Jet Quenching and the Nature of the QGP

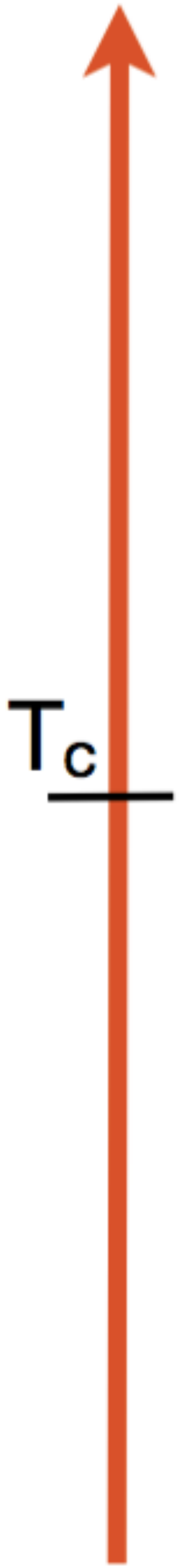
Daniel Pablos - INFN Torino

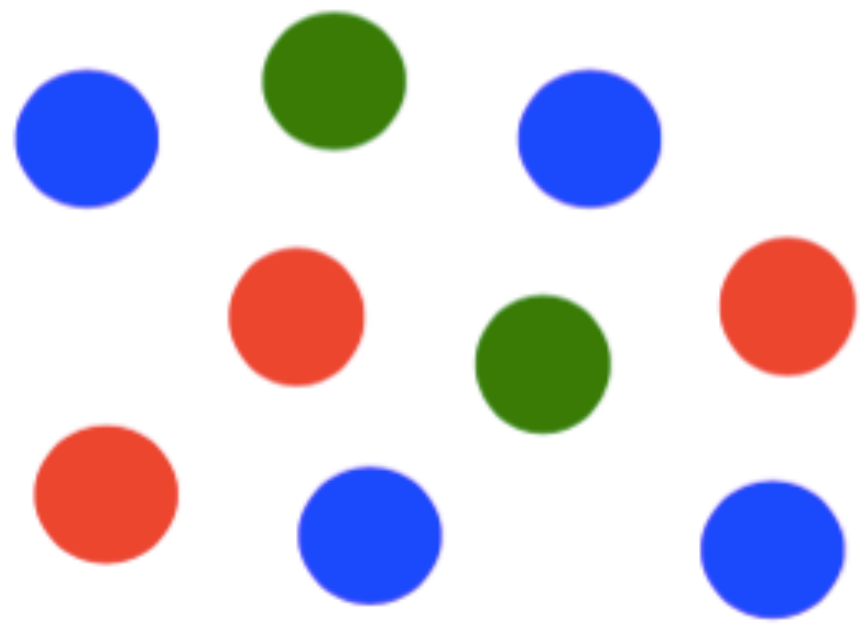
Fellini
Fellowship for Innovation at INFN

INFN
Istituto Nazionale di Fisica Nucleare

FELLINI Meeting - Ferrara '22

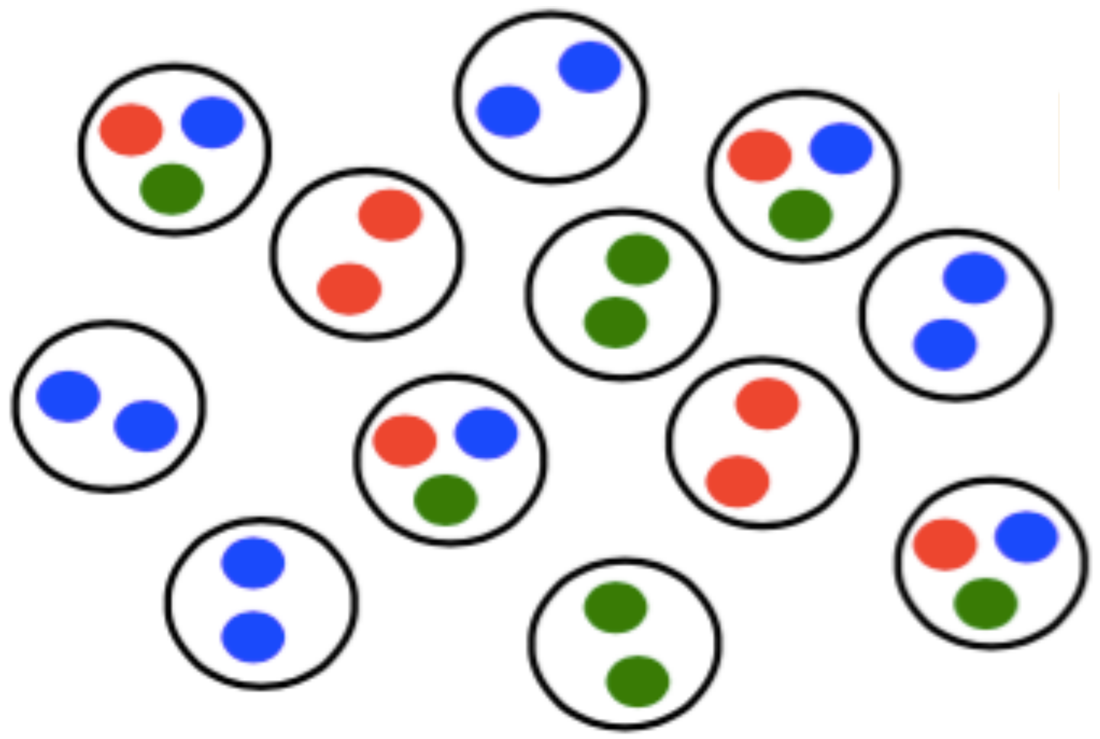
QCD Matter





"Phase transition"

$T_c \sim 2 \,.\, 10^{12}\,\mathrm{K} \;\; \sim 170\mathrm{MeV}$



A New Phase: *Quark-Gluon Plasma (QGP)*:

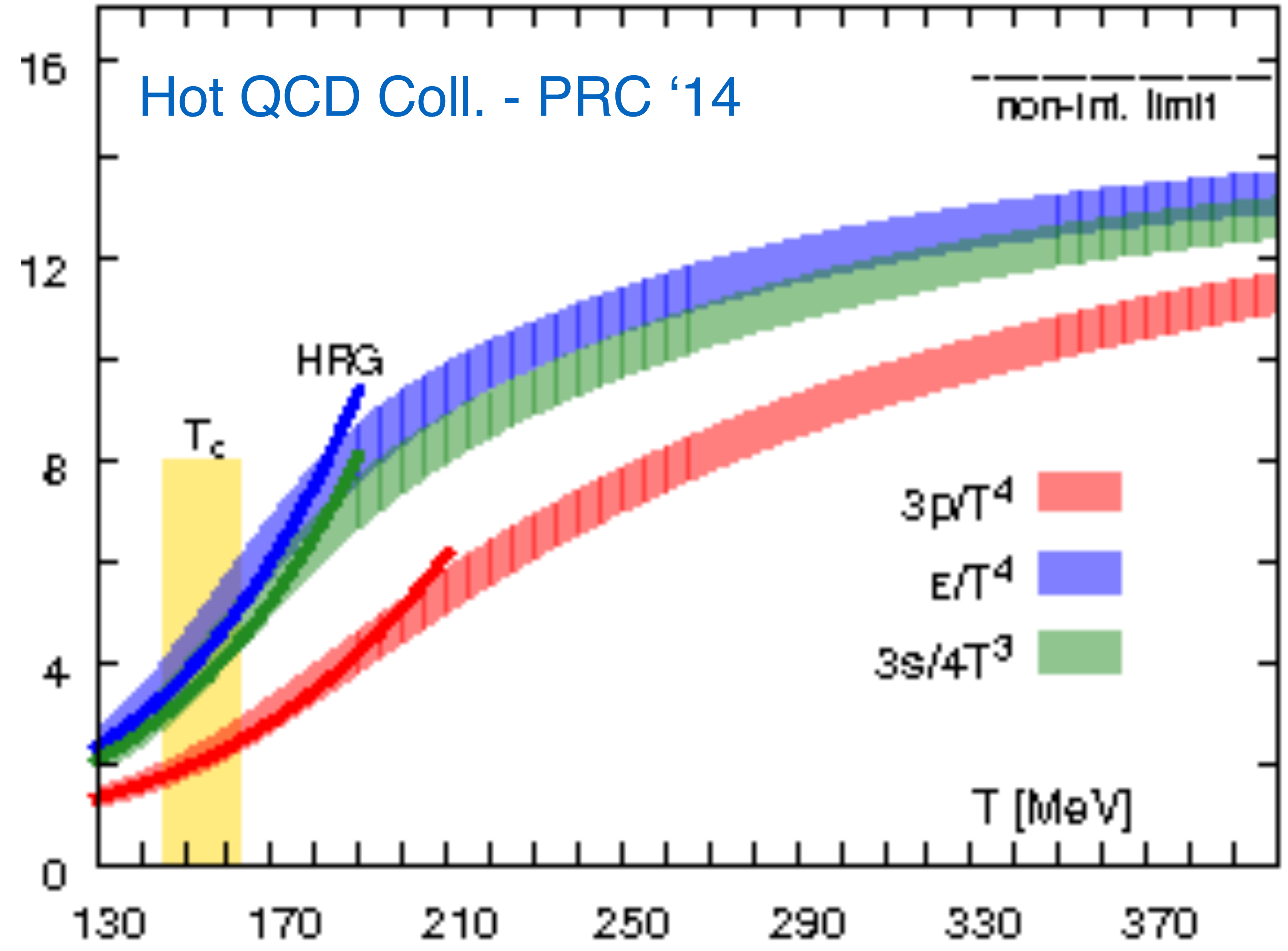
- Filled the universe µs after Big Bang.
- Colour is liberated.
- A gas of quarks and gluons.

What are the properties of the plasma close to the transition?

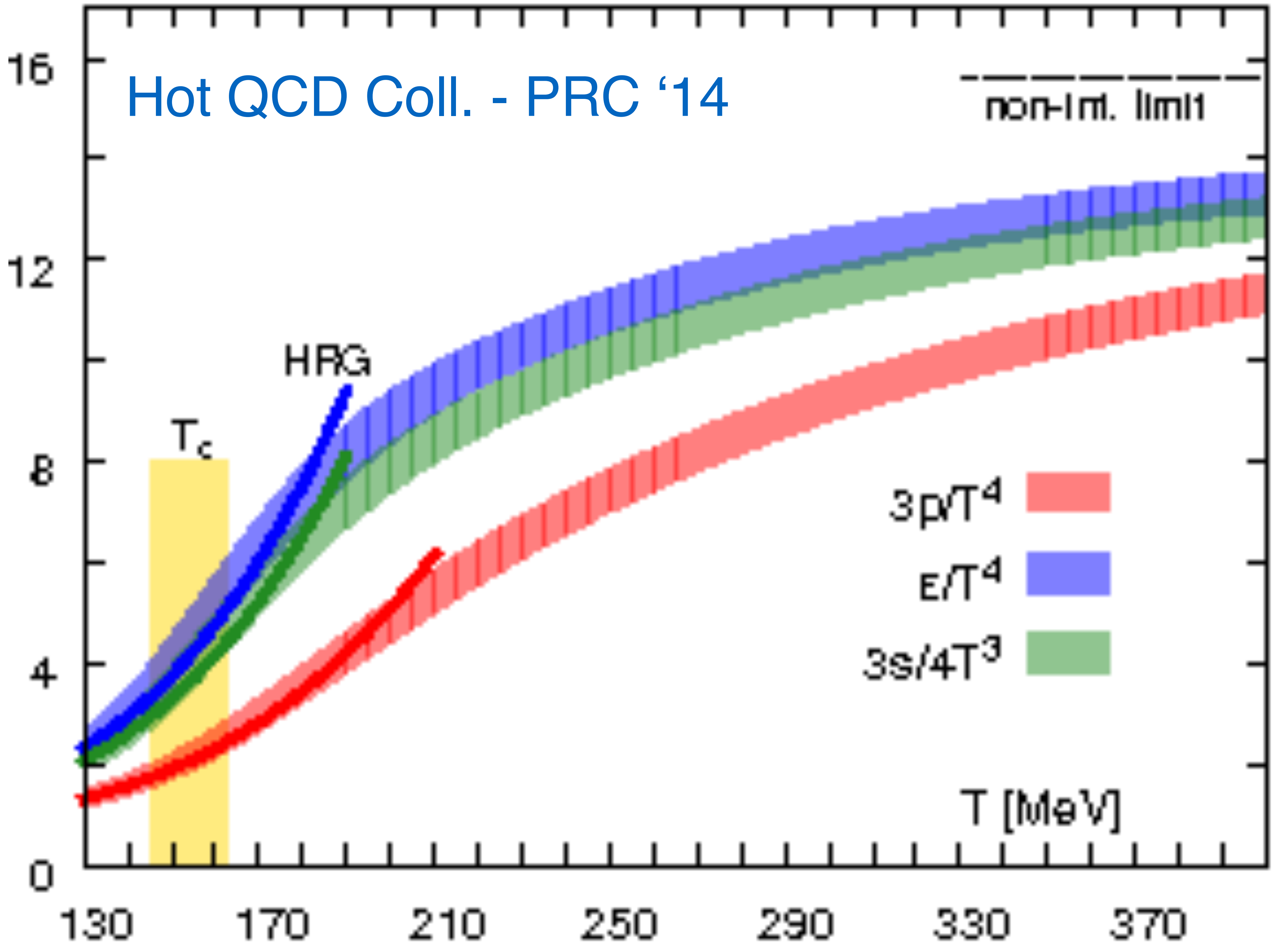
Hadron Gas:

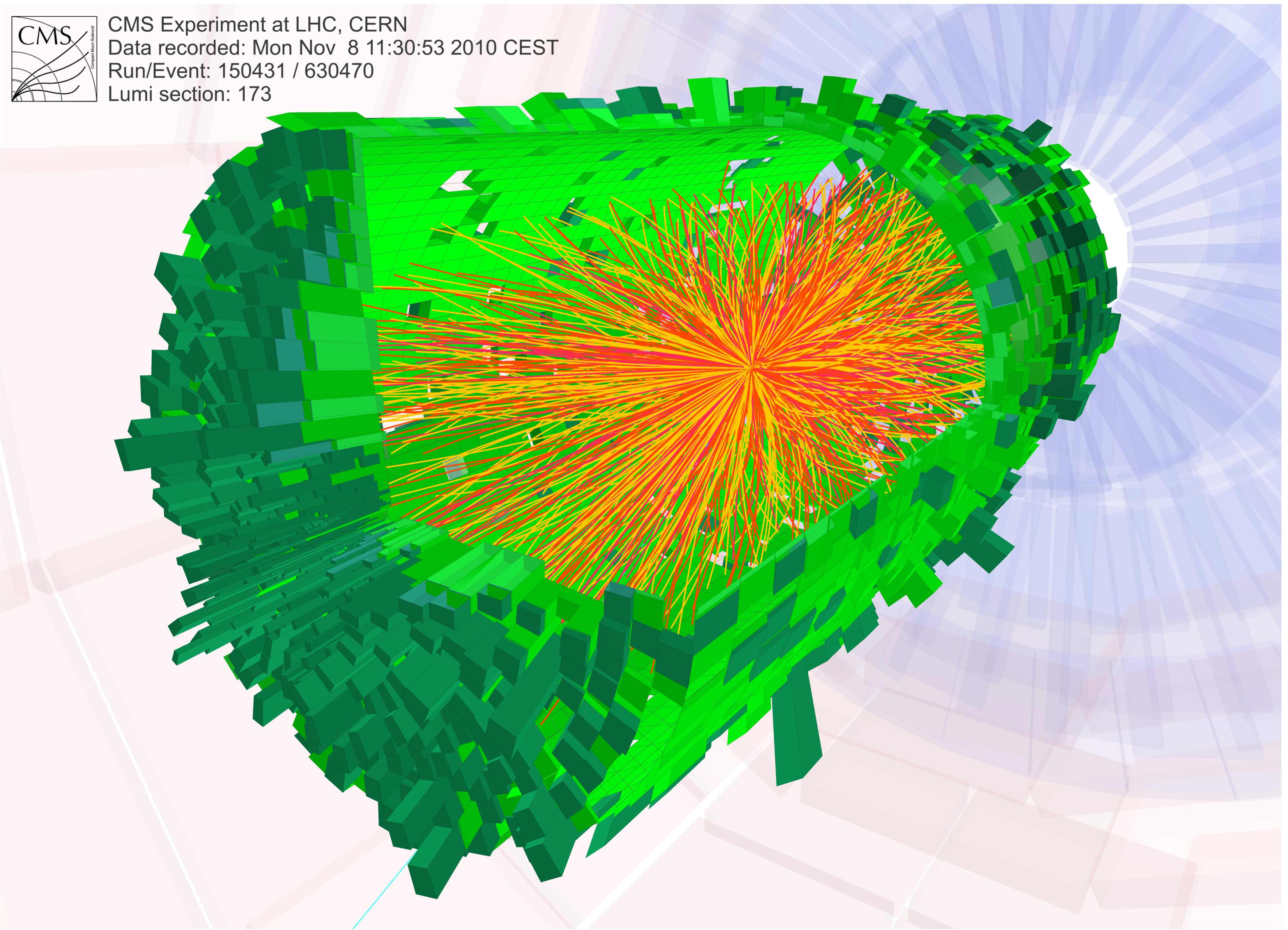
- Color is confined.
- Hadrons re-scatter.

Heavy-Ion Collisions (HIC): The Little Bangs



- Equation of State from Lattice QCD:
  - Rapid crossover transition.
  - Deconfined matter: rapid increase of # d.o.f. above T_c.
  - Asymptotycally approaches non int. limit.



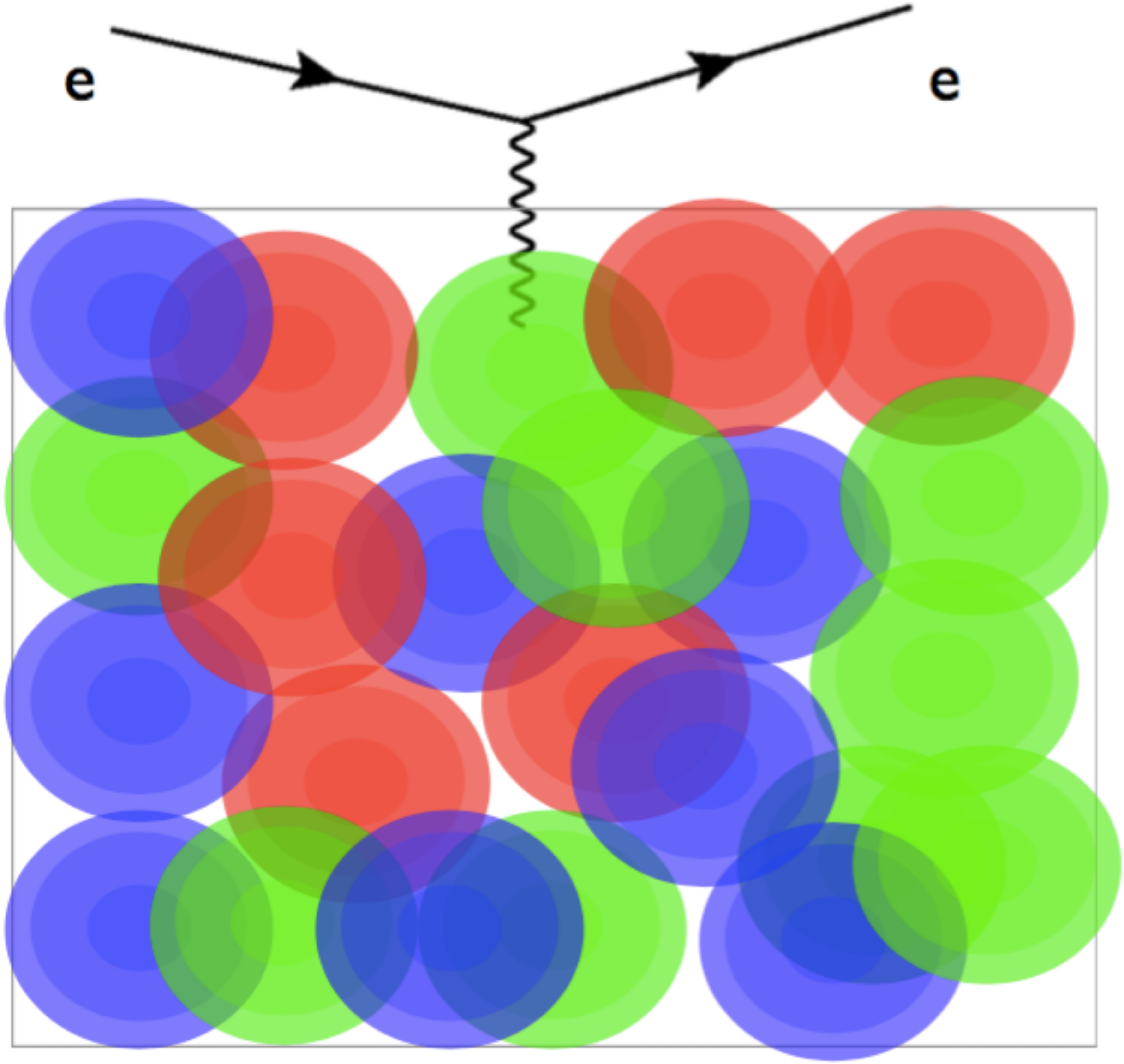


RHIC $\sqrt{s} \sim 0.2$ ATeV

LHC $\sqrt{s} \sim 4$ ATeV

- Deconfined matter in experiments:
  - Very strong collective effects.
  - Thousands of particles correlated according to initial geometry.
  - Hydrodynamic explosion!

How Can We Probe the QGP?



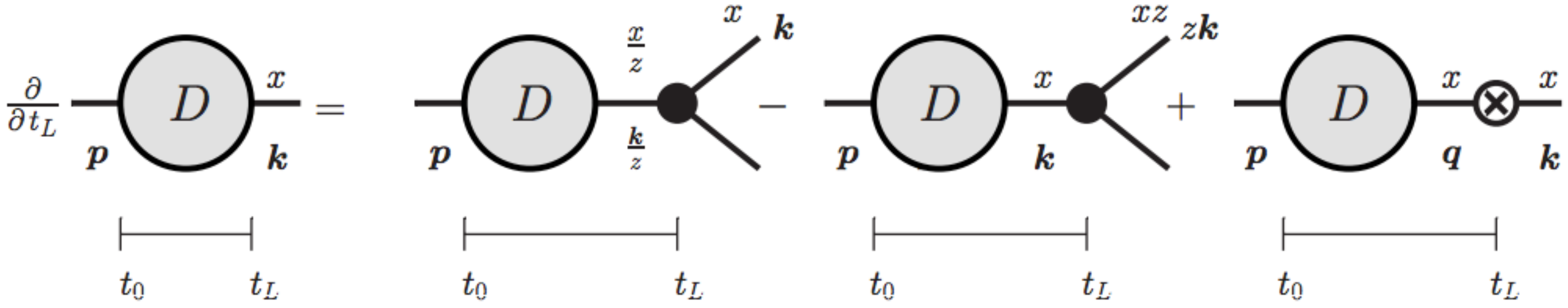
Motivation

- Hypothesis: *The QGP is a very good fluid.*

pQCD

High energy partons in the QGP:

→ emit quanta, which in turn emit more quanta, and should (eventually) hydrodynamize.



$D(x, \boldsymbol{k}, t)$ is one-gluon distribution.

Blaizot et al. - JHEP ‘13 & ‘14, PRL ‘13

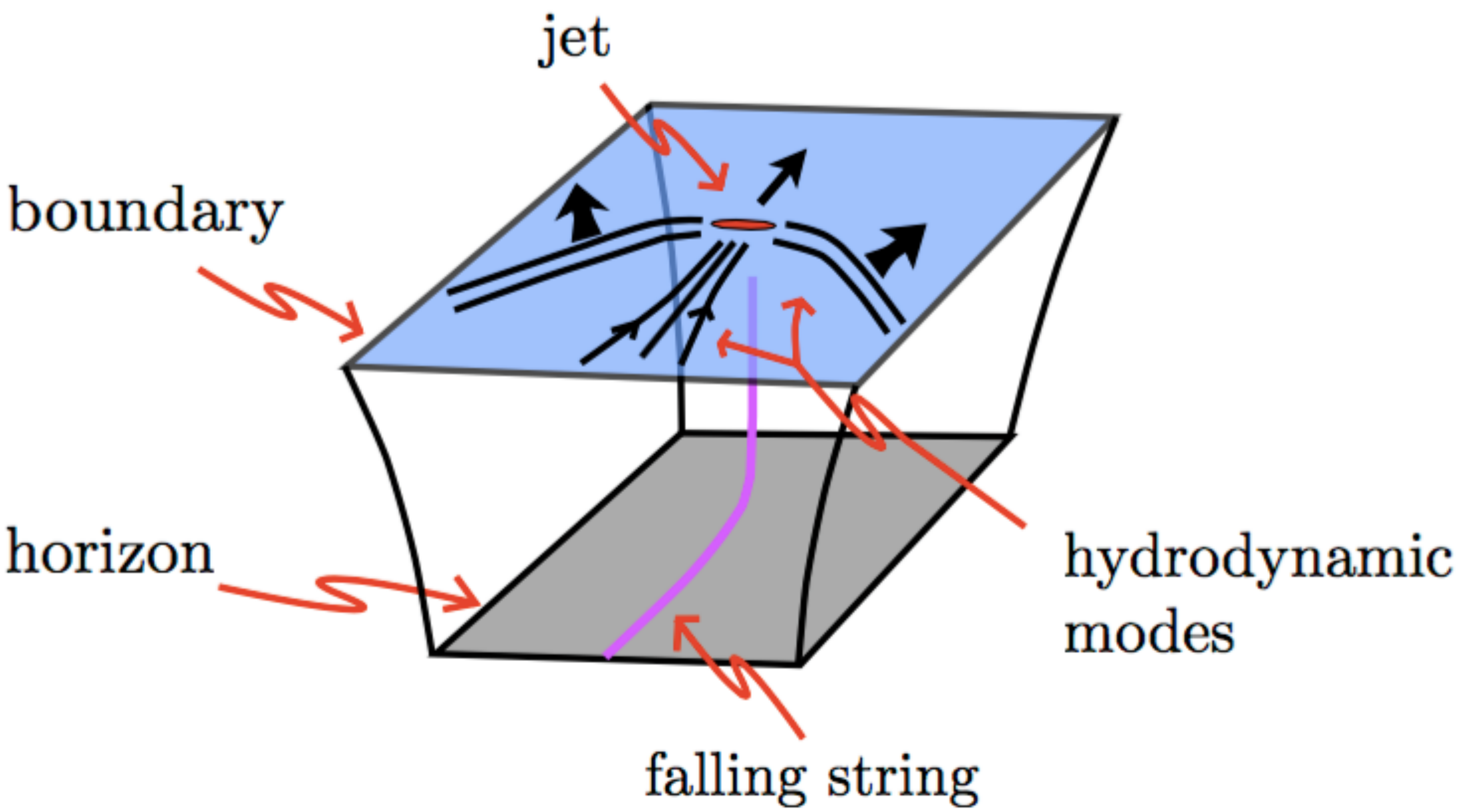
- Turbulent cascade develops, with a sink at E ~ T.
- Necessary length to reach the turbulent regime?

- Hypothesis: *The QGP is a very good fluid.*

npSYM

High energy partons in the QGP:

→ are dual to strings falling into a black hole, hydrodynamizing.



$$\langle \Delta T^{\mu\nu}(t,\boldsymbol{x})\rangle = \frac{L^3}{4\pi G_{\text{Newton}}} H^{(4)}_{\mu\nu}(t,\boldsymbol{x})$$

"Jet" induced EM tensor: hard + soft modes.

Perturbed metric @ boundary.

↓ Long wavelength limit (hydrodynamization rate):

Energy lost per unit length; suitable for pheno.

Chesler & Rajagopal - PRD '14, JHEP '16

The Wake of a Quark

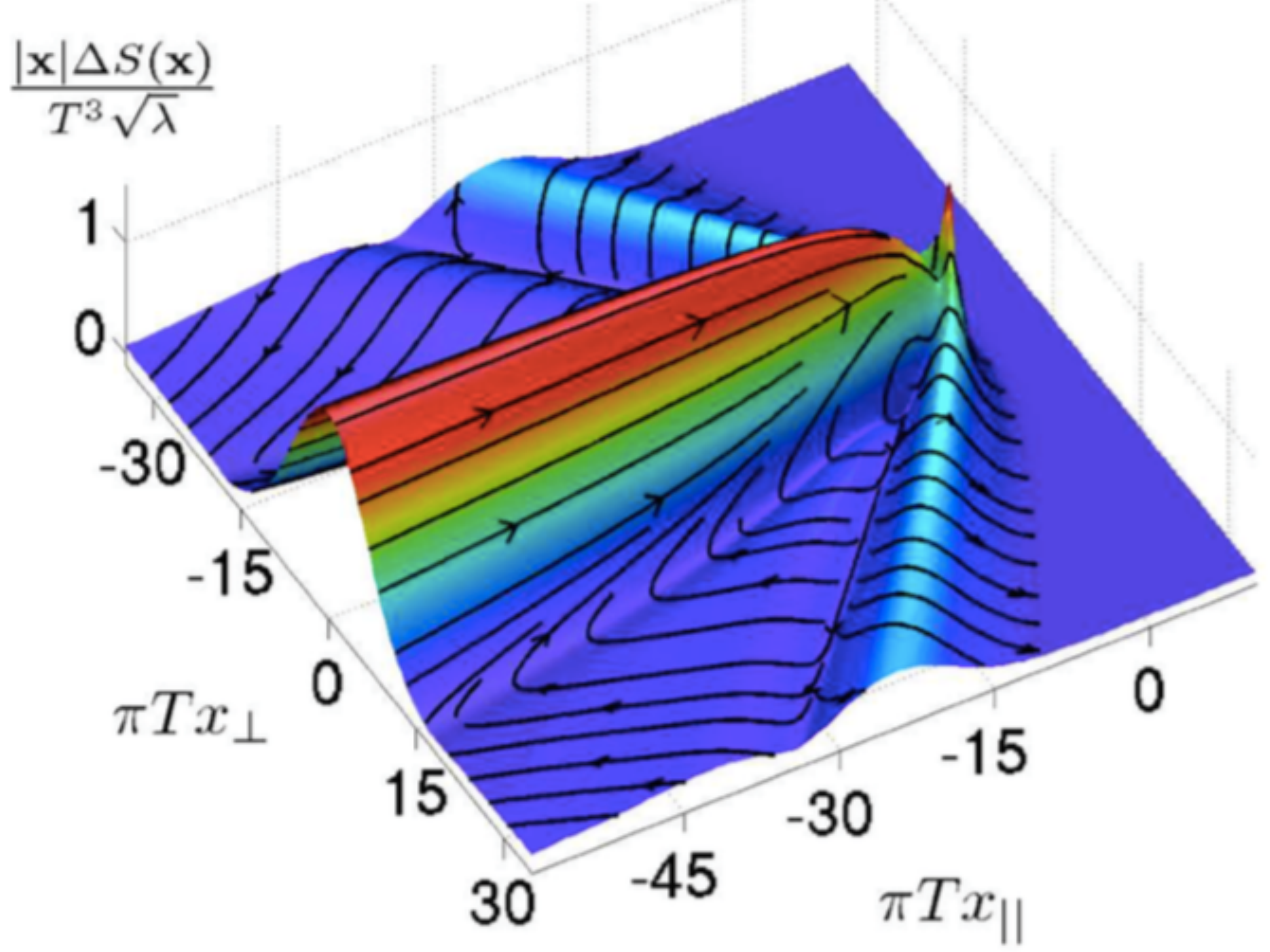
- At strong coupling:

  - Modification of stress-energy tensor due to supersonic quark contains sound and diffusive modes.

  - Effective source for hydro corresponds to drag force on the quark.

  - Agreement between hydrodynamics & wake of a quark even for small distances ~ 1/T.

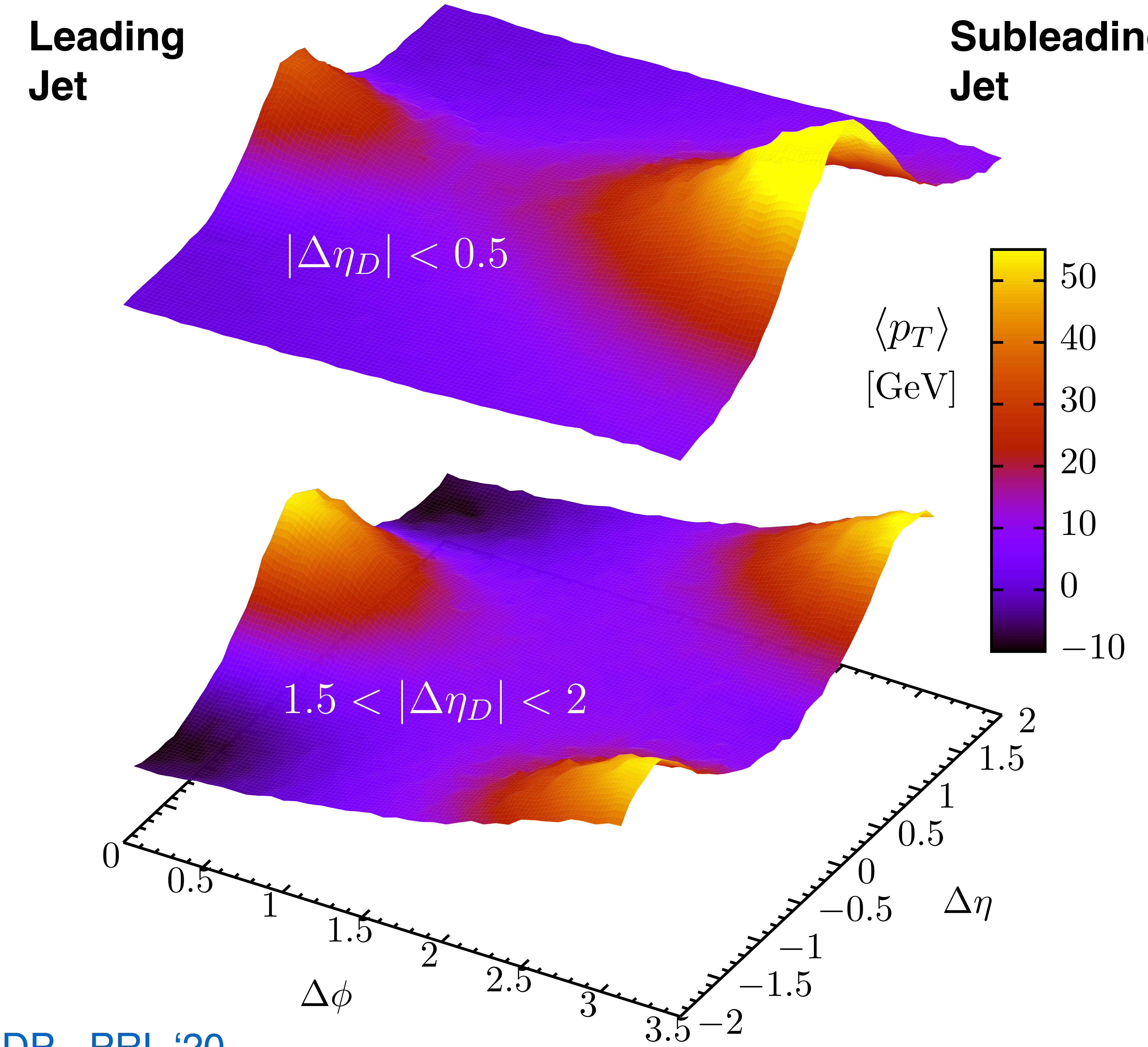
Energy flux



Fulfils Energy-Momentum Conservation in the Jet+Plasma Interplay.

Chesler & Yaffe - PRD ‘07

The Effect of the Recoiling Jet



DP - PRL '20

$\langle p_T \rangle$ density of wake hadrons w.r.t leading jet axis.

Aligned in rapidity

Subleading jet's QGP trough hits leading jet.

Separated in rapidity

Subleading jet's QGP trough misses leading jet.

$p_T^L > 250$ GeV

$p_T^S > 80$ GeV

$\Delta\phi_D > 2\pi/3$

differential in

$|\eta_D| \equiv |\eta_L - \eta_S|$

DP - PRL '20

A new observable.

R = 0.4

leading jet area easy to miss;
small effect from QGP trough.

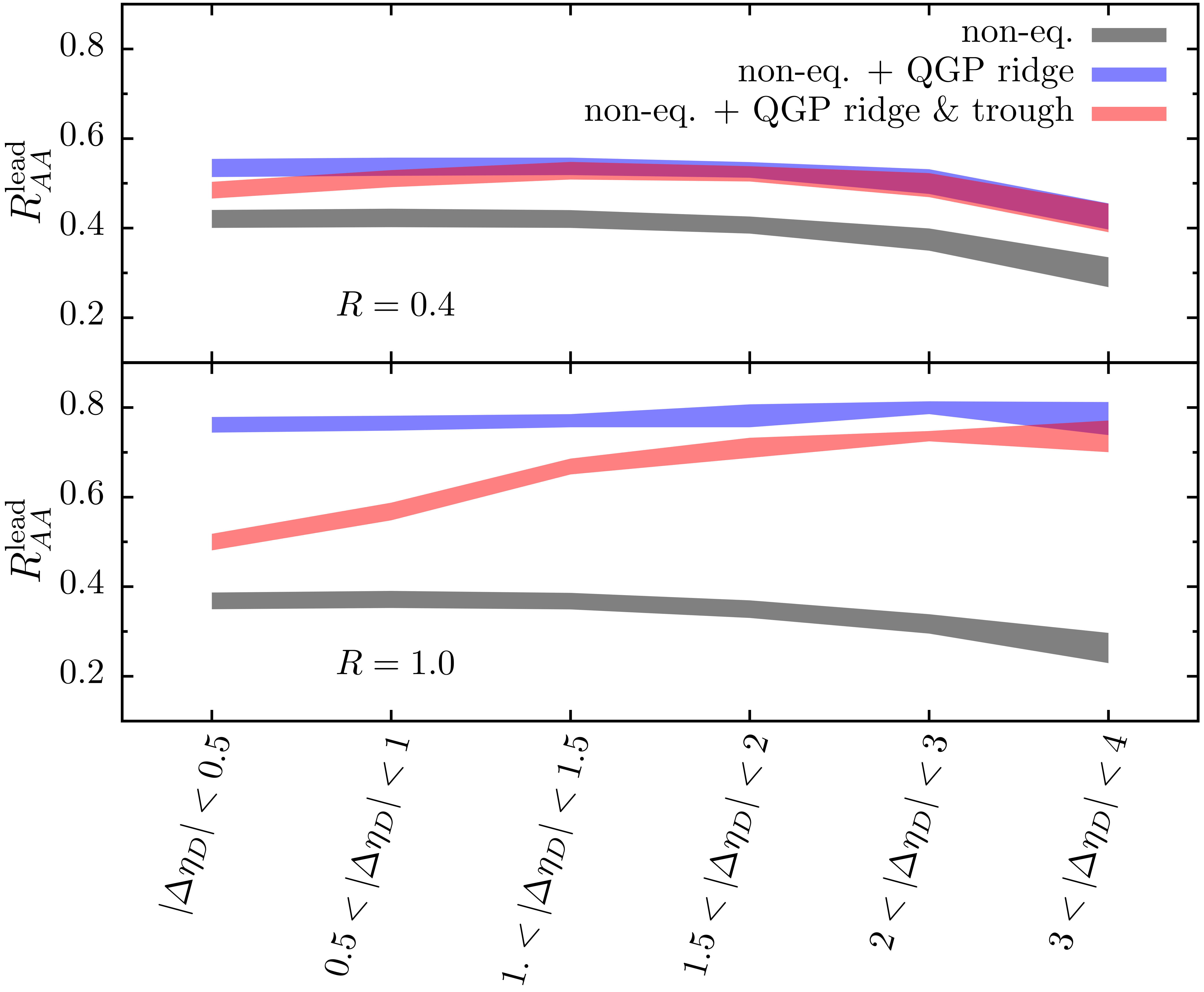
R = 1.0

strong dependence on $|\eta_D|$;
knee visible when $|\eta_D|\sim R$.

$$p_T^L > 250 \text{ GeV}$$
$$p_T^S > 80 \text{ GeV}$$
$$\Delta\phi_D > 2\pi/3$$

differential in

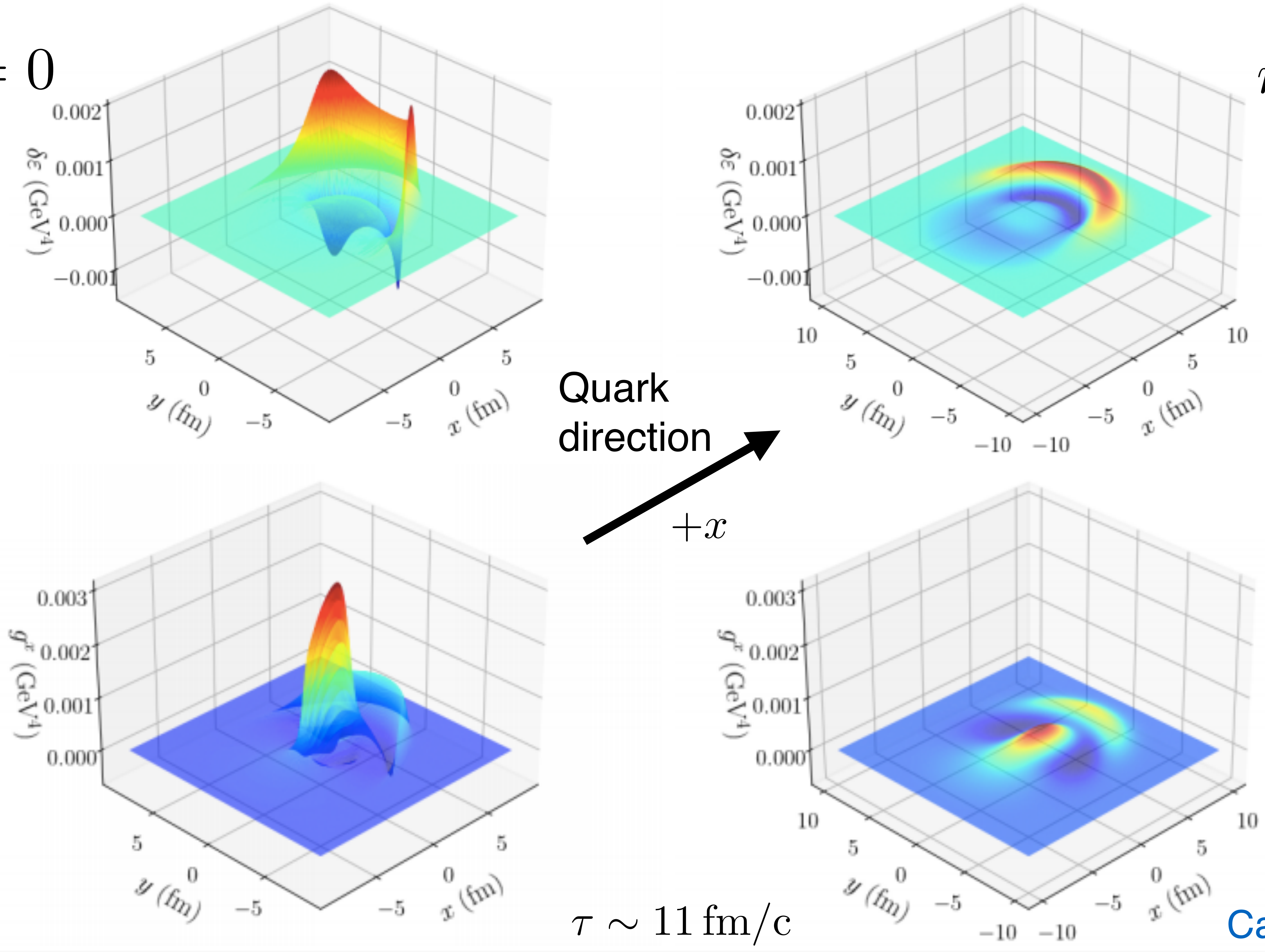
$$|\eta_D| \equiv |\eta_L - \eta_S|$$



Linearized Hydrodynamics

- Analytic, but over-simplified medium response needs to be improved:
  - ➜ Starting point: linearised hydro eqs. for perturbations on top of viscous Bjorken flow.

$\eta = 0$ $\qquad$ $\eta = \frac{s}{4\pi}$



- $\delta\epsilon$: energy density pert.

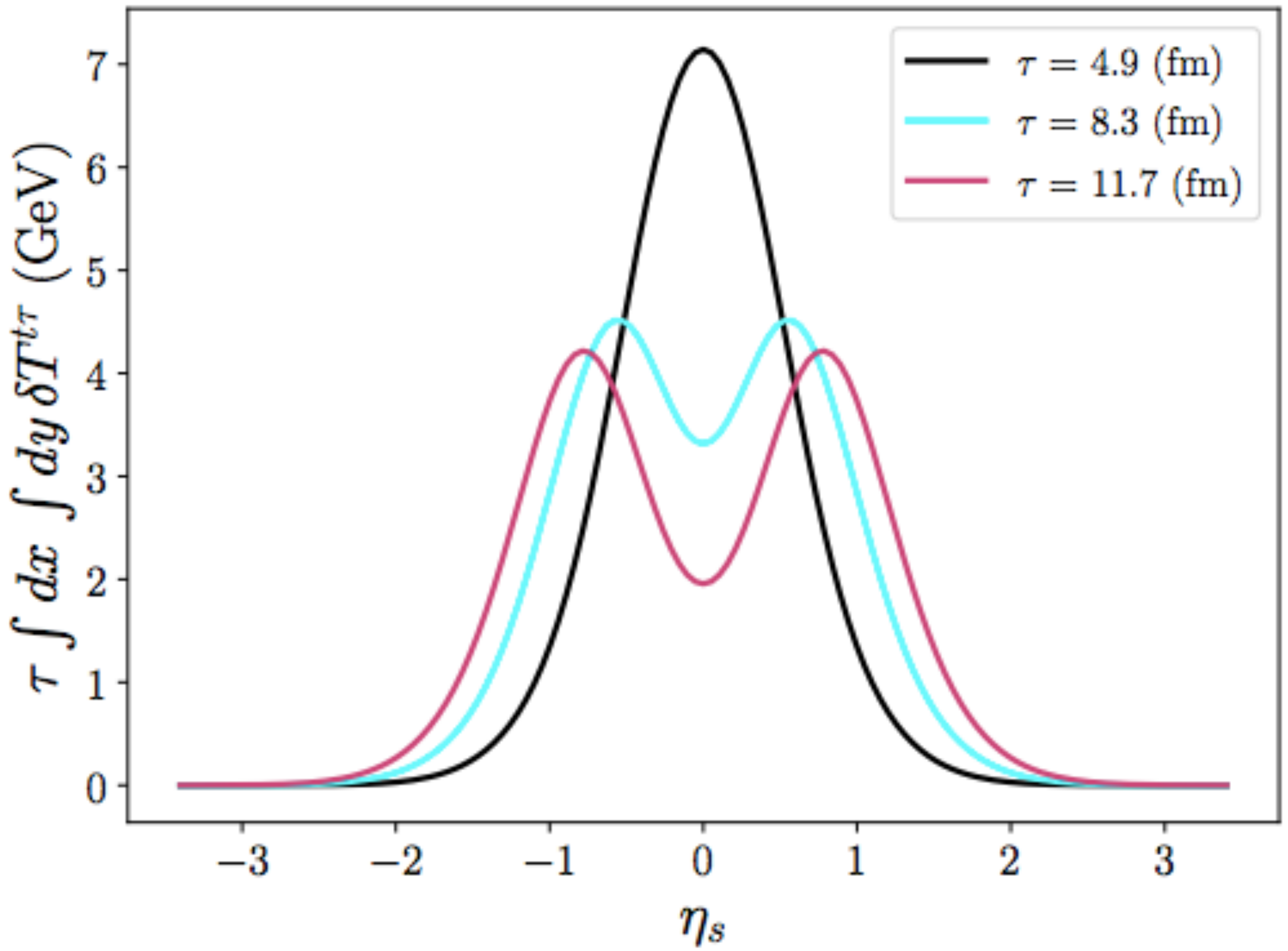
  Wavefront structure (Mach cone) diffuses due to viscosity.

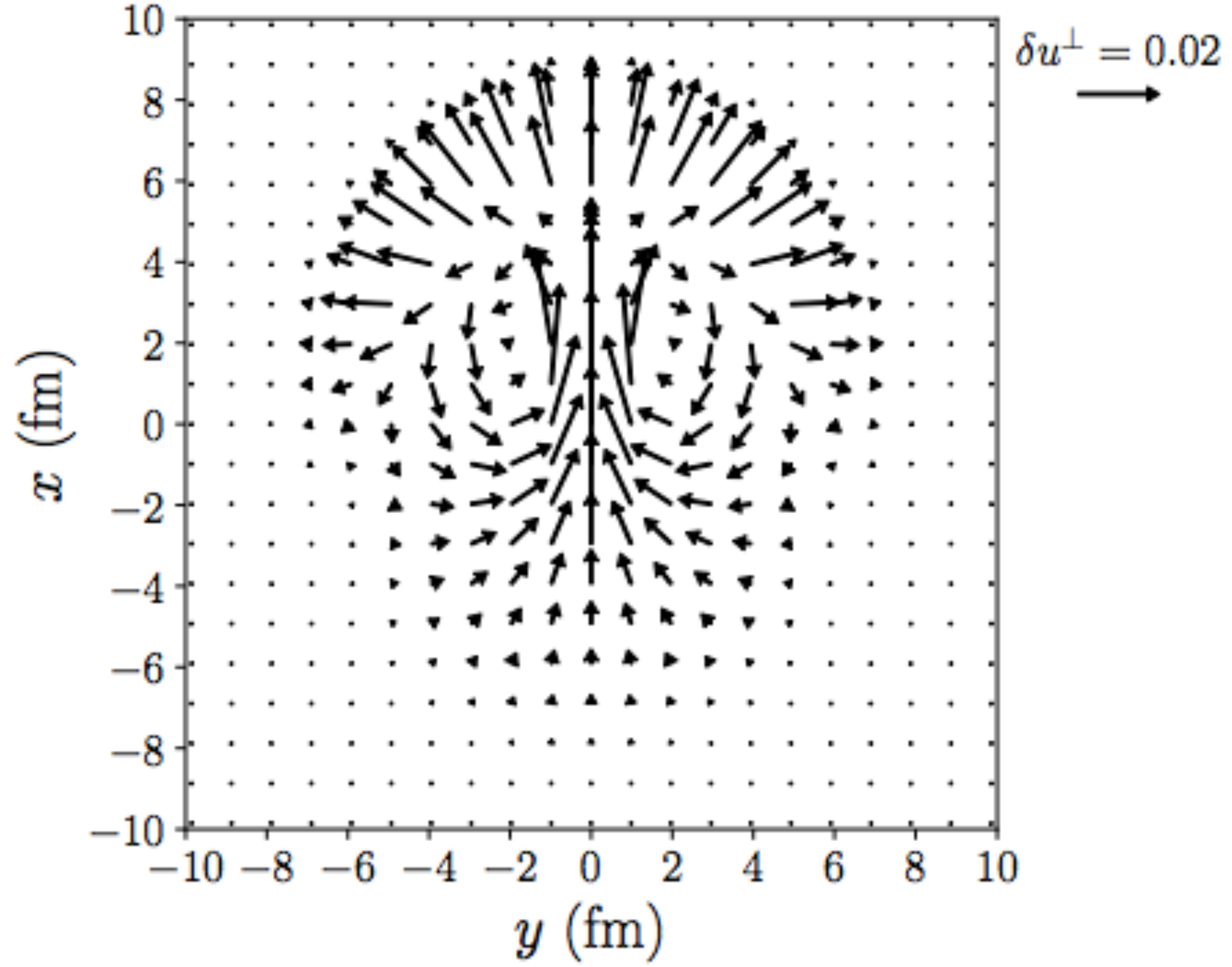
- g_x : momentum pert.

  Wing shaped structure diffuses due to viscosity (diffusion wake).

Casalderrey, Milhano, DP, Rajagopal, Yao - JHEP ‘21

Linearized Hydrodynamics





- Sound modes make wake energy spread in rapidity with time.
- Jet breaks long. boost invariance.

Casalderrey, Milhano, DP, Rajagopal, Yao - JHEP '21

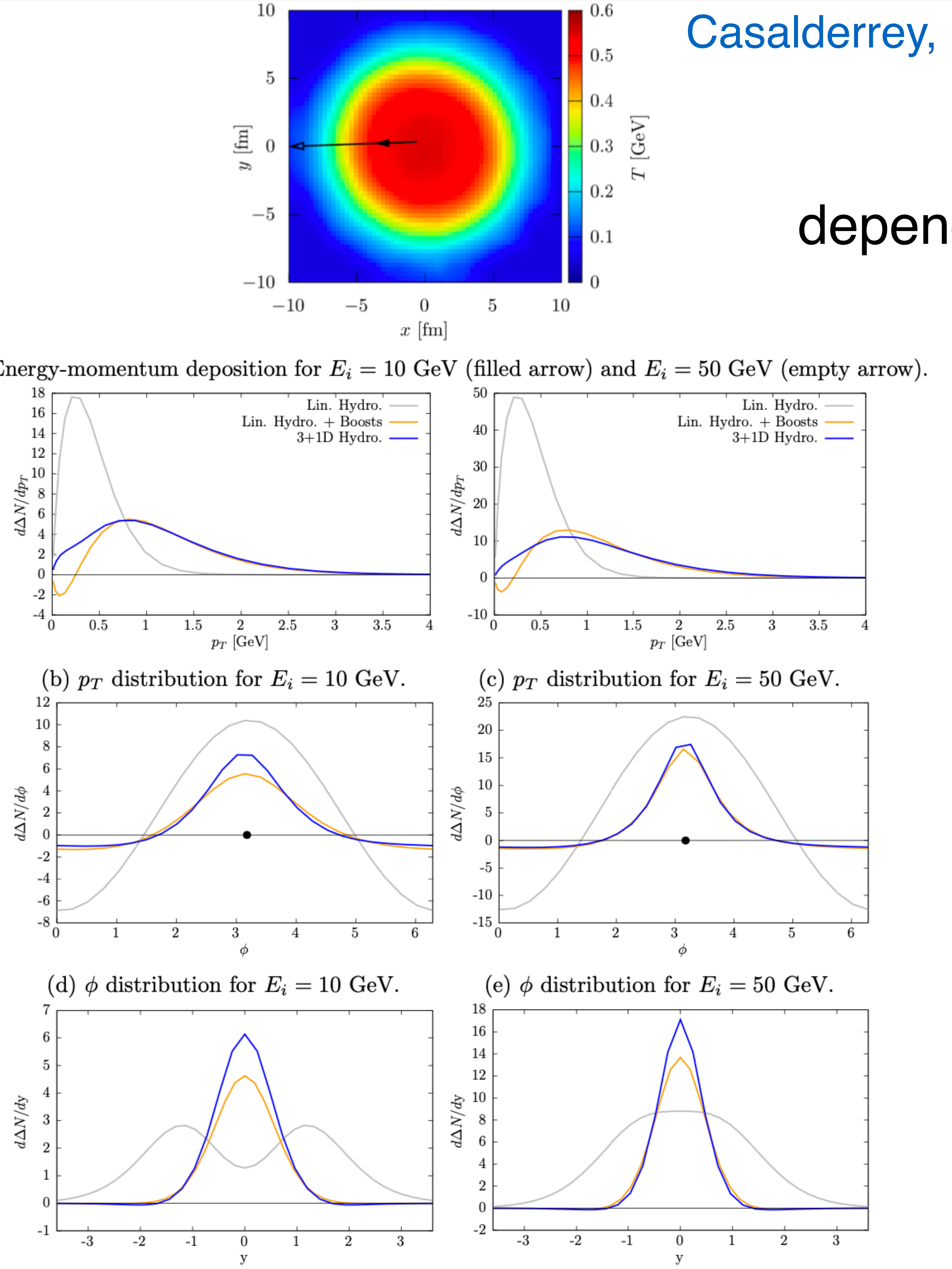
- Vortex ring around jet direction.

→ Imprints on Λ polarisation?

Serenone et al. - PLB '21

Green’s Functions for the Wake

Casalderrey, Milhano, DP, Rajagopal, Yao - in preparation



(a) Energy-momentum deposition for $E_i = 10$ GeV (filled arrow) and $E_i = 50$ GeV (empty arrow).

(b) p_T distribution for $E_i = 10$ GeV. (c) p_T distribution for $E_i = 50$ GeV.

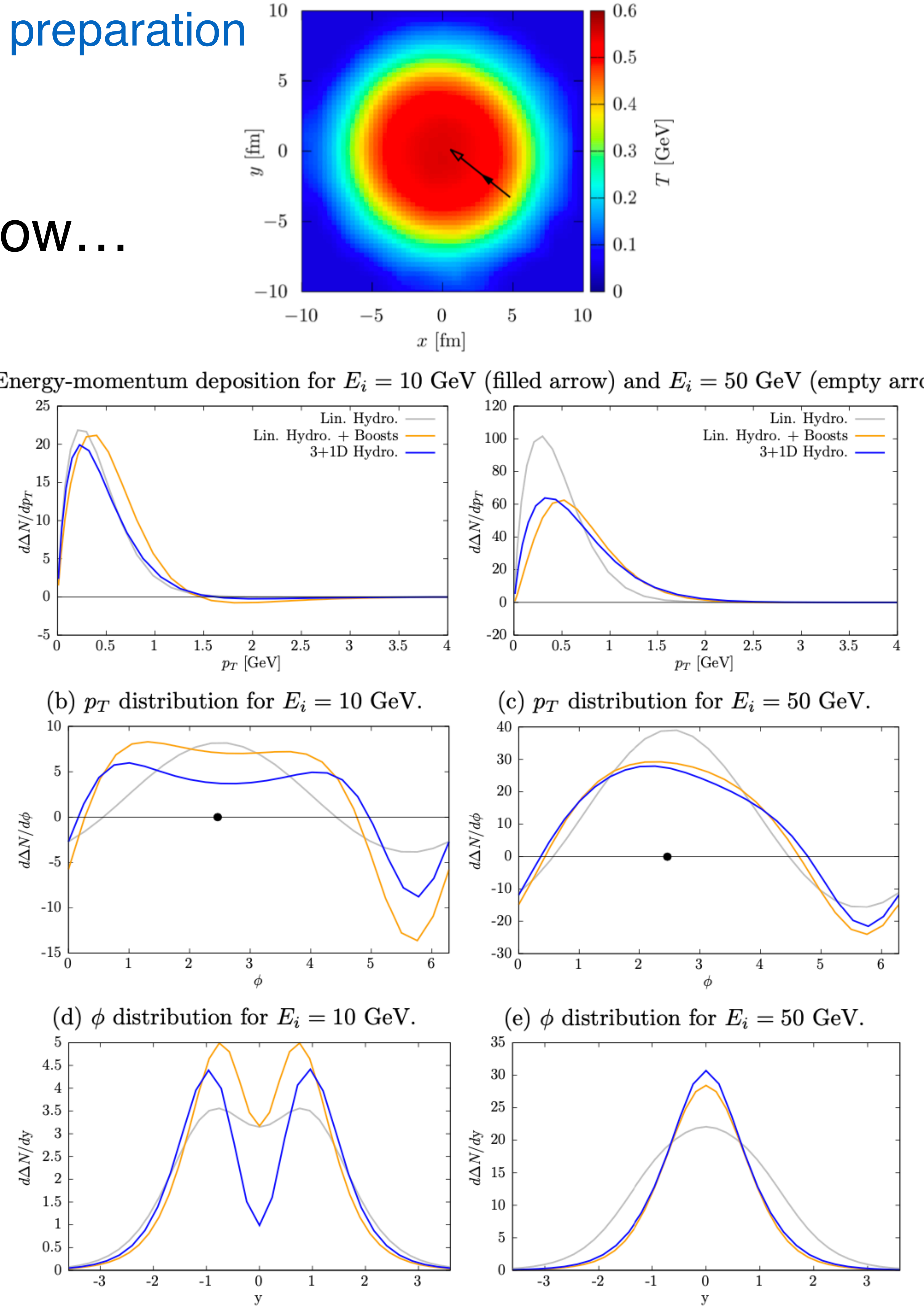
(d) ϕ distribution for $E_i = 10$ GeV. (e) ϕ distribution for $E_i = 50$ GeV.

(f) y distribution for $E_i = 10$ GeV. (g) y distribution for $E_i = 50$ GeV.

Hadrons from the wake
depend on evolution time, local flow…

3+1D Hydrodynamics
~ 2 hours

Green’s Functions
in Bjorken flow
+
Trans., Rot., & Boosts
~ 3 seconds



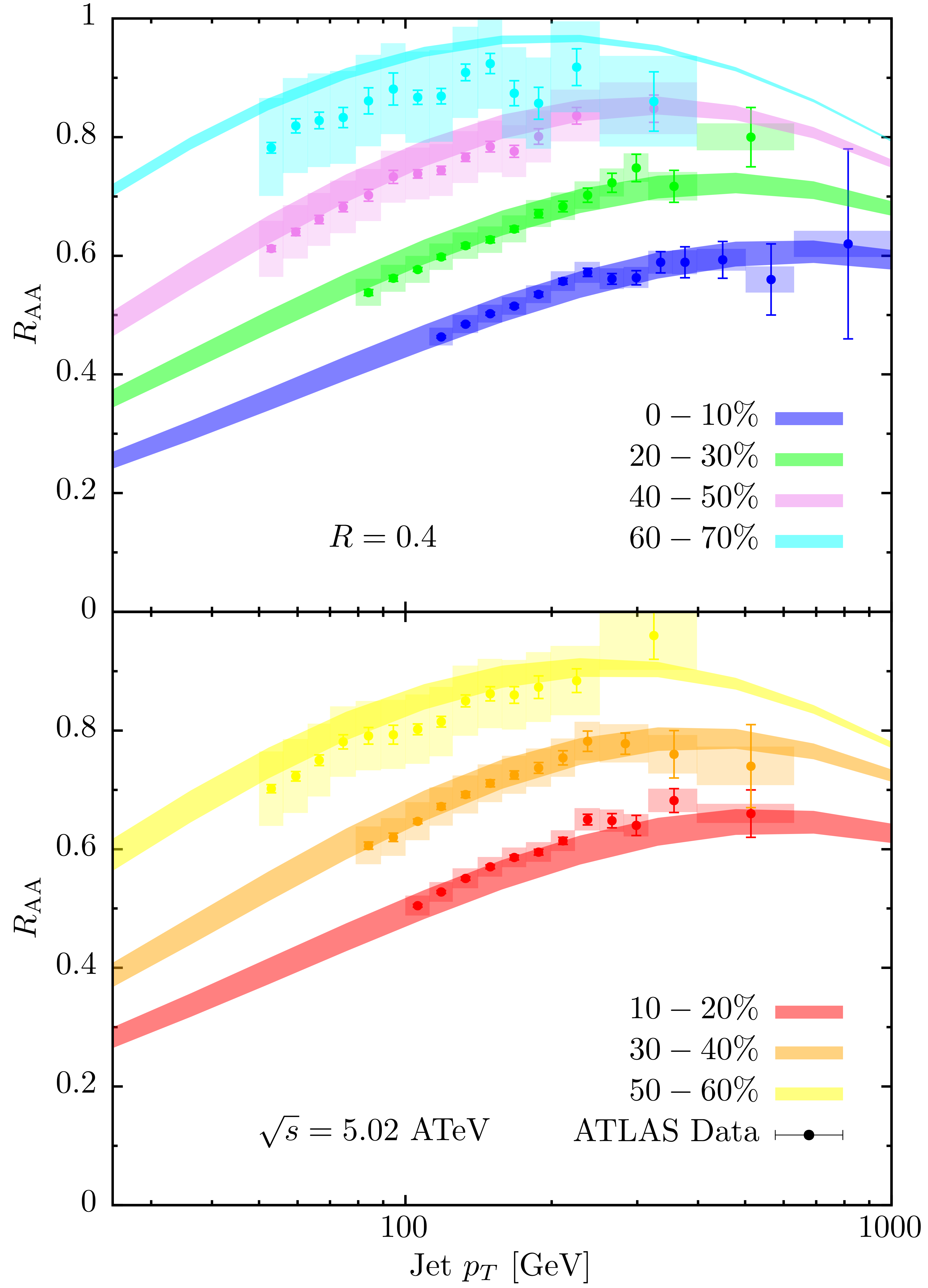
(a) Energy-momentum deposition for $E_i = 10$ GeV (filled arrow) and $E_i = 50$ GeV (empty arrow

(b) p_T distribution for $E_i = 10$ GeV. (c) p_T distribution for $E_i = 50$ GeV.

(d) ϕ distribution for $E_i = 10$ GeV. (e) ϕ distribution for $E_i = 50$ GeV.

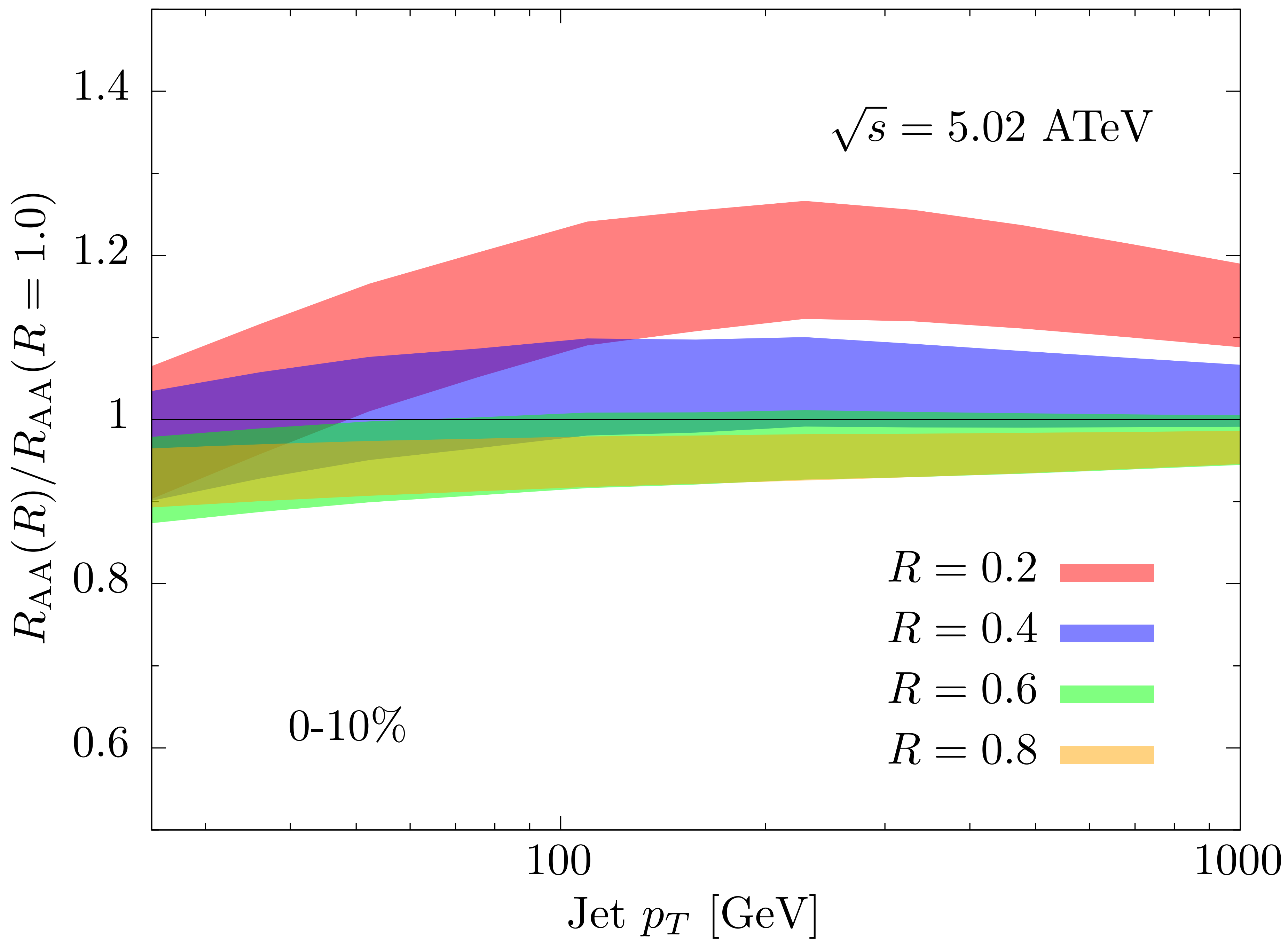
(f) y distribution for $E_i = 10$ GeV. (g) y distribution for $E_i = 50$ GeV.

Analytic Jet Suppression



Encouraging description of data across:

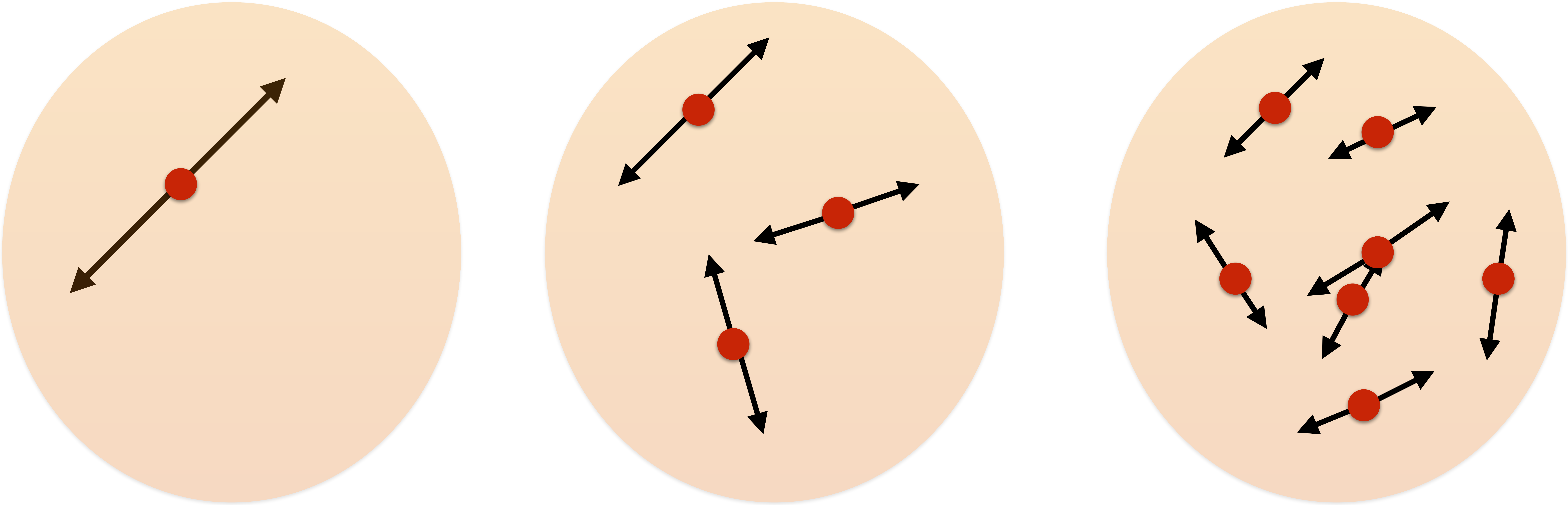
- Jet p_T.
- Centrality.
- Size R.



- Modelling uncertainties:
  - Non-perturbative sector relatively unimportant up to R<0.6
  - NLO contribution to radiative energy loss is very small.
  - Most important: Determination of quenched phase space. Can be systematically improved in pQCD.

Mehtar-Tani, DP, Tywoniuk - PRL '21

Minijets Hydrodynamization

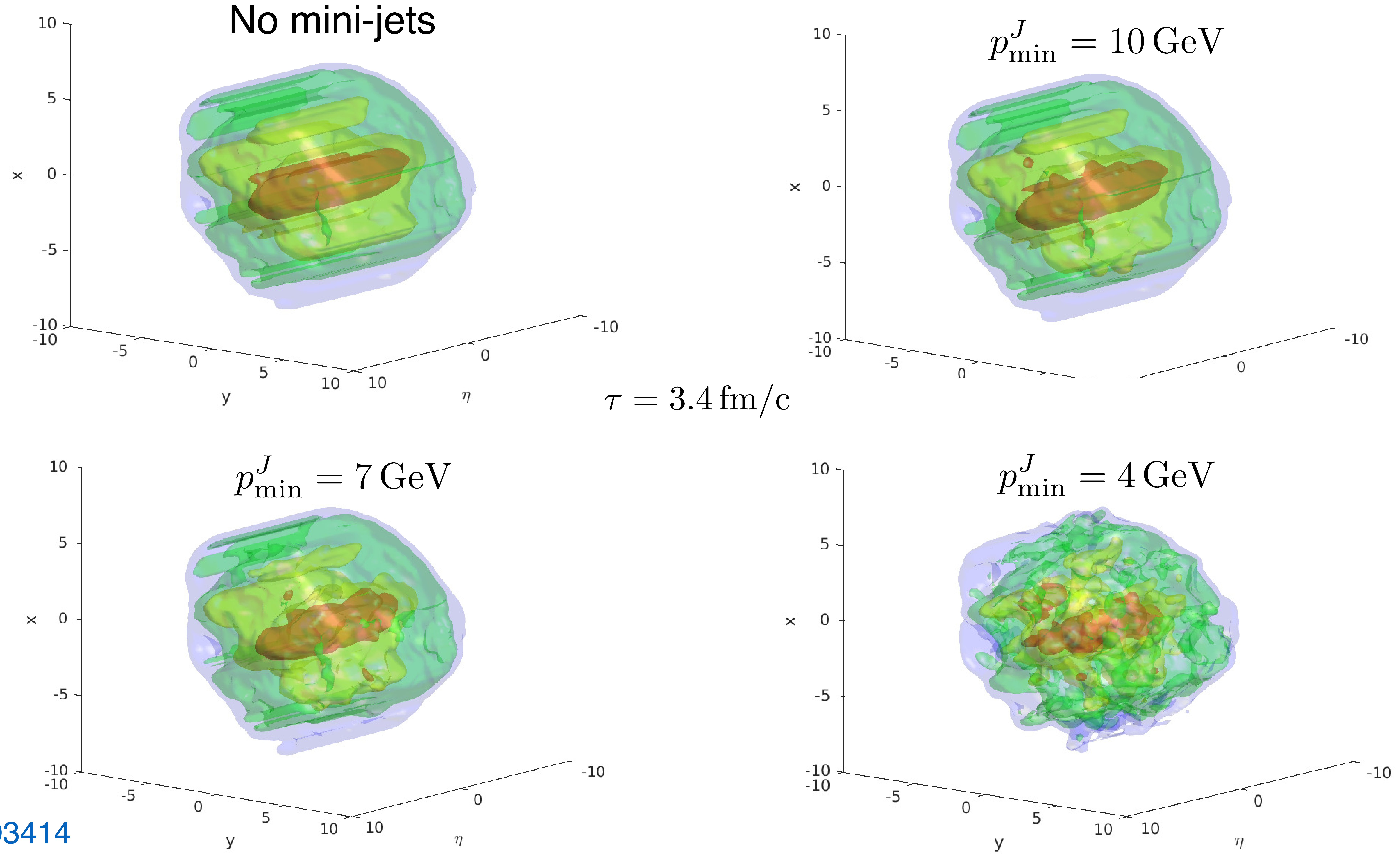


- At high p_T, usually consider single hard scattering producing dijet pair.

  → As we consider lower p_T, minijet production becomes increasingly abundant…

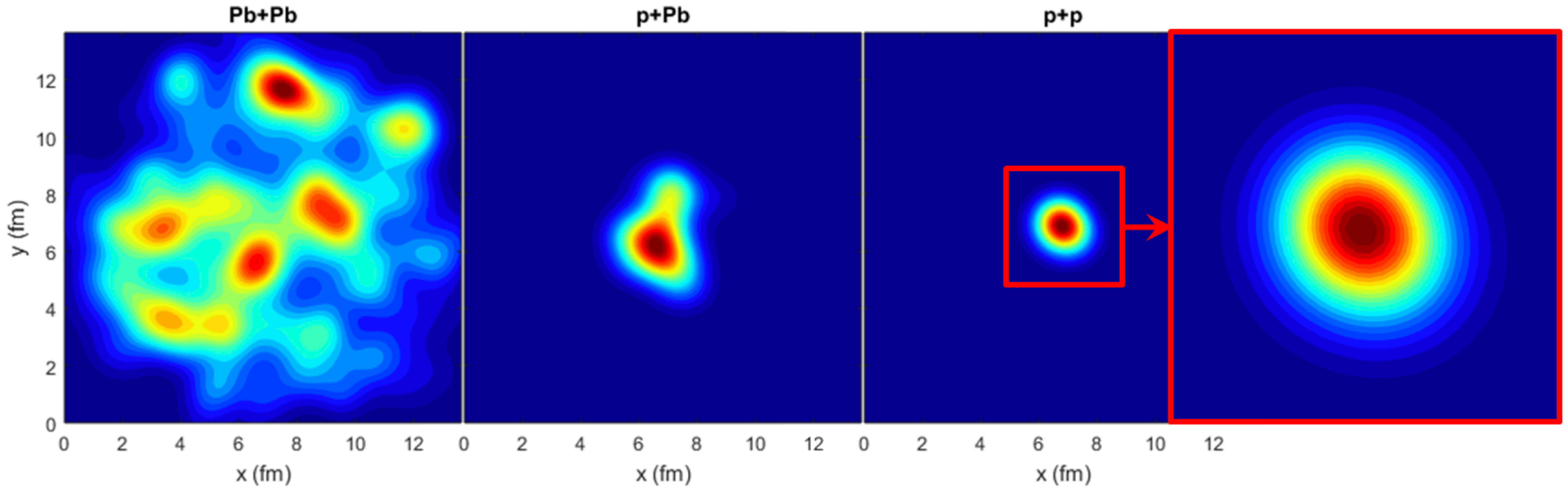
A Spikier Evolution

3D isotherms at temperatures
220 MeV (red),
195 MeV (yellow),
170 MeV (green)
and 145 MeV (blue).



DP, Singh, Gale, Jeon - 2202.03414

Collectivity in Small Systems



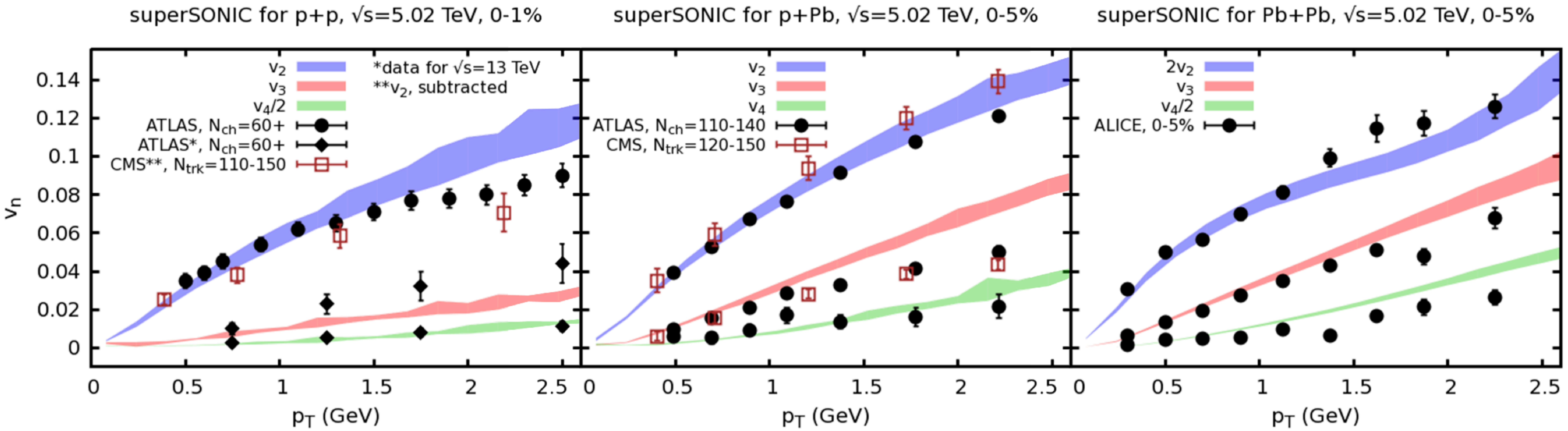
- Collectivity signatures observed in smaller systems (proton-proton, proton-nucleus):
  - Is it QGP? System size can be smaller than expansion rate… (attractors?)
  - What is it?

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1+\sum_{n=1}^{\infty} 2v_n \cos[n(\phi-\Psi_R)]\right)$$

v_2

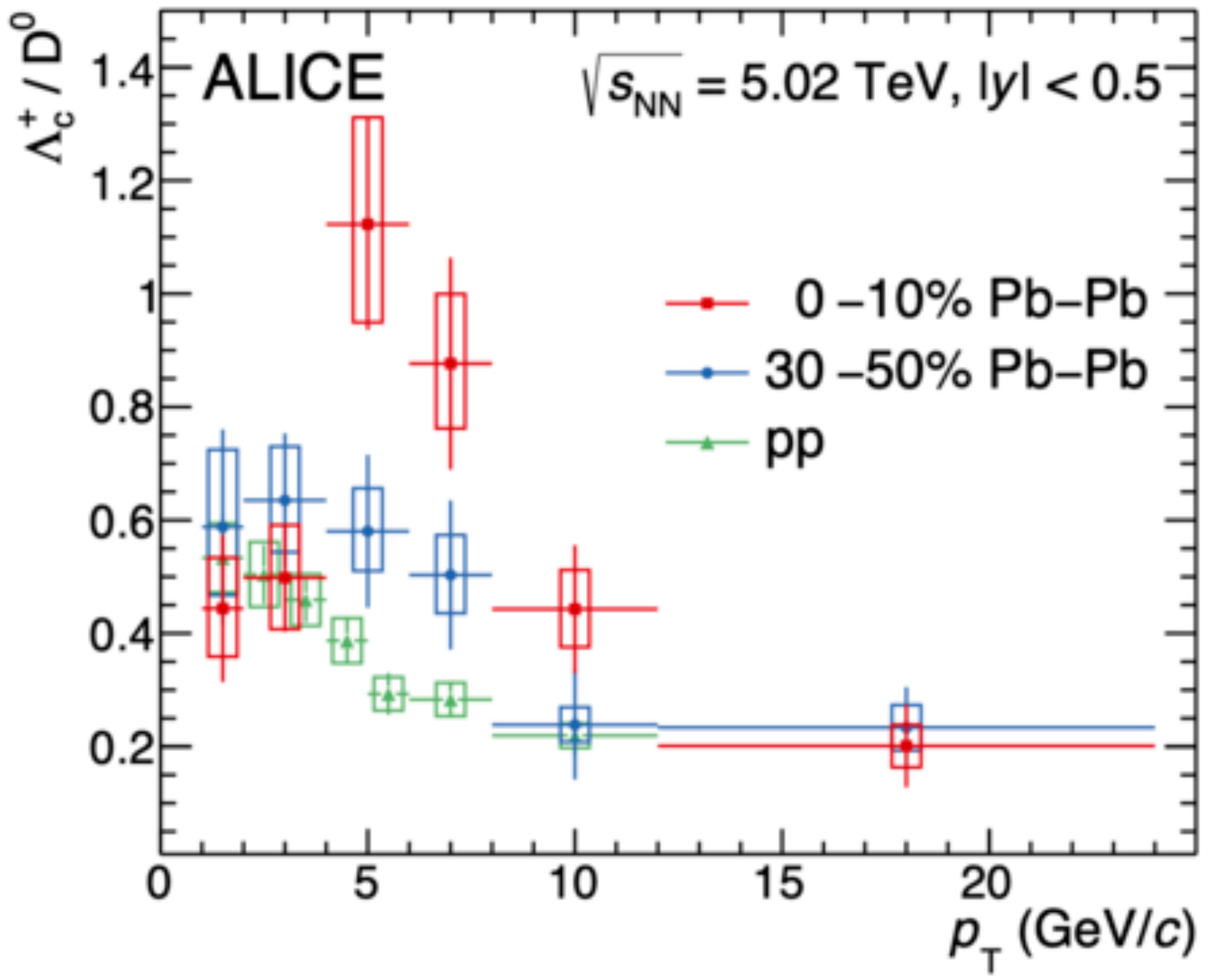
v_3

v_4



Weller & Romatschke - PLB '17

Collectivity in Small Systems



Baryon to meson enhancement observed also in pp collisions.

- Hadron spectra and yields can be described by thermal distribution… even in proton-proton!

➔ Connection with microscopic description of hadronization? Colour-reconnection, entanglement…

- Improve understanding of hadronization, in large and small systems, using heavy quark probes.

➔ Model proton-proton system as a droplet of liquid QGP.

➔ Use novel hadronization mechanisms involving recombination.

Beraudo, De Pace, Nardi, Prino, DP - in preparation

Thanks for your attention!