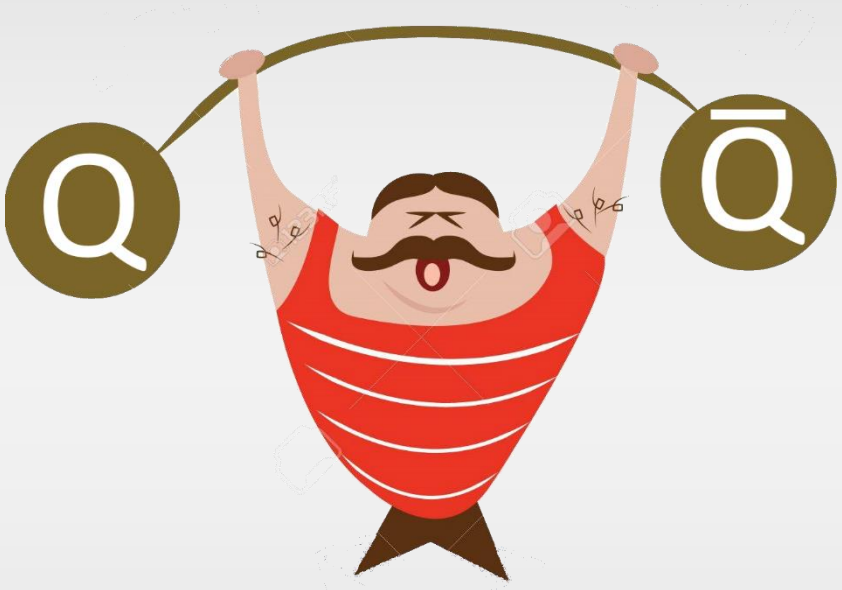
Day 4: Off-equilibrium effects
The Nantes Schrödinger-Langevin approach



Quarkonia Task Force

Roland Katz and Pol-Bernard Gossiaux

EMMI Rapid Reaction Task Force – GSI Darmstadt
19/12/2019

Schrödinger-Langevin approach

Main ideas:

- Langevin-like Schrödinger equation to mock open quantum systems
- Real time dynamics of coherences, dissociation, recombination & transitions

$$i\hbar\frac{\partial\Psi_{Q\bar{Q}}(\mathbf{r},t)}{\partial t} = \left(\underbrace{\widehat{H}_{\mathrm{MF}}(\mathbf{r})}_{\text{Mean Field}} \underbrace{-\,\mathbf{F_R}(t).\mathbf{r}}_{\text{Fluctuations}} \underbrace{+\,A\big(S(\mathbf{r},t)-\langle S(\mathbf{r},t)\rangle_{\mathbf{r}}\big)}_{\text{Dissipation}}\right)\Psi_{Q\bar{Q}}(\mathbf{r},t)$$

Mean Field:
T-dependent screened potential from lQCD

Fluctuations
Stochastic force scaled such as $T_{Q\bar{Q}} = T_{QGP}$ at equilibrium

Dissipation
$S(\mathbf{r},t) = \arg\big(\Psi_{Q\bar{Q}}(\mathbf{r},t)\big)$
- non-linear, real and ohmic
- brings to the lowest state
- A(T): Drag

- Most quantum features ok – Allows quantum initial/final states
- Mixed state from statistics – Easy to implement
- Leads to local « thermal » distributions: Boltzmann behaviour for at least the low lying states
- A priori not related to a quantum master equation

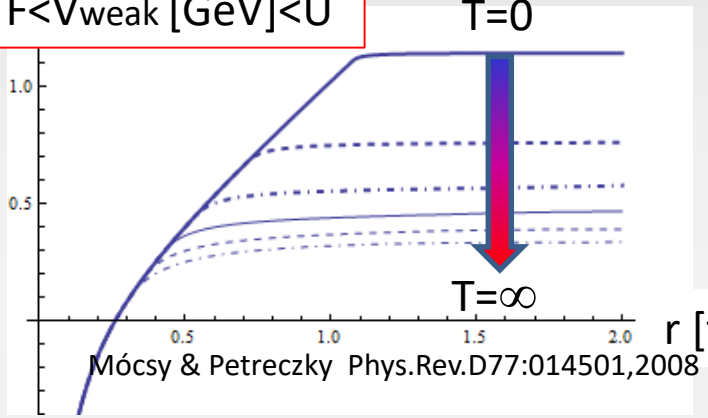
TODAY

Influence of initial state and potential on observables within time-dependent temperature scenarios

$Q\bar{Q}$ potentials used in SL equation

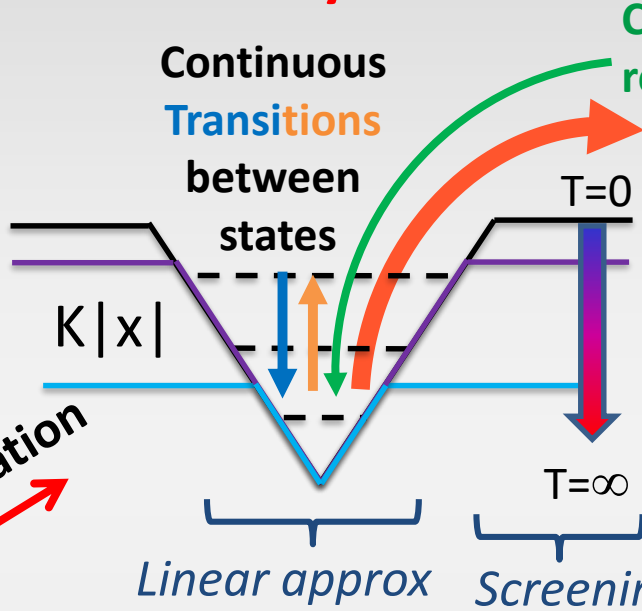
simplified <u>1D singlet</u> model => insights on the dynamics

F<Vweak [GeV]<U

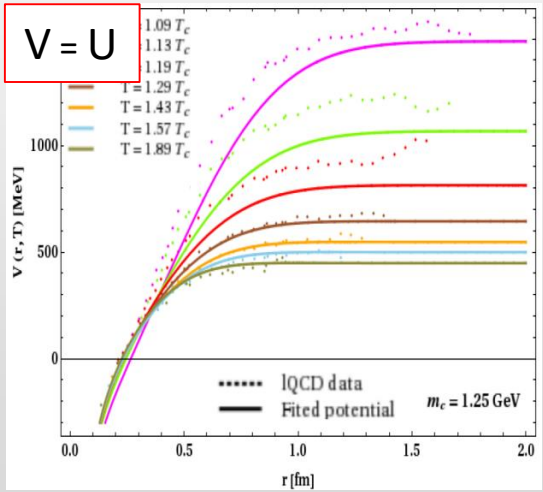


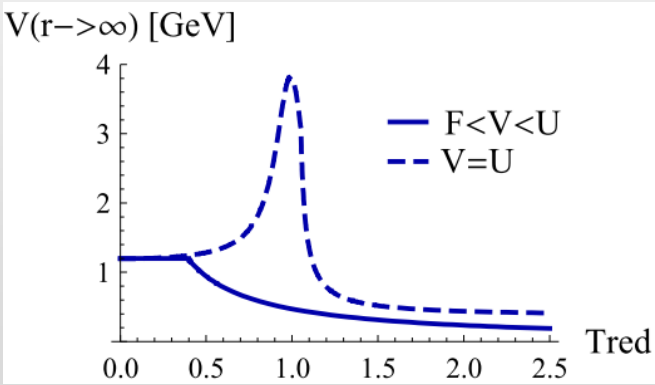
Mócsy & Petreczky Phys.Rev.D77:014501,2008

1D simplification



V = U

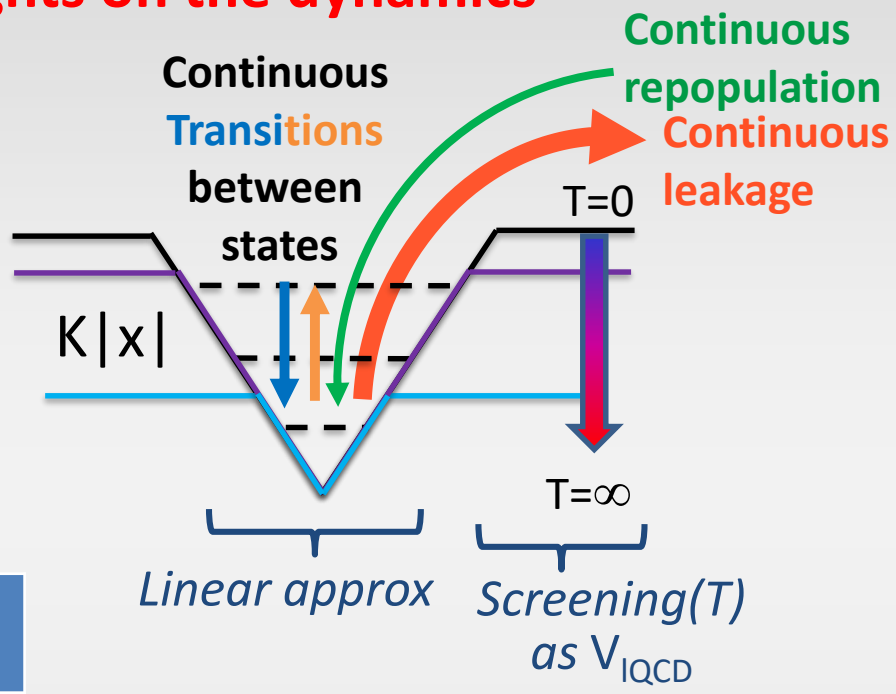




$Q\bar{Q}$ potentials used in SL equation

simplified <u>1D singlet</u> model => insights on the dynamics

Parameters (K, Vmax) chosen to reproduce quarkonium spectrum + BB or DD threshold



Bottomonium 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

Initial $Q\bar{Q}$ pair wavefunction ?

$Q\bar{Q}$: produced at the very beginning
BUT state formation times subject to debate
=> test 2 extrem behaviours:

- $Q\bar{Q}$ fully decoupled into eigenstates:
$\psi_{Q\bar{Q}}(t=0)=\psi_i(T=0)$

or

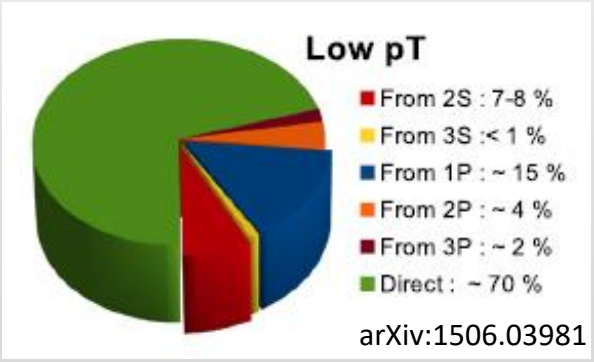
- $Q\bar{Q}$ pair not decoupled:

$\psi_{Q\bar{Q}}(t=0)$="a mixture of Gaussian S and P components"

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

tuned to obtain correct feed-downs and production ratios in pp collisions

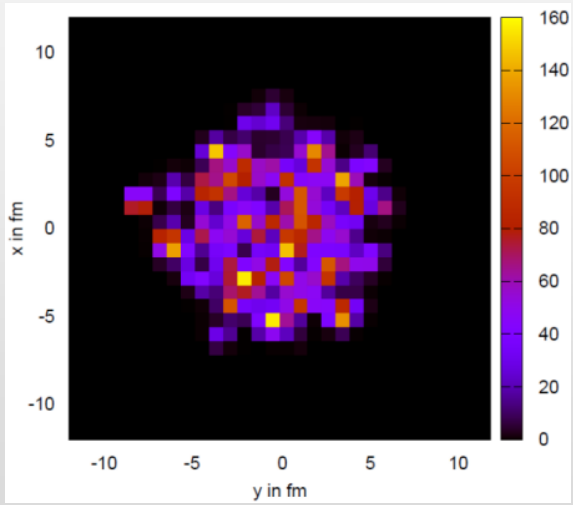
e.g.: contribution to Y(1S) from feed downs:

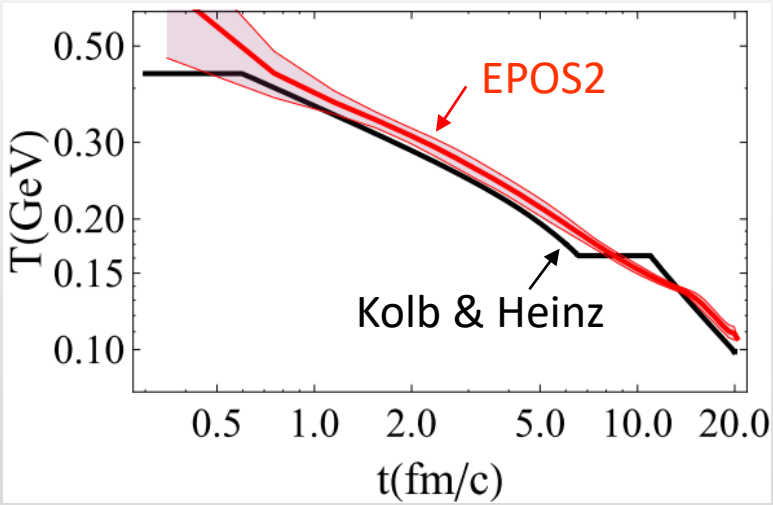


arXiv:1506.03981

Evolution of the $Q\bar{Q}$ pairs on EPOS initial conditions + hydro background (EPOS2)

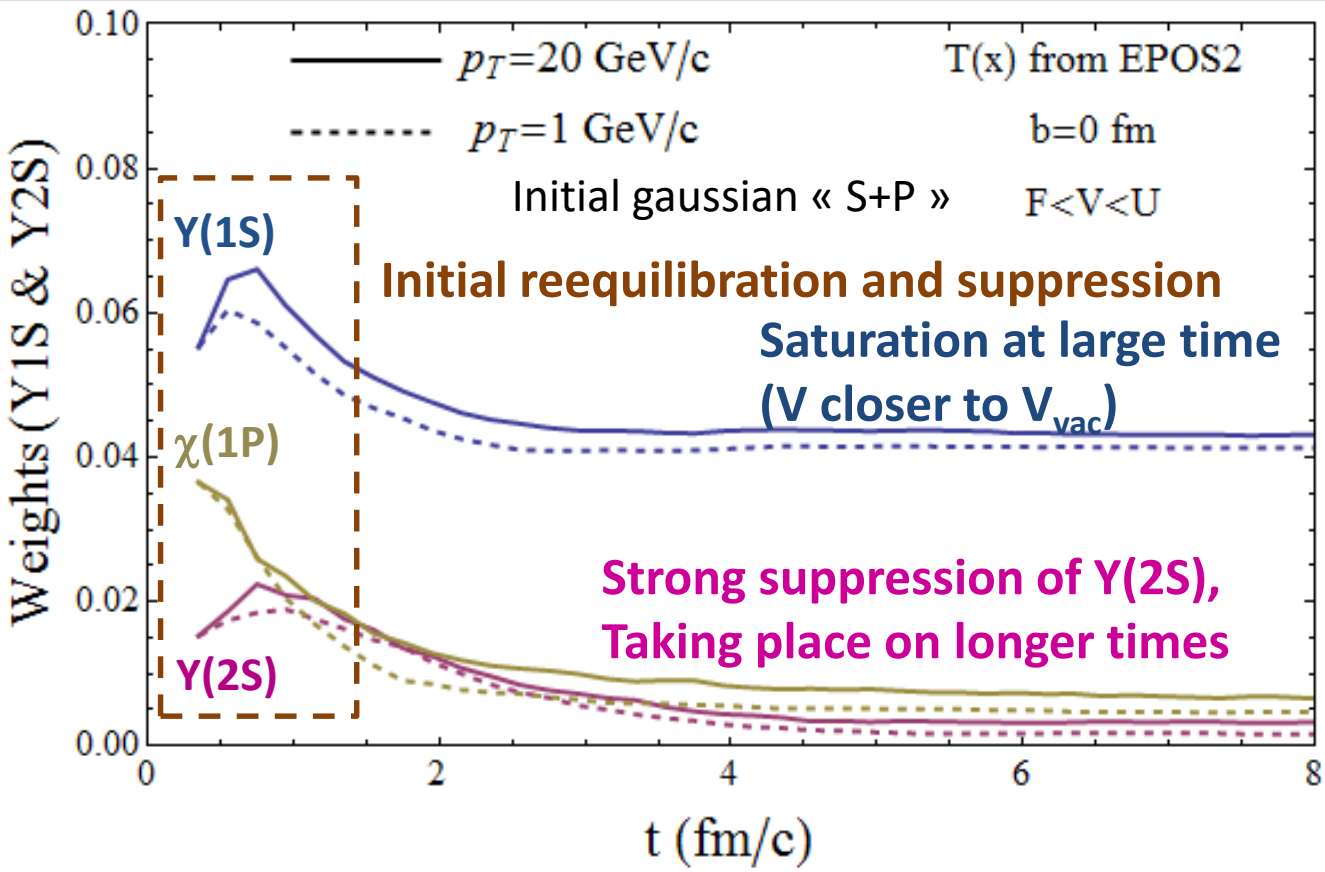
- Very good model for heavy ion collisions with initial fluctuations and ideal 3D hydrodynamics
- $Q\bar{Q}$ pairs initial positions: given by Glauber model
- No Cold Nuclear Matter effects (no shadowing and no hadronic scatterings)
- $Q\bar{Q}$ pair center-of-mass motion: along straight lines with no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





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

Example of evolution at LHC (2.76 TeV):

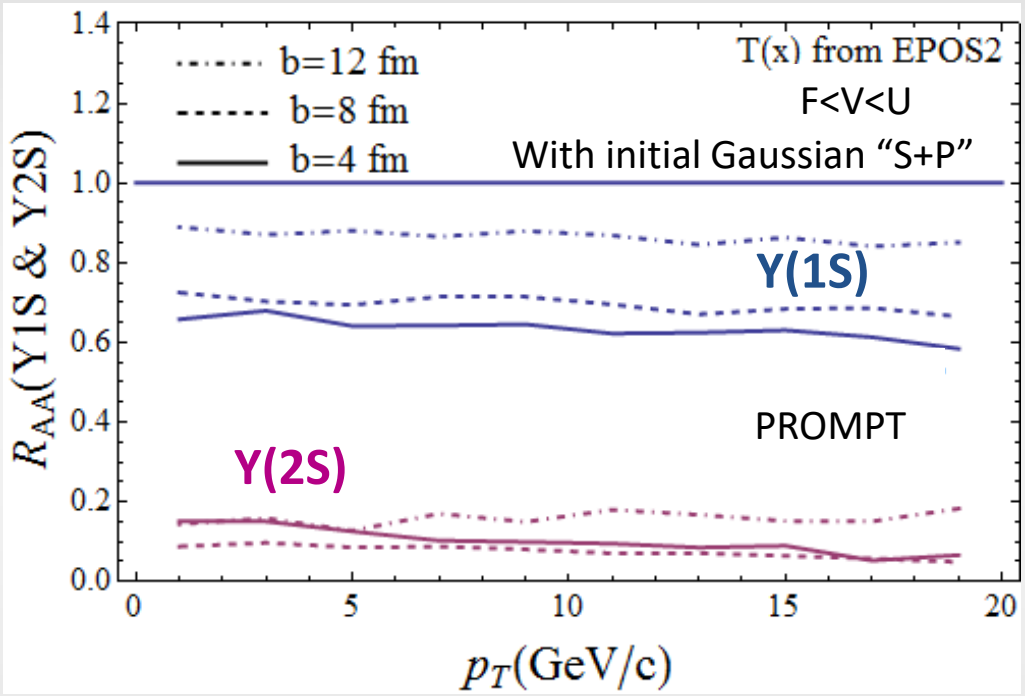


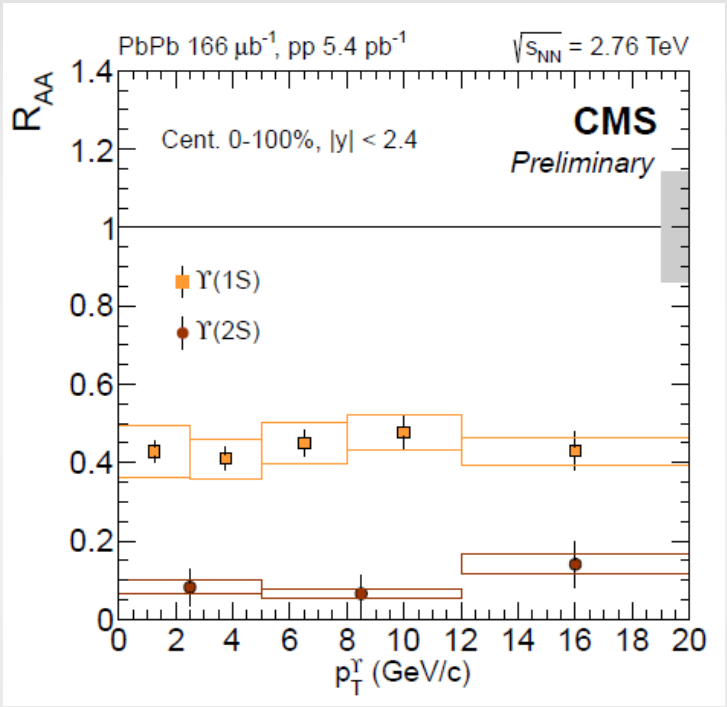
Observations

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

LHC (2.76 TeV): $R_{AA}(p_T)$

Survival probability $S_i(t)=W_i(t)/W_i(t=0)$ convoluted with pp coll. p_T-y spectra => R_{AA}





Bottomonia:

R_{AA} depend on Npart (mainly: influence of initial temperature)

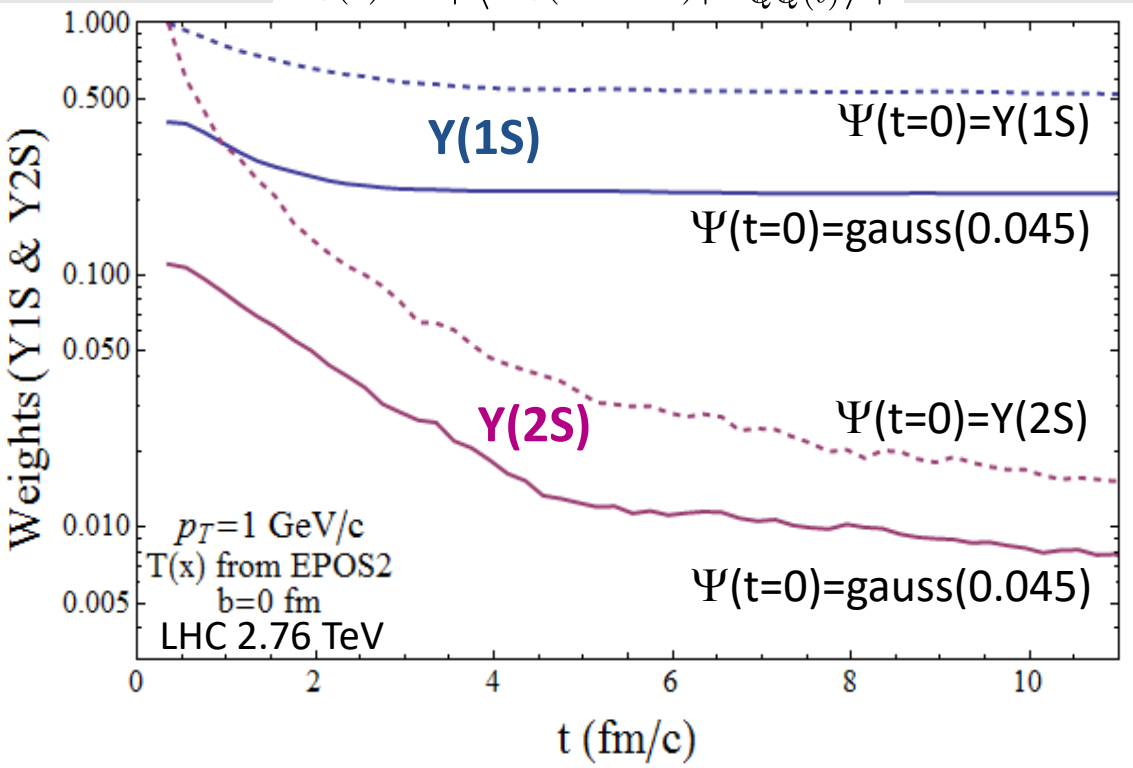
R_{AA} almost independent of p_T

(helped by approximations: drag A and feed downs independent of momentum)

Influence of initial state

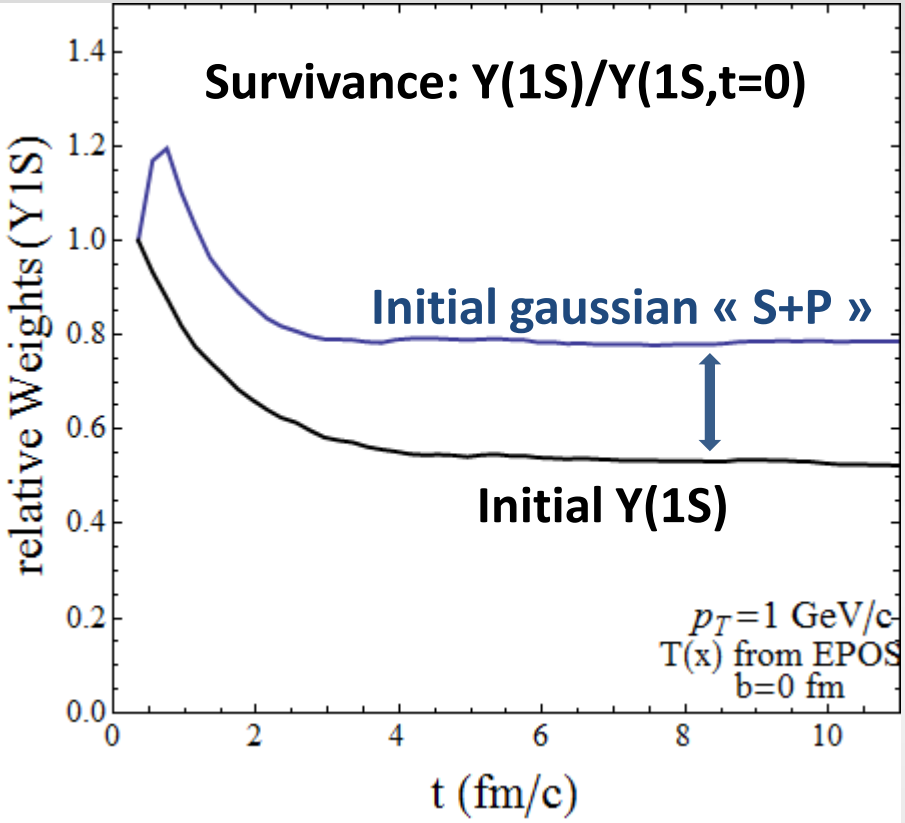
Previously: if T constant => similar populations at « equilibrium » whatever the initial state

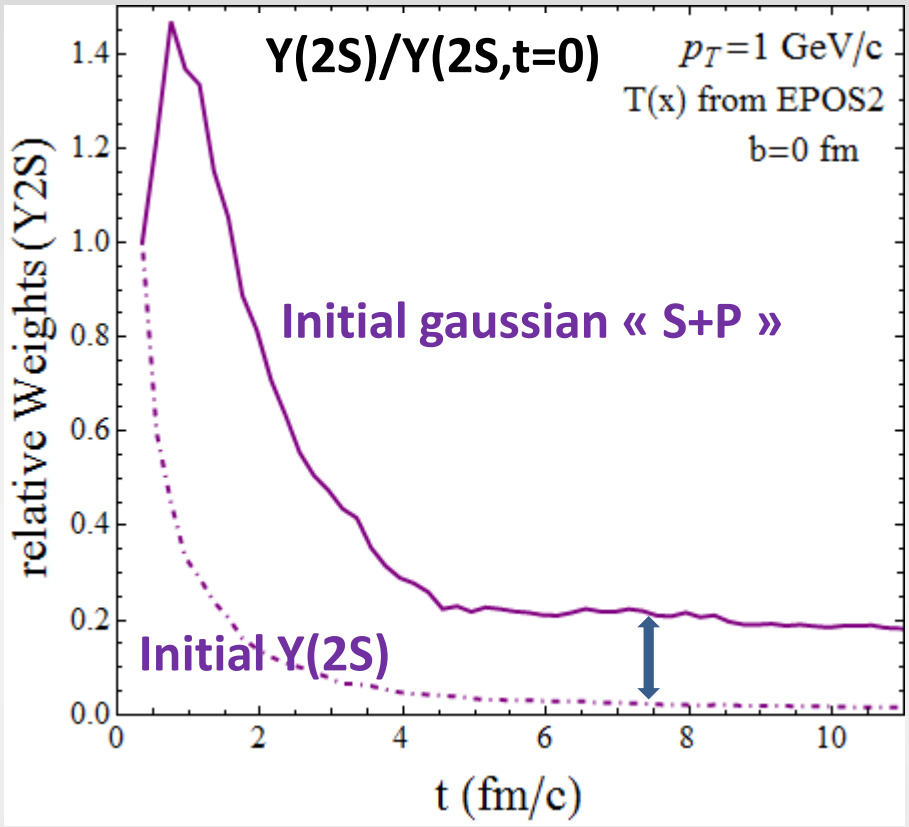
$$W_i(t) = |\left\langle \Psi_i(T=0) | \Psi_{Q\bar{Q}(t)} \right\rangle|^2$$



With T(t): the initial state has a strong influence on populations
=> interplay between transitions scales and T evolution scales
=> incomplete thermalizations

Influence of initial state





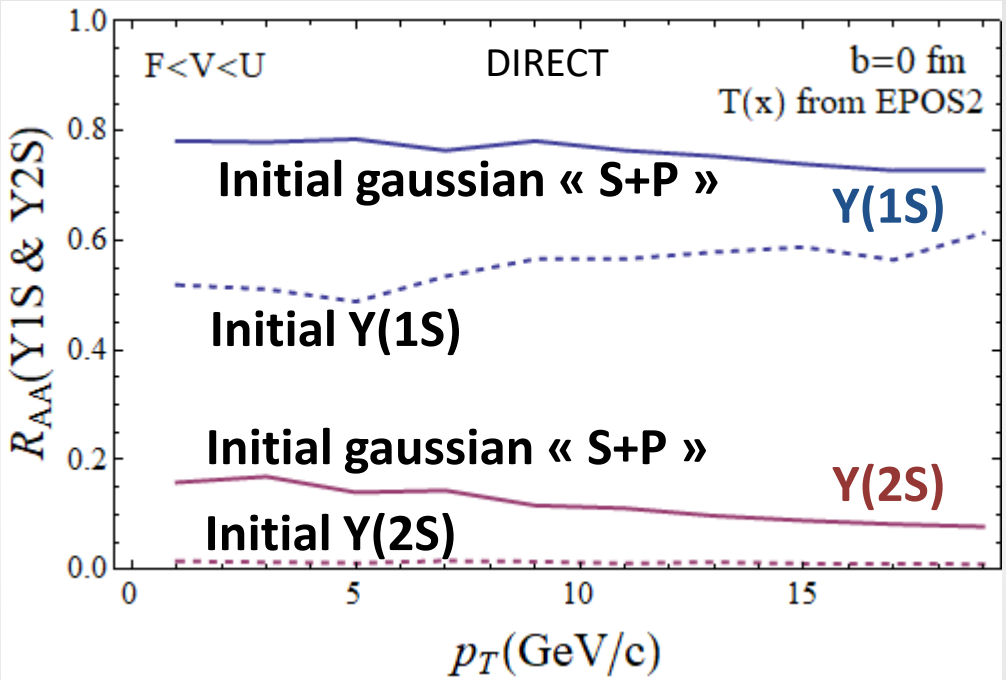
1P component feeds the Y(1S) at small times

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

The survival probabilities depend strongly on the initial state

Influence of initial state

LHC (2.76 TeV): $R_{AA}(p_T)$

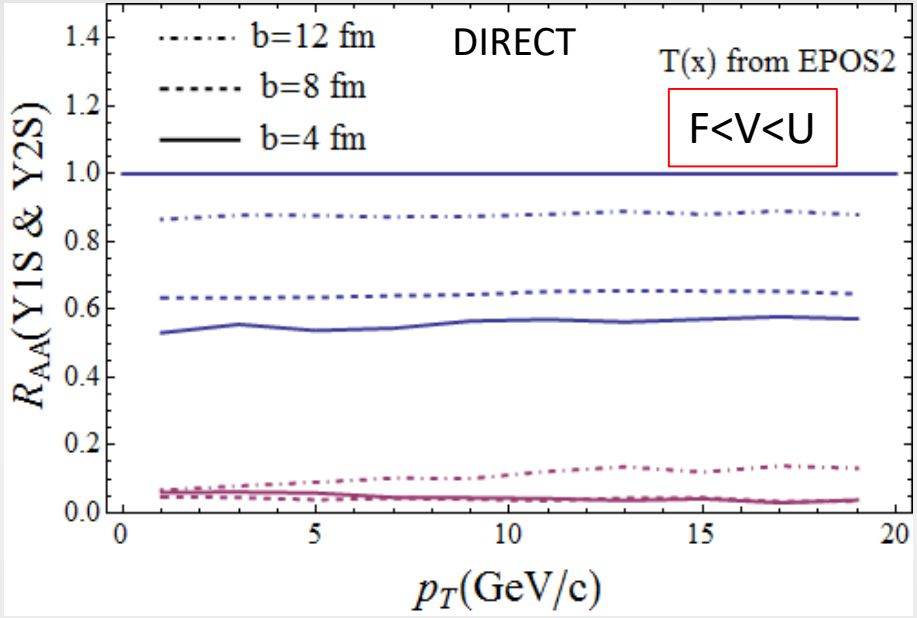


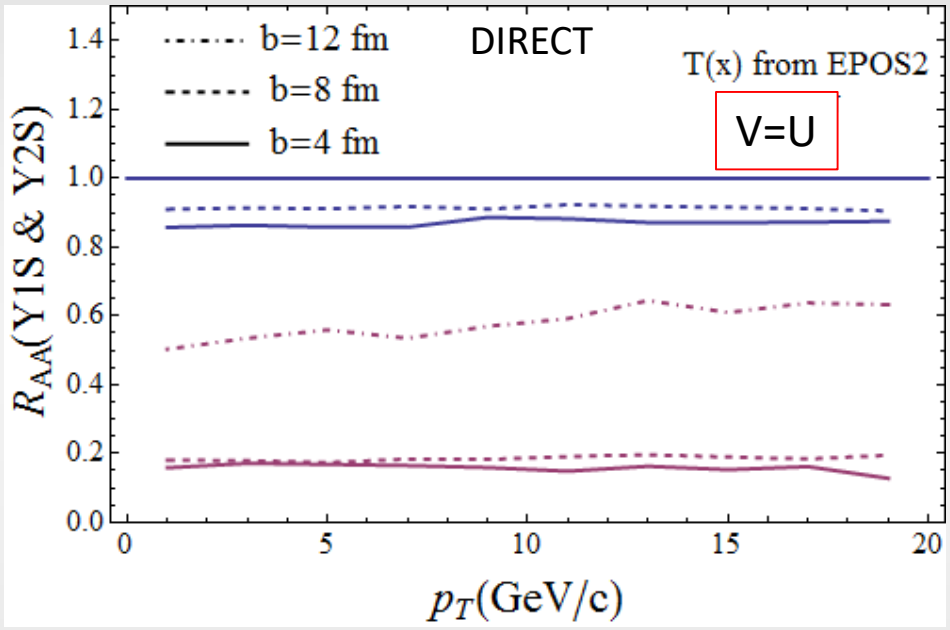
Choice of initial state: strong influence on R_{AA}
=> "quantum memory": the initial coherences impact the observables

Influence of potential

LHC (2.76 TeV): $R_{AA}(p_T)$

With initial Gaussian "S"





Choice of potential: strong influence on R_{AA}

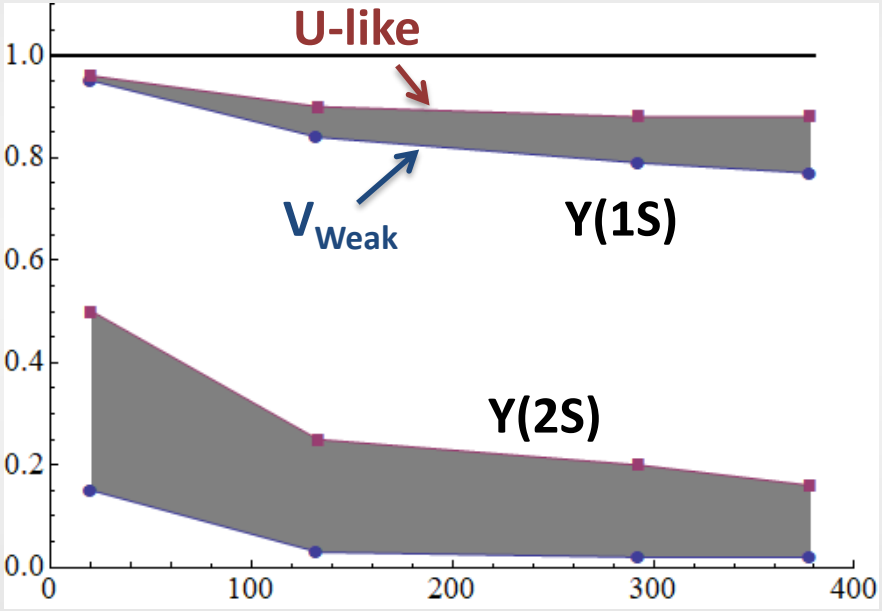
R_{AA}(F<V<U) < R_{AA}(V=U)

Influence of initial state and potential

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

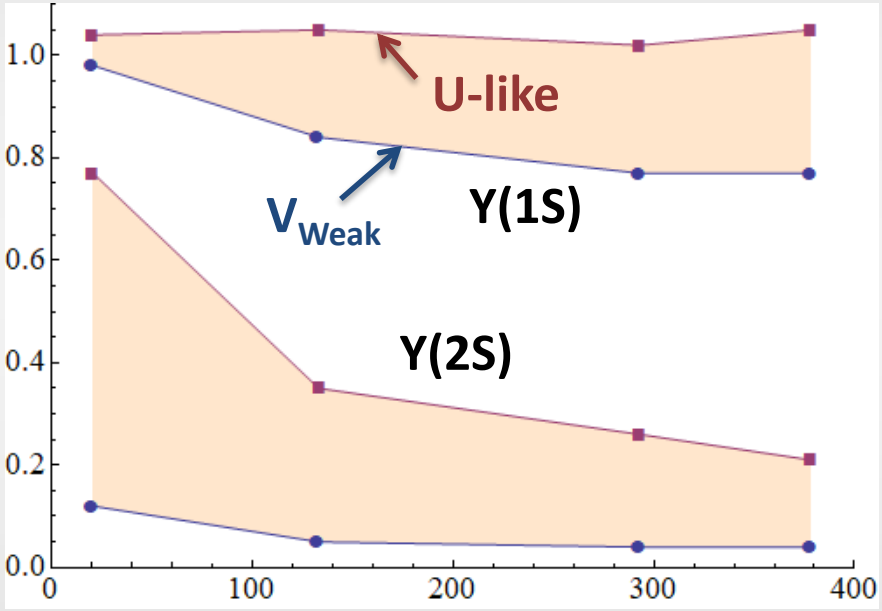
With Kolb-Heinz QGP background

R_{AA} **decoupled initial states: Y(1S) or Y(2S)**



N_{part}

R_{AA} **Initial Gaussian "S" state**



N_{part}

No feed-downs

The initial state has a larger influence when using U-like potential

Thank you

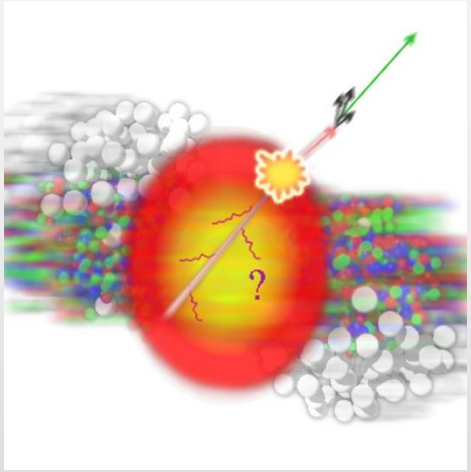
Back-up

Hard probes

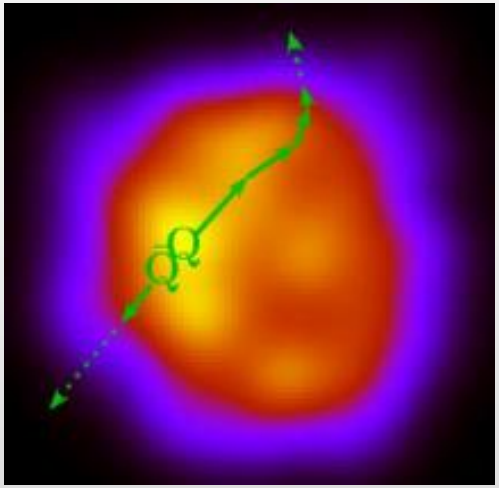
To study the medium properties beyond the freeze out «horizon»…

✓ 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)



Jet quenching



Open heavy flavours and quarkonia propagations

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

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

And quarkonia specifically ?

✓ 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

Can be mastered to probe the QGP temperature and deconfinement

✓ However: the state formation times are subject to debate
=> states form before, in-medium or at the freeze out ?

Common models of quarkonia suppression in QGP

Sequential suppression
(Matsui and Satz)

- Based on states T_{diss}
- If $T_{QGP} > T_{diss}$ the state is dissociated forever
- If $T_{QGP} < T_{diss}$ the state evolves adiabatically

=> *Quarkonia as early QGP thermometer*

Statistical hadronisation
(Braun-Munzinger, Stachel…)

- All $Q\bar{Q}$ pairs are dissociated
- Statistical recombination at freeze-out

=> *Quarkonia as thermometer of T_c*

Transport models
(Zhao, Rapp, Zhuang…)

- Sequential suppression like but
- Quarkonia ↔ $Q+\bar{Q}$ possible during the evolution

=> *Quarkonia as continuous QGP thermometer*

T. Matsui and H. Satz, Phys. Lett. B 178 (1986) 416
P. Braun-Munzinger and J. Stachel, Nucl. Phys. A 690 (2001) 119126
X. Zhao and R. Rapp, Nucl. Phys. A 859 (2011) 114; L. Yan, P. Zhuang, and N. Xu, Phys. Rev. Lett. 97 (2006) 232301

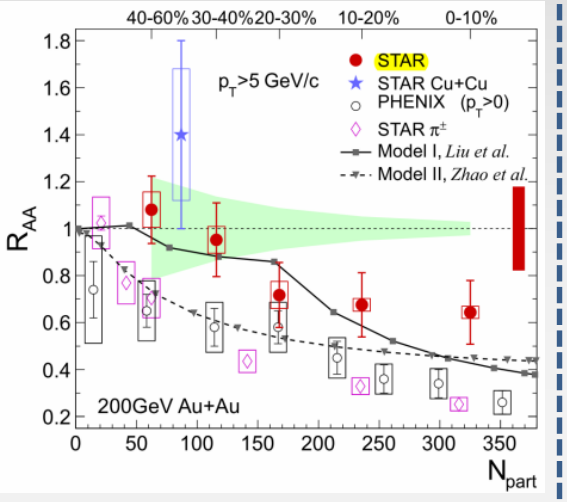
Description of the data

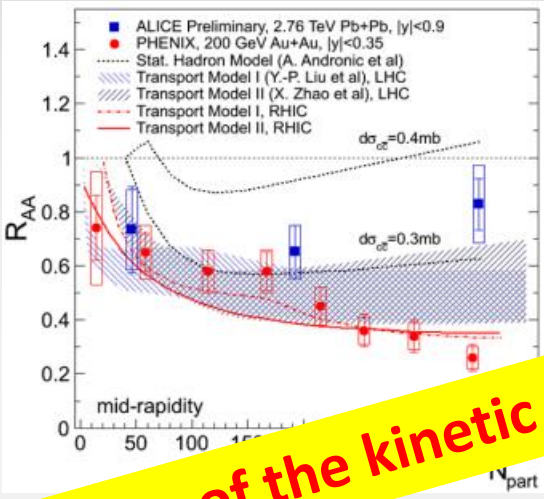
RHIC

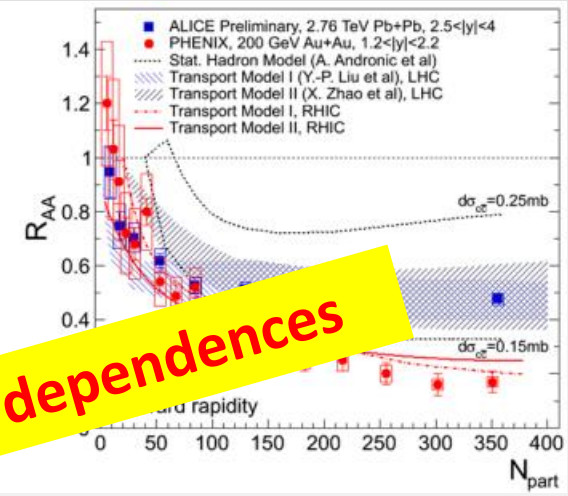
LHC run 1

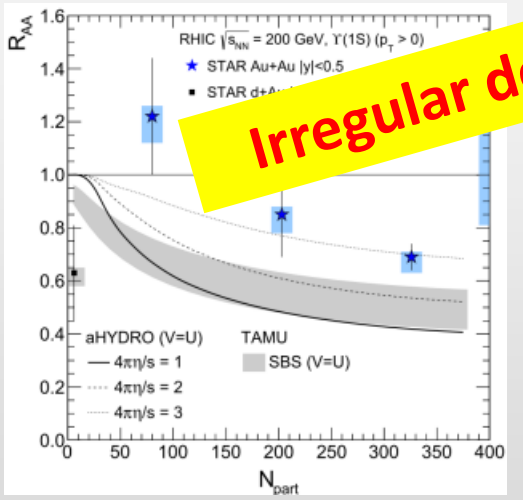
J/ψ

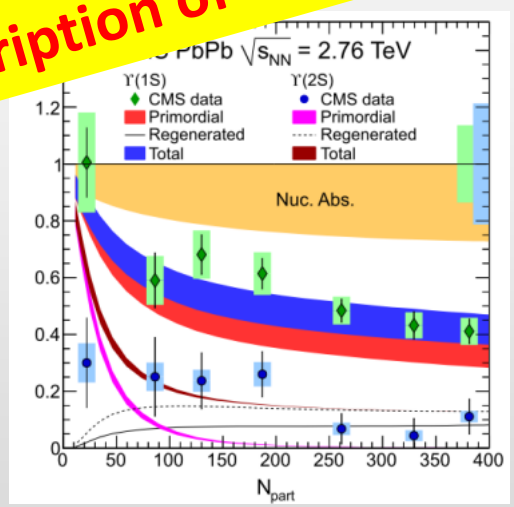
BOTTOMONIA

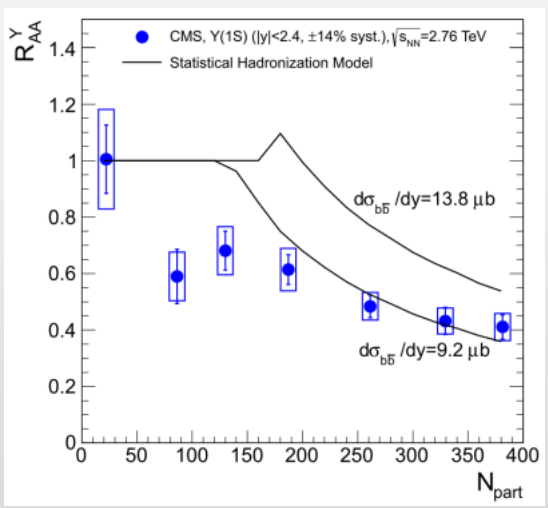










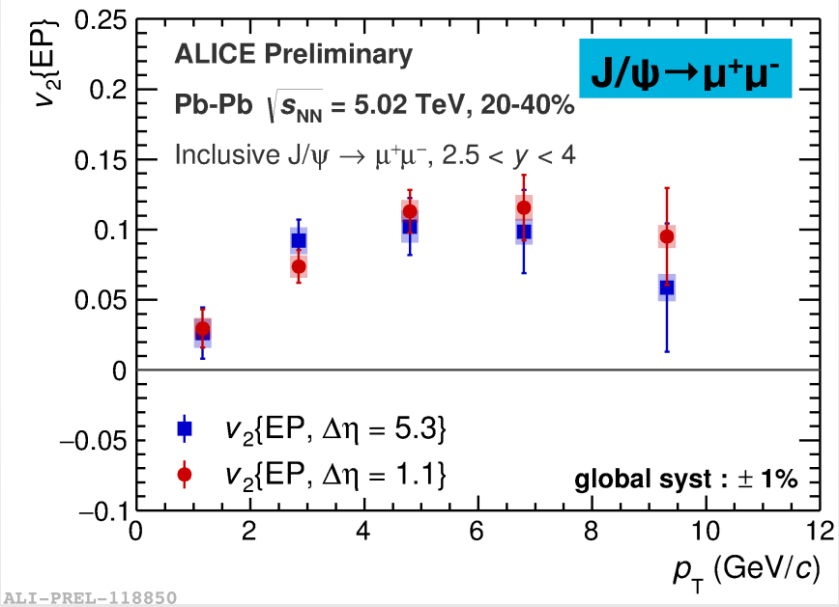


Irregular description of the kinetic dependences

Looking at recent data

✓ **Hints for some recombination into low pT J/ψ**

Significant v_2

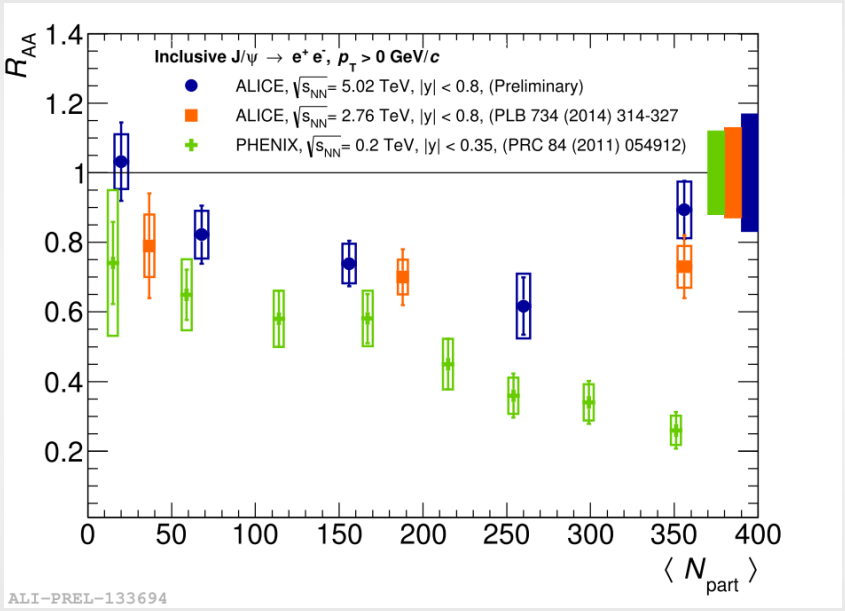


(Alternative idea: partial thermalisation of color octet states ?)

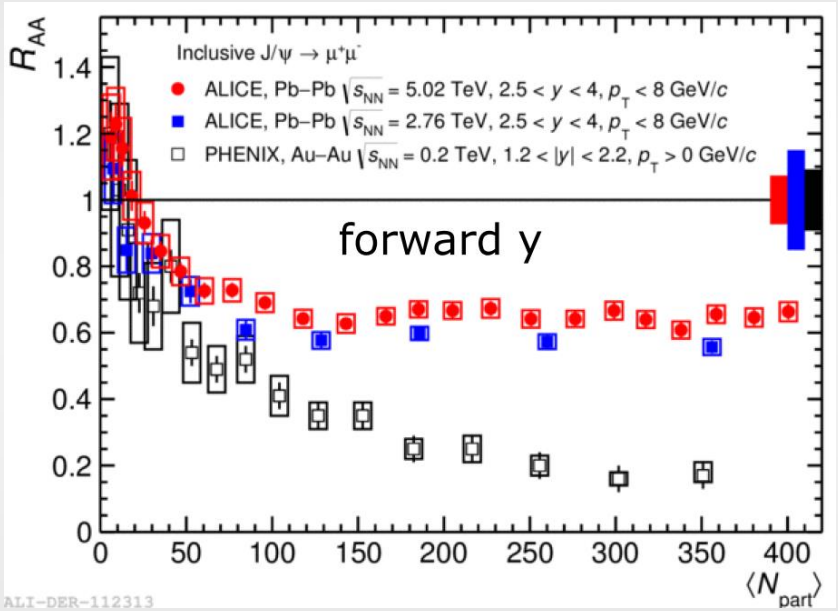
Looking at recent data

✓ **Hints for some recombination into low pT J/ψ**

At mid-y: ordering with s_{NN}



At forward-y: ordering with s_{NN}



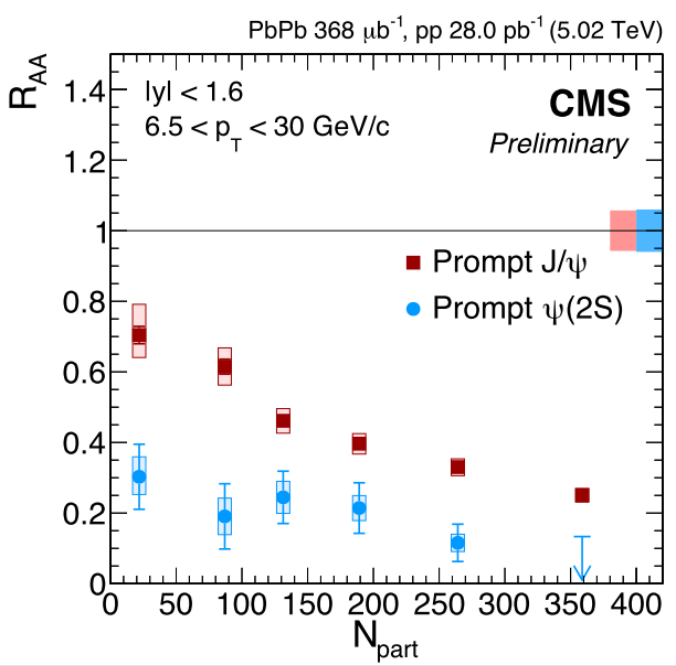
while not observed for the bottomonia (more suppression as s_{NN} increases)

-> Considering some recombination of uncorrelated charm/anticharm quarks is most probably necessary to any model aiming to describe the data

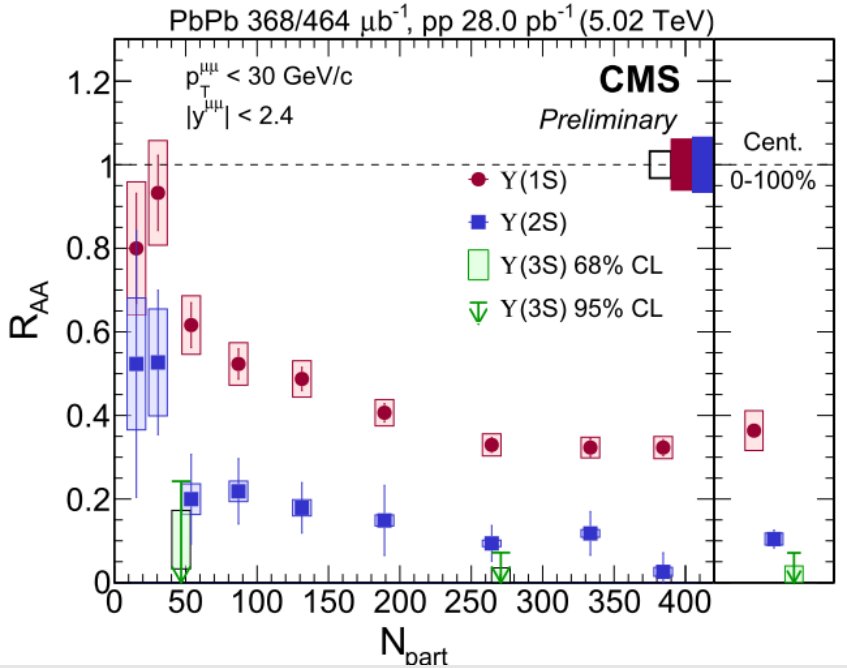
Looking at recent data

✓ **Relative sequential-like suppression between the quarkonium states**

Charmonia



Bottomonia



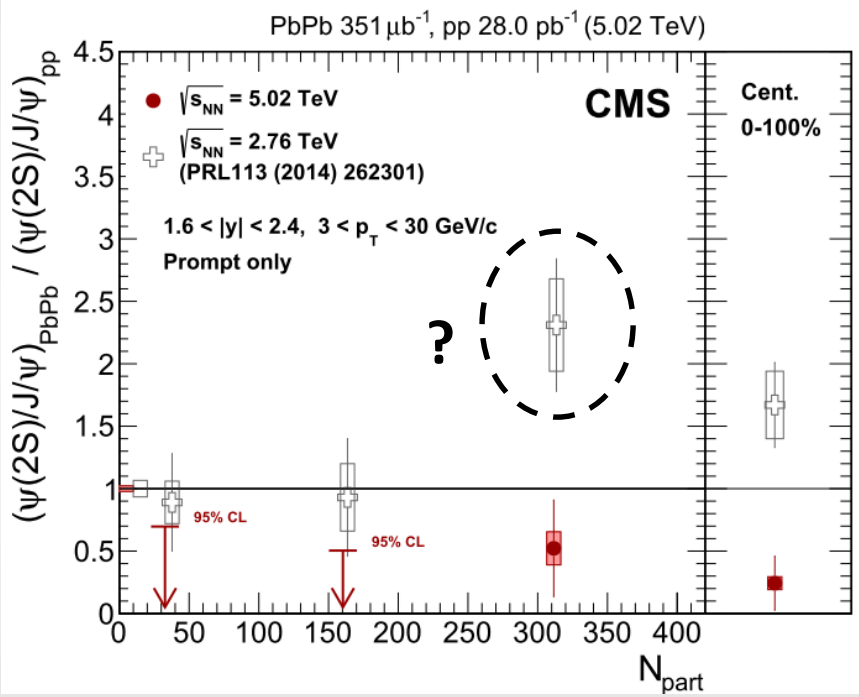
But: smooth evolution with centrality (not really « steps-like » behaviour)

CMS arXiv:1611.01510v2 and CMS PAS HIN-16-023

Looking at recent data

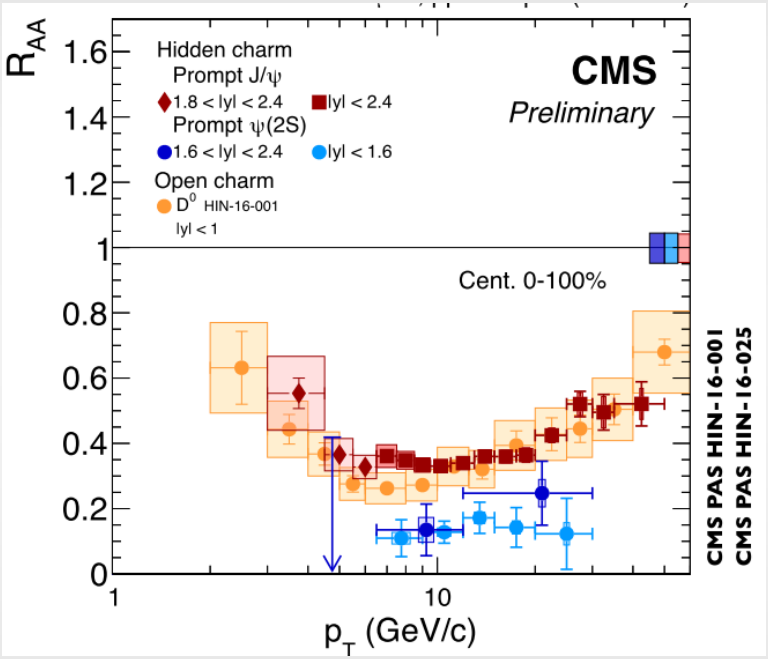
But a bit puzzling...

Ratio ψ(2S) / J/ψ at forward-y



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

Comparison J/ψ and D^0



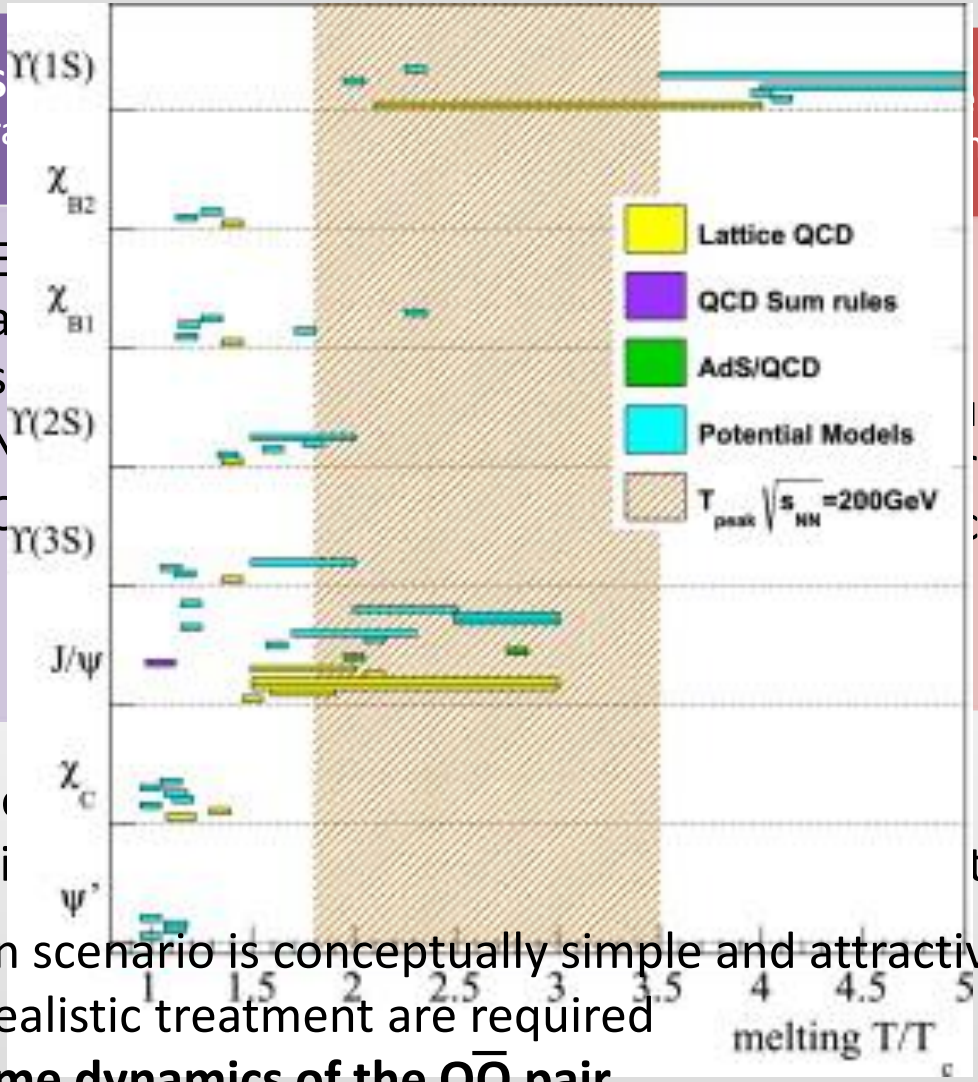
Similar RAA even at higher pT:
- cannot be recombination
- troubling that sequential-like (J/ψ) and Eloss/diffusion+fragmentation (D^0) dynamics give the same behaviour...

CMS arXiv:1611.01438v1

Common model assumptions

Sequential suppression
(Matsui and Satz)

- Everything happens at the BEGINING in a quasi-stationnary medium
- Questionable T_{diss}
- Adiabatic evolution
- No recombinations



Problem: very dynamic m
no effects from non-dissociative i
tates...

A screening + recombination scenario is conceptually simple and attractive
but more realistic treatment are required
-> real-time dynamics of the $Q\bar{Q}$ pair
(and not only of its bound states)

Cesar Luiz da Silva, Nuclear Physics A, Volume 931 (2014)

Our motto

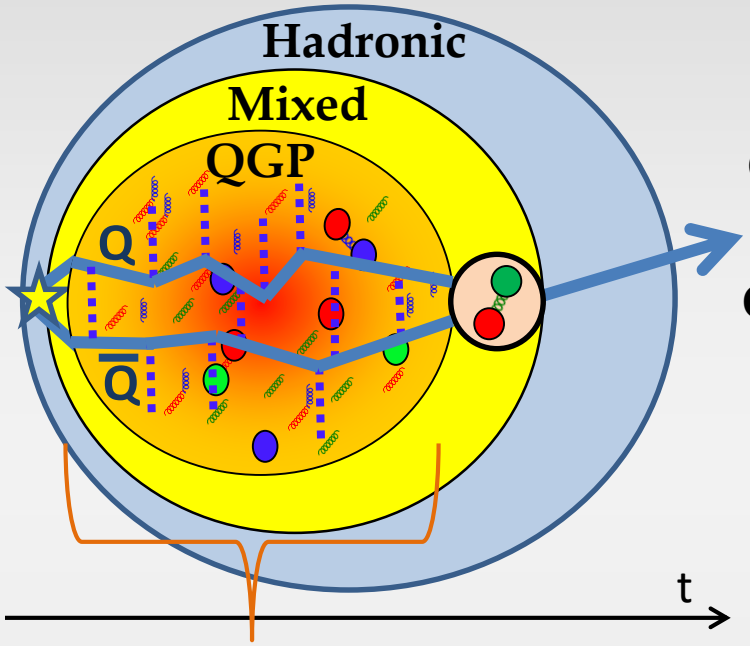
Consider:
color sreening, thermal effects and QGP dynamics

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.

+

$Q\bar{Q}$ PAIRS EVOLUTION IN QGP
Realistic t-dependent background:
Monte-Carlo event generator with initial fluctuations

Inner dynamics ? -> back to concepts



Quarkonium

?

Open mesons

only resolved at the end of the evolution

Beware of quantum coherences during the whole evolution !

How ?

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

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

QGP = thermal bath

The common open quantum system approach

- **Idea:** density matrix and {quarkonia + bath} => bath integrated out

  $\Rightarrow$ non unitary evolution + decoherence effects

  $\Rightarrow$ 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

$\Rightarrow$ complex potential / master equations

$\Rightarrow$ 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 ?

* N. Borghini et al., Eur. Phys. J. C 72 (2012) 2000;

** Y. Akamatsu Phys.Rev. D87 (2013) 045016; Phys. Rev. D 91, 056002 (2015); Kajimoto, Akamatsu, Asakawa & Rothkopf (2017) 1705.03365

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

* Katz and Gossaiux J.Phys.Conf.Ser. 509 (2014) 012095 ; ** Young and Shuryak 2009 Phys. Rev. C 79: 034907 ;

Inner dynamics: semi-classical model

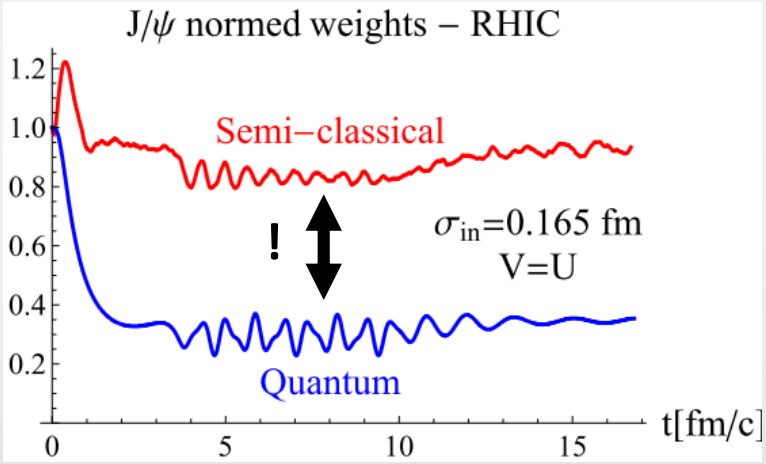
In few words: Evolution of Wigner distributions with a classical Langevin dynamic

=> 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 !!

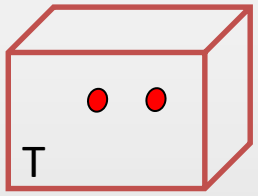
Inner dynamics: Schrödinger-Langevin (SL) equation

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

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

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

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



F : 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

* Kostin The J. of Chem. Phys. 57(9):3589–3590, (1972) ** Garashchuk et al. J. of Chem. Phys. 138, 054107 (2013)
Mócsy & Petreczky Phys.Rev.D77:014501,2008 ; Kaczmarek & Zantow arXiv:hep-lat/0512031v1

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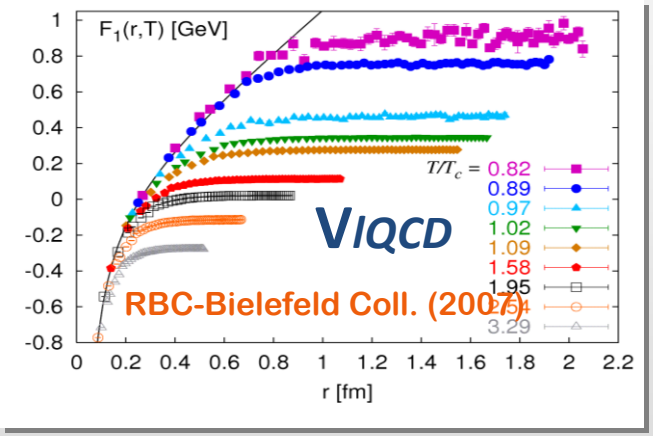
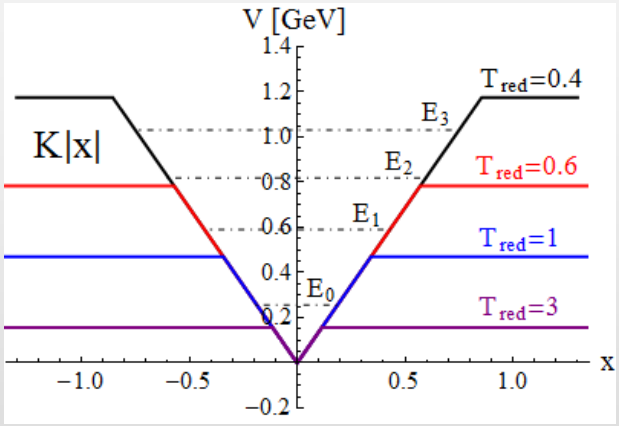
Hamiltonian: Mean Field: T-dependent color screened potential
Generally taken from lattice-QCD. Only singlet for now.

3D not easy to implement => 1D simplified model
not aim to reproduce the data but rather gives insights on the dynamics.



1D

simplification



Linear approx

Screening(T) as VIQCD

Parameters (K, Vmax) chosen to reproduce
quarkonium spectrum + $B\bar{B}$ or $D\bar{D}$ threshold

Inner dynamics: SL equation

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

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Fluctuations: thermal excitation

Taken as a « classical » white stochastic force/noise scaled such as to obtain $T_{Q\bar{Q}} = T_{QGP}$ 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.

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).
R. Katz and P.B. Gossiaux, Annals Phys. 368 (2016) 267-295

Inner dynamics: SL equation

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

Dissipation: thermal de-excitation

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

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

✓ real and ohmic

✓ brings the system to the lowest state

✓with A(T) α T^2 the Drag coefficient from a microscopic model (pQCD - HTL) by Gossiaux and Aichelin

P.B. Gossiaux and J. Aichelin, Phys.Rev. C78 (2008) 014904
R. Katz and P.B. Gossiaux, Annals Phys. 368 (2016) 267-295

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:

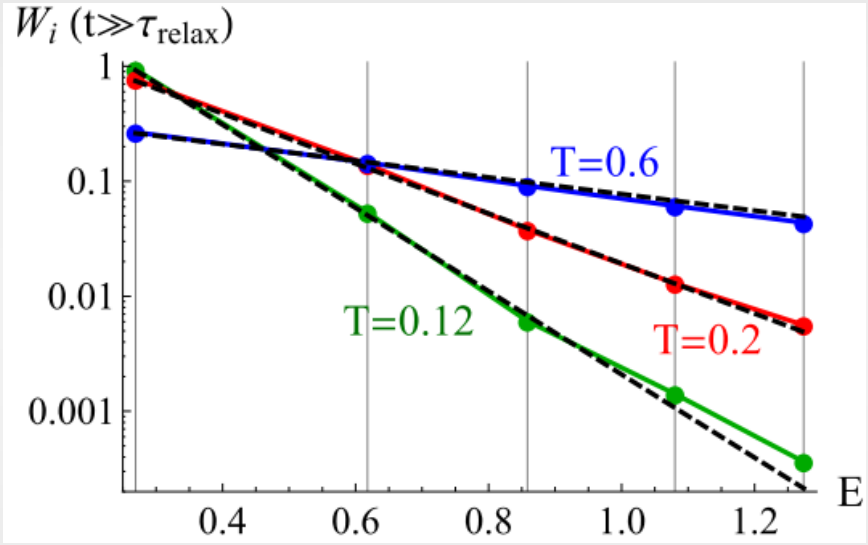
$$\left\langle \langle \psi(t)|\hat{O}|\psi(t)\rangle \right\rangle_{\text{stat}} = \lim_{n_{\text{stat}}\to\infty} \frac{1}{n_{\text{stat}}} \sum_{r=1}^{n_{\text{stat}}} \langle \psi^{(r)}(t)|\hat{O}|\psi^{(r)}(t)\rangle$$

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

R. Katz and P.B. Gossiaux, Annals Phys. 368 (2016) 267-295

Properties of the SL equation

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



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 !!

R. Katz and P.B. Gossiaux, Annals Phys. 368 (2016) 267-295

Initial $Q\bar{Q}$ pair wavefunction ?

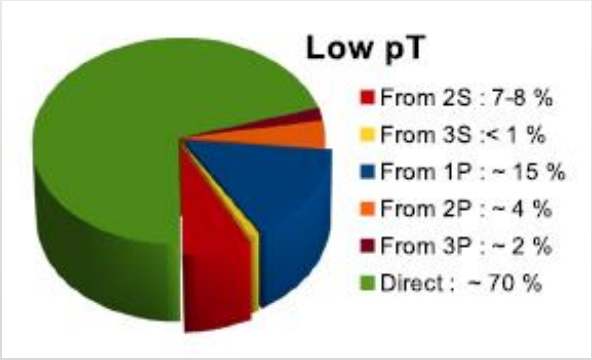
The $Q\bar{Q}$ pairs are produced at the very beginning
BUT state formation times are subject to debate
=> we test the two extrem behaviours:

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

or

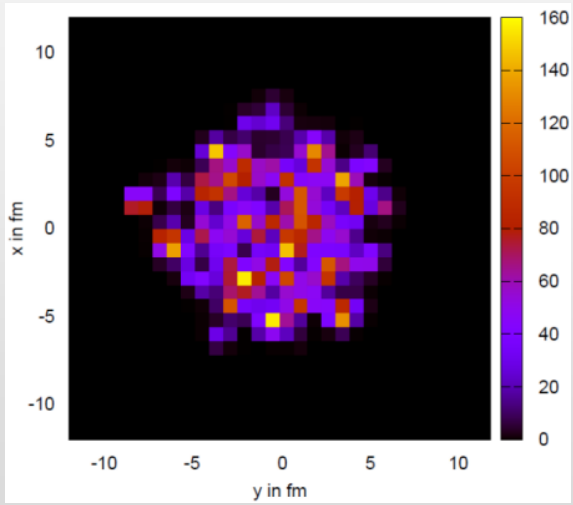
- the $Q\bar{Q}$ pair is not decoupled:
$\psi_{Q\bar{Q}}(t=0)$="a mixture of Gaussian S and P components"
tuned to obtain correct feed-downs and production ratios.

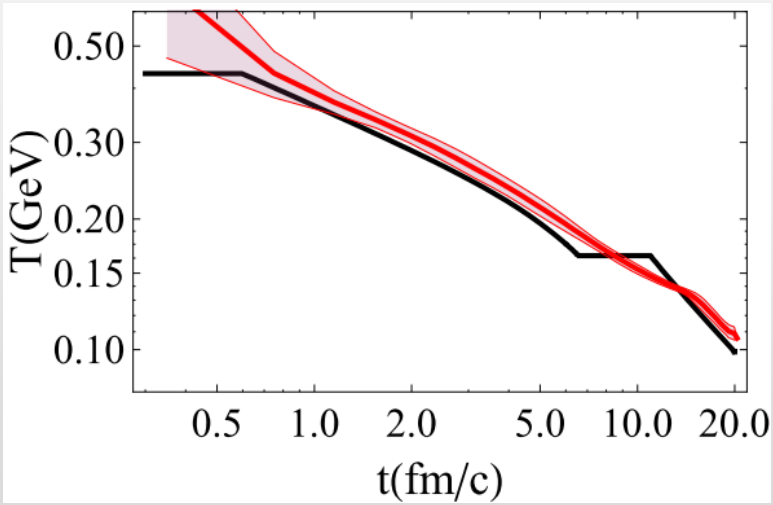
e.g.: contribution to Y(1S) from feed downs:



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_{loss} (assumed to be color singlet)
- Focus on bottomonia for now (CNM and statistical recombination small)





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

Observables

« weight » (population) W_i :

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

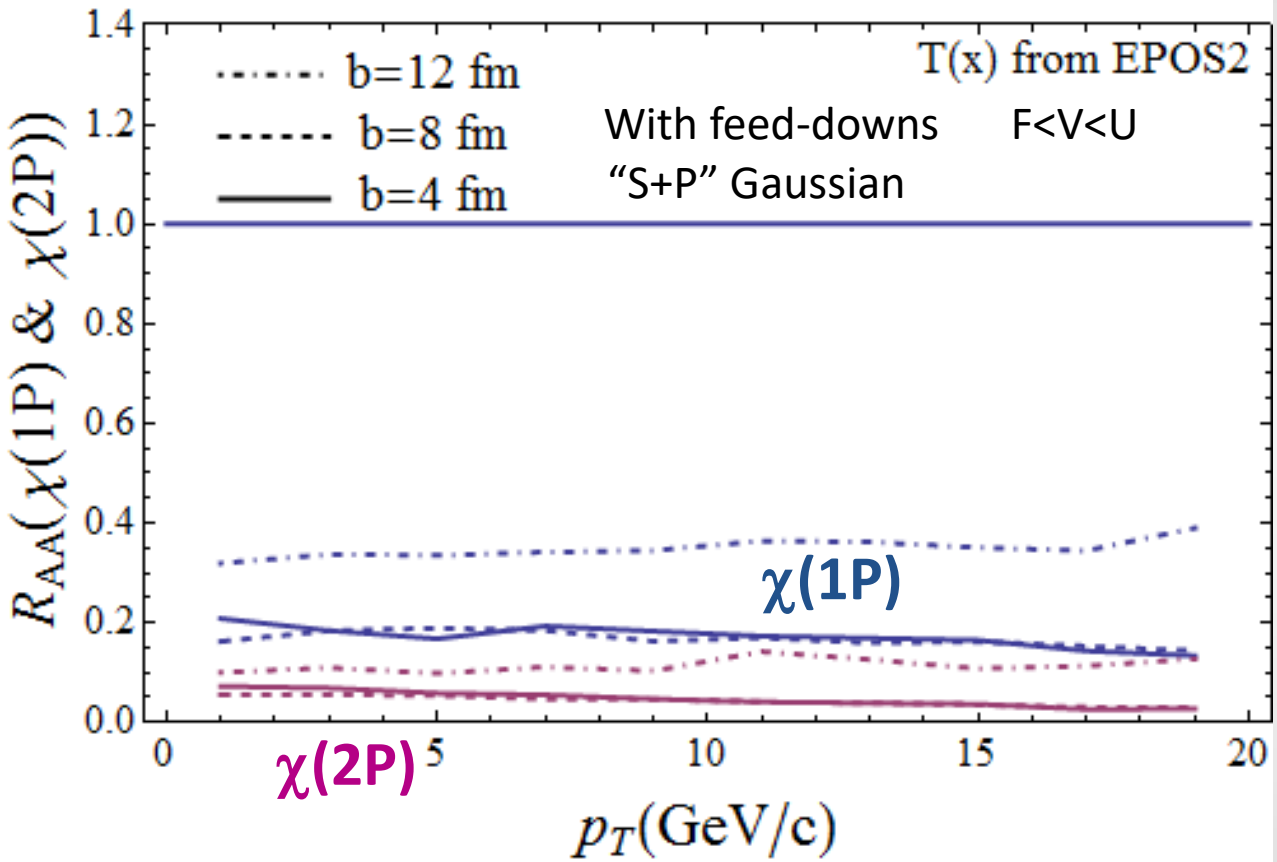
Normed weights S_i :

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

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

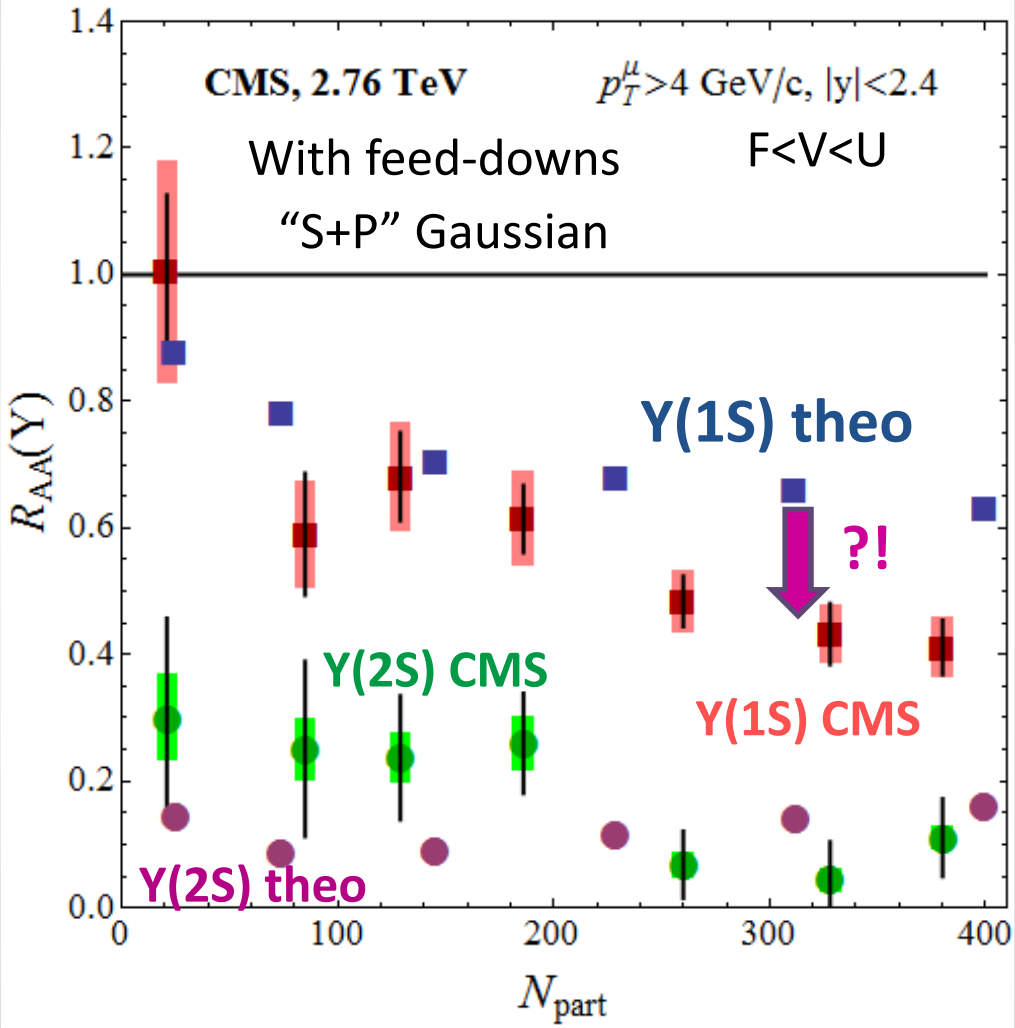
$S_i(t)$ at freeze out convoluted with p_T-y spectra in pp collisions => R_{AA}

LHC (2.76 TeV): $R_{AA}(p_T)$



Same idea for P states

LHC (2.76 TeV): $R_{AA}(N_{part})$

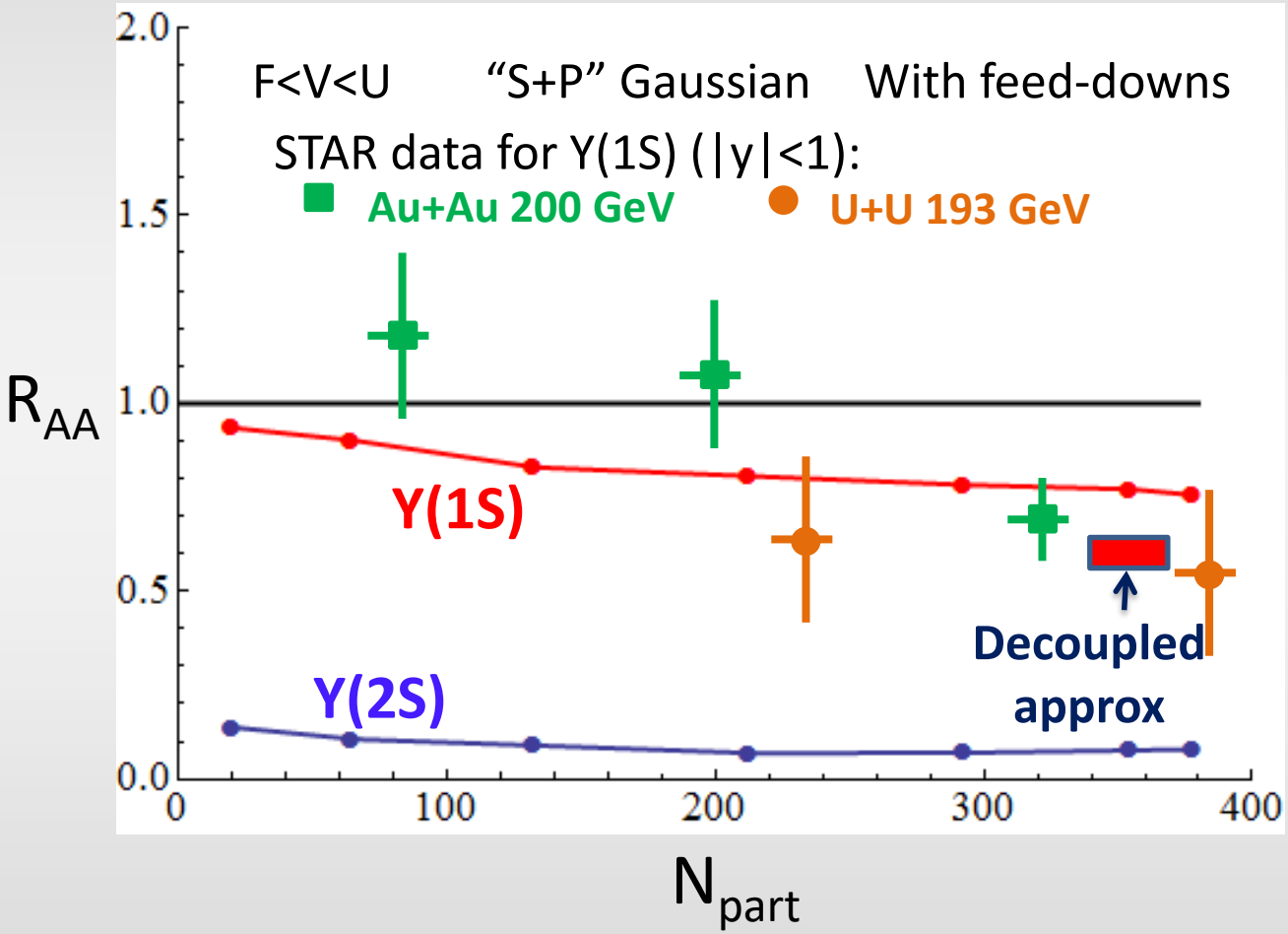


lack of suppression in most central events (CNM ?)

P.B. Gossiaux and R. Katz, J.Phys.Conf.Ser. 779 (2017) no.1, 012041

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

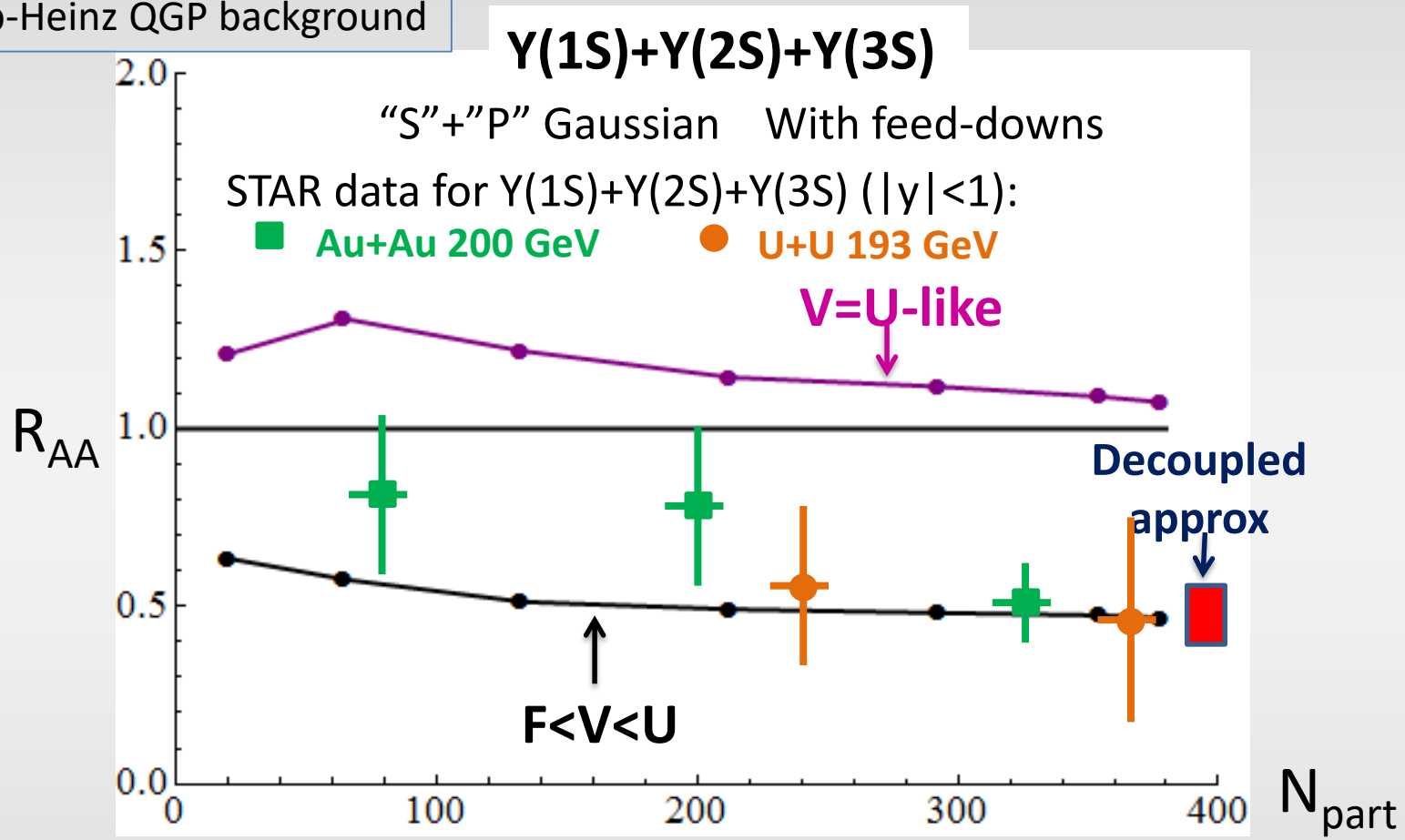
With Kolb-Heinz QGP background



Roughly good agreement with the data (with $F<V_{weak}<U$)

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

With Kolb-Heinz QGP background



With potential U : less good results as compared to data