JetQGP

Jet Quenching and the Nature of the Quark-Gluon Plasma

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G.A. 754496

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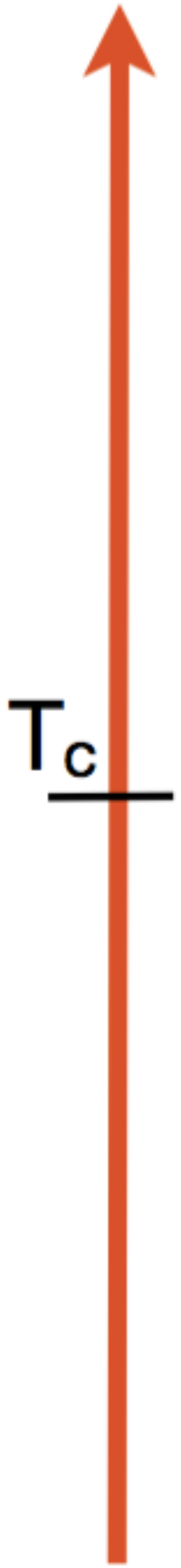
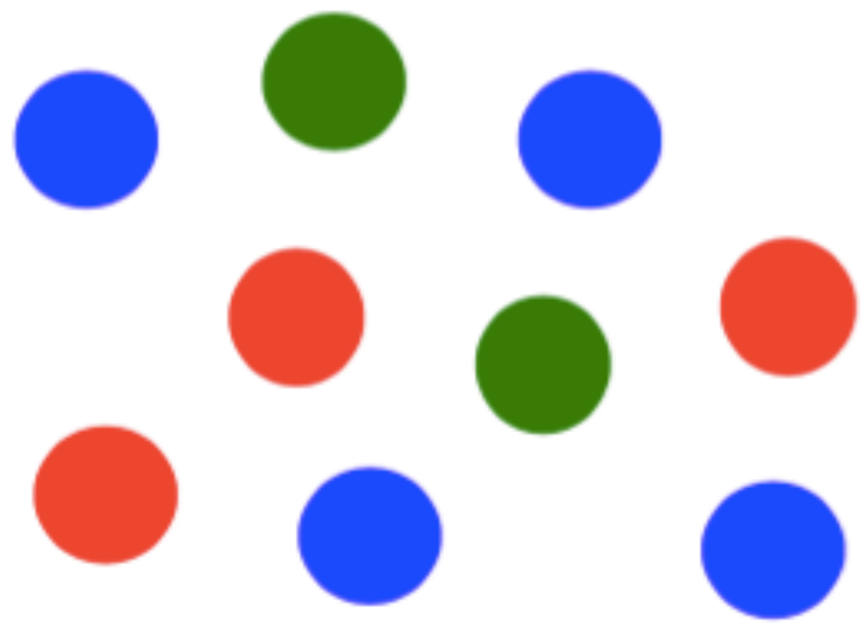
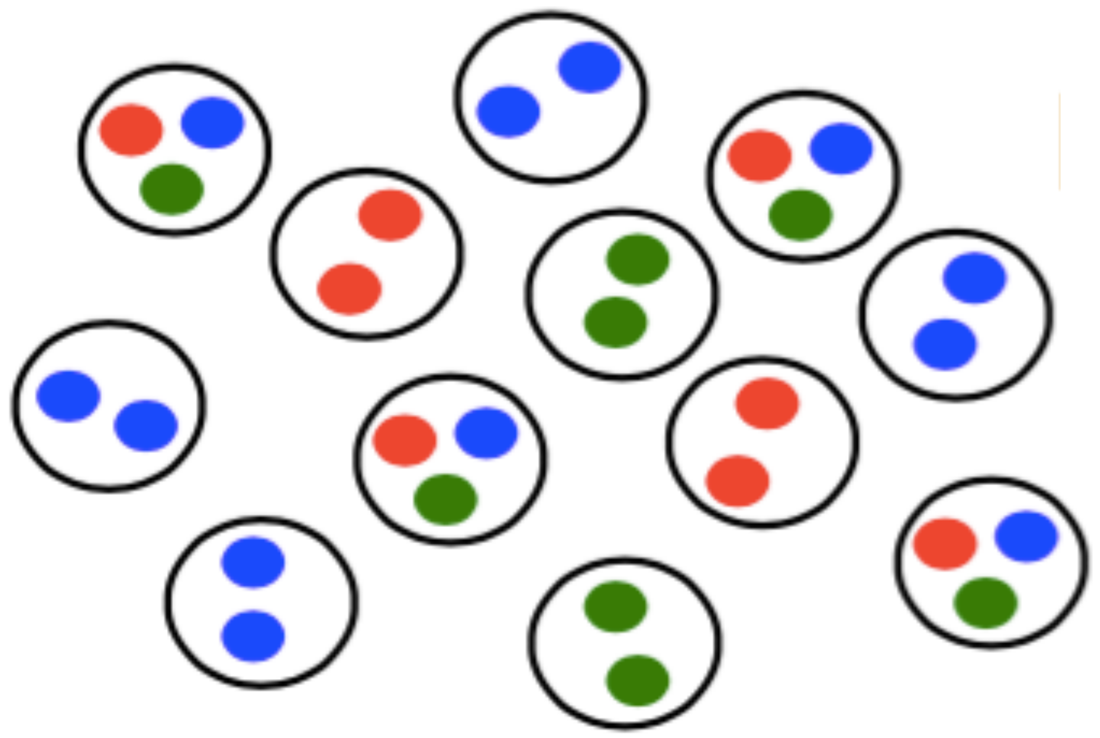
QCD Matter





"Phase transition"

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



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

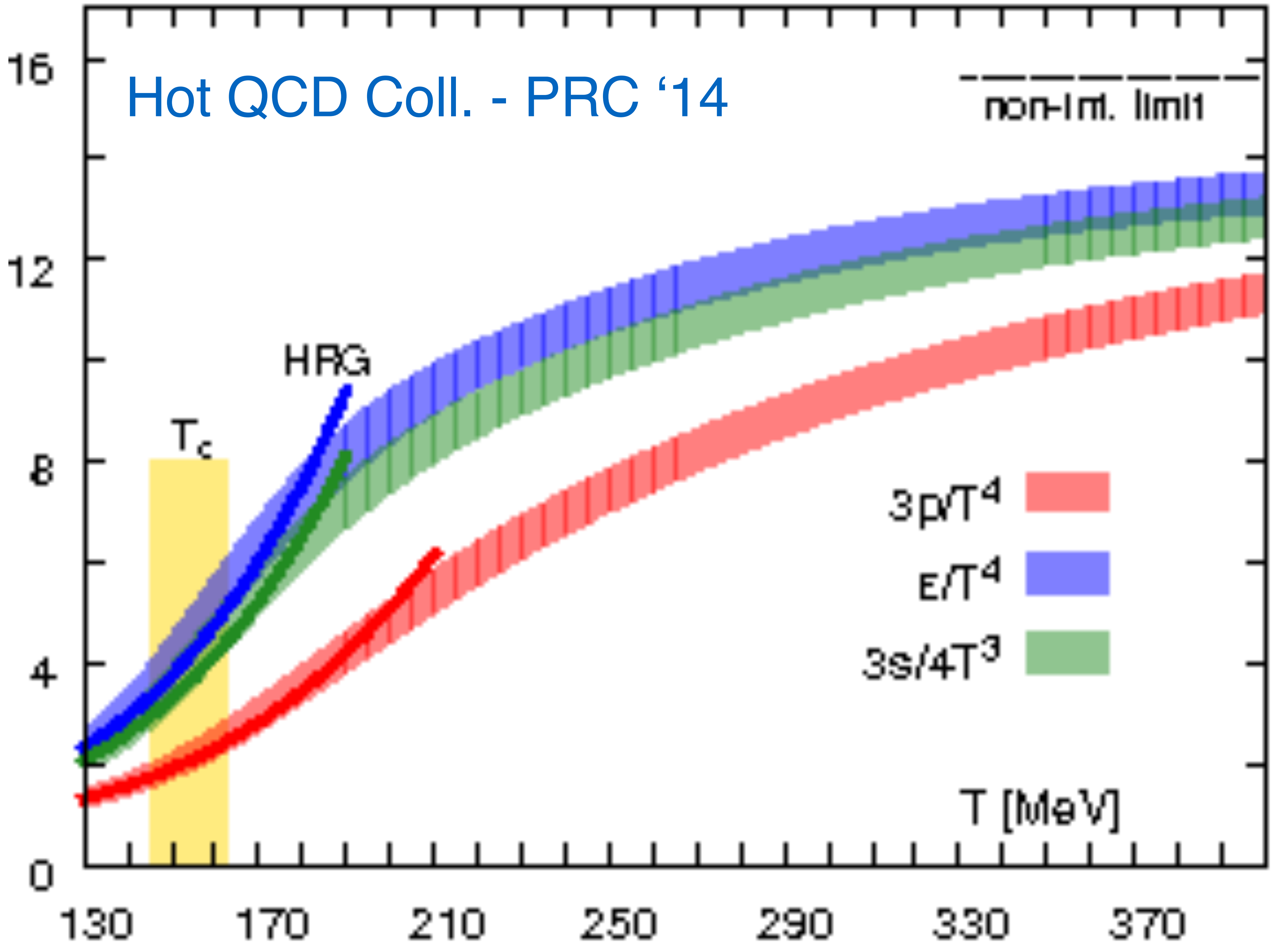
- Filled the universe μs after Big Bang.
- Colour is liberated.
- A gas of quarks and gluons.

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

Hadron Gas:

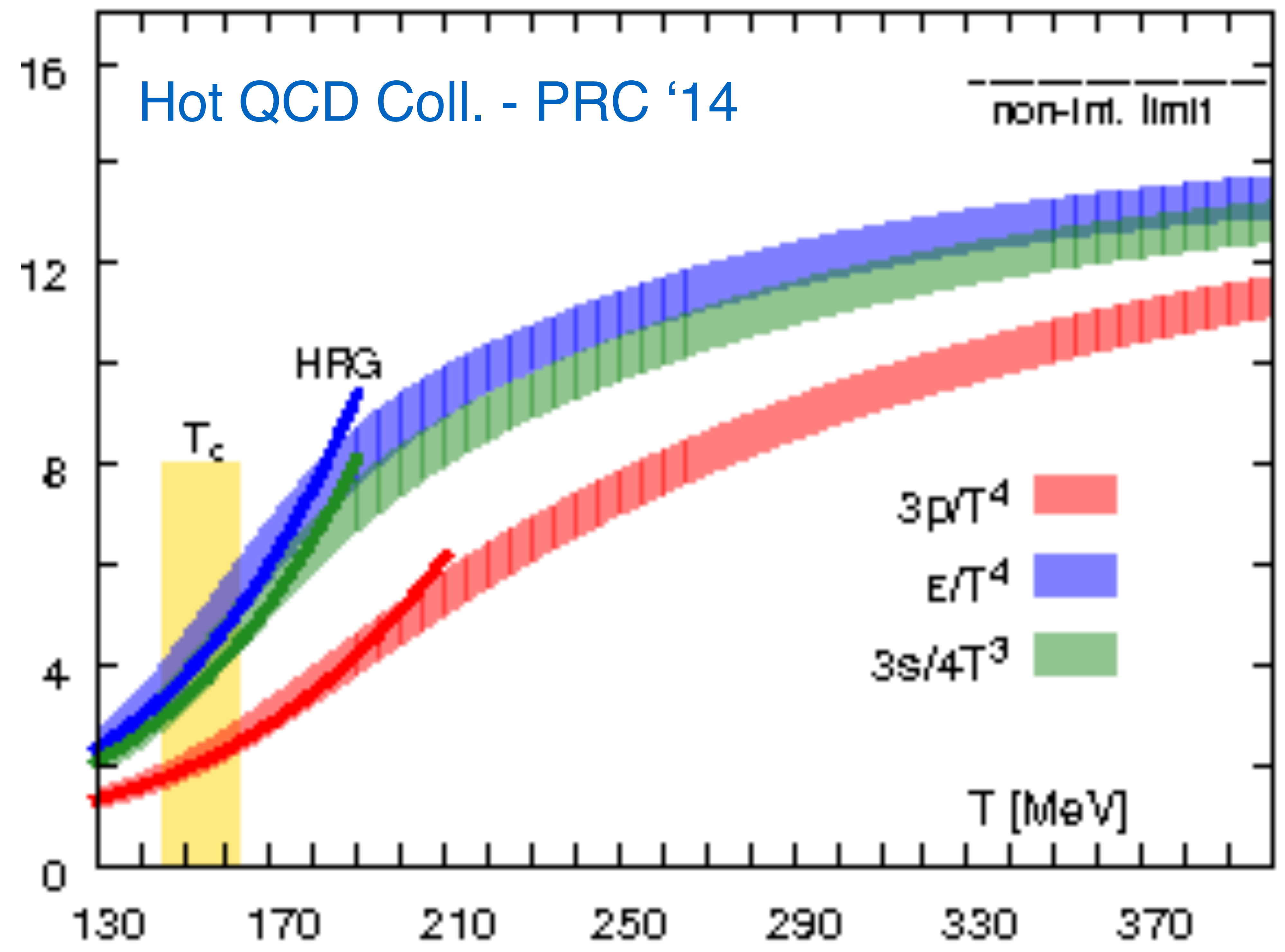
- Color is confined.
- Hadrons re-scatter.

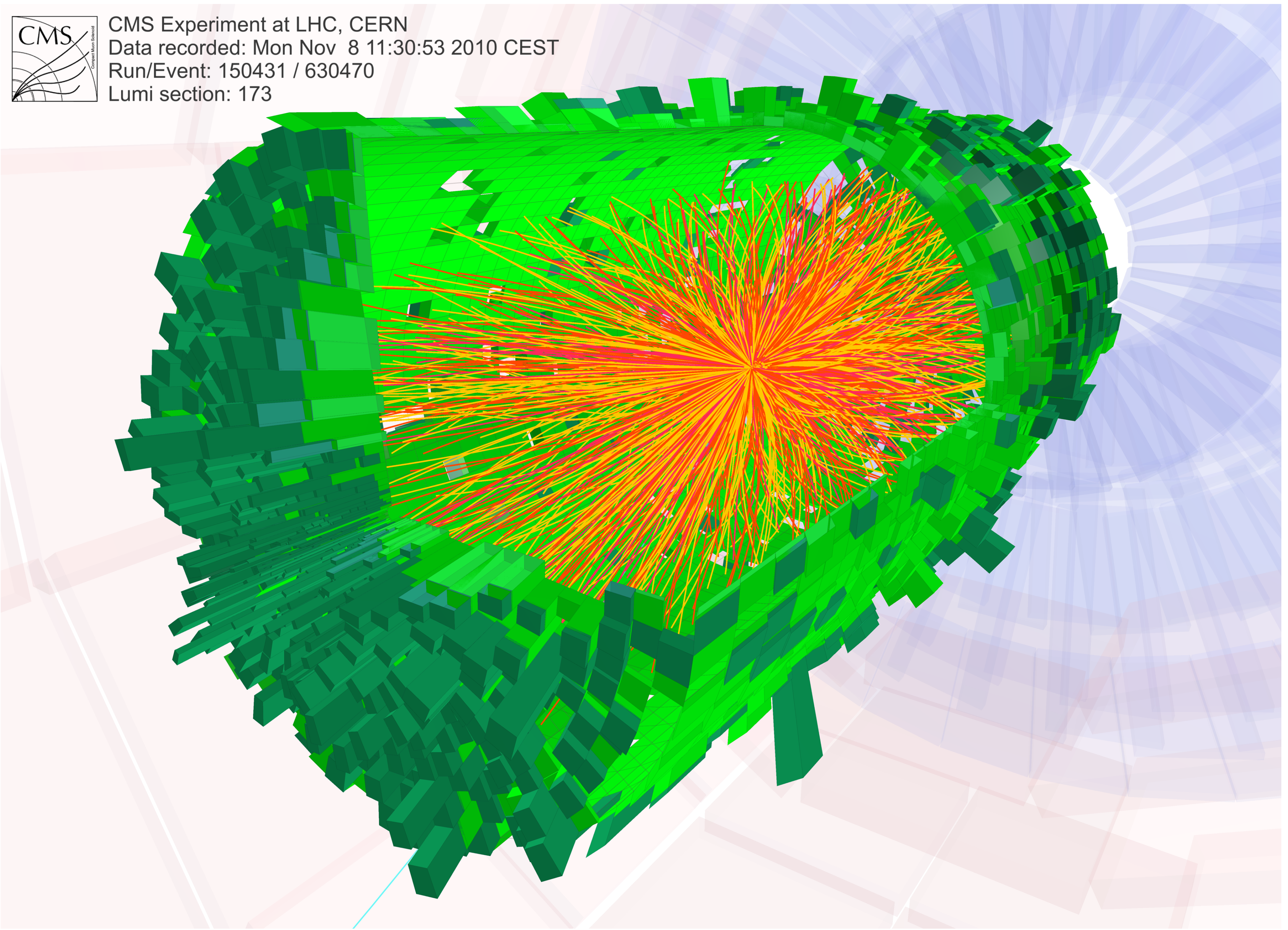
Heavy-Ion Collisions (HIC): The Little Bangs



- 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.

Heavy-Ion Collisions (HIC): The Little Bangs



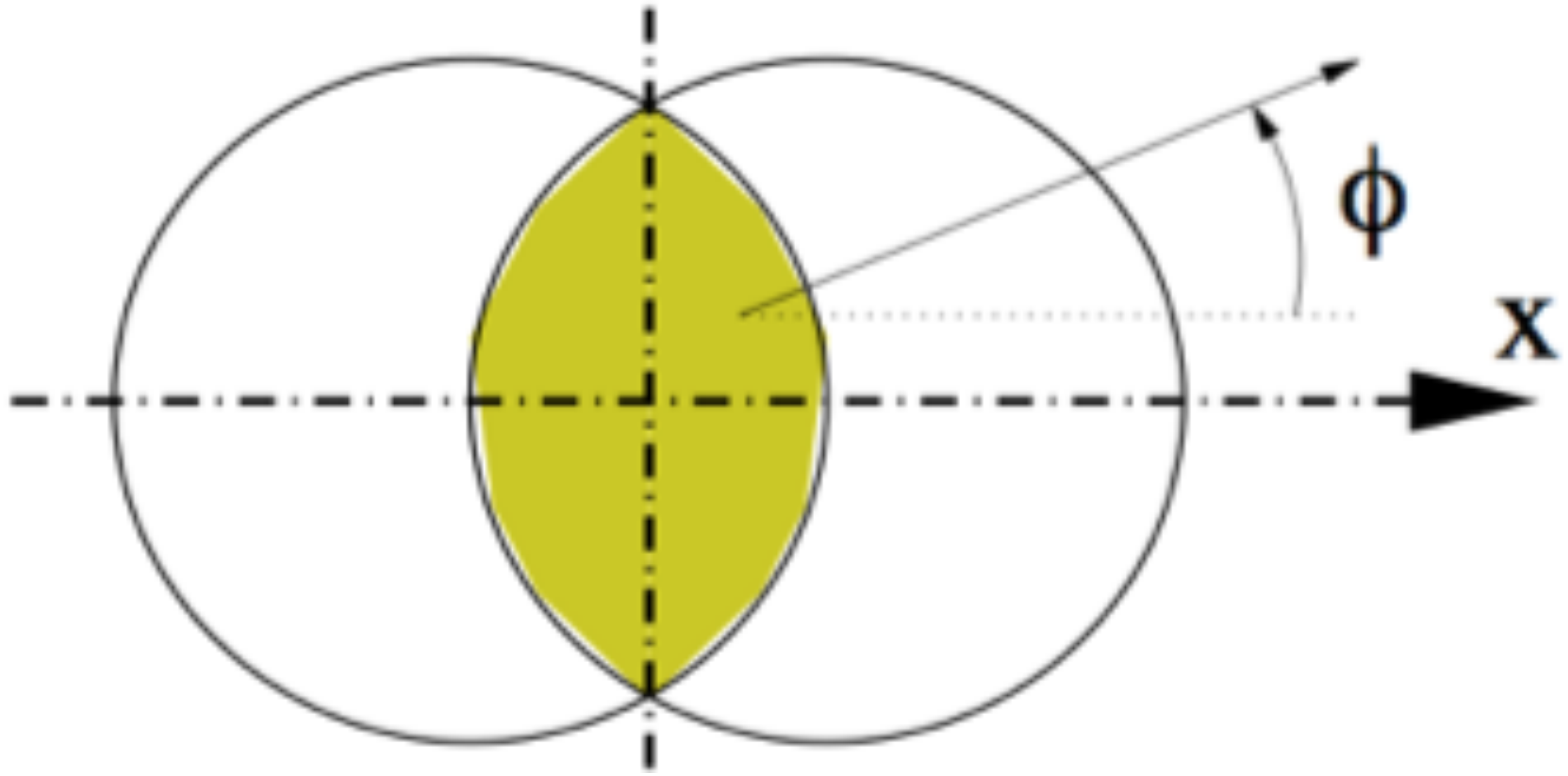


RHIC $\sqrt{s} \sim 0.2\,\mathrm{ATeV}$

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

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

QGP: Most Perfect Liquid

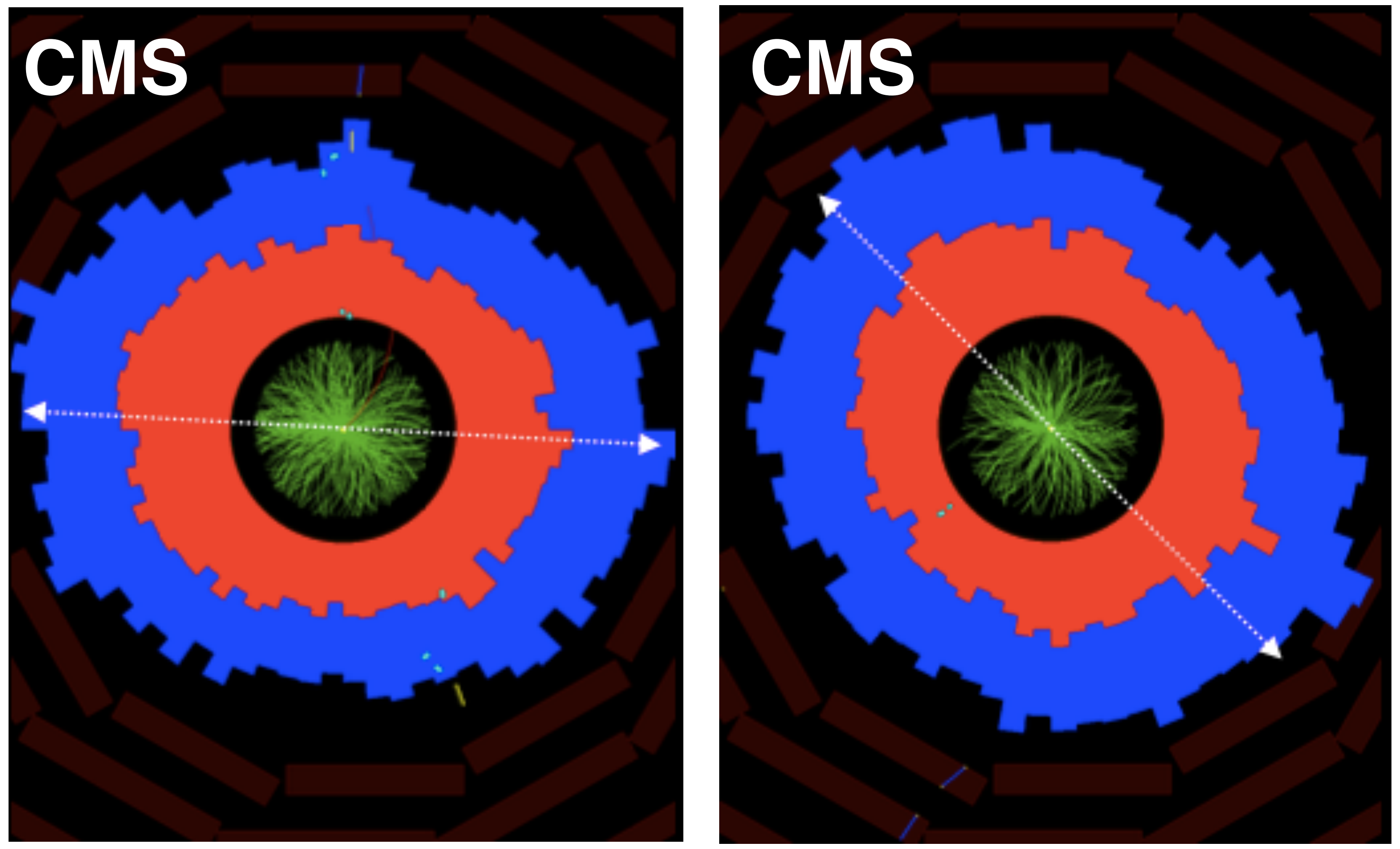


Hydrodynamics:

Spatial anisotropies.

↓

Pressure gradients.



- Correlations quantified in the experiments through so-called flow coefficients:

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

Ψ_R is event plane angle.

v_2

v_3

v_4

etc…

- Hydrodynamic simulations point to almost ideal fluid:

$$\left(\frac{\eta}{s}\right)_{T_c} \simeq 0.08$$

Bernhard et al. - PRC ‘16

$$\frac{\eta_{\lambda\to 0}}{s_{\lambda\to 0}} = \frac{A}{\lambda^2 \log\left(B/\sqrt{\lambda}\right)}$$

N=4 SYM @ weak coupling

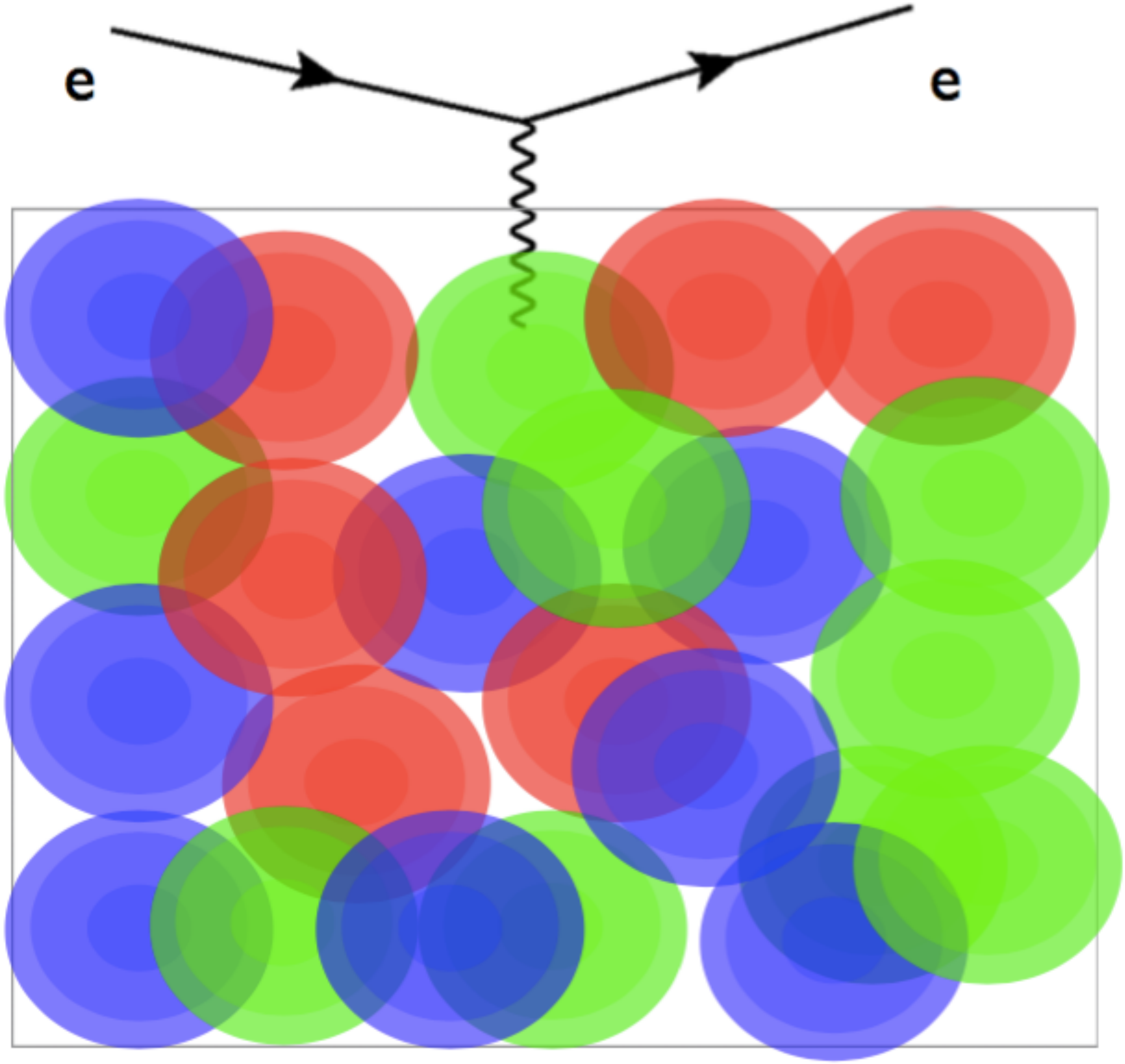
Preferred by data

$$\frac{\eta_{\lambda=\infty}}{s_{\lambda=\infty}} = \frac{1}{4\pi}$$

N=4 SYM @ strong coupling

Gauge/String Duality, Hot QCD and Heavy Ion Collisions - Cambridge University Press ‘14

How Can We Probe the QGP?

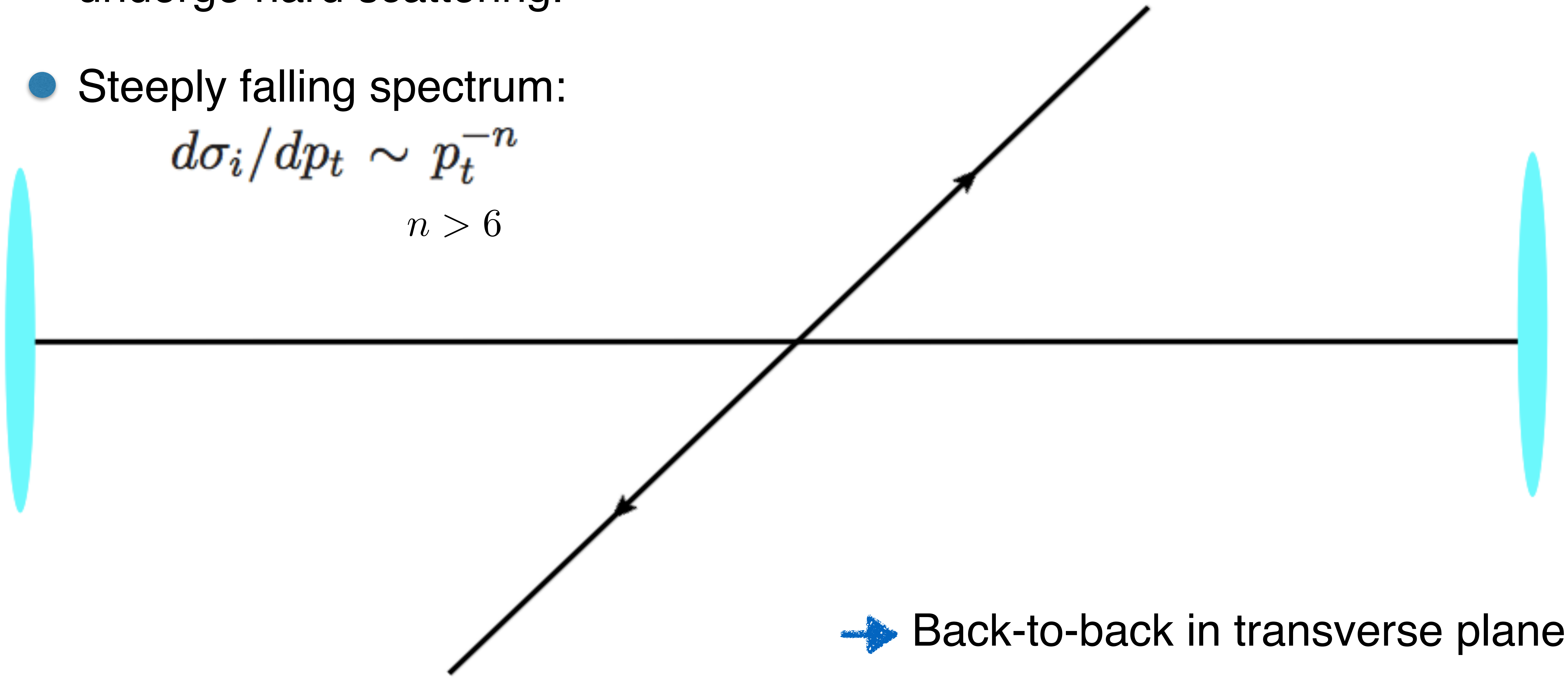


Jets

- Incoming partons from nucleons undergo hard scattering.
- Steeply falling spectrum:

$$d\sigma_i/dp_t \sim p_t^{-n}$$

$$n > 6$$

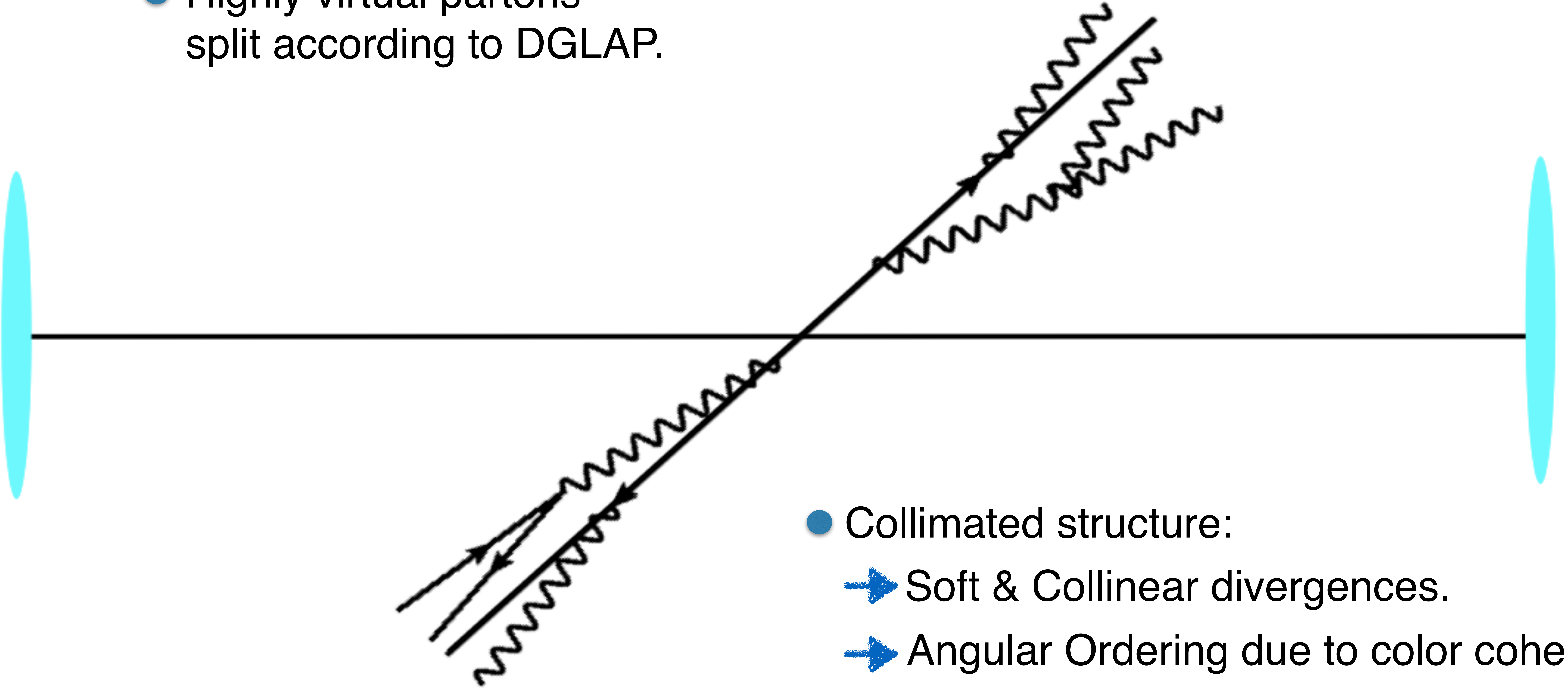


➔ Back-to-back in transverse plane.

➔ *Not* back-to-back in rapidity.

Jets

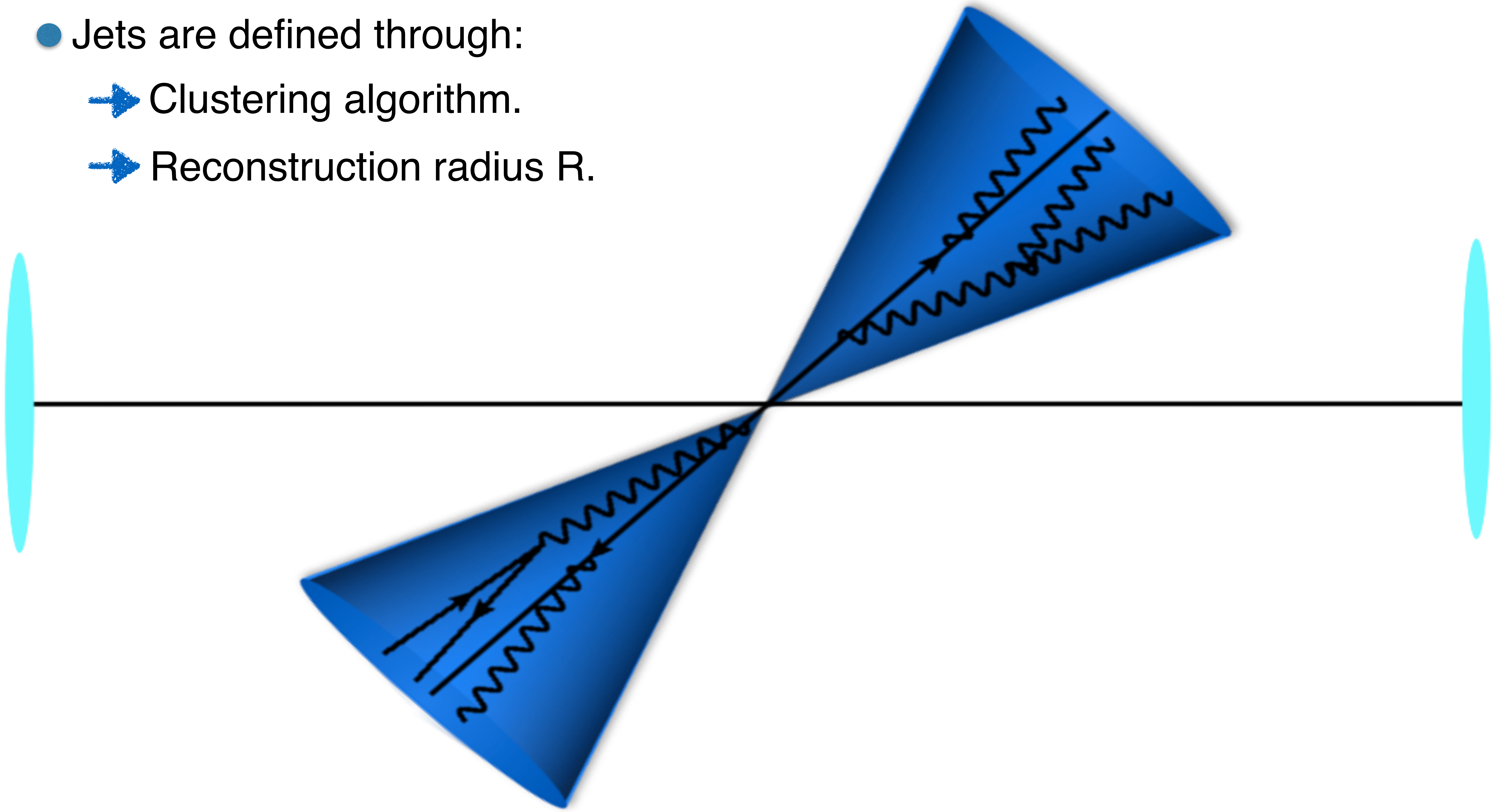
- Highly virtual partons split according to DGLAP.



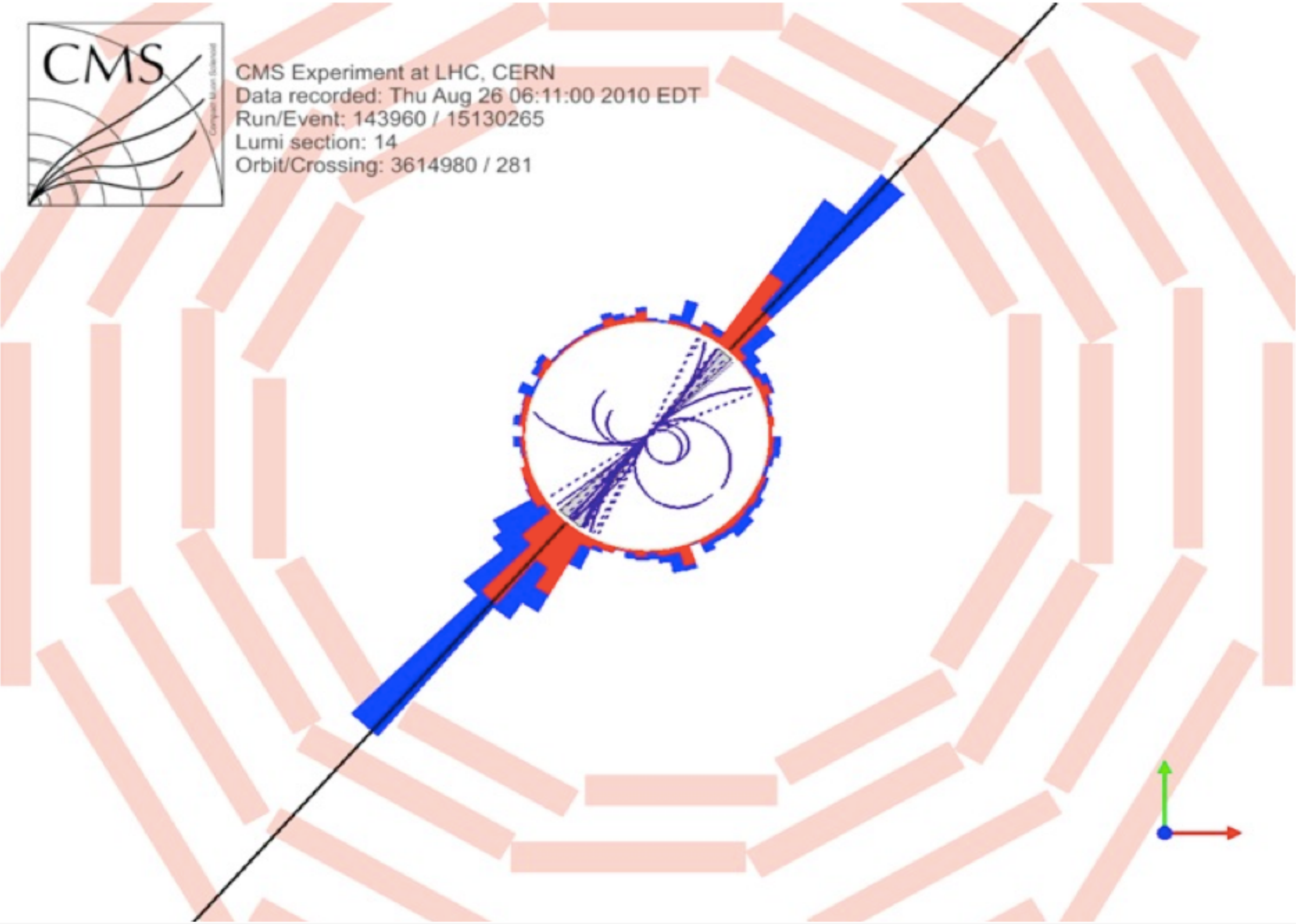
- Collimated structure:
  - Soft & Collinear divergences.
  - Angular Ordering due to color coherence.

Jets

- Jets are defined through:
  - Clustering algorithm.
  - Reconstruction radius R.

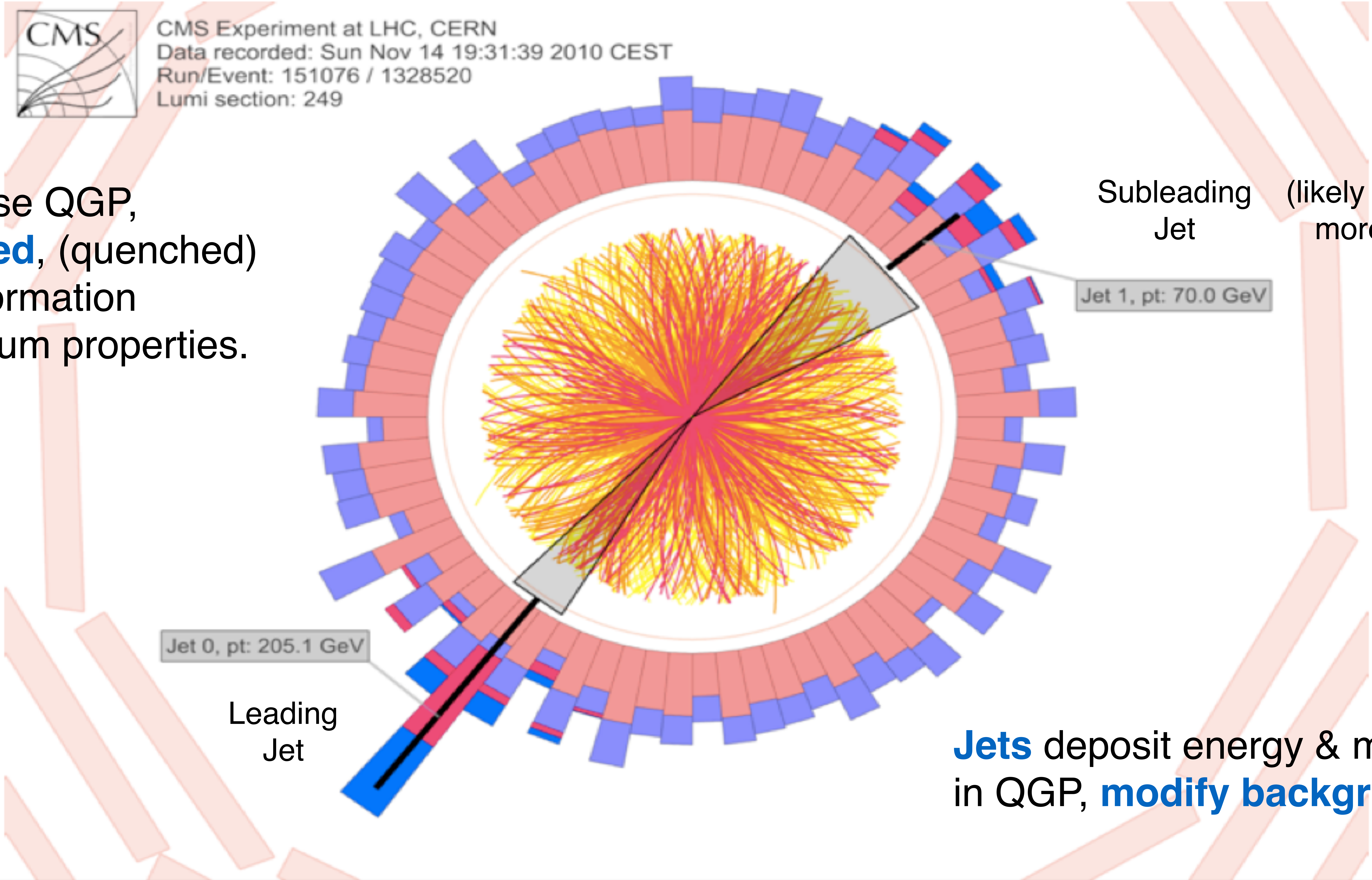


Jets in Proton-Proton Collisions



Jets in HIC

Jets traverse QGP,
get modified, (quenched)
provide information
about medium properties.



Jets deposit energy & momentum
in QGP, **modify background**.

What I Have Been Doing Lately

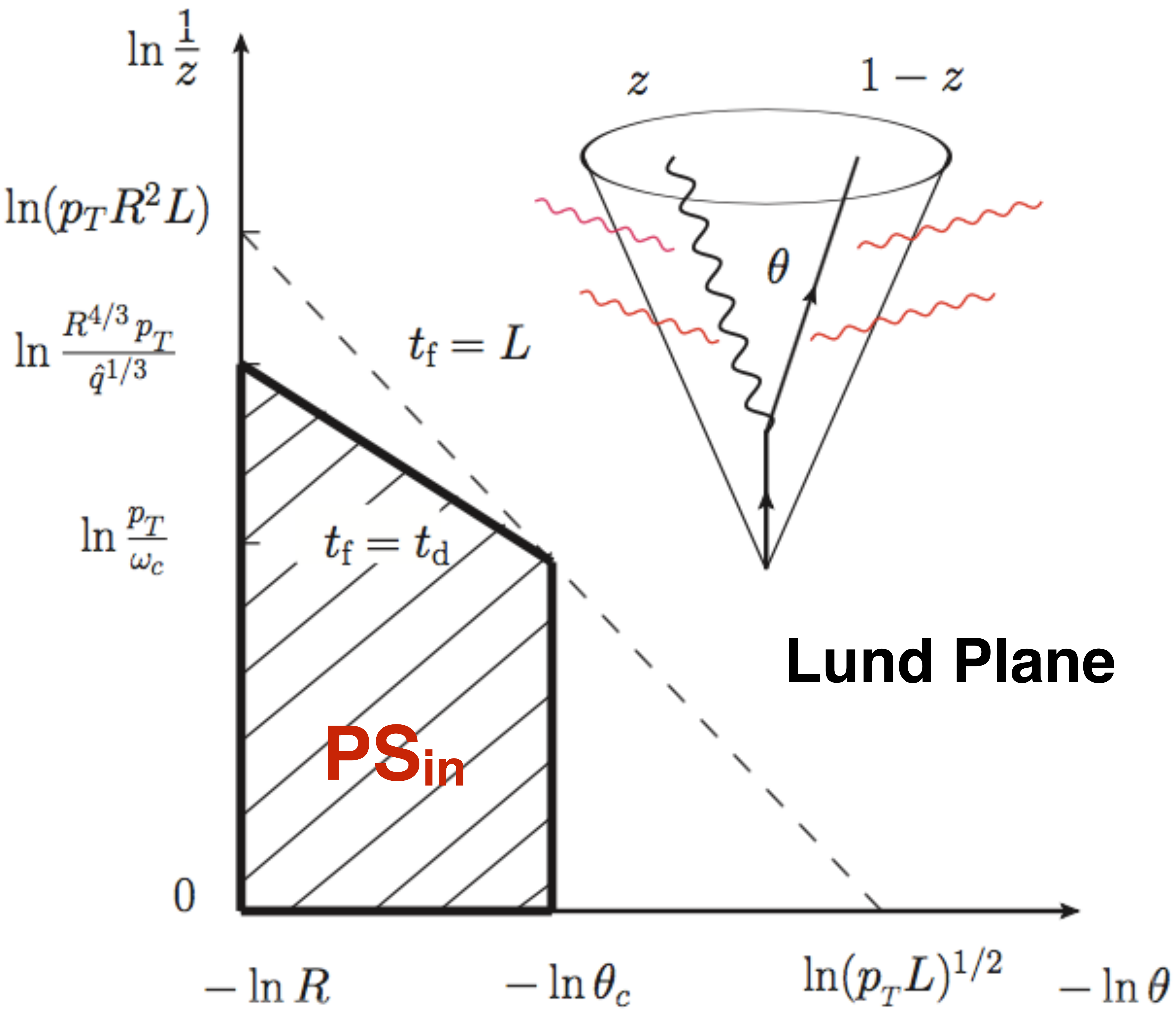
Jet interaction with strongly coupled QGP: multi-scale, multi-particle problem.

→ Interdisciplinary field, lots of avenues to be explored!

- First analytical computation of R dependent inclusive jet suppression.
- Impact of hydrodynamization of jet energy in jet observables.
- Diagnose energy loss jet-by-jet using deep learning techniques.

Jet Suppression: Quenched Phase Space

- Jet energy loss needs to include their multi-particle nature.
  - ➔ Quenched phase space depends on jet p_T, size R and coherence effects.



- Only those jet modes that:
  - ➔ are formed inside the medium, and,

    $t_f < L$ (medium length)
  - ➔ are resolved by the medium,

    t_d … $t_f < t_d$ (decoherence time)

contribute to double-logarithmic enhancement of quenched phase space:

$$\text{PS}_{in} = \bar{\alpha} \int_{t_f < t_d < L} \frac{d\theta}{\theta} \int \frac{dz}{z} \equiv \bar{\alpha} \ln \frac{R}{\theta_c} \left(\ln \frac{p_T}{\omega_c} + \frac{2}{3} \ln \frac{R}{\theta_c} \right)$$

Mehtar-Tani, Tywoniuk - PRD '18
Caucal, Iancu, Mueller, Soyez - PRL '18

Jet Suppression: Framework

- Use microjet distributions derived using Generating Functional (GF) framework:

Dasgupta et al. - JHEP '14

Vacuum evol. obeys DGLAP:
$$\frac{df^{\text{incl}}_{j/i}(z,t)}{dt} = \sum_k \int_z^1 \frac{dz'}{z'} P_{jk}(z')\, f^{\text{incl}}_{k/i}(z/z',t)$$

- Extend GF in the medium to resum energy loss effects due to multi-particle nature of jet:

$$\frac{\partial Q_i(p,\theta)}{\partial \ln\theta} = \int_0^1 \mathrm{d}z\, \frac{\alpha_s(k_\perp)}{2\pi} p^{(k)}_{ji}(z)\,\boxed{\Theta_{\text{res}}(z,\theta)} \times \left[Q_j(zp,\theta)Q_k((1-z)p,\theta) - Q_i(p,\theta)\right]$$

PS_{in} constraint

Initial condition at zero angle is single charge quenching factor:

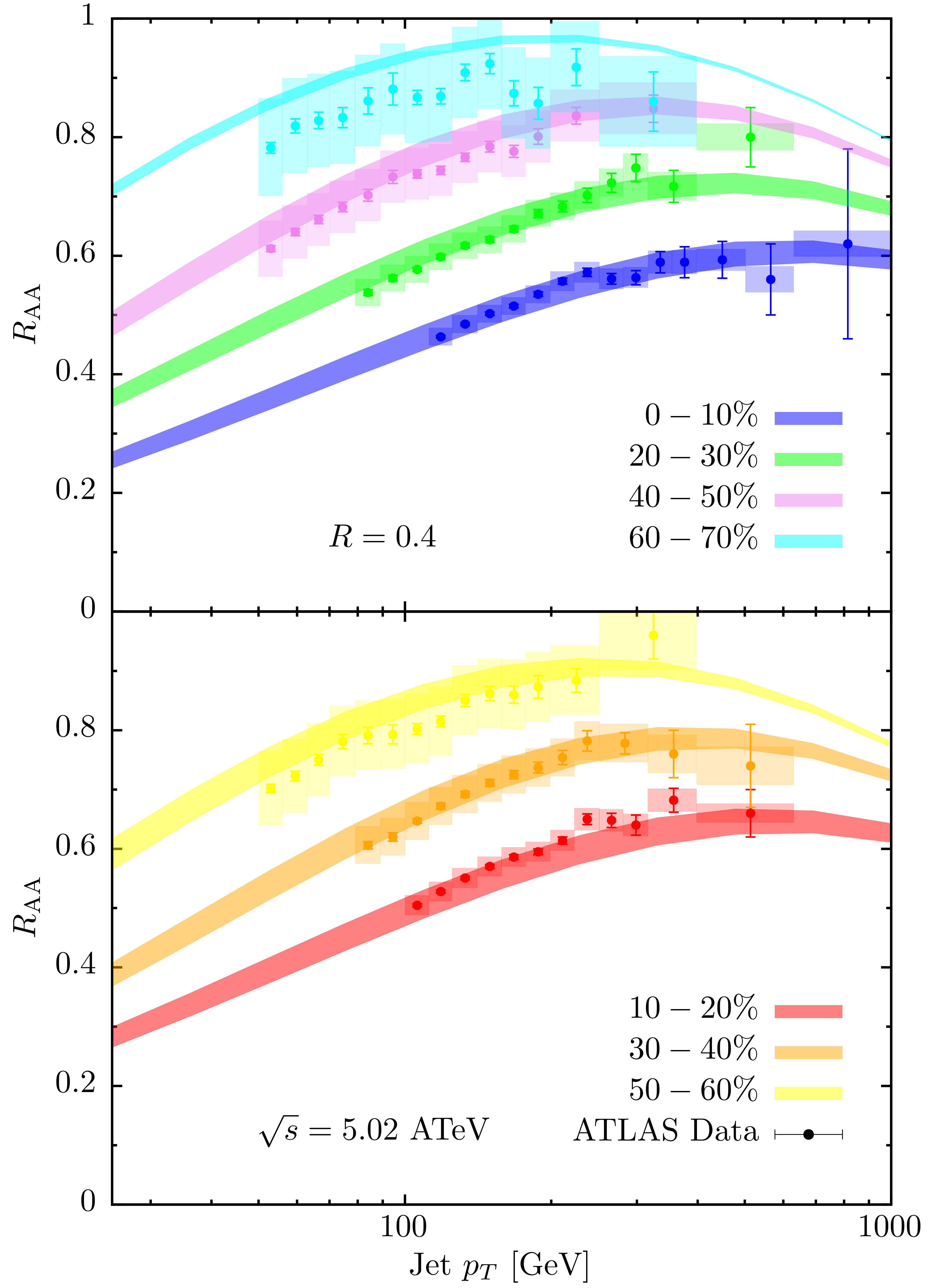
$$Q_i(p,0) = Q^{(0)}_{\text{rad},i}(p_T)\,Q^{(0)}_{\text{el},i}(p_T)$$

Radiative energy loss — Elastic energy loss

- Energy loss versus R displays non-monotonic behaviour. Competing effects:
  - Increasing R means more likely to retain emitted (or thermalised) quanta: less quenching.
  - Increasing R means larger quenched phase space: more quenching.

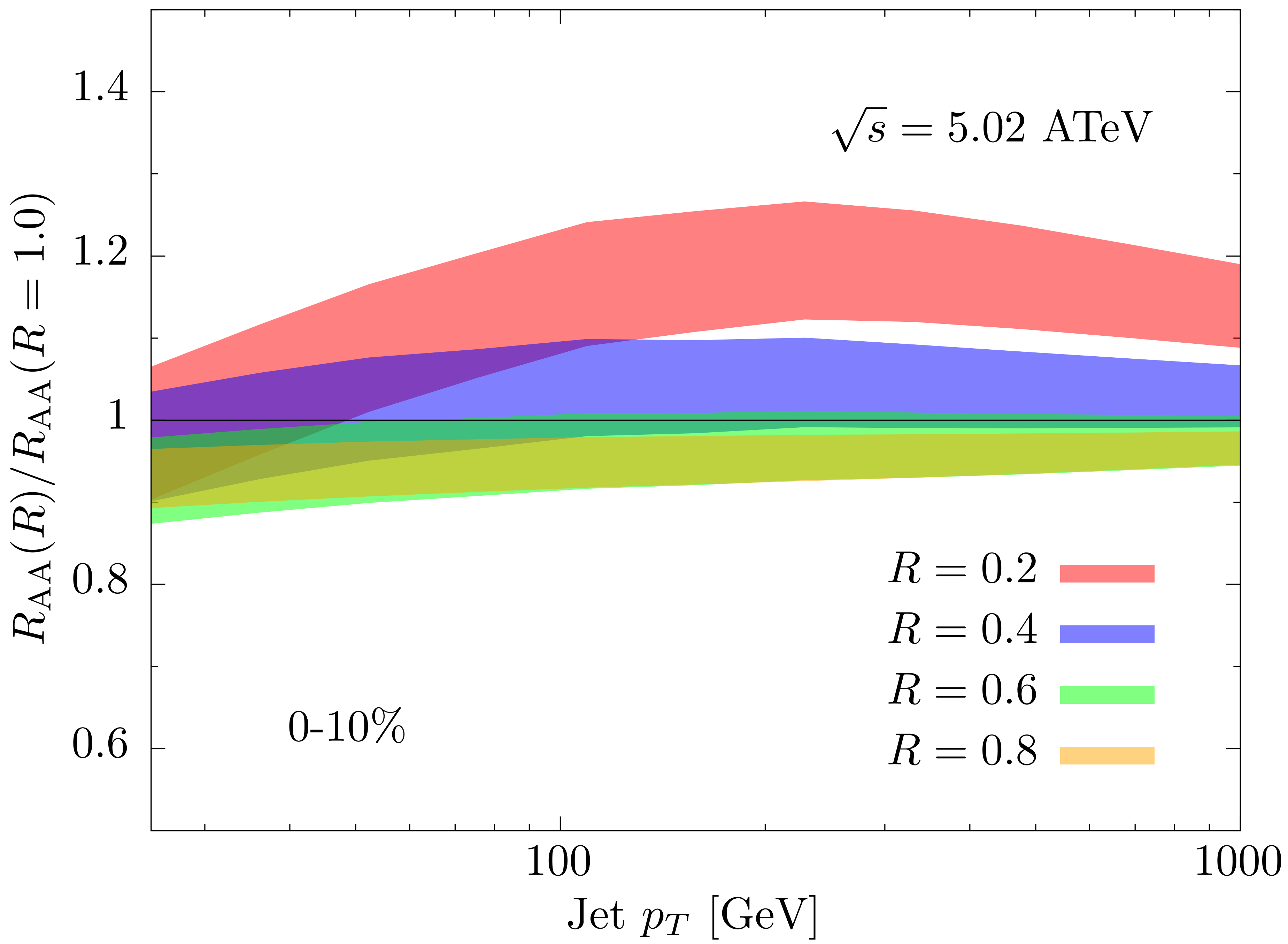
Mehtar-Tani, DP, Tywoniuk - 2101.01742

Jet Suppression: Results



Encouraging description of data across:

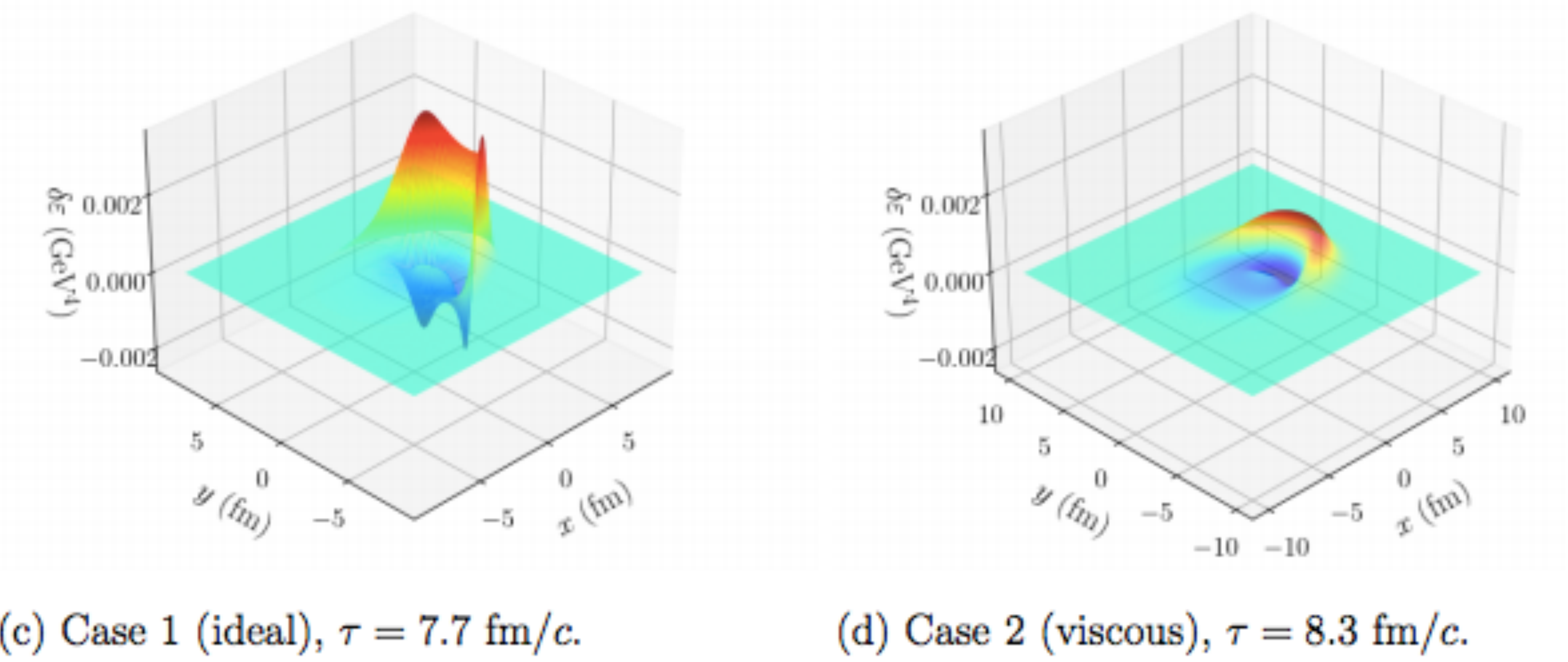
- Jet p_T.
- Centrality.
- Size R.



- 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 - 2101.01742

Jet Induced Wake on the QGP



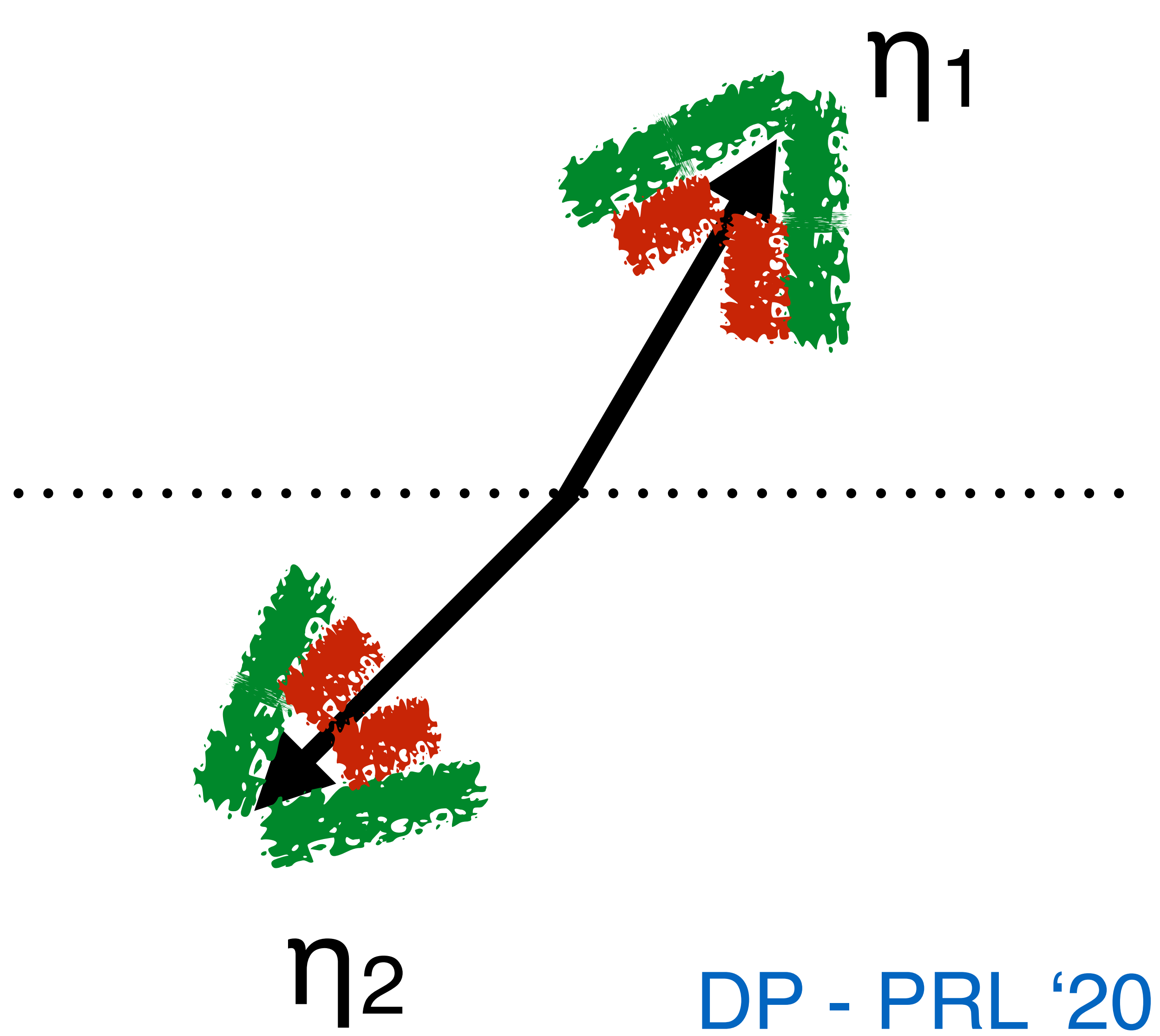
Casalderrey, Milhano, DP, Rajagopal, Yao - 2010.01140

- Jets deposit energy and momentum in the QGP:

$$\nabla_\mu T^{\mu\nu}_{(0)} = 0$$

$$\nabla_\mu \delta T^{\mu\nu} = J^\nu$$

- A jet induced wake develops: convenient scenario of hydrodynamization process.
  - → Sensitive to value of viscosity.
  - → Sensitive to local background flow.

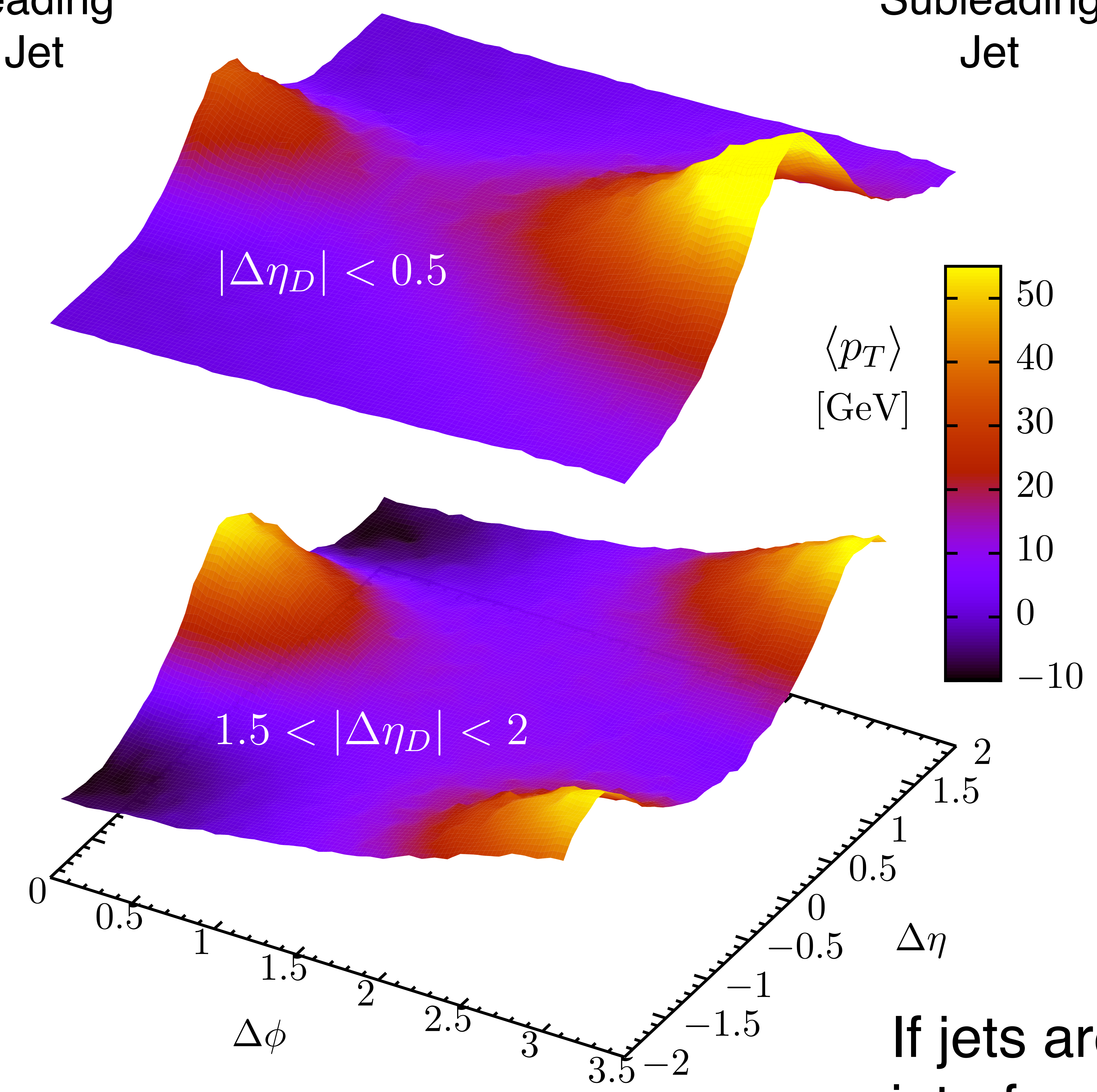


DP - PRL '20

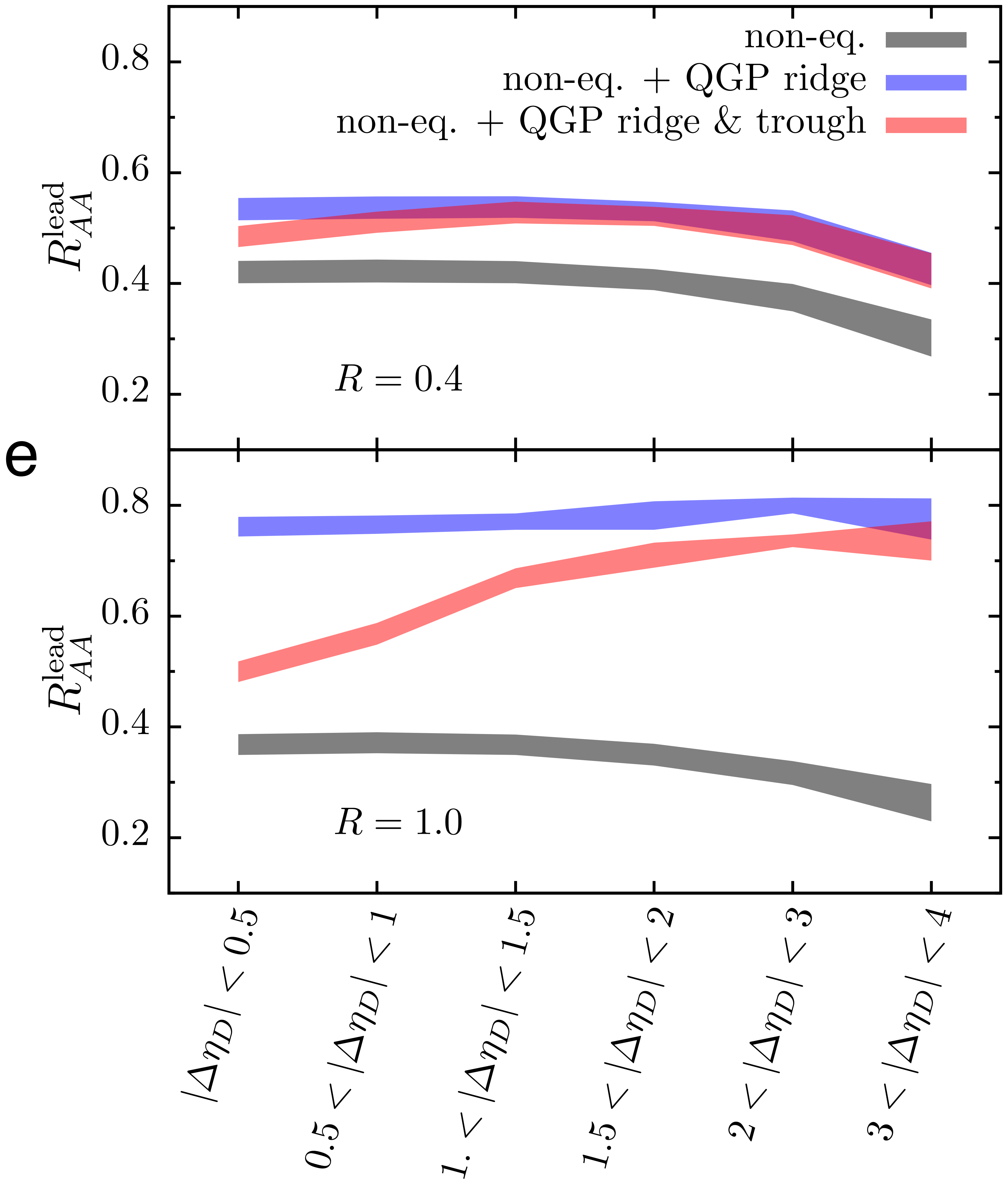
- Jets always come in pairs:
  - → Rapidity extent of each wake is narrow.
  - → Rapidity decorrelation of dijet pair is wide.

Study jet modifications based on rapidity gap.

Leading Jet Suppression vs Rapidity Gap



New observable proposed.



If jets are aligned in rapidity, interference of diffusion wakes leads to jet suppression (specially at large R).

DP - PRL ‘20

Diagnosing Jet Energy Loss

- Experimentally, so far is impossible to know how much energy a given jet has lost.
- Moreover, due to steep falling jet spectrum, what we observe is jets that lost the least energy. → Selection (or survival) bias.

→ Hinders our ability to analyse true effects of energy loss. E.g.:

- Measure jets above pT>100 GeV.
- Observe that they are narrower in PbPb than in pp:
  - ★ Energy loss makes jets narrower?
  - ★ Observe the surviving (less quenched) jets, which are narrow?

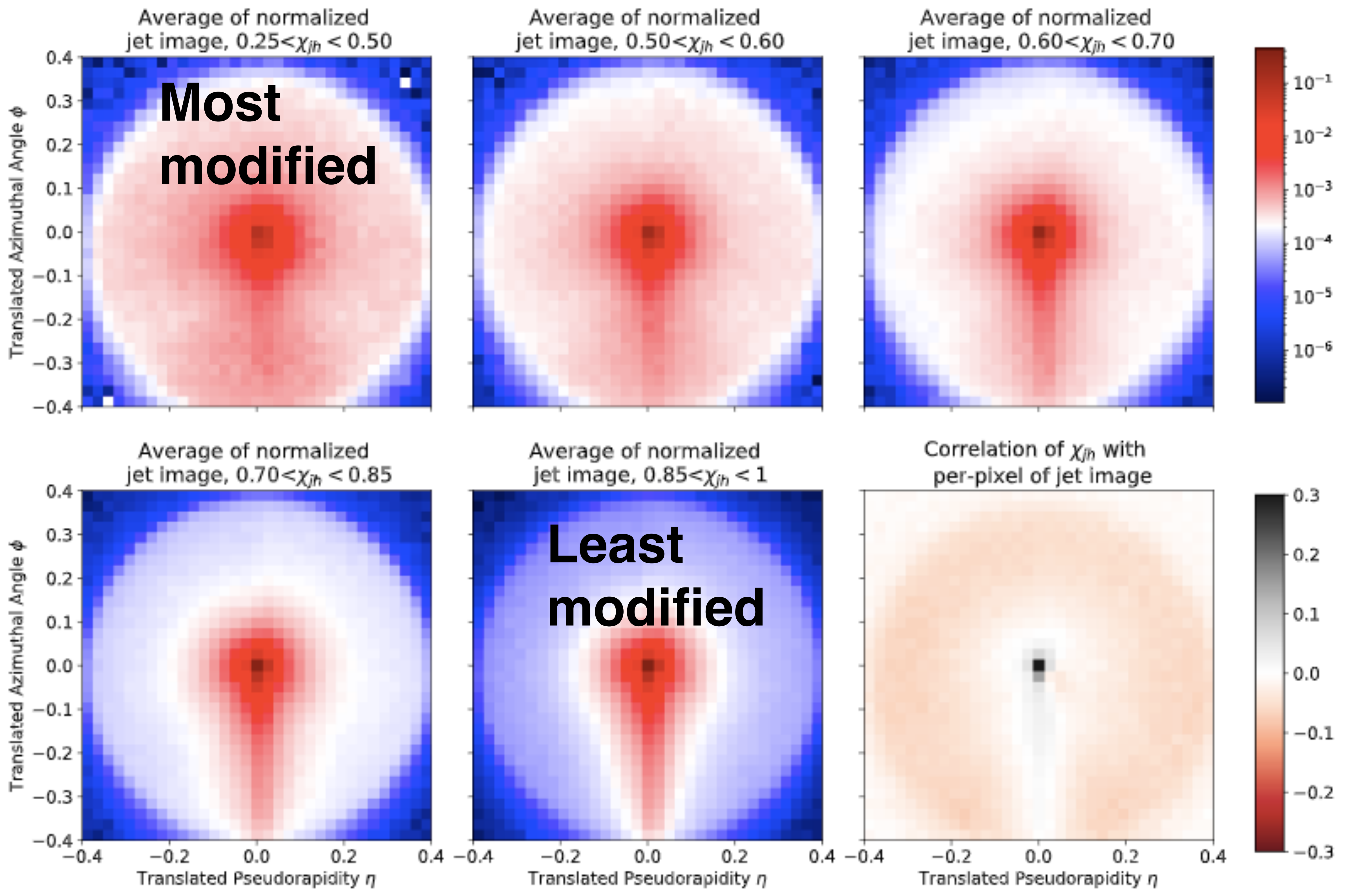
- Exploit deep learning techniques to extract energy loss jet-by-jet.

Energy loss ratio: $$\chi \equiv \frac{E_f}{E_i}$$

E_f: Final, measurable jet energy.

E_i: Vacuum energy (had there been no medium).

Deep Learning Jet Modifications

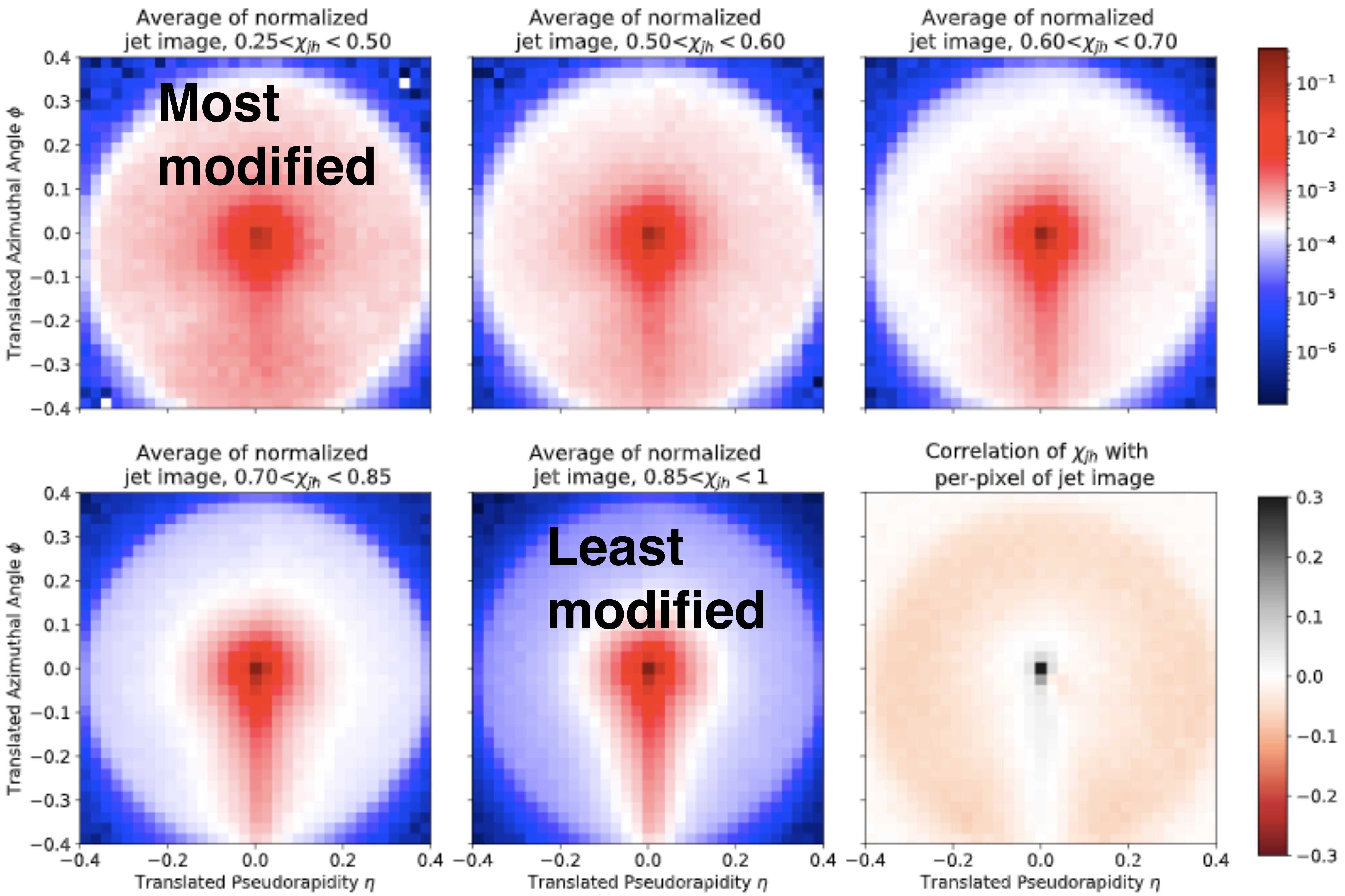


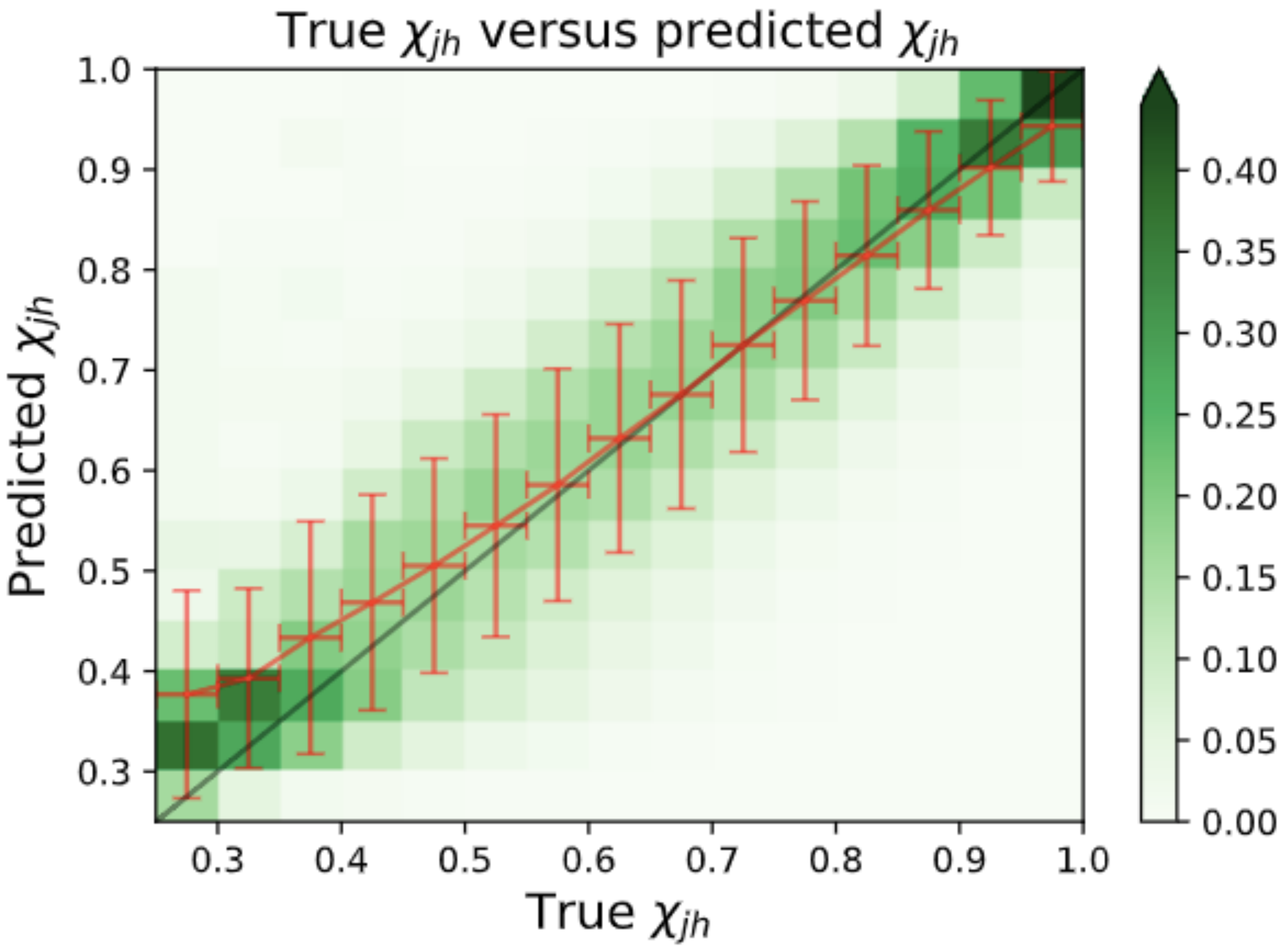
- Most models: Energy loss transfers jet energy to large angles in the form of soft particles.

- Use jet images as inputs for CNN. Main result.
- Use jet observables as inputs for FCNN. Mainly used for interpretability.

Du, DP, Tywoniuk - 2012.07797

Deep Learning Jet Modifications





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Du, DP, Tywoniuk - 2012.07797

Good performance across a wide range in χ

- Consistency check: pp (vacuum) jets get $\chi \simeq 1$

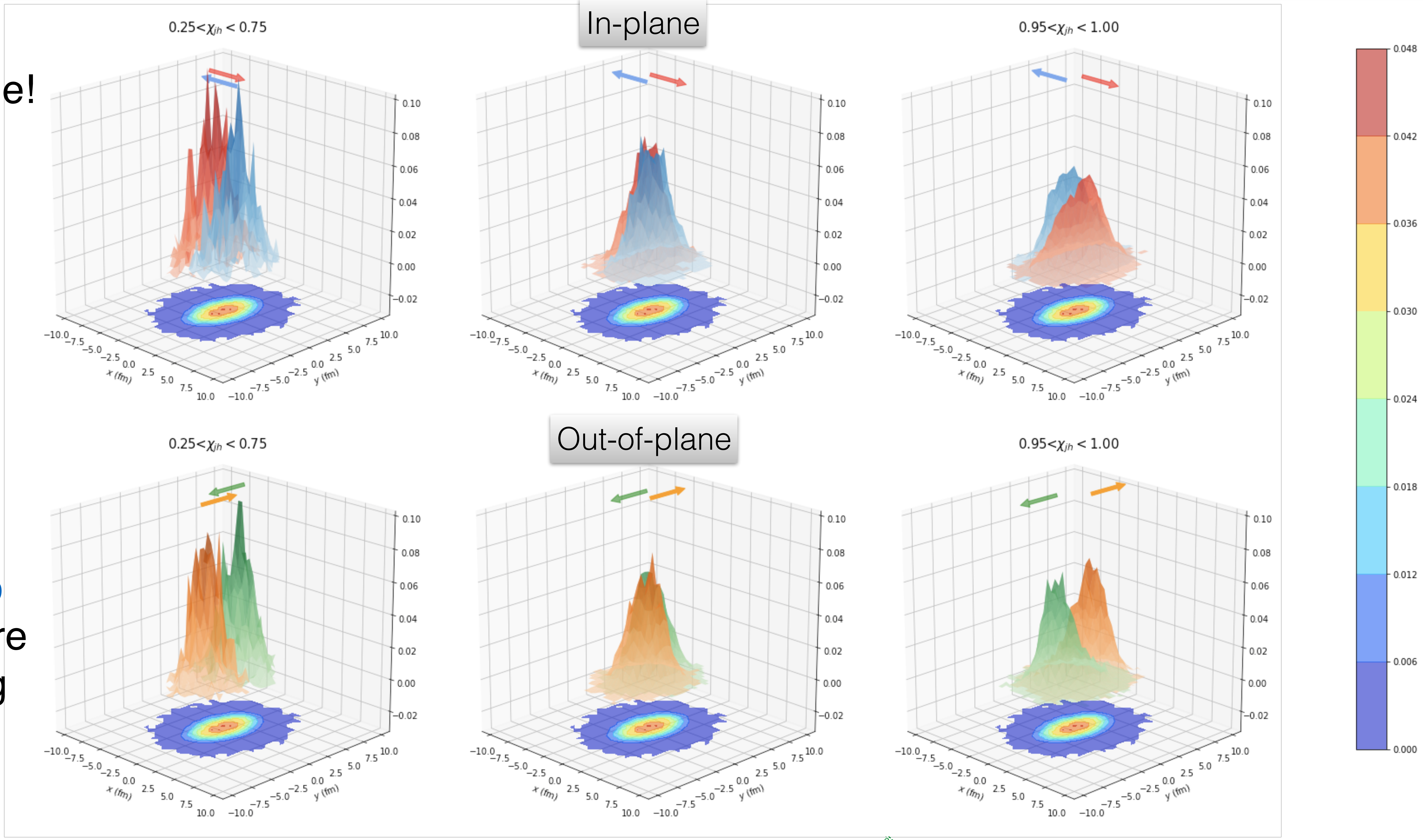
Jets as Tomographic Probes of QGP

Can access production point in transverse plane!

Differential in:

- Orientation w.r.t. event plane (easy)
- Energy loss ratio *(new)*

Production points swap in order to traverse more medium with increasing energy loss.



Du, DP, Tywoniuk - in preparation

more quenched ← χ → less quenched

Outlook

- Jets have to resolve quasi-particles d.o.f. QGP at short length scales.
  - Implement large angle Molière scattering in jet energy loss Monte Carlo.

Hulcher, DP - in preparation

- Abundant mini-jets deposit energy into QGP: new sources of fluctuations.
  - Develop concurrent jet+hydro evolution: J-MUSIC.

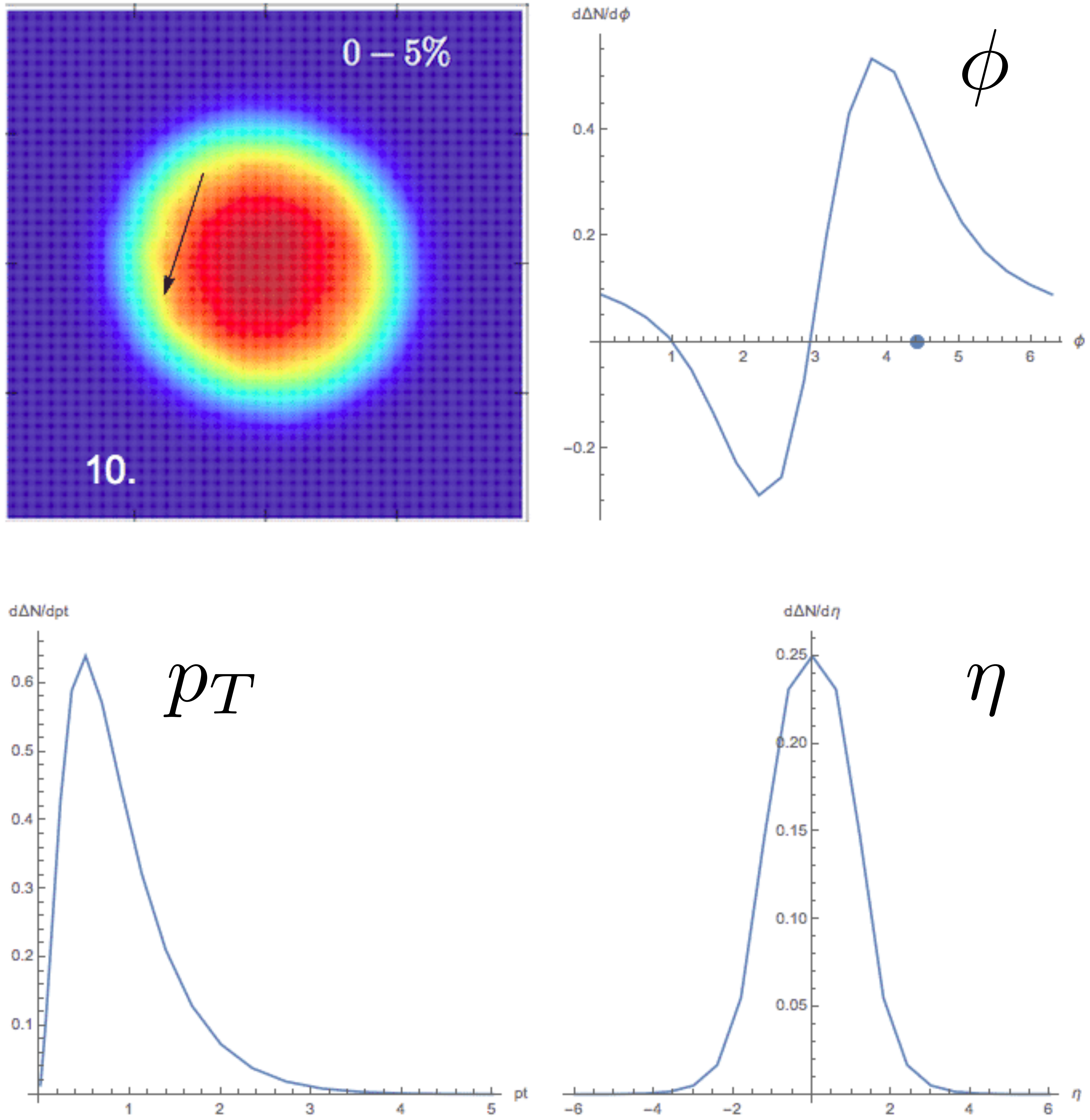
DP, Singh, Gale, Jeon - in preparation

- Space-time structure of parton shower depends on choice of DGLAP evolution variable.
  - Study implications of different choices on quenched jet observables.

DP, Takacs, Tywoniuk - in preparation

- Angular and momentum distribution of hadrons coming from the wake depend on local fluid properties.
  - Extend linearised wake + local boost framework for jet-by-jet, event-by-event scenario.

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



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

Thanks for your attention!