Physics at the LHC: Theoretical Promise

Urs Achim Wiedemann
CERN TH and SUNY Stony Brook

Despite the catchy title given to me, I won't make promises but I shall ask questions.

Heavy Ion Physics at the LHC

LHC Experiments: 3 out of 4

- ALICE Grazyna Odyniec
- ATLAS Helio Takai
- CMS Bolek Wyslouch

Major topics which carry theoretical promise:

- Low x: Raju Venugopalan
- Jet Quenching: Ivan Vitev
- Electromagnetic probes: Ralf Rapp
- Soft Physics: Gunther Roland
- Heavy Quarks: Andrea Dainese
- Quarkonia: Ramona Vogt

Physics in the neighborhood of heavy ions:

- p+A physics Brian Cole
- UPC Spencer Klein
- pp Mark Strikman

And the Role of RHIC Tom Ludlam

Fundamental questions accessible at RHIC

(From the NSAC 2002 Long Range Plan)

1) In relativistic heavy-ion collisions, how do the created systems evolve ? UI
   Does the matter approach thermal equilibrium ? Y
   What are the initial temperatures achieved ? UI

2) Can signatures of the deconfinement phase transition be located as the hot matter produced in relativistic heavy-ion collisions cools ? UI-TBD

3) What are the properties of the QCD vacuum and what are its connections to the masses of the hadrons ? TBD
   What is the origin of chiral symmetry breaking ? TBD

4) What are the properties of matter at the highest energy densities ? UI
   Is the basic idea that such matter is best described using fundamental quarks and gluons correct ? UI

How can LHC contribute to these questions?
How can LHC go beyond these questions?

Y = Yes, UI=Under Investigation, TBD=To Be Determined

Extending the range of questions

Based on RHIC, more advanced questions can be asked:

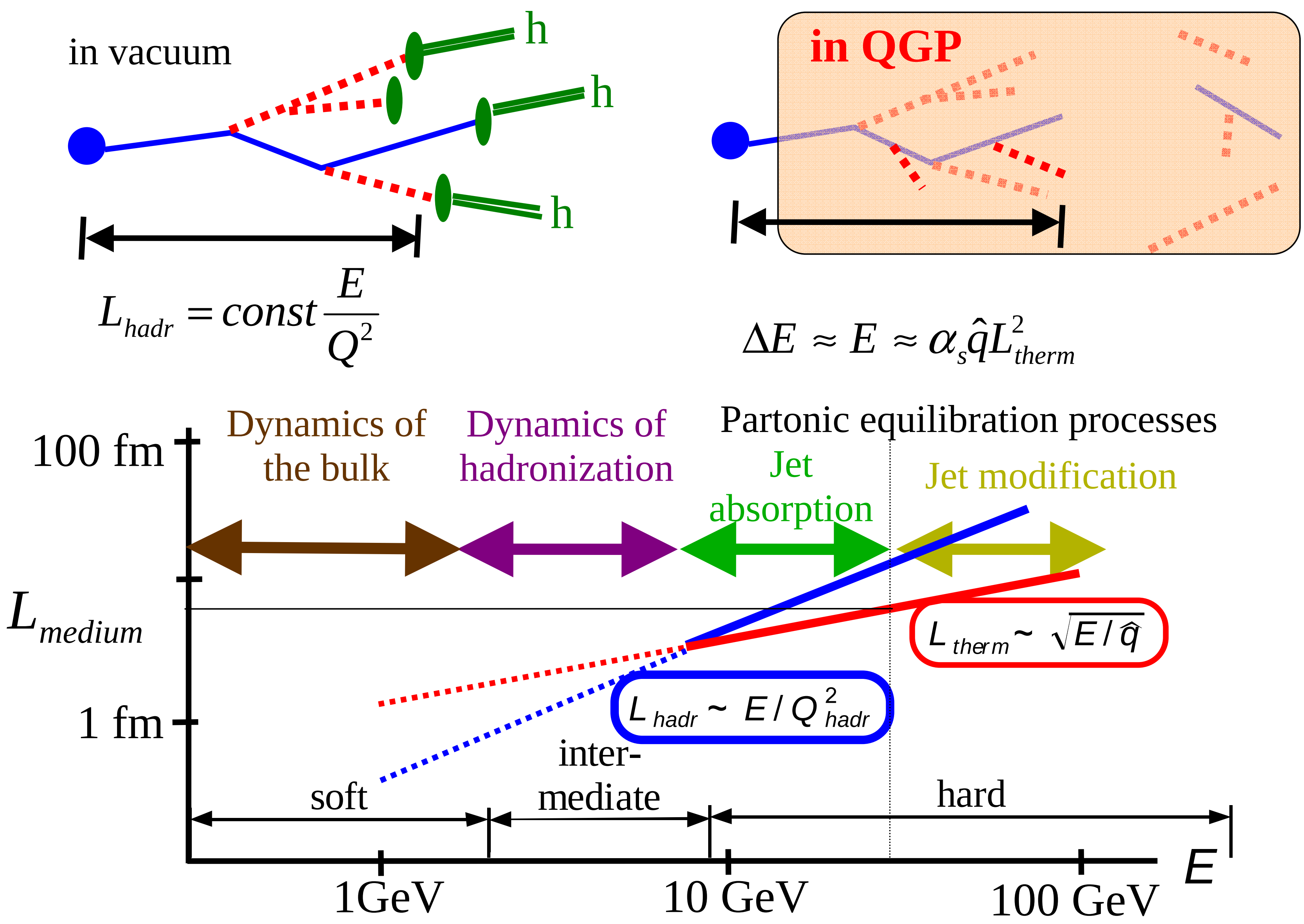
1) How do thermal and chemical equilibration processes proceed microscopically in the strong interactions, and what determines their characteristic time-scales in dense QCD matter?
   In particular: What is the microscopic basis of jet quenching ?

2) Do heavy ion collisions at LHC support the hydrodynamic picture advocated at RHIC? In particular: can we constrain specific properties of the produced dense matter, such as its viscosity, its conductivity with respect to heat, baryon number etc. ?

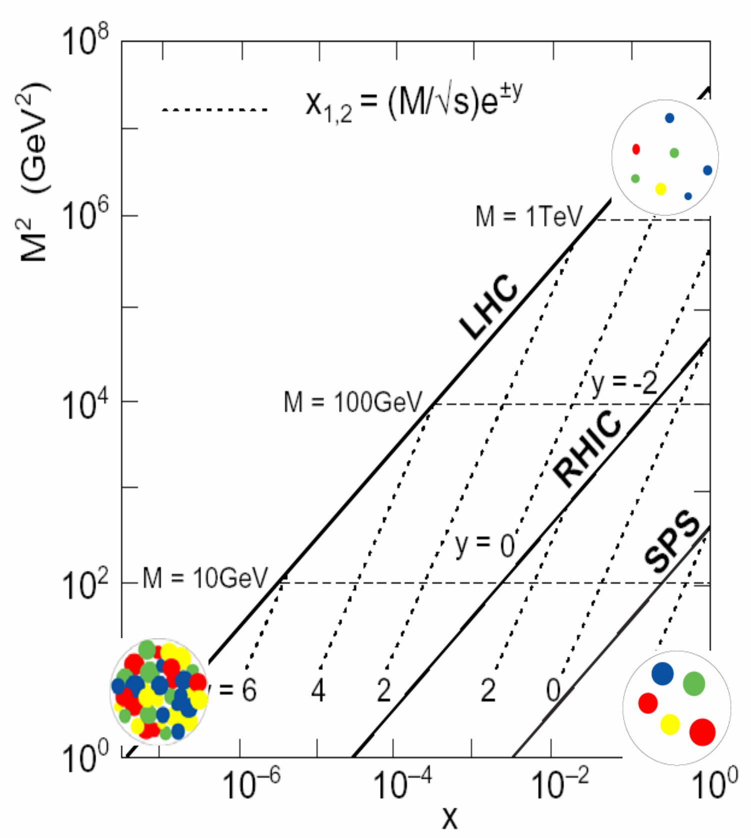
3) Can we determine the energy and rapidity dependence of these properties of matter ? Is there a difference between energy and rapidity dependence ? In particular: how can we disentangle and tests effects from non-linear small-x evolution? Is the medium at LHC mid rapidity dominated by phenomena of perturbative saturation?

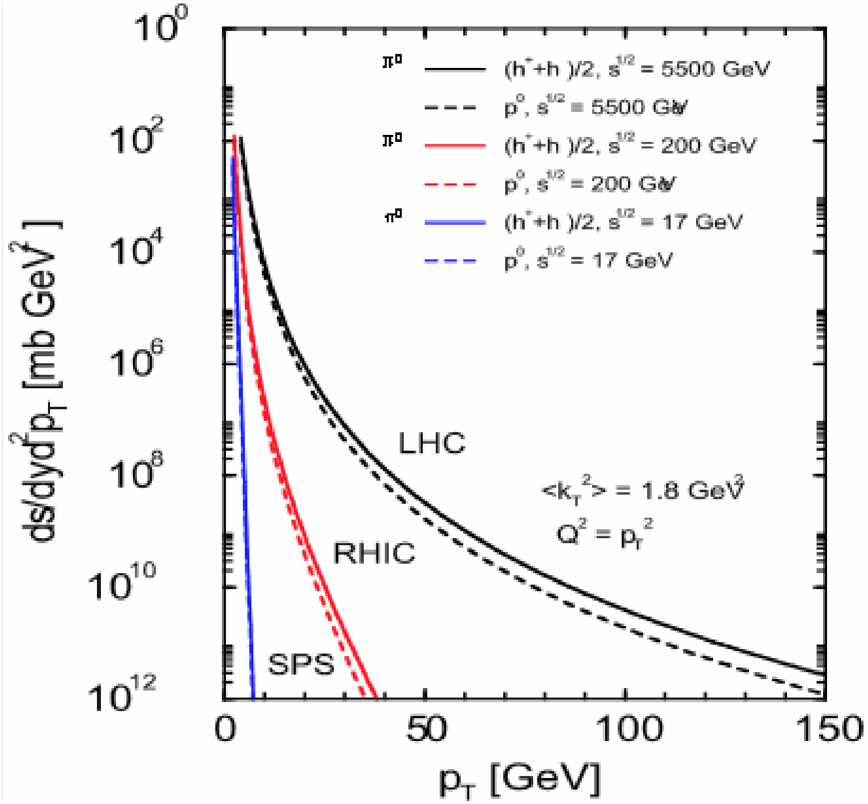
4) …

Times scales: hadronization vs.thermalization



Hard high-Q^2 processes are abundant at collider energy





- Production of hard partons is a standard candle, unaffected by medium

$$1/Q \ll \Delta r_{medium}, \Delta t_{medium} \qquad Q \gg T$$

- Hard partons interact with medium during propagation

Rates of Hard Processes at the LHC

The most elementary equation for why detailed experimentation of dense matter is possible at the LHC:

Abundant yield
of hard probes
+ robust signal
(jet quenching
>> uncertainties)

= detailed study

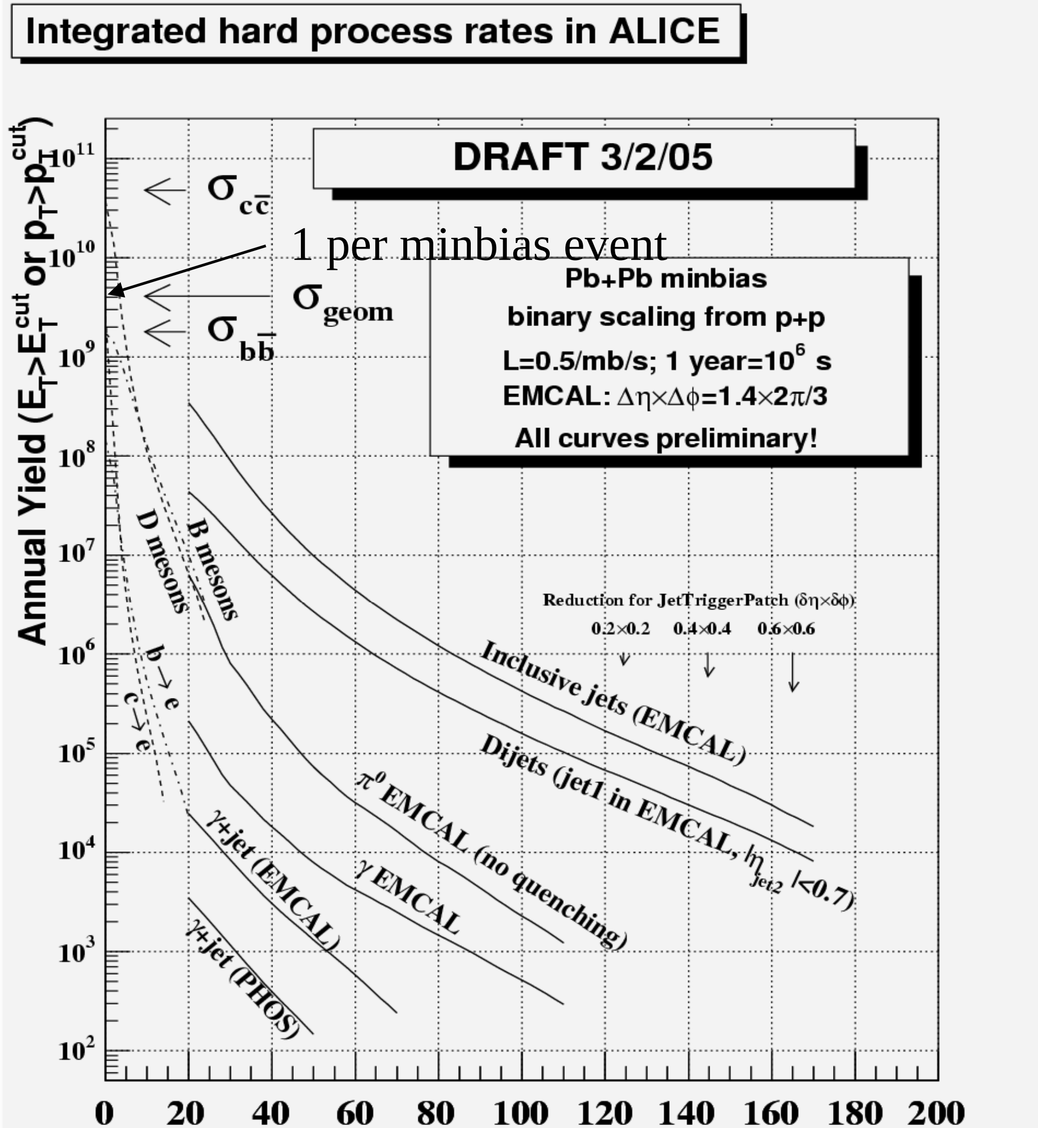
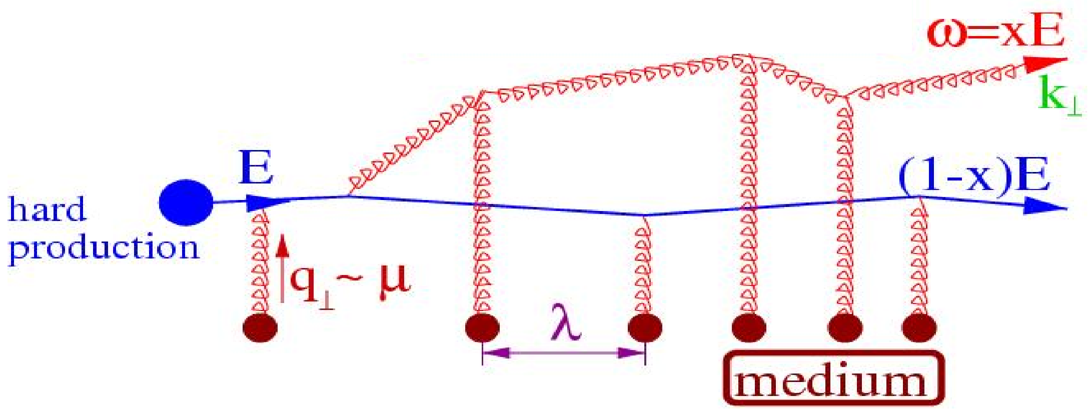


Fig. from P. Jacobs

The medium-modified Final State Parton Shower

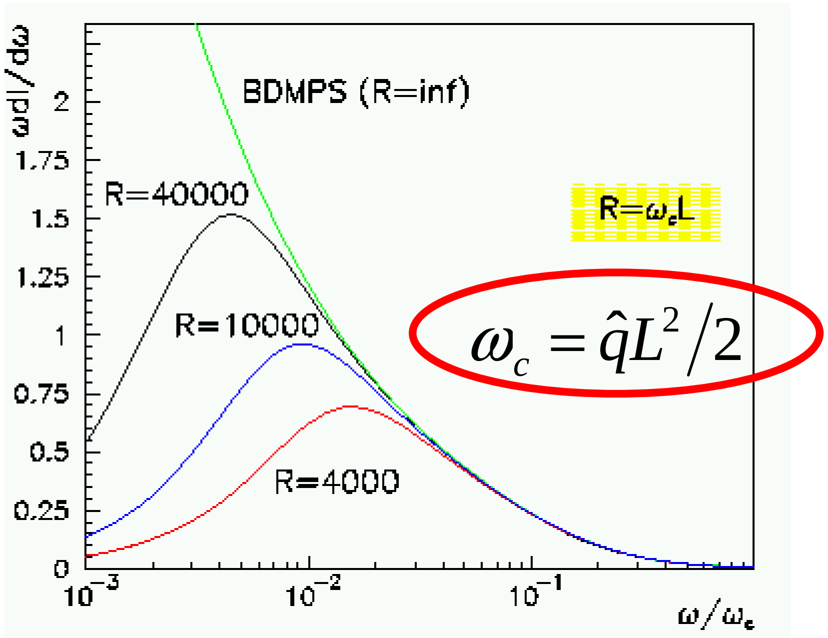
Baier, Dokshitzer, Mueller, Peigne, Schiff (1996); Zakharov (1997); Wiedemann (2000); Gyulassy, Levai, Vitev (2000); Wang ...

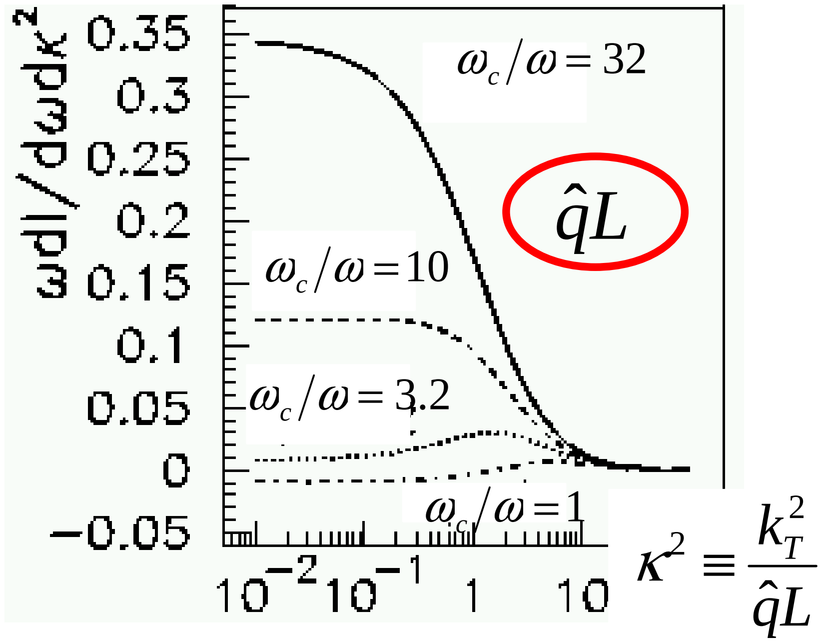


Medium characterized by transport coefficient:

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

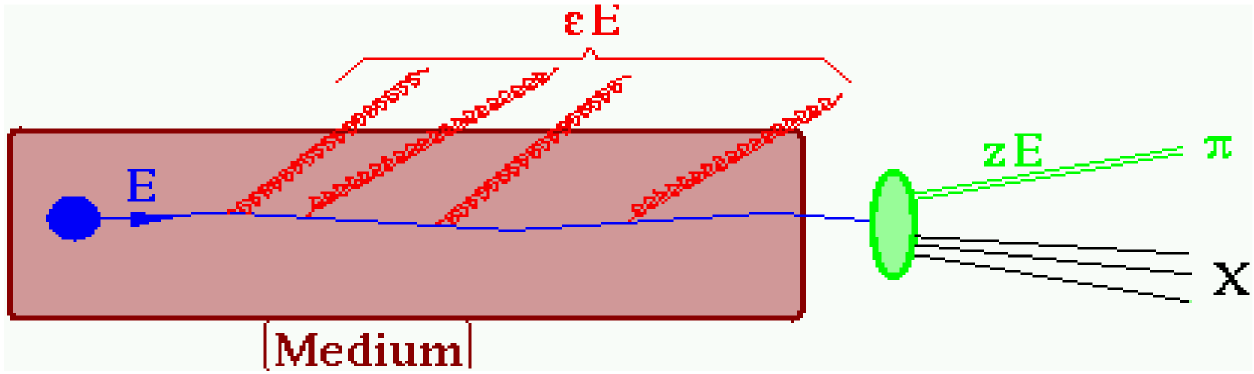
- energy loss of leading parton
- pt-broadening of shower





Salgado,Wiedemann PRD68:014008 (2003)

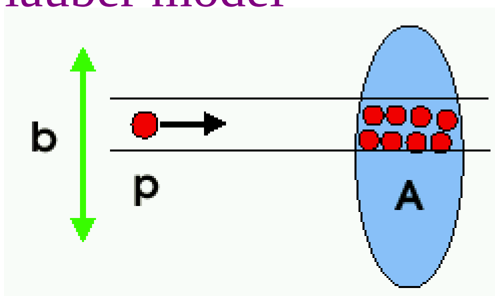
High p_T Hadron Spectra



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

$$\frac{T_{AA}(b)\sigma_{NN}}{\sigma_{AA}(b)}$$

Glauber model



The fragility of leading hadrons

- Why is $R_{AA} \sim p_T$-independent?

  Trigger bias more severe for large p_T

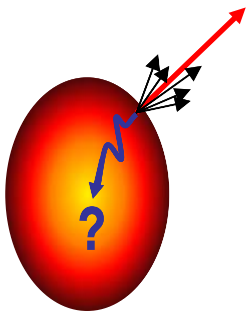
$$\sigma \propto \int dz \frac{z^{n(p_T)-1}}{p_{T,hadr}^{n(p_T)}} D_{h/q}^{frag}(z,Q^2)$$

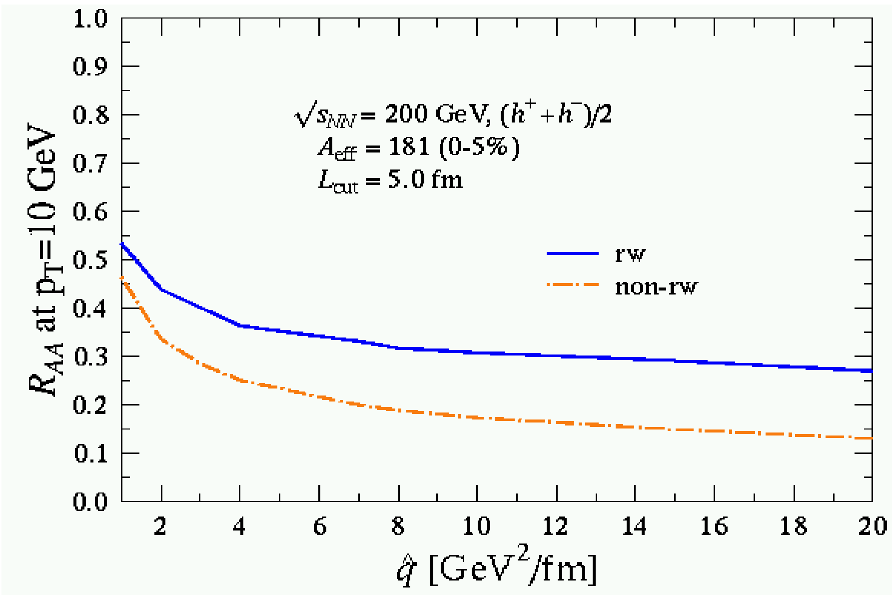
QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

Eskola, Honkanen, Salgado, Wiedemann NPA 747 (2005) 511, hep-ph/0406319

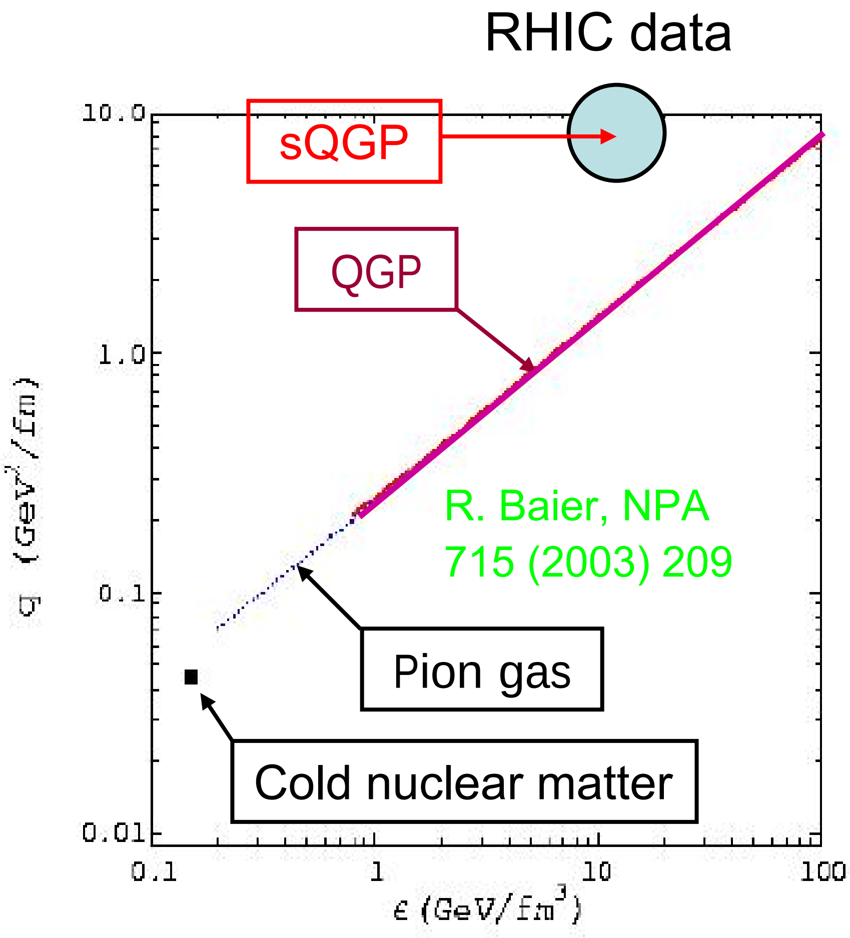
- Why is $R_{AA} = 0.2$ natural ?

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





The produced matter is opaque - why ?



- $\hat{q}$ traces energy density

$$\hat{q}(\tau) = c\,\varepsilon^{3/4}(\tau) \quad \Leftarrow c^{QGP}_{ideal} \approx 2$$

- Time-averaged $\hat{q}$ is very large. Dynamical scaling implies

$$c = \frac{\hat{q}}{\varepsilon^{3/4}(\tau_0)} \frac{2-\alpha}{2} (L/\tau_0)^{\alpha}$$

for the values favored by RHIC-data

$$c > 5\,c^{QGP}_{ideal}$$

"Opacity problem"

Nuclear Modification factor at the LHC

Microscopic dynamics of high-pt hadron suppression at RHIC is not yet firmly established.
Medium-induced gluon radiation is prime candidate, but

- Numerical value of transport coefficient is not yet understood
  - dynamical explanation (jet quenching measures combination of energy density and flow)
  - theoretical estimate of qhat needs improvement
  - jet quenching formalism needs improvement (test further predictions of jet quenching
- Beyond leading particle spectra, experimental evidence is still weak.
  Kinematical window for testing associated radiation just opening up with Run 4 data,
  but LHC is much better positioned

1) Above which pt is the nuclear modification factor particle species independent?

2) Does the nuclear modification factor stay pt-independent up to the highest transverse momenta?

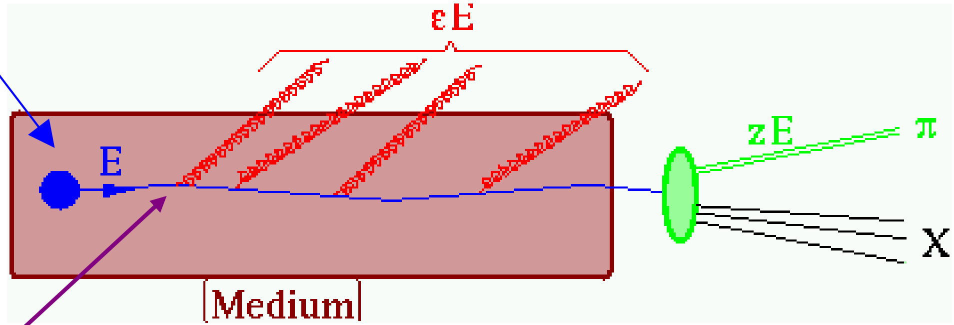
3) What about the Q^2-dependence of parton energy loss?
   One may expect, e.g., that for $Q \sim E_T \sim 100$ GeV $\gg T$
   first parton splittings occur on too short distances to be modified by medium.
   Logarithmically wide pt-range at LHC necessary to study Q^2-dependence of parton energy loss.

Borghini, Wiedemann, hep-ph/0506218

Testing the microscopic dynamics expected to underlie jet quenching

How does this parton thermalize ?

Where does this associated radiation go to ?



How can one determine the dependence on parton identity ?

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

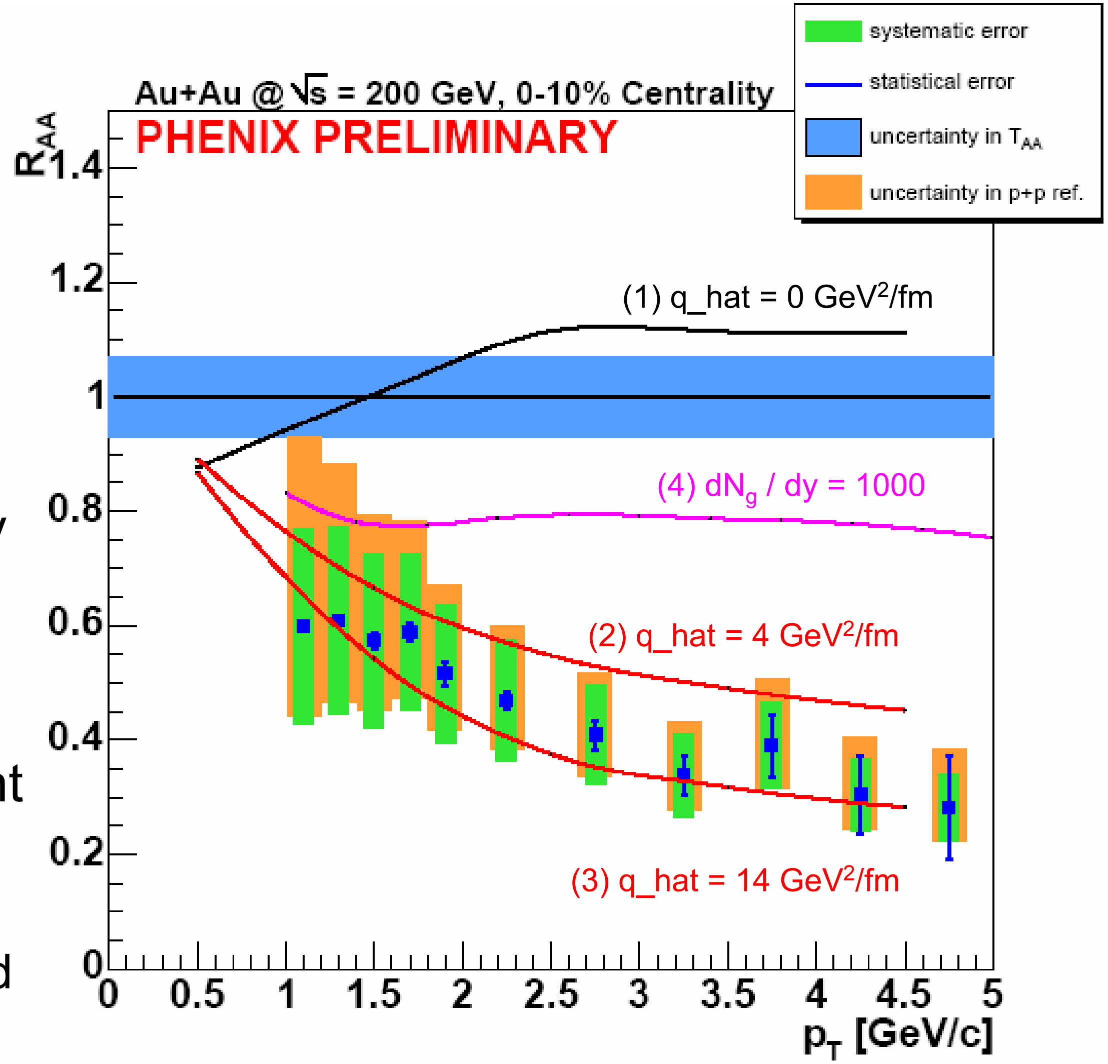
Inclusive single electron spectrum in Au+Au

- Parton energy loss is sensitive to parton identity

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

- Single electron spectrum at high transv. Momentum dominated by b- and c-decays.

- Observed suppression consistent with quenching of light hadrons.
  (But significant uncertainties in ratio of b/c perturbative cross section and in b/c fragmentation.)



Future tests at RHIC and at the LHC

Armesto, Dainese, Salgado, Wiedemann, PRD71:054027,2005

At high p_T :

Massless "c/b"

Massive c/b

- Charm is sufficiently light, so that double ratio tests:

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

$$R_{D/h}$$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

- Beauty is sufficiently heavy, so double ratio dominated by mass dependence:

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

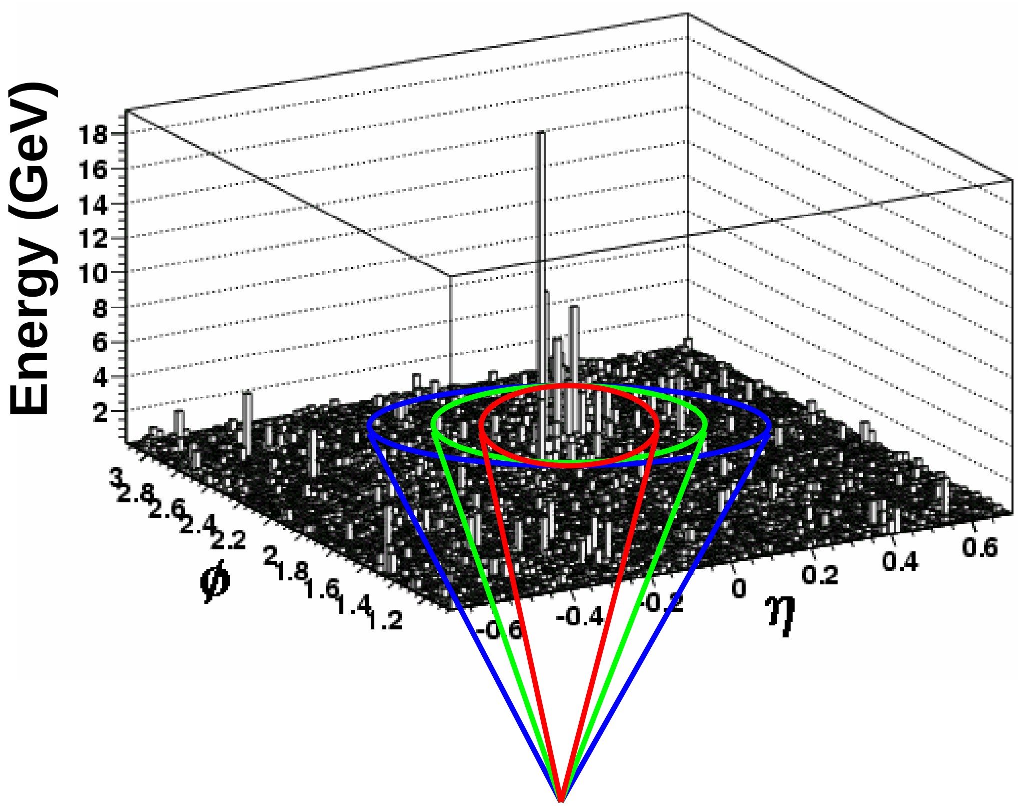
$$R_{B/h}$$

Jets in Heavy Ion Collisions at the LHC

- How can one characterize the medium-modification of jets in a high multiplicity environment ?

  - full jet reconstruction ?
  - jet trigger ?
  - jet-like particle correltions ?
  - …

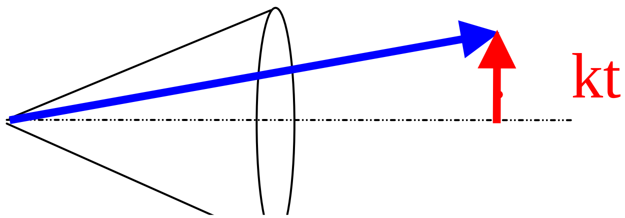
100 GeV jet in central Pb+Pb

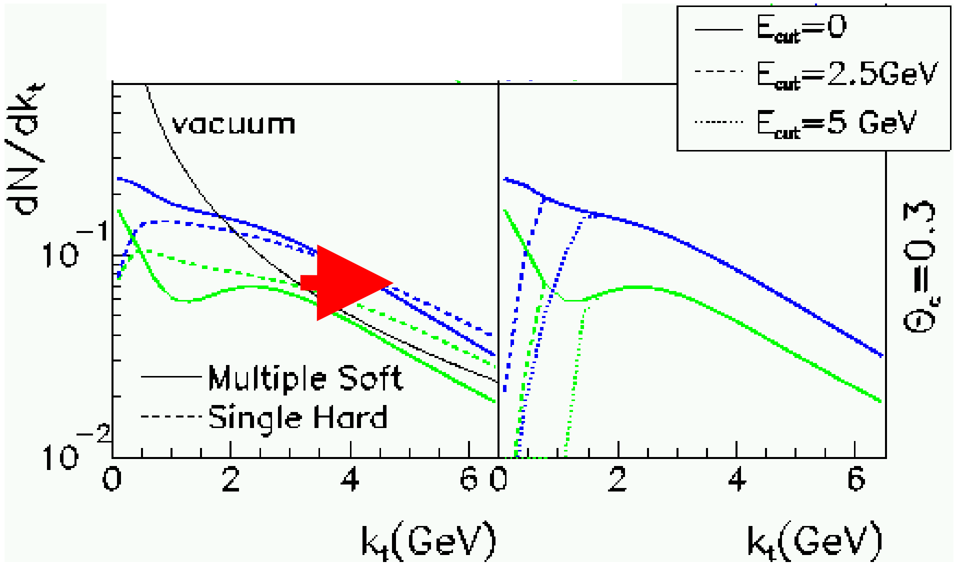


The Onset of Jet Heating - transverse

Salgado, Wiedemann, Phys. Rev. Lett. 93: 042301 (2004)

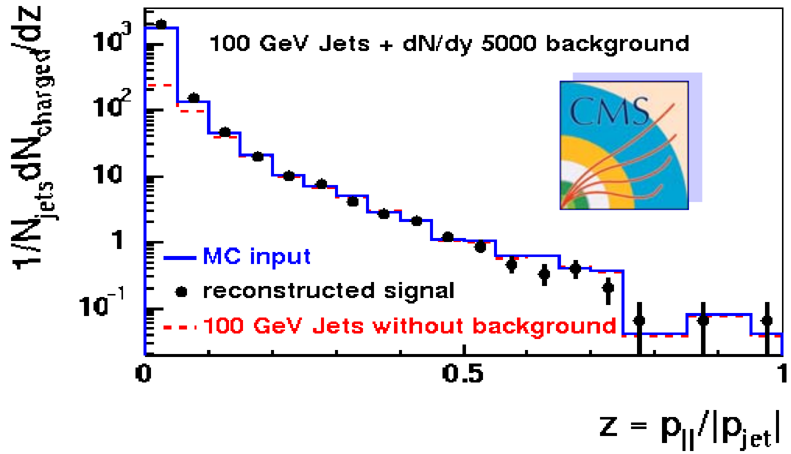
- Multiplicity within small jet cone broadens significantly



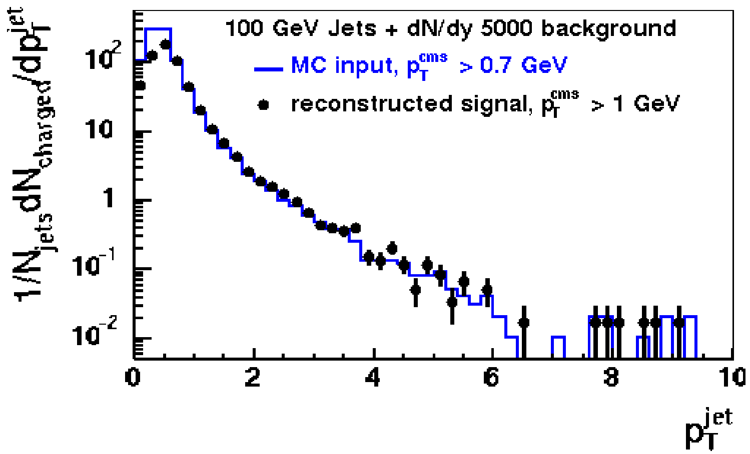


Unaffected by high-multiplicty background !

Longitudinal momentum fraction z along the thrust axis of a jet:



p_T relative to thrust axis:



Longitudinal Jet Heating

Borghini,Wiedemann, hep-ph/0506218

- Medium expected to soften and increase the longitudinal multiplicity of ‘true jets’.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

- Softening in qualitative agreement with triggered particle correlations.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

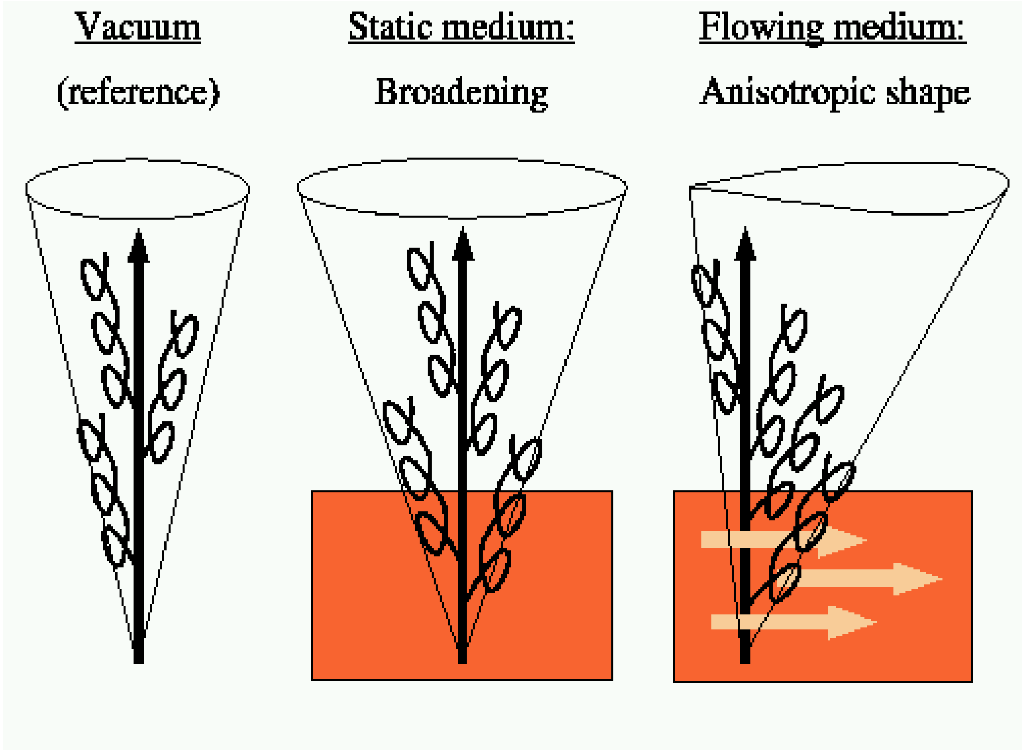
- Awaits detailed test at the LHC.

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

Jets in pionic winds and partonic storms

If medium shows strong collective flow, what are additional measurable consequences at LHC ?

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



Hard partons are not produced in the rest frame comoving with the medium

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

Flow effect

$$E_T^{jet} = 100\ GeV$$
$$\hat{q}\, L = (1\ GeV)^2$$
$$(\hat{q}\, L)_{flow} = \hat{q}\, L$$

QuickTime™ and a
TIFF (LZW) decompressor
are needed to see this picture.

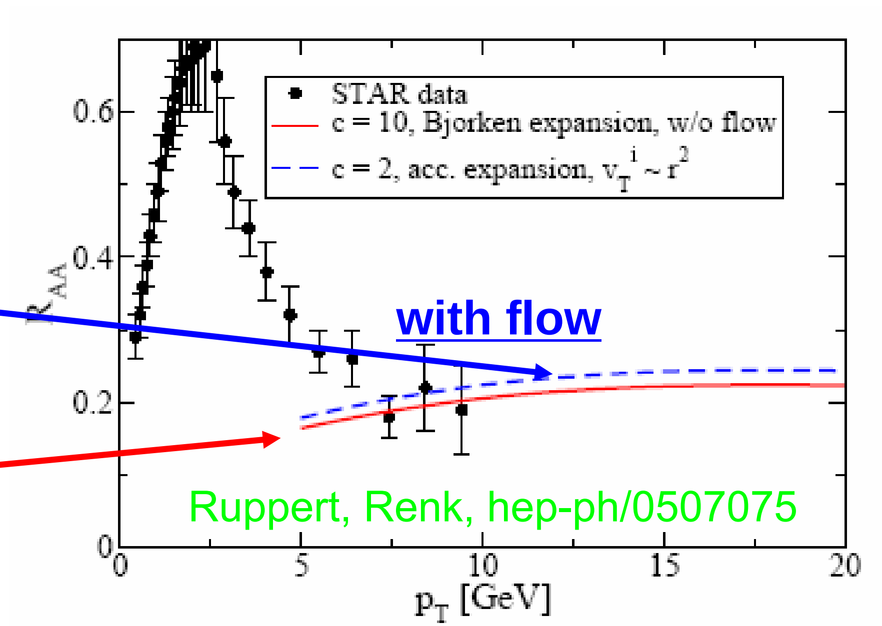
Flow effects on Hard Probes

- Very strong transverse flow may resolve the opacity problem

$$\hat{q}(\tau) = c\, \varepsilon^{3/4}(\tau) \quad \Leftarrow c_{ideal}^{QGP} \approx 2$$

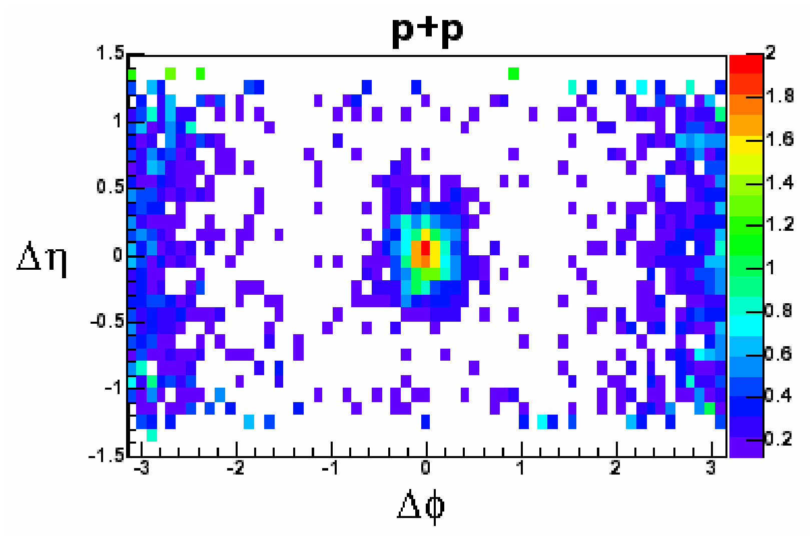
$$c > 5\, c_{ideal}^{QGP}$$

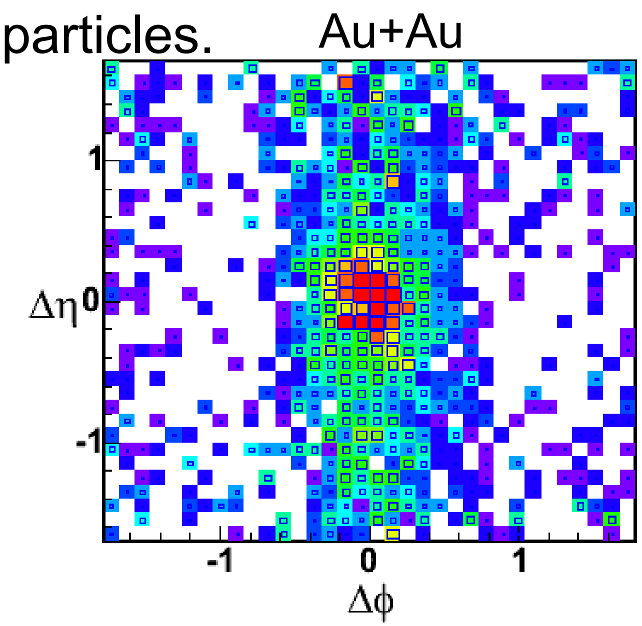
without flow



- Strong longitudinal flow may account for broadened multiplicity distribution associated to high-pt trigger particles.

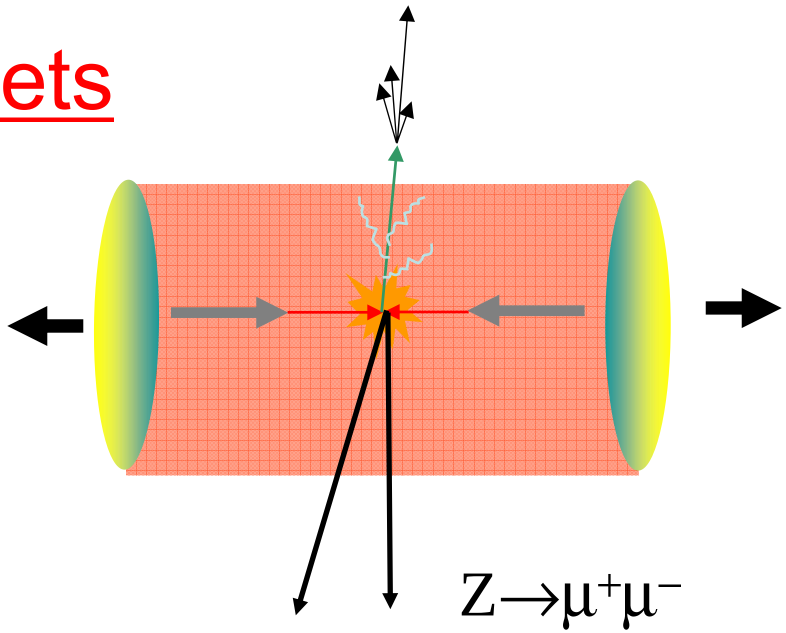
Data: D. Magestro (STAR), preliminary





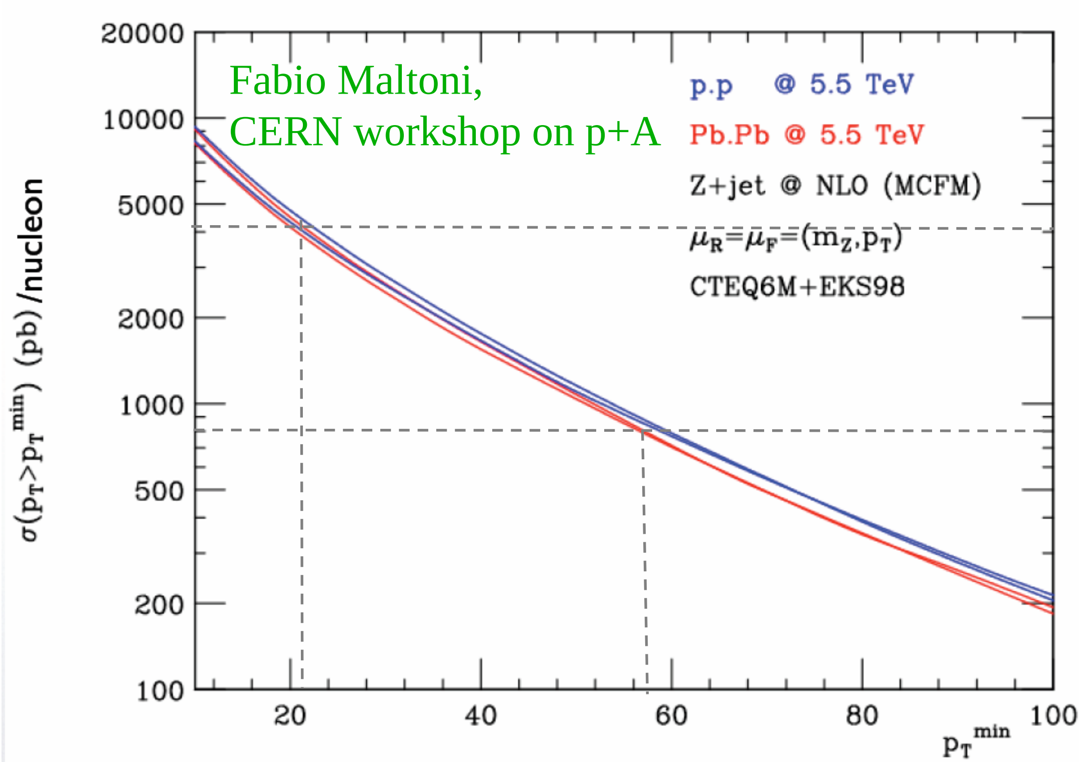
Tagged Jets

- Z,photon has no color
  → no in-medium interactions



- Precise calibration of recoil jet
  → access to medium-effects on jet fragmentation

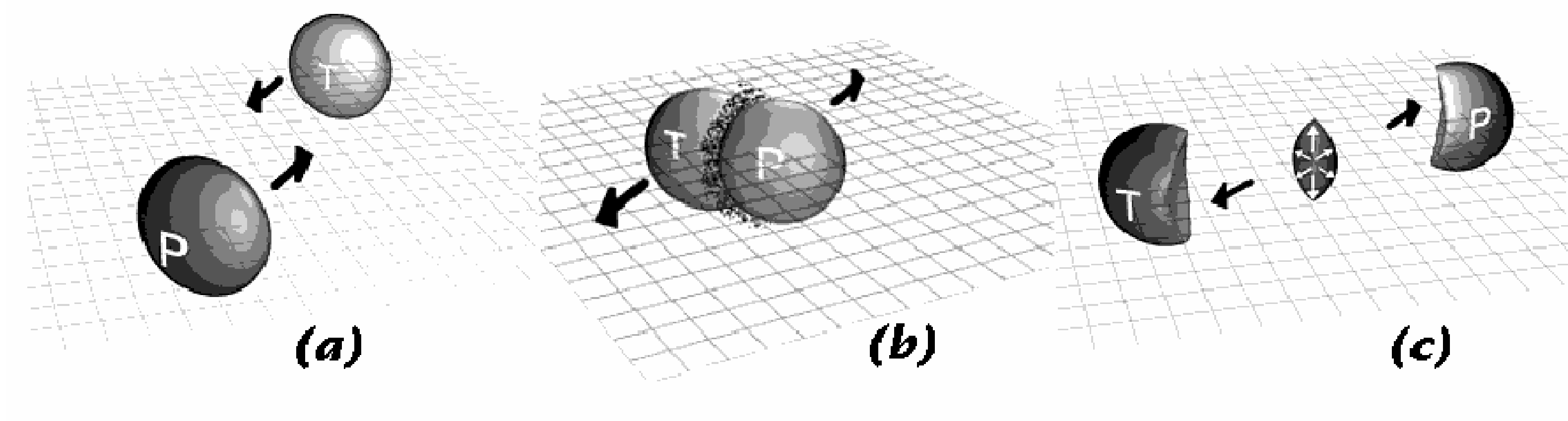
- Z-tagging is statistics limited even at the LHC



- photon rates may be modified by medium interactions
  $\pi^0 \to \gamma\gamma, \quad q,g \to \gamma$

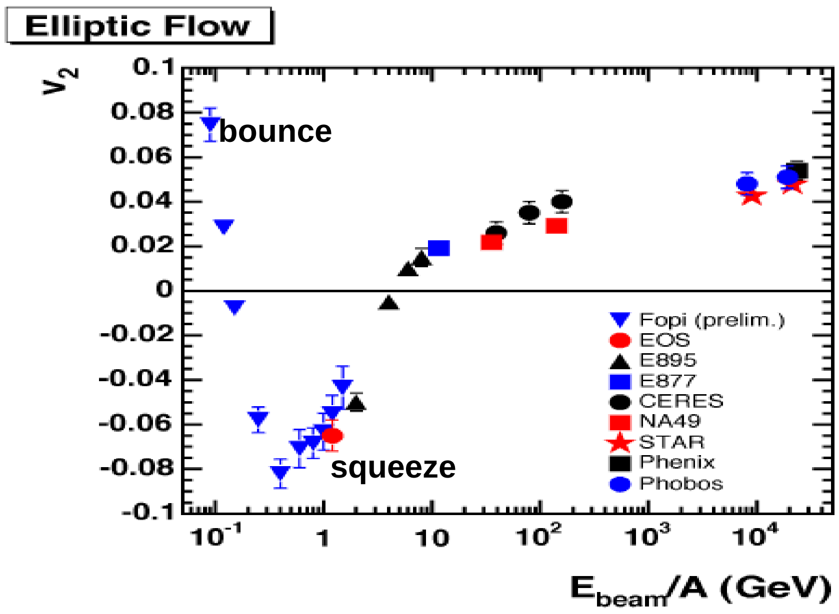
F. Arleo et al., JHEP 0411:009,2004

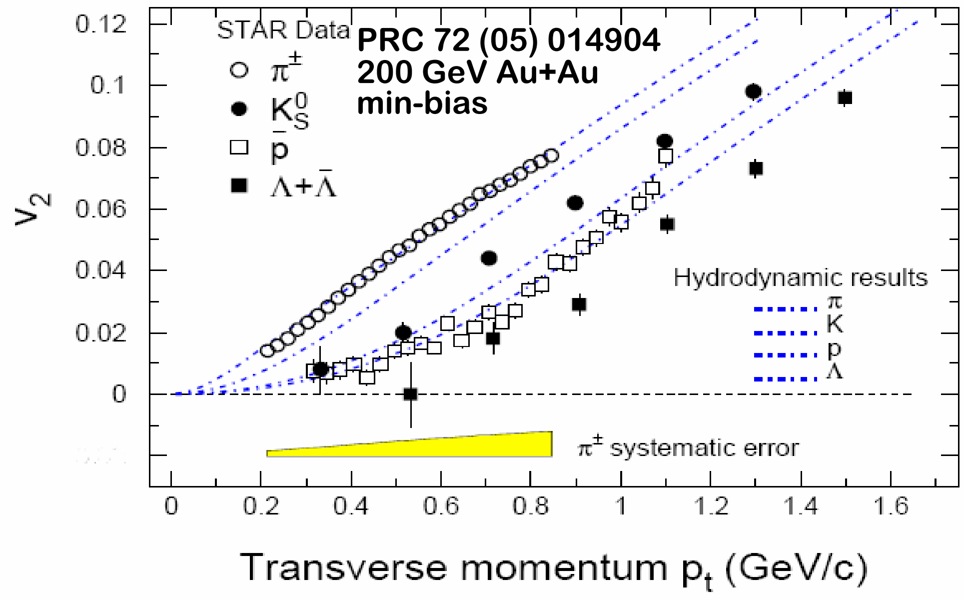
Elliptic flow: hallmark of a collective phenomenon



$$\frac{dN}{d\phi} \sim [1 + 2v_1 \cos(\phi) + 2v_2 \cos(2\phi)]$$

Azimuthal particle distribution at RHIC in qualitative agreement with hydrodynamic picture of the collision





Elliptic Flow vs. Theory: open questions

• Viscosity Problem/Property

Hydro simulations require an extremely small ratio of viscosity over entropy.

D. Teaney

$$\Gamma_s \equiv \frac{4\eta}{3sT}$$

QuickTime™ and a TIFF (LZW) decompressor are needed to see this picture.

- **Can one calculate viscosity in QCD ?**
- **Are there independent tests that dissipative processes are negligible ?**

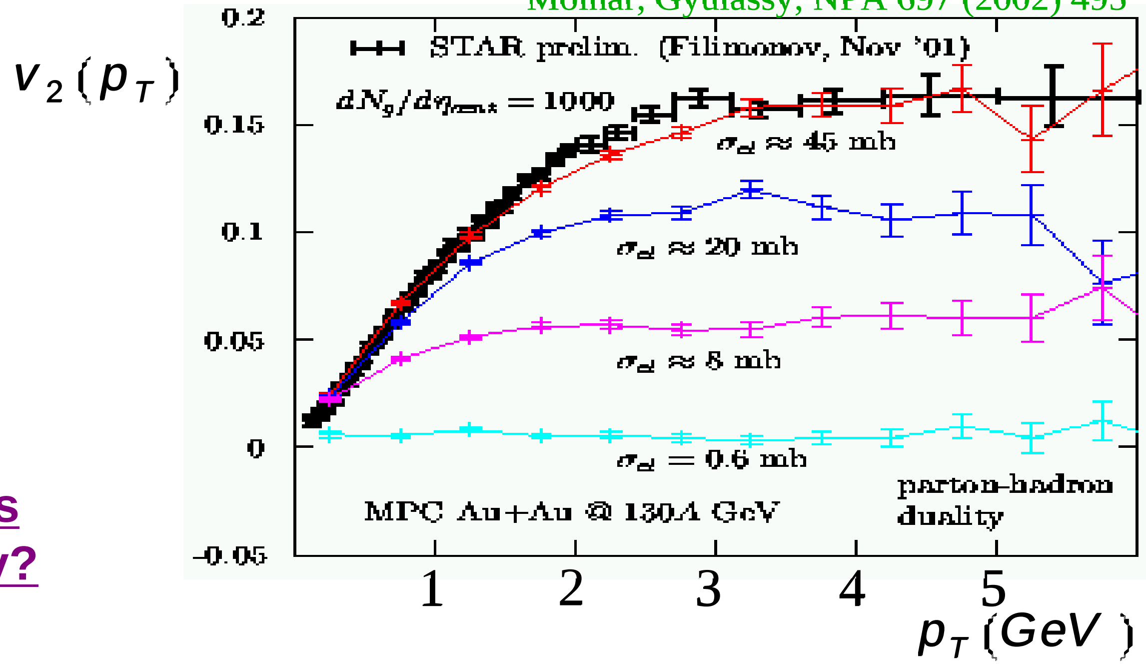
• Opacity Problem

Parton cascades require unnatural large partonic cross sections

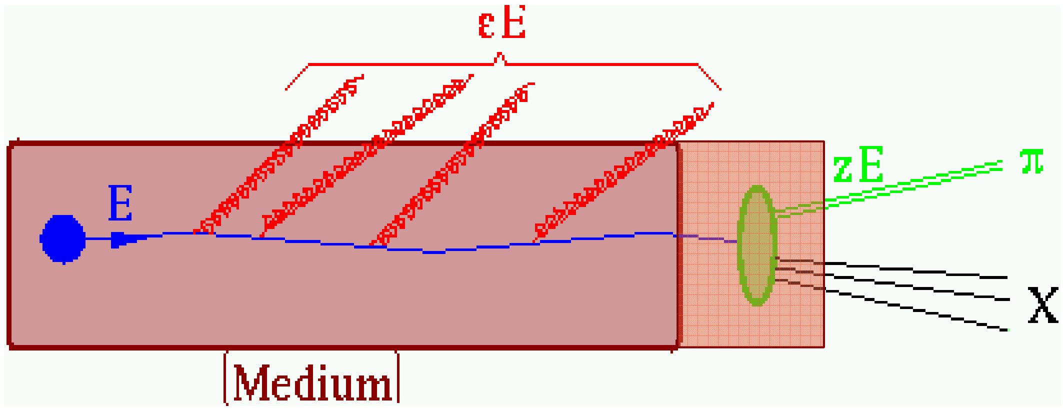
$$\sigma_{parton} > 5\,\sigma_{parton}^{pQCD}$$

How can we test the microscopic dynamics underlying collectivity?

Molnar, Gyulassy, NPA 697 (2002) 495



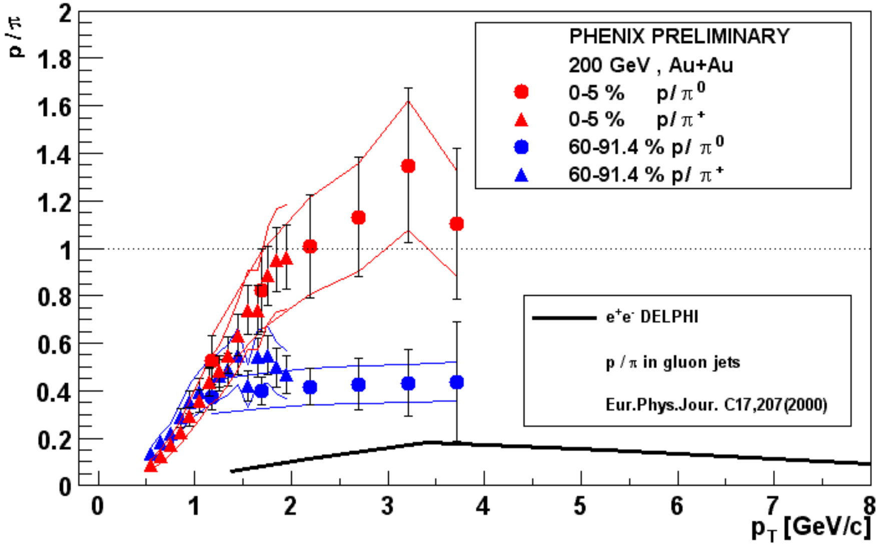
Intermediate p_T

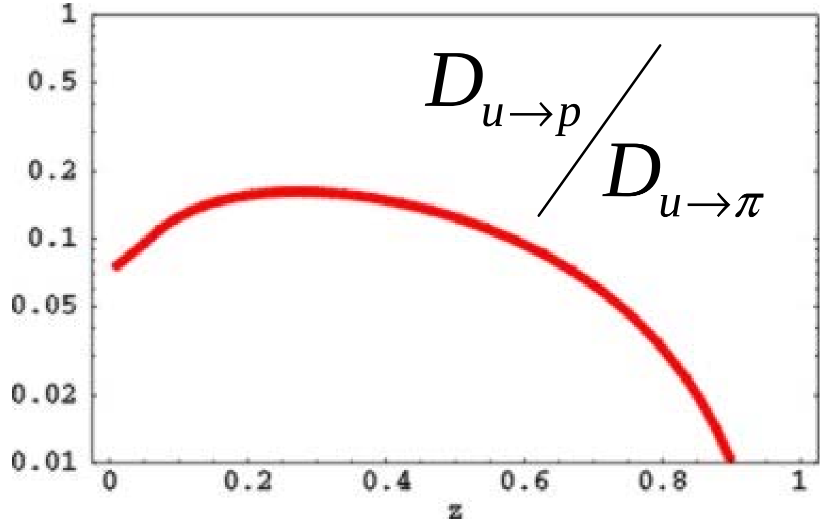


Hadronization inside the medium:
what happens now ?

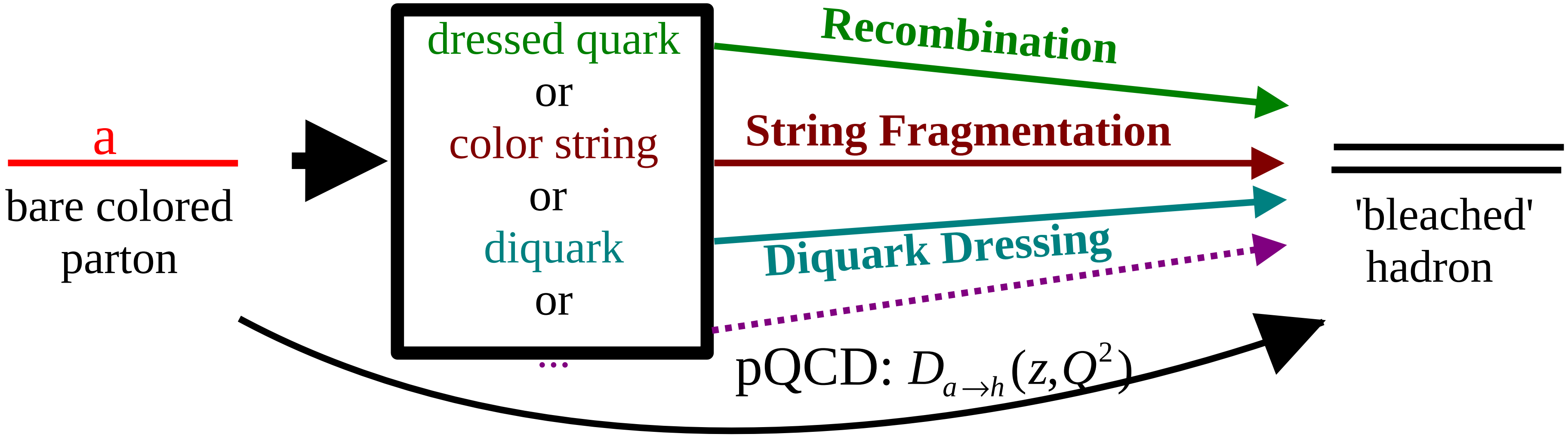
Breakdown of independent fragmentation

- Parton e-loss does not affect $D_{u\to p}/D_{u\to\pi}$ in contrast to observation





- How does the bleaching of color charges proceed dynamically ?



Fragmentation vs. recombination (a model)

start from quark spectrum: $w(p/z)$

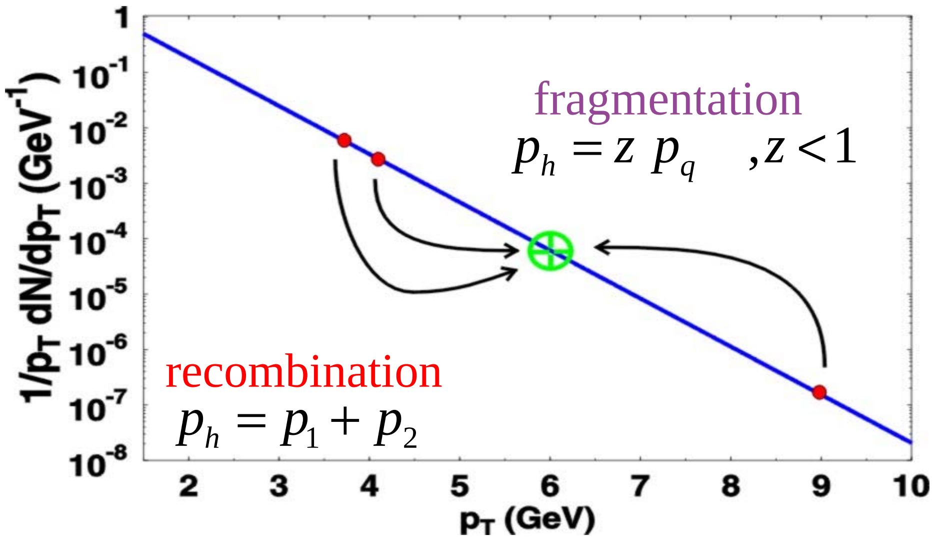
- Fragmentation:

$$E\frac{dN_h}{d^3p} = \int \frac{dz}{z^2}\, w(p/z)\, D_{q\to h}(z)$$

- Recombination

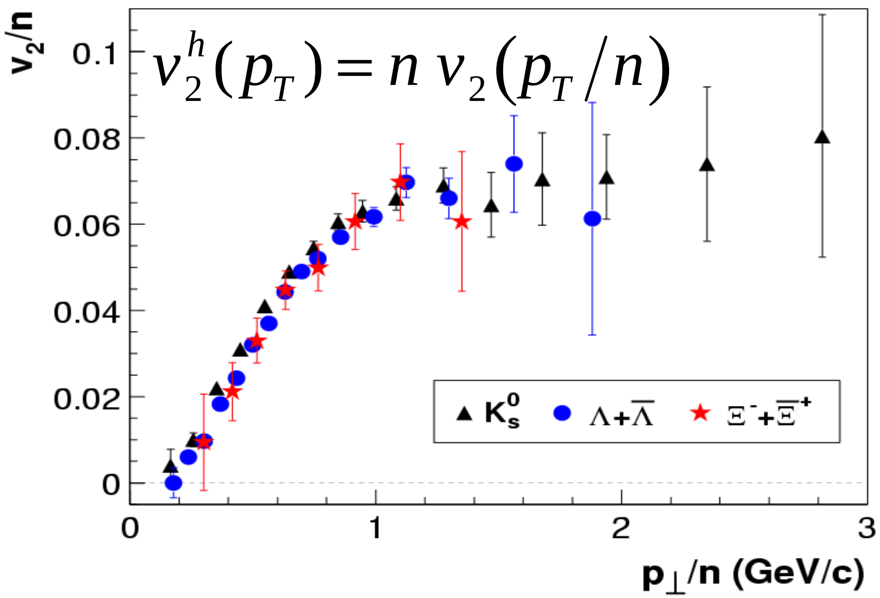
$$E\frac{dN_M}{d^3p} \propto C_M \left[w(p/2)\right]^2 \int d^3q \left|\Phi_M(q)\right|^2$$

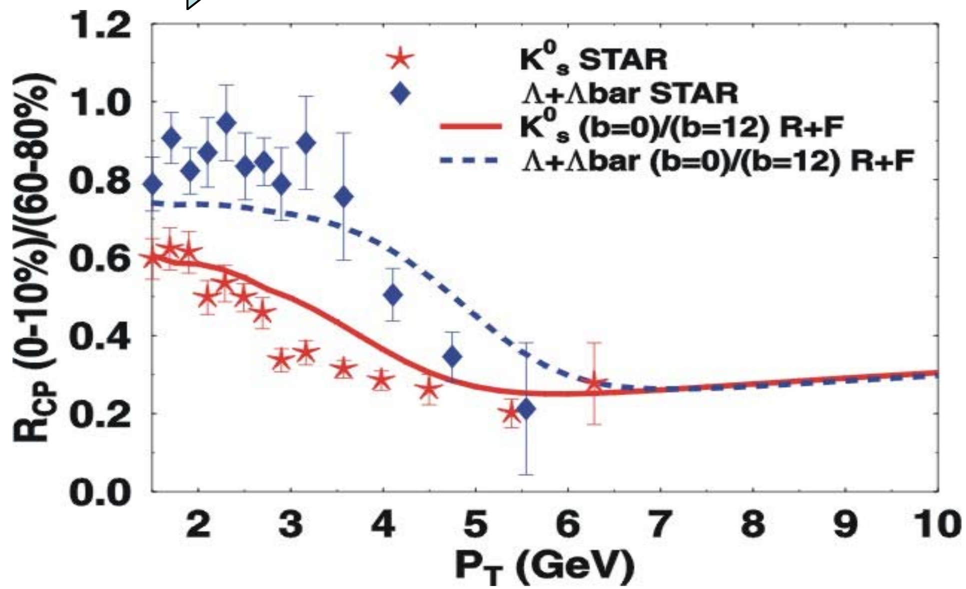
$$E\frac{dN_B}{d^3p} \propto C_B \left[w(p/2)\right]^3$$



Exp. Spectrum: recombination dominates
Powerlaw tail: fragmentation dominates

upper bound on p_T





More questions for the LHC (but also for RHIC)

- Discovery regime: Surprises ? Higher $\sqrt{s}$ = stronger medium effects?
  [Don’t ignore speculations: e.g. can we test strong CP- or P-violation?]

- Can LHC test the microscopic mechanism underlying ‘recombination-like’ phenomena, e.g. by testing associated particle production in a wider kinematical range? Can we determine the dynamics underlying simple \ quark counting rules?

- Can we establish and quantify at LHC thermal radiation from the medium, e.g. by having better control over the many background sources.

- How do we test the dynamical origion of the expected suppression pattern of heavy quarkonia? How do we disentangle and correct for possible recombination effects?

- How can we better connect lattice-QCD based predictions to the phenomenology of a strongly evolving dynamical environment?
  How do we broaden the reach of the experimental heavy ion program to other fundamental theoretical approaches?