Momentum anisotropy effects for quarkonium in a weakly-coupled QGP below the melting temperature

Simone Biondini

Albert Einstein Center, Institute for Theoretical Physics - University of Bern

in collaboration with N. Brambilla, M. Escobedo and A. Vairo

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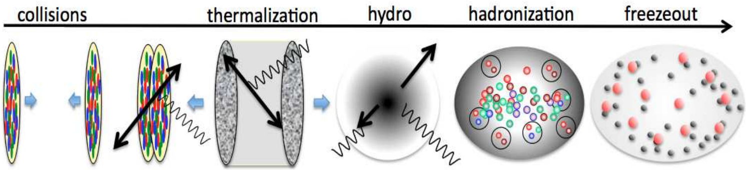
Outline

QGP in the (big) lab

- QGP is established in heavy-ion collisions (see talk by W. Florkowski)

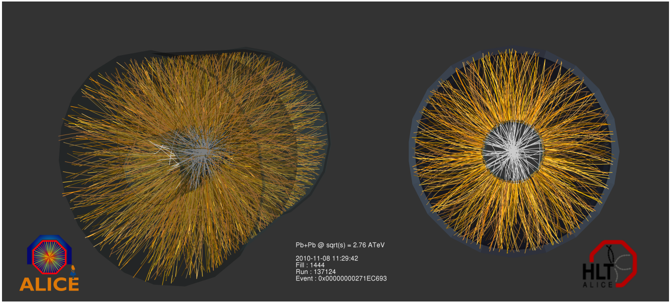


Time scales for Quark Gluon Plasma

- Formation time $\tau_0 \sim [0.1, 1]$ fm and $T_{\text{max}} \approx 500$ MeV W. M. Alberico et al (2013)
- Kinematics and viscous medium: parton momentum anisotropies
  $\rightarrow$ system gets colder in the longitudinal direction (beam axis)
- Life time of deconfined (anisotropic) medium $\tau \sim [7, 10]$ fm

W. Florkowski and R. Ryblewski (2010 and 2013); M. Martinez and M. Strickland (2010); D. Bazow, U. W. Heinz and M. Strickland (2013)

What comes out from QGP?



- very high particle multiplicity in the final state
- demanding and challenging experimental analysis
- clean probes are needed...

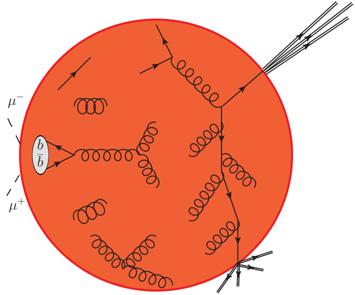
Hard probes for QGP

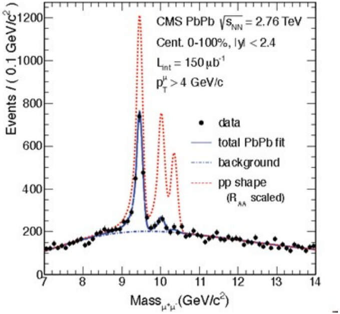
How can we get information about a so short-lived state ?

- A possible way is by exploiting hard probes, *T. Matsui and H. Satz (1986)*

1. jet quenching
2. quarkonia suppression

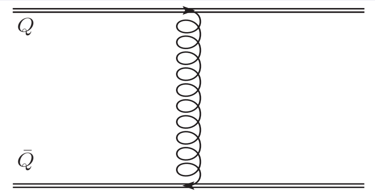
$$\boxed{\text{Typical time scale} \quad \tau_0^{\text{h.p.}} \lesssim \tau_0}$$





Heavy quarkonium in vacuum and in medium

Bound state of heavy quark and anti-quark



- Coulomb potential (short distance part)

$$\boxed{V(r) = -C_F \frac{\alpha_s}{r}}$$

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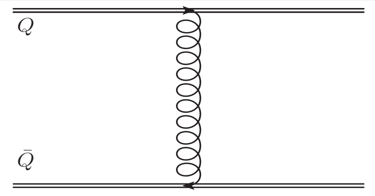

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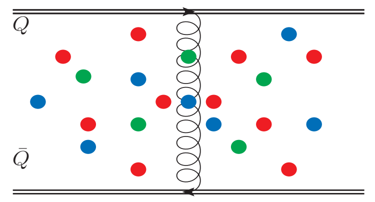
Let us put it in a QCD medium...Debye mass $m_D(T) \sim gT$



- Yukawa screened potential

$$\boxed{V_T(r) = -C_F \alpha_s \frac{e^{-rm_D}}{r}}$$

- Fourier transform of:

$$\frac{i}{\mathbf{q}^2} \rightarrow \frac{i}{\mathbf{q}^2 + m_D^2}$$

Energy scales for heavy quarkonium

Many energy scales...

1) Non-relativistic scales for $Q\bar{Q}$ state:

$$M \gg Mv \gg Mv^2, \Lambda_{\mathrm{QCD}}$$

G. T. Bodwin, E. Braaten, and G. P. Lepage (1995); M. Beneke (1997);
S. Fleming, A. K. Leibovich, I. Z. Rothstein (2001)

2) Thermodynamic scales (only true in the weak coupling regime):

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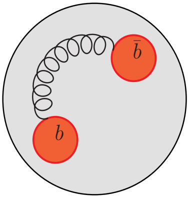

- The hierarchy may hold for $\Upsilon(1S)$, where $v^2 \sim 0.1$ A. Vairo (2010)

$$5\text{GeV} > 1.5\text{GeV} > 0.5\text{GeV}$$

- Bottomonium is not melted for $T \lesssim 4T_c$

  A. Mocsy, P. Petreczky, M. Strickland (2013);

  A. Andronic et al (2016)

EFT for QCD

How to disentangle the different scales from QCD?

$$\mathcal{L}_{QCD} = -\frac{1}{4} G^{\mu\nu,a} G^{a}_{\mu\nu} + \bar{Q}\left(i\not{D} - M\right) Q + \mathcal{L}_{Light}$$

- A useful way: Effective Field Theory
  1. Select the right degrees of freedom
  2. Build the effective Lagrangian
  3. Perform calculations with a simplified version of $\mathcal{L}_{QCD}$

- We are interested in the spectrum of $Q\bar{Q} \Rightarrow$ binding energy ($\sim Mv^2$)

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- pNRQCD: the EFT at the ultra-soft scale Mv^2,
  N. Brambilla, A. Pineda, J. Soto and A. Vairo (1999); A. Pineda and J. Soto (1998)
- The Lagrangian acquires a Schrodinger equation-like form

$$\boxed{V(r) \text{ obtained from QCD}}$$

pNRQCD in vacuum

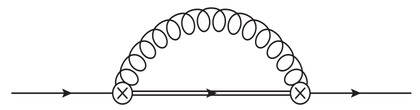
pNRQCD Lagrangian

- Assuming the hierarchy $M \gg Mv\,(\sim \frac{1}{r}) \gg Mv^2, \quad v \sim \alpha_s$

$$\mathcal{L}_{\rm pNRQCD} = \int d^3\mathbf{r}\, Tr\left\{S^\dagger\left(i\partial_0 - h_s\right)S + O^\dagger\left(iD_0 - h_s\right)O\right\}$$
$$+ gTr\left\{O^\dagger\vec{r}\cdot\vec{E}S + S^\dagger\vec{r}\cdot\vec{E}O\right\} - \frac{1}{4}G^{\mu\nu,a}G^{a}_{\mu\nu} + \cdots$$

- where we have defined

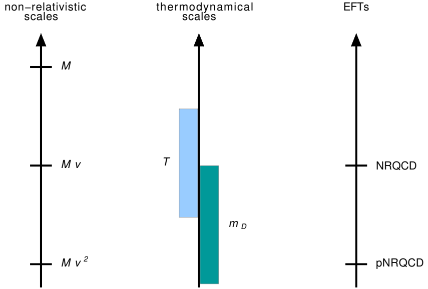
1. Singlet field S, Octet field O
2. $h_{s,o} = \frac{\mathbf{p}^2}{m} + V_{s,o}^{(0)} + \frac{V_{s,o}^{(1)}}{M} + \ldots$
3. $V_s^{(0)} = -C_F\frac{\alpha_s}{r}$ and $V_o^{(0)} = 2N_c\frac{\alpha_s}{r}$

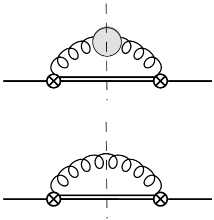


All the scales larger than Mv^2 contribute to the potential $V_{s,o}^{(0)}$

And if the temperature enters...

- Different arrangements of the non-relativistic and thermal scales





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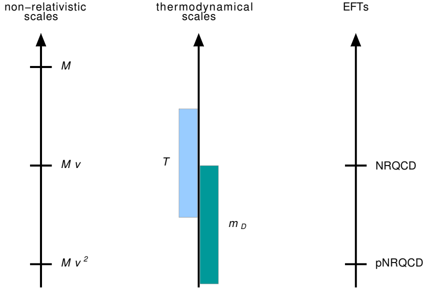

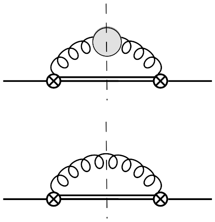

Main result:

$$V(r, T, m_D) = V_R(r, T, m_D) + iV_I(r, T, m_D)$$

M. Laine, O. Phillipsen, P. Romatschke, M. Tassler (2007); N. Brambilla, J. Ghiglieri, P. Petreczky and A. Vairo (2008);
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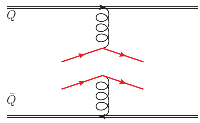
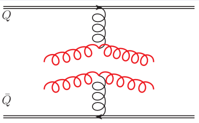
What is a thermal width?

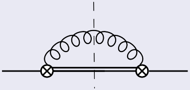
Interactions with the medium can break the $Q\bar{Q}$ bound state via:

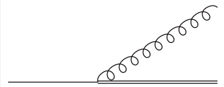
1. Landau Damping: imaginary part of the HTL resummed gluon propagator





2. Gluo-dissociation (singlet-to-octet break up in EFTs): traced back to the imaginary part of the one-loop diagram in pNRQCD





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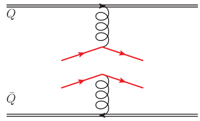

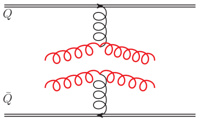

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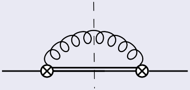

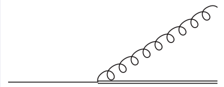

the thermal width enters the R_{AA} (suppression factor)

- $R_{AA} = e^{-\zeta}$, where $\zeta \approx \theta(\tau_f - \bar{\tau}_0) \int d\tau \, \Gamma(\tau, \xi, \ldots)$ M. Strickland and D. Bazow (2012)

$\Rightarrow$ knowledge of the thermal width for a broad temperature range

An example: $\Upsilon(1S)$ state in QGP

- Hierarchy: $m \gg m\alpha_{\mathrm{s}} \gg \pi T \gg m\alpha_{\mathrm{s}}^2 \gg m_D, \Lambda_{\mathrm{QCD}}$ N. Brambilla et al (2010-2013)
- In an expanding and cooling QGP the regime is met, for $T \lesssim 2T_c \approx 0.3$ GeV

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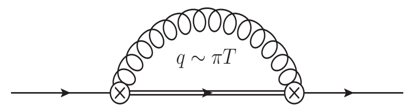
Integrate out the T scale: match pNRQCD onto pNRQCD$_{\rm HTL}$



$$\langle \Omega | \mathrm{T}\, S(t,\mathbf{r},\mathbf{R})\, S^\dagger(0,\mathbf{0},\mathbf{0}) | \Omega \rangle = -4\pi\alpha_{\rm s} C_F \int_P e^{-iP_0 t + i\mathbf{P}\cdot\mathbf{R}} \langle \mathbf{r} | \frac{i}{P_0 - h_s + i\epsilon}\, r_i I_{ij} r_j\, \frac{i}{P_0 - h_s + i\epsilon} | \mathbf{0} \rangle$$

- The thermal part of the loop reads

$$I_{ij} = \int_q \frac{i(q_0)^2\, 2\pi\, \delta(q^2)}{P_0 - q_0 - h_o + i\epsilon} \left(\delta_{ij} - \frac{q_i q_j}{|\mathbf{q}|^2} \right) f_B(|\mathbf{q}|)\,, \quad f_B(|\mathbf{q}|) = \left(e^{\frac{|\mathbf{q}|}{T}} - 1 \right)^{-1}$$

Result for the scale T

- The color-singlet potential of pNRQCD$_{\mathrm{HTL}}$ turns out to be the same as in pNRQCD plus a thermal correction δV_s that reads

$$\delta V_s = -i4\pi\alpha_{\mathrm{s}} C_F \; r_i I_{ij} r_j\big|_{q\sim\pi T}$$

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EXPAND THE OCTET PROPAGATOR IN THE LOOP INTEGRAL

$$\delta V_s = \frac{2\pi\alpha_s C_F T^2}{3m} + \frac{\pi\alpha_s^2 C_F N_c T^2 r}{9}$$

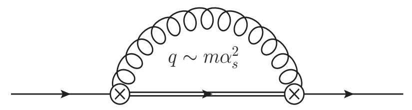
OBSERVATIONS

- no Debye screened potential, only powers of T
- no imaginary part: $(Q\bar{Q})_s \to (Q\bar{Q})_o + g$ is kinematically forbidden

Thermal corrections to the spectrum I

- The process we are looking at is **again** a singlet-to-octet transition

Actual calculation in pNRCD



- contribution from the momentum region $q \sim m\alpha_{\mathrm{s}}^2$ to the self-energy

$$\delta\Sigma_s = -i4\pi\alpha_{\mathrm{s}} C_F r_i \, I_{ij} r_j\big|_{q\sim m\alpha_{\mathrm{s}}^2} \,, \quad f(\mathbf{q}) = \left(e^{\frac{|\mathbf{q}|}{T}} - 1\right)^{-1} \approx \frac{T}{|\mathbf{q}|} \,,$$

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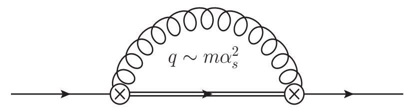

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Observations

- The self-energy has a vanishing real part
  $\Rightarrow$ no contribution to the real part of the spectrum (only from $q \sim \pi T$)
- The self-energy has a finite imaginary $\rightarrow$ thermal width!

Thermal corrections to the spectrum II

Real part of the spectrum: shift on binding energy

- Expectation value: $\delta E_{\mathrm{bind}} = \langle n\,\ell\,m|\delta V_s|n\,\ell\,m\rangle$
- By assumption our state is Coulombic, then one obtains

$$\delta E_{\mathrm{bind}} = \frac{2\pi\alpha_{\mathrm{s}} C_F T^2}{3m} + \frac{\pi\alpha_{\mathrm{s}} N_c T^2}{9m}\left[3n^2 - \ell(\ell+1)\right]$$

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Imaginary part of the spectrum: thermal width

- The thermal width is defined as follows

$$\Gamma = -2\langle n\ell m|{\rm Im}\,(\delta\Sigma_s)|n\ell m\rangle$$

- the result is (singlet-to-octet break up)

$$\Gamma = \frac{4}{3}\alpha_{\rm s}^3 T\left(\frac{C_F N_c^2}{4} + \frac{C_F^2 N_c}{n^2} + \frac{C_F^3}{n^2}\right)$$

Anisotropic QGP

QGP is a rather complicated system…

- Longitudinal (beam axis) expansion larger than the radial expansion

1) $P_T \gg P_L$: different partons momenta
2) *different temperatures* of the medium

Local momentum anisotropy : ξ

- Spectrum and width of the $Q\bar{Q}$ **depend on** in medium parton distributions

$$\delta E_{\mathrm{bind}}(T) \to \delta E_{\mathrm{bind}}(T,\xi)\,, \quad \Gamma(T) \to \Gamma(T,\xi)$$

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Modelling the anisotropy P. Romatschke, M. Strickland (2003)

$$f_B(\mathbf{q},\xi) = N(\xi) f_{iso,B}(\sqrt{q^2+\xi(\mathbf{q}\cdot\mathbf{n})^2}) = N(\xi)\left(e^{\frac{\sqrt{q^2+\xi(\mathbf{q}\cdot\mathbf{n})^2}}{T}} - 1\right)^{-1}$$

Normalization of the distribution function

Different normalizations

- $N(\xi) = 1$ widely used in the literature

  Paul Romatschke, Michael Strickland (2003); Adrian Dumitru, Yun Guo, Michael Strickland (2009); Matthew Margotta, Kyle McCarty, Christina McGahan, Michael Strickland, David Yager-Elorriaga (2013)

- $N(\xi) = \sqrt{1+\xi}$ O. Philipsen, M. Tassler (2009)
  - guarantees the same number of particles for the anisotropic and isotropic distribution functions

$$n = \int_{\mathbf{p}} f_{iso}(\mathbf{p}) = \int_{\mathbf{p}} f(\mathbf{p}, \xi)$$

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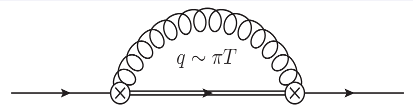
- well-known result of the potential for the case $\pi T \gg 1/r$:
  HTL resummation with anisotropic parton distribution

  A. Dumitru, Y. Guo and M. Strickland (2008); A. Dumitru, Y. Guoa and M. Strickland (2008); Y. Burnier, M. Laine and M. Vepsalainen (2009); M. Nopoush, Y. Guo and M. Strickland (2017)

- NEW: we calculate the anisotropic potential in a complementary temperature range

Small anisotropy in pNRQCD: $0 < \xi \leq 1$

Same hierarchy: $1/r \gg \pi T \gg Mv^2 \gg m_D$



1. Matching of pNRQCD onto pNRQCD$_{\rm HTL}$
2. Spectrum in pNRQCD$_{\rm HTL}$

Matching: different distribution function for gluons

$$I_{ij} = \int_q \frac{i(q_0)^2\, 2\pi\, \delta(q^2)}{P_0 - q_0 - h_o + i\epsilon} \left(\delta_{ij} - \frac{q_i q_j}{|\mathbf{q}|^2} \right) f_B(\mathbf{q}, \xi)\,,$$

Final result for the singlet potential

$$\delta V_s = \frac{2\pi \alpha_{\rm s} C_F T^2}{3m} \mathcal{F}_1(\xi) + \frac{\pi \alpha_{\rm s}^2 C_F N_c T^2 r}{12} \mathcal{F}_2(\xi) + \underbrace{\frac{\pi \alpha_{\rm s}^2 C_F N_c T^2 (\mathbf{r}\cdot\mathbf{n})^2}{12 r} \mathcal{F}_3(\xi)}_{\text{entirely due to anisotropy}}\,,$$

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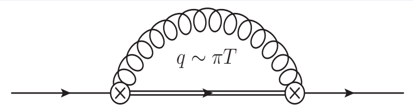

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Spectrum with anisotropy

$$
\begin{aligned}
\delta E_{\mathrm{bind}} &= \frac{2\pi\alpha_{\mathrm{s}} C_F T^2}{3m} \mathcal{F}_1(\xi) \\
&+ \frac{\pi\alpha_{\mathrm{s}} N_c T^2}{12m} \left[3n^2 - \ell(\ell+1)\right] \left(\mathcal{F}_2(\xi) + \frac{\mathcal{F}_3(\xi)}{3} + \frac{2}{3}\mathcal{F}_3(\xi)\, C^{\ell\,0}_{2\,\ell\,0\,0}\, C^{\ell\,m}_{2\,\ell\,0\,m} \right),
\end{aligned}
$$

Spectrum with anisotropy

$$\delta E_{\mathrm{bind}} = \frac{2\pi\alpha_{\mathrm{s}} C_F T^2}{3m}\mathcal{F}_1(\xi) + \frac{\pi\alpha_{\mathrm{s}} N_c T^2}{12m}\left[3n^2 - \ell(\ell+1)\right]\left(\mathcal{F}_2(\xi) + \frac{\mathcal{F}_3(\xi)}{3} + \frac{2}{3}\mathcal{F}_3(\xi)\, C^{\ell\,0}_{2\,\ell\,0\,0}\, C^{\ell\,m}_{2\,\ell\,0\,m}\right),$$

$$\Gamma = \frac{4}{3}\alpha_{\mathrm{s}}^3 T\left(\frac{C_F N_c^2}{4} + \frac{C_F^2 N_c}{n^2} + \frac{C_F^3}{n^2}\right)\mathcal{G}_1(\xi) + \alpha_{\mathrm{s}}^3 T\left(\frac{C_F N_c^2}{4} - \frac{C_F^2 N_c}{2n^2} + \frac{C_F^3}{n^2}\right)\mathcal{G}_2(\xi)\, C^{\ell\,0}_{2\,\ell\,0\,0}\, C^{\ell\,m}_{2\,\ell\,0\,m}$$

S. B., N. Brambilla, M. A. Escobedo and A. Vairo (2017)

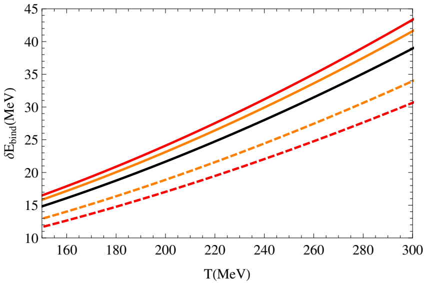
- the anisotropic functions entering the thermal width are

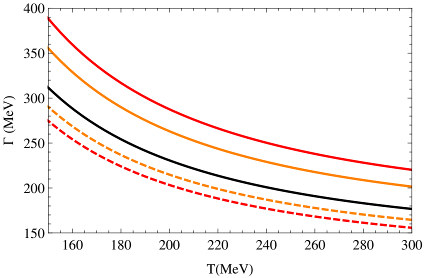
$$\mathcal{G}_1(\xi) = N(\xi)\frac{\mathrm{arcsinh}\left(\sqrt{\xi}\right)}{\sqrt{\xi}}, \quad \mathcal{G}_2(\xi) = N(\xi)\frac{(1+2\xi/3)\,\mathrm{arcsinh}\left(\sqrt{\xi}\right) - \sqrt{\xi(1+\xi)}}{\sqrt{\xi^3}}$$

Plot I

Binding-energy shift and thermal width

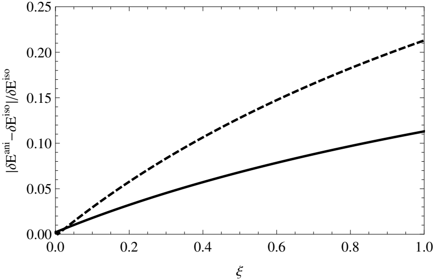
- **solid black line**: isotropic case ($\xi = 0$)
- **solid orange**: anisotropic $\xi = 0.5$, **solid red**: anisotropic $\xi = 1$; with $N(\xi) = \sqrt{1+\xi}$
- dashed orange: anisotropic $\xi = 0.5$, dashed red: anisotropic $\xi = 1$; with $N(\xi) = 1$

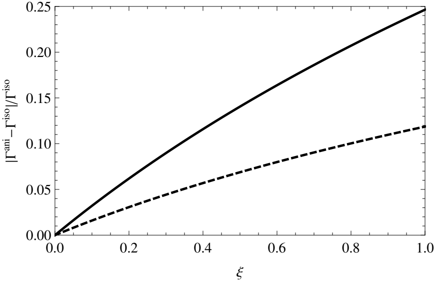


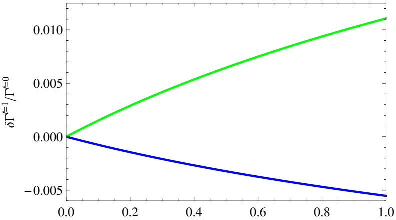


Plot II

- **solid black line**: $N(\xi) = \sqrt{1+\xi}$; dashed lines: $N(\xi) = 1$







- Widths of $1P(n=2, l=1)$ and $2S(n=2, l=0)$
- Blue: $m = \pm 1$, Green: $m = 0$

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Outlook

- cover more general temperature regimes with pNRQCD, $\pi T \approx 1/r$
- couple to hydrodynamical models in order to calculate R_{AA}: $\tau(T,\xi)$
  1. open quantum systems and Linblad equations
     isotropic pNRQCD see N. Brambilla, M. Escobedo, J. Soto and A. Vairo (2016),
     see also poster by D. De Boni at XQCD 2017
  2. study the case of strongly-coupled QGP

Definition of the anisotropic parameter

$$\xi = \frac{1}{2}\frac{\langle p_T^2 \rangle}{\langle p_{\|}^2 \rangle} - 1$$

- for $\xi > 0$ the transverse component is larger and then it corresponds to a spatial expansion in the beam axis direction
- in the case the anisotropic function is obtained from f_{iso}, it is related to the shear viscosity

strongly-coupled QGP N. Brambilla, M. Escobedo, J. Soto and A. Vairo (2016)

- give up with the assumption $\pi T \gg m_D \Rightarrow \pi T \sim m_D$ $\left(T = T_0 \left(\frac{\tau_0}{\tau}\right)^{v_s^2}\right)$

$$\Sigma_s = \frac{g^2}{6N_c} r^2 \int_{t_0}^{t} dt_2 \langle E^{a,i}(t,\mathbf{0}) E^{a,i}(t_2, 0) \rangle$$

- then the thermal width is: $\Gamma = -2\langle \mathrm{Im}(-i\Sigma_s)\rangle = 3a_0^2\kappa$
- Lattice determination of κ brings to $\Gamma \approx 100$ MeV for $T = 1.5\,T_c$

  A. Francis, O. Kaczmarek, M. Laine, T. Neuhaus and H. Ohno