(A microscopic model of) quarkonia production (in heavy ion collisions)

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Based on arxiv 2206.01308 (accepted for publication in PRC) and on 2305.10750 (freshly submitted)

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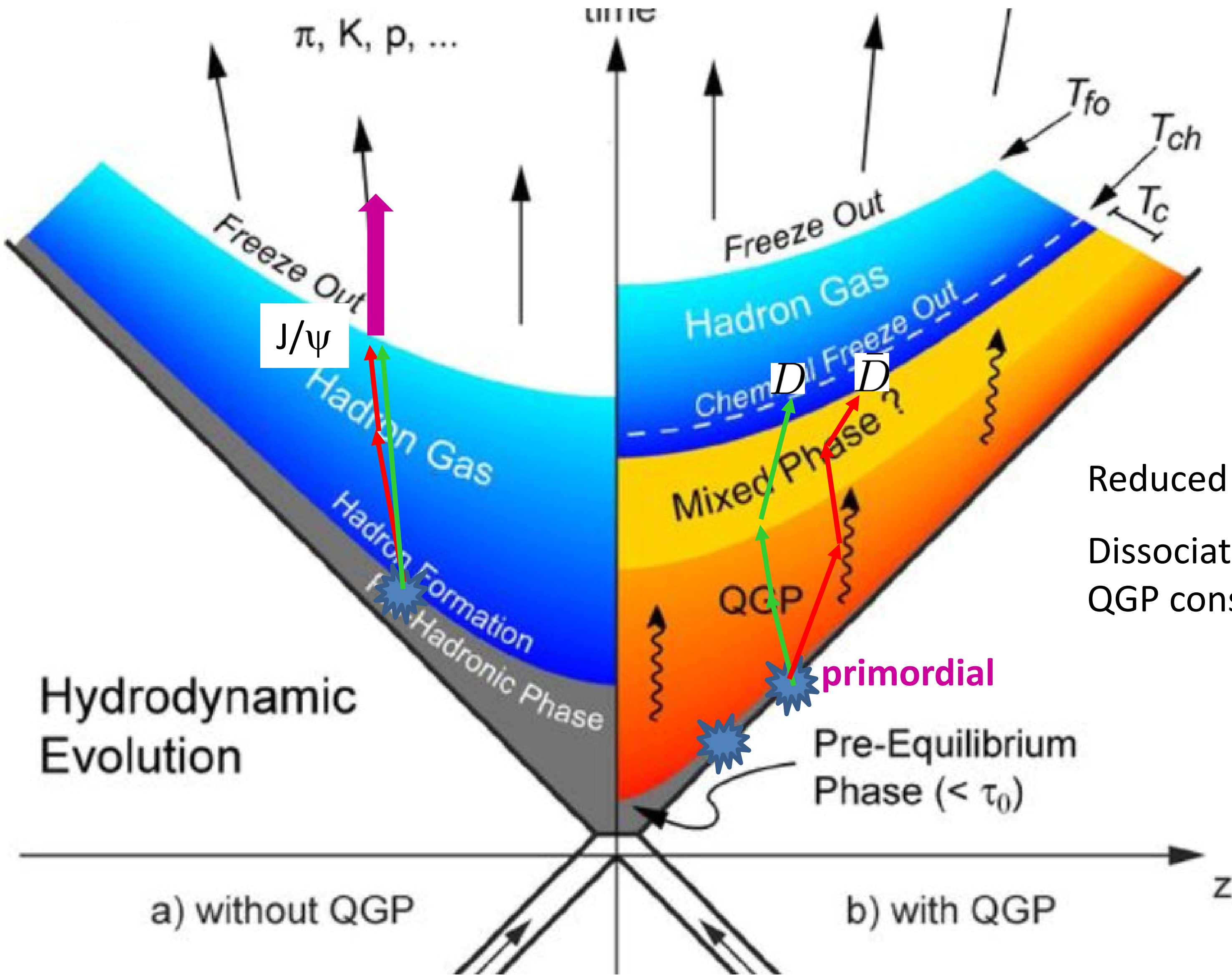
and Pays de la Loire

Quarkonia production in Heavy Ion Collisions

Two main effects if Quark Gluon Plasma: (sequential) **suppression** Matsui & Satz 1986

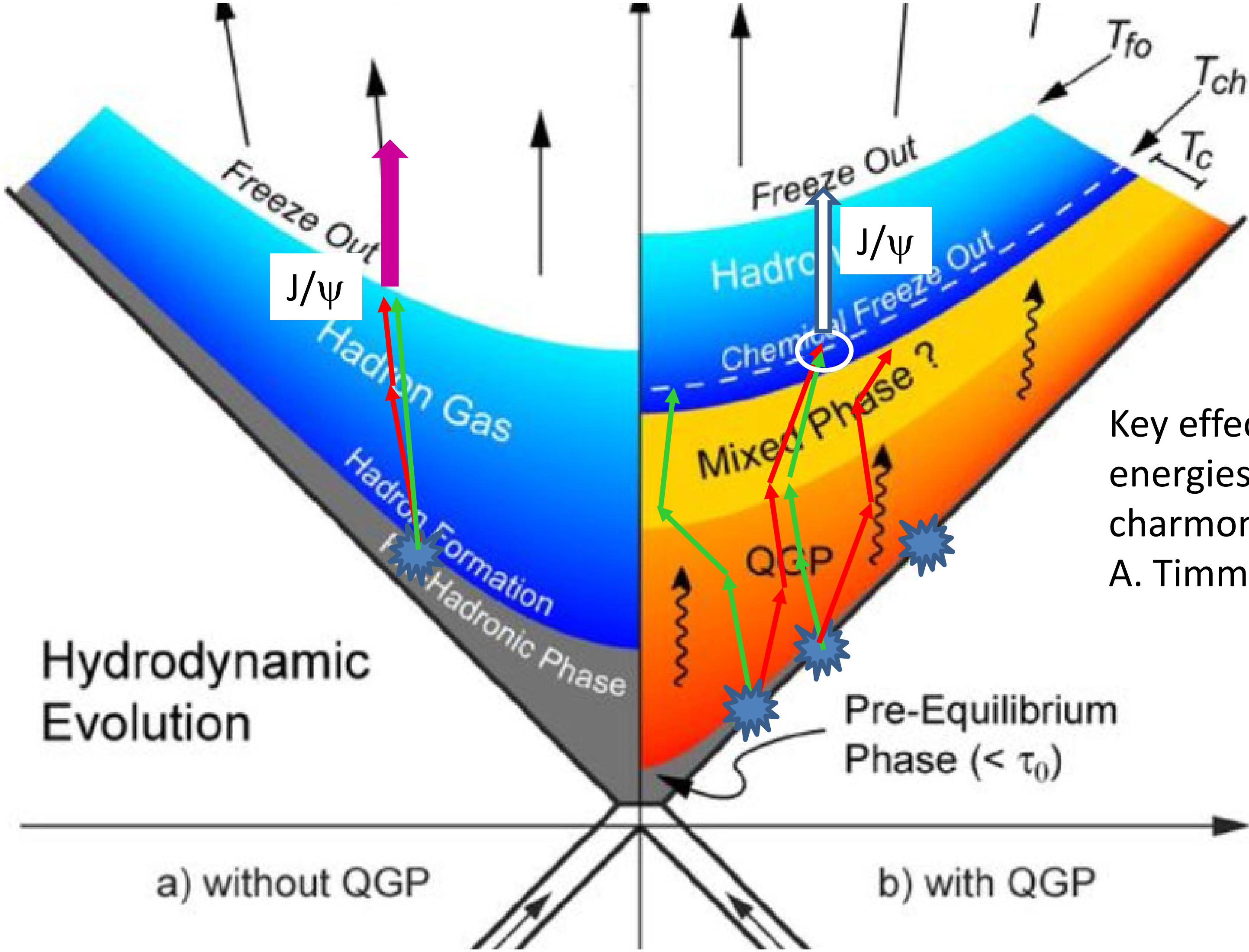


Reduced binding

Dissociation by QGP constituents

Quarkonia production in Heavy Ion Collisions

Two main effects if Quark Gluon Plasma: **Regeneration (production from 2 distinct initial Q-Qbar pairs)** Braun-Munzinger, Stachel & Andronic + Thews (early 2000)



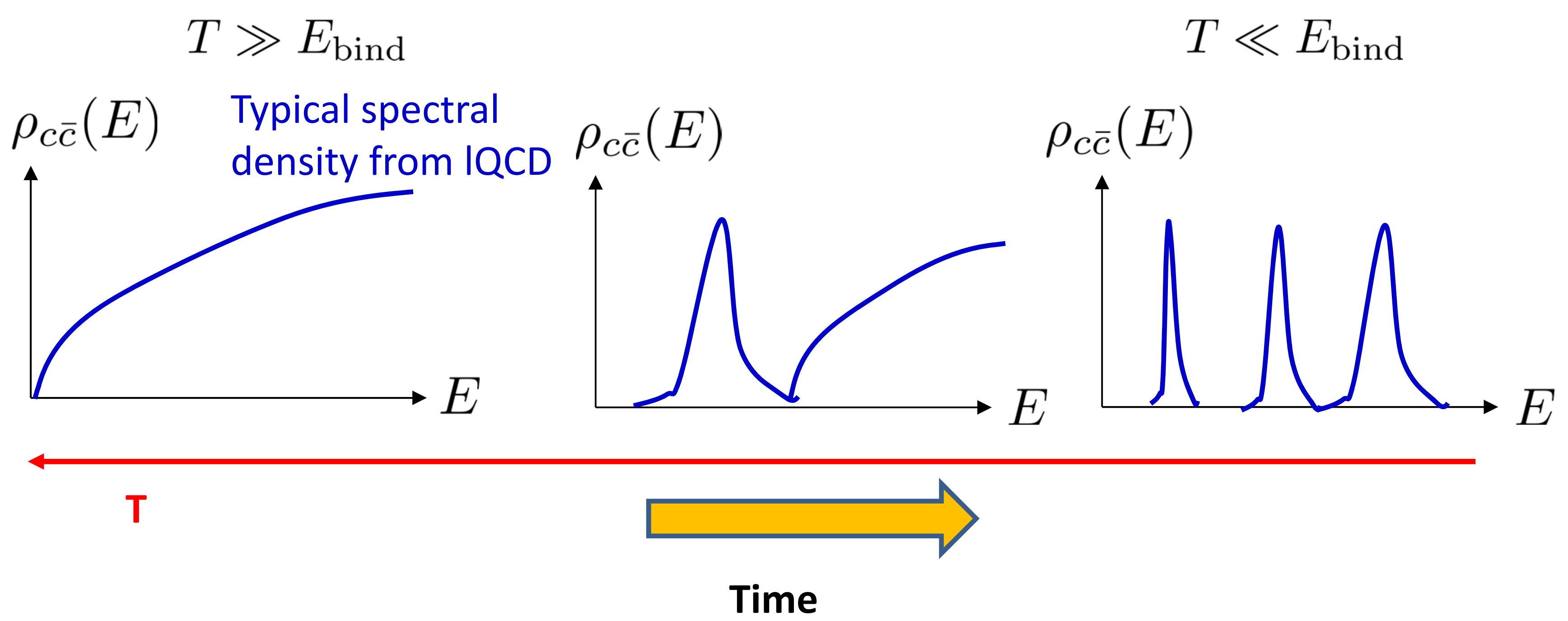
Key effect at LHC energies for charmonia (see A. Timmins talk)

Quarkonia production in Heavy Ion Collisions

These 2 mechanisms and the abundance of experimental data have the potentialities to better understand the forces acting on HQ inside QGP and probe its (short lived) evolution.

BUT

One is facing a dual question : what is the nature of a quarkonia inside a QGP ?



Two types of dynamical modelling

(and a 3rd class of its own: statistical hadronization)

$T \gg E_{\text{bind}}$	$T \sim E_{\text{bind}}$	$T \ll E_{\text{bind}}$
Quantum Brownian Motion		Quantum Optical Regime

- Correlations growing with cooling QGP
- Best described in position-momentum space
- Time short wrt quantum decoherence time

Quantum Master Equations for **microscopic dof (QS and Qbars)**

?

- Well identified resonances
- Time long enough wrt quantum decoherence time

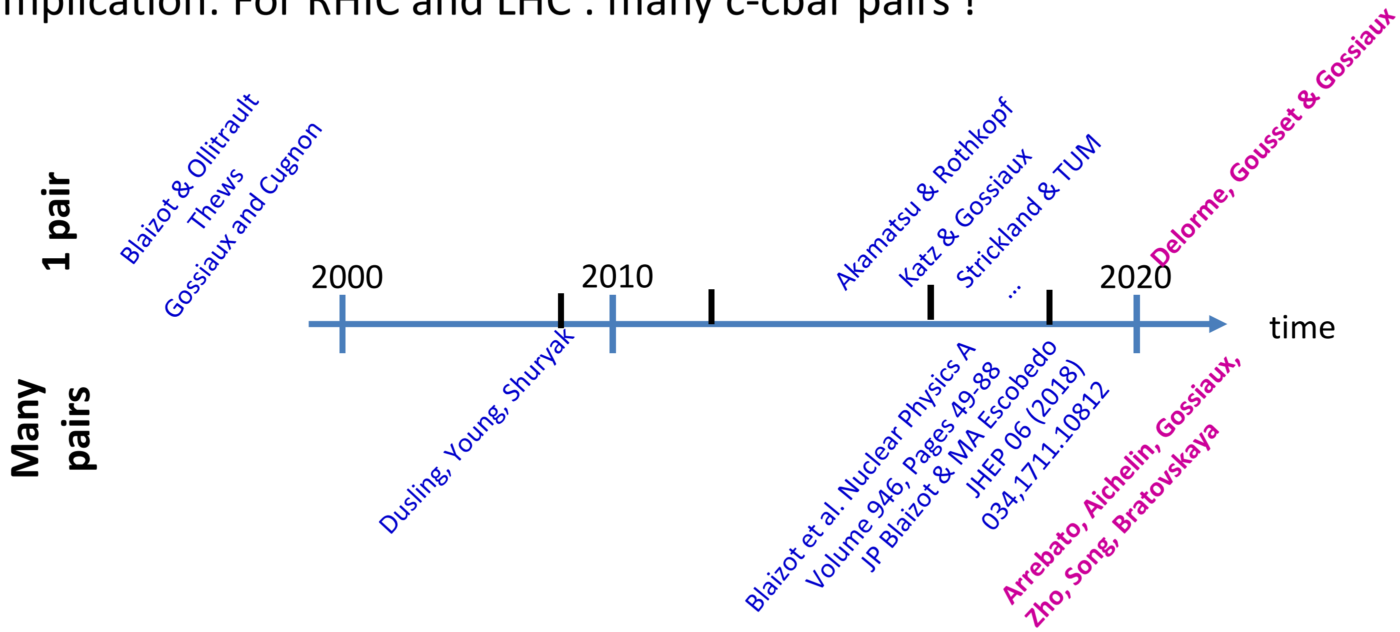
Good description with transport models (TAMU, Tsinghua, Duke)

Central quantities :
2->2 and 2->3 Cross sections, decay rates

Since one is facing both dissociation and recombination, obtaining a correct equilibrium limit of these model is an important prerequisite !!!

Several motivations to go microscopic & quantum

- The in-medium quarkonia are not born as such. One needs to develop an **initial compact state** to fully bloomed quarkonia
- The dissociation-recombination reactions affecting quarkonia are **not instantaneous**… In dense medium, the notion of cross section should be replaced by the more rigorous open-quantum system approach (**continuous transitions**)
- Better suited for **« from small to large »**
- Extra complication: For RHIC and LHC : many c-cbar pairs !



Pioneering work of **Blaizot and Escobedo** for many c-cbar pairs => Semi-Classical Fokker-Planck + gain/loss rates for color transitions; awaits for implementation in realistic conditions

The spirit of the method…

$$P^{\Psi}(t) = \mathrm{Tr}\left[\hat{\rho}^{\Psi}_{Q\bar{Q}}\hat{\rho}_N(t))\right]$$ Simply taken at the end of the evolution (ideal world)

$$\hat{\rho}^{\Psi_i}_{Q\bar{Q}} = \sum_i |\Psi^i_{Q\bar{Q}}\rangle\langle\Psi^i_{Q\bar{Q}}|$$

$$\frac{d\hat{\rho}_N(t)}{dt} = -i\left[\hat{H}_N, \hat{\rho}_N(t)\right]$$

Various Quarkonia bound states (in vacuum)

Unfortunately… all N-body practionners know that **modelling the full system up to the last stage is quite challenging !** Issues of stability, energy conservation,…

Clear lesson from the « old » cascade and QMD codes for fragment formation

Replace « final » => « initial » + Sum of time steps and chop off at the appropriate time scale

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

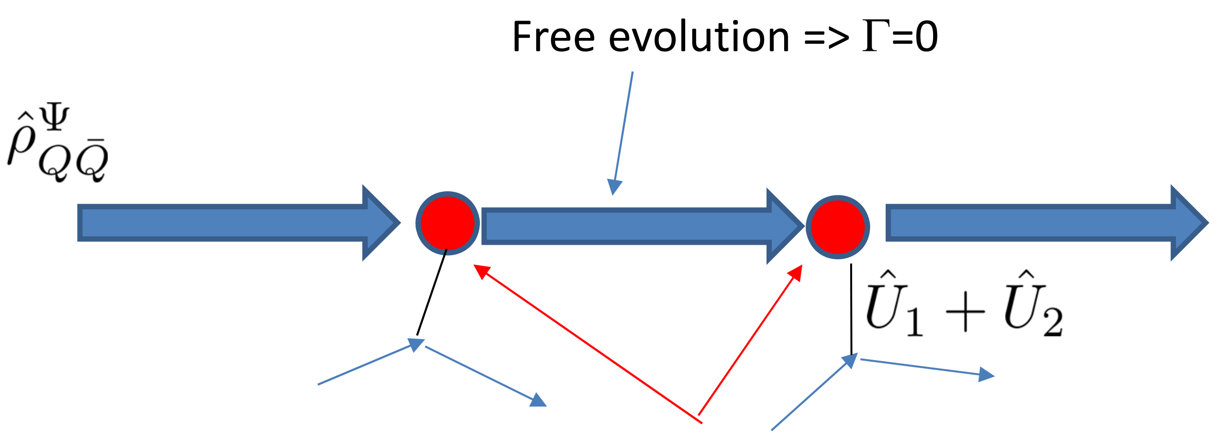
Caution : Not the usual decay rate

Convergence towards statistical equilibrium in a fixed temperature QGP recently demonstrated in arxiv 2302.14001

The spirit of the method…

Dealing with the dynamics ? **Von Neumann equation**

If eigenstates of the « internal » 2-body (QQbar) interaction



No « late time » evolution in this eigenbasis

Interaction with a 3rd body => modification of the $\hat{\rho}^{\Psi}_{Q\bar{Q}}$

… $\Gamma^{\Psi}(t) = -iTr[\hat{\rho}^{\Psi}[\hat{U}_1 + \hat{U}_2, \hat{\rho}_N(t)]]$

Total interaction of Q and Qbar with all light partons

Source of « destruction » ⇔ imaginary potential

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Remler Formalism at work

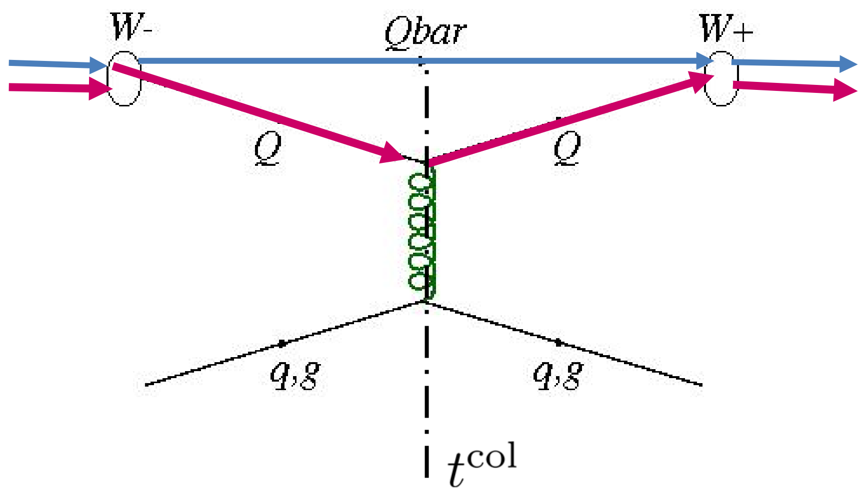
E.A. Remler, ANNALS OF PHYSICS 136, 293-316 (1981)

Level of the modelling : **semi classical** for the Q-Qbar evolution => Wigner distributions instead of density operators

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

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

- The quarkonia production in this model is a three body process; the HQs interact only by collisions with the QGP !!!
- The "details" of H_{int} between HQ and bulk partons are incorporated into the evolution of W_N after each collision / time step (nice feature for the MC simulations)
- Dissociation and recombination treated in the same scheme



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

Interaction of HQ with the QGP are carried out by EPOS2+MC@HQ (good results for D and B mesons production) Eur. Phys. J. C (2016) 76:107

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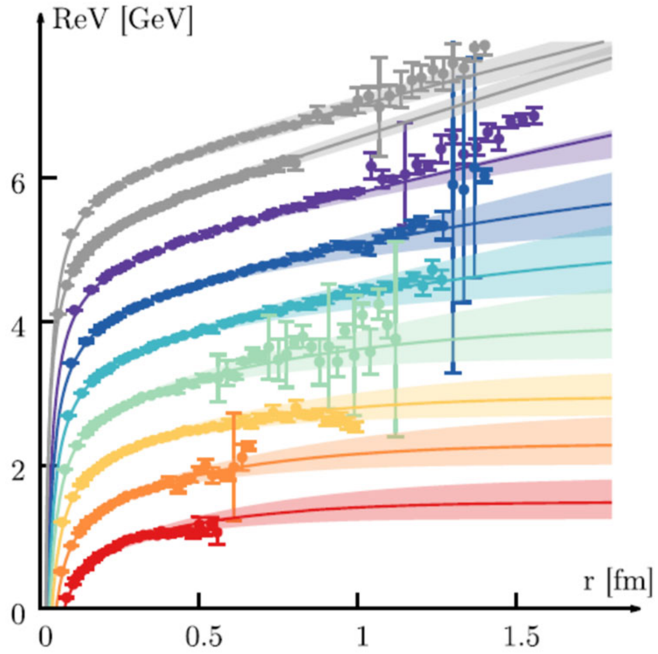
Extension of the Remler formalism

- **Confining $Q\bar{Q}$ forces inside the MC evolution ; large impact on the # of close pairs… and correlated trajectories.**



(No internal potential in early applications dedicated to deuteron production in low energy AA collisions; advocated to be negligible… as only the « hot zone » was contributing

But for quarkonia, it turns out not to be the case => need for in-medium potential

D. Lafferty and A. Rothkopf,
PHYS. REV. D 101, 056010 (2020)

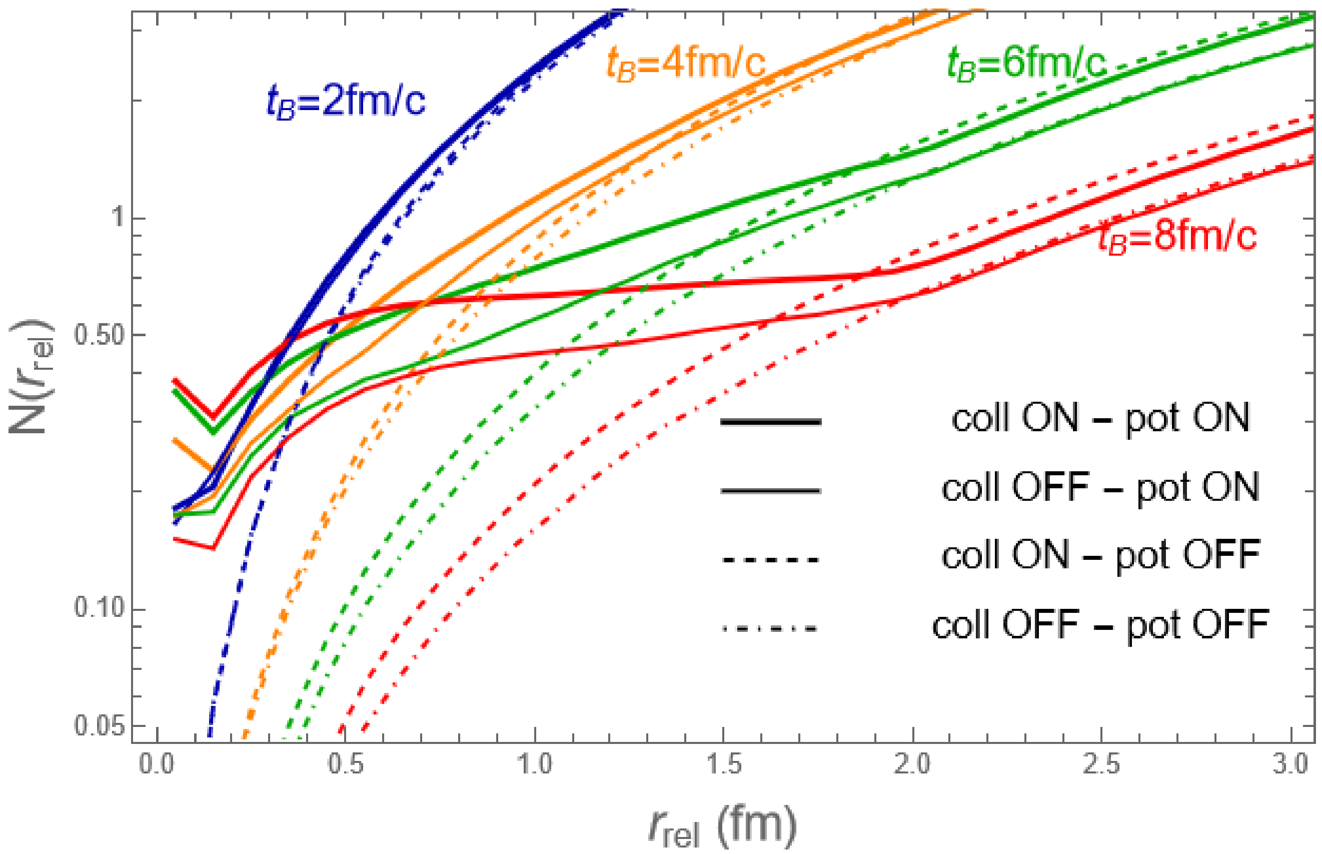
Correlated SC trajectories

Complicated relativistic N-body problem… Only stable at « not too high » p_T

The 3 layers of the numerical modelling

	Initial state		evolution
Background	EPOS initial condition +transverse positions of the NN collisions	→	Fluid dynamics
	↓		↓ {T(x),v(x)}
HQ level	Initialisation of c-cbar pairs according to FONLL[2] ⊗ EPOS positions	→	Evolution of HQ according to MC@HQ **+ c-cbar in-medium potential**
			↓
			Correlated SC trajectories

The dynamics of c-cbar correlation



- The c-cbar potential (« pot ON ») leads to a **huge increase of the c-cbar probability at close distance** at large times (not a random Poisson distribution !)…
- … Especially when the collisions with the QGP (« coll ») are switched ON as well

The 3 layers of the numerical modelling

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	↓		↓ Correlated SC trajectories
Quarkonia level	Initial $J/\psi(T)$ $P(t_0)$ when $T(x) < T_{diss}$	→	Evaluation of Γ according to improved Remler + $\Gamma_{loc.}$

We do not have J/ψ quasi particles in our approach, just correlated c-cbar trajectories

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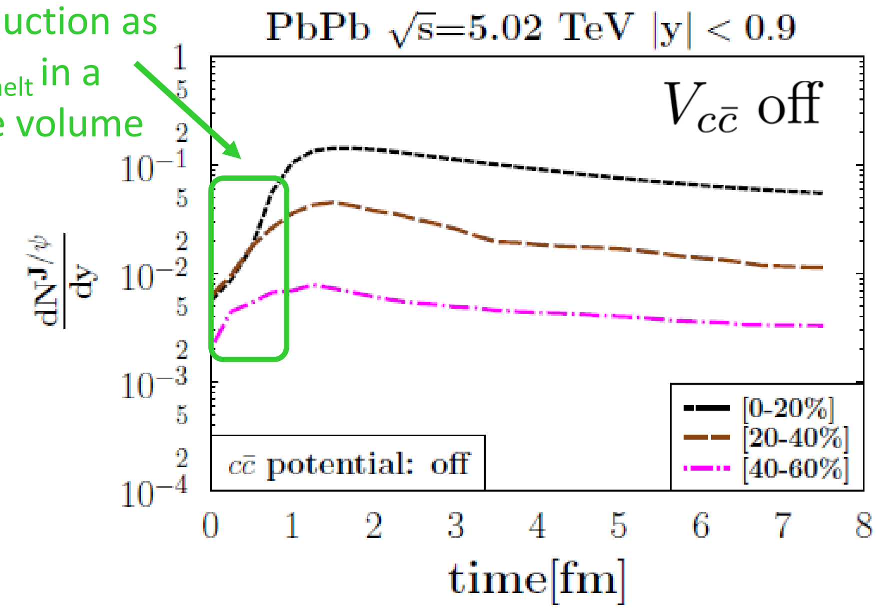
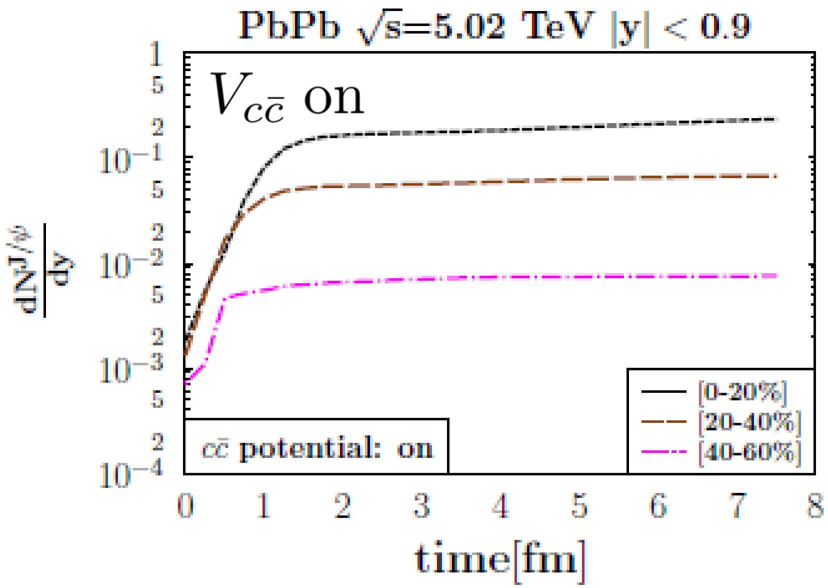
Results : J/ψ production vs time

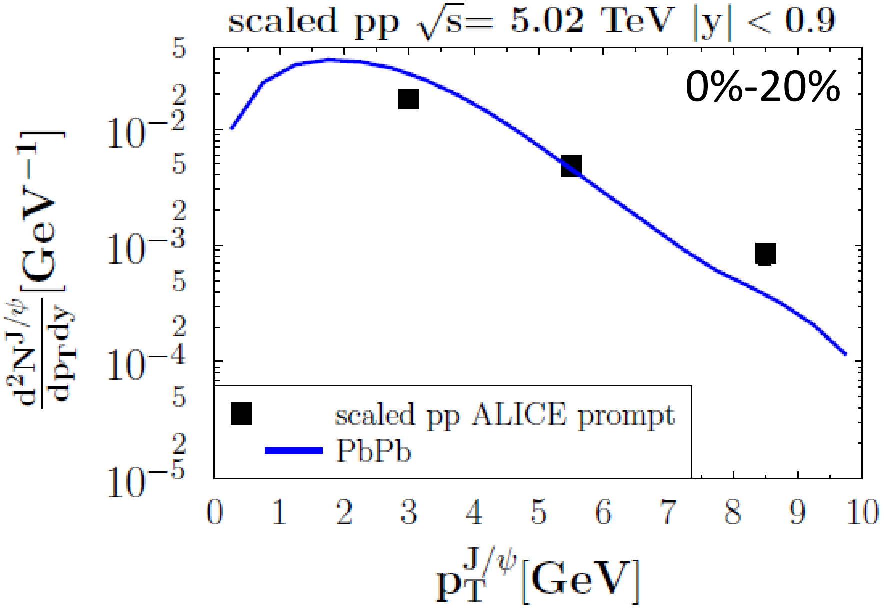
Delayed initial production as $T>T_{melt}$ in a large volume

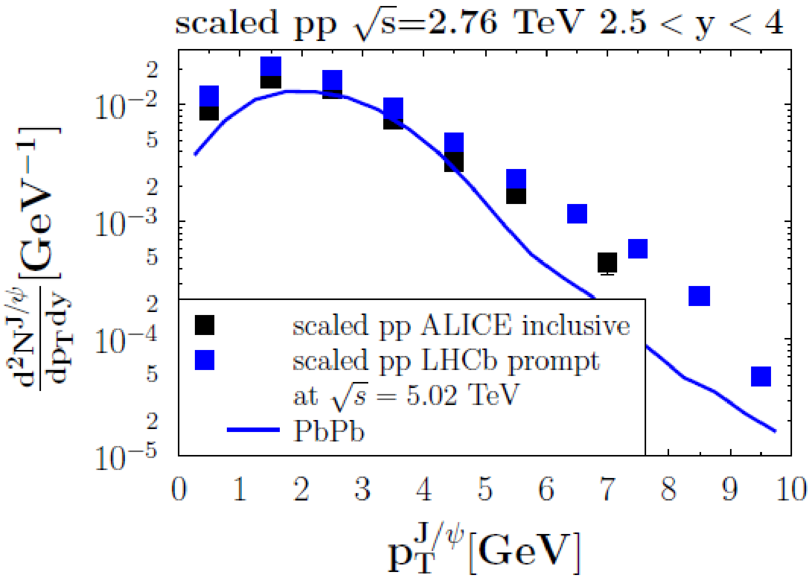




- Without interaction potential between c and cbar, the collisions with the medium manage to destroy the native J/ψ (left)
- With the interaction potential between c and cbar « on », one observes a steady rate of J/ψ creation (increase of Γ^{col}, increase of Γ^{local})… No adiabaticity, but **no instantaneous formation** either.

Results : J/ψ production vs p_T



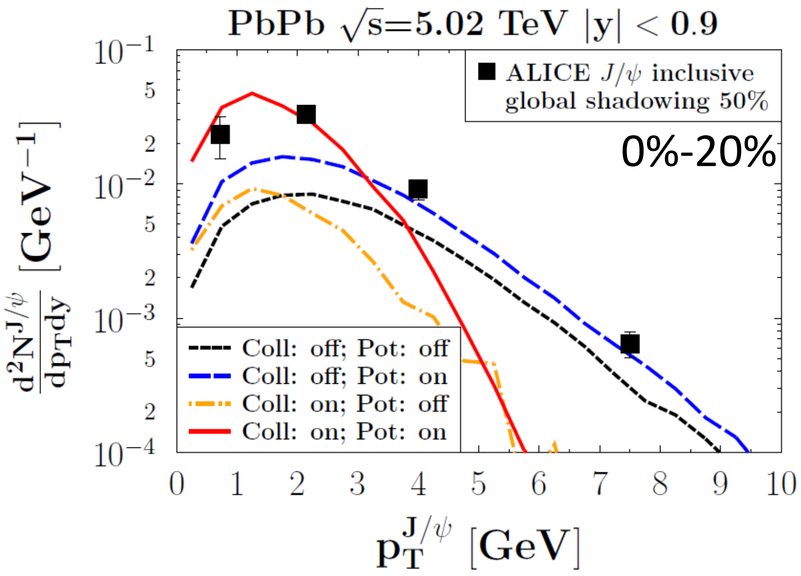


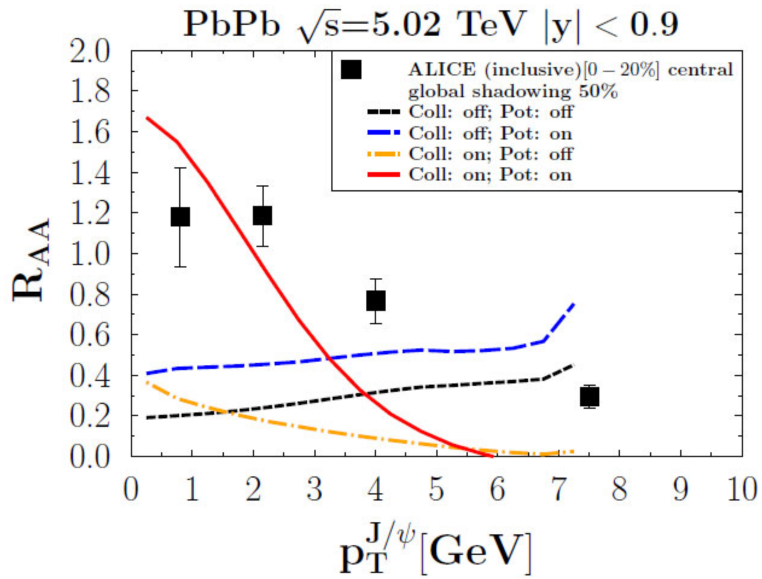
- **Equivalent pp production** (the denominator of the R_{AA}) : c-cbar according to FONLL[2] without any correlation, then coalescence with the Wigner distribution.
- No feed-down from higher states (to be implemented)

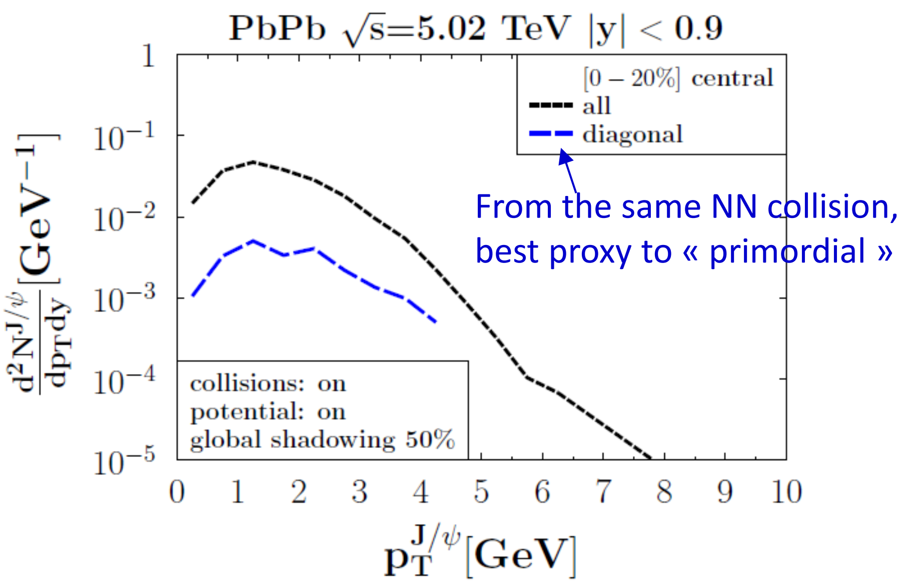
- Acceptable for $p_T < 5$ GeV/c, but deviations for higher p_T.

- To investigate : more appropriate scheme for c-cbar production, including c-cbar correlation : EPOS4

Results : J/ψ production vs p_T

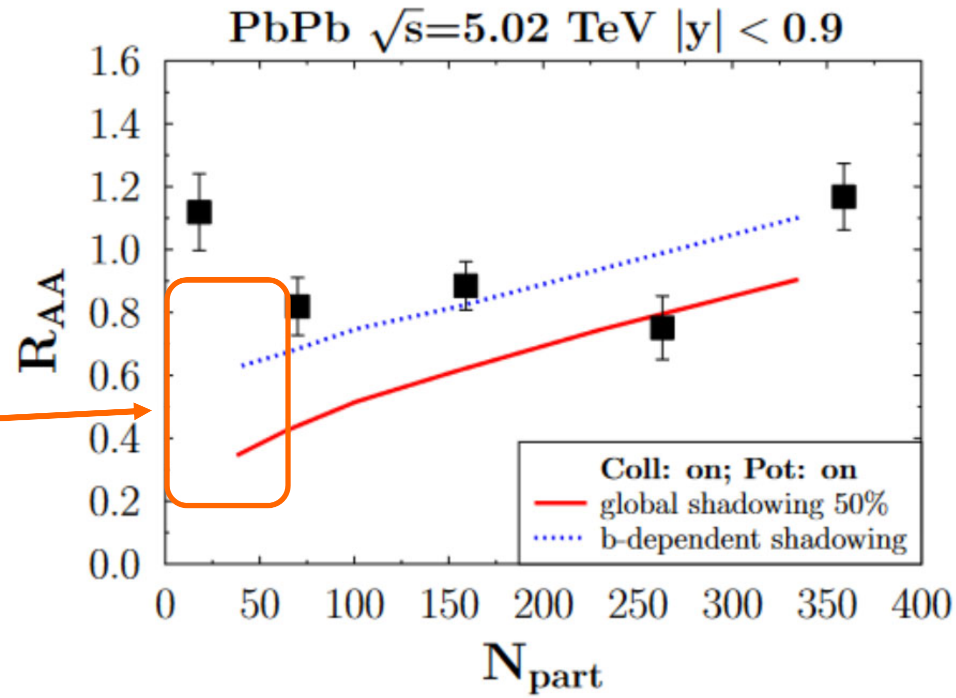






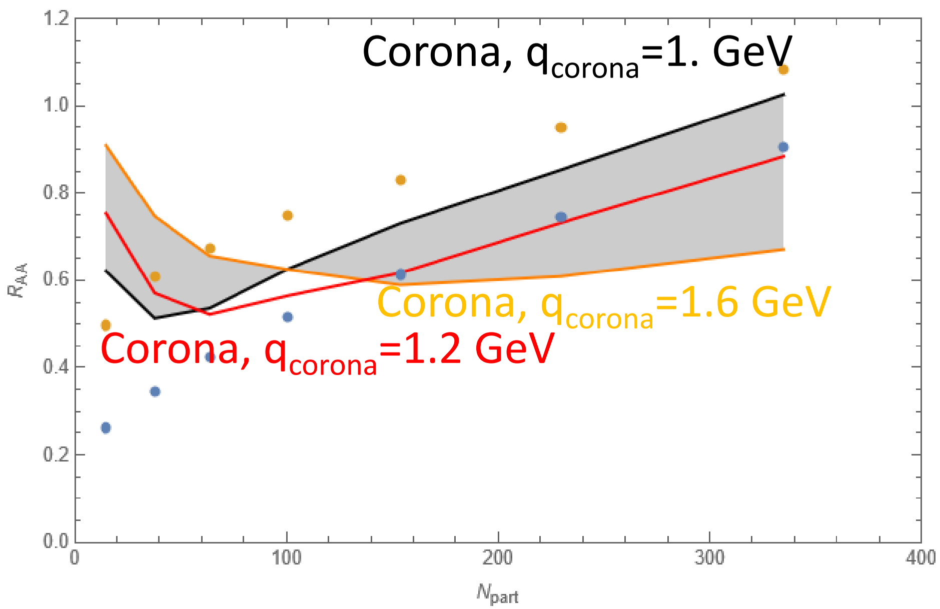
- Dynamical recombination is quite effective at low p_T
- At higher p_T, we are missing J/ψ as compared to the experimental value.
- Several possible reasons, under investigation:
  - in terms of transport model : « primordial too much suppressed »
  - lack of c-cbar correlation in the IS
  - …

R_{AA} vs N_{part}



Caveat : too crude modelling of the thermalization in the bulk… assumed to happen after 0.35 fm/c independent of the centrality

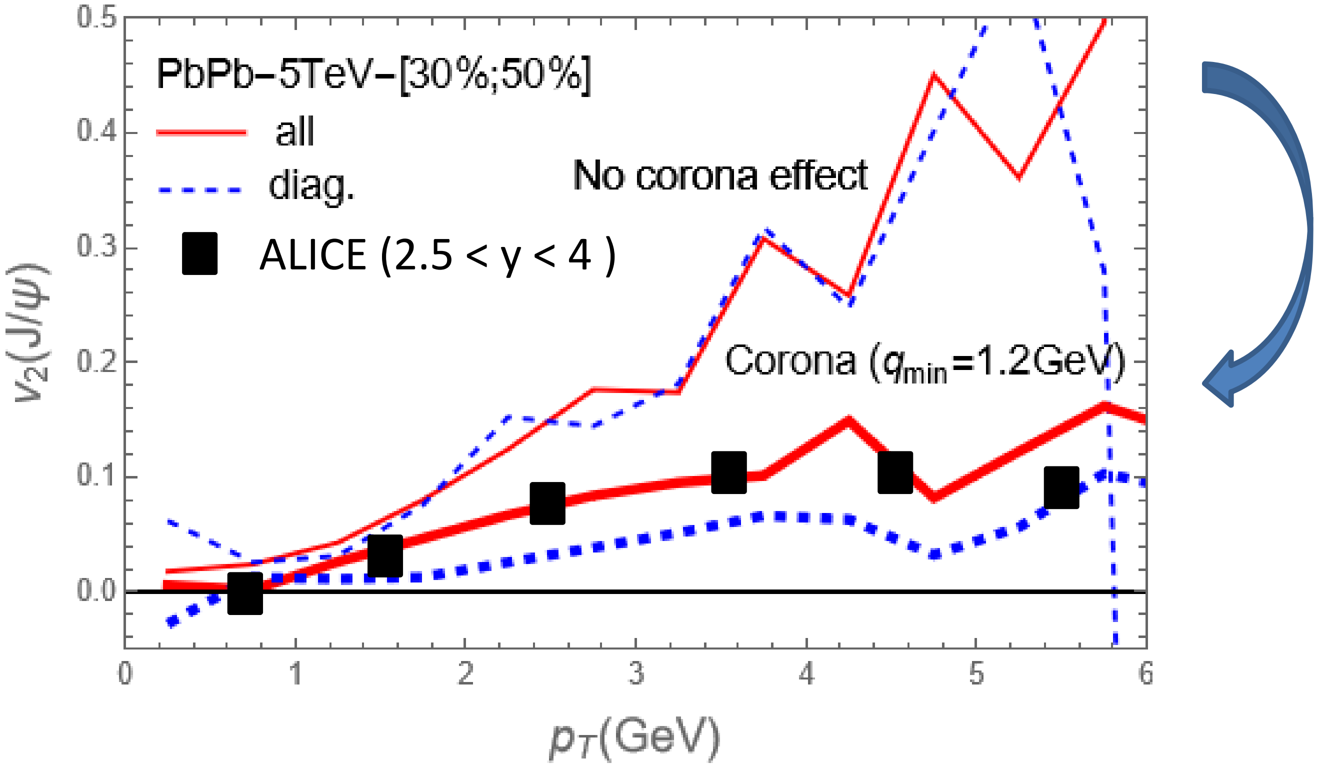
=> c and cbar created at t≈0 have the time to diffuse away => reduction of the production



One possible solution : core – corona model for c-quarks : c-quarks with momentum transfer < q_{corona} are considered to combine -> quarkonia as in vacuum…

Optimal value : Corona, q_{corona}=1.2 GeV

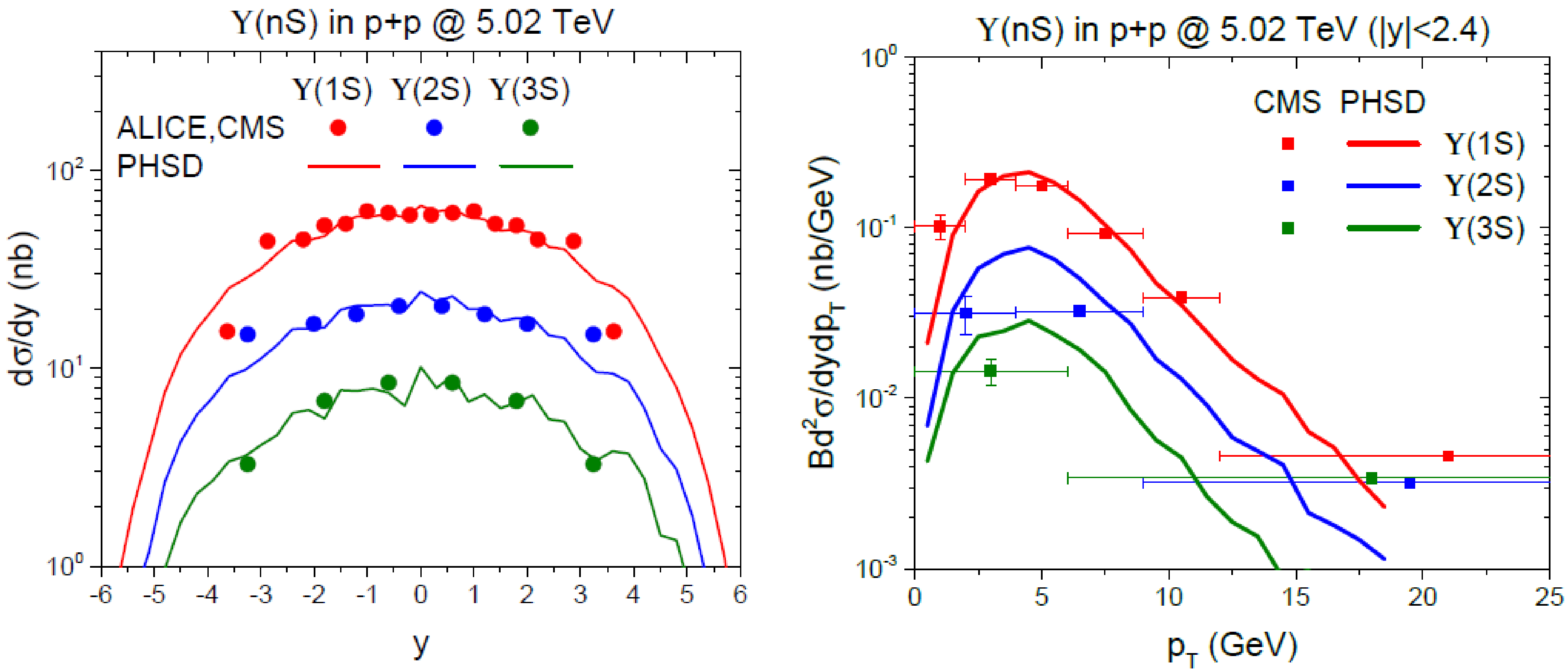
Results : J/ψ v_2



- v_2 excess as compared to experimental data (**late formation** of the J/ψ due to binding potential under restoration)
- Without corona, the « diagonal » contribution shows no difference wrt the full production, what is a bit conter-intuitive
- Corona has large effect on v2, even with moderate q_{thresh}. As the corona mostly affects the diagonal part, one recovers $v_2^{\rm diag} < v_2^{\rm all}$

Recent news

Applying the Wigner coalescence approach for bottomonia in pp (and in PbPb), starting from b-bbar pQCD spectra: 2305.10750



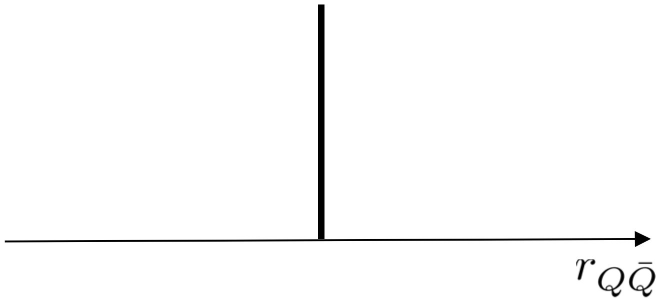
Good overall description with a pretty simple model

Conclusions and Perspectives

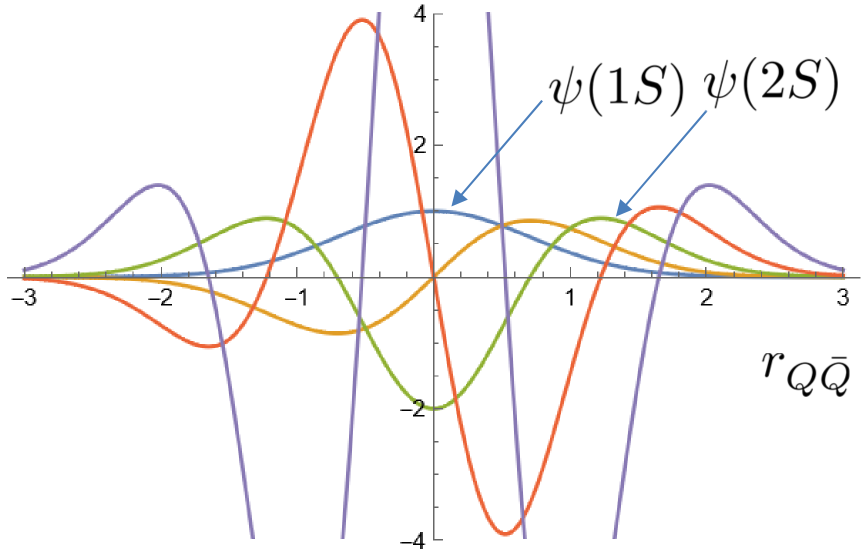
- First move towards a microscopic approach based on individual c and cbar dynamics implementing some of the open quantum systems features for charmonia production in realistic HI conditions : **dynamical coalescence**
- Encouraging results, but still many features to be refined
- Rooms for improvement :
  - Include excited states decay
  - Including color transparency and more generally color dynamics
  - More reliable treatment of the fully relativistic evolution of a N-body coupled system (under construction)
  - Upgrading to EPOS4 => More realistic « initial state » for the c-cbar pairs, including correlations at intermediate p_T.
  - Late interactions with hadronic phase
  - …

Back up

Quantum coherence at early time



$= \Sigma$



Initial compact state : δ

Dissociation rate: $\Gamma(r_{Q\bar{Q}}) \propto \alpha_S T \times \Phi(m_D r_{Q\bar{Q}}) \sim \alpha_S^2 T^3 \times r_{Q\bar{Q}}^2$

Coherence

Neglect of coherence

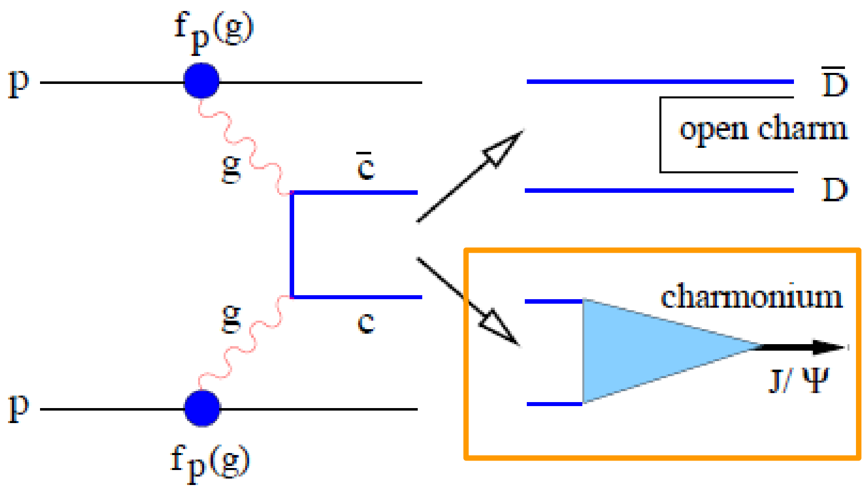
$$\Gamma(r_{Q\bar{Q}}) \approx 0 \propto \sum c_j^\star c_i \langle \psi_j | r^2 | \psi_i \rangle \longrightarrow \Gamma \propto \sum_i |c_i|^2 \langle \psi_i | r^2 | \psi_i \rangle \approx \sum_i |c_i|^2 \Gamma_i \neq 0$$

Crucial to include coherence !

N.B. : one can model this effect by phenomenological formation time, but lack of control

Quantum coherence

Picture behind transport theory :



Open heavy flavor and quarkonia assumed to be uncorrelated

Formed after some "formation time" τ_f (typically the Heisenberg time), usually assumed to be independent of the surrounding medium

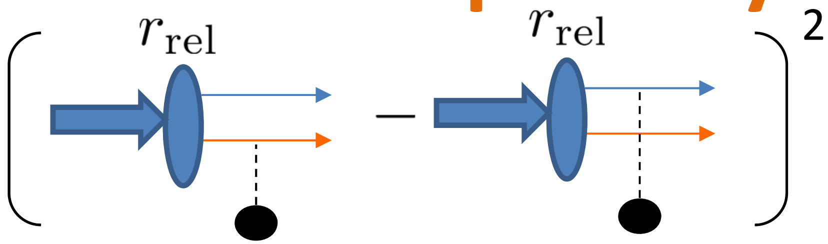
Common belief in the transport community:

Quarkonia initially « formed » in QGP and survive with an *individual* survival probability

$$S(t) = e^{-\int_{\tau_f}^{t} \Gamma(T(t'))dt'}$$

The two sides of color transparency

Q-Qbar propagation in QGP. $\sigma \propto$



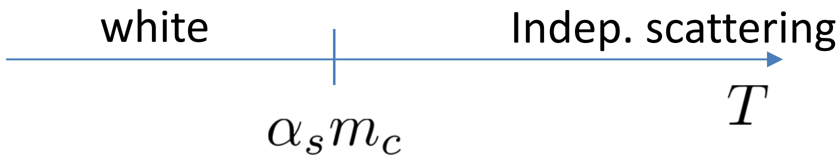
If $r_{rel} << l_{correl}$: **white object** => no Energy loss

If $r_{rel} >= l_{correl}$: 2 HQ interact individually with QGP.

$$l_{\rm correl} \sim \frac{1}{m_D}$$ (soft modes)

Small T : $r_{\rm rel} \approx \frac{1}{\alpha_s m_c}$

Large T : $r_{\rm rel} \gtrsim \frac{1}{m_D} \approx \frac{1}{gT}$



- 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 too large v_2 resulting from this prescription…

Remler's formalism for dynamical coalescence

Generic idea : describe charmonia (Ψ) production using density matrix

$$P^{\Psi}(t) = \mathrm{Tr}\left[\hat{\rho}^{\Psi}_{Q\bar{Q}}\hat{\rho}_N(t))\right]$$

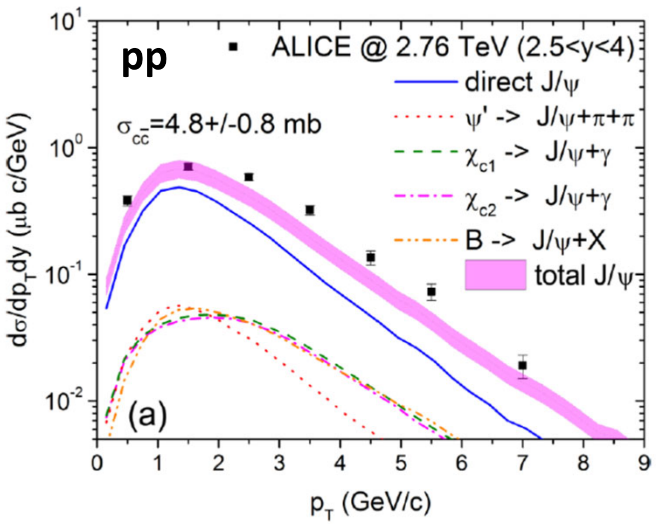
$$\hat{\rho}^{\Psi_i}_{Q\bar{Q}} = \sum_i |\Psi^i_{Q\bar{Q}}\rangle\langle\Psi^i_{Q\bar{Q}}|$$

Single quarkonia density operator

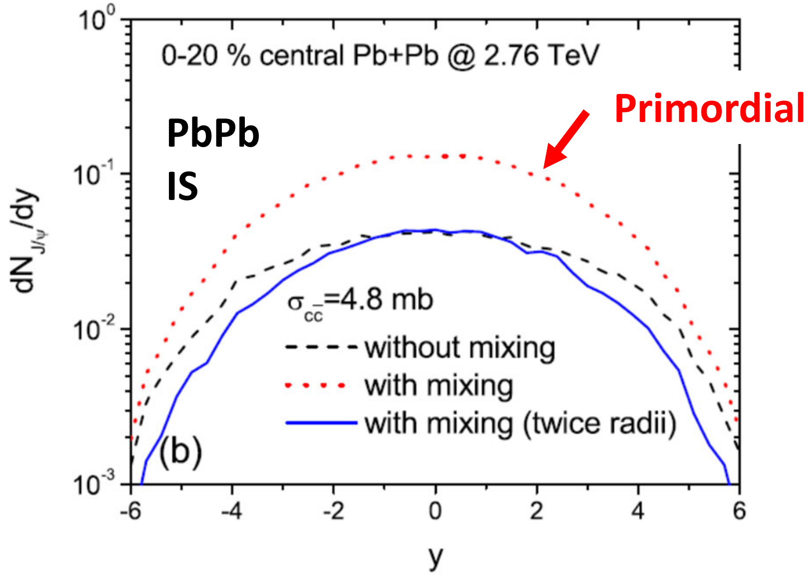
N-body density matrix (bulk partons + many c and many cbar)

"Just" looking at the initial stage brings interesting features:

T. Song, J.Aichelin and E.Bratkovskaya, PRC 96. 014907 (2017)



Good reproduction of pp -> J/ψ + x !!!

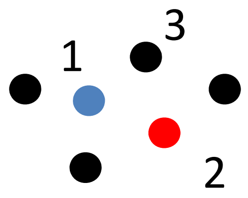


considerable enhancement of primordial J/ψ (in the **initial** state): **large off-diagonal contributions**

Remler formalism at work

Combining the rate definition + VN equation : $\Gamma^{\Psi}(t) = -iTr[\rho^{\Psi}[H_N, \rho_N(t)]]$

Generic case where $H_N = \Sigma_i K_i + \Sigma_{i>j} V_{ij}$



1 & 2 : $c \,\&\, \bar{c}$

3, 4, …… : light quarks

Strictly speaking, not QCD. Important process partly missing : gluo-dissociation

$$H_N = H_{1,2} + H_{N-2} + U_1 + U_2$$

$c\bar{c}$ Internal Hamiltonian

Light quarks

$\Sigma_{i>2} V_{i1}$ $\Sigma_{i>2} V_{i2}$

Heavy – light interaction

$$\Gamma^{\Psi}(t) = -iTr[\rho^{\Psi}[H_N, \rho_N(t)]] = -iTr[\rho_N(t)[\rho^{\Psi}, H_N]]$$

Only U_1 and U_2 => ≠0 (as $[\rho^{\Psi}, H_{1,2}] = 0$)

$$\Gamma^{\Psi}(t) = -iTr[\hat{\rho}^{\Psi}[\hat{U}_1 + \hat{U}_2, \hat{\rho}_N(t)]]$$

Sub-part of the VN equation, still impossible to deal with exactly at the quantum n-body level

Remler formalism at work

<u>Passing to the Wigner representation</u>:

$$W_N(\{r\},\{p\}) = \int \Pi d^3y e^{ipy} \langle r - \frac{y}{2}|\hat{\rho}_N|r + \frac{y}{2}\rangle$$

Direct space

$$\partial\rho_N(t)/\partial t = -i\Sigma_j[K_j,\rho_N(t)] -i\Sigma_{j>k}[V_{jk},\rho_N(t)]$$

Wigner space....

$$\partial W_N(t)/\partial t = \langle\Sigma_i v_i \cdot \partial_r W_N(\mathbf{r},\mathbf{p},t)\rangle + \langle\Sigma_{i\geq j}\Sigma_n \delta(t-t_{ij}(n))\times (W_N(\mathbf{r},\mathbf{p},t+\epsilon) - W_N(\mathbf{r},\mathbf{p},t-\epsilon))\rangle$$

One to one correspondance

... treated at the semi-classical level :

Wigner distribution ⇔ {trajectories in phase space}

⇨ $[\hat{U}_1 + \hat{U}_2, \hat{\rho}_N(t)]$ can be modelized from the trajectories evolution in Wigner space

Remler formalism at work

The effective rate for quarkonia state creation (dissociation) in the medium is

$$\Gamma^{\Psi}(t) = -iTr[\hat{\rho}^{\Psi}[\hat{U}_1 + \hat{U}_2, \hat{\rho}_N(t)]]$$

Working in the phase space through Wigner distribution

$$W_{Q\bar{Q}}^{\Psi_i} = \int d^3y e^{ipy} \langle r - \frac{y}{2}|\Psi^i\rangle\langle\Psi^i|r + \frac{y}{2}\rangle$$

Quarkonia: Double Gaussian approximation

$$W_{Q\bar{Q}}^{\Psi}(r_{\rm rel}, p_{\rm rel}) = Ce^{r_{\rm rel}^2\sigma^2} \times e^{\frac{p_{\rm rel}^2}{\sigma^2}}$$

Parameter: The Gaussian width $\sigma \approx 0.35$ fm

$$[\frac{\hbar^2}{2\mu}\nabla^2 + V(r)]\Psi_{QQ}(r) = E_{QQ}\Psi_{QQ} \longrightarrow \langle r^2\rangle \longrightarrow W^{\Psi}$$

W_N : Semi-classical approach

$$W_N = \Pi_i \hbar^3 \delta(x_i - x_{i0}(t))\delta(p_i - p_{i0}(t))$$

… but no explicit description of W_N required (as it appears in the trace)

and (less trivial) : generalisation at finite 4-velocity u; fully relativistic… to warrant orthogonality of states

$$\mathrm{Tr}[W_u^{J/\psi} W_u^{\psi'}] = 0$$

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Extension of the Remler formalism

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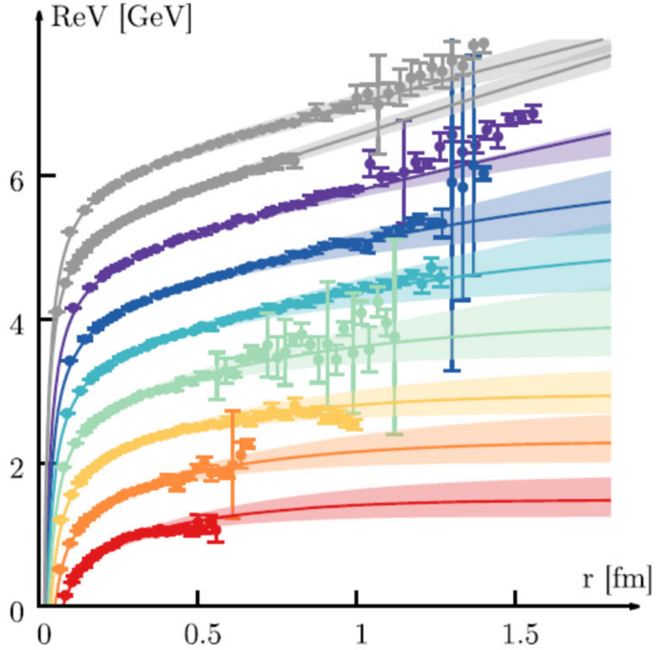
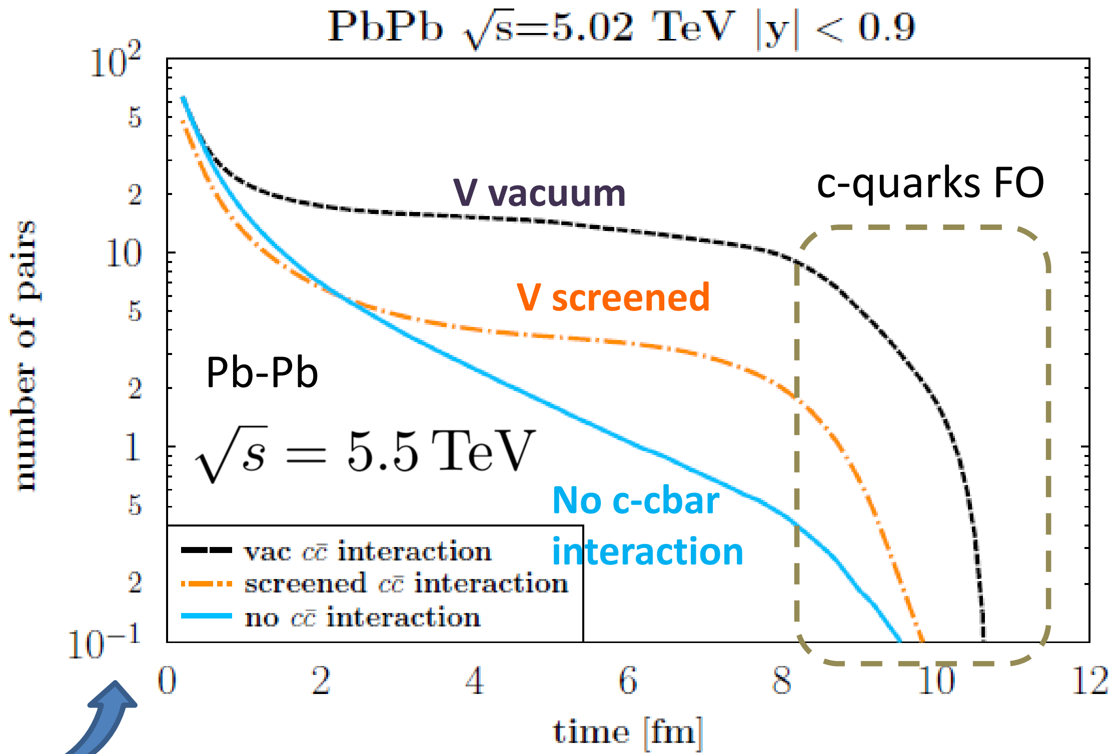


Instantaneous # of Q-Qbar at (invariant) distance < 1fm

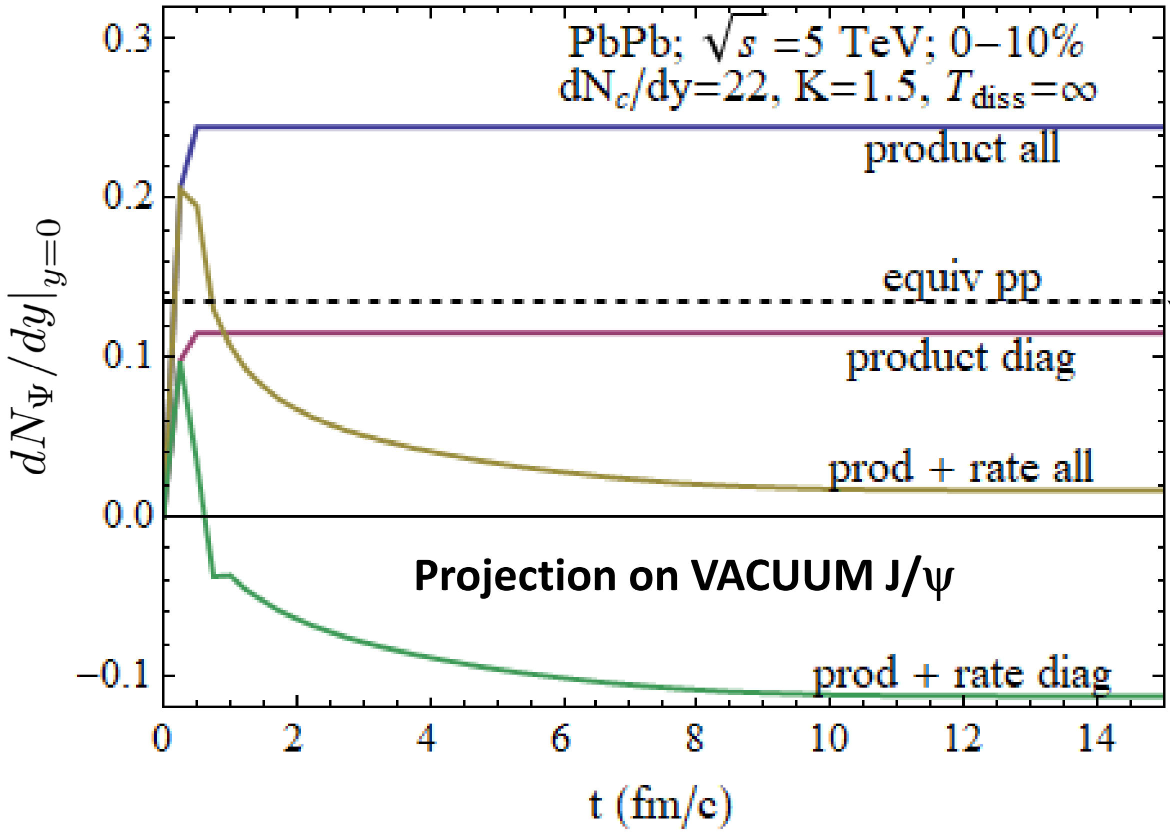


- Extra source of Γ due to "local-T" basis evolution with time : Γ^{loc}
- Generalization to relativistic Wigner density (boosted quarkonium states)

Preliminary results for J/ψ production in Pb-Pb

Word of caution: Exploratory phase => not meant to have an exact comparison with exp. data

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



Cumulated « production » (if no rate equation), indeed oveshoots pp due to off-diagonal contributions

The denominator in the R_{AA}

The full production (i.e. the numenator in the R_{AA})

First answer to puzzle found in Song et al: the primordial production is killed rather fast by the « loss » rate.

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Remler formalism for the QGP : last ingredient

Combining the rate definition + VN equation : $\Gamma^{\Psi}(t) = -iTr[\rho^{\Psi}[H_N, \rho_N(t)]]$

$$H_N = H_{1,2} + H_{N-2} + U_1 + U_2$$

$c\bar{c}$ Internal Hamiltonian ... ...

In QGP, 2 body T-dependent effective potential => ....

$$\Gamma^{\Psi}(t) = -iTr[\rho^{\Psi}[H_N, \rho_N(t)]] = -iTr[\rho_N(t)[\rho^{\Psi}, H_N]]$$

$$[\rho^{\Psi}, H_{1,2}(T)] = 0$$

$$= -iTr[\hat{\rho}^{\Psi}(T)[\hat{U}_1 + \hat{U}_2, \hat{\rho}_N(t)]]$$

One only preserves the structure of the Remler « collisional rate » if one works in the « local » basis ρ^{Ψ} (T) !!!

Accessible for T > T_{dissoc}^{Ψ} (=0.4 GeV for J/ψ)

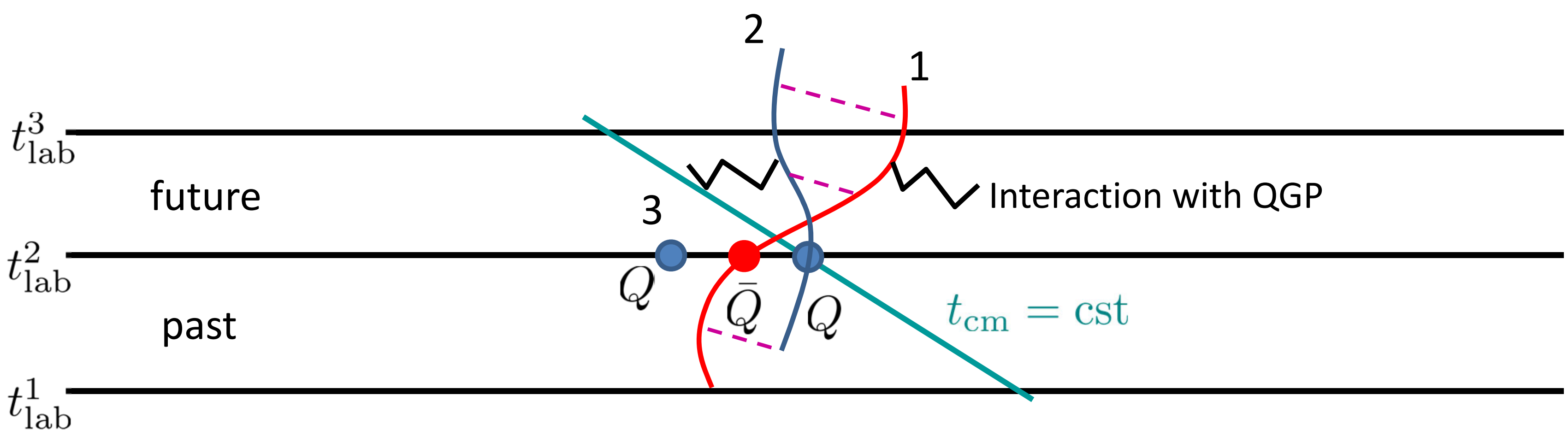
Back to the rate : $\Gamma^{\Psi}(t) = \frac{dP^{\Psi}(t)}{dt} = \mathrm{Tr}\left[\hat{\rho}^{\Psi}_{Q\bar{Q}} \frac{d\hat{\rho}_N(t)}{dt}\right]$

$$\Gamma^{\Psi}(t) = \mathrm{Tr}\left[\hat{\rho}^{\Psi}_{Q\bar{Q}}(T(t))\frac{d\hat{\rho}_N(t)}{dt}\right] + \frac{dT}{dt}\mathrm{Tr}\left[\frac{\partial\hat{\rho}^{\Psi}_{Q\bar{Q}}(T)}{\partial T}\hat{\rho}_N(t)\right]$$

New contribution to the rate (so-called « local rate »)

The Q-Qbar dynamics… the CM strategy

- Main objective : evaluate the propagation towards future of N Q-Qbar interacting pairs
- Strategy (adopted presently) : For each time step in the laboratory frame, pass to the cm frame and perform the evolution in the cm frame (where the potential is well defined)



- “Issue” : slicing the global time evolution (usual strategy in MC) is not 100% compatible with passing to c.m. frame as 2 particles are usually not at the same relative time in both frames (residual glitches ⇔ numerical noise)

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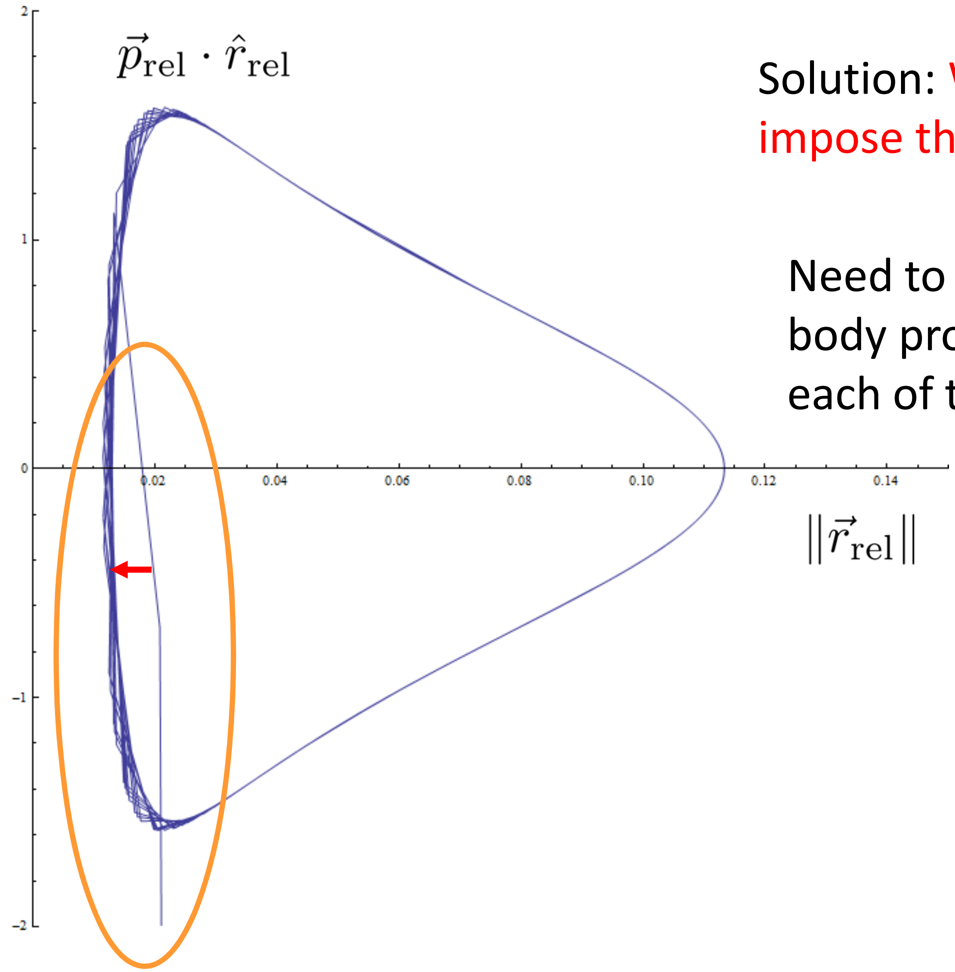
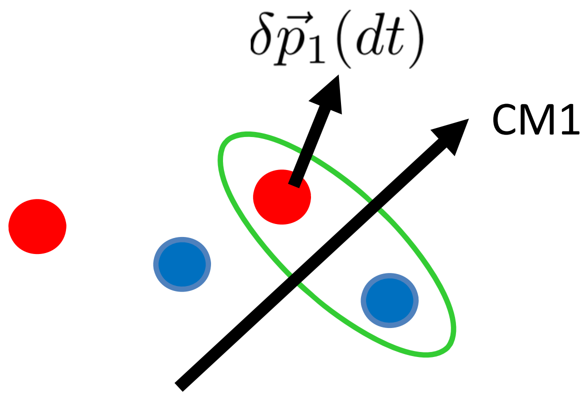
The Q-Qbar dynamics… the CM strategy

- "Minor problem" #1: Classical equations of motion are **unstable** (in the CM):



Solution: Work in Hamilton – Jacobi coordinates or impose the conserved quantities (L and Etot)

Need to factorize the N-body problem as an {} of 2-body problems for some evolution over time step dt, each of them to be solved in the CM



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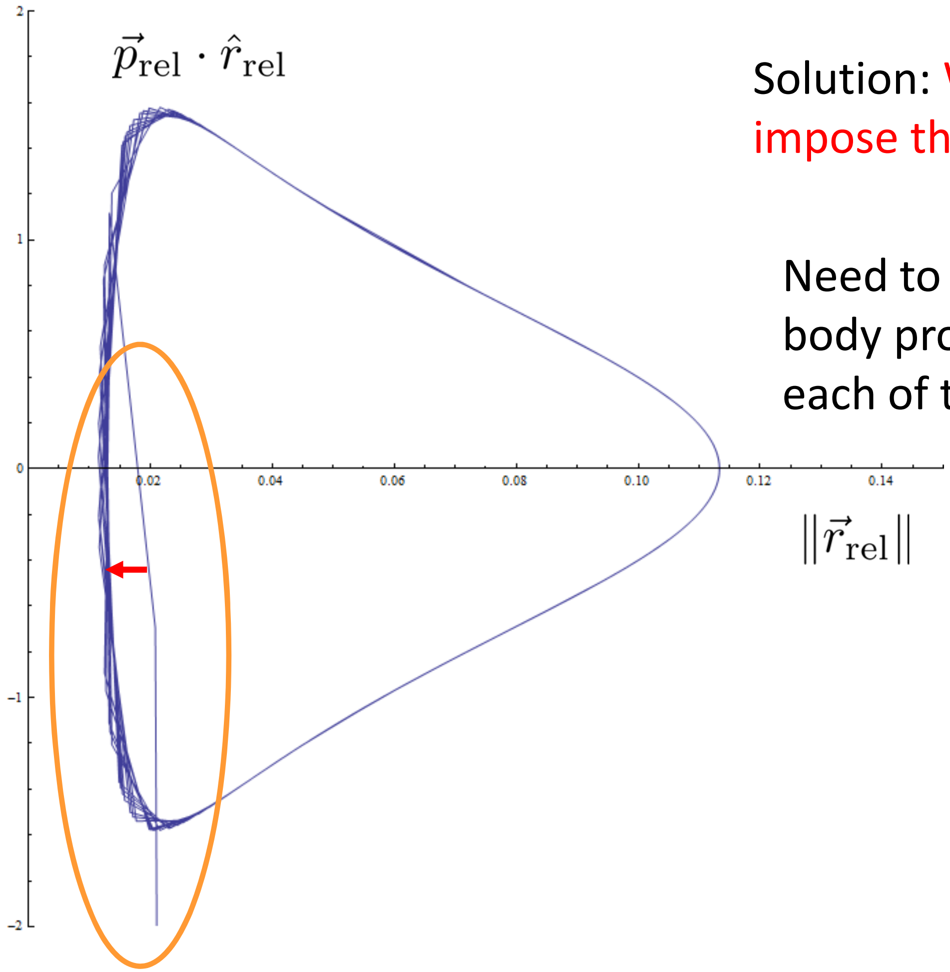

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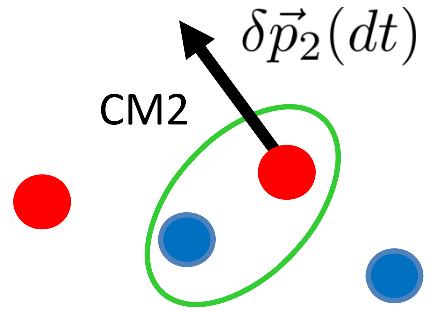

The Q-Qbar dynamics… the CM strategy

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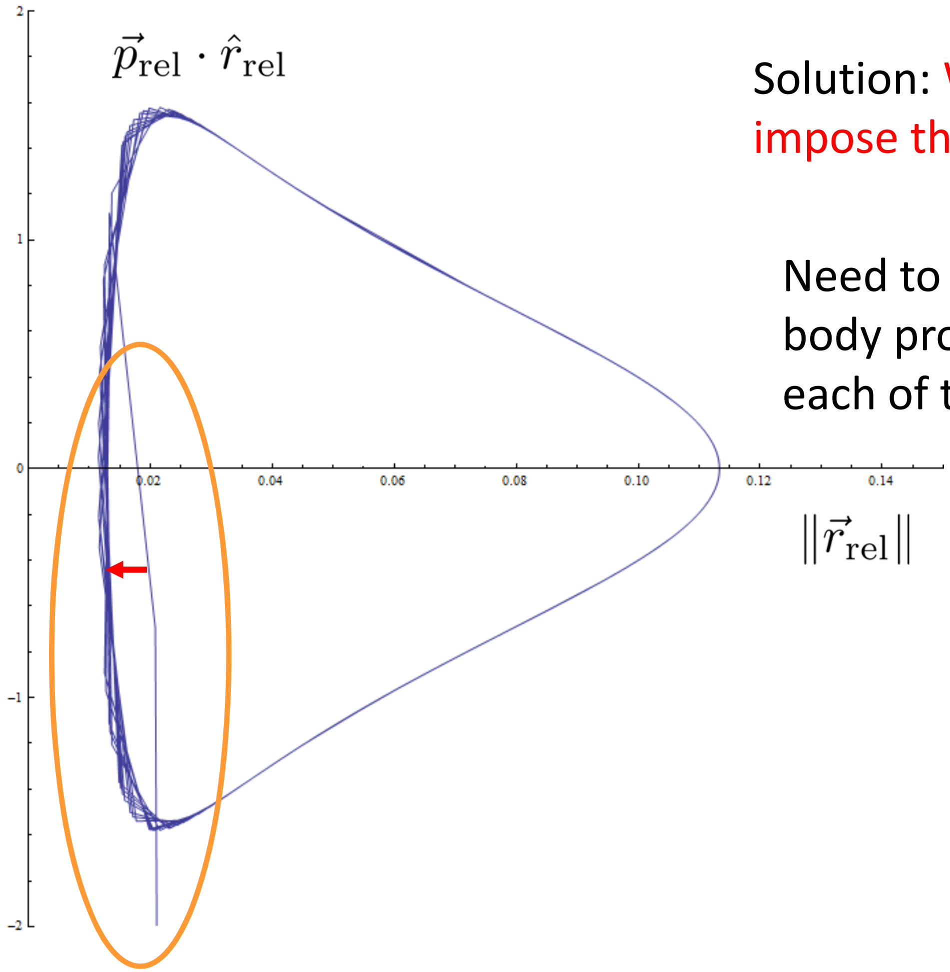

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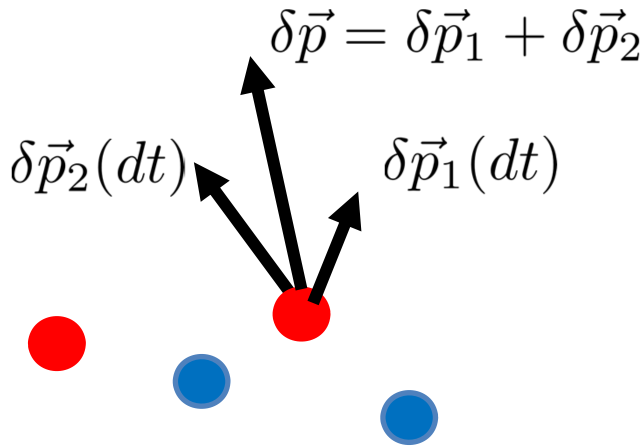

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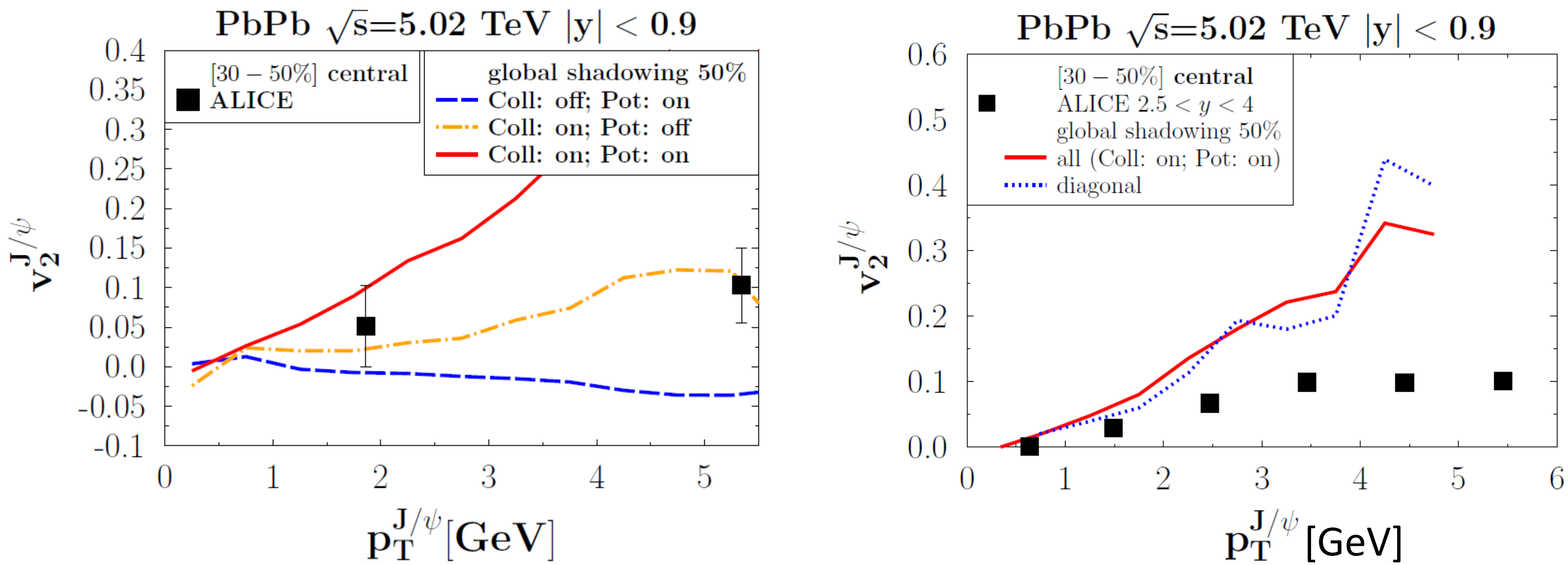
Results : J/ψ v_2

[30-50%] [30-50%]



- v_2 excess as compared to experimental data (**late formation** of the J/ψ due to binding potential under restoration)
- The « diagonal » contribution shows no difference wrt the full production, what is a bit conter-intuitive

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