

Interplay between hydrodynamics and jets

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Second conference on heavy ion collisions in the LHC era and beyond, Quy Nhon, July 2015

mainly based on

- Hydrodynamics and Jets in Dialogue [Eur. Phys. J. C 74, 3189 (2014), with K. C. Zapp]
- Interplay between hydrodynamics and jets [Nucl. Phys. A 931, 388 (2014), with K. C. Zapp]

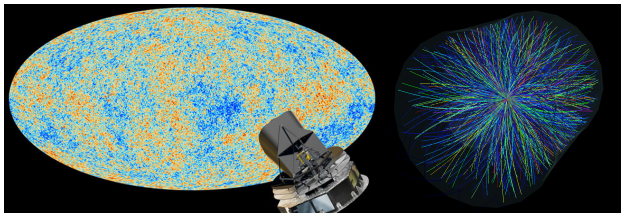
Evolution in time after heavy ion collision

- Non-equilibrium evolution at early times
 - initial state at from QCD? Color Glass Condensate? ...
 - thermalization via strong interactions, plasma instabilities, particle production, ...
- Local thermal and chemical equilibrium
 - strong interactions lead to short thermalization times
 - evolution from relativistic fluid dynamics
 - expansion, dilution, cool-down
 - jets propagate in fluid medium, loose energy & momentum
- Chemical freeze-out
 - for small temperatures one has mesons and baryons
 - inelastic collision rates become small
 - particle species do not change any more
- Thermal freeze-out
 - elastic collision rates become small
 - particles stop interacting
 - particle momenta do not change any more

Fluid dynamic regime

- Assumes strong interaction effects leading to local equilibrium.
- Fluid dynamic variables
 - thermodynamic variables: e.g. $\epsilon(x)$, $n(x)$,
 - fluid velocity $u^\mu(x)$,
 - shear stress tensor $\pi^{\mu\nu}(x)$,
 - bulk viscous pressure $\pi_{\text{Bulk}}(x)$.
- Can be formulated as derivative expansion for $T^{\mu\nu}$.
- Hydrodynamics is universal: many details of microscopic theory not important.
- Some macroscopic properties are important:
 - ideal hydro: needs equation of state $p = p(T, \mu)$ from thermodynamics
 - first order hydro: needs also transport coefficients like shear viscosity $\eta = \eta(T, \mu)$ and bulk viscosity $\zeta(T, \mu)$ from linear response theory
 - second order hydro: needs also relaxation times τ_{Shear} , τ_{Bulk} etc.

Similarities to cosmological fluctuation analysis



- fluctuation spectrum contains info from early times
- many numbers can be measured and compared to theory
- can lead to detailed understanding of evolution
- to learn something about the evolution one needs to know some *universal* properties of initial state, for example $P(k) \sim k^{n_s-1}$

What perturbations are interesting and why?

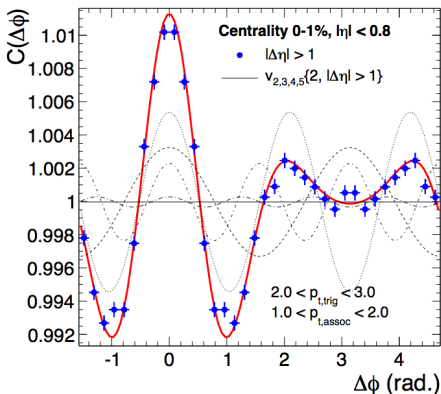
- **Initial fluid perturbations:** Event-by-event fluctuations around an average of fluid fields at time τ_0 and their evolution:
 - energy density ϵ
 - fluid velocity u^μ
 - shear stress $\pi^{\mu\nu}$
 - more general also: baryon number density n , electric charge density, electromagnetic fields, ...
- **Perturbations from non-thermalized particles**
- **Thermal fluctuations**
 - governed by universal evolution equations
 - can be used to constrain **thermodynamic and transport properties**
 - contain interesting information from early times

Two-particle correlation function

- normalized two-particle correlation function

$$C(\phi_1, \phi_2) = \frac{\langle \frac{dN}{d\phi_1} \frac{dN}{d\phi_2} \rangle_{\text{events}}}{\langle \frac{dN}{d\phi_1} \rangle_{\text{events}} \langle \frac{dN}{d\phi_2} \rangle_{\text{events}}} = 1 + 2 \sum_m v_m^2 \cos(m(\phi_1 - \phi_2))$$

- Interestingly v_2, v_3, v_4, v_5 and v_6 are all non-zero!



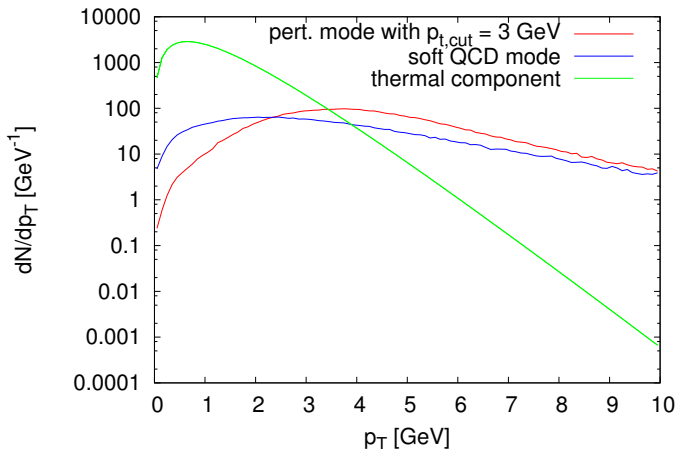
[ALICE 2011, similar results from CMS, ATLAS, Phenix, Star]

A program to understand fluid perturbations

- 1 Characterize initial perturbations
- 2 Propagated them through fluid dynamic regime
- 3 Determine influence on particle spectra and harmonic flow coefficients
- 4 Take also perturbations from non-hydro sources (jets) into account
[this talk]

Distinction between jets and medium

- perturbative jet cross-section is IR divergent, set $p_{t,\text{cut}} = 3 \text{ GeV}$
- also regulated in PYTHIA soft QCD mode
- very soft jets are part of medium



Energy exchange between jets and medium

- total energy-momentum tensor is conserved

$$\partial_\mu (T_{\text{bulk}}^{\mu\nu} + T_{\text{hard}}^{\mu\nu}) = 0$$

- Energy-momentum tensor of bulk described by hydro

$$T_{\text{bulk}}^{\mu\nu} = \epsilon u^\mu u^\nu + (p + \pi_{\text{bulk}}) \Delta^{\mu\nu} + \pi^{\mu\nu}$$

with

$$\Delta^{\mu\nu} = g^{\mu\nu} + u^\mu u^\nu$$

- Source function for bulk evolution from energy-momentum loss of jets

$$J^\nu = -\partial_\mu T_{\text{hard}}^{\mu\nu} = \sum_i \Delta p_i^\nu \delta^{(4)}(x - x_i)$$

- Energy-momentum conservation equation becomes

$$\partial_\mu T_{\text{bulk}}^{\mu\nu} = J^\nu$$

Fluid equations with source terms

- Evolution of energy density

$$u^\mu \partial_\mu \epsilon + (\epsilon + p) \partial_\mu u^\mu + \pi^{\mu\nu} \partial_\mu u_\nu + \pi_{\text{bulk}} \partial_\mu u^\mu = -u_\nu J^\nu$$

describes how energy is dissipated to the fluid's internal energy.

- Second law of thermodynamics

$$\underbrace{-\pi^{\mu\nu} \partial_\mu u_\nu}_{\text{shear viscous dissipation}} \geq 0, \quad \underbrace{-\pi_{\text{bulk}} \partial_\mu u^\mu}_{\text{bulk viscous dissipation}} \geq 0, \quad \underbrace{-u_\nu J^\nu}_{\text{jet dissipation}} \geq 0.$$

- Evolution of fluid velocity

$$(\epsilon + p + \pi_{\text{bulk}}) u^\mu \partial_\mu u^\alpha + \Delta^{\alpha\beta} \partial_\beta (p + \pi_{\text{bulk}}) + \Delta^\alpha{}_\nu \partial_\mu \pi^{\mu\nu} = \Delta^\alpha{}_\nu J^\nu$$

describes how momentum is transferred to the fluid.

Statistical description

- For fluid description, only energy and momentum transfer J^μ important.
- Can be decomposed to scalar source $J_S = u_\mu J^\mu$ and vector source $J_V^\mu = \Delta^\mu_\nu J^\nu$
- Do *not* want to solve this event-by-event
- Event ensembles described by functional probability distribution

$$p[J_S, J_V]$$

- Equivalently, in terms of correlation functions

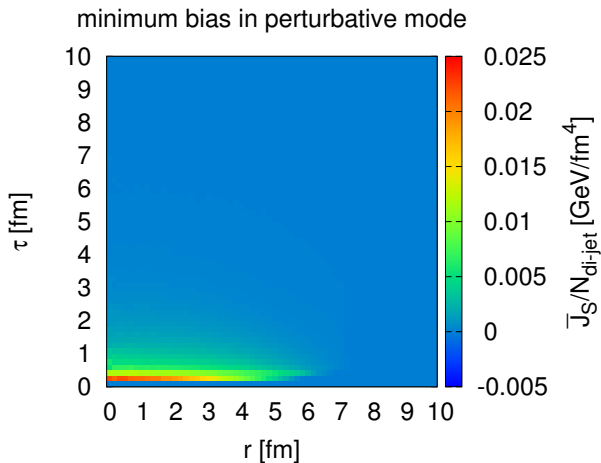
$$\langle J_S(x) \rangle, \quad \langle J_V^\mu(x) \rangle, \quad \langle J_S(x) J_S(y) \rangle, \quad \dots$$

- Concentrate first on expectation values or averages of sources

$$\bar{J}_S = \langle J_S(x) \rangle,$$

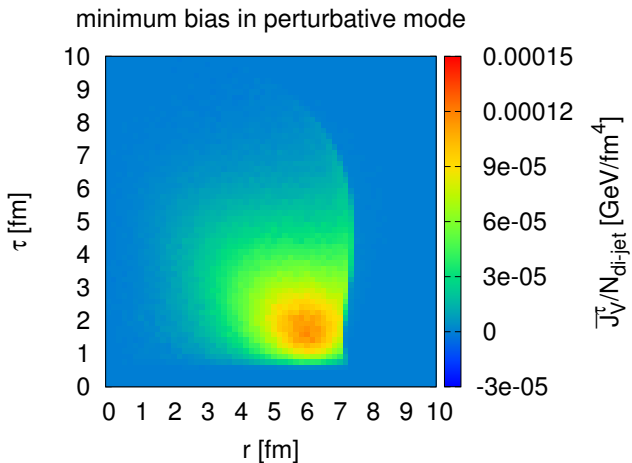
Energy and momentum source functions

scalar source $\bar{J}_S(\tau, r)$ from jet quenching Monte Carlo code JEWEL



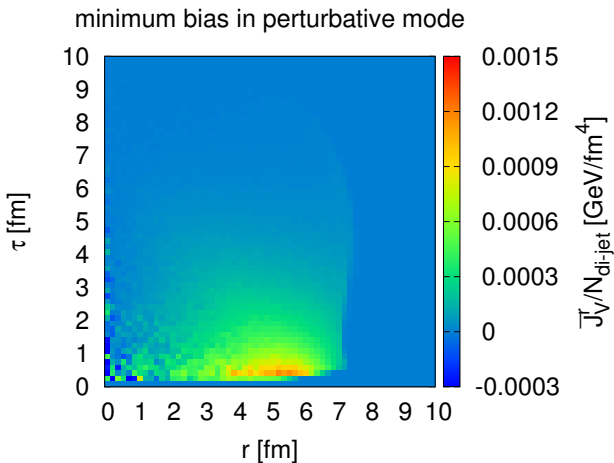
Energy and momentum source functions

vector source $\bar{J}_V^\tau(\tau, r)$ from jet quenching Monte Carlo code JEWEL

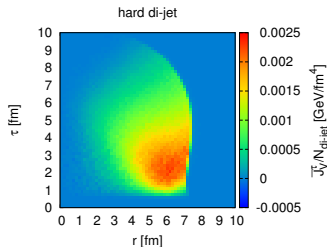
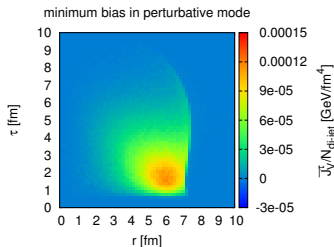
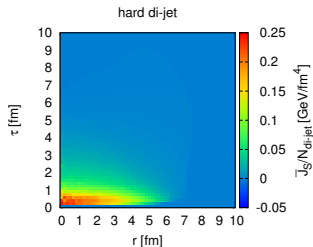
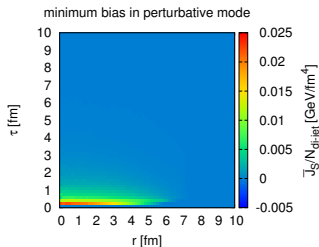


Energy and momentum source functions

vector source $\bar{J}_V^r(\tau, r)$ from jet quenching Monte Carlo code JEWEL



Minimum bias versus hard jet

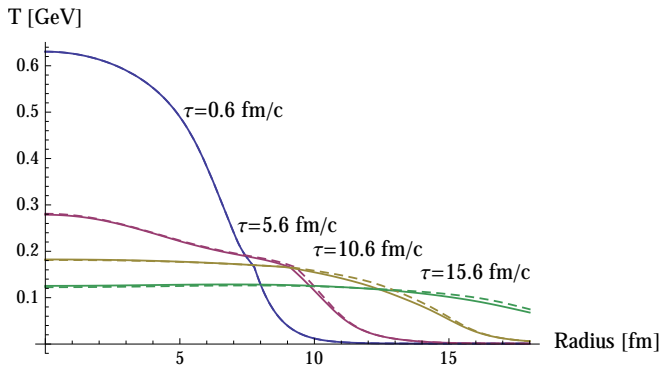


minimum bias: $p_{\perp} > 3$ GeV

hard jet: $p_{\perp} > 100$ GeV

Fluid evolution with averaged sources

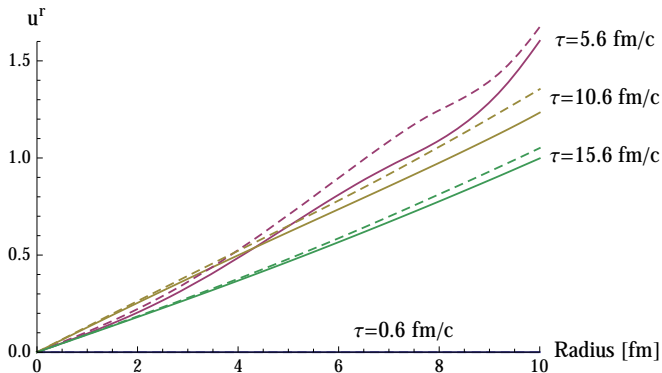
Temperature



- solid: without source terms
- dashed: with source terms
- main effect is slightly larger radial flow
- effect quantitatively rather small

Fluid evolution with averaged sources

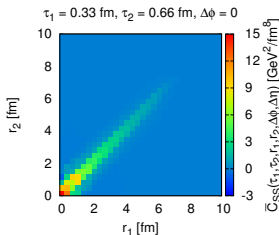
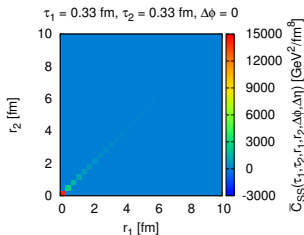
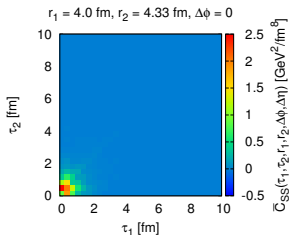
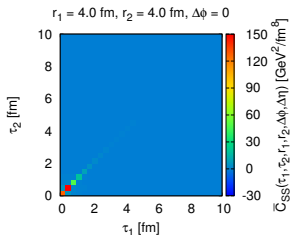
Fluid velocity



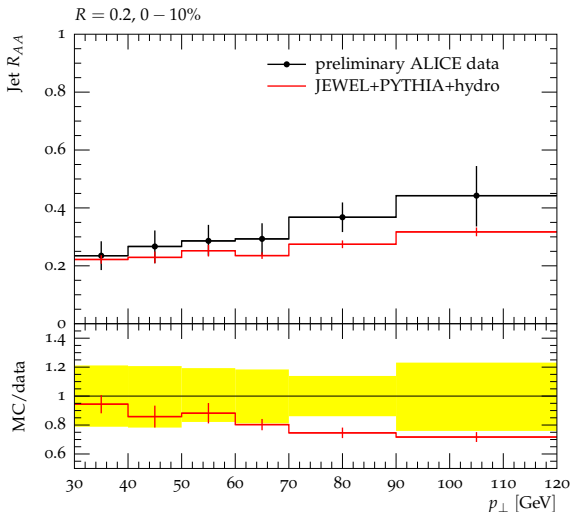
- solid: without source terms
- dashed: with source terms
- main effect is slightly larger radial flow
- effect quantitatively rather small

Correlation functions of sources

$$\bar{C}_{SS}(x, y) = \langle J_S(x) J_S(y) \rangle - \bar{J}_S(x) \bar{J}_S(y)$$

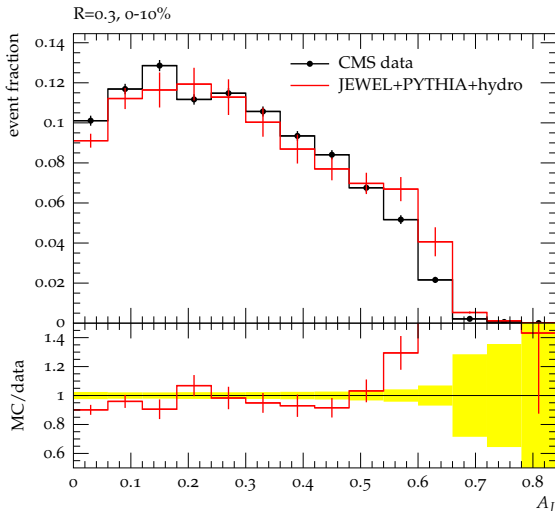


Nuclear modification factor



Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Jets reconstructed for $|\eta| < 0.5$ and leading track $p_{\perp} > 5$ GeV. Data from [\[ALICE, J Phys CS 446, 012006 \(2013\)\]](#)

Di-jet asymmetry



Di-jet asymmetry $A_J = (p_{\perp,1} - p_{\perp,2}) / (p_{\perp,1} + p_{\perp,2})$ in Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Data from [CMS, PLB 712, 176 (2012)]

Conclusions

- JEWEL with realistic fluid dynamic background gives good quantitative description of jet energy loss observables.
- Jets deposit energy and momentum in the fluid. Can be described by source term in fluid dynamic equations.
- Statistical description in term of event averages and correlation functions avoids expensive combined event-by-event simulations of jets and fluid.
- Event-averages source functions largest at early times τ and for small radii r .
- Small increase in temperature by heating.
- Increase in radial flow by up to 10 % from momentum transfer: jets drag fluid outwards.
- Correlation functions of energy and momentum transfer have been determined and can be used in fluid dynamics in the next step.