SEMI-REALISTIC DYNAMICAL BOTTOMONIUM SUPPRESSION IN A REALISTIC AA BACKGROUND

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(Charm) Strangeness (& Beauty) in Quark Matter 2016
Berkeley (USA)
27/06/2016 – 1/07/2016

Subatech and TOGETHER Pays de la Loire

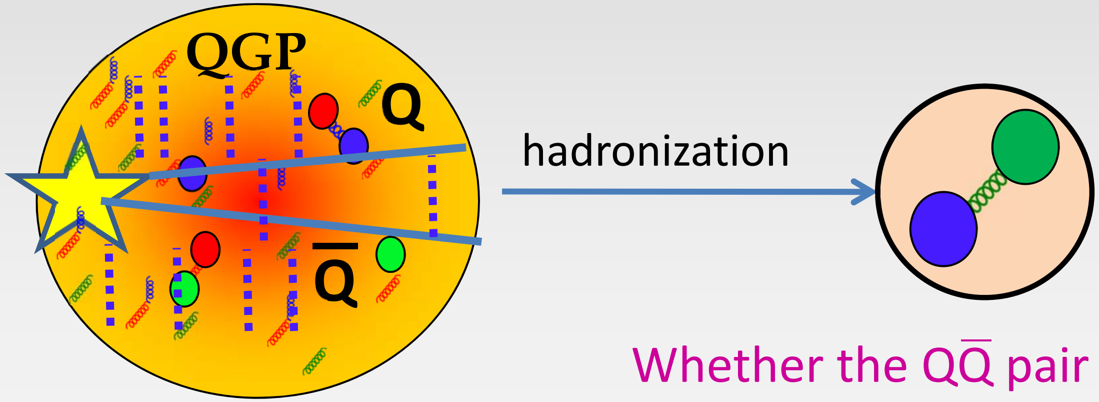
Motivation

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) !!!

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>

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

Beware of quantum coherence during the evolution !

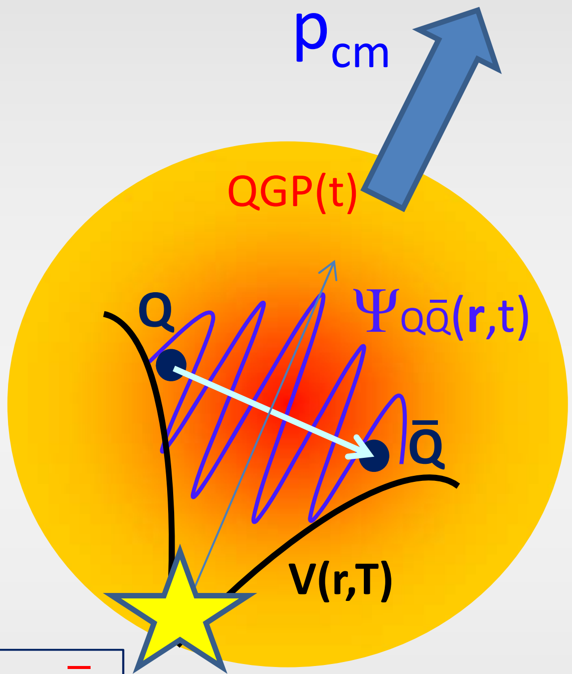
Need for full quantum treatment

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 ?

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	Schrödinger-Langevin equation	Others
See our SQM 2013 proceeding ***	presented at SQM 2015	Failed at low/medium temperatures

Semi-classical and Schrödinger-Langevin equation: Effective thermalisation from fluctuation/dissipation

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* 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. Gossaiux J.Phys.Conf.Ser. 509 (2014) 012095

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 **

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

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* 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)**

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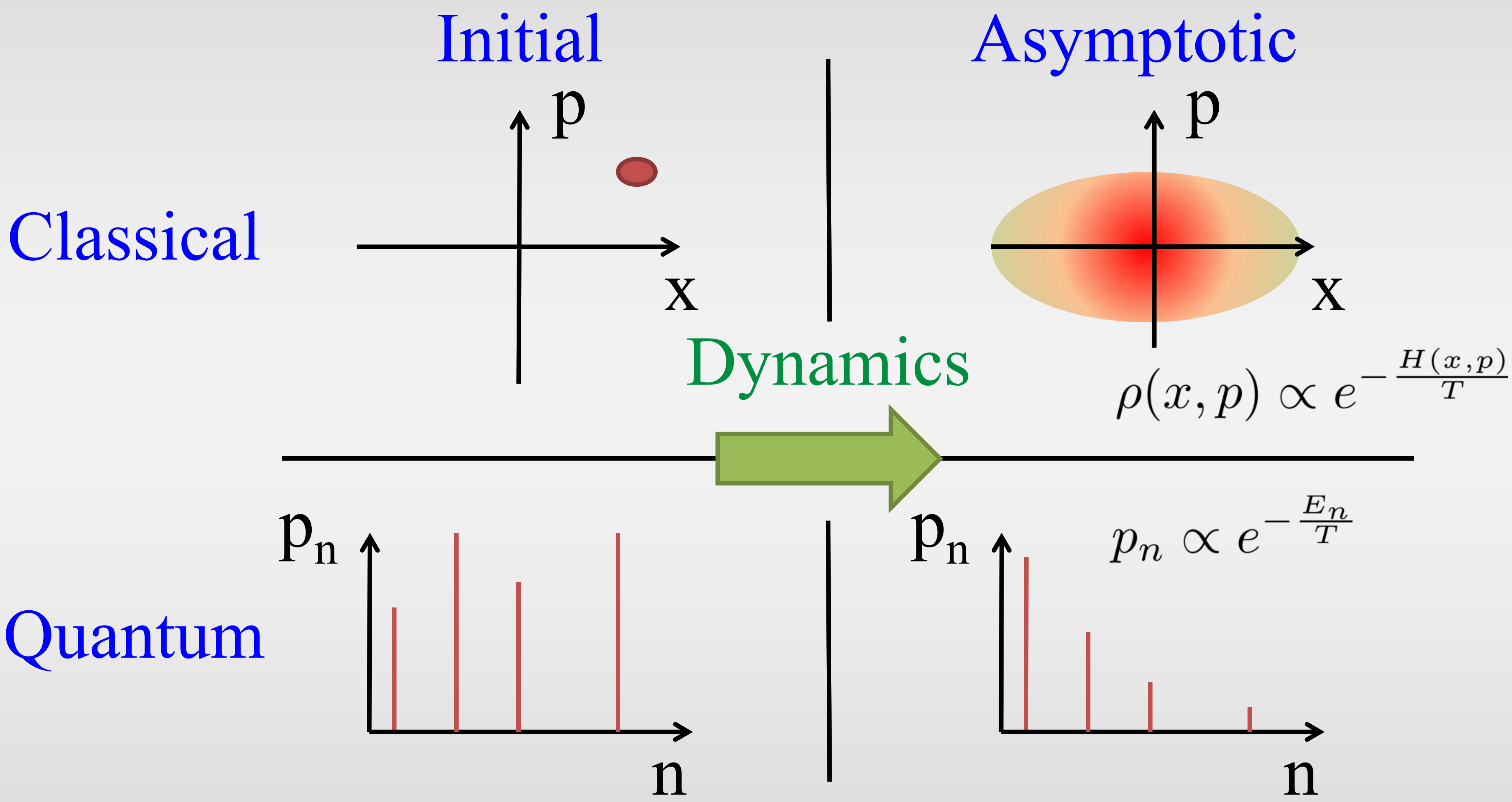
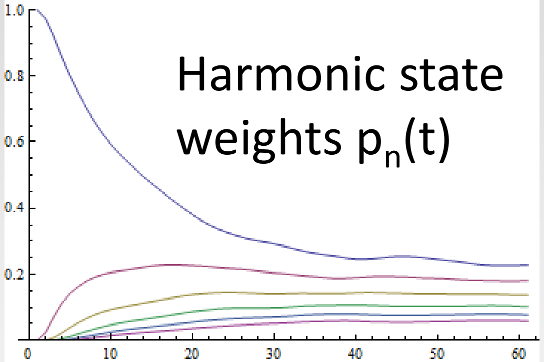
Important feature of Langevin Dynamics

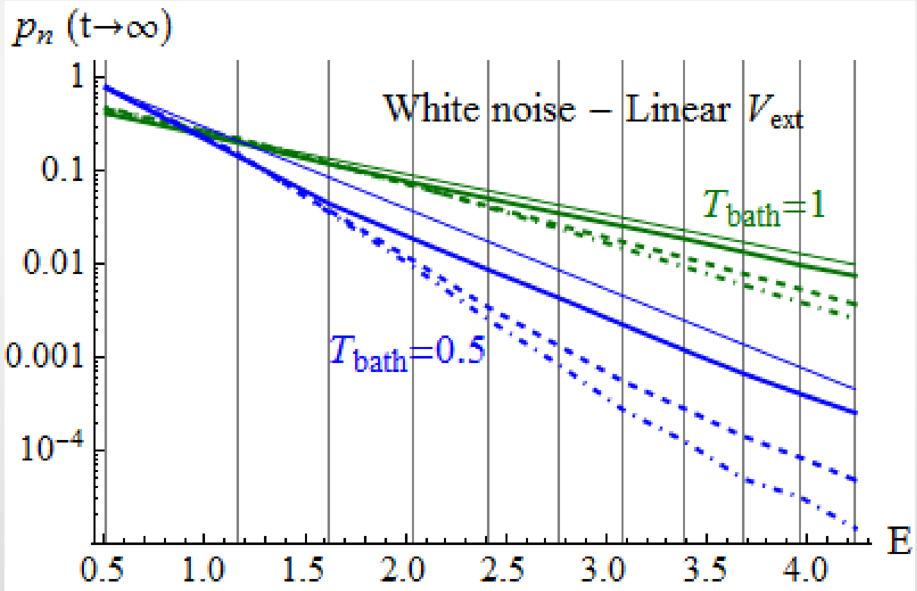


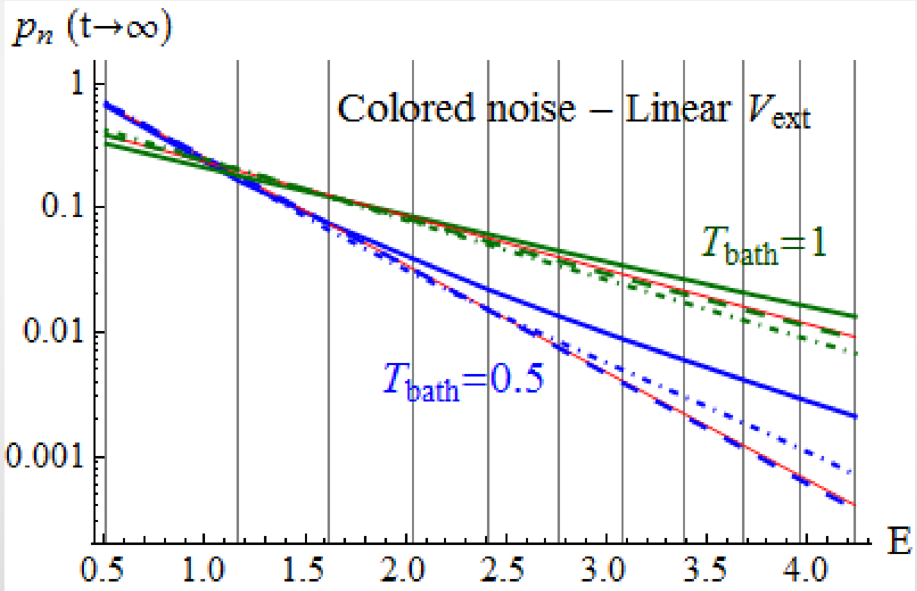
Need for Einstein relation aka fluctuation-dissipation theorem: challenge for effective approaches

Equilibration with SL equation



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



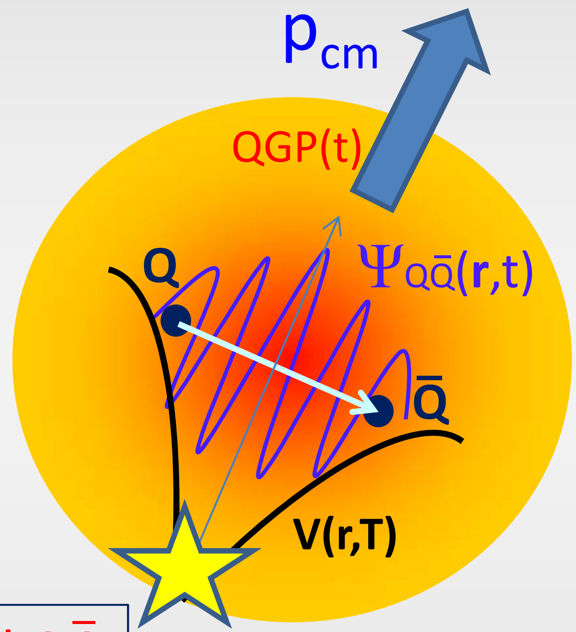


See R. Katz and P. B. Gossiaux, Annals of Physics (2016), pp. 267-295, arXiv:1504.08087 [quant-ph]

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

+

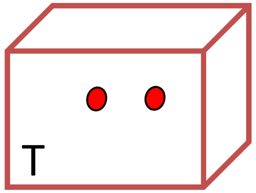
Thermalisation and diffusion: √ need $A(T,p_{cm})$

Direct interactions with the thermal bath

+ Dynamical scheme √

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

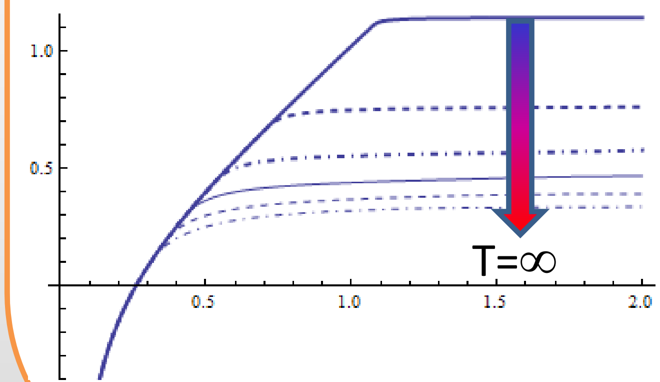
Static lQCD calculations (maximum heat exchange with the medium):



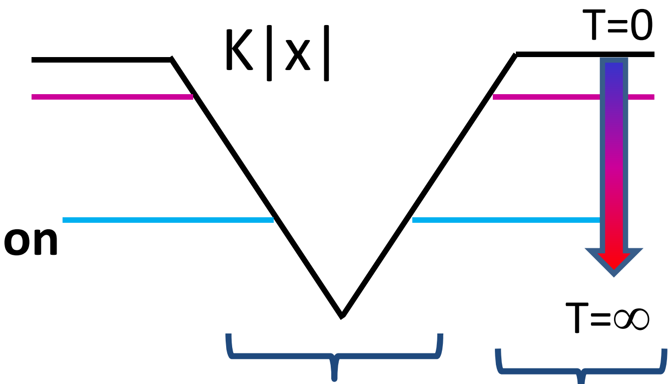
F : free energy
S : entropy

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

- "Weak potential" F<Vweak<U * => some heat exchange
- "Strong potential" V=U ** => adiabatic evolution



1D simplification



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

In vacuum: $V(T_{red}=0, r)$

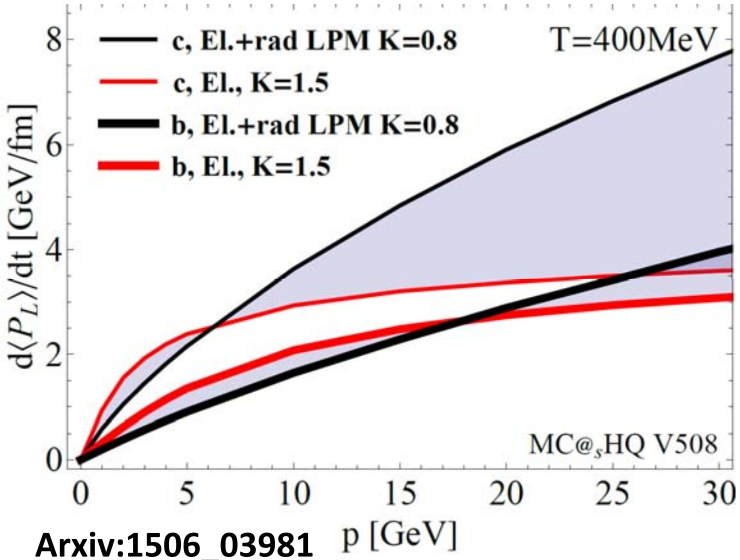
Parameters chosen to reproduce Upsilon spectrum + BBbar threshold

state	Mass calc	Mass exp	Diff exp-calc
1S	9.46	9.460	0.
1P	9,77	9,86	0.09
2S	9,99	10.023	0.01
2P	10.18	10.255	0.075
3S	10.35	10.355	0.0
3P	10.51	10.51	0.0

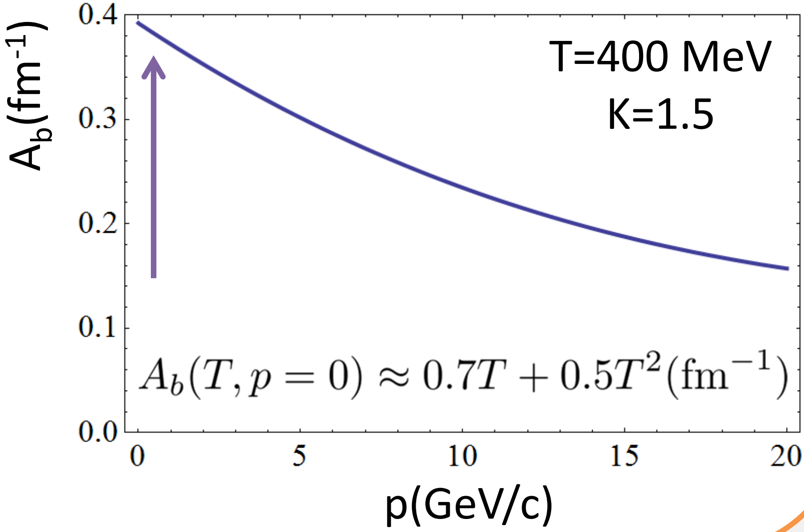
mb=4.61, K_l=2.491 GeV/fm & Vmax=1.338 GeV

Drag coefficient A_b

- Obtained within our running α_s approach*



Arxiv:1506_03981



Initial $Q\bar{Q}$ wavefunction

- Produced at the very beginning : $\tau_f^{Q\bar{Q}} \sim \hbar/(2m_Q\,c^2) < 0.1\ \text{fm/c}$

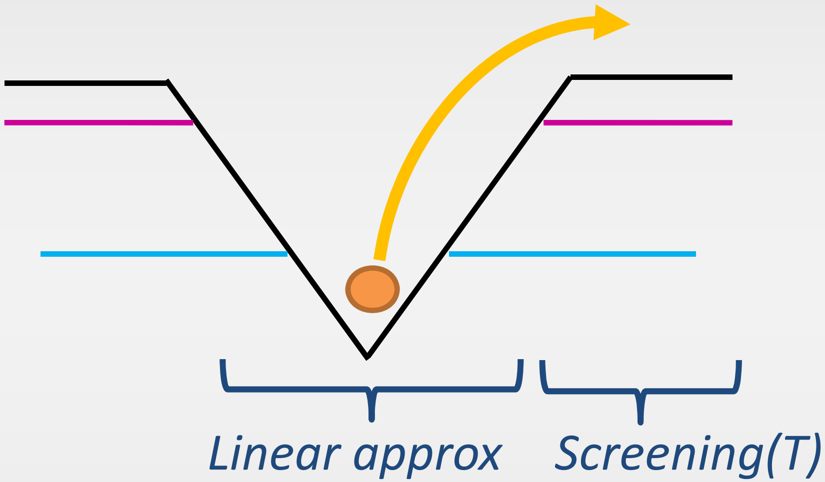
* P.B. Gossiaux and J. Aichelin 2008 Phys. Rev. C 78 014904

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

Evolutions at constant T: understanding the model

SQM 2015

- Simplified Potential but contains the essential physics



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

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

Initial QQ wavefunction

- We assume either a formed state (Υ(1S) or Υ(2S)) OR Gaussian wavefunction

Going realistic

Initial QQ wavefunction

➢ Can we cope with the p-p data at LHC, including the various feed-down ?

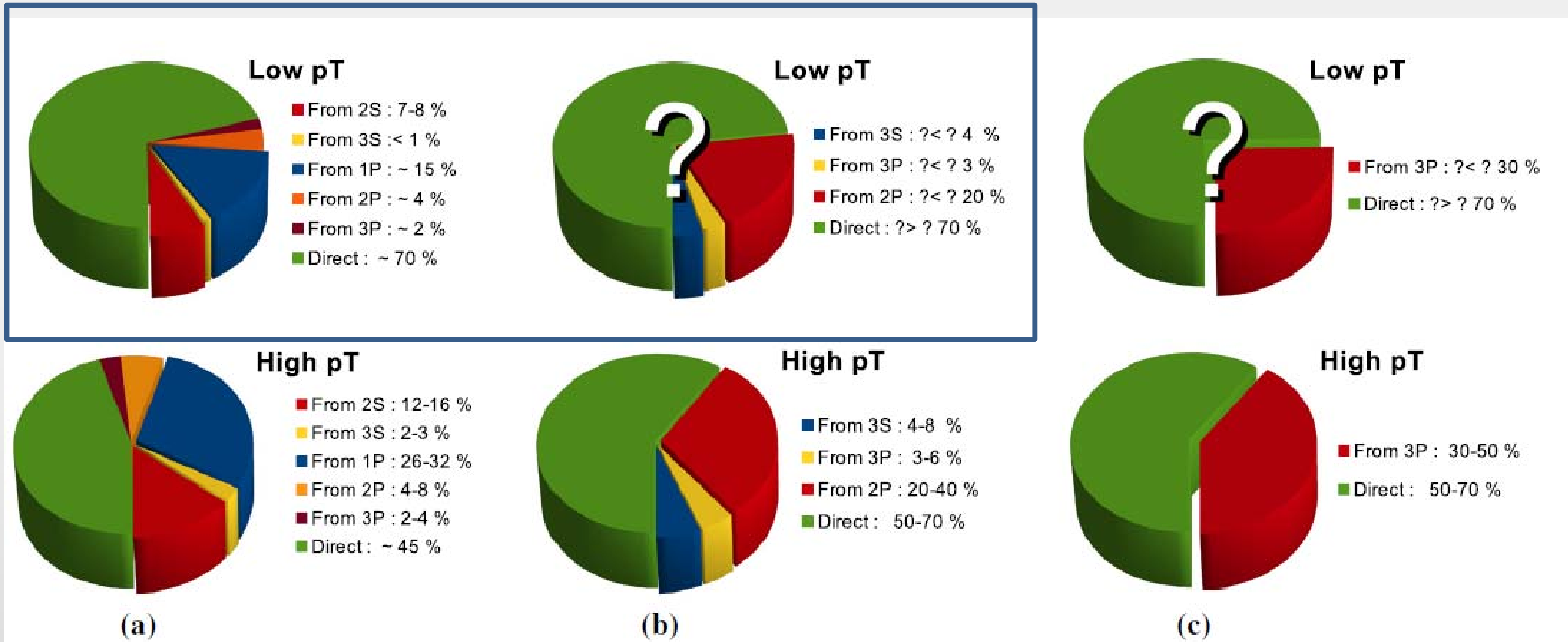


Fig. 14 Typical sources of $\Upsilon(nS)$ at low and high p_T. These numbers are mostly derived from LHC measurements [197–199, 203–208] assuming an absence of a significant rapidity dependence. **a** $\Upsilon(1S)$; **b** $\Upsilon(2S)$; **c** $\Upsilon(3S)$

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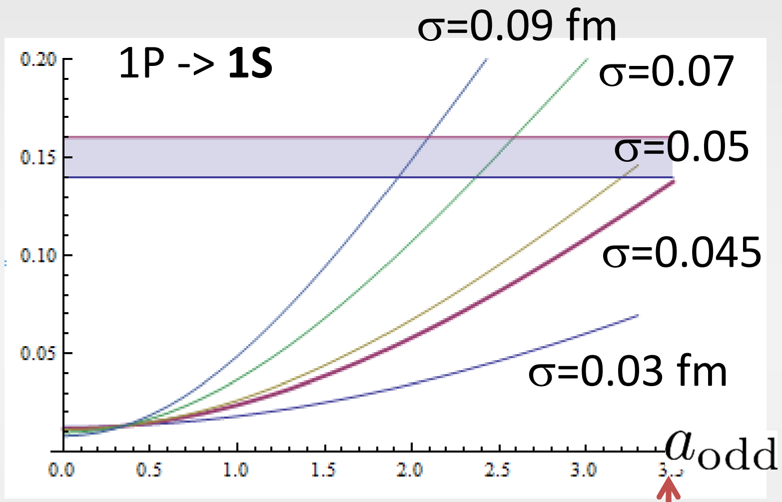
Initial State has S-like and P-like components

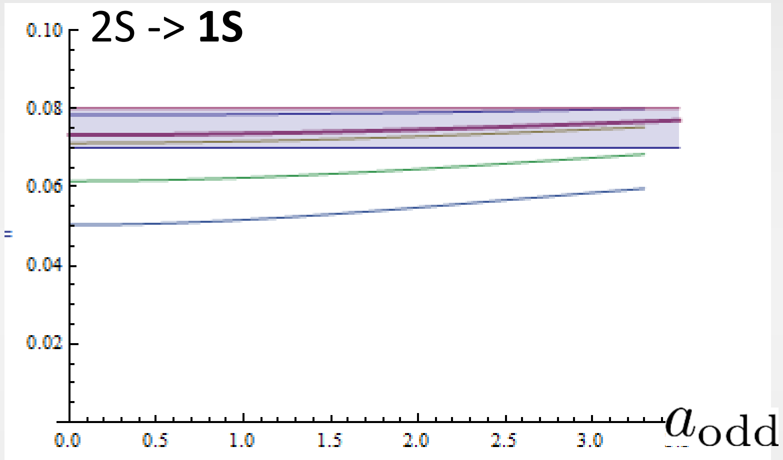
Trial initial state:

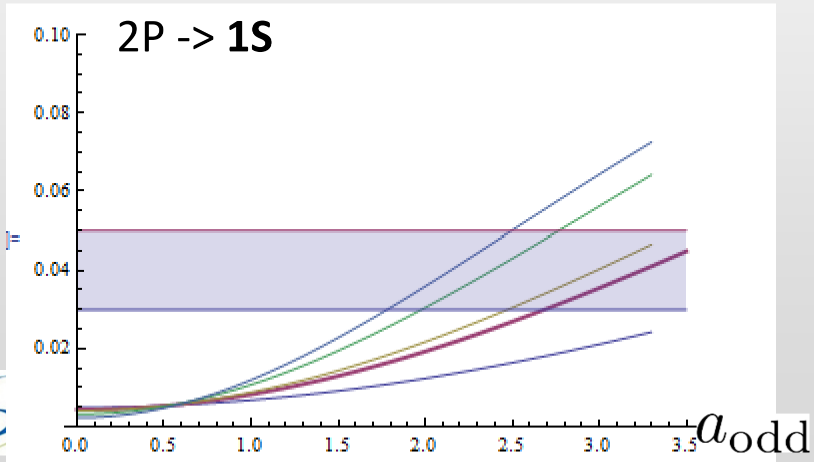
$$\psi_{b\bar{b}}(t=0,x) \propto e^{-\frac{x^2}{2\sigma^2}}\left(1 + a_{\mathrm{odd}}\,\frac{x}{\sigma}\right)$$

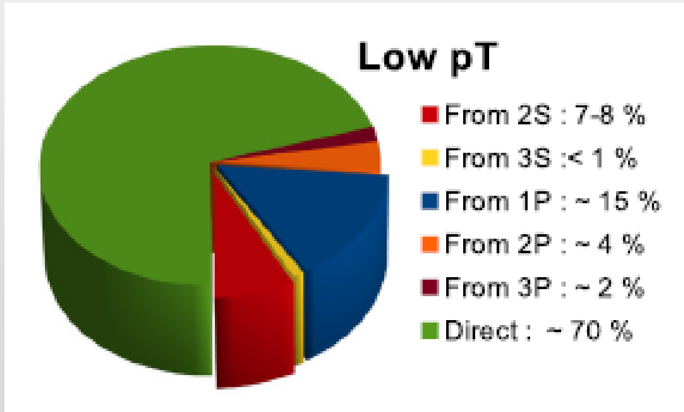
Looking at integrated production as a proxy for **low p_T:**

$$\sigma = 0.045\ \mathrm{fm} \quad a_{\mathrm{odd}} = 3.5$$









7-8%
1 %
14%
4 %
0 %

Trial initial state:

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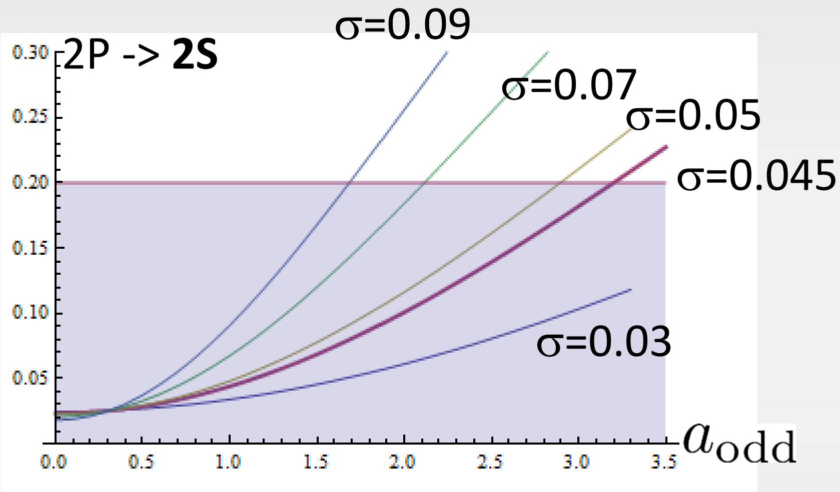
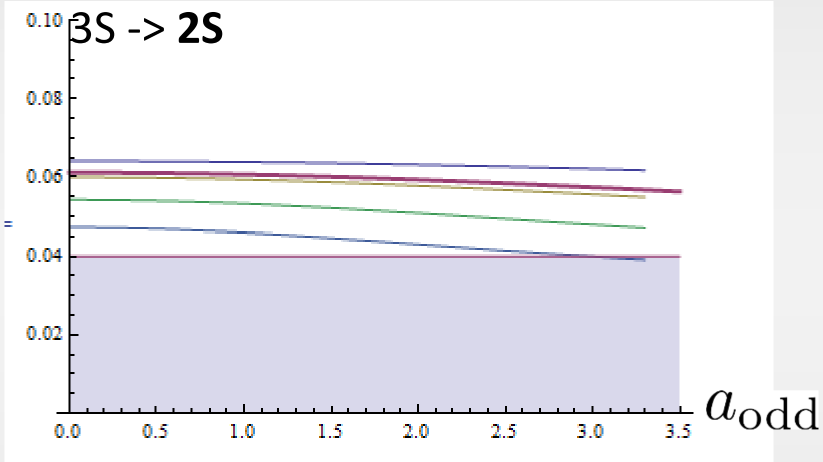
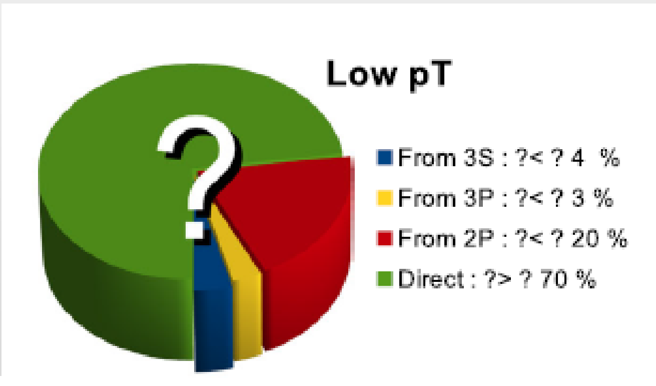






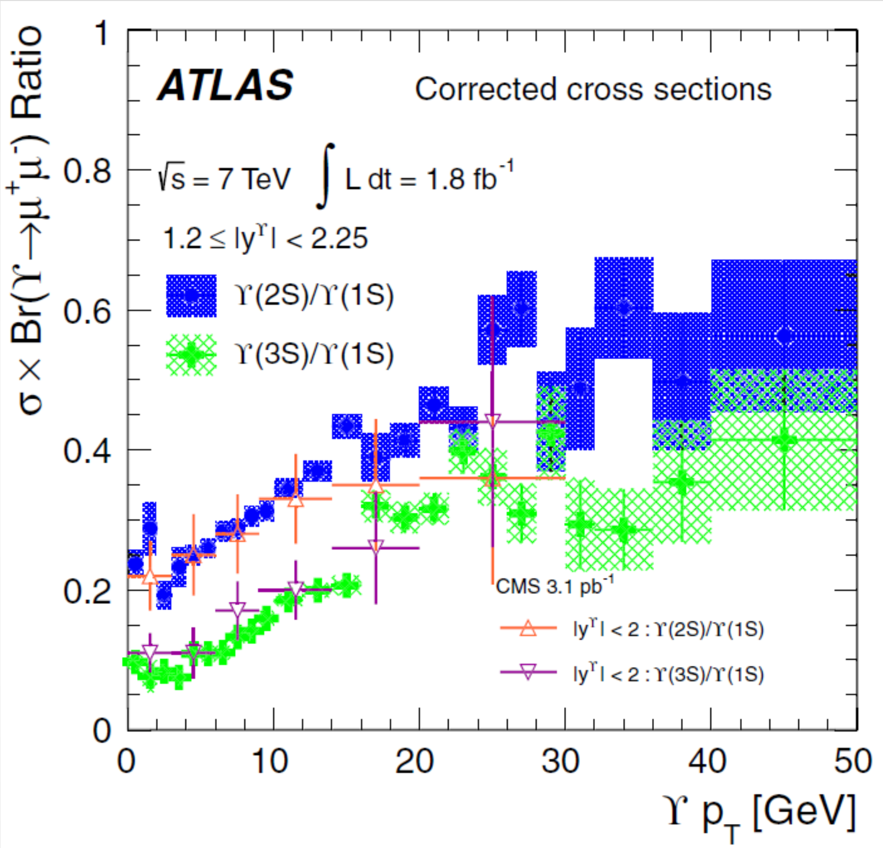
6%
0 %
22 %

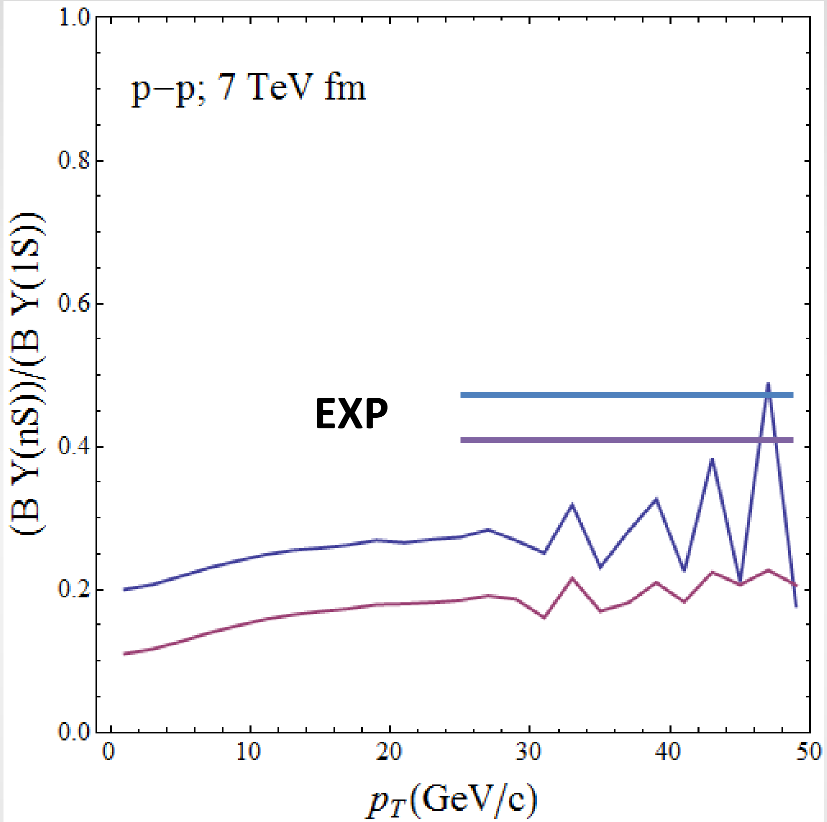
Good « fit » at low p_T

Enables us to deal with feed down

… But other possibilities exist

Going high p_T:





Mild increase vs p_T but saturates too low

Need for a better understanding of quarkonium production at high p_T. If mere gluon splitting + Eloss, our model doesn't apply anyhow

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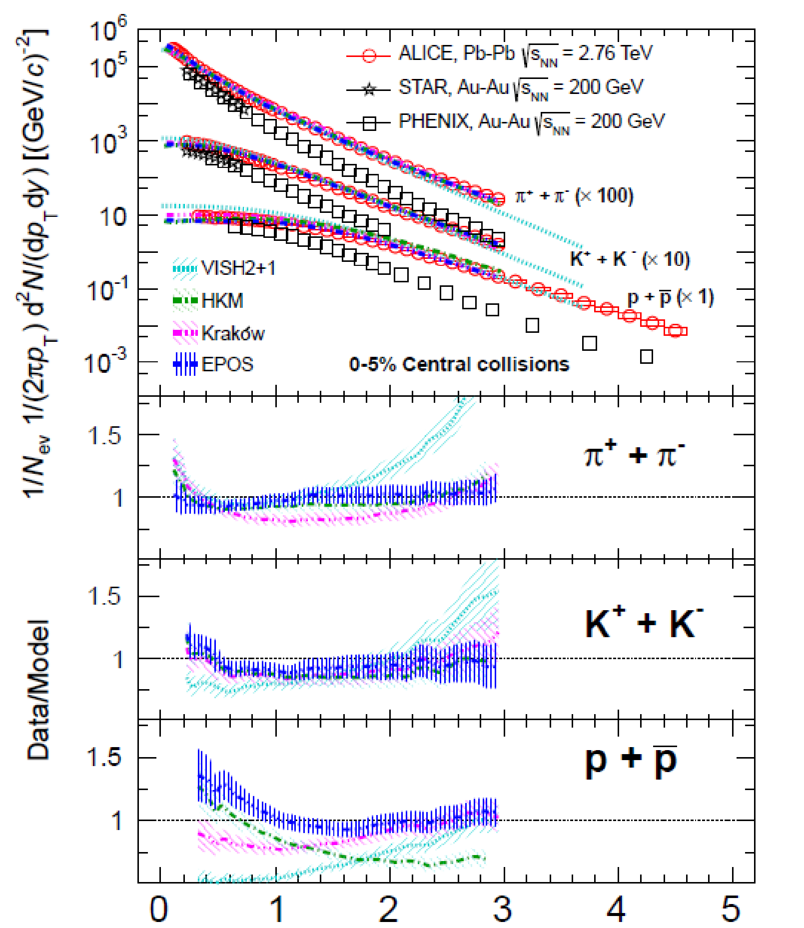
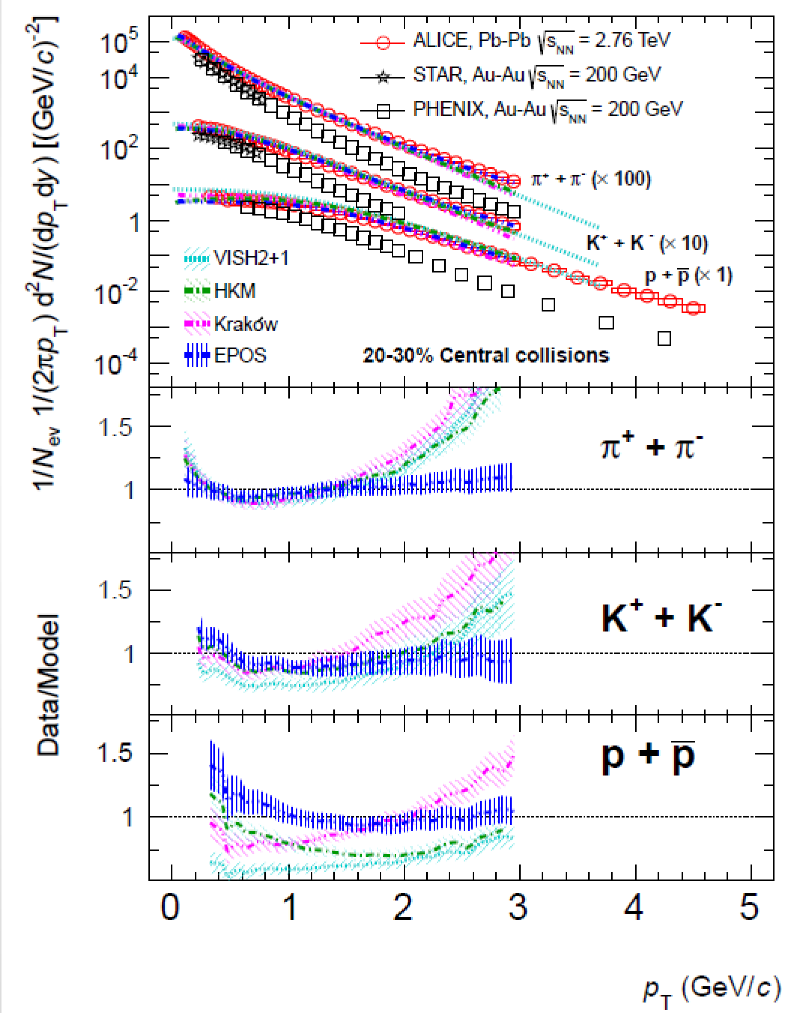
Going realistic

- **Evolution in EPOS2 background (very good model for AA*)**



ALICE Collaboration
Phys. Rev. C 88, 044910 (2013)



* 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

Going realistic

- **Evolution in EPOS2 background (very good model for AA*)**
- Glauber model for initial position of the b-bar pairs, No CNM effects
- b-bars assumed to be color singlets and then moving straight line with no Energy loss
- Initial internal b-bar state chosen as a gaussian (1S+1P)
- Observables:
  - **Weight :** $W_i(t) = \left\langle |\langle \psi_i(T=0) | \psi_{b\bar{b}}(t) \rangle|^2 \right\rangle_{\text{stat}}$
  - **Survivance :** $S_i(t) = W_i(t) / W_i(t=0)$

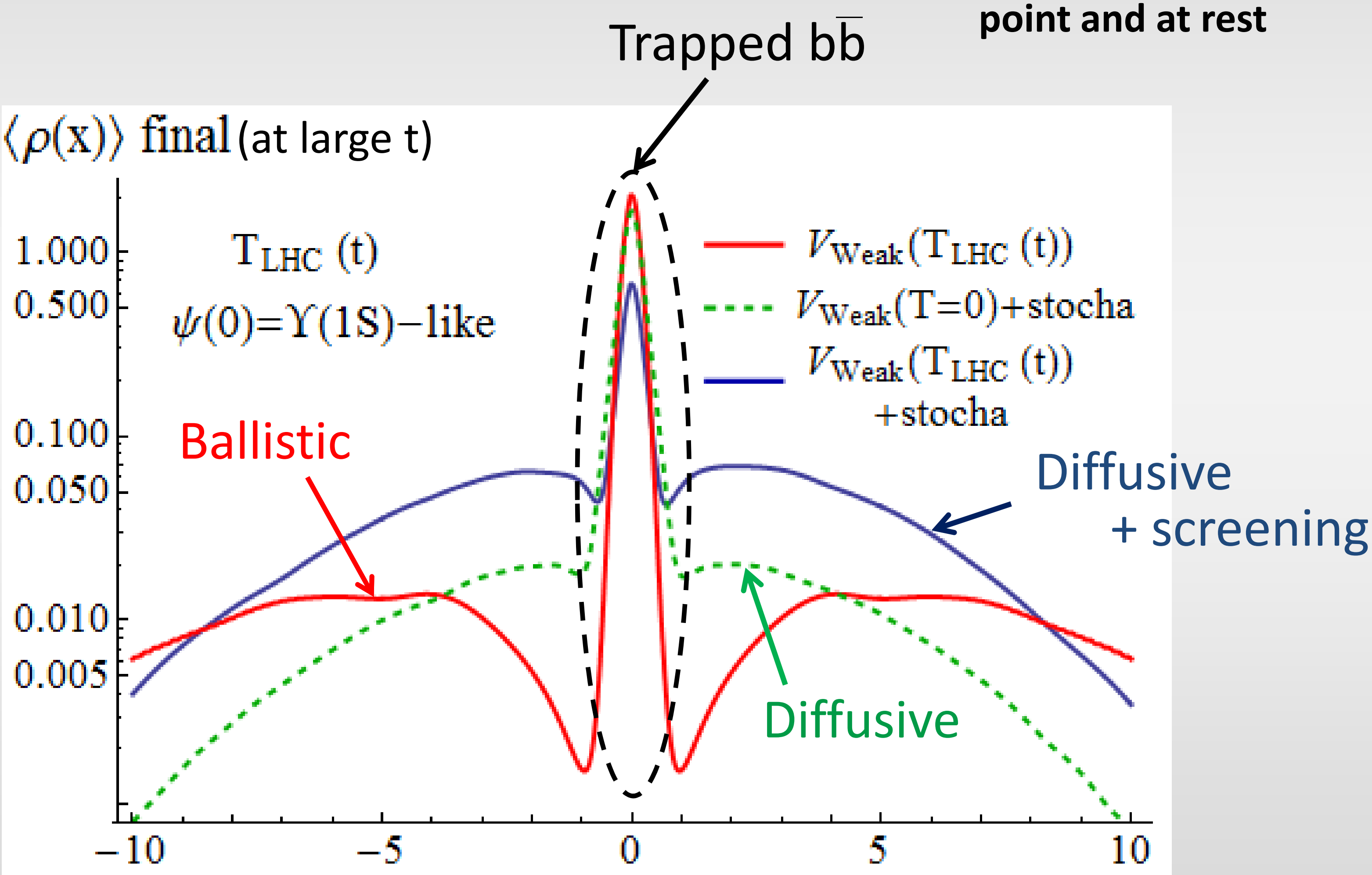
Convoluted with p_T-y spectra => R_{AA}

- STILL NOT AIMED to reproduce exp. data (just grasp the global trends): **proof of principle**

* 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

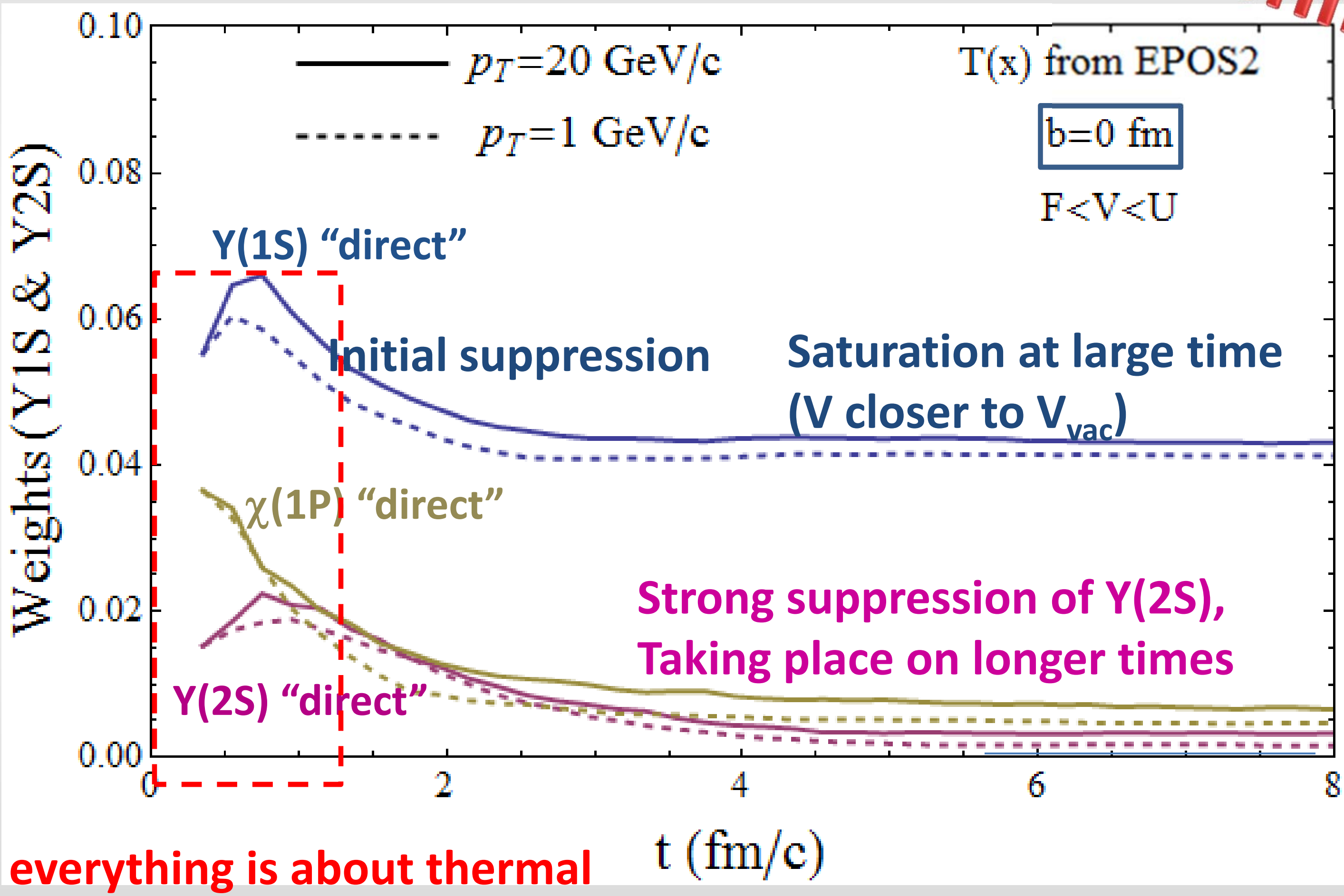
Density with V(TLHC(t,0)) and initial Y(1S)

Case of bbar at hottest QGP point and at rest



Full EPOS2 evolutions

Preliminary

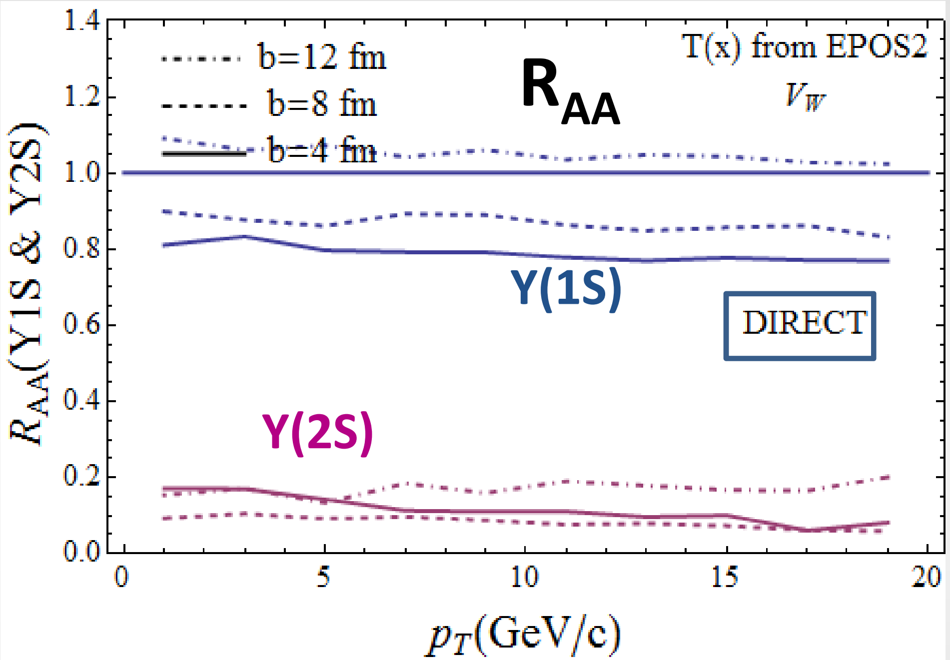


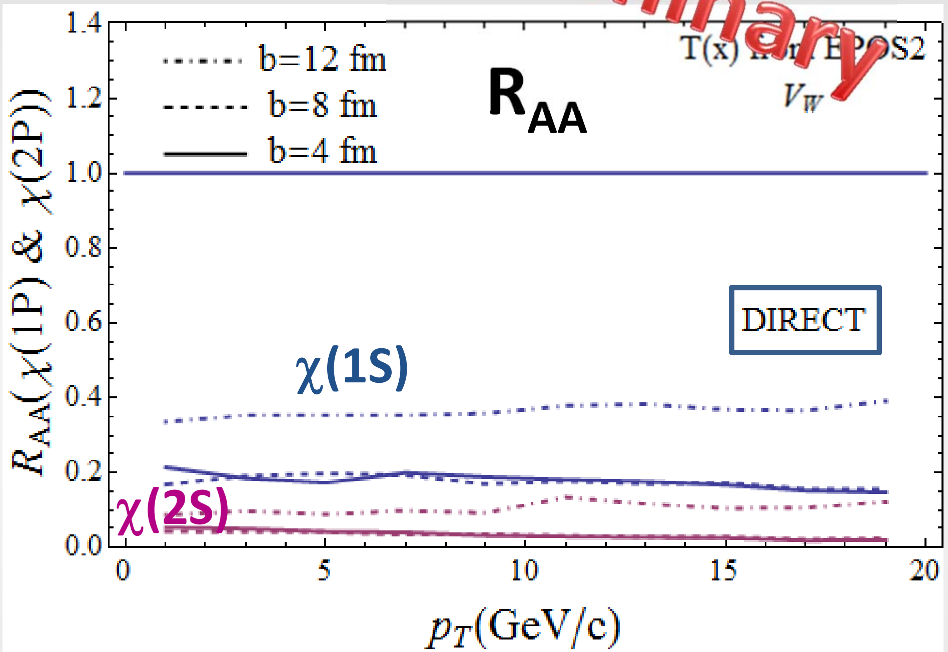
Not everything is about thermal decay widths !!!

NO STRONG p_T DEPENDENCE

Final suppression (1): vs p_T

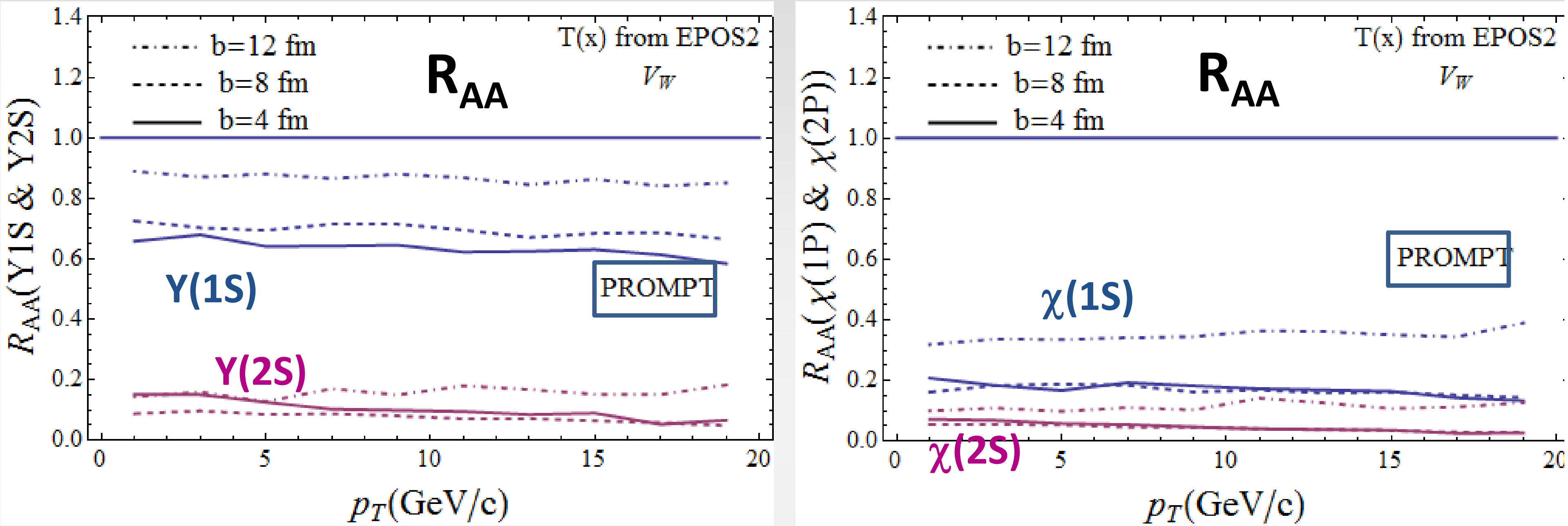
Preliminary





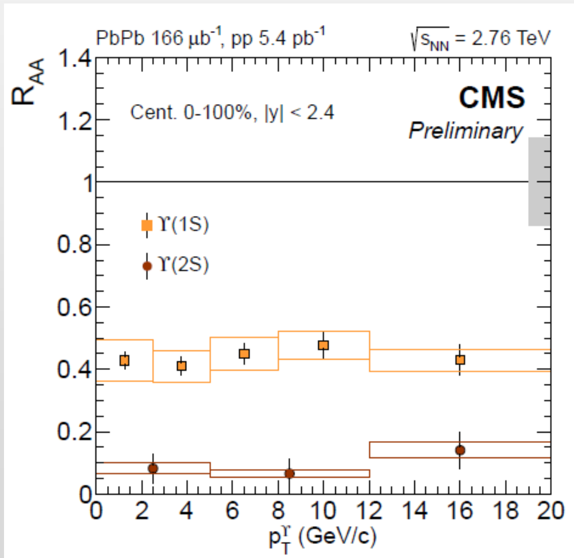
Flatish $R_{AA}(p_T)$ for all Bottomonium states

Final suppression (2): vs p_T



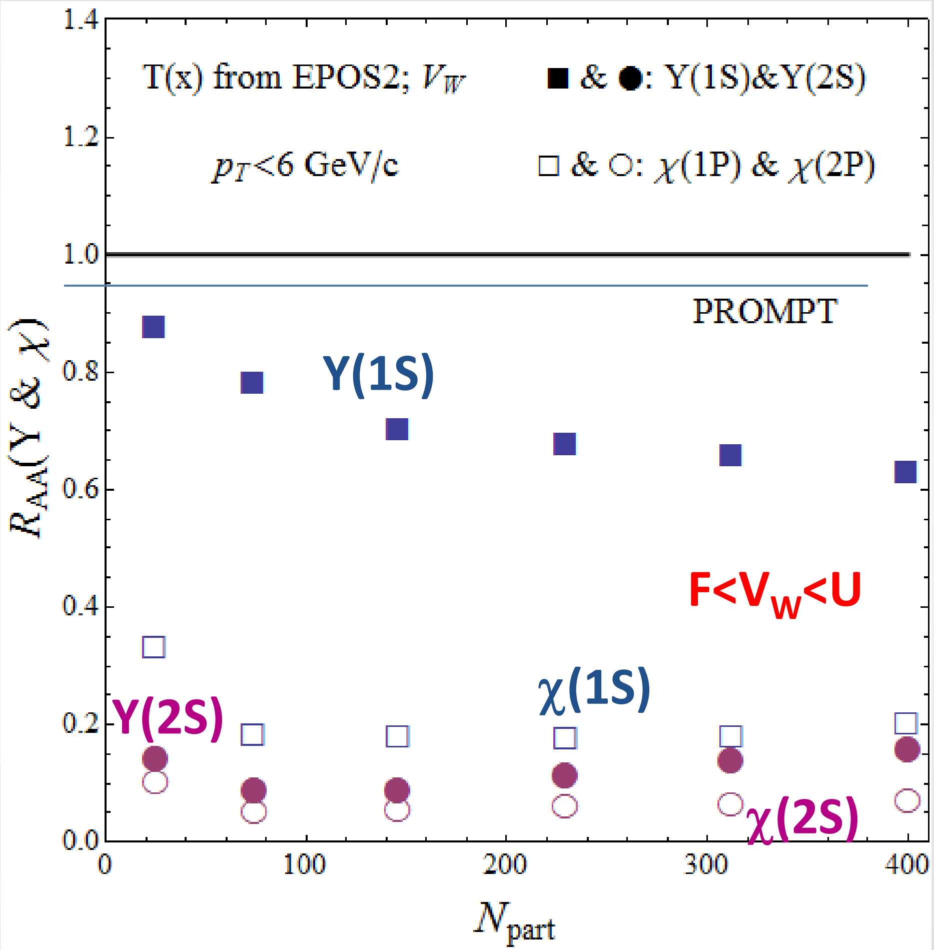
Simple rule for Upsilon decay:

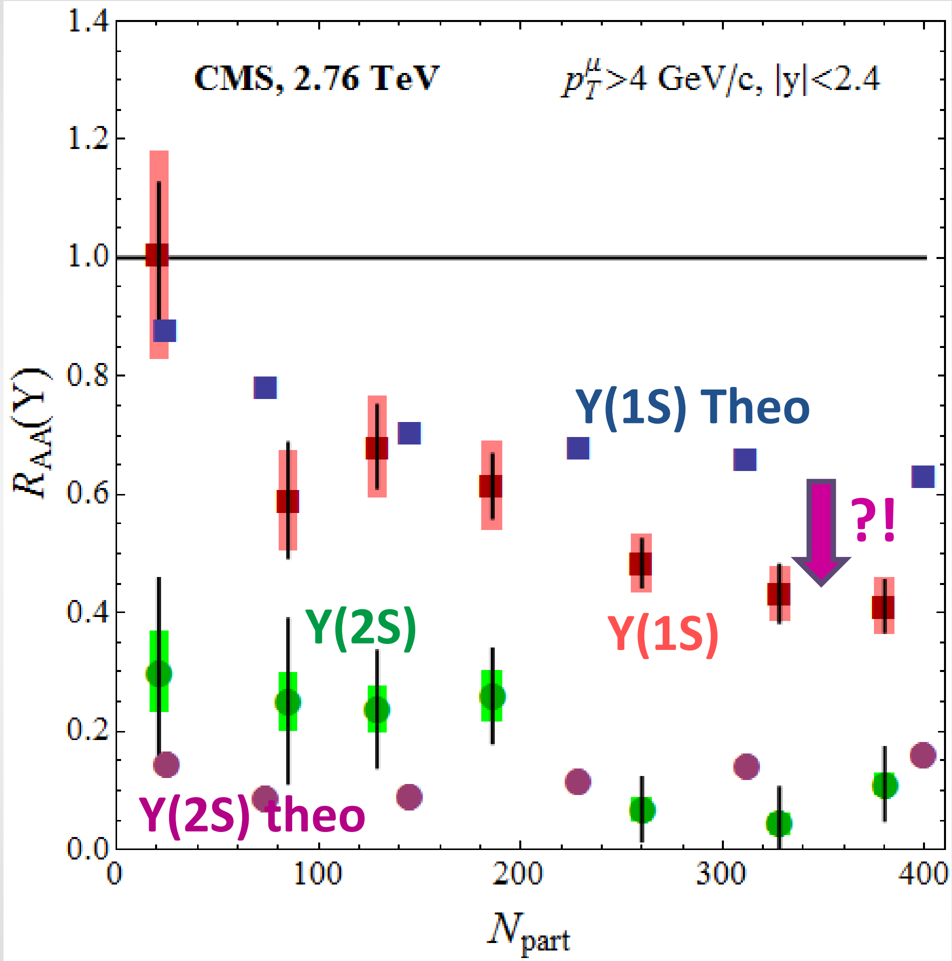
$$\mathbf{p}_{\text{daughter}} = \frac{M_{\text{daughter}}}{M_{\text{mother}}} \mathbf{p}_{\text{mother}}$$



Trends well reproduced but absolute values too high (lack of suppression)

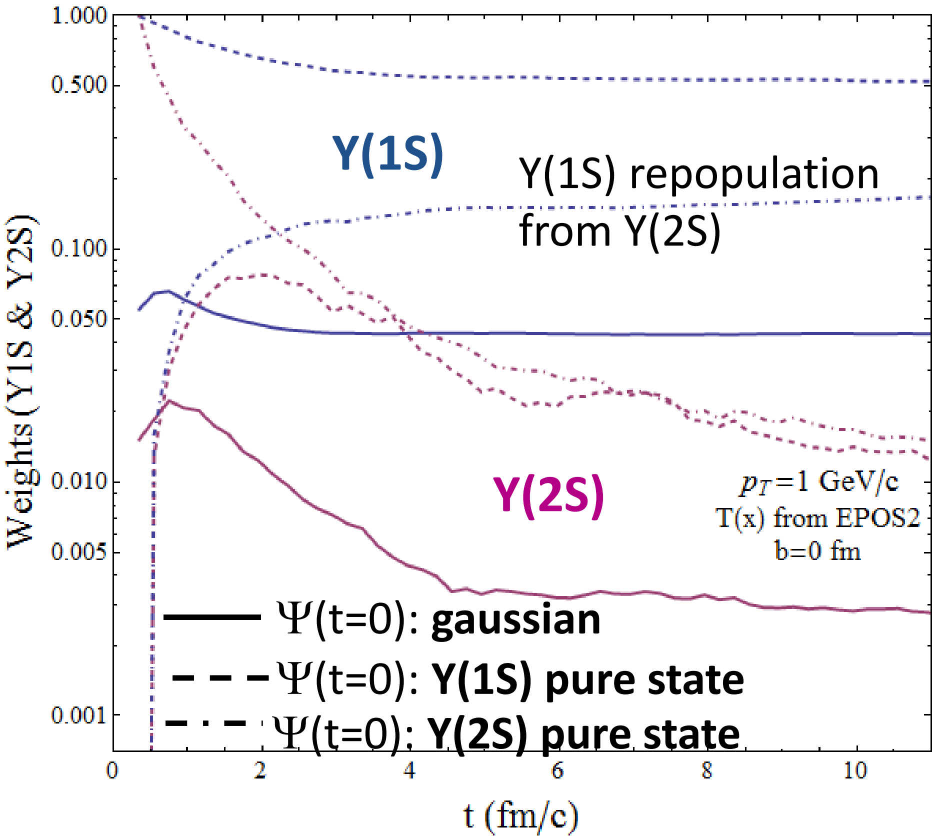
Final suppression (3): vs N_{part}





We miss a some suppression in most central events (under investigation)

Refined analysis: Role of initial bbar state

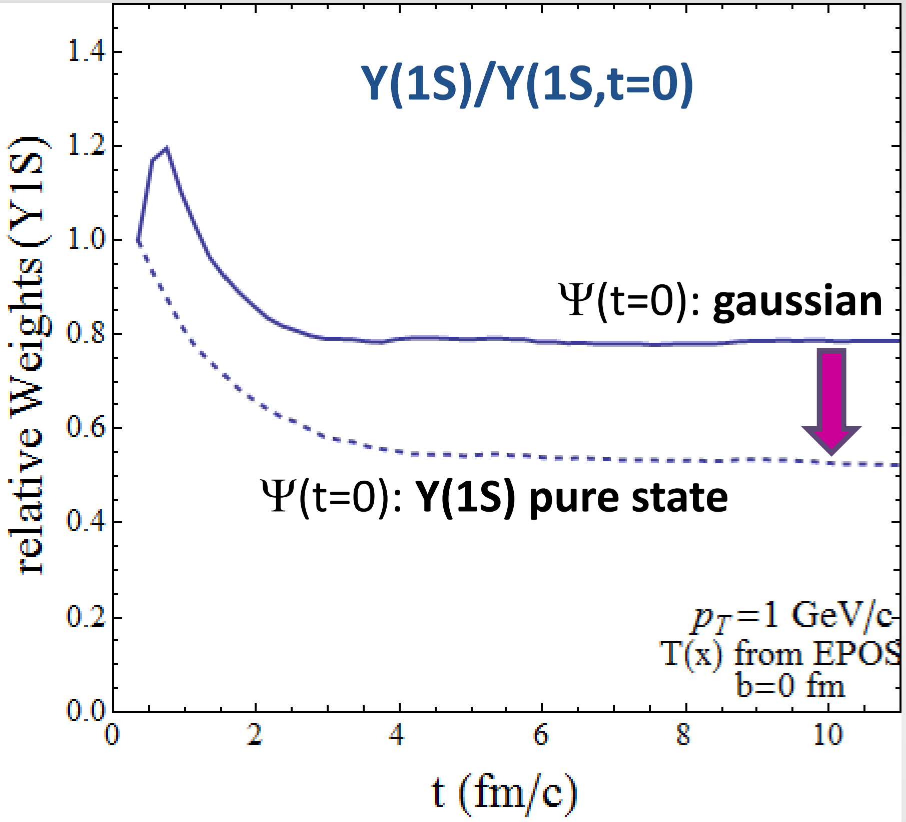


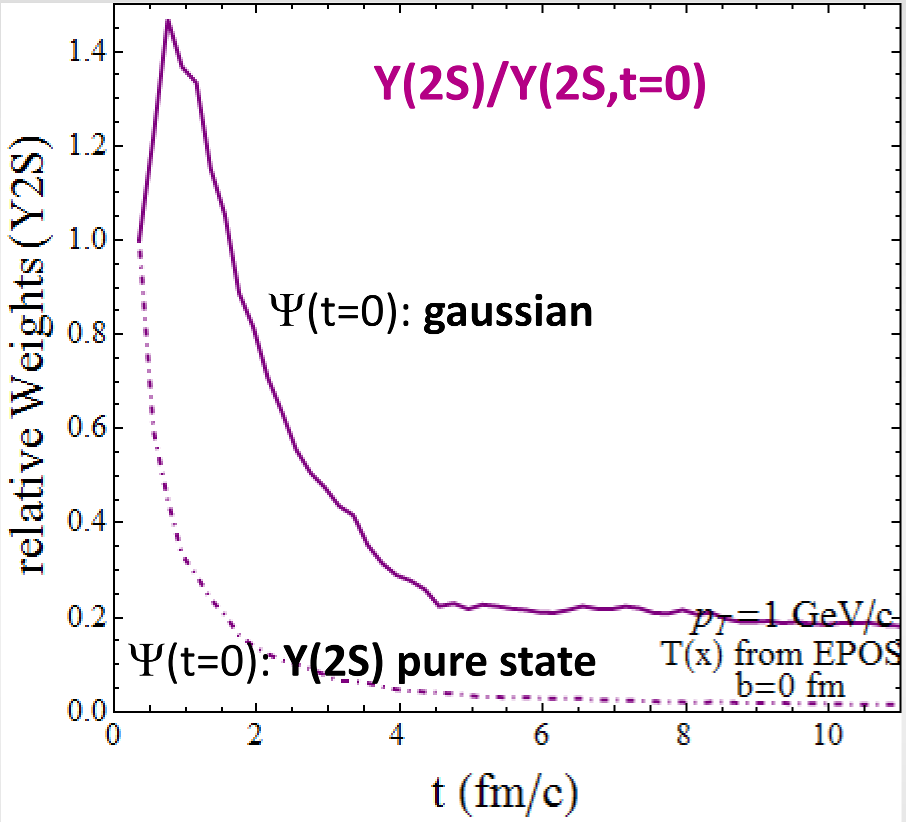
Original Y(2S) would survive with a probability less then 2%

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 initial bbar state





Does the missing suppression at final time stem from "artificial" coherence at t=0 ?

Summary and perspectives

- 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) with feed downs, 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)
- ❑ Better understanding of the initial state
- ❑ Deeper rooting to lQCD (spectra functions)

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Conclusion

Dealing with a quantum nature of quarkonia in medium (using SLE or any other scheme) is theoretical “must be”, although phenomenological consequences might not be large…

… It however requires to address simultaneously deeper questions that are usually ignored in classical treatments.