Jet structure in integrated EPOS3-HQ approach

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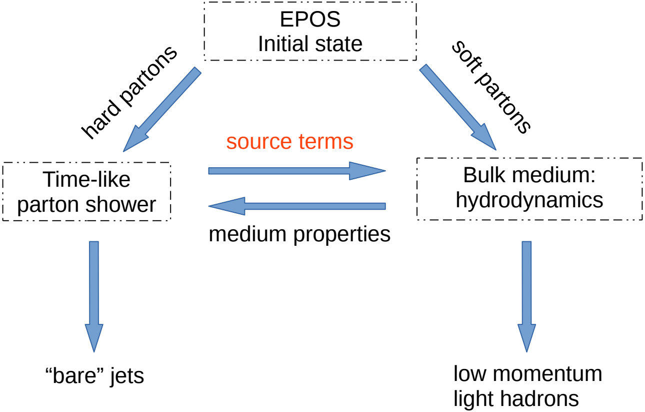
The goal

To fully integrate jets into the EPOS3 model.



EPOS
Initial state

hard partons

soft partons

source terms

Time-like
parton shower

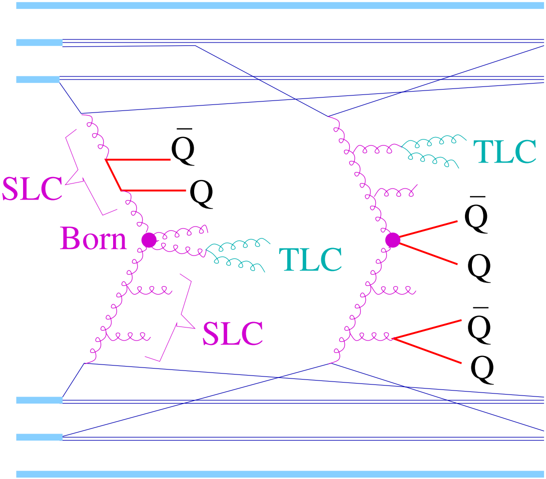
Bulk medium:
hydrodynamics

medium properties

“bare” jets

low momentum
light hadrons

EPOS initial state



Parton-Based Gribov-Regge Theory

H. J. Drescher, M. Hladik, S. Ostapchenko, T. Pierog, K. Werner, Phys. Rept. 350, 93, 2001

Pomeron = parton ladder, treated as a kinky string.

Spacelike cascades including Born process in the EPOS IS provide partons with all p_T which are further separated into core and corona.

Hydrodynamic background

For this study and in order to explore the effects in a clear way:

Averaged(smooth) hydrodynamic initial state compartible with EPOS3.

Equation of state: Laine & Schroeder '06, compartible with s95p-v1.2 EoS.
M. Laine, Y. Schroeder Phys. Rev. D73 (2006) 085009

3+1 dimensional viscous hydrodynamics:

$$T^{\mu\nu} = (\varepsilon + p)u^{\mu}u^{\nu} - p \cdot g^{\mu\nu} + \pi^{\mu\nu}$$

$$\partial_{;\nu}T^{\mu\nu} = 0, \quad \partial_{;\nu}N^{\nu} = 0$$

$$< u^{\gamma}\partial_{;\gamma}\pi^{\mu\nu} >= -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\text{NS}}}{\tau_{\pi}} - \frac{4}{3}\pi^{\mu\nu}\partial_{;\gamma}u^{\gamma}$$

solved with vHLLE code, Comput. Phys. Commun. 185 (2014), 3016
`https://github.com/yukarpenko/vhlle`

Time-like parton shower

Core algorithm made by **Martin Rohrmoser**:

- Monte Carlo simulation of DGLAP equations for a parton shower between virtuality scales $Q_\uparrow$ (from Born process in EPOS) and $Q_\downarrow = 0.6$ GeV.
- Radiative energy loss (virtuality gain) a là YaJEM:
  $\frac{dQ^2}{dt} = \hat{q}_R(t,x), \quad \hat{q}_R(t,x) = \frac{210}{1+53\cdot T} T^3(t,x)$
- Collisional energy loss: longitudinal drag
  $\frac{dp_\parallel}{dt} = -A(t,x), \quad A = \frac{\hat{q}_R}{0.09+0.715\cdot T(t,x)/0.16}$
- Mean lifetime of a parton between the branchings is $\Delta t = E/Q^2$.

Caveats

- No hadronization model plugged in yet (in progress).
- No jet reconstruction algorithm plugged in yet (in progress).

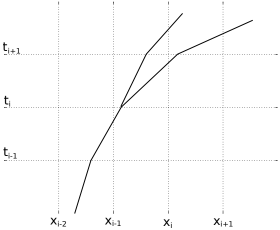
⇒ **I do not draw any comparison to experimental data.**

Jet-medium interaction

- Fluid and jet evolutions run in parallel:

fluid timestep → jet timestep → fluid timestep → …

- The temperature and flow velocity are taken from the hydrodynamic evolution



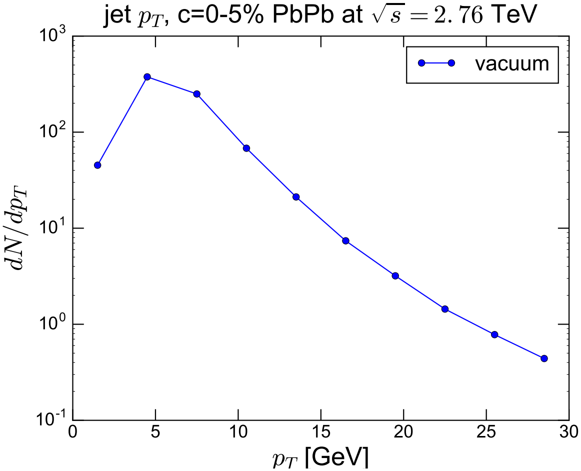
- Jet partons lose energy/momentum in the local rest frame (LRF) of the fluid:

(global frame) boost to LRF → solve $\frac{dQ^2}{dt} = \hat{q}_R(t,x)$, $\frac{dp_\parallel}{dt} = -A(t,x)$ → boost back to global frame → calculate lost energy/momentum

- Once the energy of a parton in the fluid rest frame drops below $\alpha \cdot T(t,x)$, the parton is melted into the fluid: its energy/momentum is distributed around nearby fluid cells, and the parton is removed from the parton cacsade.

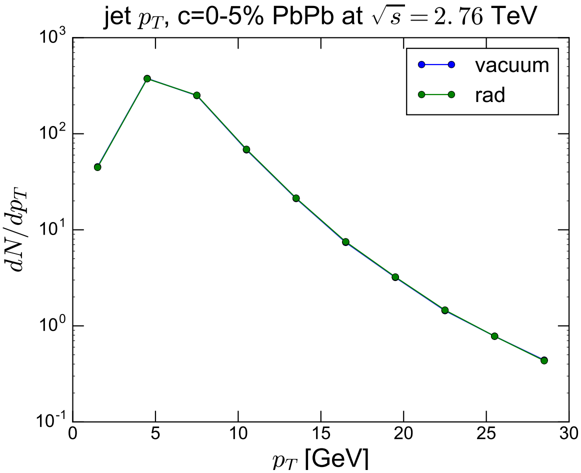
- The fluid acquires the lost energy/momentum (absorption) via the source terms: $\partial_{;\nu} T^{\mu\nu} = J^\mu$

Results: jet p_T



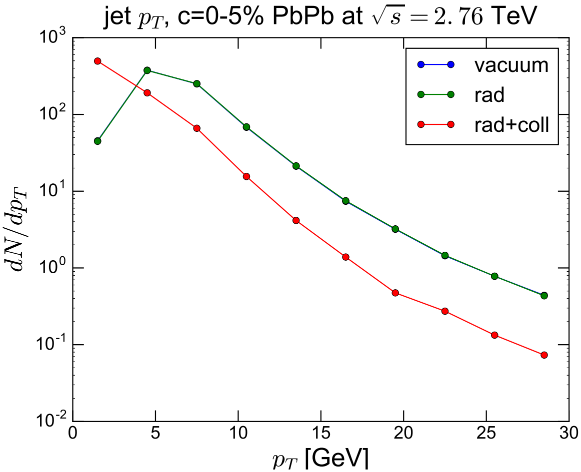
● vacuum

Results: jet p_T



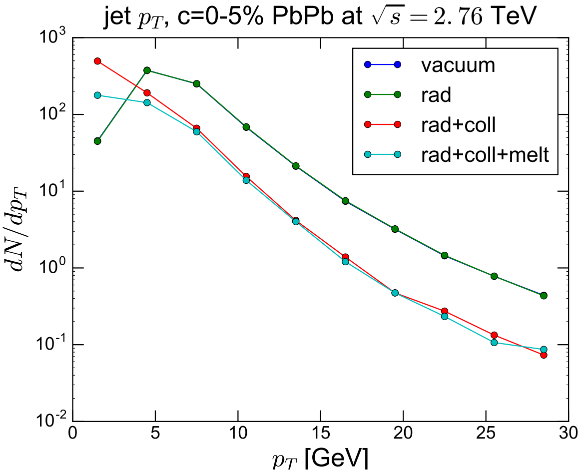
- vacuum
- radiative

Results: jet p_T



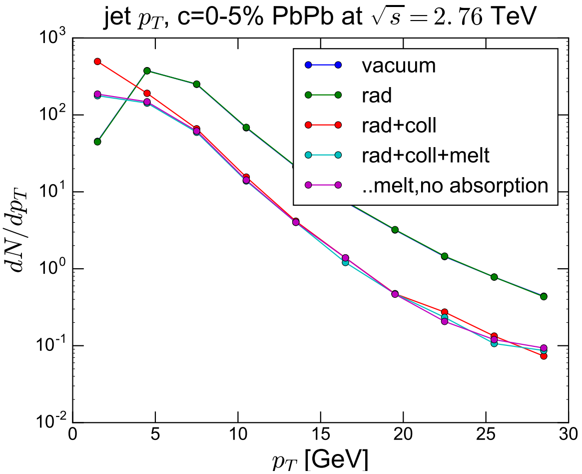
- vacuum
- radiative
- coll+rad

Results: jet p_T



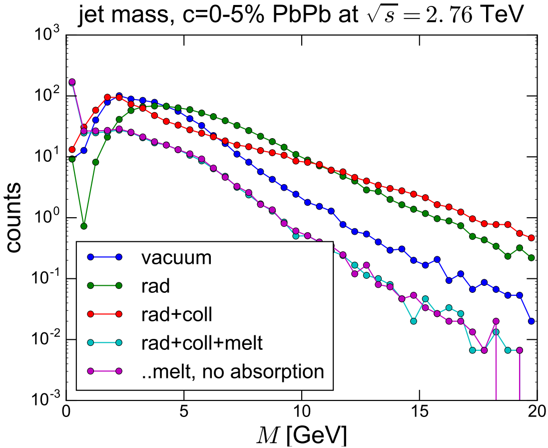
- vacuum
- radiative
- coll+rad
- ...+melting
  $E < 3 \cdot T$

Results: jet p_T



- vacuum
- radiative
- coll+rad
- ...+melting
  $E < 3 \cdot T$
- ...+no absorption
  by the fluid

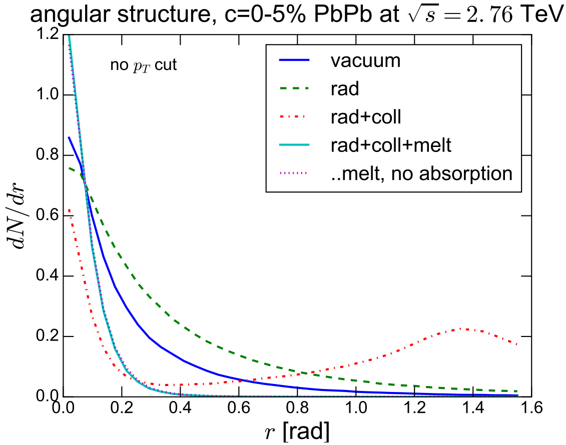
Jet mass



$$M^2 = \left(\sum_{i\in jet} p_i^\mu\right)^2$$

- Jet mass distribution at high M is very sensitive to the melting scenario.
- Turning the absorption on/off does not make difference for the jet itself (which is naively expectable).

Angular structure of a jet

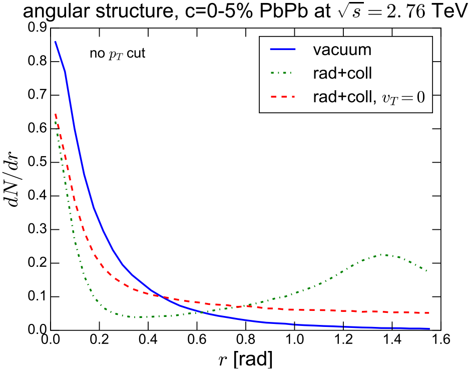


- Radiative EL → broadening (more secondary splittings)
- Collisional EL → 1) grooming at small ρ and 2) a wide peak around $\approx \pi/2$
- Parton melting kills the peak around $\approx \pi/2$
- Switching the absorption off does not influence the jet structure

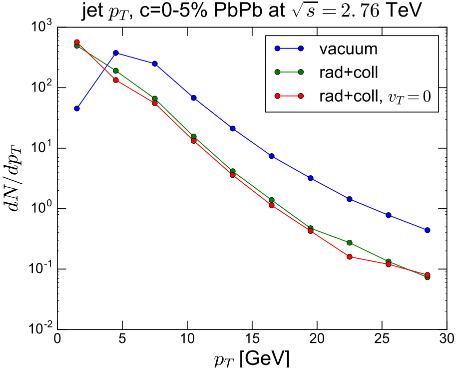
Effects of radial flow

The structure around $\rho \approx \pi/2$ is an effect of radial flow.

Effect for dN/dr



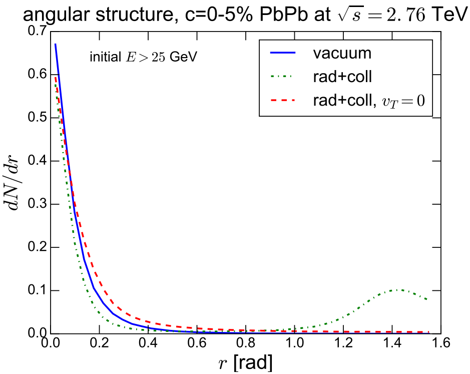
No effect for jet p_T



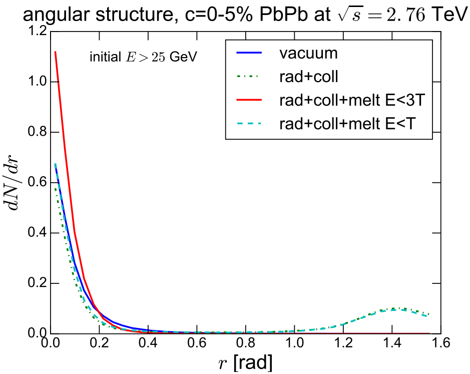
- Switching the transverse expansion off kills the peak in the ρ distribution.
- Influence on the p_T distribution is tiny: the main effect of radial flow (switched off here) is faster system cooling, and so smaller energy loss.

Other effects

- larger initial jet energy selection



- different parton melting criterion

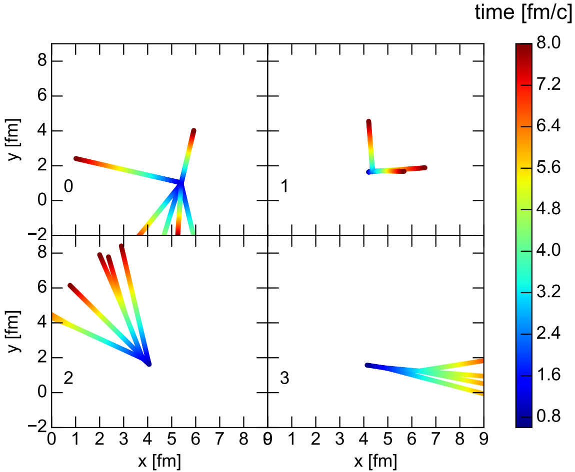


- cut on initial E_{jet}: less differences at small r, the large r peak survives.
- Parton melting at $E < 3T$ destroys the peak, however milder melting criterion $E < T$ preserves it.

Effects of radial flow (2)

Space trajectories of 4 randomly chosen jets.

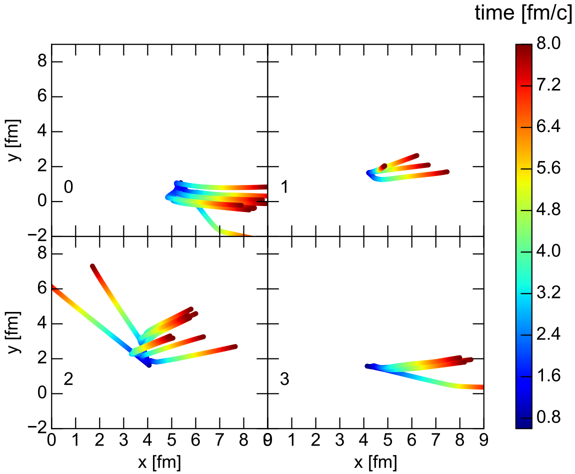
No medium interaction:



Effects of radial flow (2)

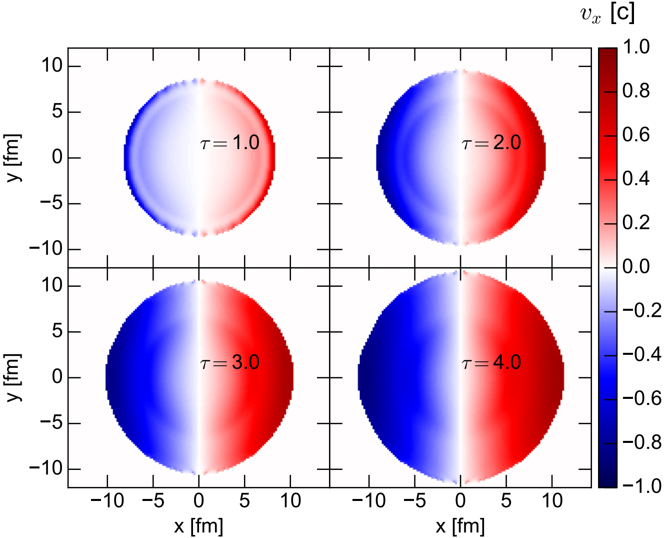
Space trajectories of 4 randomly chosen jets.

radiative+collisional energy loss, no melting:



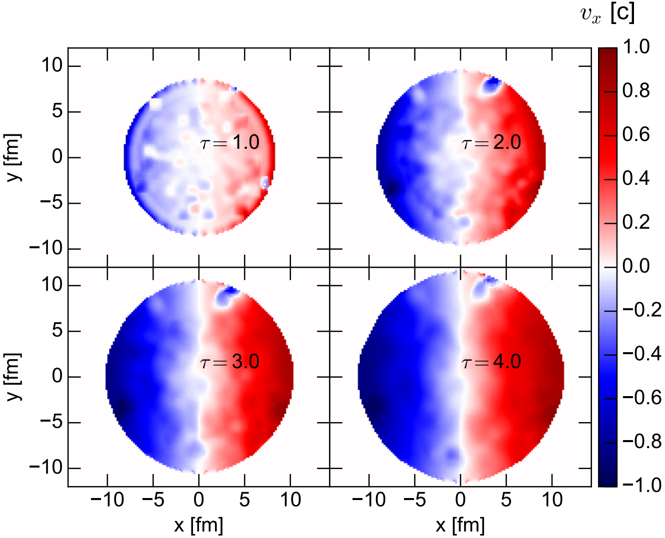
Back reaction on the fluid

Snapshots of the x component of fluid velocity at different times.
On this slide: **fluid with no absorption (benchmark/to guide the eye).**



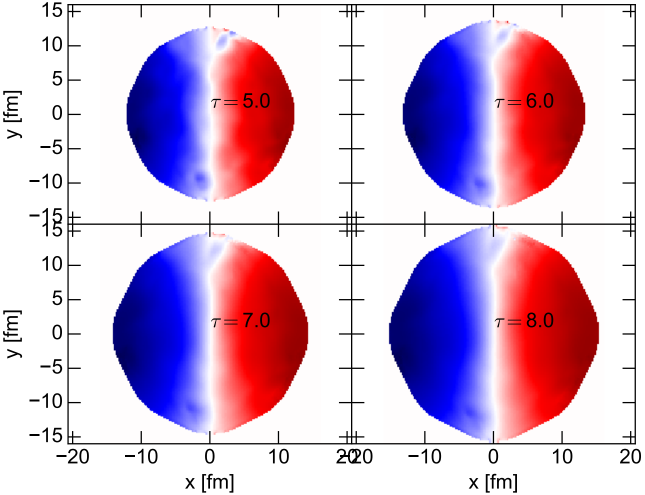
Back reaction on the fluid

Snapshots of the x component of fluid velocity at different times.
On this slide: **jet energy/momentum absorption at early times.**



Back reaction on the fluid

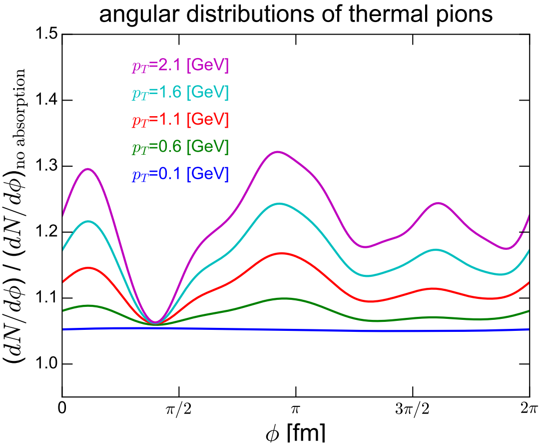
Snapshots of the x component of fluid velocity at different times.
On this slide: **Hydro smears out the perturbations at late times.**



Corresponding aziumthal distributions of hydro-born hadrons (pions)

Cooper-Frye prescription at $\varepsilon = \varepsilon_{\mathrm{sw}} = 0.5$ GeV/fm^3:

$$p^0 \frac{d^3 n_i}{d^3 p} = \sum f(x,p) p^\mu \Delta\sigma_\mu, \qquad f(x,p) = f_{\mathrm{eq}} \cdot \left(1 + (1 \mp f_{\mathrm{eq}}) \frac{p_\mu p_\nu \pi^{\mu\nu}}{2T^2(\varepsilon + p)}\right)$$



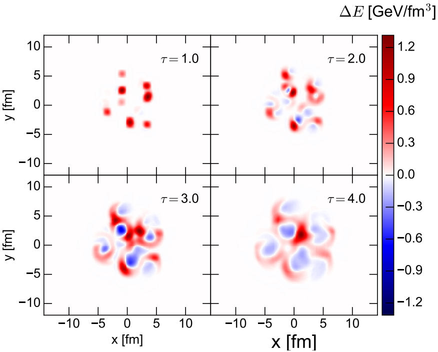
In hydrodynamics:

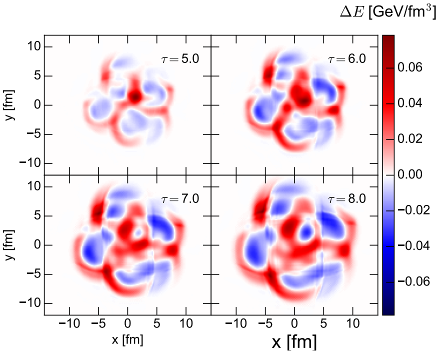
- low-p_T hadrons are dominantly produced at late times
- high-p_T hadrons are dominantly produced at early times from the periphery

  $\Downarrow$
- high-p_T hadrons are sensitive to the perturbations in the medium

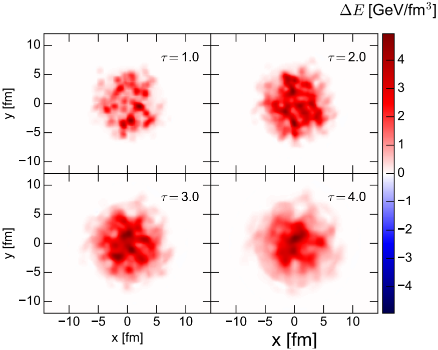
Mach cones!

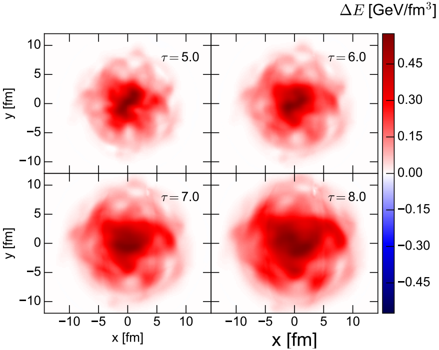
A simplified setup: few most energetic jet partons with initial $Q > 20$ GeV.





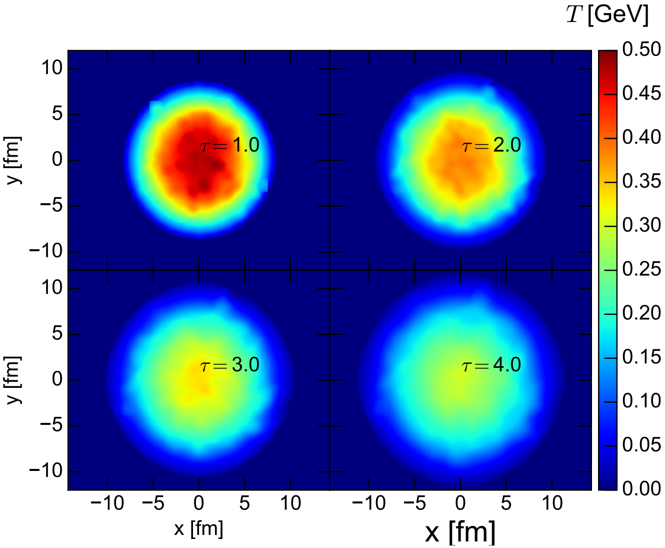
A more realistic case at LHC energy: jet partons with initial $Q > 2$ GeV.





Back reaction on the fluid (2)

Corresponding temperature profiles at different times:

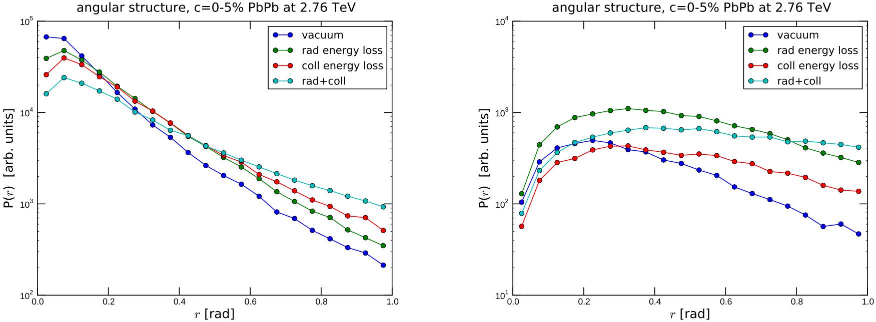


Updated calculation (NEW)

- Event-by-event 3D viscous hydro for the medium
- Random transverse kicks to the jet partons: $d\langle p_\perp\rangle^2/dt = \hat{q}_C$
- Jet angular structure a-la CMS (CMS-PAS-HIN-16-020):

$$P(r) = \frac{1}{\delta r}\frac{\sum_{\mathrm{jets}}\sum_{\mathrm{tracksin(r,r+\delta r)}} p_\perp}{\sum_{\mathrm{jets}}\sum_{\mathrm{tracks}} p_\perp}$$

$p_{\mathrm{trk}} > 1$ GeV $\quad\quad$ $0.7 < p_{\mathrm{trk}} < 1$ GeV



Summary

We have presented a first calculation where jets and bulk hydrodynamic evolution run in parallel mode.

- Initial conditions and initial jet partons: EPOS
- Timelike parton cascade by Martin Rohrmoser
- 3+1 dimensional viscous hydrodynamics for the medium
- Bi-directional interaction between the two

Some lessons:

- Radial flow causes a spread of a fraction of jet energy to a relatively large angle $\approx \pi/2$.
- Back reaction of the jet energy loss to the fluid has a negligible effect for the jet itself (no jet recoil here!).
- However, the energy absorption causes perturbations in the hydro evolution which are strongest at early times and therefore influence thermal hadron production at "large thermal" momenta $> 1 - 1.5$ GeV.
- → This influences the correlations of high-p_T jet hadrons with their $p_T > 1.5$ GeV "thermal" colleagues.

Obviously, work in progress.