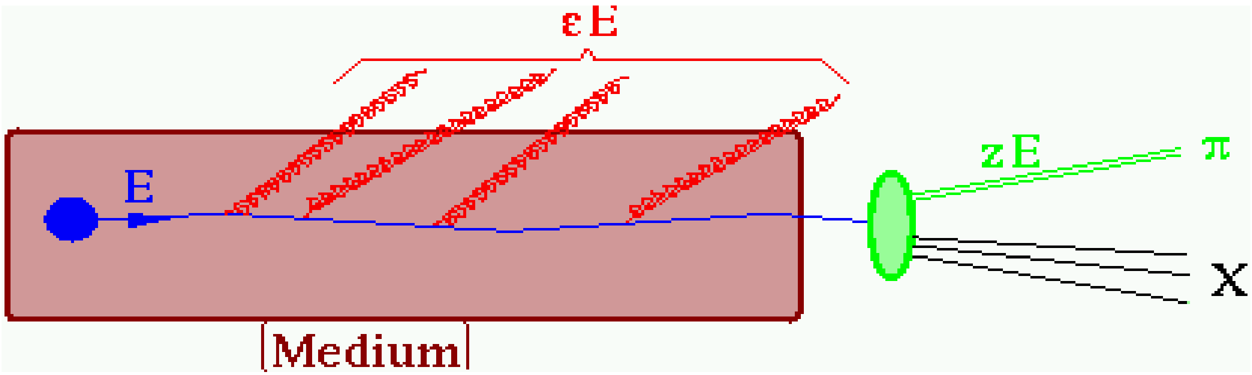
Parton Energy Loss in Monte Carlo Simulations

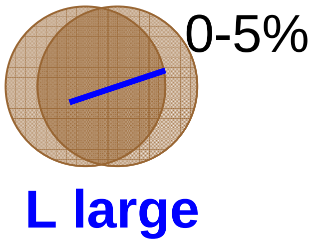
Urs Achim Wiedemann
CERN PH-TH

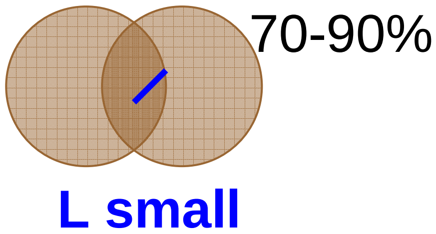
High p_T Hadron Spectra



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

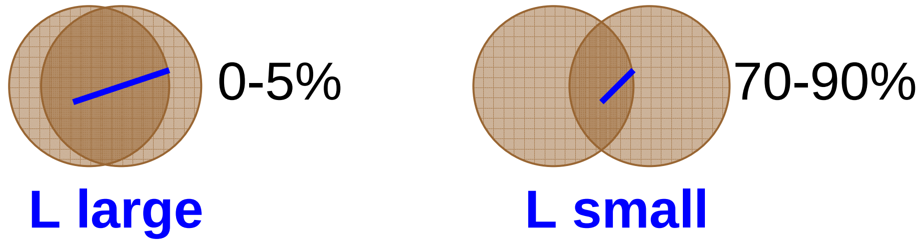
Centrality dependence:

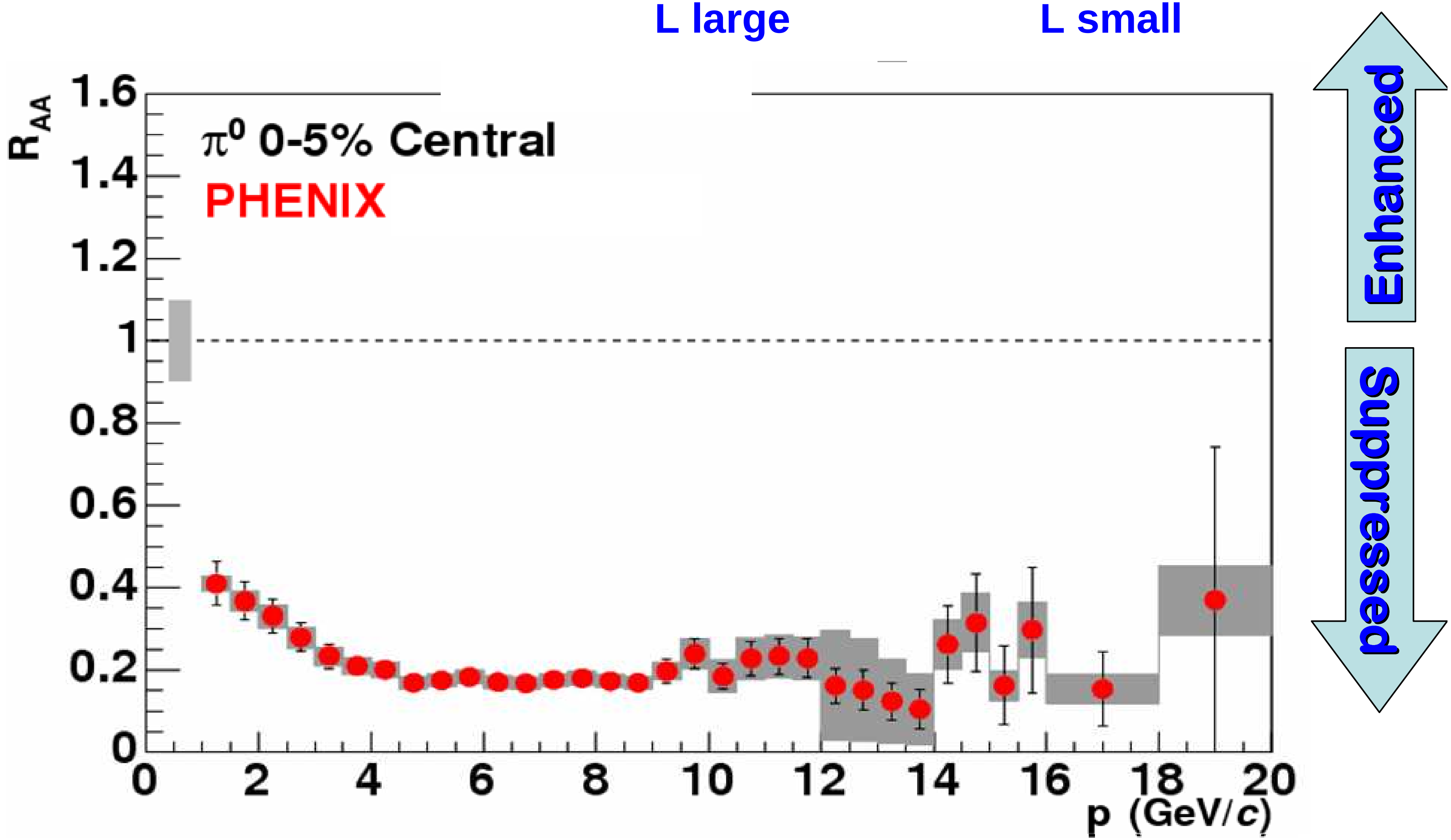




Strong suppression persists to highest p_T

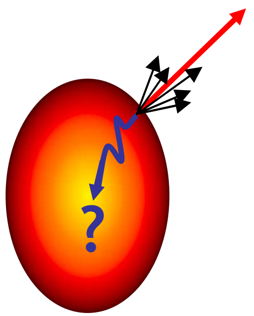
Centrality dependence:





@ RHIC, radiative energy loss accounts for:

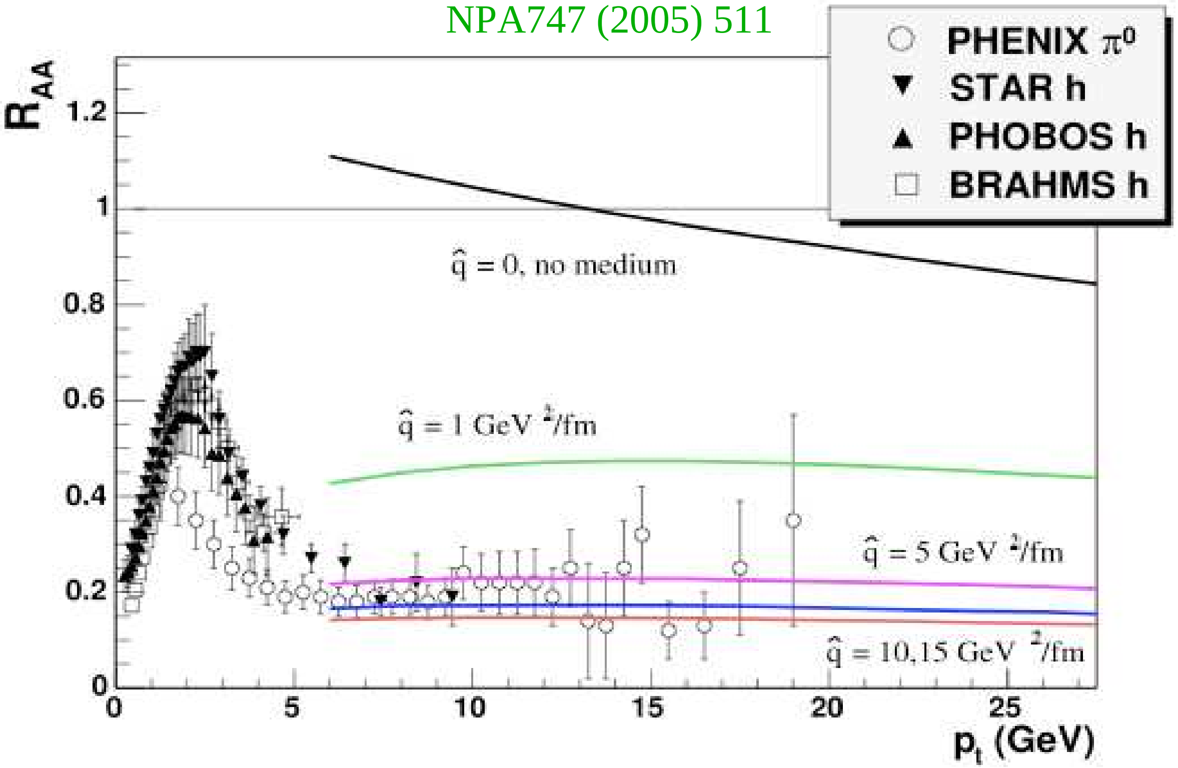
- Nuclear modification factor
- Centrality dependence
- Back-to-back correlations
- R_{AA} = 0.2 is a natural limit due to surface emission



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 $\hat{q}$

@ RHIC, suppression of hadron spectra is strong (~ 5-fold) and unattenuated up to highest p_T (~ 20 GeV).

=> ***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

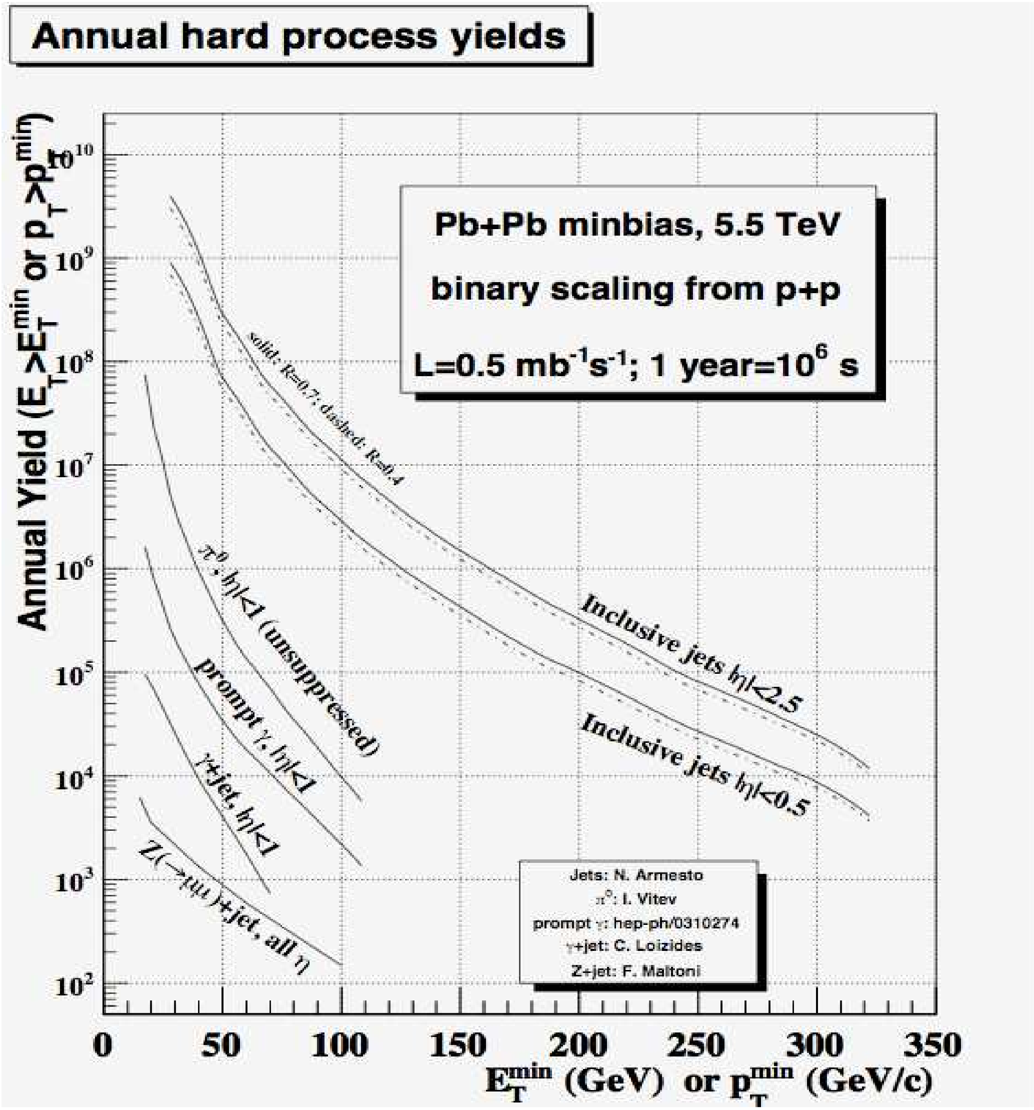
+ robust signal

(medium sensitivity

>> uncertainties)

= detailed understanding

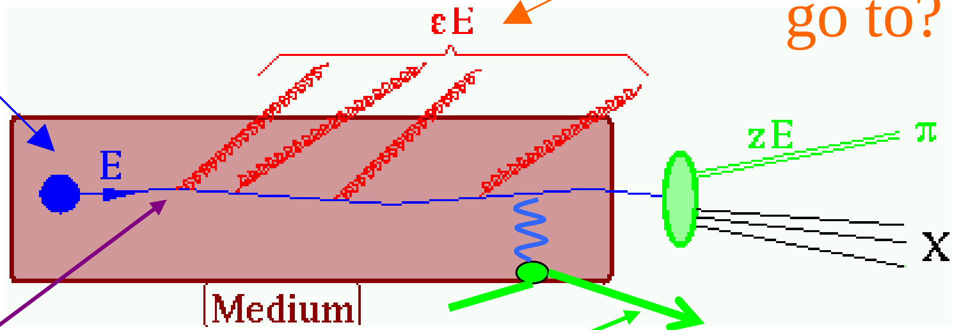
of dense QCD matter



Suppression of leading hadrons ⟷ Medium-modification of entire jet structure

How does this parton <u>thermalize</u>?

Where does this <u>associated radiation</u> go to?



What is the dependence on parton identity?

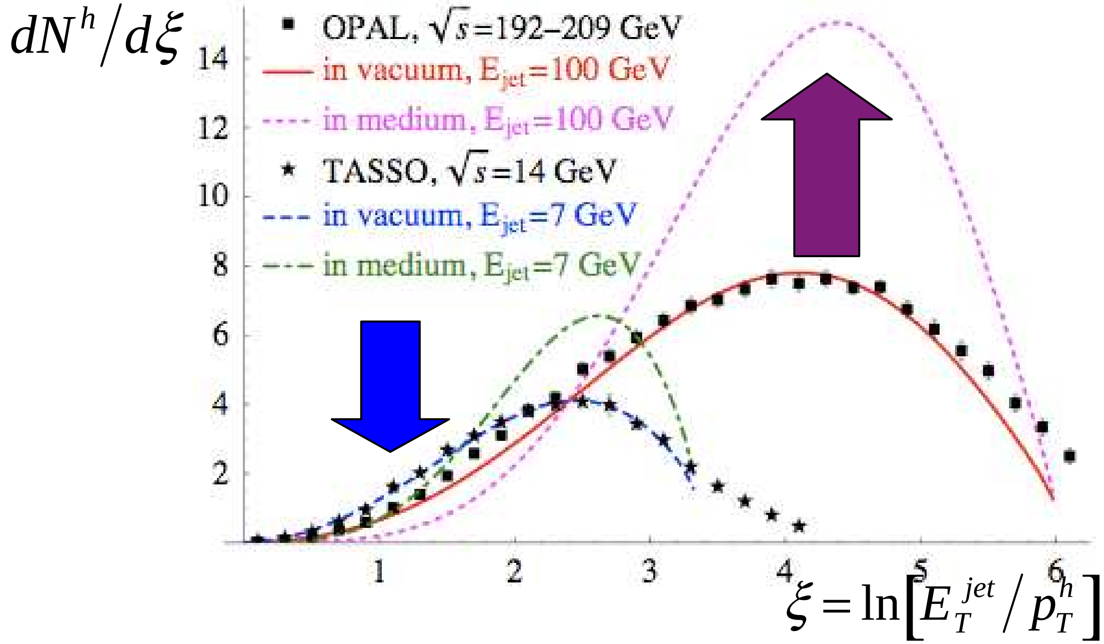
$$\Delta E_{gluon} > \Delta E_{quark,\, m=0} > \Delta E_{quark,\, m>0}$$

<u>Characterize Recoil</u>: What is kicked in the medium?

Jet modifications in reach @ LHC …

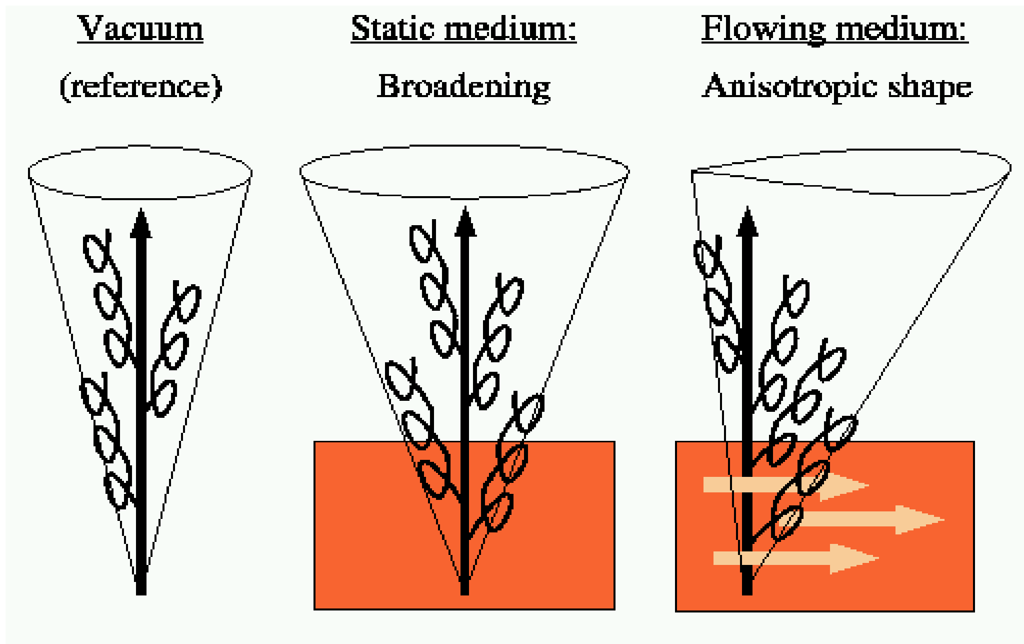
- 'Longitudinal Jet heating':
  The entire longitudinal jet multiplicity distribution softens due to medium effects.

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 modification in reach @ LHC

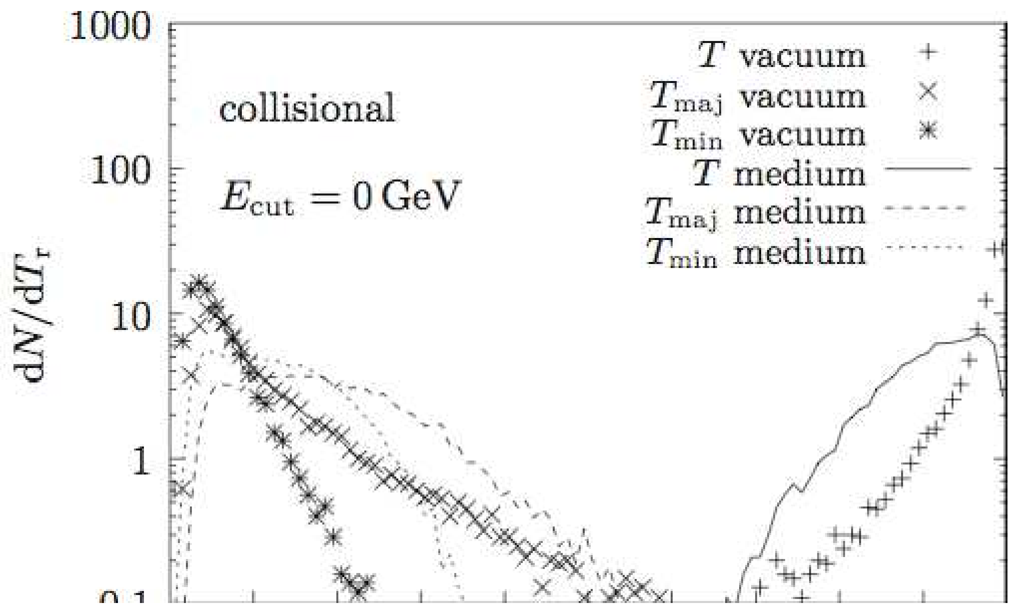
- Medium-modified jet energy flow

  Thrust, thrust major, thrust minor

  n-jet fraction,

  …

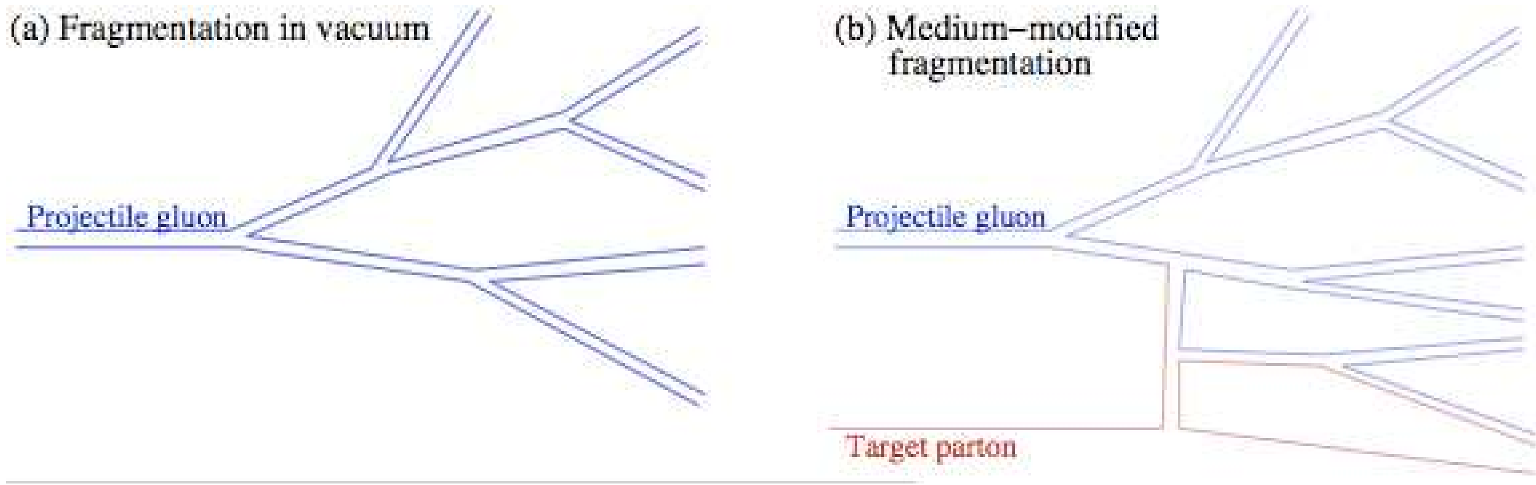
  K. Zapp, G. Ingelman, J. Rathsman, J. Stachel, U.A. Wiedemann, arXiv:0804.3568 [hep-ph]



- Jet hadrochemistry

  Interactions with medium change color flow in parton shower

  S. Sapeta, U.A. Wiedemann, Eur.Phys.J.C55:293-302,2008.



Theory of ‘jet quenching’ – basic requirements:

- must reproduce ‘vacuum baseline’ in the limit of vanishing medium-effects.

  Baseline is multi-particle final states => suggests Monte Carlo technique

- must reproduce perturbative results on medium-modifications, where available.

  Q: How to obtain analytical results on jet quenching by MC technique?

  Main challenge: probabilistic implementation of quantum interference

Here: - recall shortly some analytical results about parton energy loss

- make specific proposal for MC implementation
- show that proposal satisfies basic tests

The medium-modified Final State Parton Shower

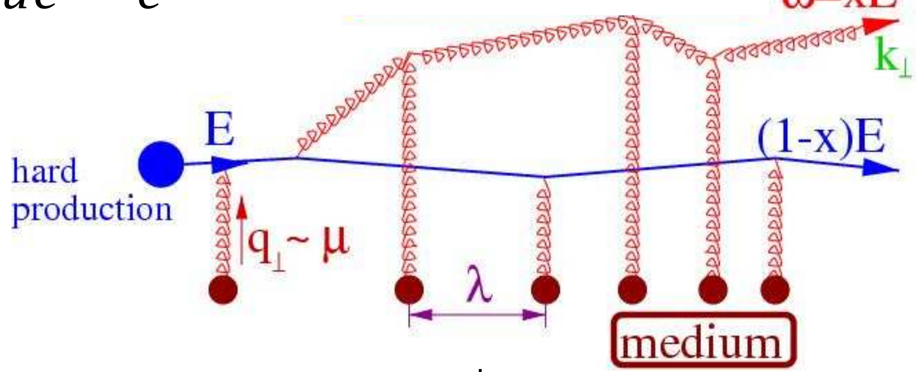
Baier, Dokshitzer, Mueller, Peigne, Schiff (1996); Zakharov (1997); Wiedemann (2000); Gyulassy, Levai, Vitev (2000); Wang ...

Here: Wiedemann, NPB 588 (2000) 303

$$\frac{dI}{d\ln\omega\, dk_T} = \frac{\alpha_s C_R}{(2\pi)^2\omega^2}\, 2\,\mathrm{Re}\int_0^\infty dy \int_y^\infty d\bar{y} \int du\, e^{-ik_T u}\, e^{\left[-\int_y^\infty d\xi\, n(\xi)\nu(u)\right]}$$

$$\times \frac{\partial}{\partial u}\cdot\frac{\partial}{\partial s} K(s=0,y;u,y\,|\,\omega)$$

Radiation off produced parton



Parton undergoes Brownian motion:

$$K(s,y;u,\bar{y}\,|\,\omega) = \int_{s=r(y)}^{u=r(\bar{y})} Dr \exp\left[i\int_y^{\bar{y}} d\xi \left\{ \left(\omega \dot{r}^2/2\right) - n(\xi)\sigma(r) \right\} \right] \xrightarrow{\omega\to\infty} e^{-\nu(s)}$$

Two approximation schemes:

1. Harmonic oscillator approximation:

$$n(\xi)\sigma(r) \approx \hat{q}(\xi)\; r^2$$

2. Opacity expansion in powers of

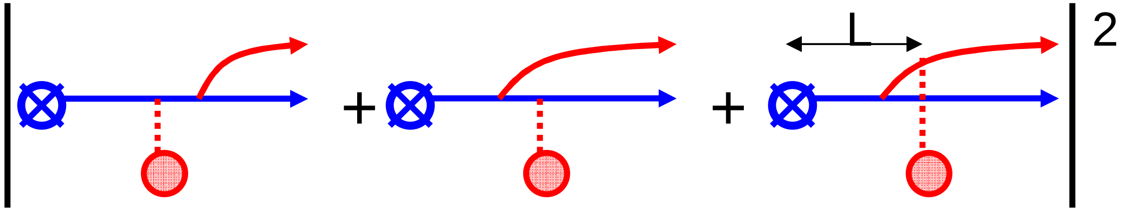
$$\left(\alpha_s \int_0^L d\xi\, n(\xi)\sigma_{el}\right)^n$$

Entire medium-dependence in density of scatterers times their cross-section.

Opacity Expansion - up to 1st order

To first order in opacity, there is a generally complicate interference between vacuum radiation and medium-induced radiation.

$$\omega \frac{dI^{(1)}}{d\omega\, dk_T} =$$

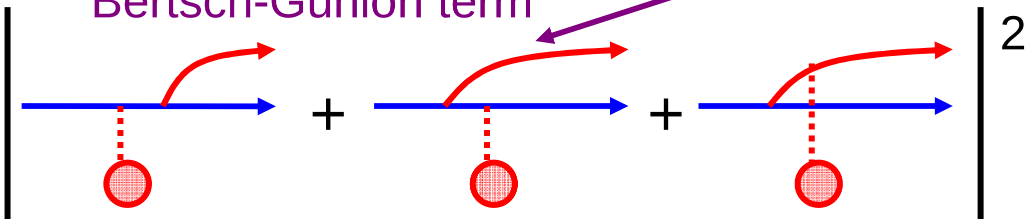


in the parton cascade limit $L \rightarrow \infty$, we identify three contributions:

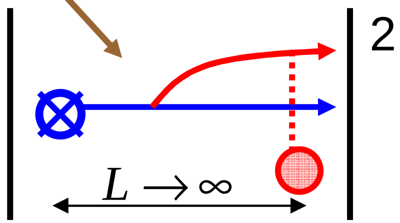
1. **Probability conservation** of medium-independent vacuum terms.
2. **Transverse phase space** redistribution of vacuum piece.
3. **Medium-induced gluon radiation** of quark coming from minus infinity

$$\lim_{\substack{L\rightarrow\infty}}^{nL=const} \omega \frac{dI^{(1)}}{d\omega\, dk_T} = -w_1 H(k_T) + nL \int_{q_T} dq_T \left[R(q_T, k_T) + H(q_T + k_T) \right]$$

Bertsch-Gunion term

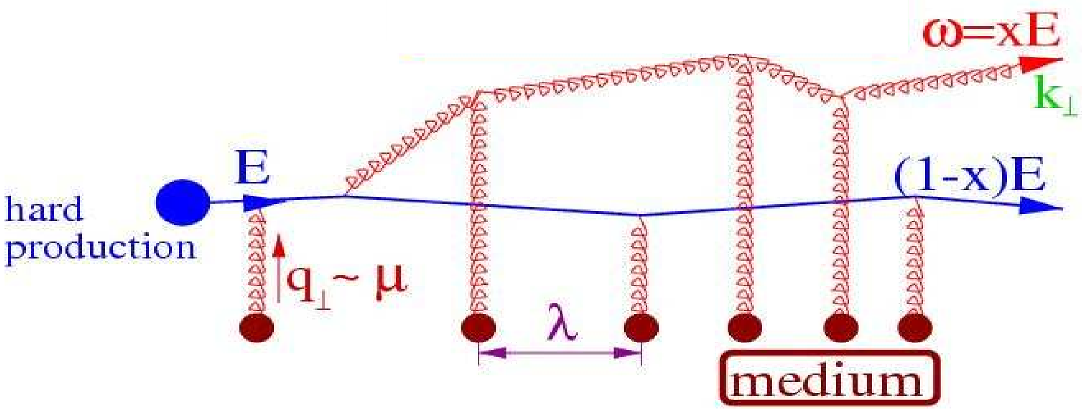


Rescattering of vacuum term



… parametric dependence of results …

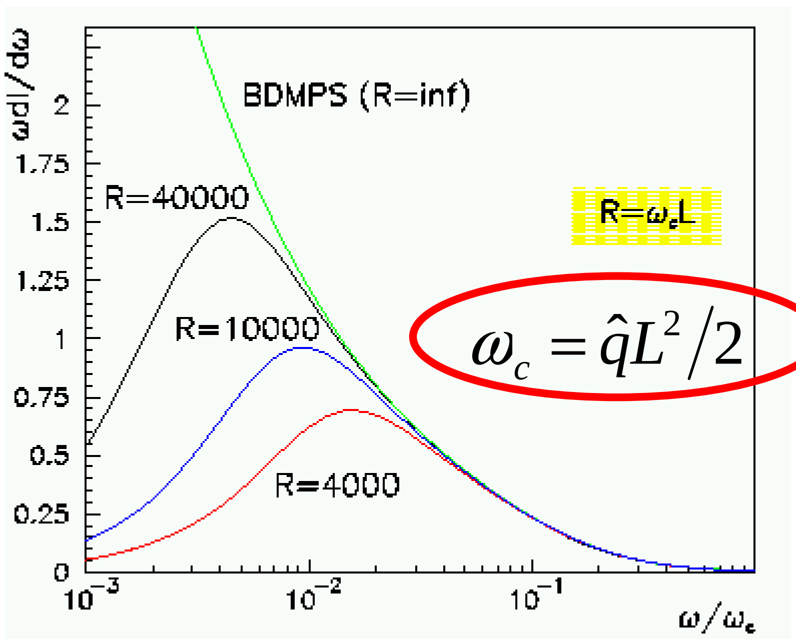
Baier, Dokshitzer, Mueller, Peigne, Schiff (1996); Zakharov (1997); Wiedemann (2000); Gyulassy, Levai, Vitev (2000); Wang ...

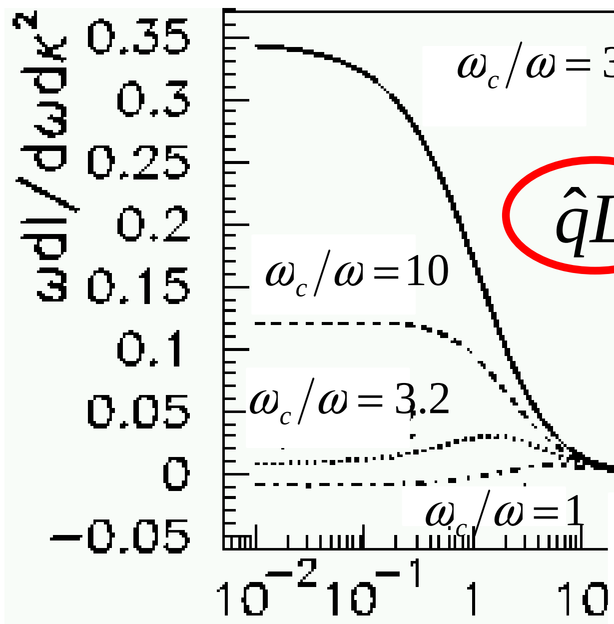


Medium characterized by transport coefficient:

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

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

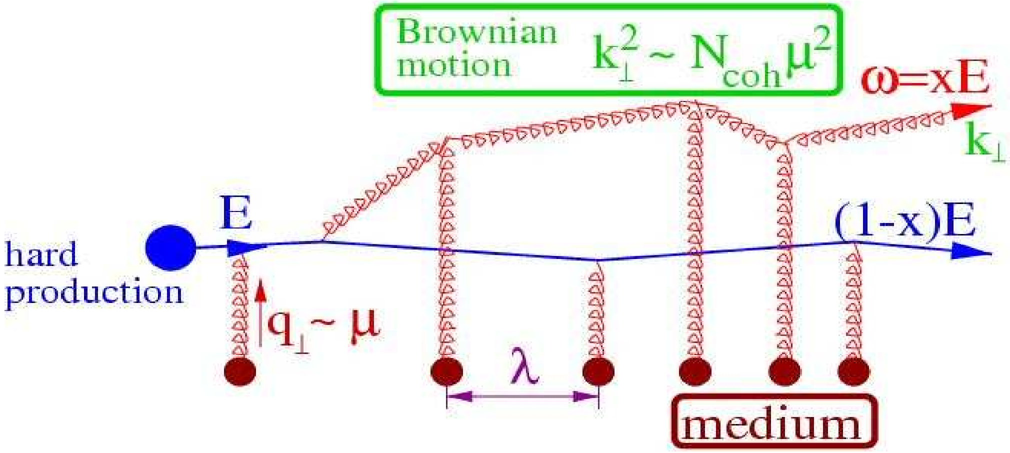




$$\kappa^2 \equiv \frac{k_T^2}{\hat{q}L}$$

Salgado,Wiedemann PRD68:014008 (2003)

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

Proposal

Quantum interference in the ‘vacuum’ parton shower can be treated by a probabilistic algorithm with angular ordering alone.

We propose that the dominant medium-induced quantum interference can be treated by implementation of a formation time constraint alone.

Implementation

Consider projectile (say: quark q) propagating through medium.

Medium is source of elastic and inelastic interactions.

To account for these, parametrize medium as
set of scattering centers Q_T with density n.

The interaction probability of q with Q_T and the kinematics is
given by elastic and inelastic cross sections

$$\sigma^{qQ_T \to qQ_T} \qquad \sigma^{qQ_T \to qQ_T g}$$

Consider first: <u>incoherent limit, on-shell quark</u>
trivial case: select scatterings with probability $[1 - S_{no\,scatt}(\tau)]$

$$S_{no\,scatt}(\tau) = \exp[-(\sigma_{el} + \sigma_{inel}) n \beta \tau]$$

iterate probabilistically

Implementation: coherence effects

(still ignoring branching in vacuum)

Consider formation time of gluon produced in inelastic process

$$t_F = 2\omega / k_T^2$$

If t_F < d (distance to next scattering center) then

-> gluon produced incoherently, probabilistic implementation trivial

If t_F > d then

-> add $q_{T,i}$ of next (ith) scattering center to get $q_{tot} = \sum_i q_{T,i}$

-> recalculate inelastic process under constraint that

q_{tot} is transferred from medium (i.e. assume coherent production)

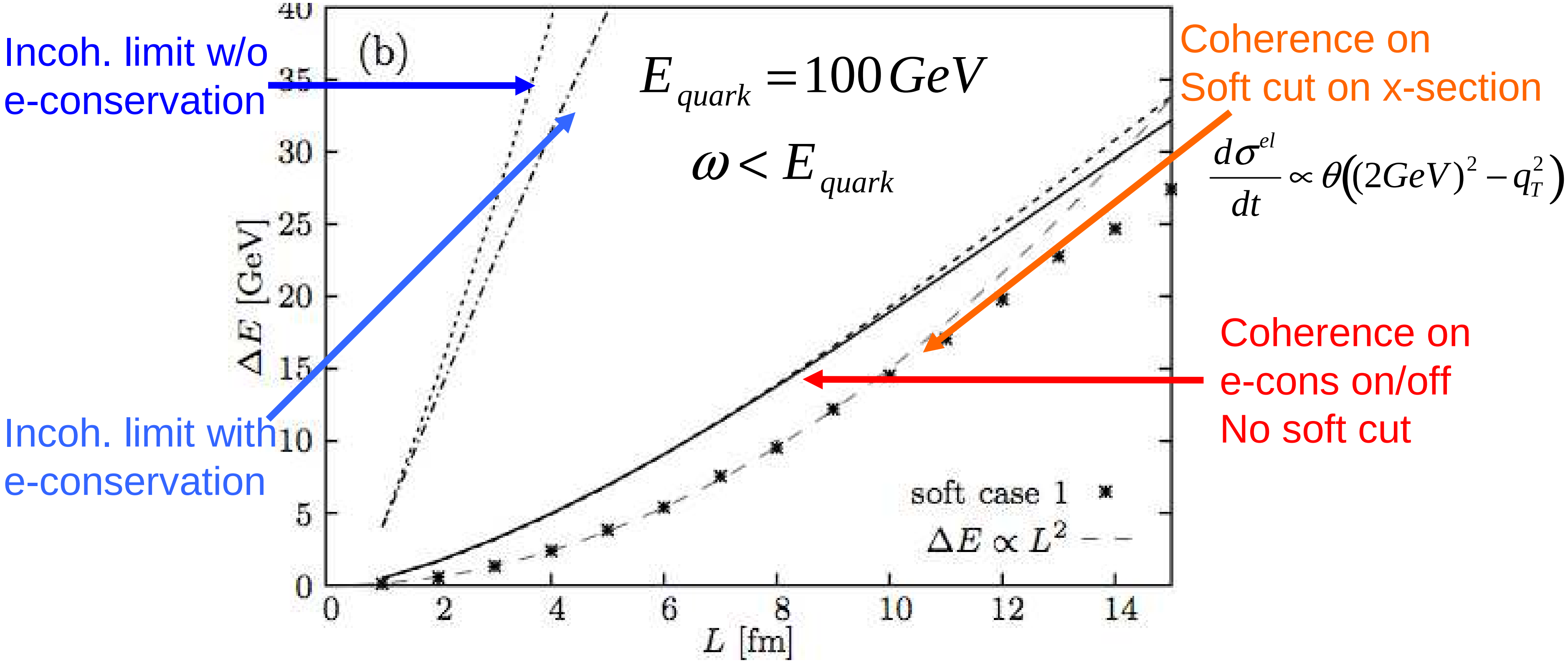
-> determine new formation time

-> check whether **t'_F < d** , else repeat $t'_F = 2\omega / (k_T + q_{tot})^2$

L-dependence of average energy loss

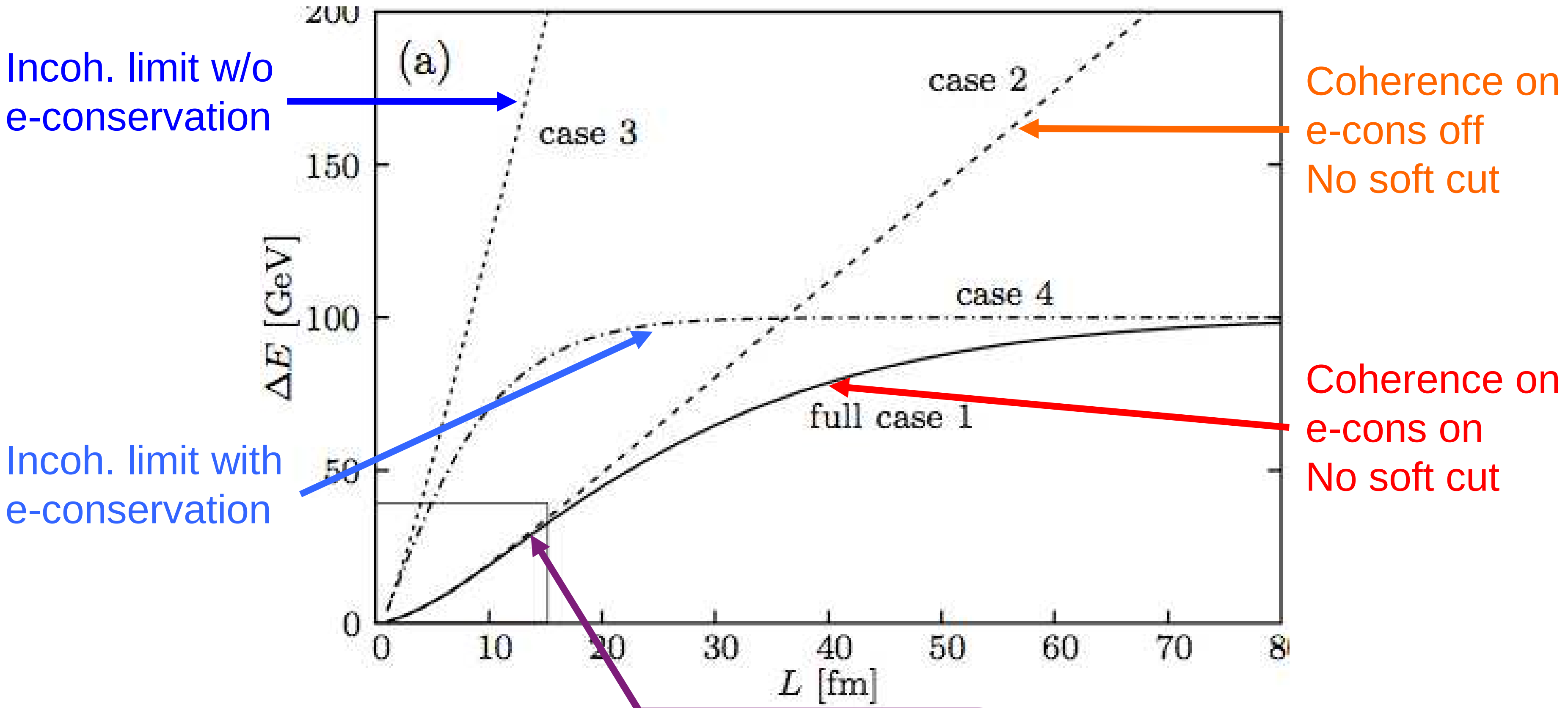
Use $$\frac{d\sigma^{qQ_T \to qQ_T}}{d|t|} = \frac{\pi \alpha_s^2}{s^2} C_R \frac{s^2+u^2}{t^2}$$ and $$\frac{d\sigma^{qQ_T \to qQ_T g}}{d\omega} = g^2 C_F \sigma^{qQ_T \to qQ_T} \frac{1}{\omega}$$

K. Zapp, J. Stachel, U.A. Wiedemann, arXiv:0812.3888



MC-implementation reproduces **L²-dependence in BDMPS-limit**.
Hard momentum transfers reduce formation time and
result in an dependence of average energy loss **weaker than L²**.

Average energy loss at large L



Medium acts **incoherently**
over distances $L>L_c$
=> linear L-dependence

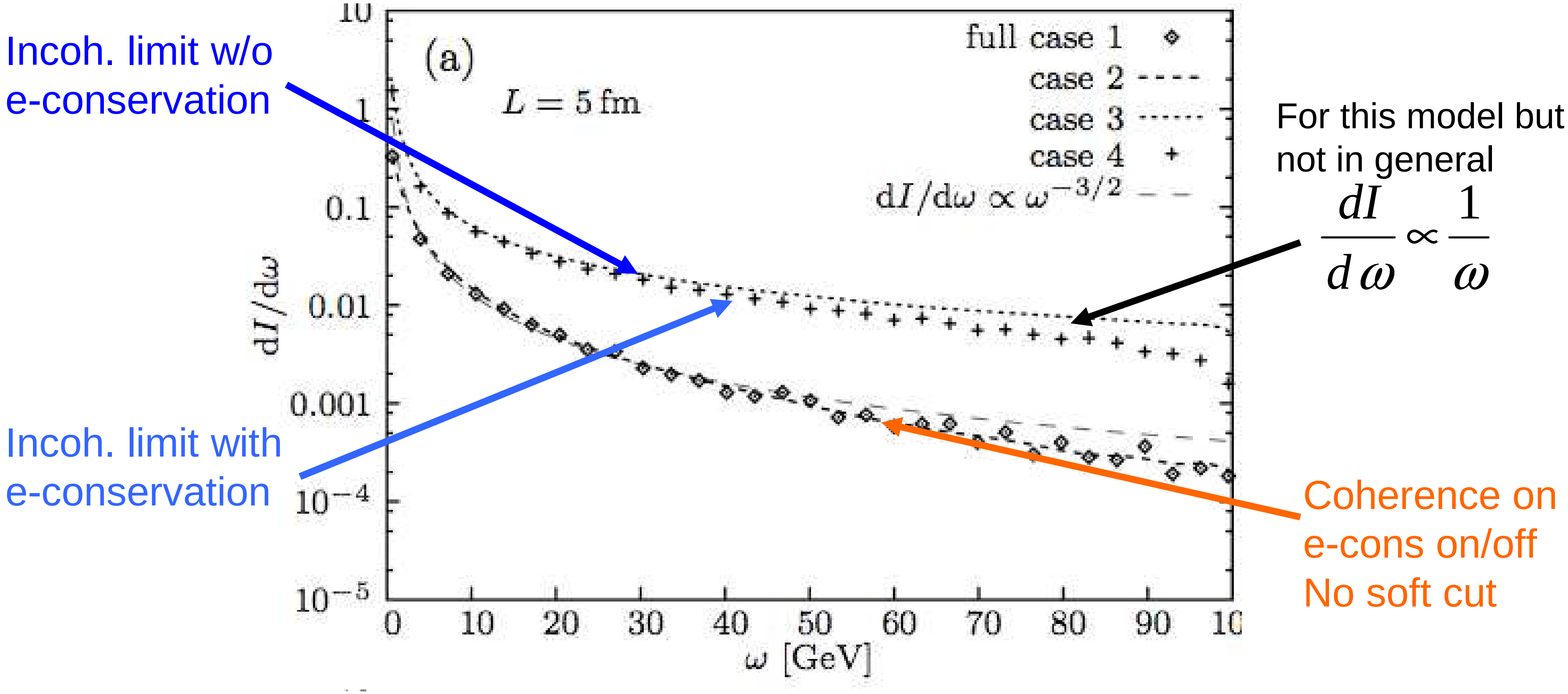
$$L > L_c = \sqrt{\frac{4\omega_{max}}{\hat{q}}};$$

$$\hat{q} \equiv n \int dq_T^2 q_T^2 \frac{d\sigma^{qQ_T \to qQ_T}}{dq_T^2}$$

Note: numerical results here use $\hat{q} = 1 GeV^2 / fm$

if $\hat{q}$ larger, than energy conservation effects more important for path lengths realized in HI collisions.

L-dependence of gluon energy distribution

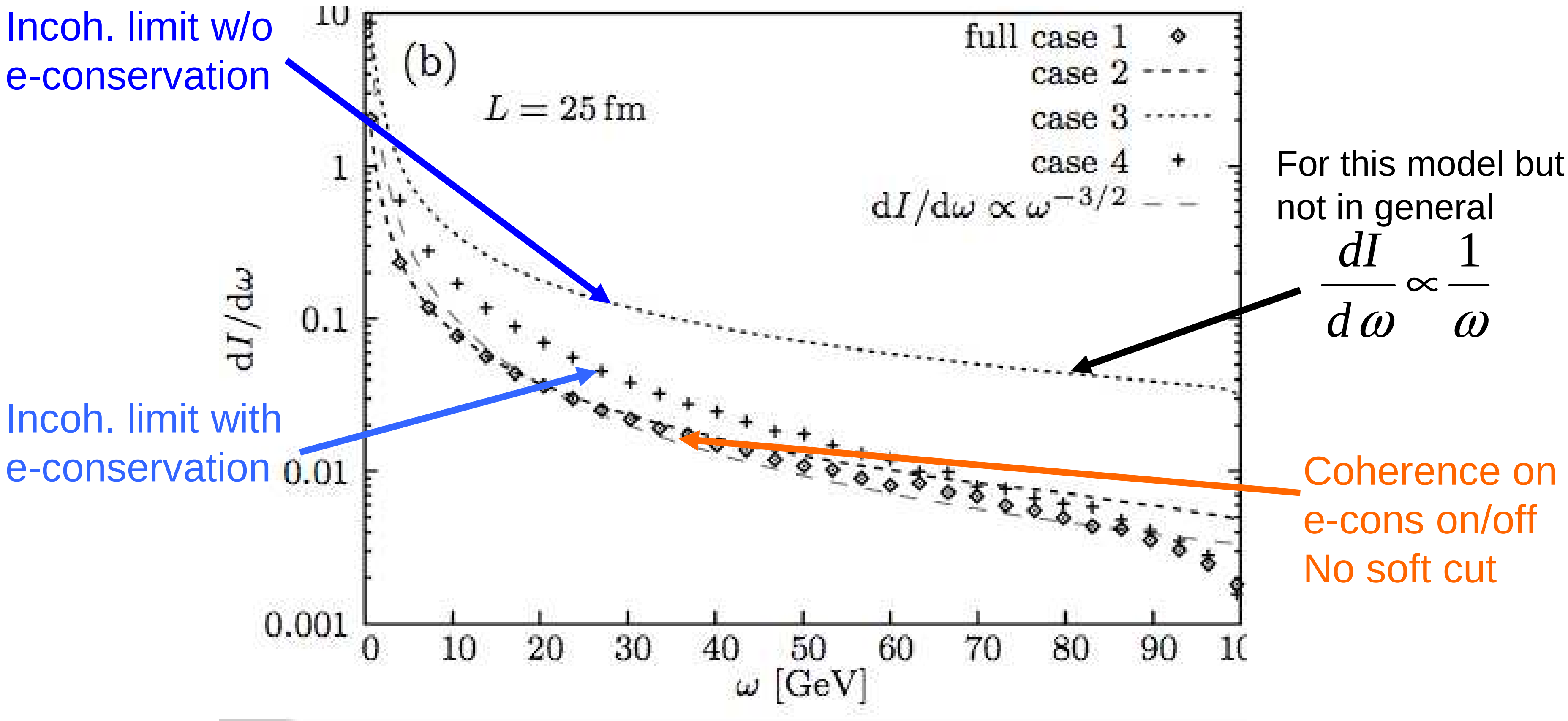


MC-implementation reproduces **characteristic $dI/d\omega \propto \omega^{-3/2}$ in BDMPS-limit**.

Our model $d\sigma^{inel}/d\omega \propto 1/\omega$ overestimates yield at large ω

For more realistic inel x-section, $dI/d\omega$ drops faster near $\omega \sim \omega_{max} = 100\,GeV$

Same for larger L



MC-implementation reproduces **characteristic $dI/d\omega \propto \omega^{-3/2}$ in BDMPS-limit**.

Energy conservation leads to steeper gluon energy distribution.

In the same way in which quantum interference in the vacuum shower can be treated by a probabilistic algorithm with angular ordering alone, we have shown that the dominant medium-induced quantum interference can be treated by implementation of a formation time constraint alone.

JEWEL- Jet Evolution With Energy Loss

(v1: only elastic interactions with medium)

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

- Baseline: stand-alone Q^2-ordered PYTHIA-type final state parton shower without keeping track of color flow (since this would complicate medium interaction)

  Hadronization models: string fragmentation (associating strings between nearest neighbors in momentum space)

- Medium effects:

  Q^2-ordering used to embed parton shower in nuclear geometry.

  Lifetime of virtual state: $$\tau = \left(E/Q_f^2\right) - \left(E/Q_i^2\right)$$

  determines probability of no scattering

  $$S_{no\ scatt}(\tau) = \exp\left[-\sigma_{elas} n \beta \tau\right]$$

  with probability 1-S, parton undergoes elastic scattering

  $$\frac{d\sigma_{elas}}{d|t|} = \frac{\pi \alpha_s^2}{s^2} C_R \frac{s^2 + u^2}{t^2}$$

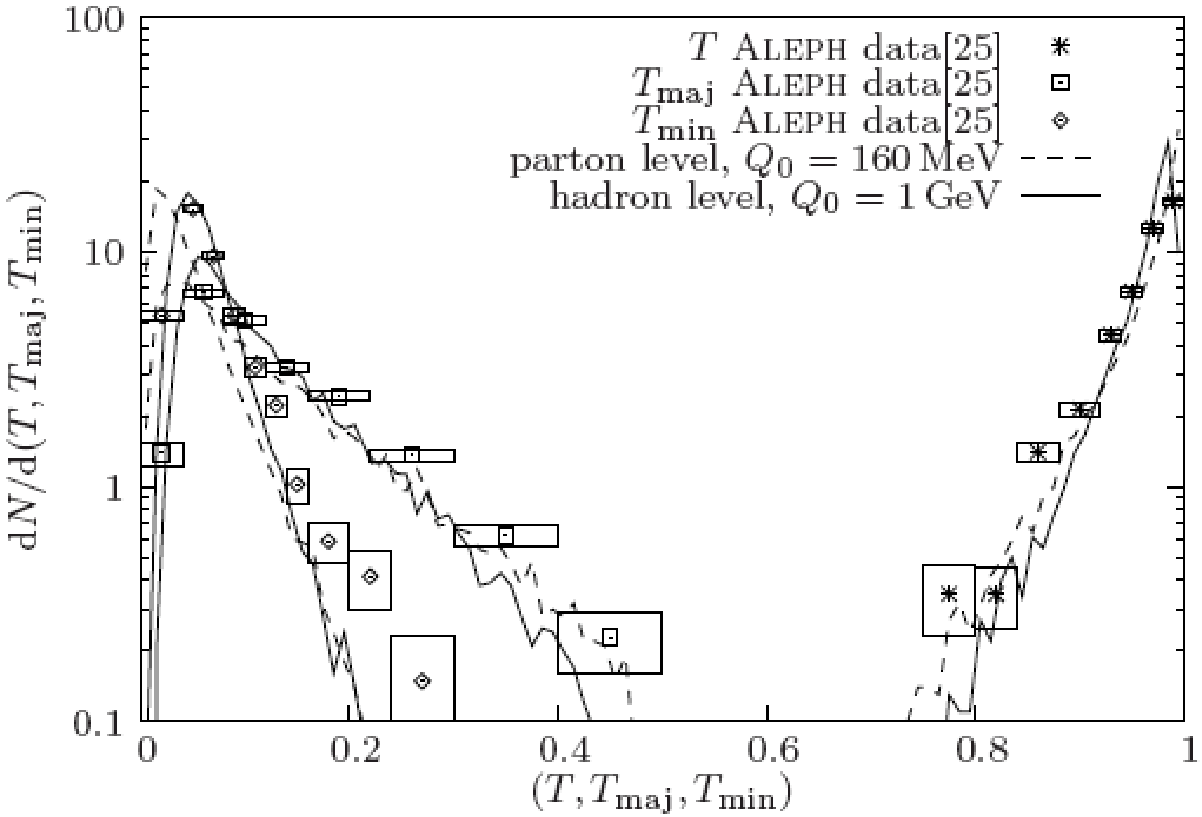
  radiative e-loss modeled by f_{med}-enhanced splitting functions (so far).

JEWEL gets the vacuum baseline

$$T \equiv \max_{n_T} \frac{\sum_i |p_i \cdot n_T|}{\sum_i |p_i|}$$

$$T_{maj} \equiv \max_{n_T \cdot n = 0} \frac{\sum_i |p_i \cdot n|}{\sum_i |p_i|}$$

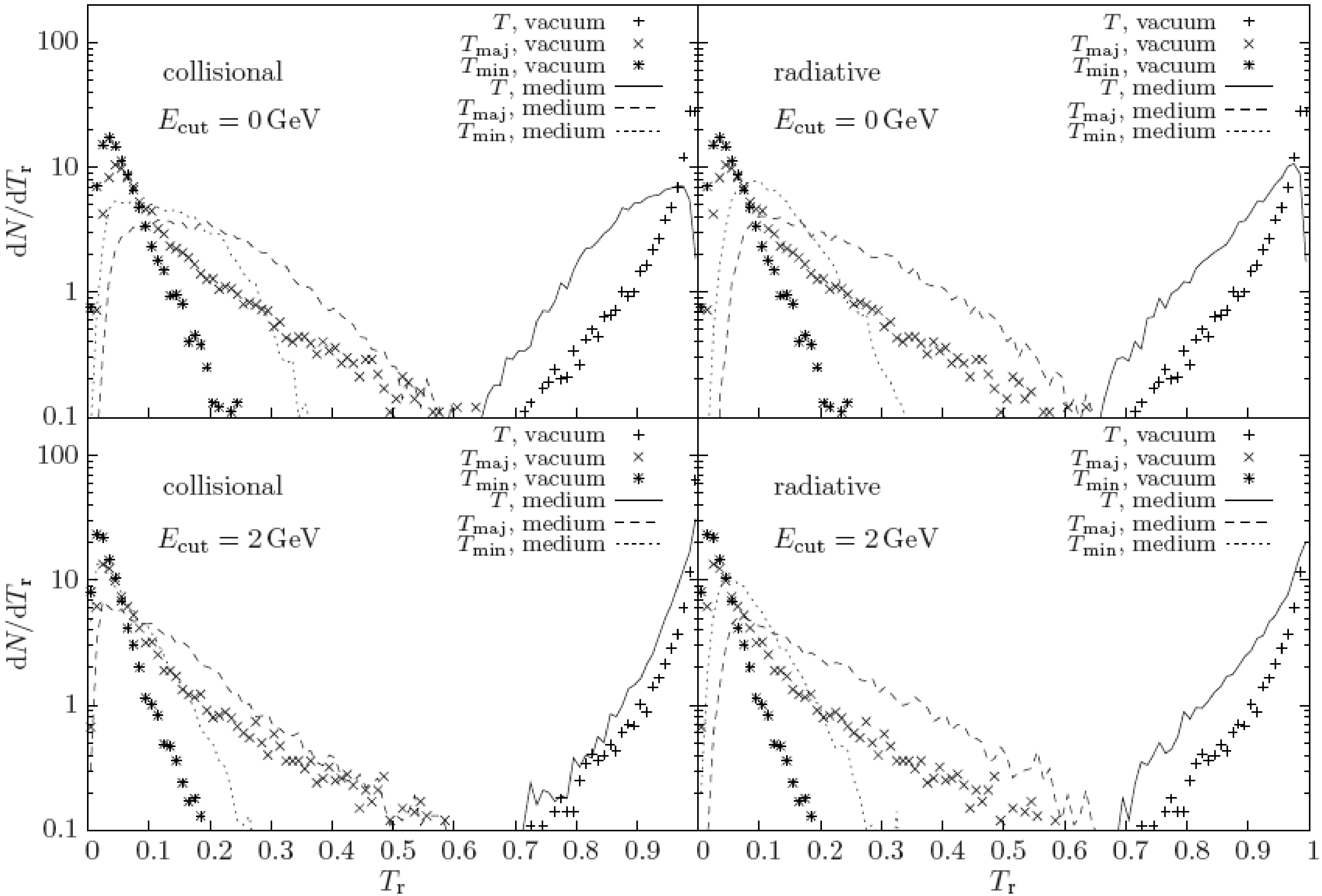
$$T_{\min} \equiv \frac{\sum_i |p_{ix}|}{\sum_i |p_i|}$$



For these jet shape observables, results are insensitive to details of hadronization.

JEWEL: disentangling elas / inelas processes

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



JEWEL vacuum baseline for n-jet fraction

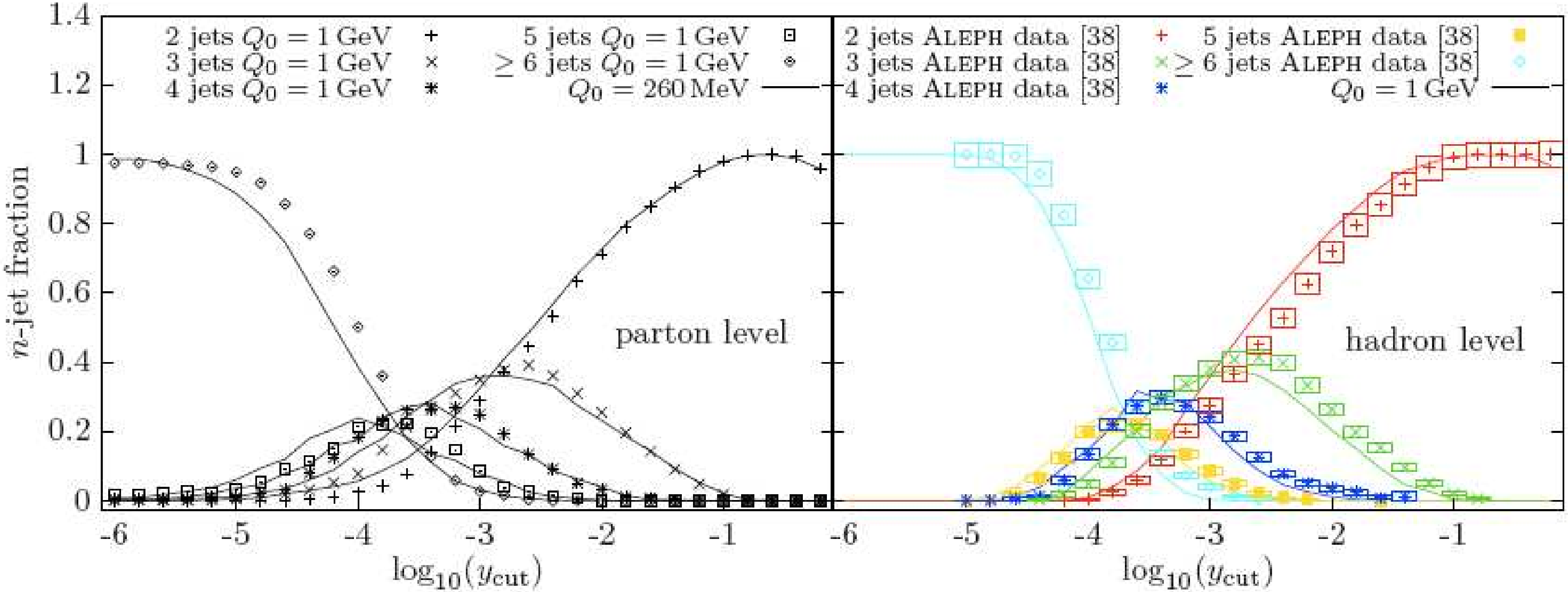
K. Zapp, G. Ingelman, J. Rathsman, J. Stachel, U.A. Wiedemann, arXiv:0804.3568 [hep-ph]

Durham cluster algorithm: define distance between particles

$$y_{ij} \equiv 2\min\left(E_i^2, E_i^2\right)\left(1-\cos\theta_{ij}\right)/E_{cm}^2$$

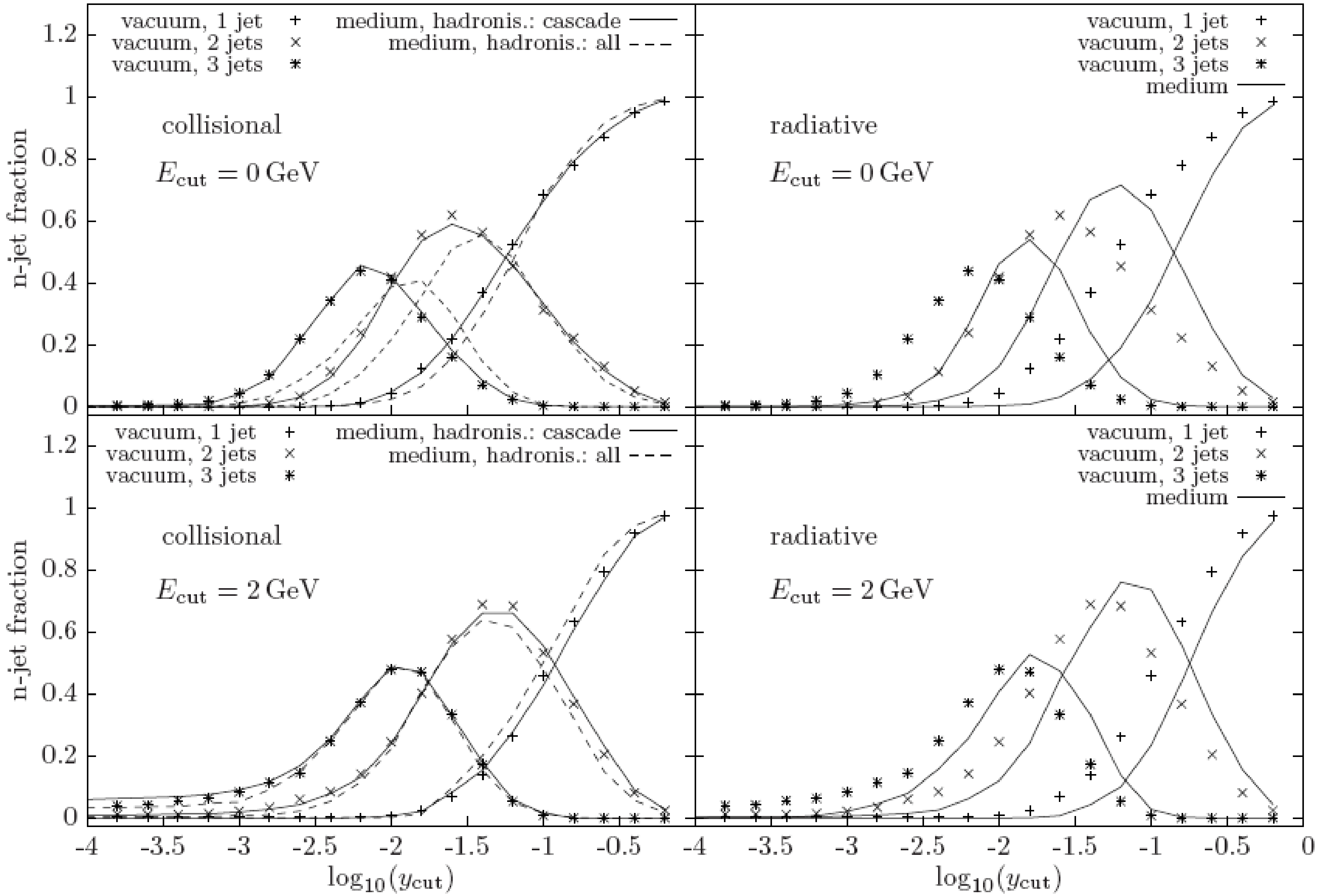
particle belong to same jet if

$$y_{ij} < y_{cut}$$



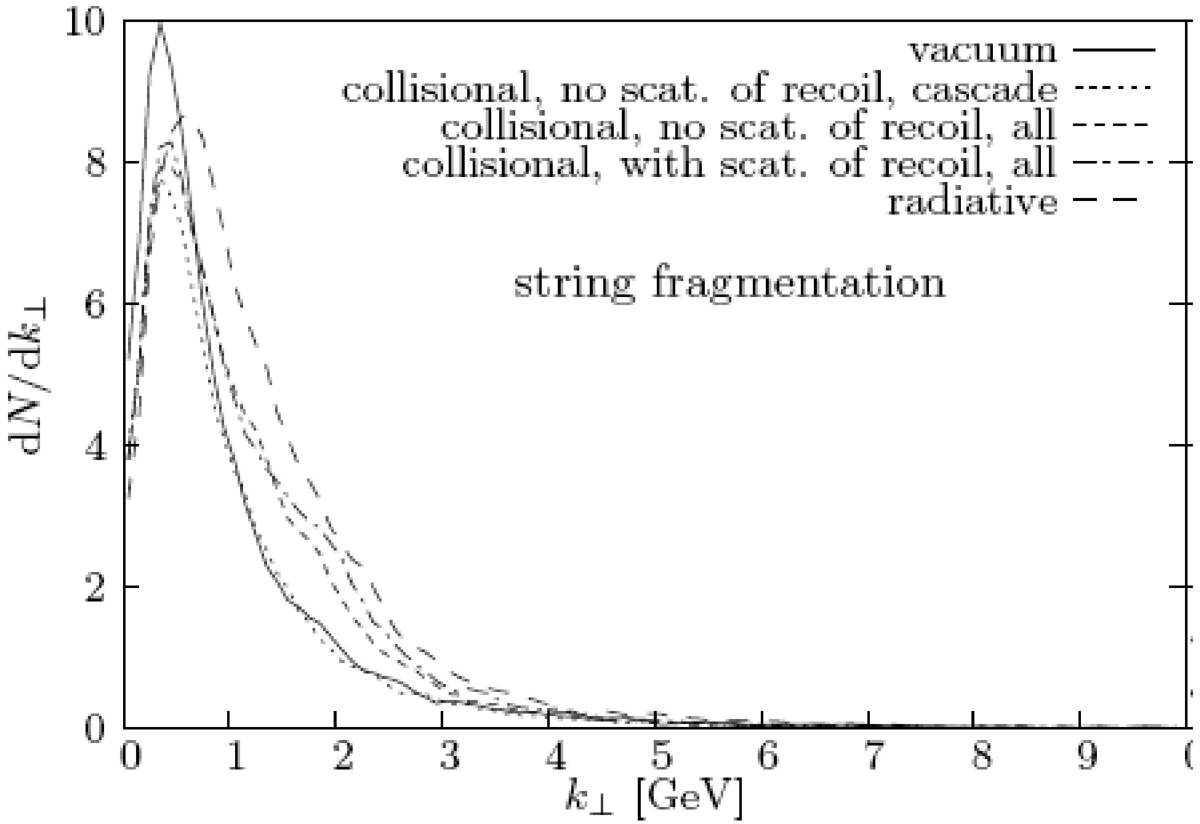
JEWEL: disentangling elas / inelas processes

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



JEWEL: e-loss with minor pt-broadening

K. Zapp, G. Ingelman, J. Rathsman, J. Stachel, U.A. Wiedemann, arXiv:0805.4759 [hep-ph]



Almost no broadening despite extreme choices:
E=100 GeV, T=500 MeV, L=5fm, f_{med} = 3

END