Medium-Evolved Jets and Fragmentation Functions

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Outline

- We present our modeling of the evolution of jets in a QGP medium [Armesto,Cunqueiro,Salgado,Xiang, JHEP 0802:048,2008].
- The Bonus are:
  - Energy and momentum are conserved at each splitting. The treatment of the FF is refined.
  - This is needed as we approach LHC where :
    - There will be many high energy jets ($E_{jet} > 100$ GeV) disentangled from the vacuum.
    - a good reconstruction of the FF will be possible
  - Medium and vacuum are evolved in the same footing
  - Ignoring the evolution in virtuality, good agreement in the relevant z range with QW $\rightarrow$ a collateral check of the QW formalism
- Monte Carlo implementations $\rightarrow$ access to more differential and unbiased observables.

Hard probes: jets

- A jet is produced in a hard elementary interaction (with high virtuality t)
- so it can be treated perturbatively:

  $\sigma^{AB\to h} = f_A(x_1,t) f_B(x_2,t) \otimes \sigma(x_1,x_2,t) \otimes D_{i\longrightarrow h}(z,t)$

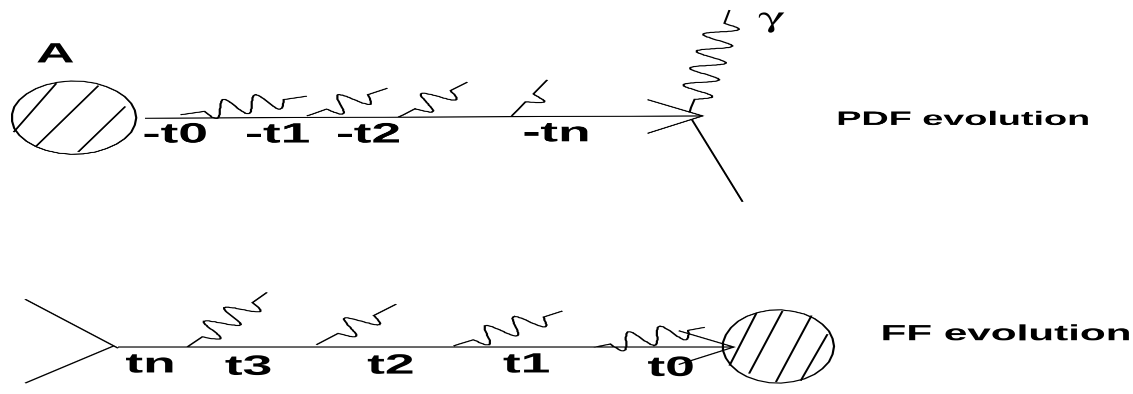
- Its production is faster $t_o \simeq t^{-1}$ than soft interactions.

  The jet is produced before/during the bulk formation.

- As a consequence, the PDF's $(f_A(x_1,t) f_B(x_2,t))$ and the partonic cross section are the same as in cold nuclear matter.

  The medium will only modify the fragmentation $D_{i\longrightarrow h}(z,t)$. Any deviation of the jet fragmentation structure with respect to vacuum characterizes the medium.

DGLAP evolution



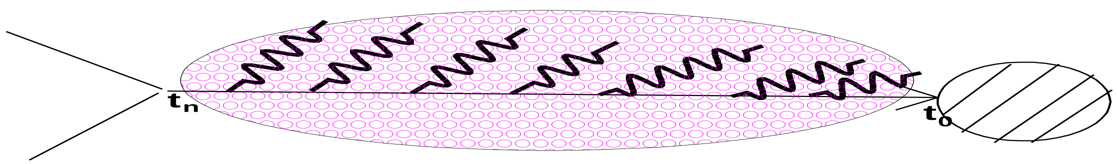
DGLAP is the equation for the evolution of virtuality ordered splittings:

$$\frac{\partial D(z,t)}{\partial t} = \frac{1}{t}\int_z^1 \frac{d\epsilon}{\epsilon}\frac{\alpha_S}{2\pi}P(\epsilon)D(\frac{z}{\epsilon},t)$$

being D(z,t) the PDF's or the FF's

How can we implement medium modifications in this evolution?

DGLAP evolution



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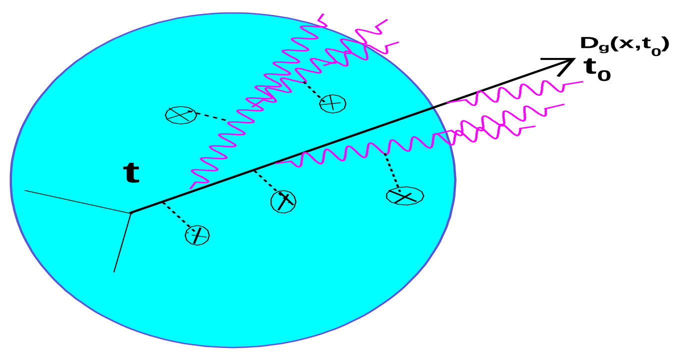
Medium-induced gluon radiation

- Medium-Induced Radiation: In a QCD medium (QGP) a hard parton looses virtuality by the induced emission of soft gluons. Their emission and their further (strong) interactions with the medium are the dominant energy loss for high energy projectiles.
- The hard parton looses virtuality from the initial scale t to the final hadronization one $t_0 \simeq \lambda^2_{QCD}$. Hadronization happens outside the medium (for $p_T \geq 7$ GeV/c at RHIC)



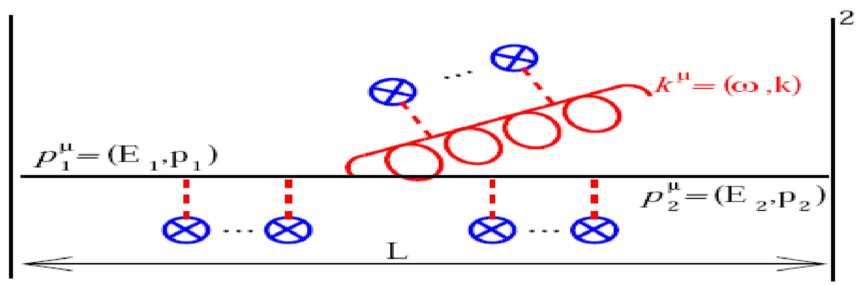
- D(x,t) is changed:
  - energy loss of the leading parton($\Delta E \simeq \alpha_S \hat{q} L^2$)
  - angular broadening of the jet cone ($\Delta k_T > \simeq \hat{q} L$)
  - an increase and a softening of the shower multiplicity.
- -Induced gluon radiation is the standard explanation for Jet Quenching observed at RHIC.

Introduction:Medium-induced gluon radiation

- The single inclusive distribution of medium induced gluons with energy ω and k_t from a parent parton of energy E [Wiedemann, Nucl.Phys.B 588]:

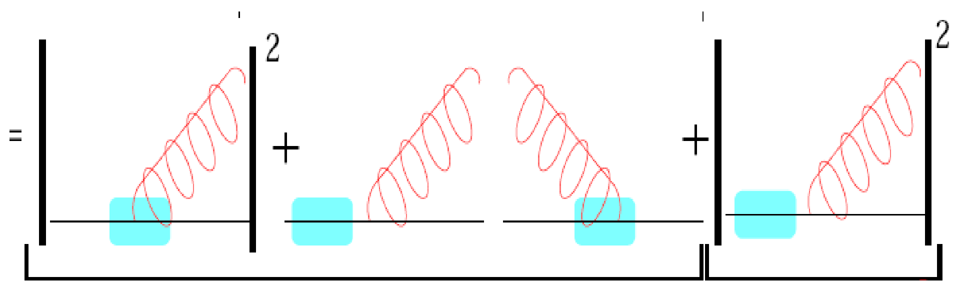
$$\omega \frac{dI}{d\omega dk_T} = \frac{\alpha_S C_R}{(2\pi)^2 \omega^2} 2Re \int_0^\infty dy_l \int_{y_l}^\infty d\overline{y_l} \int du e^{-i\mathbf{k_T} u} e^{-\frac{1}{2}\int_{\overline{yl}}^\infty d\zeta n(\zeta)\sigma(u)}.$$

$$\frac{\partial}{\partial y}\frac{\partial}{\partial u}\int_{y=0=r(y_l)}^{u=r(\overline{y_l})} \mathcal{D}r e^{i\int_{y_l}^{\overline{y_l}} d\zeta \frac{\omega}{2}(\dot{r}^2 - \frac{n(\zeta)\sigma(r)}{i\omega})}$$



Introduction:Medium-induced gluon radiation

- There is no analytical solution to MIGRS, two approximations:
- Single hard scattering (GLV),expanding in powers of $n(\zeta)\sigma(\zeta)$.
- Multiple soft scattering (BDMPS-Z) (brownian motion).
  $n(\zeta)\sigma(r) \simeq \frac{1}{2}\hat{q}(\zeta)r^2$
  - $\hat{q}(\zeta) \longrightarrow < q_T^2 > /\lambda$. (**Transport coefficient, contains the information about the scattering potential**)
  - The path integral is the one of an harmonic oscillator, three contributions to the amplitude:



- A numerically tractable solution can be obtained:
  $\omega \frac{dI}{d\omega dk_T} \longrightarrow F(\frac{\omega}{\omega_C}, \kappa^2)$, $\omega_C = \frac{1}{2}\hat{q}L^2$, $\kappa^2 = \frac{k_T^2}{\hat{q}L}$

Previous MMFF Calculations

- A Poissonian distribution of independent radiations was assumed (**BMDS**)

$$P_E(\epsilon) = \sum_{n=0}^{\infty} \frac{1}{n!}[\prod_{i=1}^{n} \int d\omega_i \frac{d(I(\omega_i))}{d\omega}]\delta(\epsilon - \sum_{i=1}^{n} \frac{\omega_i}{E})e^{-\int d\omega \frac{dI}{d\omega}}$$

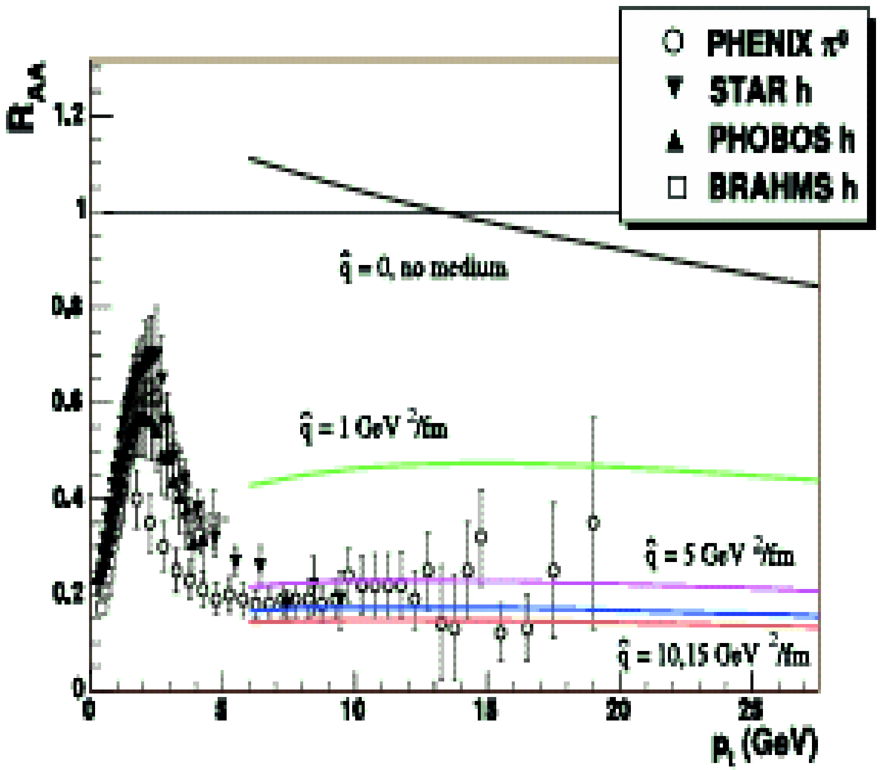
- The MMFF were calculated shifting the vacuum ones

$$D_{k\to h}^{(med)}(z, Q^2) = \int_0^{1-z} d\epsilon P_E(\epsilon) \frac{1}{1-\epsilon} D_{k\to h}(\frac{z}{1-\epsilon}, Q^2)$$

- Limitations:
  - Energy and momentum are not conserved (only a posteriori)
  - There's no evolution in virtuality
  - Medium and vacuum are treated differently

- However, data is well described

Previous MMFF Calculations



[Eskola, Honkanen, Salgado, Wiedemann (2004)]

Data favours a transport coefficient of $5 < \hat{q} < 15$ GeV^2/fm.
The slow dependence with $\hat{q}$ at high $\hat{q}$ is due to the surface bias.

Now:Medium-modified splitting functions

- In vacuum: $\frac{dI^{vac}}{dzdk_T^2} = \frac{\alpha_s P(z)^{vac}_{z\longrightarrow 1}}{2\pi k_T^2}$, $P(z)^{vac}_{z\longrightarrow 1} \simeq \frac{2C_R}{1-z}$, $z = 1 - x$

- Our ansatz is an extension of the former eq. to medium [**Salgado-Polosa**]:

$$\frac{dI}{dzdk_T^2}^{MED} = \frac{\alpha_s P(z)^{MED}_{z\longrightarrow 1}}{2\pi k_T^2} \text{ , } P(z)^{med}_{z\longrightarrow 1} = \frac{2\pi zt}{\hat{q}L} F(\frac{\omega}{\omega_c}, \kappa^2)$$

- The total splitting function is taken to be the vacuum + medium ones:

$$P^{TOTAL} = P^{VACUUM}(z) + P^{MEDIUM}(z, t, \hat{q}, L)$$

  - Everything is consistent: MIGR formalism is a high energy approach and previous relations are also valid in the collinear(high energy) limit.
    Still $P_g^{TOTAL} = \frac{9}{4} P_q^{TOTAL}$ as in vacuum.

[Borghini-Wiedemann] proposal:medium multiplicative factor, [Guo-Wang-Majumder] medium by higher twist corrections in DIS $\rightarrow P(z) = P(z) + \delta P(z)$.

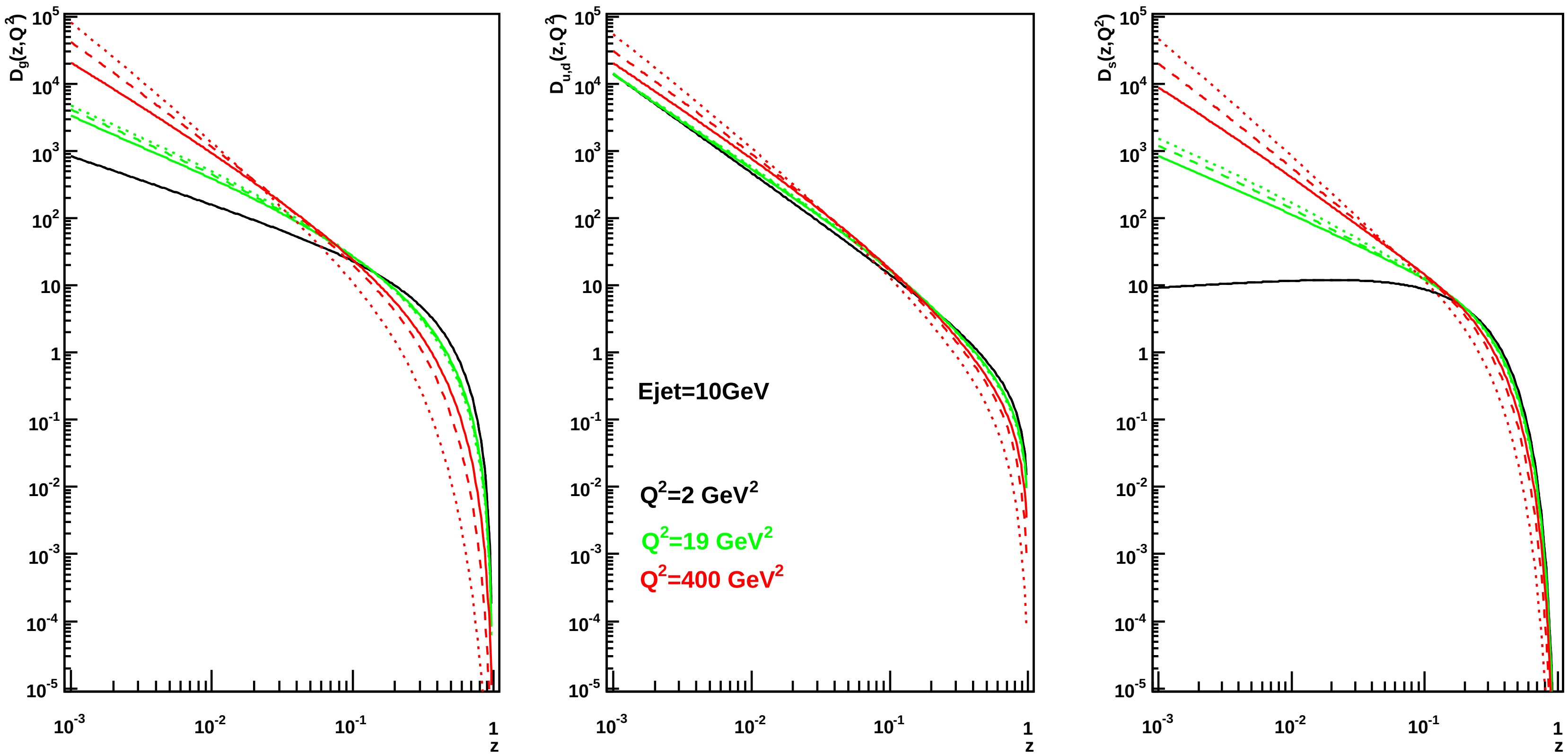
DGLAP in Medium

- We obtain our MMFF by solving DGLAP with medium modified splitting functions supplemented.

$$\frac{\partial D(x,t)}{\partial t} = \frac{1}{t}\int_x^1 \frac{dz}{z}\frac{\alpha_S}{2\pi}(P(z) + \Delta P(z,t,\hat{q},L))D(\frac{x}{z},t)$$

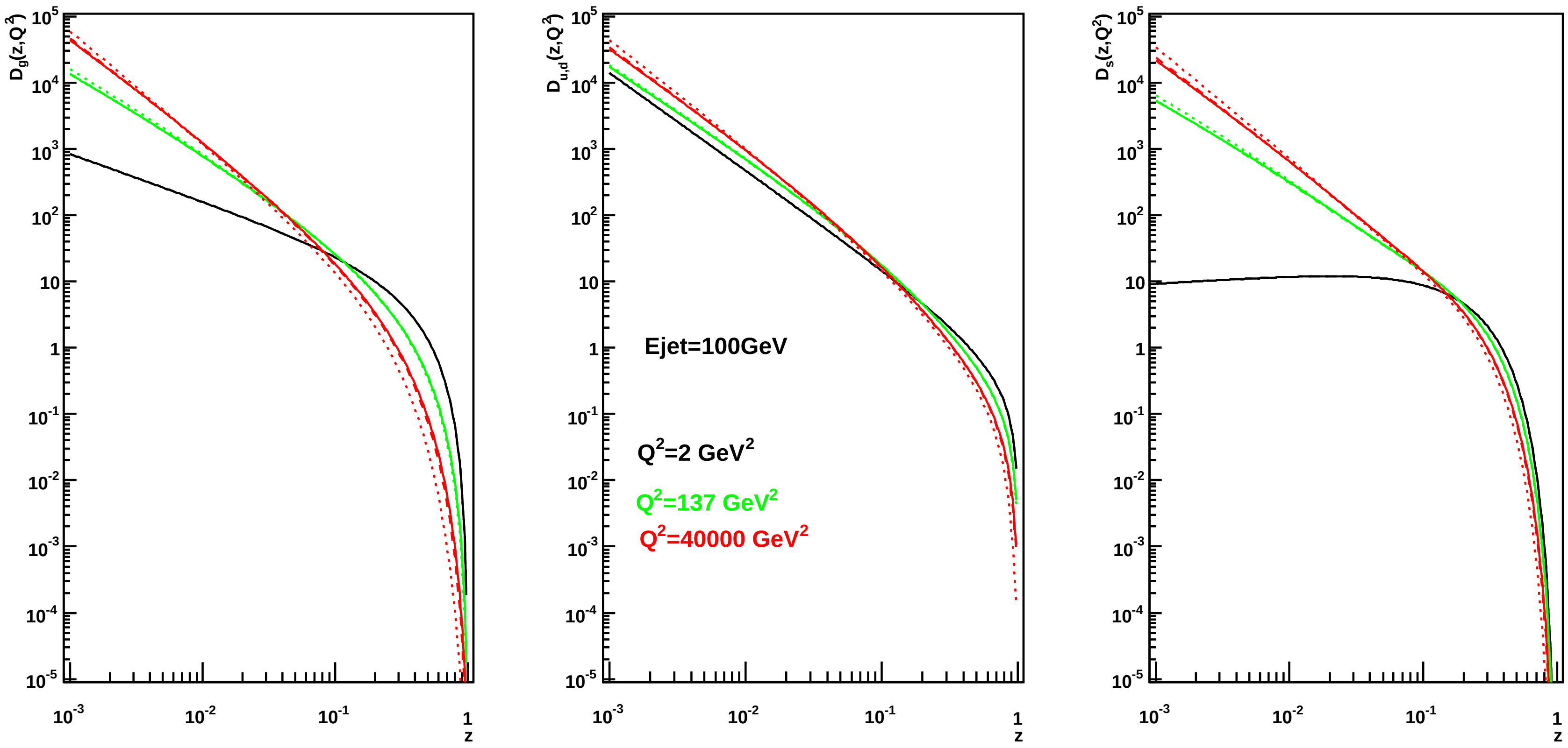
- We consider only 3 flavors(u,d,s) and massless.
- $\alpha_{renor} = t(1-z)z = k_T^2$ of the emitted gluon.
- $D(z,t_0) = D^{VAC}(z,t_0)$=KKP FF at $t_0 = 2$ GeV^2. (so we discard hadronization in medium, we have to look to high pt particles.)
- $t_0 < t < 4E^2$ and $t_0/t < z(t) < 1 - t_0/t$.
- The number of splittings grows and the rough effect is an acceleration of the evolution

Medium Modified Fragmentation Functions



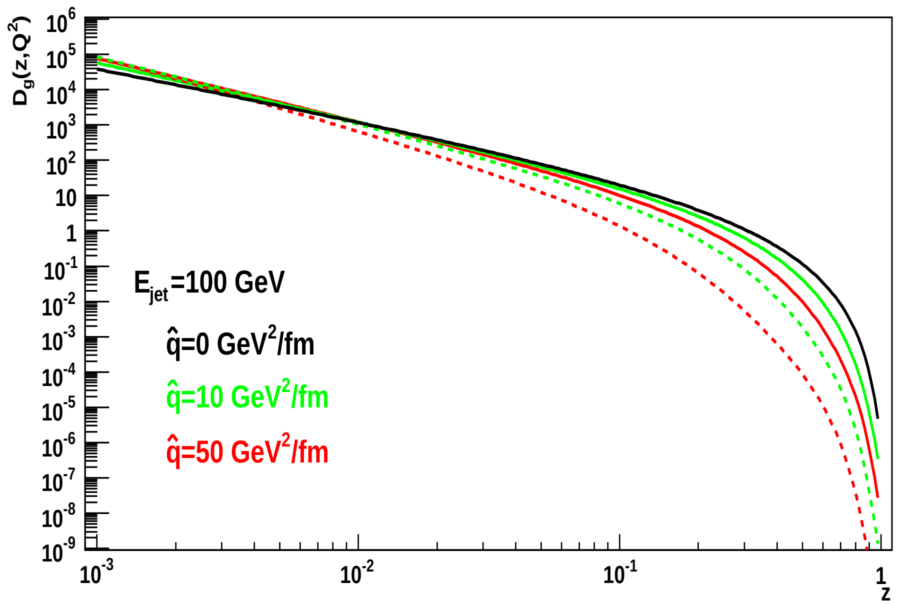
Fragmentation Functions for gluons, u,d and s quarks of initial energy $E_{jet} =$ 10 GeV into charged pions. **Solid/dashed/dotted** $\hat{q} = 0, 1, 10$ **GeV^2/fm**. The fragmentation function is softened.

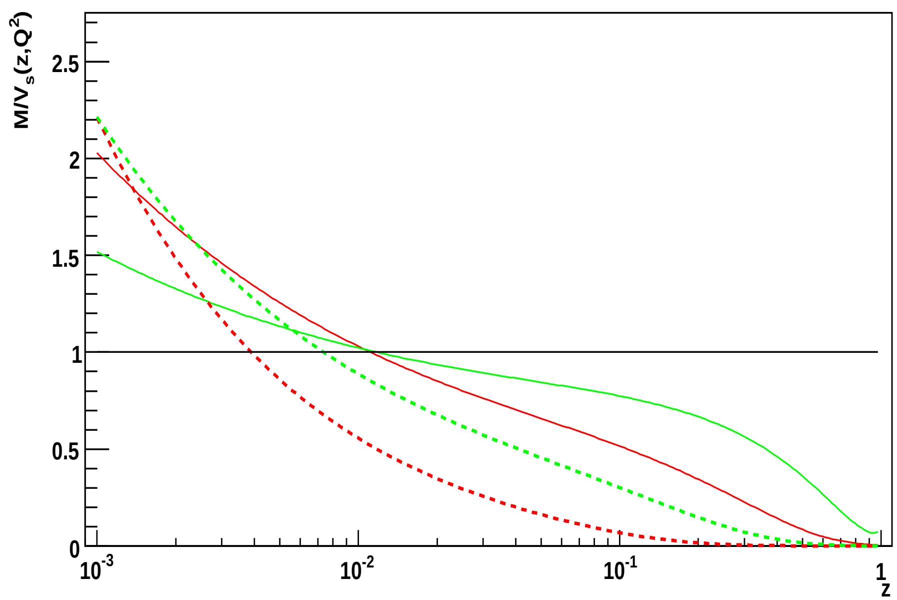
Medium Modified Fragmentation Functions



$E_{jet} = 100$ GeV, **solid/dashed/dotted** $\hat{q} = 0, 1, 10$ **GeV^2/fm**. The energy loss is independent of the parent parton energy thus the higher the energy the smaller the effect.

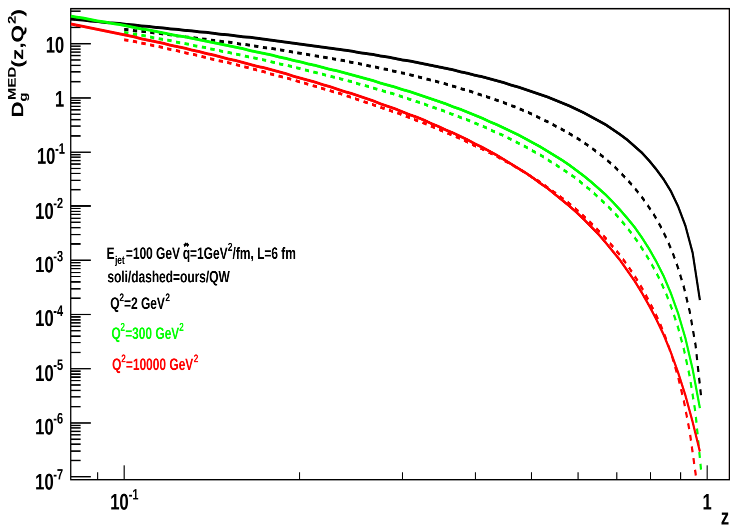
Medium Modified Fragmentation Functions:LHC

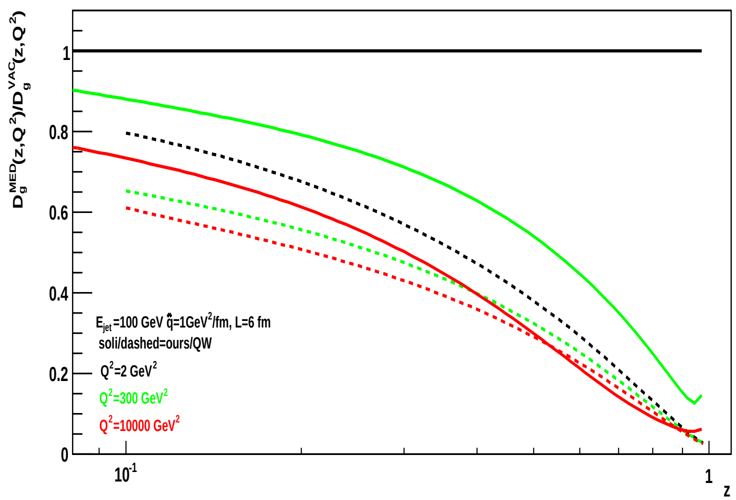




Solid/dashed=L=2,6 fm, $Q = E_{jet}$. The medium effects are enhanced with the medium length.

Comparison: QW vs our new approach





- For $Q^2 << E^2_{jet}$ QW overestimate suppression
- At $Q^2 \simeq E^2_{jet}$, it can be shown that this new method equals QW.
  - good agreement in the relevant z range for inclusive particle production.

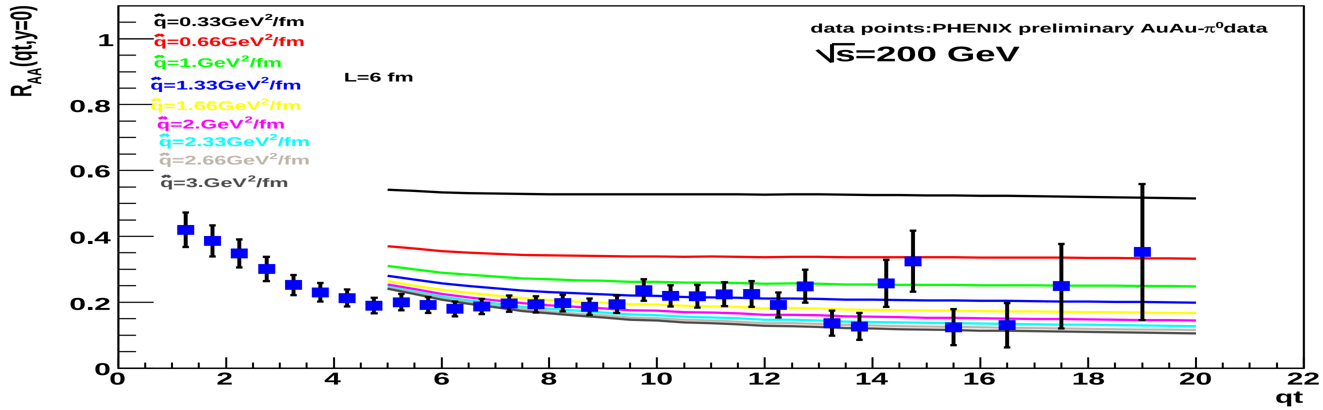
Particle Spectra: formalism

- A typical hard cross section can be written in the form:
- $\sigma^{AB\to h} = f_A(x_1, Q^2) f_B(x_2, Q^2) \otimes \sigma(x_1, x_2, Q^2) \otimes D_{i\longrightarrow h}(z, Q^2)$
  - $D_{i\longrightarrow h}(z, Q^2)$ long distance non perturbative object $\longrightarrow$ we modify its perturbative evolution.
- We define the nuclear modification factor as:

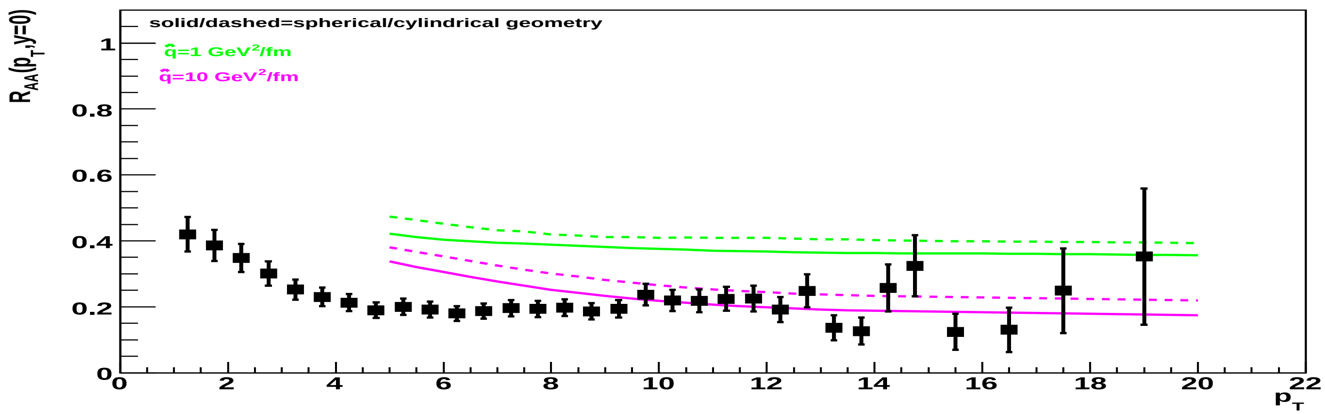
$$R_{AA} = \frac{\frac{d\sigma}{dydq_T^2}(pdf + EKS + MMFF)}{\frac{d\sigma}{dydq_T^2}(pdf + VACFF)} \tag{1}$$

- EKS**[Eskola-Honkanen-Salgado]** corrections for non free nucleons.

Nuclear Modification Factor



$\hat{q} \simeq 1$ GeV^2/fm at a fixed length of 6 fm. (the same as with the QW)



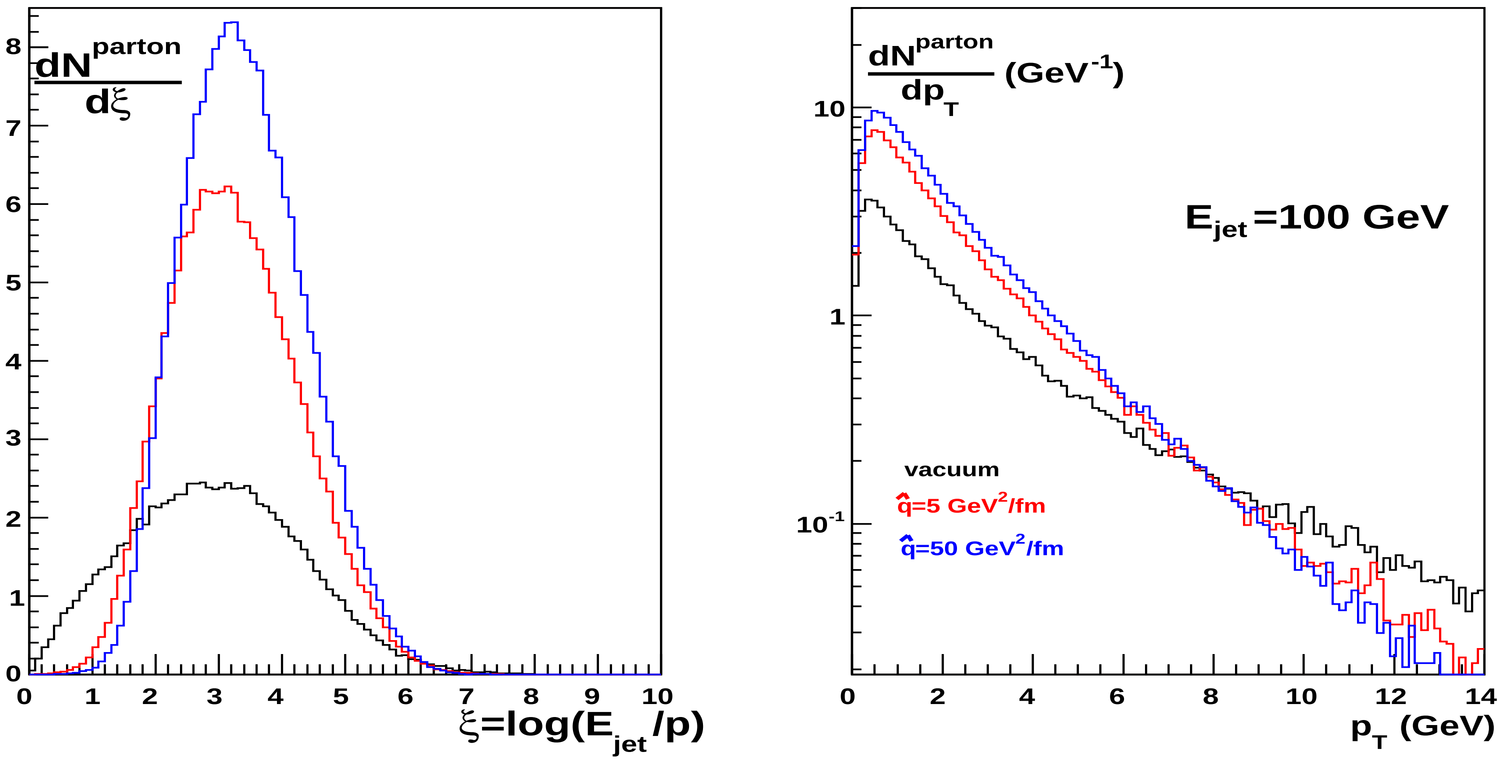
Considering a path lenght distribution in a cylinder and in a sphere, the value of $\hat{q}$ grows up to 10 GeV^2/fm.

Monte Carlo implementations

- A simple medium-modification can be implemented in Monte-Carlo codes by changing the splitting functions by the vacuum+medium ones.
- This is interesting because it will allow us to compute observables beyond single inclusive production like two (back to back azimuthal) or three particle correlations.
- our DGLAP approach neglects evolution in medium length (all the splittings are evaluated at the same L). With a Monte Carlo we will explore this dependence.
- work is in progress [also with G.Corcella in HERWIG]

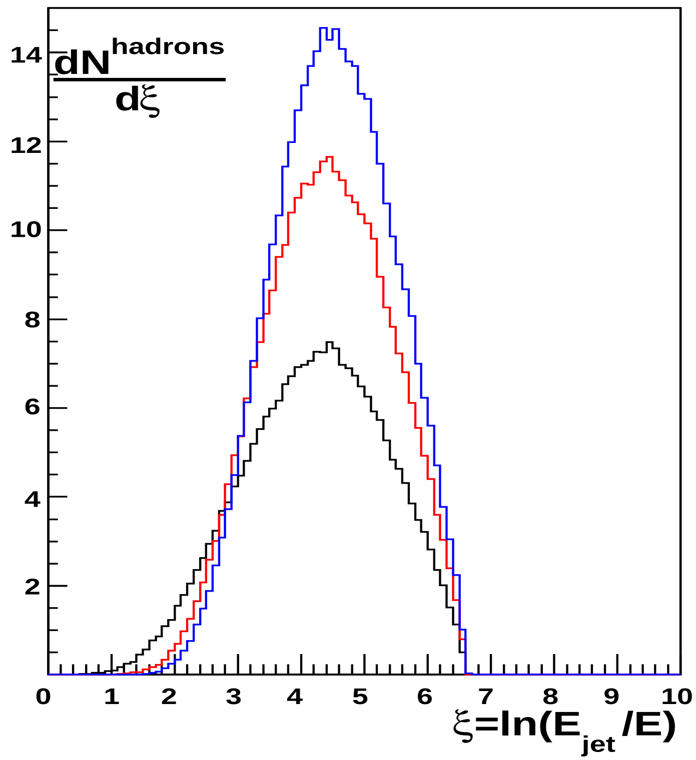
[Armesto-Cunqueiro-Salgado]

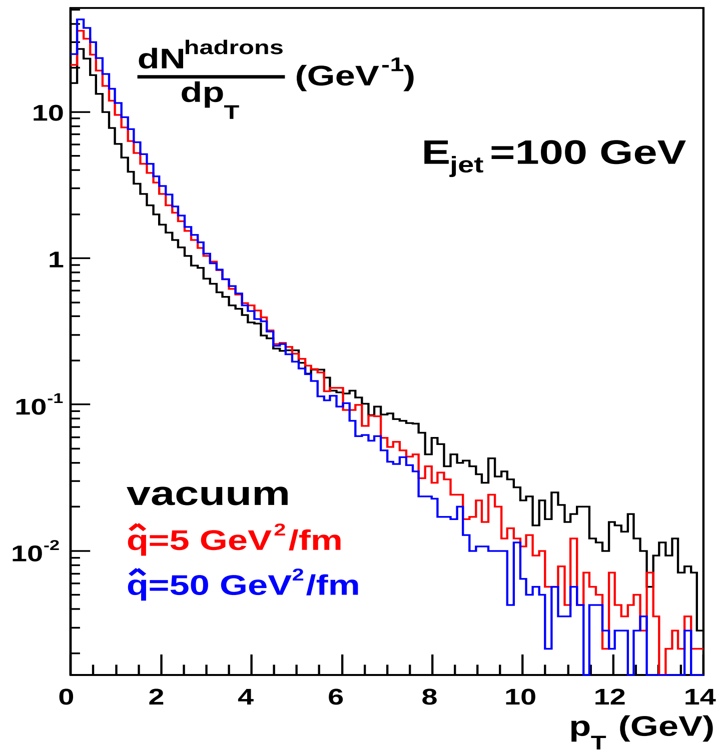
Medium in Pythia, some preliminary results



As a vacuum code, Pythia has no medium giving energy to the jet. The pt broadening is not clear due to energy conservation. Soft multiplicity is very much enhanced

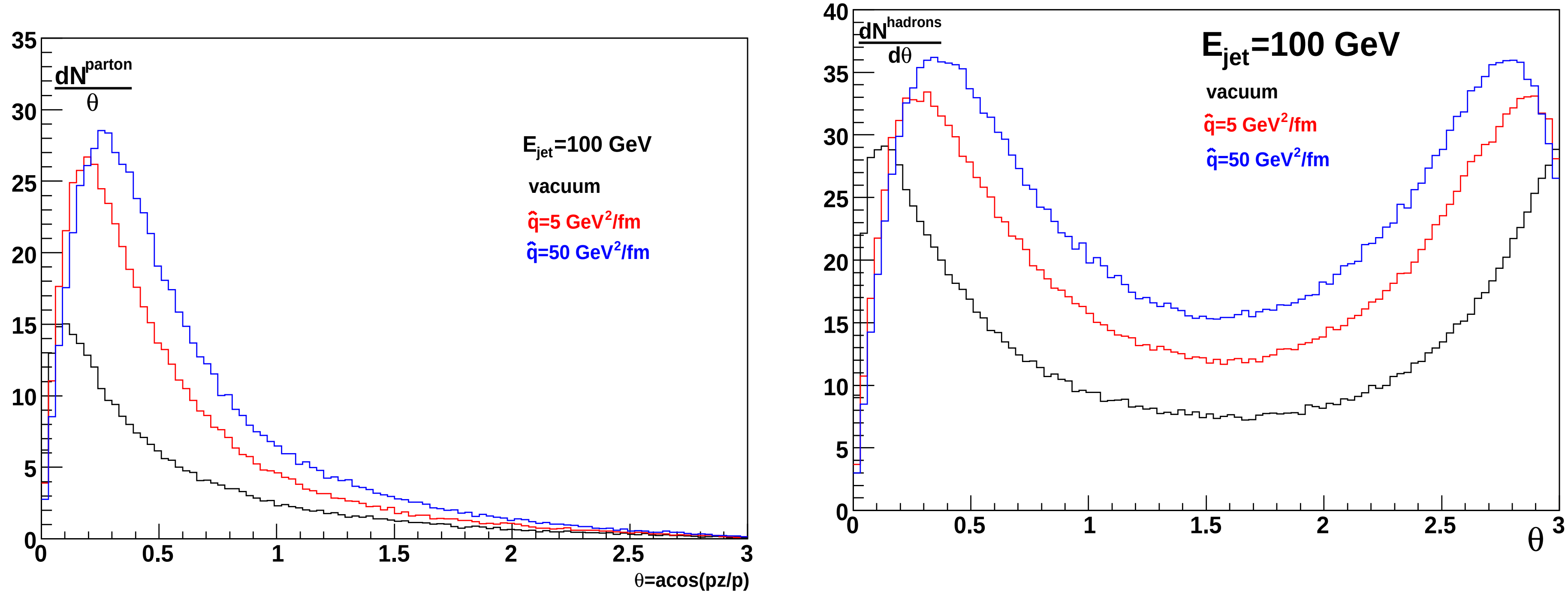
Medium in Pythia, some preliminary results





Hadronization sweeps out soft effects

Medium in Pythia, some preliminary results



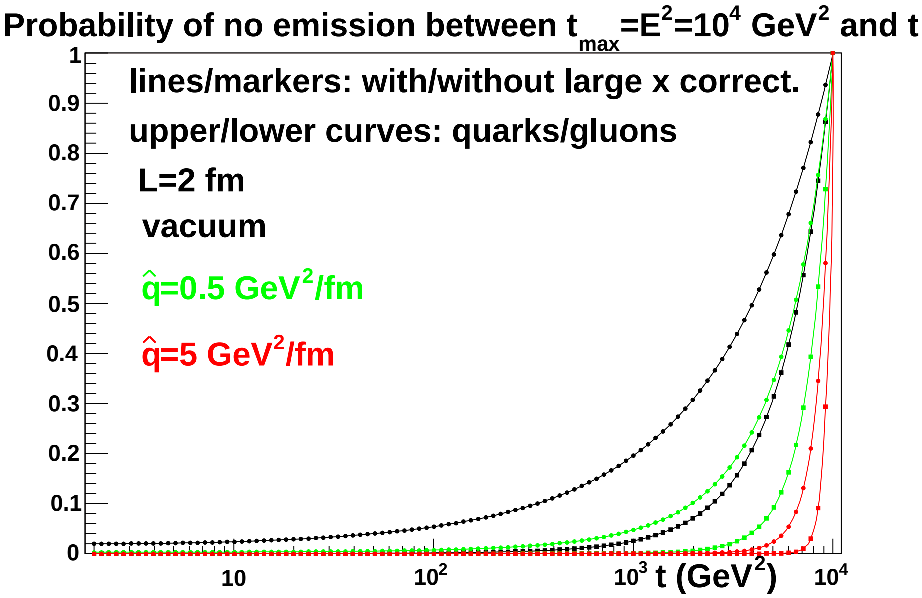
Left/Right=partons/hadrons. The jet polar angle distribution is broadened.

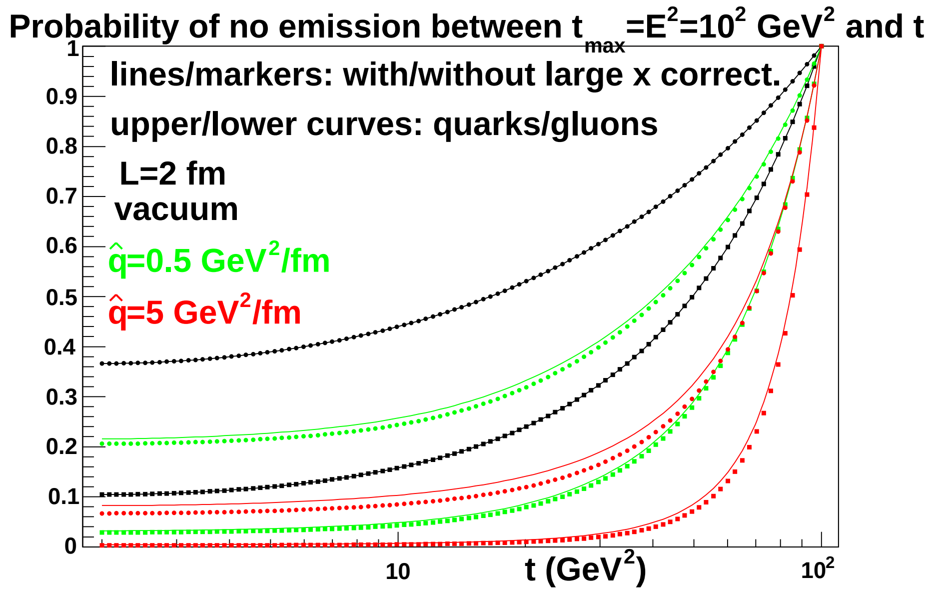
Conclusions

- We have presented our modeling of the evolution of jets in a QGP medium [Armesto,Cunqueiro,Salgado,Xiang, JHEP 0802:048,2008].
  - Energy and momentum are conserved at each splitting.
  - Medium and vacuum are evolved in the same footing
  - Ignoring the evolution in virtuality, good agreement in the relevant z range with QW $\rightarrow$ a collateral check of the QW formalism
  - Drawbacks: no elastic energy loss, no conversions considered.

- Monte Carlo implementations $\rightarrow$ access to more differential and unbiased observables.

EXTRAS

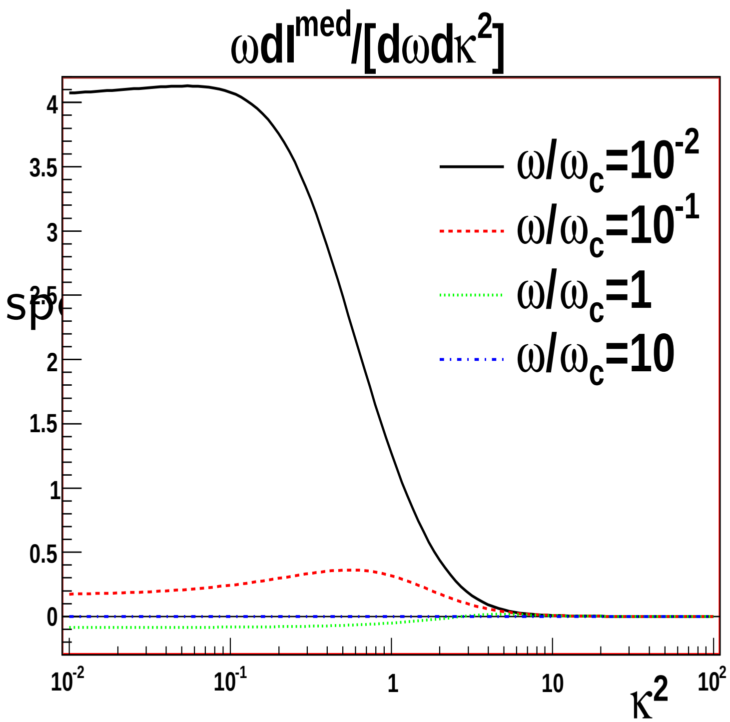


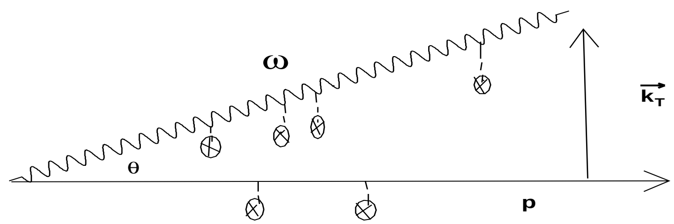


Medium effects at the level of the Sudakovs.
Large x corrections simply means to multiply by $(1+z^2)/2$ the quark colinear splitting and to multiply by z and symmetrize around $1/2$ the gluon colinear one.

EXTRAS

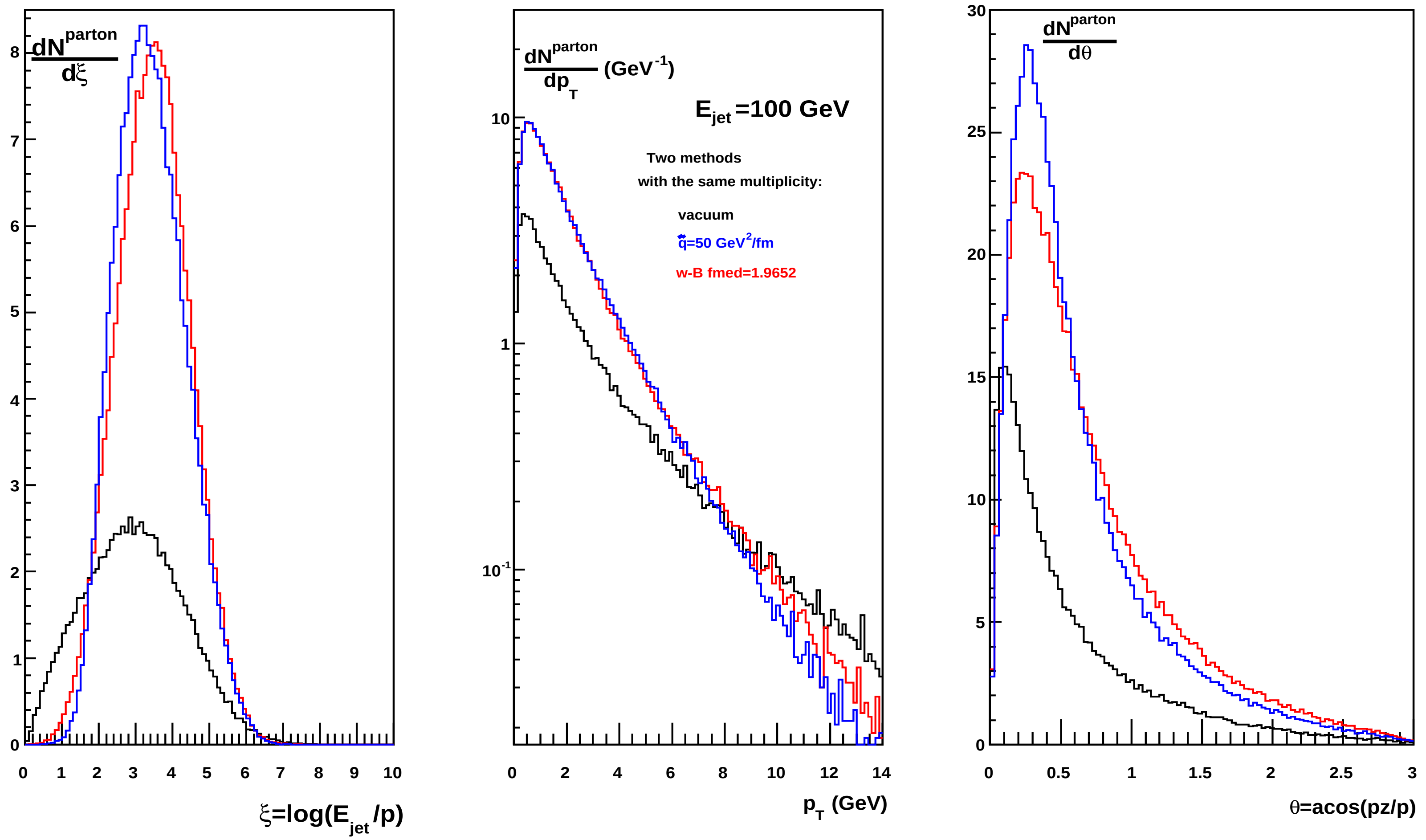
The splitting function is modified according to the shape of the MIGRS





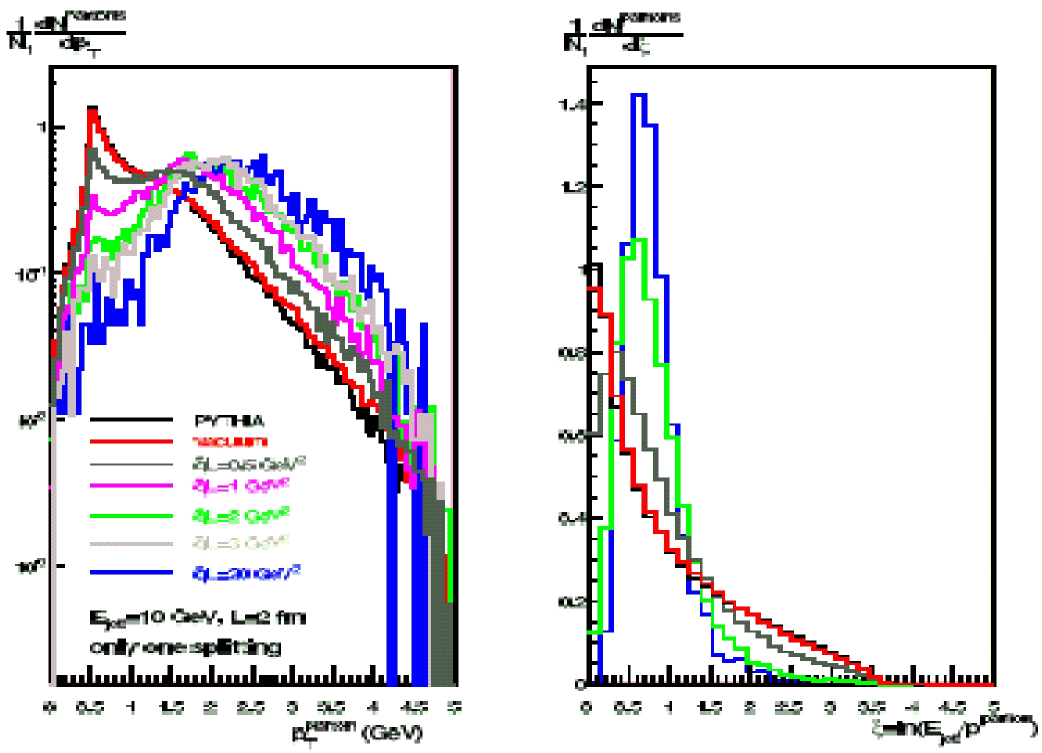
- Like in QED, the emission of a gluon has a phase $\phi = \frac{k_T^2 \Delta z}{2\omega}$.
- To strip the gluon out $\phi \sim 1 \longrightarrow l_{coh} \sim 2\omega/k_t^2$
- D = average distance between the scattering centers= L/N
- if $l_{coh} \geq D \longrightarrow$ there is suppression of the radiation due to LPM coherence.
- This happens at low k_t^2 and/or great ω. ($\kappa^2 = \frac{k_t^2}{\hat{q}L}$ and $\omega_c = \frac{1}{2}\hat{q}L^2$)

EXTRAS



Comparisson between our approach and Borghini-Wiedemann's fixing fmed to obtain the same multiplicity

EXTRAS



When forcing PYTHIA to only one splitting, a clear pt broadening is observed.