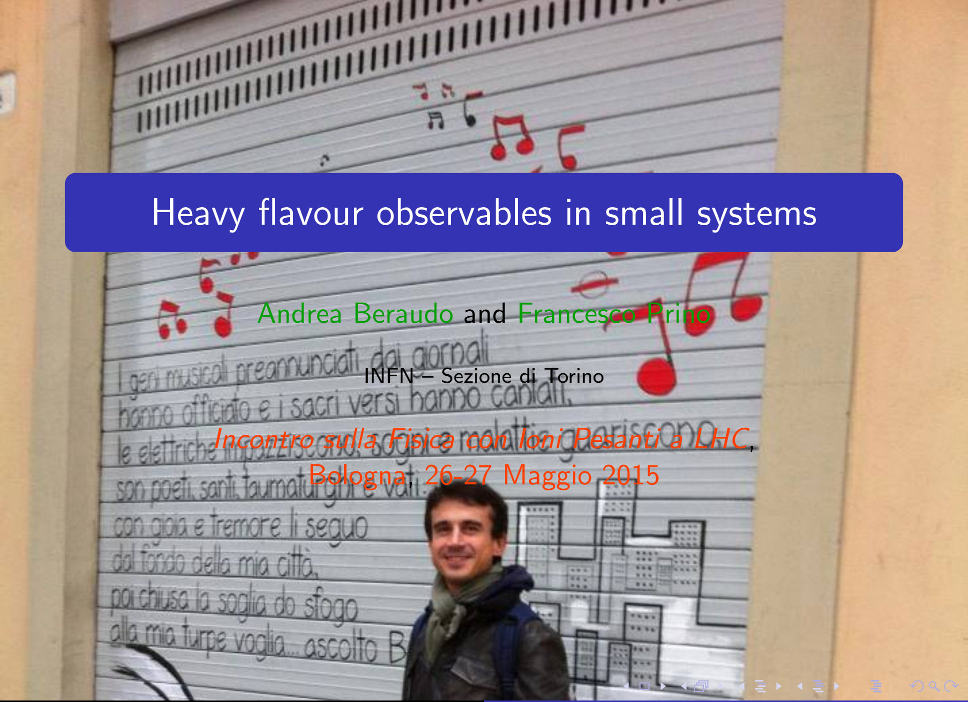


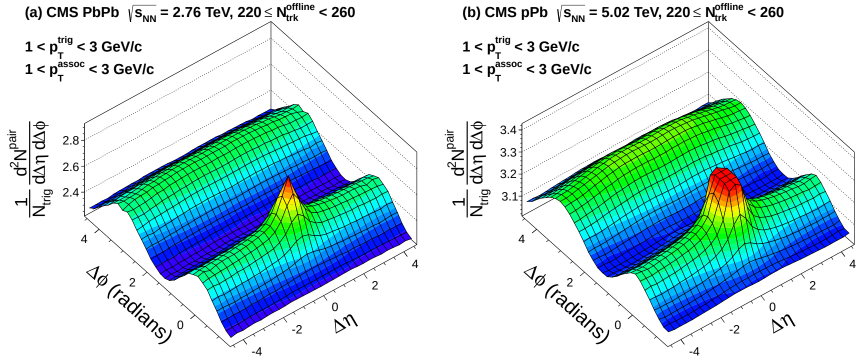
Heavy flavour observables in small systems

Andrea Beraudo and Francesco Prino

INFN – Sezione di Torino

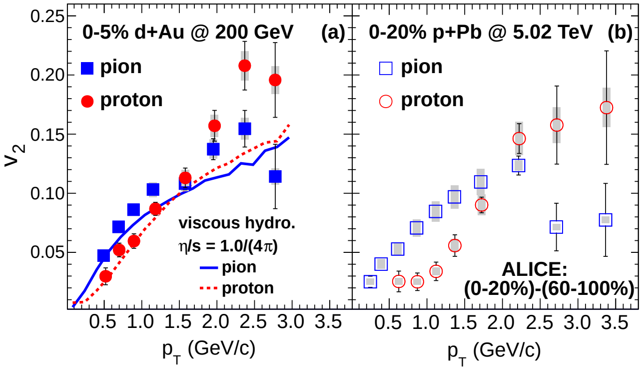
Incontro sulla Fisica con Ioni Pesanti a LHC, Bologna, 26-27 Maggio 2015

Soft observables in p-A collisions: hot-medium effects?



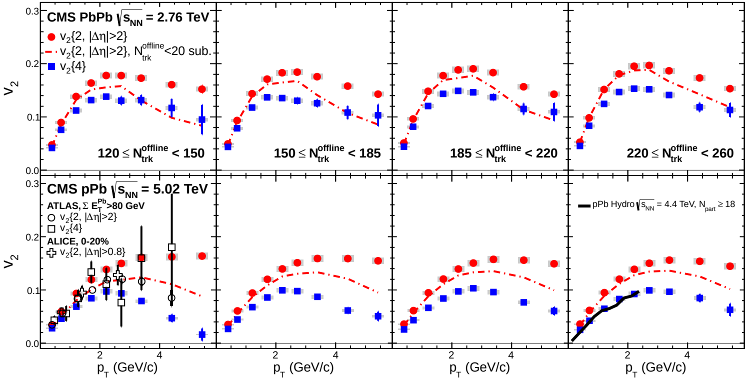
- Long-range rapidity correlations in high-multiplicity p-Pb events: collectiv flow?

Soft observables in p-A collisions: hot-medium effects?



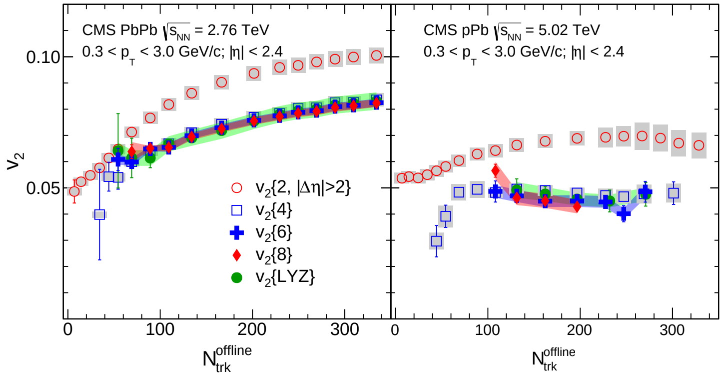
- Long-range rapidity correlations in high-multiplicity p-Pb events: collectiv flow?
- Evidence of non-vanishing elliptic flow v_2 (and mass ordering) in d-Au and p-Pb.

Soft observables in p-A collisions: hot-medium effects?



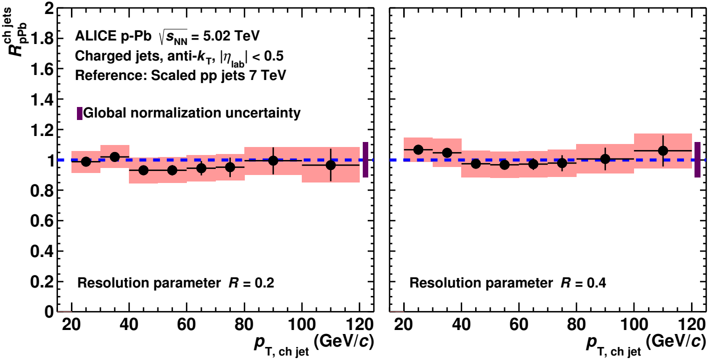
- Long-range rapidity correlations in high-multiplicity p-Pb events: collectiv flow?
- Evidence of non-vanishing elliptic flow v_2 (and mass ordering) in d-Au and p-Pb. CMS cumulants analysis: common correlation of all the particles with the event-plane Ψ_2

Soft observables in p-A collisions: hot-medium effects?



- Long-range rapidity correlations in high-multiplicity p-Pb events: collectiv flow?
- Evidence of non-vanishing elliptic flow v_2 (and mass ordering) in d-Au and p-Pb. CMS cumulants analysis: common correlation of all the particles with the event-plane Ψ_2

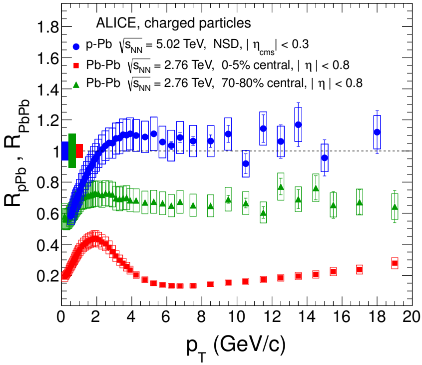
Hard observables in p-A collisions: no medium effect?



No evidence of medium effects in the nuclear modification factor

- neither of jets

Hard observables in p-A collisions: no medium effect?



No evidence of medium effects in the nuclear modification factor

- neither of jets
- nor of charged particles

NB *Lack of a p-p reference* at the same center-of-mass energy source of systematic uncertainty

Hard and soft probes: different sensitivity to the medium

The quenching of a high-energy parton is described by the pocket formula

$$\langle \Delta E \rangle \sim C_R \alpha_s \hat{q} L^2 \sim T^3 L^2$$

with a strong dependence on the temperature and medium thickness.

Hard and soft probes: different sensitivity to the medium

The quenching of a high-energy parton is described by the pocket formula

$$\langle \Delta E \rangle \sim C_R \alpha_s \hat{q} L^2 \sim T^3 L^2$$

with a strong dependence on the temperature and medium thickness.
If one believes that also in p-A collisions soft physics is described by hydrodynamics ($\lambda_{\rm mfp} \ll L$), then starting from an energy-density profile

$$\epsilon(x,y) \sim \exp\left[-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}\right]$$

and employing the Euler equation (for $v \ll 1$)

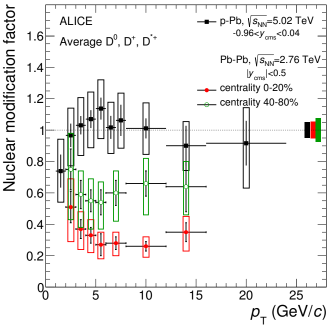
$$(\epsilon + P)\frac{d}{dt}\vec{v} = -\vec{\nabla} P \quad \underset{P=c_s^2\epsilon}{\longrightarrow} \quad \partial_t v^i = -\frac{c_s^2}{1+c_s^2}\frac{\partial \ln \epsilon}{\partial x^i}$$

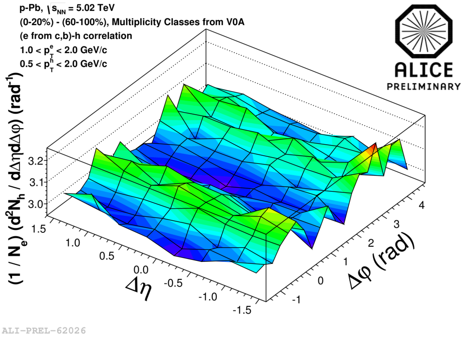
whose solution and mean square value over the transverse plane is

$$v^i = \frac{c_s^2}{1+c_s^2}\frac{x^i}{\sigma_i^2}t \quad \longrightarrow \quad \overline{v}^{x/y} = \frac{c_s^2}{1+c_s^2}\frac{t}{\sigma_{x/y}}$$

The result has a much milder temperature dependence ($c_s^2 \approx 1/3$) wrt $\hat{q}$ and, although the medium has a ($\approx$3 times) shorter lifetime, radial flow develops earlier, due to the larger pressure gradient

Heavy Flavour in p-A: experimental indications



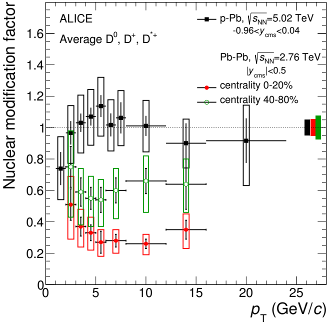


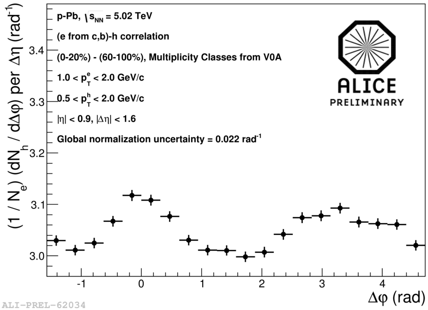
So far, experimental data don't allow one to draw firm conclusions

- D-meson $R_{\mathrm{AA}} \approx 1$ over a wide p_T-range;
- e-h correlations provide *hints* of a double-ridge structure

How to reconcile the two observations?

Heavy Flavour in p-A: experimental indications



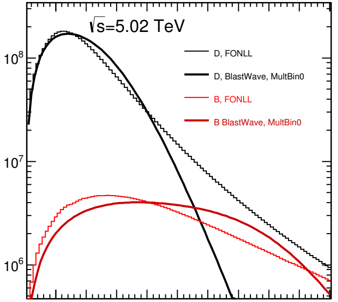


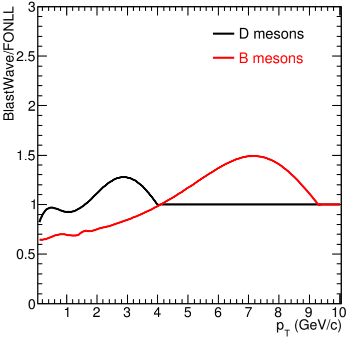
So far, experimental data don't allow one to draw firm conclusions

- D-meson $R_{AA} \approx 1$ over a wide p_T-range;
- e-h correlations provide *hints* of a double-ridge structure

How to reconcile the two observations?

Extreme scenario: HF flowing with the medium

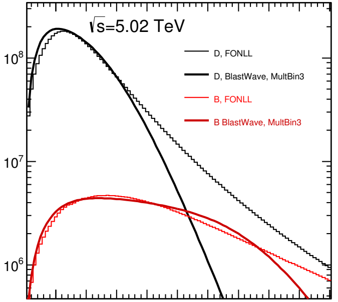


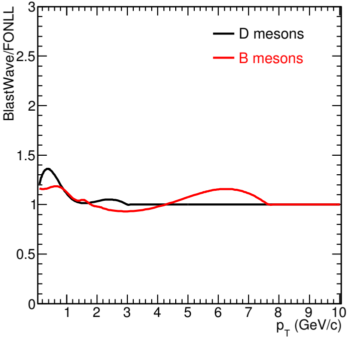


At 5.02 TeV, for a quite wide p_T interval, FONLL and blast-wave spectra don't differ so much: it looks in principle possible for charm quarks to flow with the medium having nevertheless $R_{\mathrm{AA}} \approx 1$

Can one attempt a more quantitative analysis?

Extreme scenario: HF flowing with the medium





At 5.02 TeV, for a quite wide p_T interval, FONLL and blast-wave spectra don't differ so much: it looks in principle possible for charm quarks to flow with the medium having nevertheless $R_{\rm AA} \approx 1$

Can one attempt a more quantitative analysis?

HF in small-systems: transport setup

In order to investigate medium effects on HF production it is necessary

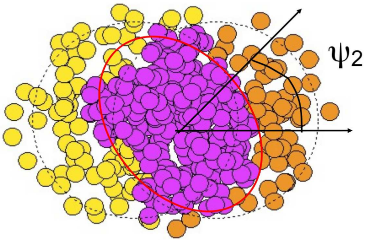
- to have a realistic model of the background medium (hydrodynamics validated with exp. soft-physics data)
- to simulate the HF transport in such a small hot medium (relativistic Langevin equation)
- to account for possible medium modifications of HF hadronization

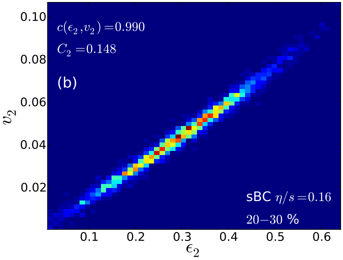
Medium modeling: event-by-event hydrodynamics

Event-by-event fluctuations (e.g. in the nucleon positions) leads to an initial *eccentricity*

$$s(\mathbf{x}) = \frac{K}{2\pi\sigma^2}\sum_{i=1}^{N_{\rm coll}} \exp\left[-\frac{(\mathbf{x}-\mathbf{x}_i)^2}{2\sigma^2}\right] \quad \longrightarrow \quad \epsilon_2 = \frac{\sqrt{\{y^2-x^2\}^2+4\{xy\}^2}}{\{x^2+y^2\}}$$

which translates into a non-vanishing elliptic flow

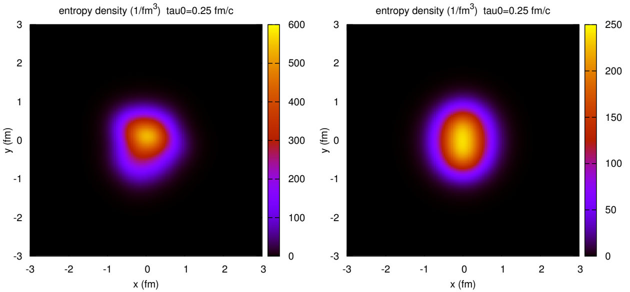




Notice the linear rensponse to the initial eccentricity observed in event-by-event studies of AA collisions!

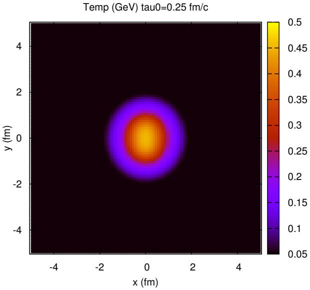
Medium modeling with ECHO-QGP

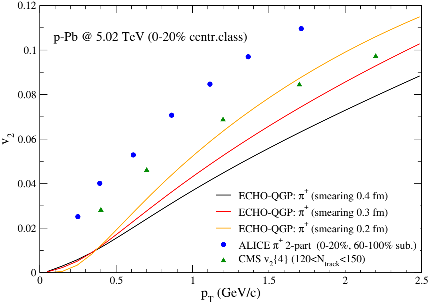
A full event-by event hydro+transport study requires huge computing resources (time and storage). One can exploit the strong correlation $v_2 \sim \epsilon_2$ considering an *average background* obtained summing all the events of a given centrality class rotated of the *event-plane* angle ψ_2



Medium modeling with ECHO-QGP

A full event-by event hydro+transport study requires huge computing resources (time and storage). One can exploit the strong correlation $v_2 \sim \epsilon_2$ considering an *average background* obtained summing all the events of a given centrality class rotated of the *event-plane* angle ψ_2



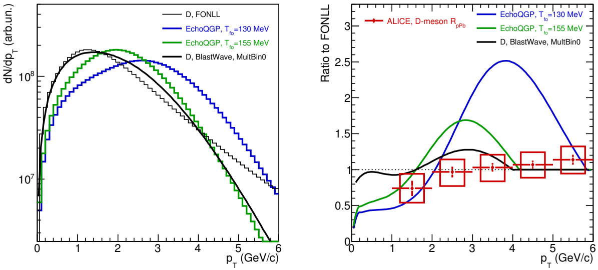


One can reproduce the light-hadron elliptic flow, although – with such a small system – there is a sensitivity to the smearing parameter ($\neq$ AA collisions): doing better would require knowing the proton structure

The limit of full kinetic thermalization

Having at our disposal a full hydrodynamical simulation one can go beyond the blast-wave approach and compare the pQCD spectrum with the one from a Cooper-Frye decoupling

$$E(dN/d\vec{p}) = \int_{\Sigma_{\rm FO}} p^\mu d\Sigma_\mu e^{-p\cdot u(x)/T_{\rm FO}}$$



- ECHO-QGP: 0-20% centrality class
- Blast-wave: high-multiplicity bin

Heavy-quark transport: the Langevin equation

The Langevin equation allows one to follow the dynamics of each individual quark in the medium

$$\frac{\Delta p^i}{\Delta t} = -\underbrace{\eta_D(p)p^i}_{\text{determ.}} + \underbrace{\xi^i(t)}_{\text{stochastic}},$$

with the properties of the noise encoded in

$$\langle\xi^i(\mathbf{p}_t)\xi^j(\mathbf{p}_{t'})\rangle = b^{ij}(\mathbf{p}_t)\frac{\delta_{tt'}}{\Delta t} \qquad b^{ij}(\mathbf{p}) \equiv \kappa_\parallel(p)\hat{p}^i\hat{p}^j + \kappa_\perp(p)(\delta^{ij} - \hat{p}^i\hat{p}^j)$$

Heavy-quark transport: the Langevin equation

The Langevin equation allows one to follow the dynamics of each individual quark in the medium

$$\frac{\Delta p^i}{\Delta t} = -\underbrace{\eta_D(p)p^i}_{\text{determ.}} + \underbrace{\xi^i(t)}_{\text{stochastic}} ,$$

with the properties of the noise encoded in

$$\langle \xi^i(\mathbf{p}_t)\xi^j(\mathbf{p}_{t'})\rangle = b^{ij}(\mathbf{p}_t)\frac{\delta_{tt'}}{\Delta t} \qquad b^{ij}(\mathbf{p}) \equiv \kappa_{\|}(p)\hat{p}^i\hat{p}^j + \kappa_{\perp}(p)(\delta^{ij} - \hat{p}^i\hat{p}^j)$$

Transport coefficients to calculate:

- *Momentum diffusion* $\kappa_{\perp} \equiv \frac{1}{2}\frac{\langle \Delta p_{\perp}^2 \rangle}{\Delta t}$ and $\kappa_{\|} \equiv \frac{\langle \Delta p_{\|}^2 \rangle}{\Delta t}$;
- *Friction* term (dependent on the discretization scheme!)

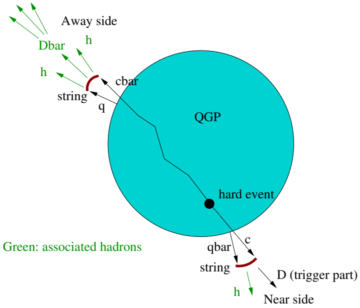
$$\eta_D{}^{\rm Ito}(p) = \frac{\kappa_{\|}(p)}{2TE_p} - \frac{1}{E_p^2}\left[(1-v^2)\frac{\partial \kappa_{\|}(p)}{\partial v^2} + \frac{d-1}{2}\frac{\kappa_{\|}(p) - \kappa_{\perp}(p)}{v^2}\right]$$

fixed in order to assure approach to equilibrium (Einstein relation):

From quarks to hadrons

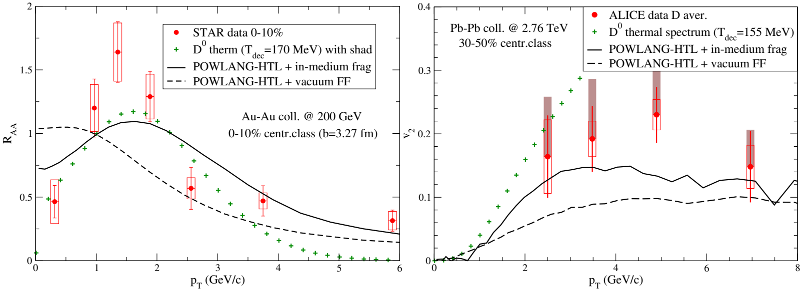
In-medium hadronization may affect the $R_{AA}/R_{\rm pA}$ and v_2 of final D-mesons due to the *collective flow* of light quarks. We estimate the effect through this model interfaced to our POWLANG transport code:

- At $T_{\rm dec}$ c-quarks coupled to light $\overline{q}$'s from a local *thermal distribution*, eventually *boosted* ($u^\mu_{\rm fluid} \neq 0$) to the lab frame;
- Strings are formed and given to PYTHIA 6.4 to simulate their fragmentation and produce the final hadrons ($D + \pi + \dots$)



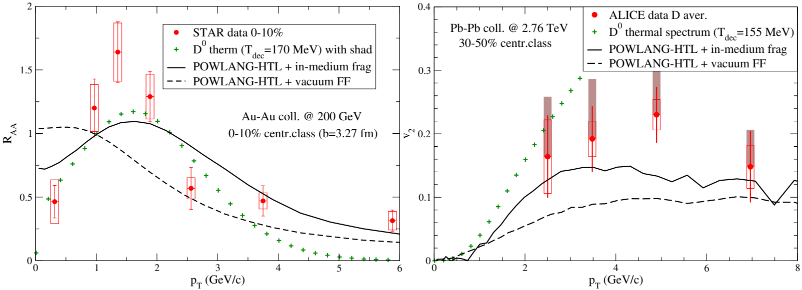
In-medium hadronization: effect in AA collisions

Experimental data display a peak in the R_{AA} and a sizable v_2 one would like to interpret as a signal of *charm radial flow and thermalization*



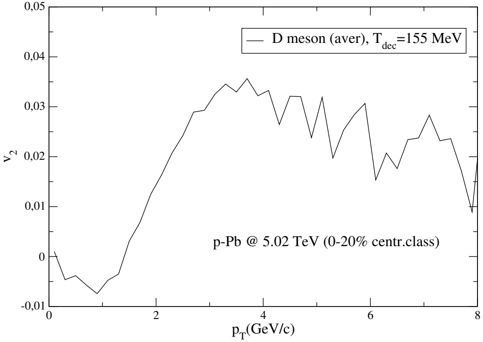
In-medium hadronization: effect in AA collisions

Experimental data display a peak in the R_{AA} and a sizable v_2 one would like to interpret as a signal of *charm radial flow and thermalization*



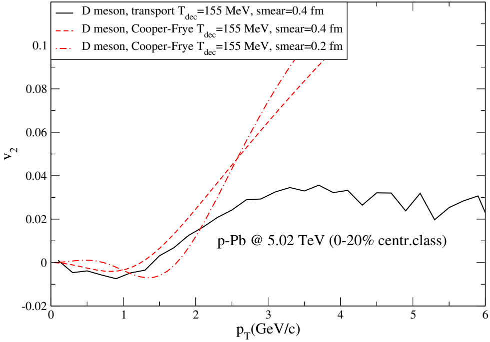
However, *comparing transport results with/without the boost* due to $u^{\mu}_{\rm fluid}$, at least part of the effect might be due to the radial and elliptic flow of the light partons from the medium picked-up at hadronization.

HF transport in p-A collisions: preliminary results



Preliminary results obtained with ECHO-QGP + Langevin + in-medium hadronization are shown. All the flow of D-mesons comes from the one of light partons.

HF transport in p-A collisions: preliminary results



Preliminary results obtained with ECHO-QGP + Langevin + in-medium hadronization are shown. All the flow of D-mesons comes from the one of light partons.

Summary

With the combination of hydrodynamics and transport calculations it will be possible to estimate the modifications of HF observables also in small systems, putting upper limits (full thermalization) on the size of the expected effects and challenging experimental measurements to reach the required amount of accuracy and precision in order to discriminate the different scenarios