# Heavy Flavor spectra in nucleus-nucleus collisions

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Work done in collaboration with A.Beraudo, A.De Pace, A.Molinari, M.Monteno, M.Nardi and F.Prino, Eur. Phys. J C (2011) 71:1666

# Outline

- Heavy quarks as a hard probe of the Quark Gluon Plasma
- Theoretical Framework
  - relativistic Langevin equation in an expanding medium
  - evaluation of the transport coefficients
- Numerical results of a full simulation:
  for RHIC (200 GeV) and LHC (2.6 and 5.5 TeV)
  from the initial $Q\bar{Q}$ spectrum 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 probes of the 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 loose their energy and perform multiple collisions with the medium.

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- Therefore $p_T$ spectra of D, B hadrons and of the electrons from their semi/leptonic decays are a good probe to perform QGP diagnostic, since they provide a measure of the energy dissipation (quenching) of heavy quarks while propagating in the hot QCD matter.
- The energy lost by heavy quarks through soft-gluon radiation is expected to be less important than for light quarks. However RHIC spectra show a substantial suppression of heavy-flavor non-photonic electrons: collisions of HQ with plasma particles might be the explanation.

## 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

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

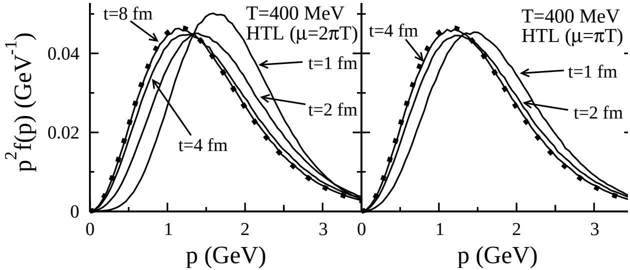
**Transport coefficients** to calculate:

- *Momentum diffusion* $\kappa_T \equiv \frac{1}{2}\frac{\langle \Delta p_T^2 \rangle}{\Delta t}$ and $\kappa_L \equiv \frac{\langle \Delta p_L^2 \rangle}{\Delta t}$;
- *Friction* term (dependent on the discretization scheme!)

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

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

## In a static medium...




For $t \gg 1/\eta_D$ one approaches a relativistic Maxwell-Jüttner distribution[1]

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

(Test with a sample of $c$ quarks with $p_0 = 2$ GeV/c)

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

## In an expanding fluid...

The fields $u^\mu(x)$ and $T(x)$ are taken from the output of two longitudinally boost-invariant ("Hubble-law" longitudinal expansion $v_z = z/t$)

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

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

hydro codes[2].

- $u^\mu(x)$ 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.

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[2] 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

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

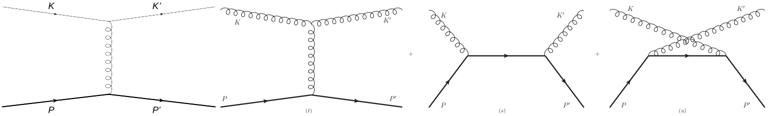
We account for the effect of binary collisions in the medium.
The interaction rate must be weighted by the squared transverse/longitudinal exchanged momentum.

*Intermediate cutoff* $|t|^* \sim m_D^2$ *introduced to separate*[3] *the contributions of*

- soft collisions ($|t| < |t|^*$): Hard Thermal Loop approximation (*resummation of medium effects*)
- hard collisions ($|t| > |t|^*$): kinetic pQCD calculation
  Two calculations, with $g(\mu)$ evaluated at:
  1. $\mu \sim T$, as for the soft component (HTL1)
  2. $\mu = |t| = -Q^2$ (HTL2)

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

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

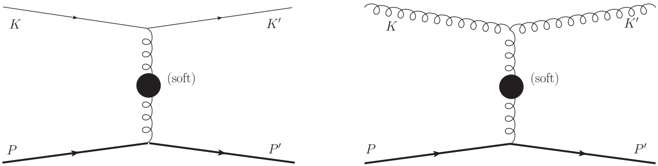



$$\kappa_T^{g/q(\mathrm{hard})} = \frac{1}{2}\frac{1}{2E}\int_k \frac{n_{B/F}(k)}{2k}\int_{k'}\frac{1 \pm n_{B/F}(k')}{2k'}\int_{p'}\frac{1}{2E'}\theta(|t|-|t|^*)\times$$
$$\times\,(2\pi)^4\delta^{(4)}(P+K-P'-K')\left|\overline{\mathcal{M}}_{g/q}(s,t)\right|^2 q_T^2$$

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

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

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



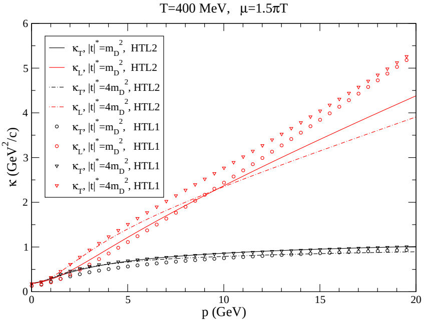

When the exchanged 4-momentum is **soft** the t-channel gluon feels the presence of the medium and requires **resummation**.
The *blob* represents the *dressed gluon propagator*, which has longitudinal and transverse components:

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

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

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

Combining together the hard and soft contributions:

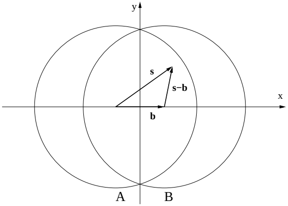



- The dependence on the intermediate cutoff $|t|^*$ is very mild.
- Larger growth with $p$ of $\kappa_L$ with respect to $\kappa_T$.
- Slower increase with $p$ of $\kappa_L$ in the HTL2 case.

## Multi-step full simulation

- Initial generation of $Q\bar{Q}$ pairs: in pQCD, with POWHEG + possible nuclear effects (corrections to nPDFs, $k_T$-broadening).
- Langevin evolution in the QGP: hydro codes provide a description of the background medium with $(T(x), u^\mu(x)$, used to evaluate the *local* value of the *transport coefficients* of the expanding fluid and to update position and 4-momentum of the HQ.
- Hadronization: at $T_c$ are made hadronize via fragmentation mechanism (not yet well under control, other mechanisms can be relevant, like coalescence)
- Final decays: heavy quark hadrons are made decay into electrons $(D \to X\nu e$, $B \to XJ/\psi ...)$, by using PYTHIA decayer with updated version of branching ratios table (PDG 2010)

## Initial heavy-quark spectra

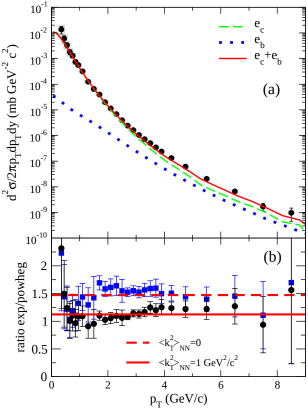



- Single inclusive HQ spectra $E(dN/d^3p)$ generated with POWHEG (pQCD @ NLO) using the PDF set CTEQ6M (+EPS09 in AA)
- HQ distributed in the transverse plane according to the nuclear overlap $dN/d\mathbf{x}_\perp \sim T_{AB}(x,y) \equiv T_A(x+b/2,y)\,T_B(x-b/2,y)$, with

$$T_{A/B}(\mathbf{x}_\perp) \equiv \int_{-\infty}^{+\infty} dz\, \rho_{A/B}(\mathbf{x}_\perp, z)$$

- Each quark is given a random $\mathbf{k}_\perp$ broadening extracted from a gaussian distribution, with $\langle k_\perp^2 \rangle = \langle k_\perp^2 \rangle_{pp} + \langle \delta k_\perp^2 \rangle_{AB}(\vec{b}, \vec{s})$.

## Some results: $pp$ @ $\sqrt{s} = 200$ GeV




PHENIX heavy-flavor electrons
vs POWHEG results[a] with "default" parameters ($M_{c/b}=1.5/4.8$ GeV, $\mu_R=\mu_F=m_T$):

- Nice agreement with a $k_T$-broadening $\langle k_T^2\rangle=1$ GeV$^2$
- Underestimation of the data without $k_T$-broadening

[a] W.M. Alberico *et al.*, EPJC 71, 1666 (2011)

# Heavy-flavor hadrons

Around $T_c$ HQs are made hadronize *like in the vacuum* with

- *momentum fractions* taken from a Peterson fragmentation function ($\epsilon = 0.04/0.005$ for $c/b$)
- *branching fractions* $f(c \to D, \Lambda_c)/f(b \to B, \Lambda_b)$ taken from the PDG ($D = D^0, D^+, D_s^+$ + anti-particles, the same for B), as measured in elementary collisions (e.g. at HERA)

## Heavy-flavor electrons

- From *charm*: $D \to X\nu e$
- From *beauty*:

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

## Non-prompt $J/\psi$

- Several *exclusive channels*

$$\begin{aligned} B &\to J/\psi\, X \\ B &\to \chi_c\, X \to J/\psi\,\gamma\, X \\ B &\to \psi'\, X \to J/\psi\, Y\, X \\ B &\to \psi'\, X \to \chi_c\,\gamma\, X \to J/\psi\,\gamma\,\gamma\, X \end{aligned}$$

## Analysis strategy

3 energies, 5 centrality intervals + Minimum Bias

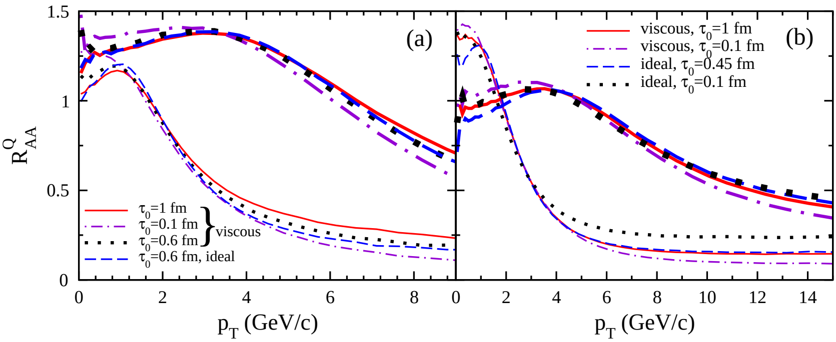
- RHIC 200 GeV pp, Au-Au
- LHC 5.5 TeV pp, Pb-Pb
- LHC 2.76 TeV pp, Pb-Pb, only 1 central bin (0-10%) + MB

Analyzed cases for different choices of input parameters and hydro code

- $\mu$ scale in HTL calculation of $\kappa_{soft}$: $\mu = \pi T \div 2\pi T$
- QGP thermalization time $\tau_0$
- Viscous/ideal hydrodynamics code
- $\mu$ scale in pQCD calculation of $\kappa_{hard}$: HTL1 or HTL2 (only for LHC)

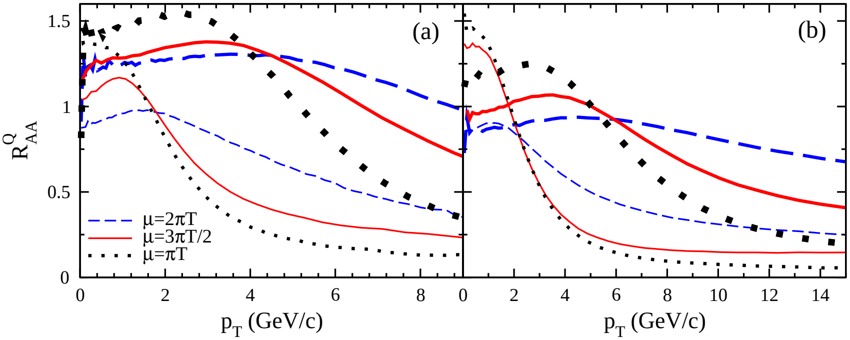
## Systematics on $R_{AA}$: role of hydrodynamics

charm thin lines, bottom thick lines




- very small influence from the hydrodynamics (viscous or ideal)
- Some sensitivity to the initial $\tau_0$

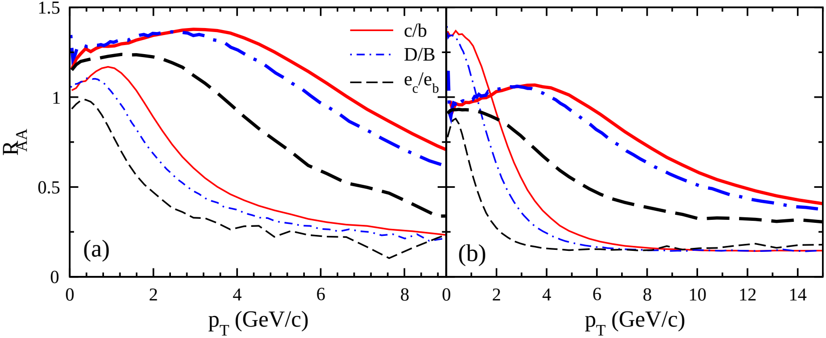
## Systematics on $R_{AA}$: role of the coupling




- Strong dependence upon the scale $\mu$ at which the coupling $\alpha_s$ is evaluated;
- NB: at $T = 200$ MeV $\alpha_s(\pi T) \simeq 0.34$, $\alpha_s(2\pi T) \simeq 0.63$

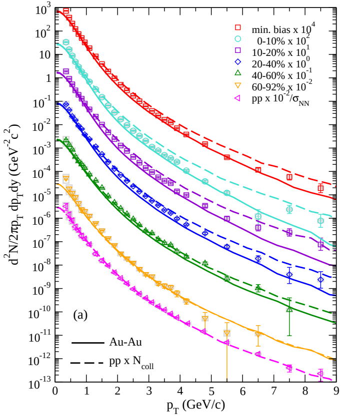
## Systematics on $R_{AA}$: effect of fragmentation and decays

charm thin lines, bottom thick lines



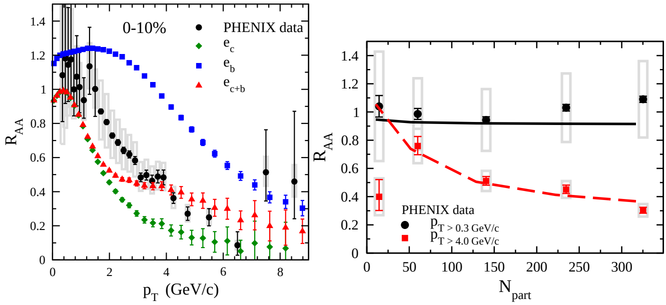

- Fragmentation and semi-leptonic decays lead to a quenching of $R_{AA}$

## Heavy-flavor electrons: invariant spectra at RHIC



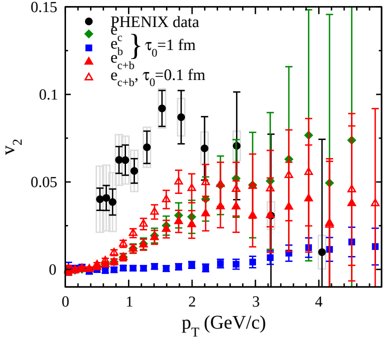

- Continuous curves: after Langevin evolution;
- Dashed curves: *pp* result scaled by $\langle N_{\rm coll} \rangle$

## Heavy-flavor electrons: $R_{AA}$



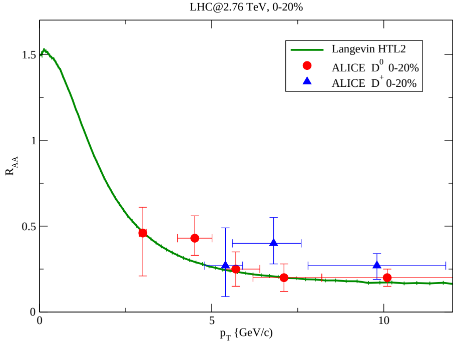

- Left panel: $R_{AA}(p_T)$ in central events;
- Right panel: integrated $R_{AA}$ vs centrality
- Viscous hydro, $\tau_0 = 1$

## Heavy-flavor electrons: *elliptic flow*




- Flow at low-$p_T$ results underestimated;
- With a very small $\tau_0 \sim 0.1$ fm discrepancy *reduced*, but *still present*
- $v_2$ would be increased by coalescence (not included here).

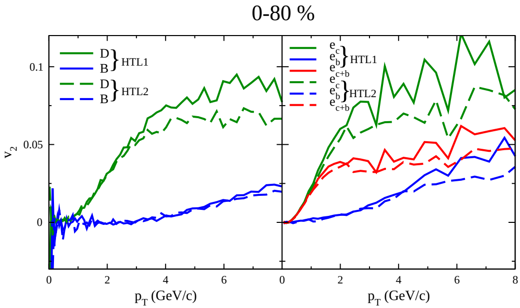
## LHC: D mesons vs ALICE results




High-$p_T$ D-meson suppression nicely reproduced[4]

[4]Data points from Dainese, plenary talk @QM2011

# Elliptic flow (hadrons vs electrons)



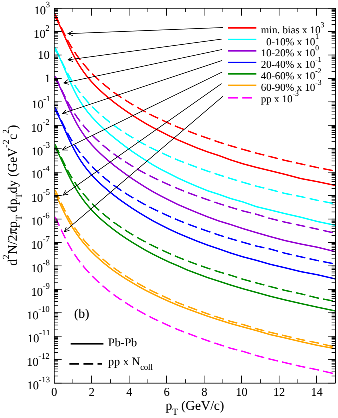

- Charm has a much larger elliptic flow with respect to RHIC
- Modest elliptic flow of bottom
- HTL2 calculation displays a lower $v_2$.

# Summary

- Relativistic Langevin equation is a powerful tool to study the HQ dynamics in the QGP
- The required transport coefficients $\kappa_{L/T}$ have been evaluated considering only $2 \to 2$ collisions and distinguishing soft and hard scatterings, with the aim of delivering a benchmark weak-coupling calculation.
- for large $p_T$ it is possible to accomodate RHIC data for the single electrons spectra: the actual values of $\kappa_{L/T}$ should be realistic
- Preliminary results for the LHC were presented both for electrons and D/B meson yields: comparison with the fresh data from experiments is in progress.
- The results of our study support the relevance of collisional energy loss in describing heavy-quark propagation in the medium.
- Further efforts required, e.g., for hadronization mechanisms (coalescence...)

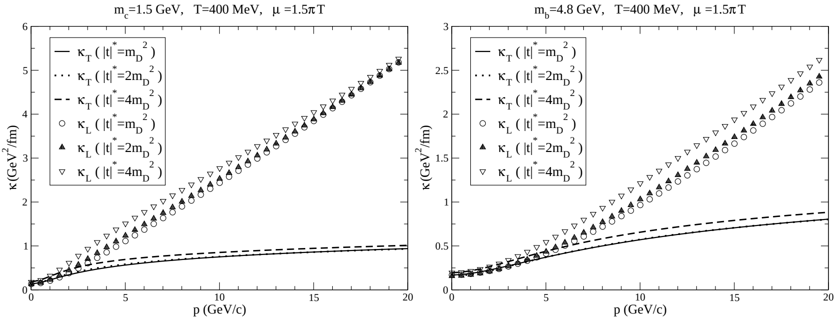
# Back-up slides

# Heavy-flavor electrons: invariant spectra at LHC



# Transport coefficients: numerical results

Combining together the hard and soft contributions...




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

# POWHEG

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

| $\sqrt{s_{NN}}$ | $\sigma_{c\bar{c}}^{pp}$ $(mb)$ | $\sigma_{c\bar{c}}^{AA}$ $(mb)$ | $\sigma_{b\bar{b}}^{pp}$ $(mb)$ | $\sigma_{b\bar{b}}^{AA}$ $(mb)$ |
|---|---|---|---|---|
| 200 GeV | 0.254 | 0.236 | $1.77\times10^{-3}$ | $2.03\times10^{-3}$ |
| 2.76 TeV | 1.947 | 1.513 | 0.091 | 0.085 |

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

# 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[5].

- $u^{\mu}(x)$ 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.

| | $\eta/s = 0$ | | | $\eta/s = 0.08$ | | |
|---|---|---|---|---|---|---|
| | $\tau_0$ (fm) | $s_0$ (fm$^{-3}$) | $T_0$ (MeV) | $\tau_0$ (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[6] |

[5] 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

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