Round Table on Quarkonia production in AA

Pol-Bernard Gossiaux

ROUND TABLE ON QUARKONIA PRODUCTION IN AA

Quarkonia as Tools
Aussois (France)
13/01/2020 - 18/01/2020

Pol B Gossiaux,

SUBATECH (NANTES)

Subatech and Pays de la Loire

Topic I: Charmonia as a hard probe of QGP ?

Topic II: the “standard” (and not so standard) factorization for AA *

Topic III: (the unbearable flatness of) $R_{AA}(N_{part})$

Topic IV: the flows… and possible benefits from higher states **

Topic V: HQ interaction in the medium and with the medium *

Topic VI: Quarkonia at intermediate and high pT *

Topic VII: Quarkonia and HF in small systems

Topic VIII: correct references ?

- Other topic ? For Instance: Evidence for QGP, ηc state, comovers vs QGP suppression, Definition of quarkonium melting, quarkonium interaction with hadronic matter, what are we precisely probing with quarkonia ? J/psi at UPC

Topic 0: most recent progress on understanding quarkonia in AA

https://indico.gsi.de/event/9314/

Suppression and (re)generation of quarkonium in heavy-ion collisions at the LHC

16-20 décembre 2019
GSI Helmholtzzentrum für Schwerionenforschung GmbH
Europe/Berlin timezone

- Overview
- Timetable
- Venue and Travel information
- Accommodation
- Registration
  - Modify my Registration
- Participant List
- Open symposium
- Poster
- Data protection

Support
emmi-office@gsi.de

EMMI Rapid Reaction Task Force (RRTF)

Suppression and (re)generation of quarkonium in heavy-ion collisions at the LHC

The meeting is by invitation only.
The symposium on Monday, December 16th, is open for all interested (no registration needed).

This Rapid Reaction Task Force will scrutinize the theoretical and phenomenological description of quarkonium production in high-energy heavy-ion collisions, aimed at distinguishing between current approaches, narrow down uncertainties in the input parameters and set the path for future developments of reliable dynamical models of quarkonium transport. The overarching goal is to establish firm connections between heavy-quarkonium phenomenology in heavy-ion collisions and the microscopic properties of hot QCD matter.

Démarre 16 déc. 2019 08:00
Finit 20 déc. 2019 18:00
Europe/Berlin

GSI Helmholtzzentrum für Schwerionenforschung GmbH
KBW lecture hall
Planckstr. 1
64291 Darmstadt
Germany

Andronic, Anton
Gossiaux, Pol-Bernard
Petreczky, Peter
Rapp, Ralf
Strickland, Michael

Airliner

Topic I: Charmonia as a hard probe of QGP ?

Should charmonia (still) be considered as a hard probe of the QGP ?

In most of the talks this week: benefit from large mass as compared to Λ_{QCD}. For a while, this property was considered to lead to preserved bound states that would « melt » / « dissociate » sequentially (as a function of the temperature). Mc >> T (but not >> 3T)

However, larger J/Psi rates at LHC as compared to RHIC => significant role of (re)generation at later stages: Q+Qbar -> Φ.

Provocative statement: Is it possible that (at least at LHC) ALL production of quarkonia happens *around* Tc (as advocated in the statistical hadronization model)

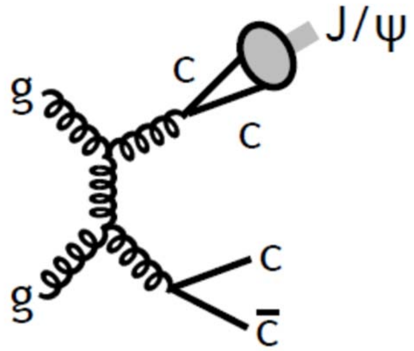
Big challenges:

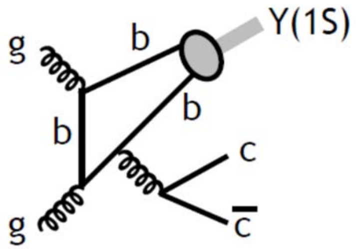
- Understand the time scales associated with quarkonia « chemistry » (production at $t(T_c)-t_{equil}$)
- For the models, be able to deal with the « chemical equilibration limit» (EMMI RRTF day 3)

In all cases, the statistical hadronization results could always be considered as an « asymptotic » baseline from which deviations should be searched and understood.

Topic II: the “standard” factorization for AA

pp





Description in
momentum space

AA (transport approach)

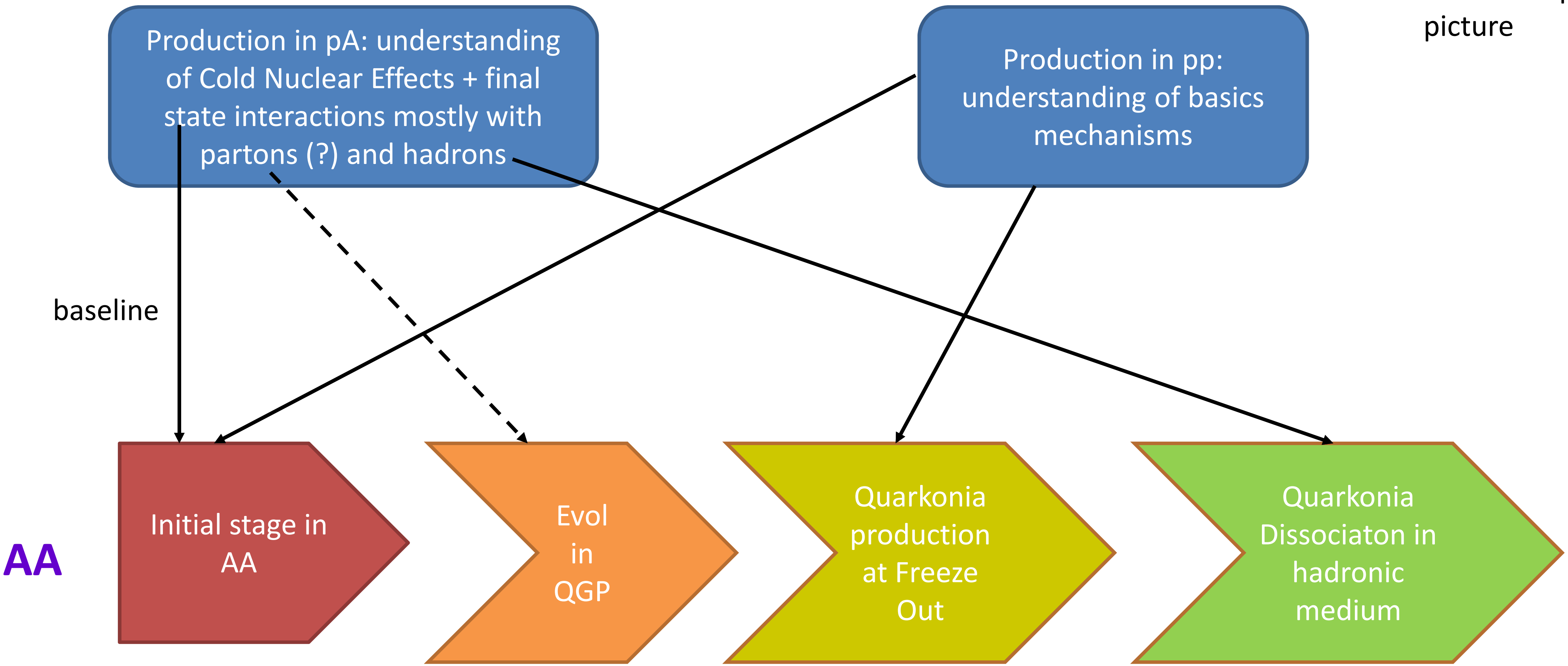
- Production of quarkonia at initial time:
  - From pp + nPDF at asymptotic time
  - Possibly including formation time to mock the heisenberg uncertainty
- Possible veto on formation according to the local temperature (sequential suppression)
- Evolution of quarkonia distribution assuming some rate equations (most often, based on inelastic cross section or imaginary potential)
- Color issue not systematically addressed (color states are unbound => do not survive)

Description both in momentum and physical space

Marrying those 2 pictures sounds feasable (80% compatibility on MEETIC)

Topic II: the “standard” factorization for AA

Not so simple picture

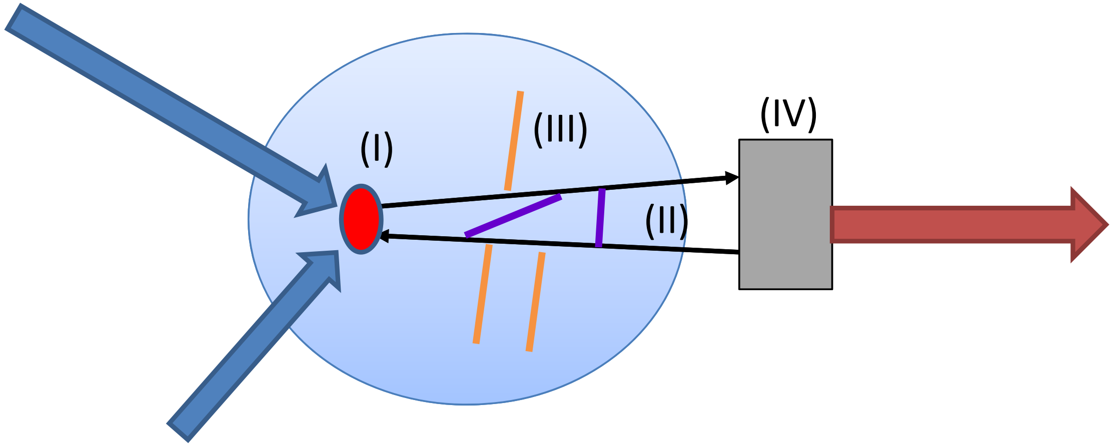


Topic II: the “standard” factorization for AA: many issues

- Applying melting at a fixed temperature although we are not in a stationnary environment
- Notion of formation time is not so well defined. Using this criteria blindly => abrupt jumps in the probability of formation that does not correspond with a genuine quantum calcultion (Gossiaux and Cugnon, early 90’s)
- What do we do for bottomonium at early stages, i.e. formed before thermalization ? (does not mean we know how to treat it properly in alternate approach though).
- …

Topic II: the "standard" factorization for AA

A general « QFT fundamental » propagation of quarkonium (sketchy)



Need several « ingredients »:

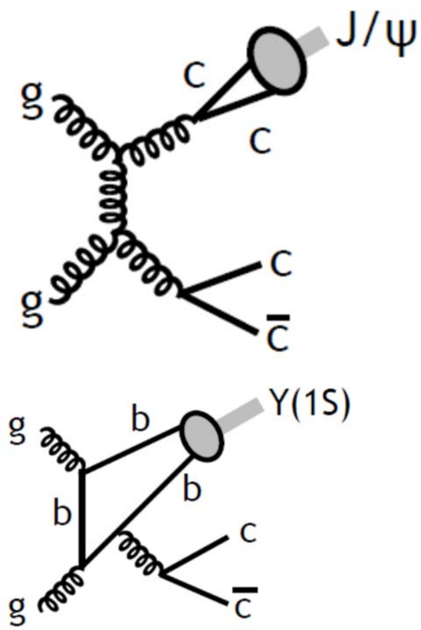
- (I) and (IV) should be ideally extracted from (or at least compatible with) pp
- (II) and (III) ⇔ time dependent evolution of Q-Qbar state

Complicated QFT problem (also due to the evolving nature of the QGP that mixes several scales)… only started to be addressed at face value recently… but allows to deal with different system (pp, pA, AA)

N.B.: Sequential suppression -> Equilibration with the medium

Topic II: the “standard” factorization for AA

pp



Description in
momentum space

AA in Open Quantum System

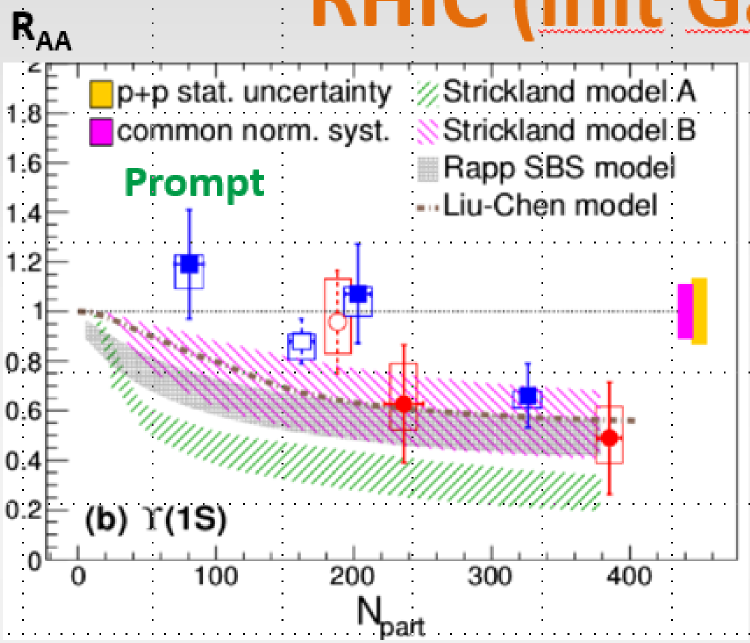
However, modern approaches aim at providing a full quantum treatment of the QQbar evolution (even coupling the singlet and the octet channels) : Open Quantum System

- Requires knowledge of Q-Qbar quantum state at « initial » time (including all possible correlations): Inputs from pp community ?
- Evolution of quantum state according to Lindlad (density operator) or Stochastic Schroedinger equation (wave function),…
- At the end, need to convert singlet and octet states -> vacuum states… According to which prescription ? NRQCD ? Should LDME also apply in this situation where the « underlying event » is quite different ? J. Qiu: No !
- … Not even to speak about the inclusion of NLO effets in the production, nor CNM effects like coherent energy loss !

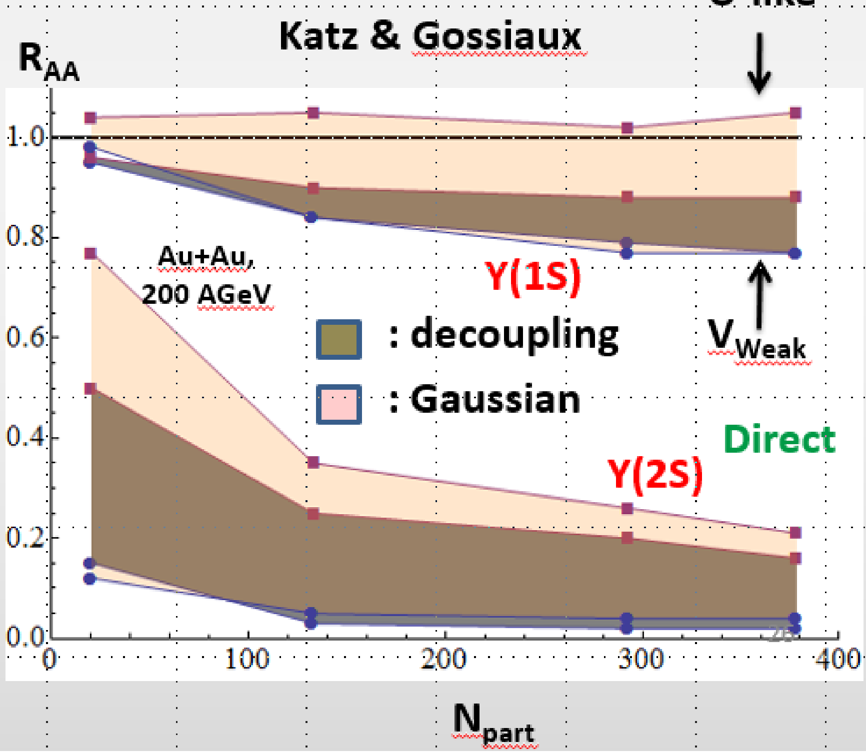
Marrying those 2 pictures sounds quite hard (20% compatibility on MEETIC) … Real breakthrough needed if we aim at precise description of the data.

PB Gossiaux
& R Katz
Hard probes
2016

RHIC (init Gaussian S-like)



Quarkonia as tools !
Constraining initial state through QGP filtering ?

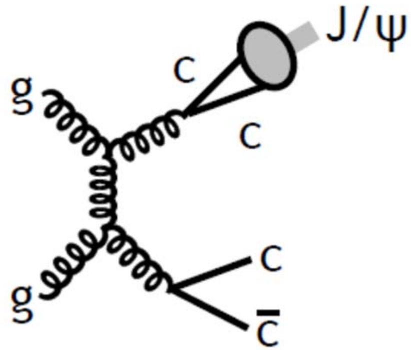


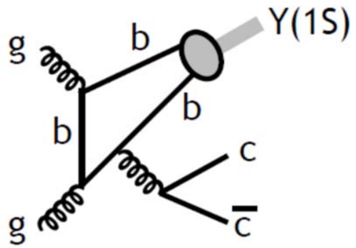
U-type potential more sensitive to the initial state

Topic II: the "standard" factorization for AA

pp

AA in Open Quantum System





However, modern approaches aim at providing a full quantum treatment of the QQbar evolution (even coupling the singlet and the octet channels) : Open Quantum System

XiaoJun : Why not use the OQS (Q-Qbar + background + dynamics) to evaluate the final yield of quarkonia from Q-Qbar in pp as well (alternate to LDME)

Description in momentum space

Topic III: (the unbearable flatness of) $R_{AA}(N_{part})$

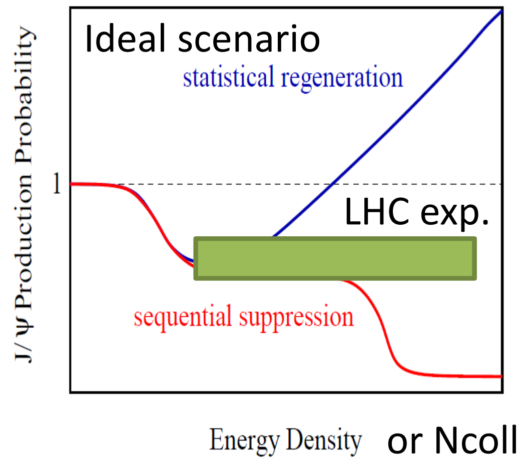
- Naive thought in the community :

$$\frac{dN_{\text{reco}}}{dy} \propto \frac{dN_c}{dy} \times \frac{dN_{\bar{c}}}{dy}$$

- Large increase as a function of Ncoll… Not seen in the data!

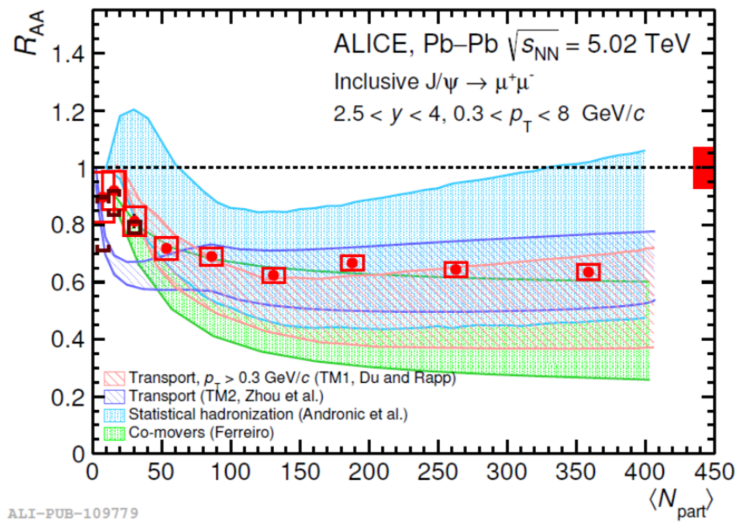
- Better model: $\frac{dN_{\text{reco}}}{dV\,dy} \propto \frac{1}{V^2}\frac{dN_c}{dy} \times \frac{dN_{\bar{c}}}{dy} \Rightarrow \frac{dN_{\text{reco}}}{dy} \propto \underbrace{\frac{1}{V}}\frac{dN_c}{dy} \times \frac{dN_{\bar{c}}}{dy}$

Also increase as a function of centrality => flattening



or Ncoll

- However, still a rising trend in most of the models:



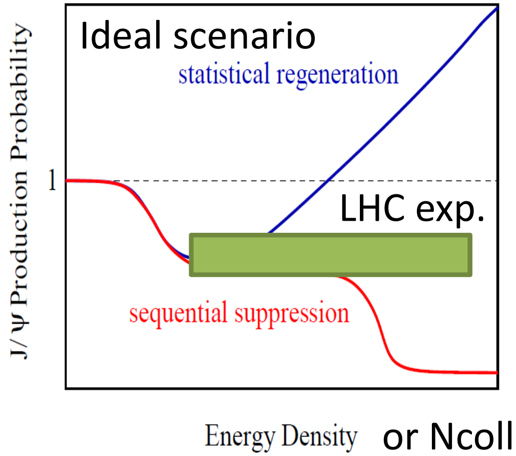
For sure more to understand

Topic III: (the unbearable flatness of) $R_{AA}(N_{part})$

- Naive thought in the community :

$$\frac{dN_{\rm reco}}{dy} \propto \frac{dN_c}{dy} \times \frac{dN_{\bar{c}}}{dy}$$

- Large increase as a function of Ncoll… Not seen in the data!

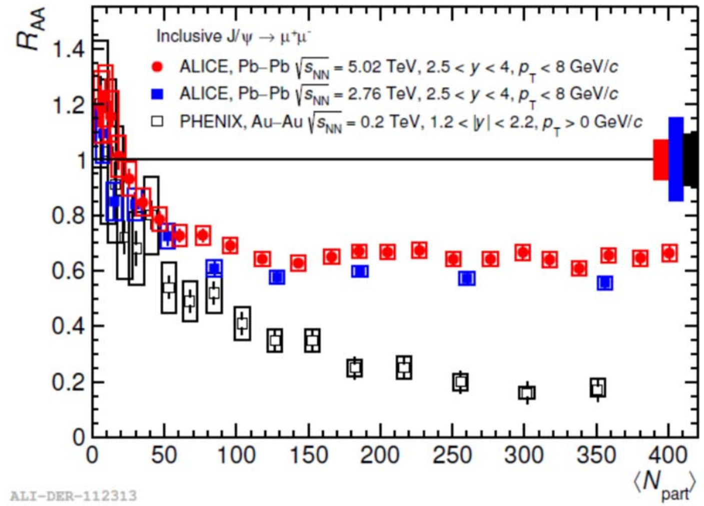


- Better model: $\frac{dN_{\rm reco}}{dV\,dy} \propto \frac{1}{V^2}\frac{dN_c}{dy} \times \frac{dN_{\bar{c}}}{dy} \Rightarrow \frac{dN_{\rm reco}}{dy} \propto \underbrace{\frac{1}{V}}\frac{dN_c}{dy} \times \frac{dN_{\bar{c}}}{dy}$

Also increase as a function of centrality => flattening

- However, No evolution from 2.76 -> 5 TeV

Some miraculous compensation ?... Or something we do not understand ?



Topic III: (the unbearable flatness of) $R_{AA}(N_{part})$

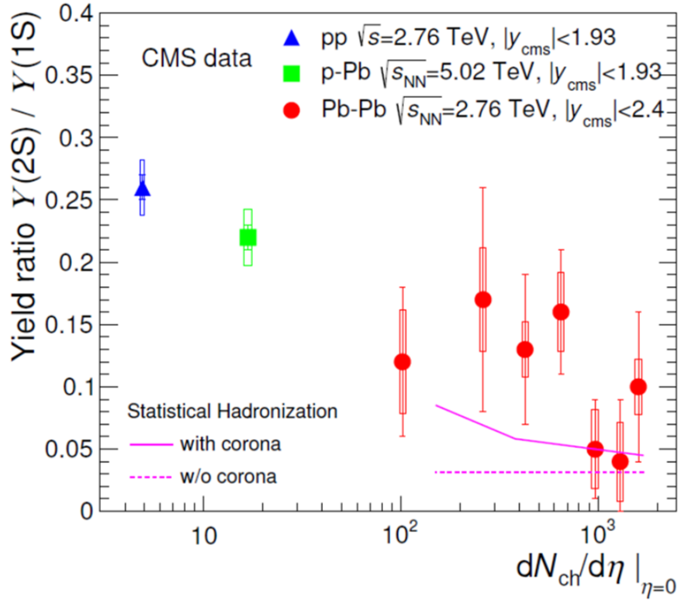
Beauty sector: good overall consistency of the following facts:

- Similar production of Y(1S) production from RHIC -> LHC
- Higher states strongly suppressed
- Washing out of the spectral function (but the Y(1S) which survive up to T = 0.45 GeV)

Upsilon probe the potential at smaller distance => different sensitivity to the medium effects

With the interpretation that higher states (which contribute to the prompt Y(1S)) are suppressed both at RHIC and LHC in the QGP, while the gound state Y(1S) survive and is thus a genuine hard QGP probe; higher states could be produced (partly) through recombination

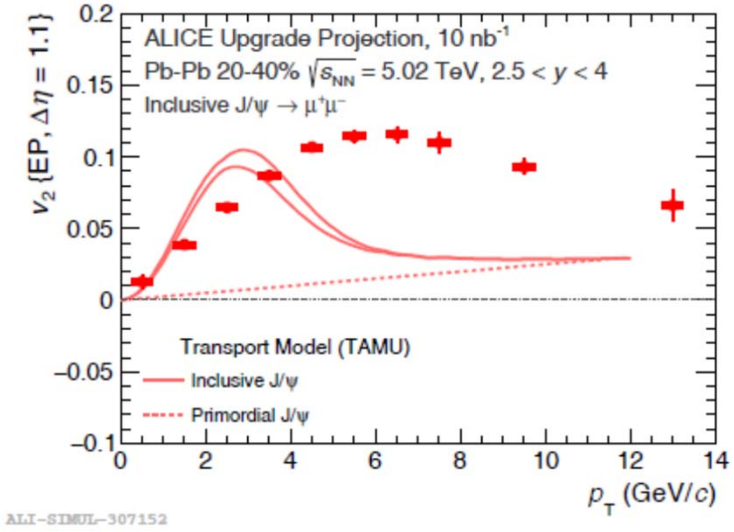
N.B.: Statistical ratio for Y(2S)/Y(1S) overshot at LHC for central and semi-central



Does not obviously fit into the global scheme (let us discuss this if you wish)

Topic IV: the flows… and possible benefits from higher states

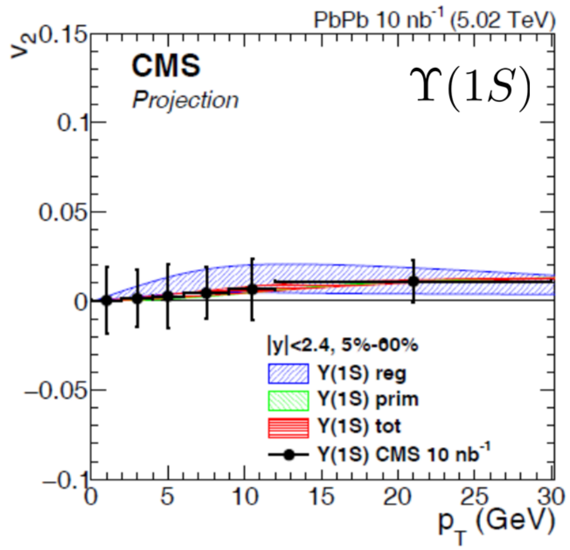
Charm sector

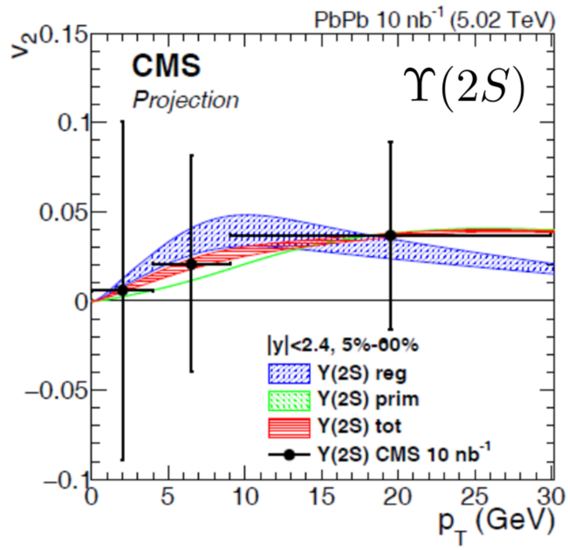


- v_2(J/ψ) ≈ v_2(D)
- Usually considered as a strong hint for regeneration
- => one expects similar $v_2(\psi')$

Pretty unique picture, hopefully seen in run 3 and 4.

Beauty sector



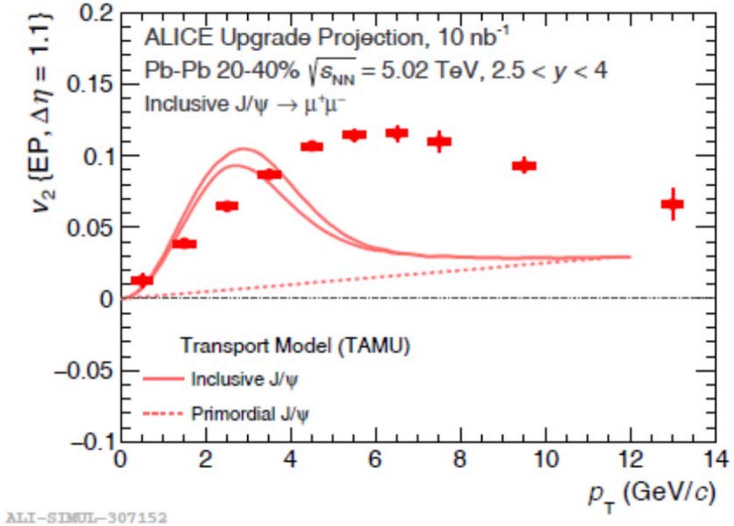


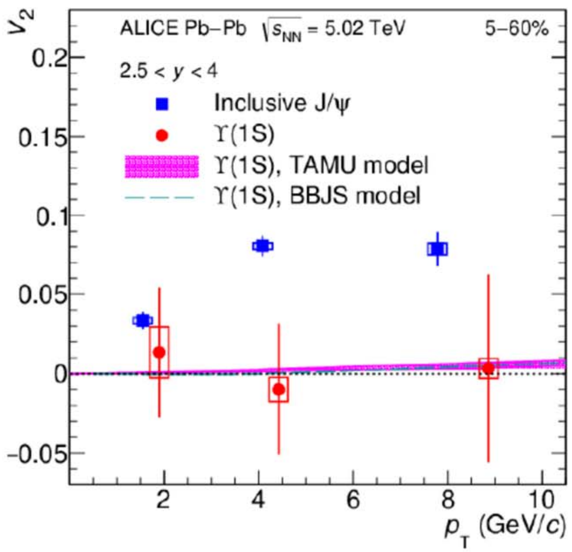
- Expected survival of primordial Υ(1S) but melting of Υ(2S)
- => one expects $v_2(\Upsilon(1S)) < v_2(\Upsilon(2S)) \approx v_2(\Upsilon(3S))$

However:
- Not understood in pA
- Elastic – like cross section + magnetic field

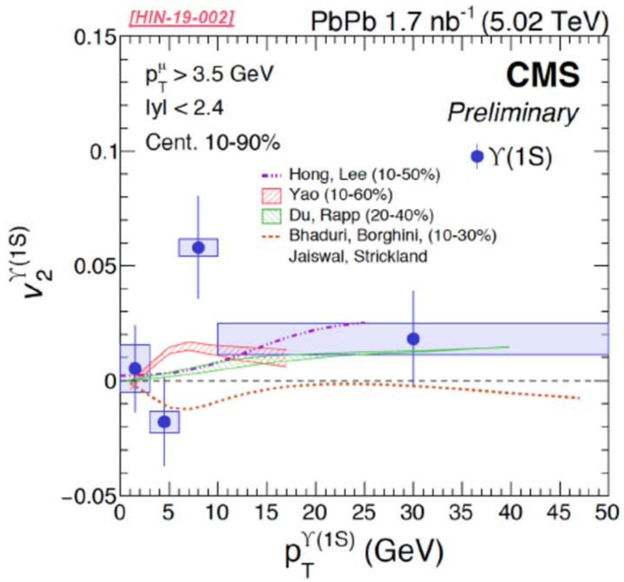
Topic IV: the flows… and possible benefits from higher states

Charm sector





Beauty sector



- $v_2(J/\psi) \approx v_2(D)$
- Usually considered as a strong hint for regeneration
- => one expects similar $v_2(\psi')$

Pretty unique picture, hopefully seen in run 3 and 4.

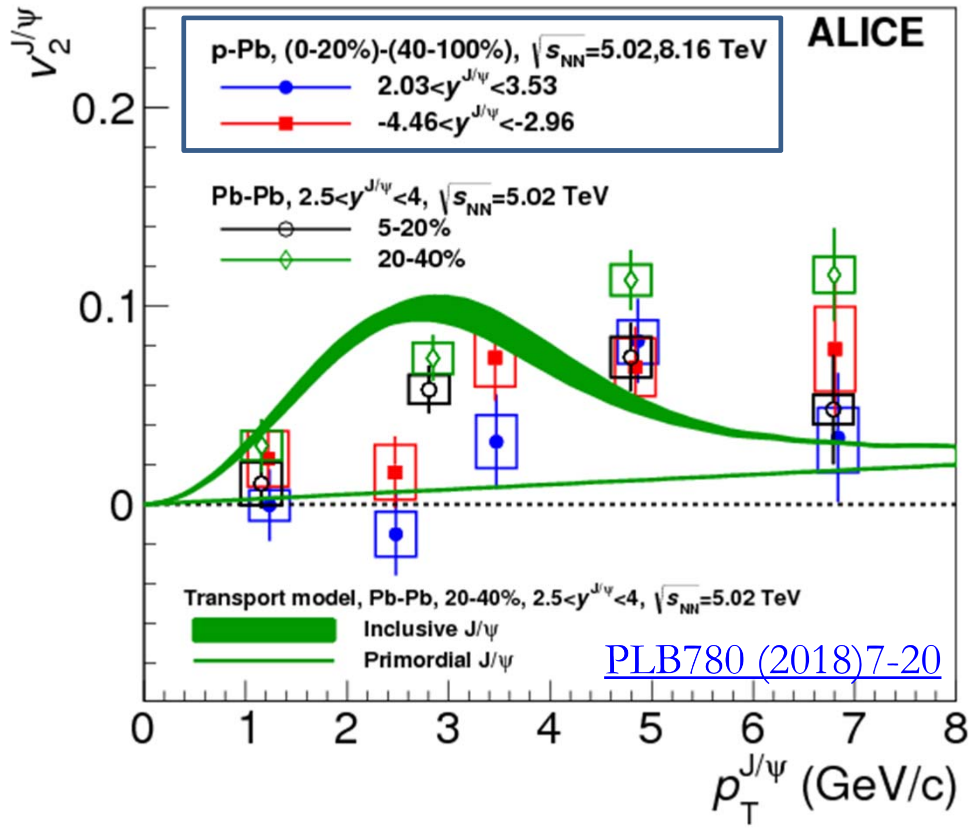
- Both measurement compatible with 0 and with all current model predictions
- Confirms that the $\Upsilon(1S)$ dissociation is limited to the early stage of the QGP evolution

?!

However:
- Not understood in pA
- Elastic – like cross section + magnetic field

Topic IV: the flows… and possible benefits from higher states

- **J/ψ flows in pPb as well !!! => No need for recombination?**
- Undermine our « global » understanding of quarkonia production in AA. Of course one may argue that $v_2(J/\psi)$ in pPb is mostly >0 at intermediate p_T where it is not well understood in AA either.



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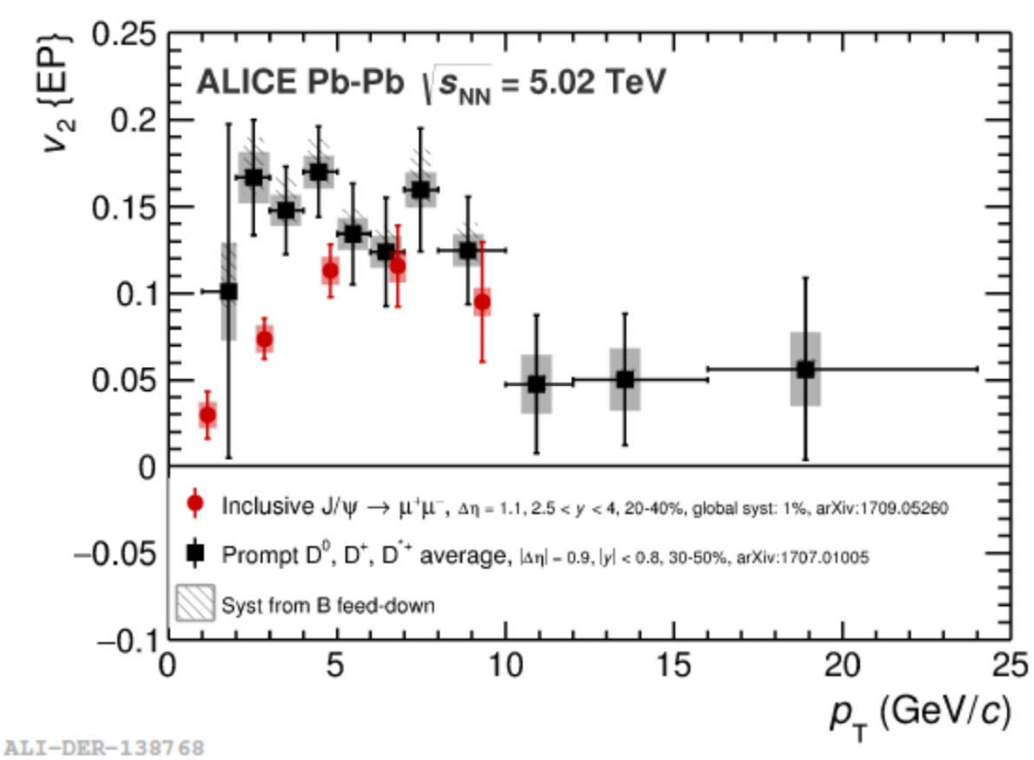
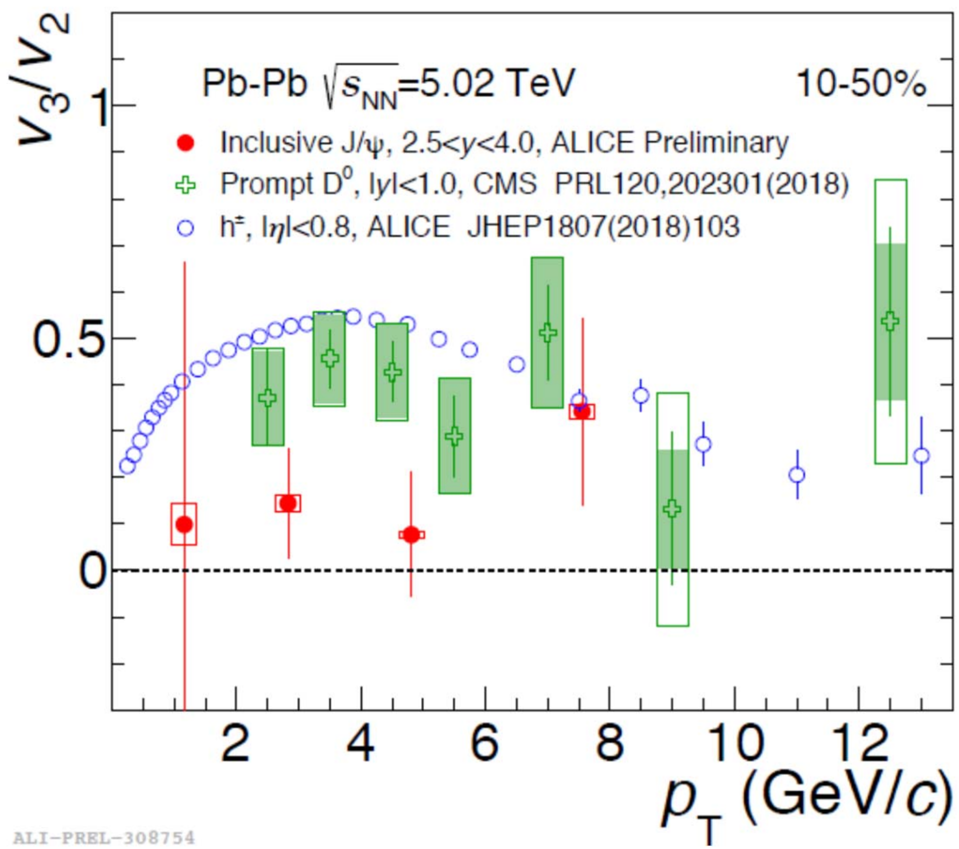
Topic IV: the flows… and possible benefits from higher states

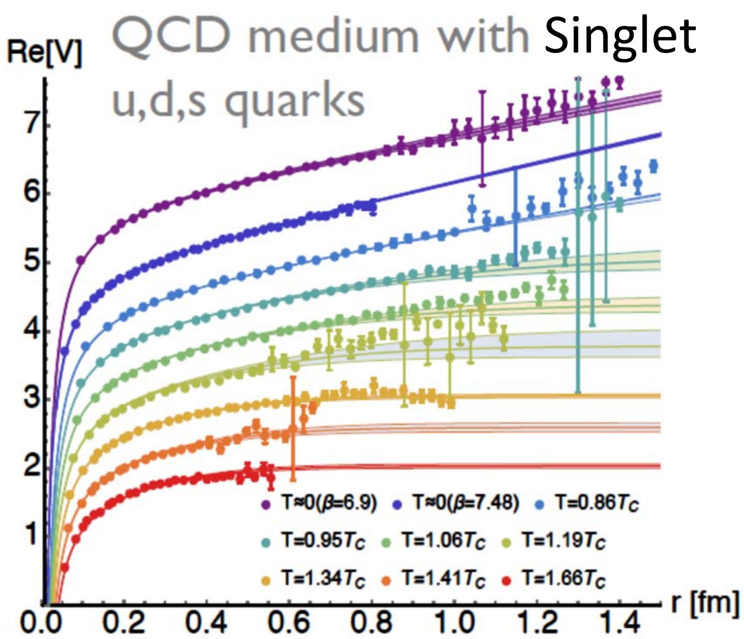




Puzzling ! V3 does not benefit from recombination ?

Topic V: HQ interaction in the medium and with the medium

Protential (recent lQCD calculations)



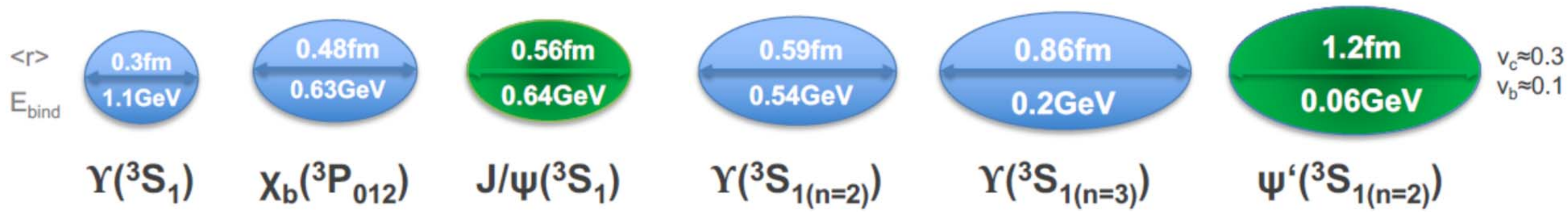
At T=0, well described by the Cornell shape:

$$V(r) = -\frac{\alpha}{r} + Kr$$

<u>Quarkonia scales</u>

- m_Q
- In vacuum: Binding energy / separation energy btwn levels: $\Delta E \; \alpha \; m_Q$ g^4 (Coulomb part) => v α g^2
- Radius : $(m_Q$ g^2$)^{-1}$
- For a linear potental $\hbar\omega_0 = \left(\frac{\hbar^2 K_l^2}{m_b/2}\right)^{\frac{1}{3}} \approx 0.504 \text{ GeV}$

$$v \propto \left(\frac{K_l}{m_b^2}\right)^{\frac{1}{3}}$$



Topic V: HQ interaction in the medium and with the medium

Quarkonia a probe of the in medium force ? Is it worth it when a simple comover approach gets it ?

2 main ingredients : « melting » + « dissociation »

simple

sophisticated

Shadowing + 2-components model (comovers + statistical generation at FO)

Open quantum system with $H_{interaction}$ tuned on lQCD constrains

Where should we position the « cursor » in order to claim hard probing QGP with quarkonia ?

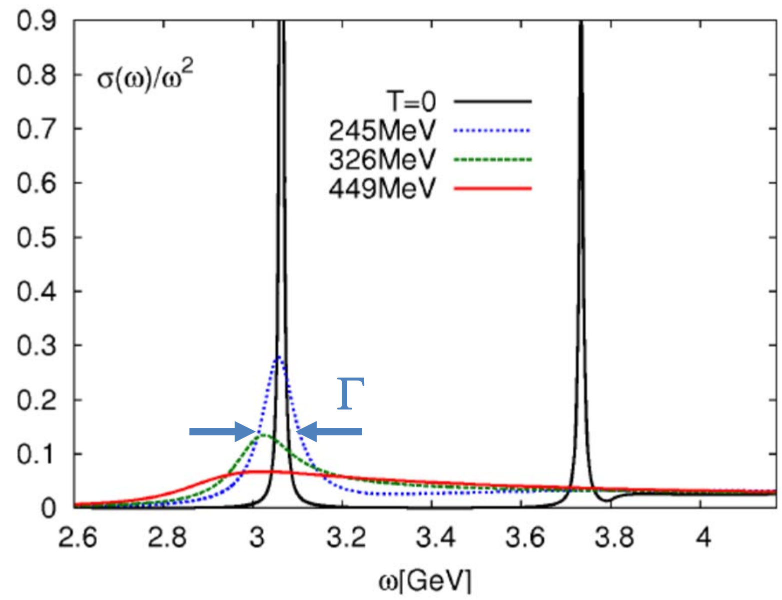
I invite you to make you own judgment !

Topic V: HQ interaction in the medium and with the medium

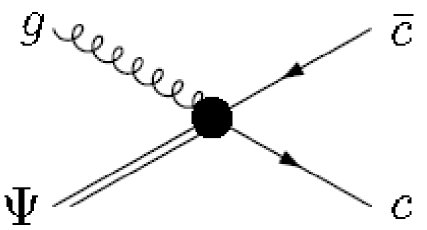
- Besides arguments based on the Debye mass / screening, it was pointed out already in the 90's that interactions with partons in the QGP could lead to dissociation of bound states (whose spectral function thus acquire some width Γ corresponding to the dissociation rate)

- Microscopic evaluation of the decay rate

$$\Gamma_\Psi(\vec{x},\ \vec{p},\ \tau) = \sum_i \int \frac{d^3k}{(2\pi)^3}\ f^i(\omega_k; T(\tau))\ \sigma^{diss}_{\Psi i}\ v_{rel}$$



Typical dissociation process:



$$\sigma_{J/\psi}(\omega) = A_0 \frac{(\omega/\epsilon_{J/\psi} - 1)^{3/2}}{(\omega/\epsilon_{J/\psi})^5}$$

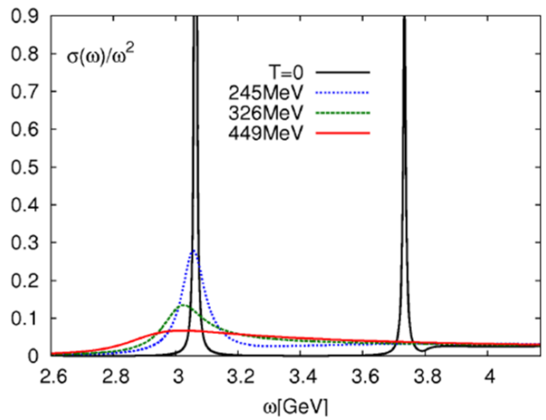
ω: gluon energy in the J/Psi rest frame

One has to abandon the idea of using quarkonia as some « static thermometer » towards concepts and methods more compatible with the dynamical nature of the QGP evolution including both « melting » and dissociation.

Modern era

Topic V: HQ interaction in the medium and with the medium

- Yet, these pictures might still be compatible with the notion of sequential « suppression »…
- However, this notion has to be made more precise : (LQCD) spectral function lQCD



$$\rho(\omega,p,T)=\frac{1}{2\pi}\mathrm{Im}\int_{-\infty}^{\infty}dte^{i\omega t}\int d^3xe^{ipx}\langle[J(x,t),J(0,0)]\rangle_T$$

At T=245 MeV, ψ' has disappeared but J/ψ still surviving for $\approx 1/\Gamma \approx$ a couple of fm/c … which needs to be compared with the local QGP cooling time τ_{cool} : $\Gamma \times \tau_{cool} > 1 \Leftrightarrow$ suppressed

$\vec{v}$

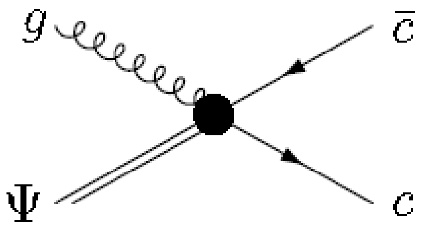
- N.B.: The opposite phenomenom might also be relevant: some state above the « melting » temperature can survive (for a short while $< 1/\Gamma$) before getting lost definitively.

Will it melt (even party) ?

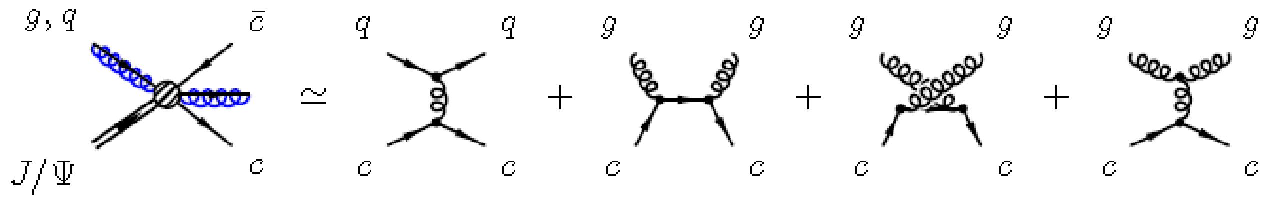
- Modern vision : do the quarkonia states (chemically) equilibrate with the QGP ?

Topic V: HQ interaction in the medium and with the medium

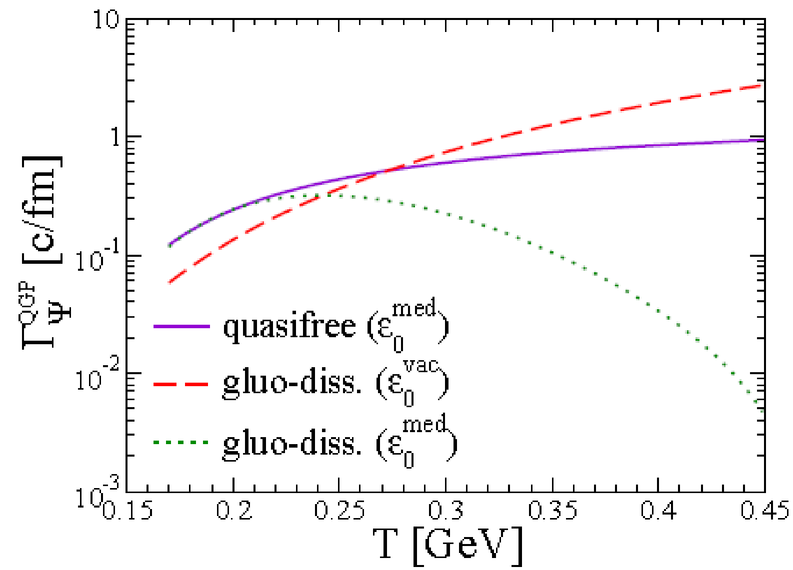
II. Transport models : more sophisticated approach based on some cross section to describe the interaction of quarkonium with QGP:

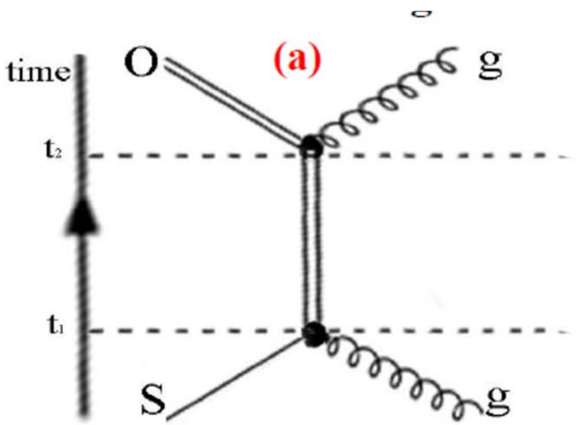


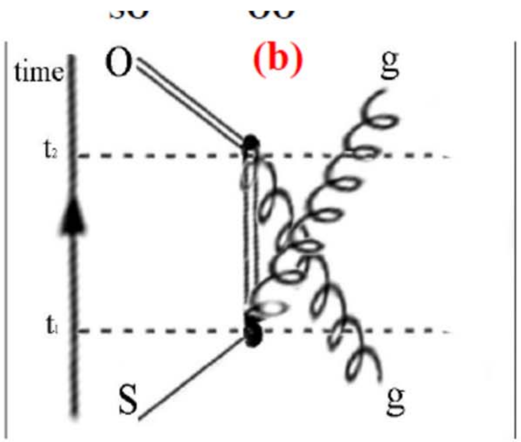
gluo dissociation (common in all approaches)



quasi free dissociation;
dominant at large temperature





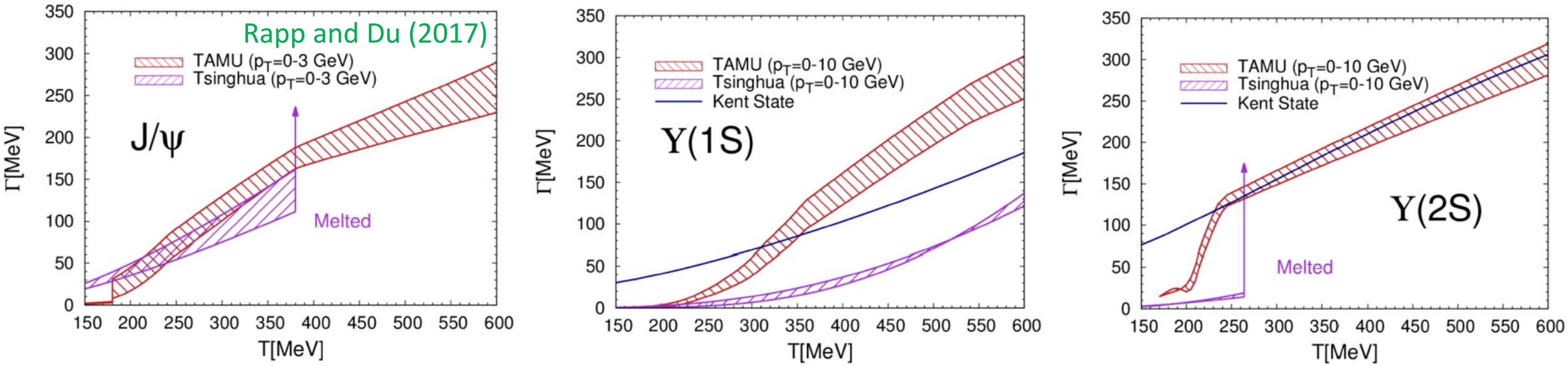


Recent systematic NLO calculation by M. He based on some effective Low Energy Hamiltonian

Topic V: HQ interaction in the medium and with the medium

II. Transport models : … with significant subtle variations in each model:

- Underlying binding force between Q & Qbar
- Whether, on the top of dissociation, some « melting » is allowed
- ….



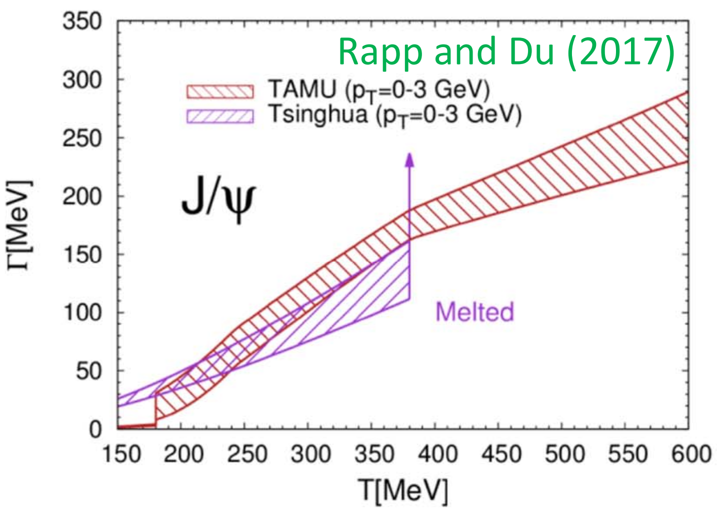
With significant consequences on the dissociation rate !

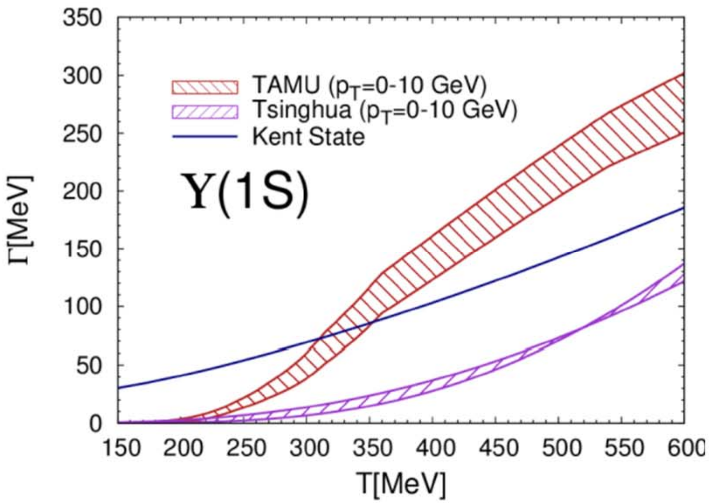
Yet, the working horse of most concrete predictions for quarkonium predictions in AA

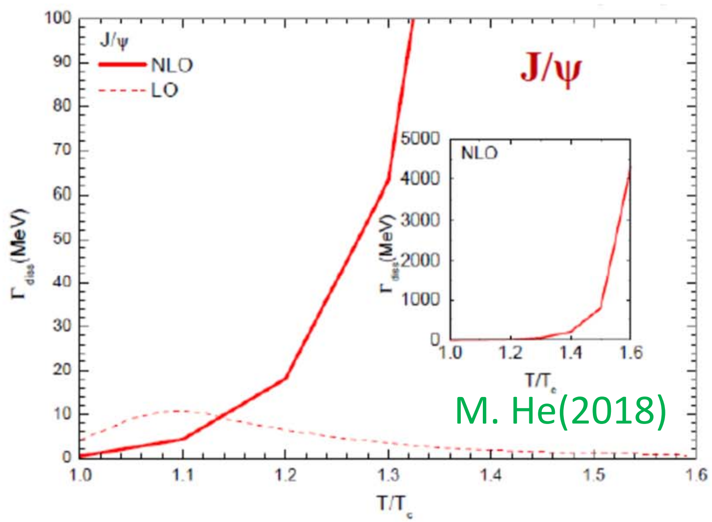
Topic V: HQ interaction in the medium and with the medium

II. Transport models : … with significant subtle variations in each model:

- Underlying binding force between Q & Qbar
- Whether, on the top of dissociation, some « melting » is allowed
- ….







With significant consequences on the dissociation rate !

In some schemes (not most of them): connection with the force acting on single HQ (=> possible calibration; nice !)

Topic V: HQ interaction in the medium and with the medium

II. Transport models (and rate equations) : different levels of « implementation »

$$\frac{dN_\Phi}{dt} = -\Gamma(T(t))\,(N_\Phi - N_{\Phi,\mathrm{eq}}(T(t)))$$

Global kinetic equation

Automatically takes care of the recombination at time t assuming HQ are in thermal equilibrium

Physics in Γ(T) can be more or less sophisticated (weakly coupled, strongly coupled,…)

$$\frac{dn_\Phi(\vec{x})}{dt} = -\Gamma(T(t,\vec{x}))\,(n_\Phi(\vec{x}) - n_\Phi(\vec{x},\mathrm{eq})(T(t,\vec{x})))$$

Local kinetic equation; well suited for implementation in fluid dynamics

Local transport equation in phase space (physical space + momentum)

Well suited to include off-equilibrium effects in HQ distribution, quarkonia production at finite p_T,… but there is a trade off: one thus needs more microscopic knowledge about the medium – onium interaction (typically: cross section)

Topic V: HQ interaction in the medium and with the medium

III. Rate equations

In pNRQCD, Schroedinger – like equation for the correlation : $\langle\psi_s(t)|\psi_s(0)\rangle$

$$i\partial_t\langle\psi_s(t)\psi_s(0)\rangle = \left(V^{QCD}(R) + \mathcal{O}(m_Q^{-1}) + \Theta(R,t)\right)\langle\psi_s(t)\psi_s(0)\rangle$$

Laine et al. (JHEP 0703 (2007) 054) : real time formalism to deduce the potential V:

- Real part: « usual » screening at short distance
- Imaginary part: corresponding to gluo-dissociation and dissociation by scattering with external parton (appears as « Landau Damping » in the formalism

⇒ Eigenstate for $\langle\psi_s(t)|\psi_s(0)\rangle$: $E = E_R + \boxed{i\,E_i} = E = E_R + i\,\Gamma/2$

Interpreted as the dissociation ->
octet Q-Qbar states above threshold

⇒ Dissociation rate

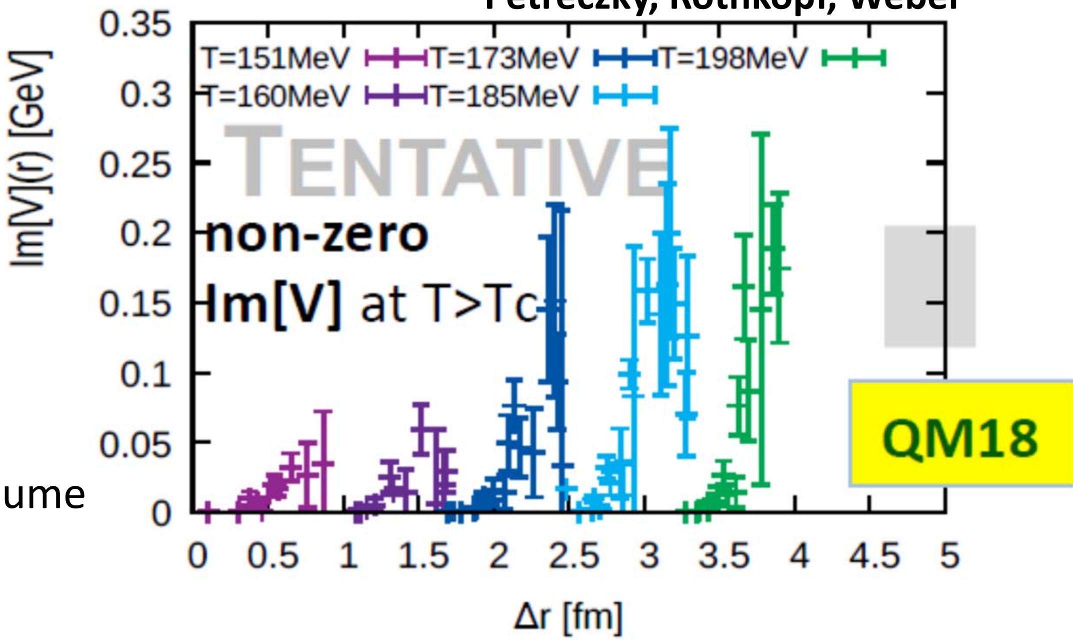
Topic V: HQ interaction in the medium and with the medium

III. Rate equations

- At small distance (r<1/T): rare process in the QGP => can be interpreted in terms of usual cross sections

- Interesting feature: can also be evaluated at larger distances (where the interpretation in terms of individual collisions is less obvious) by implementing NRQCD on the lattice :

Petreczky, Rothkopf, Weber



- => Bottomonium probability to survive:

$$S = \int_0^{+\infty} e^{-\Gamma(T(t))} dt$$

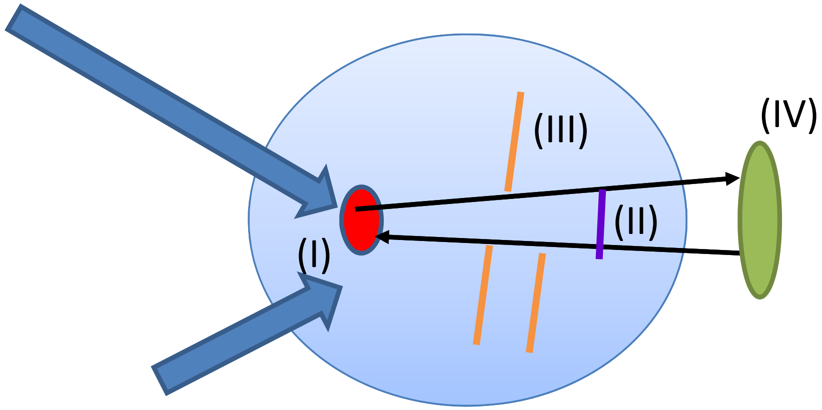
Averaged on the QGP volume

- Approach initiated by Kent State University (see slide « n-4 » for comparison with transport)

N.B.: lQCD still cannot solve the full problem but provides more and more valuable information

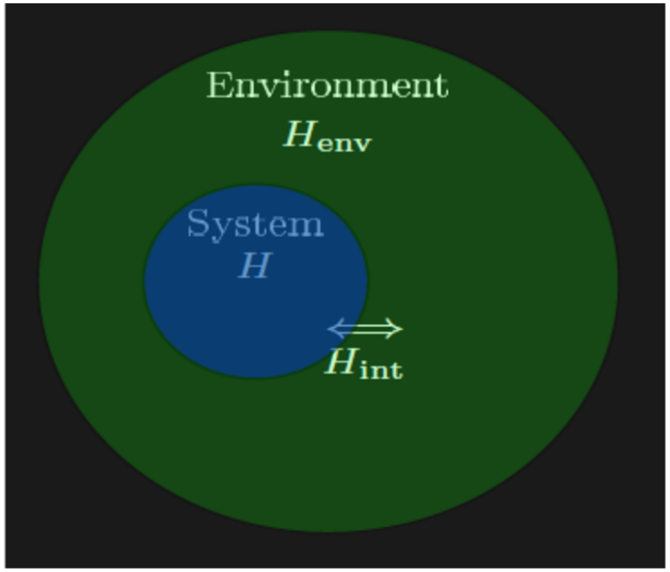
Topic V: HQ interaction in the medium and with the medium

More sophisticated : transport (or transport inspired schemes). Different level of descriptions…



… but:

a) they all neglect (for good or bad reasons) quantum interference between states
b) If Γ relies on the notion of cross section: too large rates not compatible with independence between 2 reactions



One thus has to deal with the problem of the evolution of some quantum system coupled to an external heat bath: *iv) Open Quantum Systems*

$\Rightarrow$ Need to trace out the dof of the HB to concentrate on the Q-Qbar state. Such operation is not defined on the full quantum state $|\Psi\rangle$

$\Rightarrow$ Consider the density operator $\hat{\rho} = |\Psi\rangle\langle\Psi|$

$\Rightarrow$ $\hat{\rho}_{Q\bar{Q}} = \mathrm{tr}_{\mathrm{med}}\hat{\rho}$ whose time evolution can be treated

Topic V: HQ interaction in the medium and with the medium

If you are interested:
- E. Ferreiro QM plenary talk
- A. Rothkopf QM student lecture

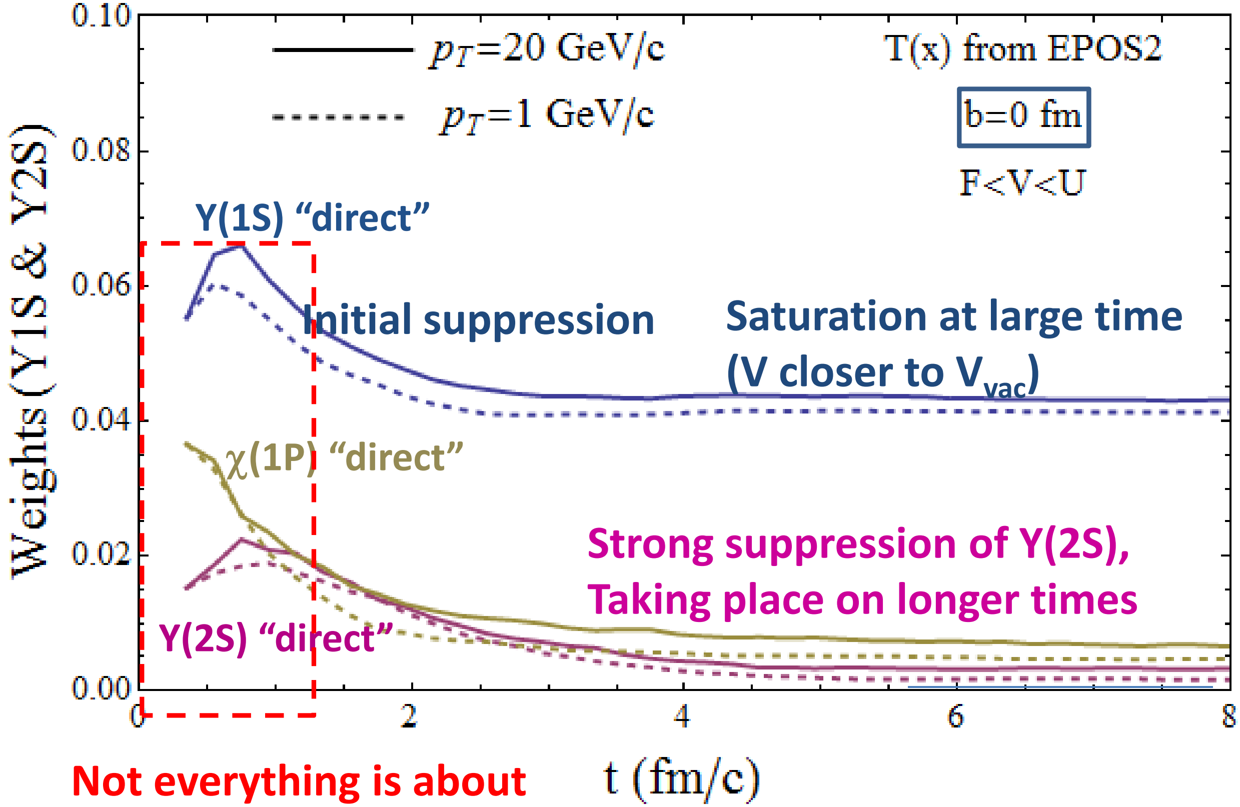
Non trivial effects founds (non monotoneous time evolution)

Nice feature: S <-> O continuous transitions

New vision Quarkonium suppression -> Quarkonium equilibration -> quantum decoherence (of the initial state)

BUT: need to know the initial quantum state !
Non trivial (see following discussion on pp)

PB Gossiaux, SQM 2017



Not everything is about thermal decay widths !!!

Topic VI: Quarkonia at intermediate and high pT

As an echo to topic 1: for open HF: situation becomes a bit boring at low pT => go for intermediate pT… could be the case for quarkonia as well

Does it make the physics easier ? For which ingredients precisely ?

Color screening or (more or less) usual energy loss ?

Energy loss (Arleo and Peigne):

- « If radiation, the quarkonia would dissolve immediately » (I. Vitev)

« SCET_G » :

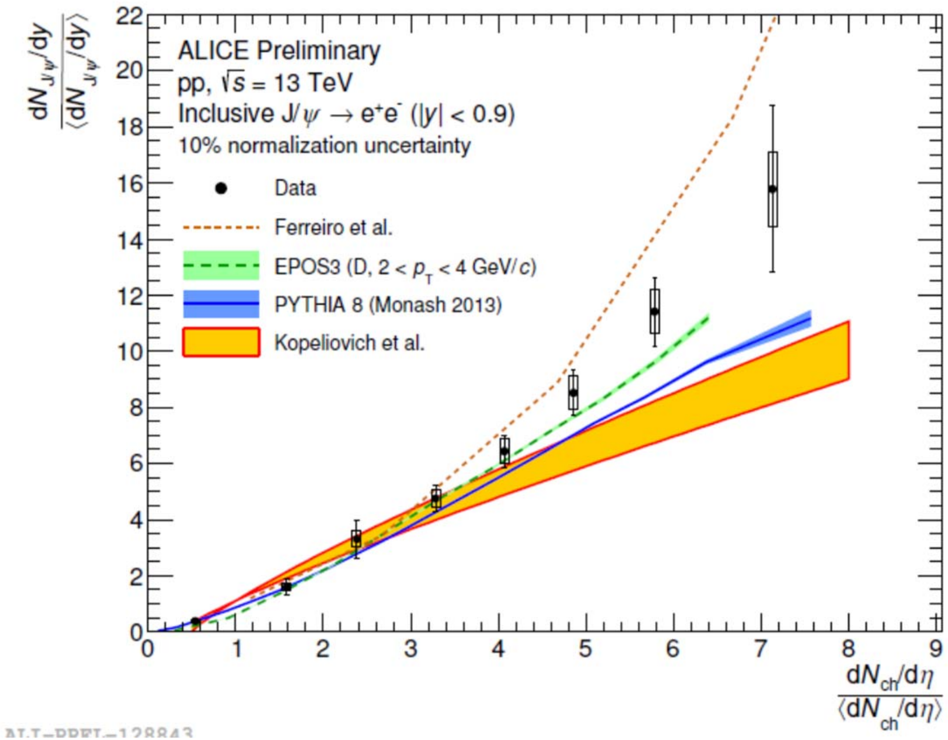
- How does if contradict Peigne and Arleo picture ? (apart from looking at the internal dynamics)
- How do we model thermal physics for a system at large velocity ? Scales ?
- Where is the transition region in pT ?
- Can we reproduce pA results with this approach ?

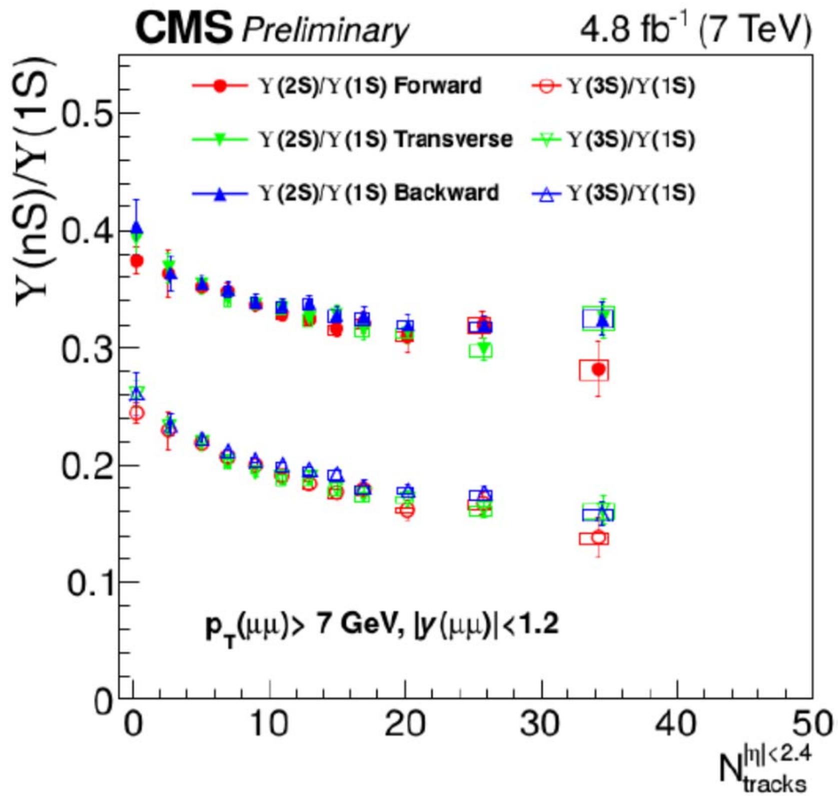
Generic question : How far can an octet propagate in a nucleus (seen as a color reservoir) ?

Topic VII: Quarkonia and HF in small systems

Why is it good for ?   Clear view = Mess^2 or the future of our field ?

Same mechanisms ? What are we probing ?





Topic VII: Quarkonia and HF in small systems

Some thoughts:

- Very difficult topic, even in the light sector
- What does m_Q bring to the problem ?

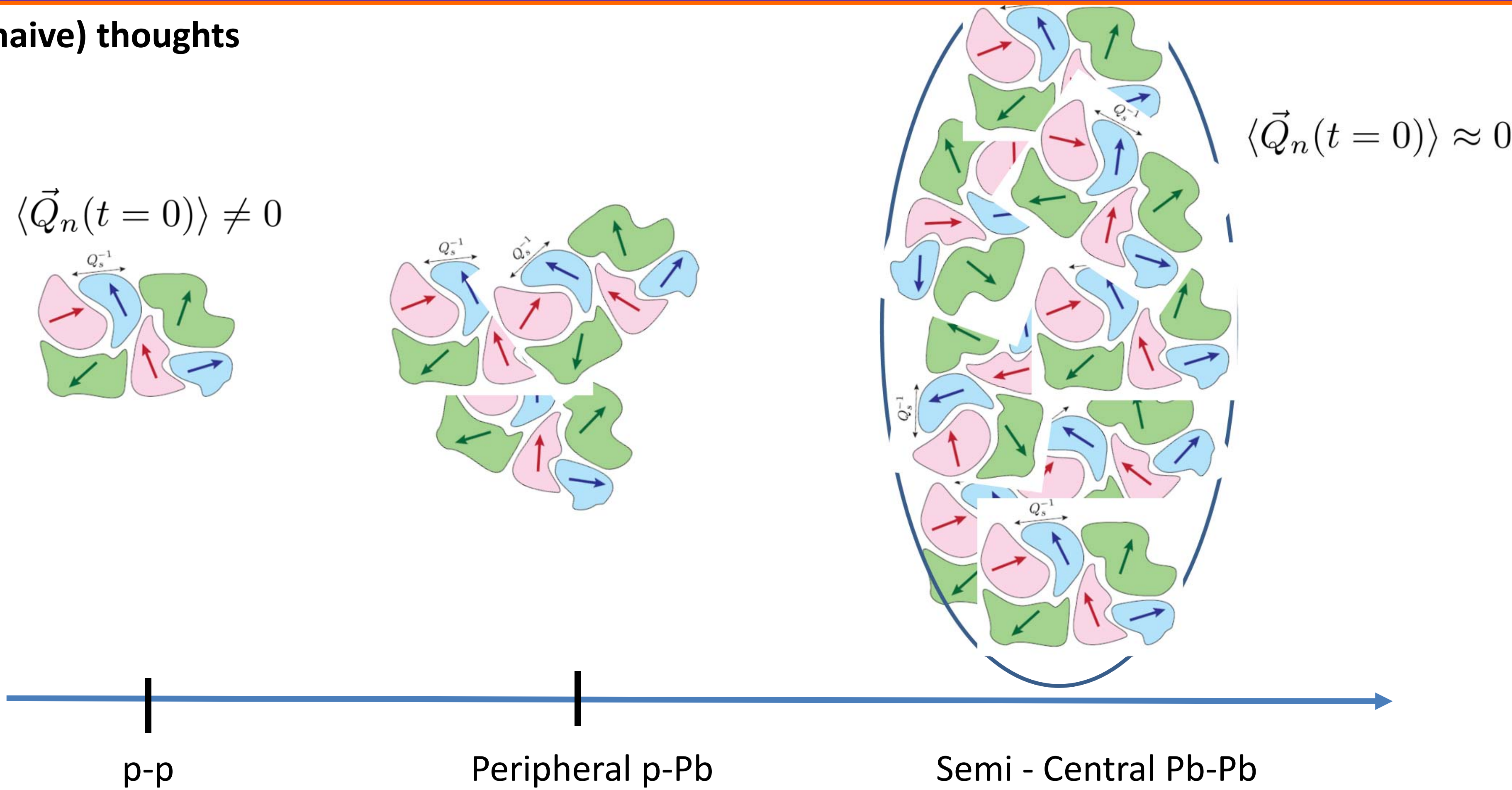
favor CGC	disfavor CGC	Pro hydro	disfavor hydro
Effect deeply rooted in the production mechanism	?	Other indications of collectivity in p-Pb	Theoretical status of hydro in p-Pb unclear (see M. Strickland's talk)
K Watanabe: « From the CGC view point, heavy mesons should be more correlated than light hadrons" (reinteraction less efficient).			Recombination in small systems not under control (large differences due to technical implementation)
			Absolute value found up to now too low: $v2(B)<v2(D)<v2(\pi)$

- It might well be that the mass ordering differs between the mechanisms. Need further study
- In any case studies incorporating both (like the one of M Greif et al. in the light sector) would be interesting.

M. Greif et al, Phys. Rev. D 96, 091504 (2017)

Topic VII: Quarkonia in small systems

Some futher (naive) thoughts



Gradual transition from CGC fluctuation -> geometry ?