Heavy-flavour dynamics in (proton-proton and) nucleus-nucleus collisions at LHC

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work done in collaboration with
A. Beraudo, A. De Pace, M. Monteno, F. Prino (INFN Torino)

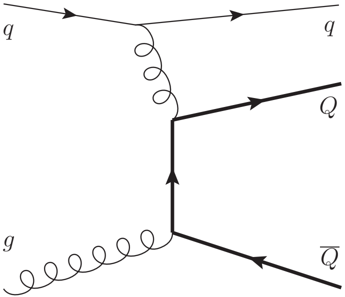
Outline

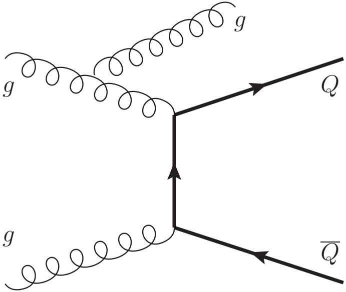
1. POWLANG setup:
   - $Q\bar{Q}$ production and hadronization in pp
   - $Q\bar{Q}$ production in AA
   - $Q\bar{Q}$ propagation: effects of the (non-static) medium
   - $Q\bar{Q}$ hadronization in AA
2. Results:
   - R_{AA} vs p_T for D mesons
   - Elliptic flow coefficient for D mesons
   - $D-h$ and $e-h$ azimuthal correlations in p-p and Pb-Pb
3. Discussion and future improvements

Published papers: A.Beraudo et al., Nucl. Phys. A 831 (2009) 59
W.Alberico et al., Eur. Phys. J. C71 (2011) 1666
W.Alberico et al., Eur. Phys. J. C73 (2013) 2481

Production

The large mass of c and b quarks makes their partonic production cross-section accessible to pQCD calculations.
We rely on a standard pQCD public tool, POWHEG-BOX (based on collinear factorization), in which the hard $Q\overline{Q}$ event is interfaced with a shower stage described by PYTHIA.





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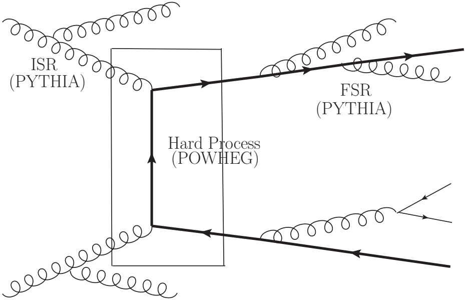

Hadronization
(independent fragmentation approach)

We adopt the same fragmentation setup employed by FONLL which was carefully tuned to reproduce experimental e^+e^--data.

Heavy quarks are made hadronize by sampling different hadron species from c and b fragmentation fractions extracted from experimental data.[1]

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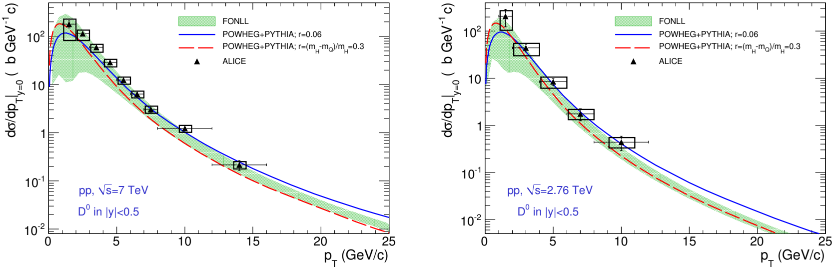
Next plots: we display the outcomes of the POWHEG-BOX setup in p-p collisions at different energies, compared to experimental data.

[1] Details in: W.Alberico et al., Eur. Phys. J. C71 (2011) 1666, W.Alberico et al., Eur. Phys. J. C73 (2013) 2481

pp at LHC



ALICE Collab., JHEP 1201, 128 (2012); JHEP 1201, 191 (2012); arXiv:1208.5411.

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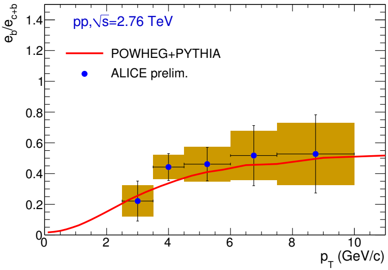
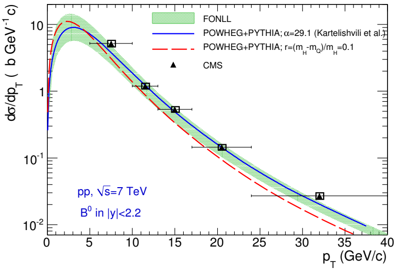
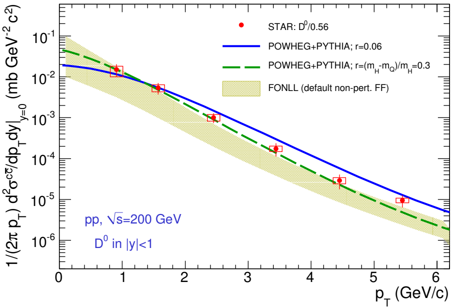




ALICE Collab., JHEP 1201, 128 (2012); JHEP 1201, 191 (2012); arXiv:1208.5411.
CMS Collab., Phys. Rev. Lett. 106, 252001 (2011)

pp at RHIC



D^0 p_T-differential cross-section in pp collisions at $\sqrt{s}=200$ GeV, measured by the STAR collaboration [2], compared to the predictions of the POWHEG+PYTHIA setup employed in the present work.

[2] STAR Collab., Phys. Rev. D 86, 072013 (2012)

Heavy flavours in *AA* collisions

Initial $Q\bar{Q}$ production

The initial hard $Q\overline{Q}$ production in AA collisions was simulated through the POWHEG+PYTHIA setup described previously for pp, with some differences:

- We include the EPS09 nuclear corrections to the PDFs.
- The position of each $Q\bar{Q}$ pair is distributed in the transverse plane according to the local density of binary collisions, taken from an optical Glauber calculation.[3]
- The colliding partons acquire, on the average, a larger transverse momentum, proportional to the size of the traversed medium. To get a realistic estimate for $\langle k_T^2 \rangle_{AA}$ we have adopted the same Glauber approach.

[3] W.M. Alberico, A. Beraudo, A. De Pace, A. Molinari, M. Monteno, M.N. and F. Prino, Eur.Phys.J. C71 (2011) 1666

Medium evolution: Relativistic Hydrodynamics

Hydrodynamics provides the full space-time evolution of the properties of the expanding medium — such as temperature, flow velocity and energy density. The results shown in this talk are obtained through hydrodynamical calculations performed with a viscous 2+1 code [4]. The parameter used for its initialization are

Nuclei	$\sqrt{s_{\rm NN}}$	τ_0 (fm/c)	s_0 (fm^{-3})	T_0 (MeV)
Au-Au	200 GeV	1.0	84	333
Pb-Pb	2.76 TeV	0.6	278	475

Longitudinal invariance is assumed: the results are valid at midrapidity.

[4] P. Romatschke, U. Romatschke, Phys. Rev. Lett. **99**, 172301 (2007); M.Luzum, P. Romatschke, Phys. Rev. C 78, 034915 (2008)

Heavy quarks in the medium: Relativistic Langevin Equation

The time-evolution of the momentum of a relativistic Brownian particle is provided by the following stochastic differential equation

$$\frac{\Delta\vec{p}}{\Delta t} = -\eta_D(p)\vec{p} + \vec{\xi}(t), \tag{1}$$

The *drag coefficient* $\eta_D(p)$ describes the deterministic friction force acting on the heavy quark, whereas the term $\vec{\xi}$ accounts for the random collisions with the constituents of the medium. The effect of the stochastic term is determined by the temporal correlation function, assumed to be

$$\langle \xi^i(t)\xi^j(t')\rangle = b^{ij}(\vec{p})\delta_{tt'}/\Delta t, \tag{2}$$

entailing that collisions at different time-steps are uncorrelated.

The tensor $b^{ij}(\vec{p})$ can be decomposed with a standard procedure according to

$$b^{ij}(\vec{p}) \equiv \kappa_L(p)\hat{p}^i\hat{p}^j + \kappa_T(p)(\delta^{ij} - \hat{p}^i\hat{p}^j), \tag{3}$$

with the coefficients $\kappa_L(p)$ ($\kappa_T(p)$) representing the squared longitudinal (transverse) momentum per unit time exchanged by the quark with the medium:

$$\kappa_L = \left\langle \frac{\Delta \mathbf{q}_L^2}{\Delta t} \right\rangle \quad \text{and} \quad \kappa_T = \frac{1}{2}\left\langle \frac{\Delta \mathbf{q}_T^2}{\Delta t} \right\rangle. \tag{4}$$

Finally, the drag coefficient $\eta_D(p)$ is fixed in order the approach to equilibrium (thermal Maxwell-Jüttner distribution):

$$\eta_D(p) \equiv \frac{\kappa_L(p)}{2TE_p} + \text{discr. corr.}, \tag{5}$$

where the corrections on the right hand side depend on the discretization scheme. Equations (3–5) are defined in the rest frame of the background medium.

The heavy-flavour transport coefficients $\kappa_{L/T}(p)$ are, in principle, obtained from first-priciple calculations.
We have tested two different approaches:

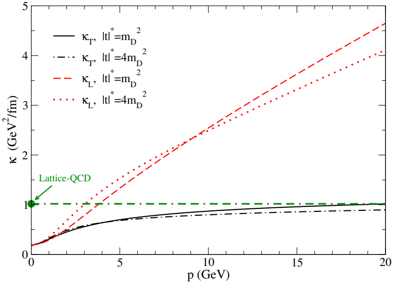
1. within a weakly-coupled scenario (pQCD + HTL) [5];
2. with non-perturbative lattice-QCD simulations [6], for static quarks.

[5] A. Beraudo et al., Nucl.Phys. A **831** 59 (2009)
W.M. Alberico et al., Eur. Phys. J. C **71** 1666 (2011)

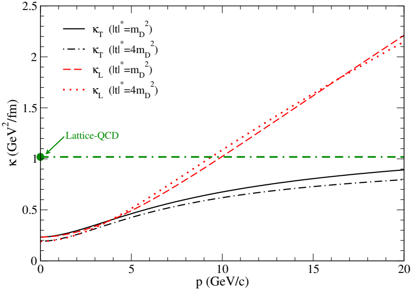
[6] A. Francis et al., PoS LATTICE2011 (2011) 202
D. Banerjee et al., Phys.Rev. D85 (2012) 014510

$\kappa_{L/T}(p)$: comparisons

Transport coefficients for heavy quarks in the QGP:



c quarks



b quarks

Weak coupling (HTL+pQCD) results for $\kappa_{L/T}(p)$ are compared to the data provided by the lattice-QCD calculations at $p = 0$ (and arbitrarily extrapolated at finite p_T).

The curves refer to the temperature $T = 400$ MeV.

To study the propagation of a heavy quark through the QGP:

1. We determine the initial four-momentum p^μ and the initial space-time position x^μ of the heavy quark (in the laboratory system) (POWHEG+PYTHIA)

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5. We update the space-time step made by the quark in the fluid rest frame ($\Delta\bar{x}^\mu = (\bar{p}^\mu/E_{\bar{p}})\Delta\bar{t}$), boost it to the laboratory ($\Delta\bar{x}^\mu \to \Delta x^\mu$) and use it to update the quark position ($x^\mu \to x'^\mu$).

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6. Given the new momentum p'^μ and the new position x'^μ the procedure is started again until the conditions for hadronization are met.

Hadronization in AA

We describe the in-medium hadronization with a simple model:

1. Every heavy quark Q hadronizes when, during its propagation in the fireball, it reaches a fluid cell with temperature lower than $T_{\rm dec}$.
2. One extracts a light antiquark $\overline{q}$ from a thermal momentum distribution corresponding to the temperature $T_{\rm dec}$ in the Local Rest Frame (LRF) of the fluid; the 4-momentum of $\overline{q}$ is then boosted to the lab. frame.

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In agreement with PYTHIA, in evaluating their momentum distribution, light quarks are taken as "dressed" particles with the effective masses $m_{u/d} = 0.33$ GeV and $m_s = 0.5$ GeV.

Concerning T_{dec} the values 0.155 and 0.17 GeV are explored.

With this improvement we have a realistic estimate of the role of light quarks in the D meson spectra at low and moderate p_T.

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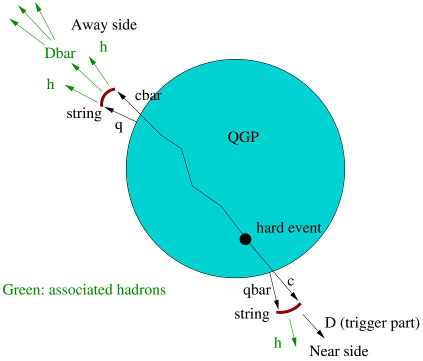
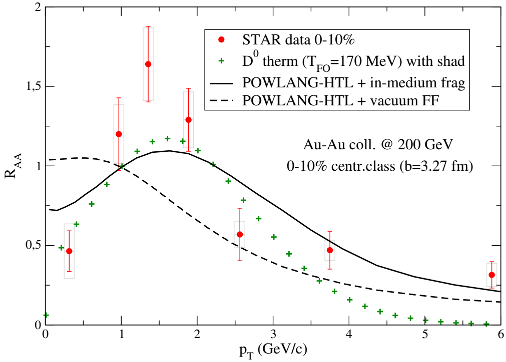
Moreover, the complete information on all the final state particles arising from the fragmentation of the strings allows to provide theory predictions for observables like D–h, e–h, e^+–e^- correlations.



Results / 1

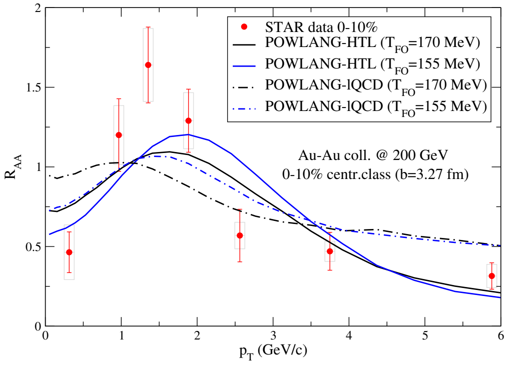
Nuclear modification factor R_{AA}

$$R_{AA} = \frac{\mathrm{d}N_{AA}/\mathrm{d}p_T}{N_{coll}\,\mathrm{d}N_{pp}/\mathrm{d}p_T}$$

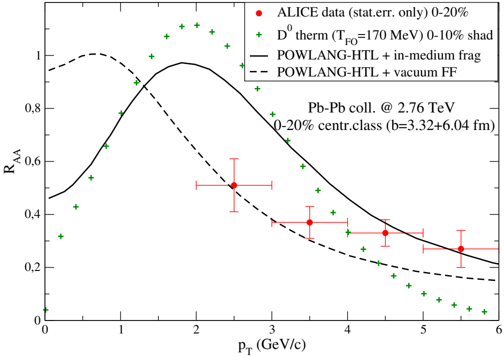


The R_{AA} of D^0 mesons in central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV.
POWLANG results obtained with HTL transport coefficients and a decoupling temperature $T_{\rm dec} = 170$ MeV are displayed.
Also shown for comparison is the limiting case of full kinetic thermalization of D mesons. Theory curves are compared to STAR data [7].

[7]STAR Collaboration (L. Adamczyk *et al.*), arXiv:1404.6185 [nucl-ex]

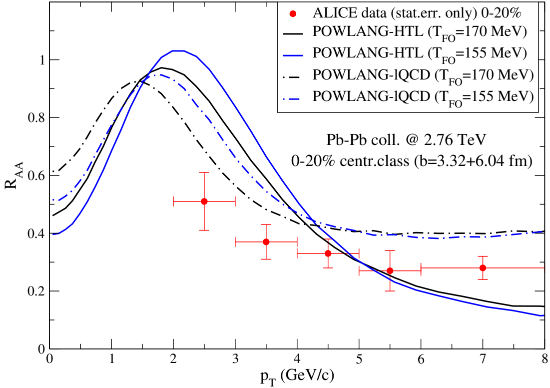


The R_{AA} of D^0 mesons in central Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV. POWLANG results are displayed for the transport coefficients calculated in the HTL framework and constant (extrapolated from L-QCD) and two decoupling temperatures: $T_{\rm dec} = 170$ and 155 MeV. In all cases heavy quarks are hadronized via recombination with light partons. Theory curves are compared to STAR data.

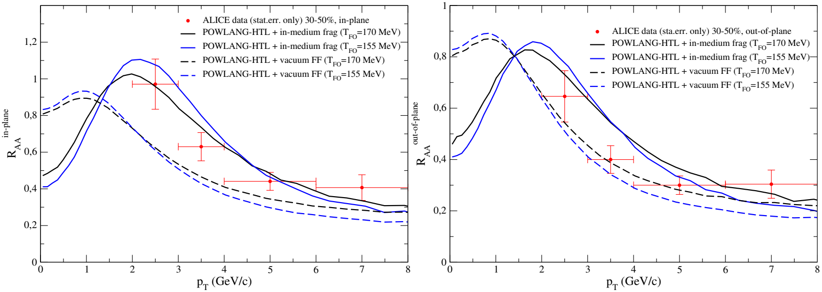


The R_{AA} of D^0 mesons in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. POWLANG results with in-vacuum and in-medium HQ fragmentation and decoupling temperature $T_{\rm dec} = 170$ MeV are compared to ALICE data[8] in central $(0 - 20\%)$ collisions.

[8] ALICE Coll. (B. Abelev *et al.*), JHEP 1209 (2012) 112; ALICE Coll. (Z. Conesa del Valle), Nucl.Phys.A 904-905 (2013) 178c.



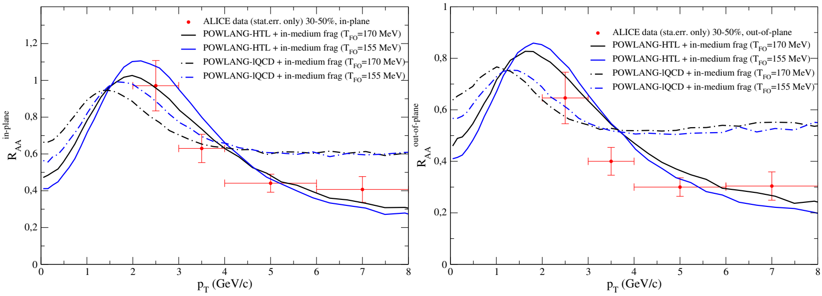
The R_{AA} of D^0 mesons in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.



The R_{AA} in-plane (left) and out-of-plane (right) of D mesons.

ALICE data in the $30-50\%$ centrality class [9] are compared to POWLANG results obtained with different hadronization mechanisms (in-medium, solid curves, and vacuum fragmentation, dashed curves) and decoupling temperatures ($T_{\rm dec}=170$, black curves, and 155 MeV, blue curves).

[9] ALICE Collaboration (B. Abelev *et al.*), arXiv:1405.2001 [nucl-ex]



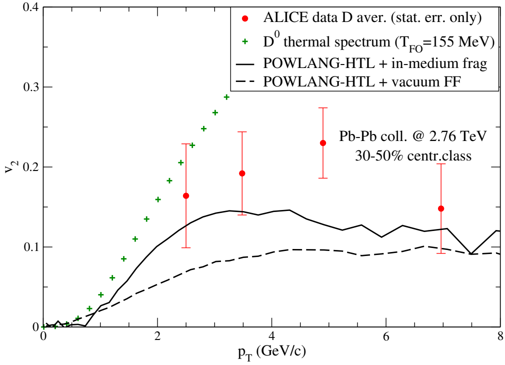
The R_{AA} in-plane (left) and out-of-plane (right) of D mesons.

ALICE data in the 30−50% centrality class are compared to POWLANG results obtained with different transport coefficients (HTL, continuous curves, and L-QCD, dashed curves) and decoupling temperatures ($T_{\rm dec}=170$, black curves, and 155 MeV, blue curves).

Results / 2

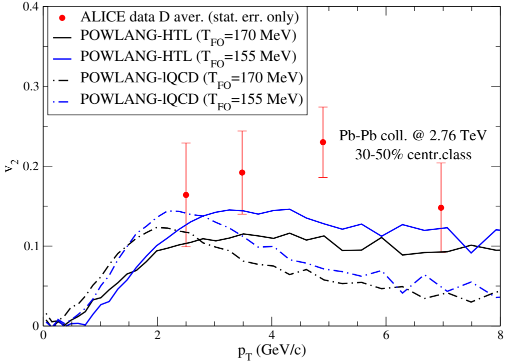
Elliptic flow coefficient v_2

$$\frac{\mathrm{d}N}{p_t \mathrm{d}p_t \mathrm{d}p_z \mathrm{d}\phi} = \frac{\mathrm{d}N}{p_t \mathrm{d}p_t \mathrm{d}p_z} \left(1 + 2\, v_2 \, \cos 2\phi\right)$$



The v_2 of D mesons in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

POWLANG results (with HTL transport coefficients) with in-vacuum and in-medium HQ fragmentation at the decoupling temperature $T_{\rm dec} = 155$ MeV compared to ALICE data in the 30-50% centrality class and to the limit of kinetic thermalization.



The v_2 of D mesons in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.
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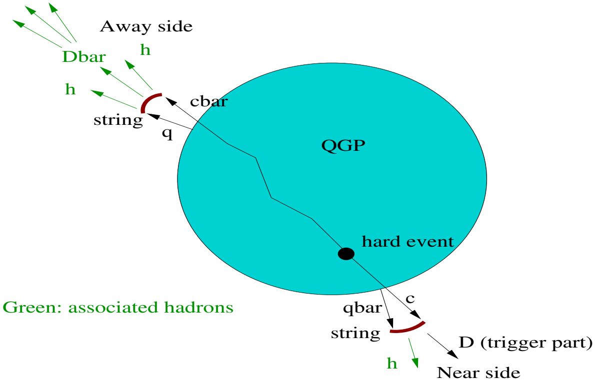
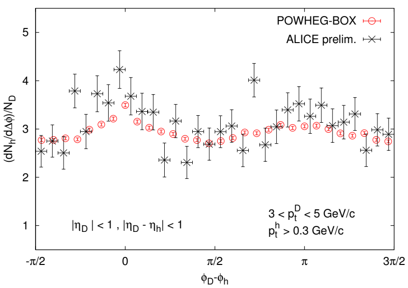
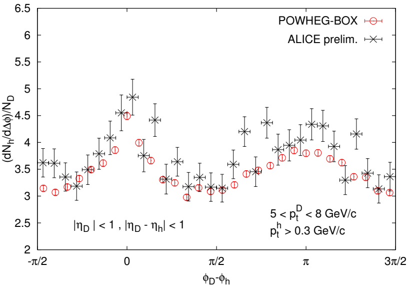
Results / 3

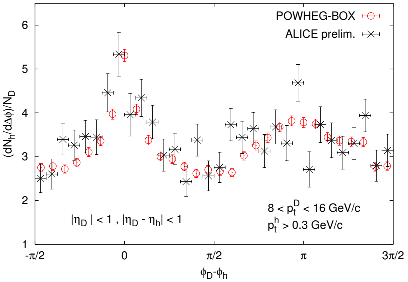
Azimuthal correlations



D-h azimuthal correlations in pp collisions



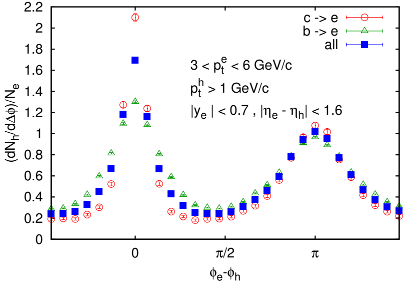


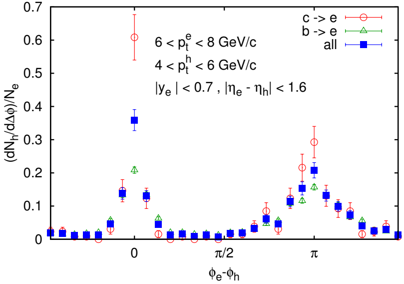


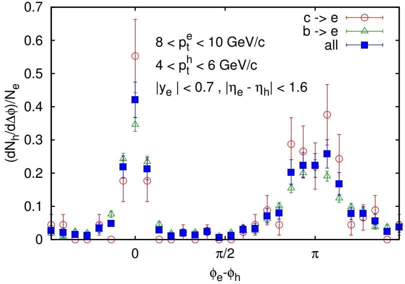
Azimuthal *D*–*h* correlations in pp collisions at $\sqrt{s} = 7$ TeV for various p_T-cuts of the trigger particle (D), compared to preliminary ALICE data[9].

[9][S. Bjelogrlić (for the ALICE Collaboration), Quark Matter 2014 proceedings.]

e-h azimuthal correlations in pp collisions







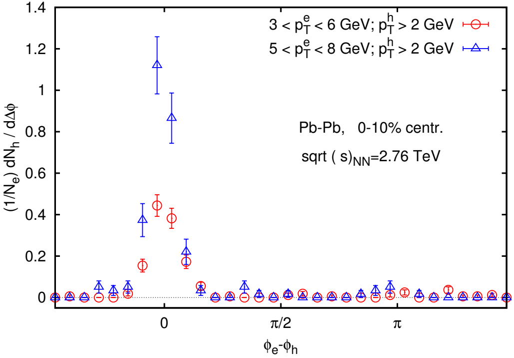
Azimuthal *e*–*h* correlations in *pp* collisions at $\sqrt{s} = 7$ TeV for various p_T-cuts of the trigger particle (e).

Red points: *e*'s from *D*;

Green points: *e*'s from *B* (incl. $B \to D \to e$);

Blue points: all *e*'s.

e-h azimuthal correlations in Pb-Pb collisions



Azimuthal $e-h$ correlations in $Pb-Pb$ collisions at $\sqrt{s}=2.76$ TeV for different p_T-cuts of the trigger particle (e). (Only e's from c's).

Conclusions

The implementation of a new, in-medium hadronization routine has improved the agreement between POWLANG results and the experimental data, both at RHIC and LHC energies: R_{AA} peak at small p_T, larger v_2, better in-plane out-of-plane description.
It allows us to make quantitative predictions also for $D - h$ and $e - h$ angular correlations.

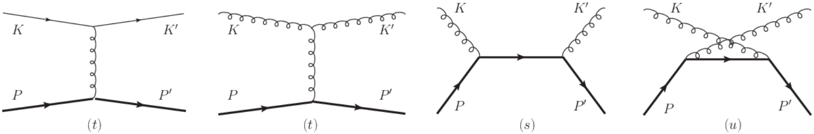
We plan to make further improvements, in particular

- we will extend our calculations at non-zero rapidity by interfacing our transport setup with the output of a viscous 3+1 hydrodynamical code (ECHO-QGP), currently under development;
- we will include the study of the transport of D mesons in the hadronic phase (so far neglected).

Extra Slides

Perturbative $\kappa_{L/T}(p)$

The momentum broadening (and degradation) of heavy quarks in the medium must arise from their interaction with the other constituents of the plasma: light quarks and gluons.
Within a perturbative setup the lowest order diagrams to consider for the hard scattering of a heavy quark off a light (anti-)quark and a gluon are



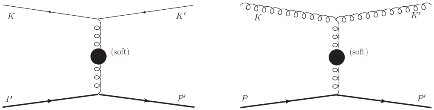
If the four-momentum exchange is sufficiently hard ($|t|>|t|^*$, where $t\equiv\omega^2-\mathbf{q}^2$) one is dealing with a short-distance process and the result is given by a kinetic pQCD calculation:

$$\kappa_{L,\mathrm{hard}}^{g/q} = \frac{1}{2E}\int_k \frac{n_{B/F}(k)}{2k}\int_{k'} \frac{1\pm n_{B/F}(k')}{2k'}\int_{p'} \frac{\theta(|t|-|t|^*)}{2E'} \times (2\pi)^4\delta^{(4)}(P+K-P'-K')\left|\overline{\mathcal{M}}_{g/q}(s,t)\right|^2 \mathbf{q}_L^2 \quad (1)$$

and

$$\kappa_{T,\mathrm{hard}}^{g/q} = \frac{1}{2E}\int_k \frac{n_{B/F}(k)}{2k}\int_{k'} \frac{1\pm n_{B/F}(k')}{2k'}\int_{p'} \frac{\theta(|t|-|t|^*)}{2E'} \times (2\pi)^4\delta^{(4)}(P+K-P'-K')\left|\overline{\mathcal{M}}_{g/q}(s,t)\right|^2 \frac{\mathbf{q}_T^2}{2}. \quad (2)$$

If the momentum transfer is soft ($|t| < |t|^*$), the scattering involves the exchange of a long wavelength gluon, which requires the resummation of medium effects, as in



This can be done in hot-QCD within the Hard Thermal Loop approximation.

Eventually, one has to sum-up the soft and hard contributions to the transport coefficients

$$\kappa_{L/T} = \kappa_{L/T}^{\text{soft}} + \kappa_{L/T}^{\text{hard}},$$

checking that the final result is not too sensitive to the artificial intermediate cutoff $|t|^*$.
The strong coupling g (for soft collisions) was evaluated at the scale $\mu = 1.5\pi T$, representing the central value of the systematic band explored in our study.

Hadronization in AA collisions

The Hydrodynamical code is based on a 2-phase EOS (QGP and HG) with a mixed phase. We assume that hadronization takes place during the mixed phase.
The fraction of QGP in the mixed phase is defined by

$$f_{QGP} = \frac{\varepsilon - \varepsilon_H}{\varepsilon_{QGP} - \varepsilon_H}.$$

The Langevin propagation of the heavy quark stops according to the following prescription:

1. we extract the medium energy density at the heavy-quark space-time position;
2. if $f_{QGP} > 1$ the Langevin propagation is carried on another step; otherwise
3. we treat $1 - f_{QGP}$ as a transition probability.