

Jet-fluid interaction in EPOS3-Jet framework

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with Martin Rohrmoser², Joerg Aichelin¹, Pol Gossiaux¹, Klaus Werner¹

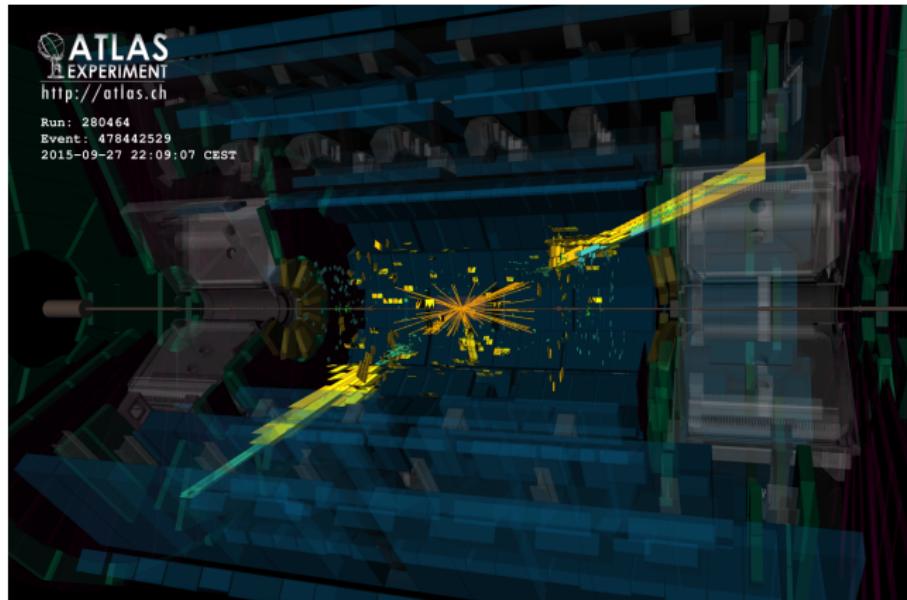
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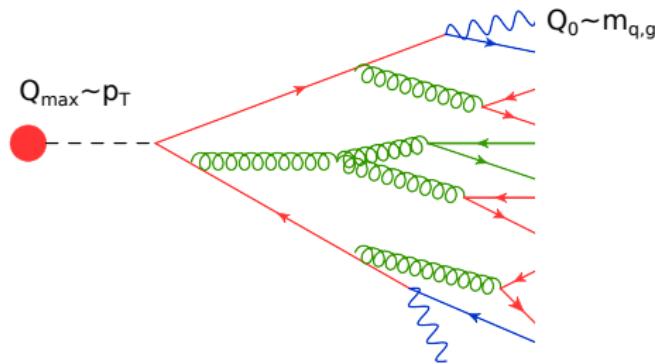
Outline

- Ideas and ingredients
- Results: basic jet properties
- Jet reconstruction

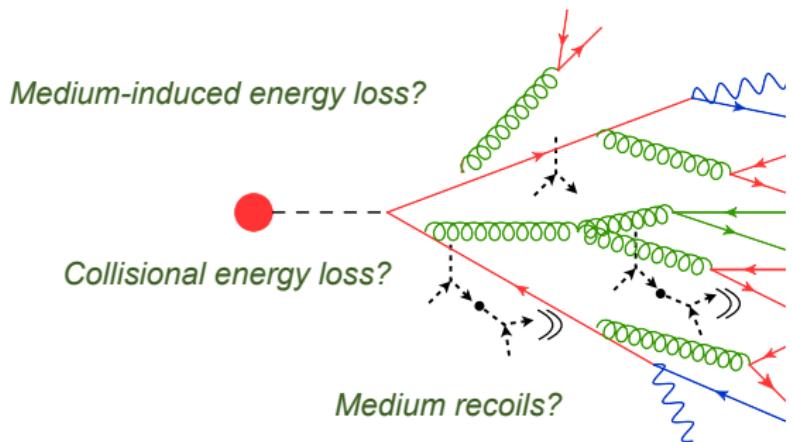


Jet is:

- a collimated spray of hadrons in detector
- a result of fragmentation of energetic quark/gluon



- parton shower in vacuum is well established (DGLAP)



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- medium effects in AA: radiative, collisional energy loss, medium recoil
→ a hard probe of HIC

JQ MC: (Partial) Summary

	Model	Parton Shower	Radiative energy Loss	Collisional Energy Loss	Medium Response	Thermalization	Jet-induced effects
Fully Dynamic	Q-PYTHIA	Pythia 6 with Modified Sudakov	BDMPS	X	X	X	X
	MATTER	Virtuality ordered with Modified Sudakov	Higher-Twist	X	X	X	X
	JEWEL	Pythia 6 with medium scatterings	pQCD + LPM effect	pQCD	Yes	X	X
Afterburners	PYQUEN	Pythia 6 Shower + Energy Loss	BDMPS	pQCD	X	X	X
	MARTINI	Pythia 8 initialisation + MC Rate Equations	AMY	pQCD	Yes	Yes	X
	Co-LBT	Pythia 6 Shower + Energy Loss	Higher-Twist	pQCD	Yes	Yes	Yes
	Hybrid	Pythia 6 Shower + Energy Loss	X	AdS/CFT	Yes	Yes (resulting effect at the final spectra)	
Analytical Approach (not MC)	Coupled Jet-Fluid	Pythia 6 initialisation + jet Evolution Equations	Higher-Twist	pQCD	Yes	Yes	Yes

(sorry for the ones that are not in this list...)

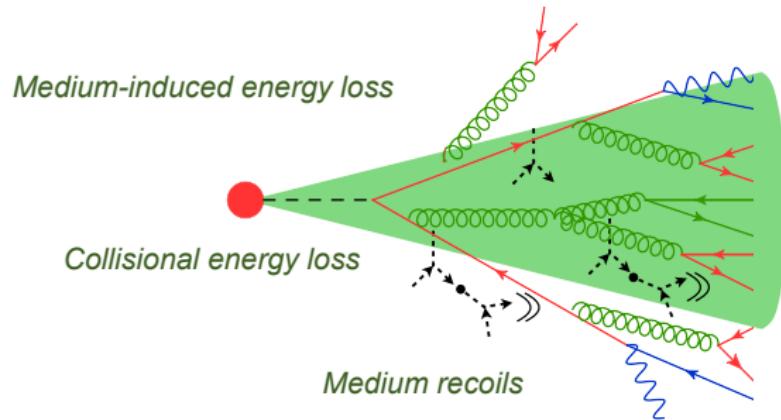
L. Apolinário

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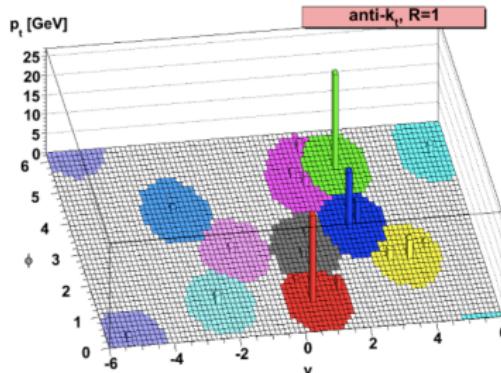
Jets in QCD matter: Monte Carlo approaches

(Taken from: Liliana Apolinário, Hard Probes 2018 talk)

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- parton shower in vacuum is well established (DGLAP)
- medium effects in AA: radiative, collisional energy loss, medium recoil
→ a hard probe of HIC
- jet is defined by a jet finding algorithm, both in experiment and in theory!
Typically: anti- k_T algorithm with different cone size R .



Anti- k_T :

Sequential clustering of objects in event (calo towers, tracks etc) with a particular distance measure:

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2},$$

$$d_{iB} = k_{ti}^{2p}, \quad p=-1$$

Results in cone-shaped, approximately R-sized jets

Gunther Roland

Hard Probes of the Hot Medium

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QM'15 Student Day

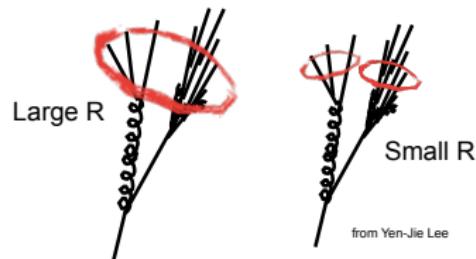
[Slide taken from Gunther Roland's student lecture at QM2015]

2008: Fastjet revolution

Cacciari, Salam, Soyez, JHEP 0804 (2008) 063

“anti- k_T ” replaced zoo of prior algorithms:

- conceptually simple
- theoretically sound
 - infrared safe
 - collinear safe
- computationally efficient & robust
- part of Fastjet package

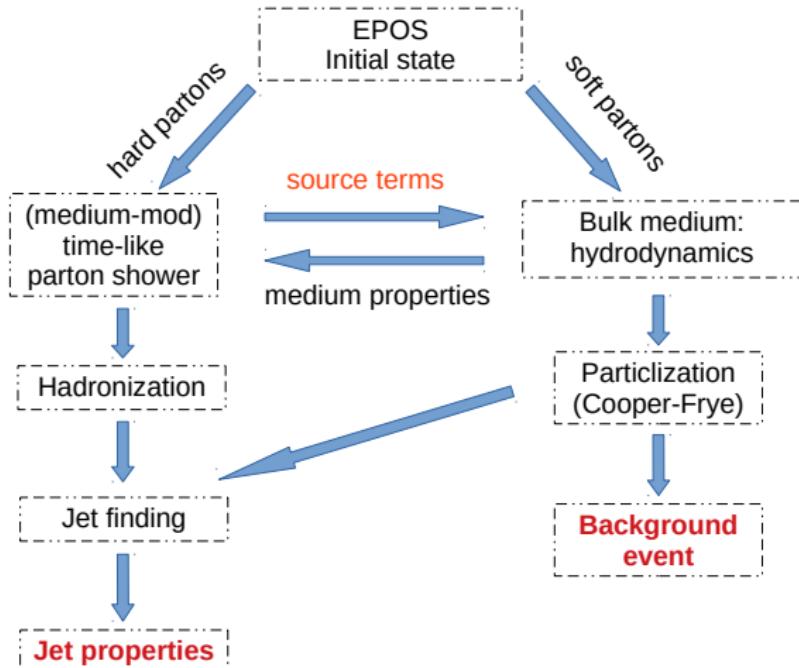


Which jets are found depends on anti- k_T resolution parameter

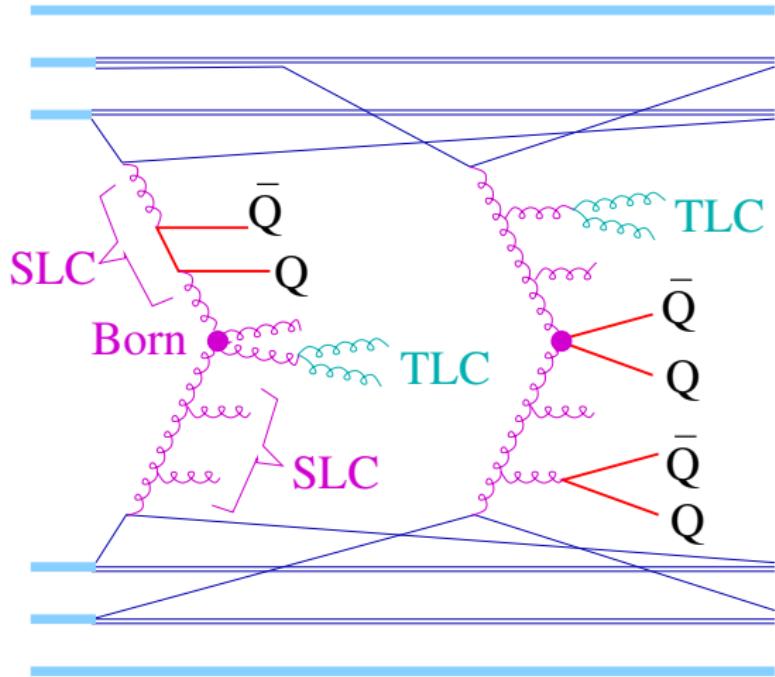
Our project

Our project

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, compatible with s95p-v1.2 EoS.
M. Laine, Y. Schroeder Phys. Rev. D73 (2006) 085009

3+1 dimensional viscous hydrodynamics:

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

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

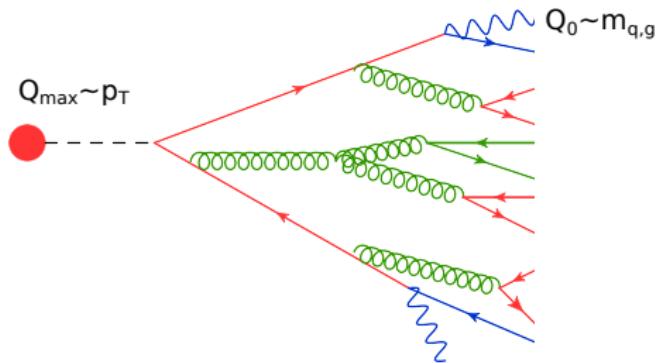
$$\langle u^\gamma \partial_{;\gamma} \pi^{\mu\nu} \rangle = -\frac{\pi^{\mu\nu} - \pi_{\text{NS}}^{\mu\nu}}{\tau_\pi} - \frac{4}{3} \pi^{\mu\nu} \partial_{;\gamma} u^\gamma$$

solved with vHLLC code, Comput. Phys. Commun. 185 (2014), 3016

<https://github.com/yukarpenko/vhllc>

Time-like parton shower

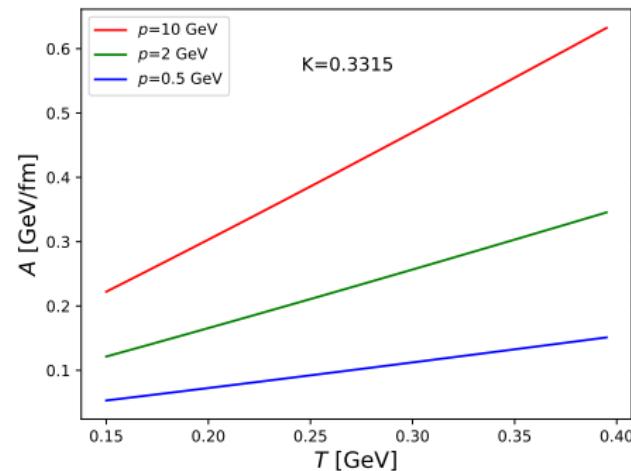
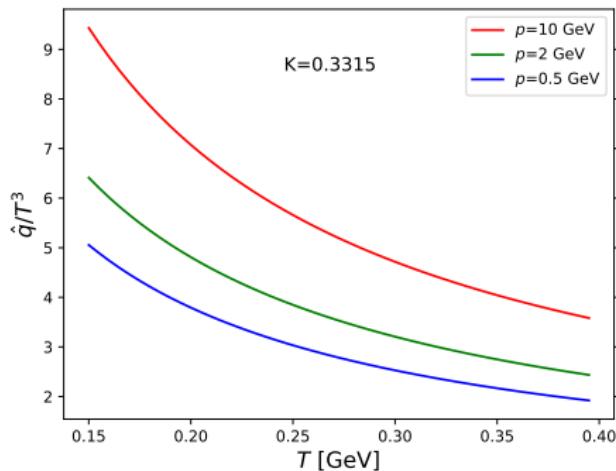
- Monte Carlo simulation of DGLAP equations for a parton shower between virtuality scales Q_{\uparrow} (from Born process in EPOS) and $Q_{\downarrow} = 0.6$ GeV.
Core algorithm made by **Martin Rohrmoser**



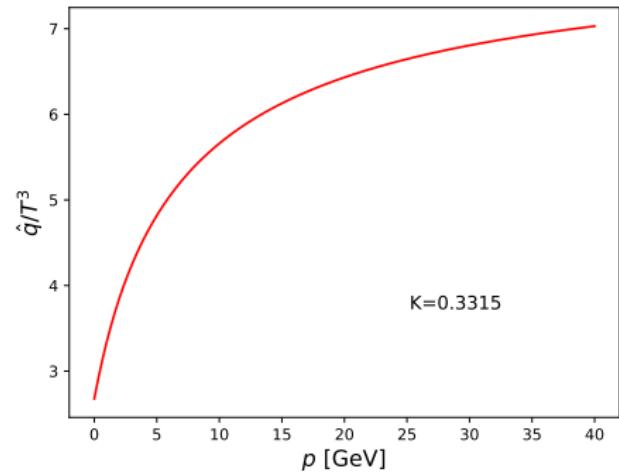
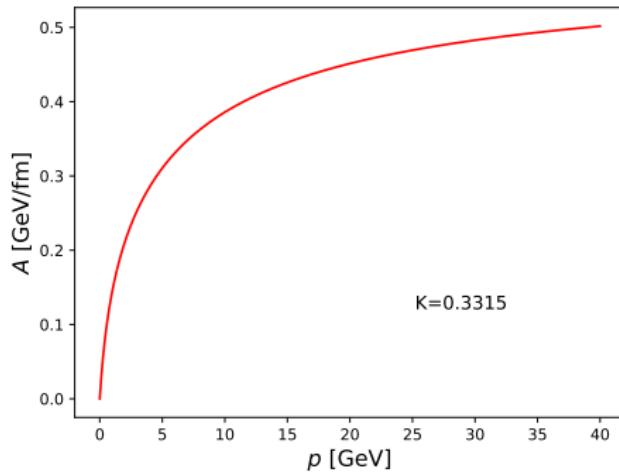
- Medium modified radiation (splittings) à la YaJEM: $\frac{dQ^2}{dt} = +\hat{q}_R(t,x)$
 - Collisional energy loss: longitudinal drag $\frac{dp_{\parallel}}{dt} = -A(t,x)$
 - Collisional energy loss: transverse kicks $\Delta p_{\perp} = n_{\perp} \sqrt{\hat{q}_C \cdot \Delta t}$
 - Mean lifetime of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

Transport coefficients

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



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



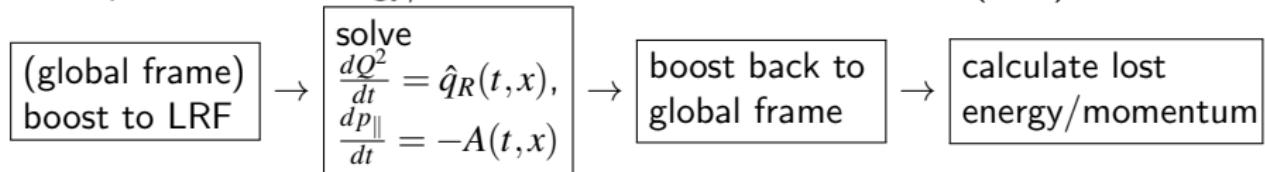
Jet-medium interaction

- Fluid and jet evolutions run in parallel:

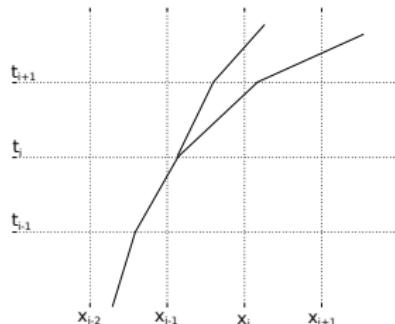


- The temperature and flow velocity are taken from the hydrodynamic evolution

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

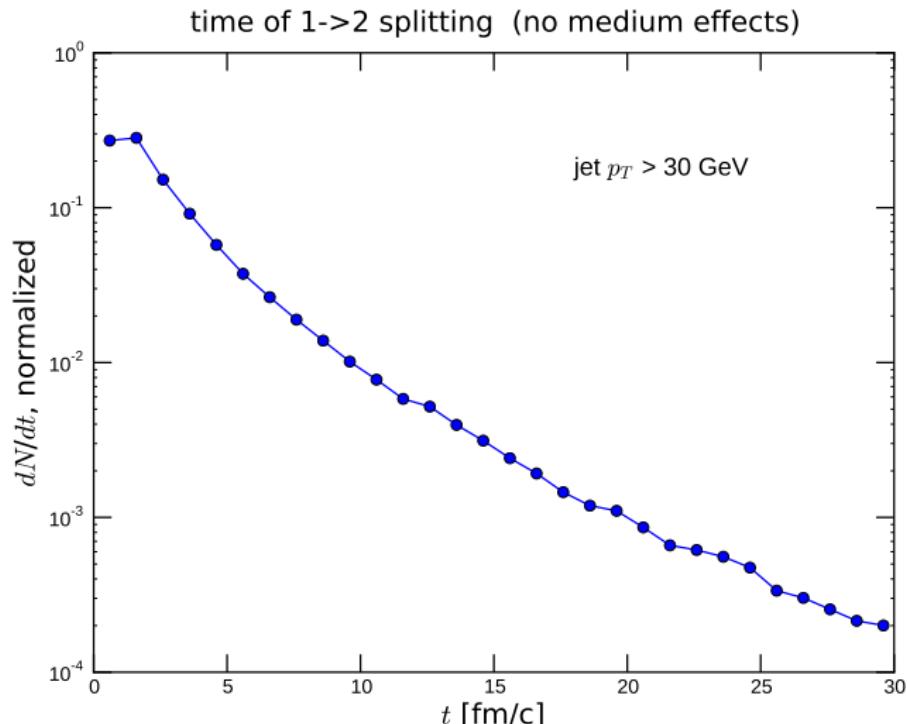


- Once the energy of a parton in the fluid rest frame drops below $\alpha \cdot T(t,x)$, the parton is “melted” into the fluid: its energy/momentum is distributed around nearby fluid cells, and the parton is removed from the parton cascade.
- The fluid acquires the lost energy/momentum (**absorption**) via the source terms: $\partial_{;\nu} T^{\mu\nu} = J^\mu$



Sample jet evolution and medium response

Timeline of parton splittings

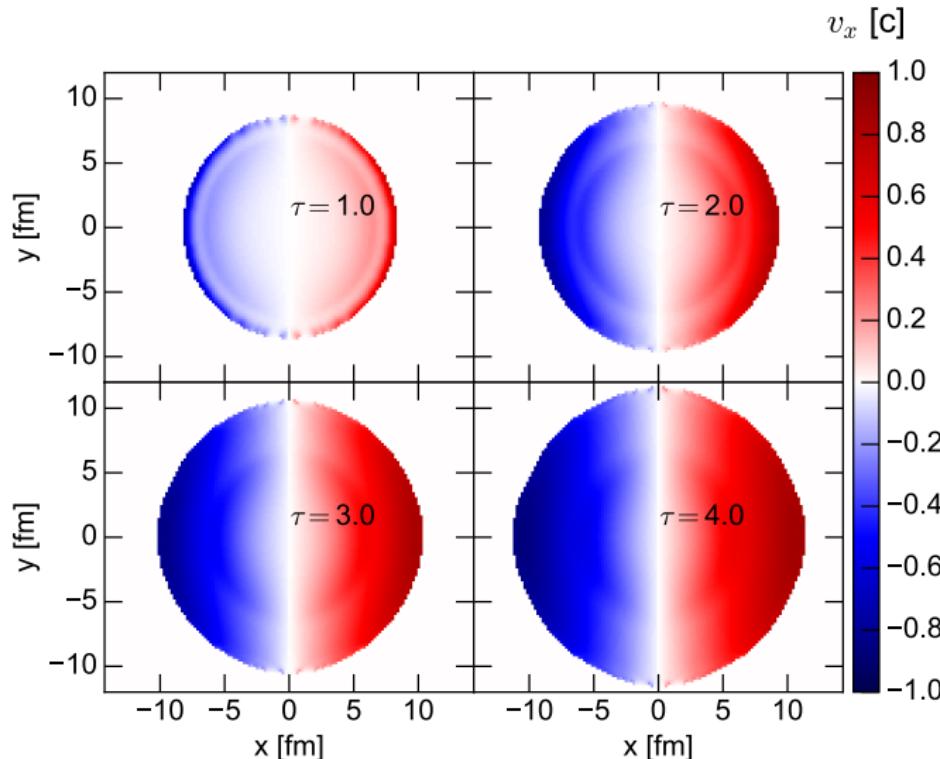


Majority of splittings happen at early times, assuming $\Delta t = E/Q^2$ ansatz.

Medium recoil

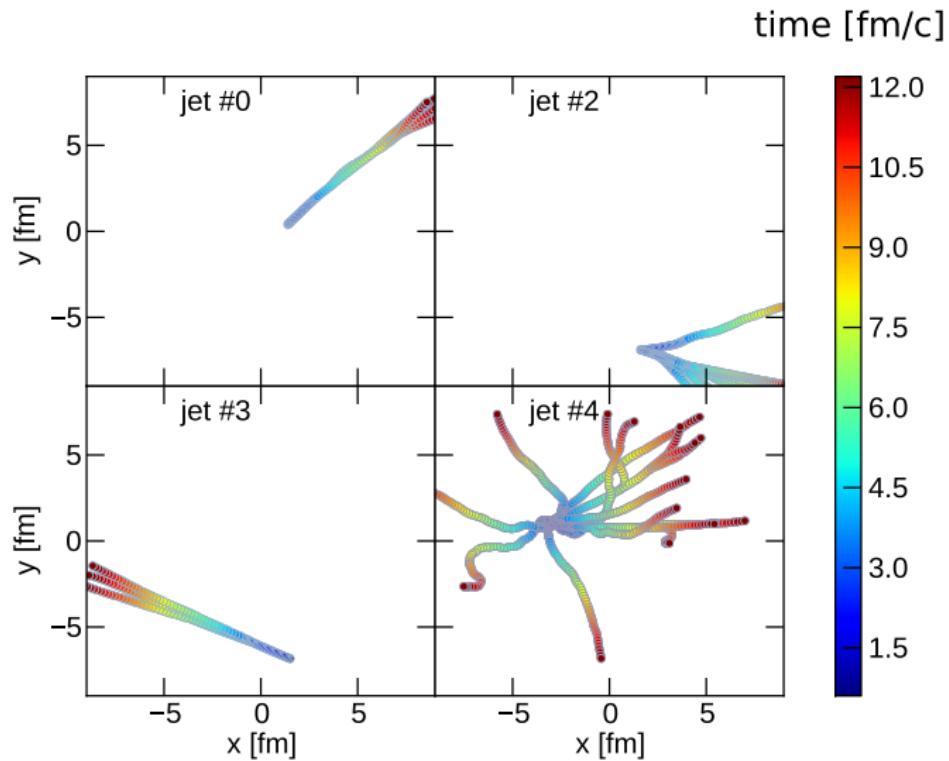
Snapshots of the x component of fluid velocity at different times.

Unperturbed fluid: (benchmark/to guide the eye).



Medium recoil (2)

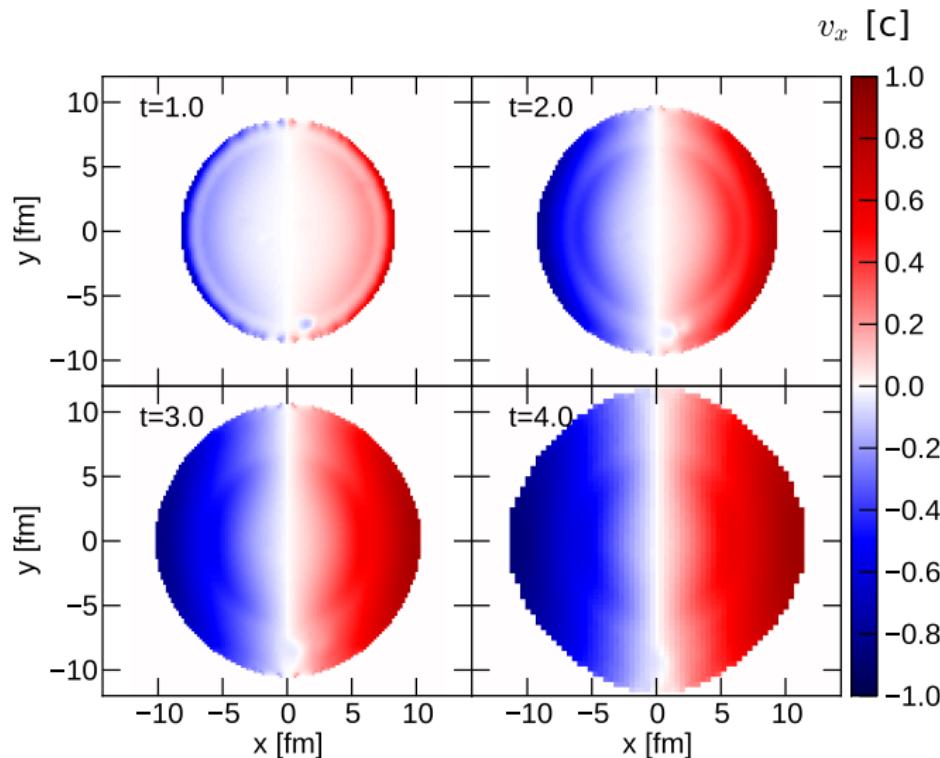
A randomly picked jet event.



Medium recoil (3)

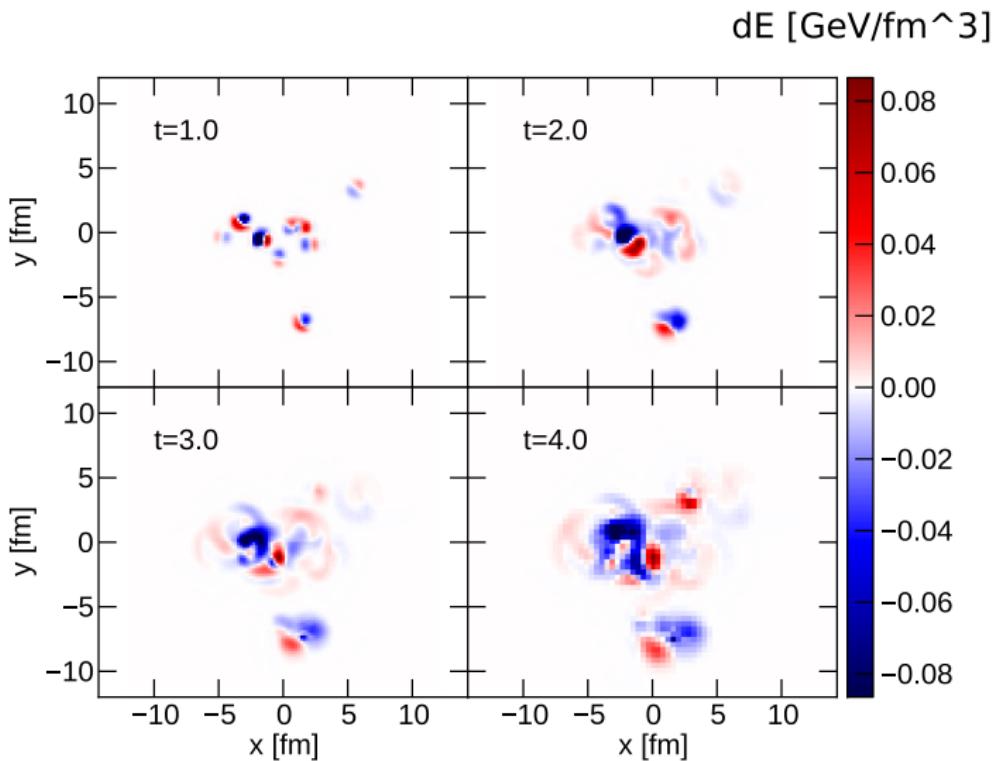
Snapshots of the x component of fluid velocity at different times.

Perturbations in the fluid at early times:



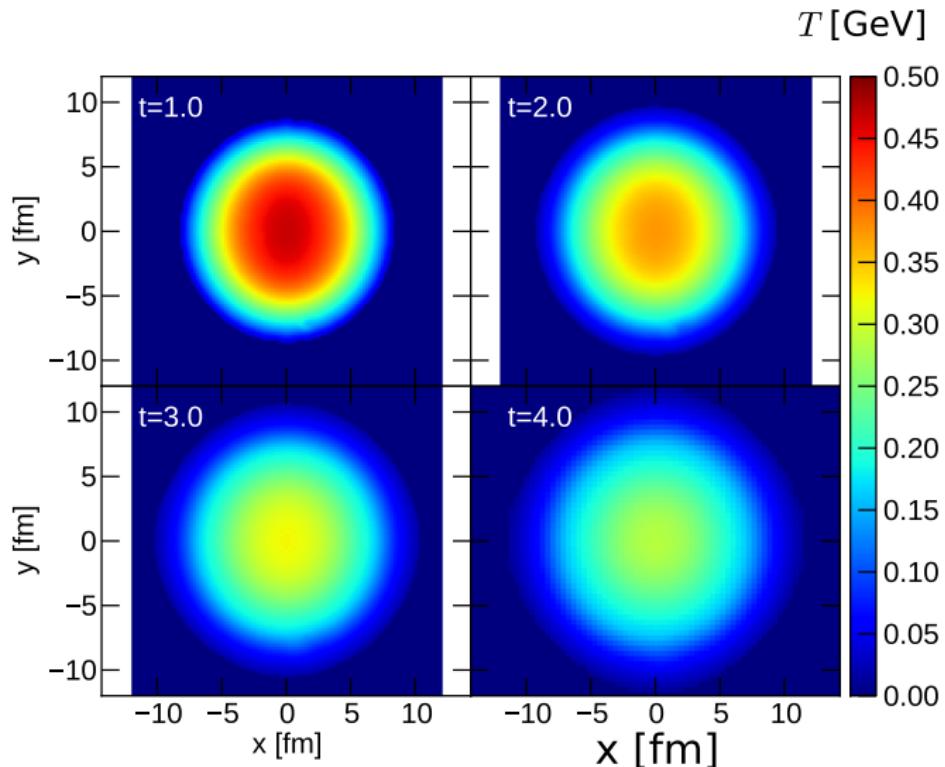
Medium recoil (4)

Mach cones. (notice the scale of ΔE !)



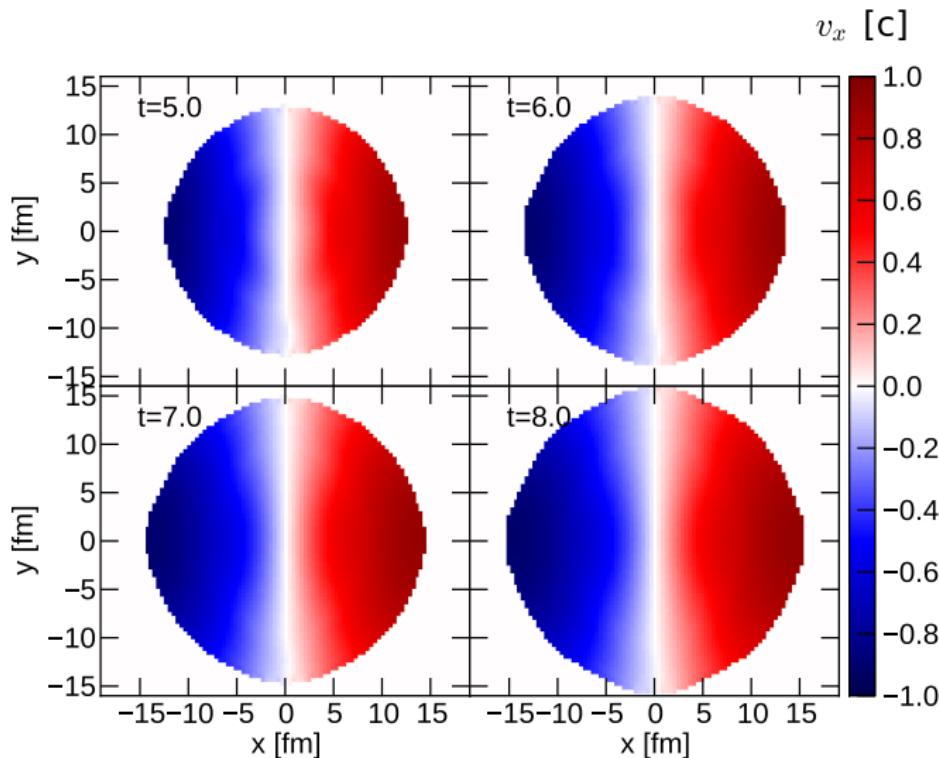
Medium recoil (5)

Perturbations to the temperature profile are tiny.



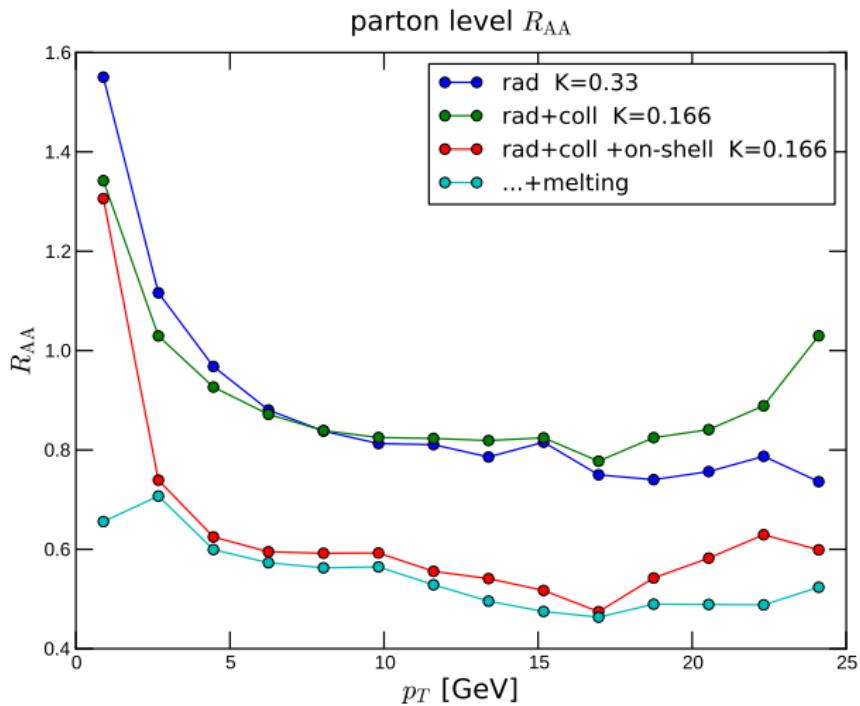
Medium recoil (6)

Hydro smears out the velocity perturbations at late times.



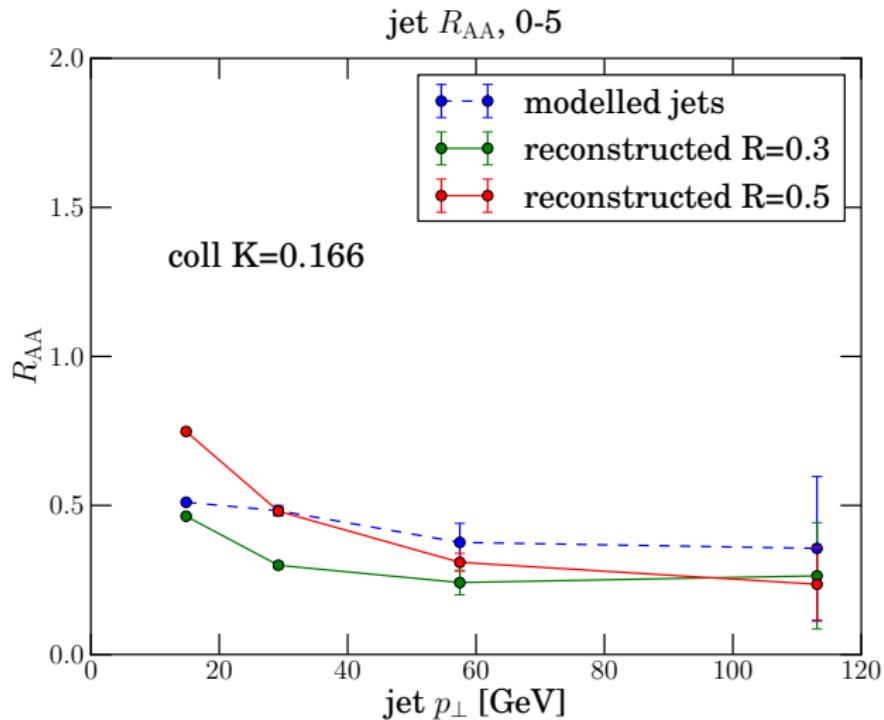
Results: jet properties

Results: parton level R_{AA} , 0-5% central PbPb at $\sqrt{s_{NN}} = 2.76$ TeV



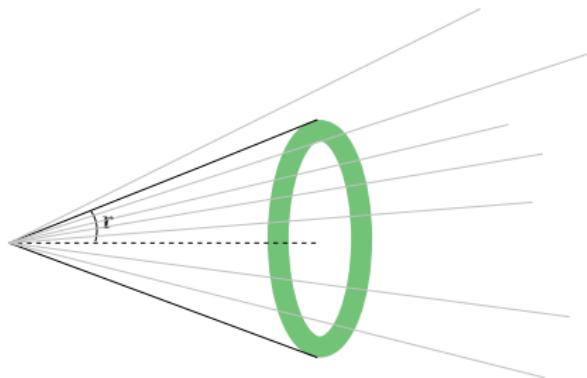
- ‘radiative energy loss’: enhancement at low- p_\perp + suppression of high- p_\perp
- the rest of suppression comes from the collisional EL for ‘on-shell’ partons.

Results: jet R_{AA} , 0-5% central PbPb at $\sqrt{s_{NN}} = 2.76$ TeV



- R dependence (more about that in couple slides)

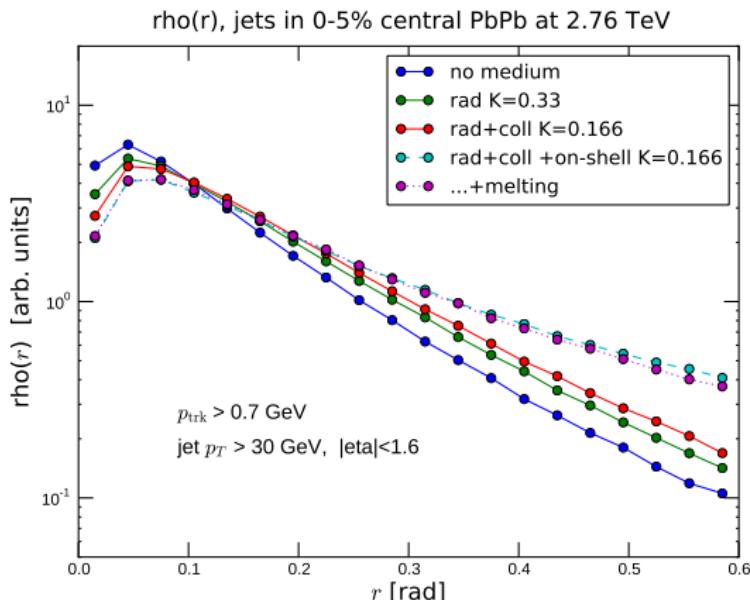
Jet Cones



$$\text{jet shape } \rho(r) = \frac{p_T \text{ in annulus}}{p_T \text{ of jet}}$$

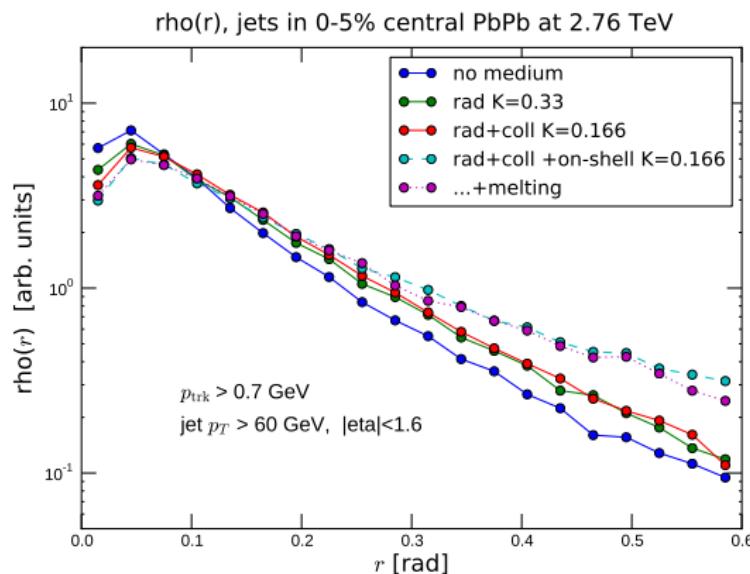
Angular structure of a jet (jet shape)

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



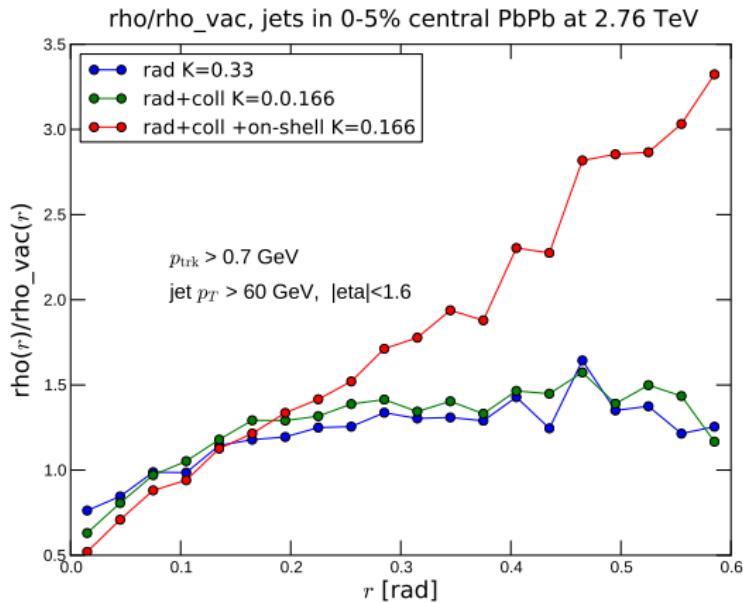
- Radiative EL → broadening (more secondary splittings)
- Collisional EL → broadening
- +on-shell collisional EL → even more broadening
- parton melting: hardly any effect

Same effects for higher jet p_{\perp} threshold:



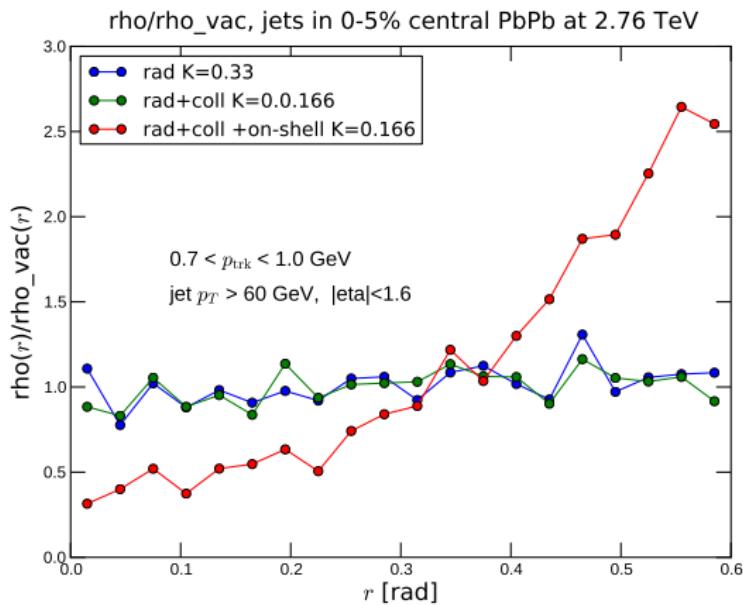
- Radiative EL \rightarrow broadening
(more secondary splittings)
- Collisional EL \rightarrow broadening
- +on-shell collisional EL \rightarrow even more broadening
- parton melting:
hardly any effect

Ratio of medium modified / “vacuum” * jet shapes:



* “vacuum” = no medium modification

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



Jet reconstruction

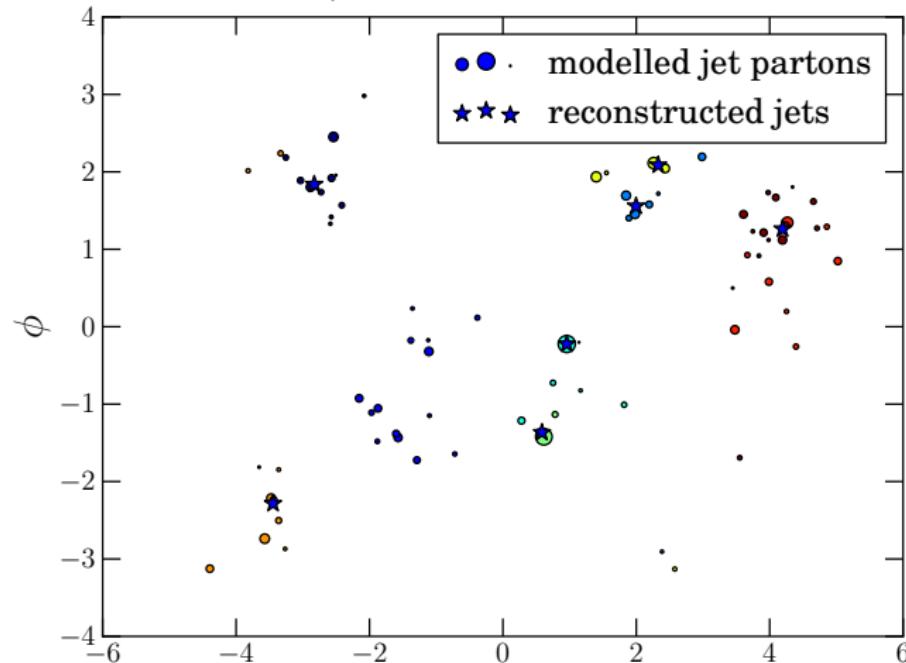
Jet reconstruction

A current shortcut:

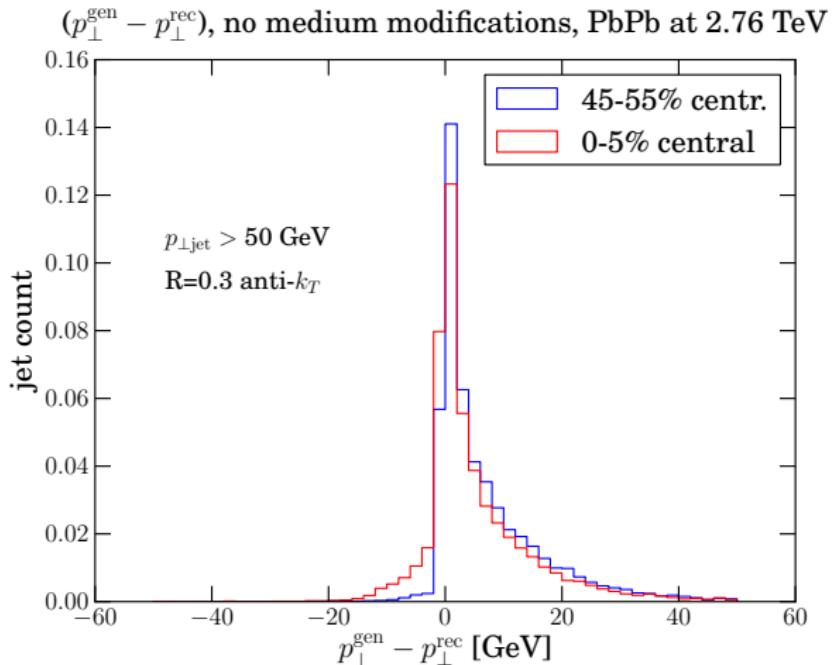
Final state of a jet (partons) \rightarrow **no** hadronization \rightarrow jet finding.

Jet finding: vanilla FASTJET 3.3, anti- k_T algorithm

0-5% central PbPb $\sqrt{s_{\text{NN}}}=2.76$ TeV, vacuum case, event 10002



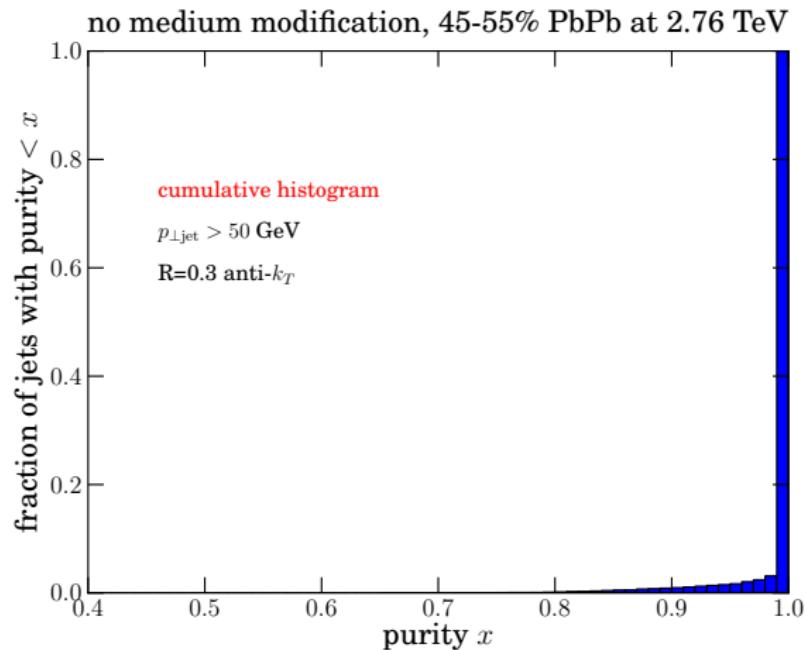
The artefacts



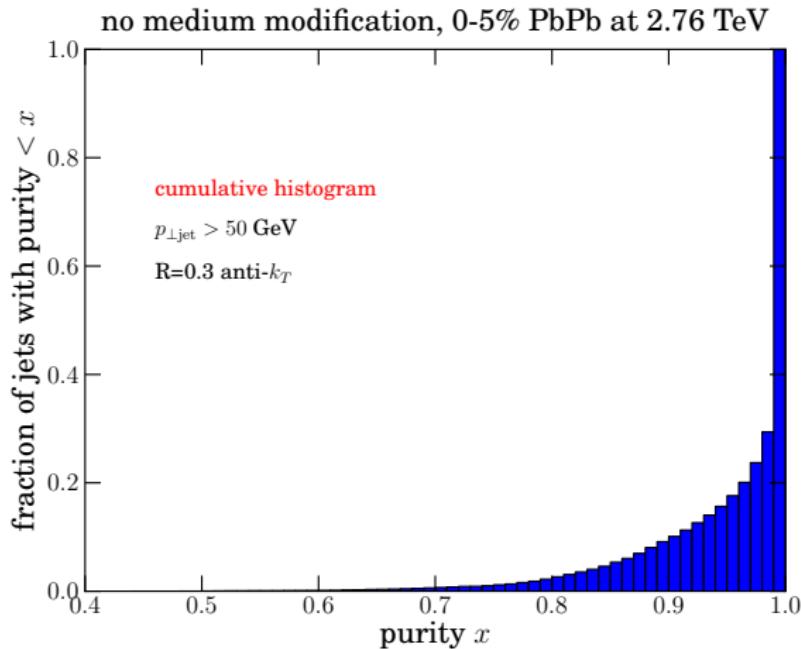
- ‘runaway’ jet partons are not clustered with the rest
- partons from neighbouring jets are clustered together

“Jet purity”, noncentral PbPb

We define it as a leading fraction of reconstructed jet momentum coming from an underlying simulated jet.



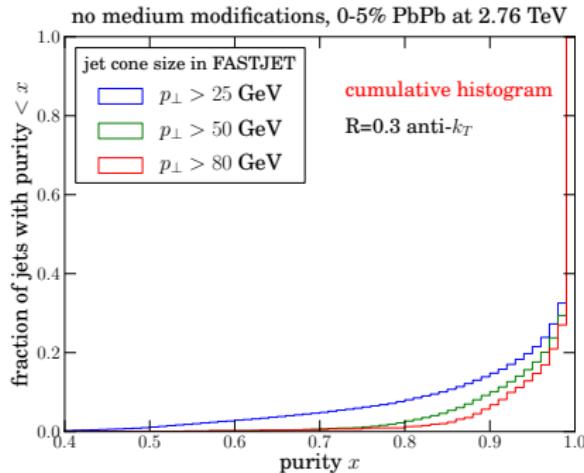
“Jet purity”, central PbPb



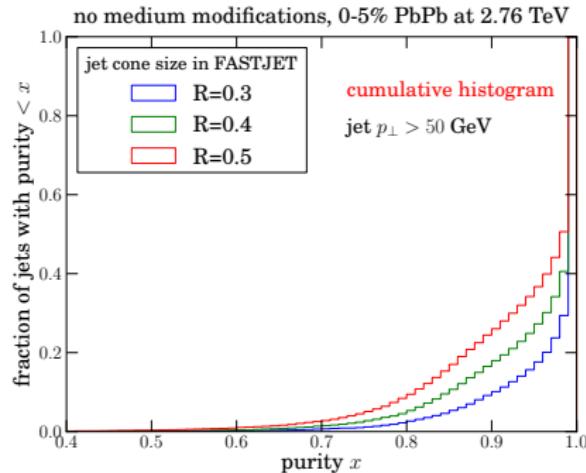
- about 1/3 of the reconstructed jets (or simply jets) have various contributions to their momentum from jet overlap.

"Jet purity", jet p_{\perp} and R dependencies

Left: $P(\text{purity} > x)$ at different jet p_{\perp}



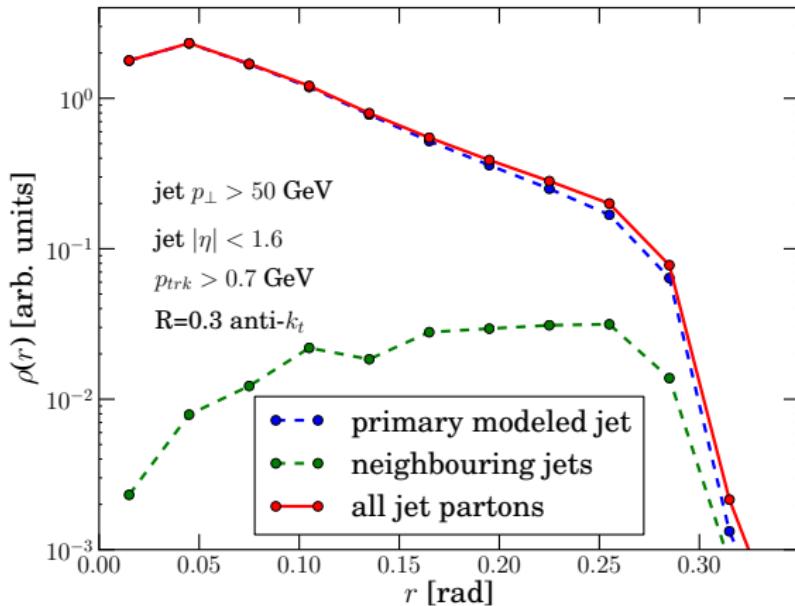
Right: $P(\text{purity} > x)$ for different R



- harder jets are more collimated, so less overlap with neighbours
- with larger jet cone one picks up more neighbouring partons

Jet shape

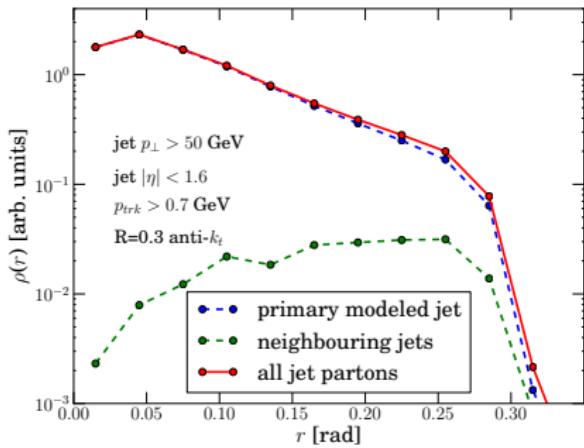
no medium modifications, 0-5% central PbPb at 2.76 TeV



- The core of the jet ($r < 0.2$) has negligible contribution from the jet overlap.
- For the periphery of the jet the jet overlap starts to be important.

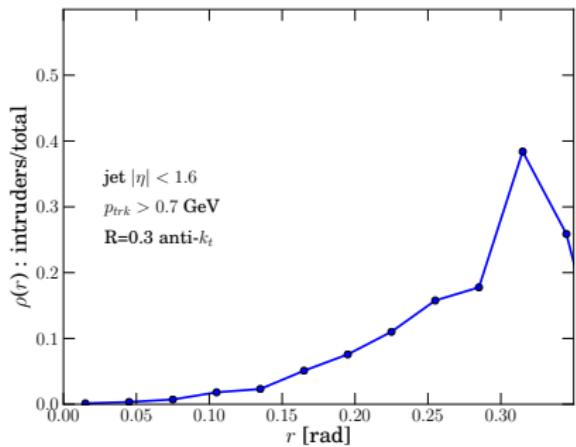
Jet shape

no medium modifications, 0-5% central PbPb at 2.76 TeV



Right: ratio of neighbours/principal

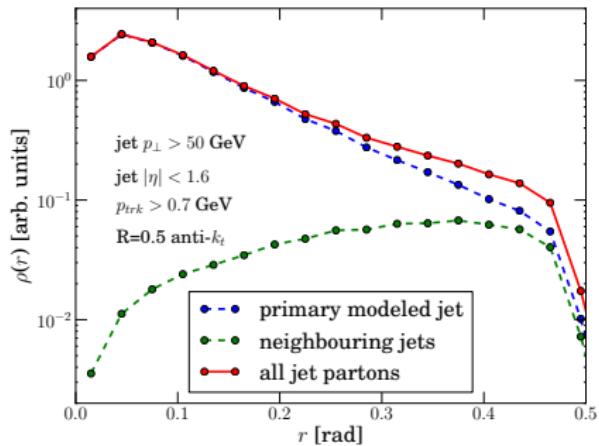
no medium modifications, 0-5% central PbPb at 2.76 TeV



- The effect goes up to 20% at the boundary of the jet cone.

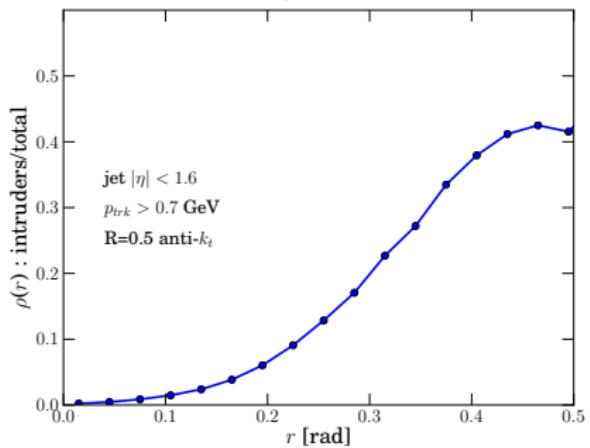
Same thing for $R = 0.5$ cone size

no medium modifications, 0-5% central PbPb at 2.76 TeV



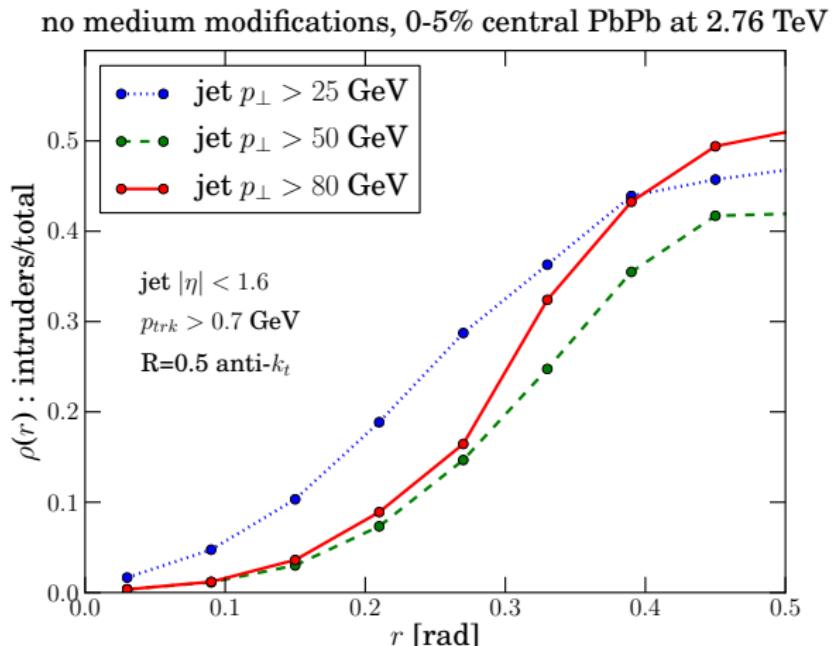
Right: ratio of neighbours/principal

no medium modifications, 0-5% central PbPb at 2.76 TeV



- As the jet cone extends further in r , the contribution from jet overlap grows further.

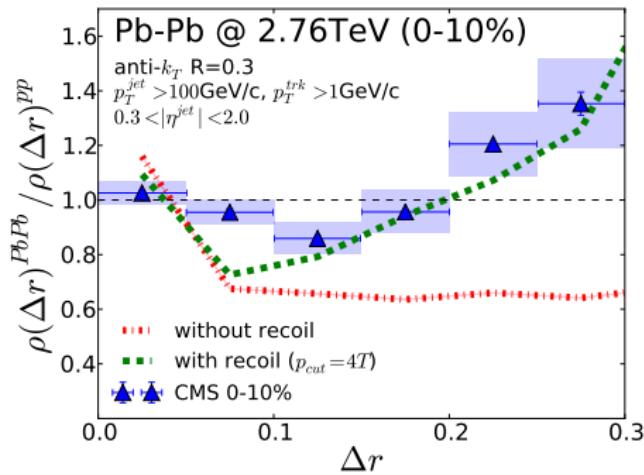
Jet p_{\perp} dependence of the effect



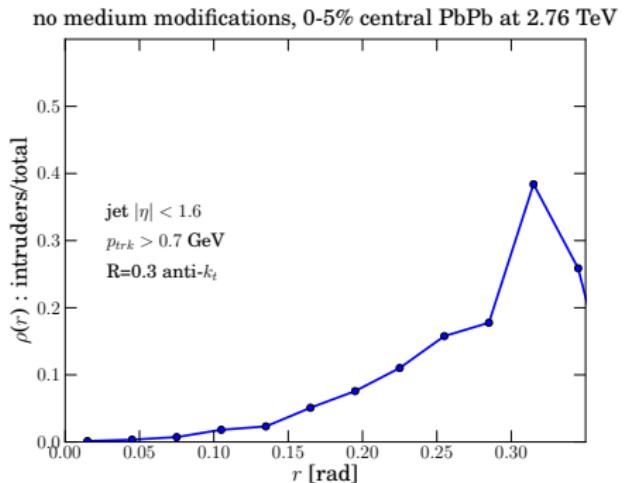
- The jet shape contamination by overlapping jets persists as jet p_{\perp} increases!

Medium recoil vs 'trivial' jet overlap?

Jet shape modf. in AA explained by medium recoil, C. Park at QM2018



This study: jet overlap.



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_{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.
- Jet reconstruction: the effect of jet overlap in momentum space in AA affect the jet shape.

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