EFT and Lattice approaches for hard probes in QCD matter

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Hard Probes 2018

Outline

Special features of **hard probes**

- The energy needed to create them is much larger than thermal scales $\rightarrow T = 0$ physics.
- However, once they are created they are affected by the presence of the medium. (Jets will quench, quarkonium will melt,...).
- They are relatively well understood in the vacuum.
- So comparing results in AA and pp collisions we can learn something about the medium.

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Hard probes as a multi-scale problem

Hard probes always involved at least two well separated energy scales:

- The hard scale that is involved in its creation process.
- The temperature of the medium and related scales.

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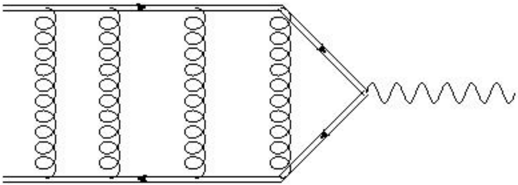
Hard probes as a multi-scale problem

Why does it matter?

Consider for example the annihilation of a heavy pair of particles in an s-wave vector state into a virtual photon (to later produce leptons).



- Every rung in the ladder gives a contribution of order $\frac{\alpha_s}{v}$.
- Break down of naive perturbative expansion if v is small.
- This is a well-known effect (Sommerfeld factor).

Effective Field Theories (EFTs)

How to know which diagrams need to be resummed? One can use Effective Field Theories (EFTs)[1] .

- A theory which gives the same results as QCD but is limited to low energy degrees of freedom.
- In a problem where very separated energy scales are important it is usual to find unexpected suppressions and enhancements. EFTs are a very useful tool to deal with this problem.
- The Lagrangian of the EFT can be deduced knowing the symmetries of the full theory and the degrees of freedom active at low energies.

[1]Weinberg (1979)

Example. Non-relativistic EFTs to study bound states at $T = 0$

- QCD
  Quarks and gluons.
- NRQCD
  Caswell and Lepage (1986), Bodwin, Braaten and Lepage (1994). Integrate out the mass m_Q. Non-relativistic quarks and gluons.

$$\mathscr{L}_{NRQCD} = \sum_n \frac{1}{m_Q^n} \mathscr{L}_n$$

- pNRQCD
  Pineda and Soto (1998), Brambilla, Pineda, Soto and Vairo (2000). Integrate out also the inverse of the radius $\frac{1}{r}$. Color singlet field, color octet field and gluons.

$$\mathscr{L}_{pNRQCD} = \sum_{n,m} \frac{1}{m_Q^n} r^m \mathscr{L}_{n,m}$$

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EFTs for Hard Probes

Jet quenching

Soft-Collinear Effective Theory (SCET). See Ringer's talk and many parallel talks.

Quarkonium suppression

Non-relativistic EFTs. NRQCD, pNRQCD...

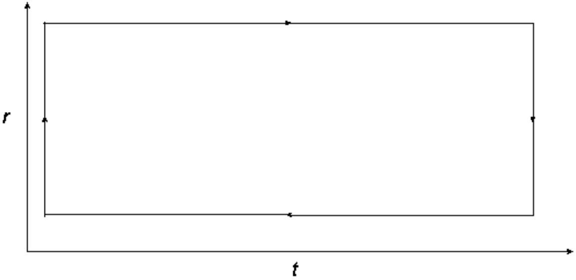
Open heavy flavor

At $T = 0$ have been described with Heavy Quark Effective Theory (HQET). A way to justify the use of non-relativistic Lagrangian.

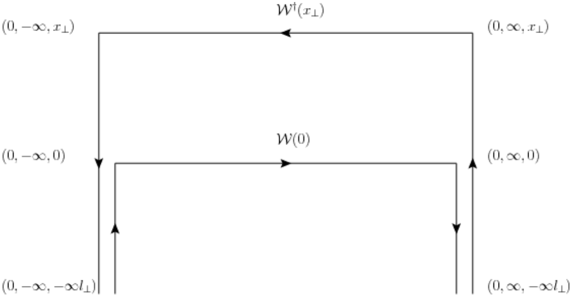
Lattice QCD and hard probes

- Hard probes are sensitive to the medium, the medium might be non-perturbative.
- In many cases the influence of the medium can be encoded in well-defined operators that can be computed on the lattice.

The heavy quark potential can be extracted from the Wilson loop



A Wilson loop in the light-cone direction is related to $\hat{q}$



Outline

Questions that can be answered with an EFT framework

- In which cases can a potential model describe thermal modifications?
- What is the definition of the potential when the potential model picture is applicable?
- What is the relation of this potential to the free energy or the internal energy?[2]

[2] I am not going to discuss this. A detailed study can be found in Berwein, Brambilla, Petreczky and Vairo (2017) and references there.

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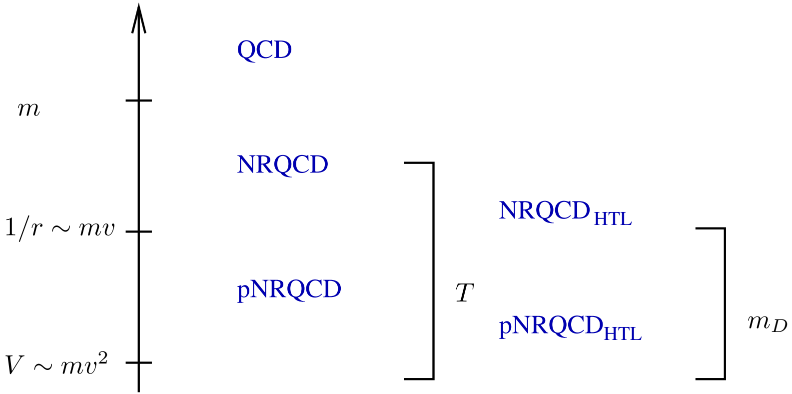
Effective Field Theories



Brambilla, Ghiglieri, Vairo and Petreczky (PRD78 (2008) 014017)
M. A. E and Soto (PRA78 (2008) 032520)

pNRQCD[3] Lagrangian at T=0

$$\mathscr{L}_{pNRQCD} = \int d^3\mathbf{r}\, Tr\left[S^\dagger\left(i\partial_0 - h_s\right)S\right.$$
$$\left.+O^\dagger\left(iD_0 - h_o\right)O\right] + V_A(r)\,Tr(O^\dagger \mathbf{r} g \mathbf{E} S + S^\dagger \mathbf{r} g \mathbf{E} O)$$
$$+\frac{V_B(r)}{2}\,Tr(O^\dagger \mathbf{r} g \mathbf{E} O + O^\dagger O \mathbf{r} g \mathbf{E}) + \mathscr{L}_{gluons} + \mathscr{L}_{q-light}$$

- Degrees of freedom are singlets (S), octets (O), gluons and light-quarks. $h_{s,o}$ is the singlet/octet non-relativistic Hamiltonian.
- Allows to obtain manifestly gauge-invariant results. Simplifies the connection with Lattice QCD.
- If $1/r \gg T$ we can use this Lagrangian as starting point. In other cases the matching between NRQCD and pNRQCD will be modified.
- In the next slides we are going to discuss different expectation values in pNRQCD that give information about quarkonium in the medium

[3] Brambilla, Pineda, Soto and Vairo (2000)

Information contained in singlet time-ordered correlator

$$\langle \mathscr{T} S(t,\mathbf{r},\mathbf{R}) S^\dagger(0,\mathbf{0},\mathbf{0})\rangle$$

- Tells us about the in-medium dispersion relation. We can obtain binding energy and decay width modifications.
- At $T=0$ it fulfills a Schrödinger equation. At finite temperature this will also be the case in some situations.
- It does not contain information about the number of bound states in the medium.
- If $T \gg E$ it can be described by a Schrödinger equation with a complex potential.
- Survival amplitude of the singlet without altering the medium.
- It has been computed in perturbation theory in a wide range of temperature regimes (from $1/r \gg T \gg E \gg m_D$ to $1/r \gg T \sim m_D$).

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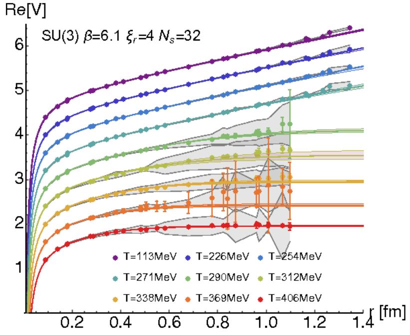
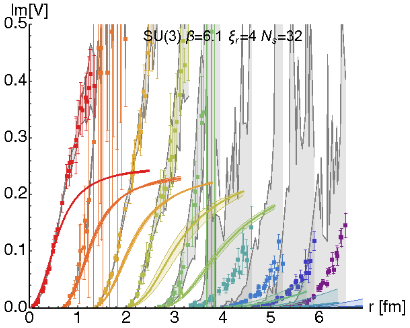
The potential and lattice QCD

- In pNRQCD the potential is defined as a Wilson coefficient appearing in the Lagrangian.
- It can be deduced by computing a time-ordered Wilson loop in NRQCD. It can be computed non-perturbatively in lattice QCD.[4]





[4] Plots taken from Burnier and Rothkopf (2016).

Towards a computation of R_{AA} in EFT

- Until now we have discussed the decay width and corrections to the binding energy. Both can be found in the EFT by studying the pole of the singlet time-ordered propagator.
- To compute R_{AA} we need to know how the state of the heavy quarks in the medium changes with time.

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Evolution of the number of singlets in the case $1/r \gg T$

Brambilla, M.A.E., Soto and Vairo (2017-2018)

$$f_s(x,y) = Tr(\rho S^\dagger(x) S(y))$$

f_s is the density matrix ρ projected to the subspace in which there is one singlet (so the probability to find a 1S state is $\langle 1S|f_s|1S\rangle$).
We can use perturbation theory but expanding in r instead of α_s. In the interaction picture

$$i\partial_t S = [S, H_0]$$
$$i\partial_t \rho = [H_I, \rho]$$

Evolution of the number of singlets in the case $1/r \gg T$

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$$\partial_t f_s = -i(H_{s,eff} f_s - f_s H^\dagger_{s,eff}) + \mathscr{F}(f_o)$$

- $H_{s,eff} = h_s + \Sigma_s$ where Σ_s corresponds to the self-energy that can be obtained in pNRQCD by computing the time-ordered correlator.
- $\mathscr{F}(f_o)$ is a new term that takes into account the process $O \to g + S$. It ensures that the total number of heavy quarks is conserved.

Very similar reasoning.

$$f_o^{ab}(x,y) = Tr(\rho O^{\dagger,a}(x) O^b(y))$$

$$\partial_t f_o = -i(H_{o,eff} f_o - f_o H^\dagger_{o,eff}) + \mathscr{F}_1(f_s) + \mathscr{F}_2(f_o)$$

The $\frac{1}{r} \gg T, m_D \gg E$ regime

Brambilla, M.A.E., Soto and Vairo (2017-2018)

Because all the thermal scales are smaller than $\frac{1}{r}$ but bigger than E the evolution equation is of the Lindblad form.

$$\partial_t \rho = -i[H(\gamma), \rho] + \sum_k (C_k(\kappa)\rho C_k^\dagger(\kappa) - \frac{1}{2}\{C_k^\dagger(\kappa)C_k(\kappa), \rho\})$$

$$\kappa = \frac{g^2}{6\,N_c} \mathrm{Re} \int_{-\infty}^{+\infty} ds \, \langle \mathrm{T}\, E^{a,i}(s, \mathbf{0}) E^{a,i}(0, \mathbf{0}) \rangle$$

$$\gamma = \frac{g^2}{6\,N_c} \mathrm{Im} \int_{-\infty}^{+\infty} ds \, \langle \mathrm{T}\, E^{a,i}(s, \mathbf{0}) E^{a,i}(0, \mathbf{0}) \rangle$$

No lattice QCD information on γ but we observe that we reproduce data better if it is small. For comparison, in pQCD

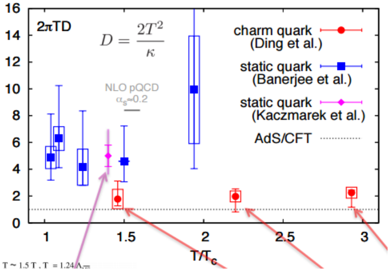
$$\gamma = -2\zeta(3)\, C_F \left(\frac{4}{3} N_c + n_f\right) \alpha_s^2(\mu_T)\, T^3 \approx -6.3\, T^3$$

The parameter κ

$$\kappa = \frac{g^2}{6N_c}\mathrm{Re}\int_{-\infty}^{+\infty} ds\,\langle \mathrm{T}\,E^{a,i}(s,\mathbf{0})E^{a,i}(0,\mathbf{0})\rangle$$

quantity also appearing in heavy particle diffusion, recent lattice QCD evaluation in Francis, Kaczmarek, Laine, Neuhaus and Ohno (2015)

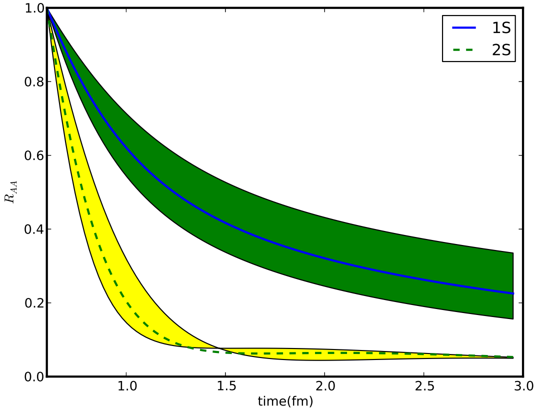
$$1.8 \lesssim \frac{\kappa}{T^3} \lesssim 3.4$$



Picture taken from O. Kaczmarek talk in "30 years in J/Ψ suppression".

Results. $30-50\%$ centrality. $\sqrt{s_{NN}} = 2.76\ TeV$

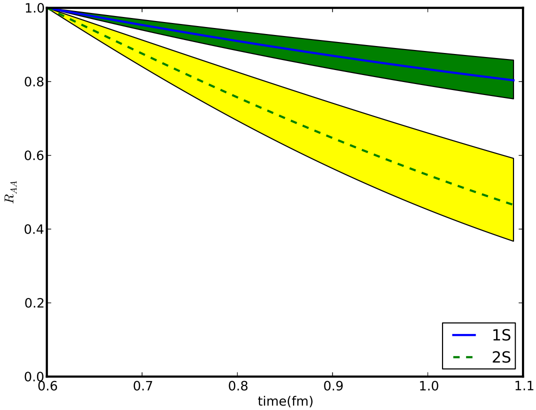
Brambilla, M.A.E., Soto and Vairo. PRD97 (2018) no. 7, 074009



Error bans only take into account uncertainty in the determination of κ. γ is set to zero.

Results. $50-100\%$ centrality. $\sqrt{s_{NN}} = 2.76\ TeV$

Brambilla, M.A.E., Soto and Vairo. PRD97 (2018) no. 7, 074009



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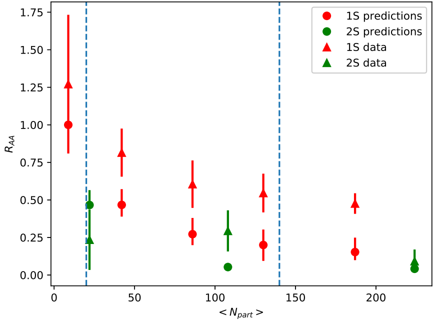
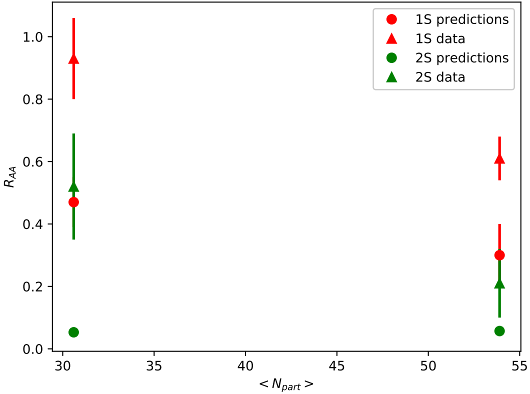


Comparison between the CMS data[5] and our computation.

[5] Phys.Lett. B770 (2017) 357-379

Results. $\sqrt{s_{NN}} = 5.02\ TeV$



[6]

[6] Data taken from CMS paper (arXiv:1805.09215)

Outline

What is Soft-collinear Effective Theory[7]?

- It is a theory that gives the same results as QCD in which particles with virtuality larger than Q^2 have been integrated out.
- It allows us to reorganize the computation as an expansion in $\frac{\lambda}{Q}$ where λ is a lower energy scale.
- It is commonly used to study jet phenomena in the vacuum.
- Calculations can be done in a gauge invariant way. Convenient to combine with lattice computations.

[7] Bauer, Fleming and Luke (2000), Bauer, Fleming, Pirjol and Stewart (2001), Bauer and Stewart (2001), Bauer, Pirjol and Stewart (2002), Bauer, Fleming, Pirjol, Rothstein and Stewart (2002), Beneke, Chapovsky, Diehl and Feldmann (2002).

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The degrees of freedom

- Collinear particles. Particles with high energy but a very small virtuality (λ^2). At the end of the day they are detected as jets.
- Hard-collinear particles. Particles with high energy but a not so small virtuality (λQ). Virtual particles.
- Particles that populate the medium.
  - Soft particles. When they hit a collinear particle it will become a hard-collinear particle.
  - Glauber particles[8]. When they hit a collinear particle it keeps being collinear. Momentum perpendicular to the one of the jet.

[8] Studied in SCET in Idilbi and Majumder (2009)

Jet broadening and jet quenching in SCET

- Jet broadening is the transverse momentum acquired by a jet while traversing the plasma. Its strength can be encoded in a parameter called $\hat{q}$.
- Jet quenching is the process in which a jet loses energy while traversing a plasma. In many models all the information needed from the medium is contained in $\hat{q}$.
- Jet broadening can be studied with a combination of SCET and lattice QCD.
- Jet quenching can also be studied directly using SCET but I am not going to discuss it here.[9]

[9] See talk of Ringer today and the parallel talks of Li, Chien, Yin and Kumar.

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The broadening probability

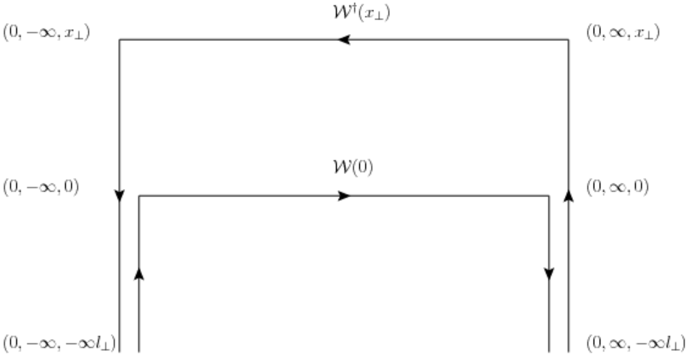
$P(k_\perp)$ is the probability that an initial parton with momentum $(0, Q, 0)$ transforms into a parton with momentum $(\frac{k_\perp^2}{2Q}, Q, k_\perp)$ after going through medium.[10]

$\hat{q}$ can be defined as

$$\hat{q} = \frac{1}{L}\int \frac{d^2k_\perp}{(2\pi)^2} k_\perp^2 P(k_\perp)$$

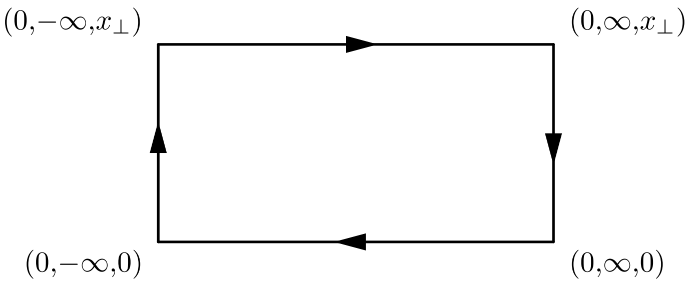
[10] Momenta are written in light-cone coordinates $(p^+, p^-, p_\perp)$.

Gauge-invariant $P(x_\perp)$



- Covariant gauge version was known before the application of SCET: Baier et al. (1997), Zakharov (1996), Casalderrey-Solana and Salgado(2007).
- Rederived using SCET in covariant gauge (D'Eramo, Liu and Rajagopal (2011)) and later in a gauge-invariant generalization (Brambilla, Benzke, M.A.E. and Vairo (2013)).

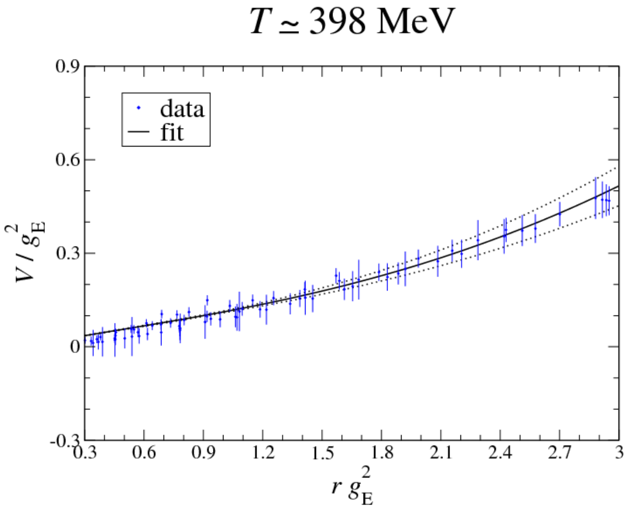
$P(x_\perp)$ in Electrostatic QCD and in Lattice QCD



- Electrostatic QCD (EQCD) is an EFT obtained from QCD in Euclidean space after integrating out the energy scale πT.
- In Caron-Huôt (2009) it was shown that the contribution from the scales below πT to $P(k_\perp)$ can be computed in Euclidean space without need of analytic continuation.
- It is possible to use EQCD on the lattice to learn about jet broadening.

$P(x_\perp)$ in Electrostatic QCD and in Lattice QCD

Results from Panero, Rummukainen and Schäfer (2013)



$$V = -\lim_{L\to\infty} \frac{1}{L} \log P(x_\perp, L)$$

$$g_E^2 = g^2 T$$

A similar study has been made in Classical Lattice QCD (Laine and Rothkopf (2013)). A computation with a slightly different definition of $\hat{q}$ can be found in Majumder (2012).

Outline

Conclusions

- It is useful to separate the hard from the soft scales using EFTs in order to understand hard probes.
- EFTs allow to make computations in a manifestly gauge invariant setting. This is convenient to suggest quantities that can be computed non-perturbatively in Lattice QCD.
- Is a specific temperature regime $1/r \gg T, m_D \gg E$ one can describe quarkonium evolution in a medium using only two non-perturbative parameters.
- Theoretical studies have allowed to set a framework in which soft effects on jet broadening can be computed on the lattice.

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