IV Sakharov Conference
22.05.2009

Stochastic jet quenching in nuclear collisions

M. Kirakosyan, A. Leonidov, V. Nechitailo

P.N. Lebedev Physics Institute

IM-QCD ➔ IRM-QCD

- Color randomness kills specific effects related to color coherence, e.g. angular ordering in QCD cascades.

- Density fluctuations induce fluctuations of dielectric permittivity

- => Energy loss of fast particle in random inhomogeneous medium

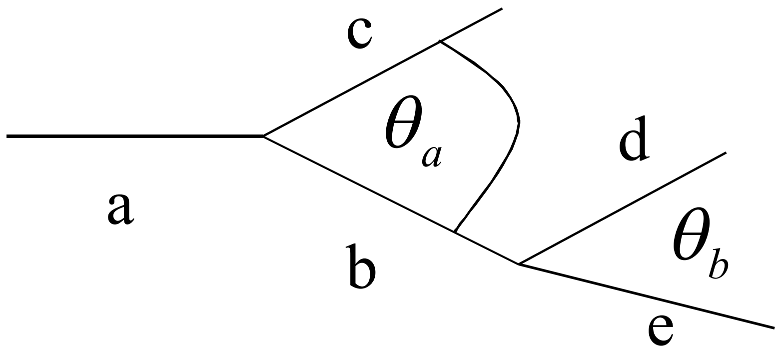
- => Energy loss through critical opalescence

Motivation:

Early stage of high energy nuclear collisions is inevitably strongly inhomogeneous in color, momentum, energy, etc. on the event-by-event basis due to semihard partonic degrees of freedom.

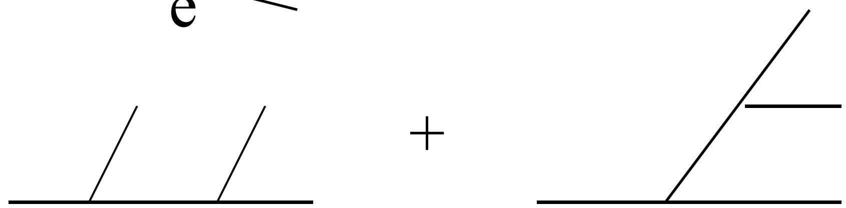
Angular ordering in QCD cascades

A.L., V. Nechitailo



$$\theta_b < \theta_a$$

Origin:



Monte Carlo implementation:

- Exact ordering $\quad \sin\theta$
- Webber ordering $\quad \xi = \dfrac{(p_a, p_b)}{E_a E_b}$
- PYTHIA ordering $\quad \dfrac{Q_b^2}{z_b(1-z_b)} < \dfrac{Q_a^2 z_a}{(1-z_a)}$

Color randomization is the fastest process in dense matter

M. Guylassy, A. Selikhov (1991)

Color relaxation time:

$$t_c = \left[4\alpha_s^2 T \ln(1/\alpha_s) \right]^{-1}$$

Momentum relaxation time:

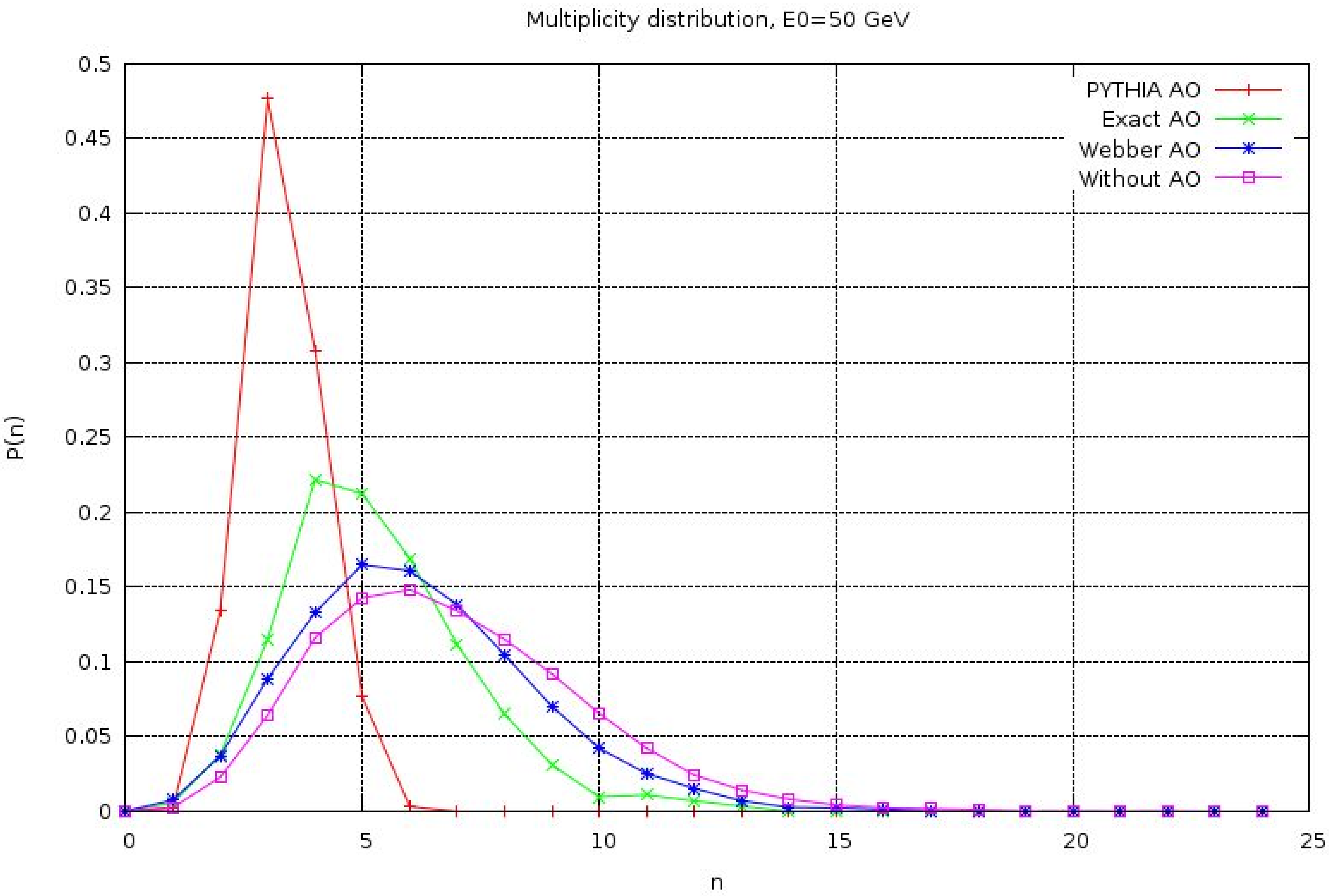
$$t_p = \left[4\alpha_s T \ln(m_E / m_M) \right]^{-1}$$

$t_c \ll t_p$ → Color coherence disappears before momentum of the mode can change

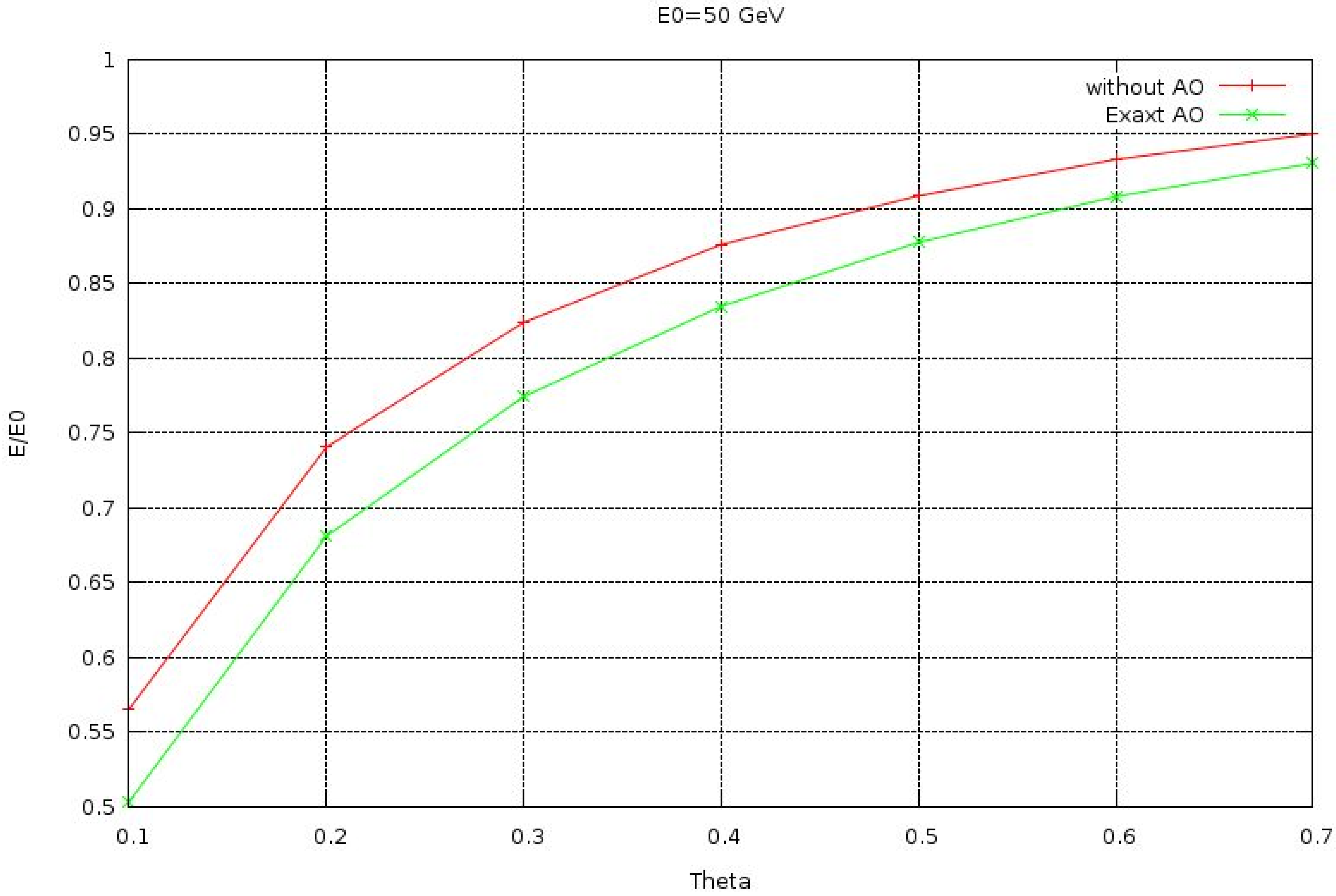
QCD cascade in dense matter is to a first approximation that without angular ordering

K.Zapp et al., arXiv:0804.3568 (JEWEL)

Multiplicity distributions with and without AO

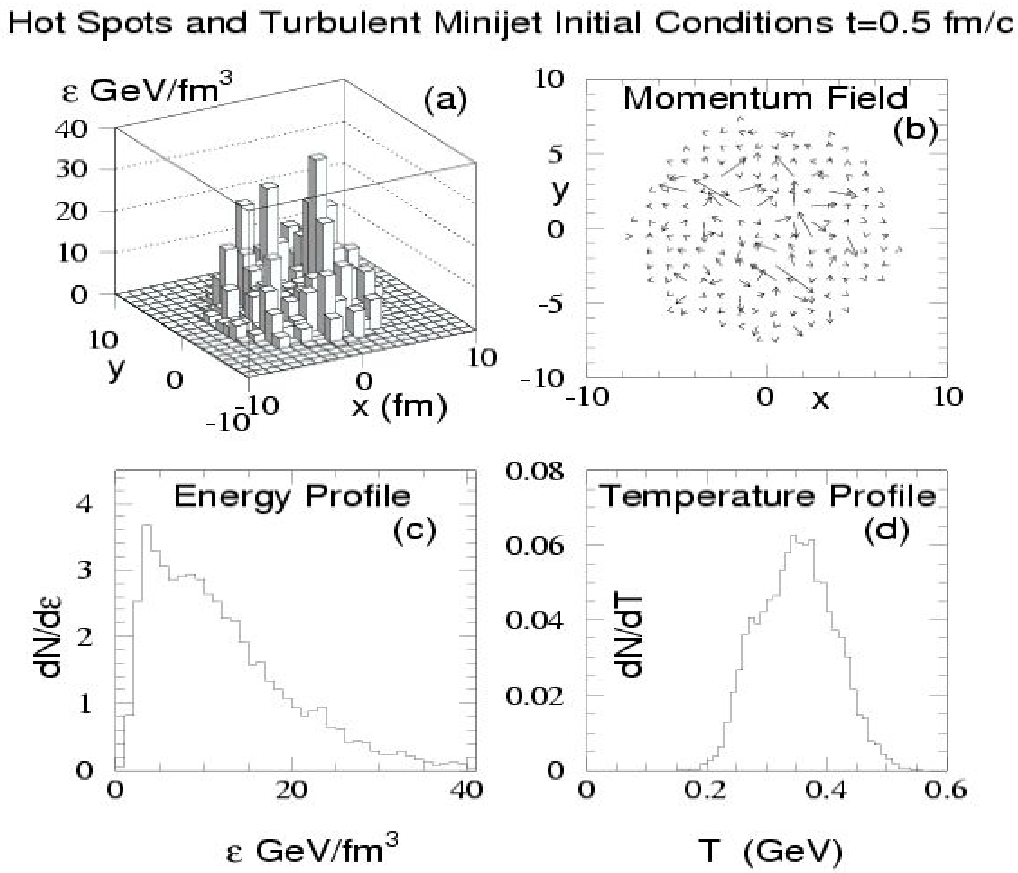


Energy within a cone of given size



M. Guylassy, D. Rischke, B. Zhang, Nuclear Physics A613 (1997), 397

Turbulent energy density in nuclear collisions:

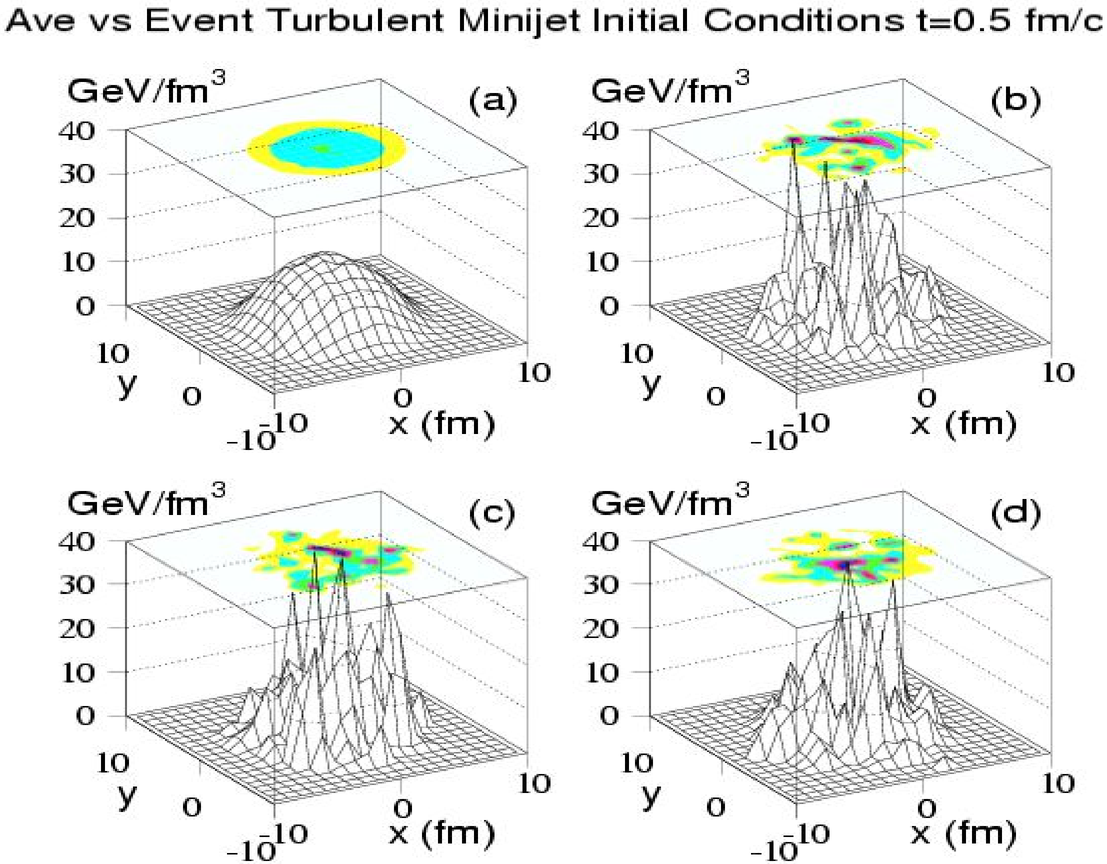


Such a hot-spot structure means that the gluon density is

- random
- strongly correlated

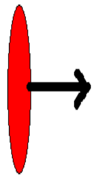
M. Guylassy, D. Rischke, B. Zhang, Nuclear Physics A613 (1997), 397

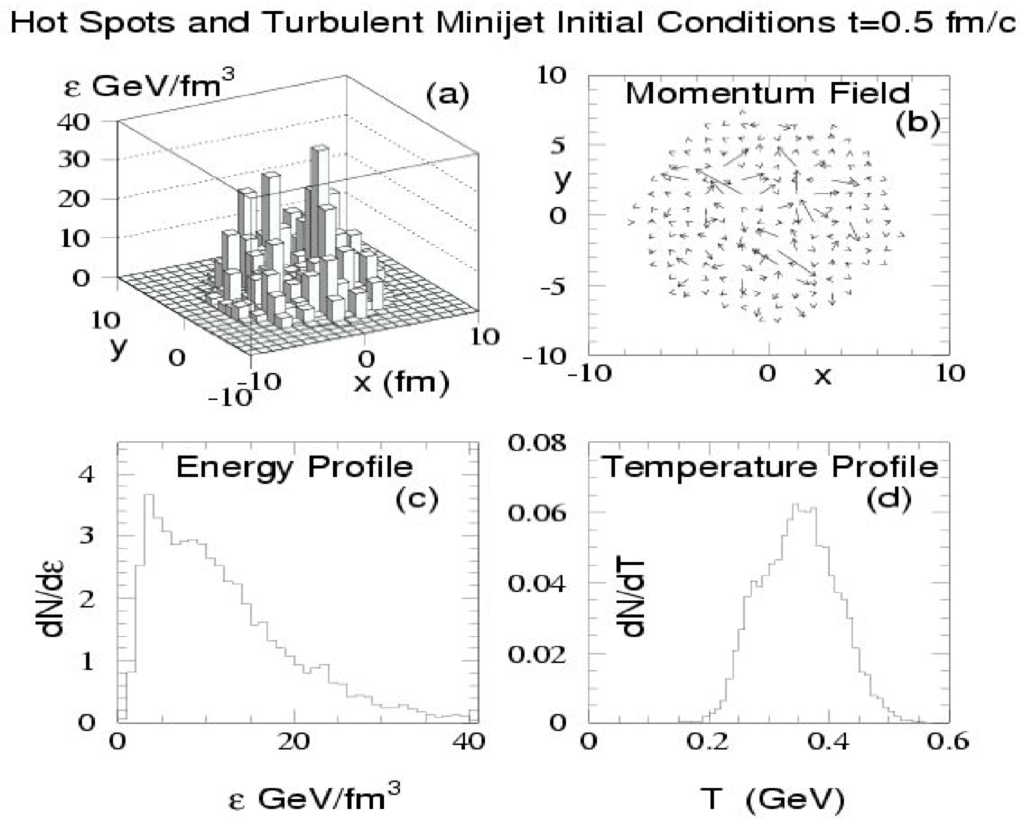
Event-by-event versus averaging:



Energy losses of uniformly moving particle:

Particle's proper filed (WW glue) scatters on random medium:





Energy loss: spraying of WW gluon modes due to
their interaction with the medium
=> medium-induced radiative loss

- Cherenkov radiation: resonance decoupling of WW glue for special values of dielectric permittivity
- Transition radiation: resonance decoupling of WW glue due to inhomogeneities in dielectric permittivity

The medium is characterized by the dielectric permittivity tensor

$$\varepsilon_{ij}(w,k) = \left(\delta_{ij} - \frac{k_i k_j}{k^2} \right) \varepsilon^t(w,k) + \frac{k_i k_j}{k^2} \varepsilon^l(w,k)$$

(w,k) : energy and momentum of gluon modes

Specifying dielectric permittivity fully specifies energy loss of an ultrarelativistic charged particle with energy p moving along the z axis

$$\frac{dW}{dz} = -\frac{2C_{F(V)}\alpha_s}{\pi}\int d^3k \left\{ \frac{w}{k^2}\left[\mathrm{Im}\frac{1}{\varepsilon^{\parallel}(w,k)} - (w^2 - v^2k^2)\,\mathrm{Im}\frac{1}{w^2\varepsilon^{\perp}(w,k) - k^2} \right] \right\}_{w=k_z}$$

Random medium:

Homogeneous background + density fluctuations => Full tensor structure of dielectric permittivity

$$\varepsilon_0(w)\delta_{ij} \oplus \xi(r) \quad => \quad \varepsilon_{ij}(w,k)$$

$\xi(r)$: spatially random perturbation

- Gaussian ensemble:

$$\langle \xi(r) \rangle = 0; \qquad \langle \xi(r_1)\xi(r_2) \rangle = g(|r_1 - r_2|)$$

- Exponential correlation function

$$g(r) = \sigma^2 e^{-r/r_c}$$

- Effective permittivity tensor

$$\varepsilon_0(w)\delta_{ij} \oplus \xi(r) \quad \Rightarrow \quad \varepsilon_{ij}(w,k \,|\, \sigma, r_c)$$

:

M.R. Kirakosyan, A.V. Leonidov, arXiv0809.2179[hep-ph]

- Analytical computation of $\varepsilon_{ij}(w,k\,|\,\sigma,r_c)$ to all orders in σ in the limit $\sigma^2(k\cdot r_c) \ll 1$

- Dielectric permittivity:

$$\varepsilon_{ij}(w,k\,|\,\sigma,r_c) = \left(1 - \frac{1}{\varepsilon_0 w^2}\Pi_{ij}(w,k\,|\,\sigma,r_c)\right)$$

$$\equiv \left(\delta_{ij} - \frac{k_i k_j}{k^2}\right)\varepsilon^t(w,k\,|\,\sigma,r_c) + \frac{k_i k_j}{k^2}\varepsilon^l(w,k\,|\,\sigma,r_c)$$

Analytical expressions for polarization operator:

$$\Pi^t(w,k\,|\,\sigma,r_c)=\sigma^2\kappa^2\left(\begin{array}{l}\dfrac{\kappa^2}{(\kappa+i\delta_c)^2-k^2}-\dfrac{\delta_c(\delta_c+i\kappa))}{2k^2}+\\ \dfrac{\delta_c(\delta_c{}^2+\kappa^2+k^2)}{k^2}\cdot\dfrac{1}{k}\cdot\arctan\left(\dfrac{ik}{\kappa+i\delta_c}\right)\end{array}\right)$$

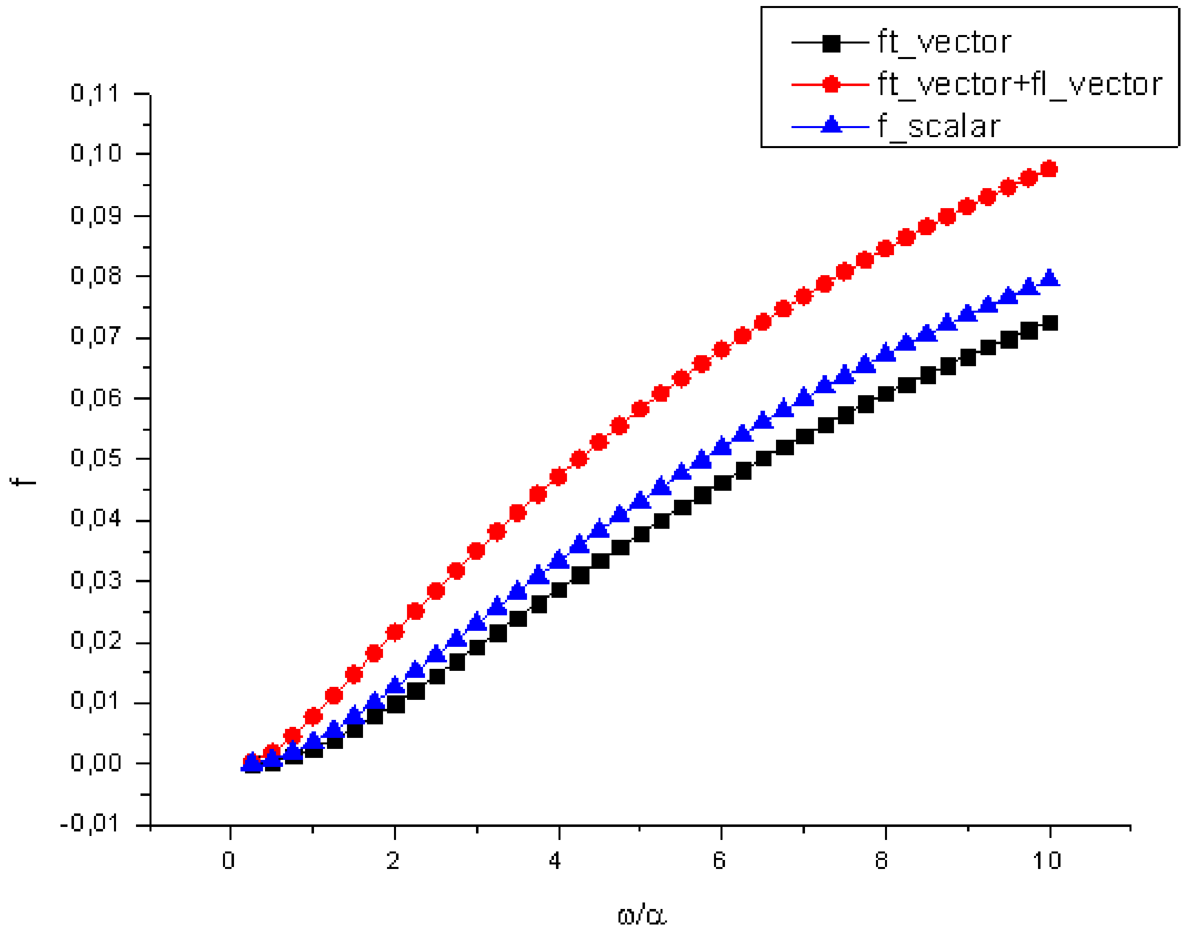
$$\Pi^l(w,k\,|\,\sigma,r_c)=\sigma^2\kappa^2\left(\begin{array}{l}1+\dfrac{\delta_c(\delta_c+i\kappa))}{2k^2}-\\ \dfrac{\delta_c(\delta_c{}^2+\kappa^2+k^2)}{k^2}\cdot\dfrac{1}{k}\cdot\arctan\left(\dfrac{ik}{\kappa+i\delta_c}\right)\end{array}\right)$$

$$\kappa=\sqrt{\varepsilon_0}\,w \qquad\qquad \delta_c=1/r_c$$

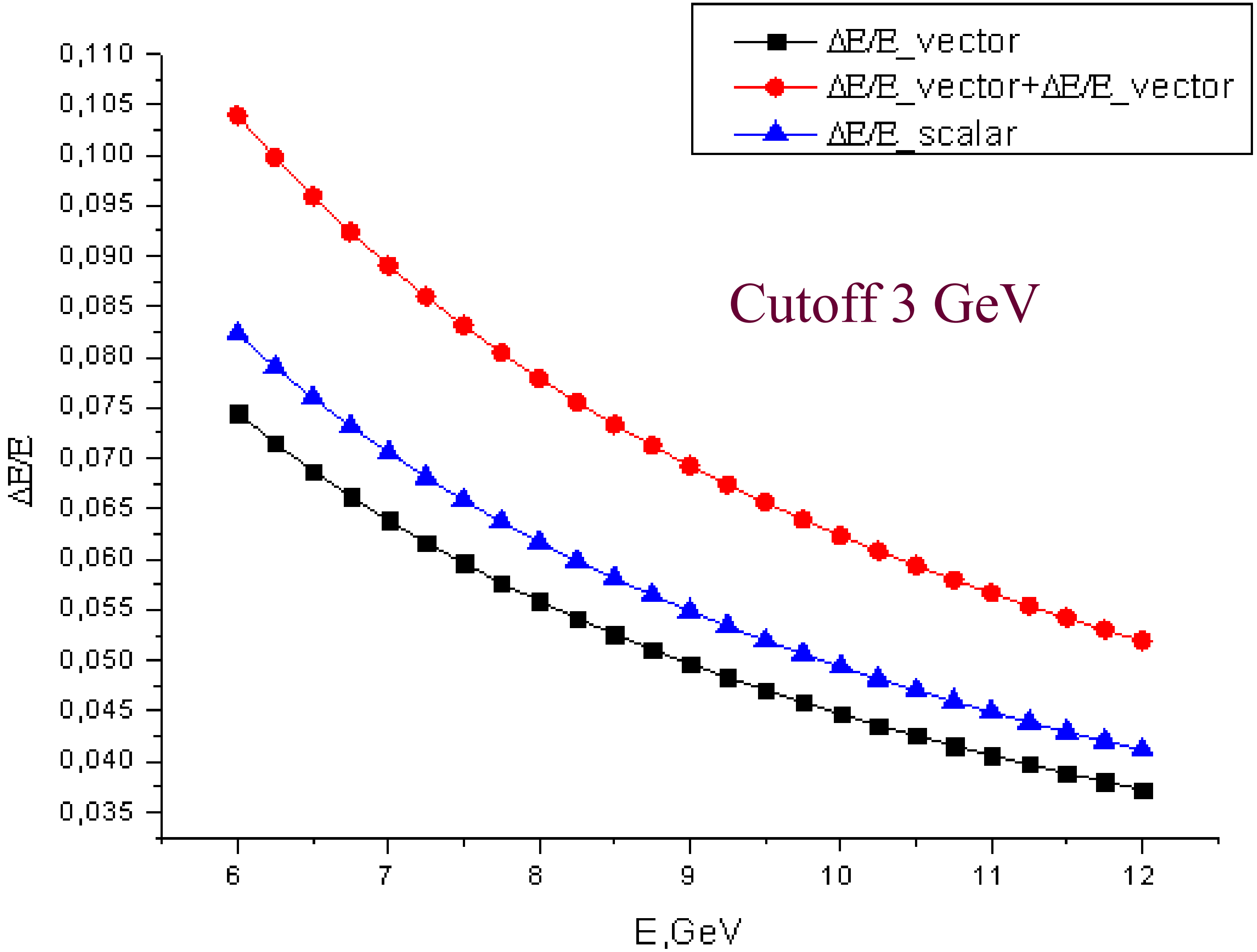
$$\frac{dW}{dwdz} = -2C_{V(F)}\alpha_s \frac{1}{r_c}\left[f_t(wr_c \mid \sigma, \varepsilon_0) + f_l(wr_c \mid \sigma, \varepsilon_0) \right]$$

$$\sigma = 0.2$$

$$\varepsilon_0 = 0.8$$



Fractional energy loss at L=5 fm



Mode quenching through critical opalescence

Basic mechanism:

Scattering of gluon modes on density fluctuations in the medium

Intensity of incoming glue: $I_0(w)$

$$\Downarrow$$

Intensity of scattered glue: $I(w,\theta)$

Same story as before, but now with an emphasis on dependence on correlation properties that experience, e.g., dramatic changes in the vicinity of a critical point.

Uncorrelated density fluctuations $r_c = 0$:

$$\frac{I(w,\theta)}{I_0(w)} = \frac{1}{16\pi^2 R^2} \left\langle \delta\varepsilon^2 \right\rangle w^4 (1+\cos^2\theta) dv^2$$

or

$$\frac{I(w,\theta)}{I_0(w)} = \frac{TV}{16\pi^2 R^2} \left(\rho \frac{\partial\varepsilon}{\partial\rho} \right)^2 \frac{w^4 (1+\cos^2\theta)}{\gamma}$$

In the critical point

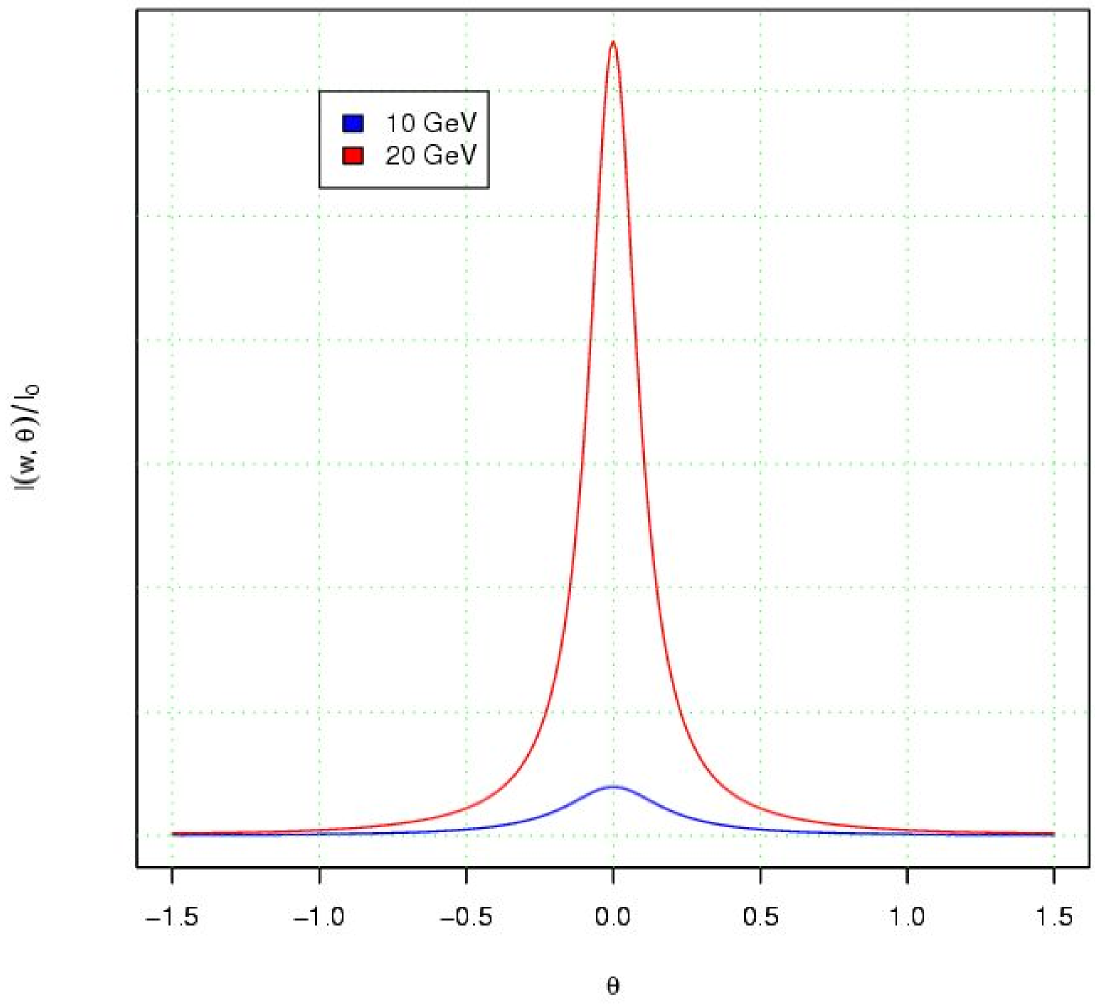
$$\gamma = -v \, {}^{\partial p}\!/_{\partial v} \to 0$$

Correlated density fluctuations:

$$\frac{I(w,\theta)}{I_0(w)} = \frac{TV}{16\pi^2 R^2}\left(\rho\frac{\partial\varepsilon}{\partial\rho}\right)^2 \frac{w^4(1+\cos^2\theta)}{\gamma + 4\alpha\gamma^2\sqrt{\varepsilon_0}\,w^2\sin^2\theta/2}$$

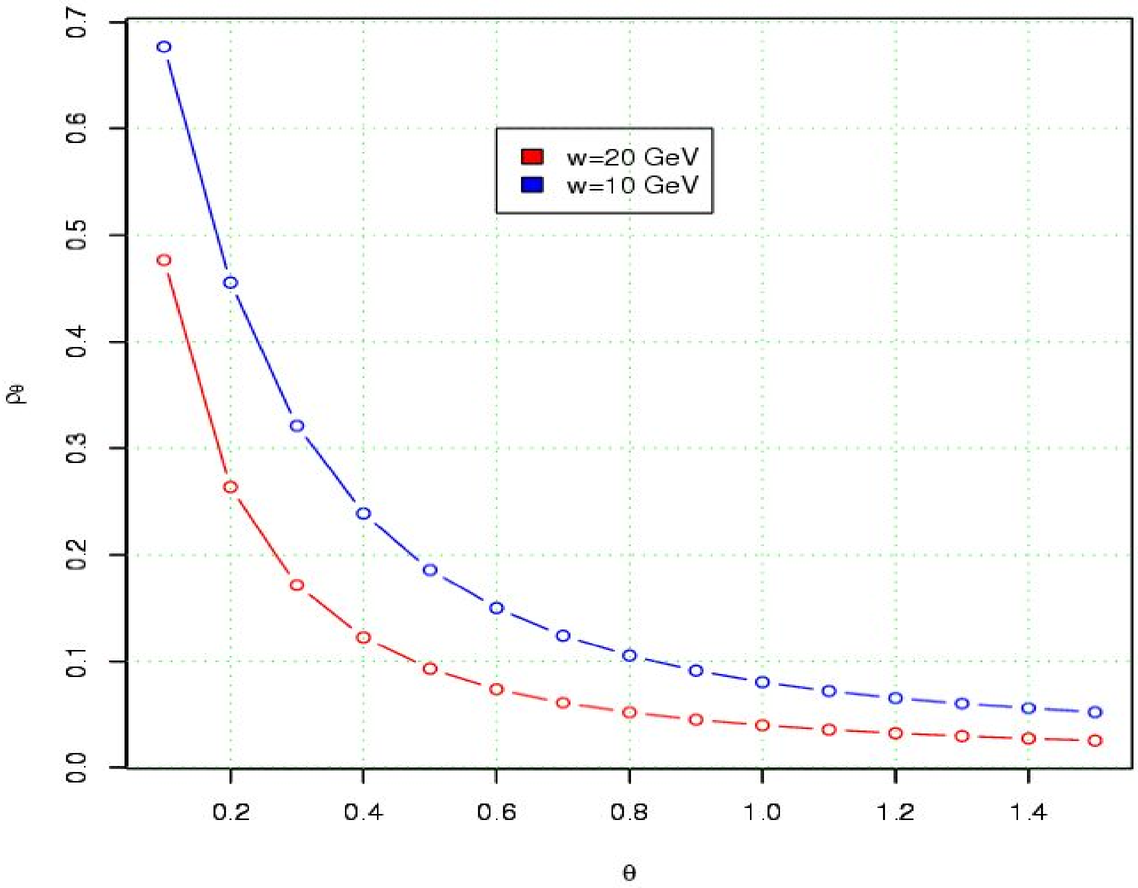
In the vicinity of a critical point where fluctuations are enhanced both energy dependence and angular pattern of mode quenching experience dramatic changes (critical opalescence)

Energy dependence of an angular pattern of energy loss:



Fraction of energy flow outside a given cone

$$\rho_\theta = 1 - \int_{-\theta}^{\theta} d\theta\, I(w,\theta) \Big/ \int_{-\pi/2}^{\pi/2} d\theta\, I(w,\theta)$$



- Stochastic jet quenching is a phenomenologically interesting mechanism of energy loss in the medium created in high energy nuclear collisions. I[R]M QCD approach allows to grasp effects that are, at present, very difficult to understand in microscopic terms.

- To become really quantitative (in particular, to have a well-defined domain of applicability) the I[R]M QCD picture has to be matched with microscopic picture of the medium.

- Quantitative description of the properties of the properties of parton medium on the event-by-event basis (MC) and development of theoretical tools describing non-abelian energy loss in random media in microscopic terms necessary.