Particules de grandes impulsions transverses au RHIC

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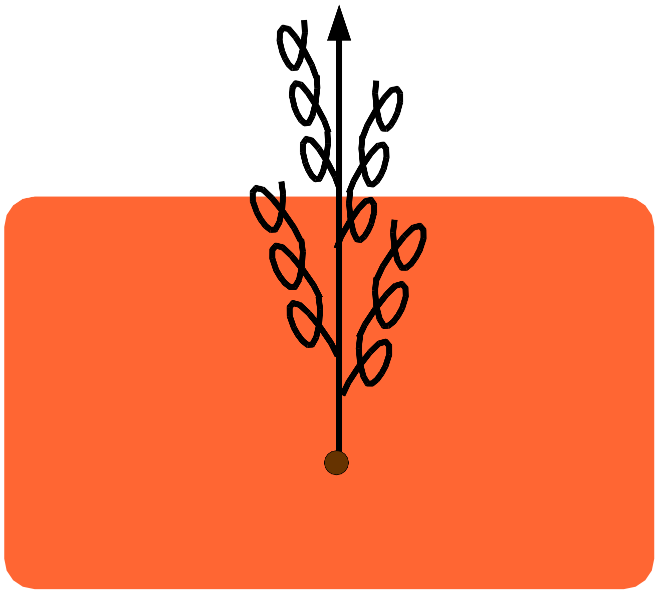
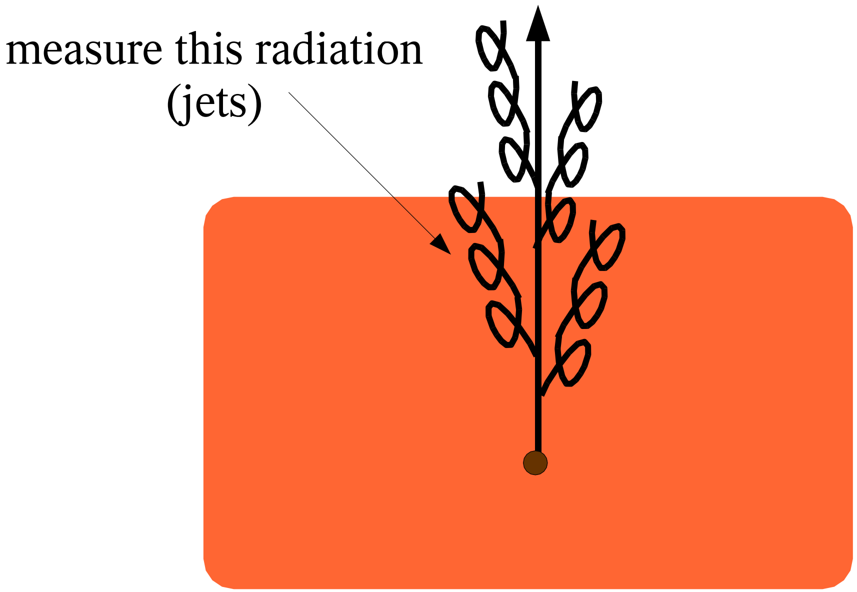
Jet quenching



⇛ Suppression of light particles at high-p_t observed at RHIC.

- Well described by energy loss due to medium-induced gluon radiation
- Problems: surface emission, trigger bias...

Jet quenching



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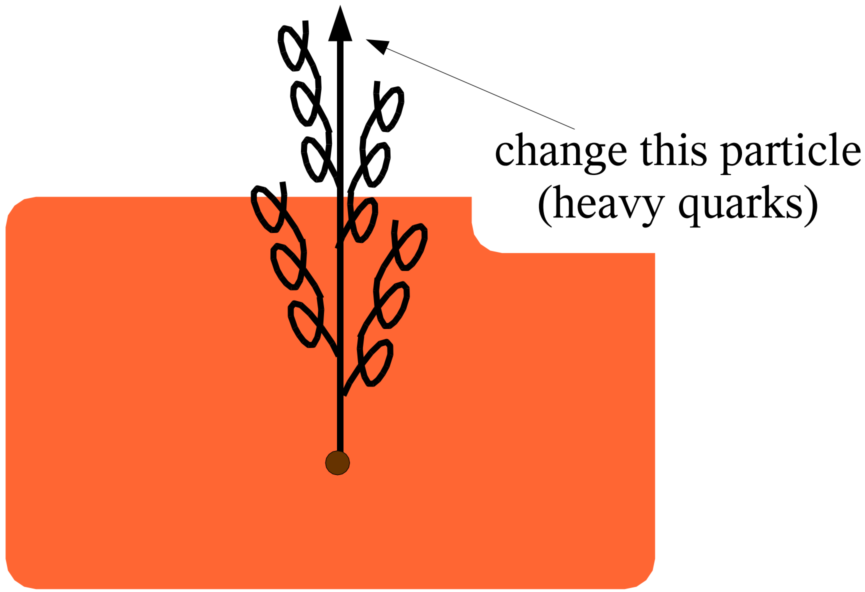
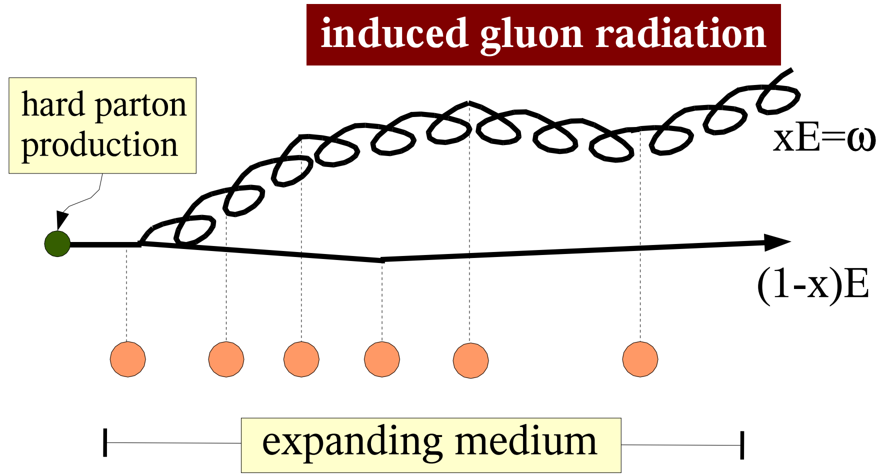
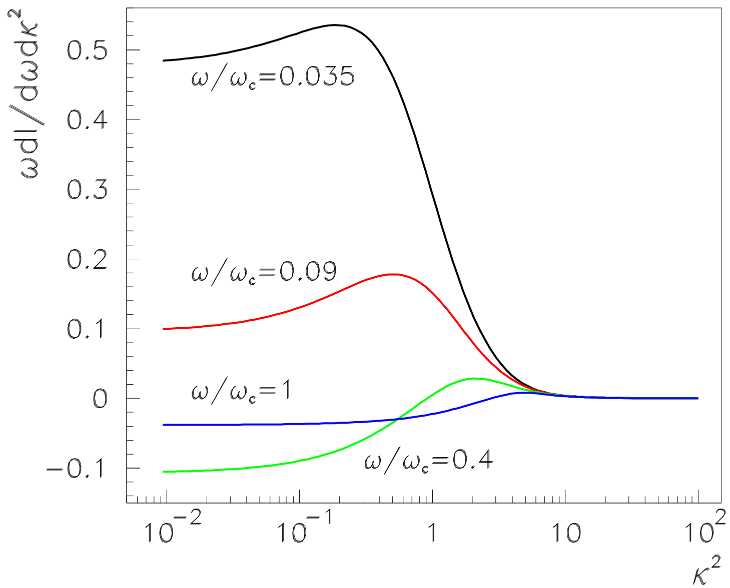
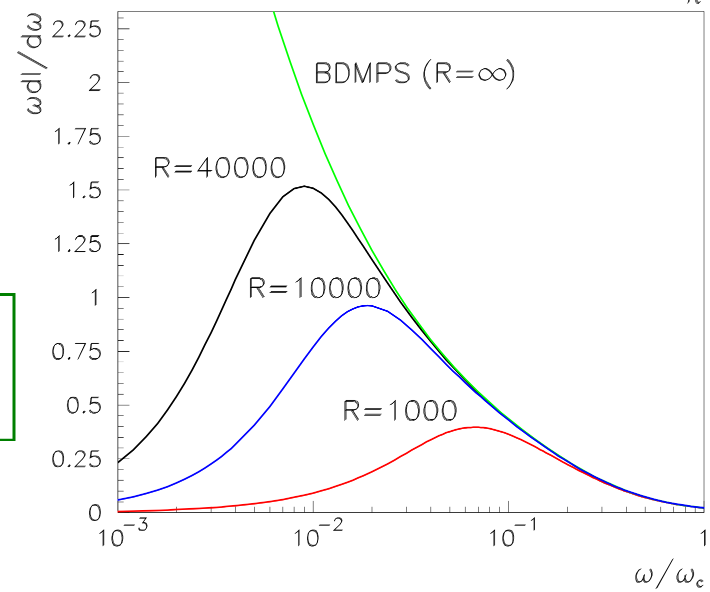


- Suppression of light particles at high-p_t observed at RHIC.
  - Well described by energy loss due to medium-induced gluon radiation
  - Problems: surface emission, trigger bias...
- Measure the structure of radiated particles $\rightarrow$ jets
- Change the composition of the primary $\rightarrow$ heavy quarks

Medium–induced gluon radiation (m=0)







Medium properties: length L,
transport coefficient $\hat{q} \sim \frac{\mu^2}{\lambda}$

⇒ $k^2_{\perp,\,\max} \sim \hat{q}L$; $\boxed{\kappa^2 \equiv k^2_\perp/\hat{q}L}$

⇒ Accumulated phase

$$\varphi = \left\langle \frac{k^2_\perp}{2\omega}\Delta z \right\rangle \sim \kappa^2\,\frac{\omega_c}{\omega}; \quad \boxed{\omega_c \equiv \frac{1}{2}\hat{q}L^2}$$

Rad. suppressed by coherence

$$\varphi \lesssim 1 \Longleftrightarrow \kappa^2 \lesssim \omega/\omega_c$$

Angular distribution

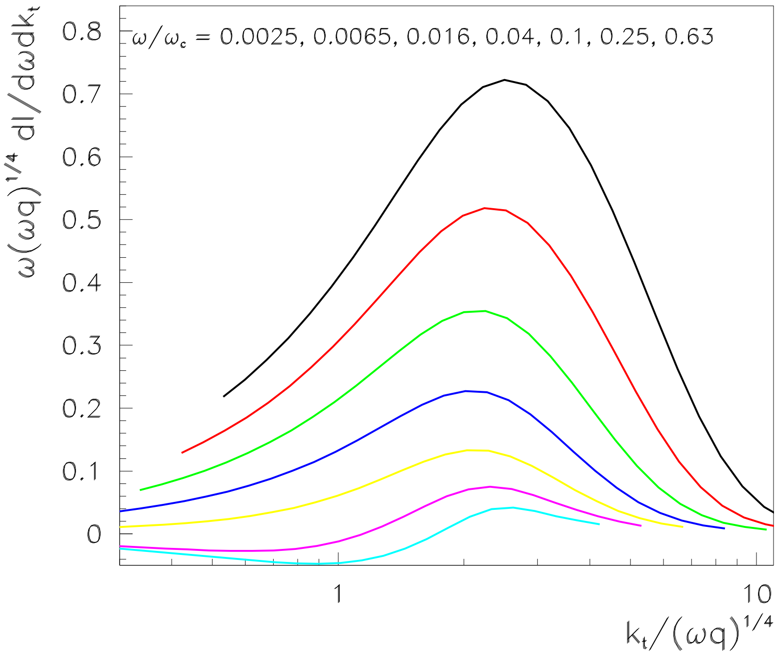
The same spectrum in different variables ω/ω_c, $k_t^2/\sqrt{\omega\hat{q}}$

Heuristic argument

$$t_{\rm form} \sim \frac{\omega}{k_t^2} \quad k_t^2 \sim \mu^2 \frac{t_{\rm form}}{\lambda}$$

The transport coefficient is defined as $\hat{q} = \frac{\mu^2}{\lambda}$

$$k_t^2 \sim \hat{q}\, t_{\rm form} \implies k_t^2 \sim \sqrt{\omega\hat{q}}$$

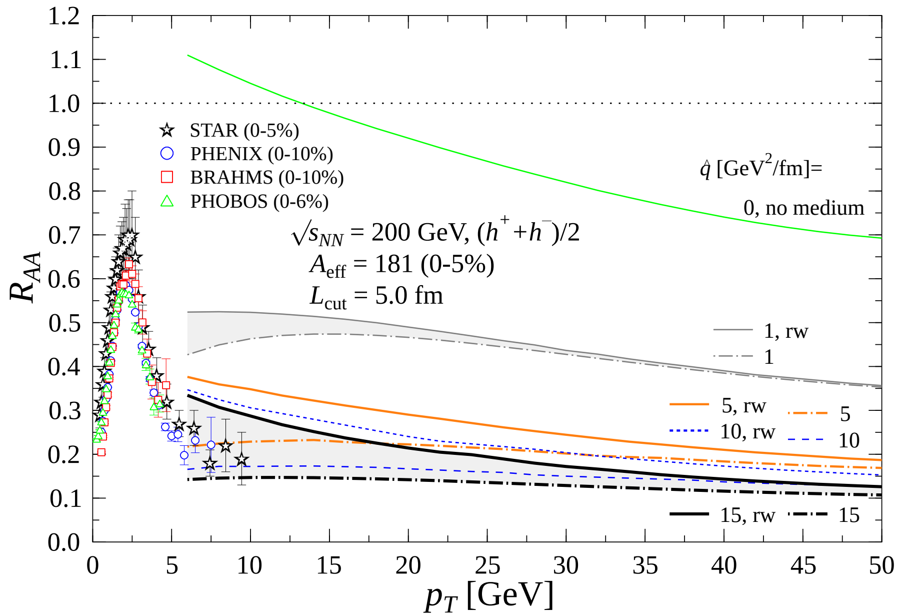


So the radiation is suppressed for

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

Application of the formalism

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



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

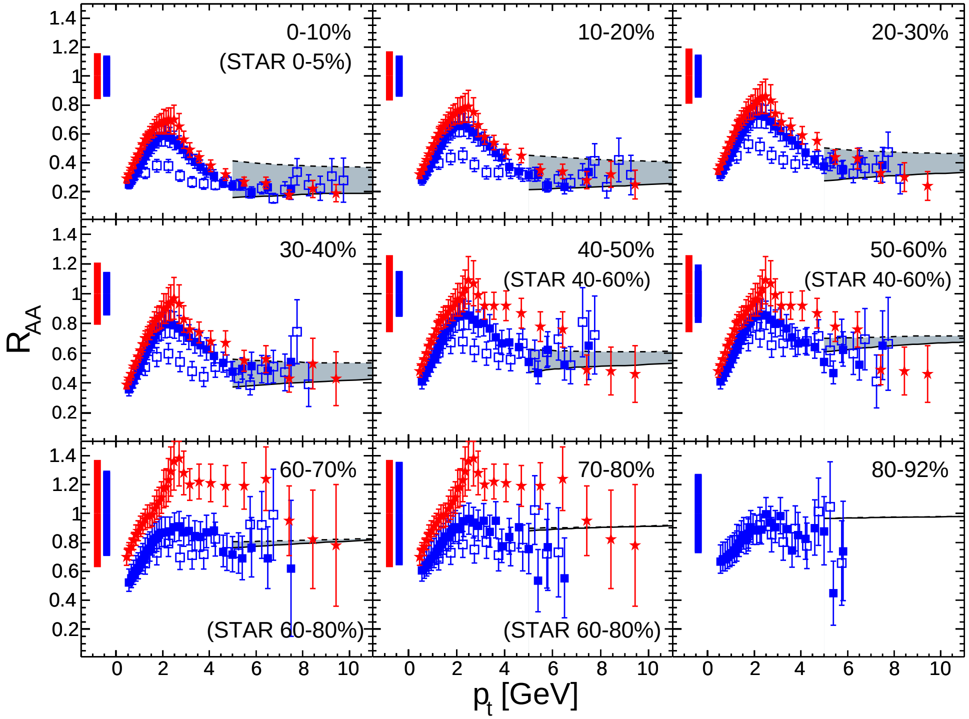
⇛ Data favors a large time-averaged transport coefficient

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

[Many other groups describe these data: Gyulassy, Levai, Vitev, Wang, Drees, Feng, Jia, Arleo, Dainese, Loizides, Paic...]

Centrality dependence

$\hat{q} \propto$ density



[Dainese, Loizides, Paic (2005)]

Opacity problem

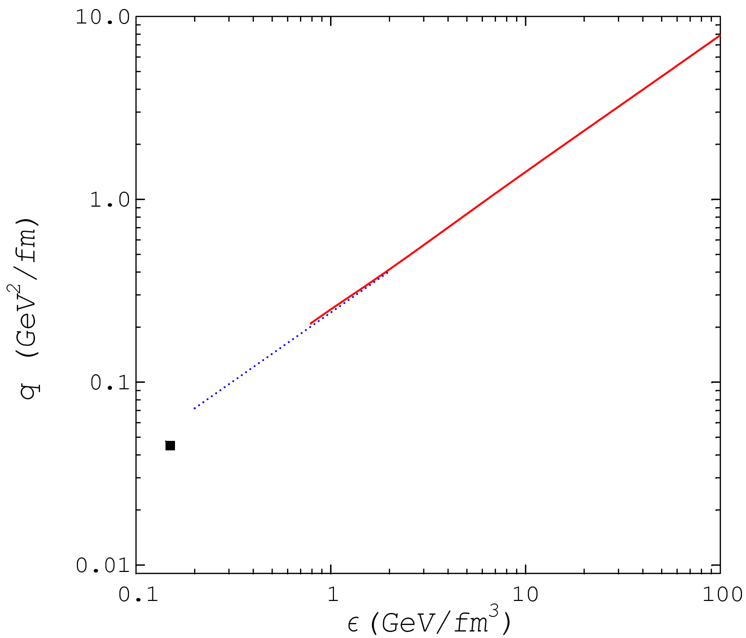
- $\hat{q} = c\epsilon^{3/4}$ for an ideal QGP $c_{ideal}^{QGP} \sim 2$
- We obtain [Eskola, Honkanen, Salgado, Wiedemann (2004)]

$$\bar{\hat{q}} = \frac{2}{L^2}\int_{\tau_0}^{\tau_0+L} d\tau(\tau-\tau_0)\hat{q}(\tau) \Longrightarrow$$

$$c = \frac{\hat{q}}{\epsilon^{3/4}(\tau_0)}\frac{2-\alpha}{2}\left(\frac{L}{\tau_0}\right)^{\alpha} \Rightarrow \boxed{c > 5c_{ideal}^{QGP}}$$

[taking $\epsilon(\tau_0) < 100\frac{\text{GeV}}{\text{fm}^3}$, $L/\tau_0 \sim 10$, $\alpha = 1$]

- Remember $\hat{q}$ proportional to the density times cross section $\Rightarrow$



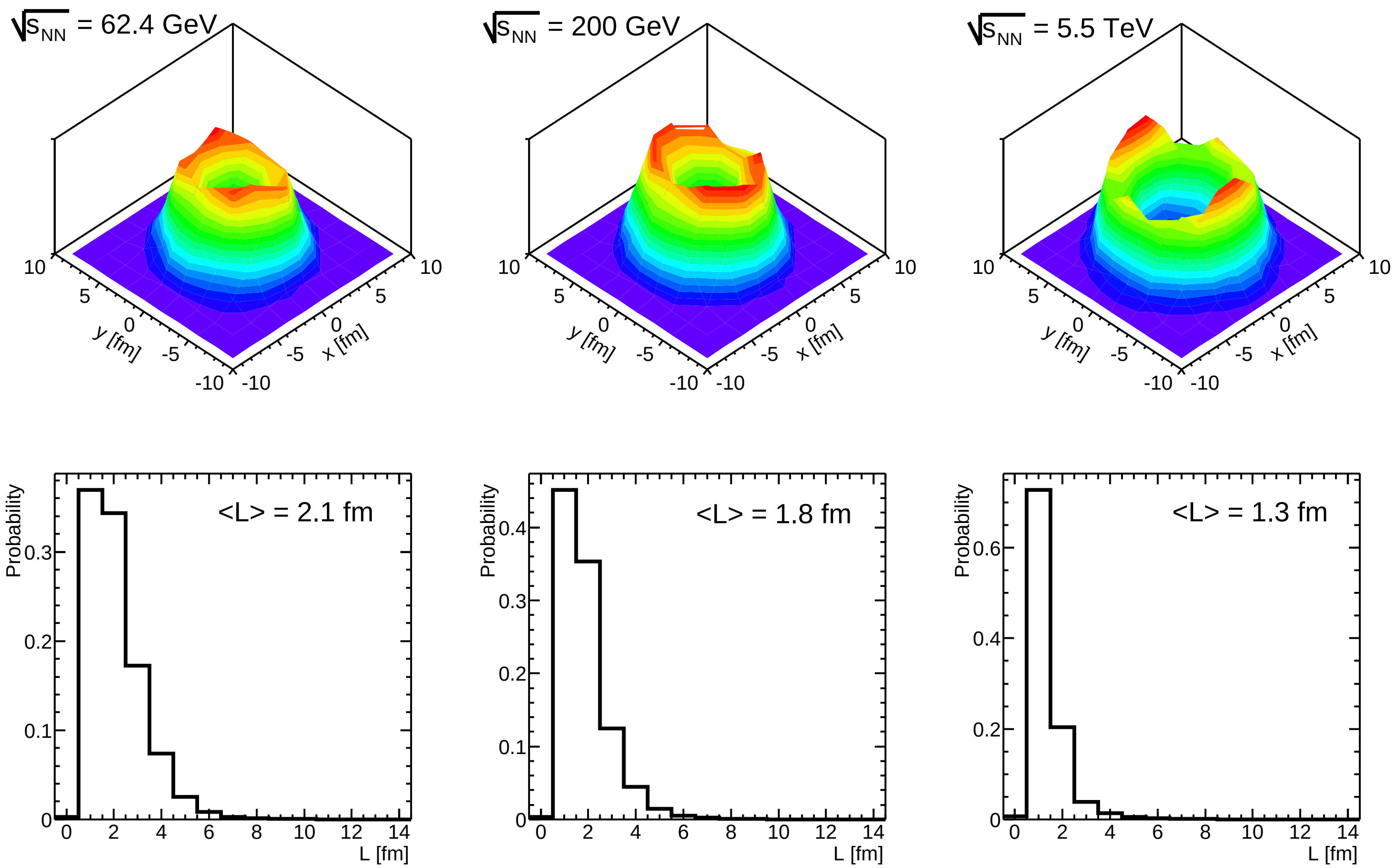
[Baier 2002]

The interaction of the hard parton with the medium is much stronger than expected.

Corona effect

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)]



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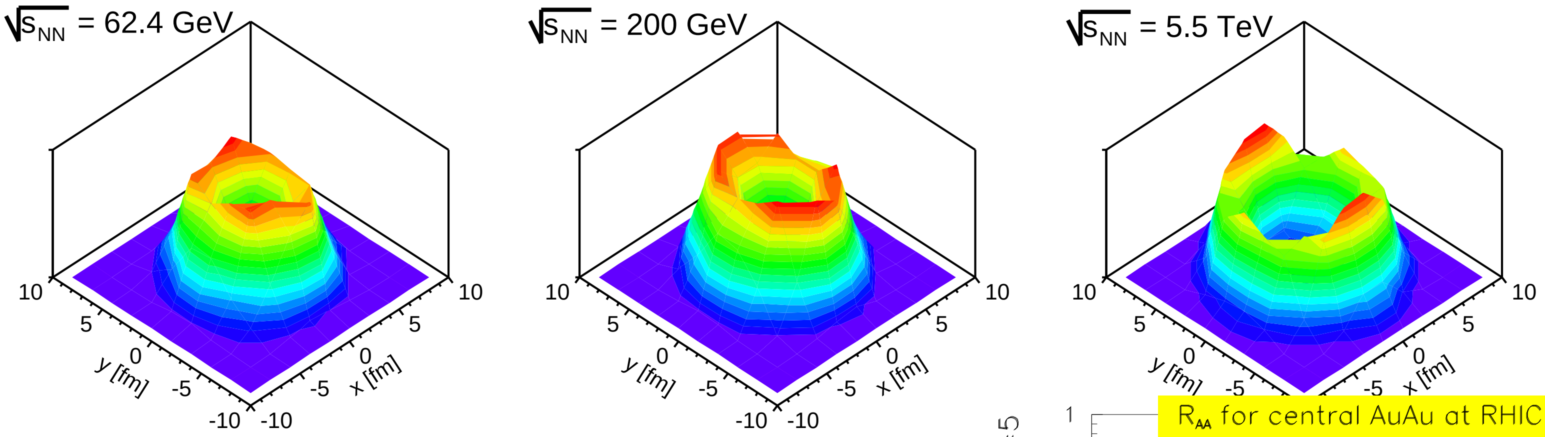
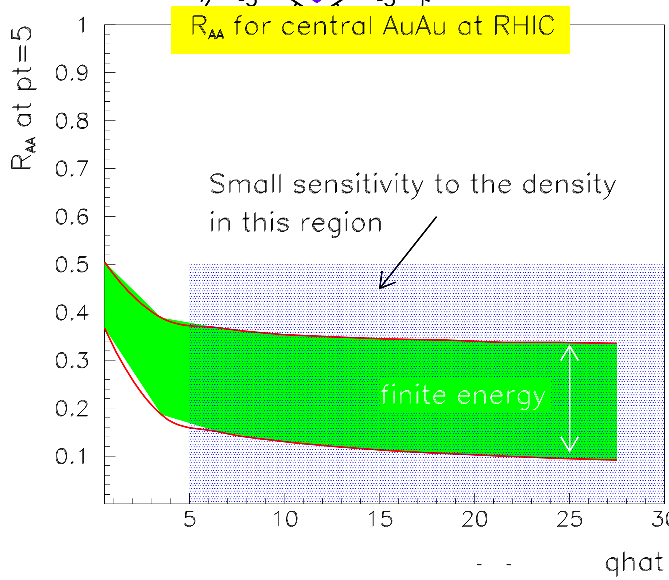


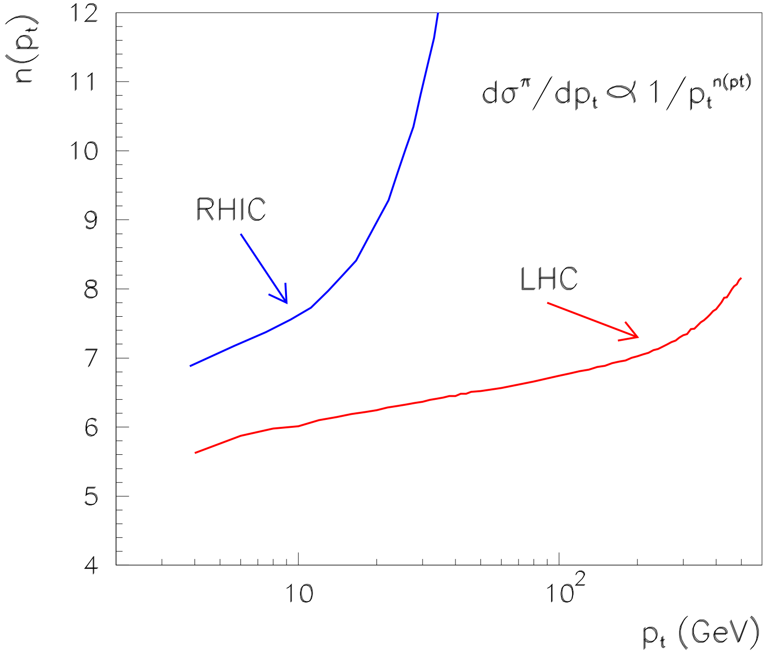
In this case, the sensitivity to $\hat{q}$ becomes small (bad determination of the medium density)

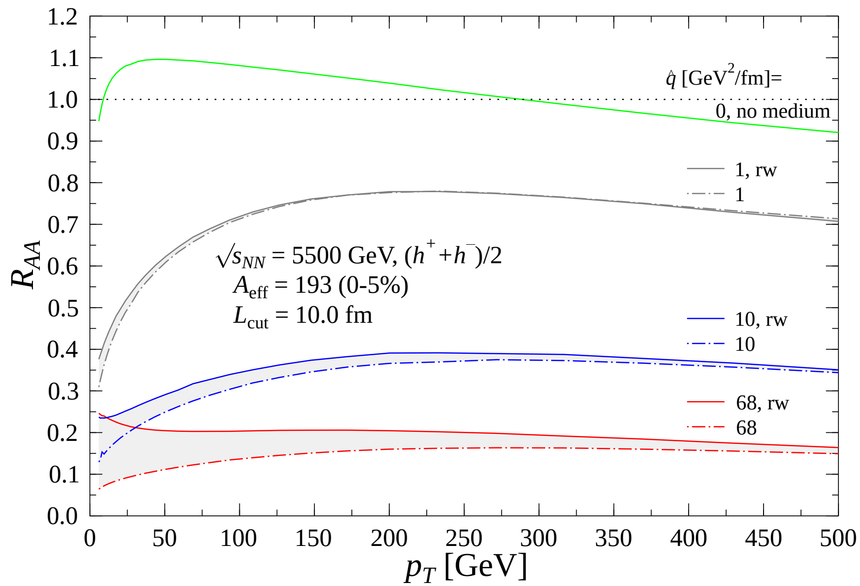


Flatness of the suppression

Trigger bias

⇛ Steepness of the spectrum $\frac{d\sigma}{dp_t} \sim \frac{1}{p_t^n} \Longrightarrow$ small z, ϵ





R_{AA} flat also for the LHC

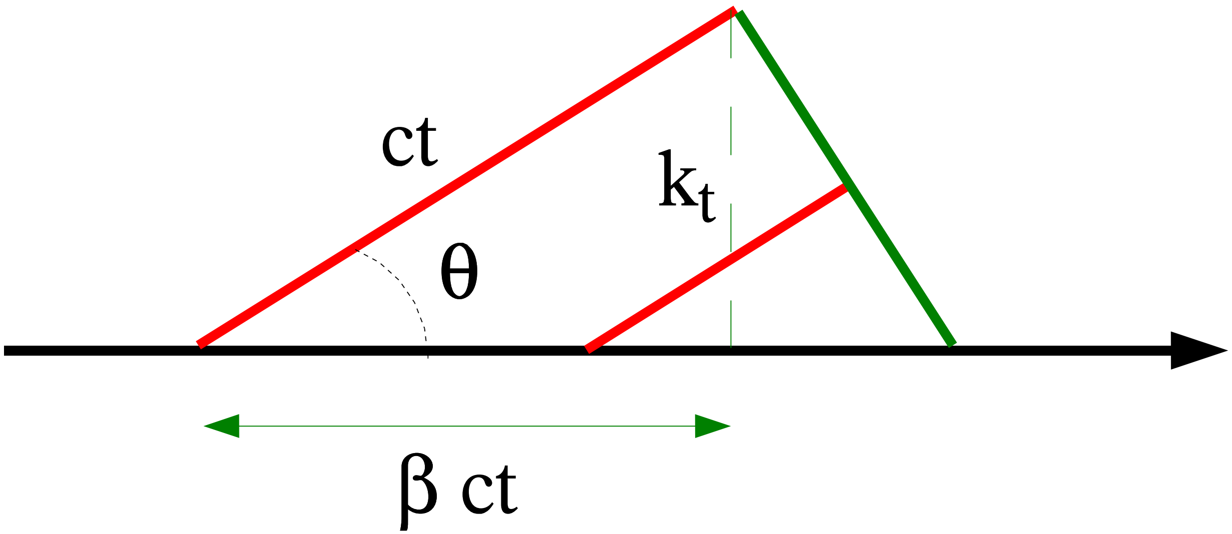
⇛ High-p_t hadrons are fragile objects – more fragile the highest the p_t

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

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)]

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

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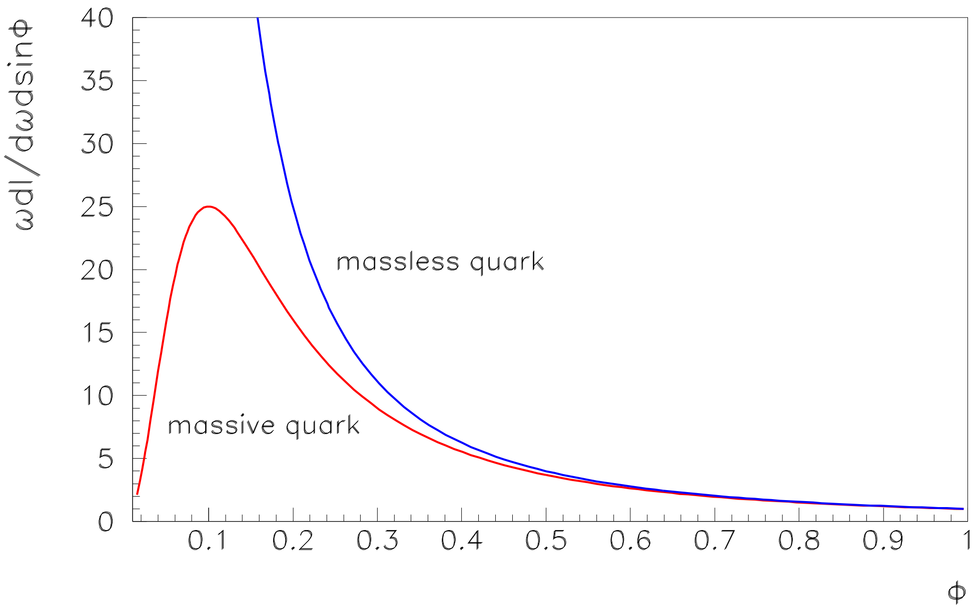

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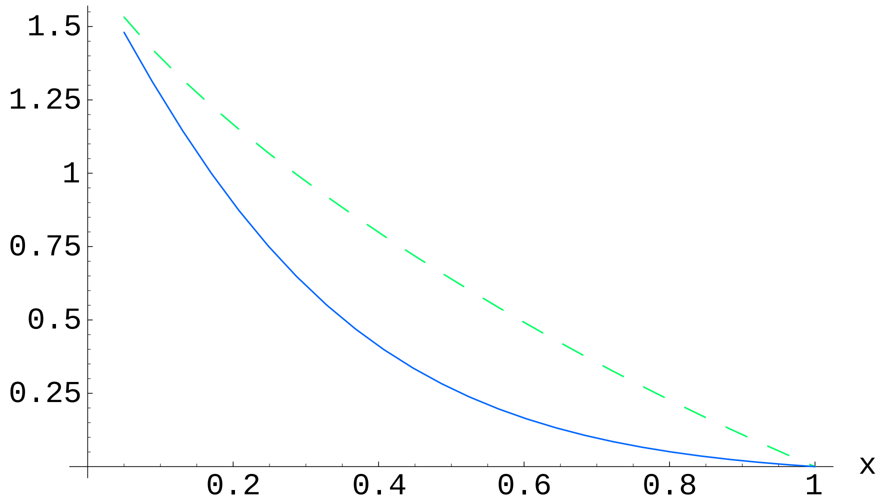
Heavy quark energy loss

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

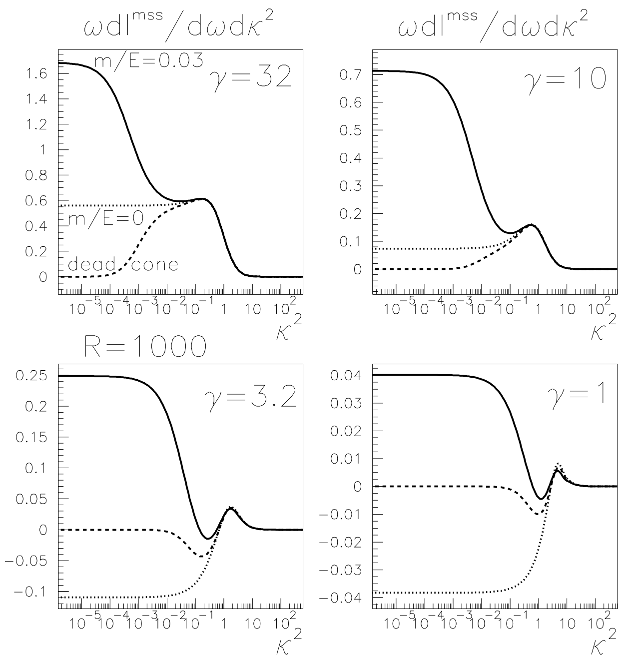
$$\omega \frac{dI_{\rm med}^{\rm mass}}{d\omega} = \frac{1}{\left(1+\frac{\theta_0^2}{\theta^2}\right)^2} \omega \frac{dI_{\rm med}^{\rm m=0}}{d\omega}$$



- 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)]

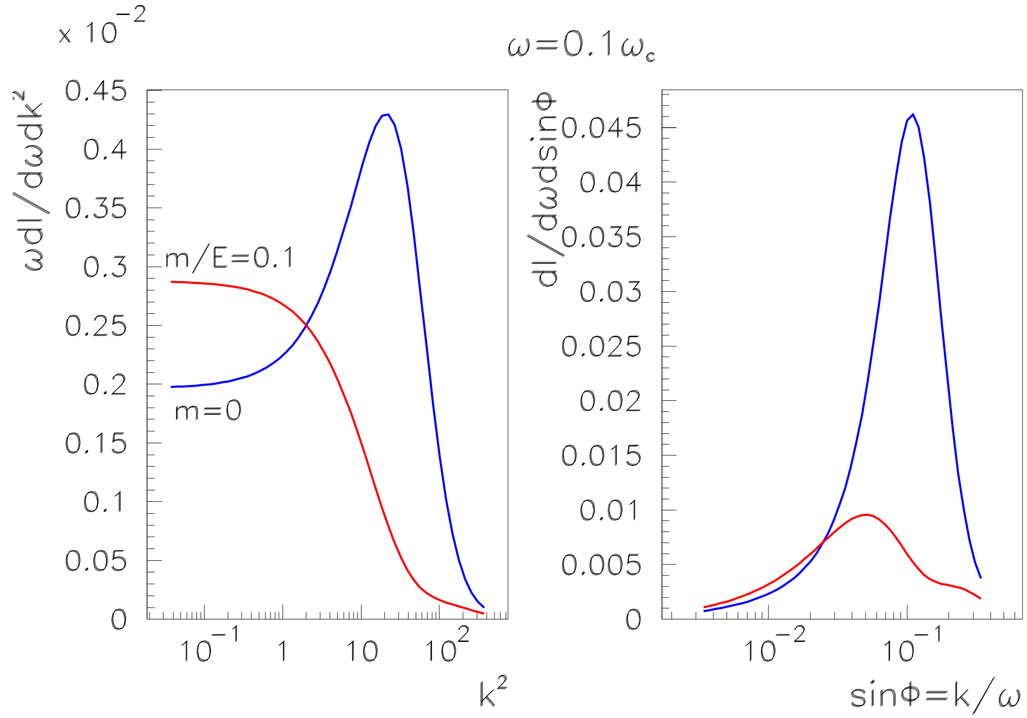
⇛ New phase term in the massive case:

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

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

Angular distribution

⇛ The angular distribution is modified



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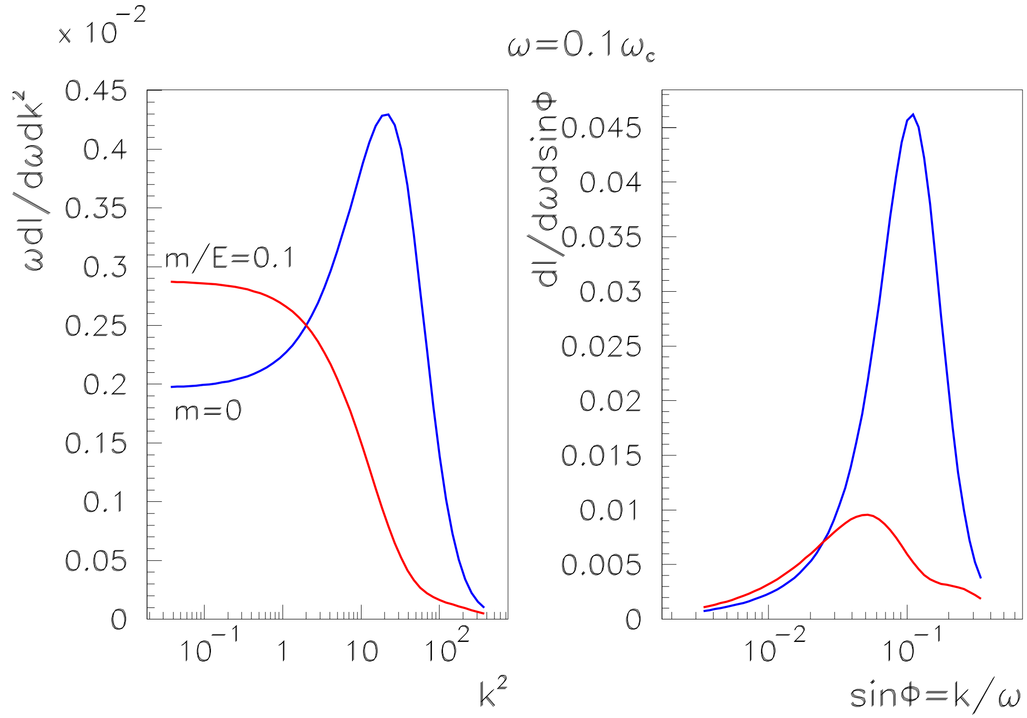
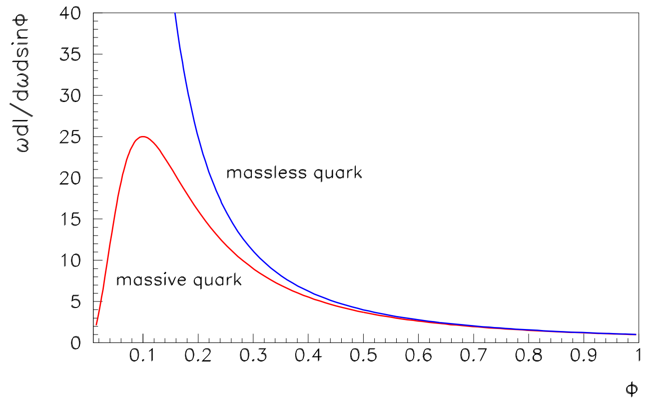
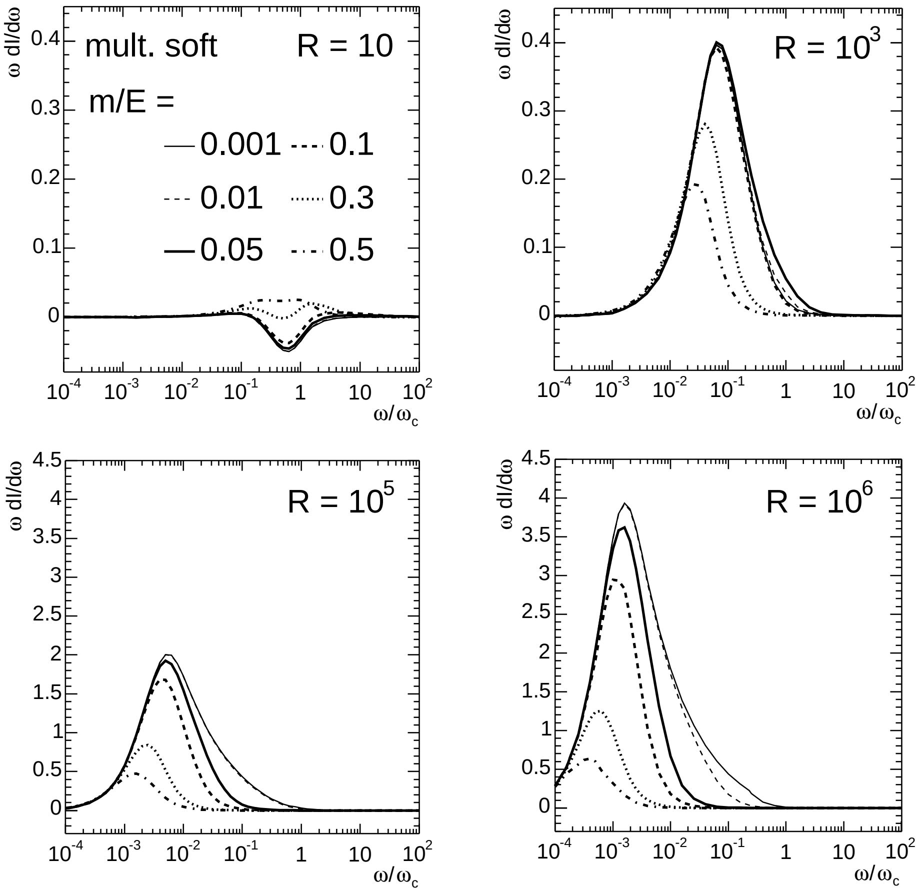




(vacuum)

- 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

Energy spectrum for different masses



$$R \equiv \omega_c L$$

Notice that the effect of the mass increases with the length L

Practical applications

Formalism

$$d\sigma^{AA\to h+X}_{(\text{med})} =$$

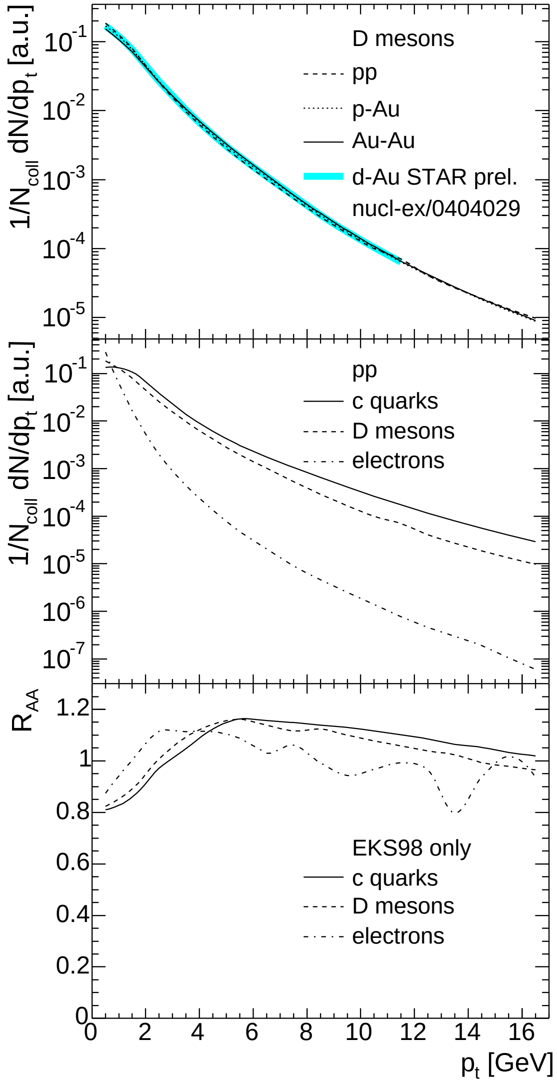
$$d\sigma^{AA\to f+X}_{(\text{vac})} \otimes P\left(\frac{\Delta E}{\omega_c}, R, \frac{m}{E}\right) \otimes D^{(\text{vac})}_{f\to h}$$

- $P\left(\frac{\Delta E}{\omega_c}, R, \frac{m}{E}\right)$ probability of losing ΔE due to medium-induced radiation ($R = \omega_c\, L$)
- In the vacuum

$$P\left(\frac{\Delta E}{\omega_c}, R, \frac{m}{E}\right) = \delta(\Delta E)$$

- We tuned PYTHIA to reproduce the shape of the data from STAR on the D meson p_t distribution in dAu.

  [Armesto, Dainese, Salgado, Wiedemann (2005); Same method as in Dainese, Loizides, Paic (2004)]

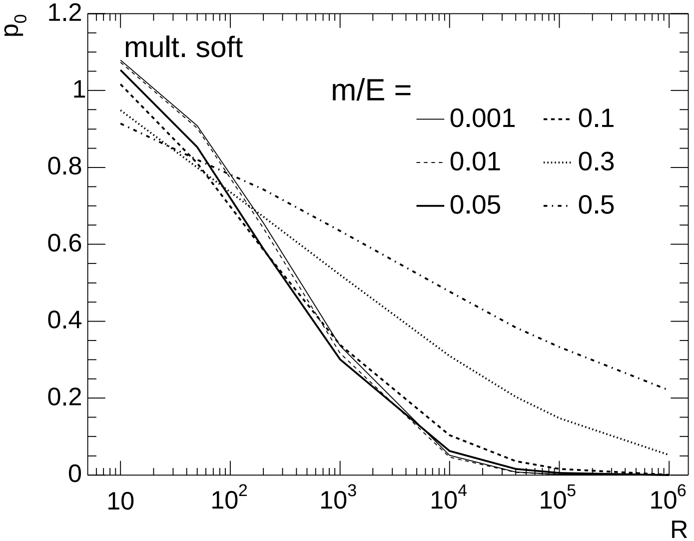


Quenching weights

⇒ In the independent gluon emission approximation [Baier *et al* (2001)]

$$P\left(\frac{\Delta E}{\omega_c}, R, \frac{m}{E}\right) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI^{\rm med}(\omega_i)}{d\omega}\right] \delta\left(\Delta E - \sum_{i=1}^{n} \omega_i\right) \exp\left[-\int d\omega \frac{dI^{\rm med}}{d\omega}\right]$$

probability of no-energy loss



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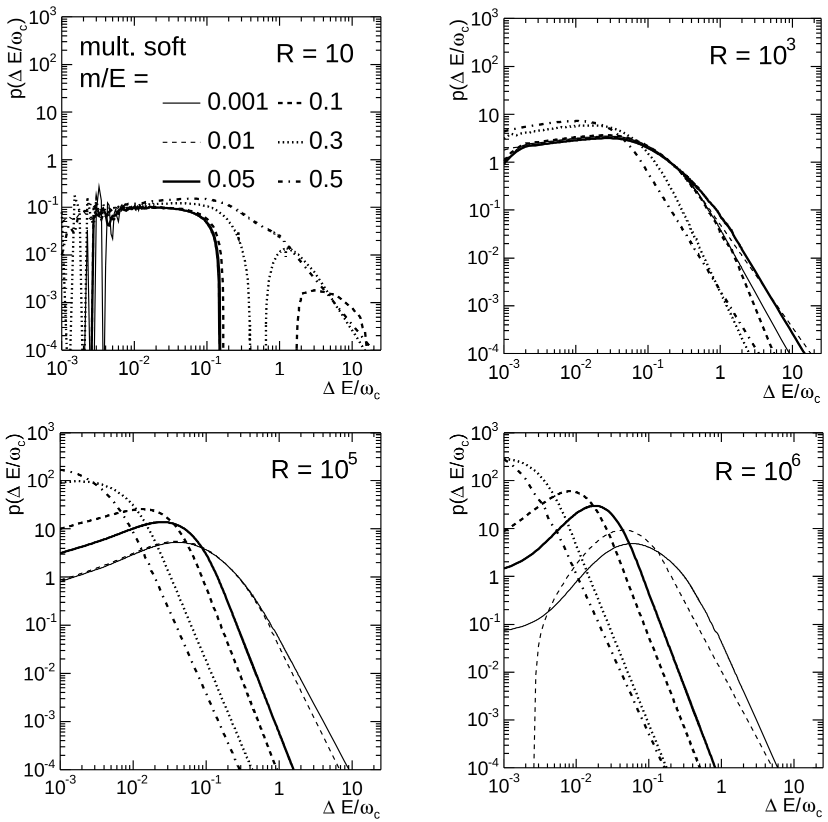
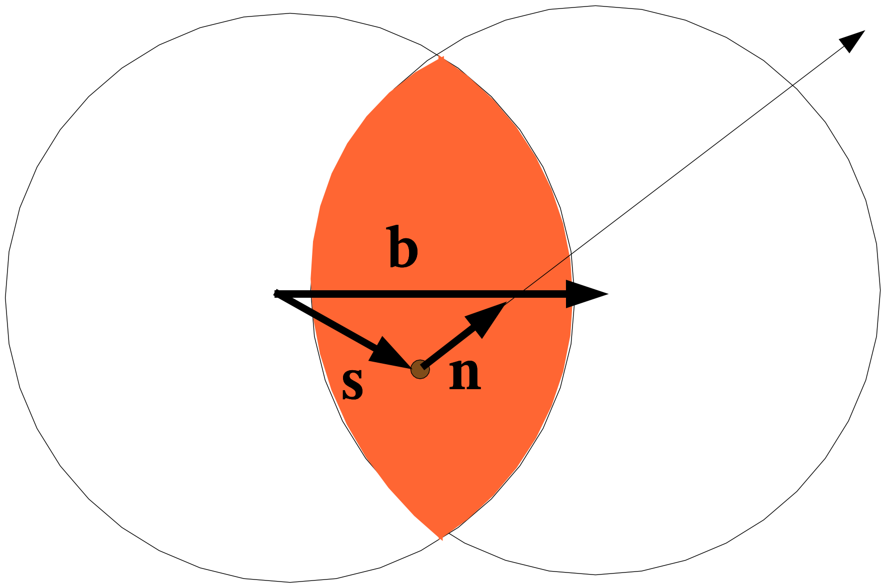


[Armesto, Dainese, Salgado, Wiedemann (2005)]

[tabulated in: http://www.pd.infn.it/~dainesea/qwmassive.html]

Geometry

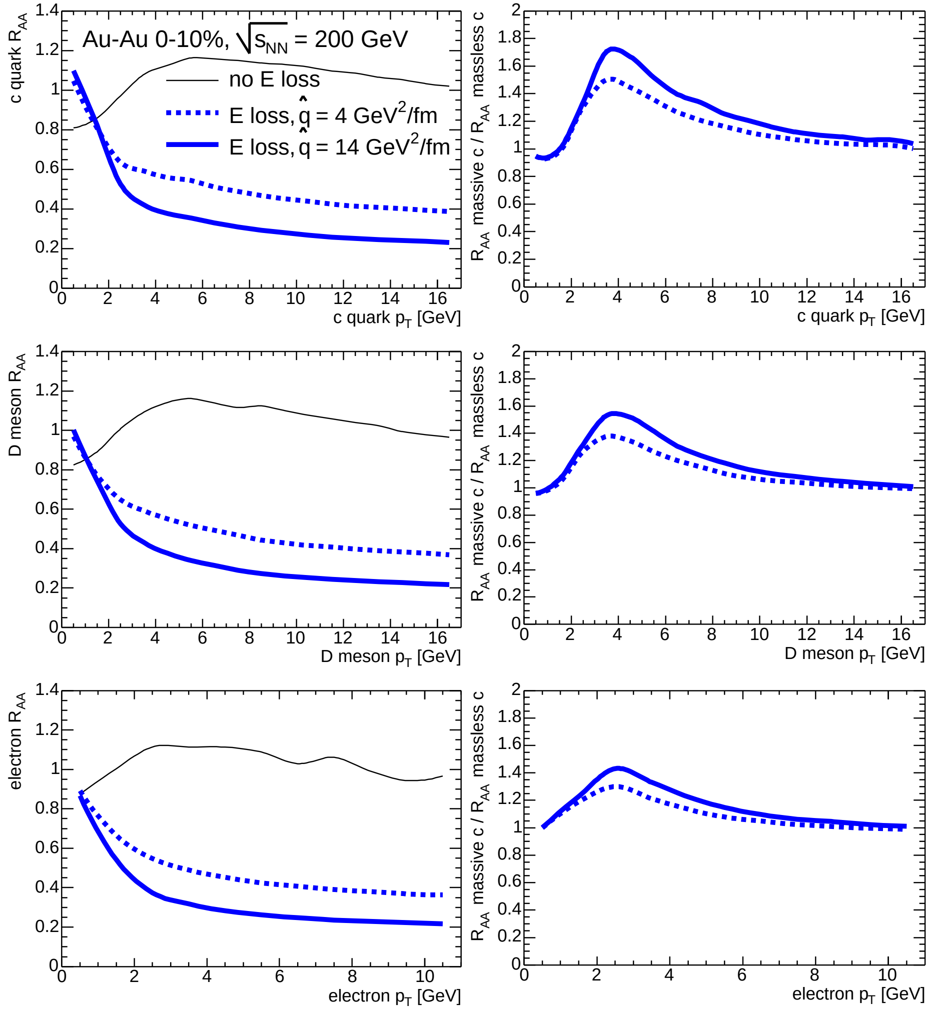


$$\hat{q}(\xi) = kT_A(\mathbf{s} + \xi\mathbf{n})T_B(\mathbf{b} - [\mathbf{s} + \xi\mathbf{n}])$$

$$\omega_c = \int_0^\infty d\xi\, \xi\, \hat{q}(\xi)\ ; \quad R = \frac{2\omega_c^2}{\int_0^\infty d\xi\, \hat{q}(\xi)}$$

[Dainese, Loizides, Paic (2004); Armesto, Dainese, Salgado, Wiedemann (2005)]

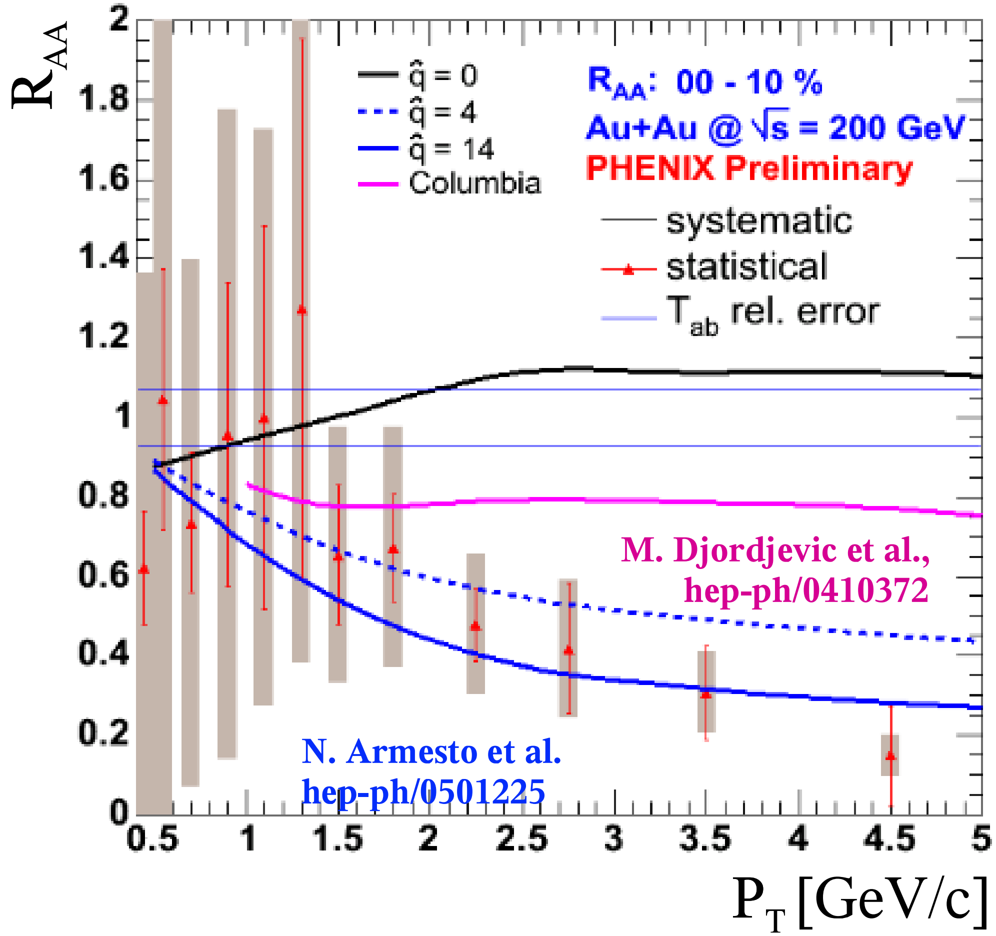
Results for RHIC



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

Comparison with preliminary data

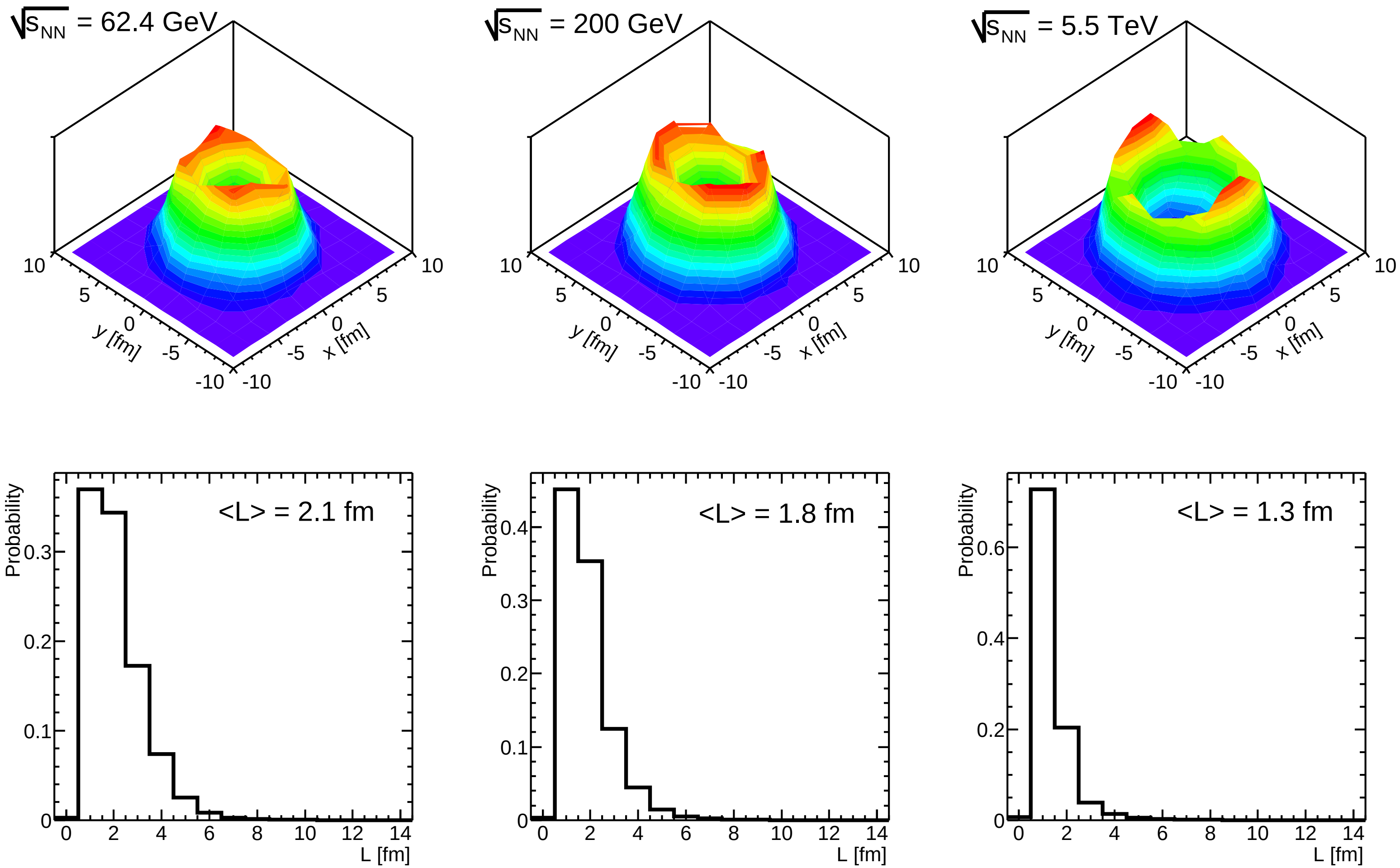
PHENIX: Averbeck, Moriond '05



Almost the same suppression as for light quarks

Surface emission with mass terms

- Suppression for charm and light quarks very similar unexpected?
- Remeber that mass effects small for small lenghts



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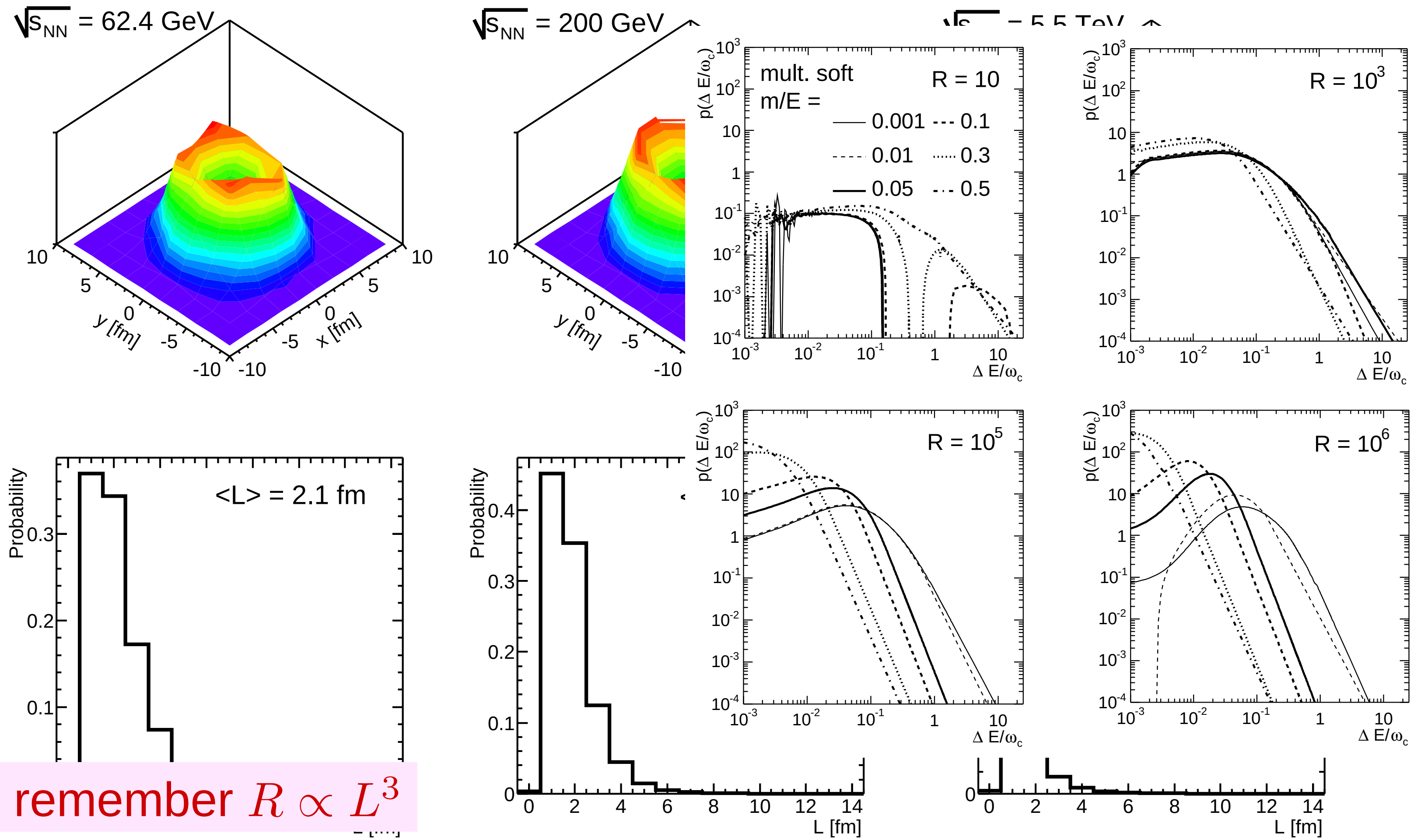
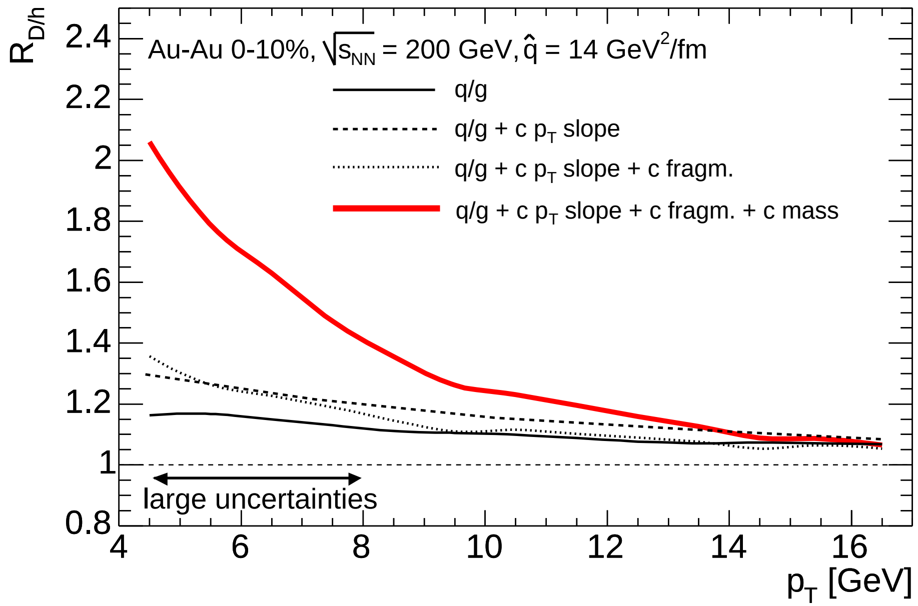


remember $R \propto L^3$

Massive over light particle ratio



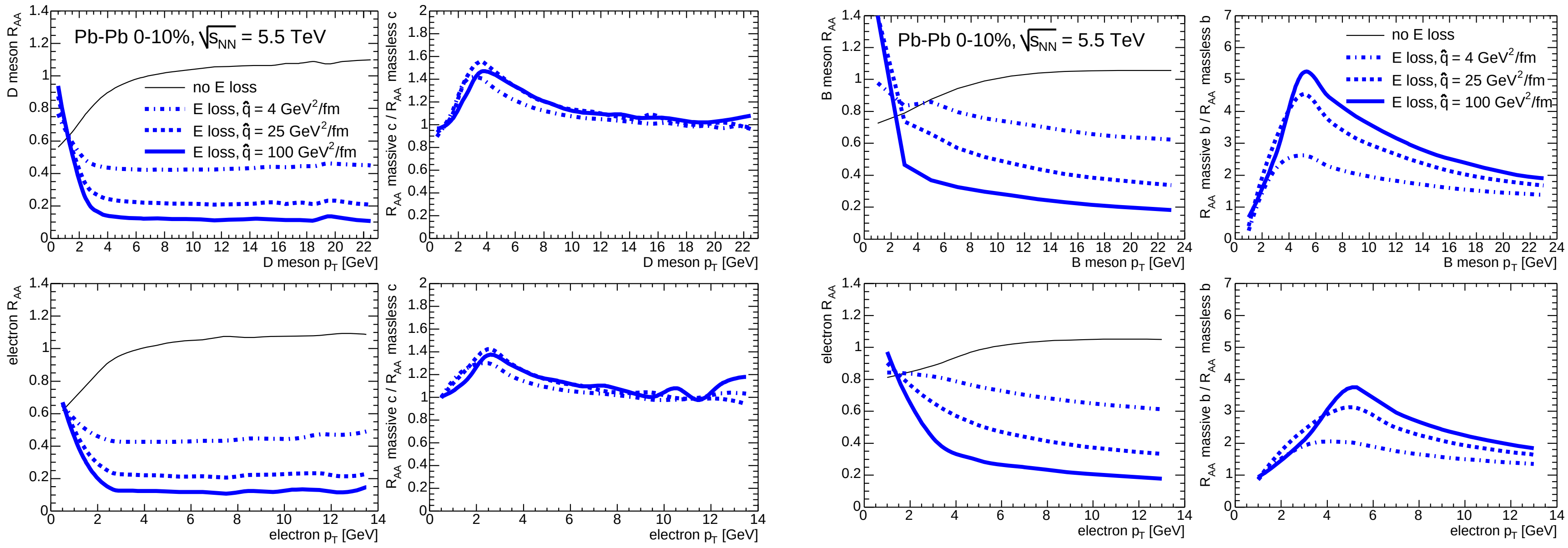
[Armesto,Dainese,Salgado,Wiedemann 2005]

- 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 $R_{D/h}$

Extrapolations to the LHC

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

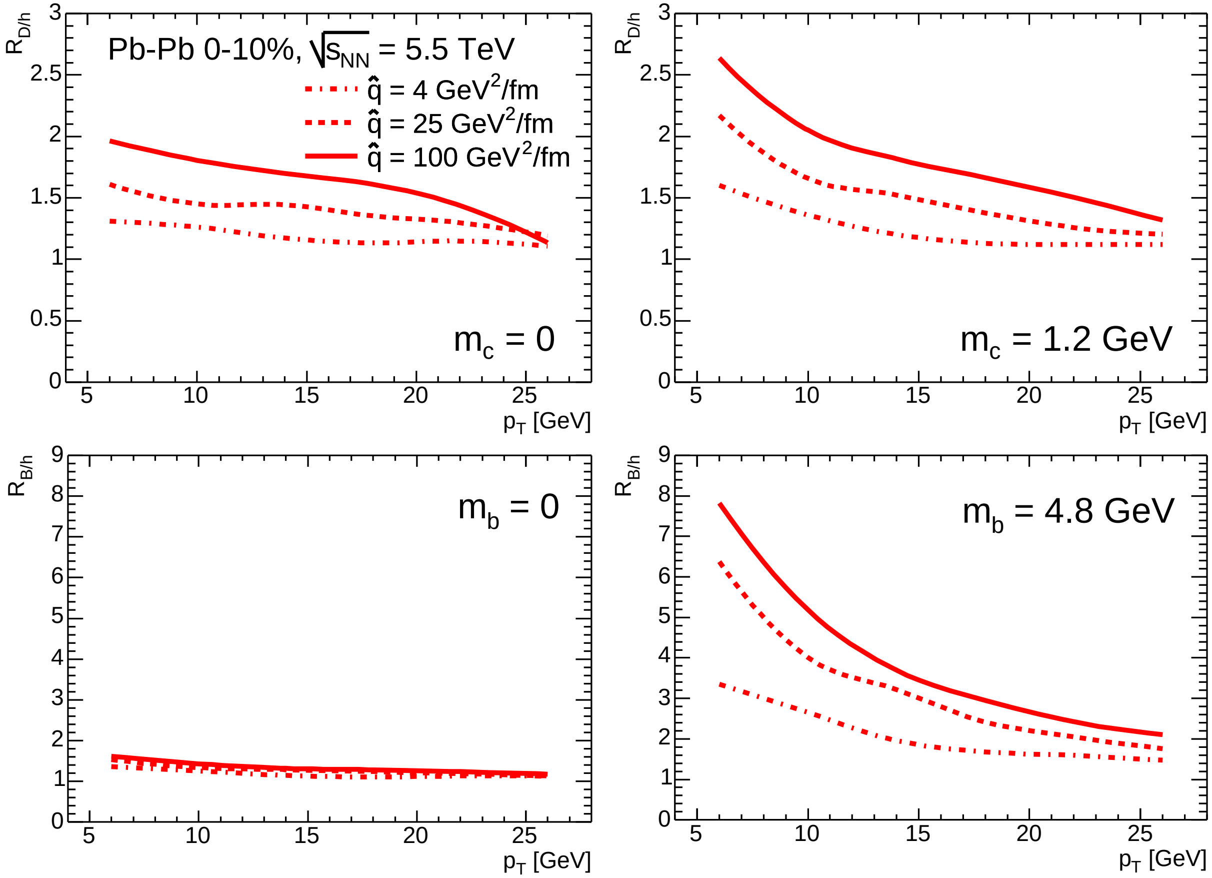
⇛ We take a factor 7 from Eskola *et al* (2000) [probably too large]



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

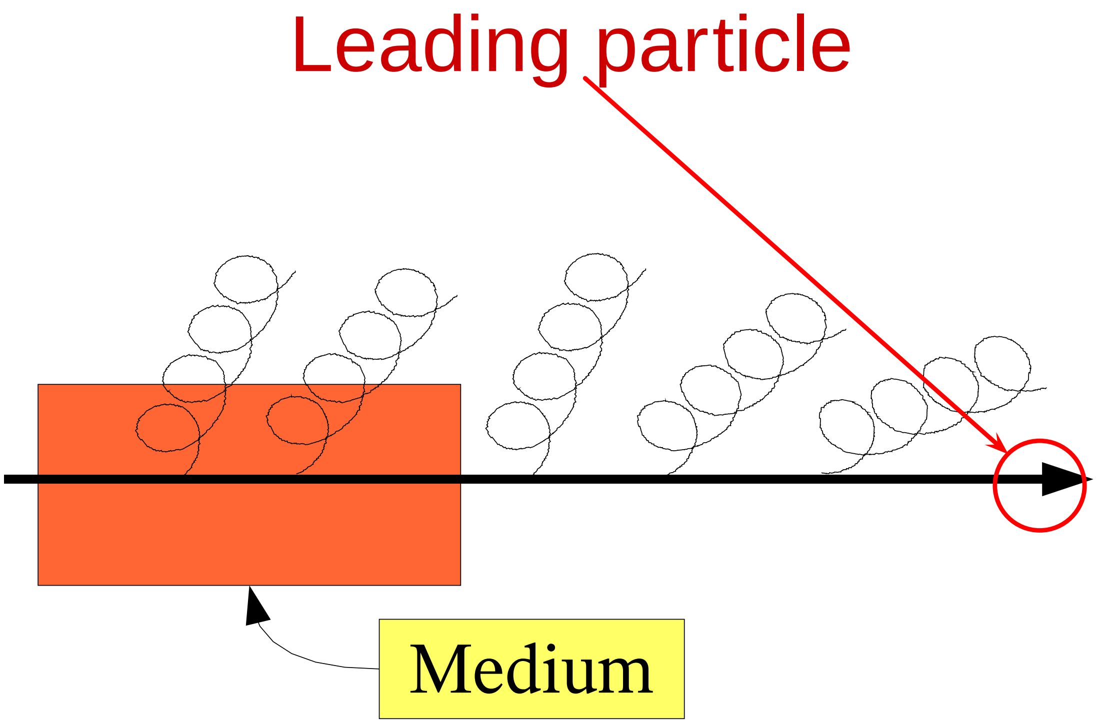
Heavy-to-light ratios at the LHC

⇛ D/h and B/h ratios for the LHC



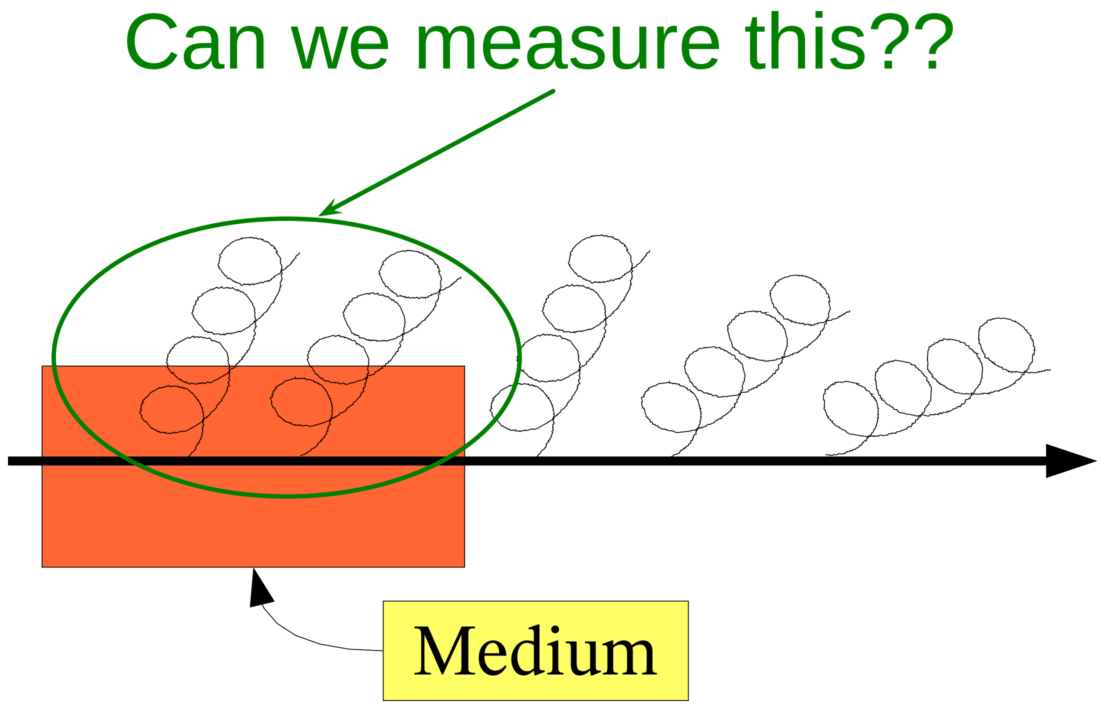
[Armesto, Dainese, Salgado, Wiedemann (2005)]

Jets



⇒ Inclusive particle measures the density of the medium: $\Delta E \propto \alpha_S \hat{q} L^2$

Jets



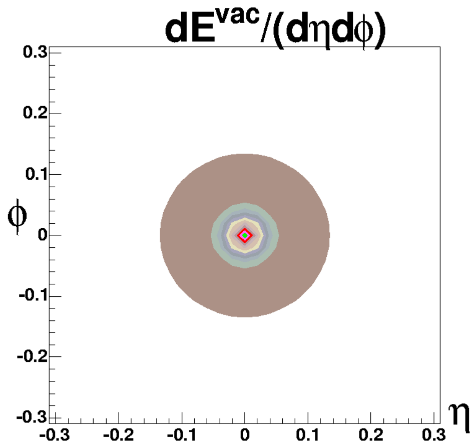
⇒ Inclusive particle measures the density of the medium: $\Delta E \propto \alpha_S \hat{q} L^2$

⇒ The jet broadening $\langle k_t^2 \rangle \sim \hat{q} L$

Jet shapes in the $\eta \times \phi$ plane.

Vacuum

(reference)



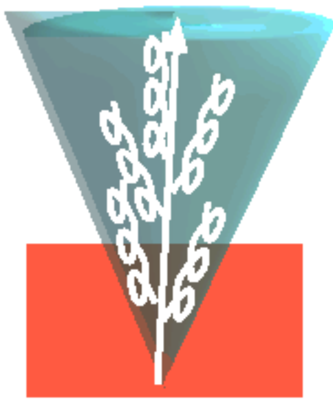
Jet shapes in the $\eta \times \phi$ plane.

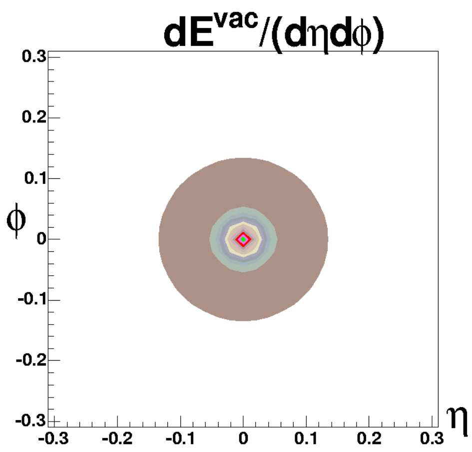
Vacuum

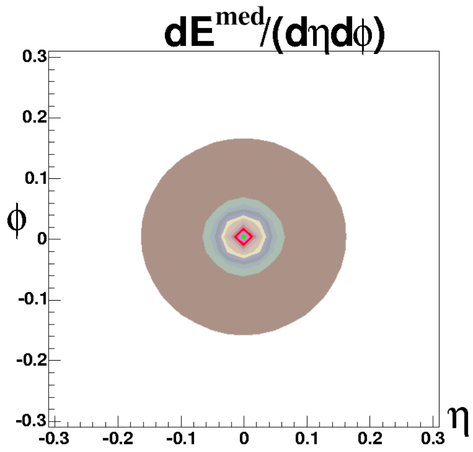
(reference)

Medium:

broadening



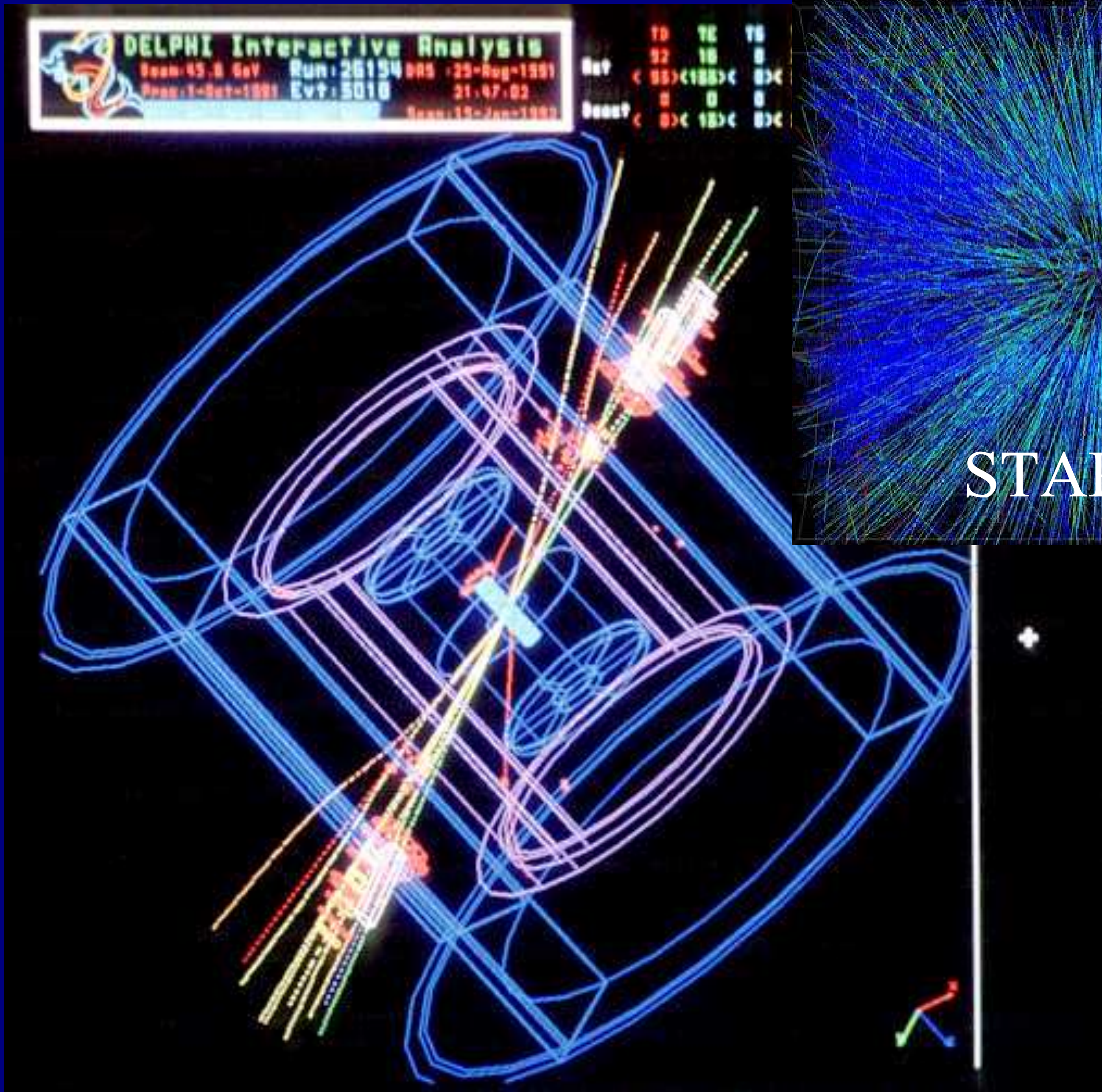


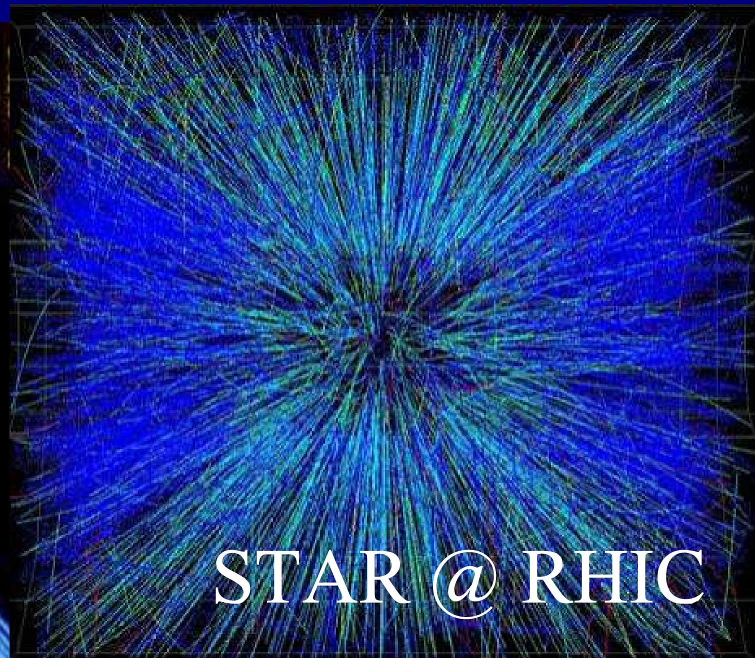


Jets in HIC???

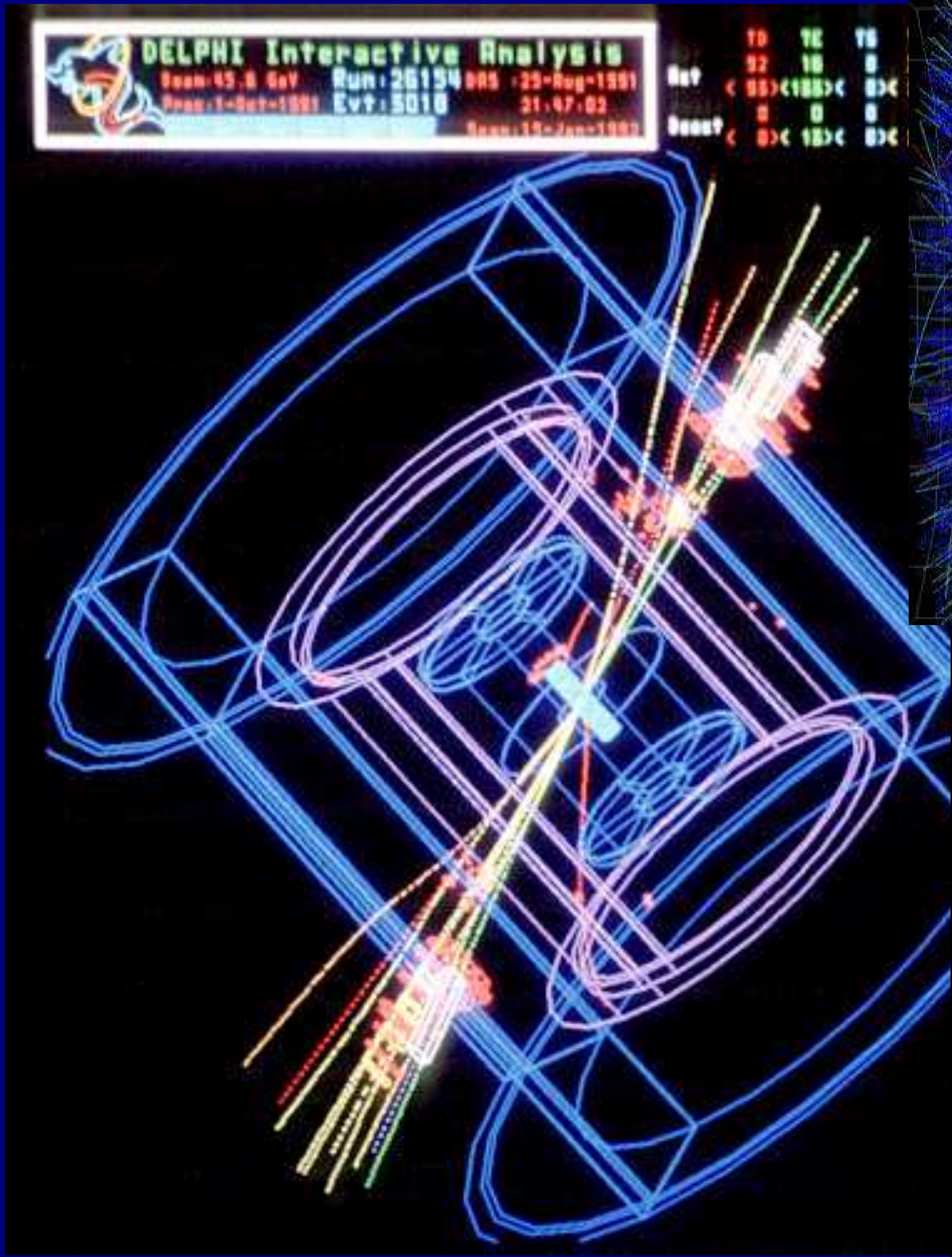

DELPHI Interactive Analysis
DELPHI
ENDCAPS
BARREL
CENTRAL
Return

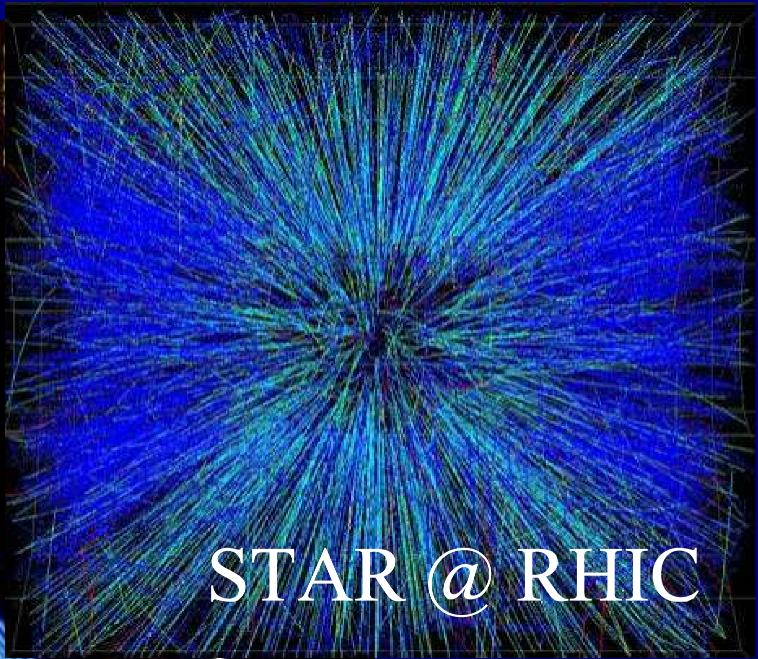
Jets in HIC???





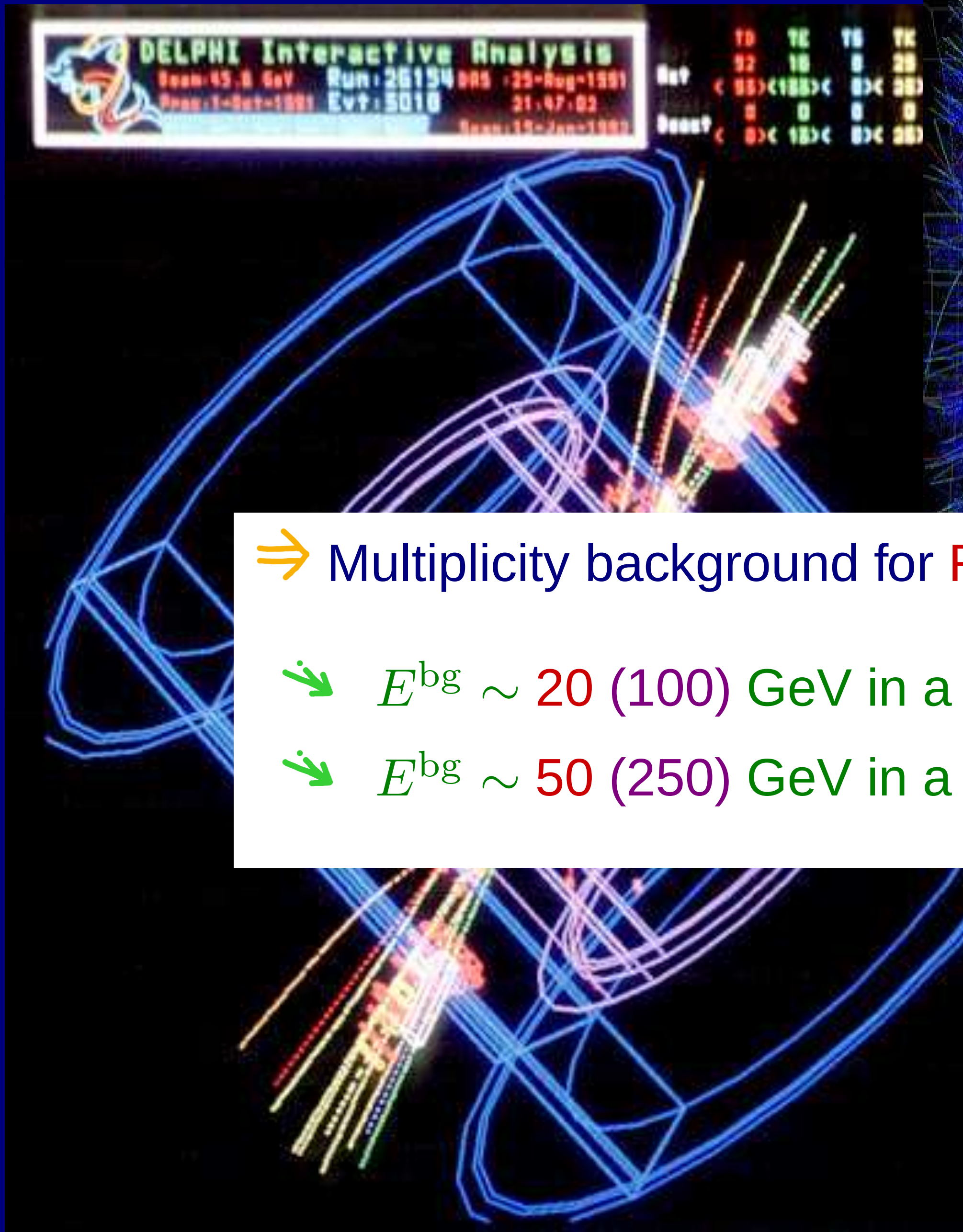
Jets in HIC???

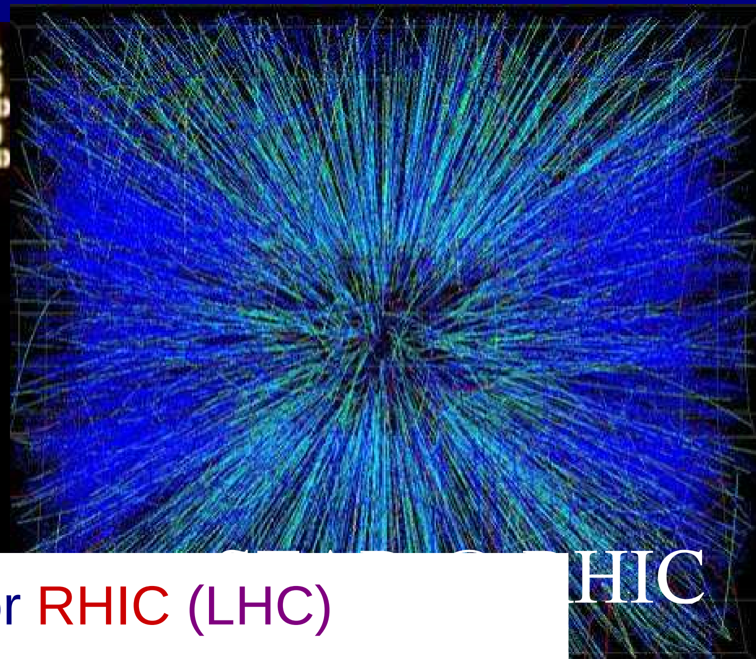

DELPHI Interactive Analysis
Run: 26154
Evt: 5010

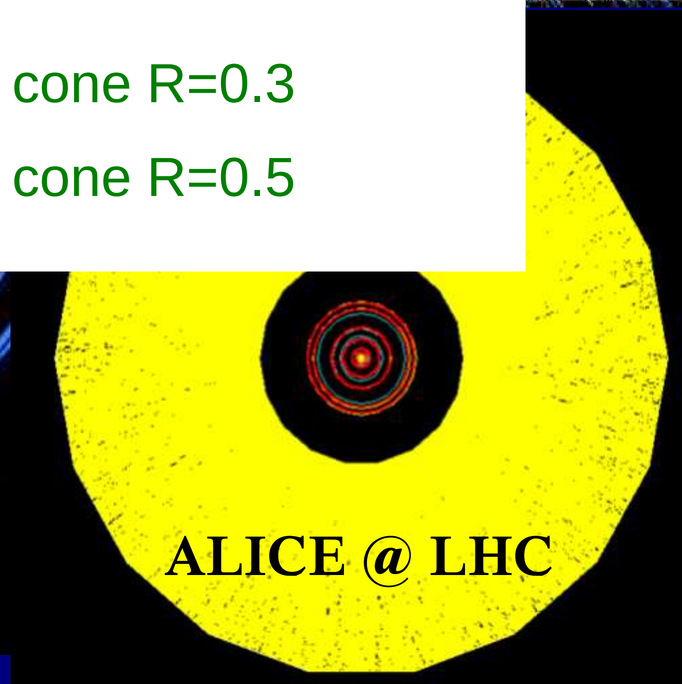

STAR @ RHIC


Alice event: 0, Run:0
Nparticles = 36276 Nhits = 1943104
ALICE @ LHC

Jets in HIC???







⇒ Multiplicity background for RHIC (LHC)

- $E^{\rm bg} \sim$ 20 (100) GeV in a cone R=0.3
- $E^{\rm bg} \sim$ 50 (250) GeV in a cone R=0.5

Jet shapes

$\rho(R)$, fraction of the jet energy inside a cone $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

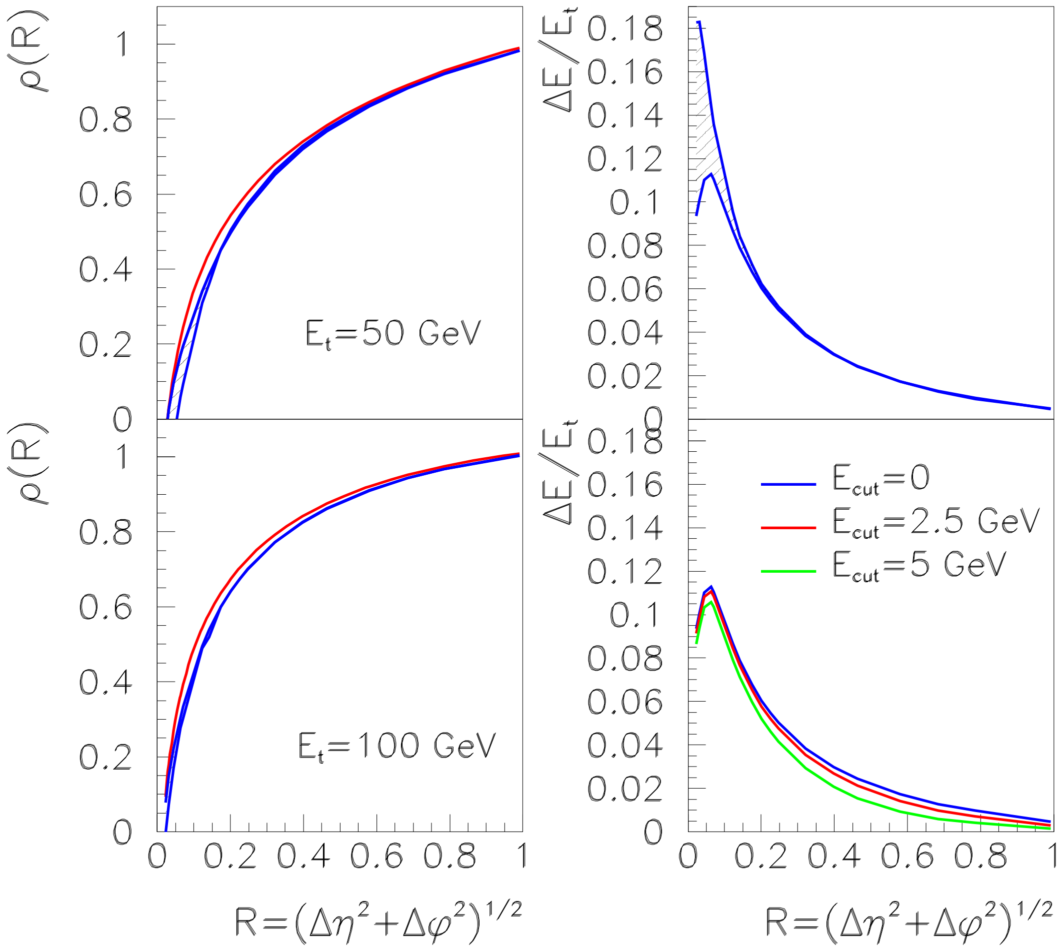
$$\rho_{\rm vac}(R) = \frac{1}{N_{\rm jets}} \sum_{\rm jets} \frac{E_t(R)}{E_t(R=1)}$$

$$\rho_{\rm med} = \rho_{\rm vac} - \frac{\Delta E_t(R)}{E_t(R=1)} + \frac{\Delta E}{E_t}(1 - \rho_{\rm vac}(R))$$

Small modification $\rightarrow$ can jet energy be determined experimentally above background??
Scaling with number of collisions for large cone angle.

Small sensitivity to IR cuts

[Salgado, Wiedemann (2003)]



Vacuum D0 data: Fermilab-PUB-97/242-E

Gluon multiplicity inside the jet.

The characteristic angular distribution of the medium–induced gluon radiation could be better observed in the quantity

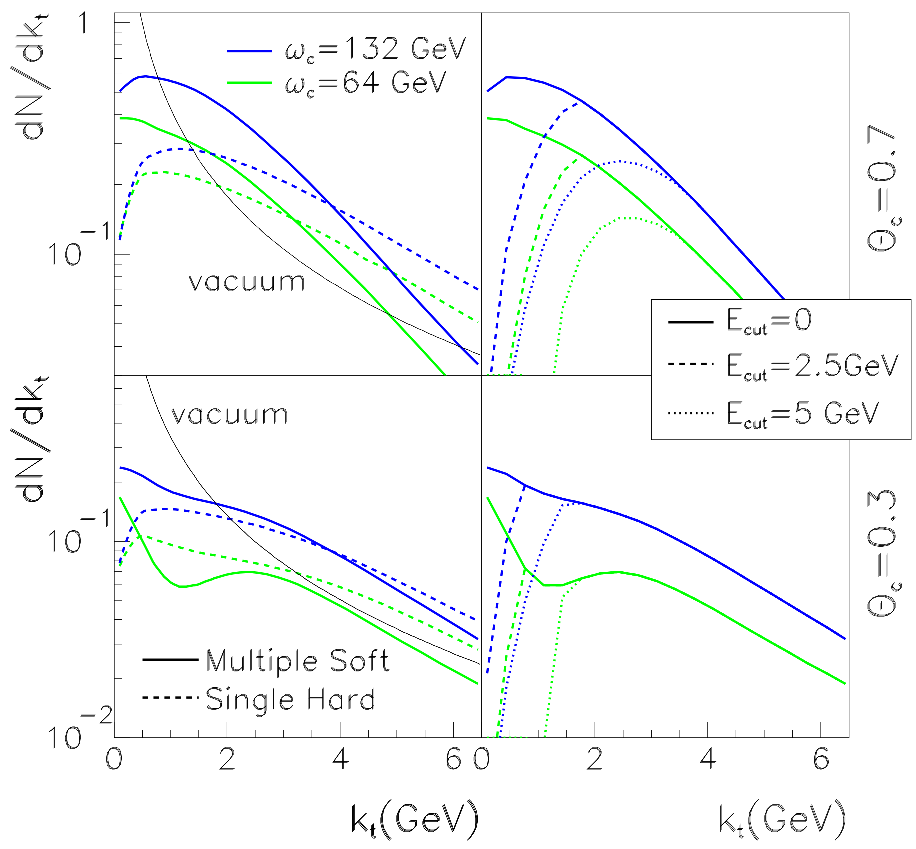
$$\frac{dN^{\rm jet}}{dk_\perp}=\int_{k_\perp/sin\theta_c}^{E} d\omega\,\frac{dI}{d\omega dk_\perp}$$

For the vacuum we simply use

$$\frac{dI_{\rm vac}}{d\omega dk_\perp}\sim\frac{1}{\omega}\frac{1}{k_\perp}$$

Needs a more quantitative analysis (hadronization...).

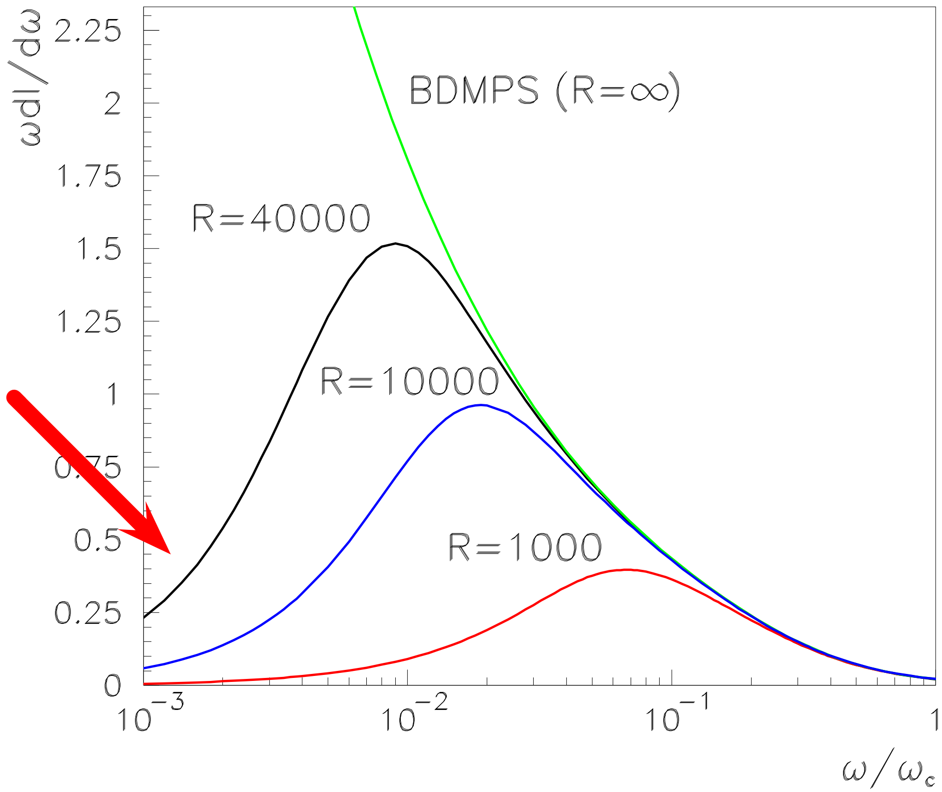
But, effect based mainly on kinematics remember $k_t^2\sim\hat{q}L(\sim Q^2_{\rm sat})$



(100 GeV jet)

IR cuts

- The fact that the results show small sensitivity to IR cuts is due to the shape of the spectrum

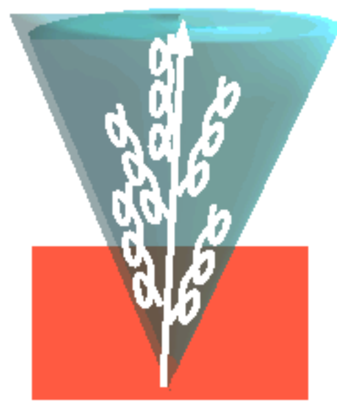


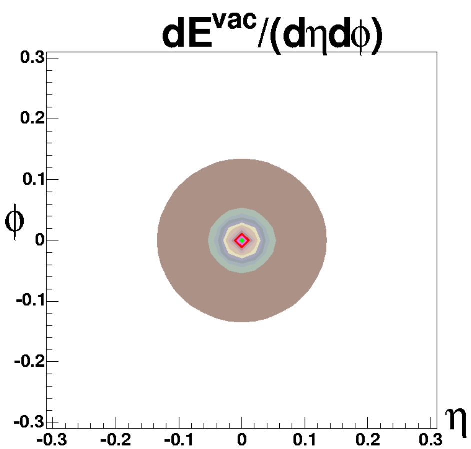
- As we have seen, this is due to formation time effects.

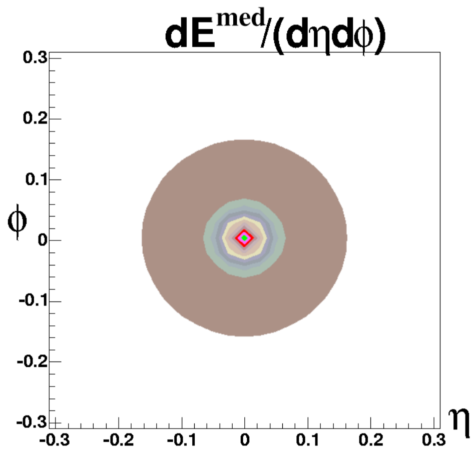
Jet shapes in a flowing medium

Vacuum
(reference)

Medium:
broadening

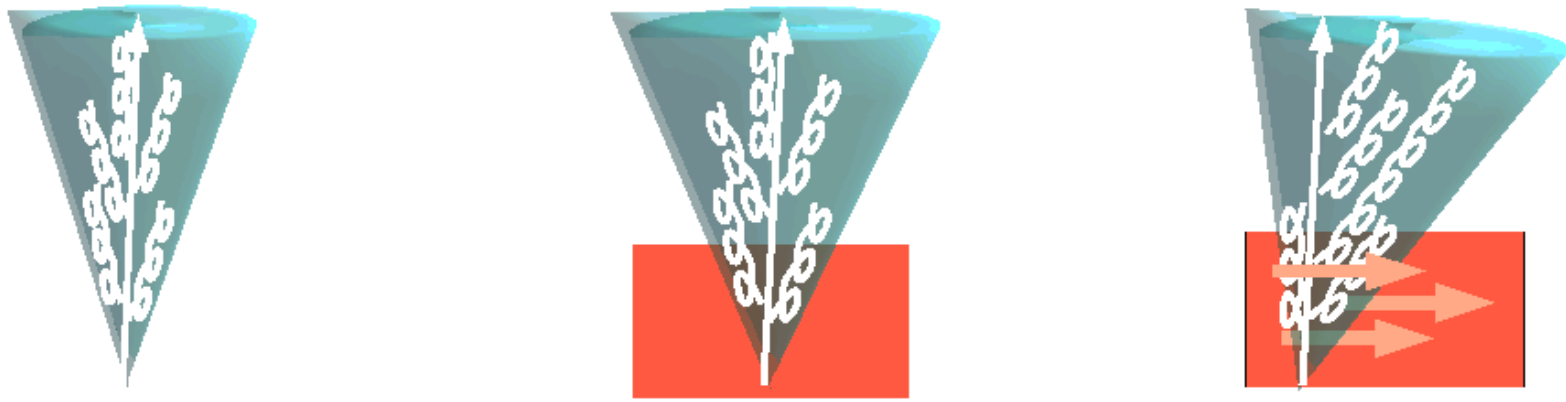


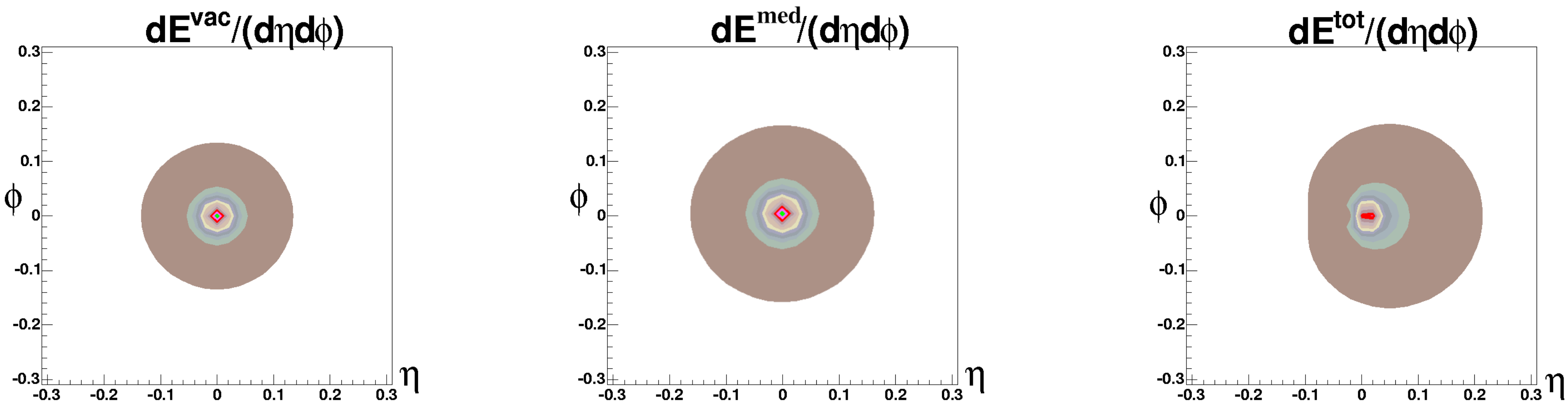




Jet shapes in a flowing medium

Vacuum	Medium:	Flowing medium:
(reference)	broadening	anisotropic shape





Formalism

In the single–hard scattering approximation

$$\omega \frac{dI^{\rm med}}{d\omega\, d\mathbf{k}} = \frac{\alpha_s}{(2\pi)^2} \frac{4\, C_R\, n_0}{\omega} \int d\mathbf{q}\, |a(\mathbf{q})|^2\, \frac{\mathbf{k}\cdot\mathbf{q}}{\mathbf{k}^2} \frac{-L\frac{(\mathbf{k}+\mathbf{q})^2}{2\omega} + \sin\left(L\frac{(\mathbf{k}+\mathbf{q})^2}{2\omega}\right)}{\left[(\mathbf{k}+\mathbf{q})^2/2\omega\right]^2},$$

we shift the Yukawa potential by a 3-momentum $q_0 = (\mathbf{q_0}, q_l)$ proportional to the flow field.

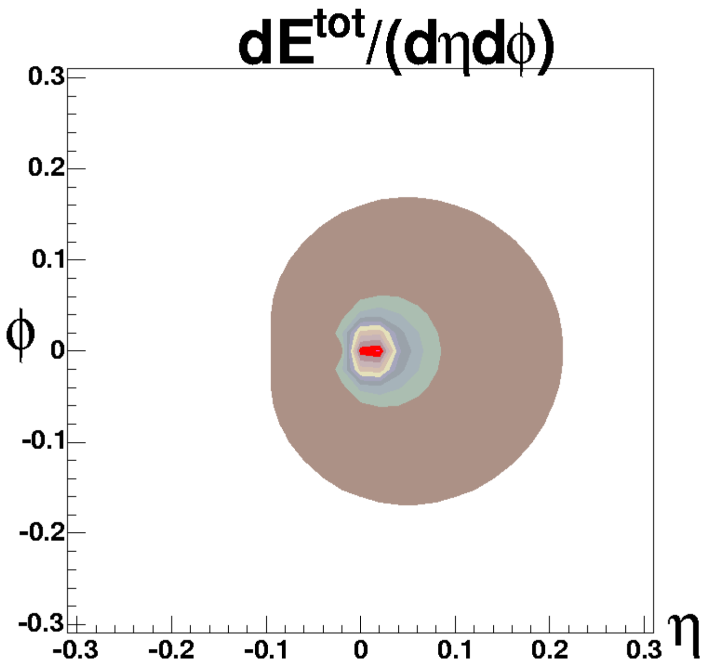
(Armesto, Salgado, Wiedemann hep-ph/0405301)

$$|a(\mathbf{q})|^2 = \frac{\mu^2}{\pi\left[\mathbf{q}^2+\mu^2\right]^2} \longrightarrow \frac{\mu^2}{\pi\left[(\mathbf{q}-\mathbf{q}_0)^{\,2}+\mu^2\right]^2}.$$

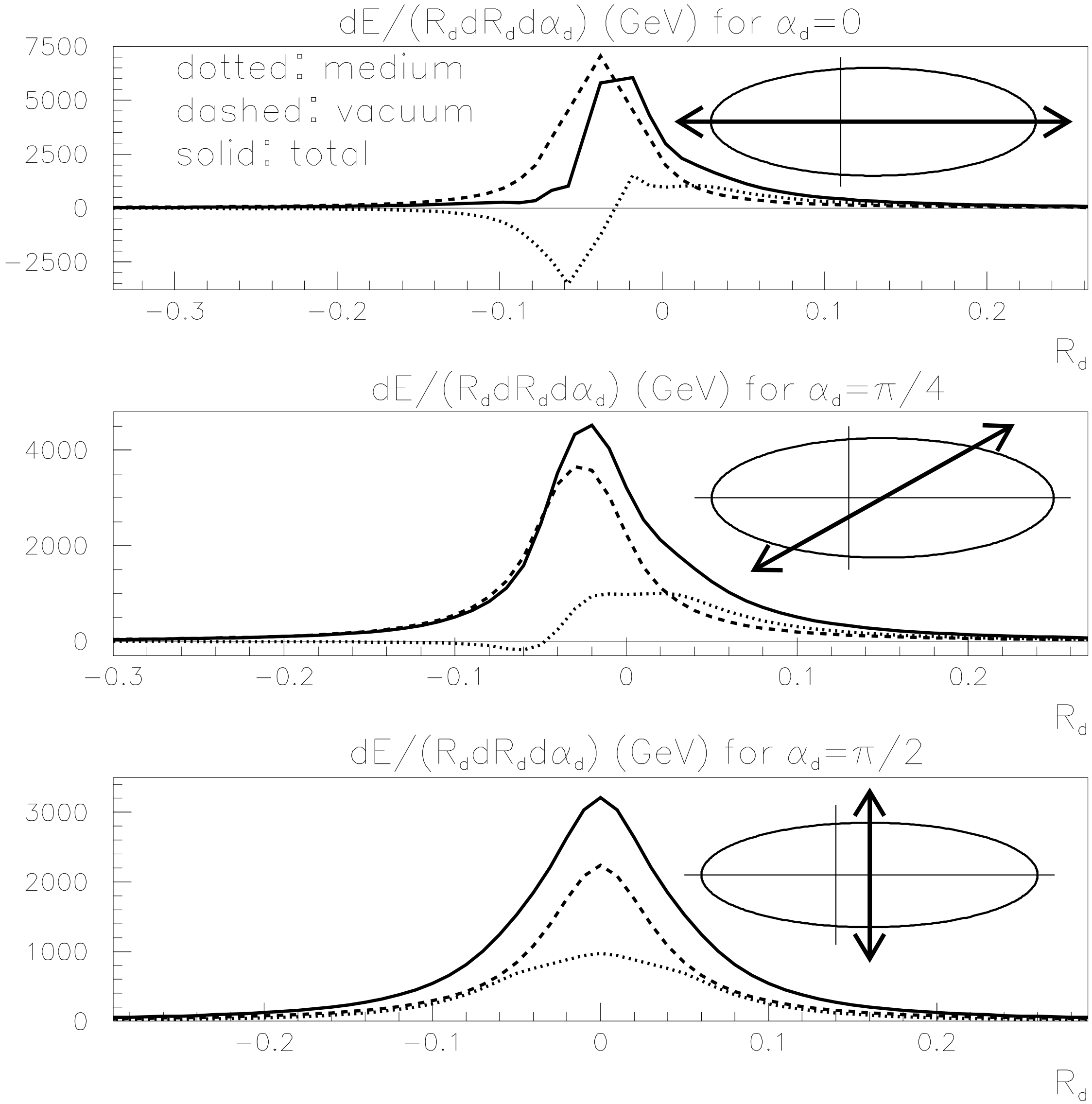
⇒ In the comoving frame $\langle k^2\rangle \sim \mu^2$, $\Delta E \sim \alpha_S n_0 \mu^2 L^2$.

⇒ $\mathbf{q_0}$ characterizes the additional (asymmetric) momentum transfer.

Jet energy distribution

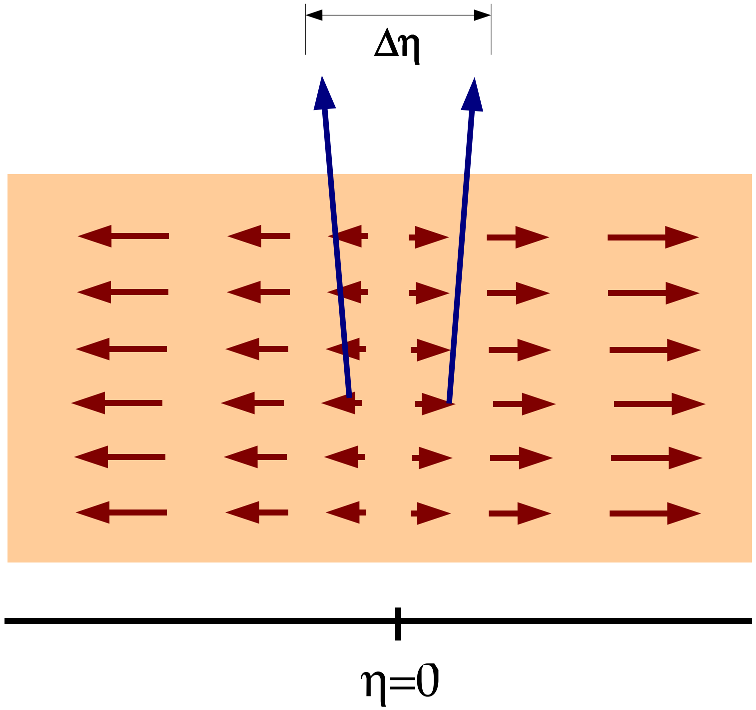


Flow in the $+z$ direction



Where to look for

Longitudinal flow: jets are not in the longitudinally comoving frame



For symmetric $\Delta\eta$ our previous results need to be symmetrized by adding the corresponding $\pm q_0$.

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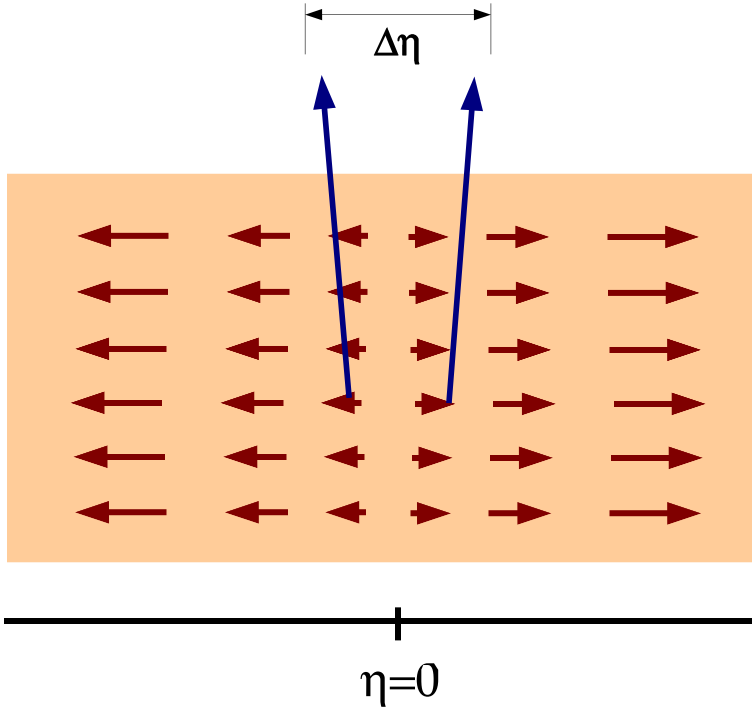

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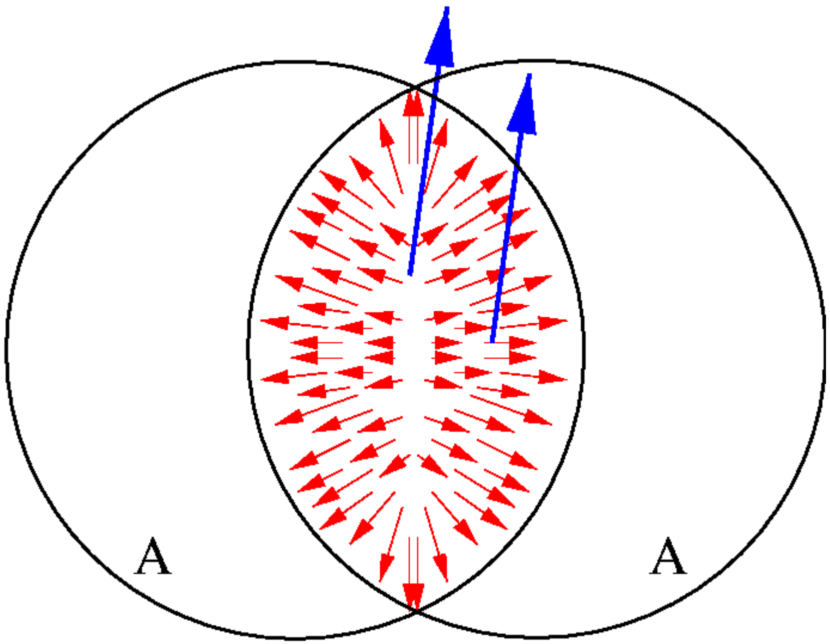
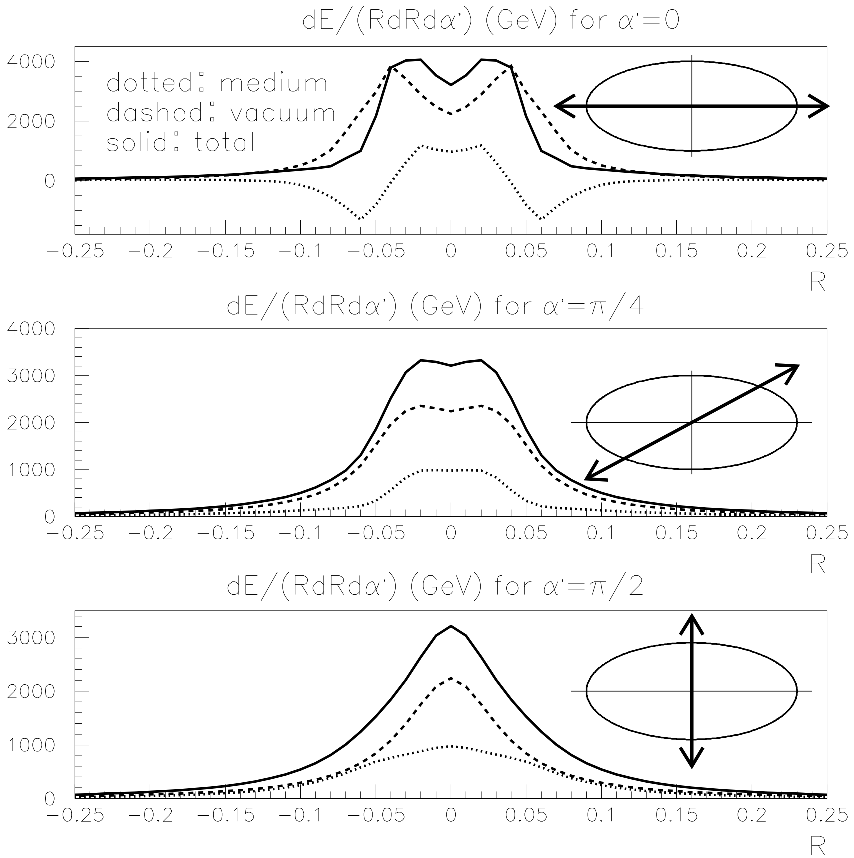
Radial flow



Could it be seen in the elliptic flow v_2?

Longitudinal flow

Jet energy distributions for a flow directed in the $\pm z$ directions.



$E_{\text{jet}} = 100$ GeV, $\Delta E = 23$ GeV.

$q_0 = \mu$

Longitudinal flow

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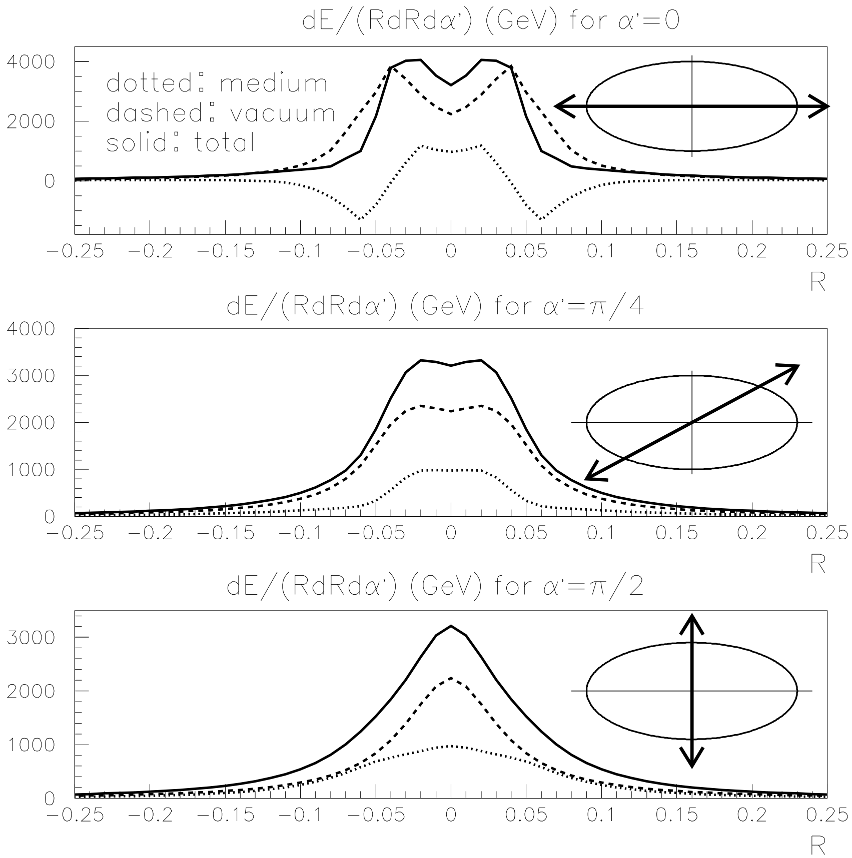

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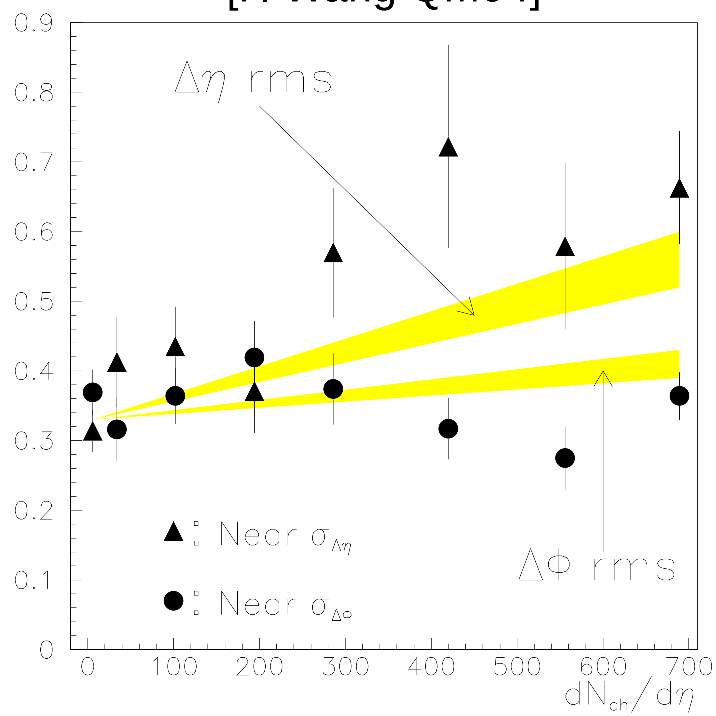
Estimation of the effect for the case of RHIC (STAR preliminary)

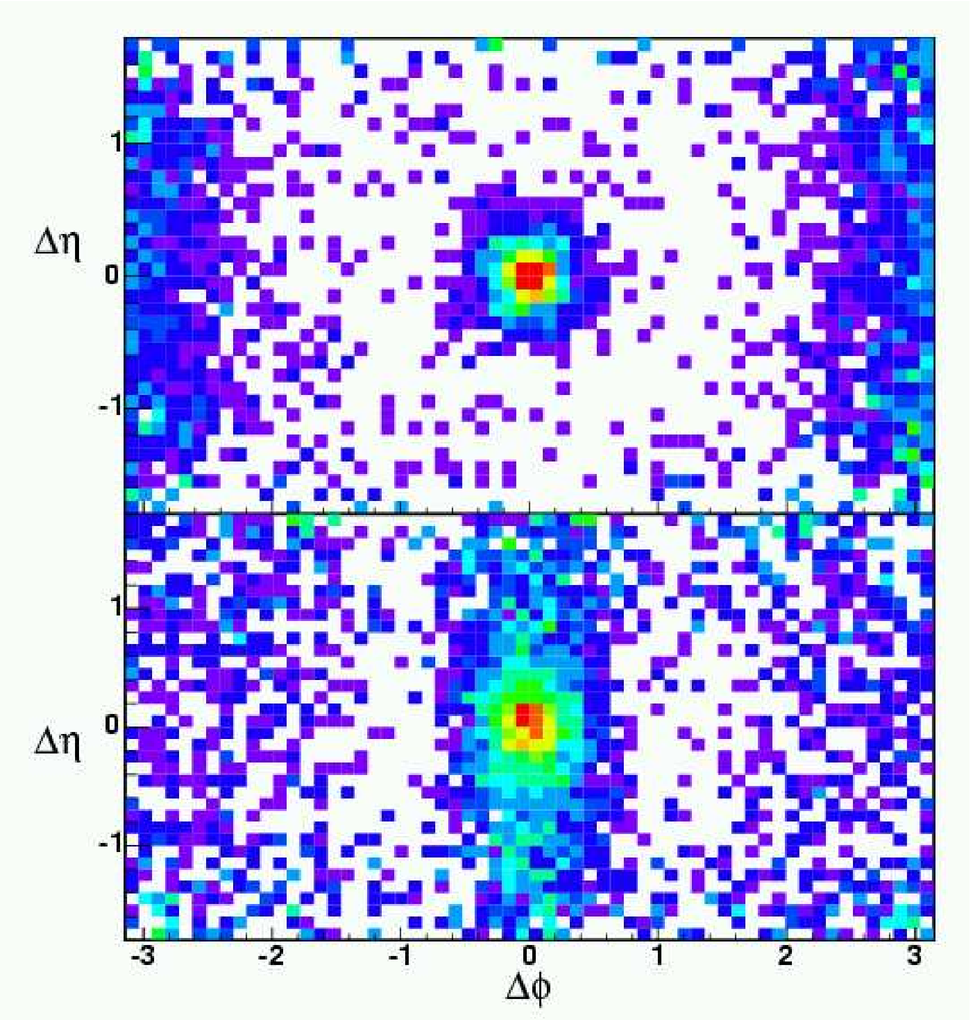
[F. Wang QM04]



Band corresponds to $q_0/\mu = 2 \div 4$
Broadening in the η-direction more important than in ϕ-direction.

Elongation in η-direction

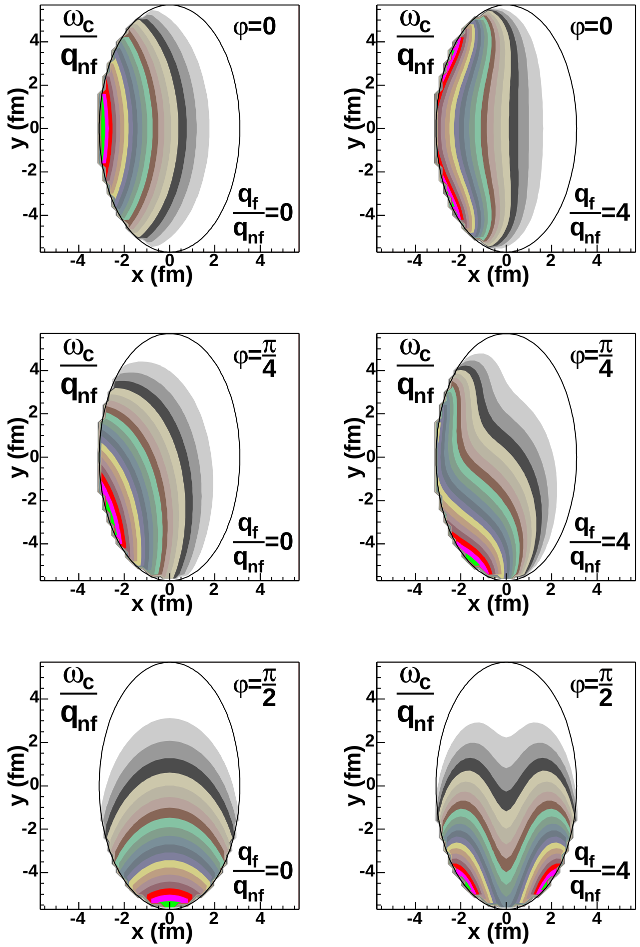
[STAR preliminary, D. Magestro HP04]



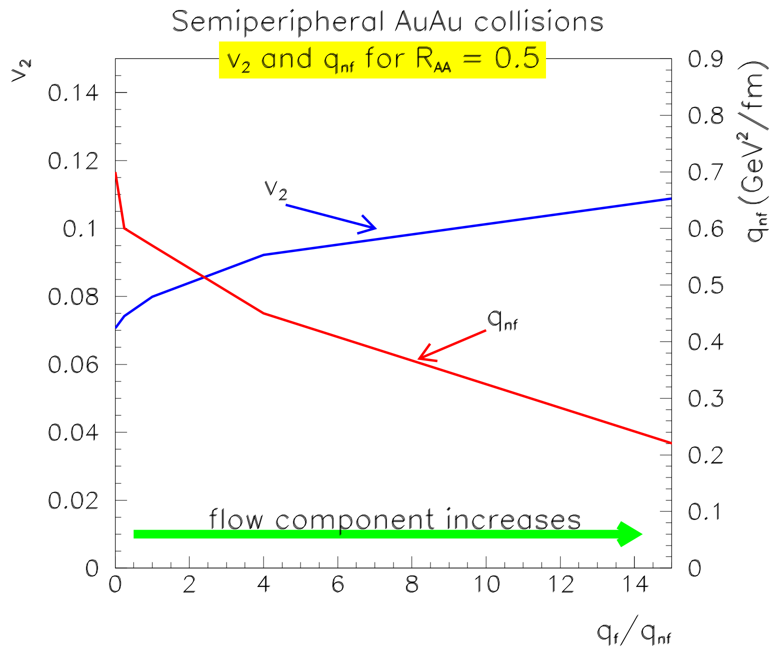
$3\,\mathrm{GeV} < p_t^{\mathrm{trigg}} < 6\,\mathrm{GeV};\ 2\,\mathrm{GeV} < p_t^{\mathrm{assoc}} < p_t^{\mathrm{trigg}}$

Inclusive particle and elliptic flow

$$\Delta E \sim \omega_c(\mathbf{r_0}, \phi) = \int d\xi \xi \left(q_{nf} + q_f |u_T(\mathbf{r_0}(\xi)) \cdot \mathbf{n}_T|^2 \right) \Omega(\mathbf{r_0}, \phi)$$



[Armesto, Salgado, Wiedemann (2004)]

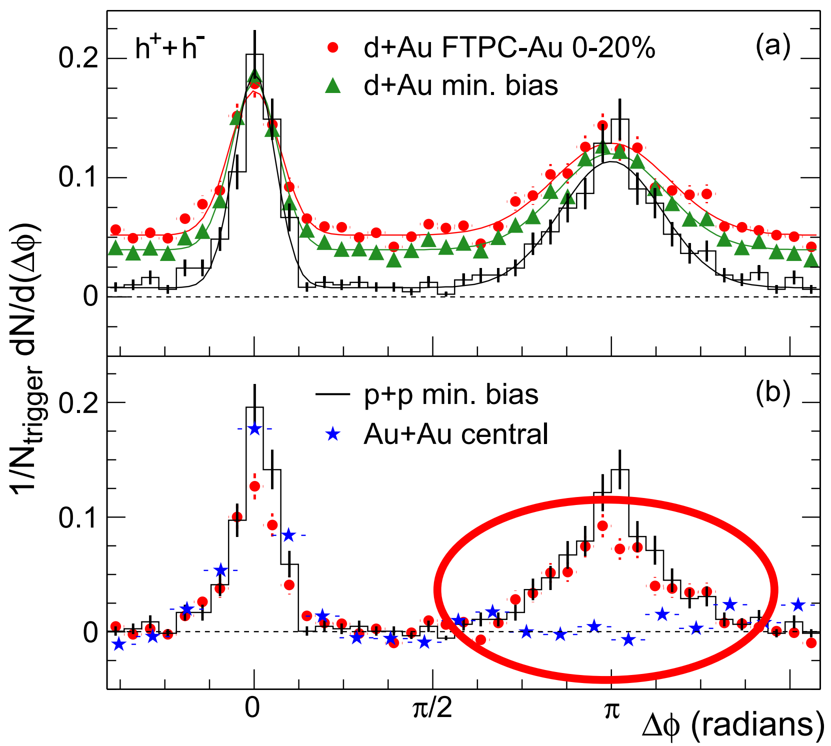


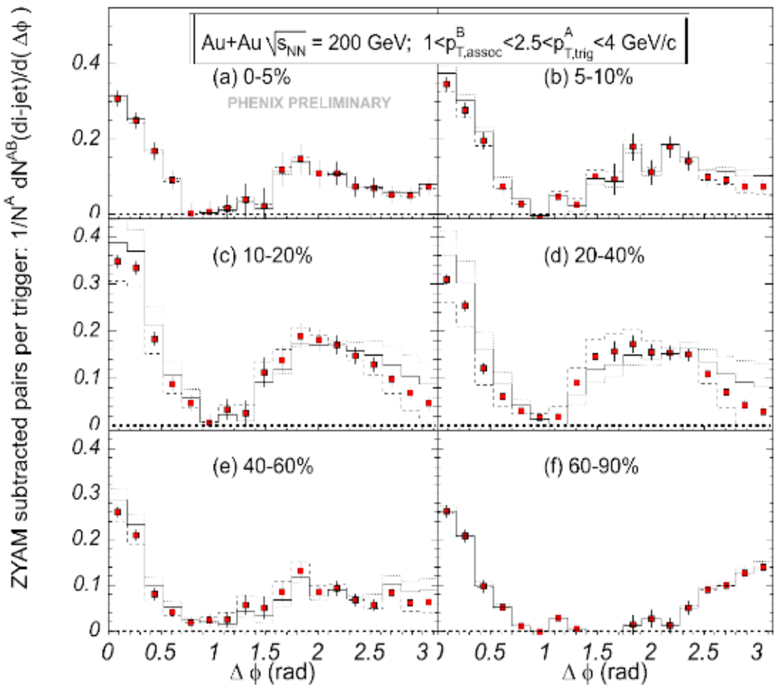
⇛ Correlation of the suppression w.r.t the reaction plane (v_2) affected by the flow component.

⇛ More flow $\Rightarrow$ smaller density for the same suppression

Associated particles

Where does the 'away-side jet' go? $\Longrightarrow$ smaller p_t associated particles.





[PHENIX preliminary]

⇛ Not jet-like structure in the backwards hemisphere

- Thermalization of the high-p_t particle??
- Sonic shock waves?? [Casalderrey-Solana, Shuryak, Teaney]

Large angle radiation

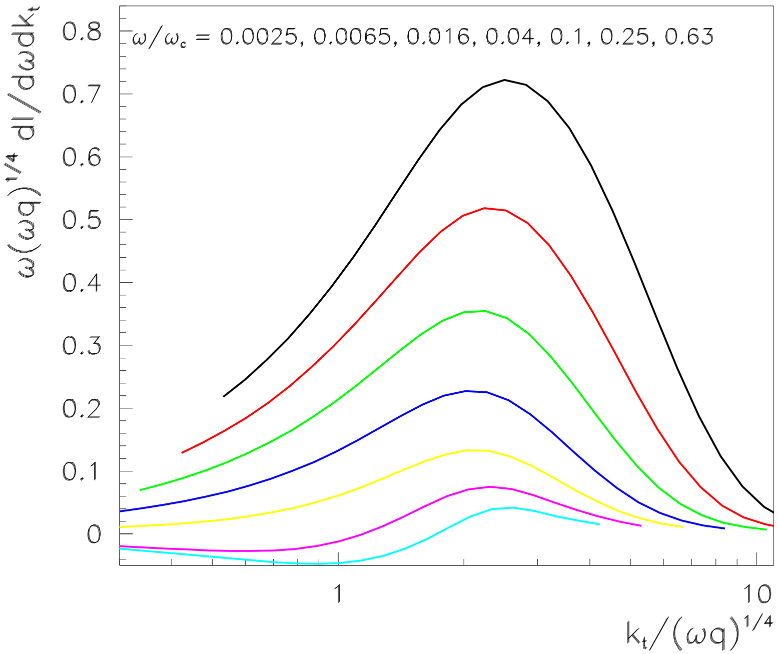
Remember the spectrum

The radiation is suppressed for

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

Radiation is large angle for

$$\omega \lesssim \omega_{\rm min} \sim \hat{q}^{1/3}$$



In qualitative agreement with the away-side signal ?

Conclusions

- Inclusive particle production presents limitations in the characterization of the medium.
  - Study less inclusive observables
- Heavy quarks: Smaller medium-induced radiation
  - Surface emission makes the mass effect smaller
  - LHC will measure mass effects in a large p_t range with B mesons
- Jet–broadening directly related to energy loss by medium–induced gluon radiation.
  - Measure jet structure in HIC (control over multiplicity background).
- A flow field in the medium produces additional (anisotropic) gluon radiation
  - Asymmetric jet shapes (elongation in η-direction).
  - Contributes to v_2 and suppression (can this explain the opacity problem?)