Quarkonia production in AA collisions

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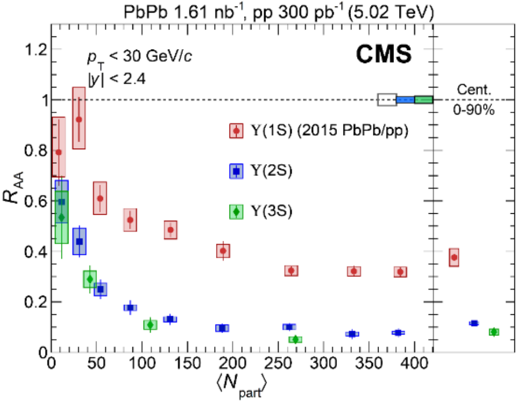
Quarkonia as Tools 2025

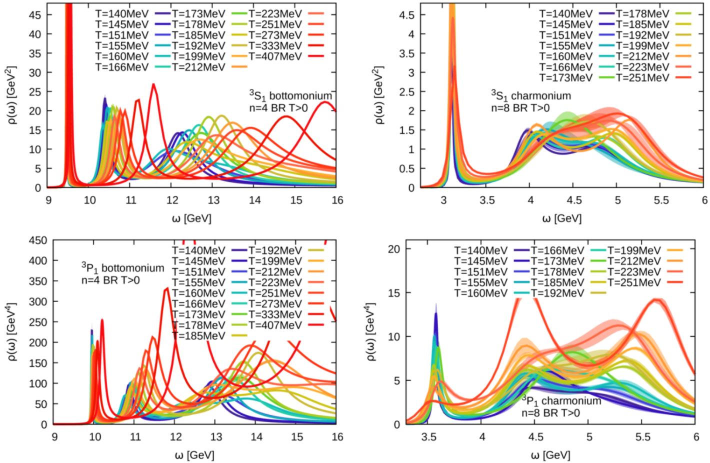
Quarkonium suppression

- Matsui & Satz (1986): Sequential suppression
- Quarkonium states have different binding energies
  $\Rightarrow$ Different dissociation temperatures
- Quarkonia viewed as thermometer

$$R_{AA} = \frac{N_{AA}}{\langle N_{\mathrm{coll}} \rangle N_{pp}}$$



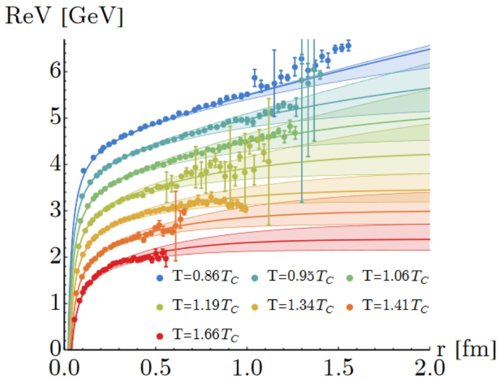
Spectral functions



S. Kim,P. Petreczky, A. Rothkopf (2018)

- Encode in-medium properties of quarkonia
- Broadening of the peaks
- Mass shifts

Screening

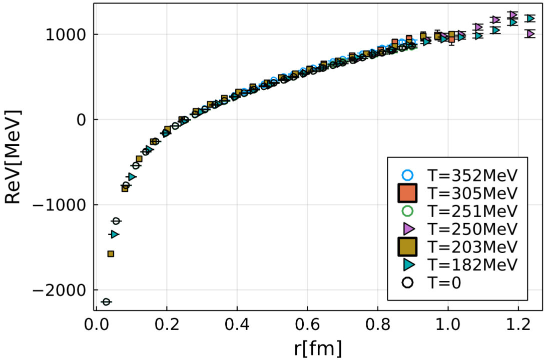


D. Lafferty, A. Rothkopf (2020)

T $\neq$ 0 $\rightarrow$ Suppression of color attraction

Melting of pairs at high T
$\Rightarrow$ Suppression

Screening?



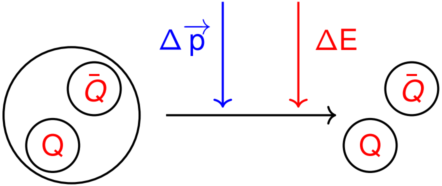
$$\rho_r^{\text{peak}}(\omega, T) = \frac{1}{\pi}\,\mathrm{Im}\,\frac{A_r(T)}{\omega - \mathrm{Re}\,V(r,T) - i\Gamma(\omega,r,T)}$$

- Reconstruction of spectral functions heavily dependent on the extraction strategy
- Different extraction, using a Lorentzian parametrization
- No screening observed!
- Which picture is correct?

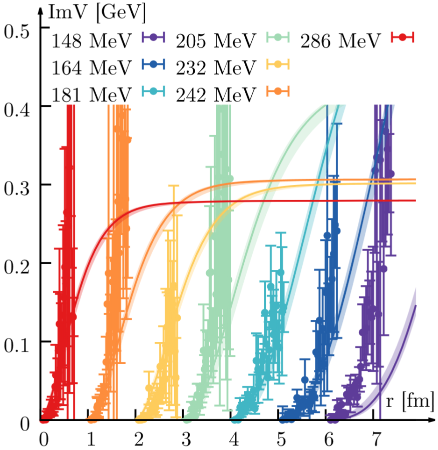
A. Bazavov et al. (HotQCD Collaboration) (2024)

Dynamical effects

- Collisions with medium partons
  → Pair dissociation
  ⇒ Suppression

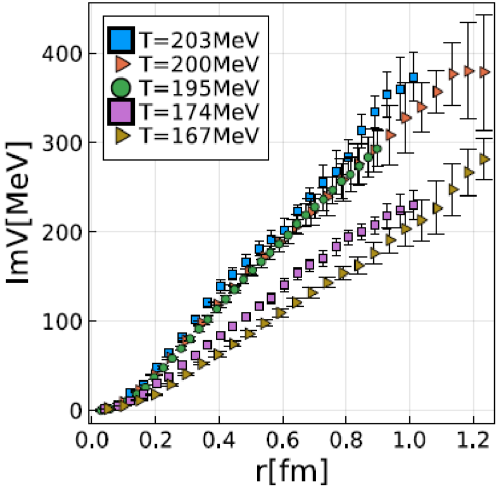


Often described by an imaginary potential



D. Lafferty, A. Rothkopf (2020)

Dynamical effects

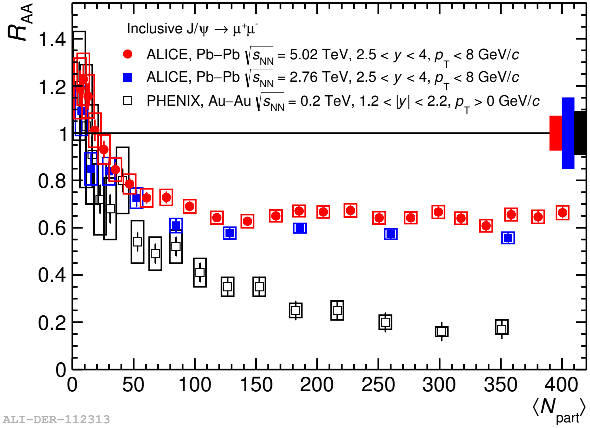


A. Bazavov et al. (HotQCD Collaboration) (2024)

$$\rho_r^{\text{peak}}(\omega, T) = \frac{1}{\pi}\,\text{Im}\,\frac{A_r(T)}{\omega - \text{Re}\,V(r,T) - i\Gamma(\omega,r,T)}$$

- Same lattice extraction
- No saturation observed at higher temperatures
- No screening, but stronger imaginary part?

Recombination



- Picture more complex
- Higher energy → more pairs produced
  ⇒ Recombination
- Effect that cannot be neglected at LHC energies

Recombination

Bottomonia

- Low amount of $b\bar{b}$ pairs
- Only quarks initially close to each other will lead to bottomonia states
- Full quantum treatment possible

Charmonia

- High amount of $c\bar{c}$ pairs
- Recombination can also happen from originally uncorrelated quarks
- Full quantum treatment out of reach

- When does recombination happens?
- Different models and viewpoints

Models

- 3 main classes of models aim to describe quarkonia in AA

Statistical Hadronization

- Classical quarkonium
- No in-medium bound states
- Only generated at the phase boundary

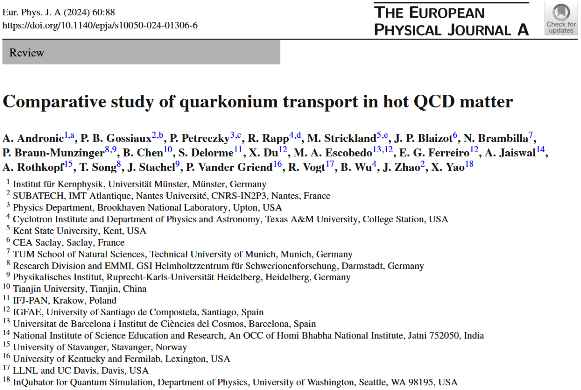
Transport

- (Semi)classical quarkonium
- Dissociation and recombination during QGP phase

Open Quantum Systems

- Fully quantum quarkonium
- Dissociation and (diagonal) recombination during QGP phase

Models



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THE EUROPEAN PHYSICAL JOURNAL A

Review

Comparative study of quarkonium transport in hot QCD matter

A. Andronic[1,a], **P. B. Gossiaux**[2,b], **P. Petreczky**[3,c], **R. Rapp**[4,d], **M. Strickland**[5,e], **J. P. Blaizot**[6], **N. Brambilla**[7], **P. Braun-Munzinger**[8,9], **B. Chen**[10], **S. Delorme**[11], **X. Du**[12], **M. A. Escobedo**[13,12], **E. G. Ferreiro**[12], **A. Jaiswal**[14], **A. Rothkopf**[15], **T. Song**[8], **J. Stachel**[9], **P. Vander Griend**[16], **R. Vogt**[17], **B. Wu**[4], **J. Zhao**[2], **X. Yao**[18]

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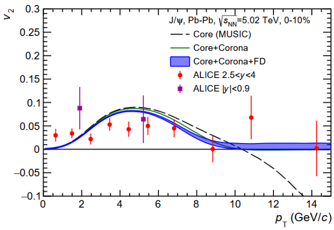
- Review from the EMMI Rapid Reaction Task Force
- Global comparison of models

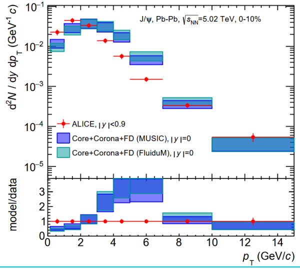
Statistical Hadronization Model

- Assumes that all heavy quarks are produced in primary hard collisions and thermalize.
- Yield $N_{c\bar{c}}^{dir}$ computed in NLO pQCD for pp collisions and then scaled to AA collisions.

$$N_{c\bar{c}}^{dir} = \frac{1}{2} g_c N_{oc}^{th} \frac{I_1(g_c N_{oc}^{th})}{I_0(g_c N_{oc}^{th})} + g_c^2 N_{c\bar{c}}^{th}$$

g_c: fugacity parameter



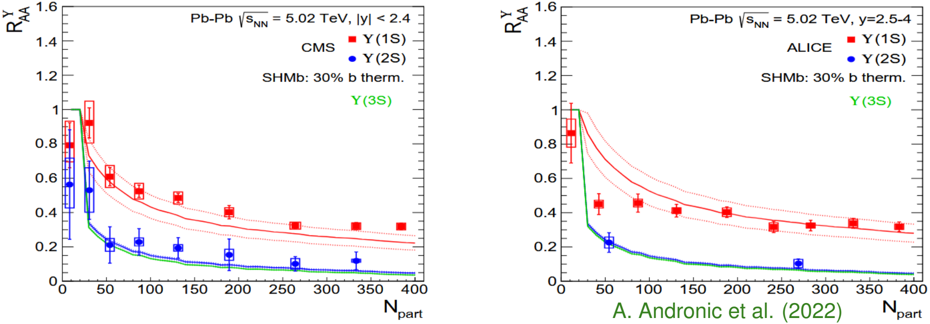


A. Andronic et al. (2024)

- Predictions also for higher states, open charm...

Statistical Hadronization Model

- Similar formalism for bottomonia
- Investigation of the potential partial thermalization of bottom quarks



A. Andronic et al. (2022)

- Around 30% of b quarks aren't thermalized (lower estimate)

Transport models

- 2 main types of transport models

Boltzmann

$$p^\mu \partial_\mu f_\Psi = -\alpha f_\Psi + \beta$$

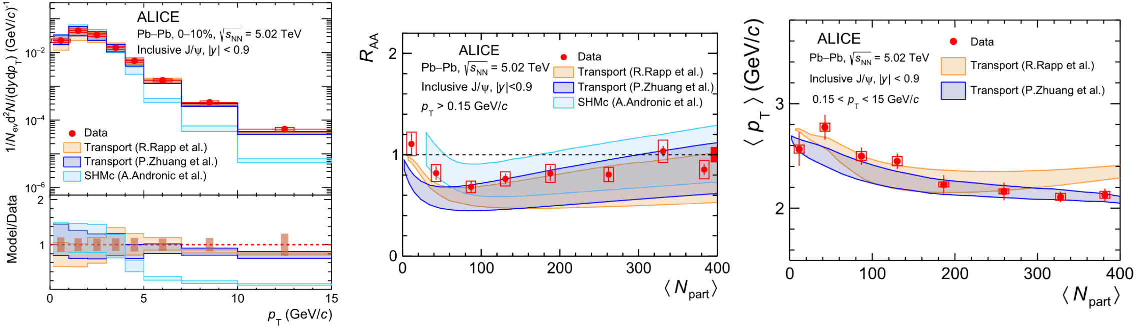
- αf_Ψ : gluon-dissociation
- β : regeneration
- Detailed balance
- Tsinghua model
- Can be obtained from open quantum systems (Duke-MIT)

Rate equation

$$\frac{dN_\Psi(\tau)}{d\tau} = -\Gamma_\Psi(T(\tau))\left[N_\Psi(\tau) - N_\Psi^{eq}(T(\tau))\right]$$

- Γ_Ψ : dissociation rate
- N_Ψ^{eq} : equilibrium limit
- TAMU model

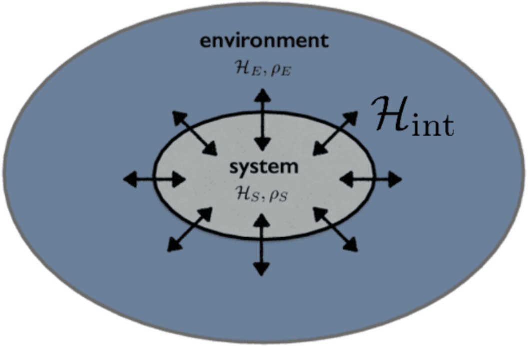
Transport models



ALICE Collaboration (2024)

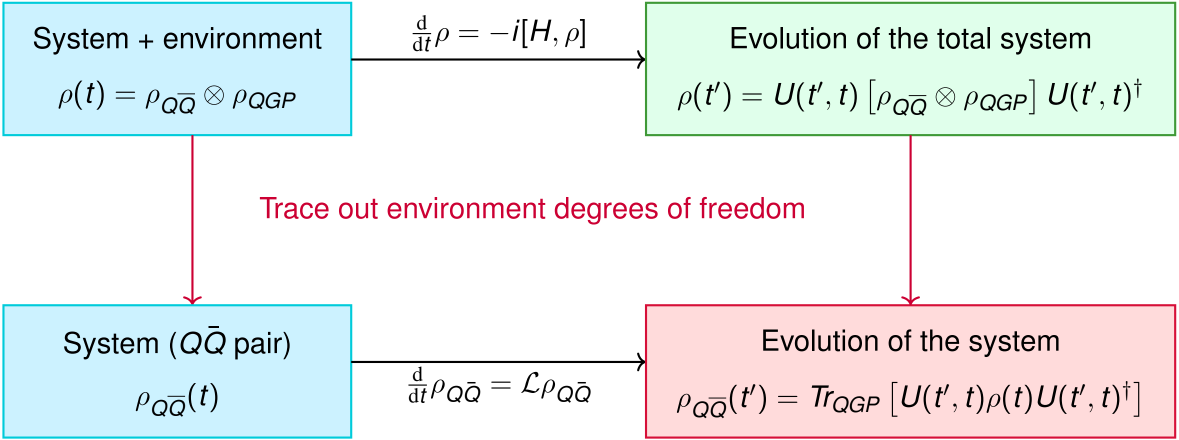
- Transport models reproduce well recent experimental data from ALICE

Open quantum systems



- System ($Q\overline{Q}$) in interaction with an environment (QGP)
- System building correlation with the environment over time
- $H = H_0 + H_{QGP} + H_{\text{int}}$

Open quantum systems



System + environment

$$\rho(t) = \rho_{Q\overline{Q}} \otimes \rho_{QGP}$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho = -i[H, \rho]$$

Evolution of the total system

$$\rho(t') = U(t', t)\left[\rho_{Q\overline{Q}} \otimes \rho_{QGP}\right] U(t', t)^\dagger$$

Trace out environment degrees of freedom

System ($Q\bar{Q}$ pair)

$$\rho_{Q\overline{Q}}(t)$$

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_{Q\bar{Q}} = \mathcal{L}\rho_{Q\bar{Q}}$$

Evolution of the system

$$\rho_{Q\overline{Q}}(t') = Tr_{QGP}\left[U(t', t)\rho(t)U(t', t)^\dagger\right]$$

Lindblad equation

- Case of a Markovian time-evolution ⇒ Lindblad equation

$$\frac{\mathrm{d}}{\mathrm{d}t}\rho_{Q\bar{Q}}(t) = -i\left[H_{Q\bar{Q}}, \rho_{Q\bar{Q}}(t)\right] + \sum_i \gamma_i \left[L_i \rho_{Q\bar{Q}}(t) L_i^\dagger - \frac{1}{2}\left\{L_i L_i^\dagger, \rho_{Q\bar{Q}}(t)\right\}\right]$$

$H_{Q\bar{Q}}$: $Q\bar{Q}$ kinetics + vacuum potential V + screening

L_i : Collapse operators (or dissipators), depend on the properties of the medium

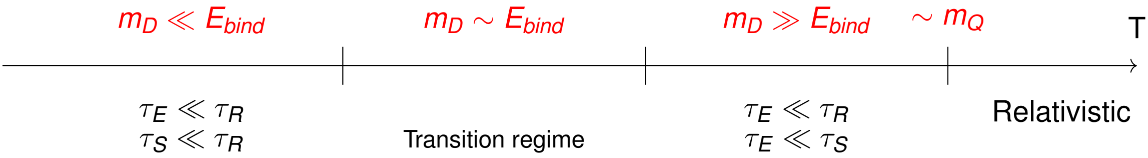
$\langle n\vert\rho_{Q\bar{Q}}\vert n\rangle \geq 0 \; \forall \; n$	$\rho^\dagger_{Q\bar{Q}} = \rho_{Q\bar{Q}}$	$\mathrm{Tr}\left[\rho_{Q\bar{Q}}\right] = 1$
(Positivity)	(Hermiticity)	(Norm conservation)

Can be turned into a Stochastic Schrödinger Equation

Timescales

- 3 relevant timescales:
- τ_R : system relaxation time
  - $\tau_R = \frac{1}{\Gamma} \sim \frac{1}{\alpha_S T}$
- τ_E : environment autocorrelation time
  - $\tau_E \sim \frac{1}{m_D} \approx \frac{1}{CT} \quad C \approx 2$
- τ_S : system intrinsic time
  - $\tau_S \sim \frac{1}{E_{bind}}$
- Markovianity realized if $\tau_E \ll \tau_R$ (environment correlation losing memory during the system relaxation)
- Hierarchy between scales leads to different temperature regimes

Temperature regimes



$m_D \ll E_{bind}$ | $m_D \sim E_{bind}$ | $m_D \gg E_{bind}$ | $\sim m_Q$ | T

$\tau_E \ll \tau_R$

$\tau_S \ll \tau_R$

Transition regime

$\tau_E \ll \tau_R$

$\tau_E \ll \tau_S$

Relativistic

Quantum optical regime

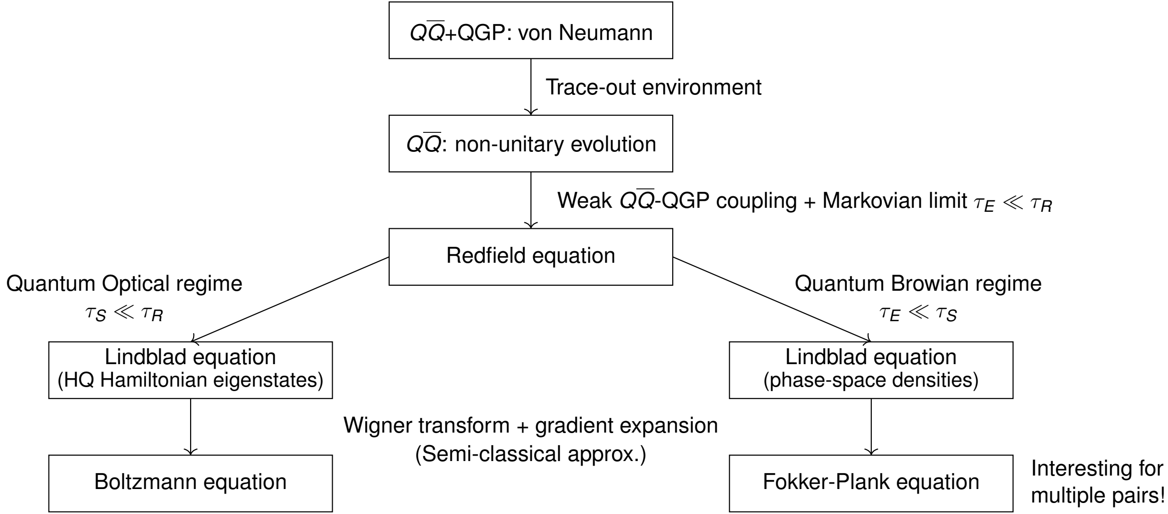
- Well identified states
- Long quantum decoherence time
- Realm of transport models
- Classical limit
  → Boltzmann/Rate equations

Quantum brownian regime

- Broader states
- Short quantum decoherence time
- QME for Q and $\overline{Q}$
- Classical limit
  → Fokker-Plank equations

How to deal with the transition regime?

Schematic view



$Q\overline{Q}$+QGP: von Neumann

Trace-out environment

$Q\overline{Q}$: non-unitary evolution

Weak $Q\overline{Q}$-QGP coupling + Markovian limit $\tau_E \ll \tau_R$

Redfield equation

Quantum Optical regime

$\tau_S \ll \tau_R$

Quantum Browian regime

$\tau_E \ll \tau_S$

Lindblad equation
(HQ Hamiltonian eigenstates)

Lindblad equation
(phase-space densities)

Wigner transform + gradient expansion
(Semi-classical approx.)

Boltzmann equation

Fokker-Plank equation

Interesting for
multiple pairs!

Overview

- 3 main ways of solving QMEs

Direct resolution

- Nantes-Saclay

Stochastic approaches

- TUM-KSU (Quantum Jump)
- Osaka (Quantum State Diffusion)

See talk by Jorge!

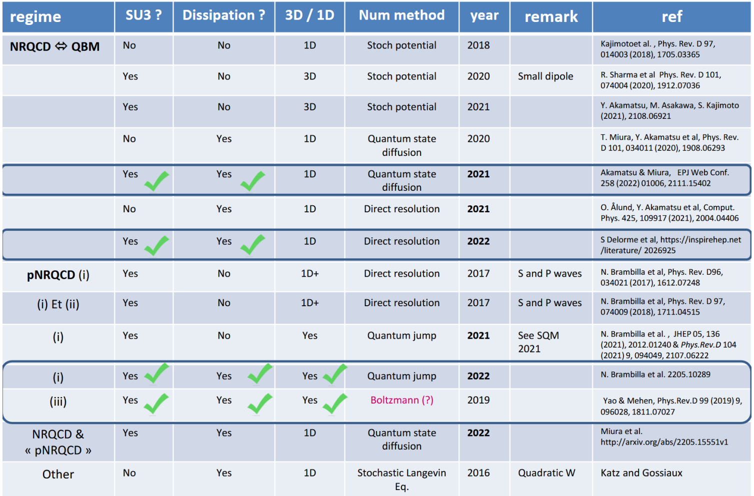
Semi-classical

- Duke-MIT (Boltzmann)
- Nantes-Saclay (Fokker-Plank)

See talk by Pol!

- Approaches either using NRQCD (Nantes-Saclay, Osaka) or pNRQCD (TUM-KSU, Duke-MIT)
- Almost all in Quantum Brownian regime, with the exception of Duke-MIT

Overview



regime	SU3 ?	Dissipation ?	3D / 1D	Num method	year	remark	ref
NRQCD ⇔ QBM	No	No	1D	Stoch potential	2018		Kajimotoet al. , Phys. Rev. D 97, 014003 (2018), 1705.03365
	Yes	No	3D	Stoch potential	2020	Small dipole	R. Sharma et al Phys. Rev. D 101, 074004 (2020), 1912.07036
	Yes	No	3D	Stoch potential	2021		Y. Akamatsu, M. Asakawa, S. Kajimoto (2021), 2108.06921
	No	Yes	1D	Quantum state diffusion	2020		T. Miura, Y. Akamatsu et al, Phys. Rev. D 101, 034011 (2020), 1908.06293
	Yes ✓	Yes ✓	1D	Quantum state diffusion	**2021**		Akamatsu & Miura, EPJ Web Conf. 258 (2022) 01006, 2111.15402
	No	Yes	1D	Direct resolution	**2021**		O. Ålund, Y. Akamatsu et al, Comput. Phys. 425, 109917 (2021), 2004.04406
	Yes ✓	Yes ✓	1D	Direct resolution	**2022**		S Delorme et al, https://inspirehep.net /literature/ 2026925
pNRQCD (i)	Yes	No	1D+	Direct resolution	2017	S and P waves	N. Brambilla et al, Phys. Rev. D96, 034021 (2017), 1612.07248
(i) Et (ii)	Yes	No	1D+	Direct resolution	2017	S and P waves	N. Brambilla et al, Phys. Rev. D 97, 074009 (2018), 1711.04515
(i)	Yes	No	Yes	Quantum jump	**2021**	See SQM 2021	N. Brambilla et al. , JHEP 05, 136 (2021), 2012.01240 & *Phys.Rev.D* 104 (2021) 9, 094049, 2107.06222
(i)	Yes ✓	Yes ✓	Yes ✓	Quantum jump	**2022**		N. Brambilla et al. 2205.10289
(iii)	Yes ✓	Yes ✓	Yes ✓	Boltzmann (?)	2019		Yao & Mehen, Phys.Rev.D 99 (2019) 9, 096028, 1811.07027
NRQCD & « pNRQCD »	Yes	Yes	1D	Quantum state diffusion	**2022**		Miura et al. http://arxiv.org/abs/2205.15551v1
Other	No	Yes	1D	Stochastic Langevin Eq.	2016	Quadratic W	Katz and Gossiaux

- ▶ Not fully exhaustive

Nantes-Saclay approach

- NRQCD formalism in the Quantum Brownian regime in 1D

$$\frac{d}{dt}\begin{pmatrix}\mathcal{D}_s\\ \mathcal{D}_o\end{pmatrix} = \mathcal{L}\begin{pmatrix}\mathcal{D}_s(\mathbf{s},\mathbf{s}',t)\\ \mathcal{D}_o(\mathbf{s},\mathbf{s}',t)\end{pmatrix}$$

$$\mathcal{L} = \begin{pmatrix}\mathcal{L}_{ss} & \mathcal{L}_{so}\\ \mathcal{L}_{os} & \mathcal{L}_{oo}\end{pmatrix}$$

$$\mathcal{L}_0\mathcal{D} = -i\,[H_Q,\mathcal{D}]$$

$$\mathcal{L}_1\mathcal{D} = -\frac{i}{2}\int_{xx'} V(x-x')\,[n^a_x n^a_{x'},\mathcal{D}]$$

$$\mathcal{L}_2\mathcal{D} = \frac{1}{2}\int_{xx'} W(x-x')\,(\{n^a_x n^a_{x'},\mathcal{D}\} - 2n^a_x\mathcal{D}n^a_{x'})$$

Fluctuations

$$\mathcal{L}_3\mathcal{D} = -\frac{i}{4T}\int_{xx'} W(x-x')\left(\dot{n}^a_x\mathcal{D}n^a_{x'} - n^a_x\mathcal{D}\dot{n}^a_{x'} + \frac{1}{2}\{\mathcal{D},[\dot{n}^a_x,n^a_{x'}]\}\right)$$

Dissipation

$$\mathcal{L}_4\mathcal{D} = \frac{1}{32T^2}\int_{xx'} W(x-x')\,(\{\dot{n}^a_x\dot{n}^a_{x'},\mathcal{D}\} - \dot{n}^a_x\mathcal{D}\dot{n}^a_{x'})$$

Positivity preservation

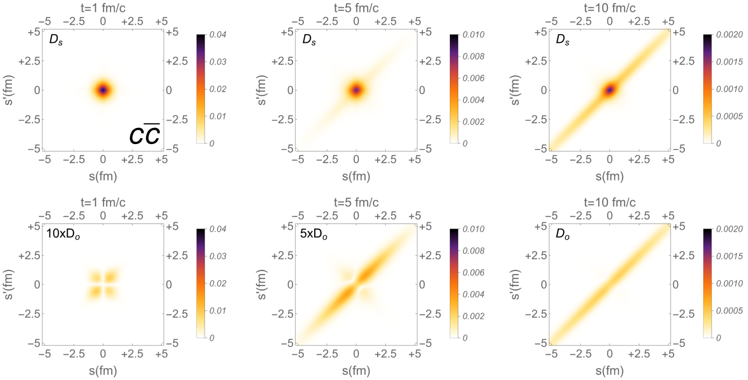
J.-P. Blaizot, M. A. Escobedo (2018)

R.Katz, S.Delorme, P.-B. Gossiaux (2022)

S. Delorme et al. (2024))

- Assume screening of potential
- Different medium configurations and initial states
- Application to $c\bar{c}$ and $b\bar{b}$
  - $b\bar{b}$: Phenomenological study using EPOS4
  - $c\bar{c}$: Benchmark for semi-classical treatment (see Pol's talk)

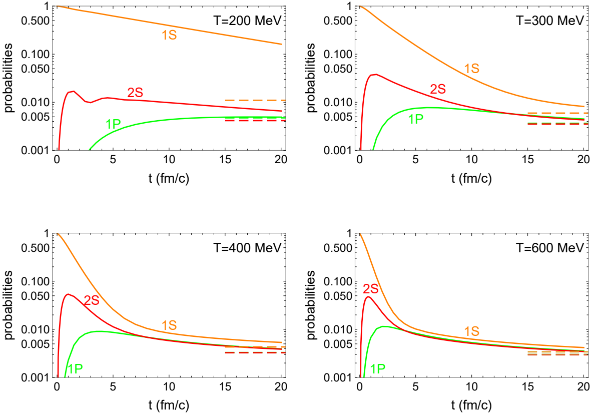
Nantes-Saclay approach



- Initial singlet in-medium 1S state at T = 300 MeV
- Octet populated via dipolar transitions
- Repulsive octet potential ⇒ delocalization
- Delocalization in singlet channel via transitions
- Surviving central peak in singlet channel

No dipole approx: can model the pair at finite distance

Nantes-Saclay approach



- 2S and 1P states generated during the evolution
- Faster evolution with increasing T
- Close asymptotic values as T increases ($\mathcal{D}_s$ nearly diagonal)

Conclusion

- The finite-temperature potential encodes the in-medium properties of quarkonia. Recent work points to a non-screened real part and a stronger imaginary part.
- Several models aim at describing the evolution of quarkonia in the Quark-Gluon Plasma.
- The statistical hadronization model and transport models can reproduce fairly well experimental data
- Open Quantum Systems models aim at developing a real-time evolution framework from first principles, including all quantum effects.
- Lots of progress made but important problems left to solve: treatment of multiple pairs, description of the transition regime