Heavy Ion Physics at the LHC

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CERN TH

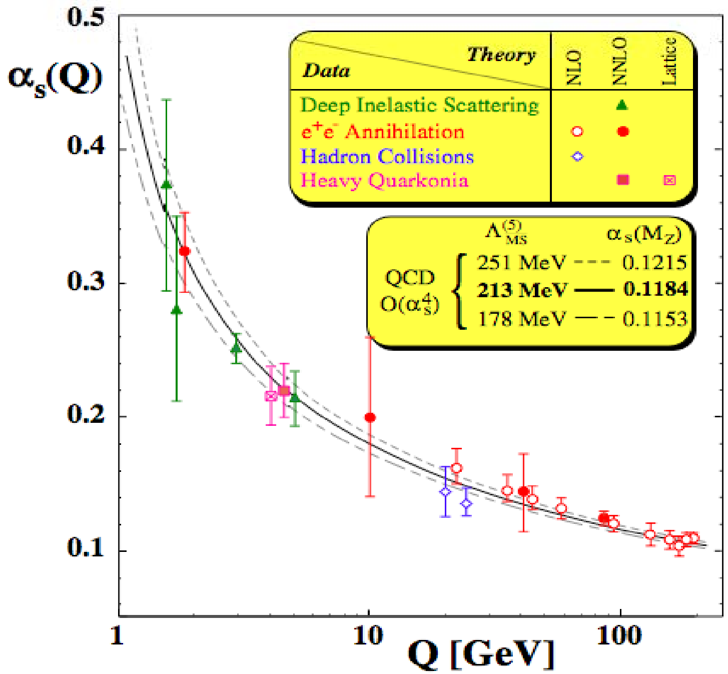
From elementary interactions to collective phenomena

1973: asymptotic freedom

⇨ QCD = quark model
+ gauge invariance

Today: mature theory with
a precision frontier

- background in search for new physics
- TH laboratory for non-abelian gauge theories

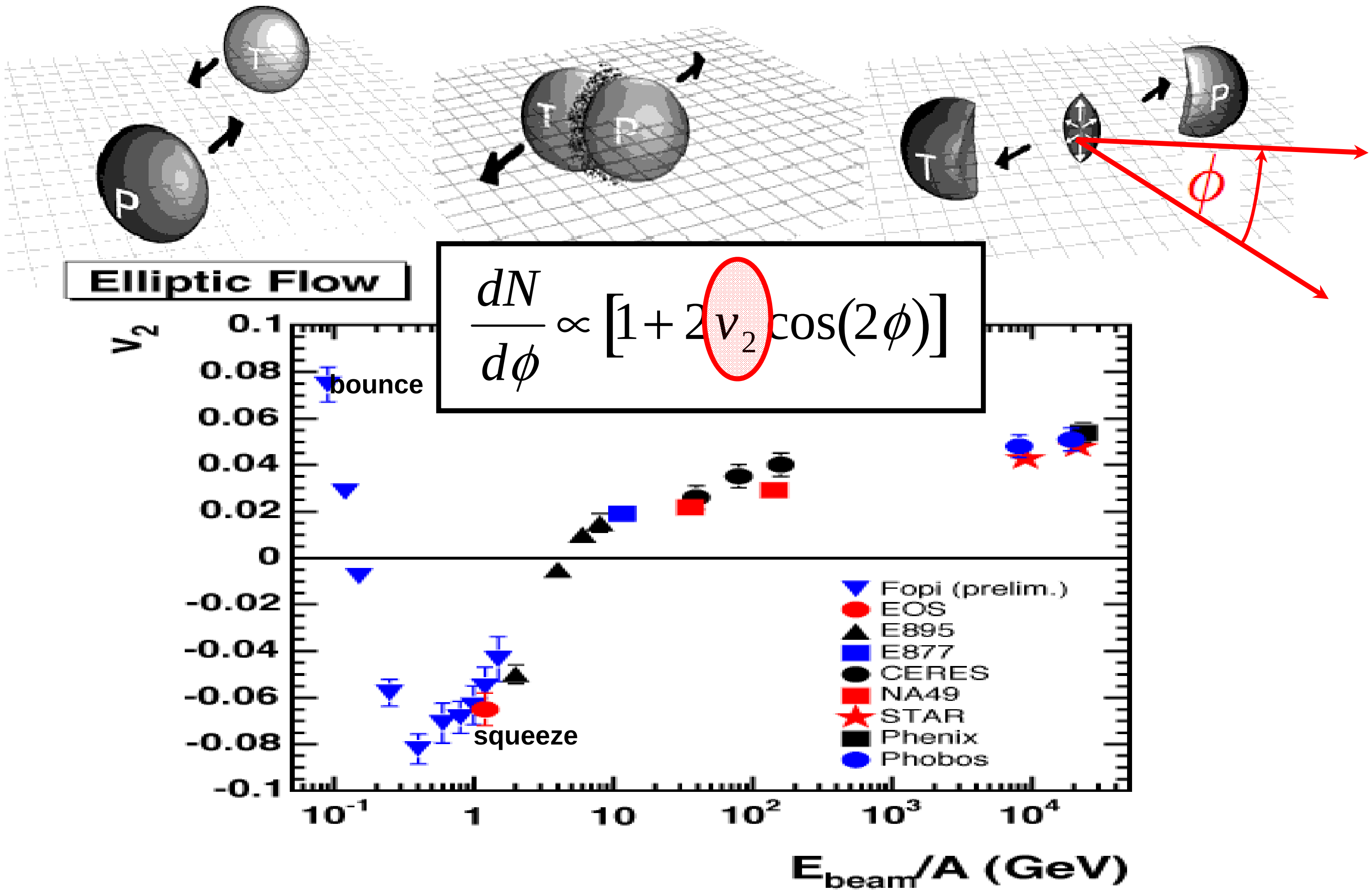


How do collective phenomena and macroscopic properties of matter emerge from fundamental interactions?

⇨ QCD much richer than QED:

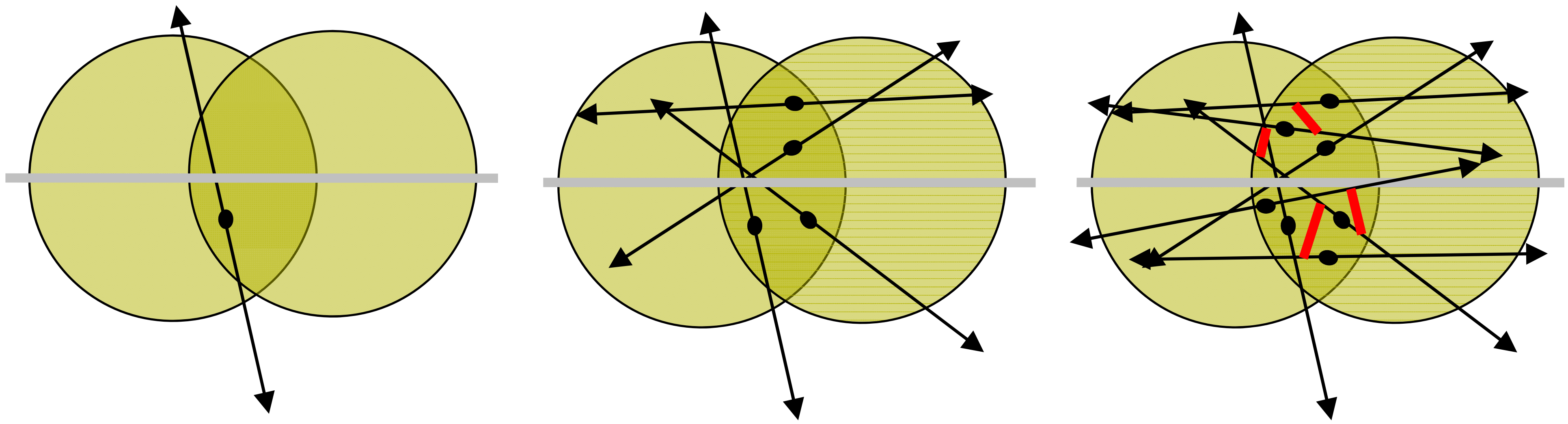
- non-abelian theory
- degrees of freedom change with Q^2

Elliptic Flow:
Hallmark of a collective phenomenon



$$\frac{dN}{d\phi} \propto \left[1 + 2 v_2 \cos(2\phi)\right]$$

Particle production w.r.t. reaction plane



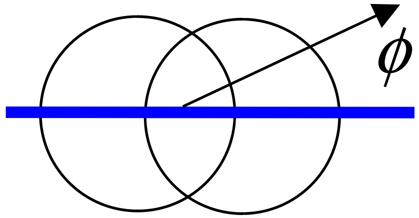
- Single 2->2 process
- Maximal asymmetry
- NOT correlated to the reaction plane

- Many 2->2 or 2-> n processes
- Reduced asymmetry $\sim 1/\sqrt{N}$
- NOT correlated to the reaction plane

- final state interactions
- asymmetry caused not only by multiplicity fluctuations
- collective component is correlated to the reaction plane

Particle production w.r.t. reaction plane

- Want to measure particle production as function of angle w.r.t. reaction plane



$$v_n(D) = \left\langle e^{i n \phi} \right\rangle_D$$

But reaction plane is unknown ...

- Have to measure particle correlations:

$$\left\langle e^{i n(\phi_1 - \phi_2)} \right\rangle_{D_1 \wedge D_2} = v_n(D_1)\, v_n(D_2) + \left\langle e^{i n(\phi_1 - \phi_2)} \right\rangle_{D_1 \wedge D_2}^{corr}$$

"Non-flow effects"

$$\sim O(1/N)$$

But this requires signals $v_n > \dfrac{1}{\sqrt{N}}$

- Improve measurement with higher cumulants: Borghini, Dinh, Ollitrault, PRC (2001)

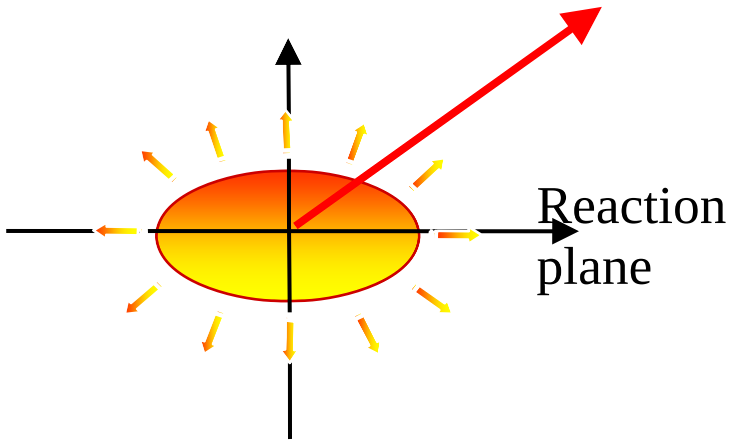
$$\left\langle e^{i n(\phi_1 + \phi_2 - \phi_3 - \phi_4)} \right\rangle - \left\langle e^{i n(\phi_1 - \phi_3)} \right\rangle \left\langle e^{i n(\phi_2 - \phi_4)} \right\rangle - \left\langle e^{i n(\phi_1 - \phi_4)} \right\rangle \left\langle e^{i n(\phi_2 - \phi_3)} \right\rangle = -v_n^4 + O\left(1/N^3\right)$$

This requires signals $v_n > \dfrac{1}{N^{3/4}}$

Elliptic flow: v_2

- Momentum space:

$$E\frac{dN}{d^3p} = \frac{1}{2\pi}\frac{dN}{p_T dp_T d\eta}\left[1+2v_2(p_T)\cos(2\phi)\right]$$



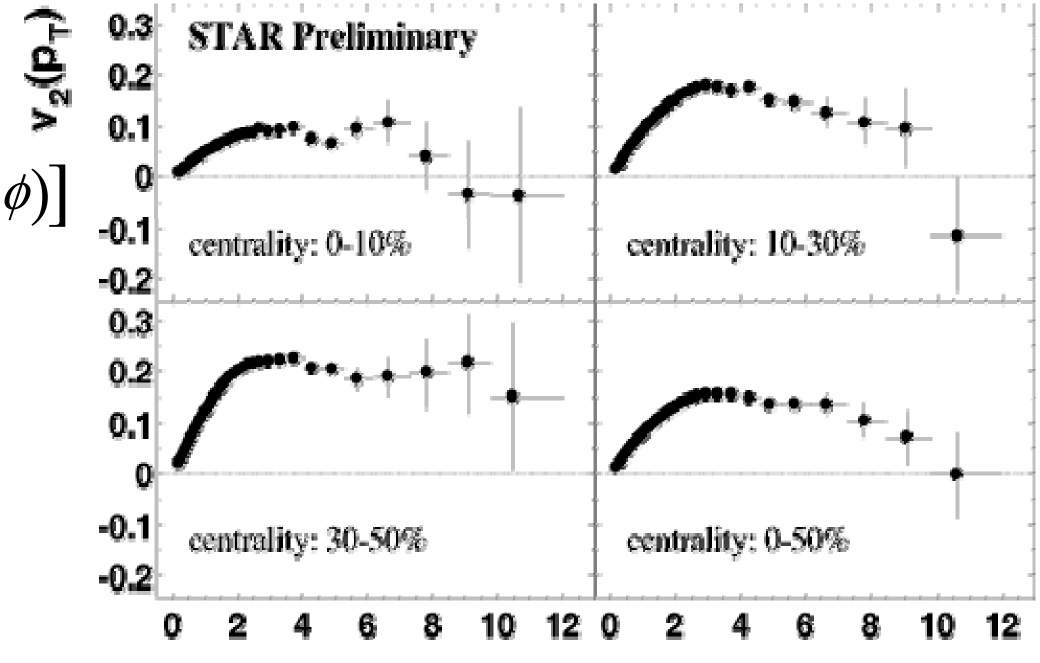
- 'Non-flow' effect for 2nd order cumulants

$$N \sim 100 \Rightarrow 1/\sqrt{N} \sim O(v_2)$$

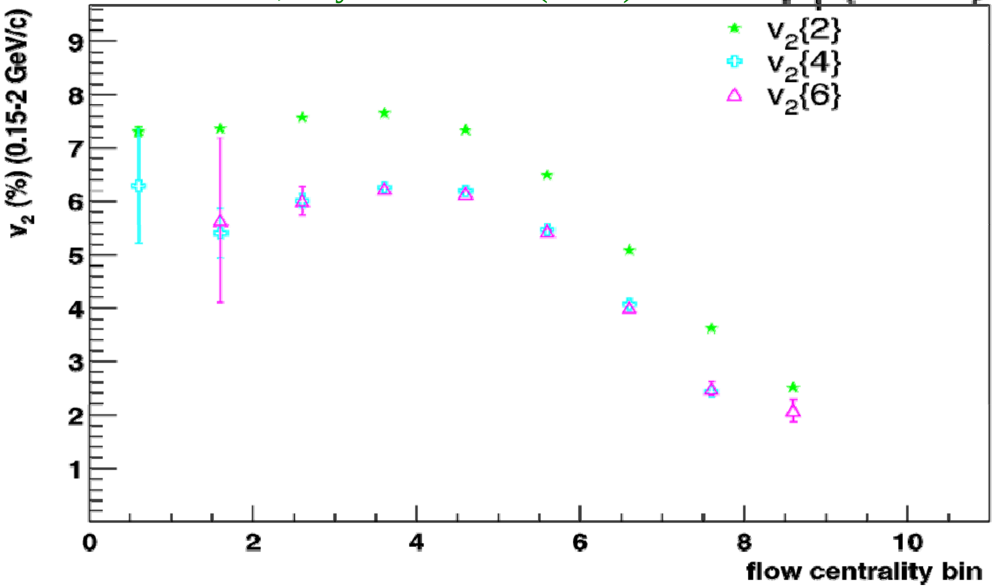
for 4th order cumulants

$$1/N^{3/4} \sim 0.03 \ll v_2$$

strong collectivity



STAR Coll, Phys. Rev. C66 (2002) 034904



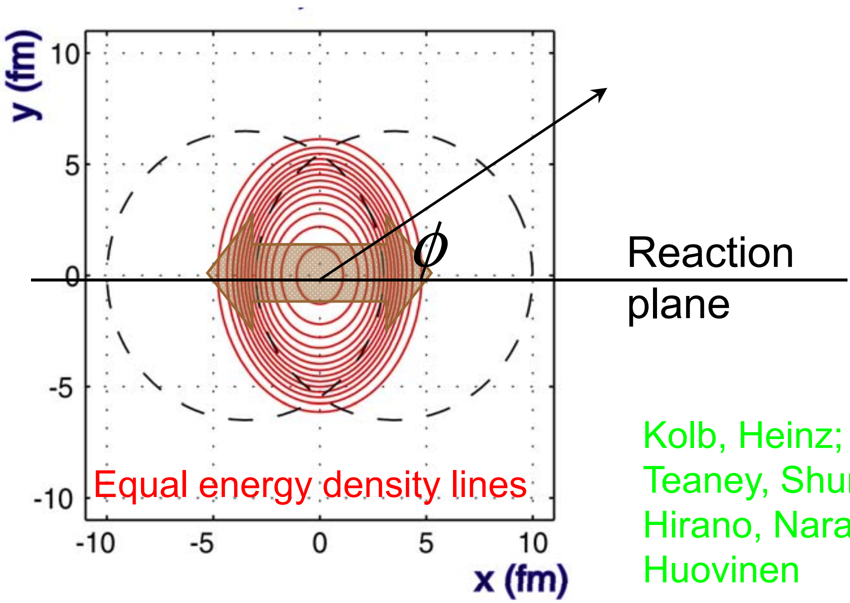
Elliptic flow vs. hydrodynamic simulations

Assumptions:

- perfect (non-dissipative) liquid

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

- Bjorken boost invariance
- 'realistic' equation of state
- 'realistic' initial conditions
- 'realistic' decoupling (freeze-out)



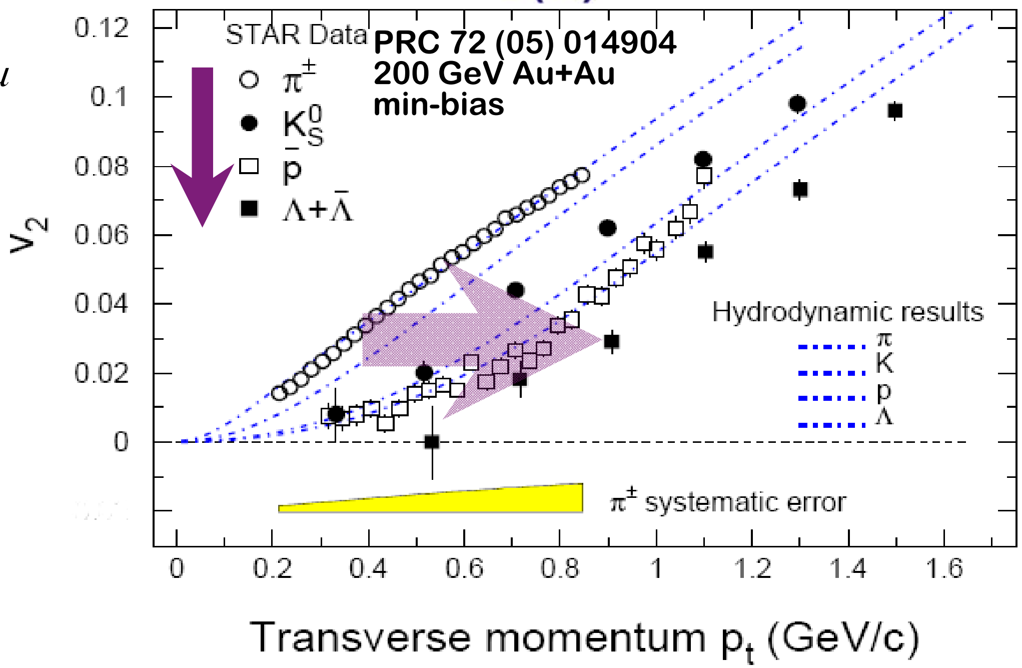
Kolb, Heinz;
Teaney, Shuryak;
Hirano, Nara;
Huovinen

Results:

- initial **transverse pressure gradient**
  ⇒ ϕ - dependence of flow field u_μ
  ⇒ elliptic flow $v_2(p_T)$

- size and pt-dependence of v_2 data accounted for by hydro ('maximal')

- characteristic **mass dependence**, since all particle species emerge from common flow field u_μ



Strong claims at RHIC …
Ideal hydro works

Viscosity: Bounds from theory

- Viscosity η controls entropy s increase

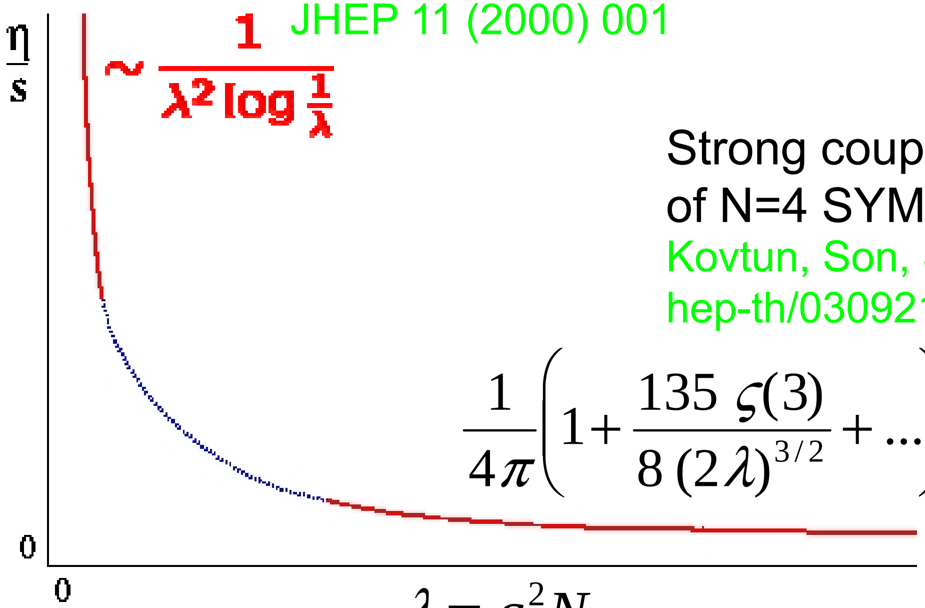
$$\frac{d(\tau s)}{d\tau} = \frac{\frac{4}{3}\eta}{\tau T}$$

- Hydrodynamics is valid, if

$$\frac{\eta}{\tau T}\frac{1}{s} \ll 1$$

- Constraint from string theory

Arnold, Moore, Yaffe,
JHEP 11 (2000) 001



$$\sim \frac{1}{\lambda^2 \log \frac{1}{\lambda}}$$

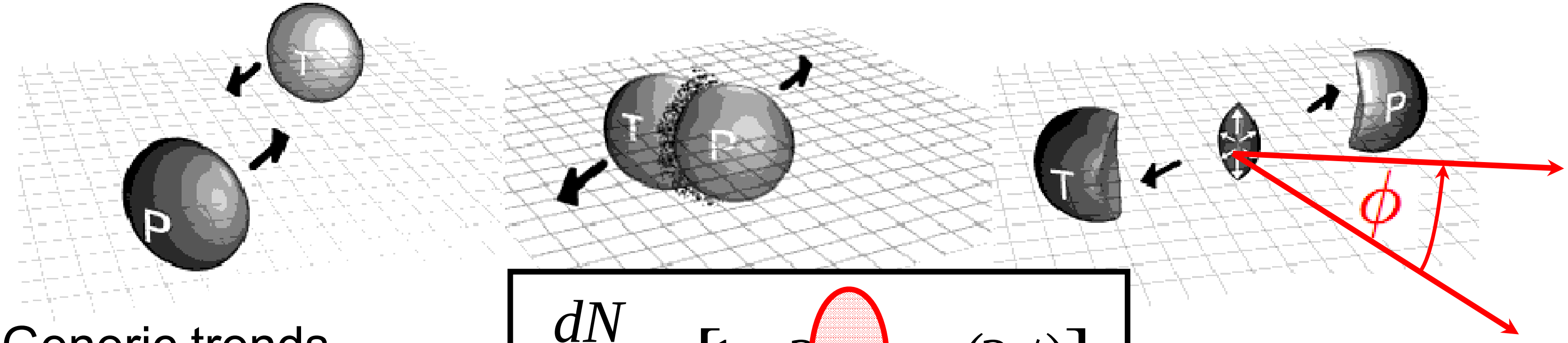
Strong coupling limit
of N=4 SYM
Kovtun, Son, Starinets,
hep-th/0309213

$$\frac{1}{4\pi}\left(1+\frac{135\,\varsigma(3)}{8\,(2\lambda)^{3/2}}+\ldots\right)$$

$$\frac{\eta}{s} > \frac{1}{4\pi}$$

$$\lambda \equiv g^2 N_c$$

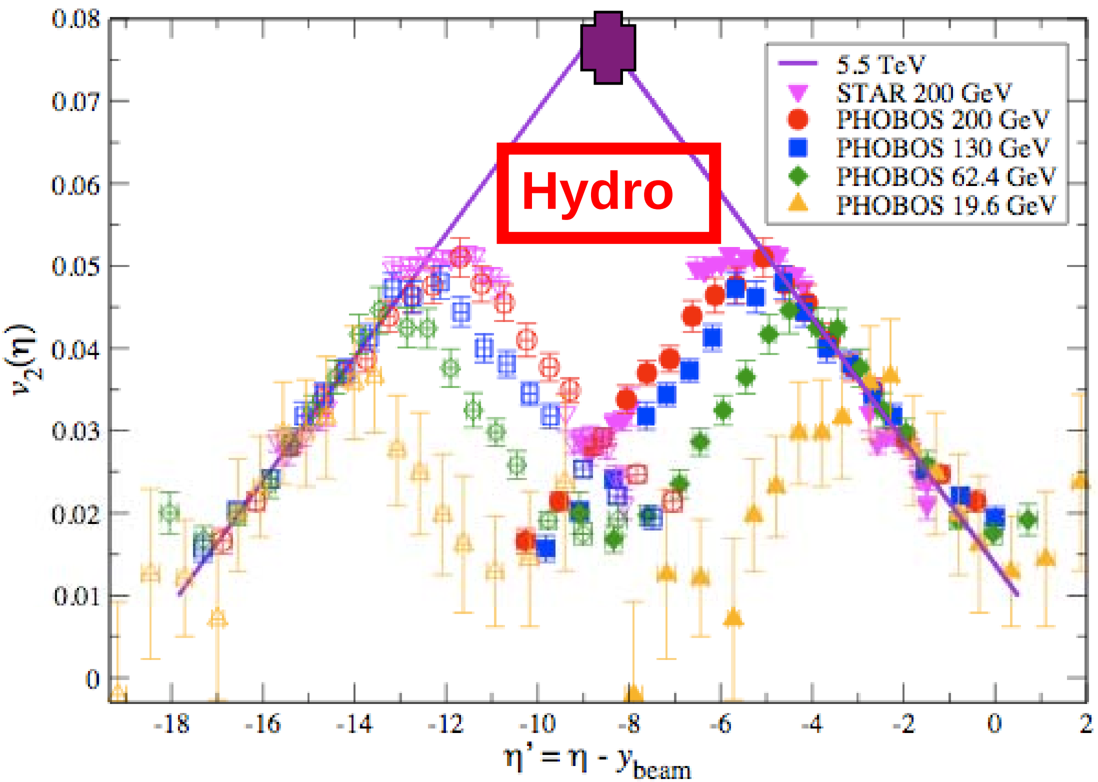
LHC 1st year running tests hallmark of collectivity



Generic trends in the data:

$$\frac{dN}{d\phi} \propto \left[1 + 2v_2 \cos(2\phi)\right]$$

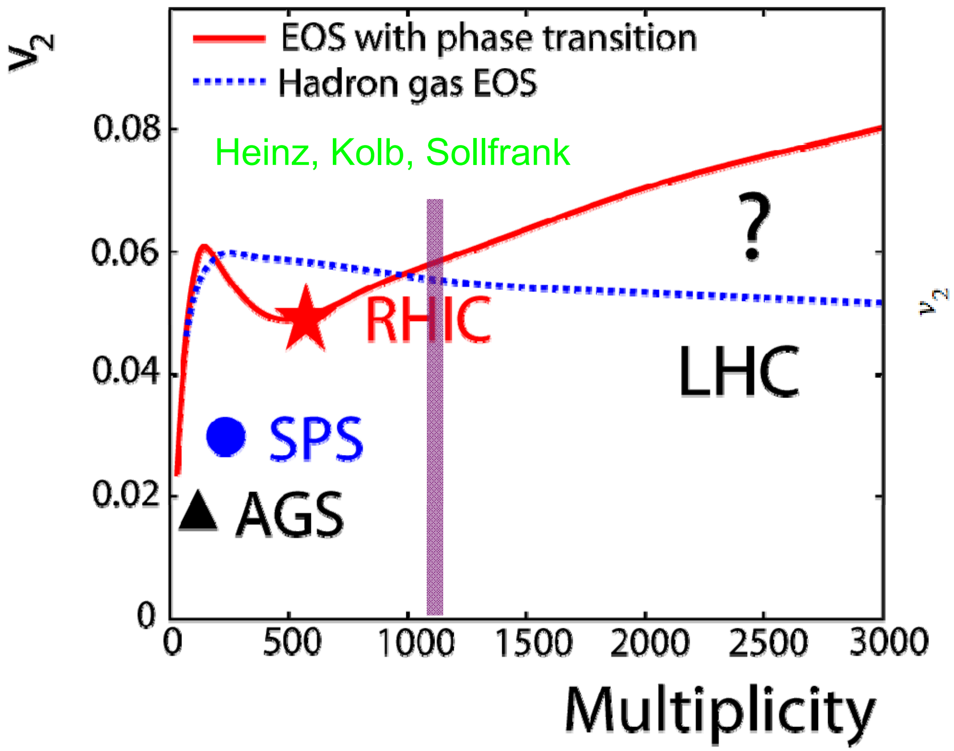
What if they **persist** or **fail**?



LHC tests the hydro-paradigm

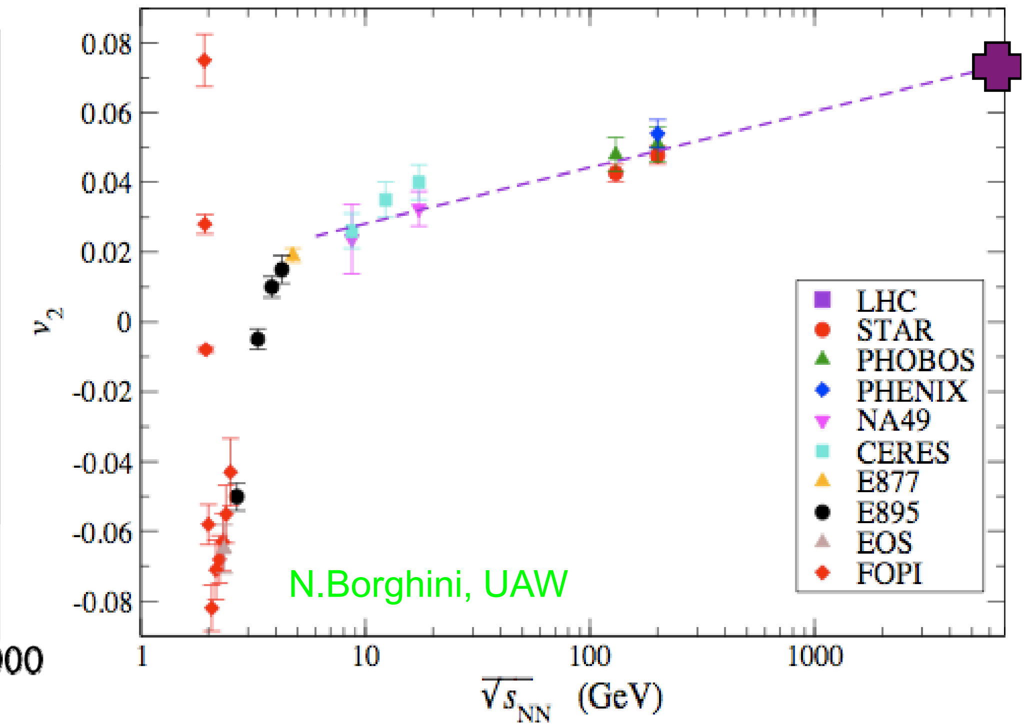
- Hydro prediction for low LHC multiplicity

$$v_2 \approx 0.055$$



- Extrapolation of generic RHIC trend

$$v_2 \approx 0.075$$



(In)consistency with generic trend ⟷ Characterization of microscopic dynamics underlying collectivity

Day 1 @ LHC: event multiplicity at y=0

- generic trends in $dN^{ch}/d\eta$
  - extended longitudinal scaling
  - self-similar trapezoidal shape

$\Rightarrow$ $dN^{ch}/d\eta\big|_{\eta=0} \propto \ln\sqrt{s_{NN}}$

- Saturation models predict

Armesto, Salgado, Wiedemann, PRL94 (2005) 022002

$$\frac{1}{N_{\rm part}}\frac{dN^{AA}}{d\eta}\bigg|_{\eta\sim 0} = N_0 \sqrt{s}^{\lambda} N_{\rm part}^{\frac{1-\delta}{3\delta}}$$

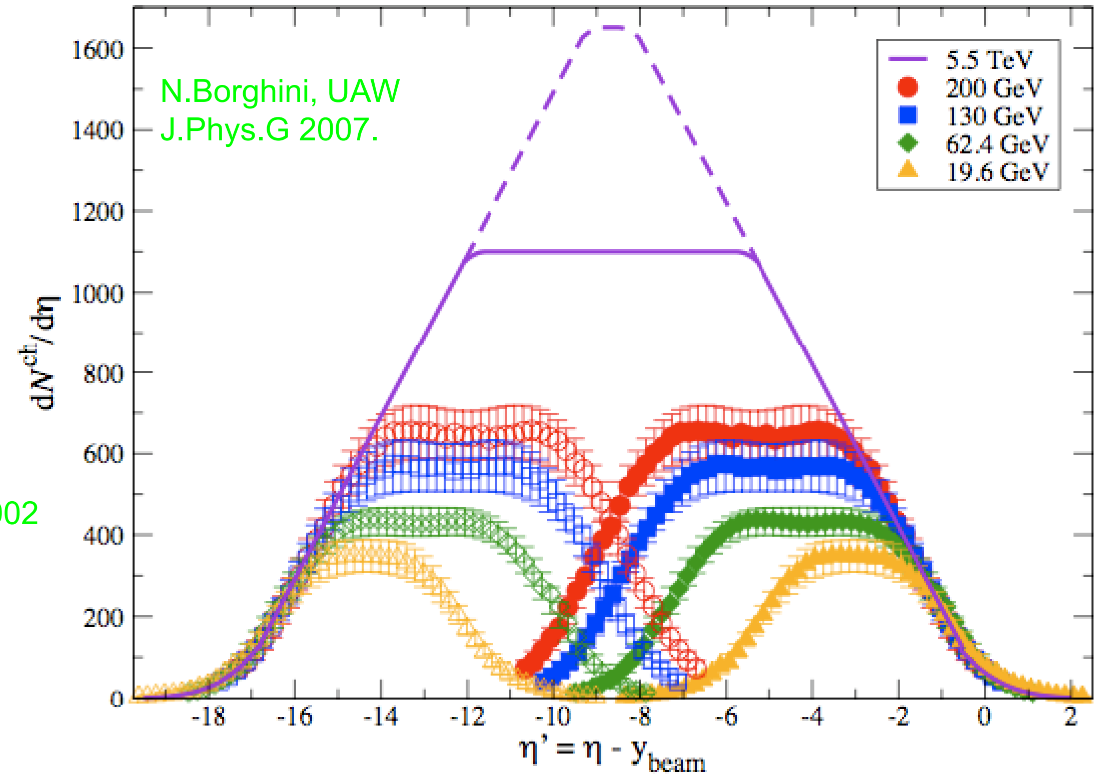
$\Rightarrow$ $dN^{ch}_{LHC}/d\eta\big|_{\eta=0} \approx 1650$

or Kharzeev, Levin, Nardi, NPA747 (2005) 609.

$\Rightarrow$ $dN^{ch}_{LHC}/d\eta\big|_{\eta=0} \approx 1800-2100$

Both consistent with main trends at RHIC, but …

PHOBOS, PRC74 (2006) 021901; W. Busza .



Extrapolations to LHC deviate from so-far generic trends in data

$\Rightarrow$ Impact for understanding the dynamical origin of soft physics at RHIC and LHC.

First year of Pb+Pb@LHC:

- Physics not luminosity dictated

- First characterization of collective phenomena at 5.5 TeV

- Physics impact: Hydrodynamics? Hadrochemistry? Multiplicity distributions as first handle of saturation?

Strong reasons to run Pb+Pb in 2009 even if run is short.

Question:

Why do we need collider energies

$$\sqrt{s_{NN}} = 200\, GeV \quad [RHIC]$$

$$\sqrt{s_{NN}} = 5500\, GeV \quad [LHC]$$

to test properties of dense QCD matter
which arise on typical scales

$$T \approx 150\, MeV, \quad Q_s \approx 1-2\ GeV \text{ ?}$$

Answer 1: Large quantitative gains

Increasing the center of mass energy implies

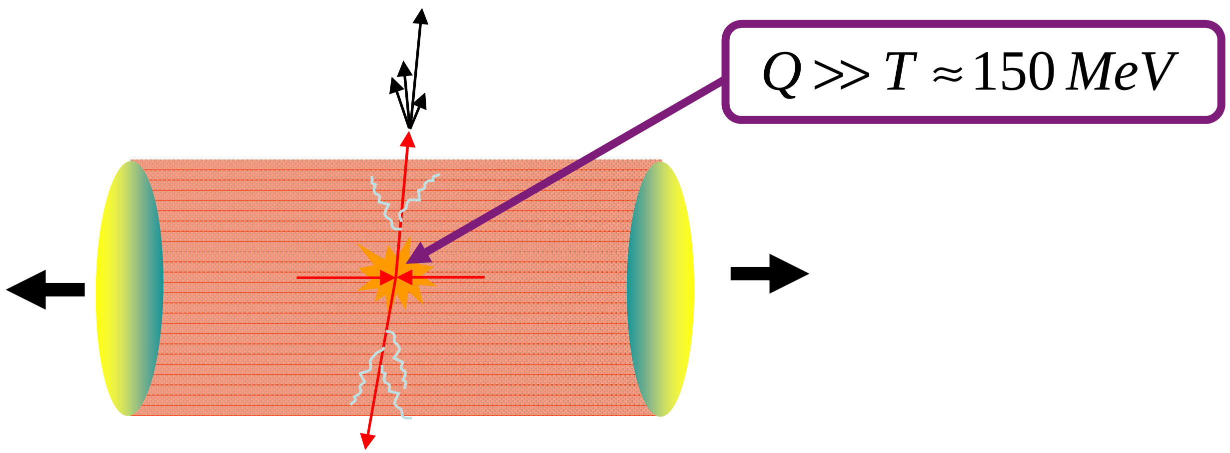
- ⇨ Denser initial system
- ⇨ Longer lifetime
- ⇨ Bigger spatial extension
- ⇨ Stronger collective phenomena

A large body of experimental data from the CERN SPS and RHIC supports this argument.

Answer 2: Qualitatively novel access to properties of dense matter

To test properties of QCD matter, large- Q^2 processes provide well-controlled tools (example: DIS).

Heavy Ion Collisions produce auto-generated probes at high $\sqrt{s_{NN}}$



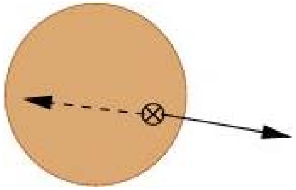
Q: How sensitive are such 'hard probes'?

Bjorken's original estimate and its correction

Bjorken 1982: consider jet in p+p collision, hard parton interacts with underlying event ⇨ collisional energy loss

$$dE_{coll}/dL \approx 10\, GeV/fm$$ (error in estimate!)

Bjorken conjectured monojet phenomenon in proton-proton

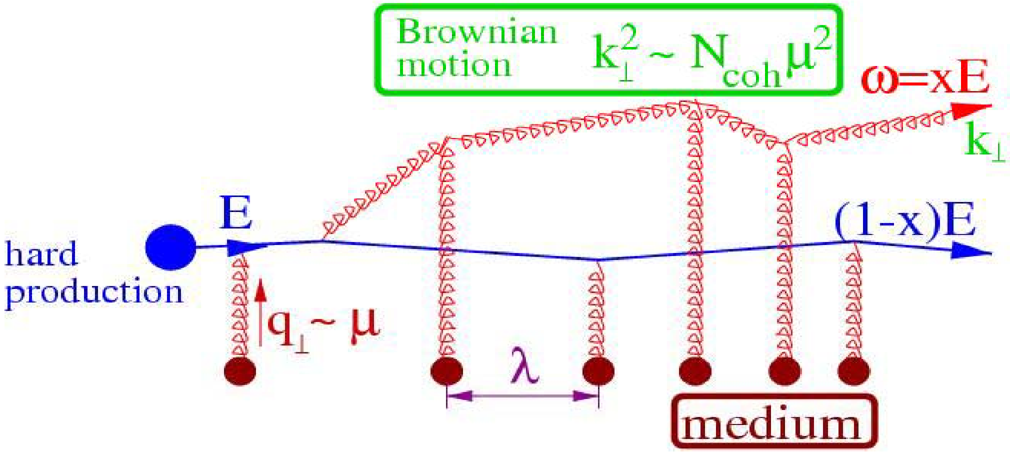


But: radiative energy loss expected to dominate

$$\Delta E_{rad} \approx \alpha_s \hat{q} L^2$$ Baier Dokshitzer Mueller Peigne Schiff 1995

- p+p: $L \approx 0.5\ fm, \quad \Delta E_{rad} \approx 100\ MeV$ Negligible !
- A+A: $L \approx 5\ fm, \quad \Delta E_{rad} \approx 10\, GeV$ Monojet phenomenon! Observed at RHIC

Parton energy loss - a simple estimate



Medium characterized by transport coefficient:

$$\hat{q} \equiv \frac{\mu^2}{\lambda} \propto n_{density}$$

- How much energy is lost ?

Phase accumulated in medium: $\left\langle k_T^2 \Delta z \big/ 2\omega \right\rangle \approx \frac{\hat{q}L^2}{2\omega} = \frac{\omega_c}{\omega}$ Characteristic gluon energy

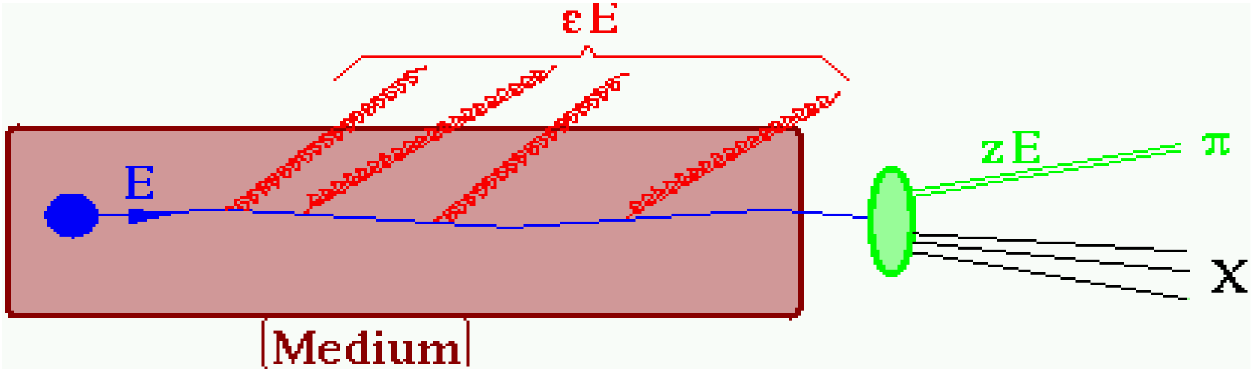
Number of coherent scatterings: $N_{coh} \approx \frac{t_{coh}}{\lambda}$, where $t_{coh} \approx \frac{2\omega}{k_T^2} \approx \sqrt{\omega/\hat{q}}$

$k_T^2 \approx \hat{q}\, t_{coh}$

Gluon energy distribution: $\omega \frac{dI_{med}}{d\omega\, dz} \approx \frac{1}{N_{coh}} \omega \frac{dI_1}{d\omega\, dz} \approx \alpha_s \sqrt{\frac{\hat{q}}{\omega}}$

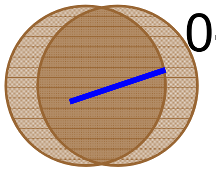
Average energy loss $\Delta E = \int_0^L dz \int_0^{\omega_c} d\omega\, \omega \frac{dI_{med}}{d\omega\, dz} \sim \alpha_s \omega_c \sim \alpha_s \hat{q} L^2$

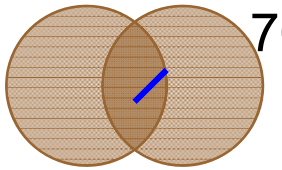
High p_T Hadron Spectra



$$R_{AA}(p_T,\eta) = \frac{dN^{AA} / dp_T d\eta}{n_{coll}\; dN^{NN} / dp_T d\eta}$$

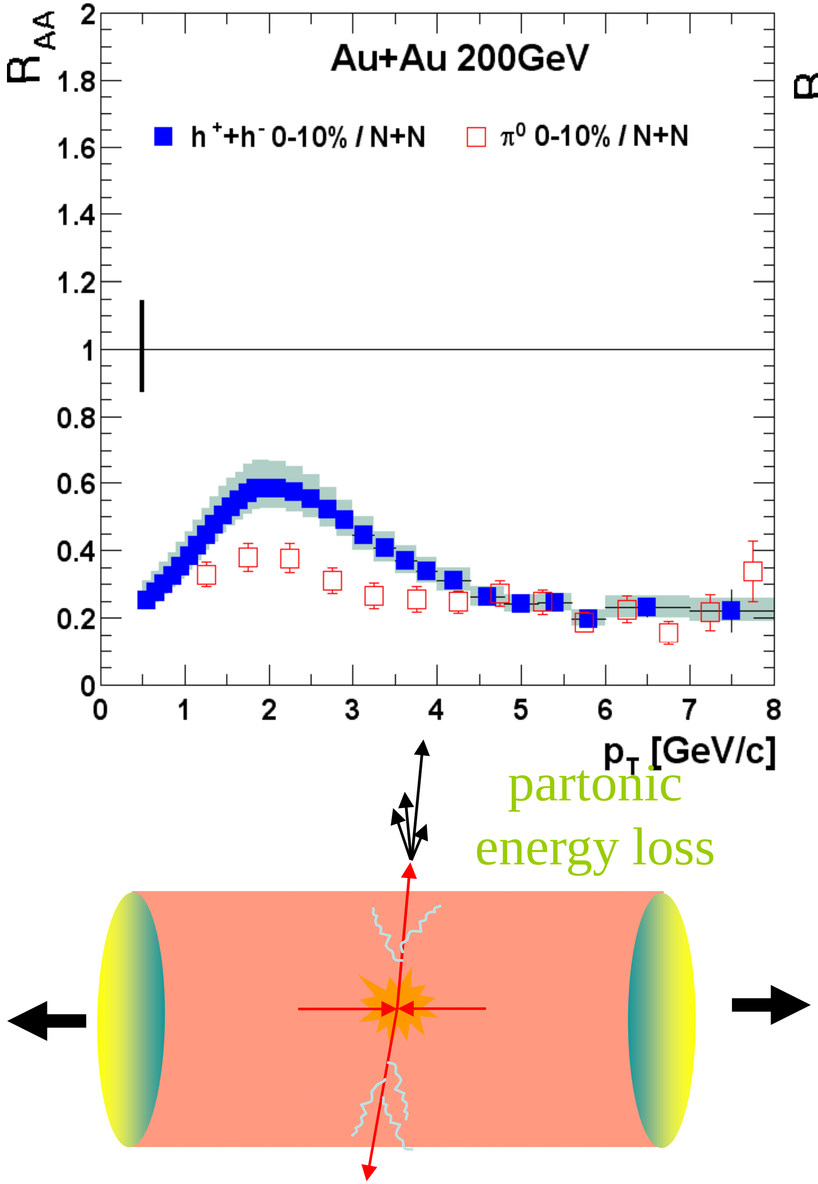
Centrality dependence:

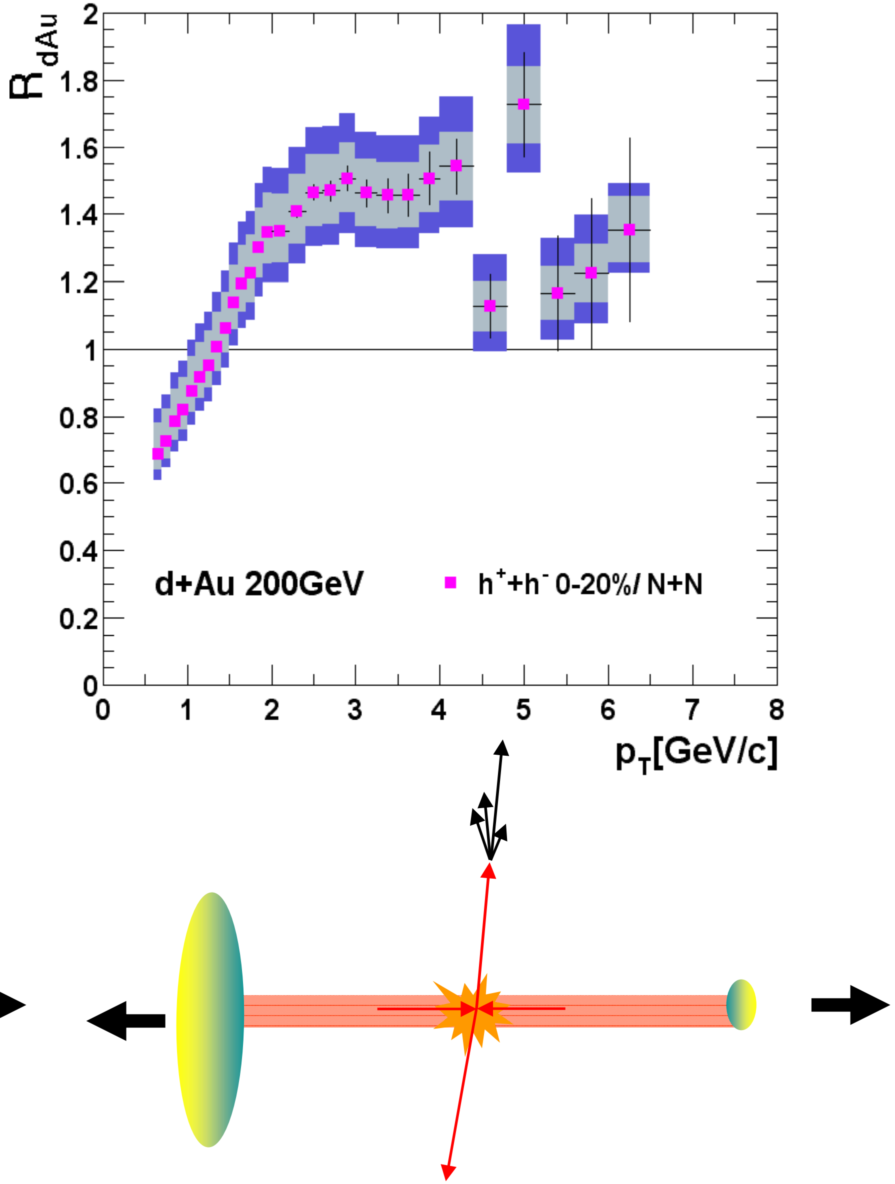




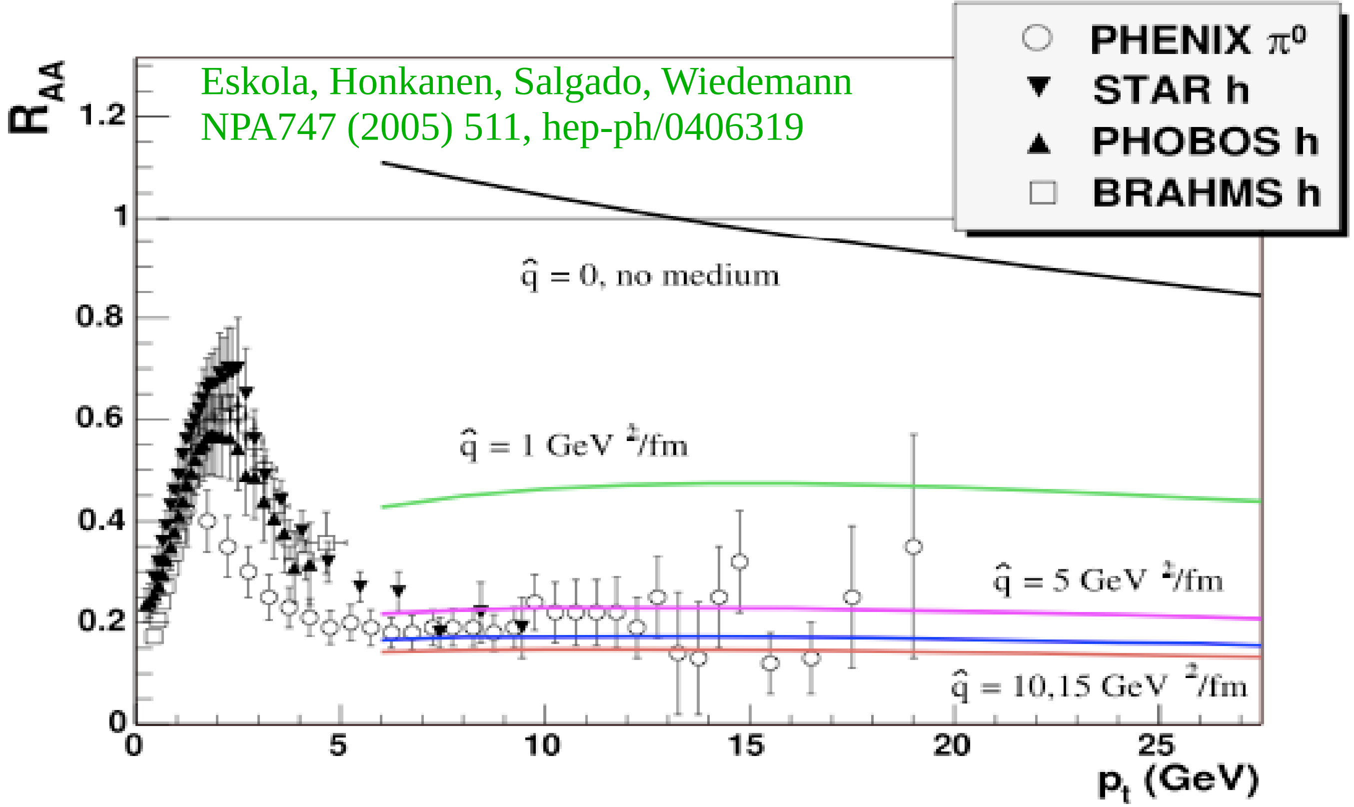
Centrality dependence: Au+Au vs. d+Au

- Final state suppression
- Initial state enhancement



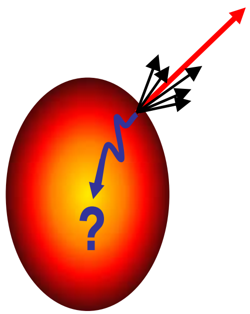


The fragility of leading hadrons



- Why is R_{AA} = 0.2 natural ?

  Surface emission limits sensitivity to $\hat{q}$



- The quenching is anomalously large

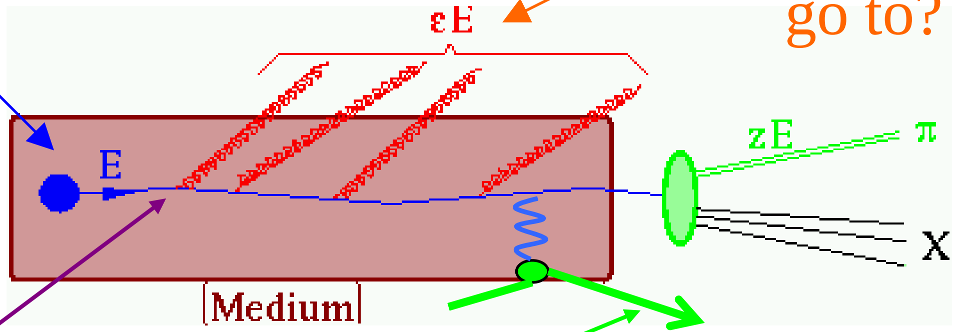
  (I.e. exceeds the perturbative estimate by ~ 5)

$$\hat{q}(\tau = 1\ fm/c) \geq 5 \frac{GeV^2}{fm} \approx 5 \hat{q}_{QCD}^{pert}$$

How does a hard probe interact in the medium?

How does this parton thermalize?

Where does this associated radiation go to?



What is the dependence on parton identity?

$$\Delta E_{gluon} > \Delta E_{quark,\, m=0} > \Delta E_{quark,\, m>0}$$

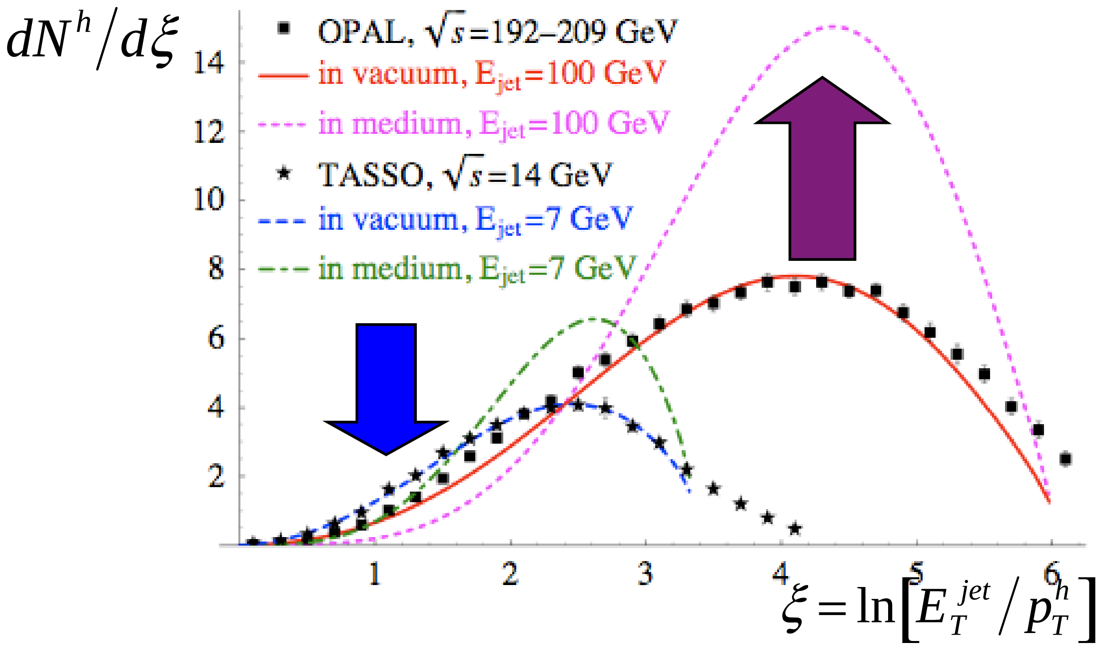
Characterize Recoil: What is kicked in the medium?

Jet multiparticle final states provide qualitatively novel characterizations of the medium.

Jet modifications in dense QCD matter

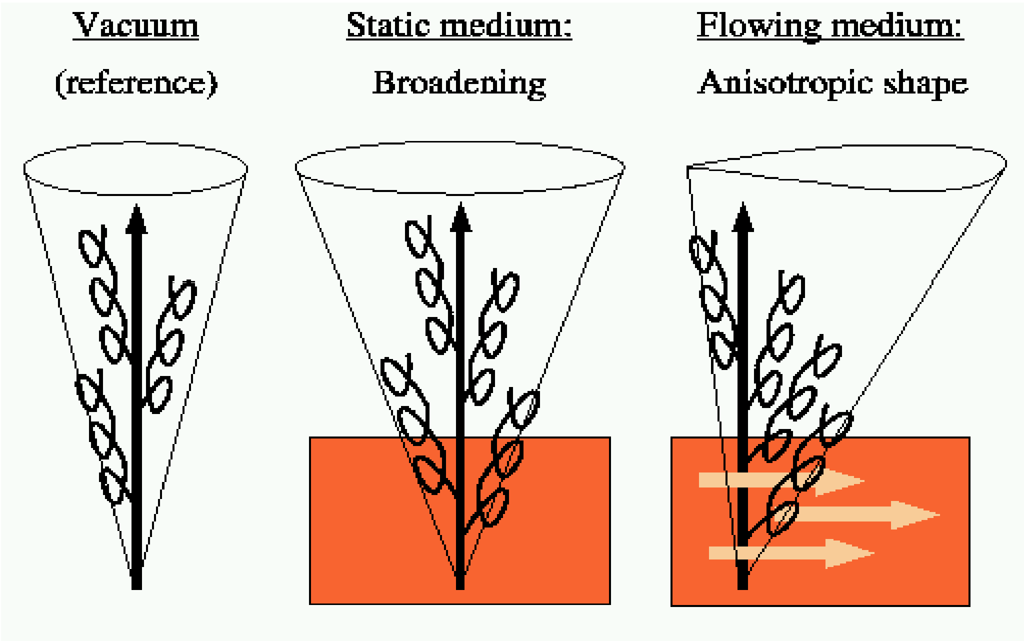
- <u>'Longitudinal Jet heating':</u>
  The entire longitudinal jet multiplicity distribution softens due to medium effects.

Borghini,Wiedemann, hep-ph/0506218



- Jets <u>'blown with the wind'</u>
  Hard partons are not produced in the rest frame comoving with the medium

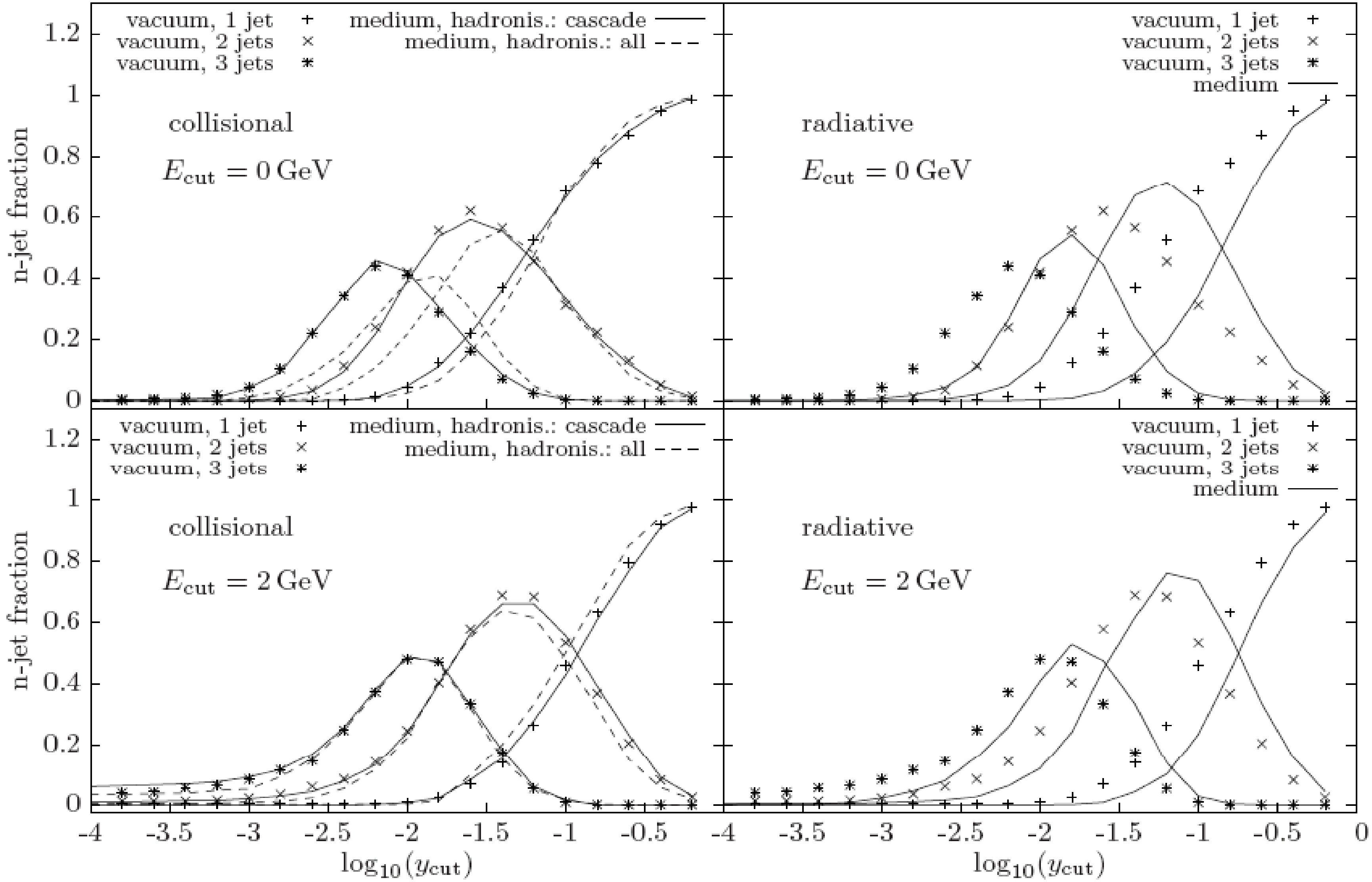
Armesto, Salgado, Wiedemann,
Phys. Rev. Lett. 93 (2004) 242301



JEWEL: Jet Evolution With Energy Loss

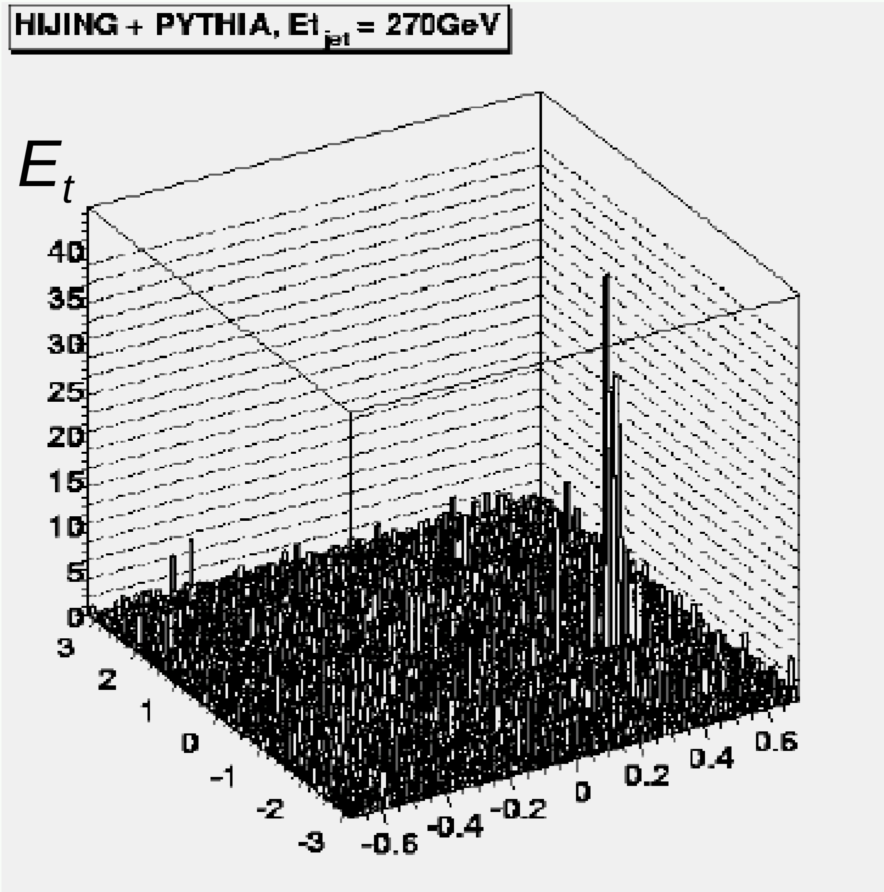
Disentangling radiative & collisional mechanisms

K. Zapp, G. Ingelman, J. Rathsman, J. Stachel, U.A. Wiedemann, arXiv:0804.3568 [hep-ph]



Jets in Heavy Ion Collisions at the LHC

- The physics:
  Jet rates are abundant at LHC.
  'True' jets not in kinematical reach of RHIC.



- The jet as a thermometer:
  jets as a far out-of-equilibrium probe participating in equilibration processes.

- Sensitive jet features:

  - jet shapes (i.e. calorimetry)
  - jet multiplicity distributions (in trans. and long. momentum)
  - jet-like particle correlations
  - jet composition (i.e. hadrochemistry)

- The challenge:
  characterize medium-modifications of jets in high multiplicity background.

Prerequisite: determine E_T-distribution of final state hadrons.

LHC: the richness of hard probes

The probes:

- Jets
- identified hadron specta
- D-,B-mesons
- Quarkonia
- Photons
- Z-boson tags

The range:

Q^2 ,x, A, luminosity

Abundant yield

of hard probes

+ robust signal

(medium sensitivity

>> uncertainties)

= detailed understanding

of dense QCD matter