Phenomenological study of quarkonium suppression and the impact of the energy gap between singlets and octets

Miguel A. Escobedo

Instituto Galego de Física de Altas Enerxías
Universidade de Santiago de Compostela

May 5, 2022
Based on ... 

- Escobedo and Ferreiro, Simple model to include initial-state and hot-medium effects in the computation of quarkonium nuclear modification factor, Phys. Rev. D 105 (2022) 1, 1.
Outline

1. Introduction
2. Initial-effect model
3. The initial temperature
4. Computation of $R_{AA}$
5. Conclusions
A new state of matter, the quark-gluon plasma (QGP), appears at high temperatures and densities.
Quarkonium suppression

- A new state of matter, the quark-gluon plasma (QGP), appears at high temperatures and densities.
- The QGP is created in heavy ion collisions. However, it is challenging to deduce its properties from what we observe.
A new state of matter, the quark-gluon plasma (QGP), appears at high temperatures and densities.

The QGP is created in heavy ion collisions. However, it is challenging to deduce its properties from what we observe.

Quarkonium is a good probe of the QGP. Not only it is formed in the initial instants of the collision but also it was predicted by Matsui and Satz that quarkonium melts in the QGP. Therefore, by measuring quarkonium suppression we can infer the properties of the medium.
Quarkonium suppression

- A new state of matter, the quark-gluon plasma (QGP), appears at high temperatures and densities.
- The QGP is created in heavy ion collisions. However, it is challenging to deduce its properties from what we observe.
- Quarkonium is a good probe of the QGP. Not only it is formed in the initial instants of the collision but also it was predicted by Matsui and Satz that quarkonium melts in the QGP. Therefore, by measuring quarkonium suppression we can infer the properties of the medium.
- Moreover, a heavy ion is not equivalent to an uncorrelated ensemble of protons. This can also modify the probability of quarkonium formation. *Initial state effects.*
A heavy ion collision

Relativistic Heavy-Ion Collisions

made by Chun Shen

Initial energy density

QGP phase

Hadronization

Hadron gas phase

Kinetic freeze-out

final detected particle distributions

Collision overlap zone

pre-equilibrium dynamics

viscous hydrodynamics

collision evolution

\( \tau \sim 0 \text{ fm/c} \)  \( \tau \sim 1 \text{ fm/c} \)

\( \tau \sim 10 \text{ fm/c} \)  \( \tau \sim 10^{15} \text{ fm/c} \)

\( \pi \)

\( K \)

\( p \)

\( \gamma \)

\( e^+ \)

\( e^- \)
$R_{AA}$, the nuclear modification factor

In the Glauber model, the nucleus is seen as a collection of uncorrelated protons moving eikonally on the longitudinal direction.

\[ R_{AA} = \frac{N_{AA}^{HQ}}{N_{col} N_{HQ}} \]

where

- $N_{AA}^{HQ}$ is how much quarkonium is produced in a heavy ion collision.
- $N_{col}$ is the number of nucleon-nucleon collisions in that heavy ion collision.
- $N_{HQ}$ is how much quarkonium produce in a proton-proton collision.
$R_{AA}$, the nuclear modification factor

In the Glauber model, the nucleus is seen as a collection of uncorrelated protons moving eikonally on the longitudinal direction.

$$R_{AA} = \frac{N_{AA}^{HQ}}{N_{col} N_{HQ}}$$

where

- $N_{AA}^{HQ}$ is how much quarkonium is produced in a heavy ion collision.
- $N_{col}$ is the number of nucleon-nucleon collisions in that heavy ion collision.
- $N_{HQ}$ is how much quarkonium produce in a proton-proton collision.

$R_{AA}$ is not one if

- There are medium effects.
- There are initial effects, i.e. if a heavy ion collision is not equivalent to $N_{col}$ proton-proton collisions.
**Hot medium effects**

| Phenomena that modify quarkonium population in a QGP |
|---------------------------------------------------|
| - Screening of chromoelectric fields at large distances. Inhibits quarkonium formation if quarkonium’s size is larger than screening length. |
| - Medium induced decay width. |
| - Recombination. A heavy quark-antiquark pair can meet inside of the medium and form a new bound state. Important for charmonium but sub-leading effect for bottomonium. |

If we ignore recombination, we can encode medium effects in a survival probability $S$. Given $S$ as a function of the initial temperature. Can we compute $R_{AA}$?
Hot medium effects

Phenomena that modify quarkonium population in a QGP

- Screening of chromoelectric fields at large distances. Inhibits quarkonium formation if quarkonium’s size is larger than screening length.
- Medium induced decay width.
- Recombination. A heavy quark-antiquark pair can meet inside of the medium and form a new bound state. Important for charmonium but sub-leading effect for bottomonium.

Survival probability

If we ignore recombination, we can encode medium effects in a survival probability $S$.

- Given $S$ as a function of the initial temperature. Can we compute $R_{AA}$?
Motivation

To develop a framework to easily compute $R_{AA}$ in the cases in which the survival probability is given by a simple analytical formula. Questions we wish to answer:

- What is the initial temperature as a function of $x_\perp$?
- How does the quarkonium production probability depends on $x_\perp$?
- Compute $R_{AA}$ for a given $S$. 
Outline

1. Introduction
2. Initial-effect model
3. The initial temperature
4. Computation of $R_{AA}$
5. Conclusions
The Glauber-Gribov model and beyond

- The Glauber model can be understood as the assumption that nucleons only interact by Pomeron exchange.
The Glauber-Gribov model and beyond

- The Glauber model can be understood as the assumption that nucleons only interact by Pomeron exchange.
- In the parton language, we can relate the Pomeron with the exchange of a pair of gluons.
The Glauber-Gribov model and beyond

- The Glauber model can be understood as the assumption that nucleons only interact by Pomeron exchange.
- In the parton language, we can relate the Pomeron with the exchange of a pair of gluons.
- Corrections beyond the Glauber model can be implemented by including some non-trivial interaction between Pomerons.
The Glauber-Gribov model and beyond

- The Glauber model can be understood as the assumption that nucleons only interact by Pomeron exchange.
- In the parton language, we can relate the Pomeron with the exchange of a pair of gluons.
- Corrections beyond the Glauber model can be implemented by including some non-trivial interaction between Pomerons.
- In our case, we use a model that includes a triple Pomeron vertex.
Some definitions

The thickness function is the density of nucleons in the transverse plane

\[ T_A(x, y) = \int_{-\infty}^{\infty} \rho(x, y, z) \]

In the Glauber model, the density of collisions at a given point is proportional to

\[ n_{col}(x_\perp, b) = T_A \left( x_\perp + \frac{b}{2} \right) T_B \left( x_\perp - \frac{b}{2} \right) \]

where \( b \) is the impact parameter. Note the unconventional choice, we use a reference system in which \( x_\perp = 0 \) corresponds to the center of the overlapping region, not to the center of one of the nuclei.
Some definitions II

A participant is a nucleon that collides at least once. The density of participants at a given point in the transverse plane is

\[ n_{\text{part}}(x_\perp, b) = T_A \left( x_\perp + \frac{b}{2} \right) \left( 1 - \left( 1 - \frac{T_B \left( x_\perp - \frac{b}{2} \right) \sigma}{B} \right)^B \right) \]

\[ + T_B \left( x_\perp - \frac{b}{2} \right) \left( 1 - \left( 1 - \frac{T_A \left( x_\perp + \frac{b}{2} \right) \sigma}{A} \right)^A \right) \]

\( R_{AA} \) is often given as a function of the total number of participants \( N_{\text{part}} \). More participants implies more central collisions.
Initial-effect model

We use the shadowing model discussed in Capella and Ferreiro (2012).
Initial-effect model

We use the shadowing model discussed in Capella and Ferreiro (2012).

- It is an analytical model with simple formulas that is compatible with observations.
Initial-effect model

We use the shadowing model discussed in Capella and Ferreiro (2012).

- It is an analytical model with simple formulas that is compatible with observations.
- Compatible with the AGK rules.

\[
S_{\text{sh}}(s, b) = T_A s + b^2 \left( 1 + A F(y, p_T) \right) T_A s + b^2 T_B s - b^2 \left( 1 + B F(-y, p_T) \right) T_B s - b^2
\]

Note that it depends on both rapidity and transverse momentum.
Initial-effect model

We use the shadowing model discussed in Capella and Ferreiro (2012).

- It is an analytical model with simple formulas that is compatible with observations.
- Compatible with the AGK rules.
- The parameters of the model are fixed by the nucleon-virtual photon cross-section.
Initial-effect model

We use the shadowing model discussed in Capella and Ferreiro (2012).

- It is an analytical model with simple formulas that is compatible with observations.
- Compatible with the AGK rules.
- The parameters of the model are fixed by the nucleon-virtual photon cross-section.

In this model, the probability to create a particle at a given point in the transverse plane is proportional to

\[
S^{sh}(s, b) = \frac{T_A \left(s + \frac{b}{2}\right)}{1 + A F(y, p_T) T_A \left(s + \frac{b}{2}\right)} \frac{T_B \left(s - \frac{b}{2}\right)}{1 + B F(-y, p_T) T_B \left(s - \frac{b}{2}\right)}
\]

Note that it depends on both rapidity and transverse momentum.
Outline

1. Introduction
2. Initial-effect model
3. The initial temperature
4. Computation of $R_{AA}$
5. Conclusions
Initial temperature as a function of $x_\perp$

- We assume that the initial temperature goes as the energy density to $1/4$.
Initial temperature as a function of $x_\perp$

- We assume that the initial temperature goes as the energy density to $1/4$.
- We also assume that the energy density is dominated by pion’s multiplicity calculated based on the number of collisions corrected by the shadowing effects.
Initial temperature as a function of $x_\perp$

- We assume that the initial temperature goes as the energy density to $1/4$.
- We also assume that the energy density is dominated by pion's multiplicity calculated based on the number of collisions corrected by the shadowing effects.
- Our model does not allow to compute the initial energy density $\epsilon$. However, we can compute the ratio $\frac{\epsilon(x_\perp,b)}{\epsilon(0,0)}$. 

As a comparison, we can also compute the temperature we obtain changing $S_{\text{sh}}\pi$ to $n_{\text{part}}$ or $n_{\text{col}}$. 
Initial temperature as a function of $x_\perp$

- We assume that the initial temperature goes as the energy density to $1/4$.
- We also assume that the energy density is dominated by pion's multiplicity calculated based on the number of collisions corrected by the shadowing effects.
- Our model does not allow to compute the initial energy density $\epsilon$. However, we can compute the ratio $\frac{\epsilon(x_\perp, b)}{\epsilon(0,0)}$.
- Therefore:
  \[ T_0(x_\perp, b) = T_{00} \left( \frac{S^{sh}_\pi(x_\perp, b)}{S^{sh}_\pi(0,0)} \right)^{1/4} \]
Initial temperature as a function of $x_{\perp}$

- We assume that the initial temperature goes as the energy density to $1/4$.
- We also assume that the energy density is dominated by pion's multiplicity calculated based on the number of collisions corrected by the shadowing effects.
- Our model does not allow to compute the initial energy density $\epsilon$. However, we can compute the ratio $\frac{\epsilon(x_{\perp}, b)}{\epsilon(0, 0)}$.
- Therefore:

$$T_0(x_{\perp}, b) = T_{00} \left( \frac{S^{sh}_{\pi}(x_{\perp}, b)}{S^{sh}_{\pi}(0, 0)} \right)^{1/4}$$

- As a comparison, we can also compute the temperature that we obtain changing $S^{sh}_{\pi}$ to $n_{part}$ or $n_{col}$.
Temperature in the center of the overlapping region
Temperature by quarkonium

- $T$ depends on $x_\perp$. 

\[
\langle T_{HQ}(b) \rangle = T_0 \frac{d^2 s S_{sh}^{HQ}(s, b)}{S_{sh}^{\pi}(s, b) S_{sh}^{\pi}(0, 0)} \frac{1}{4} \frac{d^2 s S_{sh}^{HQ}(s, b)}{S_{sh}^{\pi}(s, b) S_{sh}^{\pi}(0, 0)}
\]
Temperature by quarkonium

- $T$ depends on $x_\perp$.
- The initial distribution of quarkonium goes like $S_{HQ}^{sh}$.
Temperature by quarkonium

- $T$ depends on $x_\perp$.
- The initial distribution of quarkonium goes like $S_{HQ}^{sh}$.
- The average initial temperature seen by a quarkonium state is given by

$$\langle T_{HQ}(b) \rangle = T_0 \frac{\int d^2 s S_{HQ}^{sh}(s, b) \left( \frac{S_{\pi}^{sh}(s, b)}{S_{\pi}^{sh}(0, 0)} \right)^{1/4}}{\int d^2 s S_{HQ}^{sh}(s, b)}$$
Temperature by quarkonium

- $T$ depends on $x_{\perp}$.
- The initial distribution of quarkonium goes like $S_{HQ}^{sh}$.
- The average initial temperature seen by a quarkonium state is given by

$$
\langle T_{HQ}(b) \rangle = T_{00} \frac{\int d^2s S_{HQ}^{sh}(s, b) \left( \frac{S_{\pi}^{sh}(s,b)}{S_{\pi}^{sh}(0,0)} \right)^{1/4}}{\int d^2s S_{HQ}^{sh}(s, b)}
$$

- We might ask if the temperature seen by a quarkonium state is close to the temperature at the center of the plateau.
$\langle T_{HQ} \rangle$ versus $T_0(0, b)$
Outline

1. Introduction
2. Initial-effect model
3. The initial temperature
4. Computation of $R_{AA}$
5. Conclusions
On this section...

- We are going to illustrate the use of our framework using two simple models of the survival probability of quarkonium.
On this section...

- We are going to illustrate the use of our framework using two simple models of the survival probability of quarkonium.
- A pNRQCD inspired model.
On this section...

- We are going to illustrate the use of our framework using two simple models of the survival probability of quarkonium.
- A pNRQCD inspired model.
- A model that takes into account the finite energy gap between singlets and octets.
Computation of $R_{AA}$

$$R_{AB}(b) = \frac{N_{HQ}^{AB}(b)}{N_{HQ}^{pp} T_{AB}(b)}$$

where

$$N_{HQ}^{AB}(b) = N_{HQ}^{pp} \int d^2 s S_{HQ}^{sh}(s, b) S_{med}(s, b)$$

and

$$T_{AB}(b) = \int d^2 s T_A \left( s + \frac{b}{2} \right) T_B \left( s - \frac{b}{2} \right)$$
Computation of $R_{AA}$

$$R_{AB}(b) = \frac{N_{HQ}^{AB}(b)}{N_{HQ}^{pp} T_{AB}(b)}$$

where

$$N_{HQ}^{AB}(b) = N_{HQ}^{pp} \int d^2s S_{HQ}^{sh}(s, b) S_{med}(s, b)$$

and

$$T_{AB}(b) = \int d^2s T_A \left( s + \frac{b}{2} \right) T_B \left( s - \frac{b}{2} \right)$$

- If $S_{med} = 1$ there are no medium effects. $R_{AA}^{CNM}$.
- If $S_{HQ}^{sh} = T_{AB}$ we ignore the triple Pomeron vertex. Original Glauber model. $R_{AA}^{T}$. 
pNRQCD inspired model

- The medium sees quarkonium as a small colour dipole and the binding energy is small.
The medium sees quarkonium as a small colour dipole and the binding energy is small.

The decay width goes like $\langle r^2 \rangle T^3$. 
pNRQCD inspired model

- The medium sees quarkonium as a small colour dipole and the binding energy is small.
- The decay width goes like $\langle r^2 \rangle T^3$.
- We assume Bjorken evolution of the medium.
pNRQCD inspired model

- The medium sees quarkonium as a small colour dipole and the binding energy is small.
- The decay width goes like $\langle r^2 \rangle T^3$.
- We assume Bjorken evolution of the medium.
- $S_{med}$ is

$$S_{med}(s, b) = \begin{cases} \left( \frac{T_f}{T_0(s, b)} \right)^{3t_0 \Gamma(s, b, t_0)} & T_0(s, b) \geq T_f \\ 1 & T_0(s, b) < T_f \end{cases}$$
pNRQCD inspired model
Gap model

- Model based on Blaizot and Escobedo (2021). The model uses data on the static potential from Lafferty and Rothkopf (2020).

\[
\text{med}(s, b) = \begin{cases} 
  e^{-3aT_0(s, b)3t_0}b^2e^{-bT_0(s, b)} & \text{if } T_0(s, b) > T_f \\
  \frac{1}{2}e^{-bT_f} & \text{if } T_0(s, b) \leq T_f
\end{cases}
\]
Gap model

- Model based on Blaizot and Escobedo (2021). The model uses data on the static potential from Lafferty and Rothkopf (2020).
- The decay width is computed numerically but can be fitted with a simple analytical formula.

\[
S_{\text{med}}(s, b) = \begin{cases} 
  e^{-3aT_0(s, b)}t_0b^2 & \text{if } T_0(s, b) > T_f \\
  1 + bT_0(s, b) - e^{-bT_f} & \text{if } T_0(s, b) \leq T_f
\end{cases}
\]
Gap model

- Model based on Blaizot and Escobedo (2021). The model uses data on the static potential from Lafferty and Rothkopf (2020).
- The decay width is computed numerically but can be fitted with a simple analytical formula.
- The model takes into account the finite value of the binding energy.
**Gap model**

- Model based on Blaizot and Escobedo (2021). The model uses data on the static potential from Lafferty and Rothkopf (2020).
- The decay width is computed numerically but can be fitted with a simple analytical formula.
- The model takes into account the finite value of the binding energy.
- $S_{med}$ is

\[
S_{med}(s, b) = \begin{cases} 
    e^{ - \frac{3aT_0(s,b)^3t_0}{b^2} \left( e^{-\frac{b}{T_0(s,b)}} \left( 1 + \frac{b}{T_0(s,b)} \right) - e^{-\frac{b}{T_f}} \left( 1 + \frac{b}{T_f} \right) \right) } & T_0(s, b) > T_f \\
    1 & T_0(s, b) \leq T_f
\end{cases}
\]
Gap model

![Graph showing the behavior of various ratios as a function of Npart]

- $R_{AA}$
- $R_{AA}^{CNM}$
- $R_{NN}^T$
Outline

1. Introduction
2. Initial-effect model
3. The initial temperature
4. Computation of $R_{AA}$
5. Conclusions
Conclusions

- The initial temperature follows closely $n_{\text{part}}$. 
Conclusions

- The initial temperature follows closely $n_{\text{part}}$.
- The temperature seen by quarkonium is actually quite close to the temperature at the center of the plateau.
Conclusions

- The initial temperature follows closely $n_{part}$.
- The temperature seen by quarkonium is actually quite close to the temperature at the center of the plateau.
- Suppressions due to initial effects and medium effects do not simply add up. Need to be discussed for each medium model.
Conclusions

- The initial temperature follows closely $n_{part}$.
- The temperature seen by quarkonium is actually quite close to the temperature at the center of the plateau.
- Suppressions due to initial effects and medium effects do not simply add up. Need to be discussed for each medium model.
- Qualitatively, the suppression due to initial effects is less dependent on centrality.
Conclusions

- The initial temperature follows closely $n_{part}$.
- The temperature seen by quarkonium is actually quite close to the temperature at the center of the plateau.
- Suppressions due to initial effects and medium effects do not simply add up. Need to be discussed for each medium model.
- Qualitatively, the suppression due to initial effects is less dependent on centrality.
- We have developed a simple framework to include initial state effects given $S_{med}$. 