Heavy flavours in AA collisions: production, transport and final spectra

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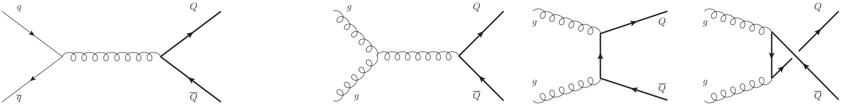
Outline

- Heavy flavor in elementary collisions as *benchmark*
  - of our understanding of pQCD,
  - to quantify medium-effects in the AA case;
- Heavy flavor in heavy-ion collisions:
  - estimating the coupling of Heavy Quarks with the medium,
  - modelling the HQ dynamics in the medium
- A particular approach: the relativistic Langevin equation[1]. Results:
  - R_{AA} and flow;
  - New results: azimuthal $Q\overline{Q}$ correlations.

[1] based on work with A. De Pace, M. Monteno, M. Nardi, F. Prino *et al.*, Eur.Phys.J. C71 (2011) 1666 and Eur.Phys.J. C73 (2013) 2481

Leading Order contribution

- The LO processes are:

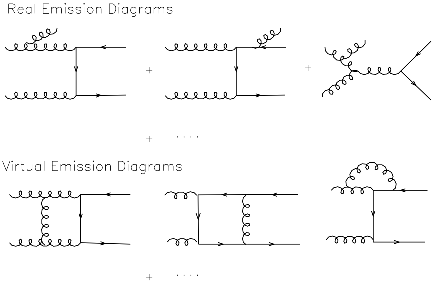


- The propagators introduce in the amplitudes the denominators:

$$(p_1 + p_2)^2 = 2m_T^2(1 + \cosh \Delta y)$$
$$(p_3 - p_1)^2 = -m_T^2 \left(1 + e^{-\Delta y}\right)$$
$$(p_3 - p_2)^2 = -m_T^2 \left(1 + e^{\Delta y}\right)$$

  - *Minimal off-shellness* $\sim m_T^2$;
  - Q and $\overline{Q}$ close in rapidity.

Next to Leading Order process



- Real emission: $|\mathcal{M}_{\text{real}}|^2 \sim \mathcal{O}(\alpha_s^3)$
- Virtual corrections: $2\text{Re}\mathcal{M}_0\mathcal{M}^*_{\text{virt}} \sim \mathcal{O}(\alpha_s^3)$

- NLO calculation gives the $\mathcal{O}(\alpha_s^3)$ result for $\sigma^{\text{tot}}_{Q\overline{Q}}$ and $E(d\sigma_Q)/d^3p$;
- It is implemented in *event generators* like POWHEG or MC@NLO;

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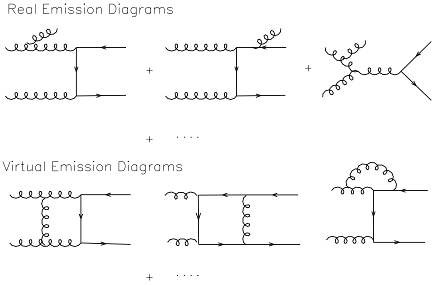

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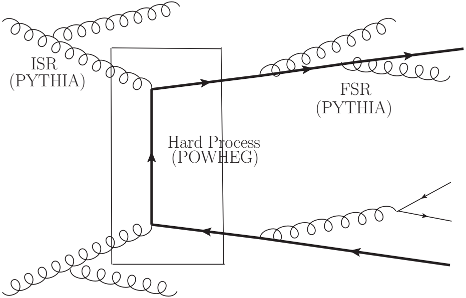
- Output of hard event can be interfaced with a Parton Shower (PYTHIA or HERWIG)

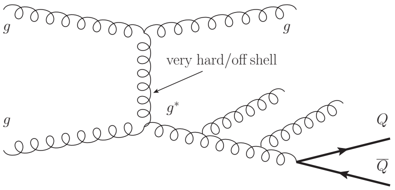
NLO calculation + Parton Shower



- The strategy is then to interface the output of a NLO event-generator for the hard process with a parton-shower describing Initial and Final State Radiation.
- This provides a *fully exclusive information on the final state*

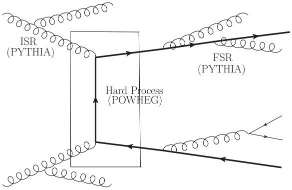
FONLL vs POWHEG+PS

FONLL



- It is a *calculation* for $d\sigma/dyd^2p_\perp$
- It includes processes missed by POWHEG (hard events with light partons)
- It provides NLL accuracy, resumming large $\ln(p_T/M)$

POWHEG+PS



- It is an *event generator*
- Results compatible with FONLL
- It is a more flexible tool, allowing to address more differential observables (e.g. $Q\overline{Q}$ correlations)

Heavy quark production in pQCD: some references

- For a general introduction: M. Mangano, hep-ph/9711337 (lectures);
- For POWHEG: S. Frixione, P. Nason and G. Ridolfi, JHEP 0709 (2007) 126;
- For FONLL: M. Cacciari, M. Greco and P. Nason, JHEP 9805 (1998) 007.
- For a systematic comparison (POWHEG vs MC@NLO vs FONLL): M. Cacciari *et al.*, JHEP 1210 (2012) 137.

Heavy flavour: experimental observables

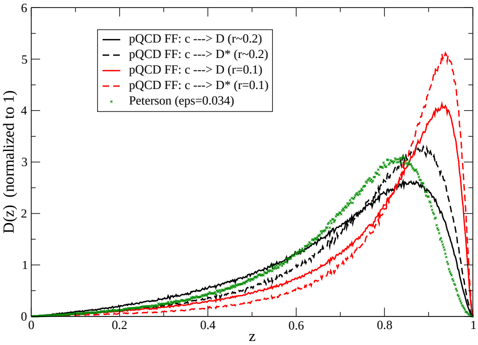
- D and B mesons;
- Non-prompt J/ψ's ($B \to J/\psi\, X$)
- Heavy-flavour electrons, from the decays
  - of charm (e_c)

$$D \to X \nu e$$

  - of beauty (e_b)

$$\begin{aligned} B &\to D\nu e \\ B &\to D\nu e \to X\nu e \nu e \\ B &\to DY \to X\nu e Y \end{aligned}$$

Fragmentation functions



FF tuned by FONLL authors to reproduce e^+e^- data[2]

- D-meson FF from HQET (Braaten *et al.*, PRD 51 (1995) 4819);

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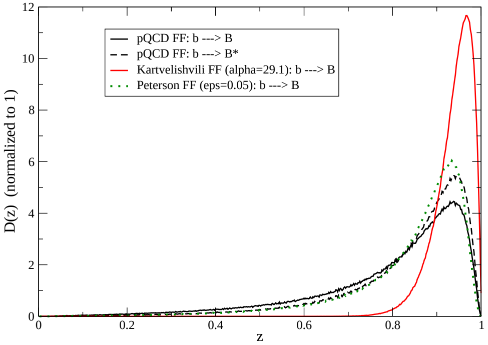

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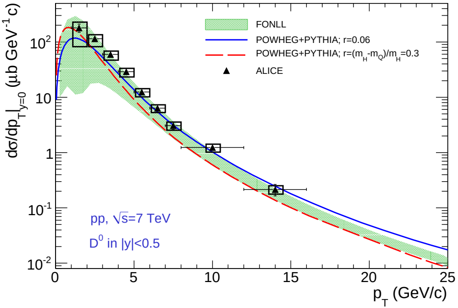
Results: D and B mesons @ 7 TeV



- With the same default parameters ($m_c = 1.5$ GeV, $m_b = 4.8$ GeV, $\mu_R = \mu_F = m_T$) and FF results in agreement with FONLL.
- For our *pp* benchmark we set $m_c = 1.3$ GeV leading to a better agreement with the data.

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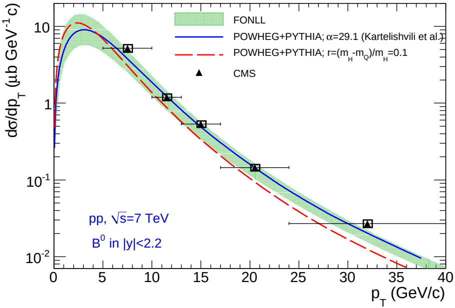

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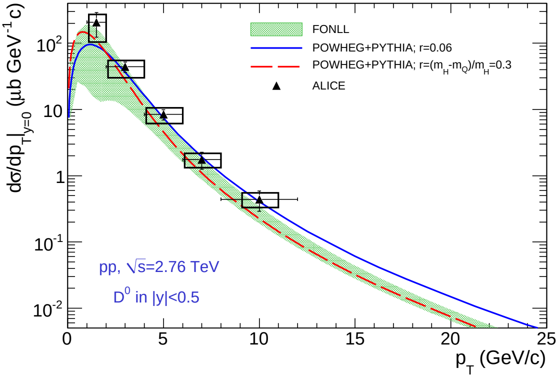

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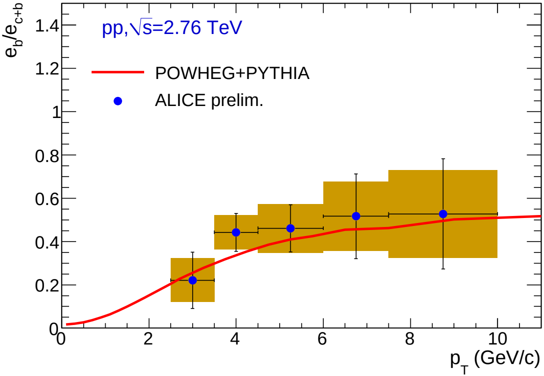

The p-p benchmark appears under control (from now on $m_c = 1.3$ GeV)

- both for the *D*-meson spectra...
- and for the heavy-flavour electrons (e_c and e_b)

HF in p-p collisions: a summary

- A setup based on a NLO pQCD event generator (POWHEG) for the hard event + a Parton-Shower stage simulated with PYTHIA is able to reproduce the experimental data;
- Such an approach provides a richer information on the final state wrt other schemes (e.g. FONLL): this can be of interest for more differential studies like azimuthal correlations

The relativistic Langevin equation

Our transport approach is based on the relativistic 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

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

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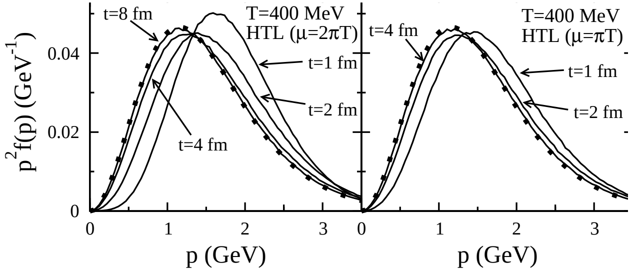
Transport coefficients to calculate:

- *Momentum diffusion* $\kappa_\perp \equiv \frac{1}{2}\frac{\langle\Delta p_\perp^2\rangle}{\Delta t}$ and $\kappa_\parallel \equiv \frac{\langle\Delta p_\parallel^2\rangle}{\Delta t}$;
- *Friction* term (dependent on the discretization scheme!)

$$\eta_D{}^{\mathrm{Ito}}(p) = \frac{\kappa_\parallel(p)}{2TE_p} - \frac{1}{E_p^2}\left[(1-v^2)\frac{\partial\kappa_\parallel(p)}{\partial v^2} + \frac{d-1}{2}\frac{\kappa_\parallel(p)-\kappa_\perp(p)}{v^2}\right]$$

fixed in order to insure the equivalence Langevin $\Leftrightarrow$ Fokker Planck eq. with steady solution $\exp(-E_p/T)$ (Einstein relation)

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)

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

The realistic case: expanding fireball

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

[4] P.F. Kolb, J. Sollfrank and U. Heinz, Phys. Rev. C **62** (2000) 054909
P. Romatschke and U.Romatschke, Phys. Rev. Lett. **99** (2007) 172301

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The fields $u^\mu(x)$ and $T(x)$ can be taken from the output of hydro codes[4]. Current public codes limited to longitudinally boost-invariant ("Hubble-law") expansion ($v_z = z/t$) case:

$$x^\mu = (\tau \cosh\eta, \mathbf{r}_\perp, \tau \sinh\eta) \quad \text{with} \quad \tau \equiv \sqrt{t^2 - z^2}$$

$$u^\mu = \gamma_\perp(\cosh\eta, \mathbf{u}_\perp, \sinh\eta) \quad \text{with} \quad \gamma_\perp \equiv \frac{1}{\sqrt{1-\mathbf{u}_\perp^2}}$$

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The Langevin equation provides a link between *what is possible to calculate in QCD* (transport coefficients) and *what one actually measures* (final p_T spectra)

[5] Our approach: W.M. Alberico *et al.*, Eur.Phys.J. C71 (2011) 1666

The Langevin equation provides a link between *what is possible to calculate in QCD* (transport coefficients) and *what one actually measures* (final p_T spectra)

Evaluation of transport coefficients:

- Weak-coupling hot-QCD calculations[5]
- Non perturbative approaches
  - Lattice-QCD
  - AdS/CFT correspondence
  - Resonant scattering

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Transport coefficients: perturbative evaluation

It's the stage where the various models differ!

We account for the effect of $2 \to 2$ collisions in the medium

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

Transport coefficients: perturbative evaluation

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We account for the effect of $2 \to 2$ collisions in the medium

Intermediate cutoff $|t|^* \sim m_D^2$[6] *separating the contributions of*

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

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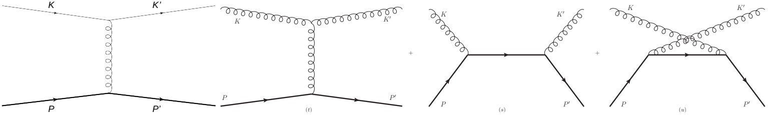
Transport coefficients $\kappa_{T/L}(p)$: hard contribution

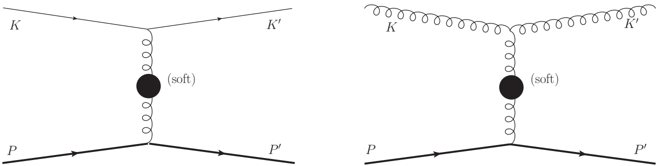


$$\kappa_T^{g/q(\mathrm{hard})} = \frac{1}{2}\frac{1}{2E}\int_k \frac{n_{B/F}(k)}{2k}\int_{k'}\frac{1\pm n_{B/F}(k')}{2k'}\int_{p'}\frac{1}{2E'}\theta(|t|-|t|^*)\times$$
$$\times(2\pi)^4\delta^{(4)}(P+K-P'-K')\left|\overline{\mathcal{M}}_{g/q}(s,t)\right|^2 q_T^2$$

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

where: $(|t|\equiv q^2-\omega^2)$

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



When the exchanged 4-momentum is **soft** the t-channel gluon feels the presence of the medium and requires **resummation**.

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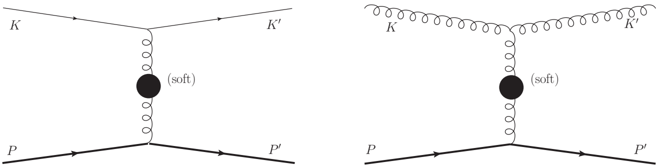


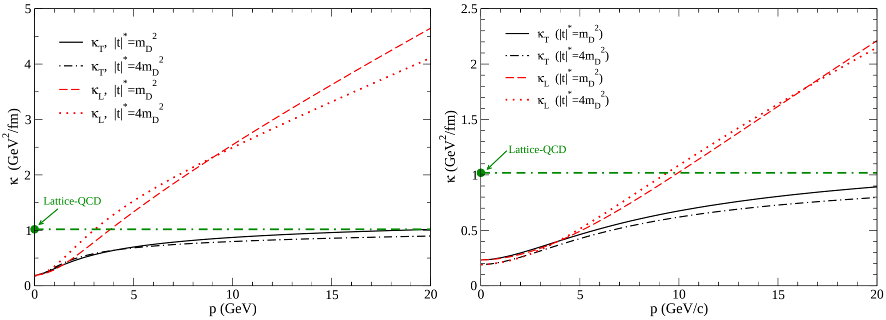
When the exchanged 4-momentum is **soft** the t-channel gluon feels the presence of the medium and requires **resummation**.
The *blob* represents the *dressed gluon propagator*, which has longitudinal and transverse components:

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

where *medium effects* are embedded in the HTL gluon self-energy.

Transport coefficients: numerical results

Combining together the hard and soft contributions...



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

Lattice-QCD transport coefficients: setup

One consider the non-relativistic limit of the Langevin equation:

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

Hence, in the $p \longrightarrow 0$ limit:

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

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In the static limit the force is due to the color-electric field:

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

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In a thermal ensemble $\sigma(\omega) \equiv D^>(\omega) - D^<(\omega) = (1-e^{-\beta\omega})D^>(\omega)$ and

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

Lattice-QCD transport coefficients: results

The spectral function $\sigma(\omega)$ has to be reconstructed starting from the *euclidean electric-field correlator*

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

according to

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

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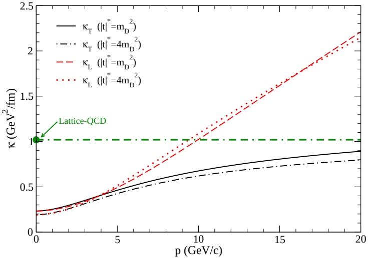
One gets[a]:

$$\kappa \approx 2.5\,T^3 - 4\,T^3$$

$\sim$3-5 times larger then the perturbative result



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

Results in *AA* collisions

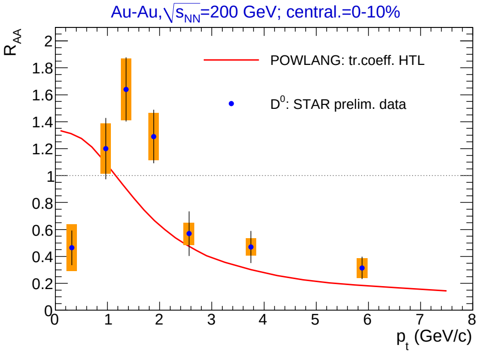
[Details in Eur.Phys.J. C73 (2013) 2481]

Initialization and cross-sections

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	1668	828

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

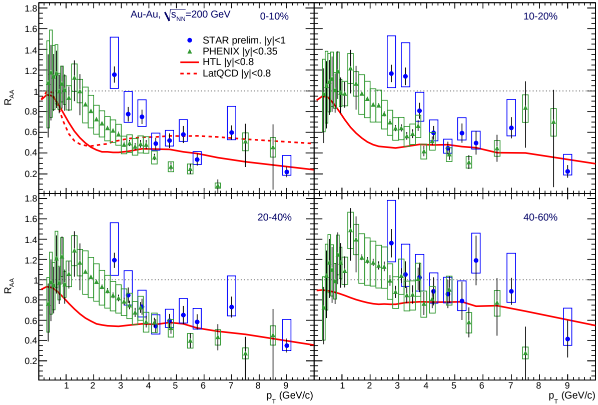
D mesons R_{AA} at RHIC



- Quenching of p_T-spectra nicely reproduced for $p_T \gtrsim 2$ GeV;
- Sharp peak around $p_T \approx 1.5$ GeV: coming from coalescence?

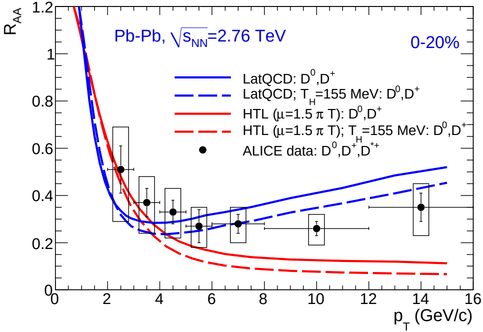
NB peak visible thanks to very fine binning at low-p_T

Heavy-flavour electrons R_{AA} at RHIC



- Rough agreement with the data for $p_T \gtrsim 4$ GeV;
- Langevin results underestimate the data at lower p_T

D-meson R_{AA} at LHC



Possibility to discriminate HTL and l-QCD results (various decoupling temperatures explored) at high-p_T, where however:

- Langevin approach becomes questionable
- No info on momentum dependence of $\kappa_{T/L}$ is available from l-QCD

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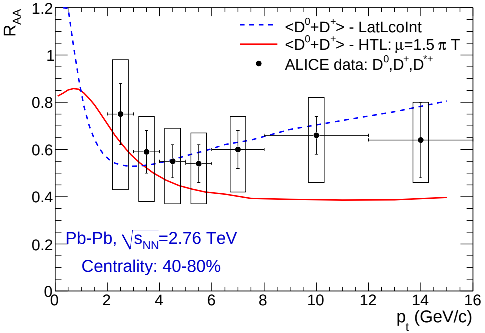

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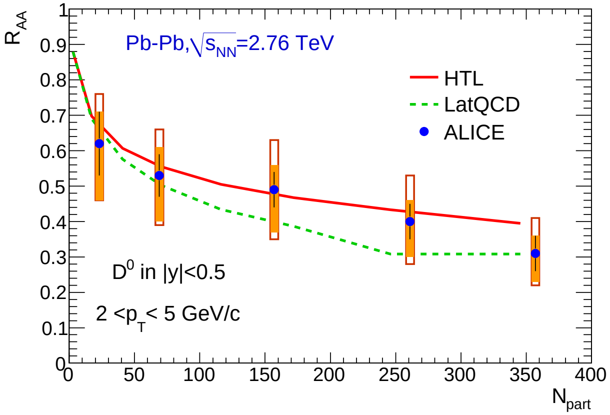
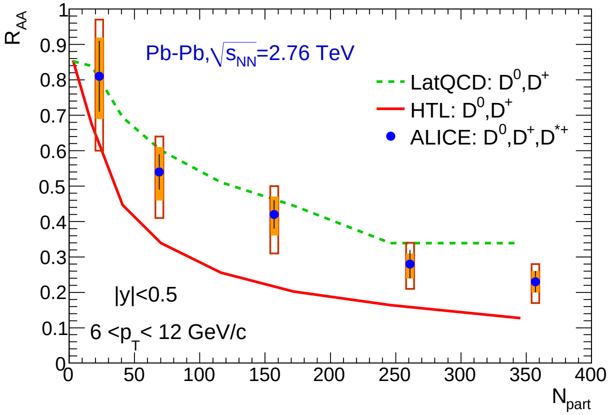
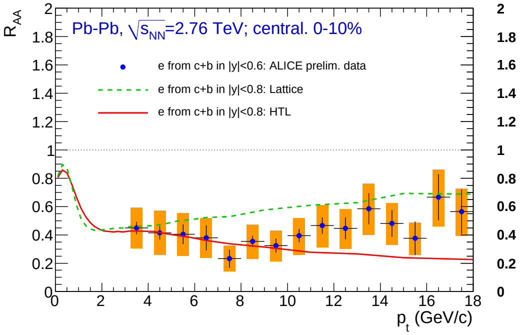
D-meson R_{AA} vs centrality



D-meson R_{AA} vs centrality



Heavy-flavour electrons R_{AA} at LHC



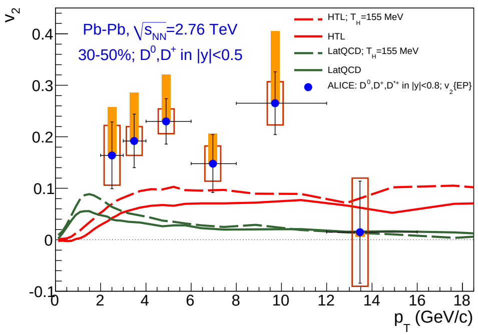
- Good agreement between HTL-Langevin and ALICE data up to ~ 10 GeV;
- For larger p_T data stays beween HTL and l-QCD predictions.

General considerations

Experimental heavy-flavour data at high-p_T always stay between the Langevin results with HTL and l-QCD tranport coefficients, suggesting for $\kappa_L(p)$ a mild rise with the quark momentum, different from

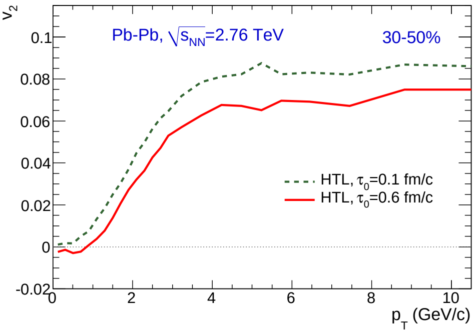
- the strong rise foreseen by the HTL+pQCD result;
- the constant behaviour assumed for the l-QCD case.

Elliptic-flow: *D*-meson v_2 at LHC



- Langevin outcomes undershoot the data, both with HTL and l-QCD transport coefficients;

Elliptic-flow: D-meson v_2 at LHC



- Langevin outcomes undershoot the data, both with HTL and l-QCD transport coefficients;
- Even assuming a very short thermalization time is not sufficient to reproduce the observed flow at low-moderate p_T.

Beauty in AA collisions

Beauty: a golden probe of the medium

- Clean theoretical setup, due to its *large mass*
  - Description via independent random collisions working over an extended p_T-range;
  - Information on transport coefficients by lattice-QCD studies performed in the static ($M \to \infty$) limit
- Less affected by systematic uncertainties due to hadronization
  - Kinematics: very hard Fragmentation Function (small p_T-loss), very small p_T-gain in case of coalescence
  - Hadrochemistry: $B \to J/\psi\, X$ less sensitive to changes in hadrochemistry

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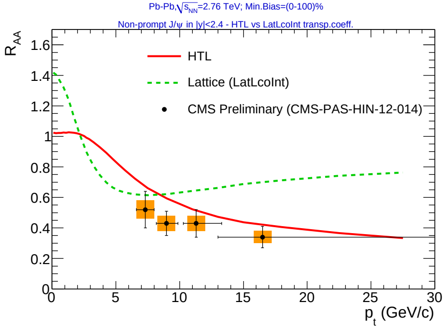
Beauty provides clean information on what happens in the partonic phase!

R_{AA} of displaced J/ψ's at LHC



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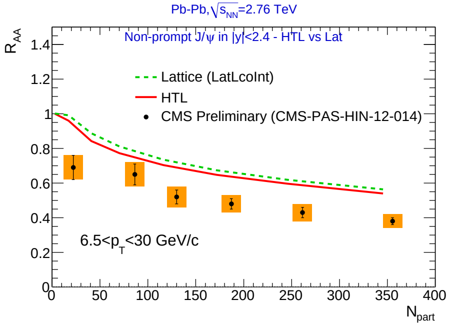

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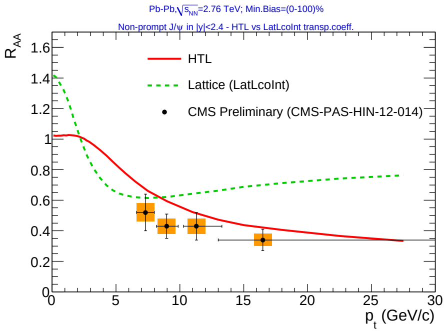
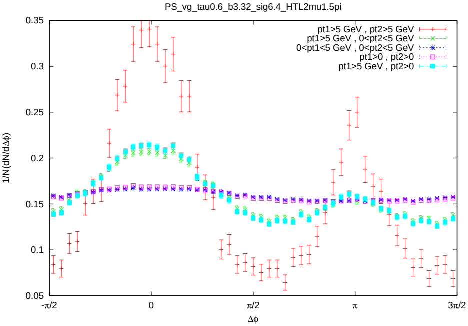


- l-QCD transport coefficients provide a *larger suppression at moderate p_T* wrt perturbative predictions;
- Ignoring momentum-dependence of l-QCD transport coefficients leads to milder suppression at high-p_T wrt HTL results;

$Q\overline{Q}$ correlations

Let us consider $c\overline{c}$ pairs at the end of the Langevin evolution...



It is possible to study the effect of different

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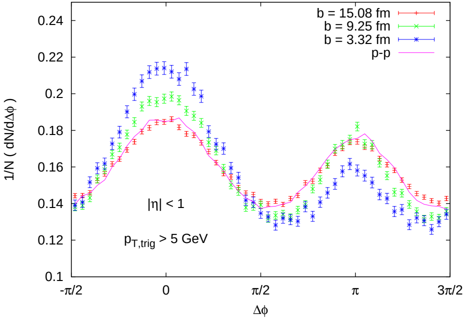
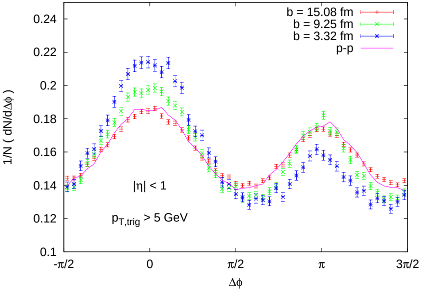


It is possible to study the effect of different

- p_T cuts;
- centrality selections

$Q\overline{Q}$ correlations: trigger biases

The relatively mild suppression of the $\Delta\phi = \pi$ peak and the enhancement of the $\Delta\phi = 0$ peak with increasing centrality can be interpreted as a *bias introduced by using the same p_T-trigger in the different classes*



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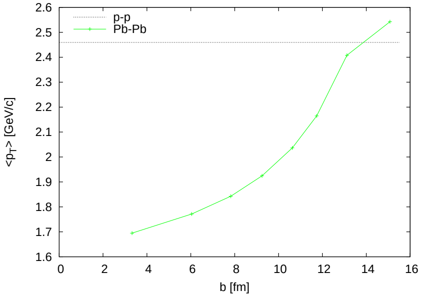

leading to select completely different kind of events, being dominated in central collisions by pairs produced close to the surface and emitted tangentially.

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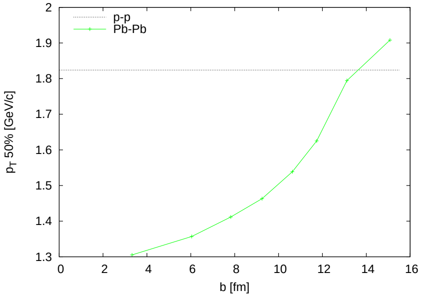

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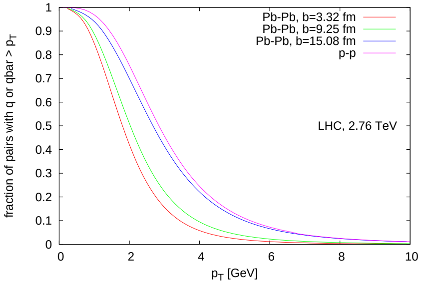

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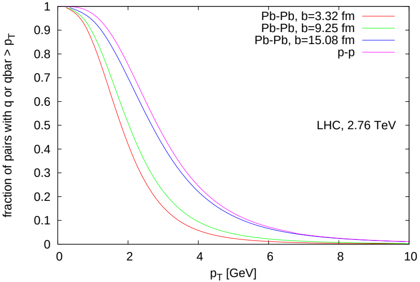

leading to select completely different kind of events, being dominated in central collisions by pairs produced close to the surface and emitted tangentially. Thinking about the best choice of p_T-triggers in order to get information on the medium is mandatory!

Summary and perspectives

- The Langevin equation is a very general tool (of which I tried to illustrate in this talk the conceptual basis):
  - it can be intefaced to different theory calculations
  - it enters into the definition itself of the transport coefficients in terms of QFT correlators;

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  - it can be intefaced to different theory calculations
  - it enters into the definition itself of the transport coefficients in terms of QFT correlators;
- Predictions with *perturbative* and *non-perturbative* transport coefficients have been displayed;
- For the near future:
  - Study and understanding of $Q\overline{Q}$ correlations (in progress);
  - Implementation of coalescence (under development): effect on p_T-spectra and HF hadrochemistry;
  - extending the analysis to forward HF observables with a realistic 3+1 hydro background: code developed (ECHO-QGP collaboration), now to be tuned to data.