News on Hadrons in a Hot Medium

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How to interpret the title?

"Hot Medium": 50 MeV $\ll T \ll$ 1000 MeV; $\mu \ll \pi T$.

"Hadrons": In this talk only those which maintain their identity...

"News": Statistics on references:

2004: X

2005: X

2006: X X X X

2007: X X X X X X X

2008: X X X X X X

2009: X X X X X X X

2010: X X X X X X X X X X X X

2011: X X X X X X X X X X

Outline

(i) "Open c, b": D, B mesons.

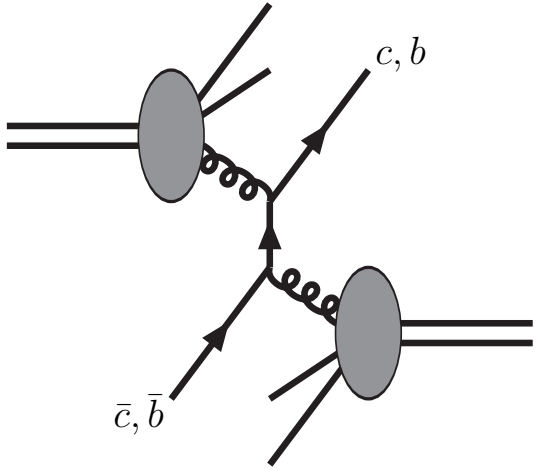
(ii) "Bound $c\bar{c}, b\bar{b}$": J/Ψ, Υ mesons.

(iii) "Virtual $c\bar{c}, b\bar{b}$": pairs from thermal fluctuations.

Apologies to $\pi, K, \eta, \rho, \omega, \ldots$! [cf. parallels & posters]

Open c, b

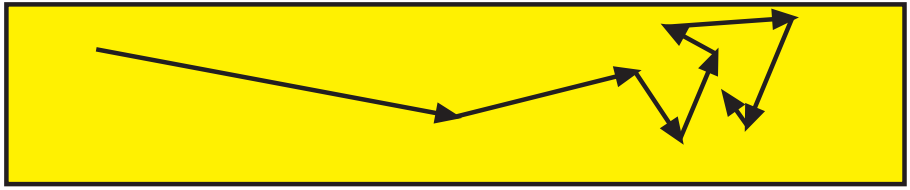
Copiously produced in an initial hard process:



e.g. Cacciari et al hep-ph/0502203

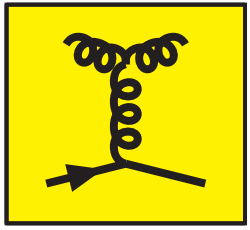
What happens afterwards?

Particularly interesting is propagation through a medium

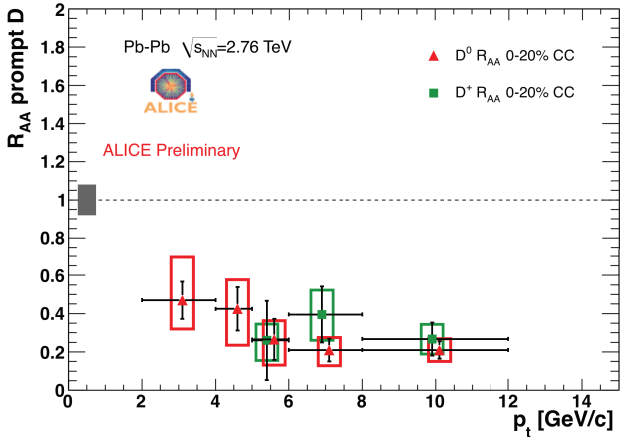


The heavy quark jets tend to get slowed down and eventually stopped, by bremsstrahlung as well as by elastic scatterings.

In the latter case some gluons can be off-shell and soft, leading to large infrared effects:

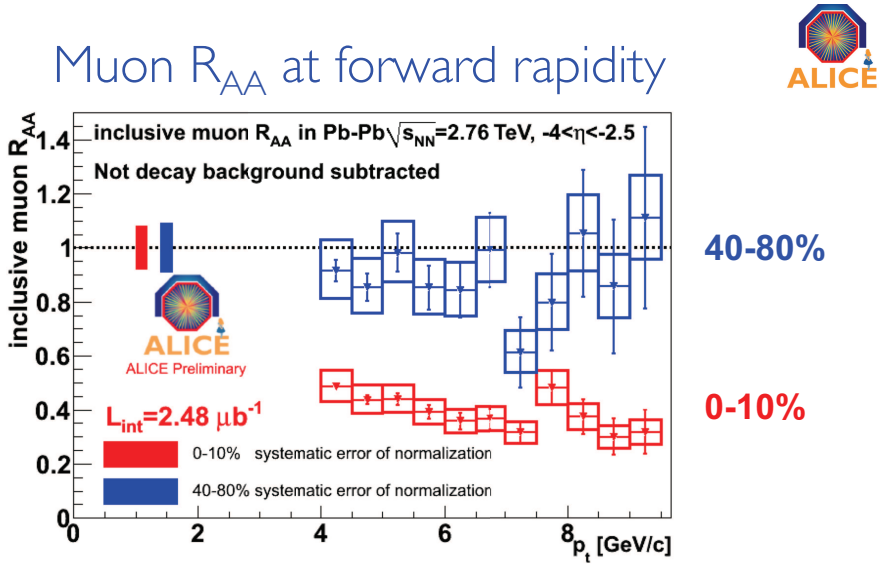


Indeed less $D \to K$ observed than expected:



- Suppression for charm is a factor 4-5 above 5 GeV/c

The same is the case for muons from B decays:



- Suppression is of about a factor 3 above 6 GeV/*c*
- According to FONLL, beauty dominant in this region

Recent theoretical literature

LO and NLO pQCD at $T \gg 200$ MeV:

Moore Teaney hep-ph/0412346; Caron-Huot Moore 0708.4232; 0801.2173.

Model studies at $T \gg 200$ MeV:

van Hees et al 0709.2884; ML et al 0902.2856; Riek and Rapp 1005.0769.

Non-perturbative formulation within QCD:

Casalderrey-Solana Teaney hep-ph/0605199; Caron-Huot et al 0901.1195.

Highlight

Towards lattice measurements:

Burnier et al 1006.0867; Meyer 1012.0234; Burnier et al 1101.5534.

Highlight

Chiral effective theory studies at $T \ll 200$ MeV:

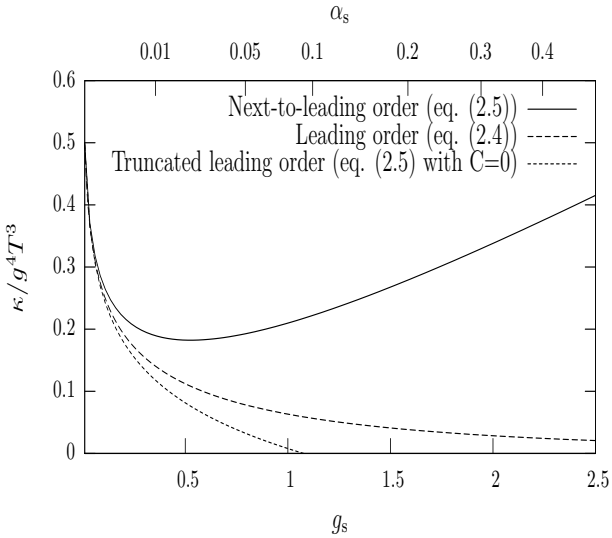
ML 1103.0372; He et al 1103.6279; Ghosh et al 1104.0163; Abreu et al 1104.3815.

Hydrodynamic + Langevin simulations:

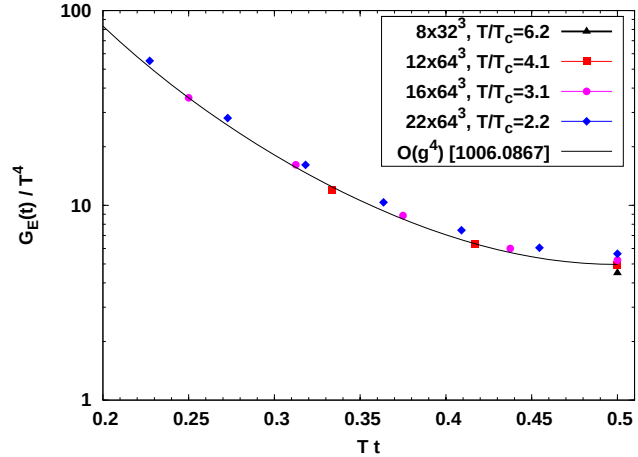
Moore Teaney hep-ph/0412346; and very many follow-ups.

Highlight 1: Towards lattice measurement

$$G_E(\tau) = -\frac{1}{3}\sum_{i=1}^{3}\frac{\langle \mathrm{Re\,Tr}[U_{\beta;\tau}\, gE_i(\tau,\mathbf{0})\, U_{\tau;0}\, gE_i(0,\mathbf{0})]\rangle}{\langle \mathrm{Re\,Tr}[U_{\beta;0}]\rangle}\,.$$



Caron-Huot Moore 0801.2173

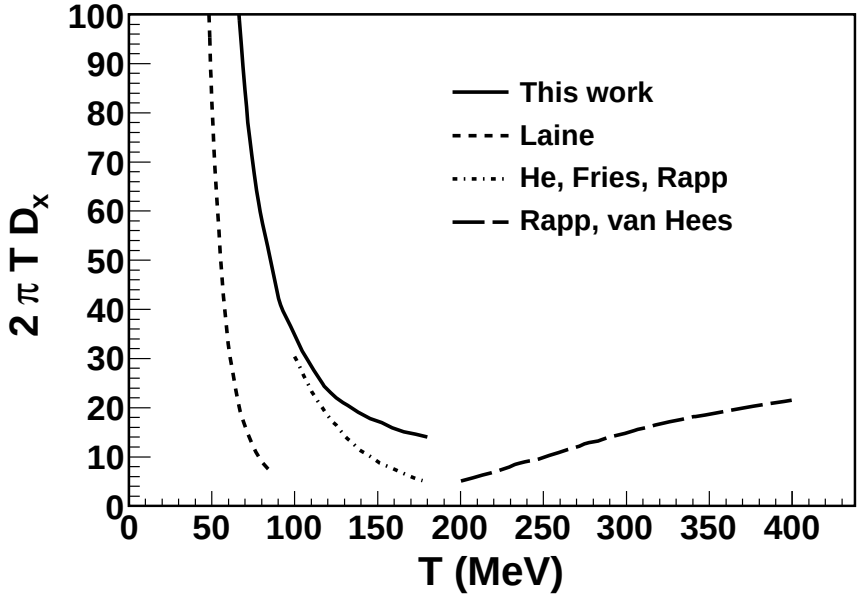


Meyer 1012.0234

$\Rightarrow$ Huge pQCD effects almost hidden on the Euclidean lattice!

Highlight 2: $T \ll 200$ MeV

Interactions strong when "diffusion coefficient" $2\pi T D_x$ is small.

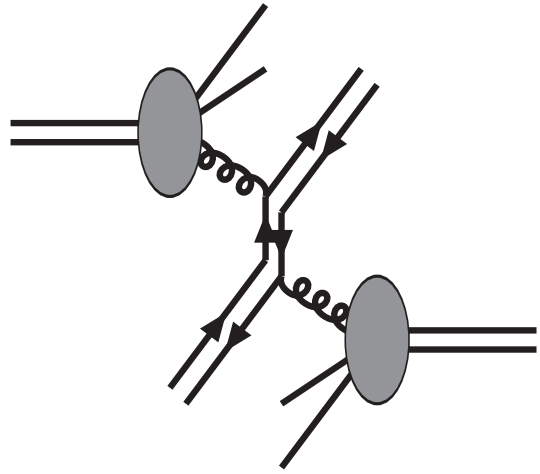


Abreu et al 1104.3815

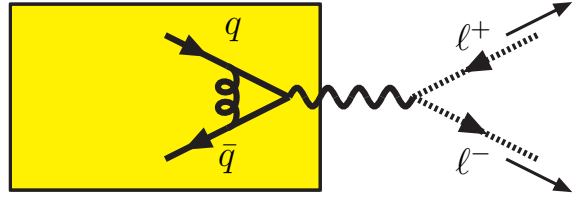
$\Rightarrow$ Strong effects could continue deep into the hadronic phase!

Bound $c\bar{c}, b\bar{b}$

Initial production:

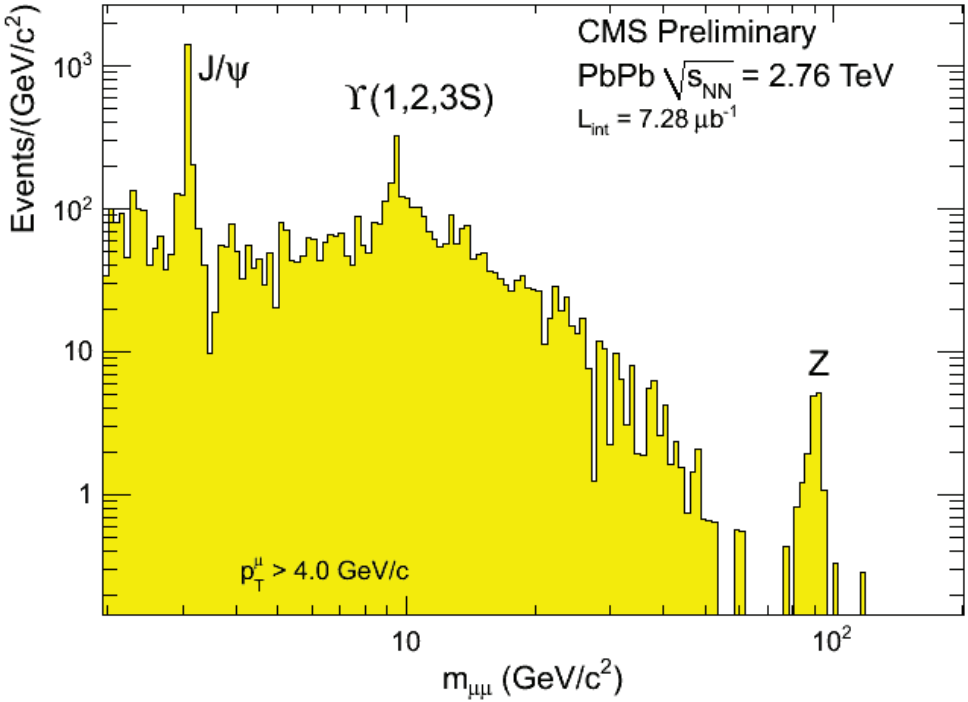


Subsequent thermally modified decay:



Quarkonium states as visible in the $\mu^+\mu^-$ spectrum:

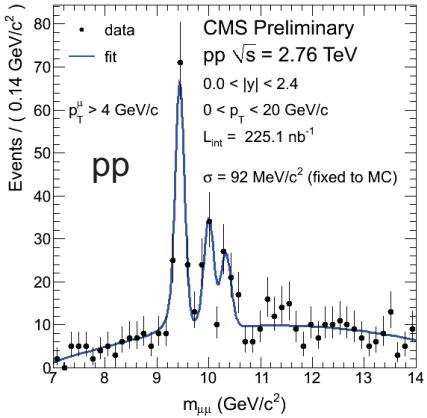
Compact Muon Solenoid: $\mu^+\mu^-$ invariant mass

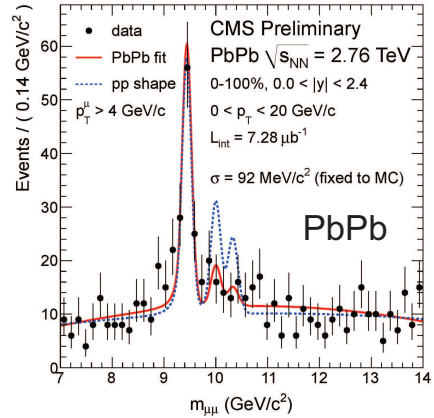


Z. Hu (TODAY), T. Dahms (Tue), C. Silvestre (Fri), J. Robles (Fri), M. Jo (Poster), D.H.Moon (Poster), H. Kim (Poster)

A possible thermal modification of the spectral shape:

Suppression of excited ϒ states





$$\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp} = 0.78^{+0.16}_{-0.14} \pm 0.02 \qquad \Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb} = 0.24^{+0.13}_{-0.12} \pm 0.02$$

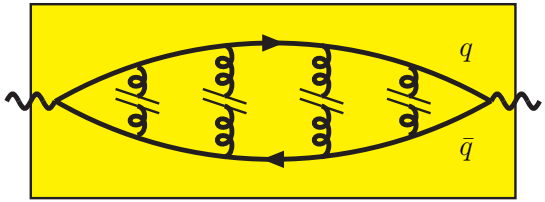
$$\frac{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{PbPb}}{\Upsilon(2S+3S)/\Upsilon(1S)\big|_{pp}} = 0.31^{+0.19}_{-0.15} \pm 0.03$$

- Excited states ϒ(2S,3S) relative to ϒ(1S) are suppressed
- Probability to obtain measured value, or lower, if the real double ratio is unity, has been calculated to be less than 1%

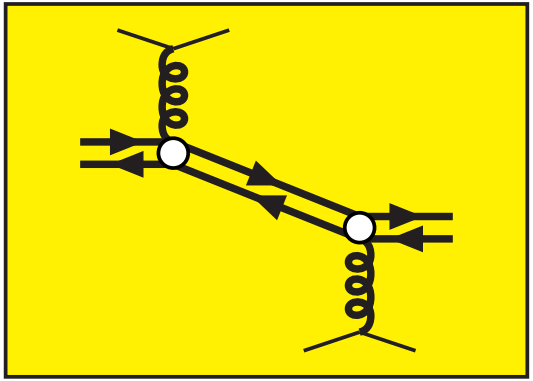
Z. Hu (TODAY), C. Silvestre (Fri)

A slight paradigm shift concerning thermal physics

Traditional view: it remains a coherent QM bound state but in a Debye-screened potential.



Modern view: coherence is (partly) lost due to random kicks from a heat bath; static potential might develop an imaginary part.



Recent theoretical literature (in the "modern" direction)

Complex real-time static potential

ML et al hep-ph/0611300; 0707.2458; 0903.3467; Beraudo et al 0712.4394; Dumitru et al 0903.4703; Noronha Dumitru 0907.3062; Philipsen Tassler 0908.1746; Chandra Ravishankar 1006.3995; Margotta et al 1101.4651.

Full-fledged effective field theory formulation ("PNRQCD$_{\mathrm{HTL}}$")

Escobedo Soto 0804.0691; 1008.0254; Brambilla et al 0804.0993; 1105.4807

Highlight

Spectral function and thermal part of $\mathrm{d}N_{\mu^-\mu^+}/\mathrm{d}^4x\,\mathrm{d}^4Q$

ML 0810.1112; Burnier et al 0711.1743; 0812.2105; Grigoryan et al 1003.1138; Riek Rapp 1005.0769; Miao et al 1012.4433.

Highlight

Bottomonium below melting; its velocity dependence

Brambilla et al 1007.4156; Dominguez Wu 0811.1058; Escobedo et al 1105.1249.

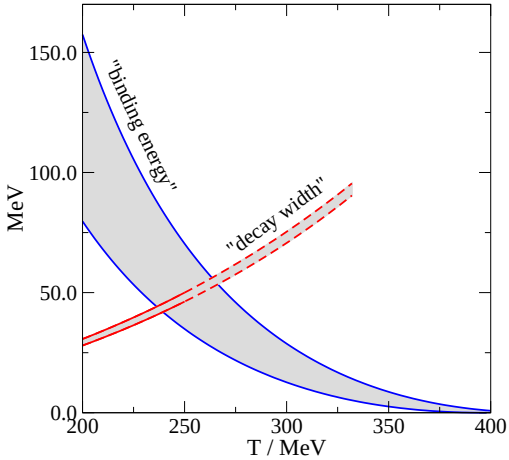
Highlight

Lattice (within full QCD or effective theory)

Jakovac et al hep-lat/0611017; Aarts et al 0705.2198; Rothkopf et al 0910.2321; Aarts et al 1010.3725; Ding et al 1011.0695.

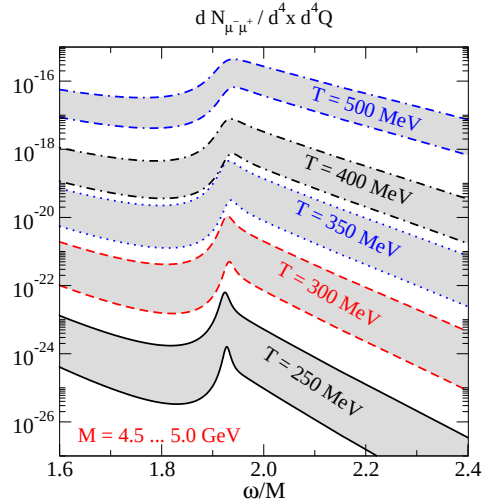
Highlight 1: from "on-off" melting towards spectral shape

Qualitatively ($b\bar{b}$):



ML et al hep-ph/0611300

$\Rightarrow$



Burnier et al 0812.2105

Quantitatively: at low T (far below "melting") width rises linearly with T and its velocity-dependence is also computable.

Brambilla et al 1007.4156; Escobedo et al 1105.1249

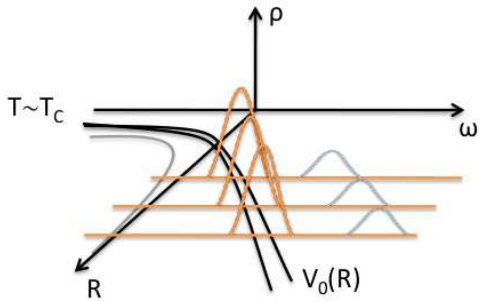
Highlight 2: lattice computations within effective theories

Either determine the spectral function through a lattice simulation within "NRQCD" ...

Aarts et al 1010.3725; in progress

... or determine a real-time static potential $V_>(\infty, r)$, perhaps to be used within "PNRQCD$_{\rm HTL}$", through spectral analysis of an imaginary-time Wilson loop.

Rothkopf et al 0910.2321; in progress



Position: $\mathrm{Re}\, V_>(\infty, r)$. Width: $\mathrm{Im}\, V_>(\infty, r)$.

Virtual $c\bar{c}, b\bar{b}$ from thermal fluctuations

When is T high enough for quarks to "chemically equilibrate", i.e. to be part of the heat bath?

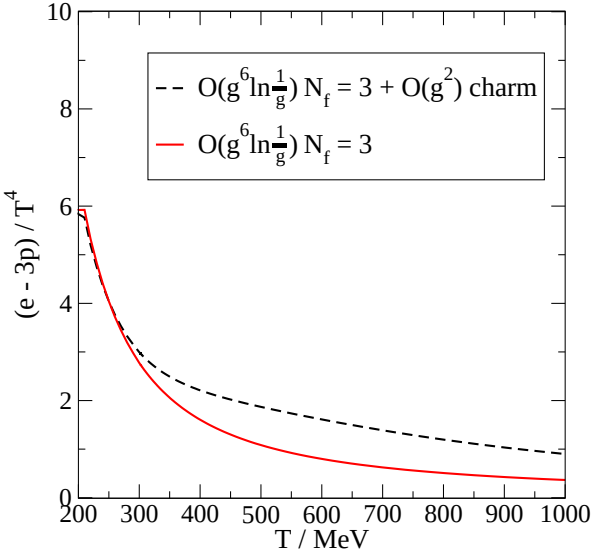
Naively: $T \gg 2m$, so that there is no Boltzmann suppression, $\exp(-\frac{2m}{T})$, of pair creation of a quark-antiquark pair.

But should one use here $m_c^{\overline{\rm MS}}(3\text{ GeV}) \approx 1$ GeV, $m_c^{\rm pole} \sim (1.5 - 2.0)$ GeV, or something else?

And should the comparison be with T or $2\pi T$ or ...?

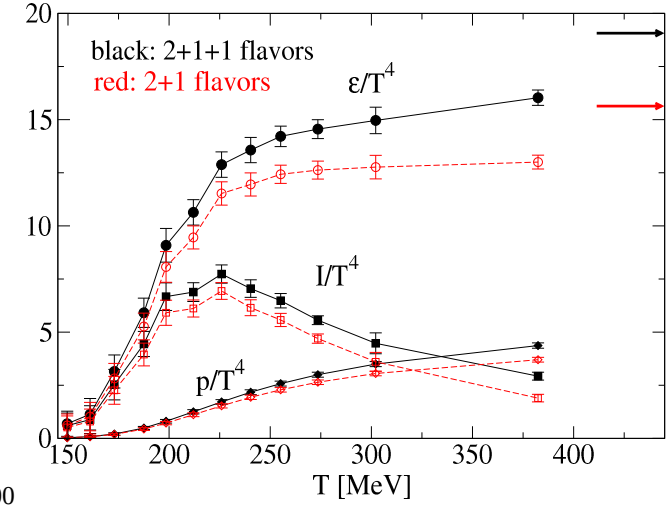
There are effects visible at surprisingly low T!

pQCD



ML Schröder hep-ph/0603048

lattice (w/o extrapolations)



DeTar et al 1003.5682

(Cheng et al 0710.4357, Borsanyi et al 1007.2580)

$\Rightarrow$ Perhaps relevant for initial stages of hydrodynamics @ LHC?

Conclusions

In heavy ion collisions at the LHC, various heavy-quark related observables are increasingly important and may turn out to yield versatile information about the dynamics of hot QCD.

Much well-defined work remains to be carried out!

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