Quarkonium suppression in HIC

– an EFT and OQS approach –

Antonio Vairo

Technische Universität München

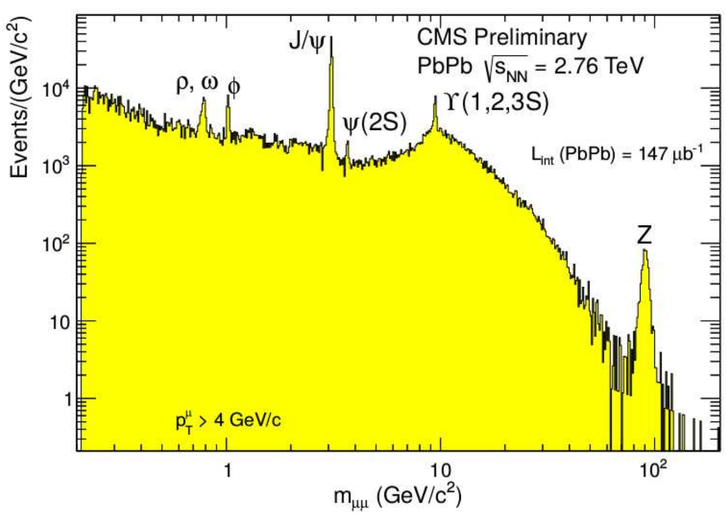
Quarkonium suppression

Quarkonium as a quark-gluon plasma probe

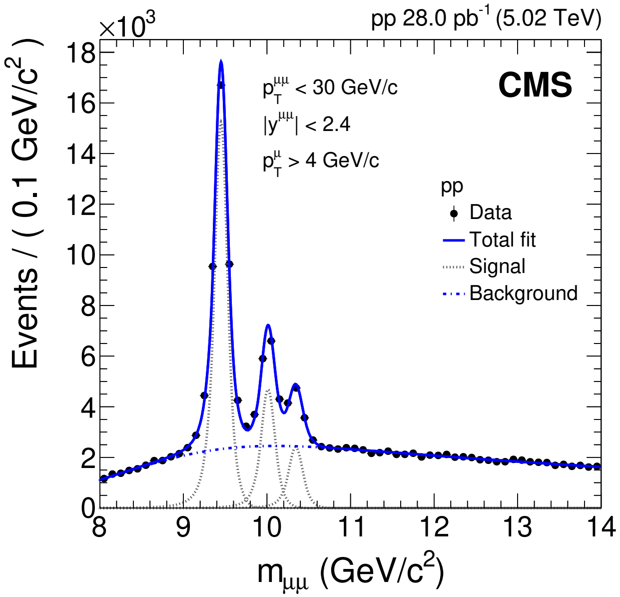
In 1986, Matsui and Satz suggested quarkonium as an ideal quark-gluon plasma probe.
○ `Matsui Satz PLB 178 (1986) 416`

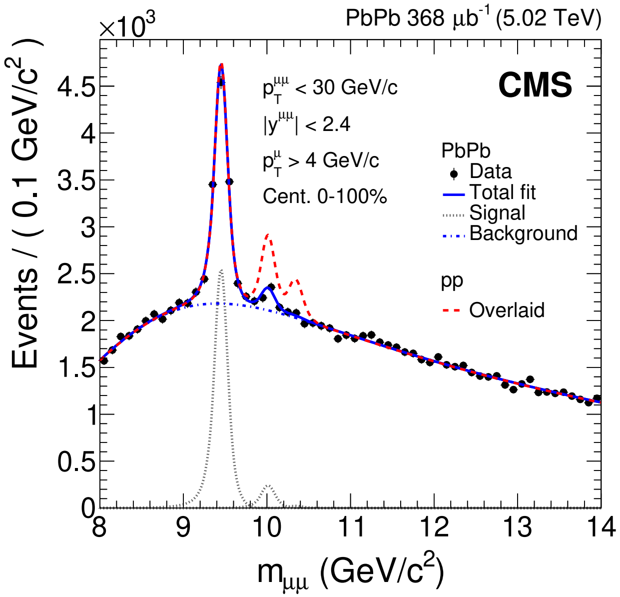
Experimentally

- Heavy quarks are formed early in heavy-ion collisions: $1/M \sim 0.1$ fm < 0.6 fm.
- Heavy quarkonium formation is sensitive to the medium.
- The dilepton signal (happening after the quark-gluon plasma has faded away) makes the quarkonium a clean experimental probe.



Υ suppression @ CMS

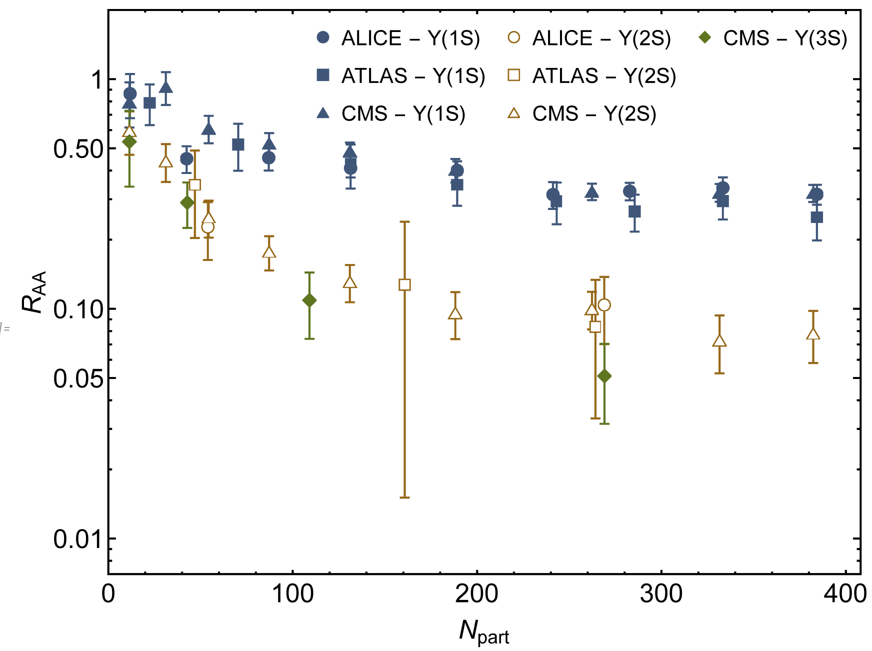




- CMS PRL 120 (2018) 142301

Υ suppression @ LHC

Out[ ]=



R_{AA} is the nuclear modification factor = yield of quarkonium in PbPb / yield in pp.

- CMS PLB 790 (2019) 270
  ALICE PLB 822 (2021) 136579
  ATLAS PRC 107 (2023) 054912

Quarkonium as a quark-gluon plasma probe

In 1986, Matsui and Satz suggested quarkonium as an ideal quark-gluon plasma probe.

Theoretically

- The heavy-quark mass introduces one or more large scales, whose contributions may be factorized and computed in perturbation theory ($\alpha_{\mathrm{s}}(M) \ll 1$).
- Low-energy scales are sensitive to the temperature.
  Low-energy contributions may be accessible via lattice calculations.
- If the heavy quark is heavy enough (bottomonium) regeneration from the medium is negligible and only suppression due to screening and thermal width is relevant.

Effective field theories

Energy scales

Quarkonium in a medium is characterized by several energy scales:

- the scales of a non-relativistic bound state
  (v is the relative heavy-quark velocity; $v \sim \alpha_{\rm s}$ for a Coulombic bound state):
  M (mass),
  Mv (momentum transfer, inverse distance),
  Mv^2 (kinetic energy, binding energy, potential V), ...

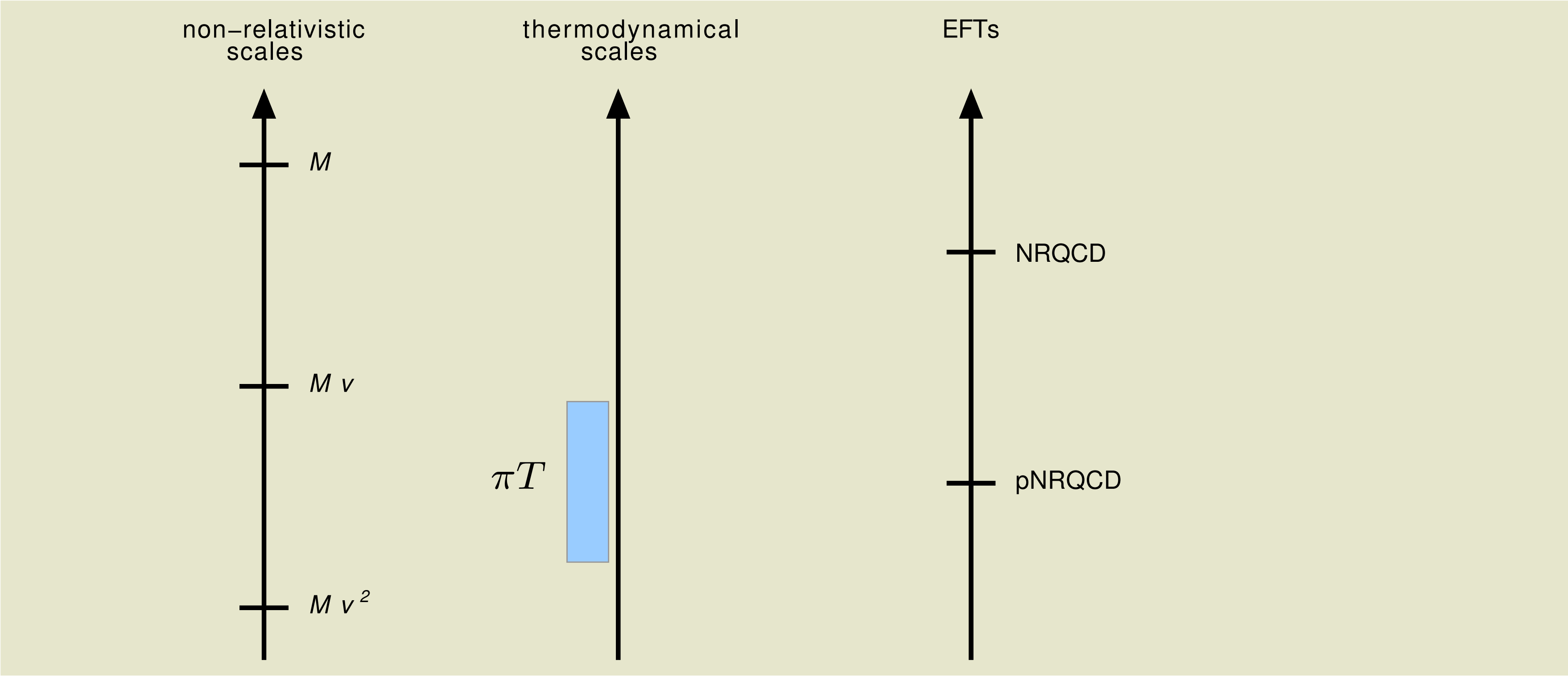
- the thermodynamical scales:
  T (temperature), ...

  T stands for a generic inverse correlation length characterizing the medium.
  For definiteness we will assume that the system is locally in thermal equilibrium so that a slowly varying time-dependent temperature can be defined.

The non-relativistic scales are hierarchically ordered: $M \gg Mv \gg Mv^2$

Non-relativistic EFTs of QCD

The existence of a hierarchy of energy scales calls for a description of the system in terms of a hierarchy of EFTs. We assume T (~ 400 MeV) $< Mv$ (~ 1.5 GeV, for Υ).



- Brambilla Pineda Soto Vairo RMP 77 (2005) 1423
  Brambilla Ghiglieri Petreczky Vairo PRD 78 (2008) 014017

Weakly coupled pNRQCD

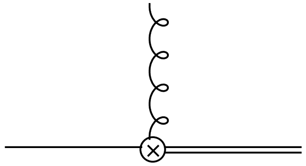
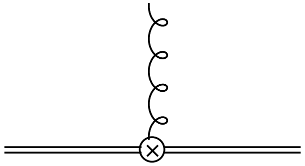
Fields:

- $S^\dagger$ creates a quark-antiquark pair in a color singlet configuration;
- $O^\dagger$ creates a (unbound) quark-antiquark pair in a color octet configuration;
- gluons and light quarks.

Propagators:

- singlet ——— and octet ═══ governed (in a Coulombic system) by the Hamiltonians $h_s = \frac{\mathbf{p}^2}{M} - \frac{4}{3}\frac{\alpha_s}{r} + \ldots$ and $h_o = \frac{\mathbf{p}^2}{M} + \frac{\alpha_s}{6r} + \ldots$, respectively.

Electric-dipole interactions:

-  $= O^\dagger \mathbf{r} \cdot g\mathbf{E}\, S$  $= O^\dagger \{\mathbf{r} \cdot g\mathbf{E},\, O\}$

Equation of motion:

$$i\partial_t S = h_s S + \mathbf{r} \cdot g\mathbf{E}^a \frac{O^a}{\sqrt{6}} + \ldots$$

Open quantum systems

Density matrix

An arbitrary statistical ensemble of quantum states can be represented by a density matrix ρ, which is

- Hermitian: $\rho^\dagger = \rho$;
- positive: $\langle\psi|\rho|\psi\rangle \geq 0$ for all states $|\psi\rangle$;
- and can be normalized to have unit trace: $\mathrm{Tr}\{\rho\} = 1$.

The time evolution of the density matrix is described by the von Neumann equation:

$$i\frac{d\rho}{dt} = [H, \rho]$$

which follows from the Schrödinger equation for $|\psi\rangle$. The evolution equation

- is linear in ρ;
- preserves the trace of ρ;
- is Markovian.

Open quantum system

In quantum information theory, one separates the full system into a subsystem of interest and its environment. A density matrix ρ for the subsystem can be obtained from the density matrix ρ_{full} for the full system by the partial trace over the environment states:

$$\rho = \mathrm{Tr}_{\mathrm{environment}} \left\{ \rho_{\mathrm{full}} \right\}$$

In general the evolution of ρ is non-Markovian.

The evolution is Markovian if the time during which the subsystem is observed is much larger than the time scale for correlations between the subsystem and the environment. We must also restrict to the low-frequency behavior of the subsystem, which can be accomplished by smoothing out over times larger than the correlation time scale.

Lindblad equation

The density matrix ρ for the subsystem necessarily satisfies three basic properties: it is Hermitian, positive, and it can be normalized.

If further the time evolution is linear in ρ, preserves the trace of ρ, is Markovian and the linear operator that determines the time evolution of ρ is completely positive
$\Rightarrow$ then this requires the time evolution equation to have the Lindblad form

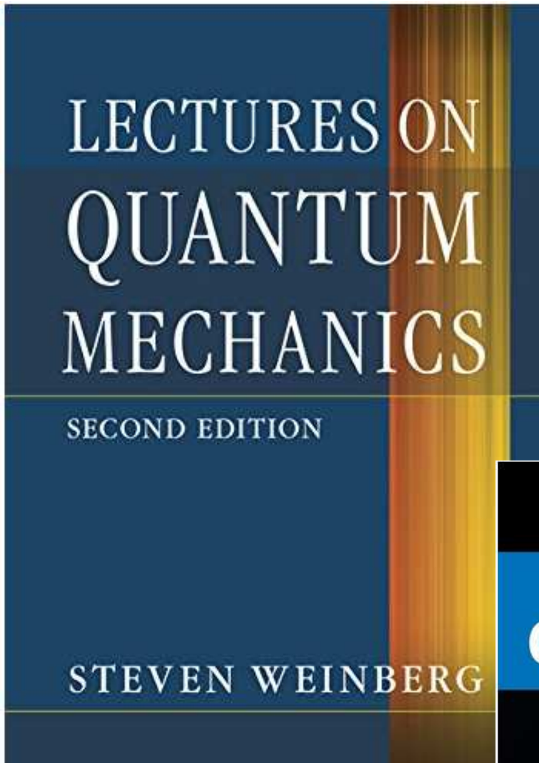
$$\frac{d\rho}{dt} = -i[H, \rho] + \sum_i (C_i \rho C_i^\dagger - \frac{1}{2}\{C_i^\dagger C_i, \rho\})$$

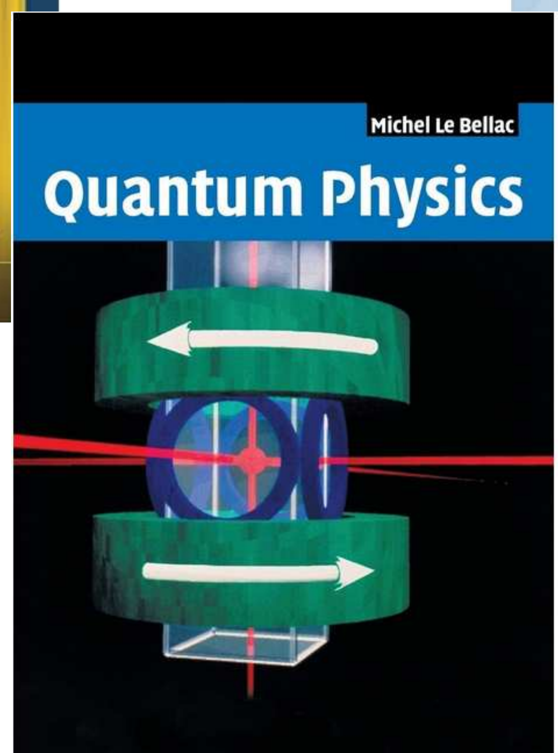
where H is a Hermitian operator and the C_n's are an additional set of operators called collapse operators.

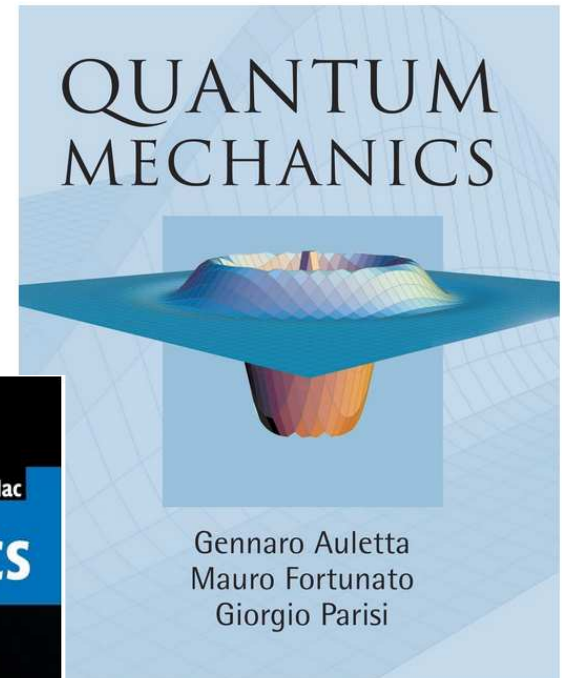
- Lindblad CMP 48 (1976) 119

  Gorini Kossakowski Sudarshan JMP 17 (1976) 821

Lindblad equation in textbooks







Quarkonium as an open quantum system

- System: heavy quarks/quarkonium
- Environment: quark gluon plasma

We may define a (reduced) density matrix for the heavy quark-antiquark pair in a color singlet and octet configuration:

$$
\begin{aligned}
\langle \mathbf{r}', \mathbf{R}' | \rho_s(t'; t) | \mathbf{r}, \mathbf{R} \rangle &\equiv \mathrm{Tr}\{\rho_{\mathrm{full}}(\tau_{\mathrm{med}})\, S^\dagger(t, \mathbf{r}, \mathbf{R}) S(t', \mathbf{r}', \mathbf{R}')\} \\
\langle \mathbf{r}', \mathbf{R}' | \rho_o(t'; t) | \mathbf{r}, \mathbf{R} \rangle \frac{\delta^{ab}}{8} &\equiv \mathrm{Tr}\{\rho_{\mathrm{full}}(\tau_{\mathrm{med}})\, O^{a\dagger}(t, \mathbf{r}, \mathbf{R}) O^b(t', \mathbf{r}', \mathbf{R}')\}
\end{aligned}
$$

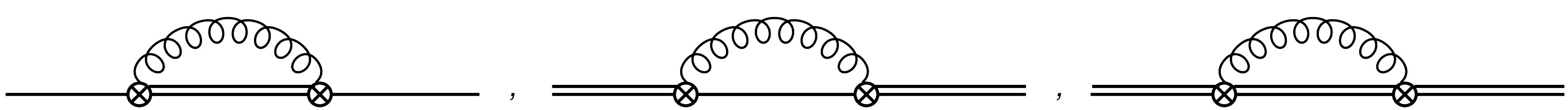
τ_{med} fm is the time formation of the plasma.

The system is in non-equilibrium because through interaction with the environment (quark gluon plasma) singlet and octet quark-antiquark states continuously transform in each other although the number of heavy quarks is conserved: $\mathrm{Tr}\{\rho_s\} + \mathrm{Tr}\{\rho_o\} = 1$.

Expansions

- The density of heavy quarks is much smaller than the one of the light d.o.f.: we expand at first order in the heavy quark-antiquark density.
- We consider T much smaller than the inverse Bohr radius of the quarkonium: we expand up to order r^2 in the multipole expansion $\Rightarrow$ weakly coupled pNRQCD.
- We follow the evolution for large times.

Relevant diagram topologies are



For each topology one quark-antiquark propagator represents a density matrix insertion.

Evolution equations

A way of writing the evolution equations is

$$\frac{d\rho}{dt} = -i[H, \rho] + \sum_{nm} h_{nm} \left(L_i^n \rho L_i^{m\,\dagger} - \frac{1}{2}\{L_i^{m\,\dagger} L_i^n, \rho\} \right)$$

$$\rho = \begin{pmatrix} \rho_s & 0 \\ 0 & \rho_o \end{pmatrix} \qquad H = \begin{pmatrix} h_s + \frac{\Sigma_s - \Sigma_s^\dagger}{2i} & 0 \\ 0 & h_o + \frac{\Sigma_o - \Sigma_o^\dagger}{2i} \end{pmatrix}$$

$$\Sigma_s(t) = r^i \, A_i^{so\,\dagger}(t) \qquad \Sigma_o(t) = \frac{r^i \, A_i^{os\,\dagger}(t)}{8} + \frac{5}{16} r^i \, A_i^{oo\,\dagger}(t)$$

$$L_i^0 = \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix} r^i \qquad L_i^1 = \begin{pmatrix} 0 & 0 \\ 0 & \frac{5}{16} A_i^{oo\,\dagger} \end{pmatrix}$$

$$L_i^2 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} r^i \qquad L_i^3 = \begin{pmatrix} 0 & \frac{1}{8} A_i^{os\,\dagger} \\ A_i^{so\,\dagger} & 0 \end{pmatrix}$$

with $A_i^{so}(t) = \frac{g^2}{6} \int_{\tau_{\rm med}}^t dt_2 \, e^{ih_s(t_2 - t)} \, r^j \, e^{ih_o(t - t_2)} \, \langle E^{a,j}(t_2, \mathbf{0}) E^{a,i}(t, \mathbf{0}) \rangle$

Positivity

The matrix h_{nm} is

$$h = \begin{pmatrix} 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

If h were a positive definite matrix then it would always be possible to redefine the operators L_i^n in such a way that the evolution equation would be of the Lindblad form.

Since, however, h is not a positive definite matrix, the Lindblad theorem does not guarantee that the equations may be brought into a Lindblad form.

A special case is the strongly-coupled case at (N)LO in E/T.
There $L_i^1 \propto L_i^0$ and $L_i^3 \propto L_i^2$, which allows to rotate L_i^n in such a way that they are orthogonal to the eigenspace of h with negative eigenvalues, eventually leading to an evolution equation of the Lindblad form.

- Brambilla Escobedo Soto Vairo PRD 96 (2017) 034021, D97 (2018) 074009
  Talk of Tom Magorsch next Tuesday

Time scales

Environment correlation time: $\tau_E \sim \dfrac{1}{T}$

System intrinsic time scale: $\tau_S \sim \dfrac{1}{E}$

System relaxation time: $\tau_R \sim \dfrac{1}{\text{self-energy}} \sim \dfrac{1}{\alpha_s a_0^2 \Lambda^3}$ $\quad a_0 =$ Bohr radius, $\Lambda = T, E$

- Because we have assumed $1/a_0 \gg \Lambda$, it follows $\tau_R \gg \tau_S, \tau_E$ which, for large times $t - \tau_{\mathrm{med}} \gg \tau_R$, qualifies the system as Markovian.

- If $T \gg E$ then $\tau_S \gg \tau_E$ which qualifies the motion of the system as quantum Brownian.

○ Akamatsu PRD 91 (2015) 056002

From the evolution equations to the Lindblad equation

Under the Markovian

$$\tau_R \gg \tau_S, \tau_E \quad \text{or} \quad \frac{1}{a_0} \gg E, T$$

and quantum Brownian motion condition

$$\tau_S \gg \tau_E \quad \text{or} \quad T \gg E$$

at (N)LO in E/T, the evolution equations can be written in the Lindblad form.

Expanding in E/T reduces the thermal contributions to the evolution equations to few moments/diffusion coefficients of chromoelectric correlators.

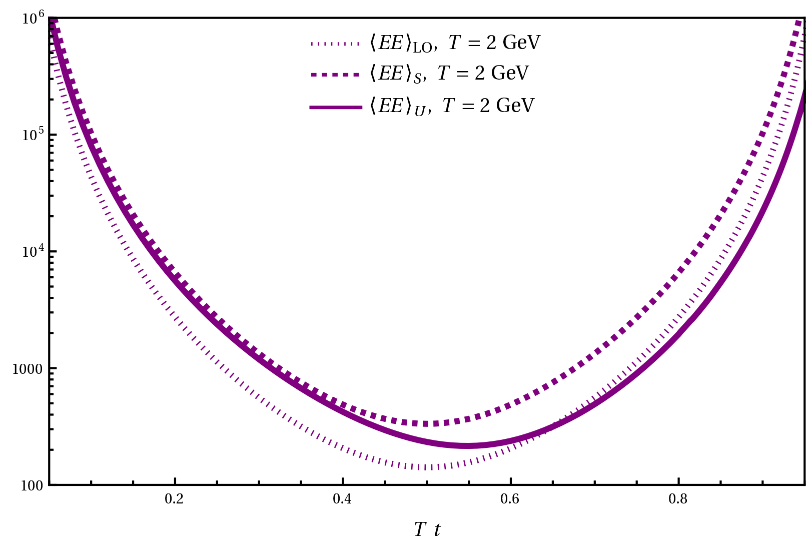
Chromoelectric correlators

$$\langle EE\rangle_U \equiv -\left\langle g_s E_i^a(0) U^{ab}(0,t) g_s E_i^b(t)\right\rangle T^{-4}$$

$$\langle EE\rangle_L \equiv -\left\langle g_s E_i^b(0) g_s E_i^a(t) U^{ab}(t,1/T)\right\rangle T^{-4} = \langle EE\rangle_U(1/T - t)$$

$$\langle EE\rangle_S \equiv -\left\langle g_s E_i^{ab}(0) U^{bc}(0,t) g_s E_i^{cd}(t) U^{da}(t,1/T)\right\rangle T^{-4}$$

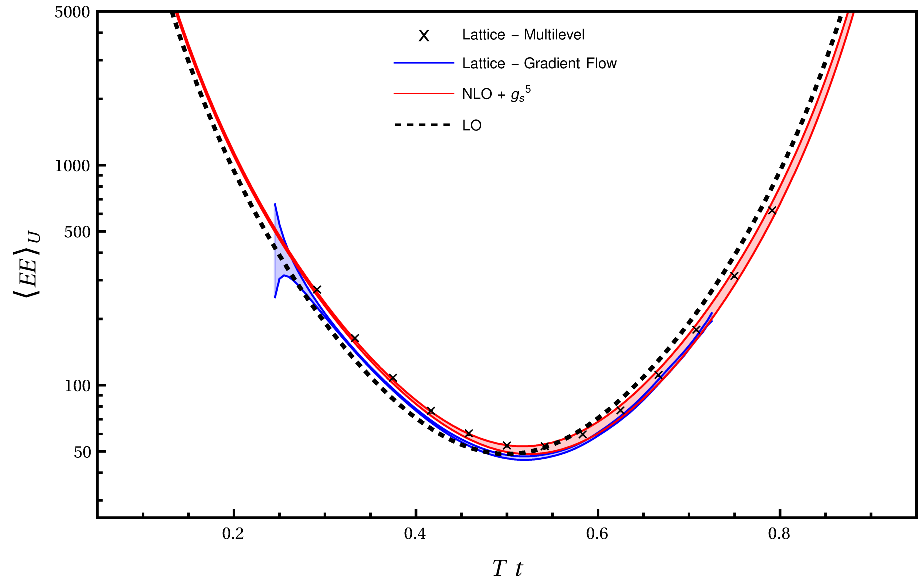
@ LO and NLO:



- Brambilla Panayiotou Sappi Vairo JHEP 08 (2025) 219

Chromoelectric correlators on the lattice

@ $T = 10^4 T_c \approx 3 \times 10^3 \text{GeV}$



○ Brambilla TUMQCD col PRD 112 (2025) 074509

As a first approximation we set the imaginary and real parts of the quarkonium diffusion coefficients following from the analytical continuation of these correlators in Minkowski spacetime equal to κ and γ.

Lindblad equation for a strongly coupled plasma

@ LO in E/T the Lindblad equation for a strongly coupled plasma reads

$$\frac{d\rho}{dt} = -i[H,\rho] + \sum_i (C_i \rho C_i^\dagger - \frac{1}{2}\{C_i^\dagger C_i, \rho\})$$

$$\rho = \begin{pmatrix} \rho_s & 0 \\ 0 & \rho_o \end{pmatrix}$$

$$H = \begin{pmatrix} h_s & 0 \\ 0 & h_o \end{pmatrix} + \frac{r^2}{2}\gamma \begin{pmatrix} 1 & 0 \\ 0 & \frac{7}{16} \end{pmatrix}$$

$$C_i^0 = \sqrt{\frac{\kappa}{8}}\, r^i \begin{pmatrix} 0 & 1 \\ \sqrt{8} & 0 \end{pmatrix}, \qquad C_i^1 = \sqrt{\frac{5\kappa}{16}}\, r^i \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

∘ Brambilla Escobedo Soto Vairo PRD 96 (2017) 034021, D97 (2018) 074009

@ NLO in E/T, H and the collaps operators get some higher order corrections.

∘ Brambilla Islam Strickland Tiwari Vairo Vander Griend JHEP 08 (2022) 303

Thermal width and mass shift

The quantity κ is related to the thermal decay width of the heavy quarkonium. In particular for $1S$ states, we have (Σ_s = self-energy)

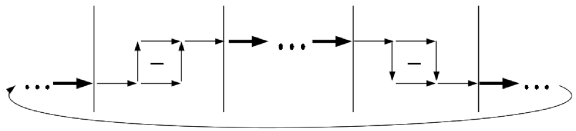
$$\Gamma(1S) = -2\langle \mathrm{Im}\,(-i\Sigma_s)\rangle = 3a_0^2\,\kappa$$

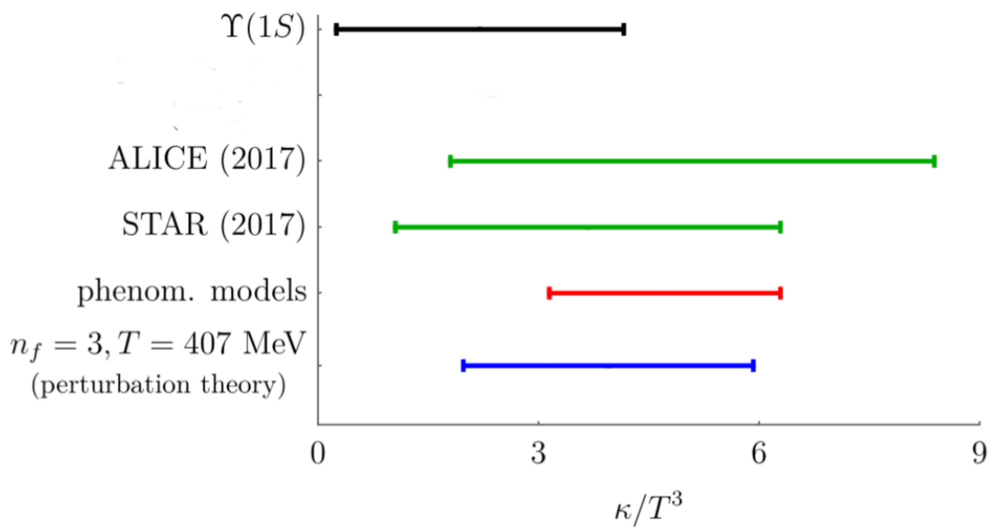
The quantity γ is related to the thermal mass shift of the heavy quarkonium. In particular for $1S$ states, we have

$$\delta M(1S) = \langle \mathrm{Re}\,(-i\Sigma_s)\rangle = \frac{3}{2}a_0^2\,\gamma$$

κ

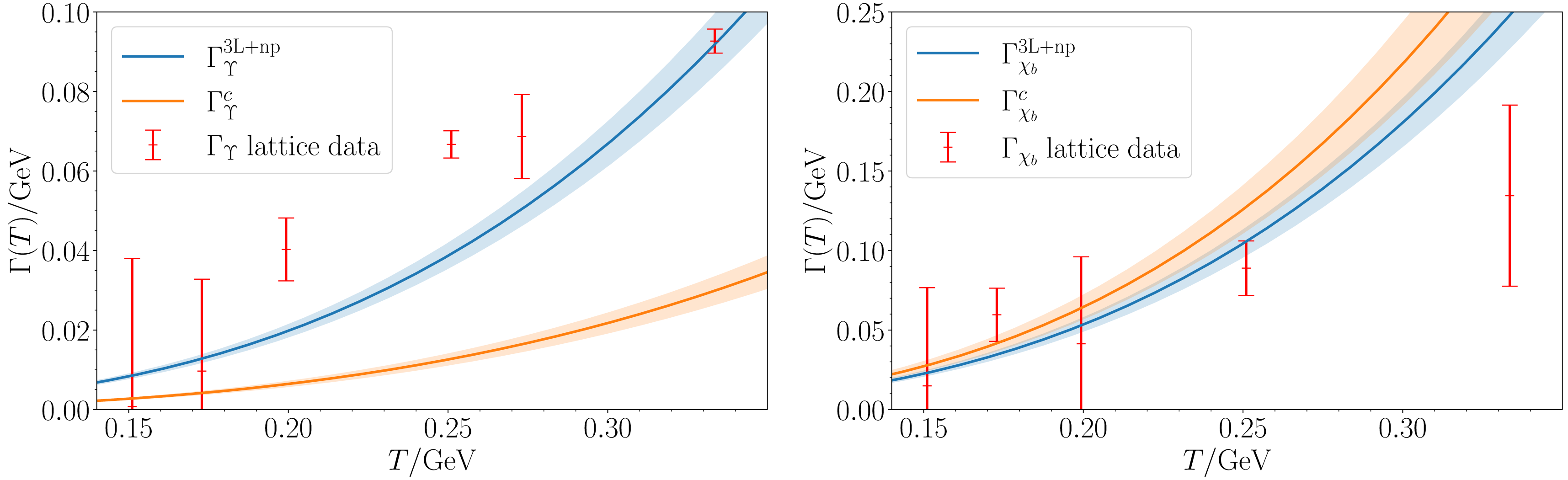
$$\kappa = \frac{g^2}{18}\,\mathrm{Re}\int_{-\infty}^{+\infty} ds\,\langle\,\mathrm{T}\,E^{a,i}(s,\mathbf{0})\,\phi^{ab}(s,0)\,E^{b,i}(0,\mathbf{0})\rangle =$$





- Brambilla Escobedo Vairo Vander Griend PRD 100 (2019) 054025
  lattice data of Aarts et al JHEP 11 (2011) 103
  and Kim Petreczky Rothkopf JHEP 11 (2018) 088

Thermal width vs lattice



Using the static potential at 3 loops + the leading non-perturbative correction the comparison with lattice data gives

$$\frac{\kappa}{T^3} = 1.88 \pm 0.16$$

- Brambilla Magorsch Strickland Vairo Vander Griend PRD 109 (2024) 114016
  lattice data of Larsen Meinel Mukherjee Petreczky PRD 100 (2019) 074506

γ

$$\gamma = \frac{g^2}{18} \,\mathrm{Im} \int_{-\infty}^{+\infty} ds \, \langle \,\mathrm{T}\, E^{a,i}(s,\mathbf{0})\, \phi^{ab}(s,0)\, E^{b,i}(0,\mathbf{0}) \rangle$$

Some lattice analyses suggest

$$\left.\frac{\gamma}{T^3}\right|_{\mathrm{thermal}} \approx 0$$

while a LO weak coupling calculation gives $\left.\frac{\gamma}{T^3}\right|_{\mathrm{thermal}} \approx -4.3 \; (N_f = 4)$

- Larsen Meinel Mukherjee Petreczky PRD 100 (2019) 074506
  for a different lattice result ($\gamma < 0$) see HOTQCD col PRD 112 (2025) 05451

Evolution set up

- After heavy-ion collision, quark-antiquarks propagate freely up to $\tau_{\rm med} = 0.6$ fm.
- From $\tau_{\rm med}$ fm to the freeze-out time t_F they propagate in medium.
- We assume the medium to be locally in thermal equilibrium.
- We use a 3+1D dissipative relativistic hydrodynamics code that makes use of the quasiparticle anisotropic hydrodynamics (aHydroQP) framework. The code uses a realistic equation of state fit to lattice QCD measurements and is tuned to soft hadronic data collected in 5.02 TeV collisions using smooth optical Glauber initial conditions.
  - `Alqahtani Nopoush Strickland PRC 92 (2015) 054910, 95 (2017) 034906`
    `Alqahtani Nopoush Strickland PPNP 101 (2018) 204`

Quantum trajectories algorithm

The QTraj code implements the quantum trajectories algorithm and the waiting time approach as follows.

1. Initialize a wave function $|\psi(t_0)\rangle$ at initial time t_0, which corresponds to the initial quantum state of the particle given by $\rho(t_0) = |\psi(t_0)\rangle\langle\psi(t_0)|$.
2. Generate a random number $0 < r_1 < 1$ and evolve the wave function forward in time with H_{eff} until $||\, e^{-i\int_{t_0}^{t} dt' H_{\text{eff}}(t')} |\psi(t_0)\rangle\, ||^2 \leq r_1$ where $H_{\text{eff}} = H - i\Gamma/2$, $\Gamma = \sum \Gamma_n$ and $\Gamma_n = C_n^\dagger C_n$. Denote the first time step fulfilling the inequality as the jump time t_j. If the jump time is greater than the simulation run time t_F, end the simulation at time t_F; otherwise, proceed to step 3.
3. At time t_j, initiate a quantum jump:
   - (a) If the system is in a singlet configuration, jump to octet. If the system is in an octet configuration, generate a random number $0 < r_2 < 1$ and jump to singlet if $r_2 < 2/7$; otherwise, remain in the octet configuration.
   - (b) Generate a random number $0 < r_3 < 1$; if $r_3 < l/(2l+1)$, take $l \to l-1$; otherwise, take $l \to l+1$.
   - (c) Apply the appropriate collapse operator C_i^j to the wavefunction, normalize.
4. Continue from step 2.

- Brambilla et al JHEP 05 (2021) 136

Jumps and probabilities

The probabilities in step 3 correspond to the branching fractions into a state of different color and/or angular momentum:

$$p_n = \frac{\langle \psi(t)|\Gamma_n|\psi(t)\rangle}{\langle \psi(t)|\Gamma|\psi(t)\rangle}$$

Each evolution of the wave function from time t_0 to t_F is called a quantum trajectory.
In practice, a large number of quantum trajectories must be generated.
As the number of trajectories considered increases, the average converges to the solution of the Lindblad equation.

- Dalibard Castin Molmer PRL 68 (1992) 580
  Daley AP 63 (2014) 77
  Sharma Tiwari PRD 101 (2020) 074004

Simulation set up

We employ a radial lattice of $\texttt{NUM}= 4096$ lattice sites and a radial length of $\texttt{L}= 80\,\mathrm{GeV}^{-1}$, corresponding to a radial lattice spacing of $a \approx 0.0195\,\mathrm{GeV}^{-1}$. The real time integration is discretized with a time step of $\texttt{dt}= 0.001\,\mathrm{GeV}^{-1}$.

@ LO in E/T, we sample approximately 7 - 9 $\times 10^5$ independent physical trajectories for each choice of κ/T^3 and γ/T^3, with approximately 50-100 quantum trajectories per physical trajectory. To generate each physical trajectory, we sample the bottomonium production point in the transverse plane using the nuclear binary collision overlap profile $N_{AA}^{\text{bin}}(x, y, b)$, the initial transverse momentum of the state p_T from an E_T^{-4} spectrum, and the initial azimuthal angle ϕ of the state's momentum uniformly in $[0, 2\pi)$. We bin the results for the survival probability as a function of centrality, p_T, and ϕ. This allows us to make predictions for differential observables such as R_{AA} as a function of p_T and elliptic flow. To ensure that the hierarchy of energy scales of the EFT is fulfilled, we evolve the state in the vacuum when the temperature falls below $T_F = 250$ MeV.

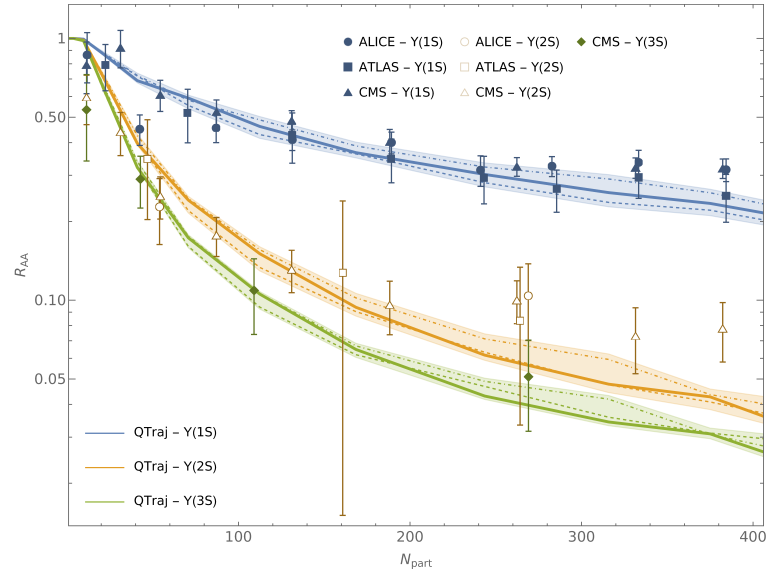
@NLO in E/T, we evaluate the evolution using an ensemble of 1-2 10^5 physical trajectories with 30 quantum trajectories per physical trajectory. To ensure that the hierarchy of energy scales of the EFT is fulfilled, we evolve the state in the vacuum when the temperature falls below $T_F = 190$ MeV.

Bottomonium results

Bottomonium nuclear modification factor @ LO in E/T and 3 loops in the potential

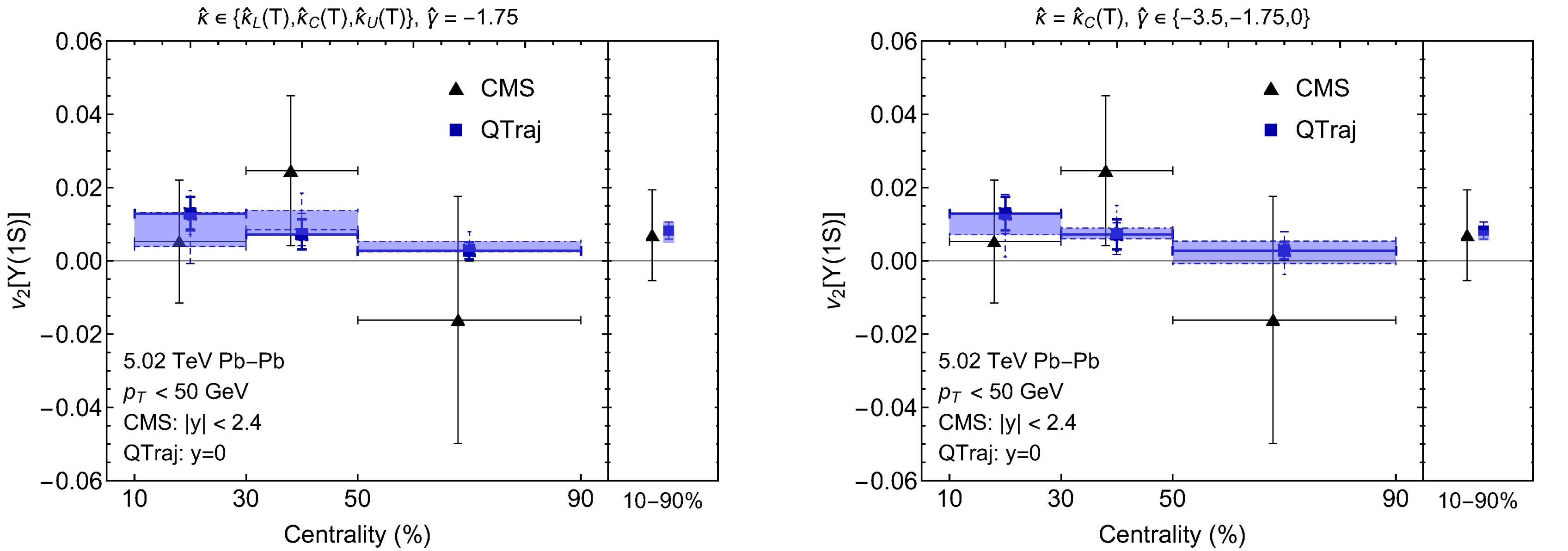
We compute the nuclear modification factor R_{AA} from

$$R_{AA}(nS) = \frac{\langle n, \mathbf{q}|\rho_s(t_F; t_F)|n, \mathbf{q}\rangle}{\langle n, \mathbf{q}|\rho_s(0; 0)|n, \mathbf{q}\rangle}$$



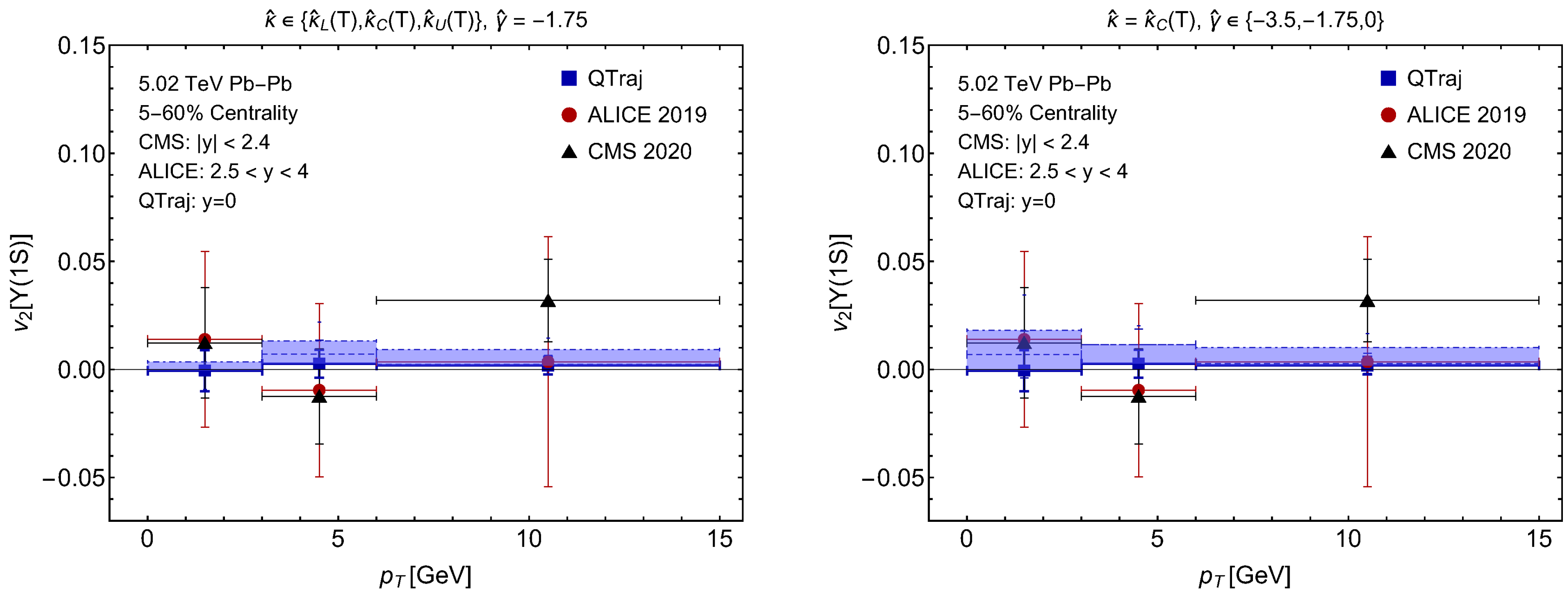
○ Brambilla Magorsch Strickland Vairo Vander Griend PRD 109 (2024) 114016

Elliptic flow v_2 of the $\Upsilon(1S)$ @ LO in E/T



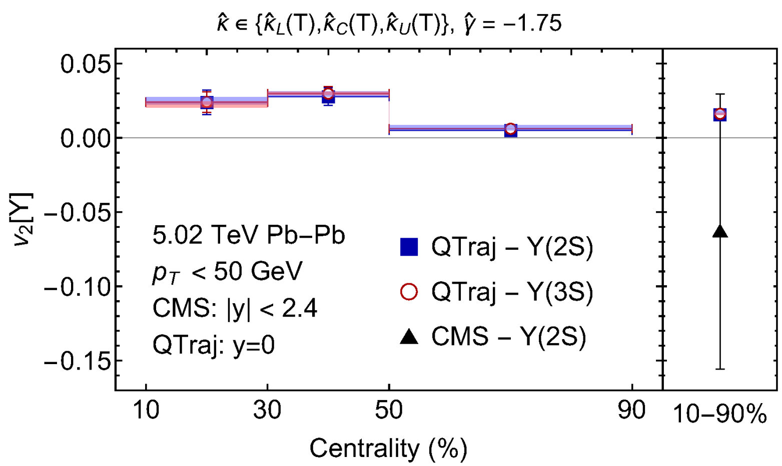
- Brambilla et al PRD 104 (2021) 094049

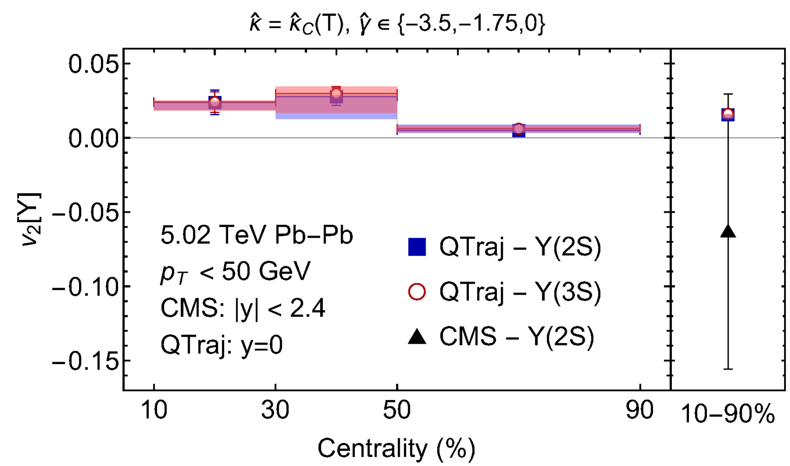
Elliptic flow v_2 of the $\Upsilon(1S)$ vs p_T @ LO in E/T



- Brambilla et al PRD 104 (2021) 094049

Elliptic flow v_2 of the $\Upsilon(2S)$ and $\Upsilon(3S)$ @ LO in E/T





- Brambilla et al PRD 104 (2021) 094049

Conclusions & outlook

Conclusions

We have shown how the heavy quark-antiquark pair out-of-equilibrium evolution can be treated in the framework of QCD non relativistic EFTs. Main features are:

- the medium may be a strongly-coupled plasma (not necessarily a quark-gluon plasma) whose characteristics are determined by lattice calculations;
- the total number of heavy quarks, i.e., $\mathrm{Tr}\{\rho_s\} + \mathrm{Tr}\{\rho_o\}$, is preserved by the evolution equations;
- the non-abelian nature of QCD is fully accounted for;
- the treatment is quantum.

The evolution equations follow from assuming the inverse size of the quark-antiquark system to be larger than any other scale of the medium and from being accurate at first non-trivial order in the multipole expansion and at first order in the heavy-quark density.

Under some conditions (large time, quasistatic evolution, quantum Brownian motion) the evolution equations are of Lindblad form. Their numerical solution provides a status of the art determination of $R_{AA}[\Upsilon(nS)]$ and differential observables in agreement with LHC data.

Outlook 1

Applications to charmonium may require to account for

- possible breaking of the nonrelativistic expansion;
  if the non-relativistic expansion is still applicable then also non-relativistic EFTs;
- thermal effects in the potential that are not encoded in the multipole expansion;
- higher order effects in the heavy quark density expansion;
- recombination from open charm in the medium.

Outlook 2

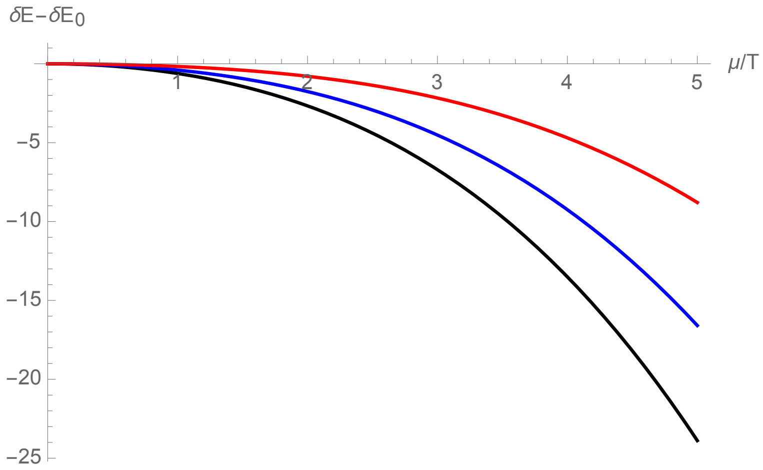
Similar frameworks and methods may be applied to the evolution of quarkonium at finite chemical potential: $n_{\mathrm{F}}(E) \to n_{\mathrm{F}}(E-\mu)$.

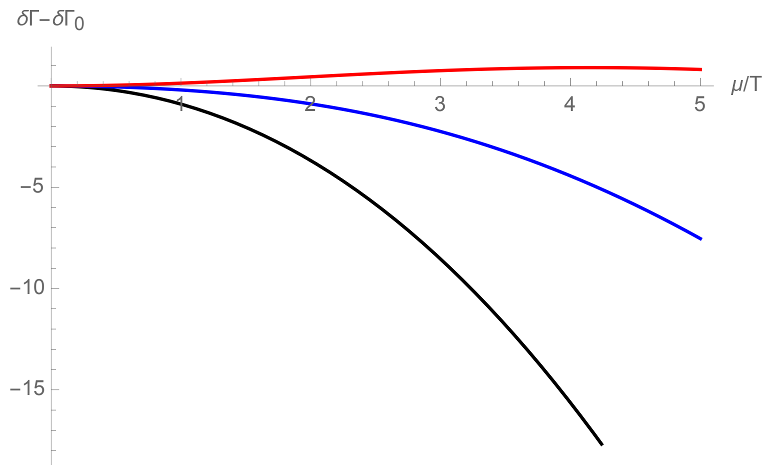
In pNRQCD thermodynamical properties at equilibrium like energy shifts and widths have been computed in weak coupling at different energy scale settings, but a proper study of evolution equations in a realistic hydrodynamical framework for a strongly coupled medium, like the one reviewed here for zero chemical potential, is missing.

Energy and width corrections for $T \gg \mu$ (and $m_D \gg E$)

$$\delta E_{nl} = \delta E_{nl}\Big|_{\mu=0} + \frac{2\alpha_s^2}{9} N_f T \mu^2 \langle r^2 \rangle_{nl} \left[-4\log 2 + \left(\frac{3}{\pi^2} g^2 \left(3 + \frac{N_f}{2} \right) \right)^{1/2} \right]$$

$$\Gamma_{nl} = \Gamma_{nl}\Big|_{\mu=0} - \frac{8\alpha_s^2 N_f T \mu^2}{9\pi} \langle r^2 \rangle_{nl} \left[2\gamma - \log\left(\frac{T^2}{m_D^2} \right) - 1 - 2\log\pi \right]$$



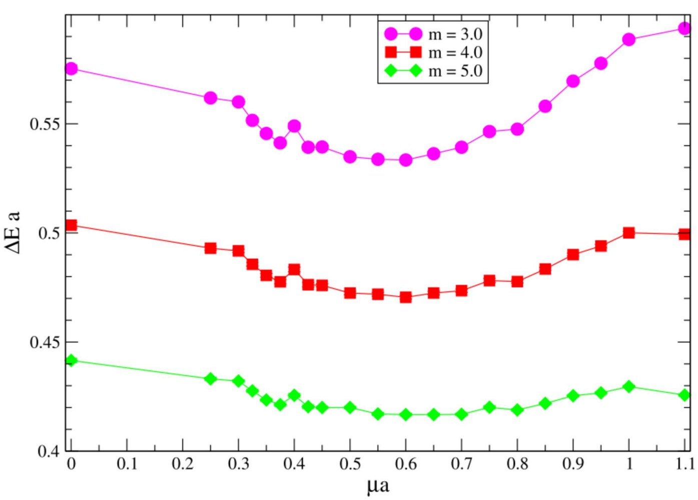


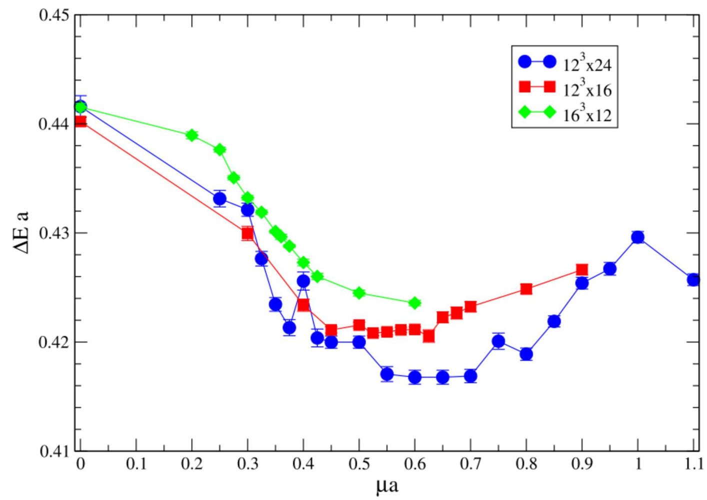
α_s=0.01, 0.1 and 0.3

○ Carignano Soto PRD 102 (2020) 116021

Energy and width corrections for $T \ll \mu$

$T > E$ is necessary for quarkonium to develop a decay width. If $T < E$, no decay width is developed, no matter how large is μ. At large μ and small T, we only expect modifications in the heavy quarkonium mass (through the binding energy), see lattice data. The dissociation mechanism would be screening, as in the original work of Matsui and Satz. This is in contrast with what happens at large T and small (zero) μ, in which case, apart from the shift in the location of the bound state peaks, a widening of the peaks is observed when the temperature is increased and melting happens when states become so broad that they lose their identity.





- Carignano Soto PRD 102 (2020) 116021
  lattice data of Hands Kim Skullerud PLB 711 (2012) 199