Hard Probes 2004: International Conference on
Hard and Electromagnetic Probes of High Energy Nuclear Collisions
Ericeira, Portugal, November 8th 2004

Flow effects on jet profiles and multiplicities

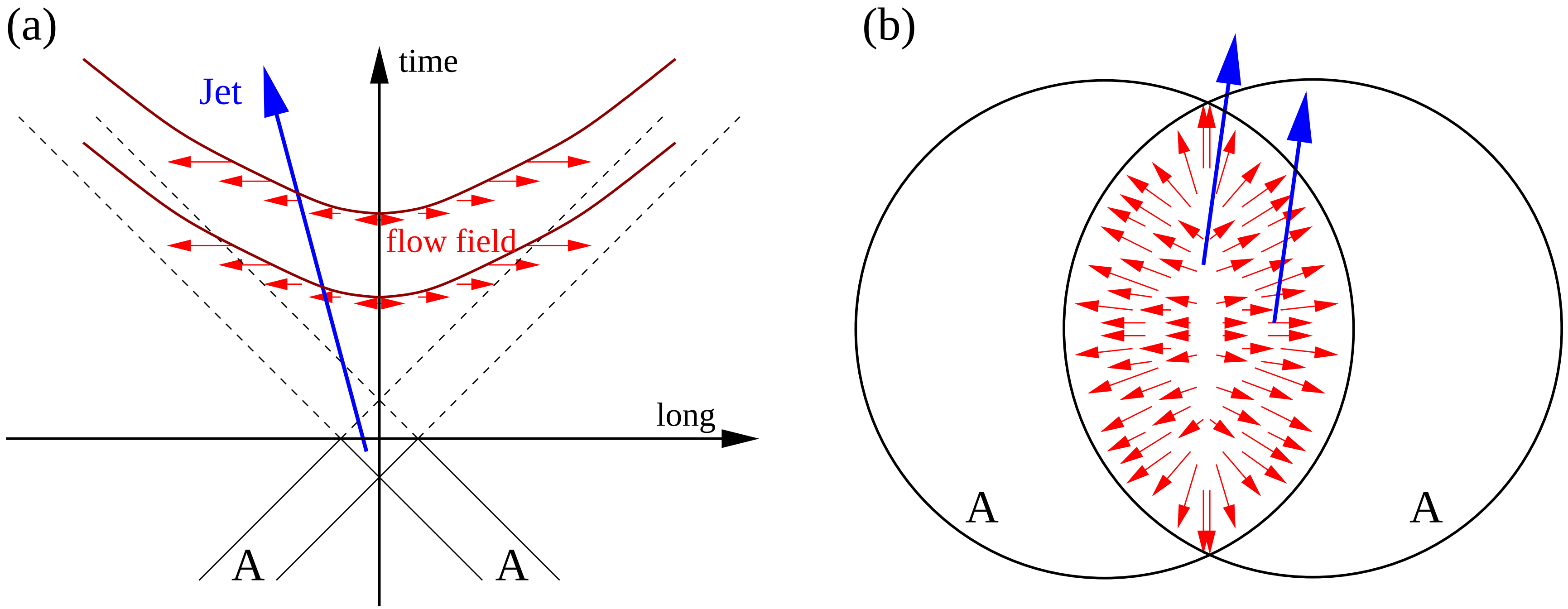
Néstor Armesto
Department of Physics, Theory Division, CERN

1. Motivation and formalism.
2. Exercises:
    - LHC: jet shapes.
    - RHIC: widths of particle distributions.
    - RHIC: elliptic flow.
3. Summary.

With C.A. Salgado and U.A. Wiedemann, hep-ph/0405301 (PRL) and in preparation.

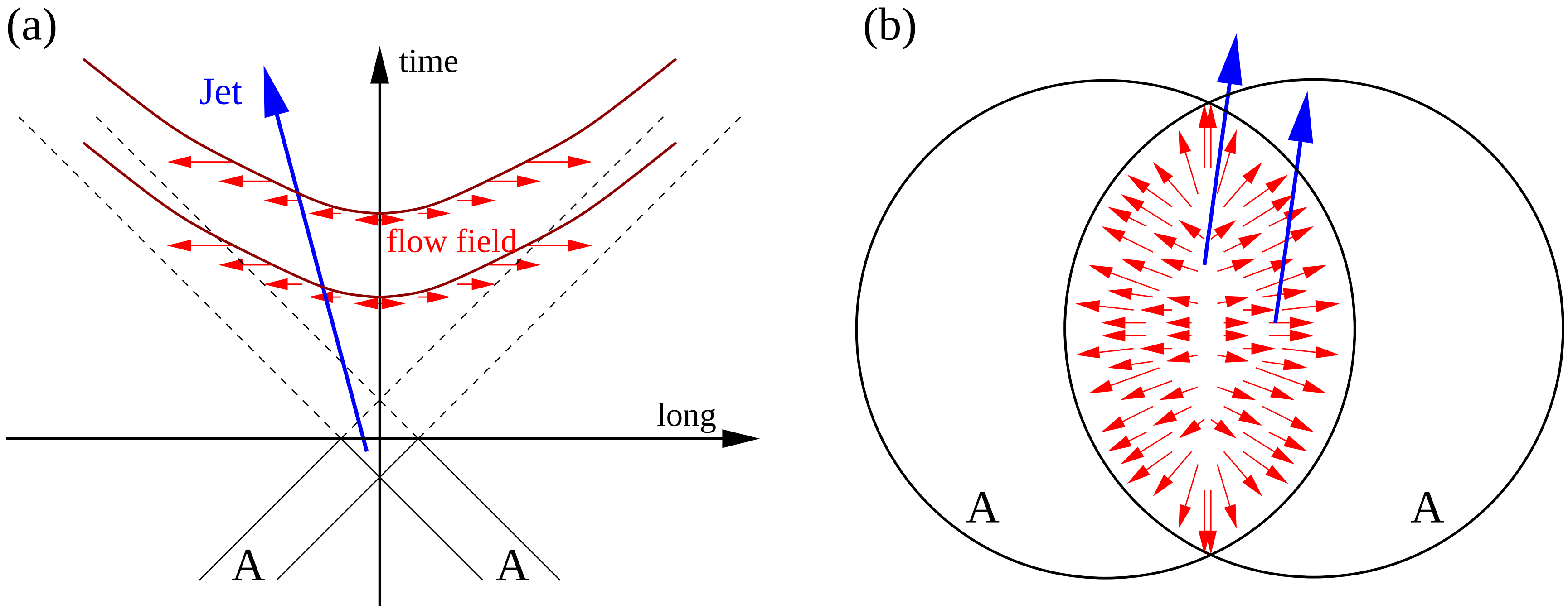
Motivation:

- Strong momentum-position correlations in the expanding medium are suggested by the success of hydro at low p_T: collective flow.



Motivation:

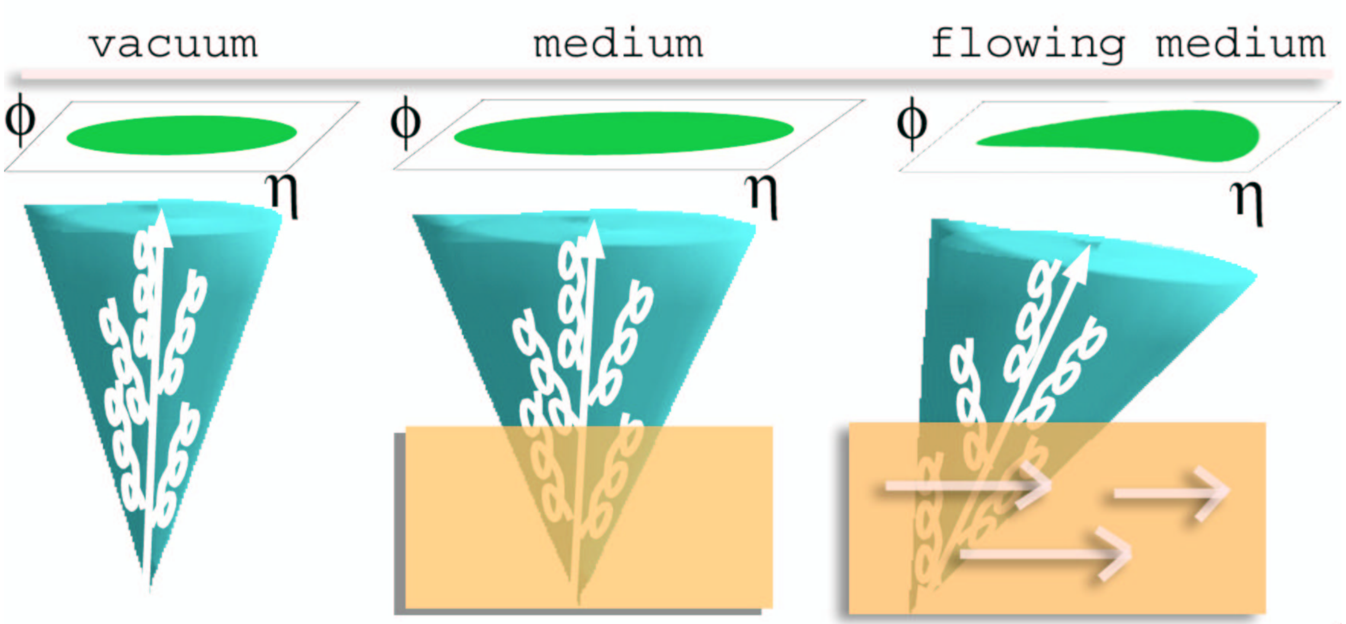
- Strong momentum-position correlations in the expanding medium are suggested by the success of hydro at low p_T: collective flow.



- Radiative energy loss is determined by momentum exchanges perpendicular to the trajectory of the parton.

Motivation:

- Strong momentum-position correlations in the expanding medium are suggested by the success of hydro at low p_T: collective flow.



- Radiative energy loss is determined by momentum exchanges perpendicular to the trajectory of the parton.

- Idea: if the jet is produced in a frame not co-moving with the collective flow, momentum exchanges become anisotropic and an additional contribution to energy loss comes from flow.

Formalism (I):

Néstor Armesto

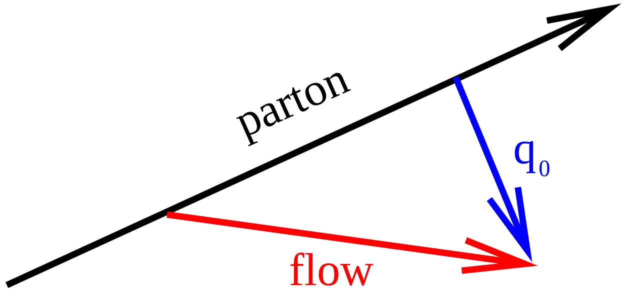
$$T^{\mu\nu}(x) = (\epsilon + p)\, u^\mu\, u^\nu\ - p\, g^{\mu\nu},\ u^\mu = \gamma(1, \vec{\beta}).$$

- Estimation: $T^{ii*} = p \rightarrow T^{ii} = p + \Delta p$, where $\Delta p = (\epsilon + p) u^i\, u^i = 4\, p\, \gamma^2 \beta^2$ (ideal EOS $\epsilon = 3\, p$) $\longrightarrow$ rapidity difference $\eta = 0.5, 1.0, 1.5$ between frames $\Longrightarrow \Delta p/p \simeq 1, 5, 18$.

Formalism (I):

$$T^{\mu\nu}(x) = (\epsilon + p)\, u^\mu\, u^\nu\ - p\, g^{\mu\nu},\ u^\mu = \gamma(1, \vec{\beta}).$$

- Estimation: $T^{ii*} = p \to T^{ii} = p + \Delta p$, where $\Delta p = (\epsilon + p) u^i\, u^i = 4\, p\, \gamma^2 \beta^2$ (ideal EOS $\epsilon = 3\, p$) $\longrightarrow$ rapidity difference $\eta = 0.5, 1.0, 1.5$ between frames $\Longrightarrow \Delta p/p \simeq 1, 5, 18$.



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

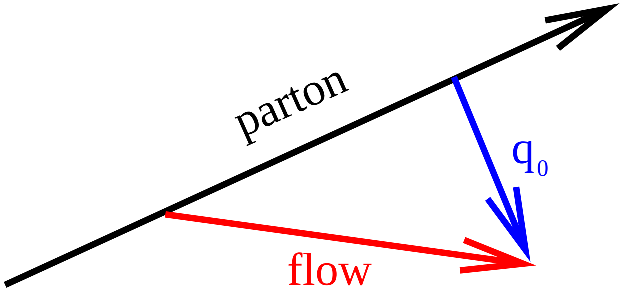
- We modify the Yukawa-like scattering potential. We consider (Baier '02)

$$\hat{q} = \frac{\mu^2}{\lambda} \propto n\, \sigma,\ \hat{q}\left[\mathrm{GeV}^2/\mathrm{fm}\right]\ =\ c\, \epsilon^{3/4}\left[(\mathrm{GeV}/\mathrm{fm}^3)^{3/4}\right] \Longrightarrow \boxed{q_0 \sim \mu.}$$

Formalism (I):

$$T^{\mu\nu}(x) = (\epsilon + p)\, u^\mu\, u^\nu\ - p\, g^{\mu\nu},\ \ u^\mu = \gamma(1,\vec{\beta}).$$

- Estimation: $T^{ii*} = p \to T^{ii} = p + \Delta p$, where $\Delta p = (\epsilon + p) u^i\, u^i = 4\, p\, \gamma^2 \beta^2$ (ideal EOS $\epsilon = 3\, p$) $\longrightarrow$ rapidity difference $\eta = 0.5, 1.0, 1.5$ between frames $\Longrightarrow \Delta p/p \simeq 1, 5, 18$.



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

- We modify the Yukawa-like scattering potential. We consider (Baier '02)

$$\hat{q} = \frac{\mu^2}{\lambda} \propto n\,\sigma,\ \ \hat{q}\left[\mathrm{GeV}^2/\mathrm{fm}\right]\ = c\,\epsilon^{3/4}\left[(\mathrm{GeV}/\mathrm{fm}^3)^{3/4}\right] \Longrightarrow q_0 \sim \mu.$$

- Dilution of the medium (Baier, Dokshitzer, Mueller, Schiff, '98; Gyulassy, Vitev, Wang, '00) can be taken into account by rescaling $\hat{q}$ (Salgado, Wiedemann, '02):

$$\langle \hat{q} \rangle = \frac{2}{L^2} \int d\tau\, \tau\, \hat{q}(\tau).$$

Formalism (II):

- In the single hard scattering approximation (Wiedemann, ’00; Gyulassy, Levai, Vitev, ’00),

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

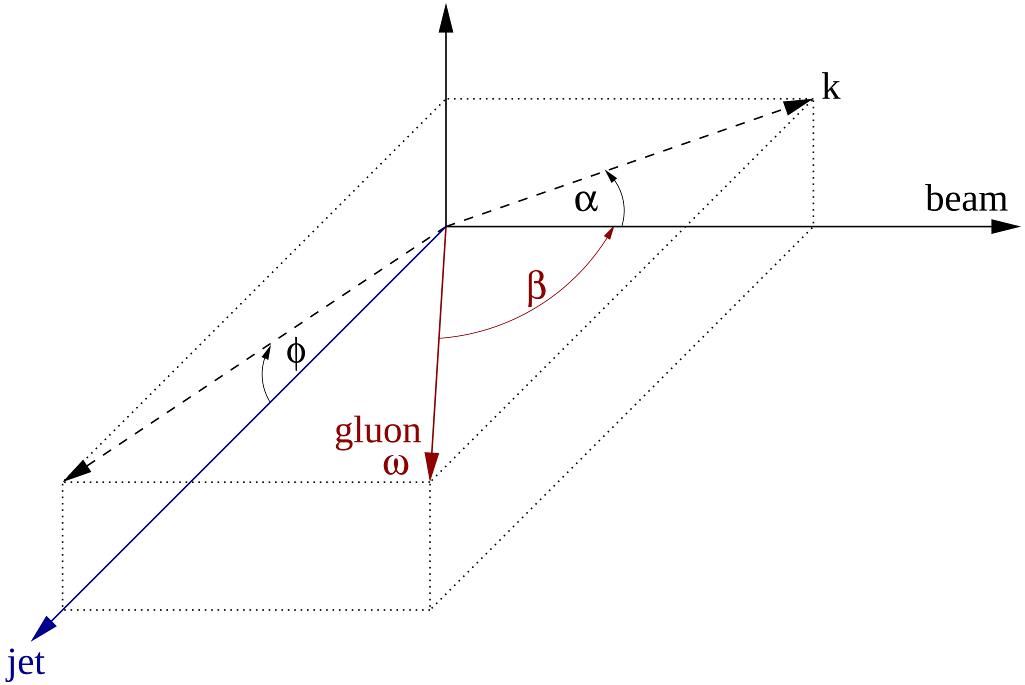
Similar results (Salgado, Wiedemann, ’03) in BDMPS (Baier, Dokshitzer, Mueller, Peigné, Schiff, ’96), $\sigma(\mathbf{r}) = 2\int d\mathbf{q}\, |a(\mathbf{q})|^2 \left(1 - e^{-i\mathbf{q}\cdot\mathbf{r}}\right)$, $n(\tau)\, \sigma(\mathbf{r}) \simeq \frac{1}{2}\, \hat{q}(\tau)\, \mathbf{r}^2$.

Formalism (II):

- In the single hard scattering approximation (Wiedemann, ’00; Gyulassy, Levai, Vitev, ’00),

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

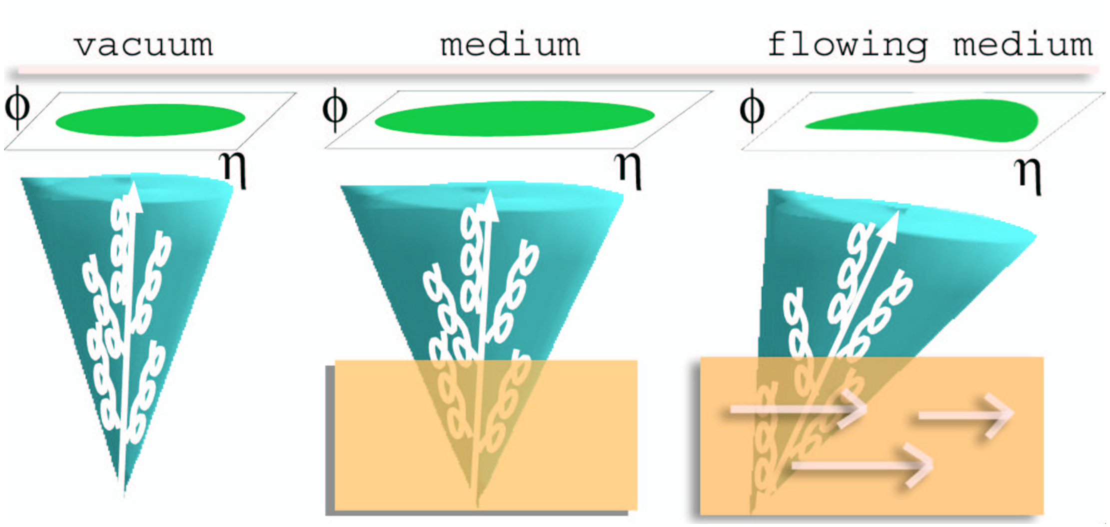
Similar results (Salgado, Wiedemann, ’03) in BDMPS (Baier, Dokshitzer, Mueller, Peigné, Schiff, ’96), $\sigma(\mathbf{r}) = 2 \int d\mathbf{q}\, |a(\mathbf{q})|^2 \left(1 - e^{-i\mathbf{q}\cdot\mathbf{r}}\right)$, $n(\tau)\, \sigma(\mathbf{r}) \simeq \frac{1}{2}\, \hat{q}(\tau)\, \mathbf{r}^2$.



$$k\, dk\, d\alpha = \omega^2\, \frac{\cos\phi}{\cosh^3\eta}\, d\eta\, d\phi$$

(it already induces an $\eta-\phi$-asymmetry).

Jet shapes with flow (I):

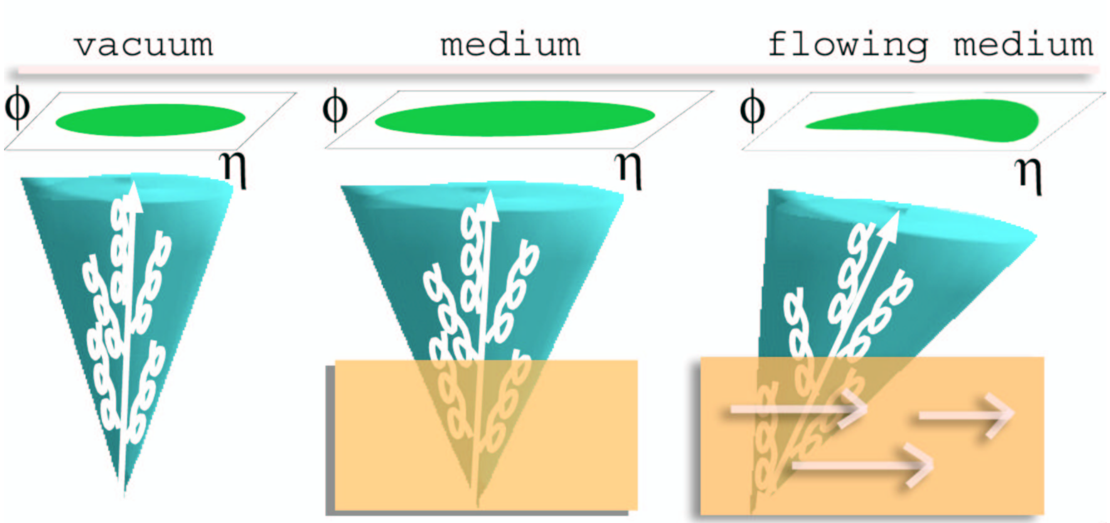


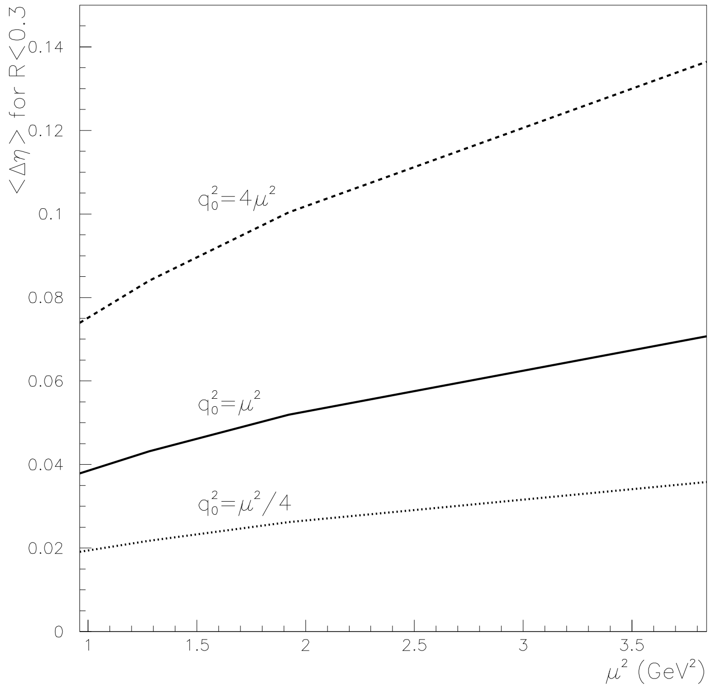
- For the vacuum, $R = \sqrt{\eta^2 + \phi^2}$,

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

taken from D0 (LHC: pp and pA references needed).

Jet shapes with flow (I):





- For the vacuum, $R = \sqrt{\eta^2 + \phi^2}$,

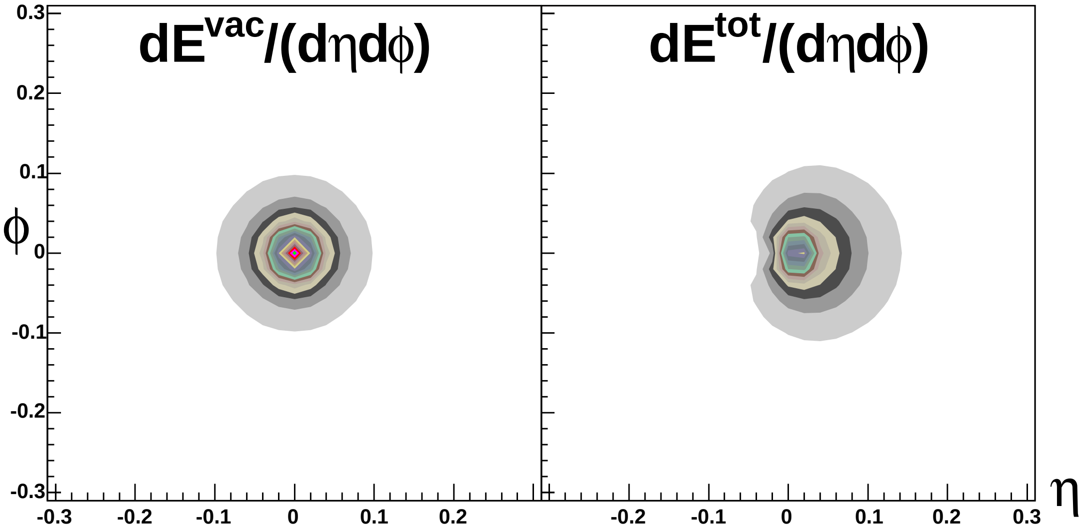
$$\rho_{\rm vac}(R) \equiv \frac{1}{N_{\rm jets}} \sum_{\rm jets} \frac{E_T(R)}{E_T(R=1)}$$

taken from D0 (LHC: pp and pA references needed).

- $n_0 \, L \, \alpha_s \, C_R = 1$, $L = 6$ fm $\Longrightarrow$

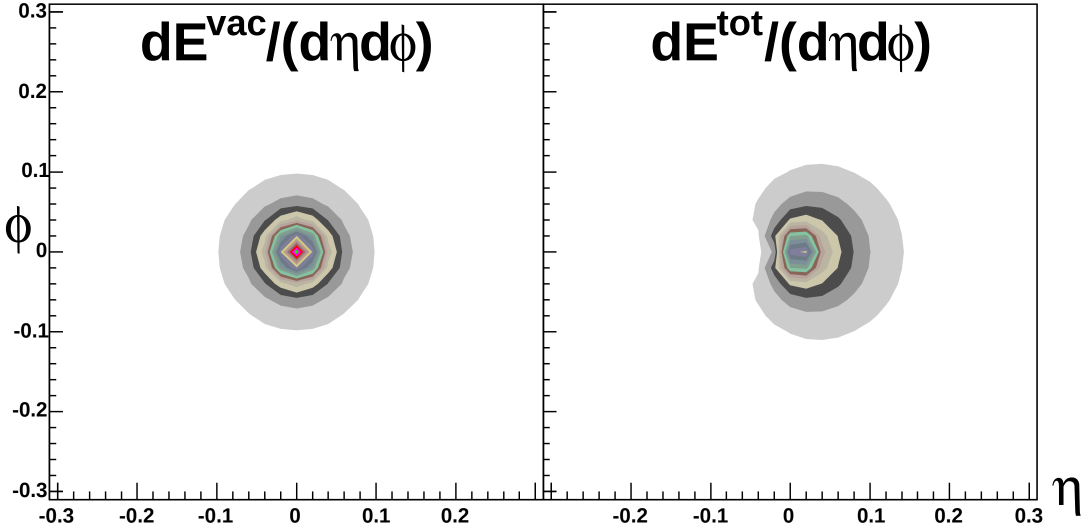
the jet center is not too displaced.
$\rightarrow$ $\bar{\rm p}$p: $R = 0.7 \div 1$ ($E_{\rm within} \simeq 100\%$).
$\rightarrow$ PbPb at LHC: $R = 0.3 \div 0.4$ ($E_{\rm within} \simeq 75 \div 80\%$).

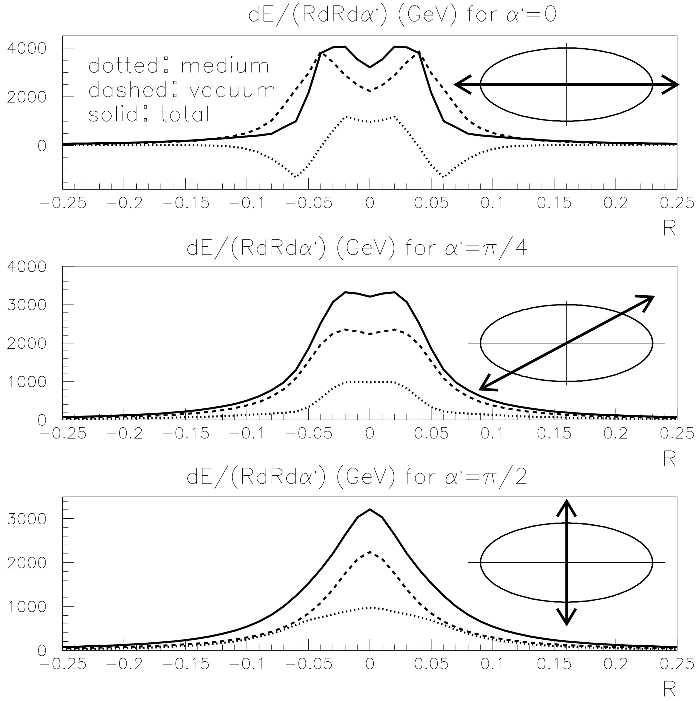
Jet shapes with flow (II):



- 100 GeV jet; $\mu = 1$ GeV, $q_0 = \mu \Longrightarrow \langle \Delta\eta \rangle_{R<0.3} \simeq 0.04$, $\Delta E_T = \int d\omega \omega \frac{dI^{\rm med}}{d\omega} = 23$ GeV redistributed by medium-induced gluon radiation.

Jet shapes with flow (II):





- 100 GeV jet; $\mu = 1$ GeV, $q_0 = \mu \Longrightarrow \langle \Delta\eta \rangle_{R<0.3} \simeq 0.04$, $\Delta E_T = \int d\omega \omega \frac{dI^{\rm med}}{d\omega} = 23$ GeV redistributed by medium-induced gluon radiation.

- Clear asymmetry. If flow comes equally from both $+\eta$ and $-\eta$, width in η becomes larger than in ϕ ($d\eta\, d\phi = R\, dR\, d\alpha'$).

Modification of ‘jet’ multiplicity:

- RHIC: no calorimetric jets $\longrightarrow$ study the associated multiplicity (radiation) (STAR: nucl-ex/0411003; talk by Magestro).

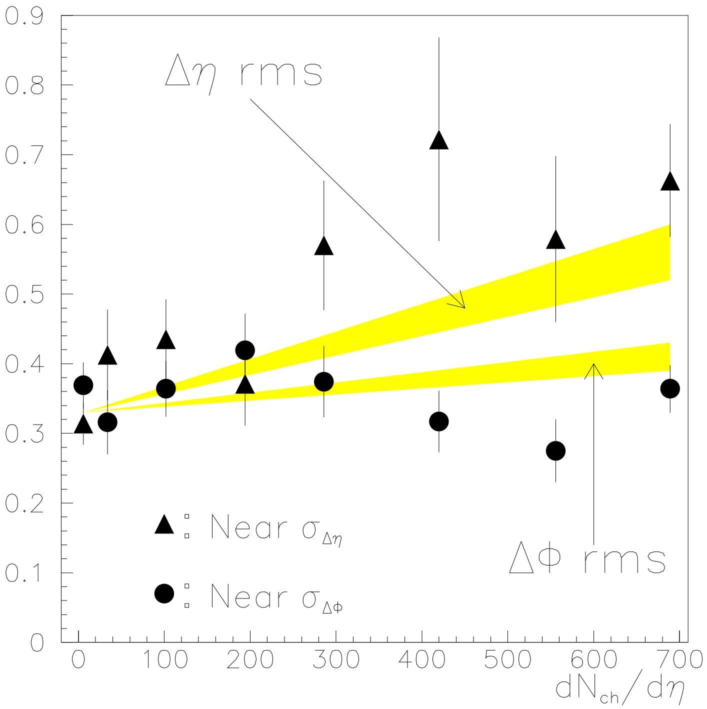
Modification of ‘jet’ multiplicity:

- RHIC: no calorimetric jets $\longrightarrow$ study the associated multiplicity (radiation) (STAR: nucl-ex/0411003; talk by Magestro).
- We compute the medium-induced gluon radiation; vacuum particle distribution is taken from pp data.

Modification of ‘jet’ multiplicity:

Néstor Armesto

- RHIC: no calorimetric jets $\longrightarrow$ study the associated multiplicity (radiation) (STAR: nucl-ex/0411003; talk by Magestro).
- We compute the medium-induced gluon radiation; vacuum particle distribution is taken from pp data.



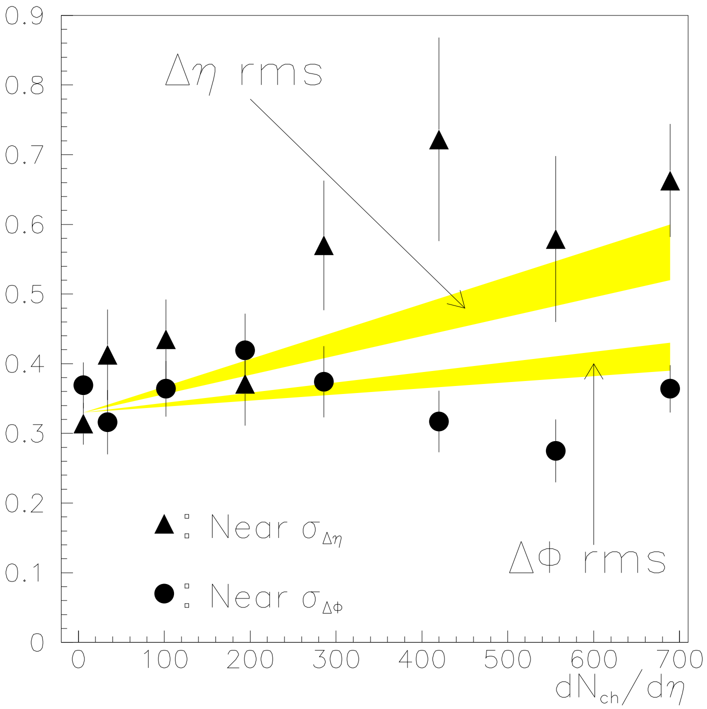
- We take a 10 GeV parton, $L = 2$ fm (near side jet), $\mu = 0.7 \div 1.4$ GeV, and $q_0/\mu = 4 \div 2$.
- Preliminary STAR data: F.Wang at QM04, near-side charged distribution associated to trigger with $4\,\mathrm{GeV} < p_T^{\mathrm{trigger}} < 6$ GeV in AuAu@200 GeV.

Modification of 'jet' multiplicity:

Néstor Armesto

- RHIC: no calorimetric jets ⟶ study the associated multiplicity (radiation) (STAR: nucl-ex/0411003; talk by Magestro).

- We compute the medium-induced gluon radiation; vacuum particle distribution is taken from pp data.



- We take a 10 GeV parton, $L = 2$ fm (near side jet), $\mu = 0.7 \div 1.4$ GeV, and $q_0/\mu = 4 \div 2$.

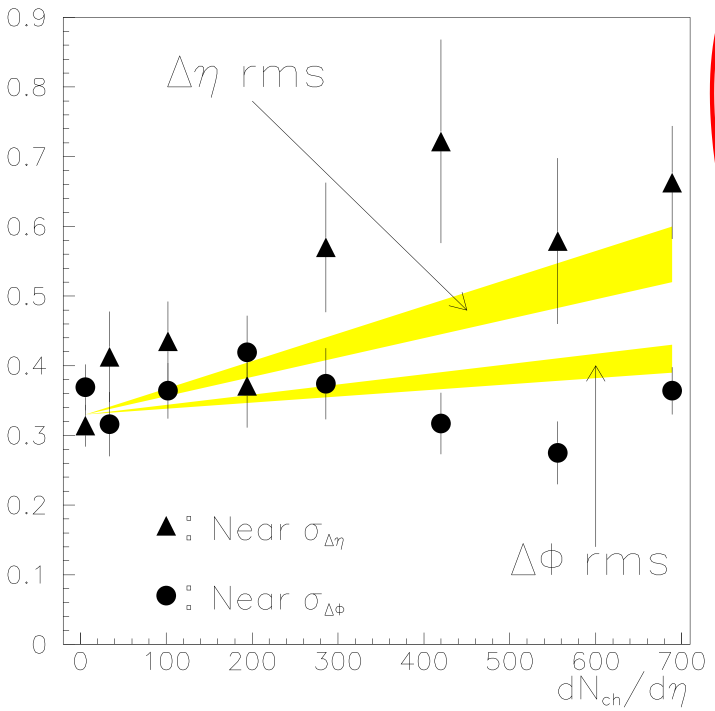
- Preliminary STAR data: F.Wang at QM04, near-side charged distribution associated to trigger with $4\,\mathrm{GeV} < p_T^{\mathrm{trigger}} < 6$ GeV in AuAu@200 GeV.

- Uncertainties at RHIC large (Salgado, Wiedemann, '03); as an example of application, ignoring them and using this preliminary data, $q_0/\mu = 4 \Longrightarrow \Delta\eta \sim 1$ between flow and hard-parton co-moving frames.

Modification of ‘jet’ multiplicity:

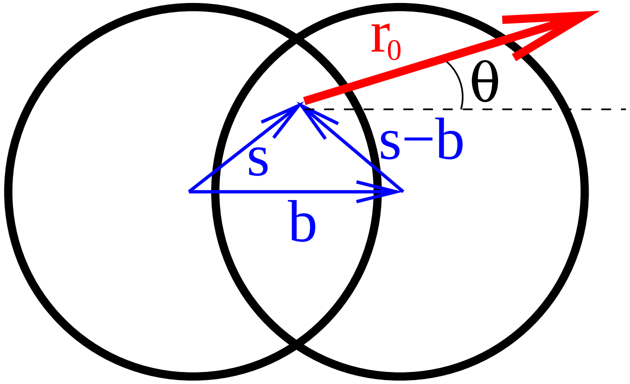
Néstor Armesto

- RHIC: no calorimetric jets $\longrightarrow$ study the associated multiplicity (radiation) (STAR: nucl-ex/0411003; talk by Magestro).
- We compute the medium-induced gluon radiation; vacuum particle distribution is taken from pp data.



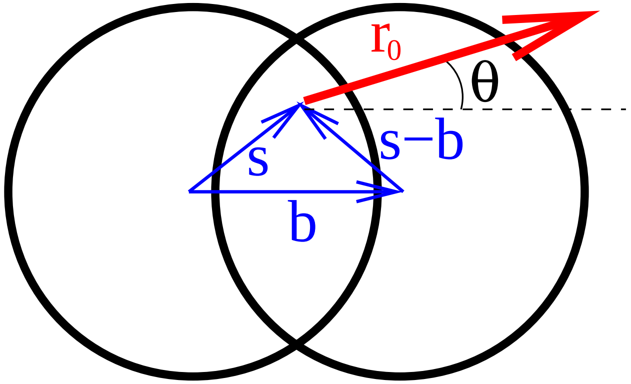
- We take a 10 GeV parton, $L = 2$ fm (near side jet), $\mu = 0.7 \div 1.4$ GeV, and $q_0/\mu = 4 \div 2$.
- Preliminary STAR data: F.Wang at QM04, near-side charged distribution associated to trigger with $4\,\mathrm{GeV} < p_T^{\mathrm{trigger}} < 6$ GeV in AuAu@200 GeV.
- With radiative E-loss, the widths are expected to increase with decreasing $p_T = \omega$: $\sin^2\theta = k_T^2/\omega^2 \simeq \sqrt{\hat{q}\omega}/\omega^2$, and radiation is harder than in vacuum.
- Uncertainties at RHIC large (Salgado, Wiedemann, ’03); as an example of application, ignoring them and using this preliminary data, $q_0/\mu = 4 \Longrightarrow \Delta\eta \sim 1$ between flow and hard-parton co-moving frames.

Contribution to elliptic flow (I):



- Parton produced at (x_0, y_0) according to $T_A(\mathbf{s})\,T_B(\mathbf{b}-\mathbf{s})$, with trajectory $\mathbf{r_0}(\xi) = (x_0 + \xi\cos\theta, y_0 + \xi\sin\theta)$ uniform in θ (Gyulassy, Vitev, Wang, '00).

Contribution to elliptic flow (I):



- Parton produced at (x_0, y_0) according to $T_A(\mathbf{s})\, T_B(\mathbf{b}-\mathbf{s})$, with trajectory $\mathbf{r_0}(\xi) = (x_0 + \xi\cos\theta, y_0 + \xi\sin\theta)$ uniform in θ (Gylassy, Vitev, Wang, '00).

- Medium characteristics $\hat{q}$ and L (Baier, Dokshitzer, Mueller, Peigné, Schiff, '96), redefined (Salgado, Wiedemann, '03) in the static case to $\omega_c = \hat{q}L^2/2$, $R = \omega_c L$, are computed (Dainese, Loizides, Paic, '04; Eskola, Honkanen, Salgado, Wiedemann, '04):

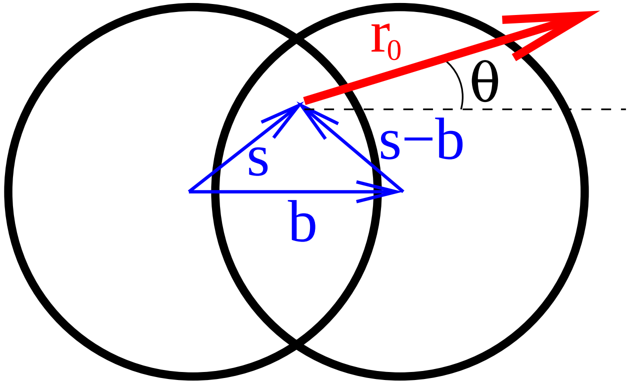
$$\omega_c(x_0, y_0, \theta) = \int_0^\infty d\xi\, \xi\, \hat{q}(\xi)\, \Omega(\mathbf{r}_0(\xi))\,,$$

$$(\hat{q}L)\,(x_0, y_0, \theta) = \int_0^\infty d\xi\, \hat{q}(\xi)\, \Omega(\mathbf{r}_0(\xi))\,, \quad R = 2\frac{\omega_c^2(x_0, y_0, \theta)}{(\hat{q}L)\,(x_0, y_0, \theta)}\,,$$

with $\Omega(\mathbf{r})$ a time-dependent density distribution of produced matter.

Contribution to elliptic flow (I):

Néstor Armesto



- Parton produced at (x_0, y_0) according to $T_A(\mathbf{s})\, T_B(\mathbf{b} - \mathbf{s})$, with trajectory $\mathbf{r_0}(\xi) = (x_0 + \xi\cos\theta, y_0 + \xi\sin\theta)$ uniform in θ (Gyulassy, Vitev, Wang, '00).

- Medium characteristics $\hat{q}$ and L (Baier, Dokshitzer, Mueller, Peigné, Schiff, '96), redefined (Salgado, Wiedemann, '03) in the static case to $\omega_c = \hat{q}L^2/2$, $R = \omega_c L$, are computed (Dainese, Loizides, Paic, '04; Eskola, Honkanen, Salgado, Wiedemann, '04):

$$\omega_c(x_0, y_0, \theta) = \int_0^\infty d\xi\, \xi\, \hat{q}(\xi)\, \Omega(\mathbf{r}_0(\xi))\,,$$

$$(\hat{q}L)\,(x_0, y_0, \theta) = \int_0^\infty d\xi\, \hat{q}(\xi)\, \Omega(\mathbf{r}_0(\xi))\,, \quad R = 2\frac{\omega_c^2(x_0, y_0, \theta)}{(\hat{q}L)\,(x_0, y_0, \theta)}\,,$$

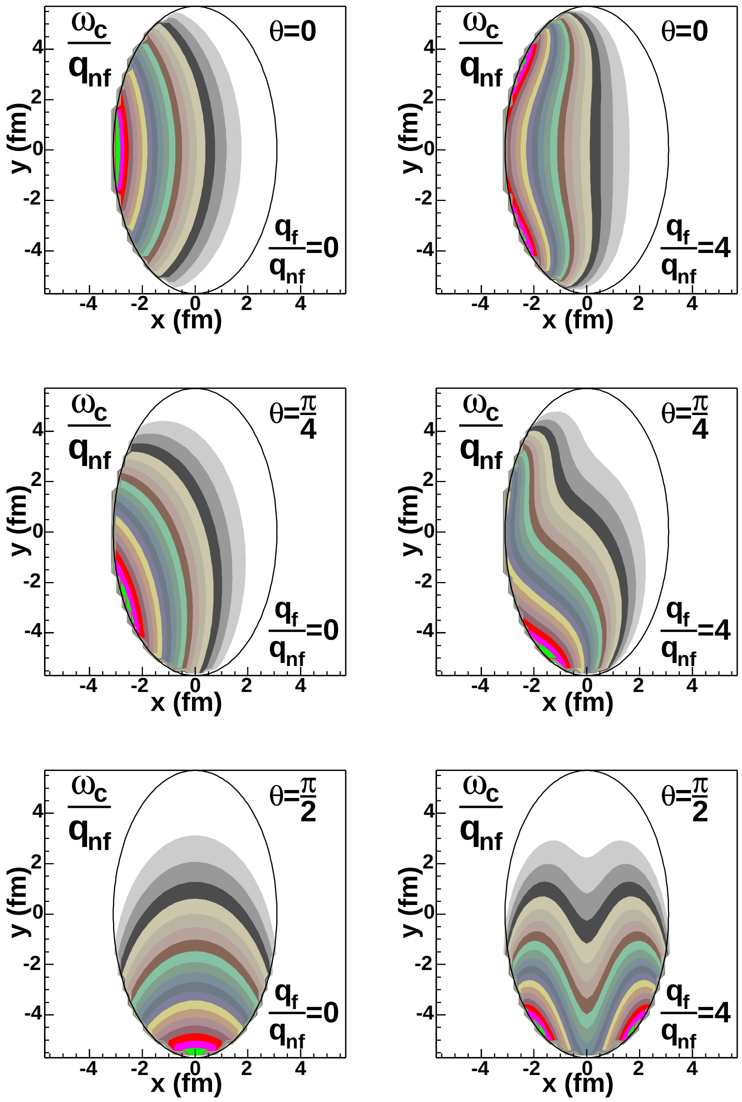
with $\Omega(\mathbf{r})$ a time-dependent density distribution of produced matter.

- For a given flow field (Lisa, Retière, '03), we take the simple ansatz

$$\hat{q}(\xi) = \bar{\hat{q}}_{nf} + \bar{\hat{q}}_{flow}|\mathbf{u}(\mathbf{r}_0(\xi)) \cdot \mathbf{n}_T|^2\,, \quad \mathbf{n}_T \cdot \mathbf{r_0}(\xi) = 0.$$

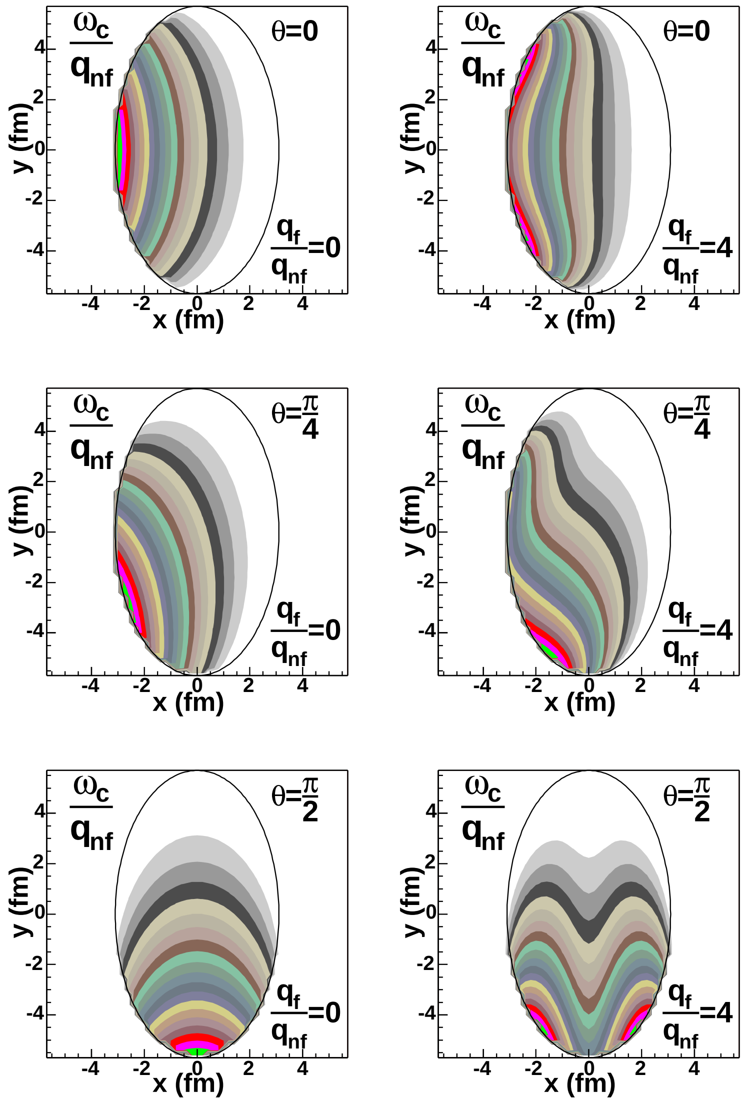
Contribution to elliptic flow (II):

- Flow effect clear in the parameters which determine E-loss:



Contribution to elliptic flow (II):

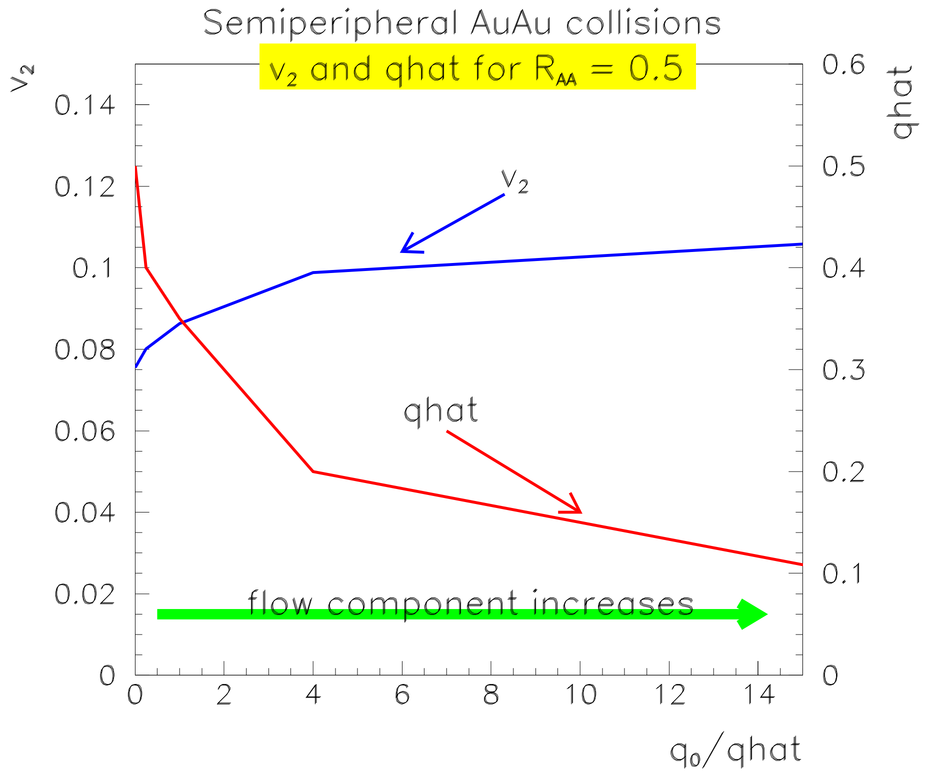
- Flow effect clear in the parameters which determine E-loss:



- Exercise for semi-peripheral AuAu:

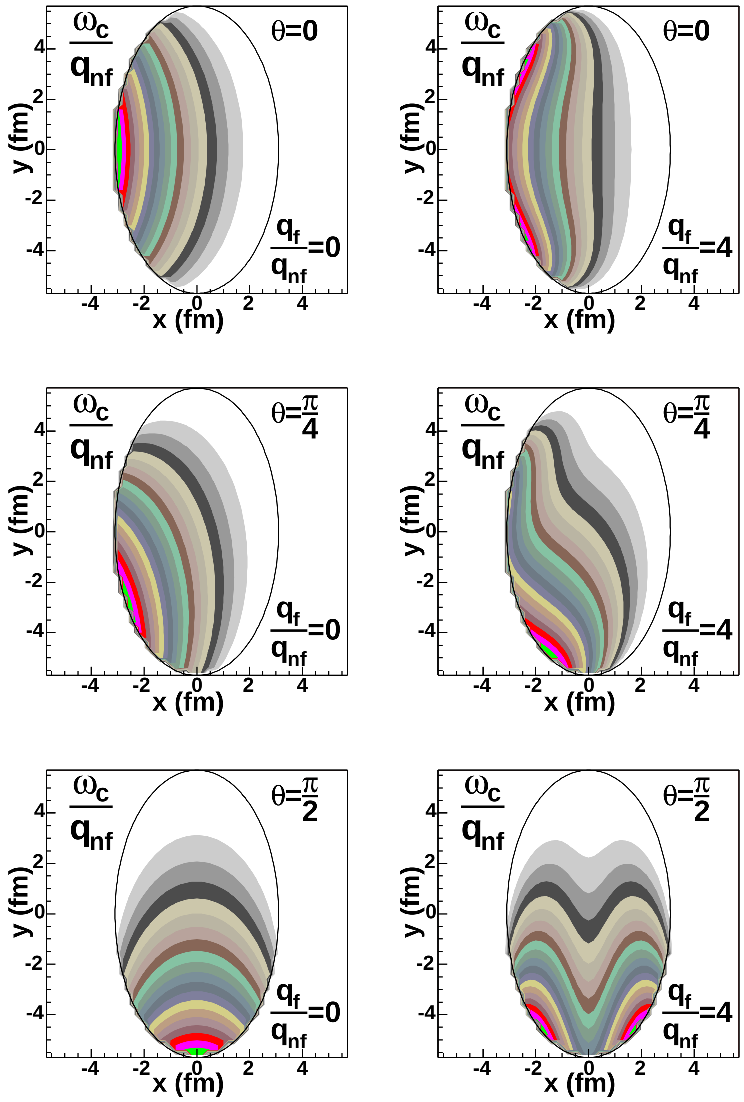
$$N(x_0, y_0, \theta, p_T) = \frac{d\sigma^{med}}{dp_T} \Big/ \frac{d\sigma^{vac}}{dp_T}, \; p_T =$$

5 GeV/c (Salgado, Wiedemann, '03),



Contribution to elliptic flow (II):

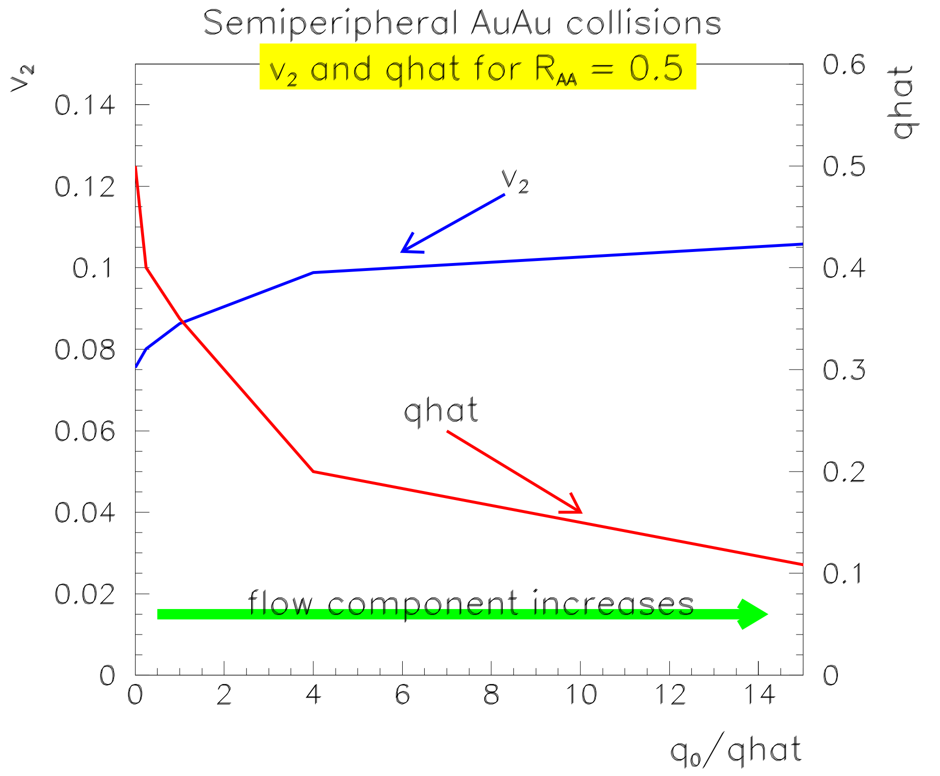
- Flow effect clear in the parameters which determine E-loss:



- Exercise for semi-peripheral AuAu:

$$N(x_0, y_0, \theta, p_T) = \frac{d\sigma^{med}}{dp_T} \Big/ \frac{d\sigma^{vac}}{dp_T}, \; p_T = 5 \text{ GeV/c}$$

(Salgado, Wiedemann, '03),



- Effect on v_2 is not large, (Wang, '03; Drees, Feng, Jia, '03); flow effects may mimic a higher density.

Summary:

- ♣ We have performed an exploratory study of the effects of flow on medium-induced energy loss by gluon radiation.

Summary:

- ♣ We have performed an exploratory study of the effects of flow on medium-induced energy loss by gluon radiation.

- ♣ Jets at LHC may show a clear $\eta - \phi$-asymmetry (they will be produced abundantly: Yellow Report on Hard Probes in HIC at the LHC, ’03; Salgado, Wiedemann, ’03).

Summary:

Néstor Armesto

- ♣ We have performed an exploratory study of the effects of flow on medium-induced energy loss by gluon radiation.

- ♣ Jets at LHC may show a clear $\eta - \phi$-asymmetry (they will be produced abundantly: Yellow Report on Hard Probes in HIC at the LHC, '03; Salgado, Wiedemann, '03).

- ♣ At RHIC: flow can produce asymmetries in associated particle production and a modest increase of elliptic flow.

Summary:

Néstor Armesto

- ♣ We have performed an exploratory study of the effects of flow on medium-induced energy loss by gluon radiation.
- ♣ Jets at LHC may show a clear $\eta - \phi$-asymmetry (they will be produced abundantly: Yellow Report on Hard Probes in HIC at the LHC, ’03; Salgado, Wiedemann, ’03).
- ♣ At RHIC: flow can produce asymmetries in associated particle production and a modest increase of elliptic flow.
- ♣ These effects may make the determination of densities from jet quenching studies more involved: flow may mimic energy density.

Summary:

- ♣ We have performed an exploratory study of the effects of flow on medium-induced energy loss by gluon radiation.

- ♣ Jets at LHC may show a clear $\eta - \phi$-asymmetry (they will be produced abundantly: Yellow Report on Hard Probes in HIC at the LHC, '03; Salgado, Wiedemann, '03).

- ♣ At RHIC: flow can produce asymmetries in associated particle production and a modest increase of elliptic flow.

- ♣ These effects may make the determination of densities from jet quenching studies more involved: flow may mimic energy density.

- ♣ Theoretical uncertainties exist: finite energy corrections, hadronization (pp and pA data required!),. . .

Summary:

- ♣ We have performed an exploratory study of the effects of flow on medium-induced energy loss by gluon radiation.

- ♣ Jets at LHC may show a clear $\eta - \phi$-asymmetry (they will be produced abundantly: Yellow Report on Hard Probes in HIC at the LHC, '03; Salgado, Wiedemann, '03).

- ♣ At RHIC: flow can produce asymmetries in associated particle production and a modest increase of elliptic flow.

- ♣ These effects may make the determination of densities from jet quenching studies more involved: flow may mimic energy density.

- ♣ Theoretical uncertainties exist: finite energy corrections, hadronization (pp and pA data required!),. . .

BUT

even a negative result provides information about the space-time evolution of the system (hard production coupled to the flow?) ⟶ compute it within a full hydrodynamical simulation (Hirano, Nara, '02; '03).