Ultrarelativistic Heavy Ion Physics: Theory

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EPS – HEP
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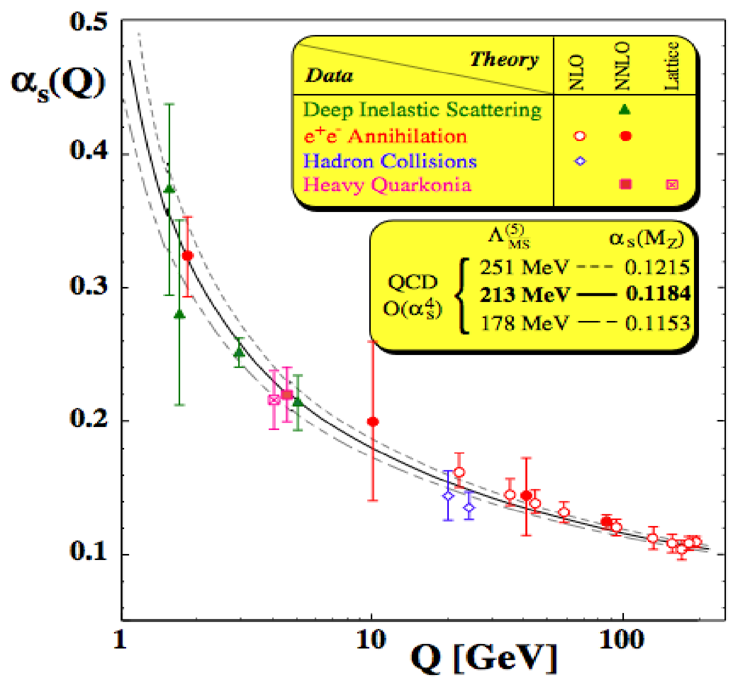
From elementary interactions to collective phenomena

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

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

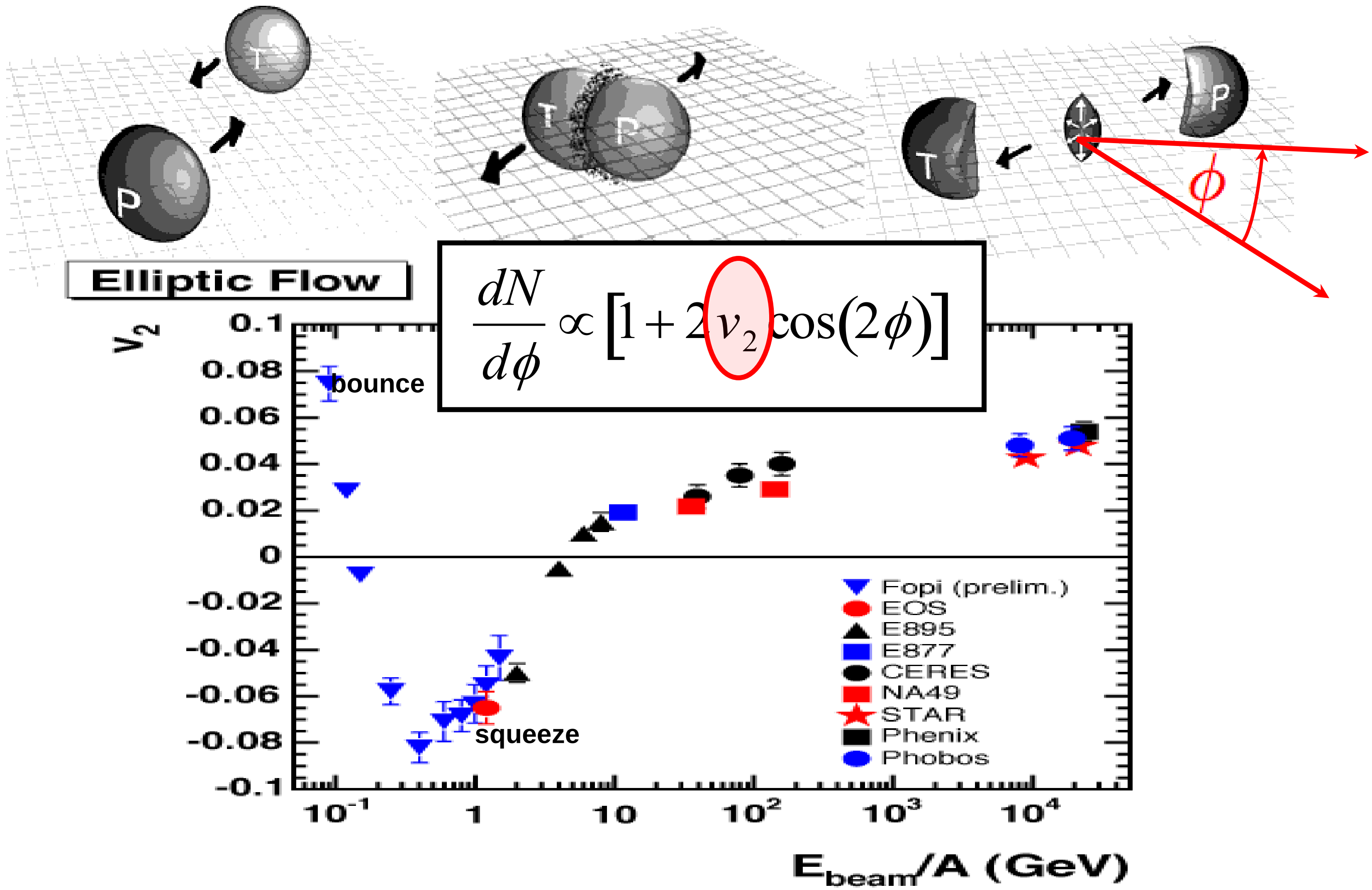
⇨ Longer lifetime

⇨ Bigger spatial extension

⇨ Stronger collective phenomena

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

Elliptic Flow:
Hallmark of a collective phenomenon



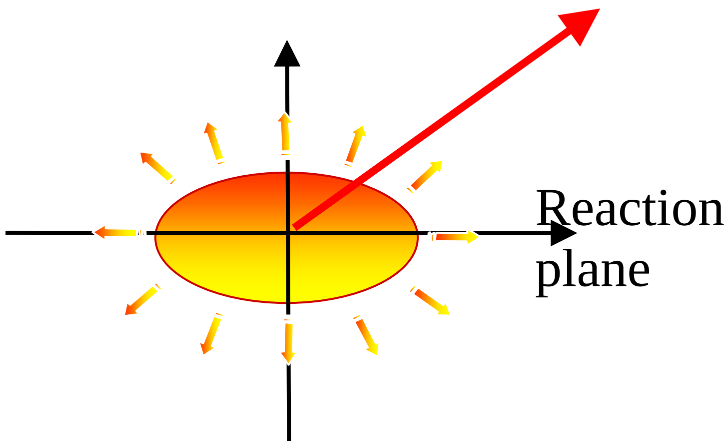
$$\frac{dN}{d\phi} \propto [1 + 2 v_2 \cos(2\phi)]$$

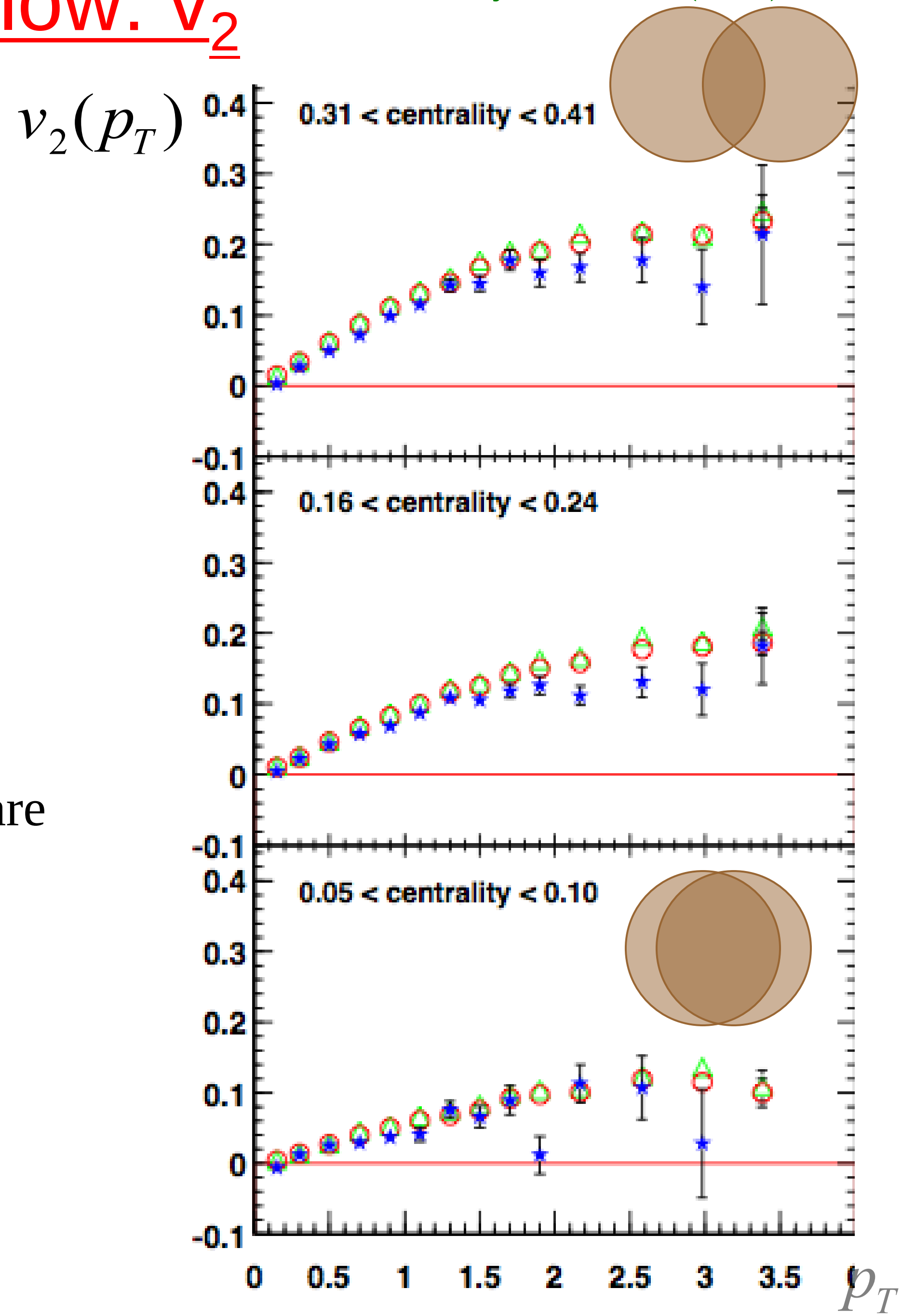
Elliptic flow: v_2

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

- Momentum space:

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





- more than twice as many high-pt particles are emitted parallel to reaction plane than orthogonal to it.

→ **strong collectivity**

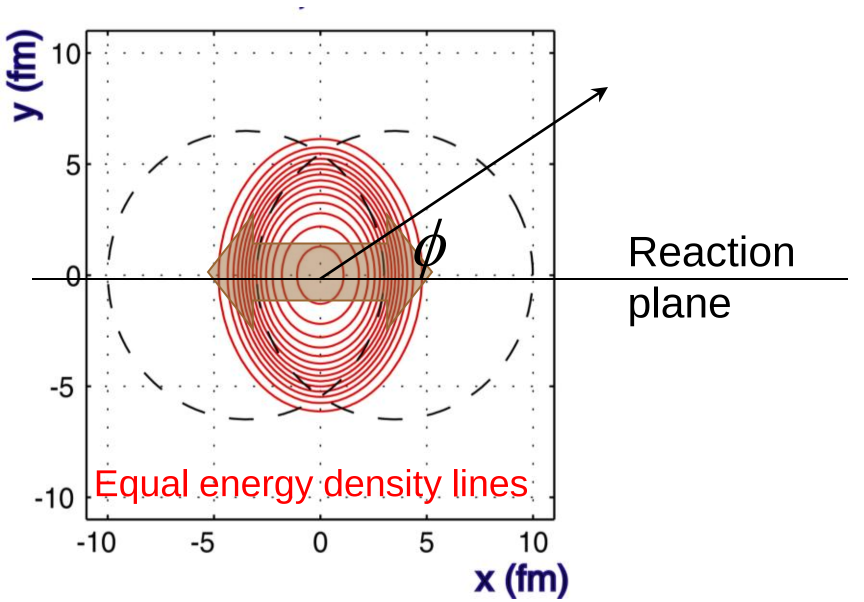
Elliptic flow vs. hydrodynamic simulations

Assumptions:

- fluid with shear viscous term

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

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



Results:

- initial **transverse pressure gradient**

⟹ ϕ - dependence of flow field u_μ

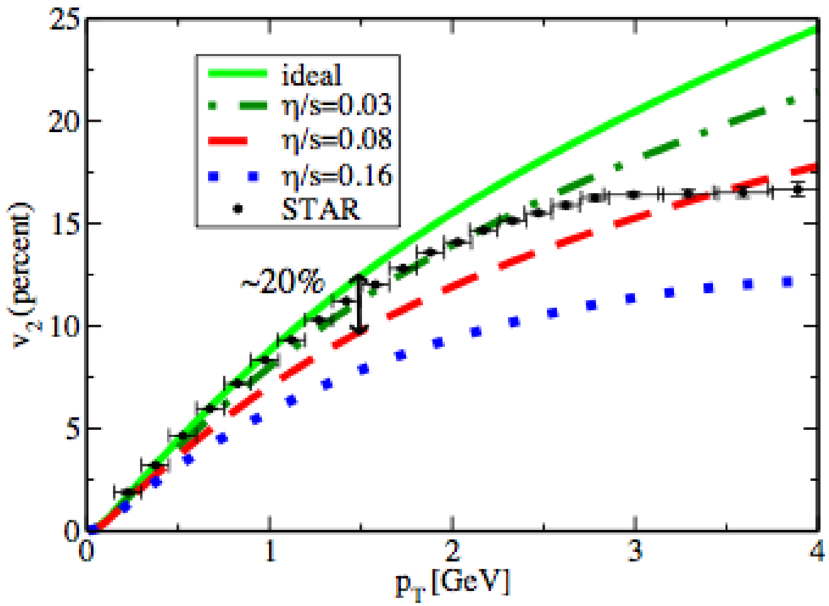
⟹ elliptic flow $v_2(p_T)$

- size and pt-dependence of v_2 data accounted for by fluid of **minimal shear viscosity**

$$\boxed{\frac{\eta}{s} << 1}$$

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

P. Romatschke arXiv.0902.3663



Viscosity: Bounds from theory

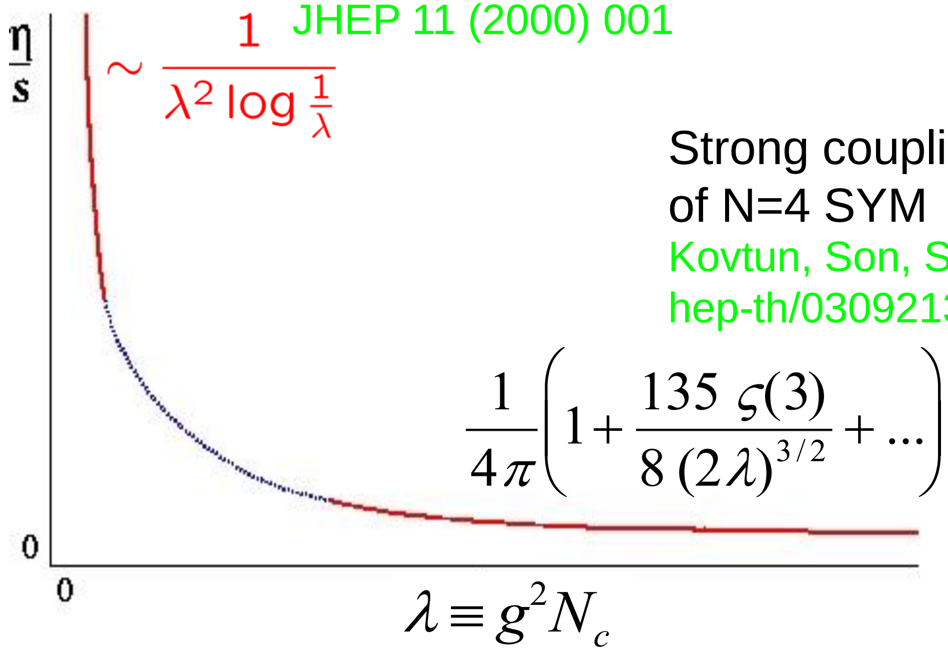
- Viscosity η controls entropy s increase

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

- Hydrodynamics is valid, if

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

- Constraint from string theory



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

Strong coupling limit of N=4 SYM

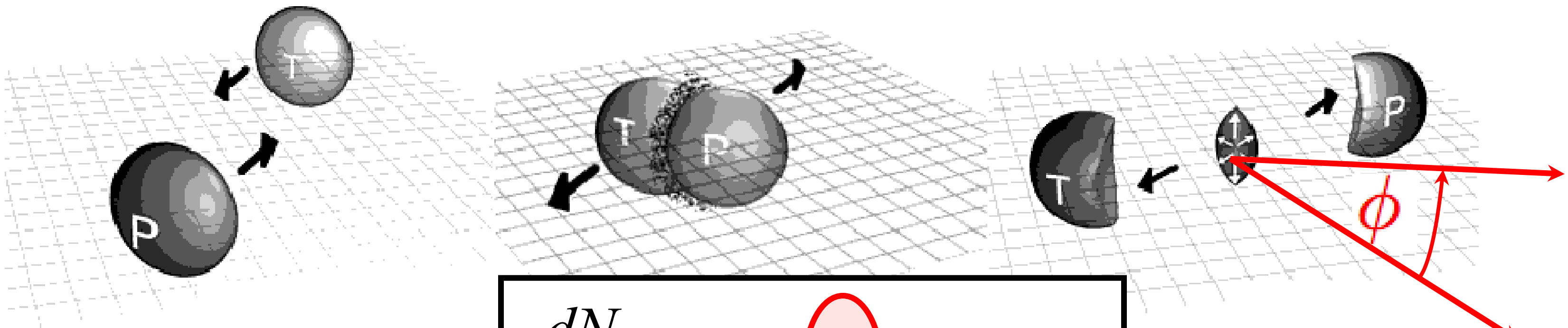
Kovtun, Son, Starinets, hep-th/0309213

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

Same trend in exploratory QCD lattice calculation

H. Meyer, arXiv:0805.4567 [hep-lat]

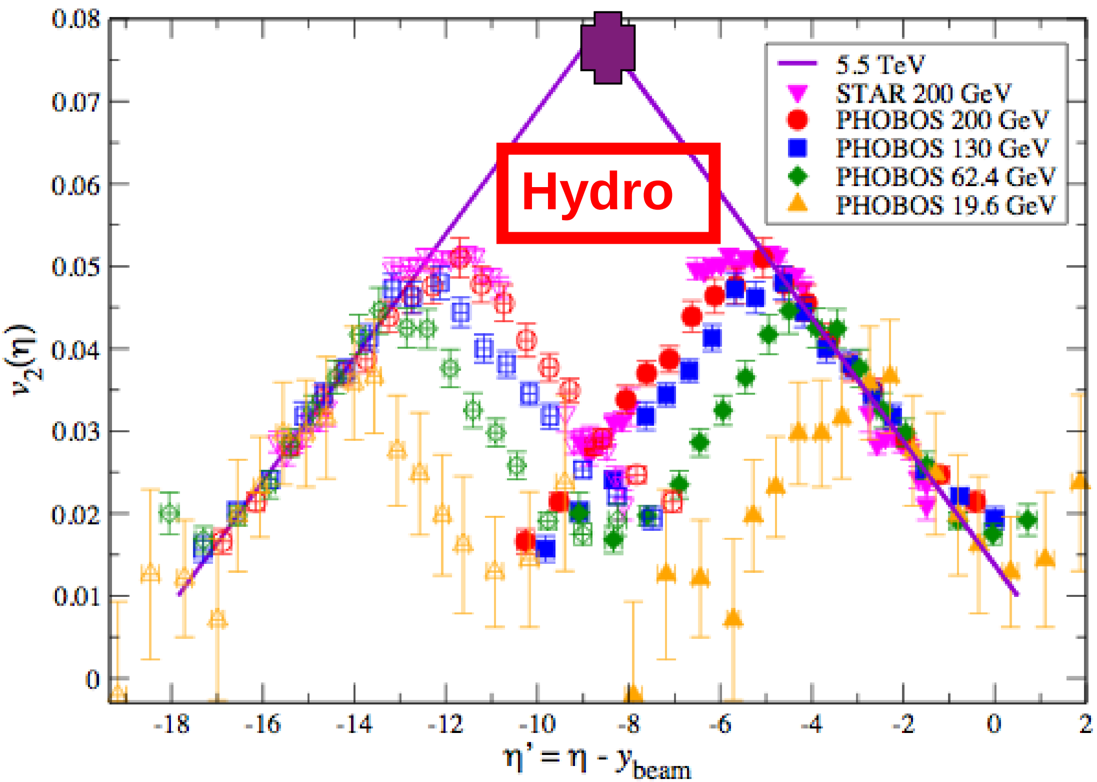
LHC 1st year running tests hallmark of collectivity



Generic trends in the data:

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

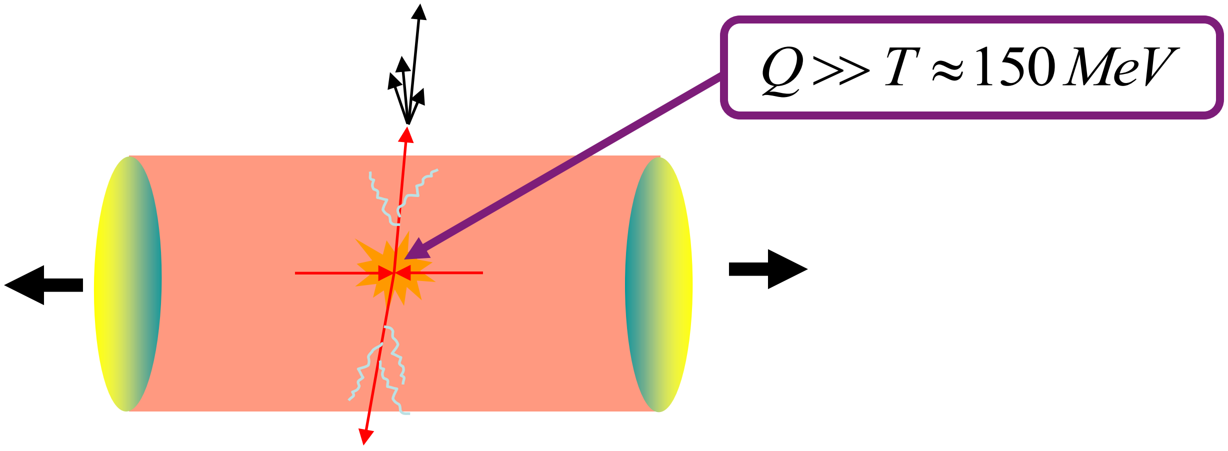
What if they **persist** or **fail**?



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’?

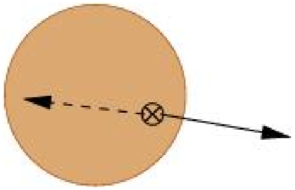
Bjorken's original estimate and its correction

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



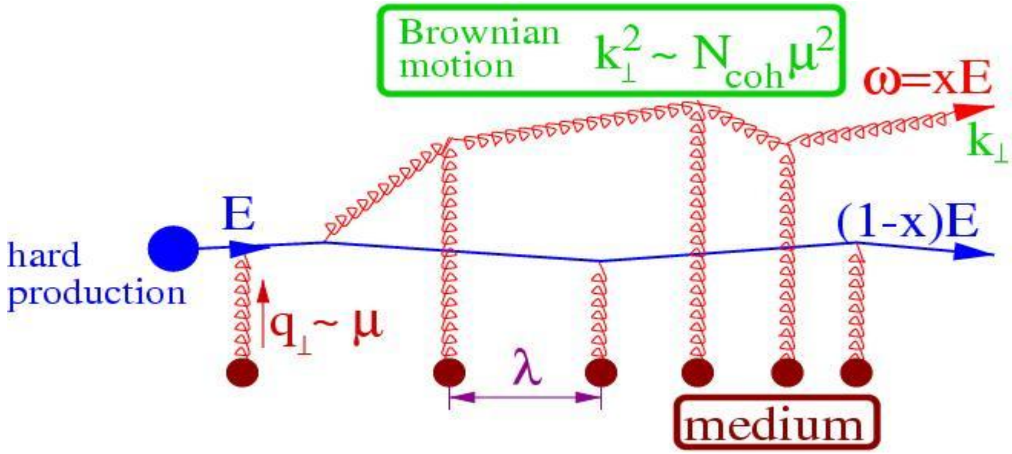
But: radiative energy loss expected to dominate

$$\Delta E_{rad} \approx \alpha_s \hat{q} L^2$$

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

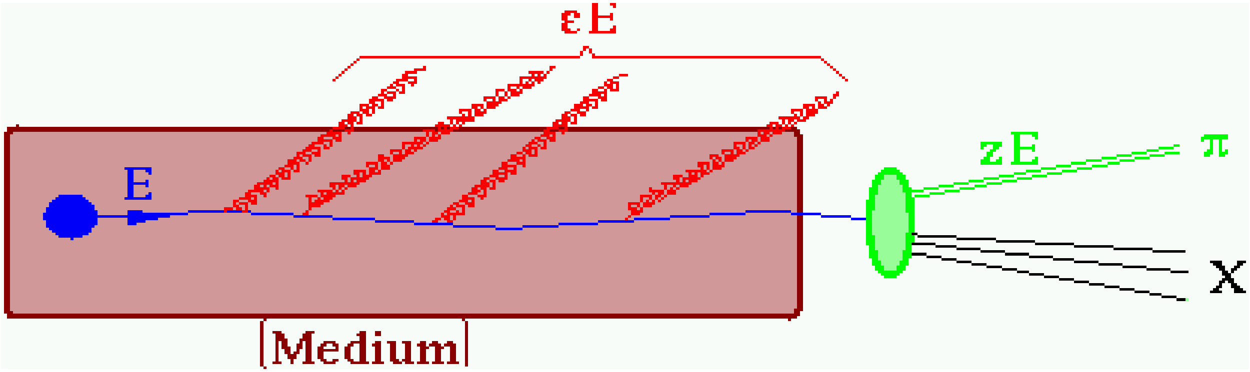
Number of coherent scatterings: $N_{coh} \approx \frac{t_{coh}}{\lambda}$, where $t_{coh} \approx \frac{2\omega}{k_T^2} \approx \sqrt{\omega/\hat{q}}$

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

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

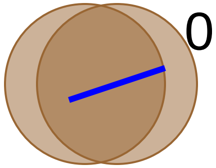
Average energy loss $\Delta E = \int_0^L dz \int_0^{\omega_c} d\omega\, \omega \frac{dI_{med}}{d\omega\, dz} \sim \alpha_s \omega_c \sim \alpha_s \hat{q} L^2$

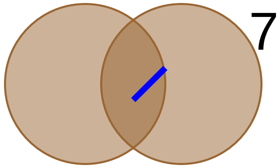
High p_T Hadron Spectra



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

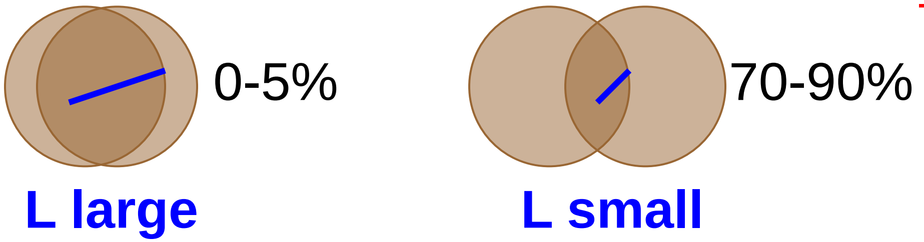
Centrality dependence:

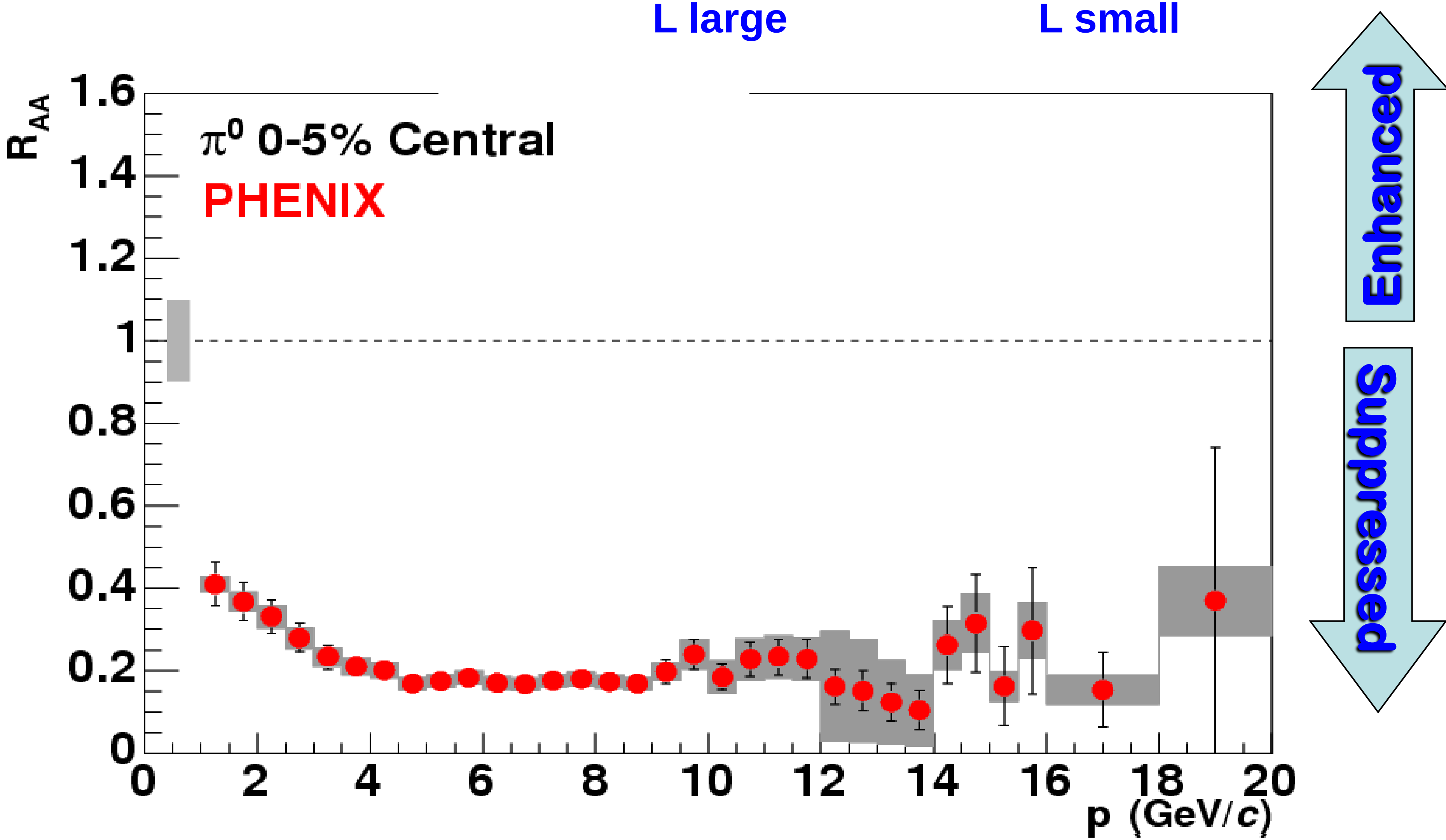




Strong suppression persists to highest p_T

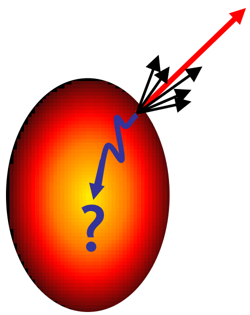
Centrality dependence:





@ RHIC, radiative energy loss accounts for:

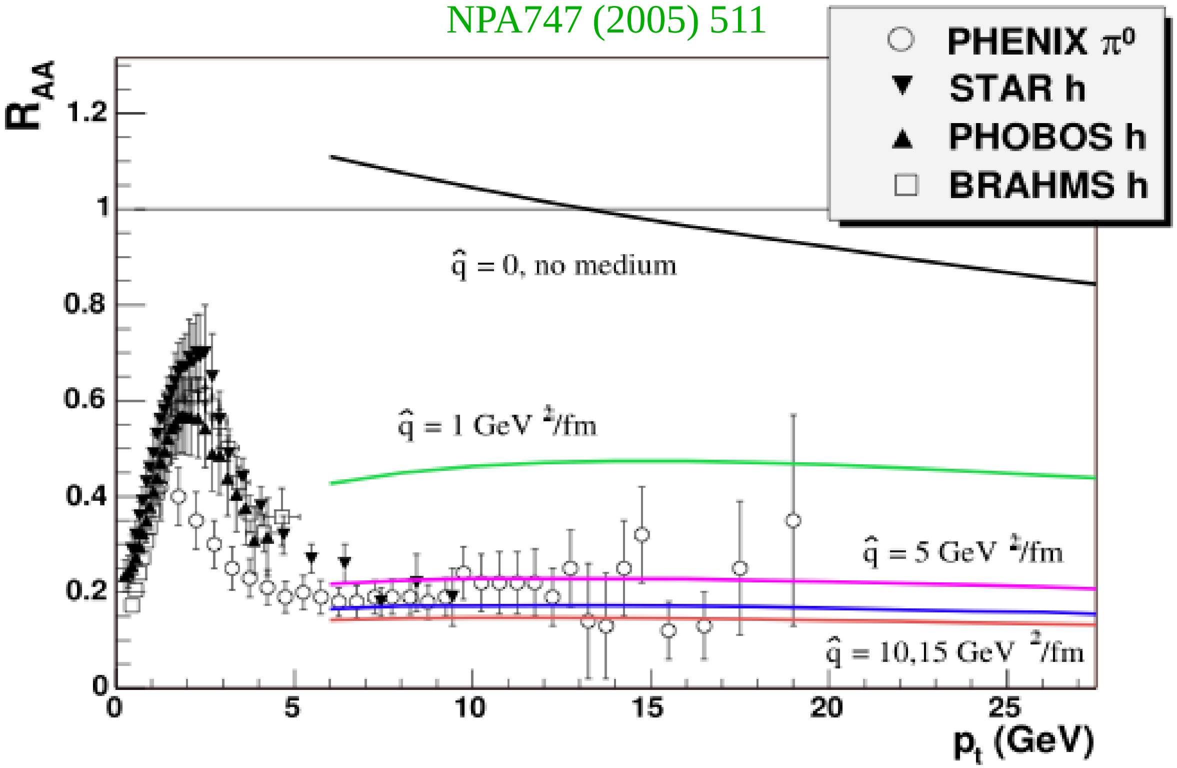
- Nuclear modification factor
- Centrality dependence
- Back-to-back correlations
- R_{AA} = 0.2 is a natural limit due to surface emission



indicates very opaque medium.

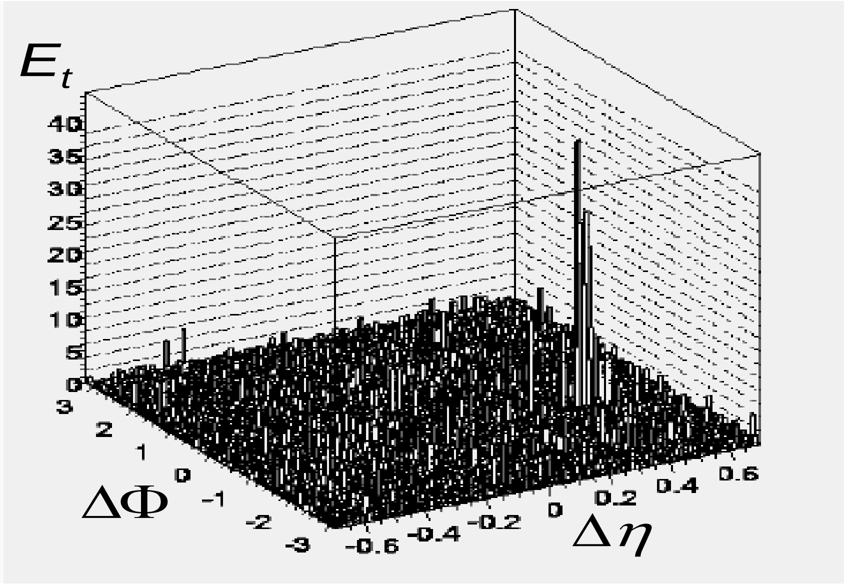
- Particle species (in)dependence

Eskola, Honkanen, Salgado, Wiedemann
NPA747 (2005) 511



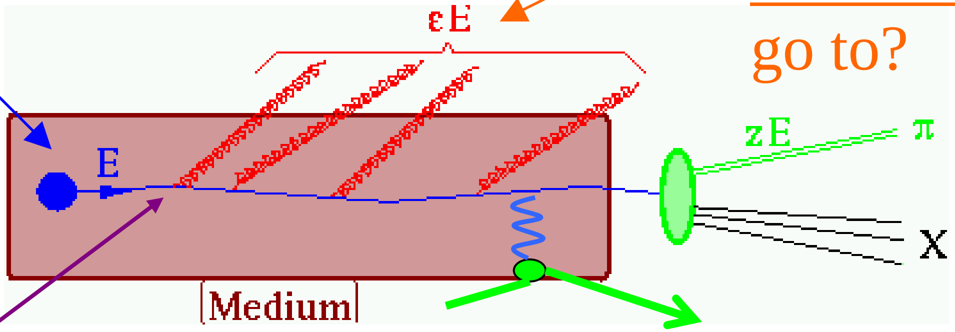
Many aspects still under debate:
- role of other e-loss mechanisms?
- Suppression of heavy flavored hadrons?
- theoretical basis and numerical consistency of model parameters such as $\hat{q}$

"True" Jets only at the LHC



How does this parton thermalize?

Where does this associated radiation go to?



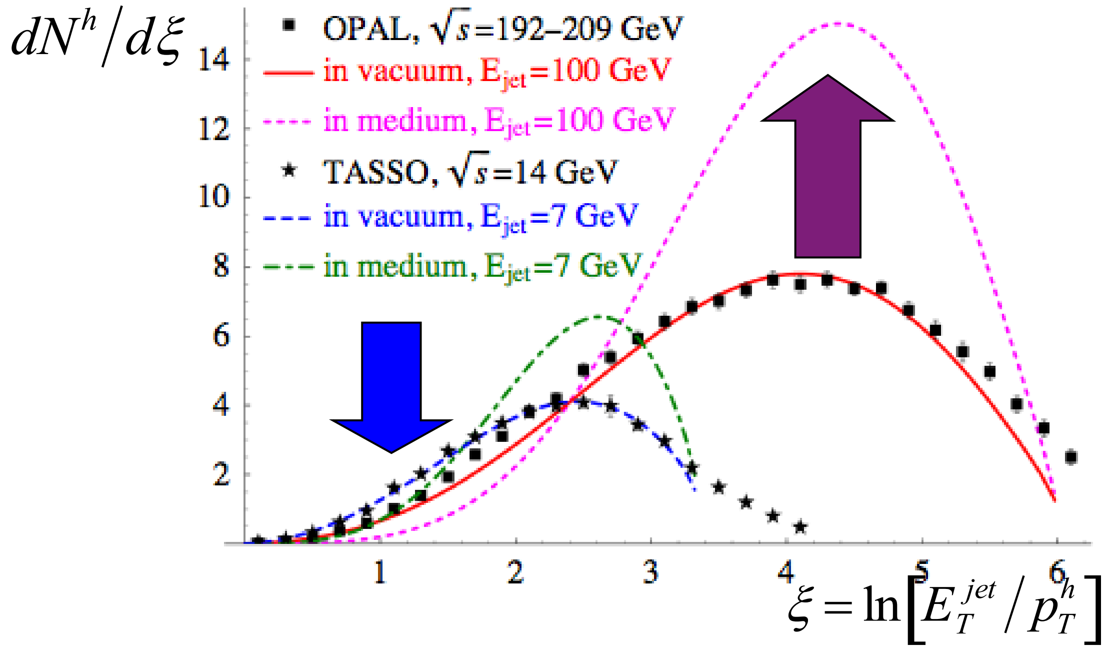
What is the dependence on parton identity?

Characterize Recoil: What is kicked in the medium?

Jet modifications in reach @ LHC …

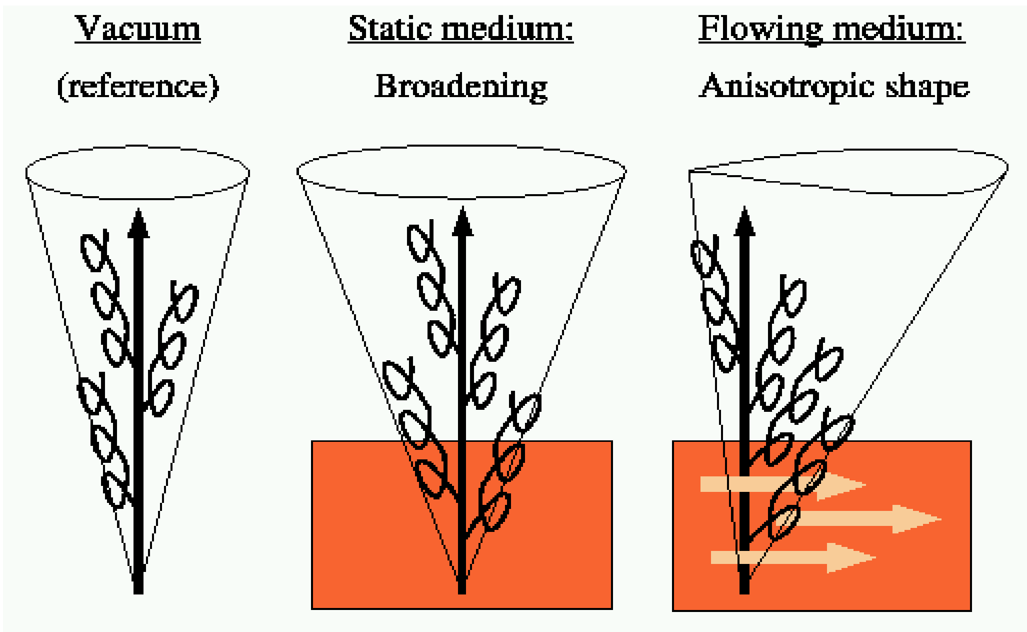
- ‘Longitudinal Jet heating’:
  The entire longitudinal jet multiplicity distribution softens due to medium effects.

Borghini,Wiedemann, hep-ph/0506218



- Jets ‘blown with the wind’
  Hard partons are not produced in the rest frame comoving with the medium

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

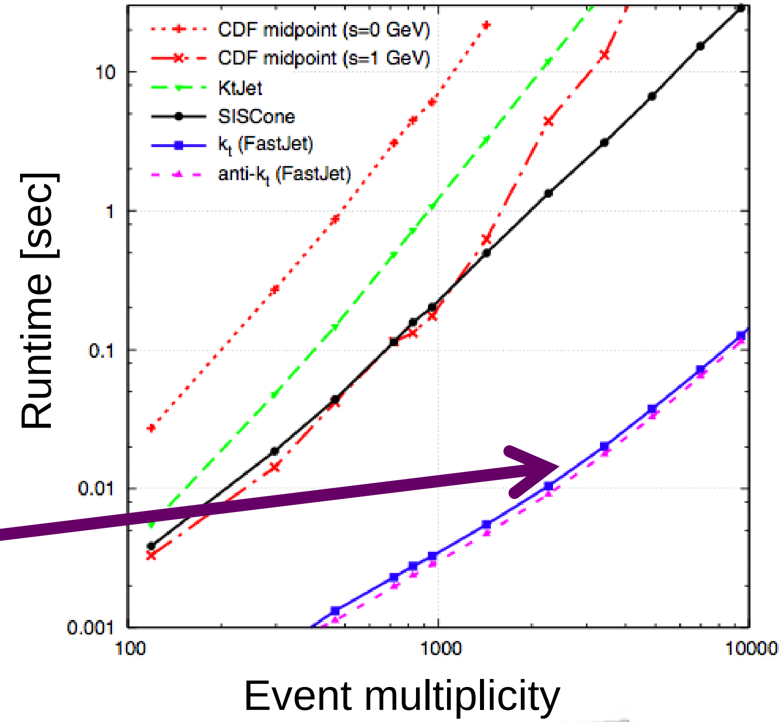


Jet Finding Algorithms

- Tremendous recent progress on jet finding algorithms

  - novel class of IR and collinear safe algorithms satisfying SNOWMASS accords
    kt(FastJet)
    anti-kt(FastJet)
    SISCone

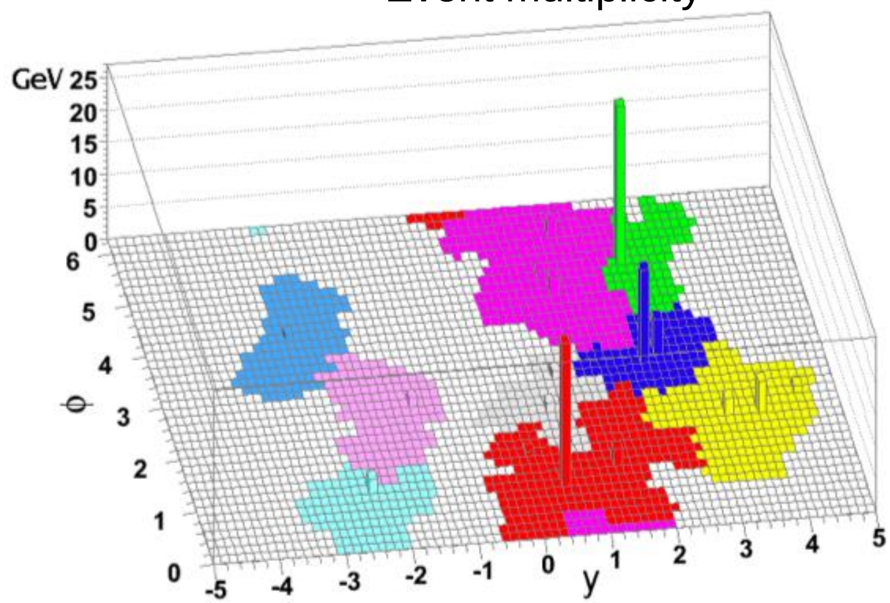
    M. Cacciari, G. Salam, G. Soyez, JHEP 0804:005,2008
  - new standard for p+p@LHC
  - fast algorithms, suitable for heavy ions!



- Catchment area of a jet

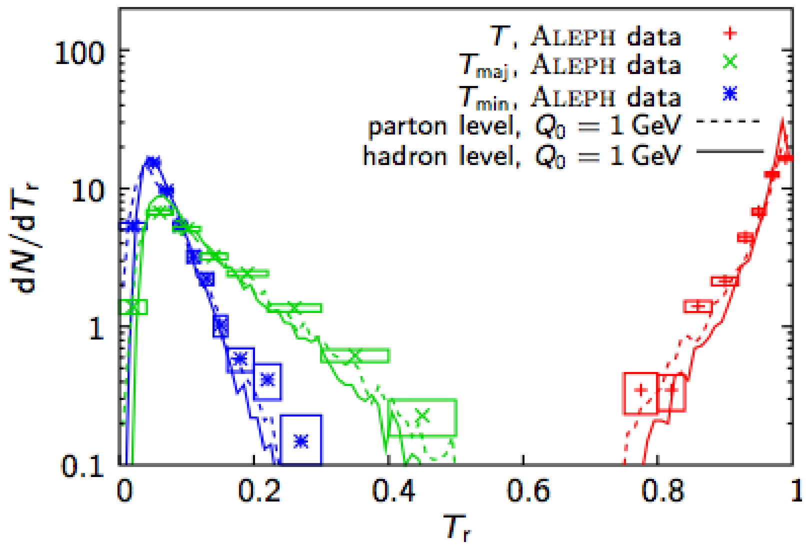
  - novel tools for separating soft fluctuations from jet remnants

  - interplay with MCs of jet quenching needed

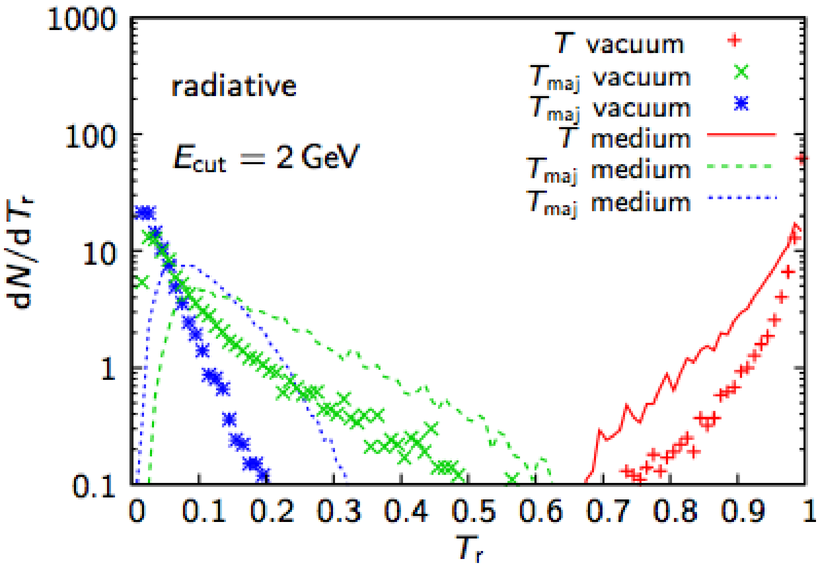


Jet shapes, energy flows

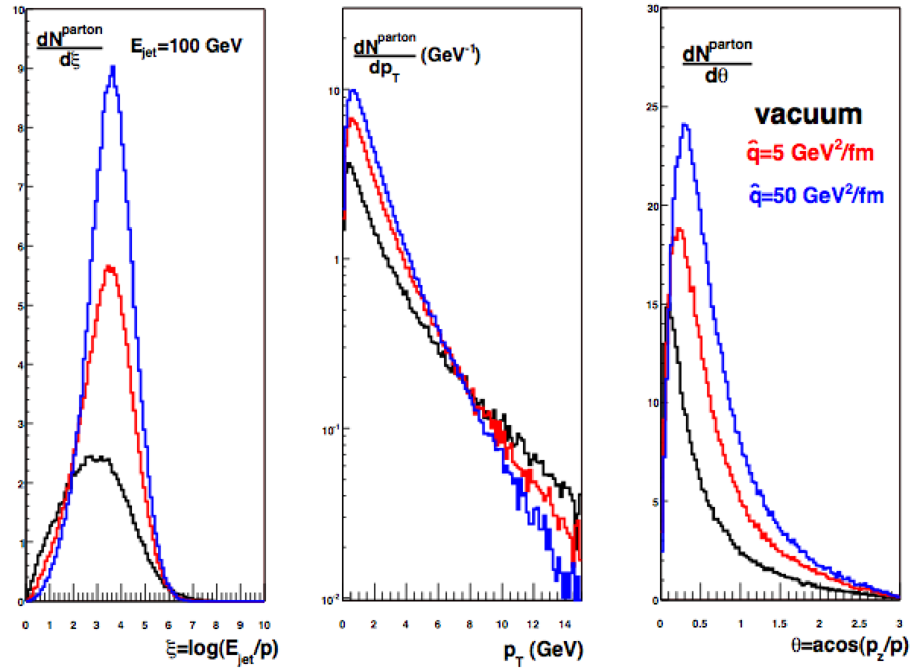
- Thrust – baseline



- Thrust – medium above baseline



- Jet multiplicity distributions



Recent jet quenching MCs:

JEWEL (K.Zapp et al.)
Q-Pythia (Santiago group)
YaJEM (T.Renk)

Monte Carlo including LPM-effect

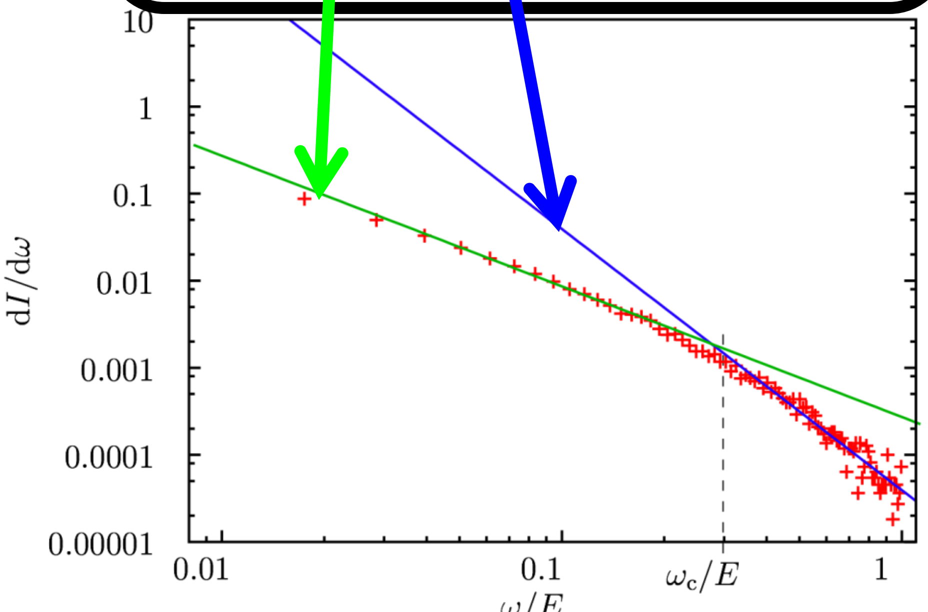
Needed: probabilistic implementation of quantum interference

K. Zapp, J. Stachel, UAW
arXiv:0812.3888

Solution: in vacuum => angular ordering only
in medium => formation time constraint implements LPM

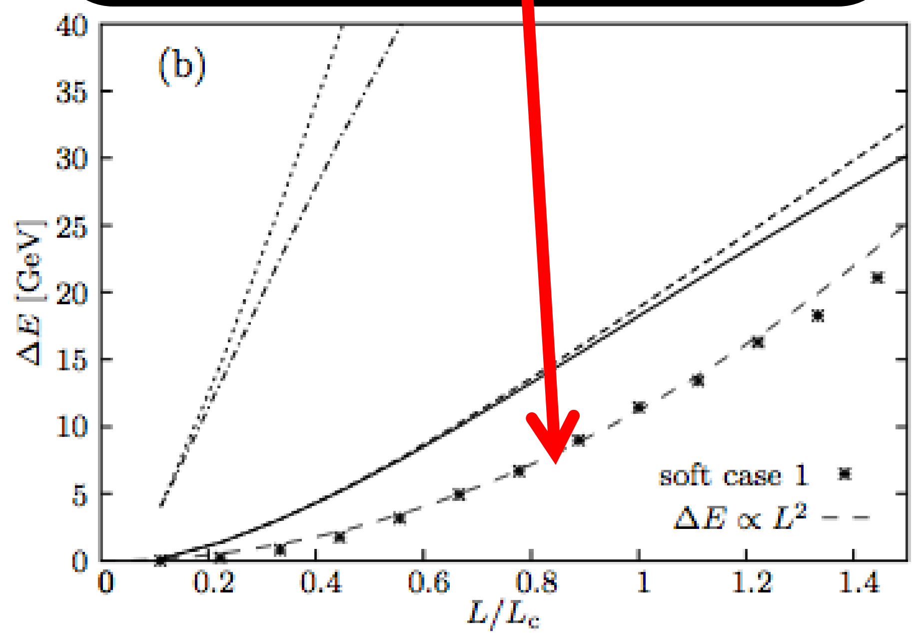
MC reproduces BDMPS-limits

$$\frac{dI}{d\omega} \propto \left\{ \begin{array}{ll} \boxed{1/\omega^{3/2}} & for \quad \omega \ll \omega_c \\ \boxed{1/\omega^{3}} & for \quad \omega \gg \omega_c \end{array} \right\}$$



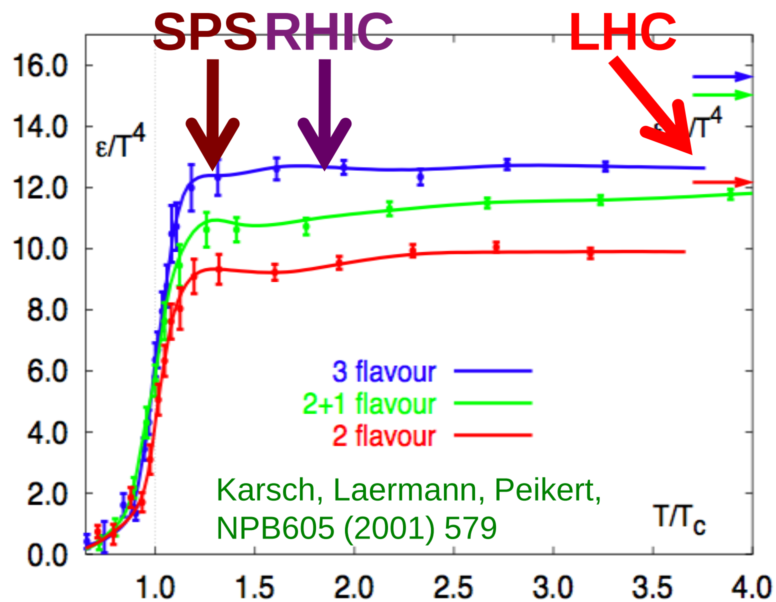
MC reproduces L²-dependence

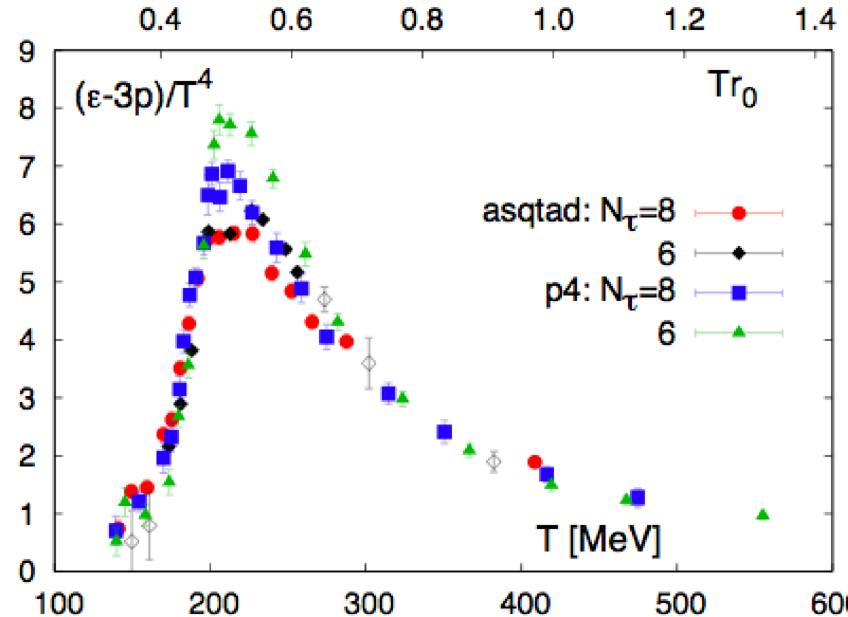
$$\Delta E \propto \hat{q}\, L^2$$



Perturbative vs. non-perturbative description

- Can the properties of dense QCD matter produced in HICs be described in terms of a quasi-particle picture?
  QCD thermodynamics is qualitatively different for $T > 2\text{-}3\ T_c$





- What is the reason for the success of AdS/CFT inspired calculations in RHIC phenomenology?
  - reproducing shear viscosity, quenching parameter

QCD vs. AdS/CFT

	N=4 SYM in vacuum	*QCD* in vacuum	*N*=4 SYM finite T	*QCD* at finite T
• chiral condensate	**NO**	**YES**	**NO**	**melted**
• asymptotic freedom	**NO**	**YES**	**NO**	**less important**
• confinement	**NO**	**YES**	**NO**	**deconfined**
• superymmetric	**YES**	**NO**	**broken**	**NO**
• conformal	**YES**	**NO**	**YES**	**approx at T >>T_c**
• degrees of freedom			Very different, but may be taken care of by normalization	

Physics near vacuum and at high energy is very different

EXP: Conceptual questions in reach of LHC

TH: Which field theoretical tools are best suited?

• quasi-particles	**NO**	**Conceivable for T>2-3 Tc only**
• $\varepsilon - 3p$	**Zero**	**Small for T>2-3 Tc only**

@ RHIC, suppression of hadron spectra is strong (~ 5-fold) and unattenuated up to highest p_T (~ 20 GeV), collectivity is strong and rising with cms energy

=> ***Collectivity expected to be even larger a LHC, suppression expected to persists in wide pT-range at LHC***

The probes:

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

Abundant yield
of hard probes
+ robust signal
(medium sensitivity >> uncertainties)
= detailed understanding
of dense QCD matter