Heavy-flavor dynamics in nucleus–nucleus collisions: from RHIC to LHC

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work done in collaboration with:
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Ref: W. M. Alberico *et al.* "Heavy-flavour spectra in high-energy nucleus–nucleus collisions", arXiv:1101.6008 [hep-ph], accepted for publication by EPJ C

Outline

- Heavy quarks as *hard* probes of the Quark Gluon Plasma.
- Theoretical framework:
  - the relativistic Langevin equation in an expanding medium
  - evaluation of the transport coefficients
- Numerical results of a full simulation
  for RHIC (200 GeV) and LHC (2.76 and 5.5 TeV):
  from the initial $Q\overline{Q}$ production to the final D, B and e-spectra:
  - Invariant yields $E(dN/d^3p)$: pp vs AA
  - Nuclear modification factor $R_{AA}(p_T)$
  - Elliptic flow coefficient $v_2(p_T)$
- Discussion of results:
  comparison with PHENIX data and predictions for LHC.

Heavy quarks as hard probes of QGP

- Heavy quarks are produced in hard pQCD processes at very early times of a heavy-ion collision. Then, when crossing the expanding fireball, heavy quarks lose their energy and perform multiple collisions with the medium.

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- However, the energy lost by heavy quarks through soft gluon radiation is expected to be depleted . Because of the large quark-mass, the spectrum of radiated gluons was shown[1] to be suppressed at large energy.

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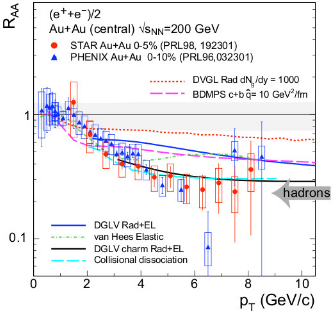

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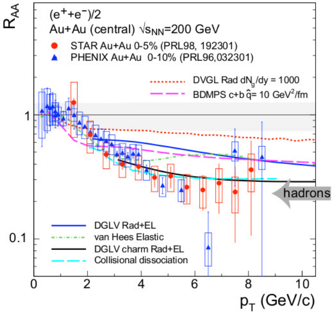

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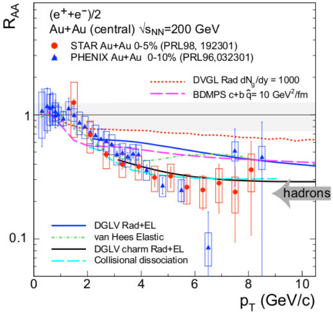

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- Different approaches were proposed to explain RHIC results, taking into account also collisions of heavy quarks with plasma particles.

The relativistic Langevin equation

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Transport coefficients to calculate:

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$$\eta_D{}^{\mathrm{Ito}}(p) = \frac{\kappa_L(p)}{2 T E_p} - \frac{1}{E_p^2} \left[(1 - v^2) \frac{\partial \kappa_L(p)}{\partial v^2} + \frac{d-1}{2} \frac{\kappa_L(p) - \kappa_T(p)}{v^2} \right]$$

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

Evaluation of transport coefficients $\kappa_{T/L}(p)$

The interaction rate (from the squared matrix element of the process) must be weighted by the squared transverse/longitudinal exchanged momentum.

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- soft collisions ($|t| < |t|^*$): Hard Thermal Loop (HTL) approximation in a weak-coupling scenario, with the running coupling costant $g(\mu)$ taken at a scale $\mu \sim T$, the Debye screening mass m_D preventing infrared divergencies.

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- hard collisions ($|t| > |t|^*$): kinetic pQCD calculation

Two calculations, with $g(\mu)$ evaluated at:

$\mu \sim T$, as for the soft component **(HTL1)**

$\mu = |t| = -Q^2$ **(HTL2)**

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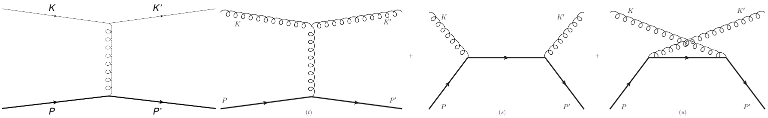
Transport coefficients $\kappa_{T/L}(p)$: hard contribution

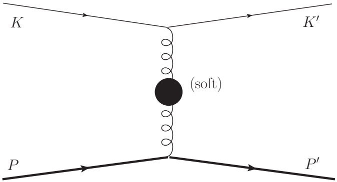


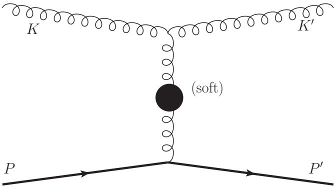
$$\kappa_T^{g/q(\text{hard})} = \frac{1}{2}\frac{1}{2E}\int_k \frac{n_{B/F}(k)}{2k}\int_{k'}\frac{1 \pm n_{B/F}(k')}{2k'}\int_{p'}\frac{1}{2E'}\theta(|t|-|t|^*)\times$$
$$\times(2\pi)^4\delta^{(4)}(P+K-P'-K')\left|\overline{\mathcal{M}}_{g/q}(s,t)\right|^2 q_T^2$$

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

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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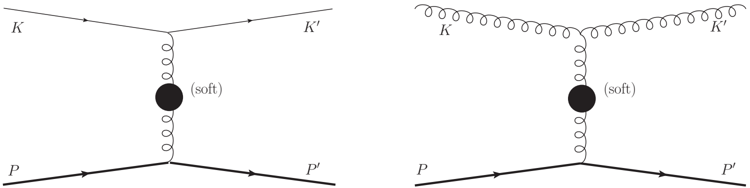

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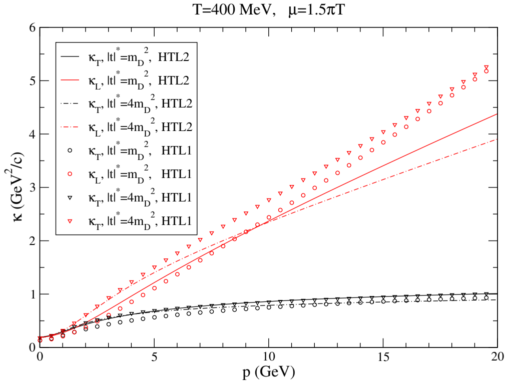
The *blob* represents the effective gluon propagator, which has a longitudinal and a transverse component:

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

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

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

Combining together the hard and soft contributions: $\kappa_{L/T}(p) \equiv \kappa^{soft}_{L/T} + \kappa^{hard}_{L/T}$



- The dependence on the intermediate cutoff $|t|^*$ is very mild.
- Larger growth with p of κ_L with respect to κ_T.
- Slower increase with p of κ_L in the calculation HTL2 with respect to HTL1 .

Implementation of a full simulation including Langevin evolution of heavy quarks in QGP

1. Initial generation of $Q\overline{Q}$ pairs with POWHEG (pQCD@NLO), and with EPS09 nuclear corrections to parton distributions (both at NLO accuracy); in addition, included Cronin effect (k_T broadening).

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5. Finally, heavy quark hadrons are made decay into electrons, by using the PYTHIA decayer with an updated version of branching-ratios table based on 2010 PDG review.

Analysis strategy

3 energies ; 5 centrality intervals + Minimum Bias

- RHIC 200 GeV pp, Au-Au $\Rightarrow$ comparison to PHENIX R^e_{AA} and v^e_2
- LHC 5.5 TeV pp, Pb-Pb
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Analyzed cases for different choices of input parameters and hydro code

- μ scale in HTL calculation of κ_{soft}: $\mu = 1\pi T \div 2\pi T$
- QGP thermalization time τ_0
- viscous/ideal hydrodynamics code
- μ scale in pQCD calculation of κ_{hard}; HTL1 or HTL2 (only for LHC at 2.76 TeV)

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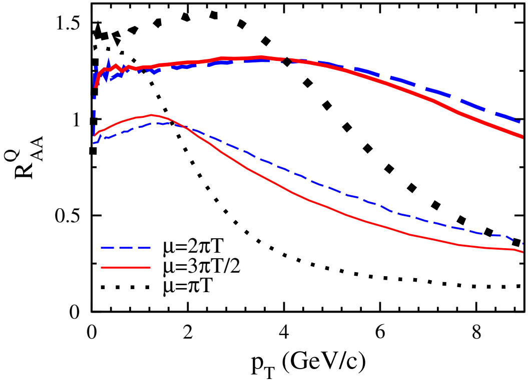
Results: contributions from c, b and from their weighted combination (c+b)

- invariant p_T spectra (in pp and AA)
- R^e_{AA} and $R^{D,B}_{AA}$ for D,B hadrons
- v^e_2 and $v^{D,B}_2$ for D,B hadrons

Acceptance cuts: $|\eta| < 0.35/0.9$ **(PHENIX/ALICE)**

Heavy-quark R_{AA} (at RHIC): role of the coupling

charm: thin lines, bottom: thick lines



Strong dependence on the scale μ at which the coupling $\alpha_s(\mu)$ is evaluated ($\mu = 1\pi T \div 2\pi T$): at $T = 200$ MeV $\alpha_s \approx 0.34$ and 0.63.

In the following we will focus on $\mu = 1.5\pi T$.

Heavy-quark R_{AA} (at RHIC): role of hydrodynamics

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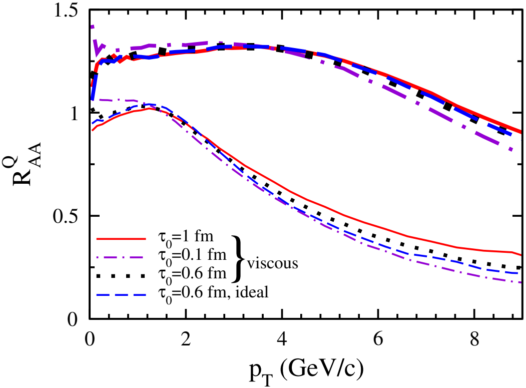

The dependence on the selected hydrodynamical scenario [3] *appears very mild*.

[3] 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

Some systematics on R_{AA}

Effects of fragmentation and decays: $h_{c/b}$ and $e_{c/b}$

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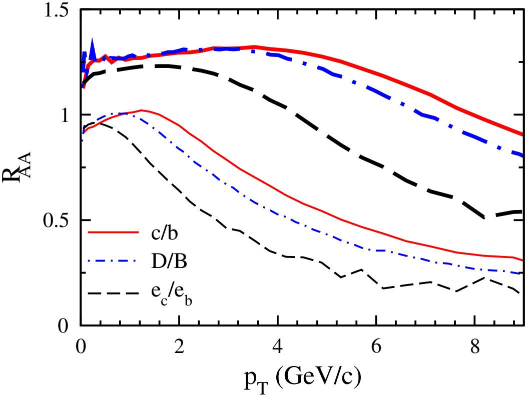
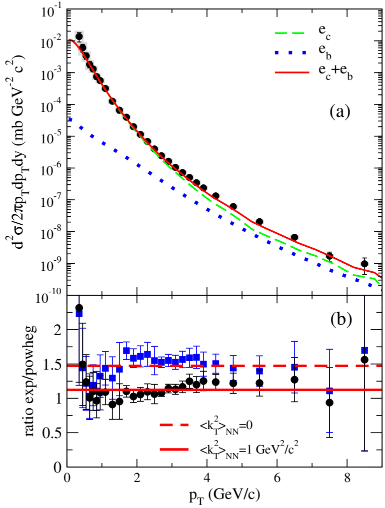


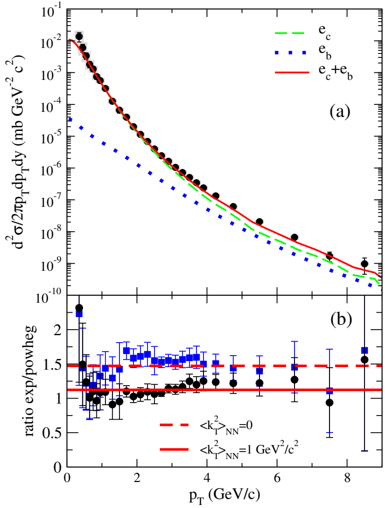
Fragmentation and semileptonic decays lead to a quenching of R_{AA}

HQ single-electron spectra: pp results at RHIC



- PHENIX data on the invariant differential cross section of electrons from heavy-flavour decay in *pp* collisions at $\sqrt{s} = 200$ GeV are nicely reproduced by POWHEG, both in shape and in absolute magnitude.

(default POWHEG values $\mu_{R/F} = m_T$, $m_{c/b}$=1.5/4.8 GeV; CTEQ6M(NLO) PDFs)



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- The discrepancy between data and theory decreases, at the level of 12%, when we include transverse momentum broadening.

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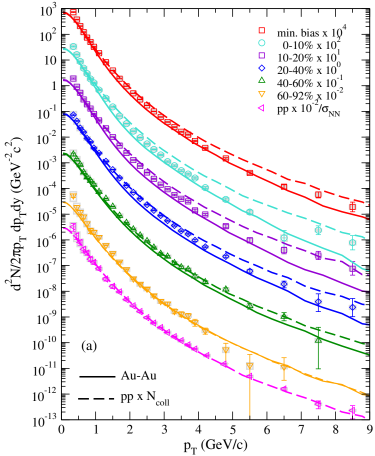
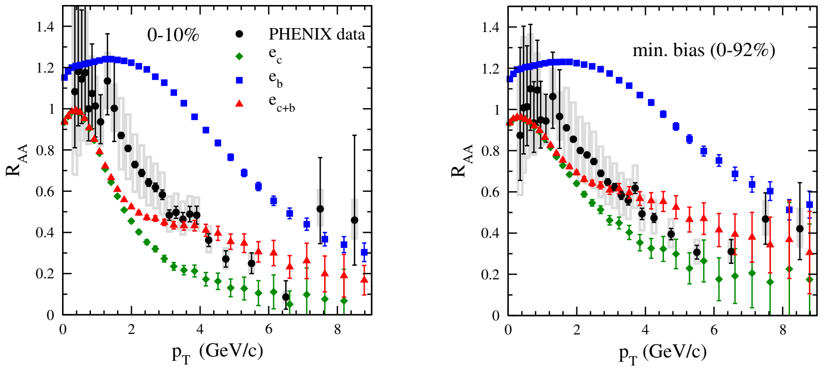
HQ single-electron spectra: AuAu results at RHIC

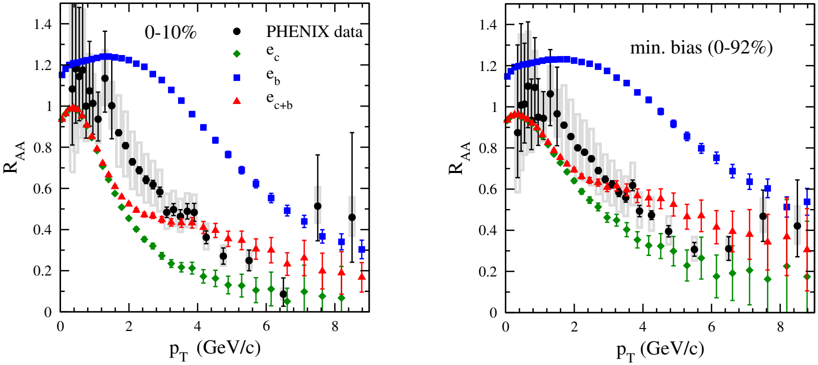


- Dashed curves: pp result scaled by $\langle N_{\rm coll}\rangle$;
- Continuous curves: AA result after Langevin (viscous hydro, τ_0=1 fm).
- Fair description of PHENIX data over many orders of magnitude!



- **Viscous hydro, τ_0=1 fm,** $\mu = 1.5\pi T$.

Results on R_{AA}(elec) at RHIC/PHENIX



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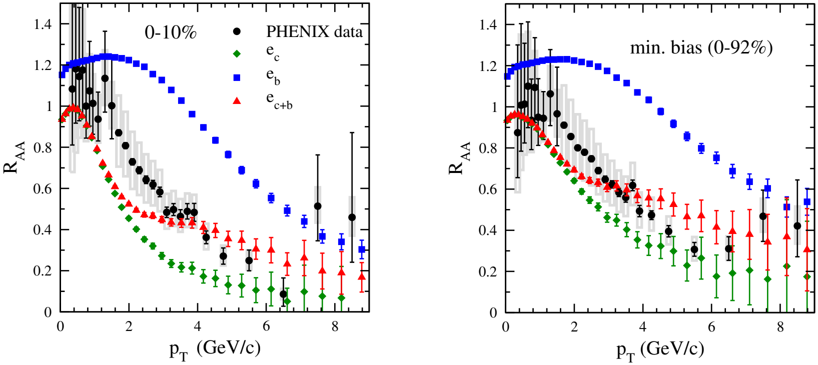

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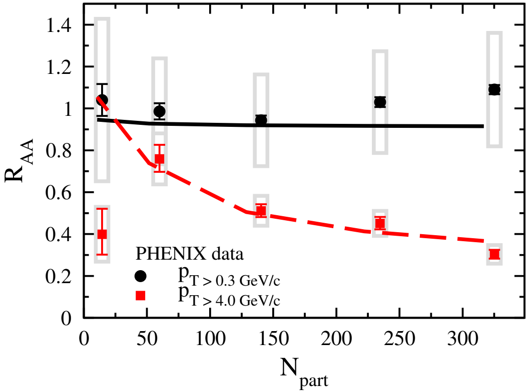
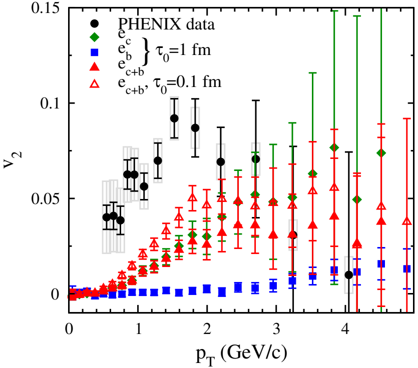
- At low p_T ($p_T \lesssim 3$ GeV/c) the data are underestimated. That could be a consequence of the adopted hadronization scheme (parameterization of pure fragmentation, with no contribution from coalescence).

R_{AA} of heavy-flavor electrons vs centrality at RHIC



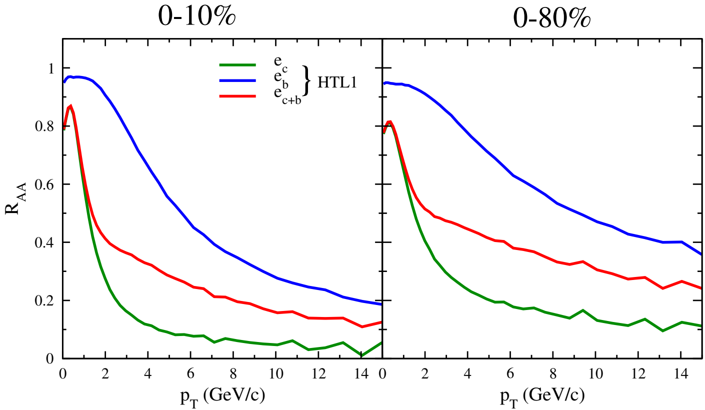
- plots done using the *integrated yields*;
- parameter set: $\mu = 3\pi T/2$ and viscous hydro with $\tau_0 = 1$ fm;
- similar general trend (medium softens the spectrum conserving N_e^{tot})
  - $p_T > 0.3$ GeV/c: flat $R_{AA} \sim 1$ ($R_{AA} \neq 1$ at LHC due to nPDFs!)
  - $p_T > 4$ GeV/c: suppression increases with centrality.

RHIC 0-92 %



- v_2 with hot-QCD + fragmentation results a bit underestimated;
- slightly better agreement with $\tau_0 = 0.1$ fm;
- v_2 could be increased by coalescence (not included here).

Results on R_{AA}(elec) at LHC(2.76 TeV)



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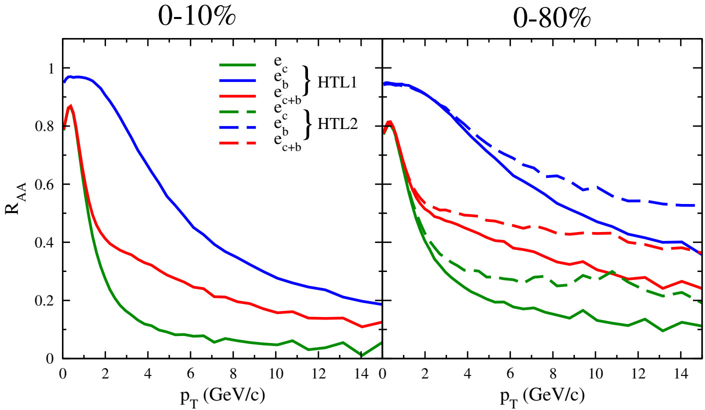
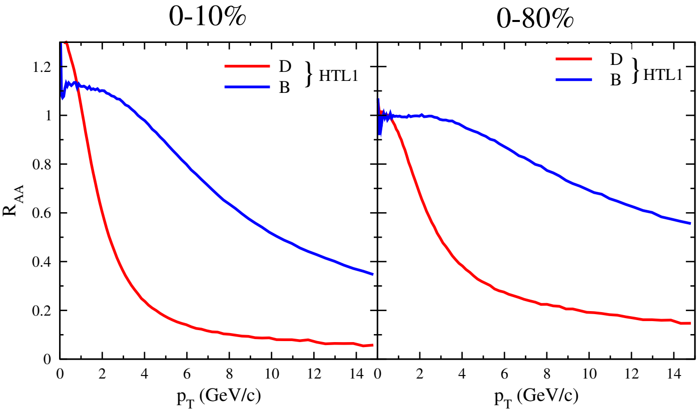


- General features of R_{AA} appear similar to those at RHIC.
- Both charm and bottom are more suppressed.
- For the centrality interval 0-80 % (an approximation of a minimum bias sample) results obtained in the scenario HTL2 display a flattening and a higher value of R_{AA} (less quenching) above $p_T > 2 \div 4$ GeV/c.

Results on R_{AA}(D,B) at LHC(2.76 TeV)



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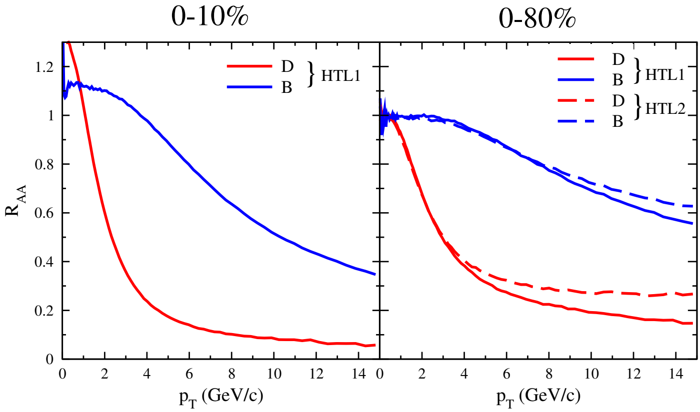
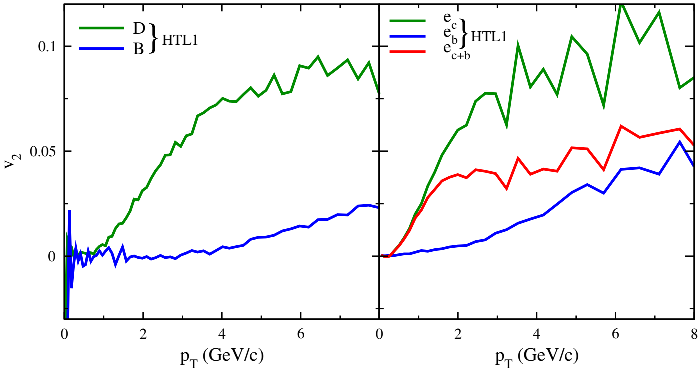


hadrons (left panel) vs electrons (right panel)

0-80%



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Elliptic flow of electrons and D,B hadrons at LHC(2.76 TeV)

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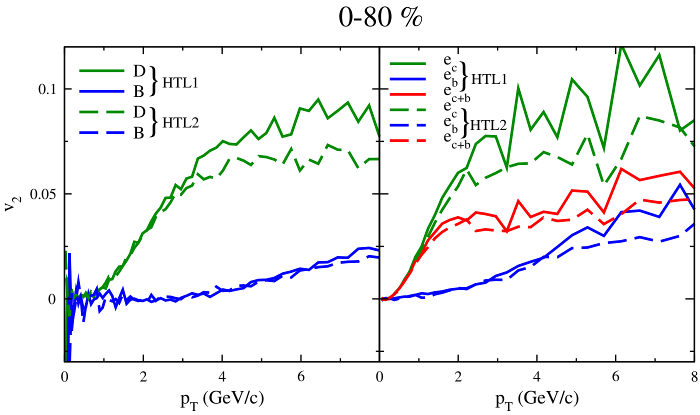

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- Modest elliptic flow of bottom
- Calculation HTL2 displays a lower saturation value of v_2, especially for electrons.

Summary and outlook

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Results of our study are in support of reconsidering the relevance of collisional energy loss in describing heavy-quark propagation in-medium.

Back-up slides

POWHEG

initial $Q\overline{Q}$ production (from POWHEG)

$\sqrt{s}_{NN}$	$\sigma^{pp}_{c\bar{c}}$ (mb)	$\sigma^{AA}_{c\bar{c}}$ (mb)	$\sigma^{pp}_{b\bar{b}}$ (mb)	$\sigma^{AA}_{b\bar{b}}$ (mb)
200 GeV	0.254	0.236	1.77×10^{-3}	2.03×10^{-3}
2.76 TeV	1.947	1.513	0.091	0.085
5.5 TeV	3.015	2.288	0.187	0.169

Huge *shadowing effects* (EPS09-NLO) for $c\bar{c}$ production in Pb-Pb @ LHC!

Glauber and $\mathbf{k}_\perp$ broadening

Each HQ is given a $\mathbf{k}_\perp$-kick extracted from a gaussian distribution with

$$\langle k_\perp^2 \rangle_{AB}(\vec{b},\vec{s}) = \langle k_\perp^2 \rangle_{pp} + \frac{a_{gN}}{2}\left[\frac{\int dz_A\, \rho_A(\vec{s},z_A) l_A(\vec{s},z_A)}{T_A(\vec{s})} + \frac{\int dz_B\, \rho_B(\vec{s}-\vec{b},z_B) l_B(\vec{s}-\vec{b},z_B)}{T_B(\vec{s}-\vec{b})}\right]$$

due to the length crossed by the incoming partons in nucleus A/B before the hard event:

$$l_A(\vec{s},z_A) \equiv \int_{-\infty}^{z_A} dz\, \rho_A(\vec{s},z)/\rho_0 \quad \text{and} \quad l_B(\vec{s}-\vec{b},z_b) \equiv \int_{z_B}^{+\infty} dz\, \rho_B(\vec{s}-\vec{b},z)/\rho_0$$

We choose

a_{gN} (GeV^2/fm)	SPS	RHIC	LHC(5.5 TeV)
c	0.072	0.10	0.17
b	0.197	0.27	0.47

Hydrodynamic codes

To model the effects of an expanding fluid the fields $u^{\mu}(x)$ and $T(x)$ are taken from the output of two longitudinally boost-invariant hydro codes[3].

- $u^{\mu}(x)$ used to perform the update each time in the fluid rest-frame;
- $T(x)$ allows to fix at each step the value of the transport coefficients.

	$\eta/s = 0$			$\eta/s = 0.08$		
	τ_0 (fm)	s_0 (fm^{-3})	T_0 (MeV)	τ_0 (fm)	s_0 (fm^{-3})	T_0 (MeV)
RHIC 200 GeV	0.6	110	357	0.1	8.4	666
				0.6	140	387
				1	84	333
LHC 2.76 TeV				0.6	278	475[4]
LHC 5.5 TeV	0.1	2438	1000	0.1	1840	854
	0.45	271	482	1	184	420

[3] 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

[4] Hirano, Huovinen and Nara , PRC 83 021902

The easiest Langevin evolution algorithm

Going to the fluid rest-frame:

$$\Delta\bar{p}^i_n = -\eta_D(\bar{p}_n)\bar{p}^i_n\Delta\bar{t} + \xi^i(\bar{t}_n)\Delta\bar{t} \equiv -\eta_D(\bar{p}_n)\bar{p}^i_n\Delta\bar{t} + g^{ij}(\bar{\mathbf{p}}_n)\zeta^i(\bar{t}_n)\sqrt{\Delta\bar{t}},$$

$$\Delta\bar{\mathbf{x}}_n = \bar{\mathbf{p}}_n/\bar{E}_n\Delta\bar{t}$$

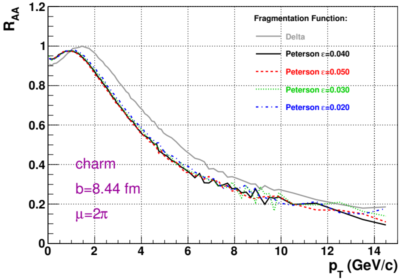
with $\Delta\bar{t} = 0.02$ fm/c (*in the fluid rest-frame!*) and

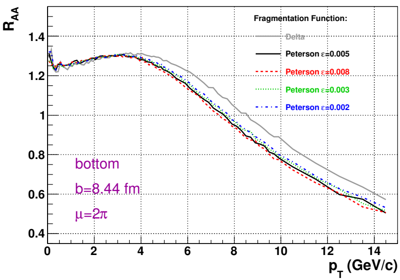
$$g^{ij}(\mathbf{p}) \equiv \sqrt{\kappa_\parallel(p)}\hat{p}^i\hat{p}^j + \sqrt{\kappa_\perp(p)}(\delta^{ij} - \hat{p}^i\hat{p}^j) \quad \text{and} \quad \langle\zeta^i_n\zeta^j_{n'}\rangle = \delta^{ij}\delta_{nn'}$$

Hence one needs simply to:

- extract three independent random numbers ζ^i from a gaussian distribution with $\sigma = 1$;
- update the momentum and position of the heavy quark;
- go back to the Lab-frame: $\mathbf{x}_{n+1}$ and $\mathbf{p}_{n+1}$.

Effects of fragmentation





Fragmentation performed with Peterson FF tends to slightly suppress R_{AA}

- Mild dependence on the parameter ϵ
- $\epsilon = 0.04$ and 0.005 (for c and b) fixed in order to reproduce HQET FFs[5]

Fragmentation fractions taken from DESY results and PDG_2009

[5] E. Braaten, K. Cheung and T.C. Yuan, Phys. Rev. D 48, 5049 (1993)