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

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References

- Blaizot and Escobedo, Quantum and classical dynamics of heavy quarks in a quark-gluon plasma, JHEP 06 (2018) 034.
- Blaizot and Escobedo, Approach to equilibrium of a quarkonium in a quark-gluon plasma, Phys.Rev.D 98 (2018) 7, 074007.
- Blaizot and Escobedo, Phenomenological study of quarkonium suppression and the impact of the energy gap between singlets and octets, Phys.Rev.D 104 (2021) 5, 054034

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- Heavy quarkonium is a bound state of heavy quarks, whose mass is larger than Λ_{QCD}.
- Heavy quarks can only be created at the beginning of the collision. It is a hard process.
- However, the existence of a medium changes the probability that a bound state is formed and its lifetime.
- Measuring R_{AA}, the ratio of quarkonium states measured in heavy-ion collisions divided by the naive extrapolation of pp data, we can extract information about the medium.

Quarkonium as an Open quantum system

- We consider a *universe* consisting in heavy quarks (system) in a medium of light quarks and gluons (environment). The density matrix $\rho(S, E)$ describes the state of the universe. Its evolution is unitary.

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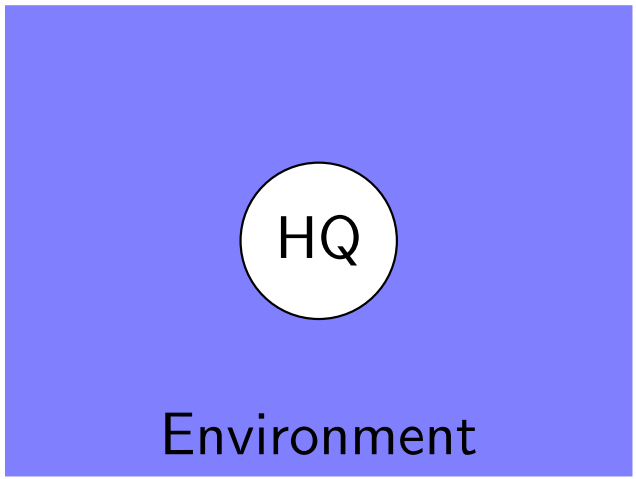

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$$\frac{d\rho}{dt} = -i[H, \rho(t)] + \mathcal{F}(t, \rho(t))$$

- We can recover the Schrödinger equation and the Boltzmann equation as limits of the master equation in specific regimes.
- We need to derive the master equation from QCD. This has been done in:
  - Perturbation theory. Akamatsu (2015,2020), Blaizot and Escobedo (2017,2018).
  - Potential non-relativistic QCD (pNRQCD) in the $\frac{1}{r} \gg T$ regime. Brambilla et al. (2016,2017).

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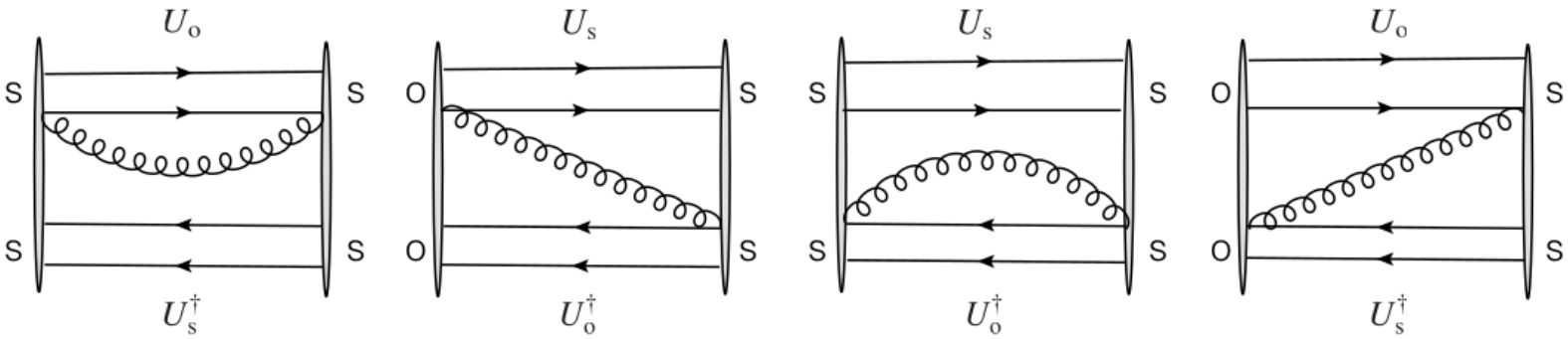
- These nice properties are lost in QCD. Crucial role of the energy gap between singlets and octets.
- We wish to understand what is the phenomenological impact of taking into account this energy gap.

Plan

The evolution of the density matrix

Diagrams that connect whatever state at time t with a singlet at time $t + dt$.



$U_{s,o}$ is the LO time evolution operator. The quantum master equation can be written schematically as

$$\frac{\mathrm{d}\mathcal{D}_Q}{\mathrm{d}t} + i[H_Q, \mathcal{D}_Q(t)] =$$

$$-\int_{\boldsymbol{x}\boldsymbol{x}'}\int_0^{t-t_0} \mathrm{d}\tau\,[n^A_{\boldsymbol{x}}, U_Q(\tau) n^A_{\boldsymbol{x}'} \mathcal{D}_Q(t-\tau) U_Q^\dagger(\tau)]\,\Delta^>(\tau; \boldsymbol{x}-\boldsymbol{x}'))$$

$$-\int_{\boldsymbol{x}\boldsymbol{x}'}\int_0^{t-t_0} \mathrm{d}\tau\,[U_Q(\tau)\mathcal{D}_Q(t-\tau) n^A_{\boldsymbol{x}'} U_Q^\dagger(\tau), n^A_{\boldsymbol{x}}]\,\Delta^<(\tau; \boldsymbol{x}-\boldsymbol{x}'),$$

where we have set $t - t' = \tau$.

$U_{s,o}$ and energy conservation

The role of $U_{s,o}$ is to inform the master equation of the size and the sign of the energy different between the state at t' and the state at t.

- If we make the approximation $U_{s,o} = 1$ all transitions are equally likely.
- If $U_{s,o}$ is not approximated there are some transitions which are more likely because they liberate energy while others are less likely because they need to absorb energy.
- $\frac{\Gamma(A \to B)}{\Gamma(B \to A)}$ is fixed by fluctuation-dissipation theorem.
- This is very important to understand QCD. An octet to singlet transition is always energetically favourable while the opposite happens for singlet to octet.

The classical limit

The relation between the density matrix in the Schrödinger picture and in interaction picture is the following

$$D(t) = e^{-iHt} D_I(t) e^{iHt}$$

In the large time limit non-diagonal elements are suppressed by the fast oscillations

$$\mathcal{D}(t) = \sum_{nm} e^{-i(E_n - E_m)t} |n\rangle\langle n|\mathcal{D}_I(t)|m\rangle\langle m| \sim p_n(t)|n\rangle\langle n|$$

Evolution equation for the density matrix $\rightarrow$ rate equation

Rate equations

In a finite volume (octet levels are discrete)

$$\frac{\mathrm{d}p_n^s}{\mathrm{d}t} = 4g^2 C_F \sum_m \left(p_m^o - p_n^s e^{-\frac{E_m^o - E_n^s}{T}} \right) \int_{\boldsymbol{q}} \Gamma^{>}(E_m^o - E_n^s, \boldsymbol{q}) |\langle n^s | \mathcal{S}_{\boldsymbol{q}\cdot\boldsymbol{r}} | m^o \rangle|^2$$

and

$$\begin{aligned}
\frac{\mathrm{d}p_m^o}{\mathrm{d}t} = & -\frac{2g^2}{N_c} \sum_n \left(p_m^o - p_n^s e^{-\frac{E_m^o - E_n^s}{T}} \right) \int_{\boldsymbol{q}} \Gamma^{>}(E_m^o - E_n^s, \boldsymbol{q}) |\langle n^s | \mathcal{S}_{\boldsymbol{q}\cdot\boldsymbol{r}} | m^o \rangle|^2 \\
& - \frac{g^2(N_c^2 - 4)}{N_c} \sum_k \left(p_m^o - p_k^o e^{-\frac{E_m^o - E_k^o}{T}} \right) \int_{\boldsymbol{q}} \Gamma^{>}(E_m^o - E_k^o, \boldsymbol{q}) |\langle m^o | \mathcal{S}_{\boldsymbol{q}\cdot\boldsymbol{r}} | k^o \rangle|^2 \\
& - g^2 N_c \sum_k \left(p_m^o - p_k^o e^{-\frac{E_m^o - E_k^o}{T}} \right) \int_{\boldsymbol{q}} \Gamma^{>}(E_m^o - E_k^o, \boldsymbol{q}) |\langle m^o | \mathcal{C}_{\boldsymbol{q}\cdot\boldsymbol{r}} | k^o \rangle|^2 .
\end{aligned}$$

Free energy minimization

$$\frac{\mathrm{d}F}{\mathrm{d}t} = -4g^2 C_F T \sum_{nm} \log\left(\frac{p_m^o}{p_n^s e^{-\frac{E_m^o - E_n^s}{T}}}\right)\left(p_m^o - p_n^s e^{-\frac{E_m^o - E_n^s}{T}}\right) \times \int_{\boldsymbol{q}} \Delta^{>}(E_m^o - E_n^s, \mathbf{q}) |\langle n^s | \mathcal{S}_{\boldsymbol{r}} | m^o \rangle|^2$$

$$-\frac{g^2 T(N_c^2 - 4)}{2N_c} \sum_{mk} \log\left(\frac{p_m^o}{p_k^o e^{-\frac{E_m^o - E_k^o}{T}}}\right)\left(p_m^o - p_k^o e^{-\frac{E_m^o - E_k^o}{T}}\right) \times \int_{\boldsymbol{q}} \Delta^{>}(E_m^o - E_k^o, \mathbf{q}) |\langle m^o | \mathcal{S}_{\boldsymbol{r}} | k^o \rangle|^2$$

$$-\frac{g^2 T N_c}{2} \sum_{mk} \log\left(\frac{p_m^o}{p_k^o e^{-\frac{E_m^o - E_k^o}{T}}}\right)\left(p_m^o - p_k^o e^{-\frac{E_m^o - E_k^o}{T}}\right) \times \int_{\boldsymbol{q}} \Delta^{>}(E_m^o - E_k^o, \mathbf{q}) |\langle m^o | \mathcal{C}_{\boldsymbol{q}\cdot\boldsymbol{r}} | k^o \rangle|^2 \leq 0\,.$$

Summary

- We can justify a rate equation if ΔE (binding energy difference) is much bigger than the decay width.
- This can be justified (in some cases) for the singlet to octet transition. Not for octet to octet at a large volume (continuous spectrum).
- However, octet to octet transitions is similar to the QED case, which is reasonably described with a Langevin equation.

Conclusion: We can combine a rate equation for singlet to octet transitions with a Langevin equation for octet to octet.

Our model

- In the large N_c limit the octet potential is zero.
- As an illustration we consider only one singlet eigenvalue (the 1S). This is not too bad since the 2S melts at a much smaller temperature.

$$\frac{\mathrm{d}p^{\mathrm{s}}}{\mathrm{d}t} = g^2 C_F \int_{\mathbf{p}} \left(p^{\mathrm{o}}_{\mathbf{p}} - p^{\mathrm{s}} \mathrm{e}^{-\frac{E^{\mathrm{o}}_{\mathbf{p}} - E^{\mathrm{s}}}{T}} \right) \int_{\mathbf{q}} \Delta^{>}(\omega^{\mathrm{o}}_{\mathbf{p}} - E^{\mathrm{s}}, \mathbf{q}) |\langle \mathrm{s}|\mathcal{S}_{\mathbf{q}\cdot\hat{\boldsymbol{r}}}|\mathrm{o}, \mathbf{p}\rangle|^2 \,,$$

and

$$\frac{\partial p^{\mathrm{o}}_{\mathbf{p}}}{\partial t} - \gamma \nabla(\mathbf{p} p^{\mathrm{o}}_{\mathbf{p}}) - \frac{T\gamma M}{2} \Delta^2 p^{\mathrm{o}}_{\mathbf{p}} =$$
$$- \frac{g^2}{2N_c} \frac{1}{\Omega} \left(p^{\mathrm{o}}_{\mathbf{p}} - p^{\mathrm{s}} \mathrm{e}^{-\frac{E^{\mathrm{o}}_{\mathbf{p}} - E^{\mathrm{s}}}{T}} \right) \int_{\mathbf{q}} \Delta^{>}(\omega^{\mathrm{o}}_{\mathbf{p}} - E^{\mathrm{s}}, \mathbf{q}) |\langle \mathrm{s}|\mathcal{S}_{\mathbf{q}\cdot\hat{\boldsymbol{r}}}|\mathrm{o}, \mathbf{p}\rangle|^2 \,,$$

Our model. Results

	$\Omega = 1\,\mathrm{fm}^3$			$\Omega = 100\,\mathrm{fm}^3$		
	$5\,\mathrm{fm/c}$	$100\,\mathrm{fm/c}$	eq.	$5\,\mathrm{fm/c}$	$100\,\mathrm{fm/c}$	eq.
$T = 200\,\mathrm{MeV}$	0.86	0.136	0.0814	0.85	0.0438	0.00089
$T = 400\,\mathrm{MeV}$	0.39	0.0515	0.0175	0.36	0.0002	0.00018

Table: p^s as obtained by solving eqs. in previous slide

Remarks

- The gap $E^o_{\mathbf{p}} - E^s$ suppresses the singlet decay width, helping to make the results compatible with experimental observations.
- E^s depends on the real part of the potential. Screening reduces the binding energy and this increases the decay width.
- The volume of the medium Ω suppresses the decay of octets into bound singlets. Also suppressed in the large-N_c limit.

Plan

Outline

In this section we are going to study the impact of considering the finite gap between singlets and octets in phenomenological applications. We are going to consider two different scenarios:

- HTL inspired case.
- Lattice inspired case, based on the static potential data of Lafferty and Rothkopf (2020).

We will compute R_{AA} for these two cases assuming Bjorken evolution of the medium.

Procedure

We solve the equation

$$\frac{dp_n}{dt} = -\Gamma_n p_n$$

and we compare the results that we get including (or not) the finite gap in the computation of Γ_n. For several temperatures:

1. We solve the Schrödinger equation to obtain the binding energy and the wave function.
2. We use the binding energy and the wave function to compute the decay width.

Once we have done this for several temperatures, we fit the decay width as a function of the temperature.

The decay width

$$\Gamma_s = 8\pi\alpha_s C_F \int_{\mathbf{p}} e^{-\frac{E_{\mathbf{p}}^{\mathrm{o}} - E^{\mathrm{s}}}{T}} \int_{\mathbf{q}} \Delta^{>}(E_{\mathbf{p}}^{\mathrm{o}} - E^{\mathrm{s}}, \mathbf{q}) |\langle \mathrm{s}| \sin\left(\frac{\mathbf{q}\cdot\hat{\mathbf{r}}}{2}\right) |\mathrm{o}, \mathbf{p}\rangle|^2$$

where $\Delta^{>}$ is the HTL A_0 propagator in the Coulomb gauge. If we neglect the energy gap between singlets and octets we obtain

$$\Gamma_s^0 = 8\pi\alpha_s C_F \int_{\mathbf{q}} \Delta^{>}(0, \mathbf{q}) \langle \mathrm{s}| \sin^2\left(\frac{\mathbf{q}\hat{\mathbf{r}}}{2}\right) |\mathrm{s}\rangle$$

Note that this is equal to the expectation value of the imaginary part of Laine potential.

Perturbative scenario

Potential

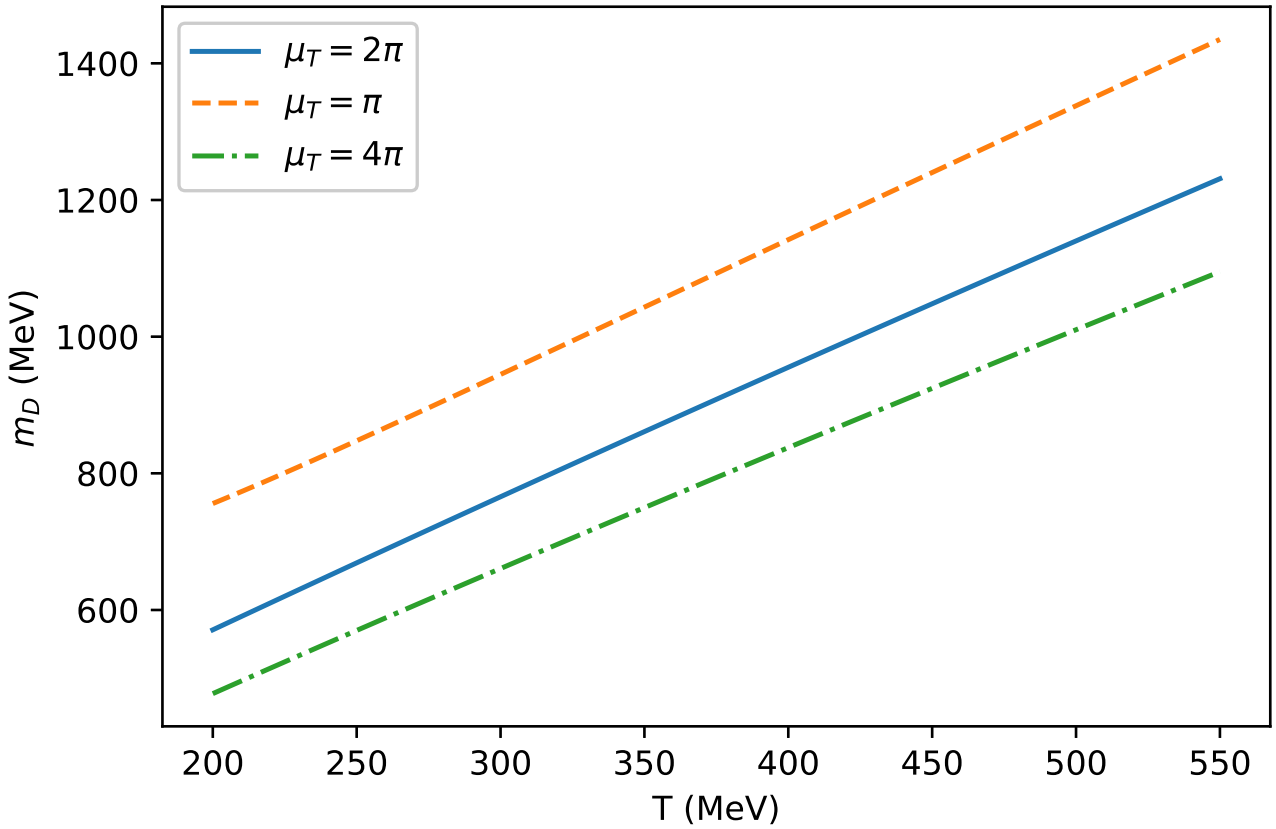
$$V_s(r) = -\frac{C_F \alpha_s(\mu_r) e^{-m_D(T,\mu_T) r}}{r}$$

where μ_r and μ_T are (independent) subtraction points. μ_r is either $\frac{1}{2a_0}$, $\frac{1}{a_0}$ or $\frac{2}{a_0}$, with a_0 the Bohr radius. μ_T is either πT, $2\pi T$ and $4\pi T$.

$$\frac{1}{a_0} = \frac{M C_F \alpha_s(1/a_0)}{2}, \qquad a_0 = 0.149\, fm$$

Perturbative scenario

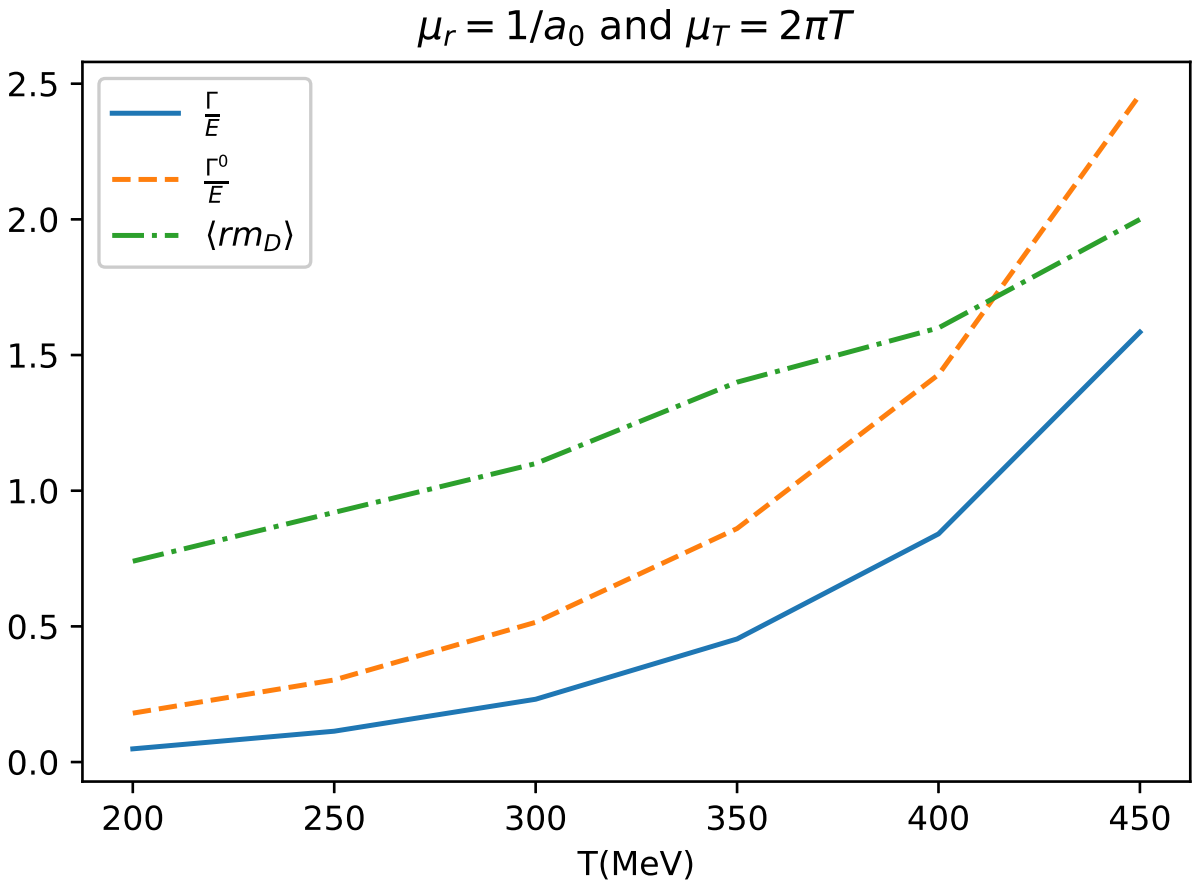
The Debye mass



$$m_D(T) = \sqrt{\frac{4\pi\alpha_s(\mu_T)(N_c + T_F N_F)}{3}}\, T$$

Perturbative scenario

Dimensionless quantities for $\Upsilon(1S)$



For $\Upsilon(2S)$ the condition $E \gg \Gamma$ is not fulfilled for this scenario.

Perturbative scenario

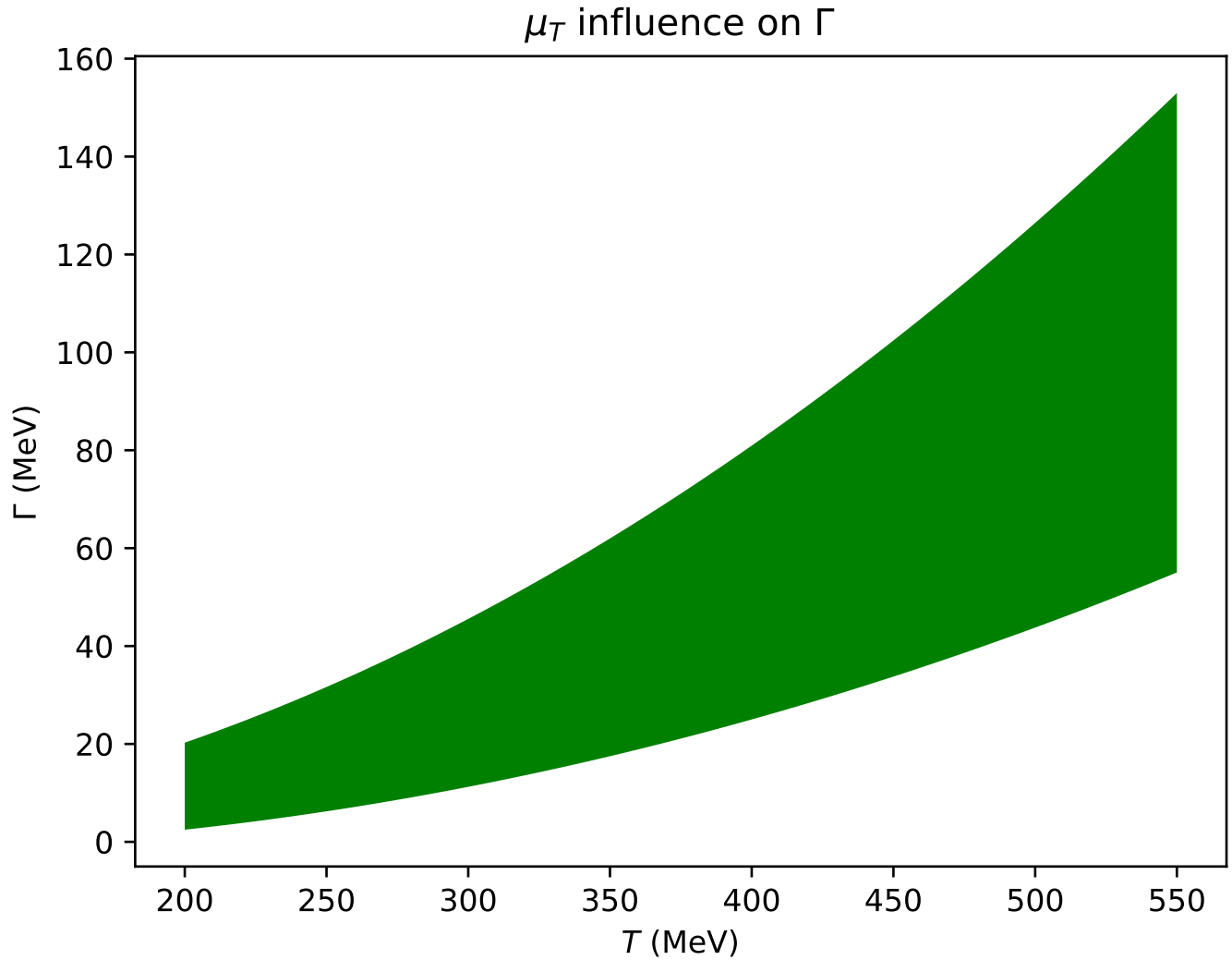
Γ, fit function

$$\Gamma \sim aT + bT^2$$

This function fits well the values of Γ for different temperatures. We computed the values of Γ from $T = 200\,MeV$ to $550\,MeV$ in intervals of $50\,MeV$

Perturbative scenario

Γ of $\Upsilon(1S)$



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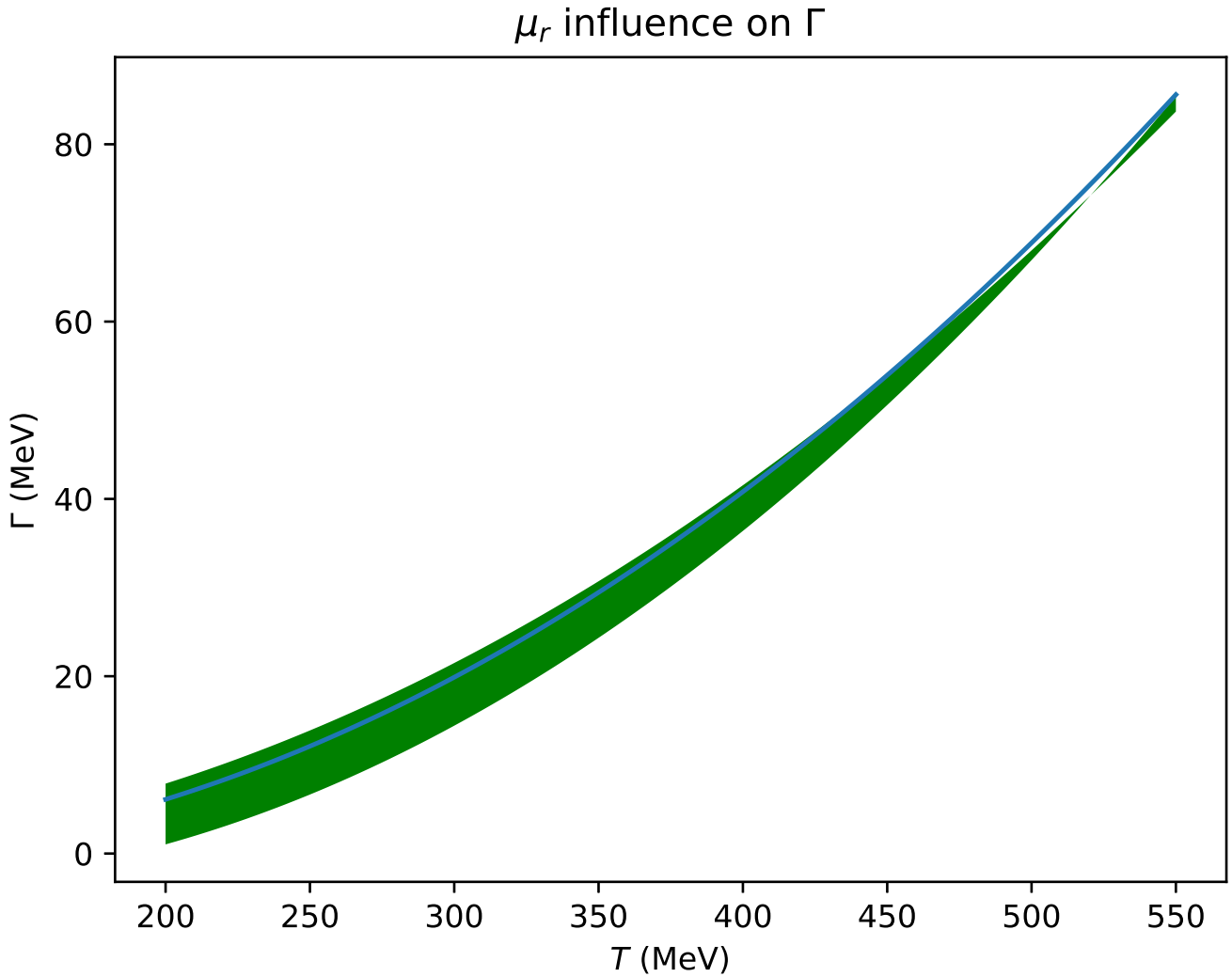
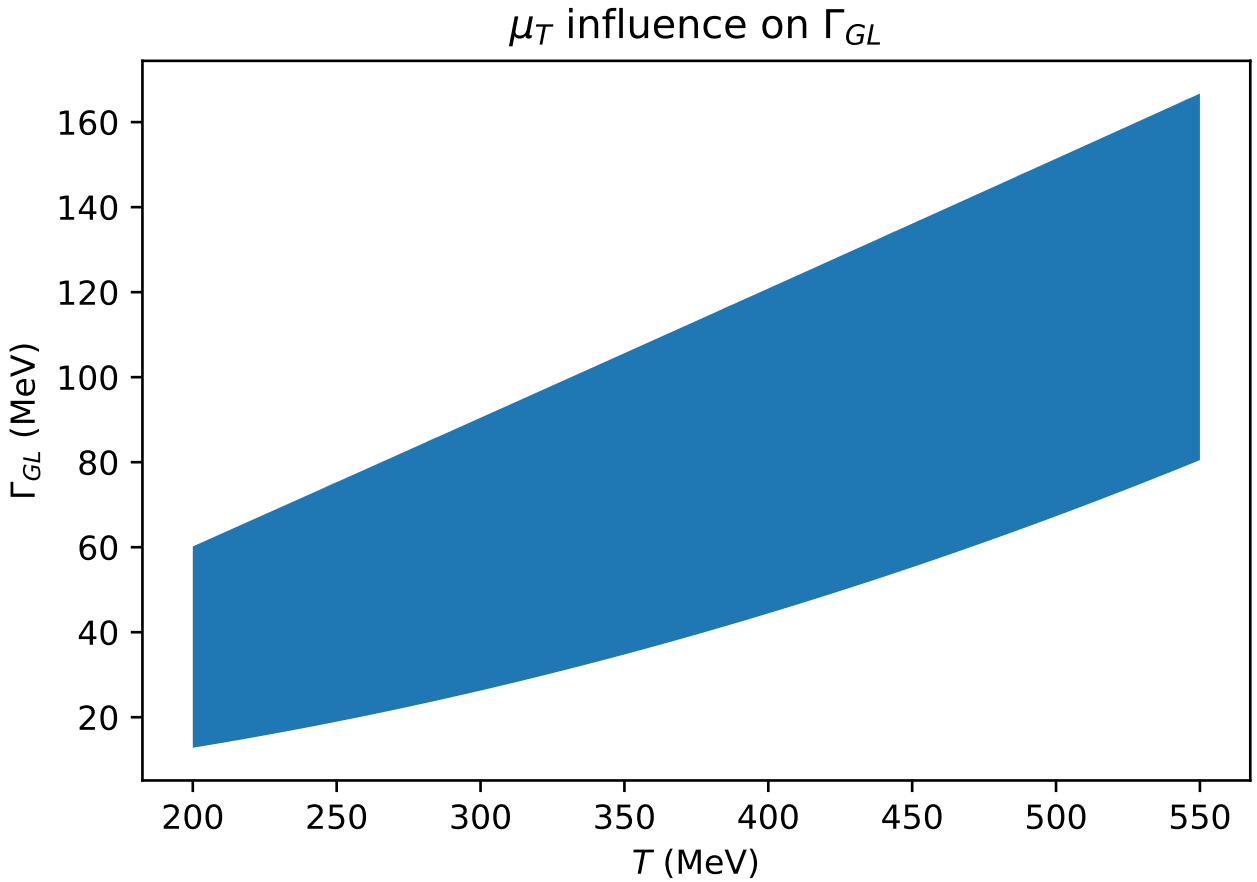


Perturbative scenario

Γ of $\Upsilon(1S)$, without gap



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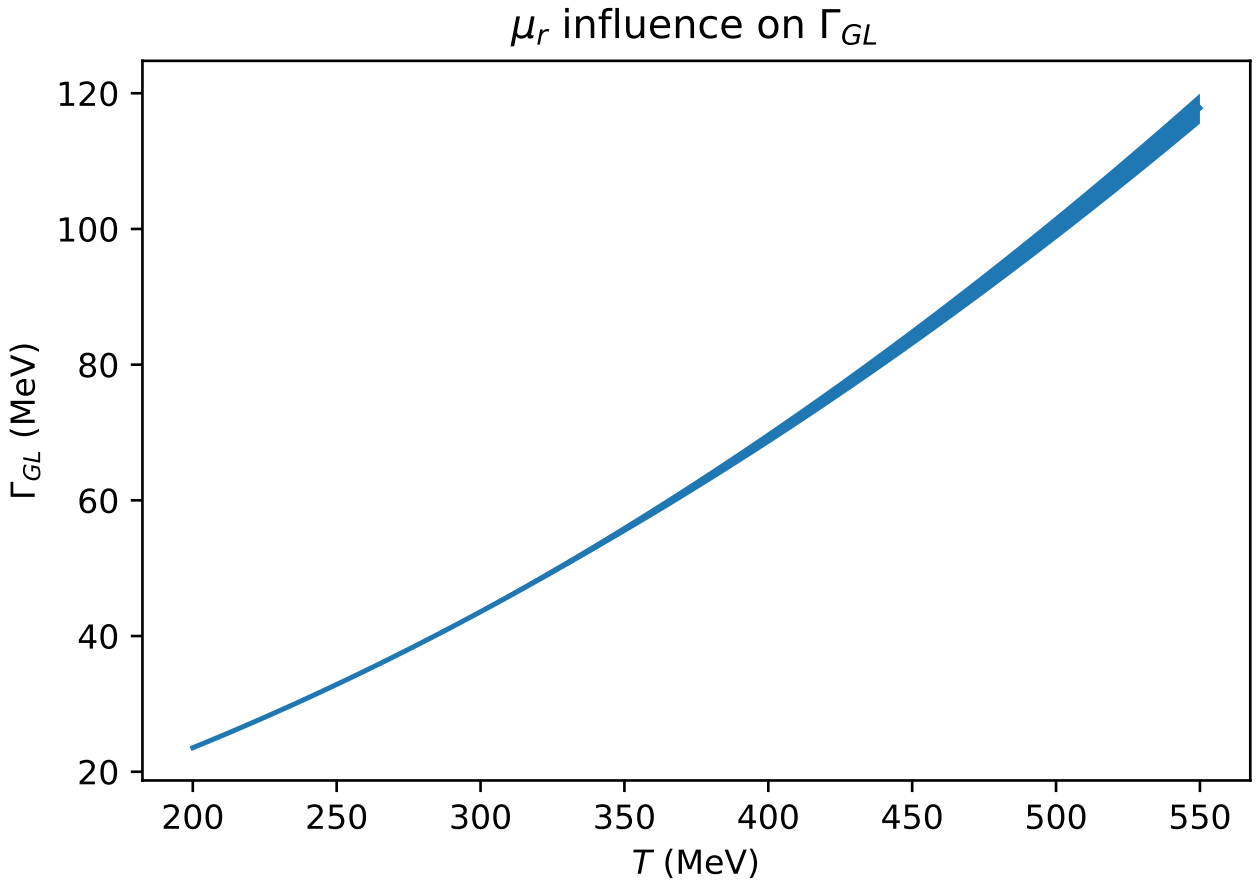

Perturbative scenario

Survival probability

$$S_{(1S)}(\boldsymbol{b},\boldsymbol{s}) = \mathrm{e}^{-1.5aT_0(\boldsymbol{b},\boldsymbol{s})t_0\left(\left(\frac{T_0(\boldsymbol{b},\boldsymbol{s})}{T_f}\right)^2-1\right)-3bT_0(\boldsymbol{b},\boldsymbol{s})^2t_0\left(\frac{T_0(\boldsymbol{b},\boldsymbol{s})}{T_f}-1\right)}$$

Survival probability of a $\Upsilon(1S)$ state with $\Gamma = aT + bT^2$ in a medium that follows Bjorken evolution up to a temperature $T_f = 200\,MeV$.

Lattice scenario

The potential

$$V_s(r) = -\frac{\alpha e^{-m_D r}}{r} - \sigma r e^{-m_D r}\left(1 + \frac{2}{m_D r}\right)$$

- Potential used in Lafferty and Rothkopf (2020) to fit lattice data. m_D is a fit parameter.

Lattice scenario

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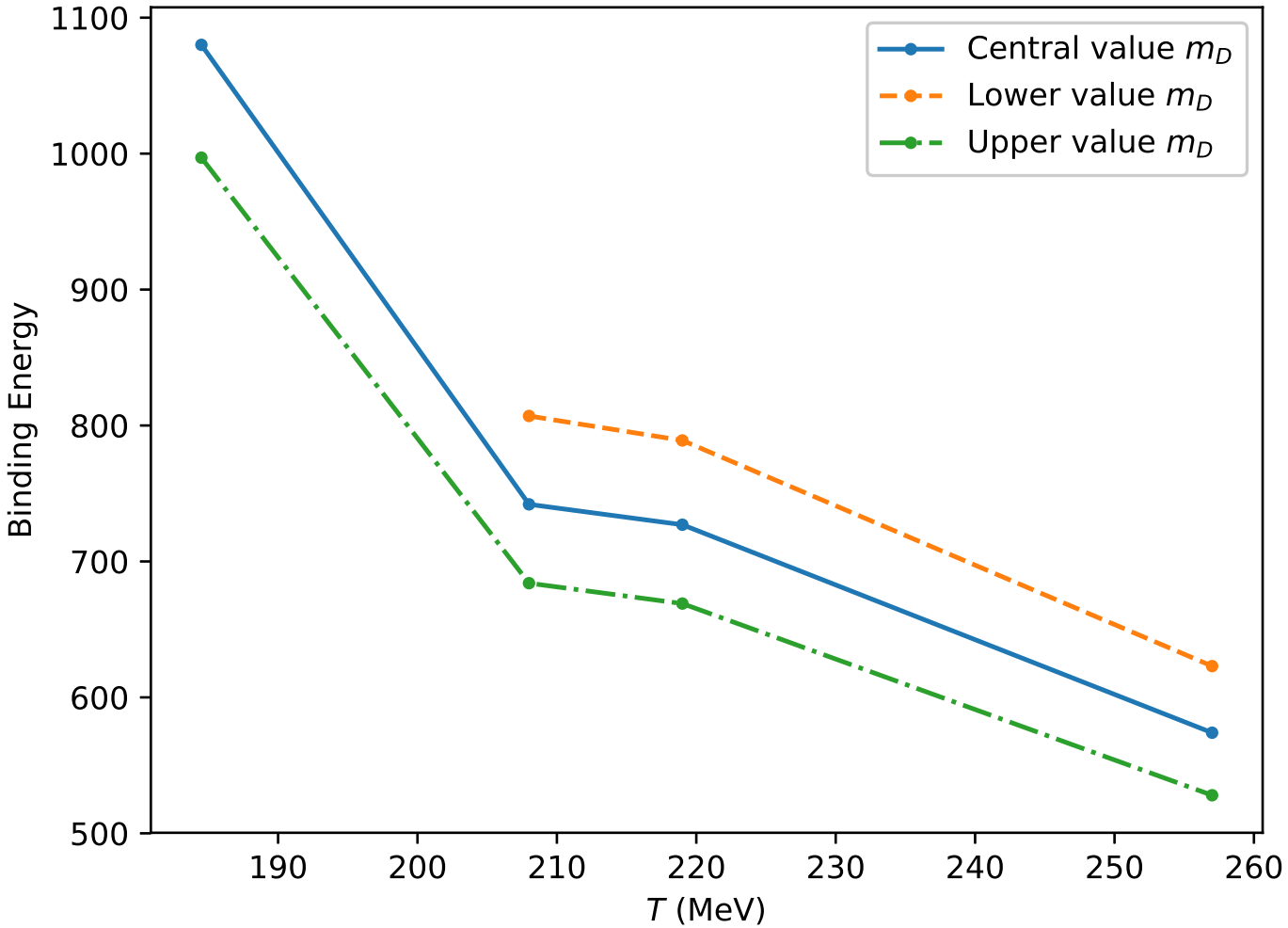
- We observe that the biggest source of uncertainty from this fit comes from the parameter m_D.
- We use this potential for temperatures such that the energy gap is smaller $2M_B - M_{\Upsilon(1S)}$. If this is not the case we assume that there are no thermal modifications.

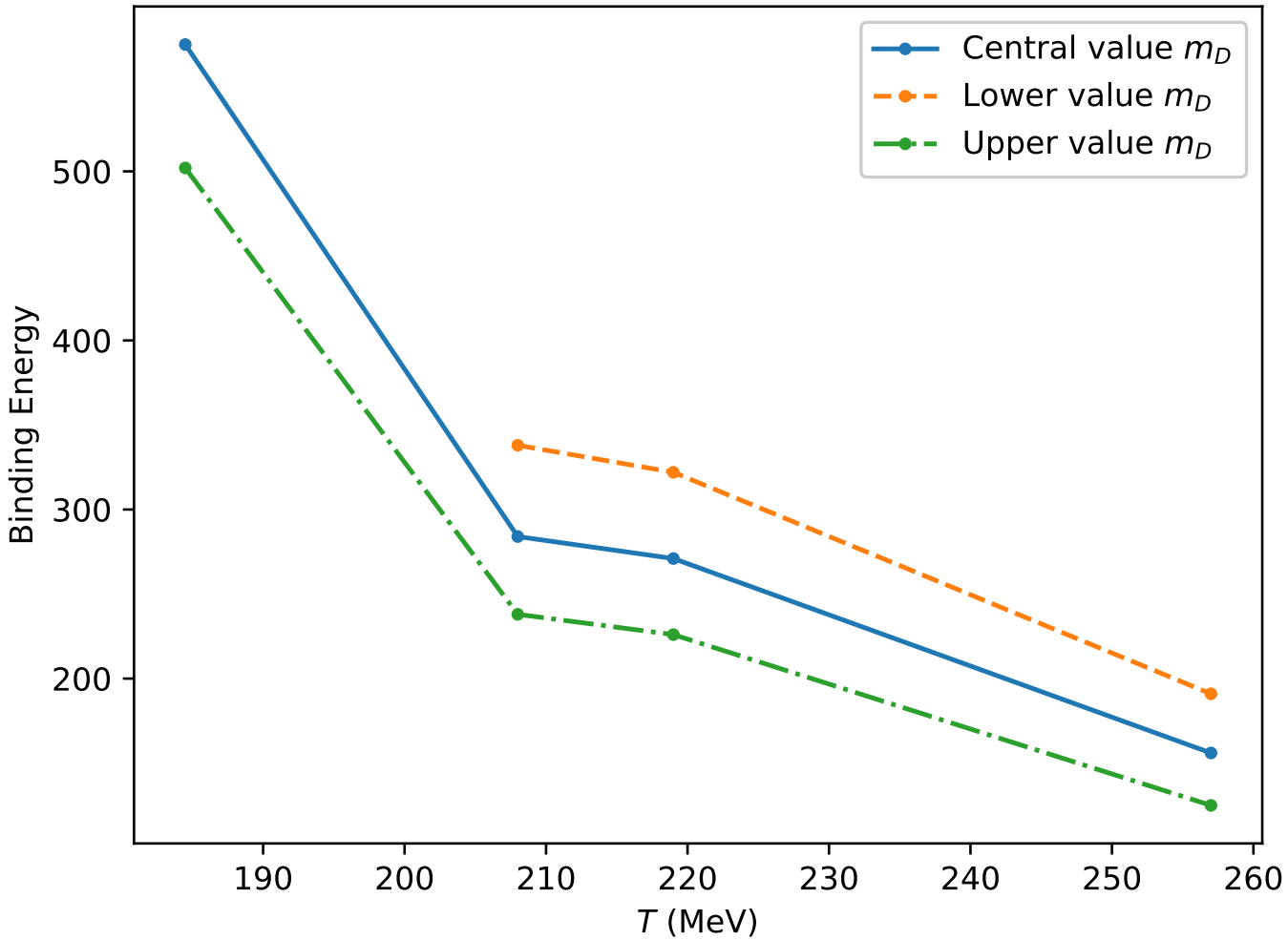
Lattice scenario

$\Upsilon(1S)$ binding energy



Lattice scenario

$\Upsilon(2S)$ binding energy



Lattice scenario

Fit function

For $\Upsilon(1S)$

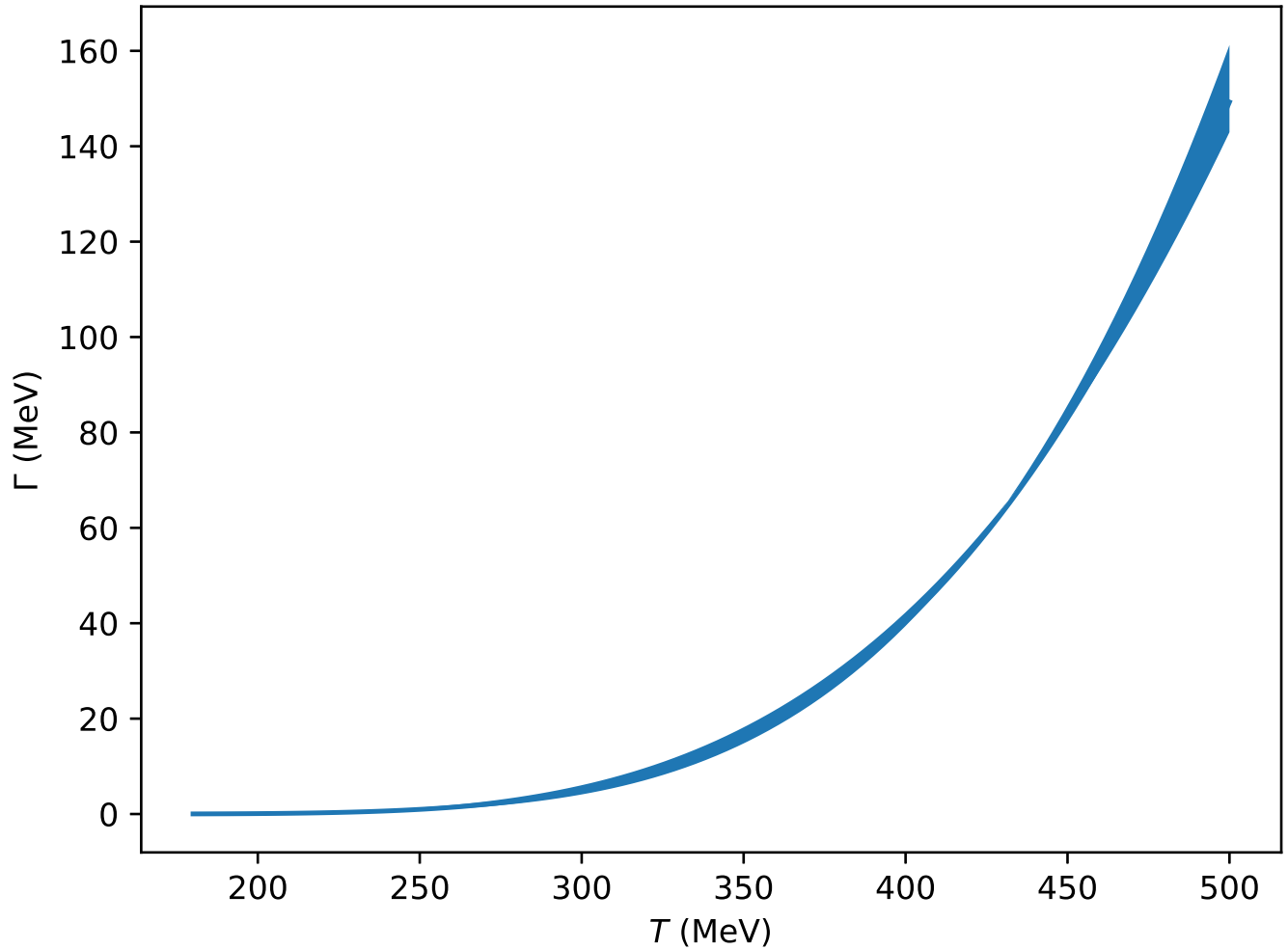
$$\Gamma_{\mathrm{s}} \sim \tilde{a} T e^{-\frac{\tilde{b}}{T}}$$

For $\Upsilon(2S)$

$$\Gamma \sim aT + bT^2$$

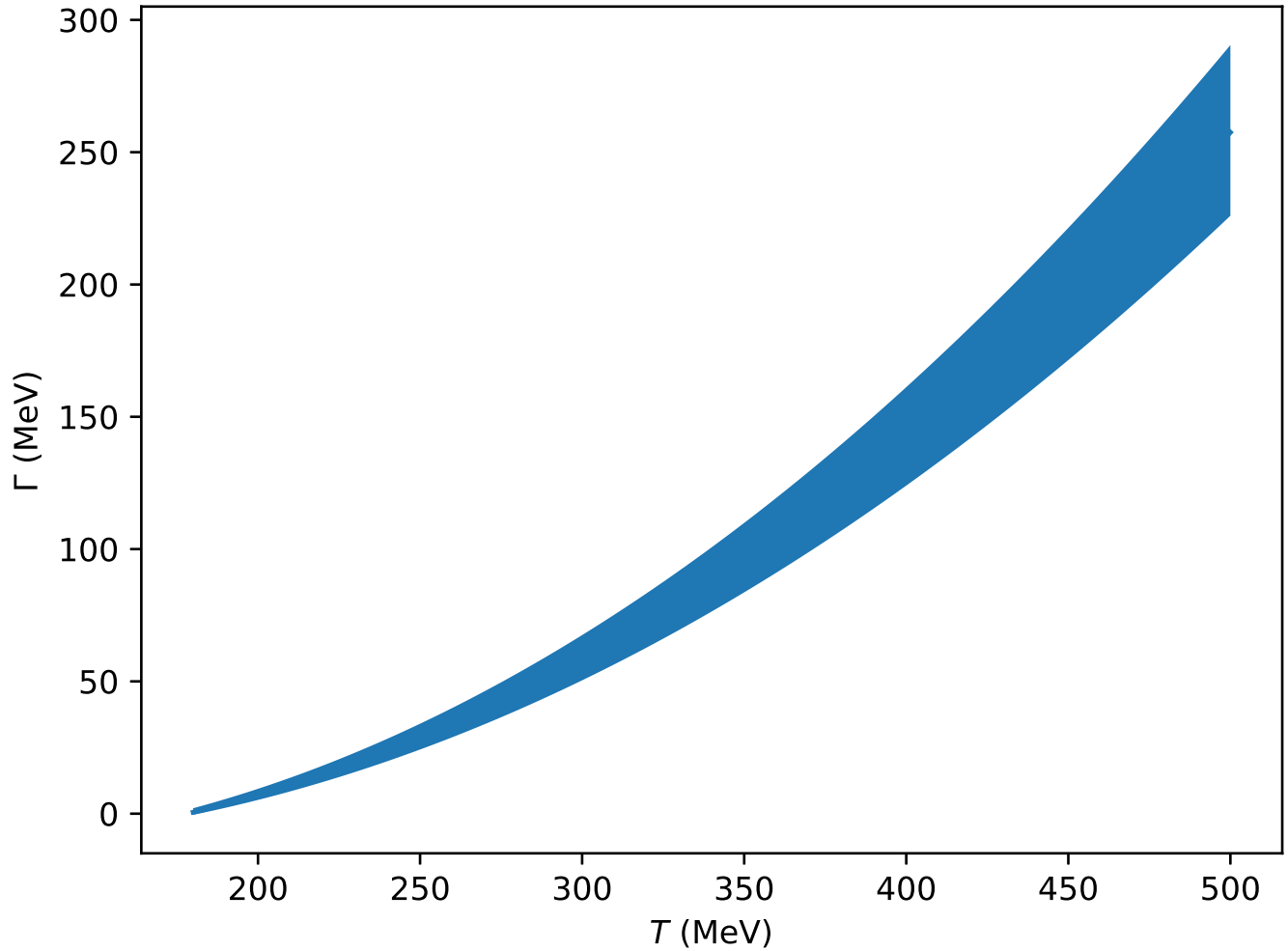
Lattice scenario

$\Upsilon(1S)$ decay width



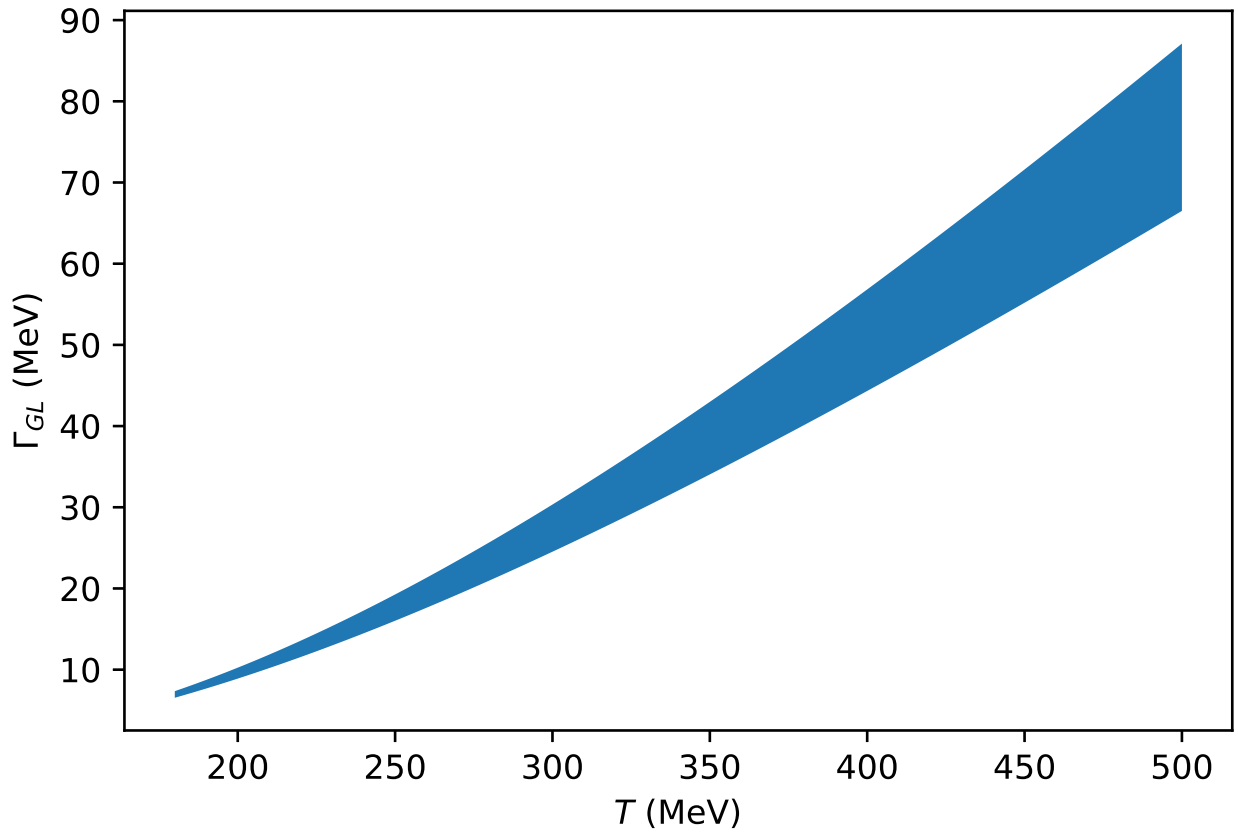
Lattice scenario

$\Upsilon(2S)$ decay width



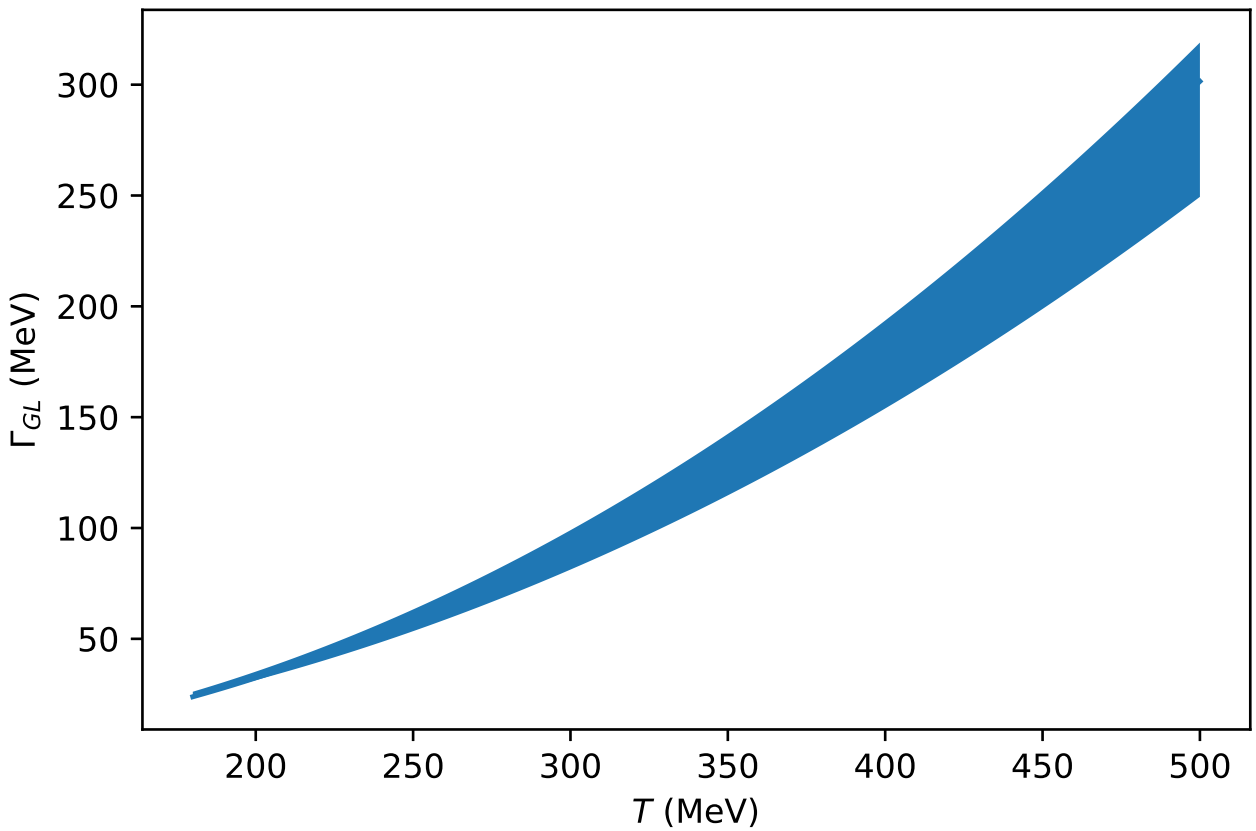
Lattice scenario

$\Upsilon(1S)$ decay width, without gap



Lattice scenario

$\Upsilon(2S)$ decay width, without gap



Lattice scenario

Survival probability

For $\Upsilon(1S)$

$$S_{(1S)}(\boldsymbol{b},\boldsymbol{s}) = e^{-\frac{3\tilde{a}T_0(\boldsymbol{b},\boldsymbol{s})^3 t_0}{\tilde{b}^2}\left(e^{-\frac{\tilde{b}}{T_0(b,s)}}\left(1+\frac{\tilde{b}}{T_0(\boldsymbol{b},\boldsymbol{s})}\right)-e^{-\frac{\tilde{b}}{T_f}}\left(1+\frac{\tilde{b}}{T_f}\right)\right)}$$

For $\Upsilon(2S)$

$$S_{(2S)}(\boldsymbol{b},\boldsymbol{s}) = \mathrm{e}^{-1.5aT_0(\boldsymbol{b},\boldsymbol{s})t_0\left(\left(\frac{T_0(\boldsymbol{b},\boldsymbol{s})}{T_f}\right)^2-1\right)-3bT_0(\boldsymbol{b},\boldsymbol{s})^2 t_0\left(\frac{T_0(\boldsymbol{b},\boldsymbol{s})}{T_f}-1\right)}$$

In both case $T_f = 180\,fm$

The temperature of the medium and its evolution

$$T_0(\boldsymbol{b},\boldsymbol{s}) = T_0(0,0)\left(\frac{T_A(\boldsymbol{s},0)\left[1-\left(1-\frac{\sigma T_A(\mathbf{s}-\mathbf{b},0)}{A}\right)^A\right]}{T_A(0,0)\left[1-\left(1-\frac{\sigma T_A(0,0)}{A}\right)^A\right]}\right)^{1/4}$$

We take $T_0(0,0) = 475 \times 1.05$ for $\sqrt{s} = 5.02\,\text{TeV}$ collisions at LHC.
We assume Bjorken flow with $t_0 = 0.6\,fm$

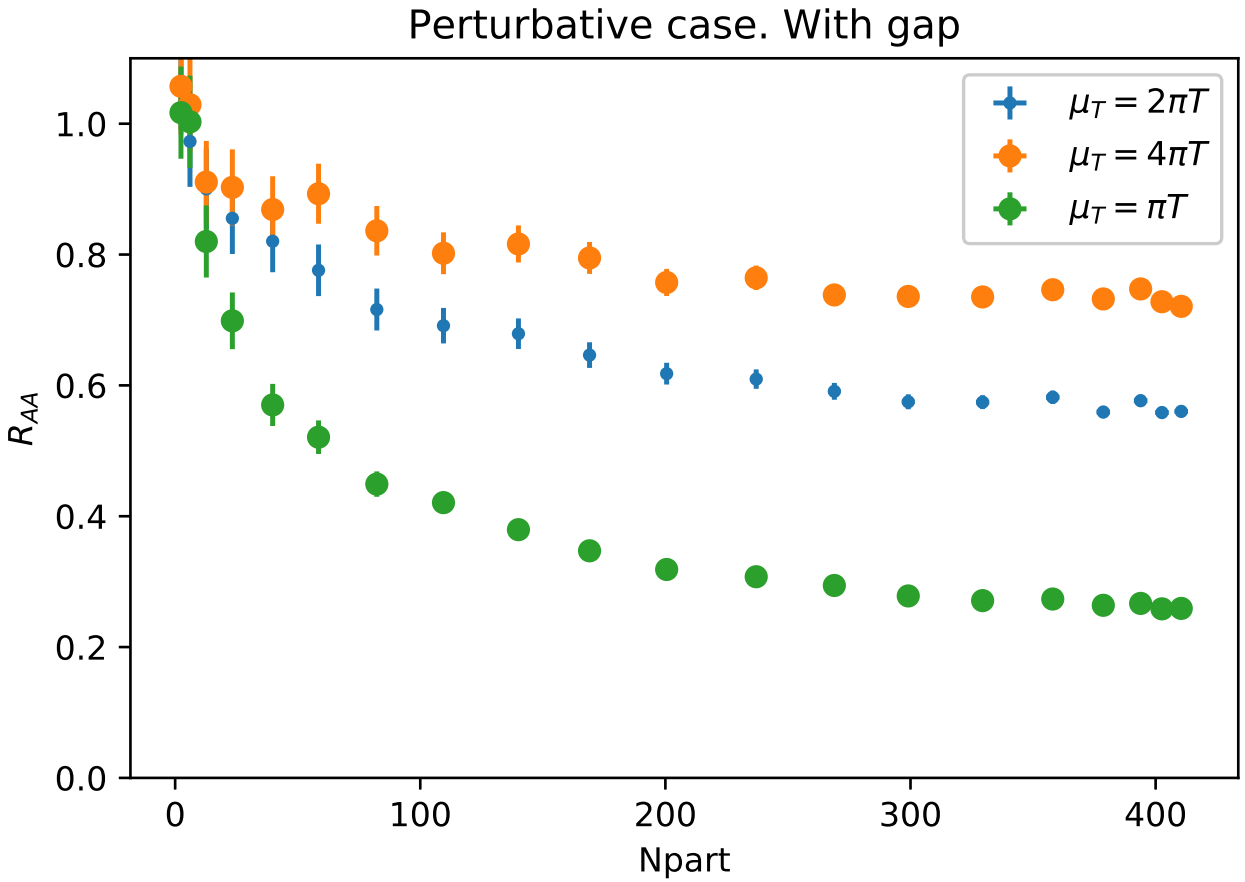
$$T(t,\boldsymbol{b},\boldsymbol{s}) = T_0(\boldsymbol{b},\boldsymbol{s})\left(\frac{t_0}{t}\right)^{\frac{1}{3}}$$

Computation of R_{AA}

$$R_{AA}(\boldsymbol{b}) = \frac{\int d^2\boldsymbol{s}\, T_A(\boldsymbol{s})\, T_A(\mathbf{s}-\mathbf{b}) S(\boldsymbol{b},\boldsymbol{s})}{\int d^2\boldsymbol{s}\, T_A(\boldsymbol{s})\, T_A(\mathbf{s}-\mathbf{b})}$$

where $S(\boldsymbol{b},\boldsymbol{s})$ is the survival probability.

R_{AA} in the perturbative scenario



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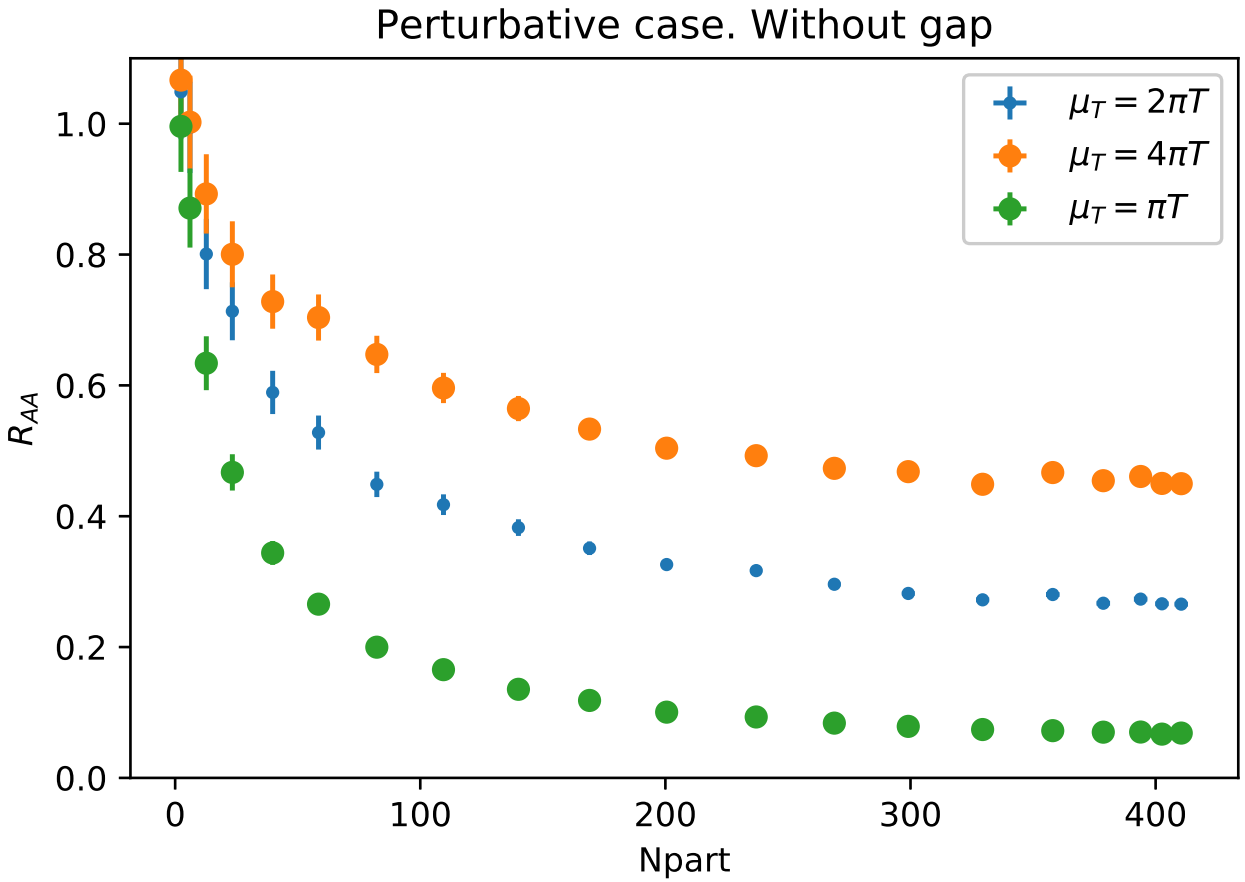
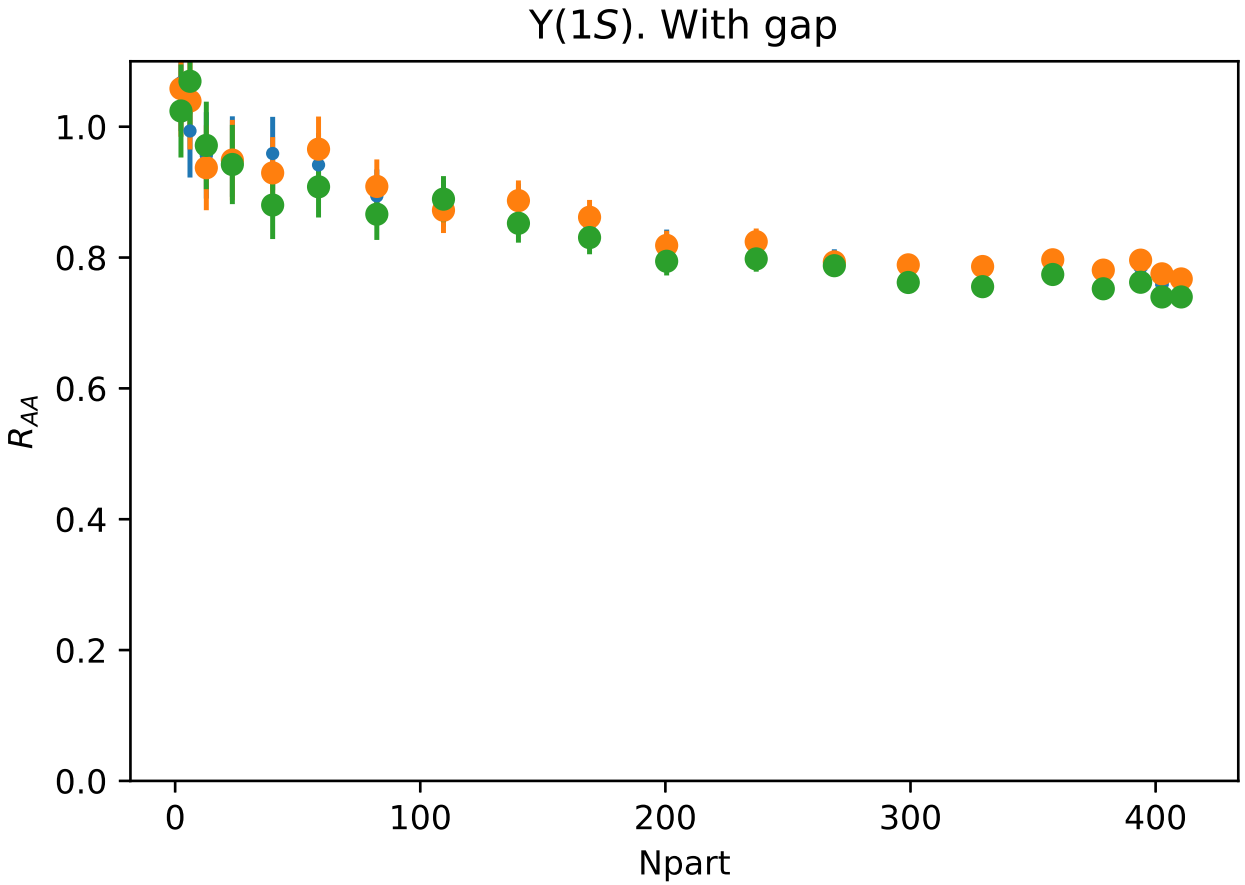
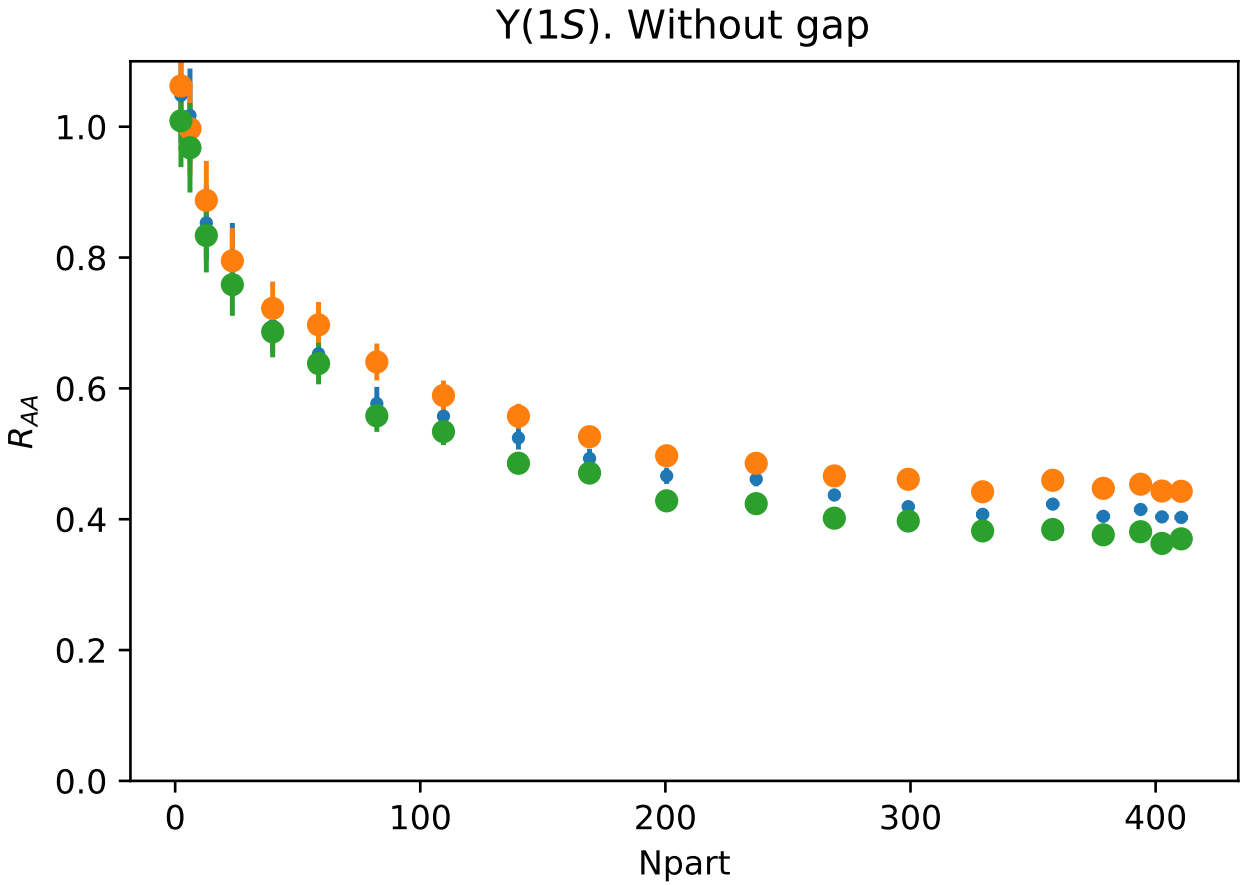


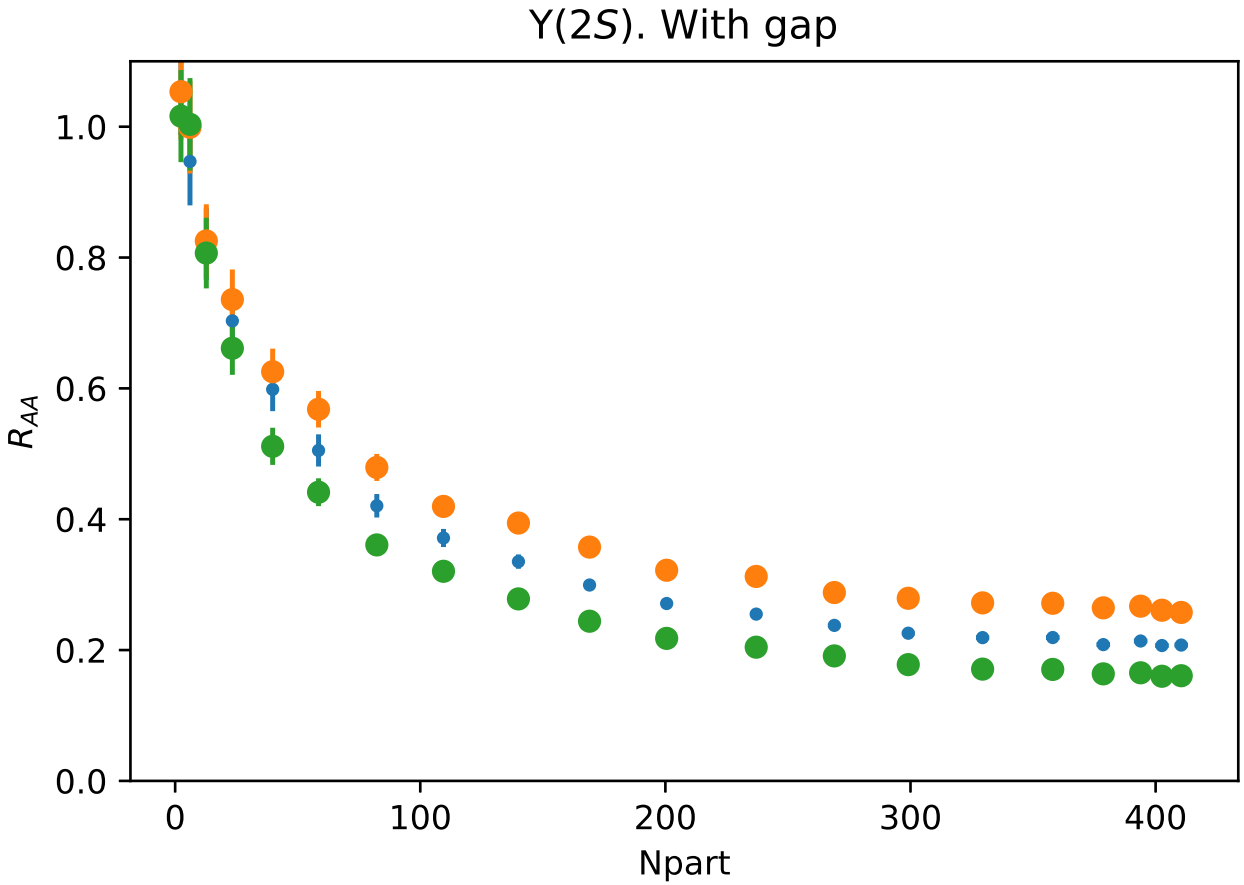
R_{AA} in the lattice scenario



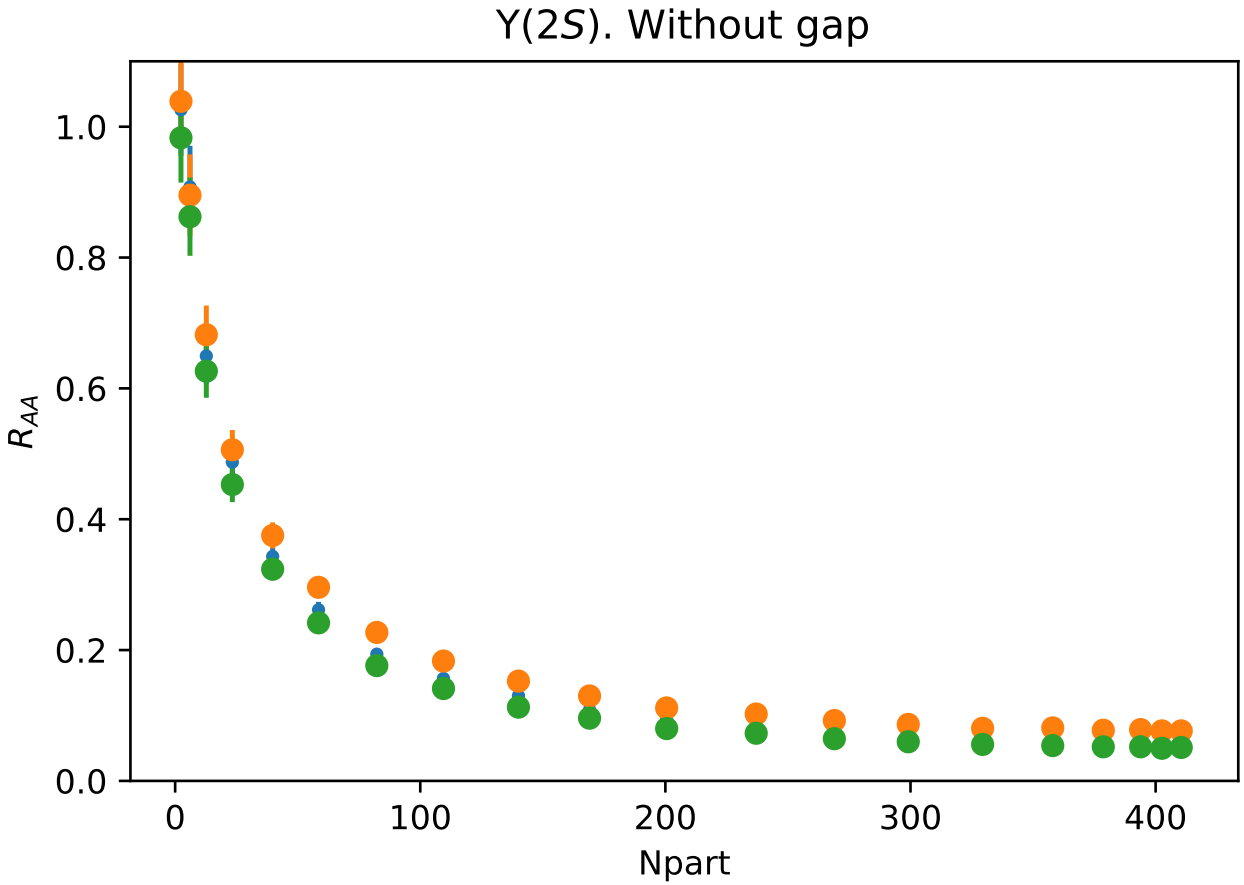
R_{AA} in the lattice scenario



R_{AA} in the lattice scenario



R_{AA} in the lattice scenario



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- The effect of the gap is around a factor of 2 in R_{AA} in all cases.
- The effect is larger in the lattice scenario. The reason is that the gap computed from the formula $2M_B - M_{\Upsilon(1S)}$ is larger than the gap computed from a Coulombic potential.

Conclusions

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- In the limit $E \gg \Gamma$ the evolution of the density matrix can be simplified to a rate equation.
- Using the $E \gg \Gamma$ approximation and the large-N_c limit, we have checked the impact of considering the gap in phenomenological applications.
- We see a substantial effect. Both in a HTL inspired scenario and in a Lattice QCD inspired scenario.