Heavy flavour measurements: a theoretical perspective

Andrea Beraudo

INFN - Sezione di Torino

Workshop on the physics of HL-LHC and perspectives at HE-LHC

Istituto Nazionale di Fisica Nucleare

Heavy Flavour 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);
- Description of jet-quenching based on energy-degradation of external probes (high-p_T partons);
- Description of heavy-flavour observables requires to employ/develop a setup (transport theory) allowing to deal with more general situations and in particular to describe *how particles would (asymptotically) approach equilibrium*. Initial (off-equilibrium!) $Q\overline{Q}$ production occurs on a very short time-scale $\tau_{Q\overline{Q}} \sim 1/2M_Q \lesssim 0.1\,\mathrm{fm/c} \ll \tau_{\mathrm{QGP}}$

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 (last part of this talk)

Heavy quarks as probes of the QGP

A realistic study requires developing *a multi-step setup*:

- Initial production: pQCD + possible nuclear effects (nPDFs, k_T-broadening) $\longrightarrow$ QCD event generators, validated on p-p data;
- Description of the background medium (initial conditions, $T(x)$, $u^\mu(x)$) $\longrightarrow$ hydrodynamics, validated on soft hadrons;
- HQ-medium interaction $\longrightarrow$ transport coefficients, in principle derived from QCD, but still far from a definite answer for the relevant experimental conditions;
- Dynamics in the medium $\longrightarrow$ transport calculations, in principle rigorous *under certain kinematic conditions*, but require transport coefficients;
- Hadronization: not well under control (fragmentation in the vacuum? recombination with thermal partons? validated on what?)
  - An item of interest in itself (*change of hadrochemistry* in A-A collisions? And also in p-p?)
  - However, *a source of systematic uncertainty for studies of parton-medium interaction*;
- Hadronic rescattering (e.g. $D\pi \to D\pi$), from effective Lagrangians, but no experimental data the on relevant cross-sections

Transport theory: general setup

Transport theory: the Boltzmann equation

Time evolution of HQ phase-space distribution $f_Q(t, \mathbf{x}, \mathbf{p})$[1]:

$$\frac{d}{dt} f_Q(t, \mathbf{x}, \mathbf{p}) = C[f_Q]$$

- Total derivative along particle trajectory

$$\frac{d}{dt} \equiv \frac{\partial}{\partial t} + \mathbf{v}\frac{\partial}{\partial \mathbf{x}} + \mathbf{F}\frac{\partial}{\partial \mathbf{p}}$$

  Neglecting $\mathbf{x}$-dependence and mean fields: $\partial_t f_Q(t, \mathbf{p}) = C[f_Q]$

- Collision integral:

$$C[f_Q] = \int d\mathbf{k}[\underbrace{w(\mathbf{p}+\mathbf{q}, \mathbf{q}) f_Q(\mathbf{p}+\mathbf{q})}_{\text{gain term}} - \underbrace{w(\mathbf{p}, \mathbf{q}) f_Q(\mathbf{p})}_{\text{loss term}}]$$

  $w(\mathbf{p}, \mathbf{q})$: HQ transition rate $\mathbf{p} \to \mathbf{p} - \mathbf{q}$

[1] Approach adopted by Catania, Nantes, Frankfurt, LBL... groups

From Boltzmann to Fokker-Planck

Expanding the collision integral for *small momentum exchange*[2] (Landau)

$$C[f_Q] \approx \int d\mathbf{q} \left[q^i \frac{\partial}{\partial p^i} + \frac{1}{2} q^i q^j \frac{\partial^2}{\partial p^i \partial p^j} \right] [w(\mathbf{p}, \mathbf{q}) f_Q(t, \mathbf{p})]$$

[2]In a relativistic gauge plasma $q \sim m_D \sim gT$

From Boltzmann to Fokker-Planck

Expanding the collision integral for *small momentum exchange*[2] (Landau)

$$C[f_Q] \approx \int d\mathbf{q} \left[q^i \frac{\partial}{\partial p^i} + \frac{1}{2} q^i q^j \frac{\partial^2}{\partial p^i \partial p^j} \right] [w(\mathbf{p}, \mathbf{q}) f_Q(t, \mathbf{p})]$$

the Boltzmann equation reduces to the *Fokker-Planck equation*

$$\frac{\partial}{\partial t} f_Q(t, \mathbf{p}) = \frac{\partial}{\partial p^i} \left\{ A^i(\mathbf{p}) f_Q(t, \mathbf{p}) + \frac{\partial}{\partial p^j} [B^{ij}(\mathbf{p}) f_Q(t, \mathbf{p})] \right\}$$

where

$$A^i(\mathbf{p}) = \int d\mathbf{q}\, q^i w(\mathbf{p}, \mathbf{q}) \longrightarrow \underbrace{A^i(\mathbf{p}) = A(p)\, p^i}_{\text{friction}}$$

$$B^{ij}(\mathbf{p}) = \frac{1}{2} \int d\mathbf{q}\, q^i q^j w(\mathbf{p}, \mathbf{q}) \longrightarrow \underbrace{B^{ij}(\mathbf{p}) = (\delta^{ij} - \hat{p}^i \hat{p}^j) B_0(p) + \hat{p}^i \hat{p}^j B_1(p)}_{\text{momentum broadening}}$$

[2] In a relativistic gauge plasma $q \sim m_D \sim gT$

From Boltzmann to Fokker-Planck

Expanding the collision integral for *small momentum exchange*[2] (Landau)

$$C[f_Q] \approx \int d\mathbf{q} \left[q^i \frac{\partial}{\partial p^i} + \frac{1}{2} q^i q^j \frac{\partial^2}{\partial p^i \partial p^j} \right] [w(\mathbf{p},\mathbf{q}) f_Q(t,\mathbf{p})]$$

the Boltzmann equation reduces to the *Fokker-Planck equation*

$$\frac{\partial}{\partial t} f_Q(t,\mathbf{p}) = \frac{\partial}{\partial p^i} \left\{ A^i(\mathbf{p}) f_Q(t,\mathbf{p}) + \frac{\partial}{\partial p^j} [B^{ij}(\mathbf{p}) f_Q(t,\mathbf{p})] \right\}$$

where

$$A^i(\mathbf{p}) = \int d\mathbf{q}\, q^i w(\mathbf{p},\mathbf{q}) \longrightarrow \underbrace{A^i(\mathbf{p}) = A(p)\, p^i}_{\text{friction}}$$

$$B^{ij}(\mathbf{p}) = \frac{1}{2} \int d\mathbf{q}\, q^i q^j w(\mathbf{p},\mathbf{q}) \longrightarrow \underbrace{B^{ij}(\mathbf{p}) = (\delta^{ij} - \hat{p}^i \hat{p}^j) B_0(p) + \hat{p}^i \hat{p}^j B_1(p)}_{\text{momentum broadening}}$$

Problem reduced to the *evaluation of three transport coefficients*, directly derived from the scattering matrix

[2] In a relativistic gauge plasma $q \sim m_D \sim gT$

Approach to equilibrium in the FP equation

The FP equation can be viewed as a continuity equation for the phase-space distribution of the kind $\partial_t \rho(t,\vec{p}) + \vec{\nabla}_p \cdot \vec{J}(t,\vec{p}) = 0$

$$\frac{\partial}{\partial t} \underbrace{f_Q(t,\mathbf{p})}_{\equiv \rho(t,\vec{p})} = \frac{\partial}{\partial p^i} \underbrace{\left\{ A^i(\mathbf{p}) f_Q(t,\mathbf{p}) + \frac{\partial}{\partial p^j}\left[B^{ij}(\mathbf{p}) f_Q(t,\mathbf{p})\right]\right\}}_{\equiv -J^i(t,\vec{p})}$$

admitting a steady solution $f_{\rm eq}(p) \equiv e^{-E_p/T}$ when the current vanishes:

$$A^i(\vec{p}) f_{\rm eq}(p) = -\frac{\partial B^{ij}(\vec{p})}{\partial p^j} f_{\rm eq}(p) - B^{ij}(\mathbf{p}) \frac{\partial f_{\rm eq}(p)}{\partial p^j}.$$

One gets then a constraint linking the three transport coefficients, which are not independent, but obey the Einstein *fluctuation-dissipation* relation

$$A(p) = \frac{B_1(p)}{TE_p} - \left[\frac{1}{p}\frac{\partial B_1(p)}{\partial p} + \frac{d-1}{p^2}(B_1(p) - B_0(p))\right],$$

quite involved due to the *momentum dependence* of the transport coefficients (*measured* HQ's are relativistic particles!)

The relativistic Langevin equation

The Fokker-Planck equation can be recast into a form suitable to follow the dynamics of each individual quark arising from the pQCD Monte Carlo simulation of the initial $Q\overline{Q}$ production: the Langevin equation

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

with the properties of the noise encoded in

$$\langle\xi^i(\mathbf{p}_t)\rangle = 0 \quad \langle\xi^i(\mathbf{p}_t)\xi^j(\mathbf{p}_{t'})\rangle = b^{ij}(\mathbf{p})\frac{\delta_{tt'}}{\Delta t} \quad b^{ij}(\mathbf{p}) \equiv \kappa_L(p)\hat{p}^i\hat{p}^j + \kappa_T(p)(\delta^{ij} - \hat{p}^i\hat{p}^j)$$

The relativistic Langevin equation

The Fokker-Planck equation can be recast into a form suitable to follow the dynamics of each individual quark arising from the pQCD Monte Carlo simulation of the initial $Q\overline{Q}$ production: the Langevin equation

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

with the properties of the noise encoded in

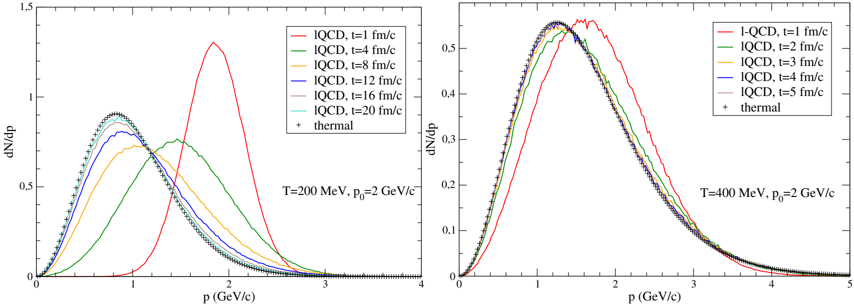
$$\langle \xi^i(\mathbf{p}_t) \rangle = 0 \quad \langle \xi^i(\mathbf{p}_t)\xi^j(\mathbf{p}_{t'}) \rangle = b^{ij}(\mathbf{p}) \frac{\delta_{tt'}}{\Delta t} \quad b^{ij}(\mathbf{p}) \equiv \kappa_L(p)\hat{p}^i\hat{p}^j + \kappa_T(p)(\delta^{ij} - \hat{p}^i\hat{p}^j)$$

Transport coefficients related to the FP ones:

- *Momentum diffusion*: $\kappa_T(p) = 2B_0(p)$ and $\kappa_L(p) = 2B_1(p)$
- *Friction* term, in the *Ito pre-point discretization scheme*,

$$\eta_D^{\text{Ito}}(p) = A(p) = \frac{B_1(p)}{TE_p} - \left[\frac{1}{p} \frac{\partial B_1(p)}{\partial p} + \frac{d-1}{p^2}(B_1(p) - B_0(p)) \right]$$

A first check: thermalization in a static medium



(Test with a sample of c quarks with $p_0 = 2$ GeV/c).
For $t \gg 1/\eta_D$ one approaches a relativistic Maxwell-Jüttner distribution

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

The larger κ ($\kappa \sim T^3$), the faster the approach to thermalization.

Transport coefficients

Transport coefficients: non-perturbative definition

One consider the non-relativistic limit of the Langevin equation for a HQ

$$\frac{dp^i}{dt} = -\eta_D p^i + \xi^i(t), \quad \text{with} \quad \langle \xi^i(t)\xi^j(t')\rangle = \delta^{ij}\delta(t-t')\kappa$$

in which the strength of the noise is given by a single number, the momentum-diffusion coefficient κ. Hence, in the $p\to 0$ limit:

$$\kappa = \frac{1}{3}\int_{-\infty}^{+\infty} dt \langle \xi^i(t)\xi^i(0)\rangle_{\rm HQ} \approx \frac{1}{3}\int_{-\infty}^{+\infty} dt \underbrace{\langle F^i(t)F^i(0)\rangle_{\rm HQ}}_{\equiv D^>(t)},$$

For a static ($M=\infty$) HQ the force is due to the color-electric field:

$$\mathbf{F}(t) = g\int d\mathbf{x} Q^\dagger(t,\mathbf{x}) t^a Q(t,\mathbf{x})\mathbf{E}^a(t,\mathbf{x})$$

Transport coefficients: non-perturbative definition

One consider the non-relativistic limit of the Langevin equation for a HQ

$$\frac{dp^i}{dt} = -\eta_D p^i + \xi^i(t), \quad \text{with} \quad \langle \xi^i(t)\xi^j(t')\rangle = \delta^{ij}\delta(t-t')\kappa$$

in which the strength of the noise is given by a single number, the momentum-diffusion coefficient κ. Hence, in the $p \to 0$ limit:

$$\kappa = \frac{1}{3}\int_{-\infty}^{+\infty} dt \langle \xi^i(t)\xi^i(0)\rangle_{\rm HQ} \approx \frac{1}{3}\int_{-\infty}^{+\infty} dt \underbrace{\langle F^i(t)F^i(0)\rangle_{\rm HQ}}_{\equiv D^>(t)},$$

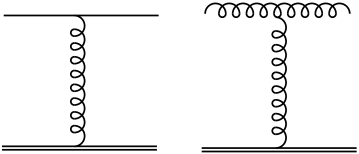
For a static ($M=\infty$) HQ the force is due to the color-electric field:

$$\mathbf{F}(t) = g\int d\mathbf{x} Q^\dagger(t,\mathbf{x}) t^a Q(t,\mathbf{x})\mathbf{E}^a(t,\mathbf{x})$$

The above non-perturbative definition, referring to the $M \to \infty$ limit, is the starting point for a thermal-field-theory evaluation based on

- weak-coupling calculations (up to NLO);
- gauge-gravity duality ($\mathcal{N}=4$ SYM)
- lattice-QCD simulations

HQ momentum diffusion: weak-coupling calculation



In the $M \to \infty$ limit the HQ exchange momentum $q^\mu = (0, \vec{q})$, with $q \sim gT$, with the medium partons. The exchanged soft gluon is dressed by the Debye mass $m_D \sim gT$, which screens IR divergences

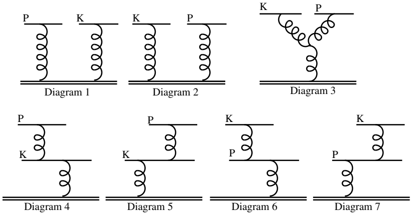
$$\kappa^{\rm LO} \equiv \frac{g^4 C_F}{12\pi^3} \int_0^\infty k^2 dk \int_0^{2k} \frac{q^3 dq}{(q^2 + m_D^2)^2}$$
$$\times \left[N_c n_B(k)(1+n_B(k)) \left(2 - \frac{q^2}{k^2} + \frac{q^4}{4k^2}\right) + N_f n_F(k)(1-n_F(k)) \left(2 - \frac{q^2}{2k^2}\right) \right]$$

Under the assumption that $q \ll k \sim T$ one can "expand" the results in a weak-coupling series

$$\kappa = \frac{C_F g^4 T^3}{18\pi} \left(\left[N_c + \frac{N_f}{2} \right] \left[\ln \frac{2T}{m_D} + \xi \right] + \frac{N_f \ln 2}{2} + \mathcal{O}(g) \right)$$

with the structure $\kappa \sim g^4 T^3 (\# \ln(1/g) + \# + \mathcal{O}(g))$, clearly meaningful only as long as $g \ll 1$.

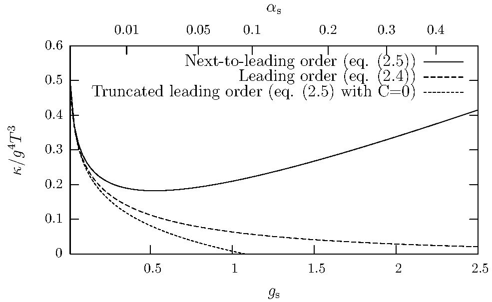
HQ momentum diffusion: weak-coupling calculation



The weak-coupling expansion for κ receives $\mathcal{O}(g)$ corrections of various origin (S. Caron-Huot and G.D. Moore, JHEP 0802 (2008) 081):

- one part is contained in the unexpanded tree-level result, arising from the region $k \sim gT$ in which $n_B(k) \sim T/k \sim 1/g$ and the approximation $q \ll k$ no longer holds;
- another part arises from a NLO correction to the screened gluon propagator, which can be easily inserted in the tree-level result;
- a last part comes from overlapping statterings. Having a total scattering rate $\sim g^2 T$ and the duration of a single scattering $\sim 1/q \sim 1/gT$ entails that a fraction $\mathcal{O}(g)$ of scattering events overlap with each other (see diagrams).

HQ momentum diffusion: weak-coupling calculation



Collecting together the various terms one gets, for $N_f = N_c = 3$,

$$\kappa = \frac{16\pi}{3}\alpha_s^2 T^3 \left(\ln\frac{1}{g} + 0.07428 + 1.9026g + \mathcal{O}(g^2) \right)$$

which shows that, for realistic values of the coupling $\alpha_s \sim 0.3$, NLO corrections to κ are positive and large: what's the guidance provided by weak-coupling calculations if NLO corrections are so large?

HQ momentum diffusion from lattice-QCD ($N_f = 0!$)

The ($p \to 0$) HQ momentum-diffusion coefficient

$$\kappa = \frac{1}{3}\int_{-\infty}^{+\infty} dt \langle \xi^i(t)\xi^i(0)\rangle_{\rm HQ} = \frac{1}{3}\int_{-\infty}^{+\infty} dt \underbrace{\langle F^i(t)F^i(0)\rangle_{\rm HQ}}_{\equiv D^>(t)}$$

is given by the $\omega \to 0$ limit of the FT of the electric-field correlator $D^>$.
In a thermal ensemble, from the periodicity of the bosonic fields, one has $\sigma(\omega) \equiv D^>(\omega) - D^<(\omega) = (1 - e^{-\beta\omega})D^>(\omega)$, so that

$$\kappa \equiv \lim_{\omega\to 0} \frac{D^>(\omega)}{3} = \lim_{\omega\to 0} \frac{1}{3}\frac{\sigma(\omega)}{1 - e^{-\beta\omega}} \underset{\omega\to 0}{\sim} \frac{1}{3}\frac{T}{\omega}\sigma(\omega)$$

HQ momentum diffusion from lattice-QCD ($N_f = 0!$)

The $(p \to 0)$ HQ momentum-diffusion coefficient

$$\kappa = \frac{1}{3}\int_{-\infty}^{+\infty} dt \langle \xi^i(t)\xi^i(0)\rangle_{\rm HQ} = \frac{1}{3}\int_{-\infty}^{+\infty} dt \underbrace{\langle F^i(t)F^i(0)\rangle_{\rm HQ}}_{\equiv D^>(t)}$$

is given by the $\omega \to 0$ limit of the FT of the electric-field correlator $D^>$.
In a thermal ensemble, from the periodicity of the bosonic fields, one has $\sigma(\omega) \equiv D^>(\omega) - D^<(\omega) = (1 - e^{-\beta\omega})D^>(\omega)$, so that

$$\kappa \equiv \lim_{\omega\to 0} \frac{D^>(\omega)}{3} = \lim_{\omega\to 0} \frac{1}{3}\frac{\sigma(\omega)}{1 - e^{-\beta\omega}} \underset{\omega\to 0}{\sim} \frac{1}{3}\frac{T}{\omega}\sigma(\omega)$$

On the lattice one evaluates then the *euclidean electric-field correlator* $(t = -i\tau)$

$$D_E(\tau) = -\frac{\langle {\rm Re\,Tr}[U(\beta,\tau)gE^i(\tau,\mathbf{0})U(\tau,0)gE^i(0,\mathbf{0})]\rangle}{\langle {\rm Re\,Tr}[U(\beta,0)]\rangle}$$

and from the latter one extract the spectral density according to

$$D_E(\tau) = \int_0^{+\infty} \frac{d\omega}{2\pi}\frac{\cosh(\tau - \beta/2)}{\sinh(\beta\omega/2)}\sigma(\omega)$$

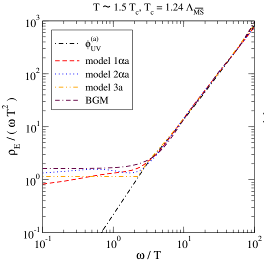
HQ momentum diffusion from lattice-QCD ($N_f = 0$!)

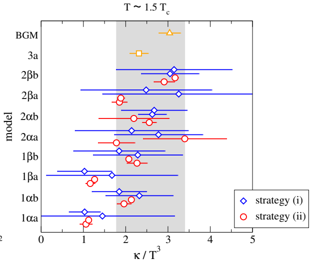
The direct extraction of the spectral density from the euclidean correlator

$$D_E(\tau) = \int_0^{+\infty} \frac{d\omega}{2\pi} \frac{\cosh(\tau - \beta/2)}{\sinh(\beta\omega/2)} \sigma(\omega)$$

is a ill-posed problem, since the latter is known for a limited set (~ 20) of points $D_E(\tau_i)$, and one wish to obtain a fine scan of the the spectral function $\sigma(\omega_j)$. A direct χ^2-fit is not applicable. Possible strategies:

- Bayesian techniques (Maximum Entropy Method)
- Theory-guided ansatz for the behaviour of $\sigma(\omega)$ to constrain its functional form (A. Francis *et al.*, PRD 92 (2015), 116003)





From the different ansatz on the functional form of $\sigma(\omega)$ one gets a systematic uncertainty band:

$$\kappa/T^3 \approx 1.8 - 3.4$$

Collisional broadening in the non-static case

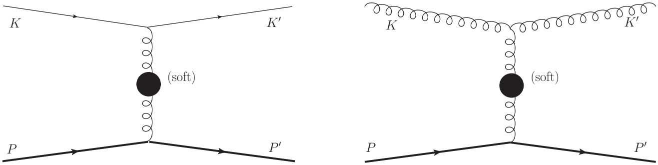
In the case of experimental interest HQ's have a large but finite mass and most of the p_T-bins for which data are available refer to quite fast, or even relativistic, HF hadrons: extending the estimates for the HQ transport coefficients to finite momentum is mandatory to provide theoretical predictions relevant for the experiment.

The effect of $2 \to 2$ collisions can be included in an "improved" tree-level calculation (W.M. Alberico *et al.*, EPJC 73 (2013) 2481) with an *Intermediate cutoff* $|t|^* \sim m_D^2$[3] separating the contributions of

- hard collisions ($|t| > |t|^*$): kinetic pQCD calculation
- soft collisions ($|t| < |t|^*$): Hard Thermal Loop approximation (*resummation of medium effects*)

[3] Similar strategy for the evaluation of dE/dx in S. Peigne and A. Peshier, Phys.Rev.D77:114017 (2008)

Transport coefficients $\kappa_{T/L}(p)$

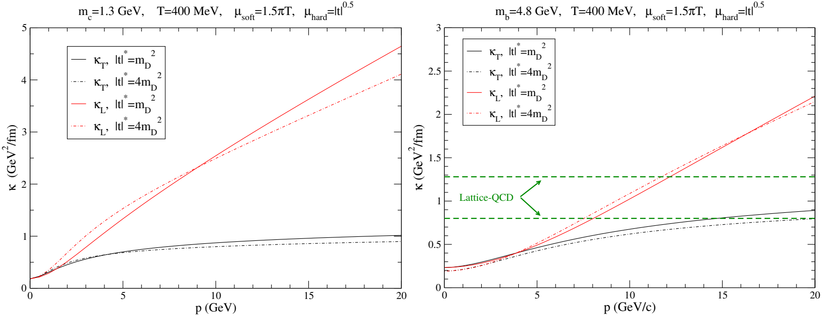


When the exchanged 4-momentum is **soft** the t-channel gluon feels the presence of the medium and requires **resummation**.
The *blob* represents the *dressed gluon propagator*, which has longitudinal and transverse components:

$$\Delta_L(z,q) = \frac{-1}{q^2 + \Pi_L(z,q)}, \quad \Delta_T(z,q) = \frac{-1}{z^2 - q^2 - \Pi_T(z,q)},$$

where *medium effects* are embedded in the HTL gluon self-energy.
NB In the corresponding static calculation only longitudinal gluon exchange, dressed simply by a Debye mass, without any energy and momentum dependence

Combining together the hard and soft contributions...



...the dependence on the intermediate cutoff $|t|^*$ is very mild!

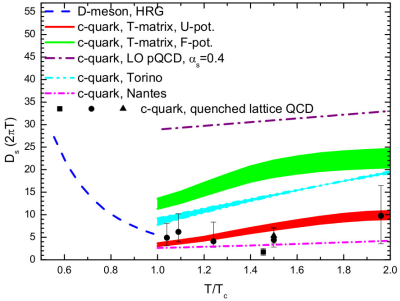
NB Notice, in the case of charm, the strong momentum-dependence of κ_L, much milder in the case of beauty, for which $\kappa_L \approx \kappa_T$ up to 5 GeV

Spatial diffusion coefficient D_S

In the *non-relativistic* limit an excess of HQ's initially placed at the origin will diffuse according to

$$\langle \vec{x}^2(t) \rangle \underset{t\to\infty}{\sim} 6 D_s t \quad \text{with} \quad D_S = \frac{2T^2}{\kappa}.$$

For a strongly interacting system spatial diffusion is very small! Theory calculations for D_s have been collected (F. Prino and R. Rapp, JPG 43 (2016) 093002) and are often used by the experimentalists to summarize the difference among the various models (BUT momentum dependence, not captured by D_s, is important!)



- lattice-QCD

$$(2\pi T) D_s^{lQCD} \approx 3.7 - 7$$

- $\mathcal{N} = 4$ SYM:

$$(2\pi T) D_s^{SYM} = \frac{4}{\sqrt{g_{SYM}^2 N_c}} \approx 1.2$$

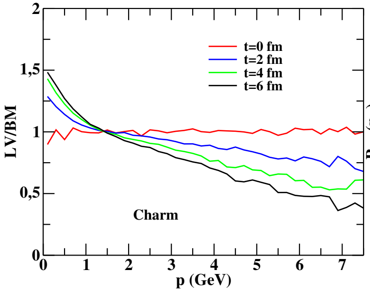
for $N_c = 3$ and $\alpha_{SYM} = \alpha_s = 0.3$.

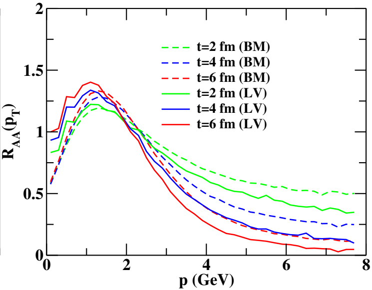
The Langevin/FP approach: a critical perspective

Although the Langevin approach is a very convenient numerical tool and allows one to establish a link between observables and transport coefficients derived from QCD...

The Langevin/FP approach: a critical perspective

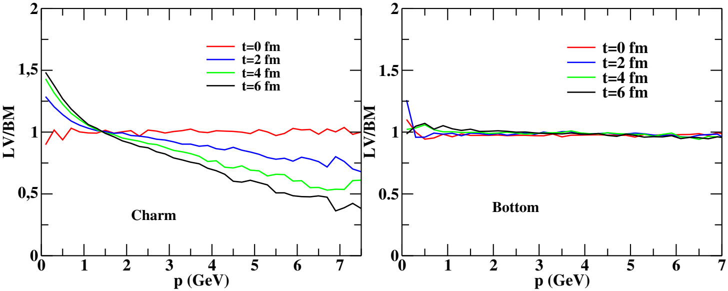
Although the Langevin approach is a very convenient numerical tool and allows one to establish a link between observables and transport coefficients derived from QCD... it is nevertheless based on a *soft-scattering expansion* of the collision integral $\mathcal{C}[f]$ truncated at second order (friction and diffusion terms), which may be *not always justified*, in particular for charm, possibly affecting the final R_{AA} (V. Greco *et al.*, Phys.Rev. C90 (2014) 044901)





The Langevin/FP approach: a critical perspective

Although the Langevin approach is a very convenient numerical tool and allows one to establish a link between observables and transport coefficients derived from QCD... it is nevertheless based on a *soft-scattering expansion* of the collision integral $\mathcal{C}[f]$ truncated at second order (friction and diffusion terms), which may be *not always justified*, in particular for charm, possibly affecting the final R_{AA} (V. Greco *et al.*, Phys.Rev. C90 (2014) 044901)



For beauty on the other hand Langevin≡Boltzmann!

From quarks to hadrons

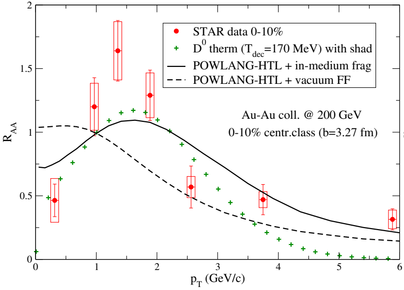
In the presence of a medium, rather then fragmenting like in the vacuum (e.g. $c \to cg \to c\overline{q}q$), HQ's can hadronize by recombining with light thermal quarks (or even *diquarks*) from the medium. This has been implemented in several ways in the literature:

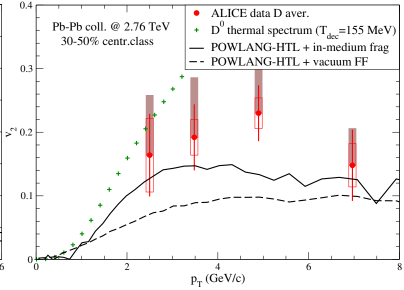
- $2 \to 1$ (or $3 \to 1$ for baryon production) coalescence of partons close in phase-space: $Q + \overline{q} \to M$
- String formation: $Q + \overline{q} \to \mathrm{string} \to \mathrm{hadrons}$
- Resonance formation/decay $Q + \overline{q} \to M^\star \to Q + \overline{q}$

In-medium hadronization may affect the R_{AA} and v_2 of final D-mesons due to the *collective (radial and elliptic) flow* of light quarks. Furthermore, it can change the HF hadrochemistry, leading for instance to and enhanced productions of strange particles (D_s) and baryons (Λ_c): no need to excite heavy $s\overline{s}$ or diquark-antidiquark pairs from the vacuum as in elementary collisions, a lot of thermal partons available nearby! Selected results will be shown in the following.

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

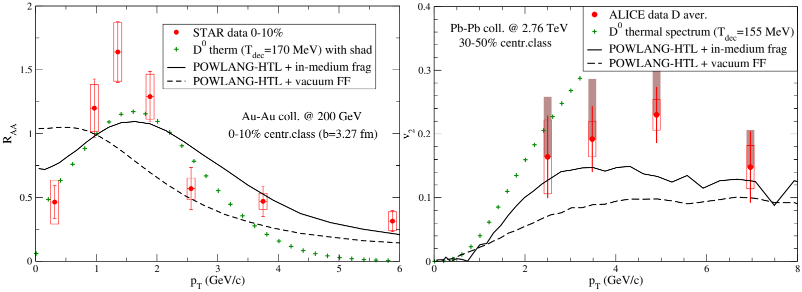
Experimental D-meson data show a peak in the R_{AA} and a sizable v_2 one would like to interpret as a signal of *charm radial flow and thermalization* (green crosses: kinetic equilibrium, decoupling from FO hypersurface)





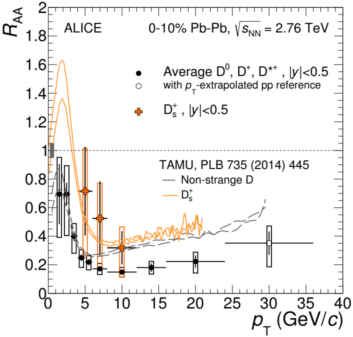
From quarks to hadrons: *kinematic* effect on R_{AA} and v_2

Experimental D-meson data show 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* (green crosses: kinetic equilibrium, decoupling from FO hypersurface)



However, 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 (POWLANG results A.B. et al., in EPJC 75 (2015) 3, 121).

The abundance of strange quarks in the plasma can lead e.g. to an enhanced production of D_s mesons wrt p-p collisions via $c + \bar{s} \to D_s$



ALICE data for D and D_s mesons (JHEP 1603 (2016) 082) compared with TAMU-model predictions (M- He et al., PLB 735 (2014) 445)

Langevin transport simulation in the QGP + hadronization modeled via

$$\left(\partial_t + \vec{v} \cdot \vec{\nabla}\right) F_M(t, \vec{x}, \vec{p}) = -\underbrace{(\Gamma/\gamma_p) F_M(t, \vec{x}, \vec{p})}_{M \to Q + \bar{q}} + \underbrace{\beta(t, \vec{x}, \vec{p})}_{Q + \bar{q} \to M}$$

$$\text{with} \quad \sigma(s) = \frac{4\pi}{k^2} \frac{(\Gamma m)^2}{(s - m^2)^2 + (\Gamma m)^2}$$

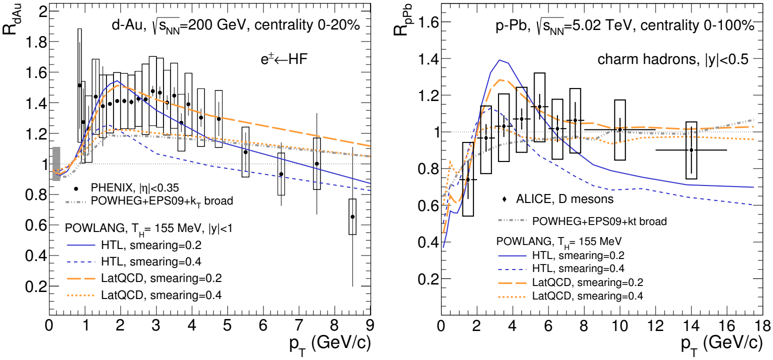
Some new predictions

In the following, some new predictions by the POWLANG setup[4] will be shown, mostly focused on

- HF observables in small systems
- Higher flow harmonic (v_2, v_3)

and compared to recent experimental data

[4] A.B. *et al.*, EPJC 75 (2015) no.3, 121 and JHEP 1603 (2016) 123 + work in progress

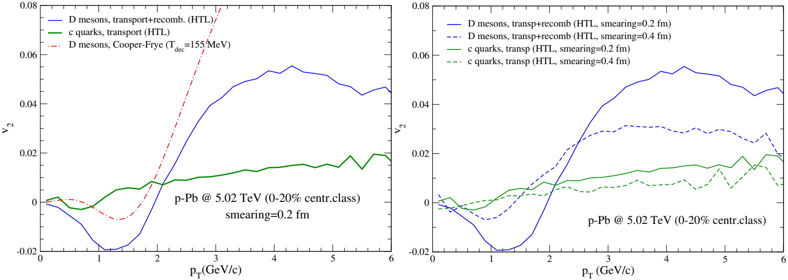


We display our predictions[5], with different initializations (source smearing) and transport coefficients (HTL vs lQCD), compared to

- HF-electron R_{dAu} by PHENIX at RHIC (left panel)
- D-mesons R_{pPb} by ALICE at the LHC (right panel)

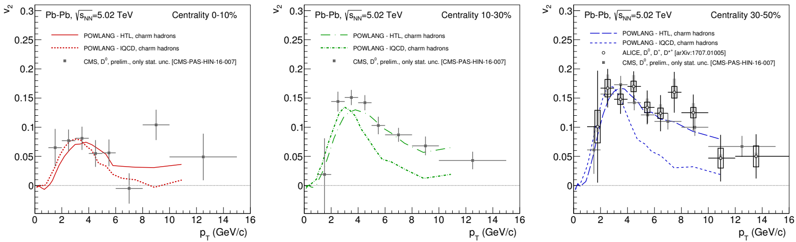
[5] A.B. et al., JHEP 1603 (2016) 123

Non-vanishing elliptic flow?



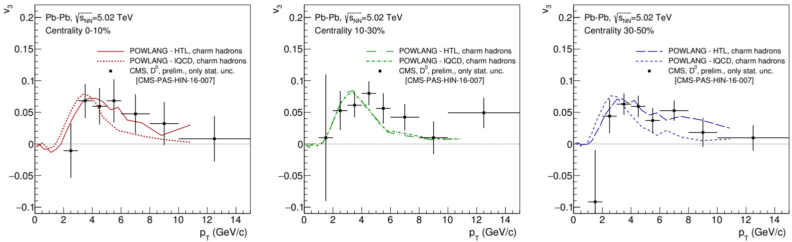
We also predict a non-vanishing v_2 of charmed hadrons, arising mainly from the elliptic flow inherited from the light thermal partons

New results at 5.02 TeV: D-meson v_2 and v_3 in Pb-Pb



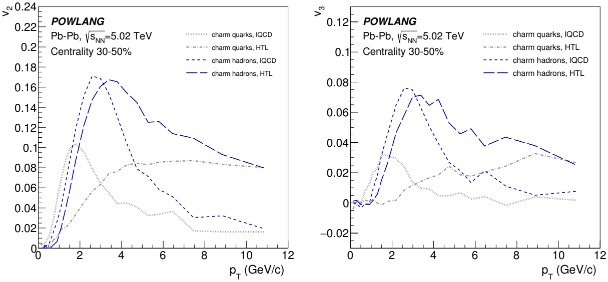
- CMS data for D-meson $v_{2,3}$ satisfactory described;
- Recombination with light quarks provides a relevant contribution;
- Further insight can come from event-shape engineering, selecting events with larger/smaller eccentricity within the same centrality class

New results at 5.02 TeV: D-meson v_2 and v_3 in Pb-Pb



- CMS data for D-meson $v_{2,3}$ satisfactory described;
- Recombination with light quarks provides a relevant contribution;
- Further insight can come from event-shape engineering, selecting events with larger/smaller eccentricity within the same centrality class

New results at 5.02 TeV: D-meson v_2 and v_3 in Pb-Pb



- CMS data for D-meson $v_{2,3}$ satisfactory described;
- Recombination with light quarks provides a relevant contribution;
- Further insight can come from event-shape engineering, selecting events with larger/smaller eccentricity within the same centrality class

Status and perspectives of transport calculations

Theory-to-experiment comparison allows one to draw some robust qualitative conclusions: c-quarks interact significantly with the medium formed in heavy-ion collision, which affects both their propagation in the plasma and their hadronization. As a result, HF-hadron spectra are quenched at high-p_T, while at low-p_T they display signatures of radial, elliptic and triangular flow.

Status and perspectives of transport calculations

Theory-to-experiment comparison allows one to draw some robust qualitative conclusions: c-quarks interact significantly with the medium formed in heavy-ion collision, which affects both their propagation in the plasma and their hadronization. As a result, HF-hadron spectra are quenched at high-p_T, while at low-p_T they display signatures of radial, elliptic and triangular flow. A number of experimental challenges or theoretical questions remain to be answered:

- Charm measurements down to $p_T \to 0$: flow/thermalization and total cross-section (of relevance for charmonium supression!)
- D_s and Λ_c measurements: change in hadrochemistry and total cross-section
- Beauty measurements in AA via exclusive hadronic decays: better probe, due to $M \gg \Lambda_{\rm QCD}, T$ (initial production, evaluation of transport coefficients and Langevin dynamics under better control)
- Charm in p-A collisions: which relevance for high-energy atmospheric muons/neutrinos (Auger and IceCube experiments)? Possible initial/final-state nuclear effects? Better measurements are needed!

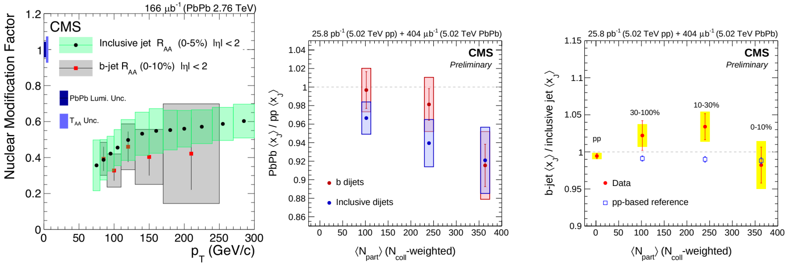
Status and perspectives of transport calculations

Theory-to-experiment comparison allows one to draw some robust qualitative conclusions: c-quarks interact significantly with the medium formed in heavy-ion collision, which affects both their propagation in the plasma and their hadronization. As a result, HF-hadron spectra are quenched at high-p_T, while at low-p_T they display signatures of radial, elliptic and triangular flow. A number of experimental challenges or theoretical questions remain to be answered:

- Charm measurements down to $p_T \to 0$: flow/thermalization and total cross-section (of relevance for charmonium supression!)
- D_s and Λ_c measurements: change in hadrochemistry and total cross-section
- Beauty measurements in AA via exclusive hadronic decays: better probe, due to $M \gg \Lambda_{\rm QCD}, T$ (initial production, evaluation of transport coefficients and Langevin dynamics under better control)
- Charm in p-A collisions: which relevance for high-energy atmospheric muons/neutrinos (Auger and IceCube experiments)? Possible initial/final-state nuclear effects? Better measurements are needed!

The challenge is to become more quantitative, with the extraction of HF transport coefficients from the data (like η/s in hydrodynamics), goal for which beauty is the golden channel

The high-energy fronteer: b-taggeg jets



b-tagging of jets/dijets allows in principle the study of the color-charge dependence of jet-quenching (C_F vs C_A for the Casimir factor). However nuclear-modification-factor and dijet asymmetry look similar for inclusive (gluon dominated) and b-tagged jets. Better study of gluon-splitting contribution (but should be negligible for back-to-back dijets!) is necessary. Error bars need to be reduced!