Dynamical quarkonia suppression with the Schrödinger-Langevin approach in a realistic AA background

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with Pol-Bernard Gossiaux

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A little curriculum

(2011-2012) Master thesis at Lund University - Sweden
\textit{J/\psi polarisation in pp collisions within the k_T-factorisation framework.}
Supervisor: R. Pasechnik

(2012-2015) PhD thesis at SUBATECH - France
\textit{(Semi-)quantum approaches to dynamical quarkonia supression in AA collisions.}
Supervisors: P.B. Gossiaux (SUBATECH) and E. Bratkovskaya (FIAS)

(2016-2018) Postdoc at the University of São Paulo - Brazil
\textit{Building a simulation (“DAB-MOD”) to study open heavy flavour propagation in event-by-event viscous hydrodynamic QGP. Exploration of their azimuthal anisotropies through the cumulant method and new observables.}

Also very interested in cosmology research.

Personal website: rolandkatz.com
Summary

- Background and motivations
- Schrödinger-Langevin model
- Results
Hard probes

To study the medium properties beyond the freeze out «horizon»...

✓ Nature ? Weakly or strongly interacting ?
✓ Density and temperature ?
✓ Transport properties (viscosity, spatial diffusion...) ?

... one can analysed the «tomography» of the medium realised by the hard probes (high $p_T$ or massive partons)
Hard probes

Why hard probes are interesting?

- Produced in pQCD processes, only at the very beginning of the collision
- Do not flow hydrodynamically but propagate/interact through other processes that are sensitive to the medium properties
- Known Q\bar{Q} initial production (CNM ?)
- Simple 2 particles systems
- Binding described by potentials
- Some bound states may survive above T_c
- Weakly affected by the final hadronic phase
- However: the state formation times are subject to debate => states form before, in-medium or at the freeze out?

They can propagate inside the QGP all along its evolution to probe it

And quarkonia specifically?

- Can be mastered to probe the QGP temperature and deconfinement

Background
Schrödinger-Langevin model
Results
Common models of quarkonia suppression in QGP

**Sequential suppression (Matsui and Satz)**
- Based on states $T_{\text{diss}}$
- If $T_{\text{QGP}} > T_{\text{diss}}$, the state is dissociated forever
- If $T_{\text{QGP}} < T_{\text{diss}}$, the state evolves adiabatically

$\Rightarrow$ *Quarkonia as early QGP thermometer*

**Statistical hadronisation (Braun-Munzinger, Stachel...)**
- All $Q\bar{Q}$ pairs are dissociated
- Statistical recombination at freeze-out

$\Rightarrow$ *Quarkonia as thermometer of $T_c$*

**Transport models (Zhao, Rapp, Zhuang...)**
- Sequential suppression like but
- Quarkonia $\leftrightarrow$ Q+$\bar{Q}$ possible during the evolution

$\Rightarrow$ *Quarkonia as continuous QGP thermometer*

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Description of the data

**Background**

**Schrödinger-Langevin model**

**Results**

**RHIC**

- STAR
- STAR Cu+Cu
- PHENIX ($p_t > 0$)
- Model I, Liu et al.
- Model II, Zhao et al.

**LHC run 1**

- ALICE Preliminary, 2.76 TeV Pb+Pb, $|y|<0.9$
- PHENIX, 200 GeV Au+Au, $|y|<0.35$
- Stat. Hadron Model (A. Andronic et al)
- Transport Model I (X. P. Liu et al), LHC
- Transport Model II (X. Zhao et al), LHC
- Transport Model I, RHIC
- Transport Model II, RHIC

Irregular description of the kinetic dependences
Looking at recent data

✓ Hints for some recombination into low $p_T J/\psi$

Significant $v_2$

(Alternative idea: partial thermalisation of color octet states ?)
Looking at recent data

✓ Hints for some recombination into low $p_T \ J/\Psi$

At mid-$y$: ordering with $s_{NN}$

At forward-$y$: ordering with $s_{NN}$

while not observed for the bottomonia (more suppression as $s_{NN}$ increases)

$\rightarrow$ Considering some recombination of uncorrelated charm/anticharm quarks is most probably necessary to any model aiming to describe the data
Looking at recent data

✓ Relative sequential-like suppression between the quarkonium states

Charmonia

But: smooth evolution with centrality (not really « steps-like » behaviour)
Looking at recent data

But a bit puzzling...

Ratio $\psi(2S) / J/\psi$ at forward-$\gamma$

Comparison $J/\psi$ and $D^0$

LHC run 1: « unexpected » ratio $> 1$
no more observed at LHC run 2

Similar RAA even at higher pT:
- cannot be recombination
- troubling that sequential-like ($J/\psi$) and
Eloss/diffusion+fragmentation ($D^0$) dynamics
give the same behaviour...

CMS arXiv:1611.01438v1
## Common model assumptions

<table>
<thead>
<tr>
<th>Sequential suppression (Matsui and Satz)</th>
<th>Statistical hadronisation (Braun-Munzinger, Stachel...)</th>
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</tr>
</thead>
<tbody>
<tr>
<td>• Everything happens at the BEGINNING in a quasi-stationary medium</td>
<td>• Everything happens at the END in a quasi-stationary medium</td>
<td>• More dynamical and all-inclusive</td>
</tr>
<tr>
<td>• Questionable $T_{\text{diss}}$</td>
<td>• No states survive</td>
<td>• Questionable $T_{\text{diss}}$</td>
</tr>
<tr>
<td>• Adiabatic evolution</td>
<td>• Only recombination</td>
<td>• Questionable cross-section approach</td>
</tr>
<tr>
<td>• No recombinations</td>
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</tbody>
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Problem: very dynamic medium, state formation times not mastered, no effects from non-dissociative interactions, no transitions between bound states...

A screening + recombination scenario is conceptually simple and attractive but more realistic treatment are required

$\rightarrow$ real-time dynamics of the QQ pair

(and not only of its bound states)

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**Common model assumptions**

**Sequential suppression** (Matsui and Satz)

- Everything happens at the BEGINNING in a quasi-stationary medium
- Questionable $T_{\text{diss}}$
- Adiabatic evolution
- No recombinations

Problem: very dynamic medium, state formation times not mastered, no effects from non-dissociative interactions, no transitions between bound states...

A screening + recombination scenario is conceptually simple and attractive, but more realistic treatments are required - real-time dynamics of the QQ pair (and not only of its bound states)

Our motto

Consider:
color screening, thermal effects and QGP dynamics

INNER DYNAMICS OF EACH $Q\bar{Q}$ PAIR
A dynamical and continuous picture of the dissociation, recombination, transitions to other bound states and energy exchanges with the QGP.

+ 

QQ PAIRS EVOLUTION IN QGP
Realistic $t$-dependent background:
Monte-Carlo event generator with initial fluctuations
Inner dynamics ? -> back to concepts

Very complicated QFT problem at finite $T(t)$ !!!

Beware of quantum coherences during the whole evolution!

How ?

Treatment within the open quantum system framework!

Other frameworks: cross sections, imaginary potentials from QFT at finite $T$, EFT and lQCD...

Dating back to Blaizot & Ollitrault, Thews, Cugnon and Gossiaux; early 90’s
Inner dynamics: open quantum systems

The common open quantum system approach

- **Idea:** density matrix and \{quarkonia + bath\} => bath integrated out
  ⇒ non unitary evolution + decoherence effects
  ⇒ At equilibrium: Boltzmann distributions \( \propto \exp\left(\frac{-E_n}{k_B T}\right) \)

**But** defining the bath/interaction is complex and application entangled

- Borghini and Gombeaud*
  simple model of bath and Einstein rate equation
  But: unable to thermalise the inner dynamics

- Akamatsu, Rothkopf et al.**
  closed-time path integral formalism + LO thermal QCD
  ⇒ complex potential / master equations
  ⇒ stochastic potential equation in the recoilless limit
  But: rising energy problem.

See also Young and Dusling (2013), Blaizot (2016), De Boni (2017)...

Will a pQCD + open quantum system formalism describe the data?

Inner dynamics: open quantum systems

Langevin-like approaches

➢ Idea: Effective equations (possibly not from first QCD principles) with few parameters to unravel/mock the open quantum approach while keeping most of the quantum features

Heavy quarks are Brownian particles ($M_Q >> T$) + Drag $A(T)$

=> need for Langevin-like equation

($A(T)$ from single heavy quark observables or lQCD calculations)

Semi-classical *
Inspired by Young and Shuryak **

Schrödinger-Langevin equation

Include fluctuation/dissipation mechanisms to mimic the dense QGP-Q$\bar{Q}$ collisions and real in-medium potentials for the screening

Inner dynamics: semi-classical model

In few words: Evolution of Wigner distributions with a classical Langevin dynamic

=> Interesting suppression patterns:
    smooth evolutions, more suppression at LHC than at RHIC...

BUT

1) Without fluctuation-dissipation:
   discrepancies with pure quantum results

2) Uncorrect thermalisation
   + violation of Heisenberg principle at low T

=> Need for a fluctuation-dissipation mechanism
   compatible with quantum mechanics !!
Inner dynamics: Schrödinger-Langevin (SL) equation

Derived from the Heisenberg-Langevin equation*, in Bohmian mechanics** ...

\[
\frac{i\hbar}{\partial t} \Psi_{Q\overline{Q}}(\mathbf{r}, t) = \left( \hat{H}_{MF}(\mathbf{r}) - \mathbf{F}_R(t) \cdot \mathbf{r} + A \left( S(\mathbf{r}, t) - \langle S(\mathbf{r}, t) \rangle_{\mathbf{r}} \right) \right) \Psi_{Q\overline{Q}}(\mathbf{r}, t)
\]

**Hamiltonian:** Mean Field: T-dependent color screened potential
Generally taken from lattice-QCD

**Static lQCD calculations** (maximum heat exchange with the medium):

\[ F : \text{free energy} \quad U = F + TS : \text{internal energy} \]  

\[ S : \text{entropy} \quad \text{(no heat exchange)} \]

- “Weak potential” \( F < V_{\text{weak}} < U \) => some heat exchange
- “Strong potential” \( V = U \) => adiabatic evolution

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Inner dynamics: Schrödinger-Langevin (SL) equation

Derived from the Heisenberg-Langevin equation, in Bohmian mechanics...

\[ i\hbar \frac{\partial \Psi_{QQ}(\mathbf{r}, t)}{\partial t} = \left( \hat{H}_{\text{MF}}(\mathbf{r}) - \mathbf{F}_R(t) \cdot \mathbf{r} + A \left( S(\mathbf{r}, t) - \langle S(\mathbf{r}, t) \rangle_{\mathbf{r}} \right) \right) \Psi_{QQ}(\mathbf{r}, t) \]

**Hamiltonian**: Mean Field: T-dependent color screened potential

Generally taken from lattice-QCD. Only singlet for now.

3D not easy to implement \(\Rightarrow\) 1D simplified model

not aim to reproduce the data but rather gives insights on the dynamics.

**1D simplification**

Parameters \((K, V_{\text{max}})\) chosen to reproduce quarkonium spectrum + \(B\bar{B}\) or \(D\bar{D}\) threshold

Linear approx Screening\((T)\) as \(\text{VIQCD}\)
Inner dynamics: SL equation

Derived from the Heisenberg-Langevin equation, in Bohmian mechanics ...

\[ i\hbar \frac{\partial \Psi_{QQ}(\mathbf{r}, t)}{\partial t} = \left( \hat{H}_{MF}(\mathbf{r}) - \mathbf{F}_{R}(t) \cdot \mathbf{r} + A \left( S(\mathbf{r}, t) - \langle S(\mathbf{r}, t) \rangle_{R} \right) \right) \Psi_{QQ}(\mathbf{r}, t) \]

Fluctuations: thermal excitation
Taken as a « classical » white stochastic force/noise
scaled such as to obtain \( T_{QQ} = T_{QGP} \) at equilibrium

The noise operator is assumed here to be a commutating c-number whereas it is a non-commutating q-number within the Heisenberg-Langevin framework.

**Inner dynamics: SL equation**

Derived from the Heisenberg-Langevin equation, in Bohmian mechanics ...

\[
i\hbar \frac{\partial \Psi_{Q\bar{Q}}(\mathbf{r}, t)}{\partial t} = \left( \hat{H}_{\text{MF}}(\mathbf{r}) - \mathbf{F}_R(t) \cdot \mathbf{r} + A \left( S(\mathbf{r}, t) - \langle S(\mathbf{r}, t) \rangle_r \right) \right) \Psi_{Q\bar{Q}}(\mathbf{r}, t)
\]

**Dissipation: thermal de-excitation**

\[
S(\mathbf{r}, t) = \arg \left( \Psi_{Q\bar{Q}}(\mathbf{r}, t) \right)
\]

✓ non-linearly dependent on \( \Psi_{Q\bar{Q}} \)
✓ real and ohmic
✓ brings the system to the lowest state
✓ with \( A(T) \alpha T^2 \) the Drag coefficient from a microscopic model (pQCD - HTL) by Gossiaux and Aichelin

Properties of the SL equation

- 2 parameters: A (Drag) and T (temperature)
- Unitarity and Heisenberg principle satisfied at any T
- Non linear => Violation of the superposition principle (=> decoherence)
- A priori not related to a quantum master equation: the decoherence effects are probably not rigorous. We might be missing some physics.

- Mixed state observables from statistics:

\[
\left\langle \left\langle \psi(t) | \hat{O} | \psi(t) \right\rangle \right\rangle_{\text{stat}} = \lim_{n_{\text{stat}} \to \infty} \frac{1}{n_{\text{stat}}} \sum_{r=1}^{n_{\text{stat}}} \left\langle \psi^{(r)}(t) | \hat{O} | \psi^{(r)}(t) \right\rangle
\]

- Easy to implement numerically (especially in Monte-Carlo generator)
Properties of the SL equation

- Leads to local « thermal » distributions: Boltzmann behaviour for at least the low lying states

\[ W_i(t \gg \tau_{\text{relax}}) \]

\[ \text{Populations } \propto \exp \left( \frac{-E_n}{k_B T} \right) \]

(weak coupling limit: no shift and broadening of the energy levels assumed)

=> Fluctuation-dissipation mechanism compatible with quantum mechanics and effective !!

Initial Q\bar{Q} pair wavefunction?

The Q\bar{Q} pairs are produced at the very beginning BUT state formation times are subject to debate => we test the two extrem behaviours:

- the Q\bar{Q} pair is fully decoupled into eigenstates:
  \[ \psi_{Q\bar{Q}}(t=0) = \psi_i(T=0) \]
  or

- the Q\bar{Q} pair is not decoupled:
  \[ \psi_{Q\bar{Q}}(t=0) = \text{"a mixture of Gaussian S and P components"} \]
  tuned to obtain correct feed-downs and production ratios.

e.g.: contribution to Y(1S) from feed downs:
Evolution of the $Q\bar{Q}$ pairs on EPOS2 background

- Very good model for heavy ion collisions with initial fluctuations and ideal 3D hydrodynamics
- $Q\bar{Q}$ pairs initial positions: given by Glauber model
- No Cold Nuclear Matter effects (no shadowing and no hadronic scatterings)
- $Q\bar{Q}$ pair center-of-masse motion: along straight lines with no $E_{\text{loss}}$ (assumed to be color singlet)
- Focus on bottomonia for now (CNM and statistical recombination small)

Observables

« weight » (population) $W_i$:

$$W_i(t) = |\langle \Psi_i(T = 0)|\Psi_{\bar{Q}Q(t)} \rangle|^2$$

Normed weights $S_i$:

$$S_i(t) = W_i(t)/W_i(t = 0)$$

The only « physical » values are at the freeze out.

$S_i(t)$ at freeze out convoluted with $p_T$-y spectra in pp collisions $\Rightarrow R_{AA}$
Example of evolution

Observations
- Smooth evolutions (especially for higher excited states)
- No strong $p_T$ dependence
- Important transitions between bound states
- Not everything is about thermal decay widths

Background
Schrödinger-Langevin model
Results

Initial gaussian « S+P »

Initial reequilibration and suppression

Saturation at large time ($V$ closer to $V_{vac}$)

Strong suppression of $Y(2S)$,
Taking place on longer times
Influence of initial state

**Background**

Schrödinger-Langevin model

**Results**

Initial $Y(1S)$

- $Y(1S)/Y(1S,t=0)$
- Initial $Y(1S)$

- Initial gaussian $\langle S+P \rangle$

- $1P$ component feeds the $Y(1S)$ at small times

Initial $Y(2S)$

- $Y(2S)/Y(2S,t=0)$
- Initial $Y(2S)$

- Initial gaussian $\langle S+P \rangle$

- $Y(2S)$ found at the end of QGP evolution are mostly the ones regenerated from the $1S$ & $1P$
LHC (2.76 TeV): $R_{AA}(p_T)$

With initial Gaussian “S+P” and feed-downs

Flatish!

( helped by approximations: drag $A$ and feed downs independent of momentum)
LHC (2.76 TeV): $R_{AA}(p_T)$

With feed-downs F<V<U “S+P” Gaussian

Same idea for P states
LHC (2.76 TeV): $R_{AA}(N_{\text{part}})$

With feed-downs "S+P" Gaussian

Background Schrödinger-Langevin model Results

lack of suppression in most central events (CNM ?)

RHIC (200 GeV): $R_{AA}(N_{\text{part}})$

With Kolb-Heinz QGP background

F<$\text{V}$<U  “S+P” Gaussian  With feed-downs

STAR data for $Y(1S)$ ($|y|<1$):

- Au+Au 200 GeV
- U+U 193 GeV

Roughly good agreement with the data (with $F<$V$_{\text{weak}}<$U)
RHIC (200 GeV): $R_{AA}(N_{\text{part}})$

With Kolb-Heinz QGP background

With potential $U$: stronger dependence on initial state

Background
Schrödinger-Langevin model
Results

No feed-downs

$R_{AA}$

U-like

$N_{\text{part}}$

V$_{\text{Weak}}$

Au+Au, 200 AGeV

$Y(1S)$

: decoupled

$Y(2S)$

: Gaussian

$N_{\text{part}}$

With potential $U$: stronger dependence on initial state
**RHIC (200 GeV): $R_{AA}(N_{\text{part}})$**

With Kolb-Heinz QGP background

$Y(1S)+Y(2S)+Y(3S)$

“S” + “P” Gaussian  With feed-downs

STAR data for $Y(1S)+Y(2S)+Y(3S)$ ($|y|<1$):

- **Au+Au 200 GeV**
- **U+U 193 GeV**

$V=U$-like

$F<V<U$

Decoupled approx

With potential $U$: less good results as compared to data
Conclusion

- Assumptions of the sequential suppression model -> unjustified.
- Semi-classical frameworks a la Young and Shuryak -> important pitfalls
- The Schrödinger-Langevin equation: interesting framework but not derived from first QCD principles. The QCD features enter in the parameters (similarly to Langevin dynamics in heavy flavor physics).
- Mandatory to consider both the screening and thermal effects
- Transitions between bound and open quantum states and between bound quantum states -> crucial role. The former -> dissociation and recombination, whereas the second -> regeneration
- Reproduce data trends with potential F<V<U
- A possible connection between dynamical and statistical models
- Drag for single heavy quarks and quarkonia -> unified description
Conclusion

Future

- EPOS at RHIC
- Better understanding of initial state
- Recombination of uncorrelated pairs
- CNM effects
- Add color octet states and potentials
- Is it a good thermometer? (↔ how sensitive are the results on the T(t) scenario and its fluctuations?)
- 3D Schrödinger-Langevin dynamics
- Comparison of the results with other models. How good it mimics more rigorous open quantum system approaches?

Thank you!

Roland Katz – 21/09/2017
Back-up
Semi-classical approach

The “Quantum” **Wigner distribution of the cc pair**:

\[
F(x, p, t) = \int e^{\frac{i p y}{\hbar}} \psi^*(x + \frac{y}{2}) \psi(x - \frac{y}{2}) \, dy
\]

... is **evolved** with the “classical”, 1\textsuperscript{st} order in \(\hbar\), Wigner-Moyal equation + FP:

\[
\left[ \left( \frac{\partial}{\partial t} + \frac{p}{m} \frac{\partial}{\partial x} \right) - \frac{\partial}{\partial p} \frac{\partial}{\partial x} V(x) \right] F(x, p, t) = \nabla_p \left( A f + \nabla_p (B f) \right)
\]

Finally, the **projection** onto the J/\(\psi\) state is given by:

\[
W_S(t) = \int F(\vec{r}, \vec{p}, t) F_S(\vec{r}, \vec{p}) \frac{d^3p d^3r}{(\hbar c)^3}
\]

**But in practice**: N test particles (initially distributed with the same gaussian distribution in (r, p) as in the quantum case), that evolve with Langevin Newton’s laws, and give the J/\(\psi\) weight:

\[
W_S(t) = \frac{1}{N} \sum_{i=1}^{N} F_S(r_i(t), p_i(t))
\]