prediction for LHC J/Ψ Enhanc-ssion from RHIC extrapolation (and a bit of physics too)

Rete Quarkonii 2010 (Nantes)

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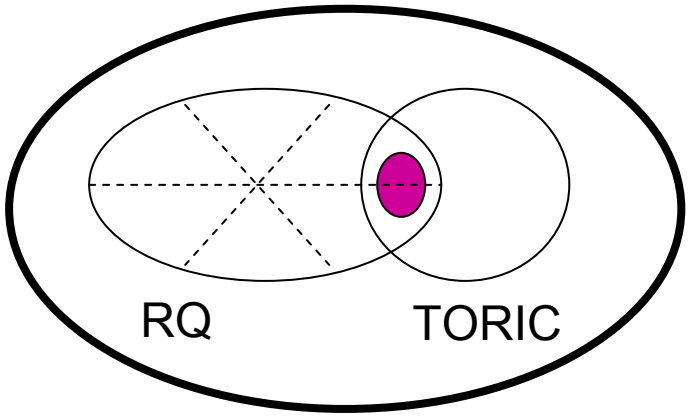
With J. Aichelin H. Berrehrah & Th. Gousset,

I. Motivation

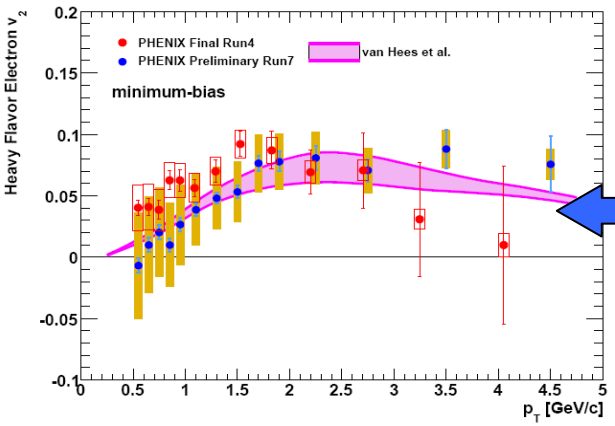
II. Understanding (partly) the present RHIC data on HQ E-loss

III. Quarkonia formation: probing the QGP ?

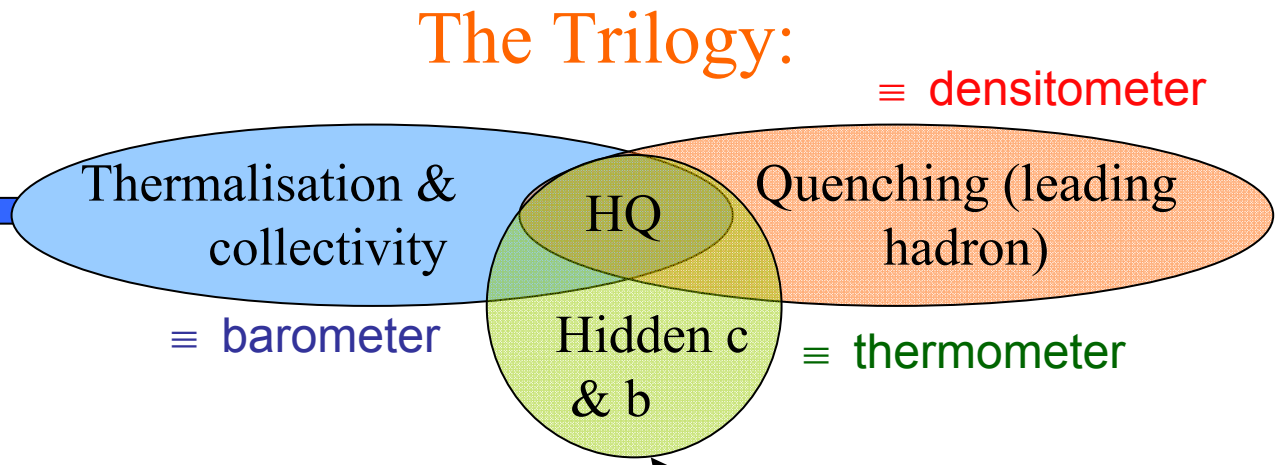


Why ♥ heavy flavors in A-A (open and hidden)?

Prejudice: Open heavy flavors are mandatory to understand Q-Qbar evolution in QGP & quarkonia production



RHIC



Quarkonia suppression and Dimuons product.

HQ are imbedded in expanding matter ⇒ they participate to collective motion and gain elliptic flow (v_2:azimutal asymmetry) at finite b

Challenges:

- Description of HQ E-loss / equilibration from fundamental theory
- Joint v_2-R_{AA} explanation …will help to better understand the theory

Quarkonia in Stationary QGP

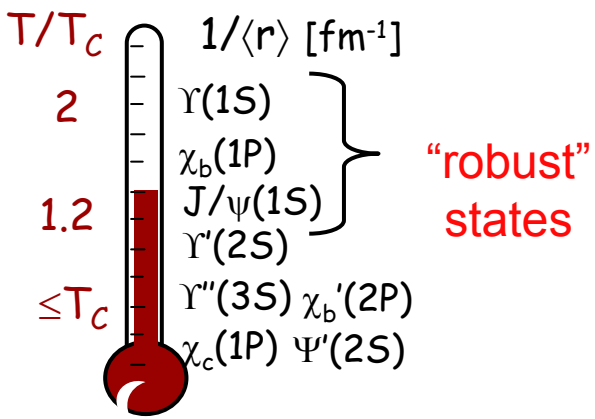
How can we prove (at best) that we have achieved is really *deconfined* state of matter ?

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

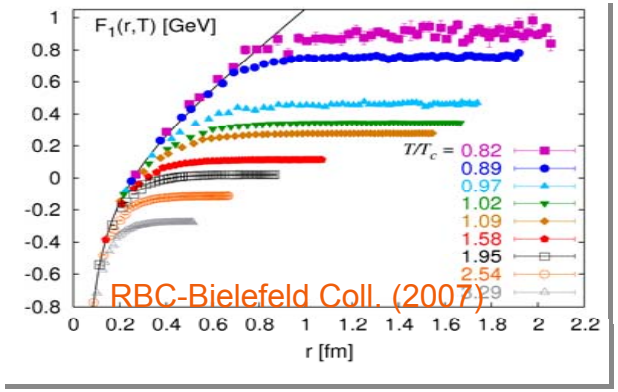
Indeed observed at SPS (CERN) and RHIC (BNL) experiments. However:

- alternative explanations, lots of unknown (also from theory side)
- no additional suppression at RHIC w.r.t. SPS !

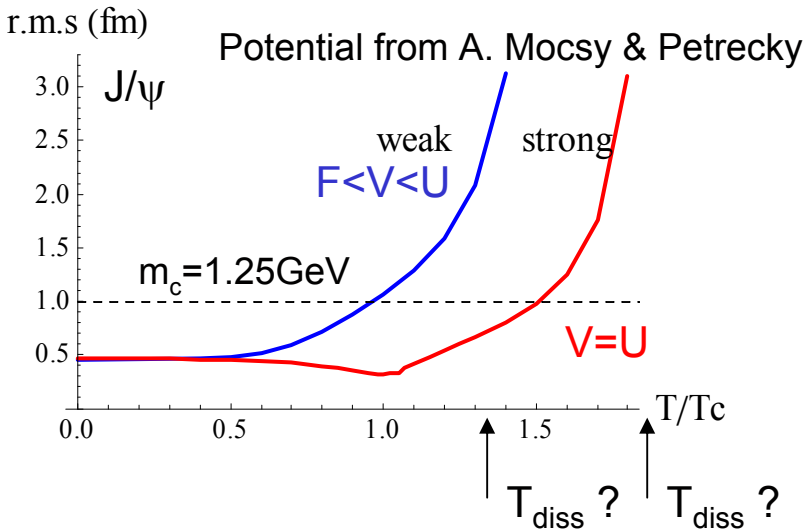
Nevertheless: Still best candidate and dedicated (di-μ) program at LHC

Caviats & Uncertainties (why  ?)

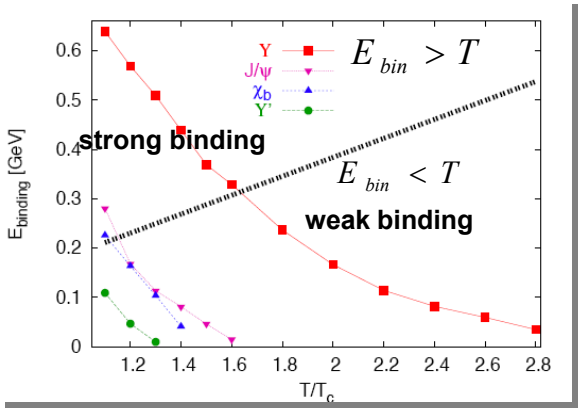
I. Quarkonia in *stationnary* medium are not understood from the fundamental LQCD theory



$\Rightarrow$ 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 ?

Quarkonia in URHIC… Can they teach us something about QGP (properties)?

Nothing quantitative ?

Nothing at all ?

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.

4. Can we transpose our "understanding" of RHIC to make some predictions for LHC ?

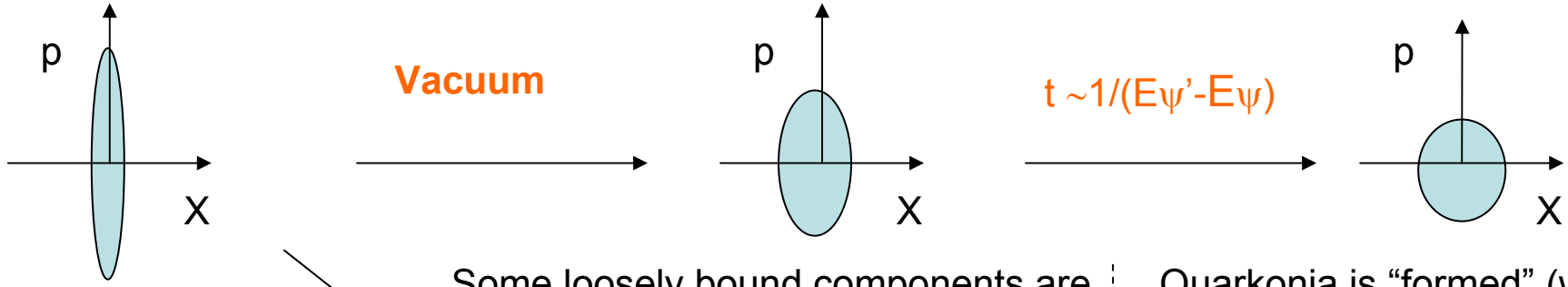
Need for a time-dependent scenario

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"

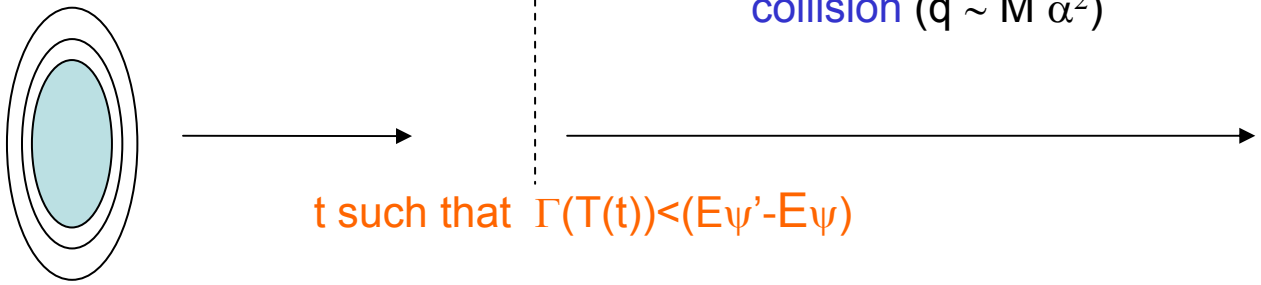


In hot (but cooling) medium

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 ($q \sim M\,\alpha^2$)

"Truth"



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

"Sharp *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)

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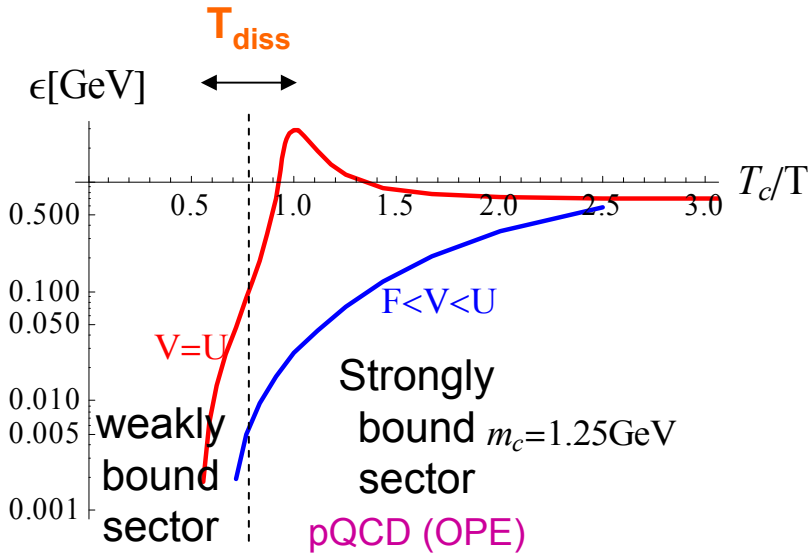
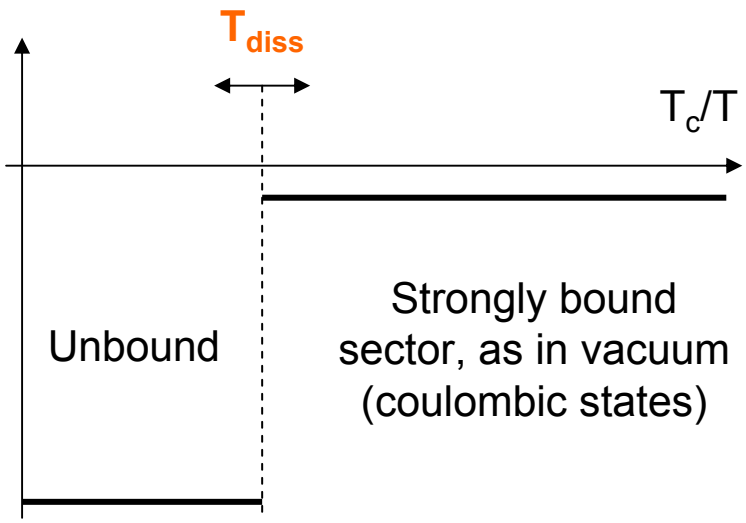
b) "Q-Qbar → Quarkonia" fusion allowed

$T>T_{diss}$

$T<T_{diss}$

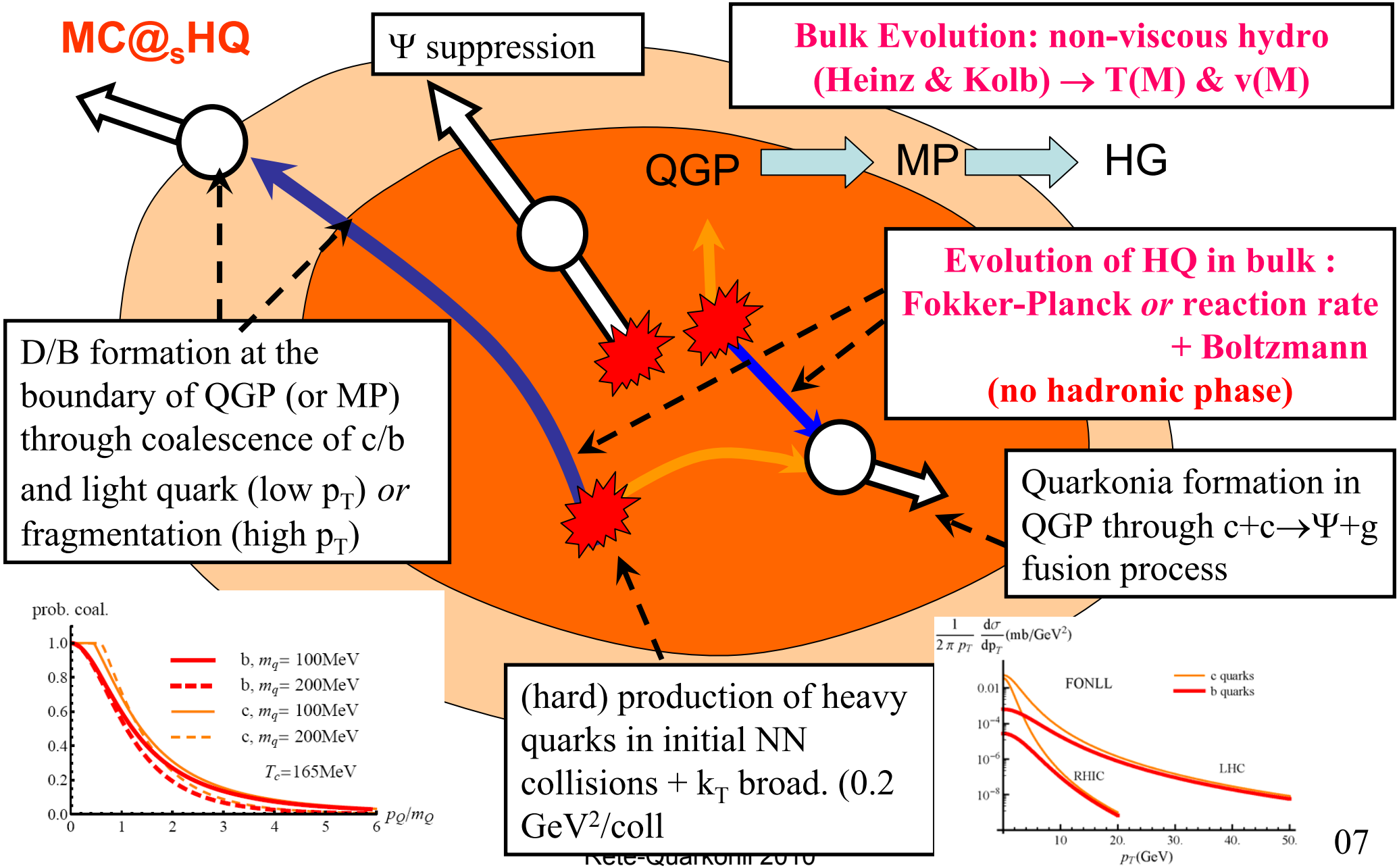


Model



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)

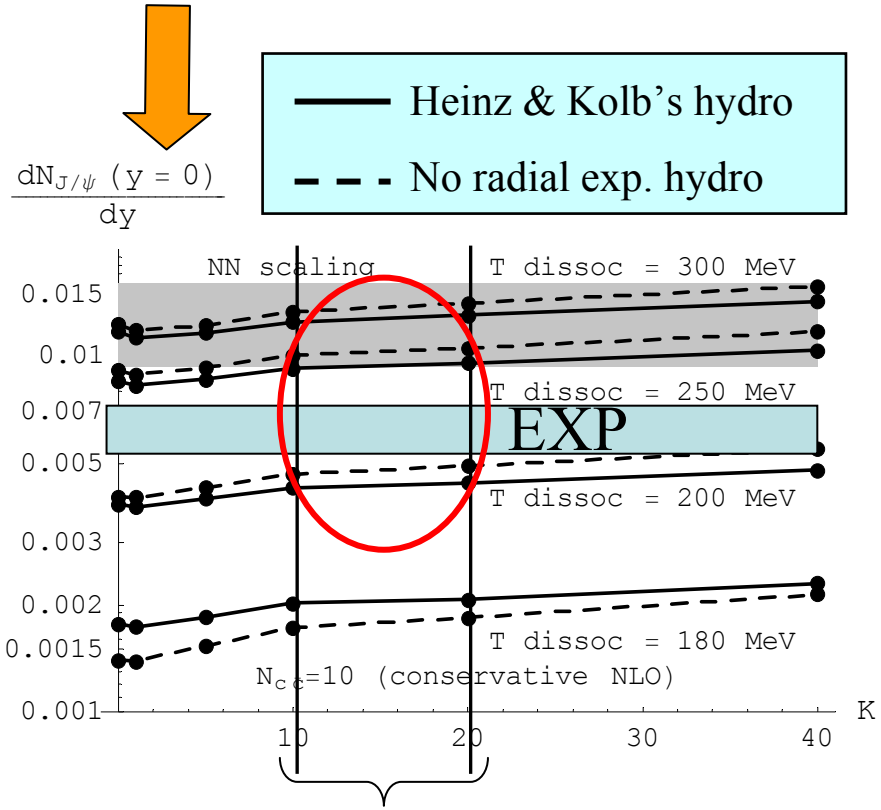
Schematic view of the global framework



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 $R_{AA}(e)$

From SQM 2004, with additional Au+Au data.

Hope that the quarkonia production would be dominated by recombination

Multiple of pQCD stopping force (αs=0.3)

I. “Understanding” the RHIC HQ-data

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

Based on

- *Heavy quarks thermalization in ultra relativistic heavy ion collisions: Elastic versus Radiative*, P.B. Gossiaux}, V. Guiho & J. Aichelin, Journal of Physics G **32** (2006) S359
- *Towards an understanding of the single electron data measured at the BNL Relativistic Heavy Ion Collider (RHIC)*, P.B. Gossiaux & J. Aichelin, Phys. Rev. C **78**, 014904 (2008); [arXiv:0802.2525]
- *Tomography of quark gluon plasma at energies available at the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC)*, P.B. Gossiaux, R. Bierkandt & J. Aichelin, Physical Review C **79** (2009) 044906; [arXiv:0901.0946]
- *Tomography of the Quark Gluon Plasma by Heavy Quarks*, P.-B. Gossiaux & J. Aichelin, J. Phys. G **36** (2009) 064028; [arXiv:0901.2462]
- *Energy Loss of Heavy Quarks in a QGP with a Running Coupling Constant Approach*, P.B. Gossiaux & J. Aichelin, Nucl. Phys. A **830** (2009), 203; [arXiv:0907.4329]
- *Competition of Heavy Quark Radiative and Collisional Energy Loss in Deconfined Matter*, P.B. Gossiaux, J. Aichelin, T. Gousset & V. Guiho, J. Phys. G: Nucl. Part. Phys. **37** (2010) 094019; [arXiv:1001.4166]
- *Gluon Radiation at small kT and Radiative Energy Loss of Heavy Quarks; I. The Bethe-Heitler Regime*, J. Aichelin, P.B. Gossiaux & Th Gousset (**In preparation)**

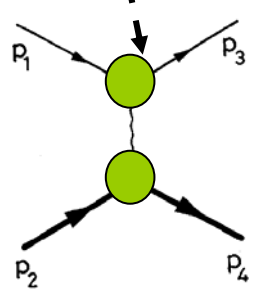
Collisional E loss : The Peshier – Gossiaux – Aichelin approach (2008)

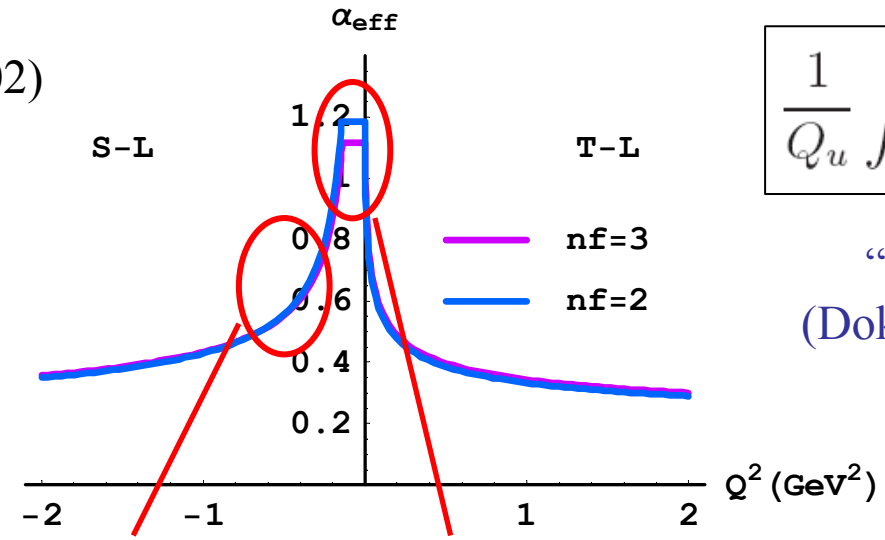
Motivation: Even a fast parton with the largest momentum P will undergo collisions with moderate q exchange and large $\alpha_s(Q^2)$. The running aspect of the coupling constant has been "forgotten/neglected" in most of approaches

Effective $\alpha_s(Q^2)$

(Dokshitzer 95, Brodsky 02)

$\alpha_{eff}(Q^2, T=0)$





$$\frac{1}{Q_u}\int_{|Q^2|\leq Q_u^2} dQ\alpha_s(Q^2) \approx 0.5$$

"Universality constrain" (Dokshitzer 02) helps reducing uncertainties:

Large values for intermediate momentum-transfer => larger cross section

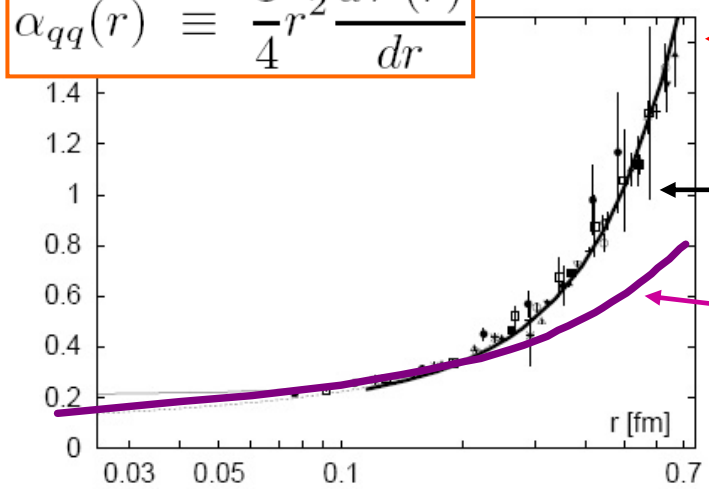
IR safe. The detailed form very close to $Q^2 = 0$ is not important does not contribute to the energy loss

A model; not a renormalizable theory

μ-local-model: Eff. Running α_s vs lQCD

T=0

$$\alpha_{qq}(r) \equiv \frac{3}{4} r^2 \frac{dV(r)}{dr}$$



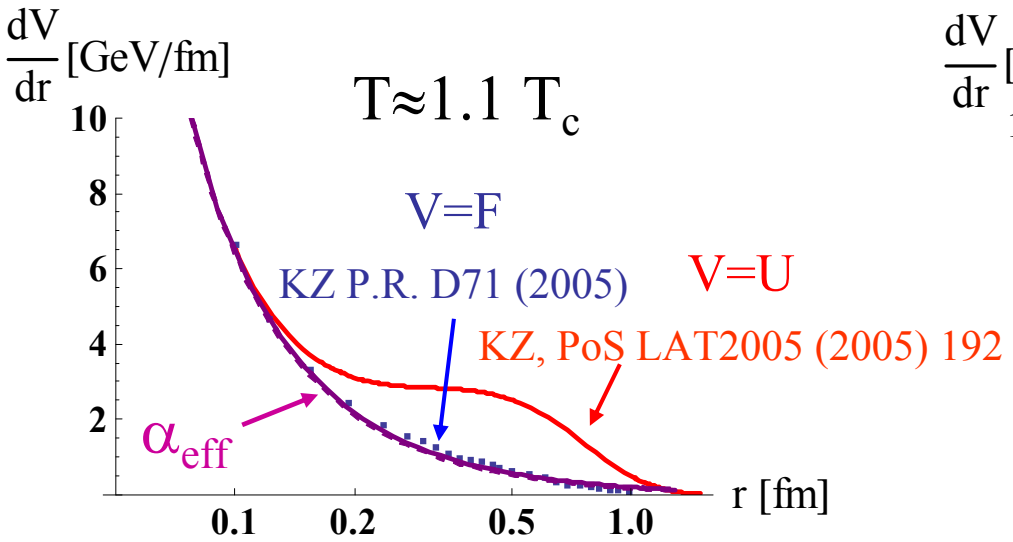
O. Kaczmarek & F. Zantow (KZ) (n_f=2 QCD), P.R.D71 (2005) 114510

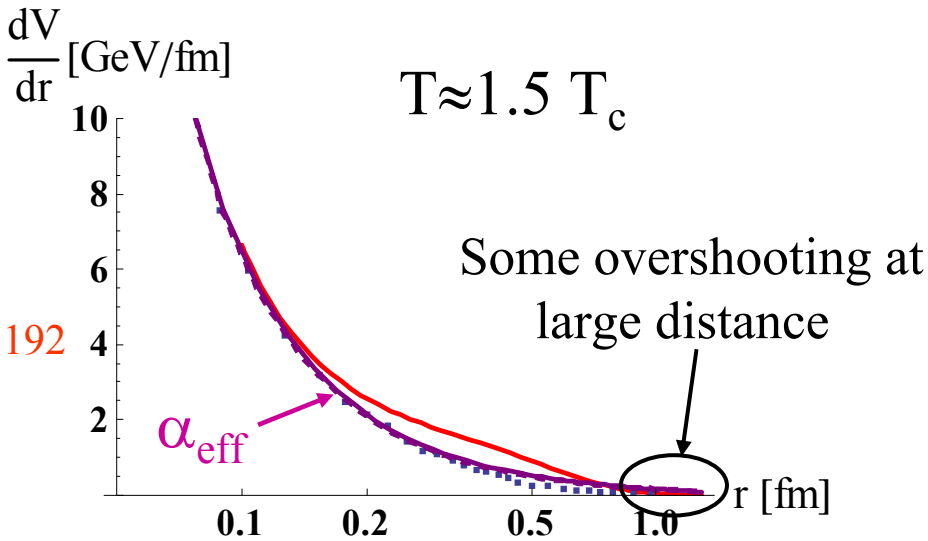
Genuine non-pert (string)

optimal μ, running α_{eff}

V:ω=0 sector; dE/dx: finite ω

Finite T





Merging at ≈2 T_c

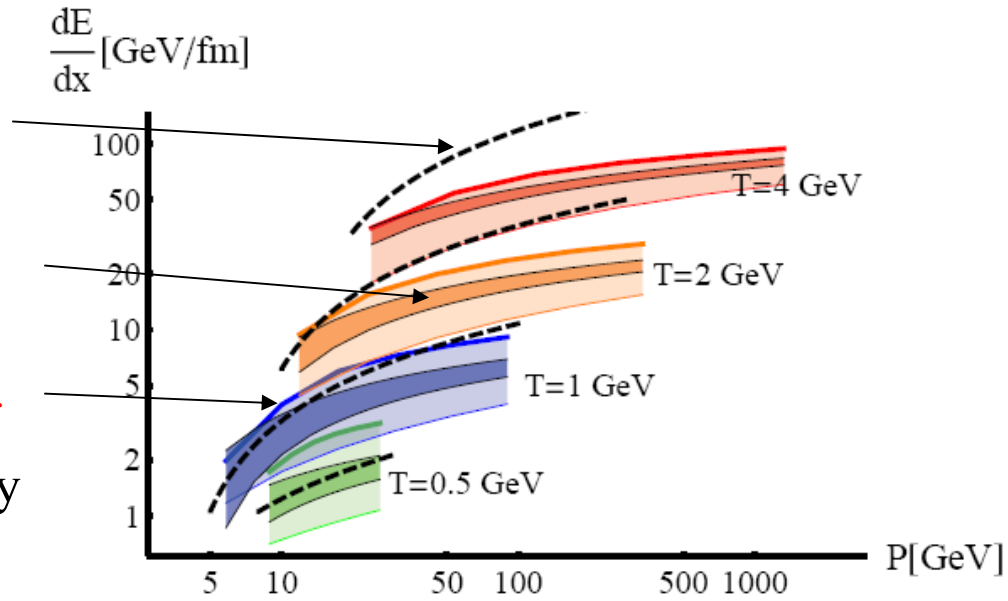
μ-local-model: Eff. Running vs fixed α_s

BT

Dark bands: Peshier & Peigné (2008)

E: optimal μ, running α_{eff}

Light bands: theoretical uncertainty related to the prescription for the HTL-hard transition



Conclusions:

- Good agreement with PP for large T and large P
- Running α_s is more than a cranking of BT (different shapes and T-dependences)

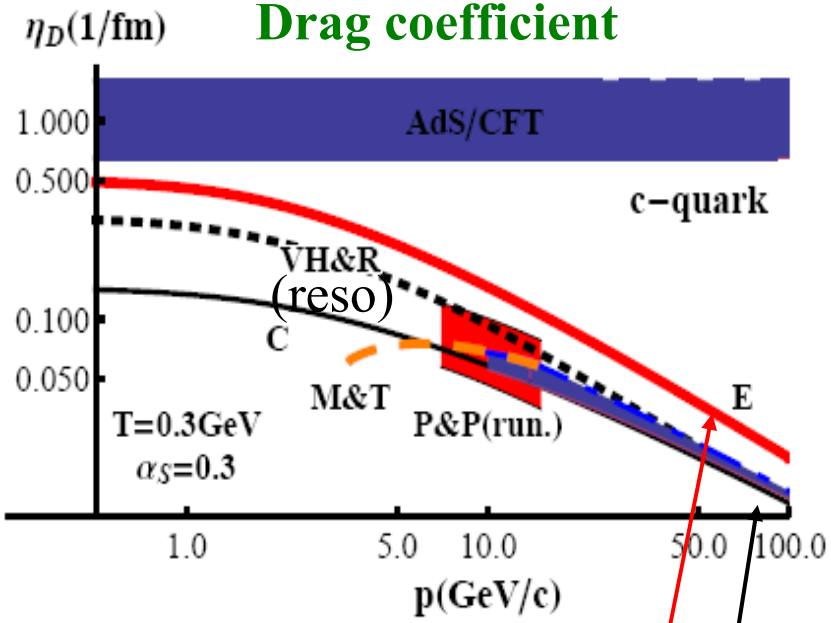
Running α_s : some Energy-Loss values for purely collisional processes

$$\frac{dE_{coll}(c/b)}{dx}$$

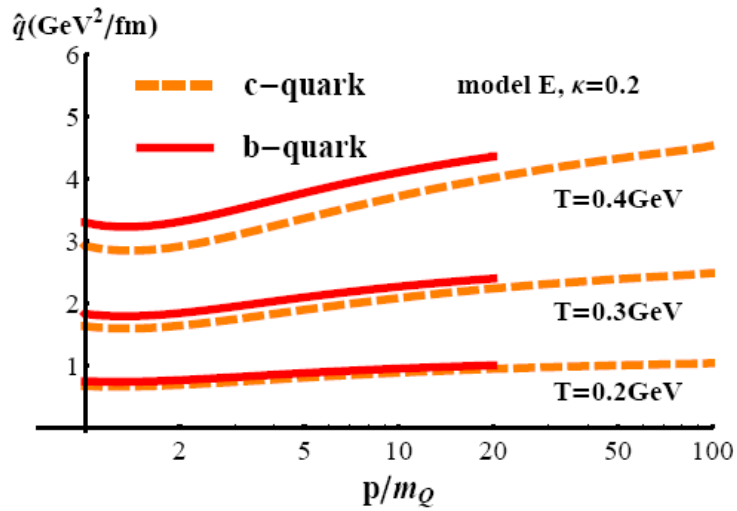
T(MeV) \ p(GeV/c)	10	20
200	**1 / 0.65**	**1.2 / 0.9**
400	**2.1 / 1.4**	**2.4 / 2**

≈ 10 % of HQ energy

Drag coefficient



Transp. Coef …



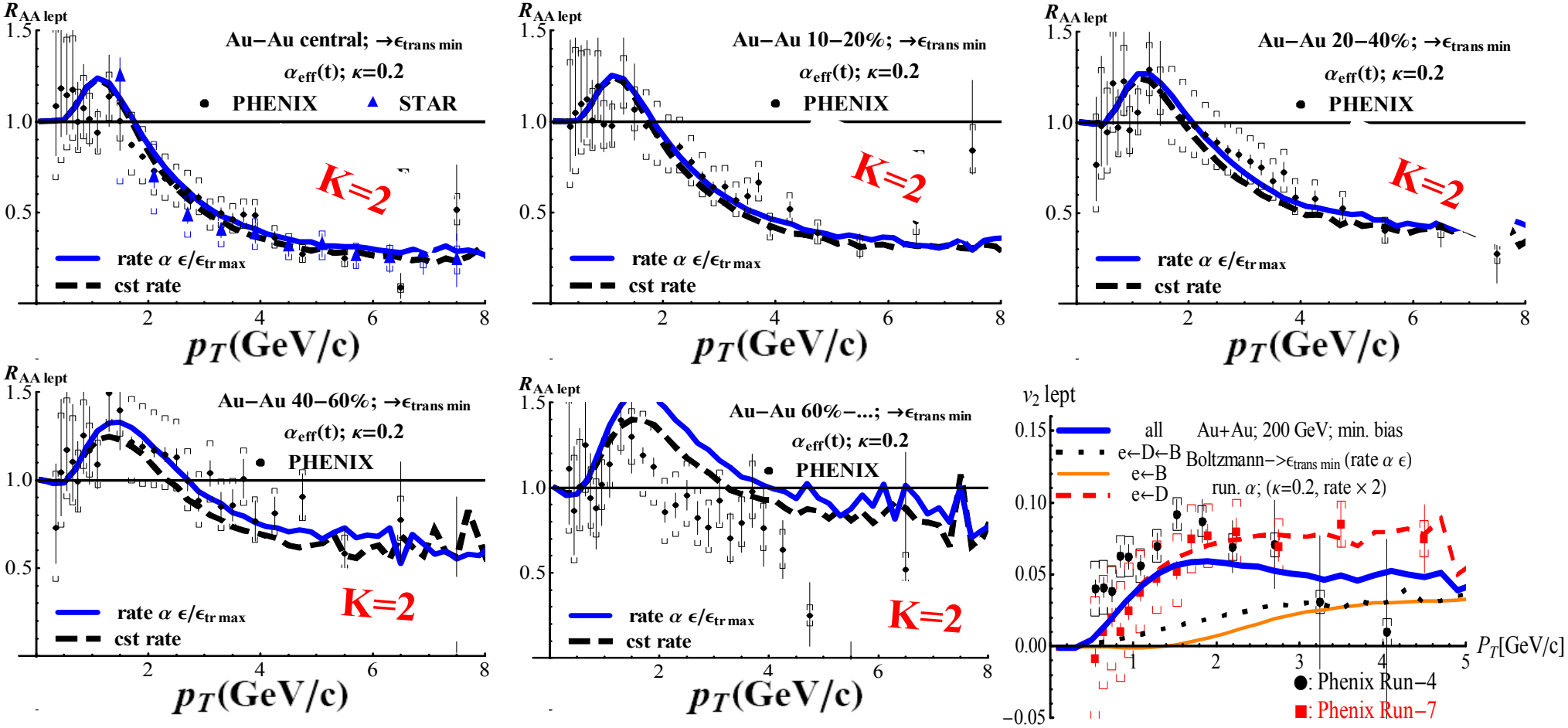
E: optimal μ, running α_{eff}

C: optimal μ, $\alpha_s(2\pi T)$

… of expected magnitude to reproduce the data (we "explain" the transport coeff. in a rather parameter free approach).

Observables (Au-Au) vs (rescaled) Model

Best observable so far: R_{AA} for single non-photonic electrons

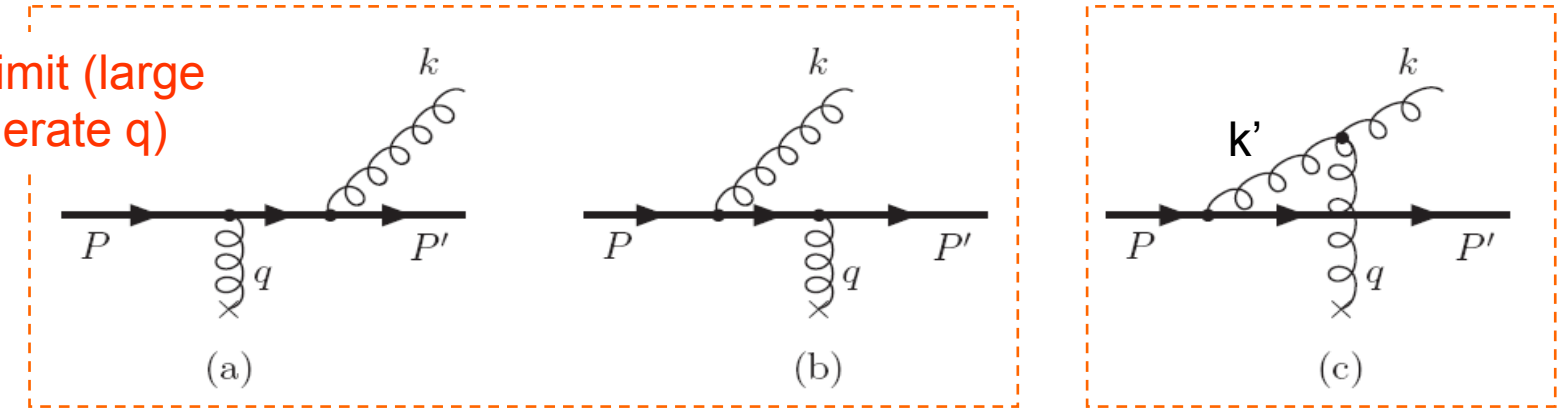


One reproduces R_{AA} *on all p_T range* with cranking K-factor ≈2 which permits to accommodate the "unknowns"

Basic (massive) Gunion-Bertsch

Radiation α deflection of current (semi-classical picture)

Eikonal limit (large E, moderate q)



Dominates as small x as one "just" has to scatter off the virtual gluon k'

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

with

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

Gluon thermal mass ~2T
(phenomenological; not in BDMPS)

Quark mass

Both cures the colinear divergences and influence the radiation spectra

Radiation spectra

$$\omega \frac{d^2\sigma^{x\ll 1}_{\text{rad}\,''\text{QCD}''}}{d\omega dq_\perp^2} \approx \frac{2N_c\alpha_s}{\pi} \ln\left(1+\frac{q_\perp^2}{3\tilde{m}_g^2}\right) \times \frac{d\sigma^{Qq}_{\text{el}}}{dq_\perp^2}$$

… to convolute with your favorite elastic cross section

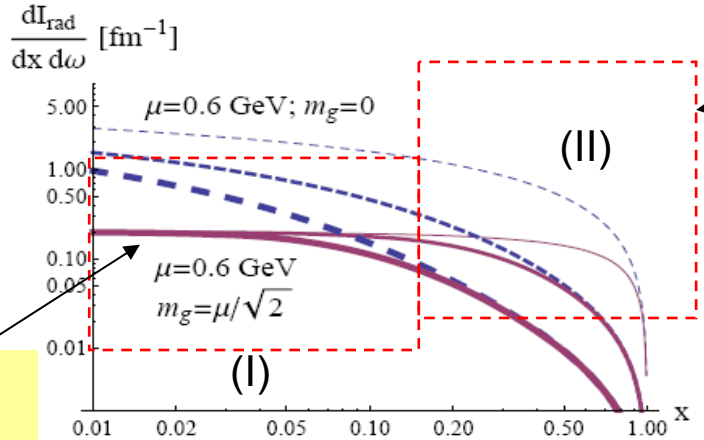
$$\tilde{m}_g^2 = (1-x)m_g^2 + x^2M^2$$

For coulomb scattering:

Light quark

c-quark

b-quark



Strong dead cone effect for $x>m_g/M_Q$ (mass hierarchy)

Little mass dependence (especially from q→c)

If typical $q_\perp \approx T$:

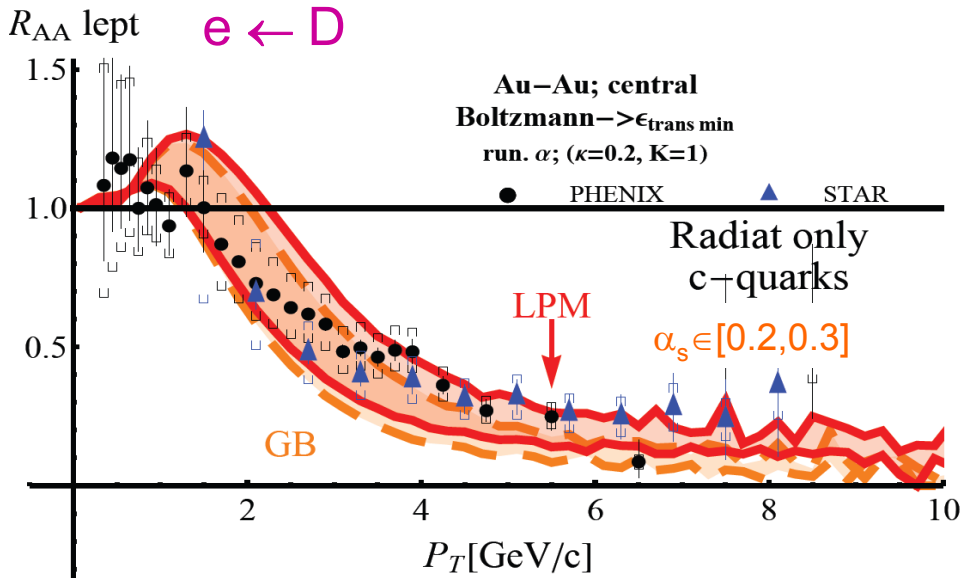
$$\frac{d^2 I^{x\ll 1}_{\text{GB}}}{dz\,d\omega} \sim \frac{2N_c\alpha_s}{3\pi} \times \frac{1}{m_g^2 + x^2M^2} \times \underbrace{\frac{\langle q_\perp^2\rangle}{\lambda}}_{\hat{q}}$$

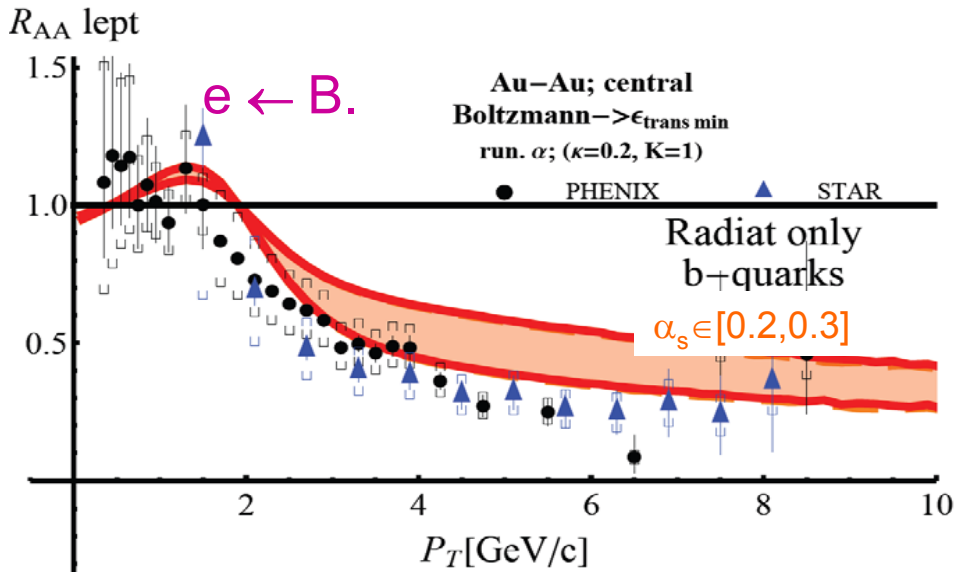
$$\boxed{\frac{dE_{\text{GB}}(Q)}{dz} \approx \frac{4N_c\alpha_s}{\pi} \times \frac{0.8\mu}{M+\mu} \times \frac{E}{\lambda_Q}}$$

Strong mass effect in the average Eloss (mostly dominated by region II), similar to AdS/CFT

Interesting *per se*, but not much connected to the quenching or R_{AA}.

Results with (Coherent) Radiation Included

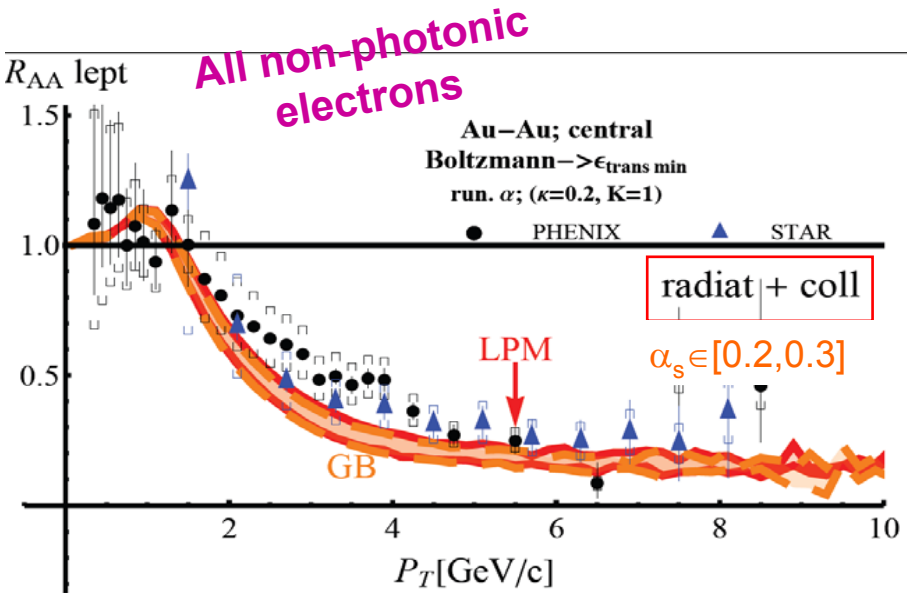




1. Coherence: Some moderate increase of R_{AA} for D at large p_T.
2. No effect seen for B

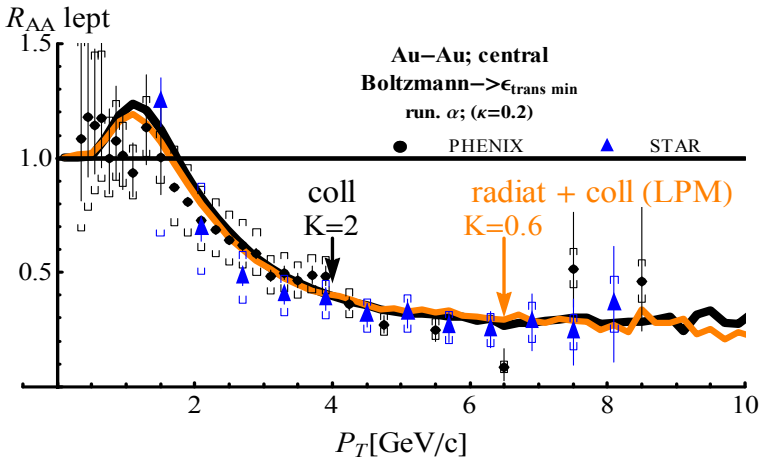
Conclusions can vary a bit depending on the value of the transport coefficient

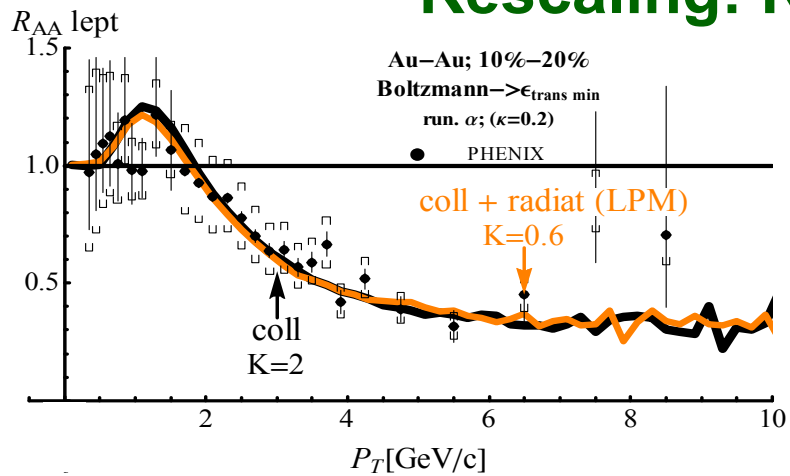
Indication that R_{AA} at RHIC is mostly the physics of rather numerous but small E losses, not very sensitive to coherence .

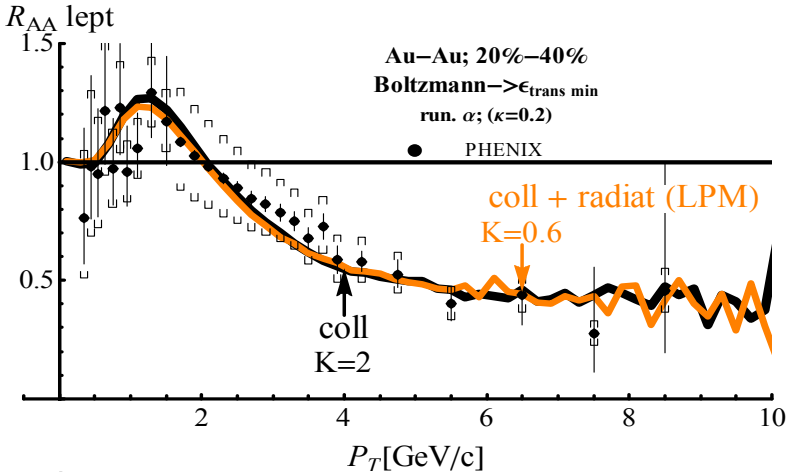


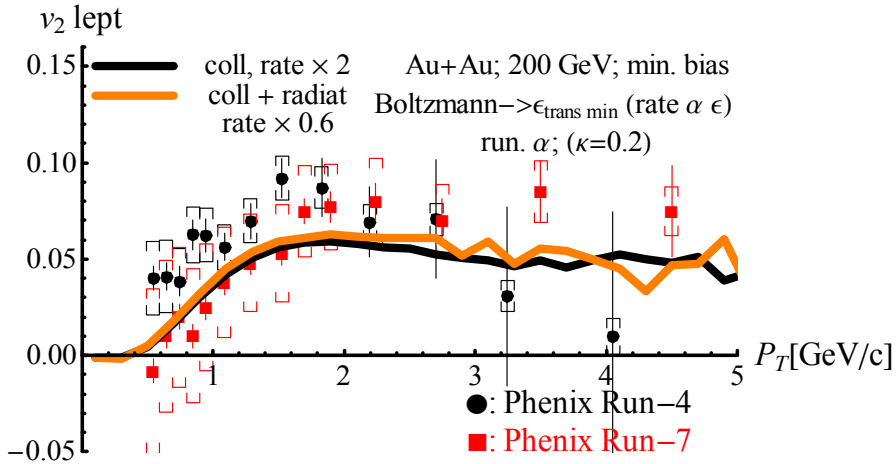
Collisional vs {Radiative + Coll}

Rescaling: K=0.6





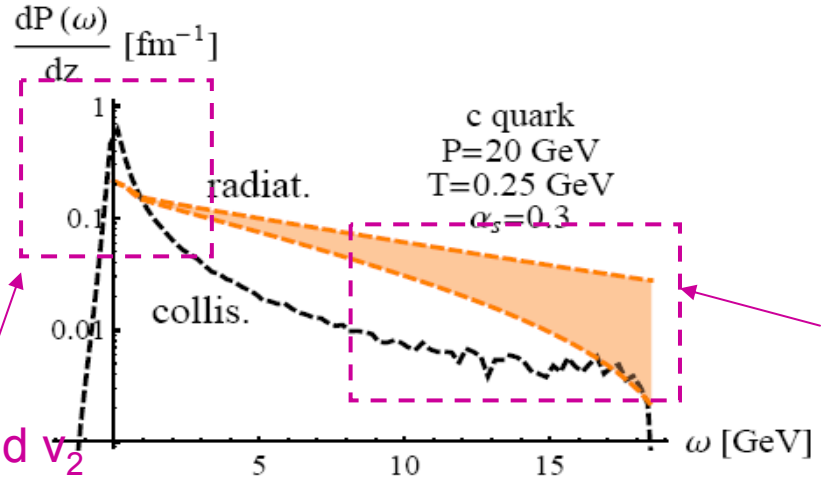




The present data cannot decipher between the 2 local microscopic E-loss scenarios

Interpretation

The heavy-quark physics at play for RHIC measured up to now (R_{AA} and v_2) is the one of small (relative) E-loss (and thus of the Fokker-Planck equation)… even at the largest p_T



R_{AA} and v_2 physics

Bad control on the theory

Explains why purely collisional models "work" so well

What we need

- D and B separately (in any case)
- tagged HQ jets and I_{AA} (and other correlations)

In our view, it is nevertheless more plausible to describe the physics in terms of a rather strong collisionnal energy loss supplied with an even stronger radiative energy loss (at least for γ ">>" 1).

QGP properties: low momentum

As we reproduce experimental data with rescaled model:

Moore-Teaney:

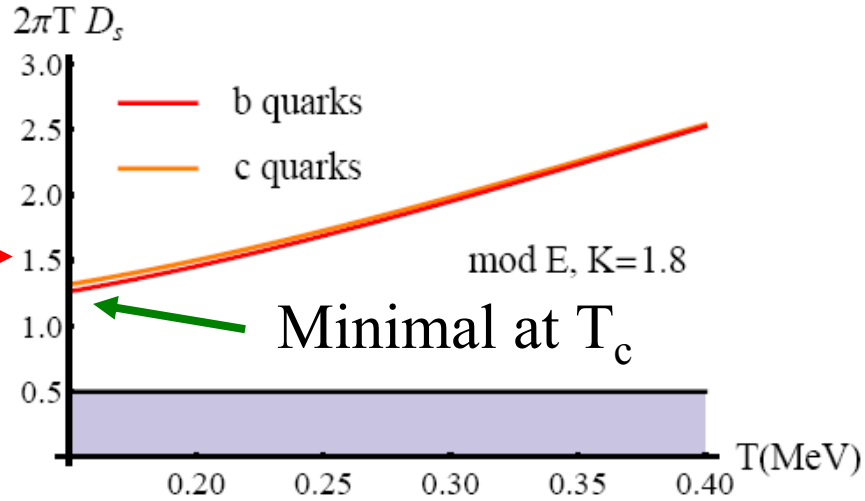
$$\frac{D}{\eta/(e+p)} \approx 6 \quad \Rightarrow \eta/s \approx DT/6$$

"robust"pQCD

$$\approx \frac{2\pi T\, D}{3 \times 4\pi}$$

$$\Rightarrow \eta/s \approx \frac{0.5}{4\pi}$$

at T_c

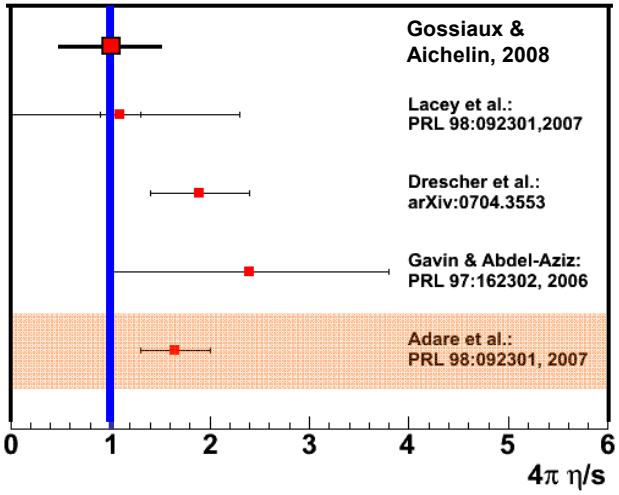


Strong coupling; AdS/CFT:

$$\eta/s \approx DT/2 \approx \frac{2\pi T\, D}{4\pi}$$

$$\Rightarrow \eta/s \approx \frac{1.5}{4\pi}$$

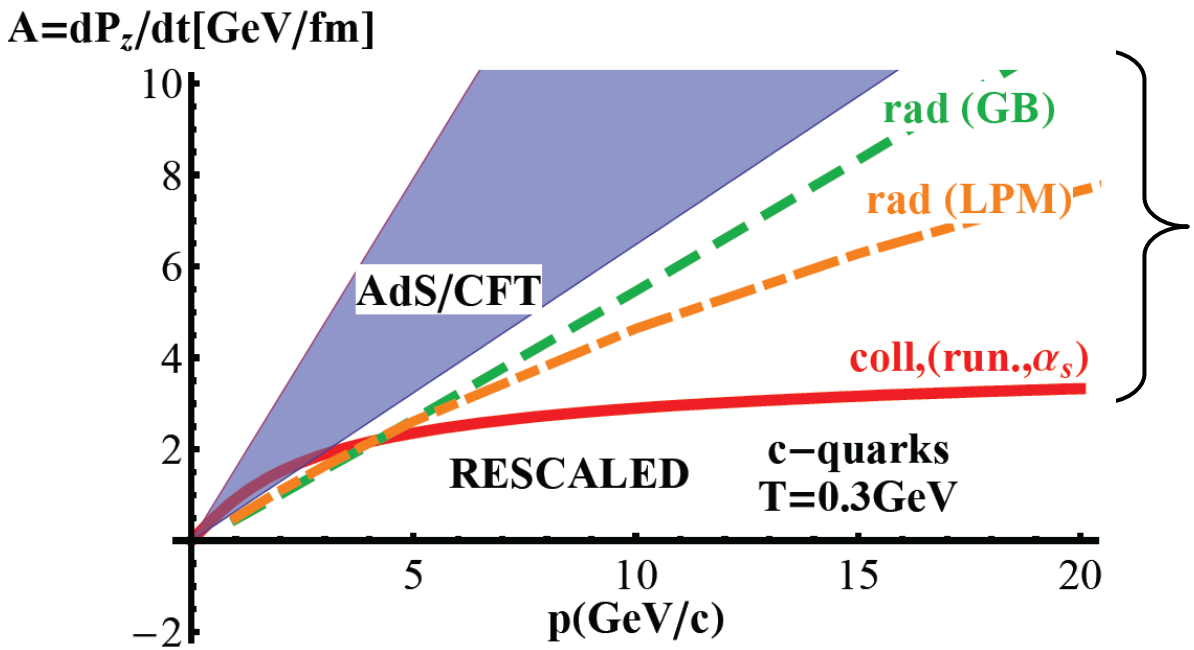
at T_c



But diffusion constant of heavy quark is already an interesting quantity in itself and could be evaluated on the lattice !!!

QGP properties: stopping power

Gathering all *rescaled* models (*coll. and radiative*):

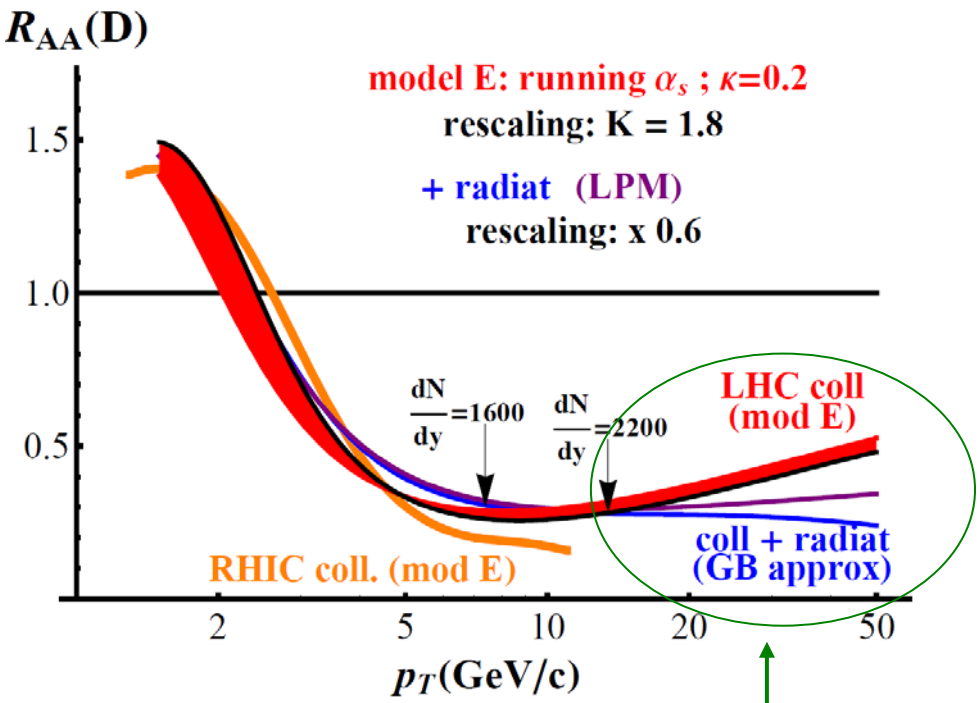


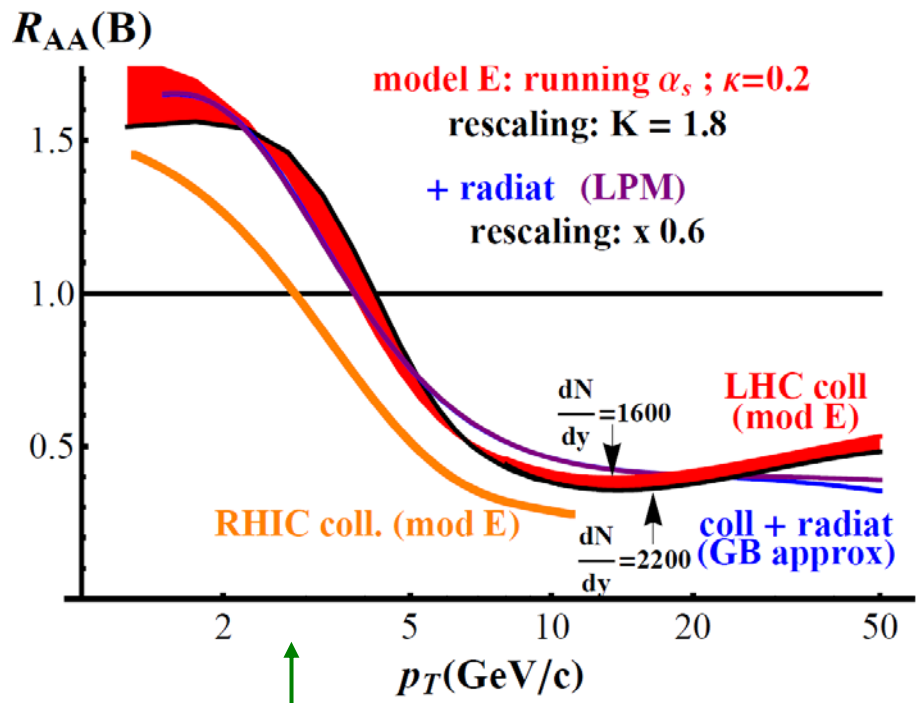
Exp. cannot resolve between those various trends

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

Noticeably enough, AdS/CFT lower bound is quite close to the incoherent radiation limit

Perspectives :D & B meson: LHC (radiat + collisional)

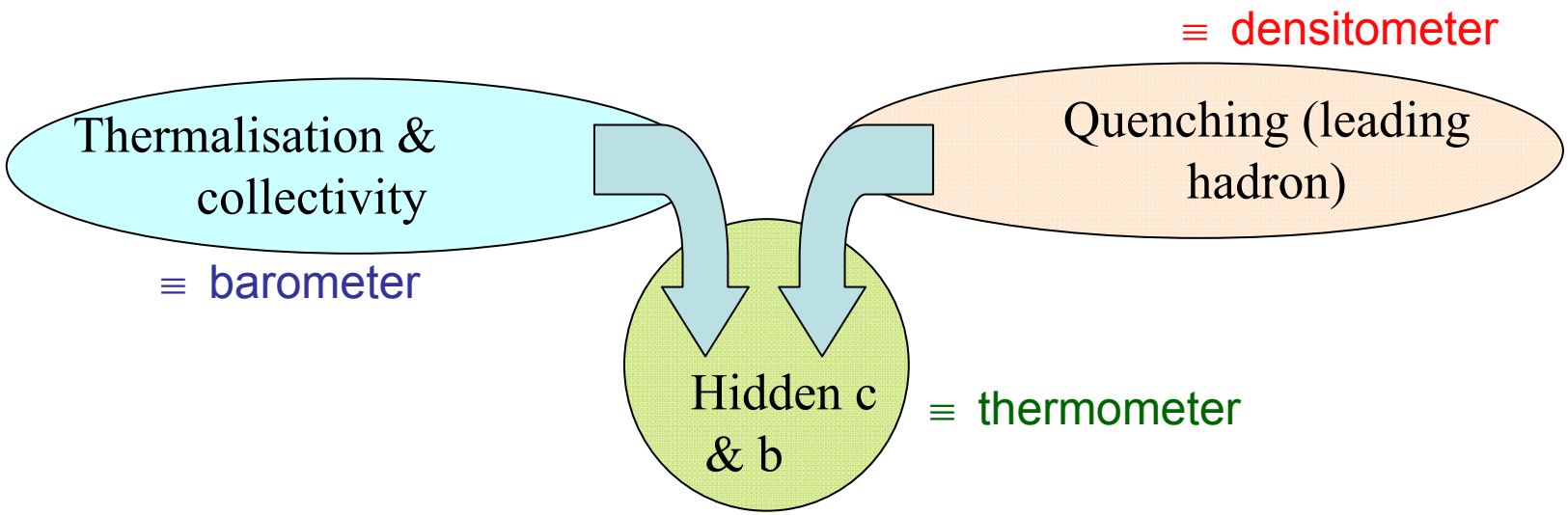




D spectra in Pb-Pb (5.5 TeV): Some window to decipher between the various Energy-loss models, for $p_T > 20$ GeV/c

B spectra in Pb-Pb (5.5 TeV): Pretty independent of E-loss model (properly calibrated w.r.t. RHIC data)

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

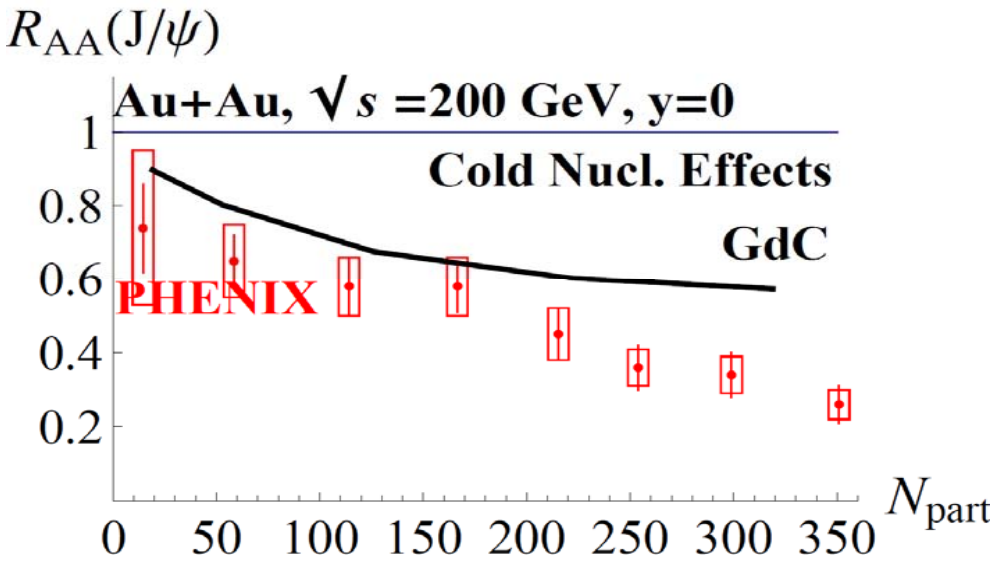


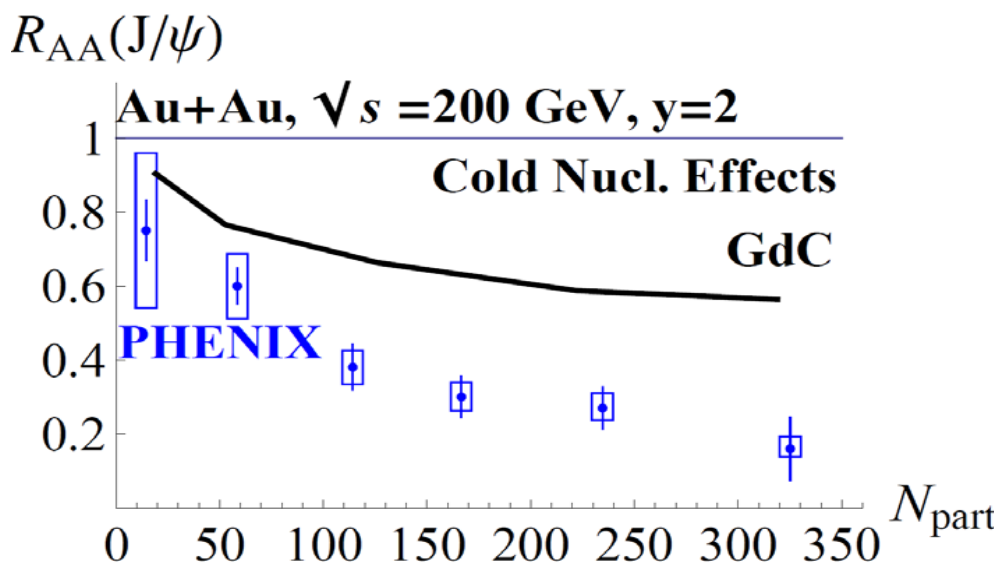
II. Quarkonia in QGP

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)

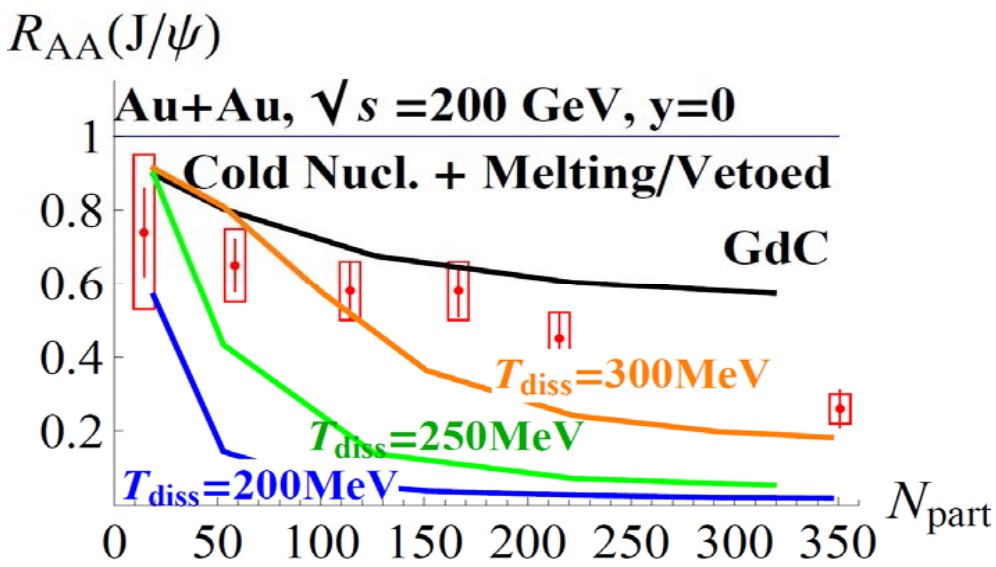


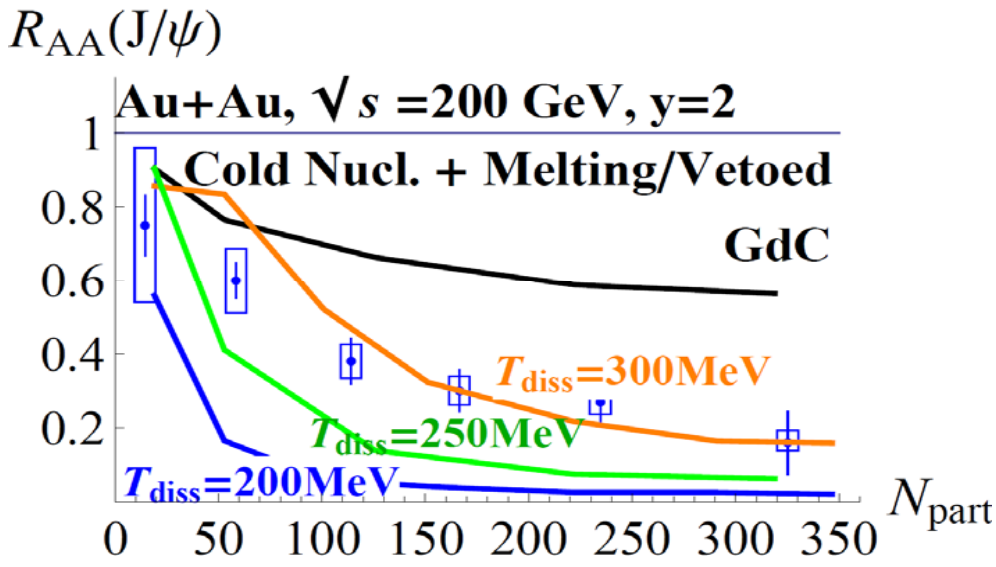


Progress to be made here

Integrated J/Ψ numbers @ RHIC

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





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

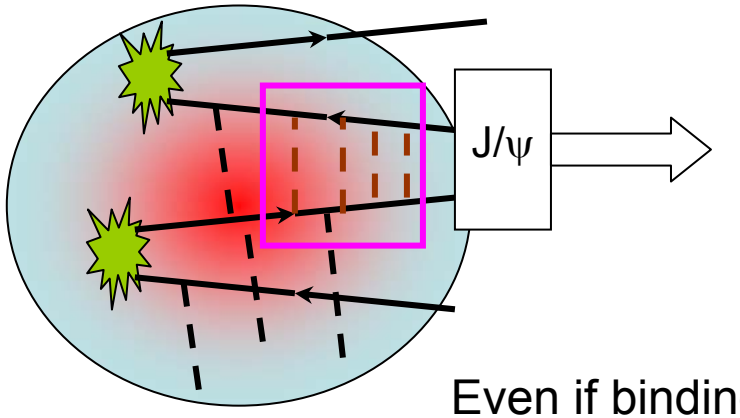
Some claims of "sequencial suppression" with a very bound J/ψ were indeed made by several physicists

``\`\`\`\`\`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):



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

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)

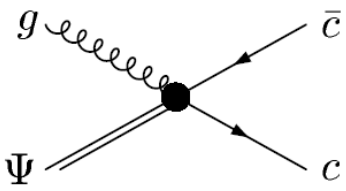
Discussion

- The majority of quarkonium suppression models ignore open heavy flavor suppression due to induced gluon radiation and collisional energy loss (charm quenching)
  - Is this omission justified? No
  - Does charm suppression affect recombination? Yes
  - Do medium effects in AA affect the formation time of quarkonia? If formation time taken as the Heisenberg time, Yes

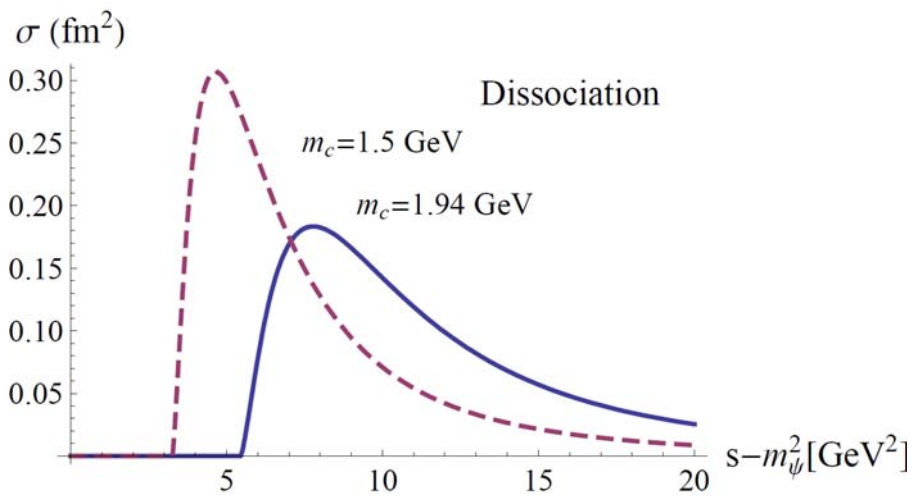
Basic Ingredients

Dissociation

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



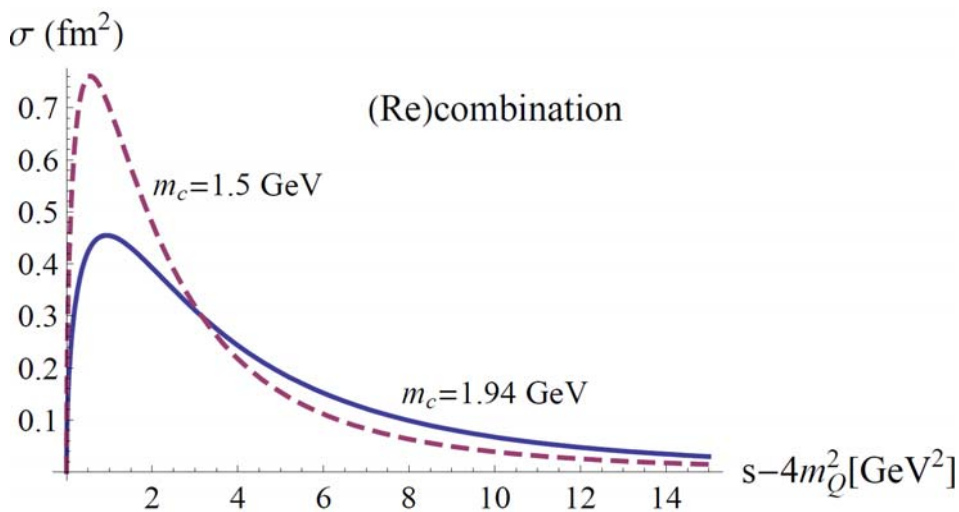
$$\sigma_{(Q\overline{Q})g}(\omega) = \frac{2^{11}}{3^4}\alpha_s \pi a_0^2 \frac{(\omega/\varepsilon(0)-1)^{3/2}}{(\omega/\varepsilon(0))^5}\Theta(\omega-\varepsilon(0))$$



Max ≈ 2 fm² at ω ≈ 500 MeV

Recombination

Cross section obtained from σ_{diss} via detailed balance



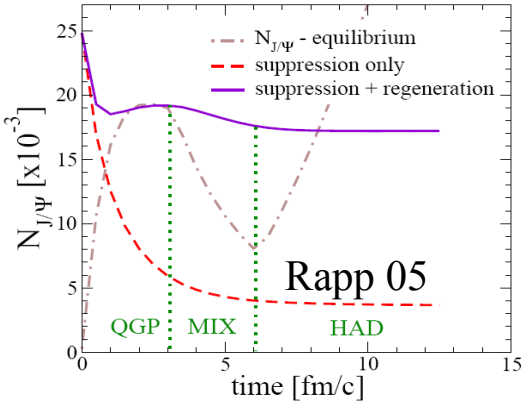
Recombination: hierarchy of approaches…

Complexity

Statistical weights (at transition). no detailed dynamics. ☹ assumes all time scales are small vs. transition time. ☺ simple to deal with. PBM, Stachel & Andronic; Gorenstein, Kostyuk;…

Rate equations: $$\frac{dN_\Psi}{dt} = -\Gamma_\Psi \left(N_\Psi - N_\Psi^{eq}\right)$$

☺ Might contain the essential physics at a global level.
☹ Model of $f_c(x,p)$ needed. ☹ no possibility of studying diff. spectra. Grandchamp, rapp and Brown; (early) Thews

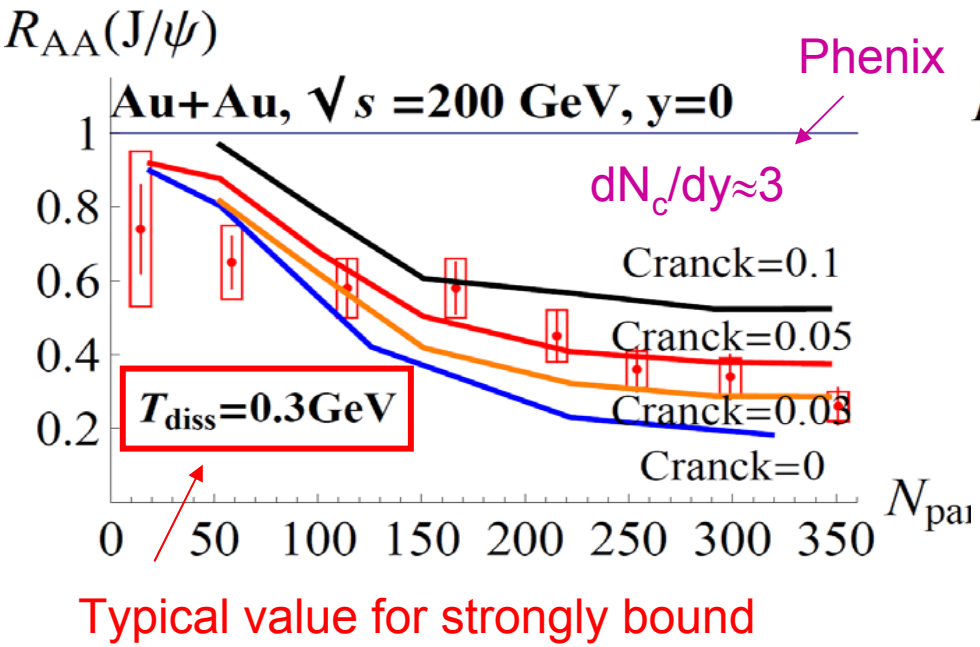


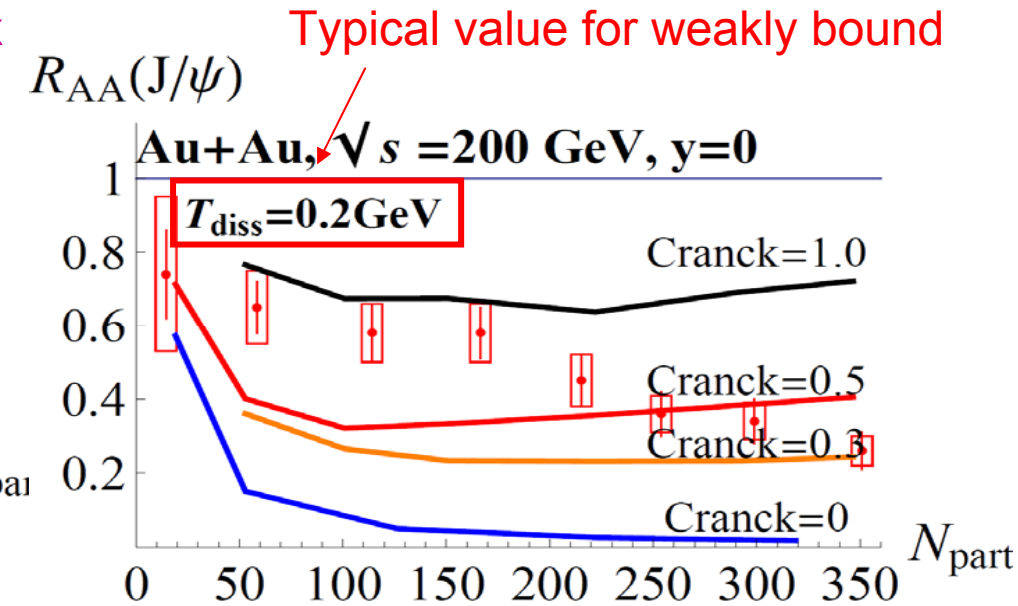
Transport theory assuming spatial homogeneous $f_i(p)$. ☺ diff spectra. ☹ misses surface effects, x-p correl, Q are not uniformly distributed. Thews and Mangano

Transport theory. ☺ solves the caviats of other approaches. ☹ may obscure the physics. Zhang (AMPT); Bratkovskaya & Cassing (HSD); Gossiaux;…

… does not mean a hierarchy of answers (hopefully)!

Turning on (re)combination + hard dissoc



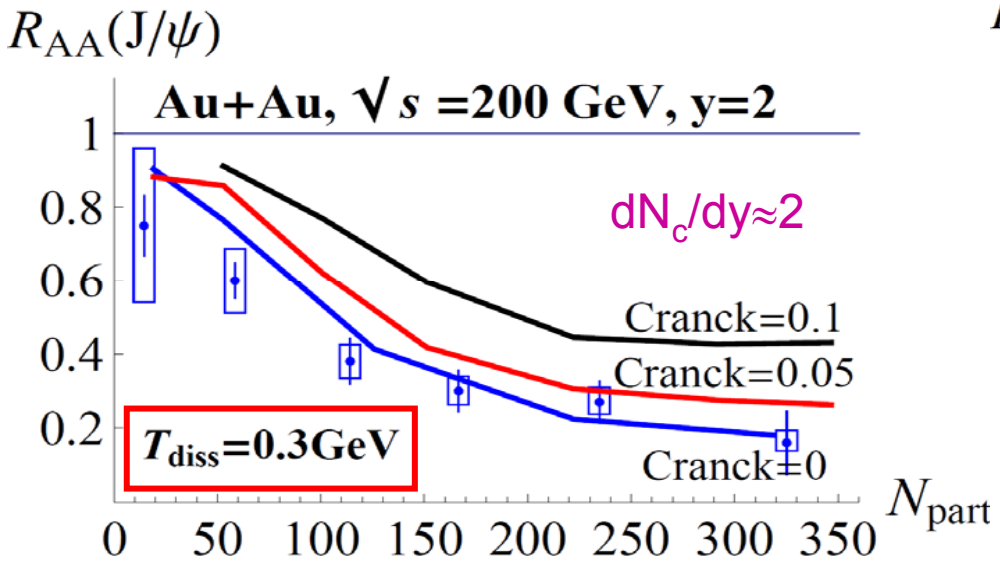


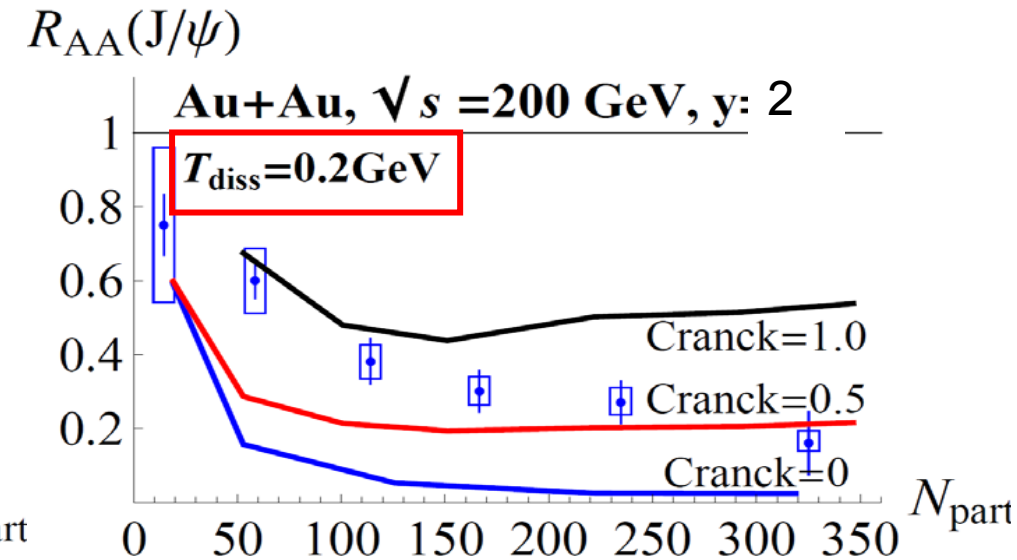
Problem: One has to reduce the fusion probability by a factor ~10 to reproduce the data (if recomb. cross section taken at face value, one arrives at R_{AA} (most central > 2 !).

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

Turning on (re)combination at y=2

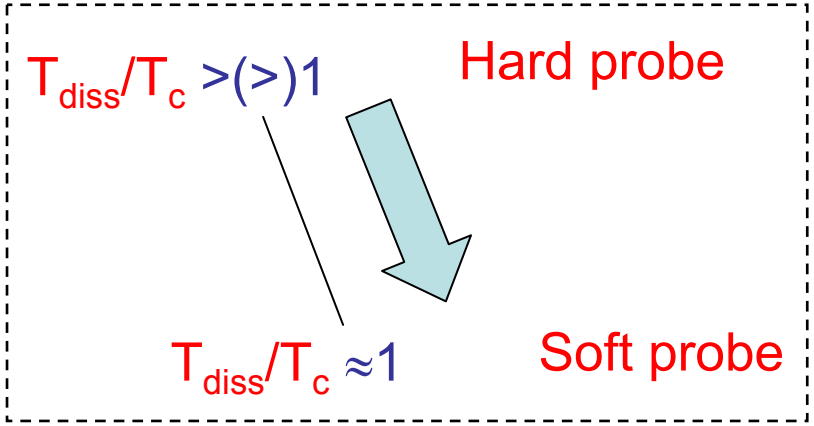




No room left for coalescence at y=2. What are the physical mechanisms for taming the fusion ?

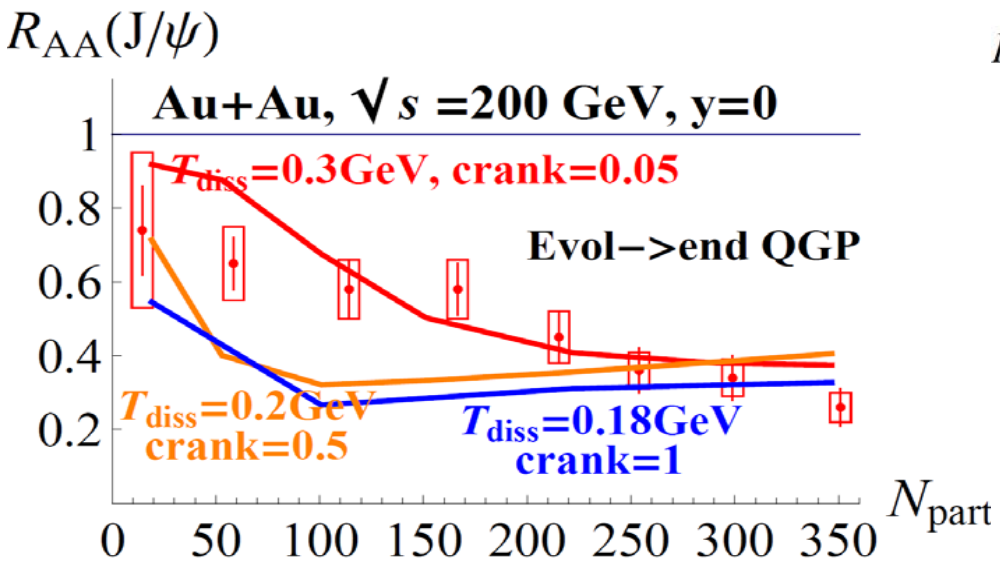
Moreover: The pQCD Bhanot and Peskin result is usually considered to be small w.r.t. other effective approaches at small s-M^2

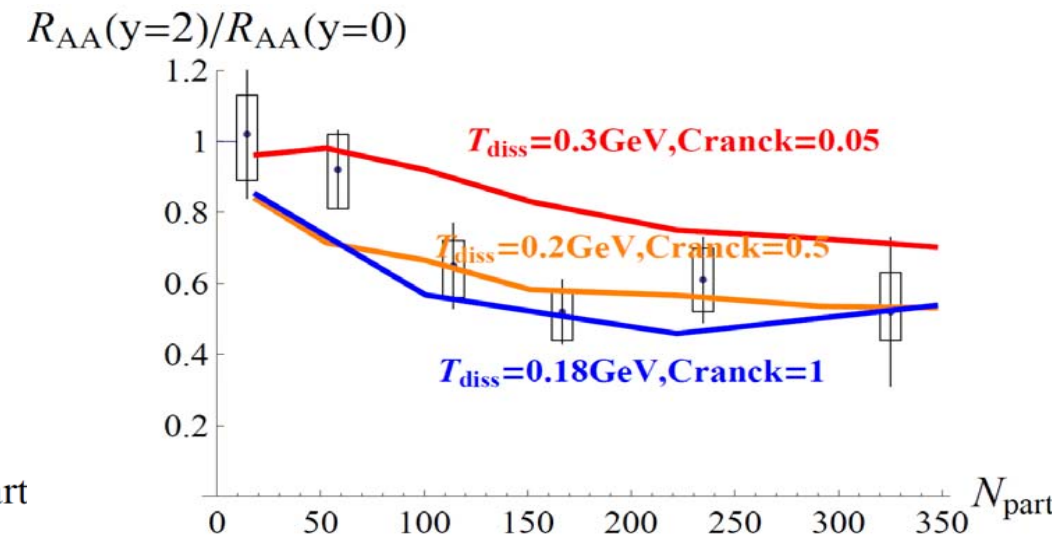
Good agreement with the same σ_{fus} band (Cranck. $\in$ [0.5,1])



Best parameters from R_{AA}

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

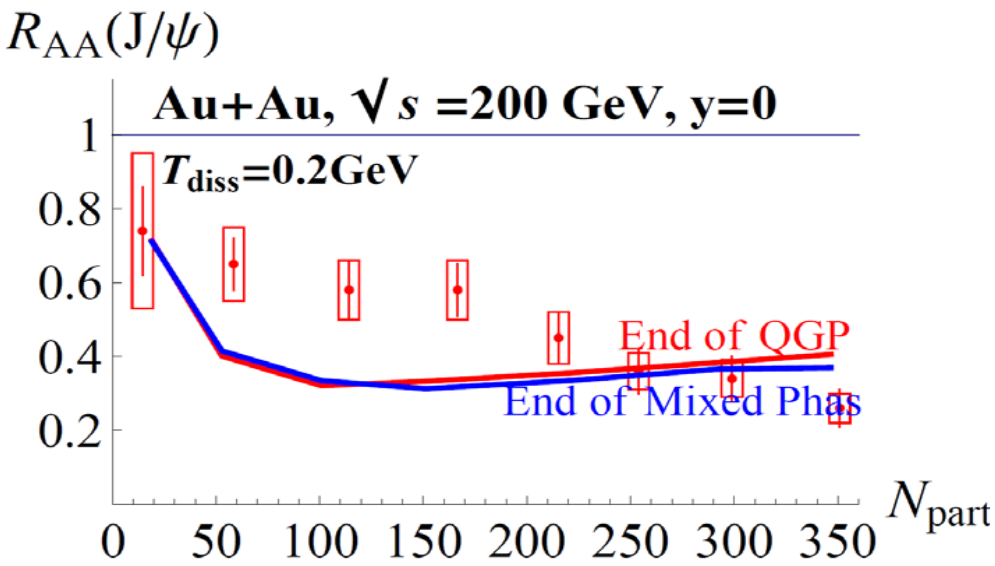




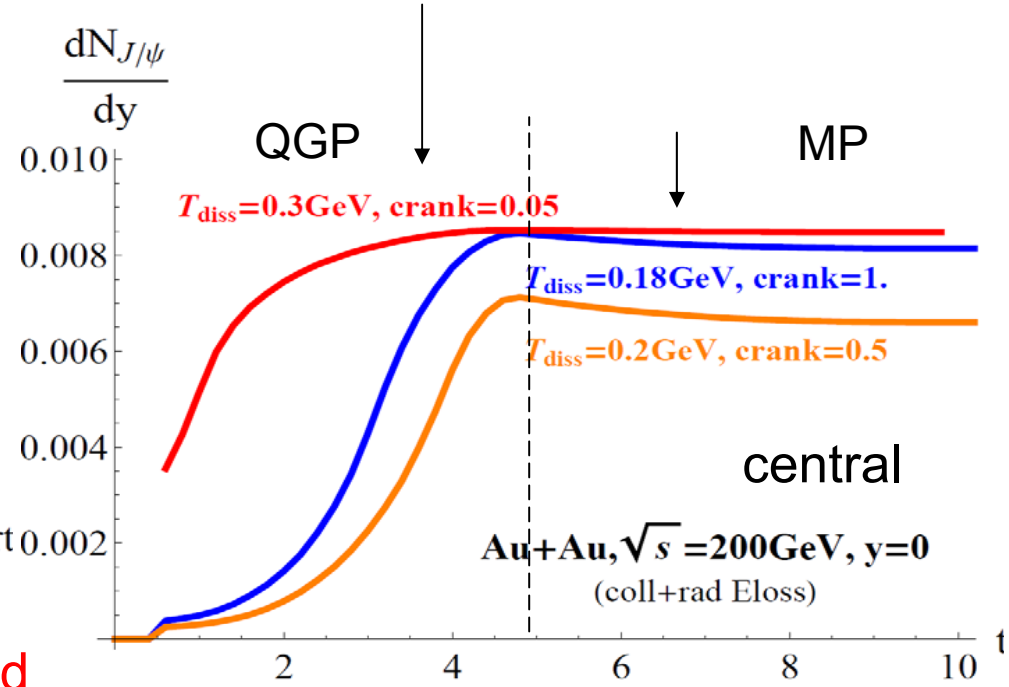
Conclusion: $T_{diss} \in [0.2,0.3]$… but difficult to go beyond

Finer analysis: Thermometer of what ?

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



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



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

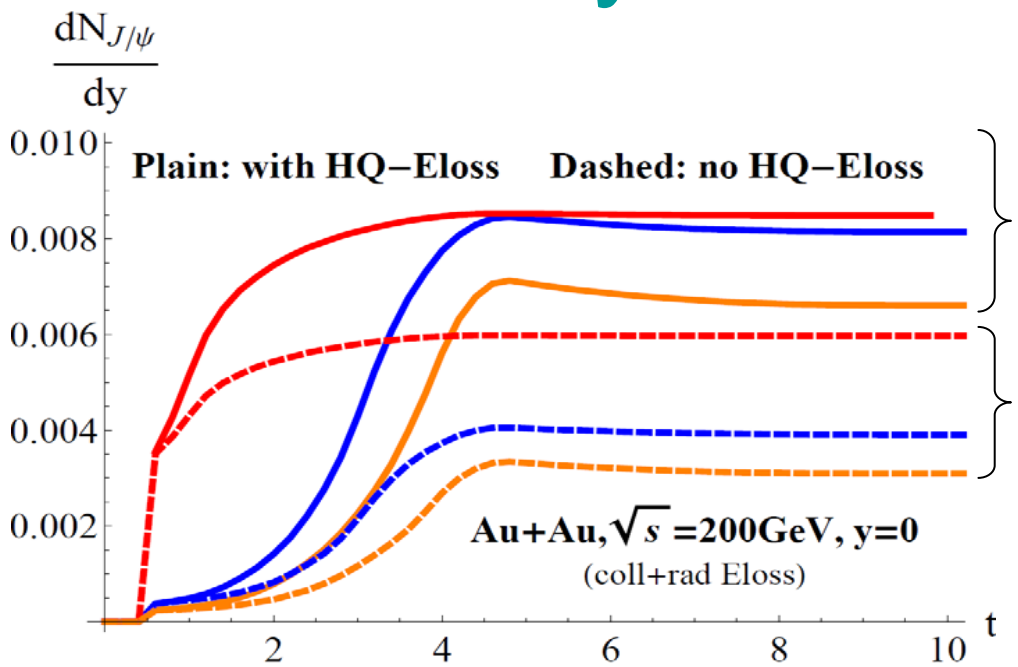
Dynamical evolution does not confirm the idea of statistical recombination in the mixed phase

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

Semi-Hard probe

$T_{diss}/T_c \approx 1$ Soft probe

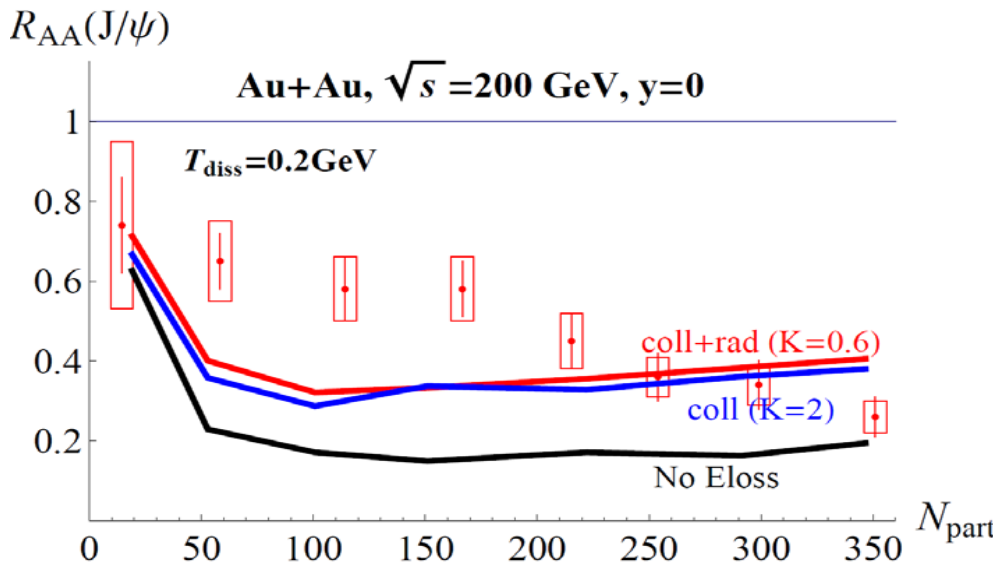
Finer analysis: role of HQ energy loss



Eloss

No Eloss

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

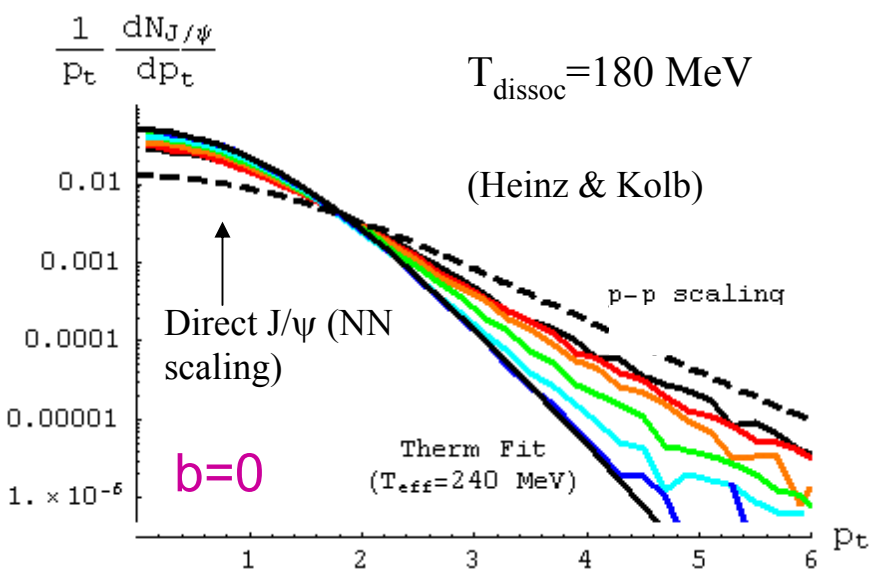


However: Once the Energy loss has been "properly" calibrated on non-photonic single-e R_{AA}, then the production rates do not depend too much on the detailed phenomena

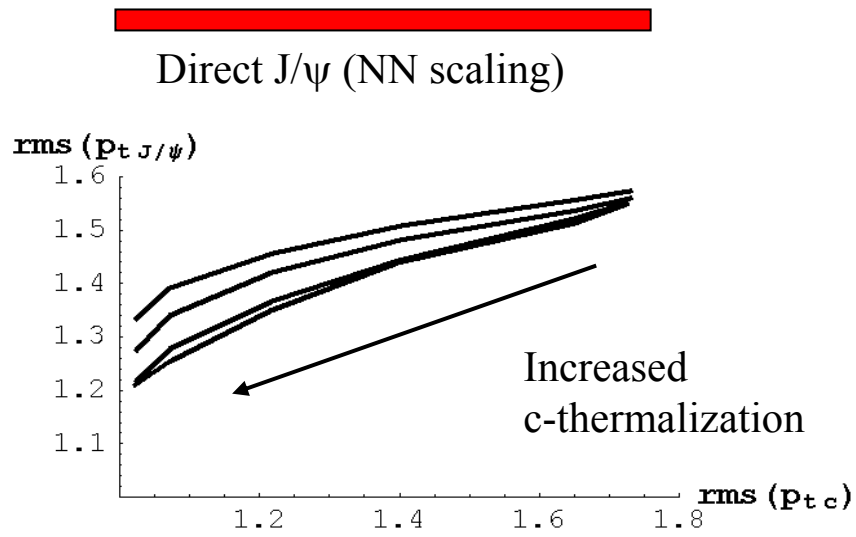
Rete-Quarkonii 2010

The P_T world

Differential production might reveal more physics



QGP "cools" the charms, even with the radial flow

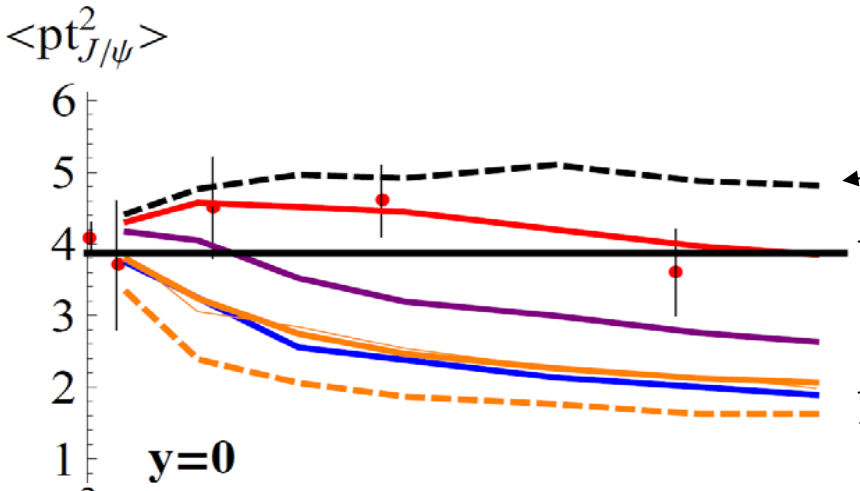


Prediction for b=0 and just recombination (2004)

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:

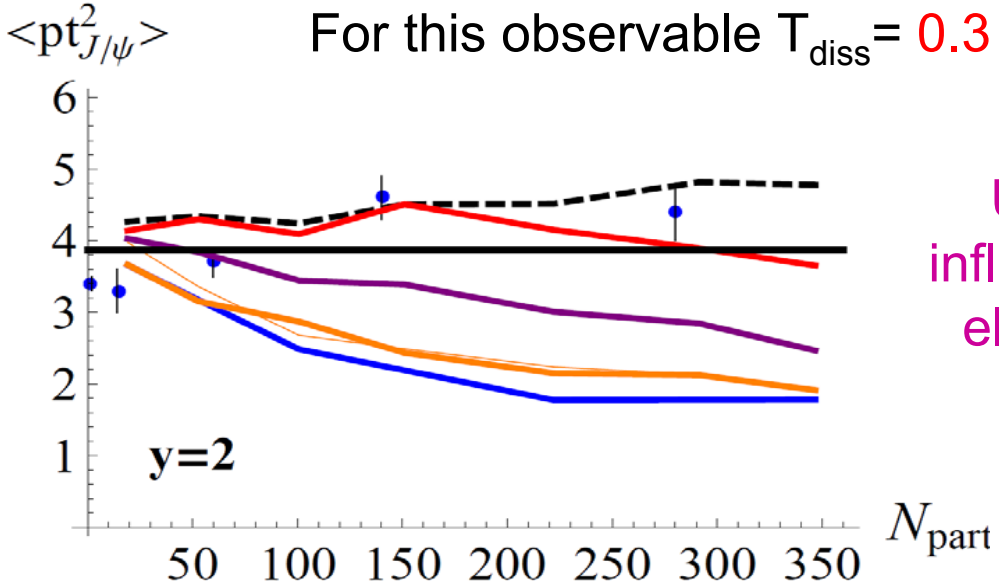


Cronin effect at initial stage (and no further effect)

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



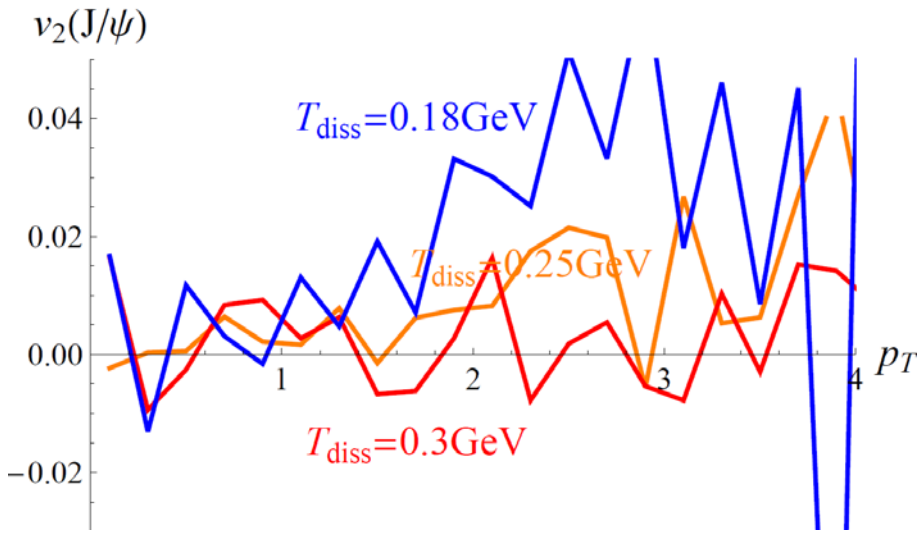
Unknown: influence of the elastic cross section

TABLE I: The mass shift $\Delta M_{J/\psi}$ and elastic J/ψ+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

Voloshin (2005)

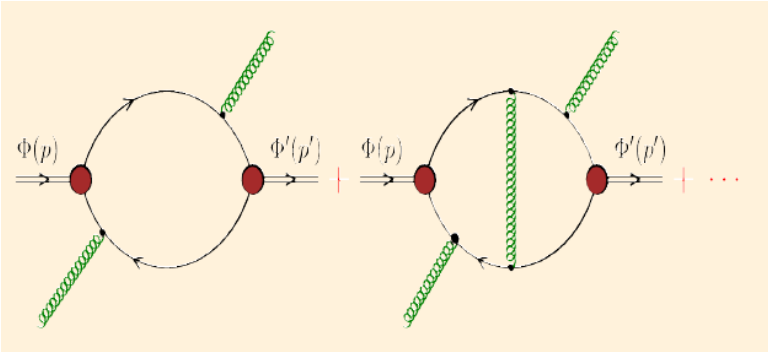
The keystone (?): v_2



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

Investigating the role of elastic processes

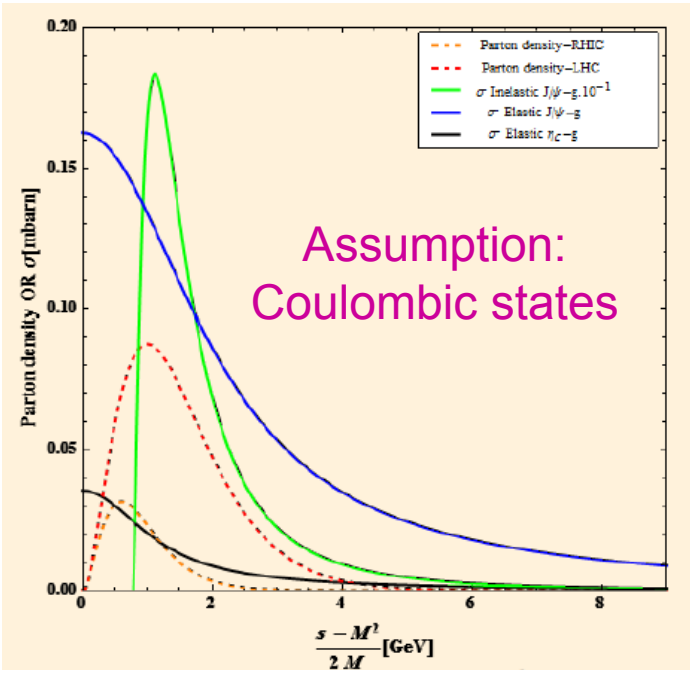
Dominant process:



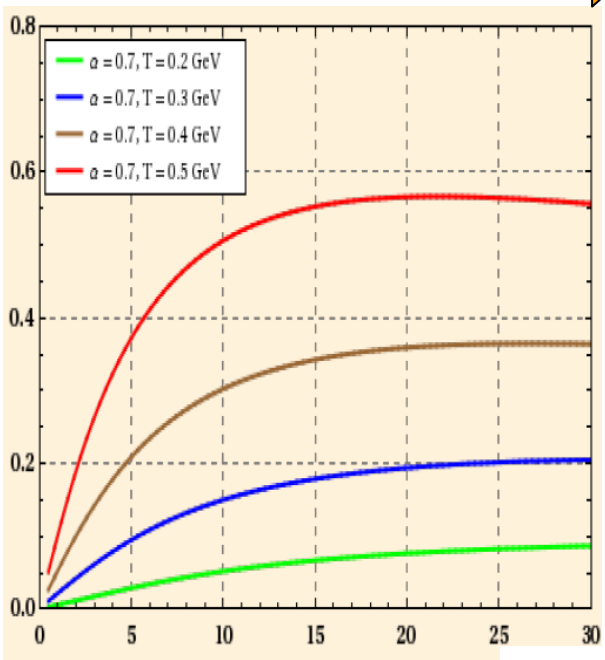
Work of H. Berrehrah (see QGP France 2009 & Hot quarks 2010)

Penalized by higher power of the coupling constant w.r.t. inelastic scattering… but no threshold

Total cross section

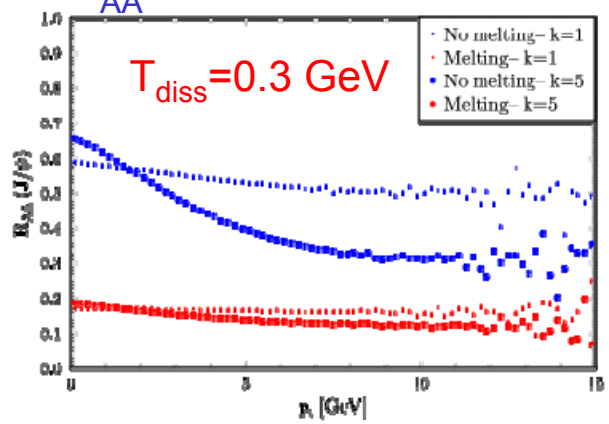


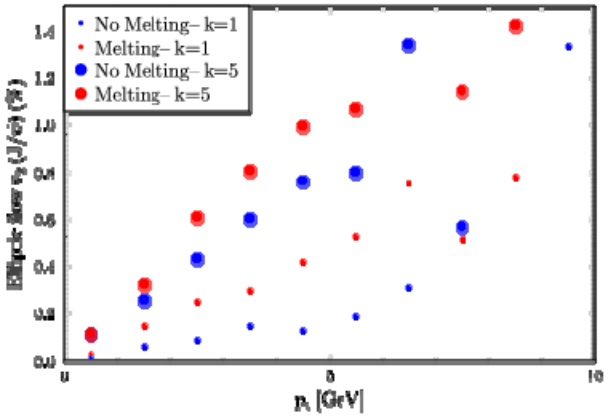
Drag force



Inclusion in MC@$_s$HQ

R_{AA}





Elliptic flow

Preliminary conclusion

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

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 ?)

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

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

Prediction for LHC:

Work to be continued during the LHC ERA:

HQ Parameters:

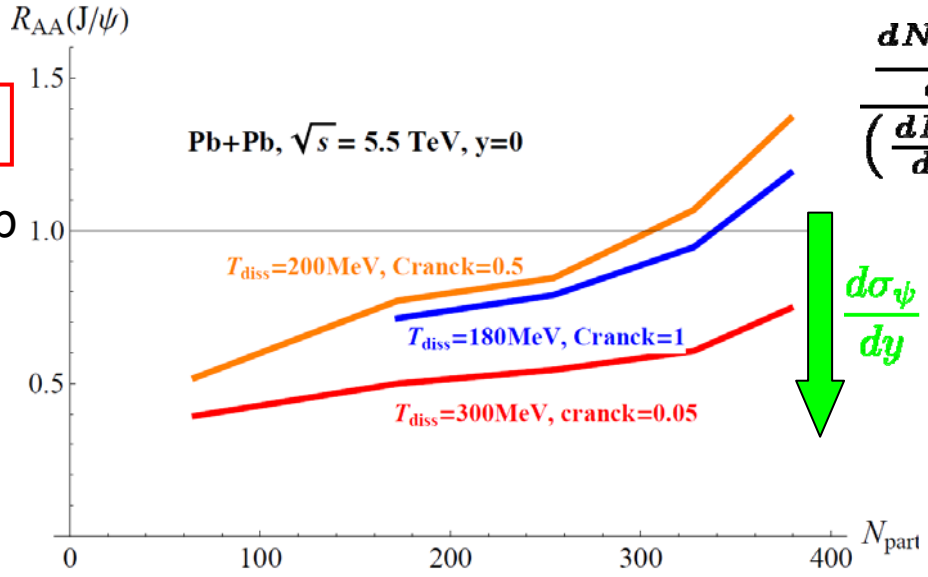
y=0 $\begin{cases} d\sigma_\psi/dy=2\mu b \text{ in pp} \\ dN_c/dy\approx 30 \text{ in PbPb} \end{cases}$

Hydro Parameters:

$s_0 = 268\ fm^{-3}$

$\equiv$

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



$$\frac{d\sigma_\psi}{dy} = 7\mu b$$

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….