Jet Medium Interactions

Yasuki Tachibana

Nishinippon Institute of Technology

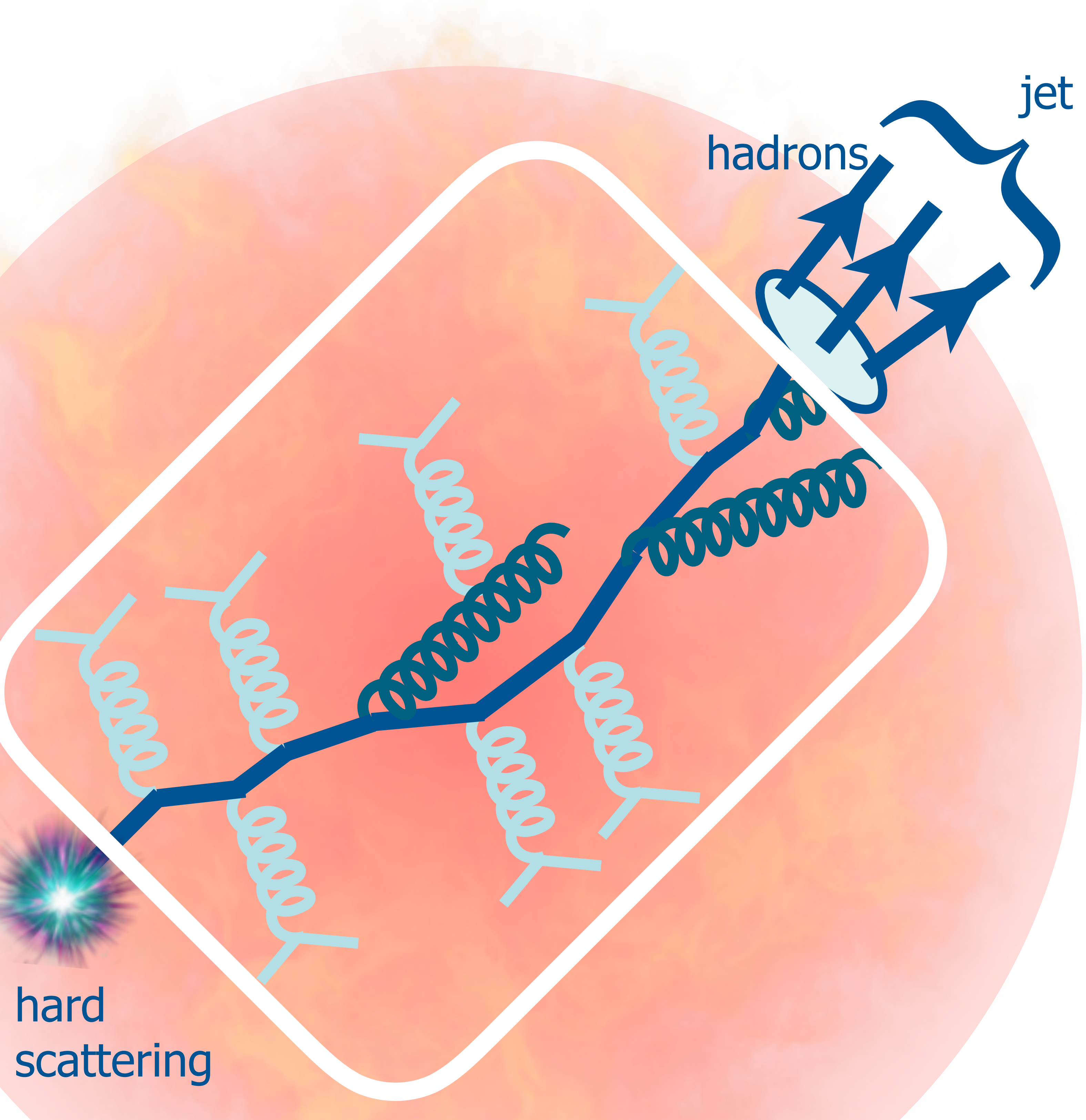
(→ Central China Normal University)

ATHIC 2016, New Delhi, India, 19 February 2016

Introduction

Jet energy loss in QGP medium

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



- Jets in heavy-ion colls.
  - produced in initial hard scattering
  - propagating through QGP medium

<u>Strong interactions with QGP</u>

- Collisional energy loss
  elastic process
- Radiative energy loss
  inelastic process

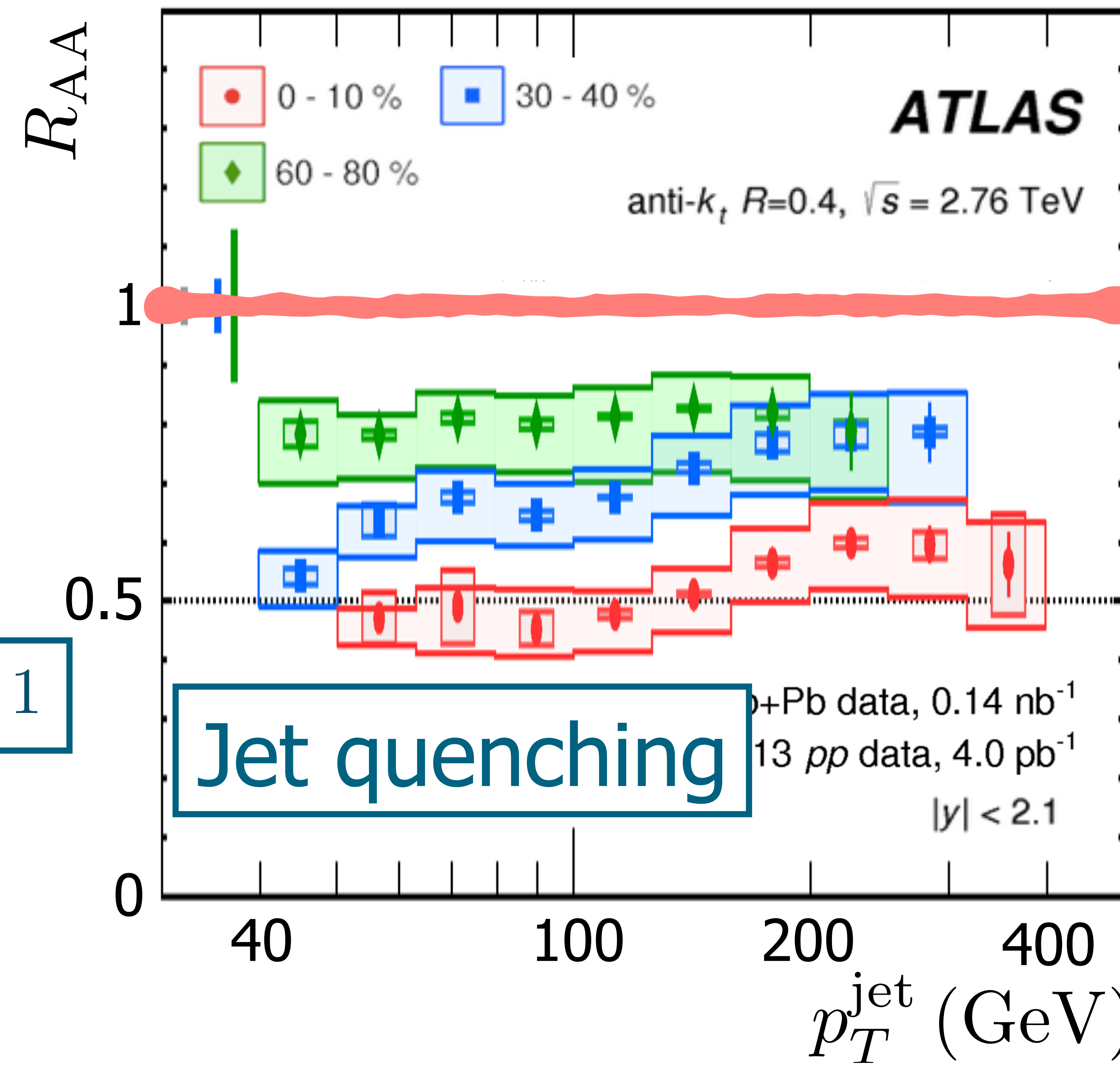
Jet quenching in heavy-ion collisions

- Jet nuclear modification factor

$$R_{\mathrm{AA}} = \frac{d^2 N^{\mathrm{AA}}_{\mathrm{jet}} / dp_T^{\mathrm{jet}} d\eta_p}{\langle T_{\mathrm{AA}} \rangle d^2\sigma^{pp}_{\mathrm{jet}} / dp_T^{\mathrm{jet}} d\eta_p}$$

Jet energy loss → $R_{\mathrm{AA}} < 1$

Figure adapted from ATLAS ('14)



Medium response to jet quenching

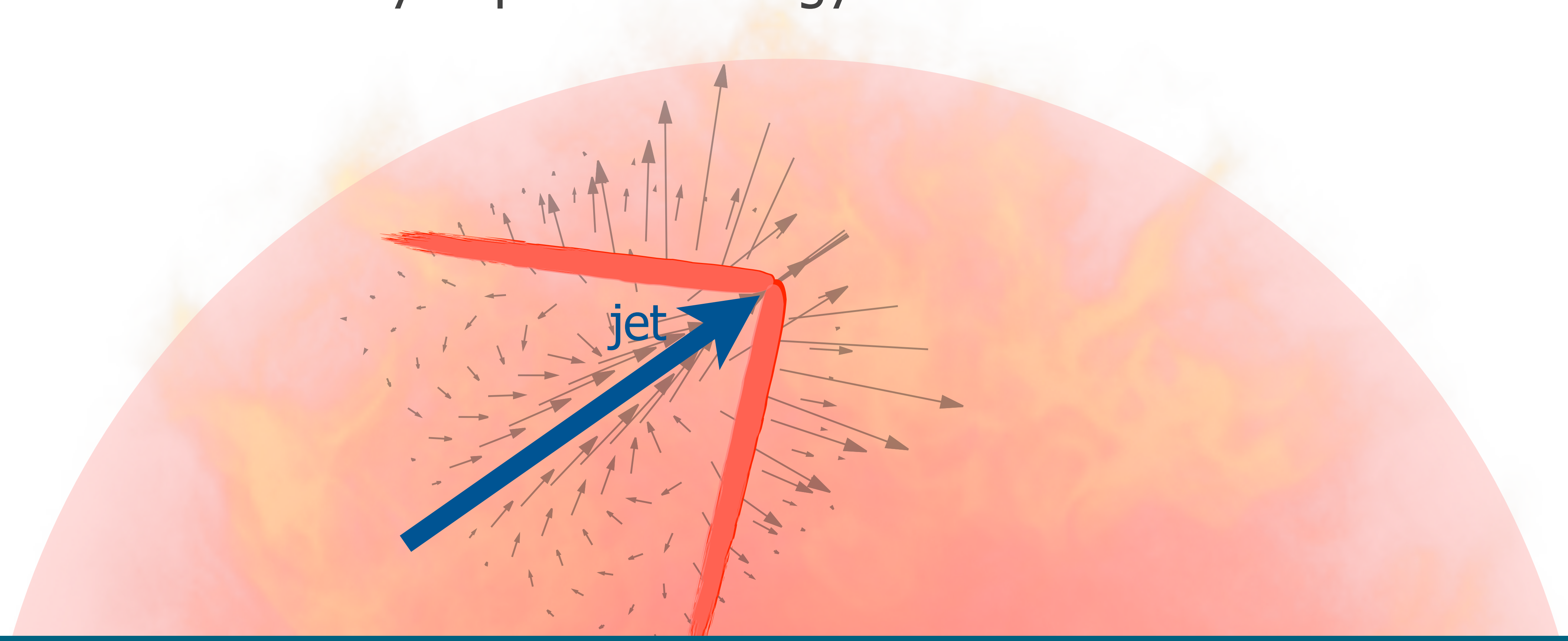
- Conventional calculation of jet evolution

  QGP fluid as a background thermal field (**No back reaction**)

  Energy and momentum are **NOT** conserved

- Energy-momentum deposition into medium

  Medium excitation by deposited energy and momentum



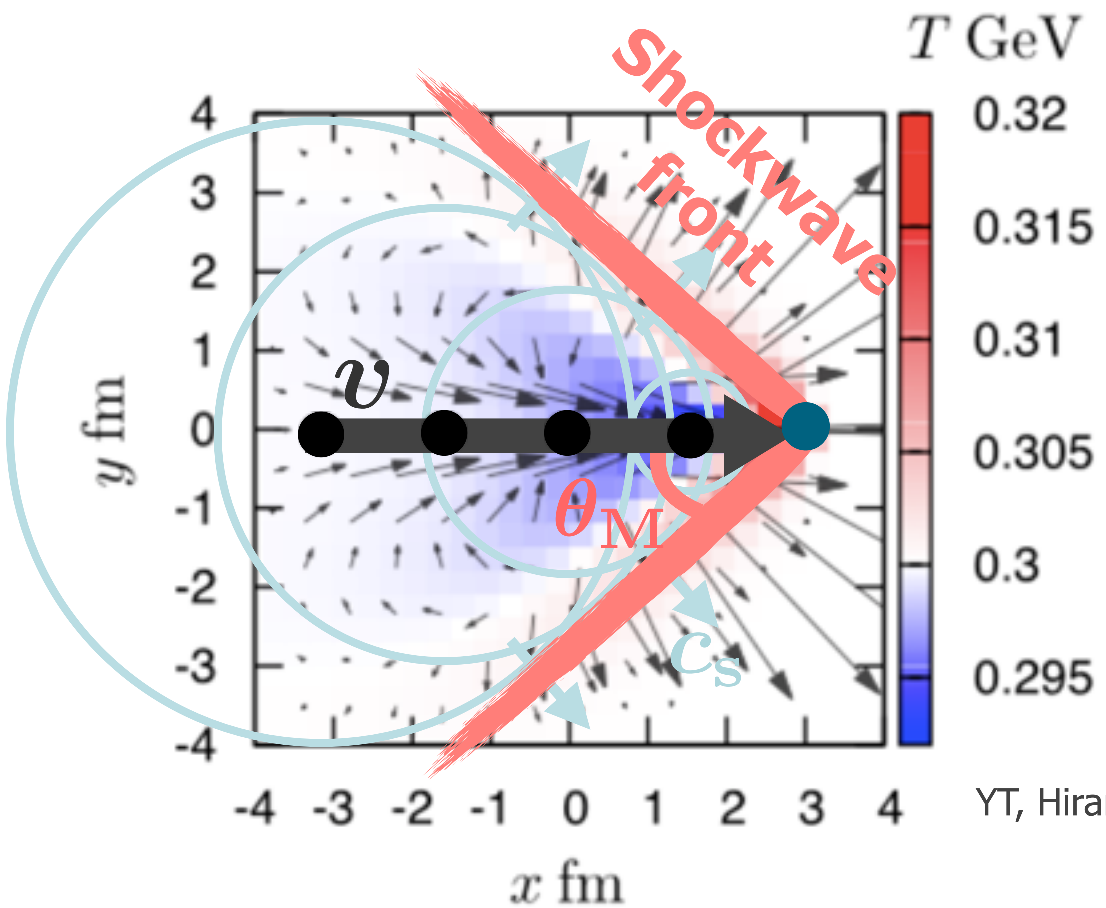
Hydrodynamic response to jet quenching

- QGP fluid   Bjorken (1983), …

Space-time evolution of the bulk QGP

Relativistic hydrodynamics

- Mach cone   Stoecker ('05), Casalderrey-Solana, Shuryak, Teaney ('05),…



YT, Hirano ('12)

$$\theta_M = \arcsin\frac{c_s}{v}, \quad v > c_s$$

Energy-momentum transport in the QGP fluid

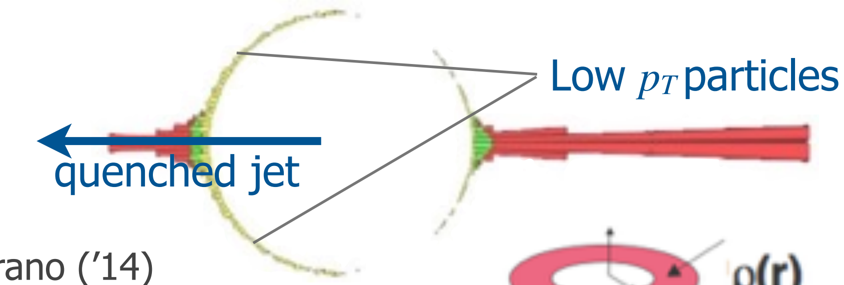
Influence of medium response

- Observables in events with large jet

  Low-p_T enhancement away from the jets

  YT, Hirano ('14)

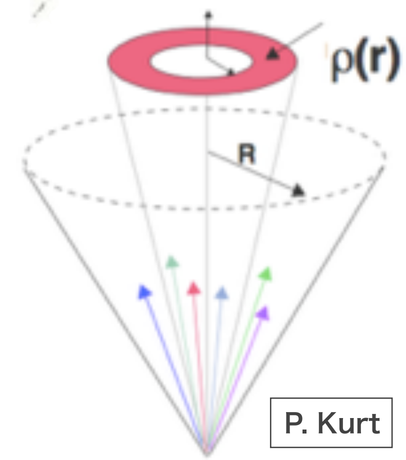
  Adapted from C. Roland (CMS)



  Jet structure inside the jet cone

  (fragmentation function, transverse profile)

  Wang, Zhu ('13), He, Luo, Wang, Zhu ('15),
  Casalderrey-Solana, Gülhan, Milhano, Pablos, Rajagopal ('15)



P. Kurt

- Influence of a large number of mini-jets

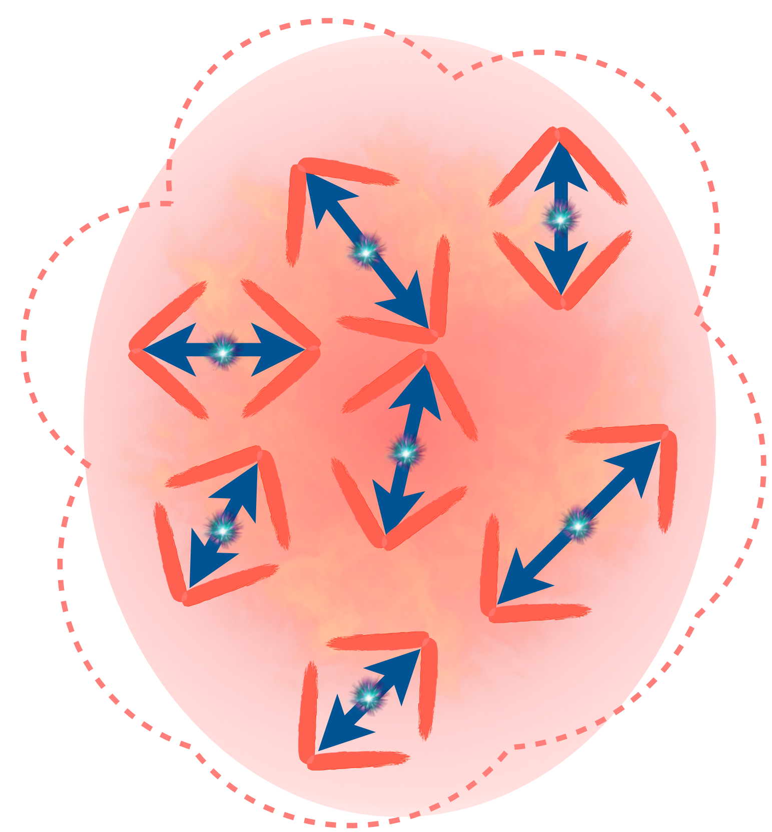
  Medium reheating

  Floerchinger, Zapp ('14)

  Anisotropic flow (modification of $v_2, v_3, \ldots$)

  Andrade, Noronha, Denicol ('14), Schulc, Tomášik ('14)

  Deformation of QGP medium



Mach cone in expanding QGP fluid

YT and T. Hirano, arXiv:1510.06966

Mach cone in expanding QGP fluid

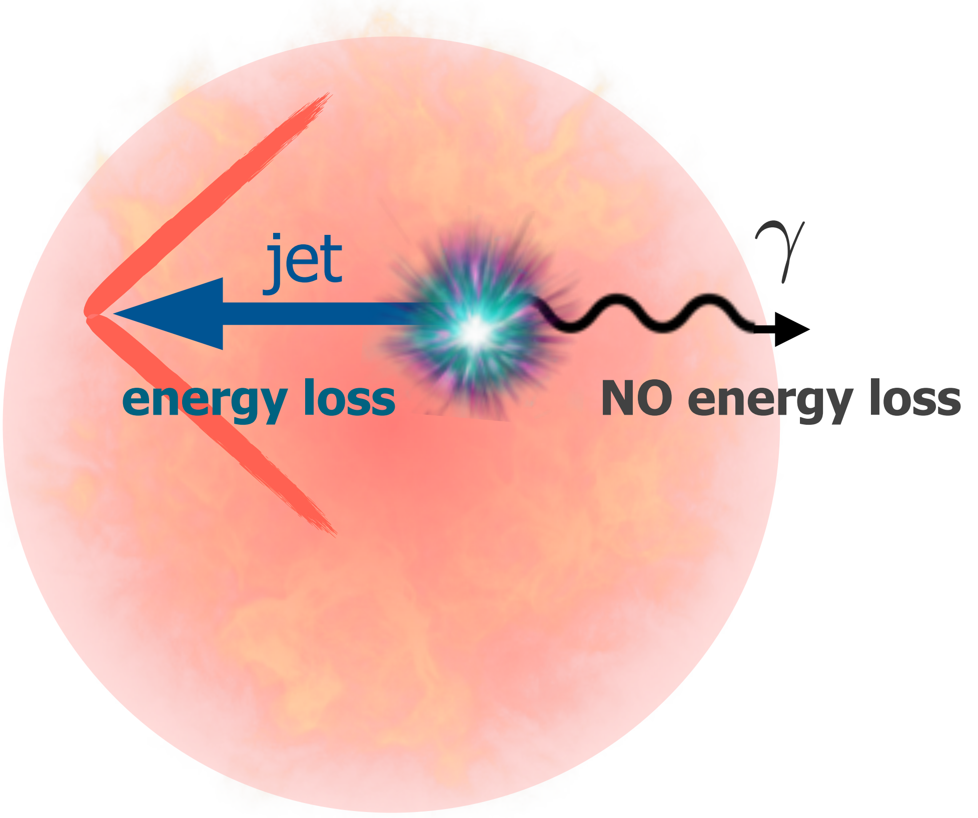
YT and T. Hirano, arXiv:1510.06966

- Purpose of this study
  - Hydrodynamic response to jet in expanding background
  - Consequent spectra of particles from medium

- Gamma-jet events in heavy-ion collisions

  Pair production of photon and parton

  One jet traveling through QGP fluid



QGP fluid + jet model

Energy and momentum incoming to the QGP fluid

- Hydrodynamic equations with source terms

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

Energy-momentum tensor of the QGP fluid

Energy and momentum deposited from the jet

Assumption

Instantaneous thermalization of deposited energy and momentum

$$J^\mu(x) = -\frac{dp^\mu_{\mathrm{jet}}}{dt}\delta^{(3)}\left(\boldsymbol{x} - \boldsymbol{x}_{\mathrm{jet}}(t)\right)$$

- Hydrodynamic response to jet
- Background expansion
- **Interplay between them**

A jet traveling through the expanding QGP

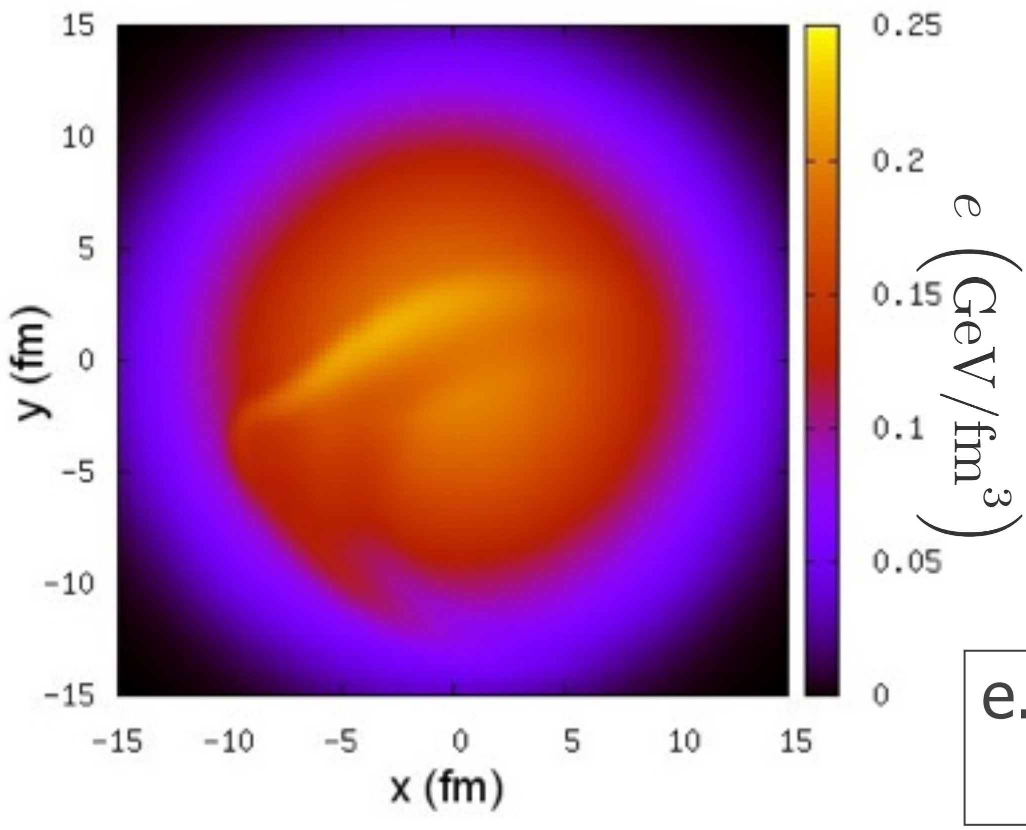
- Gamma-jet events in central Pb-Pb collisions

  - (3+1)-D ideal hydro
  - Optical Glauber model, lattice EoS
  - Energy loss $\frac{dp^0_{\mathrm{jet}}}{dt} = -\left[\frac{T\left(x_{\mathrm{jet}}\right)}{T_0}\right]^3 \left.\frac{dE}{dl}\right|_0$

$T_0 = 500\mathrm{MeV}$

$\left.\frac{dE}{dl}\right|_0 = 15\,\mathrm{GeV/fm}$

- Mach cone developing in the expanding medium



e.g.) Jet produced at $(x_0, y_0) = (3.0\,\mathrm{fm}, -3.0\,\mathrm{fm})$

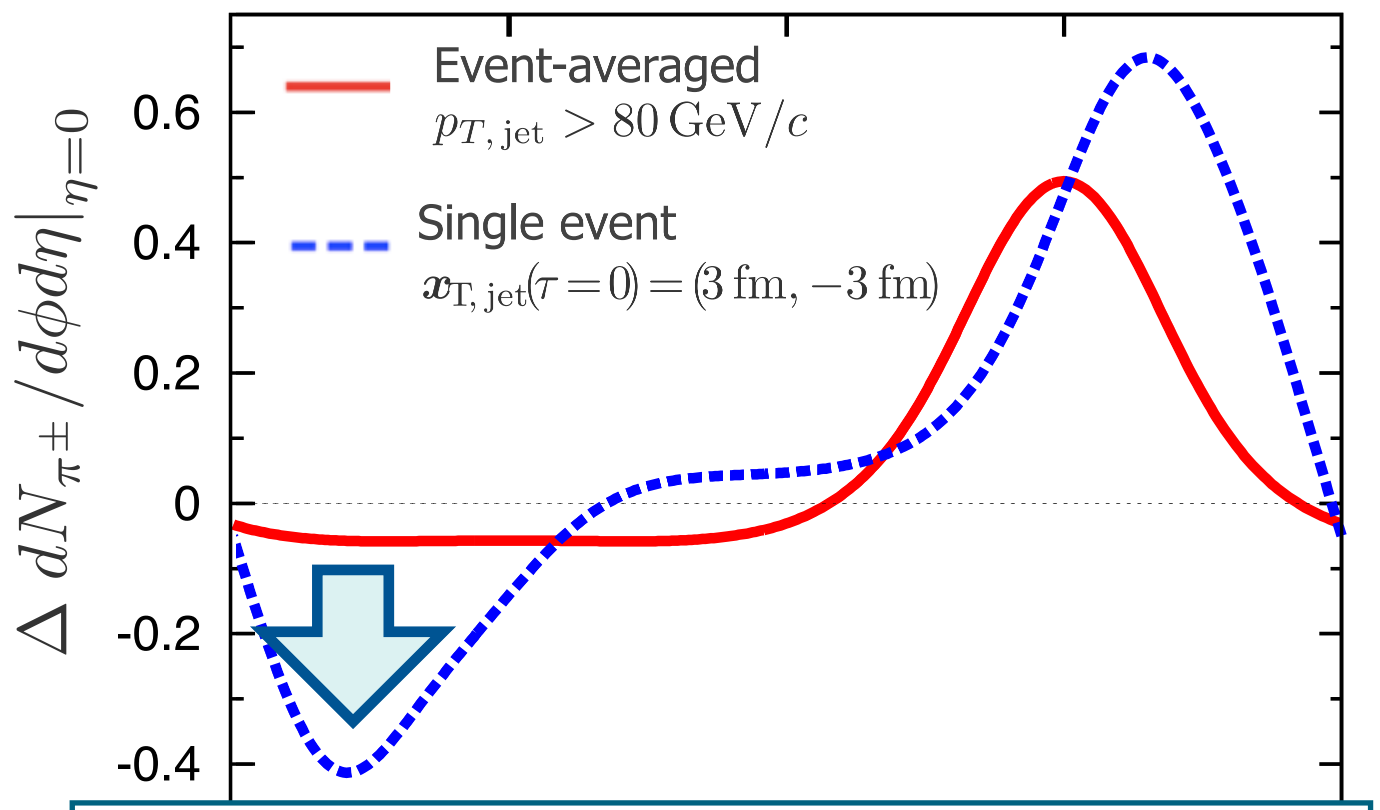
Spectra after hydro evolution

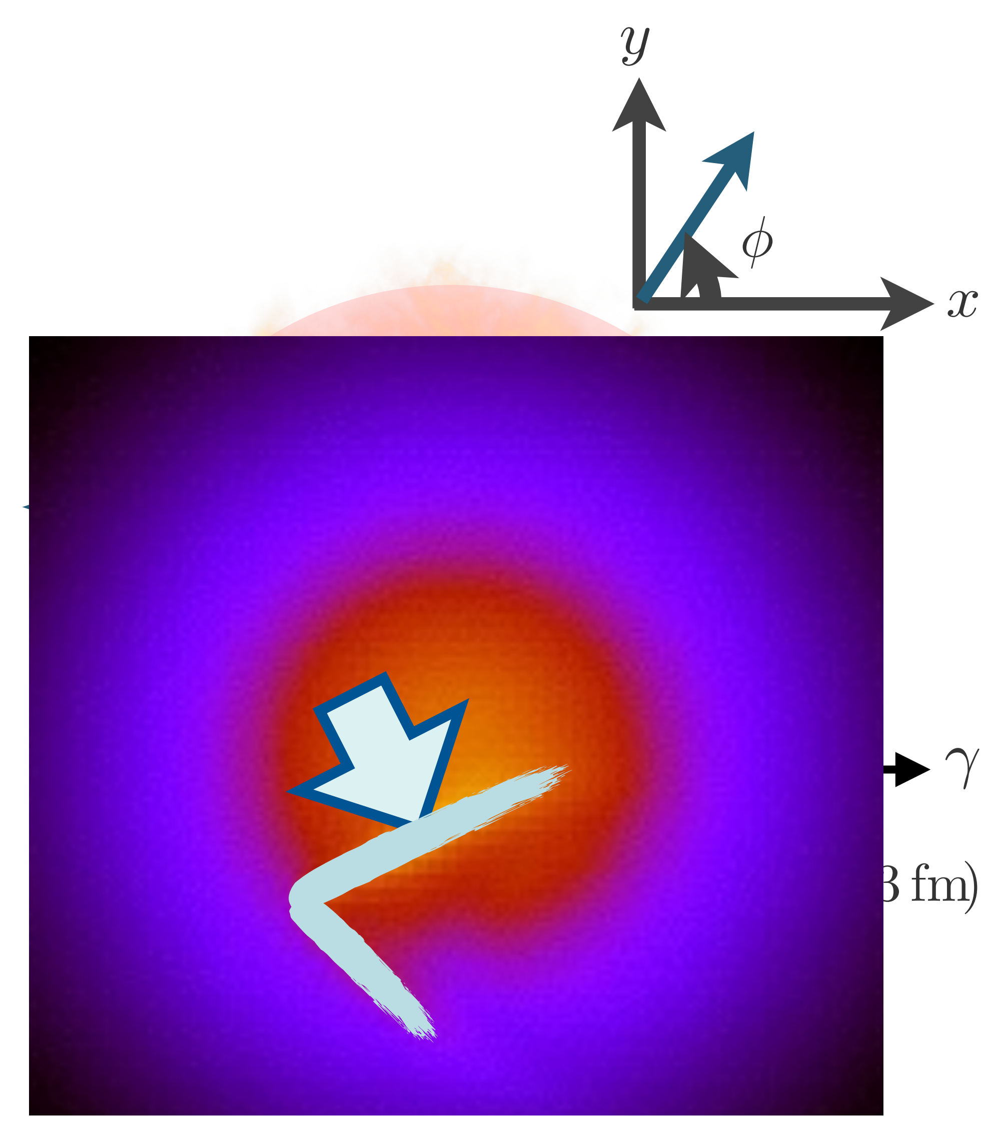
- Increase of the particles from the medium

$$\Delta \frac{dN_{\pi^\pm}}{d\phi d\eta} = \frac{dN_{\pi^\pm}}{d\phi d\eta} - \left.\frac{dN_{\pi^\pm}}{d\phi d\eta}\right|_{\rm w/o\ jet} \qquad (1 < p_T < 2\,{\rm GeV}/c)$$

Particles from jet fragmentation are not included

- Azimuthal-angle distribution





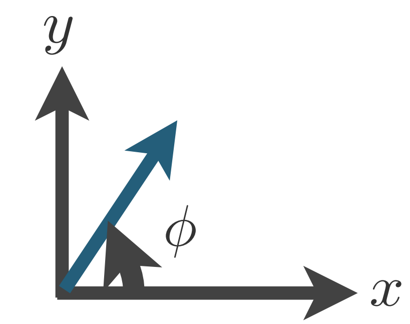
Interplay between the Mach cone and the radial flow

Constraint on the jet path

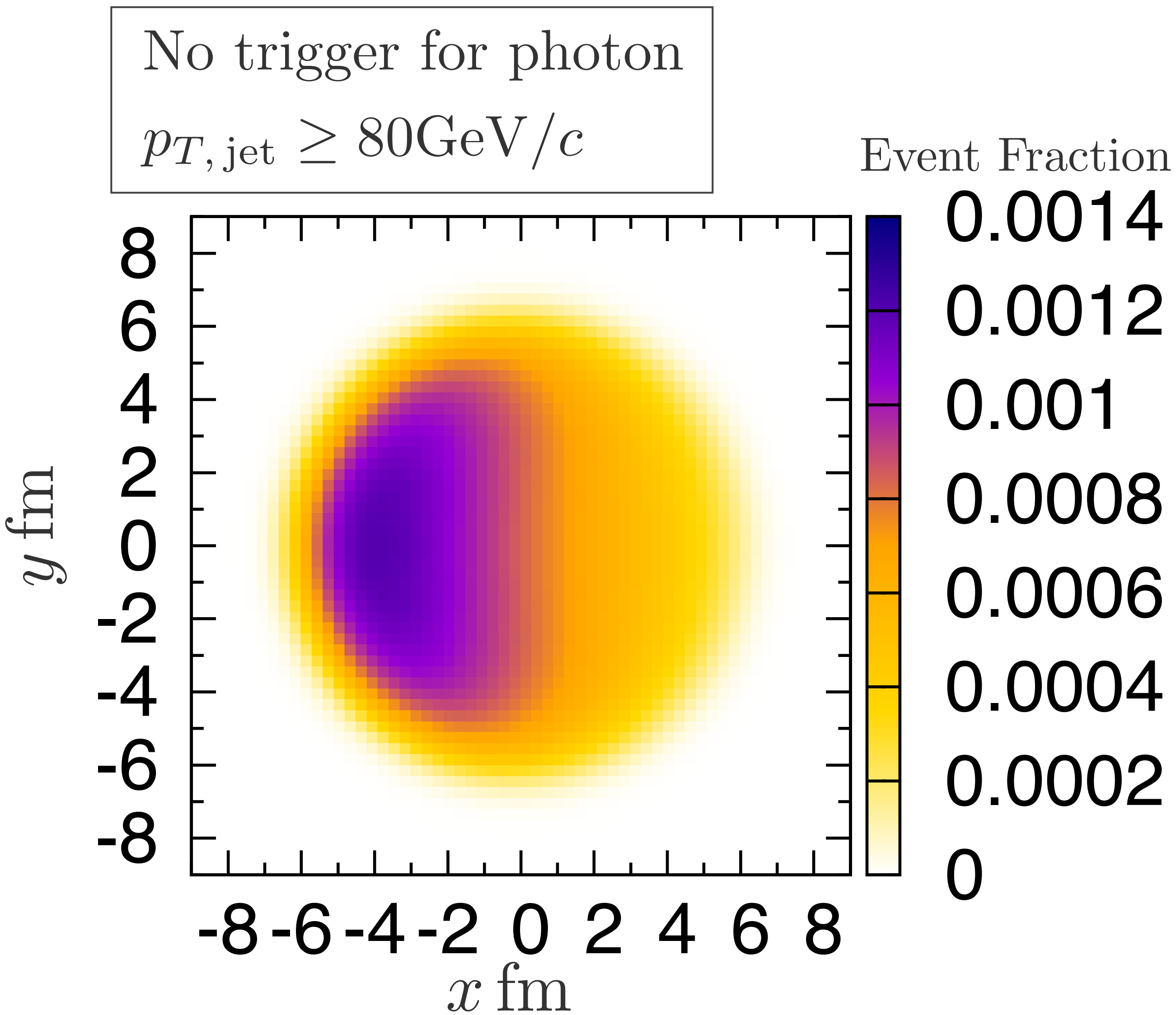
Off-central path → Dip

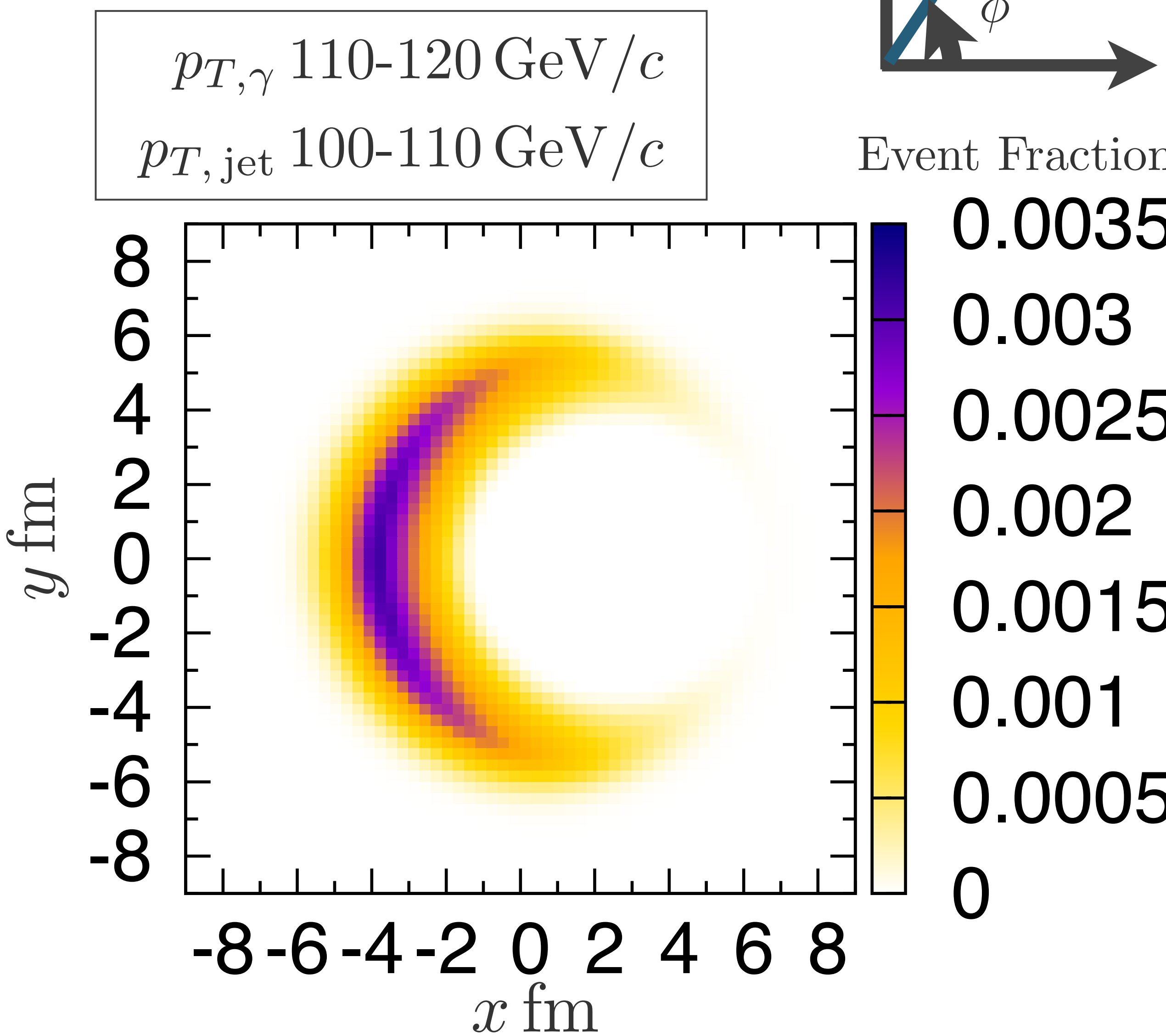
- Trigger for photon

Extract small energy-loss events



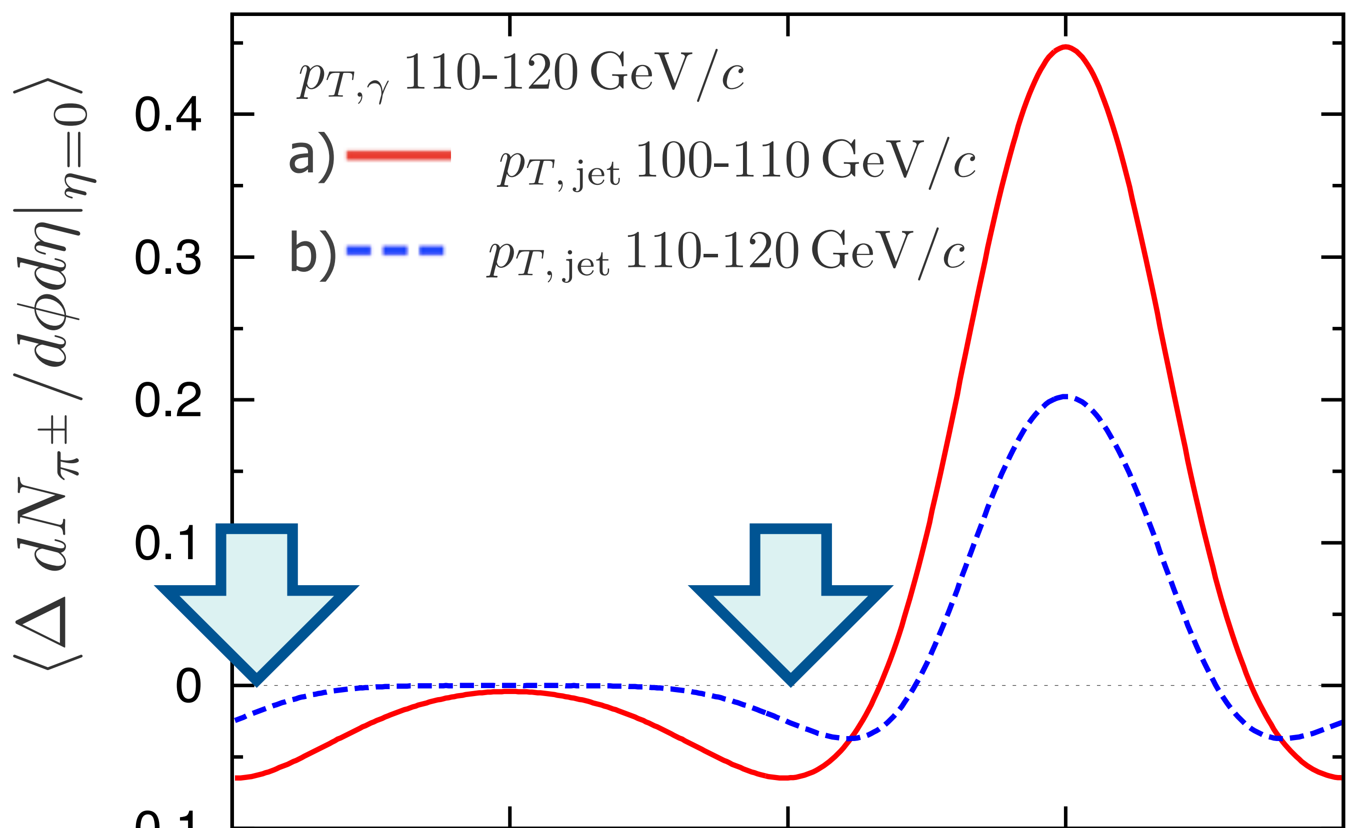
- Jet production point distribution

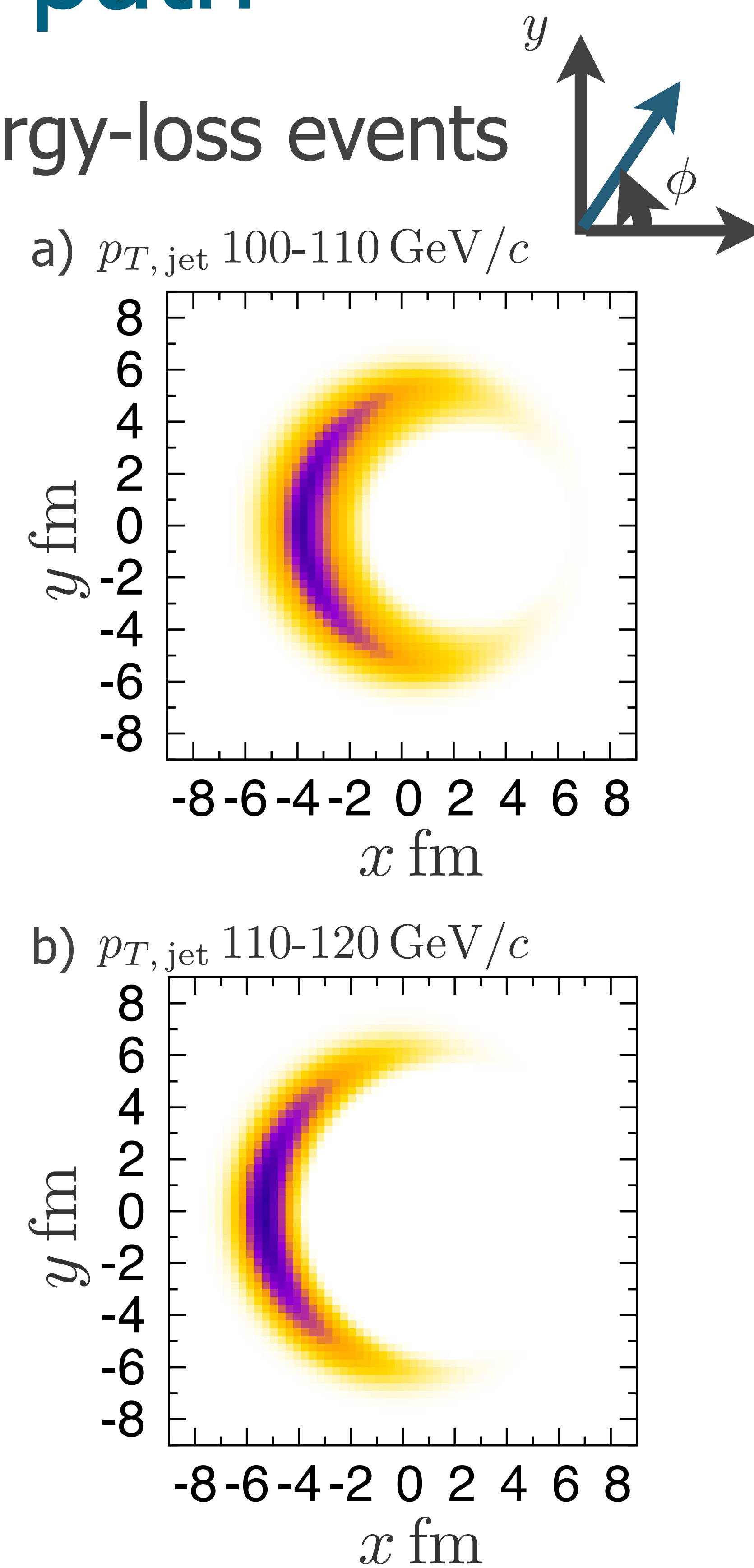




Constraint on the jet path

- Azimuthal-angle distribution for small energy-loss events





Interplay between
the Mach cone and the radial flow

Summary and Outlook

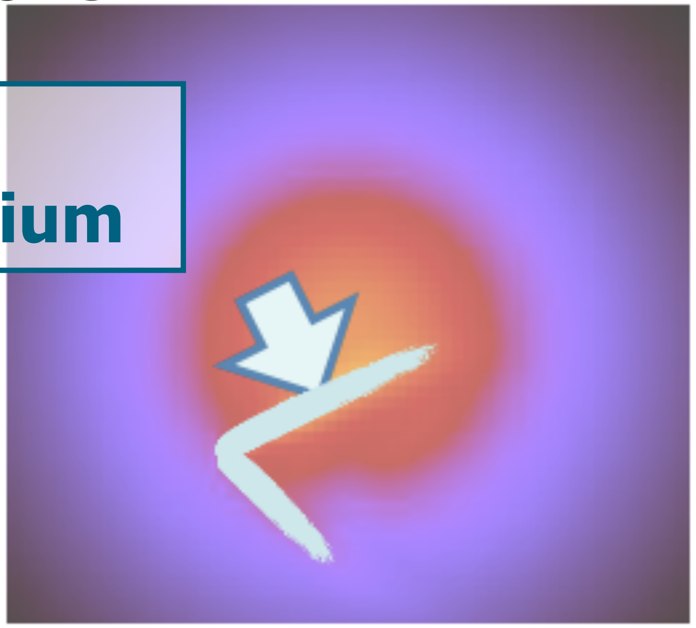
Summary

- Jet quenching in heavy ion collisions
- Medium response to jet quenching
  - Influence on many observables
- Mach cone in expanding QGP fluid

YT and T. Hirano, arXiv:1510.06966

  - Hydrodynamic eq. with source term
  - Suppression due to the push back by Mach cone

Direct signal of the Mach cone
Information about the jet path in the medium



Constraint on the jet path

Trigger also for photon in gamma-jet events

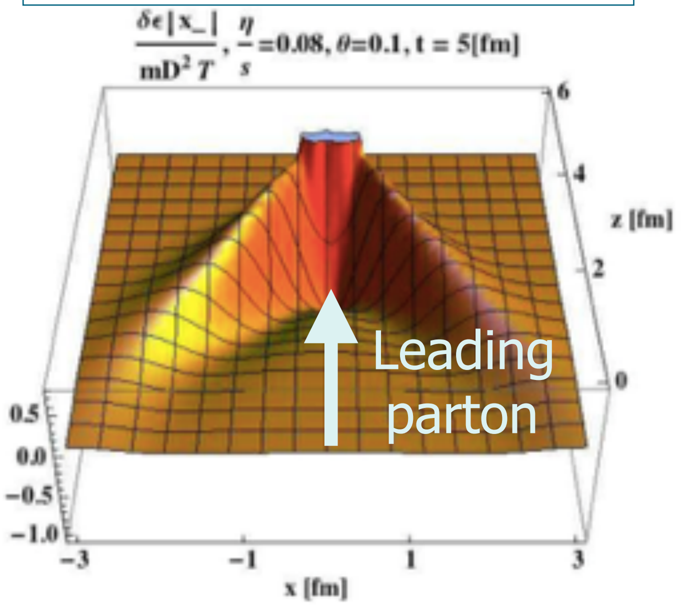
Outlook

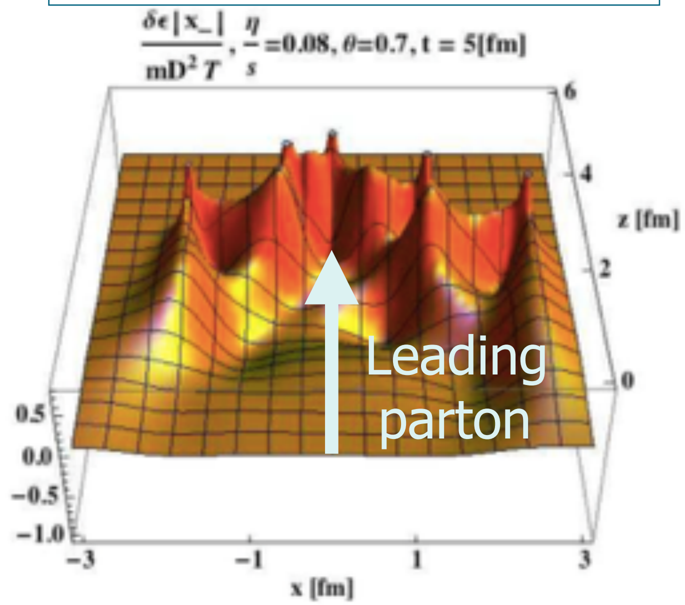
- Full jet energy deposition
  - Parton shower

small angle gluon radiation

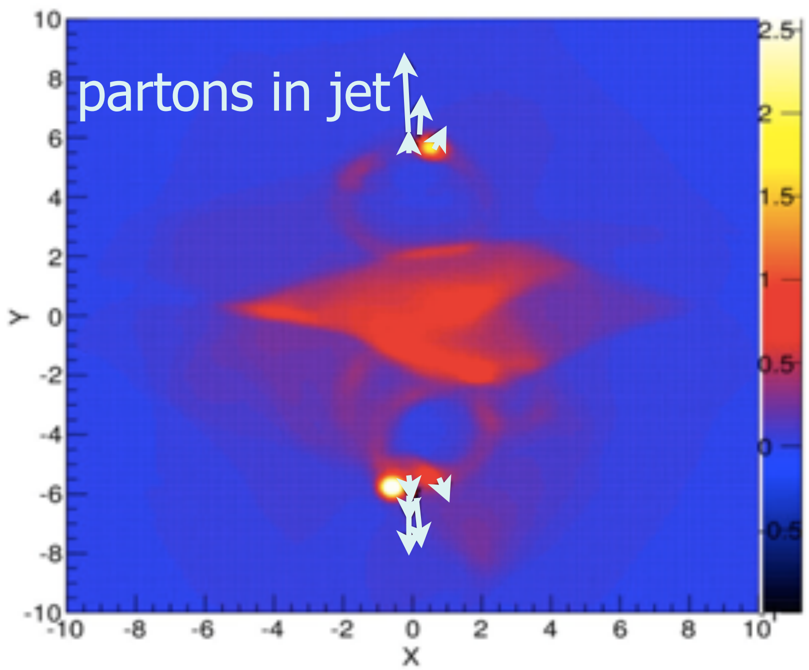
large angle gluon radiation

w/ initial fluctuation



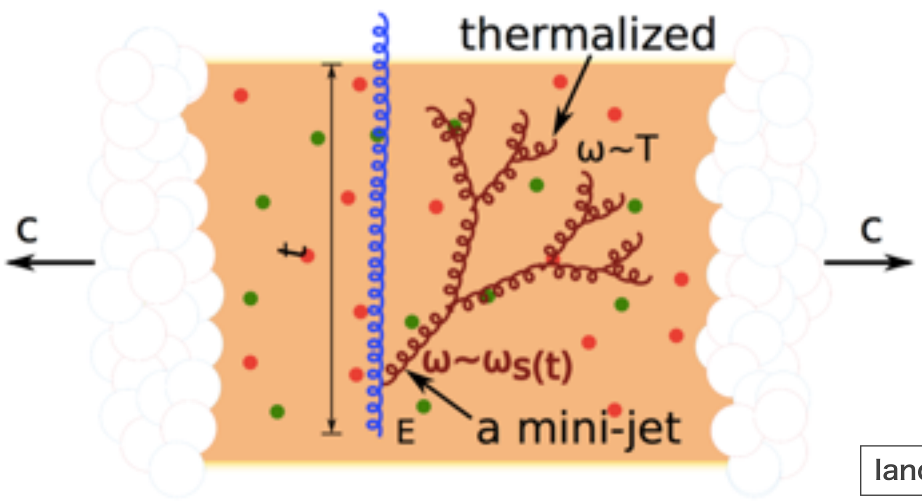


Adapted from Neufeld, Vitev ('12)

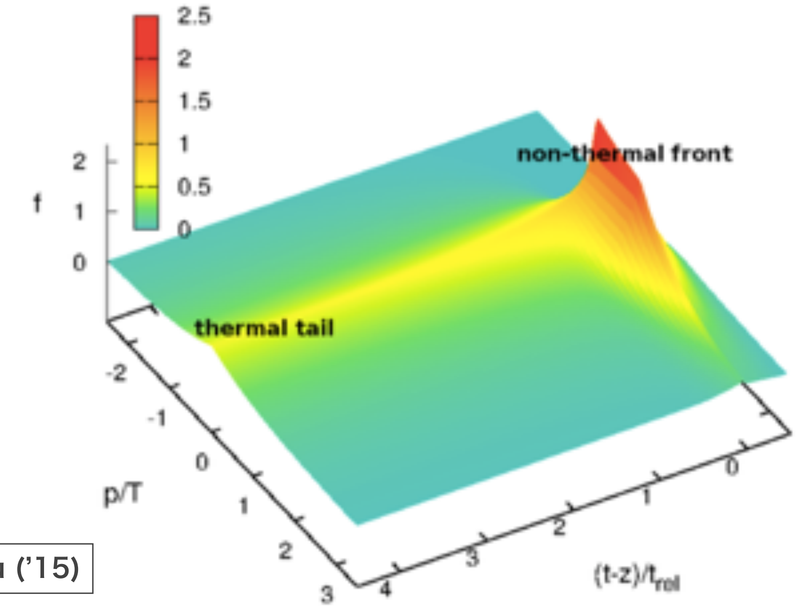


Adapted from He, Stoecker, Pang, Luo , Wang, Wang, Wei ('16)

  - Thermalization process



Iancu, Wu ('15)



How do deposited energy and momentum thermalize and diffuse in medium?