Heavy flavours in nucleus-nucleus collisions: quenching, flow and correlations

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Heavy Flavor in the QGP: the conceptual setup

- Description of soft observables based on hydrodynamics, assuming to deal with a system close to local thermal equilibrium (no matter why);
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NB At high-p_T the interest in heavy flavor is no longer related to thermalization, but to the study of the mass and color charge dependence of jet-quenching (not addressed in this talk)

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- $\overline{p}_{\rm therm} \sim \sqrt{3MT} \gg gT$ (hence $M \gg g^2 T$), with gT being the *typical momentum exchange* in the collisions with the plasma particles: many soft scatterings necessary to change significantly the momentum/trajectory of the quark.

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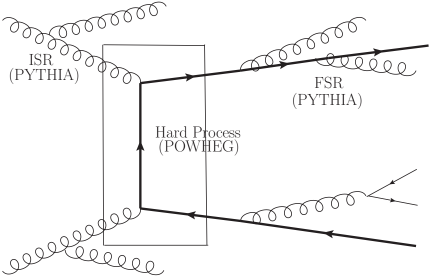
NB for realistic temperatures $g \sim 2$, so that one can wonder *whether a charm is really "heavy"*. We will always assume also the last condition to be satisfied, and we will follow HQ propagation through a Langevin equation (*soft momentum-exchange limit* of the Boltzmann equation)

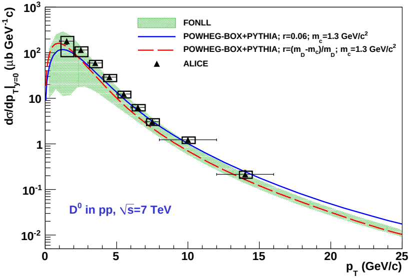
Simulating the initial hard production

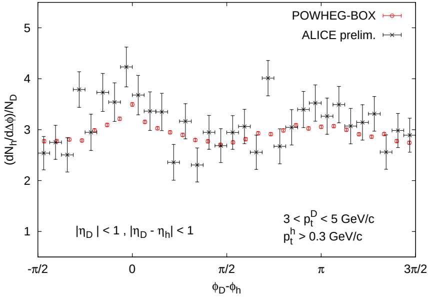


- Powerful pQCD tools[1] are available to simulate the initial $Q\overline{Q}$ production, interfacing the output of a NLO event-generator (POWHEG, MC@NLO) for the hard process with a parton-shower (PYTHIA, HERWIG) describing Initial and Final State Radiation.
- This provides a *fully exclusive information on the final state*, also thanks to the simulation of the Underlying Event and hadronization.

[1] For a systematic comparison (POWHEG vs MC@NLO vs FONLL): M. Cacciari *et al.*, JHEP 1210 (2012) 137.

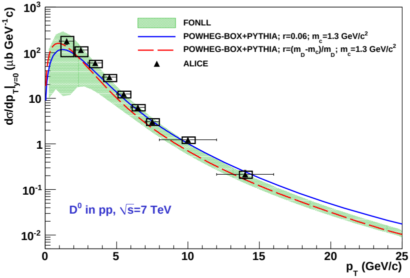
HF production in *pp* collisions: results

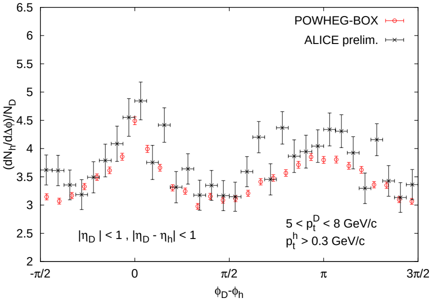




- Besides reproducing the inclusive p_T-spectra...[2]
- ...the POWHEG+PYTHIA setup allows also the comparison with $D-h$ correlation data which start getting available
- ...and the simulation of $e-h$ correlations currently in progress

[2] W.M. Alberico *et al*, Eur.Phys.J. C73 (2013) 2481





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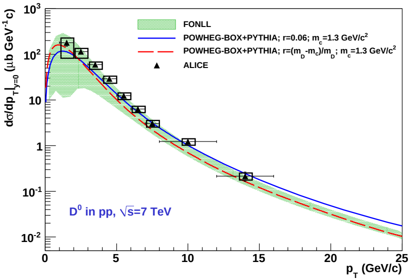

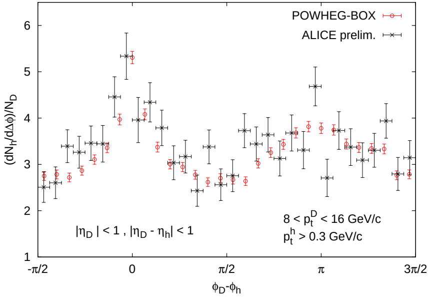

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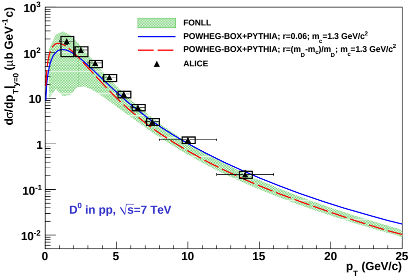

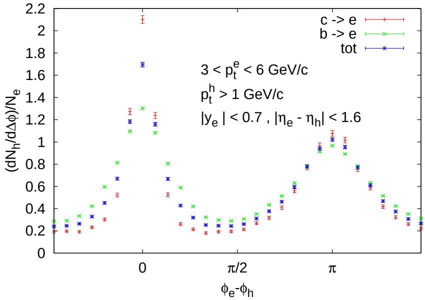

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HF in nucleus-nucleus collisions

- The theoretical tools: transport calculations (for this talk: the relativistic Langevin equation)
- The main questions we wish to answer: how close/far are heavy quarks go to/from thermalization? Are final (hadronic) observables able to answer this question?

The relativistic Langevin equation

The Langevin equation provides an algorithm to follow the dynamics of each heavy quark in the medium, updating its momentum and position

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

with the properties of the noise encoded in

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

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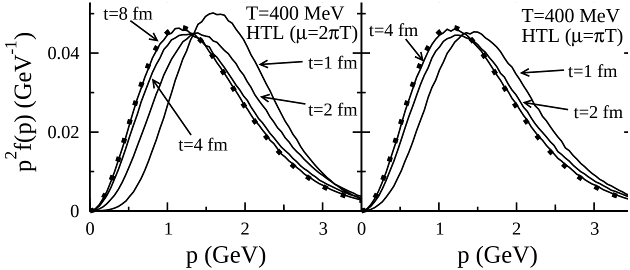
Transport coefficients to calculate:

- *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 insure approach to equilibrium (Einstein relation, *fluctuation-dissipation* theorem):

A first check: thermalization in a static medium



For $t \gg 1/\eta_D$ one approaches a relativistic Maxwell-Jüttner distribution[3]

$$f_{\rm MJ}(p) \equiv \frac{e^{-E_p/T}}{4\pi M^2 T\, K_2(M/T)}, \qquad \text{with} \int d^3p\, f_{\rm MJ}(p) = 1$$

(Test with a sample of c quarks with $p_0 = 2$ GeV/c and weak-coupling pQCD+HTL transport coefficients)

[3]A.B., A. De Pace, W.M. Alberico and A. Molinari, NPA 831, 59 (2009)

The realistic case: expanding fireball

- $Q\overline{Q}$ pairs initially produced with the POWHEG-BOX package (with nPDFs) and distributed in the transverse plane according to $n_{\rm coll}(\mathbf{x}_\perp)$ from (optical) Glauber model;

[4] P.F. Kolb, J. Sollfrank and U. Heinz, Phys. Rev. C **62** (2000) 054909
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- $Q\overline{Q}$ pairs initially produced with the POWHEG-BOX package (with nPDFs) and distributed in the transverse plane according to $n_{\rm coll}(\mathbf{x}_\perp)$ from (optical) Glauber model;
- update of the HQ momentum and position to be done at each step *in the local fluid rest-frame*
  - $u^\mu(x)$ used to perform the boost to the fluid rest-frame;
  - $T(x)$ used to set the value of the transport coefficients

  with $u^\mu(x)$ and $T(x)$ fields taken from the output of hydro codes[4];
- Procedure iterated until hadronization

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Heavy quark thermalization?

Wondering whether heavy quarks thermalize entails a number of related questions...

- Are theoretical tools able to describe their approach to *thermal* equilibrium in a evolving medium?
- What are the indications coming from experiment? Are final hadronic/leptonic observables able to provide an unambiguous answer on *what happens in the partonic stage*?
- What could be the role of experiments at larger $\sqrt{s_{\rm NN}}$? Higher temperature and radial flow, but also much harder initial $Q\overline{Q}$ spectrum...

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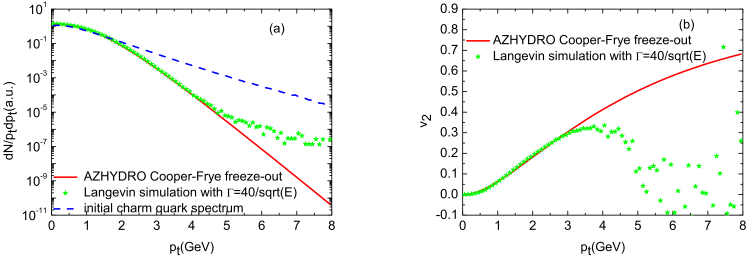
NB thermal equilibrium of HQ's at the end of the QGP phase is assumed in the description of hidden and open charm production within the Statistical Hadronization Model: answering this question may support or rule out such an hypothesis

Validation of the theoretical tools

In the limit of large transport coefficients heavy quarks should reach local thermal equilibrium and decouple from the medium as the other light particles, according to the Cooper-Frye formula:

$$E(dN/d^3p) = \int_{\Sigma_{\rm fo}} \frac{p^\mu \cdot d\Sigma_\mu}{(2\pi)^3} \exp[-p\cdot u/T_{\rm fo}]$$



This was verified to be actually the case (M. He, R.J. Fries and R. Rapp, PRC 86, 014903).

Experimental indications

It is possible to compare the *experimental* D-meson R_{AA} with the *theoretical expectation* in the case of *kinetic equilibrium*

- Spectrum in *pp* given by POWHEG+PYTHIA setup
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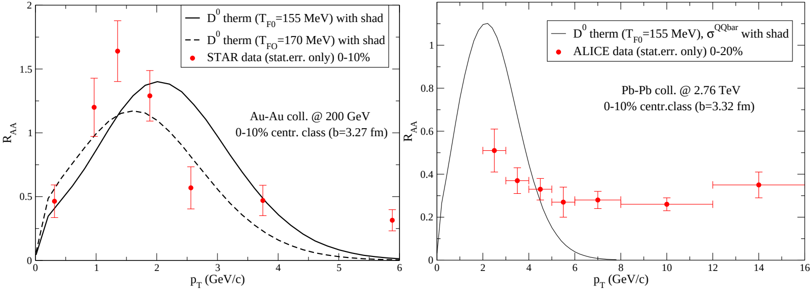

Evidence of a bump from radial flow at RHIC, while more data at low-p_T (waiting for ALICE ITS upgrade) necessary at LHC; in any case charm *partially out of kinetic equilibrium*, at least at LHC

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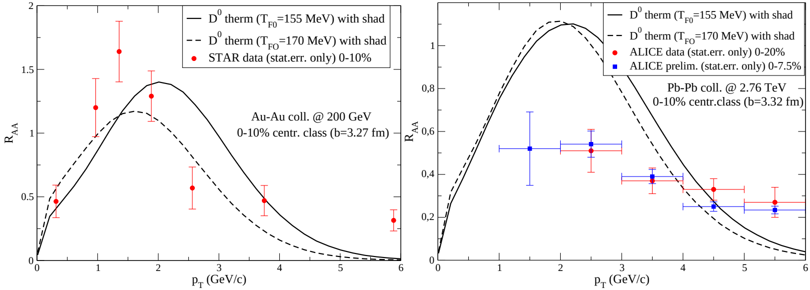

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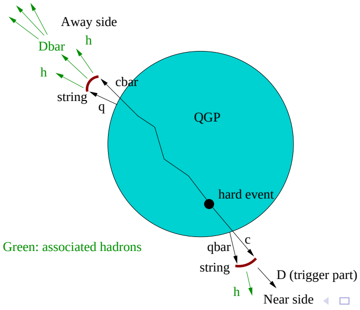
From quarks to hadrons

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

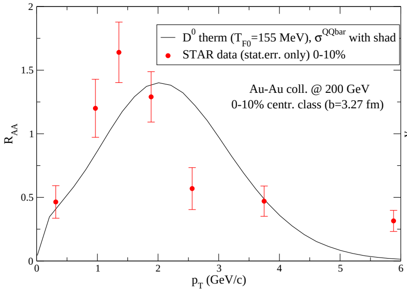
- At $T_{\rm dec}$ c-quarks coupled to light $\overline{q}$'s from a local *thermal distribution*, eventually *boosted* ($u^{\mu}_{\rm fluid} \neq 0$) to the lab frame;
- Strings are formed and given to PYTHIA 6.4 to simulate their fragmentation and produce the final hadrons ($D + \pi + \dots$)

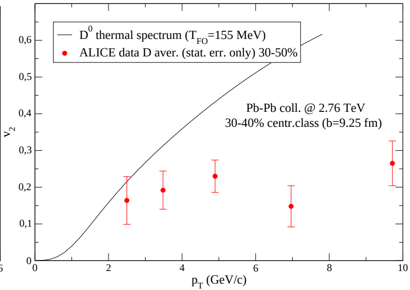
One can address the study of $D-h$ and $e-h$ correlations in AA collisions



From quarks to hadrons: effect on R_{AA} and v_2

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*





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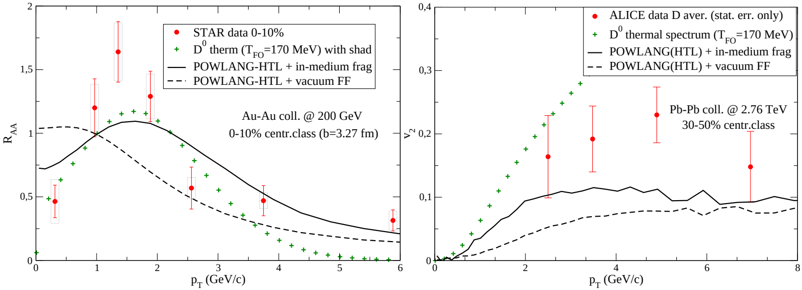

However, *comparing transport results with/without the boost* due to $u^{\mu}_{\rm fluid}$, at least part of the effect might be due to the radial and elliptic flow of the light partons from the medium picked-up at hadronization.

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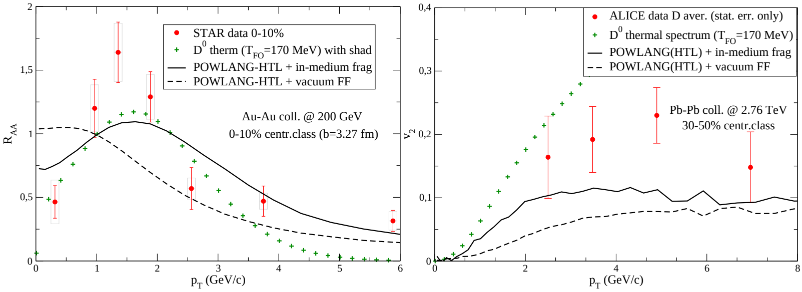
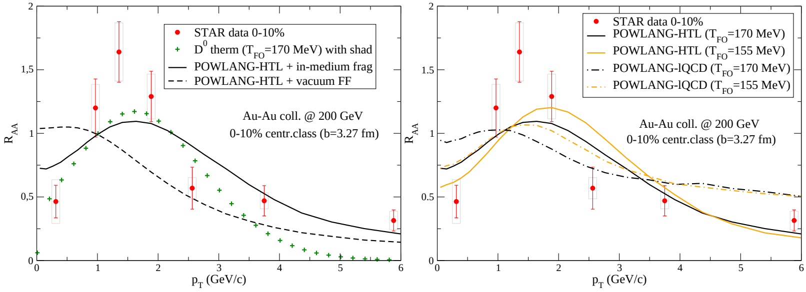


However, *comparing transport results with/without the boost* due to $u^{\mu}_{\rm fluid}$, at least part of the effect might be due to the radial and elliptic flow of the light partons from the medium picked-up at hadronization. Rescattering in the hadronic phase and its effect on v_2 should be also investigated (in progress)!

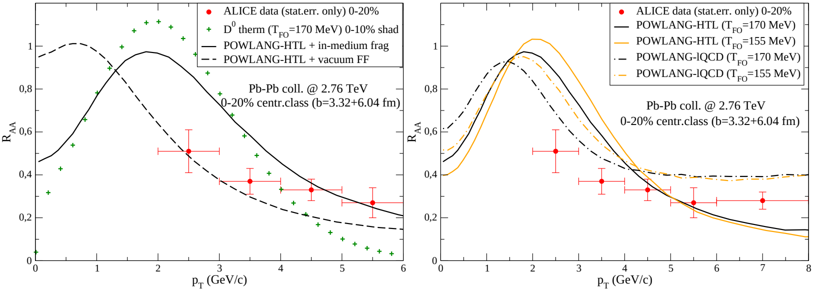
D-meson R_{AA} at RHIC



It is possible to perform a systematic study of different choices of

- Hadronization scheme (left panel)
- Transport coefficients (weak-coupling pQCD+HTL vs non-perturbative l-QCD) and decoupling temperature (right panel)

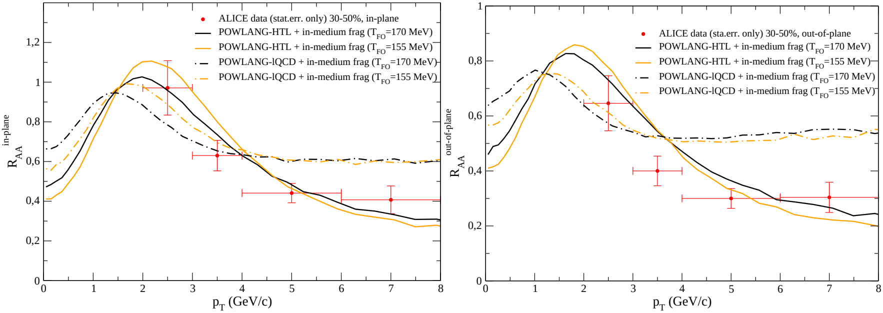
D-meson R_{AA} at LHC



Experimental data for central (0−20%) Pb-Pb collisions at LHC display a strong quenching, but – at least with the present bins and p_T range – don't show strong signatures of the bump from radial flow predicted by "thermal" and "transport + $Q\overline{q}_{\rm therm}$-string fragmentation" curves.

D meson R_{AA}: in-plane vs out-of-plane

One can study di R_{AA} in- and out-of-plane in non-central $(30-50\%)$ Pb-Pb collisions at LHC:



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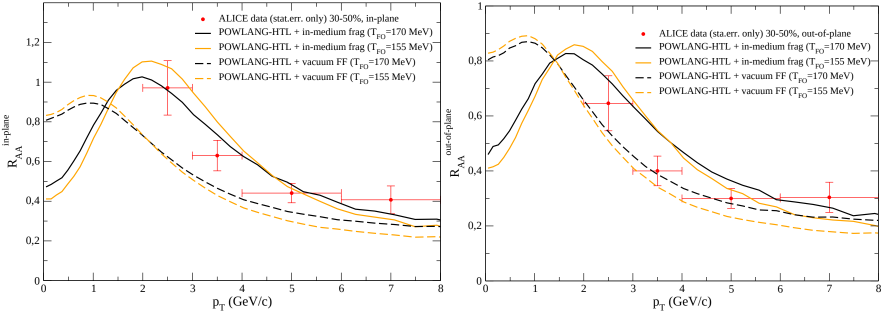

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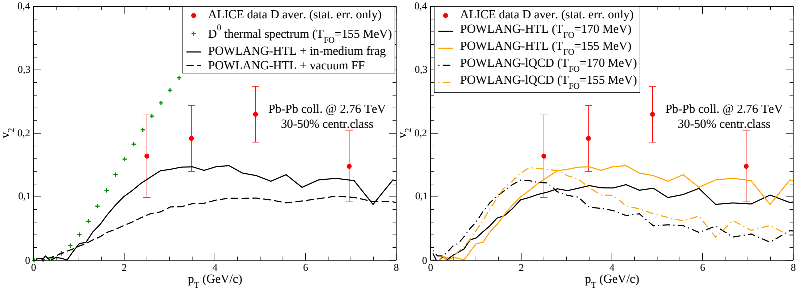
- $Q\overline{q}_{\rm therm}$-string fragmentation describes data slightly better than in-vacuum independent Fragmentation Functions.

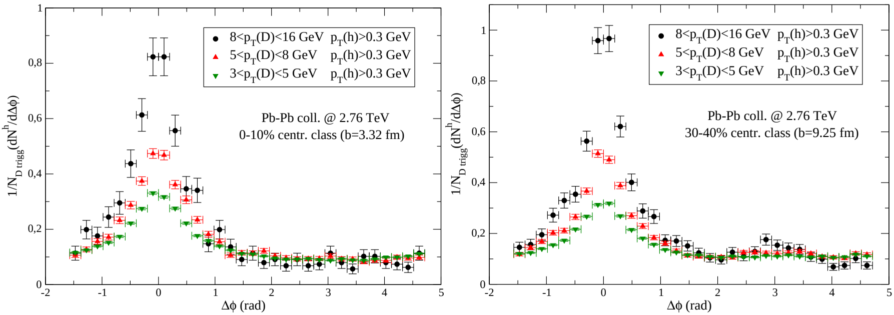
D-meson v_2 at LHC



Concerning D-meson v_2 in non-central $(30-50\%)$ Pb-Pb collisions:

- $Q\overline{q}_{\rm therm}$-string fragmentation routine significantly improves our transport model predictions compared to the data;
- HTL curves with a *lower decoupling temperature* display the best agreement with ALICE data

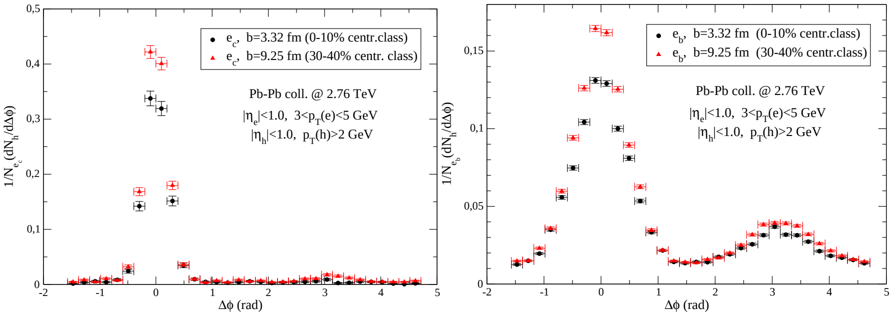
Azimuthal correlations: $D - h$



Away-side peak strongly suppressed
both in central and semi-central collisions

Azimuthal correlations: $e-h$

We plot the separate e_c (left) and e_b (right) contributions from charm and beauty decays



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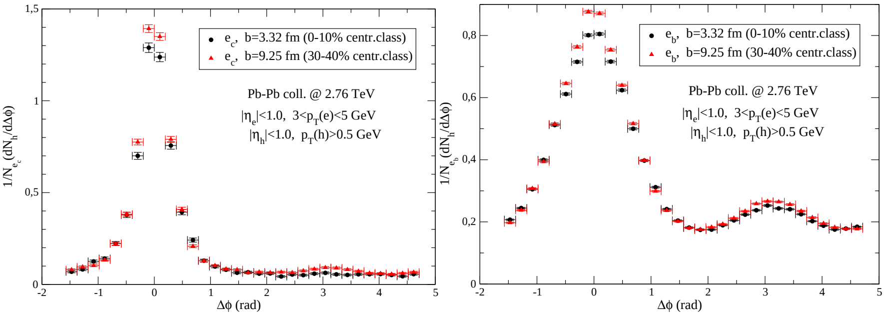

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Summary and perspectives

- We have tried to answer the question of kinetic equilibration of charm in heavy-ion collisions. We have shown how predictions of two different scenarios (hydro and transport+recombination) can be hardly distinguished within the current kinematic range covered by the experiment and they can both describe some qualitative features of the data at low-moderate p_T

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- We have presented a new hadronization routine (recombination followed by string fragmentation) interfaced to our partonic transport code, which improves the agreement of the latter with experimental data:
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- We have applied our setup to the study of azimuthal heavy-flavour ($D-h$ and $e-h$) correlations. Which information can be obtained on the HQ-medium interaction?