Jet shapes in opaque media

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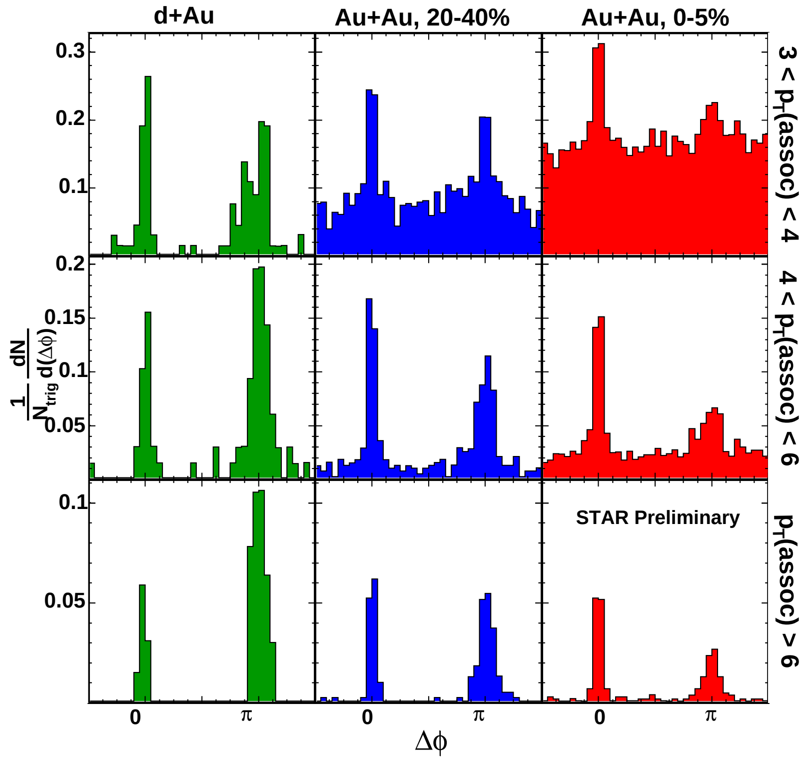
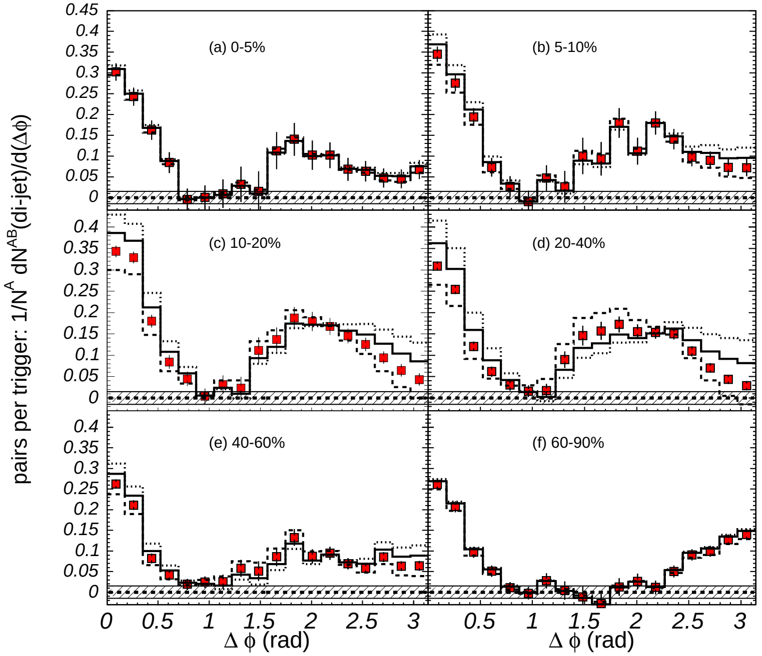
Some experimental facts

- ⇛ Strong suppression of high-p_t particles – large partonic energy loss
- ⇛ Reappearance of this energy as softer particles at large angle



[STAR 2006]

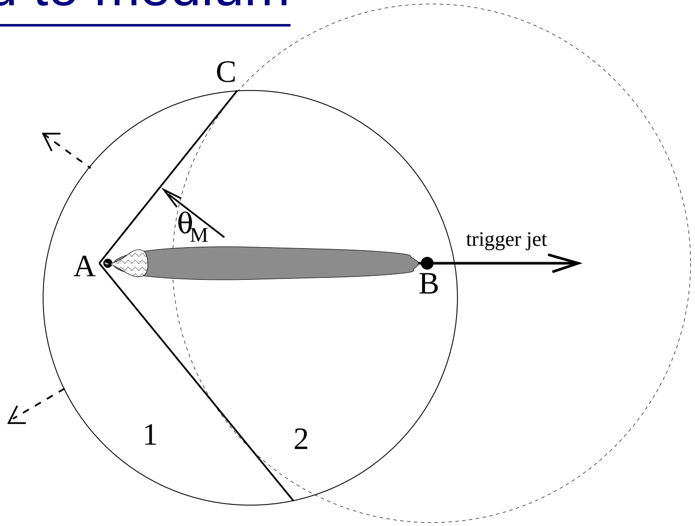


[PHENIX 2005]

Two opposite assumptions

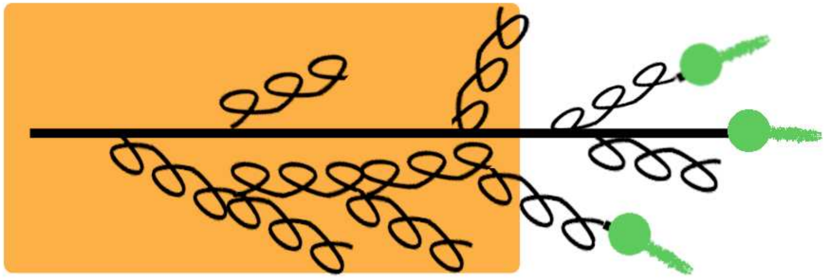
All lost energy is transferred to medium

- ⇛ Hydro evolution [Satarov, Stoeker, Mishustin 2005; Casalderrey-Solana, Shuryak, Teaney 2004]
- ⇛ Colored wakes [Muller, Ruppert, Renk 2006, Chakraborty, Mustafa, Thoma 2006]
- ⇛ Partonic transport [AMPT 2006]



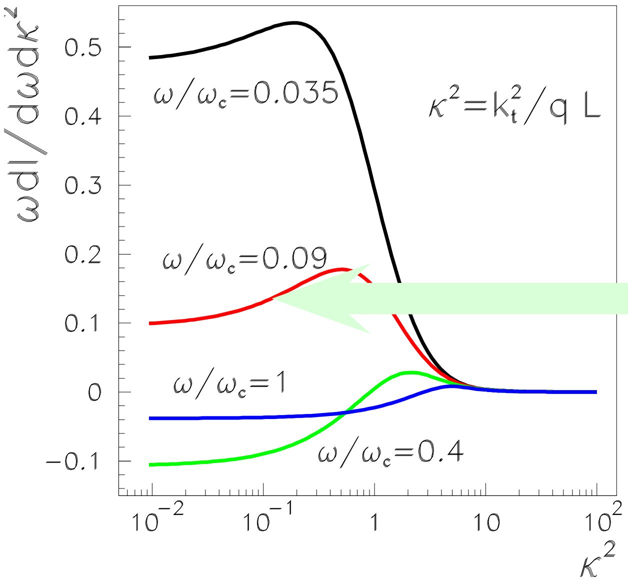
Negligible energy transferred: Energy loss is radiated as gluons

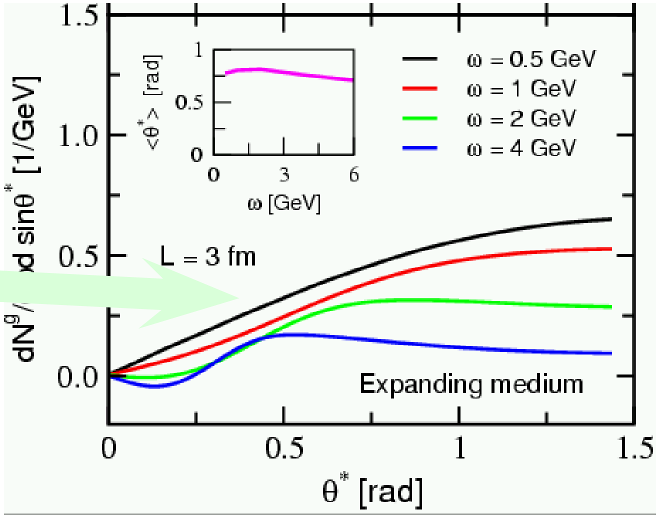
- ⇛ Cherenkov radiation [Dremin 2005; Koch, Majumder, Wang 2005]
- ⇛ Radiative energy loss [Polosa, Salgado 2006]



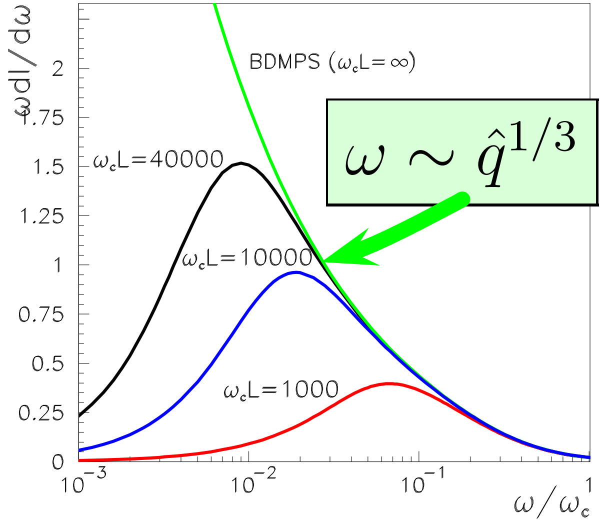
The Medium-induced gluon radiation spectrum

[BDMPS (1996); Zakharov (1997); Wiedemann (2000); GLV (2000)]





Coherence/
Formation time



$$\boxed{\omega \sim \hat{q}^{1/3}}$$

⇛ Medium: transport coefficient

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

⇛ Typical radiation angle $\Longrightarrow$ broadening

$$\sin\hat{\theta} \sim \sqrt{\sqrt{\frac{\hat{q}}{\omega^3}}}$$

⇛ $\hat{\theta}$ reaches phase space limit for $\omega \lesssim \hat{q}^{1/3}$

Need for exclusive distributions

In many experimental conditions exclusive distributions (for 1, 2,... gluons) are essential.

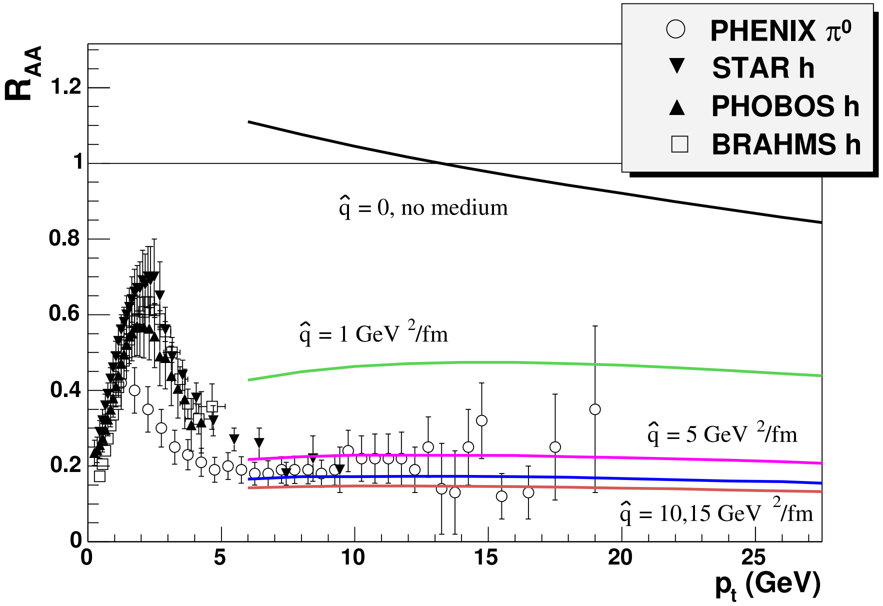
For example

- ⇛ When the energy loss is convoluted with a steeply falling spectrum – need to know exact amount of energy carried by a fixed number of gluons
  - ➘ Quenching weights used up to now
- ⇛ In two particle correlations with restrictive kinematical constrains
  - ➘ Ex. $2.5 < p_t^{\rm trigg} < 4GeV$ and $1 < p_t^{\rm assoc} < 2.5GeV$ – Energy conservation restricts the number of splittings to 1 or 2.

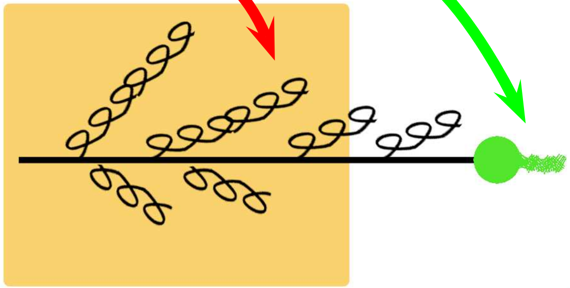
Our main goal is to construct these exclusive distributions for the medium–induced gluon radiation

R_{AA} for light mesons at RHIC

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



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



⇒ Multiple emission: Poisson distribution

⇒ Hadronization in vacuum at high-p_t

⇒ Data favors a large time-averaged transport coefficient

$$\boxed{\hat{q} \sim 5\ldots 15\frac{GeV^2}{fm}}$$

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

Improving the shower evolution

- ⇛ Independent gluon emission approximation: Quenching Weights

  [Baier, Dokshitzer, Mueller, Schiff 2001]

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

- ⇛ In the vacuum DGLAP evolution equations, or implemented in MC by Sudakov form factors

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

  giving the probability of no-branching

- ⇛ And the corresponding probability distribution for one branching

$$d\mathcal{P}(t, z) = \frac{dt}{t} \, dz \, \frac{\alpha_s}{2\pi} P(z) \, \Delta(t_{\rm max}, t) \theta(t_{\rm max} - t) \theta(t - t_{\rm min})$$

Improving the shower evolution II

Correspondence vacuum–medium

- ⇛ Inclusive distribution

$$\frac{dI^{\rm vac}}{dz dk_\perp^2} = \frac{\alpha_s}{2\pi}\frac{1}{k_\perp^2}P(z)$$

- ⇛ Medium–modified fragmentation functions computed as higher-twist corrections in nuclear-DIS [Guo, Wang 2000–2003]

$$\tilde{P}_{ji}(z,x,x_L,l_T^2) = P_{ji}(z) + \Delta P_{ji}(z,x,x_L,l_T^2)$$

Ansatz

- ⇛ Define the medium Sudakov form factors by making the change

$$\frac{dI^{\rm vac}}{dz dk_\perp^2} \longrightarrow \frac{dI^{\rm vac}}{dz dk_\perp^2} + \frac{dI^{\rm med}}{dz dk_\perp^2}$$

[Borghini, Wiedemann 2006 take $dI^{\rm med} \sim f_{\rm med}\, dI^{\rm vac}$]

Parton Shower for opaque media

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

$$\frac{dI^{\rm med}}{d\omega\, dk_t^2} \simeq \frac{\alpha_s C_R}{16\pi}\, L\, \frac{1}{\omega^2} \quad \Longrightarrow \quad \frac{dI^{\rm med}}{dz\, dk_t^2} \simeq \frac{\alpha_s C_R}{16\pi}\, L\, \frac{1}{E\, z^2}$$

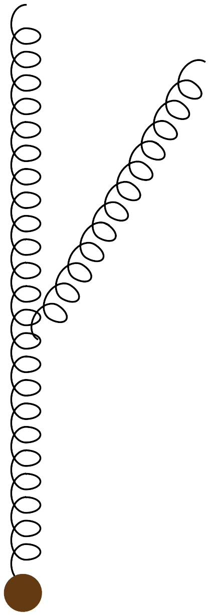
- The probability of only one splitting

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

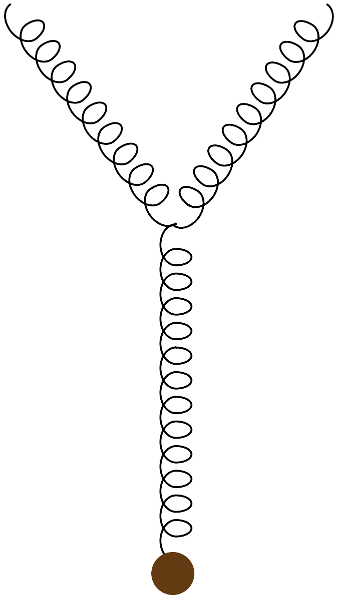
- Non-trivial angular dependence for the medium-induced gluon radiation. Two peaks in the laboratory variables η, Φ for ($\eta \simeq 0$)

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

Two simple configurations studied



J-configuration

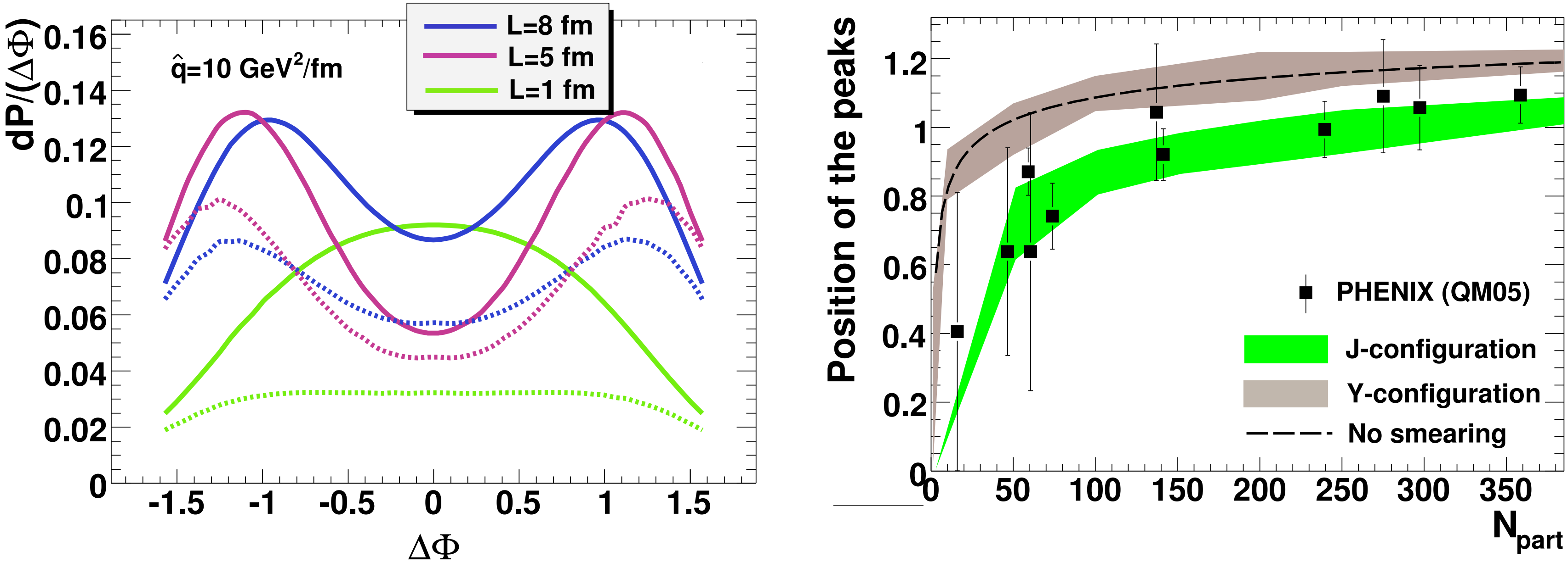


Y-configuration

A simple model to compare with data

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

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



[Polosa, Salgado hep-ph/0607295]

- ⇛ A perturbative mechanism, the medium-induced gluon radiation, is able to reproduce the observed 2-peak structure in the away side jet.

The picture

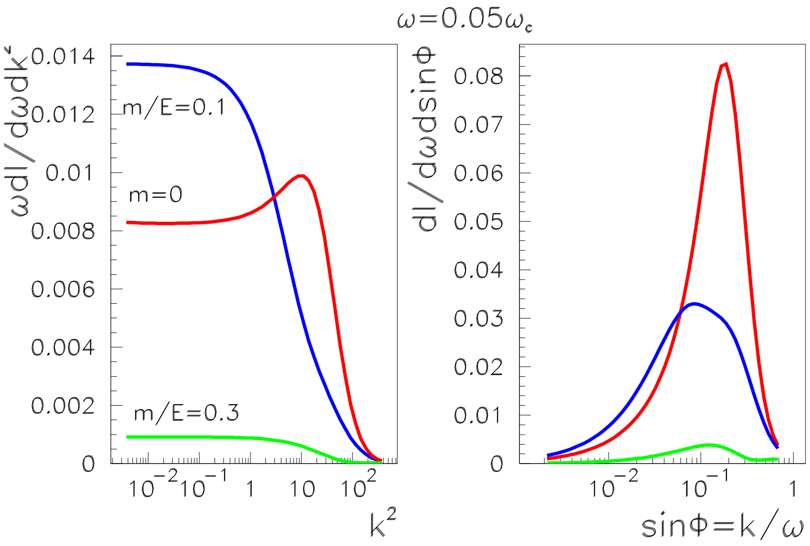
- The splitting probability in the medium presents two maxima in $\Delta\Phi$ for gluon energies $\omega \lesssim \hat{q}^{1/3} \sim$ 3 GeV for $\hat{q} \sim 10$ GeV^2/fm.
  - Using parton–hadron duality $p_t^{\mathrm{assoc}} \sim \omega$

Influence of kinematic constrains – STAR for concretenes

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

The massive case

⇒ Radiation is more collinear for massive quarks in the medium



⇒ The Sudakov suppression is also smaller

⇒ The double peak would dissapear at smaller values of $p_t^{\rm assoc}$

Conclusions and future research

- We have presented simple analytical estimates of the medium–induced splitting probability.
  - When $\omega \lesssim \hat{q}^{1/3}$ double peak structure appears
- We propose that this finding could explain the shape of the away-side azimuthal correlations in central collisions within the radiative energy loss formalism

Future plans

- Our analysis makes simplifying assumptions – spectrum, z-integration, vacuum contribution
- Improving this situation would need of a full MC simulation
  - Role of number of splittings
  - Role of hadronization
  - Vacuum contribution