Suppression of heavy flavors at RHIC & LHC

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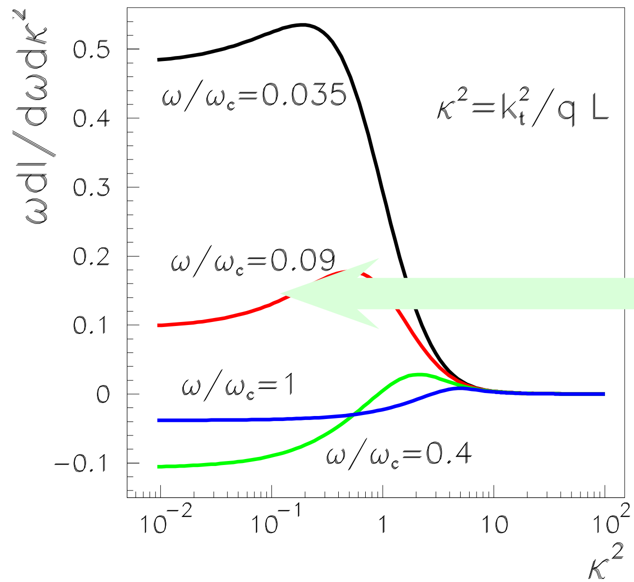
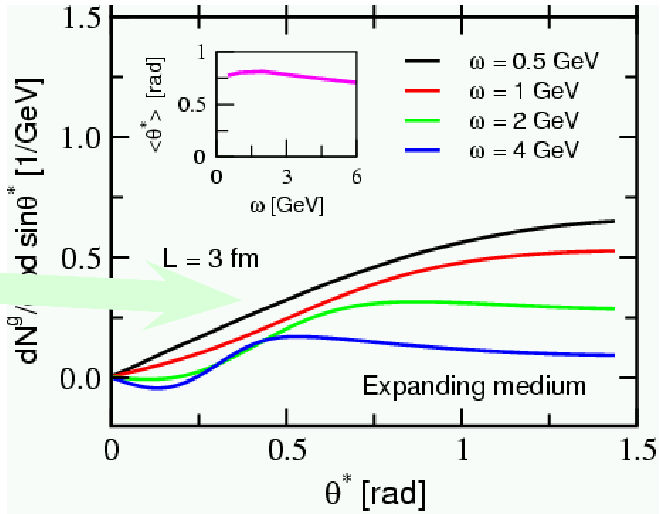
Massless case

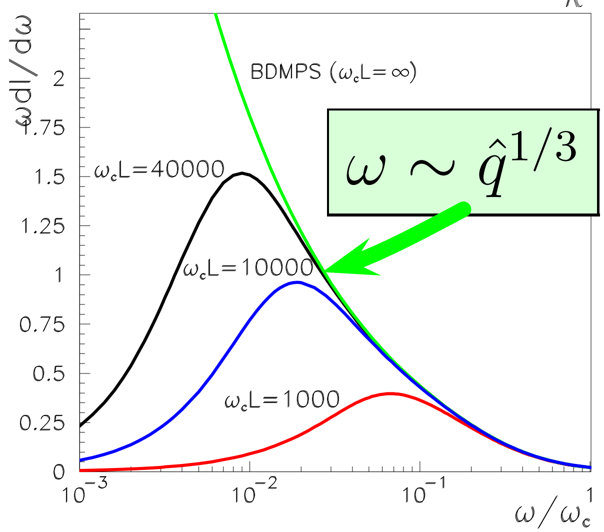
The Medium-induced gluon radiation spectrum

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



Coherence/
Formation time





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

⇛ Medium: transport coefficient

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

⇛ C_R=4/3 for quarks; C_R=3 for gluons

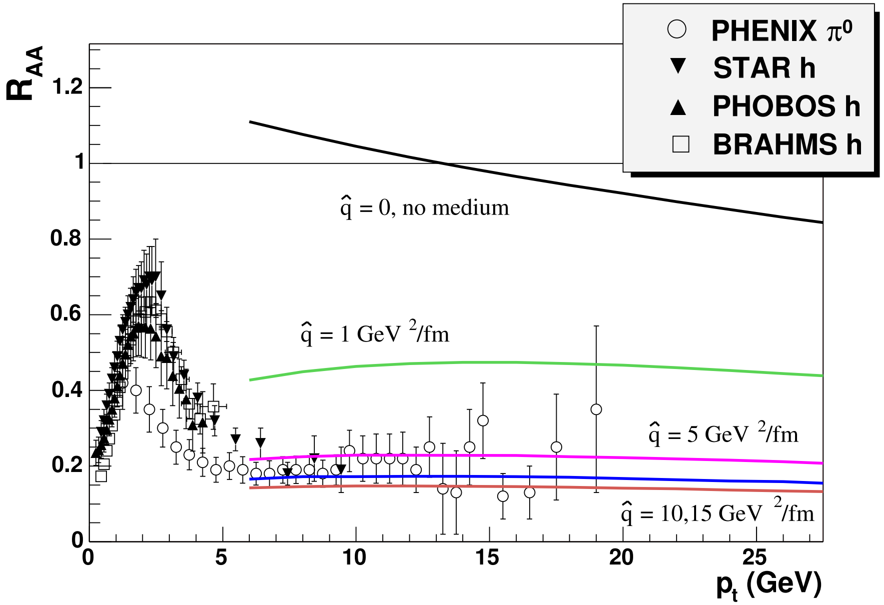
➘ More Energy loss for gluons

⇛ Typical radiation angle $\Longrightarrow$ broadening

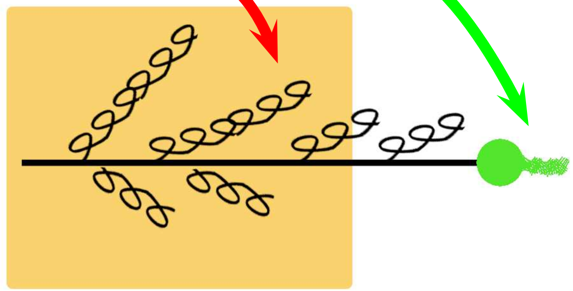
$$\sin\hat{\theta} \sim \sqrt{\sqrt{\frac{\hat{q}}{\omega^3}}}$$

R_{AA} for light mesons at RHIC

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



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



⇛ Multiple emission: Poisson distribution

⇛ Hadronization in vacuum at high-p_t

⇛ Data favors a large time-averaged transport coefficient

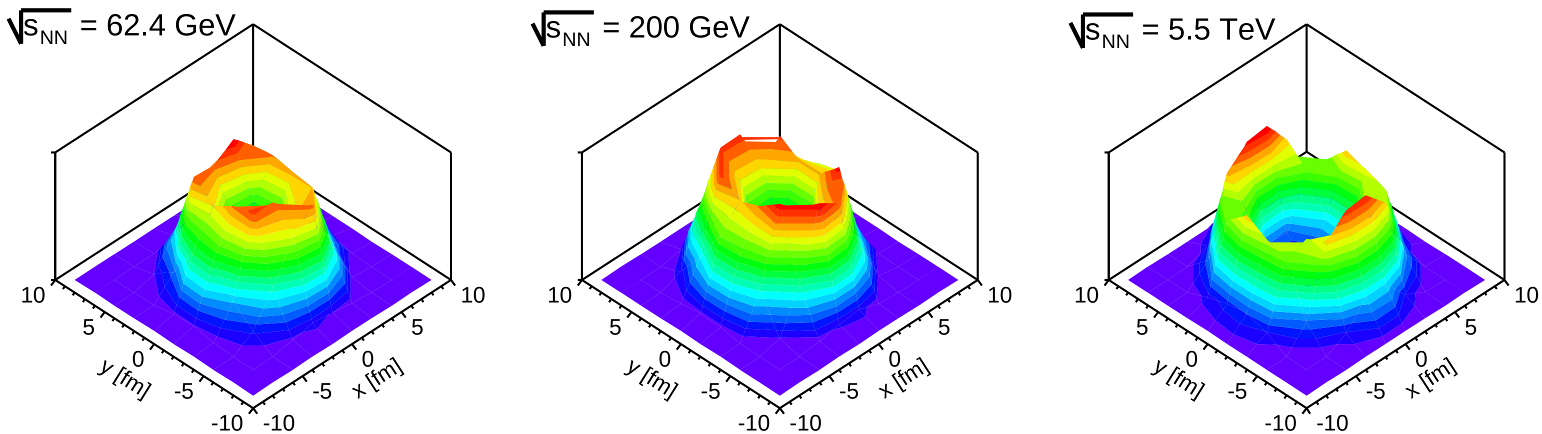
$$\hat{q} \sim 5 \ldots 15 \frac{GeV^2}{fm}$$

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

Surface emission

The medium produced at RHIC is so dense that only particles produced close to the surface can escape [Muller (2003)]

[Dainese, Loizides, Paic (2004); Eskola, Honkanen, Salgado, Wiedemann (2004)]



⇛ Inclusive particle production dominated by surface effects at RHIC

- Complementary study of the underline dynamics needs of additional well established observables

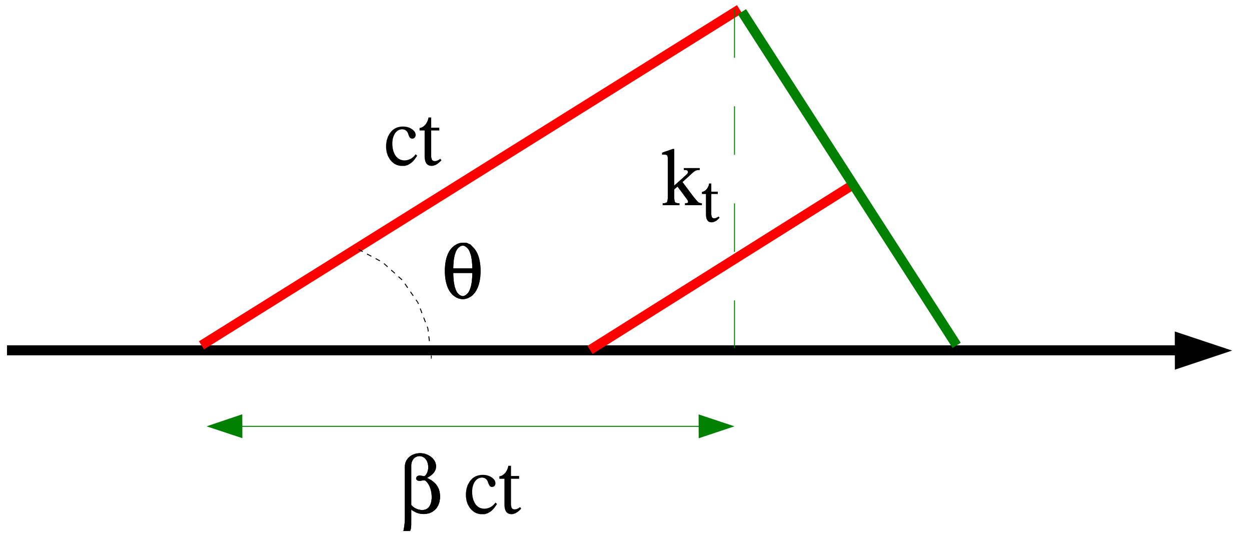
⇛ Change particle identity – heavy quarks $\longrightarrow$ novel opportunities

- Different energy loss
- Different (extended) jet structure

Heavy quarks

Vacuum radiation: Dead cone effect

$$\sin^2\theta_0 = 1-\beta^2 = \left(\frac{m}{E}\right)^2$$



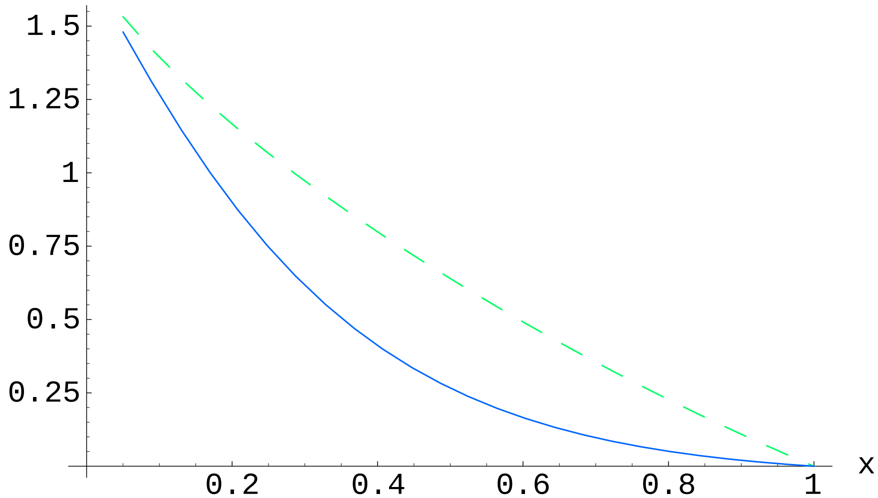
Dead cone effect Angles smaller than $\theta_0 \equiv m/E$ are suppressed in vacuum radiation [Dokshitzer, Khoze, Troyan (1991)]

$$\omega\frac{dI_{\rm vac}}{d\omega dk_t^2} \sim \frac{1}{k_t^2} \quad \longrightarrow \quad \omega\frac{dI^m_{\rm vac}}{d\omega dk_t^2} \sim \frac{k_t^2}{\left[k_t^2+\omega^2\theta_0^2\right]^2}$$

Heavy quark energy loss

⇛ Dokshitzer & Kharzeev 2001 took $\theta \sim \left(\frac{\hat{q}}{\omega^3}\right)^{1/4}$

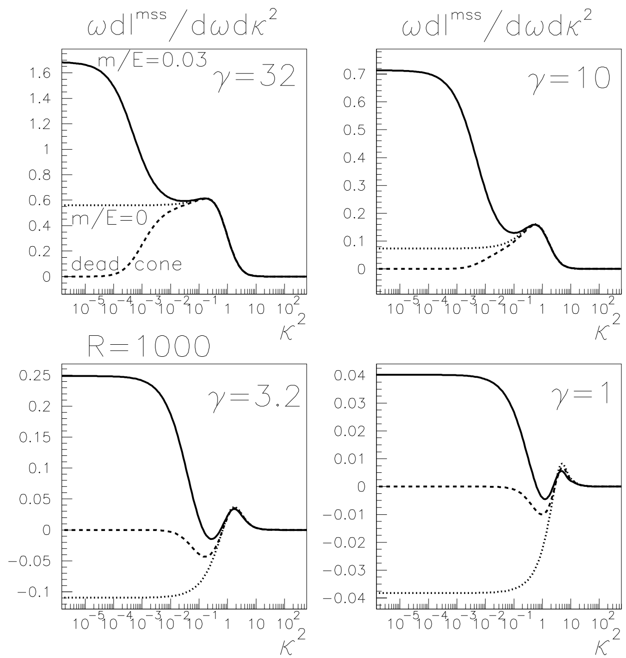
$$\omega \frac{dI_{\mathrm{med}}^{\mathrm{mass}}}{d\omega} = \frac{1}{\left(1+\frac{\theta_0^2}{\theta^2}\right)^2}\,\omega \frac{dI_{\mathrm{med}}^{\mathrm{m=0}}}{d\omega}$$



⇛ Medium-induced gluon radiation is reduced in the mass case $\Longrightarrow$ less energy loss for heavy than for light quarks.

Medium-induced gluon radiation: massive case

⇛ More refined calculations of the double differential spectrum of heavy quarks reveal a richer structure



[Armesto, Salgado, Wiedemann (2004)]

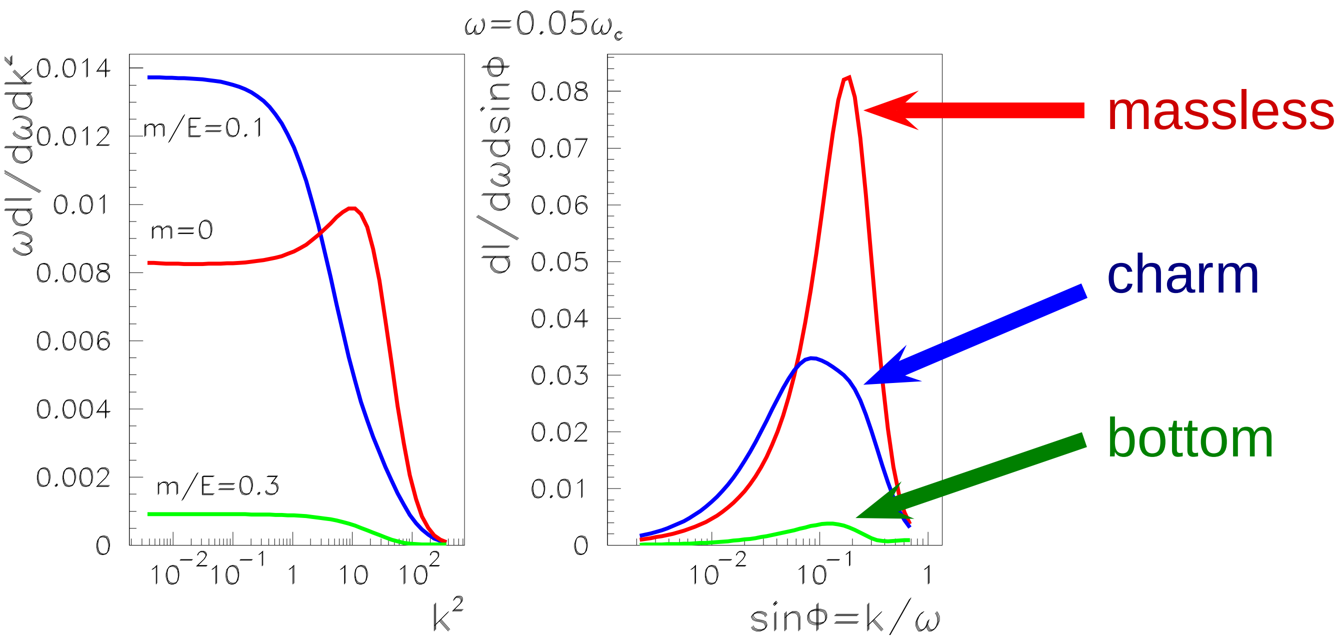
⇛ New phase term in the massive case:

$$\varphi = \left\langle \frac{k_\perp^2}{2\omega}\,\Delta z \right\rangle \longrightarrow \left\langle \frac{k_\perp^2}{2\omega}\,\Delta z + \bar{q}\,\Delta z \right\rangle ;\ \bar{q} \simeq \frac{x^2 M^2}{2\omega} ;\ \left[x = \frac{\omega^2}{E^2} \right]$$

[Similar results: Djordjevic, Gyulassy (2003); Zhang, Wang, Wang (2004)]

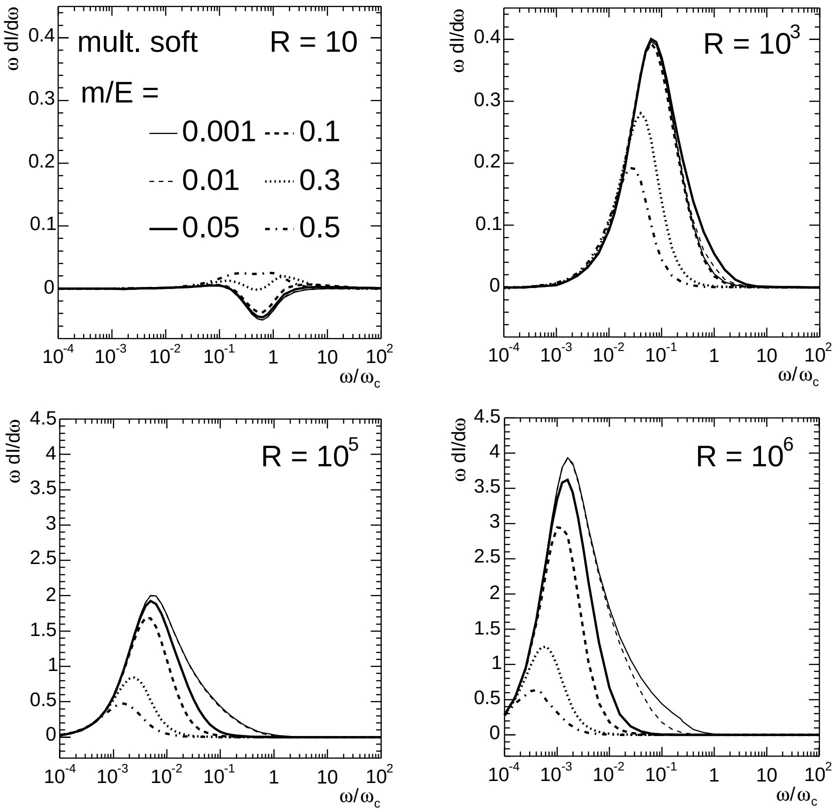
Angular dependence

- The angular distribution of medium–induced gluons depends on the mass



- The effect of the mass in the medium case is
  - Suppress radiation at large angle
  - Enhance (moderately) at small angle
- Net effect: the energy loss is smaller in the massive case

Induced–gluon energy distribution

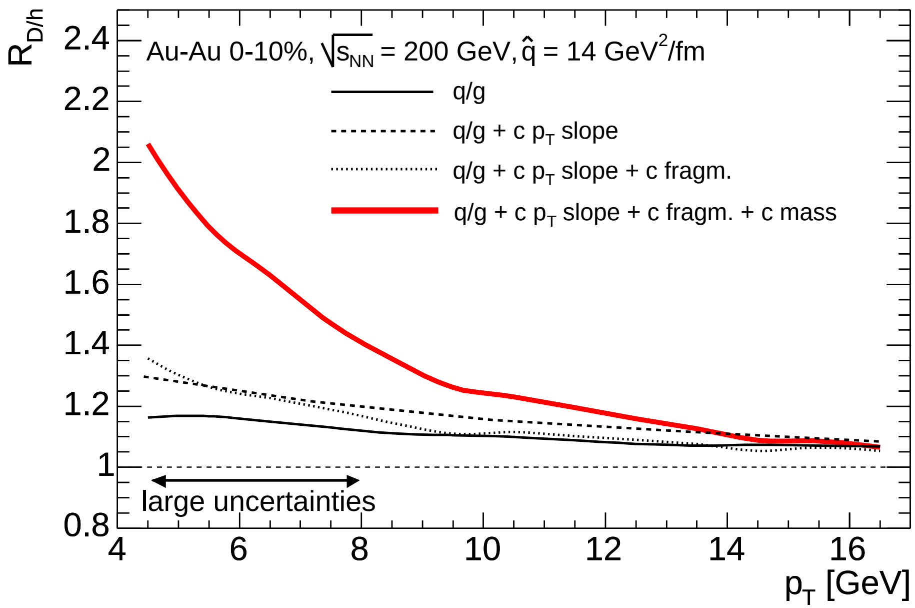


$$R \equiv \omega_c \, L$$

⇒ The effect of the mass increases with the length L

↘ Implementation of correct geometry essential

Heavy-to-light ratios at RHIC

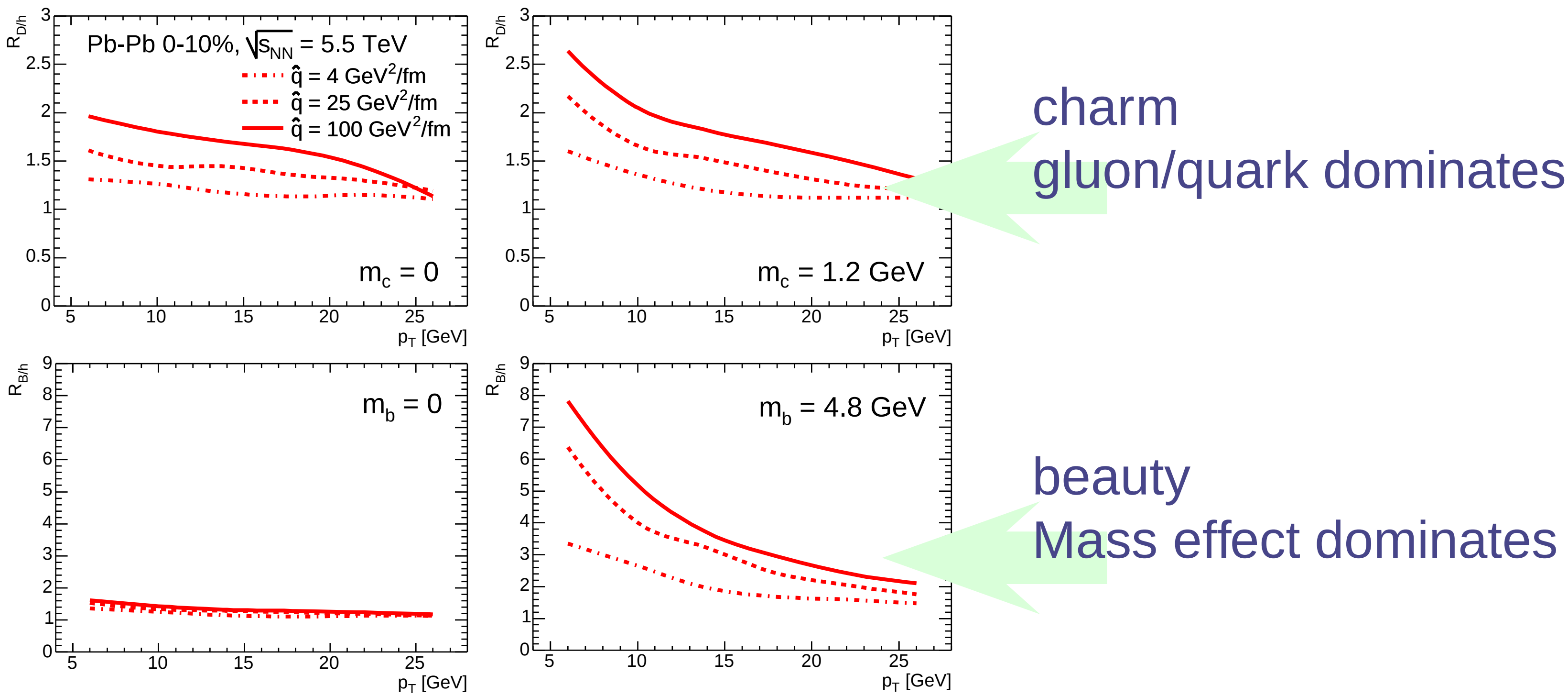


[Armesto,Dainese,Salgado,Wiedemann 2005]

- Quark vs gluon energy loss: $\Delta E^g = N_C/C_F \Delta E^{q,\mathrm{m}=0}$
  - Increases $R_{D/h}$
- Light-particle spectrum slope larger than massive one
  - Increases $R_{D/h}$
- charm fragmentation harder
  - Decreases $R_{D/h}$
- Heavy quark suppression of gluon radiation ('dead-cone')
  - Increases $R_{D/h}$

Heavy-to-light ratios at the LHC

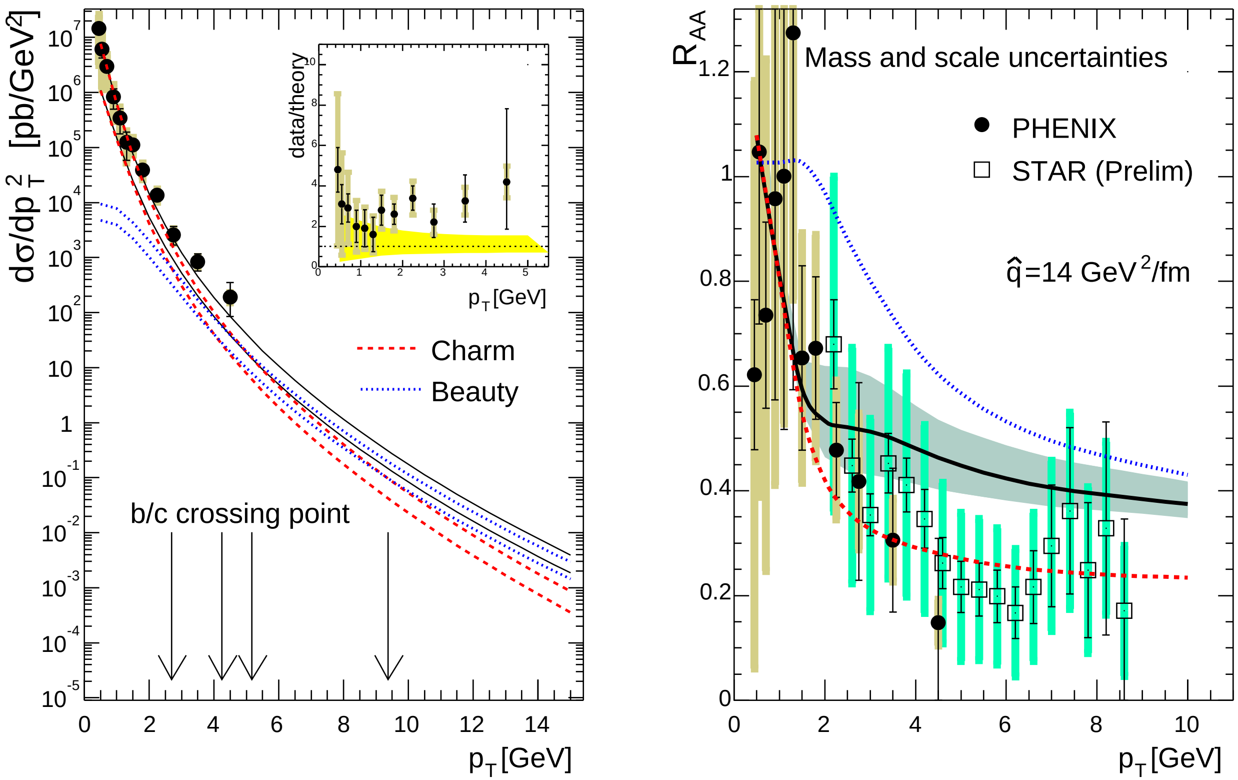
D/h and B/h ratios for the LHC



[Armesto, Dainese, Salgado, Wiedemann (2005)]

Non-photonic electron spectrum at RHIC

⇛ New data from STAR and PHENIX (QM05) for non-photonic electrons



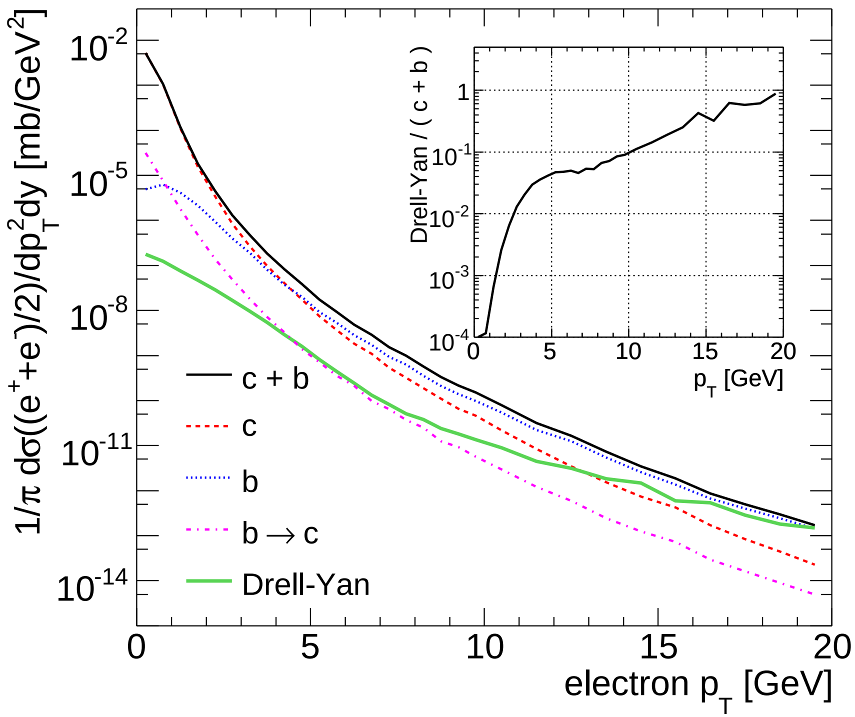
[Armesto, Cacciari, Dainese, Salgado, Wiedemann 2005]

⇛ Perturbative benchmark NOT well understood

⇛ Experimental separation c/b

Uncertainty for other sources

⇛ Drell–Yan contribution

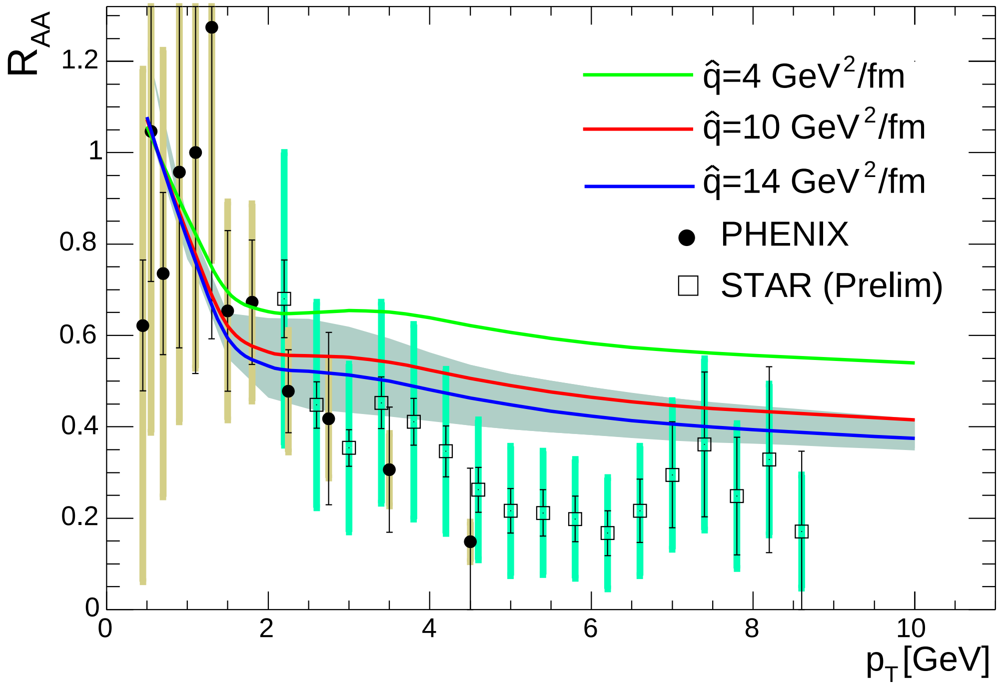


[Armesto, Cacciari, Dainese, Salgado, Wiedemann 2005]

⇛ Drell-Yan negligible for $p_t^e \lesssim 10$ GeV

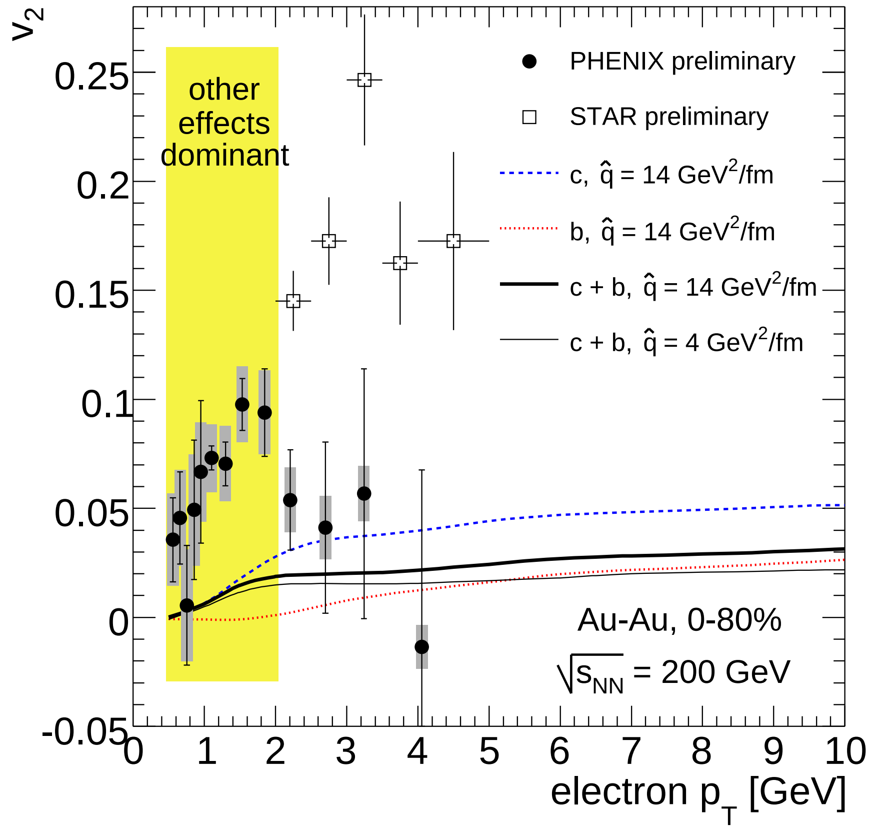
Uncertainty from $\hat{q}$

⇛ Similar effects as seen in light $\longrightarrow$ surface-dominated suppression



⇛ Uncertainty in $\hat{q}$ within the uncertainty in the perturbative baseline

v_2 for electrons at RHIC

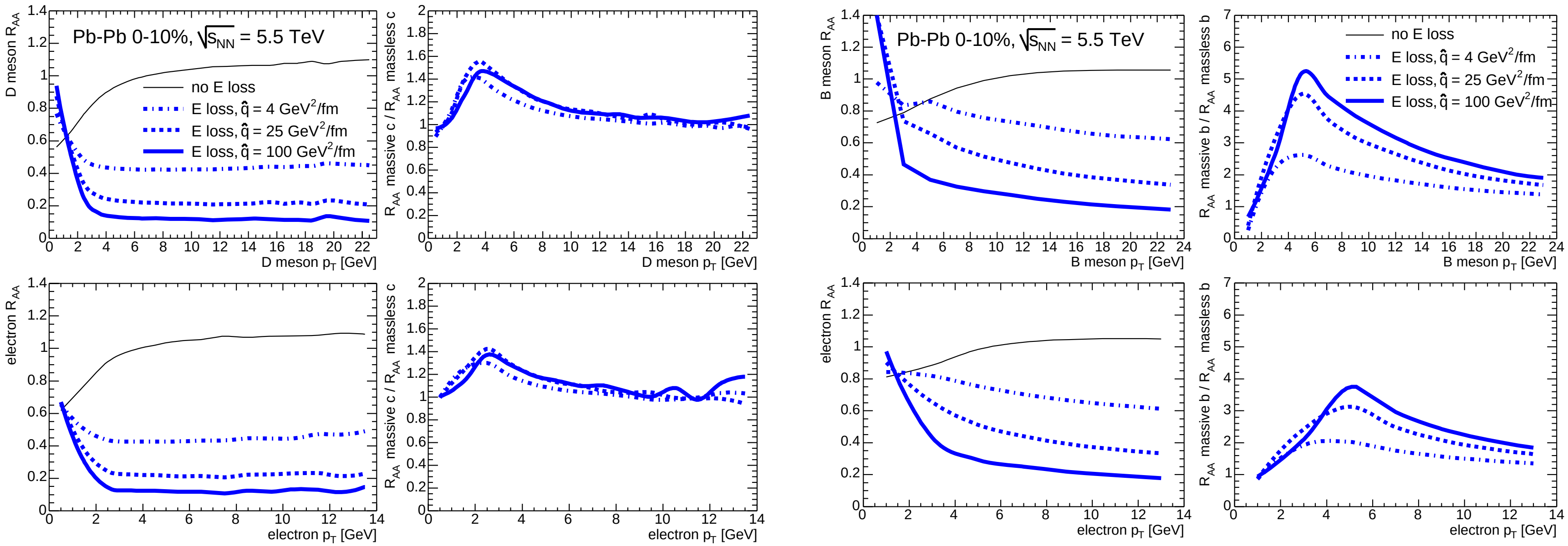


[Armesto, Cacciari, Dainese, Salgado, Wiedemann]

Extrapolations to the LHC

⇛ Extrapolation according to the expected density ($\hat{q} \propto$ density)

⇛ Range from $\sim$ 2...7 for various saturation models.

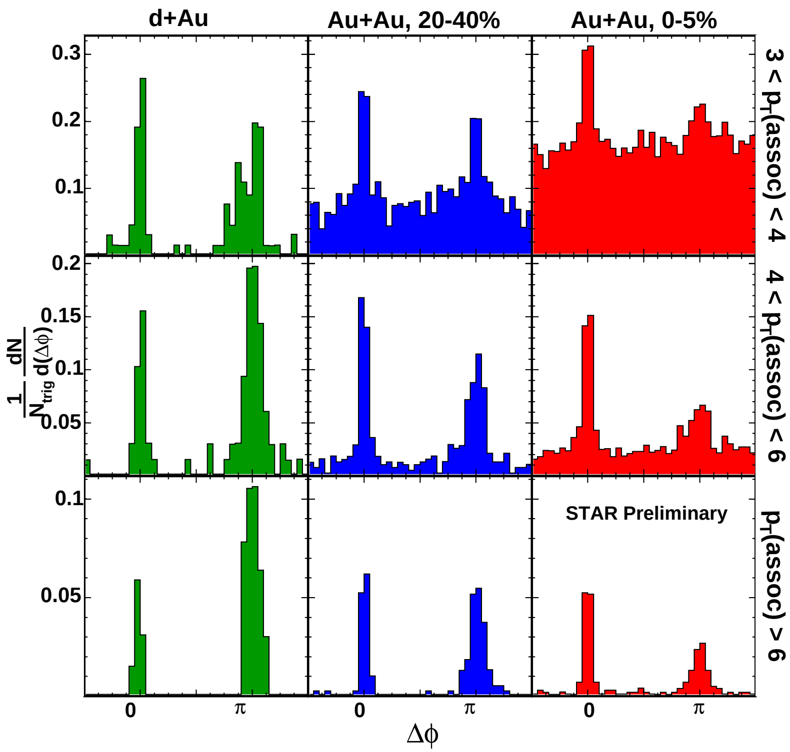


[Armesto, Dainese, Salgado, Wiedemann (2005)]

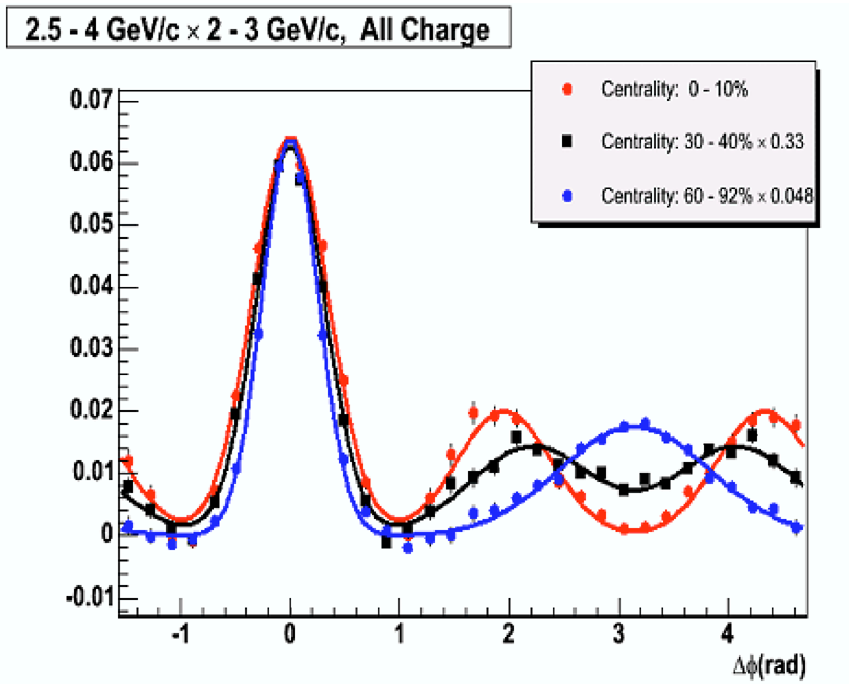
Angular distributions

Angular structure for light

Angular structure far from being trivial...



[STAR Collaboration 2006]



[PHENIX Collaboration 2005]

⇒ Cannot be understood if inclusive medium-induced spectrum is used [Vitev 2005]

Improving the shower evolution

- Beyond the independent (Poisson) gluon emission
  - Include virtuality evolution
  - Include possibility of secondary branching...
- 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

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

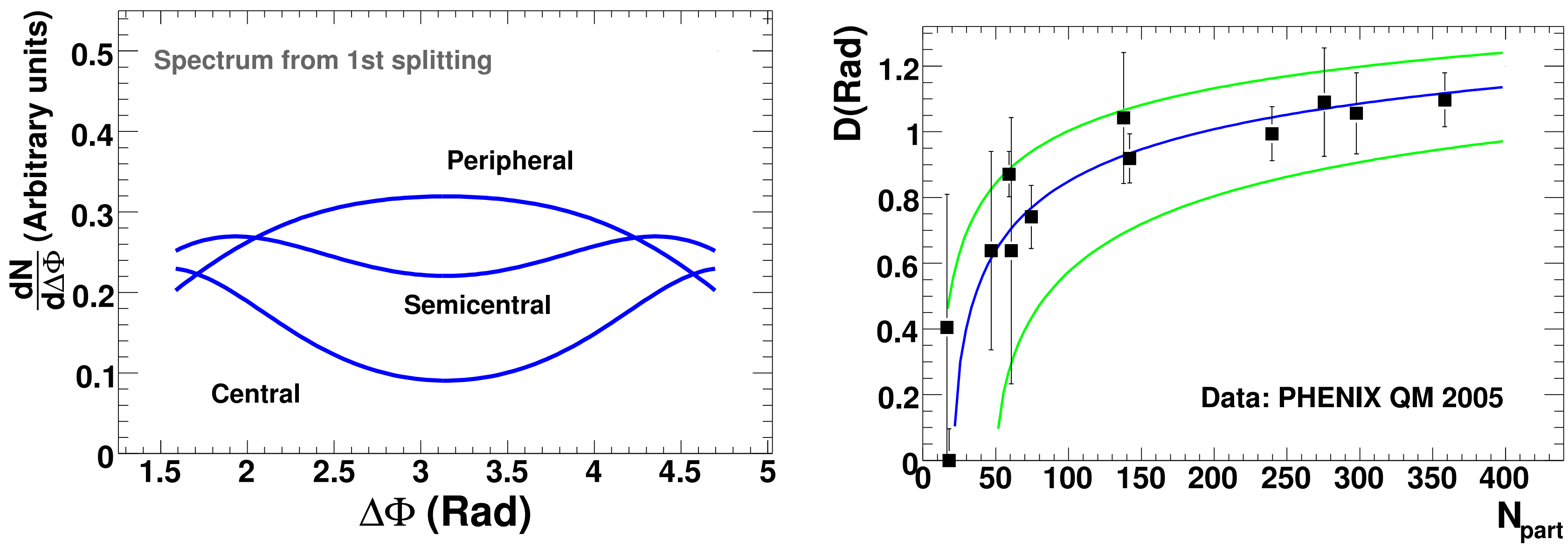
$$\tilde{P}_{ji}(z, x, x_L, l_T^2) = P_{ji}(z) + \Delta P_{ji}(z, x, x_L, l_T^2)$$

- $\Delta P_{ji}(z, x, x_L, l_T^2)$ is the medium modification

Parton Shower for opaque media

- When $p_t^{\rm assoc} \sim \omega \lesssim \hat{q}^{1/3} \sim 3$ GeV $\longrightarrow$ Large $\hat{q}$ needed
  - totally coherent limit and large angle radiation
- The probability of only one splitting

$$d\mathcal{P} \sim dz\, d\theta \sin\theta (1+\cos\theta) \exp\left\{ -A \left[\cos\theta + \frac{\cos^2\theta}{2} \right] \right\}$$

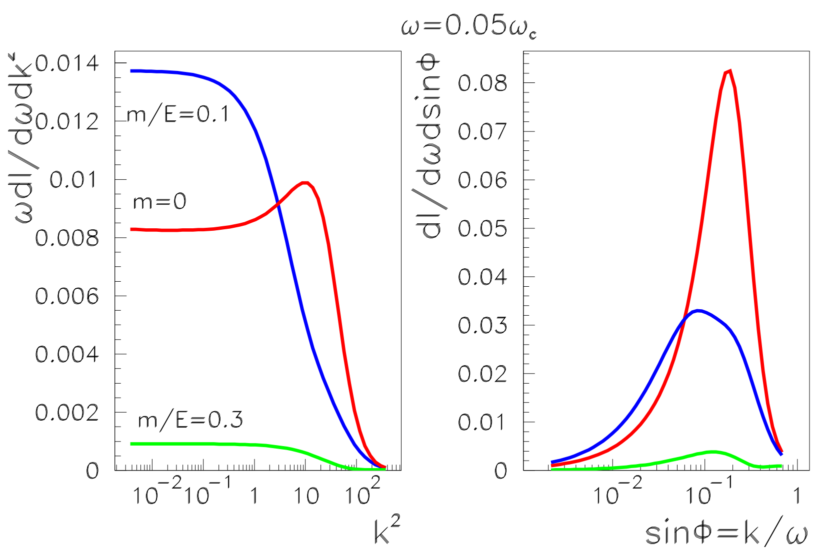


(Smearing included)

Maiani, Polosa, Salgado; work in progress

The massive case

- Picture for $m = 0$: double-peak structure for $p_t^{\rm assoc} \lesssim \hat{q}^{1/3}$
  - Increasing the number of spplitings the dip tends to be filled
- Radiation is more collinear for massive quarks in the medium



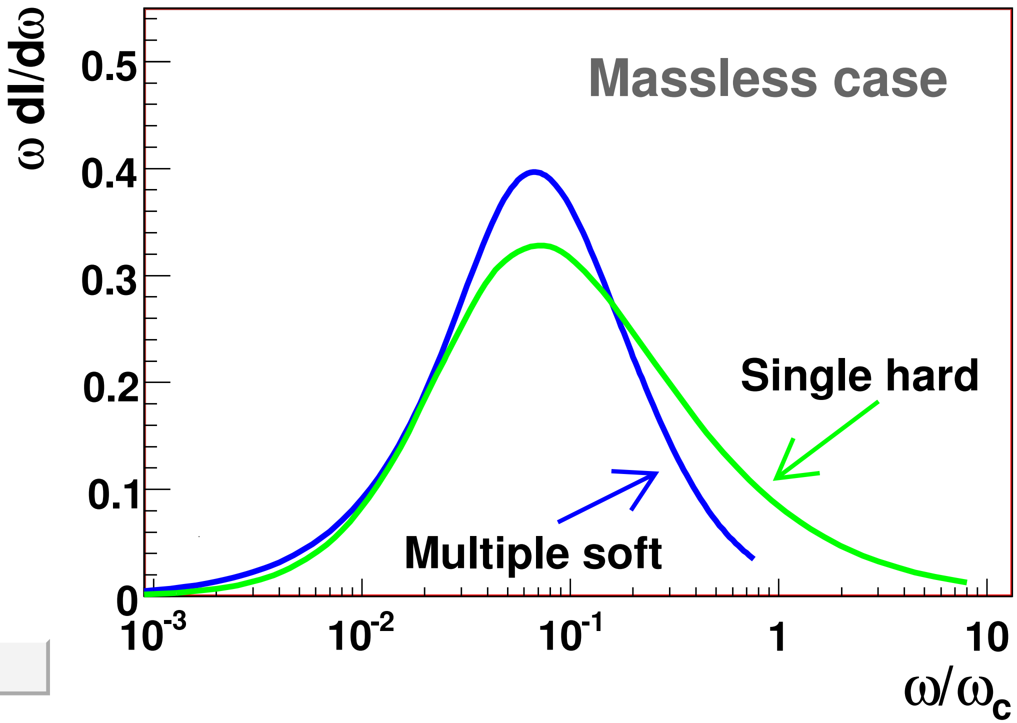
- The double peak would dissapear at smaller values of $p_t^{\rm assoc}$

Summary

- ⇛ Medium-induced gluon radiation is the standard explanation of high-p_t inclusive particle suppression. $\longrightarrow$ More observables needed
- ⇛ Heavy quarks
  - Study particle and mass dependences of energy loss with heavy-to-light ratios.
  - Small effect for charm
- ⇛ No clear dissagreement found with non-photonic electrons at RHIC
  - More clear c/b separation needed
  - Understand proton-proton data first !
- ⇛ Non trivial angular structure of medium induced gluon radiation for $p_t^{\rm assoc} \lesssim \hat{q}^{1/3}$ for the massless case
  - Provide a perturbative mechanism for away-side structures
  - Effect dissapears faster for HQ (more collinear radiation)

Differences in medium–model

⇛ Radiation in the single hard scattering approximation is harder than in the multiple soft scattering.



⇛ Mass effects cut the large part of the spectrum

- Mass effects less important in multiple soft scattering