Emission of Low Momentum Particles at Large Angles from Jet

Yasuki Tachibana

Department of physics, The University of Tokyo
Collaborator: Tetsufumi Hirano (Sophia Univ.)

Jet Modification in the RHIC and LHC Era(QM12 Satellite Workshop)
August 21st 2012, Wayne State Univ.

東京大学
THE UNIVERSITY OF TOKYO

Outline

- ■ Introduction
- ■ Hydrodynamic Model with a Source Term
- ■ Simulations and Results
- ■ Summary

Introduction

Jet Quenching

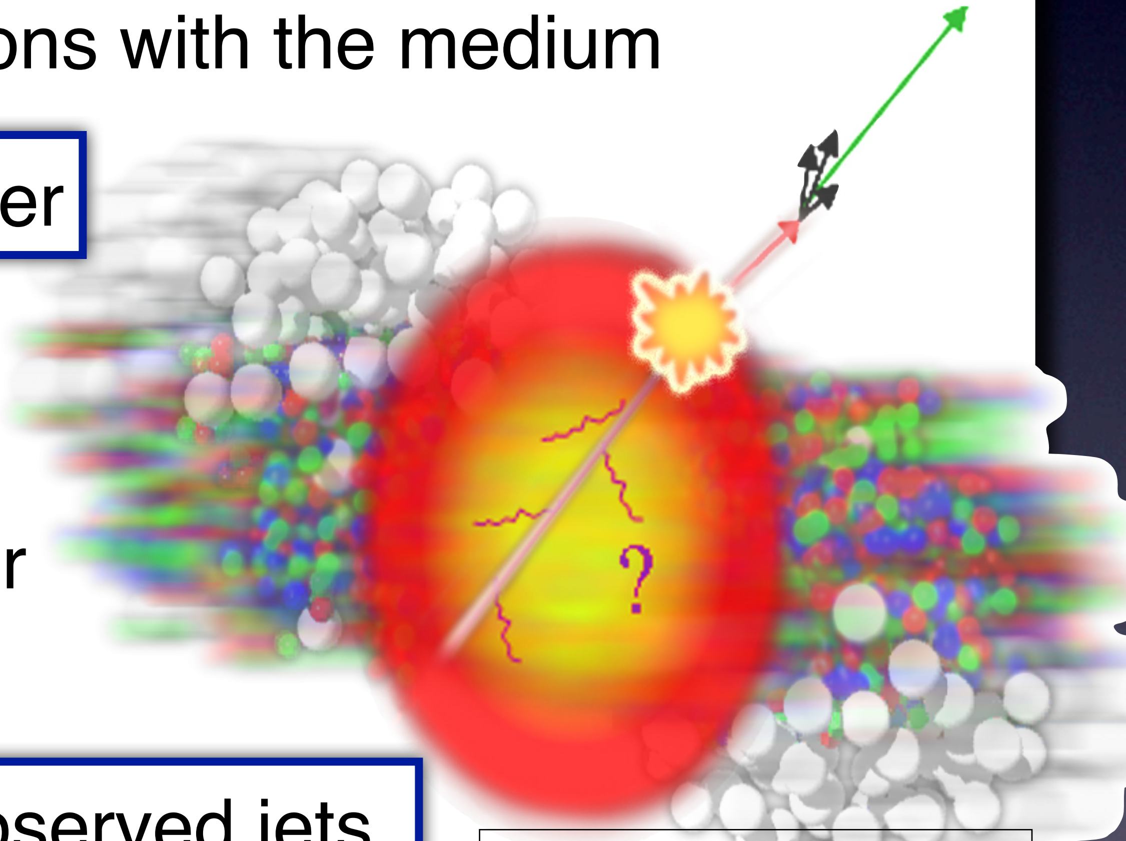
Bjorken (1983),
Gyulassy and Plumer (1990),
Gyulassy and Wang (1994),
...

- **Energy loss of high-energy partons**

Creation of high-energy partons (jets) at the same time as a QGP fluid

Energy loss of jets due to strong interactions with the medium

→ Extraction of QGP’s stopping power



Pair creations of jets

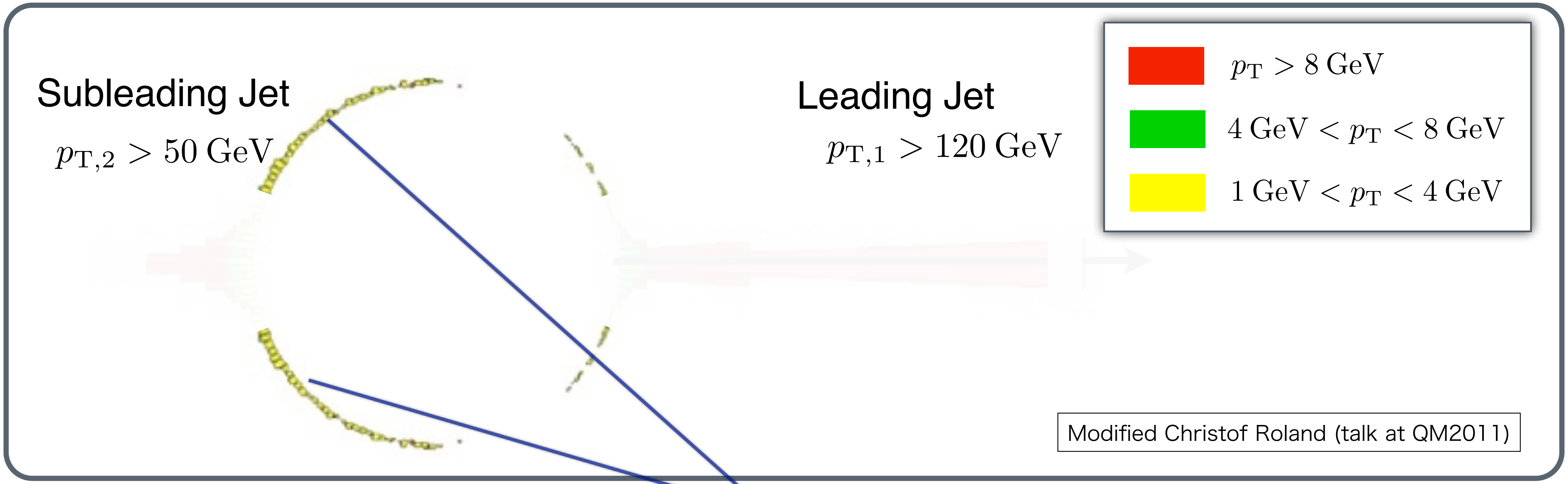
Difference of energy loss between the pair particles due to position of the creation

→ Energy difference between the observed jets

From SCIENCE @ BERKELEY LAB.

Motivation

■ **Jet quenching observed at LHC** **CMS** (2011)



Modified Christof Roland (talk at QM2011)

Large angle emission of **low-p_T particles**
(**Necessary to balance the whole p_T**)

→ Originated from the collective flow ?

■ **Purpose of the current study**

<u>Hydrodynamic Model with a Source Term</u>

Study the dynamics of the QGP fluid induced by jets

Hydrodynamic Model with a Source Term

Hydrodynamic Equation with a Source Term

- **Relativistic hydrodynamic equation**

  - Energy-momentum conservation of the fluid

$$\partial_\mu T^{\mu\nu} = 0$$

$T^{\mu\nu}$: energy-momentum tensor of the QGP fluid

- **Relativistic hydrodynamic equation with a source term**

  - Hydrodynamic equation with deposited energy and momentum

$$\boxed{\partial_\mu T^{\mu\nu} = J^\nu}$$

J^ν: **source term** (Energy and momentum deposited by jets)

Solve this nonlinear equation numerically without linearization

Describe the dynamics of jets and the QGP fluid simultaneously

Source Term

■Source term and energy loss

J^{ν}: **source term** (Energy and momentum deposited by jets)

Assume the sudden thermalization for the deposited energy and momentum

Jet energy loss mechanism

GLV, BDMPS-Z-ASW, AMY, Higher Twist, AdS/CFT, ...

In this study

The dynamics of **the QGP fluid** induced by jets

→ **use a simple model as the jet energy loss**

Source Term

■ Energy-momentum conservation in the whole system

- Distribution functions of constituents of the fluid and jet particles

$f_{\rm h}(x,p)$: fluid part $f_{\rm j}(x,p)$: jet part

- Relativistic Boltzmann equation of jet particles

$$p^\mu \partial_\mu f_{\rm j}(x,p) = C_{\rm j}[f_{\rm h},\ f_{\rm j}]$$

$C_{\rm j}[f_{\rm h},\ f_{\rm j}]$: Collision term

- Energy-momentum tensors

$$T^{\mu\nu}_{\rm h}(x) = \int \frac{d^3p}{p^0}\, p^\mu p^\nu f_{\rm h}(p,x)\,, \qquad T^{\mu\nu}_{\rm j}(x) = \int \frac{d^3p}{p^0}\, p^\mu p^\nu f_{\rm j}(p,x)$$

- Energy-momentum conservation

$$\boxed{\partial_\mu \left[T^{\mu\nu}_{\rm h}(x) + T^{\mu\nu}_{\rm j}(x) \right] = 0}$$

Source Term

■ Source term

Assume constituents of the fluid are always in local equilibrium

- Energy-momentum conservation

$$\partial_\mu T_{\mathrm{h}}^{\mu\nu}(x) = -\partial_\mu T_{\mathrm{j}}^{\mu\nu}(x)$$

- Source term

$$\begin{aligned} J(x)^\nu &\equiv -\partial_\mu T_{\mathrm{j}}^{\mu\nu}(x) \\ &= -\int \frac{d^3p}{p^0}\, p^\nu p^\mu \partial_\mu f_{\mathrm{j}}(x,p) = -\int \frac{d^3p}{p^0}\, p^\nu C_{\mathrm{j}}[f] \end{aligned}$$

2-body → 2-body elastic scatterings between a jet and a constituent of the fluid

$$\boxed{J(x)^\nu = \int \frac{d^3p}{p^0}\frac{d^3p'}{p'^0}\frac{d^3k}{k^0}\frac{d^3k'}{k'^0}\,(p-p')^\nu\, w(p',k'|p,k) f_{\mathrm{j}}(p,x) f_{\mathrm{h}}(k,x)}$$

$w(p',k'|p,k)$: transition rate

Simulations and Results

Settings

Fluid

- Perfect QGP-fluid in full (3+1)-dimensional space
- Massless, ideal gas EoS $P(e) = \frac{1}{3}e$

Source term

- Massless jet particle traveling **in a straight line**
- Neglect the effect of the flow velocity on the energy loss

$$J^0(x) = J^1(x) = \left[-\frac{dp^0_{\mathrm{jet}}(t)}{dt}\right]\delta^{(3)}\left(\boldsymbol{x} - \boldsymbol{x}_{\mathrm{jet}}(t)\right)$$

$$J^2(x) = J^3(x) = 0$$

Jet energy loss

$$-\frac{dp^0_{\mathrm{jet}}(t)}{dt}$$

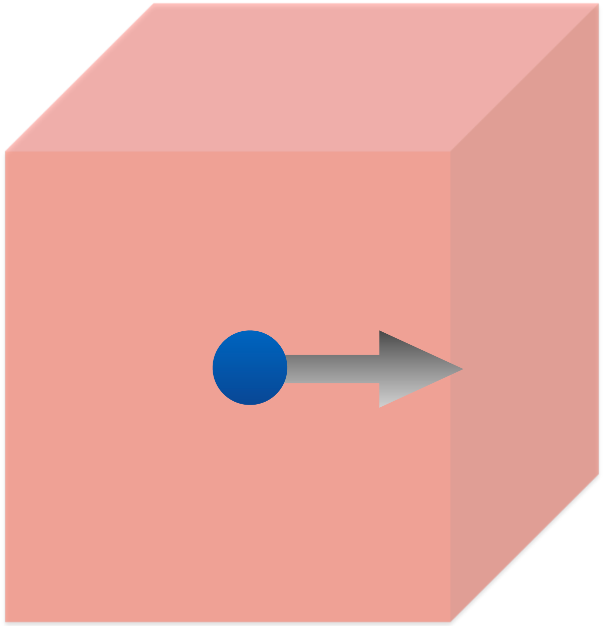
- All particles are classical
- 2-body → 2-body elastic scatterings
- t-channel dominant, Debye mass cut-off

Simulations

■ Test case

- 1-jet traveling through a uniform fluid

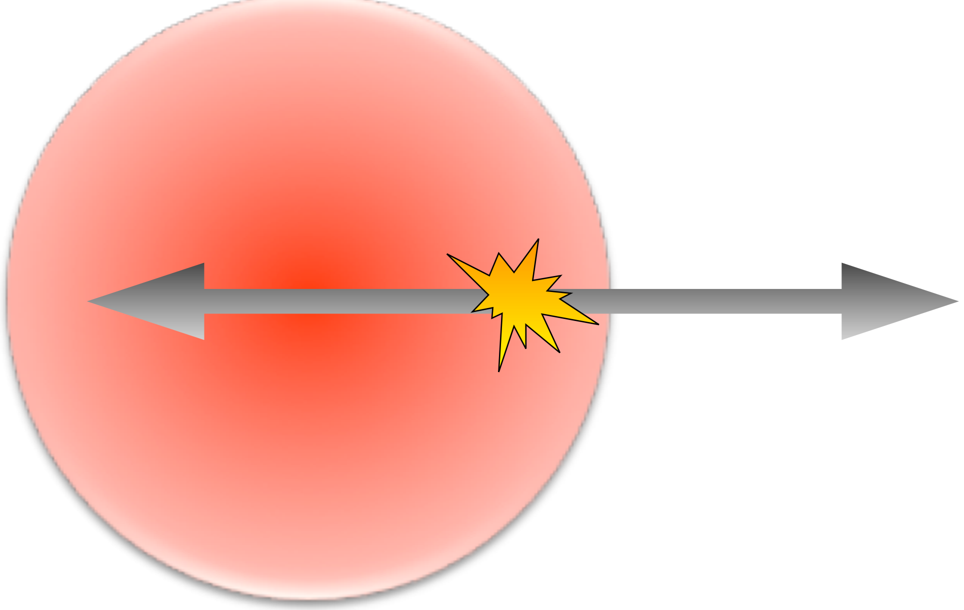
Flow induced by a jet particle



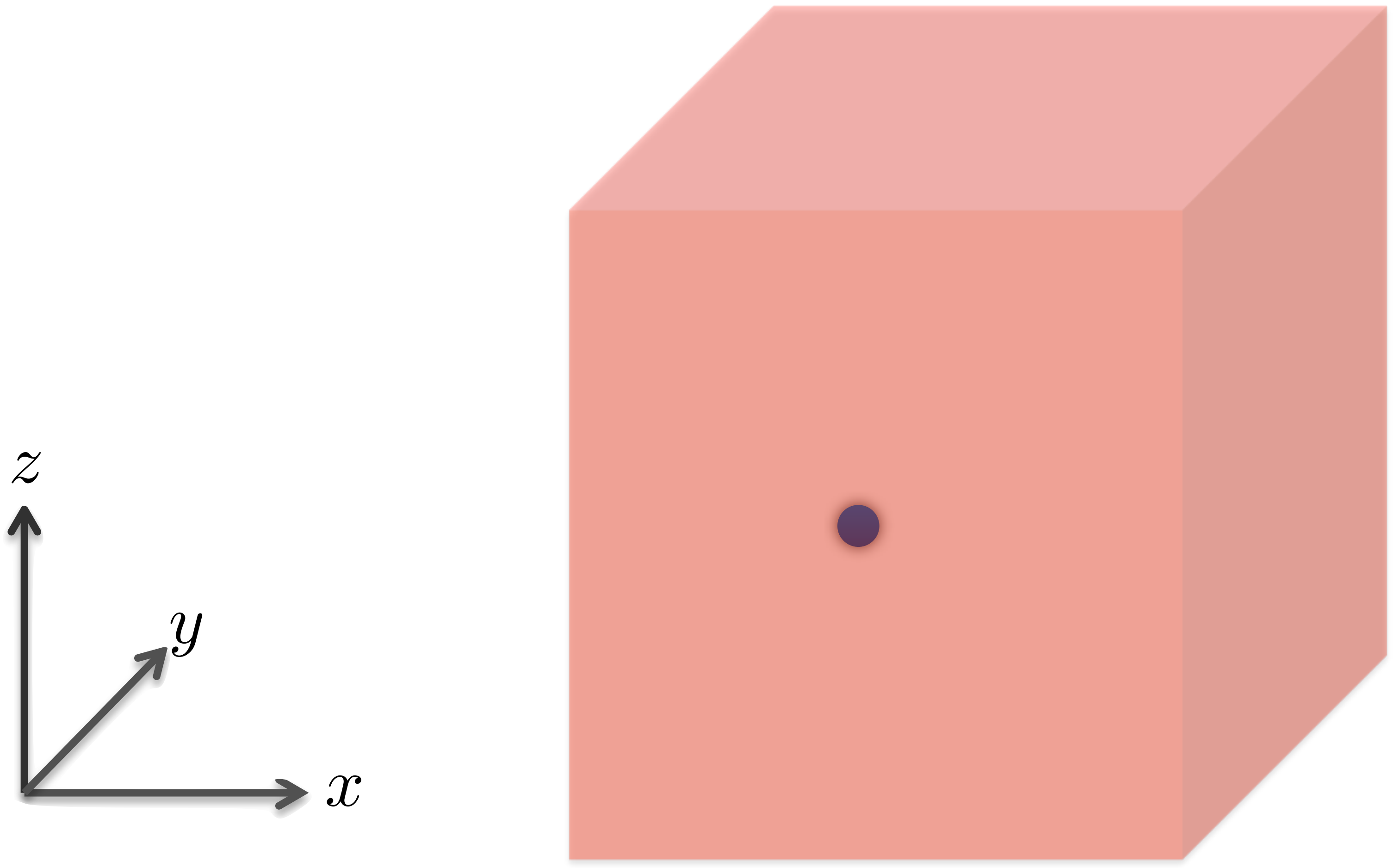
■ More realistic case

- A pair of jets traveling through an expanding fluid

Flow induced by jets
+
Radially expanding background



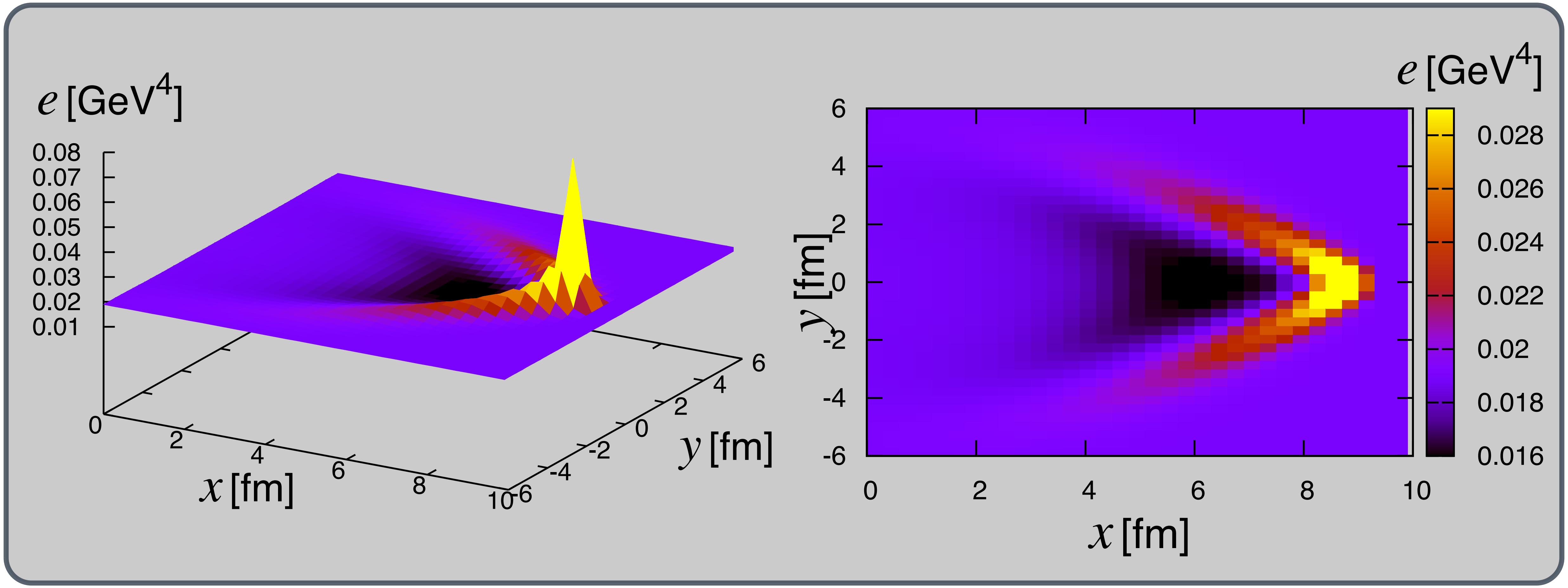
1-Jet Traveling through a Uniform Fluid



- Initial energy of the jet particle: $E_0 = 50\,\mathrm{GeV}$
- Initial temperature of the fluid: $T_0 = 0.5\,\mathrm{GeV}$

1-Jet Traveling through a Uniform Fluid

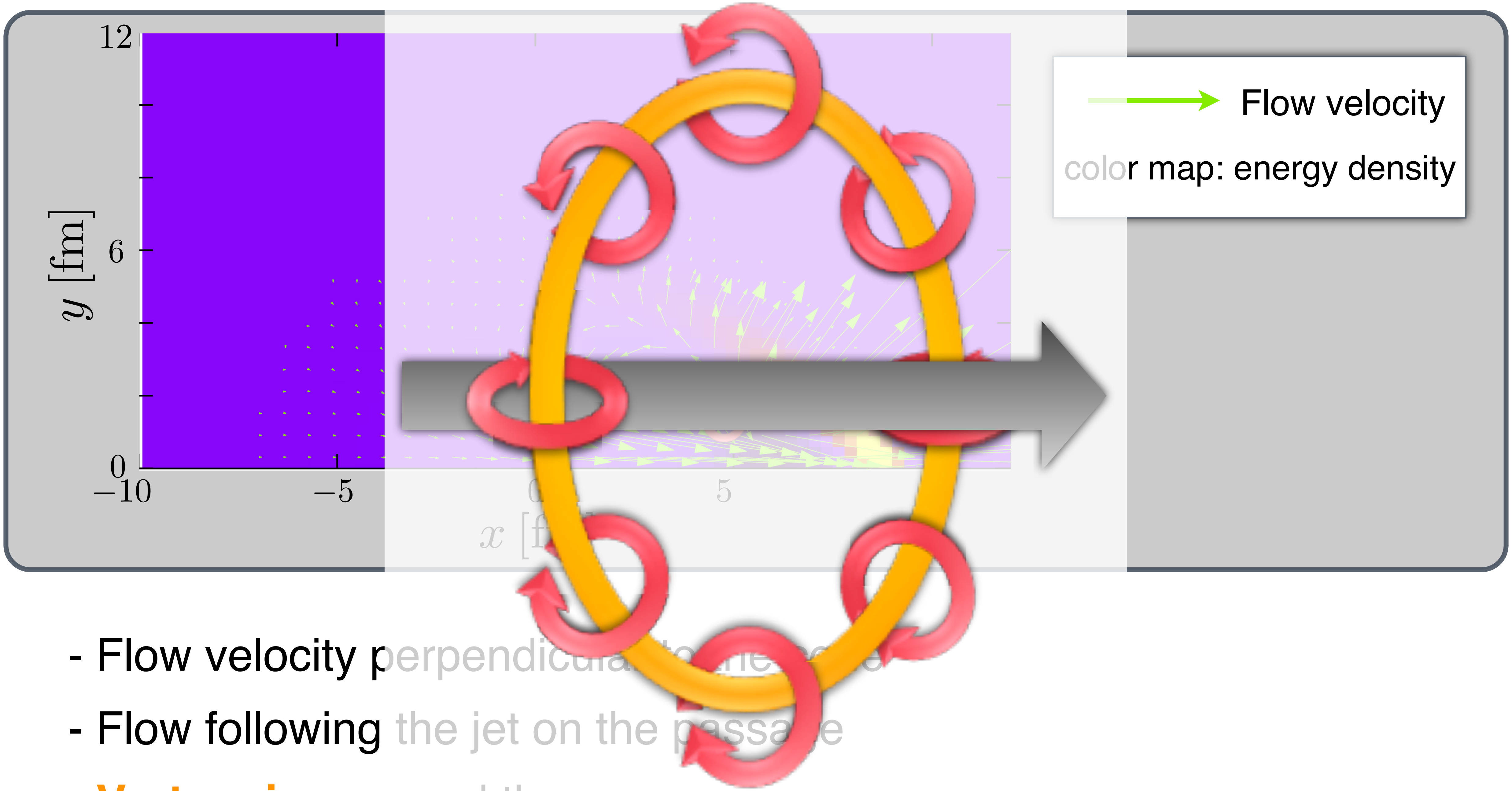
■ **Energy density** $(t = 9\ [\mathrm{fm}])$



- Peak at the position of the jet
- **Mach cone** structure
- Low energy density region inside the cone

1-Jet Traveling through a Uniform Fluid

■ Flow velocity $(t = 9\ [\mathrm{fm}])$

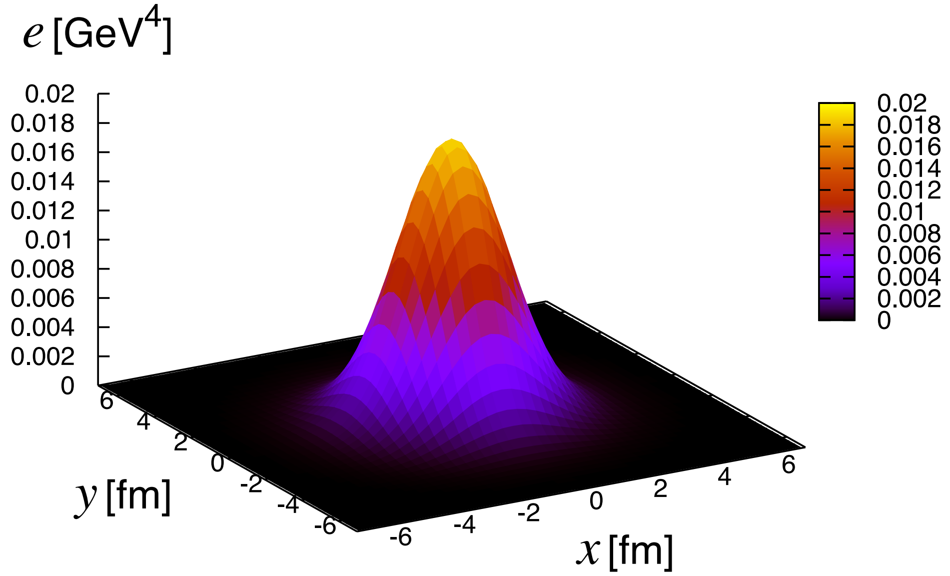


- Flow velocity perpendicular to the
- Flow following the jet on the passage
- **Vortex ring** around the passage

A Pair of Jets Traveling through an Expanding Fluid

■ A pair of jets traveling through an expanding fluid

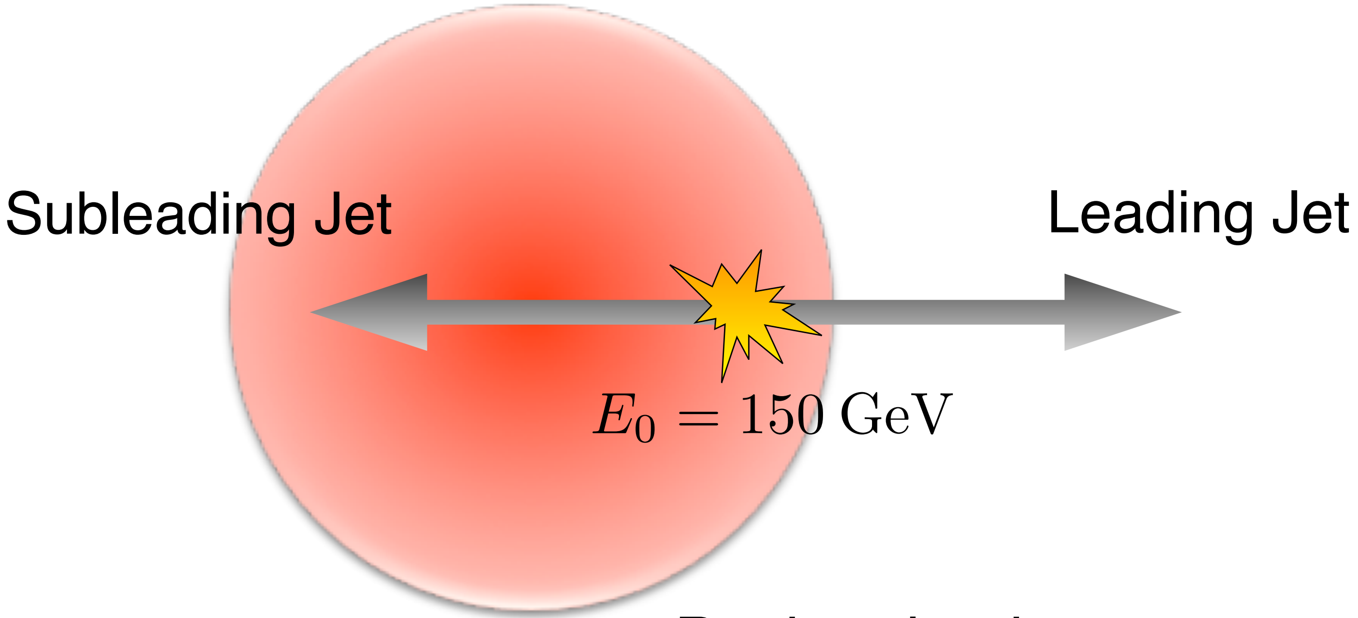
- Initial condition of the energy density: 3D-Gauss + cut-off



Initial temperature
at the center of the fluid:

$$T_0 = 0.5\ \mathrm{GeV}$$

- Jet pair created at off central position



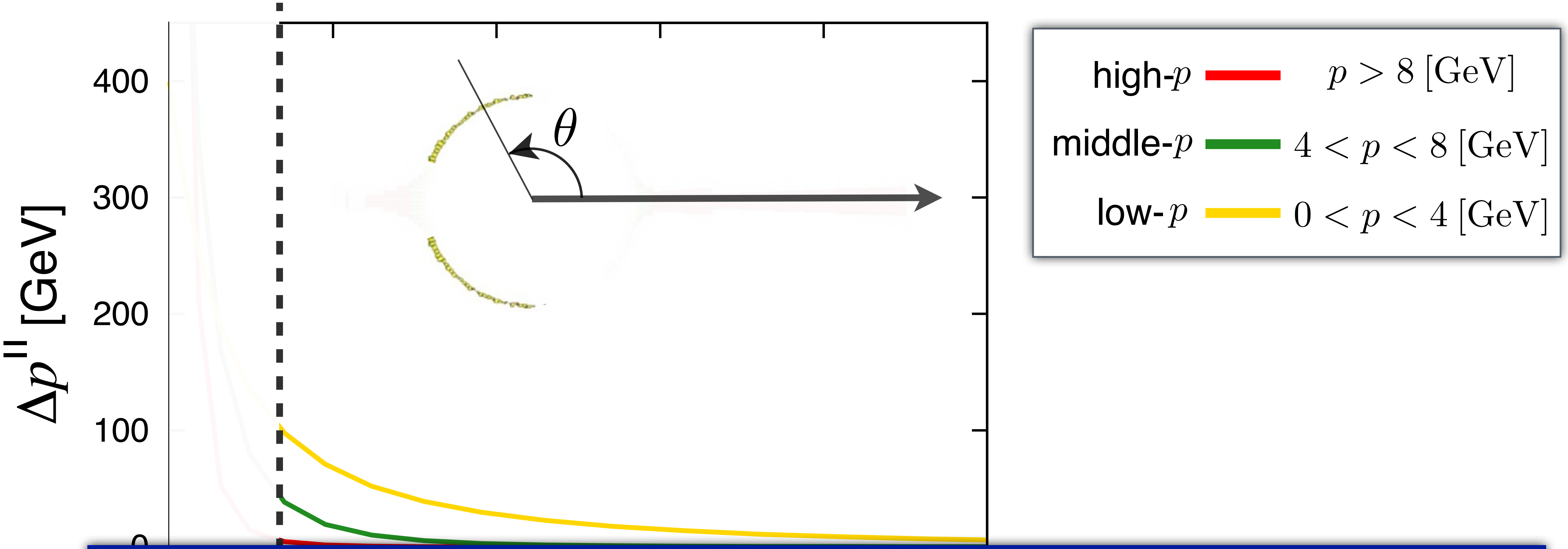
Back to back same energy jets

A Pair of Jets Traveling through an Expanding Fluid

- **Increase of momentum along the jets**

$$\Delta p_i^{||} \equiv \sum_{p\in i} p^{||} - \sum_{p\in i} p^{||}{}_{\text{no jet}}$$

$p^{||}$: momentum component of the jet direction $i=$high, middle, low



Low momentum particles are dominant at large angles from the jet

→ **Consistency with the CMS data**

Summary

Summary

- **Model building to describe the dynamics of jets and the QGP fluid simultaneously**
  - Relativistic hydrodynamic equation with a source term

$$\partial_\mu T^{\mu\nu} = J^\nu$$

  - Perfect fluid in full (3+1)-dimensional space
- **Results**
  - 1-jet traveling through a uniform fluid

    Mach cone structure

    Vortex ring around the passage of the jet inside the cone
  - A pair of jets traveling through an expanding fluid

    Low momentum particles are dominant at large angles from the jet

→ **Qualitative description of the CMS data**

Outlook

- **more realistic energy loss models**
- $\tau - \eta$ **coordinates**
- **viscosity**

.....

Back up

Back up

- **Jet energy loss**

$$-\frac{dq^0(t)}{dt} = A\,\frac{\alpha_{\mathrm{s}}^2}{2\pi}\,T^2(x)\left[(1-\gamma_{\mathrm{Euler}}) + \ln\frac{q^0(t)}{2\pi\alpha_{\mathrm{s}}T(x)}\right]$$

Back up

■ Flow velocity