Heavy-quark azimuthal correlations in proton-proton and nucleus-nucleus collisions

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work done in collaboration with

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In our framework (POWLANG), we have presented a multi-step setup for heavy-flavour study in high-energy $A - A$ collisions. The initial hard production of Q-Qbar pairs is obtained with the pQCD event generator POWHEG, interfaced with the PYTHIA parton shower. Outcomes of the calculations are compared to experimental data in $p - p$ collisions and are used as a validated benchmark for the study of medium effects. In the $A - A$ case, the propagation of the heavy quarks in the medium is obtained in the framework of the relativistic Langevin equation, while viscous hydrodynamics is used to describe the medium evolution. The numerical results have been compared to experimental data from RHIC and LHC. In particular, results for the nuclear modification factor $R_A A$ and for the elliptic flow v_2 of D and B mesons, heavy-flavour electrons and displaced J/ψ's have been presented.
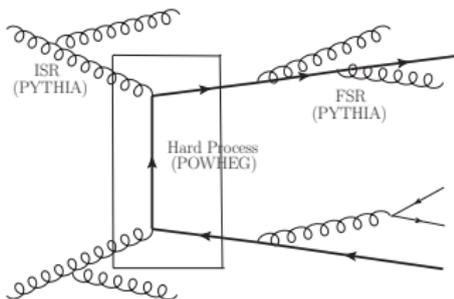
In this poster we will show preliminary results on azimuthal correlations of $c - \bar{c}$ pairs and open-charm mesons.

Heavy-flavor quarks in p-p collisions

Production and Hadronization

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 and hadronizationstage described by PYTHIA.
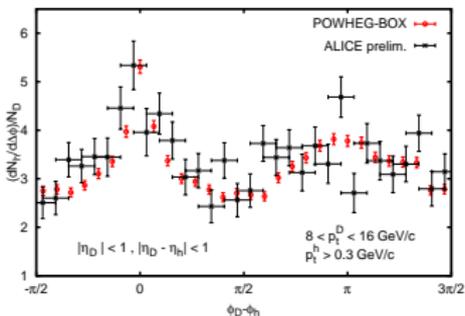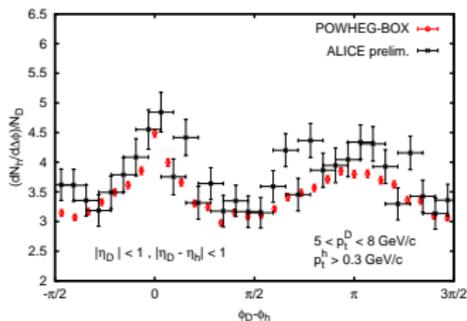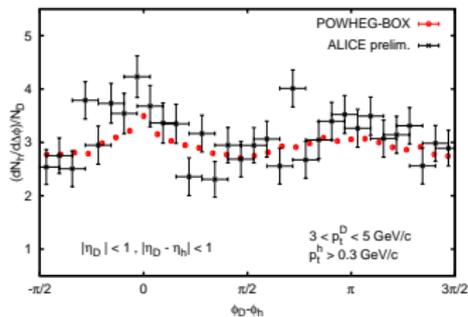

Structure of a typical event arising from the POWHEG-BOX setup, with the hard process (in the box) followed by a shower.

Results in agreement with FONLL

Full information on the final state allows the study of $Q - \bar{Q}$ and $D - h$ azimuthal correlations.

Azimuthal Correlations in $p - p$ collisions ($\sqrt{s} = 7$ TeV) between D mesons (D^0, $\overline{D}^0$, $D^{\pm}$, D^{*0}, $\overline{D}^{*0}$, $D^{*\pm}$,) and charged hadrons ($\pi^{\pm}$, $K^{\pm}$, p, $\overline{p}$)

[Exp. data from A.Rossi's talk at Hard Probes 2013, ALICE Collab.]

Heavy-flavor quarks in A-A collisions

Initial 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: 1) EPS09 nuclear corrections to the PDFs; 2) larger transverse momentum, acquired on average by the colliding partons, proportional to the size of the traversed medium.

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[1].
Longitudinal invariance is assumed: the results are valid at midrapidity.

We plan to extend our calculation at non-zero rapidity, with a 3+1 hydrodynamical code (ECHO-QGP, see V. Rolando's talk).

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[1]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

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

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

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

entailing that collisions at different time-steps are uncorrelated.
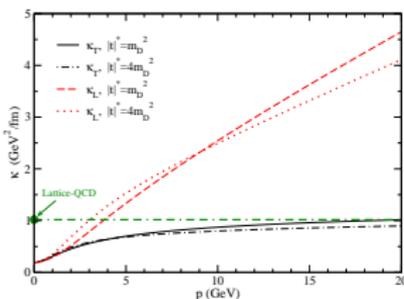The tensor $b^{ij}(\vec{p})$ can be decomposed as

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

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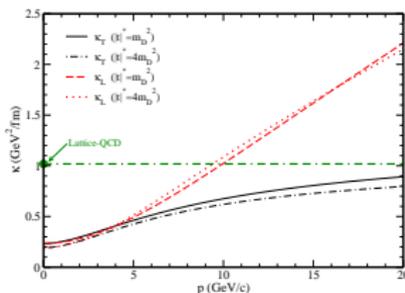
$$\kappa_L = \left\langle \frac{\Delta \mathbf{q}_L^2}{\Delta t} \right\rangle \quad \text{and} \quad \kappa_T = \frac{1}{2}\left\langle \frac{\Delta \mathbf{q}_T^2}{\Delta t} \right\rangle.$$

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) [2];
2. with non-perturbative lattice-QCD simulations [3].

c quarks   b quarks

The following results are obtained with the pQCD + HTL framework.

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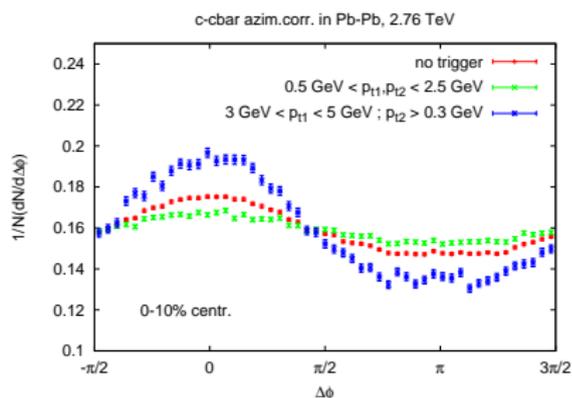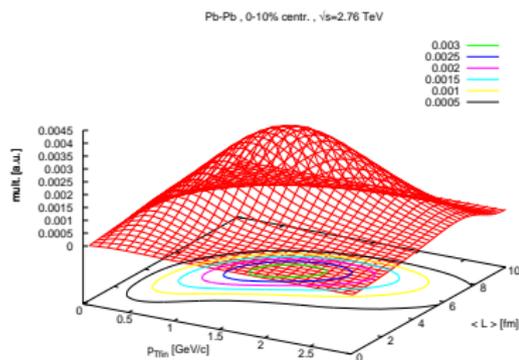W.M. Alberico et al., Eur. Phys. J. C **71** 1666 (2011)

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

$c - \bar{c}$ azimuthal correlations in Pb-Pb collisions

In our setup we can follow, individually, each c-($\bar{c}$-)quark in its propagation through the medium.

In particular, we can select those heavy quarks that have interacted more with the medium: in the next plot we show the distribution of the distance L travelled by the heavy quark inside the medium (from its creation to the hadronization), for different final transverse momentum. It is evident that c-($\bar{c}$-)quarks with final p_T in the range $0.5 \div 2.5$ GeV/c have, on average, traversed a distance $L \simeq 4 \div 6$ fm in the interacting medium.

Similar conclusions can be drawn by considering, instead of the lenght L, the energy loss of each c or $\bar{c}$.

Left: distribution of lenghts traversed by heavy quarks in the interacting medium, for different final p_T, in central (0-10%) Pb-Pb collisions.
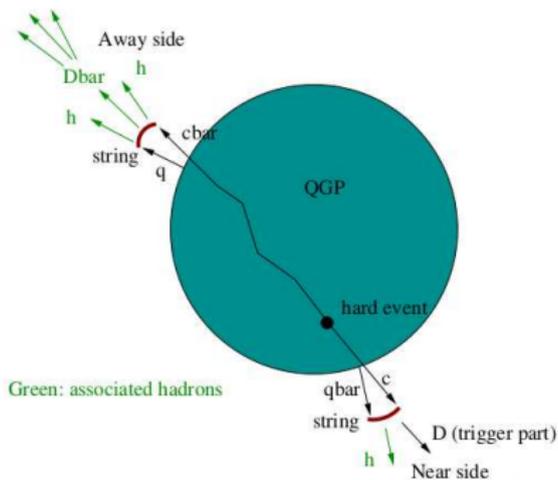
Right: Azimuthal correlations of $c - \bar{c}$ pairs in central (0-10%) Pb-Pb collisions, for different p_T-cuts. The pairs with $0.5 < p_T < 2.5$ GeV/c have the minimum back-to-back correlation. Similar conclusions hold for other centrality classes.

Final particles

In-medium hadronization may affect the spectra of final D-mesons due to the collective flow of light quarks. We tried to estimate the effect:
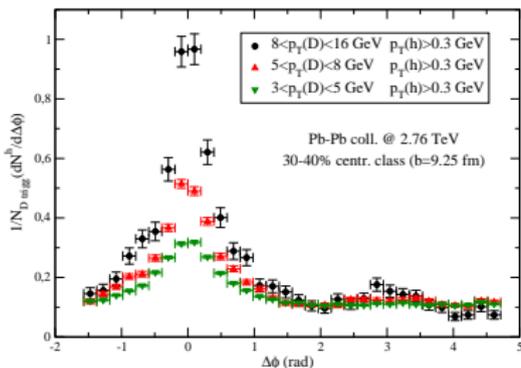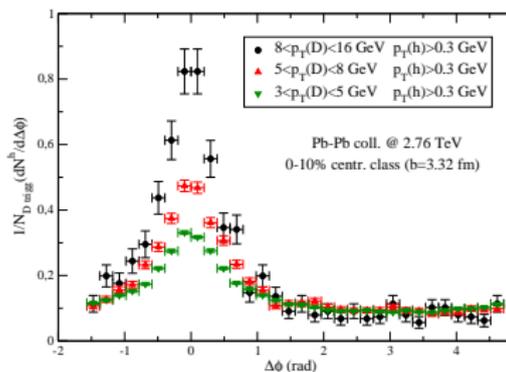
At T_{dec} c-quarks form a string with light q's from a local thermal distribution, eventually boosted to the lab frame.

Strings are given to PYTHIA 6.4 to simulate their fragmentation and produce the final hadrons $(D, \pi, \dots)$.

D-h azimuthal correlations in Pb-Pb collisions

We have used our setup to calculate the angular correlations between D's and charged hadrons in Pb-Pb central and semi-central collisions, assuming the same p_T-cuts used by the ALICE Collab. in the p-p analysis.

Conclusions

With our multistep setup we are able to calculate azimuthal
correlations of heavy quarks and mesons in p-p and A-A collisions.
By appliyng suitable p_T cuts on the trigger particles, it is possible
to select events in which the heavy quarks has traversed, on
average, different lenghts of the thermal medium, therefore
allowing a deeper insight of the deconfined phase.

References:

- Alberico et al., Eur.Phys.J. C71 (2011) 1666
- Alberico et al., Eur.Phys.J. C73 (2013) 2481