Charmonia production with a density operator model

Hard Probes 2020

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with

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Motivation & Background

The two faces of quarkonia production

Sequential dissociation

Main goal: describe with good precision the dissociation / melting of some quarkonia wannabe QQbar pair : recent progresses due to Open Quantum System approach + improved knowledge of the dissociation rate

Q-Qbar recombination

How do we understand and describe the recombination of ≈ 100 c and 100 cbar all together at LHC ?

Usual approaches:

- Detailed balance (chemistry)
- Statistical hadronization

More recently: J.P. Blaizot & M. A. Escobedo JHEP06 (2018) 034

<u>Keywords:</u>

- Interaction of heavy quarks with the bulk particles
- Expansion of the medium
- Off-diagonal contributions

Motivation & Background

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

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

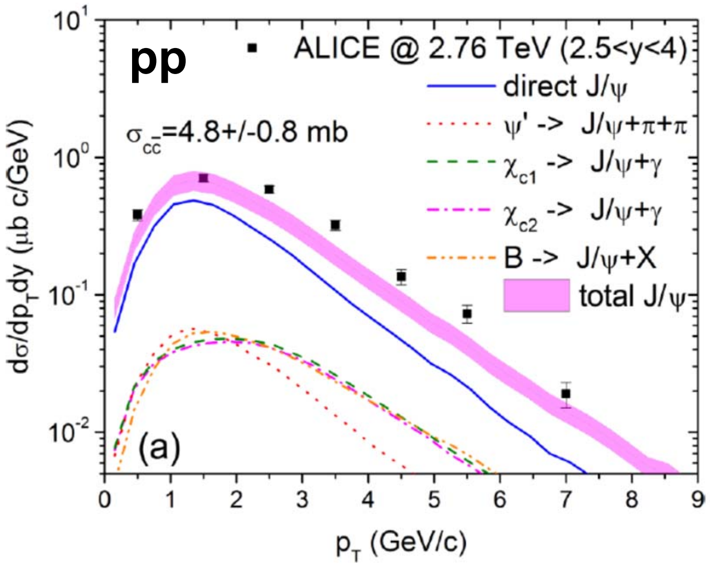
$$\rho^{\Psi}_{Q\bar{Q}} = \sum_{i} |\Psi^{i}_{Q\bar{Q}}\rangle\langle\Psi^{i}_{Q\bar{Q}}|$$

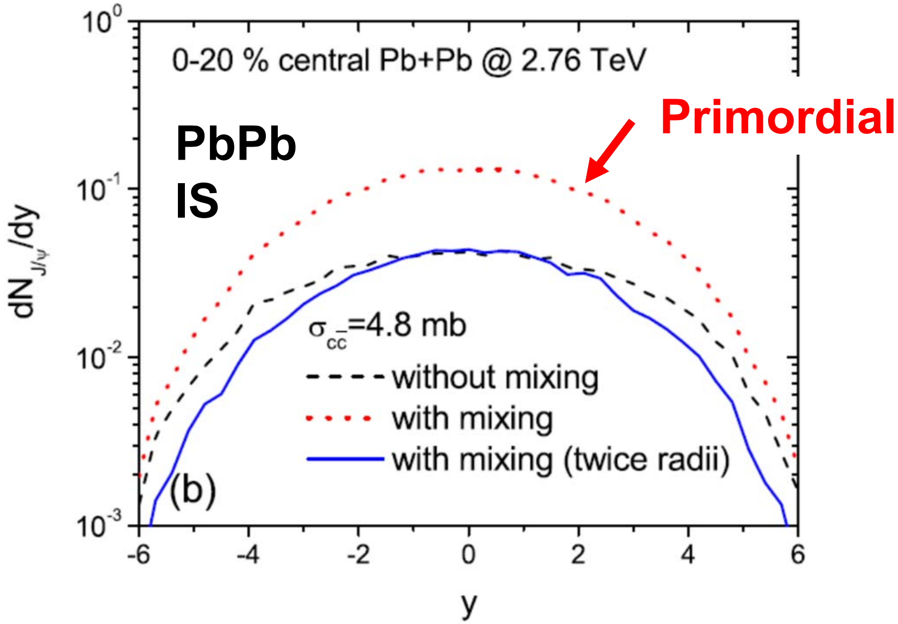
Single quarkonia density operator

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

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

Taesoo .S, 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**

Motivation & Background

$$P^{\Psi}(t)=Tr[\rho^{\Psi}_{QQ}\rho_N(t)]$$

$$\rho^{\Psi}_{QQ}=\sum_i |\Psi^i_{QQ}\rangle\langle\Psi^i_{QQ}|$$

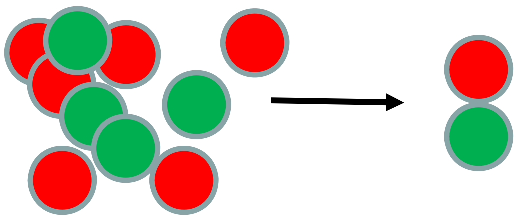
$$\frac{\partial\rho_N(t)}{\partial t}=-i[H_N,\rho_N(t)]$$

Dealing with the dynamics ?

- The idea of the formalism goes back to Remler's work
- General scheme connecting composite-particle cross section and rates with time-dependent density operators
- Applied by Remler et al to the deuteron production in (low energy) AA collisionsThe formalism is able to deal with many particles (nucleons -> deuterium)

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

1980



2020

Apply Remler formalism to quarkonia production in heavy ion collisions

Remler formalism at work

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

$$\Gamma^{\Psi}(t)=\frac{\partial P^{\Psi}(t)}{\partial t}=Tr[\rho^{\Psi}_{Q\bar{Q}}\frac{\partial \rho_N(t)}{\partial t}]$$

Working in the phase space through Wigner distribution

$$W^{\Psi^i}=\int d^3y\, e^{ipy}\left\langle r-\frac{y}{2}\middle|\Psi^i\right\rangle\left\langle\Psi^i\middle|r+\frac{y}{2}\right\rangle$$

Quarkonia: Double Gaussian approximation

$$W^{\Psi}_{QQ}(r_{rel},p_{rel})=C\,e^{r^2_{rel}\sigma^2}\,e^{\frac{p^2_{rel}}{\sigma^2}}$$

Parameter: The Gaussian width σ

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

W_N : Semi-classical approach

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

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

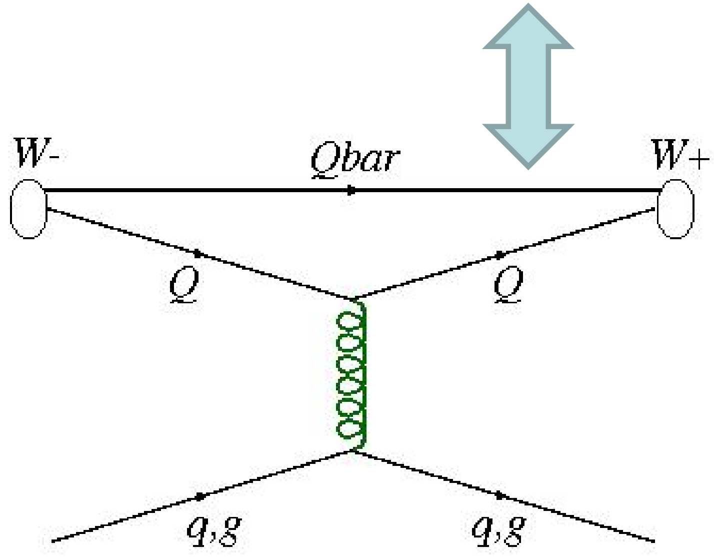
and (less trivial) : generalisation at finite velocity; fully relativistic

Remler formalism at work

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

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

- The quarkonia production in our model is a three body process, the HQ (anti-quark) interact only by collision !!!
- 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 simulation)
- $W_N(t+\varepsilon)$ and $W_N(t-\varepsilon)$ 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)

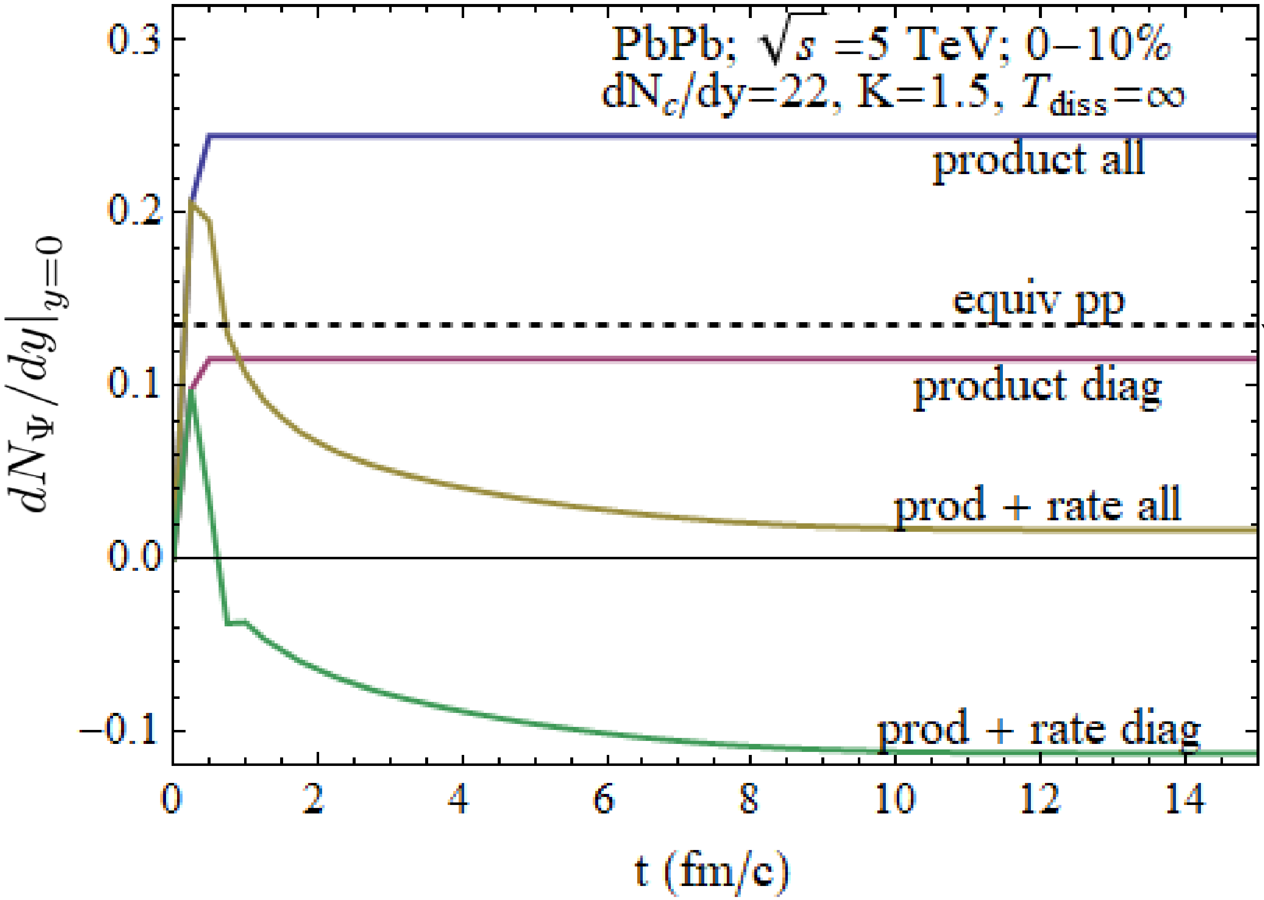
Then: $$P^{\Psi}(t)=P^{\Psi}(t^{\Psi}_{init})+\int_{t^{\Psi}_{init}}^{t}\Gamma(t)\,dt$$

NB: Also possible to generate similar relations for differential rates

Preliminary results for J/ψ

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

$$P^{\Psi}(t)=\boxed{\boxed{P^{\Psi}(t^{\Psi}_{init})}+\int_{t^{\Psi}_{init}}^{t}\Gamma(t)\,dt}$$



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.

Preliminary results for J/ψ

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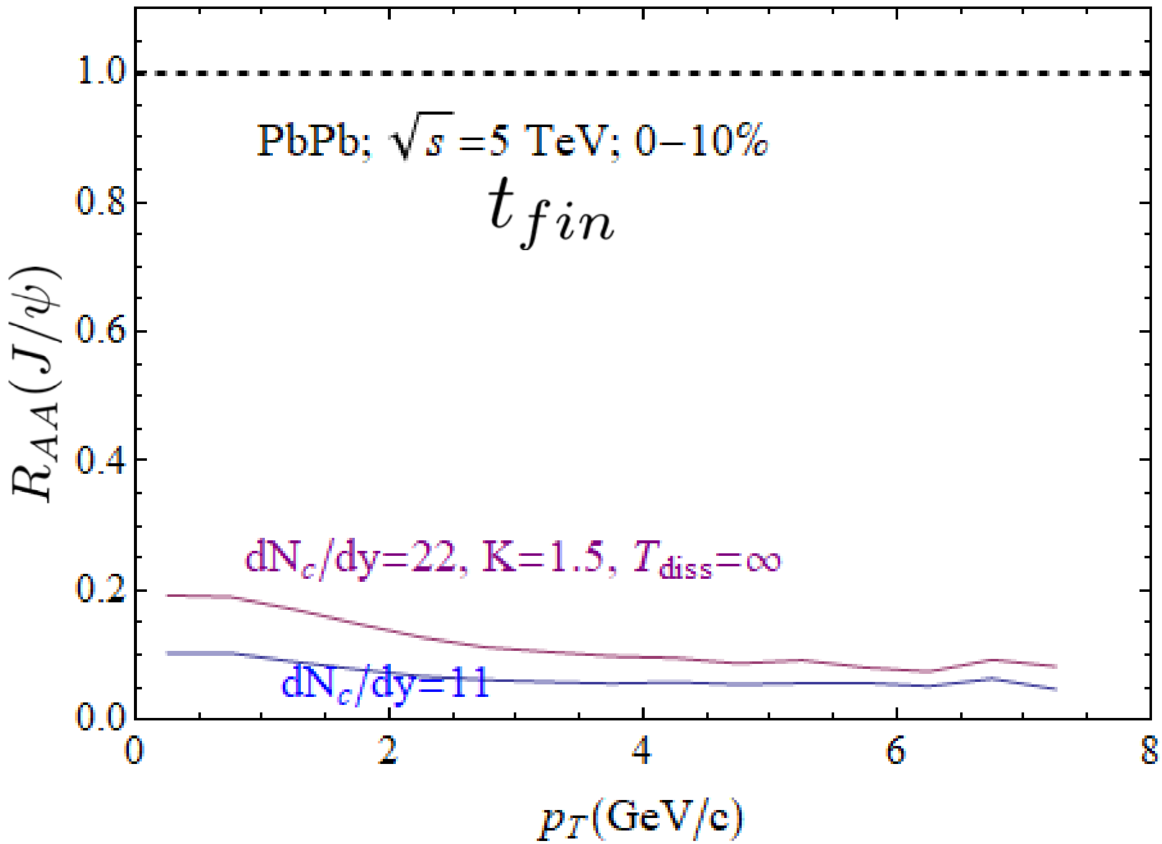
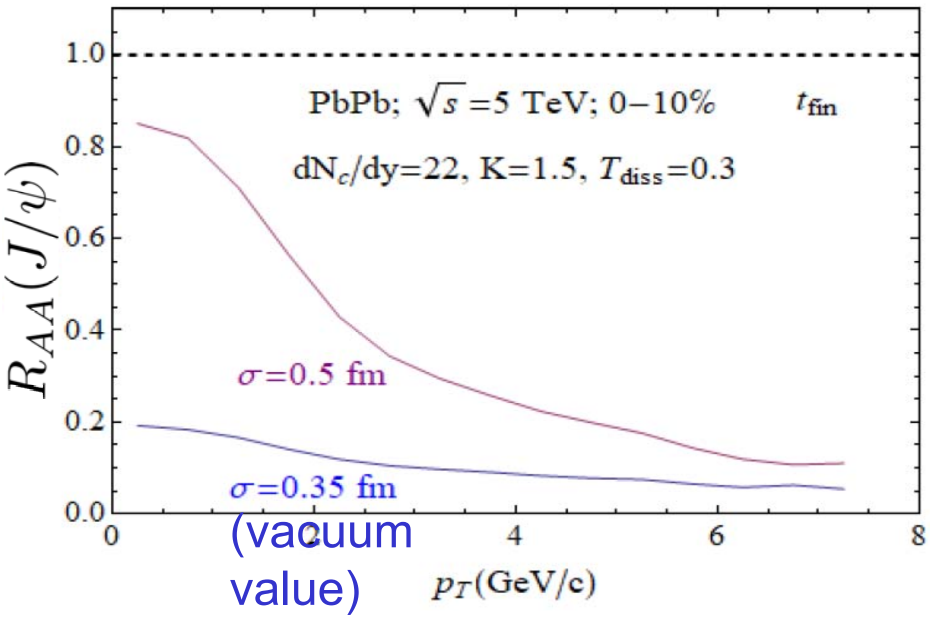


Effect of cham abundance in phase space (x2):

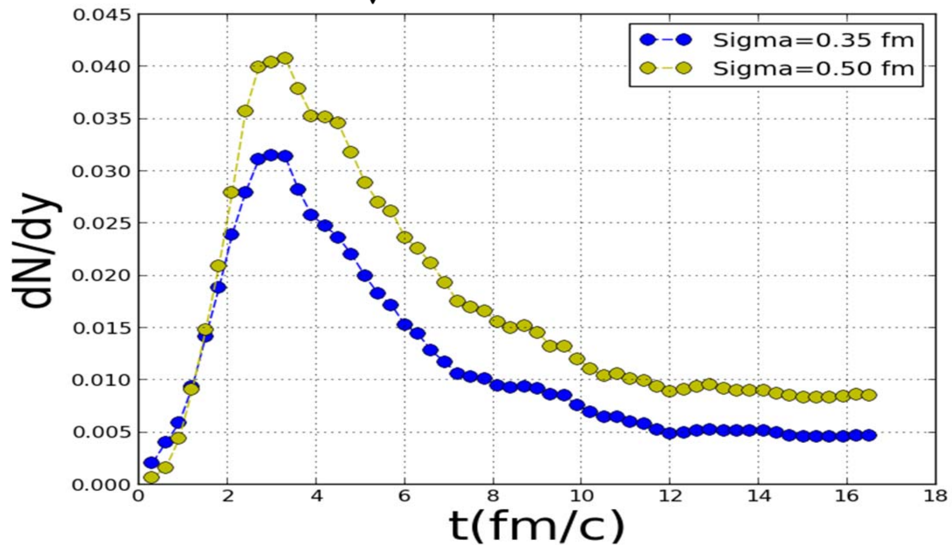
- Correct trends for charm recombination
- Absolute value too small

Preliminary results for J/ψ

Exploring the effect of « in medium » Wigner distribution through the variation of the σ parameter (spatial width):



Pb-Pb @ $\sqrt{s} = 2.76\,\mathrm{TeV}$ Mid-rapidity

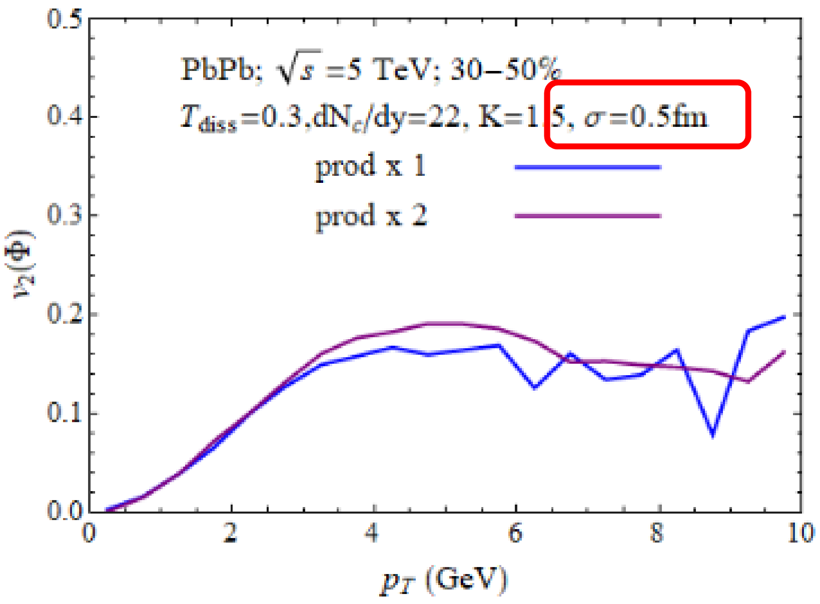


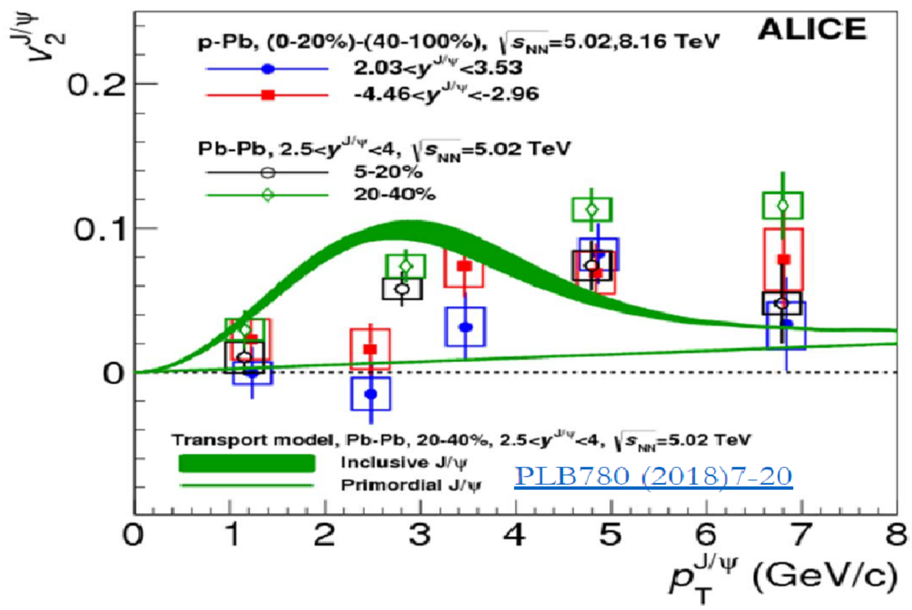
Missing ingredient for quantitative agreement:

- temperature dependent σ(T) in the Wigner function ?
- Interactions between Q & Qbar (real part of the potential, not implemented in EPOSHQ)
- … ?

Preliminary results for J/ψ

Despite quantitative undeprediction in the R_{AA}… taking the most appropriate parameter:

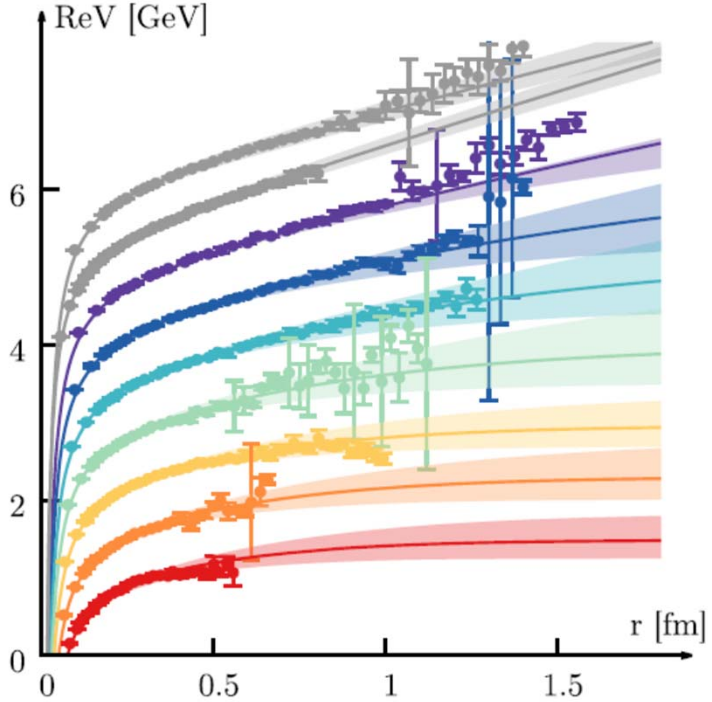




Interesting feature: Within our approach, v_2 extends at rather large p_T

The Q-Qbar interaction

- Not implemented up to now in EPOSHQ
- More and more reliable calculations are becoming available for the real part of the potential, thanks to lattice calculations:

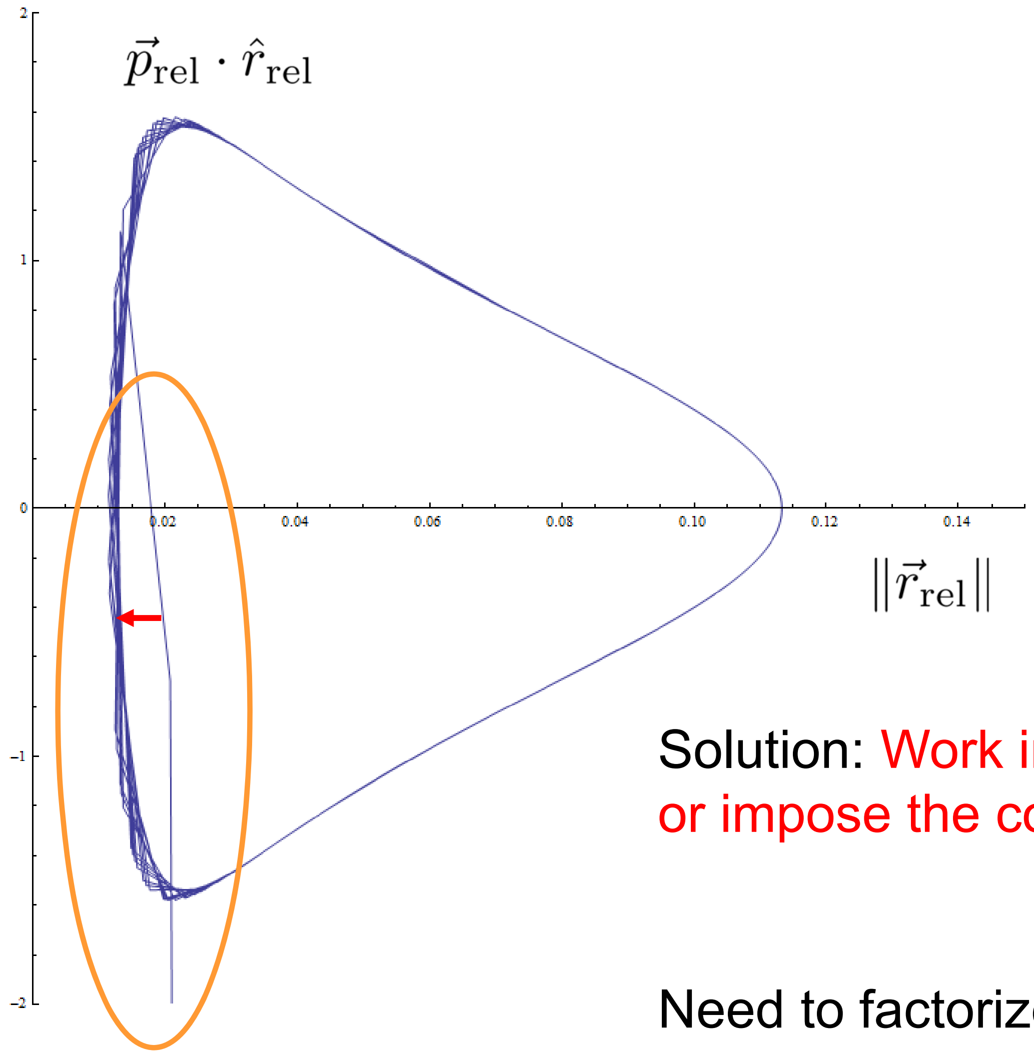


D. Lafferty and A. Rothkopf, PHYS. REV. D 101, 056010 (2020)

- Go for it !

The Q-Qbar interaction: strategy 1

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

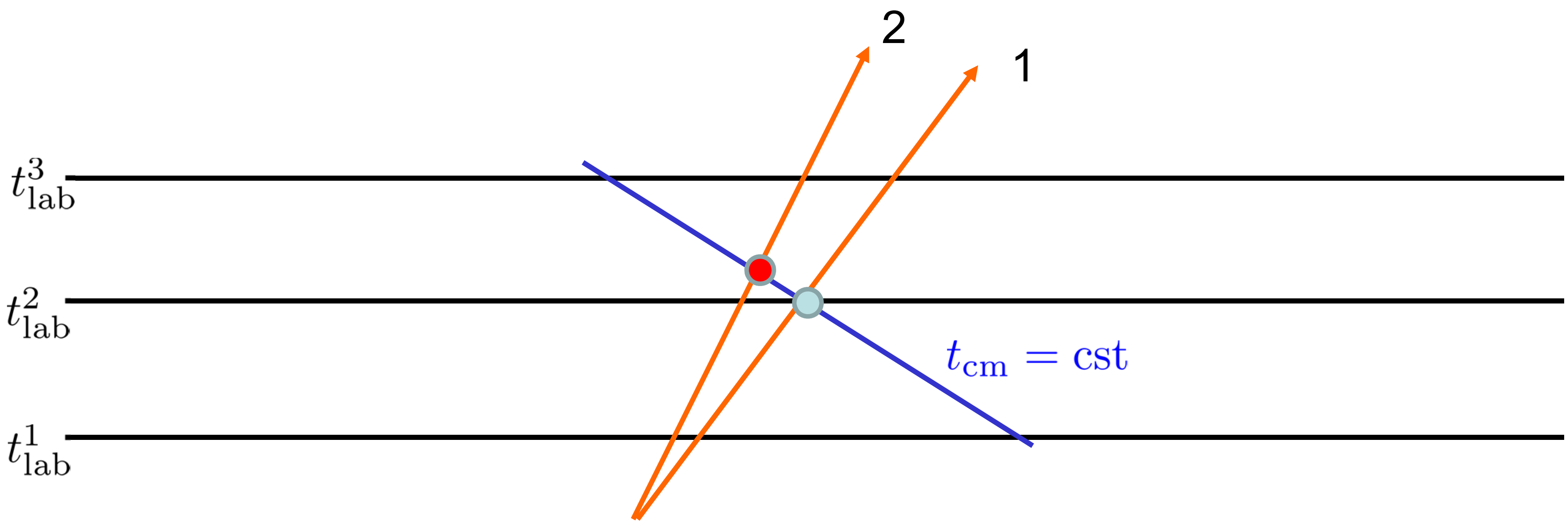


Solution: Work in Hamilton – Jacobi coordinates or impose the conserved quantities (L and Etot)

Need to factorize the N-body problem as an {} of 2-body problems

The Q-Qbar interaction: strategy 1

- “Major problem” : slicing the global time evolution (usual strategy in MC) is not compatible with passing to c.m. frame for each individual pair…

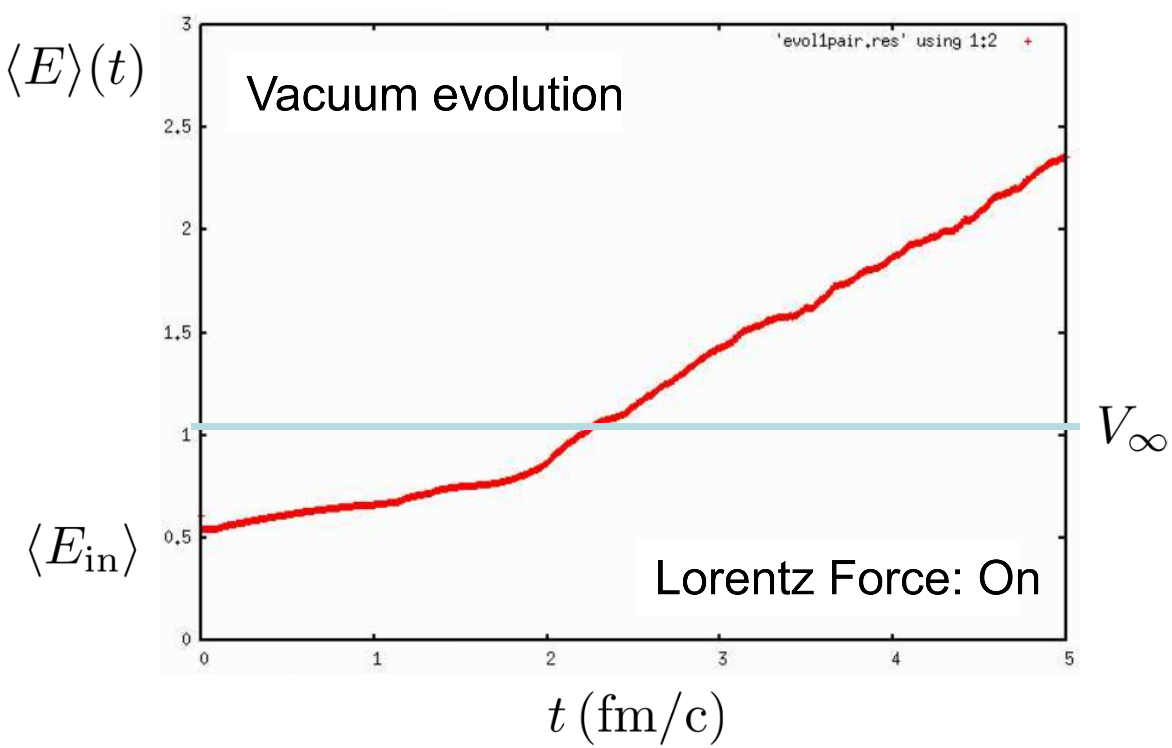


Generic need to store / describe the trajectory of particle 2 at a time $t_{lab} > t_{lab}^2$ if ones propagates particle 1 up to t_{lab}^2 by resorting to evolution in the c.m.

The Q-Qbar interaction: strategy 2

- Describe dynamics through retarded interactions… calibrated to map to the static potential in the infinite mass static case… obviously several prescriptions available, need discussion with lQCD experts !

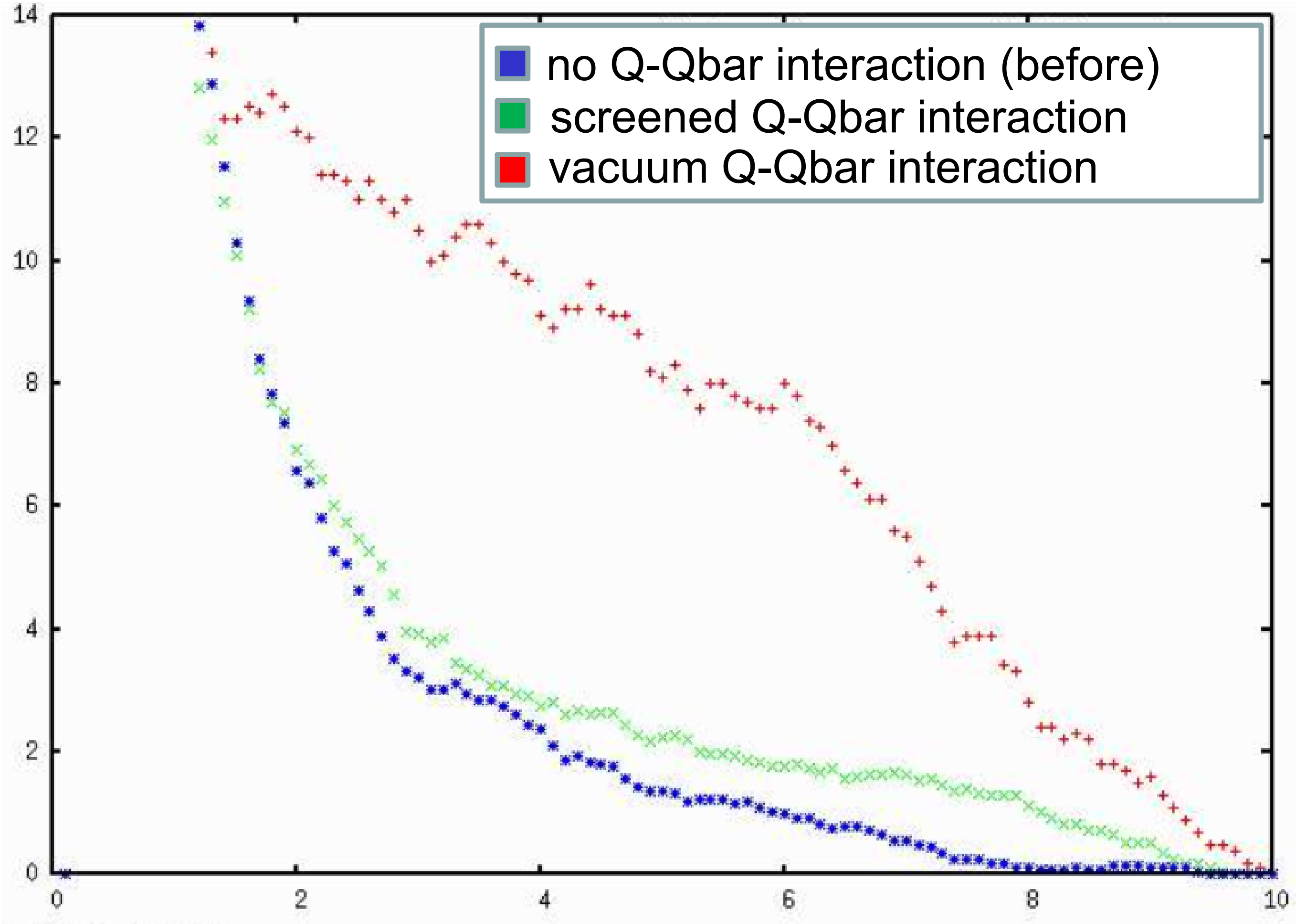
- Cures all problems encountered with strategy 1 ☺ … but (to my knowledge): No invariant associated with the retarded force (even without considering Abraham Lorentz force) => need specific methods to tame the instabilities



Stability achieved for a couple of cycles

Consequences on the charmonia in AA collisions

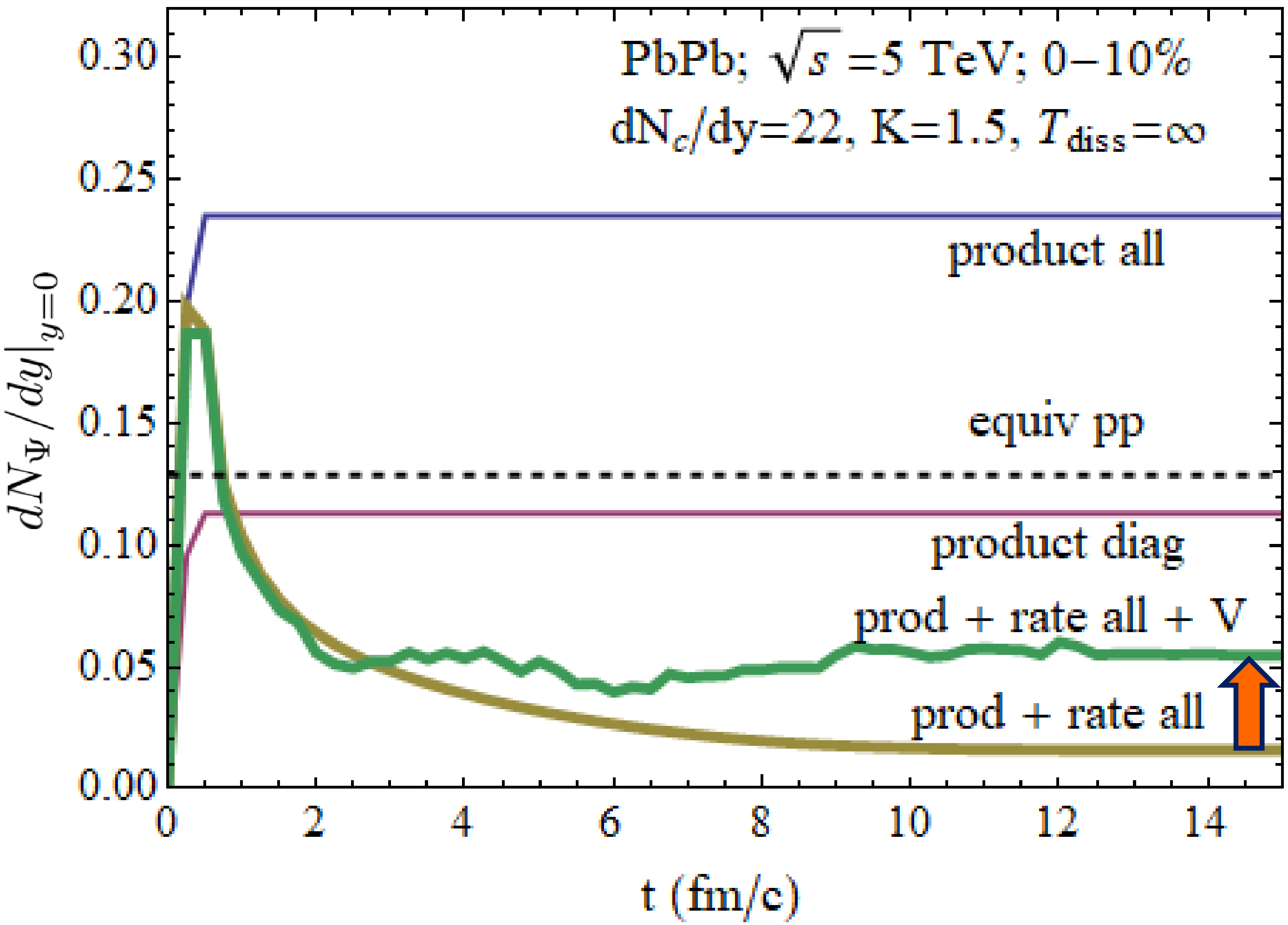
Instantaneous # of Q-Qbar at (invariant) distance < 1fm



t (fm/c)

Although screened, the Q-Qbar interaction has important consequences on the probability to find a Q-Qbar at close distance in the final stage of the evolution

Consequences on the charmonia in AA collisions



Although screened, the **Q-Qbar interaction has important consequences on the probability to find a J/ψ in the final stage of the evolution**

Conclusions

- We have presented a model based on the probability density operator that allows to obtain the evolution of the effective rate of Quarkonia production in QGP.
- This scheme treats both the dissociation and the recombination consistently
- We have implemented a first version of the Q-Qbar interaction in the EPOSHQ scheme; effect on charmonia production seems to be large, even with a screened potential
- Some further developments are still nevertheless mandatory.

Further remark : first Semi-Classical simulation of multiple c-cbar pairs in QGP: C Young et E Shuryak Phys.Rev.C81:034905 (2010)

Back up

The usual detailed balance relation

$$J/\Psi + g \Leftrightarrow c + \bar{c} + X$$

Rates Equation

$$\frac{dN_\Psi}{d\tau} = \Gamma_{recomb} N_c N_{\bar{c}} [V_{FB}(\tau)]^{-1} - \Gamma_{diss} N_\Psi$$

$$\frac{dN_\Psi}{d\tau} = -N_\Psi L\,\tau + G(\Psi) = \frac{-1}{\tau_\Psi}[N_\Psi(\tau) - N_\Psi^{eq}(\tau)]$$

Remler

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

No one to one correspondance of the gain & loss term !