Parton Energy Loss

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Department of Physics
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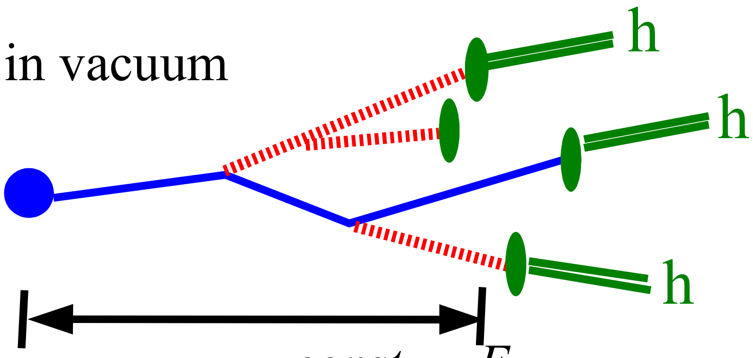
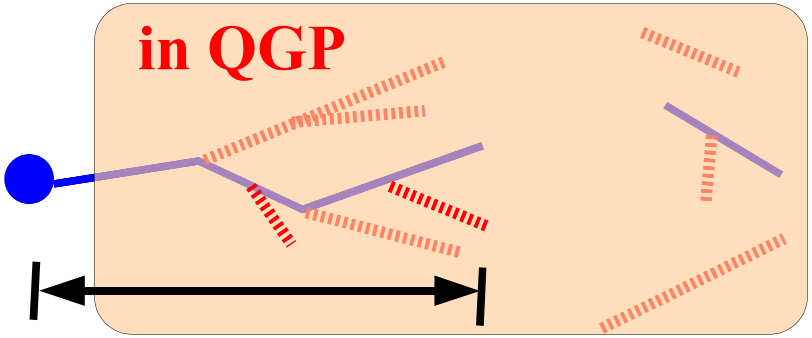
Hard Probes Conference,
Lisbon, 4-10 November 2004

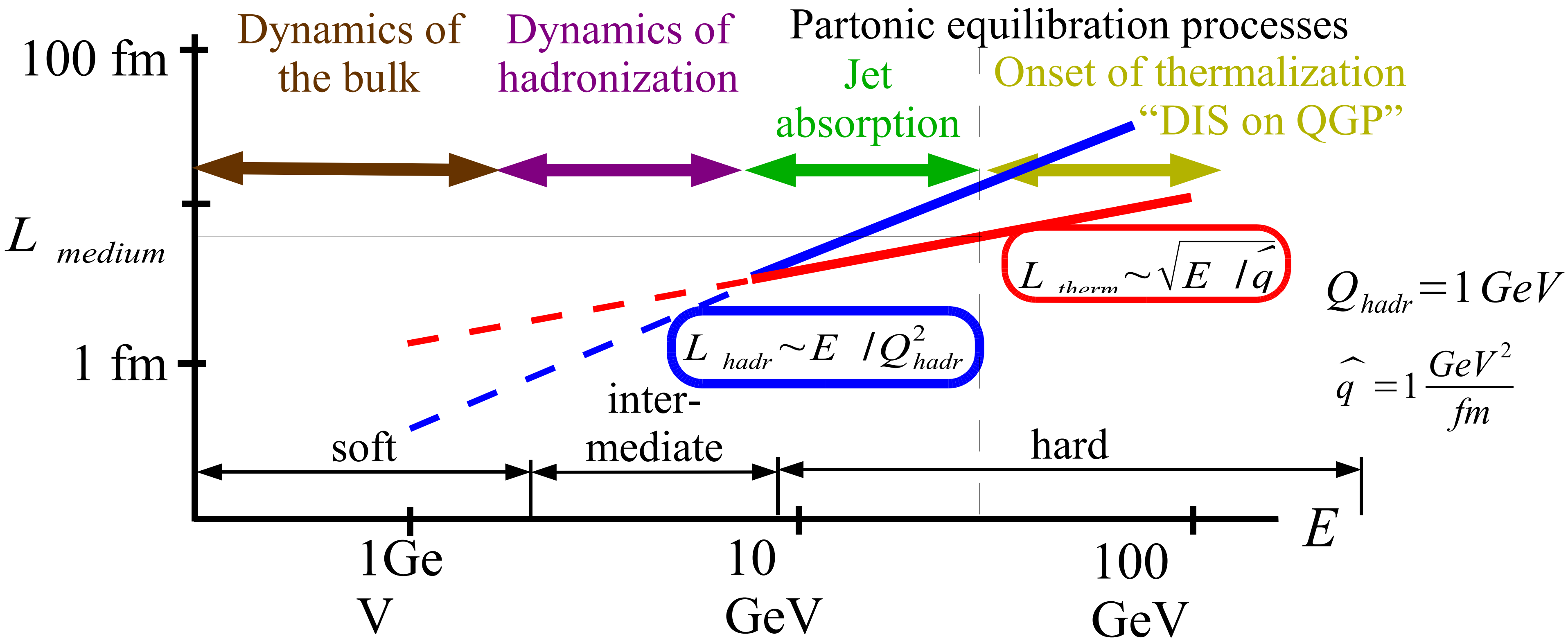
Hadronization versus Thermalization of Jets



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



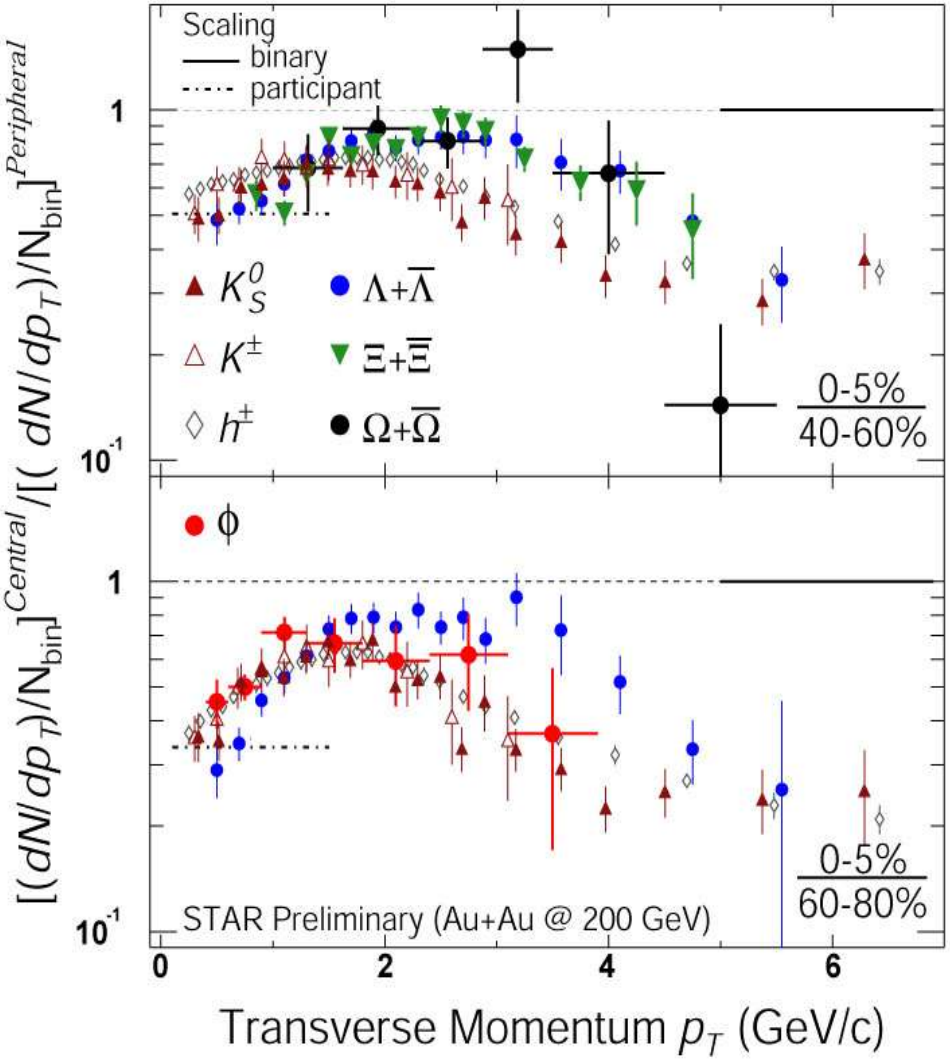
$$E \approx \Delta E = \frac{\alpha_s C_R}{4} \hat{q} L_{therm}^2$$



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

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

Setting the Transverse Momentum Scales

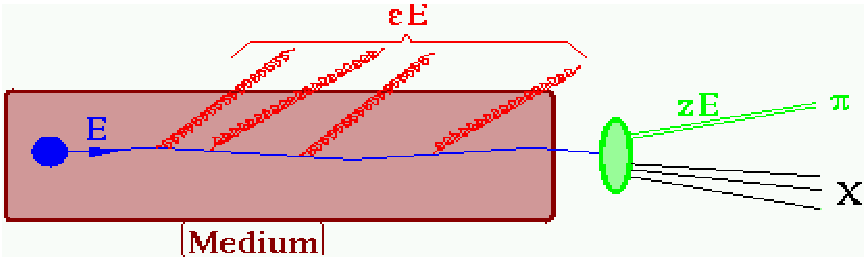


- High p $L_{hadr} > L_{therm}$

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

  parton thermalization

  jet tomography



- Intermediate p $L_{hadr} \sim L_{therm} \sim L_{med}$

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

  dynamics of hadronization

- Soft p

  $p_T^{hadr} < 2\,Ge$

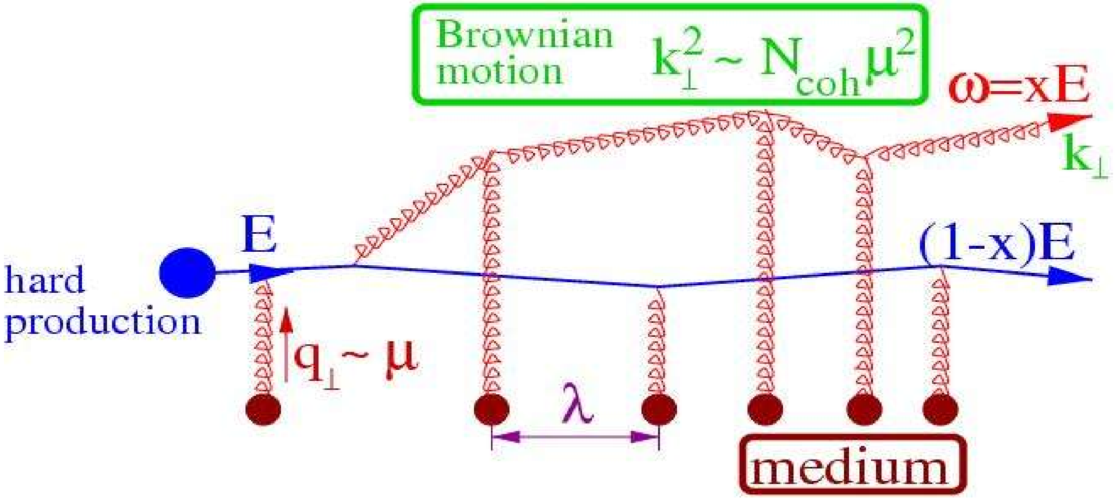
  bulk dynamics

High-pt Partons in Matter

Formalism

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:

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

- How much energy is lost ?

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

Characteristic gluon energy

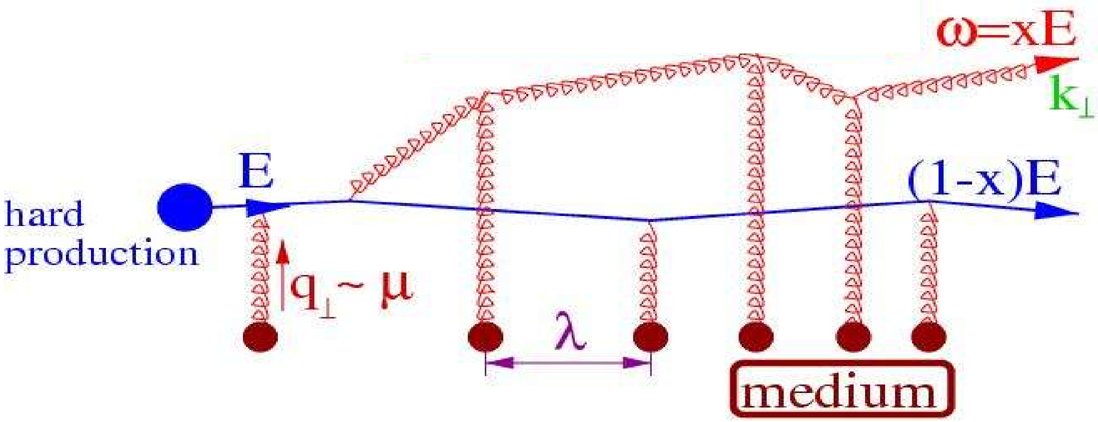
Number of coherent scatterings: $N_{coh} \simeq \frac{t_{coh}}{\lambda}$, where $t_{coh} \simeq \frac{\omega}{2k_t^2} \simeq \sqrt{\frac{\omega}{\hat{q}}}$

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

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

The medium-modified Final State Parton Shower

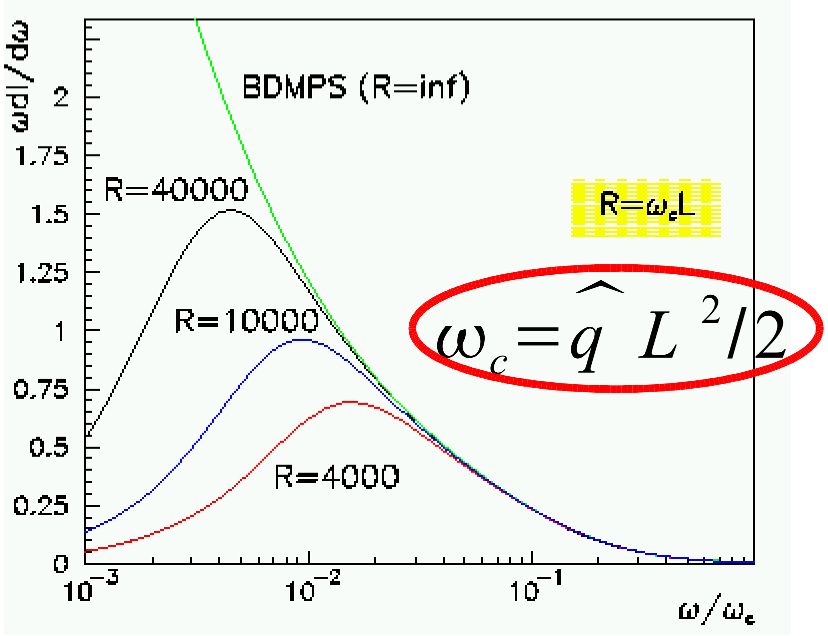
Baier, Dokshitzer, Mueller, Peigne, Schiff (1996); Zakharov (1997); Wiedemann (2000); Gyulassy, Levai, Vitev (2000); Wang ...



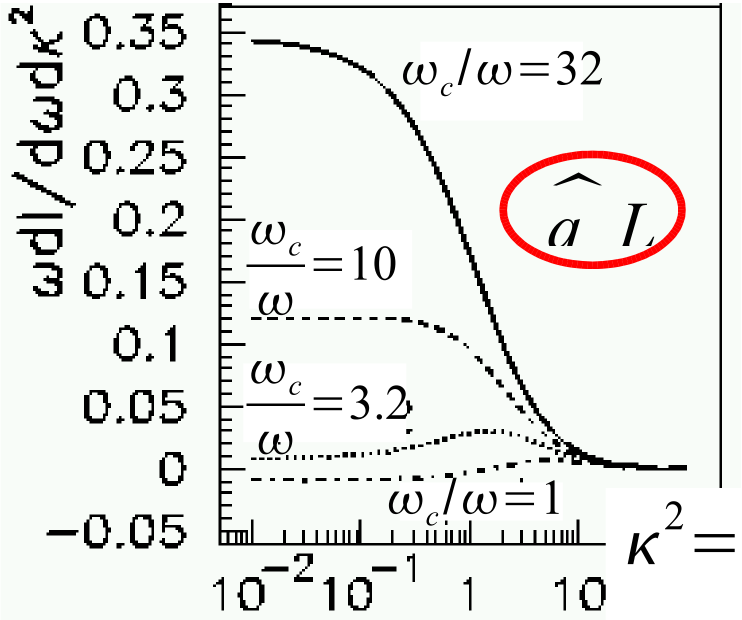
Medium characterized by transport coefficient:

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

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



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



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

Salgado,Wiedemann PRD68:014008 (2003)

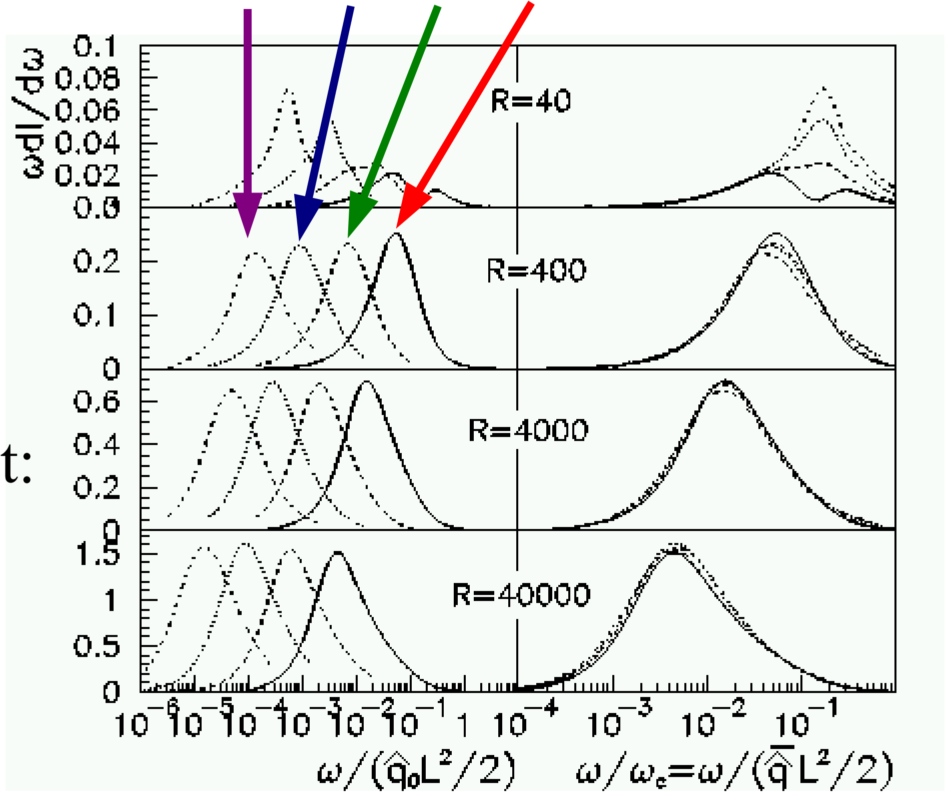
Energy Loss in a Strongly Expanding Medium

- In A-A collisions, the density of scattering centers is time-dependent:

$$\hat{q}(\tau)=\hat{q}_0\left(\frac{\tau_0}{\tau}\right)^{\alpha}$$

Salgado, Wiedemann PRL 89, 092303 (2002)

α = 1.5, 1.0, 0.5, 0



Salgado, Wiedemann PRL 89, 092303 (2002)
Baier, Dokshitzer, Mueller, Schiff PRC58 (1998) 1706
Gyulassy, Vitev, Wang, PRL86 (2001) 2537

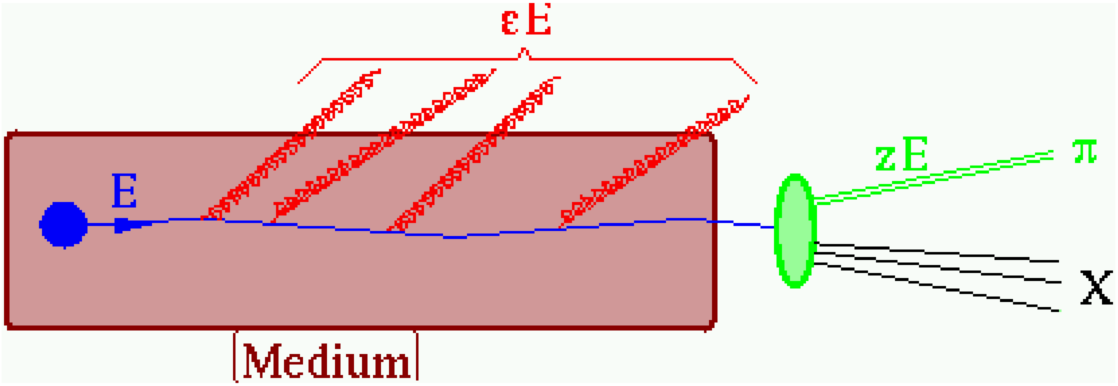
- Dynamical Scaling Law:
  same spectrum obtained for equivalent static transport coefficient:

$$\boxed{\bar{\hat{q}} \equiv \frac{2}{L^2}\int_{\tau_0}^{\tau_0+L} d\tau\,(\tau-\tau_0)\,\hat{q}(\tau}$$

- Calculations for a static medium apply to expanding systems

Rescaled spectrum

High pt Hadrons from a Dense Medium



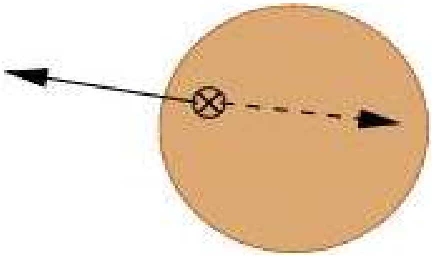
Trigger Bias Effects

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

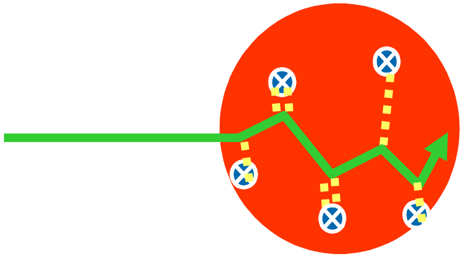
Average:

$$\boxed{\langle \epsilon \rangle = \frac{\Delta E}{E} = \int d \quad \epsilon \, \epsilon}$$

Typical:

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

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



Nuclear Modification Factor in Au+Au at RHIC

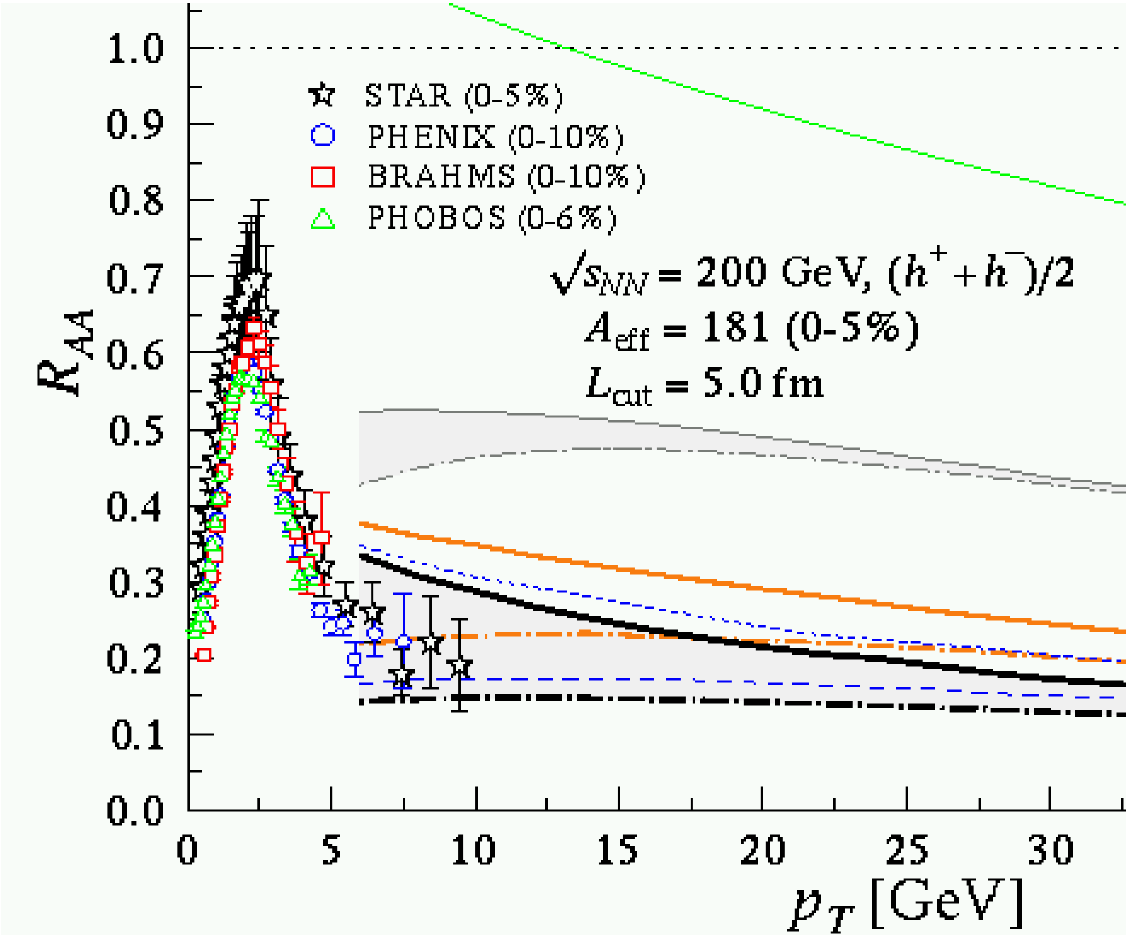
Eskola, Honkanen, Salgado, Wiedemann, hep-ph/0406319, Nucl Phys A in press

$$d\sigma^{AA\to h+X}_{(med)} = \sum_f d\sigma^{AA\to h+X}_{(vac)} \times \underbrace{P_f(\Delta E, L, \hat{q})}_{quenching\ weight}$$

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

- weak pt-dependence
- large time-averaged transport coefficient

$$\hat{q} = 5-15\,\frac{GeV^2}{fm}$$



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

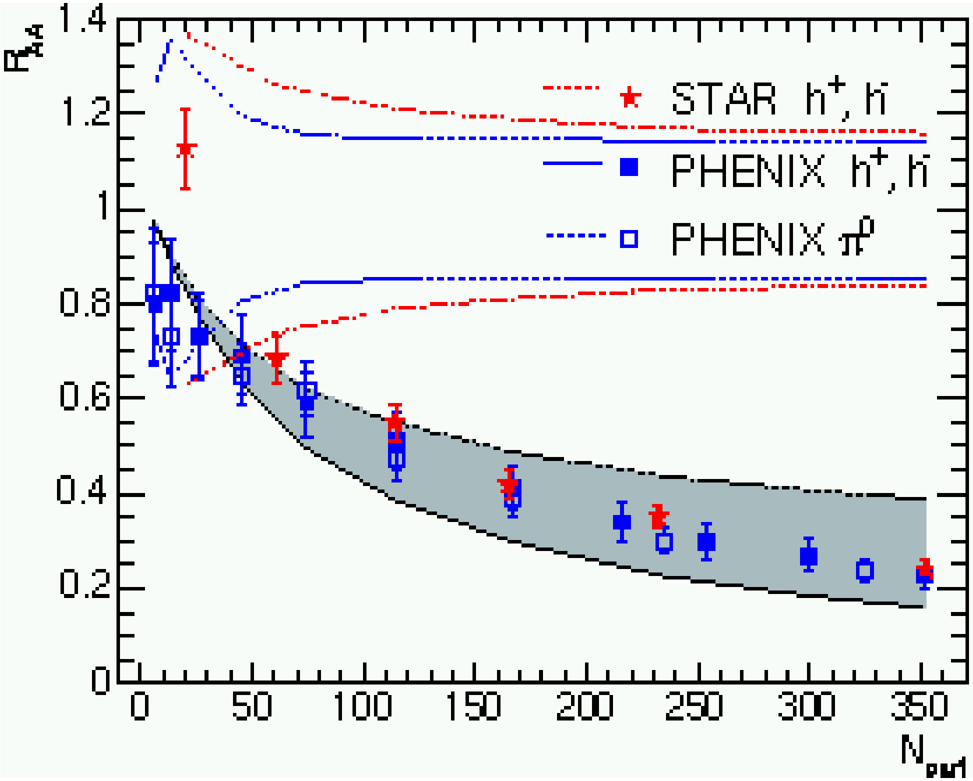
$$\hat{q} = 1\,\frac{GeV^2}{fm}$$

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

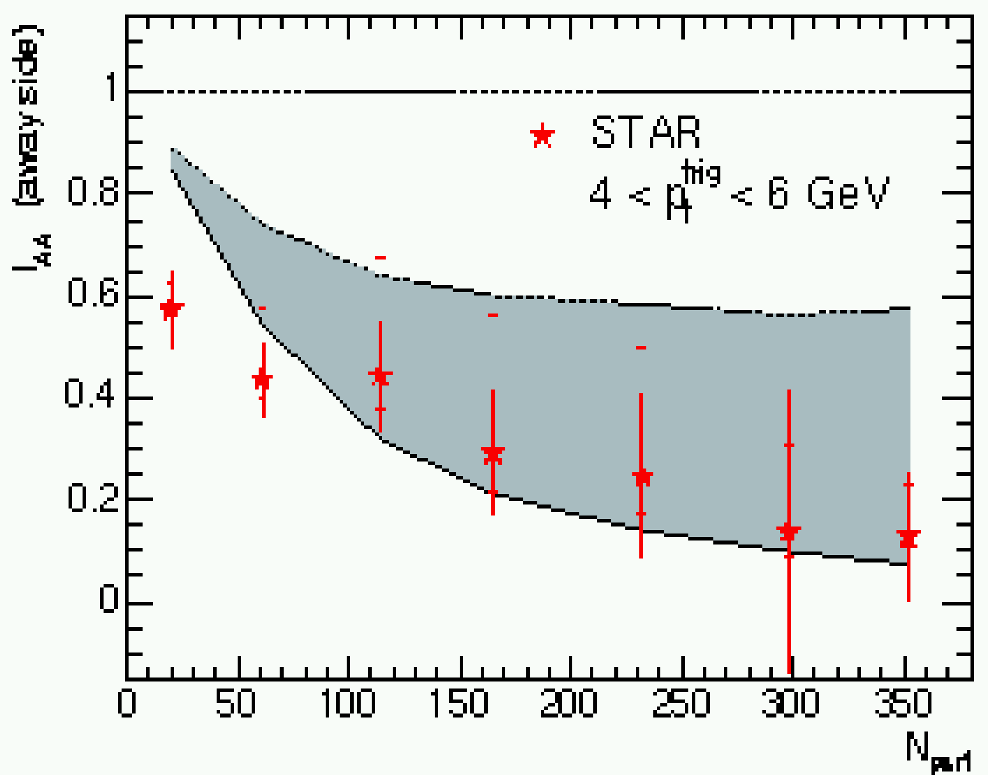
Centrality Dependence of Nuclear Modification Factor

X.N. Wang, PLB579 (2004) 299, A. Drees, H. Feng, J. Jia, nucl-th/0310044 Dainese, Loizides, Paic, hep-ph/0406201

does not provide a significant further constraint for model calculations



Dainese, Loizides, Paic, hep-ph/0406201



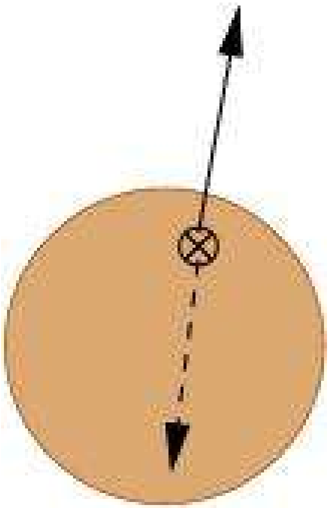
Why is $\boxed{R_{AA}\sim 0.2}$ natural ?

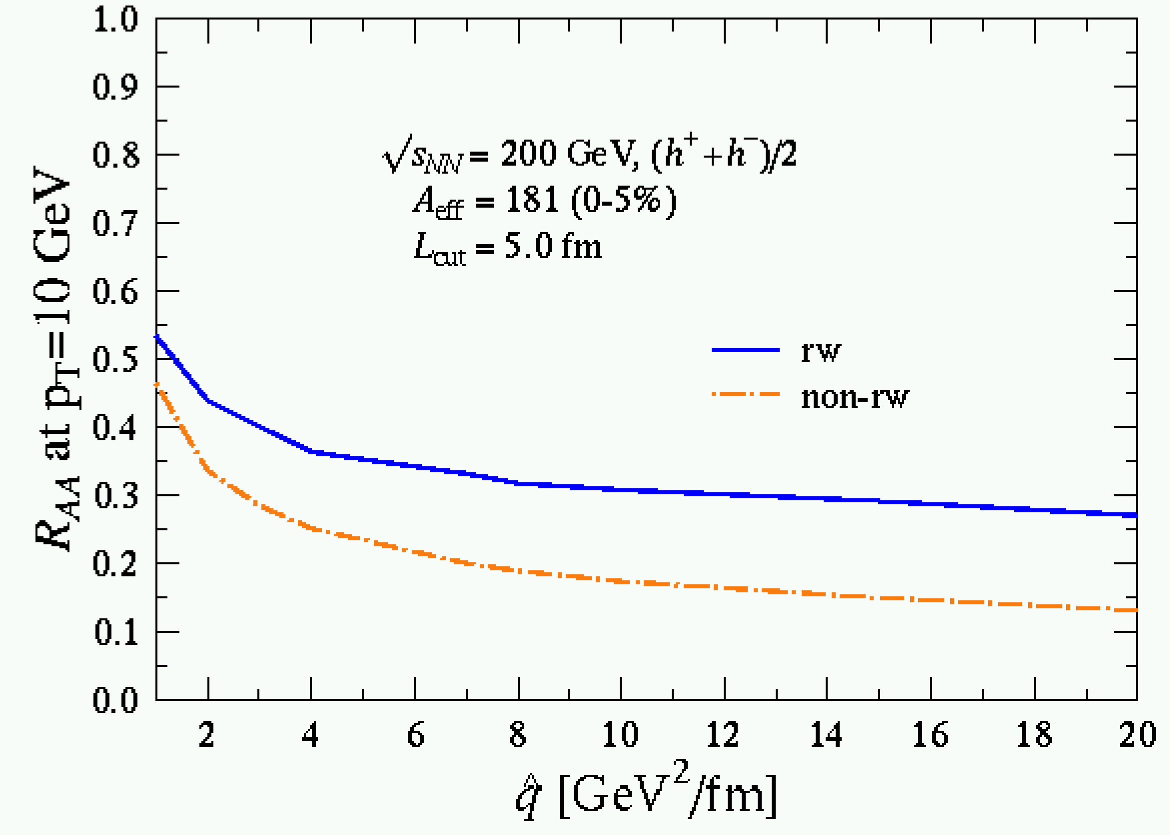
Eskola, Honkanen, Salgado, Wiedemann, hep-ph/0406319, Nucl Phys A in press

- For large $\hat{q}$, surface emission dominates.

B. Muller, PRC 67 (2003) 061901

- Surface emission limits sensitivity to precise value of $\hat{q}$





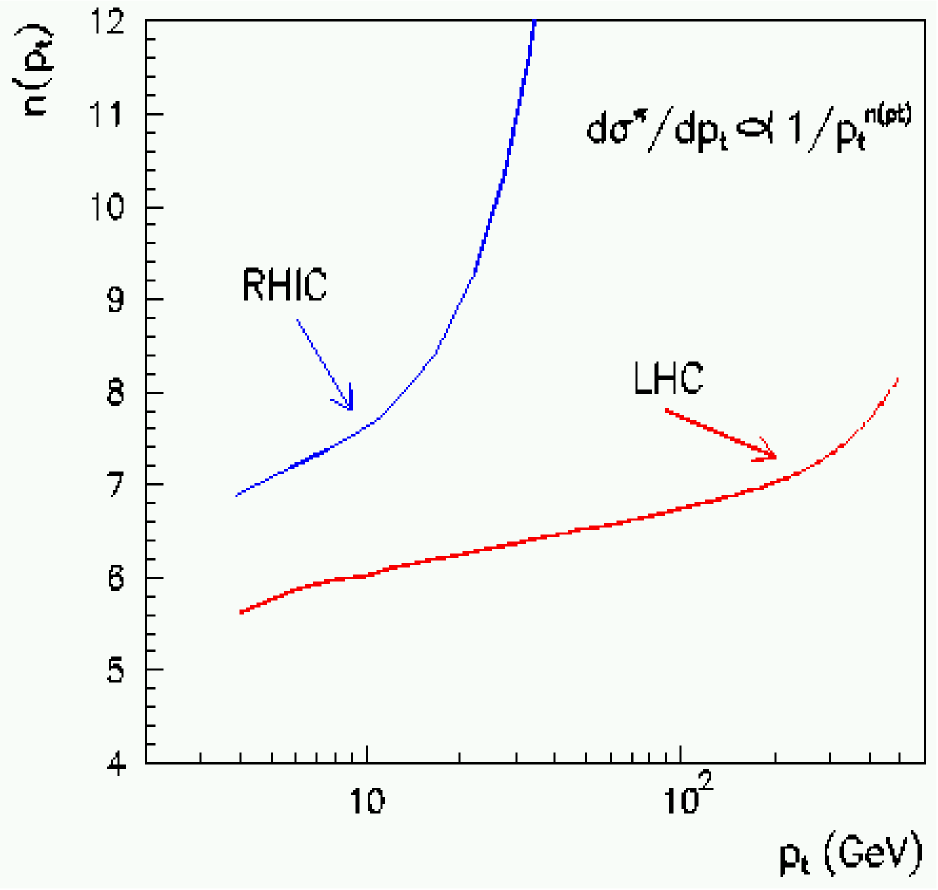
Why is R_{AA} almost pt-independent ?

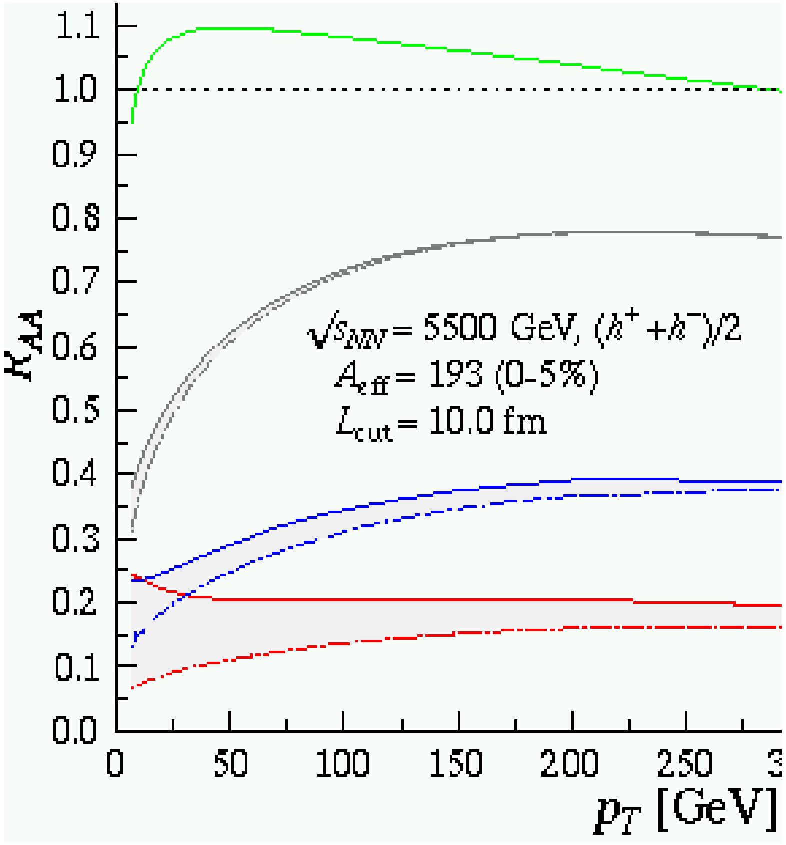
Eskola, Honkanen, Salgado, Wiedemann, hep-ph/0406319, Nucl Phys A in press

- Trigger bias is more severe for large pt

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

- Flatness is expected to persist also at the LHC (leading hadrons are fragile)





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

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

$$\hat{q} = 10 \frac{GeV^2}{fm}$$

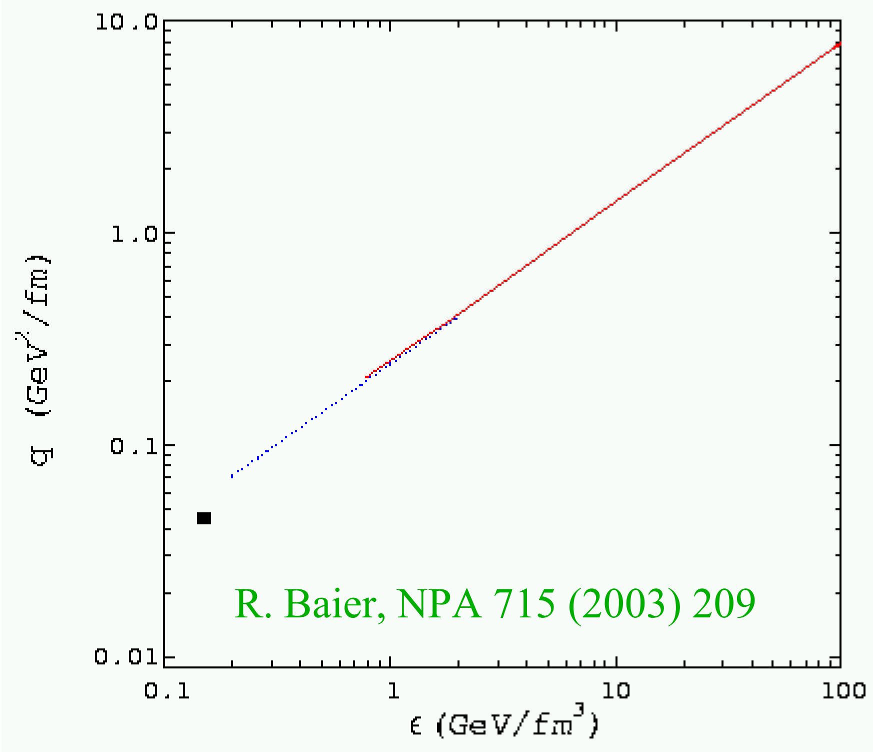
$$\hat{q} = 68 \frac{GeV^2}{fm}$$

The Opacity Problem of Jet Quenching

Eskola, Honkanen, Salgado, Wiedemann, hep-ph/0406319, Nucl Phys A in press

- $\hat{q}$ traces energy density

$$\boxed{\begin{gathered}\hat{q}(\tau)=c\,\epsilon^{3/4}(\tau)\\ c_{ideal}^{QGP}\approx 2\end{gathered}}$$



R. Baier, NPA 715 (2003) 209

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

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

for the values favored by RHIC-data

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

Opacity problem:
The interaction of the hard parton with the medium is much stronger than expected.

Massive Quarks in Dense Matter

Testing the Mechanism: E-Loss of Heavy Quarks

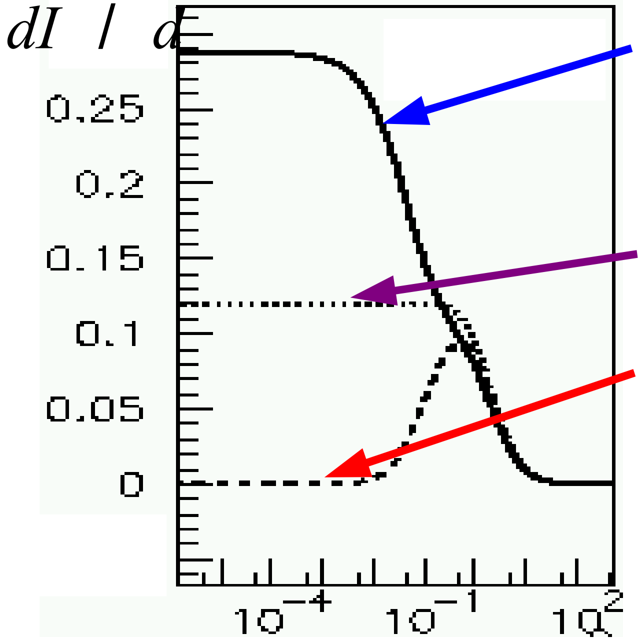
- vacuum radiation suppressed in the dead-cone $\theta < m/E$

Dokshitzer, Kharzeev, PLB 519 (2001) 199

$$\frac{1}{k_t^2} \Rightarrow \frac{k_t^2}{\left(k_t^2+\omega^2 m^2/E^2\right)^2}$$

- medium-induced radiation fills the dead-cone

Armesto, Salgado, Wiedemann, PRD69 (2004) 114003



massive

$$\frac{m}{E}=0.1$$

massless

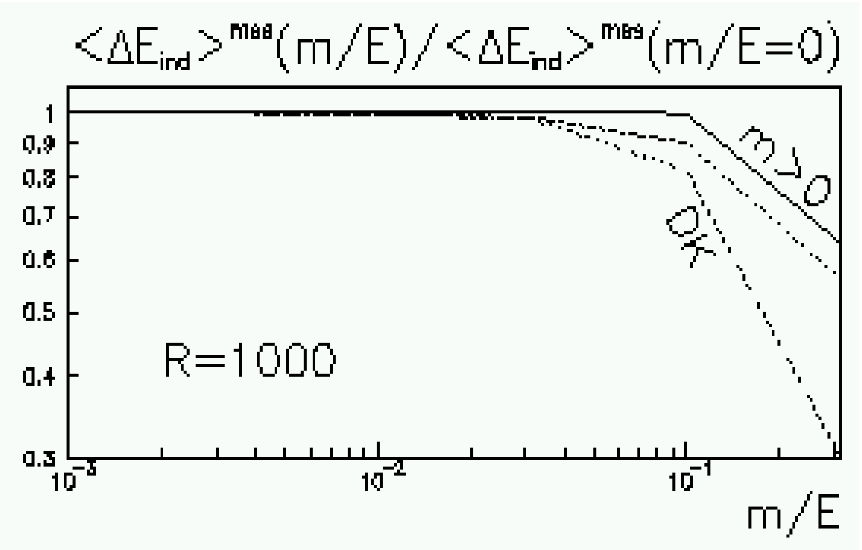
dead cone

$$\frac{\omega_c}{\omega}=10$$

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

- total energy loss comparable but smaller than in the massless case

Armesto, Salgado, Wiedemann, PRD69 (2004) 114003
B.W. Zhang, E. Wang, X.N. Wang, PRL93 (2004) 072301
Djordjevic, Gyulassy, NPA733 (2004) 265



Caveat: mass effect significant if quark is slow

→ hadronization inside medium for pt > 7 GeV

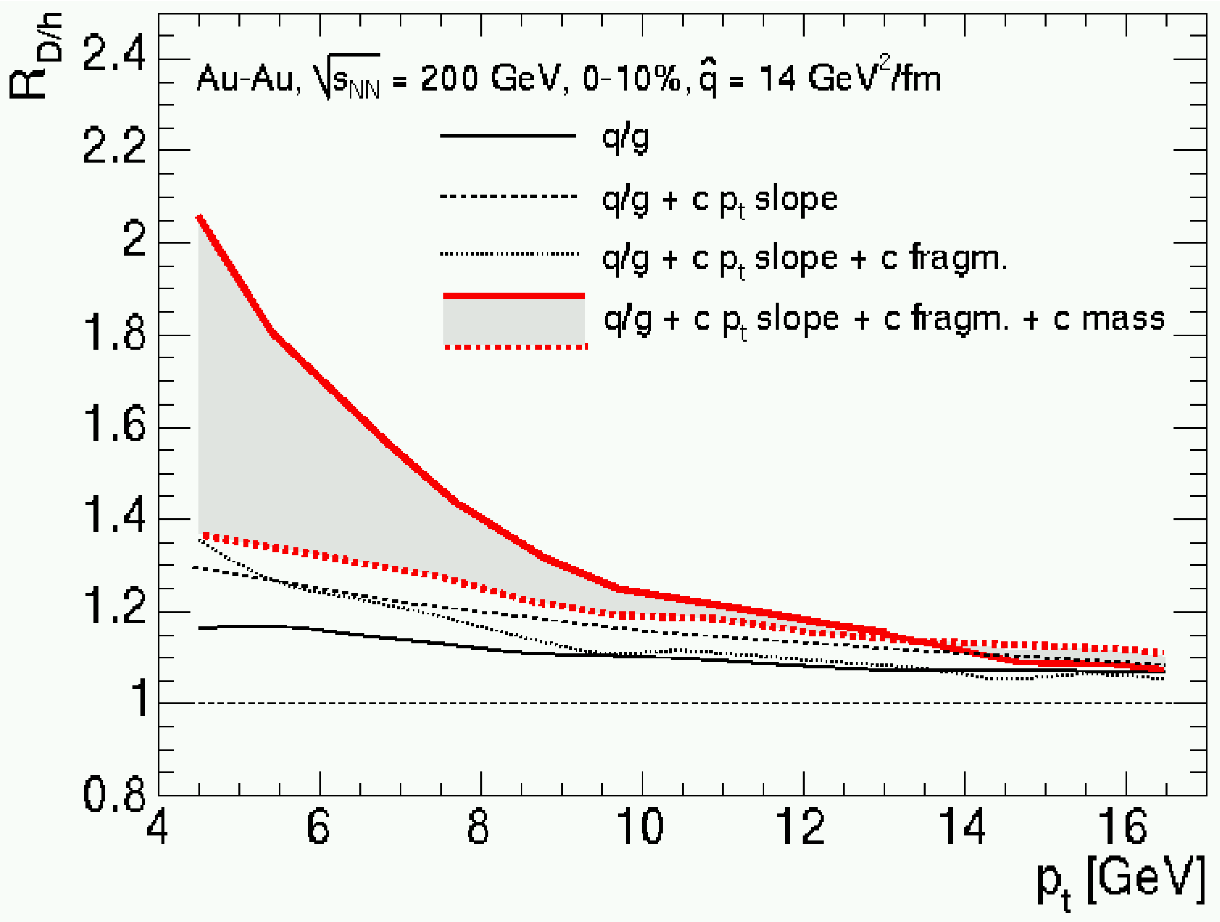
→ significant uncertainties

Energy Loss of Charm vs. Light Partons: largest contribution to $R_{D/h}$ may come from

$$\boxed{\Delta E^{gluon} > \Delta E^{quark, m=0}}$$

- Compare q, g ⟶ h with c ⟶ D

Armesto, Dainese, Salgado, Wiedemann, in preparation



1.) $\Delta E^{gluon} > \Delta E^{quark, m=0}$

⟶ $R_{D/h}$ increases

2.) trigger bias: q/g pt slope steeper than c pt-slope

⟶ $R_{D/h}$ increases

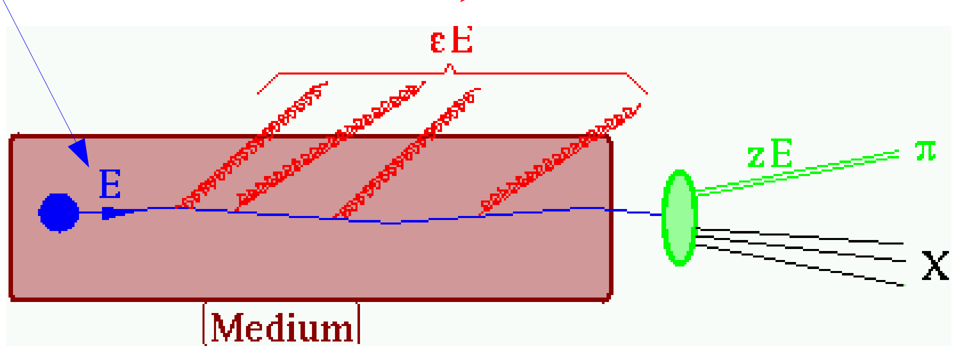
3.) charm fragmentation inside or outside medium ?

⟶ $R_{D/h}$ decreases

4.) $\Delta E^{quark, m=0} > \Delta E^{quark, m>0}$

⟶ $R_{D/h}$ increases

Beyond Leading Hadroproduction



How does this parton
thermalize ?

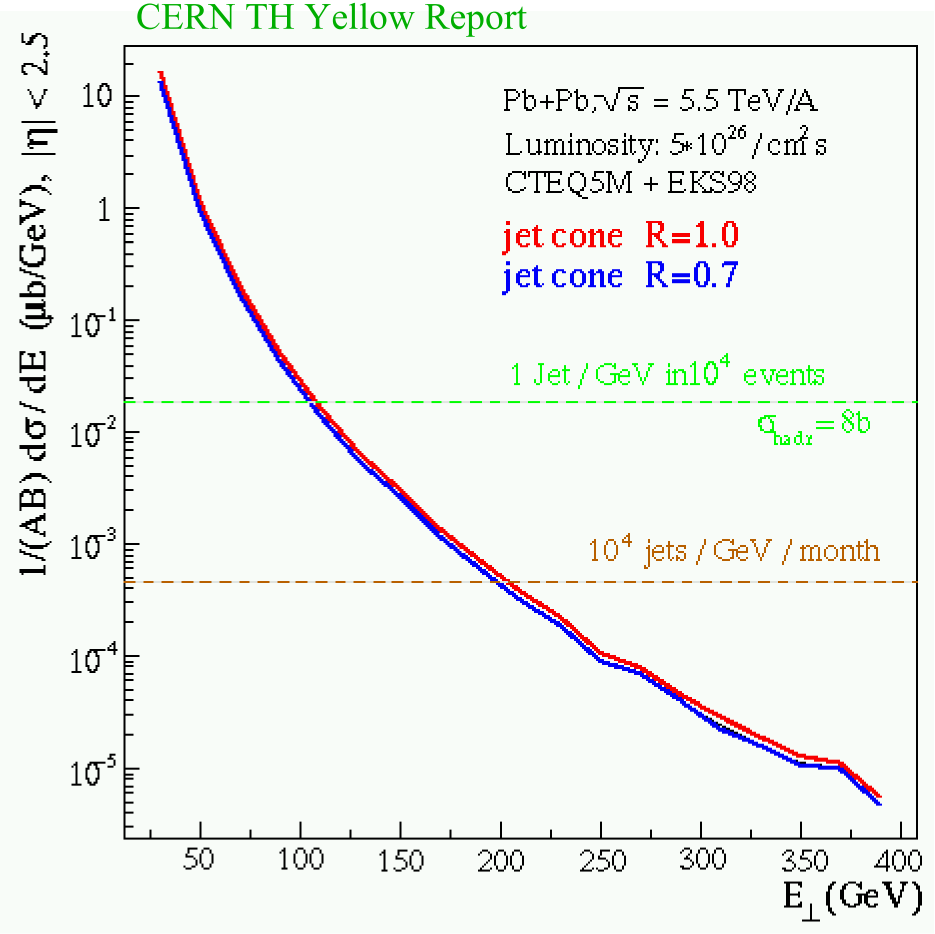
Where does this
associated radiation
go to ?

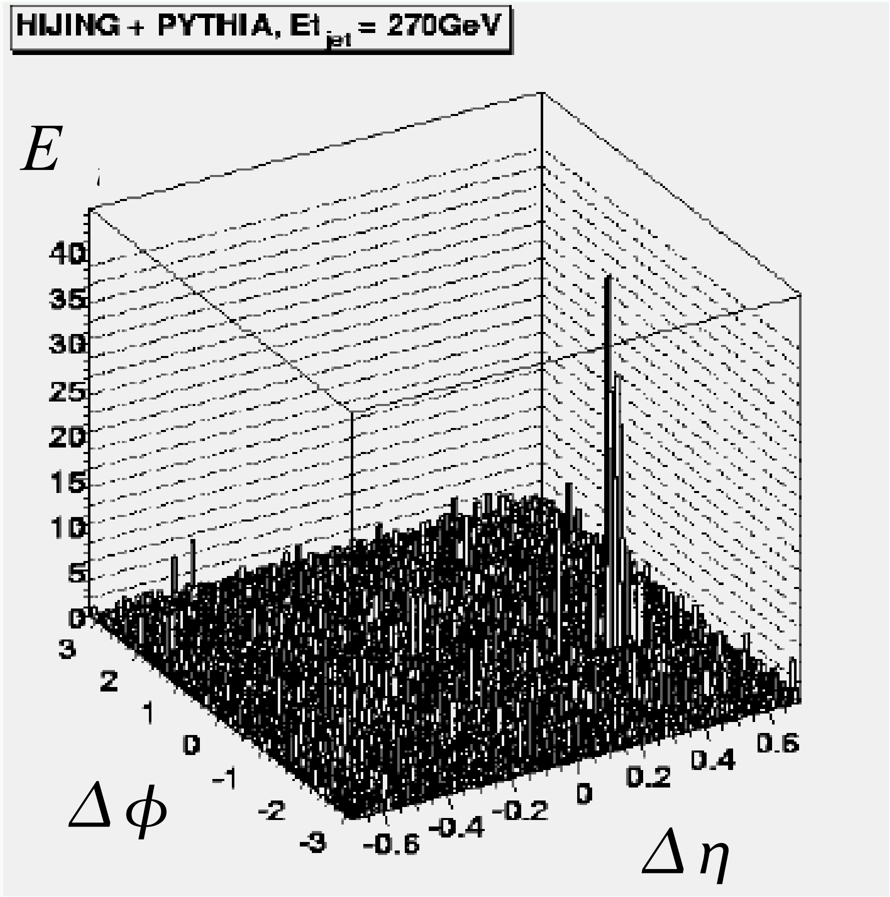
I. Jets at the LHC

II. Hadroproduction associated to
high-pt trigger particles at RHIC

Jets in Heavy Ion Collisions at the LHC

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





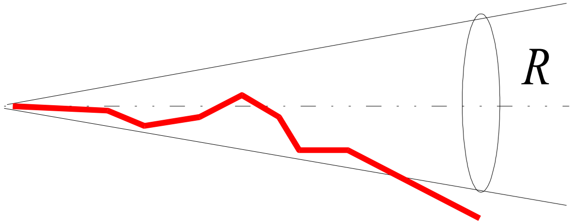
- Experiments at LHC will detect jets above background
- How can we quantify their medium modifications above background ?
  What do we learn from them ?

'Jet Heating': Jet Shapes and Jet Multiplicities

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

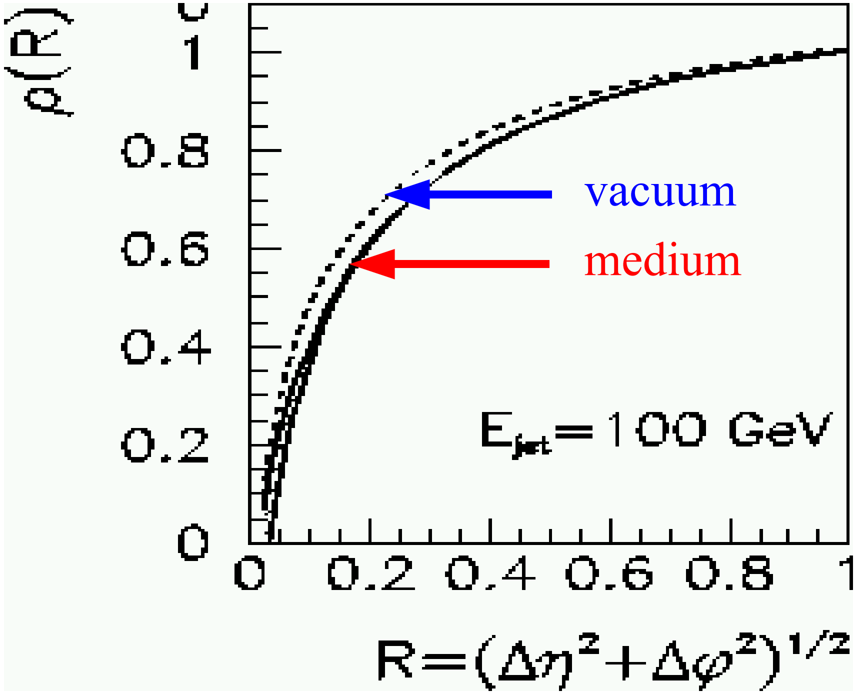
- Energy fraction in fixed jet cone

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

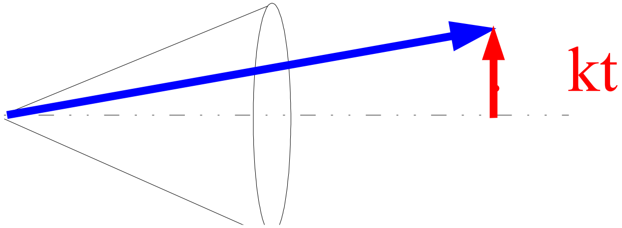


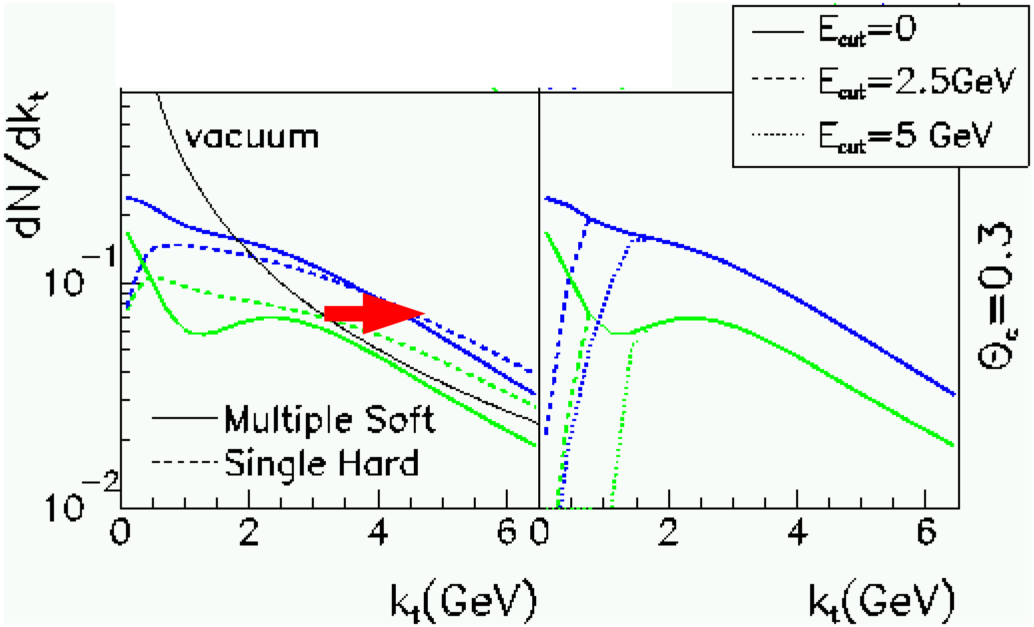
$R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

weakly dependent on medium



- Multiplicity within small jet cone broadens significantly





unaffected by high-multiplicity background !

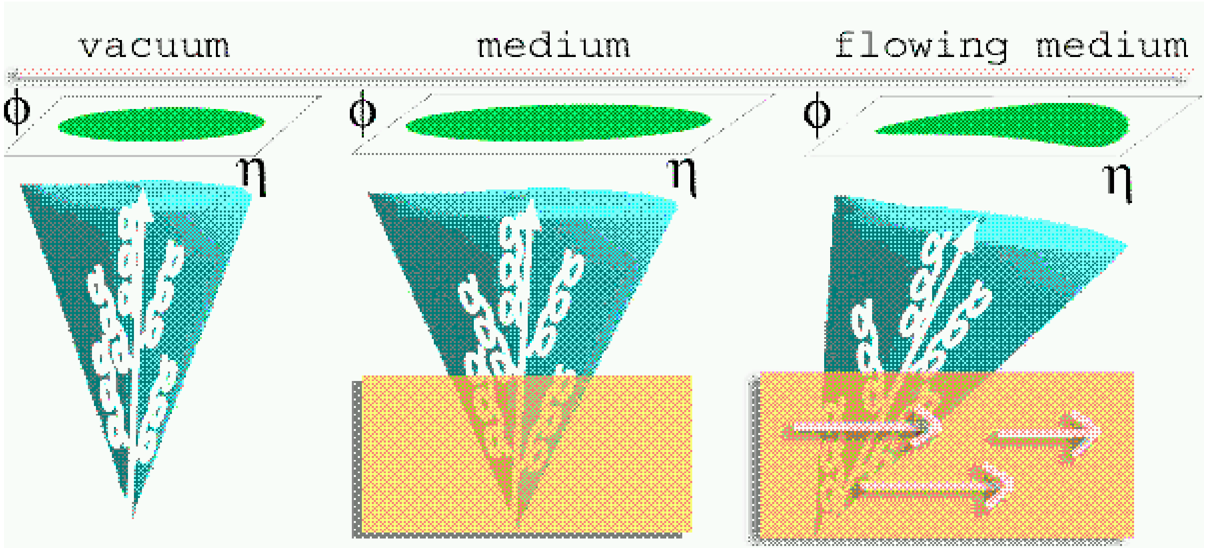
Asymmetric Jet Shapes test Collective Flow

Armesto, Salgado, Wiedemann, hep-ph/0405099, Phys. Rev. Lett. in press

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

$$T^{\mu\nu}=(\epsilon+p)\boxed{u^{\mu}u}^{\nu}-p$$

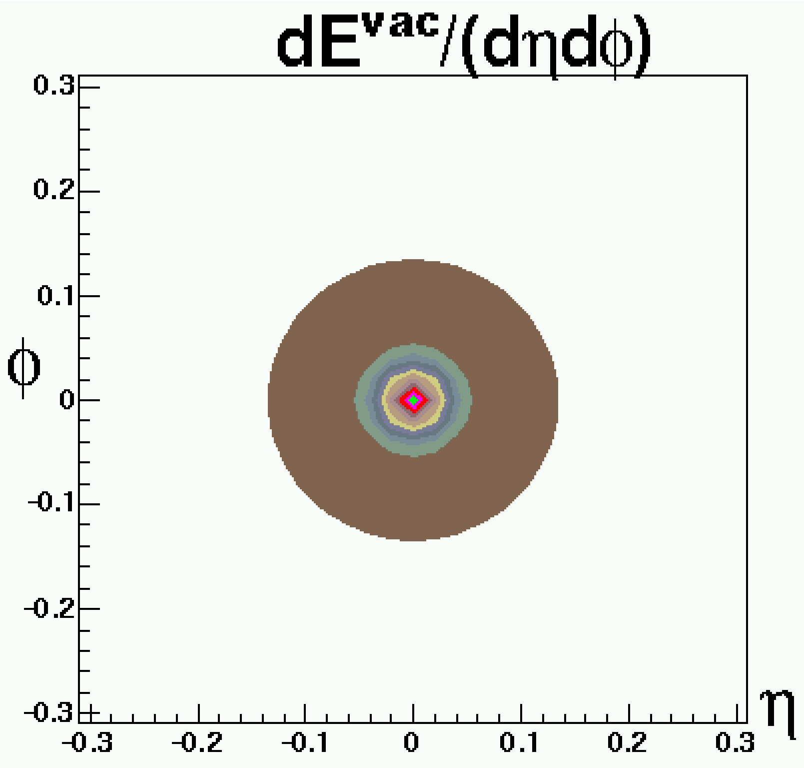
test this

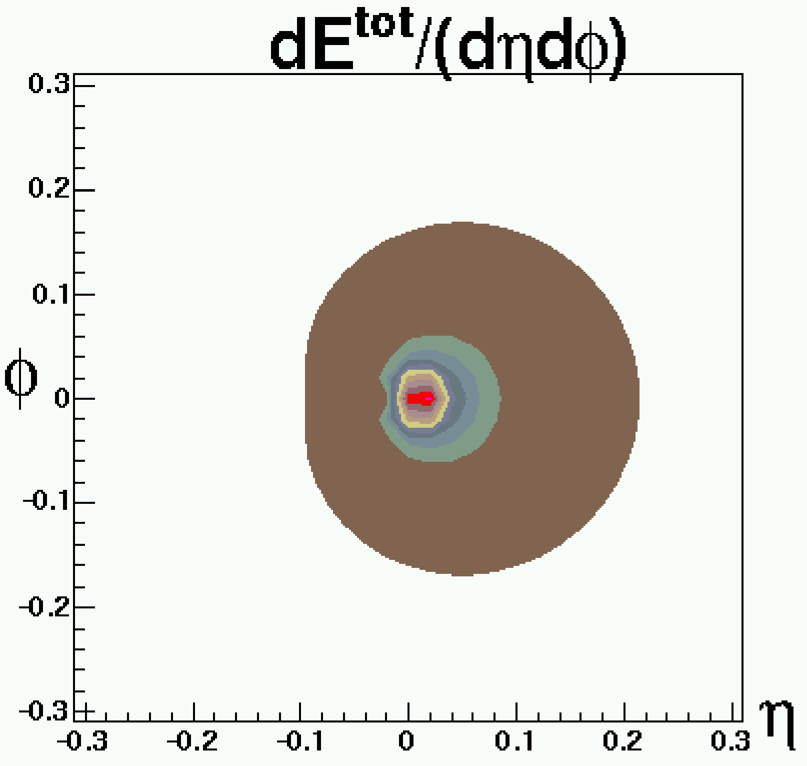


$$E_T^{jet}=100\,GeV$$

$$\hat{q}\;L=(1\,GeV)^2$$

$$(\hat{q}\;L)_{flow}=\hat{q}$$


$dE^{vac}/(d\eta d\phi)$

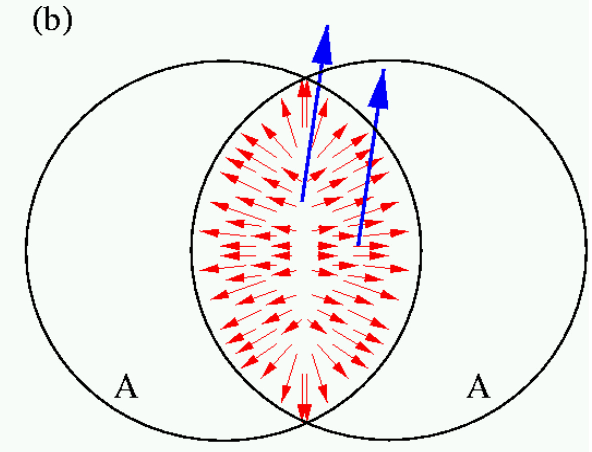

$dE^{tot}/(d\eta d\phi)$

Low-pt Flow Induces High-pt Elliptic Flow

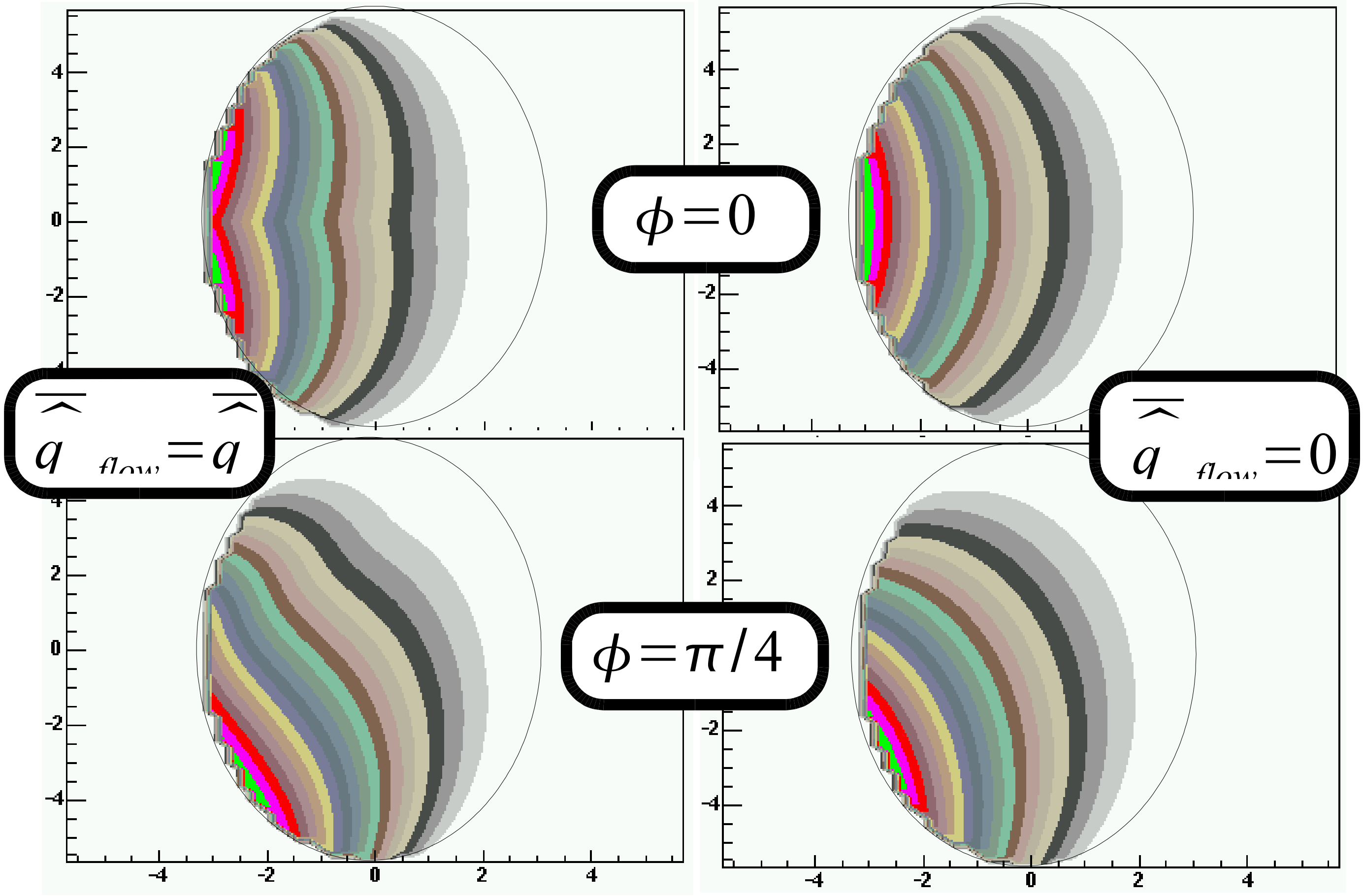
Armesto, Salgado, Wiedemann, in preparation

Energy loss for a parton passing a flow field along $r_0(\xi) = r_0 + \xi \vec{n}\,(\phi$

$$\Delta E \propto \omega_c(r_{0,}\phi) = \int_0^\infty d\xi\, \xi \left(\widehat{q} + \widehat{q}_{flow} \underbrace{|\vec{u}_T(r_0(\xi)) \cdot \vec{n}_T|^2}_{Flow\, component \perp r_0(\xi)} \right) \underbrace{\Omega(r}_{Density}$$



Contour plot of $\omega(r_{0,}\phi)$



$\phi = 0$

$\widehat{q}_{flow} = \widehat{q}$

$\widehat{q}_{flow} = 0$

$\phi = \pi/4$

- Flow field changes effective emission region as fct of ϕ
- Can this change v_2 by factor two ?

Interplay of Collective Flow and Energy Loss at RHIC

Armesto, Salgado, Wiedemann, in preparation

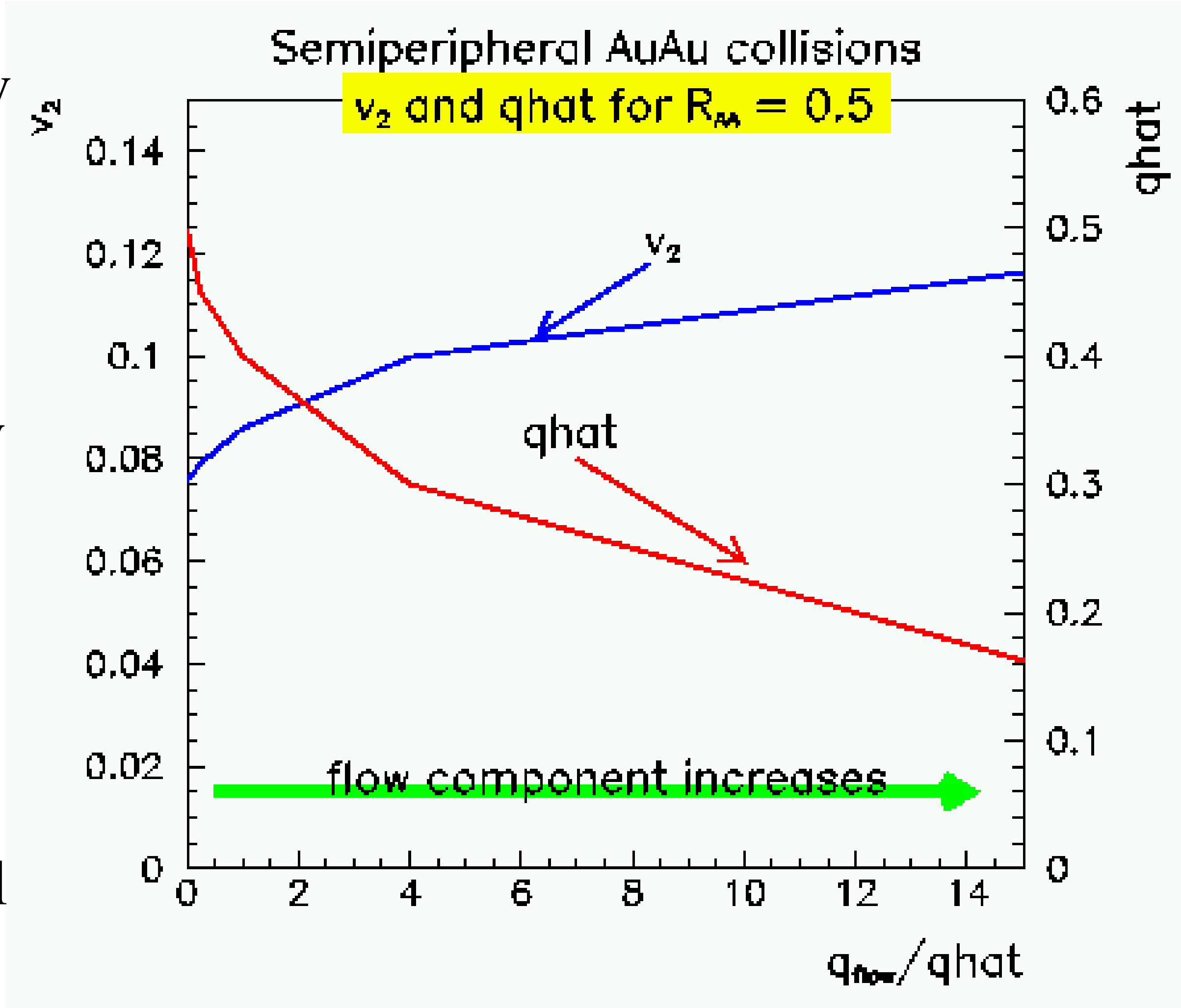
Increasing low-pt collective flow

- induces a larger elliptic flow at high transverse momentum

- requires a lower energy density to account for the same nuclear modification factor

→

full hydrodynamic simulation of these effects would be usefull

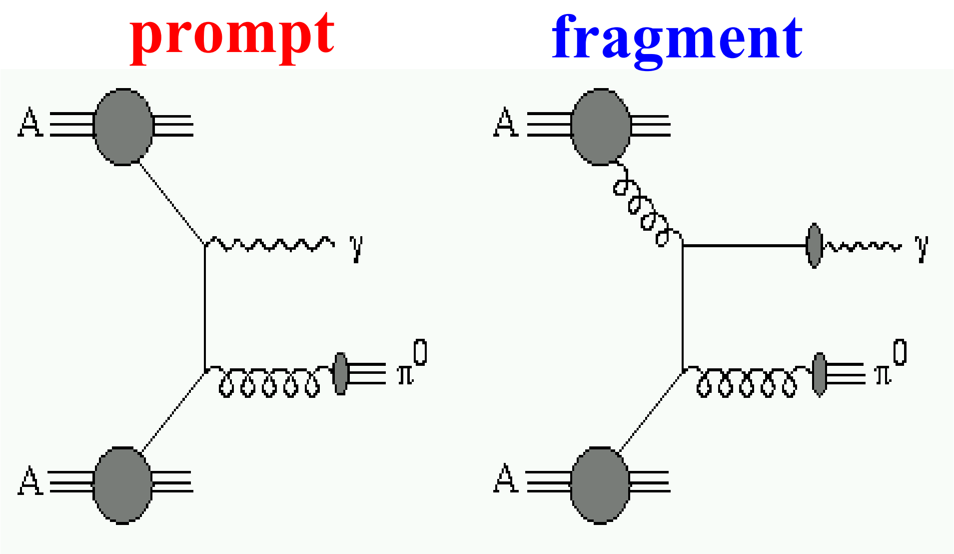


and much more ...

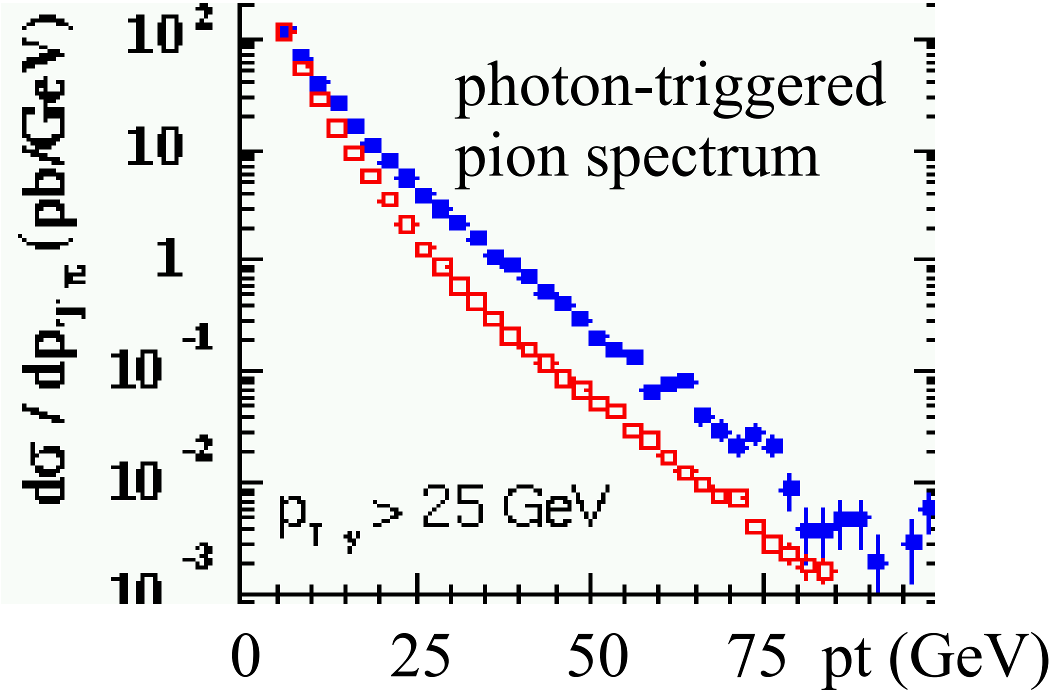
Photon-tagging of Hadrons and Jets

X.N. Wang, Z. Huang, I. Sarcevic, PRL77 (1996) 231

- fragmentation contribution



Arleo, Aurenche, Belghobsi, Guillet, hep-ph/0410088



- additional complications such as trigger bias, low rates, ...

→ More work is needed to establish photon-tagging as a reliable substitute of a calorimetric measurement

Some General Concluding Remarks

- "jet quenching" is the dominant effect in the production of high-pt hadrons in nucleus-nucleus collisions
- at the present stage, we start learning how the medium-modification of hard processes can be used as a hard probe
- the next important steps in this program are (my personal bias)
  - study of jet-like particle correlations and jets
  - sensitivity to partonic identity
  - interplay of parton energy loss and hadronization at intermediate pt