Jet reshaping in heavy-ion collisions

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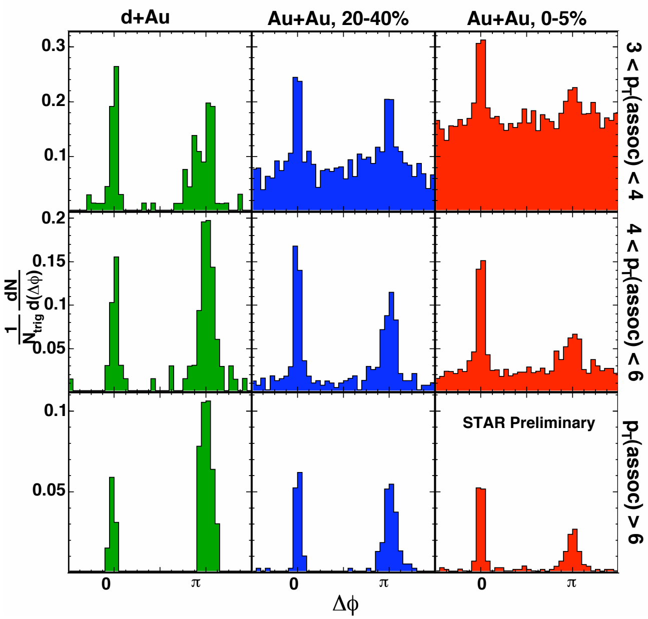
Jet studies in HIC



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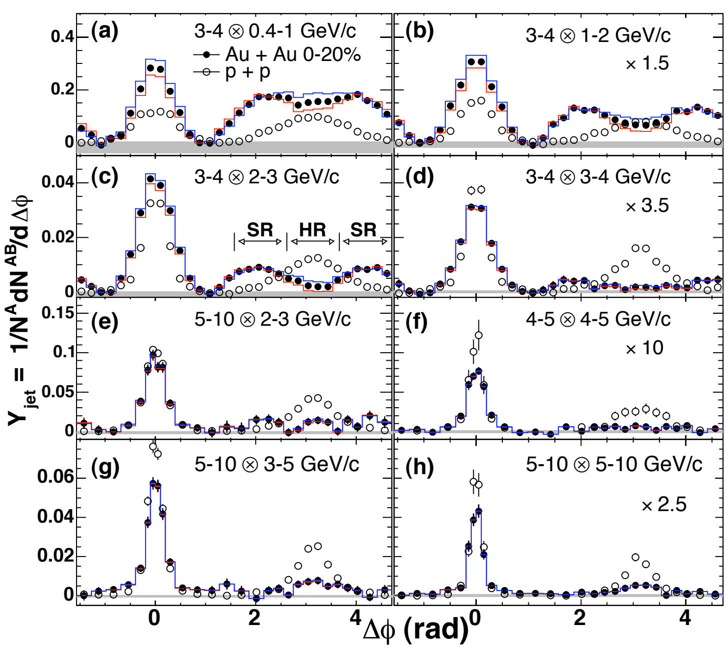
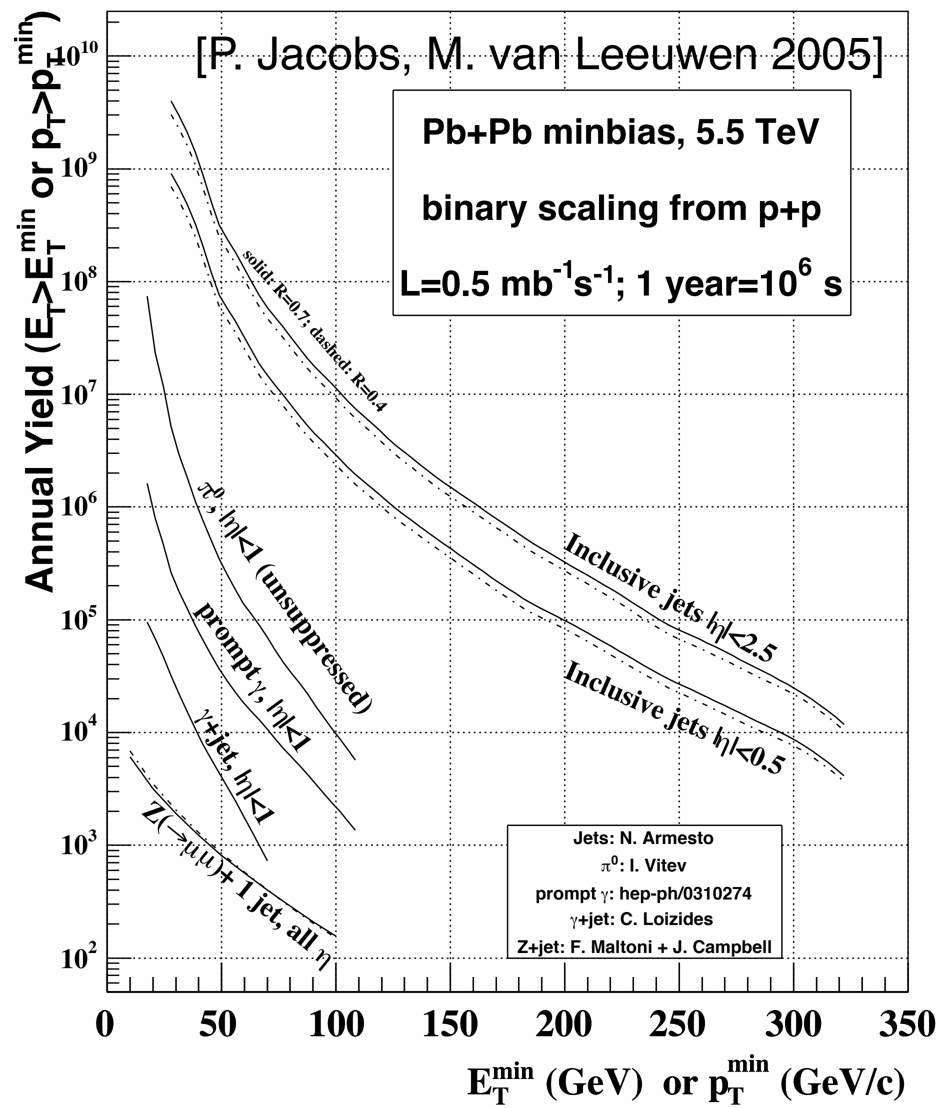


[PHENIX]

Annual hard process yields

LHC



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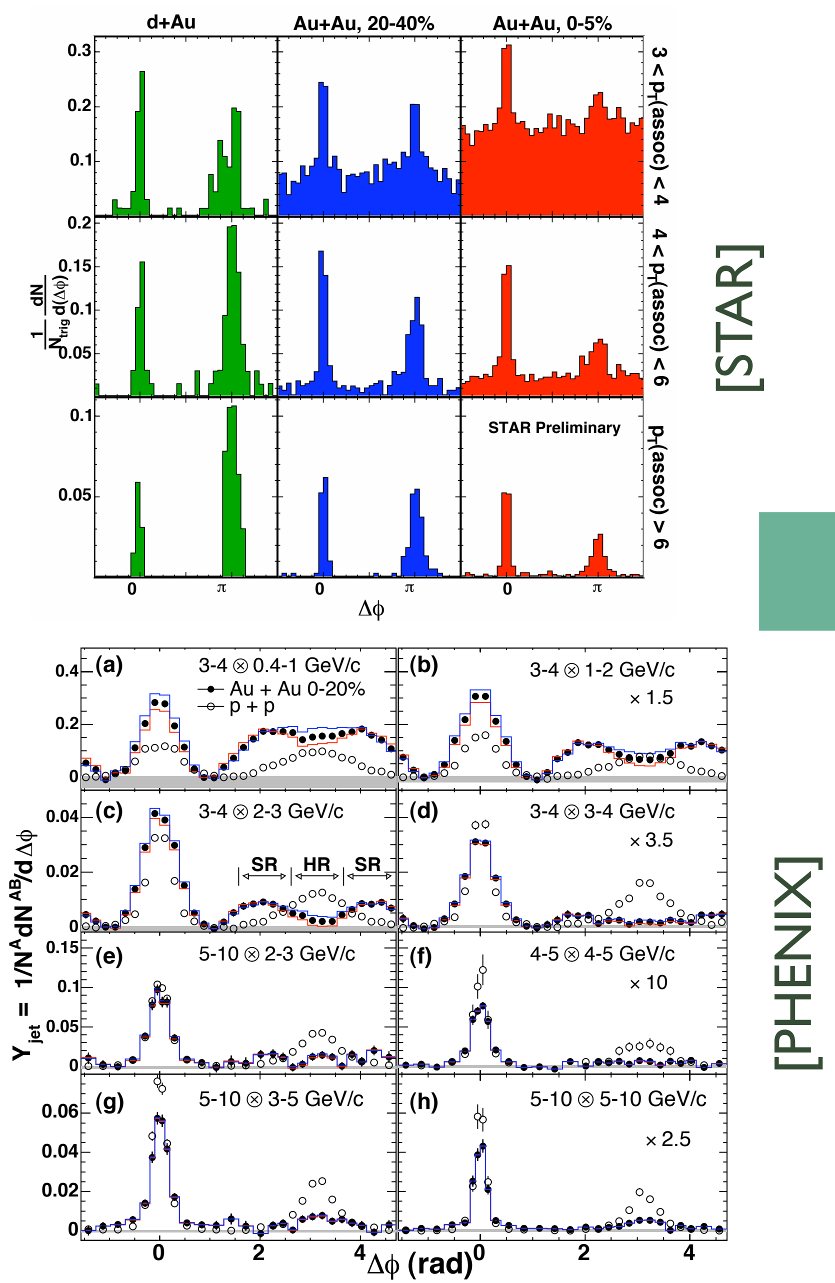
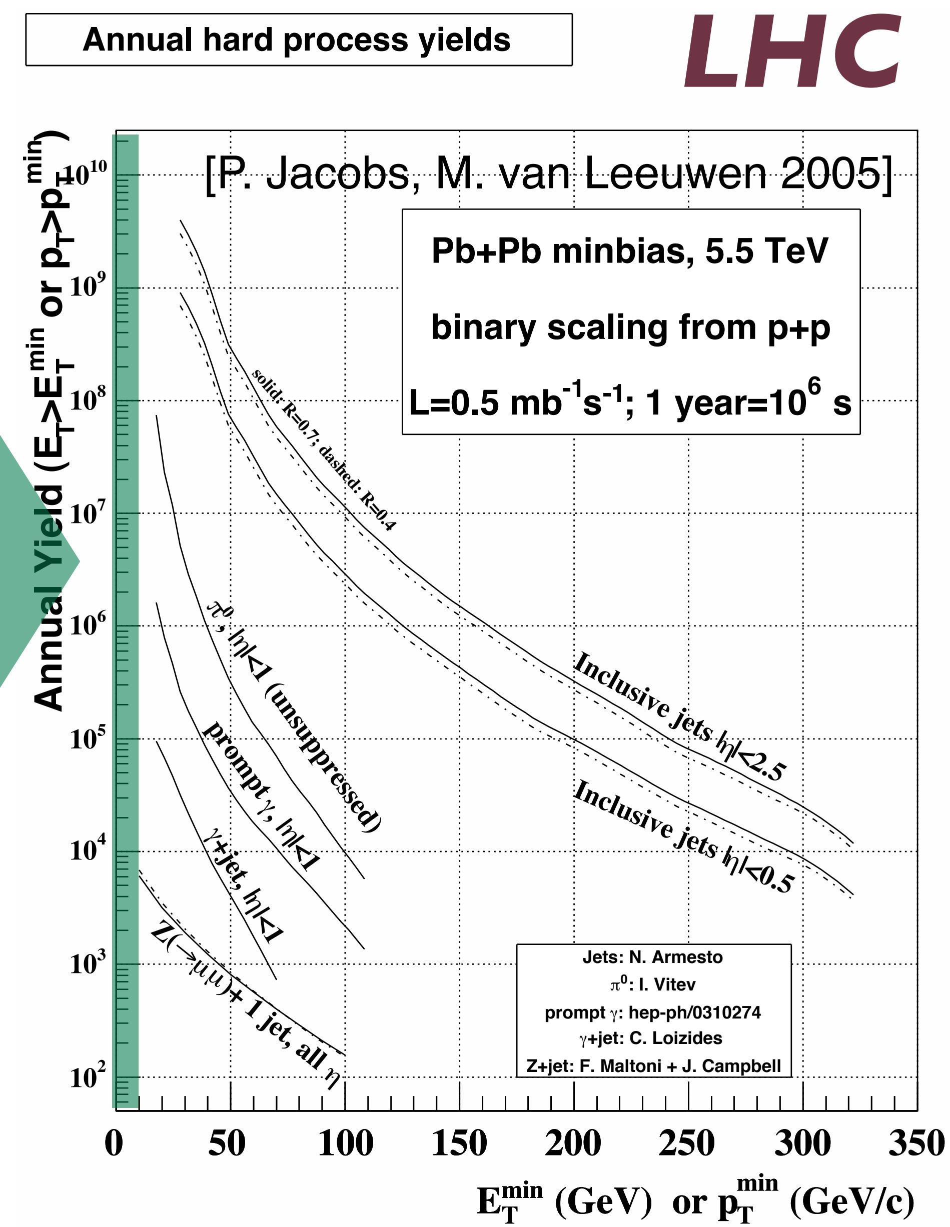
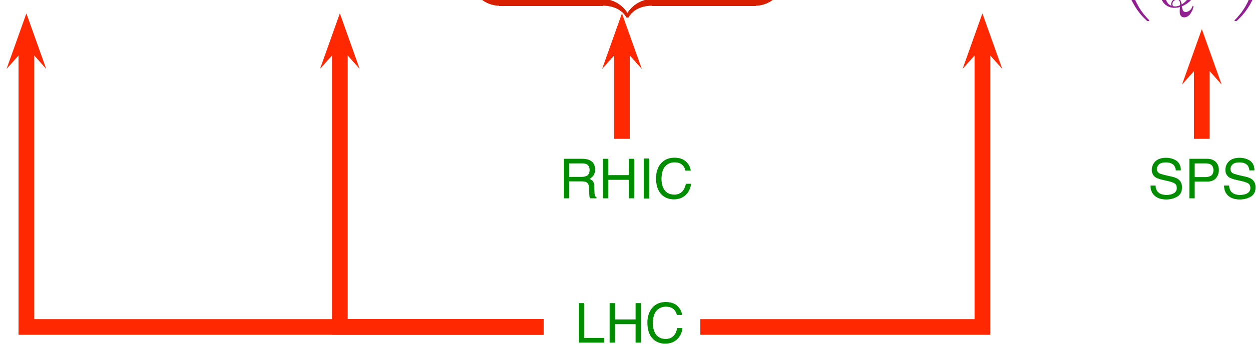




Hard probes in heavy-ion collisions

- SPS $\sqrt{s} = 20$ GeV ($Q \sim 1$ GeV) $\longrightarrow$ marginal access to HP
- RHIC $\sqrt{s} = 200$ GeV ($Q \sim 10$ GeV) $\longrightarrow$ access to HP
- LHC $\sqrt{s} = 5500$ GeV ($Q \gtrsim 100$ GeV) $\longrightarrow$ HP and QCD evolution

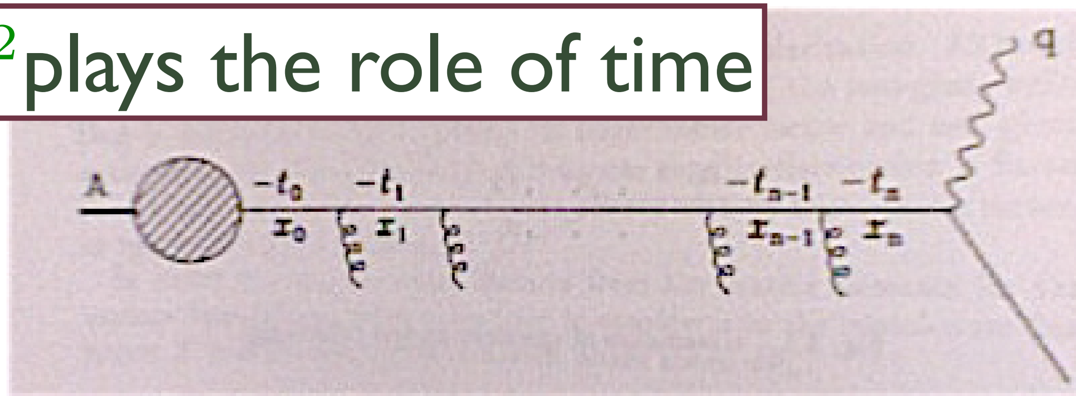
$$\sigma^{pp\to h} = f_p(x_1, Q^2) \otimes f_p(x_2, Q^2) \otimes \underbrace{\sigma(x_1, x_2, Q^2)} \otimes D(z, Q^2) + \left(\frac{1}{Q^2}\right)^n$$



- The extension of the medium modifies the long-distance terms
  - New evolution equations for $f_A(x, Q^2); D(z, Q^2)$
- Kinematical access to evolution: large-Q^2, small-x

DGLAP evolution in vacuum

$t = Q^2$ plays the role of time



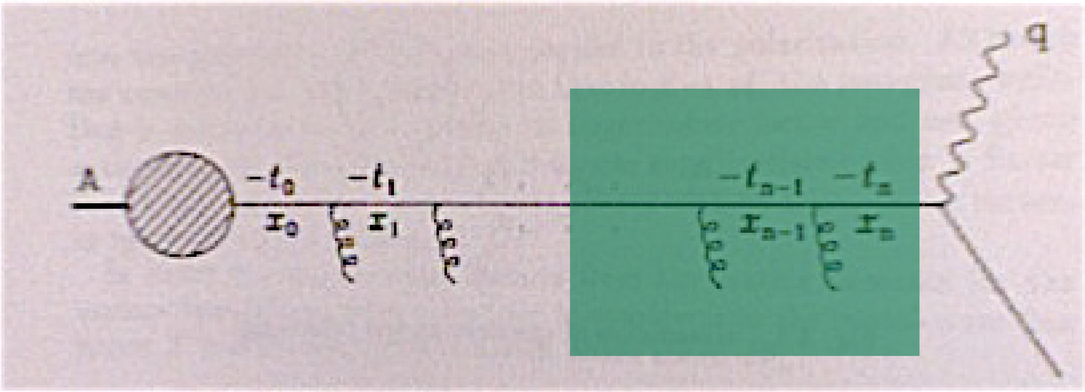
Ordered gluon splitting given by DGLAP

$$\frac{\partial f(x,t)}{\partial \log t} = \int_x^1 \frac{dz}{z} \frac{\alpha_s}{2\pi} P(z) f(x/z, t)$$

splitting function

f(x,t) are the PDFs or the FF

What is the equivalent for the medium?



⇒ First proposal: Quenching Weights [Baier, Dokshitzer, Mueller, Schiff 2001]

- Independent gluon emission
- Poisson distribution for the medium-induced radiation

$$P_E(\epsilon) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI^{\text{med}}(\omega_i)}{d\omega} \right] \delta\left(\epsilon - \sum \frac{\omega_i}{E}\right) \exp\left[-\int d\omega \frac{dI^{\text{med}}}{d\omega}\right]$$

$$p_0 = \exp\left[-\int d\omega \frac{dI^{\text{med}}}{d\omega}\right]$$

- Probability of no splitting

Some drawbacks of the QW:

- Vacuum and medium treated separately
- Energy conservation
- Role of virtuality
- Angular structures not studied

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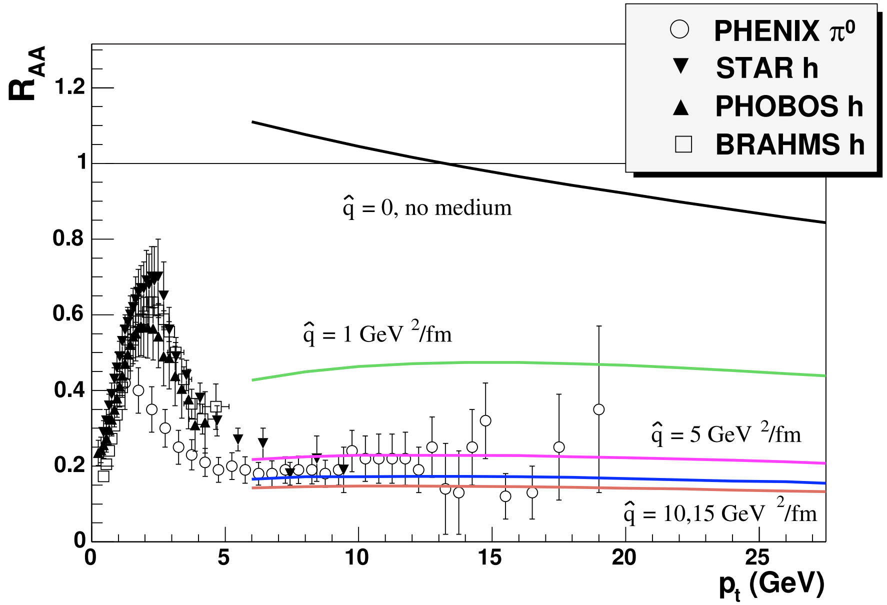
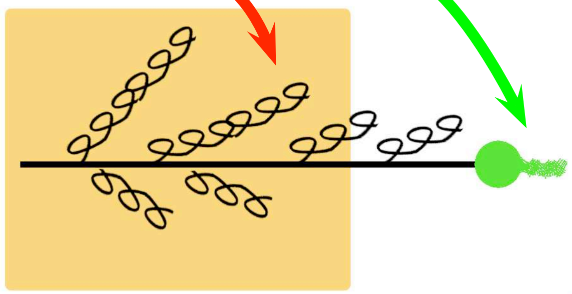
Data is, however, very well described

Description of the suppression

$$d\sigma^{AA\to h+X}_{(\mathrm{med})} = \sum_f d\sigma^{AA\to f+X}_{(\mathrm{vac})} \otimes \boxed{P_f(\Delta E, L, \hat{q})} \otimes D^{(\mathrm{vac})}_{f\to h}(z, \mu_F^2)\,.$$



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



⇛ Multiple emission: Poisson distribution

⇛ Hadronization in vacuum at high-p_t

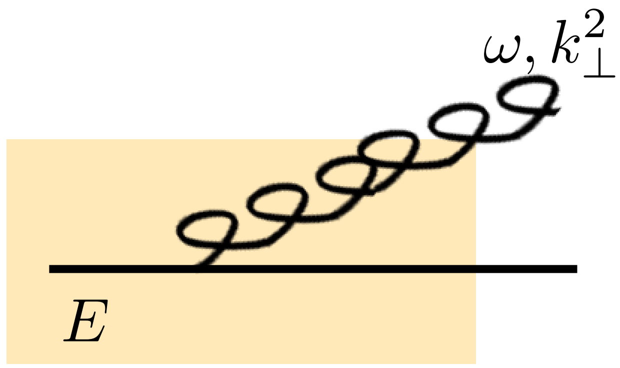
⇛ Data favors a large time-averaged transport coefficient

$$\boxed{\hat{q} \sim 5\ldots15\frac{GeV^2}{fm}}$$

[Gyulassy, Levai, Vitev 2002; Arleo 2002; Dainese, Loizides, Paic 2004; Wang, Wang 2005; Drees, Feng, Jia 2005; Turbide, Gale, Jeon, Moore 2005...]

Medium-induced gluon radiation

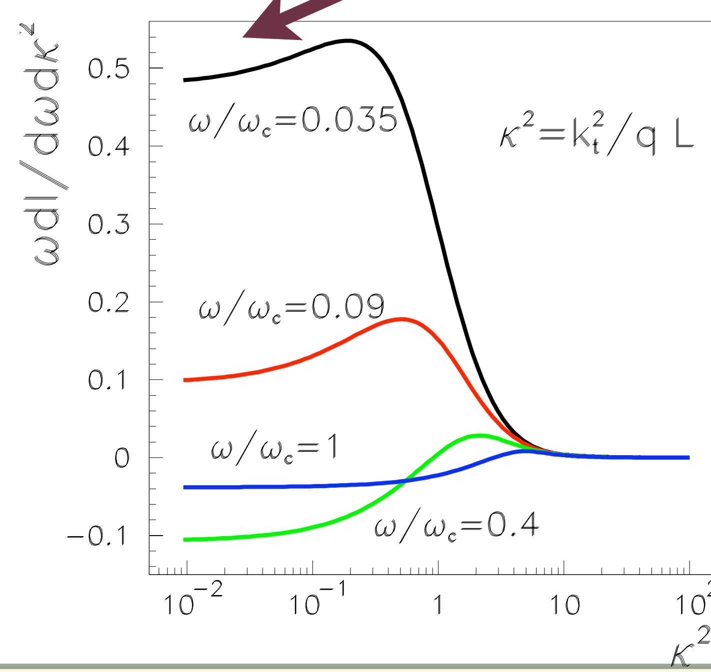
Medium-modification of the jet evolution



⇛ Gluon formation time

$$t_{\text{form}} \sim \omega / k_\perp^2$$

⇛ Radiation suppressed for $t_{\text{form}} \geq L$



⇛ Transport coefficient

$$\hat{q} \simeq \frac{\langle k_\perp^2 \rangle}{\lambda} \propto n(\xi)$$

⇛ Two main predictions

- Energy loss $\Delta E \sim \alpha_s \hat{q} L^2$
- Jet broadening $\langle k_t \rangle \sim \hat{q} L$

Vacuum: Sudakov prescription

- The probability of no radiation between two scales

$$\Delta(t) \equiv \exp\left[-\int_{t_0}^{t}\frac{dt'}{t'}\int dz\,\frac{\alpha_s}{2\pi}P(z)\right]$$

- The probability of one splitting

$$d\mathcal{P}(t,z) = \frac{dt}{t}dz\frac{\alpha_s}{2\pi}P(z)\Delta(t)$$

- Iterating, an equivalent to DGLAP is obtained (at LO in α_s)

$$f(x,t) = \Delta(t)f(x,t_0) + \int\frac{dt'}{t'}\frac{\Delta(t)}{\Delta(t')}\int\frac{dz}{z}\frac{\alpha_s}{2\pi}P(z)f(x/z,t')$$

- Probabilistic interpretation well suited for MC event generators

Medium-modification of the evolution

⇛ Total spectrum: vacuum+medium

$$\frac{dI}{dz\,dk_t^2} = \frac{\alpha_s}{2\pi}\frac{1}{k_t^2}P(z) + \frac{dI^{\text{med}}}{dz\,dk_t^2}$$

⇛ Take $$P^{\text{tot}}(z) = P(z) + \Delta P(z)$$

⇛ Two main modifications w.r.t. vacuum

- Modified radiation structure
- Enhanced number of splittings $\longrightarrow$ faster evolution

⇛ Previous related approaches

- Medium-effects as higher-twist corrections to lA DIS find similar modification of the splitting function [Guo-Wang-Majumder]
- Constant factor $P(z) \to (1 + f_{\text{med}})P(z)$ [Borghini, Wiedemann 2005]

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Including the medium: all together

⇛ The Sudakov form factor contains now the vacuum and medium

$$\Delta^{\rm tot}(t) = \exp\left[-\int_{t_0}^{t}\frac{dt'}{t'}\int dz\frac{\alpha_s}{2\pi}\left[P(z)+\Delta P(z,t)\right]\right] = \Delta^{\rm vac}(t)\Delta^{\rm med}(t)$$

⇛ Ignoring virtuality, i.e. setting the limits to the kinematical ones

$$\Delta^{\rm med}(t) = p_0 \equiv \exp\left[-\int d\omega\, dk_t^2\, \frac{dI^{\rm med}}{d\omega dk_t^2}\right]$$

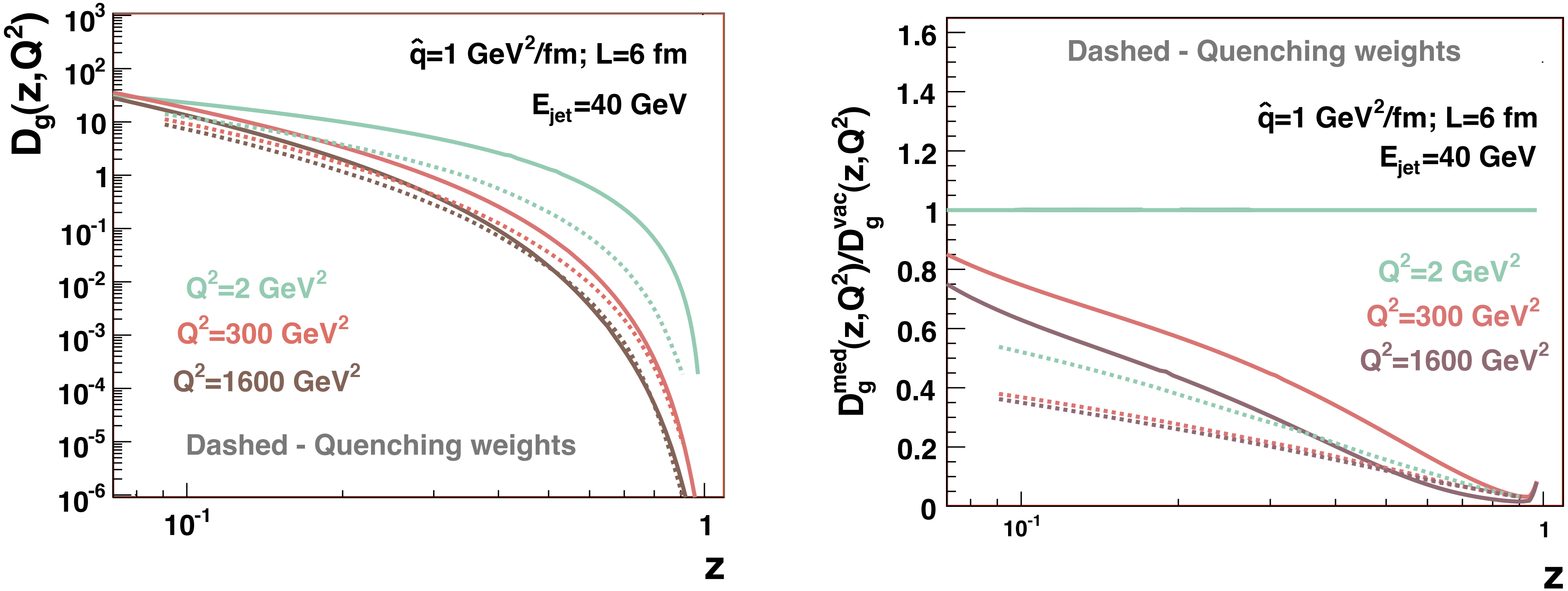
and the QW formulation for the FF is recovered for $x = 1 - z \ll 1$

$$D(x,t) \simeq \Delta^{med}(t) D^{vac}(x,t) + \Delta^{med}(t)\int \frac{d\epsilon}{1-\epsilon}\sum_{n=1}^{\infty}\frac{1}{n!}\prod_{i=1}^{n}\int_{t_0}^{t}\frac{dt_i}{t_i}\int dz_i\, P^{med}(z_i)$$

$$\times\, \delta\left(\epsilon - \sum_{j=1}^{n} x_j\right) D^{vac}\left(\frac{x}{1-\epsilon}, t\right),$$

[Armesto, Cunqueiro, Salgado, Xiang in preparation]

Results



- Softening of the fragmentation functions - energy loss
- Agreement with QW framework when $Q^2 \simeq E_{\rm jet}^2$
- QW overestimates suppression when $Q^2 \ll E_{\rm jet}^2$

[Armesto, Cunqueiro, Salgado, Xiang in preparation]

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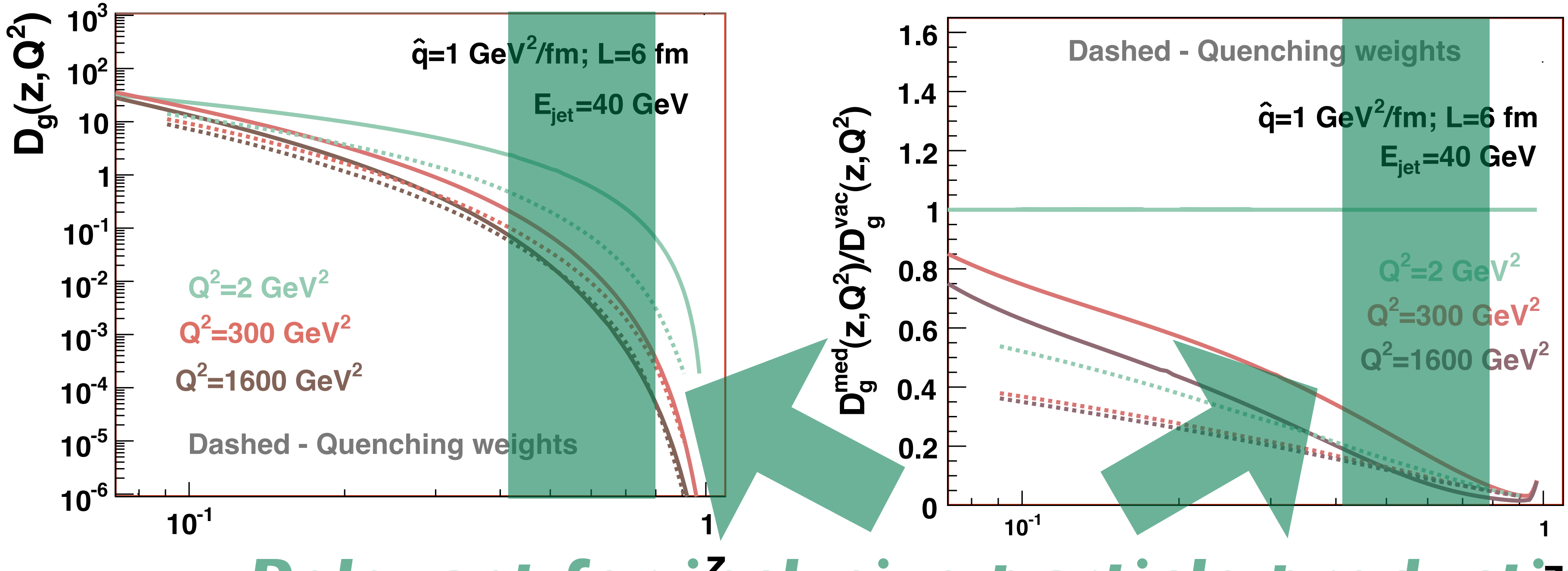

Relevant for inclusive particle production

- Softening of the fragmentation functions - energy loss
- Agreement with QW framework when $Q^2 \simeq E_{\rm jet}^2$
- QW overestimates suppression when $Q^2 \ll E_{\rm jet}^2$

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— Just change the vacuum splitting by the medium+vacuum one in the shower algorithm

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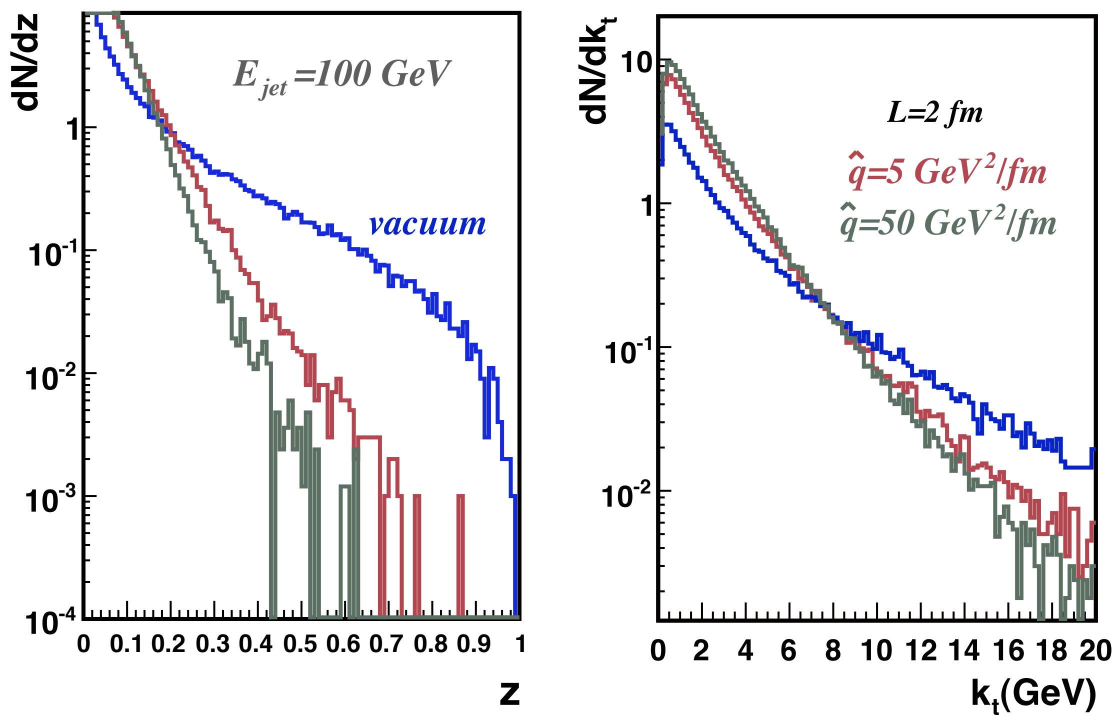
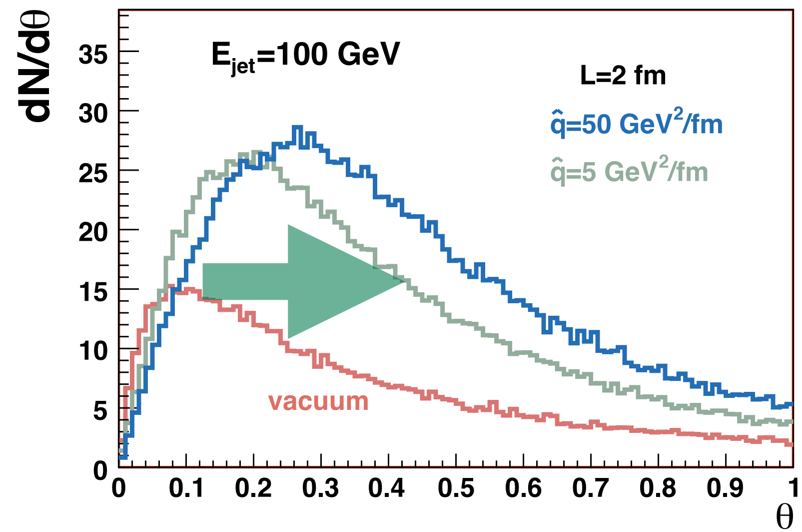
Results from an implementation in Pythia

Fragmentation function



Angular distribution



⇛ Main medium-modifications in agreement with expectations

- Particle spectrum softens (energy loss)
- Larger emission angles (jet broadening)
- Larger multiplicity

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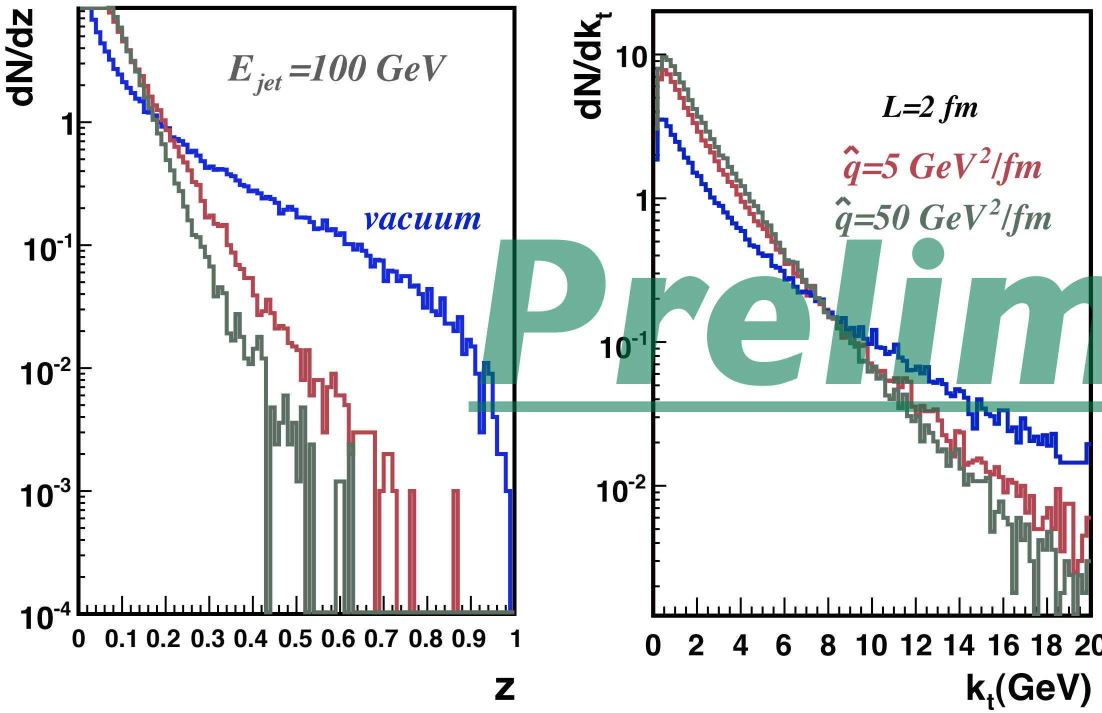

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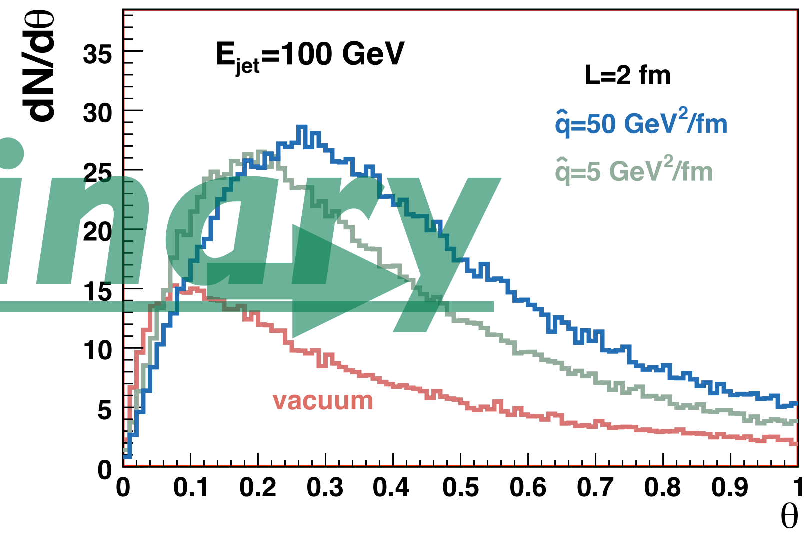

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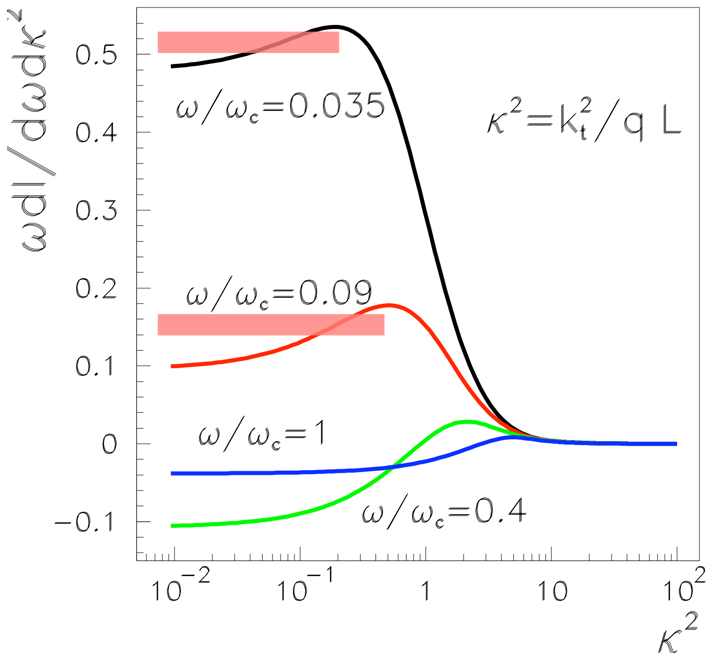
A particular case:

Jet shapes dominated by the first splitting

Parton shower for opaque media

- When $\omega \ll \hat{q}^{1/3}$
  - Totally coherent limit and large angle radiation

$$\frac{dI^{\rm med}}{d\omega dk_t^2} \simeq \frac{\alpha_s C_R}{16\pi} L \frac{1}{\omega}$$



- The probability of one splitting

$$d\mathcal{P} = dz d\theta \frac{\alpha_s C_R}{8\pi} E\, L\, \sin\theta \cos\theta \exp\left\{-\frac{\alpha_s C_R}{16\pi} E\, L\, \cos^2\theta\right\}$$

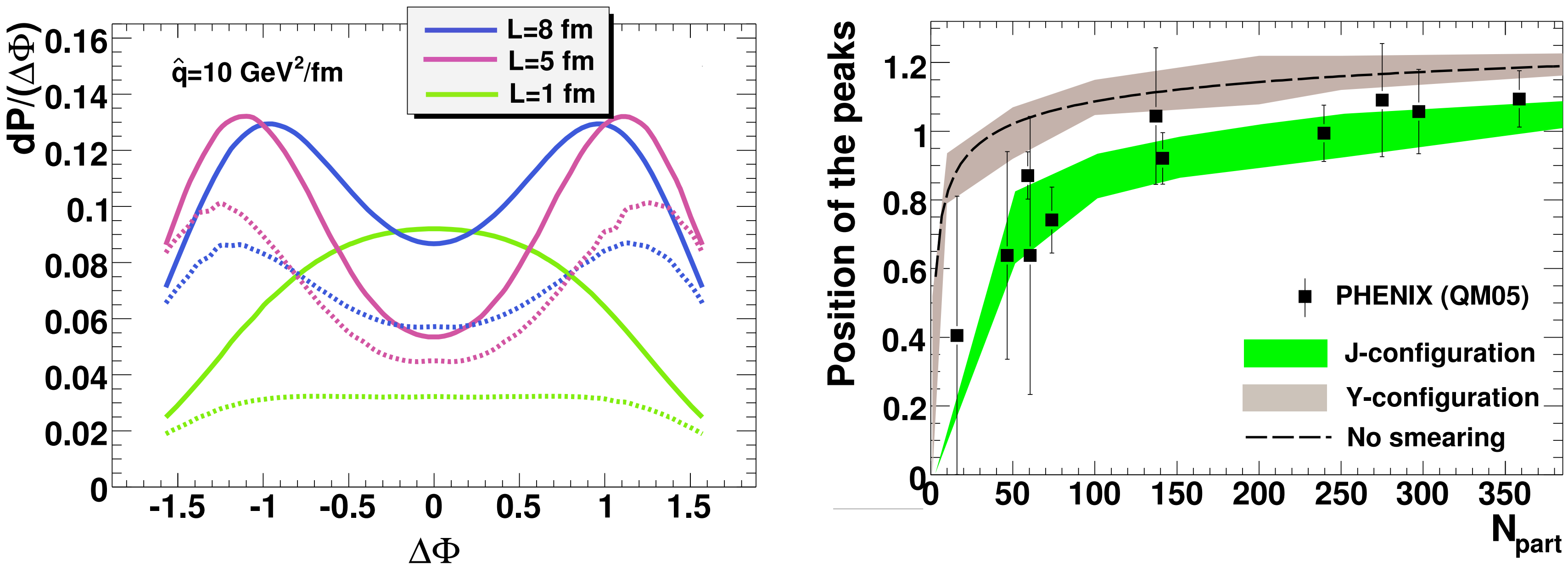
- Non-trivial angular dependence for the medium-induced gluon radiation: Two peaks in the laboratory azimuthal angle

$$\Phi_{\rm max} = \pm \arccos\sqrt{\frac{8\pi}{E\, L\, \alpha_s\, C_R}}$$

A simple model to compare with data

⇛ Smearing in longitudinal (η) and transverse (Φ) variables

$$\frac{dP}{d\Delta\Phi dz} = \frac{1}{N}\int_{-\Delta\eta}^{\Delta\eta} d\eta \int d\Phi' \frac{d\mathcal{P}}{d\Phi' dz d\eta} e^{-\frac{(\Delta\Phi-\Phi')^2}{2\sigma^2}}$$



[Polosa and Salgado 2006]

⇛ If the radiation is dominated by the first splitting a two-peak structure can be accommodated in a perturbative approach.

The picture

- The splitting probability in the medium presents two maxima in $\Delta\Phi$ for gluon energies $\omega \lesssim \hat{q}^{1/3} \sim$ 3 GeV for $\hat{q} \sim 10$ GeV^2/fm.
  - Using parton–hadron duality $p_t^{\rm assoc} \sim \omega$

Influence of kinematic constrains – STAR for concretenes

- $2.5 < p_t^{\rm trigg} < 4$ GeV and $1 < p_t^{\rm assoc} < 2.5$ GeV
  - Energy conservation restricts the number of splittings to 1 or 2.
  - Two peaks in the angular correlations
- $6 < p_t^{\rm trigg} < 10 {\rm GeV}$and $1 < p_t^{\rm assoc} < 2.5$ GeV
  - More splittings possible
  - The dip is filled – inclusive distribution does not have dip
- $p_t^{\rm assoc} > 6$ GeV $\gg \hat{q}^{1/3} \sim 3$ GeV
  - the radiation is more collinear and the dip dissapears

Improving the description of the medium:

Interplay with hydrodynamics

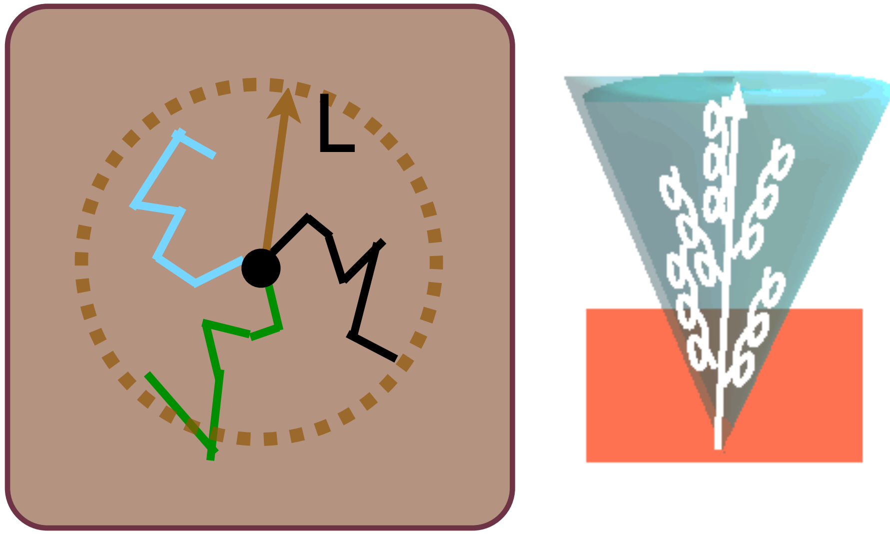
Flowing medium

$$\frac{\partial f(U^2,t)}{\partial t} = -\int f(U^2,t)V((\vec{U}-\vec{U}')^2)d^2\vec{U}' + \int f(U'^2,t)V((\vec{U}'-\vec{U})^2)d^2\vec{U}' \,.$$

[BDMPS 1996]

⇛ Static medium:

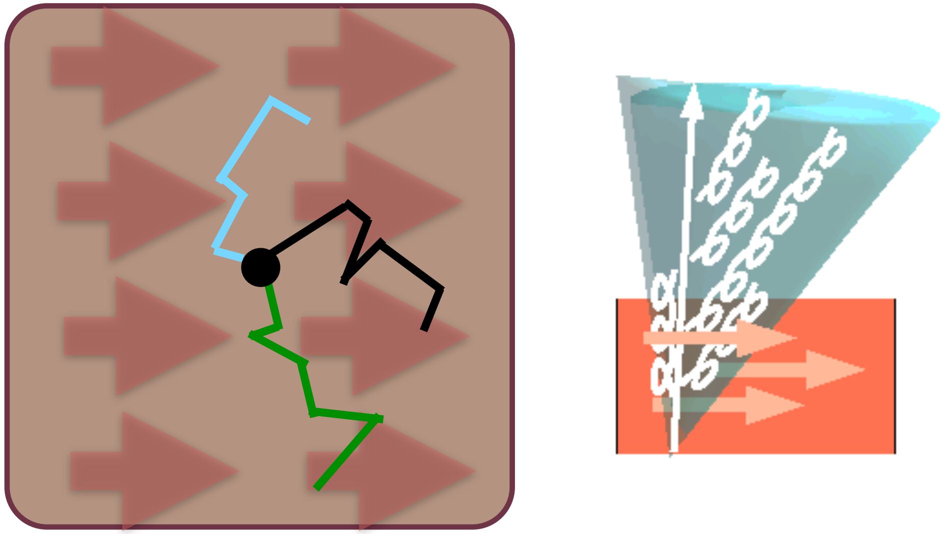
↘ Brownian motion



$$k_t^2 \simeq \hat{q}\, L$$

⇛ Flow fields

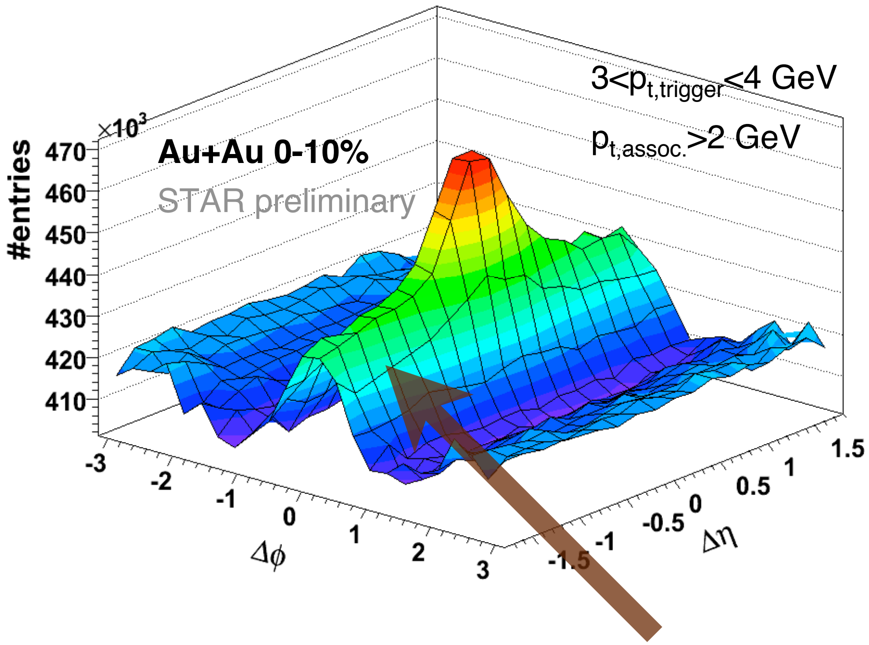
↘ Asymmetric emission



[Armesto, Salgado, Wiedemann 2004]
[Majumder, Muller, Bass 2006]

The ridge

- Transport coefficient depends on the emission angle
  - Larger for emission parallel to the flow
  - Smaller for emission perpendicular to the flow



- Simple estimate, taking

$$\hat{q} = c\,\epsilon^{3/4} \propto p^{3/4}$$

$$\Delta p/p = 1,\ 5,\ 18 \quad \text{for} \quad \eta = 0.5,\ 1,\ 1.5$$

[ASW 2004]

- More recent estimates

$$\hat{q} = \hat{q}_0\,\gamma_f\,(1 - v_f \cos\theta)$$

[Baier, Mueller, Schiff 2007;
Liu, Rajagopal, Wiedemann 2007]

- Large angle emission needs $\hat{q}_\eta \gg \hat{q}_\Phi$

$$\omega \lesssim \hat{q}_\eta^{1/3} \qquad \omega \gtrsim \hat{q}_\Phi^{1/3}$$

[More in A. Majumder's talk]

Summary

- A modified evolution of the jet shower is proposed
  - Medium-modified splitting function $\tilde{P}(z,t) = P(z) + \Delta P(z,t)$
  - Shower particles are softer and larger angle
  - Multiplicity enhances
- The quenching weights prescription is recovered for $Q \simeq E_{\rm jet}$
  - Check of the validity of the usual approach
- When the jet shape is dominated by one splitting non-trivial angular structures appear for opaque media
  - Possible origin of the experimental two-peak structures
  - More realistic analysis needed
- Flow fields expected to distort the jet shapes
  - Jet shapes trace flow fields in the medium