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]

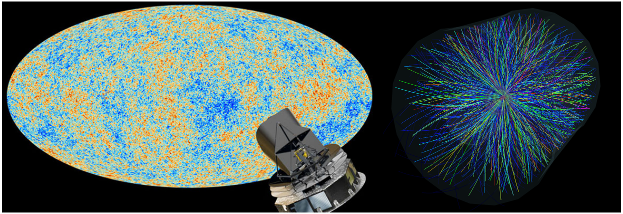
Evolution in time after heavy ion collision

- 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?

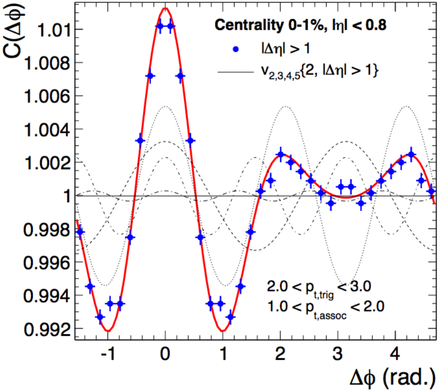
- **Initial fluid perturbations**: Event-by-event fluctuations around an average of fluid fields at time τ_0 and their evolution:
  - energy density ϵ
  - fluid velocity u^μ
  - shear stress $\pi^{\mu\nu}$
  - more general also: baryon number density n, electric charge density, electromagnetic fields, ...
- **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!



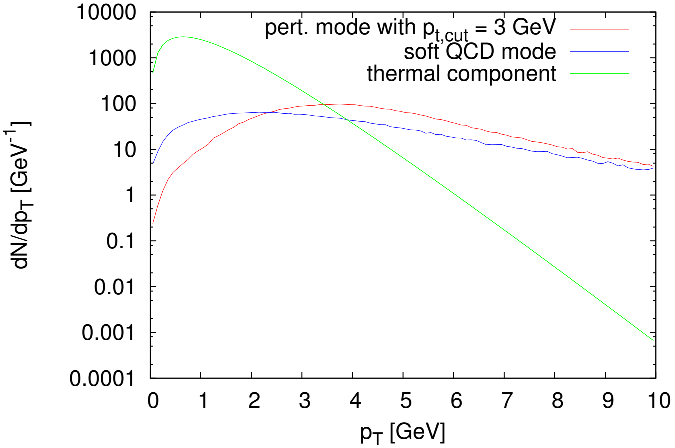
[ALICE 2011, similar results from CMS, ATLAS, Phenix, Star]

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 $p_{\text{t,cut}} = 3$ 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

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

- Energy-momentum tensor of bulk described by hydro

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

  with

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

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

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

- Energy-momentum conservation equation becomes

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

Fluid equations with source terms

- Evolution of energy density

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

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

- Second law of thermodynamics

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

- Evolution of fluid velocity

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

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

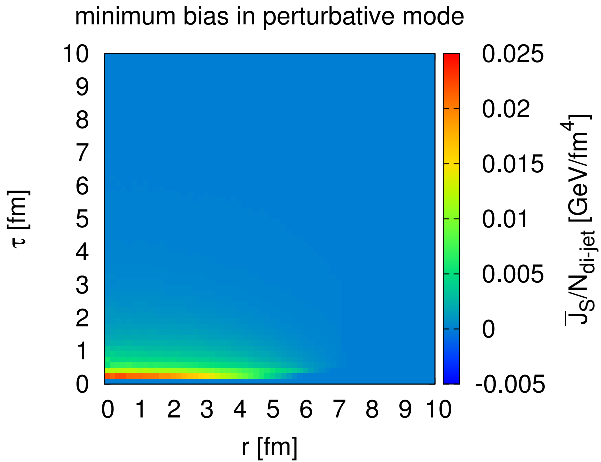
$$\langle J_S(x)\rangle, \qquad \langle J_V^\mu(x)\rangle, \qquad \langle J_S(x) J_S(y)\rangle, \qquad \ldots$$

- Concentrate first on expectation values or averages of sources

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

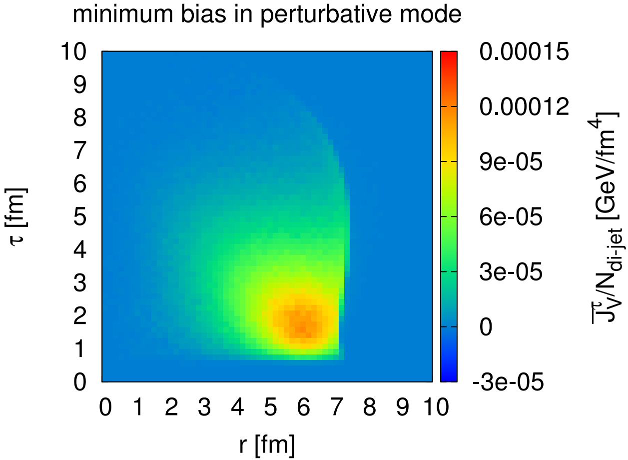
Energy and momentum source functions

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



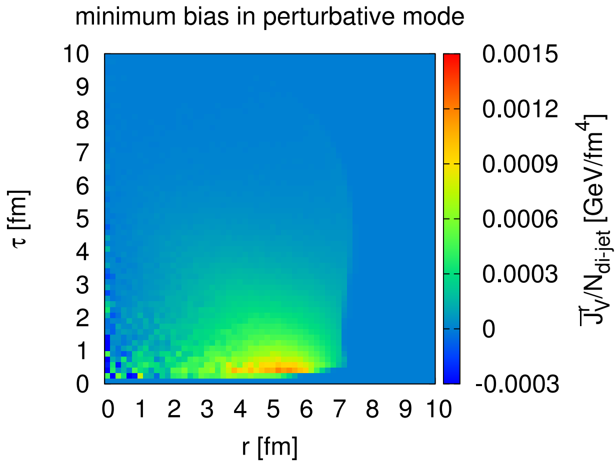
Energy and momentum source functions

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

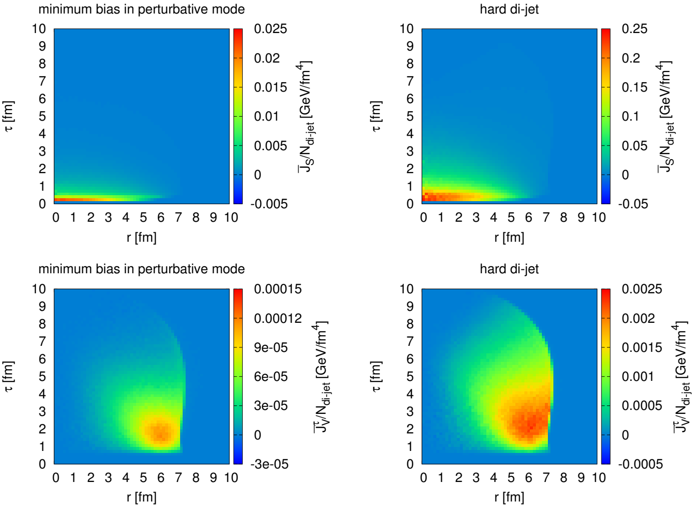


Energy and momentum source functions

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



Minimum bias versus hard jet

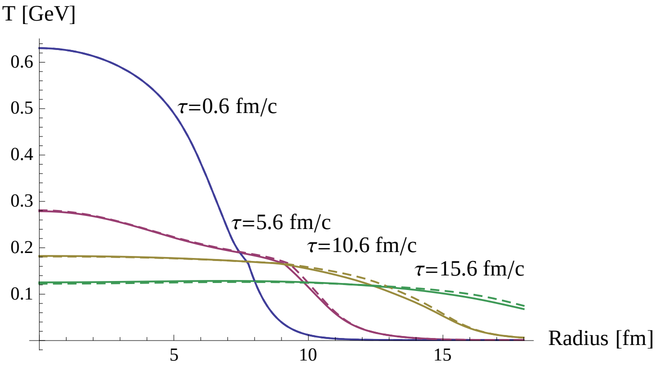


minimum bias: $p_\perp > 3$ GeV

hard jet: $p_\perp > 100$ GeV

Fluid evolution with averaged sources

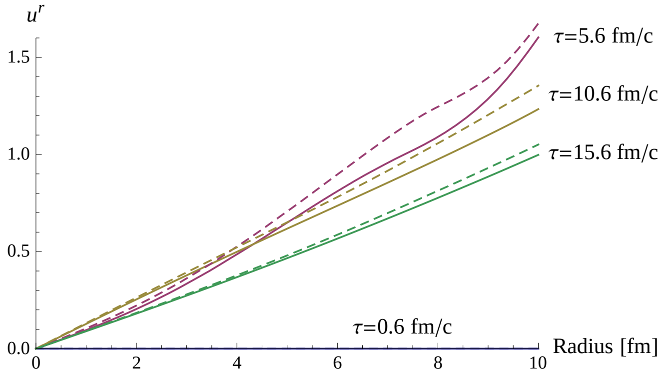
Temperature



- 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



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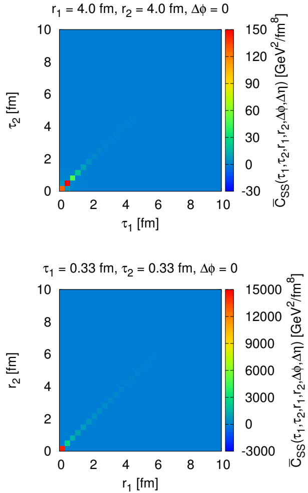
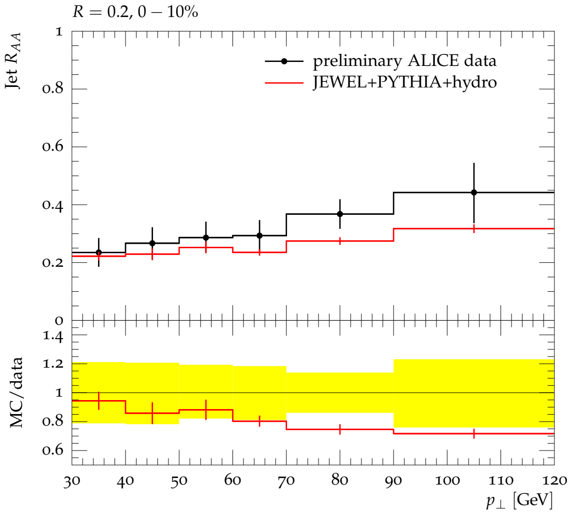
Correlation functions of sources

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

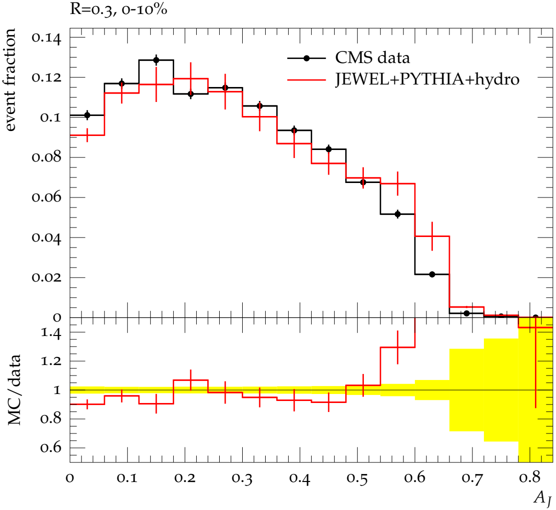


Nuclear modification factor



Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ 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 $\sqrt{s_{\rm NN}} = 2.76$ 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 depose 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.