Finite-temperature Effective Field Theories for quarkonia

Jacopo Ghiglieri, Institute for Theoretical Physics
Albert Einstein Center, University of Bern

AIAIMBQCDCHIE, Heidelberg, 16.12.2014

Quarkonium as a hard probe

J/ψ SUPPRESSION BY QUARK–GLUON PLASMA FORMATION ☆

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and

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Received 17 July 1986

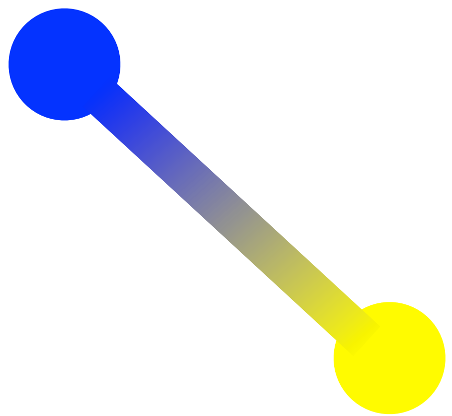
- Colour screening leads to the disappearance of the bound state

- A suppressed J/ψ yield is observed in the dilepton channel
  Matsui Satz **PLB178** (1986)

Overview of dissociation

Overview of dissociation

- Matsui/Satz: dissociation induced by colour screening of the interaction



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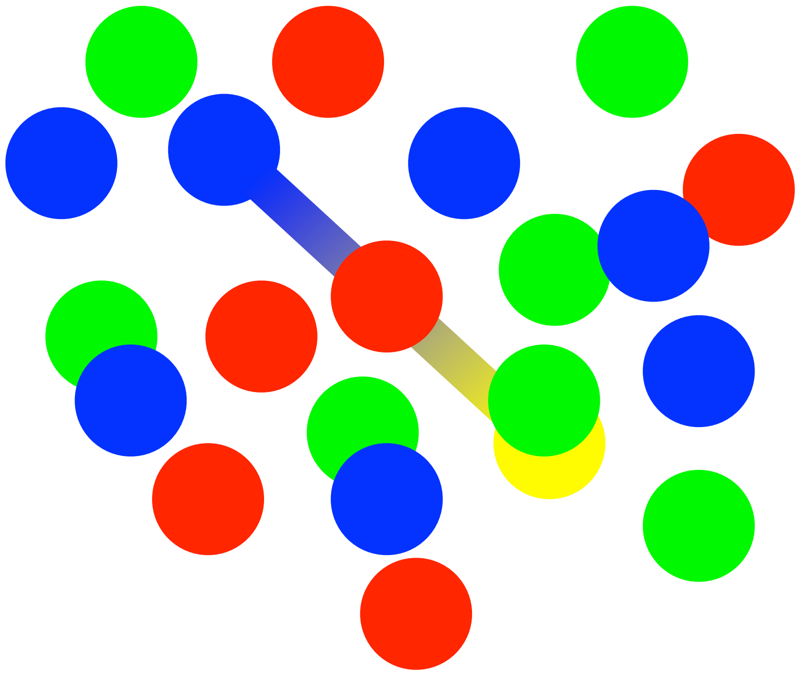

$$V(r) \sim -\alpha_s \frac{e^{-m_D r}}{r}$$

$$r \sim \frac{1}{m_D}$$ → **Bound state dissolves**

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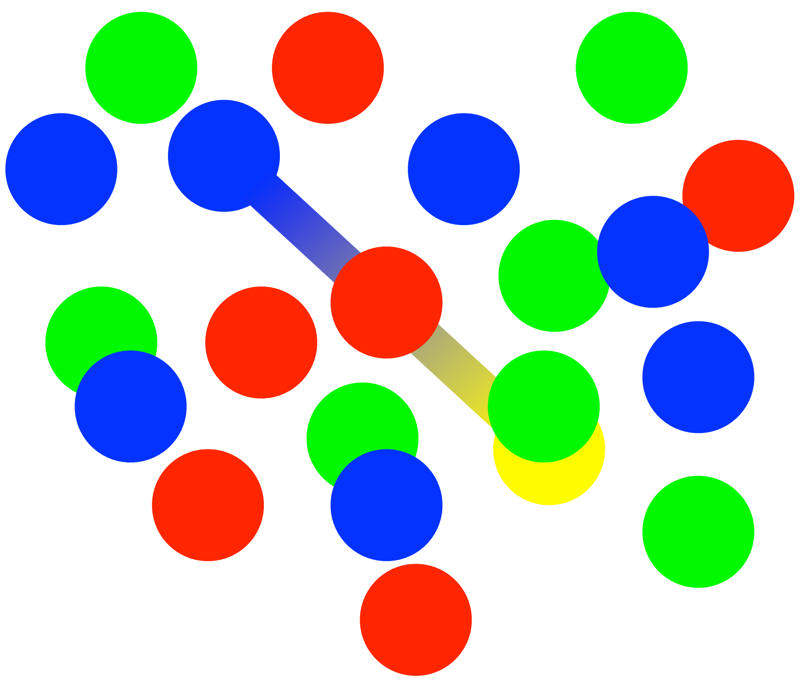

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$$r \sim \frac{1}{m_D} \longrightarrow$$ **Bound state dissolves**

- Since then, dissociation has been studied with potential models, lattice spectral functions, AdS/CFT and now with EFTs

Quarkonium suppression in experiments

- Typical observable: the nuclear modification factor

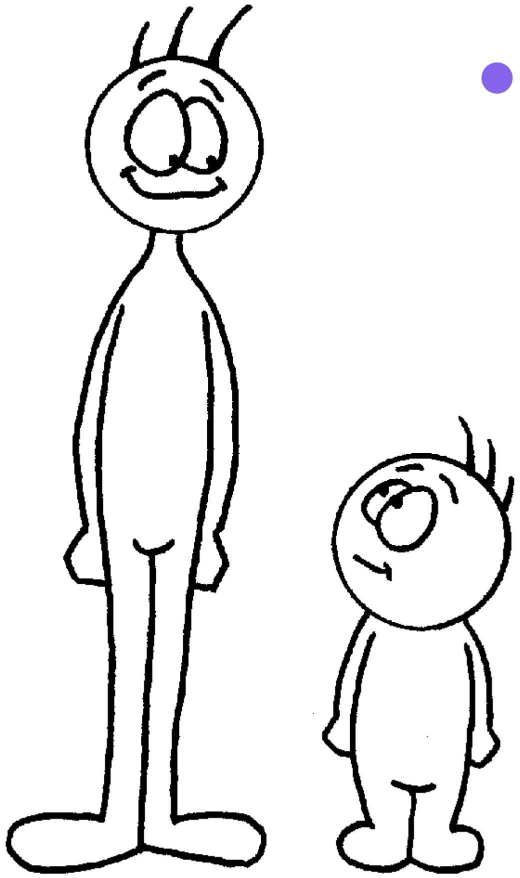
$$R_{AA} = \frac{\text{Yield}_{AA}}{\text{Yield}_{pp} \times N_{bin}}$$

- $R_{AA} \neq 1 \Rightarrow$ deviations from binary scaling. Causes:
  - Cold Nuclear Matter effects (affect production and early stages).
  - Hot Medium effects, such as screening. Reduce R_{AA}
  - Recombination effects. Increase R_{AA}

Why EFTs?

- We have a system characterized by many scales and degrees of freedom
- With EFTs we can
  - Have a clear counting
  - Integrate out unnecessary DOFs
  - Obtain an effective description with potentials rigorously obtained from QCD, including all relevant effects for the desired accuracy

Why EFTs?



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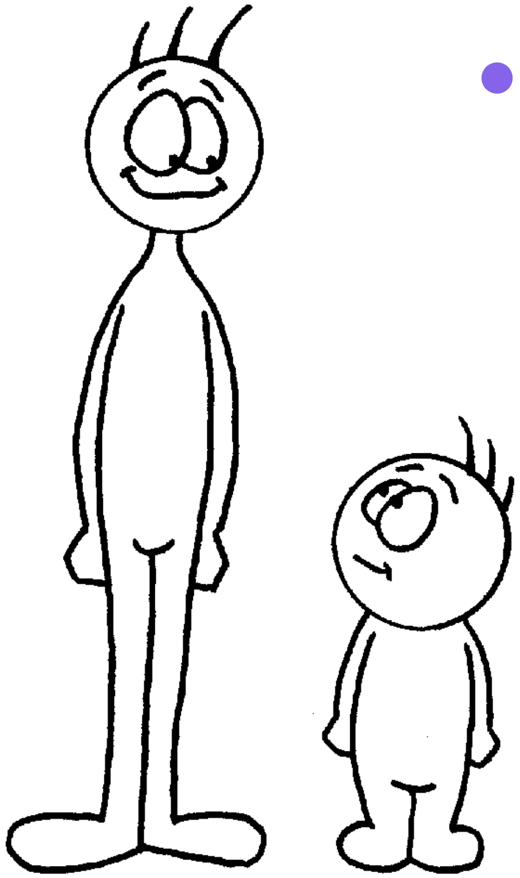

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$$\mathcal{L}_{\rm EFT} = \sum_n c_n(\mu/\Lambda) \frac{O_n}{\Lambda^{d_n-4}}$$

Wilson coefficient

Low-energy operator/ large scale

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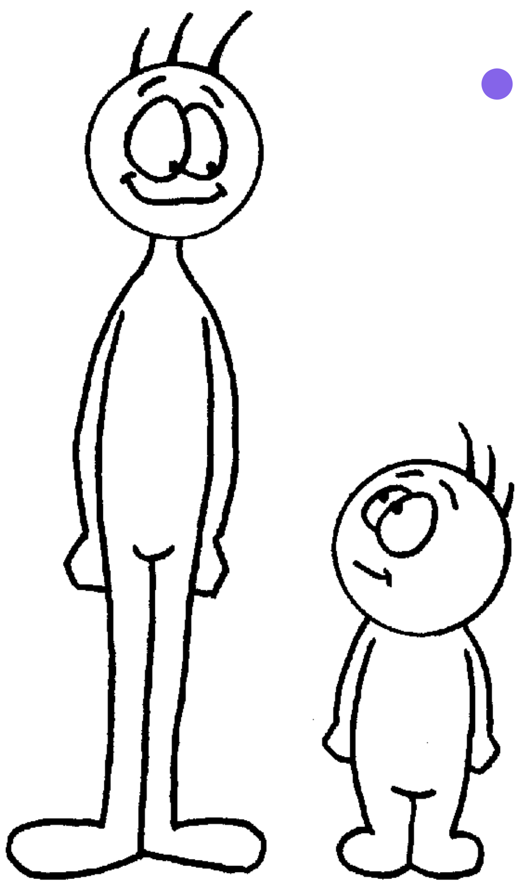

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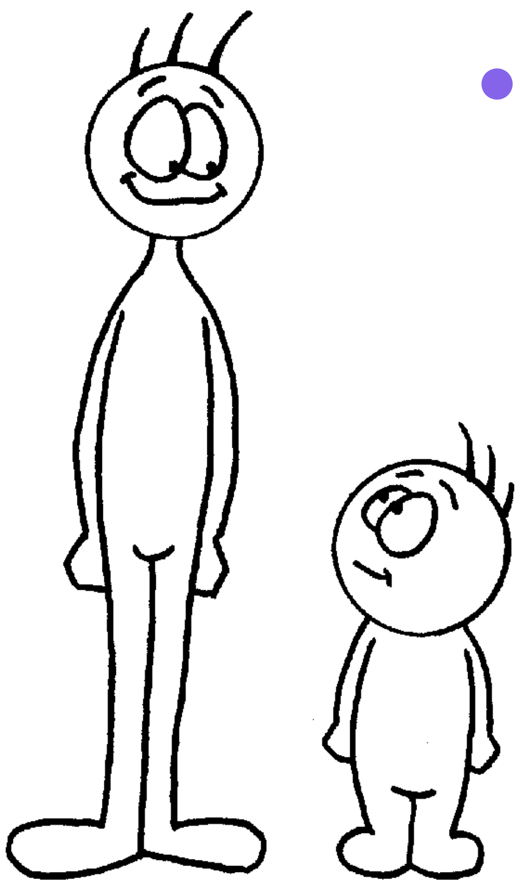

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- The procedure can be iterated $\ldots \ll \mu_2 \ll \Lambda_2 \ll \mu_1 \ll \Lambda_1$

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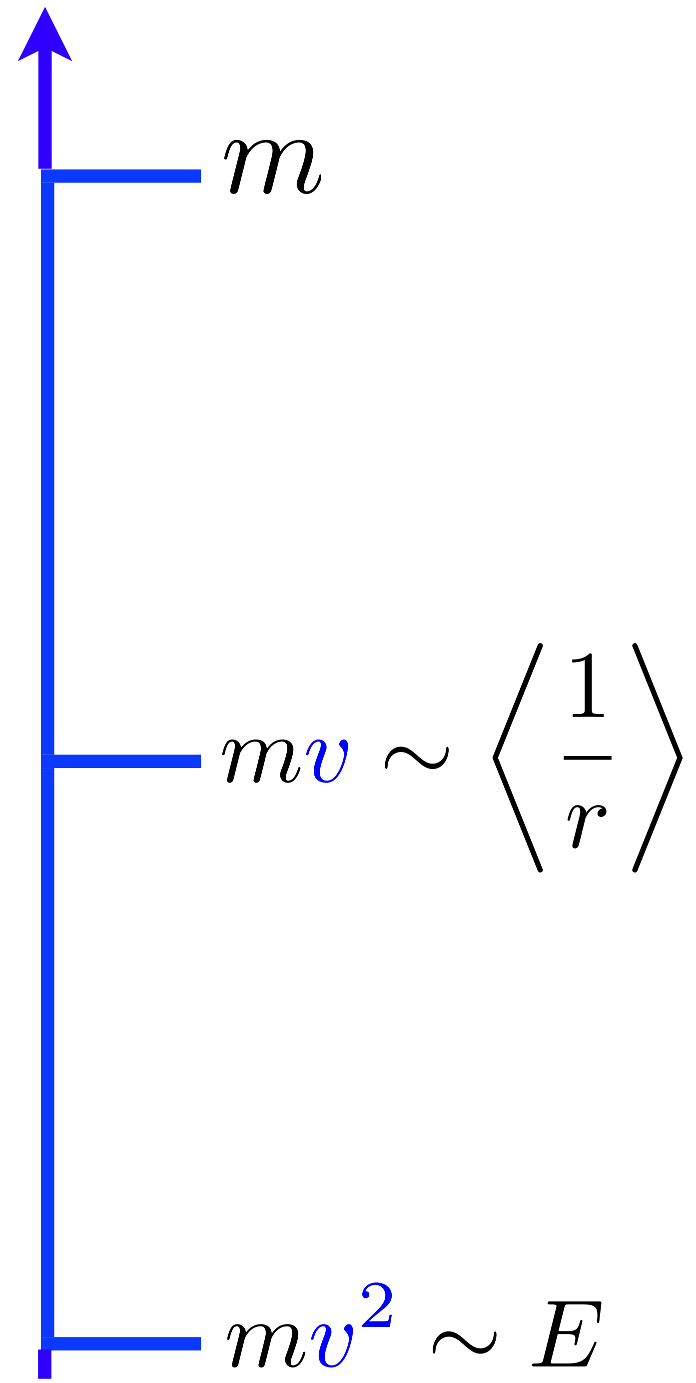
- *Non-relativistic* $Q\overline{Q}$ *bound states* are characterized by the *hierarchy* of the **mass, momentum transfer** and **kinetic/binding energy** scales



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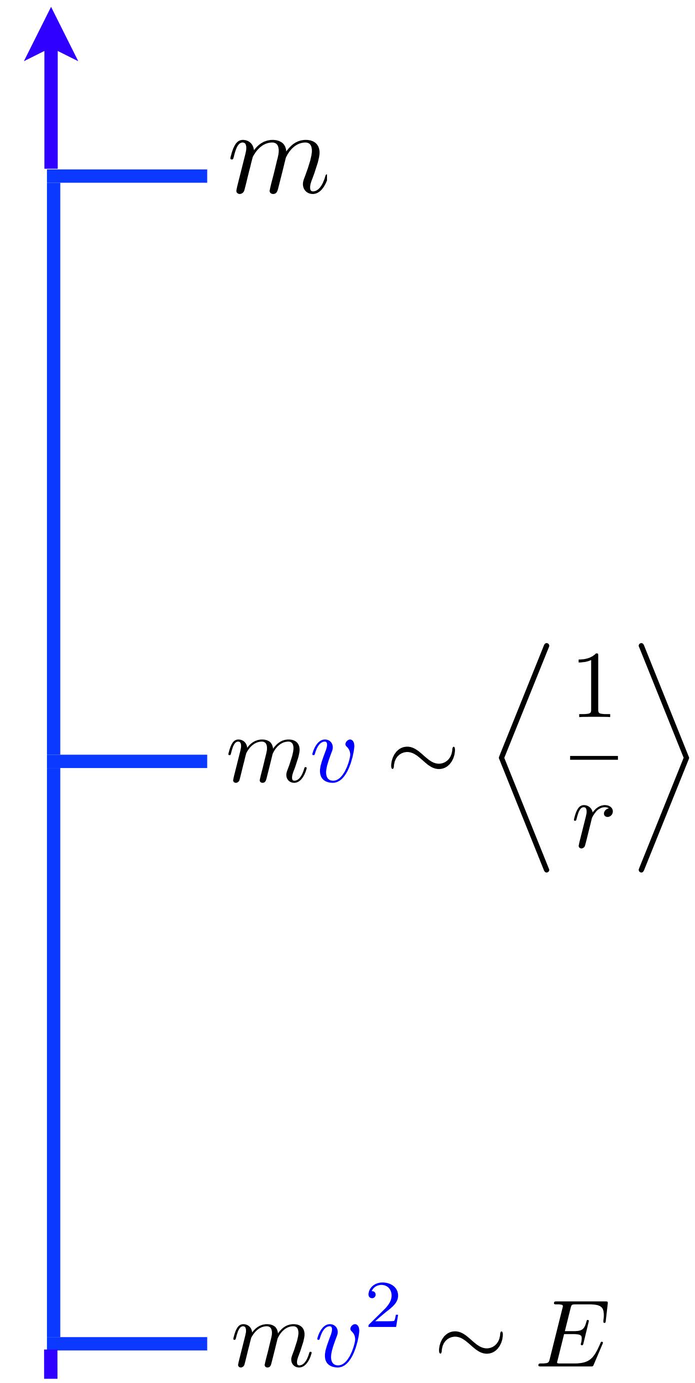

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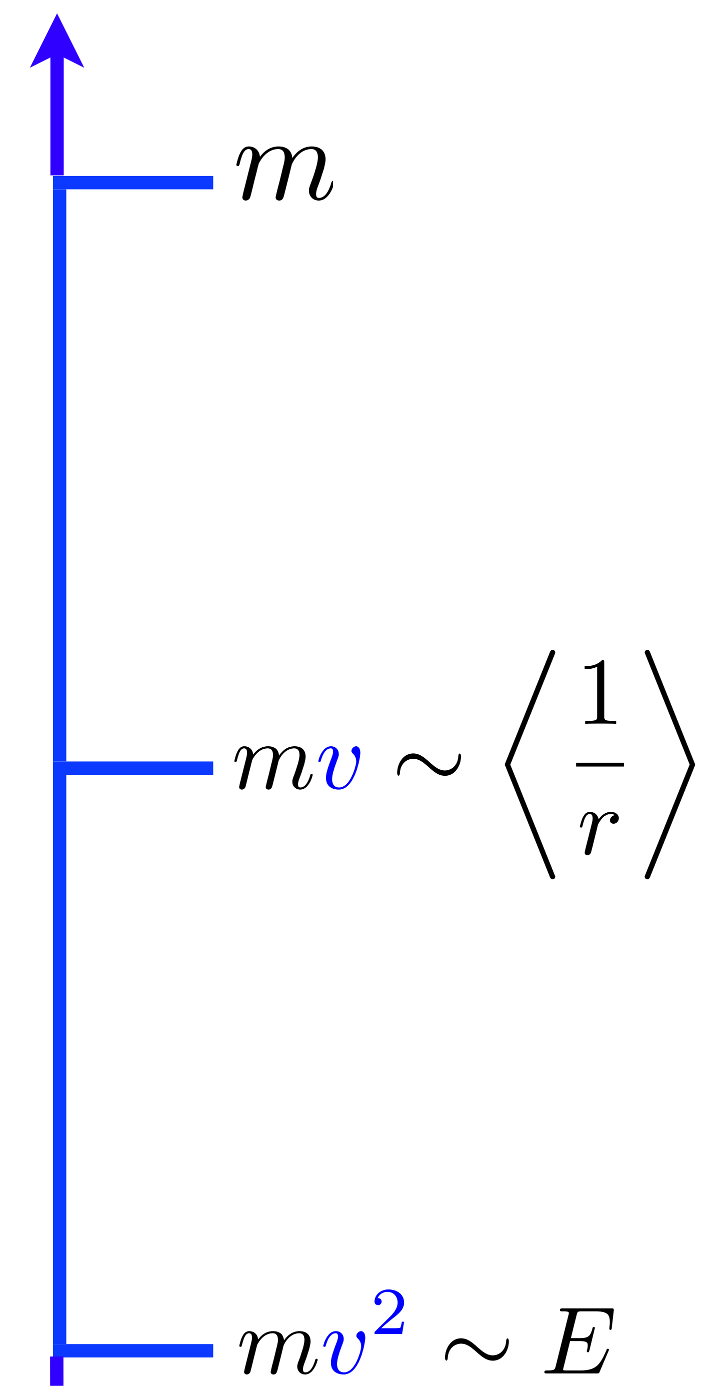
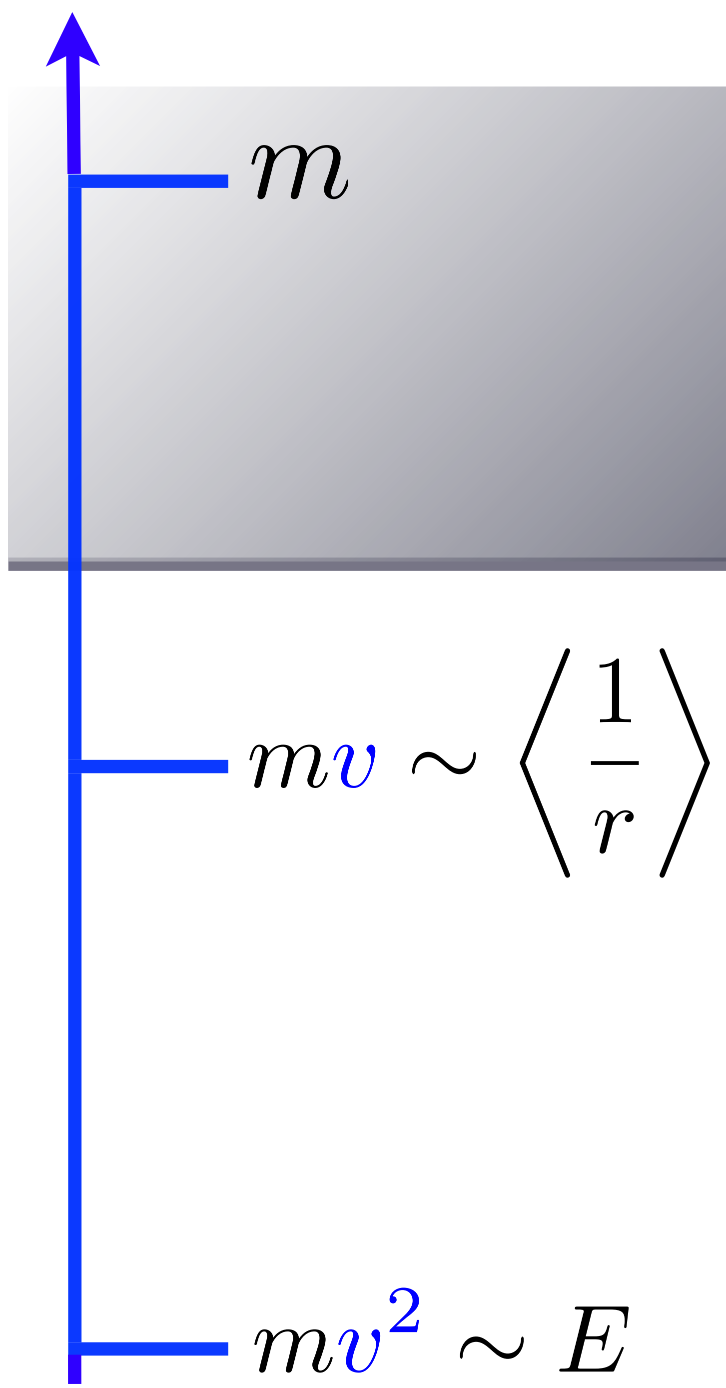
- Expand observables in terms of the ratio of the scales, v
- Construct a *hierarchy of EFTs*. Equivalent to QCD order-by-order in the expansion parameter



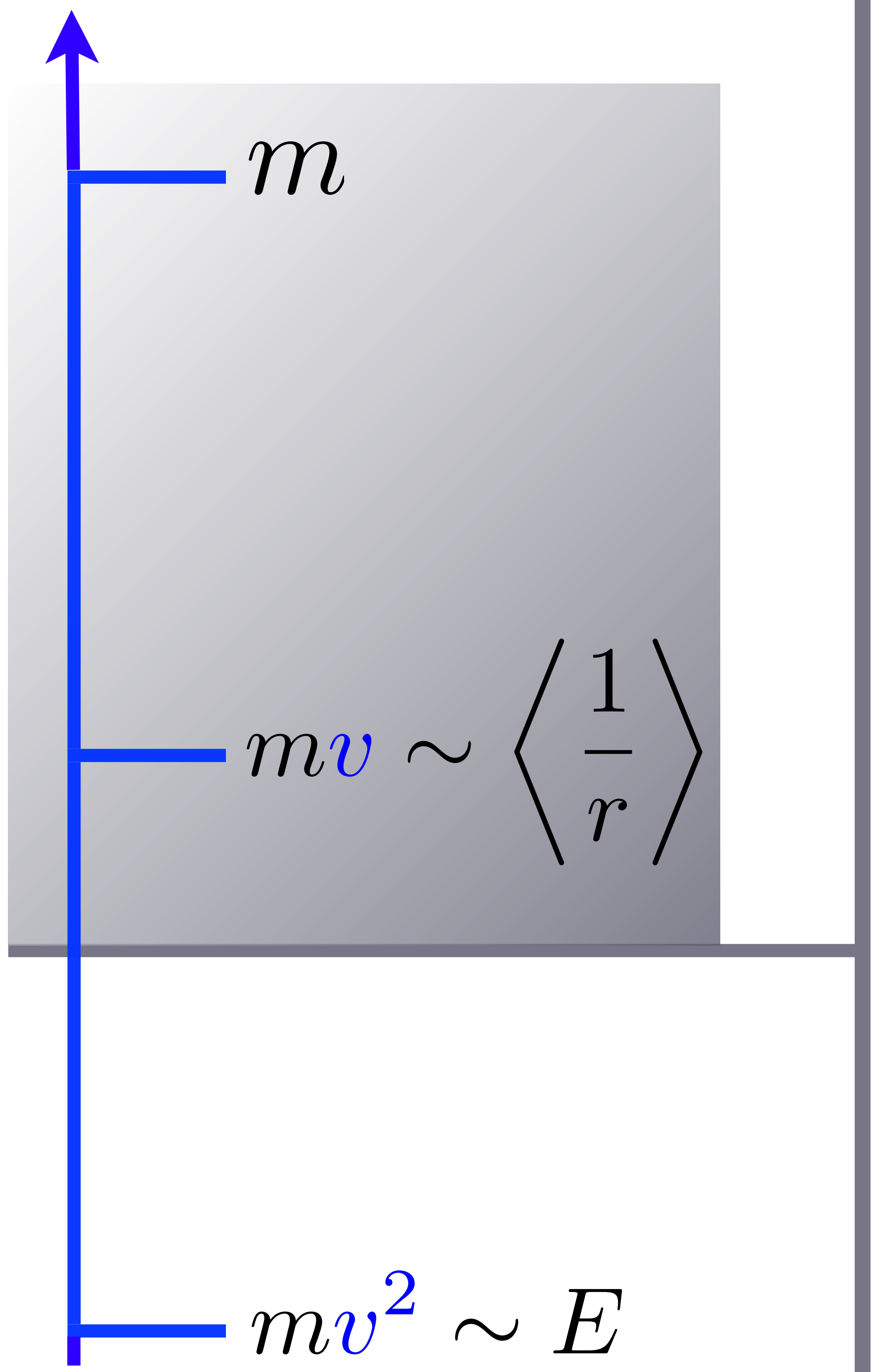


Integrating out the mass scale: Non-Relativistic QCD (NRQCD)

- The mass is integrated out and the theory becomes non-relativistic
- Factorization between contributions from the scale m and from lower-energies
- Ideal for production and decay studies

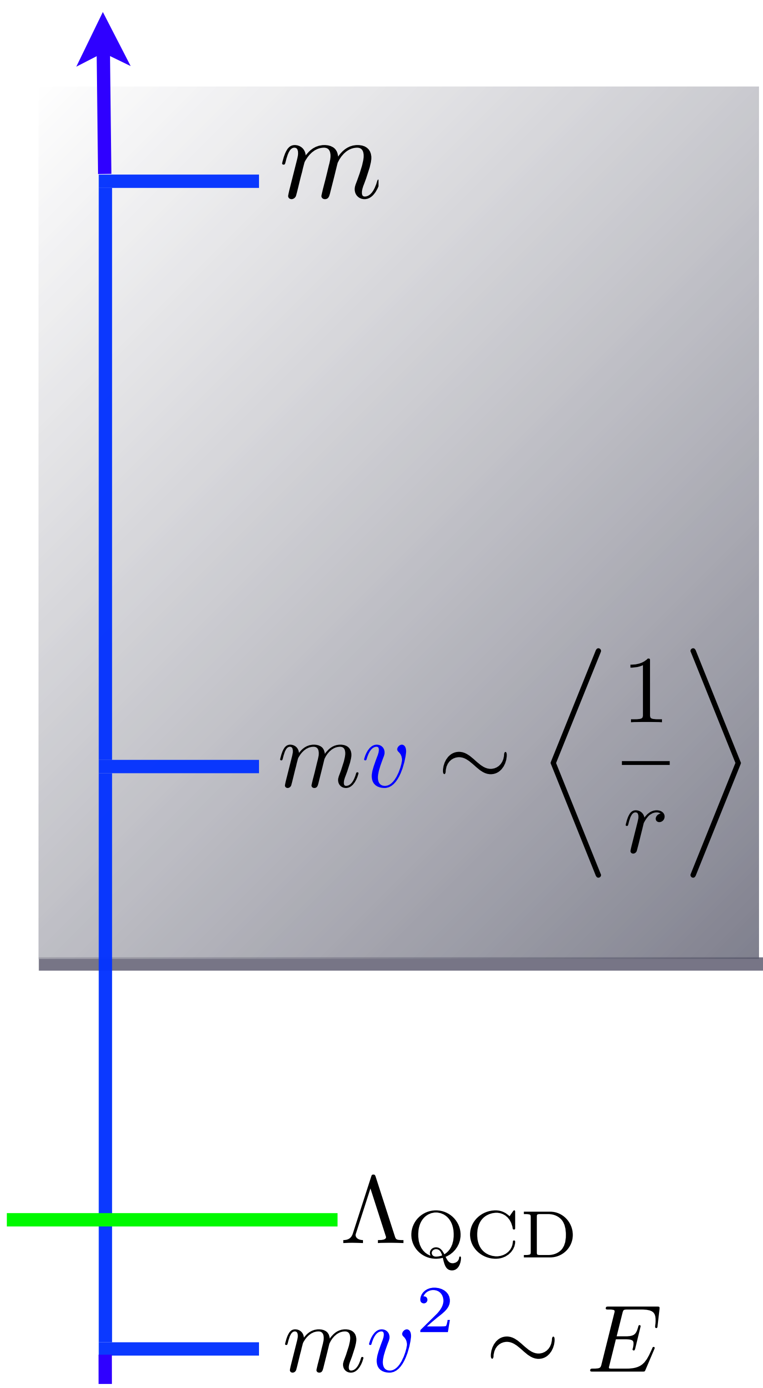
$$\mathcal{L}_{\mathrm{NRQCD}} = \sum_n c_n(\mu/m) \frac{O_n}{m^{d_n-4}}$$

Caswell Lepage **PLB167** (1986)
Bodwin Braaten Lepage **PRD51** (1995)



The scale *mv*: potential NRQCD (pNRQCD)

- Modes with momentum mv are integrated out
- This gives rise to non-local four-fermion operators. Their Wilson coefficients are the potentials, rigorously defined



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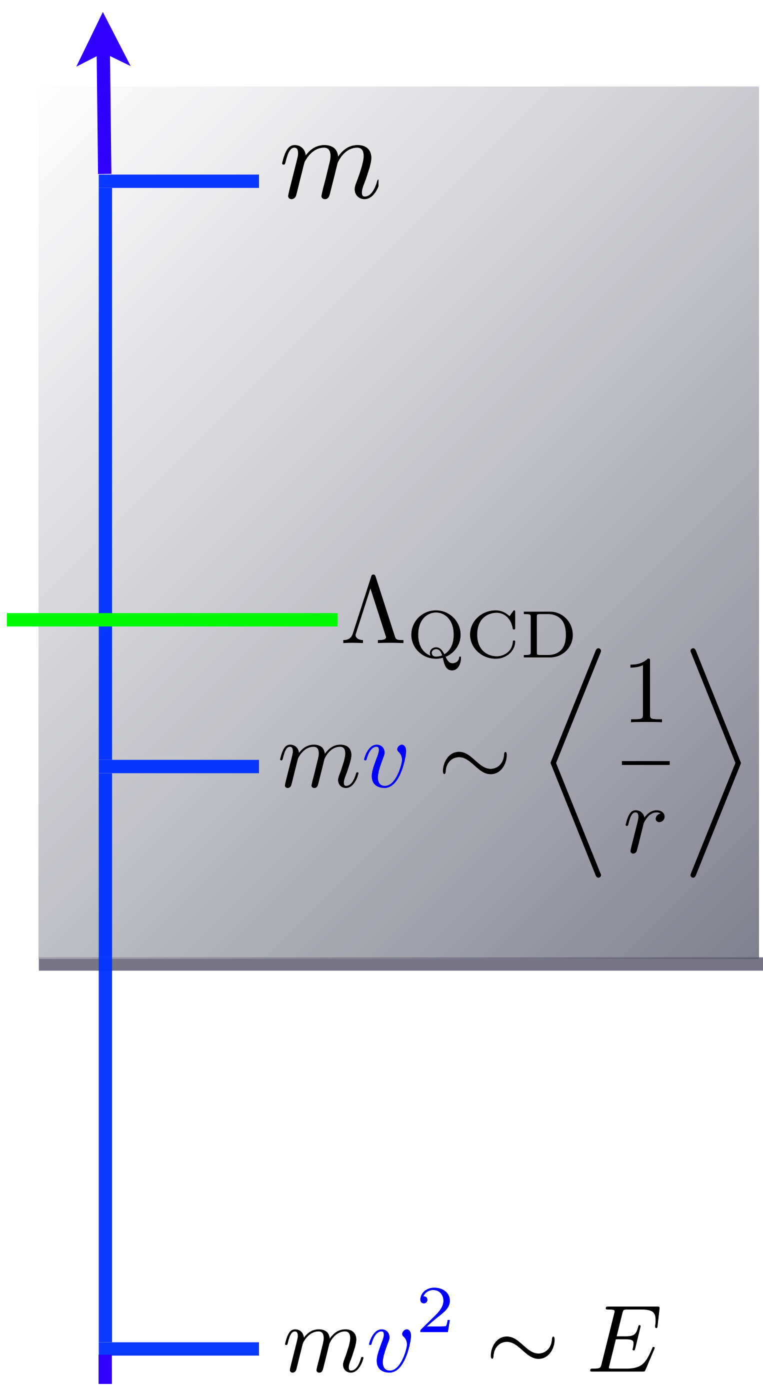
$$\mathcal{L} = \mathcal{L}_{\rm light} + {\rm Tr}\left\{ {\rm S}^\dagger \left[i\partial_0 + \frac{\nabla^2}{m} - V_s \right] {\rm S} + {\rm O}^\dagger \left[iD_0 + \frac{\nabla^2}{m} - V_o \right] {\rm O} \right\}$$

$$+{\rm Tr}\left\{ {\rm O}^\dagger \mathbf{r}\cdot g\mathbf{E}\,{\rm S} + {\rm S}^\dagger \mathbf{r}\cdot g\mathbf{E}\,{\rm O} \right\} + \frac{1}{2}{\rm Tr}\left\{ {\rm O}^\dagger \mathbf{r}\cdot g\mathbf{E}\,{\rm O} + {\rm O}^\dagger {\rm O}\mathbf{r}\cdot g\mathbf{E} \right\} + \ldots$$

Pineda Soto **NPPS64** (1998)
Brambilla Pineda Soto Vairo **NPB566** (2000)



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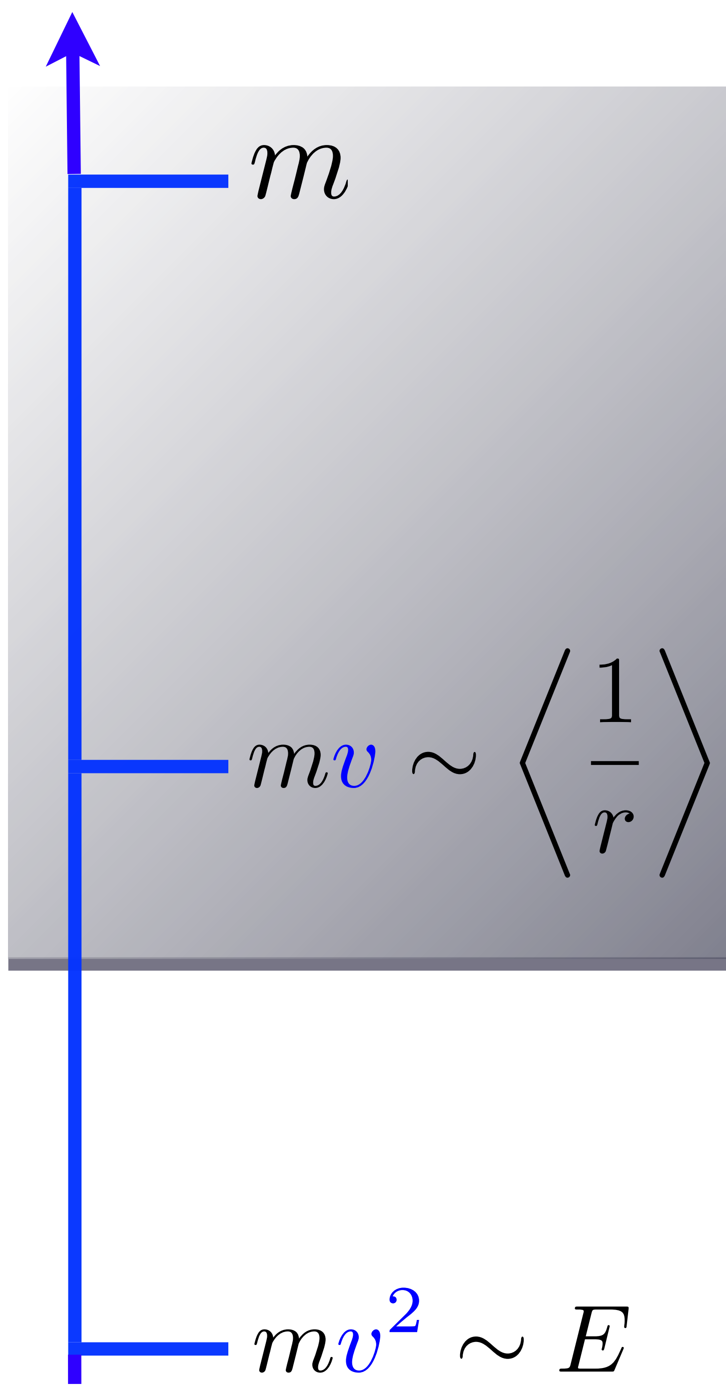

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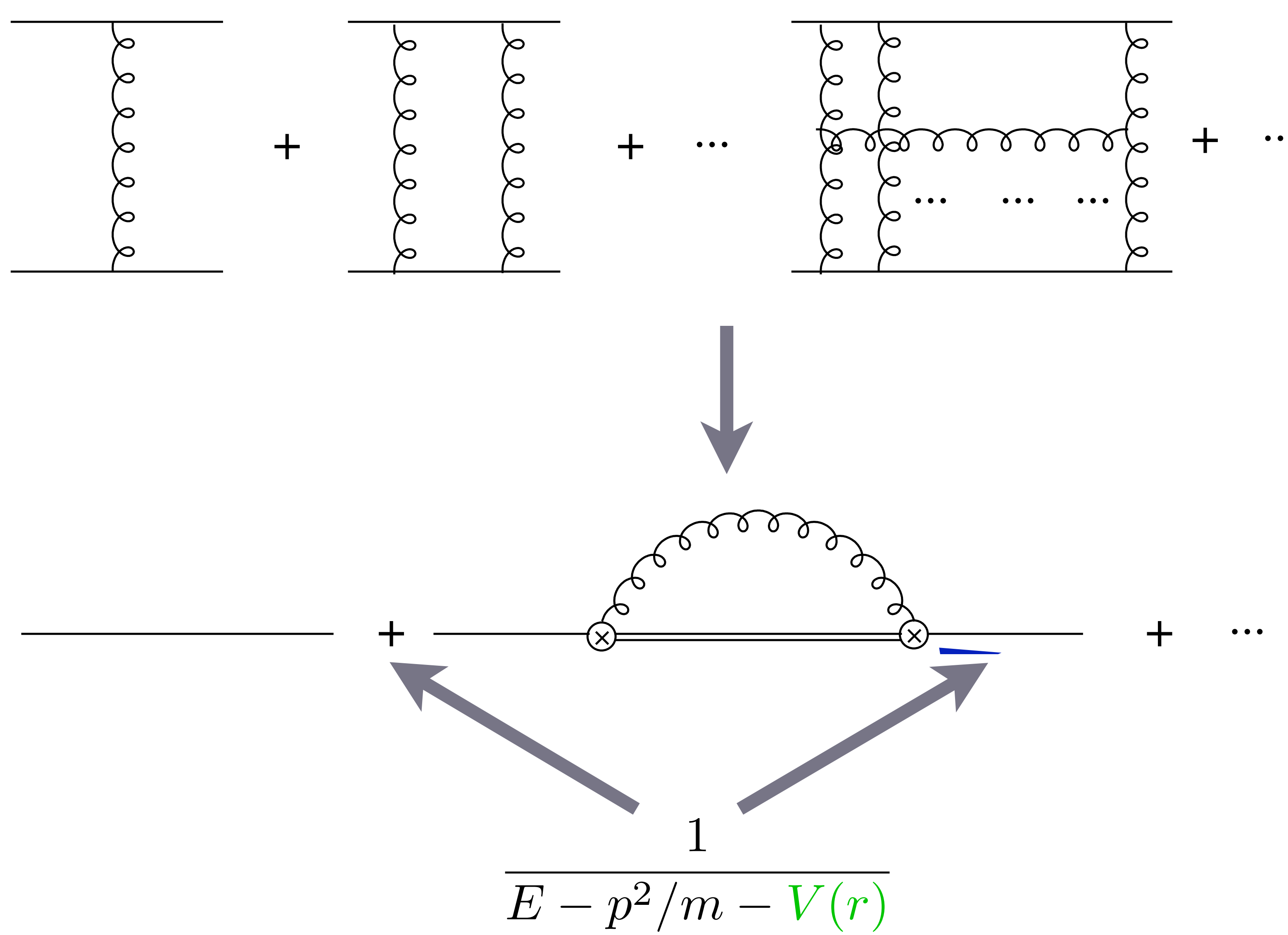

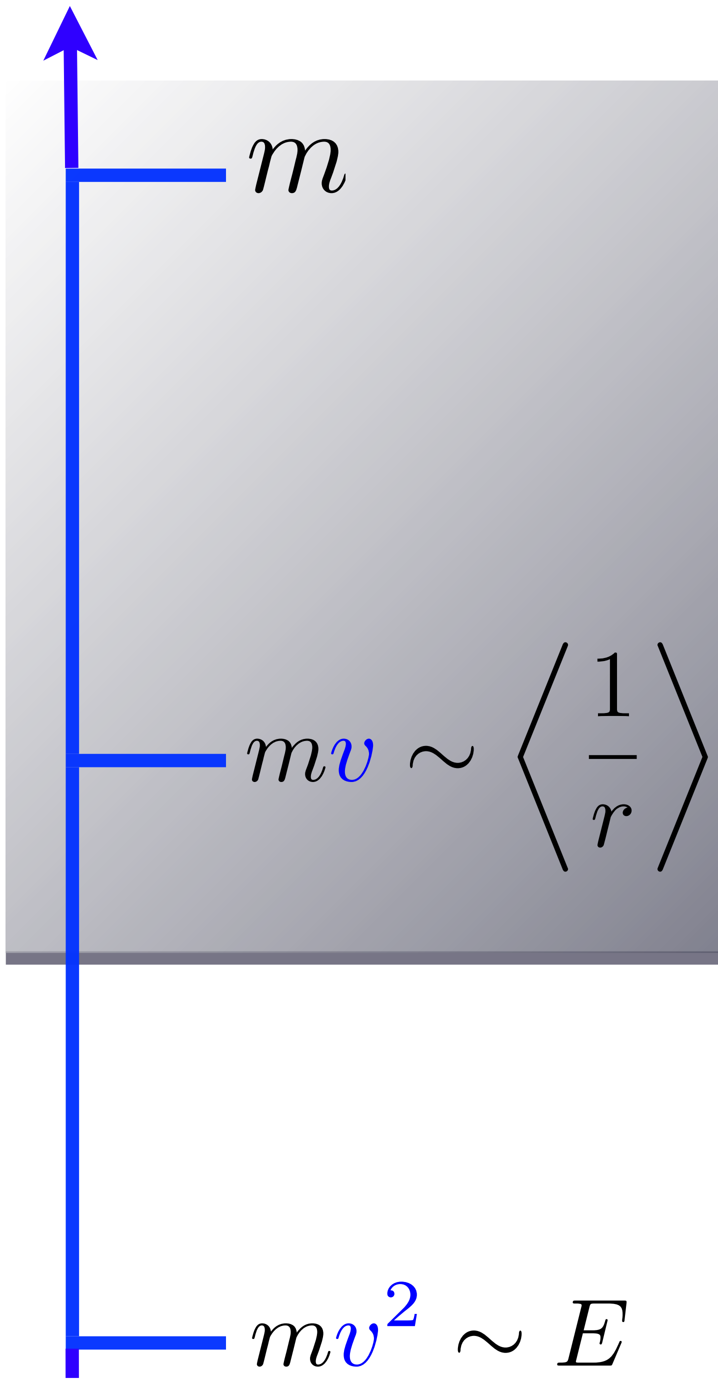

Applications of pNRQCD

- Spectroscopy
- Extraction of SM parameters (m_c, m_b, α_s)
- Comparisons of lattice and perturbation theory
- ttbar threshold production
- Reviews Brambilla *et al.* EPJC71 (2011) EPJC74 (2014)

Applications to quarkonia in HIC

- Production (NRQCD Vitev Sharma **PRC87** 2013, NRQCD+CGC with outlook to AA Kang Ma Venugopalan 2013-14)
- In-medium evolution (NRQCD, pNRQCD and variants)
  - Both perturbation theory and lattice studies

Bring in the medium

- The thermal medium introduces new scales in the physical problem
  - The temperature
  - The electric screening scale (Debye mass)
  - The magnetic screening scale (magnetic mass)
- In the weak coupling assumption these scales develop a hierarchy

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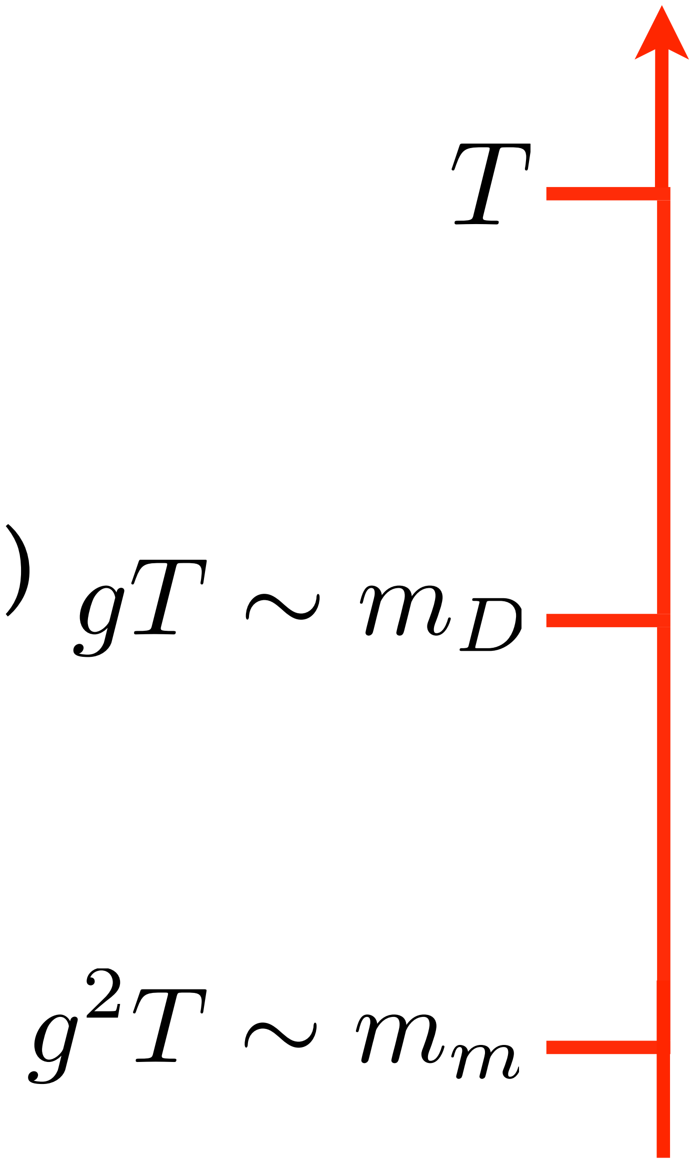


Finite-temperature NR EFT how-to

$$m \gg mv \sim m\alpha_{\rm s} \sim \langle 1/r \rangle \gg mv^2 \sim m\alpha_{\rm s}^2 \sim E$$

$$?$$

$$T \gg m_D \sim gT \gg m_m \sim g^2 T$$

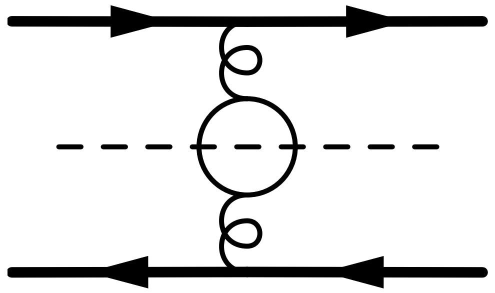
- Assume a global hierarchy between the bound-state and thermodynamical scales
- Many different possibilities have been considered in the relevant macroregions $T \ll mv$, $T \sim mv$ and $T \gg mv$ (with $T \ll m$)
- Proceed from the top to systematically integrate out each scale, creating a tower of EFTs. Make use of existing EFTs (*T=0* NR EFTs, finite *T* EFTs such as HTL)
- Once the scale *mv* has been integrated out the colour singlet and octet potentials appear. They are always complex

The complex potential

- Laine Philipsen Romatschke Tassler **JHEP0703** (2007) : analytical continuation of Wilson loop to large real time yields a complex potential in HTL-resummed PT

$$V_{\rm HTL}(T \gg 1/r, m_D) = -C_F \alpha_{\rm s} \left(\frac{e^{-m_D r}}{r} + m_D - i \frac{2T}{m_D r} f(m_D r) \right)$$

- Re V ⇒ screening. Im V ⇒ width induced by collisions with the medium. Im V >> Re V



- In the EFT: compact real-time derivation, extension to other regimes Brambilla JG Petreczky Vairo **PRD78** (2008)

The dissociation temperature

- Given the potential for $T >> 1/r >> m_D$

$$V_s(r) = -C_F\frac{\alpha_s}{r} - \frac{C_F}{2}\alpha_s\, r\, m_D^2 - i\frac{C_F}{6}\alpha_s\, r^2\, T\, m_D^2\left(-2\gamma_E - \ln(rm_D)^2 + \frac{8}{3}\right) + \ldots$$

- When $T \sim m\alpha_s^{2/3} \;\; \Rightarrow \text{Im}V \sim \text{Re}V$ **Dissociation temperature**

  Escobedo Soto **PRA78** (2008) Laine **0810.1112** (2008)

- Quantitatively, for the $\Upsilon(1S)$

m_c (MeV)	T_d (MeV)
∞	480
5000	480
2500	460
1200	440
0	420

Escobedo Soto **PRA82** (2010)

Below the dissociation temperature

- When $mv >> T >> mv^2$ the thermal medium acts as a perturbation to the potential.
  Relevant for the ground states of bottomonium:
  $m\alpha_s \sim 1.5\mathrm{GeV},\ T < 1\mathrm{GeV}$

- The EFT obtained by integrating out the temperature from pNRQCD is called $\mathrm{pNRQCD}_{\mathrm{HTL}}$

$$\mathcal{L}_{\mathrm{pNRQCD_{HTL}}} = \mathcal{L}_{\mathrm{HTL}} + \mathrm{Tr}\left\{ \mathrm{S}^\dagger \left[i\partial_0 - h_s - \delta V_s \right] \mathrm{S} + \mathrm{O}^\dagger \left[iD_0 - h_o - \delta V_o \right] \mathrm{O} \right\}$$
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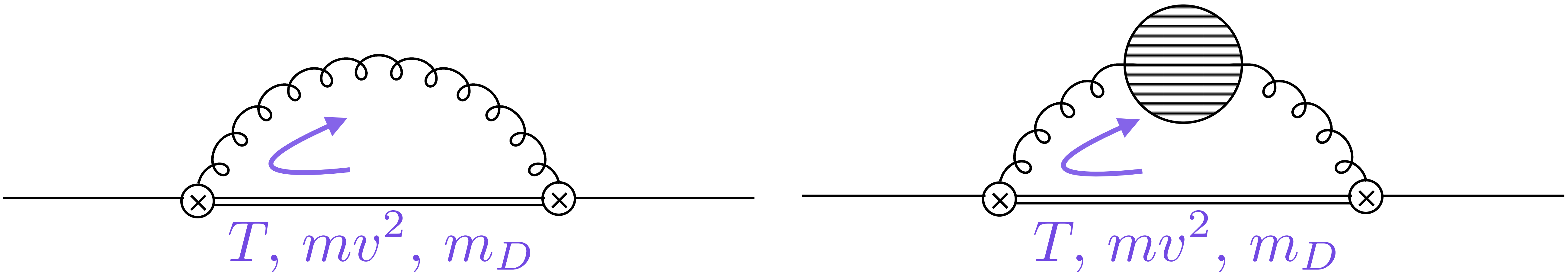
Brambilla Escobedo JG Soto Vairo **JHEP1009** (2010)
Brambilla Escobedo JG Vairo **JHEP1107** (2011)

Below the dissociation temperature

- Within this theory we computed the spectrum and the thermal width of the ϒ(1S) to order $m\alpha_s^5$ in the power counting of the EFT

- We must evaluate loop diagrams in the EFTs



Below the dissociation temperature

- The width reads

$$\Gamma_{1S} = \frac{1156}{27}\alpha_s^3 T + \frac{7225}{162} E_1 \alpha_s^3 - \frac{4}{3}\alpha_s a_0^2 T m_D^2 \left(\ln\frac{E_1^2}{T^2} + 2\gamma_E - 3 - \log 4 - 2\frac{\zeta'(2)}{\zeta(2)} - \frac{8}{3} I_{1S} \right) - \frac{32\pi}{3} \ln 2 \;\, a_0^2 \alpha_s^2 \, T^3$$

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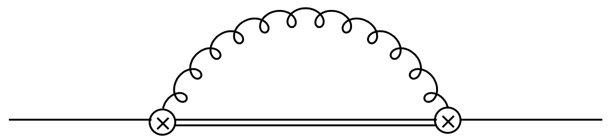
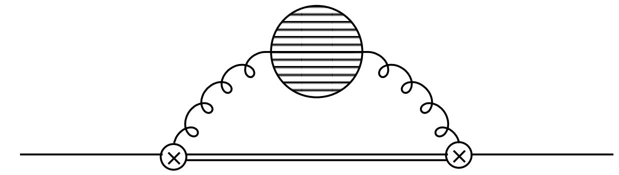
- The leading contribution is linear in the temperature
- Two mechanisms: singlet-to-octet thermal breakup and Landau damping

Below rature



Singlet-to-octet



Landau Damping

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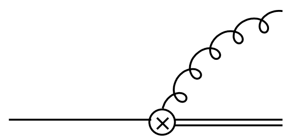

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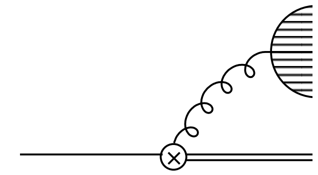

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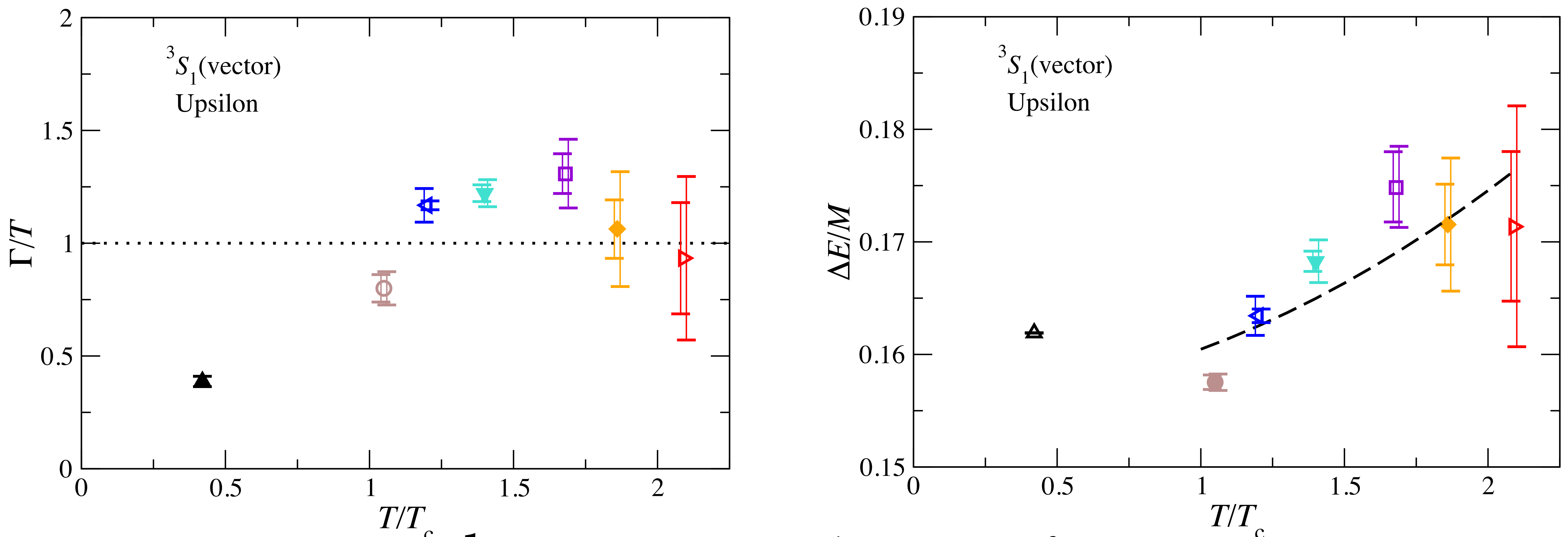
NRQCD on the lattice

- Extraction of the $b\bar{b}$ spectral function from lattice NRQCD with MEM. Mass shifts and widths are obtained by fitting



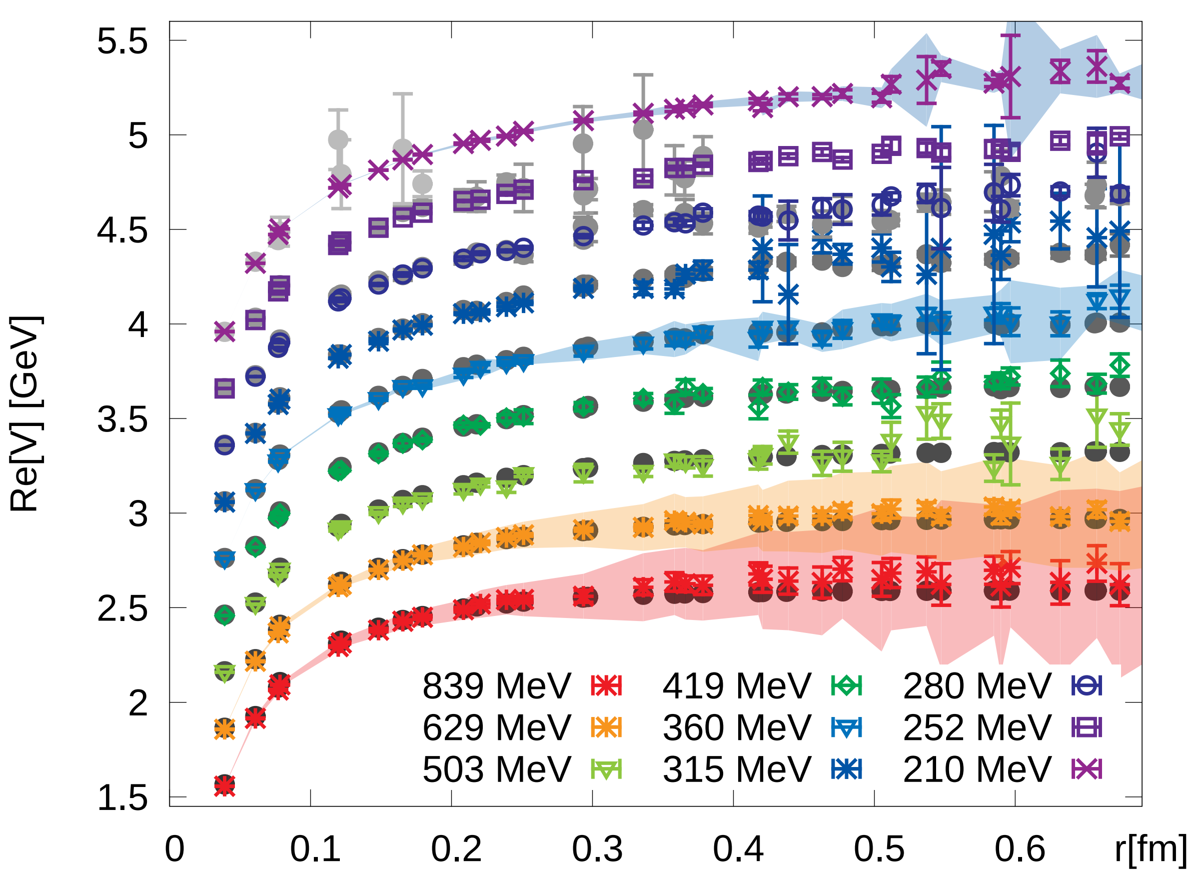
- Consistent with our LO predictions for $\alpha_s = 0.4,\ m_b = 5\,\mathrm{GeV}$ Aarts *et al.* **JHEP1111** (2011).

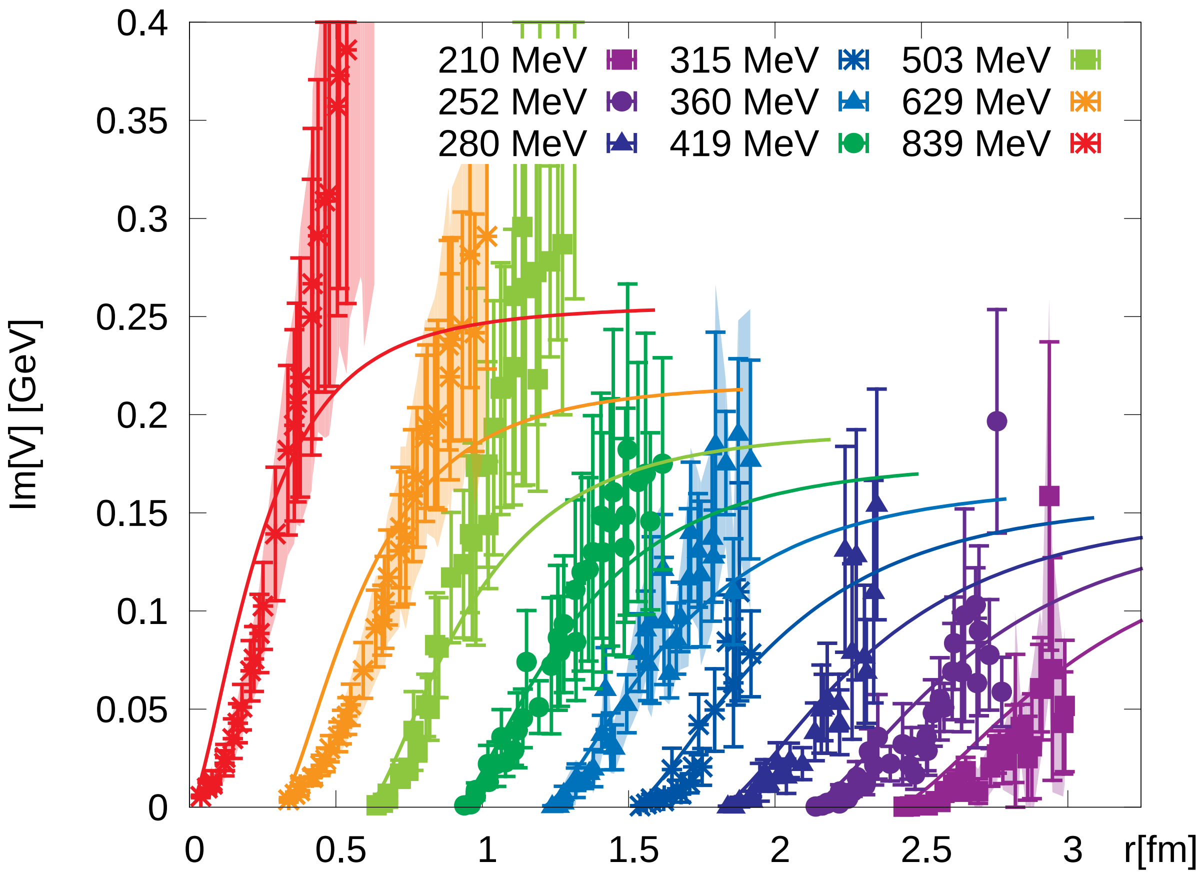
- More lattice NRQCD in Peter's talk

The complex potential at strong coupling

- Extraction of a complex static potential from Euclidean Wilson loops or correlators through novel Bayesian methods Rothkopf Hatsuda Sasaki **PRL108** Burnier Rothkopf 2012-14 Burnier Kaczmarek Rothkopf 2014

$$W(\tau) = \int d\omega e^{-\omega\tau}\rho(\omega) \leftrightarrow \int d\omega e^{-i\omega t}\rho(\omega) = W(t).$$





The imaginary part and the thermal width

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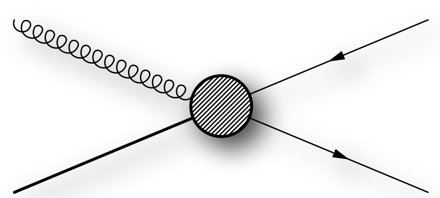
- Two processes have been considered in the literature: *gluo-dissociation* ($g + \Psi \to (Q\overline{Q})_8$) and *elastic dissociation* ($(g, q, \overline{q}) + \Psi \to (Q\overline{Q})_8 + (g, q, \overline{q})$)



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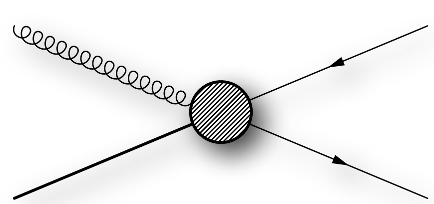


$g + \Psi \to (Q\overline{Q})_8$

$(g, q, \overline{q}) + \Psi \to (Q\overline{Q})_8 + (g, q, \overline{q})$

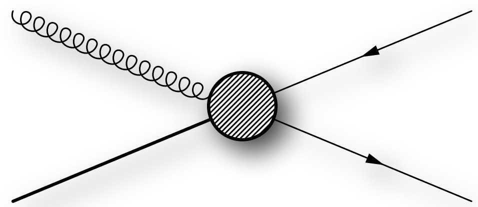
- In both cases the width is obtained by convoluting the (zero-temperature) *dissociation cross section* with a thermal distribution for the incoming light particle

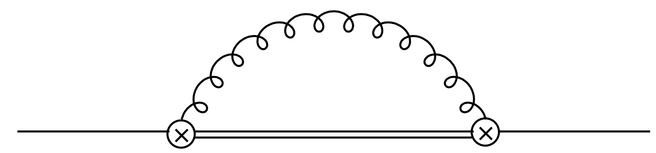
$$\Gamma = \sum_i \int \frac{d^3q}{(2\pi)^3} f_i(q,T)\, \sigma(q)\, v_{\rm rel}$$

Kharzeev Satz **PLB334** (1994) Xu Kharzeev Satz Wang **PRC53** (1996)

Grandchamp Rapp **PLB523** (2001)

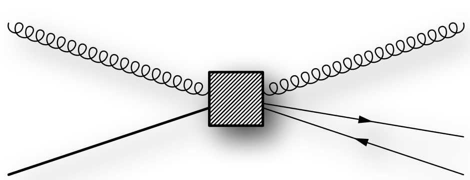
The imaginary part and the thermal width

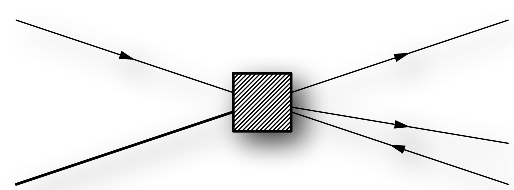


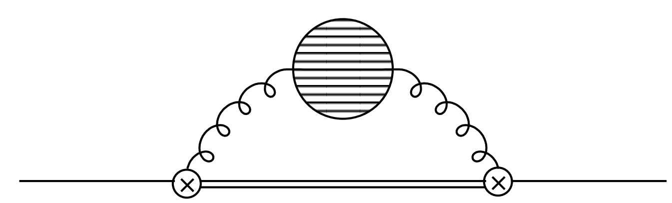


$g + \Psi \to (Q\overline{Q})_8$

- Singlet-to-octet corresponds to *gluodissociation*. The old Bhanot-Peskin cross section is a limiting case of ours.
  Bhanot Peskin **NPB156** (1979) Brambilla Escobedo JG Vairo **JHEP1112** (2011) Brezinski Wolschin **PLB707** (2011)







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- Landau damping corresponds to elastic parton scattering. Clarification of validity regions in both cases
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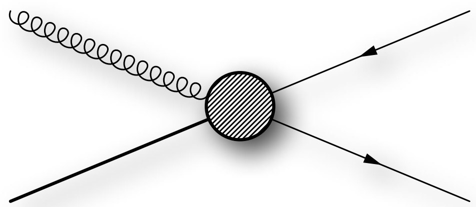

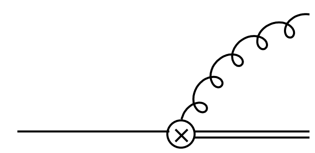

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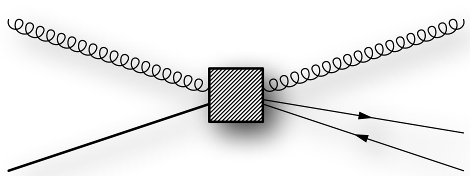

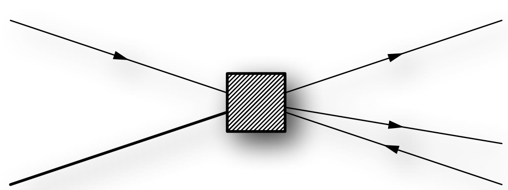

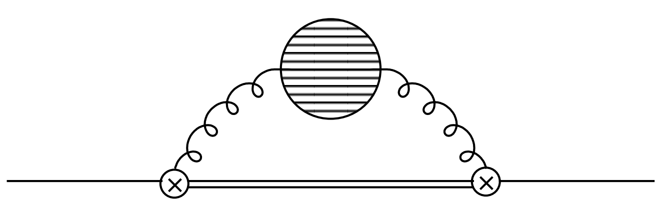

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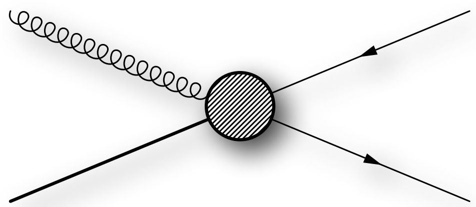
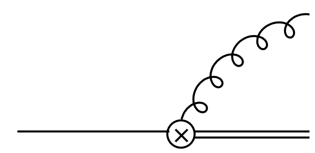

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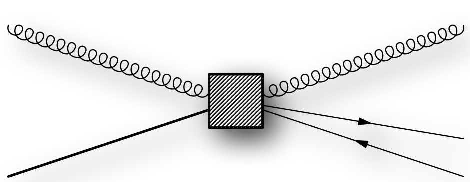
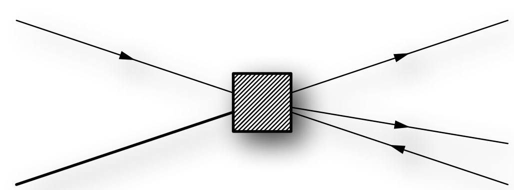
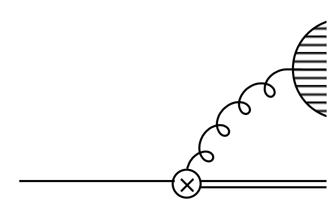

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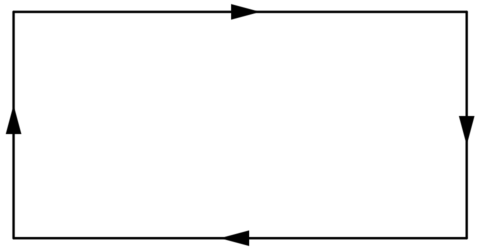
Interpreting the imaginary part

- Irrespective of any perturbative mechanism, this thermal width is not for decay into light stuff. Conserves HQ number and exists in the static limit

- It encodes the decoherence effect caused by the medium on the bound state wavefunction

- Open quantum system interpretation: correlators may decay exponentially, wave function (norm) may not
Akamatsu, Rothkopf 2011-14



$$W(r,t) \approx \langle S(r,t) S^\dagger(r,0) \rangle \to Z \exp(-iV(r)t)$$

An EFT application

- Recent results by Brambilla Escobedo Soto Vairo, presented by M. Escobedo at ConfXI

- Evolution equations for singlet and octet fields, with EFT Hamiltonians

$$f_s(x,y) = Tr(\rho S^\dagger(x) S(y))$$

$$H = \frac{H_{eff} + H_{eff}^\dagger}{2}$$

$$\Gamma = i(H_{eff} - H_{eff}^\dagger)$$

$$\partial_t f_s = -i[H, f_s] - \frac{1}{2}\{\Gamma, f_s\} + \mathcal{F}(f_o) \qquad \partial_t f_o = -i[H_o, f_o] - \frac{1}{2}\{\Gamma, f_o\} + \mathcal{F}_1(f_s) + \mathcal{F}_2(f_o)$$

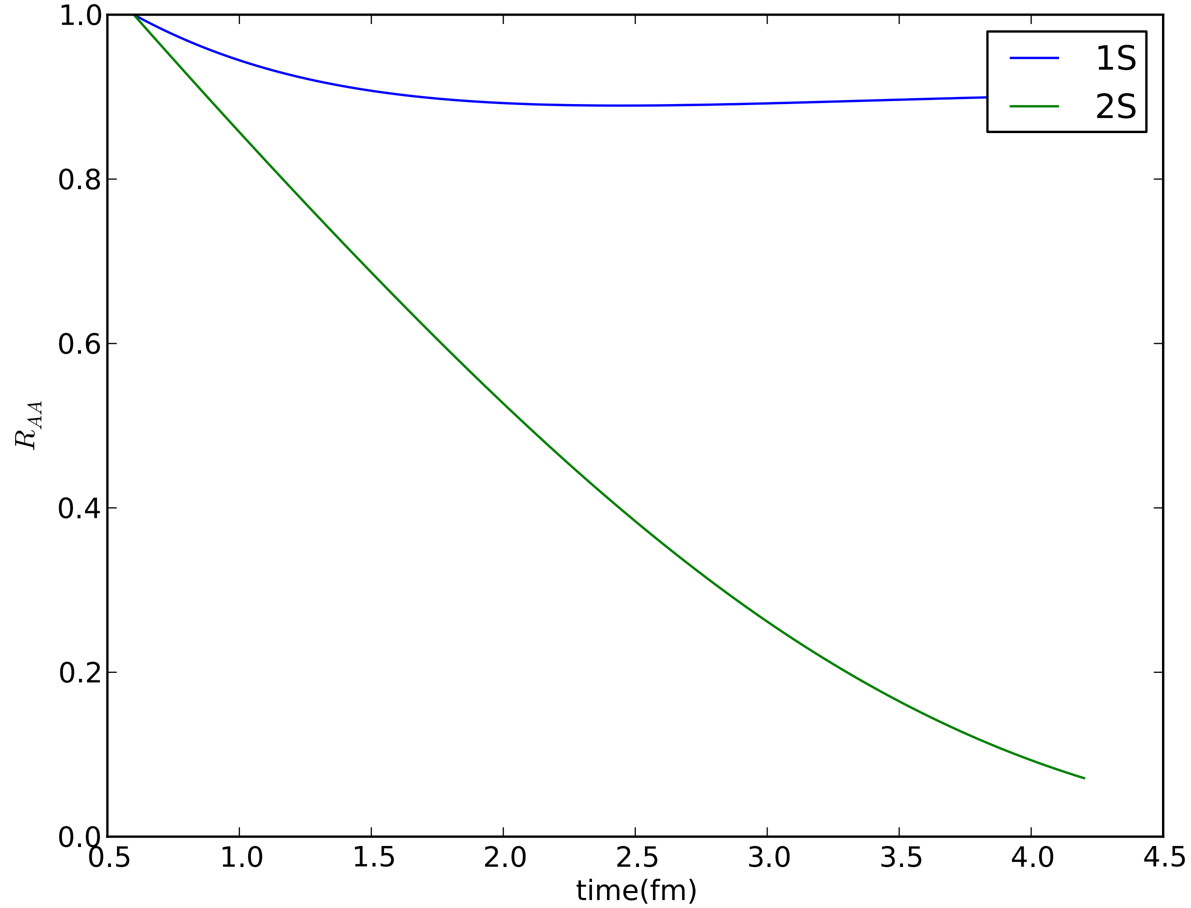
- HQ number conservation $\partial_t Tr(f_s) + \partial_t Tr(f_o) = 0$

- Numerical solution by using the Lindblad form Akamatsu 2014

$$\partial_t \rho = -i[H, \rho] + \sum_k (C_k \rho C_k^\dagger - \frac{1}{2}\{C_k^\dagger C_k, \rho\})$$

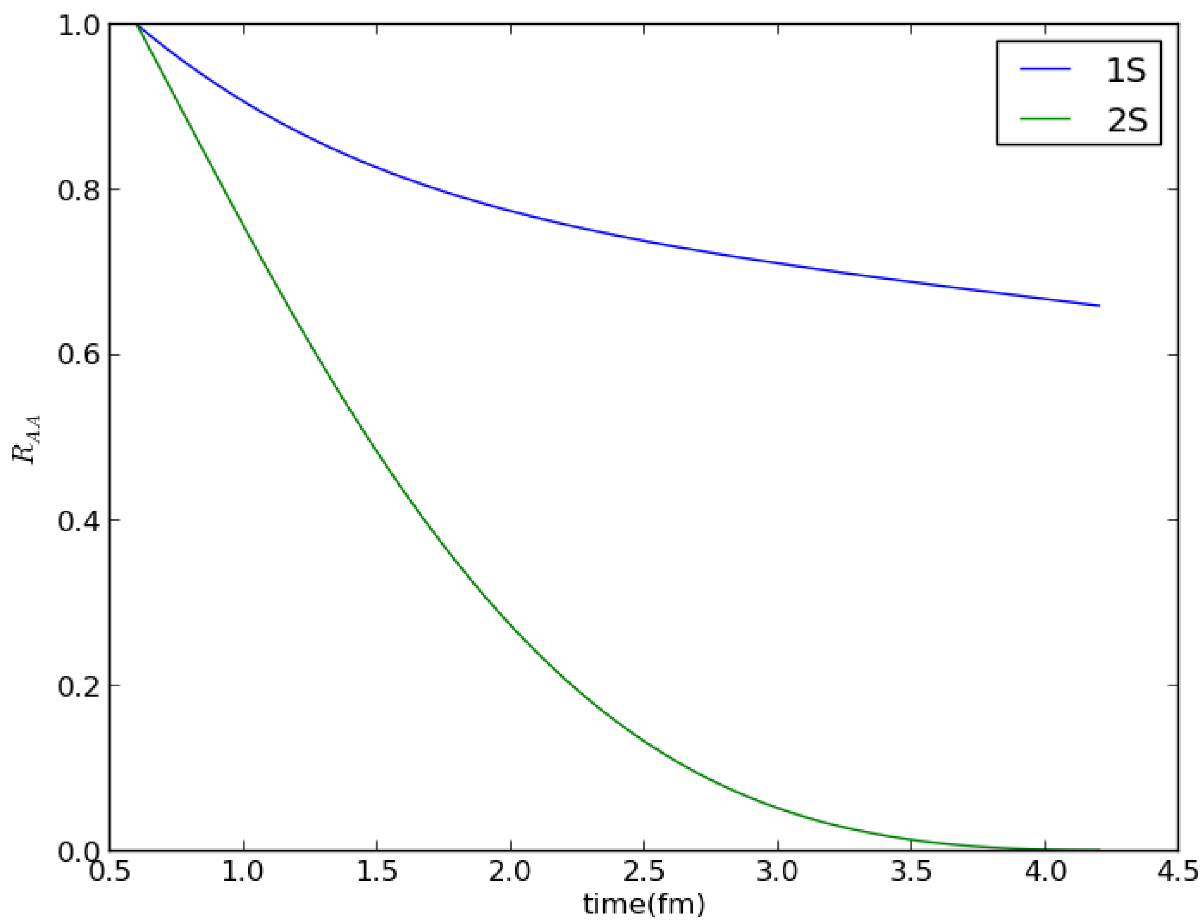
An EFT application

- First numerical results within a simple fireball, no CNM, no feeddown, simple initial conditions
- Screening only, R_{AA} for $\Upsilon(1S)$ (number of 1S states)



An EFT application

- First numerical results within a simple fireball, no CNM, no feeddown, simple initial conditions
- Width and transitions, R_{AA} for $\Upsilon(1S)$



Conclusions

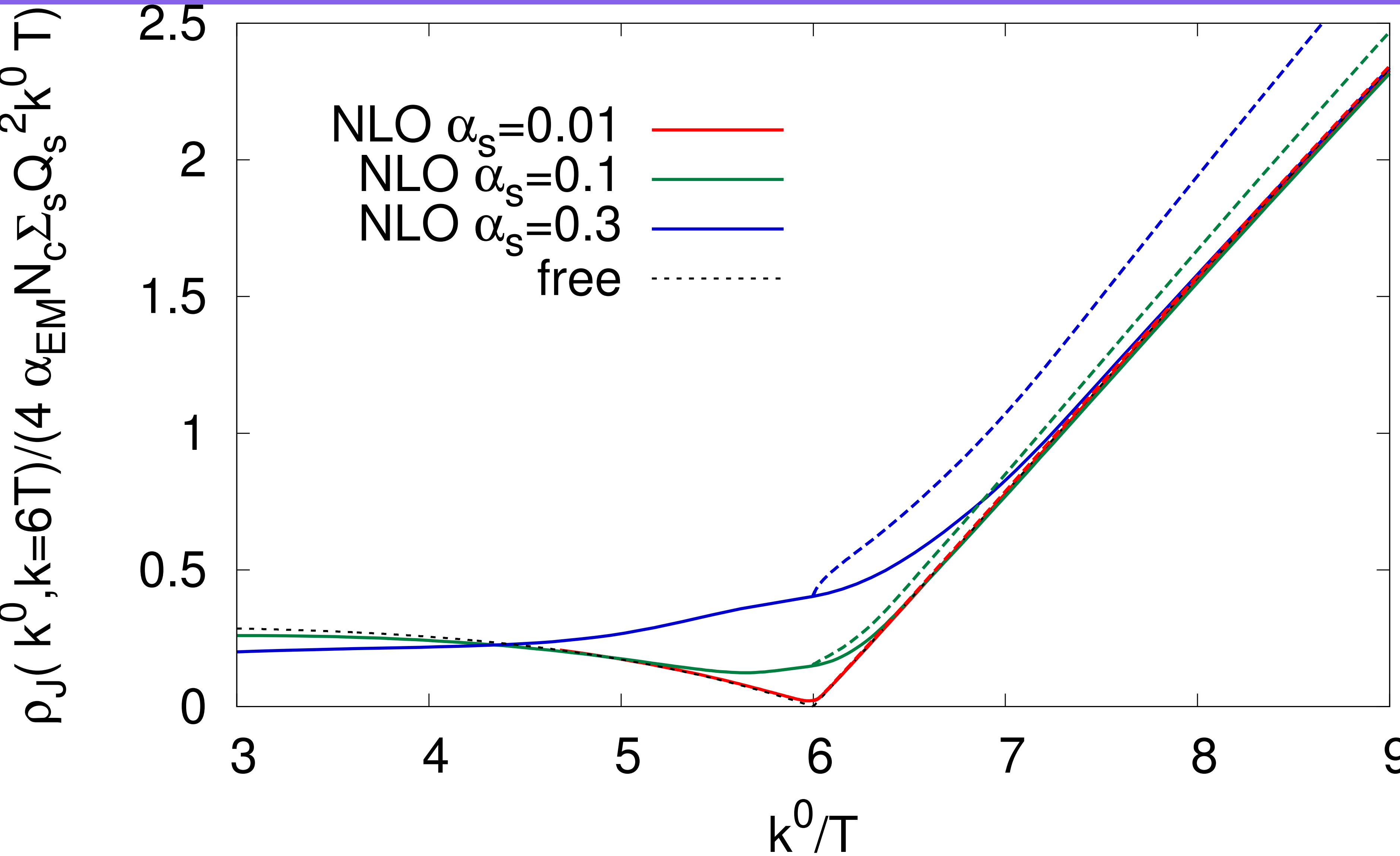
- Lessons from the EFT framework
  - Systematically take into account corrections and include all medium effects
  - Give a rigorous QCD derivations of the potential, bridging the gap with potentials models which appear as leading-order picture here
  - Importance and interpretation of the complex potential
  - Nonperturbative extensions and applications (Peter's talk)

Discussion

MAGNETIC DISCUSSION

Photons and dileptons

$$(2\pi)^4 \frac{dN_{l^+l^-}}{d^4K\,d^4X} \frac{3K^2(\exp(k^0/T)-1)}{16\alpha^2 k^0 T}$$



- Full lines: NLO calculation valid at small K^2 JG Moore (2014)
- Dashed lines: combination of the above with NLO calculation valid at large K2 Ghisoiu Laine (2014) Laine (2013)

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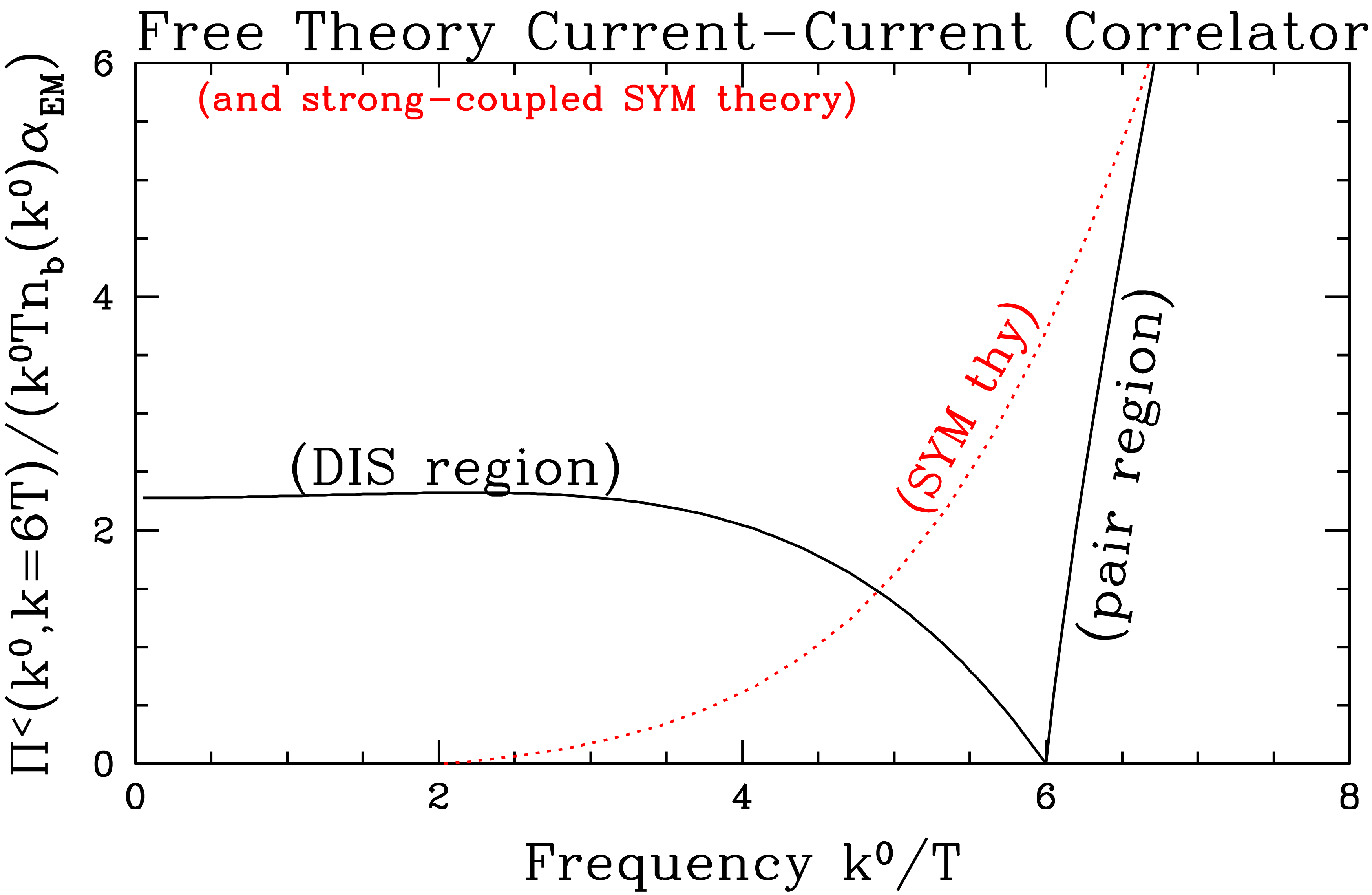

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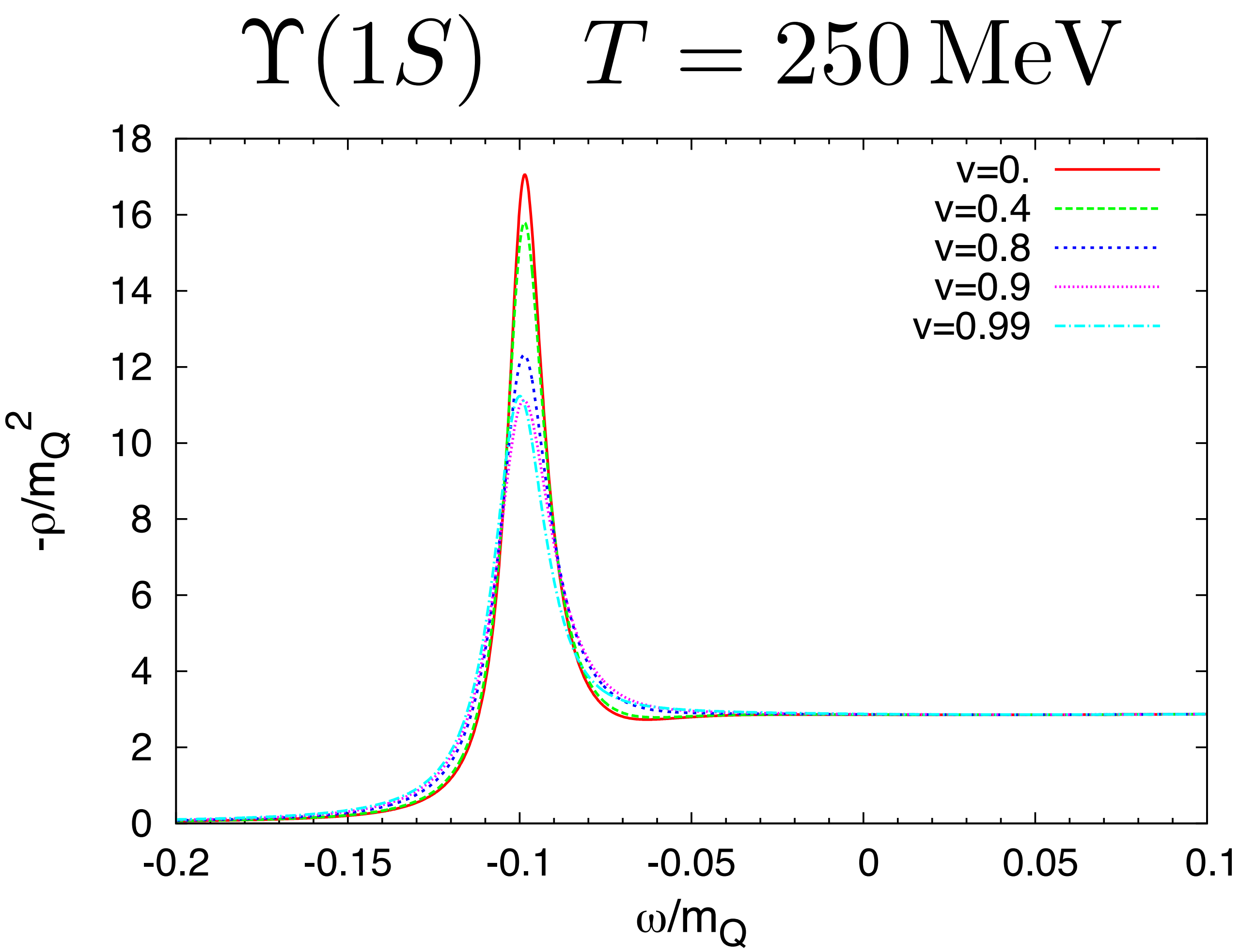
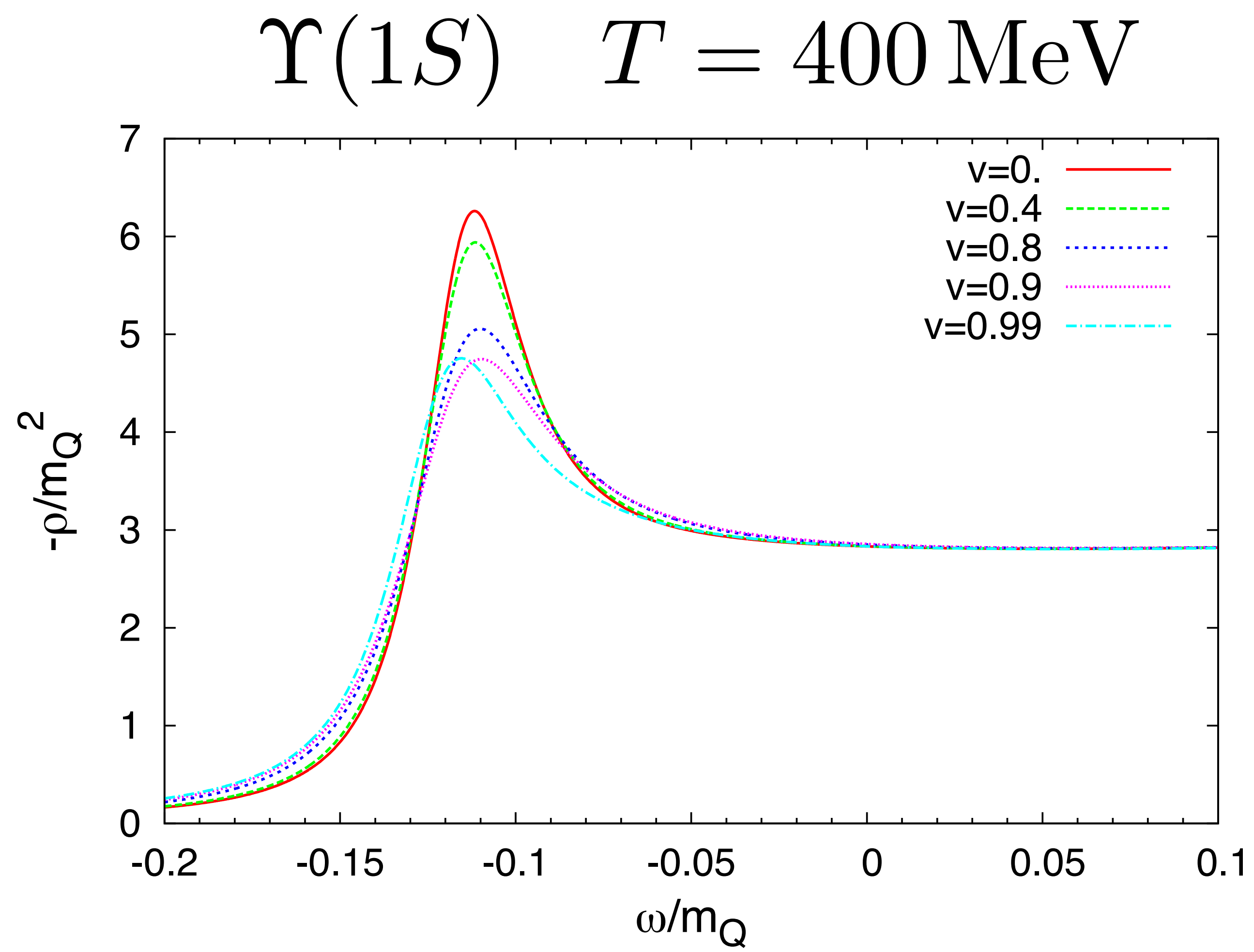
EFTs at finite temperature

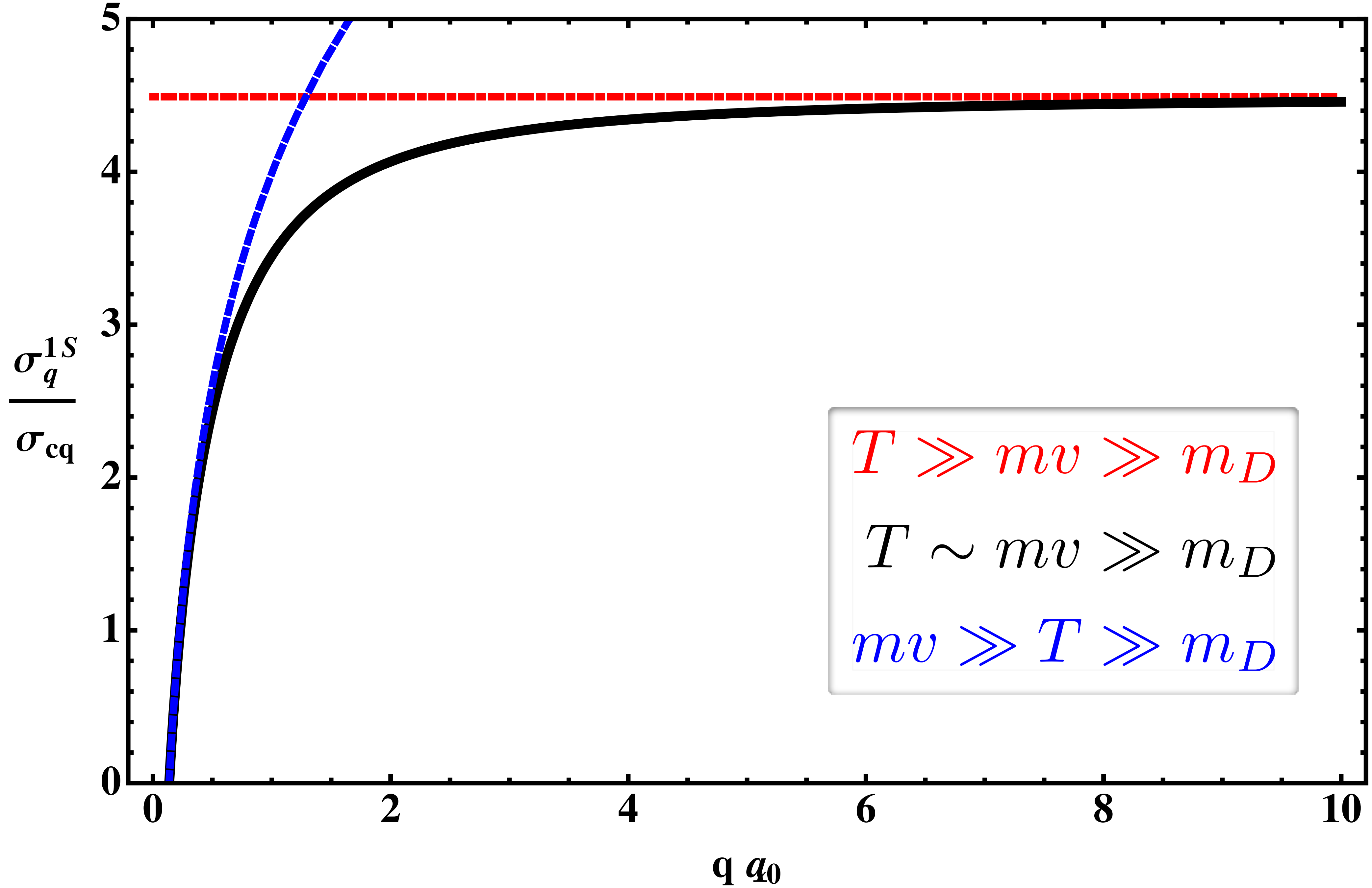




- Dependence on the relative velocity of quarkonium and medium Escobedo Giannuzzi Mannarelli Soto **PRD87** (2013)

Quasi-free cross section, quark contribution

$m_D a_0 = 0.1 \qquad \sigma_{cq} = \frac{32}{3}\pi\,\alpha_s^2\,a_0^2$



Brambilla Escobedo JG Vairo **JHEP1305** (2013)

Potentials and free energies

- Thermodynamical free energies obtained from Polyakov loops are widely used and measured on the lattice
- We have studied the **correlator of Polyakov loops** and the associated **colour-average free energy** $\langle \mathrm{Tr} L^\dagger(\mathbf{0}) \mathrm{Tr} L(\mathbf{r}) \rangle = e^{-\frac{F_{Q\overline{Q}}(r,T)}{T}}$

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- We have shown that, with pNRQCD in imaginary time, it can be decomposed at short distances into gauge-invariant colour-singlet and octet free energies
- These free energies are quantitatively different from the real-time potentials

$$\mathrm{Im}(F) = 0, \mathrm{Im}(V) \neq 0 \quad \mathrm{Re}(F) \neq \mathrm{Re}(V)$$

Brambilla JG Petreczky Vairo **PRD82** (2010)

Potentials and free energies

- These free energies are quantitatively different from the potentials

$$\mathrm{Im}(F) = 0, \mathrm{Im}(V) \neq 0 \quad \mathrm{Re}(F) \neq \mathrm{Re}(V)$$

- Intuitively

$$t \to \infty \neq it = \frac{1}{T}$$

- Extra divergences can arise for observables spanning the entire imaginary axis
  Berwein Brambilla JG Vairo **JHEP1303** (2013)