Heavy quark bound states in a quark-gluon plasma

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The quark-gluon plasma is a unique many-body system:

- color particles
- special interactions
- long range forces
- confinement/deconfinement

Hard probes (jets, quarkonia,etc)

- they are special
- they share common features
- they play the role of 'test' particles
- they can help understand transport properties of the QGP

Outline

A very nice idea

A considerable experimental effort

A difficult many-body problem !

...but some recent progress

A very nice idea

The quarkonium is a « non relativistic » system

$$H = 2m_c + \frac{p_1^2}{2m_c} + \frac{p_2^2}{2m_c} + V(r)$$

$$V(r) = -\frac{\alpha}{r} + \sigma r$$

Heavy quarks are "heavy"

$m_c \simeq 1.5\text{GeV}$ $m_b \simeq 5\text{GeV}$ $m_Q \gg \Lambda_{QCD}$

Hierarchy of scales

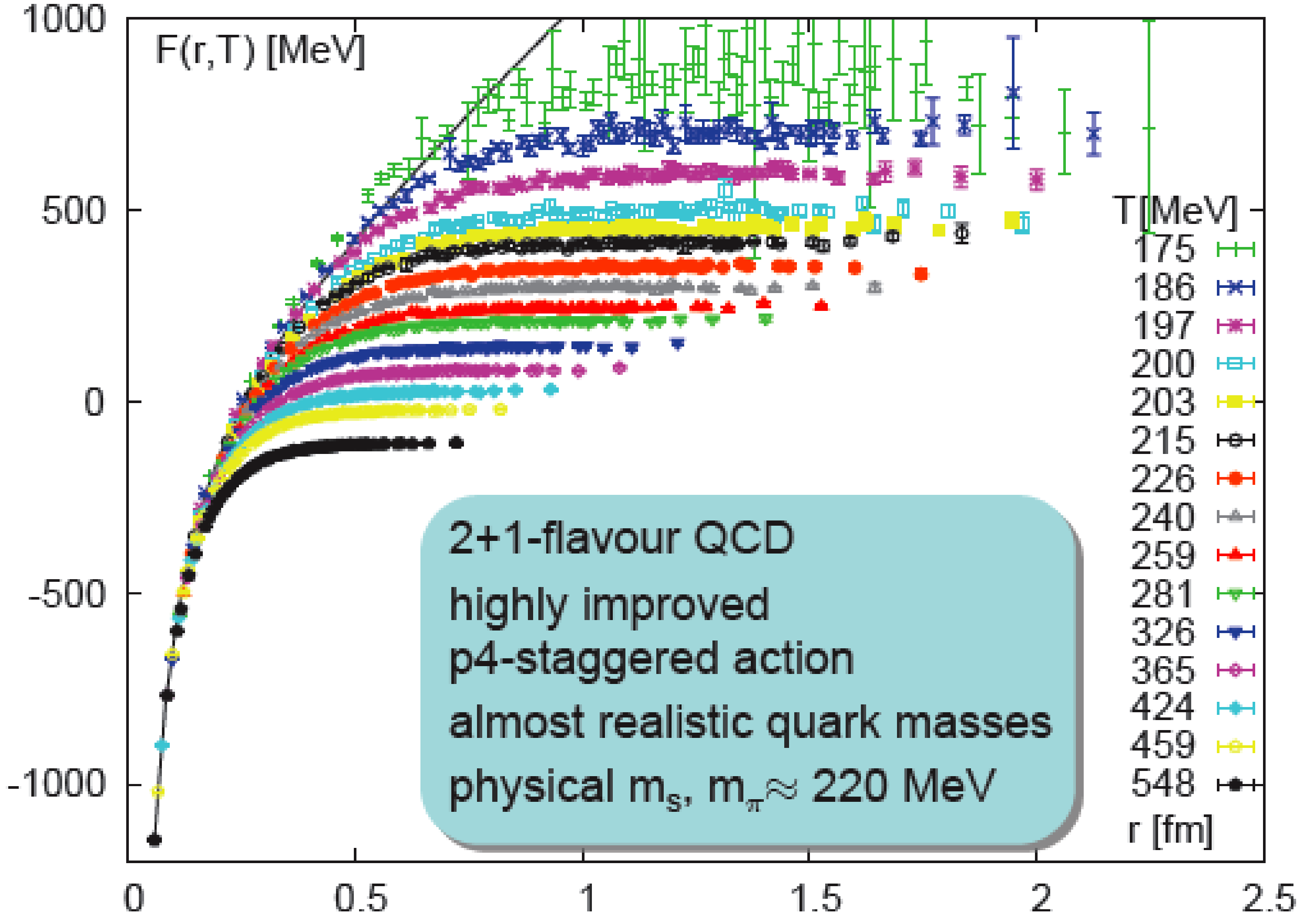
$$m \ll mv \ll mv^2 \qquad v \ll 1$$

$v_c^2 \sim 0.3$ $v_b^2 \sim 0.1$ $mv \sim 1/r$

Well suited for application of effective field theory

[Brambilla, Ghiglieri, Petreczky, Vairo, Escobedo, Soto]

Heavy quarks free energy from lattice calculations



(O. Kaczmarek et al., PLB543(2002)41,
S. Gupta et al., Phys.Rev.D77(2008)034503)

Screening of binding forces in a quark-gluon plasma

Screened potential

$$V(r) = -\frac{\alpha}{r} e^{-r/r_D(T)}$$

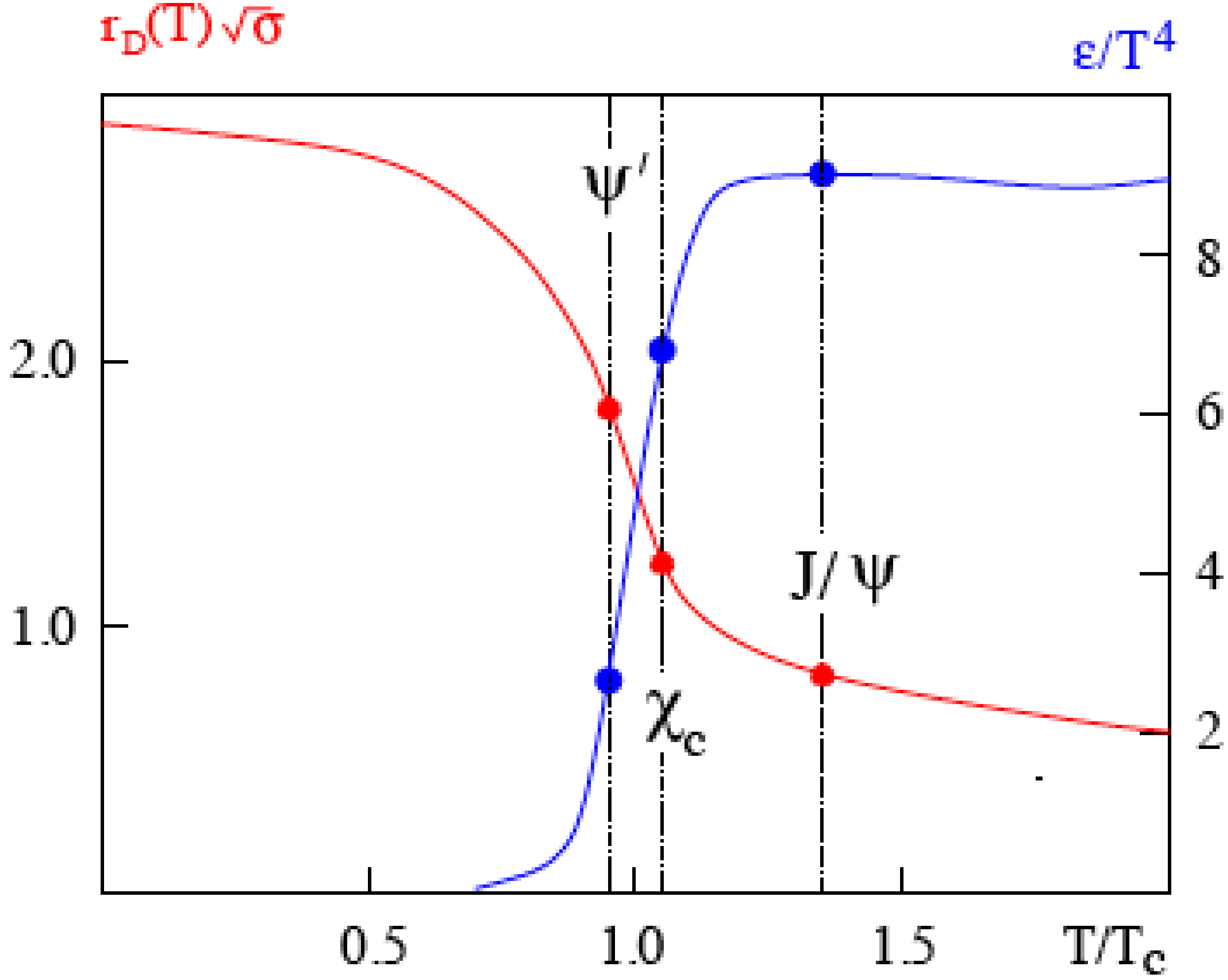
Bound state exists for

$$r_D(T) > r_D^{min}$$

that is, for

$$T < T_D$$

Melting temperature depends on size of bound state

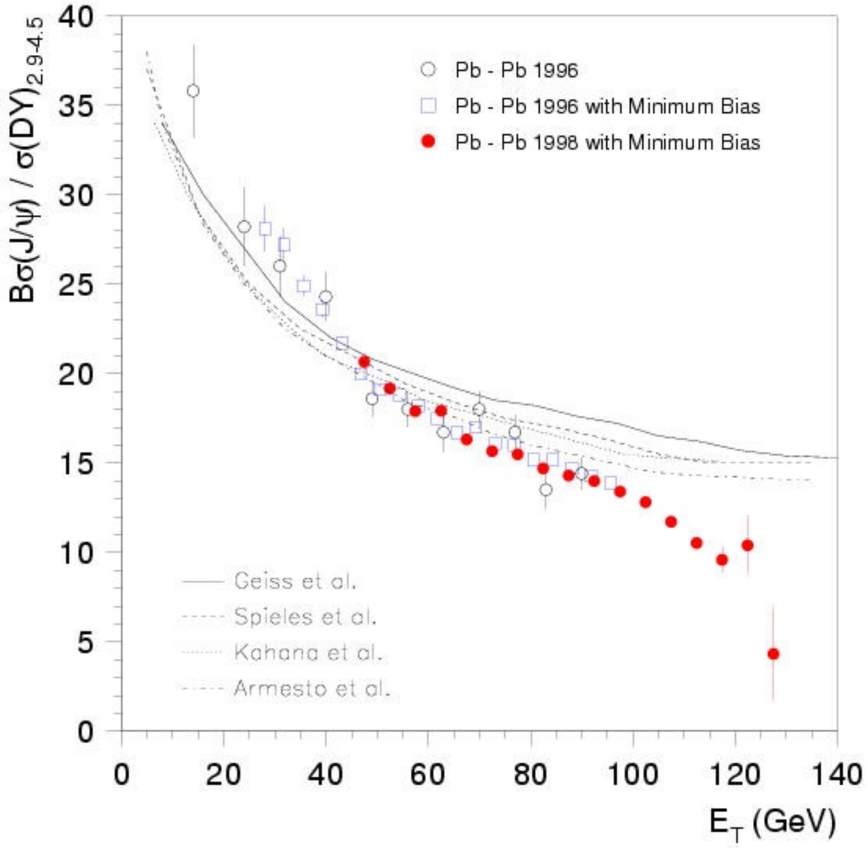


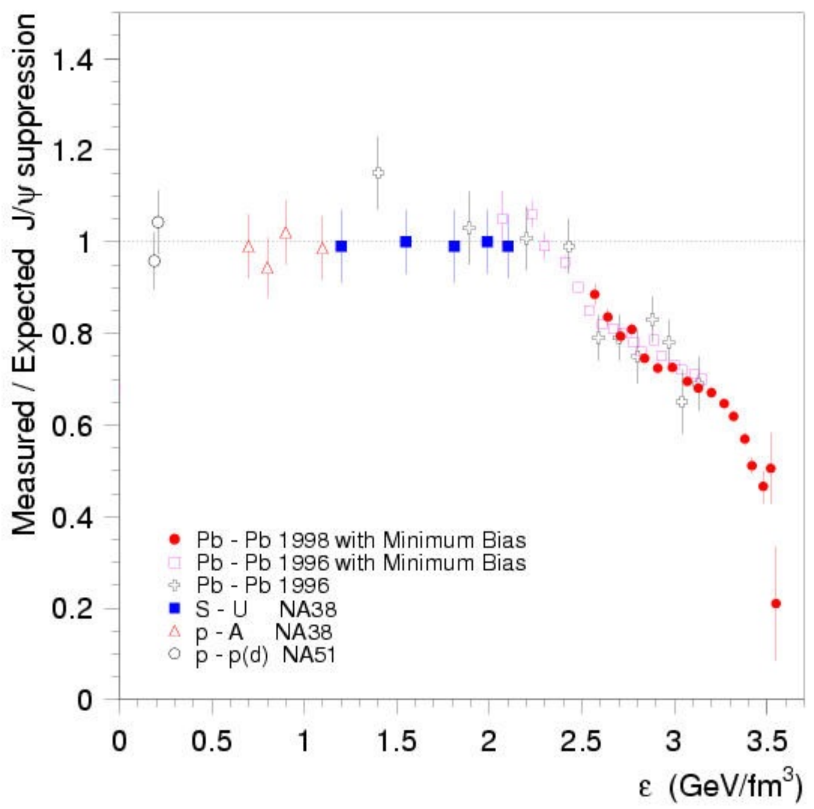
(from H. Satz, hep-ph/0602245)

A considerable experimental effort

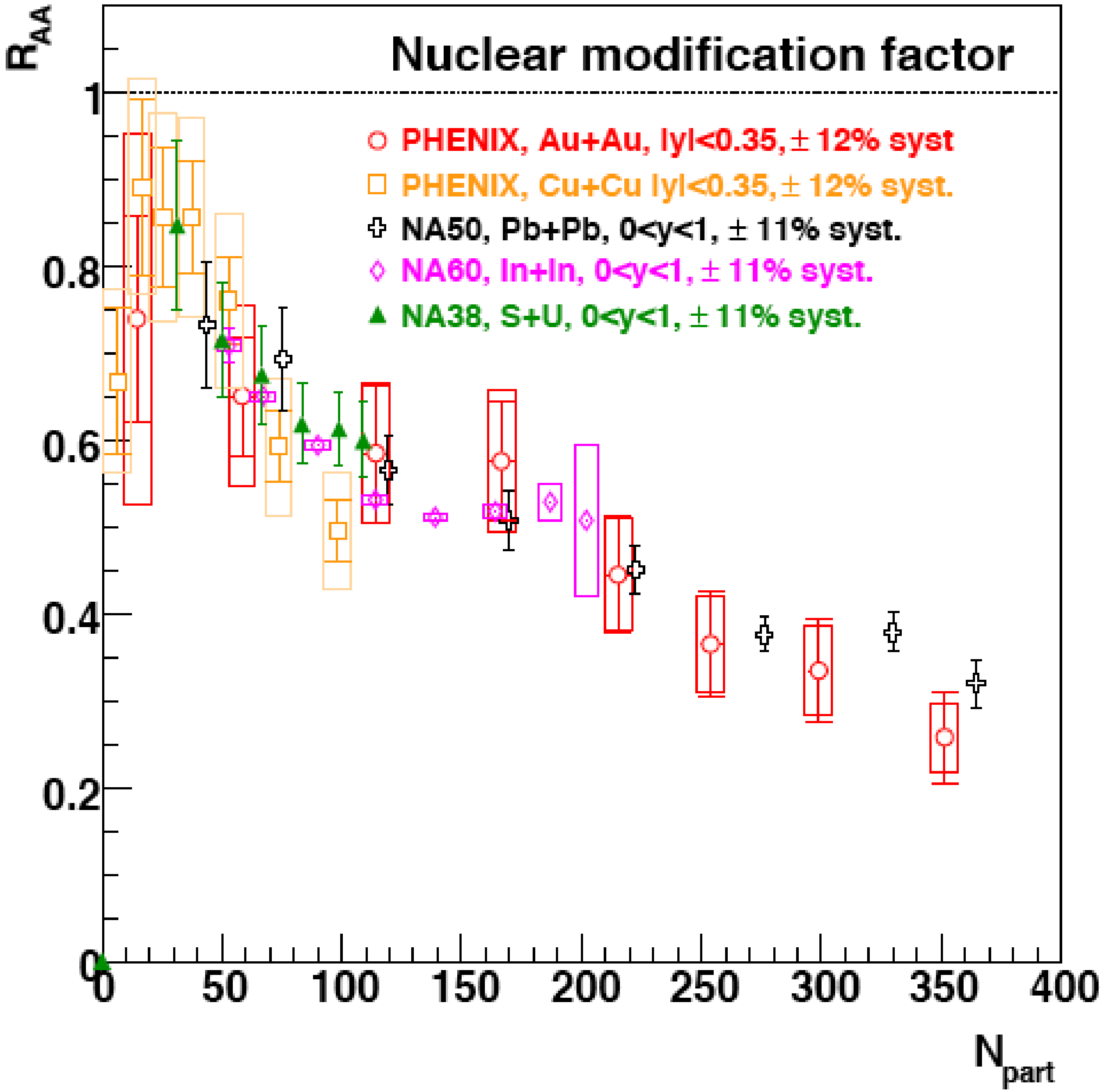
Summary of early measurements (NA38,NA50)

(CERN, 2000)

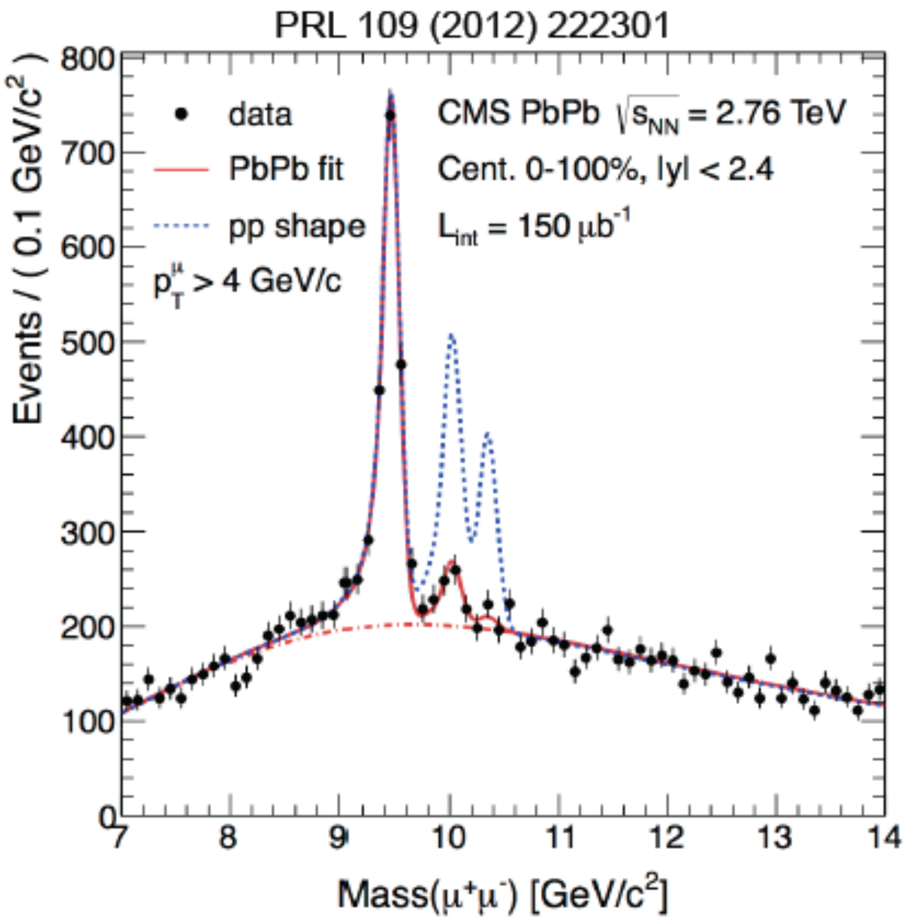


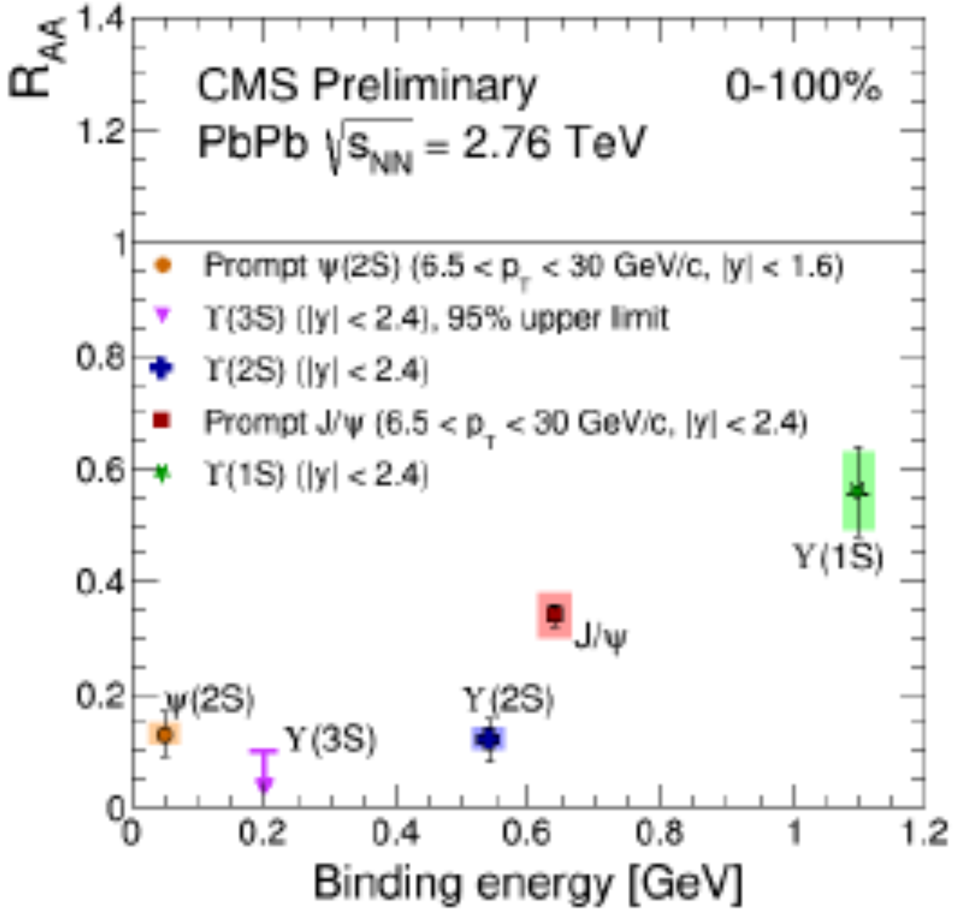


What about RHIC ?



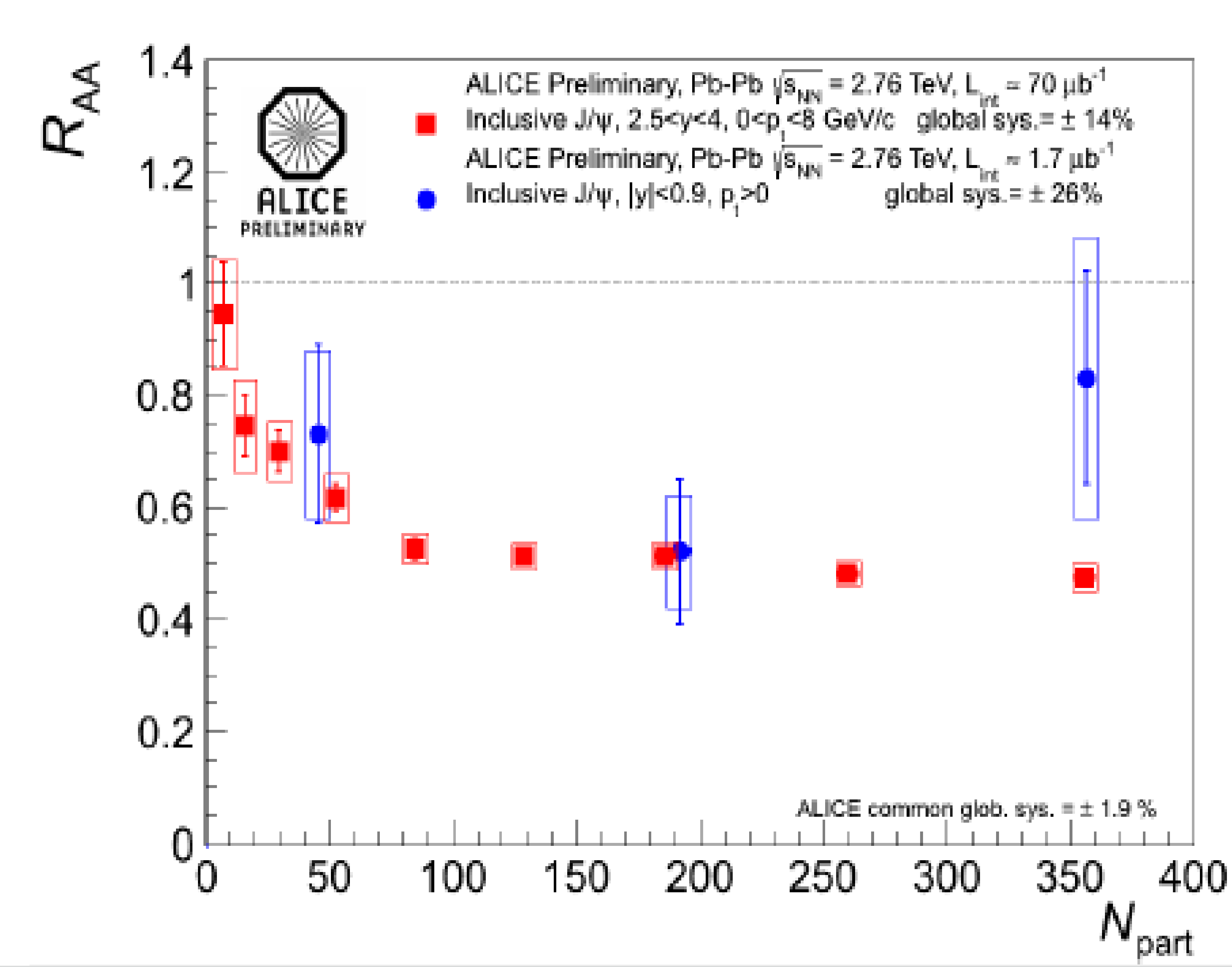
Υ suppression





excited states are more 'fragile'….

findings in line with expectations….



ALICE Preliminary, Pb-Pb √sNN = 2.76 TeV, Lint = 70 μb-1
Inclusive J/ψ, 2.5<y<4, 0<pt<8 GeV/c global sys.= ± 14%
ALICE Preliminary, Pb-Pb √sNN = 2.76 TeV, Lint ≈ 1.7 μb-1
Inclusive J/ψ, |y|<0.9, pt>0 global sys.= ± 26%
ALICE
PRELIMINARY
ALICE common glob. sys. = ± 1.9 %
RAA
Npart

A difficult many-body problem

a large variety of theoretical approaches

- -potential models
- -spectral functions
- -Euclidean correlators (lattice), maximum entropy techniques
- -coupled channels
- -path integrals
- -open quantum systems
- -effective field theory, non relativistic heavy quark effective theory
- -strong coupling techniques
- -etc

Which problem do we need to solve ?

- -full dynamics, including plasma expansion
- -dynamics of bound state formation (stationary states are not enough)
- -dynamics of dissociation and recombination

TIME SCALES MATTER!

Our goals:

- address full dynamics, keeping consistency between different processes

- provide unifying perspective and clarify the relations between different approaches

- deepen connection between energy loss, momentum broadening and quarkonium dynamics

Note: we may not have to worry about the dynamics, all is "thermal"

"principle" of statistical hadronization PBM and JS [PLB490 (2000)196]

Heavy quarks hadronize statistically at the 'phase boundary'

some recent progress

Results presented are based on
A. Beraudo, JPB, C. Ratti, NPA 806 (2008) 312 [arXiv: 0712.4394]
A. Beraudo, JPB, P. Faccioli and G. Garberoglio [arXiv: 1005.1245]
JPB, D. de Boni, P. Faccioli and G. Garberoglio, [arXiv:1503.03857]
WORK IN PROGRESS !

Similar effort by Y. Akamatsu, A. Rothkopf and others
('open quantum systems')

Dynamics

(Abelian approximation)

$$H = H_Q + H_{med} + H_{int}$$

Heavy quark

$$H_Q = M \int d^3\boldsymbol{r}\, \psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r}) + \int d^3\boldsymbol{r}\, \psi^\dagger(\boldsymbol{r}) \left(-\frac{\nabla^2}{2M}\right) \psi(\boldsymbol{r})$$

linearly coupled to gauge field

$$H_{int} = g \int d^3\boldsymbol{r}\, \psi^\dagger(\boldsymbol{r})\psi(\boldsymbol{r}) A_0(\boldsymbol{r})$$

The hot plasma

$$H_{med} = \int d^3 r\, \xi^\dagger(\boldsymbol{r}) h_0\, \xi(\boldsymbol{r}) + \frac{1}{2} \int d^3 r d^3 r' \hat{\rho}(\boldsymbol{r}) \frac{g^2}{4\pi|\boldsymbol{r} - \boldsymbol{r}'|} \hat{\rho}(\boldsymbol{r}')$$

Path integral and influence functional

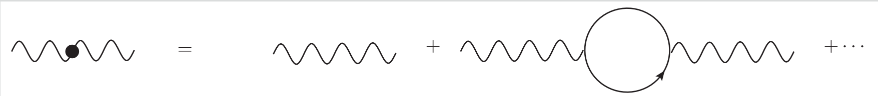
$$P(Q_f, t_f | Q_i, t_i) = \int_C DQ\, e^{iS_0[Q]}\, e^{i\Phi[Q]}$$

$$e^{i\Phi[\boldsymbol{Q}]} = \int \boldsymbol{D} A_0\, e^{-i\int_C d^4x\, g\rho(x) A_0(x)} e^{iS_2[A_0]}$$

$$\rho(x) = \sum_{j=1}^{N} (\delta(\boldsymbol{x} - \boldsymbol{q}_j(t) - \delta(\boldsymbol{x} - \bar{\boldsymbol{q}}_j(t))$$

'Integrate out' the light particles and keep the quadratic part of the resulting action (HTL approximation)

$$S_2[A_0] \;=\; -\frac{1}{2}\int_c dx \left(A_0(x)\nabla^2 A_0(x) \right) - i\ \mathrm{Tr}\ \ln\left[\ i\gamma^\mu \partial_\mu - m - e\gamma^0 A_0(x)\ \right]$$



$$\Phi[\boldsymbol{Q}] = \frac{g^2}{2}\iint_C d^4x d^4y\ \rho(x)\Delta_c(x-y)\rho(y)$$

$$\Delta(x-y) \equiv i\langle\, T_C\, [A_0(x) A_0(y)\,]\rangle$$

Physical content of the influence functional

$$\Phi[\boldsymbol{Q}] = \frac{g^2}{2} \iint_{\mathcal{C}} \mathrm{d}^4x \mathrm{d}^4y \; \rho(x) \Delta_{\mathcal{C}}(x-y) \rho(y)$$

$$\Delta(x-y) \equiv i \langle \, T_C \, [A_0(x) A_0(y) \,] \rangle$$

$$\Delta_{11}(\omega = 0, x) \sim V(x)$$ **Heavy quark potential (complex)**

$$V(r) = \alpha_s \left[m_D + \frac{\mathrm{e}^{-m_D r}}{r} \right] - i \alpha_s T \phi(m_D r)$$

(first observed by M. Laine et al hep-ph/ 0611300)

$$\Delta_{12}(\omega = 0, x) \sim \mathrm{Im} V(x) = W(x)$$ **collisions**

$$\mathcal{H}_{ij} \sim \frac{\partial^2 W}{\partial x_i \partial x_j}$$ **friction**

Low frequency expansion yields Langevin equation

$$M\,\ddot{R} = -\frac{\beta}{2}\,\mathcal{H}(R)\,\dot{R} + \mathbf{F}(R) + \Psi(R,t)$$

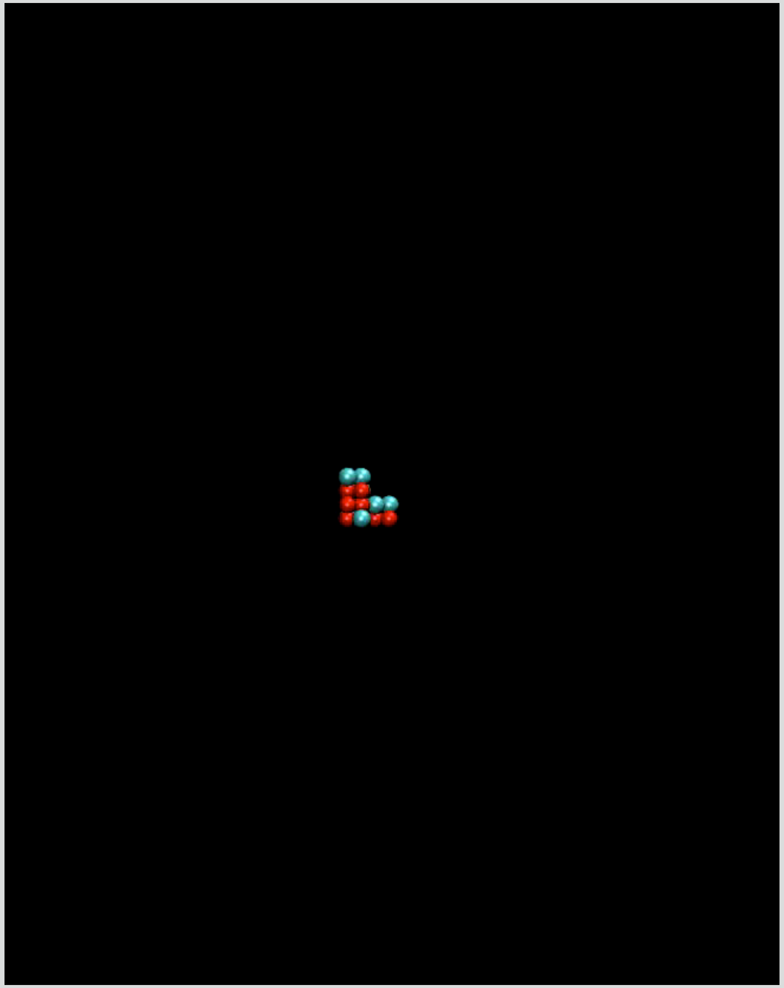
$$\mathcal{H}_{ij} \sim \frac{\partial^2 W}{\partial x_i \partial x_j} \qquad \mathbf{F}(R) \sim \nabla \mathrm{Re} V(R)$$

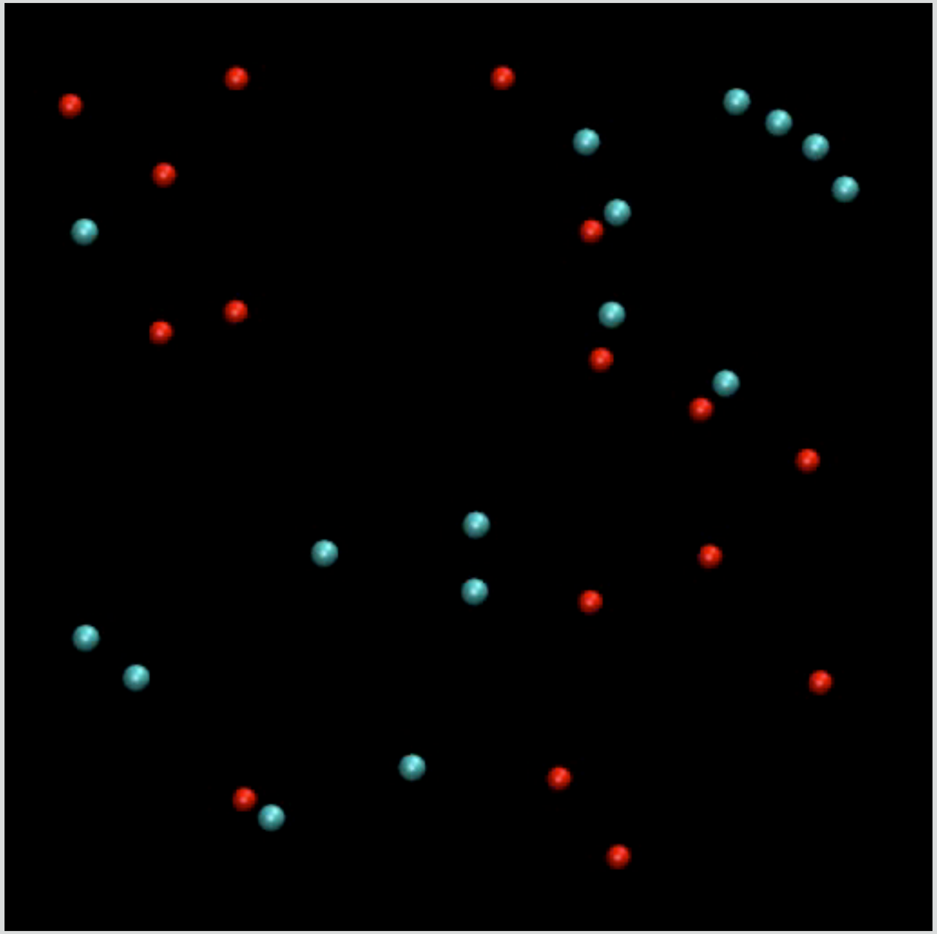
$$\langle\, \Psi(R,t)\,\rangle = 0$$

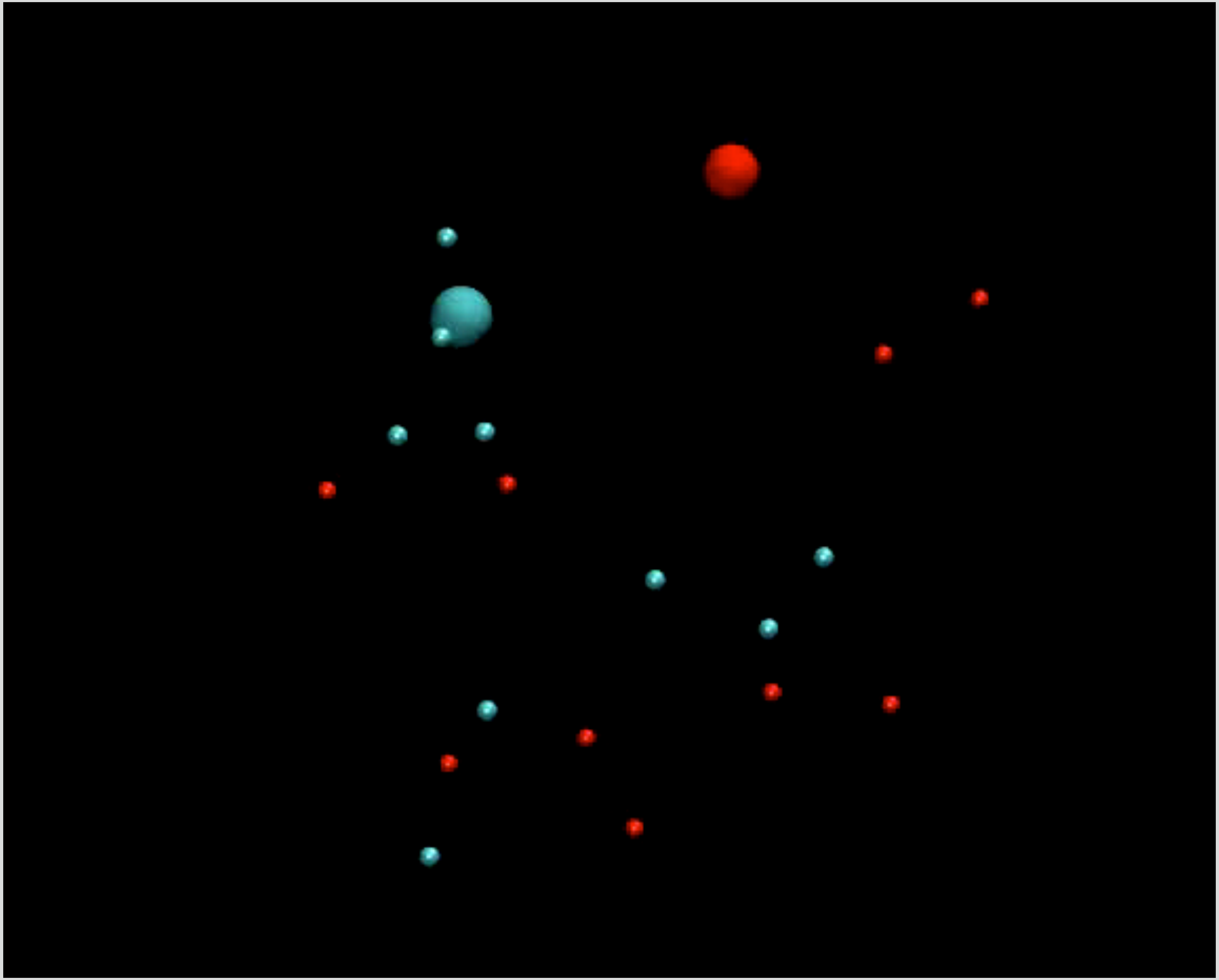
$$\langle\, \Psi_k(R,t)\,\Psi_m(R,t')\,\rangle = \mathcal{H}_{km}(R)\delta(t-t')$$

Non trivial noise (depends on the configuration R of the heavy quarks)

Selected results

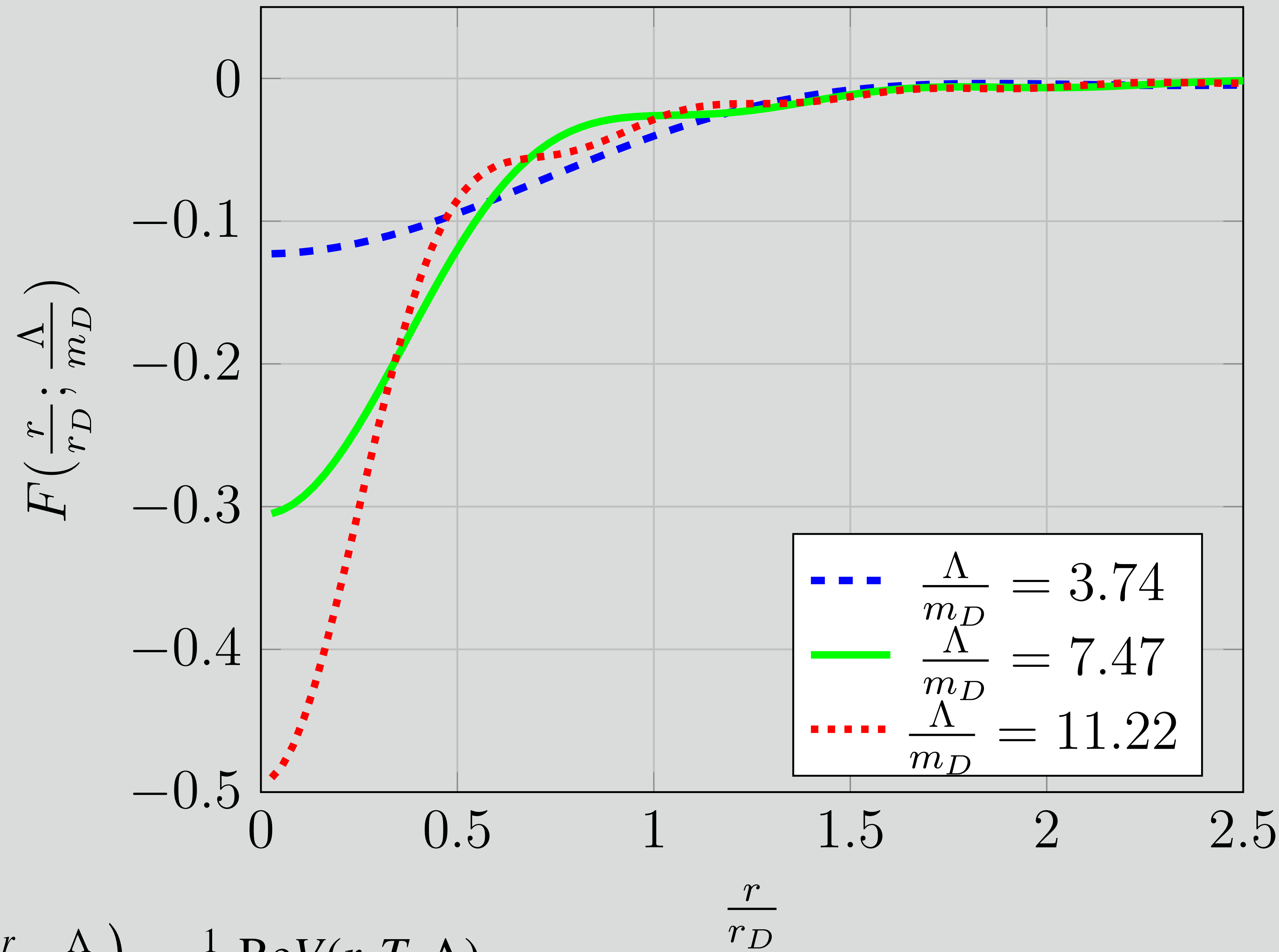






Fixing a few "details"

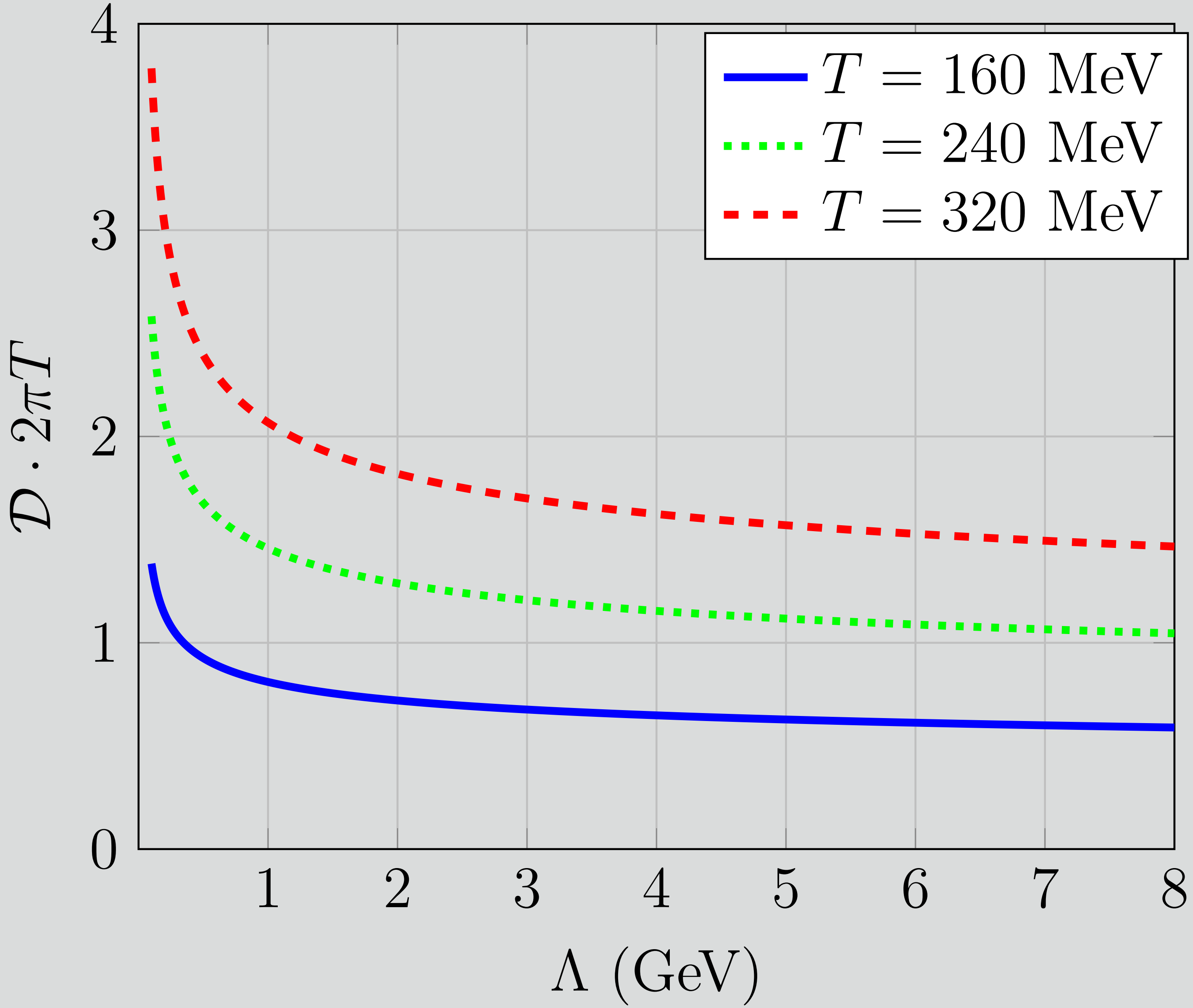
Regularized Coulomb potential



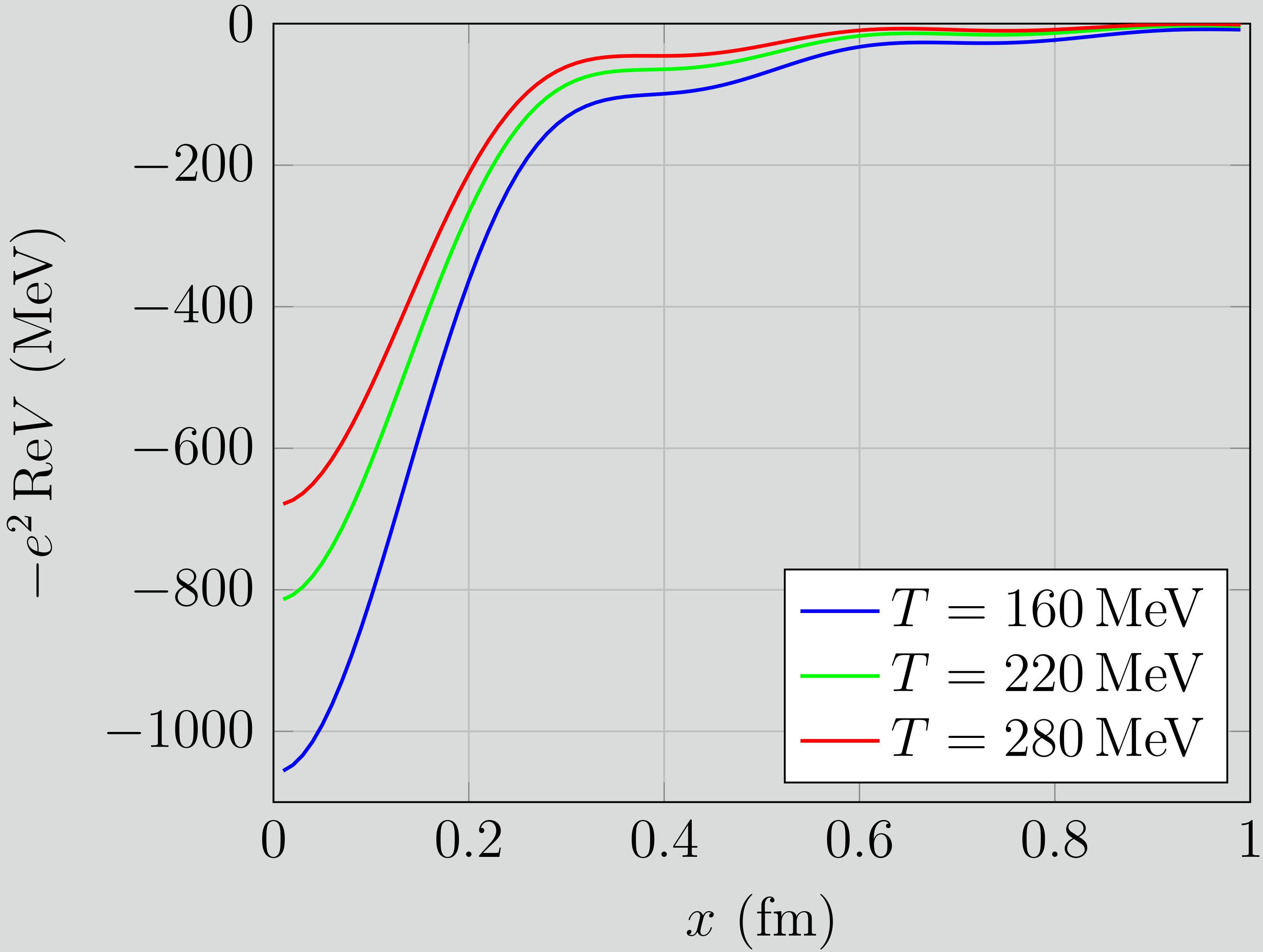
$$F\left(\frac{r}{r_D}, \frac{\Lambda}{m_D}\right) = \frac{1}{m_D}\mathrm{Re}V(r, T, \Lambda)$$

Diffusion constant

$$\mathcal{D} = \frac{T}{M\gamma}$$

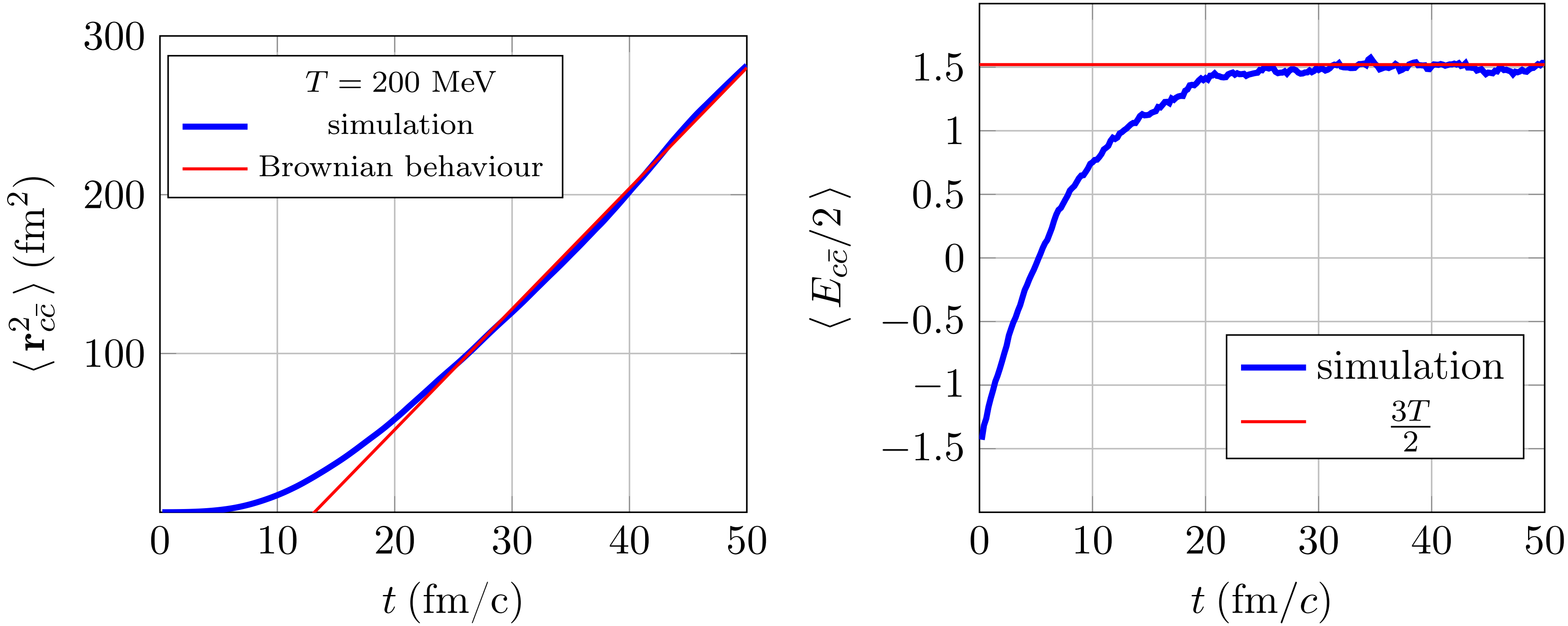


Potential (real part) - charmonium

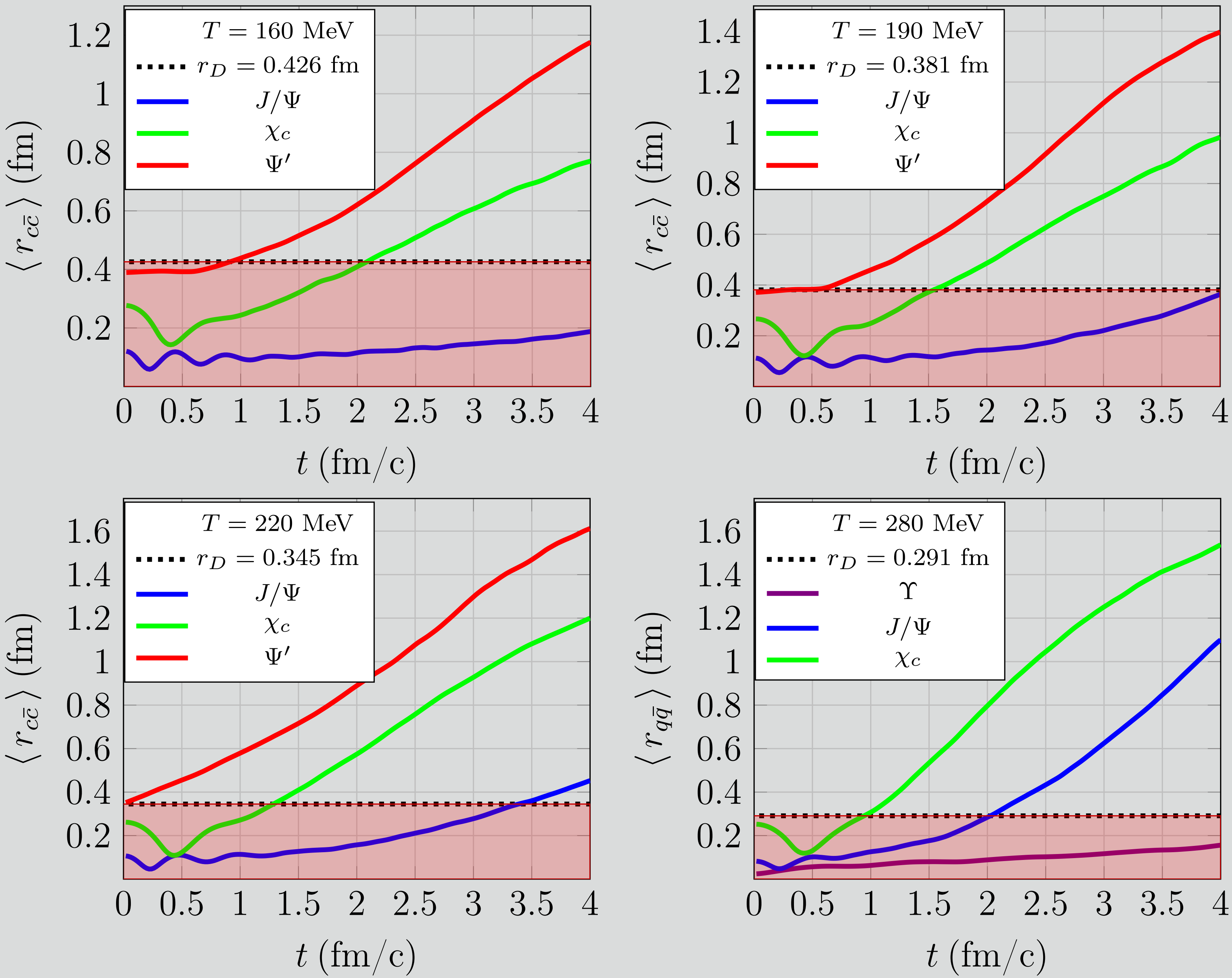


One quark-antiquark pair in the plasma

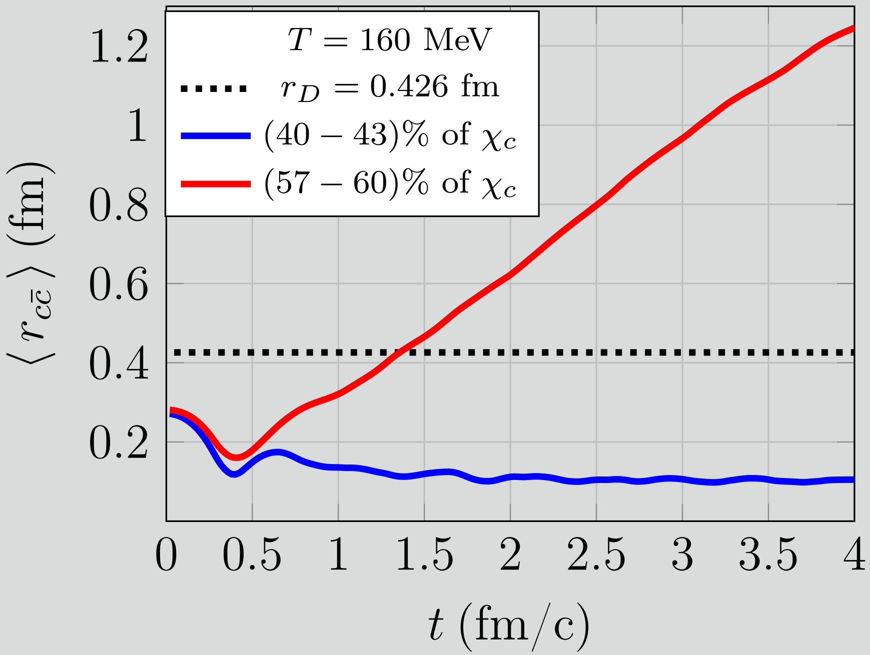
If T high enough, heavy quarks thermalize

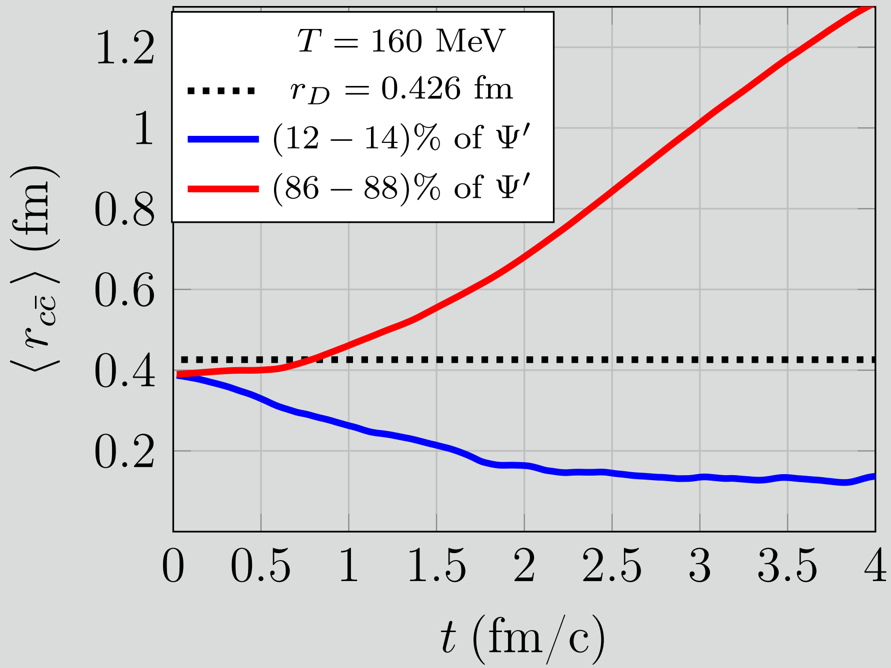


"Sequential" suppression



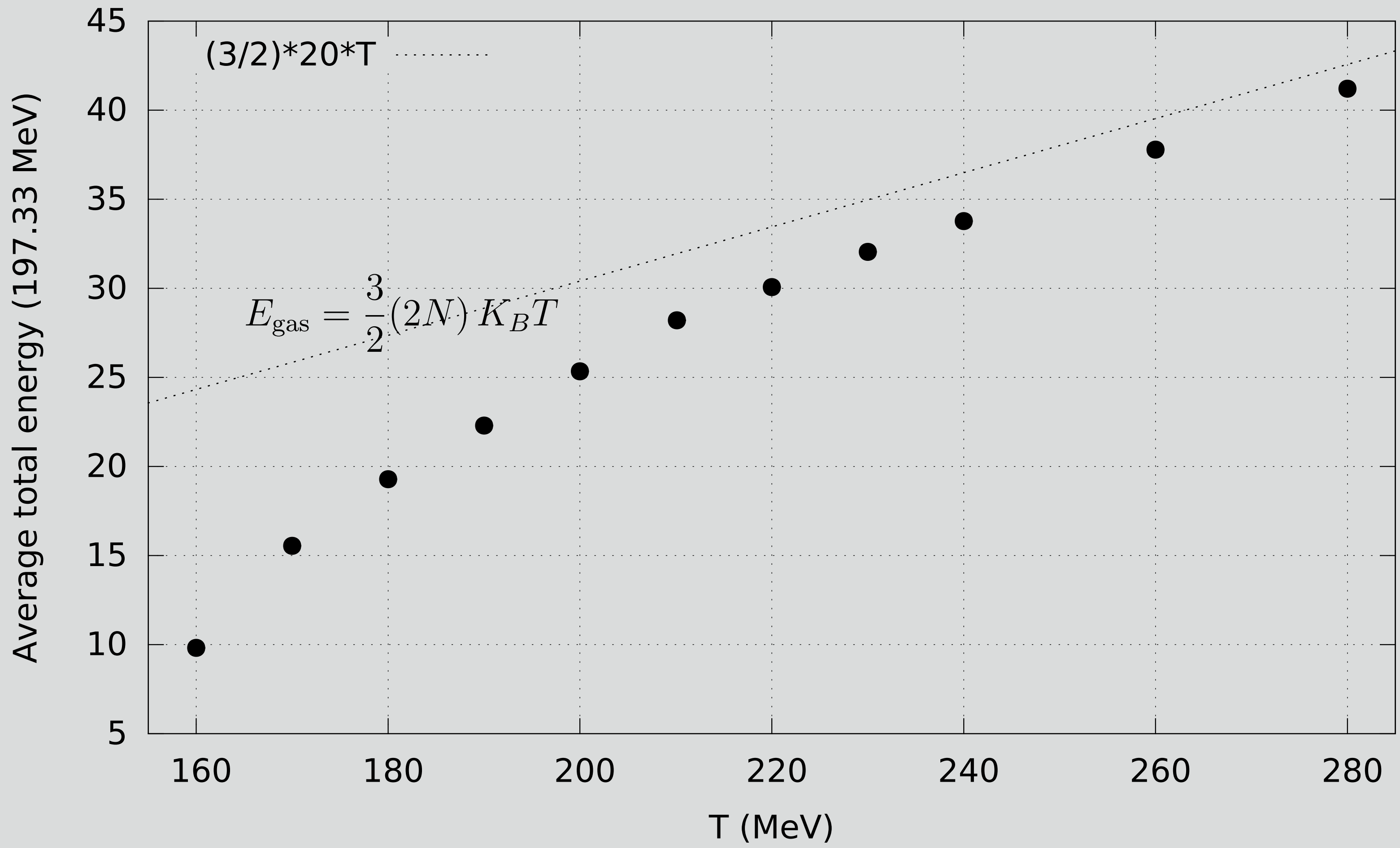
Effective feed down from excited states!



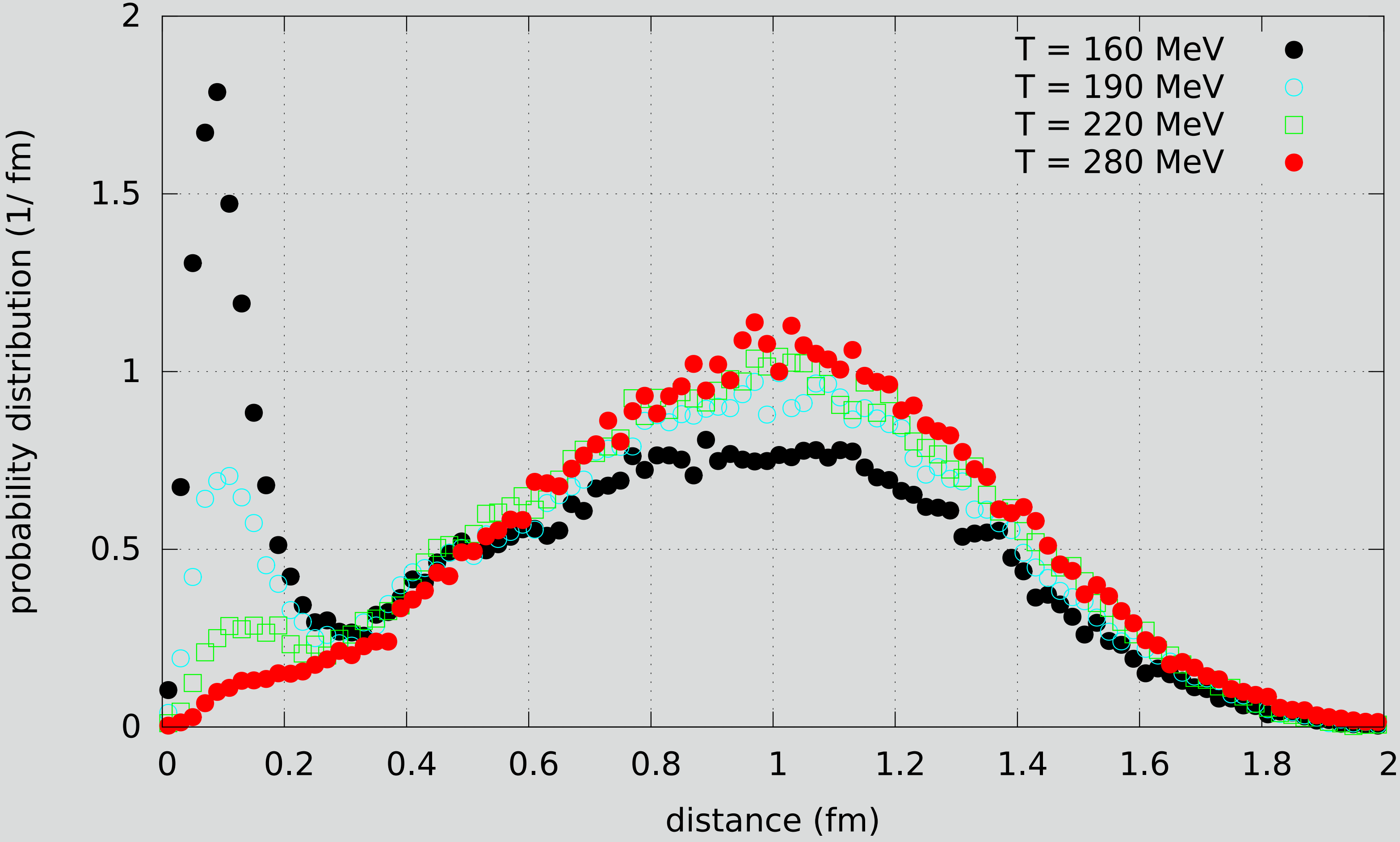


Many pairs in the plasma

10 pairs in plasma

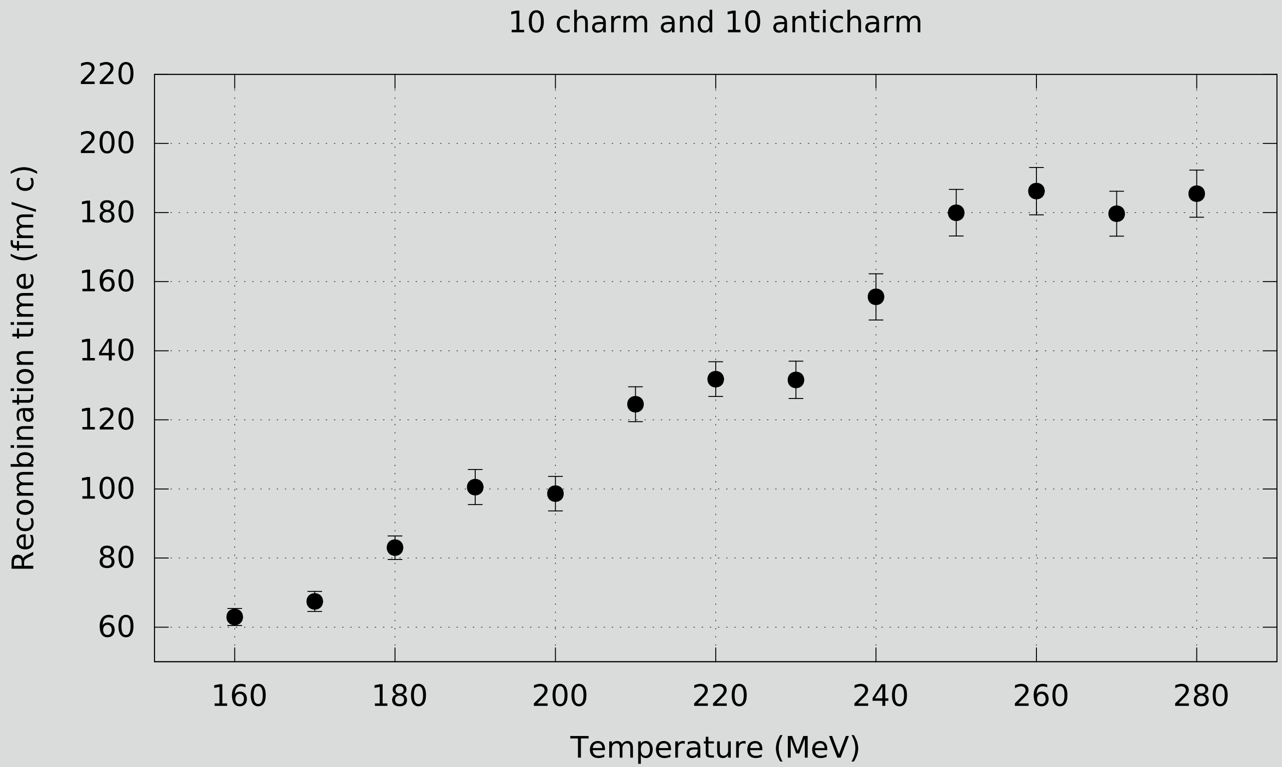


Probability distribution of distance to nearest neighbor

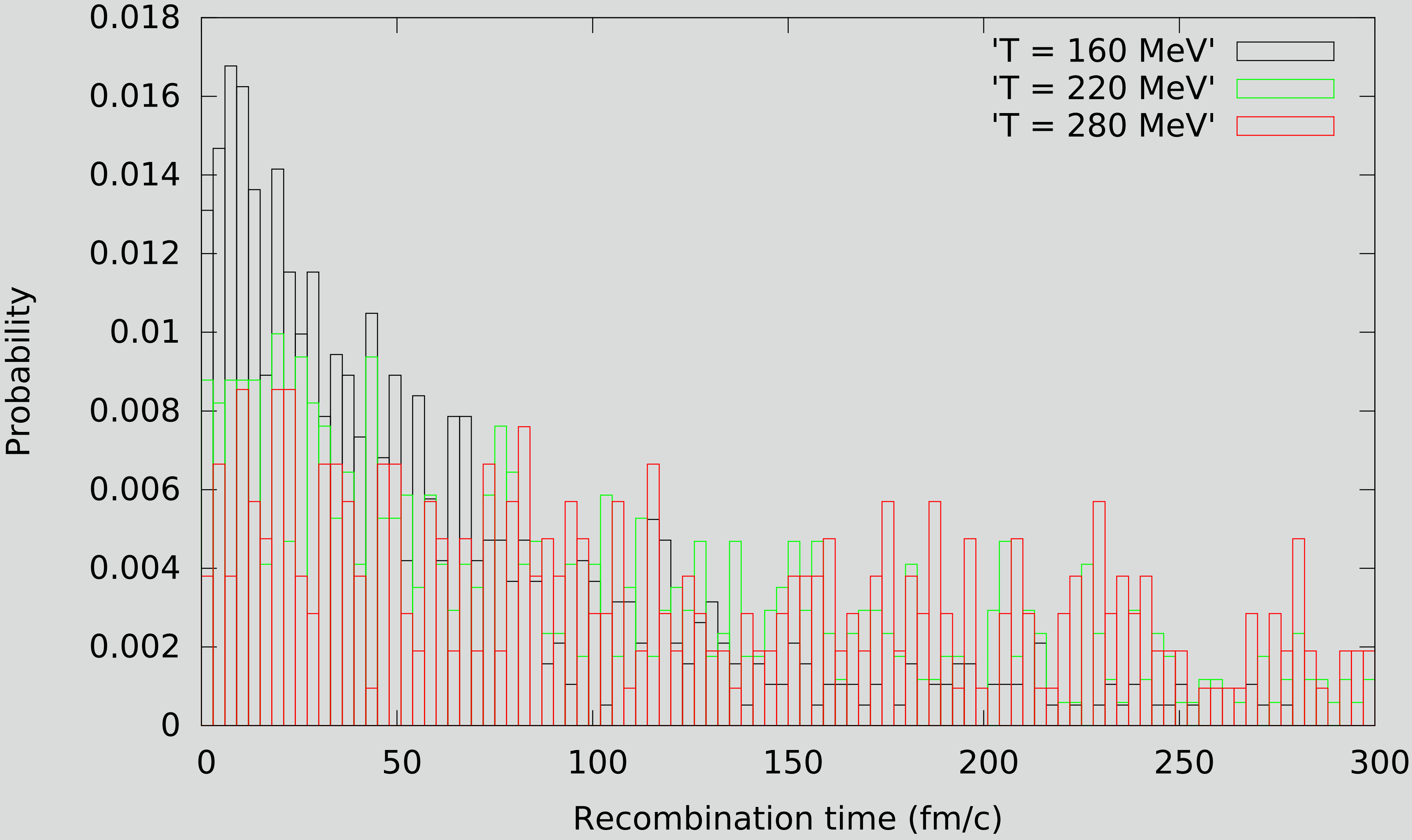


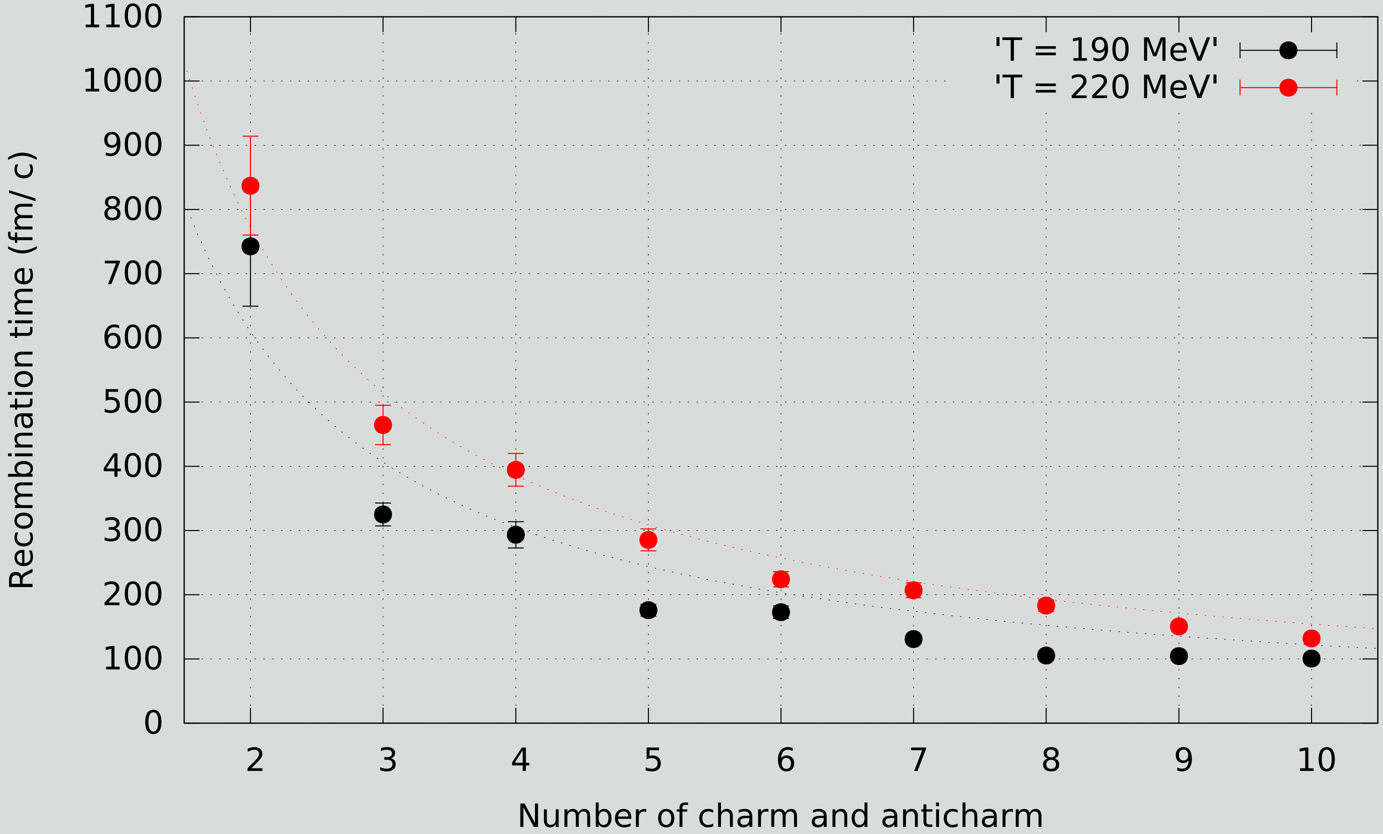
$$P^{\mathrm{ideal}}_{q\bar{q}}(r) = \frac{3}{a}\left(\frac{r}{a}\right)^2\left(1-\left(\frac{r}{a}\right)^3\frac{1}{N}\right)^{N-1} \overset{N\gg 1}{\simeq} \frac{3}{a}\left(\frac{r}{a}\right)^2 e^{-(r/a)^{\frac{1}{3}}}$$

Recombination time



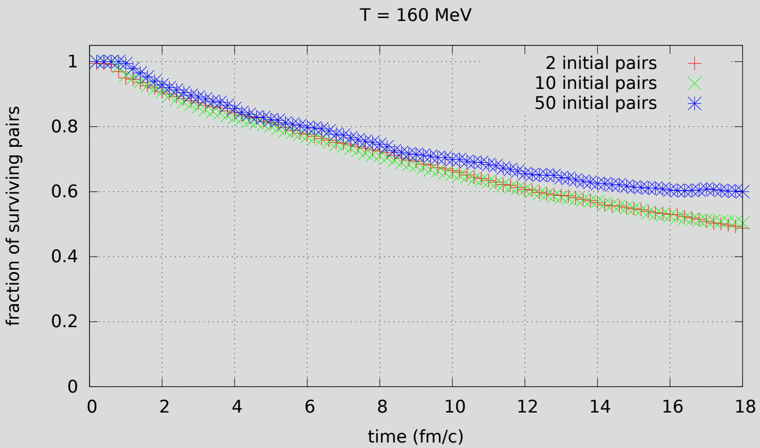
Distribution of recombination times

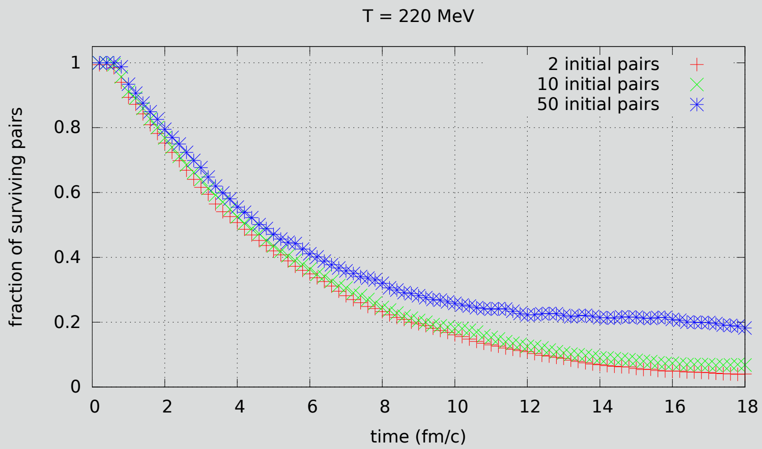


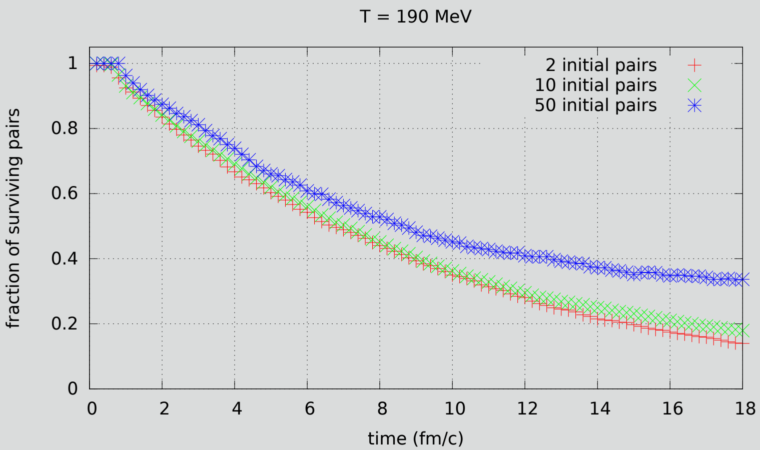


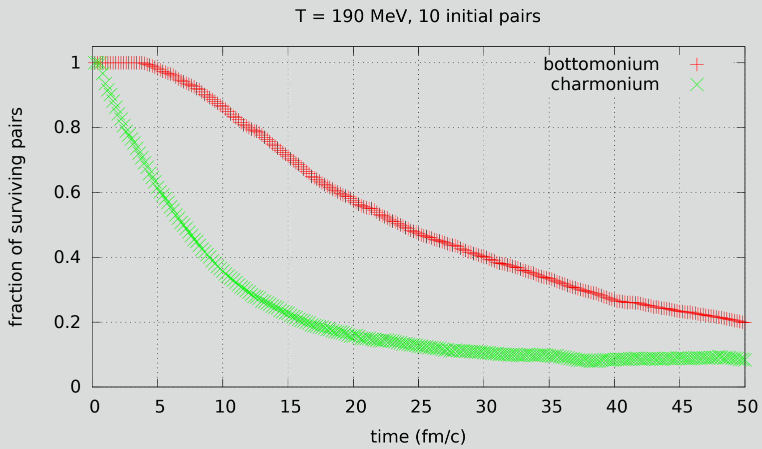
'T = 190 MeV'
'T = 220 MeV'
Recombination time (fm/ c)
Number of charm and anticharm
0
100
200
300
400
500
600
700
800
900
1000
1100
2
3
4
5
6
7
8
9
10

Dissociation/recombination

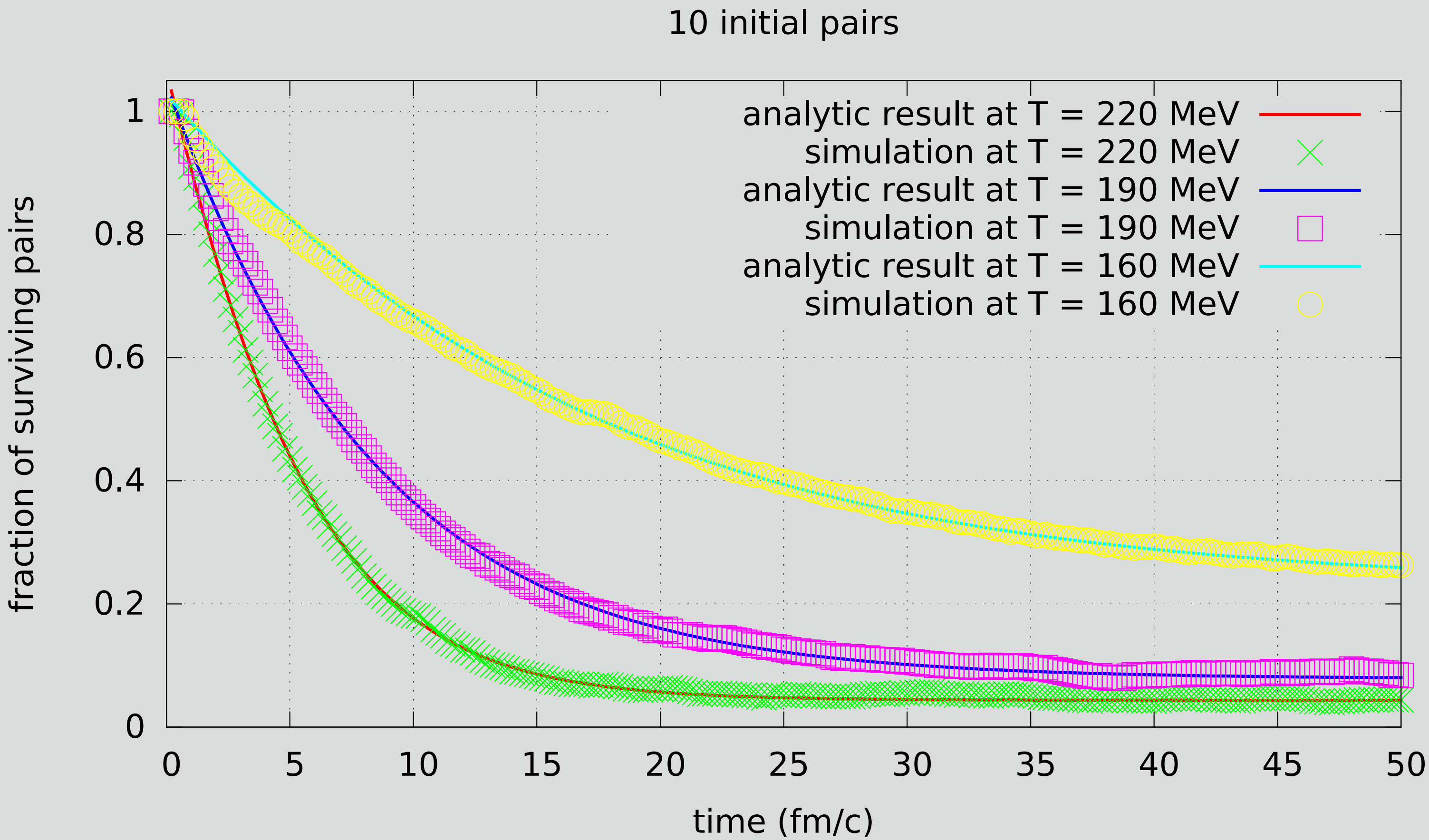








Evolution of population of bound states is well described by a simple rate equation



$$\frac{\mathrm{d}N(t)}{\mathrm{d}t} = -\lambda_D N(t) + \lambda_R N_q(t) N_{\bar{q}}(t)$$

in agreement with previous works

Summary

- first steps in an effort to describe the full dynamics of heavy quarks in a quark-gluon plasma, including bound state formation
- consistent treatment of various physical effects (screening, collisions, etc)
- systematic improvements are possible at many places (relax the abelian approximation, move from classical Langevin to quantum Schroedinger equation, etc)
- and, of course, comparison with data should be done.... after everything is under control