Selected Topics in the Theory of Heavy Ion Collisions

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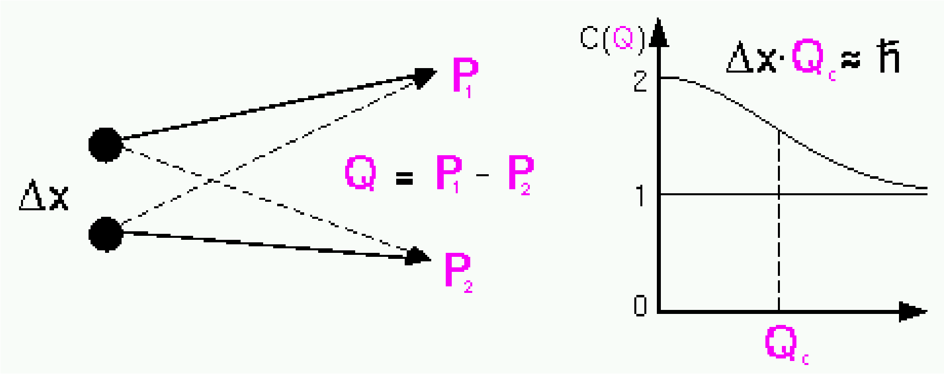
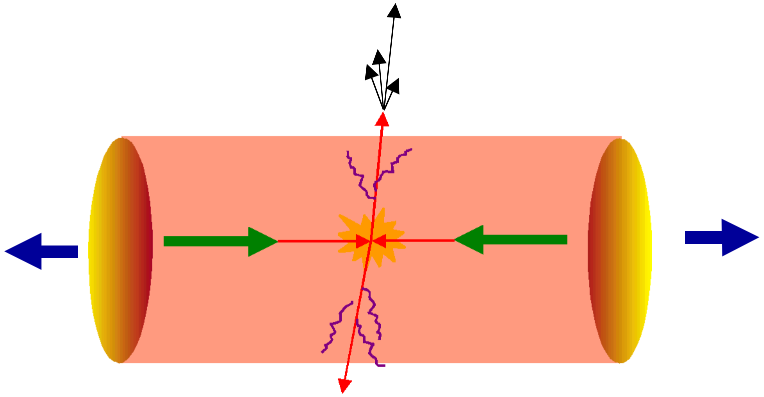
Summary of Lecture 3

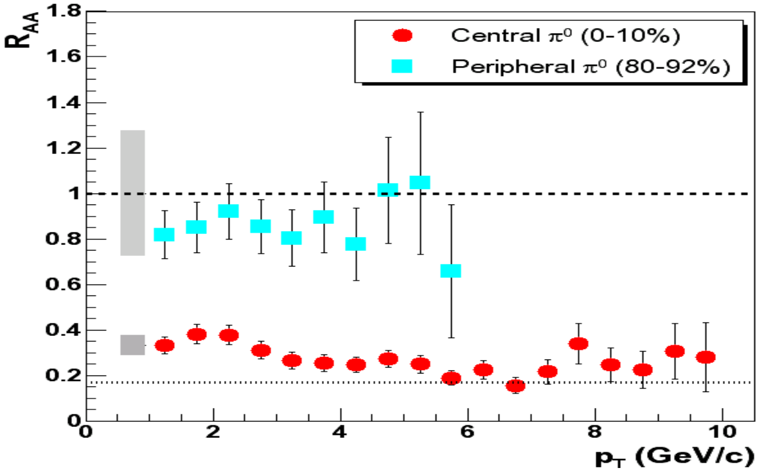


- Identical two-particle Correlations measure the space-time extension of collision region at freeze-out



- High-Q^2 processes in dense matter

  Parton propagation in matter results in
  - pt-broadening in initial and final state
  - energy loss of leading parent parton

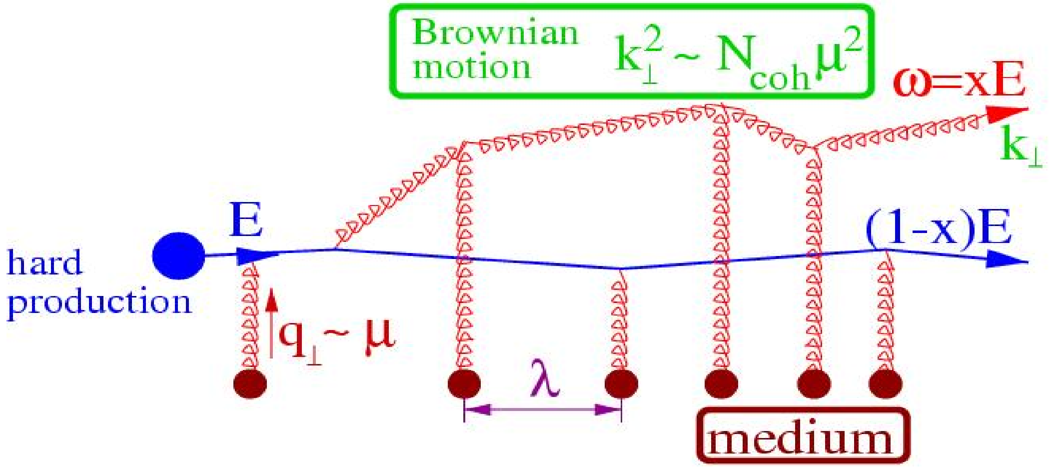


- Observable Consequences of “jet quenching”
  - suppressed leading hadron spectra
  - exp. test that this suppression is a final state effect
  - dependence on in-medium pathlength/centrality

- More consequences of “jet quenching”

→ Lecture 4

The medium-modified Final State Parton Shower



Medium characterized by transport coefficient:

$$\hat{q} = \frac{\mu^2}{\lambda} \sim n_{density}$$

- How much energy is lost ?

Characteristic gluon energy

Phase accumulated in medium: $\left\langle \frac{k_t^2}{2\omega}\Delta z \right\rangle \simeq \frac{\hat{q} L^2}{2\omega} \equiv \frac{\boxed{\omega_c}}{\omega}$

Number of coherent scatterings: $N_{coh} \simeq \frac{t_{coh}}{\lambda}, \quad \langle k_t^2 \rangle = \hat{q}\, t_{coh} \longrightarrow t_{coh} \simeq \frac{\omega}{2k_t^2} \simeq \sqrt{\frac{\omega}{\hat{q}}}$

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

Average energy loss $\Delta E \simeq \int^{\omega_c} d\omega\, \omega \frac{dI_{med}}{d\omega} \sim \alpha_s \omega_c = \boxed{\alpha_s \frac{1}{2} \hat{q} L^2}$

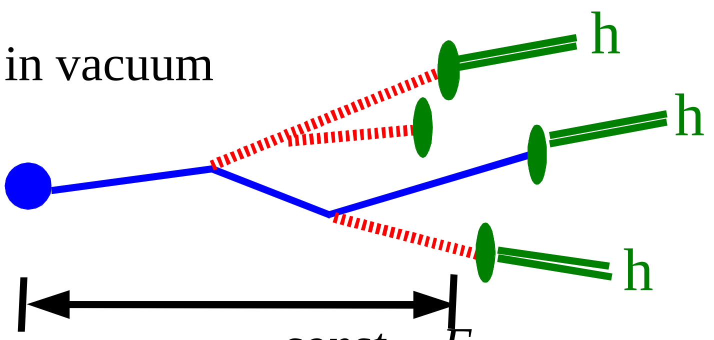
Lecture 4:
Hard Processes Escaping the Bulk

a. Leading Hadroproduction
  - Medium-modified Fragmentation Function
  - Trigger Bias
  - “Fragility” of the probe

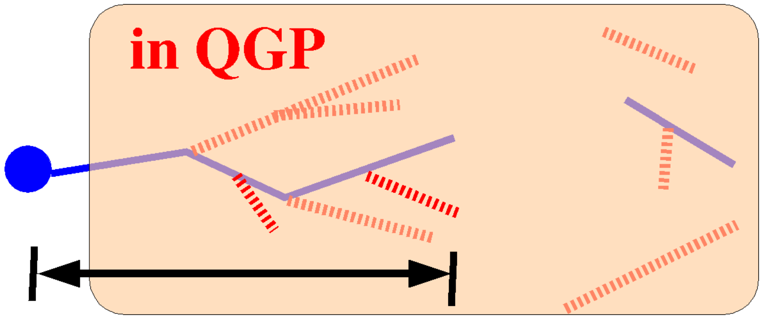
b. Jets and Jet-like particle correlations
  - Jet shapes and jet multiplicites at the LHC
  - Jet-like particle correlations at RHIC

c. Fragmentation and Hadronization at intermediate pt

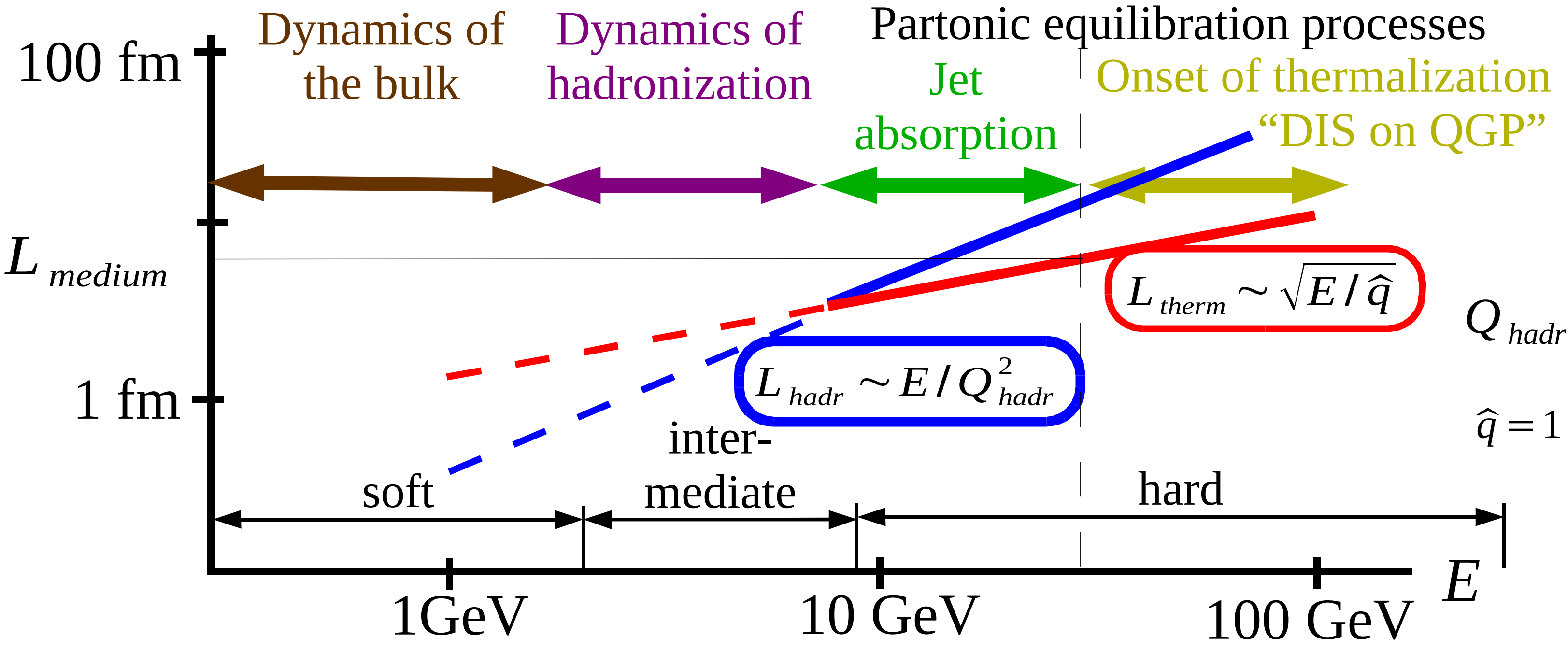
Hadronization versus Thermalization of Jets



$$L_{hadr} \sim \frac{const}{Q_{hadr}} \frac{E}{Q_{hadr}}$$



$$E \approx \Delta E = \frac{\alpha_s C_R}{4} \hat{q} L^2_{therm}$$



$$Q_{hadr} = 1\, GeV$$

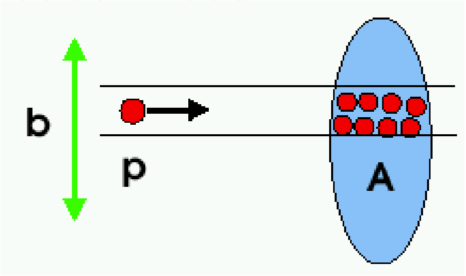
$$\hat{q} = 1 \frac{GeV^2}{fm}$$

Nuclear Modification Factor

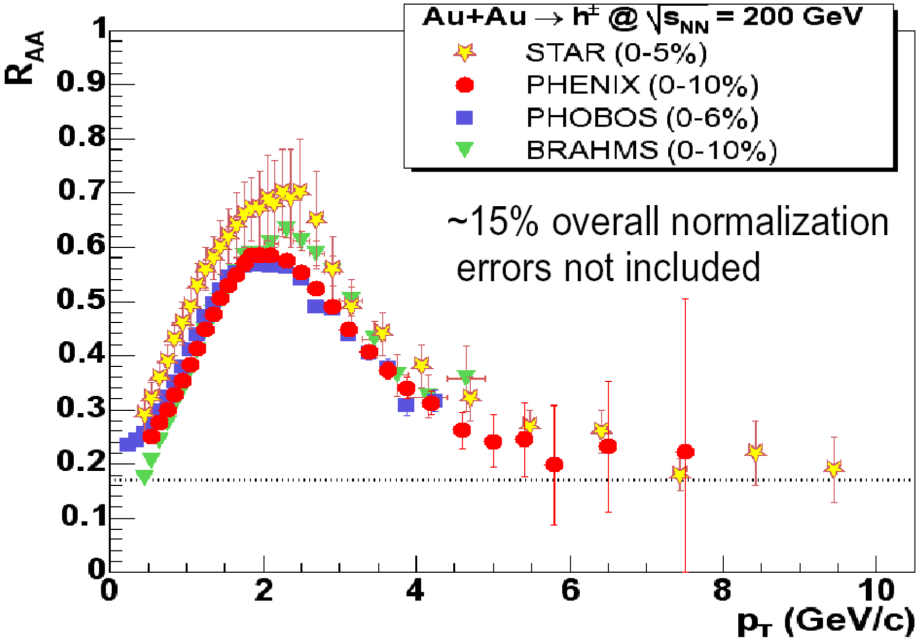
$$R_{AA}(p_t,\eta)=\frac{dN^{AA}/dp_t\,d\eta}{\boxed{n_{coll}}\,\boxed{dN^{NN}/dp_t\,d\eta}}$$

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

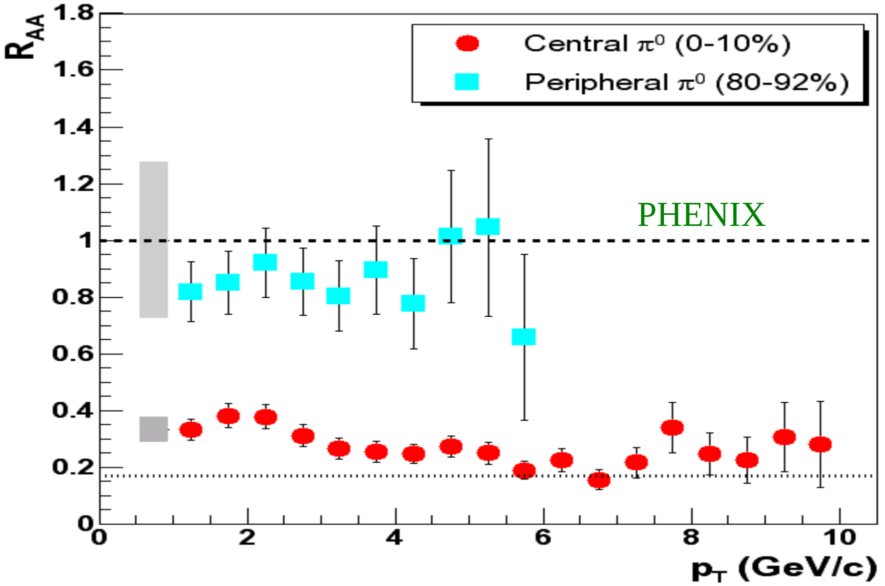
Glauber model



- Yield of leading hadrons in Au+Au
  - ➔ <u>suppressed</u> by factor 5 in 0-10 % most central collisions
  - ➔ unsuppressed in very peripheral (80-92 %) collisions



~15% overall normalization errors not included



PHENIX

Particle Species Dependence of Nuclear Modification

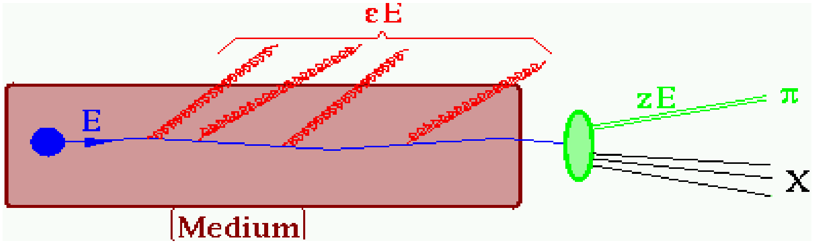
- Determines pt-range up above which hadronization occurs outside the medium

- High p_T $\quad L_{hadr} > L_{therm}$

$$p_T^{hadr} > 6-7\,GeV \Rightarrow p_T^{parton} > 8-10\,GeV$$

“parton thermalization”

(hadronization occurs outside medium)

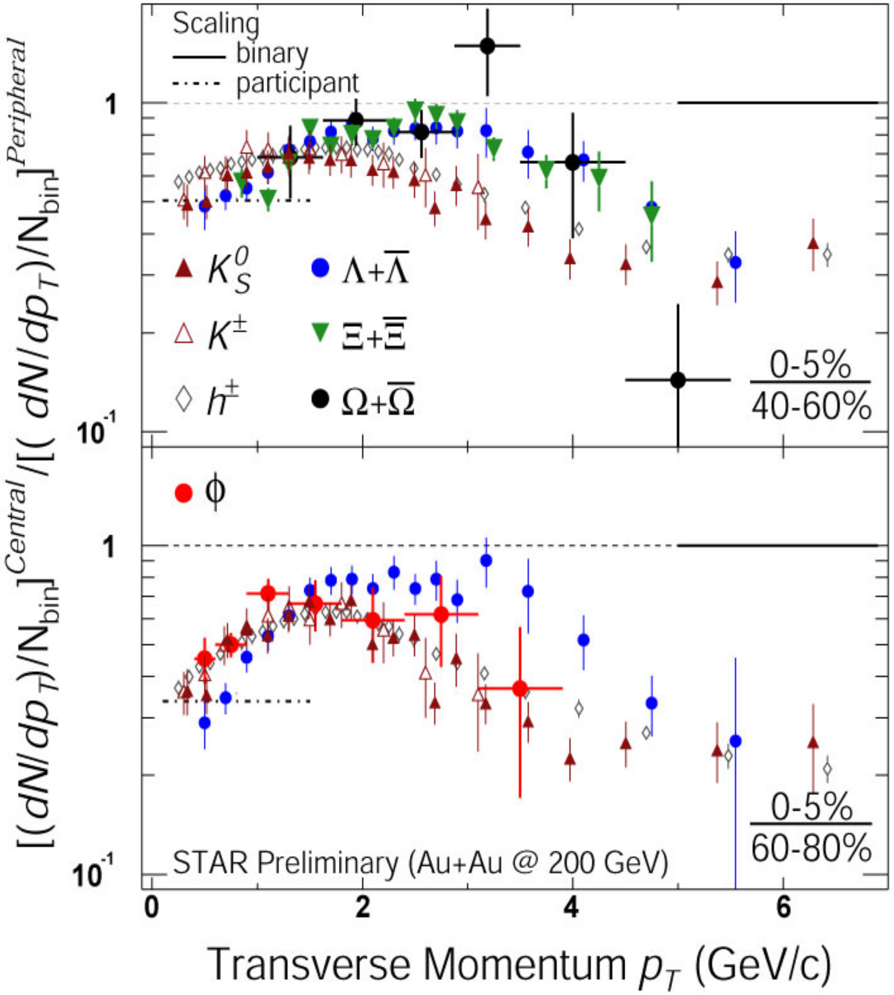


- Intermediate p_T $\quad L_{hadr} \sim L_{therm} \sim L_{med}$

$$2\,GeV < p_T^{hadr} < 6-7\,GeV$$

“dynamics of hadronization”

(hadronization interferes with the medium)

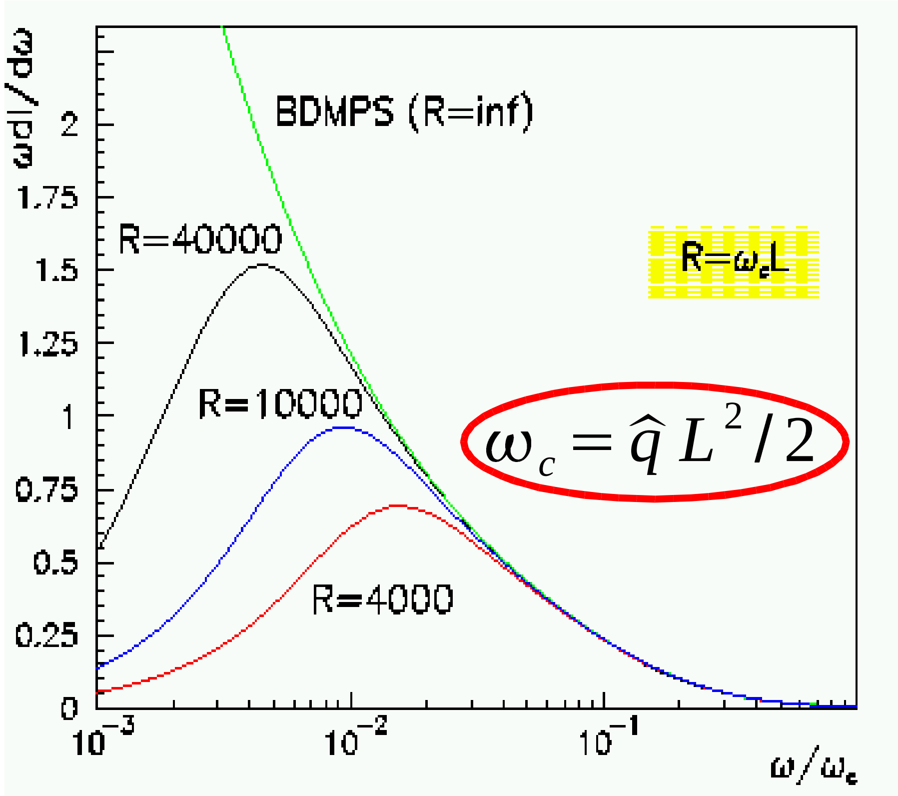


Hard Processes Escaping the Bulk

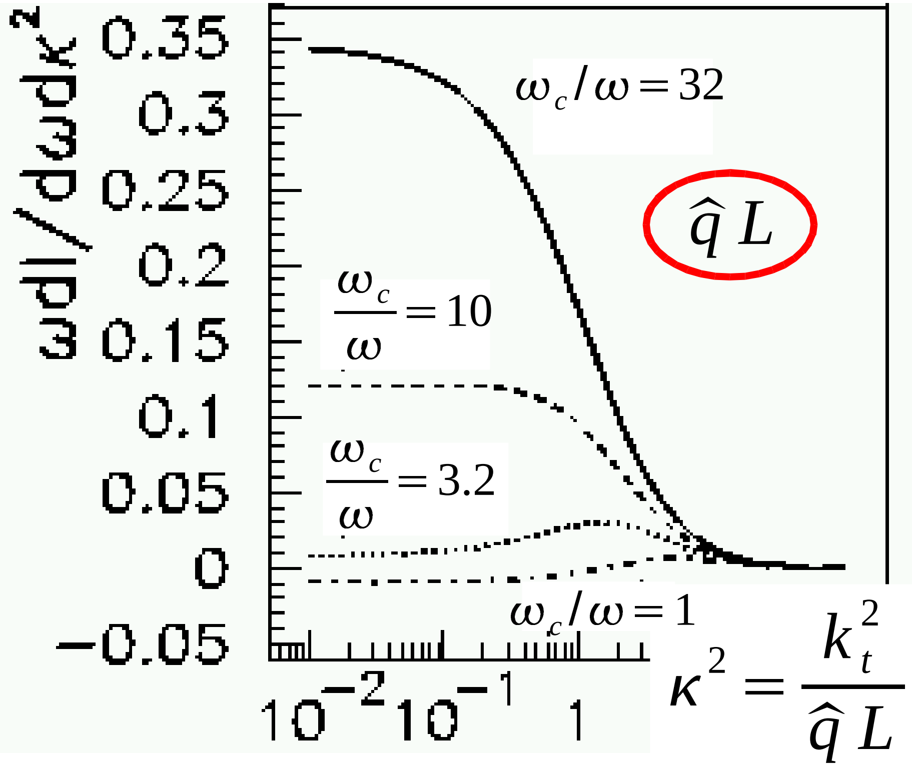
Parton Energy Loss and kt-Broadening are Connected

- energy loss of leading parton shows characteristic L^2 and $1/\sqrt{\omega}$ dependence

- kt-broadening of parton shower determined by Brownian motion $\propto L$



$\omega_c = \hat q L^2/2$



$\hat q L$

$$\kappa^2 = \frac{k_t^2}{\hat q L}$$

- k_t - integrated spectrum infrared safe

$$\frac{k_t^2}{\omega^2} \simeq \frac{\sqrt{\omega\, q}}{\omega^2} = \left(\frac{\omega}{\omega_c}\right)^{3/2} \frac{1}{R} < 1$$

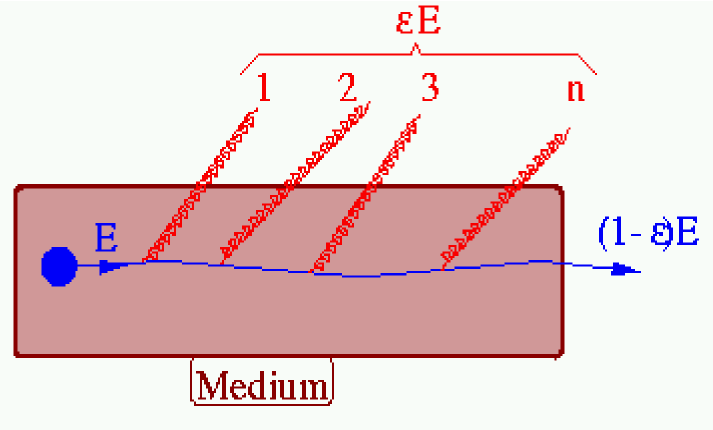
$$R = \hat q L^3/2$$

- kt-broadening determines where the energy lost by the parent parton is distributed to in phase space

Probability Distribution of Parton Energy Loss

Baier, Dokshitzer, Mueller, Schiff, JHEP 0109:033 (2001)

- Multiple independent gluon emission used to define the probability that leading parton loses fraction ϵ of its initial energy



$$P(\epsilon)=\sum_{n=0}^{\infty}\frac{1}{n!}\left[\prod_{i=0}^{n}\int d\omega_i\frac{dI}{d\omega_i}\right]\delta\left(\epsilon-\sum_i\omega_i\right)e^{-\int\omega\frac{dI}{d}\omega}=p(\epsilon)+p_0\delta(\epsilon)$$

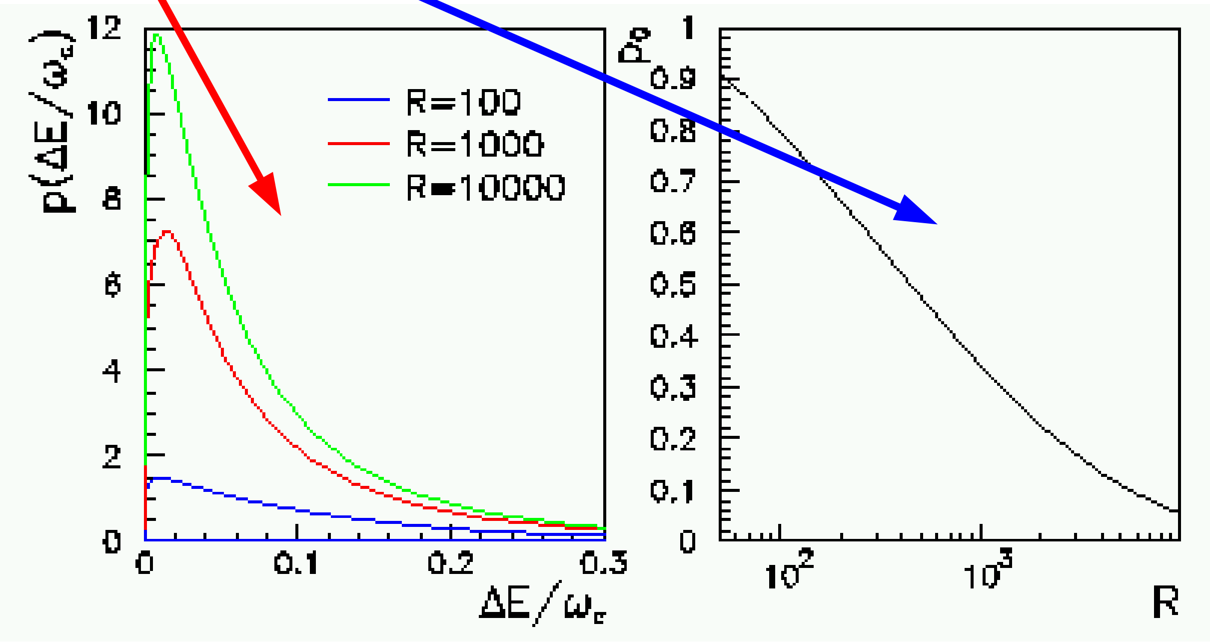
- Probability distribution of energy loss:

Average:

$$\langle\epsilon\rangle=\frac{\Delta E}{E}=\int d\epsilon\,\epsilon\,P(\epsilon)$$

Typical:

$$\epsilon_{max}<\langle\epsilon\rangle$$



Nuclear Modification Factor in Au+Au at RHIC

WORK IN PROGRESS

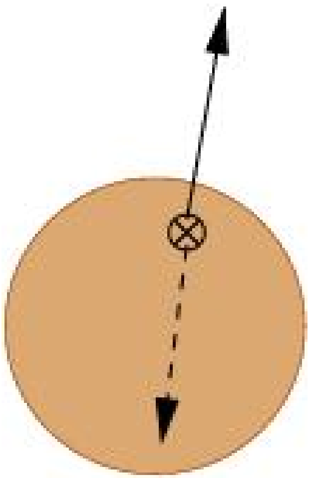
Eskola, Honkanen, Salgado, Wiedemann, in preparation

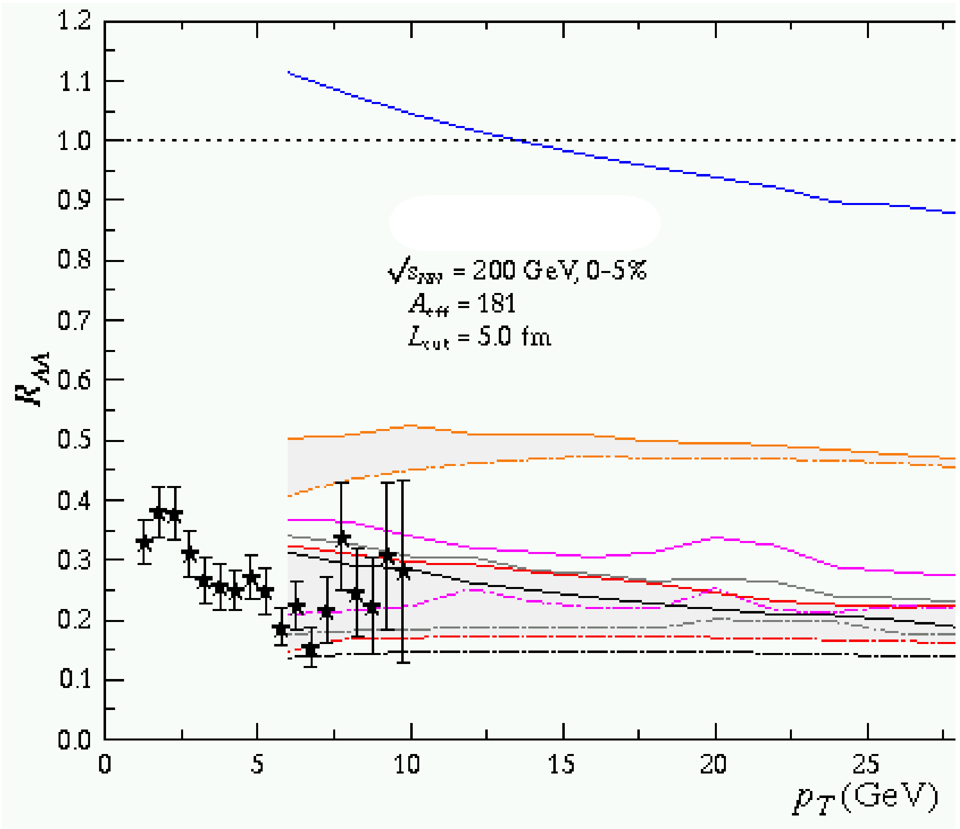
- Calculation of quenched high-pt hadronic spectra

$$d\sigma^{AA\to f+X}_{(vac)} = \sum_{ijk} \underbrace{f_{i/A}(x_1)\times f_{j/A}(x_2)}_{nuclear\ \ modified\ \ pdfs}\times\hat{\sigma}_{ij\to f+k}$$

$$d\sigma^{AA\to h+X}_{(med)} = \sum_{f} d\sigma^{AA\to h+X}_{(vac)} \times \underbrace{P(\Delta E, L, \hat{q})}_{quenching\ \ weight}\times \underbrace{D^{(vac)}_{f\to h}(z)}_{fragementation}$$

- surface emission limits sensitivity to density $\propto \hat{q}$





$$\hat{q} = 0\,\frac{GeV^2}{fm}$$

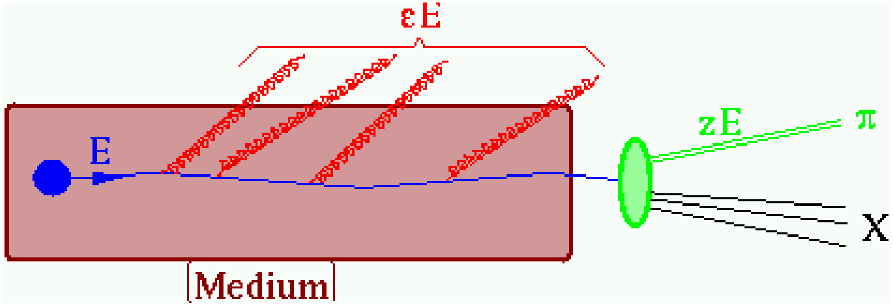
$$\hat{q} = 1\,\frac{GeV^2}{fm}$$

$$\hat{q} = 5\,\frac{GeV^2}{fm}$$

Medium-Modified Fragmentation Functions

(one element of the calculation on the previous slide)

- Basic assumption: parton energy loss occurs prior to fragmentation



$$D_{h/q}^{med}\left(z,Q^2\right)=\int_0^1 d\epsilon\, P(\epsilon)\frac{1}{1-\epsilon}D_{h/q}\left(\frac{z}{1-\epsilon},Q^2\right)$$

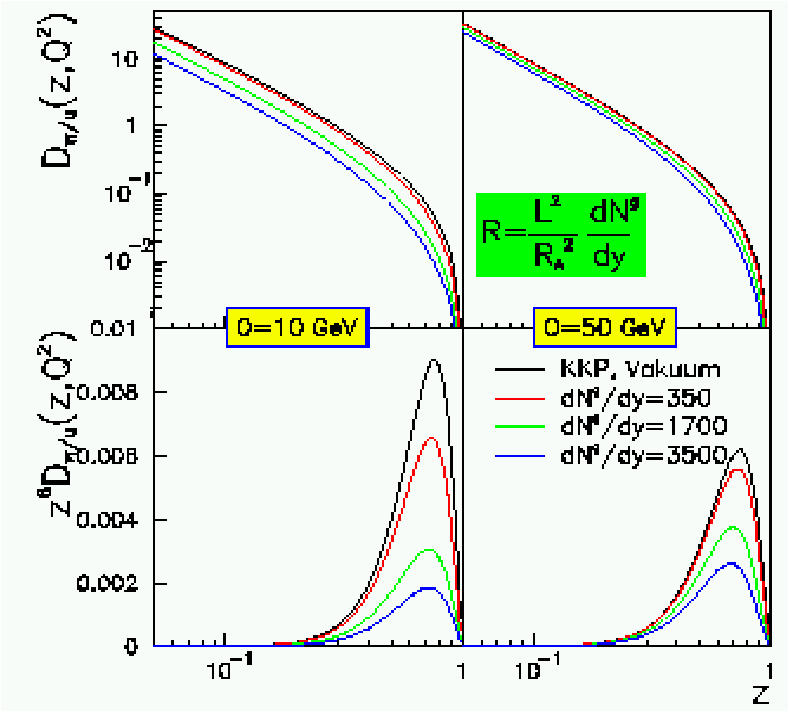
- Trigger bias:

The fragmentation and e-loss of partons show a wide probability distributions.
Hadronic pt-spectrum is dominated by the tails of the distribution for which the parton has
- a very hard fragmentation (large z)
- a very small energy loss

Quantitatively, this depends on steepness of partonic pt-spectrum

$$\propto \frac{z^n}{\left(p_T^{hadron}\right)^n} D_{h/q}^{med}\left(z,Q^2\right)$$

Salgado, Wiedemann Phys. Rev. Lett. 89, 092303 (2002)



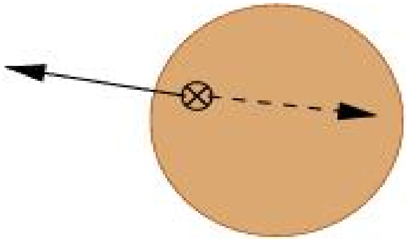
Summary Slide on Trigger Bias

Triggering on a high-pt hadron, one selects:

- a bias favouring hard fragmentation, determined by steepness of spectrum

$$\propto \frac{z^{n}}{\left(p_T^{hadron}\right)^{n}} D_{h/q}^{med}\left(z, Q^{2}\right)$$

- a bias favouring small in-medium pathlength (surface emission)



- a bias favouring small energy loss for fixed in-medium pathlength

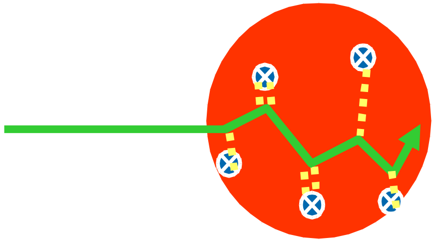
Average:

$$\boxed{\langle \epsilon \rangle = \frac{\Delta E}{E} = \int d\epsilon\, \epsilon\, P(\epsilon)}$$

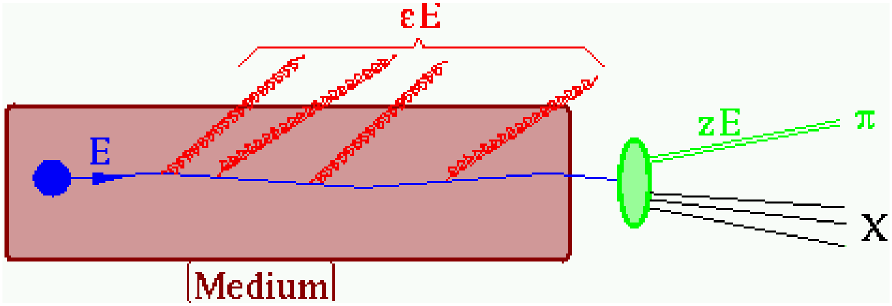
Typical:

$$\boxed{\epsilon_{max} < \langle \epsilon \rangle}$$

- a bias favouring initial-state pt-broadening in the direction of the trigger



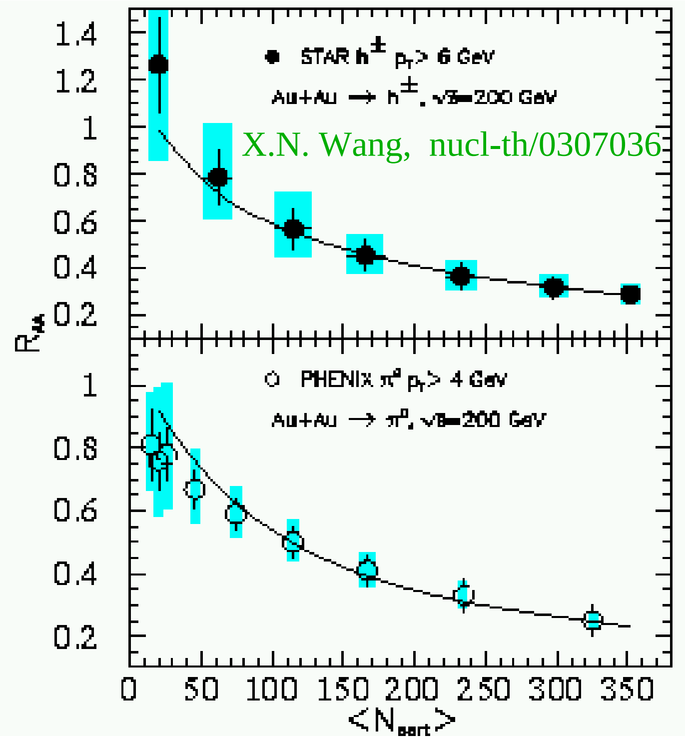
Leading Hadroproduction- Centrality Dependence



suppression of leading
hadrons governed by

$$\hat{q}L^2$$

Centrality dependence tests
interplay of density and geometry



suppression used to deduce

X.N. Wang, nucl-th/0307036

$$\epsilon\big|_{\tau = 0.2fm/c} \sim 15 \frac{GeV}{fm^3} \sim \epsilon_{Bjorken}(\tau_0)$$

scaling

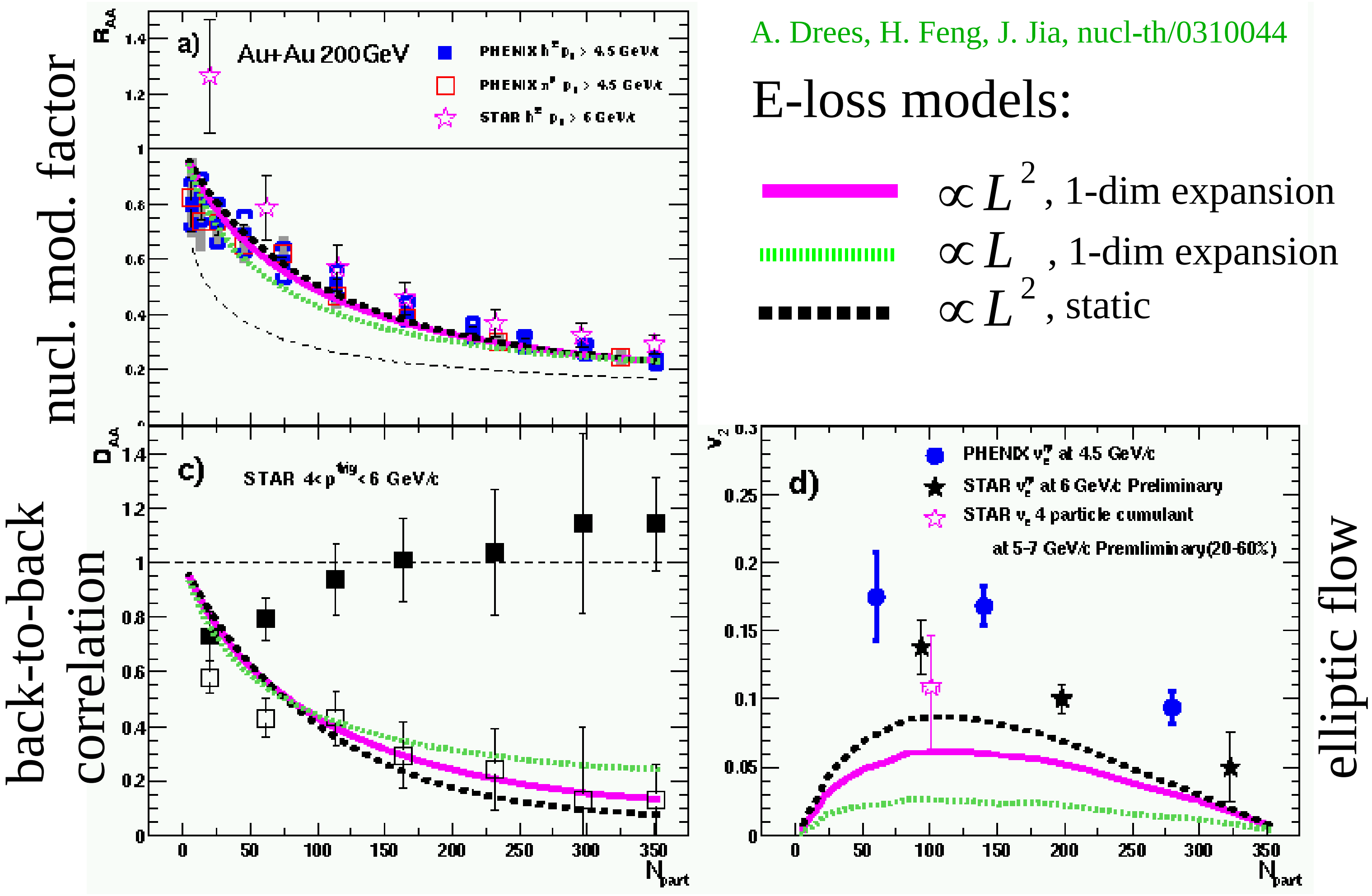
$$\longrightarrow \tau^{life}_{QGP} = 4 \pm 2 \pm ?\ fm/c$$

Uncertainties:
- modelling of dynamics and geometry
- finite energy constraints

Sensitivity of Leading Hadron Spectra

A. Drees, H. Feng, J. Jia, nucl-th/0310044

E-loss models:

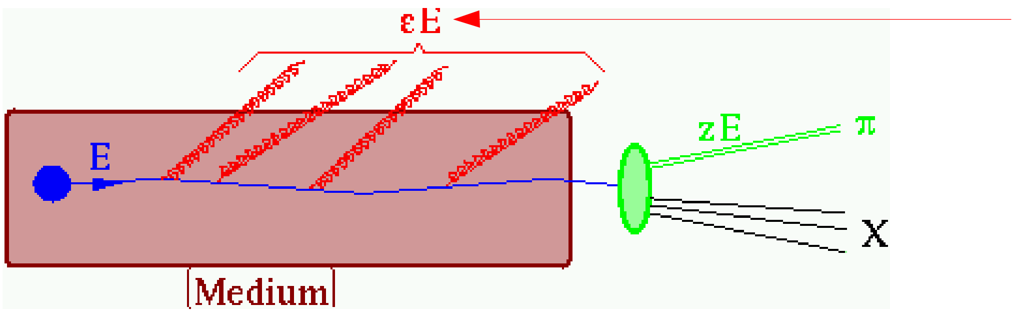


- ▬ $\propto L^2$, 1-dim expansion
- ┈ $\propto L$, 1-dim expansion
- ■■■ $\propto L^2$, static

Are there more direct tests of the energy loss mechanism ?

Going beyond Leading Hadron Spectra

How does the medium-induced radiation evolve towards thermal and chemical equilibrium ?



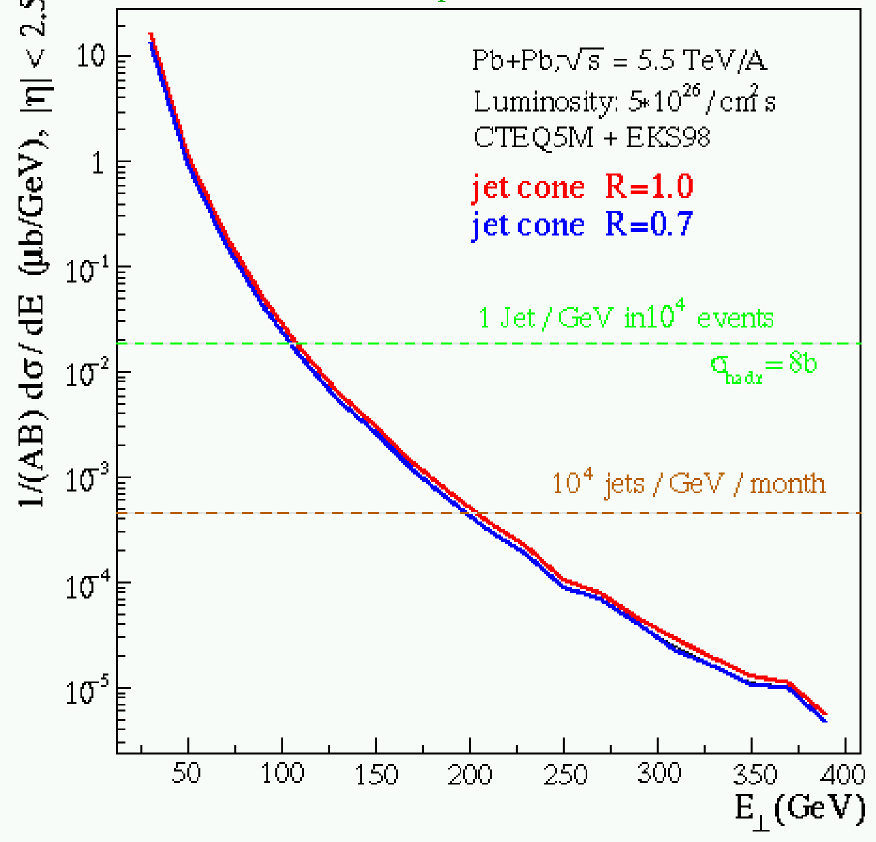
Where does this associated radiation go to ?

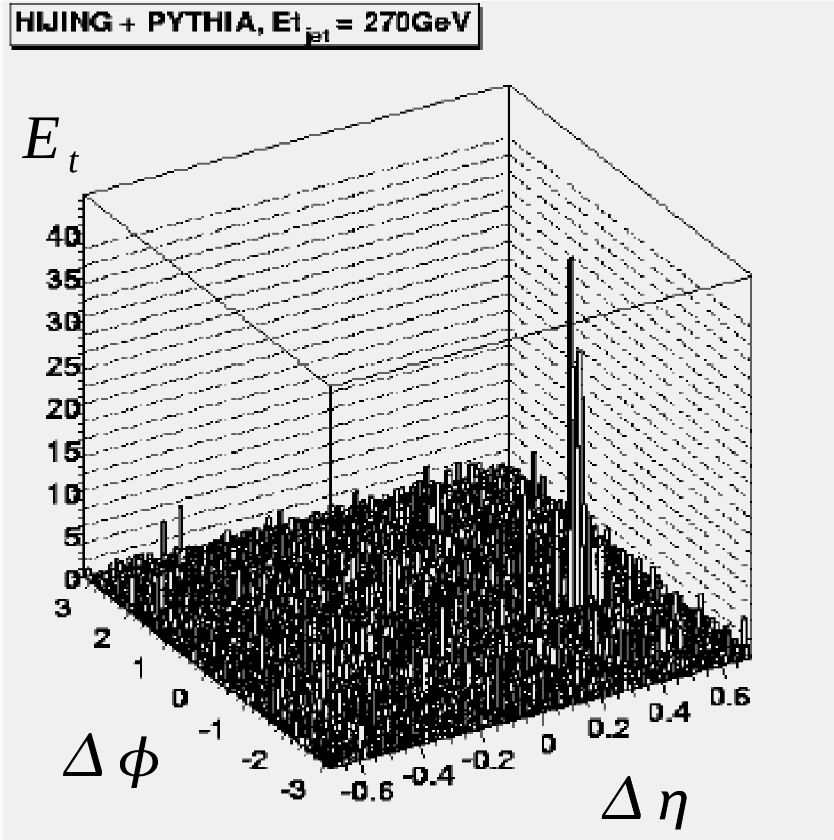
Associated radiation:

- How to distinguish from a high-multiplicity background ?
- What is the angular distribution of the radiated energy ?
- What is its spectrum ? Exponential or powerlaw ?
- Does it induce high-pt hadronic correlations ?
- What is its chemical composition ?

Jets in Heavy Ion Collisions at the LHC

A. Accardi et al., hep-ph/0310274
CERN TH Yellow Report

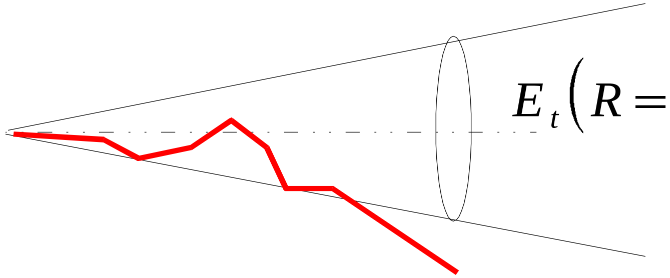




- Experiments at LHC will detect jets above background
- How can we quantify their medium modifications above background ?
  What do we learn from them ?

Medium-modified Jet Shapes

- How much energy is radiated outside the “vacuum” jet cone due to medium effects ?



$$E_t\left(R=\sqrt{\Delta\eta^2+\Delta\phi^2}\right)$$

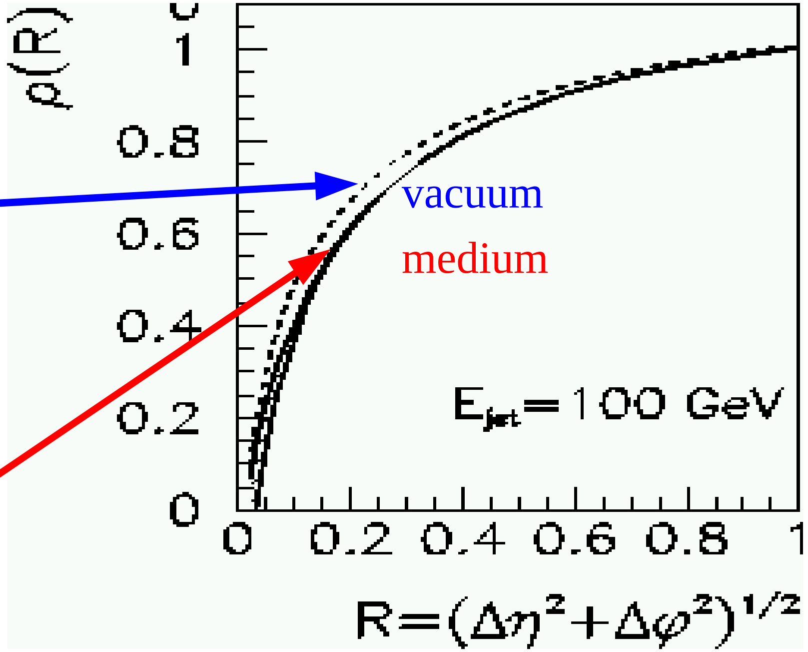
Energy fraction deposited
in fixed jet cone R decreases

$$\boxed{\rho_{vac}(R)=\frac{1}{N_{jets}}\sum_{jets}\frac{E_t(R)}{E_t(R=1)}}$$

use Fermilab D0 parametrization

$$\boxed{\rho_{med}=\rho_{vac}-\frac{\Delta E_t(R)}{E_t(R=1)}+\frac{\Delta E}{E}\left(1-\rho_{vac}\right)}$$

Salgado, Wiedemann, hep-ph/0310079



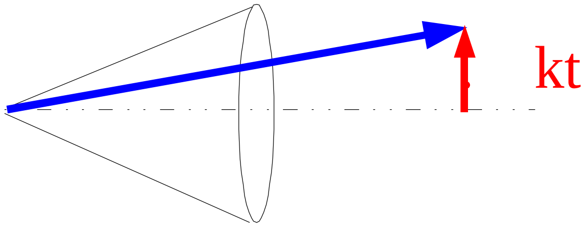
- Broadening of jet shape is small

  difficult to measure above background

- Jet Cross sections expected to scale with number of binary collisions

Medium-modified Jet Multiplicities

- Multiplicity within small jet opening cone



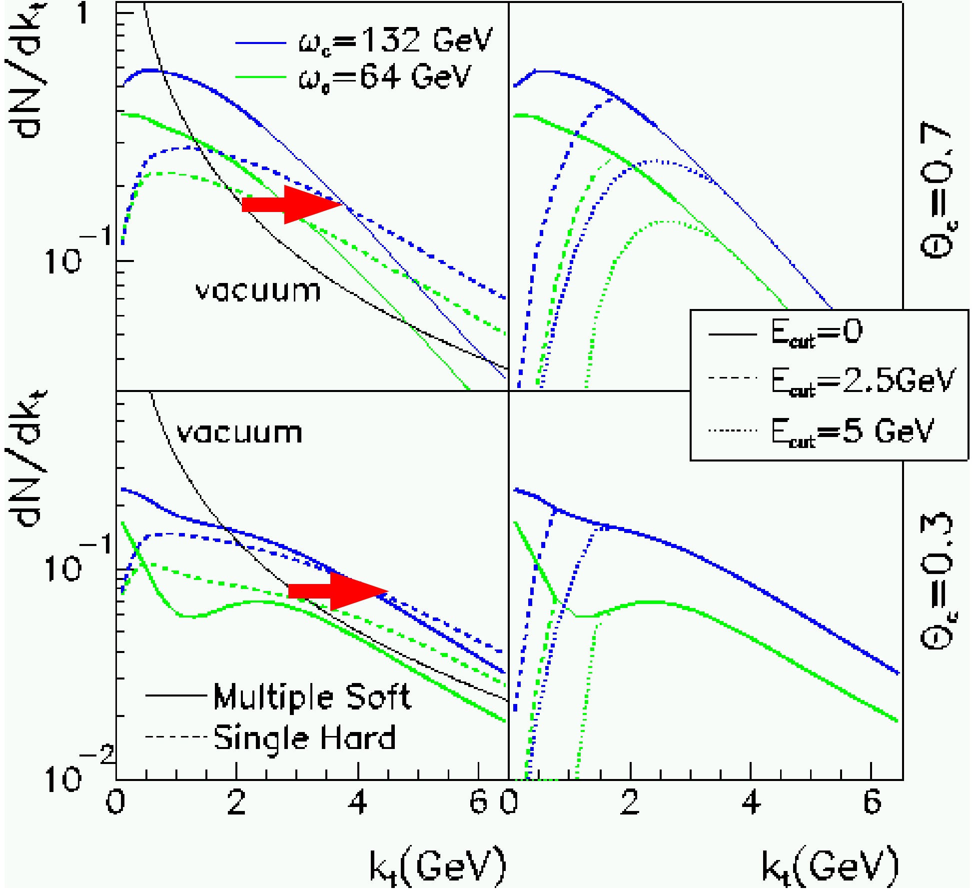
- At large kt, unaffected by soft high multiplicity background

- Kt-broadening sensitive to

$$\hat{q}\,L$$

Jet Heating

Salgado, Wiedemann, hep-ph/0310079



Theory predicts

- Characteristic L- dependence

$$\Delta E \simeq \alpha_s \omega_c = \alpha_s \frac{1}{2} \hat{q} L^2$$

- Dependence on the identity of the parent parton

- Relation between energy loss and pt-broadening

$$\Delta E \propto \hat{q} L^2 , \quad \langle p_T^2 \rangle \propto \hat{q} L$$

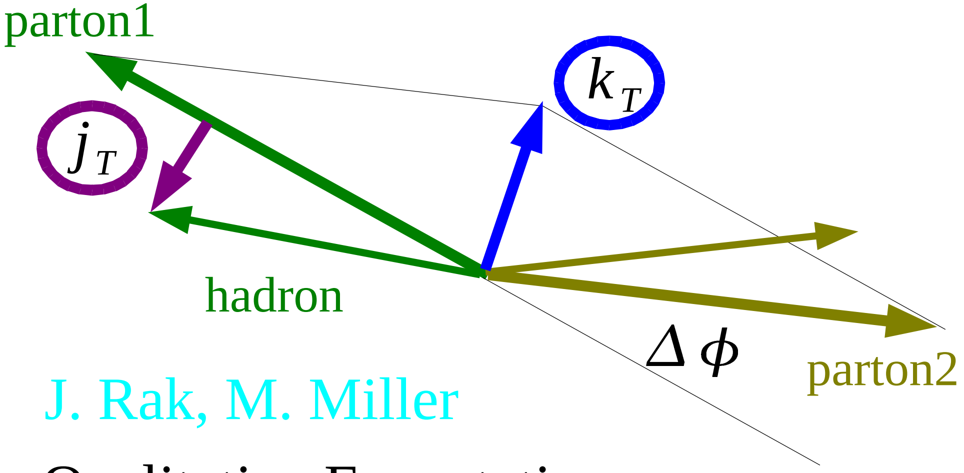
- Dependence on other properties of the medium
  (see seminar talk next month)

Experimental Tests

- ➔ leading hadron spectra
  as function of centrality and
  orientation w.r.t. reaction plane
- ➔ jets and jet-like correlations
- ➔ charmed (beauty) hadrons
- ➔ $p/\bar{p}$ - ratio at high pt
- ➔ hadroproduction associated to high-pt trigger particles
- ➔ jet shapes and jet multiplicity distributions

Some Recent Results from RHIC
on “jet-like” particle correlations

Shapes of “Jet” Fragmentation: p+p and d+Au



J. Rak, M. Miller

For jets: $k_T = p_T^{jet} \sin(\Delta\phi)$

$$j_T = p_T^{hadr} \sin(\theta_{jet-hadr})$$

For leading di-hadrons:

$$\langle|k_T|\rangle \approx \frac{\langle p_T^{hadr}\rangle}{\langle z\rangle}\sqrt{\sigma_{Far}^2 - \sigma_{Near}^2}$$

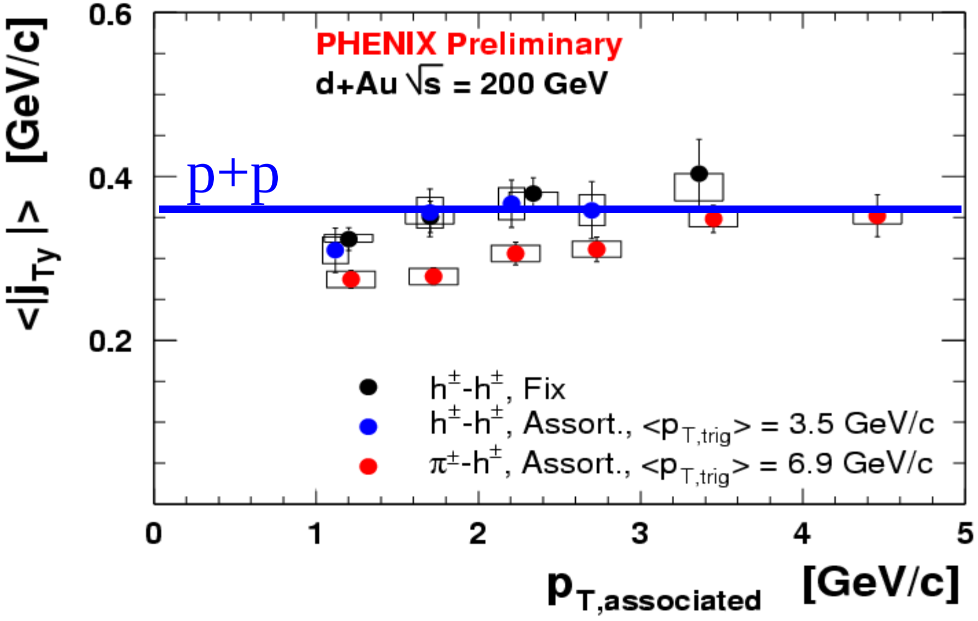
$$\langle|j_T|\rangle = \langle p_T^{hadr}\rangle \sin\left(\sigma_{Near}/\sqrt{\pi}\right)$$

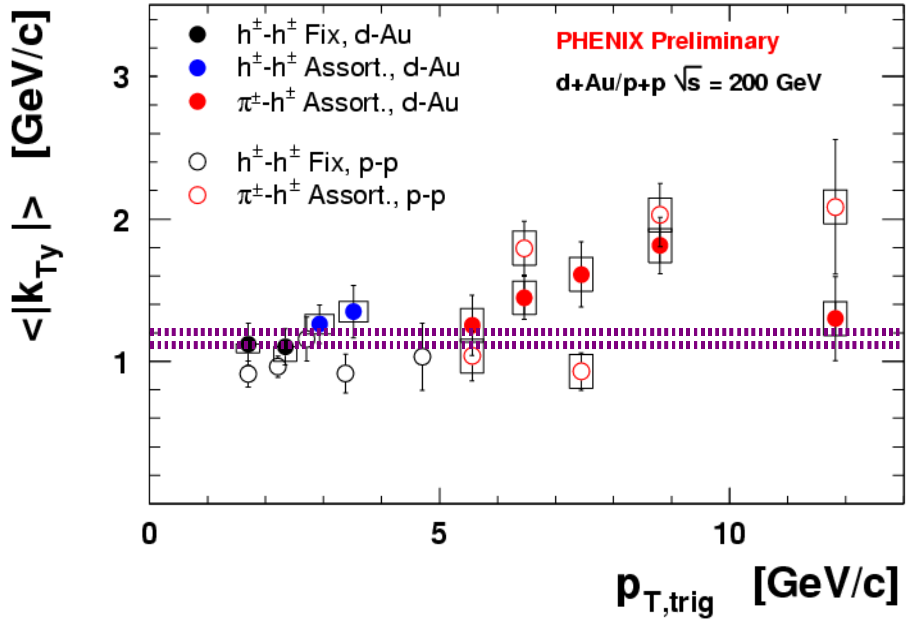
Qualitative Expectation:

jt-broadening –> final state effect

kt-broadening --> initial state effect

no significant kt-broadening in d+Au

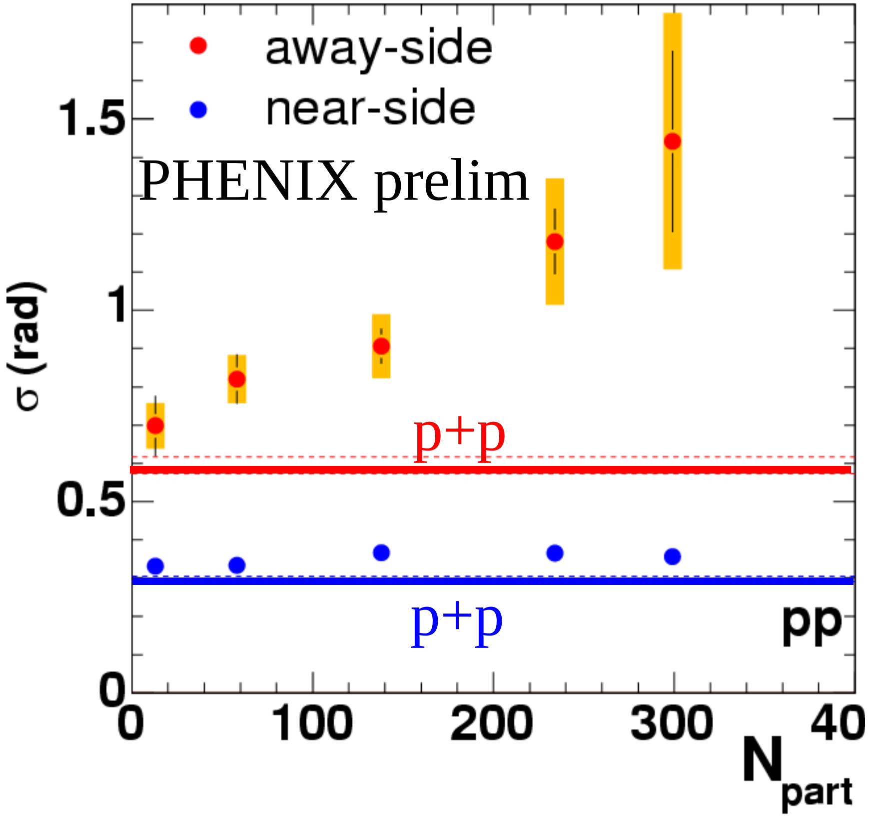




In Au+Au, away-side “Jet” broadens

$$\left(2.5 < p_T^{trig} < 4.0\right) \wedge \left(1.0 < p_T^{assoc} < 2.5\right)$$

J. Rak



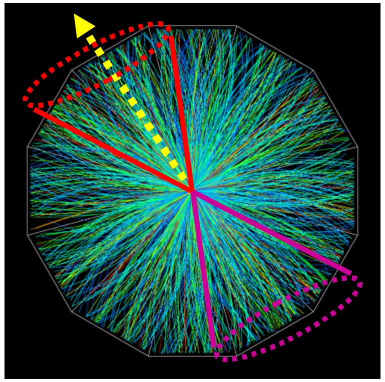
Significant interaction of away-side “jet” confirmed by broadening.

Away-side associated particle in general not leading particle of the away-side parent parton.

pt-Distribution Associated to High-pt Particle

Near: $4 < p_T^{trig} < 6\, GeV/c$

$|\Delta\phi| < 1.1, |\Delta\eta| < 1.4$



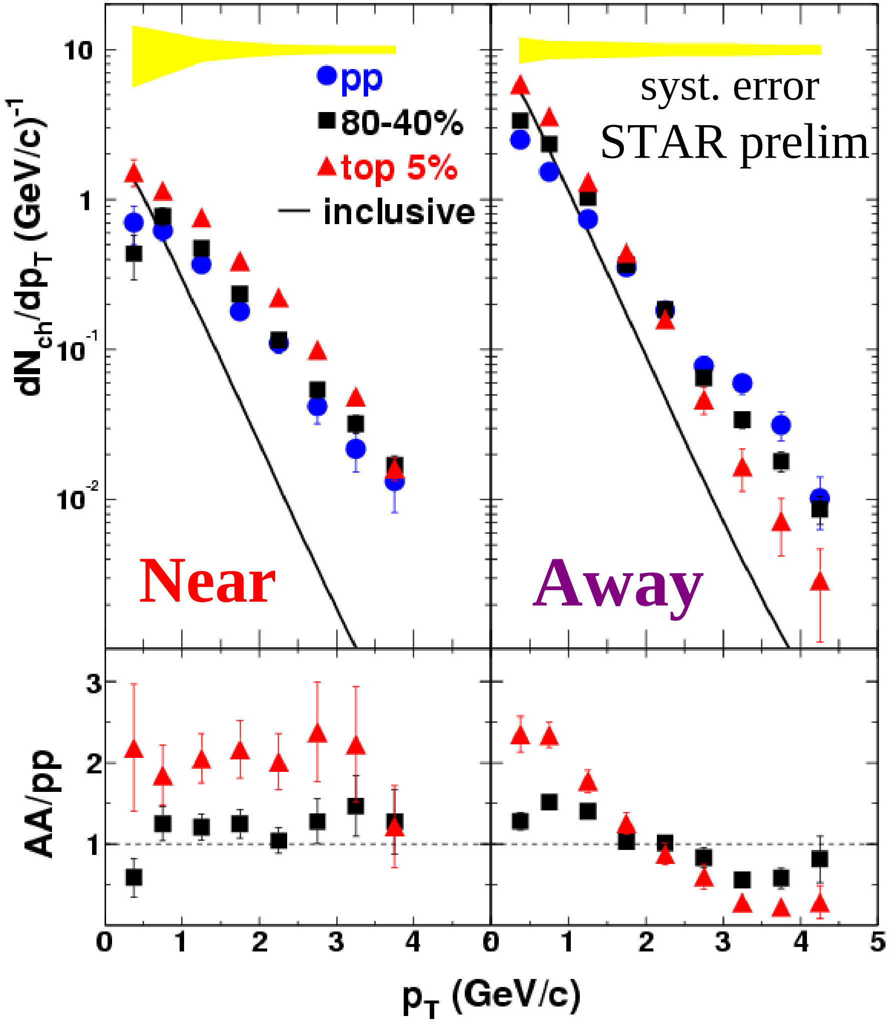
Away: $|\Delta\phi - \pi| < 1.1, |\Delta\eta| < 1.1$

Near: more multiplicity at all pt,
consequence of larger initial
parton energy for same trigger pt ?
(implies some near-side e-loss)

Away: energy of initial parton converted
to lower pt particles,
(implies larger parton e-loss in
medium but why does pt-shape differ
qualitatively from near-side ?)

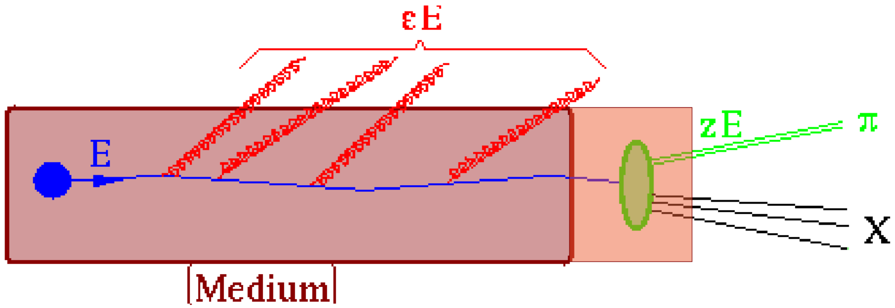
All associated pt

$0.15 < p_T^{assoc} < 4\, GeV/c$



Fuqiang Wang

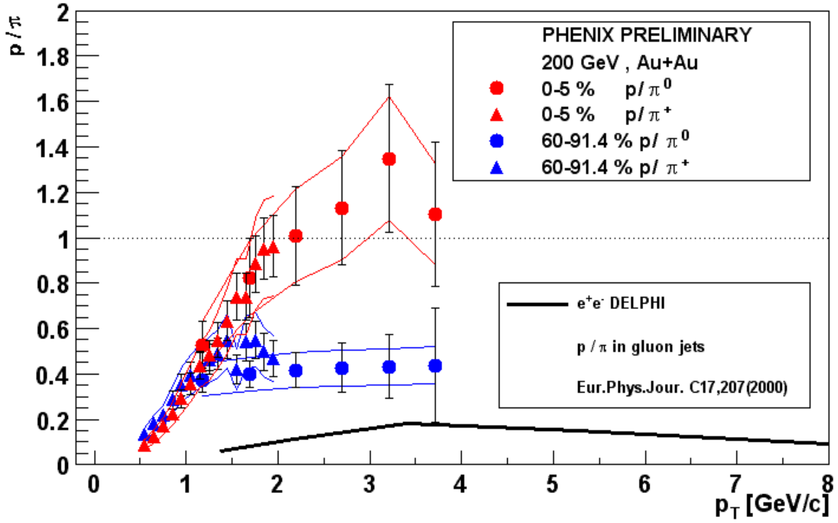
Intermediate pt

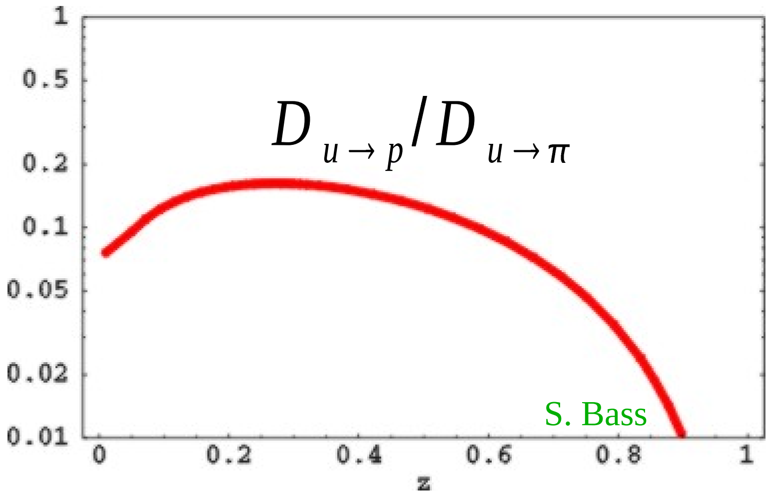


Fragmentation inside the medium:
what happens now ?

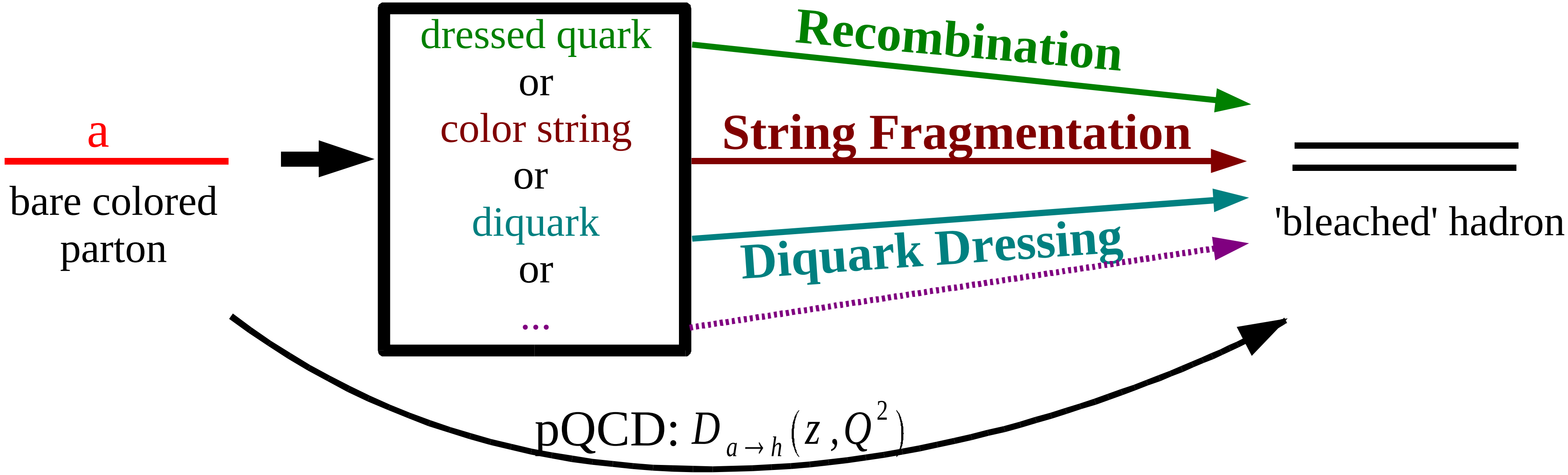
Breakdown of Independent (pert.) Fragmentation

- Parton energy loss does not affect ratio $D_{q\rightarrow p}/D_{q\rightarrow\pi}$ in contrast to intermediate pt data





- How does the bleaching of colour proceed dynamically – medium dependence tests models



a

bare colored parton

dressed quark
or
color string
or
diquark
or
...

Recombination

String Fragmentation

Diquark Dressing

'bleached' hadron

pQCD: $D_{a\rightarrow h}(z,Q^2)$

Fragmentation versus Recombination

start from quark spectrum: $w_\alpha(P/z)$

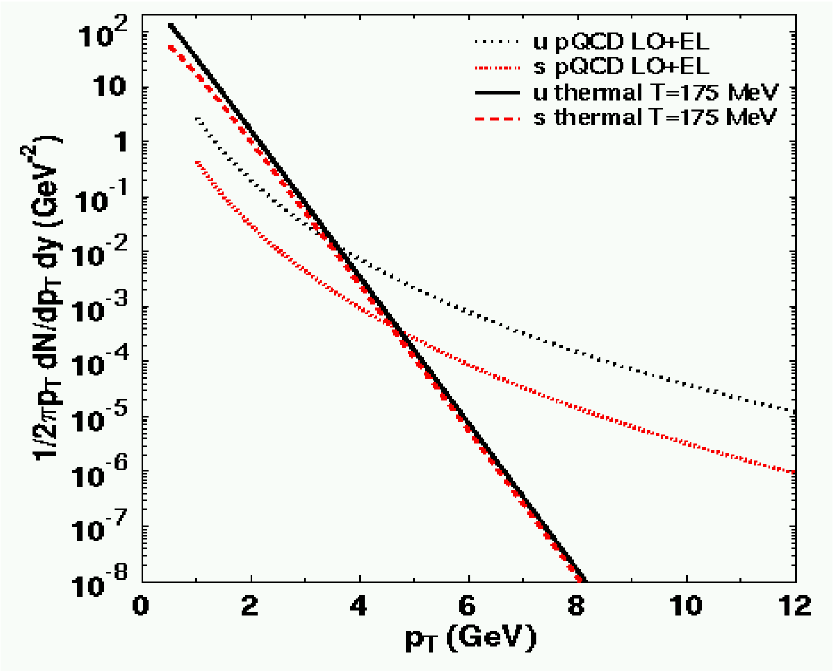
- Fragmentation:

$$E\frac{dN_h}{d^3P} = \int_0^1 \frac{dz}{z^2} w_\alpha(P/z) D_{\alpha\to h}(z)$$

- Recombination Model

$$E\frac{dN_M}{d^3P} \sim C_M [w_\alpha(P/2)]^{\textcircled{2}} \int d^3q \left|\phi_M(q)\right|^2$$

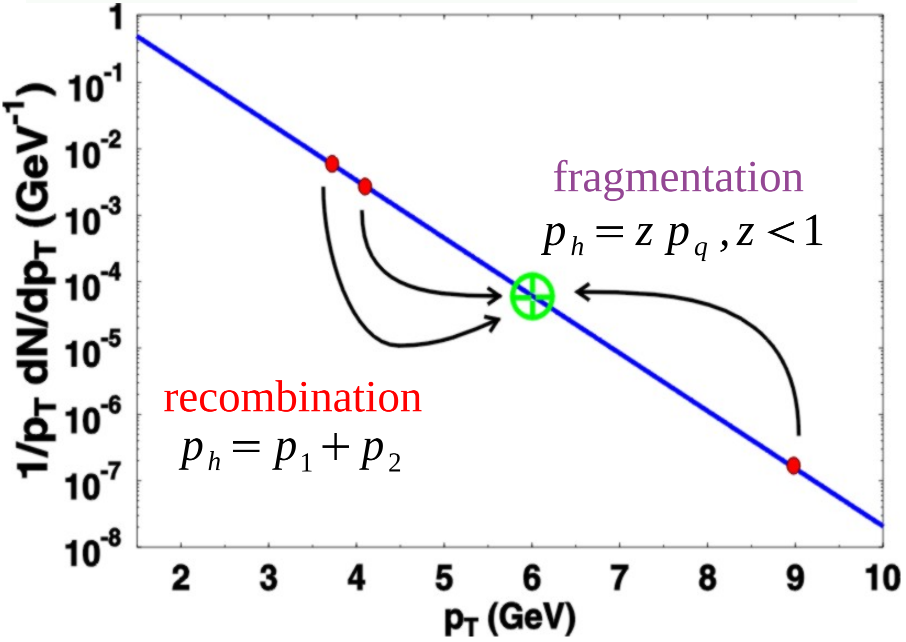
$$E\frac{dN_B}{d^3P} \propto C_B [w_\alpha(P/3)]^{\textcircled{3}}$$



Range of applicability: intermediate pt

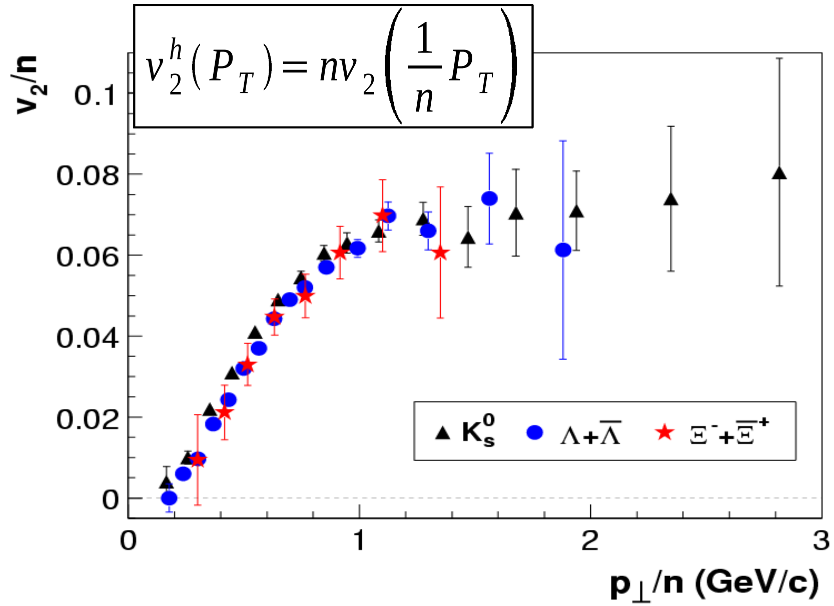
Exp. spectrum: recombination dominates
Powerlaw tail: fragmentation dominates
→ upper bound on pt

This is one of the models discussed currently to account for intermediate pt



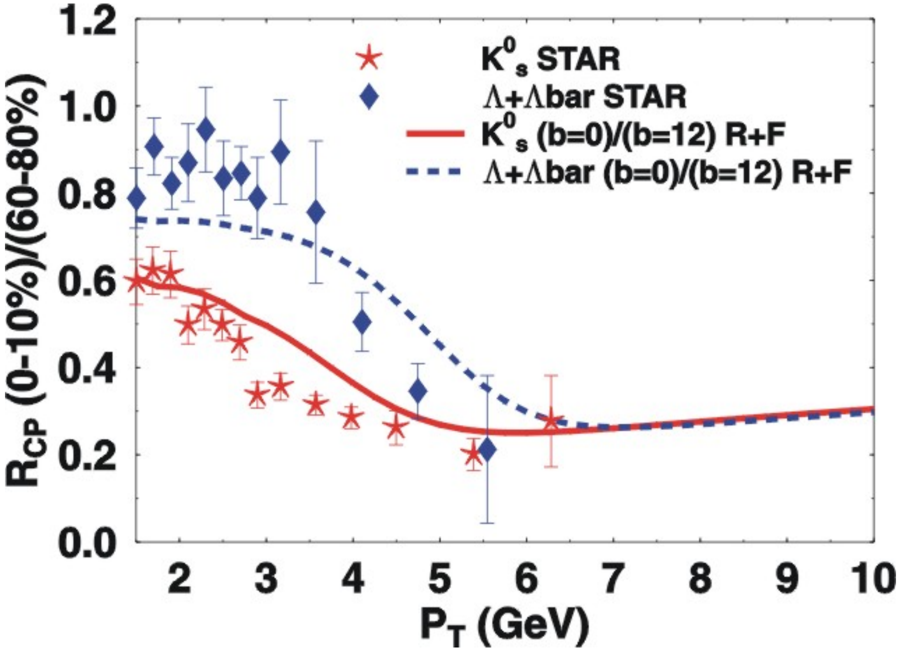
Successes and Suggestive Features of Recombination

- Elliptic Flow is significantly larger for baryons than for mesons at intermediate pt
  - if rescaled by number of valence quarks, values are consistent
  - sign of a common underlying partonic flow of size $v_2(p_t/n)$?



$$v_2^h(P_T) = n v_2\left(\frac{1}{n} P_T\right)$$

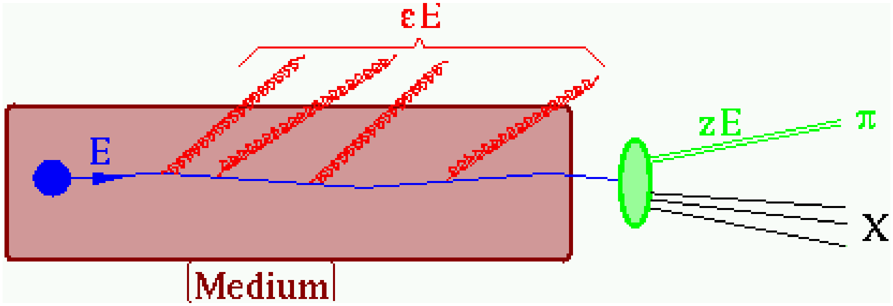
- In pt-spectra, baryon excess at intermediate transverse momentum can be accounted for, assuming recombination of valence quarks.



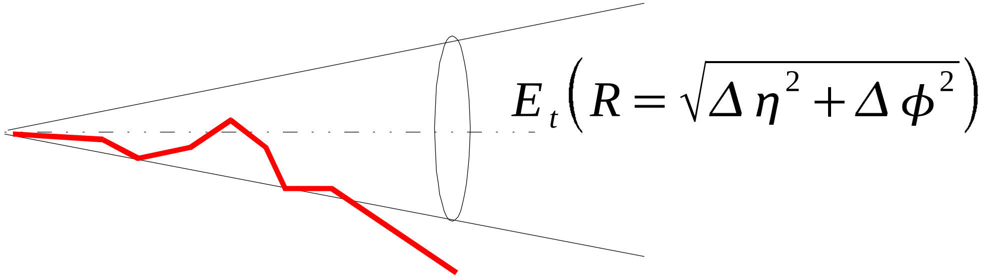
- Recombination Models do not address
  - what happens to gluonic degrees of freedom ?
  - dynamics of the recombination
  - ...

Summary of Lecture 4

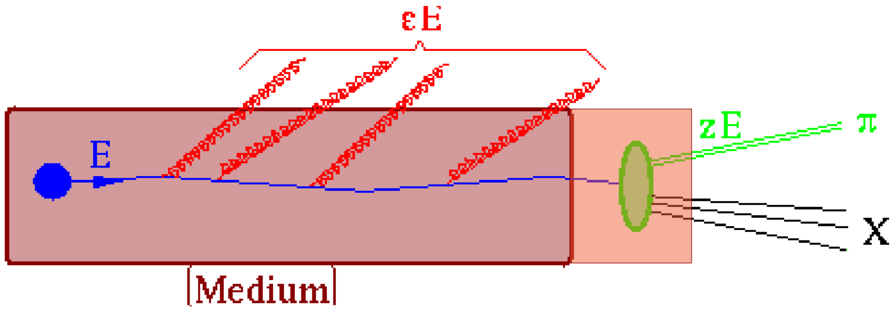
- Leading Hadroproduction
  - sensitive to in-medium pathlength and density of matter
  - sensitivity reduced by trigger bias which prefers small pathlength, small energy loss and hard fragmentation



- Jet Shapes and Jet Multiplicities
  - no trigger bias
  - sensitive to e-loss and pt-broadening
  - jet-like correlations seen at RHIC



- Hadroproduction at intermediate pt
  - neither “thermal” nor “perturbative”
  - medium interferes with hadronization process
  - characteristic changes of particle ratios



This was a narrow selection of topics

which did not touch many topics of active research

- charmonium, bottonium in A+A
- low-mass dileptons
- photons
- small-x physics in A+A and p+A
- EbyE-physics, fluctuations
- ...