



Heavy quarkonium in a moving thermal bath

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 - Weakly coupled QGP



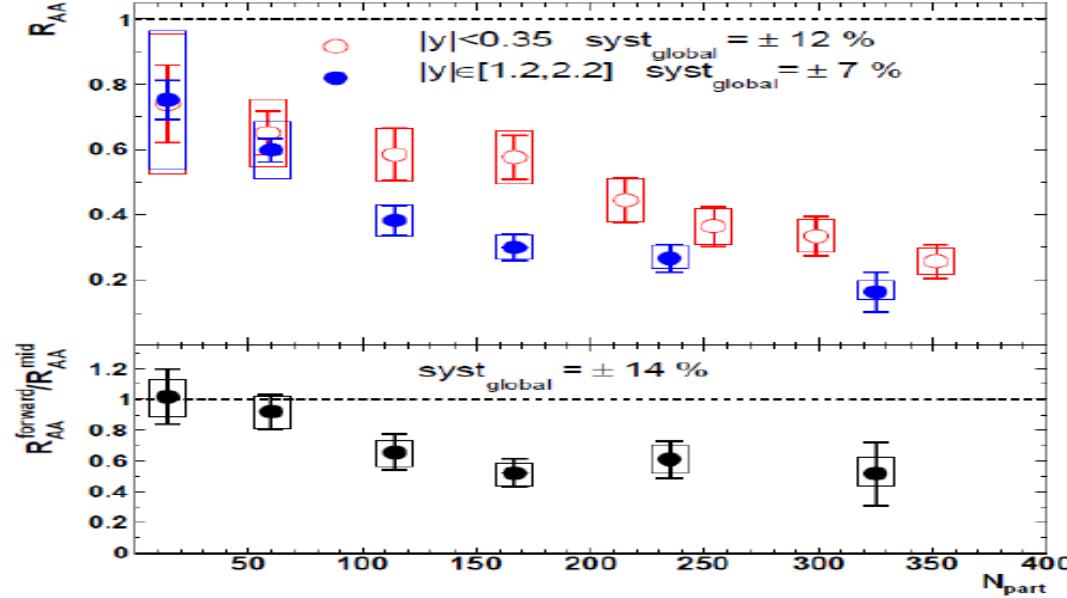


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 - Fruitful strategy in the case at rest (Miguel Angel Escobedo, JS; Phys. Rev. A 78, 032520 (2008), Phys. Rev. A 82, 042506 (2010))

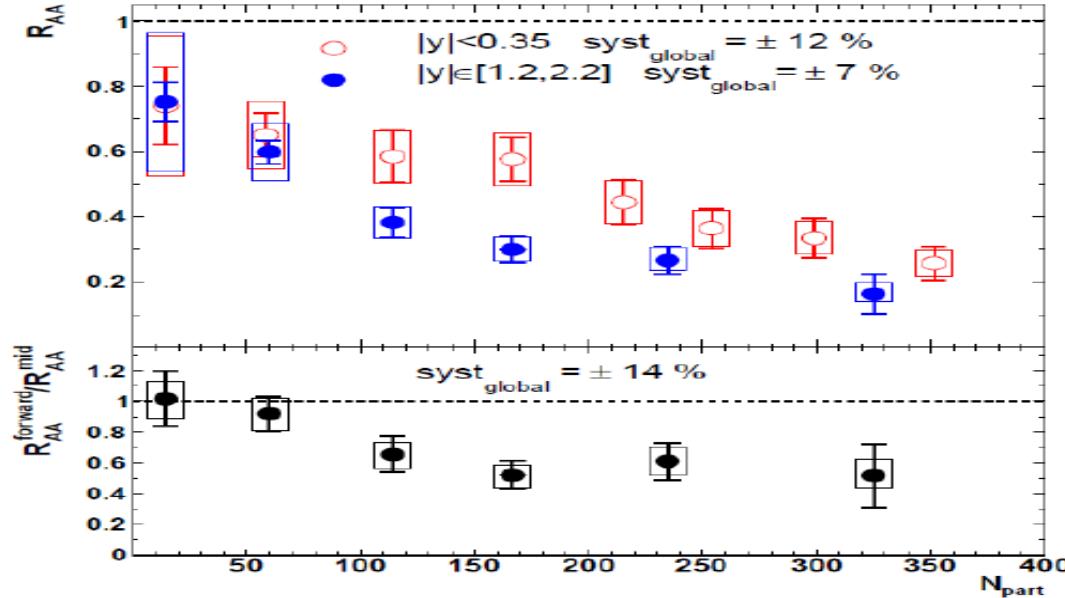


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(H. Pereira Da Costa, for the PHENIX collaboration, arXiv:1007.3688)

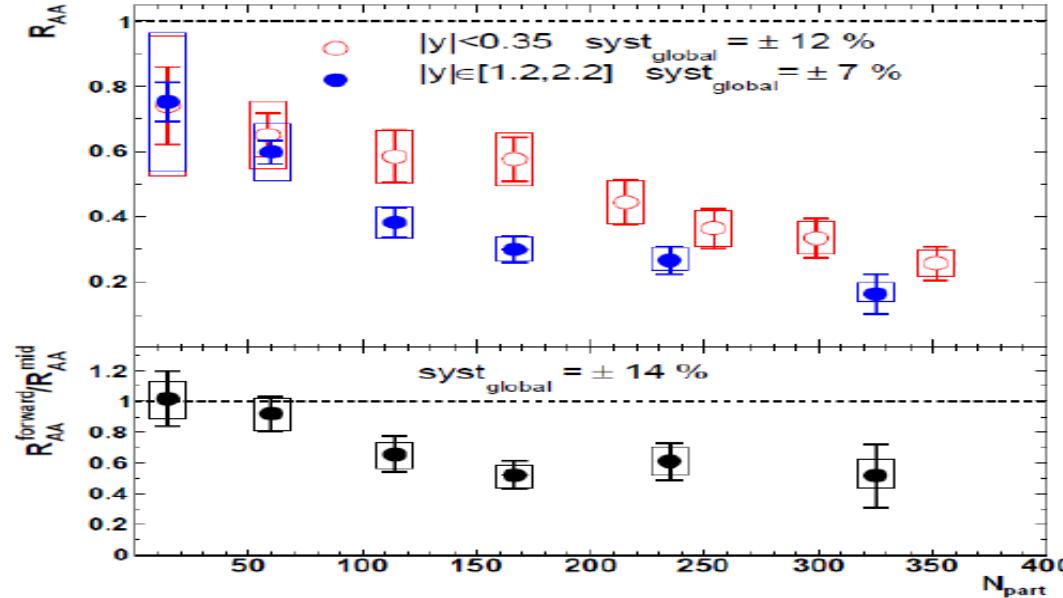
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- The J/ψ suppression depends on the rapidity
- Is this due, at least in part, to the fact that the in-medium properties of J/ψ depend on the velocity?

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- $m \neq 0, T = 0$ case:
 - 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)

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

(Caswell, Lepage, 1986)





Potential NRQED (T=0)

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

(Pineda, Soto, 1997)



Hard Thermal Loops EFT ($m=0$)

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

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

(Braaten, Pisarsky, 1992)





The $v \neq 0$ case

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

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

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

- $O(3)$ 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 $v \approx 1$ (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, $k_+ \sim k_- \sim T_-$





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

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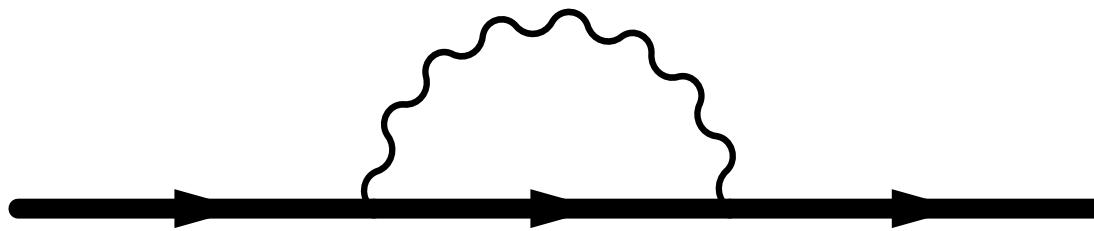
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Moderate velocity ($v \not\propto 1$)

- The $T \ll m\alpha/n$ case: pNRQED can be used as a starting point
 - The potentials remain the same as in the $T = 0$ case
 - Thermal effects are encoded in the ultrasoft photons





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





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

$$\begin{aligned} \delta E_n &= \frac{\alpha \pi T^2}{3m_e} - \frac{4Z\alpha^2}{3} \frac{|\phi_n(\mathbf{0})|^2}{m_e^2} \left(-\frac{1}{2v} \log\left(\frac{1+v}{1-v}\right) + 1 - \gamma \right) \\ &+ \frac{2\alpha}{3\pi m_e^2} \sum_r |\langle n | \mathbf{p} | r \rangle|^2 (E_n - E_r) \log\left(\frac{2\pi T}{|E_n - E_r|}\right) \times \left(1 + \mathcal{O}\left(\left(\frac{\beta m \alpha}{n^2}\right)^2\right) \right) \end{aligned}$$

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





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

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

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

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

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

- The decay width decreases as v increases !



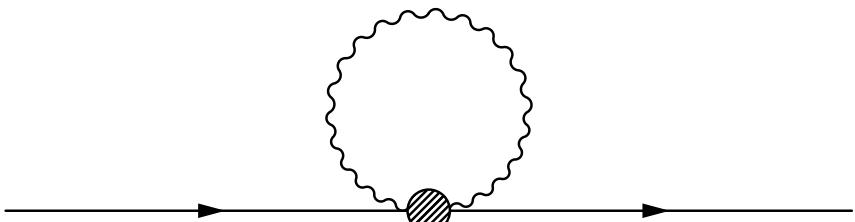
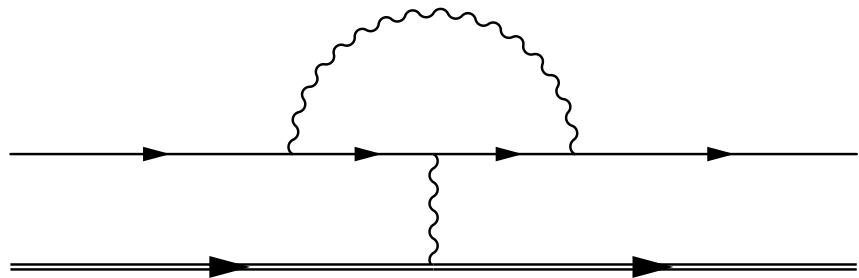
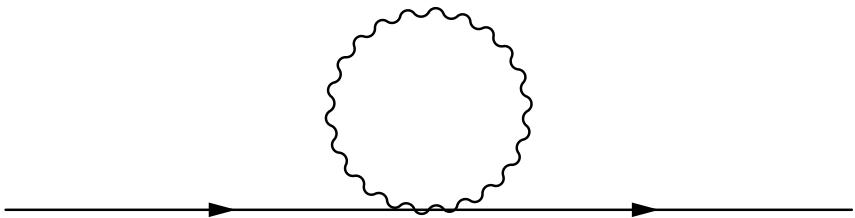
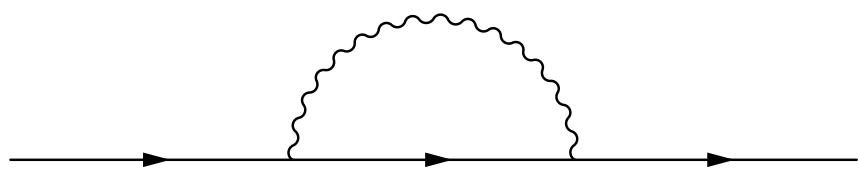
Moderate velocity ($v \not\propto 1$)

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

$$\begin{aligned}\delta\mathcal{L}_{pNRQED} = & \int d^3\mathbf{x} \left(\frac{\alpha\pi T^2}{3m_e} \psi^\dagger \psi - \frac{\pi\alpha T^2}{6m_e^3} \nabla \psi^\dagger \nabla \psi \right) \\ & + \int d^3\mathbf{x}_1 d^3\mathbf{x}_2 N^\dagger(t, \mathbf{x}_2) N(t, \mathbf{x}_2) \left[-\frac{4Z\alpha}{3m_e^2} \left(\log\left(\frac{\mu}{2\pi T}\right) - \log 2 \right. \right. \\ & \left. \left. + \gamma + \frac{3}{8v} \left(1 + \frac{1}{3v^2} \right) \log\left(\frac{1+v}{1-v}\right) - \frac{1}{4v^2} \right) \delta^3(\mathbf{x}_1 - \mathbf{x}_2) \right. \\ & \left. + \frac{\alpha\rho(v)v^i v^j \partial_{ij}^2 V_c(r)}{4\pi m_e^2 v^2} \right] \psi^\dagger(t, \mathbf{x}_1) \psi(t, \mathbf{x}_1)\end{aligned}$$

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







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

- In the ultrasoft contributions,

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





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

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





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 \rightarrow pNRQED + SCET

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

$F_{\mu\nu}$, 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

- $\delta E_n^{\text{col}} = \frac{\pi\alpha T^2}{3m_e}, \quad \delta\Gamma_n^{\text{col}} = 0$

- 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 $k_- \sim m\alpha^2/n^2(T_-/T_+)$

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

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

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

- Agreement with the $v \rightarrow 1$ limit of the $v \approx 1$ 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 $v \rightarrow 1$ limit of the $v \approx 1$ 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 $v = 0$

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

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

- 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 ,
 $\mathbf{k}\mathbf{v} = |\mathbf{k}|v \cos \theta$, 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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- The dissociation mechanism:
 - Let m_d be the momentum scale for which the real and imaginary part of the potential are equal. If $m_d \gg m_D$, as in the $v = 0$ case, we find (for $\theta \approx \pi/2$) $m_d \sim \alpha^{1/3} T \sqrt{1 - v^2}$. Hence the disociation temperature decreases. As long as $m_D \ll m_d$, the Landau damping remains the dominant mechanism





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 - Since m_D remains non-vanishing when $v \rightarrow 1$, there will be some critical v for which $m_d = m_D$ and both mechanisms Landau damping and screening compete



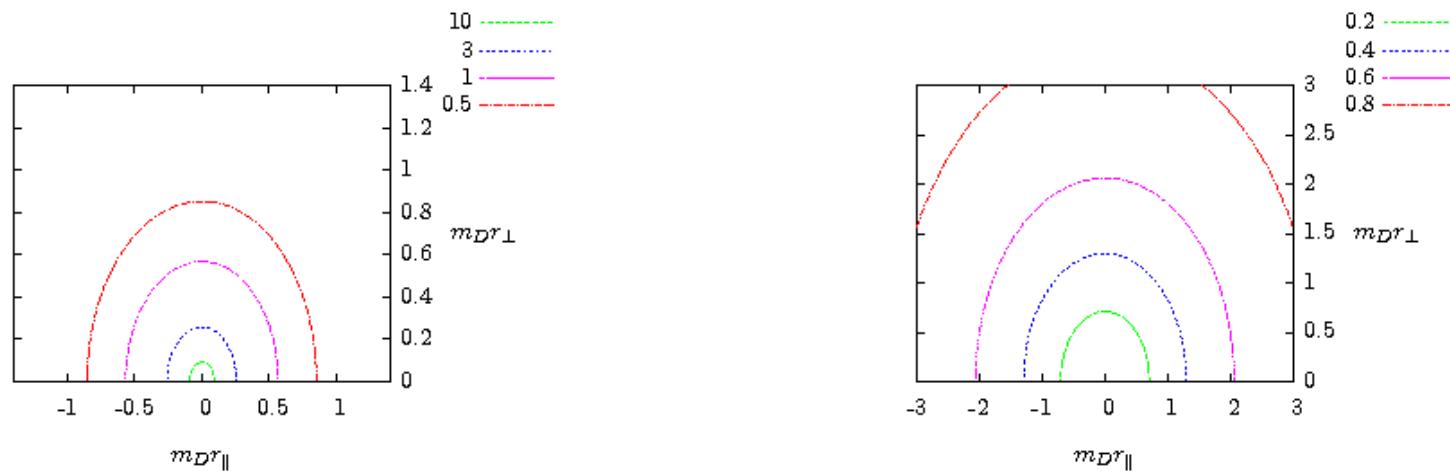


The $m\alpha/n \ll T \ll m$ case at $v \neq 0$

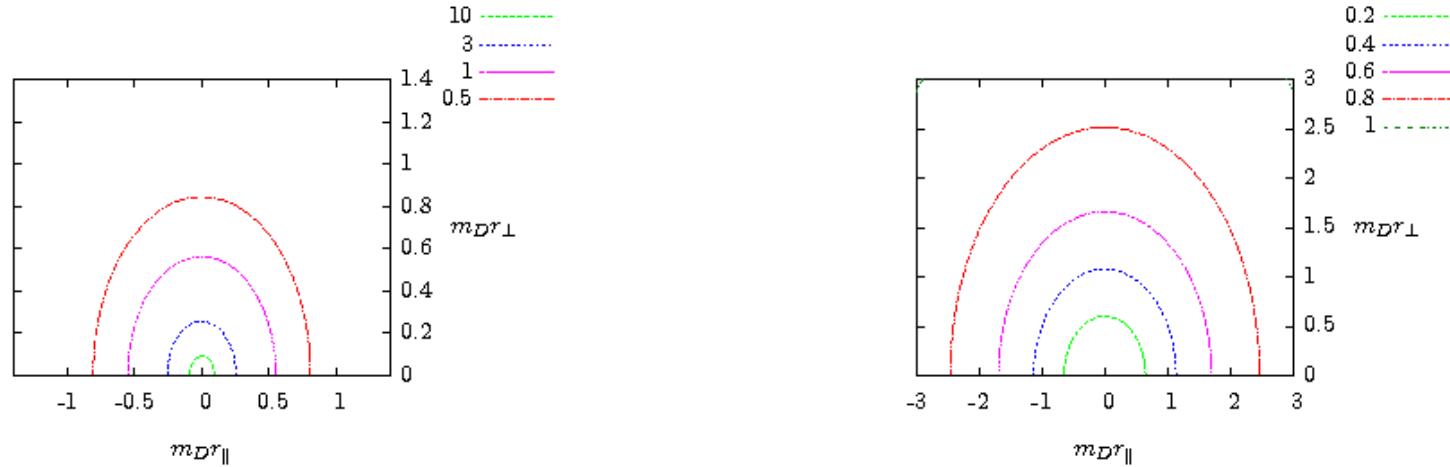
- The dissociation mechanism:
 - Let m_d be the momentum scale for which the real and imaginary part of the potential are equal. If $m_d \gg m_D$, as in the $v = 0$ case, we find (for $\theta \approx \pi/2$) $m_d \sim \alpha^{1/3} T \sqrt{1 - v^2}$. Hence the dissociation temperature decreases. As long as $m_D \ll m_d$, the Landau damping remains the dominant mechanism
 - Since m_D remains non-vanishing when $v \rightarrow 1$, 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 negligible and the dominant mechanism for dissociation is screening



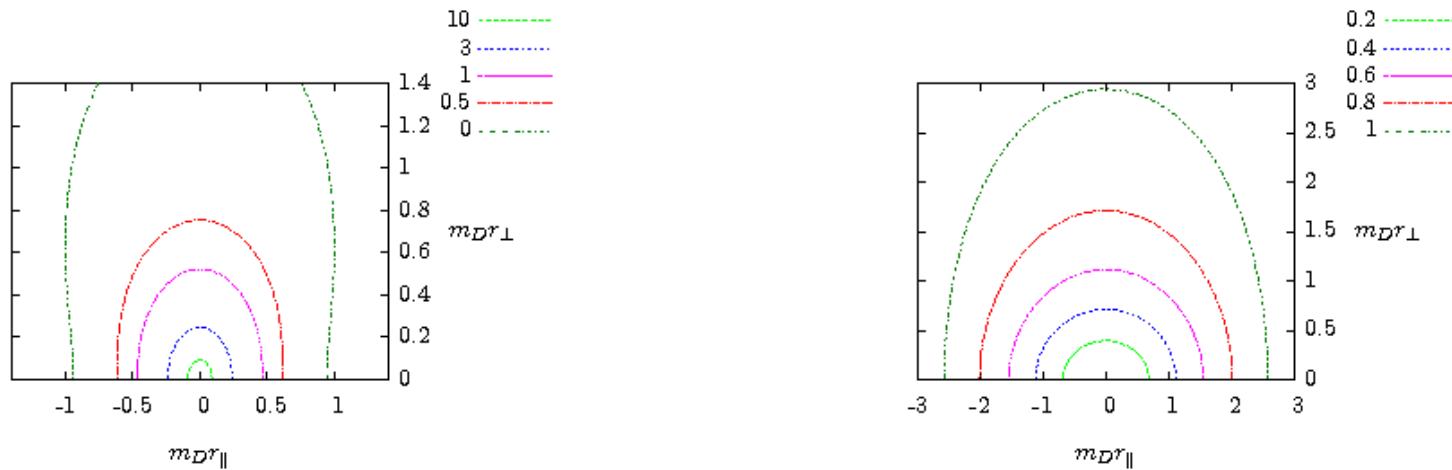
$v = 0$



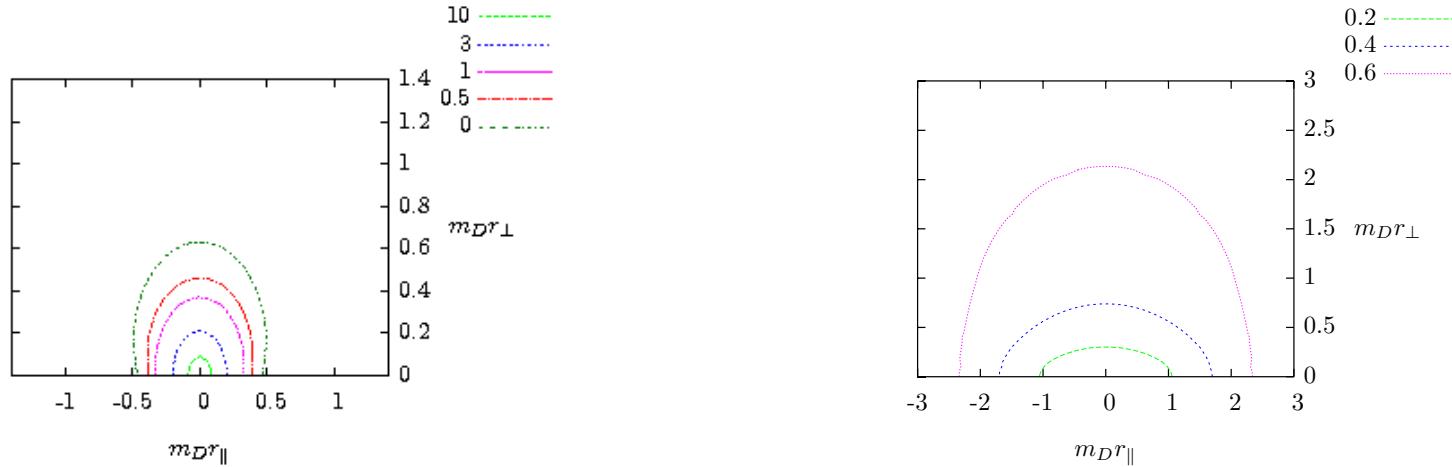
$v = 0.5$



$v = 0.9$



$v = 0.99$



Conclusions





Conclusions

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





Conclusions

- 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



