Physics at LHC

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Jet quenching

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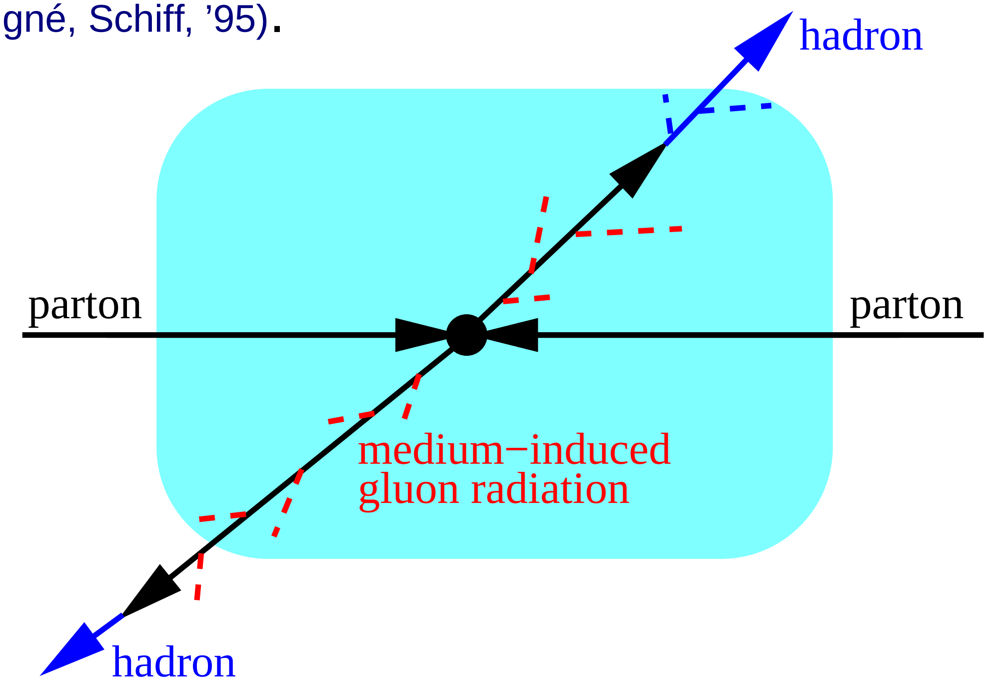
1. Introduction and formalism.
2. Mean energy loss and single particle spectra.
3. Gluon radiation off massive quarks.
4. More differential observables.
5. Remarks.

General references: Baier, Schiff, Zakharov, '00; Kovner, Wiedemann, '03; Gyulassy, Vitev, Wang, Zhang, '03; Vitev, '04.

- Historically: proposal with elastic scattering (Bjorken, '82) ⟶ bremsstrahlung in QED (Gyulassy, Wang, '94) ⟶ bremsstrahlung in QCD (Baier, Dokshitzer, Peigné, Schiff, '95).



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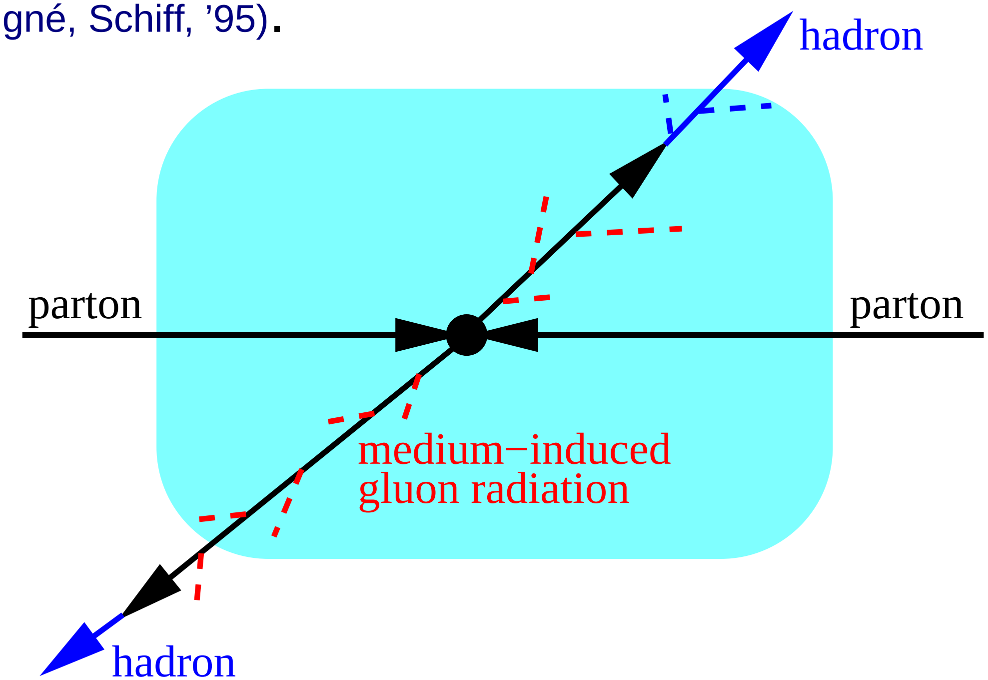

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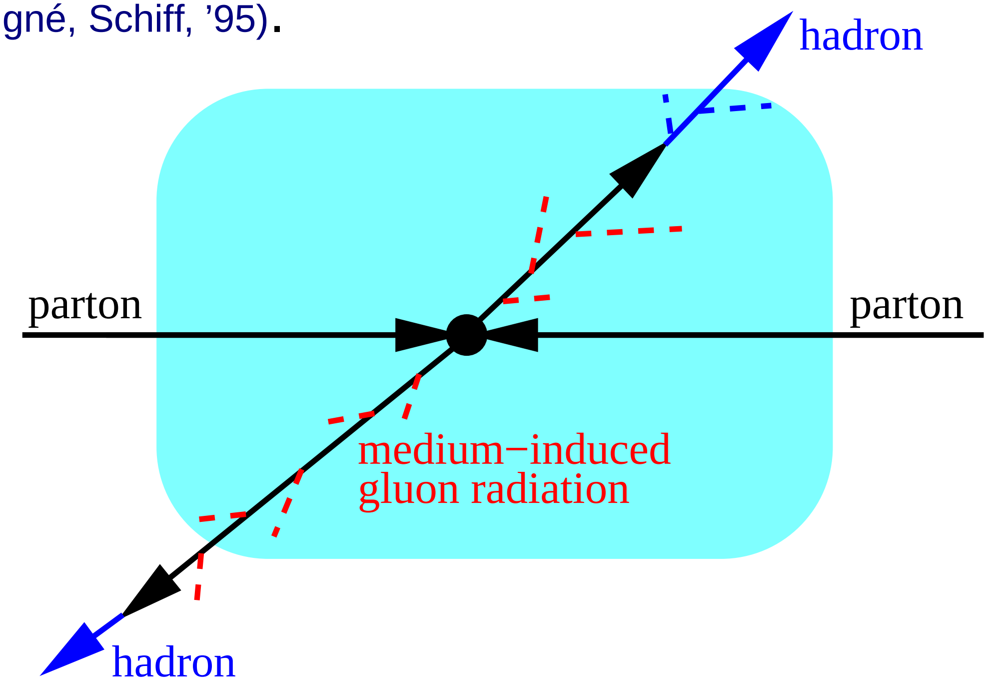

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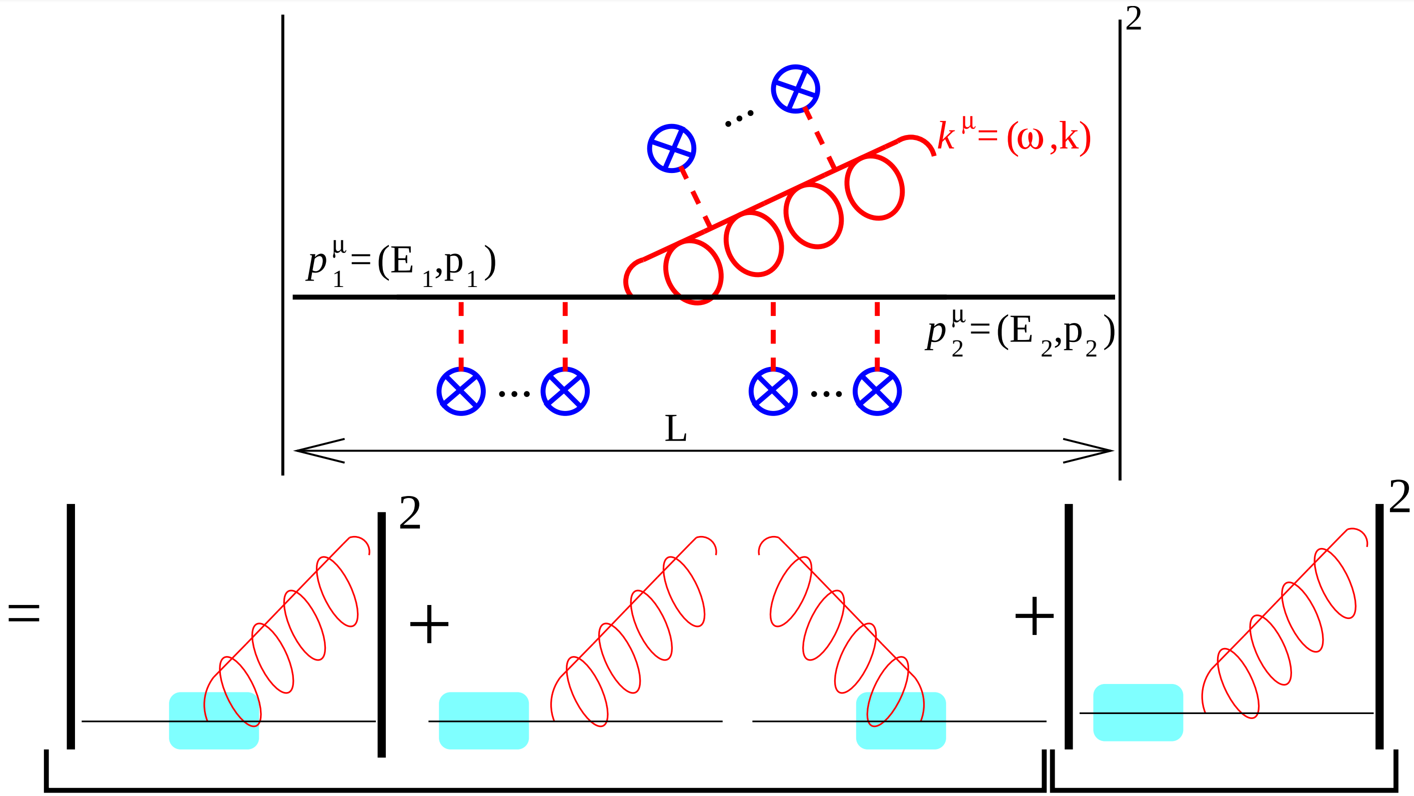
- Medium-induced gluon radiation implies:

$\Rightarrow$ Energy degradation of the leading parton.
$\Rightarrow$ Broadening of the parton shower.
$\Rightarrow$ Increase of the associated hadron multiplicity.

Formalism (Zakharov '96; Wiedemann '00):



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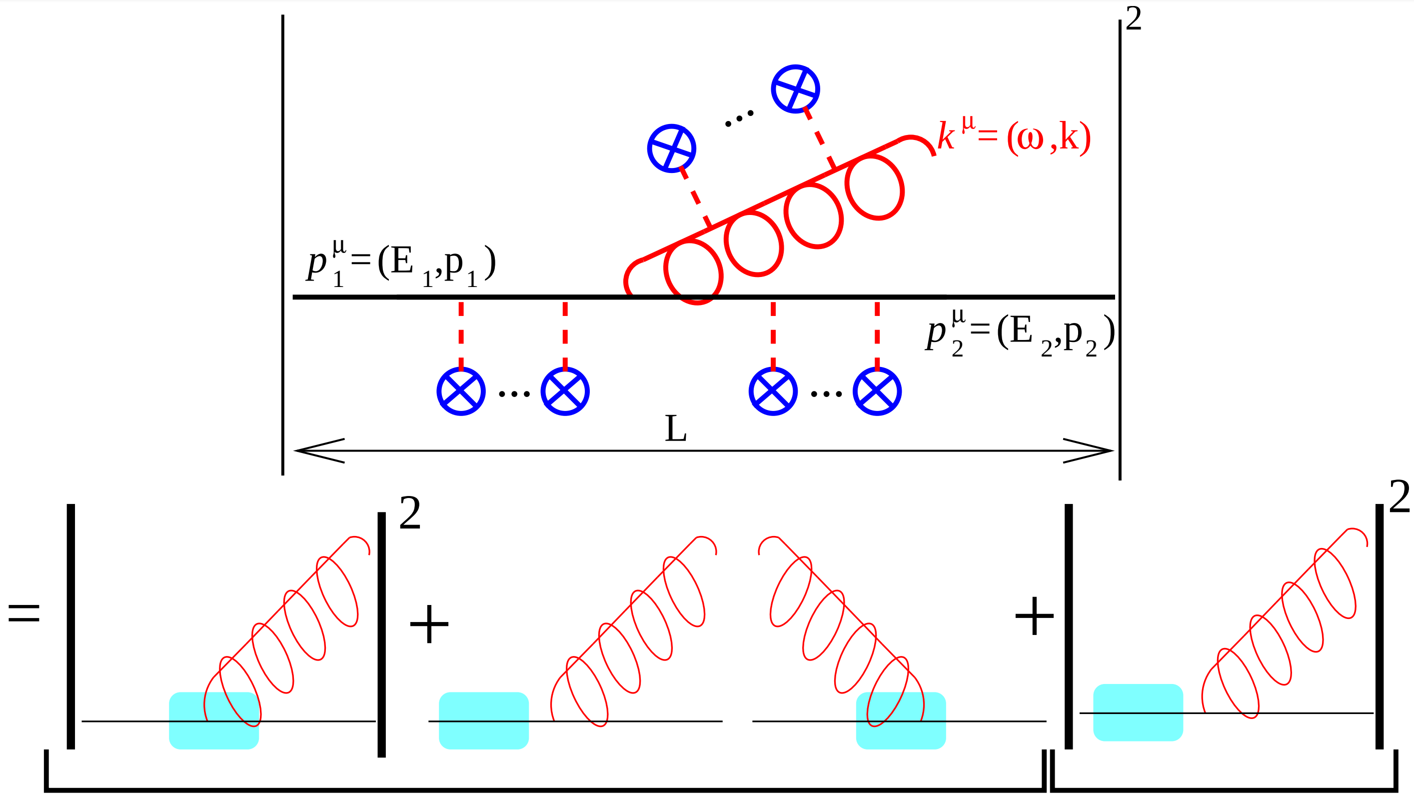
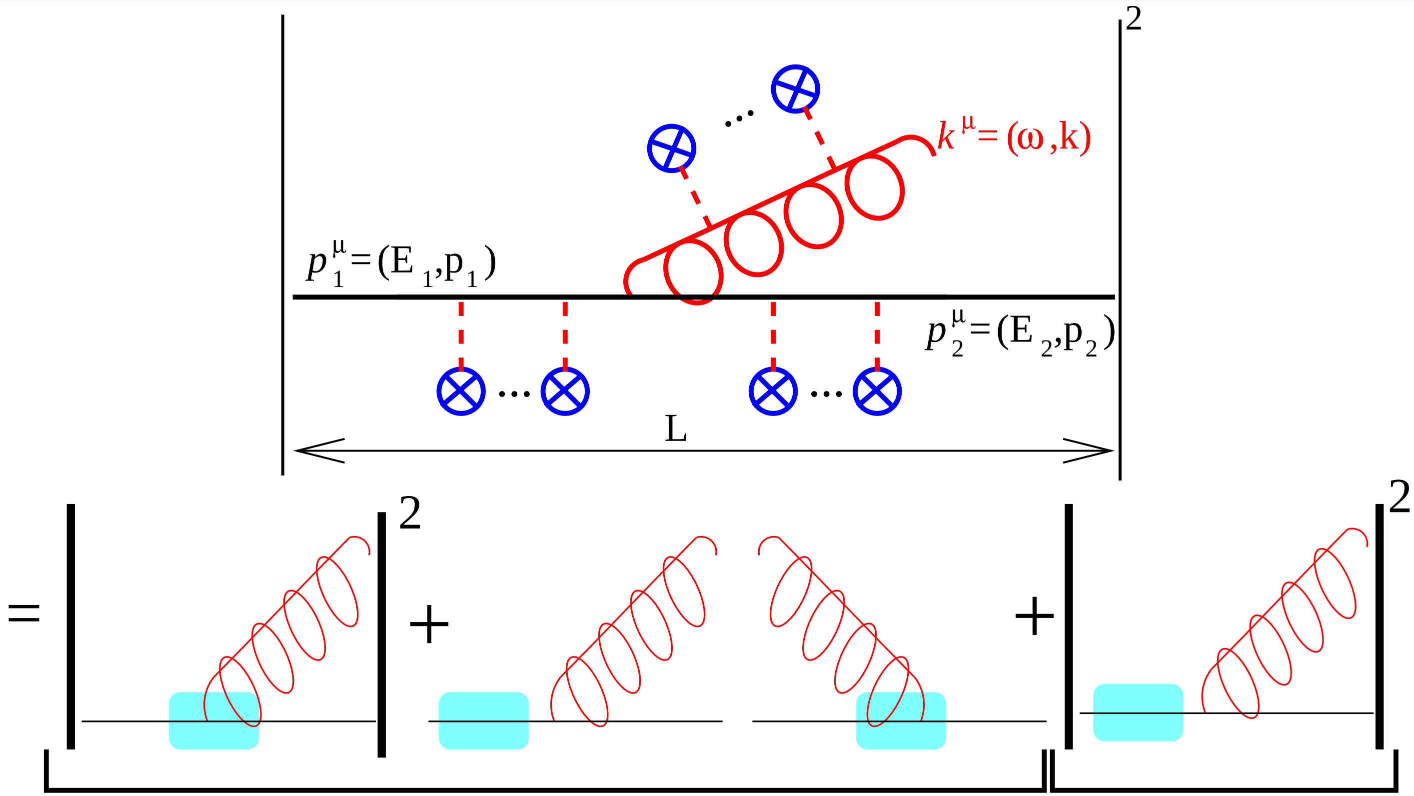


- Interference and mass effects on $\omega \frac{dI_{\rm medium}}{d\omega\, d\mathbf{k}_\perp}$, given by the crossed term, are contained in $\exp\left(-\Delta z\, \frac{k_\perp^2 + x^2 m^2}{2\omega}\right), \quad x = \frac{\omega}{E} \ll 1.$



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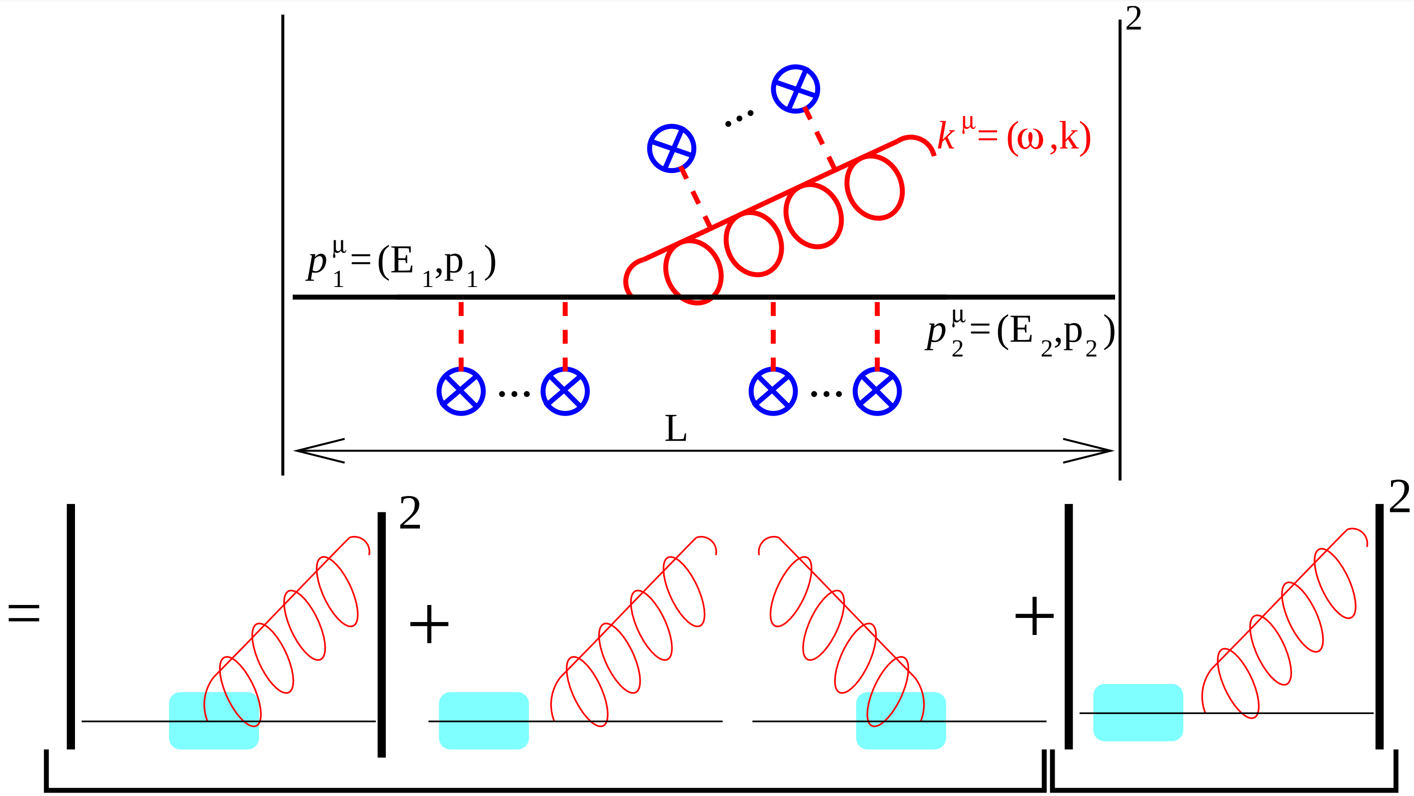

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- Baier '02: $\hat{q}=\mu^2/\lambda$, $\langle k_\perp^2\rangle \sim \sqrt{\hat{q}\omega}$, $\omega<\omega_c=\hat{q}L^2/2$, $\omega\frac{dI}{d\omega}\propto \alpha_s C_R\sqrt{\omega_c/\omega}$

$\Longrightarrow \Delta E\simeq \int d\omega\, \omega \frac{dI}{d\omega}\propto \alpha_s C_R\omega_c=\alpha_s C_R\hat{q}L^2/2.$

- Two ways have been proposed to compute the medium-modified particle spectrum (Baier, Dokshitzer, Mueller, Schiff, '01; Wang, Wang, '02; Salgado, Wiedemann, '02; Guo, Wang, '00):

$$\frac{d\sigma^{\rm medium}(p_\perp)}{dp_\perp^2} = \int d\Delta E \, P(\Delta E) \, \frac{d\sigma^{\rm vacuum}(p_\perp + \Delta E)}{dp_\perp^2} \; ;$$

$$D_{h/p}^{\rm medium}(z,Q^2) = \int d\epsilon \, \frac{P(\Delta E)}{1-\epsilon} \, D_{h/p}^{\rm vacuum}\left(\frac{z}{1-\epsilon}, Q^2\right), \; \epsilon = \frac{\Delta E}{E \simeq p_\perp(y=0)}.$$

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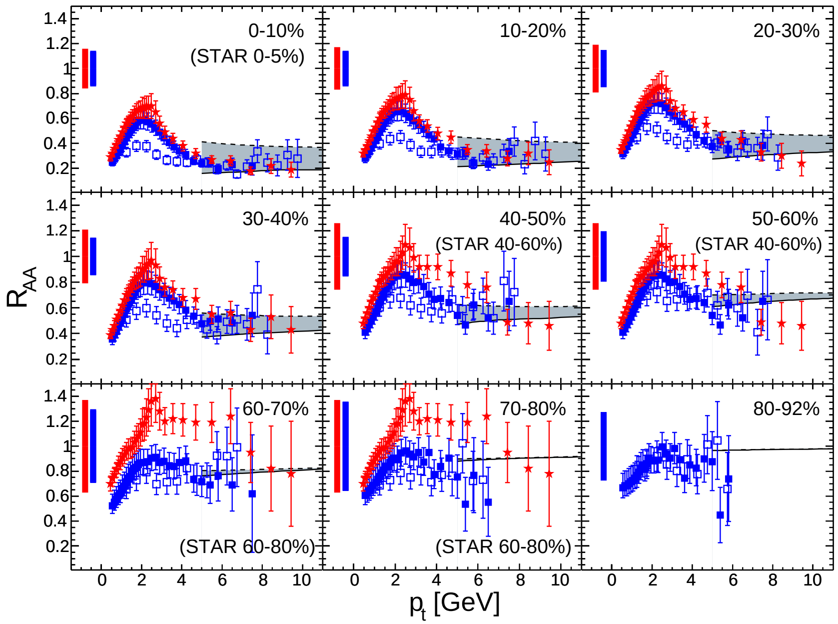
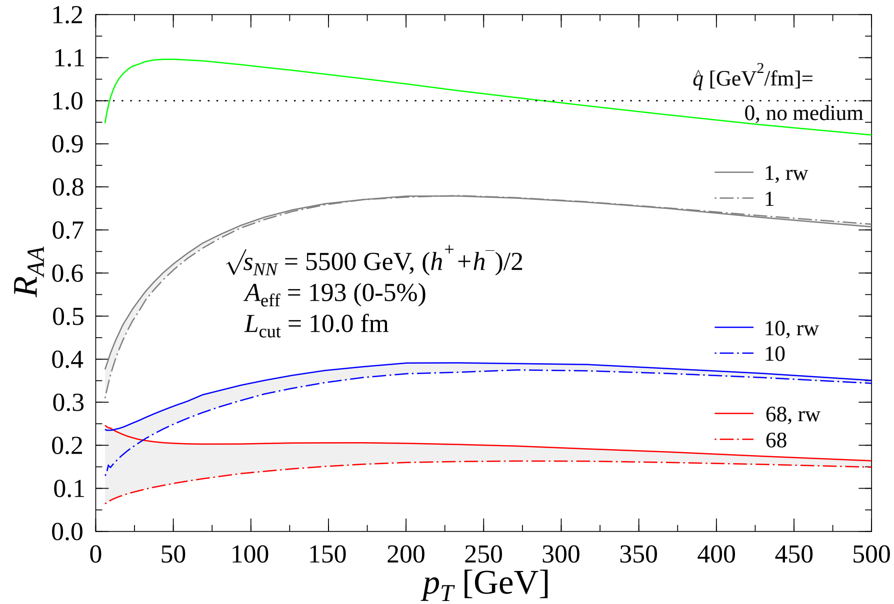
- Dynamical dilution of the medium absorbed in a redefinition of $\hat{q}$ (Baier, Dokshitzer, Mueller, Schiff, '98; Salgado, Wiedemann, '02; Vitev, Gyulassy, Levai, '02):

$$\hat{q}_{eff}(L) = \frac{2}{L^2}\int_{\tau_0}^{L} d\tau\, (\tau-\tau_0)\hat{q}(\tau).$$

Quenching of single particle spectra:



Dainese, Loizides, Paic, ’04



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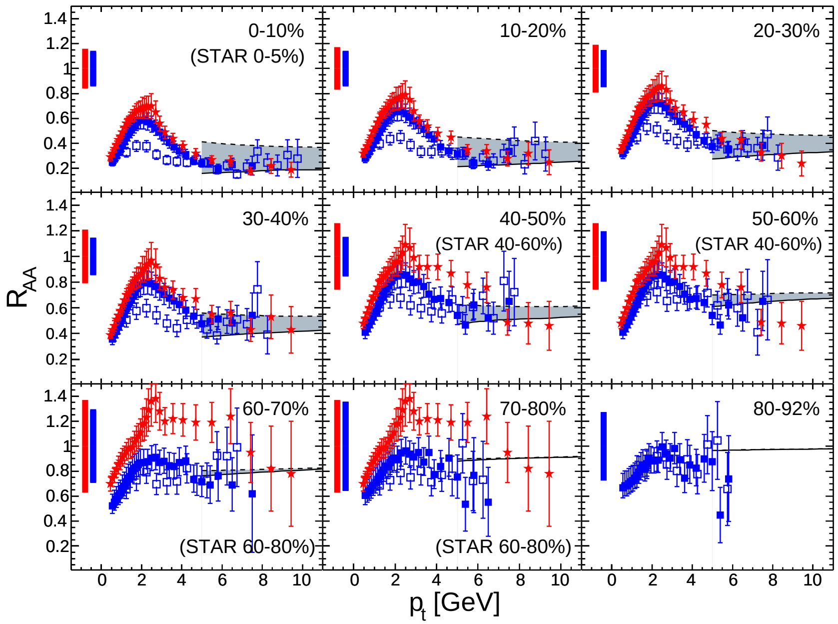

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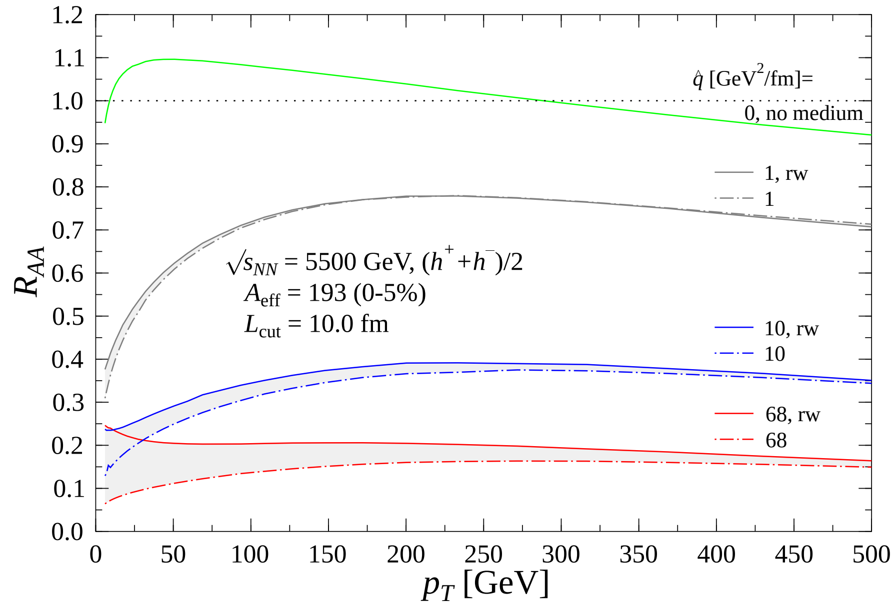

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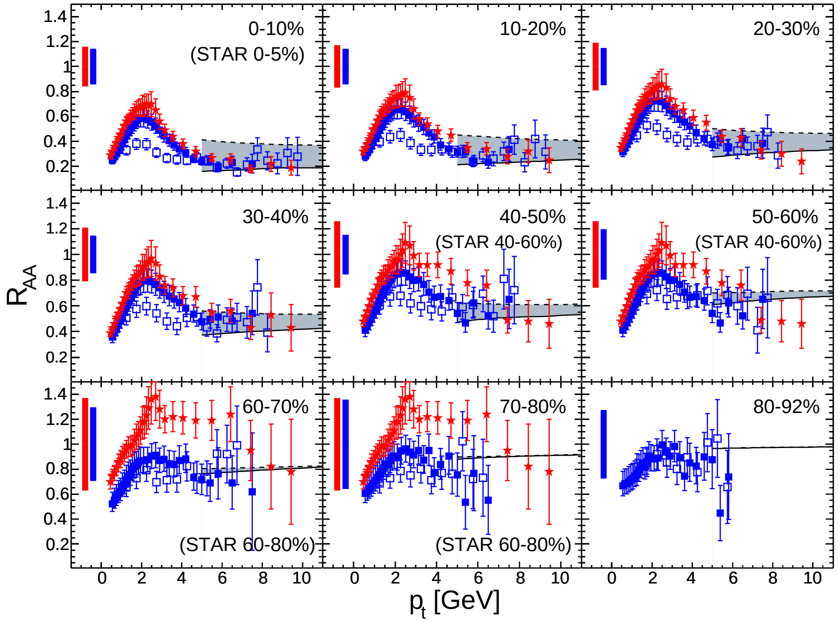

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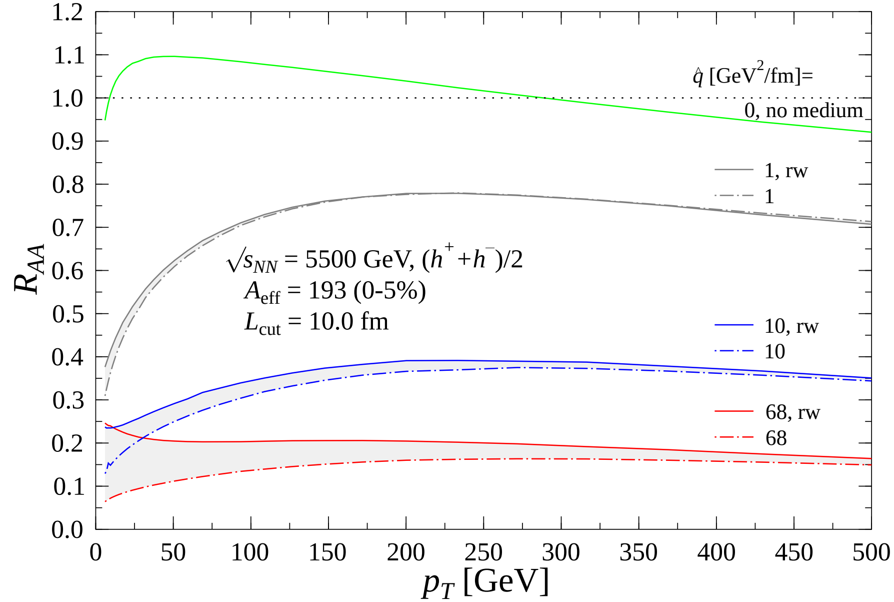

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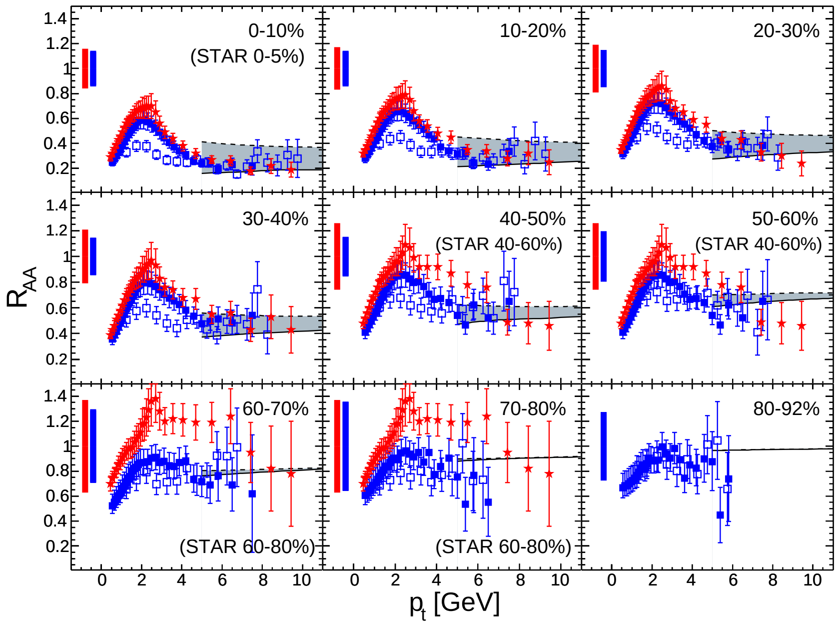

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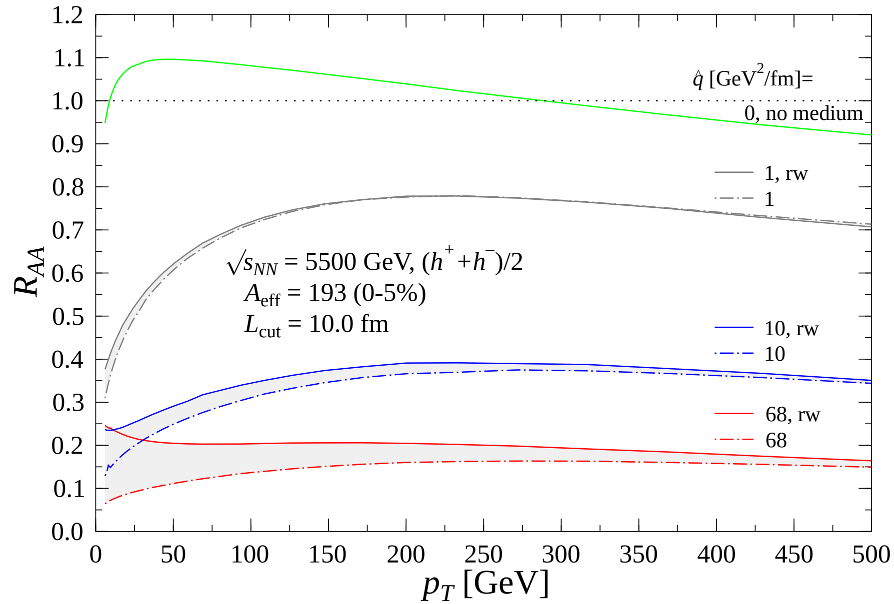

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- Uncertainties at small $p_\perp$ due to finite energy constraints, imposed *a posteriori* on the theoretical calculations.
- Predictions for different energies done by rescaling $\hat{q}$ according with multiplicities (Vitev '04; Adil, Gyulassy, '04; Wang, '03; '04).

Dead cone:

• Gluon radiation in the vacuum is modified by a mass of the parent quark: radiation for angles $\theta < m/E$ is suppressed, the dead cone effect (Dokshitzer, Khoze, Troyan, '91):

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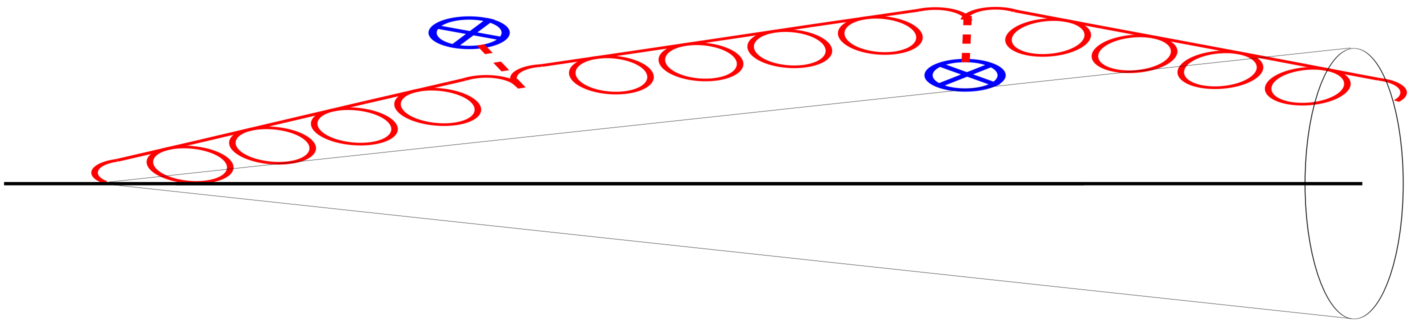

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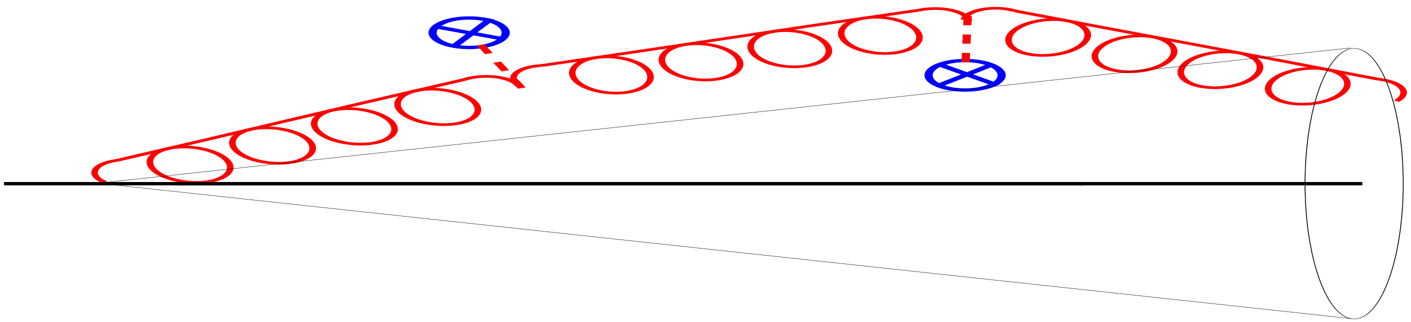
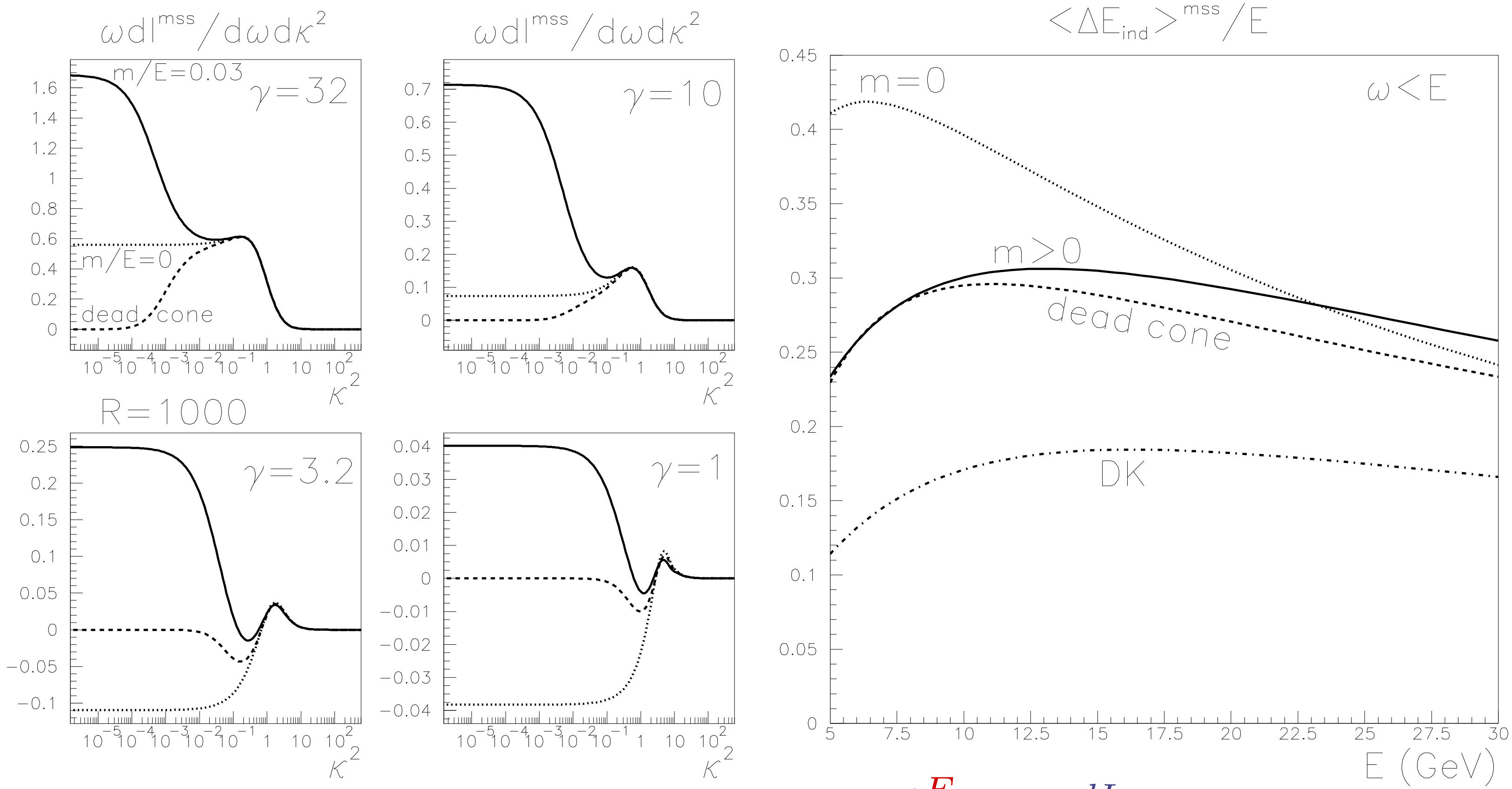


- Technically: competition between interference and rescattering $\Rightarrow$ numerics (Djordjevic, Gyulassy, '03; Zhang,Wang,Wang, '03; Armesto, Salgado, Wiedemann, '03).

Massive versus massless quarks:



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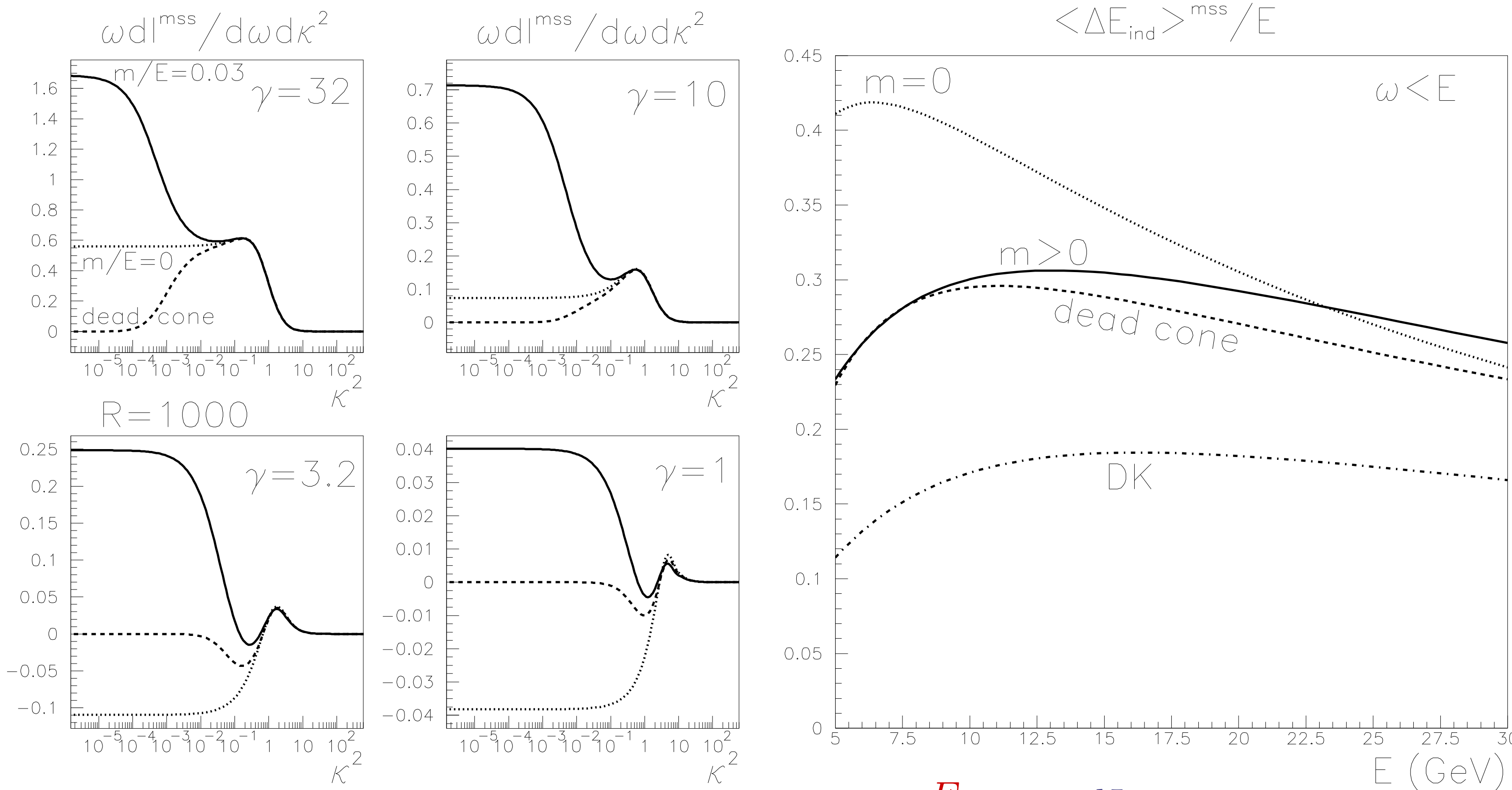

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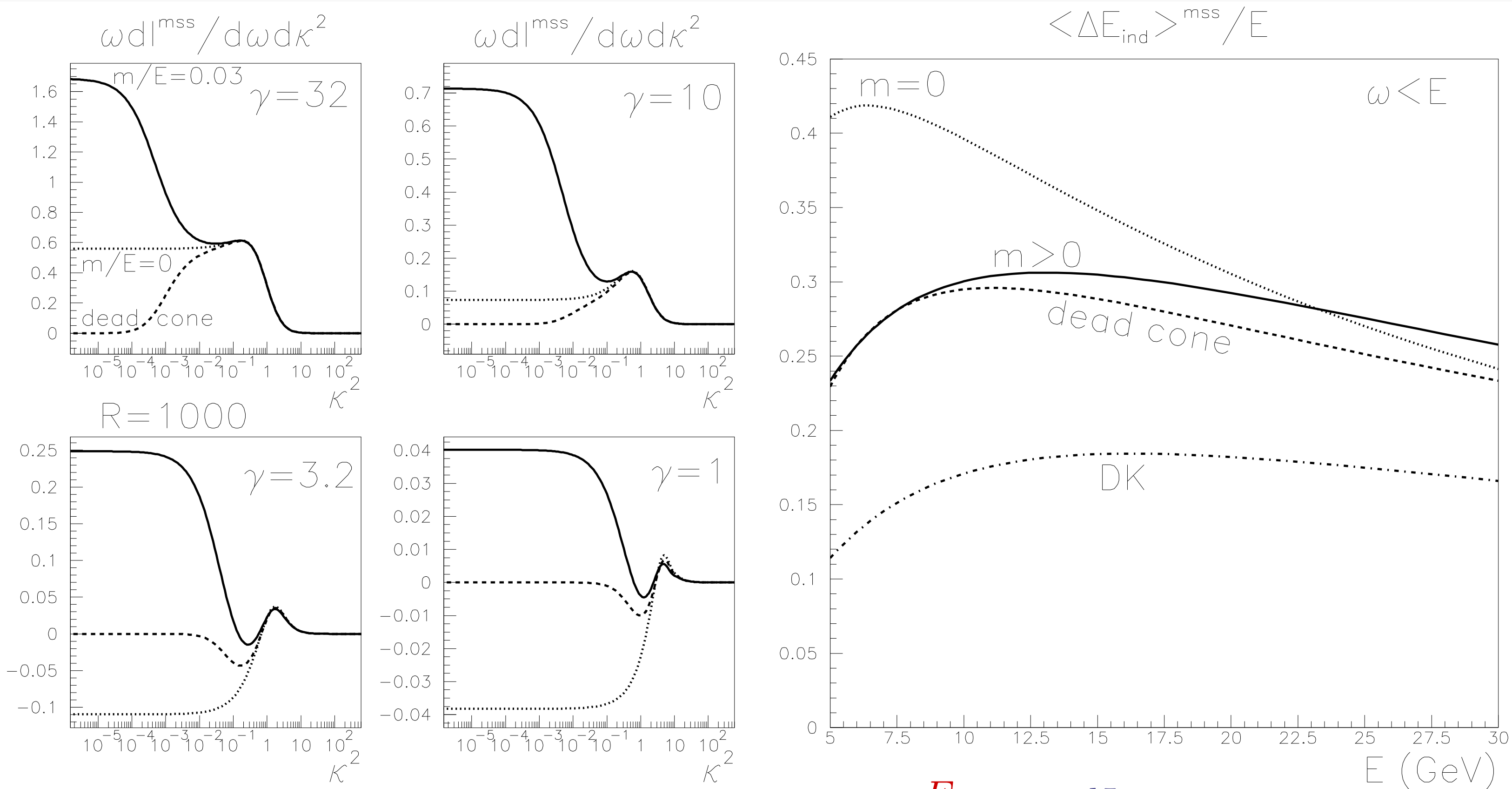

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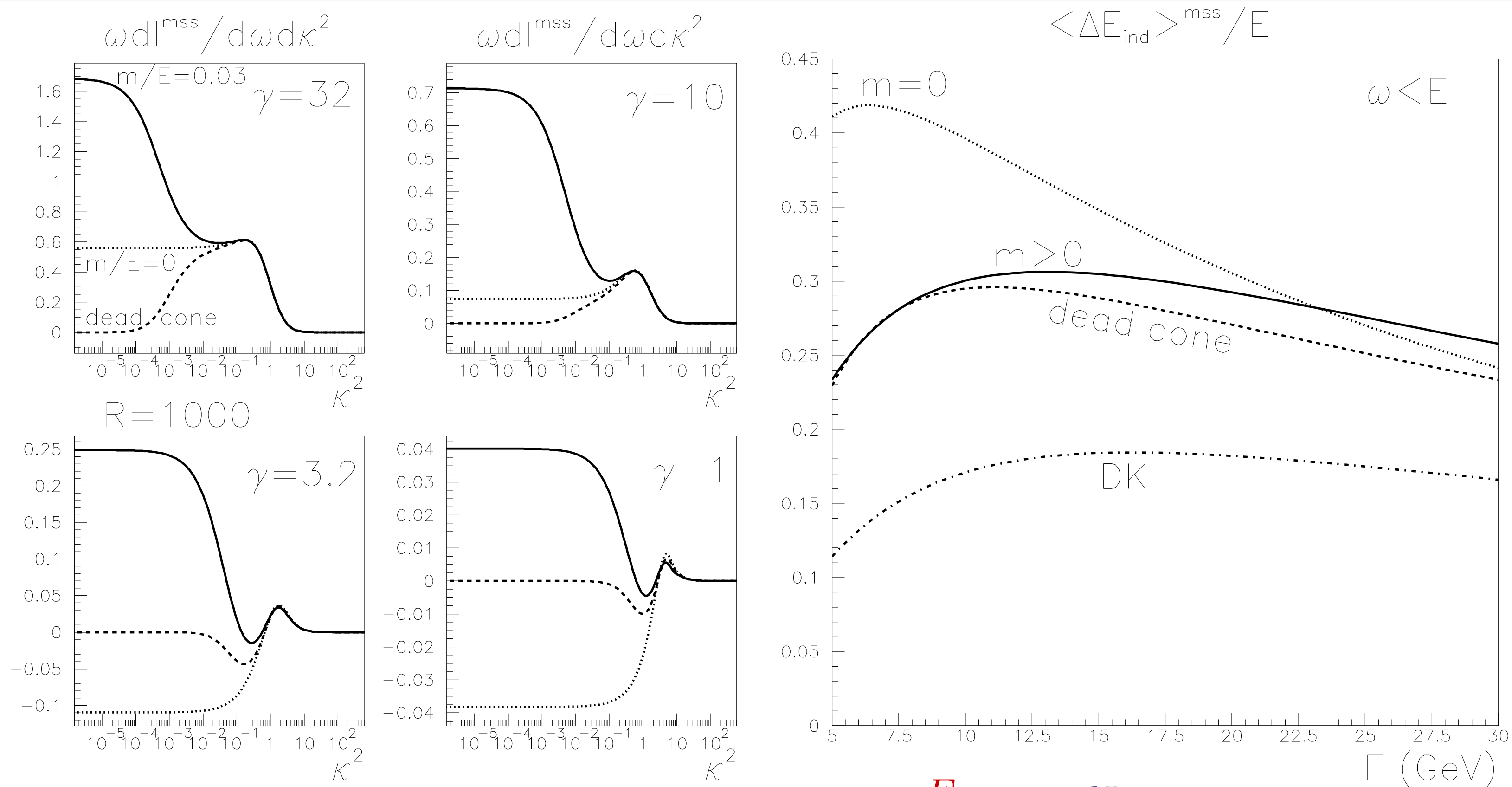

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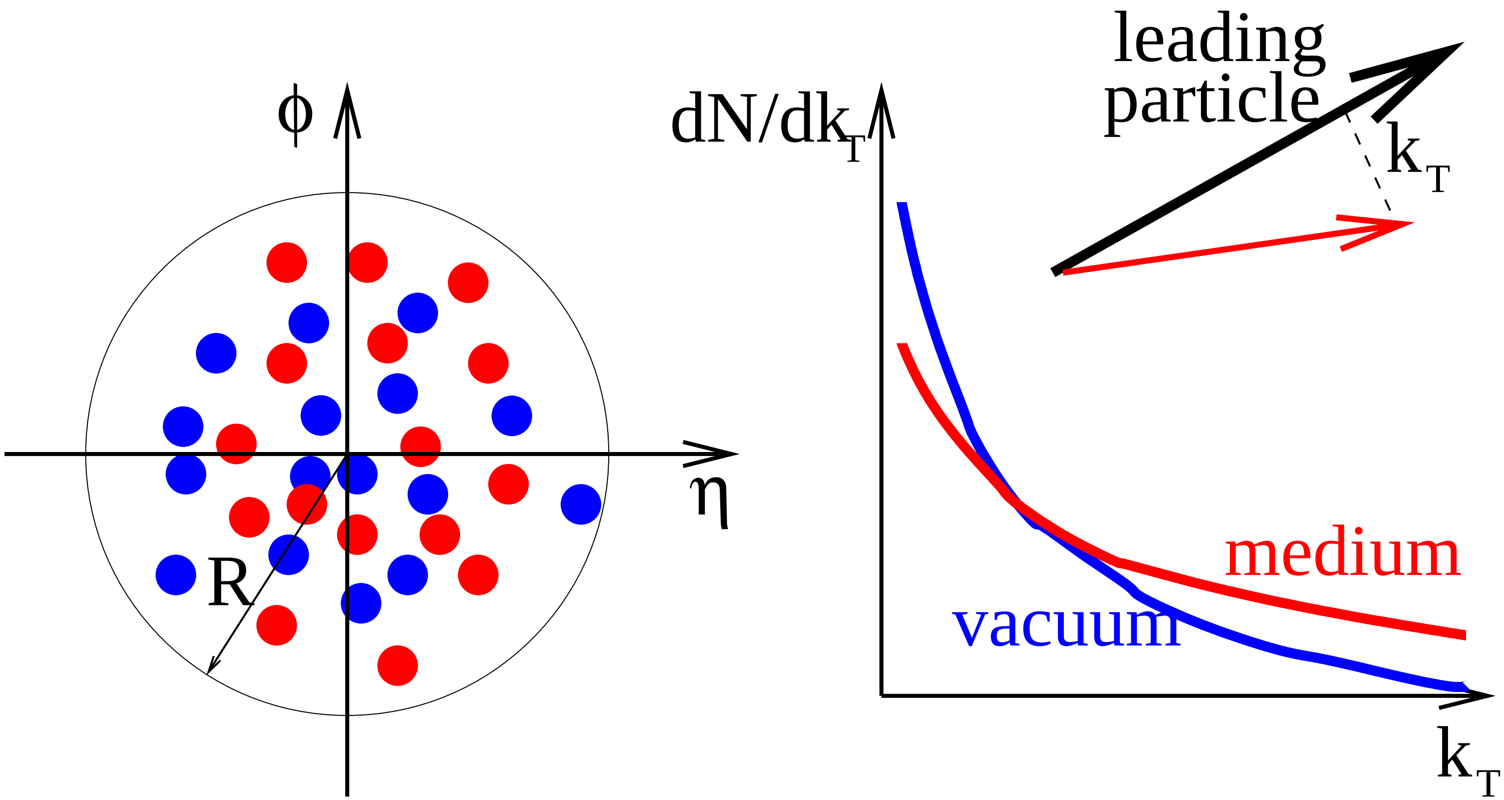
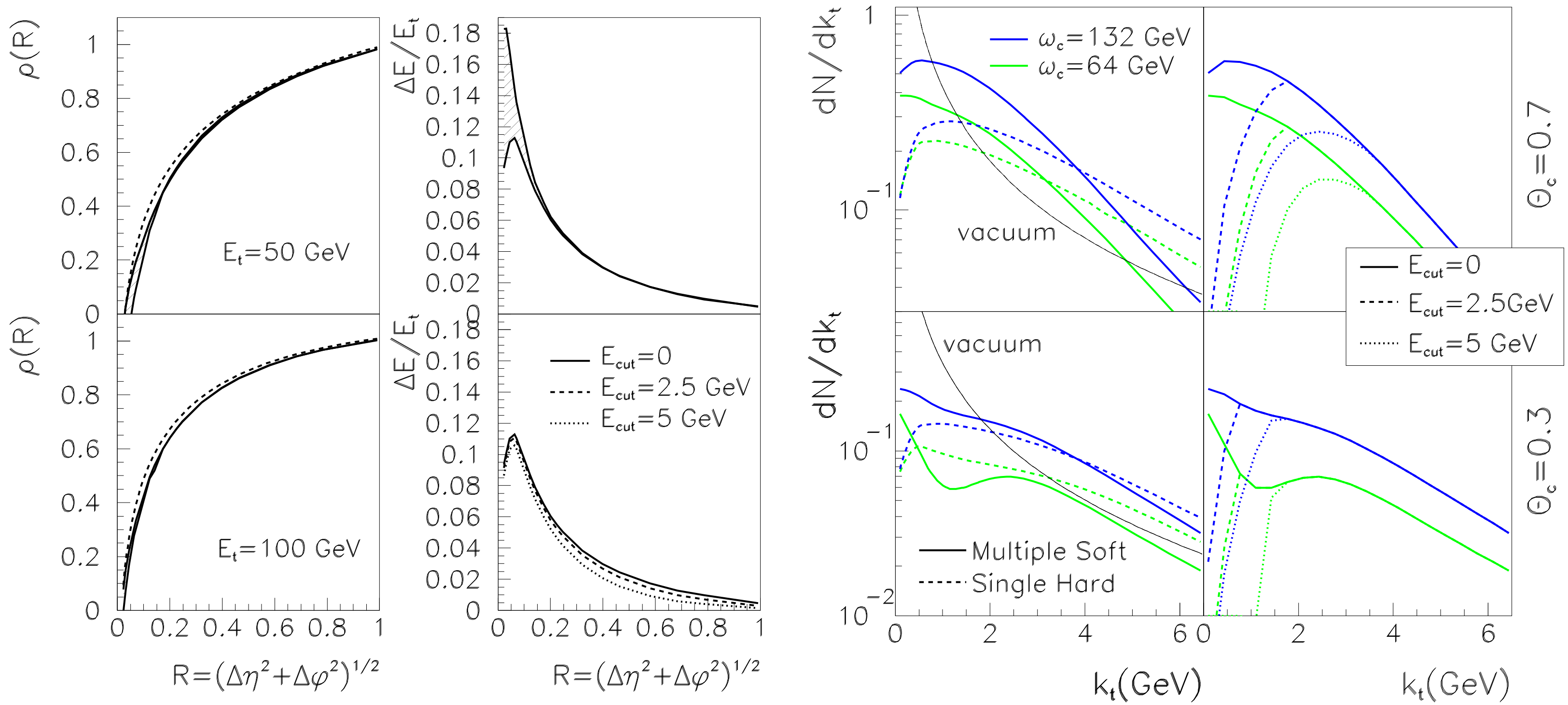
• Experimental situation (PHENIX, '02; Kelly at QM2004) unclear (single e$^-$ spectra (Batsouli, Kelly, Gyulassy, Nagle, '03); $p_\perp$ small, hadronization effects?).



- Are the energy deposition (i.e. jet definition and profile) and the distribution of sub-leading particles different for gluon radiation (fragmentation) in vacuum and in medium?

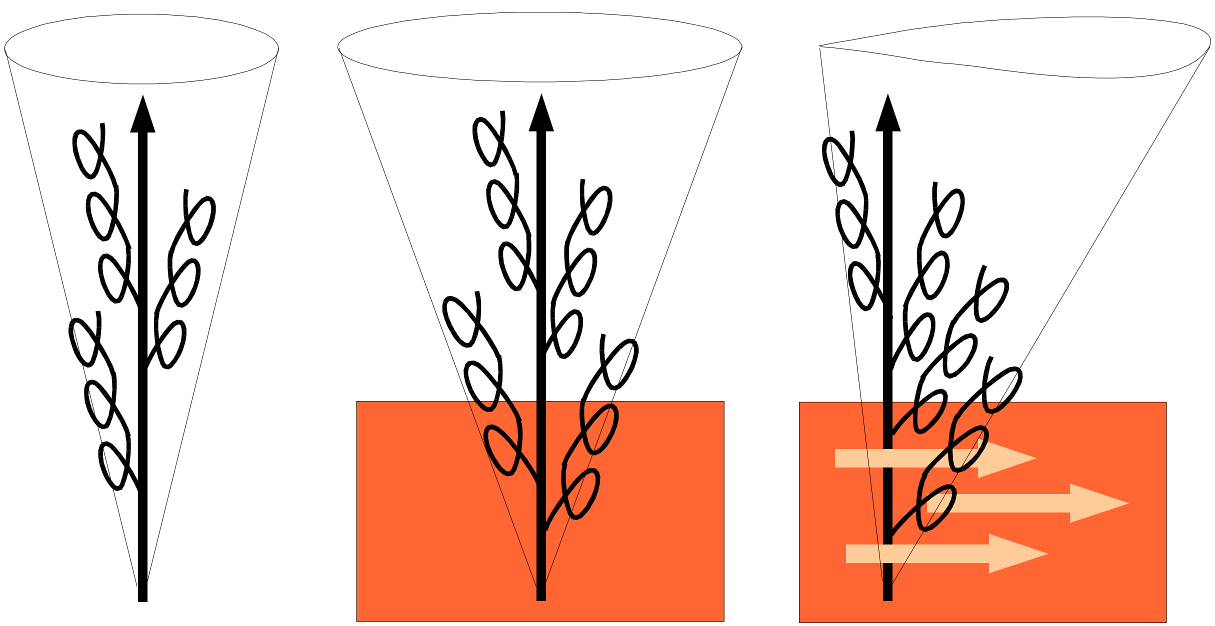
Jet shapes and multiplicities (Salgado, Wiedemann, '03):



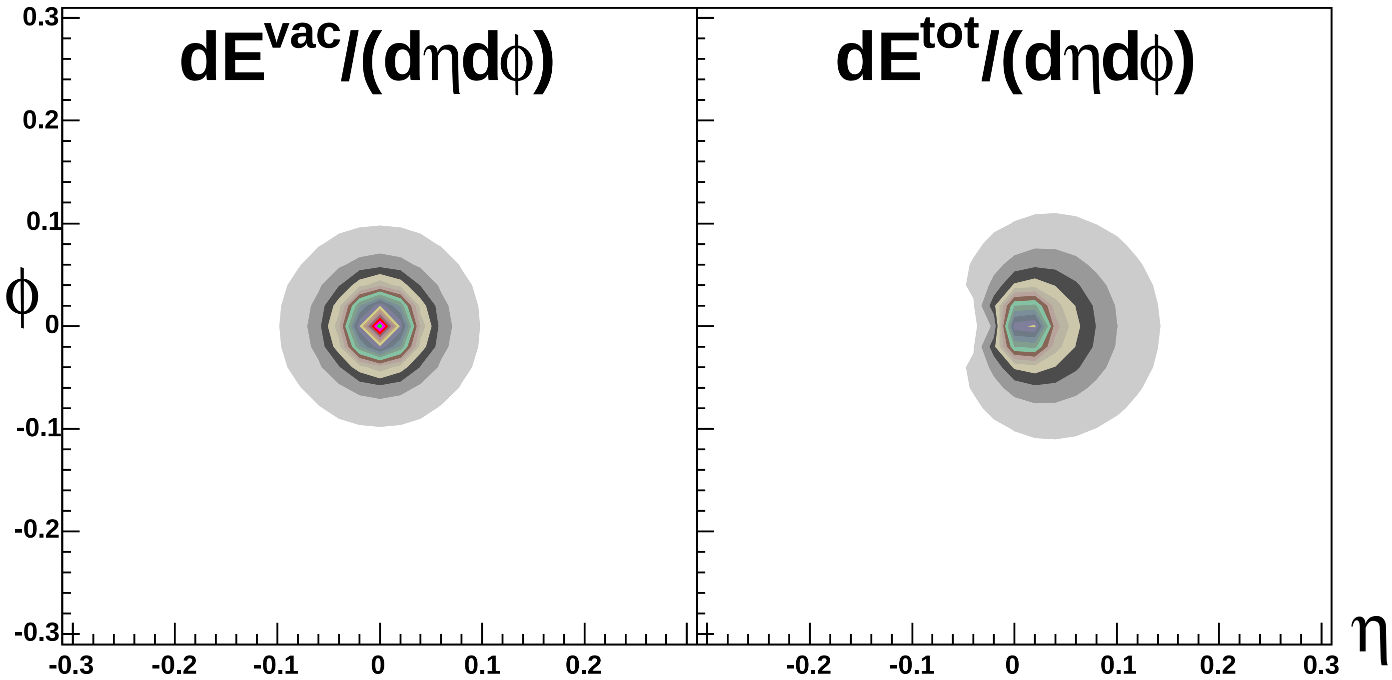
• The jet definition is stable (most energy is deposited at small R) but gluon distribution is wider in $\mathbf{k}_\perp$ (good chances to measure it at LHC, also relevant for RHIC).

• Little sensibility to IR contribution from the medium, and background apparently under control; vacuum contribution to be fixed from pp, pA.

Flow effects (Armesto, Salgado, Wiedemann, ’04):



- Flow is strongly suggested by the success of hydro at low $p_\perp \Longrightarrow$ strong position-momentum correlations expected.
- At high energies, energy loss is determined by momentum transferred perpendicularly to the parton trajectory; in the presence of collective flow, these momentum exchanges acquire a preferred direction.



- Results for a 100 GeV gluon jet: $\mu = 1$ GeV, $q_0 = \mu$ in the positive η-direction (larger values can be expected), $n_0\, L\, \alpha_s C_R = 1$, $L = 6$ fm. Vacuum: D0 parameterization (Abbott et al., ’97). With these parameters, $\langle \Delta\eta \rangle = 0.04$, $\Delta E_T = 23$ GeV.
- It leads to different jet widths in different $\eta - \phi$ directions (STAR: Wang at QM2004) and to an increase of v_2.
- It has to be considered to extract densities from quenching studies, and may help to understand the space-time picture of the collision.

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- Until now, the main focus of the phenomenological analysis is on single particle spectra; more differential observables like jet shapes and multiplicities offer valuable information. A better understanding of the vacuum (pp, pA) would help.

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- An implementation of medium-induced gluon radiation in a Monte Carlo simulation is needed (talk by Morsch).
- The opaqueness of the medium at RHIC makes the determination of densities difficult; flow effects should also be considered.
- Until now, the main focus of the phenomenological analysis is on single particle spectra; more differential observables like jet shapes and multiplicities offer valuable information. A better understanding of the vacuum (pp, pA) would help.
- At the LHC, high-E_T jets ($E_T > 50$ GeV) will be very abundant (Yellow Report on Hard Probes at the LHC, '03) $\Longrightarrow$ jet quenching studies will play a prominent role in the heavy ion program, see the talks by ALICE, ATLAS and CMS.