# Open heavy flavor and quarkonium - theoretical overview

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XXth International Conference on Ultra-relativistic Nucleus-Nucleus Collisions, 8th August, 2023

Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

EXCELENCIA MARÍA DE MAEZTU 2020-2023

Grant PID2019-105614GB-C21 funded by:

MINISTERIO DE CIENCIA E INNOVACIÓN

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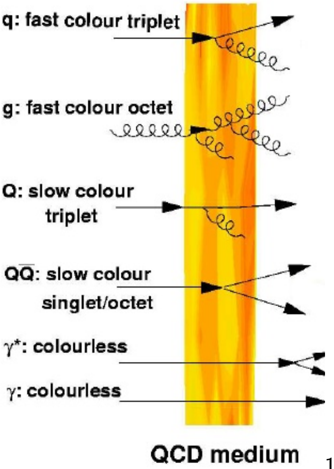
# Outline

# Hard probes



[1]

Probes that are created at the beginning of the collision (typically because its creation needs a high energy) that get modified in a substantial way and that are relatively easy to detect. In this talk, we focus on the ones related with heavy quarks.

[1] Picture taken from d'Enterria (2007)

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- In the case of quarkonium, other energy scales appear. The inverse of the typical radius $\frac{1}{r}$ and the binding energy $E$.
- Using heavy quarks, we can test the properties of the medium at different energy scales.

# Open heavy quarks and quarkonia

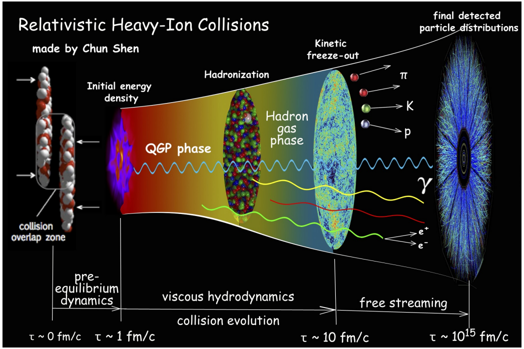
## Similarities

- Both are formed by heavy quarks.
- Sensitive to correlators of the chromoelectric field.
- In many cases a combination of EFTs and Lattice QCD is useful.
- Similar theoretical tools. Boltzmann eq., Langevin eq., T-matrix...

## Differences

- A collision with a QGP constituent might destroy the bound state but not the heavy quark.
- Heavy quarks hadronize to hadrons of a size of the order of $1/\Lambda_{QCD}$. Each quarkonium species has a different size.
- Heavy quarks have color while a quarkonium bound state is globally color-neutral. Quarkonium is less affected by infrared physics.
- Heavy quarks at very large momentum are similar to jets (but dead-cone effect).

# Stages of a heavy-ion collision




Picture taken from Shen and Heinz (2015)

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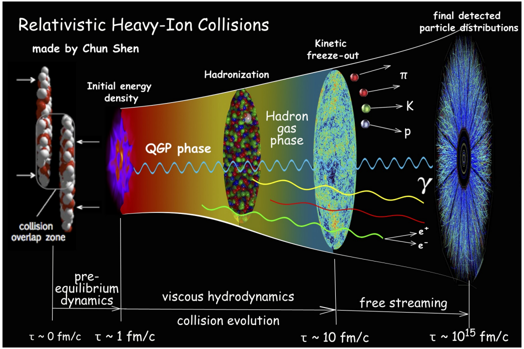


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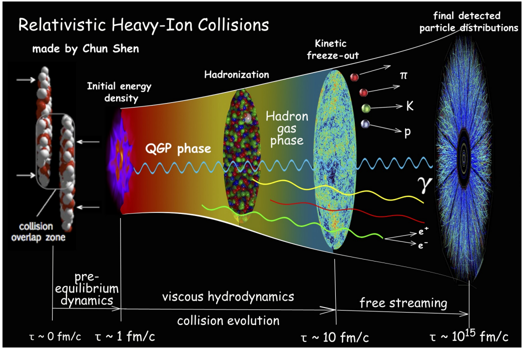


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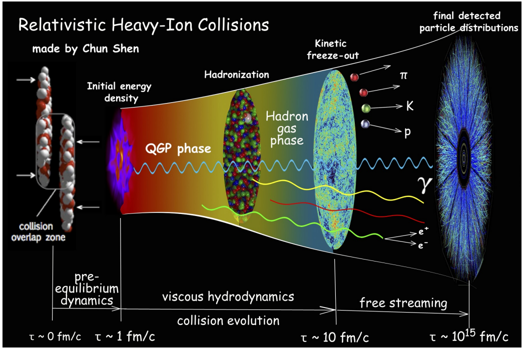


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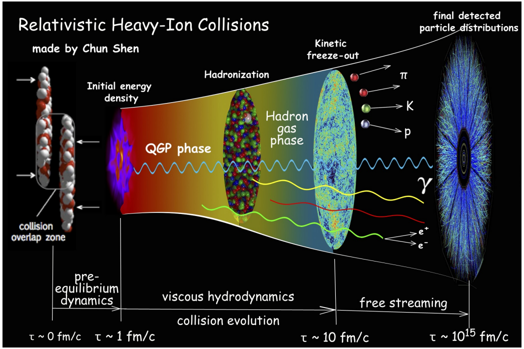


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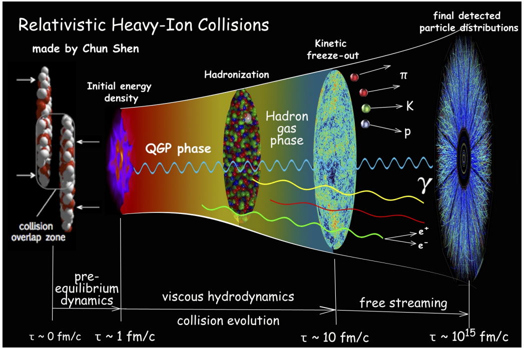


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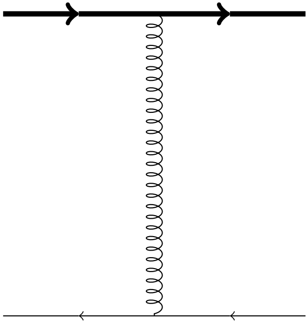
- They hadronize at the phase transition. However, quarkonium states can be much smaller.
- Both can be affected by the hadron phase.
- Final state effects might be important (feed-down).

# Outline

# How the medium affects the heavy quark.

## Collisions



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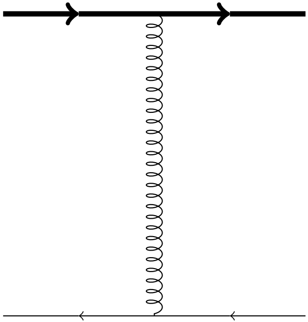

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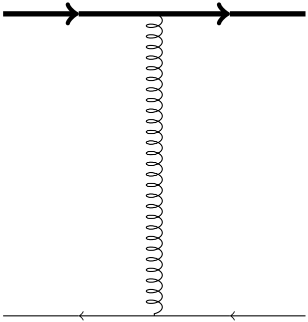

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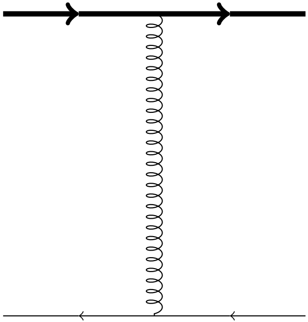

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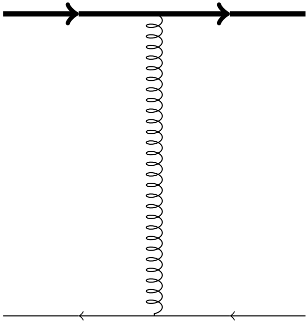

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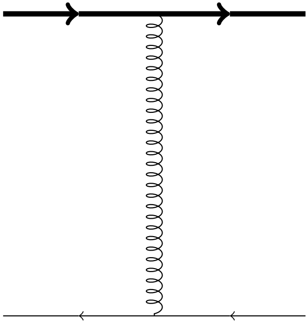

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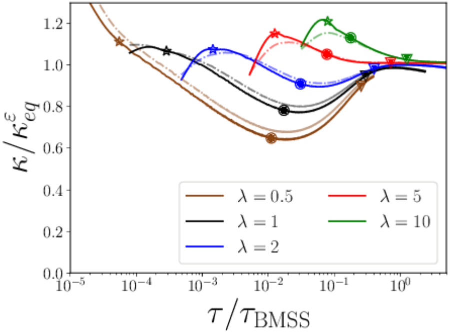
$$\kappa = \frac{g^2}{6N_c}\mathrm{Re}\int_{-\infty}^{\infty} dt \langle E^{i,a}(t,\mathbf{0})E^{i,a}(0,\mathbf{0})\rangle$$

# $\kappa$ during hydronamization

See Jarko Peuron's talk on Tuesday

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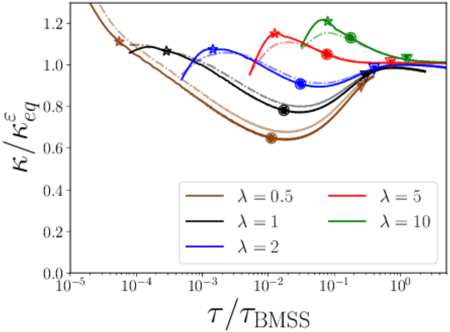


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- $\kappa$ is within 30% percent of its equilibrium value.

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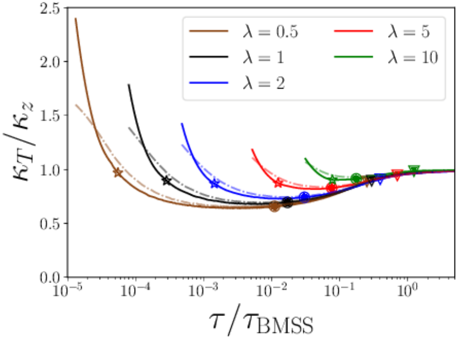
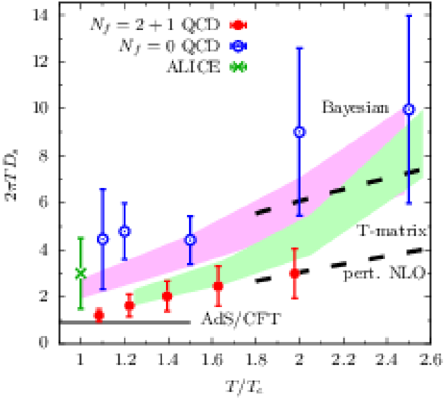



- $\kappa$ can be computed in the pre-equilibrium phase using Effective Kinetic Theory.
- $\kappa$ is within 30% percent of its equilibrium value.
- $\kappa$ is different in the longitudinal and in the transverse direction. Transverse direction enhanced at small times.

# $\kappa$ in lattice QCD

See Hai-Tao Shu's talk on Tuesday




- Note that $\kappa = \frac{2T^2}{D_s}$. New un-quenched results show significantly larger values than previous quenched results.

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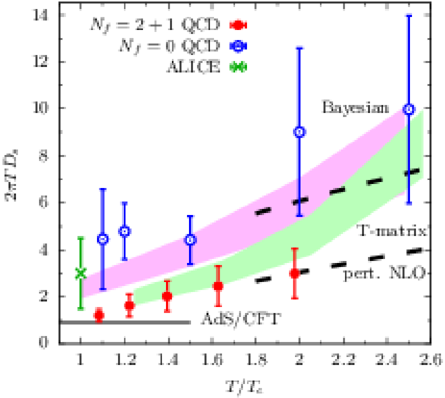
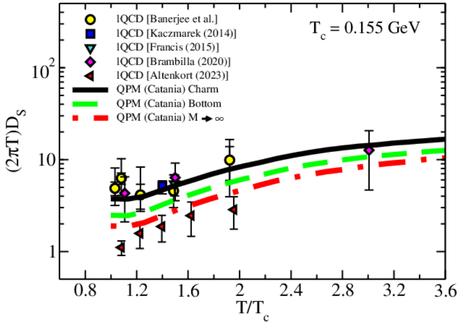



- Note that $\kappa = \frac{2T^2}{D_s}$. New un-quenched results show significantly larger values than previous quenched results.
- Un-quenched results are close to the AdS/CFT estimate at low temperatures and get close to the NLO perturbative computation at large temperatures. Also close to T-matrix results.

# $\kappa$ dependence with mass

## See Vincenzo Minissale's talk on Wednesday

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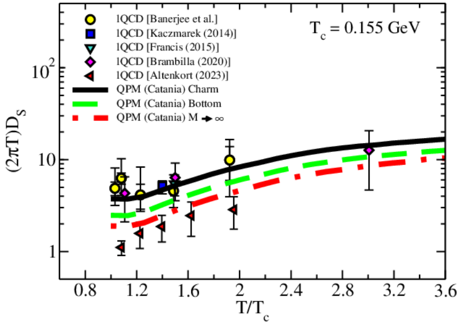


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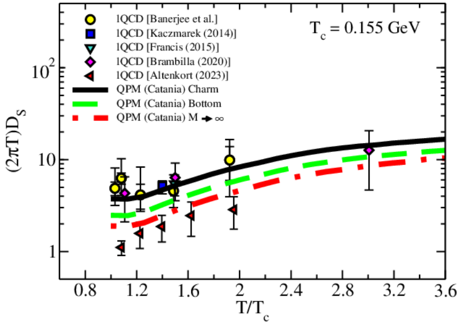


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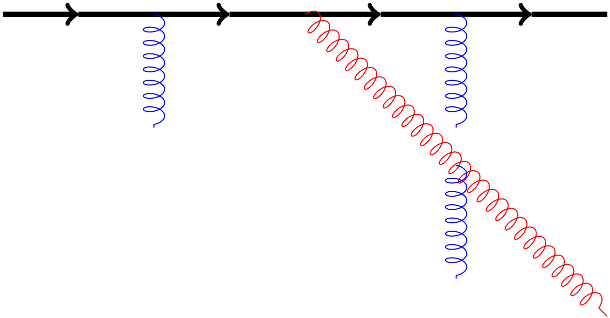
- The definition of $\kappa$ in terms of correlator of chromoelectric fields correspond to the $M \to \infty$ limit. Definition used on lattice QCD.
- Results at the $M \to \infty$ limit are compatible with recent unquenched results.

# How the medium affects the heavy quark.
## Radiation



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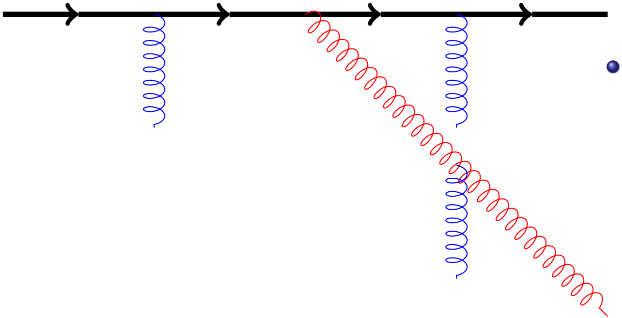

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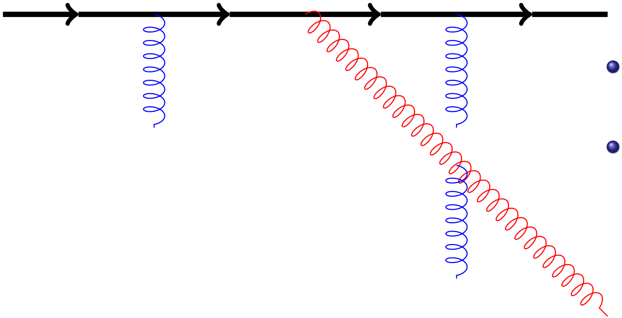

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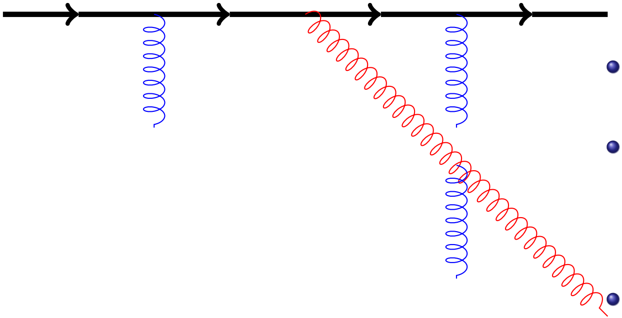

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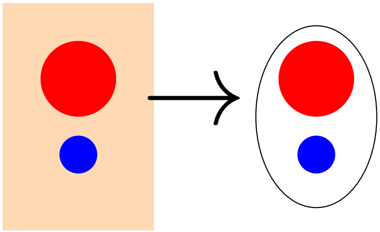
- Many models consider radiation, together with collisions.
- Radiation is suppressed at angles smaller than $M/E$, with $E$ the energy of the emitted particle. Dead-cone effect.
- This has been directly observed recently (Alice collaboration, 2022).

# Hadronization



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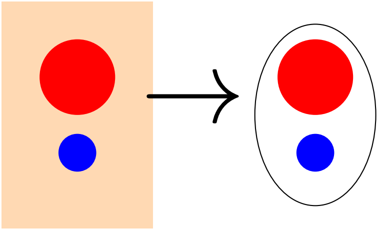

- At $T_c$ we go from a QGP to a hadron phase. Degrees of freedom change from quarks and gluons to hadrons.
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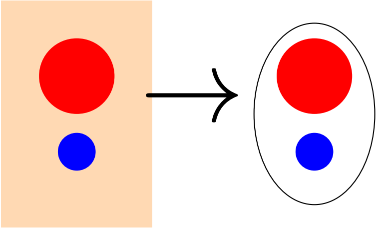

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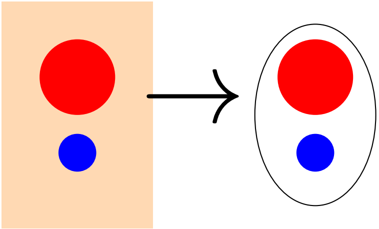

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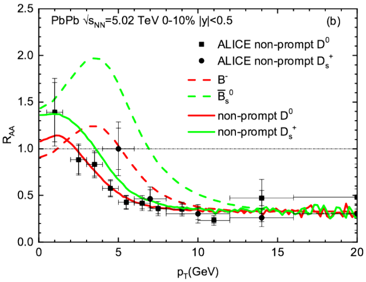
- There are several models for hadronization. At high $p$ hadronization is vacuum like (fragmentation), but at low $p$ it is affected by the medium.
- At high multiplicity pp collisions, hadronization might already be medium-like (See Andrea Beraudo's talk on Wednesday).

# Statistical Hadronization model

See Min He's talk on Tuesday




- fragmentation function computed assuming a thermal distribution of hadrons at hadronization.

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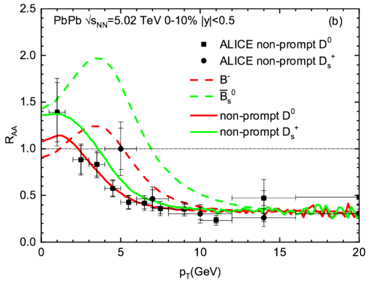


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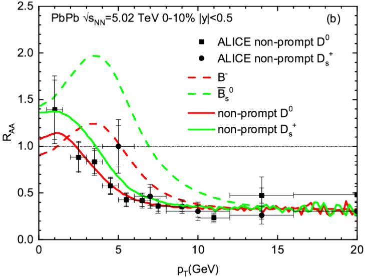
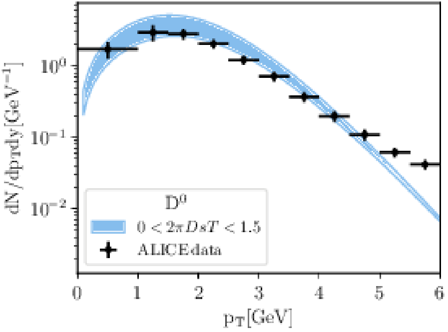



- fragmentation function computed assuming a thermal distribution of hadrons at hadronization.
- *pp* data is well-reproduced.
- Combination with medium b quark diffusion to obtain phenomenological predictions.

# The fluid-dynamic approach

## See Federica Capellino's talk

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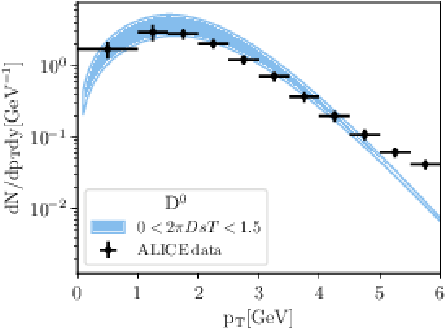


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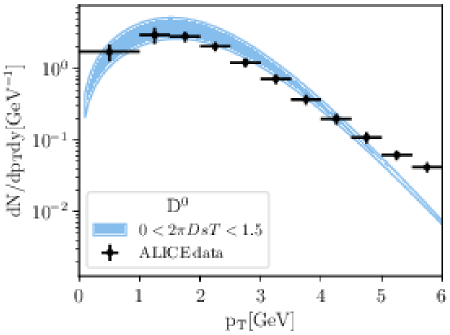


- It is assumed that heavy quarks are in local thermal equilibrium.
- The number of $Q\bar{Q}$ pairs is treated as an additional conserved current.
- A good description of charm data is achieved. However,thermalization time for bottom quarks is much larger.

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## Screening

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# The mechanisms of dissociation

## Screening

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

At finite temperature

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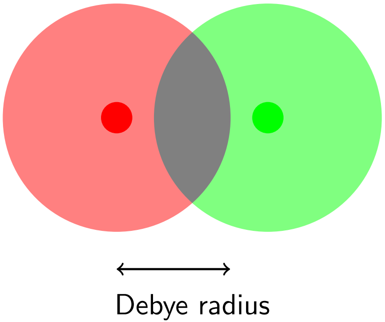

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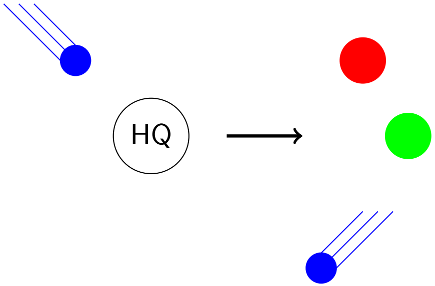
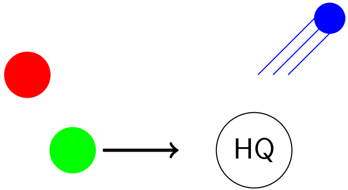


# Recombination

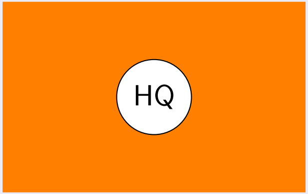



Two heavy quarks coming from different origin may recombine to form a new quarkonium state.

# Recombination: Bottomonia vs Charmonia

## Bottomonia

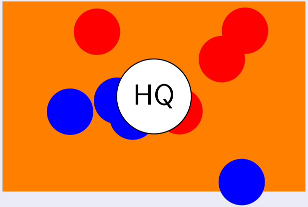
The dilute limit is valid




Recombination from uncorrelated heavy quark is unlikely

## Charmonia

The dilute limit is not valid

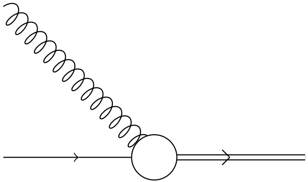



We need to consider recombination from uncorrelated heavy quarks

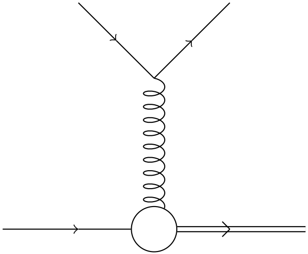
# Theoretical description of quarkonium

## Rate/Boltzmann equation approach

- A decay width is assigned to each quarkonium state.
- The decay width can be computed considering different processes and different approximations (perturbation theory, EFT, T-matrix...).
- Thermalization is achieved by the structure of the collision term.



Gluo-dissociation



Inelastic scattering

# Theoretical description of quarkonium

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- Rate/Boltzmann approach recovered for $E \gg \Gamma$.

# The Lindblad equation

Any master equation that is:

- Markovian
- Preserves the properties that a density matrix must fulfil (Hermitian, positive semi-definite, trace is conserved).

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In the case of quarkonium, the Markovian limit corresponds to the case in which the energy of the particles in the environment is larger than the binding energy.

# 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. [2]

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

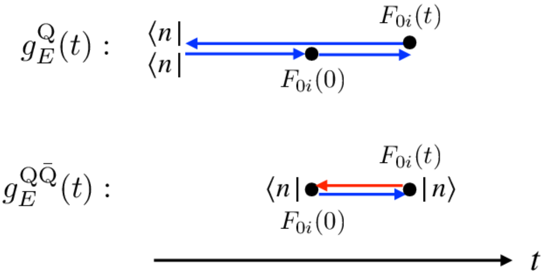
$$\kappa = \frac{g^2}{6\,N_c}\,\mathrm{Re}\int_{-\infty}^{+\infty} ds\,\langle\,\mathrm{T}\,E^{a,i}(s,\mathbf{0})E^{a,i}(0,\mathbf{0})\rangle$$

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

[2] We use a redefined field $E(t,\mathbf{x})$ such that we do not need to write explicitly the Wilson lines.

## $\kappa_{adj}$ vs $\kappa_{fund}$

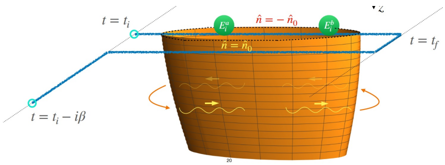
The parameter $\kappa$ appearing in the master equation of quarkonium is similar to the heavy quark diffusion coefficient but not equal.




Picture taken from Scheihing-Hitschfeld and Yao (2022)

# $\kappa_{adj}$ in AdS/CFG

See Bruno Sebastian Scheihing Hitschfeld's talk on Wednesday

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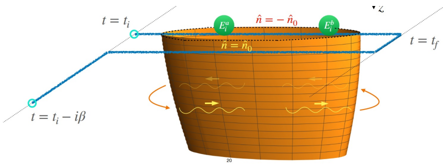


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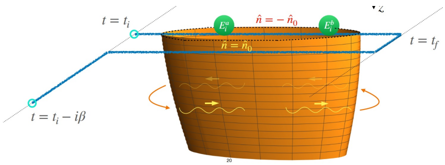


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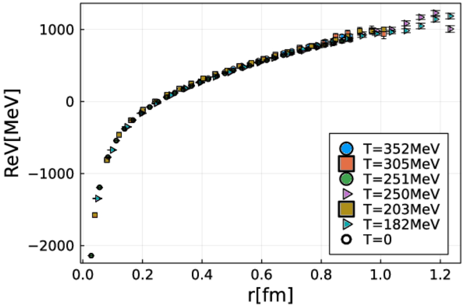
- Estimates of $\kappa_{adj}$ from the lattice decay width of quarkonium state give results compatible with (quenched) $\kappa_{fund}$ (Brambilla et al. 2019)
- However, $\kappa_{adj}$ is zero at strongly-coupled $N = 4$ SYM while $\kappa_{fund}$ is not.

# Lattice results on the potential

Bazavov et al. 2023

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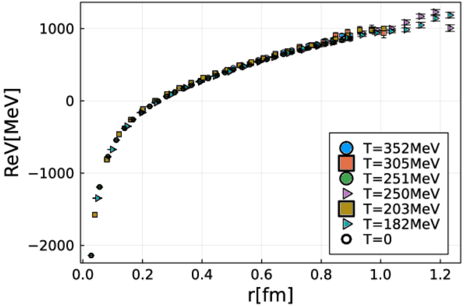


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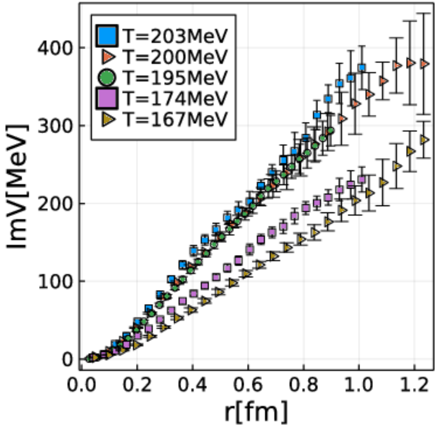


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- The influence of this new input in T-matrix computations was discussed on Wednesday at Zhanduo Tang's talk.

# Wigner function's approach

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# $E/T$ corrections

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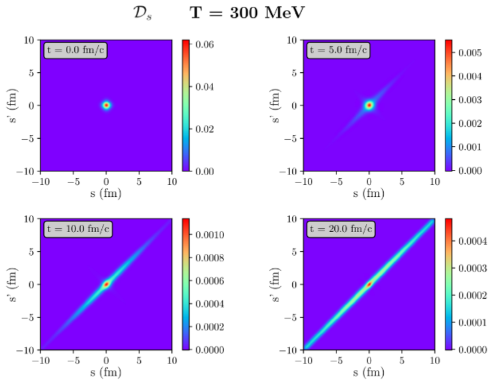
- $E/T$ corrections improve validity region and might lead to approximate thermalization.

# Nantes approach




Picture taken from Delorme's SQM2021 proceedings

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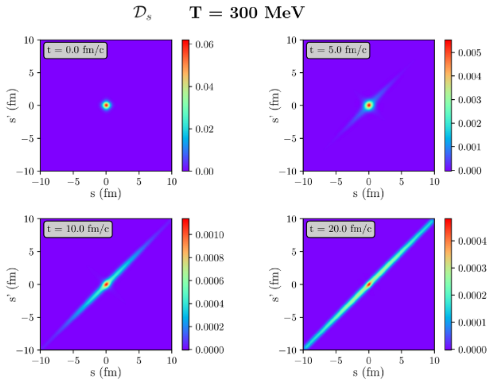


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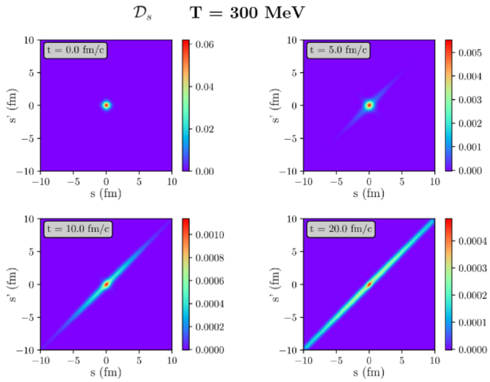


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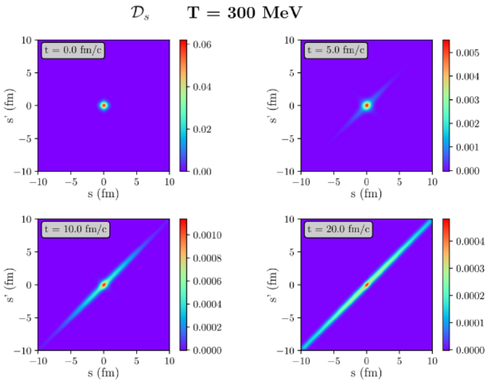


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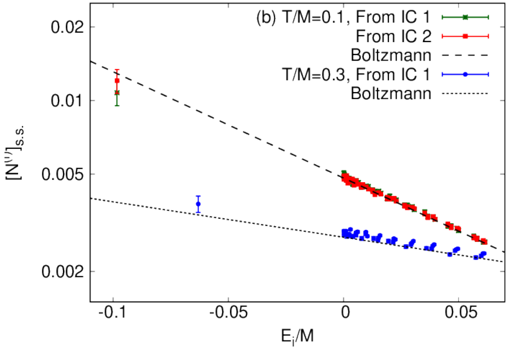
- Equations adapted to 1D case.
- Confirms that evolution naturally leads to a state in which the density matrix is almost diagonal in coordinate space. The regime in which Langevin-like equations are valid.
- However, we also see that a surviving non-diagonal structure around $\mathbf{r} = \mathbf{0}$.

# Osaka approach

Miura, Akamatsu, Asakawa and Kaida, 2022



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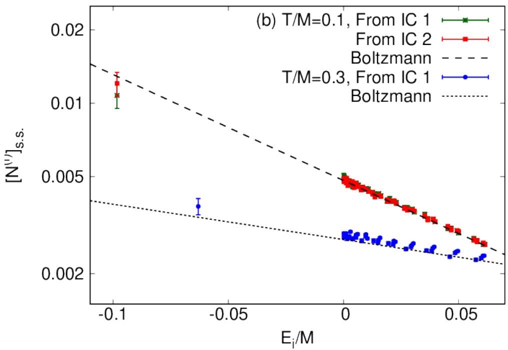


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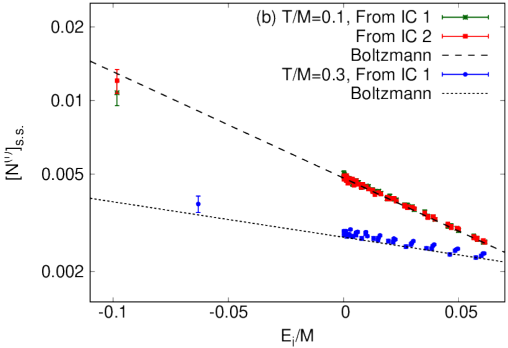


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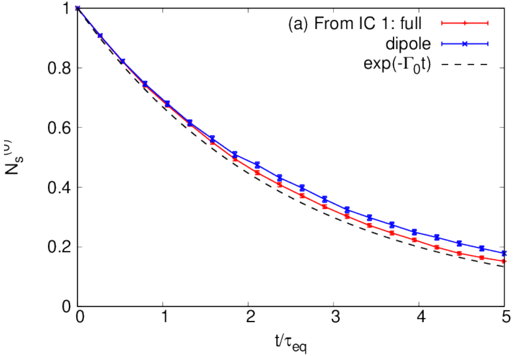


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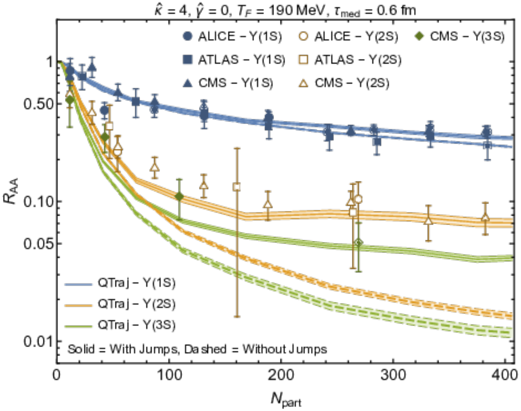
- Their full result and the dipole approximation coincide at early times.

# $E/T$ corrections in pNRQCD

Brambilla et al. 2023, also Peter Vander Griend's poster



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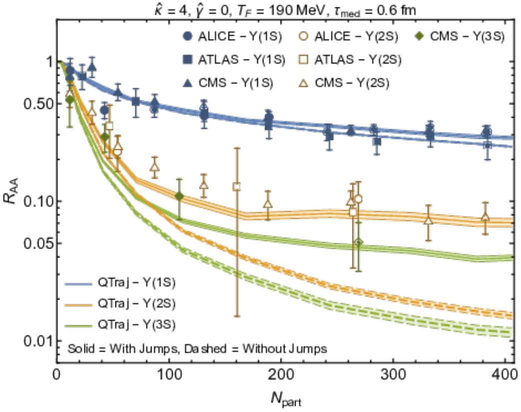


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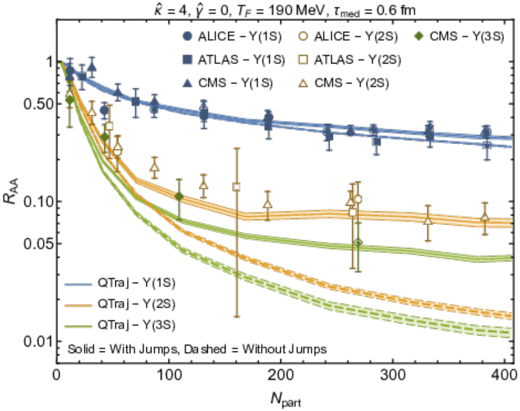


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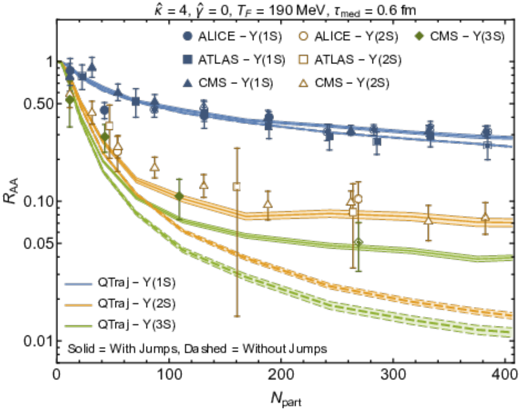


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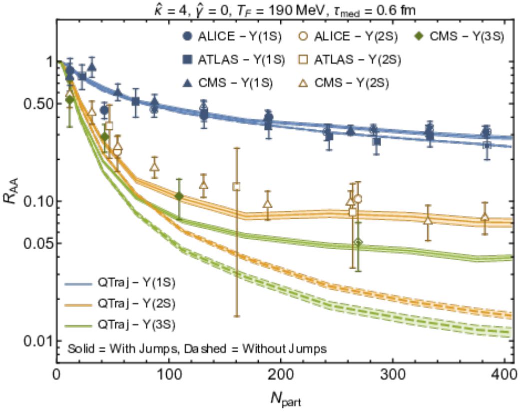


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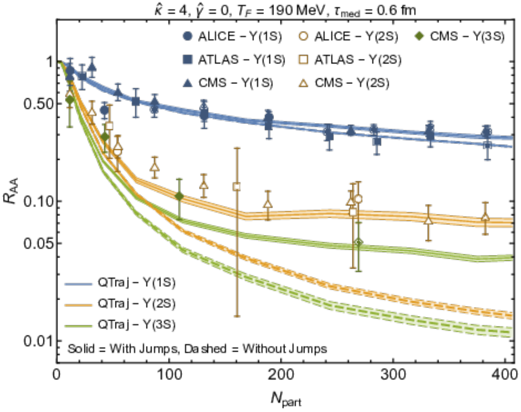


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- Correlated recombination needed to reproduce excited states data.

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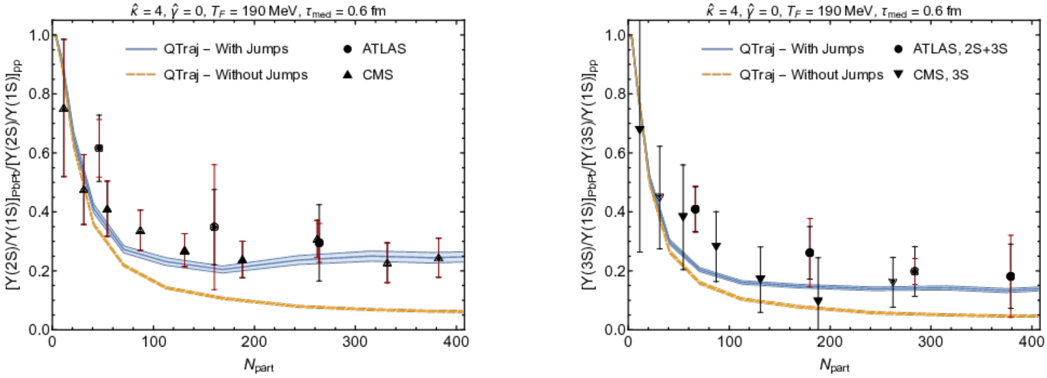

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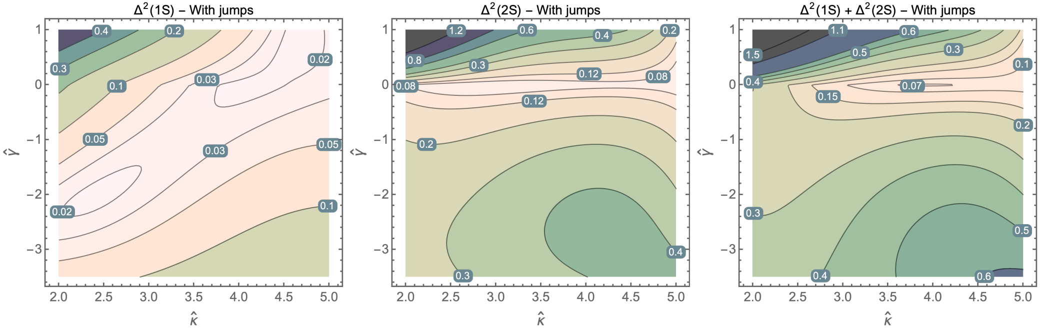
Brambilla et al. 2023, also Peter Vander Griend's poster

## Fit with recombination



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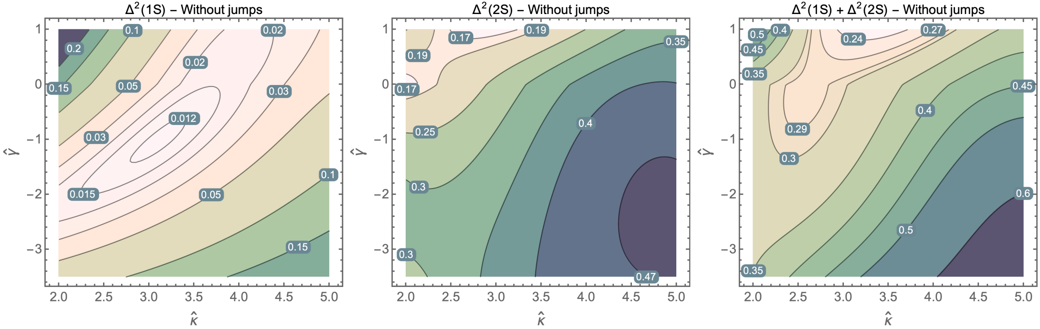

# Outline

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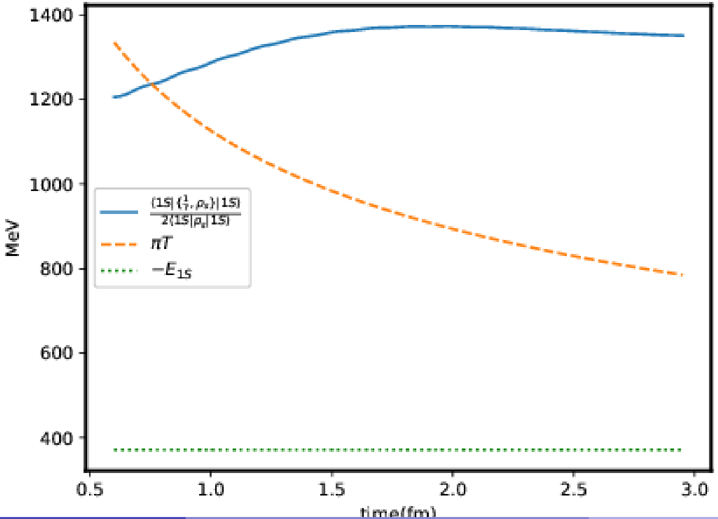
- Interesting relations between $pp$ and heavy-ion physics regarding hadronization.
- The inclusion of $E/T$ corrections leads to results compatible with observations and there are indications that they improve the approach to equilibrium.

# Back-up slides

# Scales in pNRQCD approach



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- The relation between this mass definition and the $\bar{MS}$ can be computed order by order in perturbation theory.