J/Ψ Survival in hot plasma

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I. Motivation

II. Understanding (partly) the present RHIC data on HQ E-loss

III. Quarkonia formation: probing the QGP ?

IV. Consequences of microscopic treatment of QQbar states on survival probability

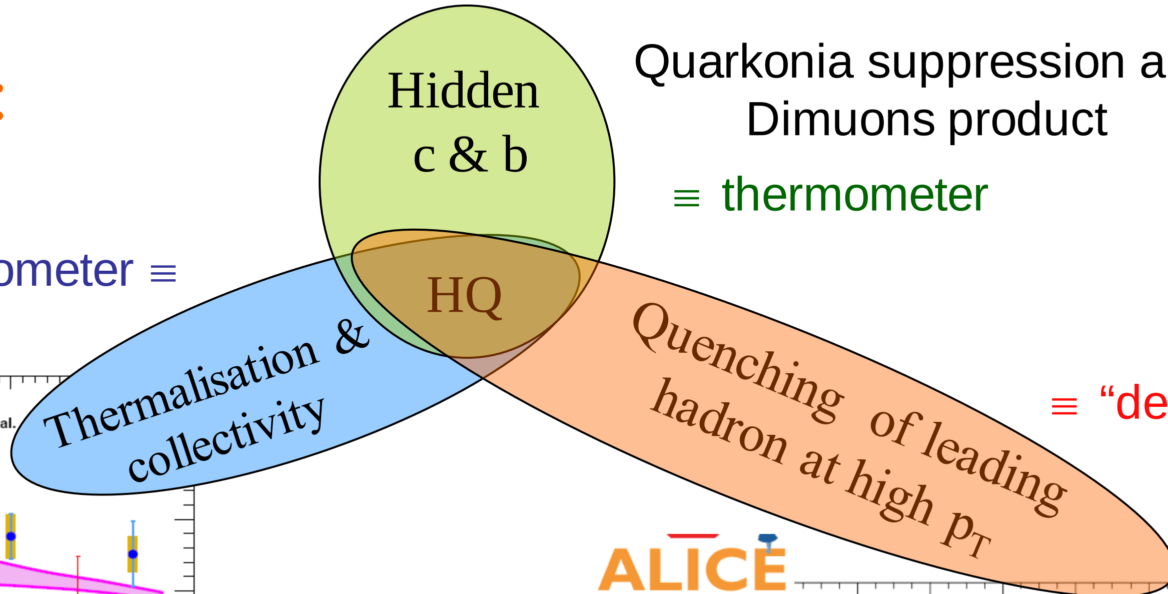
Probing QGP with heavy flavors

The Trilogy:

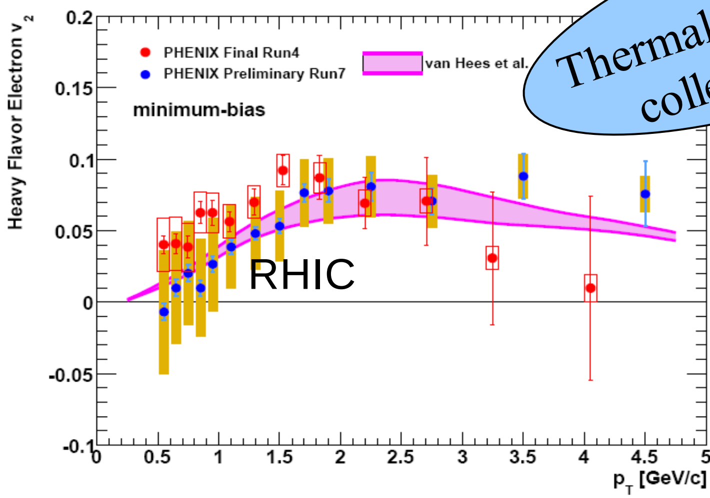
Quarkonia suppression and Dimuons product

≡ thermometer

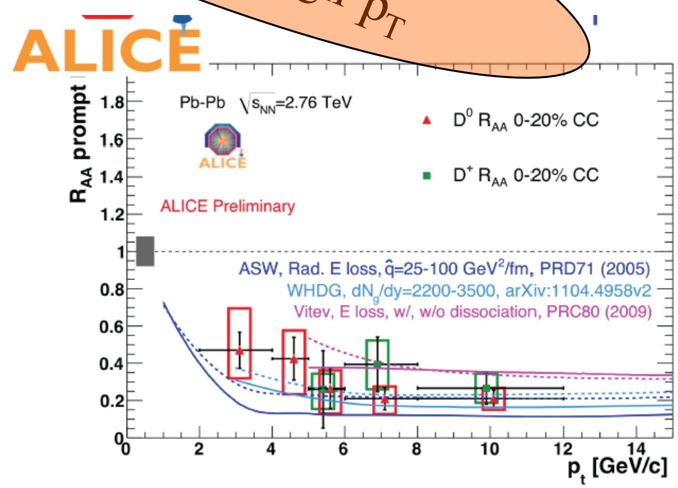
Barometer ≡



≡ "densimeter"



HQ gain elliptic flow from the surrounding medium… with some time delay (inertia)



Nuclear modification factor (R_{AA}) of D mesons probes c-quark energy loss in QGP (not seen in pA)

Quarkonia in Stationary QGP

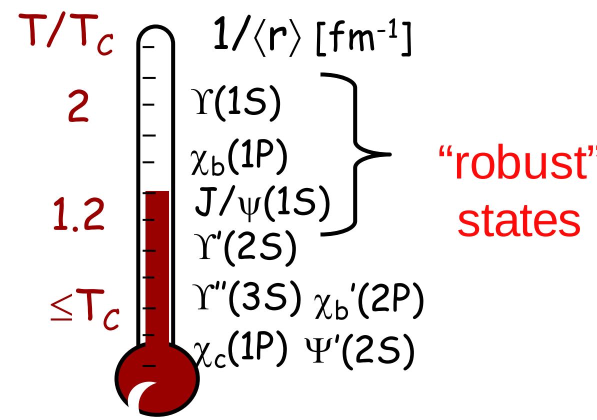
How can we prove (at best) that we have achieved is really *deconfined* state of matter ?

Challenge

"deconfinometer" ≡
- Color fluctuations
- Propagation of quarks over large distances

Best candidate:

Quarkonia (Q-Qbar bound state) sequential "suppression", i.e. melting and/or dissociation (Matsui & Satz 86)



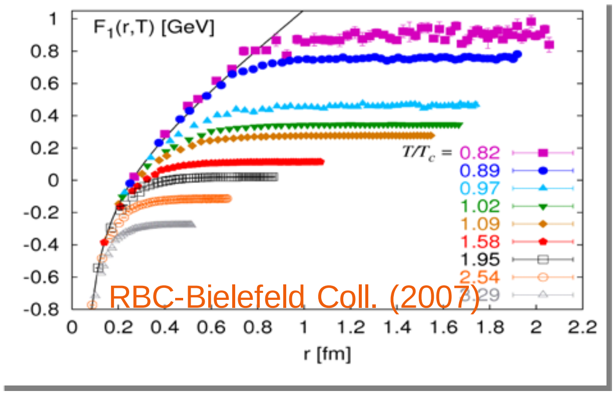
QGP Thermometer

Indeed observed at SPS (CERN) and RHIC (BNL) experiments. However:
- alternative explanations, lots of unknown (also from theory side)
- no additional suppression at RHIC w.r.t. SPS !

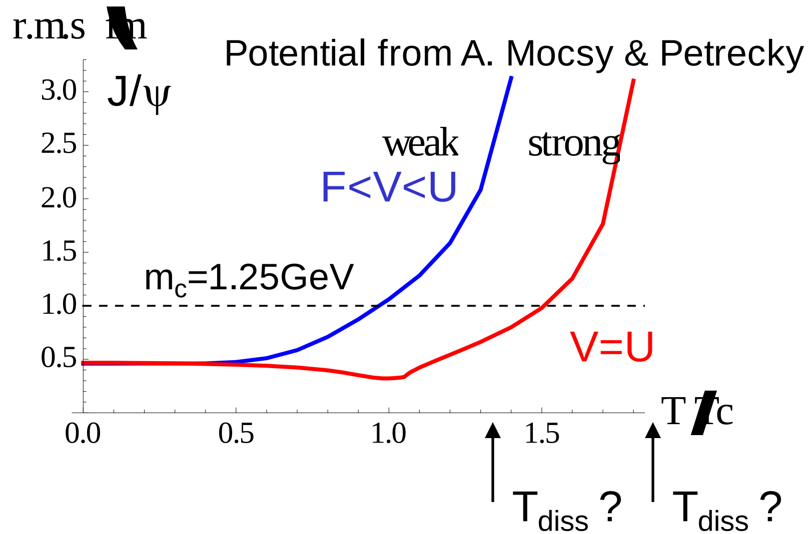
Nevertheless: Still best candidate and dedicated (di-μ) program at LHC

Caviats & Uncertainties

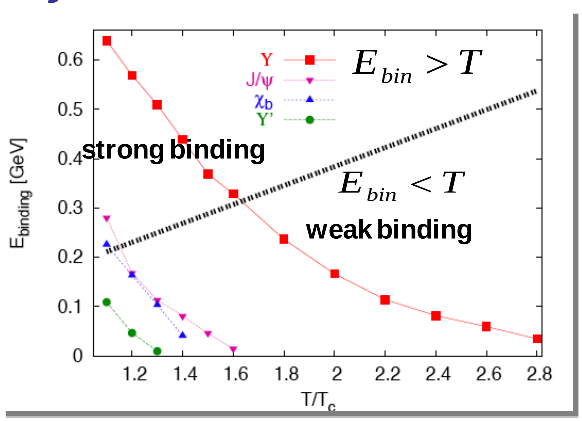
I. Quarkonia in *stationnary* medium are not understood from the fundamental LQCD theory



$\Rightarrow$ V(r,T) ?



II. Criteria for quarkonia “existence” (as an effective degree of freedom) in *stationnary* medium is even less understood



From A. Mocsy (Bad Honnef 2008)

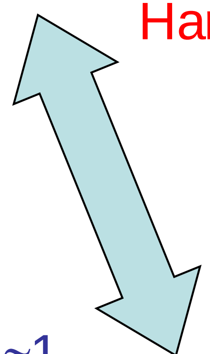
III. What does this stationary picture has to do with reality anyhow ?

Need for a time-dependent scenario

Semi-Qualitative questions

1. Are the data compatible with the picture of a strongly bound J/ψ (sequential suppression) ?

T_{diss}/T_c >(>)1 Hard probe



$T_{diss}/T_c \approx 1$ Soft probe (not so interesting)

2. Can we challenge the picture of statistical recombination (A. Andronic, PBM, J. Stachel) ?

3. Can we try to *extract* the dissociation temperature from the data ?

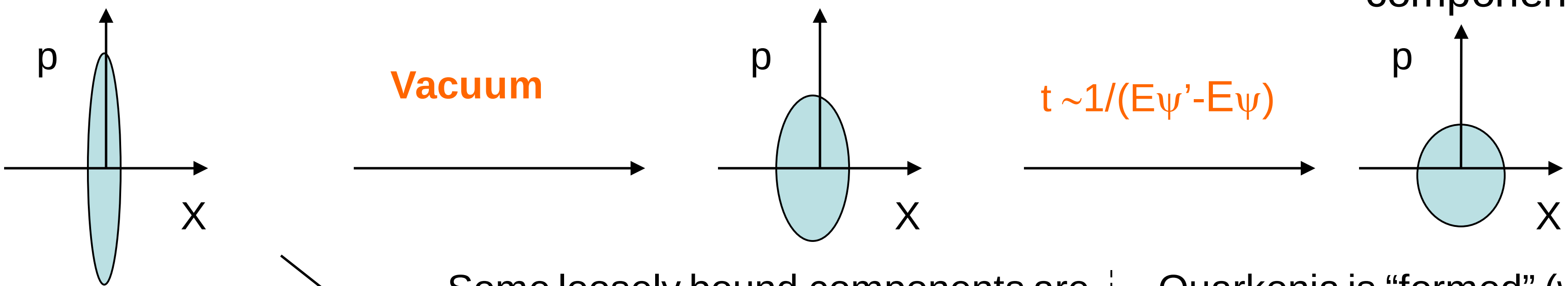
The *main* object of interest here: T_{diss} (thermometer aspect): one of the fundamental quantities of statistical QCD.

Quarkonia fate along decreasing T(t)

Initial Q-Qbar state (broad in p_{rel}, narrow in x_{rel})

State extends in x_{rel} and narrows in p_{rel} (evaporation of higher components)

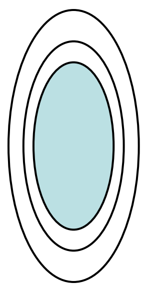
Quarkonia is "formed" (separation from other components)



In hot (but cooling) medium

Some loosely bound components are scattered while the remaining part becomes bounder

Quarkonia is "formed" (with reduced probability) in a state ~ vacuum and can only be dissociated through hard collision (q ~ M α^2)



t such that $\Gamma(T(t))<(E\psi'-E\psi)$

"Truth"

"Dual *Model*"

a) Instantaneous "melting" / thermal excitation

b) No "Q-Qbar→Quarkonia" fusion

a) Hard gluo-dissociation à la "Bhanot-Peskin"

b) "Q-Qbar → Quarkonia" fusion allowed (+g)

Quarkonia fate along decreasing T(t)

"Dual *Model*"

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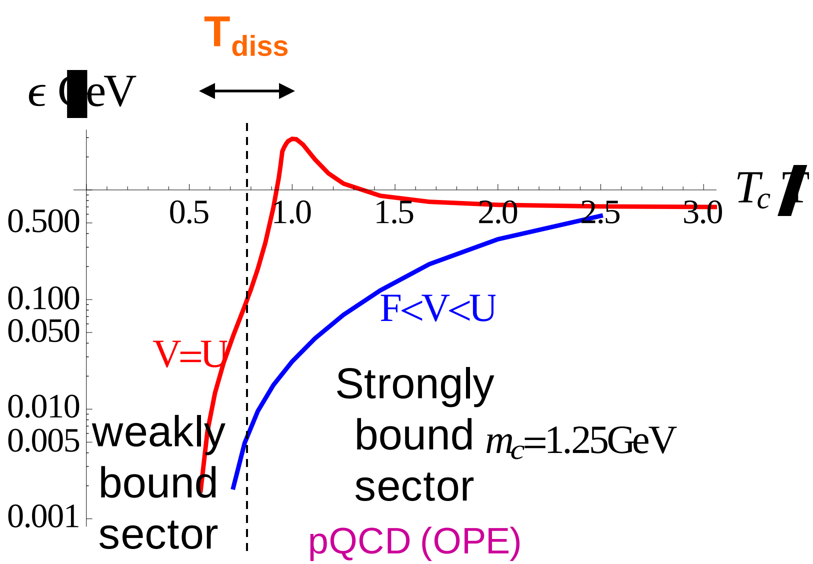
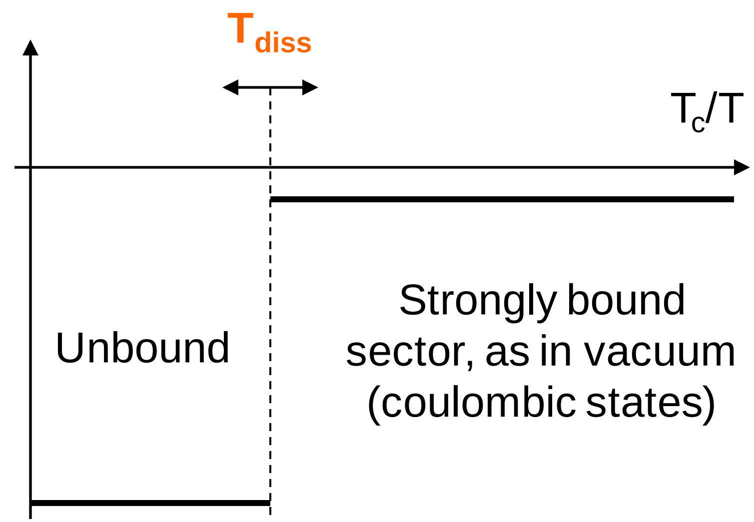
b) "Q-Qbar → Quarkonia" fusion allowed

$T>T_{diss}$

$T<T_{diss}$

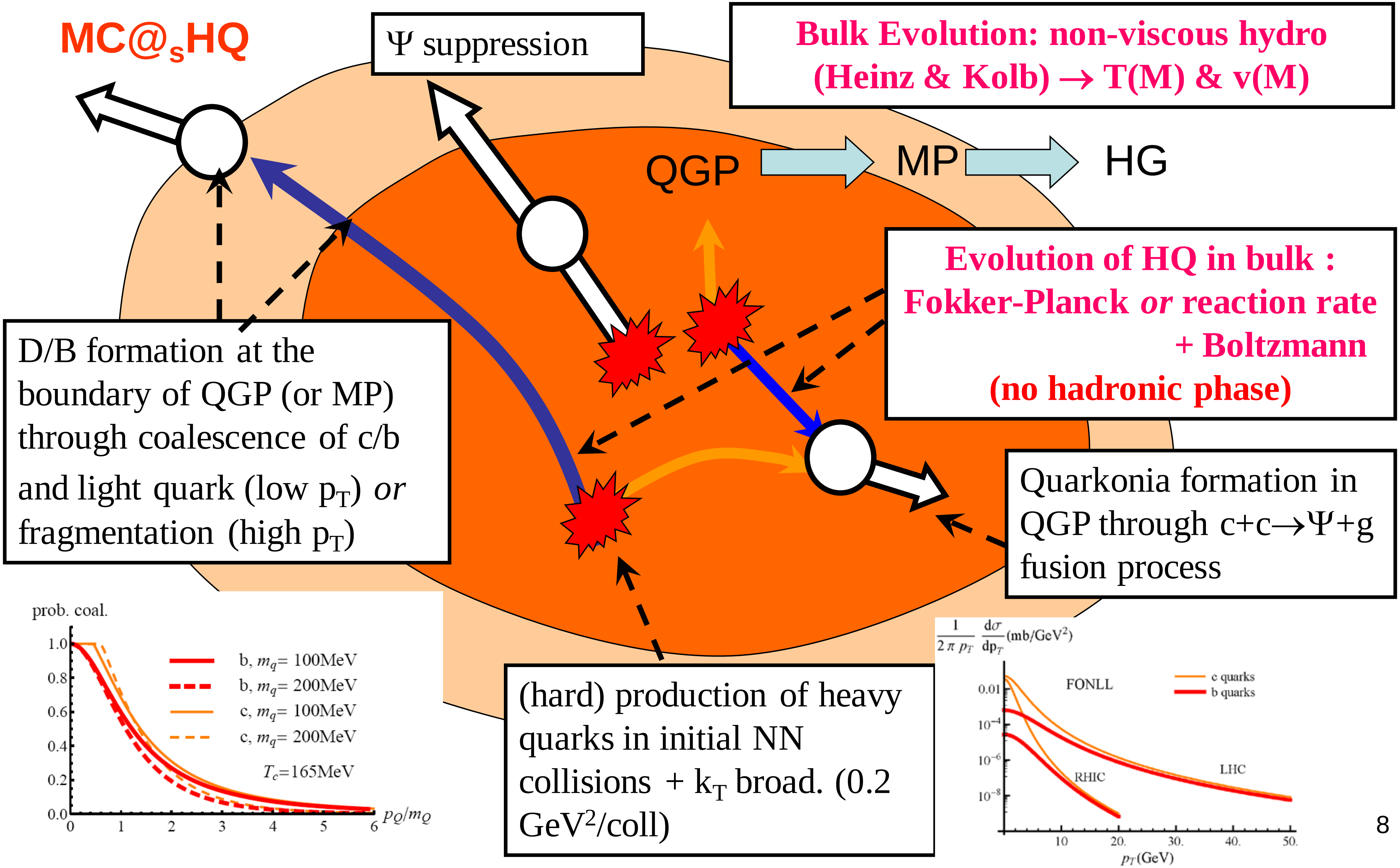


Model



The idea: AS THE LATTICE and POTENTIAL MODELS are inconclusive, let T_{diss} as a *free parameter* and see if this can be constrained by the data (hence the title)

Schematic view of « Monte Carlo @ Heavy Quark » generator

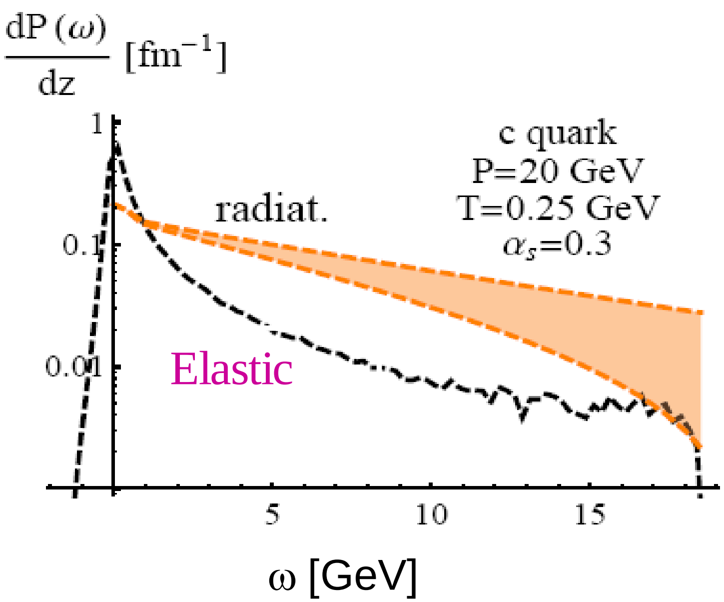


II. “Understanding” the RHIC HQ-data

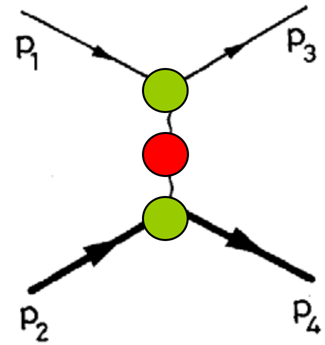
What is the dominant E loss mechanism @ RHIC ? And does its detailed origin influence the fate of quarkonia’s ?

Our basic ingredients HQ for energy loss

Probability of energy loss w per unit length (T,M,…):

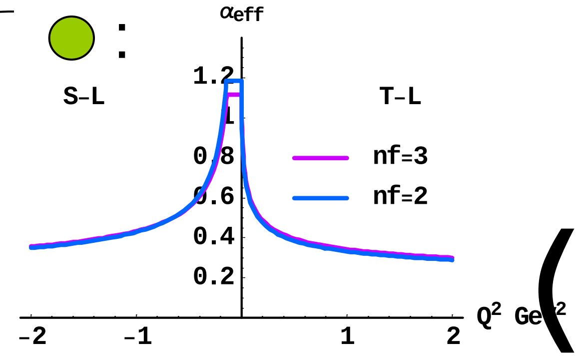


Elastic



+ u and s channels

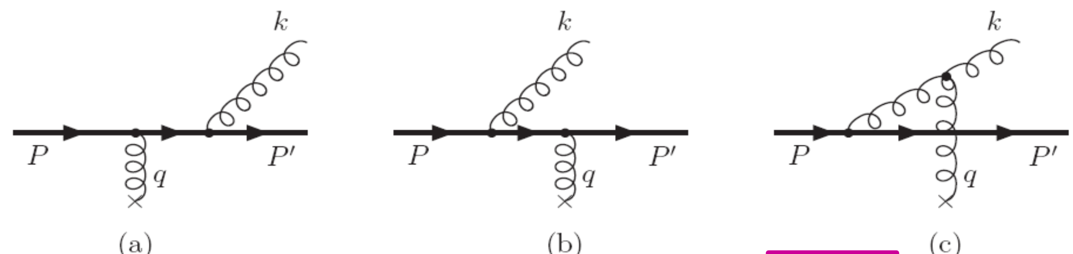
● :



● : OGE effective propagator

$m_{Dself}^2(T) = (1+n_f/6)\,4\pi\alpha_{eff}(m_{Dself}^2)\,T^2$

Uncoherent Radiative



Generalized Gunion-Bertsch for finite mass

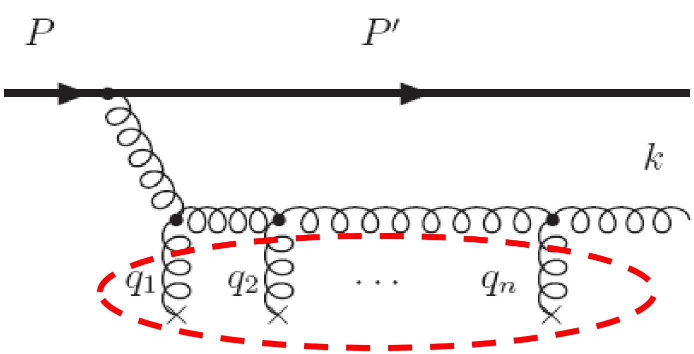
$$\omega\frac{d^3\sigma_{\rm rad}^{x\ll 1}}{d\omega d^2k_\perp dq_\perp^2} = \frac{N_c\alpha_s}{\pi^2}(1-x)\times\frac{J_{\rm QCD}^2}{\omega^2}\times\boxed{\frac{d\sigma_{\rm el}^{Qq}}{dq_\perp^2}}$$

$$\frac{J_{\rm QCD}^2}{\omega^2} = \left(\frac{\vec{k}_\perp}{k_\perp^2+x^2M^2+(1-x)m_g^2} - \frac{\vec{k}_\perp-\vec{q}_\perp}{\left(\vec{k}_\perp-\vec{q}_\perp\right)^2+x^2M^2+(1-x)m_g^2}\right)^2$$

Our basic ingredients HQ for energy loss

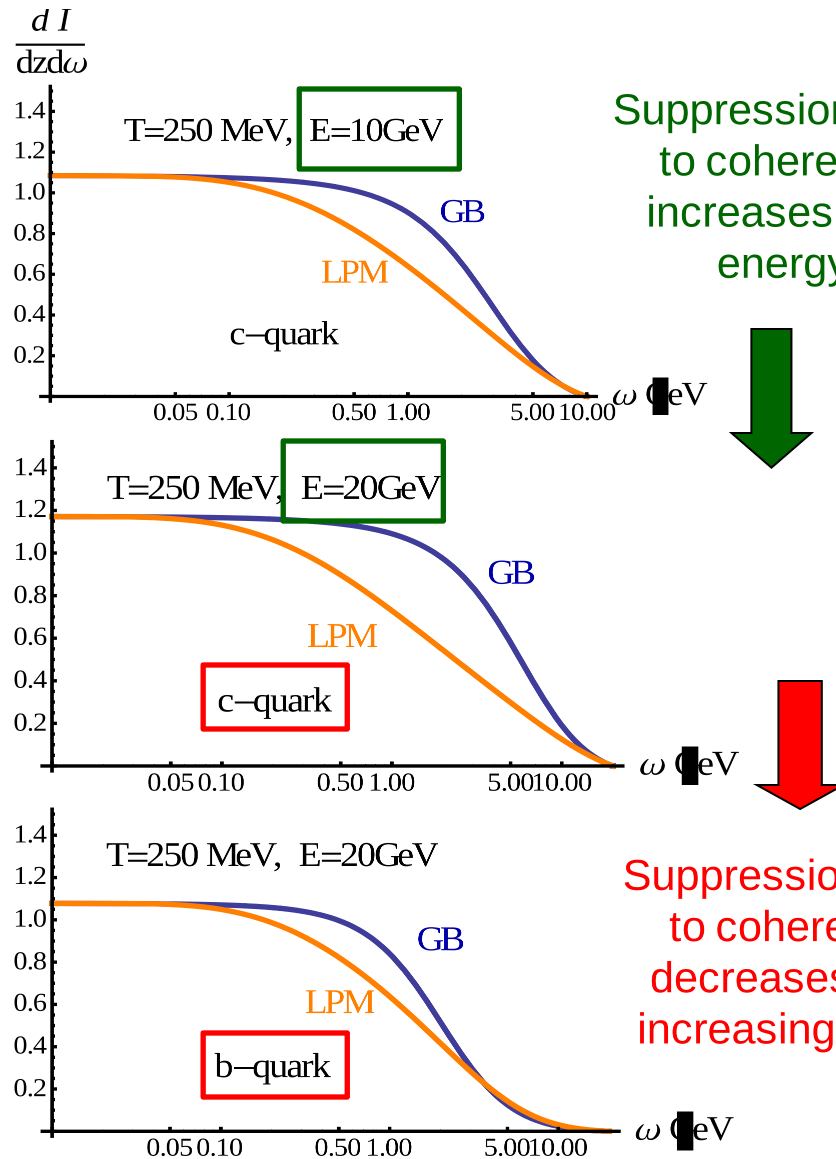
Coherent Radiative

Formation time picture: for $l_{f,mult} > \lambda$, gluon is radiated coherently on a distance $l_{f,mult}$



Model: all N_{coh} scatterers acts as a single effective one with probability $p_{N_{coh}}(Q_\perp)$ obtained by convoluting individual probability of kicks

$$\frac{d^2 I_{\rm eff}}{dz\, d\omega} \sim \frac{\alpha_s}{N_{\rm coh}\tilde{\lambda}} \ln\left(1 + \frac{N_{\rm coh}\mu^2}{3\left(m_g^2 + x^2 M^2 + \sqrt{\omega \hat{q}}\right)}\right)$$



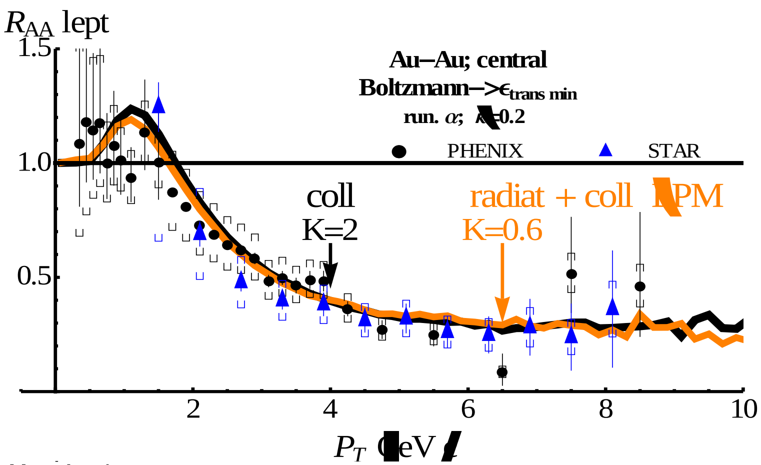
Suppression due to coherence increases with energy

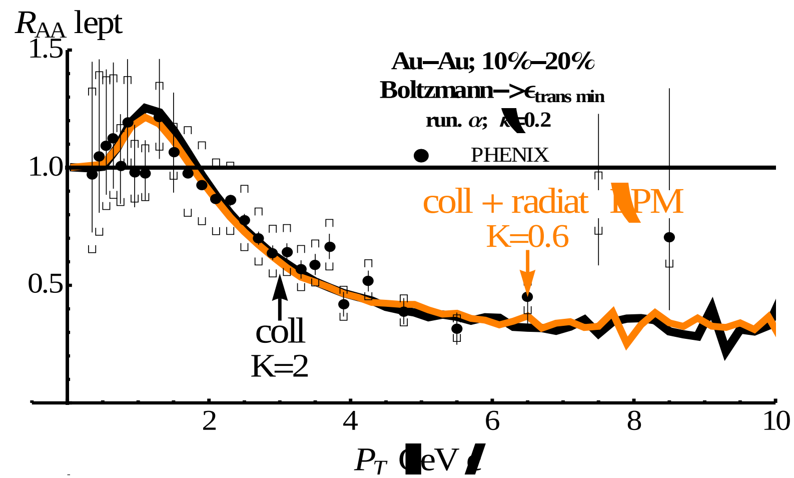
Suppression due to coherence decreases with increasing mass

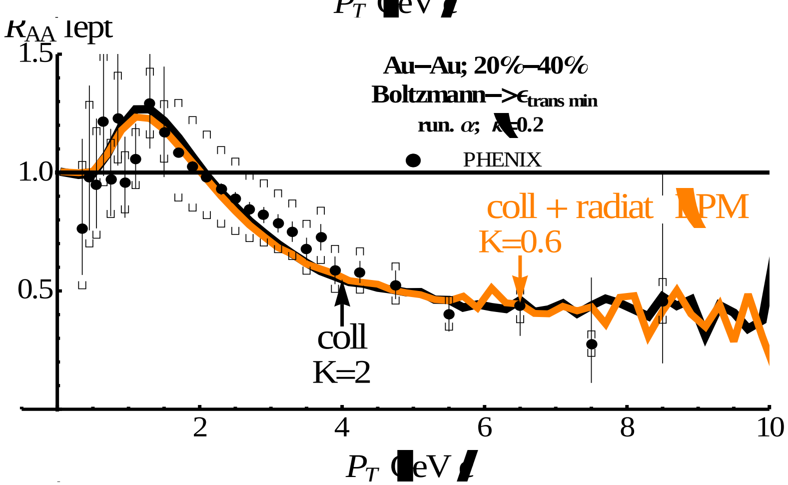
{Radiative + Elastic} vs Elastic for leptons @ RHIC

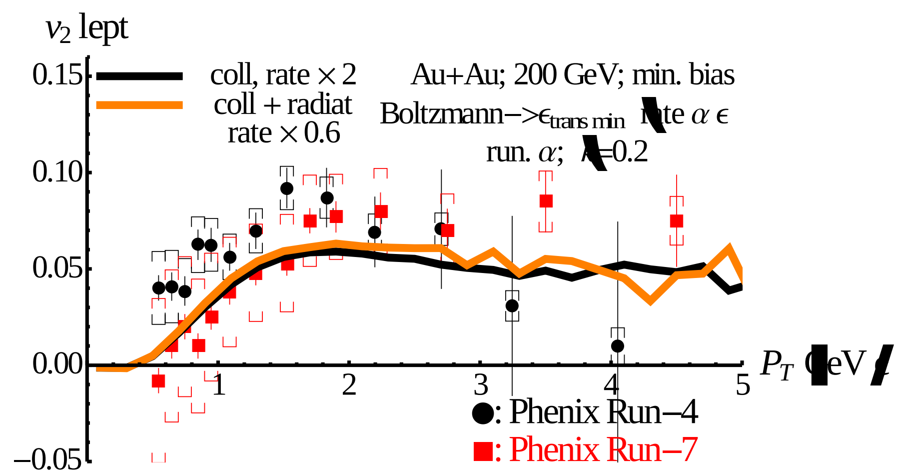
El. and rad. Eloss exhibit very different energy and mass dependences. However…

σ_{el} & σ_{rad} cocktail: rescaling by K=0.6 | **σ_{el} alone rescaling: K=2**









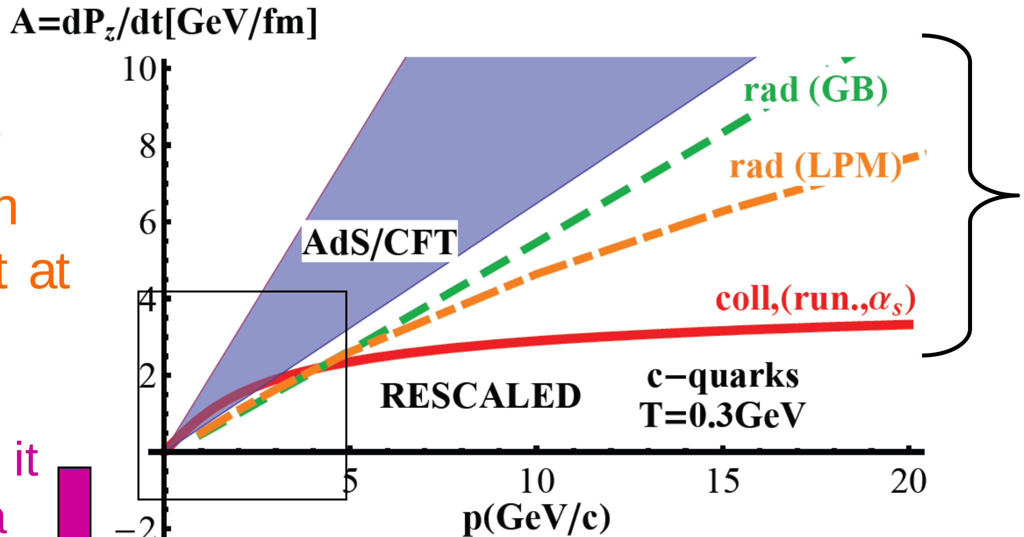
One "explains" it all with ΔE α L (for HQ)

RHIC data cannot decipher between the 2 local microscopic E-loss scenarios

QGP properties from HQ probe

Gathering all *rescaled* models (*coll. and radiative*) compatible with RHIC R_{AA}:

Similar diffusion coefficient at low p

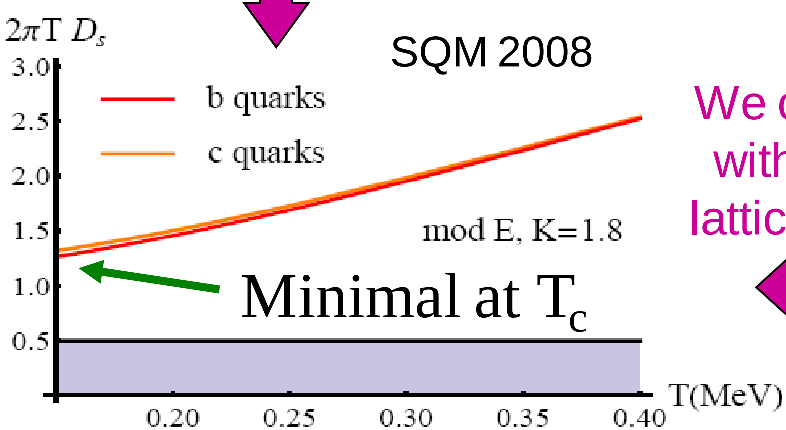


Present RHIC experiments cannot resolve between those various trends

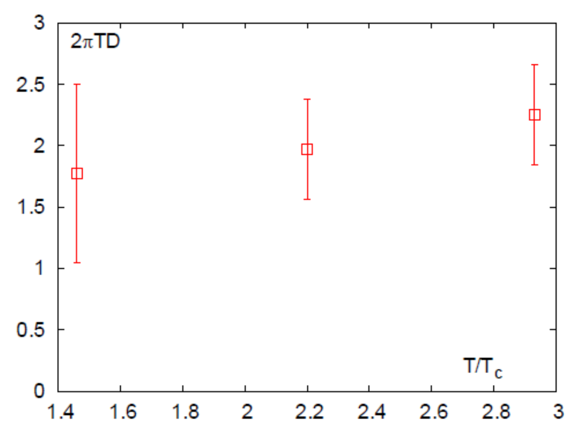
the drag coefficient reflects the average momentum loss (per unit time) => large weight on x ~ 1

Hope that LHC will do !!!

We extract it from data



We compare with recent lattice results



Kaczmarek Bad Honnef 2011

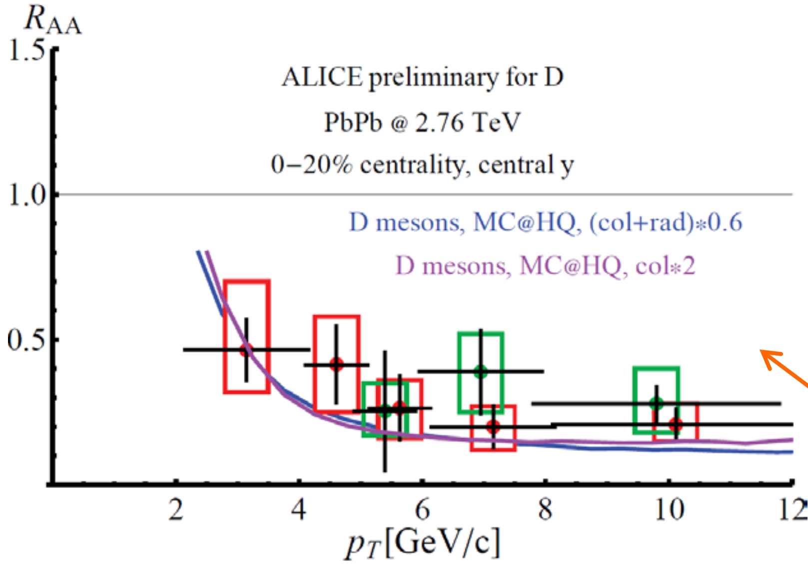
Lesson Yes, it seems possible to reveal some fundamental property of QGP using HQ probes

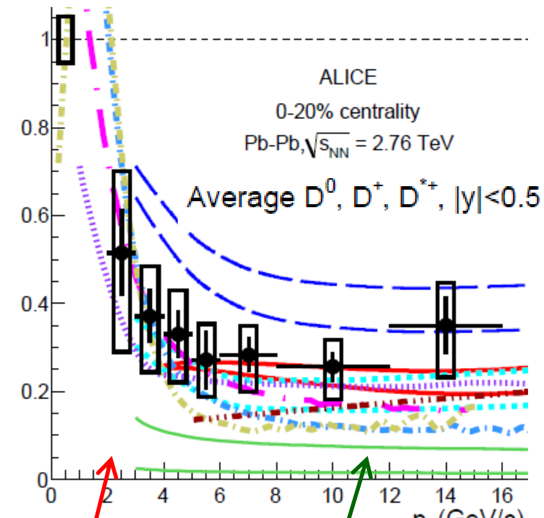
D mesons at LHC (vs ALICE)

Same ingredients as for RHIC

Kolb-Heinz Hydro ajusted to dN_{ch}/dy,

No shadowing



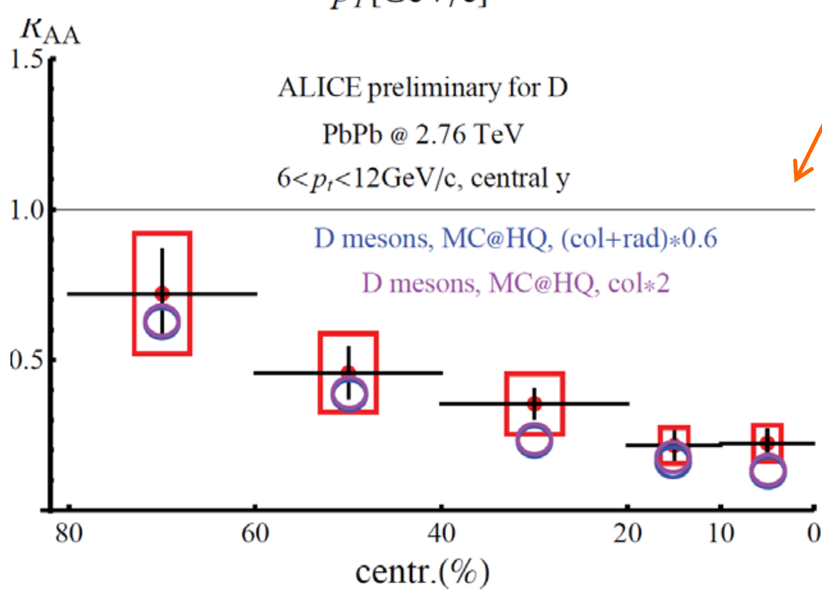


arXiv:1203.2160v1

Rather good agreement with ALICE data; some excess of quenching

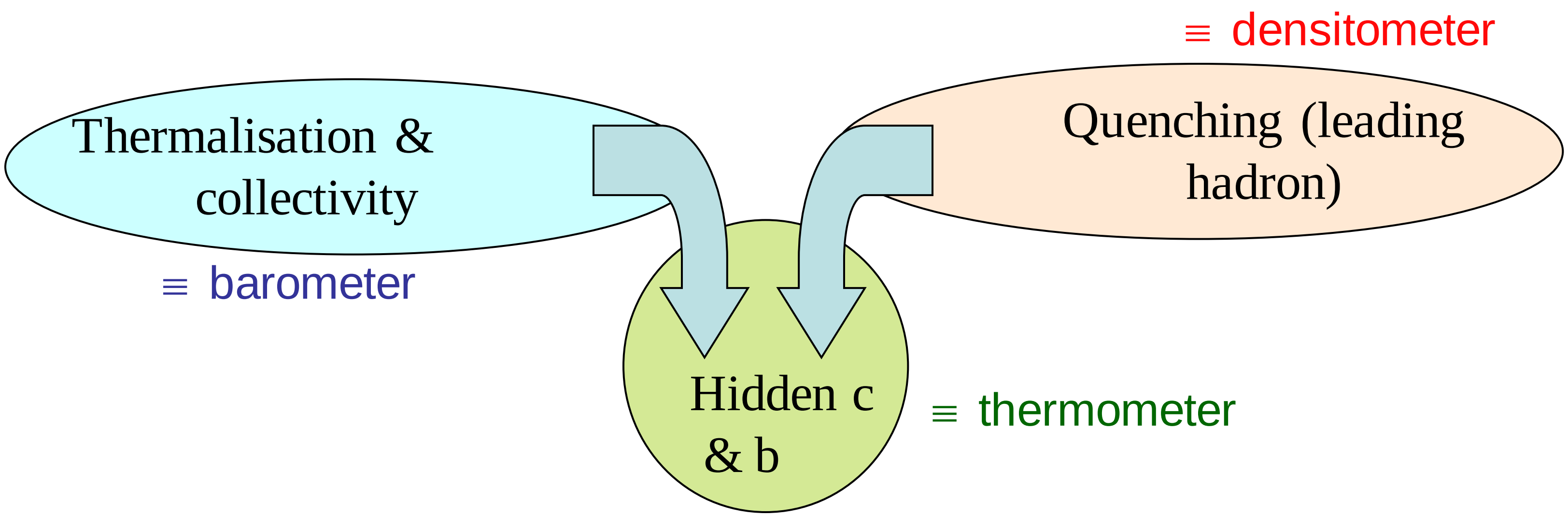
Large dispersion of model predictions

ADS/CFT



Vs centrality (important: tests path length dependence) of Eloss scenario

➢ physics of HQ at low momentum w.r.t. fluid cell seems “under control”

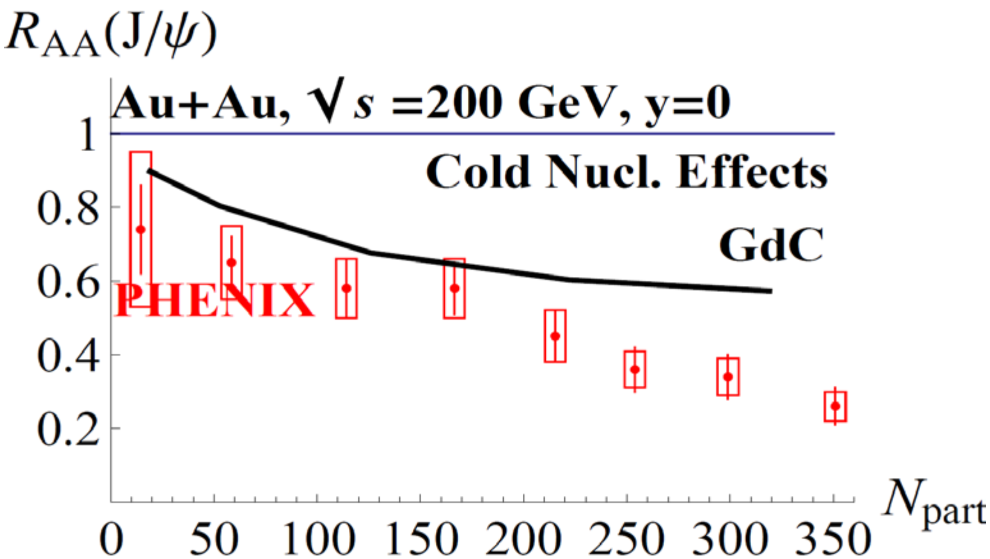


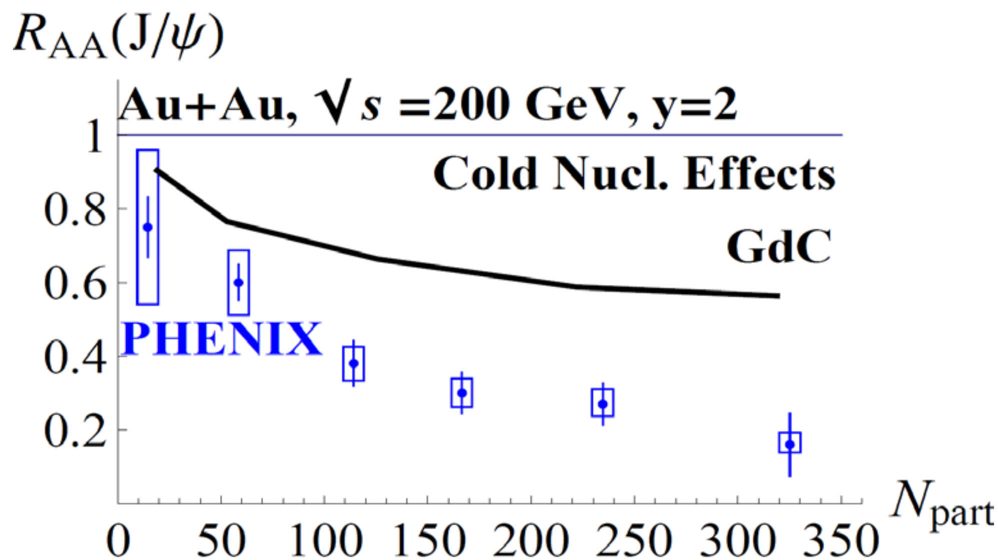
III. Quarkonia in QGP

Work in progress

Integrated J/Ψ numbers @ RHIC

First, we need a baseline taking into account the cold nuclear matter effects (Shadowing, Cronin,..); we take the picture of R. Granier de Cassagnac (2007)

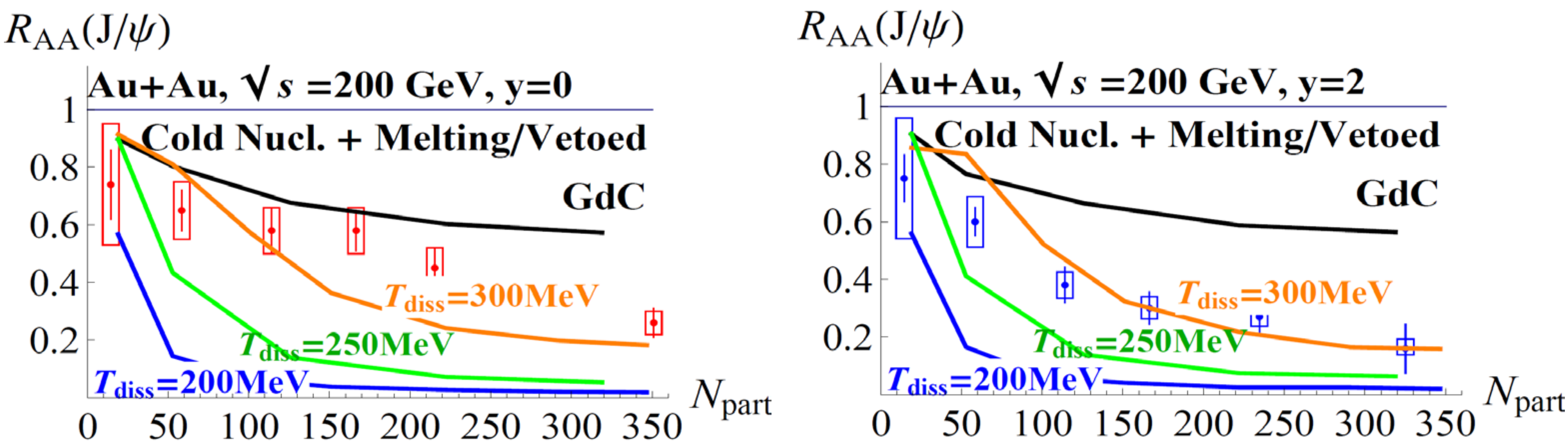




Progress to be made here

Integrated J/Ψ numbers @ RHIC

Next, the (*instantaneous*) vetoing of quarkonia formation due to melting:



Good agreement obtained with a rather large value of $T_{diss} \approx 2\ T_c$.

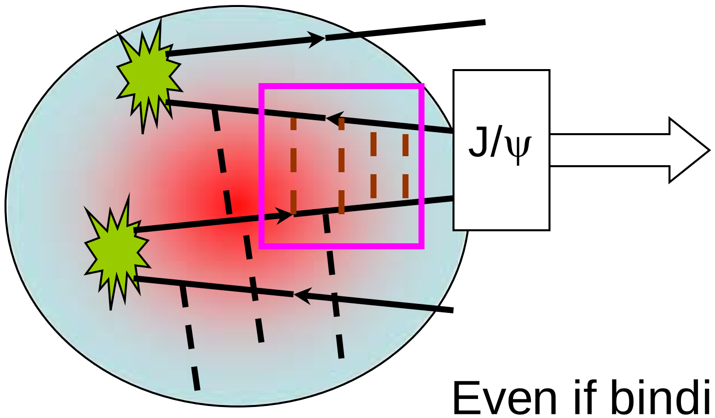
Some claims of “sequencial suppression” with a very bound J/ψ were indeed made by several physicists

``````We do not need recombination !’’’’’’…

except that Q and Qbar may be close in phase space
``````

Turning on (re)combination + hard dissoc

(Re)combination (could become dominant at LHC):



$$\underbrace{Q\bar{Q}}_{\text{Entrance channel}} \to \underbrace{J/\psi^{\star}}_{\text{Binding}} \to J/\psi$$

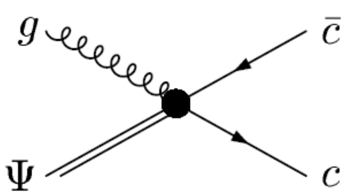
Even if binding process is fast and medium-independent (quarkonia are small bound states), the distributions of Q and Qbar in the entrance channel depend on the past history

(transport theory)

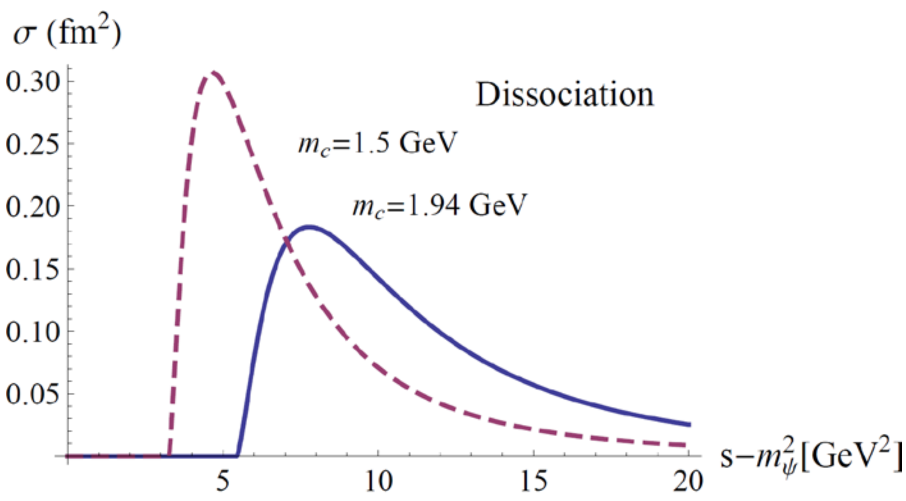
Basic Ingredients

Dissociation

hard dissociation taken according to Bhanot and Peskin + recoil correction (Arleo et al 2001)



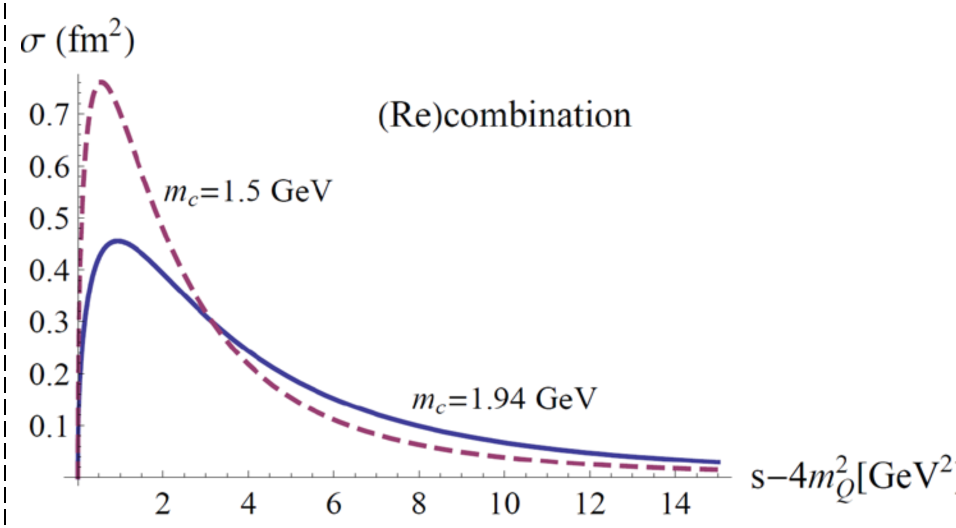
$$\sigma_{(Q\overline{Q})g}(\omega) = \frac{2^{11}}{3^4}\alpha_s \pi a_0^2 \frac{(\omega/\varepsilon(0) - 1)^{3/2}}{(\omega/\varepsilon(0))^5}\Theta(\omega - \varepsilon(0))$$



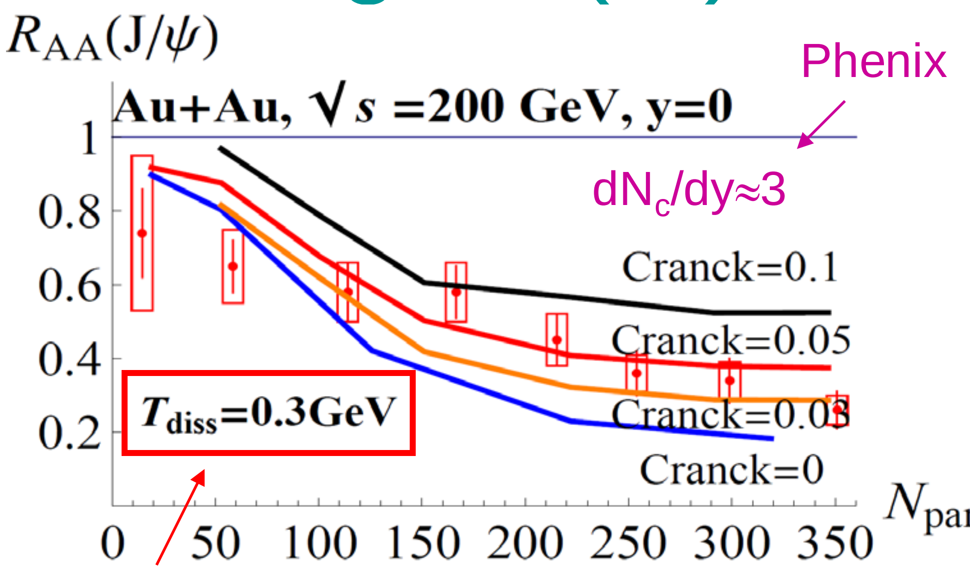
Max ≈ 2 fm^2 at ω ≈ 500 MeV

Recombination

Cross section obtained from σ_{diss} via detailed balance

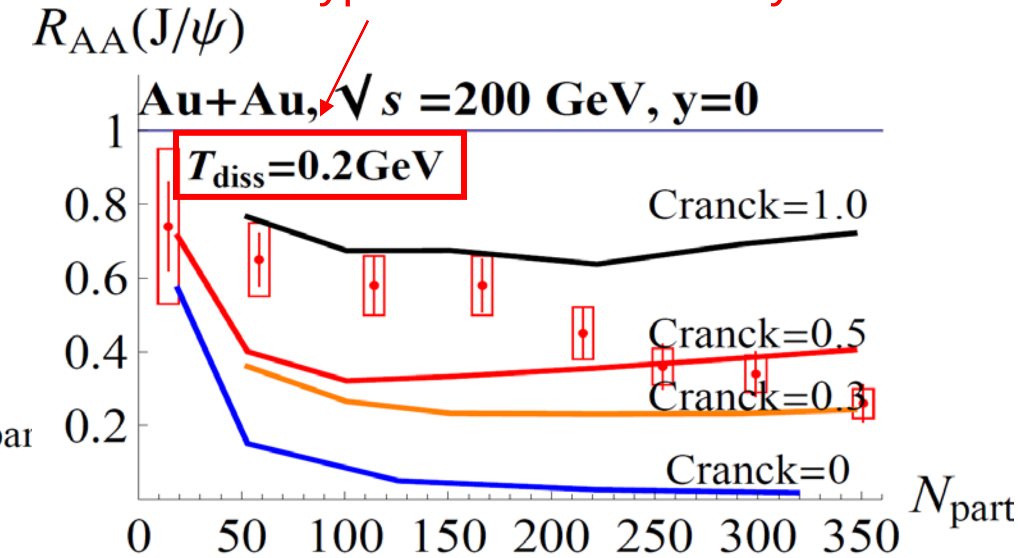


Turning on (re)combination + hard dissoc



Typical value for strongly bound

Typical value for weakly bound



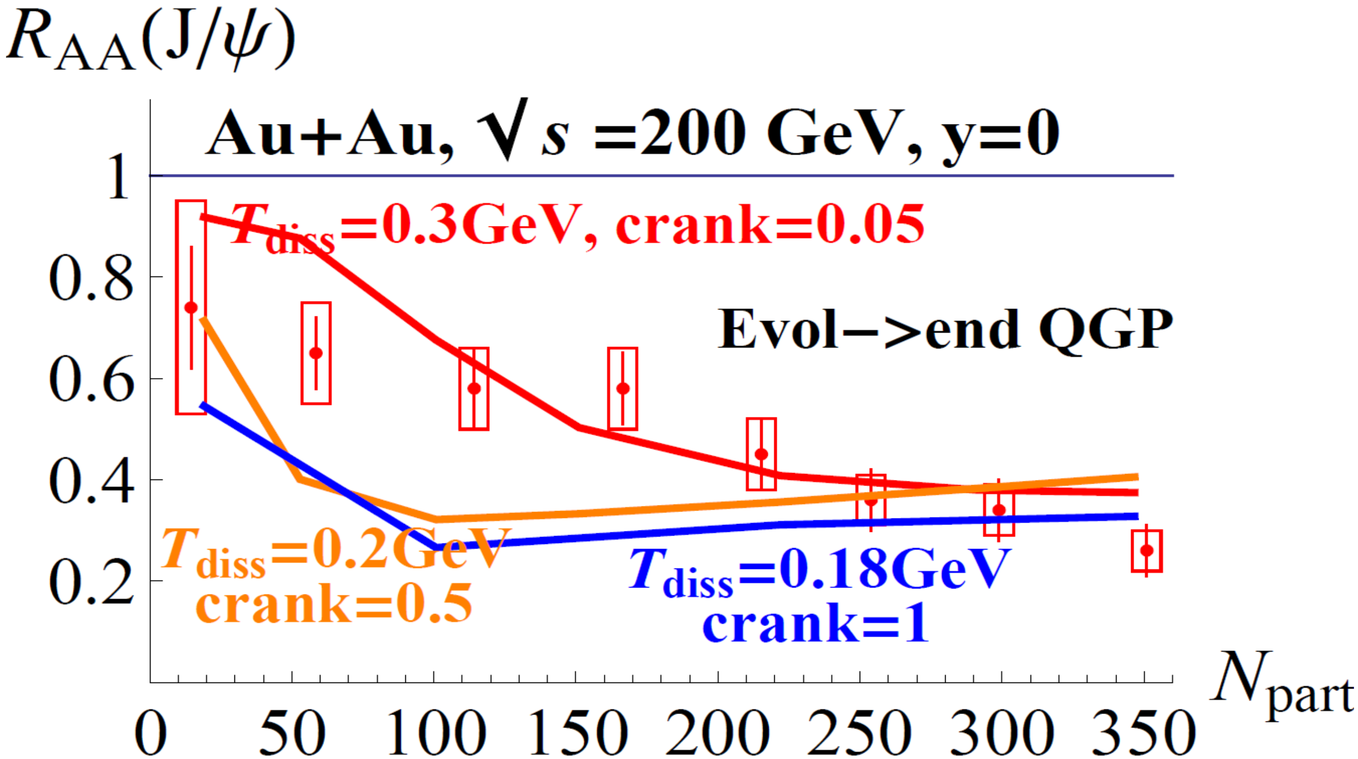
Problem: One has to reduce the fusion probability by a factor ~10 to reproduce the data (if recomb. cross section taken at face value, one arrives at R_{AA} (most central > 2 !).

Problem never comes alone: Strongly bound quarkonia are the ones for which the Bhanot-Peskin approach should be legitimate. Φ states exist early => lot of HQ pairs present in pahse space

Absolute numbers are better reproduced (if one believes in mostly canonical – cranck=0.5-1 – recombination), although the R_{AA} dependence on N_{part} is not as satisfying

Best parameters from R_{AA}

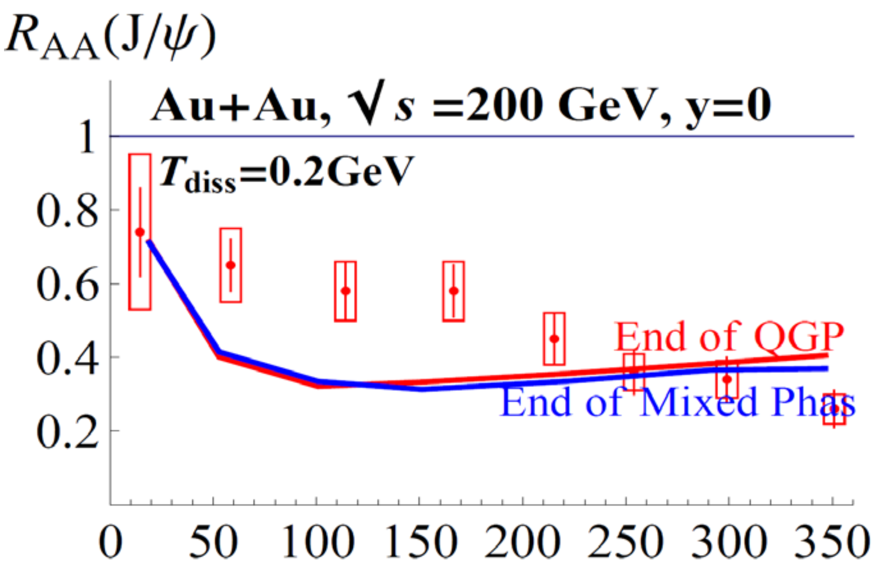
“Optimal” choices in the (T_{diss}, σ_{fus}.) parameter plane



Conclusion: $T_{diss} \in [0.2,0.3]$… but difficult to go beyond

Finer analysis: Thermometer of what ?

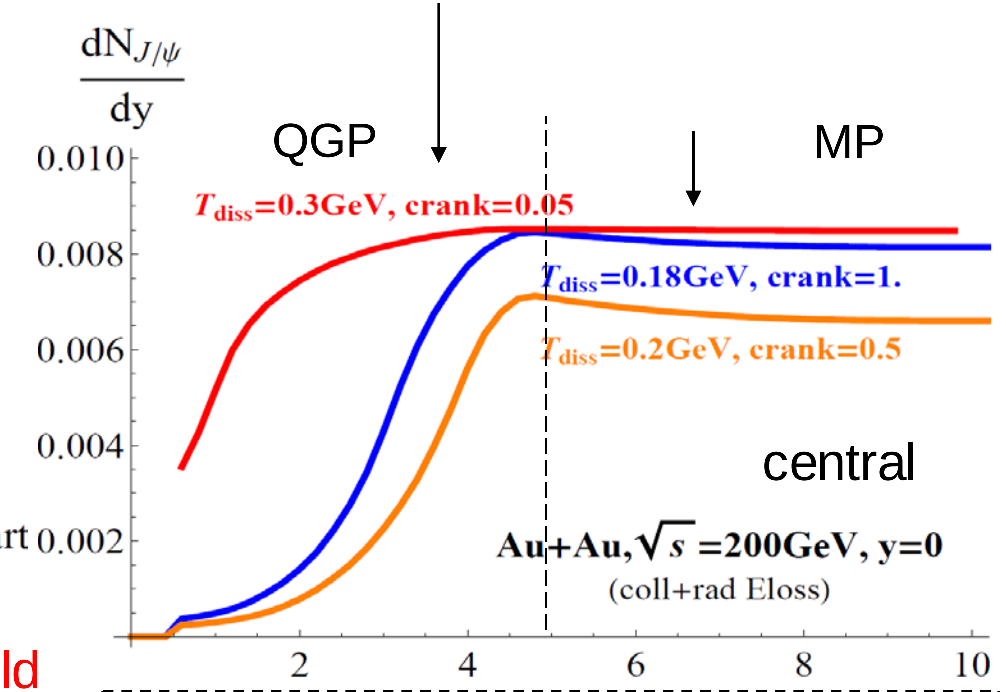
Other parameters… E_{loss}, detailed Medium evolution…

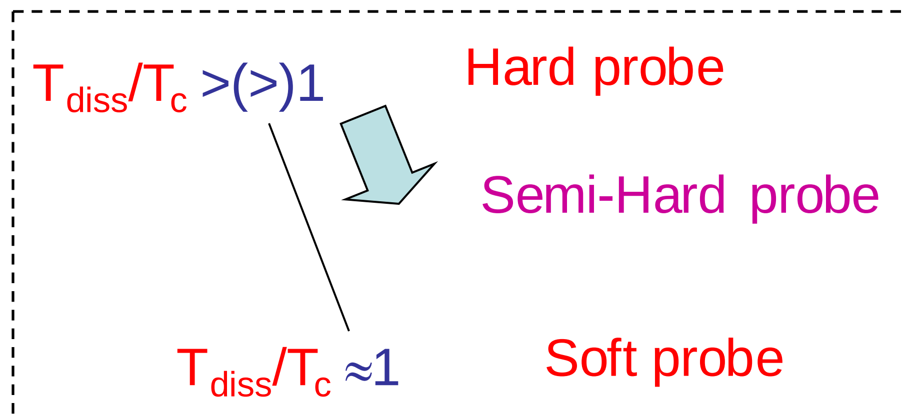


If quarkonia are a thermometer, it should be first agreed upon the phase it probes

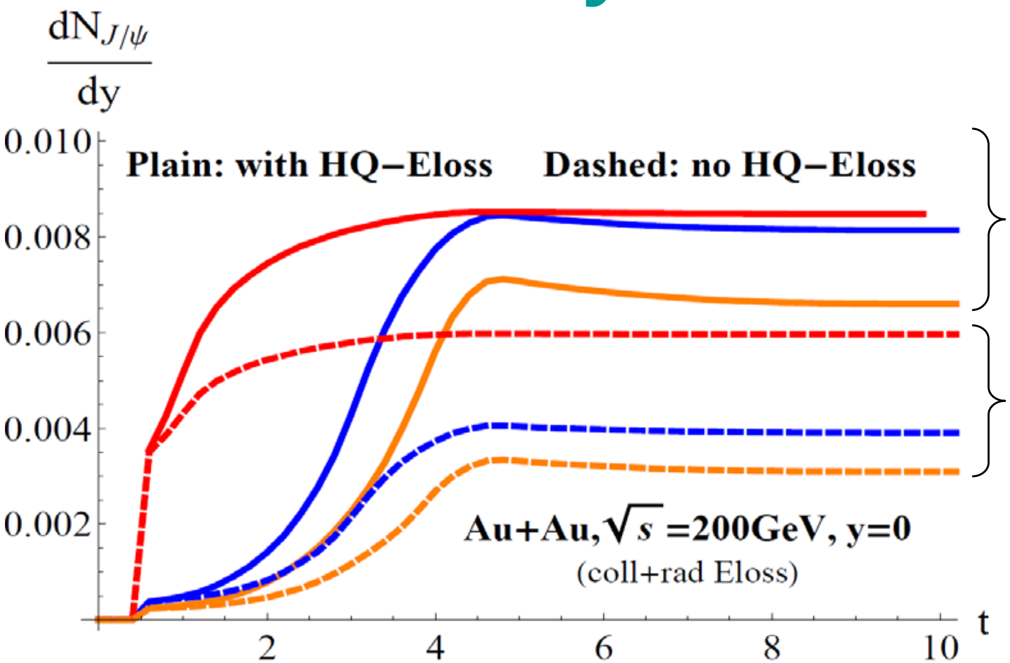
Dynamical evolution does not confirm the idea of statistical recombination in the mixed phase

Dominant production at various time depending on T_{diss}… saturates *before* the end of the QGP





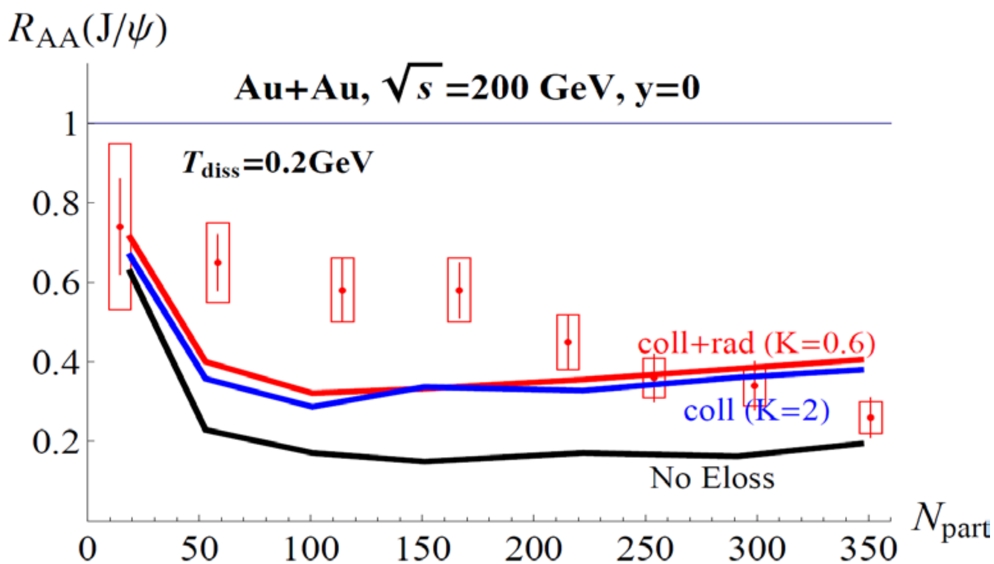
Finer analysis: role of HQ energy loss



Eloss

No Eloss

Energy loss favors the coalescence of J/ψ (brings the c quarks together in phase space)



However: Once the Energy loss has been “properly” calibrated on non-photonic single-e R_{AA}, then the production rates do not depend too much on the detailed phenomena

Prediction for LHC:

Work to be continued during the LHC ERA:

HQ Parameters:

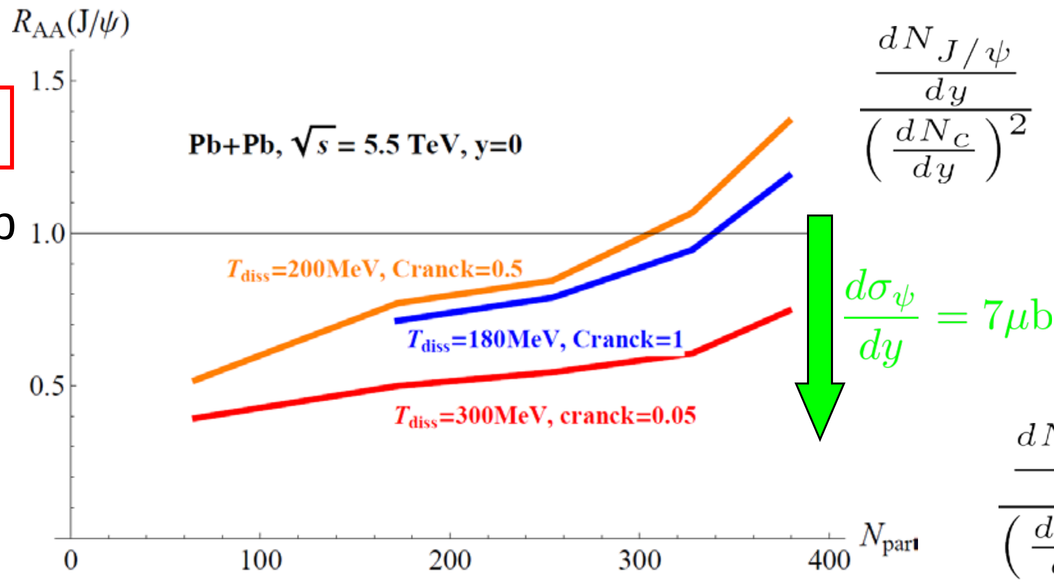
y=0: $d\sigma_\psi/dy$=2μb in pp; $dN_c/dy \approx 30$ in PbPb

Hydro Parameters:

s_0= 268 fm^{-3}

≡

$dN_{ch}/d\eta \approx 2300$ in PbPb, b=0



LHC

$$\frac{\frac{dN_{J/\psi}}{dy}}{\left(\frac{dN_c}{dy}\right)^2} \approx 0.6 - 1 \times 10^{-4}$$

(b=0)

RHIC

$$\frac{\frac{dN_{J/\psi}}{dy}}{\left(\frac{dN_c}{dy}\right)^2} \approx 4 \times 10^{-4}$$

Fusion of c-quarks at LHC: 15-25 x more probable that at RHIC, but strong increase of the prompt J/ψ as well….

Preliminary conclusions

Reasonnable agreement with RHIC data for J/ψ (for other observables (p_T, v_2): see Hamza's talk this afternoon), but difficulties to tame the recombination down

1. Are the data pointing towards the picture of a strongly bound J/ψ (sequential suppression) ?

Not so obvious to us

2. Can we challenge the picture of statistical recombination (A. Andronic, PBM, J. Stachel) ?

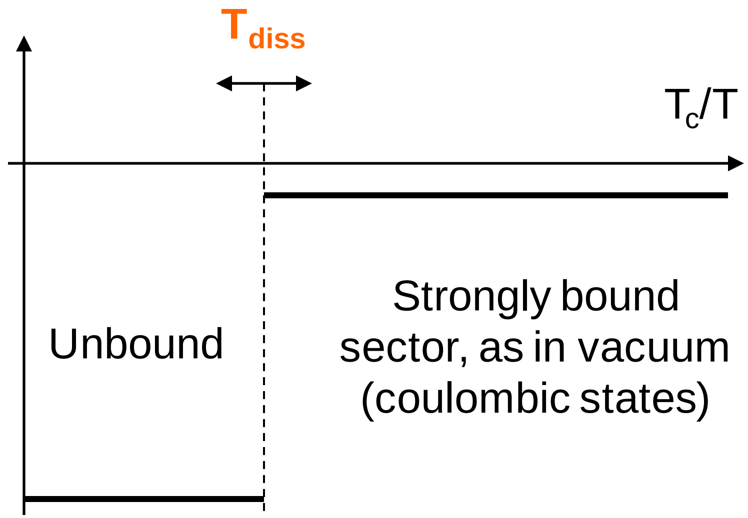
Statistical recombination picture could not be recovered from the transport theory

3. Can we try to *extract* the dissociation temperature from the data ?

A rather large effective dissociation temperature ($T_{diss}\approx$0.25-0.3 GeV) seems to be favored by the data, provided one has a good quantitative argument to explain why the recombination of HQ should be reduced by a factor 10 w.r.t. the naive Bhanot - Peskin cross section (gluon mass ? J/ψ(T) in BP ?)

Otherwise, low dissociation ($T_{diss}\approx$0.2 GeV) are unavoidable

IV. Beyond the dual model



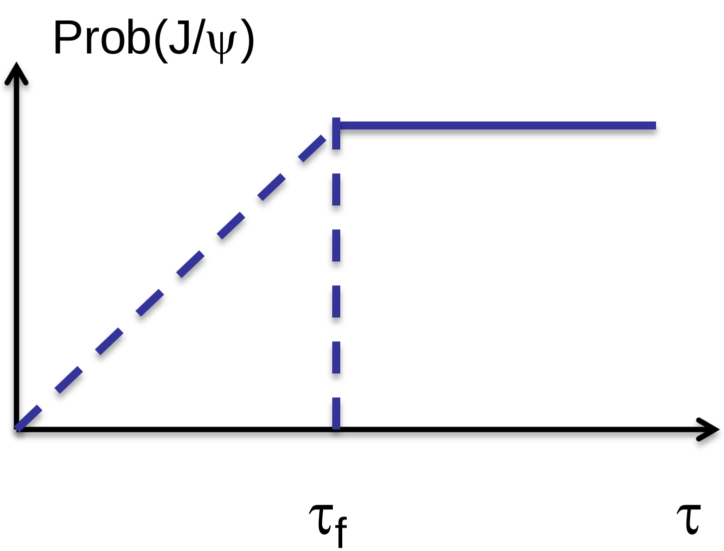
Please keep in mind: Quarkonia represent only a small % of the total QQbar state => should not be treated independently from one another (besides recombinations)

J/Psi suppression at high temperature

Standard folklore:

a) Following sequential suppression (quasi-stationnary picture)… The quarkonia which should be formed at (t_0,x_0) is not if $T(t_0,x_0)>T_{diss}$ => Q-Qbar pair is “lost” for quarkonia formation

b) Refined version wrt a) : quarkonia need some formation time tf to be resolved:



J/Psi suppression at high temperature

We let the QQbar pair evolve until $\left(t_0 + t_f, \vec{x}_0 + \vec{v}_{Q\bar{Q}} t_f\right)$ and then look whether

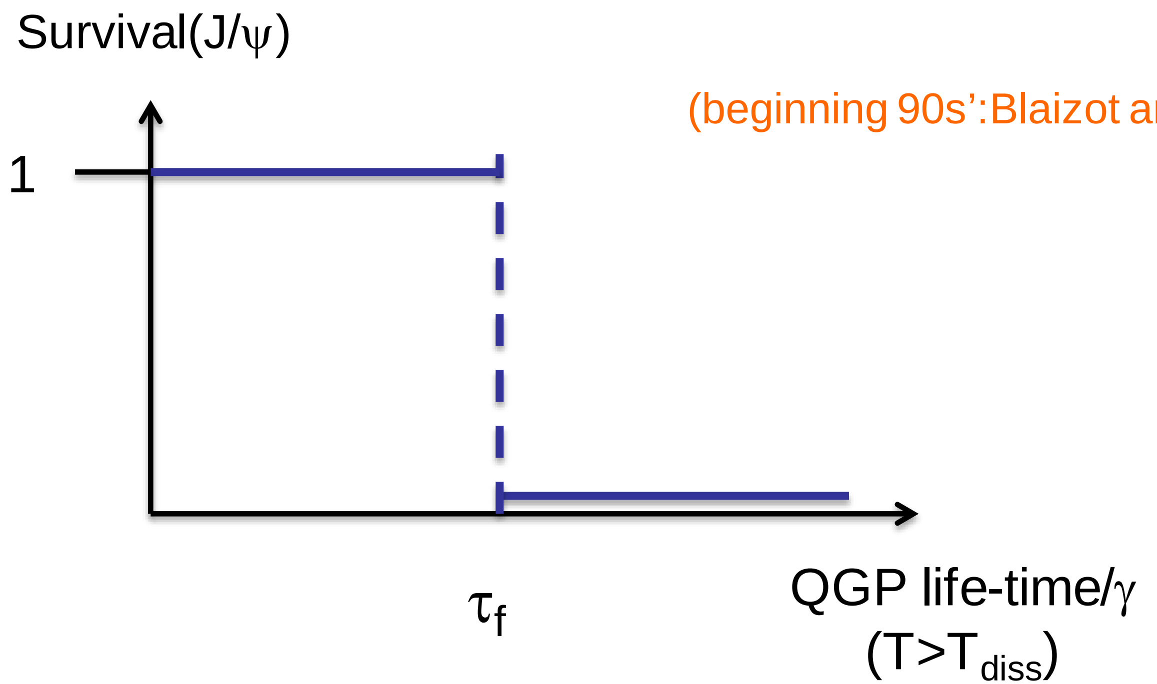
$$T\left(t_0 + t_f, \vec{x}_0 + \vec{v}_{Q\bar{Q}} t_f\right) > T_{\rm diss}$$

Not formed

$$T\left(t_0 + t_f, \vec{x}_0 + \vec{v}_{Q\bar{Q}} t_f\right) < T_{\rm diss}$$

Formed as in vacuum, then dissociated through « hard » collisions

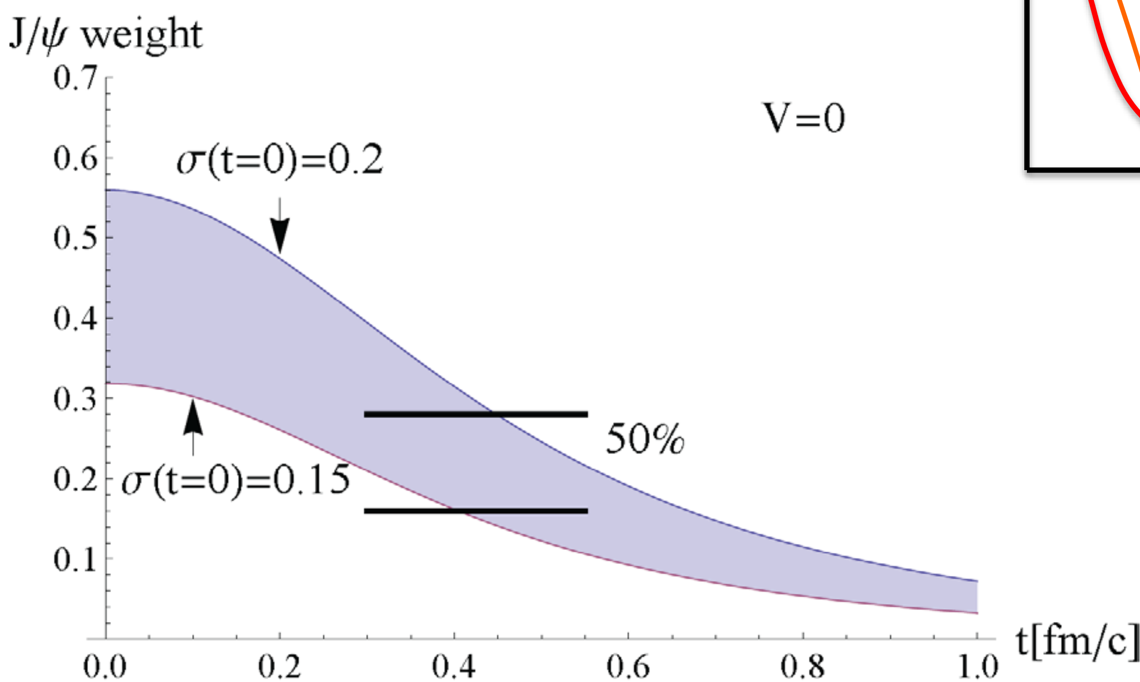
(beginning 90s':Blaizot and Ollitrault)

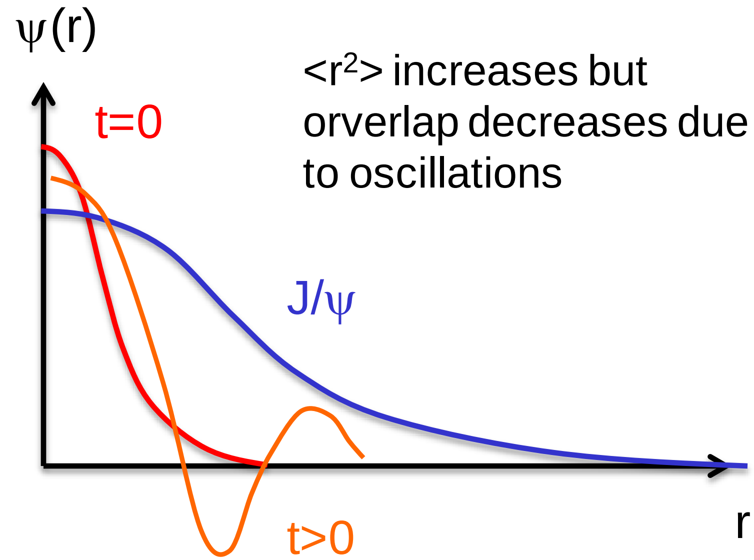


J/Psi formation at high temperature

Alternate description: Q-Qbar state described by a wave function evolving in V=0

Gaussian wave packet evolving in V=0:

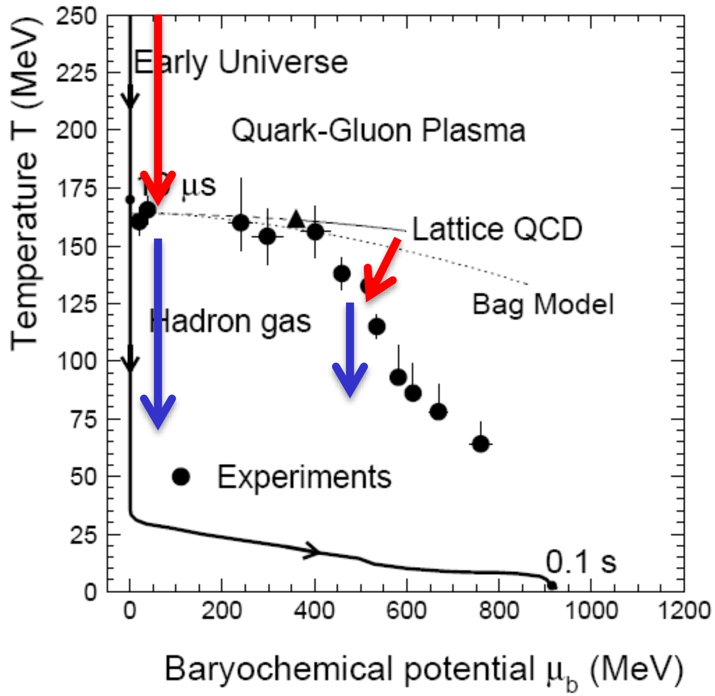


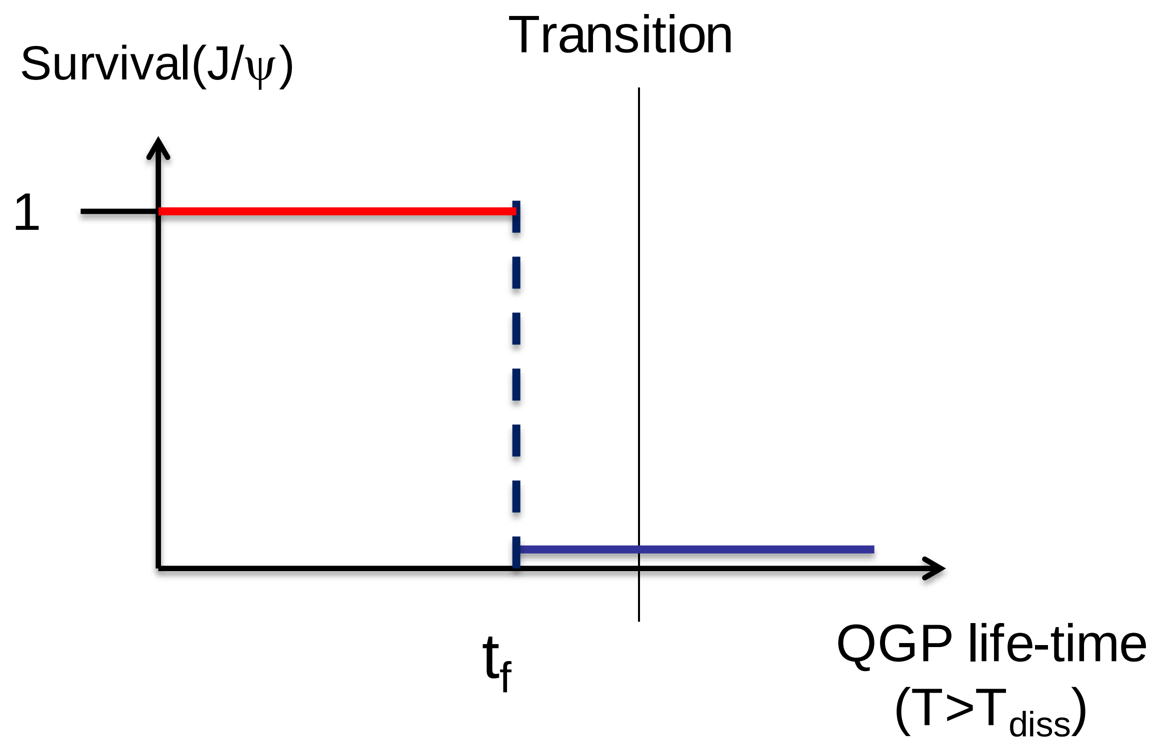


<r²> increases but orverlap decreases due to oscillations

J/Psi suppression

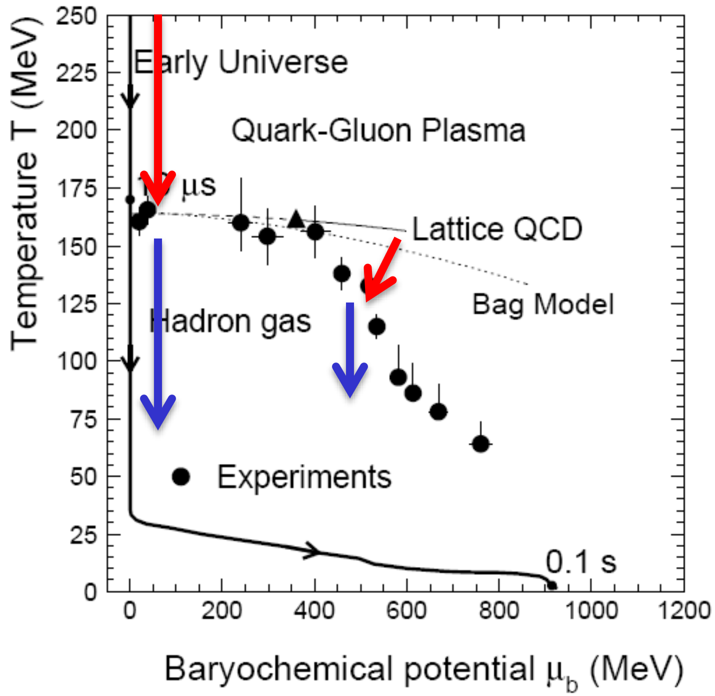
1rst crude description ("dual" model):



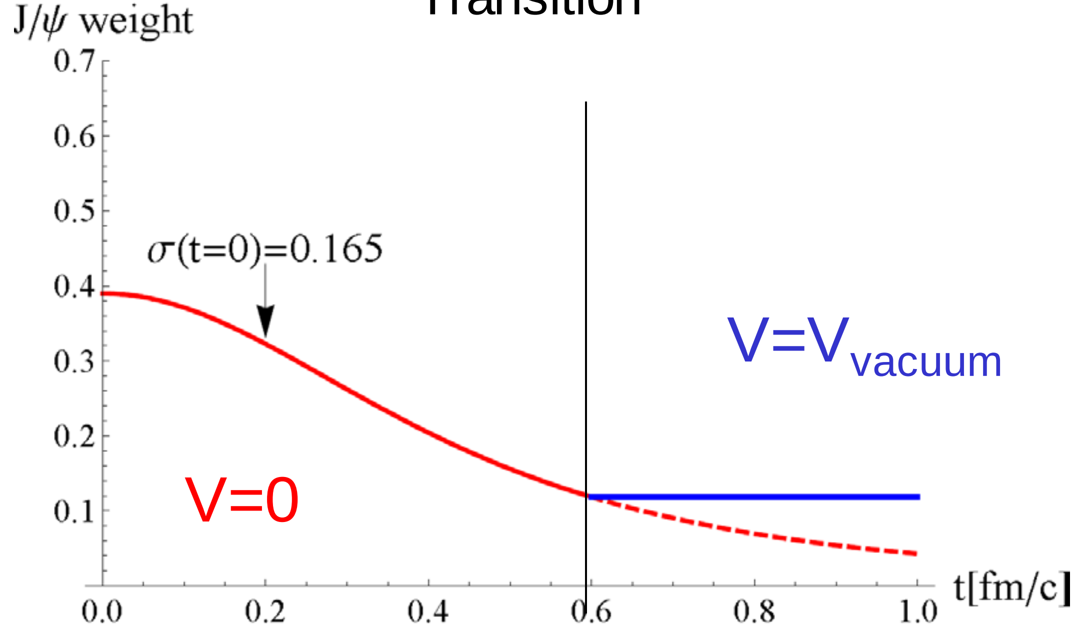


J/Psi suppression (microscopic)

Continuous evolution



Transition



For this example: Survival ≈ 0.13/0.4 ≈ 33%

Important feature: quantum evolution leads to smooth suppression patterns

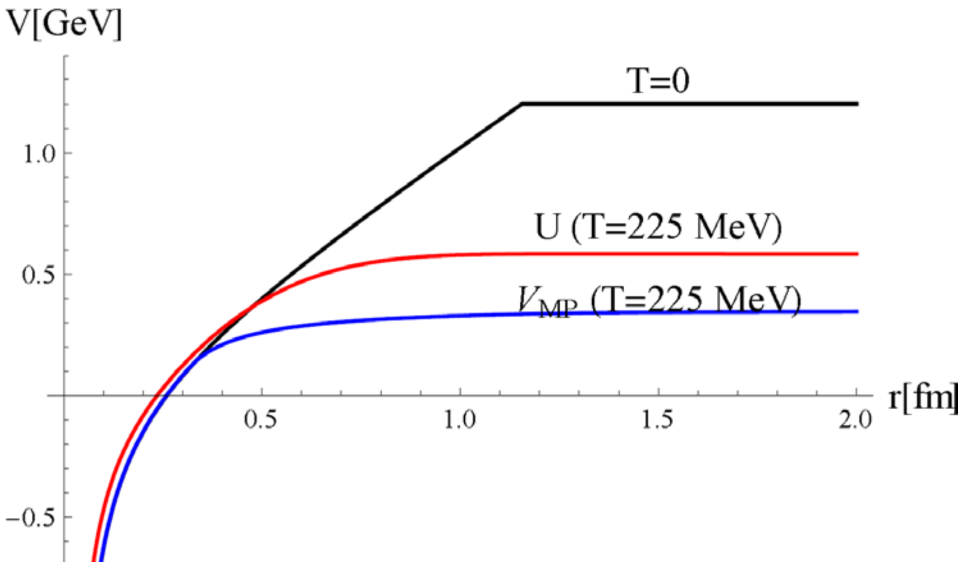
For realistic QGP lifetimes at RHIC: Survival of a few % (neglecting corona effects)

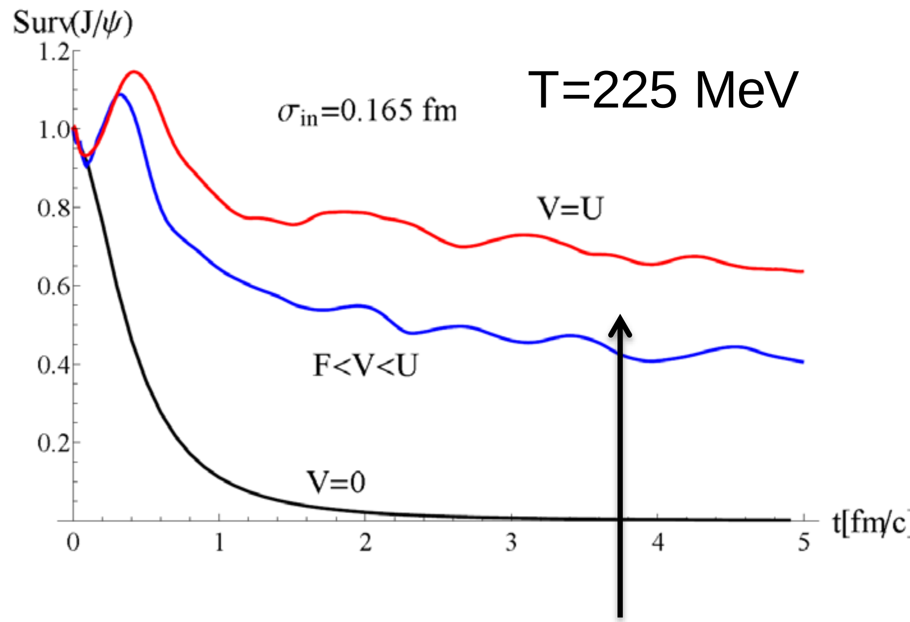
=> Should we care ?

J/Psi suppression (microscopic)

BUT: 2 missing ingredients

1. Q-Qbar forces (beginning 90s':Thews, Gossiaux and Cugnon,…) : permits to preserve some Q and Qbar at close distance





Indeed, the "residual" potential permits to slow down the suppression along time ! We converge towards asymptotic survival probabilities $\in$ [0,1]

J/Psi suppression (microscopic)

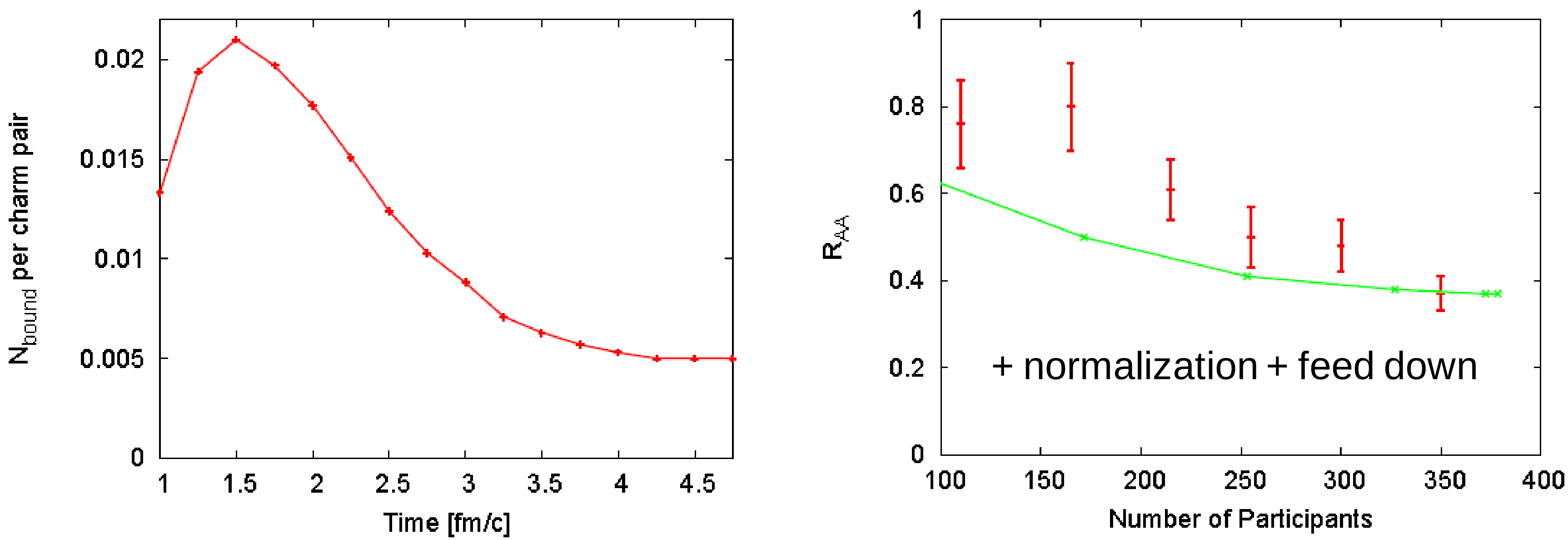
BUT: 2 missing ingredients

2. Stochastic q-Q, g-Q forces

For a long while: interactions with QGP/hot medium constituents only thought as the source for quarkonia dissociation (Bhanot – Peskin) and treated through inelastic cross-sections… True for dilute media

Shuryak & Young (08):

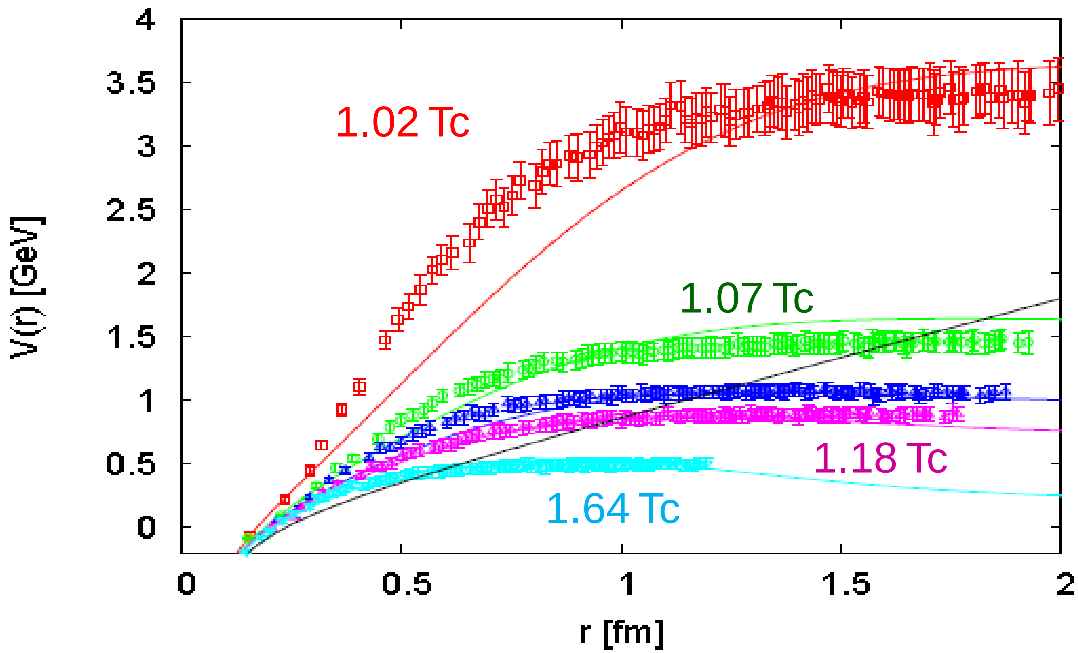
In strong QGP, diffusion of HQ slow down their separation ($<r^2> \alpha D_s$ t) and helps in reducing the suppression !!!



Suppression of suppression… Robust or not ?

Shuryak & Young (08): some ingredients

✓ U as a potential



The most “binding” choice; Around Tc: String tension up to 3 times string tension in vacuum !!!

Suppression of suppression… Robust or not ?

Shuryak & Young (08): some ingredients

✓ Dealing both with quantum evolution and stochastic forces:

Wigner Moyal distribution:

$$F(\mathbf{x}^N, \mathbf{p}^N, t) = \left(\frac{1}{\pi\hbar}\right)^{3N} \int e^{2i\mathbf{p}^N\cdot\mathbf{y}^N/\hbar} \rho(\mathbf{x}_-^N, \mathbf{x}_+^N, t)\, d\mathbf{y}^N$$

Right concept for non pure quantum system (statistical average), but also to make contact with semi-classical interpretations

Wigner-Moyal equation in relative coordinates:

$$\left(\frac{\partial}{\partial t} + \frac{\vec{p}}{\mu}\cdot\frac{\partial}{\partial\vec{x}}\right) f(\vec{x},\vec{p};t) = \frac{2}{\hbar}\sin\left(\frac{\hbar}{2}\frac{\partial}{\partial\vec{p}}\cdot\frac{\partial}{\partial\vec{x}}\right) V(\vec{x}) f(\vec{x},\vec{p};t) + I_{\rm col}$$

with $\vec{x} = \vec{x}_Q - \vec{x}_{\bar{Q}}$ and $\vec{p} = \frac{\vec{p}_Q - \vec{p}_{\bar{Q}}}{2}$

Exact equation, but difficult to solve due to sign problem

Suppression of suppression... Robust or not ?

Shuryak & Young (08): some ingredients

✓ Dealing both with quantum evolution and stochastic forces:

Semi-classical expansion => 1 body Liouville equation:

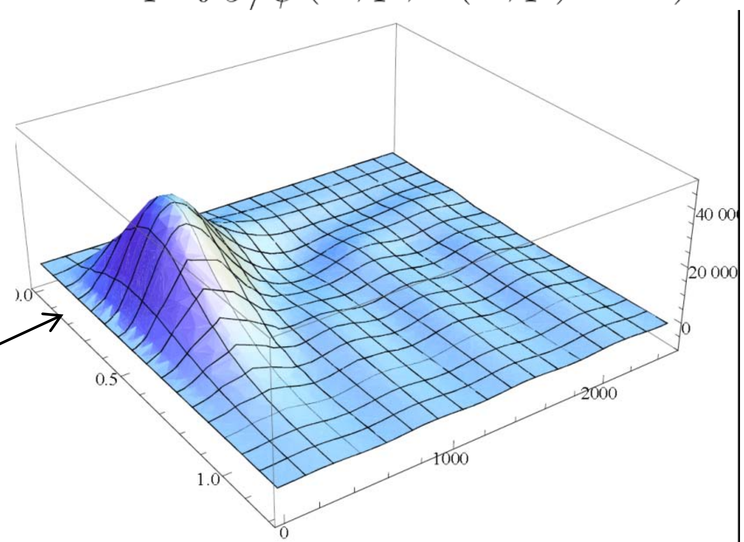
$$\left(\frac{\partial}{\partial t} + \frac{\vec{p}}{\mu}\cdot\frac{\partial}{\partial \vec{x}} - \frac{\partial V}{\partial \vec{x}}\cdot\frac{\partial}{\partial \vec{p}}\right) f(\vec{x},\vec{p};t) = I_{\mathrm{col}}$$

Test particles method, submitted to the QQbar force + stochastic external forces

Langevin evolution with binding force (♥ fast !!! ♥)

Prob J/ψ(t): $P_{J/\psi}(t) = \frac{1}{N}\sum_{i=1}^{N} f_{J/\psi}(\vec{x}_i(t),\vec{p}_i(t))$

$x^2 p^2 f_{J/\psi}(x,p,\theta(\vec{x},\vec{p})=0)$



Caviat: f is not a density (not defined positive)
semi-classical approx justified ?

Notice however that $f_{J/\psi}$ is mostly positive
(but not a full justification)

Suppression of suppression… Robust or not ?

Shuryak & Young (08): some ingredients

✓ Stochastic force on Q and Qbar are uncorrelated

… although QQbar is seen as a dipole at short distances

…but most of QQbar pairs are not at close distance already after short time => probably ok !

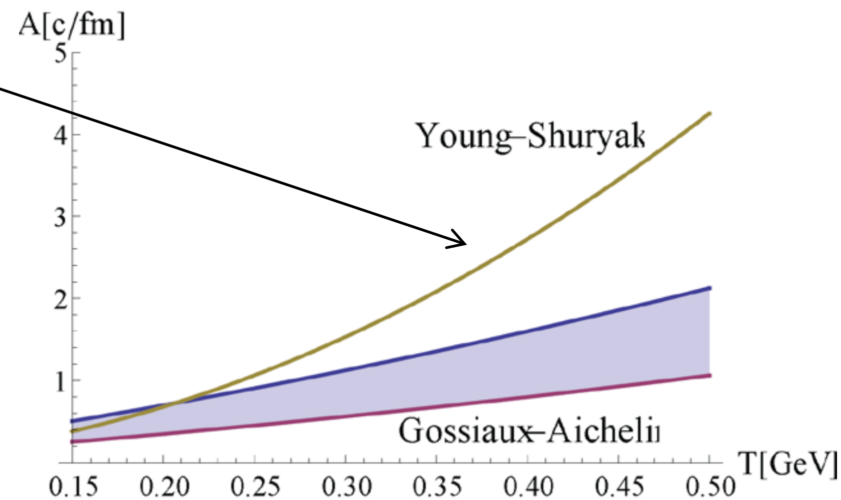
✓ Hydro evolution and HQ dynamics from Moore and Teaney (2005). In particular $D_c \times 2\pi T = 1.5\text{-}3$ =>

$$A_c = \frac{T}{M D_c} = \frac{2\pi T^2}{1.5 M}$$

Our model + detailed comparison to RHIC:

$$A_c[\mathrm{c/fm}] = K\left(1.5T[\mathrm{GeV}] + 1.25T^2\right)$$

Effective linear rise: $\alpha_s(T)$



Test of robustness

Goal of our contribution:

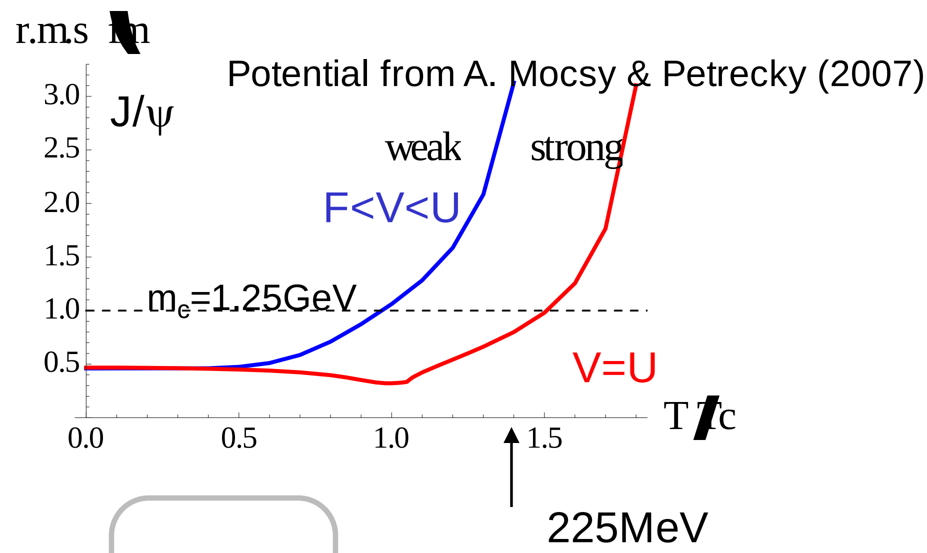
- ✓ Get acquainted with the impact of stochastic forces on quarkonia suppression
- ✓ Test the robustness of the results obtained by Young and Shuryak, modifying a) the V(T) and b) the drag coefficient A(T)

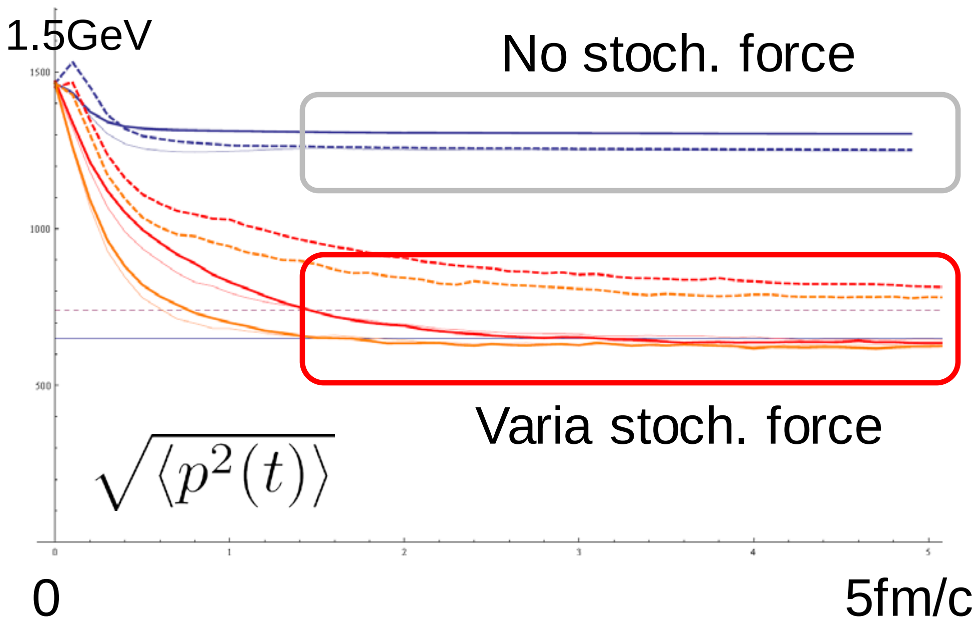
Test of robustness I

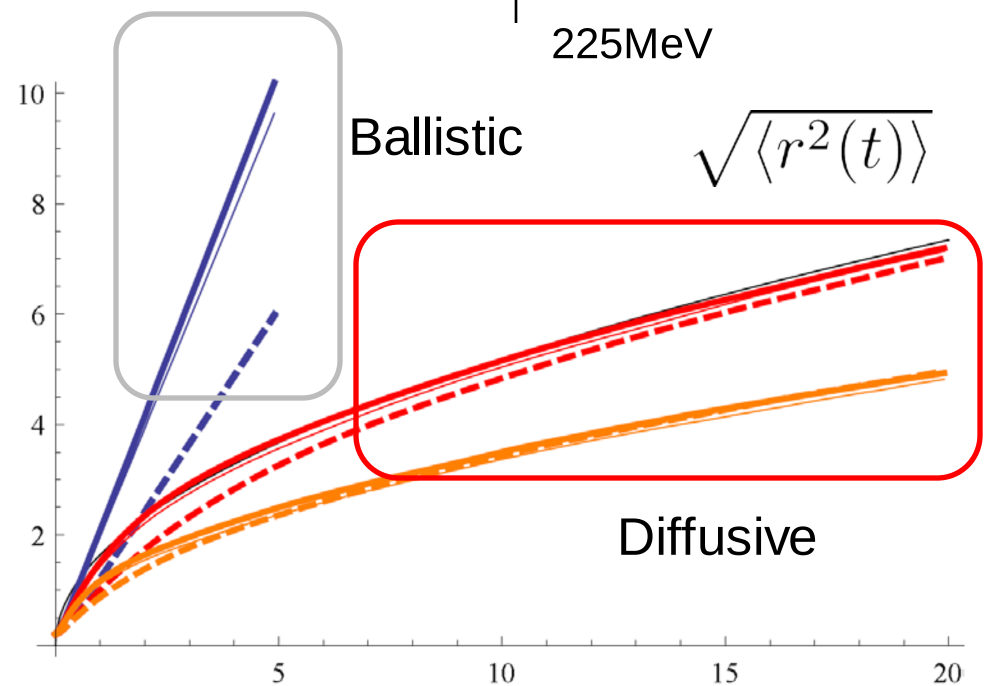
T=225 MeV (T/Tc ≈ 1.4):

Nearly unbound if one takes $V=V_{PM}$,
still strongly bound if one takes V=U

$$\sqrt{\langle r^2(t=0)\rangle} = 0.2\ \mathrm{fm}$$





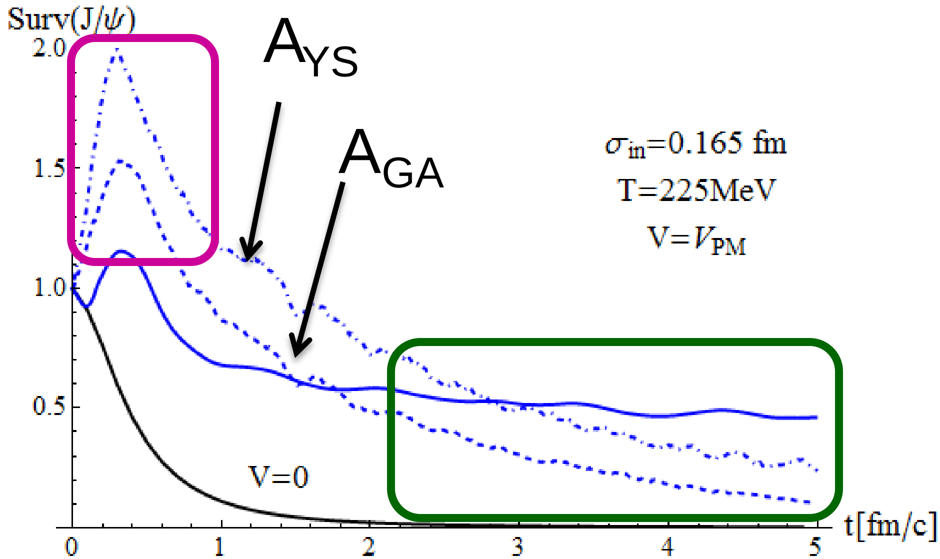


Stochastic cooling down of ccbar state

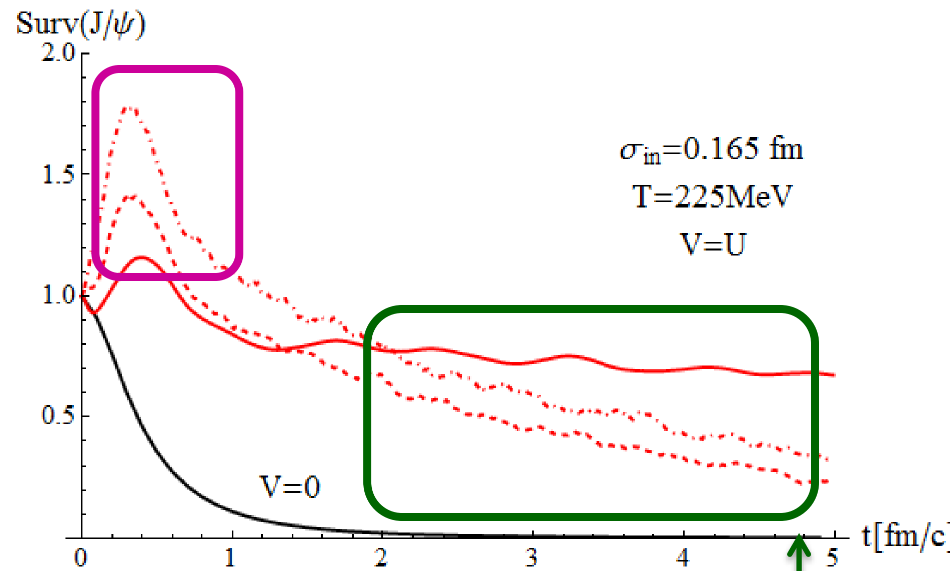
Test of robustness I

T=225 MeV (T/Tc ≈ 1.4):

V=V_{PM} (weakly bound)



V=U (strongly bound)

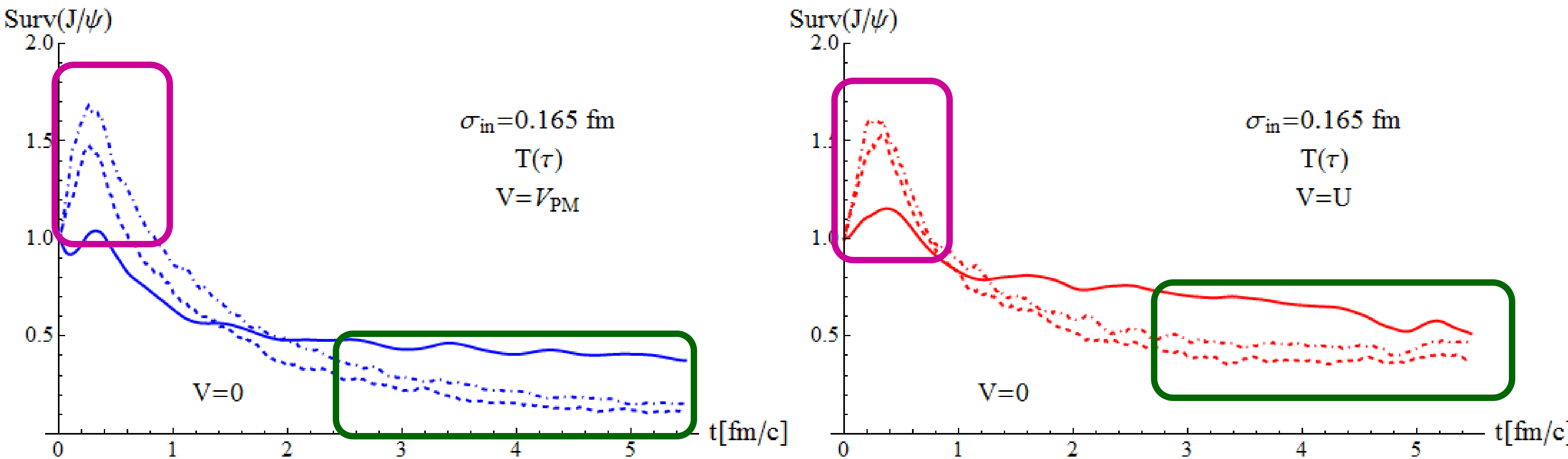


- Around initial time, cooling down by stochastic forces increase the J/ψ content of the quantum QQbar state
- At later times, the stochastic sources act as a source of dissociation of the remaining state

Test of robustness II

T(τ), central Au-Au @ RHIC, $\vec{x}_\perp = \vec{0}$

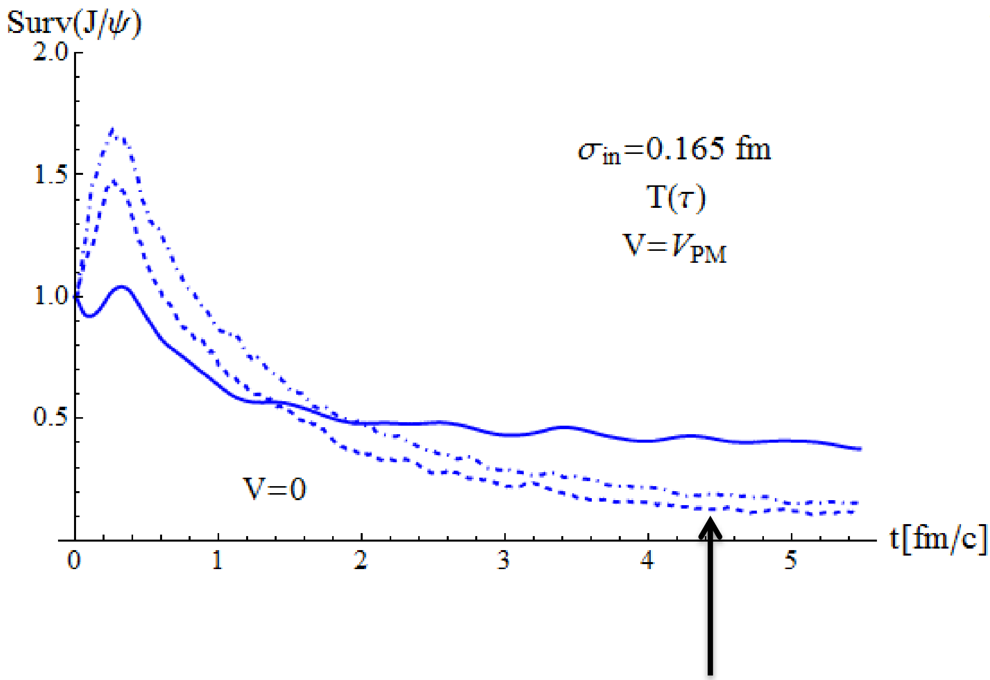
V=V_{PM} (weakly bound) V=U (strongly bound)



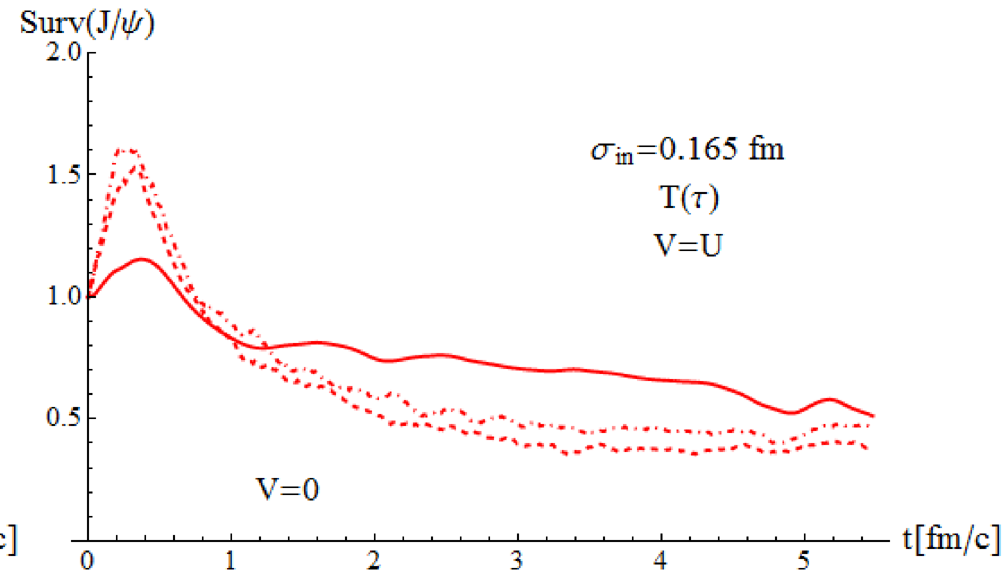
- Similar features as for T=225: rapid thermalization in p-space (-> quasi equilibrium), followed by induced leakage in r space
- For potential chosen as V=U, survival compatible to 0.5, as claimed by Young and Shuryak

Test of robustness II

$V=V_{PM}$ (weakly bound)



V=U (strongly bound)



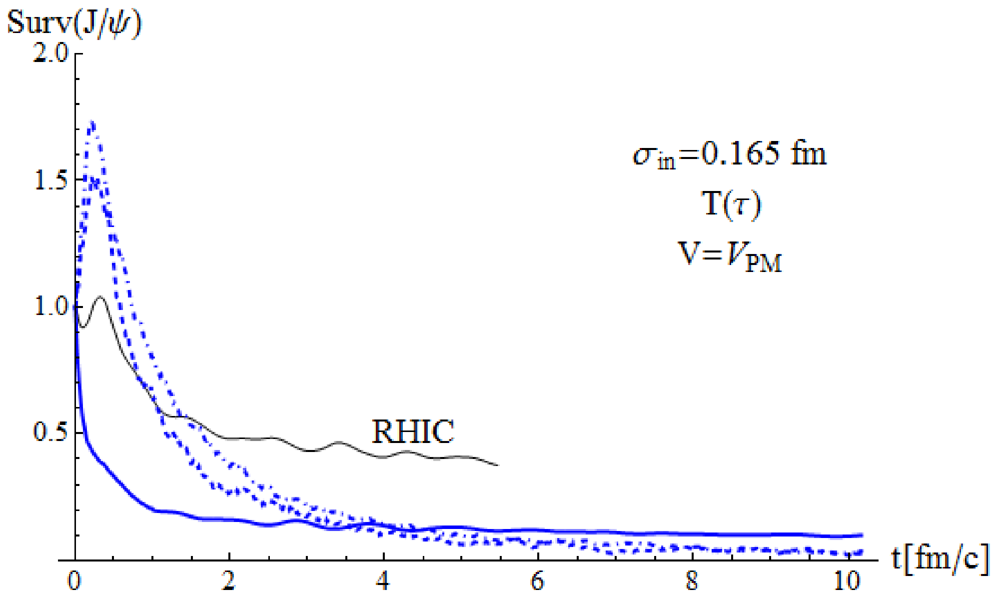
➢ No large dependence vs precise choice for drag coefficient…

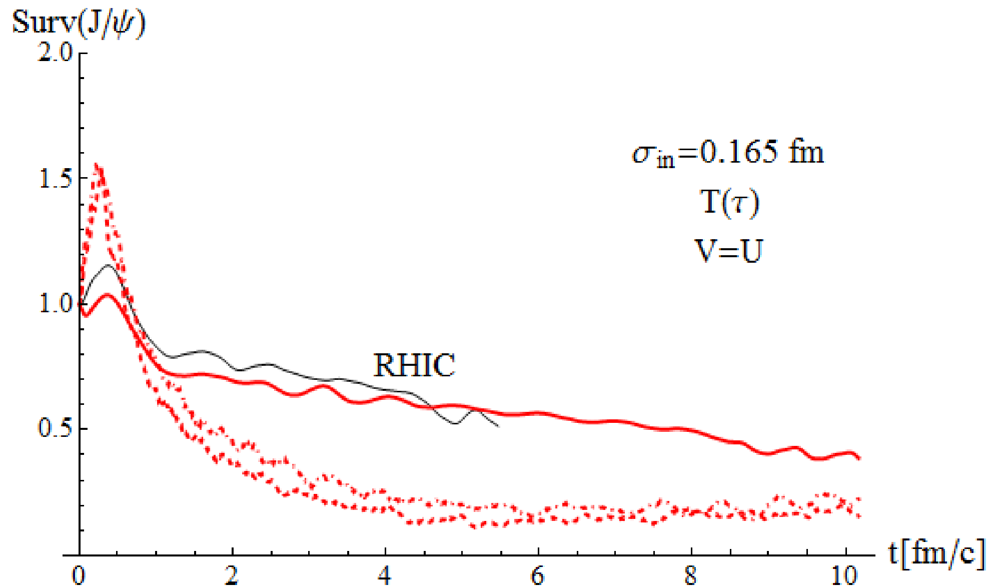
➢ But large dependence vs choice of potential, especially if one includes the stochastic forces (can dissociate weakly bound states, but rather inefficient to dissociate strongly bound states).

Survival @ LHC

T(τ), central Pb-Pb @ LHC, $\vec{x}_\perp = \vec{0}$

Preliminary





Even at LHC, up to 25% survival if V=U

Conclusion & Prospects

1. We confirm the claim of Shuryak and Young of large J/y survival… for V chosen to be the total energy U…

2. However, their choice of parameters probably correspond to the most favorable case !

Possible way to make progress on this point: evaluate $\Gamma_{J/\psi}$(T) for both types of potentials and compare with lattice

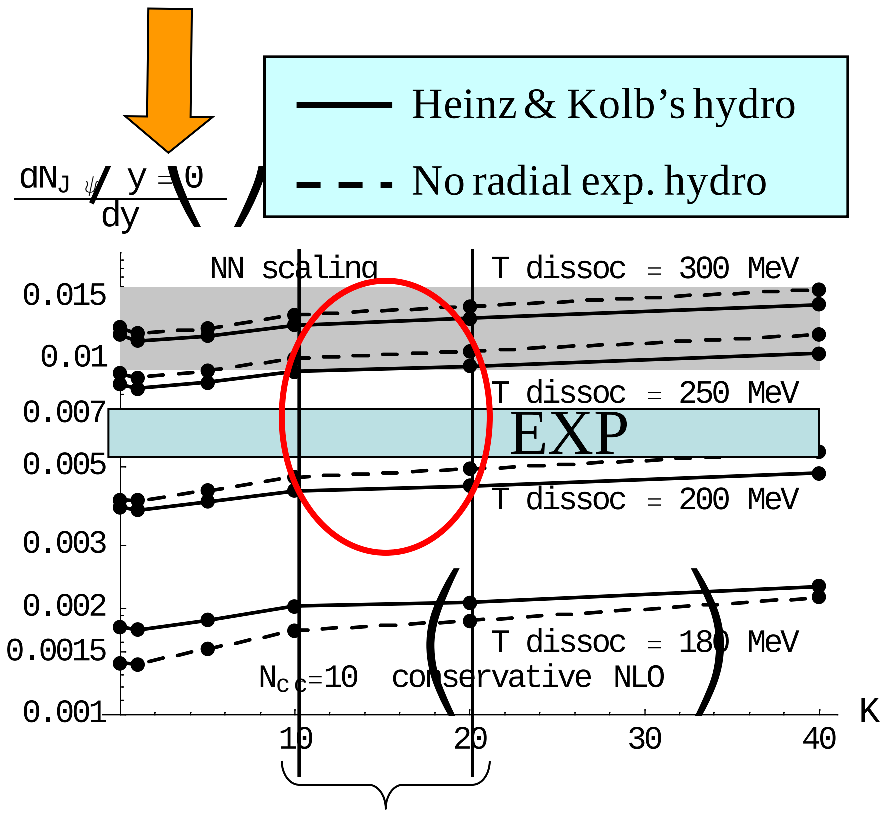
3. Important to include a time-dependent microscopic description of QQbar states in the transport codes… to be pursued

Back Up

The Landscape

Degree of thermalization of heavy quarks will not affect "too much" the integrated production rates; T_{diss} is the driving parameter for "recombined" J/ψ :

Au+Au, b=0

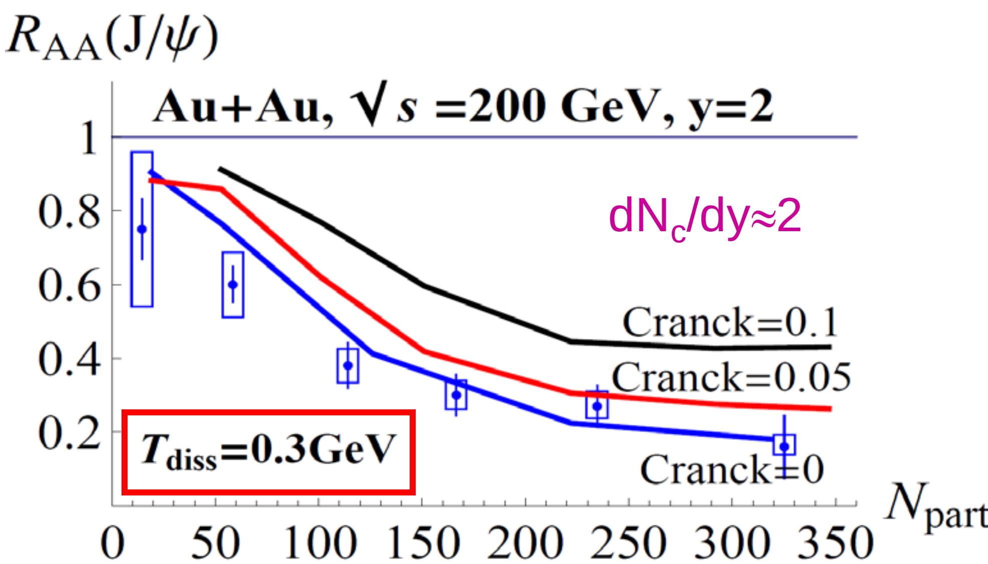


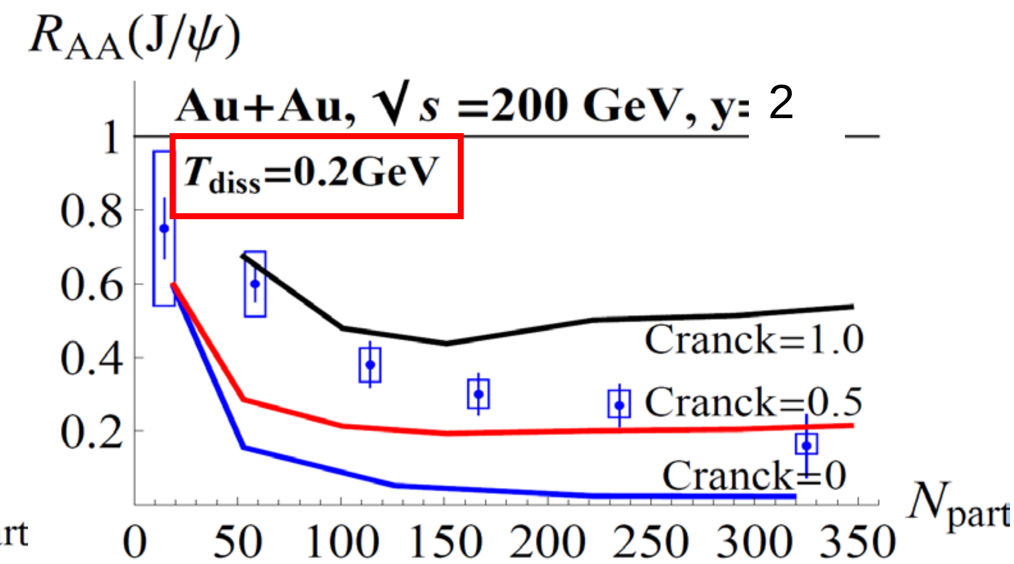
Compatible with $R_{AA}(e)$

Multiple of pQCD stopping force (αs=0.3)

From SQM 2004, with additional Au+Au data.

Turning on (re)combination at y=2

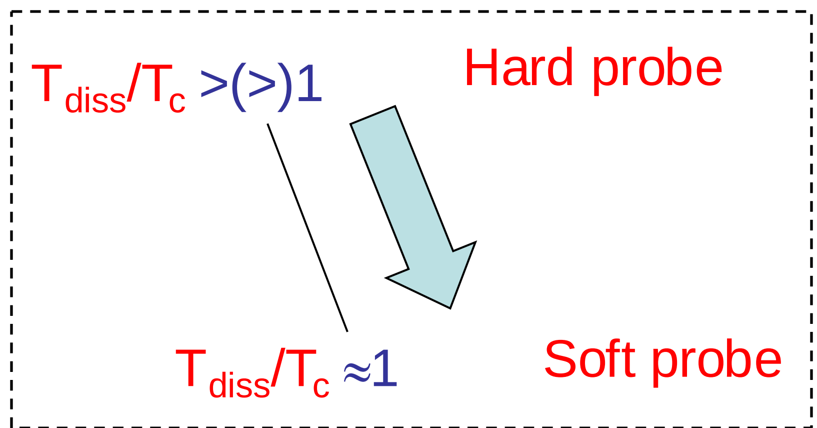




No room left for coalescence at y=2. What are the physical mechanisms for taming the fusion ?

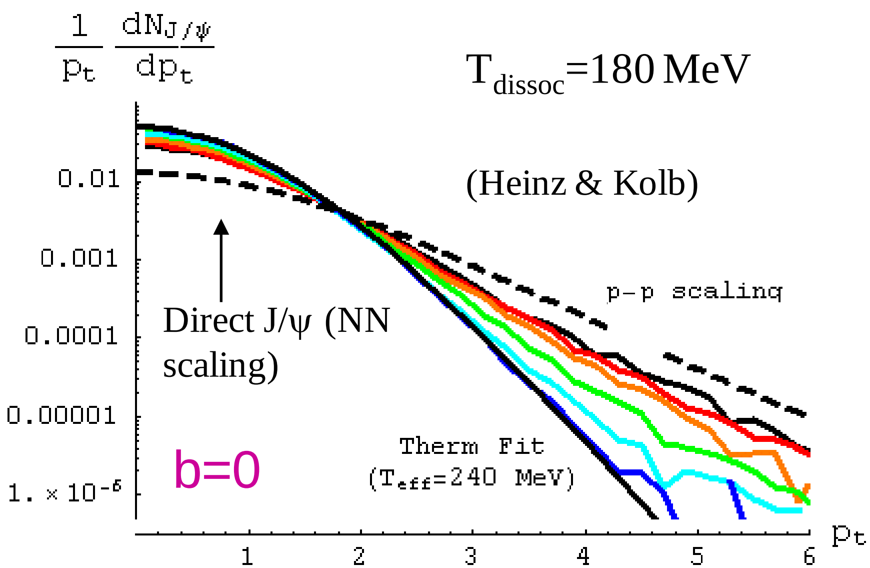
Good agreement with the same σ_{fus} band (Cranck. $\in$ [0.5,1])

Moreover: The pQCD Bhanot and Peskin result is usually considered to be small w.r.t. other effective approaches at small s-M^2

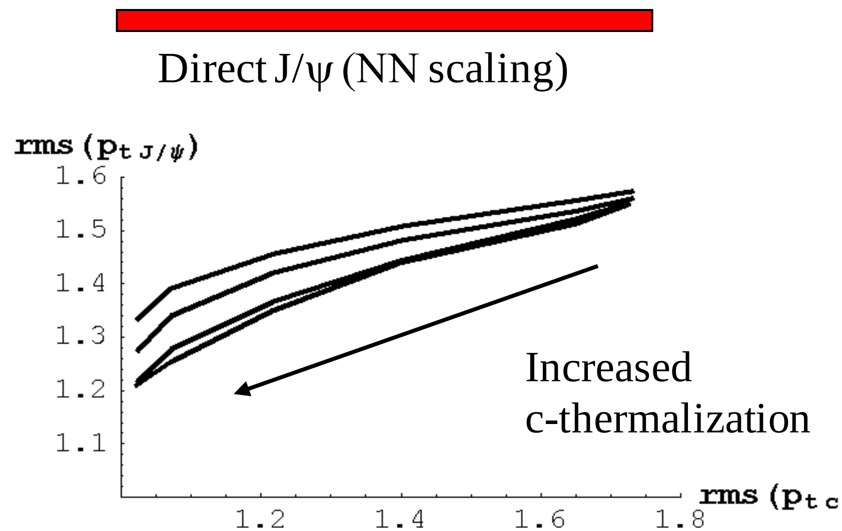


The P_T world

Differential production might reveal more physics



QGP “cools” the charms, even with the radial flow

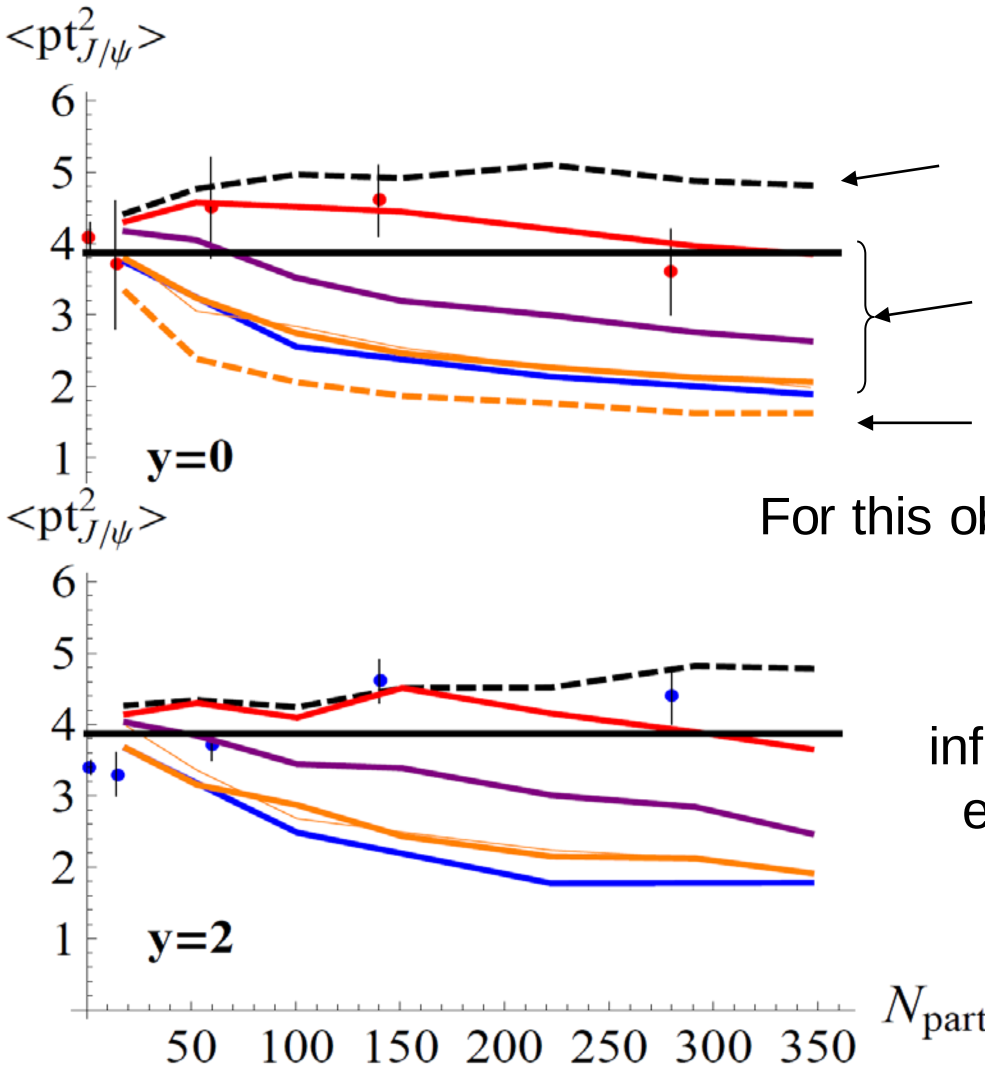


Prediction for b=0 and just recombination (2004)

Softer p_T spectrum as for direct production. Possible "p_t shrinking" in A-A. But first, understand the k_t broadening in d+Au (none seen around y=0 !?)

The P_T world

… and now compared with the data:



Cronin effect at initial stage (and no further effect)

Results for T_{diss}= 0.3, 0.25, 0.2 and 0.18 (with initial Cronin effect).

T_{diss}= 0.2 and NO Cronin effect.

For this observable T_{diss}= 0.3 should be favored

Unknown: influence of the elastic cross section

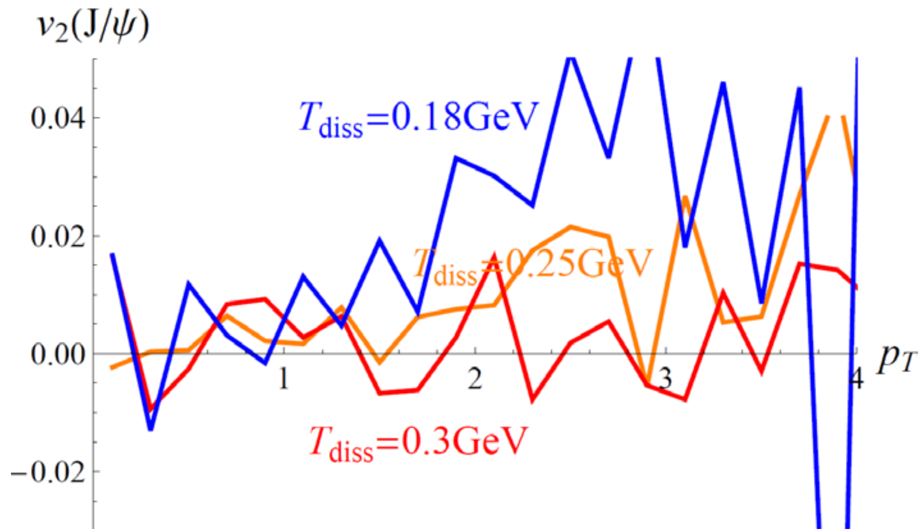
Voloshin (2005)

TABLE I: The mass shift $\Delta M_{J/\psi}$ and elastic $J/\psi + N$ cross section predicted by different models.

Ref.	$-\Delta M_{J/\psi}$ (MeV)	$\sigma_{J/\psi N}$ (mb)
[12]	3	0.3
[15]		1.5
[19]	10÷5	
[20]	7÷4	
[21]	4	
[32]	11÷8	
[33]		5
[34]		8
[35]	5	
this	$\gtrsim$ 21	$\gtrsim$ 17

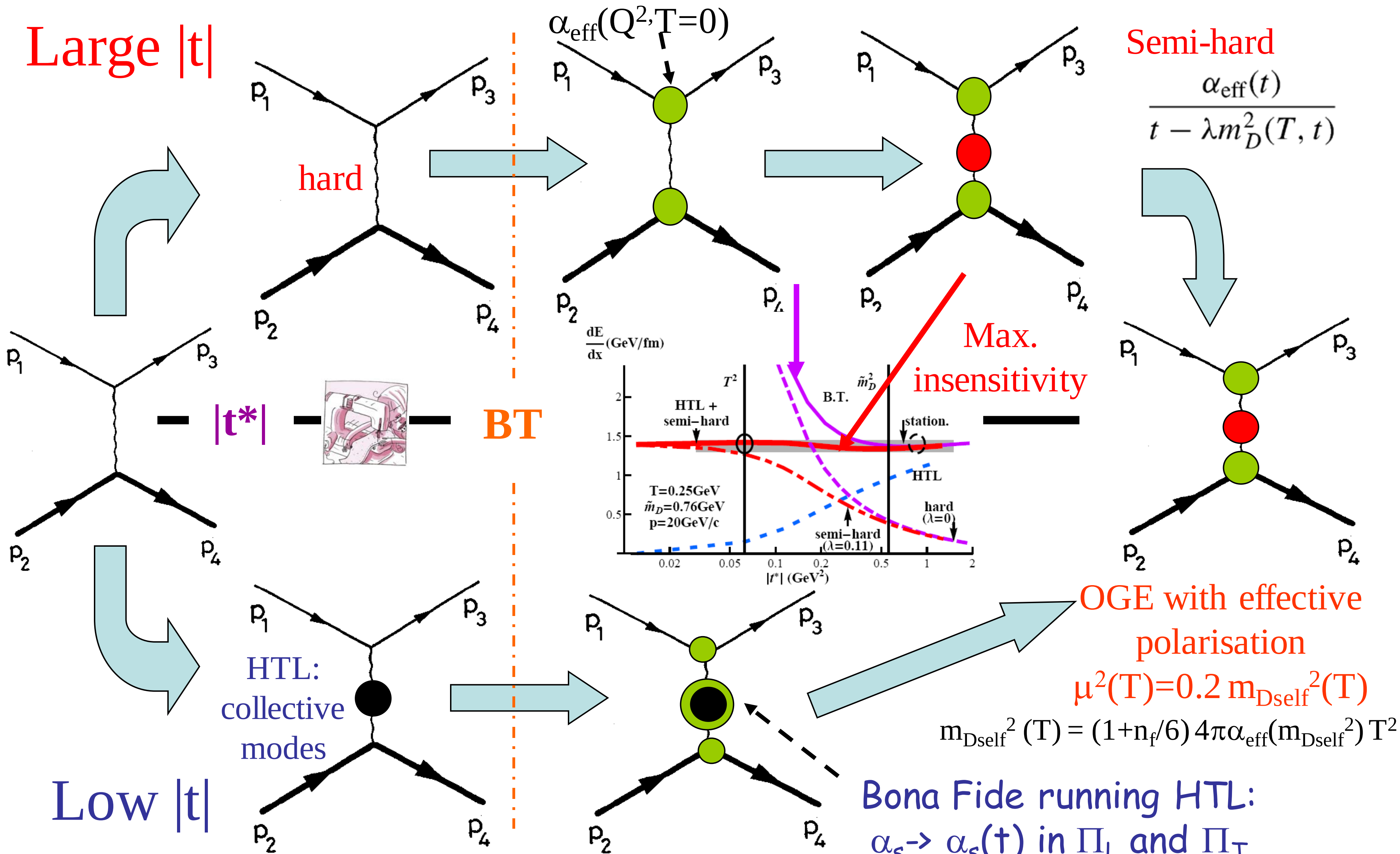
Work of H. Berrehrah (see QGP France 2009)

The keystone (?): v_2

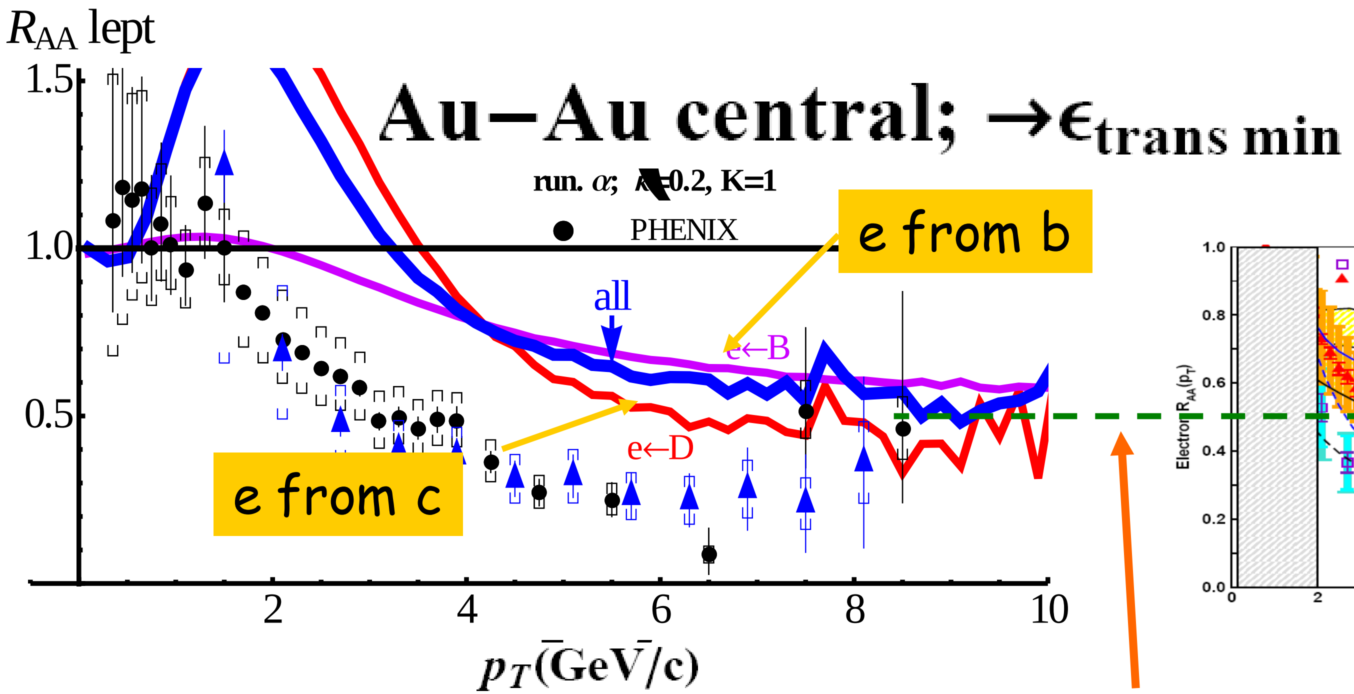


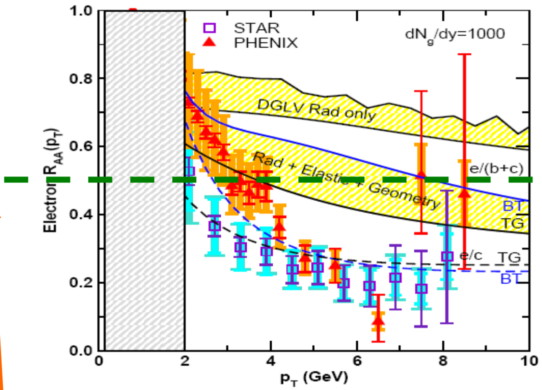
In fact, due to possible elastic cross section of J/ψ, v_2 is only conclusive if one observes NO v_2

μ-local-model: medium effects at finite T in t-channel



Central R_{AA} vs model & intermediate conclusion





I. Improved collisional Eloss plays a larger role then expected

II. Despite the unknowns (b-c crossing, precise kt broaden.,…), unlikely that collisional energy loss could explain it all *alone*

III. It is however not excluded that the "missing part" could be reproduced by some conventional pQGP process (radiative Eloss)

Monte Carlo Implementation

I) For each collision with a given $q_\perp$, we define the conditional probability of radiation:

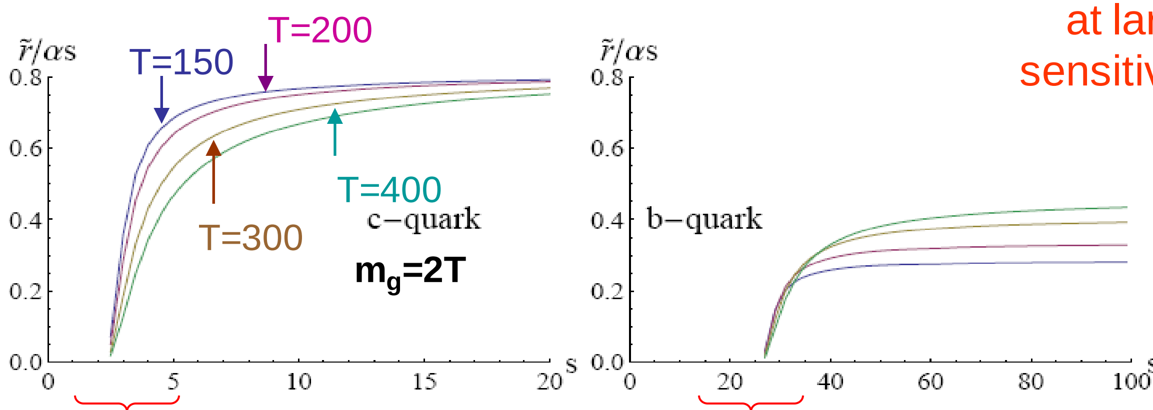
$$r(q_\perp) := \frac{\int_0^{+\infty} \frac{d^2\sigma_{\rm rad}}{d\omega\, dq_\perp^2}\, d\omega}{\frac{d\sigma_{\rm el}^{Qq}}{dq_\perp^2}}$$

In practice, ω_{min}=5% E to avoid IR catastrophy

II) For each collision with a given invariant mass squared s, we define the conditional *total* probability of radiation:

$$\tilde{r}(s) = \frac{\sigma_{\rm rad}}{\sigma_{\rm el}} \approx \frac{\int_{-|t|_{\max}}^{0} r(\sqrt{-t})\, \frac{d\sigma_{\rm el}^{Qq}(t)}{dt}\, dt}{\int_{-|t|_{\max}}^{0} \frac{d\sigma_{\rm el}^{Qq}(t)}{dt}\, dt}$$

Probes the elastic cross section at larger values of t => less sensitive to $\alpha_{\rm eff}$ at small t-values



Threshold for radiation

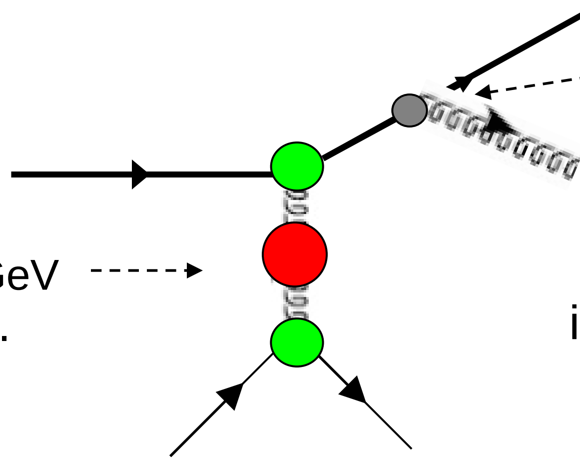
Monte Carlo Implementation

III) For a given HQ energy E, we sample the entrance channel according to the thermal distribution of light quarks and gluons and $\sigma_{el}(s)$ and accept according to the conditional probability $\tilde{r}(s)$

IV) We sample "downwards" $q_\perp$, ω and then $k_\perp$

Hard shocks with |t|>25% s are rejected (not treated properly in our formalism)

V) $P^+ \to (1\text{-}x)\, P^+$ and transverse kick of $\mathbf{q_\perp}$-$\mathbf{k_\perp}$.



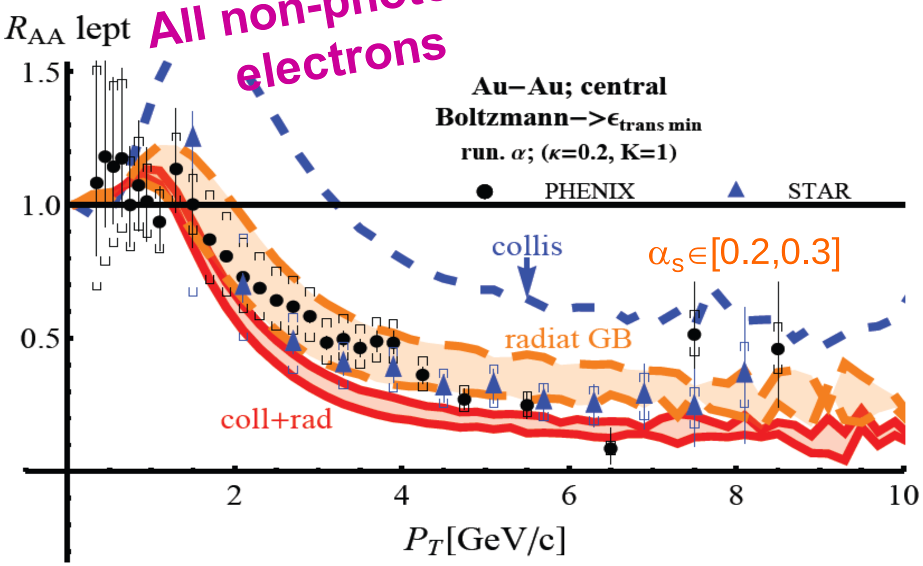
Fixed α_s

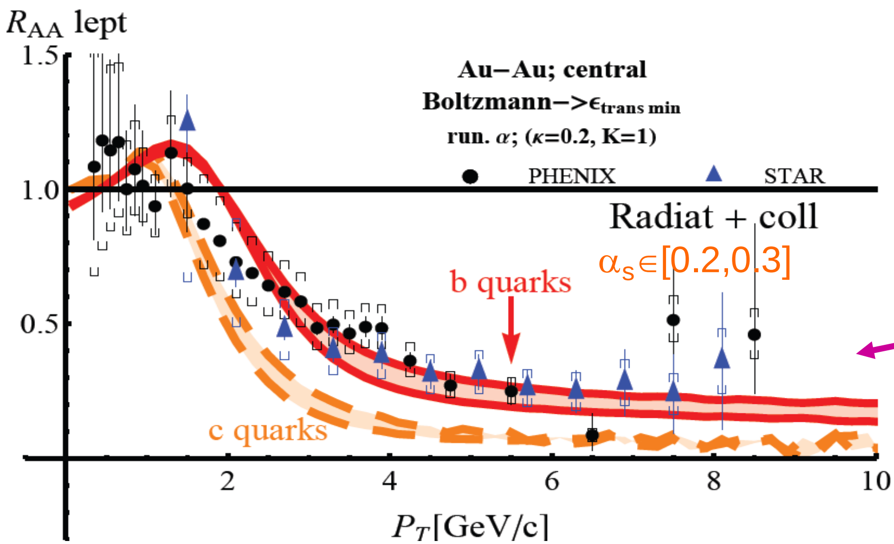
$\langle q_\perp \rangle$ from 0.6 GeV (col) $\to$ 1.1 GeV (rad) for E=15GeV and T=400.

Approximation:

In "reality", several collisions at intermediate t-values accumulate

Results

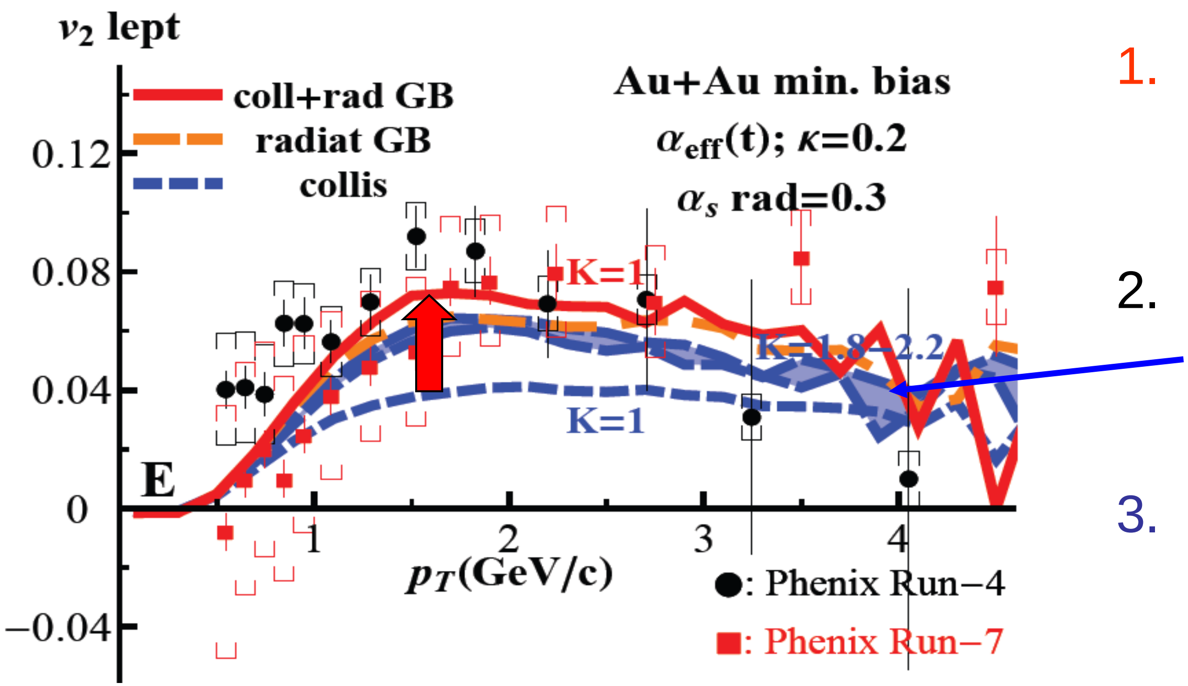




1. Too large quenching; good as we obviously overestimate the radiative Eloss
2. Radiative Eloss indeed dominates the collisional one
3. Flat experimental shape is well reproduced

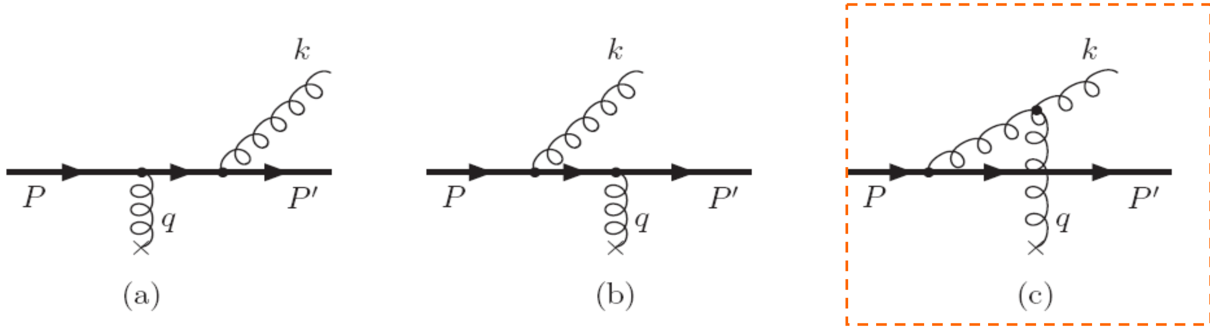
separated contributions e ← D and e ← B.

Results



1. Collisionnal + radiative energy loss + dynamical medium : *compatible* with data
2. Shape for radiative E loss and *rescaled* collisional E loss are pretty similar
3. To my knowledge, one of the first model using radiative Eloss that reproduces v_2

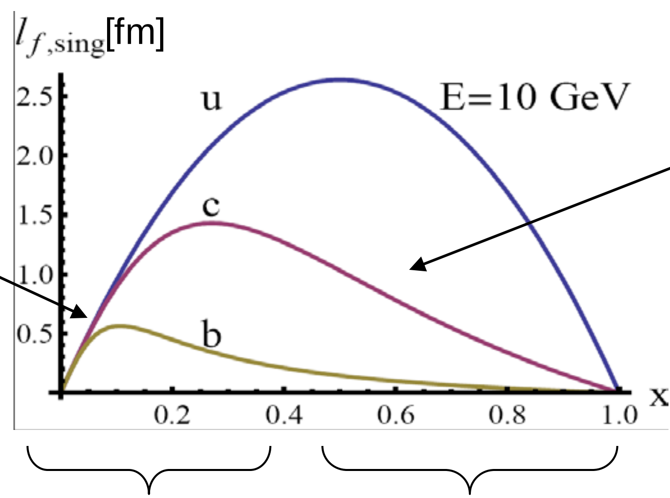
Formation time for a single coll.



$$t_f \approx \frac{2(1-x)\omega}{(\vec{k}_\perp - \vec{q}_\perp)^2 + x^2M^2 + (1-x)m_g^2}$$

At 0 deflection: $$l_{f,\text{sing}} \approx \frac{2x(1-x)E}{m_g^2 + x^2M^2}$$

For $x<x_{cr}=m_g/M$, basically no mass effect in gluon radiation

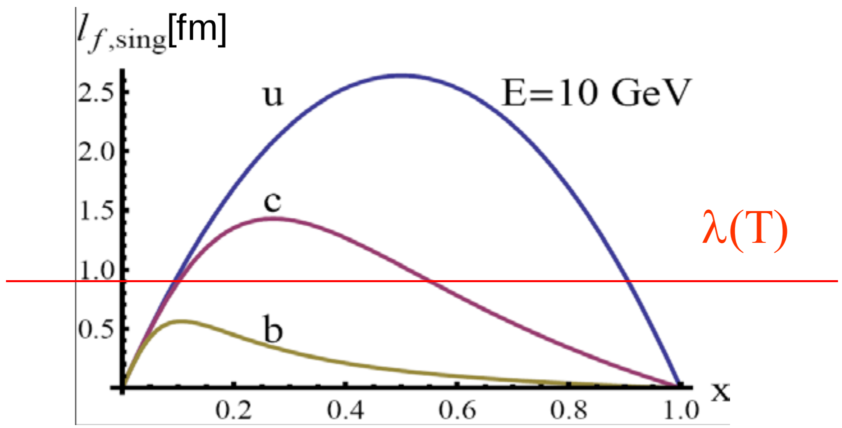


For $x>x_{cr}=m_g/M$, gluons radiated from heavy quarks are resolved in less time then those ← light quarks and gluon => radiation process less affected by coherence effects in multiple scattering

Dominant region for quenching

Dominant region for average E loss

A simplifying hypothesis



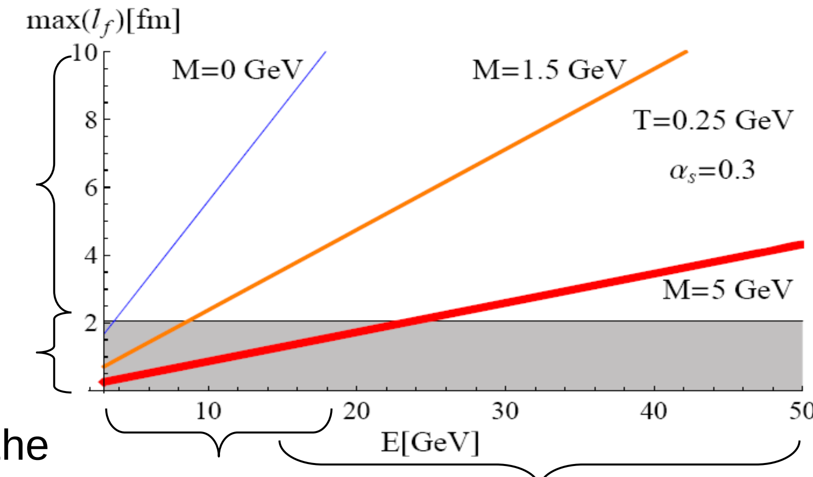
Comparing the formation time (on a single scatterer) with the mean free path:

Coherence effect for HQ gluon radiation : $\Leftrightarrow \quad \frac{E}{M} \gtrsim m_g \lambda_Q \sim \frac{1}{g_s}$

Mostly coherent

Mostly uncoherent

(of course depends on the physics behind λ_Q)



RHIC

LHC

Maybe not completely foolish to neglect coherence effect in a first round for HQ.

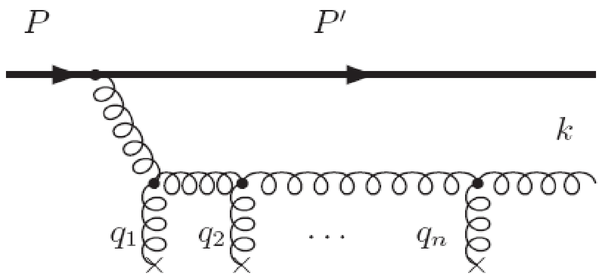
(will provide at least a maximal value for the quenching)

Basics of Coherent Radiation

Subject of numerous (mosty numerical) investigations

See Peigné & Smilga (2008) for some analytical results pertaining to HQ

Formation time in a random walk



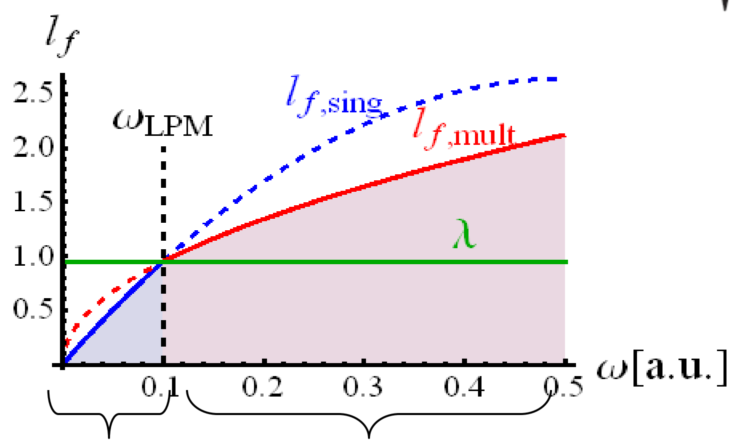
Phase shift at each collision

One obtains an effective formation time by imposing the cumulative phase shift to be Φ_{dec} of the order of unity

For light quark (infinite matter):

$$l_{f,\mathrm{mult}}(q+g) = l_{f,\mathrm{scat}}(q+g) \approx 2\sqrt{\frac{\omega \Phi_{\mathrm{dec}}}{\hat{q}}}$$

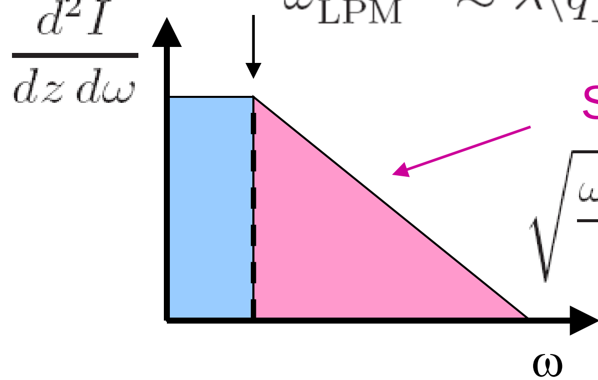
=> 3 scales: $l_{f,mult}$, $l_{f,sing}$ & λ



Uncoherent radiation

Coherent radiation (BDMPS)

$$\omega_{\mathrm{LPM}}^{(\mathrm{QCD})} \approx \tilde{\lambda}\langle q_\perp^2\rangle \sim \lambda_q \mu^2 \sim T$$



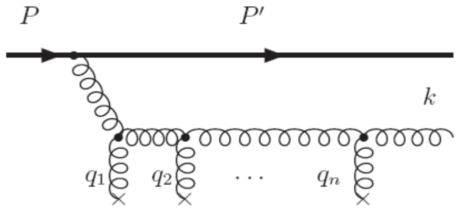
Suppression:

$$\sqrt{\frac{\omega_{\mathrm{LPM}}}{\omega} \ln\left(\frac{\omega}{\omega_{\mathrm{LPM}}}\right)}$$

Especially important for av. energy loss

$$\frac{dE_{\mathrm{BDMPS}}(q)}{dz} \sim \sqrt{\frac{\omega_{\mathrm{LPM}}}{E}} \times \frac{dE_{\mathrm{GB}}(q)}{dz}$$

Formation time and decoherence for HQ



$$l_{f,\mathrm{mult}}(Q+g) = \frac{2\omega\Phi_{\mathrm{dec}}}{\sqrt{\omega\hat{q}\Phi_{\mathrm{dec}} + \left(\frac{M^2\omega^2}{2E^2}\right)^2} + \frac{M^2\omega^2}{2E^2}}$$

"Competition" between

- decoherence" due to the masses: $m_g^2 + x^2 M^2$
- decoherence due to the transverse kicks $\langle Q_\perp^2 \rangle = l_{f,\mathrm{mult}}\,\hat{q}$

Special case: $\lambda < l_{f,\mathrm{mult}} < L_{\mathrm{QCD}}^{\star\star} := \frac{m_g^2 + x^2 M^2}{\hat{q}}$

One has a possibly large coherence number $N_{coh} := l_{f,mult}/\lambda$ but the radiation spectrum per unit length stays mostly unaffected:

Radiation on an effective center of length $l_{f,mult} = N_{coh}\,\lambda$ → $\frac{d^2 I}{dz\,d\omega}$ ← Radiation at small angle $\propto \langle Q_\perp^2 \rangle$ i.e. $\propto N_{coh}$

Compensation at leading order !

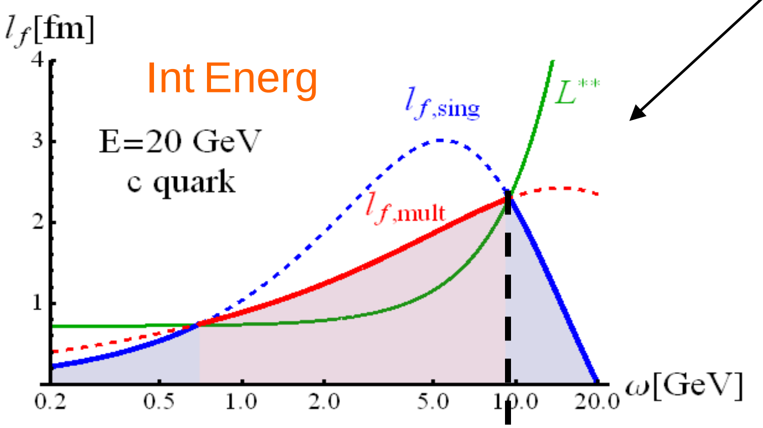
LESSON: HQ radiate less, on shorter times scales but are less affected by coherence effects than light ones !!! (dominance of 1rst order in opacity expansion)

Formation time and decoherence for HQ

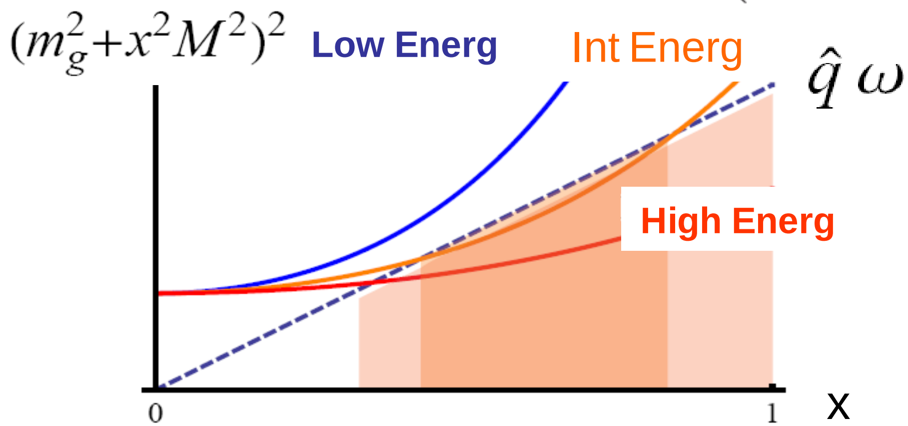
Criteria: HQ radiative E loss strongly affected by coherence provided:

$$l_{f,\mathrm{mult}}(Q) \gtrsim L^{\star\star}_{\mathrm{QCD}} := \frac{m_g^2 + x^2 M^2}{\hat{q}}$$

Equivalent to: $l_{f,\mathrm{sing}}(Q) \gtrsim 2L^{\star\star}_{\mathrm{QCD}} \quad \Leftrightarrow \quad \left(m_g^2 + \frac{\omega^2 M^2}{E^2}\right)^2 \lesssim \omega\hat{q}$



$$\omega^\star_{\mathrm{LPM}}(E) = \left(\frac{\hat{q}E^4}{2M^4}\right)^{\frac{1}{3}}$$



3 regimes (2 for light quarks)

Low energy: radiation from HQ unaffected by coherence

Intermediate energy: coherence affects radiation on an increasing part of the spectrum (up to ω_{LPM}*)

High energy: HQ behaves like a light one; coherence affects radiation from ω_{LPM} on.

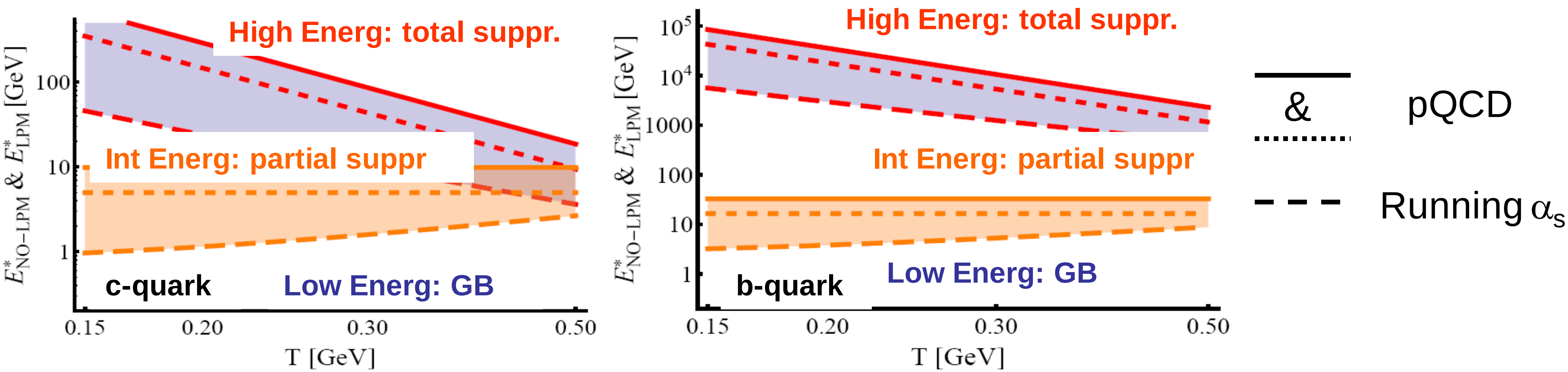
$$E^\star_{\mathrm{NO-LPM}} := 3\frac{M m_g^3}{\hat{q}} \sim \frac{M}{g_s} \qquad E^\star_{\mathrm{LPM}} := \frac{M^4}{\hat{q}}$$

Regimes and radiation spectra

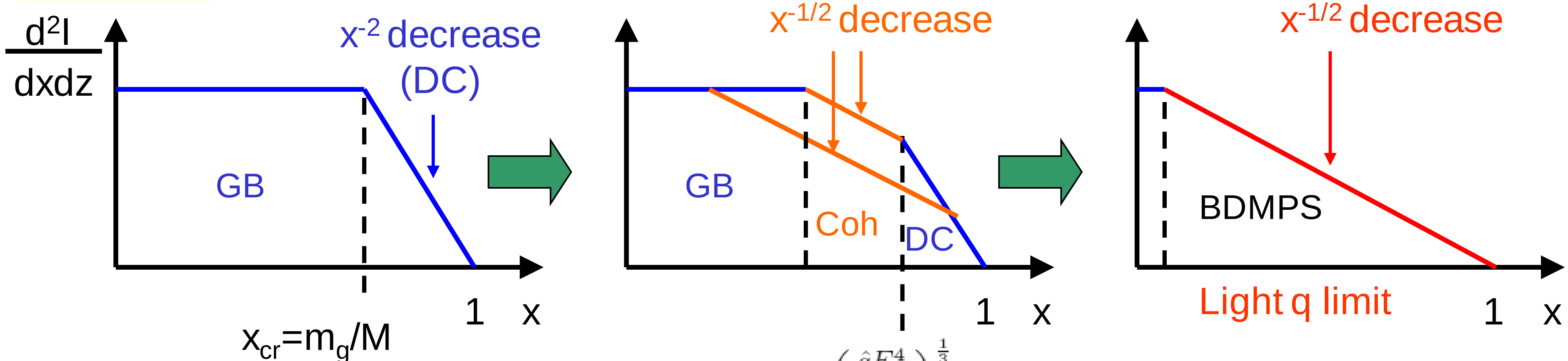
Hierarchy of scales:

$$\underbrace{E_{\rm LPM}(q)}_{T} \ll \underbrace{E^{\star}_{\rm NO-LPM}(Q)}_{\frac{M}{g_s T}\times T} \ll \underbrace{E^{\star}_{\rm LPM}(Q)}_{\left(\frac{M}{g_s T}\right)^4\times T}$$

larger coupling ⇒ Larger coherence effects

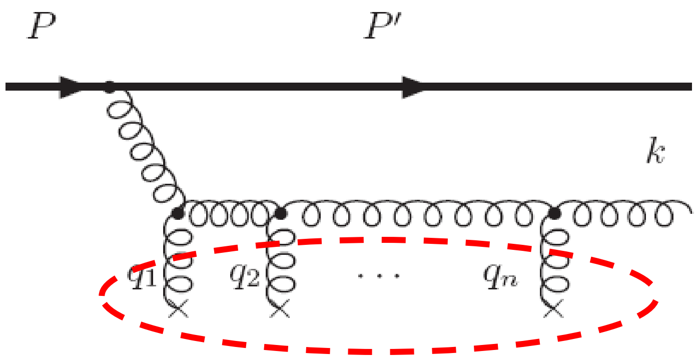


Spectra



$\omega^{\star}_{\rm LPM}(E) = \left(\frac{\hat{q}E^4}{2M^4}\right)^{\frac{1}{3}}$ Effective higher ω for av. E loss

Semi-quantitative model:



For $l_{f,mult} > \lambda$, gluon is radiated coherently on a distance $l_{f,mult}$

Model: all scatterers acts as a single effective one with probability $p_{Ncoh}(Q_\perp)$ obtained by convoluting individual probability of kicks

$$\left(\frac{d^2 I^{x\ll 1}_{\text{“QCD”}}}{dz\, d\omega}\right)_{\text{coh}} \approx \frac{2N_c\alpha_s}{\pi l_{f,\text{mult}}}\left\langle \ln\left(1+\frac{Q_\perp^2}{3\tilde{m}_g^2}\right)\right\rangle_{p_{N_{\text{coh}}}}$$

with

$$\tilde{m}_g^2 \approx m_g^2 + x^2 M^2 + \sqrt{\frac{\hat{q}\omega}{\Phi_{\text{dec}}}}$$

Prevents radiation of gluon of formation time > $l_{f,mult}$

After averaging:

$$\frac{d^2 I_{\text{eff}}}{dz\, d\omega} \sim \frac{\alpha_s}{N_{\text{coh}}\tilde{\lambda}} \ln\left(1+\frac{N_{\text{coh}}\mu^2}{3\left(m_g^2+x^2M^2+\sqrt{\omega\hat{q}}\right)}\right)$$

- Compares well to the BDMPS result (N_{coh}>>1) for light quark (up to some color factor => rescaling), including the coulombian logs.
- Naturally interpolates to the massive-GB regime for $N_{coh} \leqslant 1$.
- Incorporates all regimes discussed above.