Coherence effects In heavy quark and quarkonium production in ultrarelativistic heavy ion collisions

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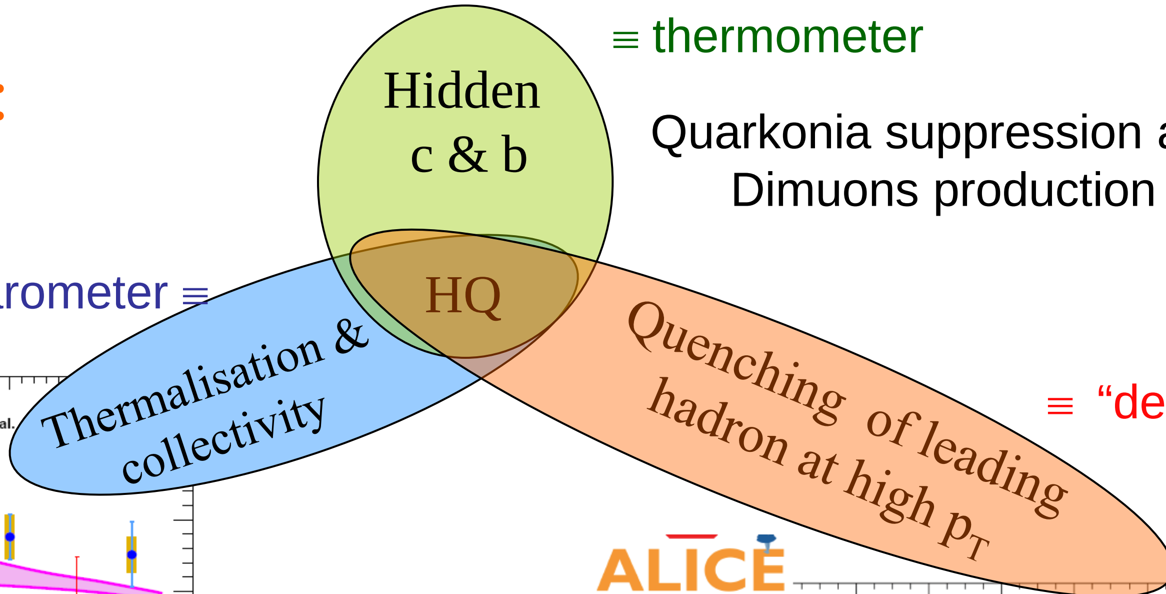
Thanks to J Aichelin, H. Berrehrah, M. Bluhm, Th. Gousset, R Katz, V Marin, M. Narhgang, S. Vogel, K. Werner

2nd International Conference on New Frontiers in Physics (Kolymbari, Greece)

Hard Probing QGP with heavy flavors

The Trilogy:

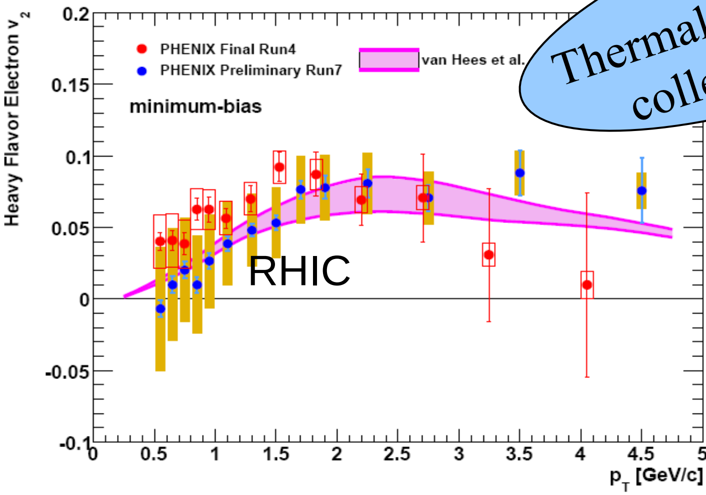


≡ thermometer

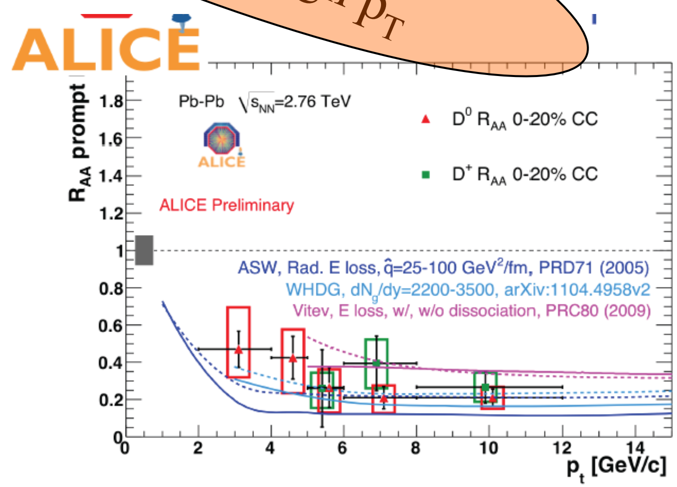
Quarkonia suppression and
Dimuons production

Barometer ≡

≡ "densimeter"



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



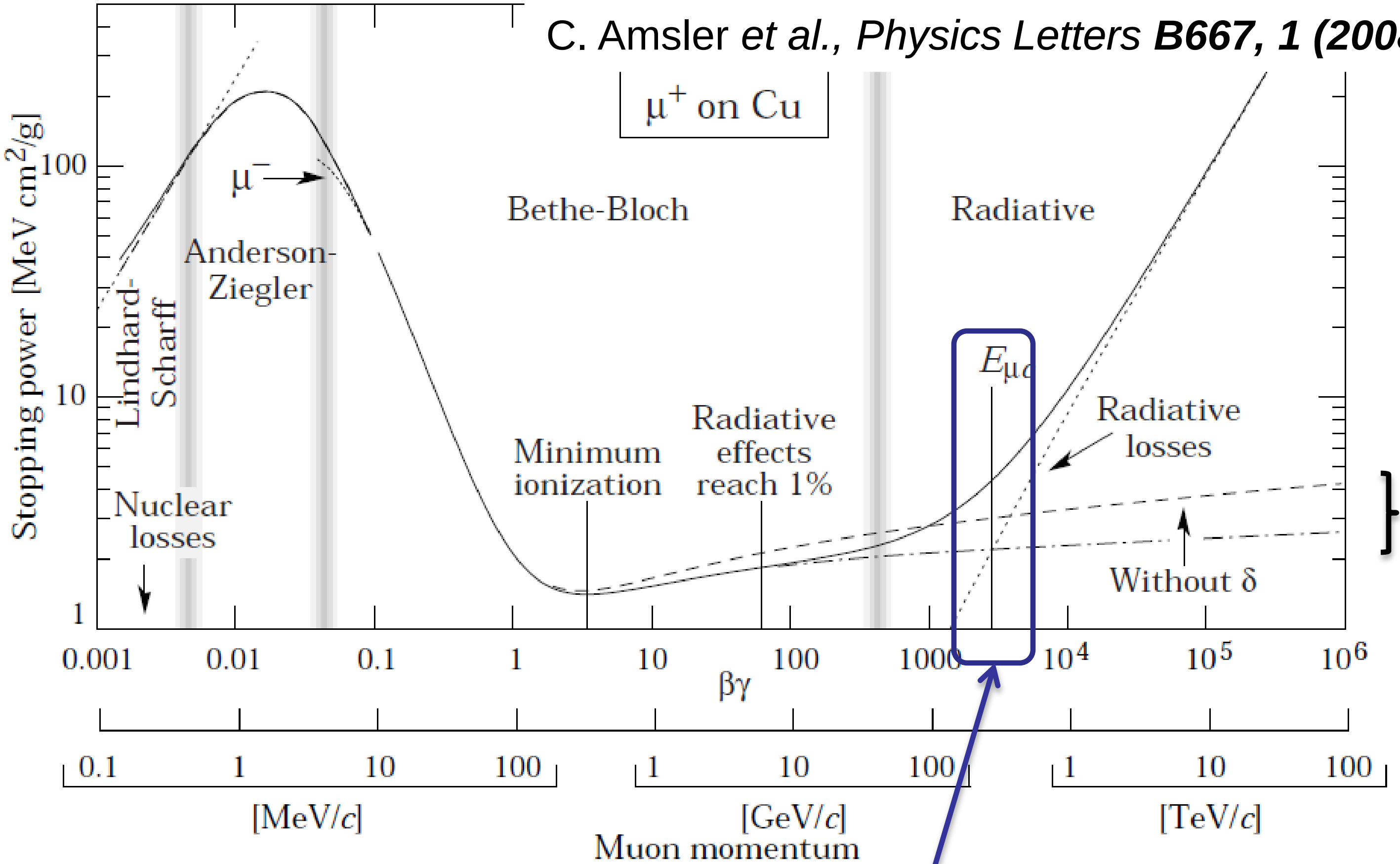
Nuclear modification factor (R_{AA}) of D mesons probes c-quark energy loss in QGP (not seen in pA)

Heavy flavor quenching

Quenching – Energy loss in cold atomic matter

Energy loss of a charged particles passing through cold atomic matter: extensive field of research in the XXth century

C. Amsler *et al.*, *Physics Letters* ***B667, 1 (2008)***



Cold Matter Effects (Fermi)

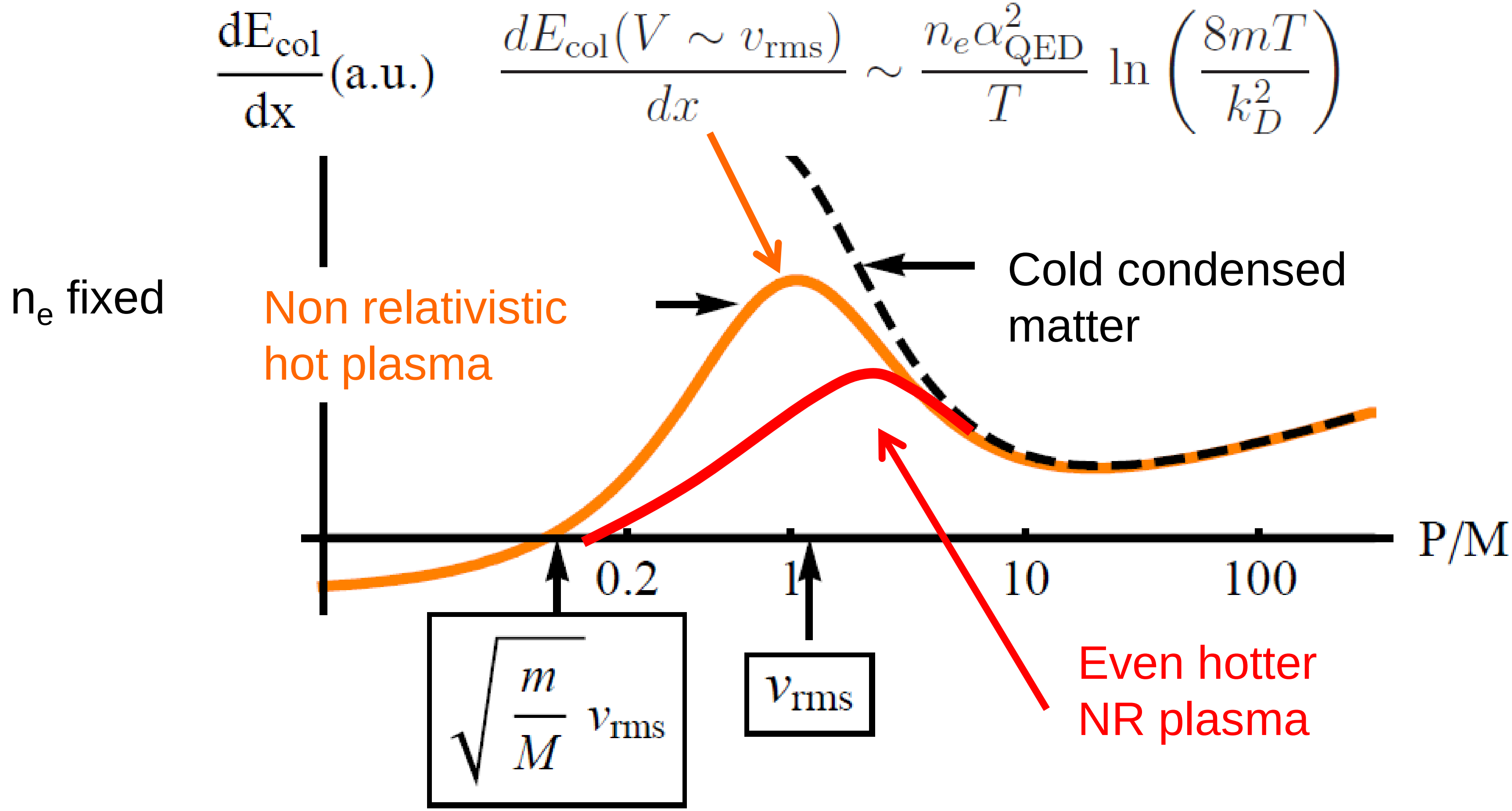
$$\left(\frac{\frac{dE_{\rm BH}}{dz}}{\frac{dE_{\rm col}}{dz}}\right)_{V\approx c} \sim Zz^2 \times \alpha_{\rm QED} \times \frac{m_e}{M} \times \gamma \;\Rightarrow\; \gamma_{\mu\,c} \approx \frac{M}{m_e} \times \frac{1}{\alpha_{\rm QED}} \times \frac{1}{Zz^2} \to \frac{M}{g^3 T}$$

QGP: not so large

fermion Energy loss in a NR (Q)ED plasma

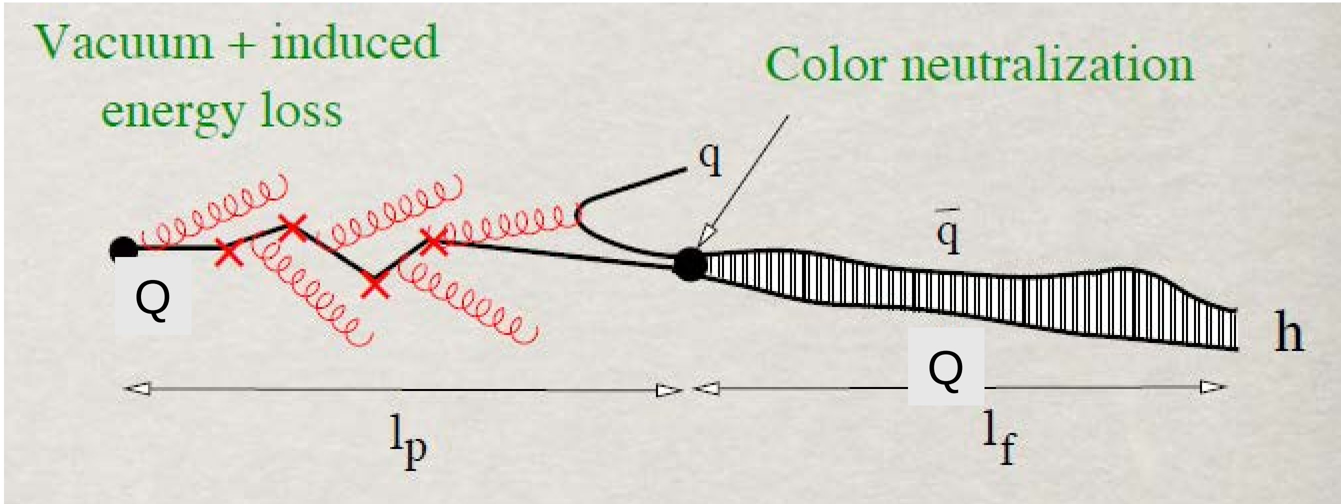
Reduction of the collisional energy loss ! (need to “touch” the plasmon pole: $v \approx v_{rms} \propto T^{1/2}$)

$$\frac{dE_{\rm col}(V \sim v_{\rm rms})}{dx} \sim \frac{n_e \alpha_{\rm QED}^2}{T} \ln\left(\frac{8mT}{k_D^2}\right)$$



What if T still increases (until m_e) and $v_{rms} \approx 1$?

Partons in QCD plasma



From B. Kopeliovich (this conf)

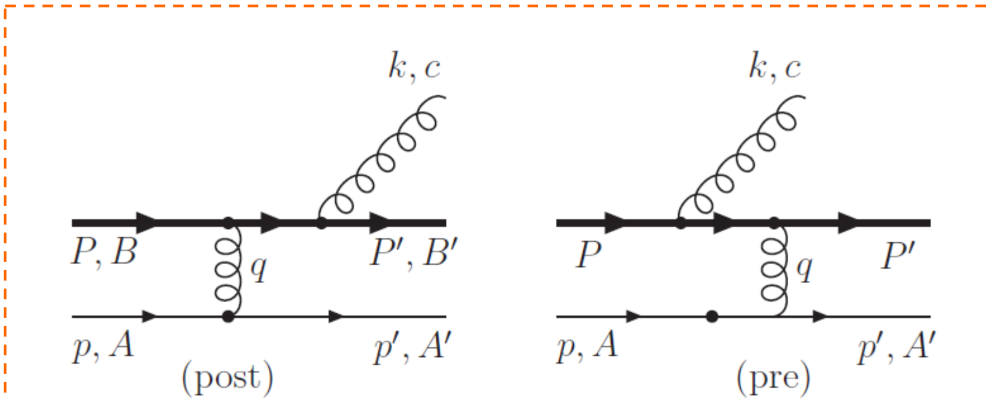
We will concentrate here on the *radiative induced* energy loss, which is the key ingredient of most of the models… (assuming the interactions with the QGP are strong enough to weaken / break the QQbar resonance)

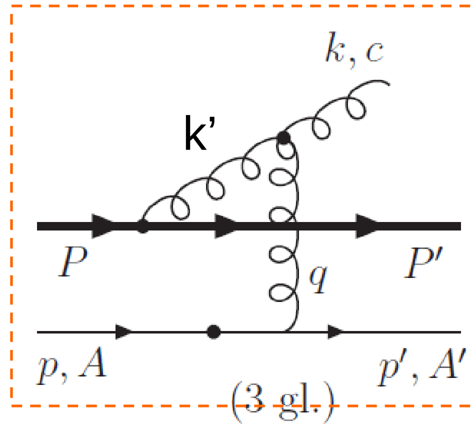
Basic of induced radiation (Gunion-Bertch)

Radiation α deflection of current (semi-classical picture)

Eikonal limit (large E, moderate q)

QED-like





Genuine QCD

ω: energy of radiated gluon; x=ω/E

Dominates as small x as one “just” has to scatter off the virtual gluon k’

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

with

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

Gluon thermal mass ~2T

Quark mass

Both cures the collinear divergences, and have large impact on the radiation spectra

Radiation spectra (incoherent)

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

… to convolute with your favorite elastic cross section

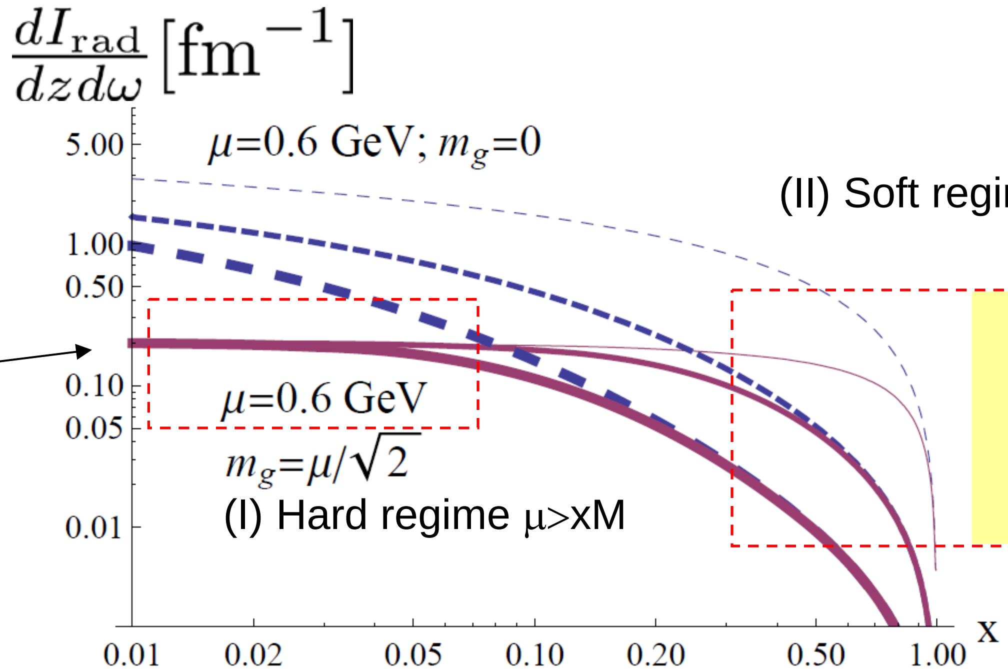
$$\tilde{m}_g^2 = (1-x)m_g^2 + x^2 M^2$$

For Coulomb screened (μ) scattering:

Light quark

c-quark

b-quark



Little mass dependence for finite "gluon mass" (especially from q→c)

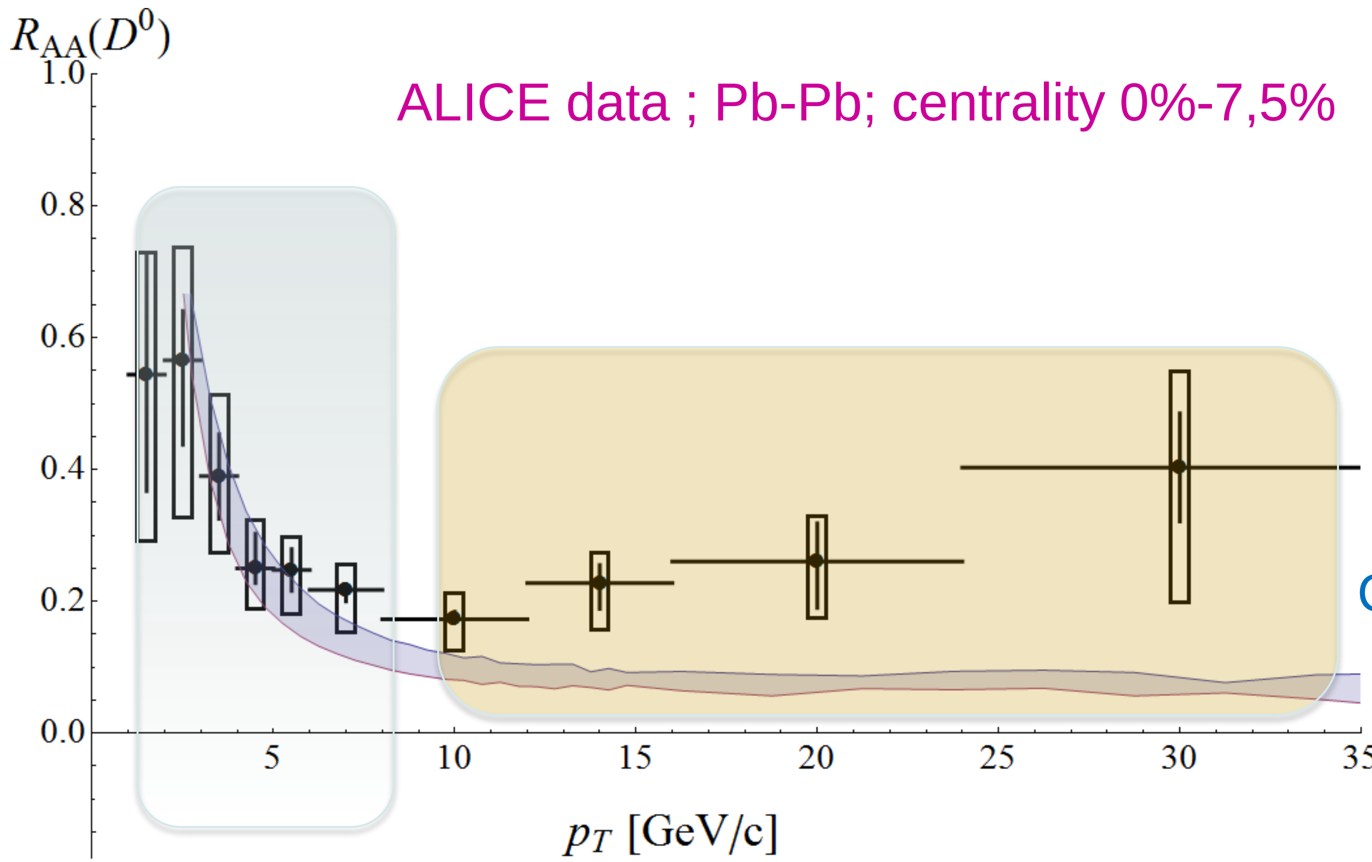
Strong mass hierarchy effect for $x > m_g/M_Q$ (but no dead cone)

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

Strong mass effect in the average Eloss (mostly dominated by region II)

Easily implemented in some MC codes like URQMD, pHSD, BAMPS…

Gunion-Bertch radiation vs data



ALICE data ; Pb-Pb; centrality 0%-7,5%

Cocktail: Elastic Energy loss + radiative GB

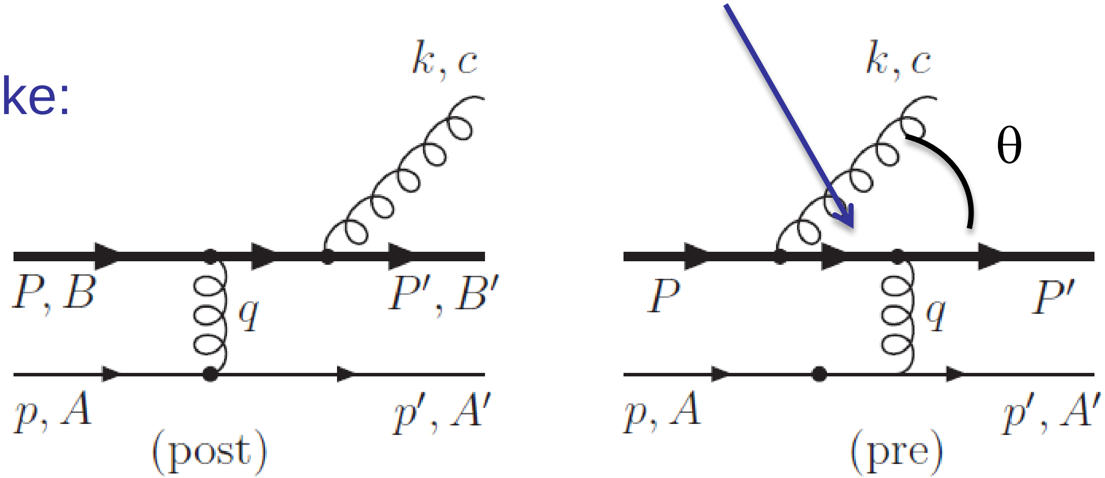
Good agreement at intermediate pT

Increasing disagreement with increasing p_T

Formation time for a single collision

Formation time extracted from the virtuality of the off shell Heavy Quark

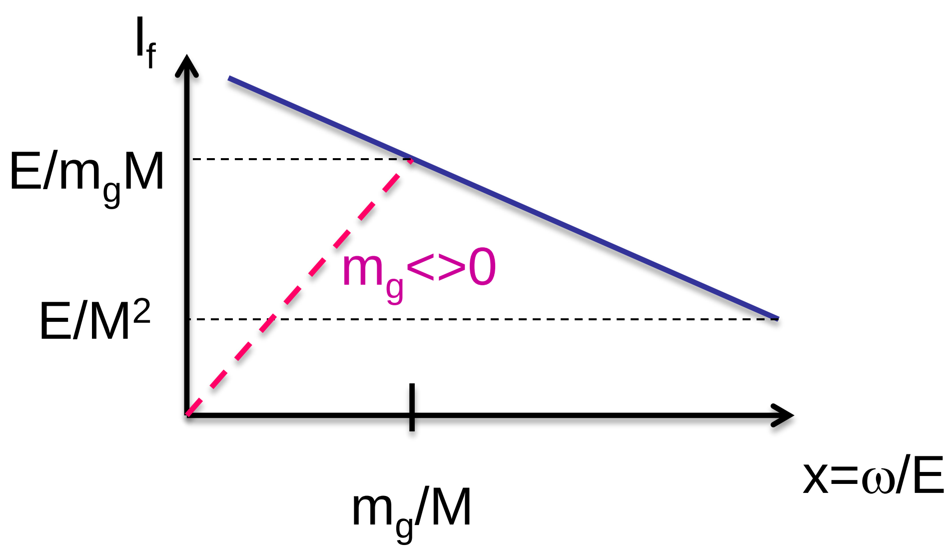
QED-like:



$$l_{f,\text{sing}}^{pre} \approx \frac{2(1-x)}{\omega\left(\frac{M^2}{E^2}+(1-x)\frac{m_g^2}{\omega^2}+\theta^2\right)}$$

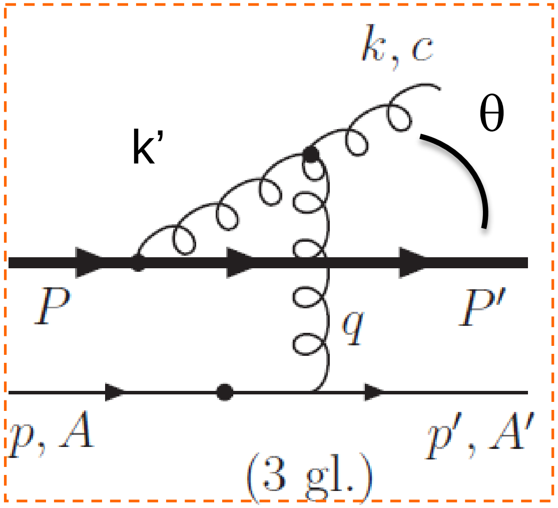
$$l_{f,\text{sing}}^{post} \approx \frac{2(1-x)}{\omega\left(\frac{M^2}{E^2}+(1-x)\frac{m_g^2}{\omega^2}+\left(\vec{\theta}-\frac{\vec{q}_\perp}{E}\right)^2\right)}$$

$$\approx \frac{1}{\omega\theta^2} \approx \frac{E^2}{\omega M^2}$$ In QED

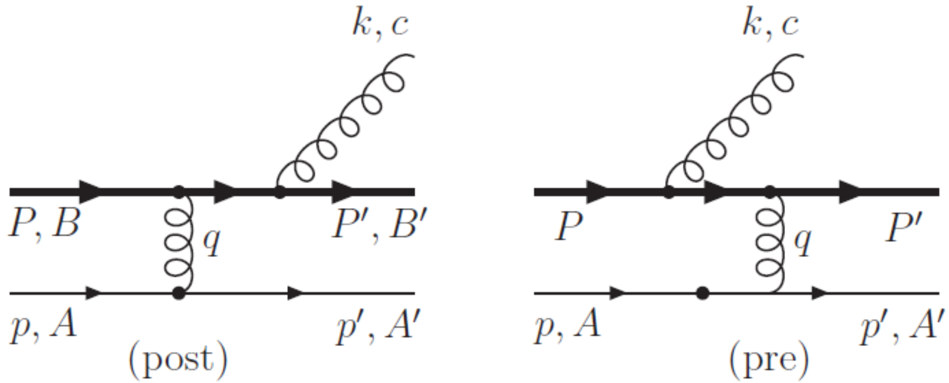


QED: Long formation times for small radiation angles and small frequencies

Formation time for a single coll.



In the genuine QCD, the pre-gluon k' is struck



$$l_{f,\mathrm{sing}}^{3\,gl} \approx t_f \approx \frac{2(1-x)\omega}{(\vec{k}_\perp - \vec{q}_\perp)^2 + x^2 M^2 + (1-x)m_g^2}$$

Radiation at wider angle; smaller formation times than for the QED-like

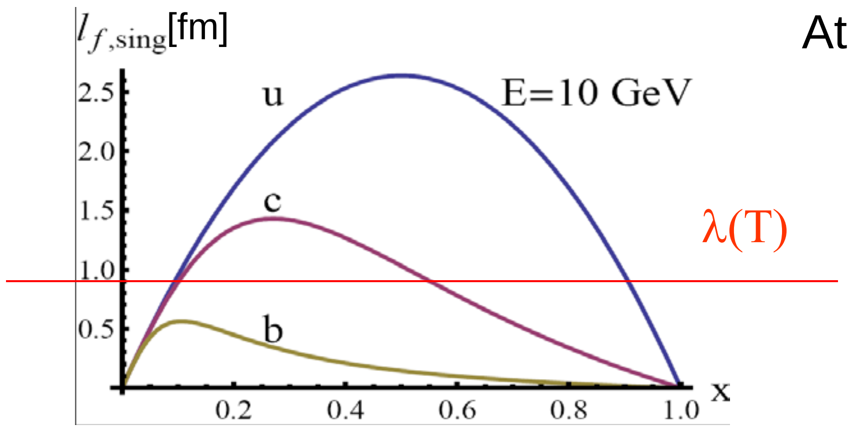
For 0 masses: still $\approx \dfrac{1}{\omega\theta^2}$

but $\theta = \dfrac{k_t}{\omega} \approx \dfrac{\mu}{\omega}$

$\approx \dfrac{\omega}{\mu^2}$

QCD: Longer and longer formation times for increasing frequencies

Formation time for a single coll.



At 0 deflection:

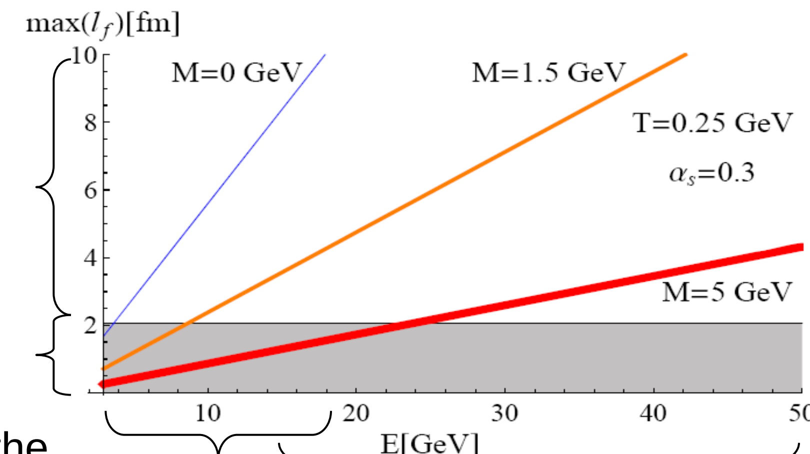
Comparing the formation time (on a single scatterer) with the mean free path:

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

Mostly coherent

Mostly incoherent

(of course depends on the physics behind λ_Q)



RHIC

LHC

Coherence effect (equiv. LPM in QED) mandatory for high p_T HQ.

(and even more for high p_T light quark)…

That will mostly affect the radiation pattern at intermediate x

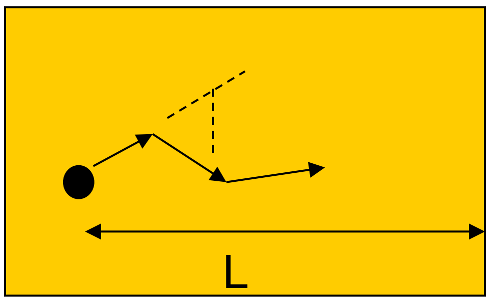
LHC: the realm for coherence !

Formation time and radiation spectra

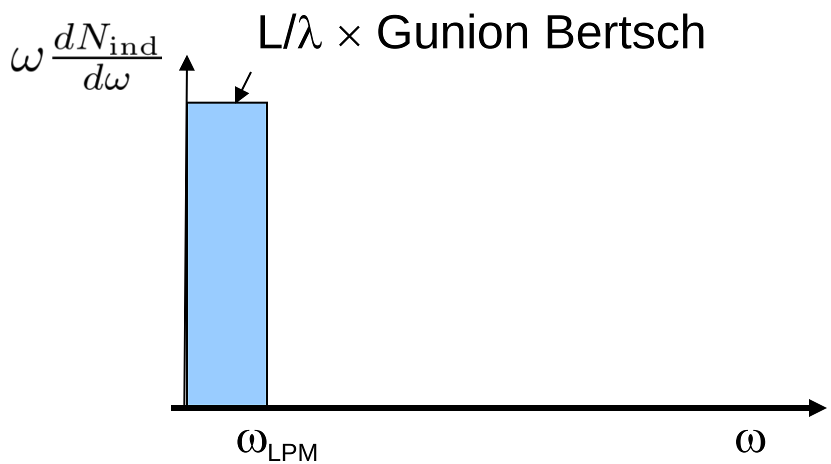
(light q)

Application for radiative energy loss in the eikonal limit

various regimes:



QGP brick



→ a) Low energy gluons: Typical formation time ω/k_t^2 is smaller than mean free path λ:

$\omega < \omega_{\rm LPM} := \frac{\hat{q}\lambda^2}{2}$ Incoherent Gunion-Bertsch radiation

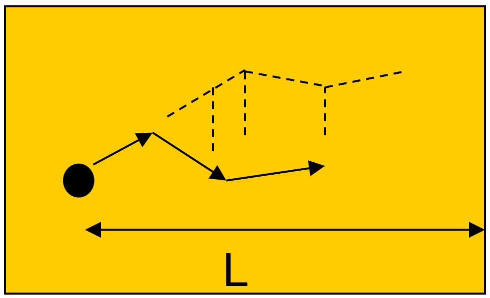
Where $\hat{q} = \frac{\langle \delta q_\perp^2 \rangle}{\lambda}$ (transport coefficient) is the average square momentum increase of the partons per unit time… Very important quantity, in principle calculable from lattice QCD

Formation time and radiation spectra

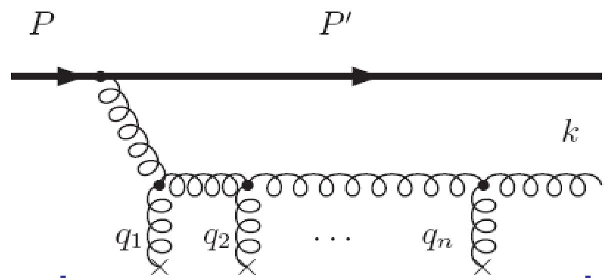
(light q)

Application for radiative energy loss in the eikonal limit

various regimes:



QGP brick



Production on N_{coh} scatterings => reduction of the GB radiation by a factor 1/ N_{coh}

→ b) Inter. energy gluons:

Produced **coherenty** on N_{coh} centers after typical formation time t_f such

$$t_f = \frac{\omega}{k_t^2} \quad \text{(as usual)} \quad \text{but also} \quad k_t^2 = \hat{q} t_f \quad \text{(stochastic propagation of the gluon)}$$

$$\Rightarrow \underbrace{t_f = \sqrt{\frac{\omega}{\hat{q}}}} \Rightarrow N_{\rm coh} = \frac{t_f}{\lambda} = \sqrt{\frac{\omega}{\omega_{\rm LPM}}}$$

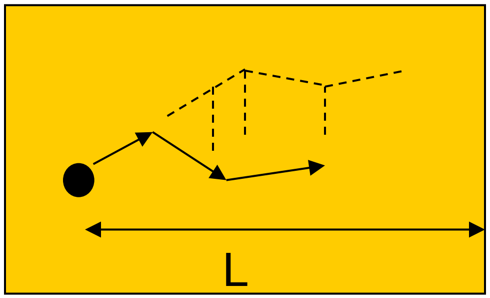
Multiple formation time

Formation time and radiation spectra

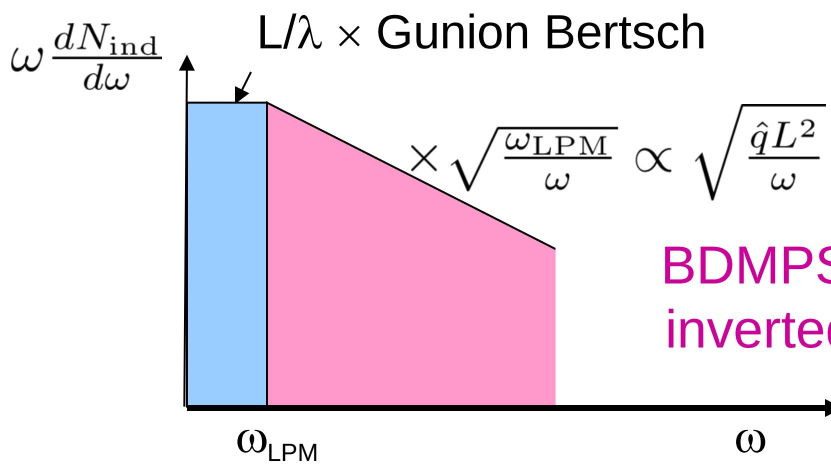
(light q)

Application for radiative energy loss in the eikonal limit

various regimes:



QGP brick



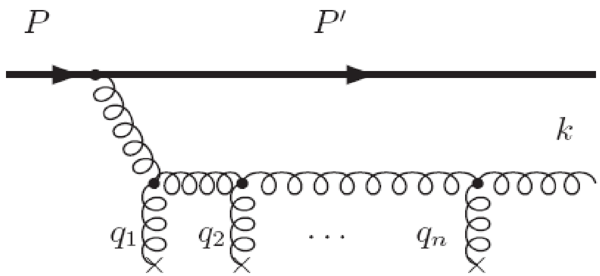
BDMPS (96-00); pattern inverted wrt LPM (gluon charged)

a) Low energy gluons: Typical formation time ω/k_t^2 is smaller than mean free path λ:

$\omega < \omega_{\rm LPM} := \frac{\hat{q}\lambda^2}{2}$ **Incoherent** Gunion-Bertsch radiation

→ b) Inter. energy gluons: Produced **coherenty** on $N_{\rm coh}$ centers after typical formation time $t_f = \sqrt{\frac{\omega}{\hat{q}}} \Rightarrow N_{\rm coh} = \frac{t_f}{\lambda} = \sqrt{\frac{\omega}{\omega_{\rm LPM}}}$ leading to an effective reduction of the GB radiation spectrum by a factor $1/N_{\rm coh}$

Formation time in a random walk



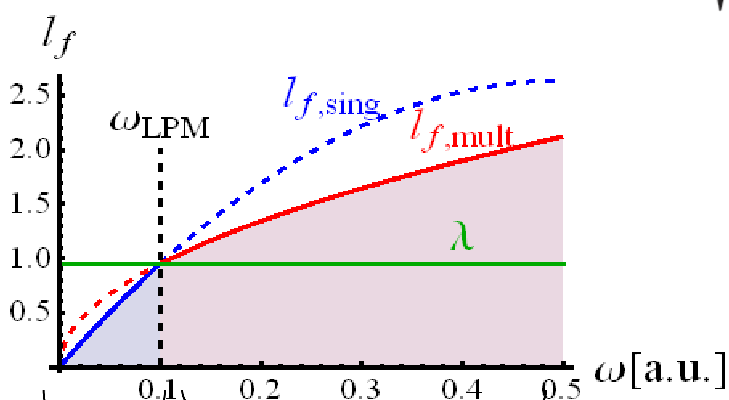
Phase shift at each collision

Following Landau-Pommeranchuk: one obtains an effective formation time by imposing the cumulative phase shift to be $\Phi_{\rm dec}$ of the order of unity

For light quark (infinite matter):

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

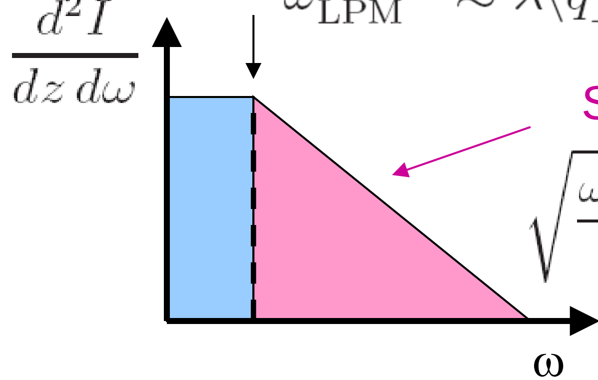
=> 3 scales: $l_{f,\rm mult}$, $l_{f,\rm sing}$ & λ



Incoherent radiation

Coherent radiation (BDMPS)

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



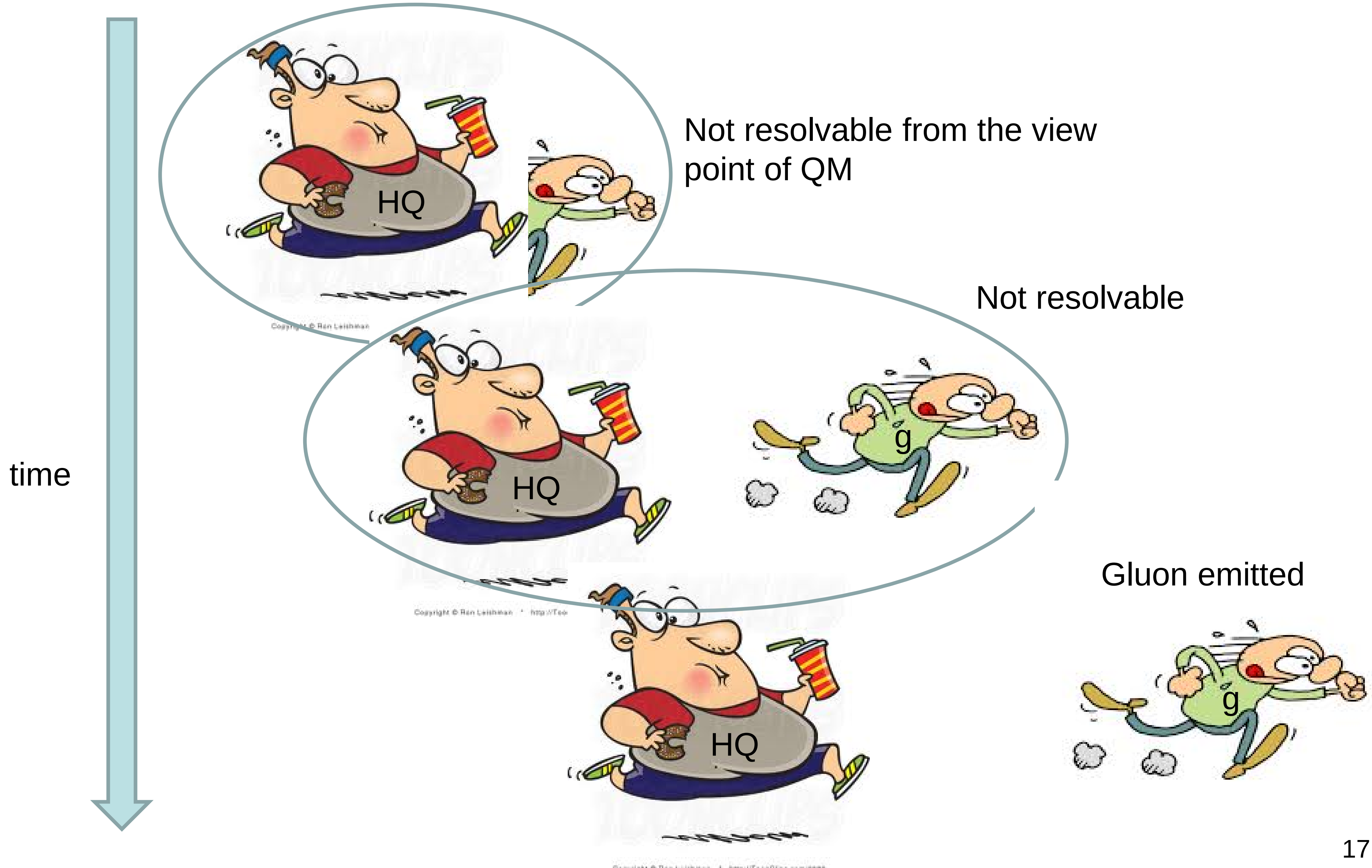
Suppression:

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

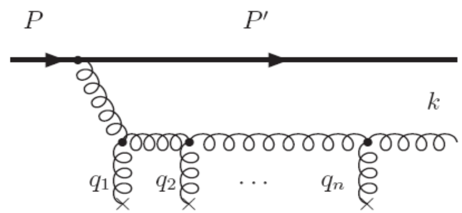
Especially important for av. energy loss

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

Gluon emission from HQ



Formation time and decoherence for HQ



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

"Competition" between

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

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

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 !

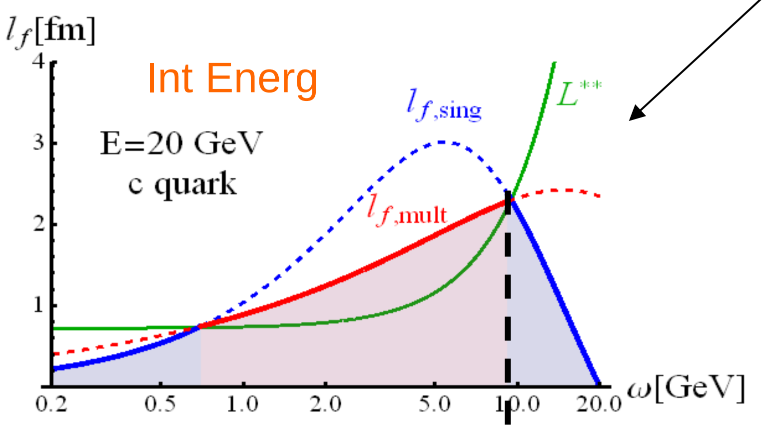
LESSON: HQ radiate less, on shorter times scales and are less affected by coherence effects than light ones !!! (dominance of 1rst order in opacity expansion)

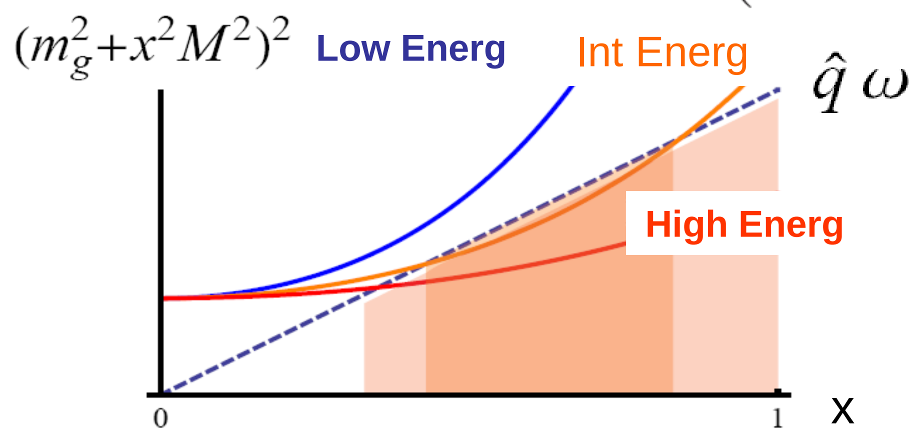
Formation time and decoherence for HQ

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





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

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.

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

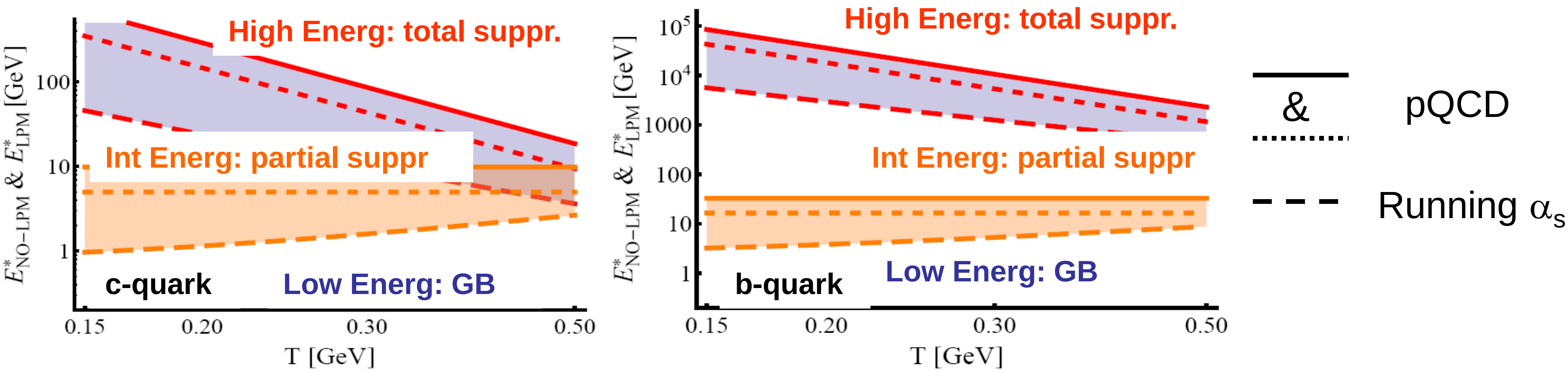
$$E^\star_{\mathrm{LPM}} := \frac{M^4}{\hat{q}}$$

Regimes and radiation spectra

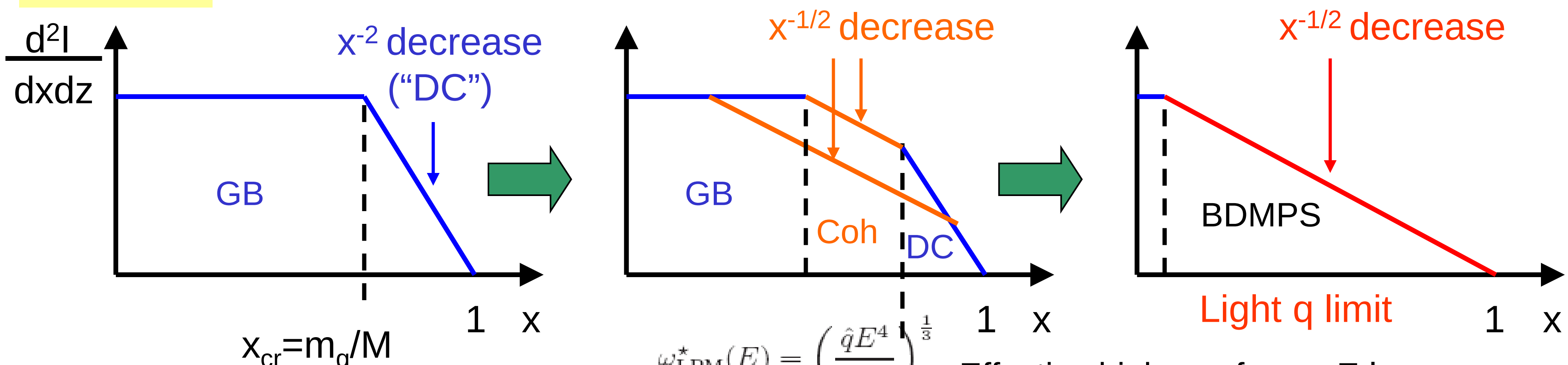
Hierarchy of scales:

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

larger coupling ⇒ Larger coherence effects



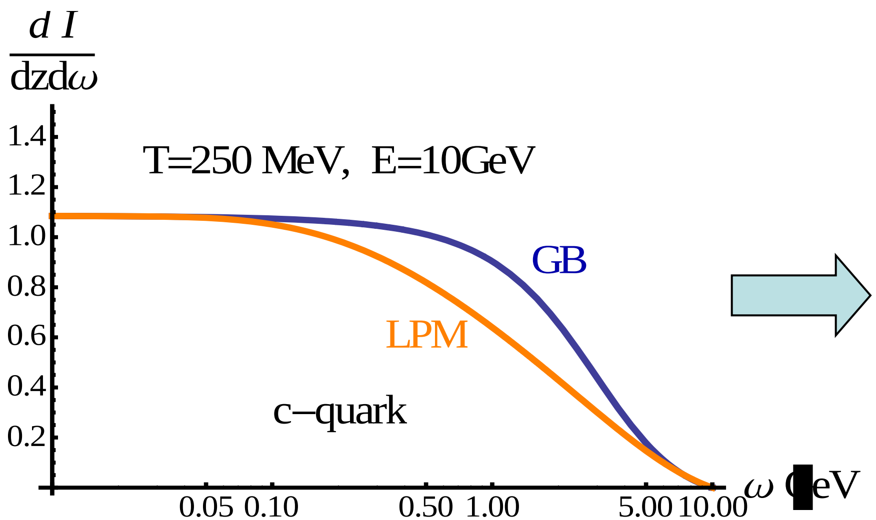
Spectra

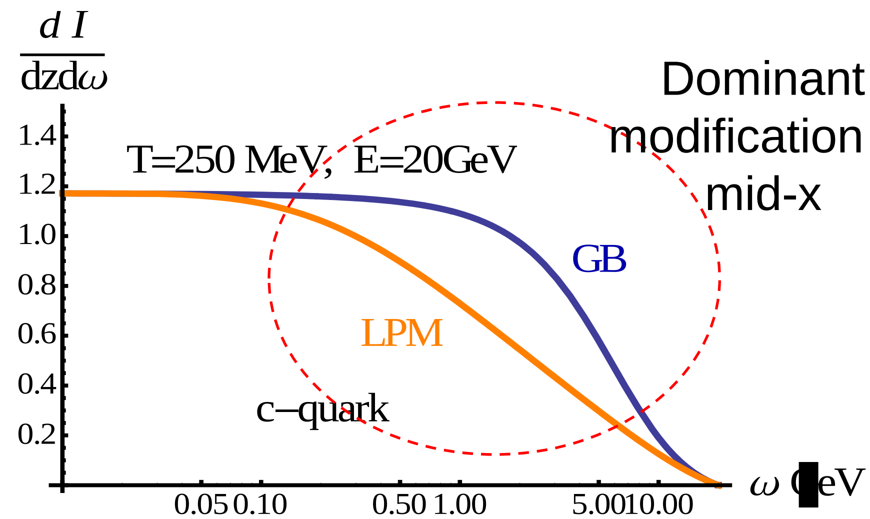


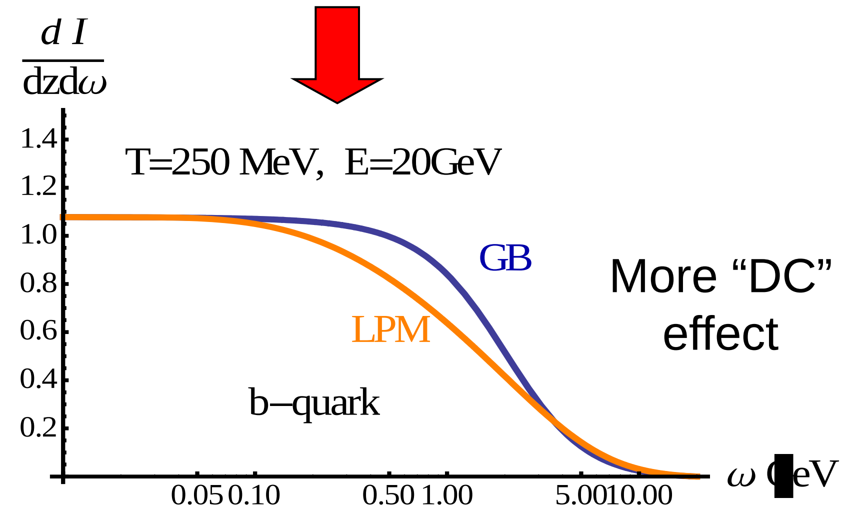
$$\omega^\star_{\rm LPM}(E) = \left(\frac{\hat{q}E^4}{2M^4}\right)^{\frac{1}{3}}$$

Effective higher ω for av. E loss

Reduced spectra from coherence in particular model







More "DC" effect

: Suppression due to coherence increases with increasing energy

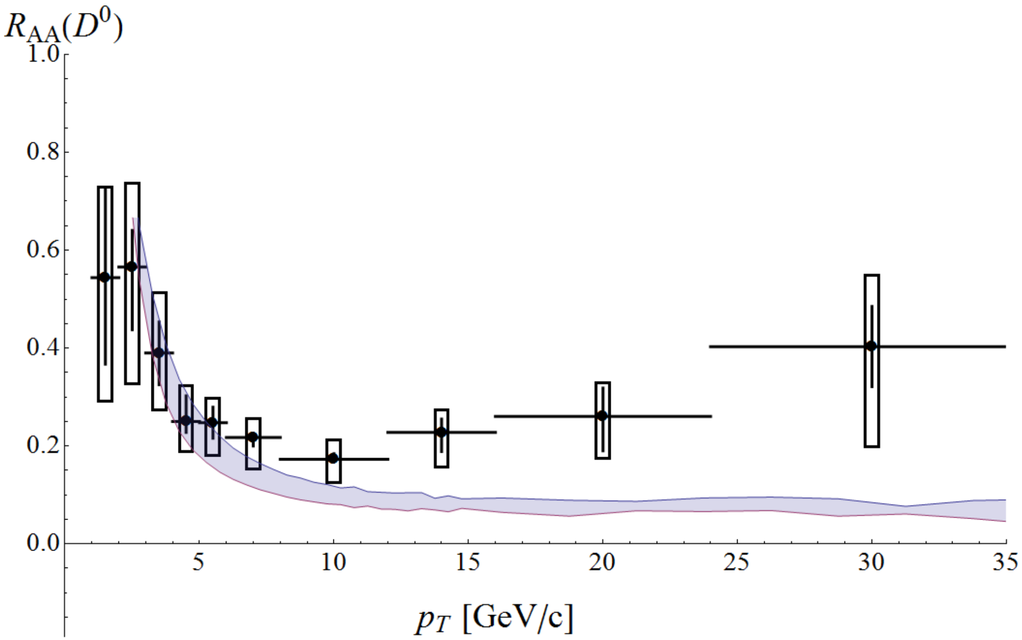
: Suppression due to coherence decreases with increasing mass

Quantum coherence: very difficult to implement in MC/hydro codes

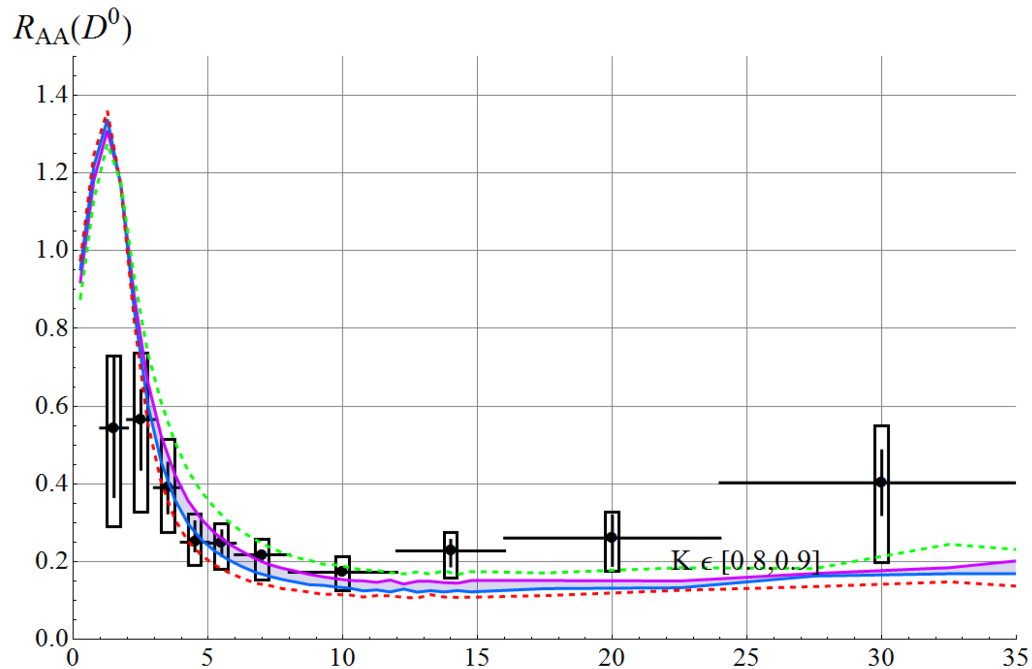
In (first) Monte Carlo implementation: we quench the probability of gluon radiation by the ratio of coherent spectrum / GB spectrum

D mesons at LHC (vs ALICE 0%-7.5%)

Coll + rad GB



Coll + rad LPM



Part of the disagreement cured by the introduction of such coherence effects… still some room for improvement:

A) Finite Path length effects

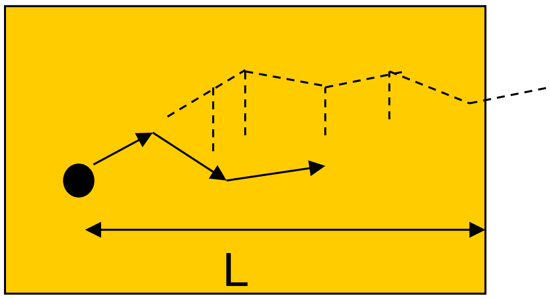
B) Other effects

Formation time and radiation spectra

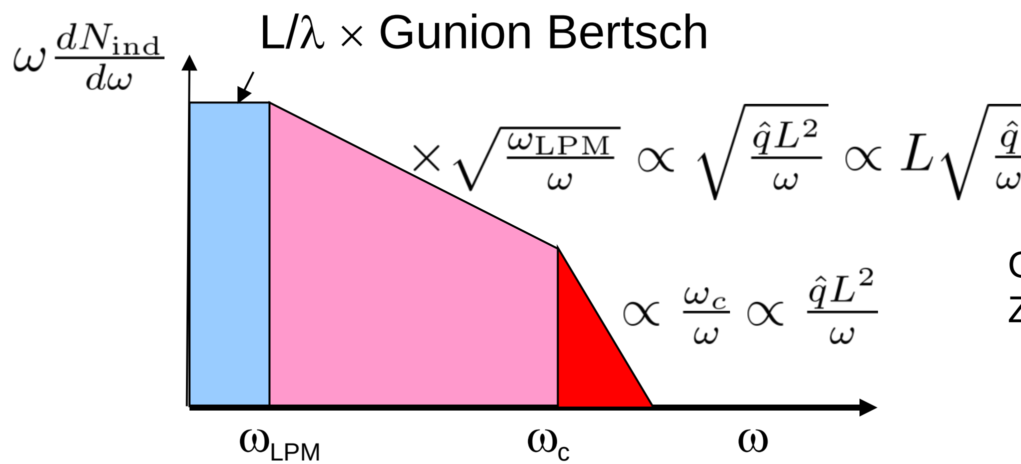
(light q)

Application for radiative energy loss in the eikonal limit

finite path length:



QGP brick



GLV (2001),
Zakharov (2001)

a) Low energy gluons: **Incoherent** Gunion-Bertsch radiation

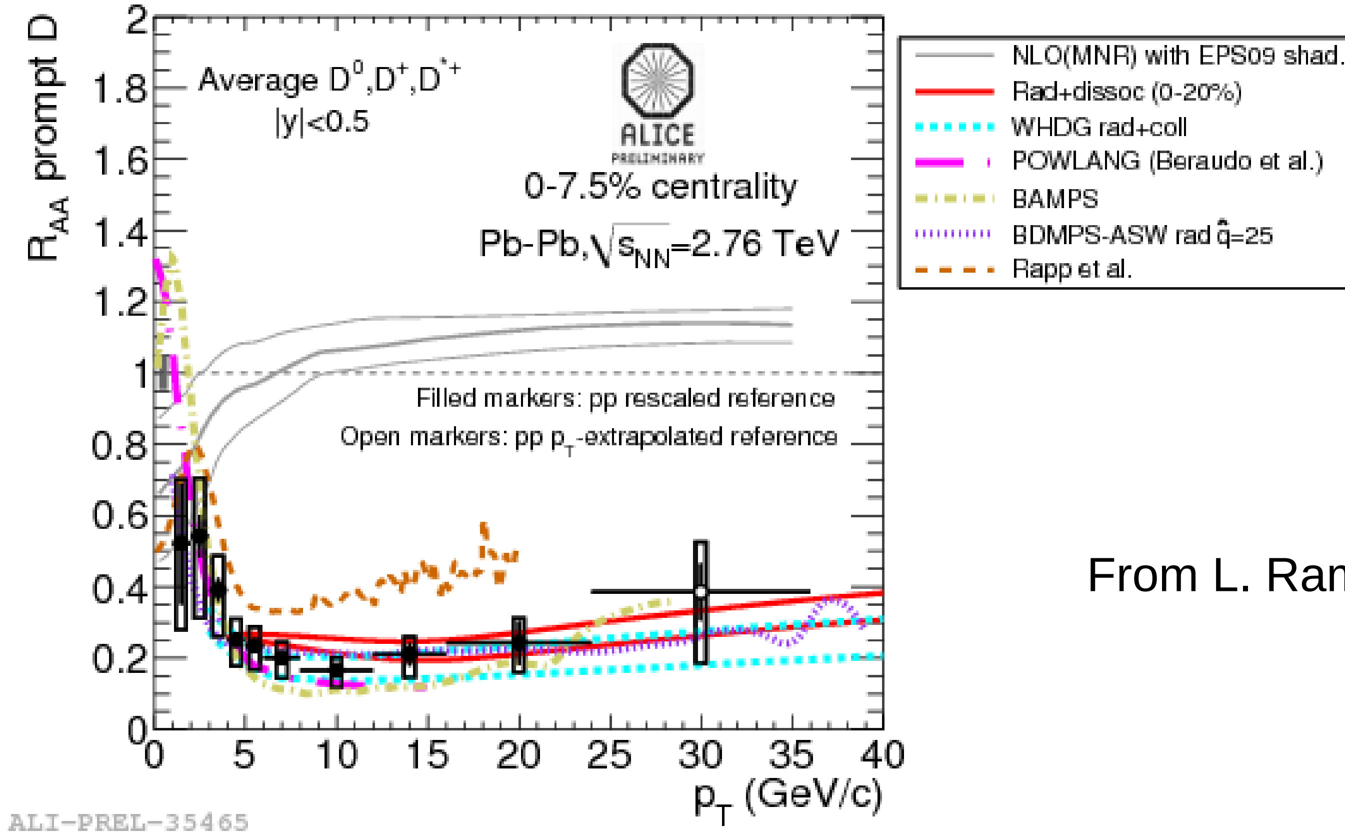
b) Inter. energy gluons: Produced **coherenty** on $N_{\rm coh}$ centers after typical formation time $t_f = \sqrt{\frac{\omega}{\hat{q}}}$

→ c) High energy gluons: Produced mostly outside the QGP… nearly as in vacuum **do not contribute significantly to the induced energy loss**

$\sqrt{\frac{\omega}{\hat{q}}} > L \Rightarrow \omega > \omega_c := \frac{\hat{q}L^2}{2}$

=> Average Energy loss along the path way: $\langle \Delta E \rangle \sim \hat{q} L^2 \ln\left(\frac{E}{\omega_c}\right)$ often the only result retained

Model vs Experiment (3rd round)



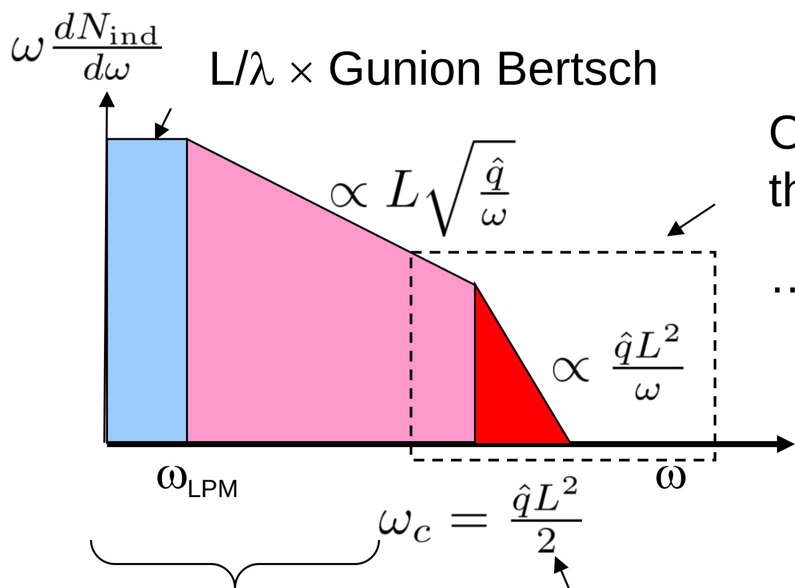
From L. Ramello (this conf)

Most of the models based on energy loss mechanism which explain the quenching reduction at large p_T include those finite path length effects… but the counter part is that they do not include proper medium evolution

Formation time and radiation spectra

(light q)

Application for radiative energy loss in the eikonal limit



Only this tail makes the L^2 dependence in the average Eloss integral …

…provided the higher boundary ω=E > ω_c.

Otherwise, everything α L

Bulk part of the spectrum still scales like path length L

Concrete values @ LHC $\begin{cases} \hat{q} \sim 25\mathrm{GeV}^2/\mathrm{fm} \\ L \sim 2\mathrm{fm} \end{cases}$

$\omega_c \sim 500\mathrm{GeV}$ Huge value !

Personal opinion: before looking on coherence effects on large distances (5-10 fm/c) let us make sure nothing was left over !

Consequences of radiation damping on energy loss

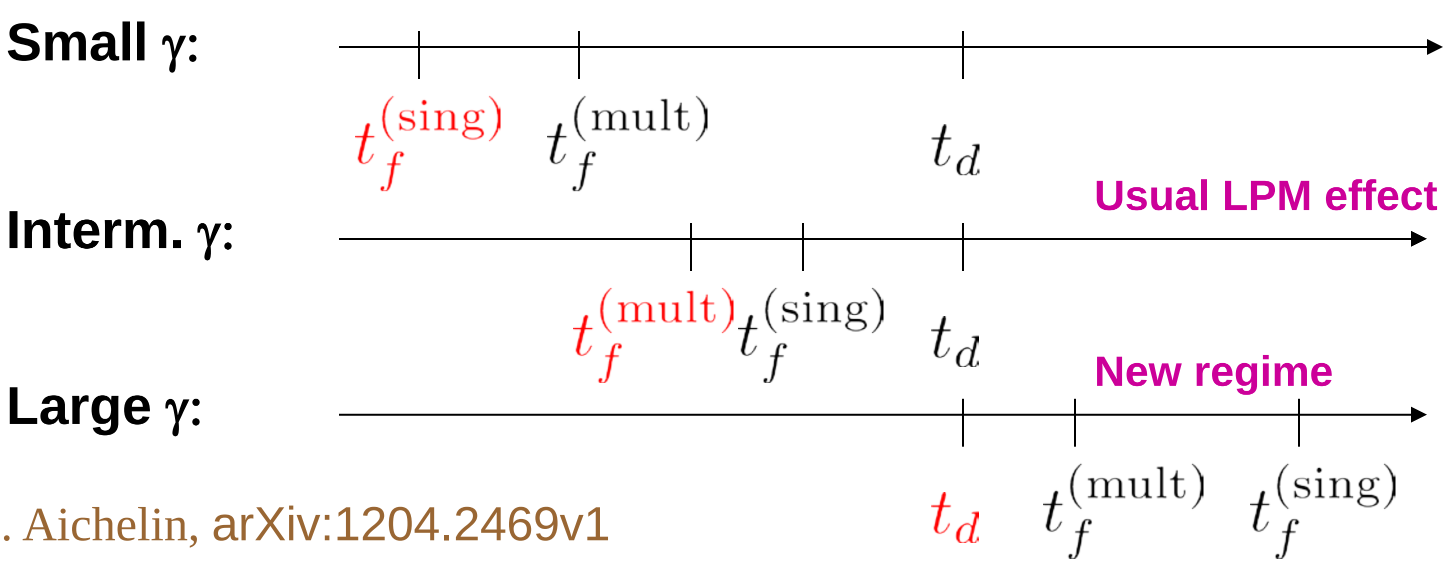
Basic question: Implications of a finite lifetime of the radiated gluon ?

Litttle attention in the litterature (V. M. Galitsky and I. I. Gurevich, Il Nuovo Cimento **32** (1964) 396 for classical electrodynamics).

Concepts

- In QED or pQCD, damping is a NLO process (damping time $t_d >> \lambda$); neglected up to now.
- However: formation time of radiation t_f increases with boost factor γ of the charge
- Expected effects when $t_f \approx t_d$ or $t_f > t_d$: in this regime, t_d should become the relevant scale (gluons absorbed while being formed)

γ - hierarchy:



M. Bluhm, PBG & J. Aichelin, arXiv:1204.2469v1

Modification of the LPM effect due to radiation damping ?

Naïve thoughts (bets) about the consequences of photon damping

a) Relaxed attitude: “Nothing special happens to the Work, as photons are absorbed after being emitted”

b) Vampirish though: as the medium “sucks” the emitted photons, the charge will have a tendency to emit more of them => increased energy loss

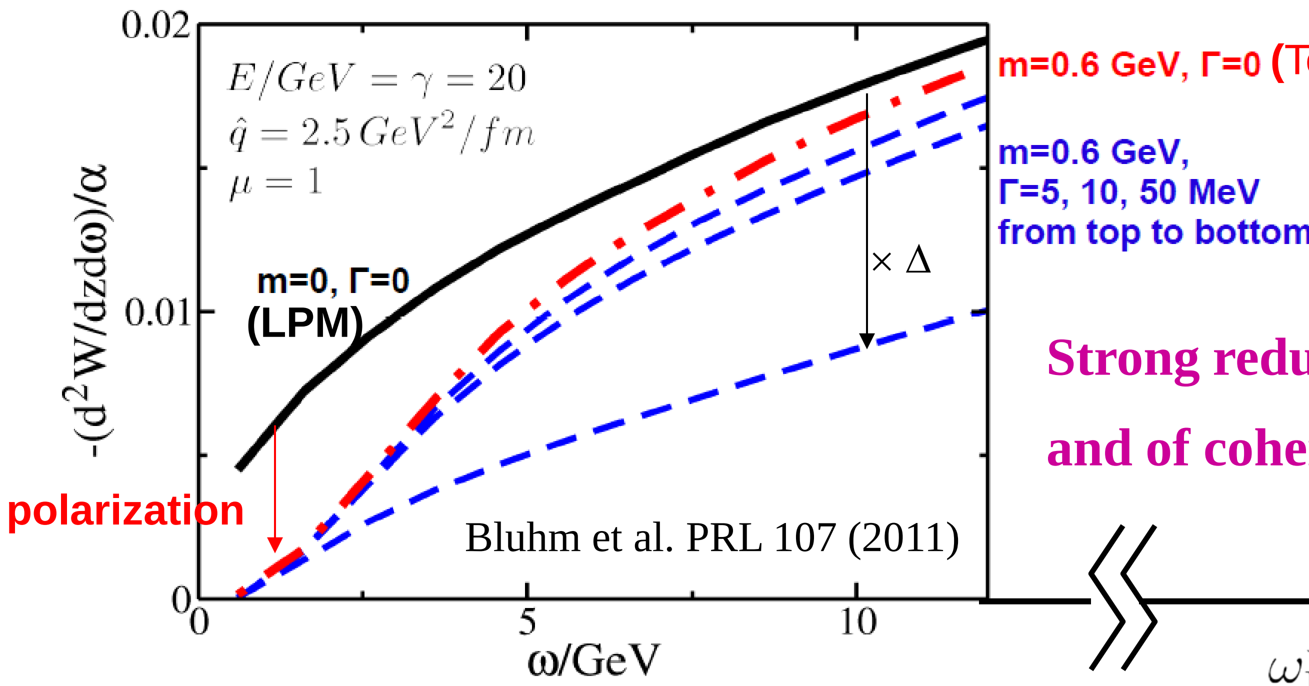
c) Less energy loss (find the argument)

Beware: we are not speaking of the radiated energy in the far distance (always reduced) but on the impact on the radiating parton

Consequences of radiation damping on energy loss

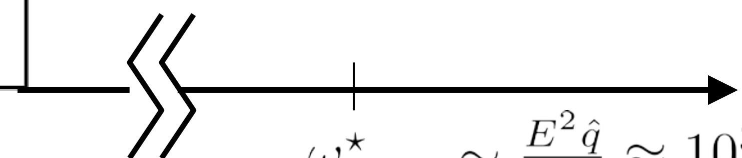
PRL 107 (2011): Revisiting LPM effect in ED using complex index of refraction, focussing on the radiation at time of formation

$$n^2(\omega) = 1 - m^2/\omega^2 + 2\,i\,\Gamma/\omega$$



Realistic numbers for QCD !

Strong reduction of radiation spectra and of coherence effects



$$\omega^{\star}_{\rm LPM} \sim \frac{E^2\hat{q}}{m_s^4} \approx 10^3 \gg E$$

No "BH" limit

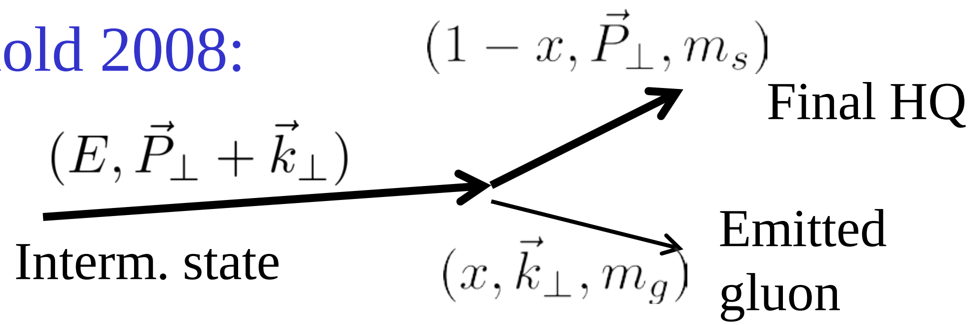
Scaling law:

$$\frac{\frac{dN}{d\omega}}{\frac{dN_{\rm sing}}{d\omega}} \approx \frac{\min(t_d, t_f^{\rm (sing)}, t_f^{\rm (mult)})}{t_f^{\rm sing}}$$

Allows for first phenomenological study in QCD case

Formation time of radiated gluon

Arnold 2008:



$$t_f \left[\frac{\langle p_B^2 \rangle + x^2 m_s^2 + (1-x) m_g^2}{2x(1-x)E} \right] \simeq 1$$

$$p_B^2 := \left((1-x)\vec{k}_\perp + x\vec{P}_\perp \right)^2 \quad \Rightarrow \quad \langle p_B^2 \rangle \approx (1-x)^2 \hat{q}_g t_f$$

In QCD: mostly gluon rescattering

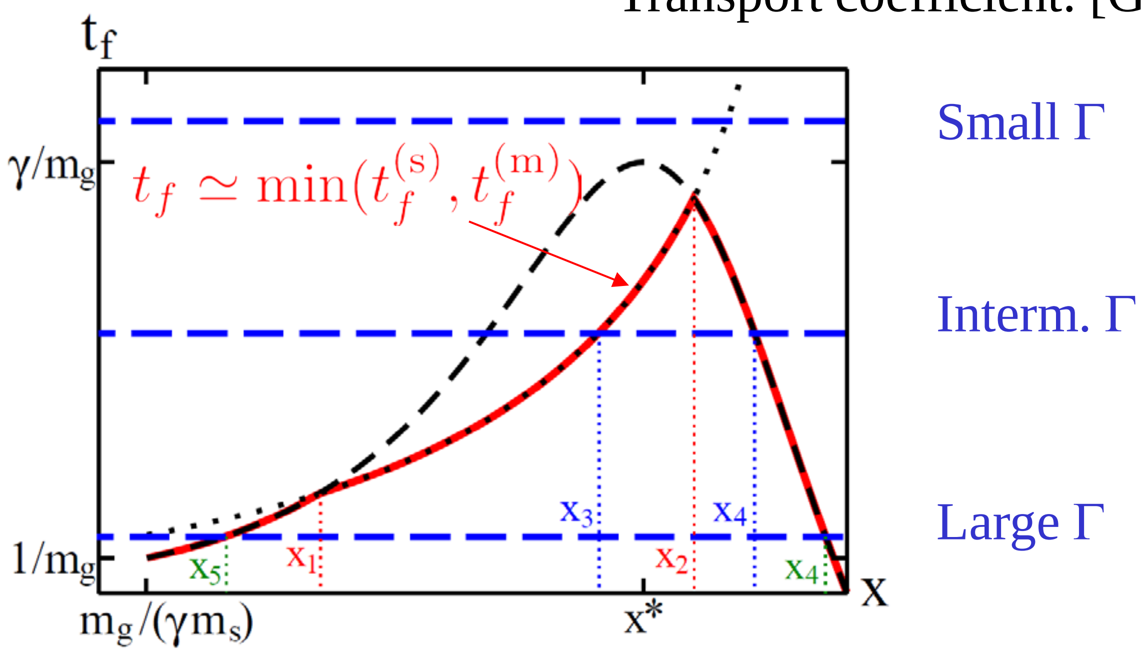
Transport coefficient: [GeV²/fm]

=> Self consistent expression for t_f

Dashed line: $t_f^{(s)} \simeq \frac{2x(1-x)E}{x^2 m_s^2 + m_g^2(1-x)}$

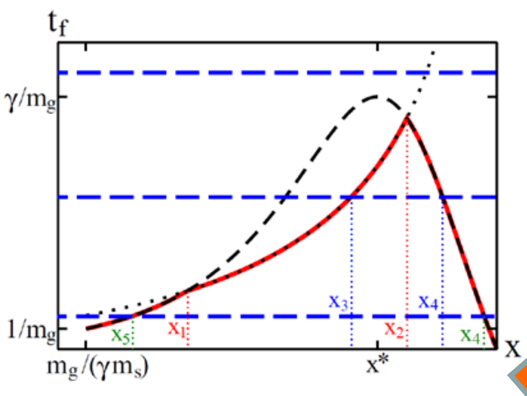
Dotted line: $t_f^{(m)} \simeq \sqrt{\frac{2xE}{(1-x)\hat{q}_g}}$

Blue dashed line: $t_d = \frac{1}{\Gamma}$

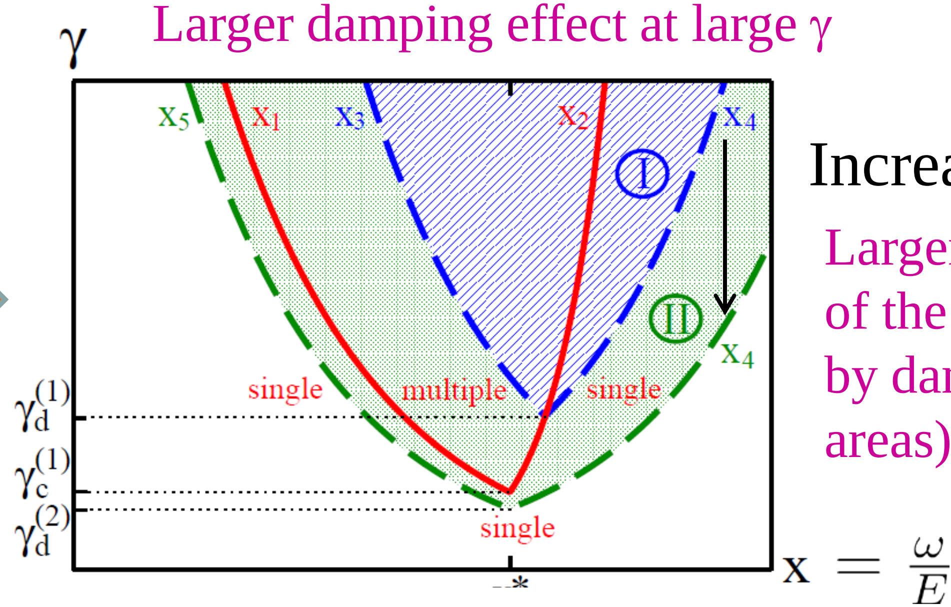


New regimes when including gluon damping

x-γ space for $\hat{q} < m_g^3$



Larger damping effect at large γ

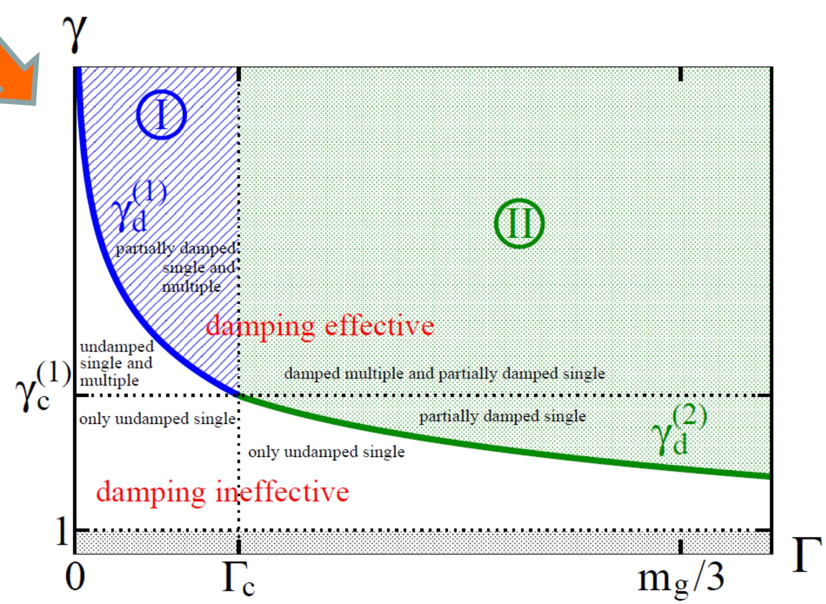


Increasing Γ

Larger and larger part of the spectrum affected by damping (shaded areas)

Γ–γ space

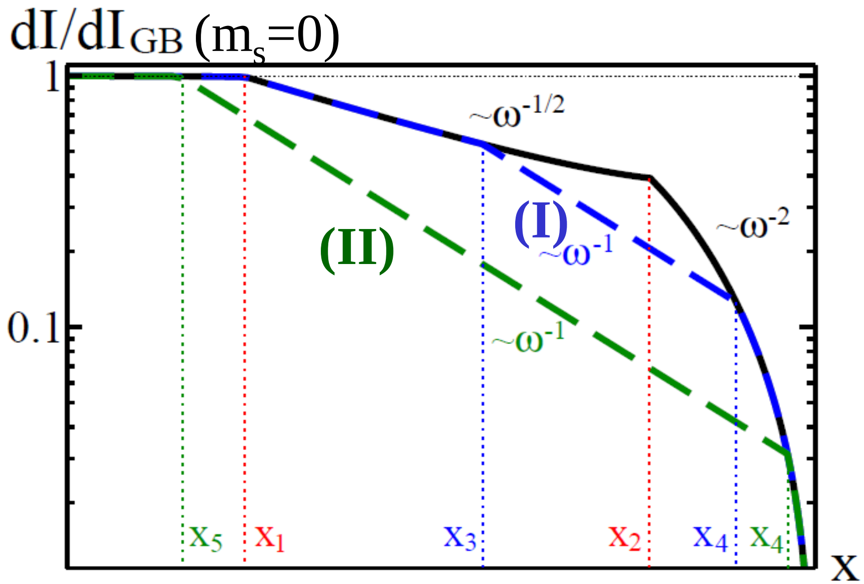
γ-scales	
$\gamma_c^{(1)}$	$\sim m_g^3/\hat{q}_g$
$\gamma_d^{(1)}$	$\sim \sqrt{\hat{q}_g/\Gamma^3}$
$\gamma_d^{(2)}$	$\sim m_g/\Gamma$



For $\Gamma > \Gamma_c \approx \frac{\hat{q}_g}{m_g^2}$ coherent radiation is totally superseeded by damping

Consequences on the power spectra

$\hat{q} < m_g^3$



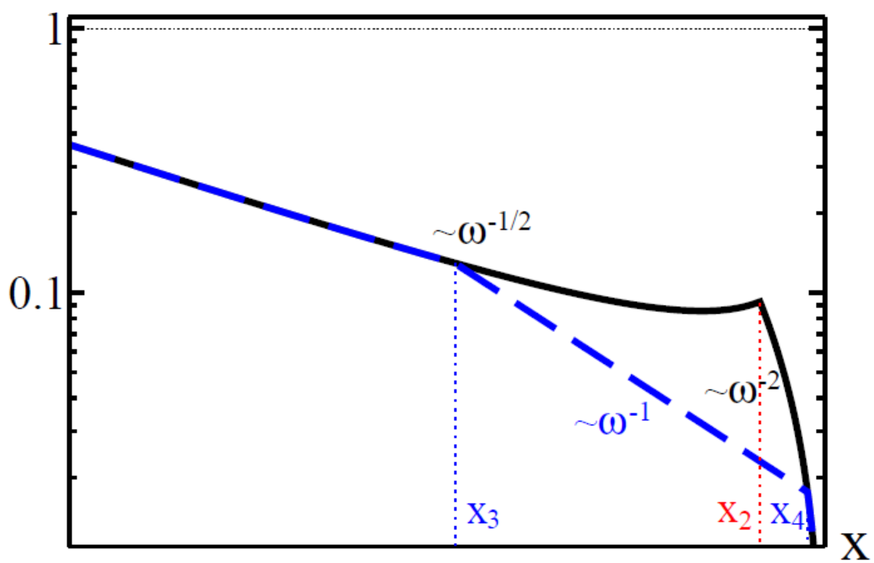
(I) and (II): moderate and large damping (see previous slide)

E= 45 GeV, m_s=1.5 GeV

m_g=0.6 GeV, $\hat{q} = 0.1\text{GeV}^2/\text{fm}$

Γ=0.05 GeV (I) & 0.15 GeV (II)

$\hat{q} > m_g^3$



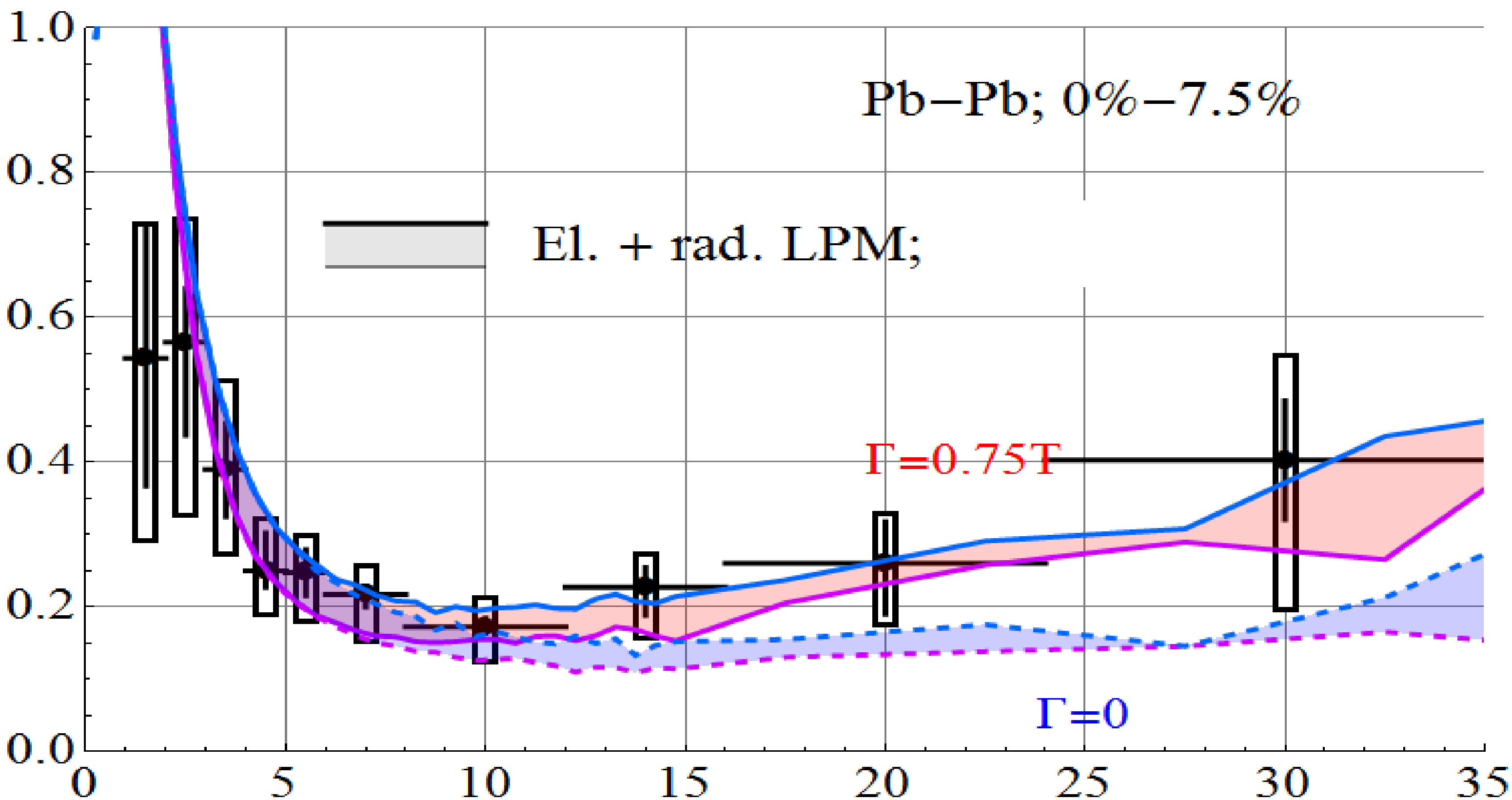
Same but

$\hat{q} = 2\text{GeV}^2/\text{fm}$

Γ=0.25 GeV

Consequences on the HQ observables

$R_{AA}(D)$



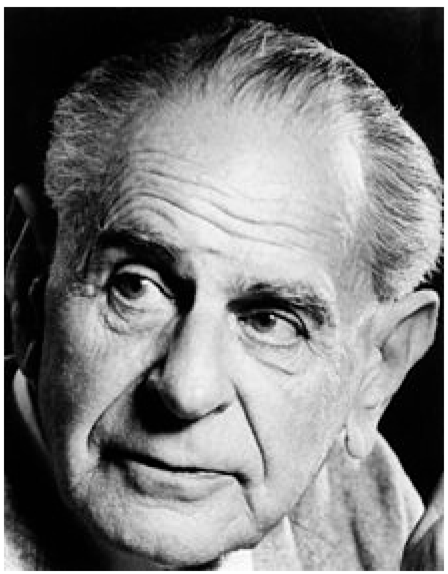
Damping of radiated gluons reduces the quenching of D mesons and allows reproducing their R_{AA}

Damping vs Finite Path Length

Quite generically, damping effects dominate over path length effects if

$$\Gamma_d > \frac{\hbar c}{L} \approx 50 \text{ MeV}$$

Realistic scale in strongly coupled système ($\Gamma_d = O(g^n)\,T$)



Falsifiability: a)path length dependence still α L with damping effects, while α L^2 with usual BDMPS argument or b) γ-D/B correlations

« turn LHC into a precision tool »… not only for Higgs and SUSY

Quarkonia production in dynamical QGP

Work in progress

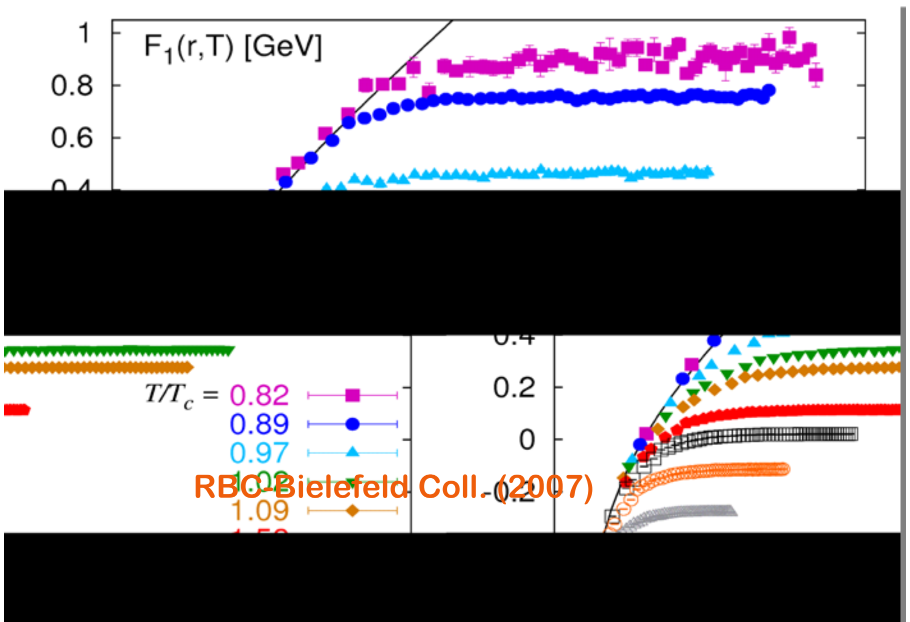
Probing deconfinement ?

How can we prove that we have really achieved a *deconfined* state of matter in ultra-relativistic heavy ions collisions ?

Challenge

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

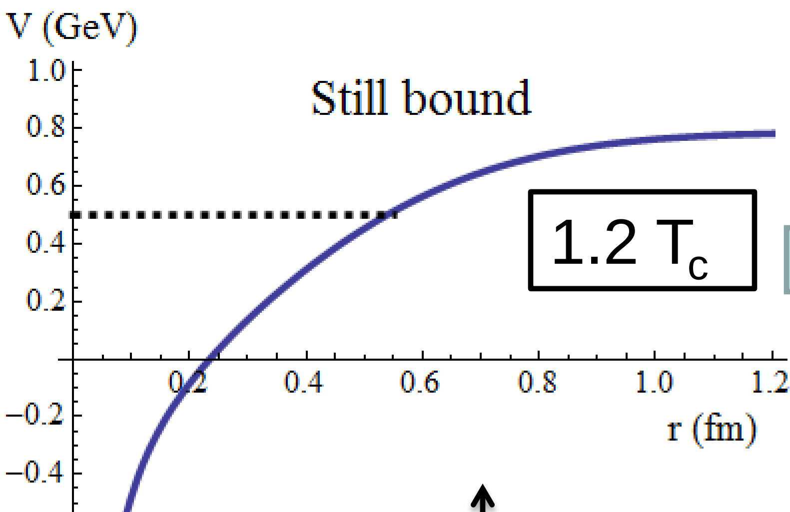
Looking at the QQbar potential on the lattice

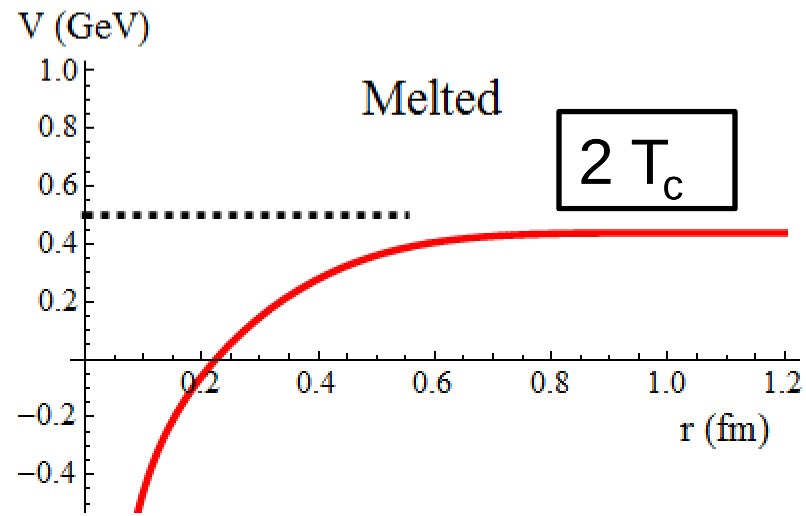


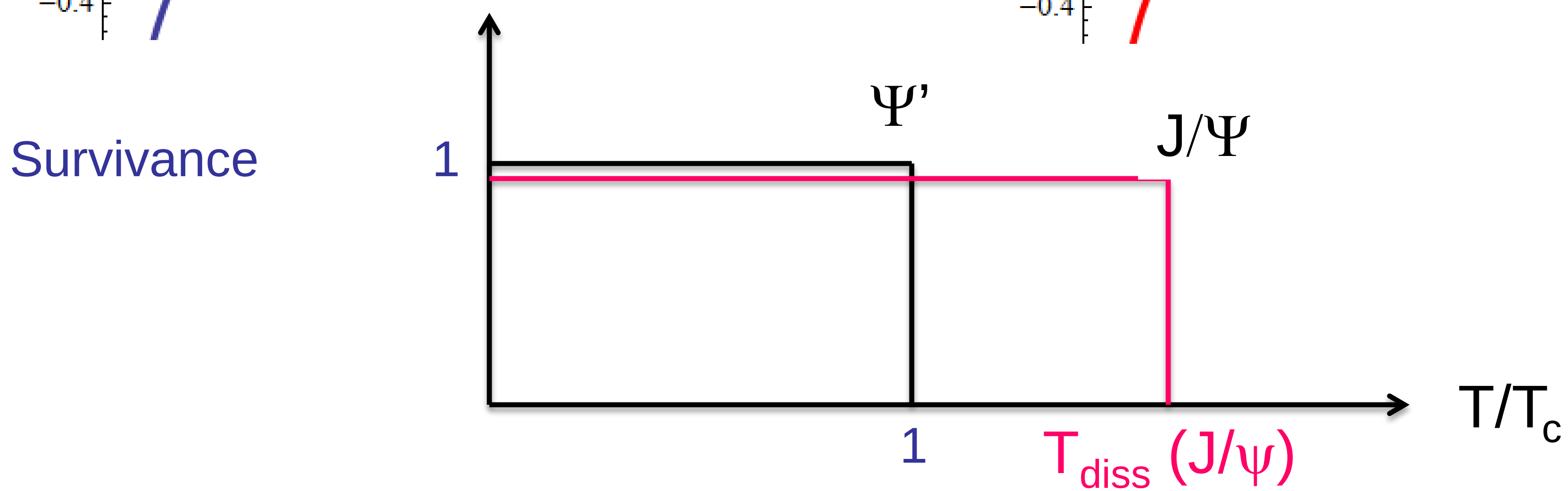
Increased screening at larger temperatures

Quarkonia in Stationary QGP

Consequence for Q-Qbar states (Q: heavy quark):

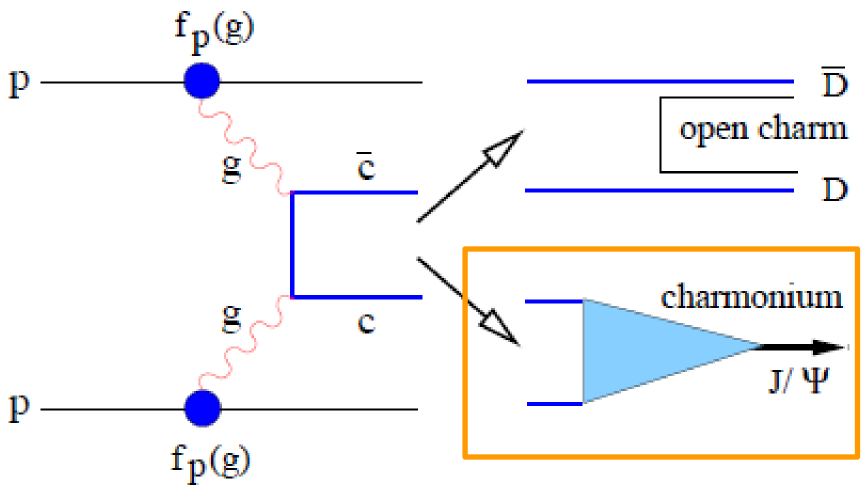






Best candidate: Quarkonia sequential "suppression", i.e. melting and/or dissociation (Matsui & Satz 86)

Dynamical version of the sequential suppression scenario



From H Satz

Formed after some "formation time"

τ_f (typically the Heisenberg time),

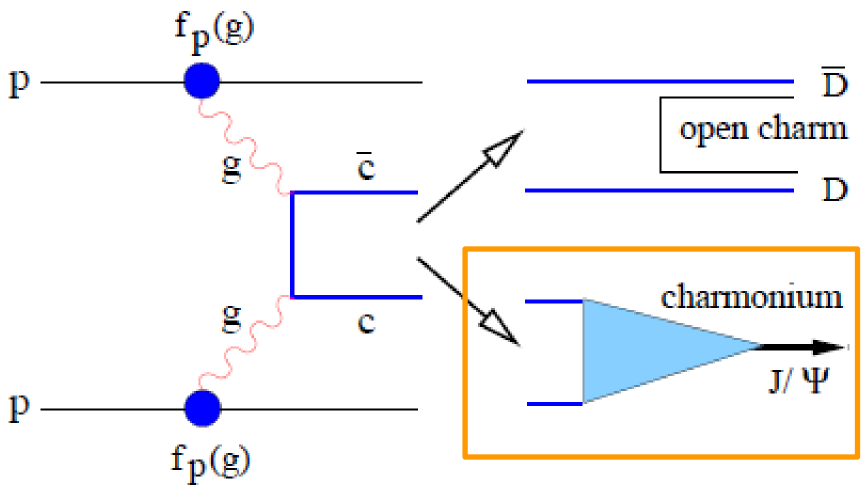
usually assumed to be independent

of the surrounding medium

Standard folklore of sequential suppression: The quarkonia which should be formed at (τ_f,x_0) is not if T(τ_f,x_0)>T_{diss} => Q-Qbar pair is "lost" for quarkonia formation

Need to know the *formation times* as well in order to have a predictive scheme (not so obvious, especially for the upsilons, which are produced during the very early stage of the nucleus-nucleus collision)

Dynamical version of the sequential suppression scenario



From H Satz

Formed after some “formation time”

τ_f (typically the Heisenberg time),

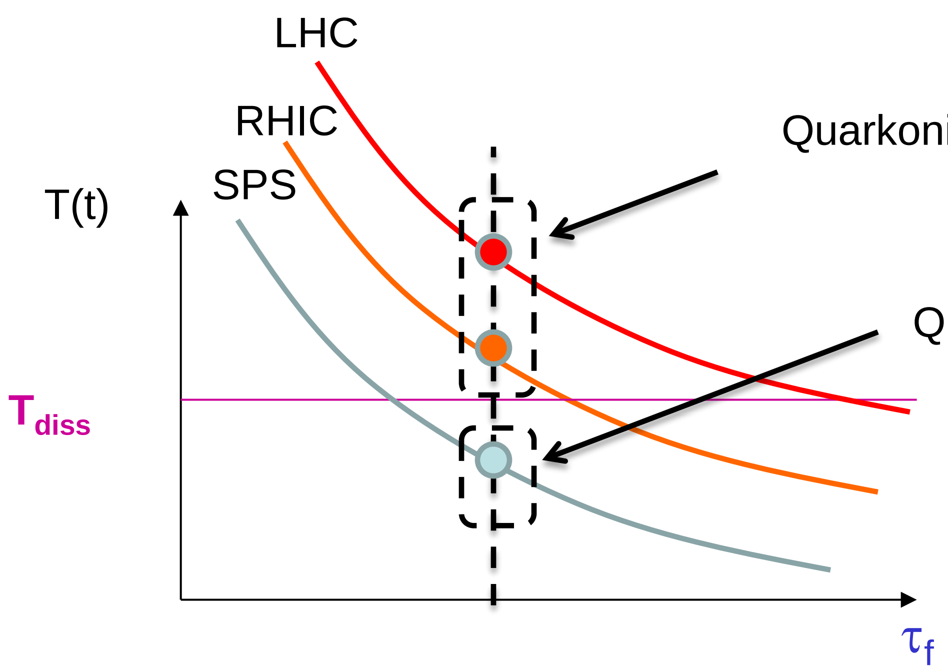
usually assumed to be independent

of the surrounding medium

Pictorially

Local temperature

at formation time



Quarkonia state “suppressed”

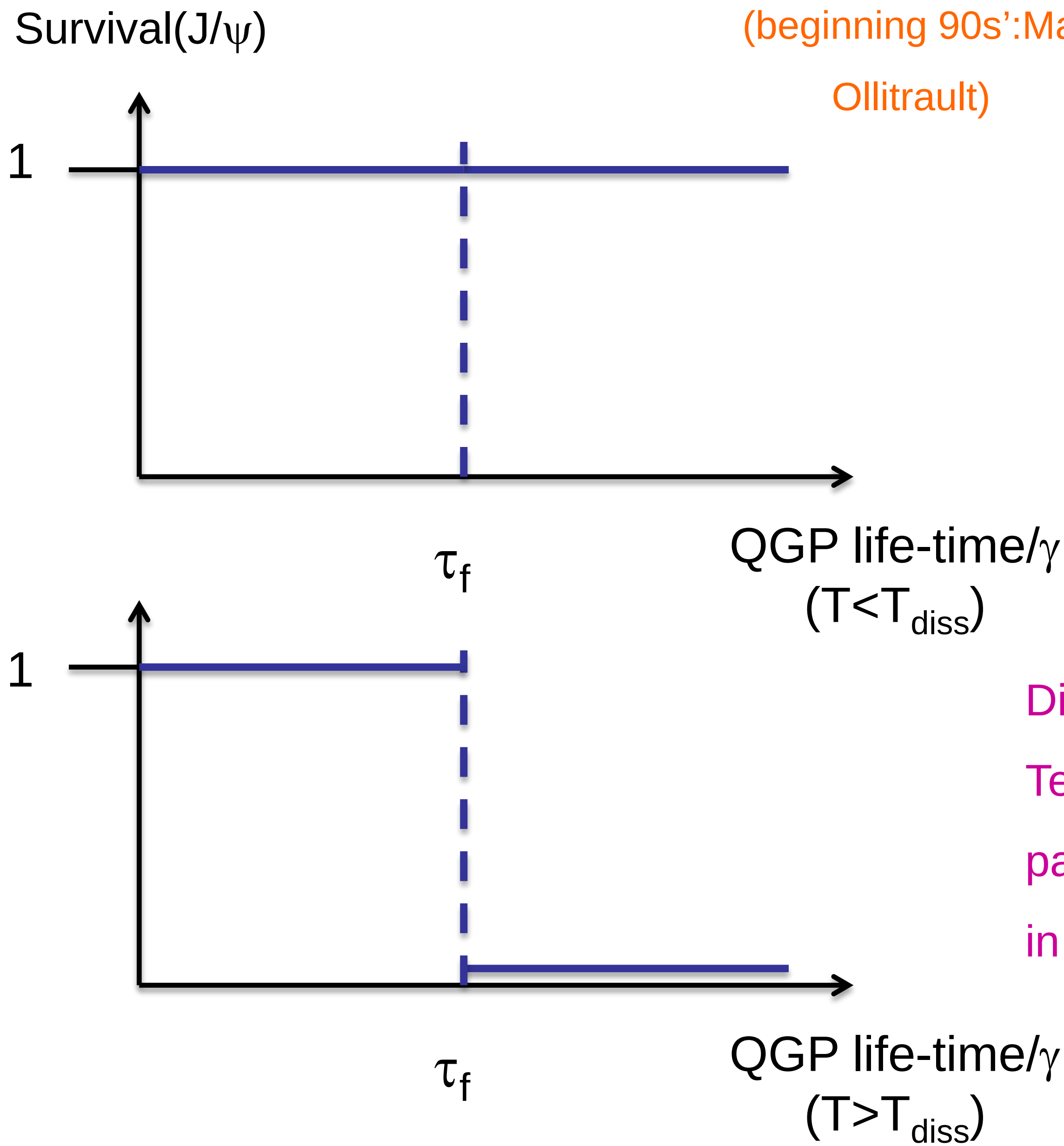
(not formed)

Quarkonia state formed as in the

vacuum

Dynamical version of the sequential suppression scenario

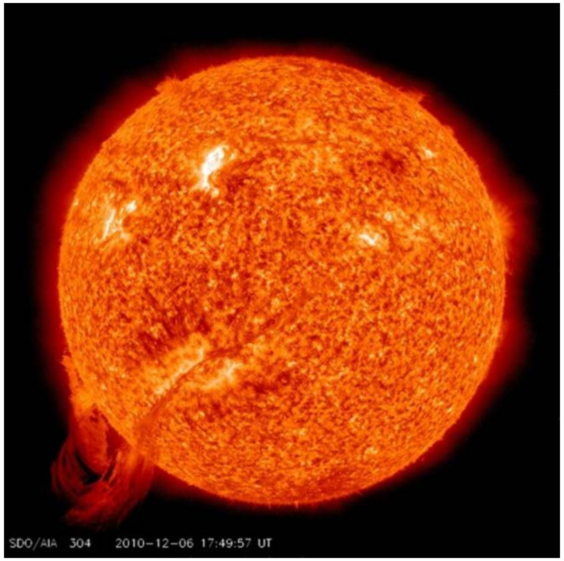
(beginning 90s':Matsui, Blaizot and Ollitrault)



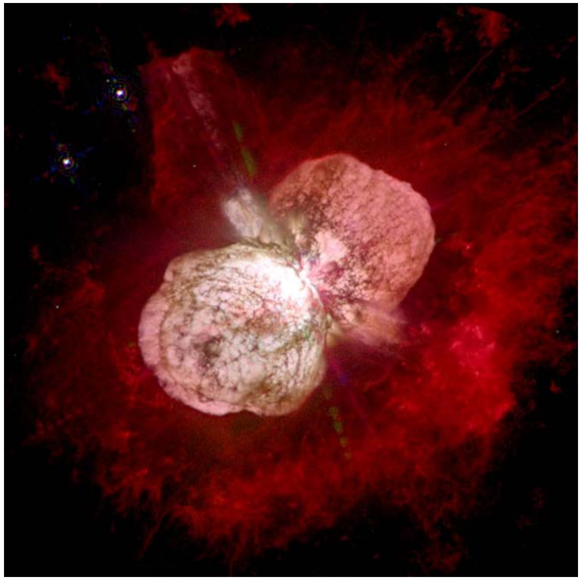
Discontinuity convoluted with Temperature profile => continuous patterns of quarkonia suppression in all parameters

Caviats & Uncertainties

What does the sequential suppression in a stationary QGP has to do with reality anyhow ?



Picture

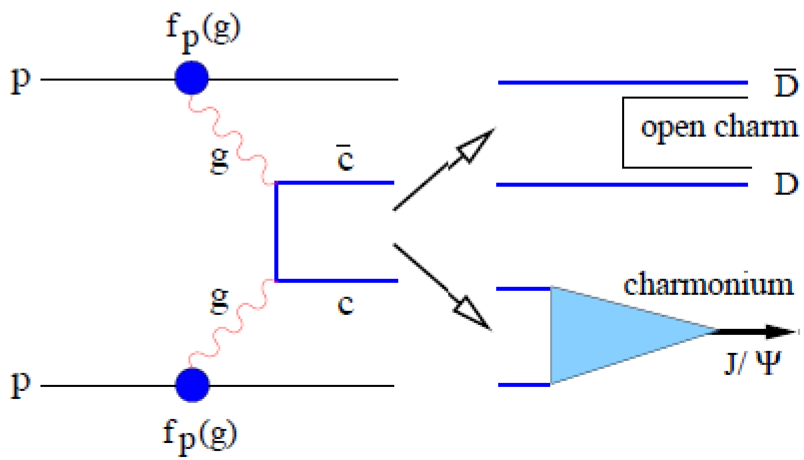


Reality

Need for a genuine time-dependent scenario

Beyond the (quasi-stationnary) sequential suppression scenario

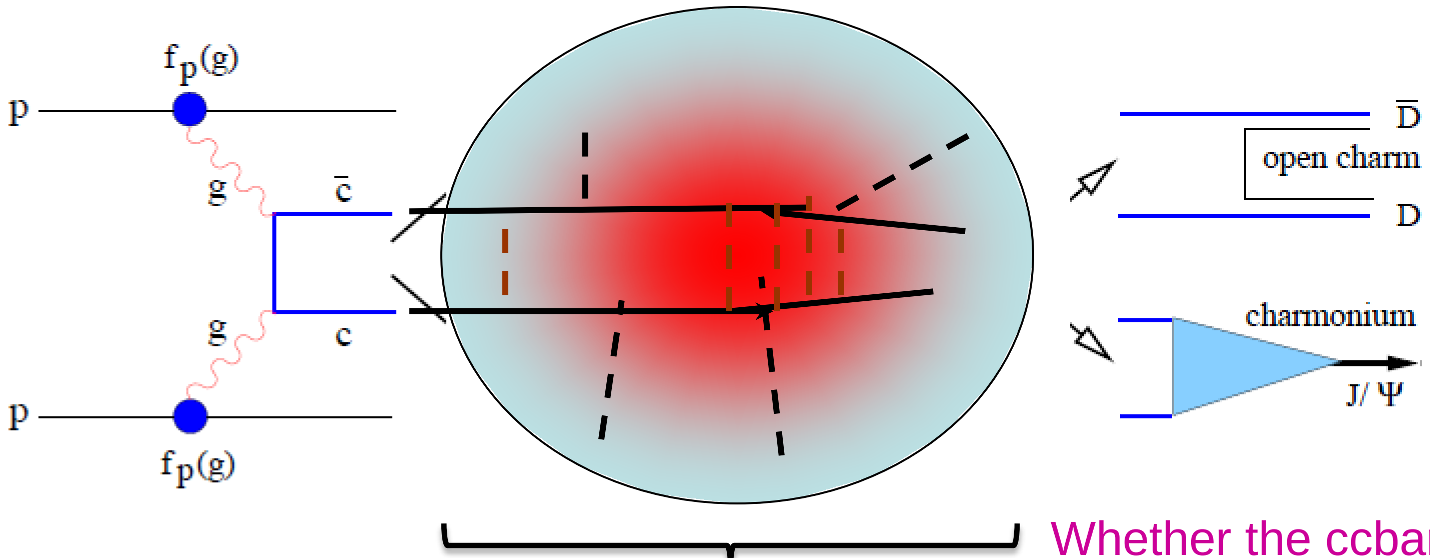
Picture



Early decoupling between various states

Beyond the (quasi-stationnary) sequential suppression scenario

Reality



Very complicated QFT

problem at finiteT(t) !!!

Whether the ccbar pair emerges as a bound quarkonia or as DDbar pair is only resolved at the end of the evolution

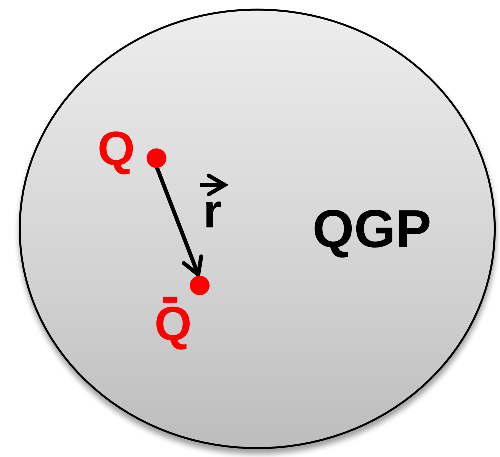
But one should aim at solving it, especially as the quarkonia content of a QQbar quantum state is at most of the order of a few % (continuous transitions under external perturbations)

1rst Quantum approach

- **Time-dependent Schrödinger equation for the $Q\bar{Q}$ pair**

Where $$\widehat{H} = 2m_q - \frac{(\hbar c)^2}{m_q}\nabla^2 + V(r, T_{\rm red})$$

$$\Psi_{Q\bar{Q}}(\mathbf{r},t) = R_{Q\bar{Q}}(r,t) \times \cancel{Y_{Q\bar{Q}}(\theta,\phi)}$$



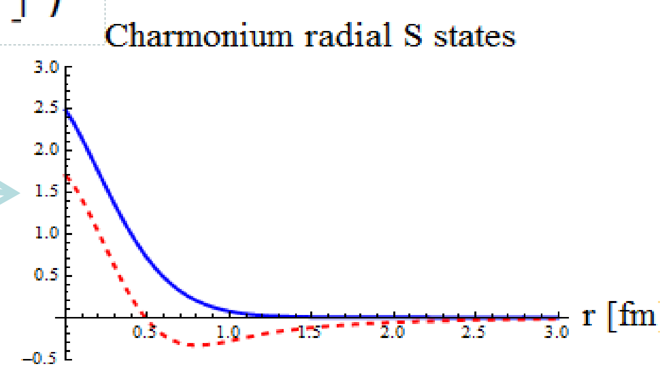
Initial wavefunction: $$R_{Q\bar{Q}}\,(r, t=0) = \left(\frac{1}{\pi a^2}\right)^{3/4} e^{-\frac{r^2}{2a^2}}$$

where $a_{c\bar{c}} = 0.165$ fm and $a_{b\bar{b}} = 0.045$ fm

- **Projection onto the S states: the S weights**

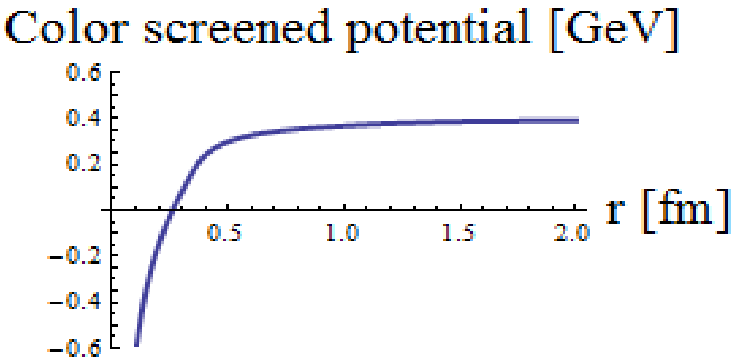
$$W_S(t) = \left(4\pi\,\mathrm{Abs}\left[\int_0^\infty R_{Q\bar{Q}}\,(r,t,T_{red}) \times R_S(r, T_{red}^{had})\; r^2\, dr\right]\right)^2$$

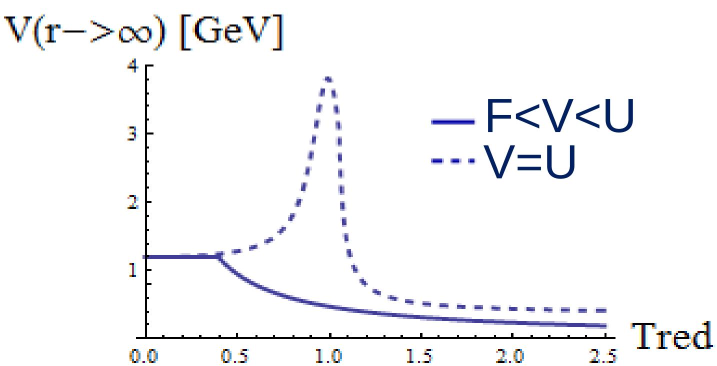
Radial eigenstates of the hamiltonian



Additional ingredients

The color potentials V(Tred, r)





- "<u>Weak potential F<V<U</u>"

$$V_{\text{close}}(r) = -\frac{\alpha}{r} + \sigma r - \frac{0.8\sigma}{m^2 r},$$

$$V_{\text{int}}(r) = \frac{V0 + g_1(r-r_0) + g_2(r-r_0)^2}{1 + g_3(r-r_0) + g_4(r-r_0)^2},$$

$$V_{\text{far}}(r) = V_\infty - \frac{4}{3}\frac{\alpha_1}{r} e^{-\sqrt{4\pi\ \tilde{\alpha}_1}Tr}$$

- "<u>Strong potential V=U</u>"

$$U = \left(-\frac{\alpha}{r} + \sigma r - \frac{0.8\sigma}{m^2 r} \right) \times e^{-(\mu r)^2} + V_0 \times \left(1 - e^{-(\mu r)^2}\right)$$

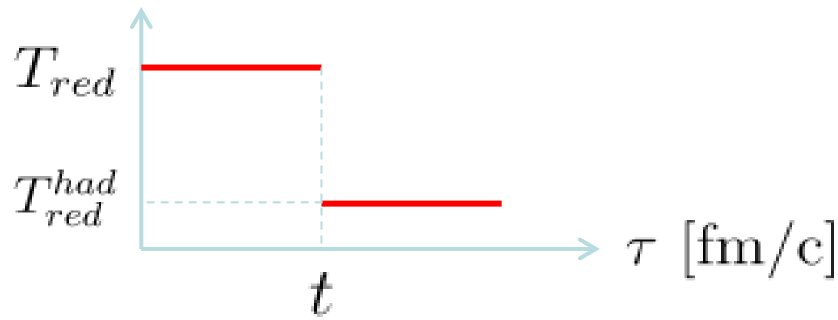
Evaluated by Mócsy & Petreczky* and Kaczmarek & Zantow** from lQCD

* Phys.Rev.D77:014501,2008 **arXiv:hep-lat/0512031v1

Additional ingredients

The temperature scenarios

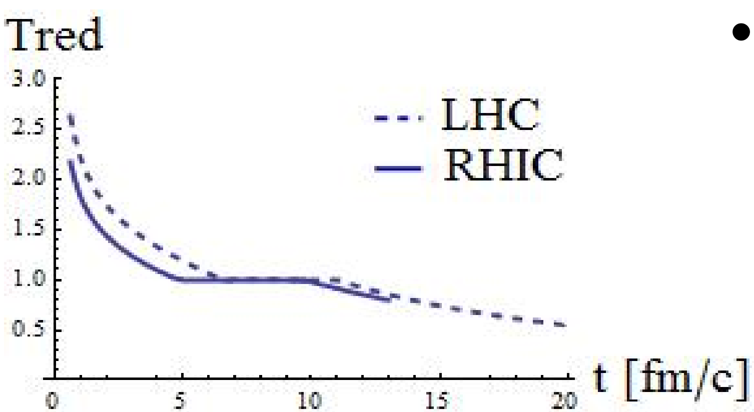
- <u>At fixed temperatures</u>



$$T_{red} = T/T_c,$$

where $T_c = 0.165$ Gev

Instantaneous transition from QGP at T_{red} to hadronisation phase $T_{red}^{had} \leq 0.4$

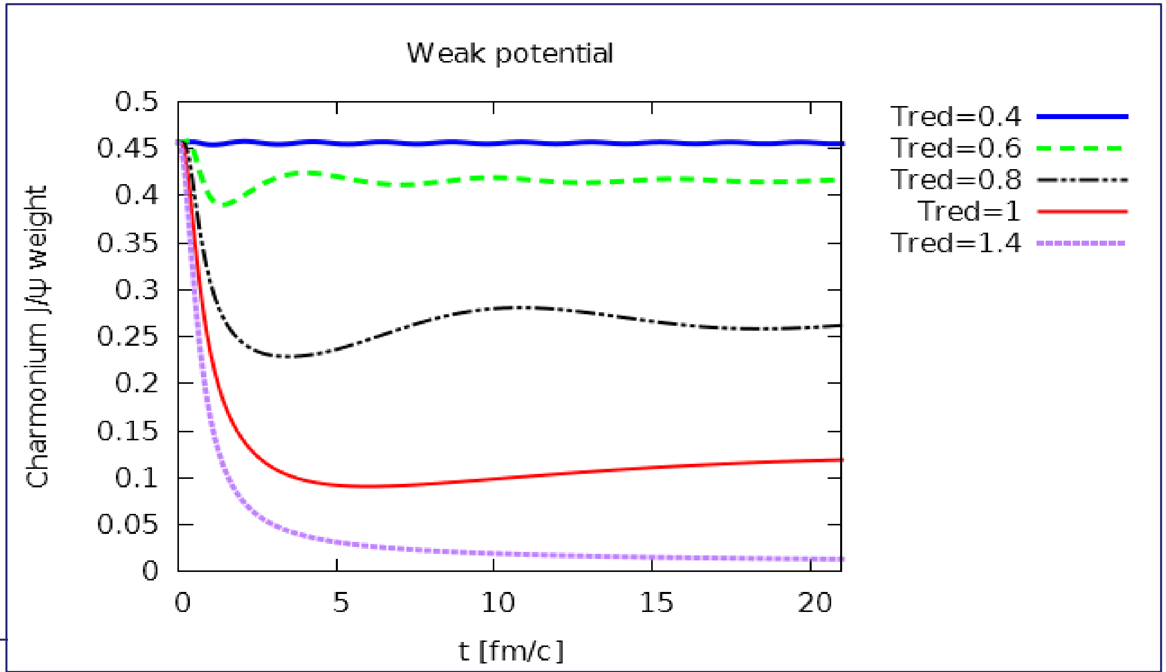


- <u>Time dependent temperature</u>
  - **Cooling** of the QGP over time by Kolb and Heinz* (hydrodynamic evolution and entropy conservation)
  - At LHC ($\sqrt{s_{NN}} = 2.76$ TeV) and RHIC ($\sqrt{s_{NN}} = 200$ GeV) energies

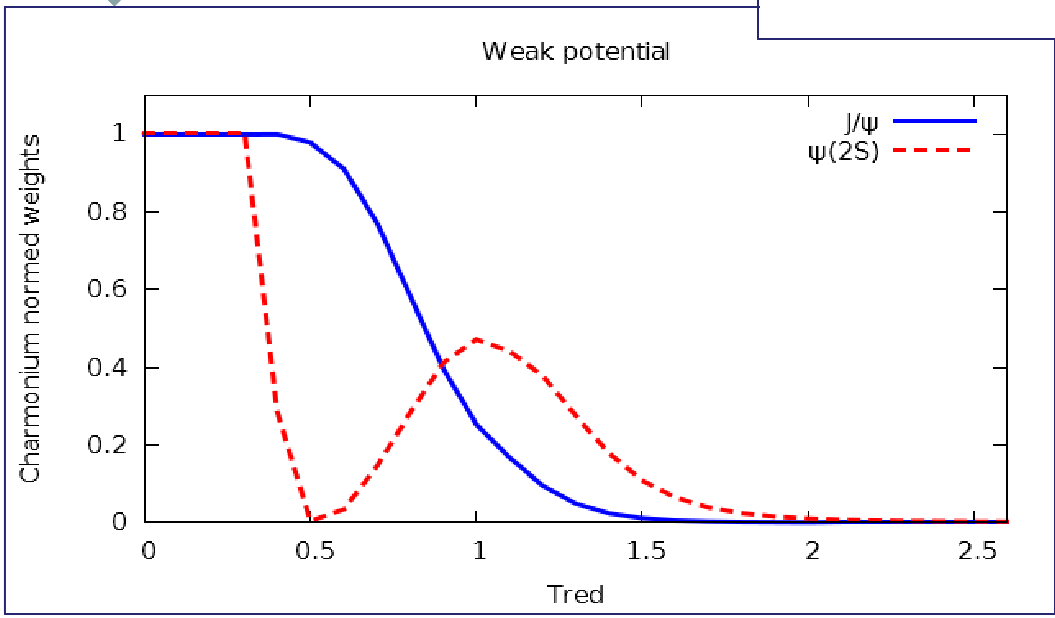
* arXiv:nucl-th/0305084v2

Evolution at fixed temperature

Charmonia and weak color potential (F<V<U)



The normed weights at t->∞ function of the temperature

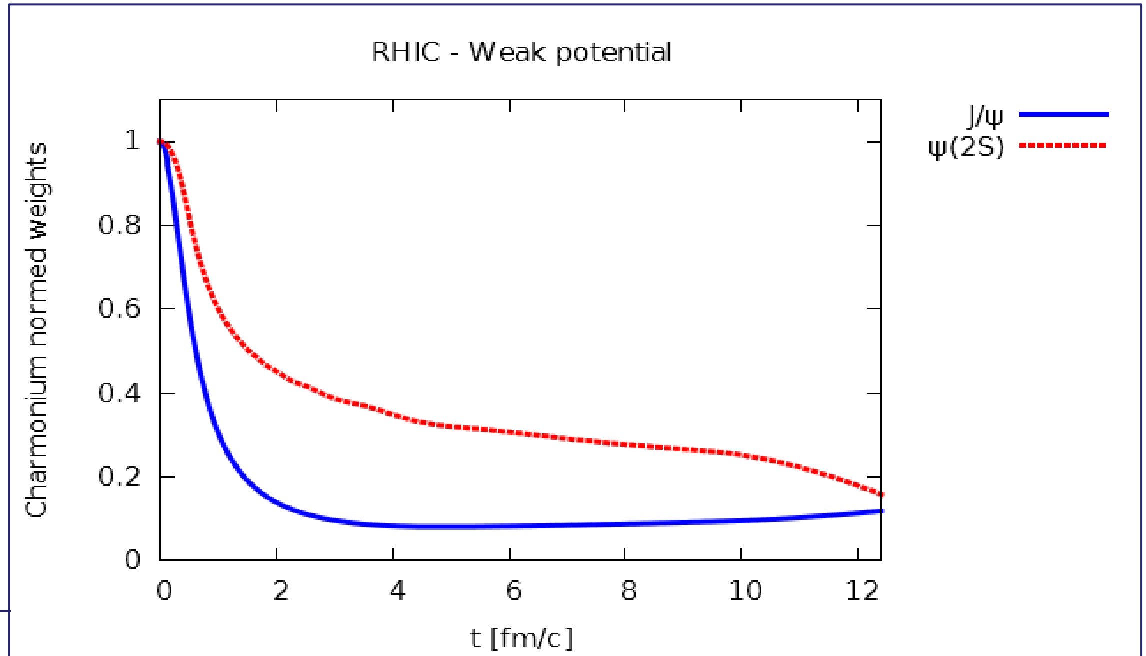


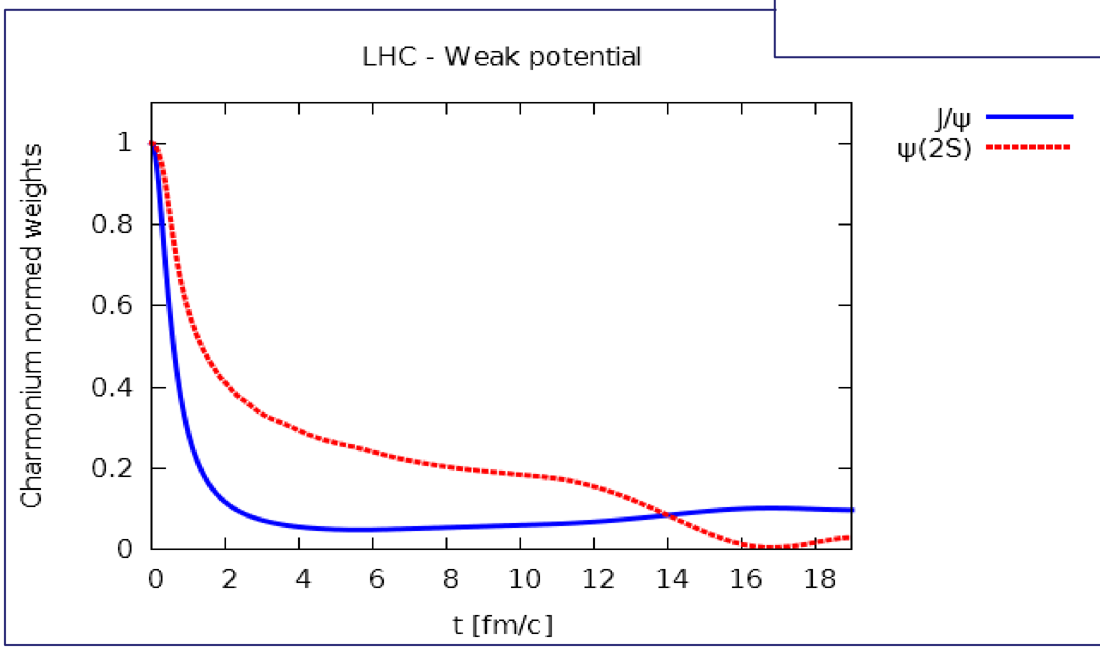
Smooth evolution and no discontinuity in the parameter space

Evolution in realistic T scenarios

Charmonia and weak color potential (F<V<U)

RHIC temperature scenario





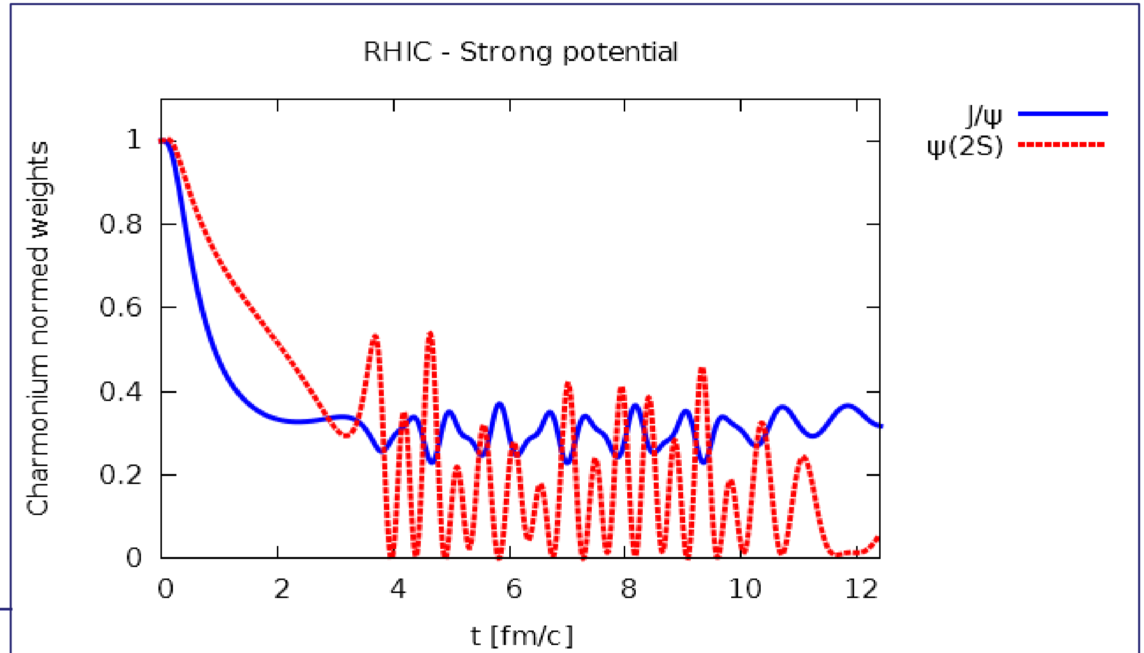
LHC temperature scenario

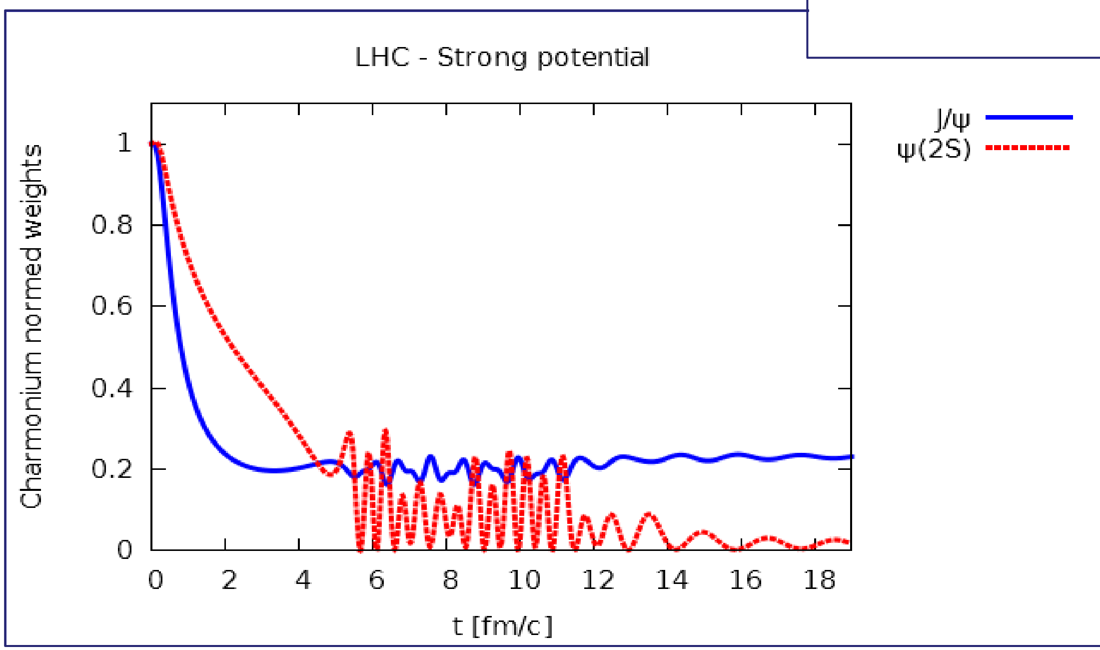
Psi' less suppressed for a while !

Evolution in realistic T scenarios

Charmonia and strong color potential (V=U)

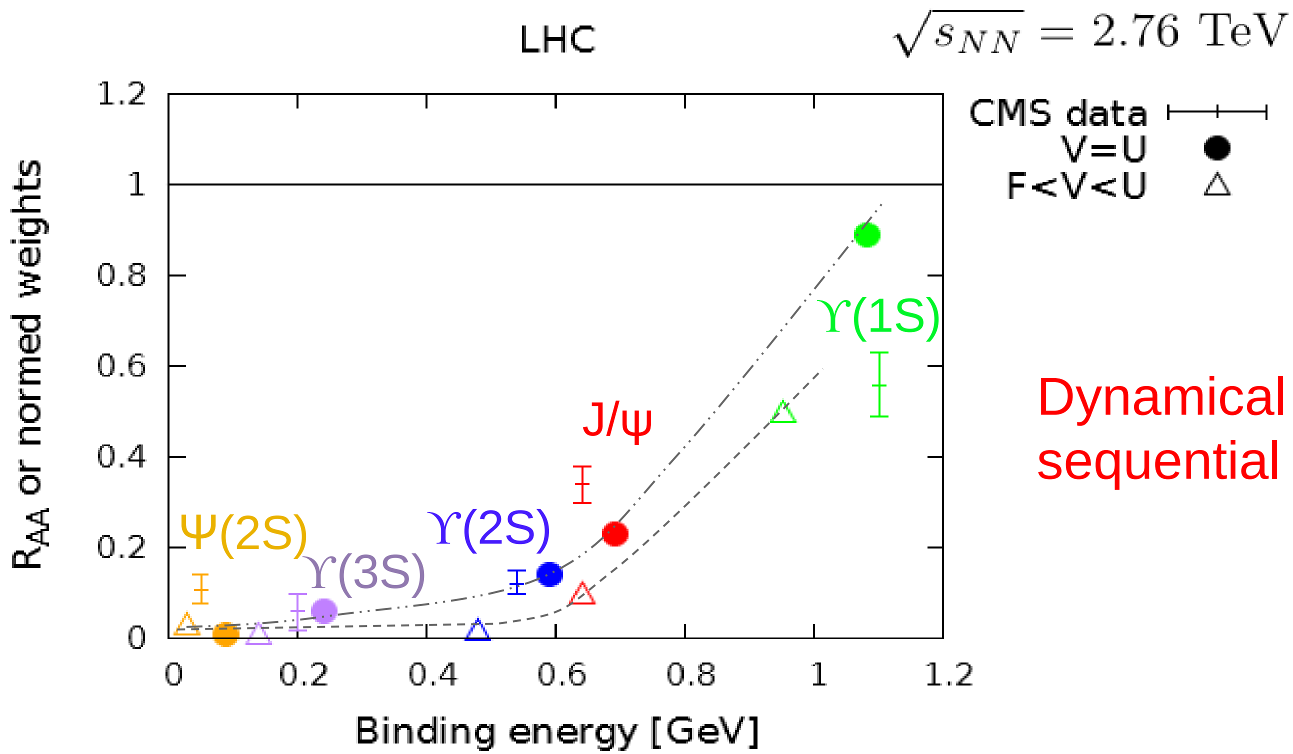
RHIC temperature scenario





LHC temperature scenario

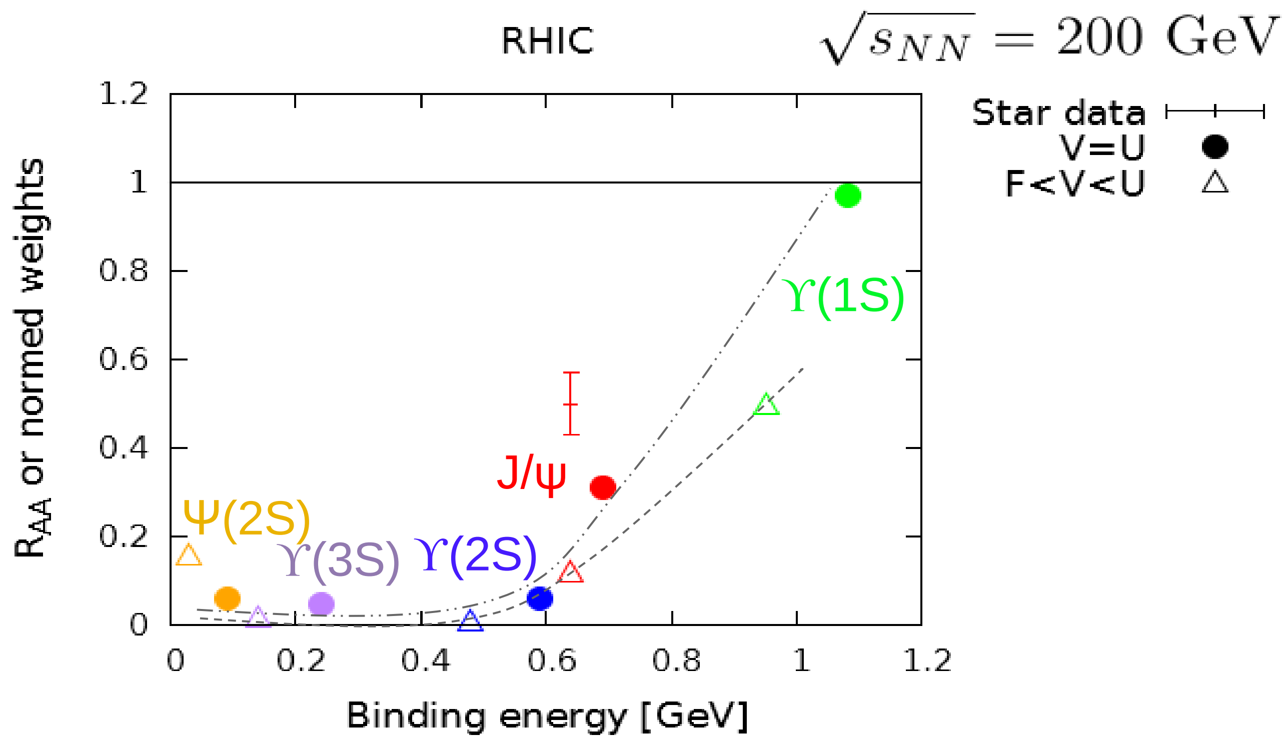
Sum up of LHC results



Dynamical quarkonia sequential suppression

- The results are quite encouraging for such a simple scenario !
- J/ψ and ψ(2S) are underestimated (room for regeneration) and ϒ(1S) overestimated
- Feed downs from exited states and CNM to be implemented

Sum up of RHIC results



- Similar suppression trends obtained for both RHIC and LHC.
- Less J/ψ suppression at RHIC than at LHC.
- ϒ(1S+2S+3S) suppression can be estimated with Star data to ~ 0.55±0.10, we obtain ~ 0.48 for V=U and ~ 0.24 for F<V<U.

A taste of quantum thermalisation

Background?

- RHIC and LHC experimental results => quarkonia thermalise partially in the QGP
- But how to thermalise our wavefunction ? Quantum friction/stochastic effects have been a long standing problem because of their irreversible nature.

The open quantum approach: ✖
Considering the whole system, quarkonia and environment, the latter being finally integrating out

Y. Akamatsu [arXiv:1209.5068]
Laine et al. JHEP 0703 (2007) 054

2^{nd} possible approach: ✓
Unravel the open quantum approach by using a stochastic operator and a dissipative non-linear potential

A. Rothkopf et al. Phys. Rev. D 85, 105011 (2012)
N. Borghini et al. Eur. Phys. J. C 72 (2012)
S. Garashchuk et al. Jou. of Chem. Phys. 138, 054107 (2013)

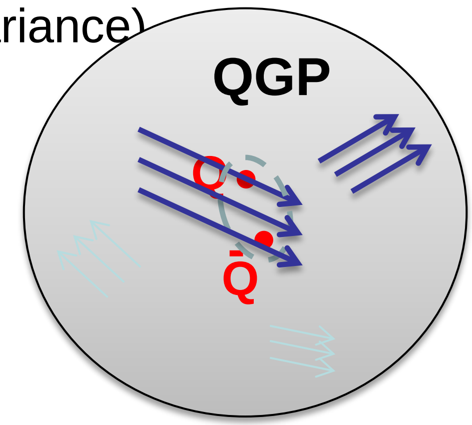
- **New Schrödinger equation**

$$i\hbar\frac{\partial\Psi_{Q\bar{Q}}(\mathbf{r},t)}{\partial t} = \left(\widehat{H}(\mathbf{r}) - \underline{\mathbf{F}(t).\mathbf{r}} + \underbrace{A\big(S(\mathbf{r},t) - \langle S(\mathbf{r},t)\rangle_{\mathbf{r}}\big)}_{\text{Friction}}\right)\Psi_{Q\bar{Q}}(\mathbf{r},t)$$

Where: $S(\mathbf{r},t) = \arg\big(\Psi_{Q\bar{Q}}(\mathbf{r},t)\big)$ and $\langle\mathbf{F}(t)\rangle = 0\,,\ \big\langle\mathbf{F}(t)\mathbf{F}(t')\big\rangle = \Gamma(t,t')$

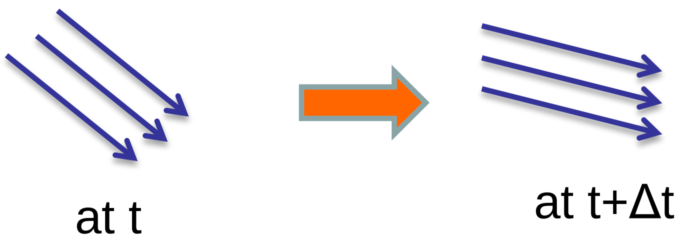
Model for a stochastic operator

- **The hierarchy** $m \gg T \;\Rightarrow\; \sigma \ll \tau_{\rm relax}$ (adiabatic invariance)



where ✓ σ is the quarkonia autocorrelation time with the gluonic fields (if $\sigma = 0$ the fluctuations are uncorrelated)
✓ $\tau_{\rm relax}$ is the quarkonia relaxation time

- $\langle \mathbf{F}(t)\mathbf{F}(t')\rangle = \Gamma(t,t')$?



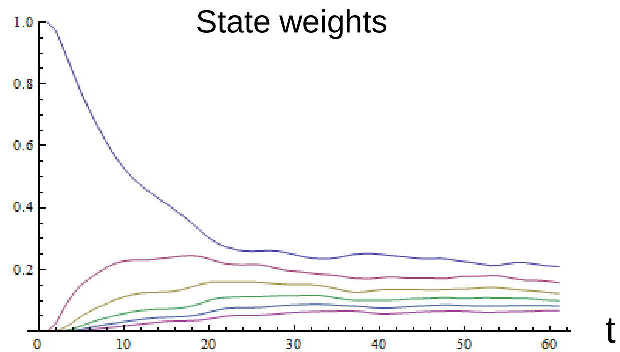
$$\Gamma(t,t') = B\,\frac{e^{-\frac{(t-t')^2}{2\sigma^2}}}{\sqrt{2\pi}\,\sigma} \;\xrightarrow[\sigma\to 0]{}\; B\,\delta(t-t')$$

- One has finally 3 parameters: A (the Drag coefficient), B (the diffusion coefficient) and σ .

First tests of stochastic Schroedinger equation

Towards asymptotic distribution ?

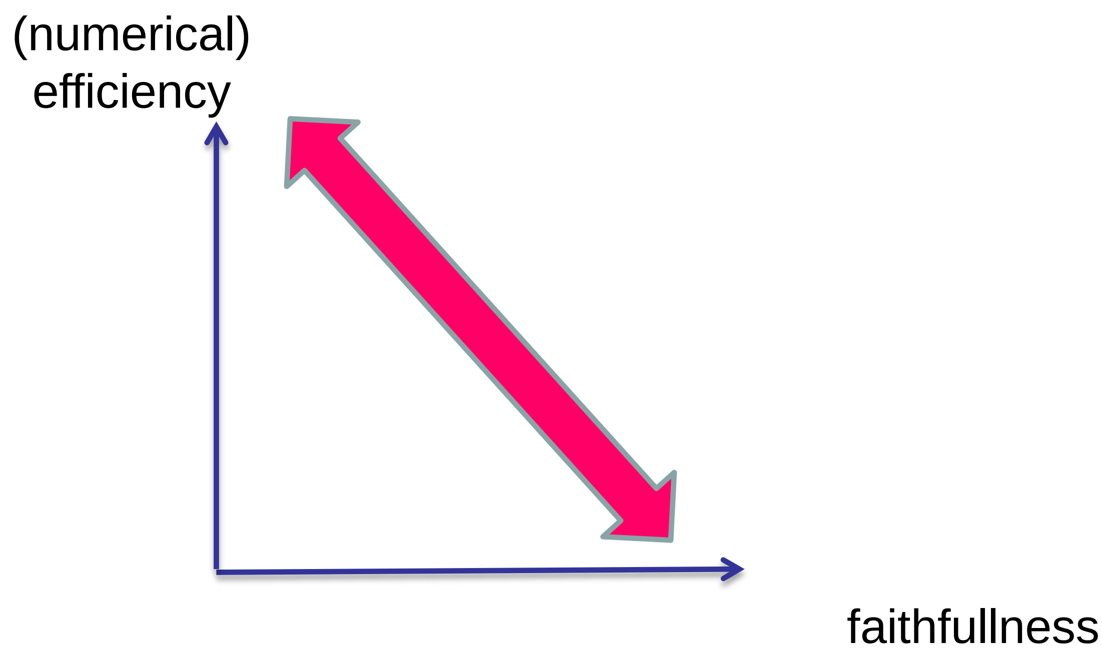
- Tested in an harmonic potential:



➞ One gets Boltzmann distributed state weights ! Independently of σ and with the Einstein relation B ≈ 2mT A between the diffusion coefficient and the Drag coefficient.
At a finite time:
➞ high pt => high velocity => smaller σ => more excited states => more suppression
➞ low pt => small velocity => higher σ => less excited states => less suppression (=> no need for regeneration ?)

➞ **Will be generalized and used to our quarkonia thermalisation in the near future !**

Conclusion: The new frontiers of my small world



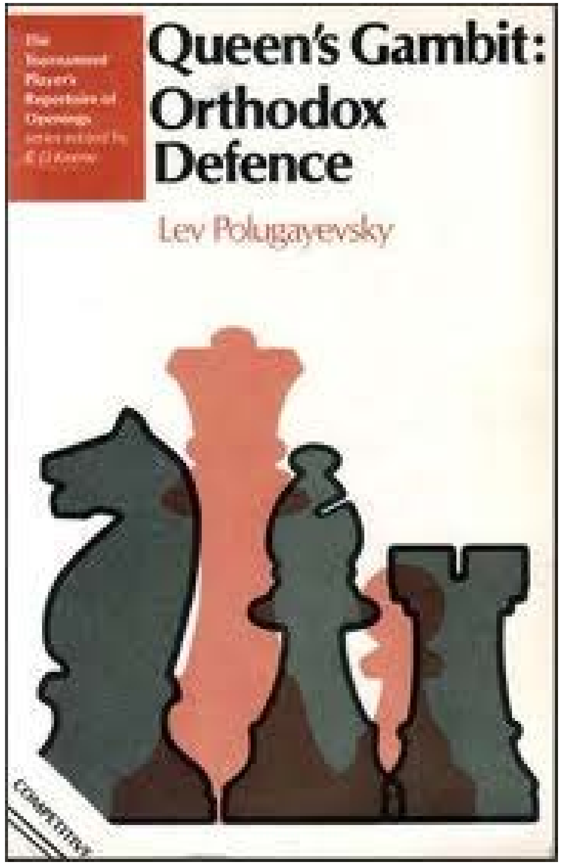
- How to implement reliable energy loss modeling that respect quantum coherence on large scales as well as medium evolution ?

- How to implement the quantum evolution of a 2-body system in a dense colored stochastic environment where the concept of cross-section is meaningless


8
7
6
5
4
3
2
1
A B C D E F G H

When I was (a lot younger)

Which (for the knowledgeable) is the



(**declined**)

The most boring defence ever ! … and I must confess I developed bad feelings with the word "orthodox"

Today

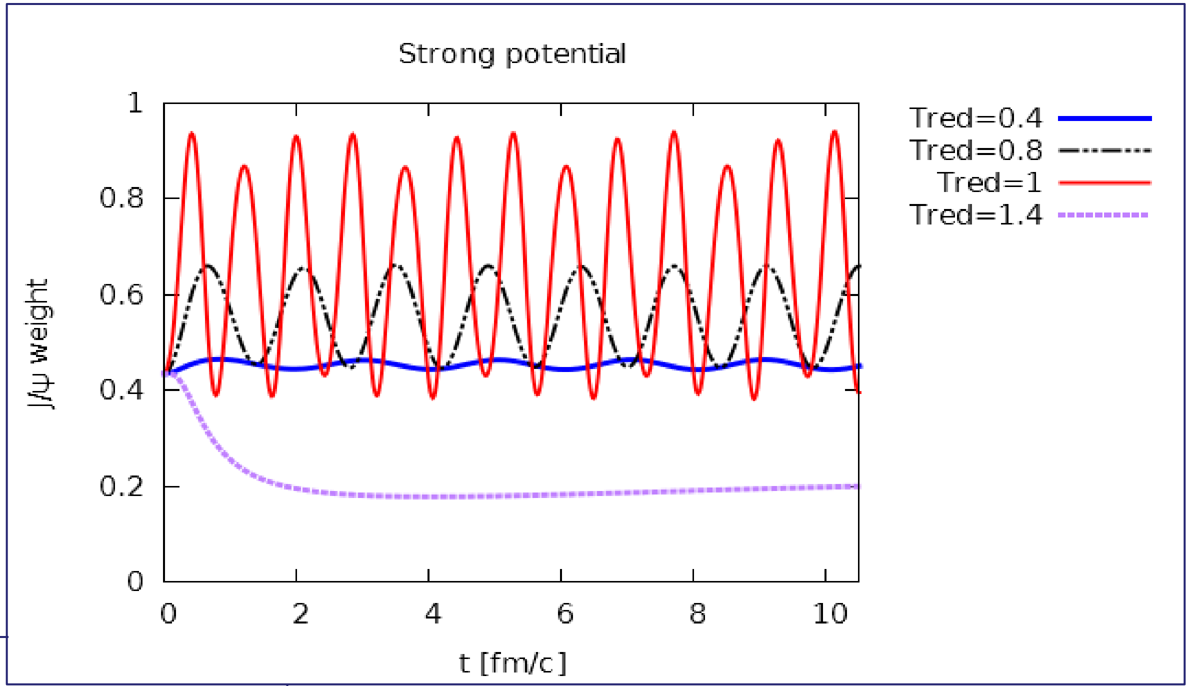
I was pleased to accept the invitation of 3 queens in this orthodox academy of Crete

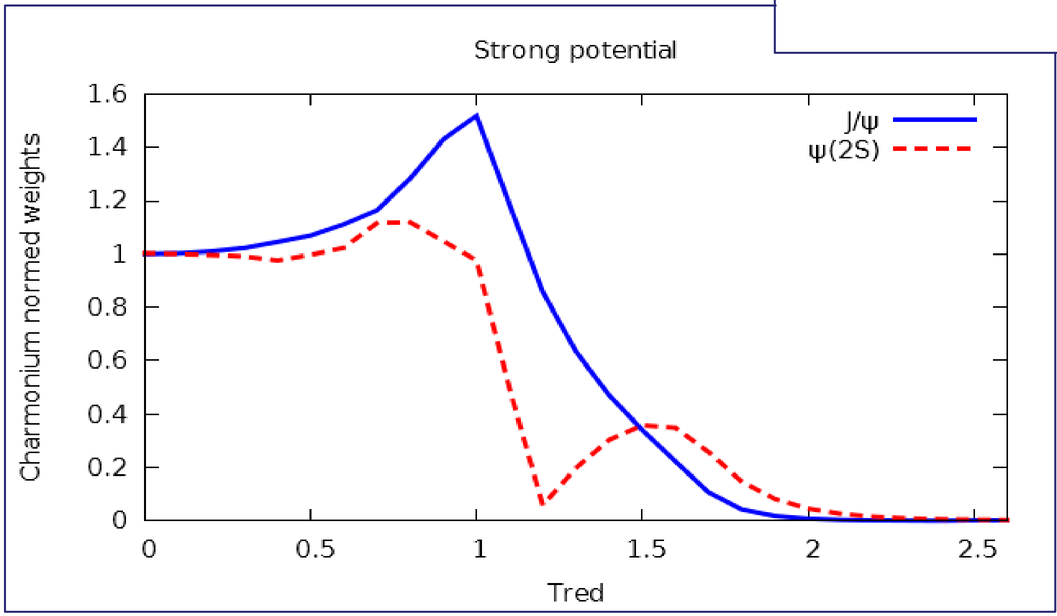
… and it was much more interesting than playing the orthodox defence !

Back up

Charmonia and strong color potential (V=U)

At fixed temperatures

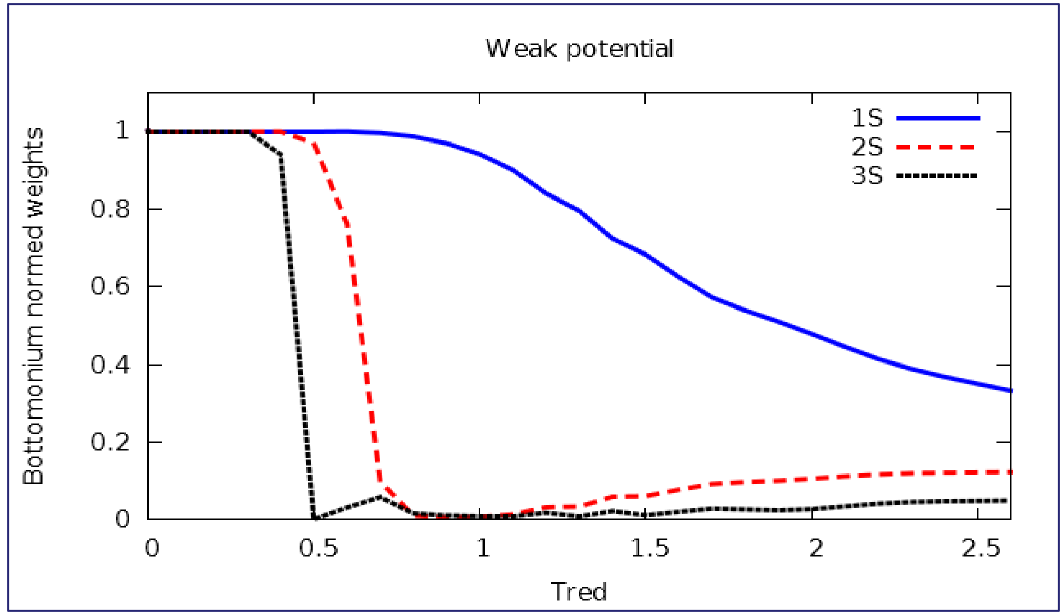




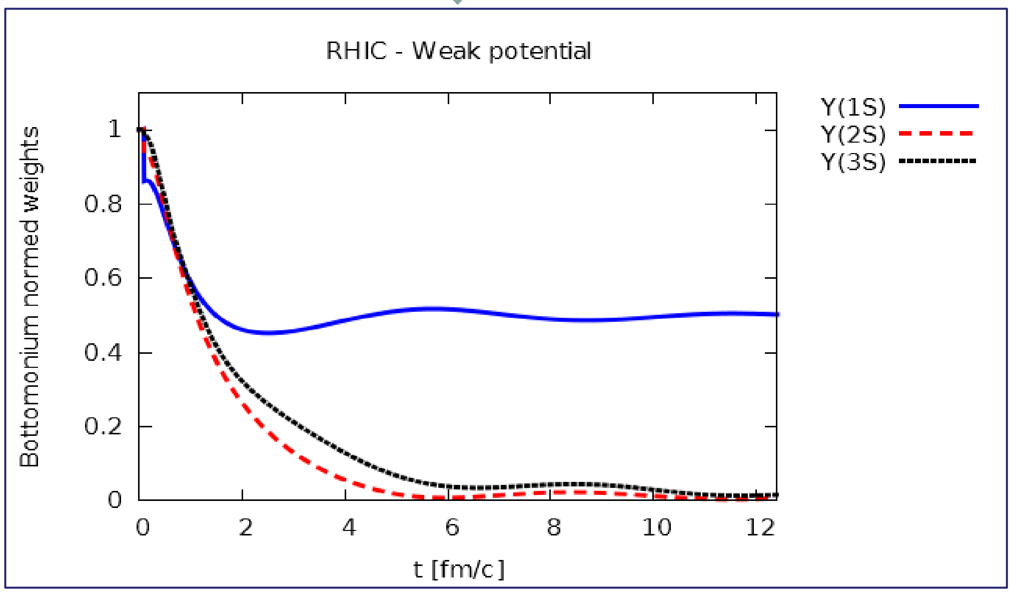
The normed weights at t->∞ function of the temperature

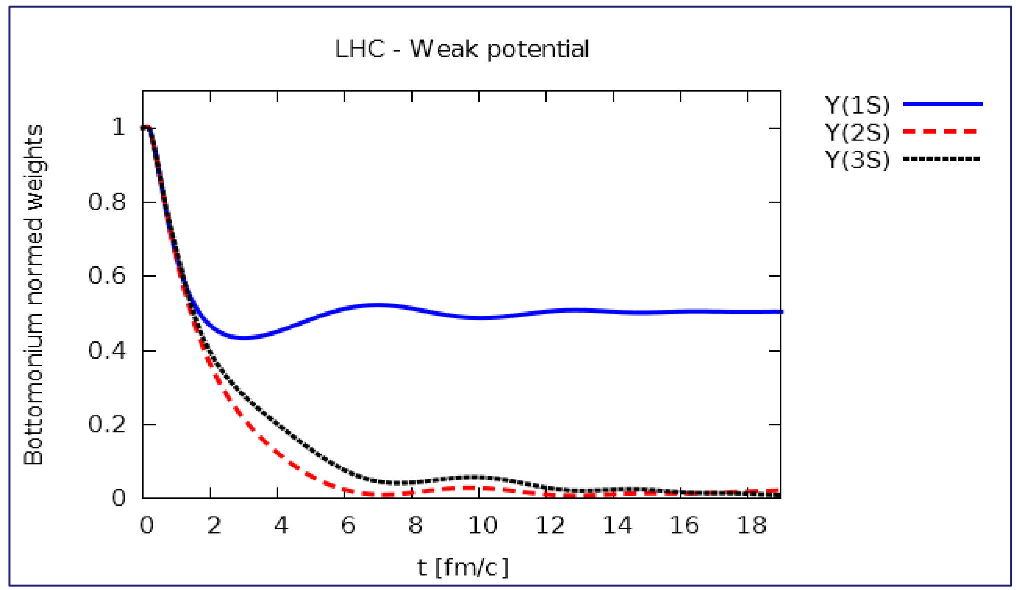
Bottomonia and weak color potential (F<V<U)

The normed weights at t->∞ function of the temperature



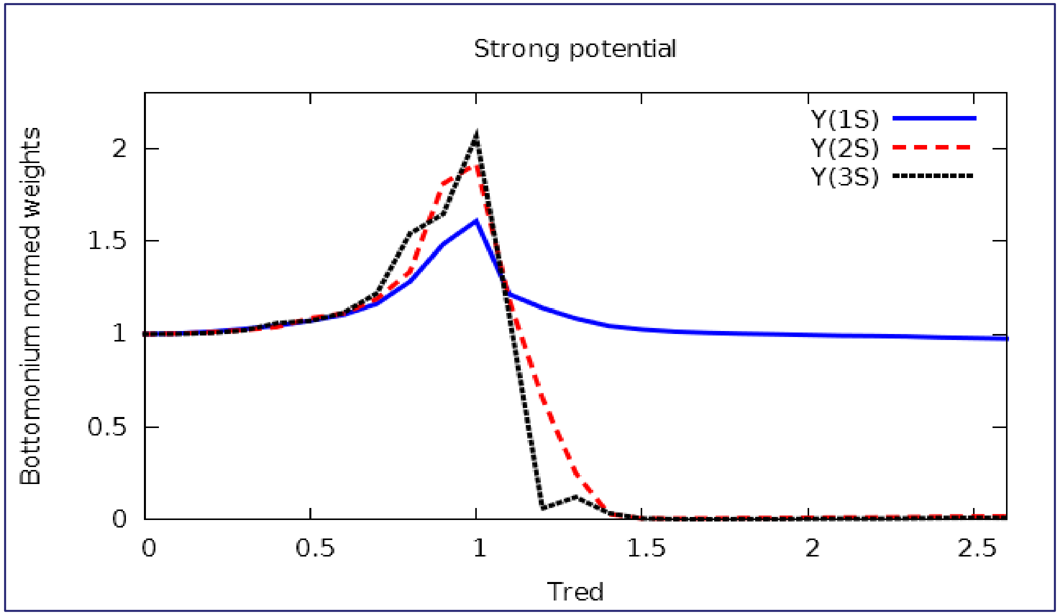
Temperature scenarios



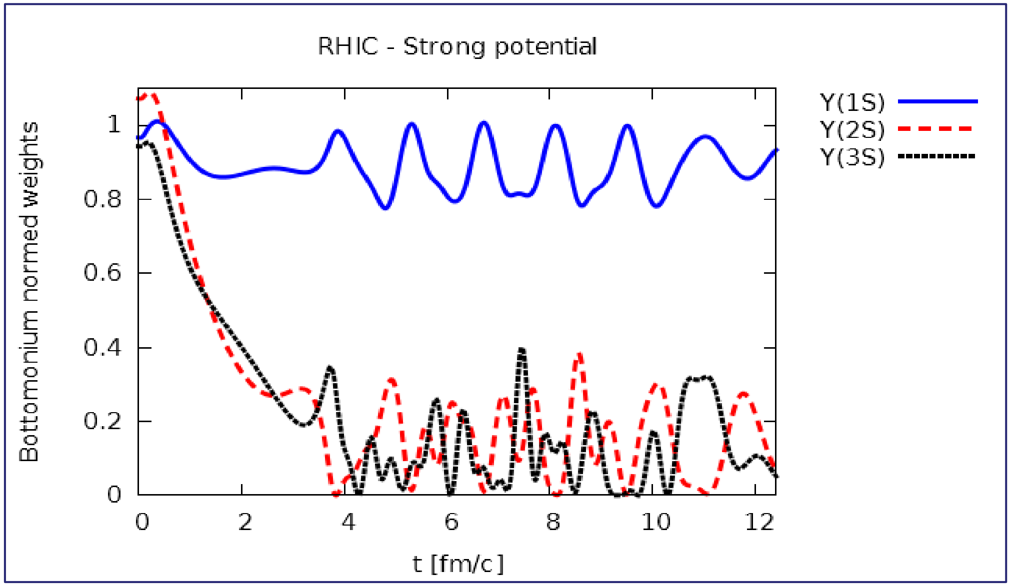


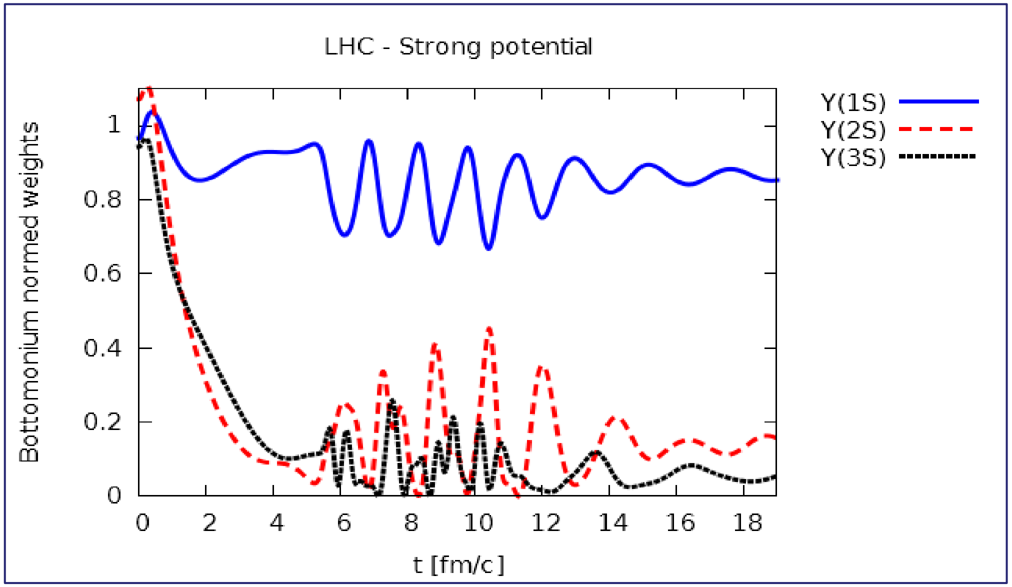
Bottomonia and strong color potential (V=U)

The normed weights at t->∞ function of the temperature

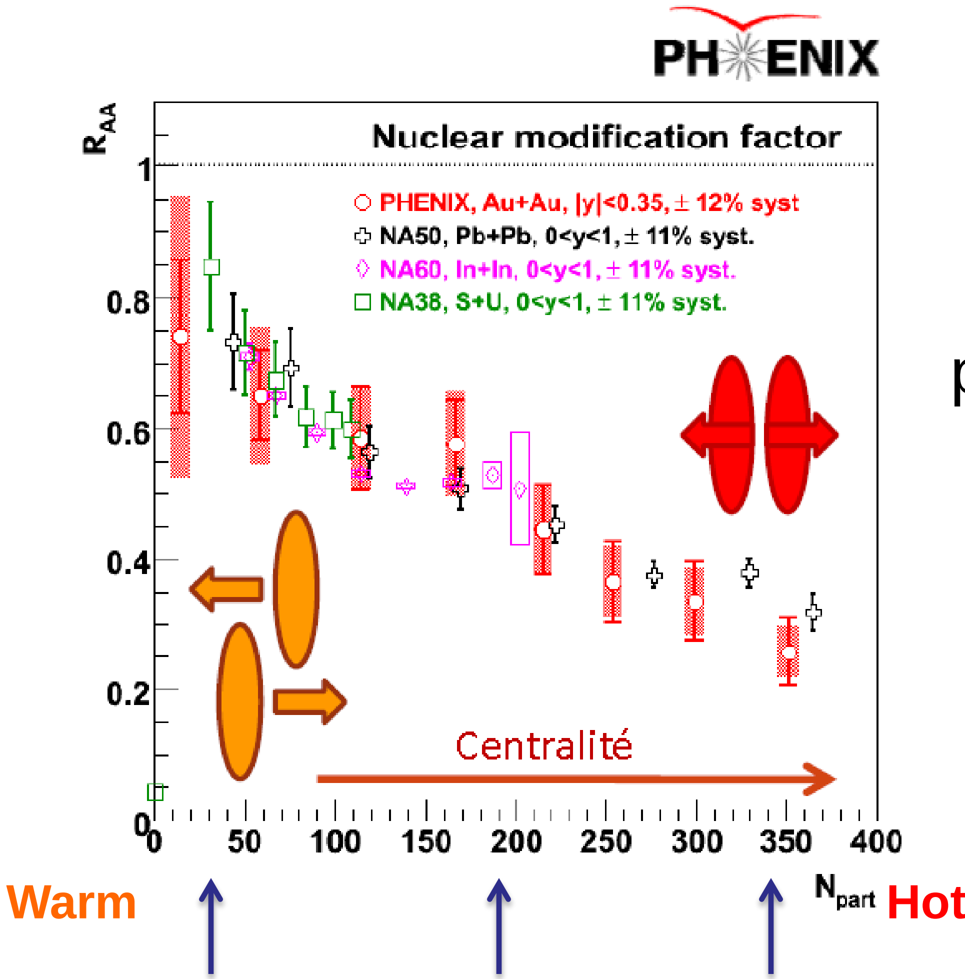


Temperature scenarios





Quarkonia in Stationary QGP



Melted ψ'   Melted χ_c J/ψ starts to melt

Observed J/ψ =

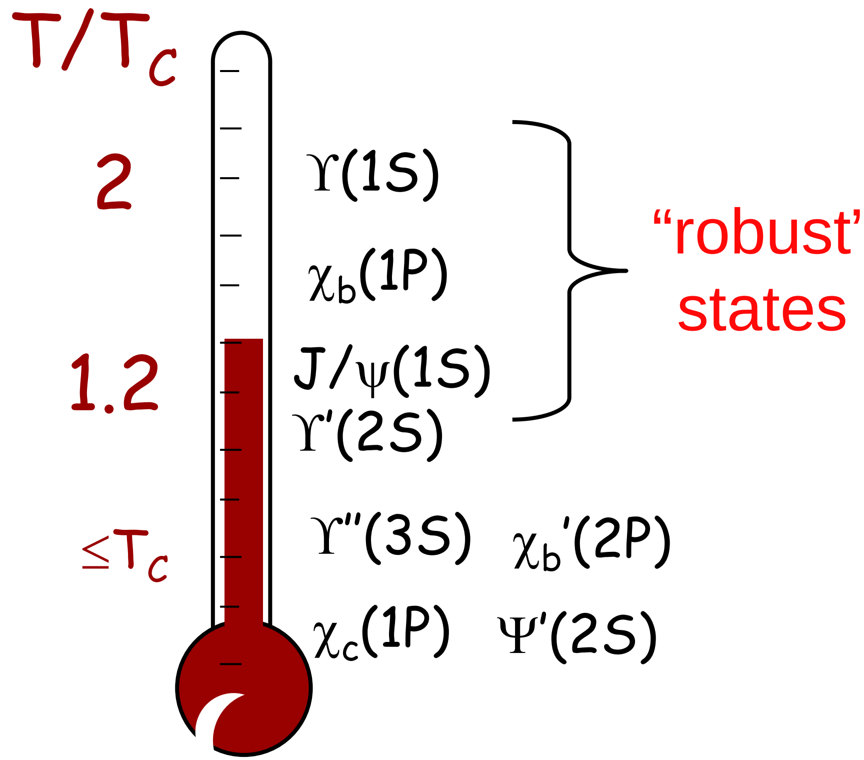
prompt J/ψ + 30% χ_c + 10 % ψ'

No further suppression at RHIC (as compared to SPS)

=> Claim that T_{diss} (J/ψ) is pretty high (strongly bound)

Quarkonia in Stationary QGP

QGP Thermometer

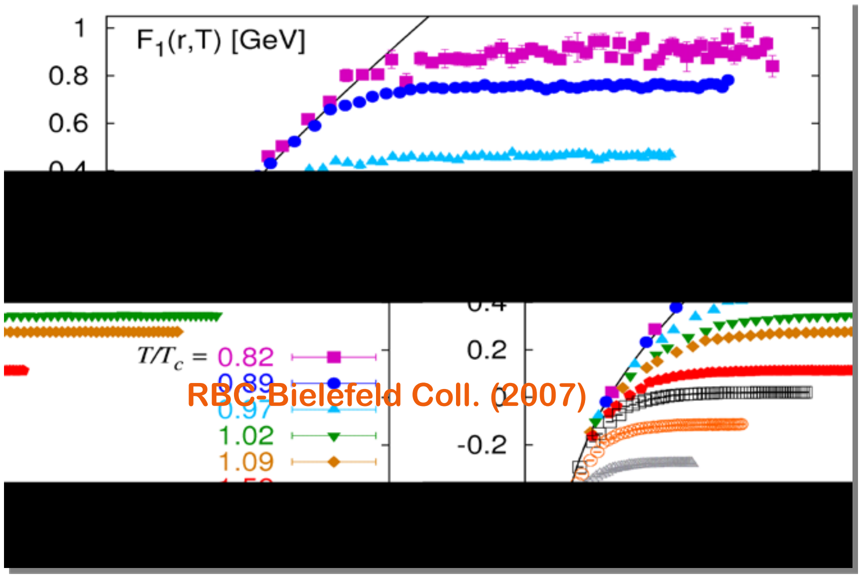


Indeed observed at SPS (CERN) and RHIC (BNL) experiments. However:

- alternative explanations, lots of unknown (also from theory side)
- less suppression at LHC

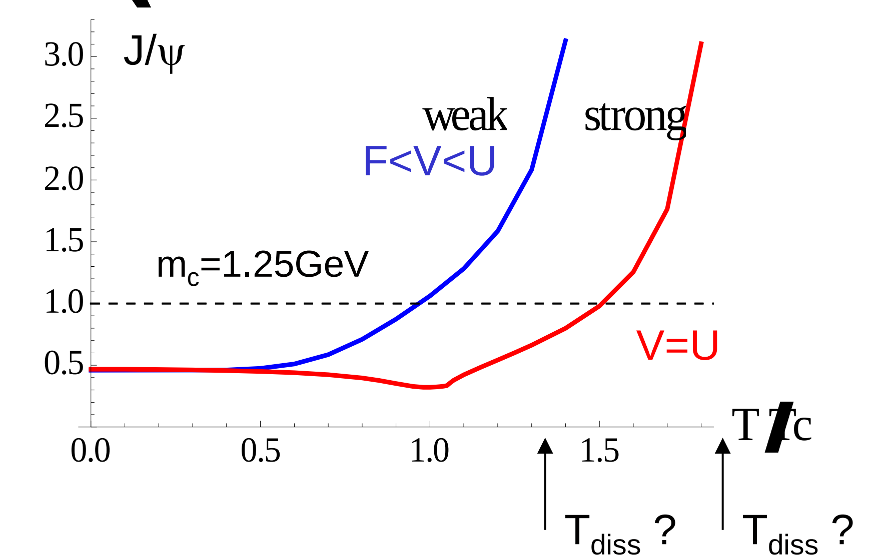
Caviats & Uncertainties

I. Quarkonia in *stationnary* medium are not well understood from the fundamental finite-T LQCD



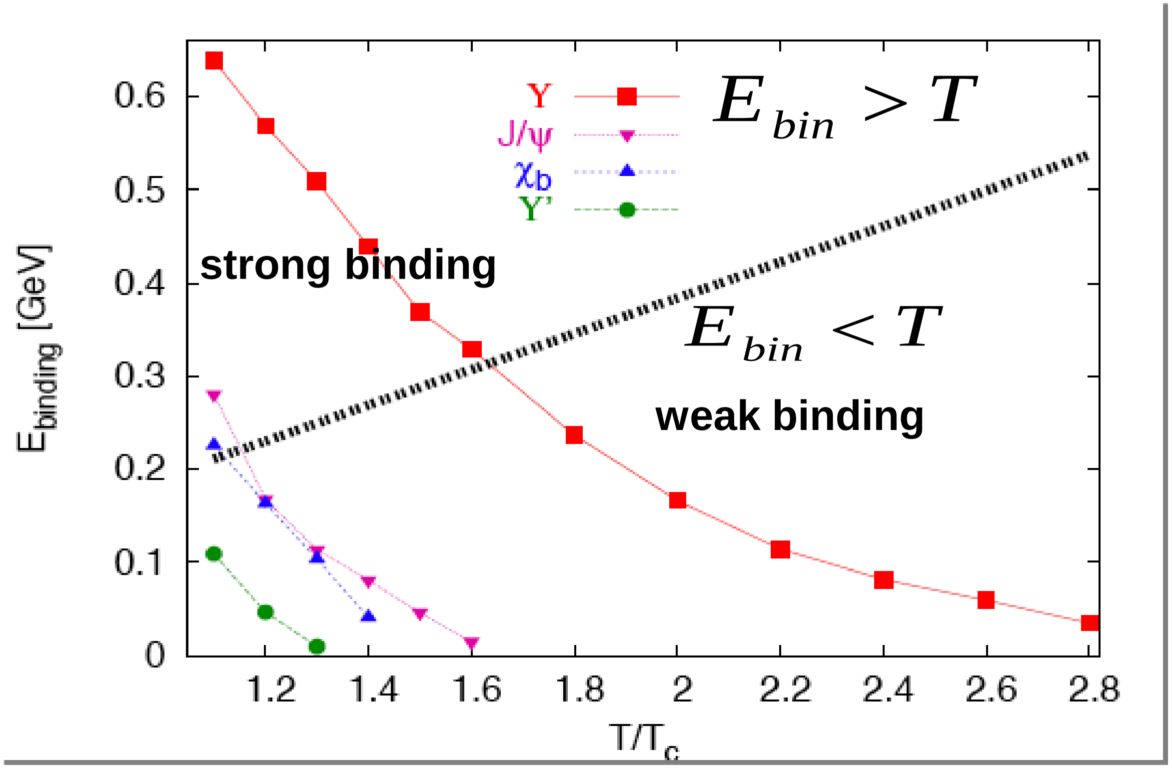
From free energy $\Rightarrow$ V(r,T) ?

Several prescriptions in litterature



Caviats & Uncertainties

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



From A. Mocsy (Bad Honnef 2008)

Semi-Qualitative questions

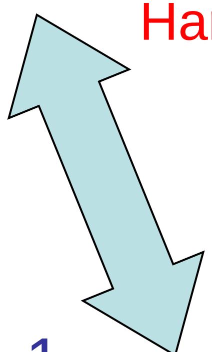
The *main* object of interest here: T_{diss}, one of the fundamental quantities of statistical QCD.

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

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

T_{diss}/T_c >(>)1

Hard probe



$T_{diss}/T_c \approx 1$

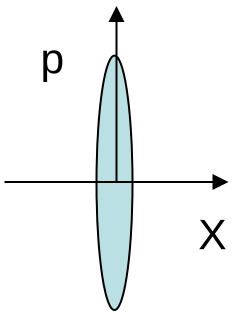
Soft probe (as usual hadrons)

3. Can we challenge the picture of statistical recombination ?

(A. Andronic, PBM, J. Stachel)

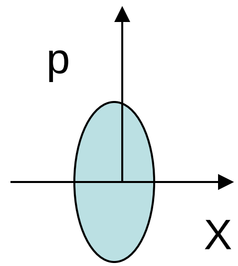
Quarkonia fate along decreasing T(t)

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



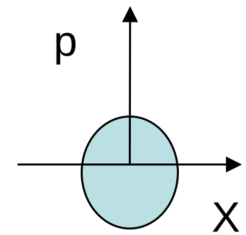
Vacuum

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



$t \sim 1/(E\psi' - E\psi)$

Quarkonia is "formed" (separation from other components)

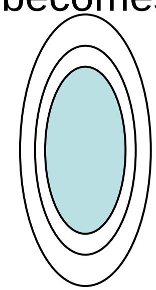


In hot (but cooling) medium

"Truth"

"Dual *Model*"

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

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

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*"

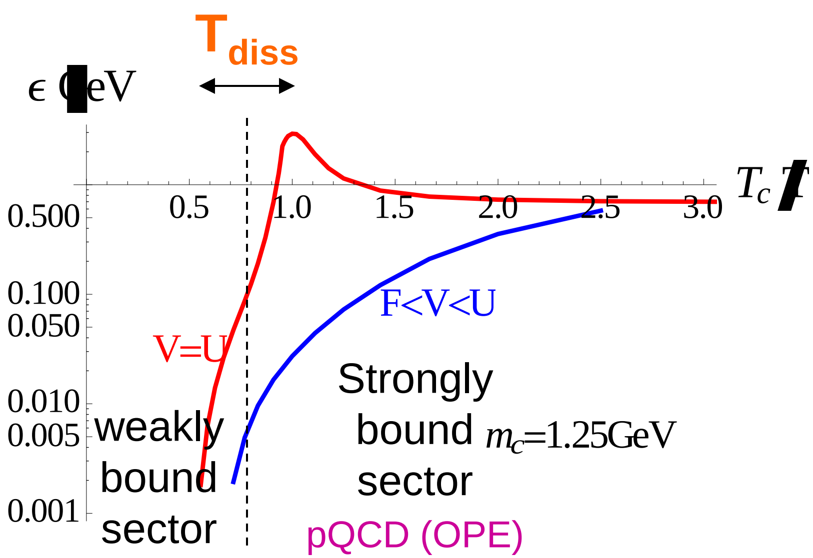
a) Instantaneous melting / thermal excitation

b) No "Q-Qbar→Quarkonia" fusion

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

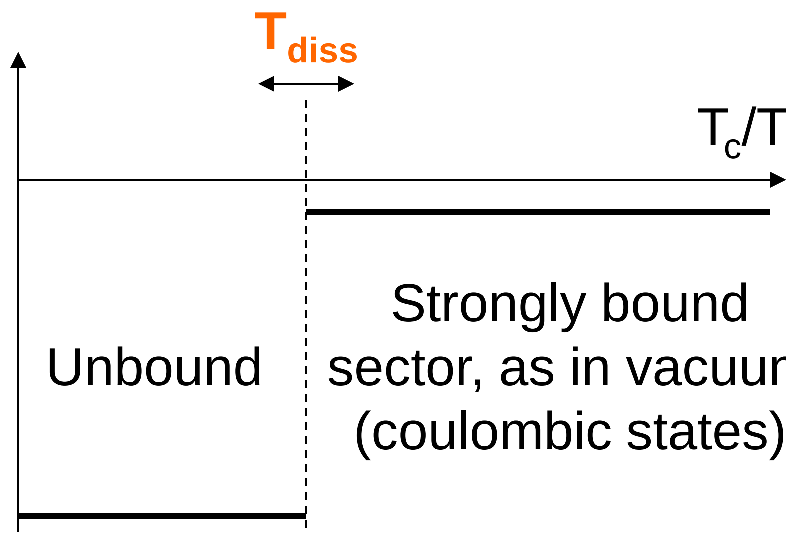
b) "Q-Qbar → Quarkonia" fusion allowed

$T > T_{diss}$



Model

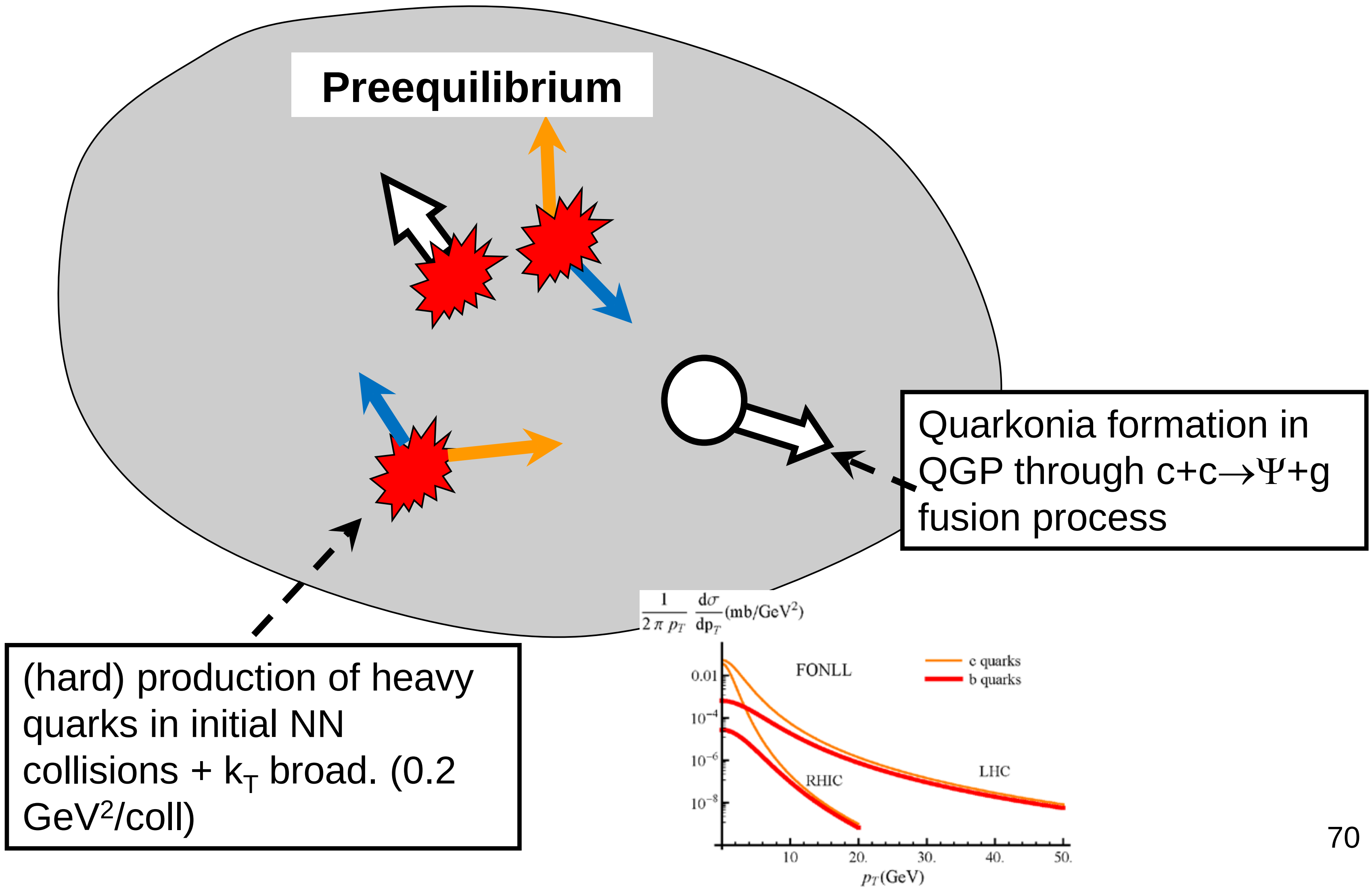
$T < T_{diss}$



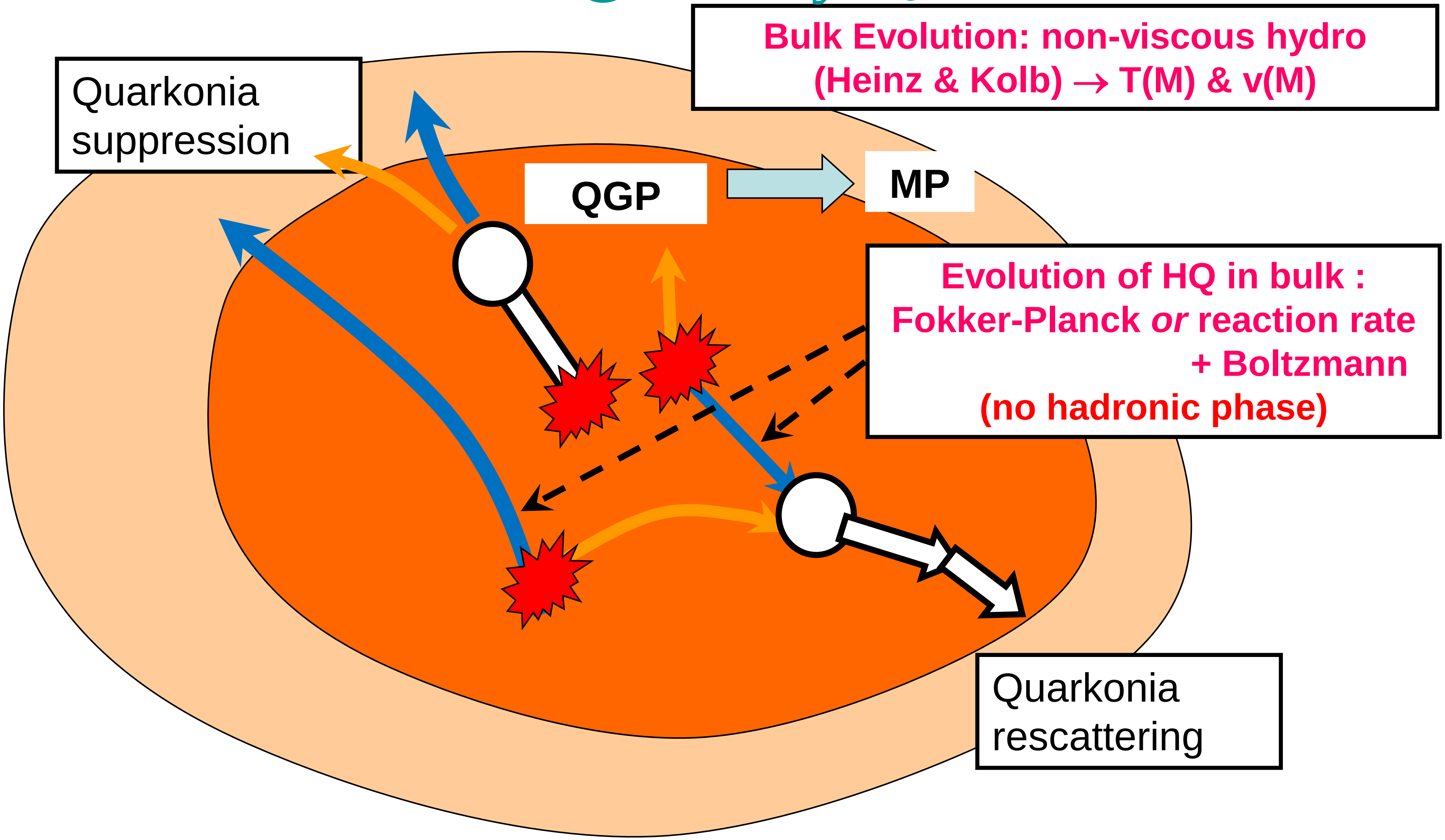
The key idea: AS THE LATTICE and POTENTIAL MODELS are inconclusive, let T_{diss} as a *free parameter* and see if this can be constrained by the data.

“Stationnary” quarkonia in evolving QGP

The Monte Carlo @ Heavy Quark Generator

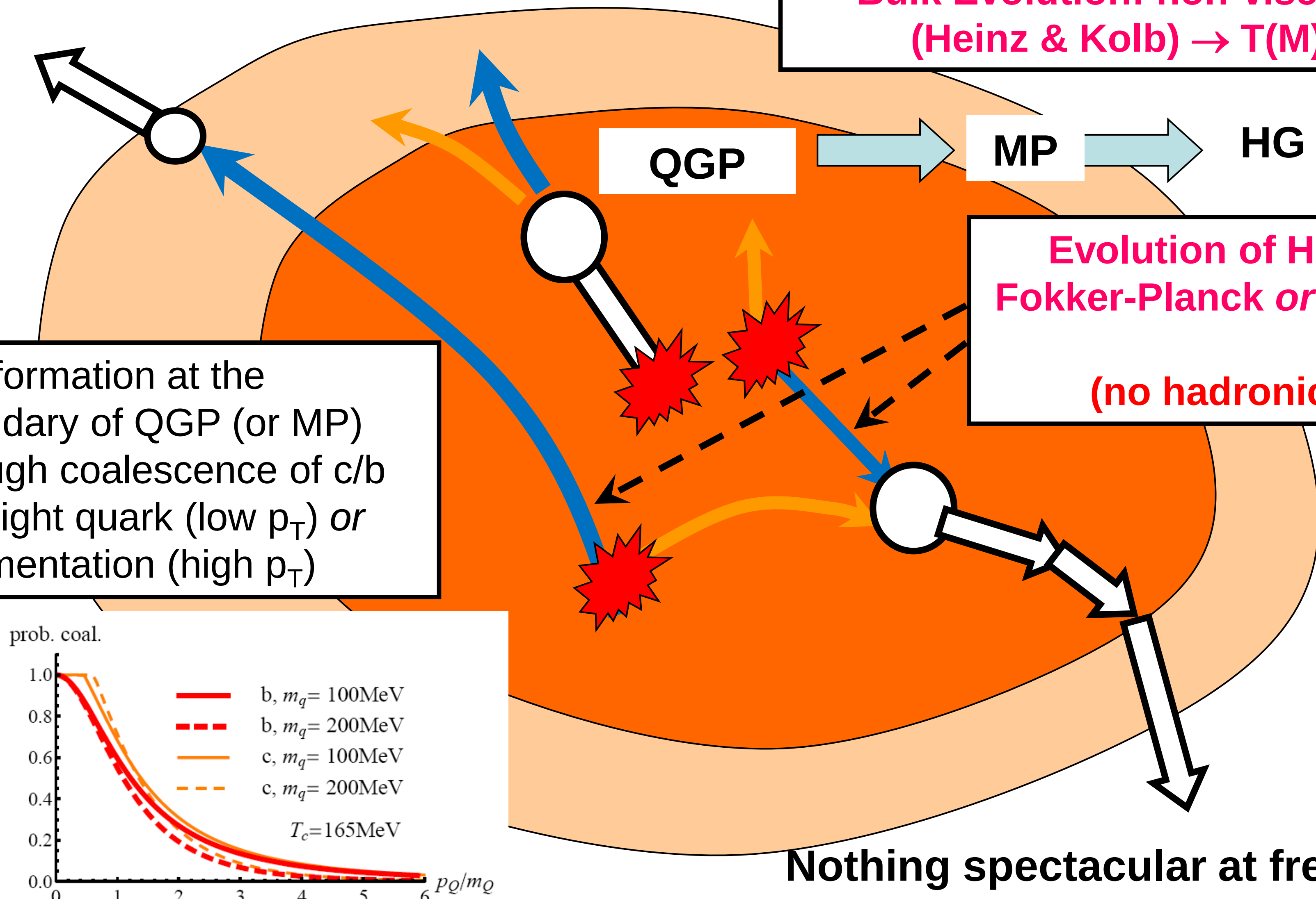


The Monte Carlo @ Heavy Quark Generator



The Monte Carlo @ Heavy Quark Generator

Bulk Evolution: non-viscous hydro (Heinz & Kolb) → T(M) & v(M)



Evolution of HQ in bulk : Fokker-Planck *or* reaction rate + Boltzmann (no hadronic phase)

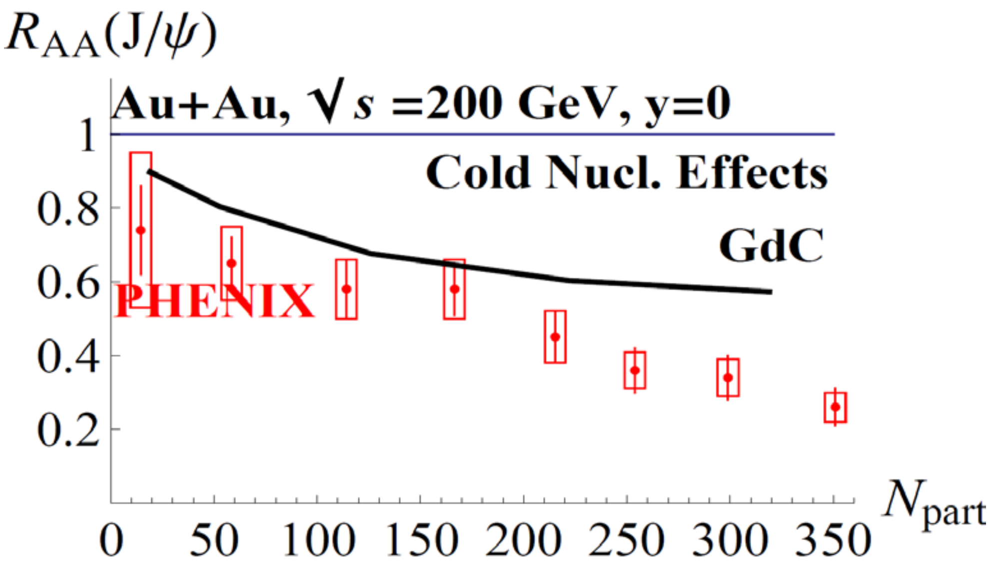
D/B formation at the boundary of QGP (or MP) through coalescence of c/b and light quark (low p_T) *or* fragmentation (high p_T)

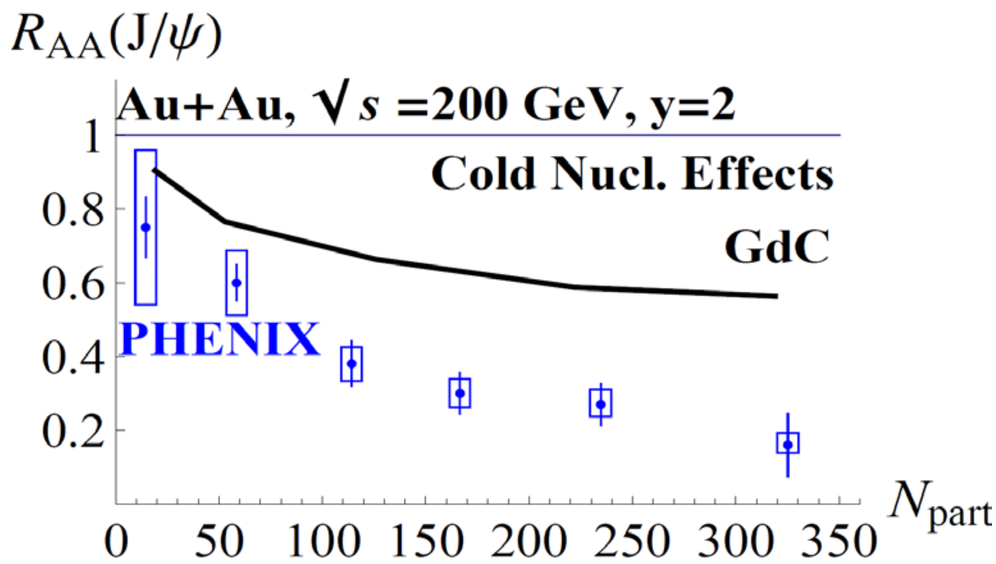
Nothing spectacular at freeze-out

(quarkonia are white objects already)

Integrated J/Ψ numbers @ RHIC

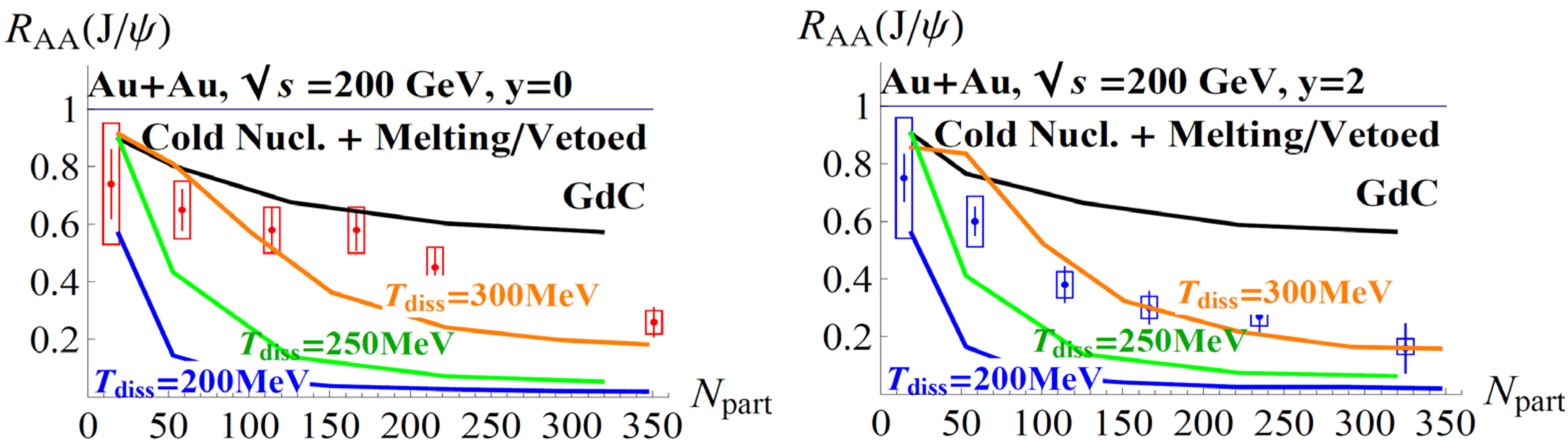
First, we need a baseline taking into account the cold nuclear matter effects (Shadowing, Cronin,..); we take the picture of R. Granier de Cassagnac (2007)





Integrated J/Ψ numbers @ RHIC

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



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

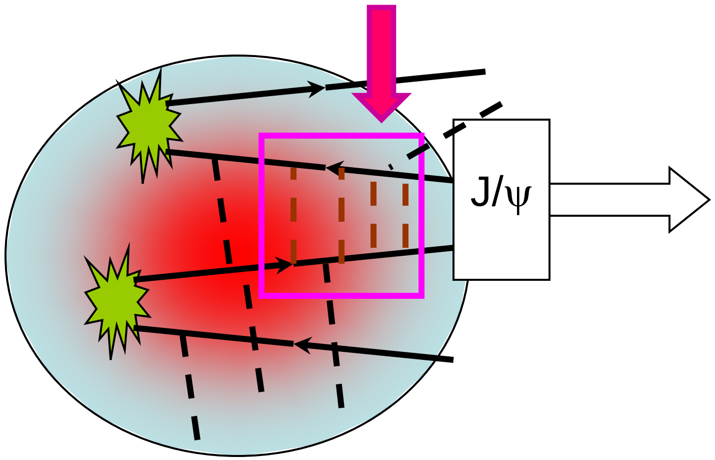
Some claims of “sequencial suppression” with a very bound J/ψ were indeed made by several physicists

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

except that Q and Qbar may be close in phase space

Turning on (re)combination + hard dissociation

(Re)combination (could be major process at LHC):



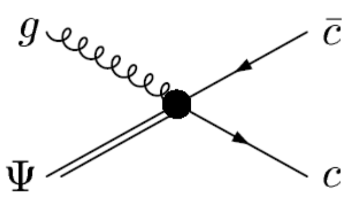
$$\underbrace{Q\bar{Q}}_{\text{Entrance channel}} \rightarrow \underbrace{J/\psi^{\star}}_{\text{Binding}} \rightarrow J/\psi$$

Often treated as a quasi-instantaneous fusion process

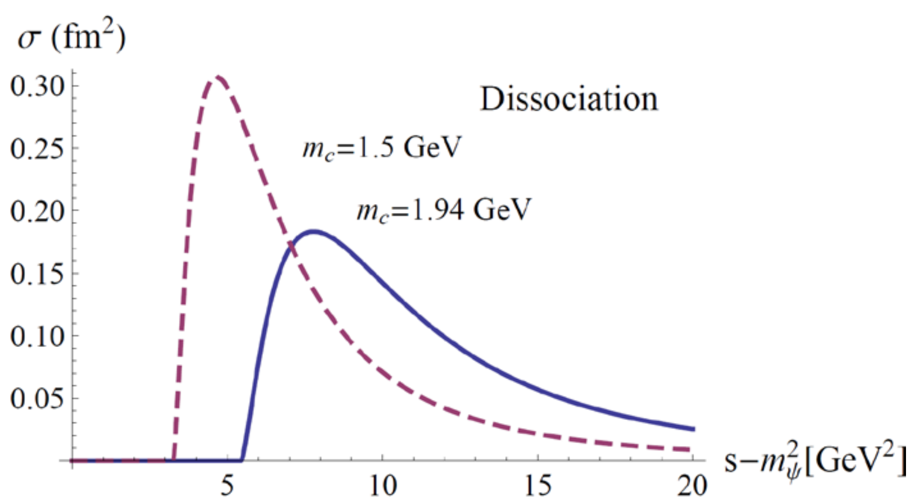
Basic Ingredients

Dissociation

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



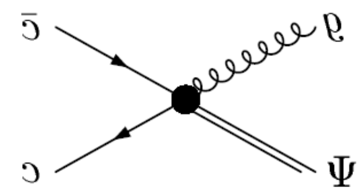
$$\sigma_{(Q\overline{Q})g}(\omega) = \frac{2^{11}}{3^4}\alpha_s \pi a_0^2 \frac{(\omega/\varepsilon(0)-1)^{3/2}}{(\omega/\varepsilon(0))^5}\Theta(\omega - \varepsilon(0))$$

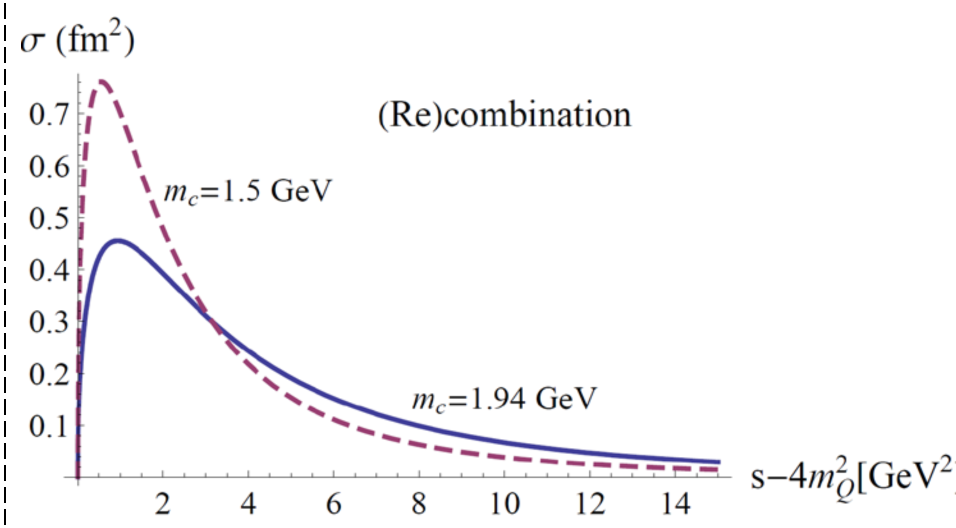


Max ≈ 2 fm² at ω ≈ 500 MeV

Recombination

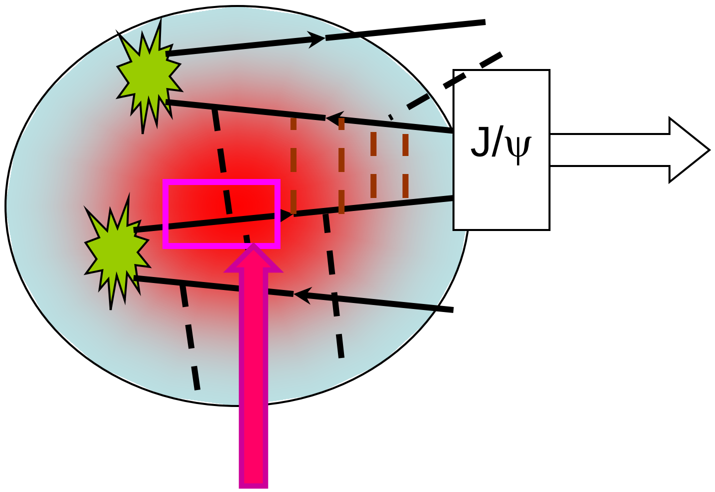
Cross section obtained from σ_{diss} via detailed balance





Turning on (re)combination + hard dissociation

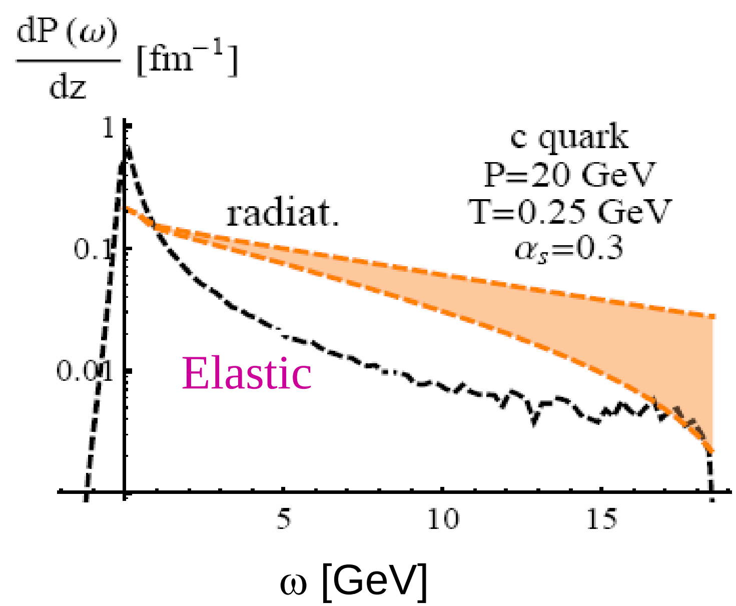
(Re)combination (could be major process at LHC):



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)

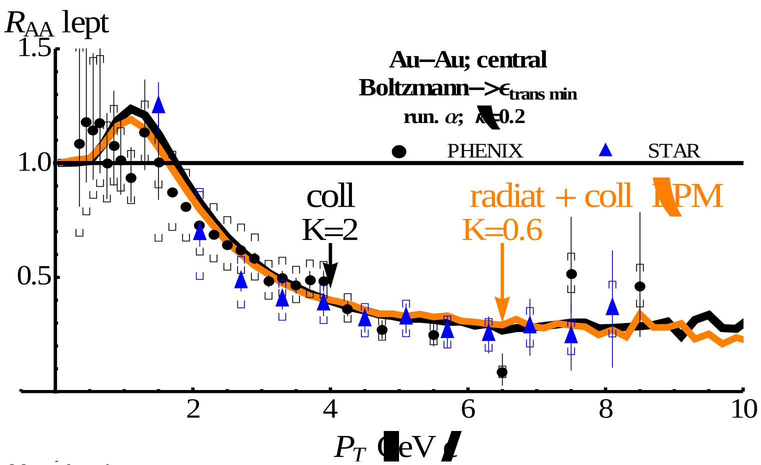
What is the dominant E loss mechanism @ RHIC and LHC ? Does its detailed origin influences the fate of quarkonia's ?

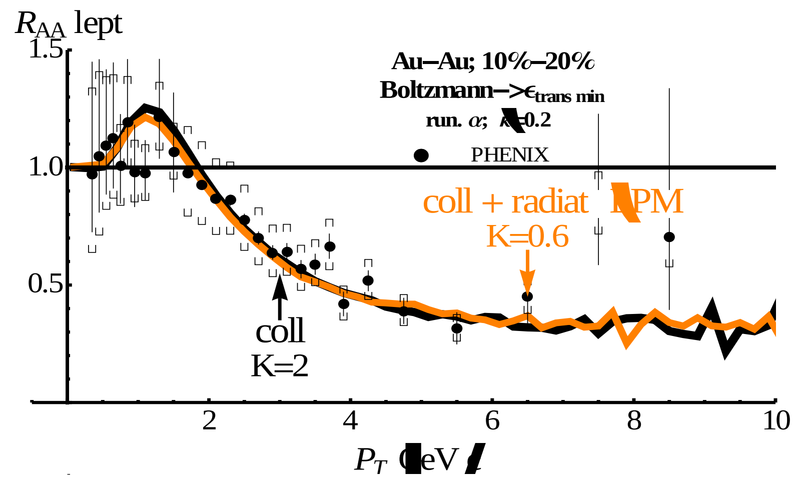


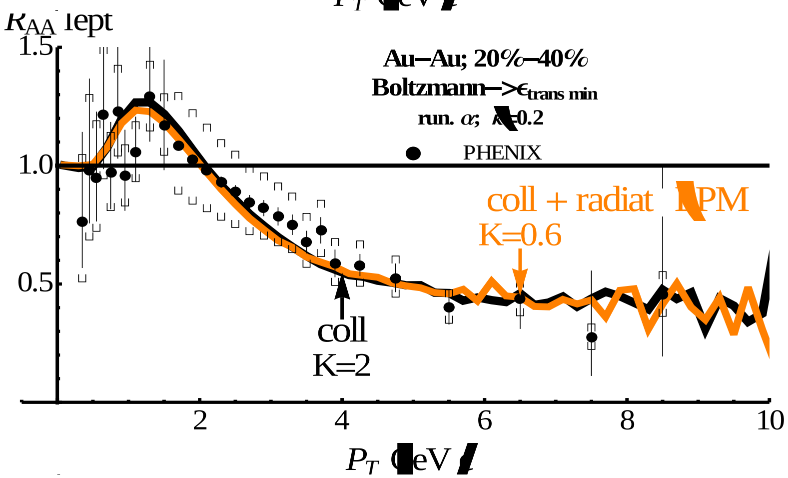
{Radiative + Elastic} vs Elastic for leptons @ RHIC

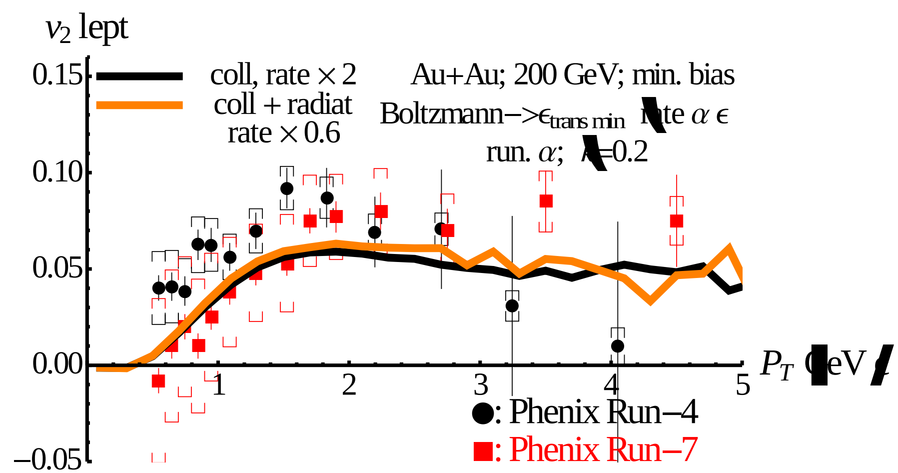
El. and rad. Eloss exhibit very different energy and mass dependences. However…

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





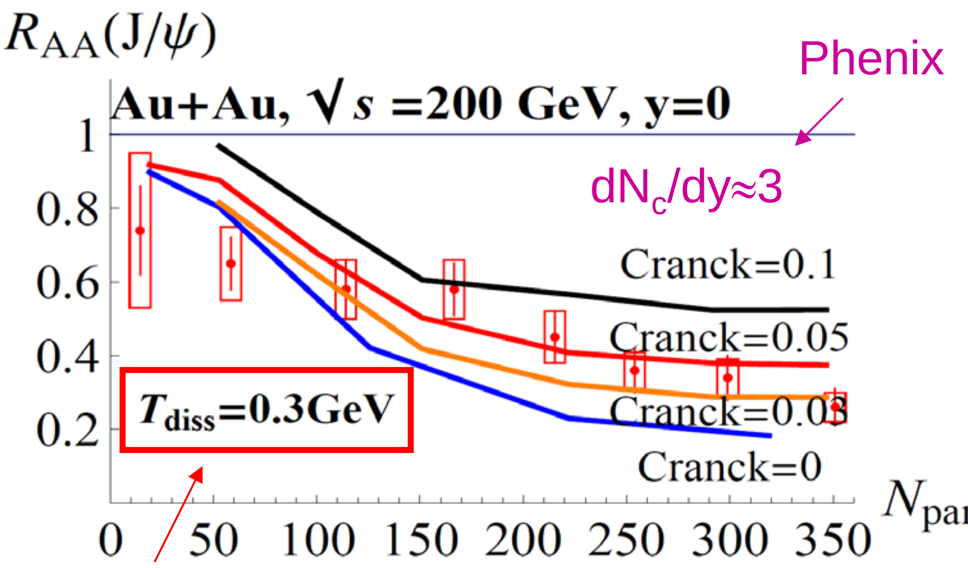




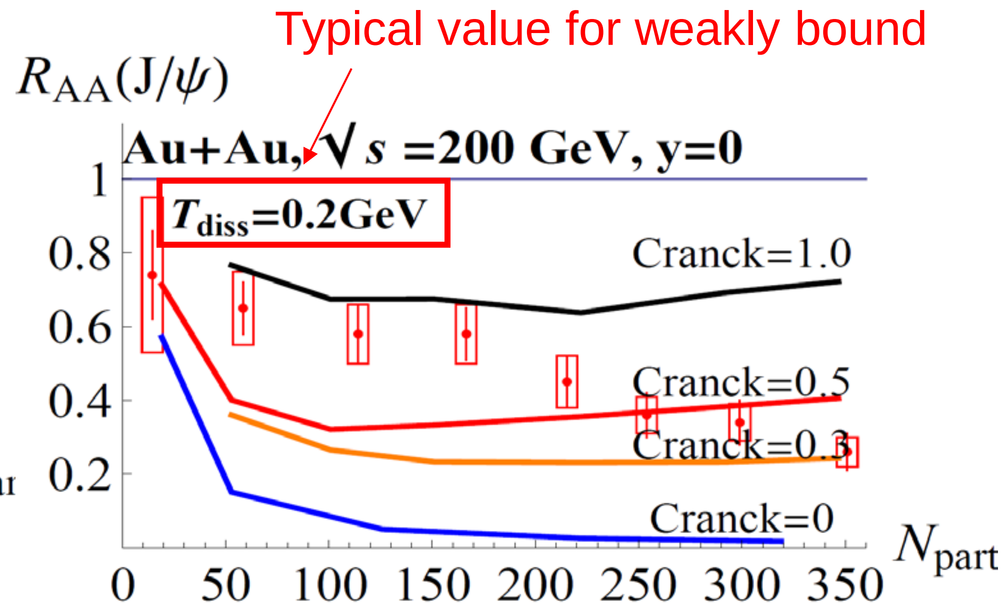
One "explains" it all with ΔE α L (for HQ)

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

Turning on (re)combination + hard dissociation



Typical value for strongly bound



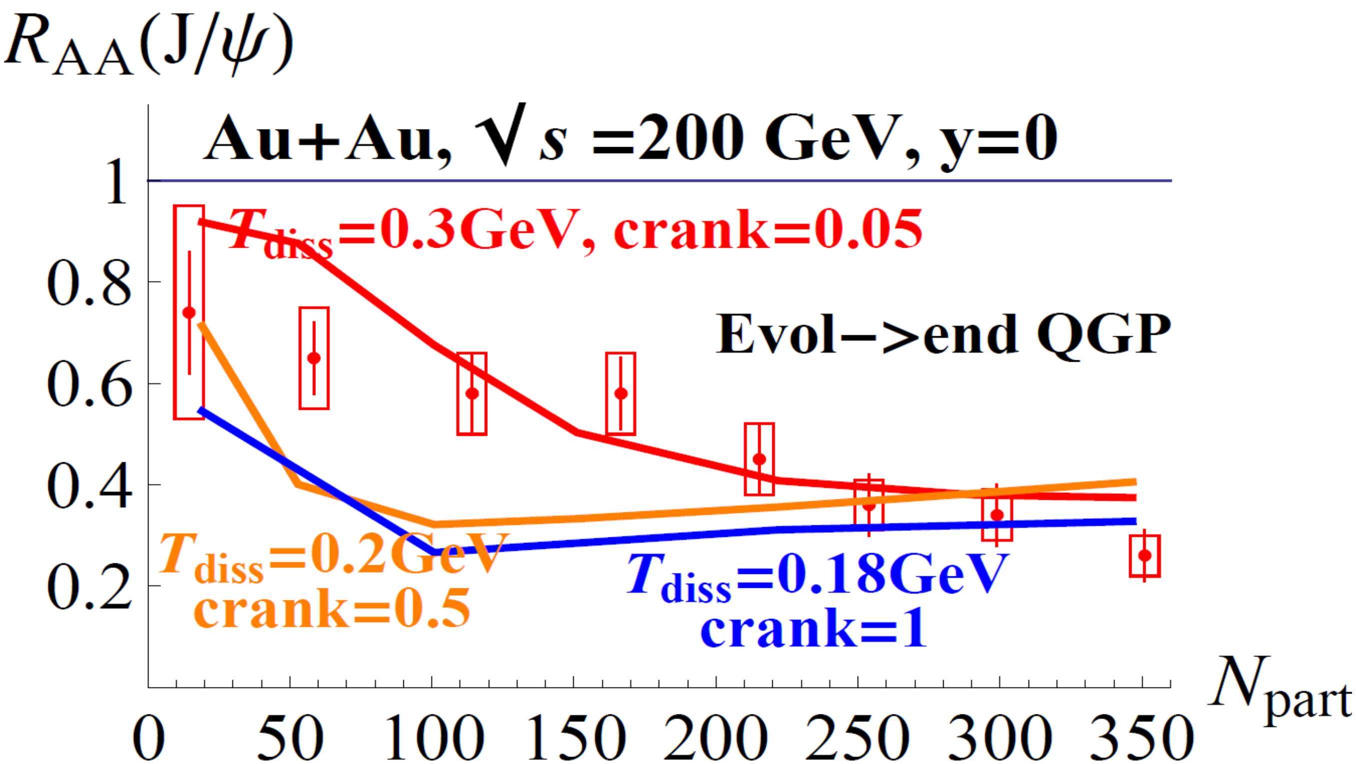
Problem: One has to reduce the fusion probability by a factor ~10 to reproduce the data (if recomb. cross section taken at face value, one arrives at R_{AA} (most central > 2 !).

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}

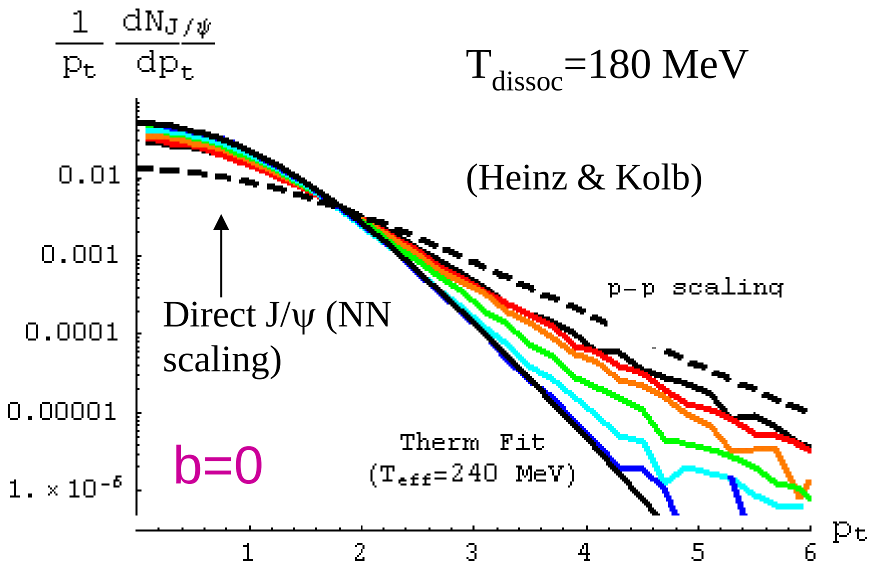
"Optimal" choices in the (T_{diss}, $\sigma_{fus.}$) parameter plane



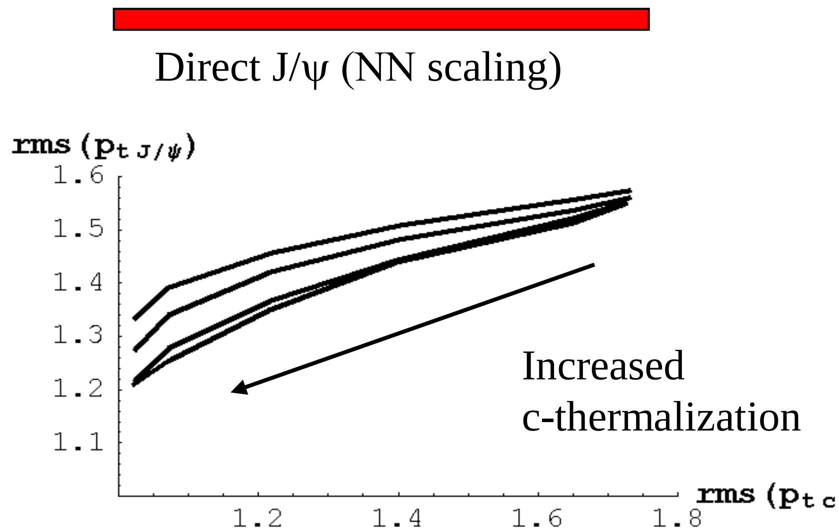
$T_{diss} \in$ [0.2 GeV,0.3 GeV]… but difficult to go beyond

The p_t world

Differential production might reveal more physics



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

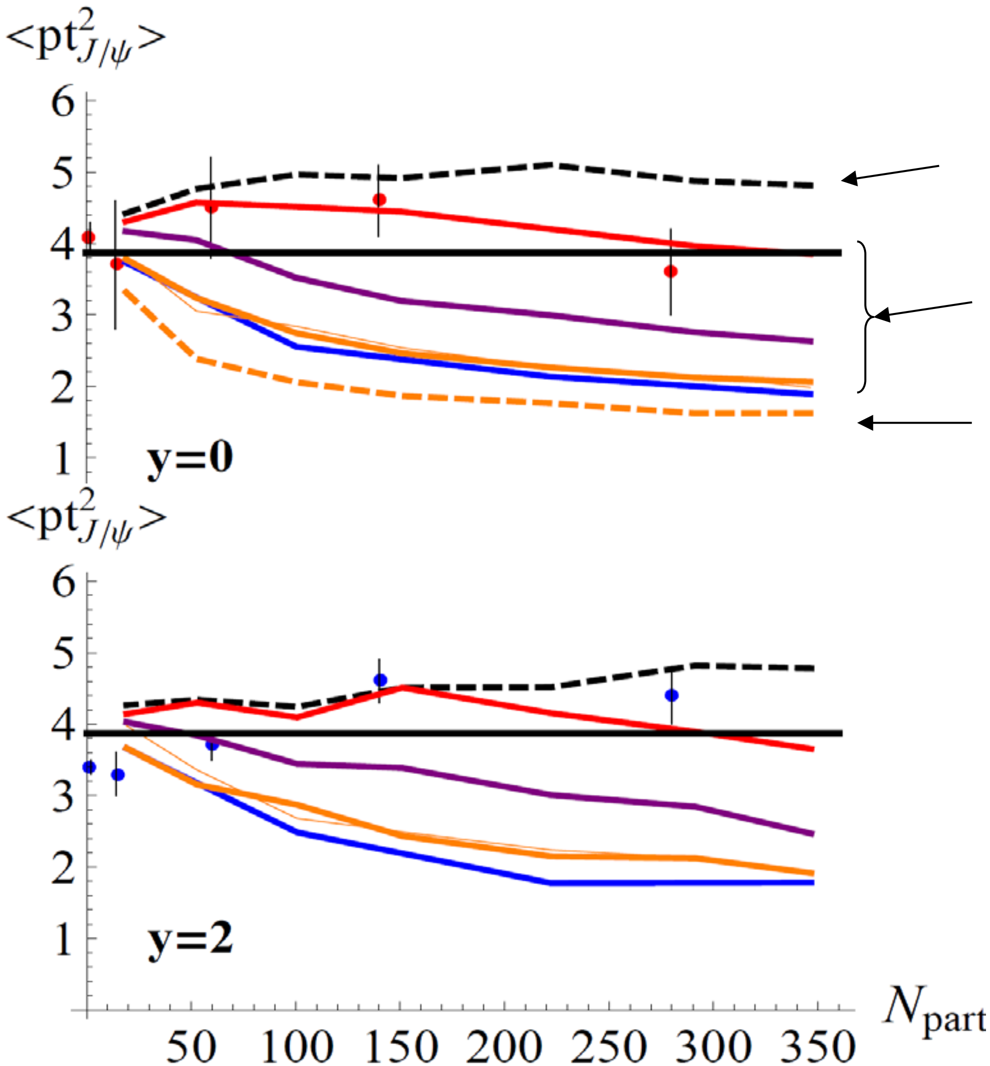


Prediction for b=0 and just recombination

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 (recently observed by PHENIX)

The p_t world

… and now compared with the data:



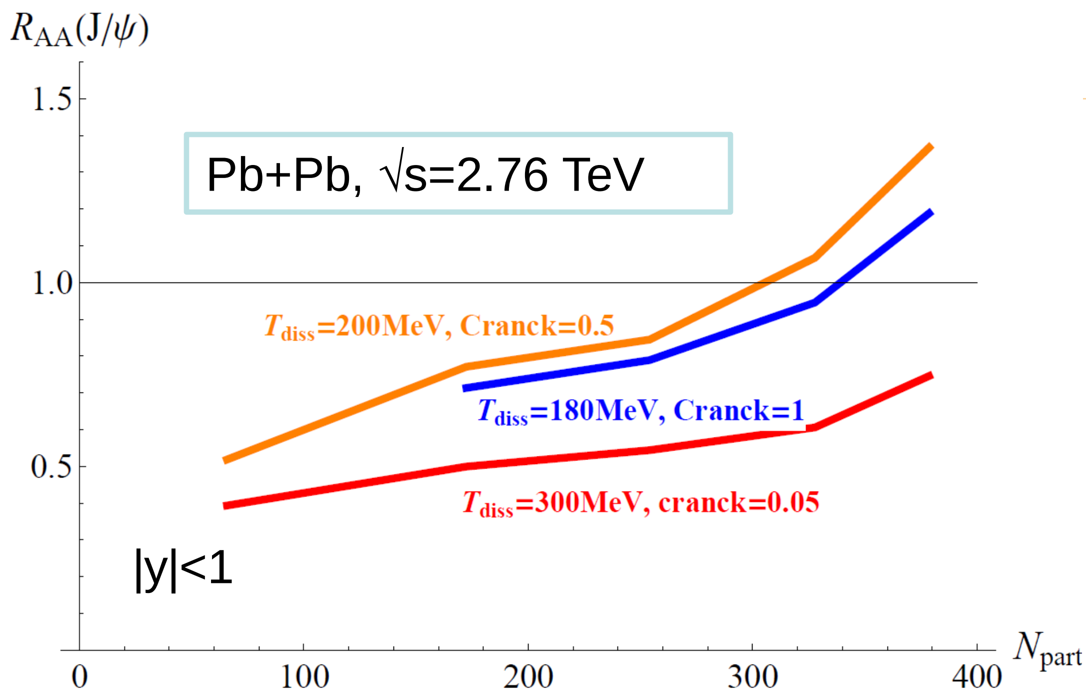
Cronin effect at initial stage (and no further effect)

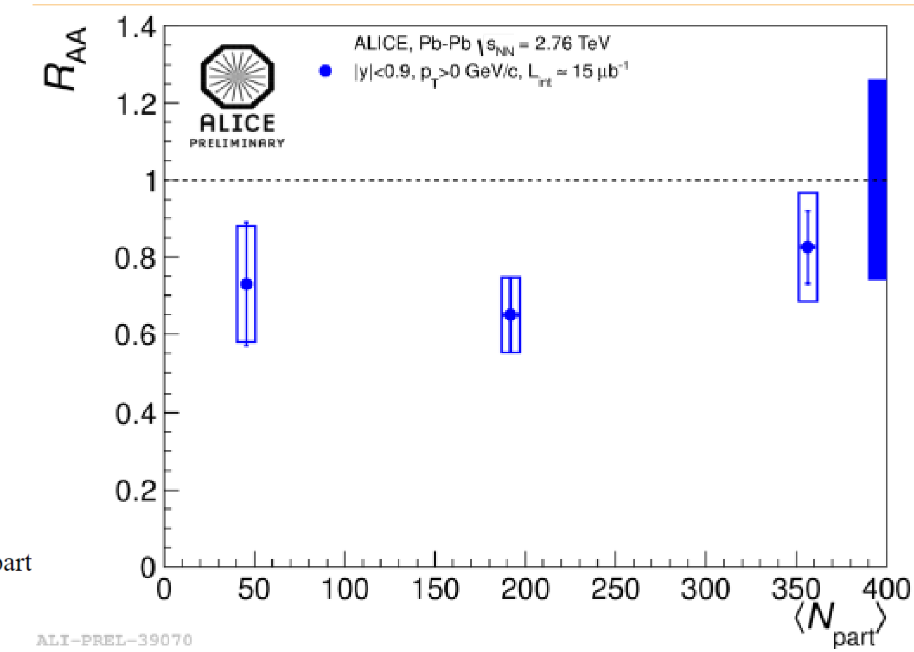
Results for T_{diss}= 0.3, 0.25, 0.2 and 0.18 (with initial Cronin effect).

T_{diss}= 0.2 and NO Cronin effect.

T_{diss}= 0.3 GeV should be favored

Prediction for LHC





Hydro Parameters:

s_0= 268 fm^{-3}

≡

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

HQ Parameters:

$dN_c/dy \approx 30$ in PbPb

$d\sigma_\psi/dy = 2\mu b$ in pp

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, but difficulties to tame the recombination down

1. 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… supported by finite J/ψ v2 seen by ALICE

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

Not clear to us… questions the OPE approach

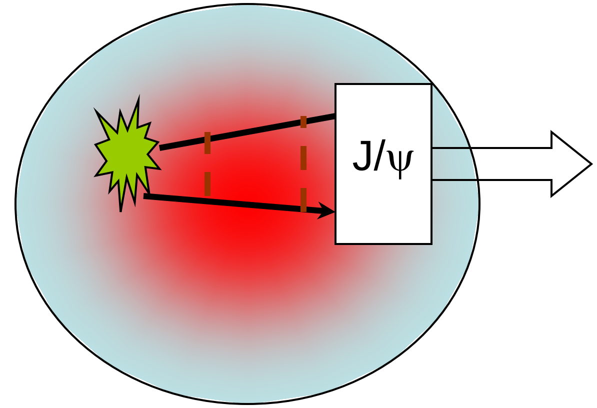
Need for a better description of Qqbar states in QGP

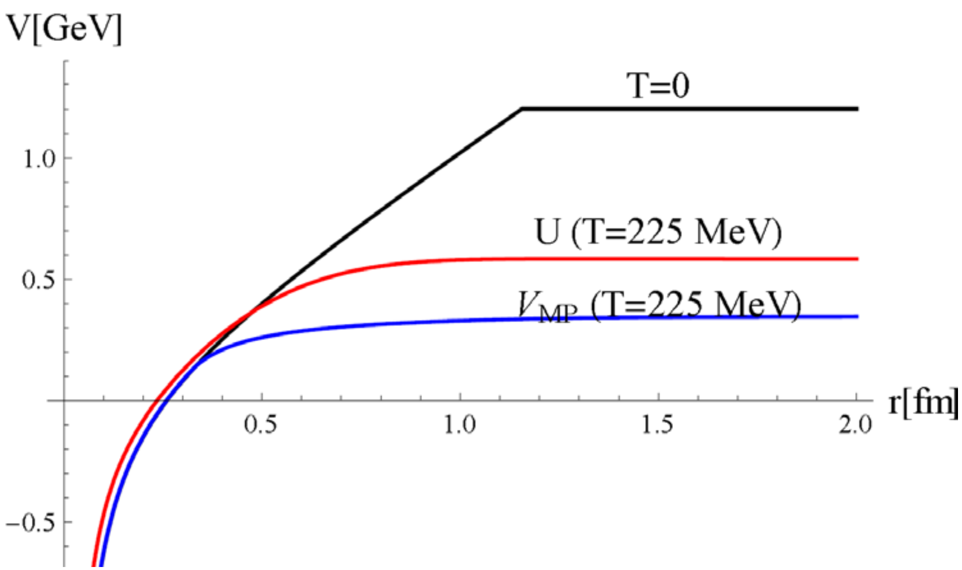
J/Ψ suppression (dynamical)

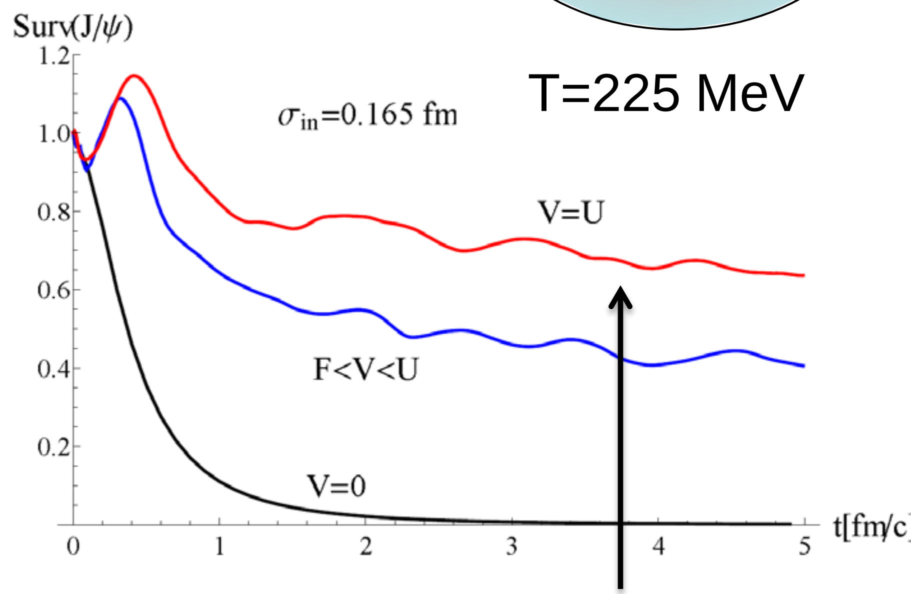
BUT: 2 missing ingredients

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 ∈ [0,1]

J/Ψ suppression (dynamical)

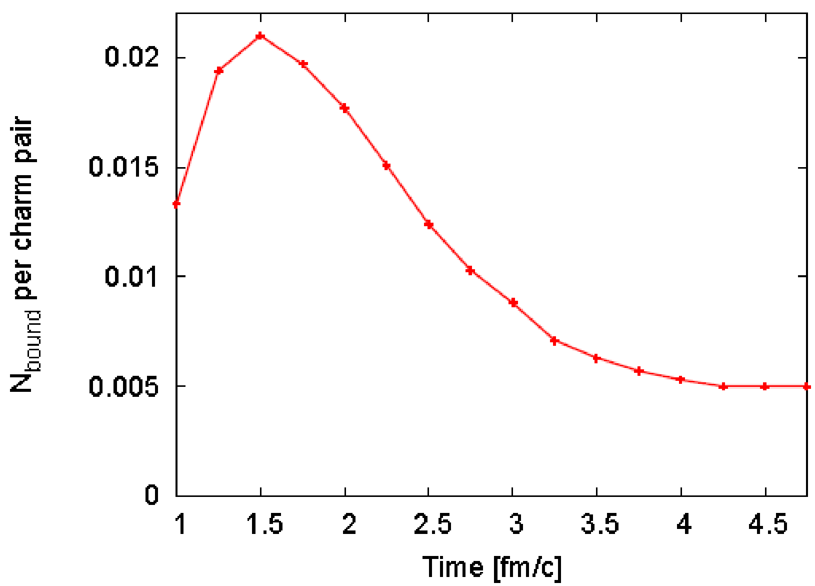
BUT: 2 missing ingredients

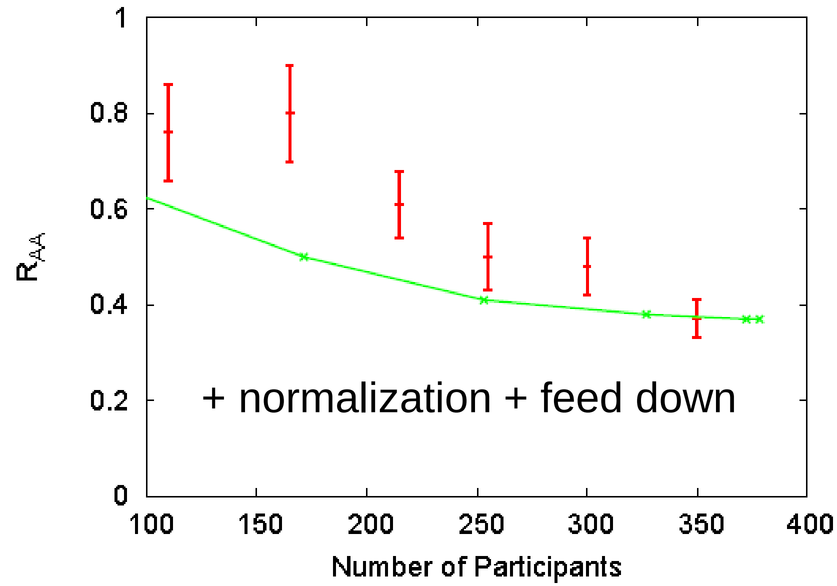
2. Stochastic q-Q, g-Q forces

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 !!!

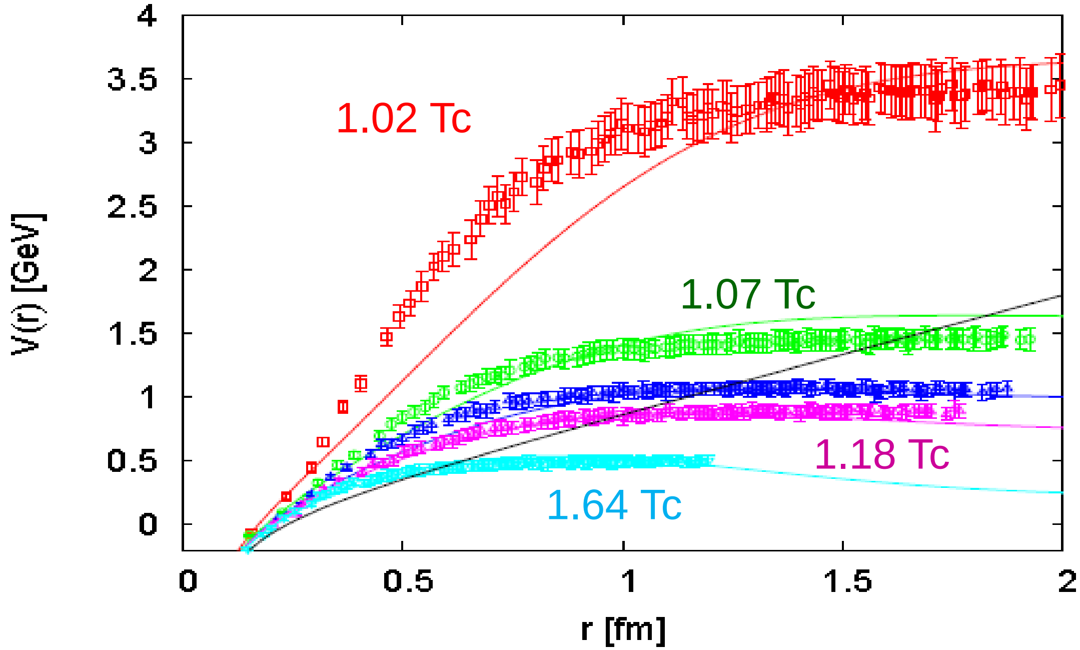




Suppression of suppression… Robust or not ?

Shuryak & Young (08): some ingredients

✓ U as a potential



The most “binding” choice; Around T_c: 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 (density operator):

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

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:

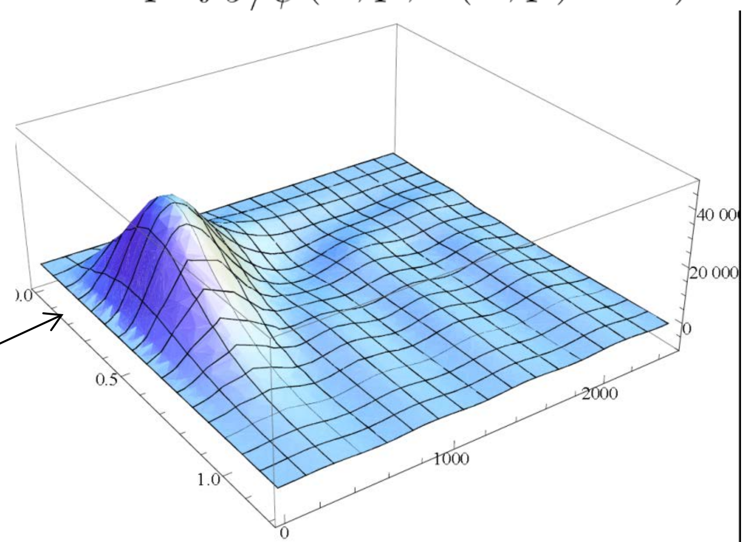
$$\left(\frac{\partial}{\partial t} + \frac{\vec{p}}{\mu}\cdot\frac{\partial}{\partial \vec{x}} - \frac{\partial V}{\partial \vec{x}}\cdot\frac{\partial}{\partial \vec{p}}\right) f(\vec{x},\vec{p};t) = I_{\rm col}$$

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

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

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

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



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

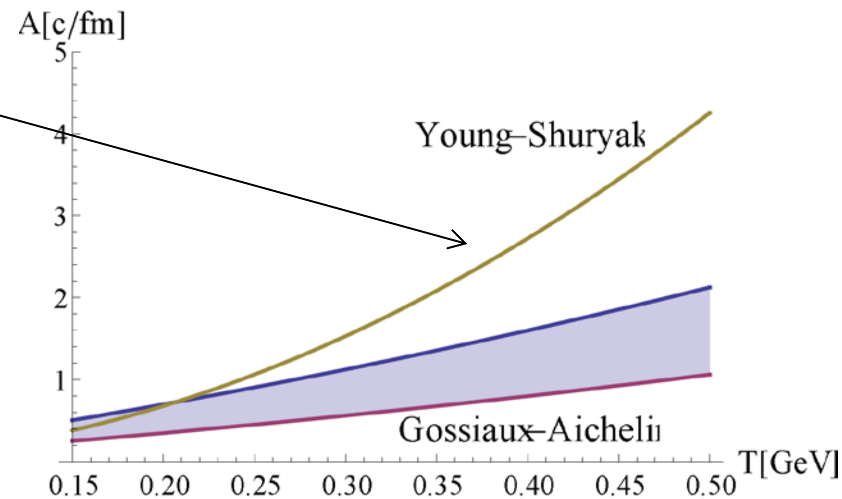
✓ Stochastic force on Q and Qbar are uncorrelated

… although QQbar is seen as a dipole at short distances

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

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

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



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)

  b) the drag coefficient A(T)

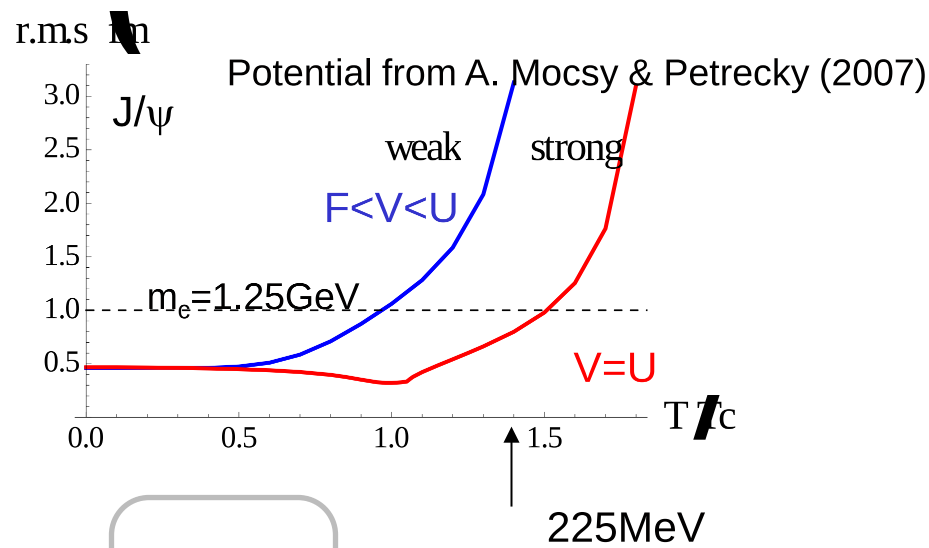
  c) the semi-classical treatment of the c-cbar evolution (tougher, not today)

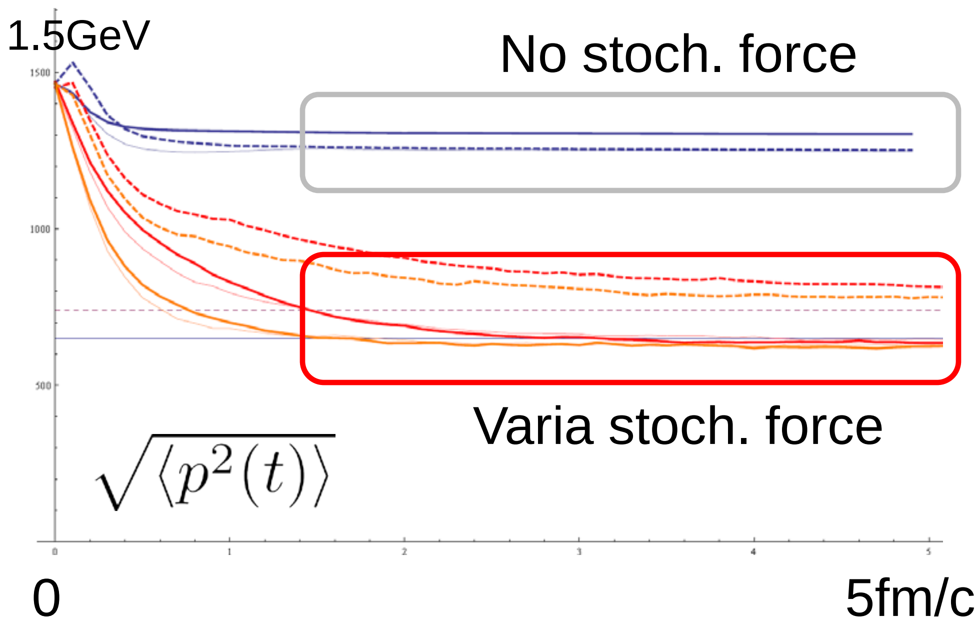
Test of robustness for stationnary QGP

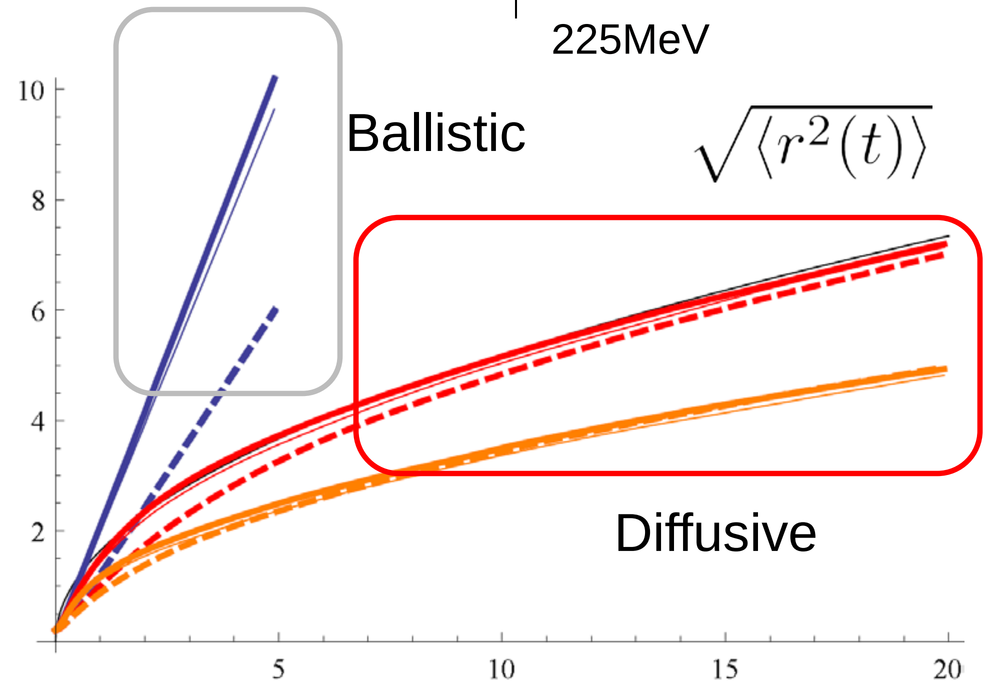
T=225 MeV (T/Tc ≈ 1.4):

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

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





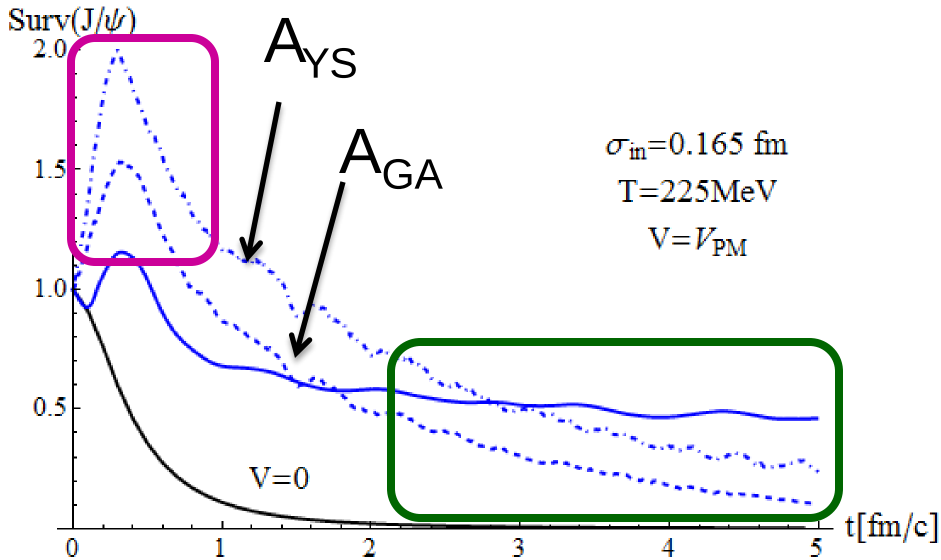


Stochastic cooling of c-cbar state

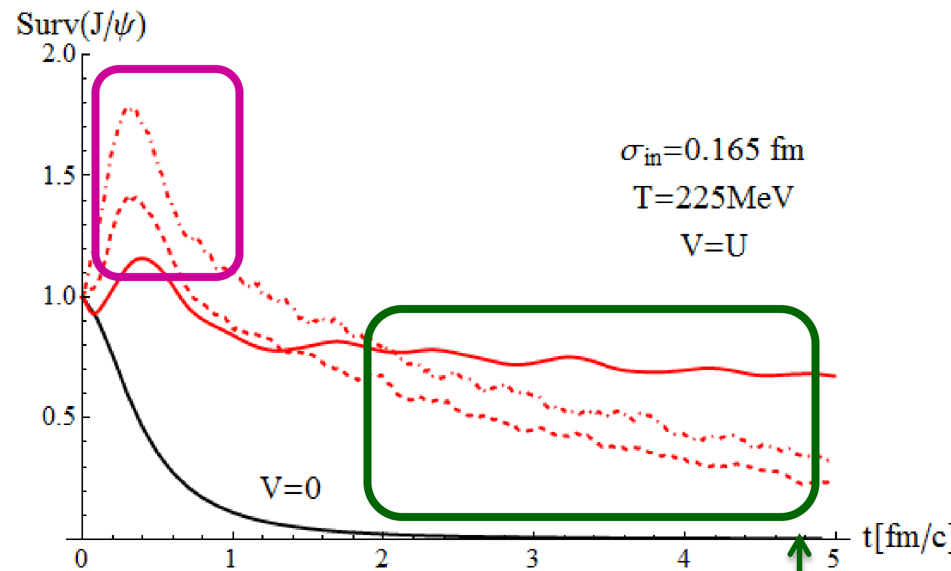
Test of robustness for stationnary QGP

T=225 MeV (T/Tc ≈ 1.4):

V=V_{PM} (weakly bound)



V=U (strongly bound)

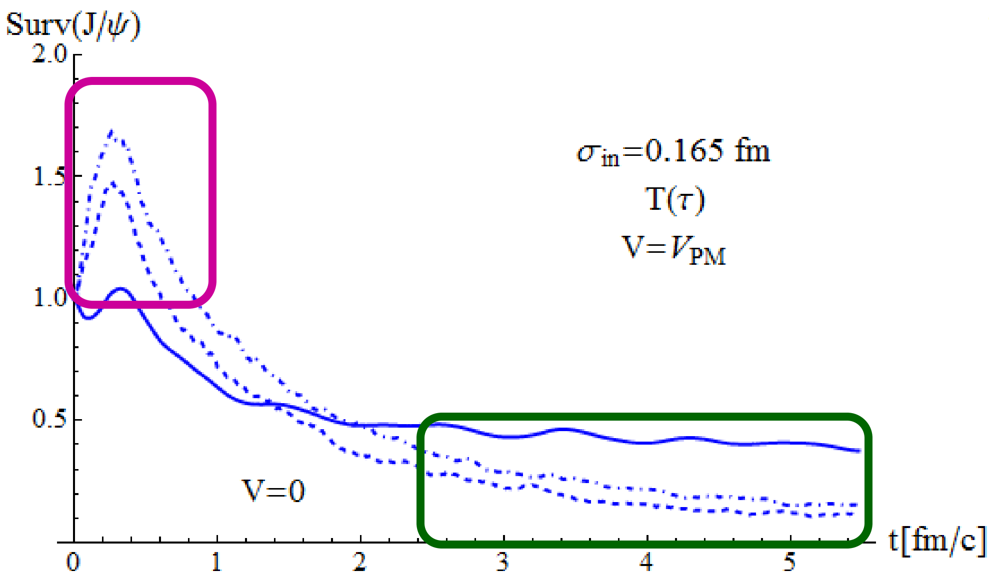


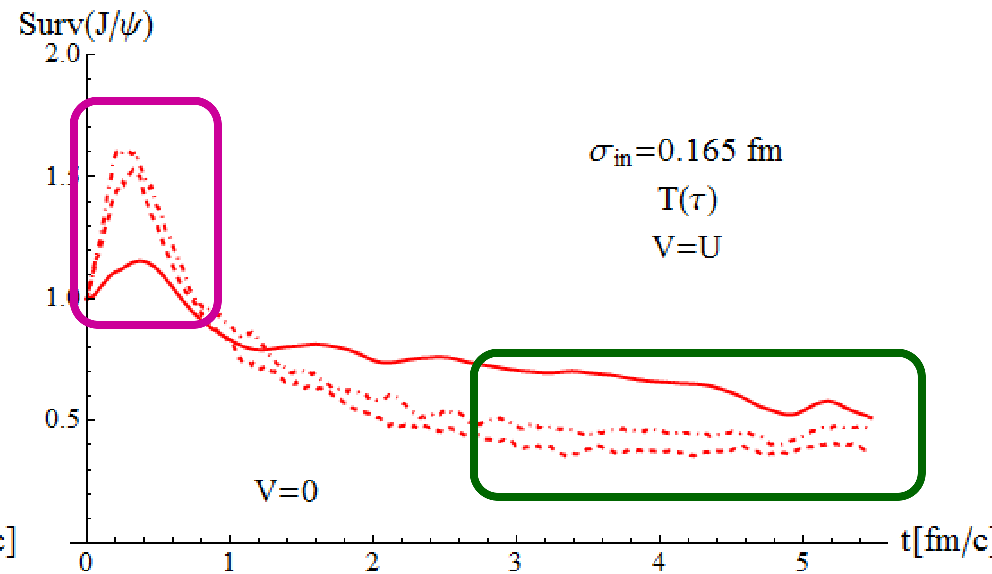
- Around initial time, cooling down by stochastic forces increase the J/ψ content of the quantum QQbar state
- At later times, the stochastic sources act as a source of dissociation of the remaining state

Test of robustness for evolving QGP

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

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



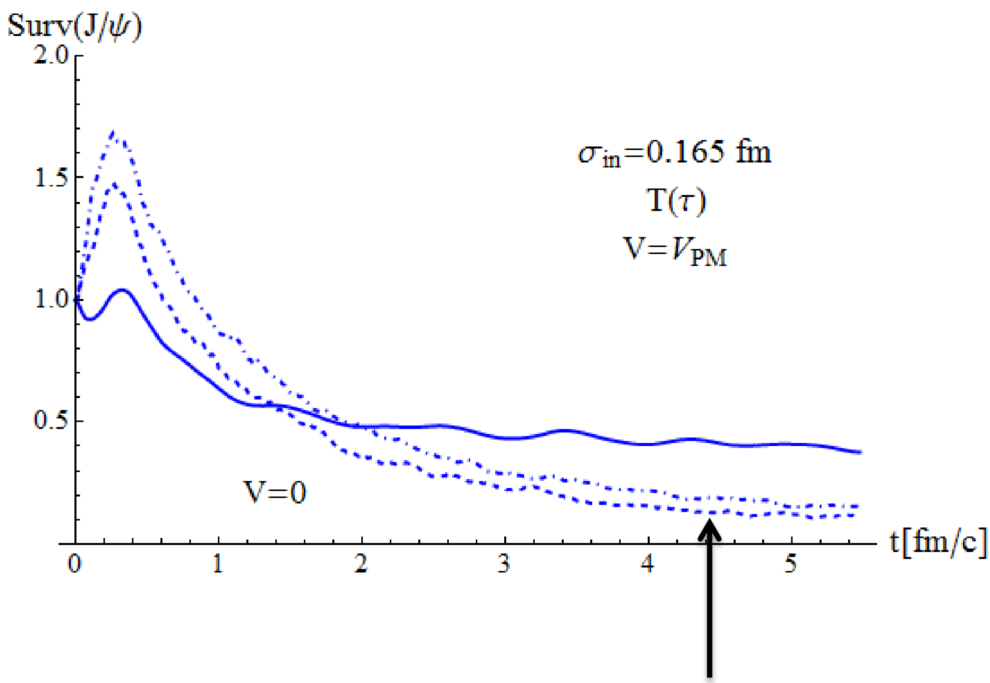


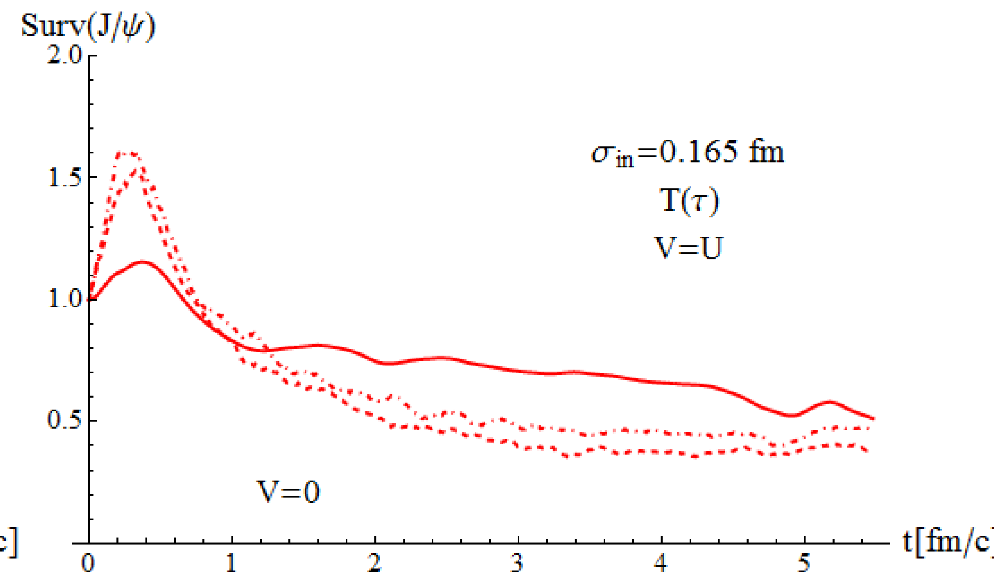
- Similar features as for T=225: rapid thermalization in p-space (-> quasi equilibrium), followed by induced leakage in r space
- For potential chosen as V=U, survival compatible to 0.5, as claimed by Young and Shuryak

Test of robustness for evolving QGP

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

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



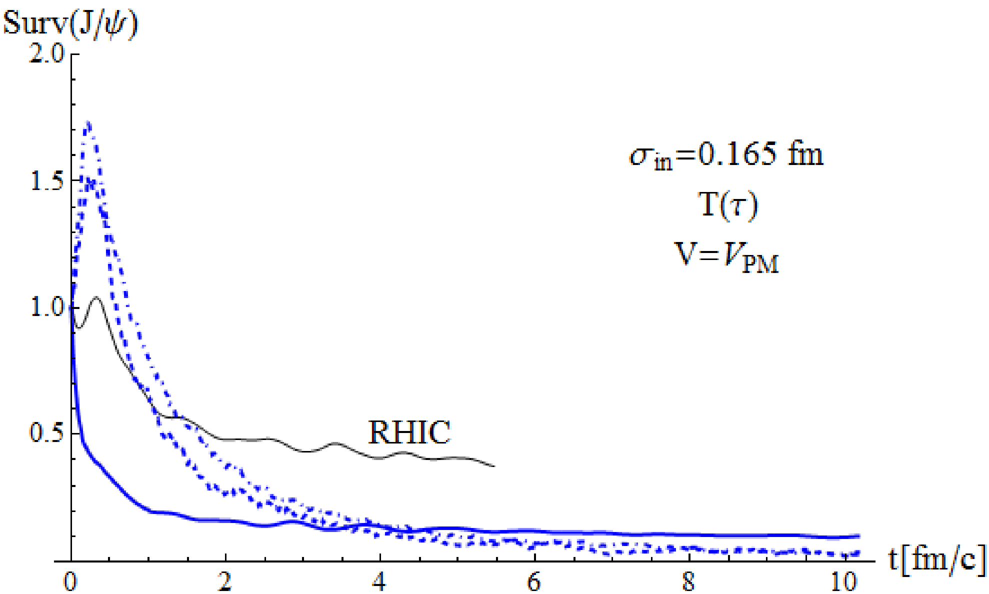


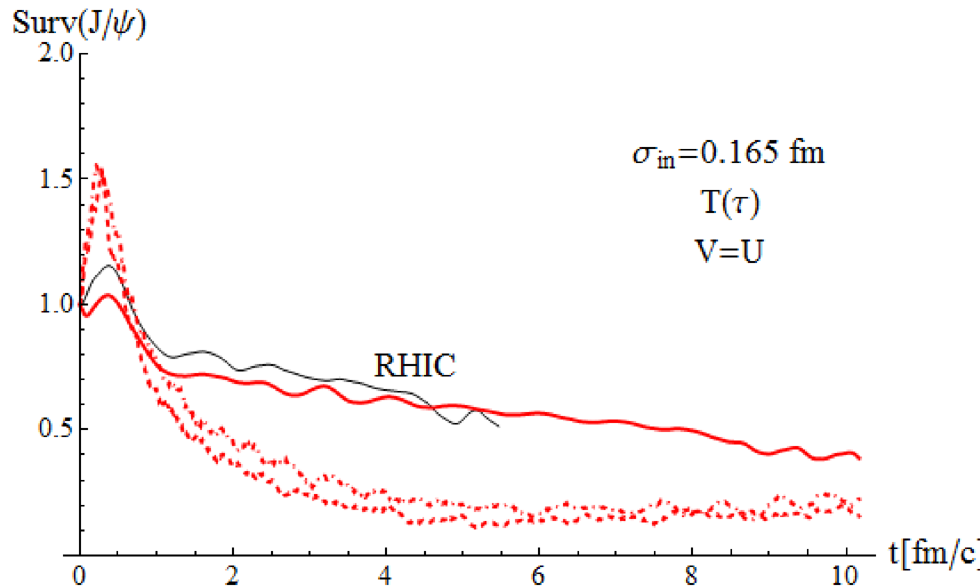
- No large dependence vs precise choice for drag coefficient…
- But large dependence vs choice of potential, especially if one includes the stochastic forces (can dissociate weakly bound states, but rather inefficient to dissociate strongly bound states).

Survival @ LHC

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

Preliminary





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

should not be neglected

Conclusion & Prospects

1. Important to include a time-dependent microscopic description of Q-Qbar states in the transport codes… to be pursued

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

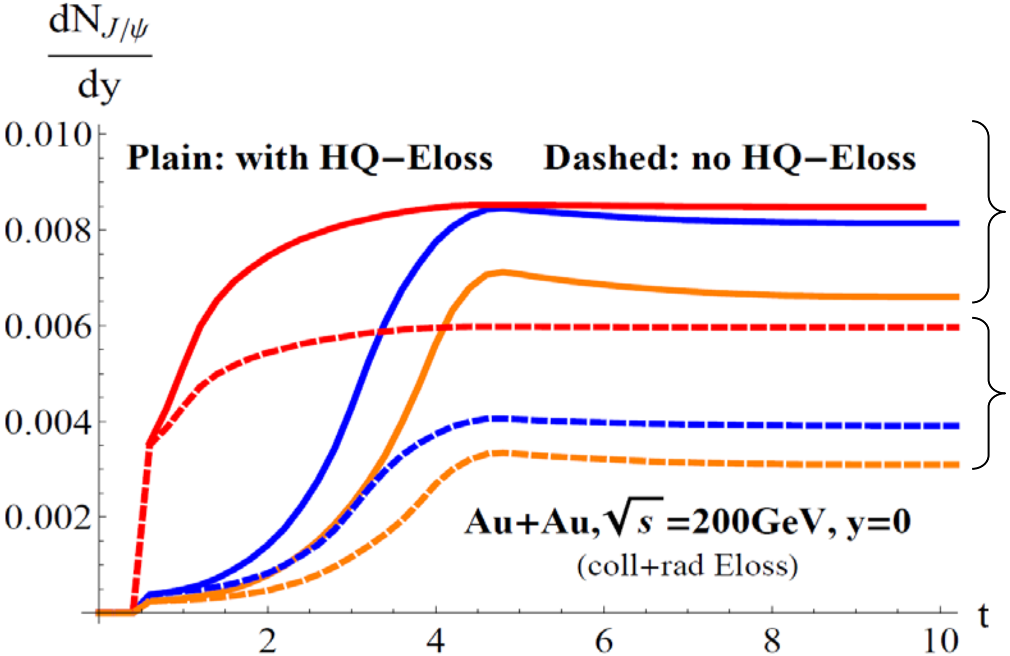
3. However, their choice of parameters probably correspond to the most favorable case !

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

4. I am very excited(QCD) about all of this

Back Up

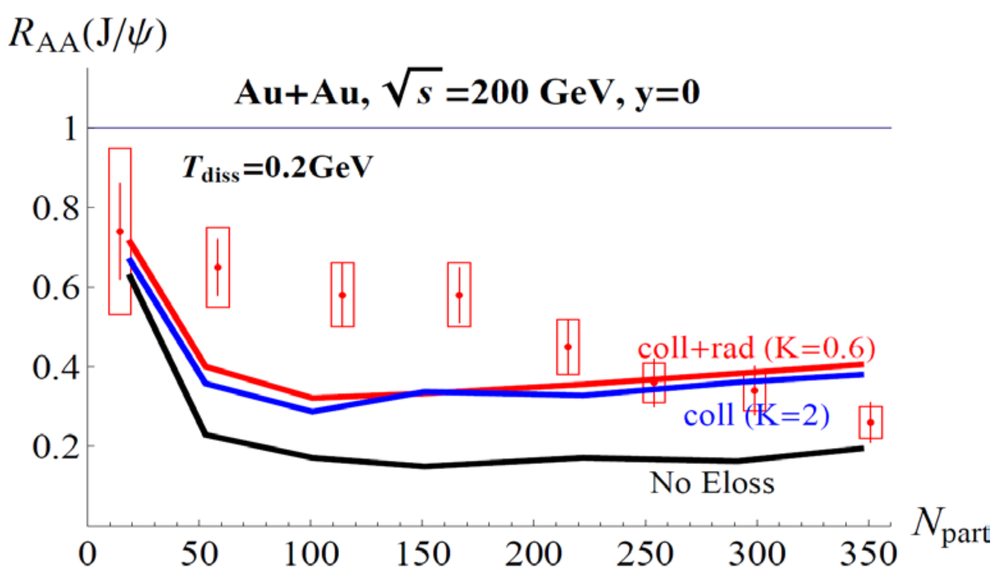
Finer analysis: role of HQ energy loss



Eloss

No Eloss

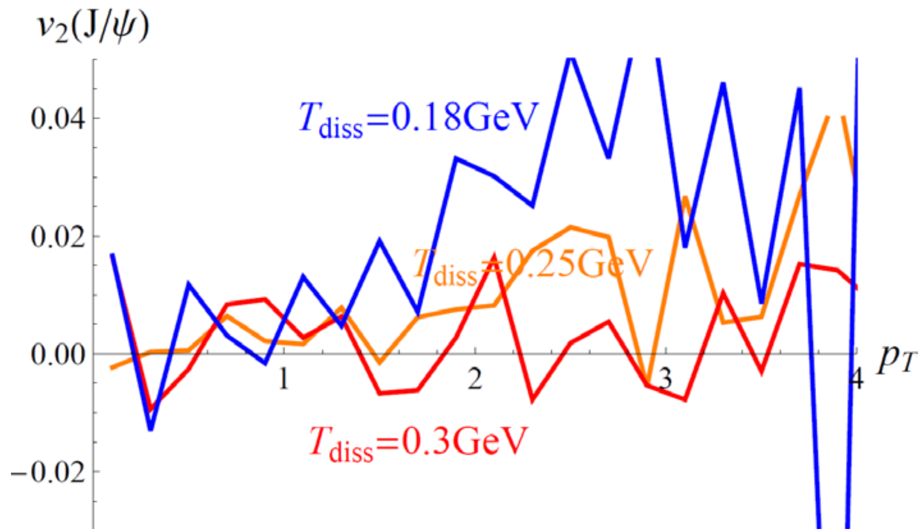
Energy loss favors the coalescence of J/ψ (brings the c quarks together in phase space)



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

The keystone (?): v_2

RHIC

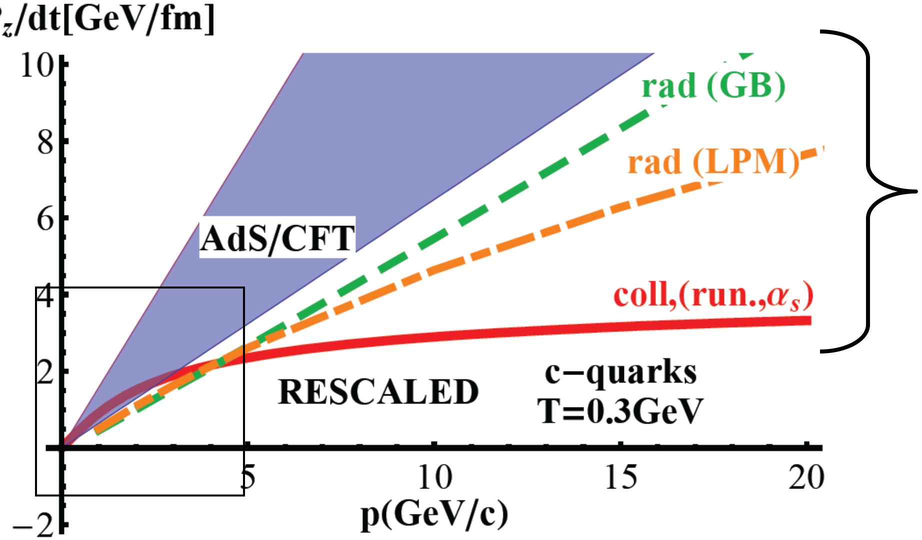


Beware of the possible role of elastic cross section of J/ψ in the experimental v2

QGP properties from HQ probe

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

Similar diffusion coefficient at low p



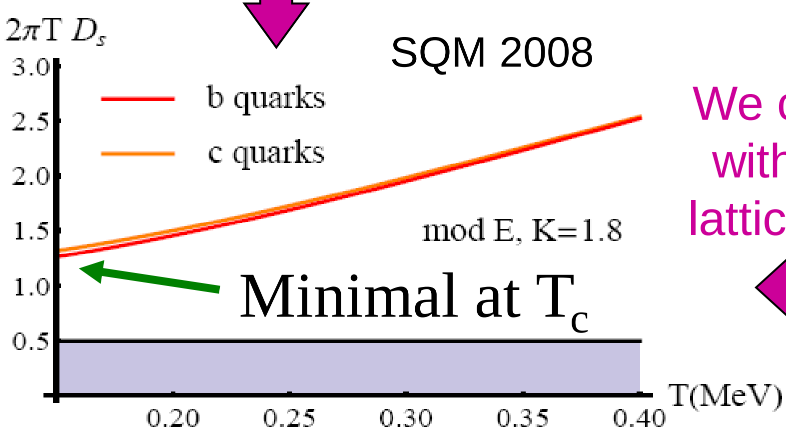
Present RHIC experiments cannot resolve between those various trends

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

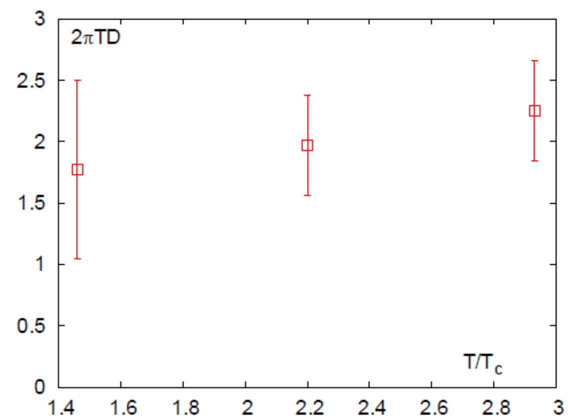
We extract it from data

Hope that LHC will do !!!

SQM 2008



We compare with recent lattice results



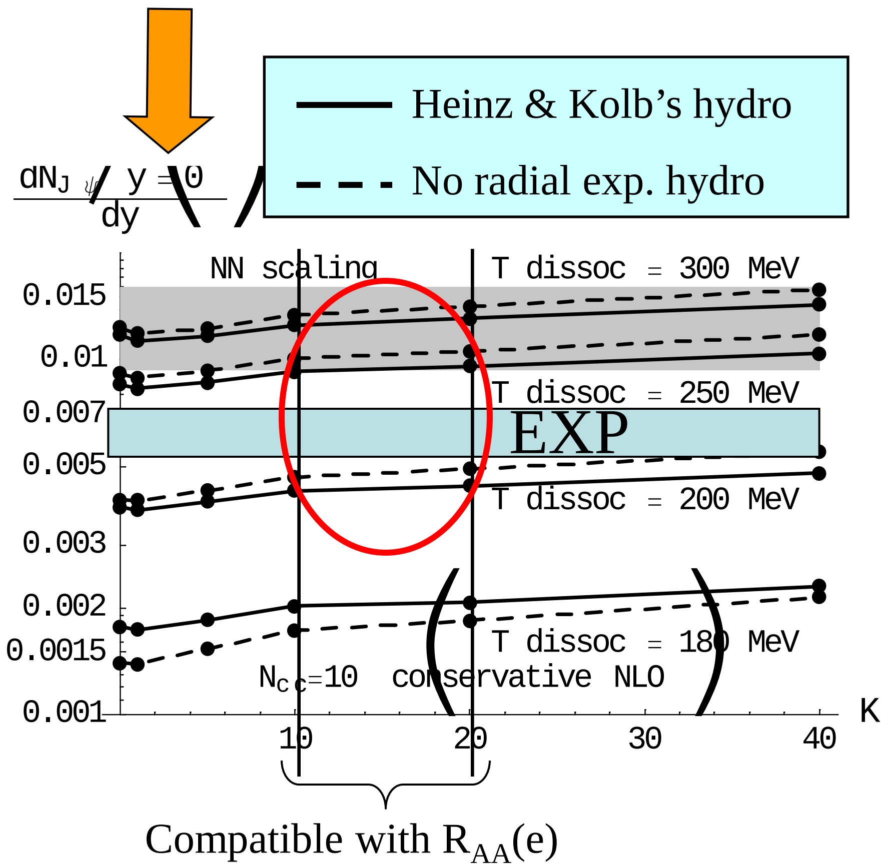
Kaczmarek Bad Honnef 2011

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

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 :

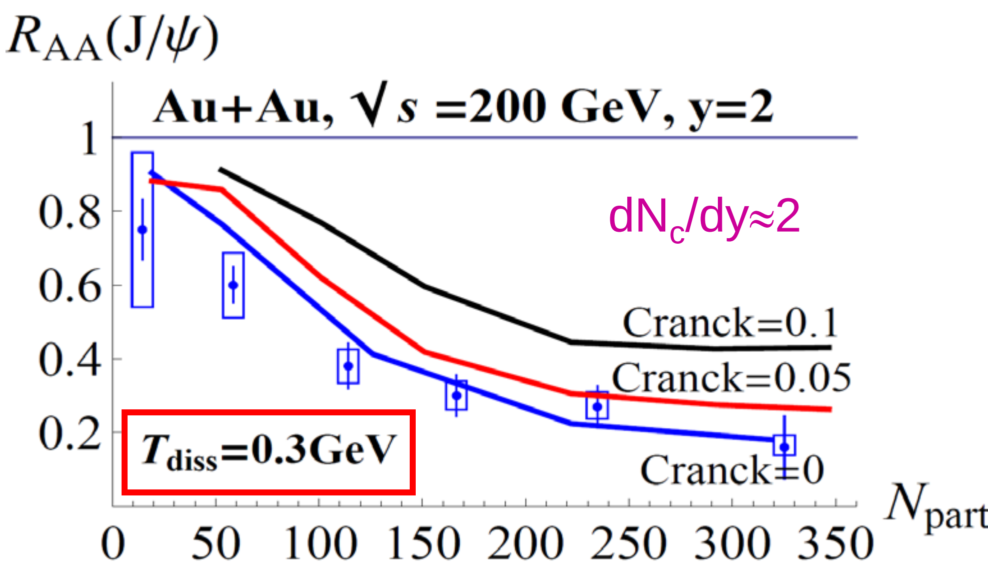
Au+Au, b=0

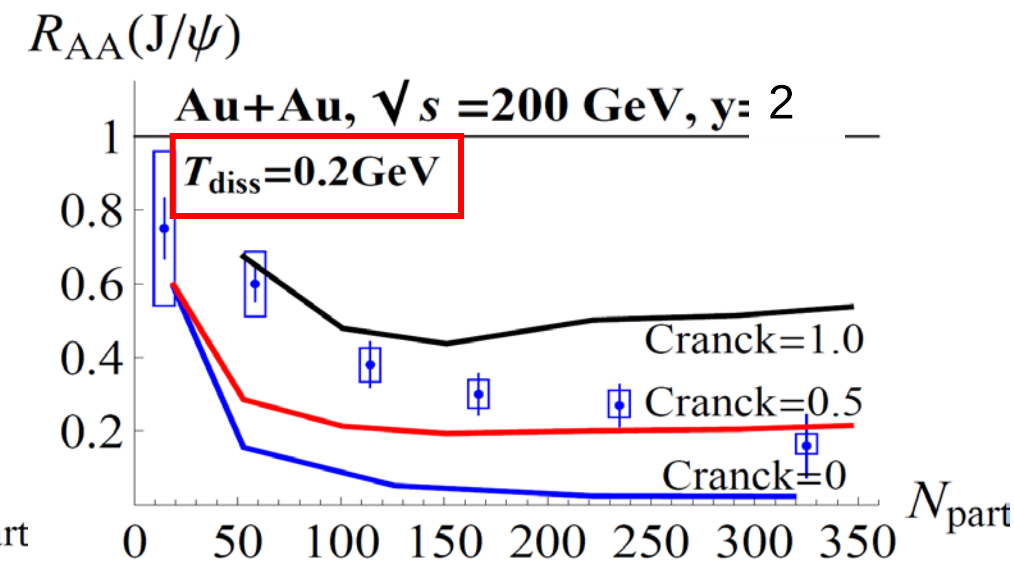


From SQM 2004, with additional Au+Au data.

Multiple of pQCD stopping force (αs=0.3)

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