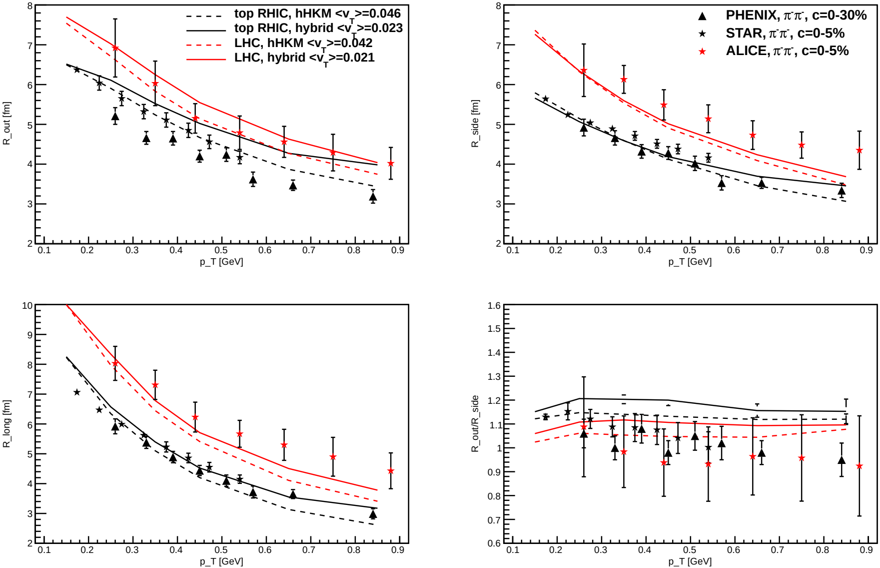
v_2 for identified hadrons, ALICE collaboration, 2.76 TeV PbPb

M. Krzewicki, QM2011 proceedings, `arXiv:1107.0080`



from RHIC to LHC

femtoscopy



Other applications of hHKM are in progress in Kiev group (Yu.Sinyukov, S.Akkelin, M.Borysova, Yu. Karpenko, V.Shapoval and post-graduate students):

- azimuthally sensitive femtoscopy for non-central collisions
- source imaging
- kaon femtoscopy
- non-identical particle correlations
- application to *pp* collisions
- ridge phenomenon

Model extensions planned:

- comparison with “raw” correlation functions (implemented with the help of FSI code by R. Lednicky)
- viscosity corrections in hydrodynamic algorithm
- matching procedure between pre-thermal and hydrodynamic stages

Conclusions

- The recent results of calculations in **hybrid hydro-kinetic approach**, where particle interactions at the latest stage of collision are treated with transport code (UrQMD) are presented.
- Monte-Carlo generators are used to generate initial conditions for hydro: Glissando code (W. Broniowski, M. Rybczynski and P. Bozek) for MC-Glauber model and MCKLN code (Y. Nara).
- Calculations for non-central collisions and simultaneous description of p_T-spectrum + v_2 + HBT radii with "uniform parameters" for all collision centralities impose more solid constraints on the initial conditions: early starting time τ_0 for hydro, and shape of energy/entropy density profile (MC-Glauber case with α_{bin} is favoured by interferometry data).
  Very early hydro starting time ($\neq$thermalization time) is consistent with the ideas of pre-thermal flow development[6].
- Non-zero initial transverse flow (magnitude proportional to transverse radius) suppresses the development of momentum anizotropy and, consequently, v_2. At the same time it increases radial transverse flows. This has similar influence on observables as viscous corrections for hydrodynamics.
- Results for femtoscopy radii at LHC energy are much improved compared to the previous results from pure hydro-kinetic model[7] due to UrQMD code which is essential for the late, highly nonequilibrium stage of matter expansion. Femtoscopic results indicate notable influence of the last, non-equilibrated stage of evolution to space-time scales at LHC energy.

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[6] Yu.M. Sinyukov, Acta Phys.Polon.B37:3343-3369,2006

[7] see backup slides

Thank you!