The wake of jets from linearized hydrodynamics Jorge Casalderrey-Solana In collaboration with G. Milhano, D. Pablos, K. Rajagopal and Xiaojun Yao



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## The fate of energy-loss



Medium back-reaction:

- Modification of the QGP dynamics as due to the jet passage
- Expected in most models of jet-medium interactions
- Leads to medium-scale particles along the jet direction that are incorporated into any reconstructed in-medium jet

see Y. Tachibana's plenary on Wednesday

#### The effect of Back-Reaction



Medium back-reaction:

 Important for the description of many observables; must be incorporated in any model seeking to describe jets data.

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JCS, Milhano, Pablos, Rajagopal, 2020

Medium back-reaction:

- Important for the description of many observables; must be incorporated in any model seeking to describe jets data.
- Hybrid model provides good examples: including medium back-reaction is essential to describing certain observables.

# Too simple⇒Too Soft & Too Wide



The simple back-reaction implemented in hybrid model:

- Captures the general features of the energy-degradation
- Produces too many soft particles at large angles

In this talk: first steps towards a better description of back-reaction

### Method: Linearised Hydro

• Why hydro?

- •The QGP is a very good fluid. So should its perturbations be
- Hydrodynamics works with large gradients, as should happen close to the jet
- Well supported by explicit microscopic calculations at strong coupling (Chesler&Yaffe 07, Chesler and Rajagopal 15)

#### • Why linearised?

The overall amount of energy deposited per jet is small compared to the total energy

$$\Delta E_{typical} \sim 10-20 \text{ GeV}$$

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# Approximation in the Hybrid Model

Particle production via Cooper Fry at fixed proper time

$$\frac{\mathrm{d}\Delta N}{p_T \,\mathrm{d}p_T \,\mathrm{d}\phi \,\mathrm{d}y} = \frac{1}{(2\pi)^3} \int \mathrm{d}^2 x_\perp \tau \,\mathrm{d}\eta \, m_T \cosh(y-\eta) \\ \times \left\{ \exp\left[-\frac{u^\mu p_\mu}{T+\delta T}\right] - \exp\left[-\frac{m_T \cosh(y-\eta)}{T}\right] \right\}.$$
 Unperturbed spectrum  $\mathbf{1}_{\mu^\mu} = (1, \delta u^x, \delta u^y, \delta u^\eta)$  =perturbed velocity

•Valid for small perturbations as long as thermalisation is achieved

- Approximation in the hybrid model:  $e^{\frac{\delta u \cdot p}{T}} \approx 1 + \frac{\delta u \cdot p}{T}$ 
  - No need to know the perturbed flow, only Eloss.
  - Strictly valid for soft particles
  - ${\ensuremath{\, \circ }}$  We expect modifications for  $p_T \gg T$

• Here we use the expression without expanding in momentum

It requires the explicit form of the flow fields

Hard Probes 2020

#### The flow field



Ideal Bjorken flow without transverse expansion

- Small (linearised) disturbance due to the jet
- Gaussian source for the stress tensor along the jet path
- Energy injection according to the ELoss rate

## A simplified setup

Ideal Bjorken flow with no transverse expansion

• Initialization time  $\tau_0=0.6$  fm<sup>-1</sup>. T( $\tau_0$ )= 400 MeV.

• The fluid propagates until a T<sub>freezeout</sub>=155 MeV

A single jet (energy source) propagates for a fixed proper time

Disappearance of the jet simulates that the jet leaves the medium

Energy loss controlled by a strongly-coupled inspired rate (Hybrid)

$$\tau_{\rm f}$$
= 4.6 fm  $\Rightarrow \Delta E_{\rm Loss}$  = 8.77 GeV

$$\tau_{\rm f}$$
= 8.1 fm  $\Rightarrow \Delta E_{\rm Loss}$  = 25 GeV

## **Spectrum of Particles**

Comparison of the full calculation with the hybrid approximation



• The spectrum becomes harder

- Reduction of the number of particles with p<sub>T</sub><1 GeV</p>
- Increase of the number of particles with p<sub>T</sub>>1 GeV
- Orrects the soft hybrid model spectrum towards data
- Hardening increases with the energy loss

# Angular distribution

Comparison of the full calculation with the hybrid approximation



Beaming of the spectrum along the jet azimuthal direction

- Harder particles are better correlated with jet azimuthal direction
- Orrects the narrow hybrid model spectrum towards data
- Less depletion of particles opposite to the jet ("negative particles") Improves the description of the R dependence of jet suppression

see D. Pablos's talk on Wednesday

# **Rapidity distribution**

Comparison of the full calculation with the hybrid approximation



Narrow rapidity distribution for hard particles

• The distribution is wider than in the approximated form (hybrid)

# Energy Recovered in a Cone

Energy of back-reacted particles in a cone of radius R around the source



Recovery of jet energy due to back-reaction

- Larger fraction of semi-hard particles around the jet
- Slower recovery of jet energy as a function of R:
  - Wider rapidity distribution

Less depletion of particles in opposite jet direction (negatives)

## Conclusions

- Improved description of the medium back-reaction
  - Leads to a harder spectrum of back-reaction particles
  - Beaming of the spectrum along the jet azimuthal direction
  - Wider rapidity distribution
- Promising results for a better description of data
  - Work in progress: many details to be implemented
    - The effect of viscosity
    - Transverse flow
    - Full jet events, full geometry, MonteCarlo implementation
      ...

• We will enjoy deconfinement as much as quarks and gluons do!