(SEMI REALISTIC) QUARKONIA (PRODUCTION) ~~AND~~ IN A REALISTIC MEDIUM

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New observables in Quarkonium Production
Trento (Italy)
29/02/2016 – 4/03/2016

Subatech **and TOGETHER Pays de la Loire**

In few words ?

Initial quasi stationary **Sequential Suppression** assumption (Matsui & Satz 86)

Final quasi stationary **Statistical Hadronisation** assumption (Andronic, Braun-Munzinger & Stachel)

???

???

Dynamical Models (implicit hope to measure T above Tc); often relies on some hypothesis not fully justified:

- (In medium) dissociation cross-section (how valid in dense medium ?)
- Prob survival $= \exp\left(-\int_{t_0}^{t_{\text{fin}}} \Gamma(T(t))dt\right)$
- …

In few words ?

Initial quasi stationary
Sequential Suppression
assumption
(Matsui & Satz 86)

Final quasi stationary
Statistical Hadronisation
assumption
(Andronic, Braun-Munzinger & Stachel)

???

Dynamical Models
implicit hope to measure T above Tc

???

➡ **a more dynamical point of view :**

- ✓ **QGP genuine time dependent scenario**
- ✓ **quantum description of the $Q\bar{Q}$**
- ✓ **screening, thermalisation**

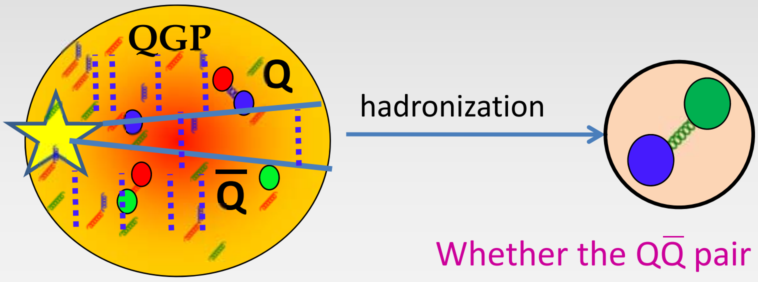
Motivation

Quarkonium formation and Q-Qbar evolution in URHIC is a deeply quantum and dynamical problem requiring

- ✓ **QGP genuine time-dependent scenario**
- ✓ **quantum description of the $Q\bar{Q}$**
- ✓ **interaction between the 2 systems (screening, « thermalisation »)**

A priori: Nothing is instantaneous, nothing is adiabatic, nothing is stationnary and nothing is *decoupled*

Motivation



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

No independent Υ(1S), Υ(2S),.. evolution during QGP history

Whether the $Q\bar{Q}$ pair emerges as a quarkonia or as open mesons is <u>only resolved at the end of the evolution</u>

Beware of quantum coherence during the evolution !

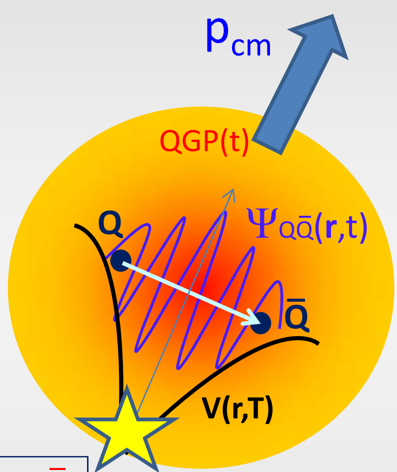
Need for full quantum treatment

Dating back to Blaizot & Ollitrault, Thews, Cugnon and Gossiaux; early 90's

Ingredients for a generic model

QGP temperature scenarios T(t,x)

Cooling QGP



Initial $Q\bar{Q}$ state

Mean field: color screened binding potential V(r,T)

polarization due to color charges

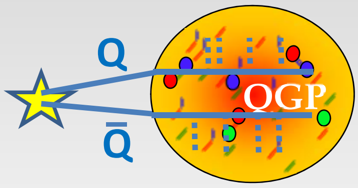
+

Thermalisation and diffusion

Direct interactions with the thermal bath

+ Dynamical scheme

Dynamical scheme ?



Partonic approach

Very complicated QFT ... lem !

NOT EFFECTIVE(1)

The com... approach

- **Idea:** density m... + bath} => bath integrated out
  ⇒ non u...tion + decoherence effects

  Akamatsu* -> complex potential
  Borghini** -> a master equation

- **But** defining the bath is complicated and the calculation entangled…

* Y. Akamatsu Phys.Rev. D87 (2013) 045016 ; ** N. Borghini et al., Eur. Phys. J. C 72 (2012) 2000

(1) See however Jean-Paul Blaizot et al: Nucl.Phys. A946 (2016)

Dynamical scheme ?

Effective: Langevin-like approaches ✓

Quarkonia are Brownian particles ($M_{Q\bar{Q}} >> T$)

+ **Drag A(T) => need for a Langevin-like eq.**

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

- **Idea:** Effective equations to unravel/mock the open quantum approach

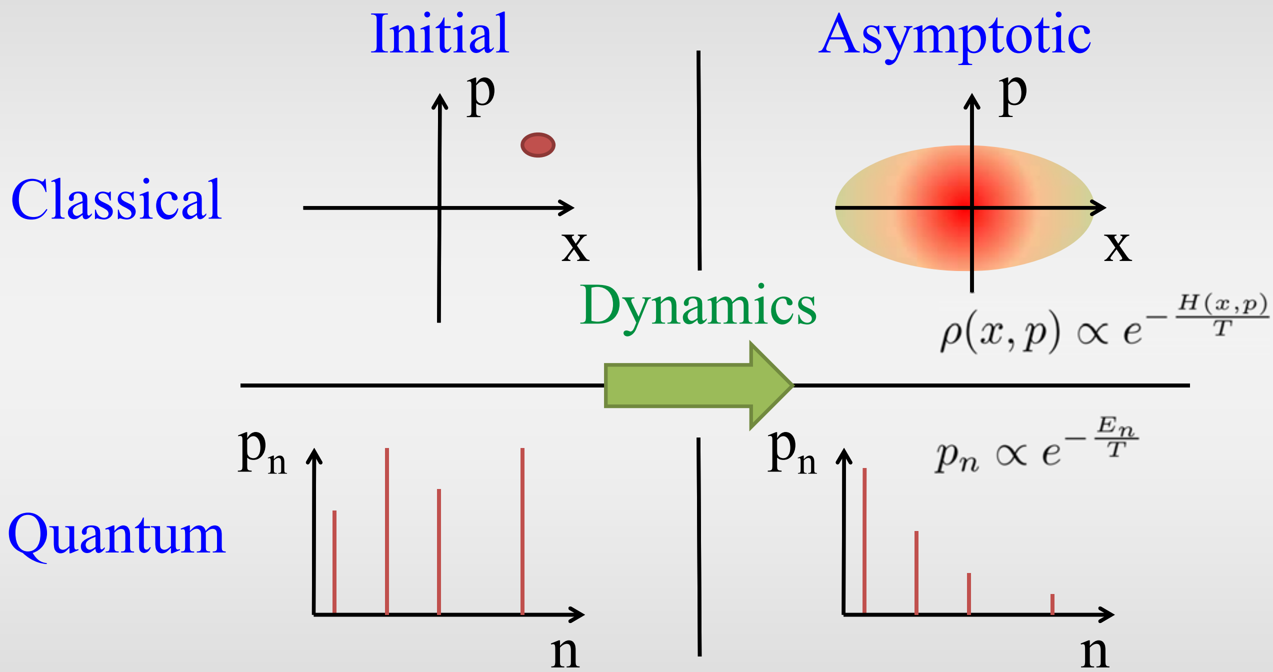
  Young and Shuryak * -> semi-classical Langevin
  Akamatsu and Rothkopf ** -> stochastic and complex potential

Semi-classical See our SQM 2013 proceeding ***	Schrödinger-Langevin equation	Others Failed at low/medium temperatures

Effective thermalisation from fluctuation/dissipation

* C. Young and Shuryak E 2009 Phys. Rev. C 79: 034907 ; ** Y. Akamatsu and A. Rothkopf. Phys. Rev. D 85, 105011 (2012) ;
*** R. Katz and P.B. Gossiaux J.Phys.Conf.Ser. 509 (2014) 012095

Important feature of Langevin Dynamics



Need for Einstein relation aka fluctuation-dissipation theorem: challenge for effective approaches

Schrödinger-Langevin (SL) equation

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

$$i\hbar \frac{\partial \Psi_{Q\bar{Q}}(\mathbf{r},t)}{\partial t} = \left(\widehat{H}_{\mathrm{MF}}(\mathbf{r}) - \mathbf{F}_{\mathbf{R}}(t).\mathbf{r} + A\big(S(\mathbf{r},t) - \langle S(\mathbf{r},t)\rangle_{\mathbf{r}}\big) \right) \Psi_{Q\bar{Q}}(\mathbf{r},t)$$

$\mathbf{r} = b - \bar{b}$ relative position

Hamiltonian includes the Mean Field (color binding potential)

* Kostin The J. of Chem. Phys. 57(9):3589–3590, (1972)
** Garashchuk et al. J. of Chem. Phys. 138, 054107 (2013)

Schrödinger-Langevin (SL) equation

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Dissipation

✓ non-linearly dependent on $\Psi_{Q\bar{Q}}$

$$S(\mathbf{r},t) = \arg\big(\Psi_{Q\bar{Q}}(\mathbf{r},t)\big)$$

✓ real and ohmic

✓ ***A*** = drag *coefficient* (inverse relaxation time)

✓ Brings the system to the lowest state

Schrödinger-Langevin (SL) equation

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

$$i\hbar\frac{\partial\Psi_{Q\bar{Q}}(\mathbf{r},t)}{\partial t} = \left(\widehat{H}_{\mathrm{MF}}(\mathbf{r}) - \mathbf{F}_{\mathbf{R}}(t).\mathbf{r} + A\big(S(\mathbf{r},t) - \langle S(\mathbf{r},t)\rangle_{\mathbf{r}}\big)\right)\Psi_{Q\bar{Q}}(\mathbf{r},t)$$

Fluctuations

taken as a « classical » stochastic force

White quantum noise *

$$\langle F_R(t)F_R(t+\tau)\rangle = 2mA\,E_0\left[\coth\left(\frac{E_0}{kT_{\mathrm{bath}}}\right) - 1\right]\delta(\tau)$$

Color quantum noise **

$$\langle N[F_R(t)F_R(t+\tau)]\rangle = \frac{2mA}{\pi}\int_0^\infty \frac{\hbar\omega}{\exp(\hbar\omega/kT_{\mathrm{bath}}) - 1}\cos(\omega\tau)\,d\omega.$$

* I. R. Senitzky, Phys. Rev. 119, 670 (1960); 124}, 642 (1961).
** G. W. Ford, M. Kac, and P. Mazur, J. Math. Phys. 6, 504 (1965).

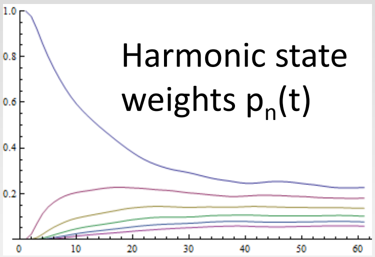
Properties of the SL equation

- 2 parameters: A (Drag) and T (temperature)
- Unitarity (no decay of the norm as with imaginary potentials)
- Heisenberg principle satisfied at any T
- Non linear => Violation of the superposition principle (=> decoherence)
- Gradual evolution from pure to mixed states (large statistics)
- Mixed state observables:

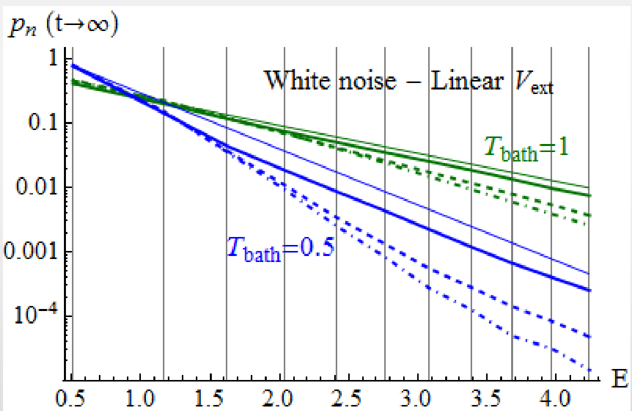
$$\left\langle \langle\psi(t)|\hat{O}|\psi(t)\rangle \right\rangle_{\text{stat}} = \lim_{n_{\text{stat}}\to\infty} \frac{1}{n_{\text{stat}}} \sum_{r=1}^{n_{\text{stat}}} \langle\psi^{(r)}(t)|\hat{O}|\psi^{(r)}(t)\rangle$$

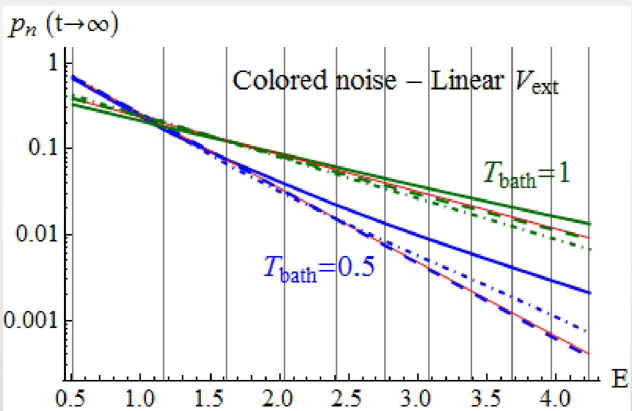
- Easy to implement numerically (especially in Monte-Carlo event by event generator)

Equilibration with SL equation



Leads the subsystem to thermal equilibrium (Boltzmann distributions) for at least the low lying states



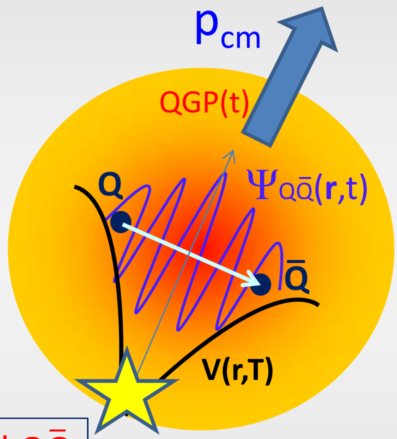


See R. Katz and P. B. Gossiaux, arXiv:1504.08087 [quant-ph]. Accepted for publication in Annals of Physics

Ingredients for a dynamical model based on Schroedinger-Langevin Equation

QGP temperature scenarios T(t,x)

Cooling QGP



Initial $Q\bar{Q}$ state

Mean field: color screened binding potential V(r,T)

polarization due to color charges

+

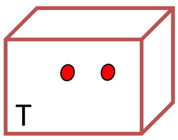
Thermalisation and diffusion: √ need $A(T,p_{cm})$

Direct interactions with the thermal bath

+ Dynamical scheme √

Mean color field : screened $V(T_{red}, r)$ binding the $Q\bar{Q}$

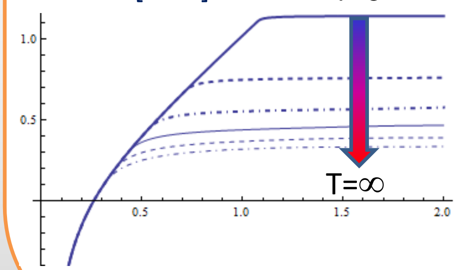
Static lQCD calculations (maximum heat exchange with the medium):



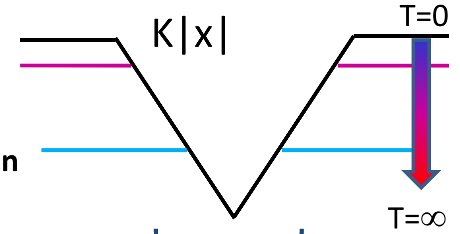
F : free energy
S : entropy

U=F+TS : internal energy (no heat exchange)

- "Weak potential" $F<V_{weak}<U$ * => some heat exchange
- "Strong potential" V=U ** => adiabatic evolution



1D simplification



Linear approx

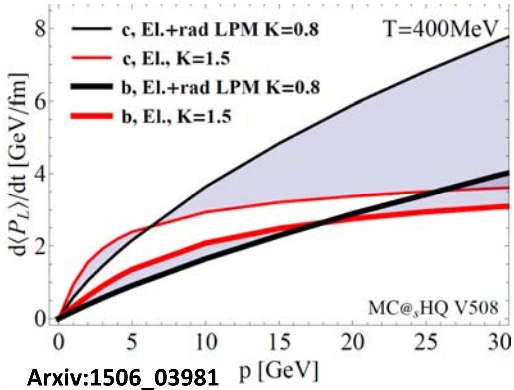
Screening(T) as Vweak

K chosen such that: $E_2-E_0 = E(\Upsilon(2S))-E(\Upsilon(1S))$

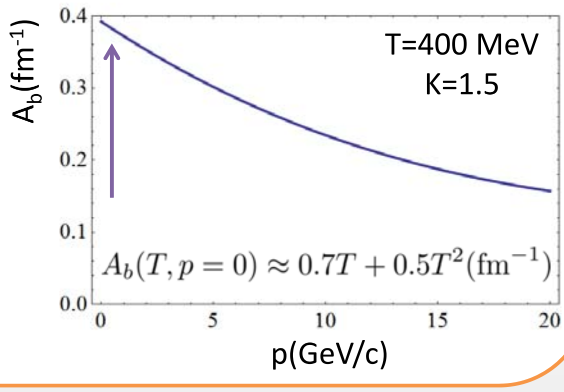
* Mócsy & Petreczky Phys.Rev.D77:014501,2008
** Kaczmarek & Zantow arXiv:hep-lat/0512031v1

Drag coefficient A_b

- Obtained within our running α_s approach*



Arxiv:1506_03981



Initial $Q\bar{Q}$ wavefunction

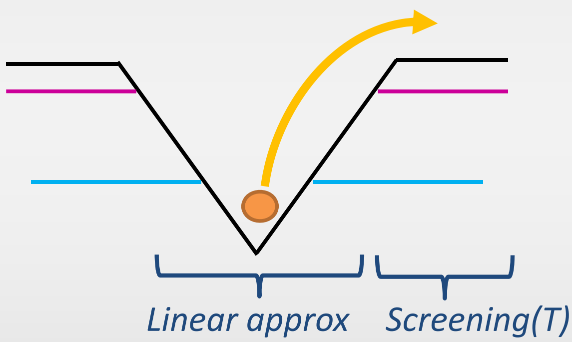
- Produced at the very beginning : $\tau_f^{Q\bar{Q}} \sim \hbar/(2m_Q c^2) < 0.1\ \mathrm{fm/c}$
- We assume either a formed state (Y(1S) or Y(2S)) OR a more realistic Gaussian wavefunction with parameter $a_{b\bar{b}} = 0.045\ \mathrm{fm}$ (from Heisenberg principle)

* P.B. Gossiaux and J. Aichelin 2008 Phys. Rev. C 78 014904

Dynamics of $Q\bar{Q}$ with SL equation

1) Evolutions at constant T

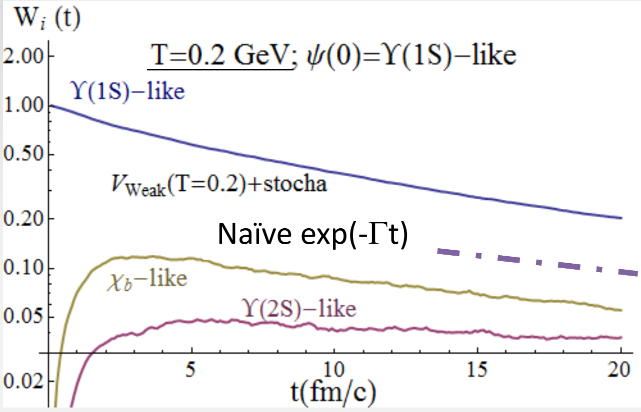
- Simplified Potential but contains the essential physics

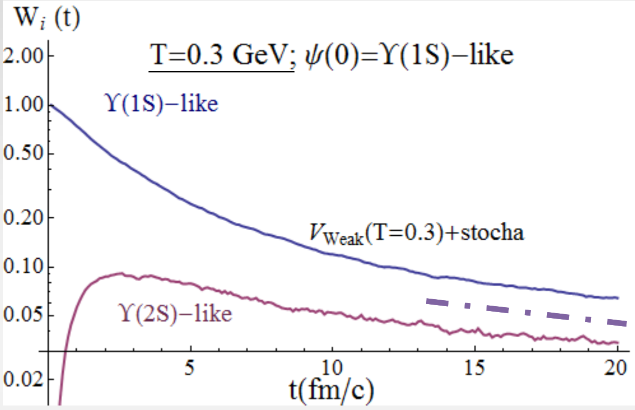


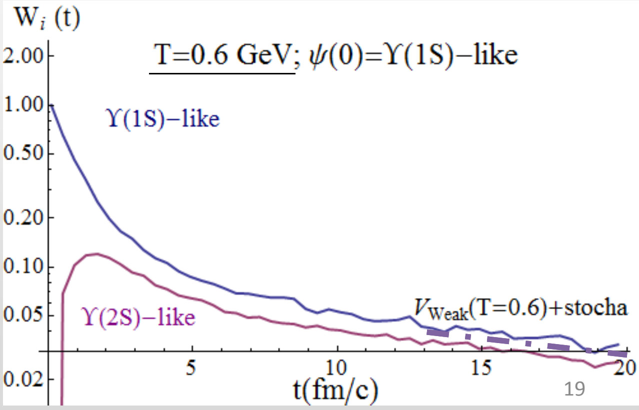
Stochastic forces => feed up of higher states and continuum => Leakage of bound component

- Observables: **Weight** $W_i(t) = \left\langle \left| \langle \psi_i(T=0) | \psi_{Q\bar{Q}}(t) \rangle \right|^2 \right\rangle_{\mathrm{stat}}$

Evolutions with V(T=cst) + Fstocha



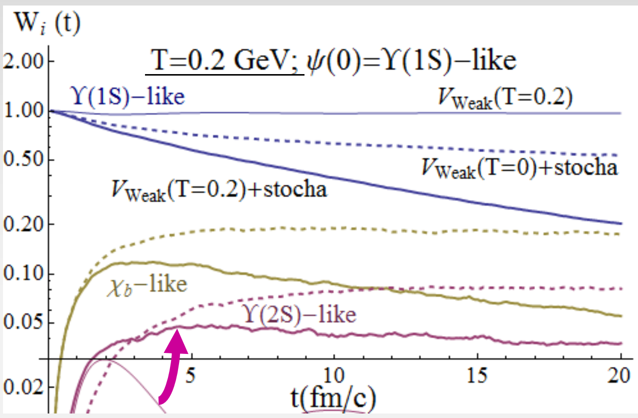


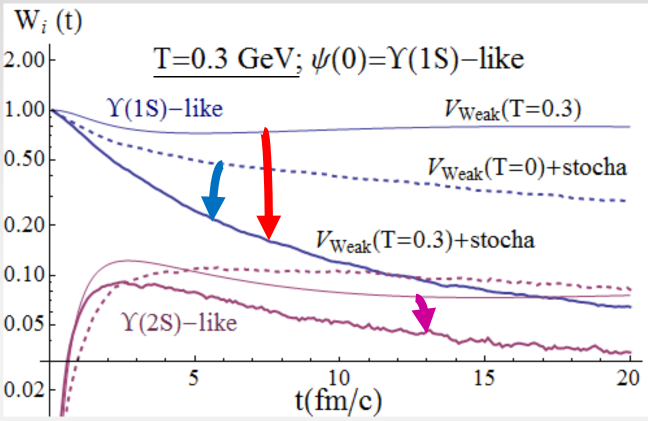


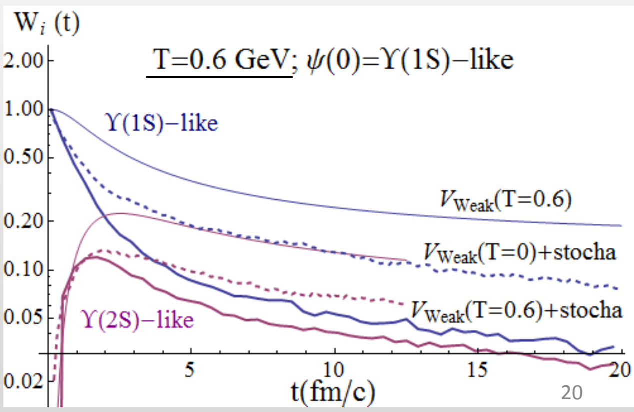
- ✓ Common decay law at large t (leakage+internal equilibration)
- ✓ Γ increases with T
- ✓ Starting from Υ(1S), higher states are asymptotically more populated at large T.

Motivation Dynamical model **Application to bottomonia** Conclusion

Evolutions with V(T=cst) + Fstocha







- ✓ Υ(1S): The stochastic forces leads to larger suppressions
- ✓ Υ(2S): ……… for T≥0.3 only
- ✓ The screening also leads to larger suppression

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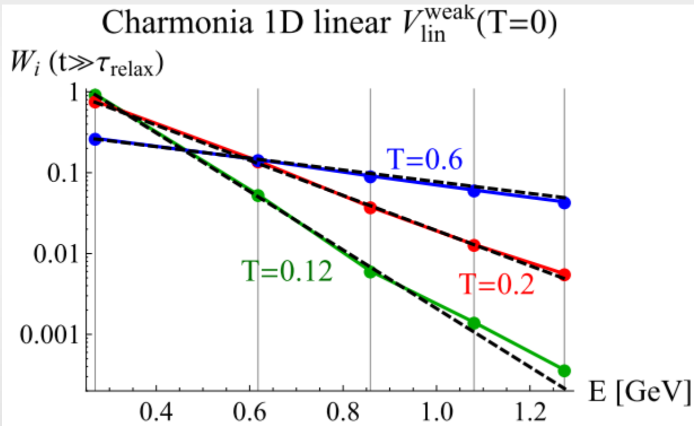
Asymptotics with V(T=0) + Fstocha

Local equilibrium -> $\propto \exp\left(\frac{-E_n}{k_B T}\right)$!



This sanity check is a unique feature of our approach

2) Evolution in EPOS2*

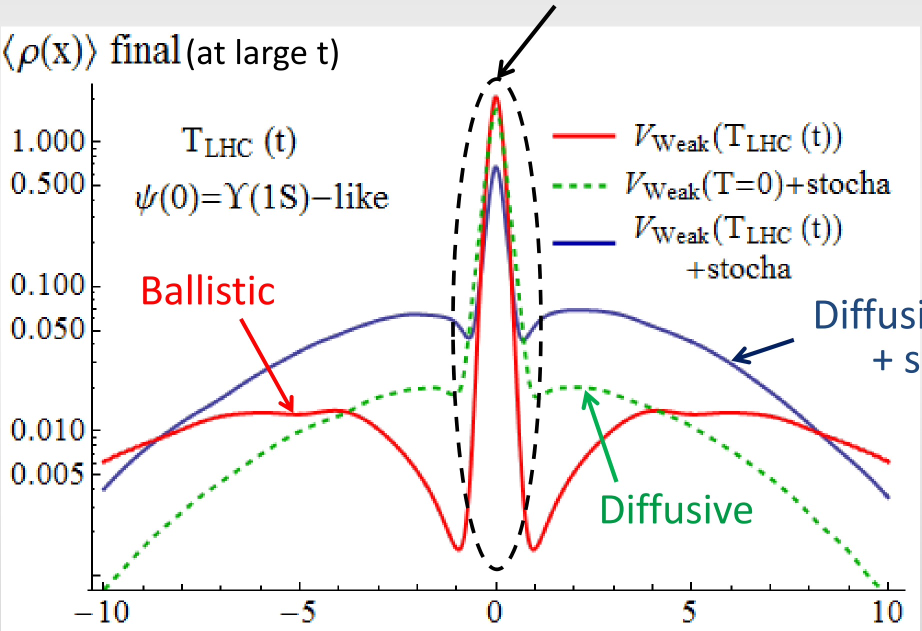
- Very good model for AA URHIC
- Glauber model for initial position of the b-bar pairs (assumed to be color singlets and then moving straight line with no Elos)
- In general, initial internal bbar state chosen as a gaussian
- Observables:
  - **Weight :** $W_i(t) = \left\langle \left|\langle \psi_i(T=0)|\psi_{Q\bar{Q}}(t)\rangle\right|^2 \right\rangle_{\rm stat}$
  - **Survivance :** $S_i(t) = W_i(t)/W_i(t=0)$ $\equiv R_{AA}$
- No CNM effects
- NOT AIMED to reproduce exp. Data (just grasp the global trends)

* K. Werner, I. Karpenko, T. Pierog, M. Bleicher and K. Mikhailov, Phys. Rev. C 82 (2010) 044904. K. Werner, I. Karpenko, M. Bleicher, T. Pierog and S. Porteboeuf-Houssais, Phys. Rev. C 85 (2012) 064907

Density with V(TLHC(t,0)) and initial Y(1S)

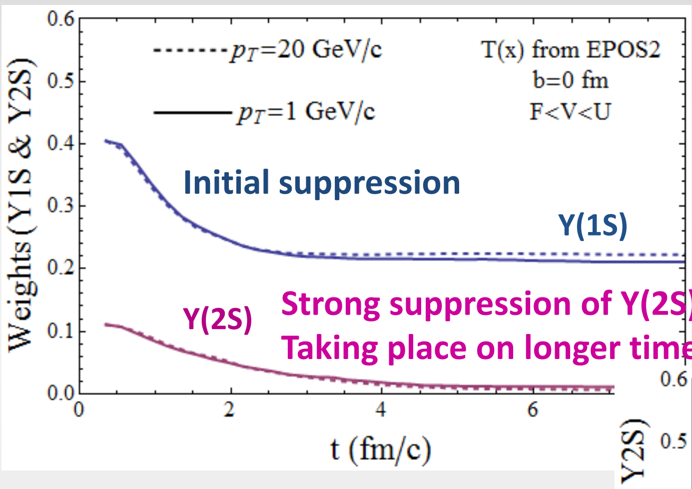
Case of bbar at hottest QGP point and at rest

Trapped $b\bar{b}$



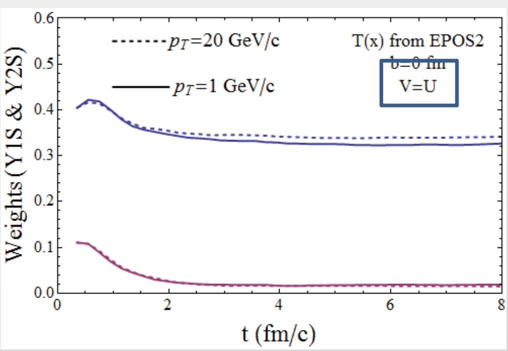
Full EPOS2 evolutions with initial Gaussian

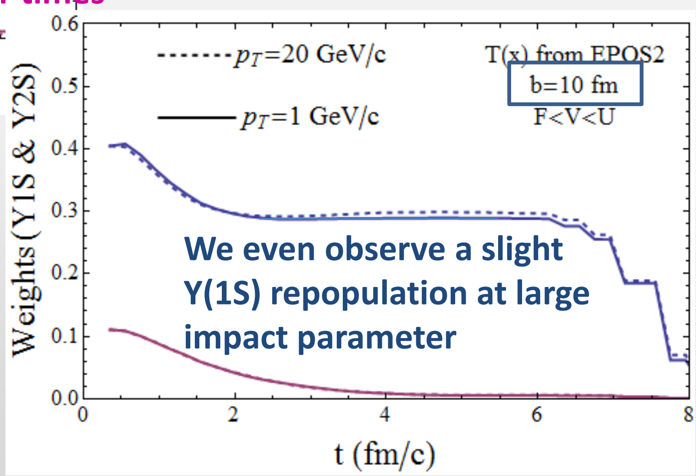
Preliminary



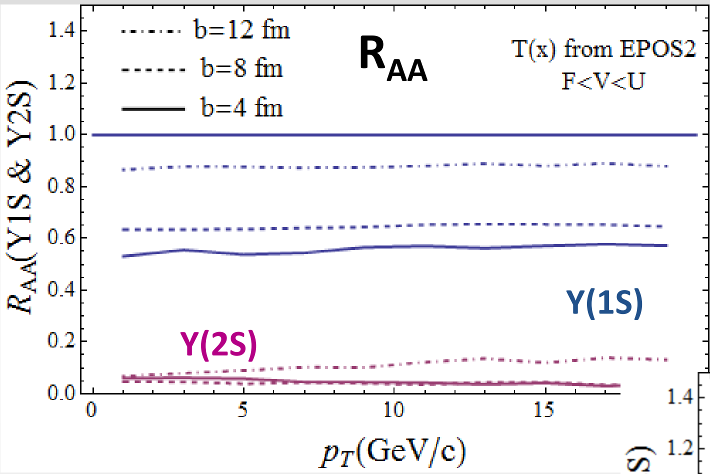
NO STRONG p_T DEPENDENCE

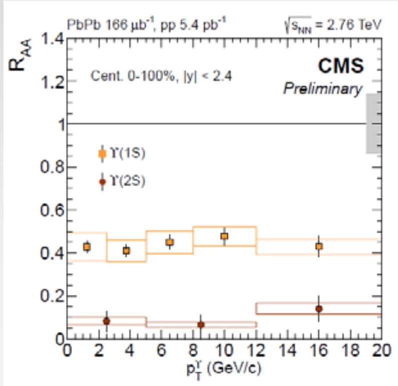
Saturation at large time (V closer to V_{vac})

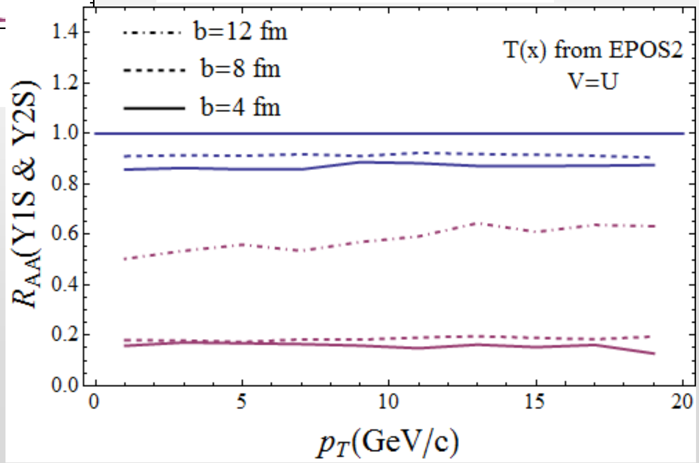




Final suppression (1)







Indeed, flatish $R_{AA}(p_T)$, except for the Y(2S) in peripheral collisions

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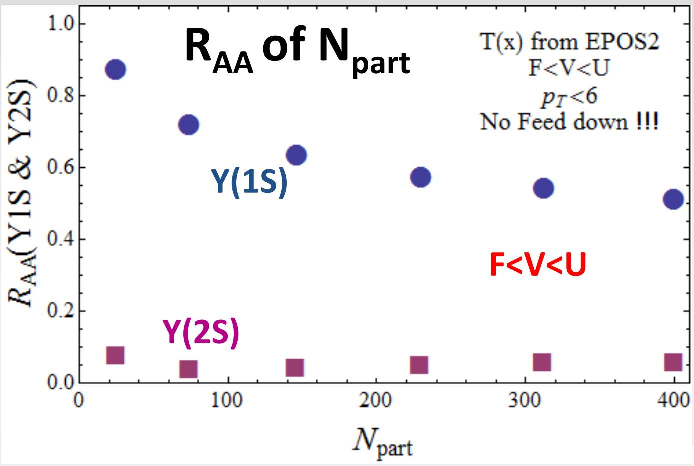
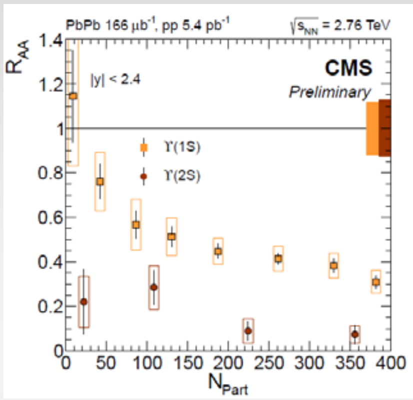
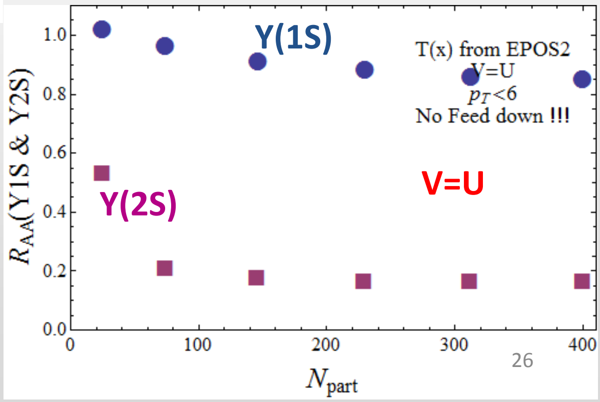
Motivation Dynamical model **Application to bottomonia** Conclusion

Final suppression (2)





From this first investigation, V=U is not favored by the CMS data



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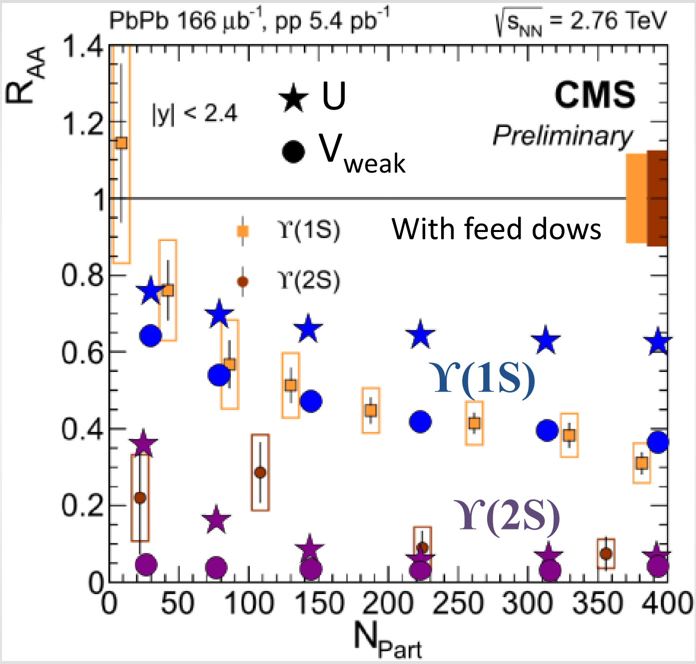
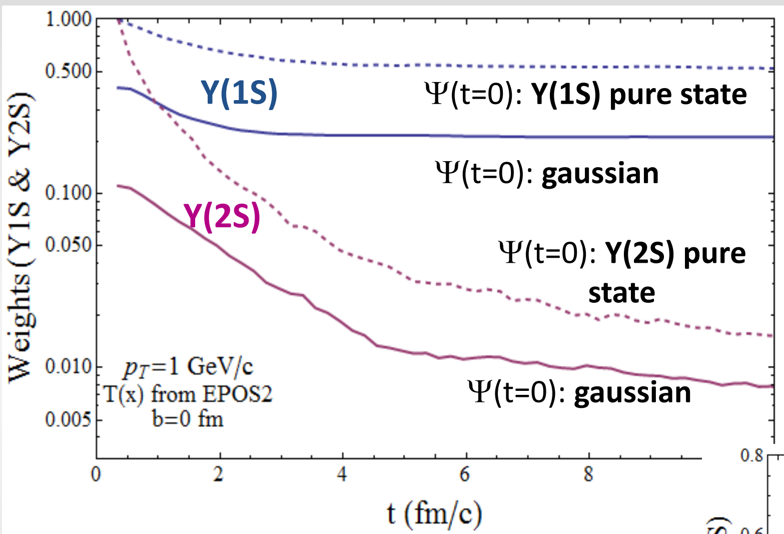
With feed down



With feed downs => V_{weak} favored by CMS data

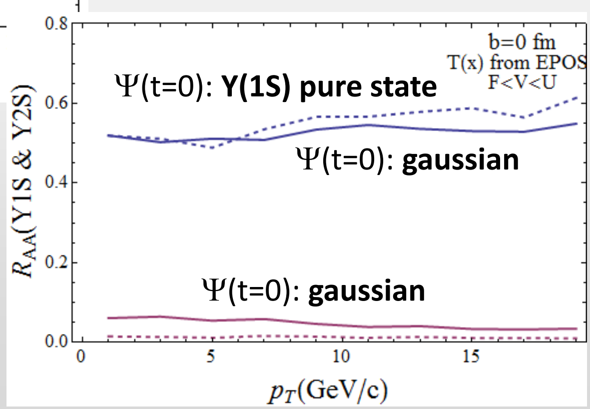
Refined analysis: Role of initial bbar state



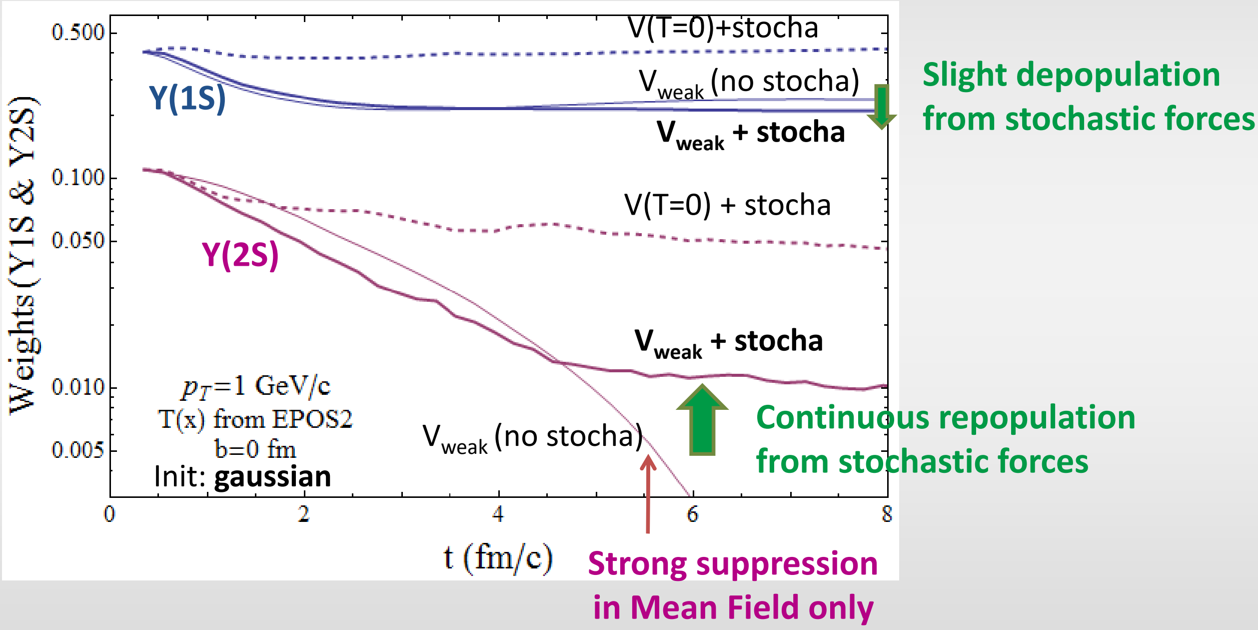
Original Y(2S) would survive with a probability less then 2%

In actual life $\psi_{init} \approx$ Gaussian =>

Y(2S) found at the end of QGP evolution are mostly the ones regenerated from the Y(1S)



Refined analysis: Role of the various contributions in the SLE



Conclusion

- SLE: Framework satisfying all the fundamental properties of quantum evolution in contact with a heat bath, “Easy” to implement numerically
- Rich suppression patterns of bbar and bottomonia states
- First implementation in “state of the art background” (EPOS)
- Reproduces experimental trends

➢ Future:
  - ❑ 3D internal dof and use of genuine potential extracted from the lattice => more reliable comparison with experiments
  - ❑ Identify the limiting cases and make contact with the other models (a possible link between statistical hadronization and dynamical models)
  - ❑ Pre-QGP and post-QGP evolution ?

New observables ?

- Application to quarkonia production in pA
- Polarization in AA ?
- Correlation between D-Dbar and B-Bbar with small invariant mass: