

# Round Table on Quarkonia Suppression and regeneration in medium

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Subatech (IMT Atlantique / Nantes Université / CNRS-IN2P3)

# Varia questions in the talks

- ▶ Treatment of multiple  $Q\bar{Q}$  pairs
- ▶ More realistic treatment of the medium
- ▶ How to treat the transition between quantum brownian regime (high temperature) and quantum optical regime (low temperature)?

## Questions of current quantum evolution calculations

- How to match lattice potential to quantum operators in quantum master equation?
- How to consider correlation between different  $Q\bar{Q}$  pairs?
- How to consider relativistic effect?

Might be OK for bottomonia (number  $N_{bb}$  small, mass  $m_b$  large)

- How to properly implement dynamical medium in open quantum system?
- What observables to test quantum effects?
- Efficient algorithms for numerical calculations for quantum evolution

# Generic discussion on Quarkonia as hard probes

**A simple and single question :**

**At what stage of the AA collision are the  $J/\psi$  created ?**

(here, mainly thinking of LHC)

# Motivation

2 competing approaches in the place :

Class I

Transport theories



Include a **primordial component** that is partially suppressed along time and witnesses QGP properties



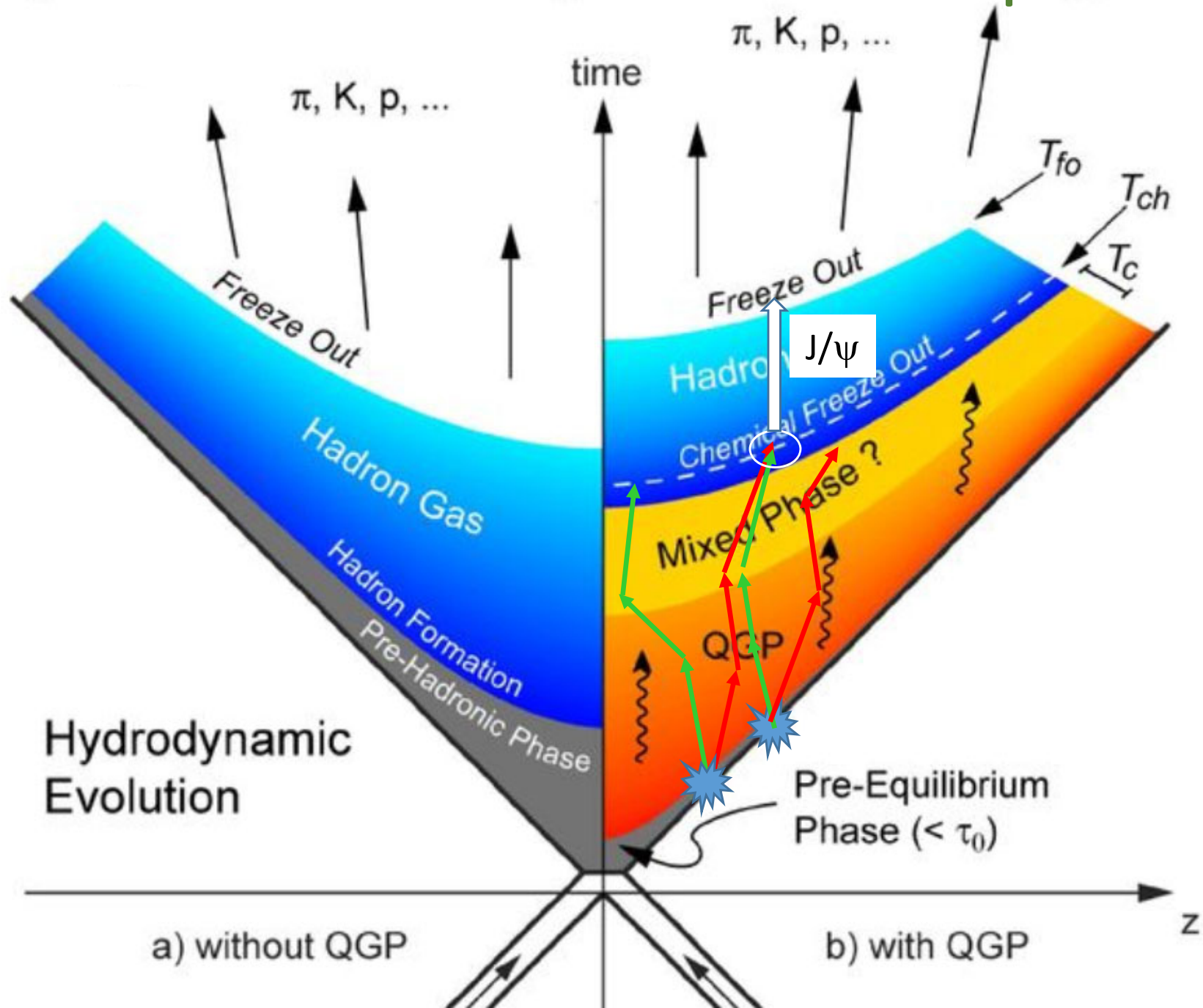
Class II

SHM and coalescence at FO

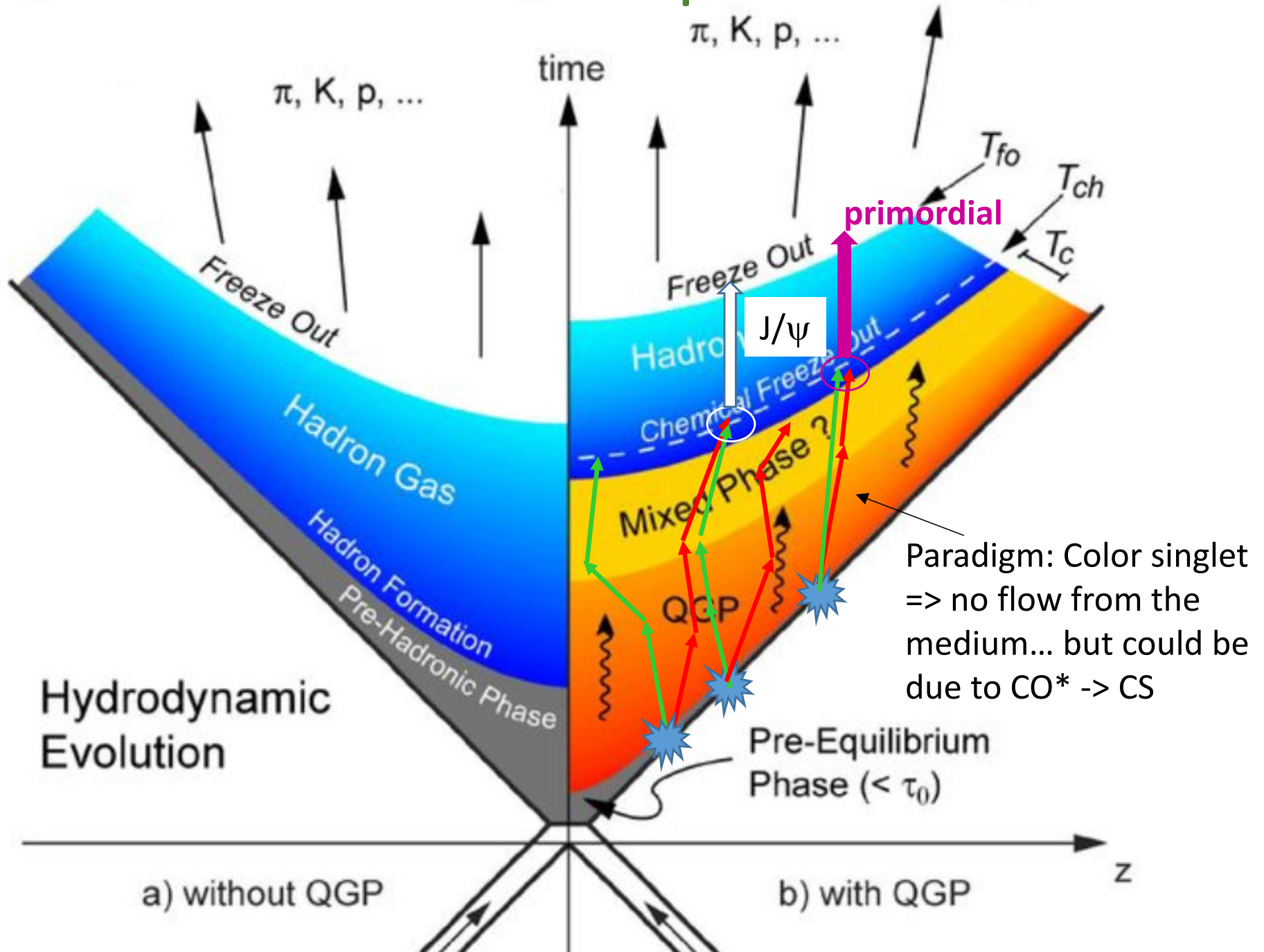


No such component, charmonia are soft probe and only probe the latest stage of QGP !

# Charmonia in the coalescence picture

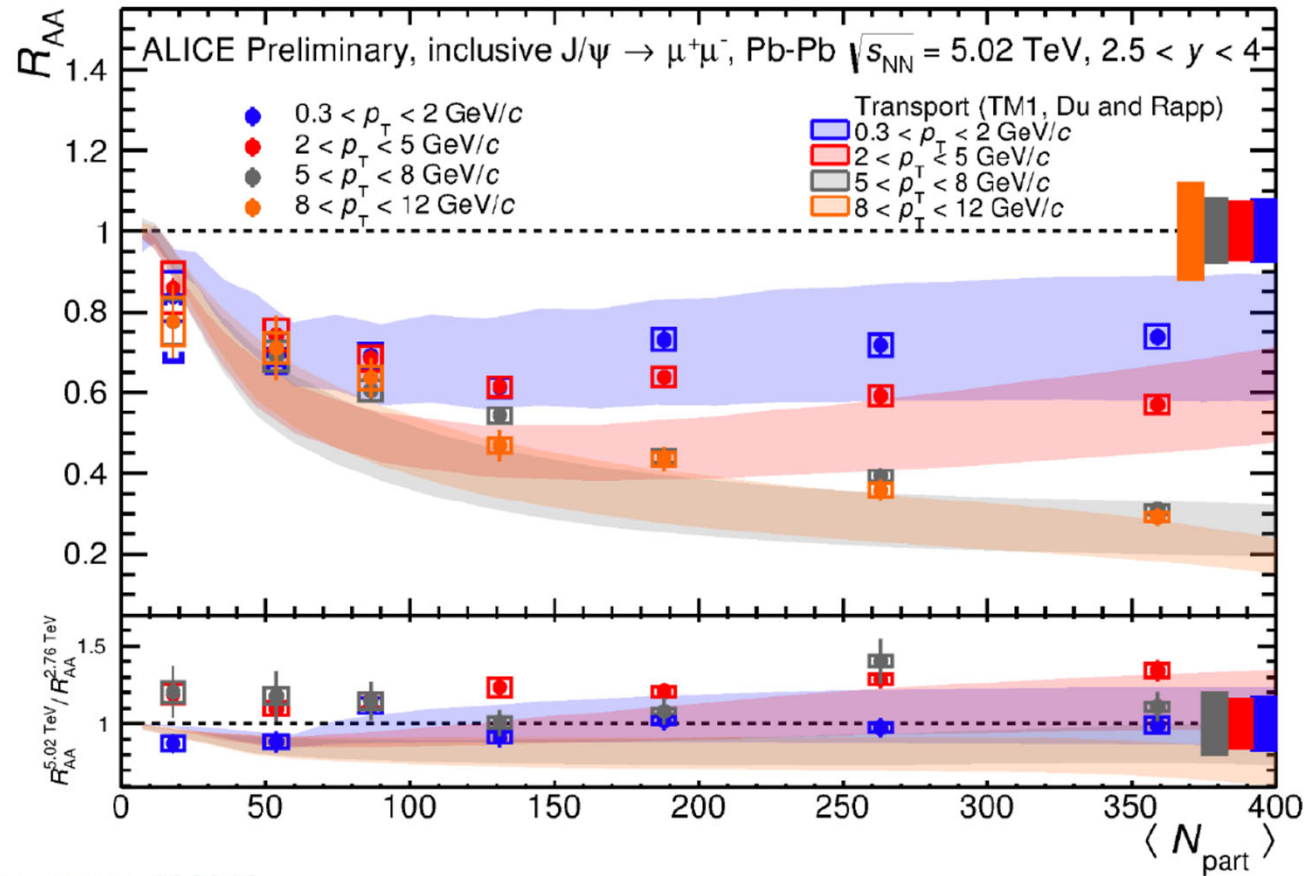


# Charmonia in transport models



# Looking at recent data

## Transport theories



ALI-PREL-120949

- In transport theory, primordial component is mandatory to reproduce the absolute production as a function of centrality &  $p_T$  class

# Motivation

**2 competing approaches in the place :**

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**Transport theories**

1



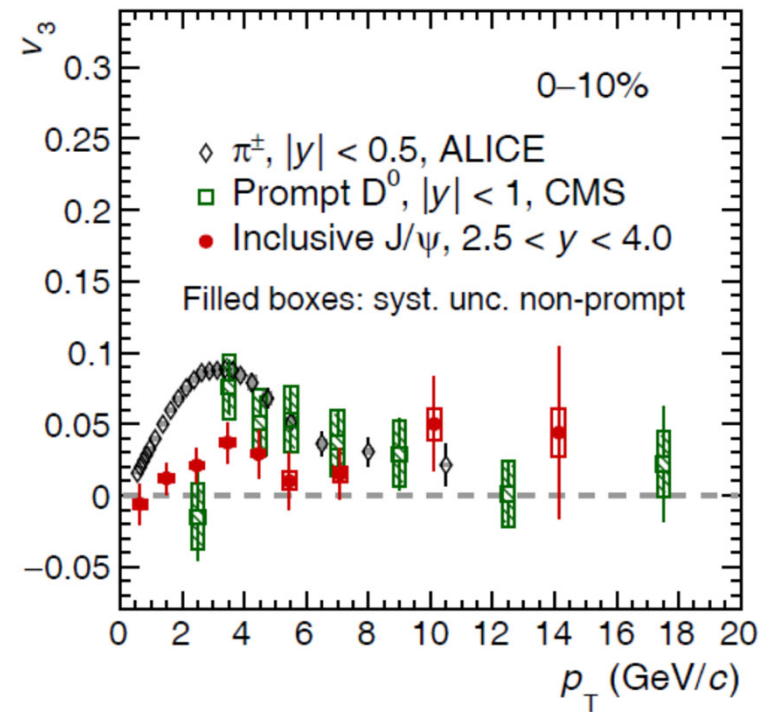
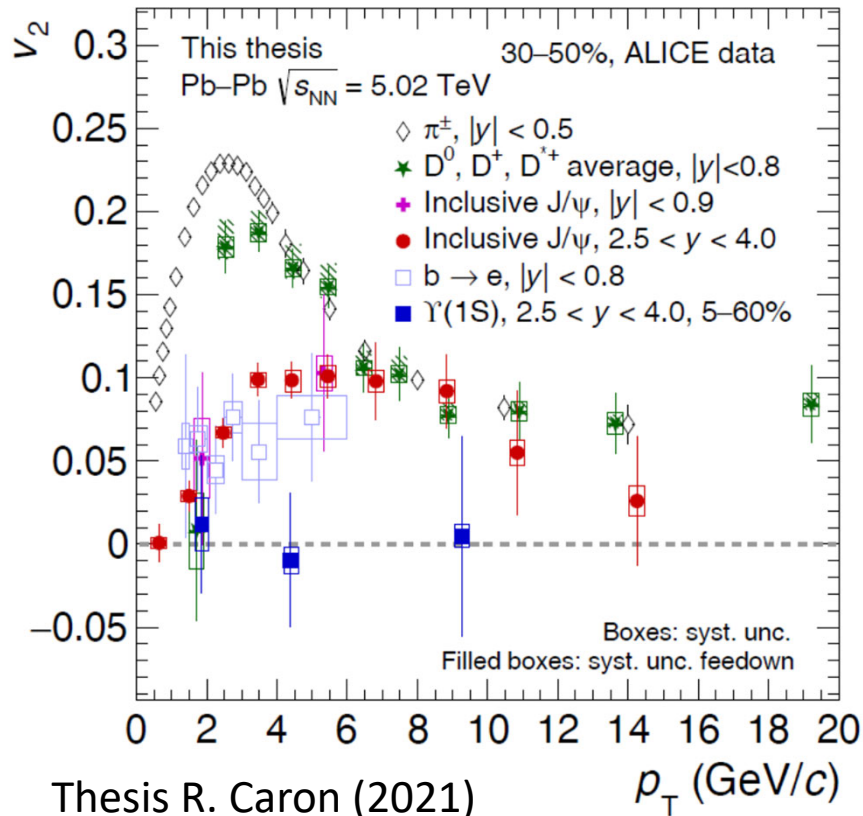
Class II

**SHM and coalescence at FO**

0

# Looking at recent data

## Recently : More global view

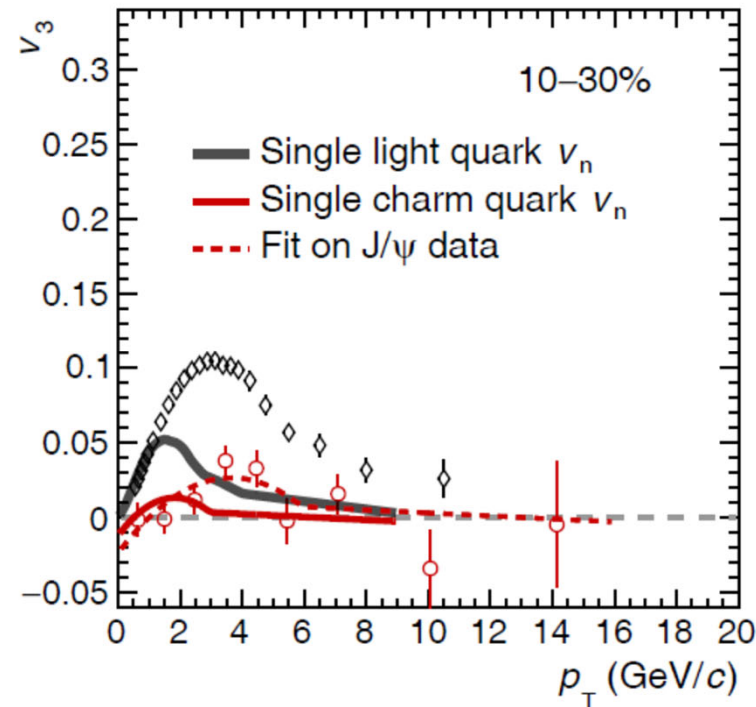
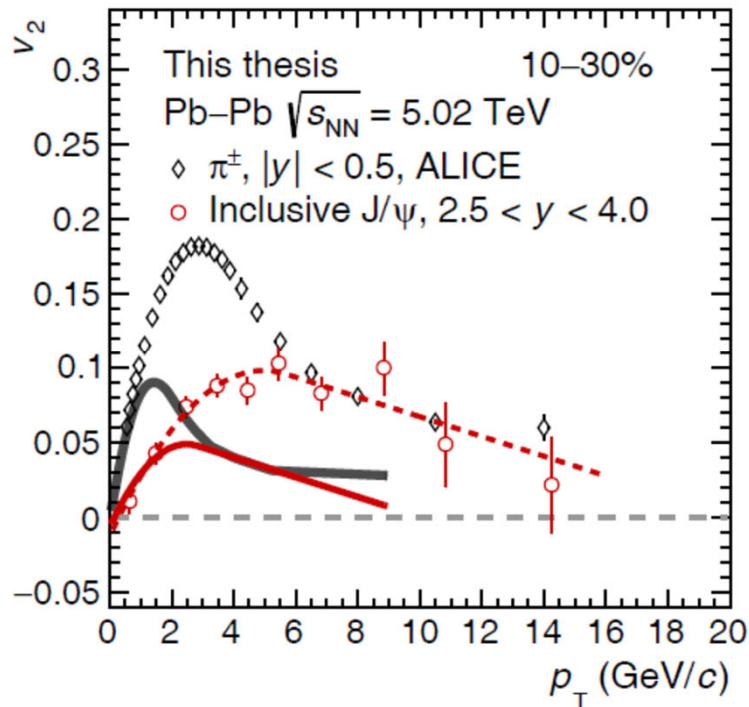


- **$v_2$  and  $v_3$**  analysis confirm that  $J/\psi$  flows
- Flow compatible with 0 for the upsilon 1S

# Looking at recent data

## Coalescence explains it all ?

- $v_2$  &  $v_3(\pi) \Rightarrow v_2$  &  $v_3(q)$  (reverse engineering)
- $v_2$  &  $v_3(\text{J}/\psi \text{ fit}) \Rightarrow v_2$  &  $v_3(c)$  (reverse engineering)

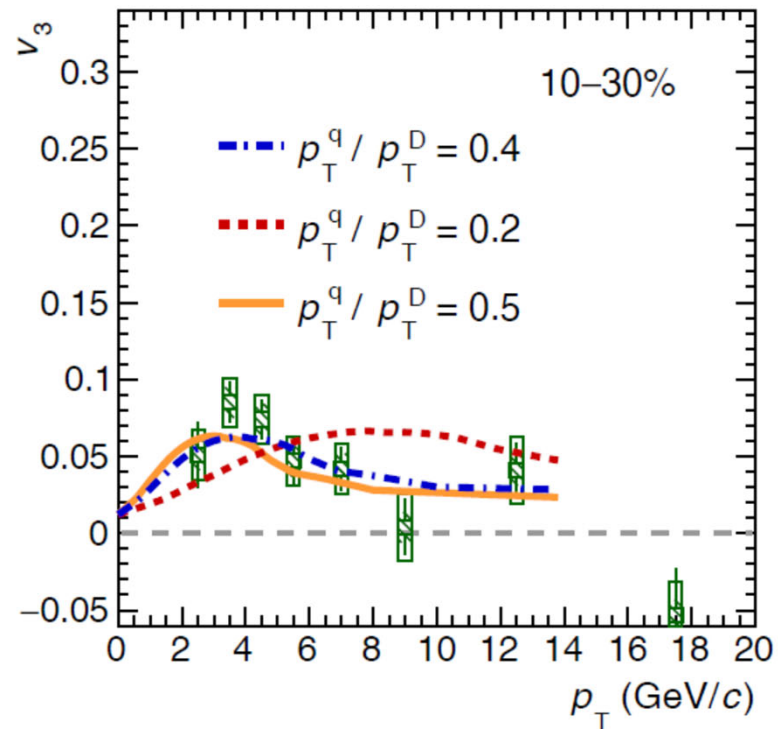
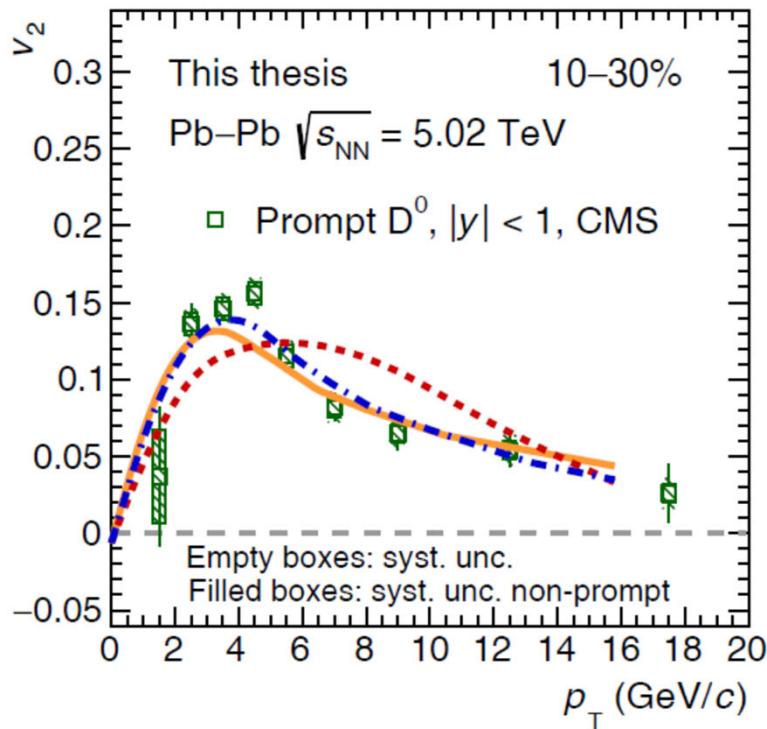


Shreyasi Acharya et al.  
(ALICE) JHEP, 10:141,  
2020.

# Looking at recent data

## Coalescence explains it all ?

- $v_n(q)$  &  $v_n(c)$  + relative weights of masses (momenta)  $\Rightarrow v_n(D)$



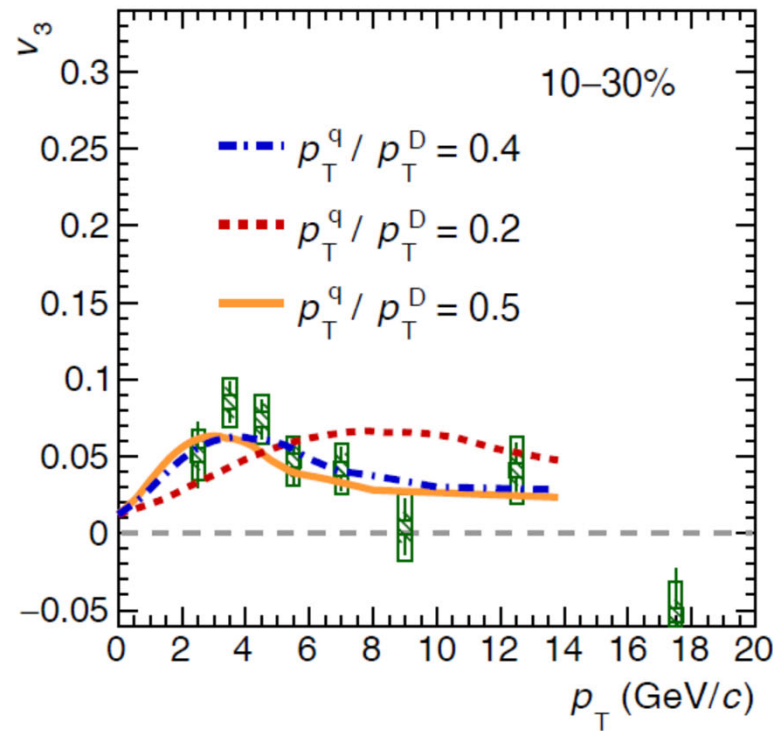
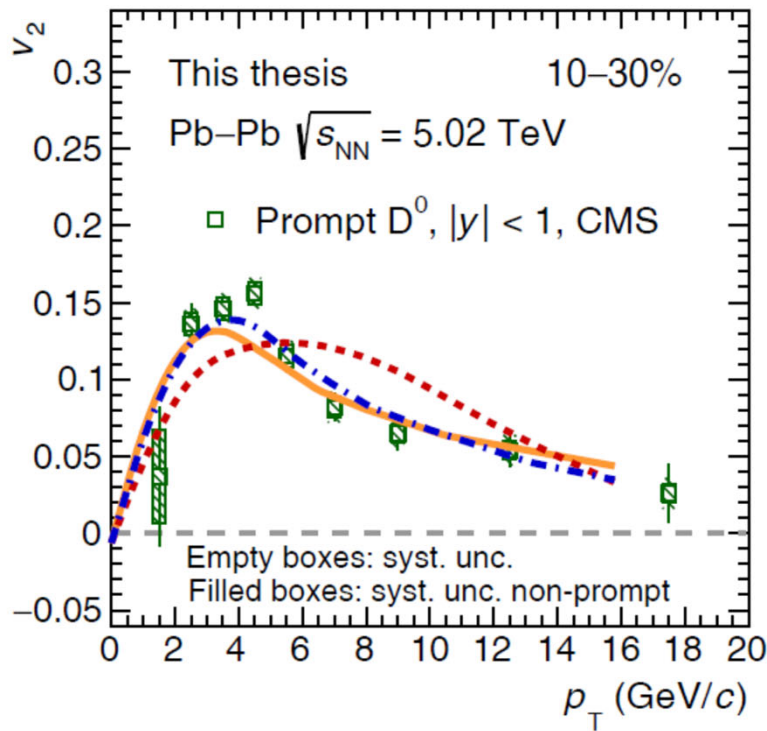
Shreyasi Acharya et al.  
(ALICE) JHEP, 10:141,  
2020.

- Good global agreement for  $p_T^q/p_T^D = 0.4 \Leftrightarrow m_q \approx 0.7 - 0.8$  GeV
- Either ... you consider that this is way too high  $\Rightarrow$  discard the plausibility of coalescence approach

# Looking at recent data

## Coalescence explains it all ?

- $v_n(q)$  &  $v_n(c)$  + relative weights of masses (momenta)  $\Rightarrow v_n(D)$



Shreyasi Acharya et al.  
(ALICE) JHEP, 10:141,  
2020.

- Good global agreement for  $p_T^q / p_T^D = 0.4 \Leftrightarrow m_q \approx 0.7 - 0.8$  GeV
- Or you consider such light-quark masses are achievable close to  $T_c \Rightarrow$  coalescence is indeed a good scheme to understand both charmonia and D mesons flows...

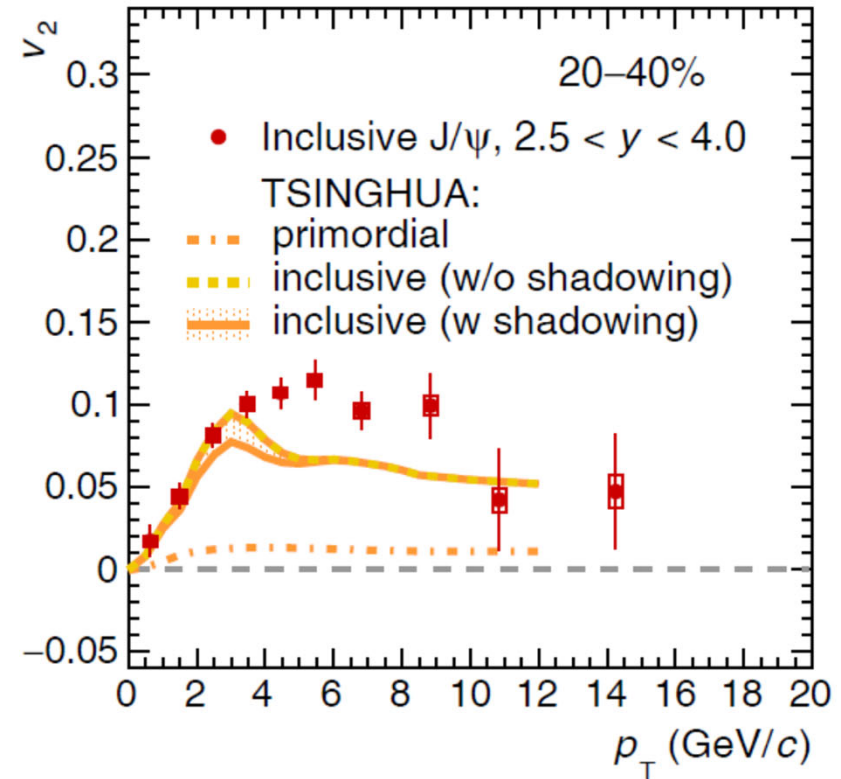
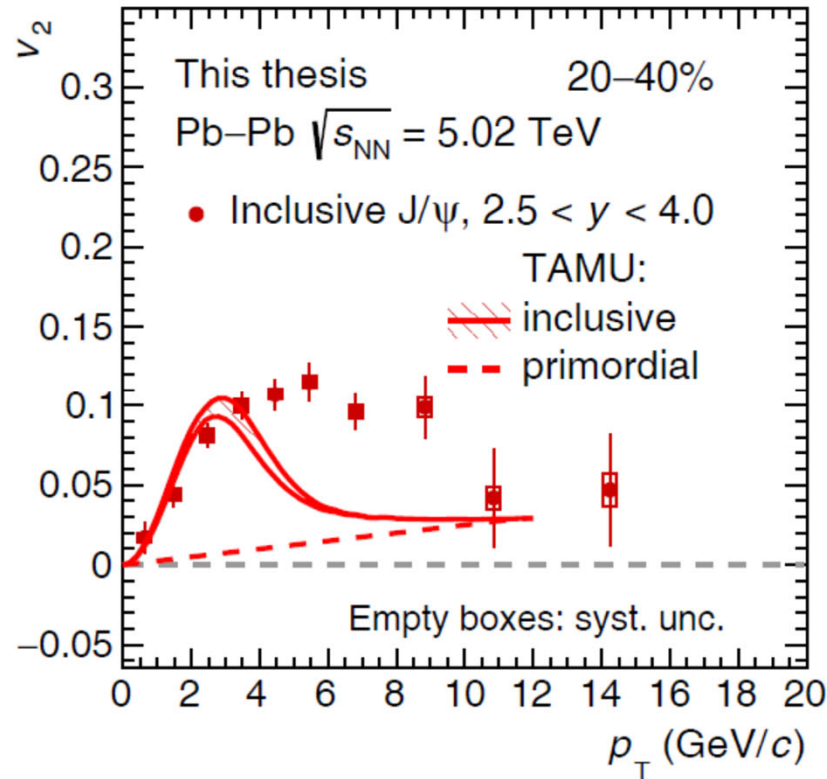


However, no attempt to explain  $R_{AA}(p_T)$

Disappearance of all  $c - \bar{c}$  correlations before FO

# Looking at recent data

## Transport theories



- Good agreement for low  $p_T$ , where  $J/\psi$  formation proceeds through recombination at FO
- Disagreement from intermediate  $p_T$  on, where primordial production starts having a large weight (crucial for the  $R_{AA}(p_T)$ )

# Motivation

**2 competing approaches in the place :**

Class I

**Transport theories**

**1**



Class II

**SHM and coalescence at FO**

**1**

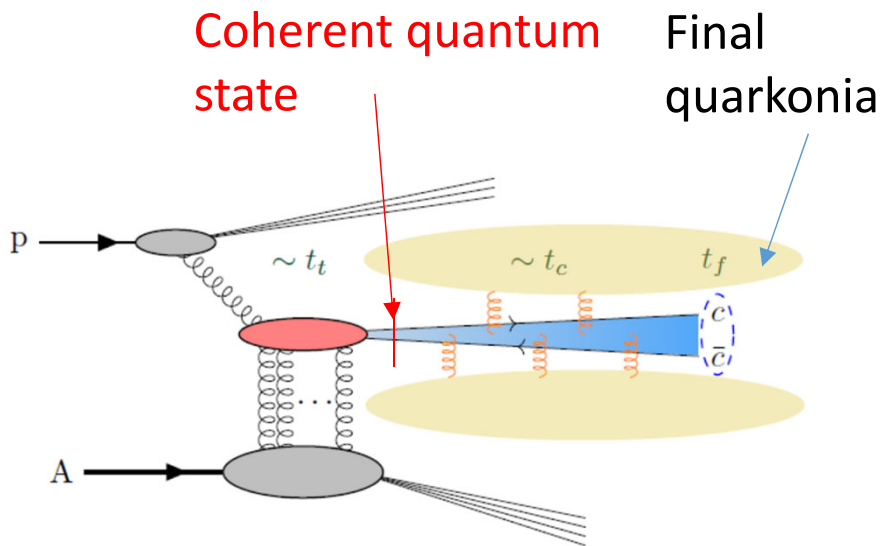
**Other possible contenders :**

- Quantum Master Equation for large # of HQ with semi-classical approximation :

Jean-Paul Blaizot and Miguel Angel Escobedo, JHEP06 (2018) 034

# Quarkonia suppression

Suppression = less than expected in experimental data .... Not « formed and then destroyed »



Evolution operator between both... can of course be evaluated in any eigenstate basis...

$$p_{\Phi_n}(t) = |\langle \Phi_n | U(t, 0) | Q\bar{Q}(t=0) \rangle|^2$$



questionnable

$$\frac{dp_n(t)}{dt} = \sum_i^{+\infty} w_{ni} p_i(t) \quad \text{With } p_i(0)$$



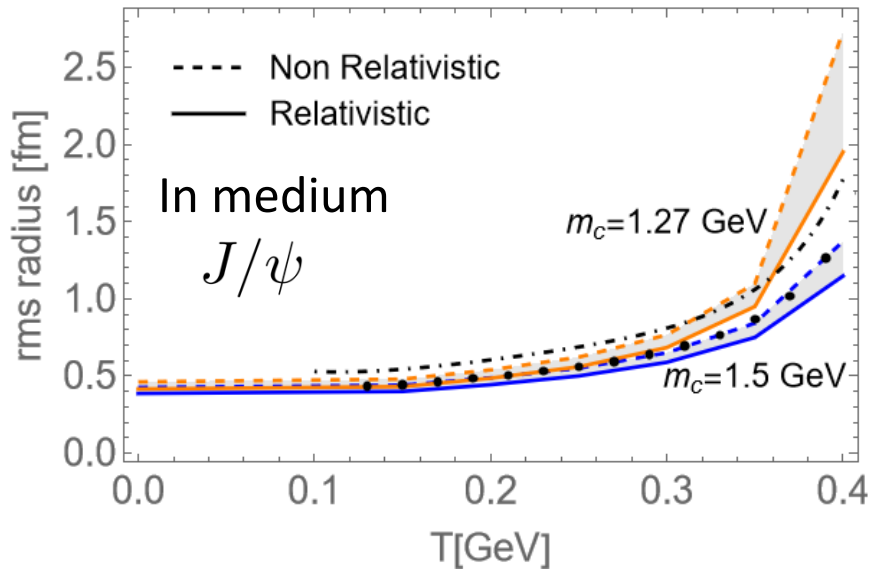
Even more questionnable

$$\frac{dp_n(t)}{dt} = -\Gamma_n p_n(t)$$

... but maybe if we want to talk about «early production », we could be closer to a faithful description by taking eigenstates of the the Debye-like screened potential : « local basis »

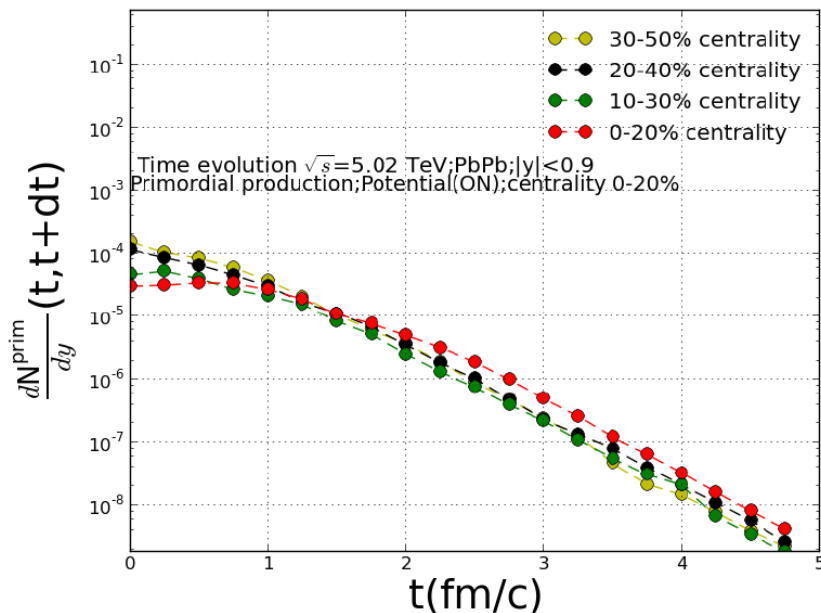
# Quarkonia production (early times)

... but maybe if we want to talk about «early production », we could be closer to a faithful description by taking eigenstates of the the Debye-like screened potential : « local basis »



No state formed for T above 0.4 GeV

Does not correspond to IQCD results on spectral function (here, interactions with the medium are not included)

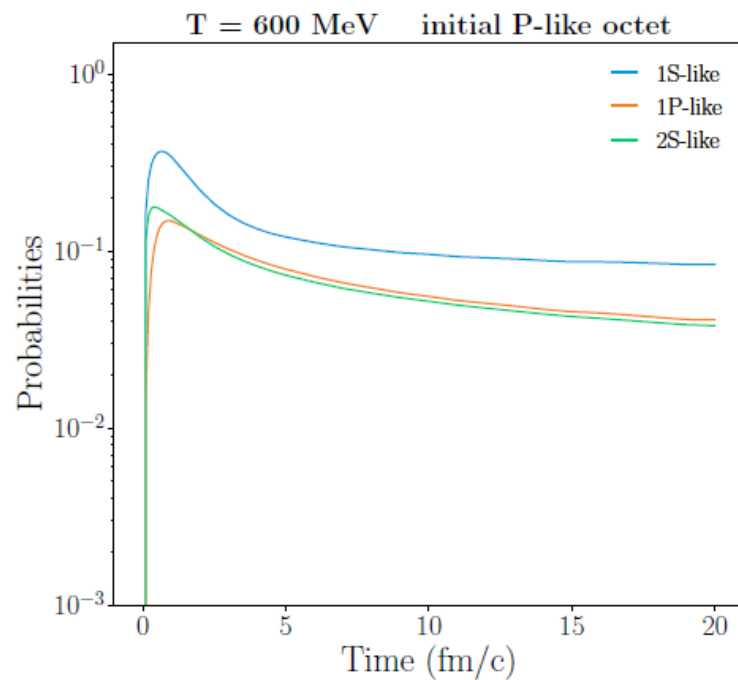
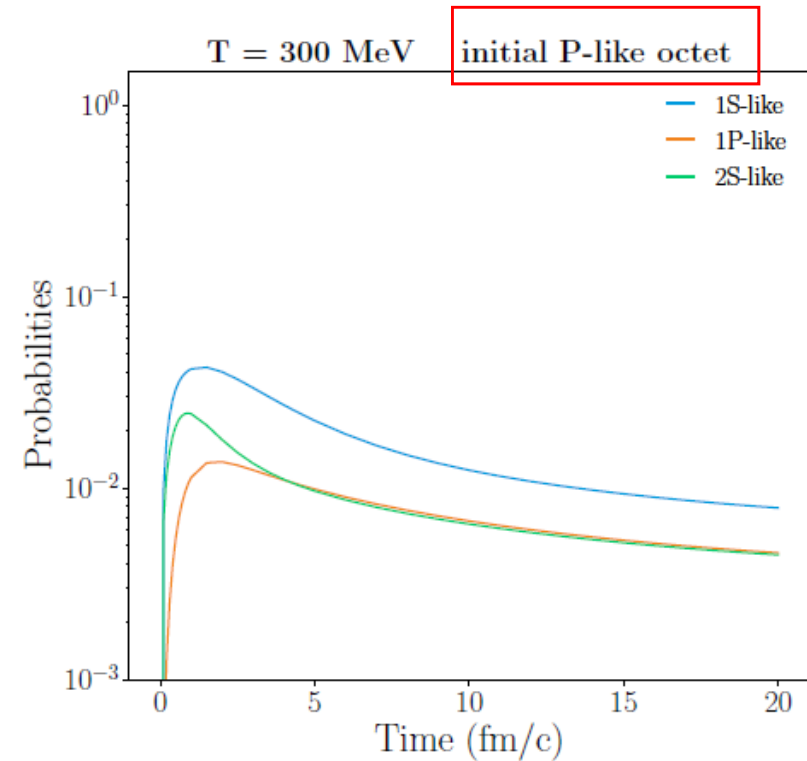
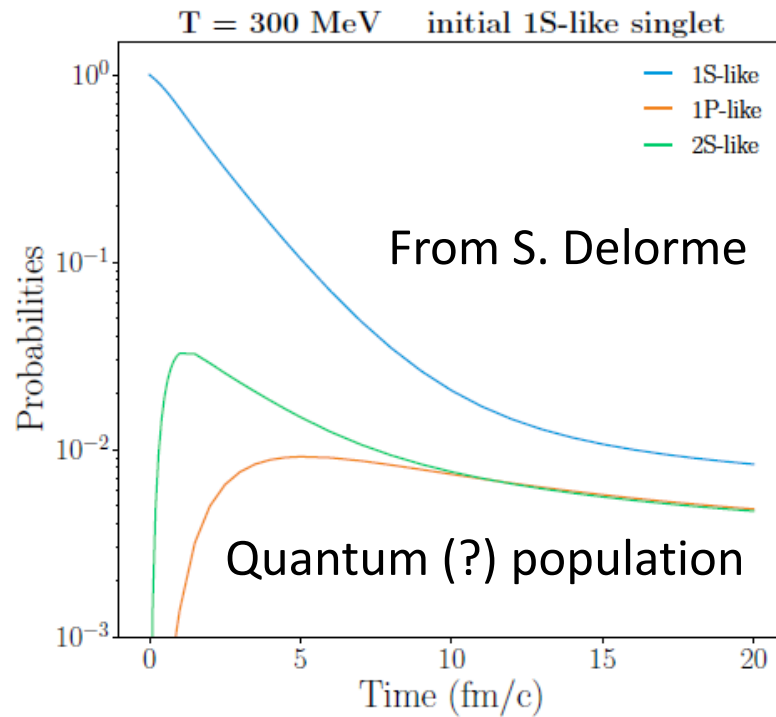


Time evolution of the J/Psi ( $T_{\text{dissoc}}$ ) primordial production at LHC (PbPb normalized by the square value of  $(dN_c/dy)$ ), for each centrality bin.

Clear delay in the most central collisions, due to higher temperatures over longer times.

N.B.: In other approaches, vacuum formation time

# Quarkonia production (intermediate times)



At T(1-2 fm/c), J/Psi are not bound in the QGP !

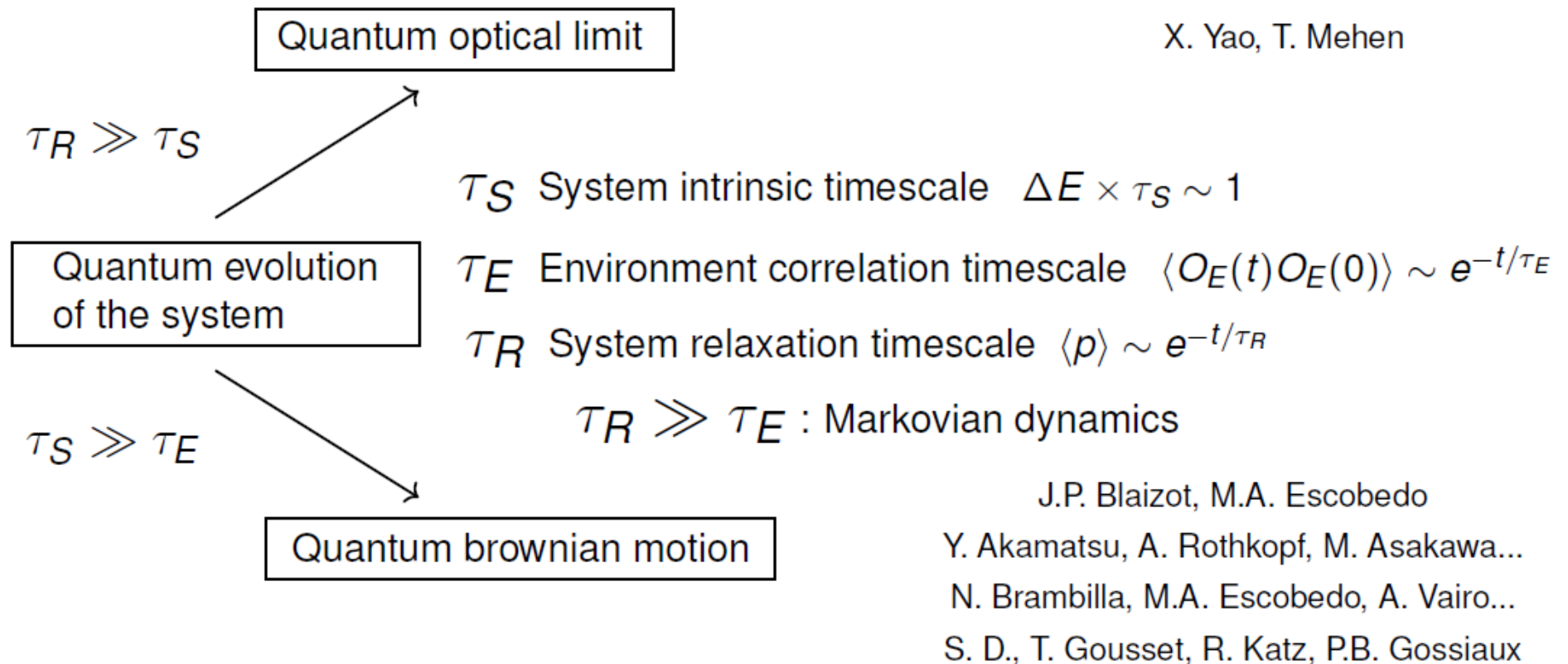
The observed peaks merely represent a correlation that will be reinforced with time.

Can these « Open Quantum Features » be addressed in more « conventional » transport theories ?

For the purpose of implem. In event generators

# Quarkonia production (intermediate times)

## Two regimes



Too abstract for me

$\tau_E$ : environment correlation time

$\tau_S$ : system intrinsic time scale

$\tau_R$ : system relax time

$$\tau_E \sim \frac{1}{T}$$

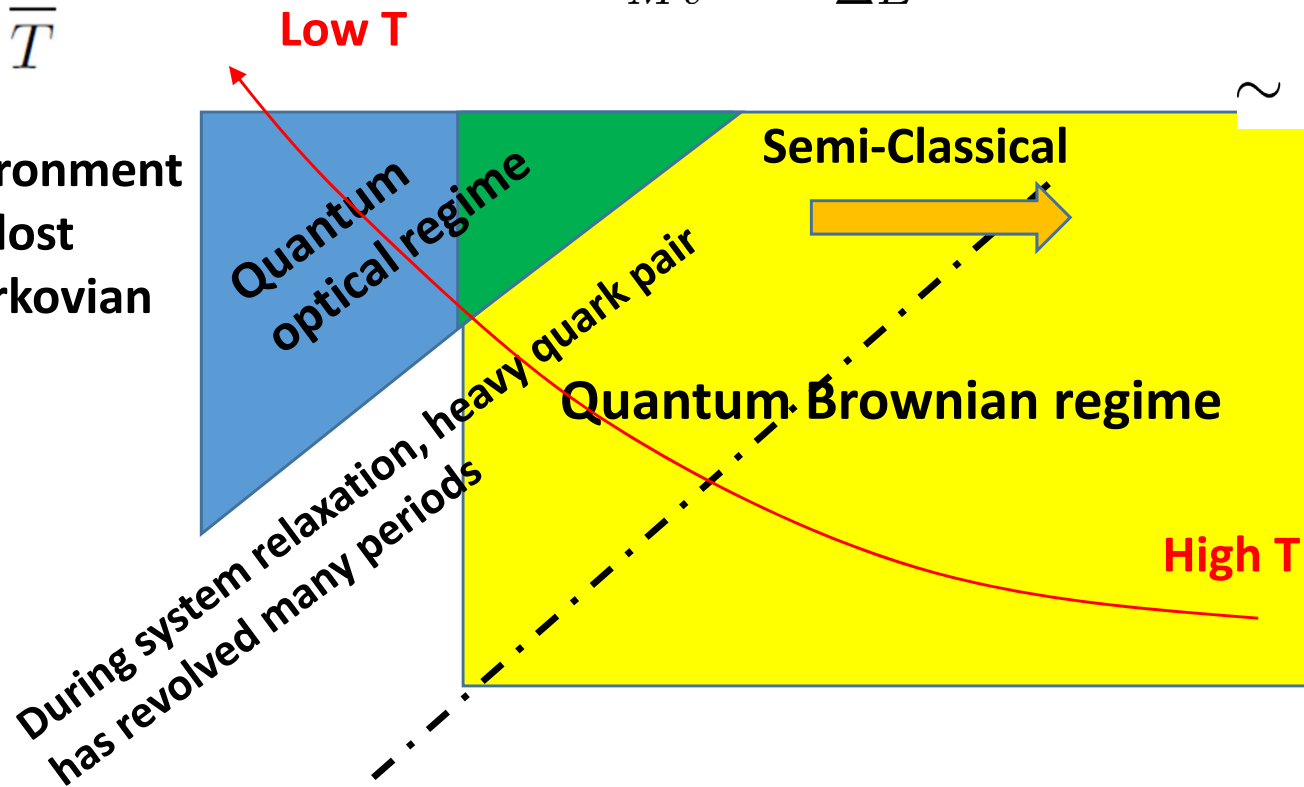
$$\tau_S \approx \frac{1}{Mv^2} \approx \frac{1}{\Delta E}$$

$$\tau_r \sim \frac{1}{\Gamma} \approx \frac{1}{\alpha T (m_D^2 \langle r^2 \rangle)}$$

$$\sim \frac{M^2}{T^3} \gg \tau_E$$

During system relaxation, environment correlation has lost memory => Markovian process

$$\tau_r / \tau_E$$



$$\frac{\tau_r}{\tau_E} \sim \frac{M^2}{T^2}$$

N.B.: Refined subregimes when playing with the scales of NRQCD (series of recent papers by N. Brambilla, M.A. Escobedo, A. Vairo et al)

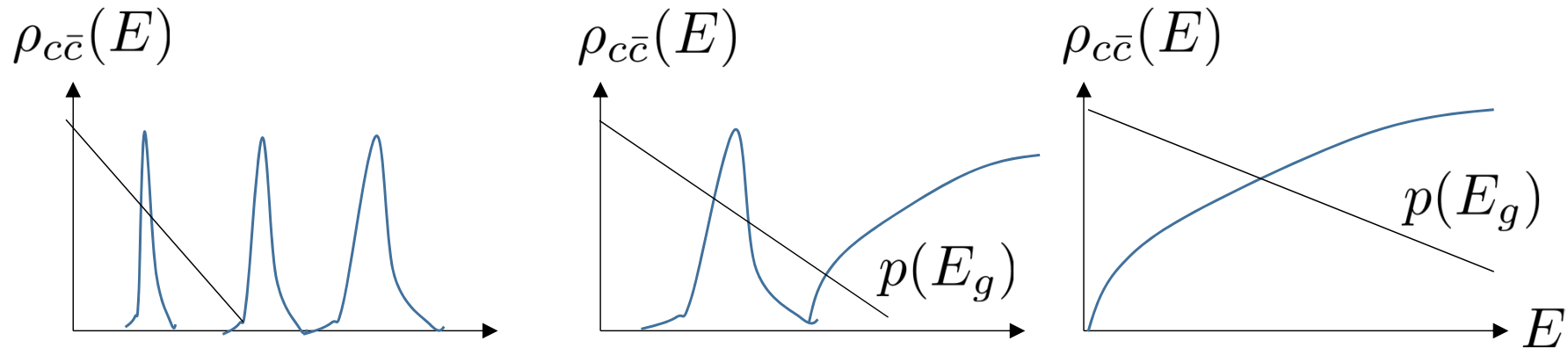
Peter's talk

System only feels low frequency part of environment correlation

$$1 \quad T = m_Q \alpha_s^2 \quad T = m_Q g_s \quad \tau_s / \tau_E \approx T / \Delta E$$

Not clear all states goes from one regime to the other at the same T

# Several regimes / effects



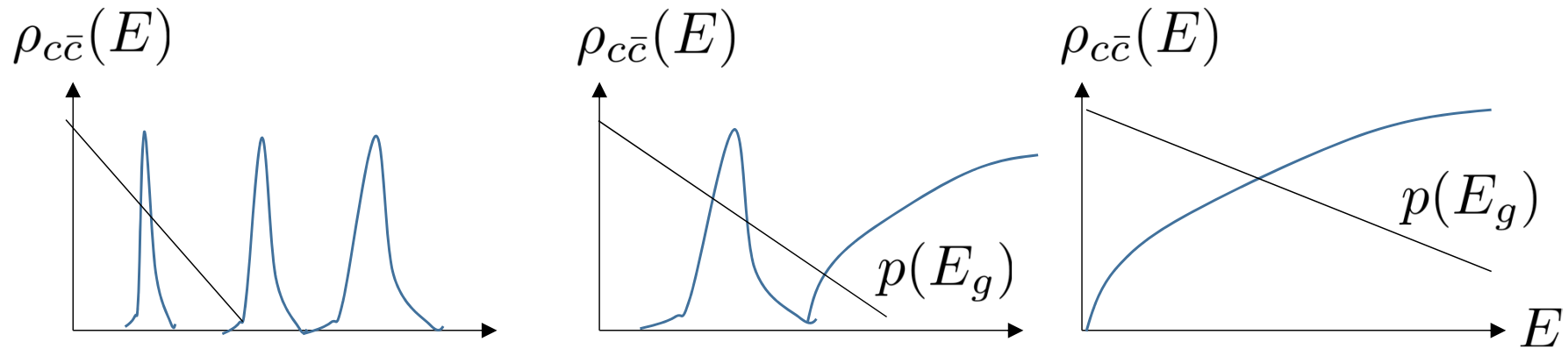
**Gluo-dissociation of well identified levels by scarce “high-energy” gluons (dilute medium => cross section ok)**

**Time**

**Multiple scattering on quasi free states**

**Well identified formalisms (Quantum Master Equation, Boltzmann transport, Stochastic equations,... ) in well identified regimes, but continuous evolution and no unique framework continuously applicable (to my knowledge)**

# Several regimes / effects



T

Linblad equations expressed on the basis of (vacuum eigenstates)

Time (slow QGP cooling)

Linblad equations expressed on the basis of  $(x, x') \leftrightarrow (p, X)$  after Wigner transform



Rate equations on the probabilities  
... as in N. Borghini

**After decoherence Time**

$$p \approx \sqrt{MT}$$



Semi-classical treatment (Fokker Planck equations)... as in Shuryak and Young

How can we estimate the decoherence time ? Is it large ?

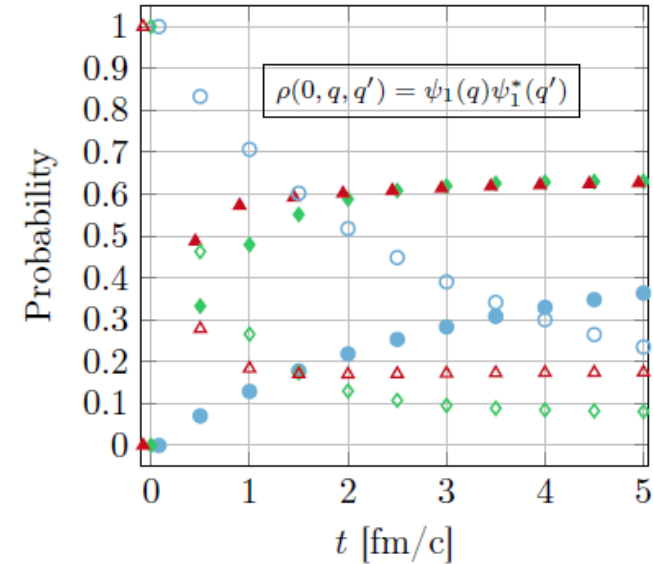
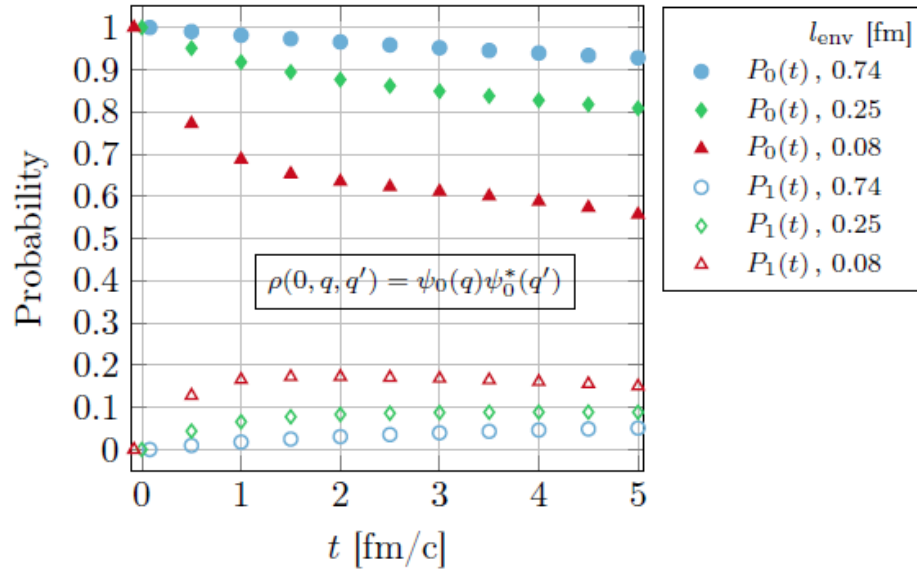
# Quantum Decoherence

De Boni, J. High Energ. Phys. (2017) 2017: 64

$$W(x) = -\frac{T}{2} \exp \left[ -\frac{1}{2} \left( \frac{x}{l_{\text{env}}} \right)^2 \right]$$

Linblad eq. from infl. functional (previously derived by De Boni and Blaizot)

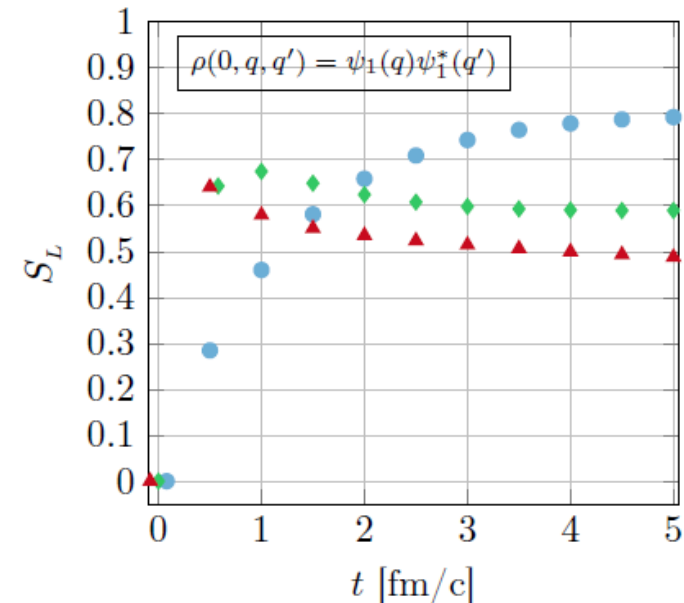
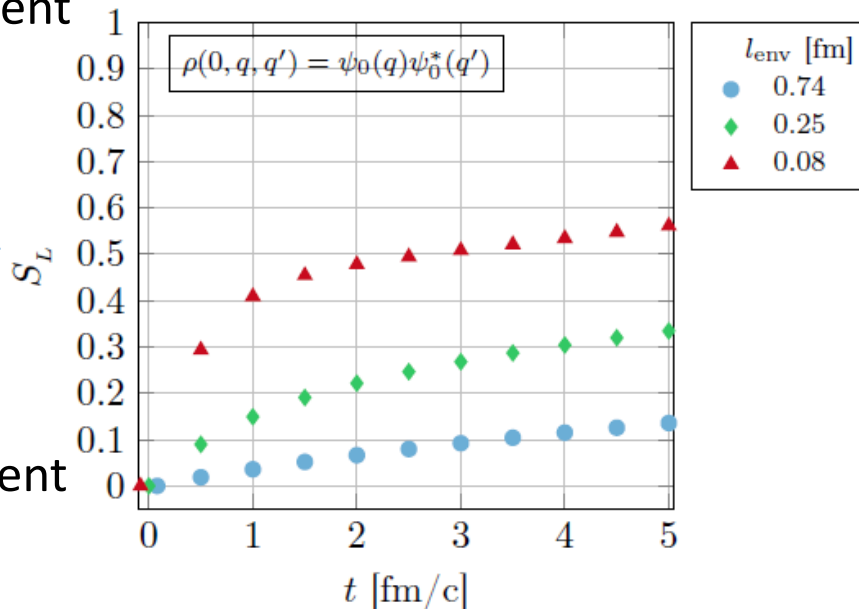
$l_{\text{env}}$  : hardness of env.



Fully decoherent

Approximate  
Quantum  
Entropy

Fully coherent



Draw your own conclusions !

# (Re)Combination (mating outside of village)

Usual treatment : kinetic theory (Rapp et al)  $\frac{dN_{\Phi}}{dt} = \dots + cN_Q N_{\bar{Q}}$

**In OQS :**

Single Q-Qbar pair :

start from diffusion state.  $\psi_{\text{scatt}}(x) = \frac{1}{\pi^{\frac{1}{4}} \sqrt{\delta}} e^{-\frac{1}{2} \left(\frac{x}{\delta}\right)^2 + \frac{i}{\hbar} x p}$

Studies by De Boni (2017) (fixed T)/ Gossiaux (2019; T(t), private communication)

Many pairs :

Blaizot and Escobedo (2017) : Semi-classical Langevin / Boltzmann equations

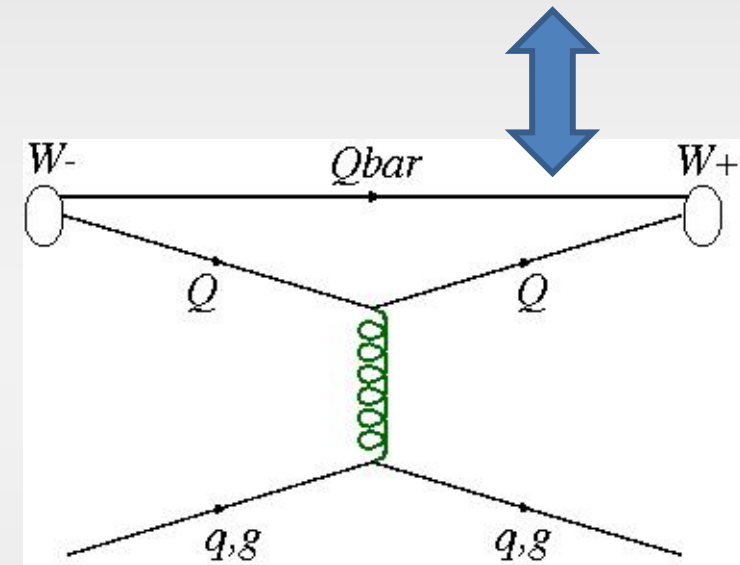
Arrebato, Aichelin & Gossiaux (preliminary results shown at QAT 2020)

# Remler formalism at work

Combining the expression of the Wigner's functions and substituting in the **effective rate equation** :

$$\Gamma^\Psi(t) = \sum_{i=1,2} \sum_{j \geq 3} \delta(t-t_{ij}) \int \frac{d^3 p_i d^3 x_i}{h^3} W_{Q\bar{Q}}^\Psi(p_1, x_1; p_2, x_2) [W_N(t+\epsilon) - W_N(t-\epsilon)]$$

- The quarkonia production in this model is a three body process, the HQ (anti-quark) interact only by collision !!!
- The “details” of  $H_{\text{int}}$  between HQ and bulk partons are incorporated into the evolution of  $W_N$  after each collision / time step (nice feature for the MC simulation)
- $W_N(t+\epsilon)$  and  $W_N(t-\epsilon)$  are NOT the equivalent of gain and loss terms in usual rate equation
- Dissociation and recombination treated in the same scheme

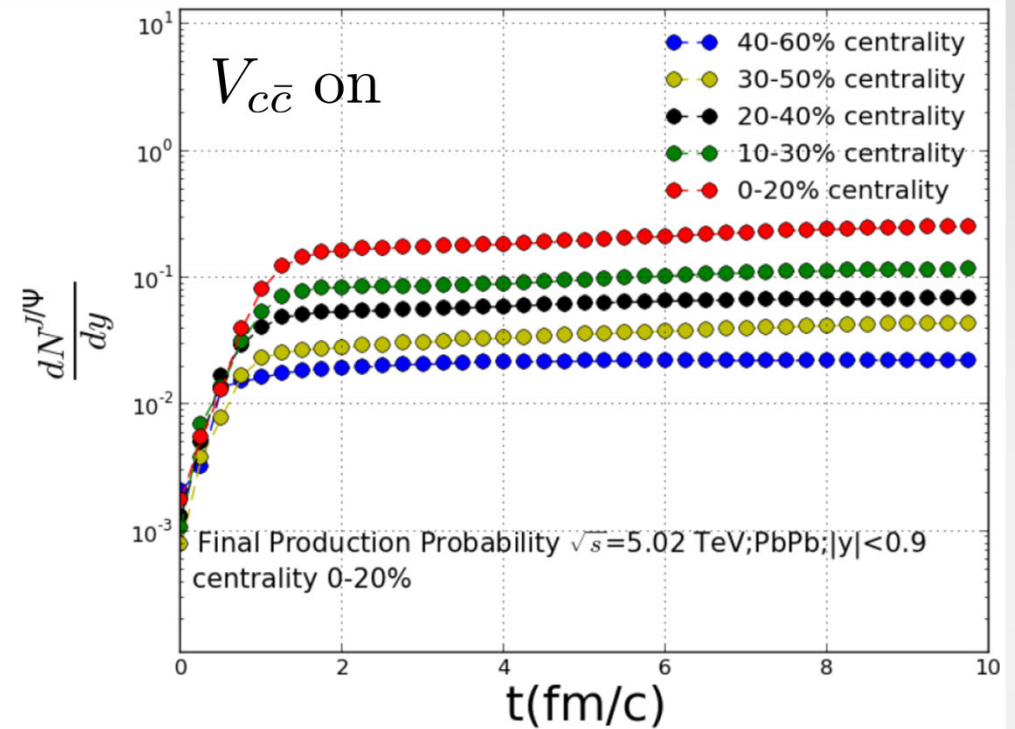
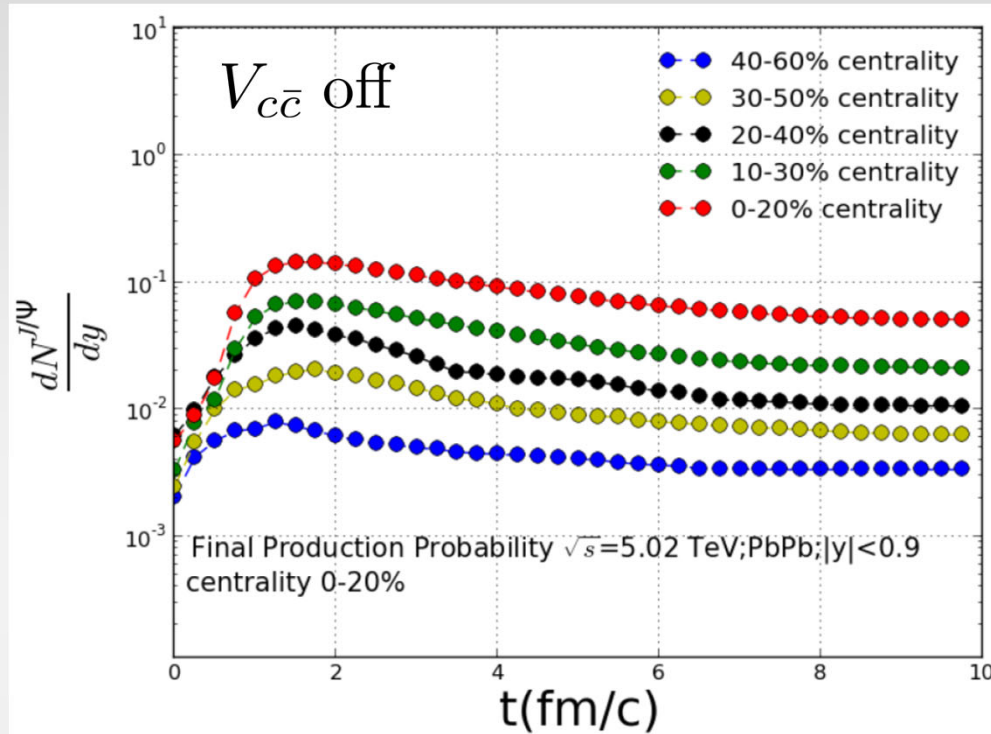


Interaction of HQ with the QGP are carried out by EPOSHQ (good results for D and B mesons production)

$$\text{Then: } P^\Psi(t) = P^\Psi(t_0) + \int_{t_0}^t \Gamma(t') dt'$$

NB: Also possible to generate similar relations for differential rates

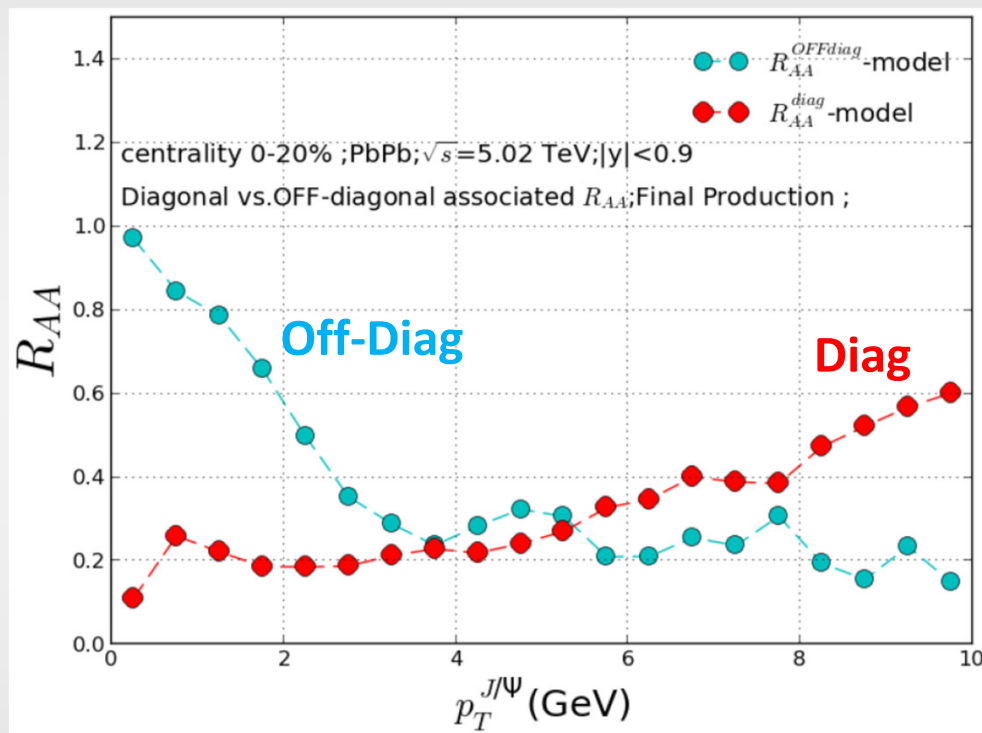
# Results : $J/\psi$ production vs time



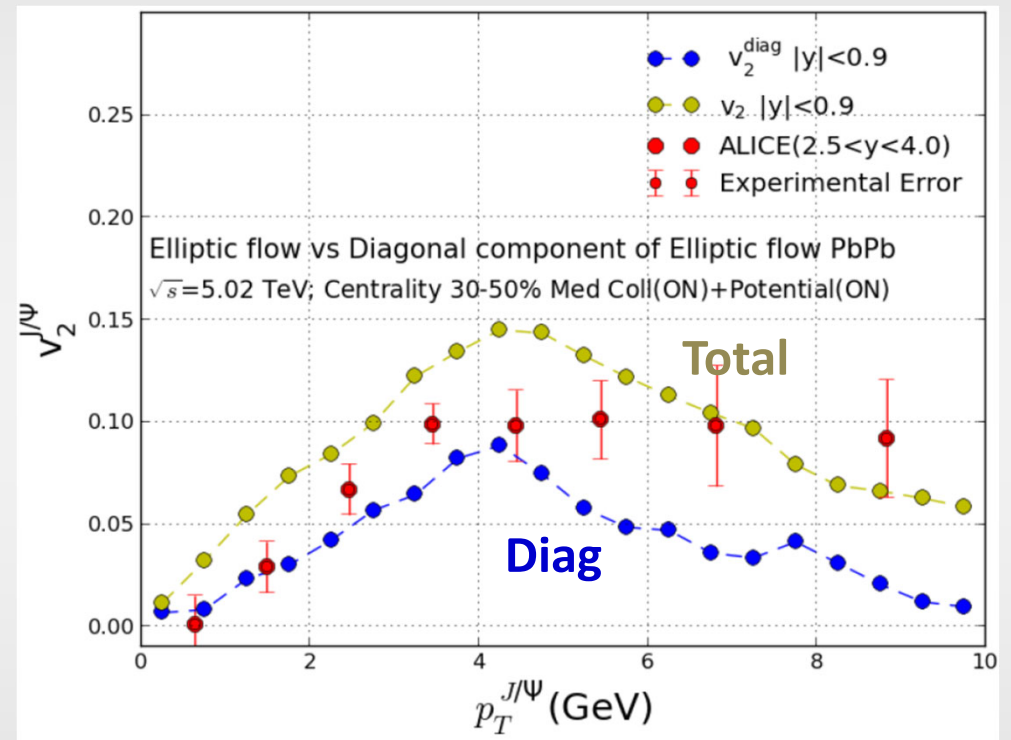
- Without interaction potential between  $c$  and  $c\bar{c}$ , the collisions with the medium manage to destroy the native  $J/\psi$ .
- With the interaction potential between  $c$  and  $c\bar{c}$  « on », one observes a steady rate of  $J/\psi$  creation (reduction of  $\Gamma^{\text{col}}$ , increase of  $\Gamma^{\text{local}}$  wrt potential « off »)
- No adiabaticity, but no instantaneous formation either.

# Results : diagonal vs off-diagonal

- « diagonal » correspond for us to c and cbar formed in the same NN collision, what is called « primordial » in other approaches
- => Decomposition of 2 main observables:



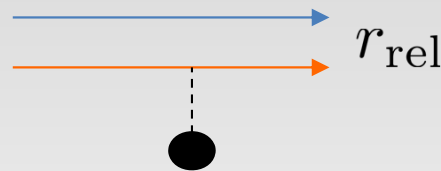
- Off-diagonal production dominates at low  $p_T$ .
- Diagonal contribution increases with larger  $p_T$  ( $\Delta E/E$  decreases )



- Large  $v_2$  from off-diagonal component
- ... but substantial flow from the diagonal contribution either !!!

# Physical picture...

Q-Qbar propagation in QGP.

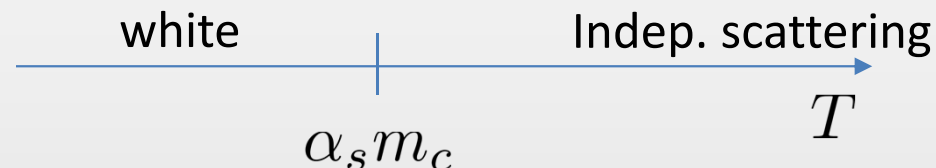


If  $r_{\text{rel}} \ll l_{\text{correl}}$  : **white object** => no  
Energy loss

If  $r_{\text{rel}} \geq l_{\text{correl}}$  : 2 HQ interact  
individually with QGP.

$$l_{\text{correl}} \sim \frac{1}{T}$$

$$\text{Small } T : r_{\text{rel}} \approx \frac{1}{\alpha_s m_c} \qquad \text{Large } T : r_{\text{rel}} \gtrsim \frac{1}{m_D} \approx \frac{1}{gT}$$



- Most of the transport models have considered up to now that primordial charmonia can just be destroyed (with a small probability), but not deflected.
- In our approach, we have investigated the consequences of considering the opposite limit... with somehow too large  $v_2$  resulting from this prescription...