J/y production in a dynamical coalescence approach

Pol B Gossiaux, SUBATECH (NANTES)

ECT* November 2021

1. **Motivation**
2. **Our approach**
3. **Results**
4. **Conclusion and perspectives**

With Joerg Aichelin and Denys Yen Arrebato Villar… Thanking Taesoo Song and Elena Bratkovskaya for fruitful discussions

and Pays de la Loire

Motivation

A simple and single question :

At what stage of the AA collision are the J/ψ created ?

(here, mainly thinking of LHC)

Motivation

2 competing approaches in the place :

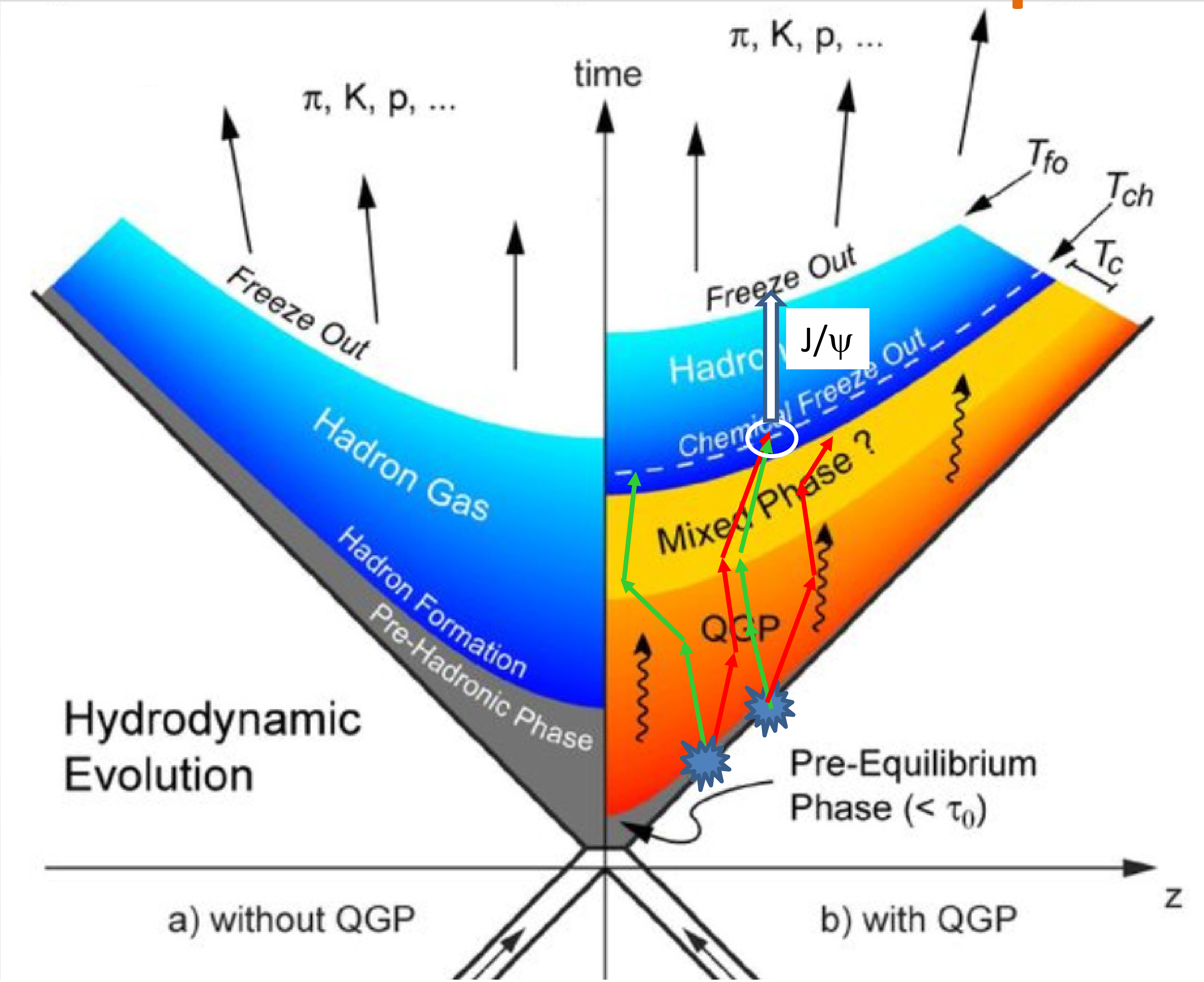
Transport theories

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

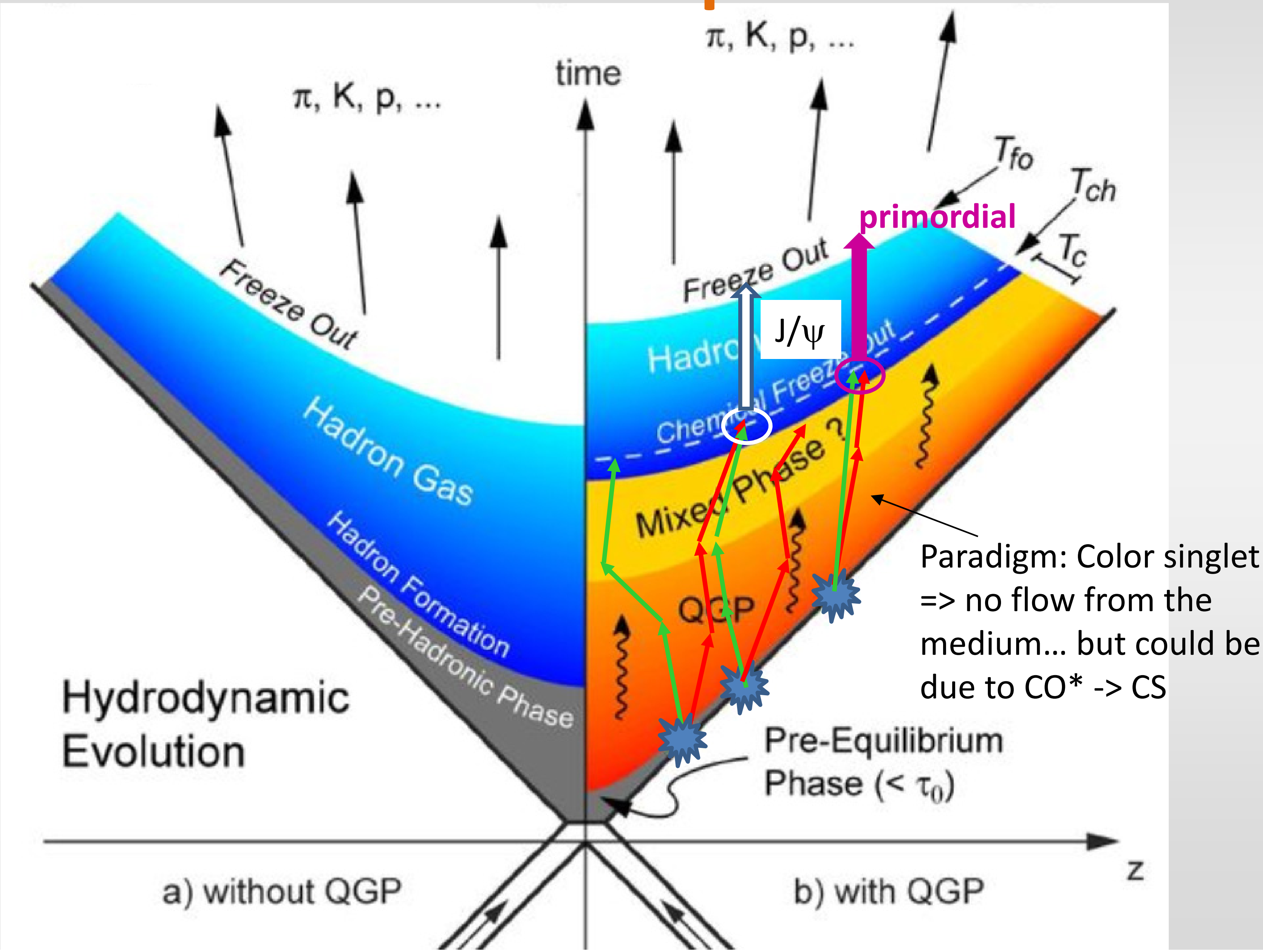
SHM and coalescence at FO

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

Charmonia in the coalescence picture

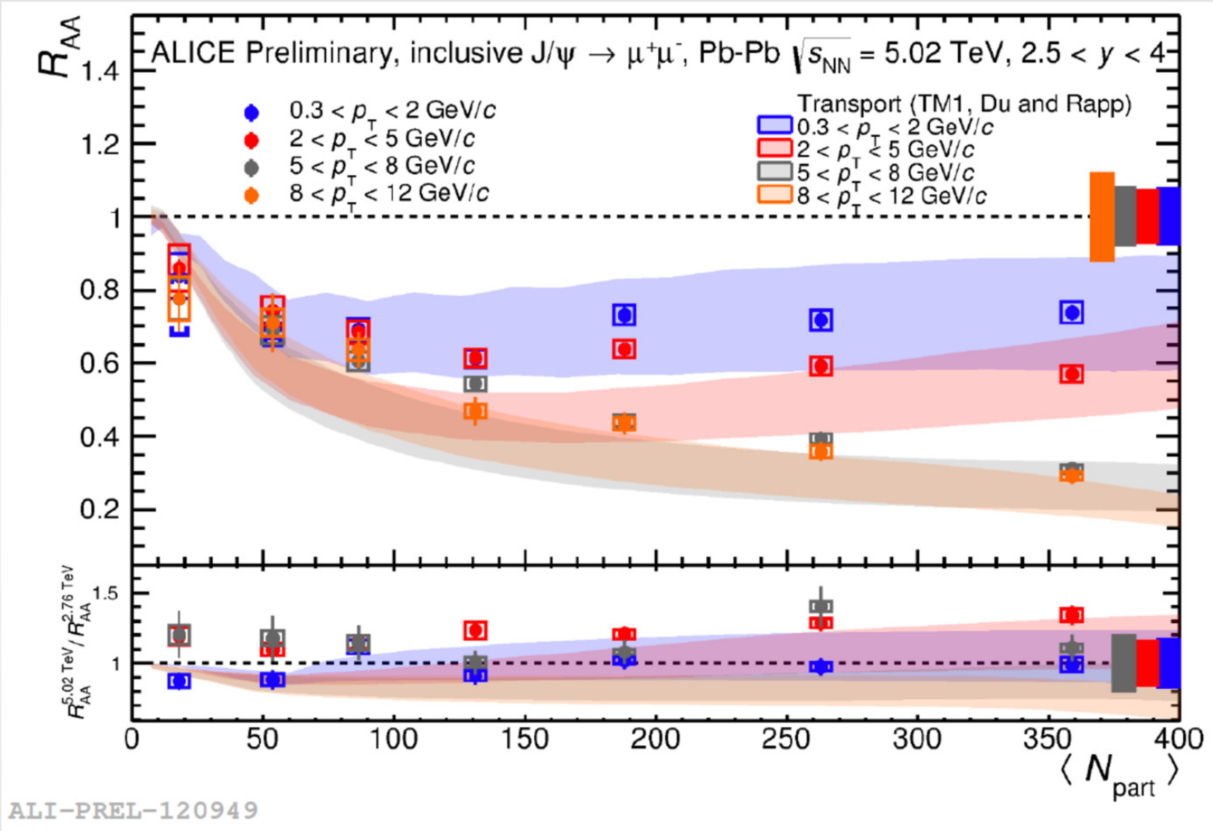


Charmonia in transport models



Looking at recent data

Transport theories



- 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 :

Transport theories

SHM and coalescence at FO

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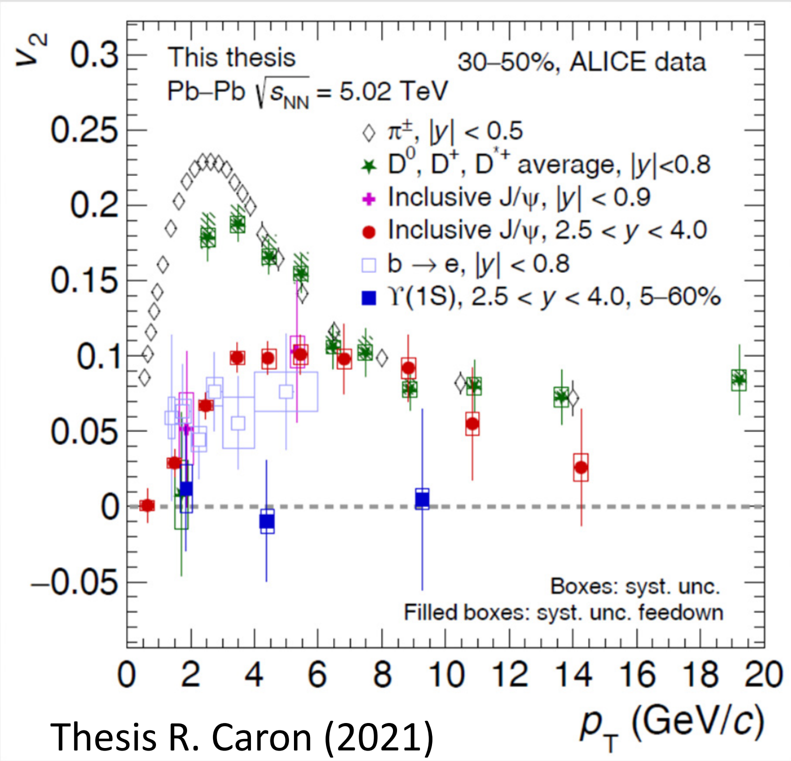
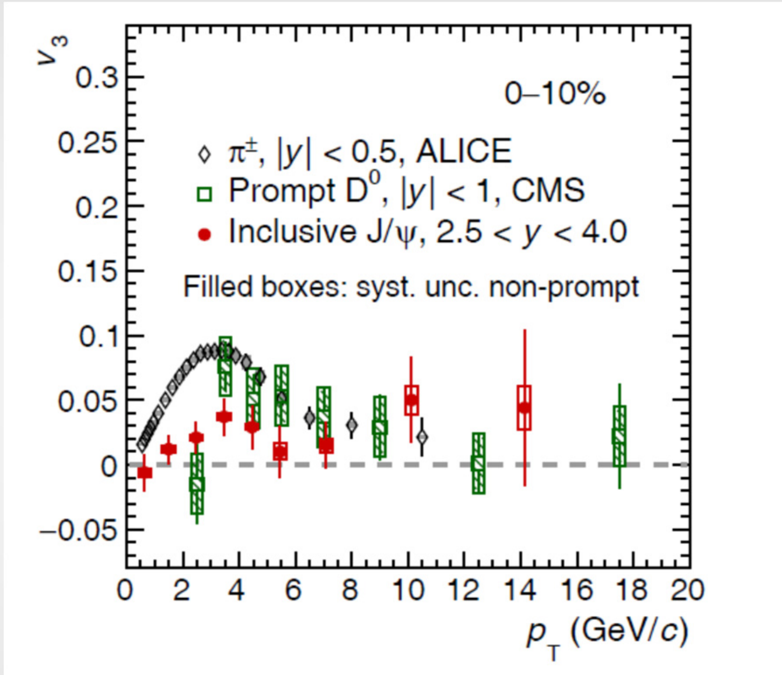
Looking at recent data

Recently : More global view



Thesis R. Caron (2021)

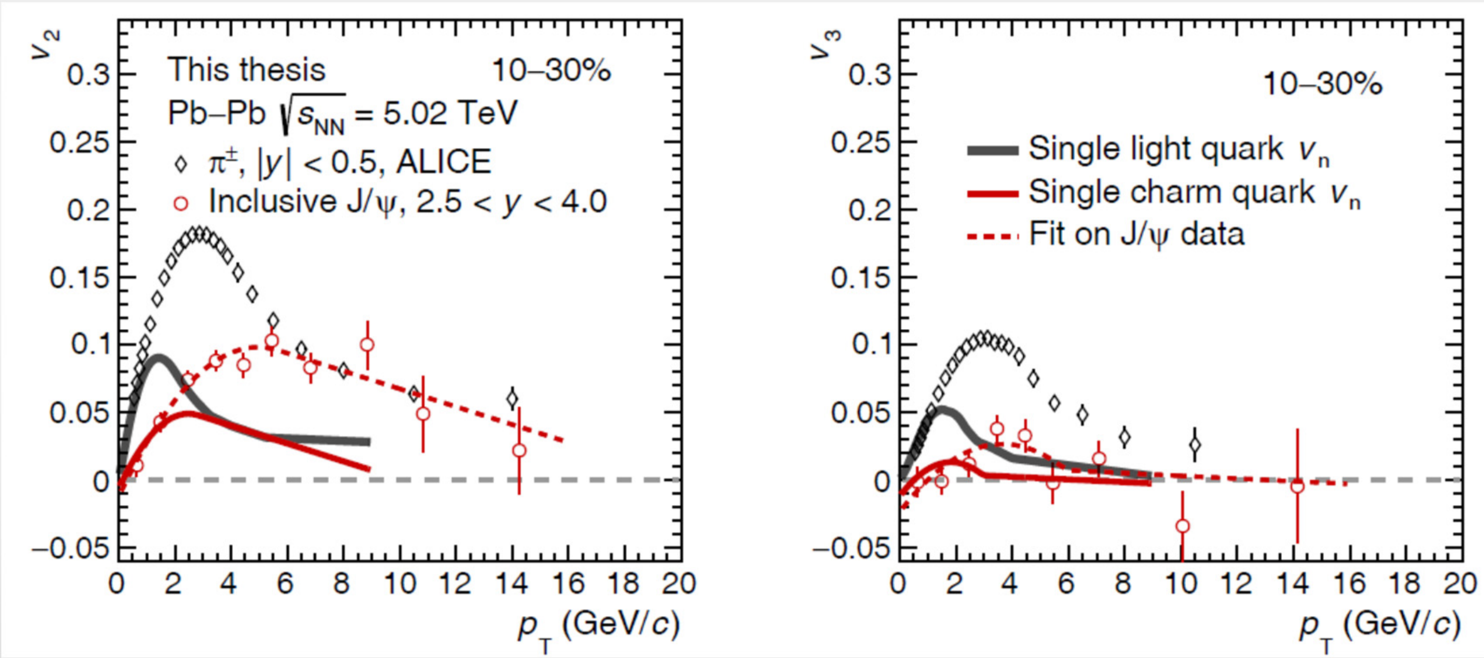


- v2 **and v3** analysis confirm that J/ψ flows
- Flow compatible with 0 for the upsilon 1S

Looking at recent data

Coalescence explains it all ?

- v_2 & $v_3(\pi)$ => v_2 & $v_3(q)$ (reverse engineering)
- v_2 & $v_3(J/\psi$ fit) => v_2 & $v_3(c)$ (reverse engineering)

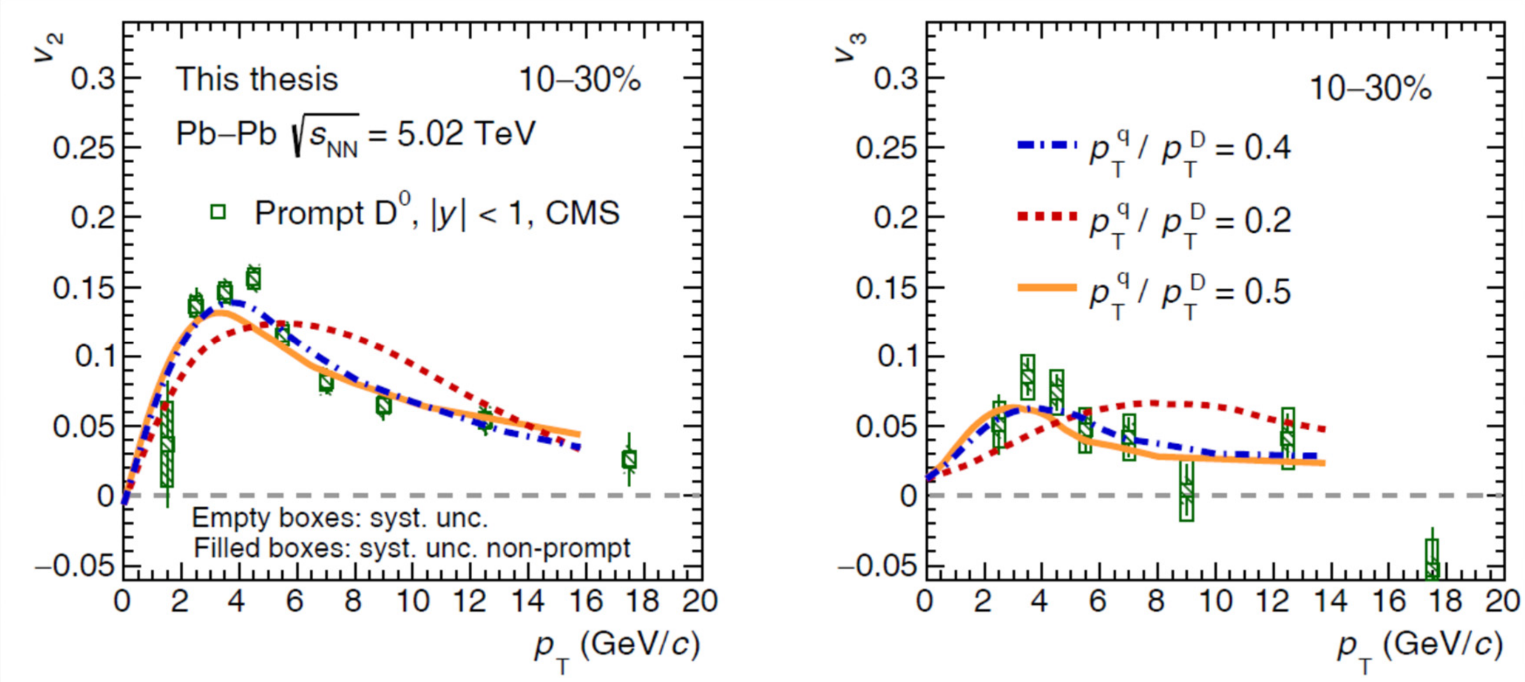


Shreyasi Acharya et al. (ALICE) JHEP, 10:141, 2020.

Looking at recent data

Coalescence explains it all ?

- $v_n(q)$ & $v_n(c)$ + relative weights of masses (momenta) => $v_n(D)$



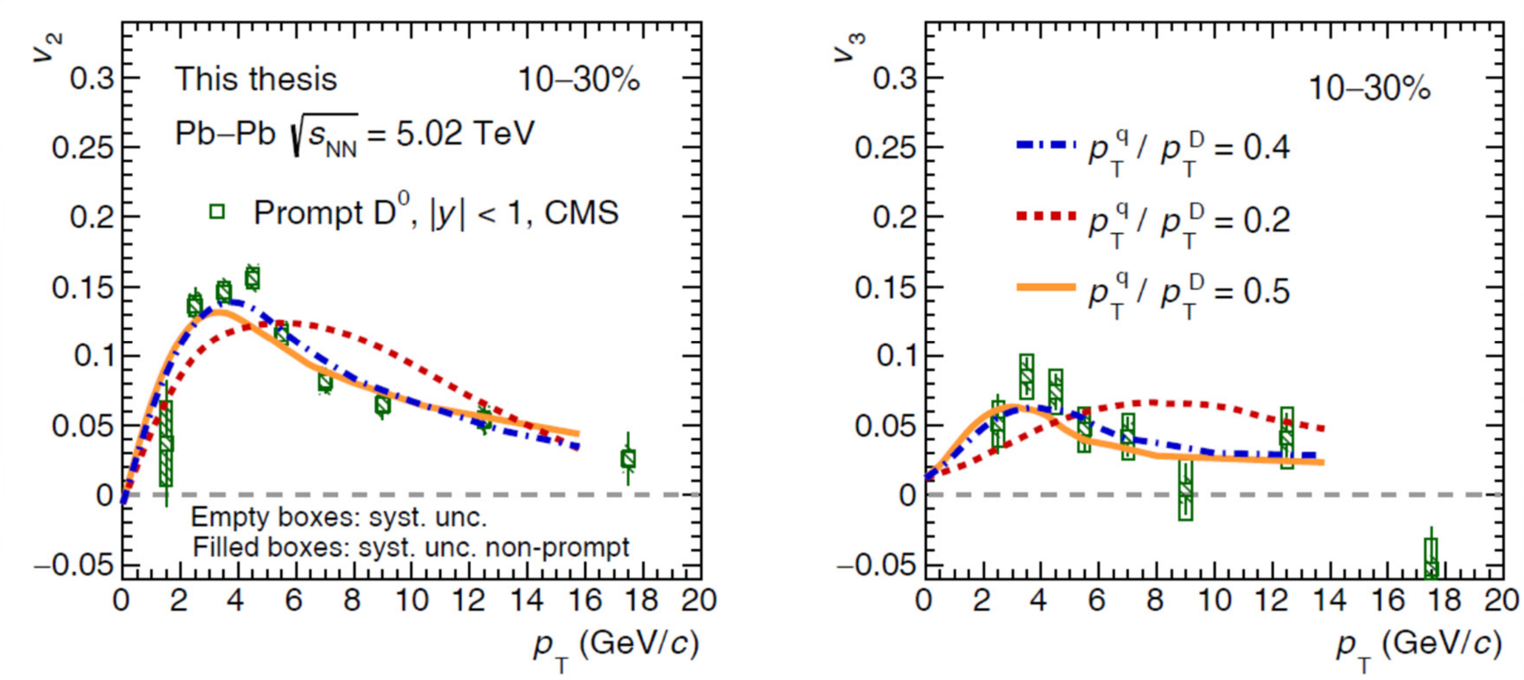
Shreyasi Acharya et al. (ALICE) JHEP, 10:141, 2020.

- 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 => 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) => $v_n(D)$



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

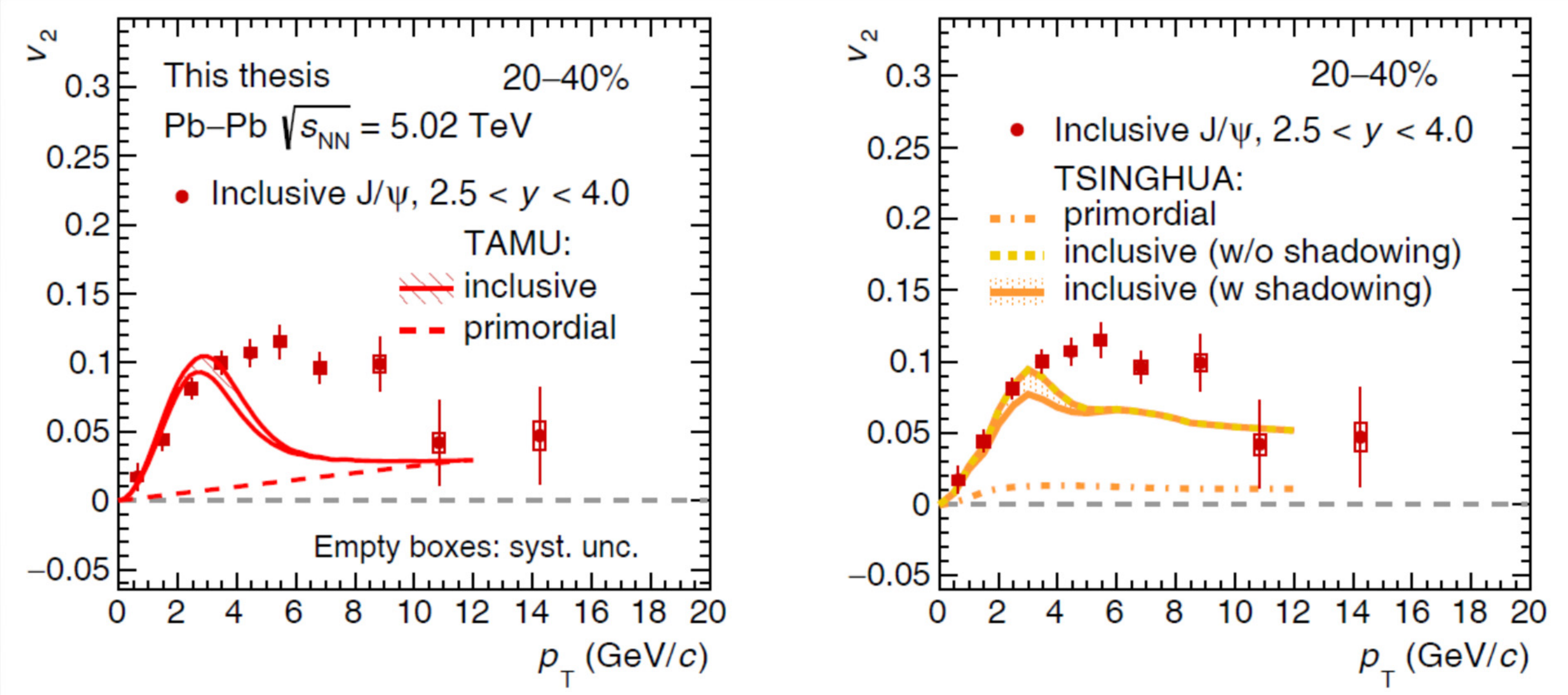
- Good global agreement for $p_T^q/p_T^D = 0.4 \Leftrightarrow m_q \approx 0.7 - 0.8$ GeV
- Or you consider such light-quark masses are achievable close to T_c => coalescence is indeed a good scheme to understand both charmonia and D mesons flows…

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/ψ 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 :

Transport theories

SHM and coalescence at FO

1

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Other possible contender :

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

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

Motivation

- Need to revisit how robustly we understand the survival of primordial component
- J/ψ are *quantum* bound states => need for a formalism that preserves *quantum* properties… and continuous transitions between bound and unbound states
- Quarkonia production should rely on a good understanding of the single HQ dynamics (as equilibration of those HQ have a significant influence on the rates)

Good in EPOS-HQ

Build a quarkonia « overlayer » to EPOS-HQ, with minimalistic modifications

Remler's formalism

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

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

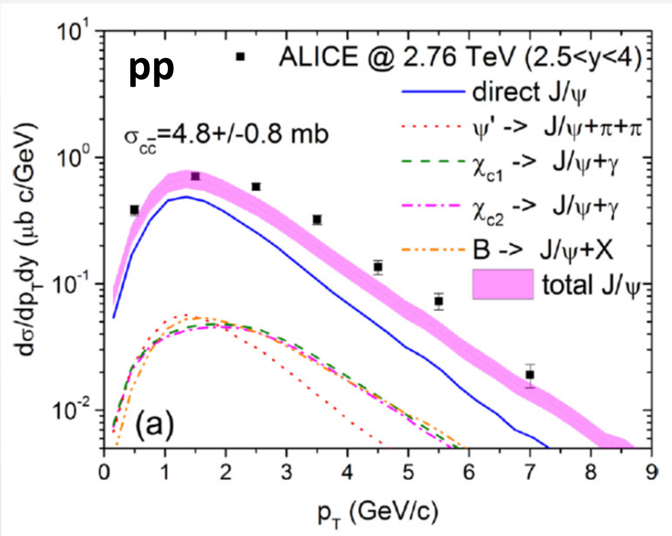
$$\hat{\rho}^{\Psi_i}_{Q\bar{Q}} = \sum_i |\Psi^i_{Q\bar{Q}}\rangle\langle\Psi^i_{Q\bar{Q}}|$$

Single quarkonia density operator

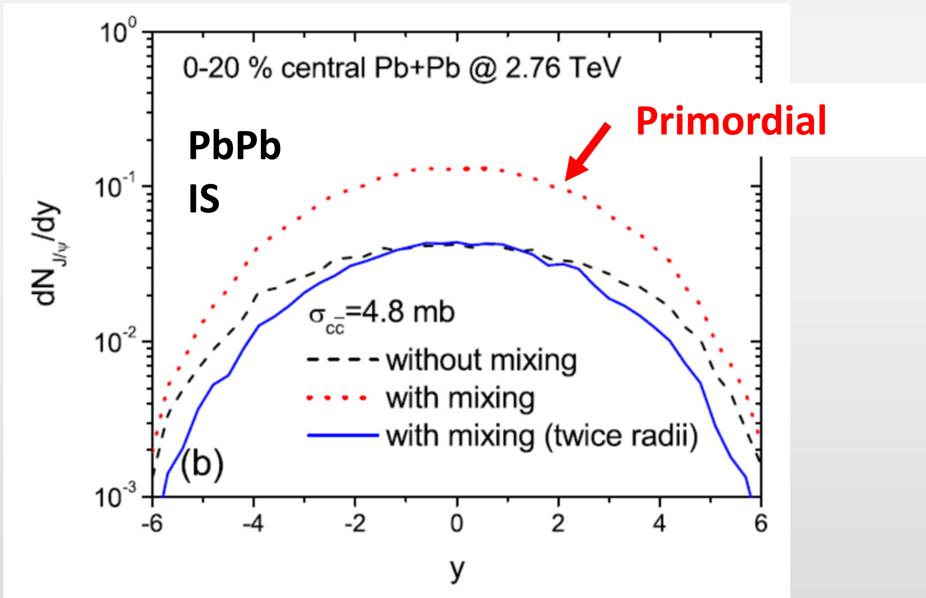
N-body density matrix (bulk partons + many c and many cbar)

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

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**

A bit of background

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

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

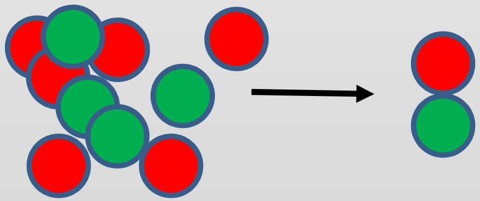
$$\frac{\partial \rho_N(t)}{\partial t} = -i[H_N, \rho_N(t)]$$

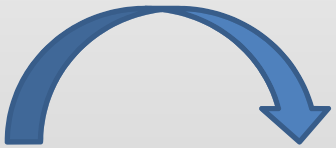
Dealing with the dynamics ?

- 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 collisions. The 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

Lessons from the past : the direct calculation is not effective for codes based on "cascade approach" (for which members of a genuine fragment are found far apart in the final stage)

⇩

Use the identity $$P^{\Psi}(t) = P^{\text{prim}}(t_{\text{init}}) + \int_{t_{\text{init}}}^{t} \Gamma^{\Psi}(t^{'})dt^{'}$$

Where :

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

$$\Gamma^{\psi}(t) = \frac{dP^{\Psi}(t)}{dt} = \text{Tr}\left[\hat{\rho}^{\Psi}_{Q\bar{Q}}\,\frac{d\hat{\rho}_N(t)}{dt}\right]$$

- $P^{\text{prim}}(t_{\text{init}})$ is the production at initial time (*primordial*)

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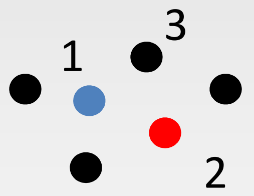
Remler formalism at work

Combining the rate definition + V.N. 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 V.N. equation, still impossible to deal with exactly at the quantum n-body level

Remler formalism at work

Passing to the Wigner representation:

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

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

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

Quarkonia: Double Gaussian approximation

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

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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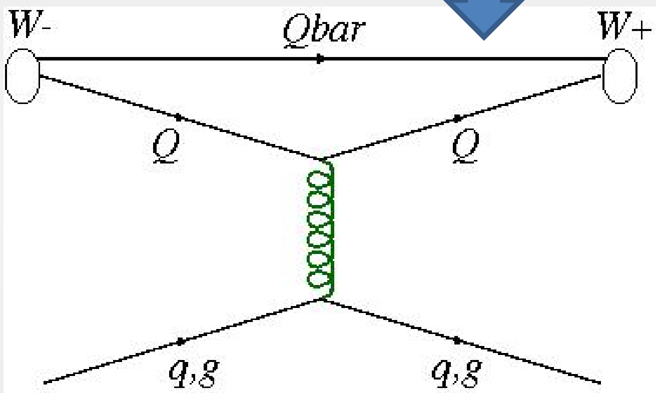
Remler formalism at work

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

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

- The quarkonia production in this 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: $P^{\Psi}(t) = P^{\Psi}(t_0) + \int_{t_0}^{t} \Gamma(t')dt'$

NB: Also possible to generate similar relations for differential rates

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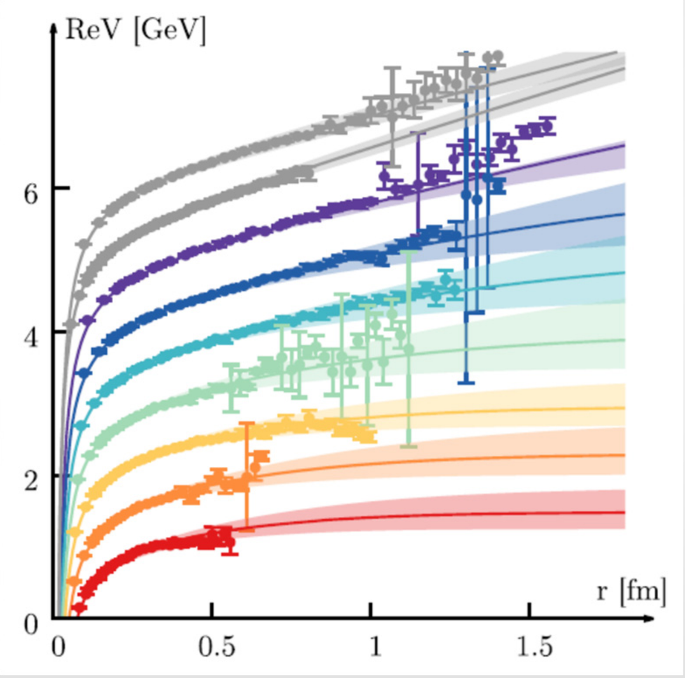
The Q-Qbar interaction

- Not implemented up to now in EPOS-HQ
- More and more reliable calculations are becoming available for the real part of the potential (for a QQbar at rest), thanks to lattice calculations:

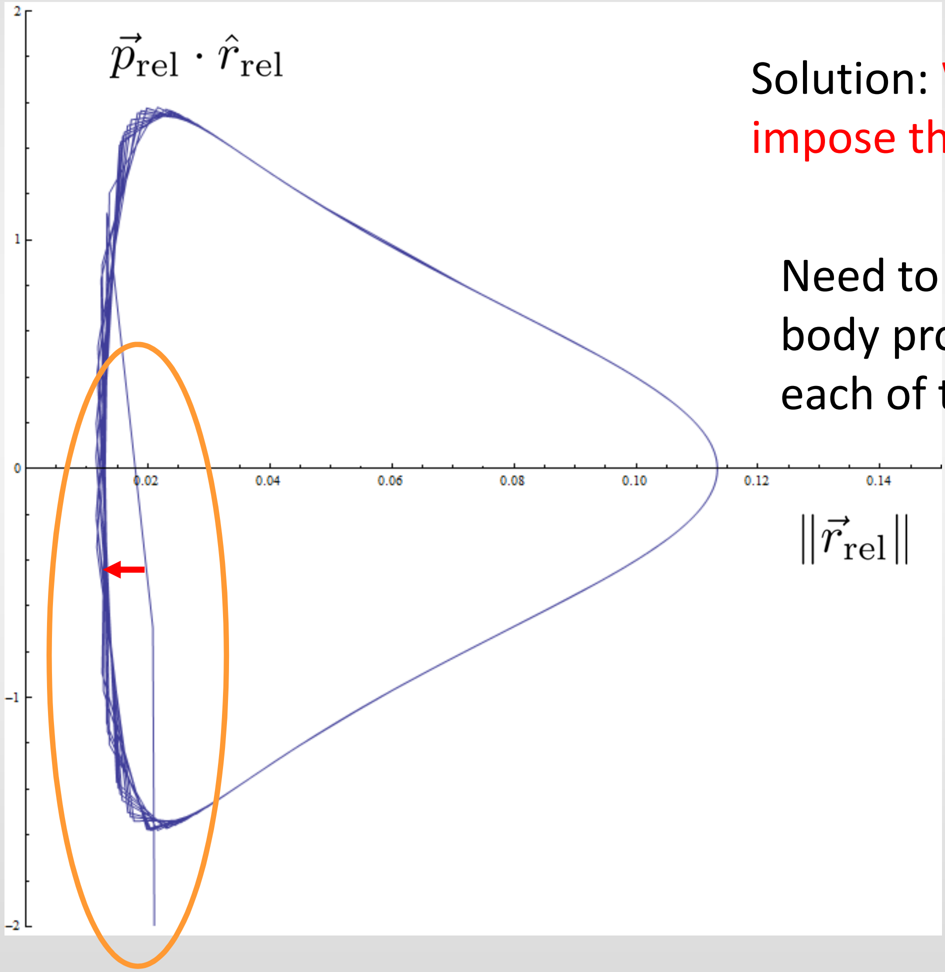


D. Lafferty and A. Rothkopf,
PHYS. REV. D 101, 056010 (2020)

- Go for it !
- **{ } of N c-quarks and N cbar-quarks interacting by these potentials based on relative distance**

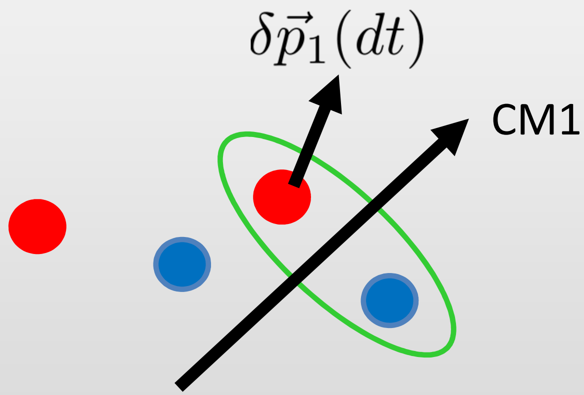
The Q-Qbar dynamics… the CM strategy

- "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



The Q-Qbar dynamics… the CM strategy

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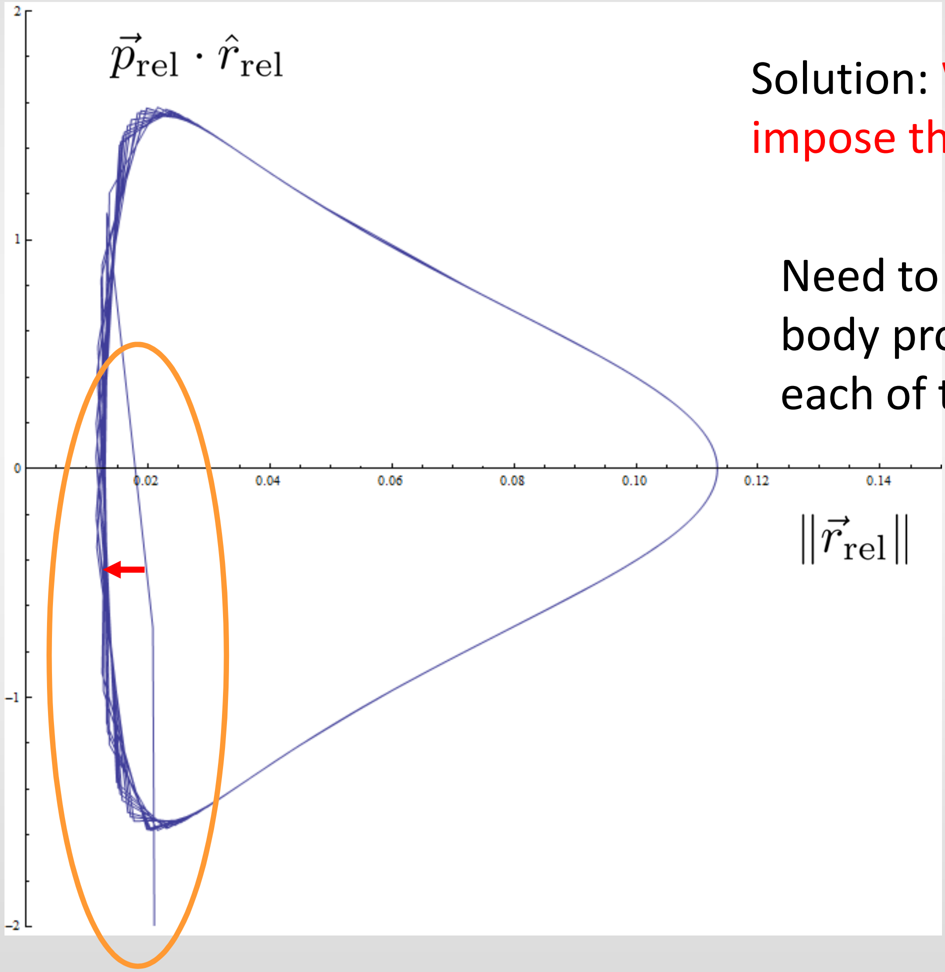

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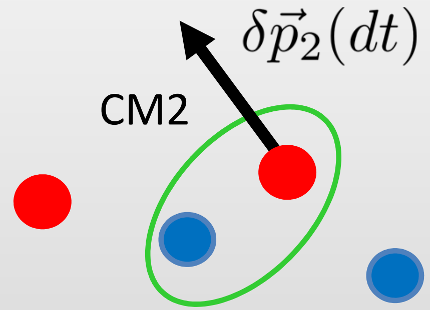

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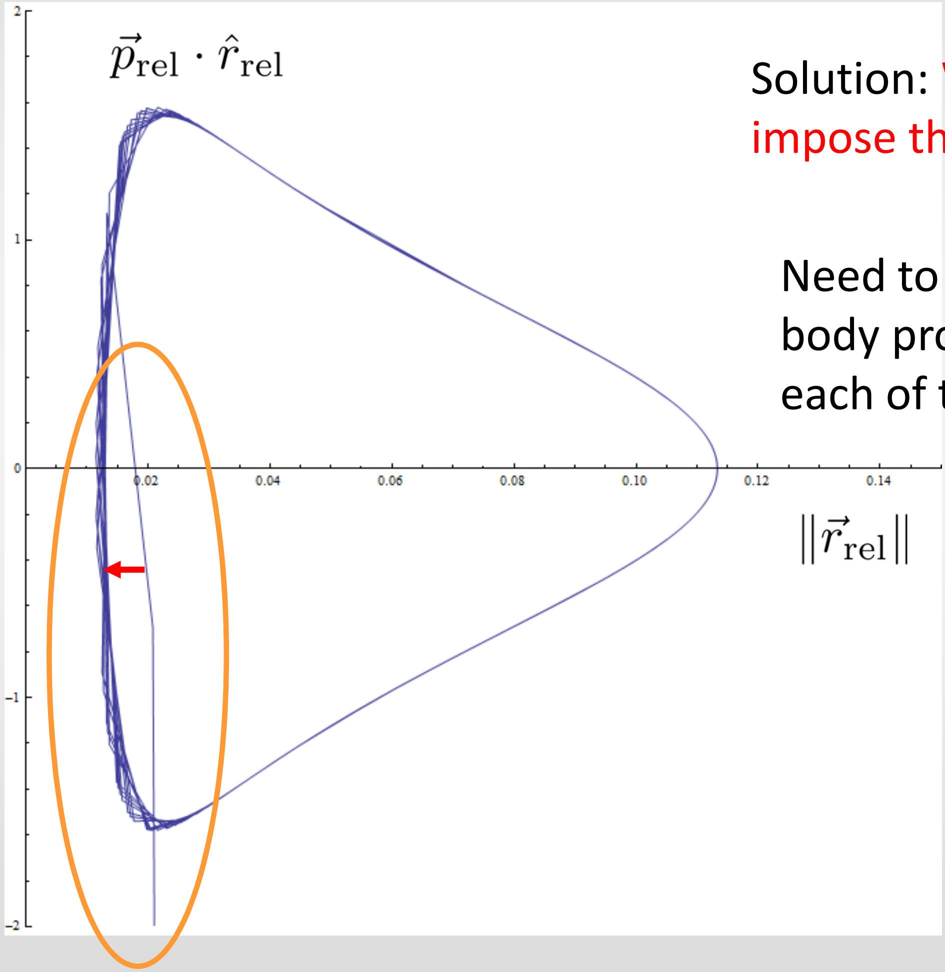

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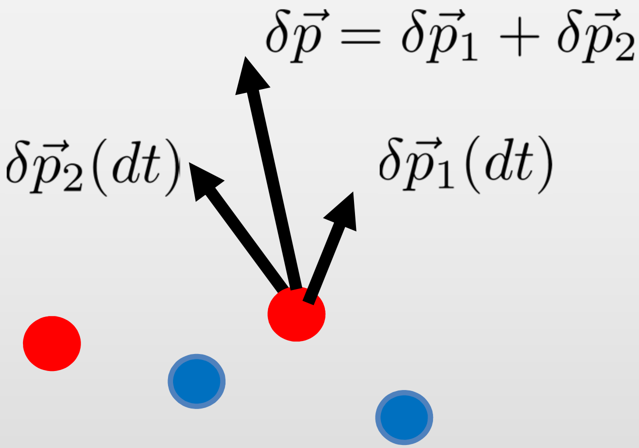

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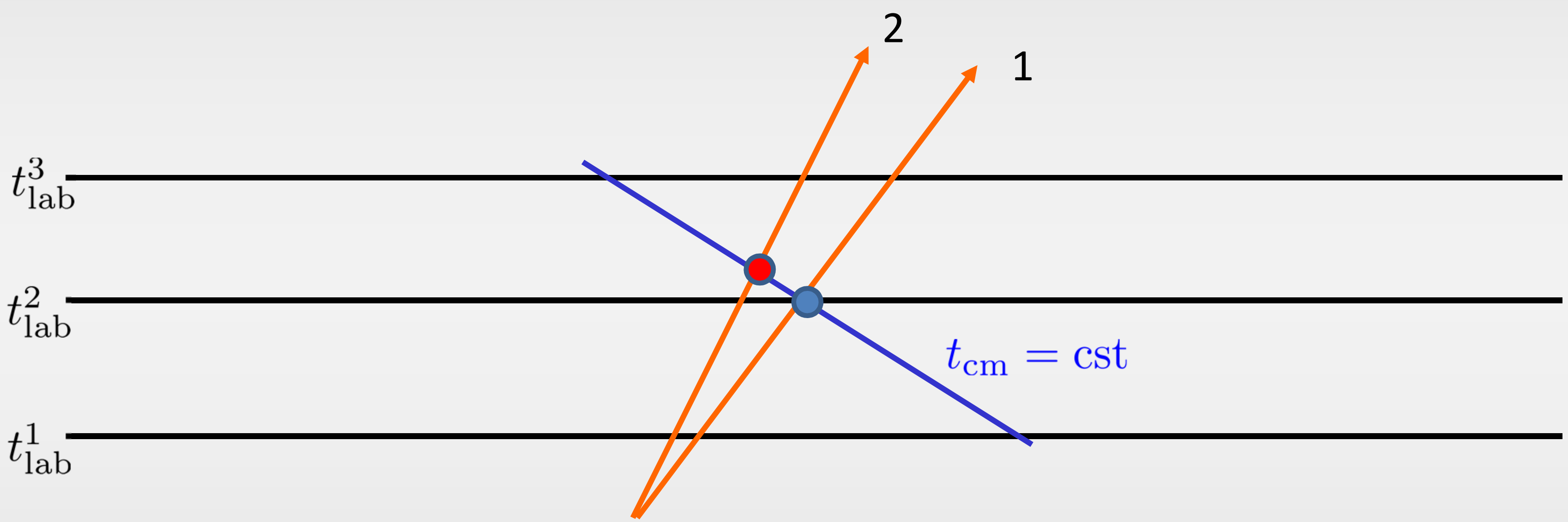
The Q-Qbar dynamics… the CM strategy

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



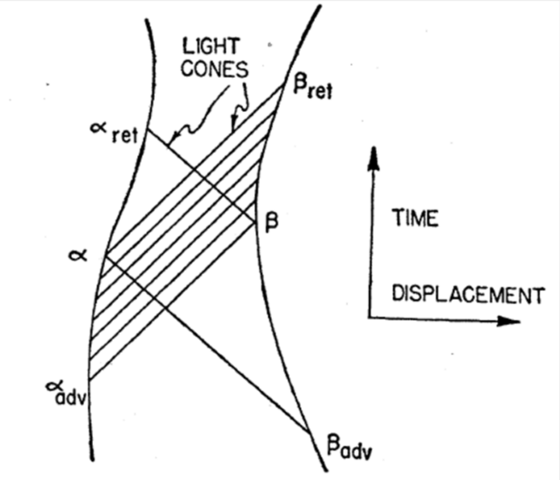
Generic need to store / describe the trajectory of particle 2 at a time $t_{lab} > t_{lab}^2$ if one propagates particle 1 up to t_{lab}^2 by resorting to evolution in the c.m.

The Q-Qbar dynamics… the « retarded force » strategy

- 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 quantity associated to the retarded force… as radiation field removing part of the available energy.

- Very few schemes developed to deal with the relativistic interactions of many particles implementing constrains such as energy/angular momentum conservation.
    - Wheeler and Feynman (1949) explicitly remove the radiation field by considering advanced + retarded propagator => effect from the future on the past in the evolution equation… difficult to cope with in the present MC code
    - Other schemes under investigation



For the time : center of mass strategy

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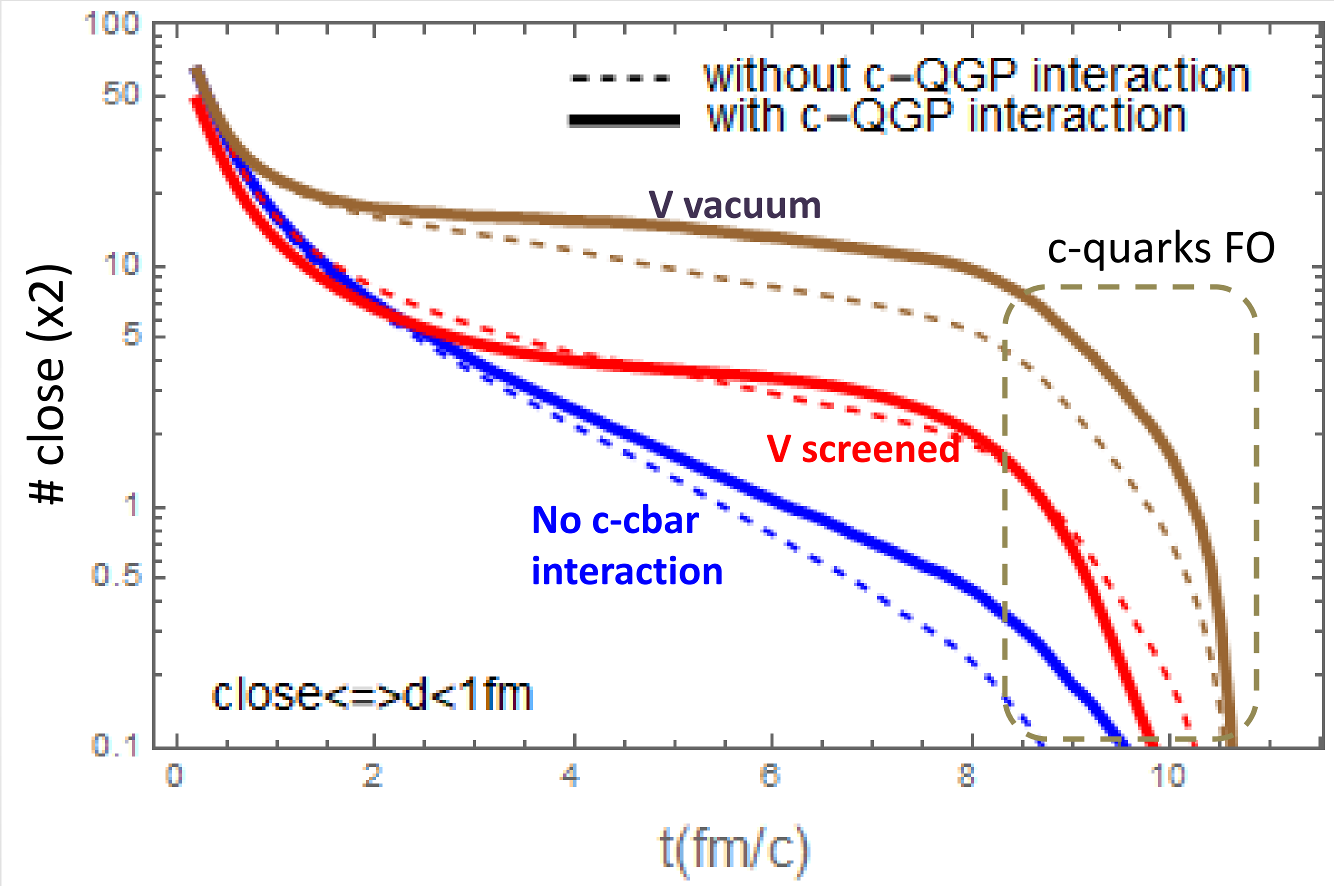
Consequences on the c-cbar trajectories in AA collisions

$$\sqrt{s} = 5.5\,\mathrm{TeV}$$

Pb-Pb

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

N.B. :Each c-cbar pair is attributed a color state (0 or 8) at formation; only singlets are sensitive to the c-cbar potential

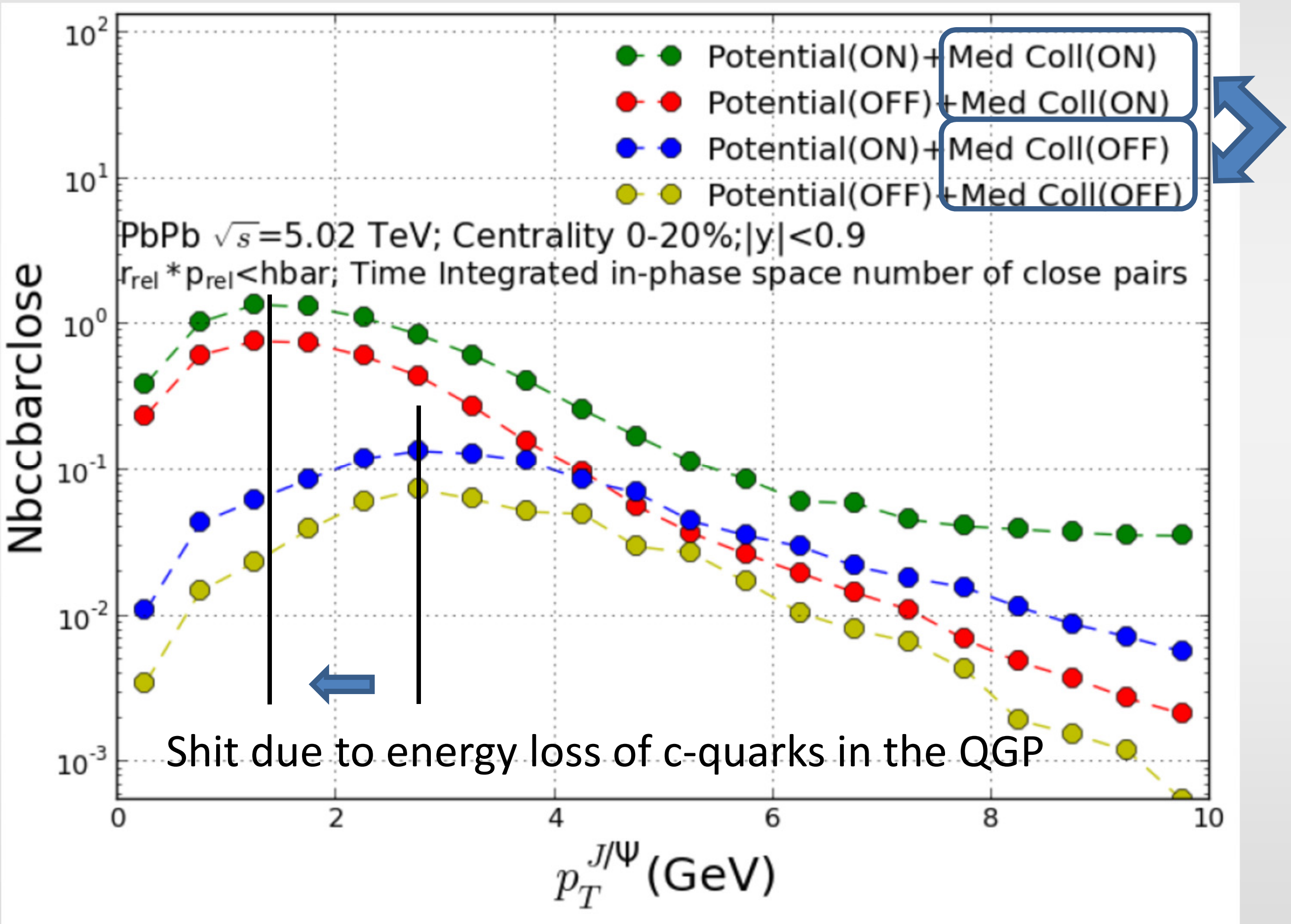


Although screened, the Q-Qbar interaction has important consequences on the probability to find a Q-Qbar at close distance in the final stage of the evolution

Consequences on the c-cbar trajectories in AA collisions

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

$$p_{\rm rel} \times r_{\rm rel} \leq \hbar$$



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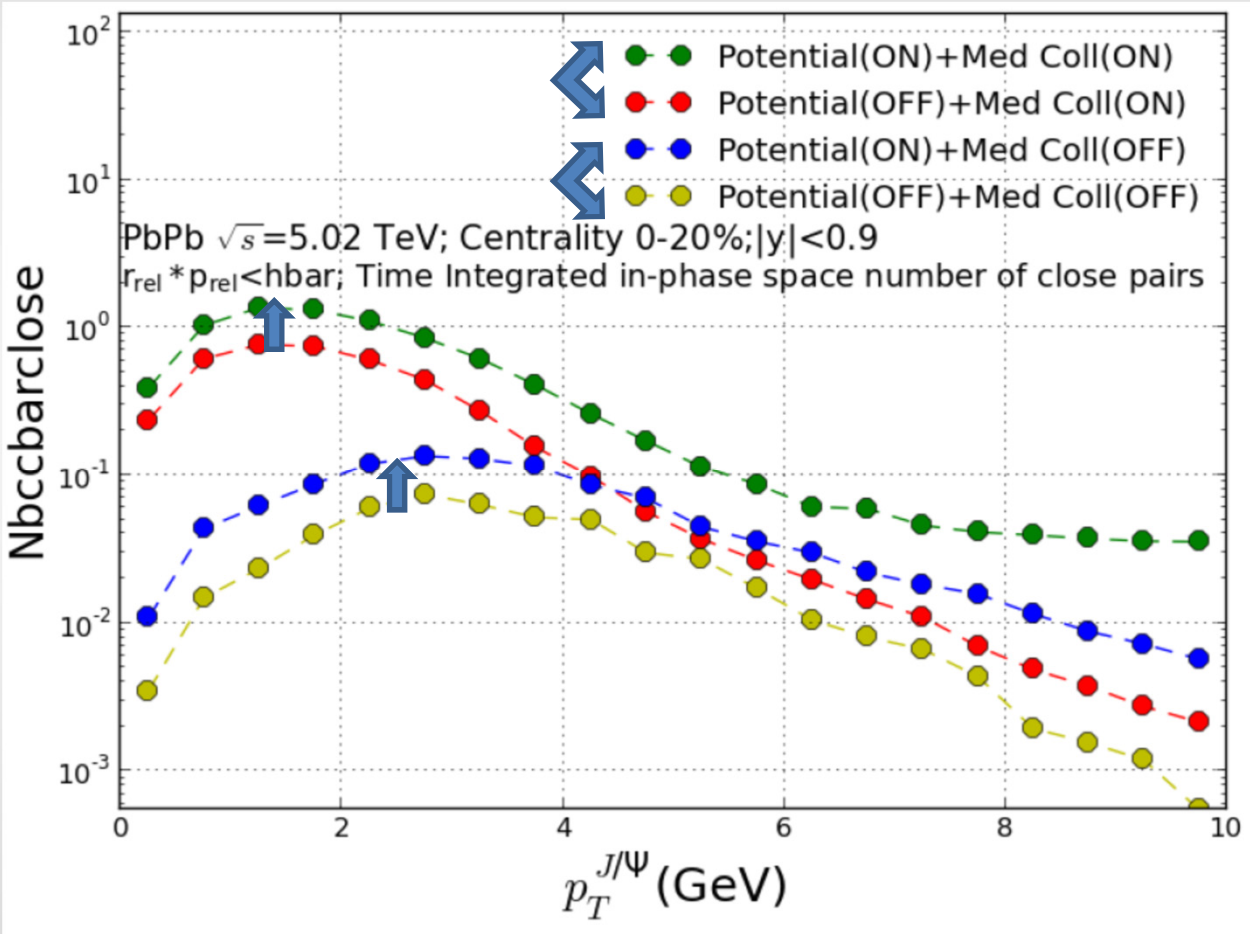


Increase of the # of close trajectories due to the interaction potential, for all p_Ts.

Most favorable case : both potential and interaction with QGP « ON » : ●

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 »)

Results : J/ψ initial production

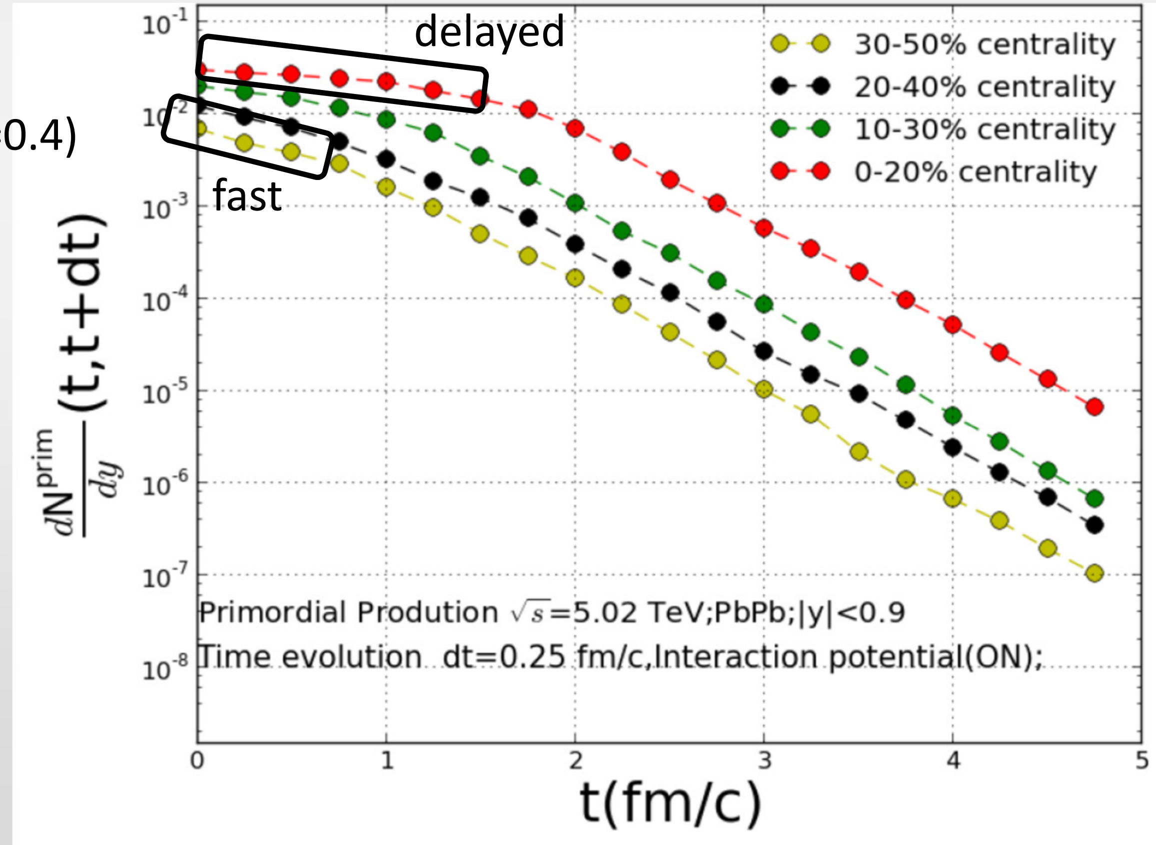
$$P^{\Psi}(t) = \boxed{P^{\Psi}(t_0)} + \int_{t_0}^{t} \Gamma(t')dt'$$

Now distributed over the initial stage of the AA collision (until local T < T_{dissoc}^{Ψ}).

c and cbar generated from independent FONLL distribution => no initial correlation

Bound state of V(T=0.4)

of «J/ψ » produced during time interval [t,t+dt]



Results : J/ψ initial production

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

centrality	$\langle N_{\rm coll} \rangle$	$\left.\frac{dN_{c\bar{c}}}{dy}\right\|_{y=0}$	$\left.\frac{dN^{\rm prim}_{J/\psi}}{dy}\right\|_{y=0}$	$\frac{\left.\frac{dN^{\rm prim}_{J/\psi}}{dy}\right\|_{y=0}}{\left.\frac{dN_{c\bar{c}}}{dy}\right\|_{y=0}}$
0-20%	1256.1	31.6373	0.07741	$2.4467 \cdot 10^{-3}$
10-30%	748.8	17.618	0.05972	$3.3897 \cdot 10^{-3}$
20-40%	431.3	10.670	0.03620	$3.3927 \cdot 10^{-3}$
30-50%	232	6.8539	0.0244	$3.5629 \cdot 10^{-3}$
40-60%	113.5	3.6448	0.0166	$4.5543 \cdot 10^{-3}$

Not increasing with centrality, contrarily to

Taesoo .S, J.Aichelin and E.Bratkovskaya ,
PRC 96. 014907 (2017)

Apparent contradiction just due to the choice of the basis.

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Results : J/ψ initial production

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

Now distributed over the initial stage of the AA collision (until local T < T_{dissoc}^{Ψ})

Bound state of V(T=0.4)

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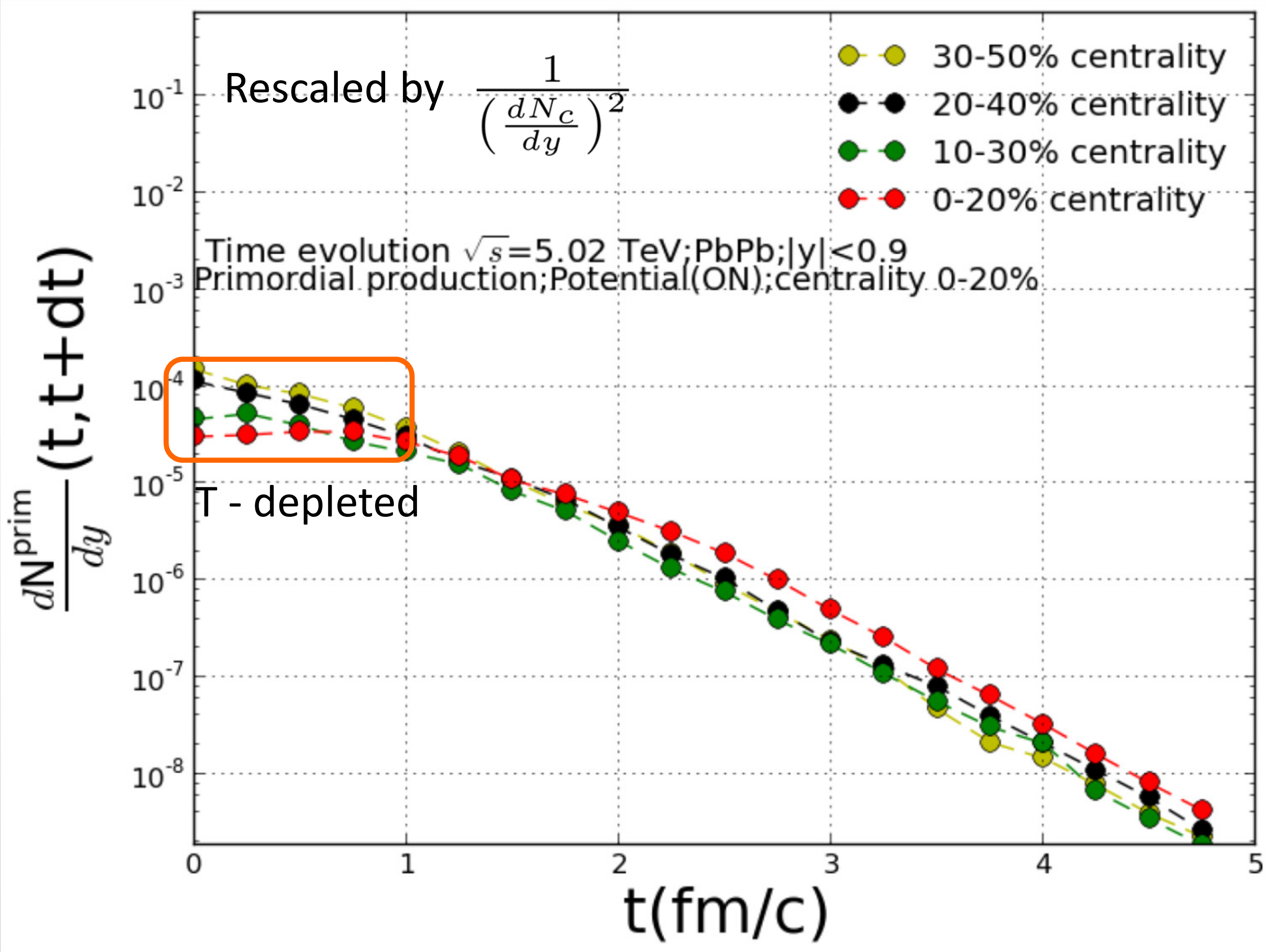
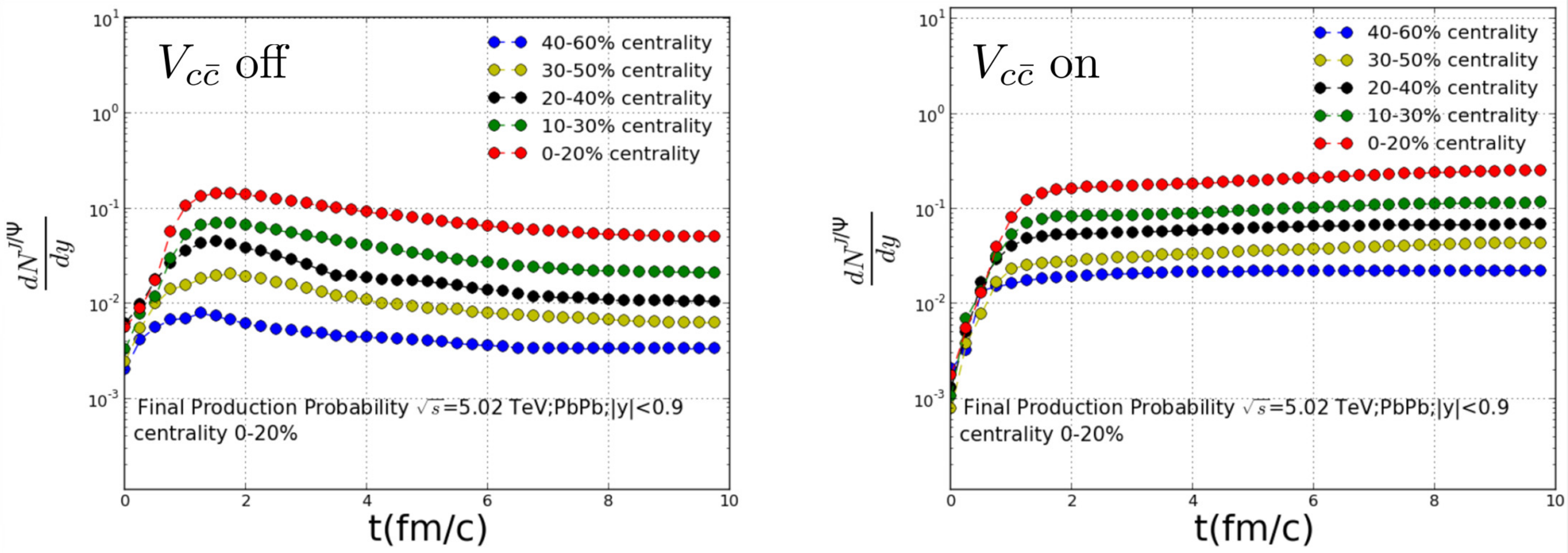
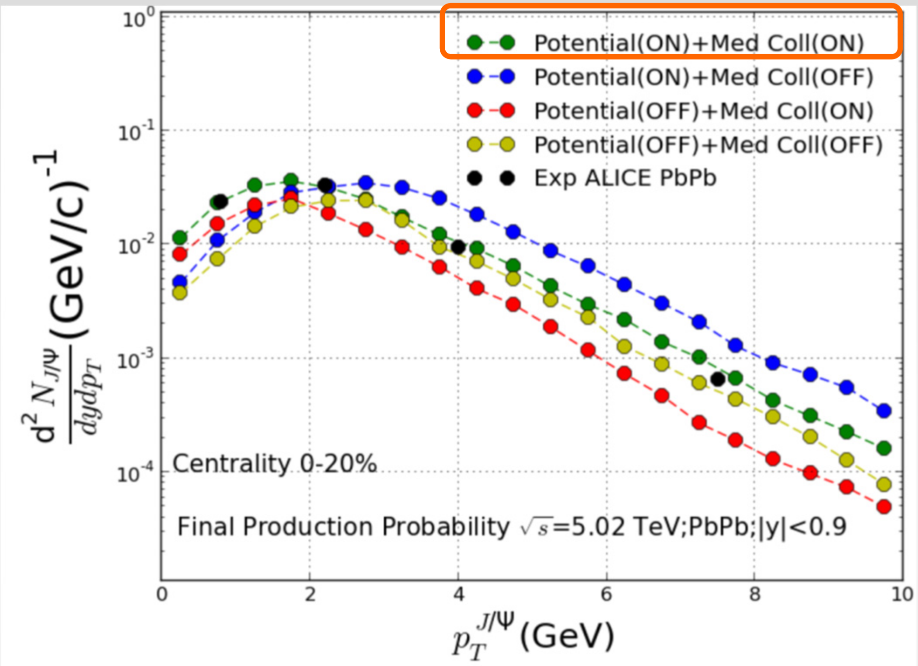


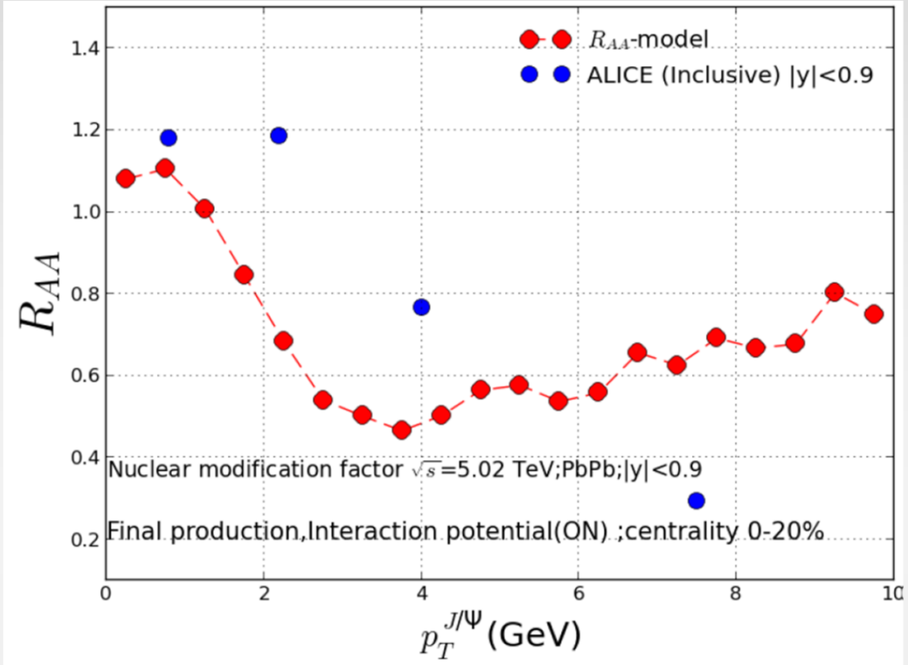
Results : J/ψ production vs time



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

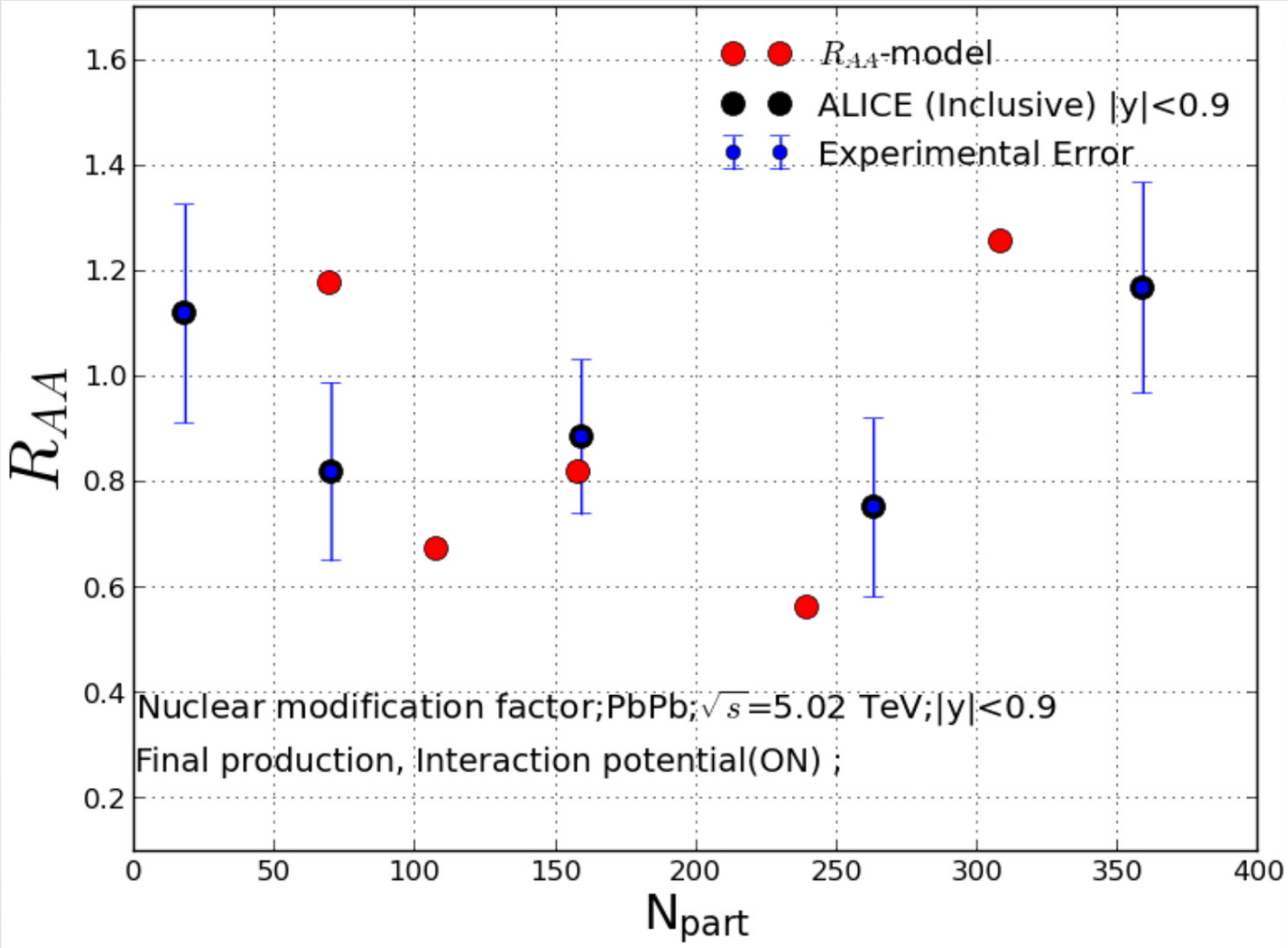
Results : final J/ψ production vs p_T





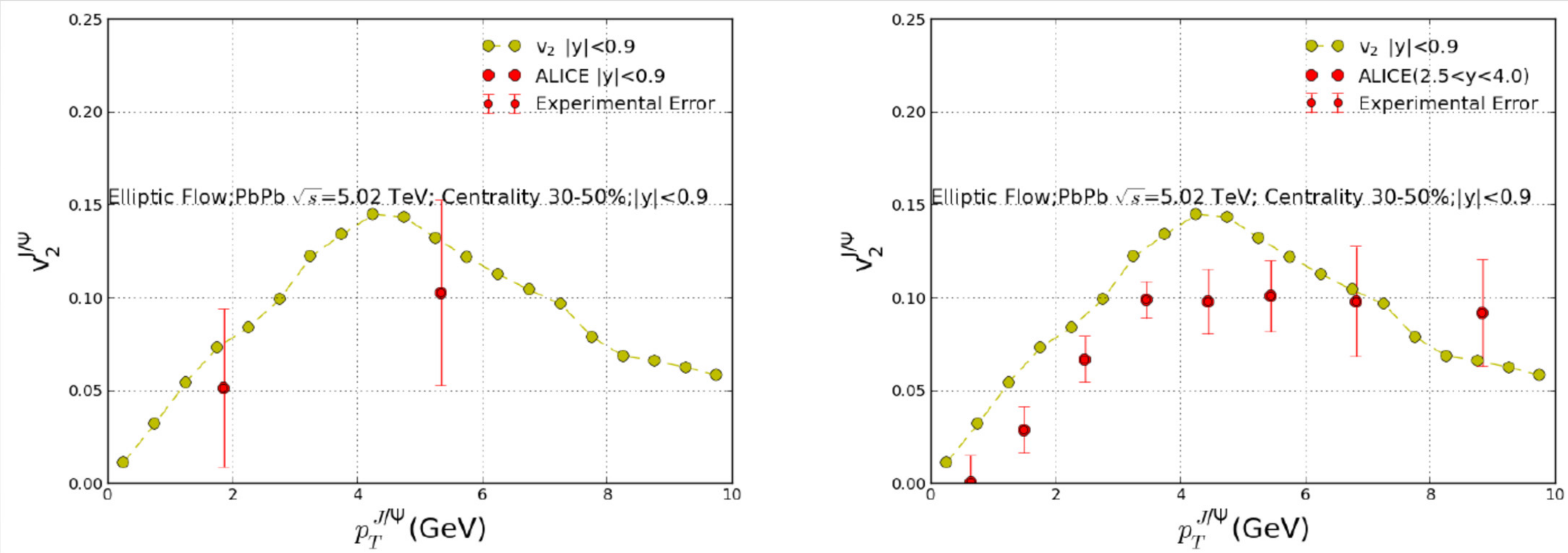
- Final p_T distribution in agreement with ALICE data (caution : no feed down from higher states up to now)
- R_{AA} just in moderate agreement with the data… but this is mostly due to the modeling of J/ψ production in pp (also based on the same approach of coalescence of c-cbar production)

Results : final J/ψ production vs centrality



- Similar « rise and fall » as in data
- Simulation at forward rapidity to be done in a near future.

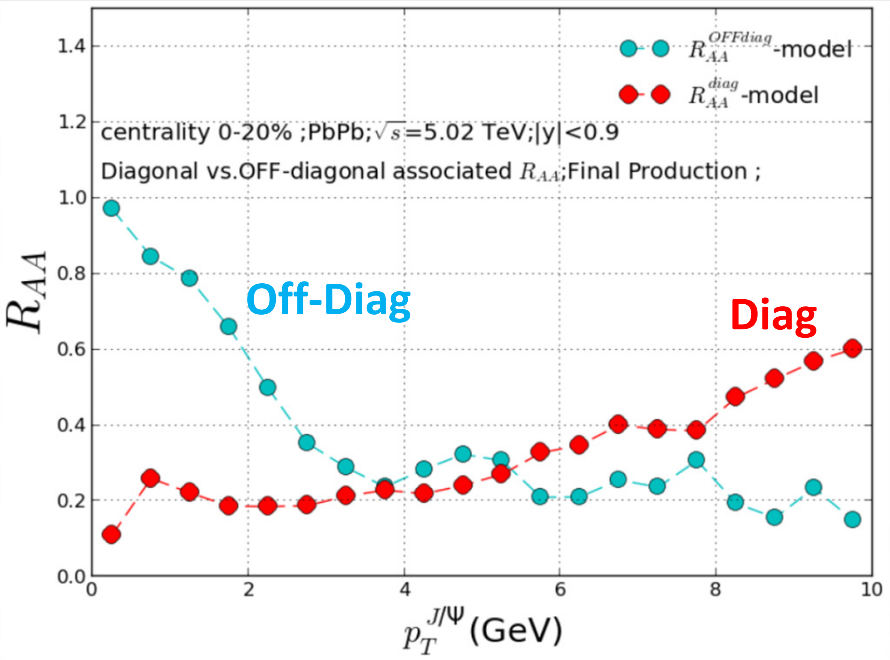
Results : final J/ψ v_2

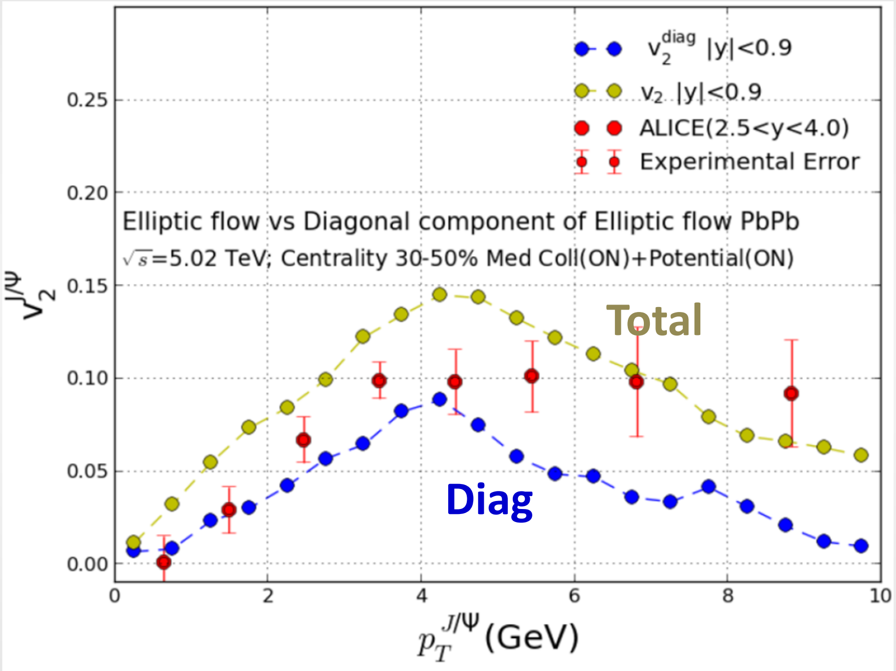


- Compatible with v_2 measured at mid-rapidity (large error bars)
- Right panel : Theorist crime : comparing prediction at mid-y with v_2 measured in the di-muons arms … at least, not « v_2 deficit » from theory.

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:



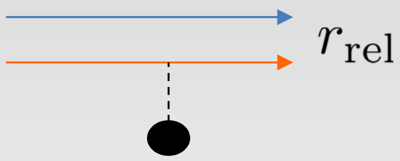


- Off-diagonal production dominates at low p_T.
- Diagonal contribution increases with larger p_T ($\Delta E/E$ decreases)

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

Physical picture…

Q-Qbar propagation in QGP.



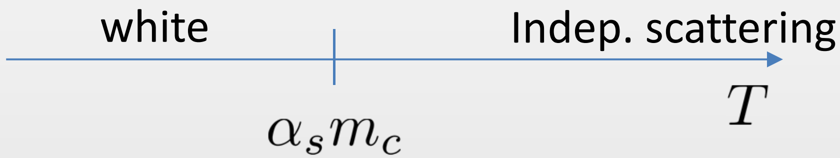
If $r_{rel} << l_{correl}$: **white object** => no Energy loss

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

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

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

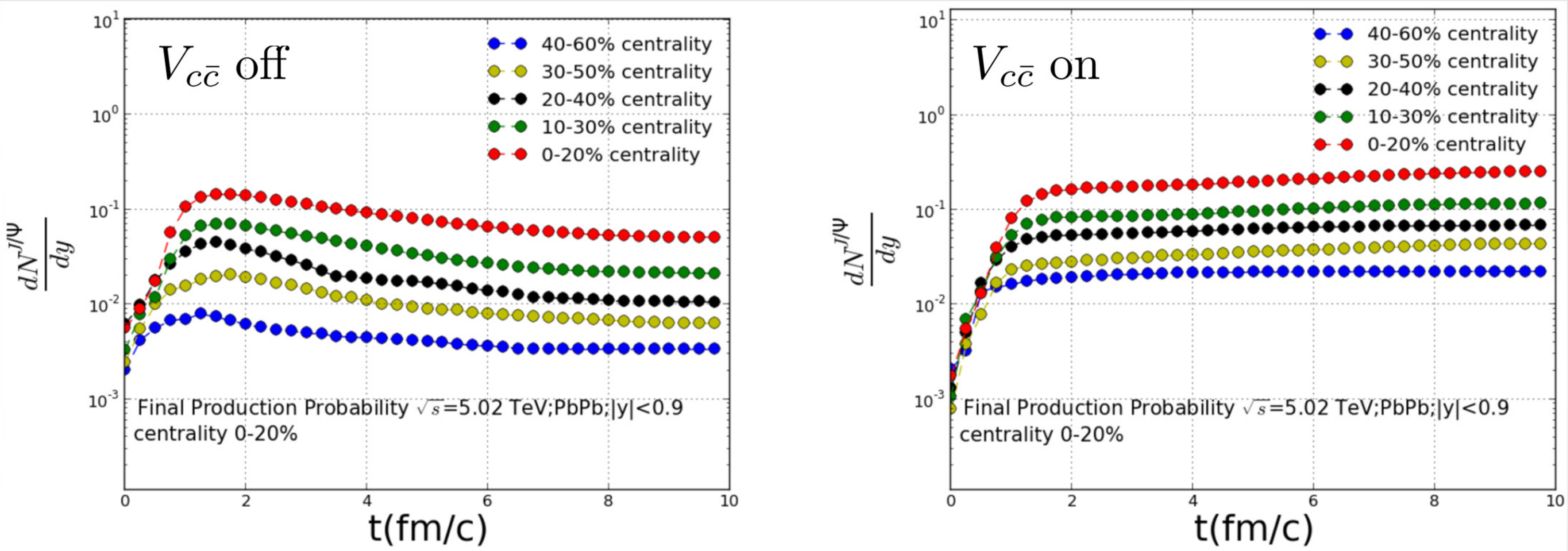
Large T : $r_{\rm rel} \gtrsim \frac{1}{m_D} \approx \frac{1}{gT}$



- 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 somehow too large v_2 resulting from this prescription…

Conclusion

At what stage of the AA collision are the J/ψ created ?



Correlation is built as soon as $T < T_{dissoc}$, and is strengthened with cooling temperature

Subatech

Perspectives

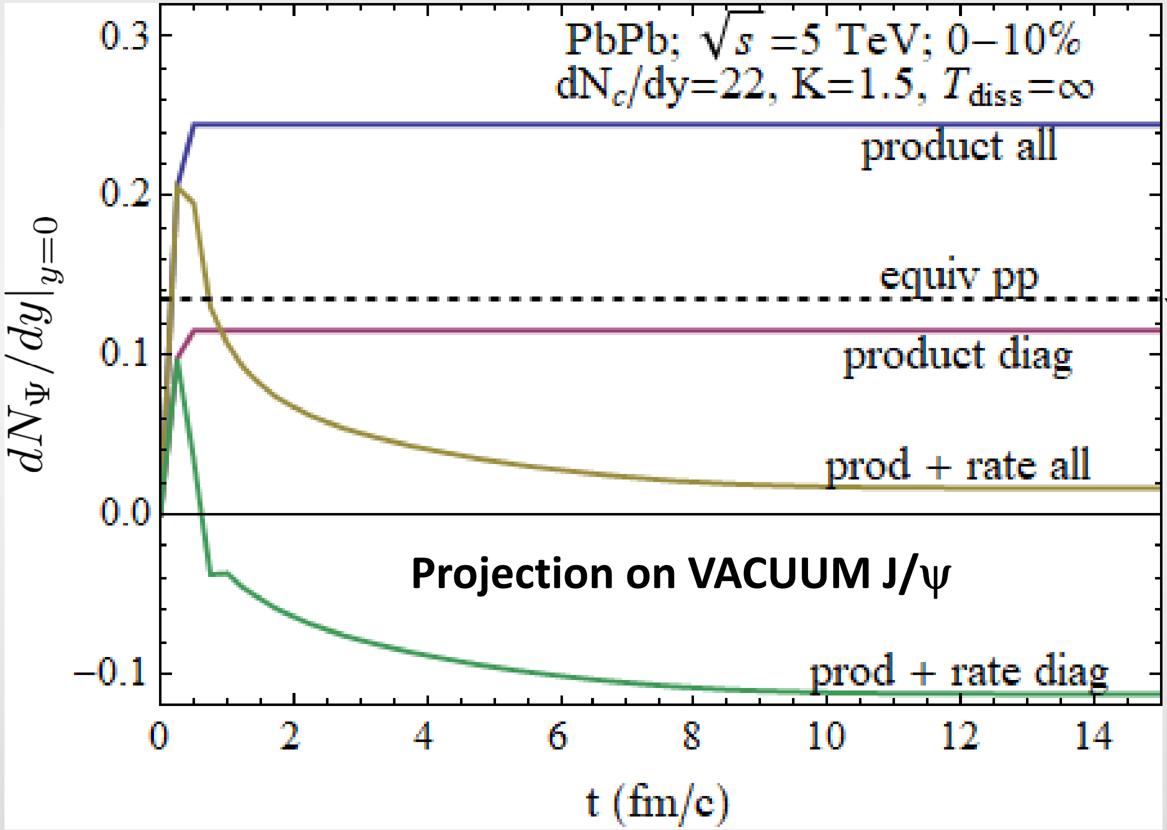
- Short term :
  - Need to include higher states feed down + shadowing
  - Include the model in EPOS4 and look at RHIC
- Mid term : consequences of our model for Bc production
- Long term : better color dynamics , Q-Qbar distance as a parameter in the Q – QGP dynamics

Back-up

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

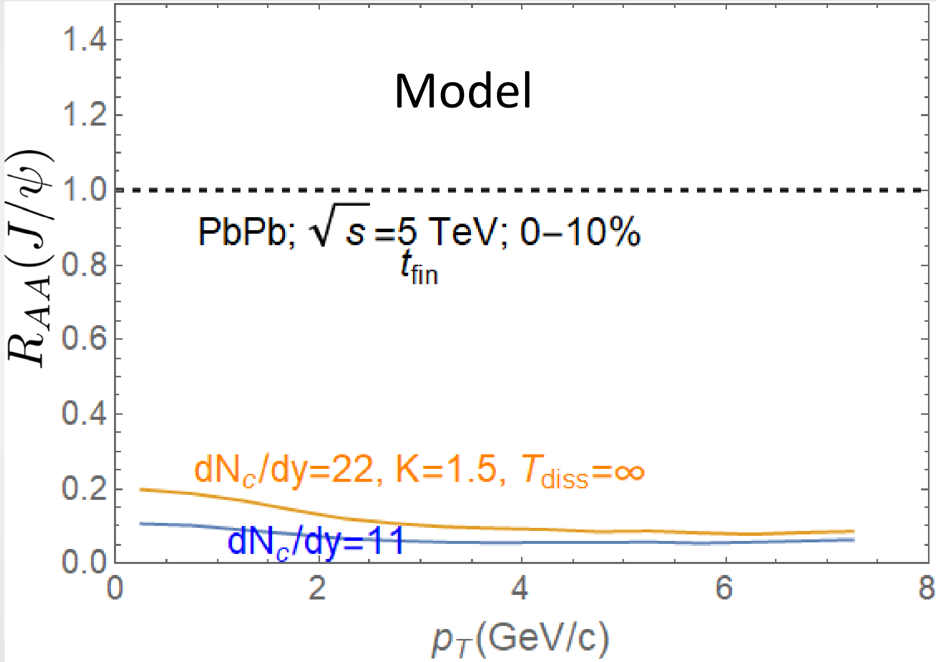
The denominator in the R_{AA}

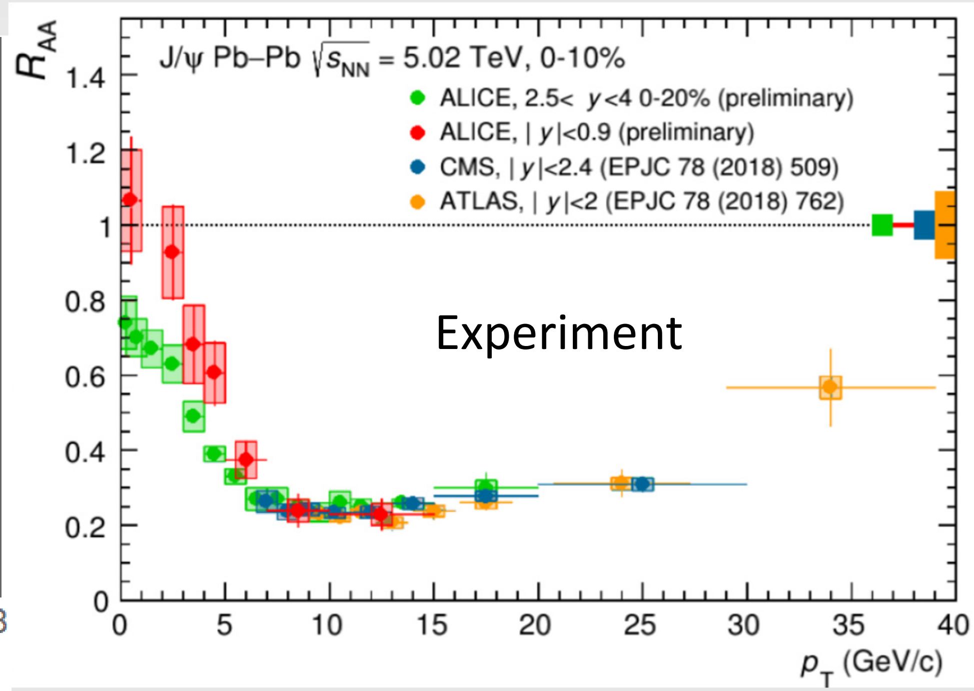
The full production (i.e. the numenator in the R_{AA})

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

Preliminary results for J/ψ production in Pb-Pb

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



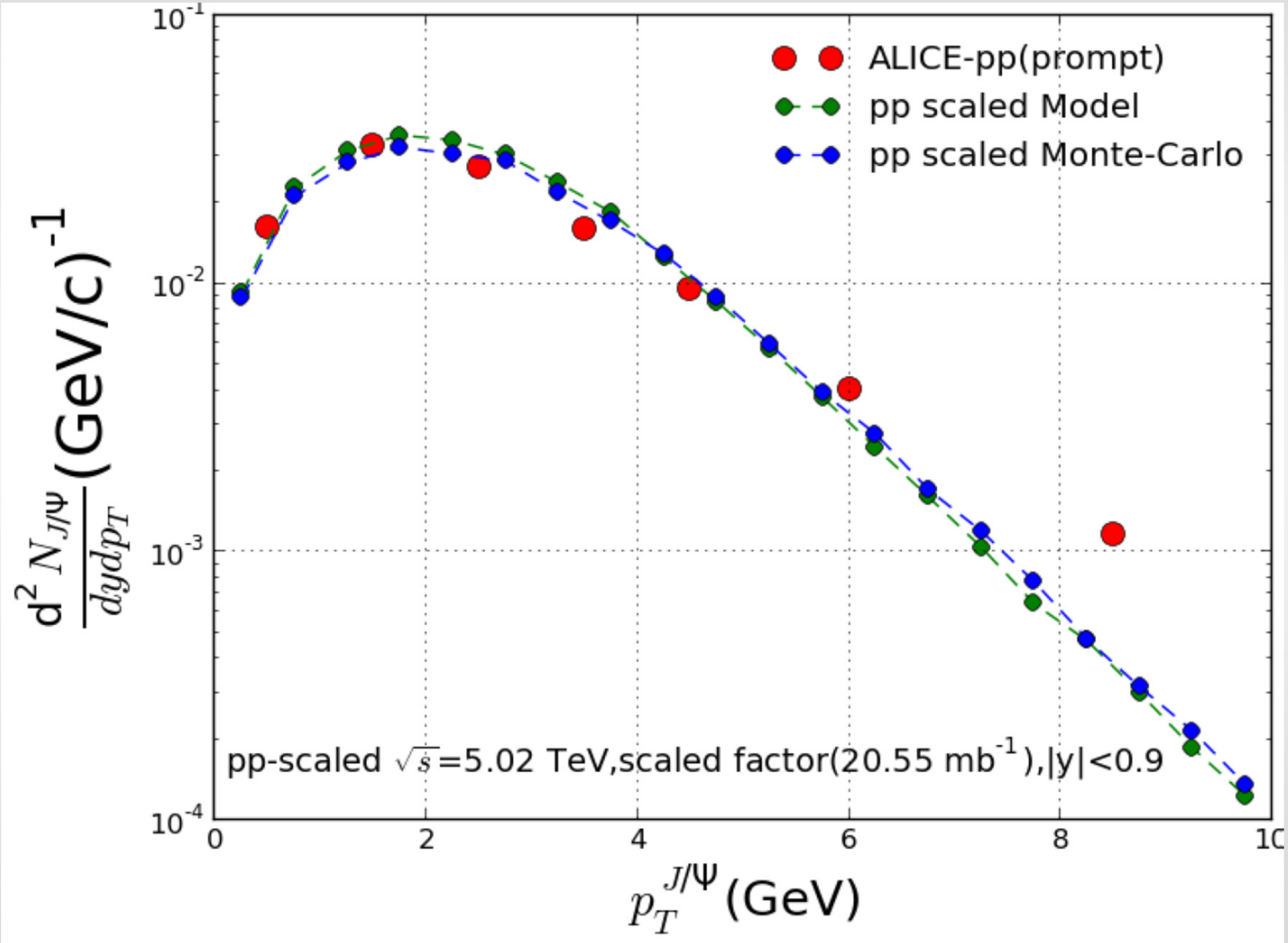


Effect of cham abundance in phase space (x2):

- **Correct trends for charm recombination**
- **Absolute value too small**

Missing ingredient for semi-quantitative agreement: Interactions between Q & Qbar (real part of the potential, not implemented in EPOSHQ)

Equivalent pp



Ratio # diag / # tot for semi-central