Heavy quarkonia at finite temperature: a probe for quark gluon plasma

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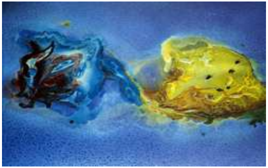
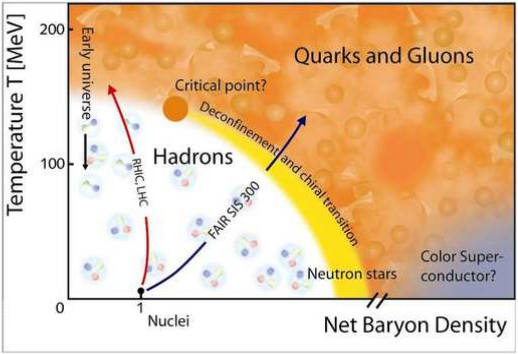


Outline

1. Motivation and introduction
2. Heavy quarkonium in a thermal bath
3. Small anisotropy in QGP
4. Conclusions

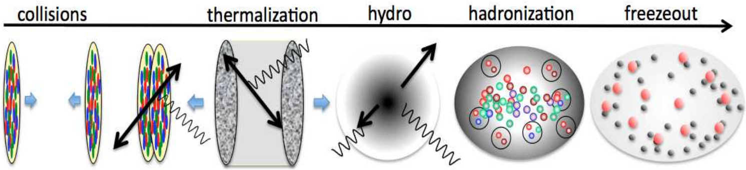
What may be the Quark Gluon Plasma?

- Transformation of nuclear matter into a deconfined phase at high temperature
- Strongly connected with the asymptotic freedom



How can we hope to reproduce it?

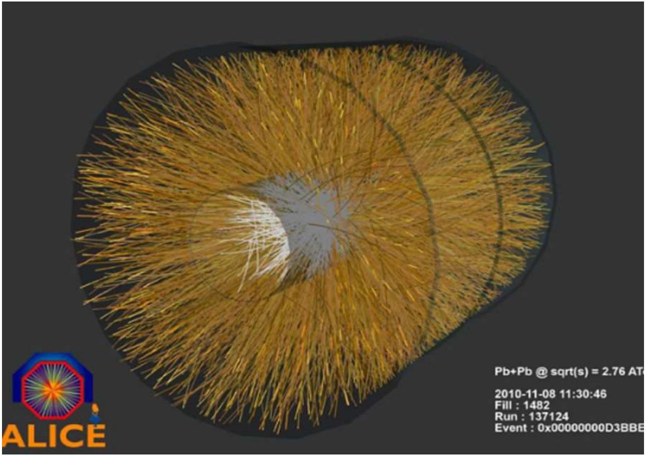
- the high energy heavy ions colliders, such as the LHC, are the right place



Time scales for Quark Gluon Plasma

- Formation time $\tau_0 \sim 1$ fm (in physical units 3.3×10^{-24} s)
- Life time of equilibrated deconfined phase $\tau \sim 10\,\mathrm{fm}$

What comes out from QGP?



- very high particle multiplicity in the final state
- demanding and challenging experimental analysis
- clean probes are needed...is it possible to have any?

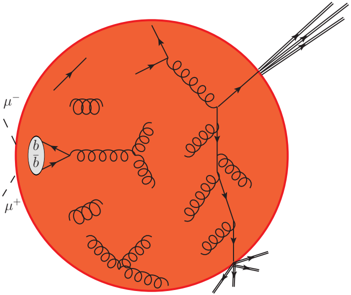
Hard probes for QGP

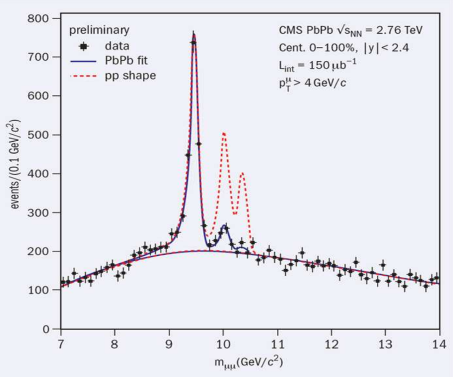
How can we get information about a so short-lived state ?

- A possible way is by exploiting hard probes, *T. Matsui and H Satz (1986)*

1. jet quenching
2. quarkonia suppression

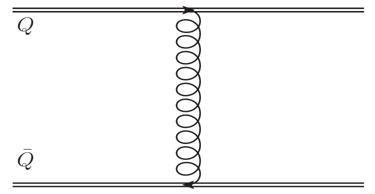
Typical time scale $\tau_{Hard} < \tau_0$





Heavy quarkonium in vacuum and in medium

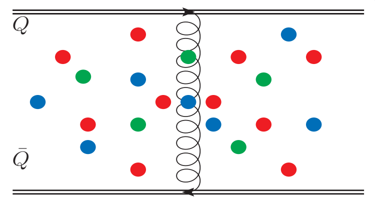
Bound state of heavy quark and anti-quark



- Coulomb potential (short distance part)

$$V(r) = -C_F \frac{\alpha_s}{r}$$

Let us put it in a QCD medium...Debye mass $m_D(T) \sim gT$



- Yukawa screened potential

$$V_T(r) = -C_F \alpha_s \frac{e^{-r m_D}}{r}$$

- Fourier transform of:

$$\frac{i}{\vec{q}^2} \to \frac{i}{\vec{q}^2 + m_D^2}$$

Energy scales for heavy quarkonium

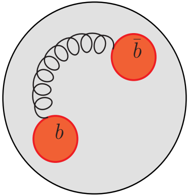
Many energy scales...

1) Non-relativistic scales (bound state):

$$M \gg Mv \gg Mv^2$$

2) Thermodynamic scales:

$$\pi T \gg m_D$$



- The hierarchy may hold for $\Upsilon(1S)$

$$5\text{GeV} > 1.5\text{GeV} > 0.5\text{GeV}$$

- The relation $\pi T > m_D$ is true in the weak coupling regime: when g is assumed to be small, $m_D \sim gT$

EFT for QCD

How to disentangle the different scales from

$$\mathcal{L}_{QCD} = -\frac{1}{4} G^{\mu\nu,a} G^{a}_{\mu\nu} + \bar{Q}\left(i\not{D} - M\right) Q + \mathcal{L}_{Light}$$

- A useful way: Effective Field Theory
  1. Select the right degrees of freedom
  2. Build the effective Lagrangian
  3. Perform calculations with a simplified version of $\mathcal{L}_{QCD}$

- We are interested in the spectrum of $Q\bar{Q} \Rightarrow$ binding energy (Mv^2)

- The EFT is pNRQCD: $E \sim Mv^2$, *N. Brambilla, A. Pineda, J. Soto and A. Vairo (1999)*
- The Lagrangian acquires a Schrodinger equation-like form

$V(r)$ obtained form QCD

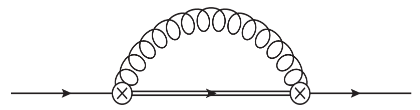
pNRQCD in vacuum

pNRQCD Lagrangian

- Assuming the hierarchy $M \gg \frac{1}{r} \gg Mv^2$

$$\mathcal{L}_{\rm pNRQCD} = \int d^3\mathbf{r}\, Tr\left\{S^\dagger\left(i\partial_0 - h_s\right)S + O^\dagger\left(iD_0 - h_s\right)O\right\}$$
$$+ gTr\left\{O^\dagger \vec{r}\cdot\vec{E}S + S^\dagger\vec{r}\cdot\vec{E}O\right\} - \frac{1}{4}G^{\mu\nu,a}G^a_{\mu\nu} + \cdots$$

- where we have defined
  1. Singlet field S, Octet field O
  2. $h_{s,o} = \frac{\mathbf{p}^2}{m} + V^{(0)}_{s,o} + \frac{V^{(1)}_{s,o}}{M} + \ldots$
  3. $V^{(0)}_s = -C_F\frac{\alpha_s}{r}$

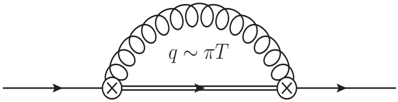


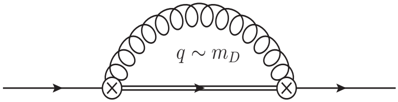
All the scales bigger than Mv^2 contribute to the potential $V^{(0)}$

And if the temperature enters...

- We take the scales πT and m_D bigger than the binding energy

$$1/r \gg \pi T \gg m_D \gg Mv^2,$$ *N. Brambilla, J. Ghiglieri, P. Petreczky and A. Vairo (2008)*





We do a matching from

- $pNRQCD \to pNRQCD_{HTL}$, where

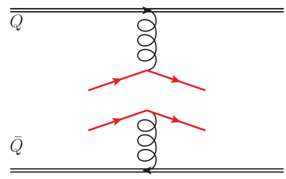
$$V(r,T,m_D) = -C_F\frac{\alpha_s}{r} + V_R(r,T,m_D) + iV_I(r,T,m_D)$$

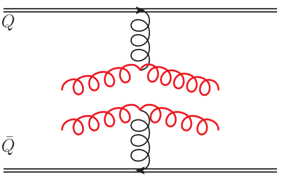
- V_R: mass of $Q\bar{Q}$ state, V_I: related to the width

$$\frac{i}{k^0 - E + i\frac{\Gamma}{2}} \Rightarrow \begin{cases} E = \langle \mathrm{Re}(V)\rangle \\ \Gamma = -2\langle \mathrm{Im}(V)\rangle \end{cases}$$

What is a thermal width?

- The interactions with the medium can break the $Q\bar{Q}$ bound state





What does V_R mean? The $Q\bar{Q}$ mass changes

- The invariant $\mu^-\mu^+$ reconstructed mass may be

$$m_{\mu\mu} > m_{\mu\mu}^{(0)} \text{ or } m_{\mu\mu} < m_{\mu\mu}^{(0)}$$

What does V_I mean? The $Q\bar{Q}$ obtains a thermal width

- For $\tau \sim 10$ fm and $\Gamma \sim 10$ MeV

$$N(Q\bar{Q}) \sim N_0 e^{-\Gamma\tau} = N_0 e^{-0.5} \sim 0.6$$

Small anisotropy

QGP is a rather complicated system...

- Longitudinal (beam axis) expansion bigger than the radial expansion

1) Different temperatures
2) Different partons momenta

Local momentum anisotropy : ξ

- Spectrum and width of the $Q\bar{Q}$ depend on in medium parton distributions

$$V_R(r,T) \to V_R(r,T,\xi) \text{ and } V_I(r,T) \to V_I(r,T,\xi)$$

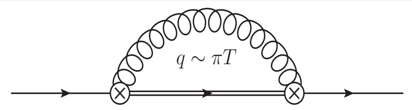
Modelling the anisotropy

$$f(\vec{q}) = f_{iso}\left(\sqrt{q^2 + \xi(\vec{q}\cdot\vec{n})^2}\right) = \left(e^{\frac{\sqrt{q^2+\xi(\vec{q}\cdot\vec{n})^2}}{T}} - 1\right)^{-1}$$

Small anisotropy in pNRQCD

- $q_\perp^2 + q_\parallel^2 + \xi(\vec{q}\cdot\vec{n})^2 \simeq q_\parallel^2(1+\xi)$, by assuming $q_\perp \ll q_\parallel$
- $\Rightarrow f(\vec{q}) = \frac{1}{e^{q_\parallel/T_{eff}}-1}$ where $T_{eff} = \frac{T}{\sqrt{1+\xi}} < T$

Calculation in pNRQCD: $1/r \gg \pi T \gg Mv^2 \gg m_D$



- 1-Loop in pNRQCD
- Matching with pNRQCD_T

$$V_R(r,T,\xi) = \left(\frac{2\pi\alpha_s C_F T^2}{3M} + \frac{\pi^2\alpha_s^2 C_F N_F T^2 r}{9}\right)\frac{\arctan\xi}{\xi}$$

- Recover the limit for $\xi \to 0$, *N. Brambilla, M. Escobedo, J. Ghiglieri, J. Soto and A. Vairo (2010)*

$$V_R(r,T,\xi) = \left(\frac{2\pi\alpha_s C_F T^2}{3M} + \frac{\pi^2\alpha_s^2 C_F N_F T^2 r}{9}\right)\left(1 - \frac{\xi}{3} + \frac{\xi^2}{5} + \cdots\right)$$

Summary

Conclusions

- Quark Gluon Plasma is a complicated system to study
- Hard probes may be useful tools

- Quarkonia suppression in medium
- Detailed study of $Q\bar{Q}$ potential at finite temperature
- Exploit EFTs to simplify the multi-scale problem

- Small anisotropy in the parton distribution

Outlook

- Address the $\mu^+\mu^-$ yield in Pb-Pb collisions

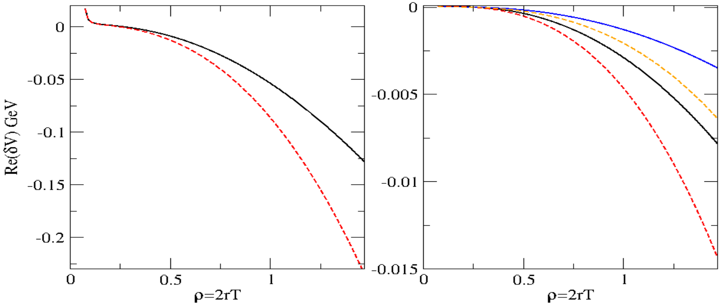
Phenomenology at LCH

What could be the scales at LCH?

- Let us focus on the $\Upsilon(1S)$ and $T_0 = 500$ MeV

$$M > \frac{1}{r} \geq \pi T > m_D > Mv^2$$

$$\pi T \simeq \pi(300, 400)\,\text{MeV} \quad \frac{1}{r} \simeq (1300, 1500)\,\text{MeV}$$



Hierarchies