EARLY EVOLUTION OF TRANSVERSALLY THERMALIZED PARTONS

based on: A. Bialas, M.Ch., and W. Florkowski, arXiv:0708.1076 (nucl-th)

and M.Ch., and W. Florkowski, arXiv:0710.5871 (nucl-th)

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Motivation

contesting the hydrodynamical picture of heavy-ion collisions at RHIC

![Graph showing early evolution of partons over time](image)
Motivation

contesting the hydrodynamical picture of heavy-ion collisions at RHIC

- system created in heavy-ion collisions at RHIC energies is best described by hydrodynamics of an almost ideal fluid
- in particular, the particle transverse-momentum spectra and $v_2$ are very well reproduced by the hydrodynamic approach

Heinz, Huovinen, Kolb, Hirano, Shuryak, Teaney, Bass, Nonaka, Hama, Kodama, Ruuskanen, .......
Motivation
contesting the hydrodynamical picture of heavy-ion collisions at RHIC

- hydrodynamic evolution requires very early thermalization of the system, since the asymmetry of the transverse flow is produced most effectively at the very early stage of the evolution, to obtain $v_2$ consistent with data it is necessary to start the hydrodynamic evolution at the time below 1 fm after the collision takes place.
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- the system lives for a rather long time before freeze-out and the ratio $R_{out}/R_{side}$ disagrees with HBT measurements, HBT puzzle.
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- in this talk the possibility is explored that, at its early stages, the hydrodynamic evolution applies only to transverse degrees of freedom of the partonic system created in high-energy collisions,

the idea pioneered by Heinz and Wong, PRC 66 (2002) 014907
Outline

1. Ansatz for the phase-space distribution function
2. Moments of the phase-space distribution function
3. Transverse hydrodynamics
4. Initial conditions and Cooper-Frye prescription
5. Results
6. Conclusions
1. Ansatz for the phase-space distribution function

1.1. Longitudinal vs. transverse dynamics

the early equilibration, if at all possible, is particularly difficult to achieve in longitudinal direction elastic collisions do not change significantly the direction of the colliding partons and thus it requires very many interactions to produce a locally isotropic distribution from the initially strongly anisotropic one.

St. Mróczyński
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transverse momentum spectra observed in nucleon-nucleon collisions are well described by the Boltzmann distribution the partonic system produced in hadronic collisions emerges already in a state close enough to equilibrium in the transverse direction.

Hagedorn, ... , Heinz+Becattini, Bialas, Kharzeev, Florkowski, ...
1. Ansatz for the phase-space distribution function

1.2. Factorization of the distribution function

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

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

- $f_\parallel$ - non-equilibrium longitudinal part, describes essentially free-streaming

- $g_{eq}$ - equilibrium transverse part, describes 2D hydrodynamic expansion
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- Useful visualization in terms of discrete independent transverse layers (clusters)
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- useful visualization in terms of discrete independent transverse layers (clusters)

- with standard definitions of rapidity $y$ and spacetime rapidity $\eta$

$$E = m_\perp \cosh y, \quad p_\parallel = m_\perp \sinh y$$

$$t = \tau \cosh \eta, \quad z = \tau \sinh \eta$$

$$\tau = \sqrt{t^2 - z^2}, \quad m_\perp = \sqrt{m^2 + p_\perp^2}$$
1.3. Longitudinal part

Partons originate at the spacetime point $t, z = 0$ and reach the point $z$ after time $t$, $v_\parallel = \frac{z}{t} = \frac{p_\parallel}{E}$, to satisfy this condition and have the correct dimension we define the longitudinal part as

$$f_\parallel = n_0 \delta(p_\parallel t - E z) = n_0 \frac{\delta(y - \eta)}{\tau m_\perp}$$

Clearly, this assumption makes sense at the early stages of the evolution.
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Note: at midrapidity we have

\[ dzdp_\parallel = m_\perp \tau dyd\eta \]

In our case, the dimensionless parameter \( n_0 \)
determines the initial parton density in rapidity.
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1.4. Transverse part

g_{eq} has the form of the two-dimensional equilibrium distribution function convoluted with the transverse flow, for simplicity we use the Boltzmann statistics and neglect the chemical potential

\[
g_{eq} = \exp \left( - \frac{m_\perp u_0 - \vec{p}_\perp \cdot \vec{u}_\perp}{T} \right)
\]

the transverse flow \(u^\mu\) has the structure

\[
u^\mu = (u_0, u_x, u_y, 0) = (u_0, \vec{u}_\perp, 0)
\]

\[
u_0^2 - \vec{u}_\perp^2 = 1
\]

\(g_{eq}\) depends on the spacetime coordinates \(\tau, \eta, \vec{x}_\perp\) via temperature \(T\) and transverse flow \(u^\mu\)
2.1. Particle current and energy-momentum tensor

we define the particle current and energy-momentum tensor in the standard way, as the first and second moment of the distribution function

\[
N^\mu = n_0 \nu g \int \frac{dy \, d^2 p_\perp}{(2\pi)^2} p^\mu \frac{\delta(y - \eta)}{\tau m_\perp} g_{\text{eq}} = \frac{n_0 \nu g T^2}{2\pi \tau} U^\mu
\]

\[
T^{\mu\nu} = n_0 \nu g \int \frac{dy \, d^2 p_\perp}{(2\pi)^2} p^\mu p^\nu \frac{\delta(y - \eta)}{\tau m_\perp} g_{\text{eq}} = \frac{n_0 \nu g T^3}{2\pi \tau} (3 U^\mu U^\nu - g^{\mu\nu} - V^\mu V^\nu)
\]

for the \(p_\perp\) integration the appropriate 2D density of states is introduced \(\nu_g/(2\pi)^2\), for gluon dominated systems \(\nu_g = 16\)
2. Moments of the distribution function

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\[ T^{\mu\nu} = n_0 \nu_g \int \frac{dy \, d^2 p_\perp}{(2\pi)^2} p^\mu p^\nu \frac{\delta(y - \eta)}{m_\perp} g_{\text{eq}} = \frac{n_0 \nu_g T^3}{2\pi T} (3U^\mu U^\nu - g^{\mu\nu} - V^\mu V^\nu) \]

for the \( p_\perp \) integration the appropriate 2D density of states is introduced \( \nu_g/(2\pi)^2 \), for gluon dominated systems \( \nu_g = 16 \)

\[ U^\mu = (\cosh \eta \, u_0, \, u_x, \, u_y, \, \sinh \eta \, u_0) \]

\[ V^\mu = (\sinh \eta, \, 0, \, 0, \, \cosh \eta) \]

the presence of the four-vector \( V^\mu \) in the energy-momentum tensor is related with special role of the longitudinal direction
2. Moments of the distribution function

2.2. Entropy current

entropy current (based on the Boltzmann nonequilibrium definition)

\[ S^\mu = -n_0 \nu g \int \frac{d\eta d^2p_\perp}{(2\pi)^2} p^\mu \frac{\delta(y - \eta)}{\tau m_\perp} g_{\text{eq}} (\ln g_{\text{eq}} - 1) = \frac{3n_0 \nu g T^2}{2\pi \tau} U^\mu \]

explicit calculation shows \( U_\nu \partial_\mu T^{\mu\nu} = T \partial_\mu S^\mu \) – the energy-momentum conservation implies the entropy conservation, as in the standard 3D hydrodynamics
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\[ S^\mu = -n_0 \nu g \int \frac{dy \, d^2 p_\perp}{(2\pi)^2} \rho^\mu \frac{\delta(y - \eta)}{\tau m_\perp} g_{eq} (\ln g_{eq} - 1) = \frac{3n_0 \nu g T^2}{2\pi \tau} U^\mu \]

Explicit calculation shows \( U_\nu \partial_\mu T^{\mu \nu} = T \partial_\mu S^\mu \) – the energy-momentum conservation implies the entropy conservation, as in the standard 3D hydrodynamics.

Global conservation laws for entropy

\[
\int_0^\infty d\tau \int_0^{2\pi} d\phi \, T^2(\tau, r, \phi) u_0(\tau, r, \phi) = \text{const}
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for 3D boost-invariant case one finds

\[
\int_0^\infty d\tau \int_0^{2\pi} d\phi \, T^3(\tau, r, \phi) u_0(\tau, r, \phi) = \frac{\text{const}}{\tau}
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Entropy current (based on the Boltzmann nonequilibrium definition)

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For 2D hydro the initial thermal energy may decrease only at the expense of increasing transverse flow, for 3D boost-invariant hydro, even without the transverse expansion the temperature drops, as is well known from the famous Bjorken model.
2.3. Relation to 2D thermodynamic quantities

In the local rest frame, the densities of our 3D system are simply related to 2D thermodynamic variables:

\[ N^0 = \frac{n_0}{\tau} n_2(T), \quad T^{00} = \frac{n_0}{\tau} \varepsilon_2(T), \quad S^0 = \frac{n_0}{\tau} s_2(T) \]

The appropriate two-dimensional densities are defined by the equations following from the two-dimensional potential \( \Omega_2 \), they satisfy all required thermodynamic identities.

\[ n_2 = \nu g \int \frac{d^2 p}{(2\pi)^2} g_{eq} = \frac{\nu g T^2}{2\pi} \]

\[ \varepsilon_2 = \nu g \int \frac{d^2 p}{(2\pi)^2} \rho_\perp g_{eq} = \frac{\nu g T^3}{\pi} \]

\[ s_2 = -\nu g \int \frac{d^2 p}{(2\pi)^2} g_{eq} (\ln g_{eq} - 1) = \frac{3\nu g T^2}{2\pi} \]
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Thermodynamic relation \( \varepsilon_2 + P_2 = Ts_2 \) gives pressure and sound velocity:

\[ P_2 = \nu \frac{T^3}{2\pi} = n_2 T = \frac{\varepsilon_2}{2}, \quad c_s^2 = \frac{1}{2} \]
3. Transverse hydrodynamics

3.1. Derivation of hydrodynamic equations

The hydrodynamic equations are obtained from the energy and momentum conservation laws:

\[ \partial_\mu T^{\mu\nu} = 0, \quad T^{\mu\nu} = \frac{n_0 \nu g T^3}{2\pi \tau} (3U^{\mu} U^{\nu} - g^{\mu\nu} - V^{\mu} V^{\nu}) \]

The energy-momentum conservation laws are consistent with the entropy conservation law:

\[ U^\nu \partial_\mu T^{\mu\nu} = T \partial_\mu S^\mu = 0, \quad S^\mu = \frac{3n_0 \nu g T^2}{2\pi \tau} U^\mu \]

In the derivation of hydro equations the following 3 combinations are used:

\[ \partial_\mu S^\mu = 0 \]
\[ U_1 \partial_\mu T^{\mu 1} + U_2 \partial_\mu T^{\mu 2} = 0 \]
\[ U_2 \partial_\mu T^{\mu 1} - U_1 \partial_\mu T^{\mu 2} = 0 \]

As the result we obtain hydrodynamic equations for 2D perfect fluid.
3.2. Boost non-invariance

**Lemma** (one of many beatiful features of this approach)

If $T^\mu_\nu$ is conserved, then $T^\mu_\nu$ multiplied by any function of $\eta$ is also conserved

$$\partial_\mu T^\mu_\nu = 0 \Rightarrow \partial_\mu [f(\eta) T^\mu_\nu] = 0$$

in particular $n_0$ may be a rapidity dependent function
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→ hydro equations $\partial_\mu T^{\mu\nu} = 0$ do not specify the $\eta$-dependence, the hydrodynamic evolution is determined separately for each transverse layer, the $\eta$-dependence is determined by the initial conditions
4.1. Initial conditions

similarly to other hydrodynamic calculations we assume that the initial energy density at the transverse position point $\vec{x}_\perp$ is proportional to the wounded-nucleon density $\rho_{WN}$ at this point, namely

$$\varepsilon_2 (\vec{x}_\perp) = \frac{n_0 \nu g T^3 (\vec{x}_\perp)}{\pi} \propto \rho_{WN} (\vec{x}_\perp).$$

this assumption used for a 2D system is equivalent to the assumption $s_3 \propto \rho_{WN}$ used in 3D hydrodynamic codes,
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$$
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$$

this assumption used for a 2D system is equivalent to the assumption $s_3 \propto \rho_{WN}$ used in 3D hydrodynamic codes,

$$
T(\tau_{\text{init}}, \vec{x}_\perp) = T_i \left[ \frac{\rho_{WN} (\vec{x}_\perp)}{\rho_{WN} (0)} \right]^{1/3}
$$

where the parameter $T_i$ is the initial central temperature.
4.2. Cooper-Frye prescription

Transverse-momentum spectra are obtained with the standard Cooper-Frye prescription

\[
\frac{dN}{dyd^2p_\perp} = \frac{n_0\nu g}{(2\pi)^2} \int d\Sigma^\mu p_\mu \frac{\delta(\eta - y)}{\tau m_\perp} g_{\text{eq}}
\]
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\]

for cylindrically asymmetric collisions and midrapidity, \( y = 0 \), the transverse-momentum spectrum has the following expansion in the azimuthal angle of the emitted particles

\[
\frac{dN}{dy d^2 p_\perp} = \frac{dN}{dy 2\pi p_\perp dp_\perp} (1 + 2\nu_2(p_\perp) \cos(2\phi_p) + \ldots)
\]

this equation defines the elliptic flow coefficient \( \nu_2 \),
4. Initial conditions and Cooper-Frye formula

4.2. Cooper-Frye prescription

Transverse-momentum spectra are obtained with the standard Cooper-Frye prescription

\[
\frac{dN}{dy d^2 p_{\perp}} = \frac{n_0 v_g}{(2\pi)^2} \int d\Sigma^\mu p_\mu \frac{\delta(\eta - y)}{\tau m_{\perp}} g_{eq}
\]

for cylindrically asymmetric collisions and midrapidity, \( y = 0 \), the transverse-momentum spectrum has the following expansion in the azimuthal angle of the emitted particles

\[
\frac{dN}{dy d^2 p_{\perp}} = \frac{dN}{dy 2\pi p_{\perp} dp_{\perp}} (1 + 2v_2(p_{\perp}) \cos(2\phi_p) + \ldots)
\]

This equation defines the elliptic flow coefficient \( v_2 \), which may be calculated from the asymmetry of the momentum spectrum

\[
v_2(p_{\perp}) = \frac{1}{2} \frac{f_N(p_{\perp}, \phi_p = 0) - f_N(p_{\perp}, \phi_p = \frac{\pi}{2})}{f_N(p_{\perp}, \phi_p = 0) + f_N(p_{\perp}, \phi_p = \frac{\pi}{2})}
\]

with \( f_N \) being a shorthand notation for \( dN/(dyd^2p_{\perp}) \).
5. Results

5.1. Transverse-momentum spectra and $v_2$

- solid line: transverse-momentum spectra of positive pions ($\times 3$) measured by PHENIX, centrality class 30-40%, $\sqrt{s_{NN}} = 200$ GeV

- dashed and dotted lines: model calculations for $T_i = 250$ MeV and for four final temperatures $T_f = 200$, 180, 160, and 140 MeV.
5.1. Transverse-momentum spectra and $v_2$

- Solid line: transverse-momentum spectra of positive pions ($\times 3$) measured by PHENIX, centrality class 30-40%, $\sqrt{s_{NN}} = 200$ GeV

- Dashed and dotted lines: model spectra of gluons for various choices of the initial and final temperature, $n_0 = 1$

- Solid line: $v_2(p_T)$ measured by PHENIX (data for pions and kaons), centrality class 20-40%, $\sqrt{s_{NN}} = 200$ GeV

- Dashed and dotted lines: model calculations for $T_i = 250$ MeV and for four final temperatures $T_f = 200, 180, 160$ and 140 MeV.
5. Results

5.2. Central vs. peripheral

\[ \pi^- + \pi^0 + \pi^+ \]

**PHENIX \( \sqrt{s_{NN}} = 200\) GeV

c = 0–5%

\[ \frac{dN}{(2\pi p_T dp_T dy)} \]

- \( c_s^2 = 1/2 \)
- \( b = 2.3\) fm
- \( \gamma_T = 16 \)
- \( r_0 = 1 \)
- \( T_f = 250\) MeV

\( T_f = 200\) MeV
\( T_f = 180\) MeV
\( T_f = 160\) MeV
\( T_f = 140\) MeV

\( \pi^+ + K^+ \)

**PHENIX \( \sqrt{s_{NN}} = 200\) GeV

c = 0–20%

\[ \frac{dN}{(2\pi p_T dp_T dy)} \]

- \( c_s^2 = 1/2 \)
- \( b = 4.59\) fm
- \( \gamma_T = 16 \)
- \( r_0 = 1 \)
- \( T_f = 250\) MeV

\( T_f = 200\) MeV
\( T_f = 180\) MeV
\( T_f = 160\) MeV
\( T_f = 140\) MeV

\( \pi^+ + K^+ \)

**PHENIX \( \sqrt{s_{NN}} = 200\) GeV

c = 40–60%

\[ \frac{dN}{(2\pi p_T dp_T dy)} \]

- \( c_s^2 = 1/2 \)
- \( b = 11.69\) fm
- \( \gamma_T = 16 \)
- \( r_0 = 1 \)
- \( T_f = 250\) MeV

\( T_f = 200\) MeV
\( T_f = 180\) MeV
\( T_f = 160\) MeV
\( T_f = 140\) MeV
5. Results

5.3. Freeze-out with THERMINATOR


the two-dimensional gluon system is replaced by the two-dimensional hadron gas,
hadronic resonances decay

\[ \text{2D transversally thermalized system} \]
\[ \text{constant sound velocity, } c_{s}^{2} = 1/2 \]
\[ \text{centrality class 20–30\%} \]
\[ b = 7.24815 \text{ fm} \]
\[ T_{i} = 300 \text{ MeV} \]
\[ T_{f} = 165 \text{ MeV} \]
\[ n_{0} = 2.5 \]

\[ \text{points: THERMINATOR (10000 events)} \]
\[ \text{lines: PHENIX at } \sqrt{s_{NN}} = 200 \text{ GeV, centrality class 20–30\%} \]
5. Results

5.4. HBT two-particle method

Red line: THERMINATOR (10000 events)
Black line: STAR $\sqrt{s_{NN}}=200$ GeV, centrality class 20–30%

2D tranversally thermalized system
constant sound velocity, $c_{s}^2=1/2$
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Further work on smooth merging of the 2D gluon system and the 2D hadron system should be done (modeling 2D phase transition)

Mikołaj Chojnacki
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HBT two-particle method

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6. Conclusions

1. The idea that the parton system created in relativistic heavy-ion collisions emerges in a state with transverse momenta close to thermodynamic equilibrium and its evolution at early times is dominated by the 2-dimensional (transverse) hydrodynamics is investigated and shown to be consistent with data (spectra and $v_2$).

2. This mechanism does not require early 3D equilibration, strong $v_2$ is produced in non-completely thermalized matter.

3. This mechanism may also help to solve the HBT puzzle, but this needs extra work.