Heavy quarkonium in a moving thermal bath

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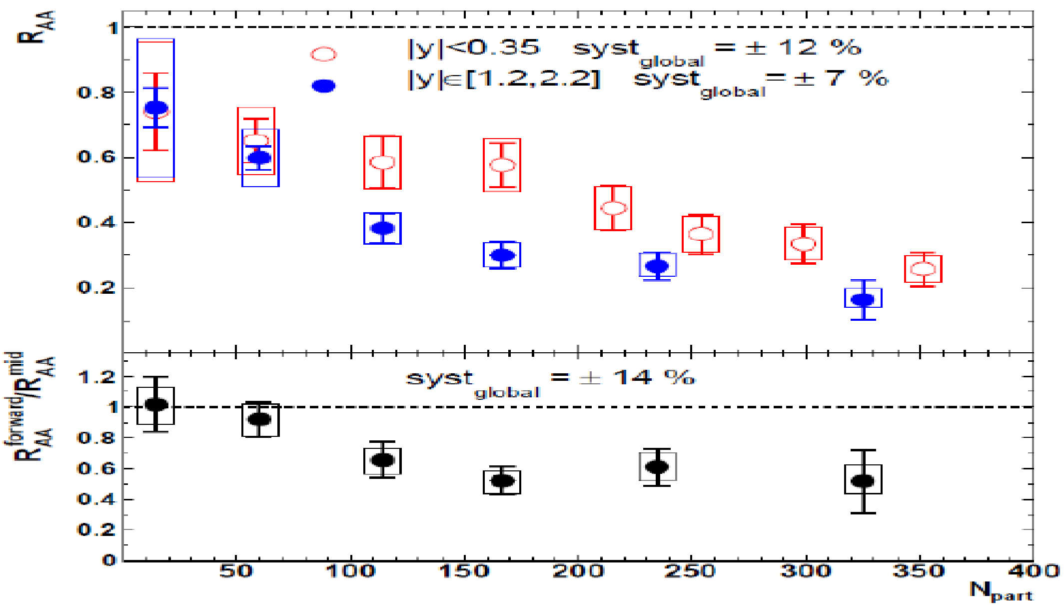
    - Weakly coupled QGP
  - Fruitful strategy in the case at rest (Miguel Angel Escobedo, JS; Phys. Rev. A 78, 032520 (2008), Phys. Rev. A 82, 042506 (2010))

Motivation



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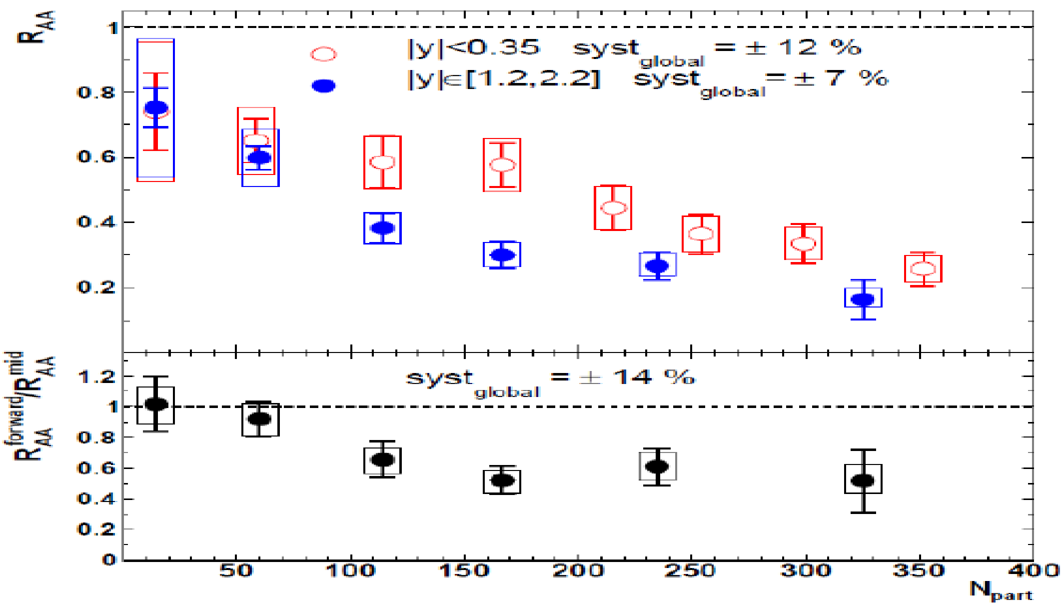

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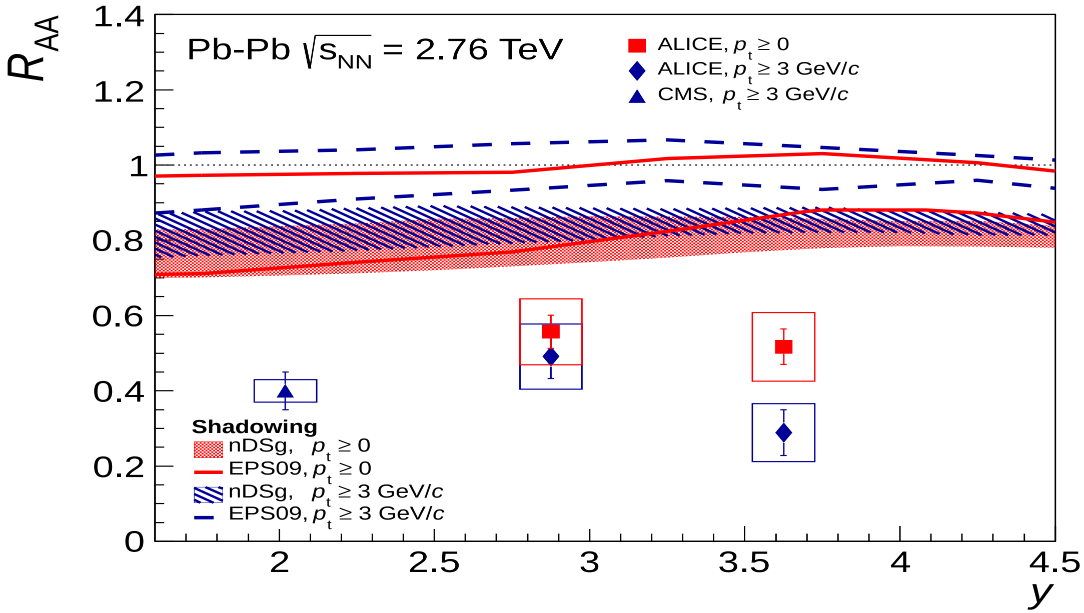

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- The J/ψ suppression may depend on the transverse momentum

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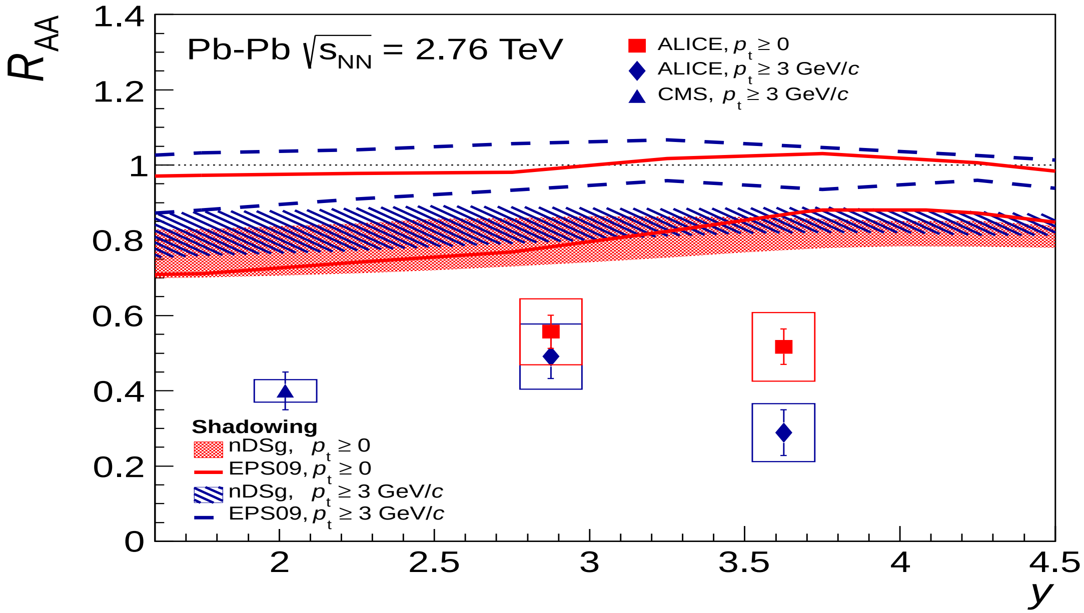

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- The J/ψ suppression may depend on the transverse momentum
- Is this due, at least in part, to the fact that the in-medium properties of J/ψ depend on the velocity ?

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  - m (hard), electron mass
  - $m\alpha/n$ (soft), inverse Bohr radius, $\alpha = e^2/4\pi$; e, electron charge
  - $m\alpha^2/n^2$ (ultrasoft), binding energy

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- $m \neq 0$, $T \neq 0$ case: what is the interplay among the scales above?

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- $m \neq 0$, $T \neq 0$ case: contributions of energies above T are exponentially suppressed by Boltzmann factors

Non-Relativistic QED (T=0)

$$\mathcal{L}_{NRQED} = -\frac{1}{4}d_1 F_{\mu\nu}F^{\mu\nu} + \frac{d_2}{m^2}F_{\mu\nu}D^2F^{\mu\nu} + N^\dagger iD^0 N +$$
$$+\psi^\dagger(iD^0 + \frac{\mathbf{D}^2}{2m} + \frac{\mathbf{D}^4}{8m^3} + c_F e\frac{\boldsymbol{\sigma}\mathbf{B}}{2m} + c_D e\frac{\boldsymbol{\nabla}\mathbf{E}}{8m^2} +$$
$$+ic_S e\frac{\boldsymbol{\sigma}(\mathbf{D}\times\mathbf{E} - \mathbf{E}\times\mathbf{D})}{8m^2})\psi$$

(Caswell, Lepage, 1986)

Potential NRQED (T=0)

$$L_{pNRQED} = -\int d^3\mathbf{x}\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \int d^3\mathbf{x}S^\dagger(t,\mathbf{x})\left(iD_0 + \frac{\boldsymbol{\nabla}^2}{2m} + \frac{Z\alpha}{|\mathbf{x}|} + \right.$$
$$\left. + \frac{\boldsymbol{\nabla}^4}{8m^3} + \frac{Ze^2}{m^2}\left(-\frac{c_D}{8} + 4d_2\right)\delta^3(\mathbf{x}) + ic_S\frac{Z\alpha}{4m^2}\boldsymbol{\sigma}\cdot\left(\frac{\mathbf{x}}{|\mathbf{x}|^3}\times\boldsymbol{\nabla}\right)\right)S(t,\mathbf{x})$$
$$+ \int d^3\mathbf{x}S^\dagger(t,\mathbf{x})e\mathbf{x}\cdot\mathbf{E}S(t,\mathbf{x})\,.$$

(Pineda, Soto, 1997)

Hard Thermal Loops EFT (m=0)

$$\delta\mathcal{L}_{HTL} = \frac{1}{2}m_D^2 F^{\mu\alpha}\int\frac{d\Omega}{4\pi}\frac{k_\alpha k_\beta}{-(k.\partial)^2}F^{\mu\beta} + m_e^2\bar{\psi}\gamma^\mu\int\frac{d\Omega}{4\pi}\frac{k_\mu}{k.\partial}\psi$$

$$k = (1, \hat{\mathbf{k}}), \qquad m_D^2 = e^2T^2/3, \qquad m_e^2 = e^2T^2/8$$

(Braaten, Pisarsky, 1992)

The $v \neq 0$ case

- Bound state at rest, the medium moves at velocity v (Weldom, 82)

$$f(\beta k^0) \rightarrow f(\beta^\mu k_\mu) = \frac{1}{e^{|\beta^\mu k_\mu|} \pm 1}\,, \quad \beta^\mu = \frac{\gamma}{T}(1, \mathbf{v})$$

$v = |\mathbf{v}|$, $\gamma = 1/\sqrt{1 - v^2}$

- $O(3)$ rotational symmetry is reduced to $O(2)$
- In light cone coordinates $k_+ = k_0 + k_3$, $k_- = k_0 - k_3$

$$\beta^\mu k_\mu = \frac{1}{2}\left(\frac{k_+}{T_+} + \frac{k_-}{T_-}\right)\,, \quad T_+ = T\sqrt{\frac{1+v}{1-v}}\,, \quad T_- = T\sqrt{\frac{1-v}{1+v}}$$

  - For $v \nsim 1$ (moderate velocities), $T_+ \sim T \sim T_-$
  - For $v \sim 1$ (relativistic velocities), $T_+ \gg T \gg T_-$
    - Collinear region, $k_+ \sim T_+$, $k_- \sim T_-$
    - Soft (ultrasoft) region, $k_+ \sim k_- \sim T_-$

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- The $T \ll m\alpha/n$ case: pNRQED can be used as a starting point
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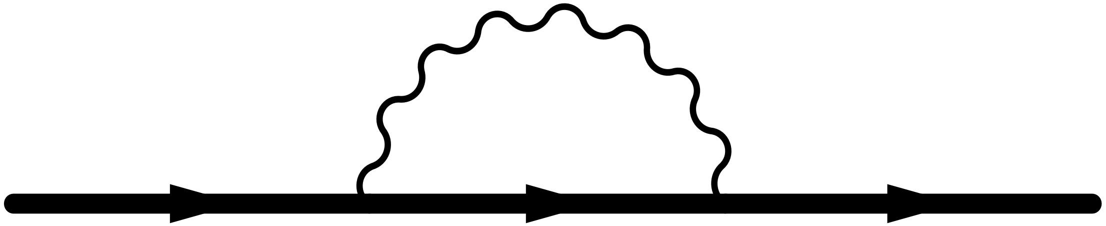
  - Thermal effects are encoded in the ultrasoft photons



$v \not\sim 1$: the $T \ll m\alpha/n$ case

$v \not\approx 1$: the $T \ll m\alpha/n$ case

- For $T = \beta^{-1} \ll m\alpha^2/n^2$:

$$\delta E_n = -\frac{4\pi^3\alpha}{45\beta^4} A_{ij}(v) \langle n|x^i \frac{\bar{P}_n}{(H_0 - E_n)} x^j |n\rangle \left(1 + \mathcal{O}\left(\left(\frac{n^2}{\beta m\alpha}\right)^2\right)\right)$$

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- For $T = \beta^{-1} \gg m\alpha^2/n^2$, $l = 0$:

$$\delta E_n = \frac{\alpha\pi T^2}{3m_e} - \frac{4Z\alpha^2}{3}\frac{|\phi_n(\mathbf{0})|^2}{m_e^2}\left(-\frac{1}{2v}\log\left(\frac{1+v}{1-v}\right) + 1 - \gamma\right)$$

$$+\frac{2\alpha}{3\pi m_e^2}\sum_r |\langle n|\mathbf{p}|r\rangle|^2 (E_n - E_r)\log\left(\frac{2\pi T}{|E_n - E_r|}\right) \times \left(1 + \mathcal{O}\left((\frac{\beta m\alpha}{n^2})^2\right)\right)$$

$$\delta\Gamma_n = \frac{2Z^2\alpha^3 T\sqrt{1-v^2}}{3n^2 v}\log\left(\frac{1+v}{1-v}\right) \times \left(1 + \mathcal{O}\left(\frac{\beta m\alpha}{n^2}\right)\right)$$

$v \not\approx 1$: the $T \ll m\alpha/n$ case

- For $T = \beta^{-1} \gg m\alpha^2/n^2$, $l \neq 0$:

$$\delta E_{nlm} = \frac{\alpha\pi T^2}{3m_e} + \frac{2\alpha}{3\pi m_e^2}\sum_r |\langle n|\mathbf{p}|r\rangle|^2 (E_n - E_r)\log\left(\frac{-E_1}{|E_n - E_r|}\right) - \frac{Z^3\alpha^2\langle 2l00|l0\rangle\langle 2l0m|lm\rangle}{2\pi m_e^2 a_0^3 n^3 l(l+\frac{1}{2})(l+1)}\rho(v)$$

$$\delta\Gamma_{nlm} = \frac{Z^2\alpha^3 T\sqrt{1-v^2}}{3n^2 v}\left(2\log\left(\frac{1+v}{1-v}\right) + \left(\left(1-\frac{3}{v^2}\right)\log\left(\frac{1+v}{1-v}\right) + \frac{6}{v}\right)\langle 2l00|l0\rangle\langle 2l0m|lm\rangle\right)$$

$$\rho(v) = \frac{1}{2v}\left(1 - \frac{1}{v^2}\right)\log\left(\frac{1+v}{1-v}\right) - \frac{2}{3} + \frac{1}{v^2}$$

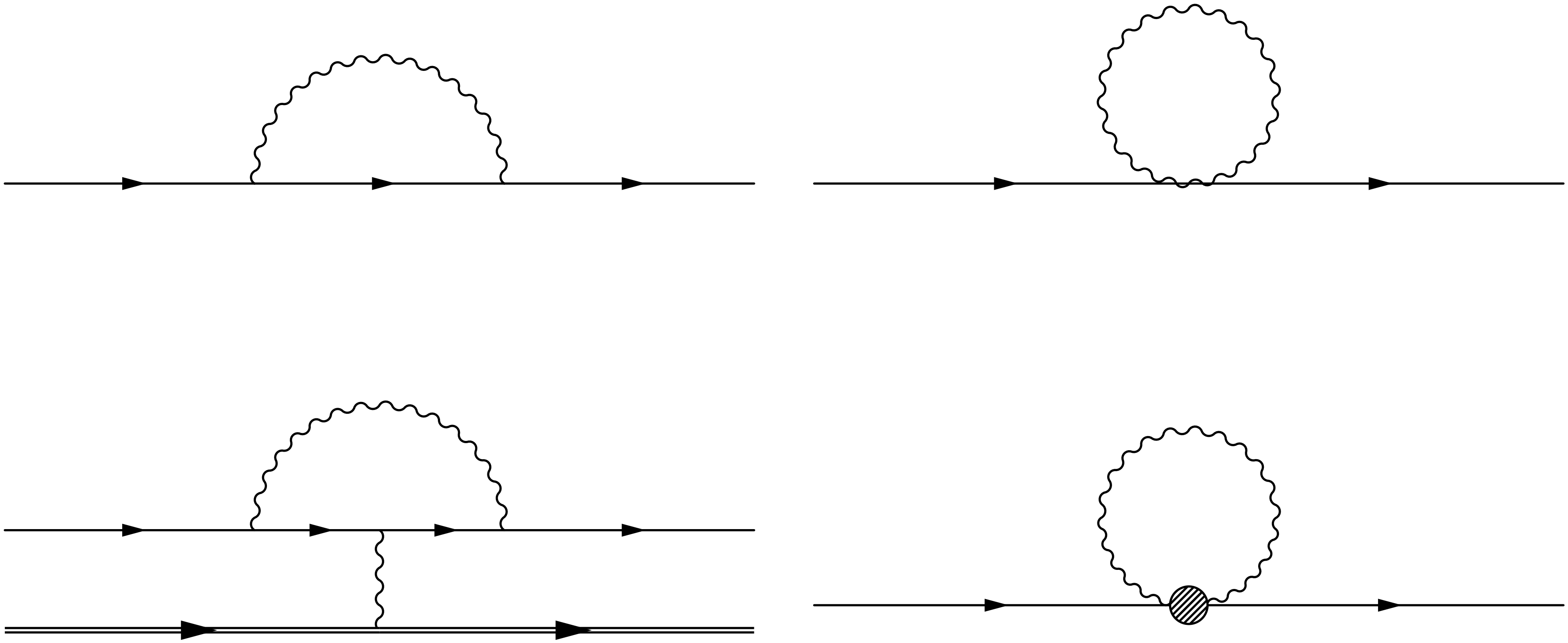
- The decay width decreases as v increases !

Moderate velocity ($v \not\propto 1$)

- The $T \ll m$ case: NRQED can be used as a starting point
  - The potentials depend on T:

$$\delta\mathcal{L}_{pNRQED} = \int d^3\mathbf{x}\left(\frac{\alpha\pi T^2}{3m_e}\psi^\dagger\psi - \frac{\pi\alpha T^2}{6m_e^3}\nabla\psi^\dagger\nabla\psi\right)$$
$$+\int d^3\mathbf{x_1}\, d^3\mathbf{x_2} N^\dagger(t,\mathbf{x_2})N(t,\mathbf{x_2})\left[-\frac{4Z\alpha}{3m_e^2}\left(\log\left(\frac{\mu}{2\pi T}\right) - \log 2\right.\right.$$
$$\left. +\gamma + \frac{3}{8v}\left(1+\frac{1}{3v^2}\right)\log\left(\frac{1+v}{1-v}\right) - \frac{1}{4v^2}\right)\delta^3(\mathbf{x_1}-\mathbf{x_2})$$
$$\left. +\frac{\alpha\rho(v)v^iv^j\partial^2_{ij}V_c(r)}{4\pi m_e^2 v^2}\right]\psi^\dagger(t,\mathbf{x_1})\psi(t,\mathbf{x_1})$$

  - μ, factorization scale arising from IR divergences, which cancels against the one of ultrasoft contributions in physical observables



$v \not\approx 1$: the $T \ll m$ case

- In the ultrasoft contributions,

$$1/(e^{|\beta^\mu k_\mu|} - 1) \to 1/|\beta^\mu k_\mu| - 1/2 + \cdots$$

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$$\delta E_{nlm} = \frac{\alpha\pi T^2}{3m_e} - \frac{\pi\alpha^3 T^2}{6m_e n^2} + \frac{4Z\alpha^2}{3m_e^2}\left(\gamma + \frac{3}{8v}\left(1 + \frac{1}{3v^2}\right) - \frac{1}{4v^2}\right)|\phi_n(\mathbf{0})|^2$$
$$- \frac{\alpha\rho(v)v^i v^j}{4\pi m_e^2 v^2}\langle n|\partial^2_{ij}V_c(r)|n\rangle + \frac{2\alpha}{3\pi m_e^2}\sum_r |\langle n|\mathbf{p}|r\rangle|^2 (E_n - E_r)\left(\log\left(\frac{2\pi T}{|E_n - E_r|}\right) + \frac{5}{6}\right)$$

$$\delta\Gamma_{nlm} = \frac{Z^2\alpha^3 T\sqrt{1-v^2}}{3n^2 v}\left(2\log\left(\frac{1+v}{1-v}\right)\right.$$
$$\left. + \left(\left(1 - \frac{3}{v^2}\right)\log\left(\frac{1+v}{1-v}\right) + \frac{6}{v}\right)\langle 2l00|l0\rangle\langle 2l0m|lm\rangle\right)$$

Relativistic velocity ($v \sim 1$)

- The $T_+ \sim m\alpha/n \gg T_- \gg m\alpha^2/n^2$ case: NRQED can be used as a starting point
  - The collinear photons ($k_+ \sim T_+$, $k_- \sim T_-$) have virtualities $\sim T^2 \ll (m\alpha/n)^2$ and hence must be kept in the effective theory: pNRQED $\to$ pNRQED + SCET

$$\delta\mathcal{L}_{SCET} = c_1 \frac{\psi^\dagger\psi}{m_e} \frac{\bar{n}^\mu F_{\mu i}}{(\bar{n}\partial)} \frac{\bar{n}^\nu F_{\nu i}}{(\bar{n}\partial)} + c_2 \frac{\psi^\dagger\psi}{m_e} \frac{\bar{n}^\mu n^\nu F_{\mu\nu}}{(\bar{n}\partial)} \frac{\bar{n}^\alpha n^\beta F_{\alpha\beta}}{(\bar{n}\partial)} + \cdots$$

$F_{\mu\nu}$, collinear photons; ψ, NR electron field
$n = (1,0,0,1)$, $\bar{n} = (1,0,0,-1)$

  - The pNRQED Lagrangian for ultrasoft photons remains the same

$v \sim 1$: the $T_+ \sim m\alpha/n \gg T_- \gg m\alpha^2/n^2$ case

- Calculation in pNRQED+ SCET
  - $\delta E_n^{\rm col} = \frac{\pi\alpha T^2}{3m_e}$, $\quad \delta\Gamma_n^{\rm col} = 0$
  - There are three relevant regions in the us contribution:
    - $k_+, k_- \sim T_-$
    - $k_+, k_- \sim m\alpha^2/n^2$
    - $k_+ \sim m\alpha^2/n^2$ and $k_- \sim m\alpha^2/n^2(T_-/T_+)$

$$\delta E_{n00}^{\rm us} = -\frac{4Z\alpha^2}{3}\left(1-\gamma+\frac{1}{2}\log\left(\frac{1-v}{1+v}\right)\right)\frac{|\phi_n(0)|^2}{m_e^2}$$

$$-\frac{2\alpha}{3\pi m_e^2}\sum_r |\langle n|\mathbf{p}|r\rangle|^2(E_n-E_r)\log\left(\frac{|E_n-E_r|}{2\pi T}\right)$$

$$\delta\Gamma_{n00}^{\rm us} = \frac{4Z^2\alpha^3 T}{3n^2}\sqrt{\frac{1-v}{1+v}}\log\left(\frac{1+v}{1-v}\right)$$

- Agreement with the $v \to 1$ limit of the $v \nsim 1$ case

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  - The collinear photons have virtualities $\gg T_-^2$ and can be integrated out in the matching to pNRQED. They produce a global energy shift.
  - The pNRQED Lagrangian for ultrasoft photons remains the same
  - Agreement with the $v \to 1$ limit of the $v \not\sim 1$ case

The $m\alpha/n \ll T \ll m$ case

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- One next matches to pNRQED, obtaining a v and T dependent potential

The $m\alpha/n \ll T \ll m$ case at $v = 0$

$$V(r,T) = -\frac{\alpha e^{-m_D r}}{r} - \alpha m_D + i\alpha T \phi(m_D r) + \mathcal{O}\left(\frac{\alpha T^2}{m_\mu}\right)$$

$$\phi(x) = 2\int_0^\infty \frac{dzz}{(z^2+1)^2}\left[\frac{\sin(zx)}{zx} - 1\right]$$

- It has an imaginary part ! (Laine, Philipsen, Romatschke, Tassler, 06; Escobedo, JS, 08; Brambilla, Ghiglieri, Vairo, Petreczky, 08)
- The disociation temperature becomes

$$T_d \sim m_\mu \alpha^{2/3} / \ln^{1/3}\alpha \, < \, m_\mu \alpha^{1/2}$$

where $m_\mu \alpha^{1/2}$ is the scale of the disociation temperature for the screening mechanism (Matsui, Satz, 86)

The $m\alpha/n \ll T \ll m$ case at $v \neq 0$

- $\Re V(r,T)$ calculated before (Chu, Matsui, 89)
- $V(r,T)$ is given by the Fourier transform of the longitudinal photon propagator $\Delta_{11}(k)$ at $k^0 = 0$ in the v-dependent HTL Lagrangian

$$\Delta_{11}(k) = \frac{1}{2}[\Delta_R(k) + \Delta_A(k) + \Delta_S(k)]$$

$\Delta_R^*(k) = \Delta_A(k)$, $\Delta_S(k)$ contains the imaginary part

- $\Delta_S(k)$ must be calculated through the following formula, which differs from the one of the $v = 0$ case (Carrington, Hou, Thoma, 97)

$$\Delta_S(k,u) = \frac{\Pi_S(k,u)}{2i\Im\Pi_R(k,u)}(\Delta_R(k,u) - \Delta_A(k,u))$$

$u = \gamma(1,\mathbf{v})$. Recall that in the real time formalism $\Pi_R = \Pi_{11} + \Pi_{12}$, $\Pi_S = \Pi_{11} + \Pi_{22}$, $\Delta_R(k) = 1/(\mathbf{k}^2 - \Pi_R)$

The $m\alpha/n \ll T \ll m$ case at $v \neq 0$

- $\Pi_R(k,u)$ is a (complex) function of v and θ, $\mathbf{kv} = |\mathbf{k}| v \cos\theta$, that reduces to $-m_D^2$ when $v = 0$
- We obtain

$$\Pi_S(k,u) = \frac{i2\pi m_D^2 T(1-v^2)^{3/2}(1+\frac{v^2}{2}\cos^2\theta)}{|\mathbf{k}|(1-v^2\sin^2\theta)^{5/2}}$$

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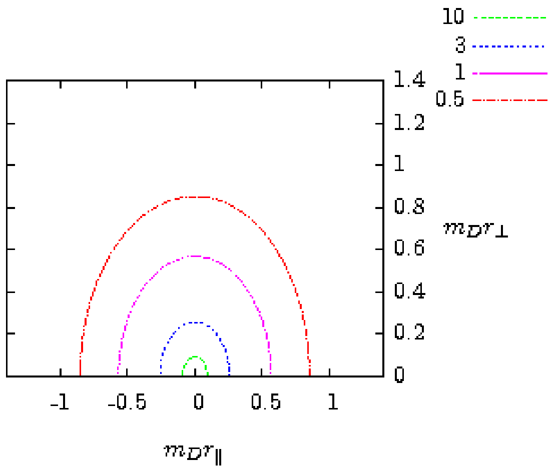
  - Since m_D remains non-vanishing when $v \to 1$, there will be some critical v for which $m_d = m_D$ and both mechanisms Landau damping and screening compete
  - For v sufficiently close to 1 the imaginary part is neglegible and the dominant mechanism for dissociation is screening

$$v = 0$$



10
3
1
0.5
1.4
1.2
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0.8
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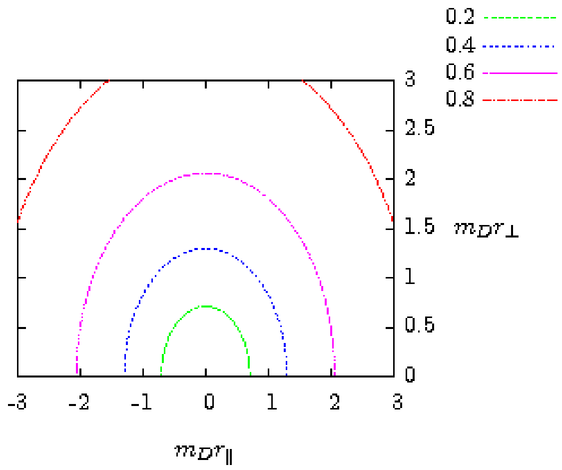
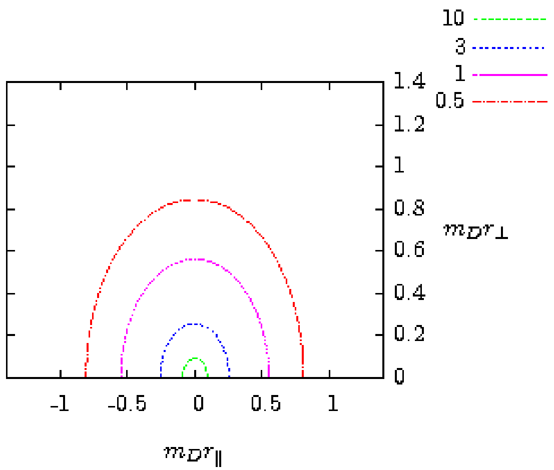
$m_D r_\perp$
$m_D r_\parallel$

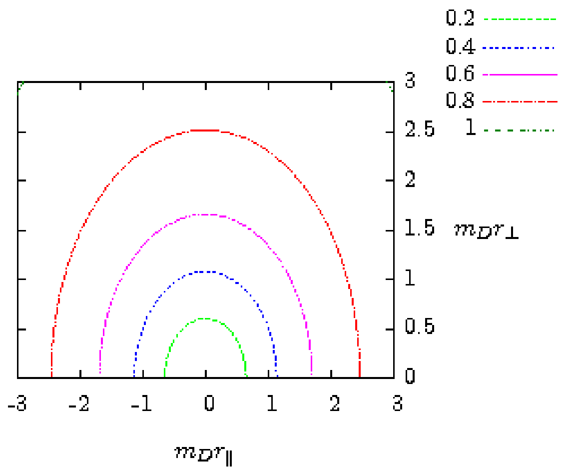


0.2
0.4
0.6
0.8
3
2.5
2
1.5
1
0.5
0
-3
-2
-1
0
1
2
3
$m_D r_\perp$
$m_D r_\parallel$

$$v = 0.5$$

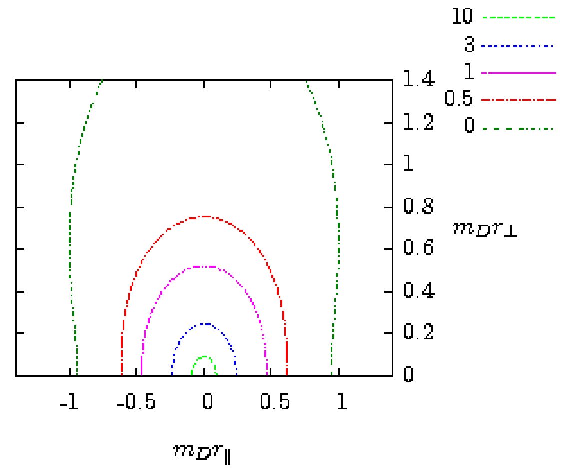


10
3
1
0.5
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-1
-0.5
0
0.5
1
$m_D r_\perp$
$m_D r_\parallel$

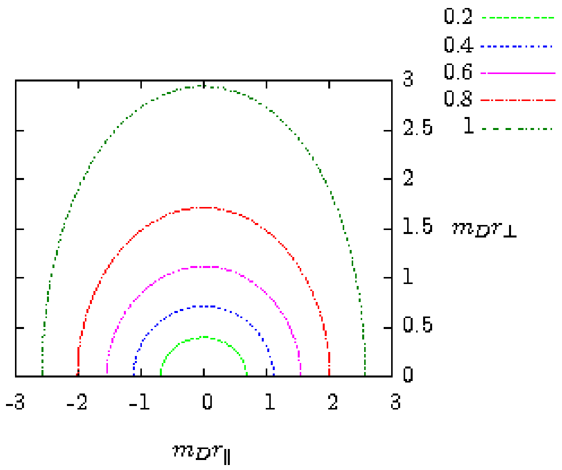


0.2
0.4
0.6
0.8
1
3
2.5
2
1.5
1
0.5
0
-3
-2
-1
0
1
2
3
$m_D r_\perp$
$m_D r_\parallel$

$v = 0.9$

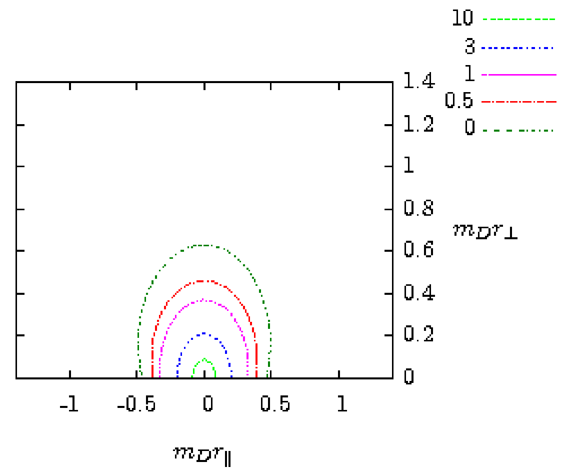


10
3
1
0.5
0
1.4
1.2
1
0.8
0.6
0.4
0.2
0
$m_D r_\perp$
-1
-0.5
0
0.5
1
$m_D r_\parallel$

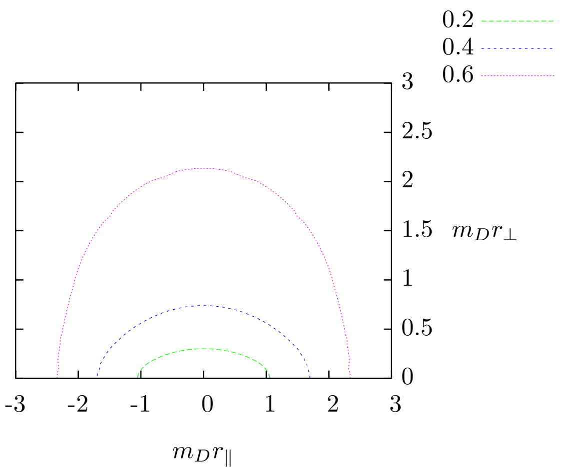


0.2
0.4
0.6
0.8
1
3
2.5
2
1.5
1
0.5
0
$m_D r_\perp$
-3
-2
-1
0
1
2
3
$m_D r_\parallel$

$v = 0.99$



10
3
1
0.5
0
1.4
1.2
1
0.8
0.6
0.4
0.2
0
$m_D r_\perp$
-1
-0.5
0
0.5
1
$m_D r_\parallel$



0.2
0.4
0.6
3
2.5
2
1.5
1
0.5
0
$m_D r_\perp$
-3
-2
-1
0
1
2
3
$m_D r_\parallel$

Conclusions

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- The decay width of a heavy quarkonium moving in a QGP decreases with its velocity

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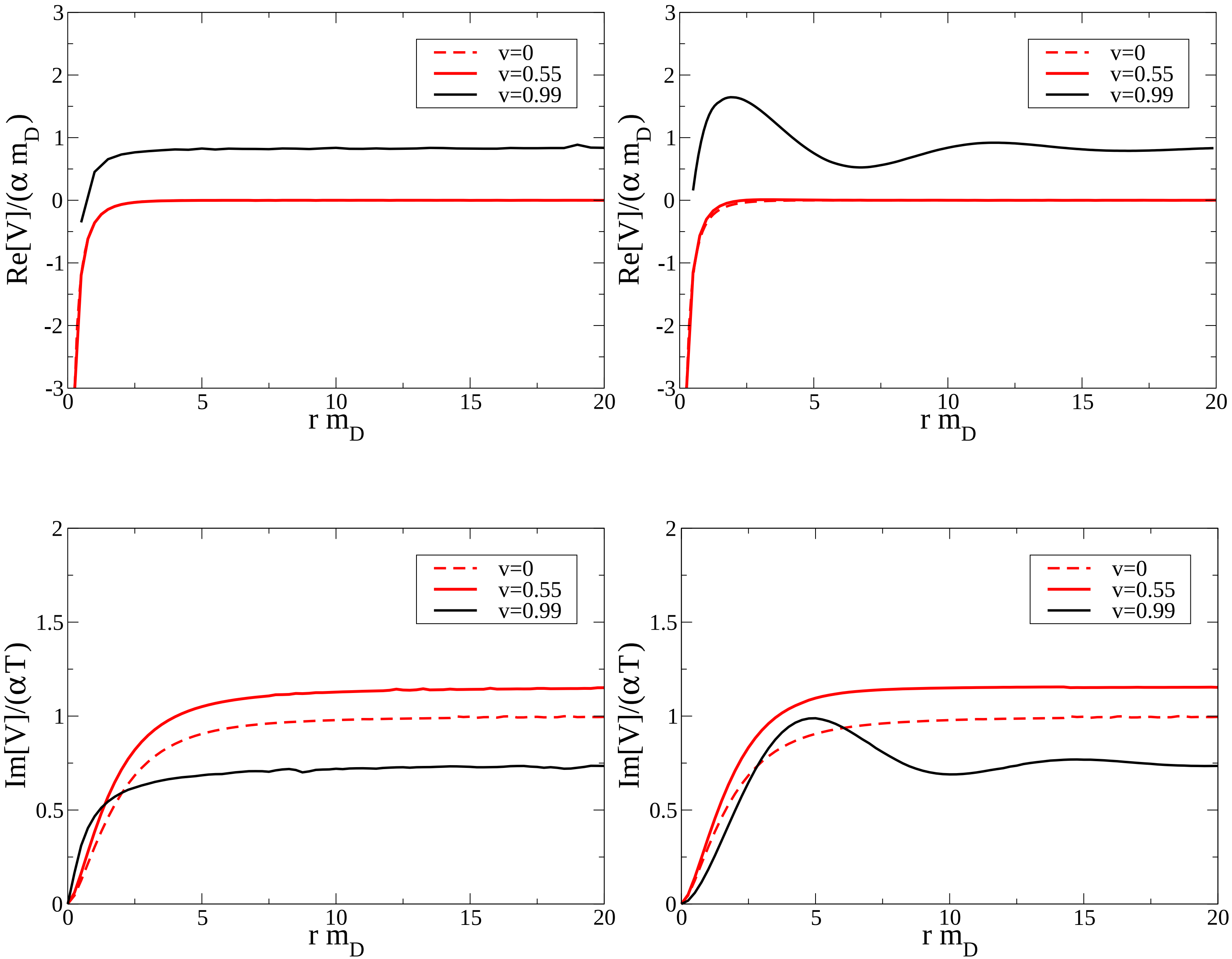
- The decay width of a heavy quarkonium moving in a QGP decreases with its velocity
- The dominant mechanism for dissociation changes from Landau damping to screening as the velocity increases


v=0
v=0.55
v=0.99
Re[V]/(α m_D)
Im[V]/(αT)
r m_D
0
5
10
15
20
3
2
1
0
-1
-2
-3
1.5
0.5