Jet-fluid interaction in EPOS3-HQ framework

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with Martin Rohrmoser[2], Joerg Aichelin[1], Pol Gossiaux[1], Klaus Werner[1]

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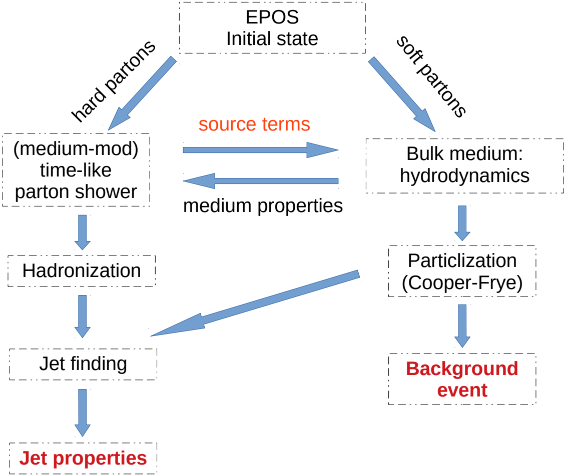
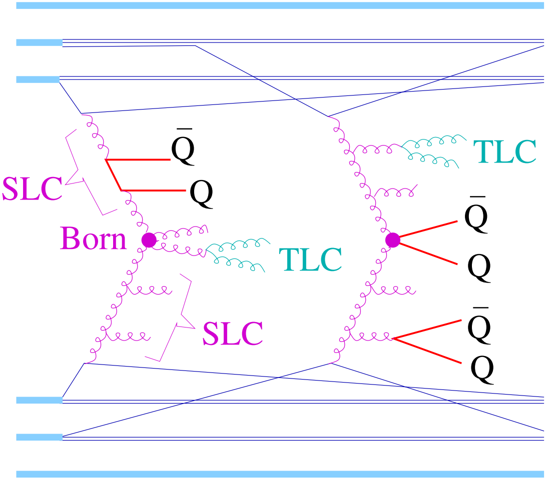
The idea

To get both hydrodynamic IS and initial hard partons from EPOS3.



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

Event-by-event initial state from EPOS.

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:

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

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

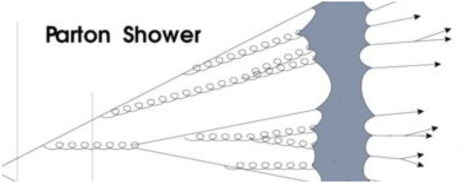
$$< u^\gamma \partial_{;\gamma} \pi^{\mu\nu} >= -\frac{\pi^{\mu\nu} - \pi^{\mu\nu}_{\mathrm{NS}}}{\tau_\pi} - \frac{4}{3}\pi^{\mu\nu}\partial_{;\gamma}u^\gamma$$

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**:

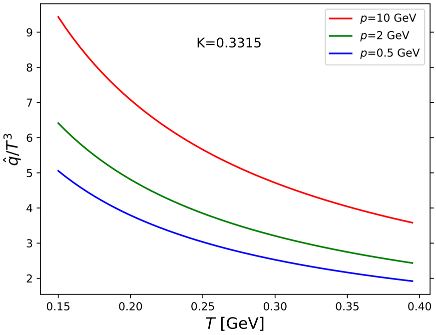
- Monte Carlo simulation of DGLAP equations for a parton shower between virtuality scales $Q_\uparrow$ (from Born process in EPOS) and $Q_\downarrow = 0.6$ GeV.

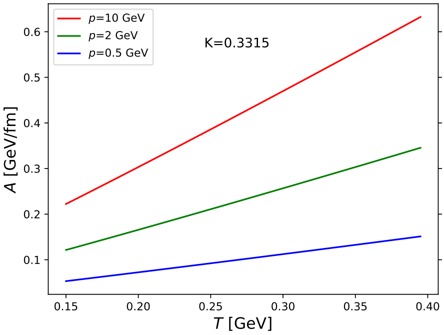


- Medium modified radiation (splittings) a là YaJEM: $\frac{dQ^2}{dt} = +\hat{q}_R(t,x)$
- Collisional energy loss: longitudinal drag $\frac{dp_\parallel}{dt} = -A(t,x)$
- Collisional energy loss: transverse kicks $\Delta p_\perp = n_\perp \sqrt{\hat{q}_C \cdot \Delta t}$
- Mean lifetime of a parton between the branchings is $\Delta t = E/Q^2$.

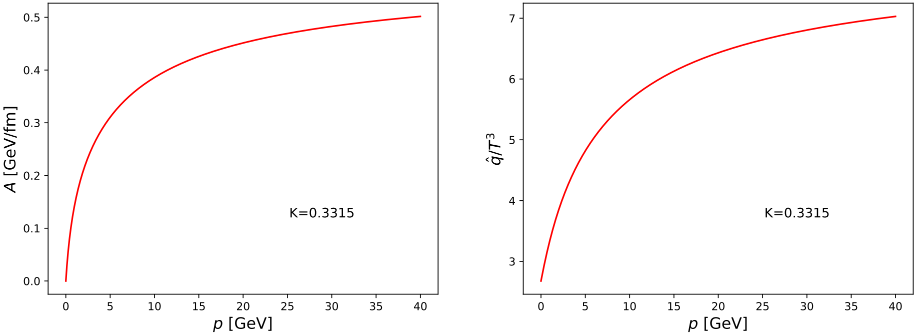
Transport coefficients

- Temperature and momentum dependence from HQ studies in:
  P.B. Gossiaux, R. Bierkandt, J. Aichelin, Phys.Rev. C79 (2009) 044906.
- multiplied by a K-factor to normalize to $\hat{q}$ in MARTINI





- both $\hat{q}$ and A are momentum dependent:

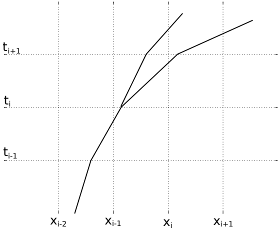


Jet-medium interaction

- Fluid and jet evolutions run in parallel:

fluid timestep	$\rightarrow$	jet timestep	$\rightarrow$	fluid timestep	$\rightarrow \dots$

- 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:

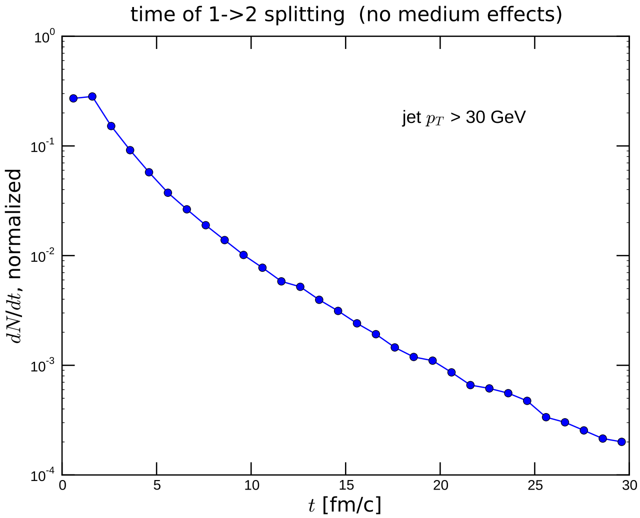
(global frame) boost to LRF	$\rightarrow$	solve $\frac{dQ^2}{dt} = \hat{q}_R(t,x)$, $\frac{dp_\parallel}{dt} = -A(t,x)$	$\rightarrow$	boost back to global frame	$\rightarrow$	calculate lost energy/momentum

- 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 cascade.

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

Sample jet evolution and medium response

Timeline of parton splittings

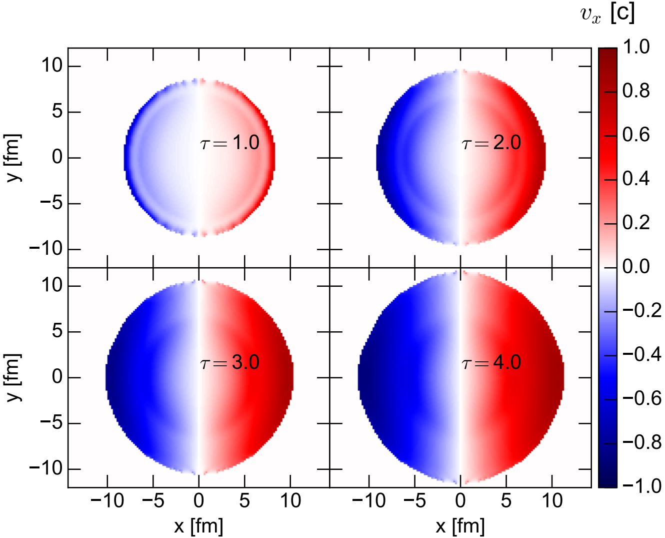


Majority of splittings happen at early times, assuming $\Delta t = E/Q^2$ ansatz.

Medium recoil

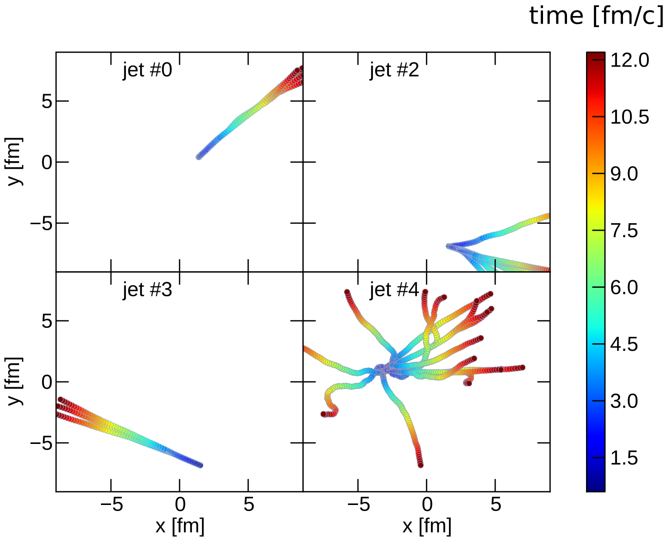
Snapshots of the x component of fluid velocity at different times.

Averaged IS, fluid with no absorption (benchmark/to guide the eye).



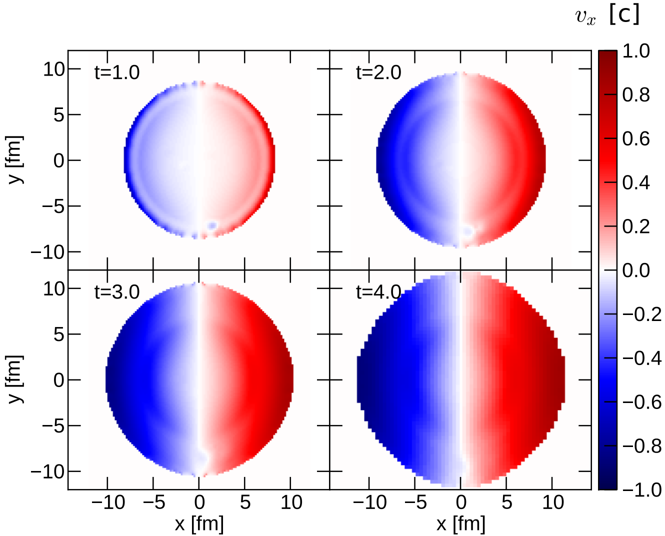
Medium recoil (2)

A randomly picked jet event.



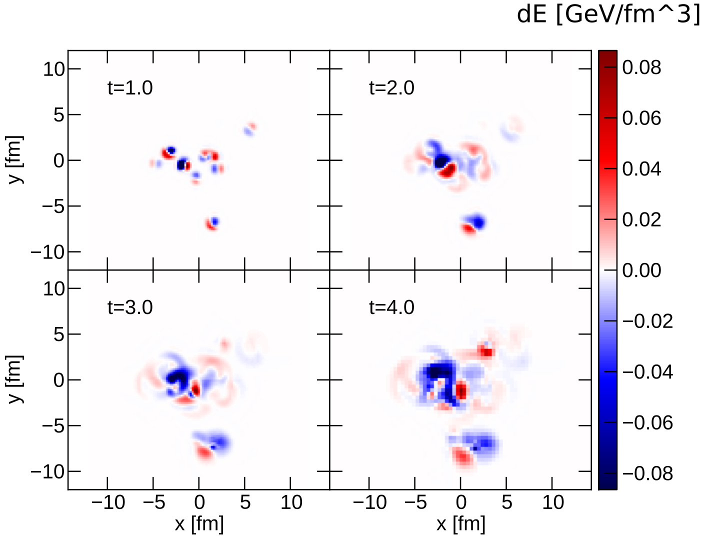
Medium recoil (3)

Snapshots of the x component of fluid velocity at different times.
jet energy/momentum absorption at early times.



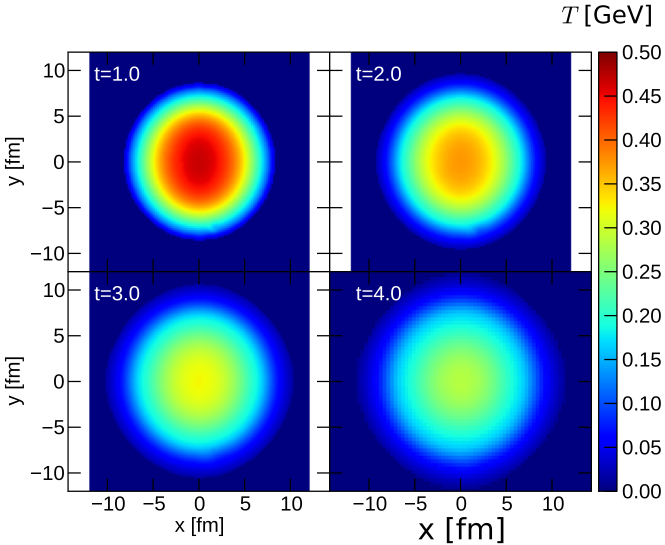
Medium recoil (4)

Mach cones. (notice the scale of ΔE !)



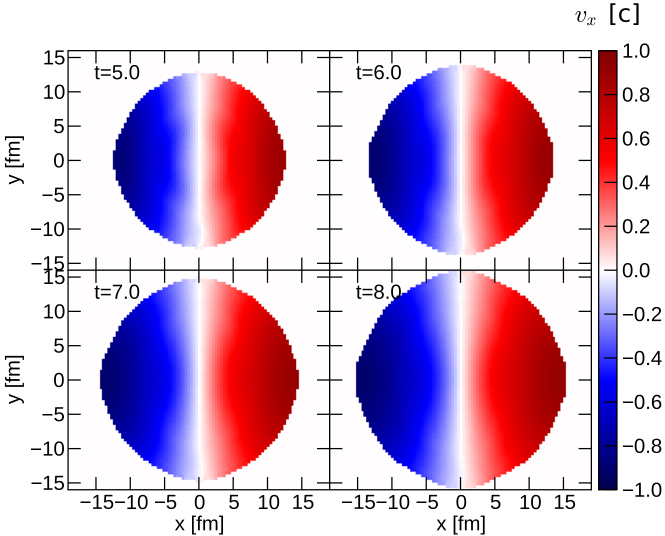
Medium recoil (5)

Perturbations to the temperature profile are tiny.



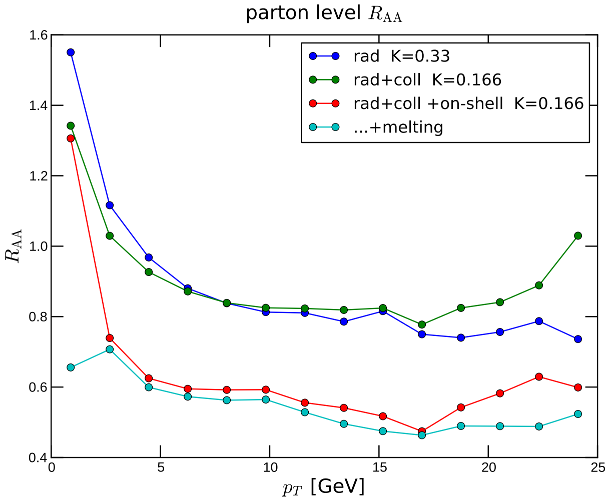
Medium recoil (6)

Hydro smears out the velocity kperturbations at late times.



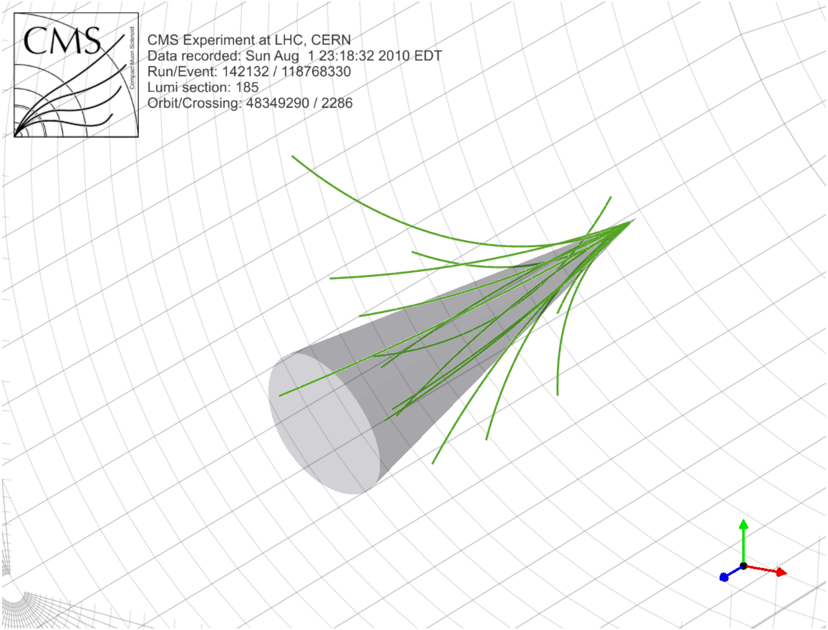
Results:
jet properties

Results: parton level R_{AA}



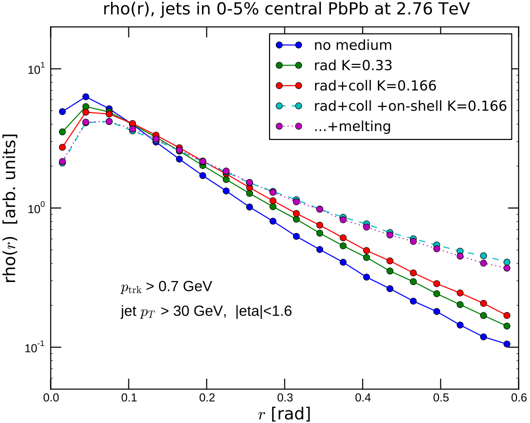
- 'radiative energy loss': enhancement at low-$p_\perp$ + suppression of high-$p_\perp$
- the rest of suppression comes from the collisional EL for 'on-shell' partons.

Jet Cones


CMS
Compact Muon Solenoid
CMS Experiment at LHC, CERN
Data recorded: Sun Aug 1 23:18:32 2010 EDT
Run/Event: 142132 / 118768330
Lumi section: 185
Orbit/Crossing: 48349290 / 2286

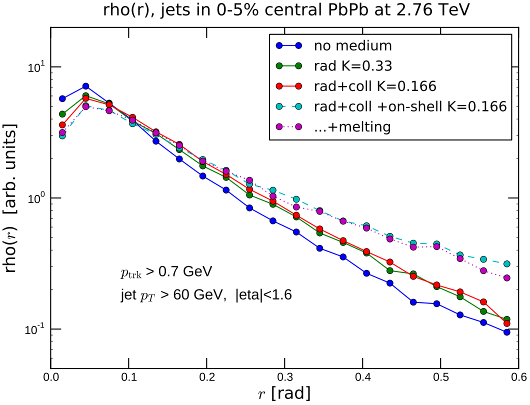
Angular structure of a jet

Jet angular structure a-la CMS (CMS-HIN-16-020): $P(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{\text{tracksin(r,r+}\delta\text{r)}} p_\perp}{\sum_{\text{jets}} \sum_{\text{tracks}} p_\perp}$



- Radiative EL → broadening (more secondary splittings)
- Collisional EL → broadening
- +on-shell collisional EL → even more broadening
- parton melting: hardly any effect

Same effects for higher jet $p_\perp$ threshold:



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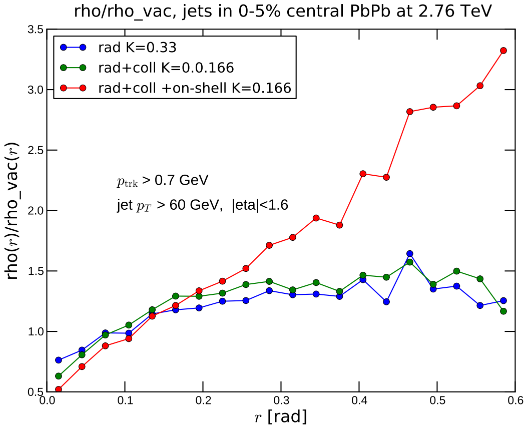
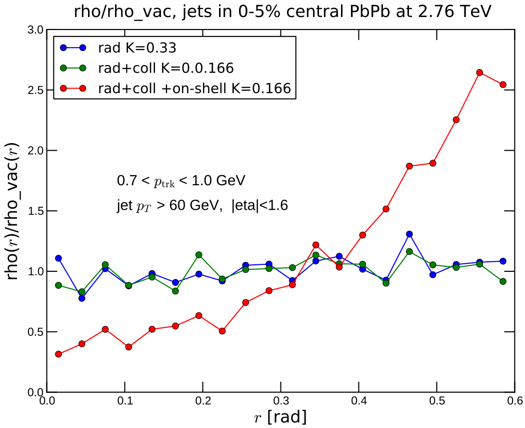
Ratio of of medium modified / "vacuum"* jet shapes:



* "vacuum" = no medium modification

Low-$p_{\rm trk}$ part of the jet is modified only by the on-shell collisional energy loss:



Summary

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

- Initial conditions and initial jet partons: EPOS3.
- Timelike parton cascade by Martin Rohrmoser.
- 3+1 dimensional viscous hydrodynamics for the medium expansion.
- Bi-directional interaction between the two.

Some lessons:

- With present $\hat{q}(T,p)$ and $A(T,p)$, a big part of the parton level $R_{\rm AA}$ and jet broadening comes from the collisional energy loss after last splittings.
- Energy lost by the jets causes perturbations in the hydro evolution which are strongest at early times.
  With the present energy loss settings, the 'medium recoil' is a small effect.

Outlook:

- Test the latter conclusion with the other bulk dynamics models.

Obviously, work in progress.

The end (so far)

Previous energy loss parametrization

Previously used energy loss parametrization:

- 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 $\Delta t = E/Q^2$.