# Jet studies in heavy ion collisions

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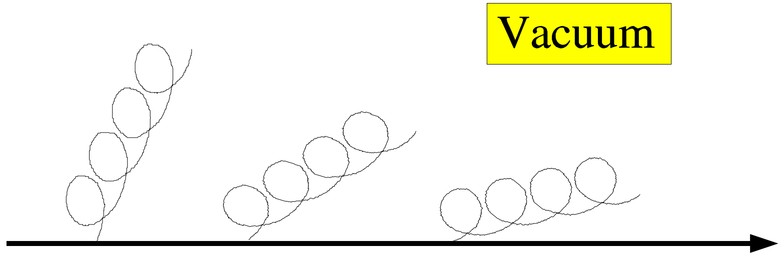
# Matter affects evolution.

⇛ A quark or gluon (traveling in vacuum) with virtuality $Q^2$ will radiate gluons to become on-shell: DGLAP-like evolution.



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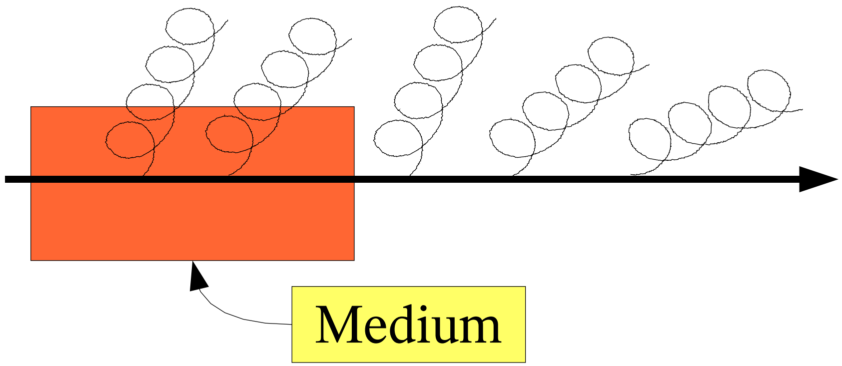
- Gluon radiation modified when the particle traverses a medium: medium-induced gluon radiation.



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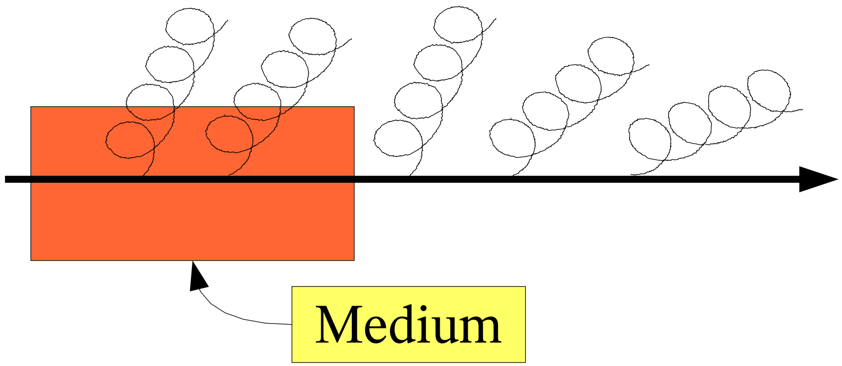
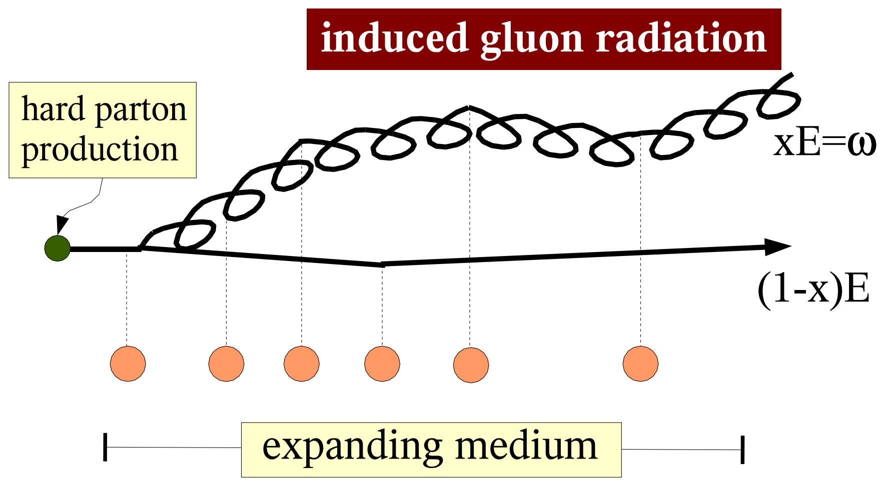



- Where to look?
  - Inclusive particle (suppression).
  - Heavy quarks
  - Jets: Jetshapes, particle correlations...

# Medium–induced gluon radiation.




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

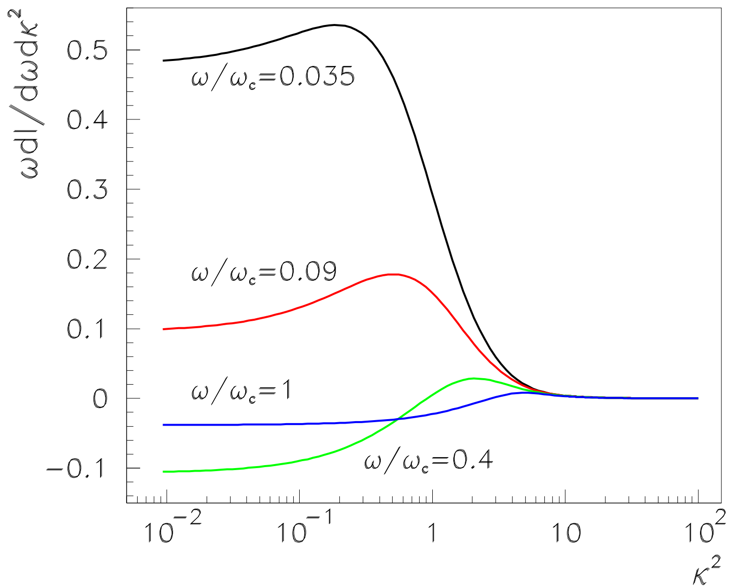
⇛ $k^2_{\perp,\,\max} \sim \hat{q}L$; $\boxed{\kappa^2 \equiv k^2_\perp/\hat{q}L}$

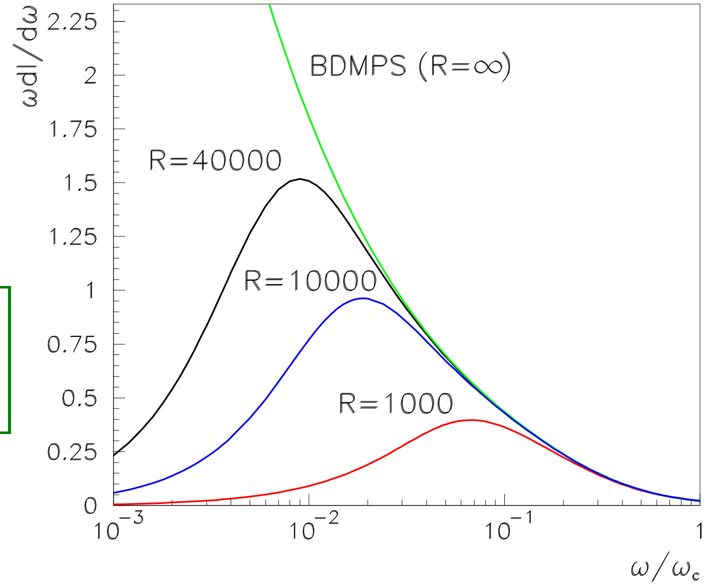
⇛ Accumulated phase

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

Rad. suppressed by coherence

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

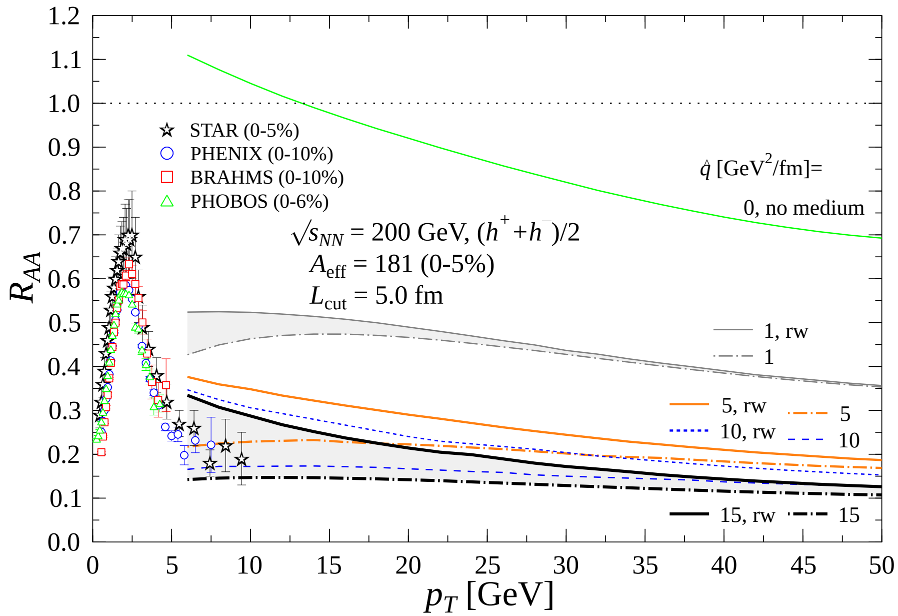


# One–particle inclusive production

# Application of the formalism

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




[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...]

# Opacity problem

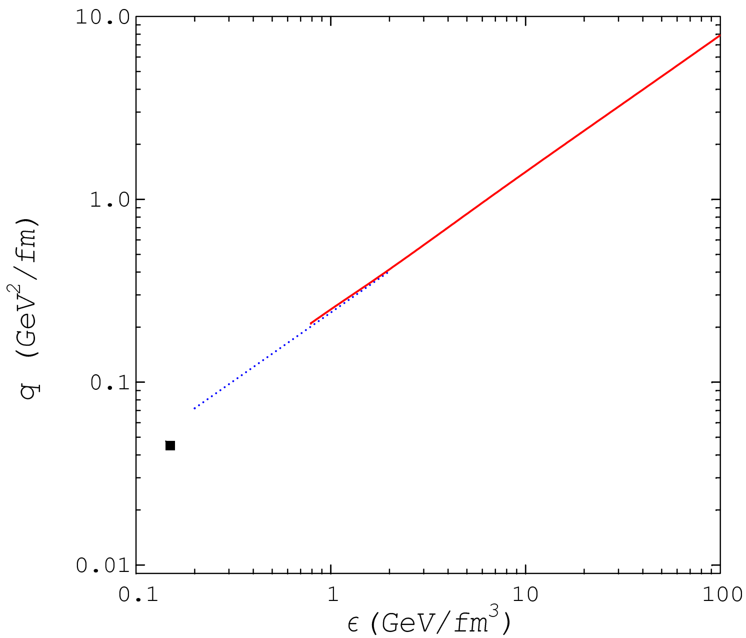
- $\hat{q} = c\epsilon^{3/4}$ for an ideal QGP $c_{ideal}^{QGP} \sim 2$
- We obtain [Eskola, Honkanen, Salgado, Wiedemann (2004)]

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

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

[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 $\Rightarrow$



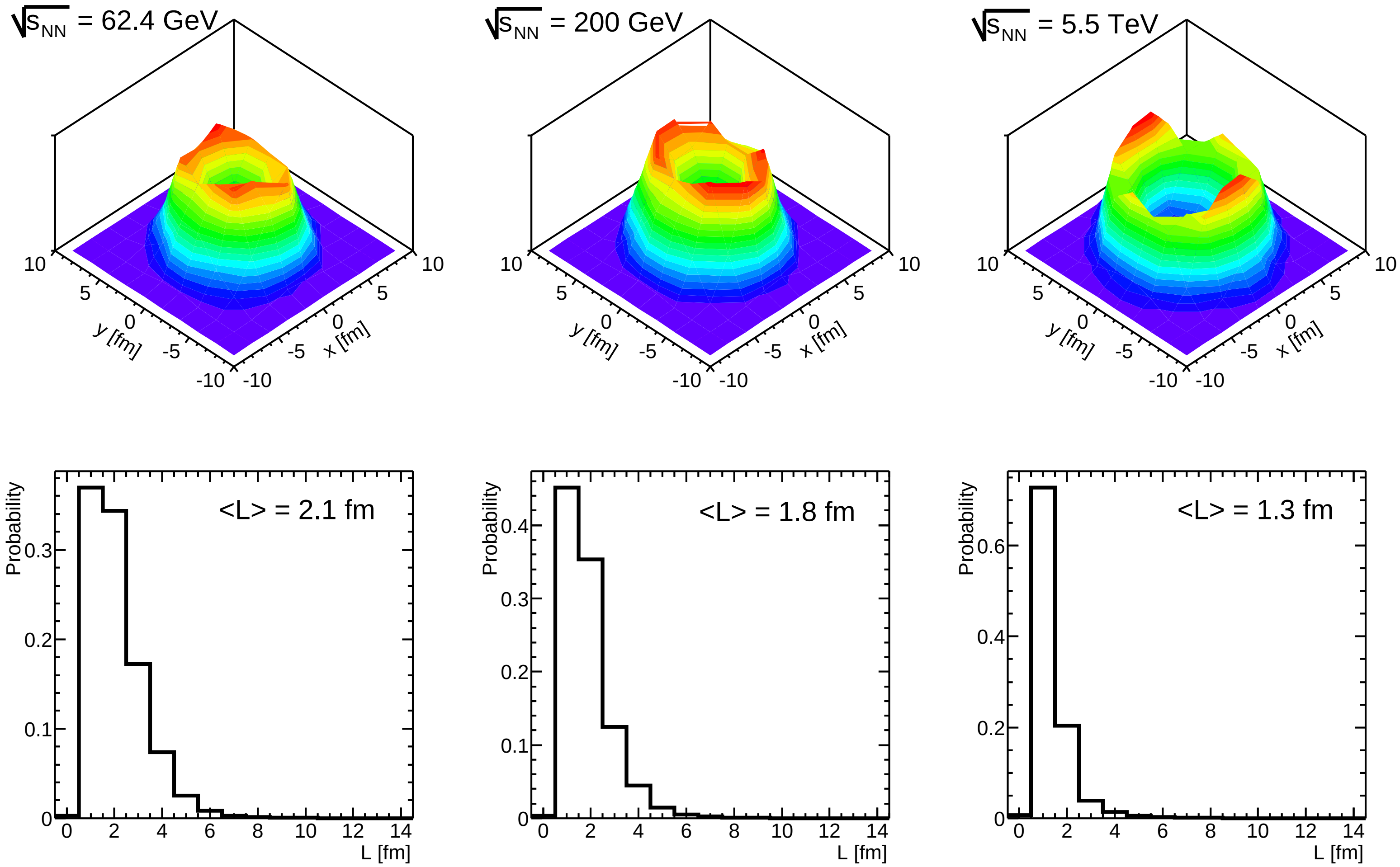

[Baier 2002]

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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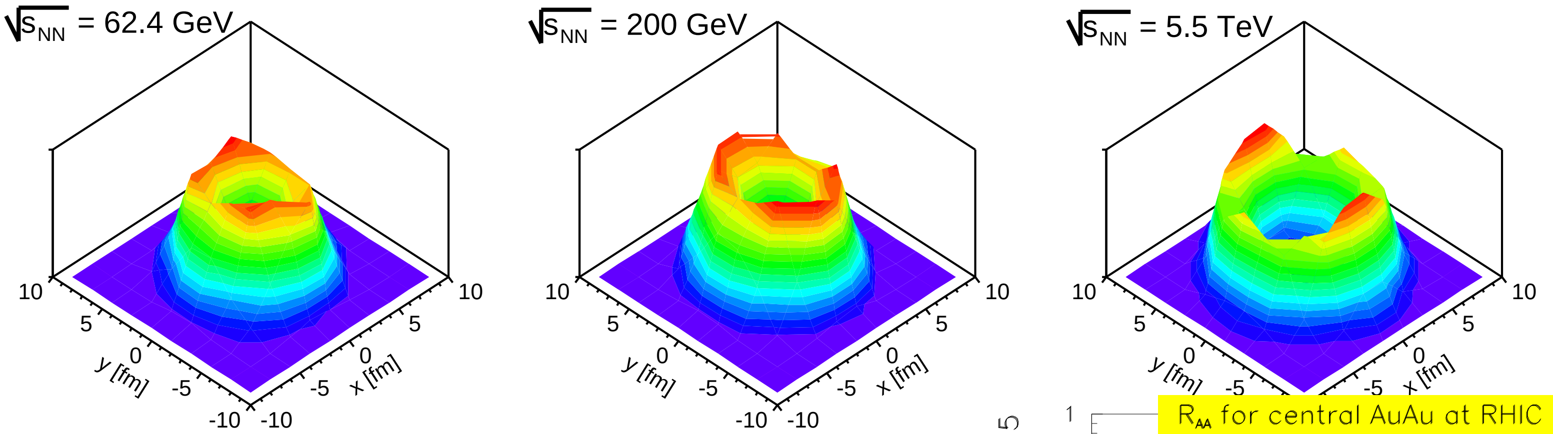
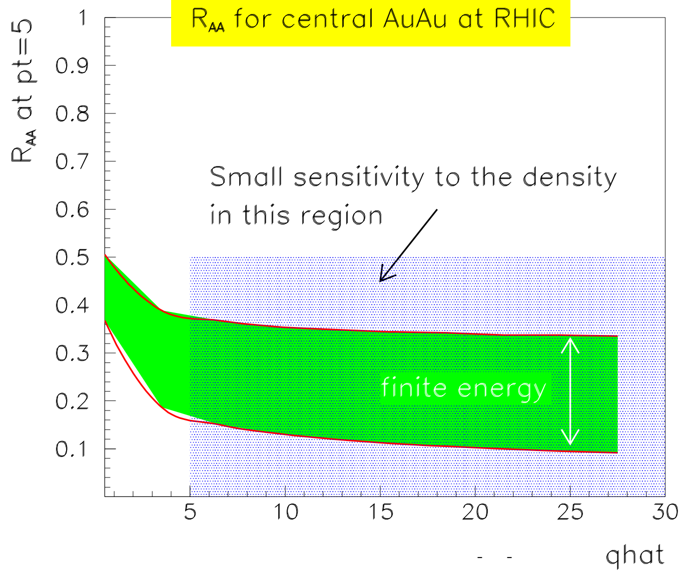


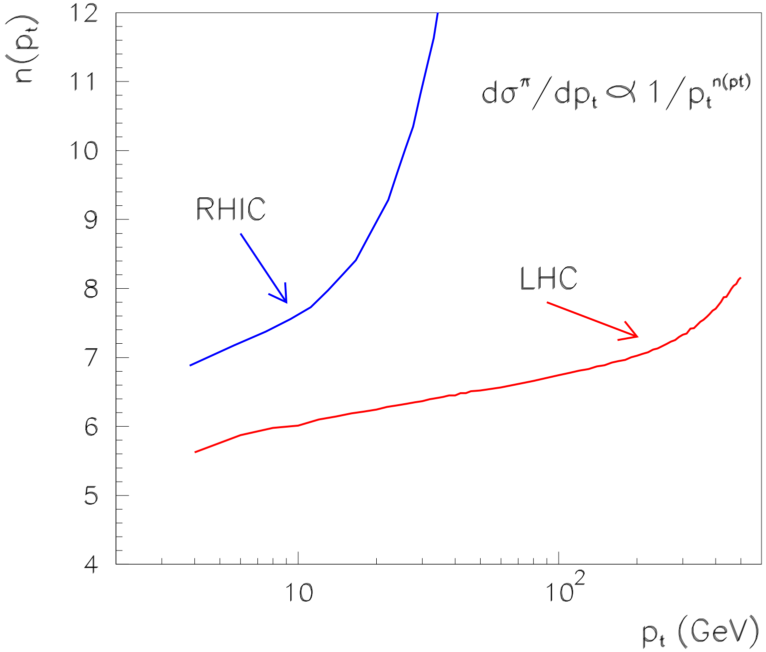

In this case, the sensitivity to $\hat{q}$ becomes small (bad determination of the medium density)

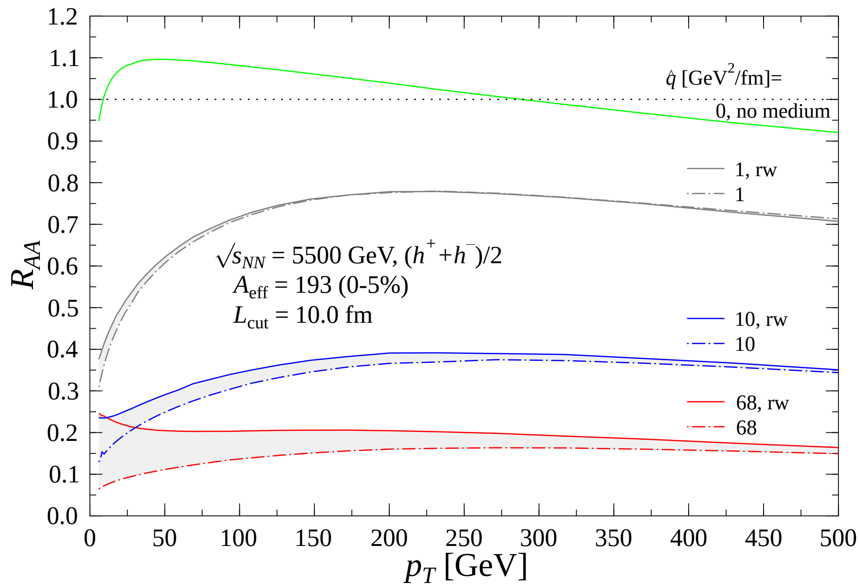


# Flatteness of the suppression

Trigger bias

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



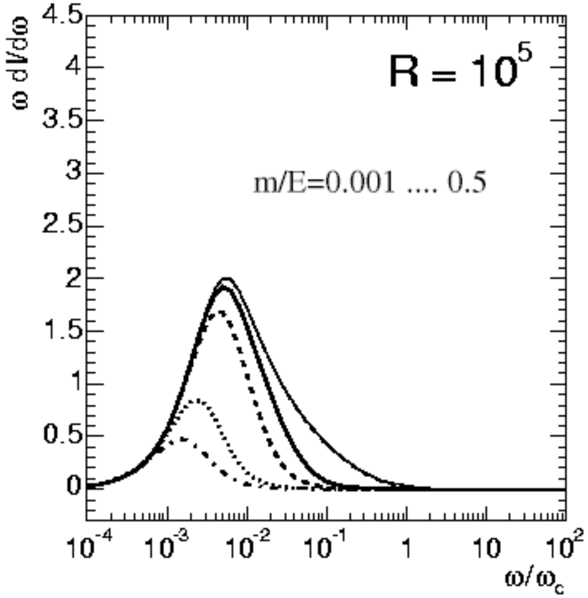

$R_{AA}$ flat also for the LHC

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

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

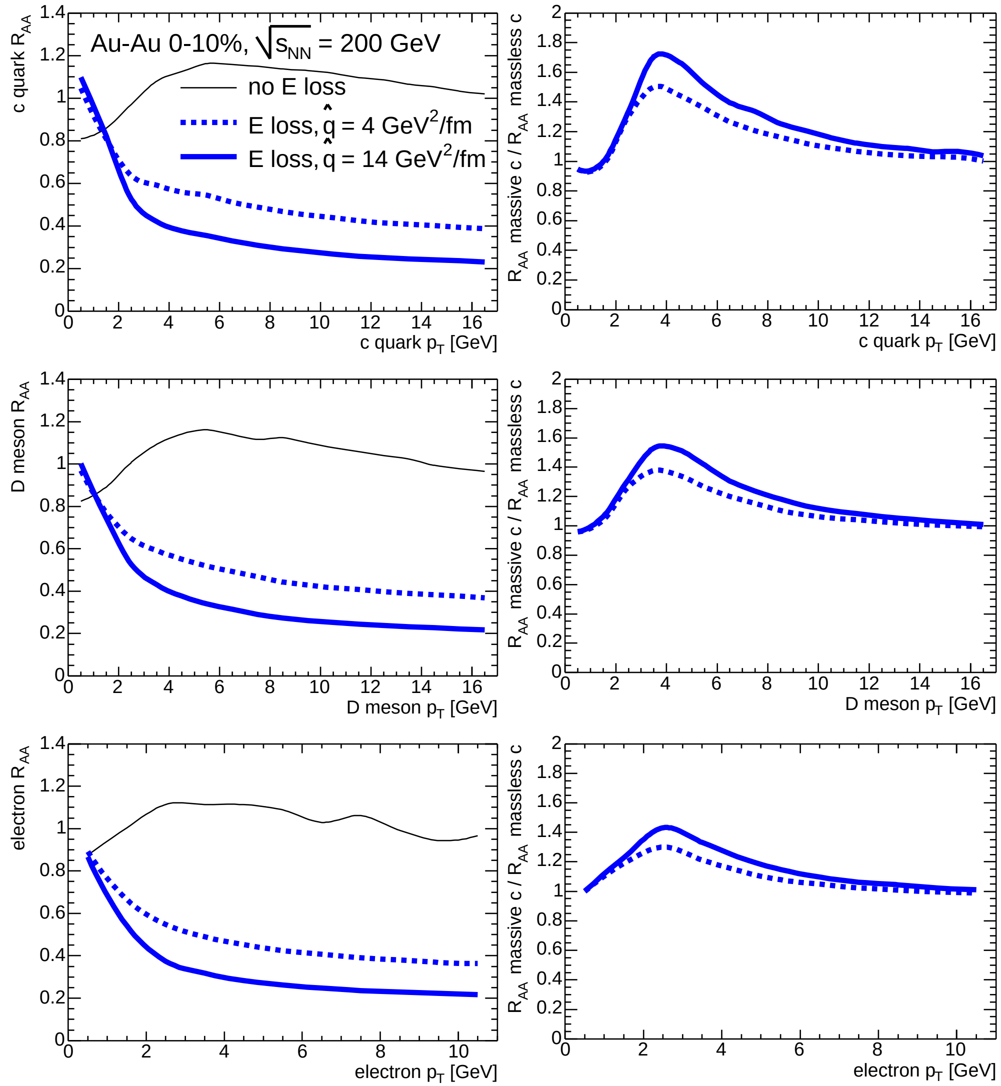
# Massive quarks

- Mass effects suppress gluon radiation [Dokshitzer, Kharzeev (2001); Zhang, Wang, Wang (2004); Djordjevic, Gyulassy (2004); Armesto, Salgado Wiedemann (2004)]



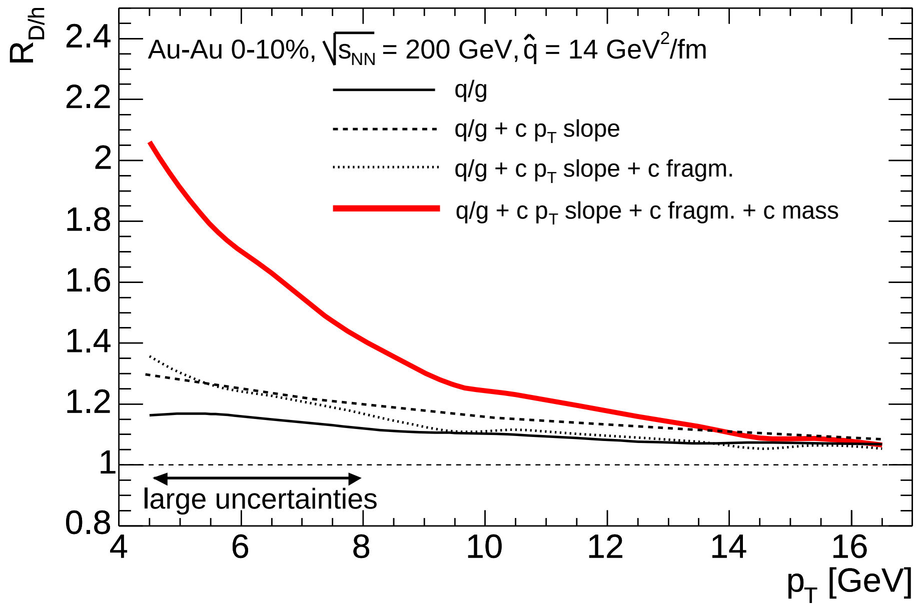

(vacuum → dead-cone effect)

- No additional parameters for predictions.




[Armesto,Dainese,Salgado,Wiedemann 2005]

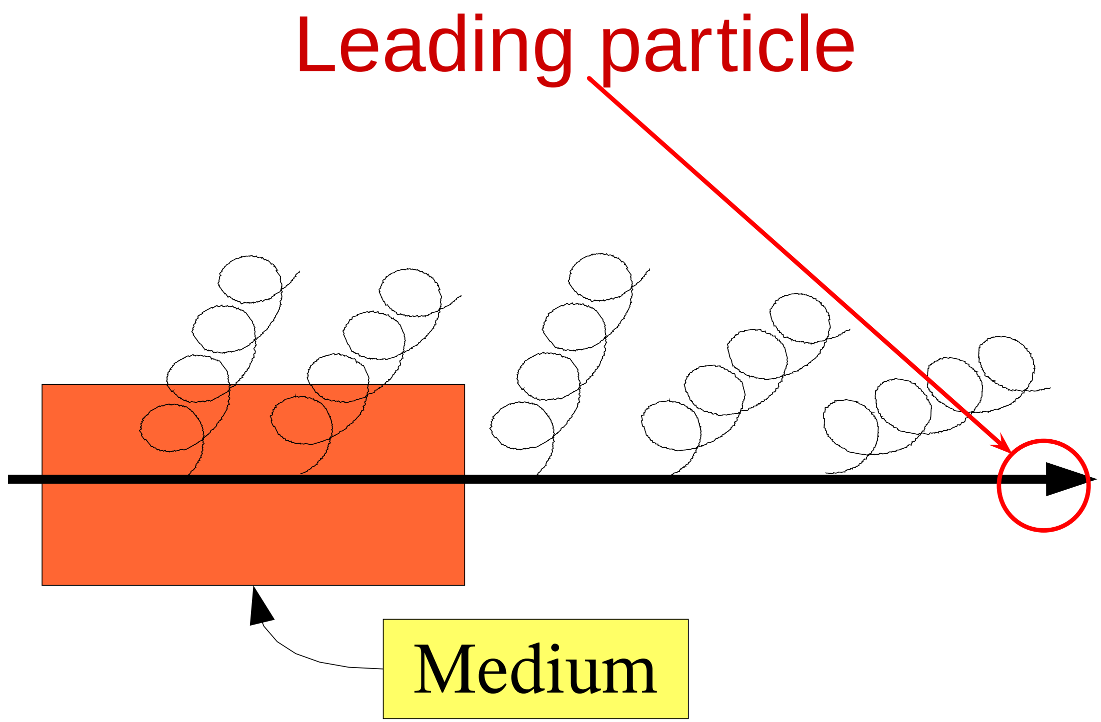
# Massive over light particle ratio




[Armesto,Dainese,Salgado,Wiedemann 2005]

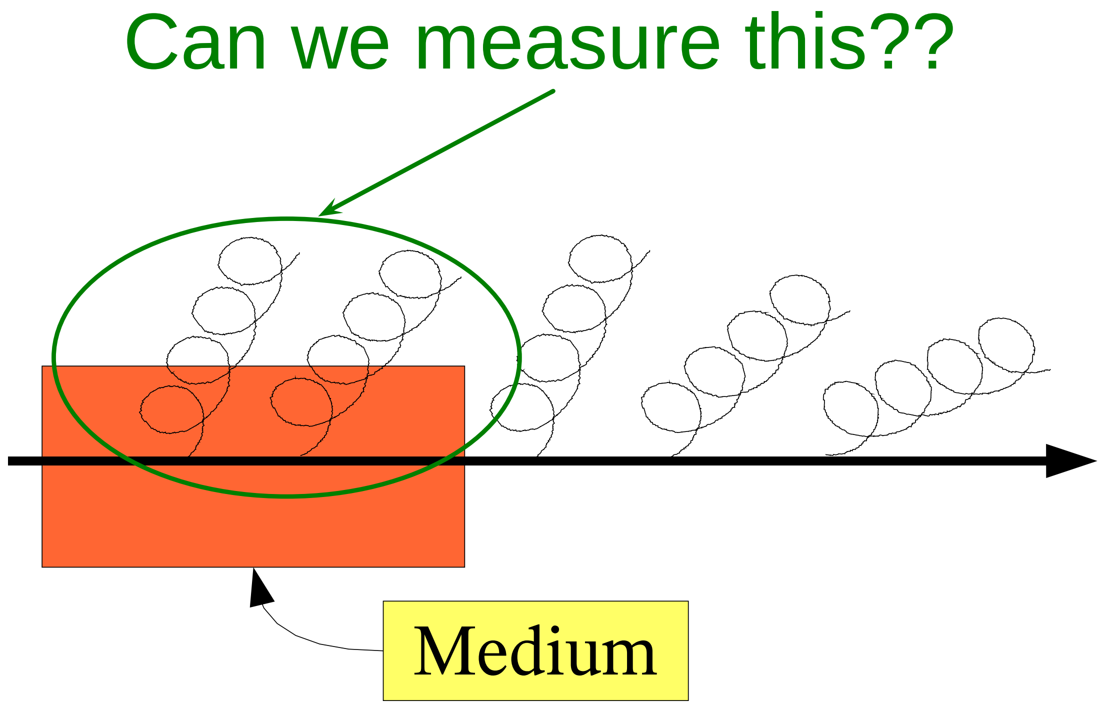
- Quark vs gluon energy loss: $\Delta E^g = N_C/C_F \Delta E^{q,\mathrm{m}=0}$
  - Increases $R_{D/h}$
- Light-particle spectrum slope larger than massive one
  - Increases $R_{D/h}$
- charm fragmentation harder
  - Decreases $R_{D/h}$
- Heavy quark suppression of gluon radiation ('dead-cone')
  - Increases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

# Jets




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

# Jets



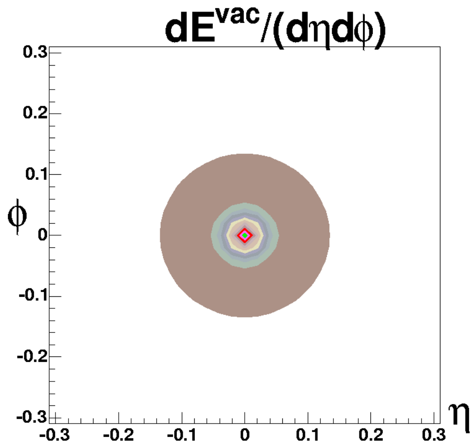

⇒ Inclusive particle measures the density of the medium: $\Delta E \propto \alpha_S \hat{q} L^2$

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

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

Vacuum

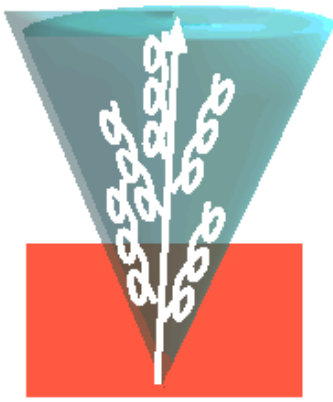
(reference)

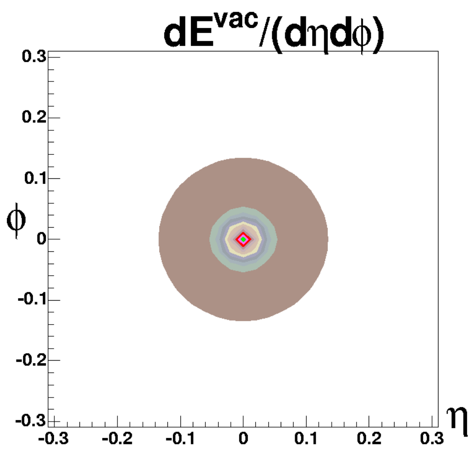


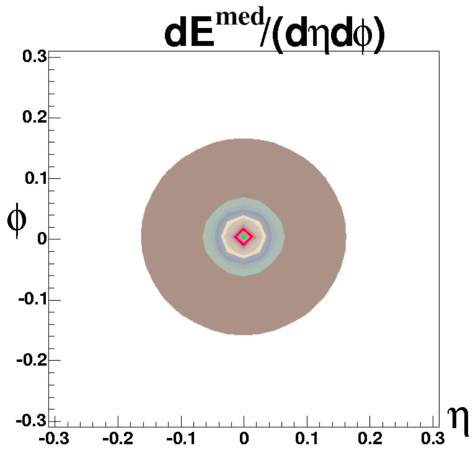
# Jet shapes in the $\eta \times \phi$ plane.

Vacuum
(reference)

Medium:
broadening



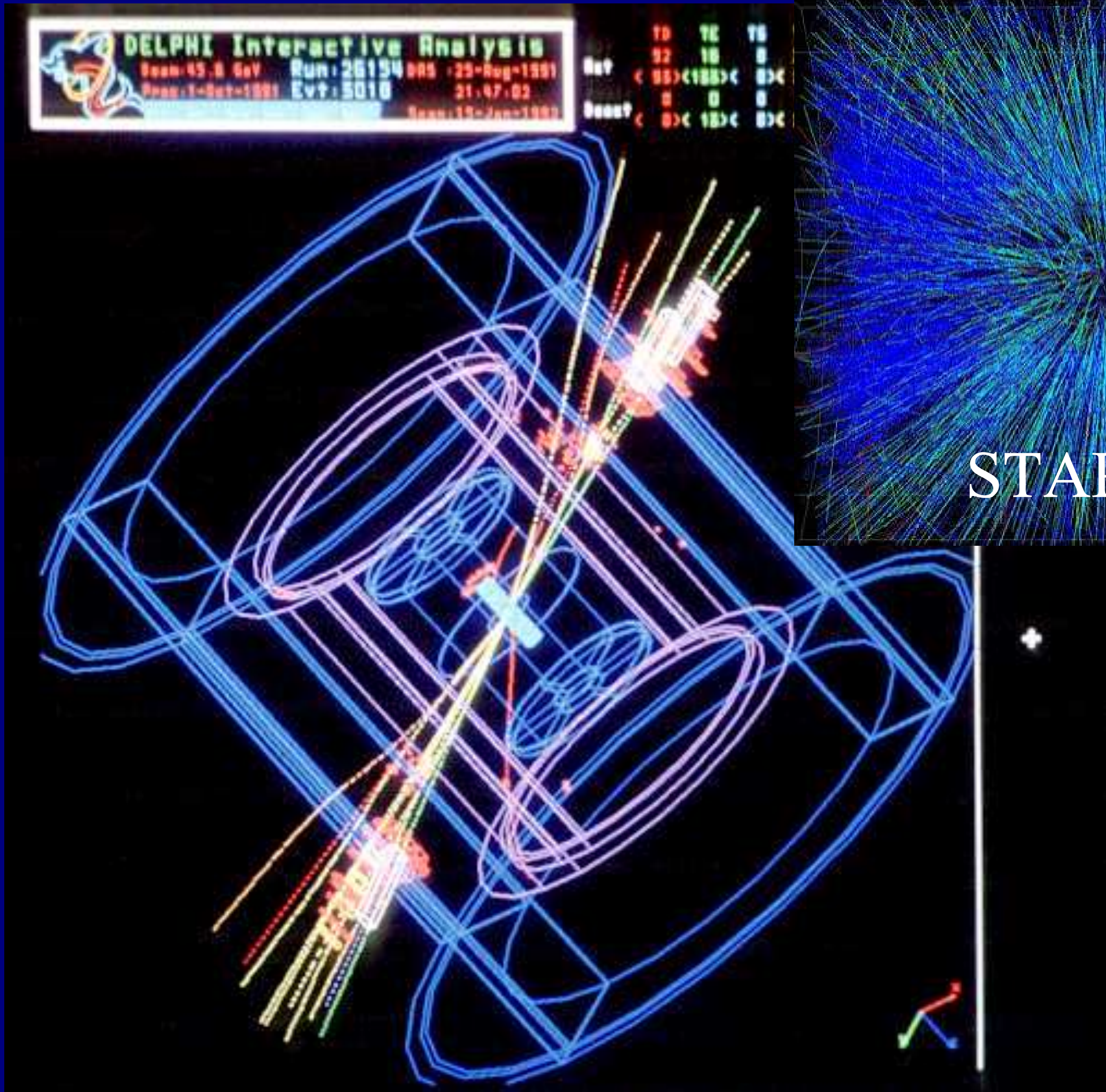


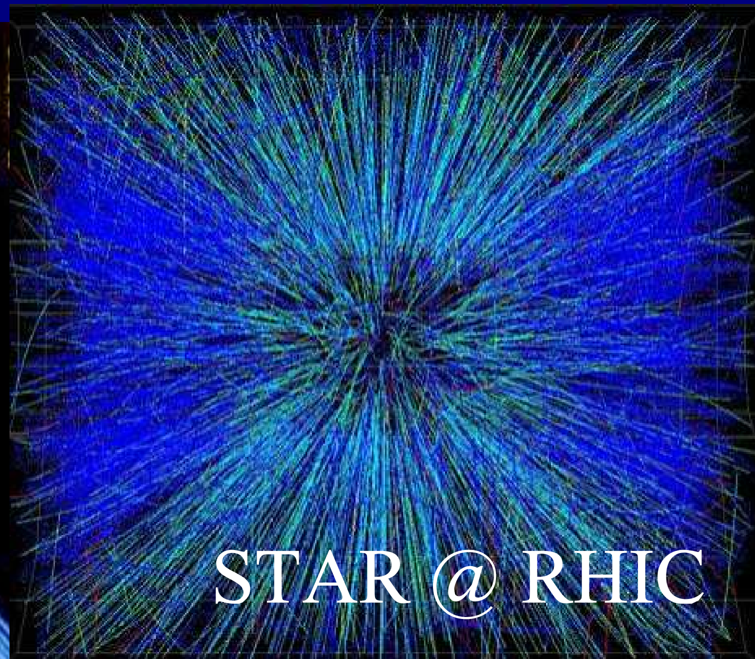



# Jets in HIC???


DELPHI Interactive Analysis
DELPHI
ENDCAPS
BARREL
CENTRAL
Return

# Jets in HIC???



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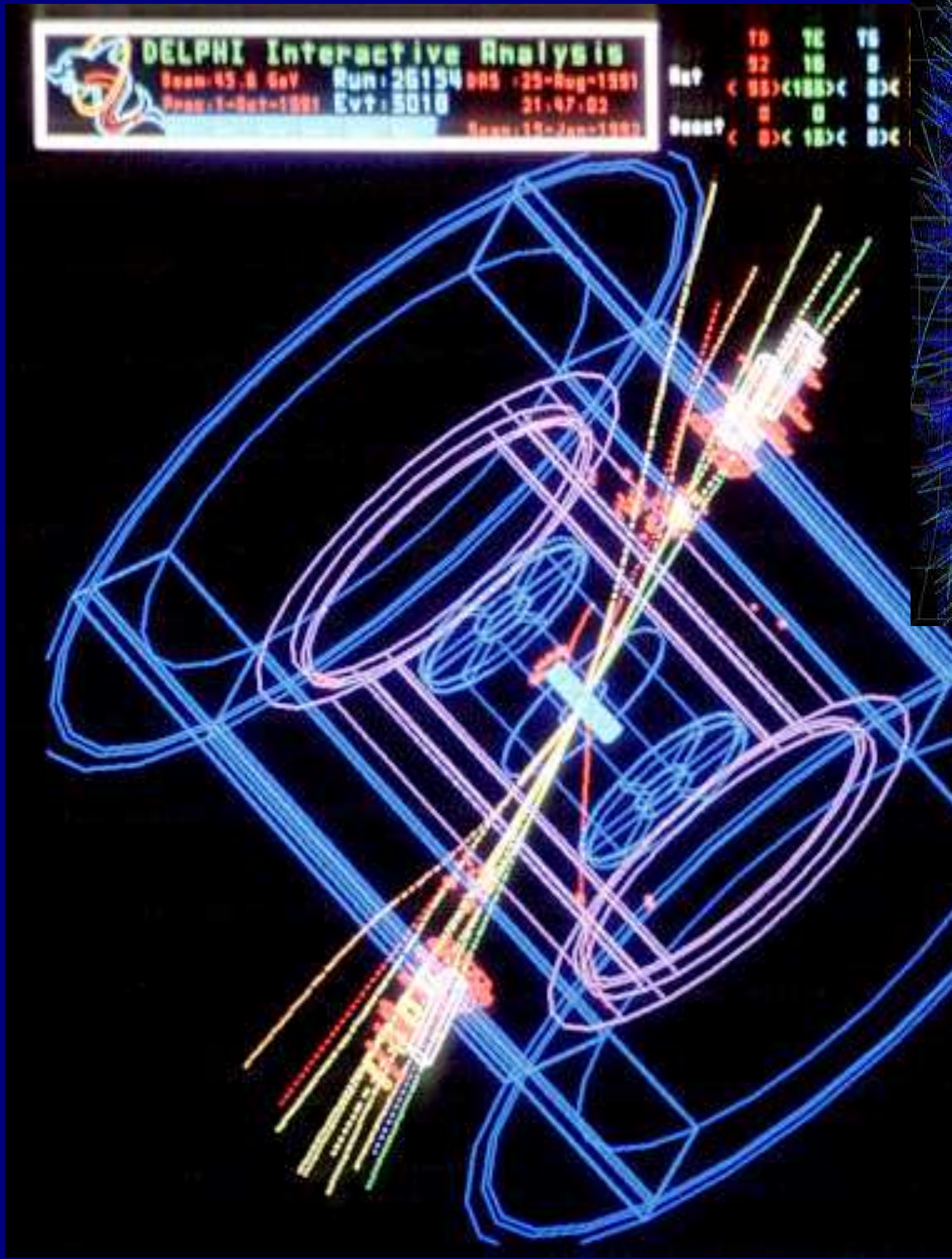
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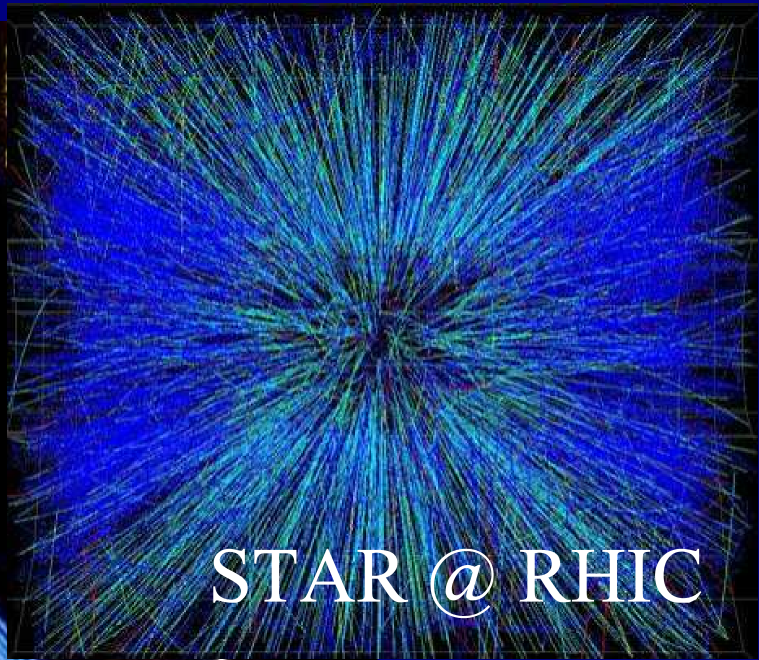
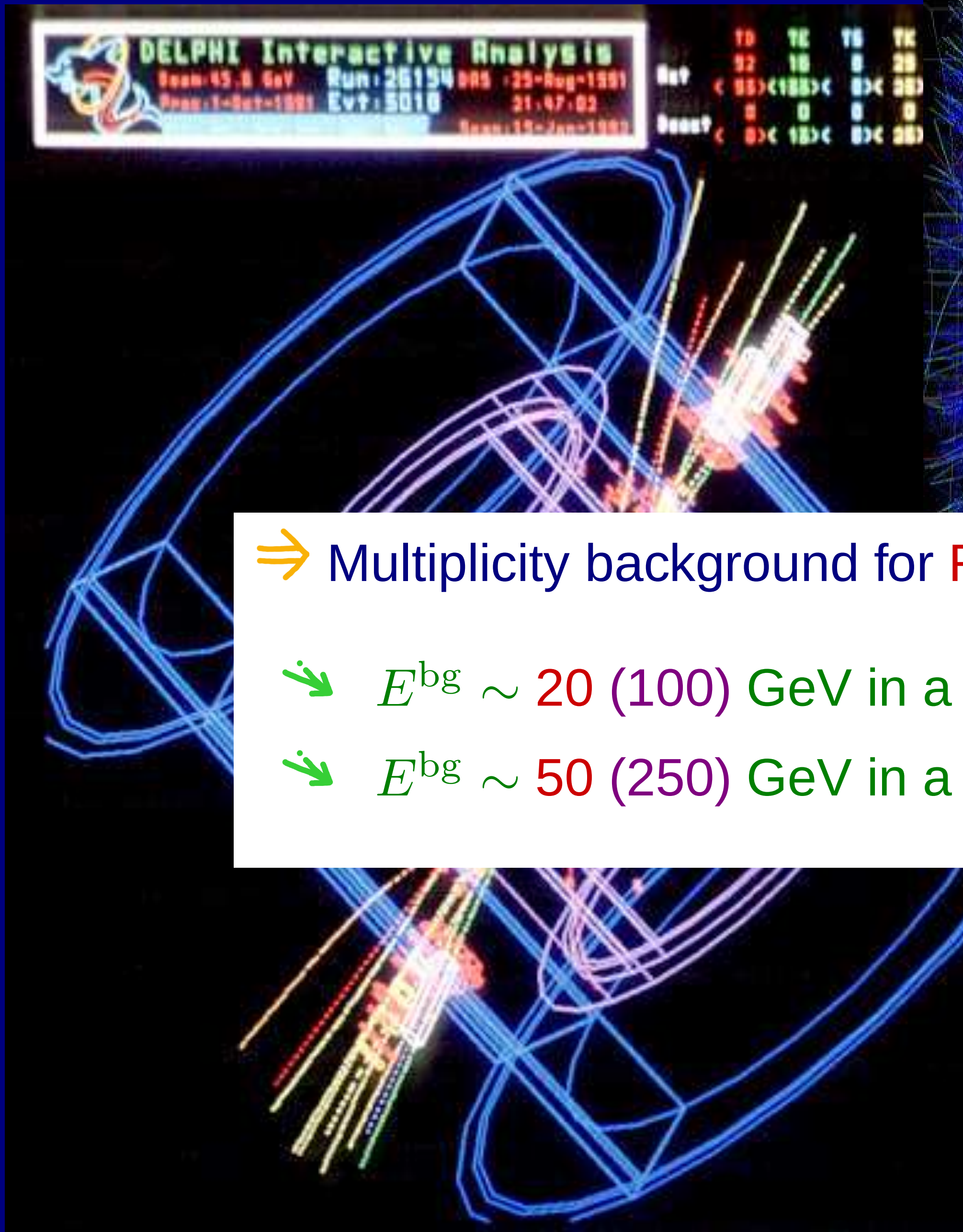
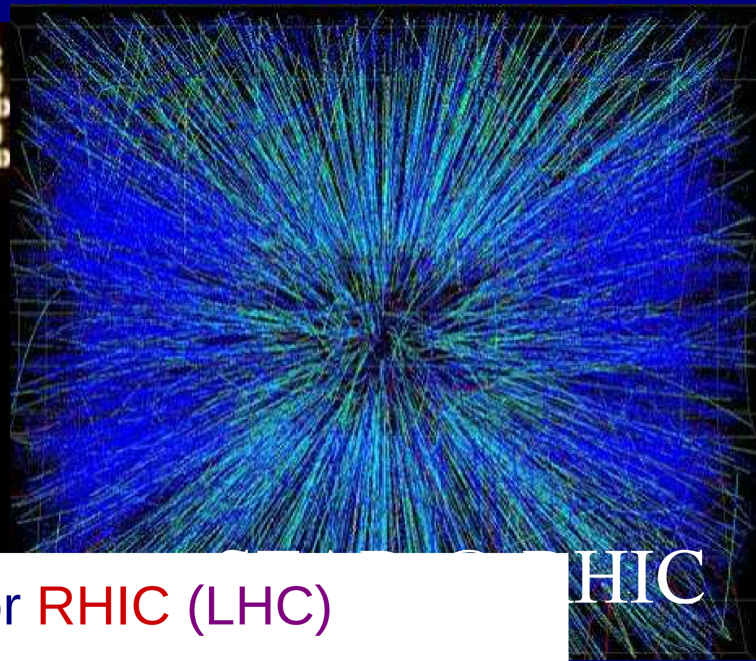
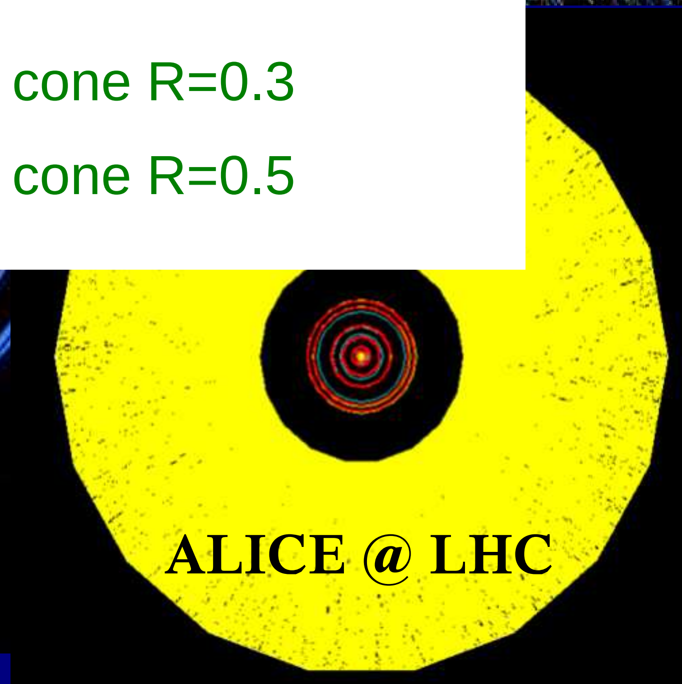

STAR @ RHIC


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

# Jets in HIC???






⇒ Multiplicity background for RHIC (LHC)

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

# Jet shapes

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

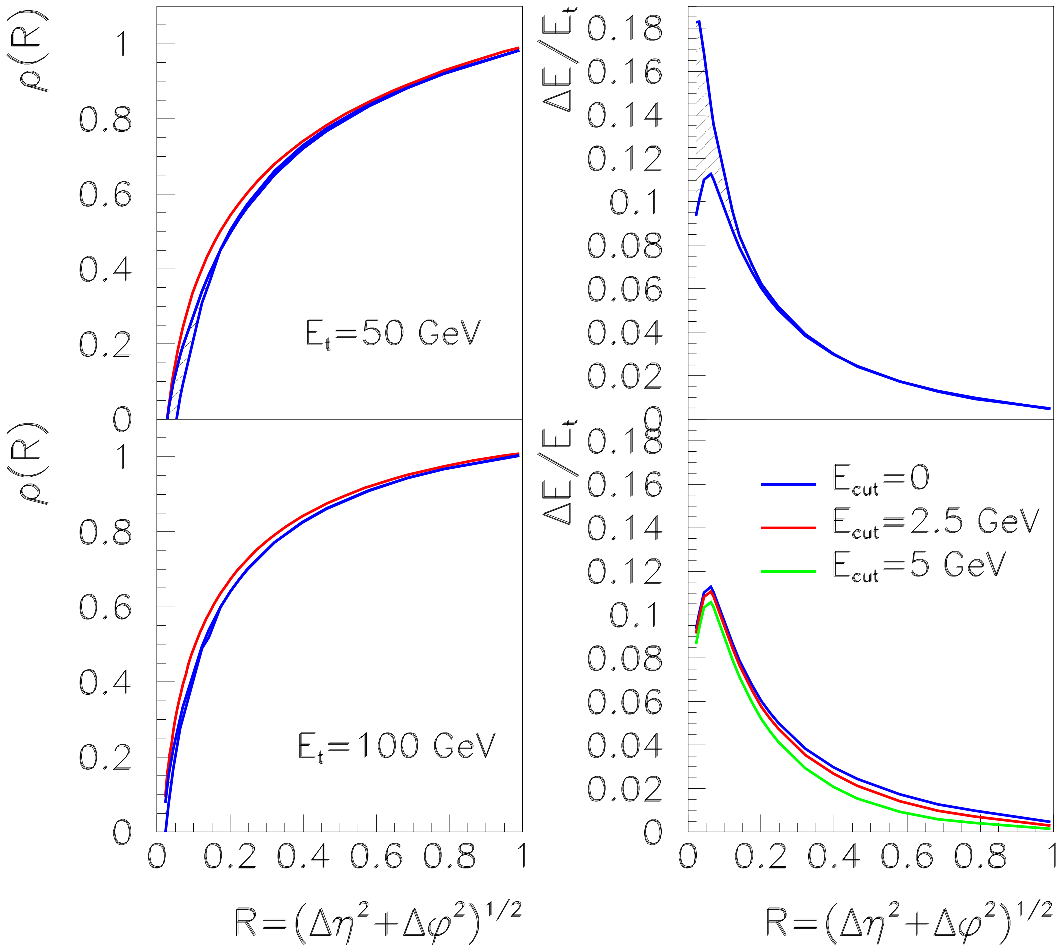
$$\rho_{\rm vac}(R) = \frac{1}{N_{\rm jets}} \sum_{\rm jets} \frac{E_t(R)}{E_t(R=1)}$$

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

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

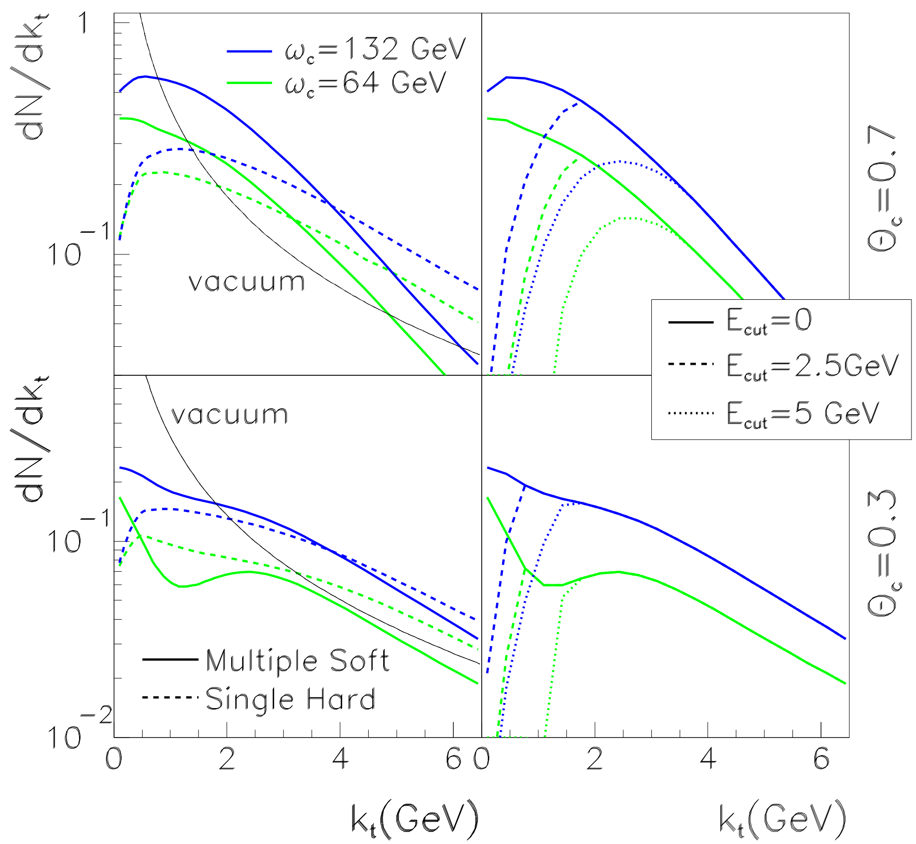
$$\frac{dN^{\rm jet}}{dk_\perp} = \int_{k_\perp/sin\theta_c}^{E} d\omega \frac{dI}{d\omega dk_\perp}$$

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...).

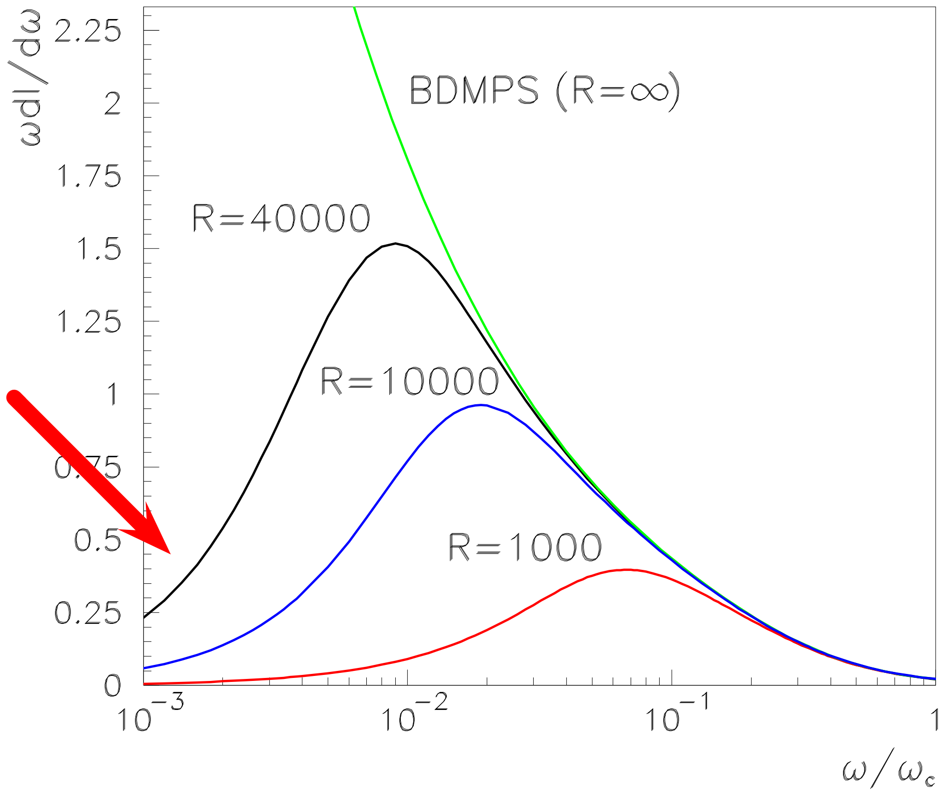
But, effect based mainly on kinematics remember $k_t^2 \sim \hat{q}L(\sim Q_{\rm sat}^2)$




(100 GeV jet)

# IR cuts

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

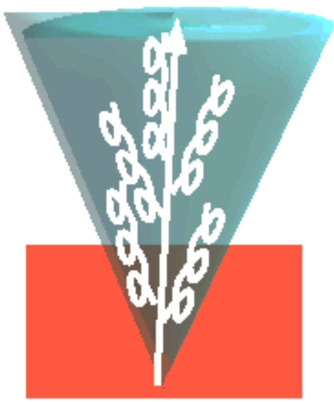


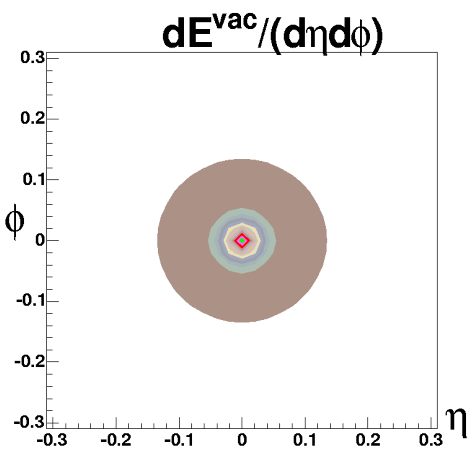

⇛ As we have seen, this is due to formation time effects.

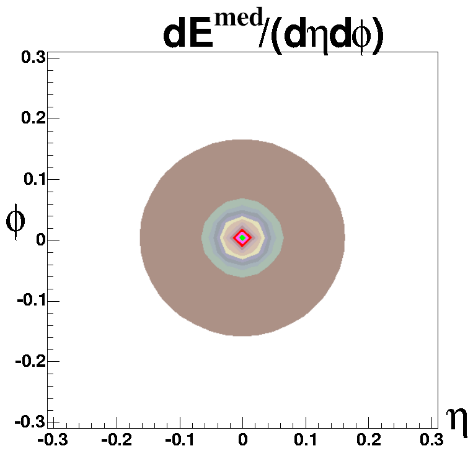
# Jet shapes in a flowing medium

Vacuum
(reference)

Medium:
broadening





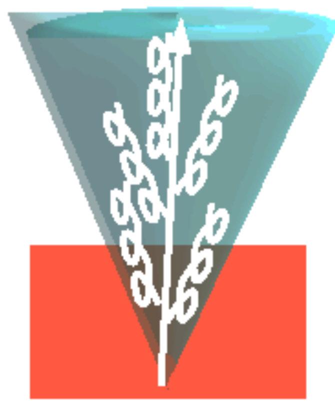
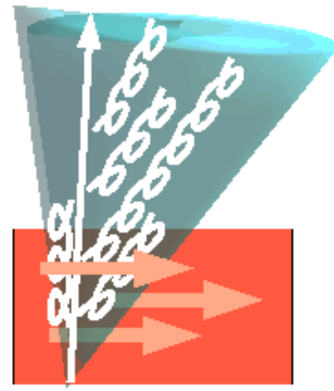



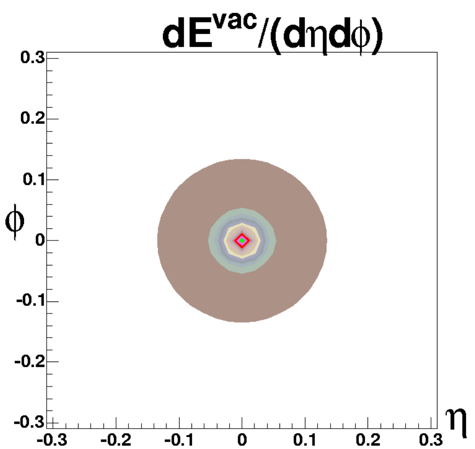
# Jet shapes in a flowing medium

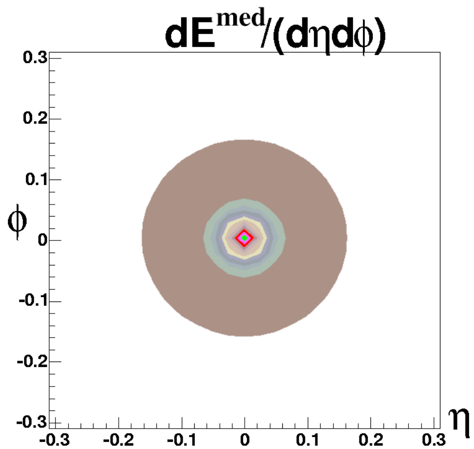
**Vacuum**
(reference)

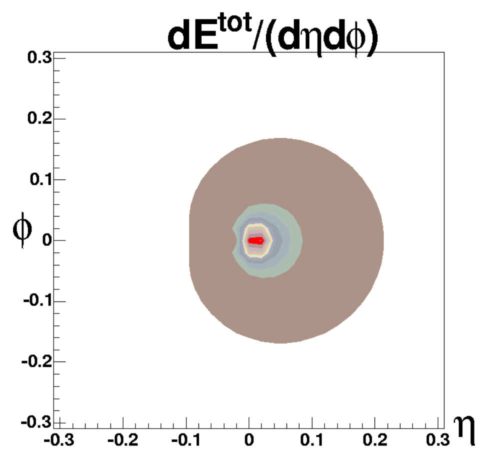
**Medium:**
broadening

**Flowing medium:**
anisotropic shape







# Formalism

In the single–hard scattering approximation

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

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

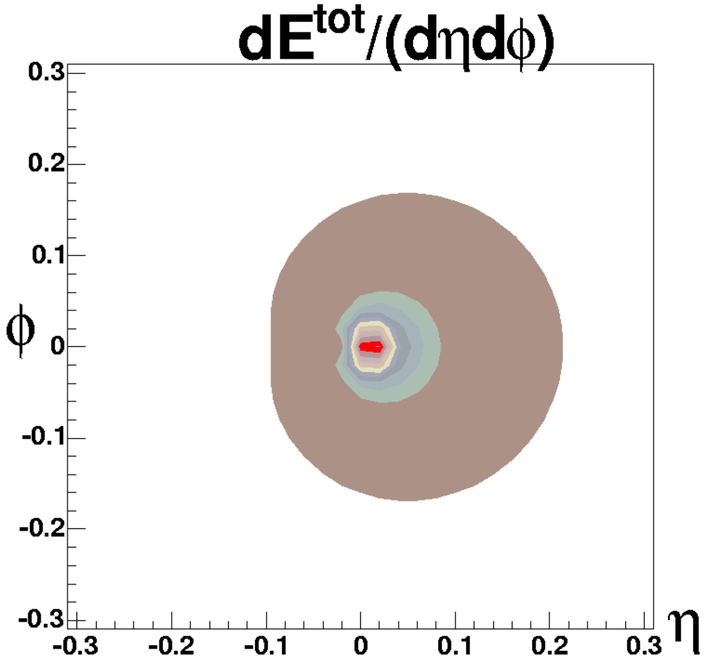
(Armesto, Salgado, Wiedemann hep-ph/0405301)

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

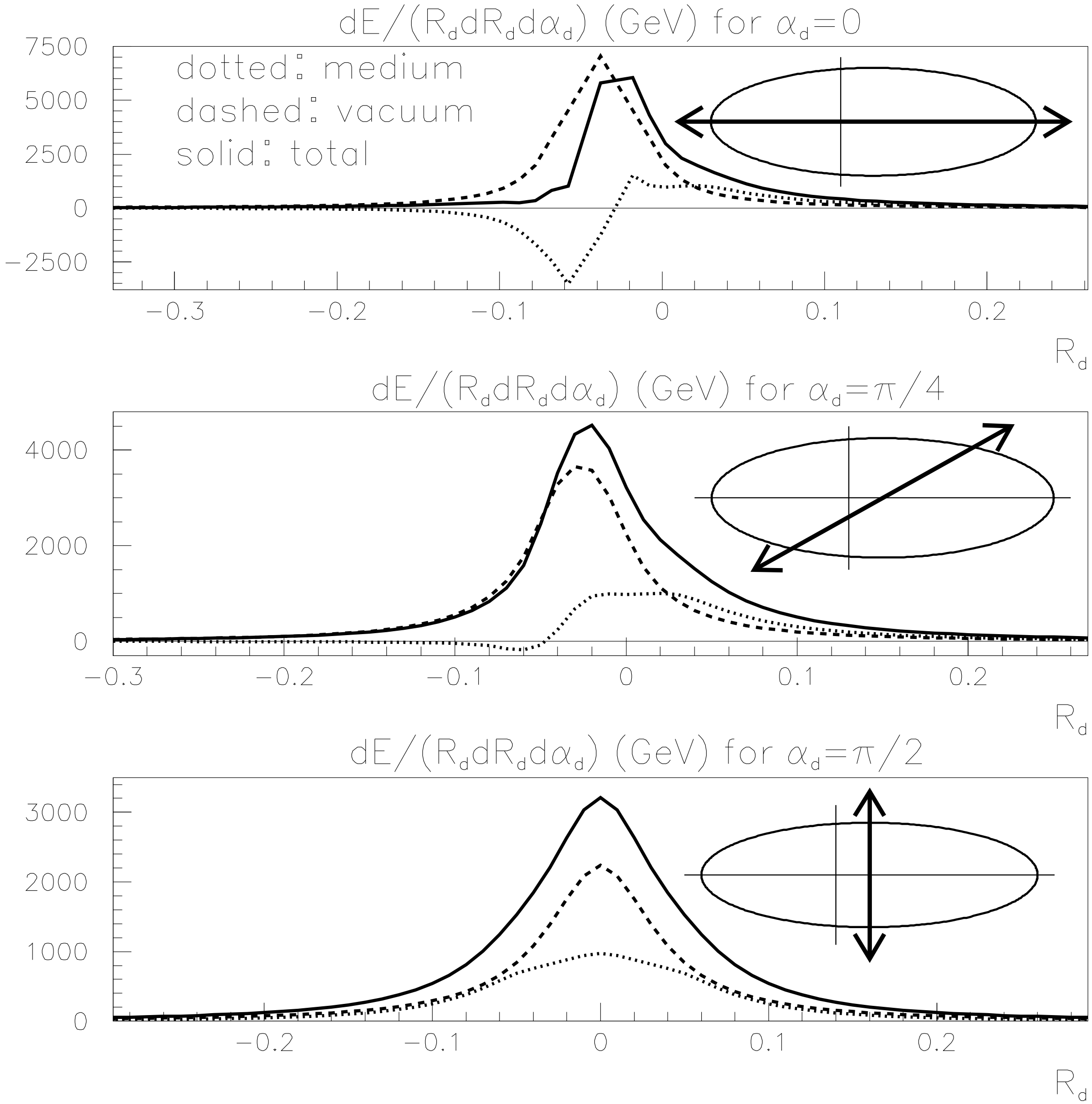
⇒ In the comoving frame $\langle k^2\rangle \sim \mu^2$, $\Delta E \sim \alpha_S n_0 \mu^2 L^2$.

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

# Jet energy distribution

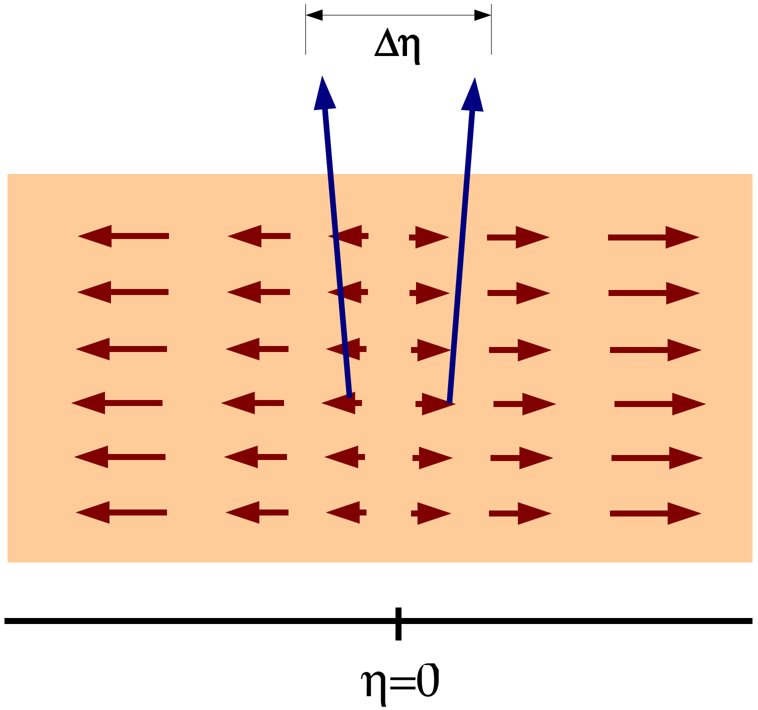



Flow in the $+z$ direction



# 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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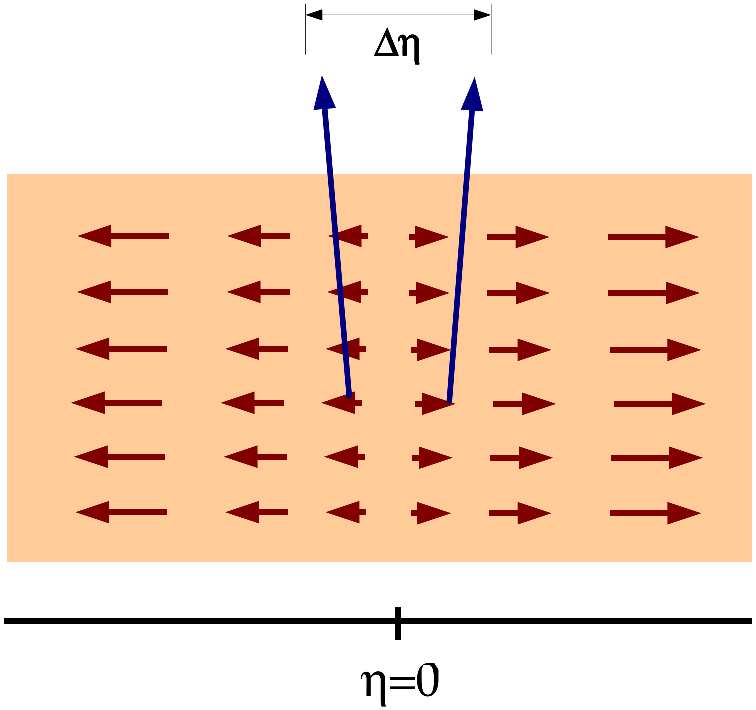


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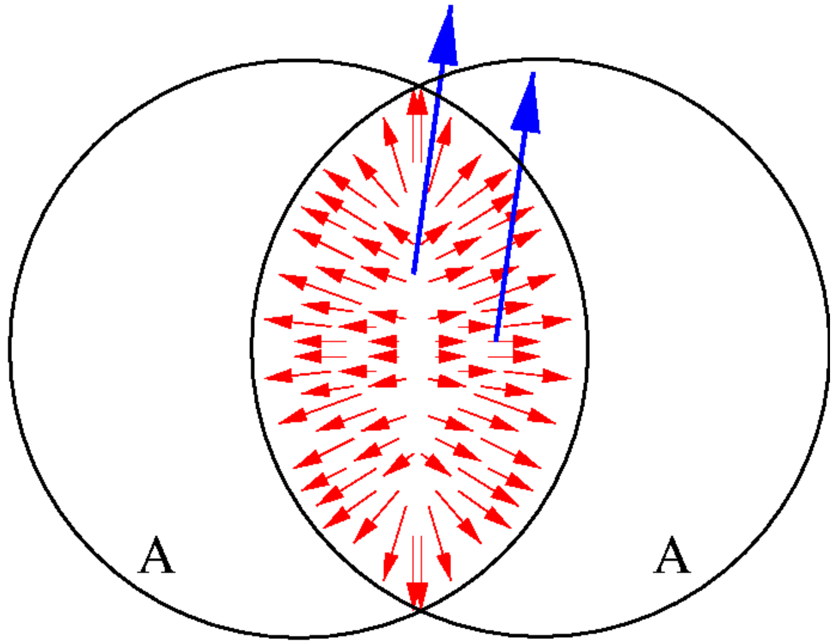
Radial flow




Could it be seen in the elliptic flow $v_2$?

# Magnitude of the effect

Energy–momentum tensor characterizes bulk properties of the medium

$$T^{\mu\nu}(x) = (\epsilon + p)\; u^{\mu}\, u^{\nu}\; - p\, g^{\mu\nu}$$

The transport coefficient $\hat{q}$ (Baier 2002)

$$\hat{q}\,\left[\mathrm{GeV}^2/\mathrm{fm}\right] \;=\; c\,\epsilon^{3/4}\left[(\mathrm{GeV}/\mathrm{fm}^3)^{3/4}\right]\;.$$

Taking $\epsilon = 3P$, $\hat{q} \propto p^{3/4}$, $p = T^{zz}$

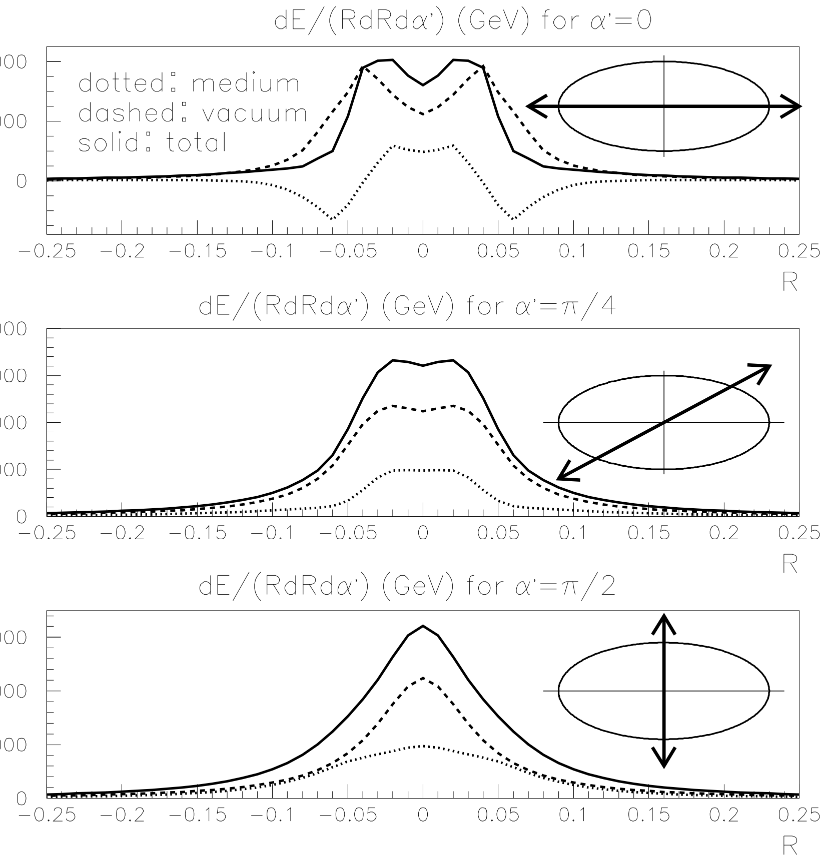
In the presence of a longitudinal flow field $u^{\mu} = \left(1, \vec{\beta}\right) / \sqrt{1-\beta^2}$

$$T^{zz} = p + \Delta p\,; \qquad \Delta p = (\epsilon + p) u^z u^z = 4p\beta^2 / \left(1 - \beta^2\right)$$

For $\eta = \frac{1}{2}\log\frac{1+\beta}{1-\beta}$=0.5, 1, 1.5 we obtain an increase $\Delta p/p =$ 1, 5, 18.

# Longitudinal flow

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




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

$q_0 = \mu$

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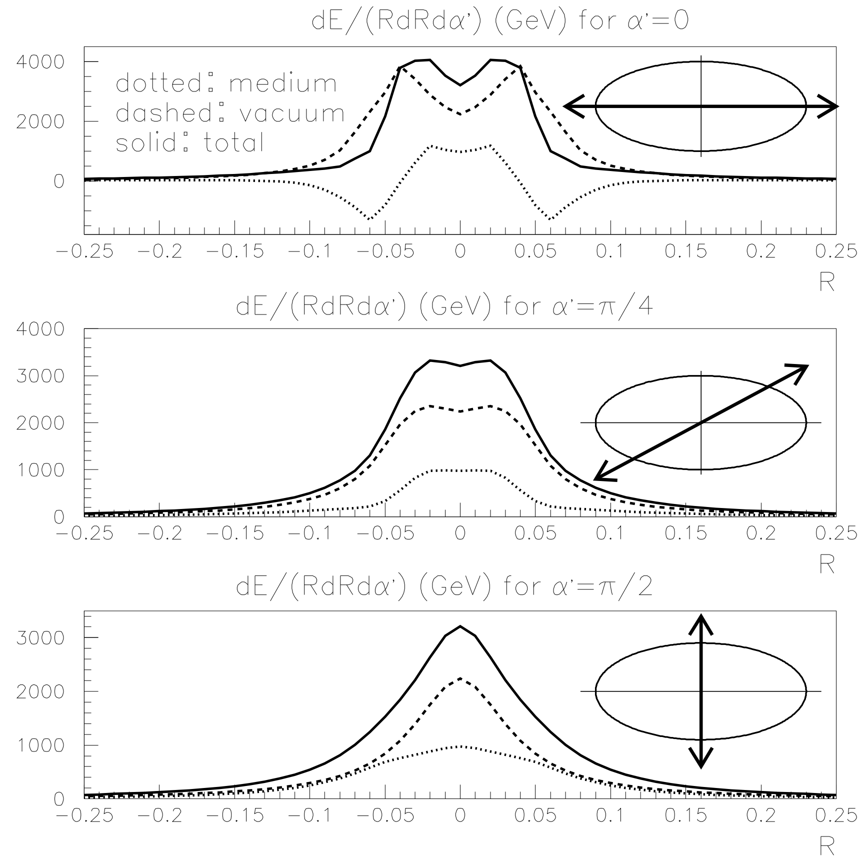
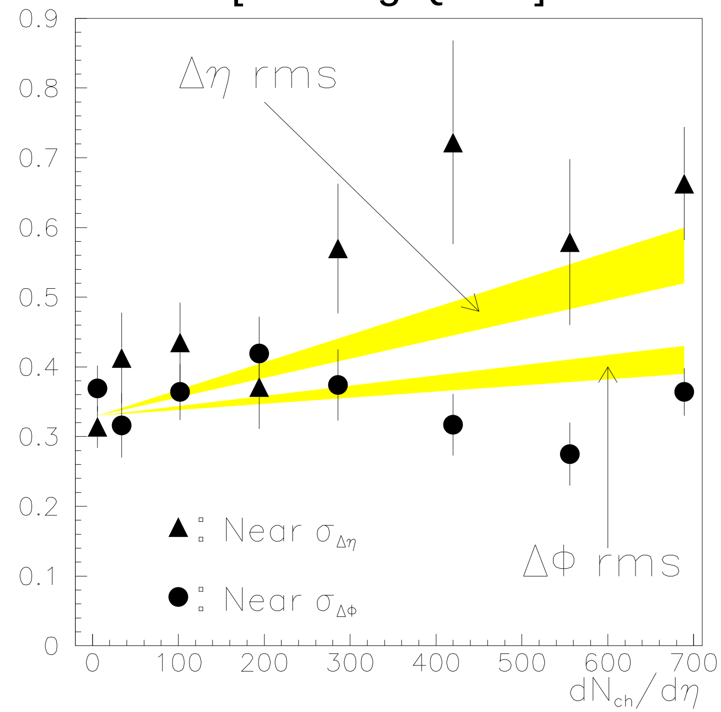



$E_{\rm jet} = 100$ GeV, $\Delta E = 23$ GeV.
$q_0 = \mu$

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

[F. Wang QM04]

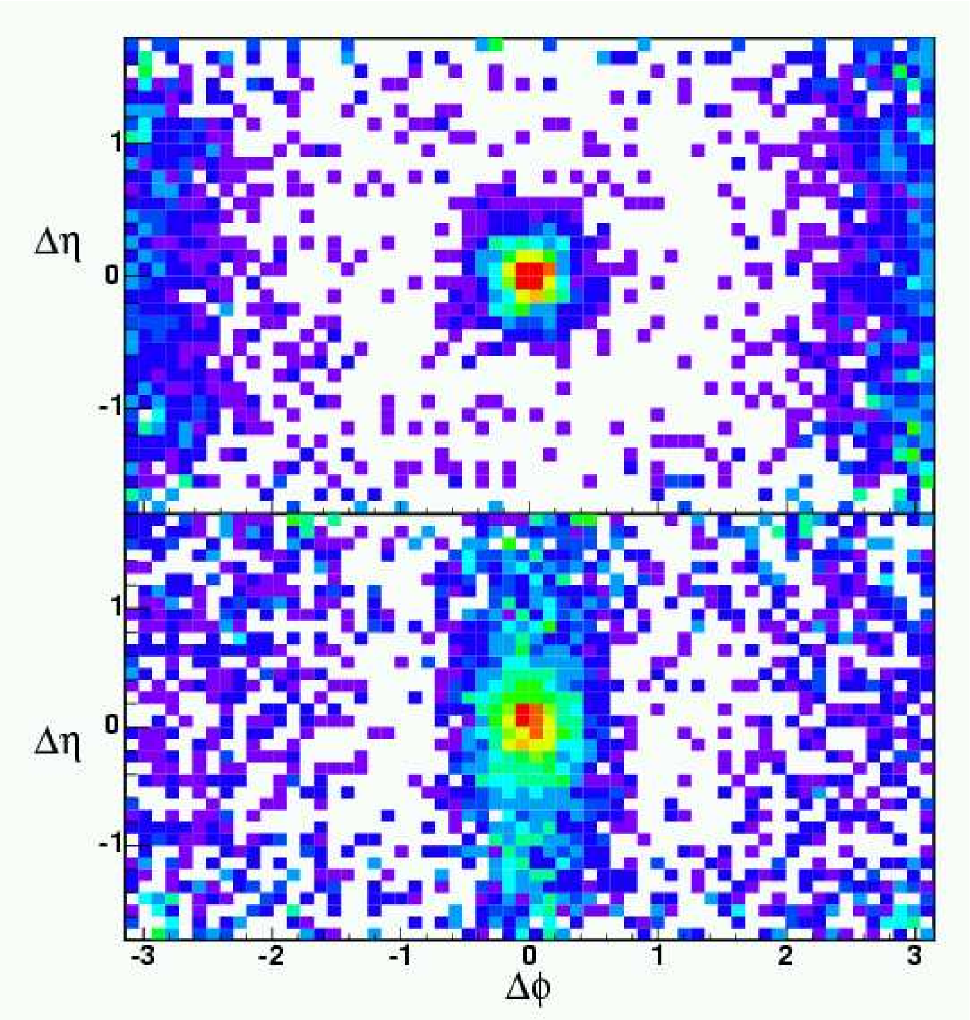



Band corresponds to $q_0/\mu = 2 \div 4$

Broadening in the $\eta$-direction more important than in $\phi$-direction.

# Elongation in $\eta$-direction

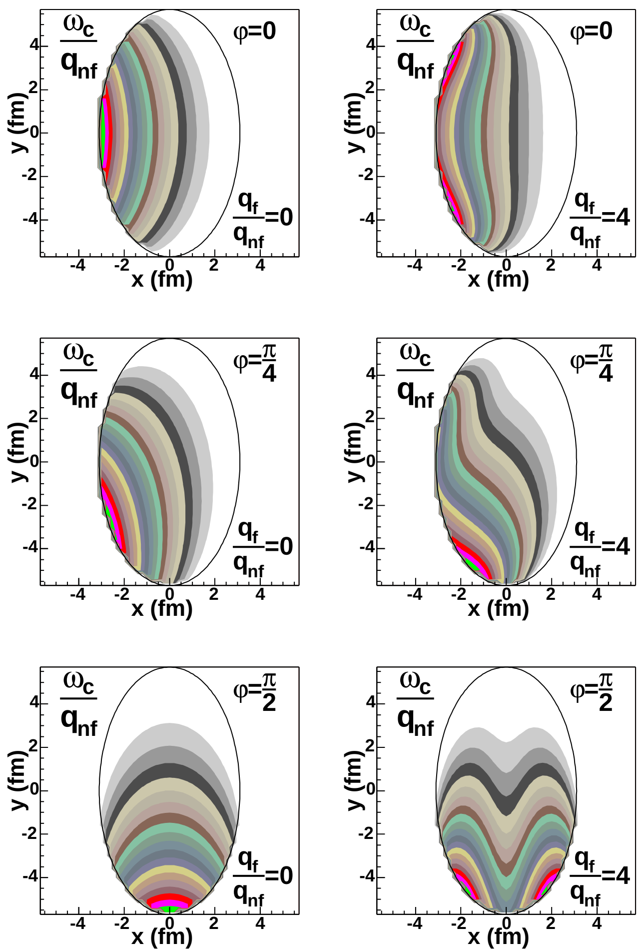
[STAR preliminary, D. Magestro HP04]

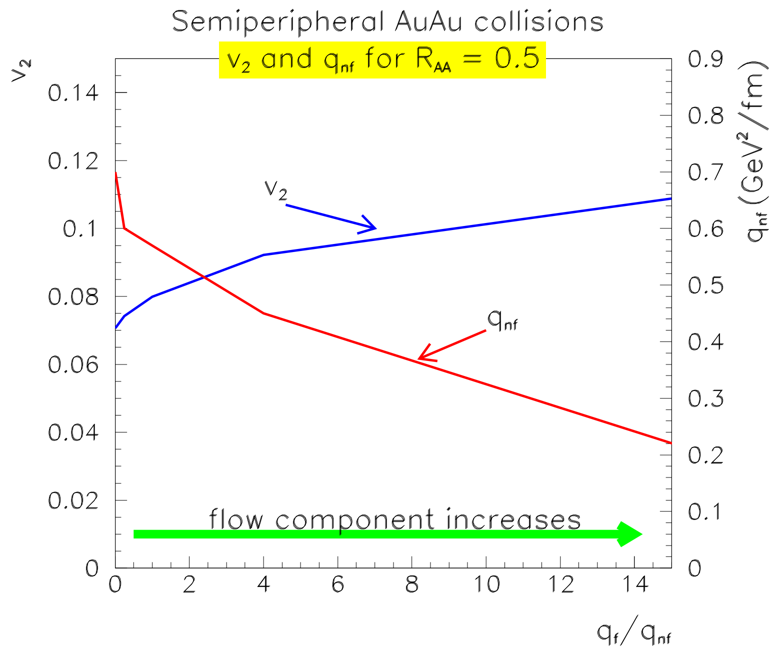



$3\,\mathrm{GeV} < p_t^{\mathrm{trigg}} < 6\,\mathrm{GeV};\;\; 2\,\mathrm{GeV} < p_t^{\mathrm{assoc}} < p_t^{\mathrm{trigg}}$

# 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 ⇒ smaller density for the same suppression

# Conclusions

- Inclusive particle production presents limitations in the characterization of the medium.
  - Study less inclusive observables
- 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 $\eta$-direction).
  - Contributes to $v_2$ and suppression (can this explain the opacity problem?)
- First jet observables sensitive to the dynamics of the medium.
  - Study the space–time–momentum picture of the collision with high-$p_t$ particles.