A strongly coupled view of the quark gluon plasma

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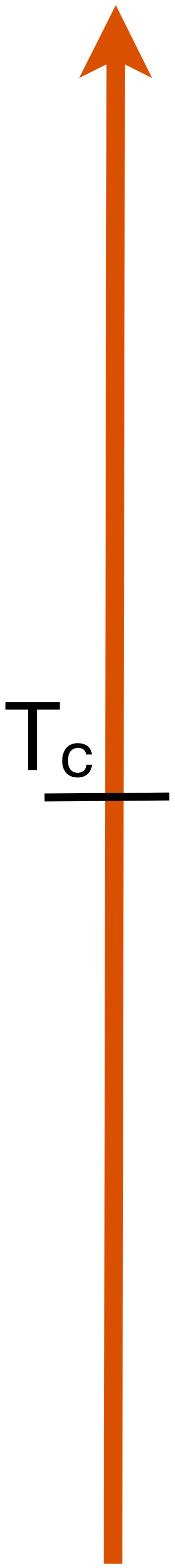
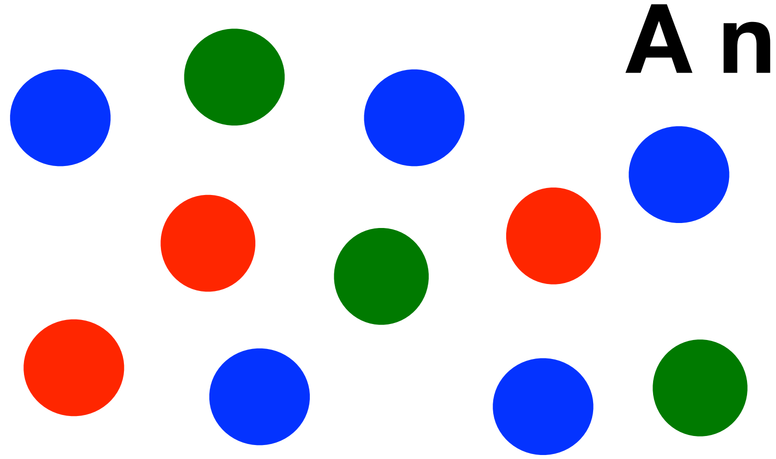
Oxford Physics

THE ROYAL SOCIETY

QCD Matters





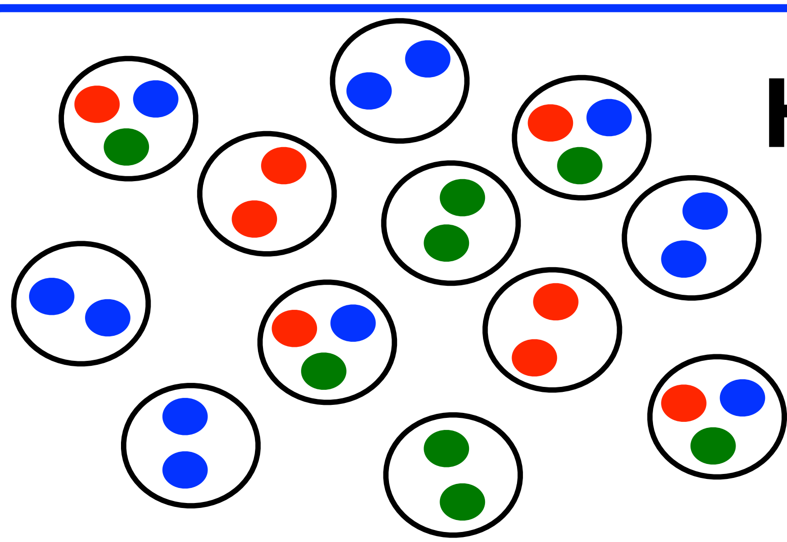
A new phase: <u>Quark Gluon Plasma</u>

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

"phase transition"

$$T_c \approx 2\times10^{12}\ \mathrm{K}$$
$$\approx 170\ \mathrm{MeV}$$

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

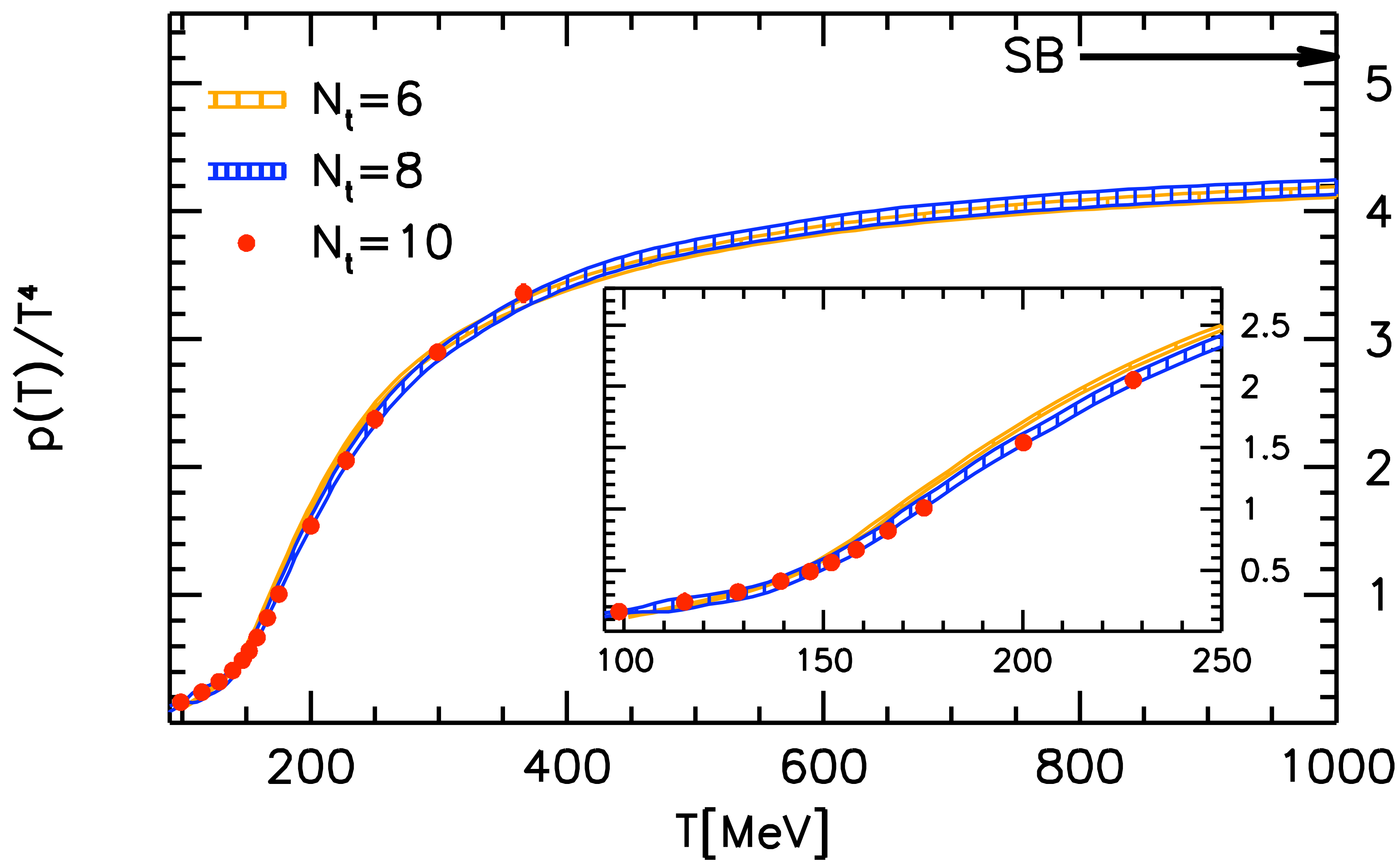


Hadron Gas

- Colour is confined
- Hadrons re-scatter

Equation of State

Wuppertal-Budapest Col. arXiv: 1007.2580

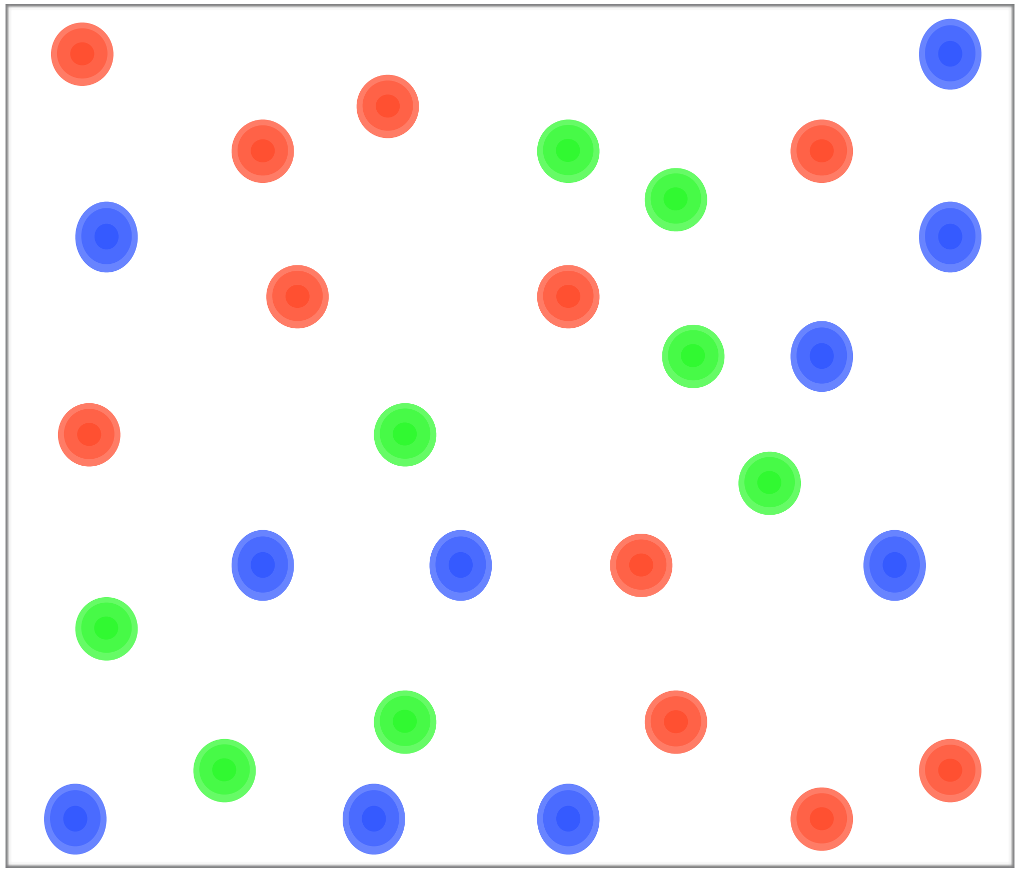


Rapid cross over transition:

- Deconfined matter
- Chiraly restored matter

A Gas of Quarks and Gluons

At $T>10^4$ GeV:



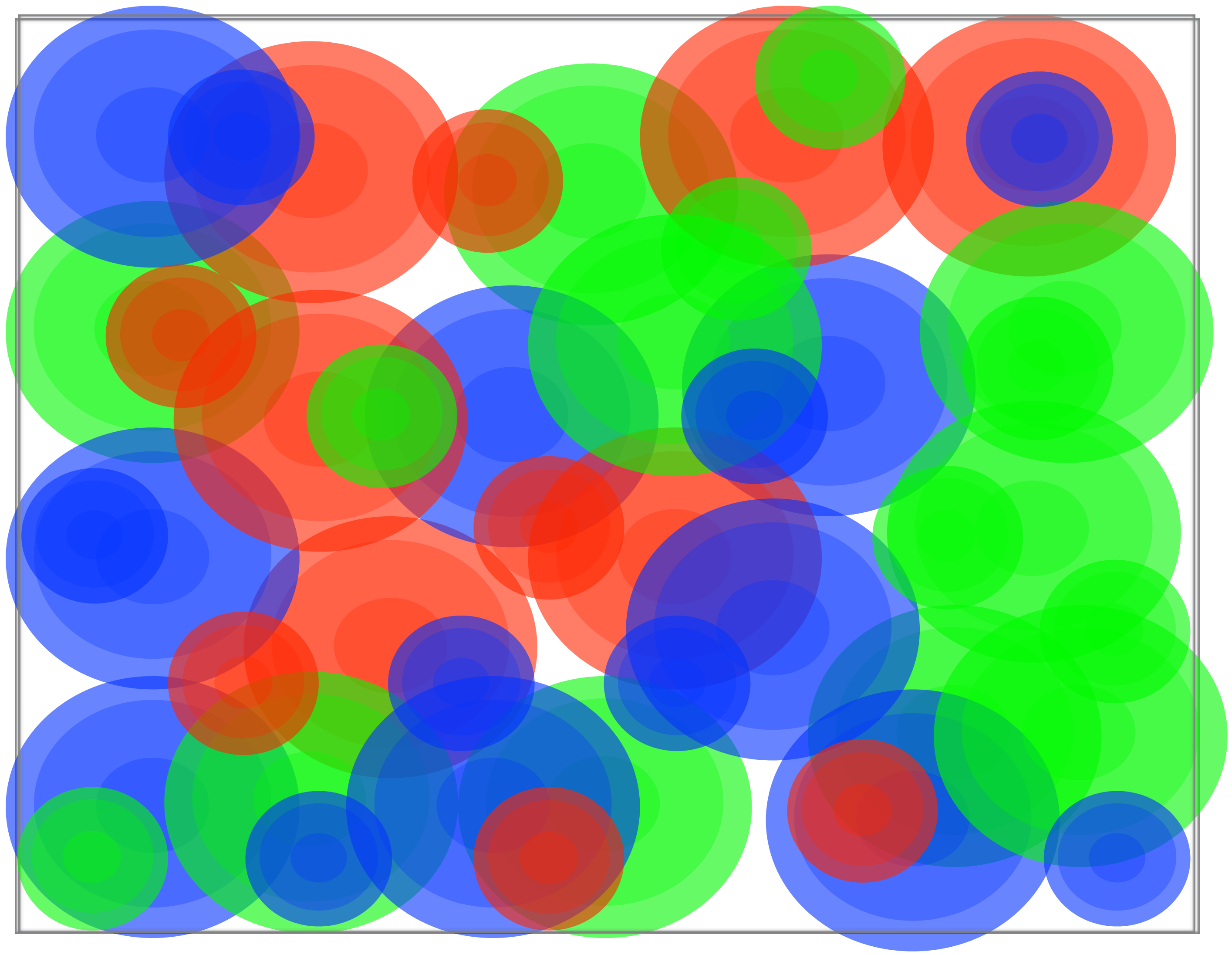
$$\frac{1}{T} \ll \frac{1}{gT} \ll \frac{1}{g^2T}$$

inter-particle spacing — Interaction range — mean free path

Resummations can extend the validity of perturbative methods to much lower temperatures!

What is the correct picture of the plasma?

At T~0.2 GeV



$\alpha_s=0.3 \Longrightarrow g=2$

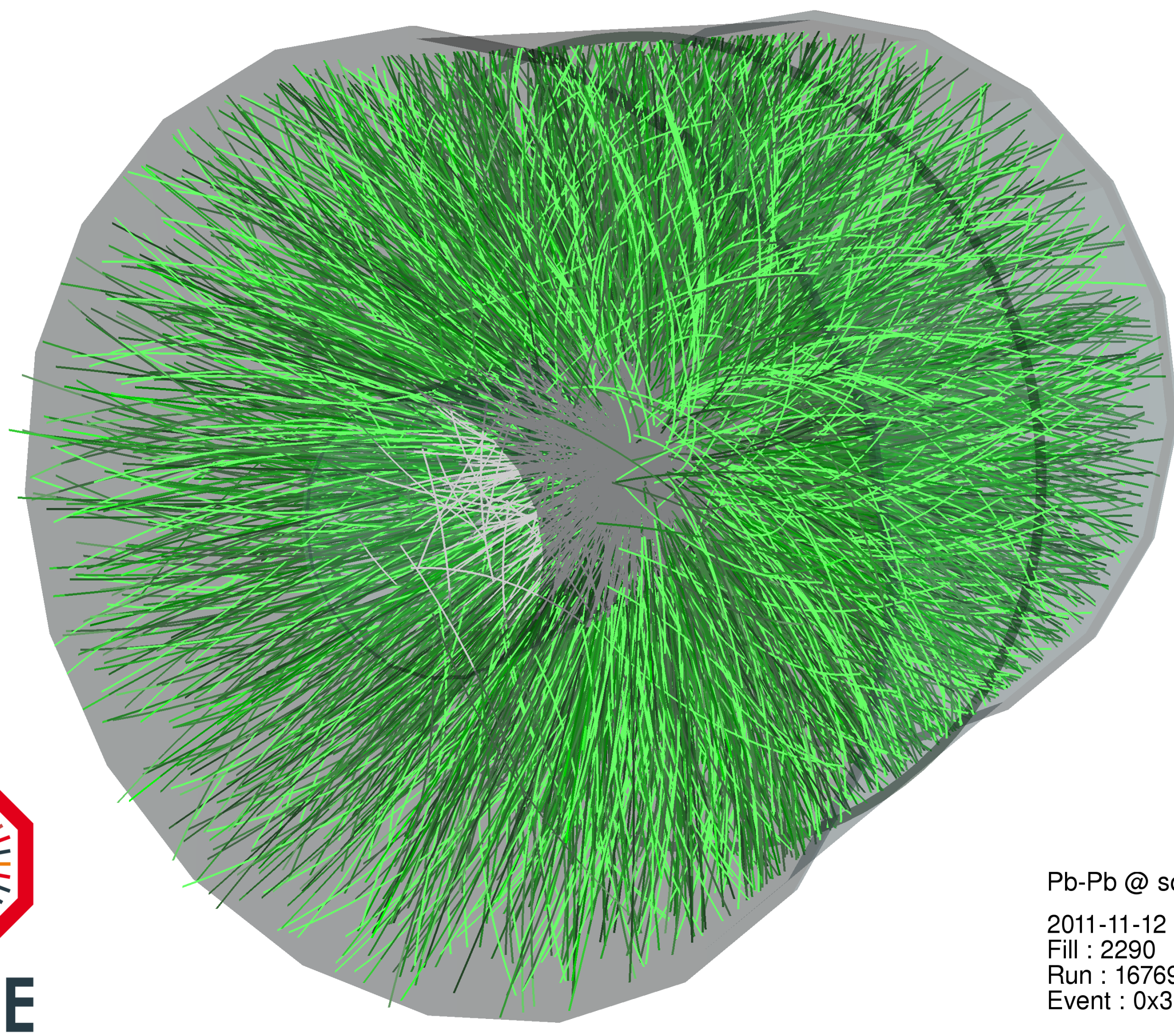
$T \sim gT \sim g^2 T$

Is it a system without quasiparticle excitations?

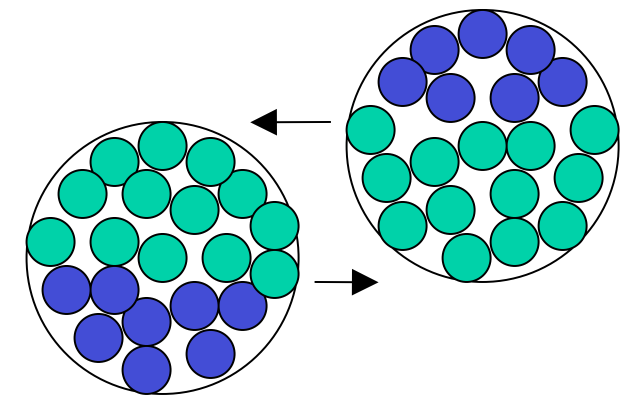
Is it a gas of quarks and gluons?

quasiparticles?

Heavy Ion Collisions at the LHC



ALICE
A JOURNEY OF DISCOVERY



- Up to 400 participating nucleons
- About 20.000 particles
- $E_T \sim 1$ GeV per particles
- Very large initial energy density

$$\varepsilon = \frac{1}{\pi R^2 \tau} \frac{dE_t}{dy}$$

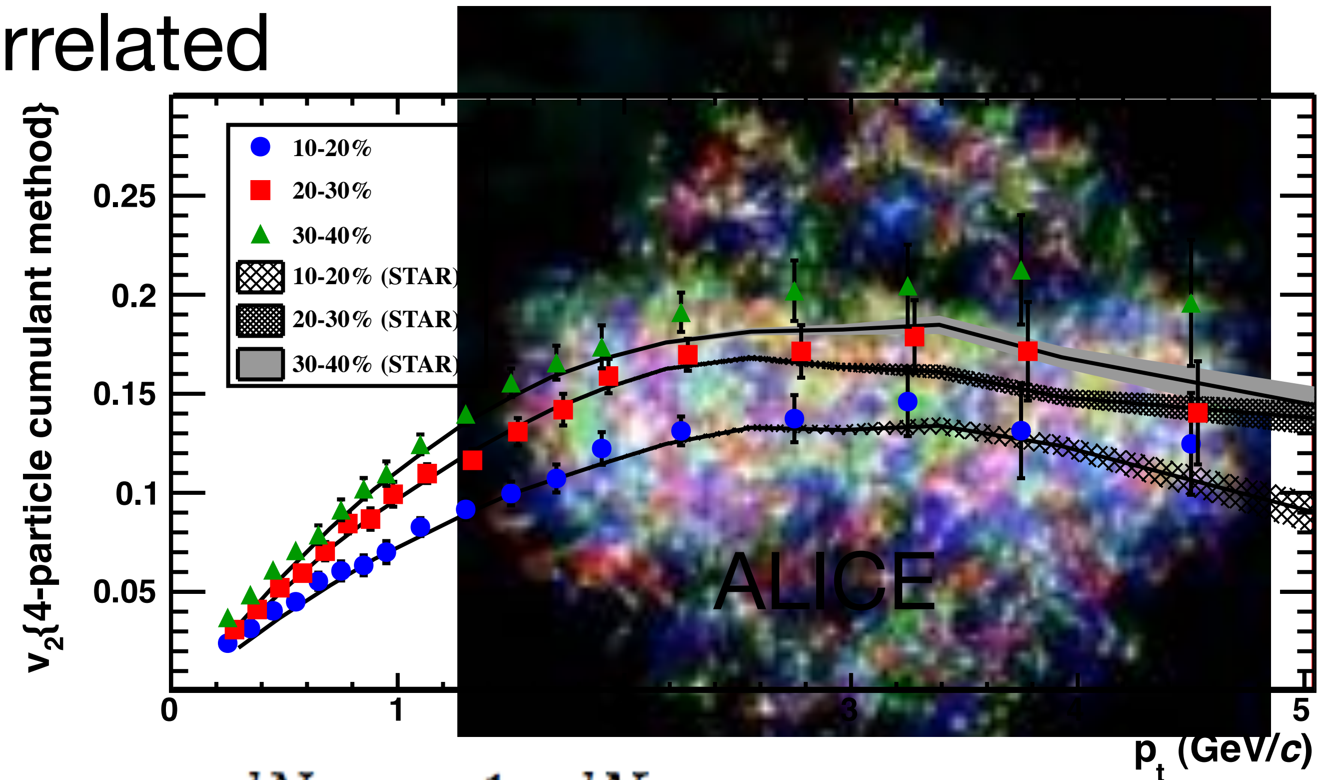
$\varepsilon\tau \sim 16$ GeV/(fm^{2}c)

Very strong collective effects

- Emission of 20.000 particles correlated with the impact parameter

- Correlation measured in terms of Fourier coefficients

- Hydrodynamic explosion



$$\frac{dN}{d^2p_T d\phi} = \frac{1}{2\pi}\frac{dN}{d^2p_T}\left(1 + 2v_2(p_t)\cos 2\phi + \ldots\right)$$

The quark … $\left(\frac{\eta}{s}\right)_{T_c} = 0.08 \pm 0.05$ … good fluid

J. Bernhard, J.S. Moreland, S. Bass, J. Liu, U. Heinz arXiv:1605.03954

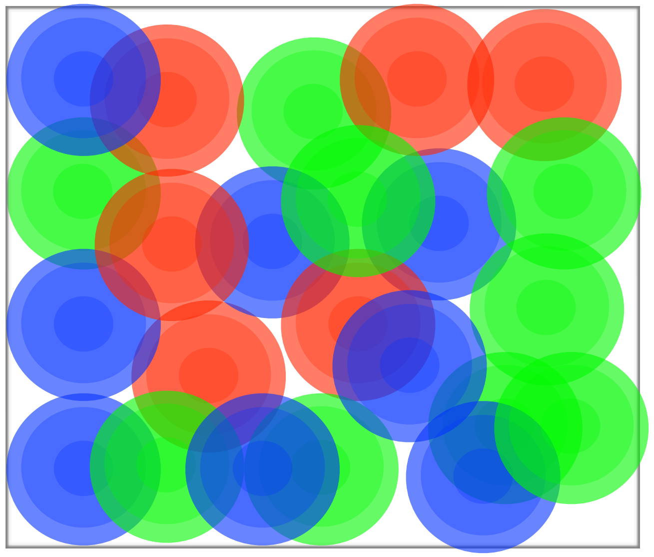
Implication of η/s Value

- It is the smallest value ever measured in any substance.

  The Quark Gluon Plasma is the most perfect fluid!

- It is incompatible with quasiparticles

  Boltzmann equation ⇒ $\tau_{qp} \sim 5 \frac{\eta}{s} \frac{1}{T} \sim \frac{1}{T}$



- It was predicted in 2001 (Policastro, Son, Starients)

$$\frac{\eta}{s} = \frac{1}{4\pi} = 0.08$$

... but for a large class of non-abelian gauge theories at infinite coupling via holography

QFT with no Quasi Particles

- This all may be a remarkable coincidence

  Different theories, different matter content, different symmetries...

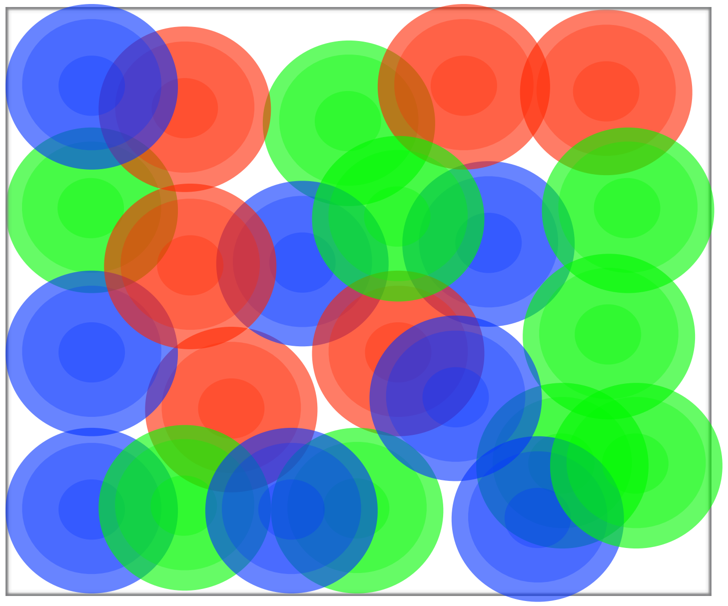
- But there is certain degree of universality

  Some properties are the same in all theories with holographic duals

  Despite:

  Different theories, different matter content, different symmetries...

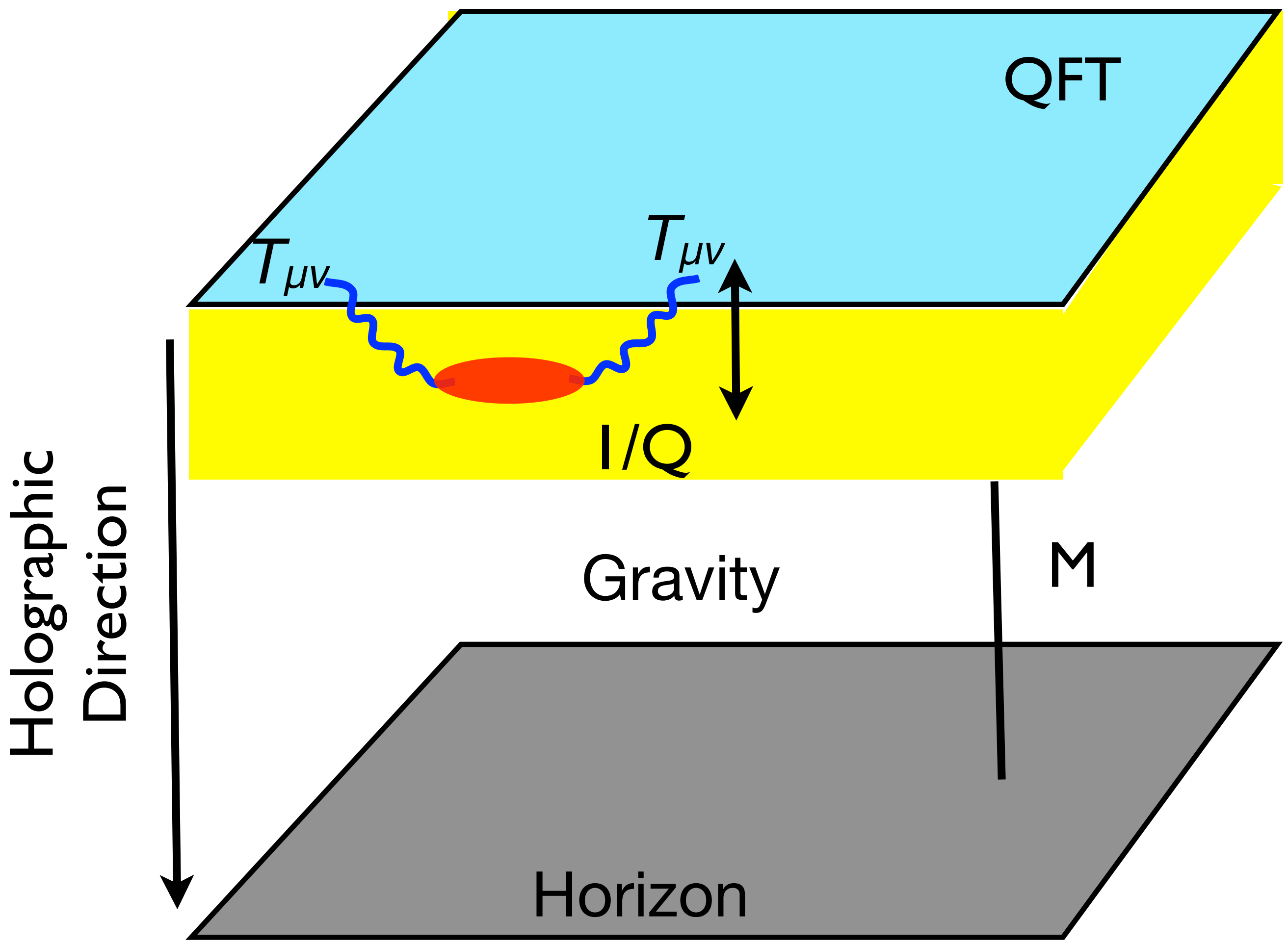
- All those strongly coupled theories have plasmas with no quasi particles



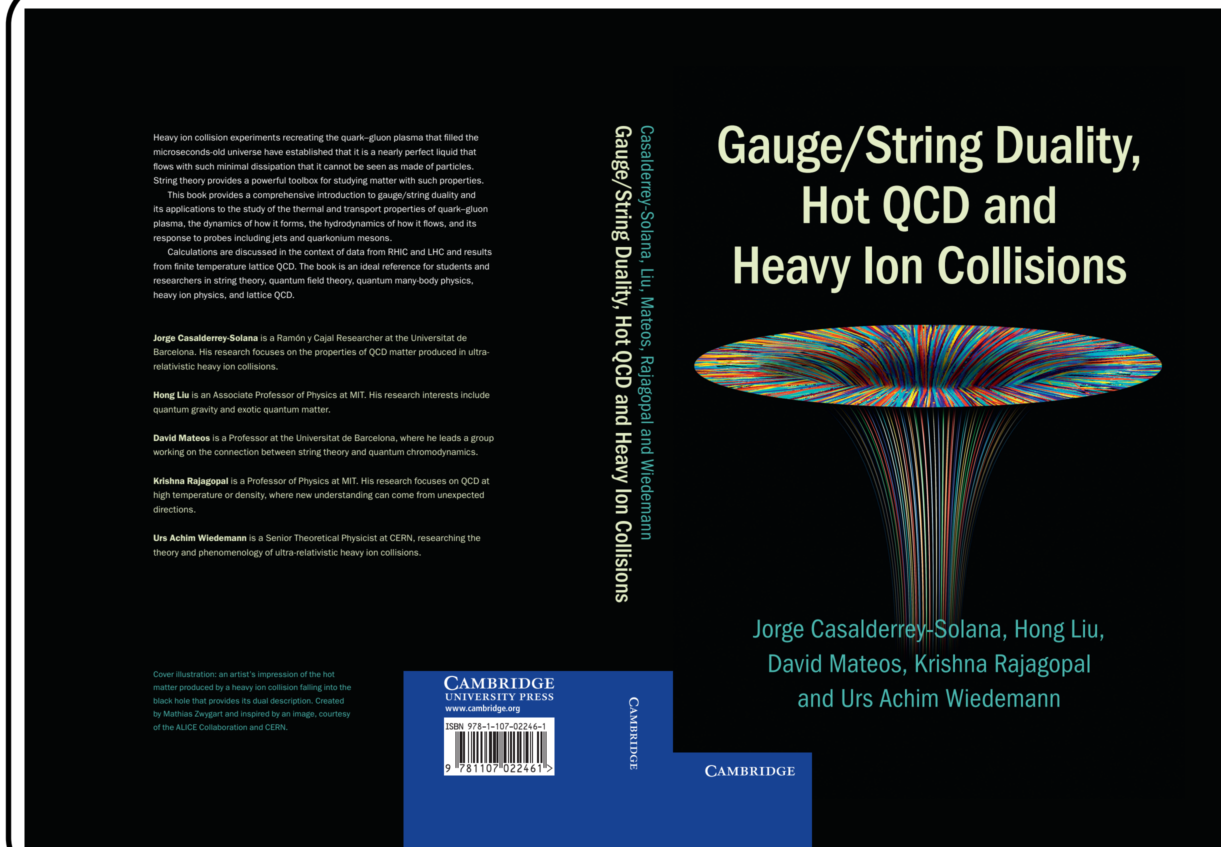
Holography

- Gauge Theories in the limit

$$\lambda = g^2 N_c \to \infty$$



J. M. Maldacena, *Adv. Theor. Math. Phys* 2, 231 *(1998)*



Dictionary

$T_{\mu\nu} \leftrightarrow g_{\mu\nu}$

$T \leftrightarrow$ *black hole*

flavor $\leftrightarrow$ *brane*

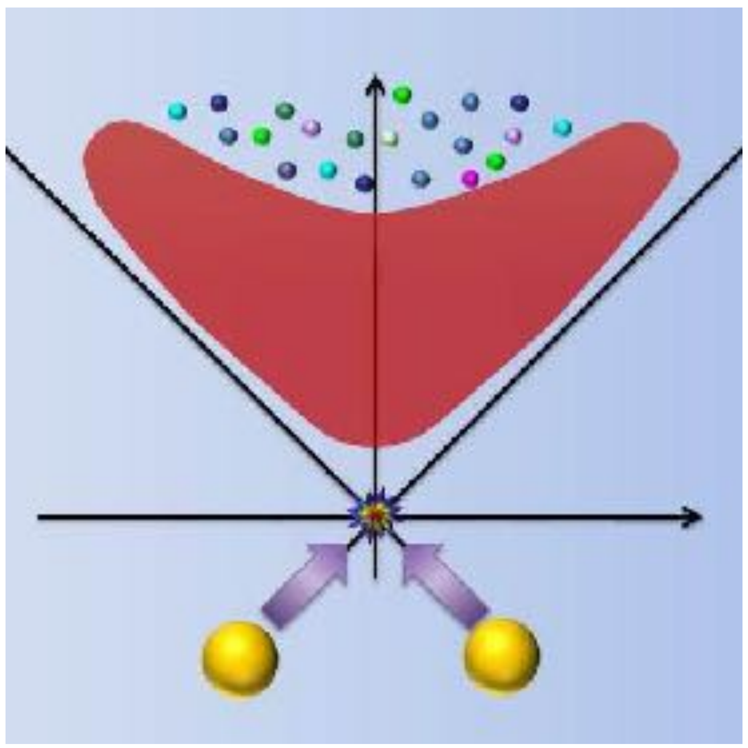
heavy quark $\leftrightarrow$ *string*

Thermalization at Strong Coupling

- Simulation of full collision dynamics
  - ➤ Collisions of lump of energies

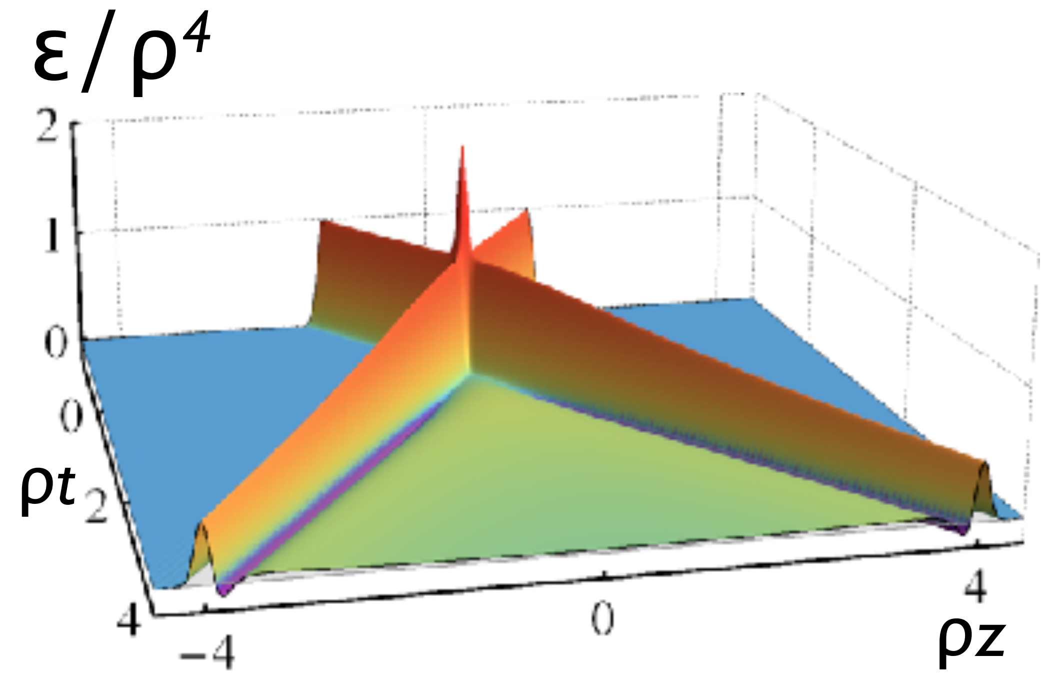
Chesler and Yaffe 11

JCS, M. Heller, D. Mateos W. van der Schee 13,14



dual model

shock wave collisions



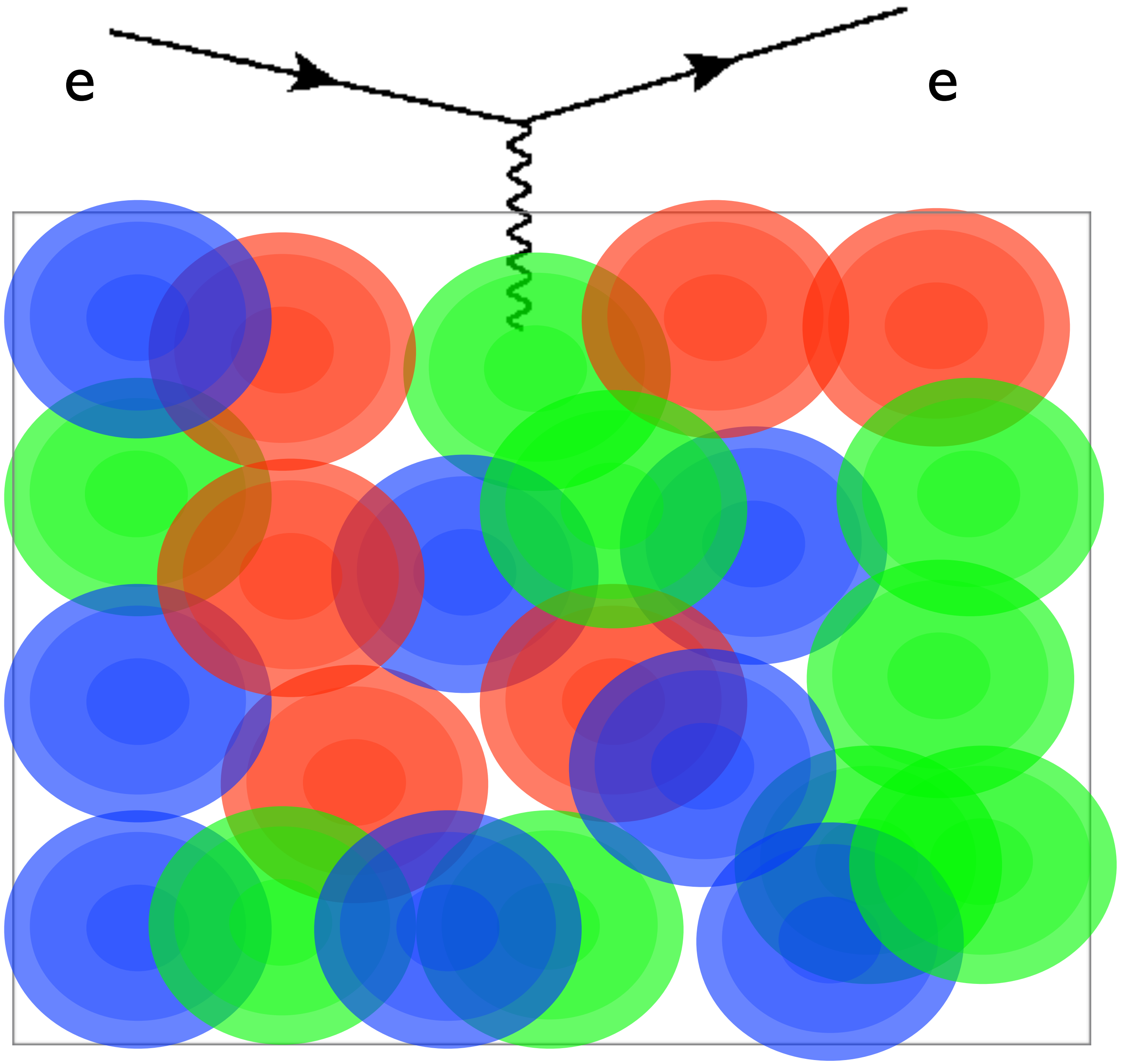
- Fast onset of hydrodynamics $t_{hydro} = 0.63 / T_{hydro}$
  - ➤ Hydrodynamics without isotropy

    Chesler & Yaffe, Wu & Romatschke, Heller, Janik & Witaszczyk, Heller, Mateos, van der Schee, Trancanelli
  - ➤ Hydrodynamics without equation of state

    Attems, JCS, et. al. 16

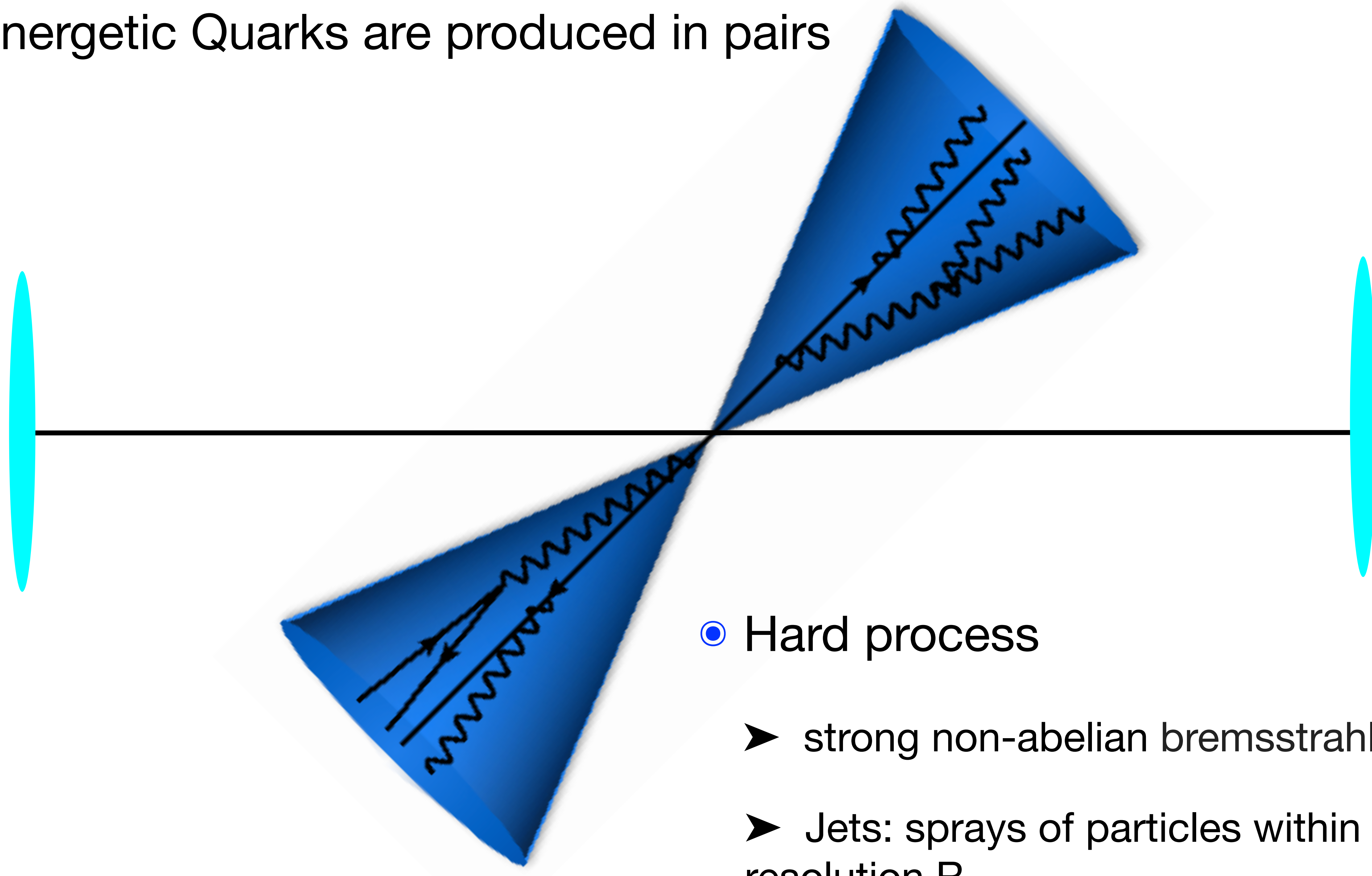
Microscopic Structure of Plasma

- Can we probe the system?



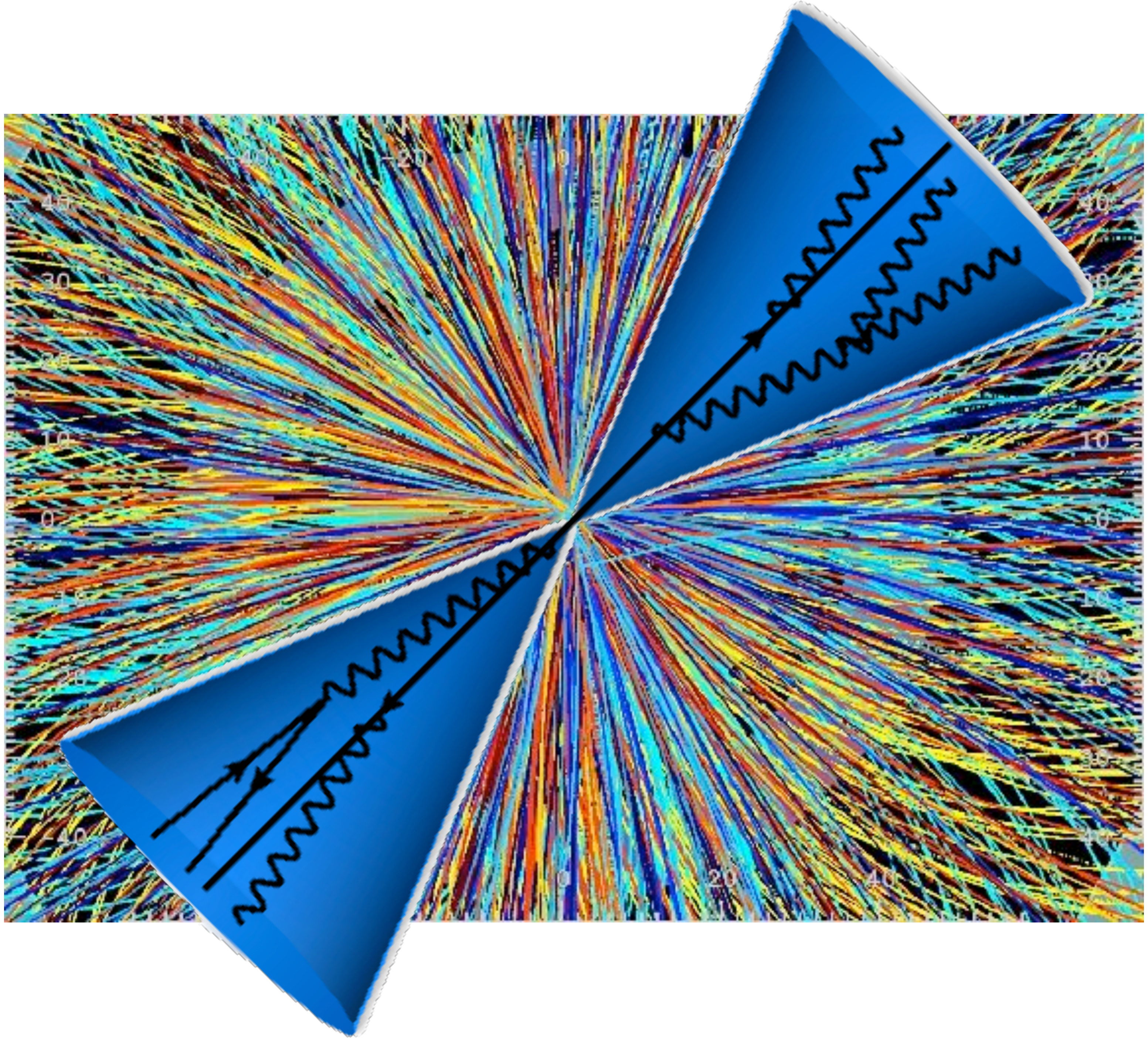
Jets

- Energetic Quarks are produced in pairs

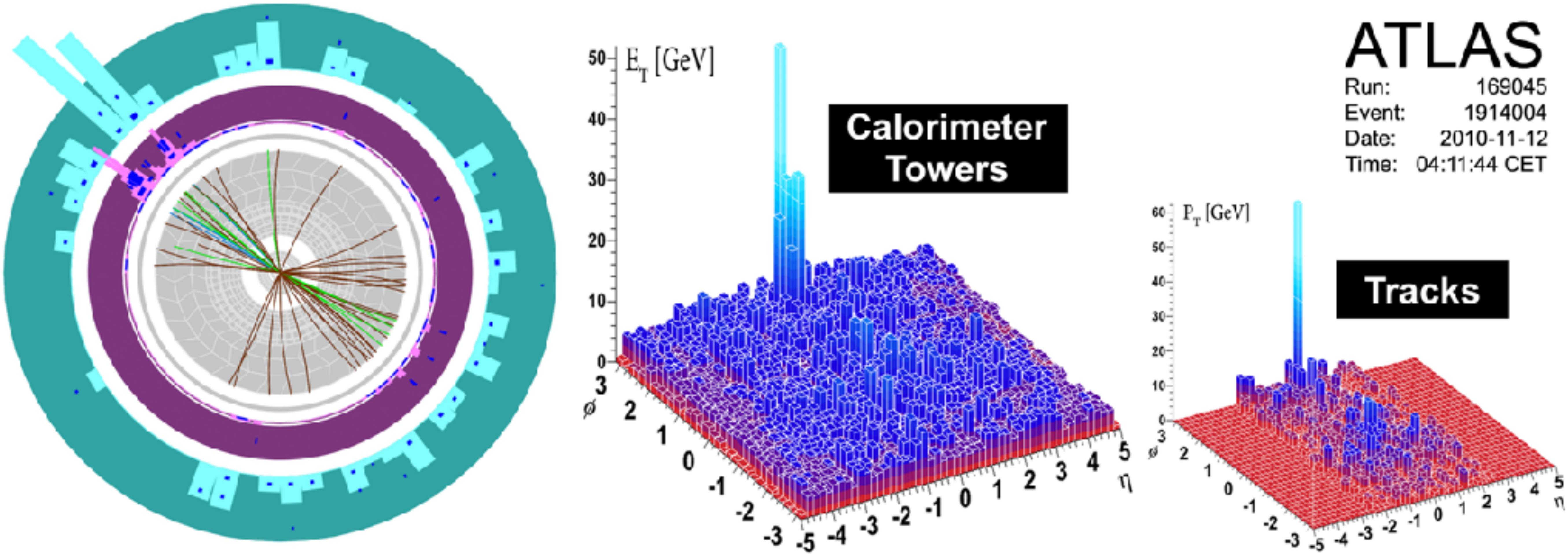


- Hard process
  - ➤ strong non-abelian bremsstrahlung
  - ➤ Jets: sprays of particles within a fixed resolution R

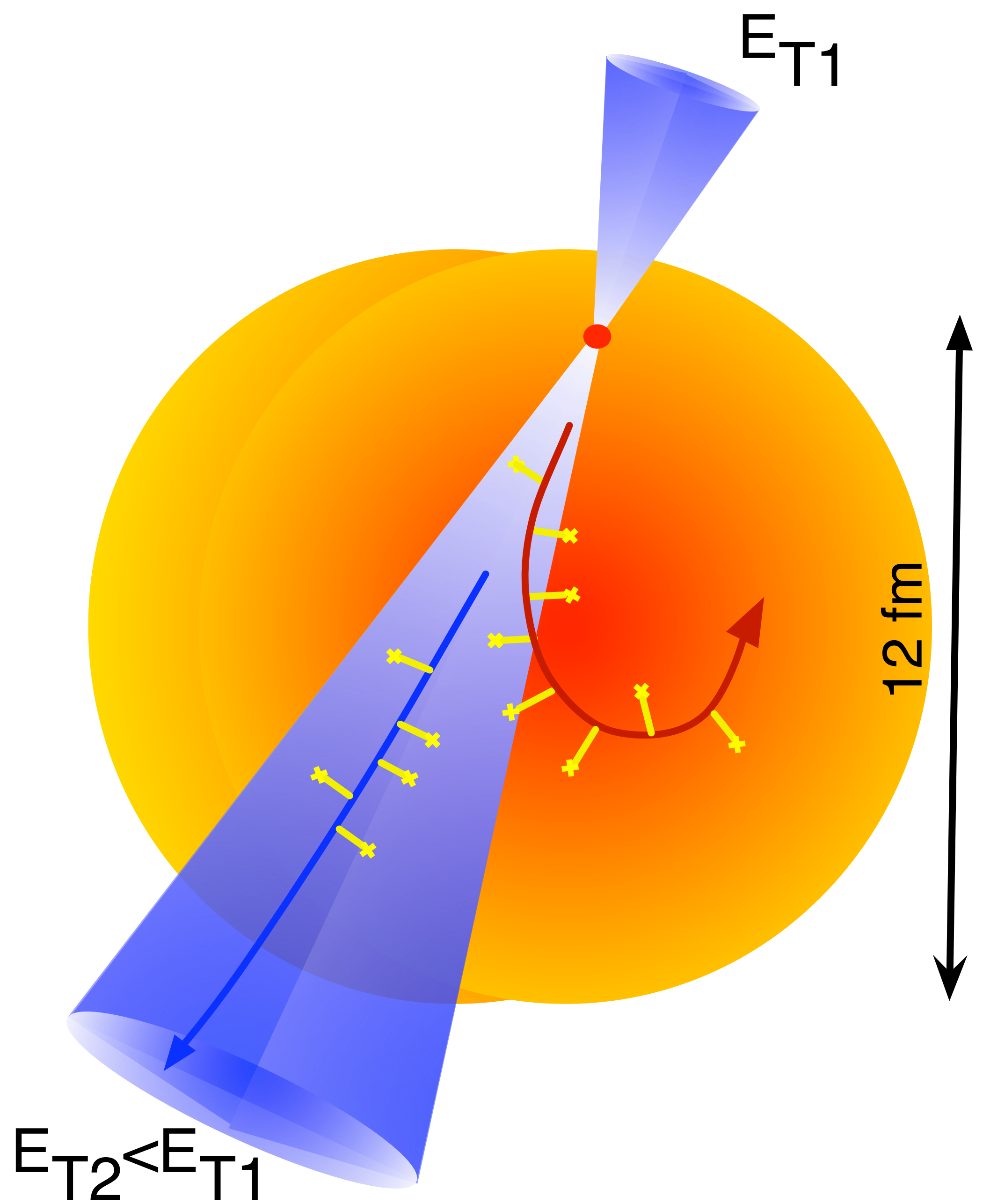
Jets as Probes



Jet Quenching



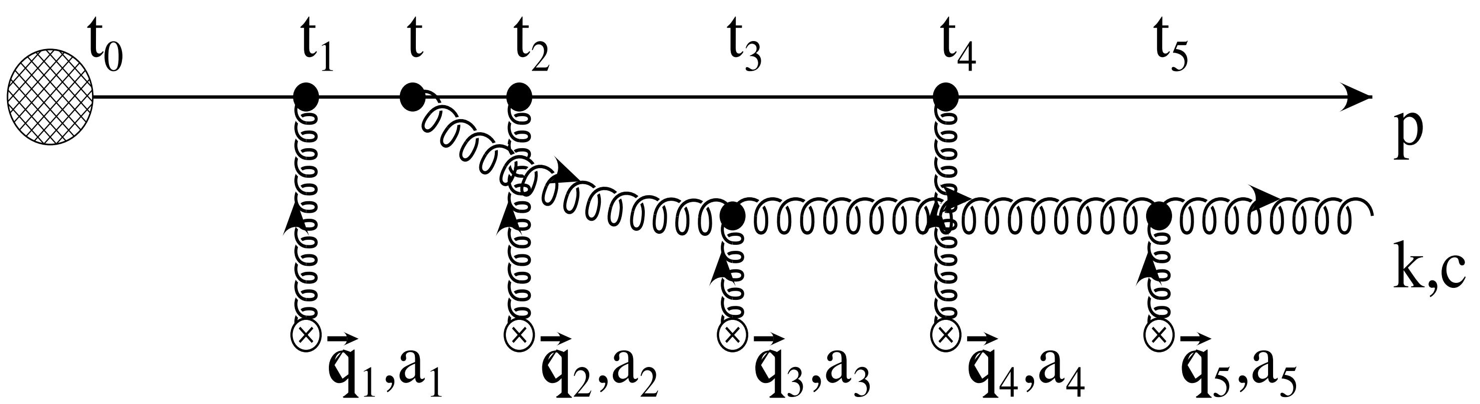
Soft Fragment Decorrelation



JCS, Milhano, Wiedemann 10

Energy Loss of a Single Quark

- Medium Induced gluon bremsstrahlung



BDMPS-Z 96

(GLV, ASW, AMY, HT ...)

(Review: JCS & C. Salgado arXiv:0712.3443)

$$\text{Range of interaction } \frac{1}{m_D} \ll \frac{1}{\lambda_{\rm m.f.p}} \text{ mean free path}$$

- Non-abelian energy loss:

$$\frac{dE}{dx} = \frac{1}{2}\hat{q}L \qquad \hat{q} = \frac{(\text{mean transferred momentum})^2}{\text{length}} \sim \frac{m_D^2}{\lambda_{\rm m.f.p}}$$

- How do jets loose energy in a system with no quasiparticles?

- Holography provides a tool to address this problem

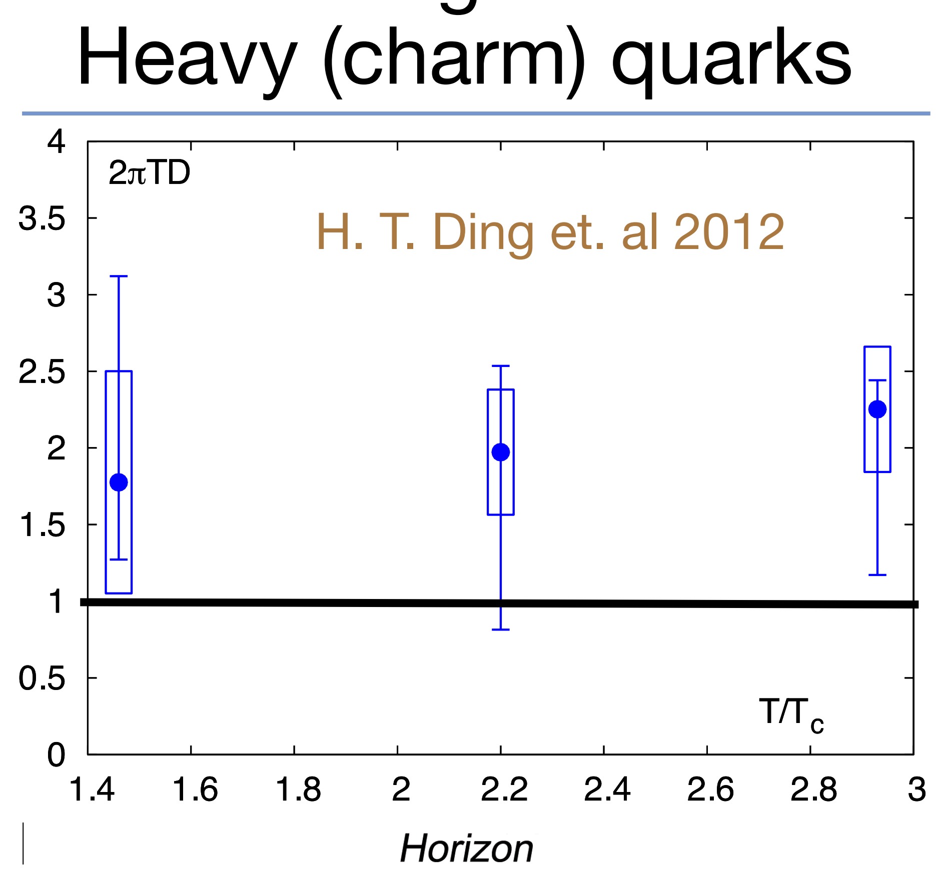
Eloss at strong coupling

- Heavy Quark ⇔ classical string attached to boundary

JCS & Teaney (2006)

Herzong, Karch, Kovtun,Kozcaz, Yaffe (2006)

S. Gubser (2006)



- Energy loss ⇔ flux of momentum along the string

$$\frac{dp}{dt} = -\eta_D p$$

Langevin

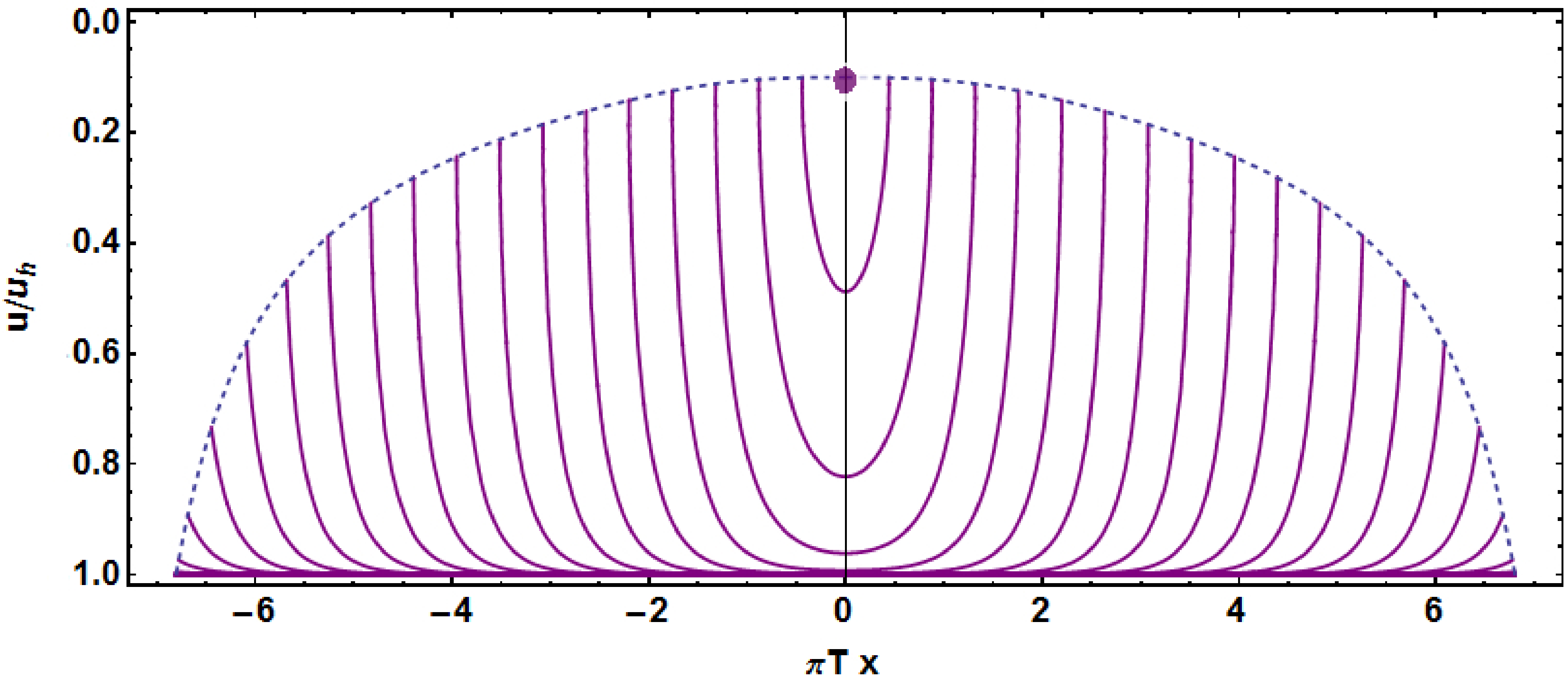
$$\eta_D = \frac{\pi\sqrt{\lambda}T^3}{2MT}$$

$$\Longrightarrow$$

$$D \approx \frac{1}{2\pi T}\left(\frac{1.5}{\alpha_{sym}N}\right)^{1/2}$$

- Compatible with lattice extractions!

- Light Quark ⇔ free end point



- Energy loss rate

$$\frac{1}{E_{\rm in}}\frac{dE}{dx} = -\frac{4}{\pi}\frac{x^2}{x_{\rm stop}^2}\frac{1}{\sqrt{x_{\rm stop}^2 - x^2}}$$

$$x_{\rm stop} = \frac{1}{2\,\kappa_{\rm sc}}\frac{E_{\rm in}^{1/3}}{T^{4/3}},$$

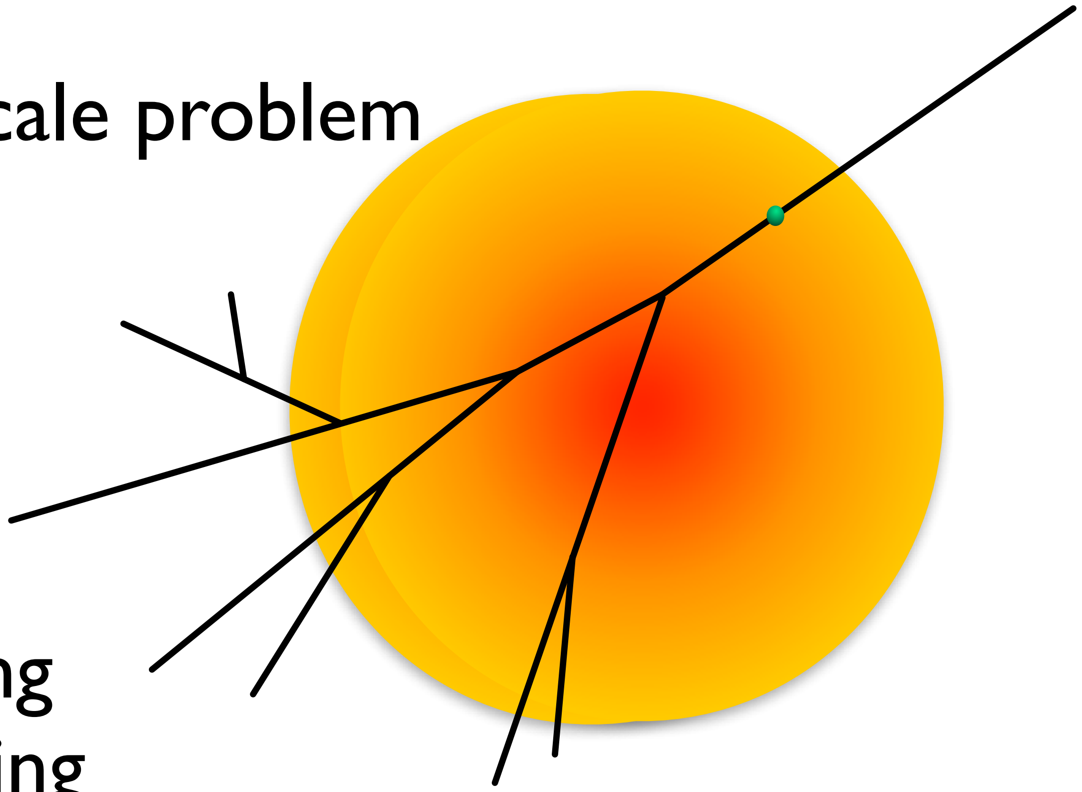
Gubser et al 08, Chesler et al. 08, Ficnar and Gubser 13

Chesler & Rajagopal 14, 15

A Hybrid Model

- Jet interaction with medium is a multi-scale problem
  - ➤ Hard production (perturbative)
  - ➤ Hard evolutions (perturbative)
  - ➤ Exchanges at medium scale
  - ➤ Soft jet fragments

  } strong coupling

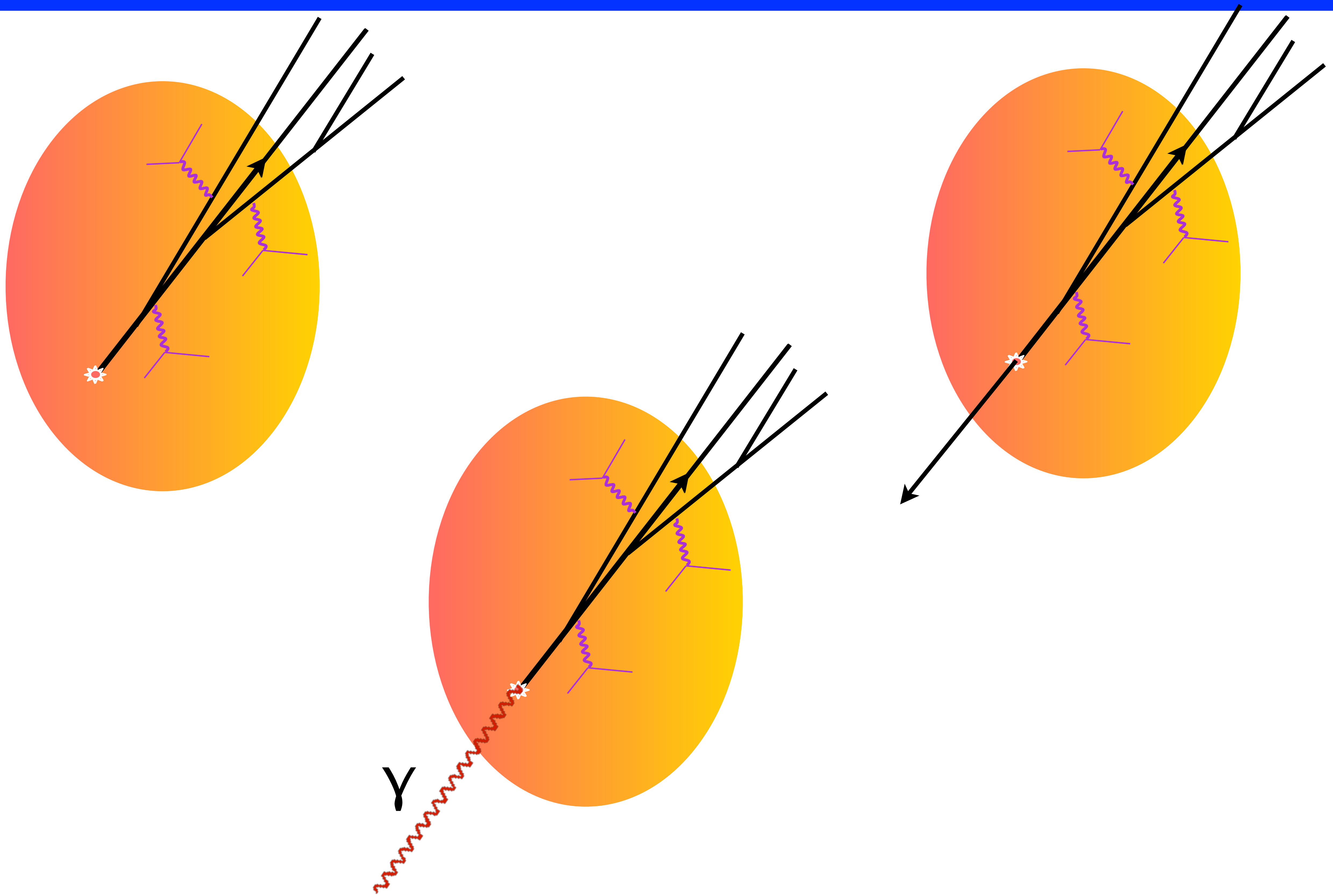


JCS, Gulhan, Milhano, Pablos and Rajagopal 2014, 2015, 2016

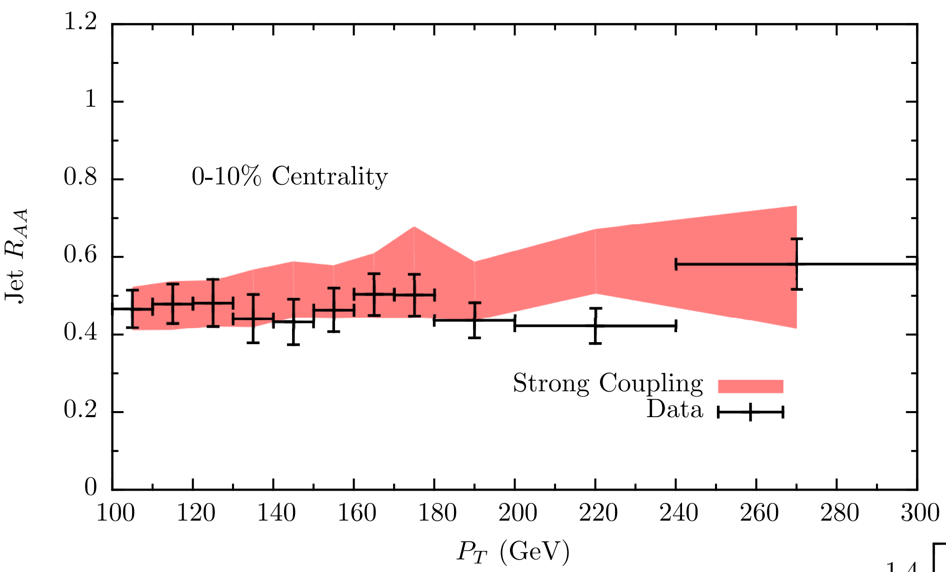
- The hybrid approach
  - ➤ Leave jet evolution unmodified (Q>>T)
  - ➤ Each in-medium parton losses energy

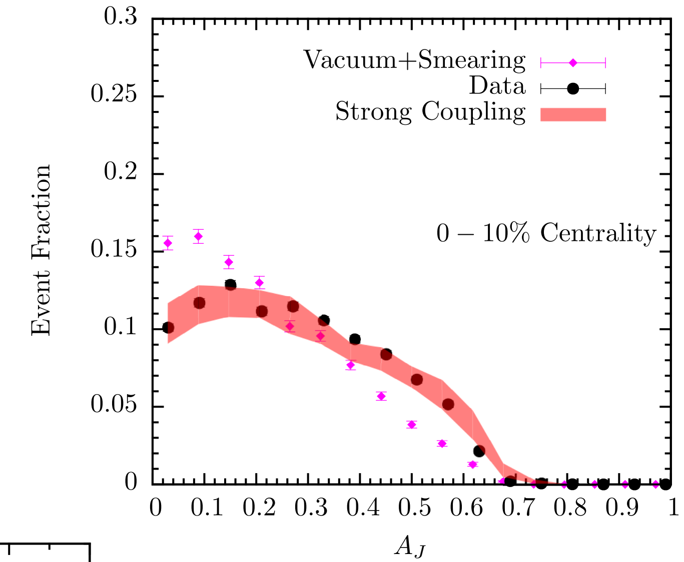
➤ We assume that all differences between theories can be packed into one single (fit) parameter

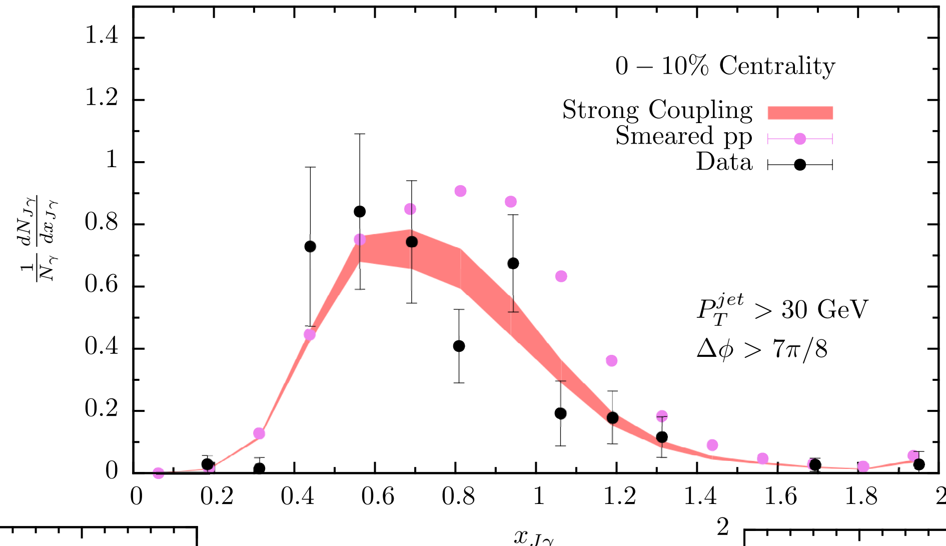
Observables



Success of the Hybrid Model



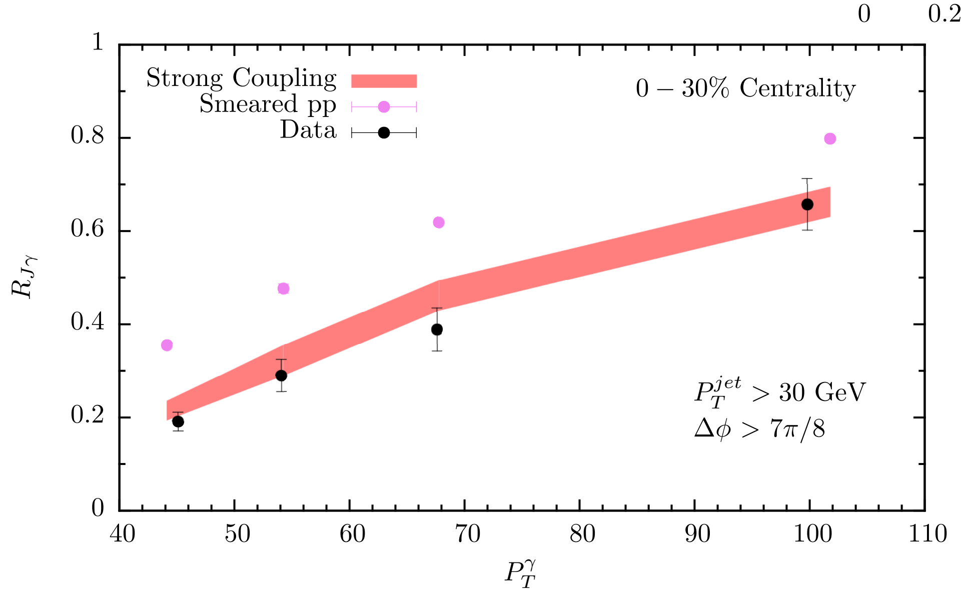


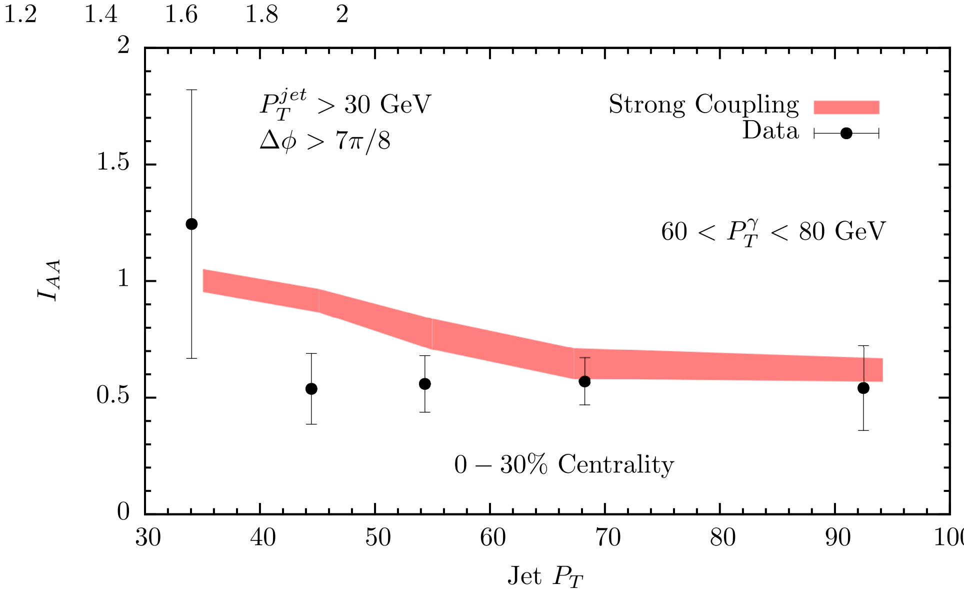


5 observables

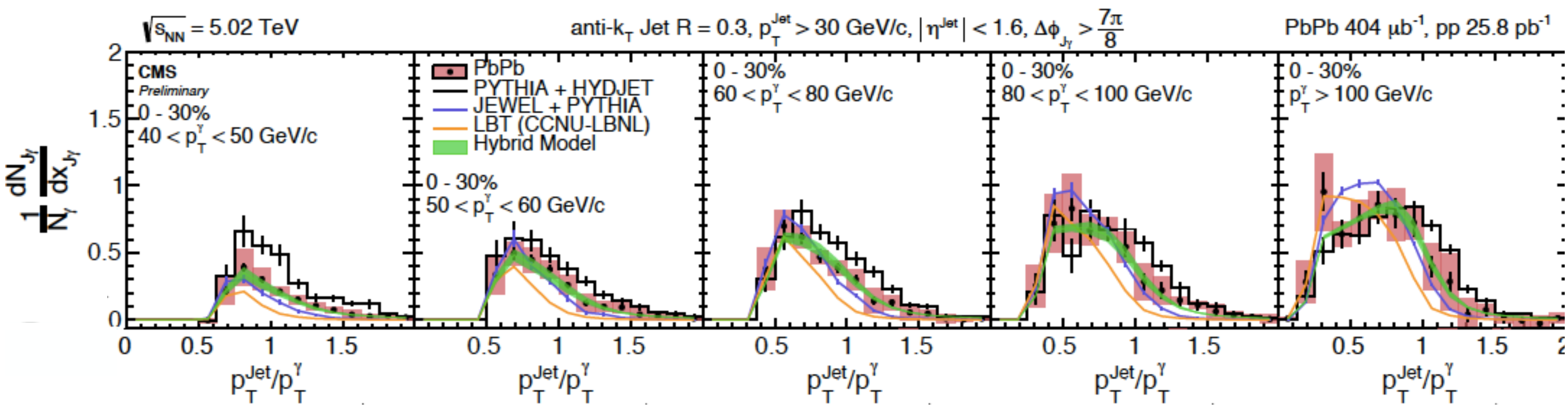
p_T and centrality

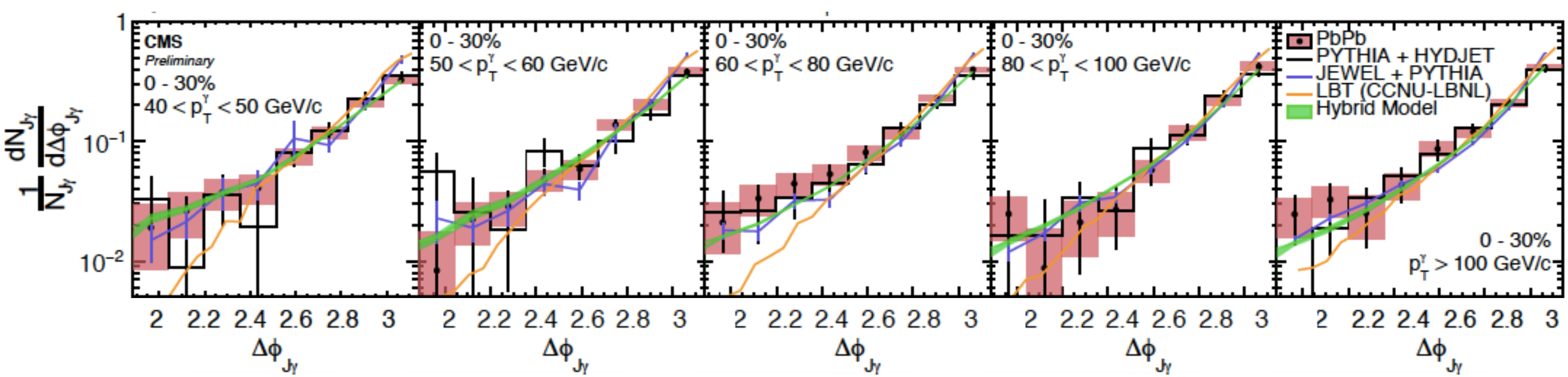
1 fit parameter





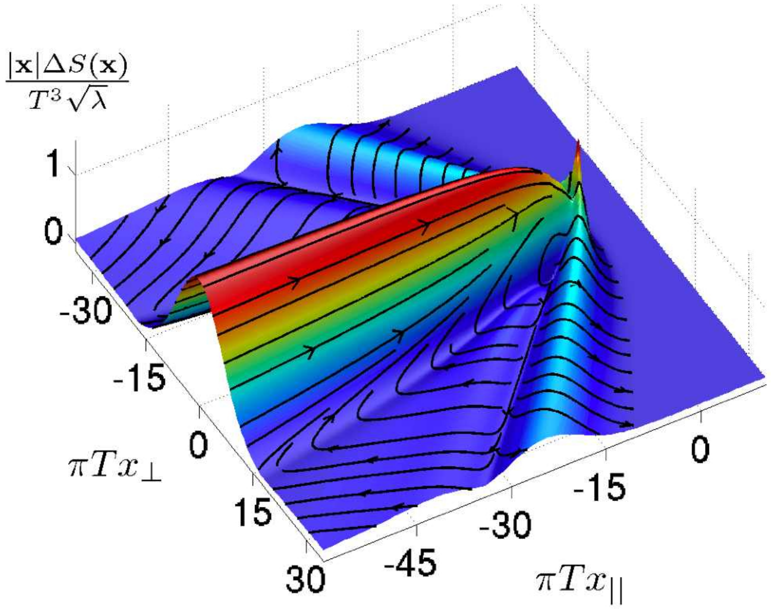
Tested Predictions





Medium Back-Reaction

Chesler &Yaffe 06

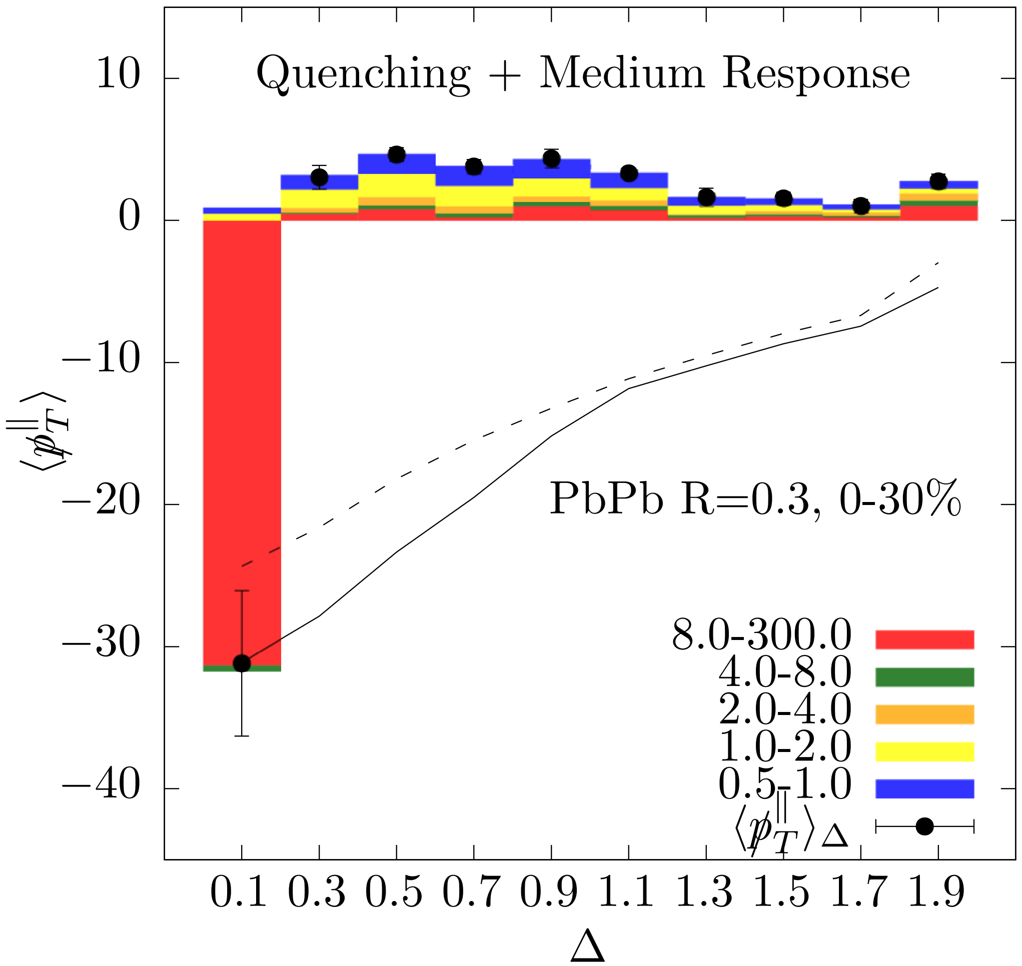


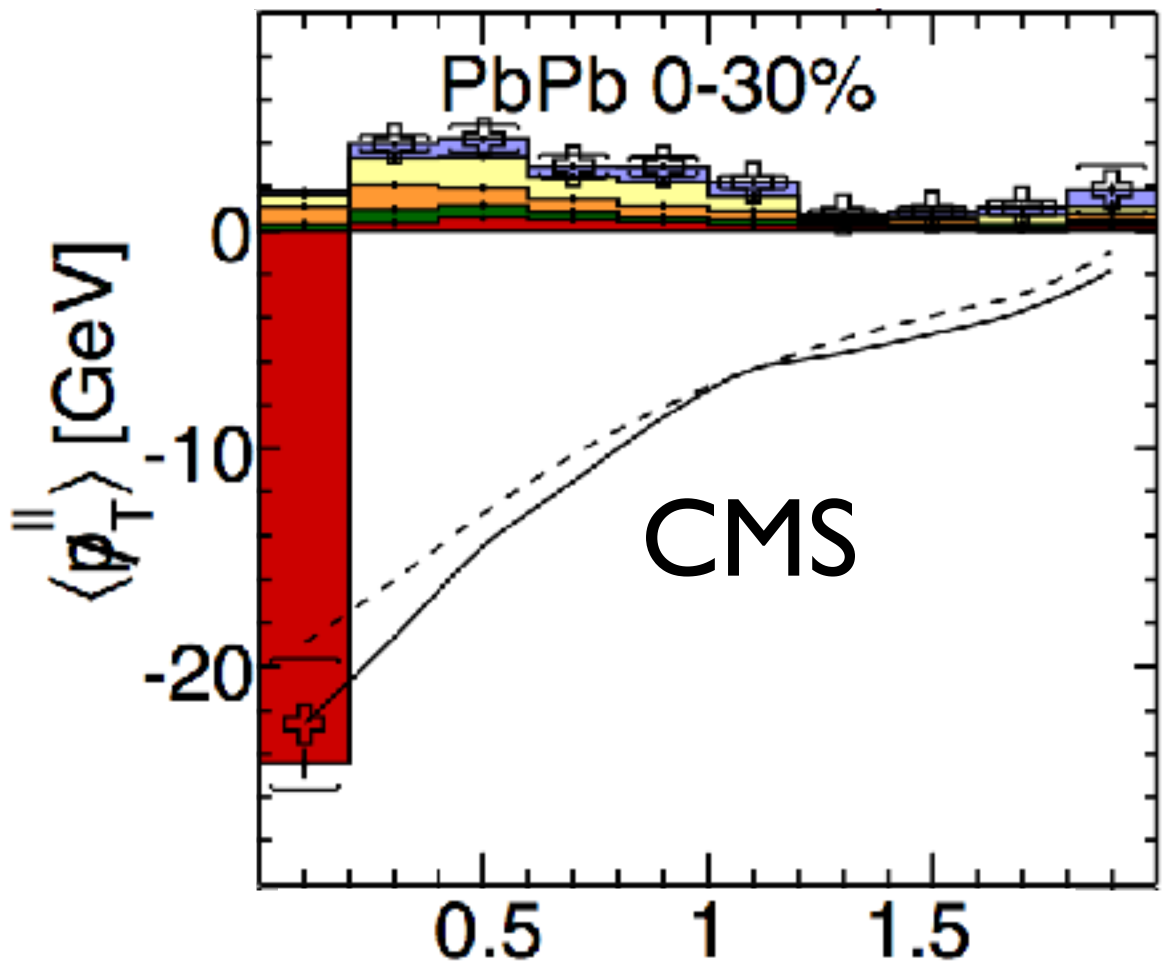
- The QGP is an extremely good fluid
  - ➤ Medium response to Eloss must be collective

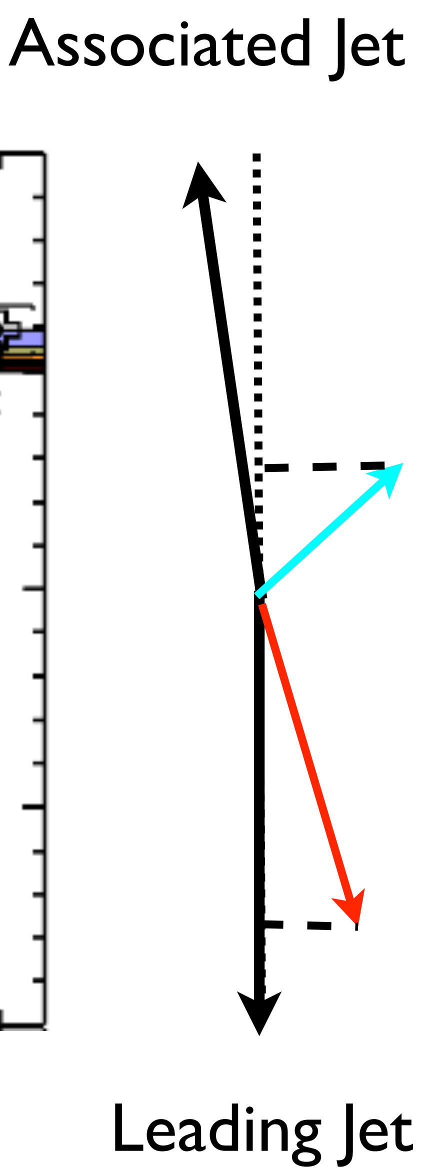
JCS, Shuryak & Teaney 06

  - ➤ Strong coupling computations provide an explicit example
    - ➤ Collectivity starts at short distance 1/T from the jet
    - ➤ There is a strong momentum flux along the jet direction
  - ➤ Essential to understand soft particle distribution around jets.

Recovering Jet Energy

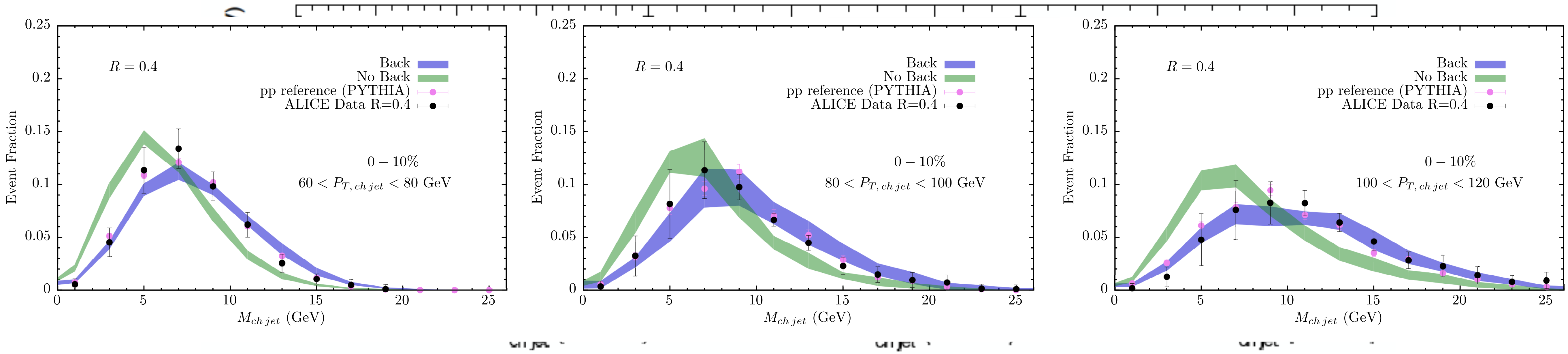






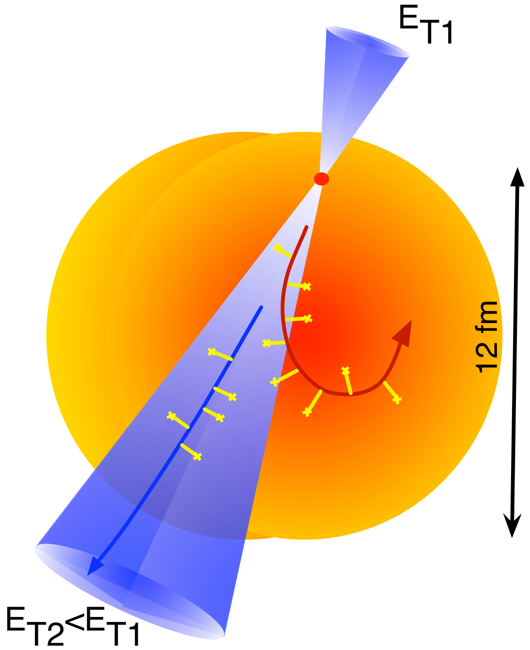
- Medium response completely fixed by Eloss
  - ➤ No additional parameters

Jet Masses



- Little sensitivity to strong quenching!
  - ➤ Puzzling result
  - ➤ Removing soft fragments ⇒

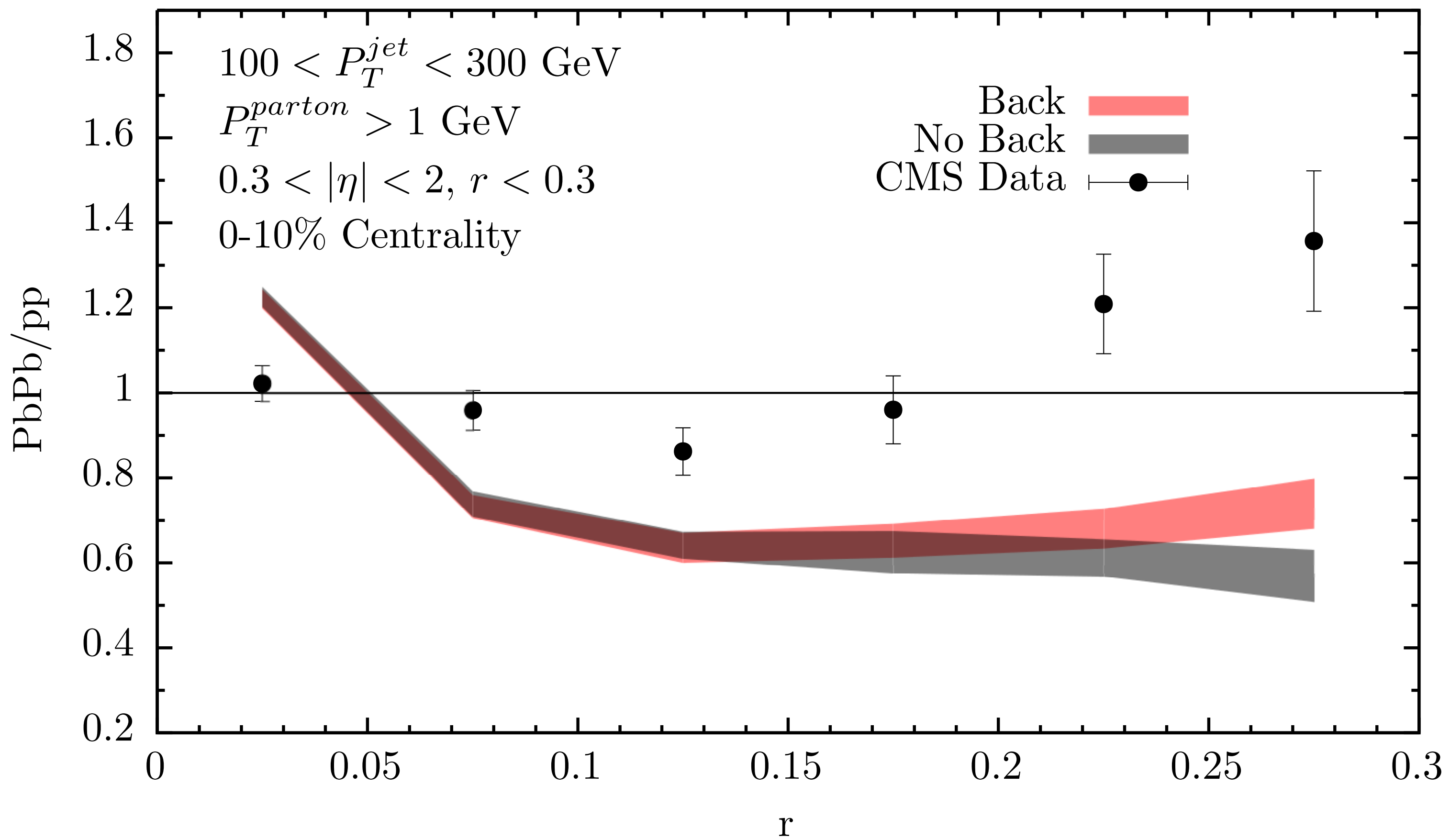
    Jet mass narrowing

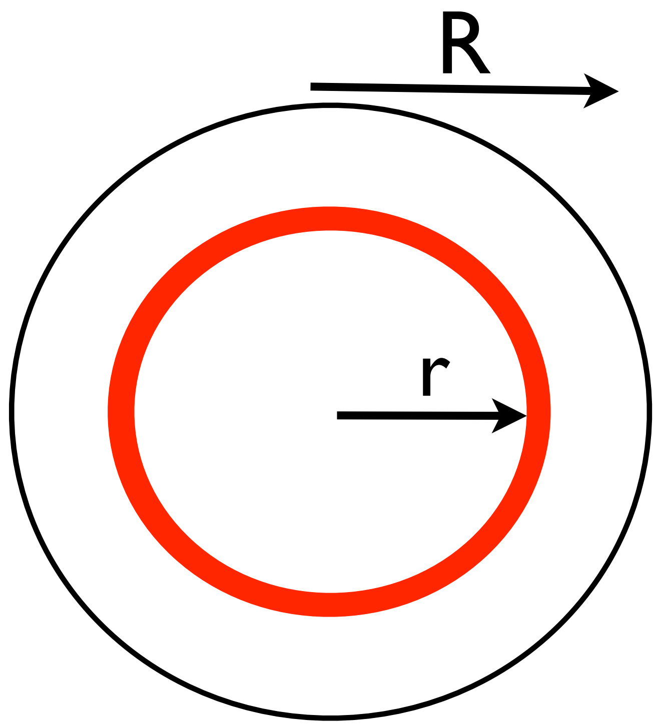


- Medium response regenerates the missing mass

Not Everything Works: Jet Shapes

JCS, Gulhan, Milhano, Pablos and Rajagopal 16

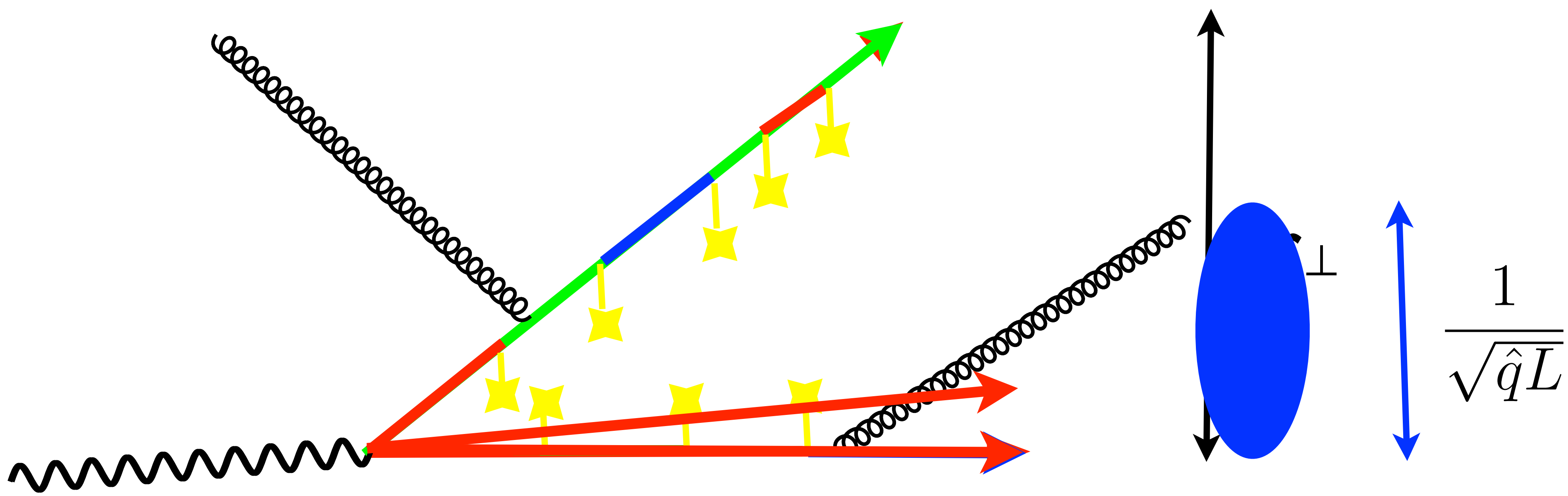




- Jet Narrowing too strong for this observable
- Overall description of jets is competitive
    - ➤ All current models fail in *some* observable
- Trash the model?
- Are there physics missing?

Transverse Size Resolution

- Perturbative analysis of non-abelian classical currents



- Colour exchanges decorrelate the currents
- Coherence is lost at a time

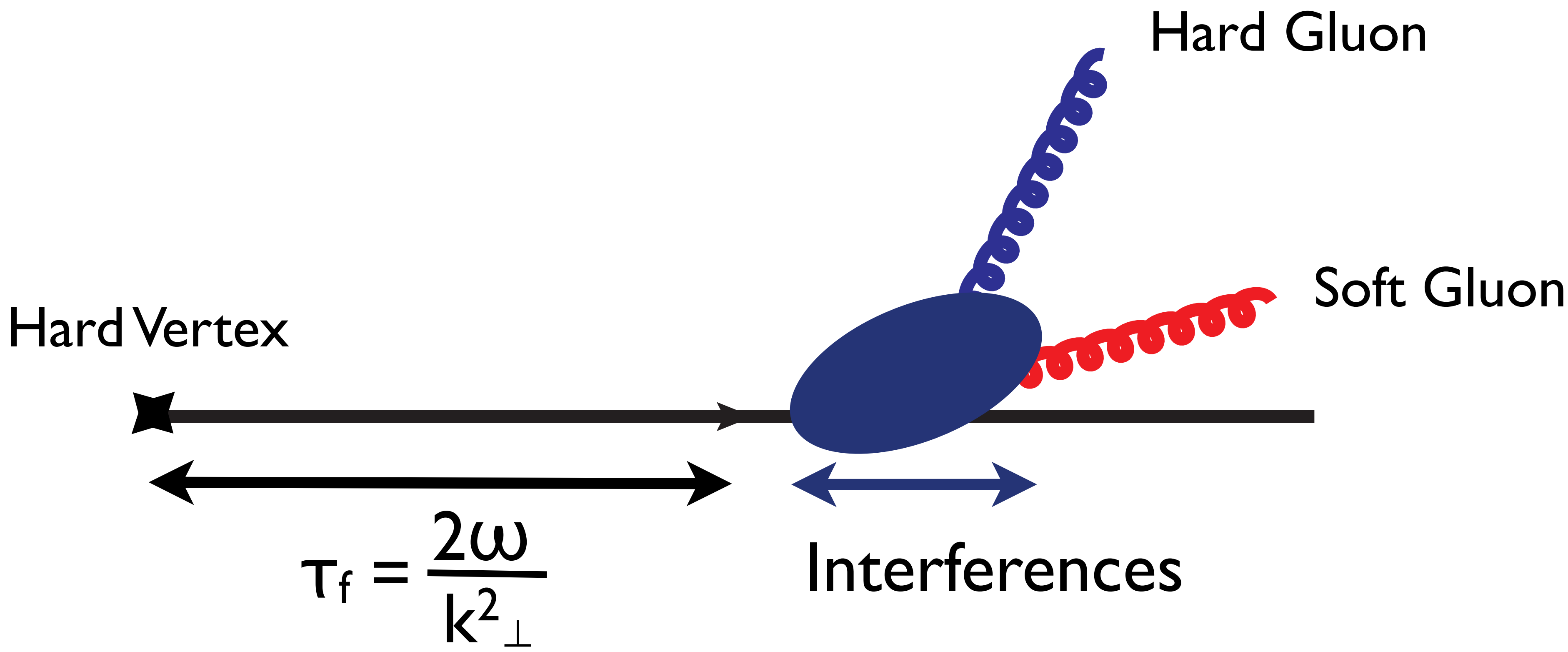
JCS, Iancu **arXiv:1105.1760**
Mehtar-Tani, Tywoniuk, Salgado **arXiv:1009.2965, 1102.4317**
arXiv:1112.5031, 1205.5739

$$\tau_{coh} = \left(\frac{\theta_c}{\theta_{q\bar{q}}}\right)^{2/3} L \qquad \theta_c^2 = \frac{1}{\hat{q}L^3}$$

- Fragments at small angles cannot be resolved

Quantum Calculation

- Double emission rate off in-medium quark



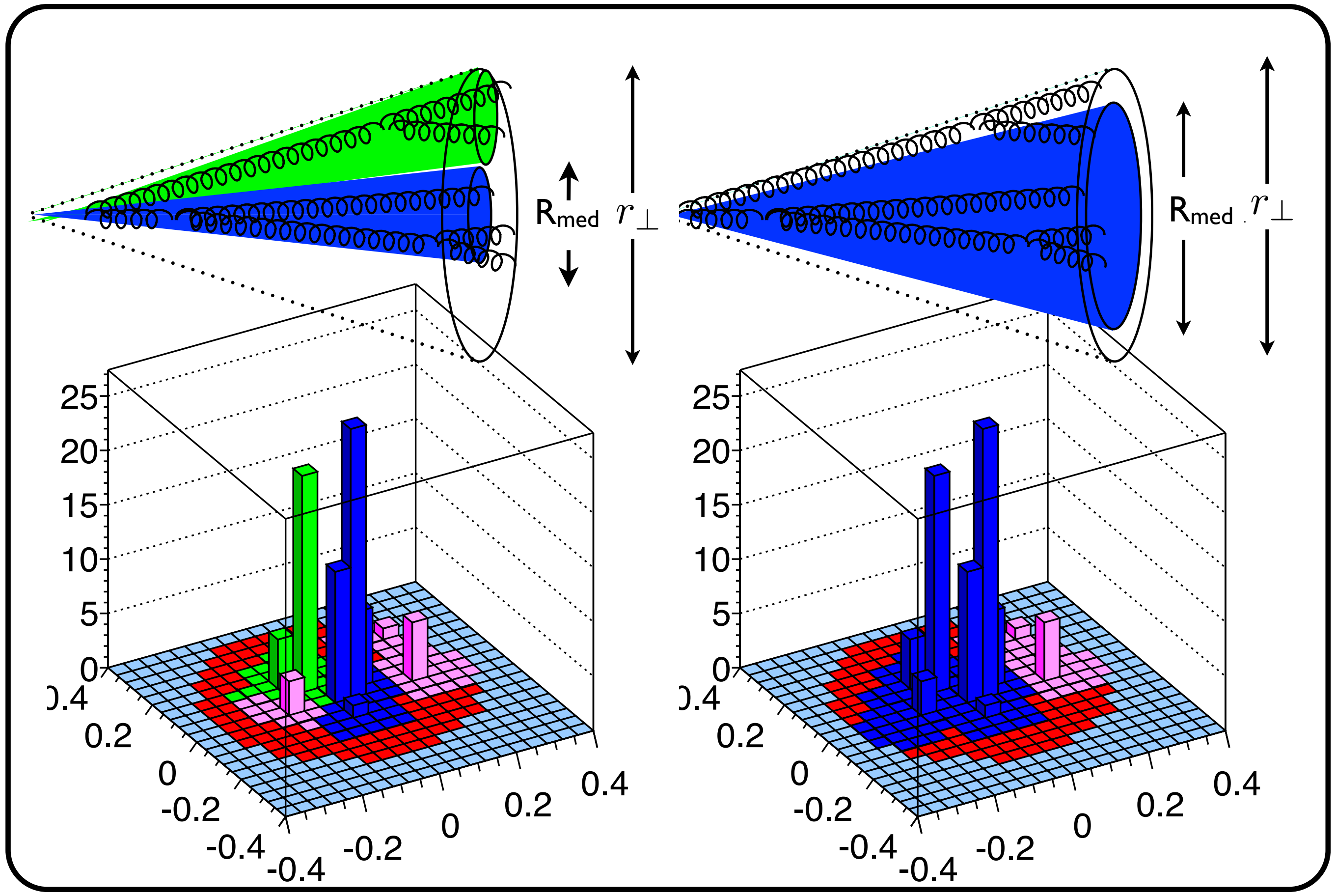
➤ Confirms the classical calculation on interferences

➤ Supplements time structure of the process

JCS, Pablos and Tywoniuk **16**

New Picture for Jet Quenching

JCS, Mehtar-Tani, Tywoniuk, Salgado **arXiv:1210.7765**



- Jet substructure is resolved by the medium

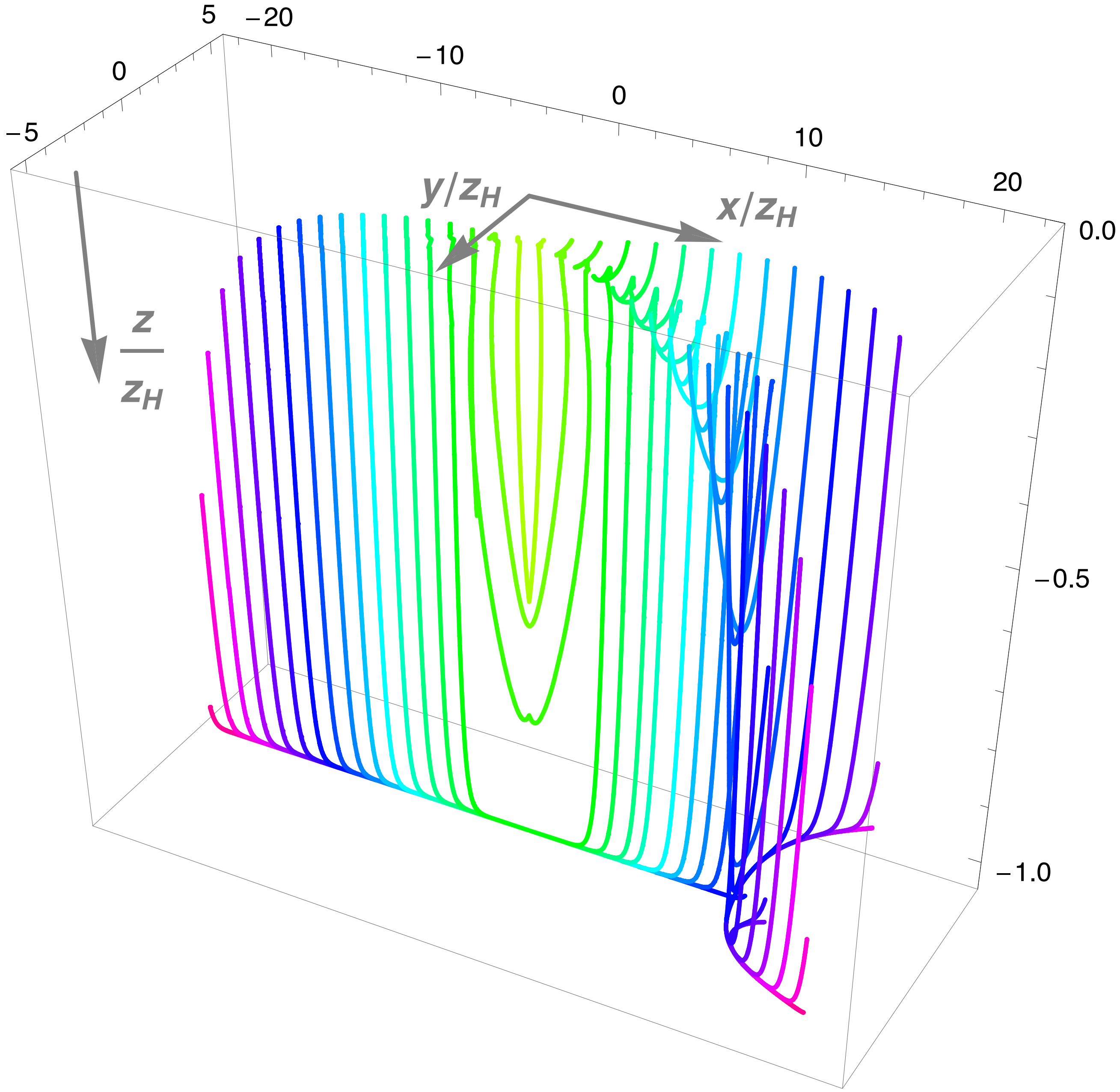
$$R_{\rm med} \equiv 2 \left(\int d\xi \, \xi^2 \hat{q}(\xi) \right)^{-1/2}$$

ξ ≡ path length

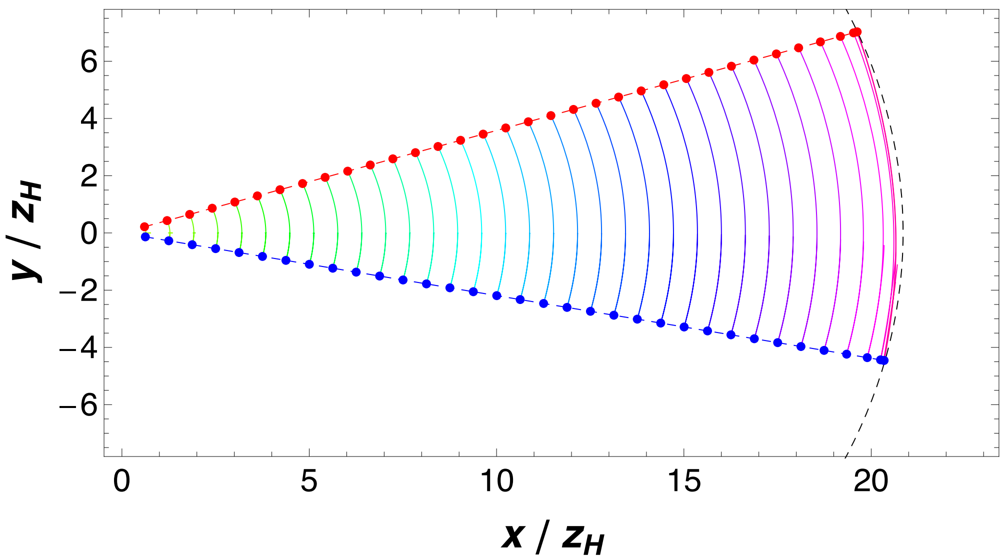
➤ Effective emitters control energy loss fluctuations

Finite Resolution at Strong Coupling

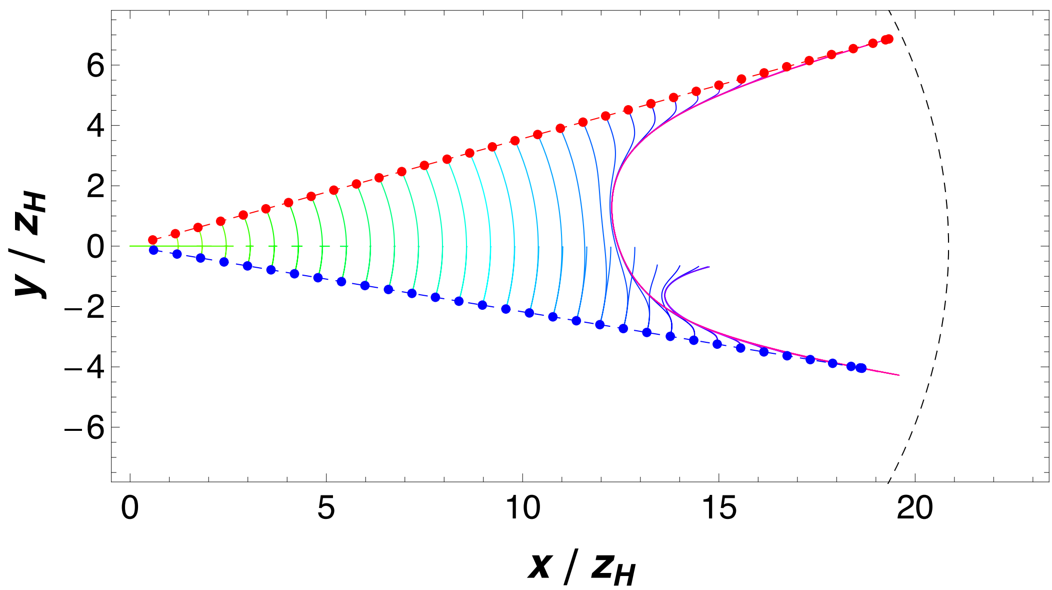
JCS, Ficnar 1512.00371



un-resolved jets



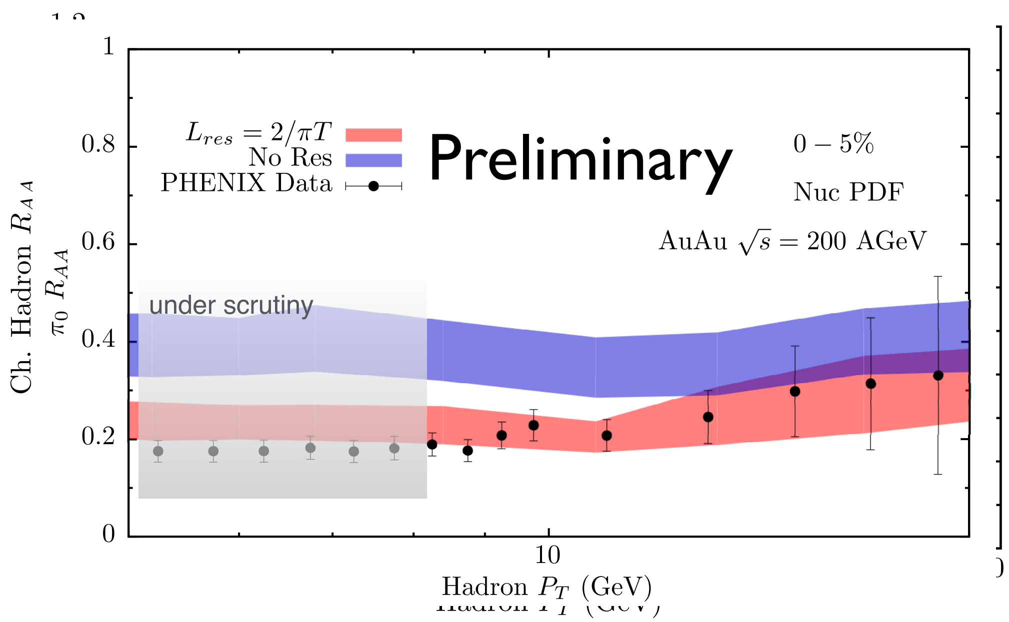
resolved jets

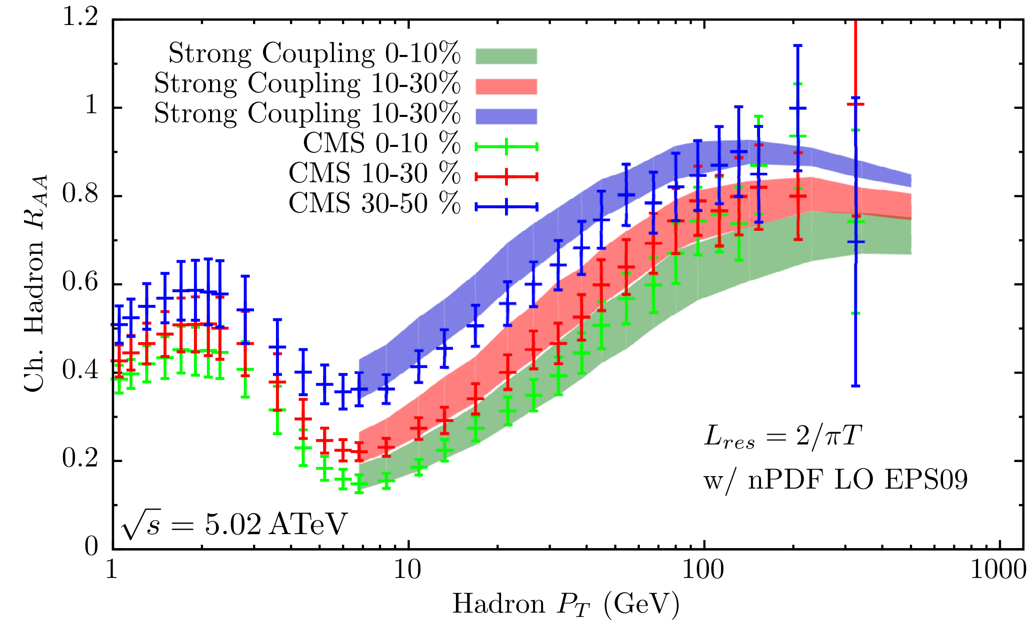


Single Particle Spectra

JCS, Gulhan, Hylcher, Milhano, Pablos, Rajagopal
in preparation

- Resolution effects are important for single particle suppression





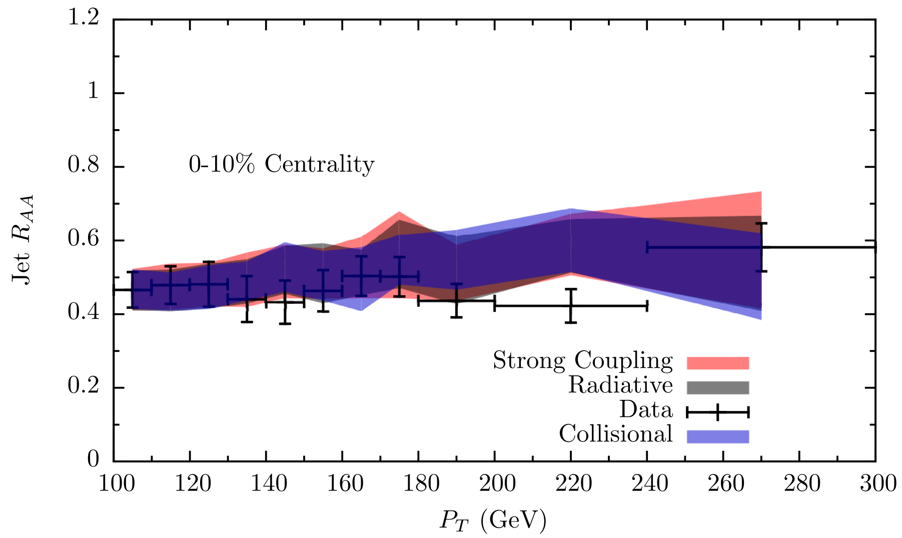
- But also to reconcile the √s dependence of quenching
  - A common problem in all models of jet quenching

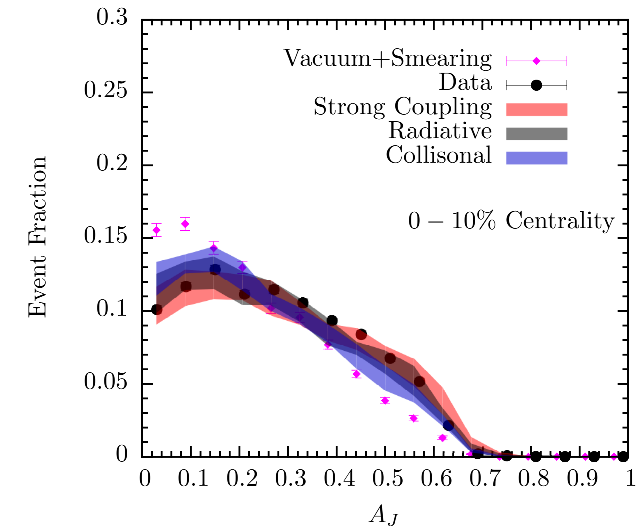
Conclusions

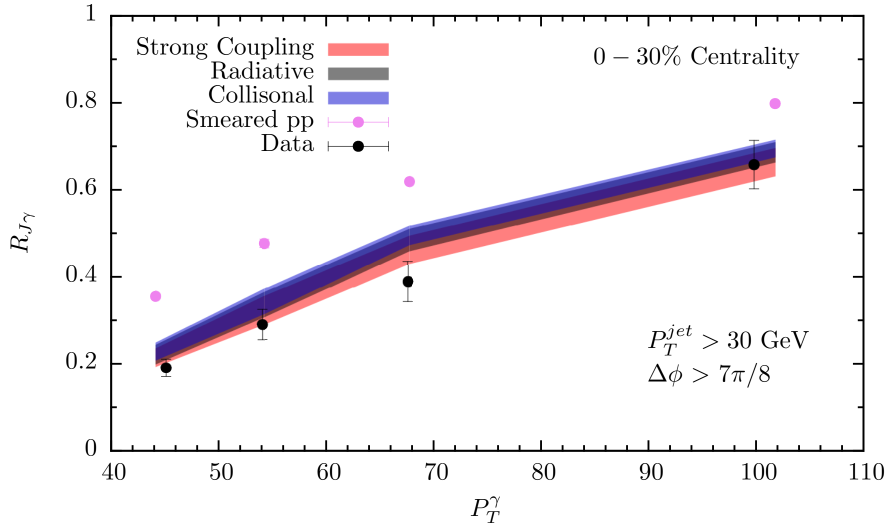
- Heavy ion collisions provide access to the QGP
  - ➤ Deconfined matter
  - ➤ A very good fluid
  - ➤ A system with no quasiparticles
- Hard probes provide access to the microscopic dynamics
  - ➤ Promising description based on strong coupling techniques
  - ➤ Dynamical implementation: allows us to understand successes and limitations
  - ➤ Ultimate goal: can we understand the nature of plasma degrees of freedom from these measurements?

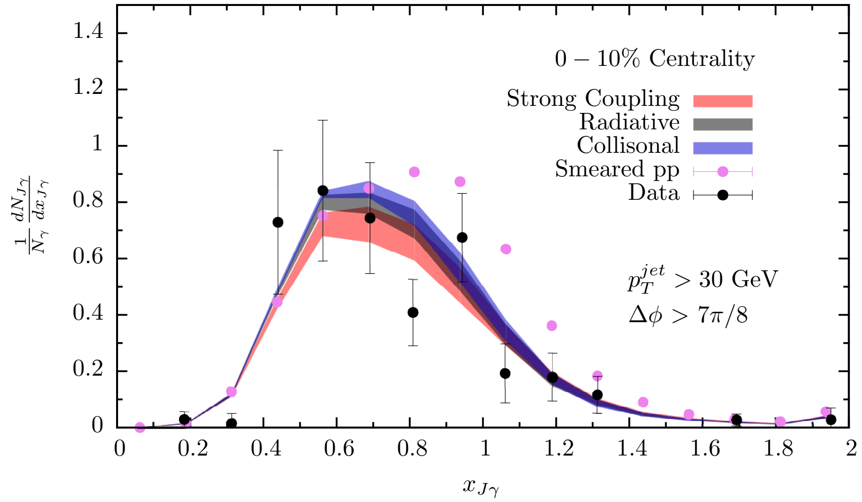
Back up

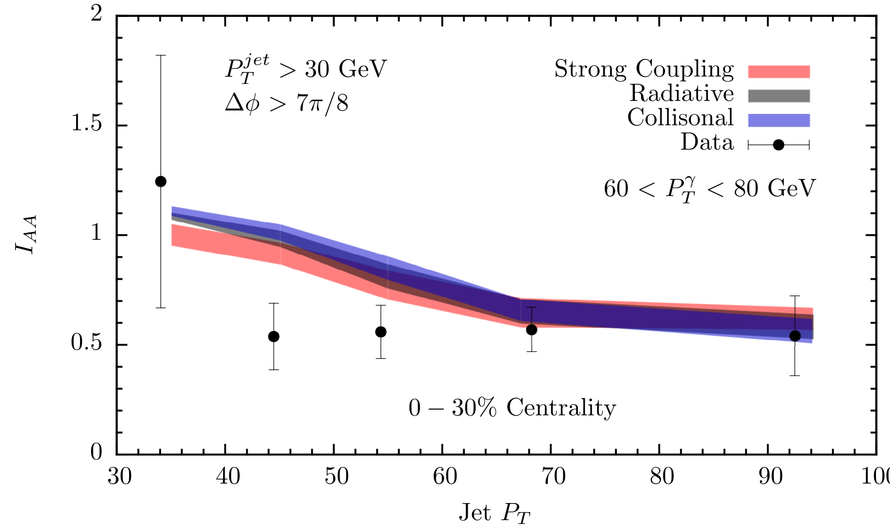
Insensitivity

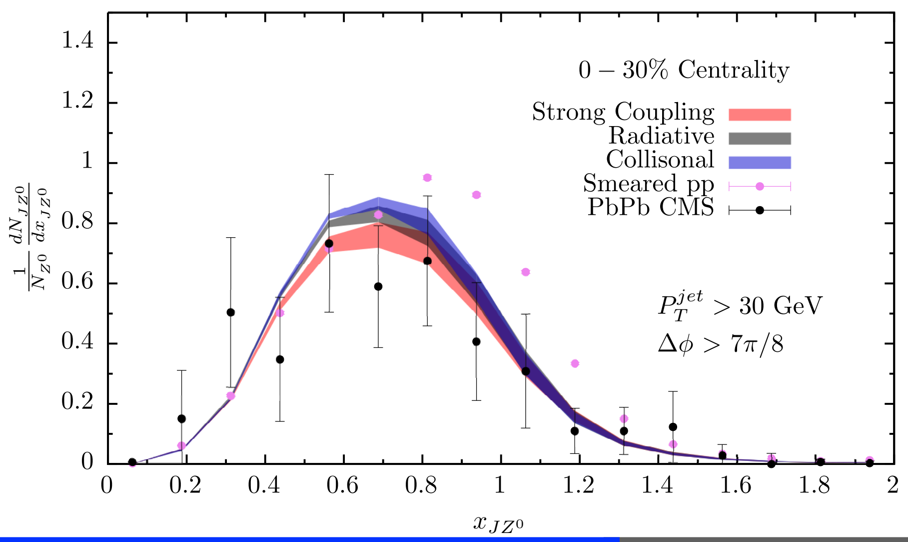


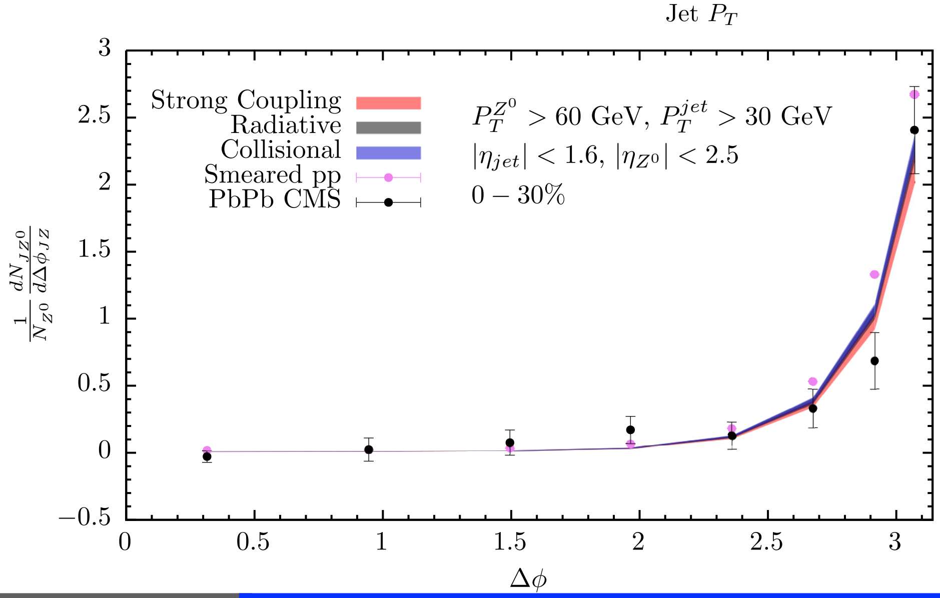






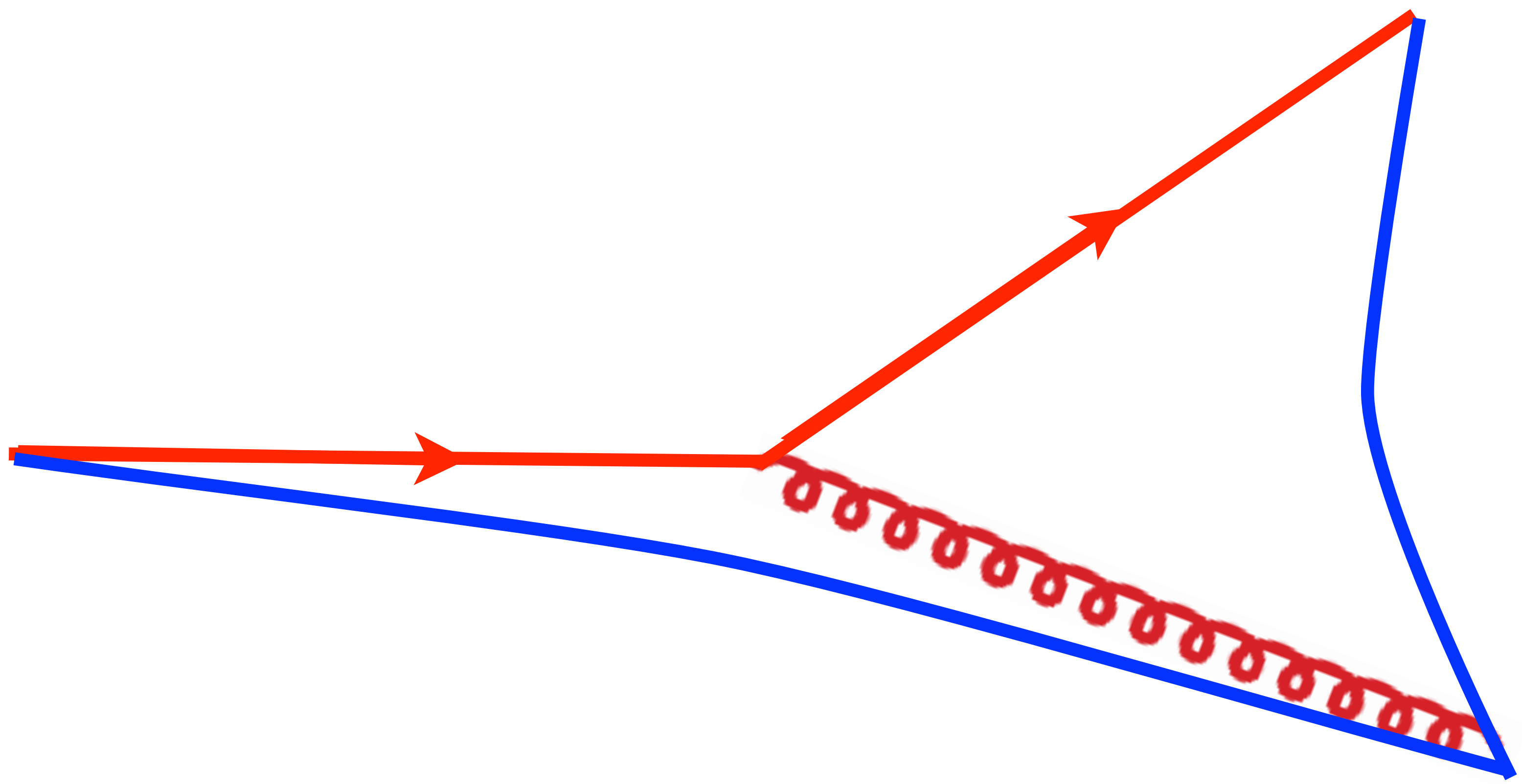






3-Jet events

- Hard gluon emission by an energetic q-q̄ pair



➤ Soft fields between colour objects

Lund string model: gluons associated to kinks in the string

Strong vs Weak

- Resolution angle infinite medium

$$\theta_{\mathrm{res}} = \frac{2^{4/3}}{\pi} \frac{\Gamma(3/4)^2}{\Gamma(5/4)^2} \left(\frac{E}{\sqrt{\lambda} T} \right)^{-2/3}$$

- At weak coupling:

$$\theta_{\mathrm{res}}^{\mathrm{dense}} \sim \frac{1}{\sqrt{\hat{q} L^3}}$$

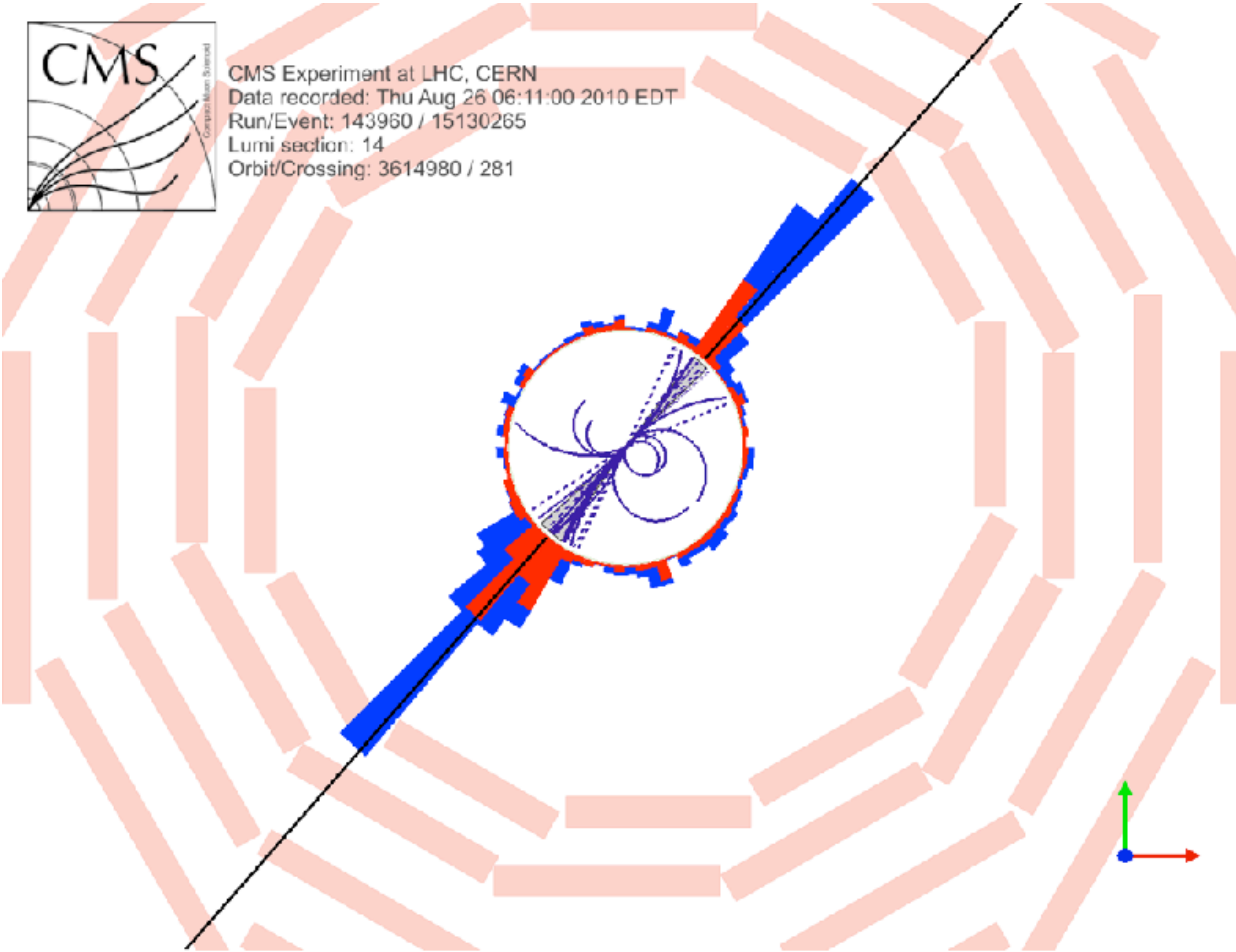
Finite length medium

- Infinite medium, maximal length= stopping distance $\Delta x_{\mathrm{stop}}^{pQCD} \sim \sqrt{\frac{E}{\hat{q}}}$

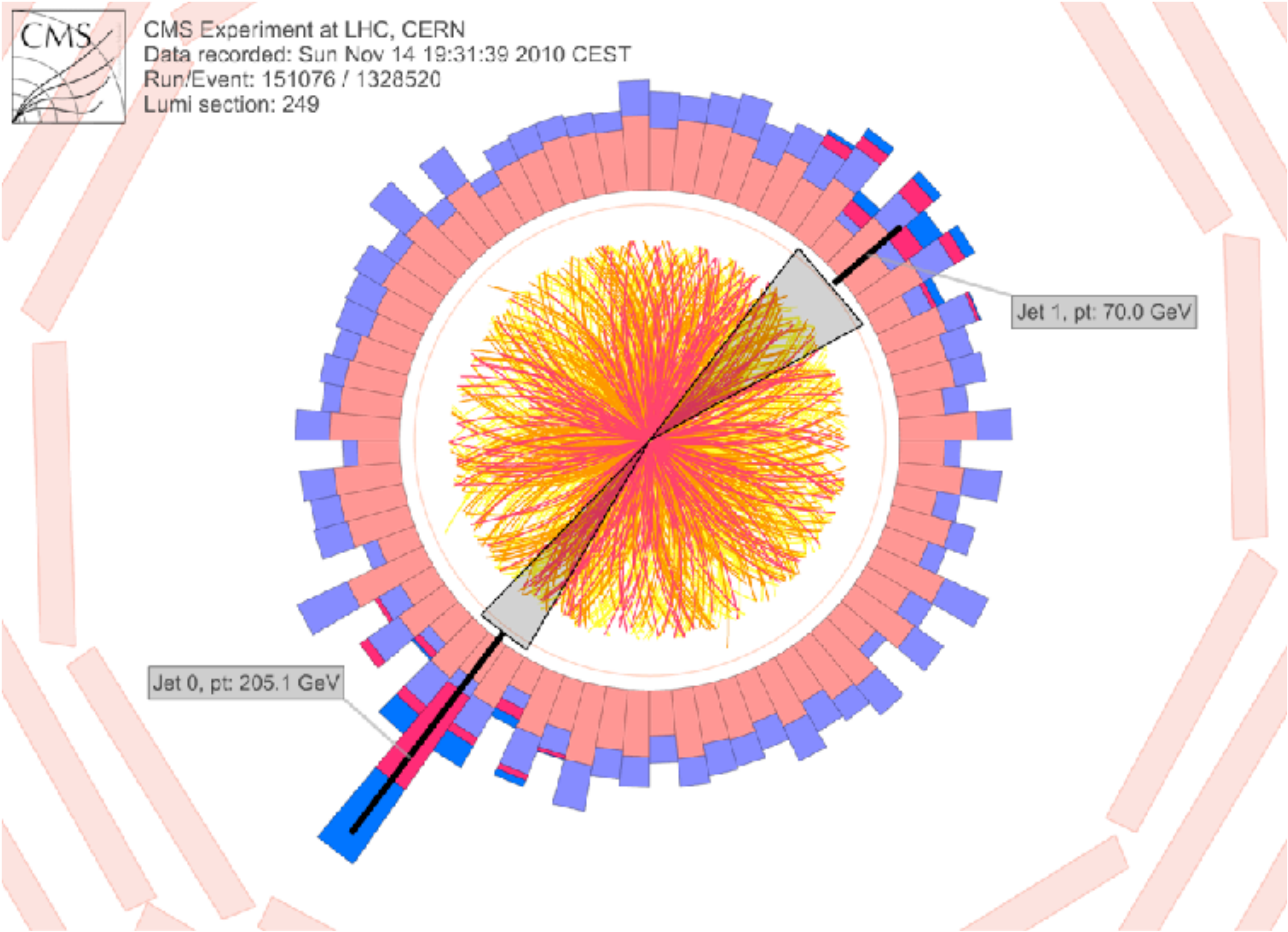
$$\theta_{\mathrm{res}}^{\mathrm{pQCD}} \propto E^{-3/4}$$

- Fluctuations in jet energy loss may help distinguish between the different microscopic realisations

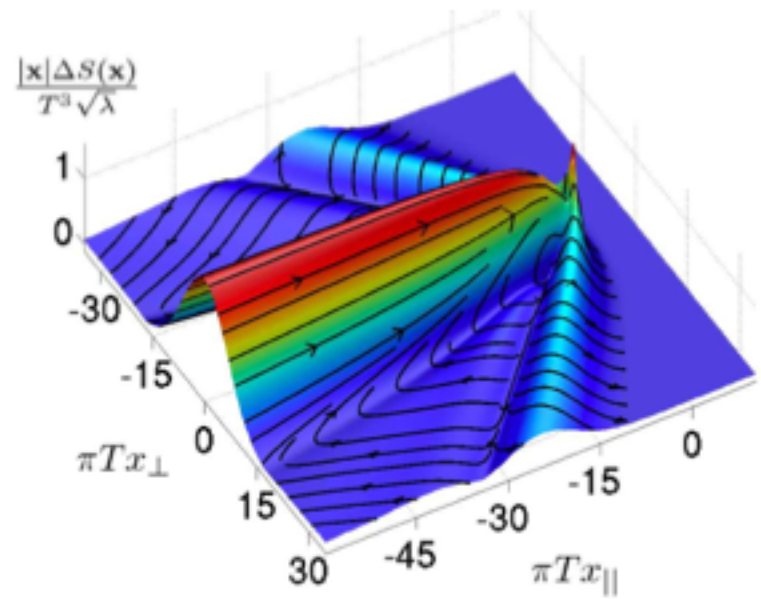
Jets in Vacuum



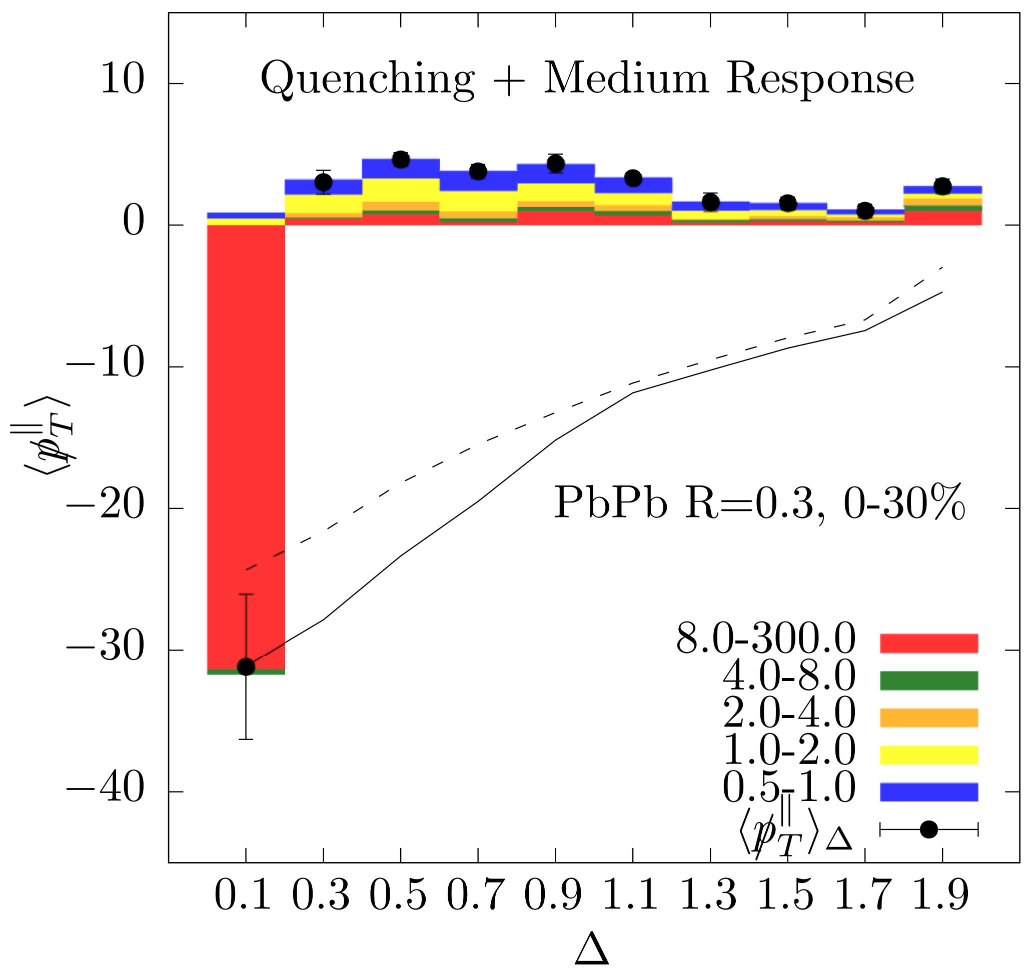
Jets in Pb-Pb

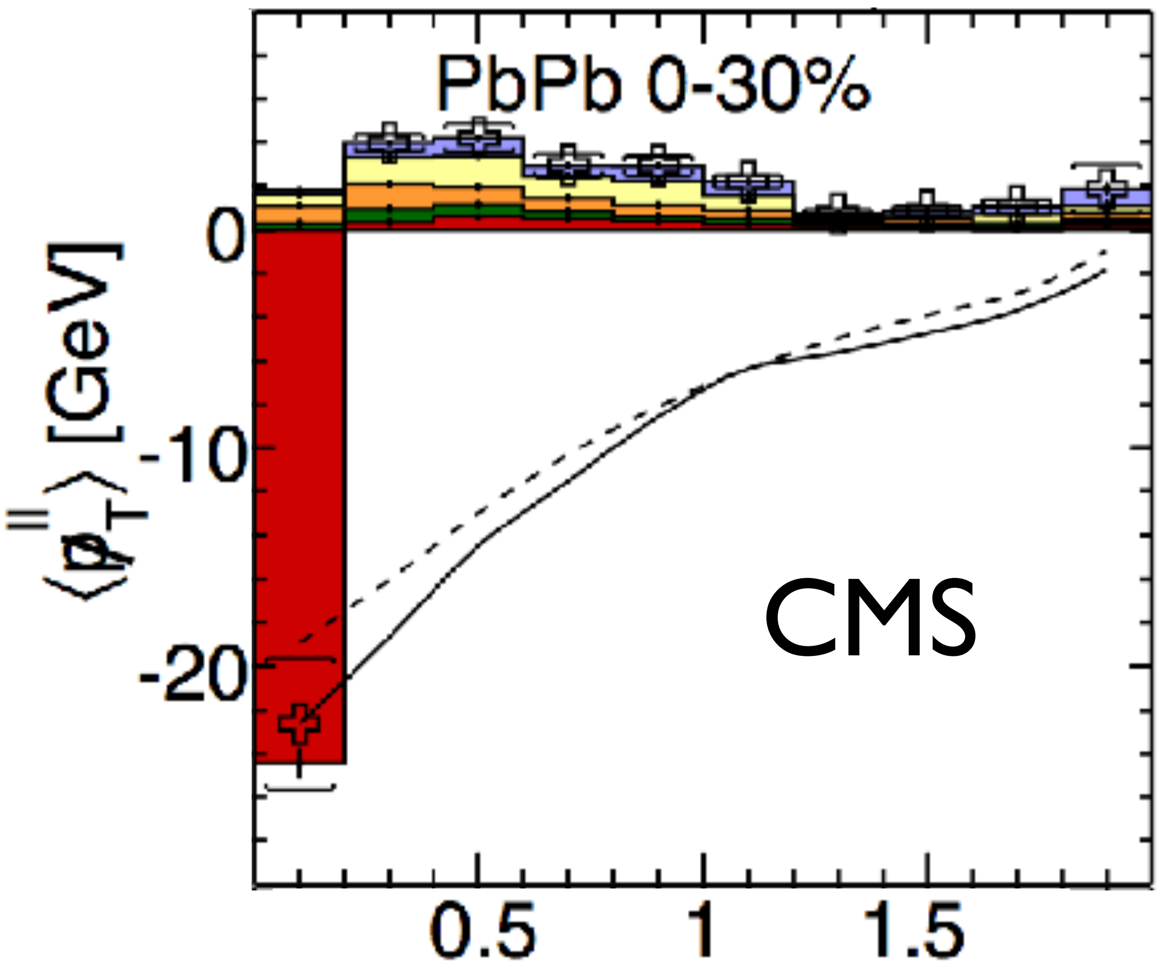

CMS
CMS Experiment at LHC, CERN
Data recorded: Sun Nov 14 19:31:39 2010 CEST
Run/Event: 151076 / 1328520
Lumi section: 249
Jet 1, pt: 70.0 GeV
Jet 0, pt: 205.1 GeV

Recovering Jet Energy



- Comment on crude hadronic treatment


Quenching + Medium Response
PbPb R=0.3, 0-30%
8.0-300.0
4.0-8.0
2.0-4.0
1.0-2.0
0.5-1.0
$\langle \not{p}_T^{\parallel} \rangle_\Delta$
$\langle \not{p}_T^{\parallel} \rangle$
10
0
−10
−20
−30
−40
0.1 0.3 0.5 0.7 0.9 1.1 1.3 1.5 1.7 1.9
Δ


PbPb 0-30%
CMS
$\langle \not{p}_T^{\parallel} \rangle$ [GeV]
0
-10
-20
0.5
1
1.5