A transport set-up for heavy-flavour observables in nucleus-nucleus collisions at RHIC and LHC

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work done in collaboration with
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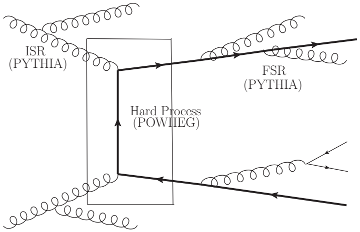
Outline

1. $Q\bar{Q}$ production and hadronization in pp; comparison to data (ALICE, CMS, STAR)
2. $Q\bar{Q}$ production and hadronization in AA
3. $Q\bar{Q}$ propagation: effects of the (non-static) medium
4. Results:
   - R_{AA} vs p_T and N_{part} for D mesons and non-photonic electrons, compared to experimental data;
   - Elliptic flow coefficient for D mesons, compared to experimental data;
   - **D-$\bar{D}$ and B-$\bar{B}$ azimuthal correlations.**
5. Discussion and future improvements

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.



Structure of a typical event arising from the POWHEG-BOX setup, with the hard process (in the box) followed by a shower

The results are in agreement with FONLL calculations on the inclusive charm/beauty production cross-sections.

Hadronization

- 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.
- Then, hadron momenta are sampled from Fragmentation Functions (FFs) calculated in heavy-quark effective theory (HQET[1]).
- To evaluate the systematic uncertainties associated to this stage we have tested different FFs [2] (with their parameters tuned to reproduce experimental data).

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

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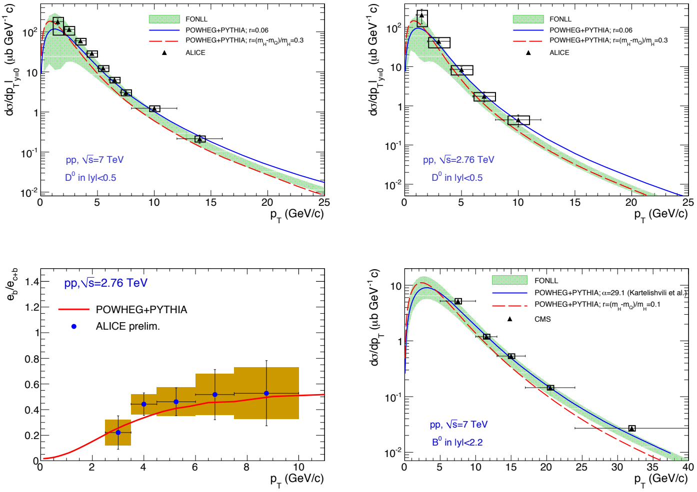
[1] E. Braaten et al., Phys. Rev. D **51**, 4819 (1995)

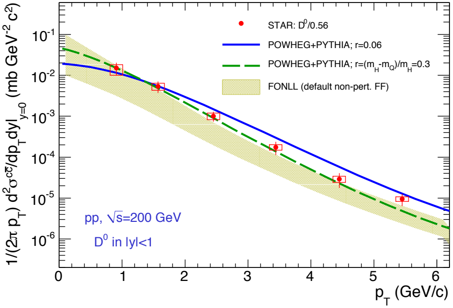
[2] M. Cacciari, P. Nason, J. High Energy Phys. **0309**, 006 (2003);
V. G. Kartvelishvili et al., Phys. Lett. B **78**, 615 (1978);
M. Cacciari et al., J. High Energy Phys. **0407**, 033 (2004)

pp at LHC



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

CMS Collab., Phys. Rev. Lett. 106, 252001 (2011)



D^0 p_T-differential cross-section in pp collisions at $\sqrt{s} = 200$ GeV, measured by the STAR collaboration [3], compared to the predictions of the POWHEG+PYTHIA setup employed in the present work.

[3] 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 two corrections:

- EPS09 nuclear corrections to the PDFs.
- larger transverse momentum, acquired on average by the colliding partons, proportional to the size of the traversed medium. To get a realistic estimate for $\langle k_T^2 \rangle_{AA}$ we have adopted a Glauber approach[4] to have a realistic dependence on the impact parameter and on the position of the $Q\bar{Q}$ pair in the transverse plane.

[4] W.M. Alberico et al., 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[5]. 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

[5] P. Romatschke, U. Romatschke, Phys. Rev. Lett. **99**, 172301 (2007)

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

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

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

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

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 time step in the rest frame, which enters in updating the quark position and also the quark momentum through the Langevin equation, in our calculations has the value $\Delta\bar{t} = 0.02$ fm.

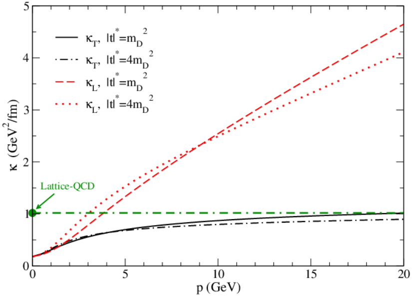
The heavy-flavour transport coefficients $\kappa_{L/T}(p)$ are, in principle, obtained from first-priciple calculations.
We have tested two different approaches:

1. within a weakly-coupled scenario (pQCD + HTL) [6];
2. with non-perturbative lattice-QCD simulations [7].

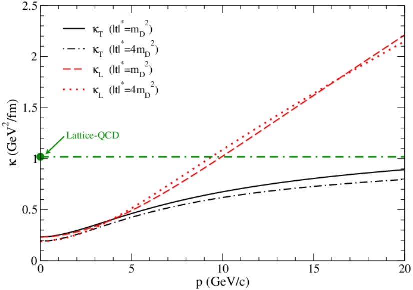
[6] A. Beraudo et al., Nucl.Phys. A **831** 59 (2009)
W.M. Alberico et al., Eur. Phys. J. C **71** 1666 (2011)

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

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



c quarks

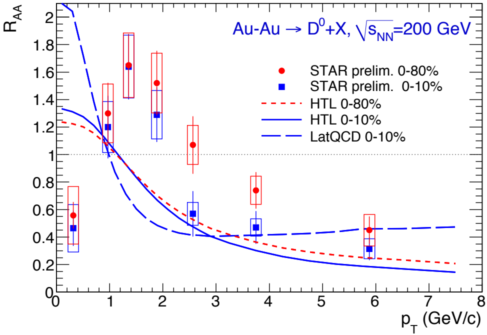


b quarks

Transport coefficients for heavy quarks in the QGP. 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).

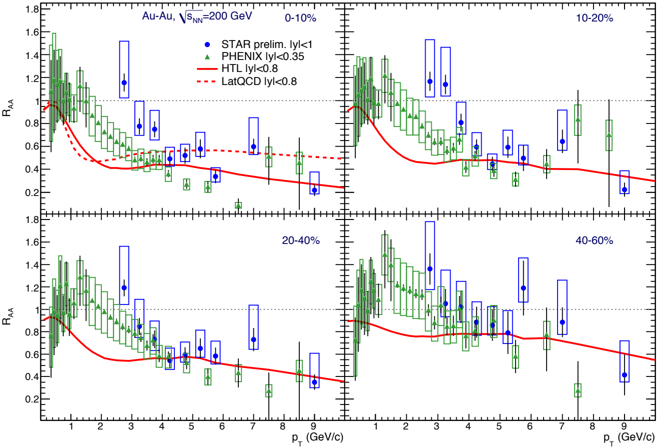
The curves refer to the temperature $T = 400$ MeV

Results



R_{AA} of D^0 mesons with HTL and constant (lattice-QCD) transport coefficients, in central ($0-10\%$, blue) and minimum-bias ($0-80\%$, red) Au-Au collisions at $\sqrt{s_{NN}} = 200$ GeV compared to preliminary STAR data [8]

[8]STAR Collab., Nucl. Phys. A 904-905, 639c (2013)

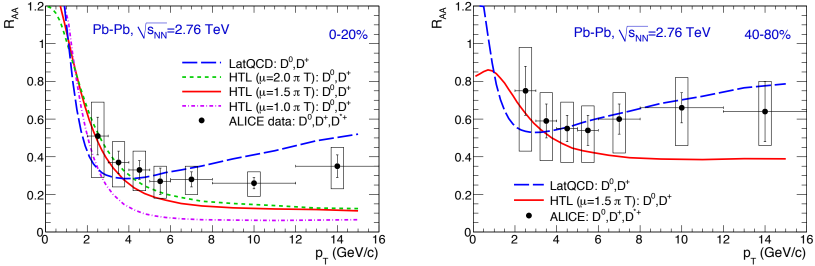


R_{AA} of non-photonic electrons (e_{c+b}), from charm and beauty decays, compared to PHENIX[9] and preliminary STAR[10] data.

Calculation performed with HTL transport coefficients.

[9] PHENIX Collab., Phys.Rev.C 84, 044905 (2011)

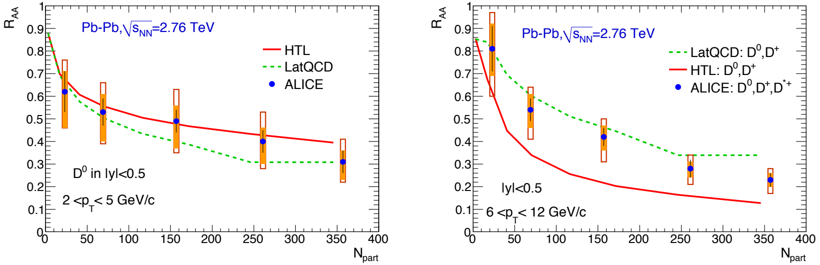
[10] STAR Collab. Nucl.Phys.A 904-905, 665c (2013)



D-meson nuclear modification factor for different choices of the transport coefficients.
In the HTL case the scale of the coupling varies from $\mu = \pi T$ to $\mu = 2\pi T$.
Results obtained with lattice-QCD transport coefficients are also shown for comparison.

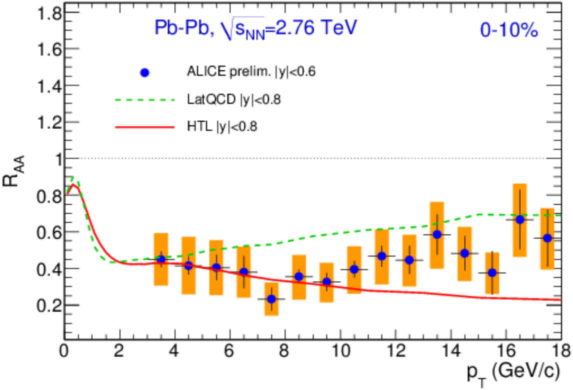
Our results are compared to ALICE data collected in the $0 - 20\%$ most central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV [11] (left panel) and in semi-periphal events ($40 - 80\%$, right panel).

[11] ALICE Collab., J. High energy Phys. 1209, 112 (2012)



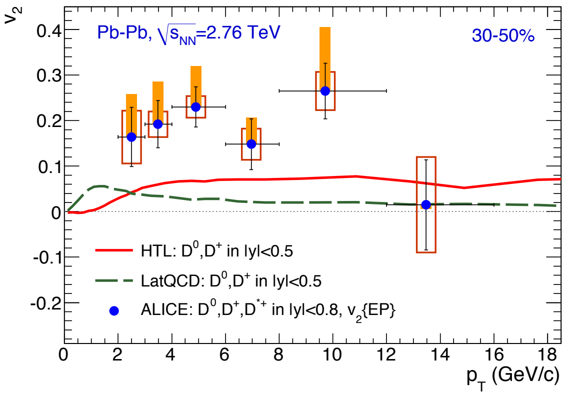
Centrality dependence of the D-meson R_{AA} in Pb-Pb collisions.
Results with different transport coefficients are compared to ALICE data [12] at moderate (left panel) and large (right panel) momenta.

[12] ALICE Collab., J. High energy Phys. 1209, 112 (2012)



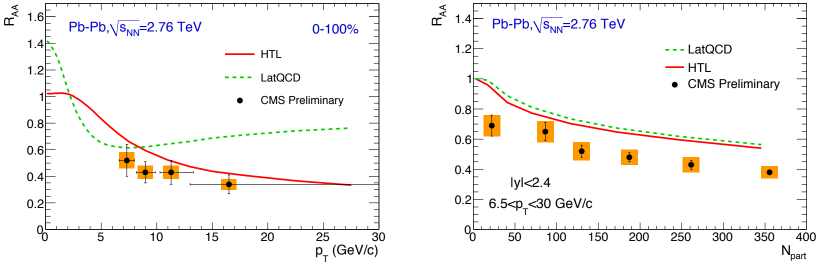
Results (with HTL and lattice-QCD transport coefficients) for heavy-flavour decay electrons from charm and beauty (e_{c+b}) in Pb-Pb collisions at the LHC compared to preliminary ALICE experimental data [13] in $0-10\%$ most central events.

[13] ALICE Collab., Nucl. Phys. A 904-905, 661c (2013)



Elliptic flow of D meson in semi-peripheral ($30-50\%$ centrality class) Pb-Pb collisions at the LHC compared to ALICE data [14]. Results obtained with HTL and lattice-QCD transport coefficients are displayed.

[14] ALICE Collab., arXiv:1305.2707

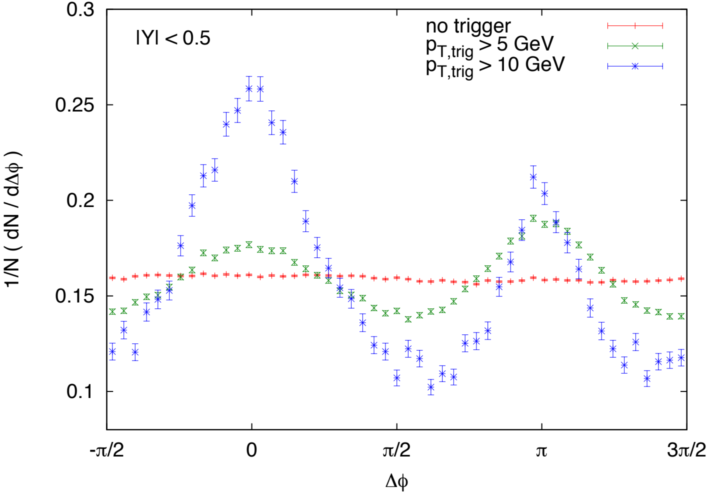


Left panel: R_{AA} as a function of p_T of non-prompt J/ψ's (from B decays) in minimum-bias Pb-Pb collisions at the LHC. Results of our setup (with HTL and lattice-QCD transport coefficients) are compared to preliminary CMS data [15].

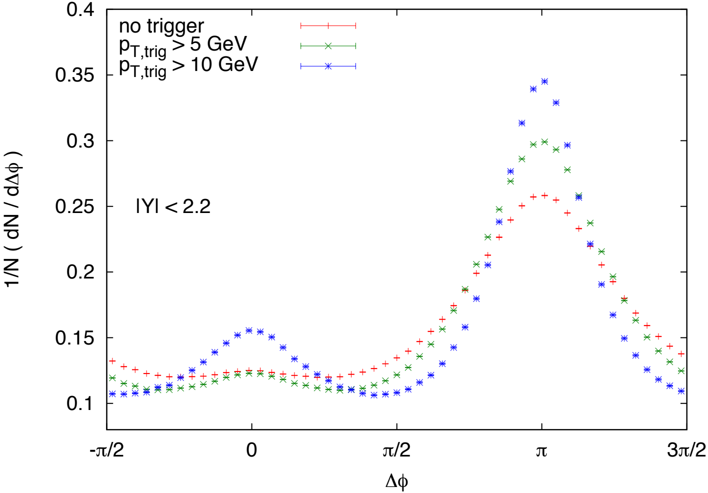
Right panel: Centrality dependence of the R_{AA} of non-prompt J/ψ's.

[15] CMS Collab., CMS-PAS-HIN-12-014

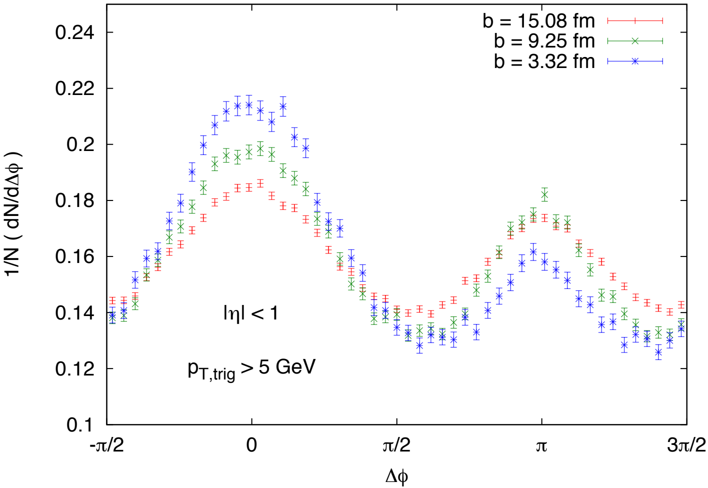
D-$\bar{D}$ azimuthal correlations



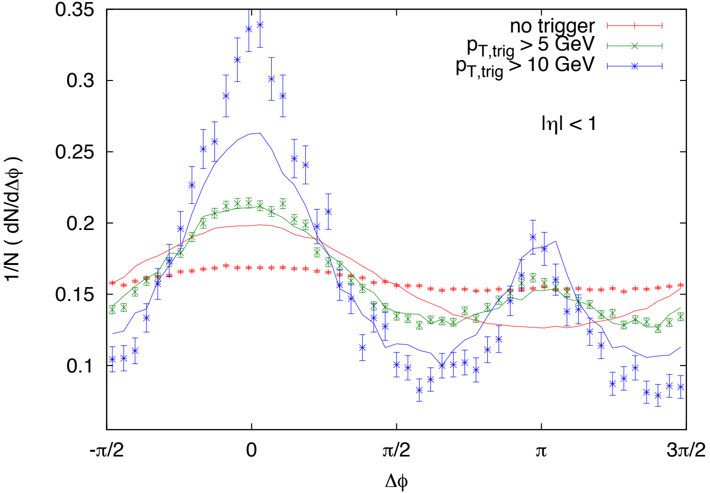
D-$\bar{D}$ azimuthal correlations in p-p collisions at LHC ($\sqrt{s} = 2.76$ TeV), for different p_T-trigger.



B-$\bar{B}$ azimuthal correlations in p-p collisions at LHC ($\sqrt{s} = 2.76$ TeV), for different p_T-trigger.



c-$\bar{c}$ azimuthal correlations in Pb-Pb collisions at LHC ($\sqrt{s} = 2.76$ TeV), for p_T-trigger > 5 GeV. Comparison between centrality classes.



c-$\bar{c}$ azimuthal correlations in Pb-Pb collisions at LHC ($\sqrt{s} = 2.76$ TeV), for different p_T-triggers. Comparison between the transport coefficients calculated with HTL+pQCD (points) and lattice-QCD (lines).

Conclusions

- The experimental heavy-flavour R_{AA} can be reproduced reasonably well over most of p_T range experimentally accessible but a consistent description, within the same setup, of the flow of charm is still lacking, signalling that coalescence might play a significant role.
- We expect B mesons to be less affected by effects arising from hadronization and, at the same time, theory predictions (in particular the ones provided by lattice-QCD) should be more reliable.
  Results for the R_{AA} of non prompt J/ψ's from B decays have been compared with preliminary CMS data: a decent agreement was found in the HTL case.

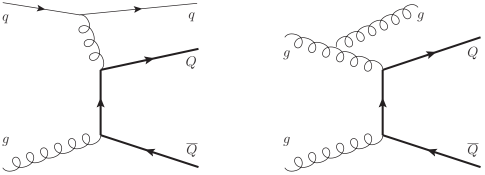
Future improvements

Two important items remain to be addressed (...almost ready!).

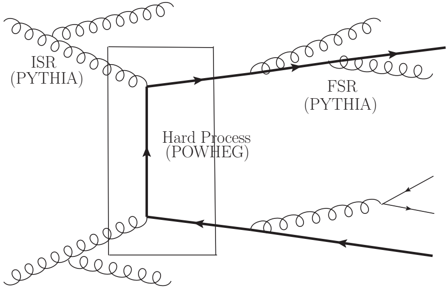
- A modelling of coalescence, necessary in order to provide predictions for the flow of charm at low p_T.
- Extending the setup to the forward-rapidity region, so that one can study also the rapidity dependence of the various heavy-flavour observables and face also the single-muon data measured by the ALICE experiment. This step would require to interface our transport setup with the output of a viscous 3+1 hydrodynamic code which is currently under development.

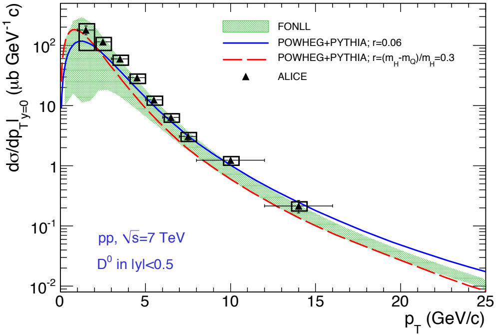
Extra Slides

Some of the NLO processes contributing to the $Q\overline{Q}$ cross-section, e.g. $qg \to qQ\overline{Q}$ and $gg \to Q\overline{Q}g$:



Structure of a typical event arising from the POWHEG-BOX setup, with the hard process (in the box) followed by a shower:

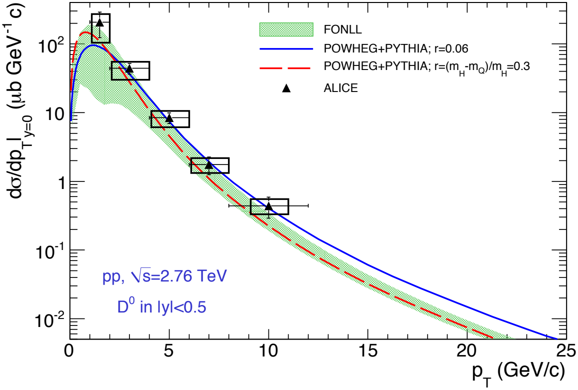




POWHEG-BOX predictions for D-meson spectra at $\sqrt{s}=7$ TeV (with different parameter choices for the fragmentation stage) compared with ALICE data [1] and with the FONLL systematic uncertainty band. Data includes the "primary" production ($c \to D$) as well as the D^* feed-down ($c \to D^* \to D$).

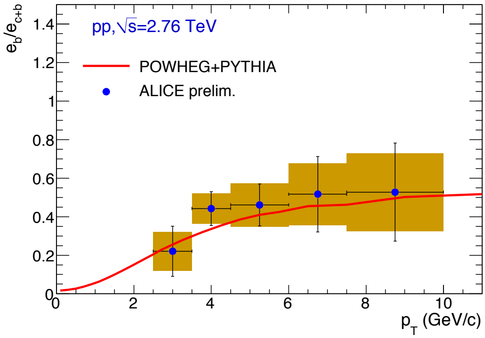
Analogous results hold for the other open-charm mesons (D^+ and D^*)

[1] ALICE Collaboration, JHEP 1201, 128 (2012)



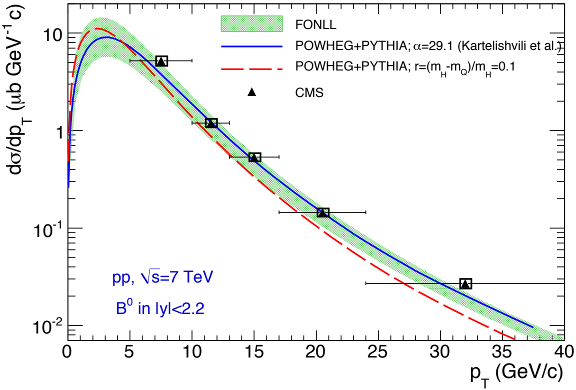
POWHEG+PYTHIA predictions with for D^0 spectra at $\sqrt{s} = 2.76$ TeV (with different fragmentation schemes) compared with ALICE data [2]

[2] ALICE Collaboration, JHEP 1201, 191 (2012)



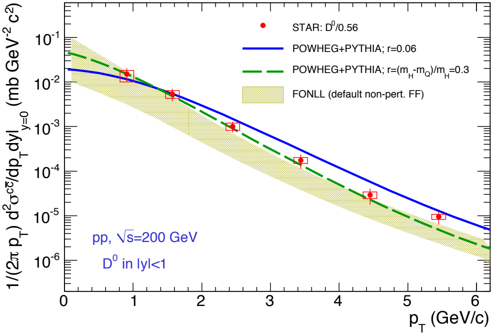
The ratio of electrons e_b from beauty decays over the total number of non-photonic electrons e_{c+b} in pp collisions at $\sqrt{s}=2.76$ TeV at the LHC. POWHEG+PYTHIA results are compared to preliminary ALICE data [3]

[3] ALICE Collaboration, arXiv:1208.5411



POWHEG+PYTHIA predictions for B^0 meson spectra at $\sqrt{s} = 7$ TeV (with different fragmentation schemes) compared to CMS data [4] and to the FONLL systematic uncertainty band.

[4] CMS Collab., Phys. Rev. Lett. 106, 252001 (2011)



D^0 p_T-differential cross-section in pp collisions at $\sqrt{s}=200$ GeV, measured by the STAR collaboration [5], compared to the predictions of the POWHEG+PYTHIA setup employed in the present work; note that the curves are normalized to the $c\bar{c}$ production cross-section.

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

Initial $Q\bar{Q}$ production in AA collisions

The initial hard $Q\overline{Q}$ production was simulated through the POWHEG+PYTHIA setup described previously for *pp*, supplemented in the *AA* case by EPS09 nuclear corrections to the PDFs.
In principle, the density probed by the colliding partons should depend on the impact parameter b: in describing nucleus-nucleus collisions we have made the simple choice of employing the EPS09 scheme for impact parameters $b < 2R$ and of neglecting nuclear corrections for $b > 2R$ (R being the radius of the nuclear density distribution).
Total $c\overline{c}$ and $b\overline{b}$ cross sections in p-p and *AA* collisions at RHIC and LHC (for *NN* event):

Collision	$\sqrt{s_{\rm NN}}$	$\sigma_{c\overline{c}}$ (mb)	$\sigma_{b\overline{b}}$(mb)
p-p	200 GeV	0.405	1.77×10^{-3}
Au-Au	200 GeV	0.356	2.03×10^{-3}
p-p	2.76 TeV	2.425	0.091
Pb-Pb	2.76 TeV	1.828	0.085

An important effect one has to consider in AA collisions is the larger transverse momentum acquired on average by the colliding partons, because of the large size of the traversed medium. To get a realistic estimate for $\langle k_T^2 \rangle_{AA}$ in nucleus-nucleus collisions we have adopted a Glauber approach[6]. One gets an average squared transverse momentum that depends not only on the impact parameter of the collision and on the nuclei involved, but also on the transverse position of the $Q\bar{Q}$ pair.
At RHIC energy one gets in Au-Au collisions, depending upon the impact parameter, $\langle k_T^2 \rangle_{AA} \sim 1.3 \div 1.5\ \mathrm{GeV}^2/\mathrm{c}^2$ for charm and $\langle k_T^2 \rangle_{AA} \sim 1.8 \div 2.3\ \mathrm{GeV}^2/\mathrm{c}^2$ for bottom.
At the LHC ($\sqrt{s} = 5.5$ TeV): $\langle k_T^2 \rangle_{AA} \sim 1.5 \div 1.8\ \mathrm{GeV}^2/\mathrm{c}^2$ for charm and $\langle k_T^2 \rangle_{AA} \sim 2.5 \div 3.3\ \mathrm{GeV}^2/\mathrm{c}^2$ for bottom in Pb-Pb collisions.

[6] 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 — that are needed to follow the propagation of the heavy quarks. We have chosen two different implementations of the relativistic hydrodynamic equations, whose codes are publicly available, namely ideal and viscous hydrodynamics, both assuming exact longitudinal boost invariance. The two models differ not only in the ideal/viscous implementation (with the ratio of shear viscosity to entropy density taken to be $\eta/s = 0.08$ in the viscous case), but also in the choice of the equation of state (EOS) and of the initial conditions.
The initial energy density distribution is computed in both cases according to the Glauber model, using either the number of participating nucleons ($N_{\rm part}$) or the number of binary collisions ($N_{\rm coll}$). [7]

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

The results shown in this talk are obtained through hydrodynamical calculations performed with a viscous 2+1 code[8]. 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
Pb-Pb	2.76 TeV	0.1	1688	828

The "standard" value for the initial time is $\tau_0 = 0.6 \div 1$ fm/c. As a check of the sensitivity on the thermalization time in a few cases we have used the extreme value $\tau_0 = 0.1$ fm/c.

[8] P. Romatschke, U. Romatschke, Phys. Rev. Lett. **99**, 172301 (2007)

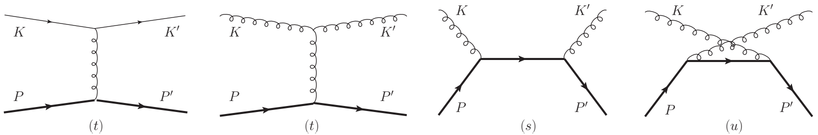
To study the propagation of a heavy quark through the QGP:

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)
2. Given the position x^μ, we use the information from the hydrodynamic simulation to obtain the fluid local temperature $T(x)$, velocity $u^\mu(x)$ and energy density $\varepsilon(x)$.
3. We check whether the conditions for hadronization apply: in this case the procedure is ended; otherwise
4. we make a Lorentz transformation ($p^\mu \to \bar{p}^\mu$) to the fluid rest frame, employ Eqs. (**??-??**) to update the quark momentum ($\bar{p}^\mu \to \bar{p}'^\mu$) and boost it back to the laboratory ($\bar{p}'^\mu \to p'^\mu$).
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 ($x^\mu \to x'^\mu$).
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 is the same as in pp (no coalescence).

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



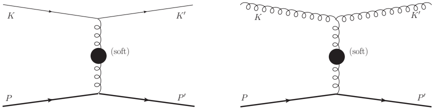
If the four-momentum exchange is sufficiently hard ($|t|>|t|^*$, where $t\equiv\omega^2-\mathbf{q}^2$) one is dealing with a short-distance process and the result is given by a kinetic pQCD calculation:

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

and

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

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

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

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.

Non-perturbative $\kappa_{L/T}(p)$

An independent way to extract the transport coefficients from the underlying microscopic theory comes from lattice QCD simulations. The results we will employ in the calculations were obtained in the static ($m_Q \to \infty$, $p \to 0$) limit (no information on the momentum-dependence is then available) and refer to the momentum diffusion coefficient κ [9]

We arbitrarily assume a constant value as a function of p_T.

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

Hadronization in AA collisions

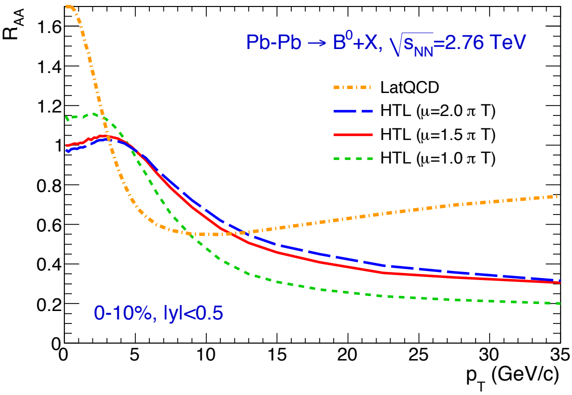
The Hydrodynamical code is based on a 2-phase EOS (QGP and HG) with a mixed phase. We assume that hadronization takes place during the mixed phase.

The fraction of QGP in the mixed phase is defined by

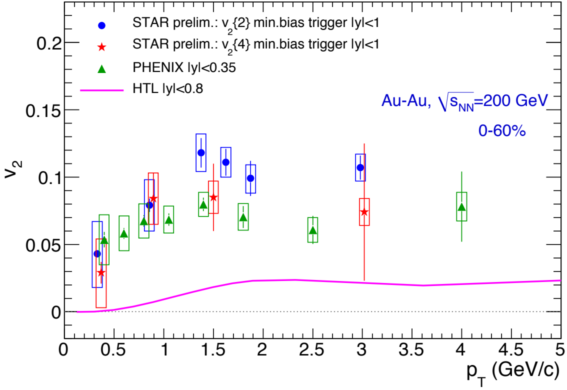
$$f_{QGP} = \frac{\varepsilon - \varepsilon_H}{\varepsilon_{QGP} - \varepsilon_H}.$$

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.



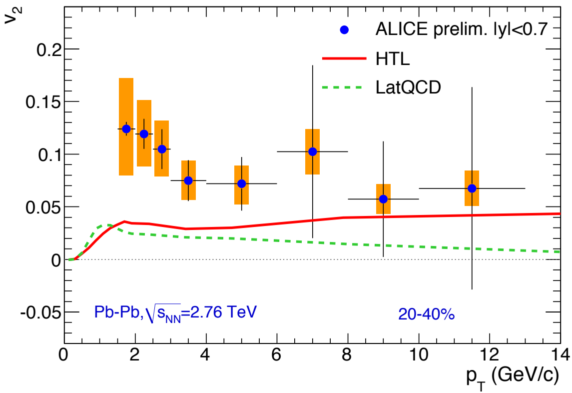
Nuclear modification factor of B^0 mesons in central Pb-Pb collisions at the LHC provided by our setup for different choices of the transport coefficients (weak-coupling HTL calculations vs lattice-QCD simulations).



Elliptic flow of non-photonic electrons: preliminary PHENIX [10] and STAR [11] data are compared to the outcomes of our Langevin calculations with HTL transport coefficients.

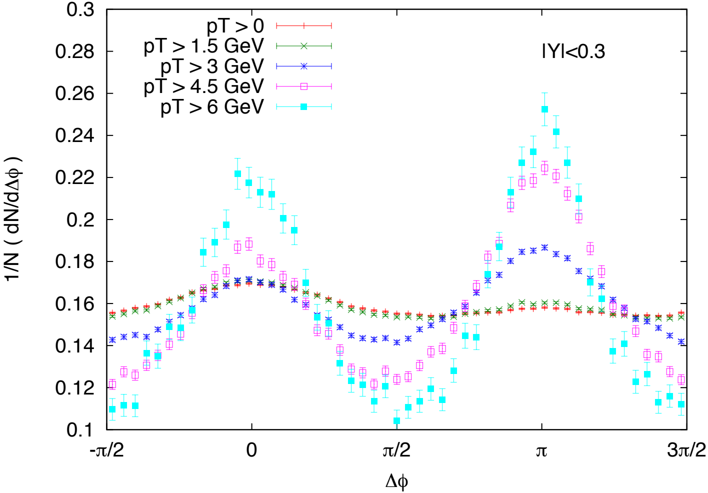
[10] PHENIX Collab., Phys. Rev. C 84, 044905 (2011)

[11] STAR Collab., Nucl. Phys.A 904-905, 665c (2013)

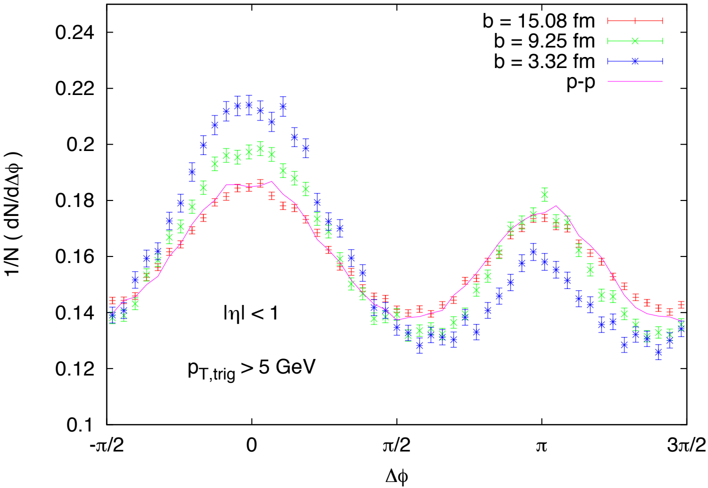


Elliptic flow of non-photonic electrons: preliminary ALICE data [12] are compared to the outcomes of our Langevin calculations with HTL and lattice-QCD transport coefficients.

[12] ALICE Collab., Nucl. Phys. A 904-905, 661c (2013)



D-$\bar{D}$ azimuthal correlations in p-p collisions at RHIC, for different p_T-trigger.



c-$\bar{c}$ azimuthal correlations in Pb-Pb collisions at LHC ($\sqrt{s} = 2.76$ TeV), for p_T-trigger > 5 GeV. Comparison with c-$\bar{c}$ azimuthal correlations in p-p.