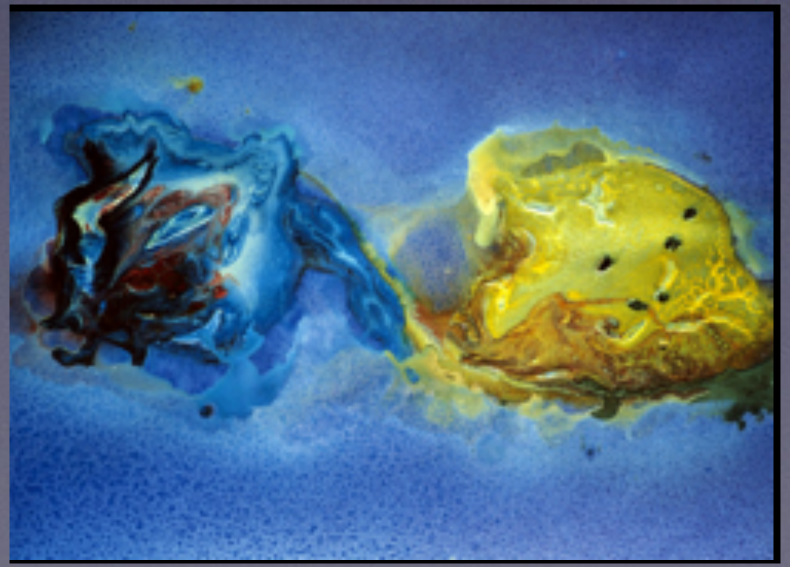
Quarkonium as a probe of hot/dense matter

with potential NonrelativisticQCD and Open Quantum Systems



PHYSIK DEPARTMENT TUM
T30F

NORA BRAMBILLA

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- To do involves extending the description to charmonium, B_c

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- What I discuss is not depending on the medium :
  it can be a hot medium or a dense medium, weakly or strongly coupled

  in what I will present T may be substituted as the inverse of a correlation length characterising the system

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- What I discuss can be generalised to X Y Z using BOEFT (Born-Oppenheimer EFT that we developed) and open quantum systems

Material for discussion/references

N. Brambilla, M. A. Escobedo, J. Soto and A. Vairo, Phys. Rev. D **96** (2017) no.3, 034021 [arXiv:1612.07248 [hep-ph]].

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Non-equilibrium evolution in QGP

M. Escobedo *Phys.Rev.D* 103 (2021) 3, 034010 • e-Print: 2010.10424 [

#4

N. Brambilla,J. Ghiglieri, A. Vairo, Peter Petreczky
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JHEP 09 (2010) 038 • e-Print: 1007.4156 [hep-ph]

Potential and energies in medium

N. Brambilla, V. Leino, Peter Petreczky, A. Vairo
Phys.Rev.D102 (220) 074503 • e-Print 2007.10078 [hep-ph]

Lattice calculation of the heavy quark transport coefficient

Heavy quarks are QGP probes

- heavy quark are produced at the beginning and remain up to the end

- The heavy-quark mass introduces one or more large scales, whose contributions may be factorized and computed in perturbation theory ($\alpha_s(M) \ll 1$).

- Low-energy scales are sensitive to the temperature.
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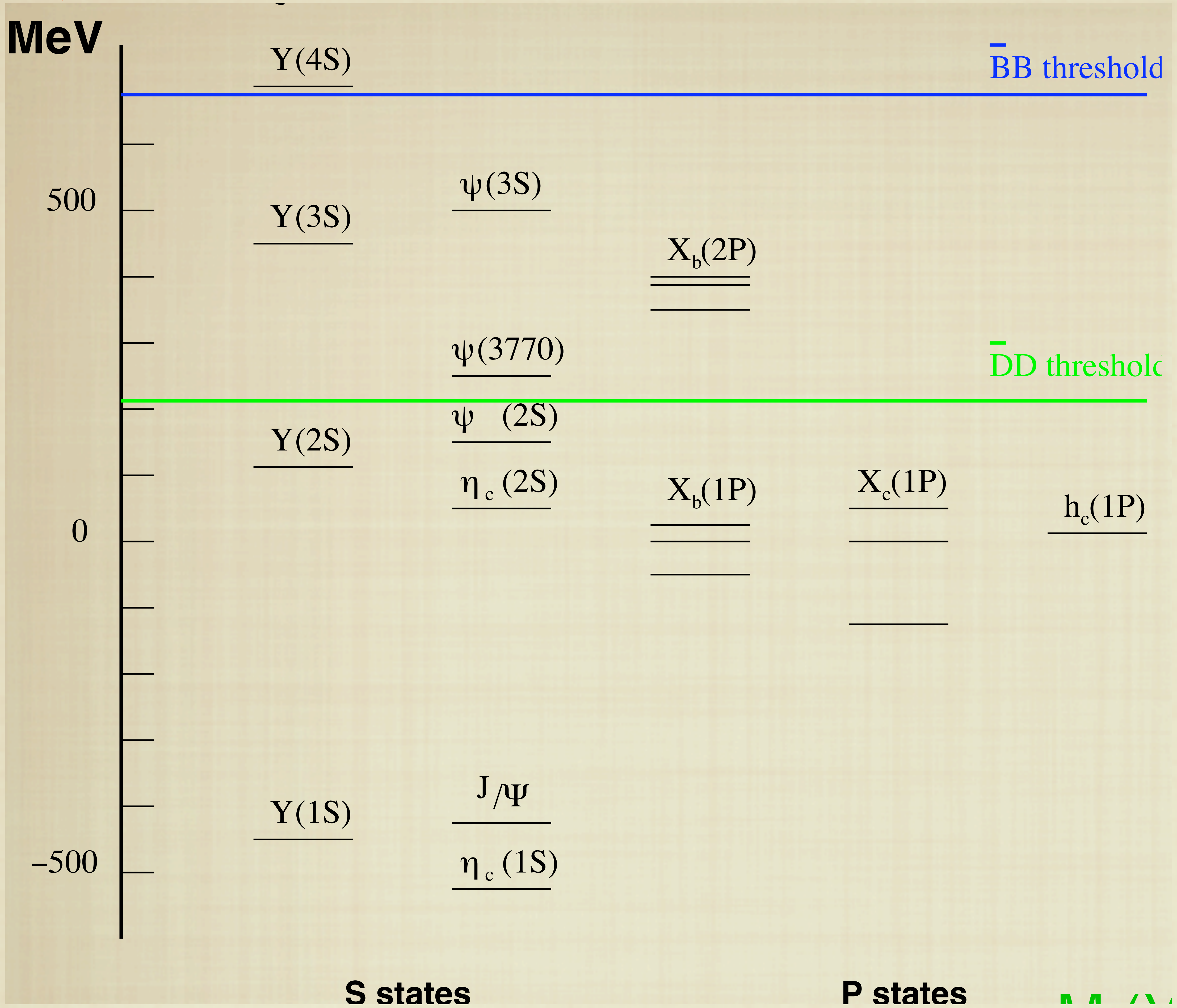
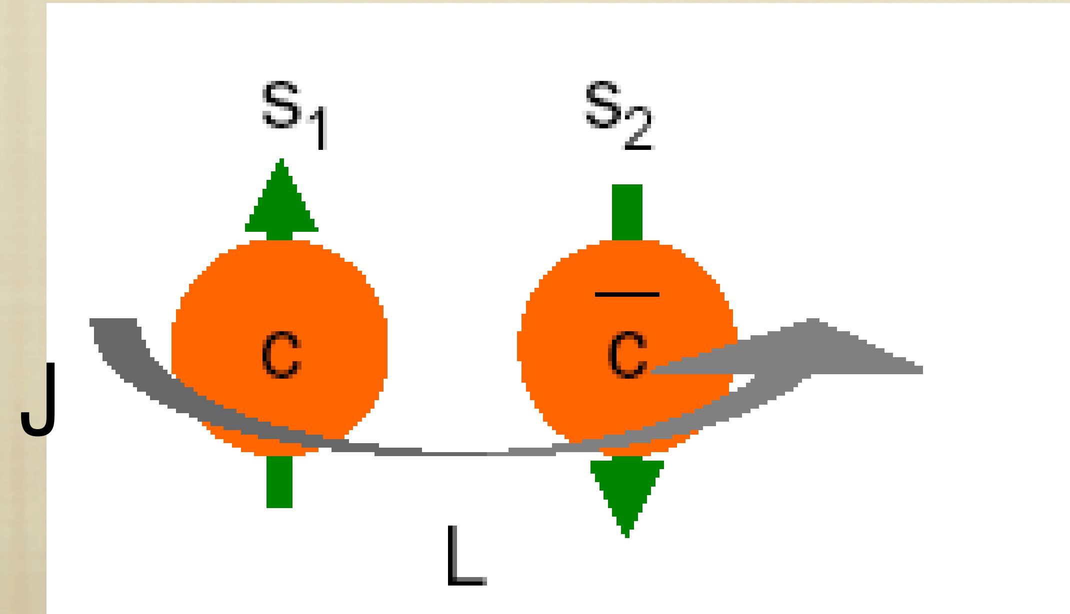
Quarkonia are better hard probes
because they are multi scale systems

Quarkonium scales



Normalized with respect to $\chi_b(1P)$ and $\chi_c(1P)$

$^{2S+1}L_J$



THE MASS SCALE IS PERTURBATIVE

$$m_Q \gg \Lambda_{\mathrm{QCD}}$$

$$m_b \simeq 5\,\mathrm{GeV};\, m_c \simeq 1.5\,\mathrm{GeV}$$

M (Υ (1S)) = 9460 GeV

M (J/) = 3097 GeV

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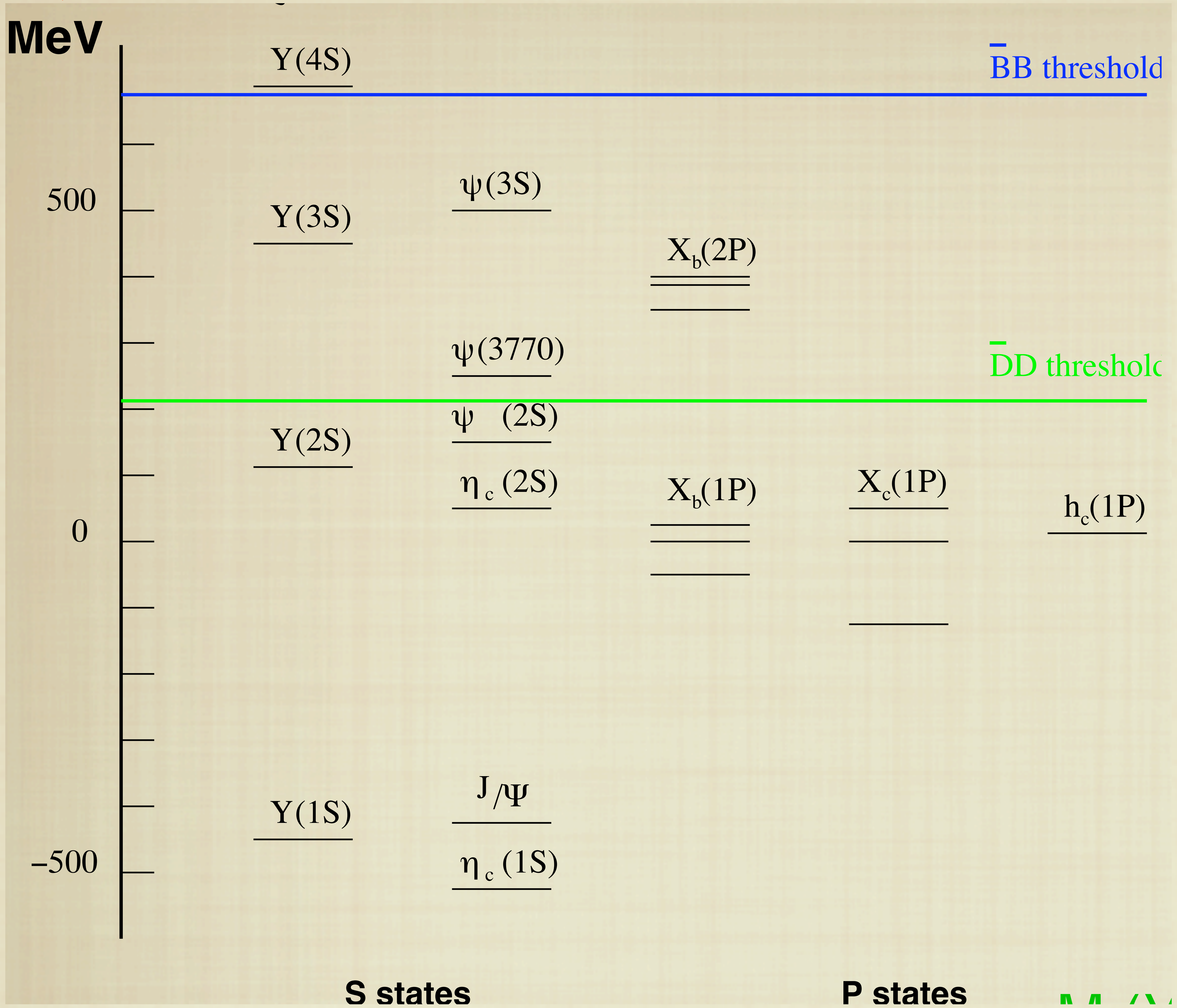

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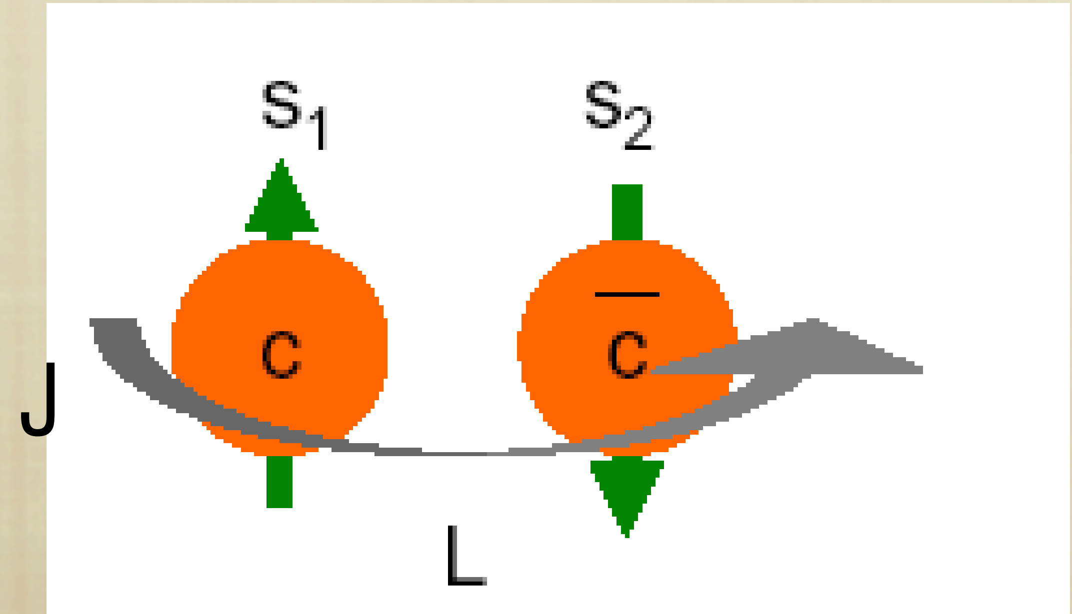

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The system is nonrelativistic(NR)

$$\Delta E \sim mv^2, \Delta_{fs} E \sim mv^4$$

$$v_b^2 \sim 0.1, v_c^2 \sim 0.3$$

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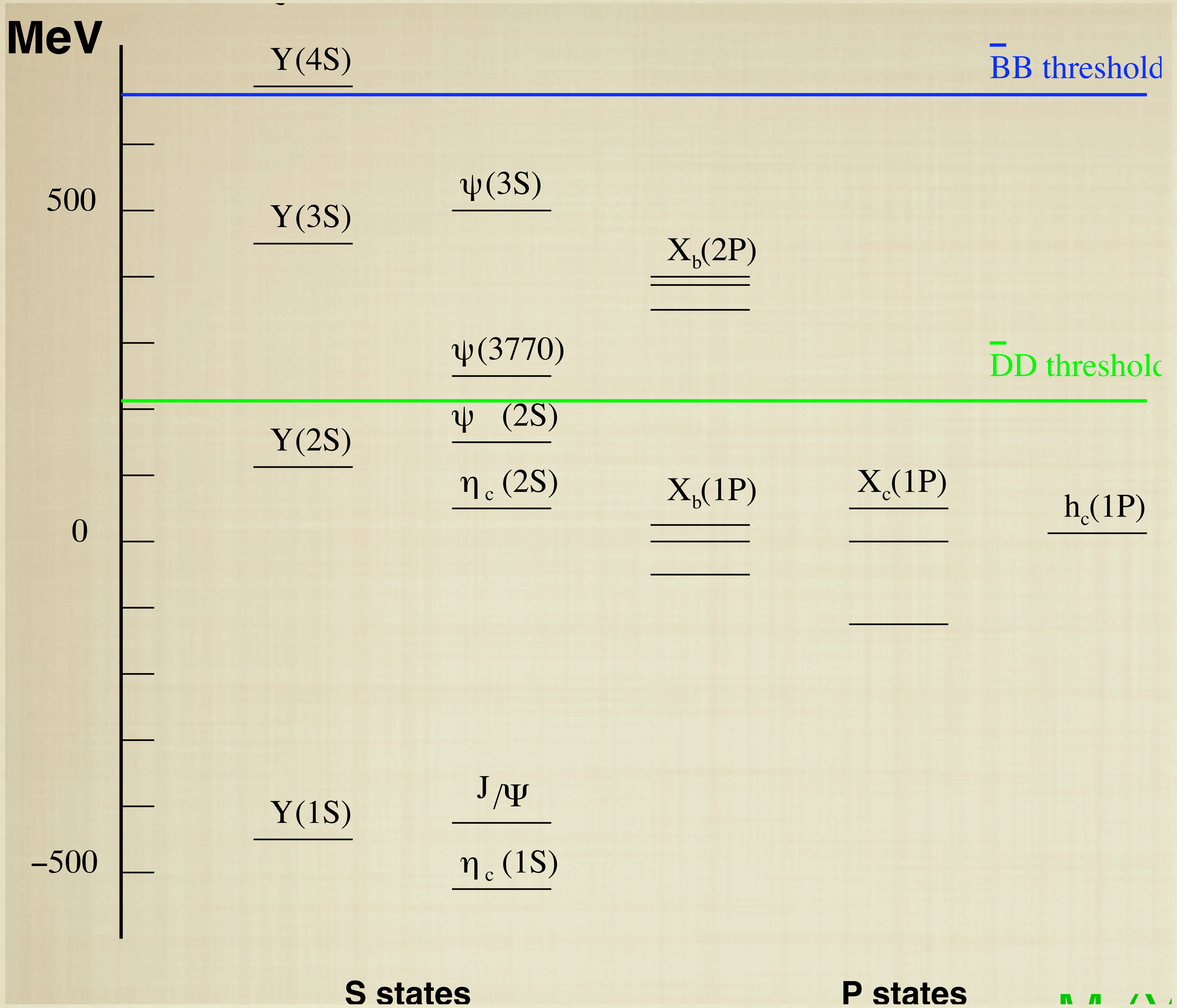

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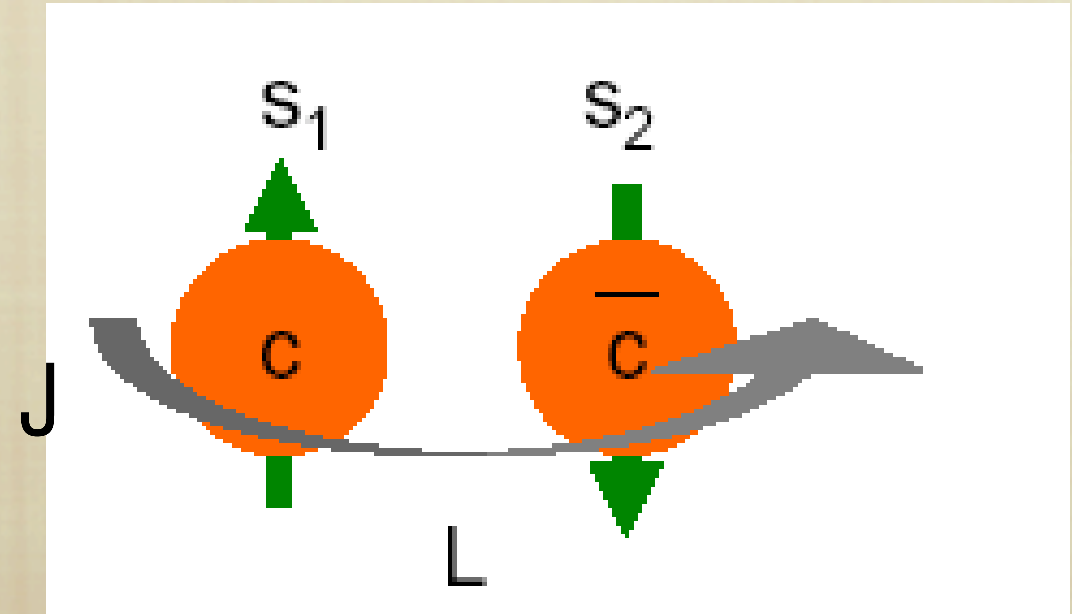

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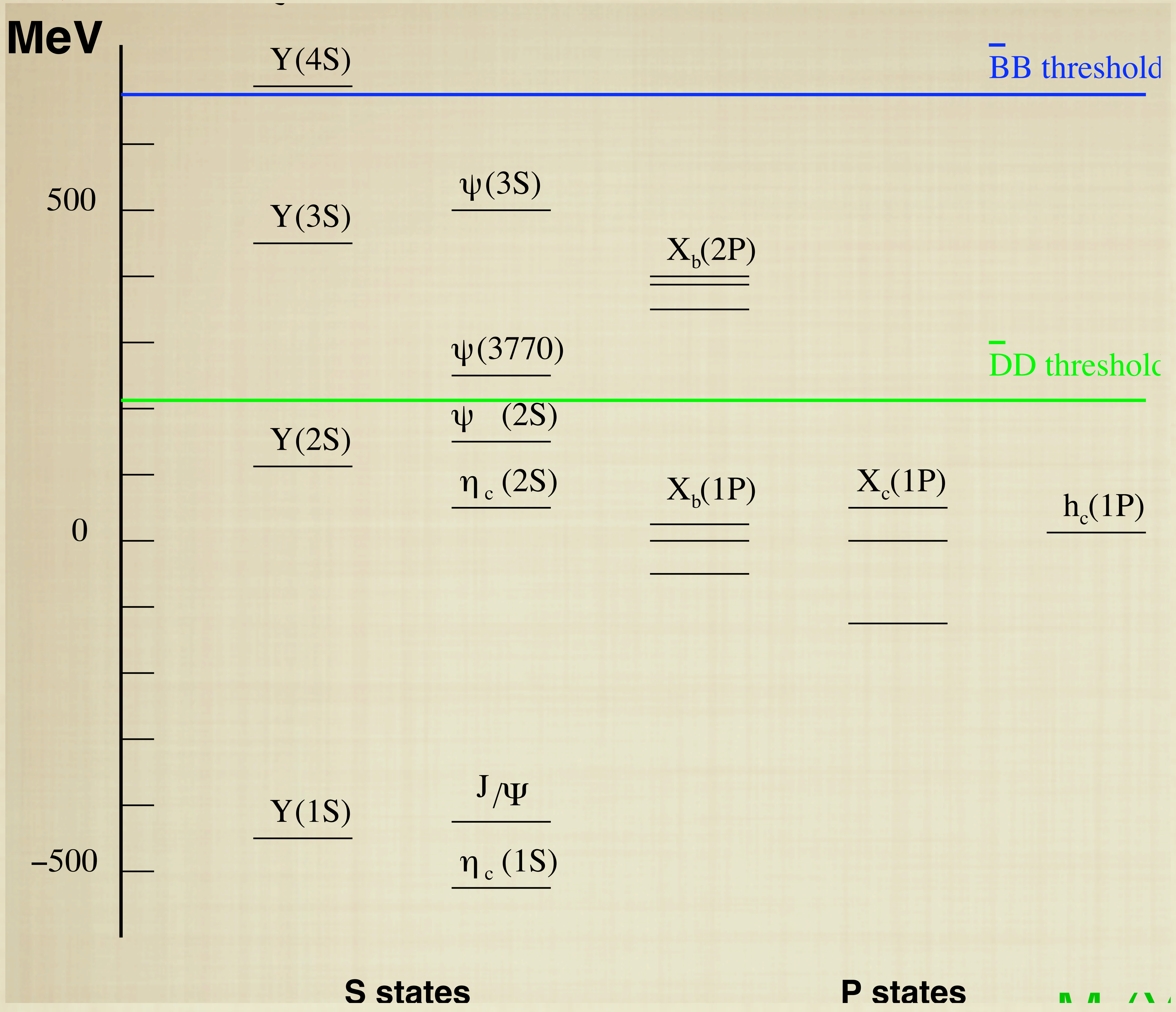

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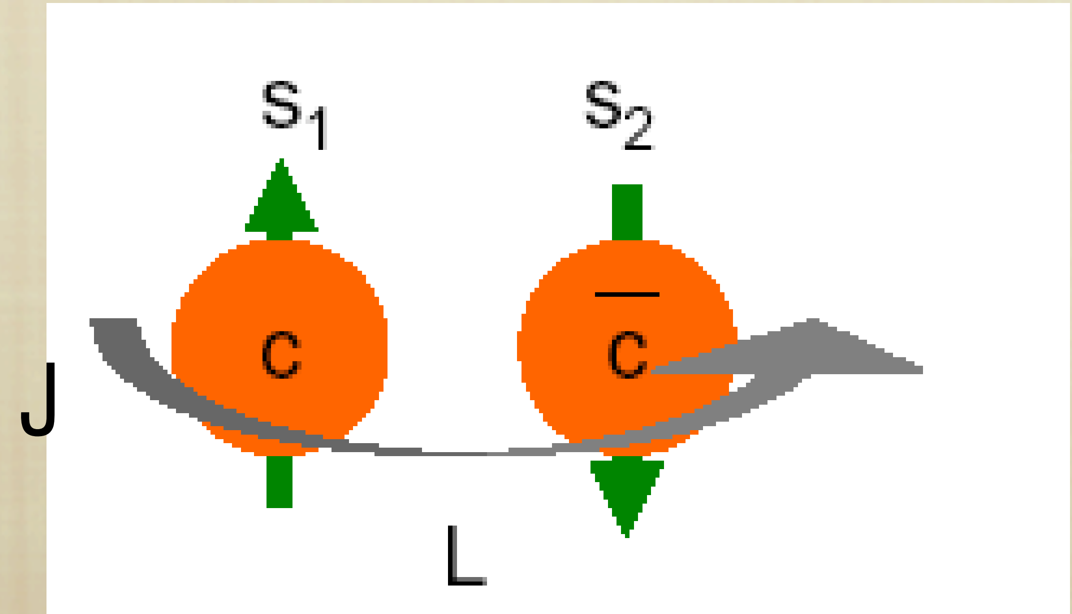

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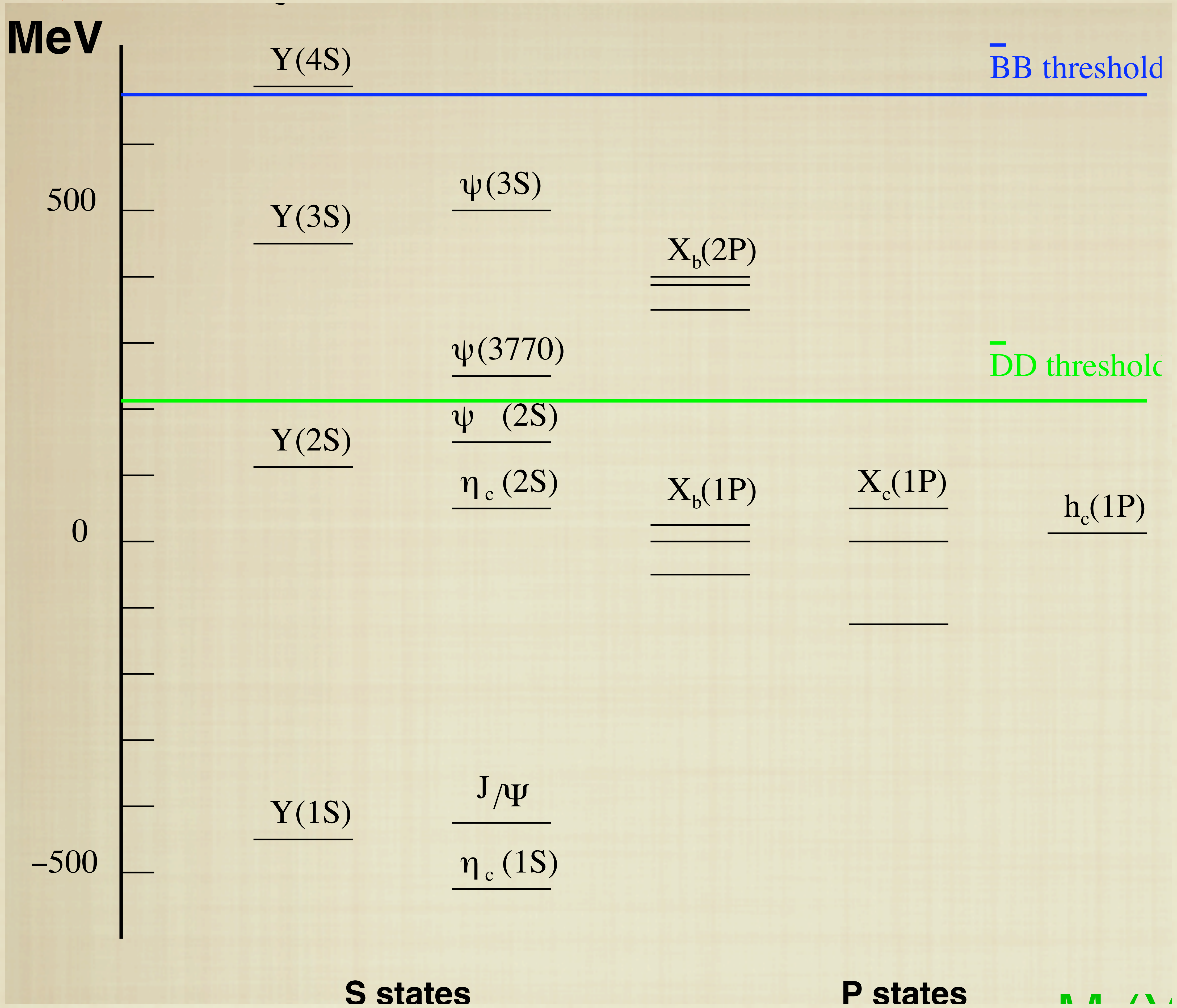

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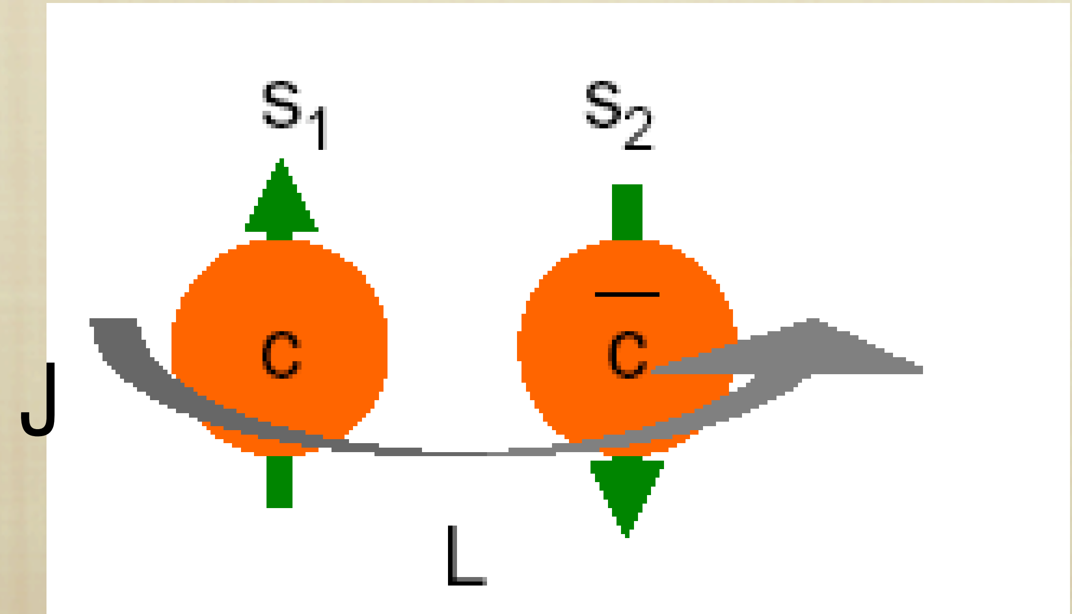

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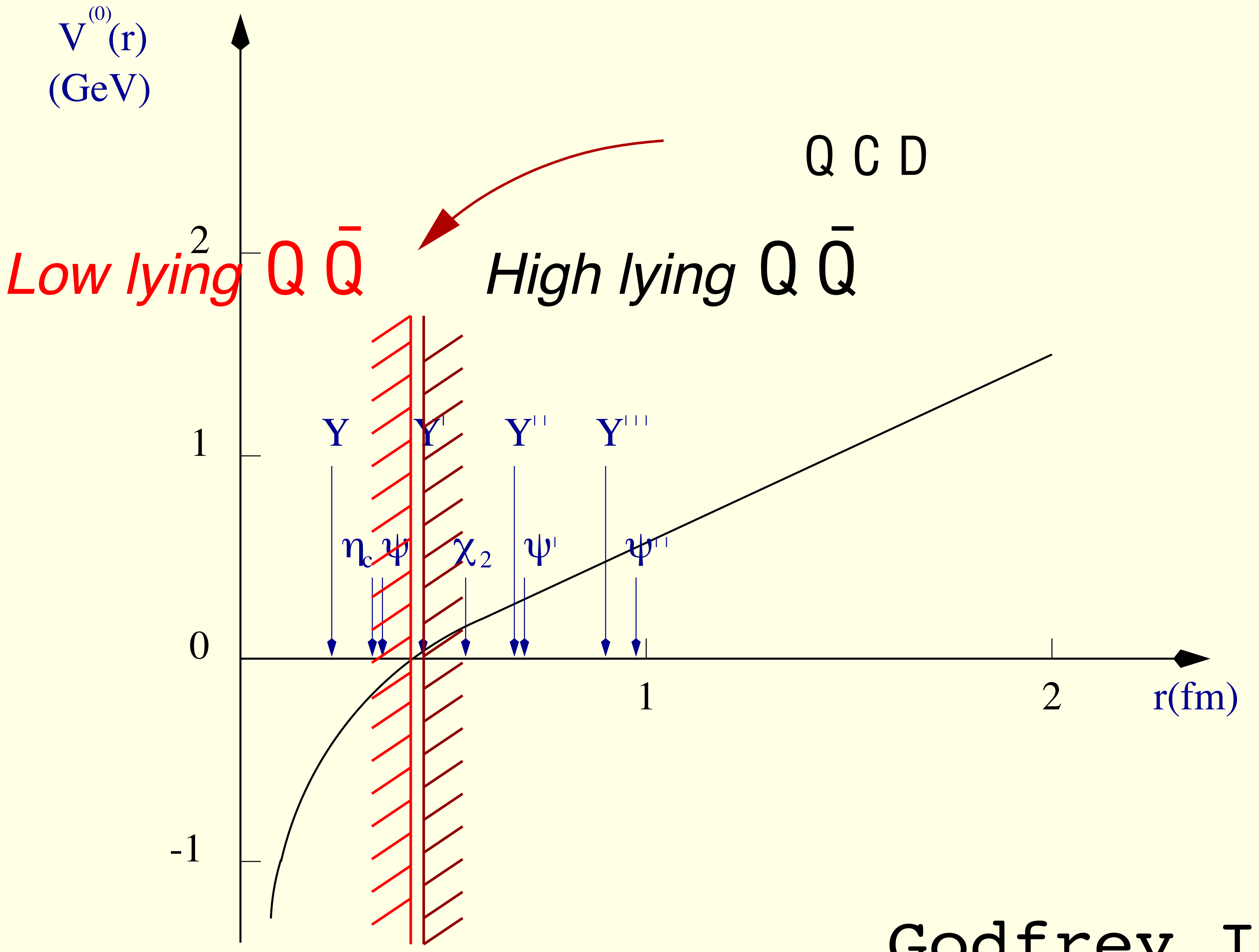
Quarkonium as a confinement probe

The rich structure of separated energy scales makes QQbar an ideal probe

At zero temperature

- The different quarkonium radii provide different measures of the transition from a Coulombic to a confined bound state.



Godfrey Isgur PRD 32(85)189

quarkonia probe the perturbative (high energy) and non perturbative region (low energy) as well as the transition region in dependence of their radius r

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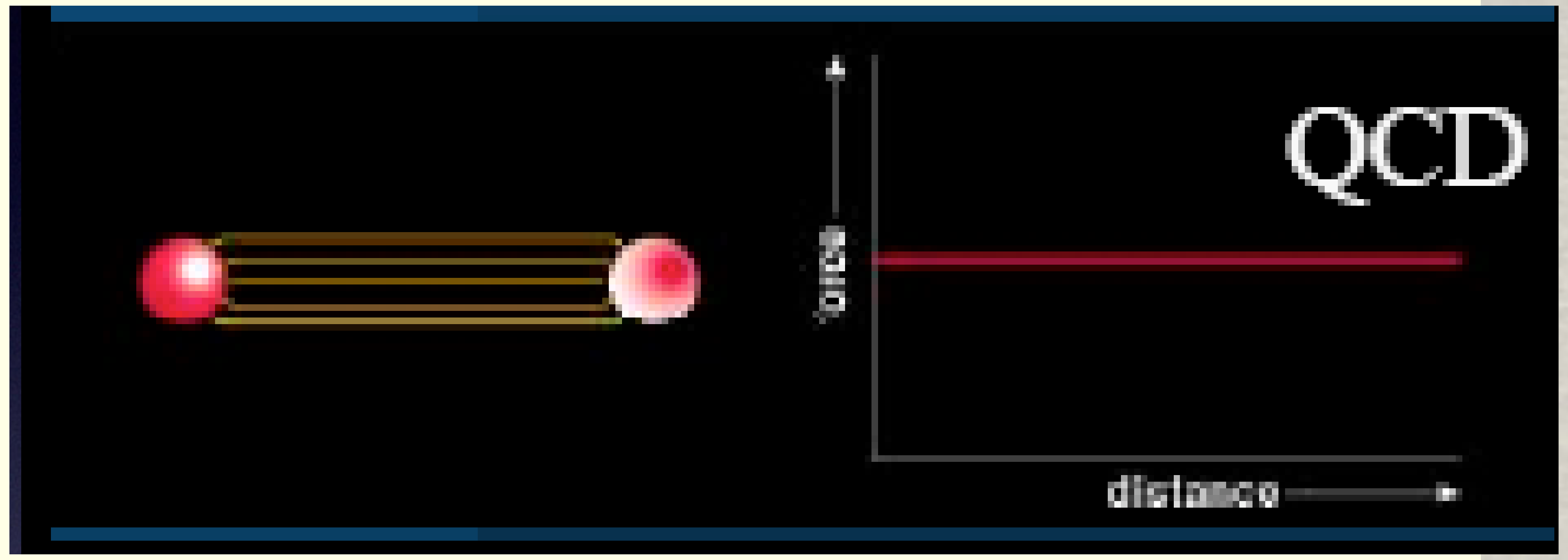

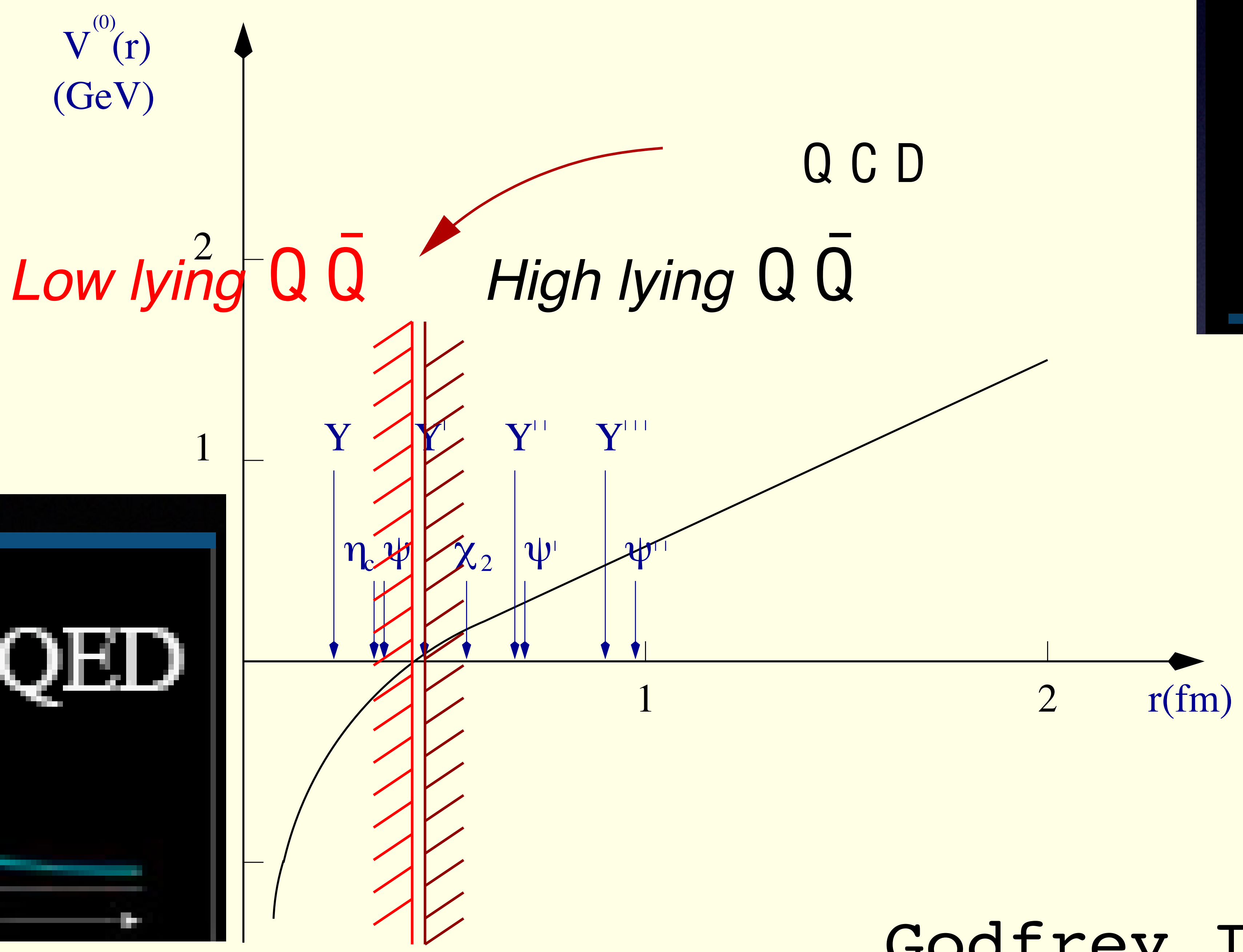

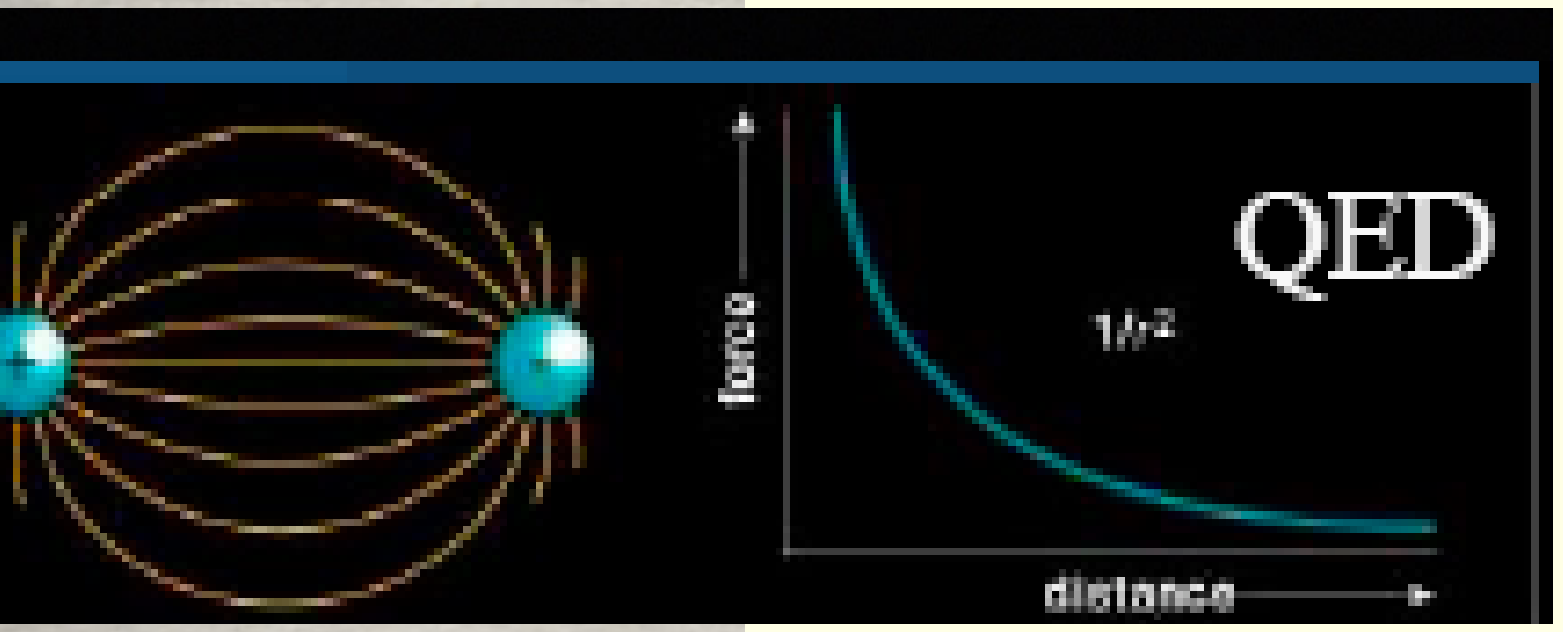

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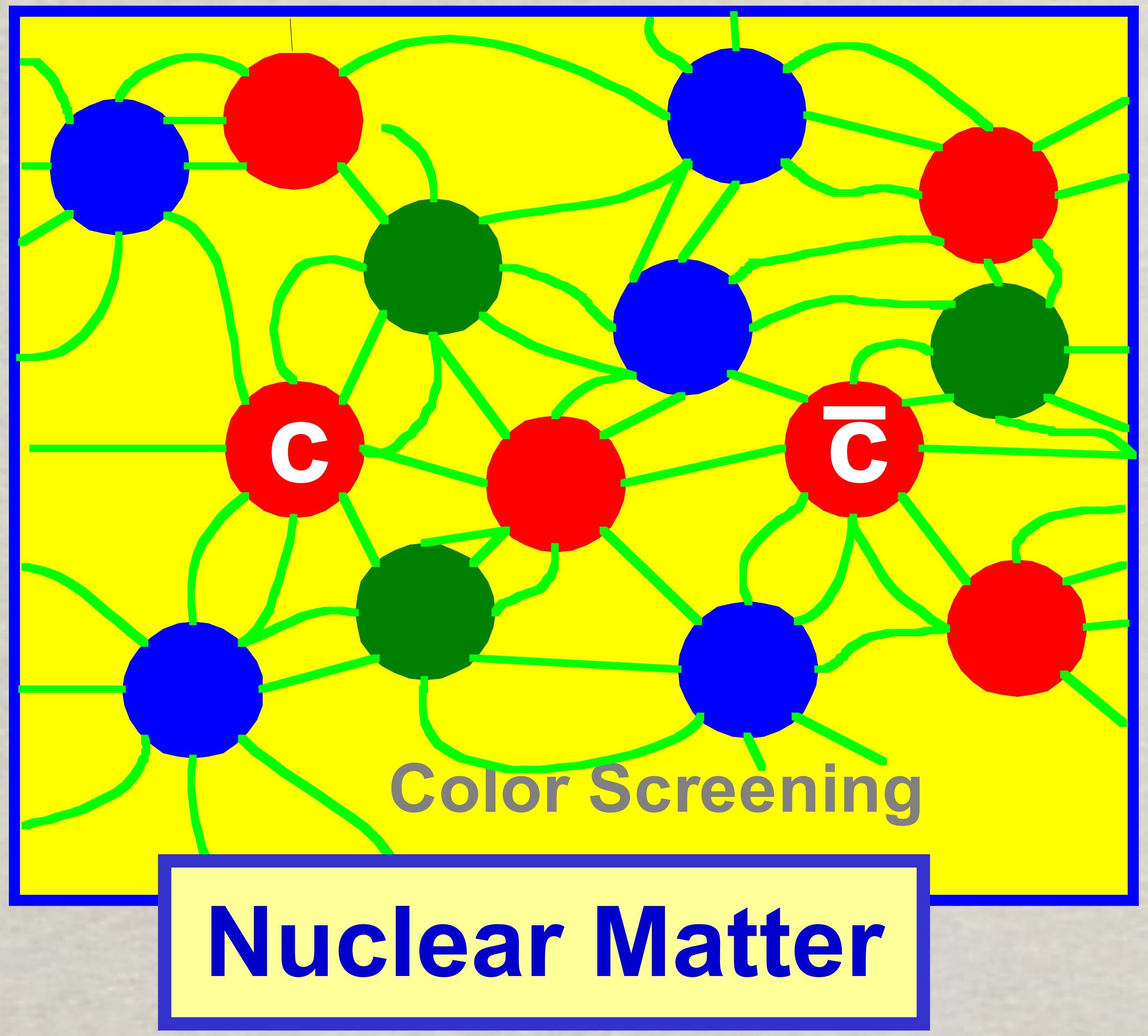
Quarkonium as a confinement and deconfinement probe

At finite temperature T they are sensitive to the formation of a quark gluon plasma via color screening



Debye charge screening $m_D \sim gT$

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Matsui Satz 1986

A simulated collision of lead ions, courtesy the A
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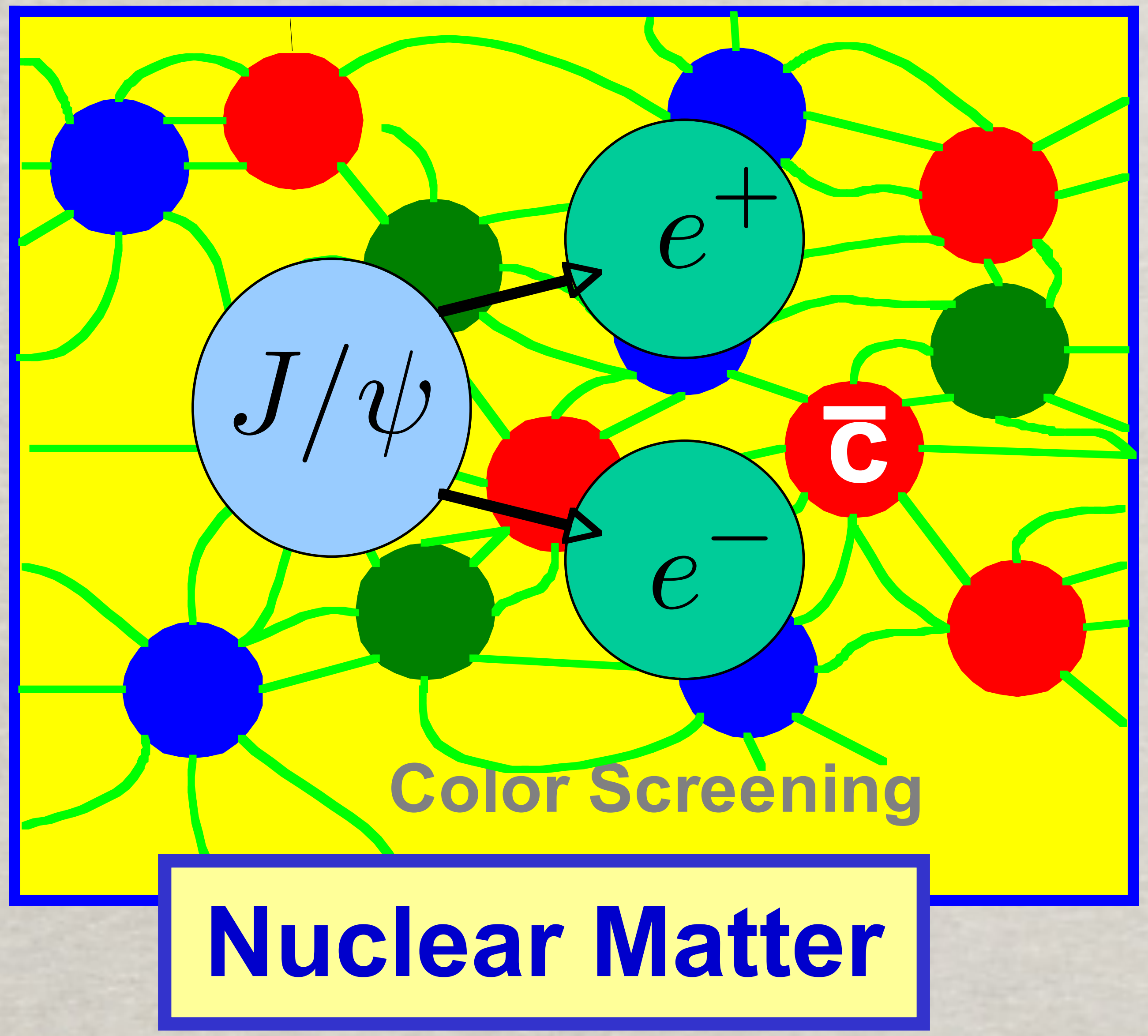

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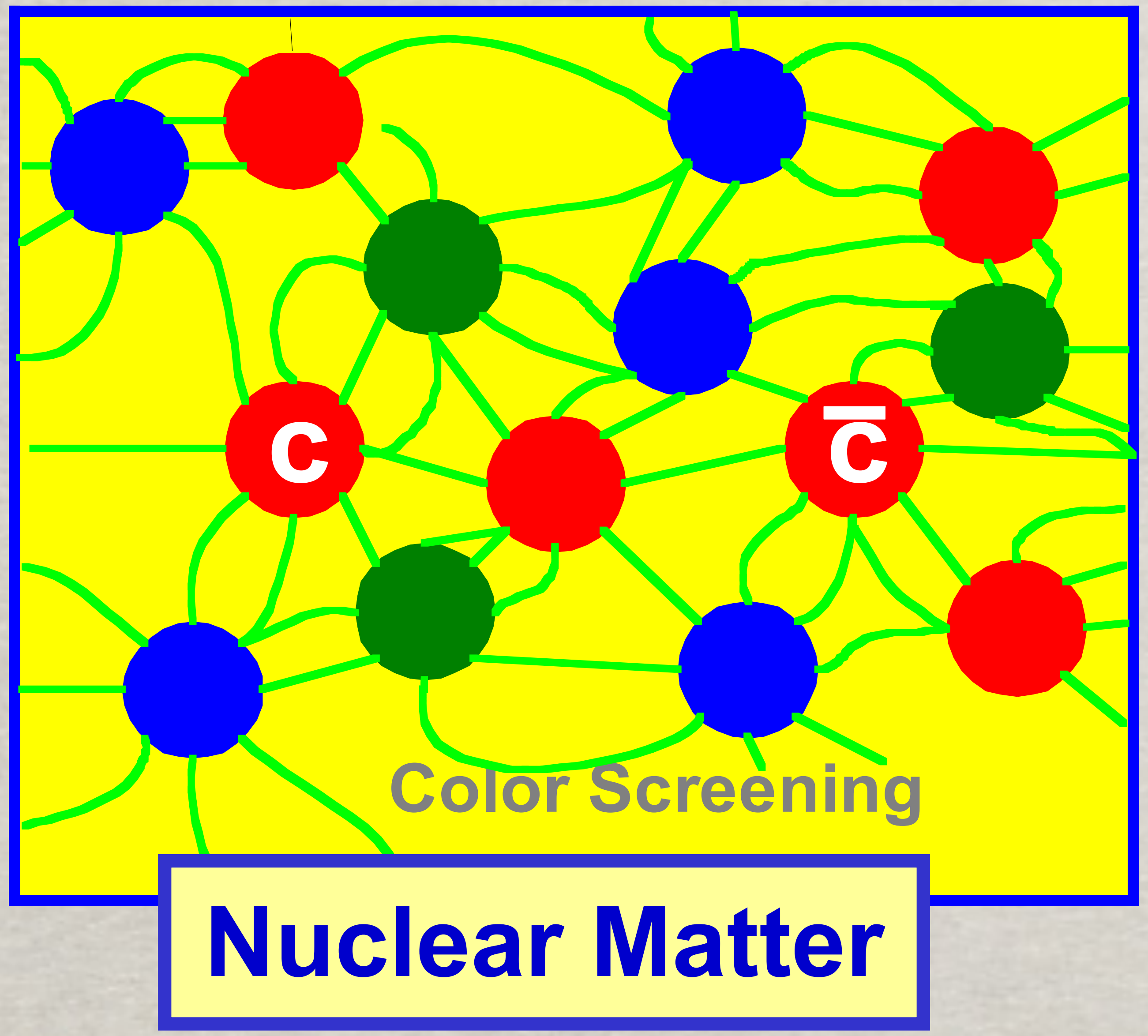

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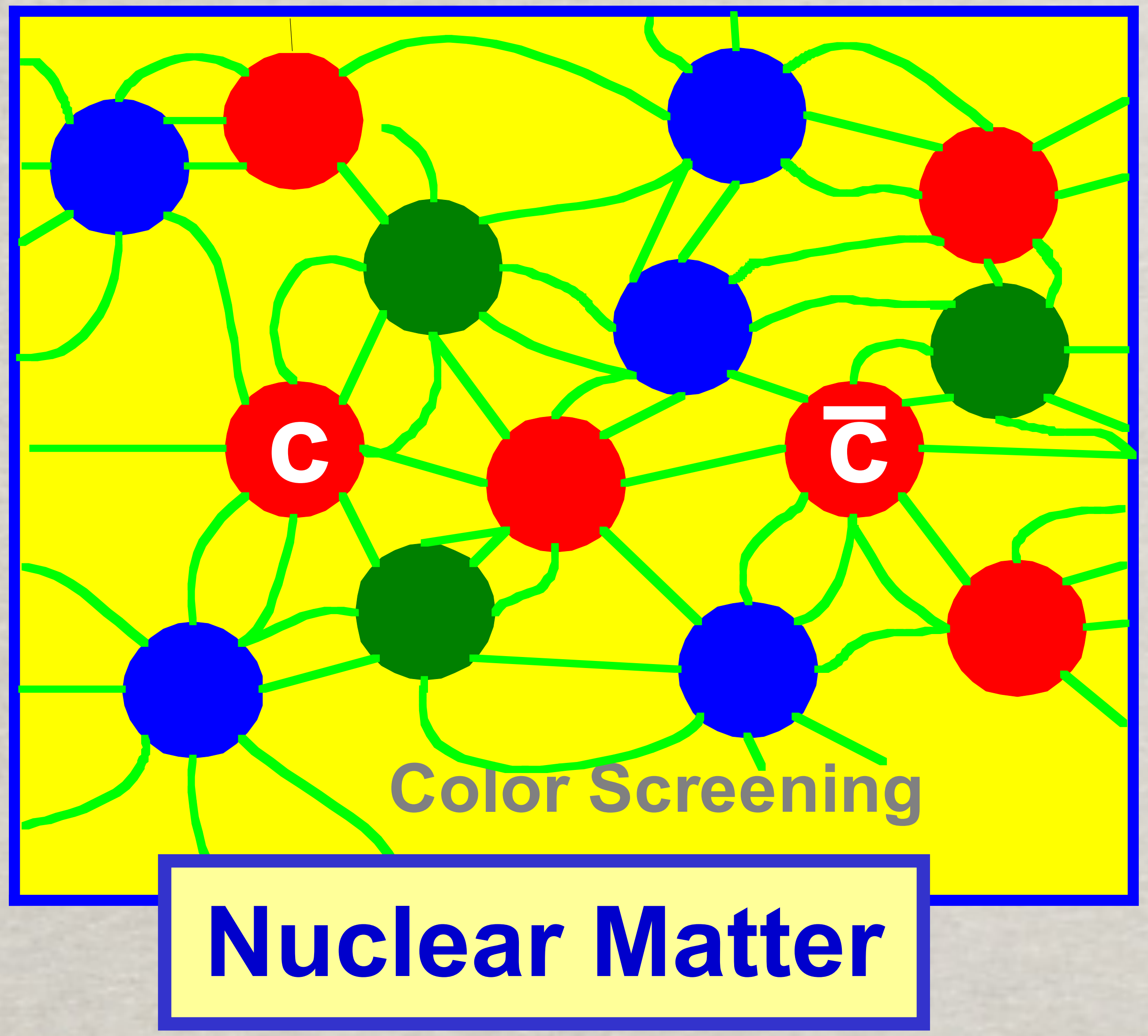

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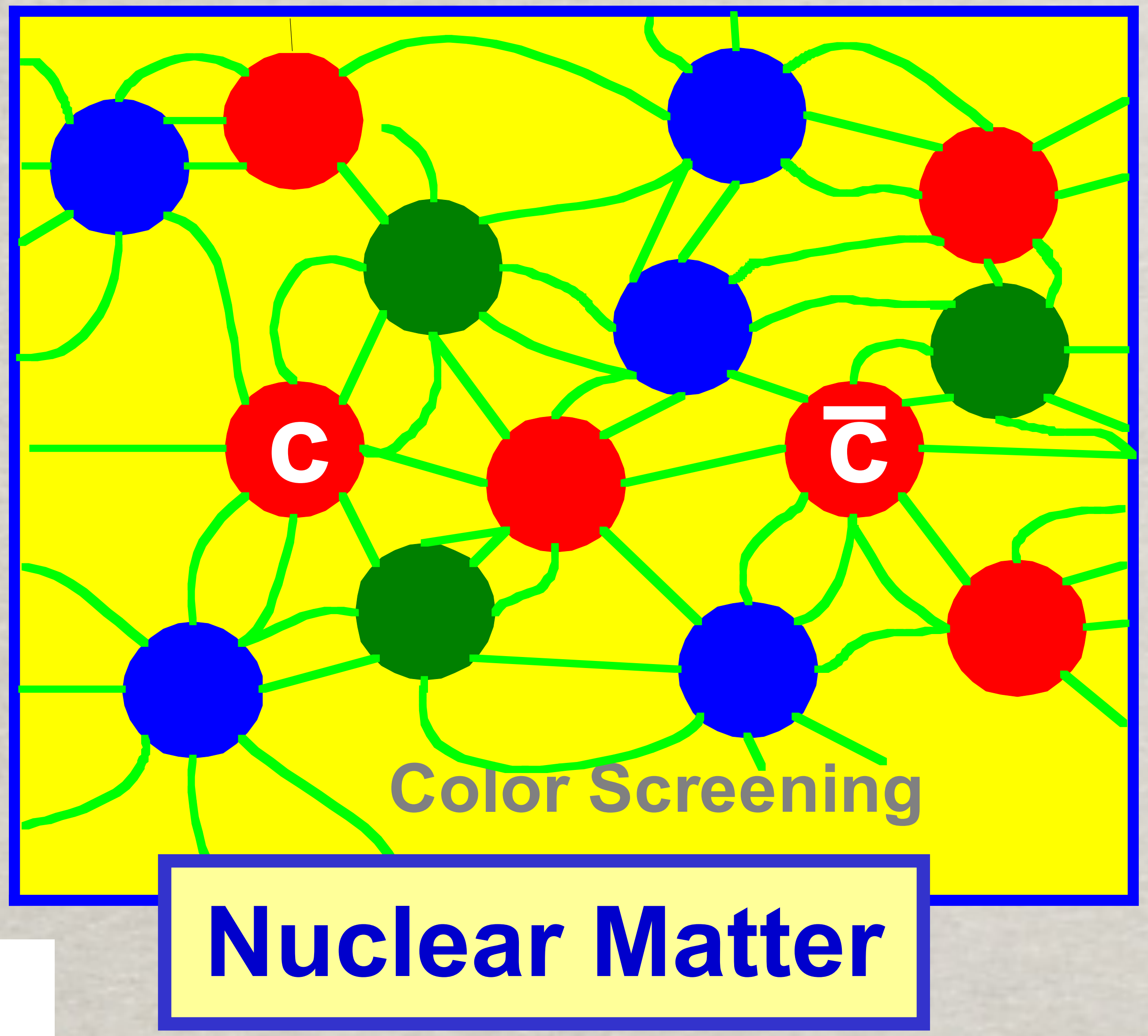

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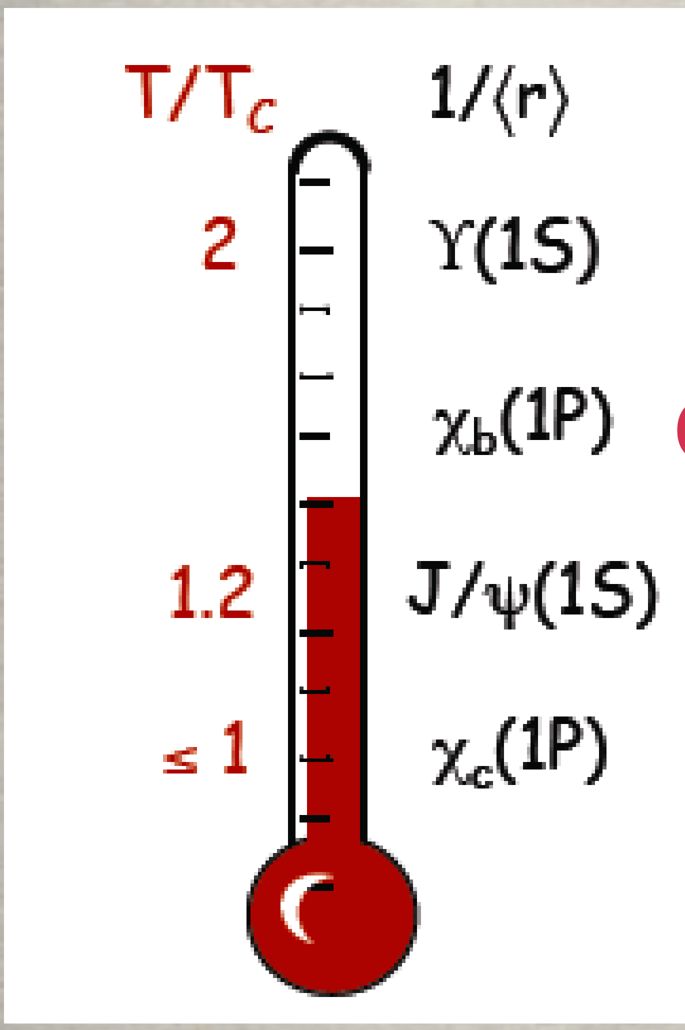

quarkonia dissociate at different temperature in dependence of their radius: they are a Quark Gluon Plasma thermometer

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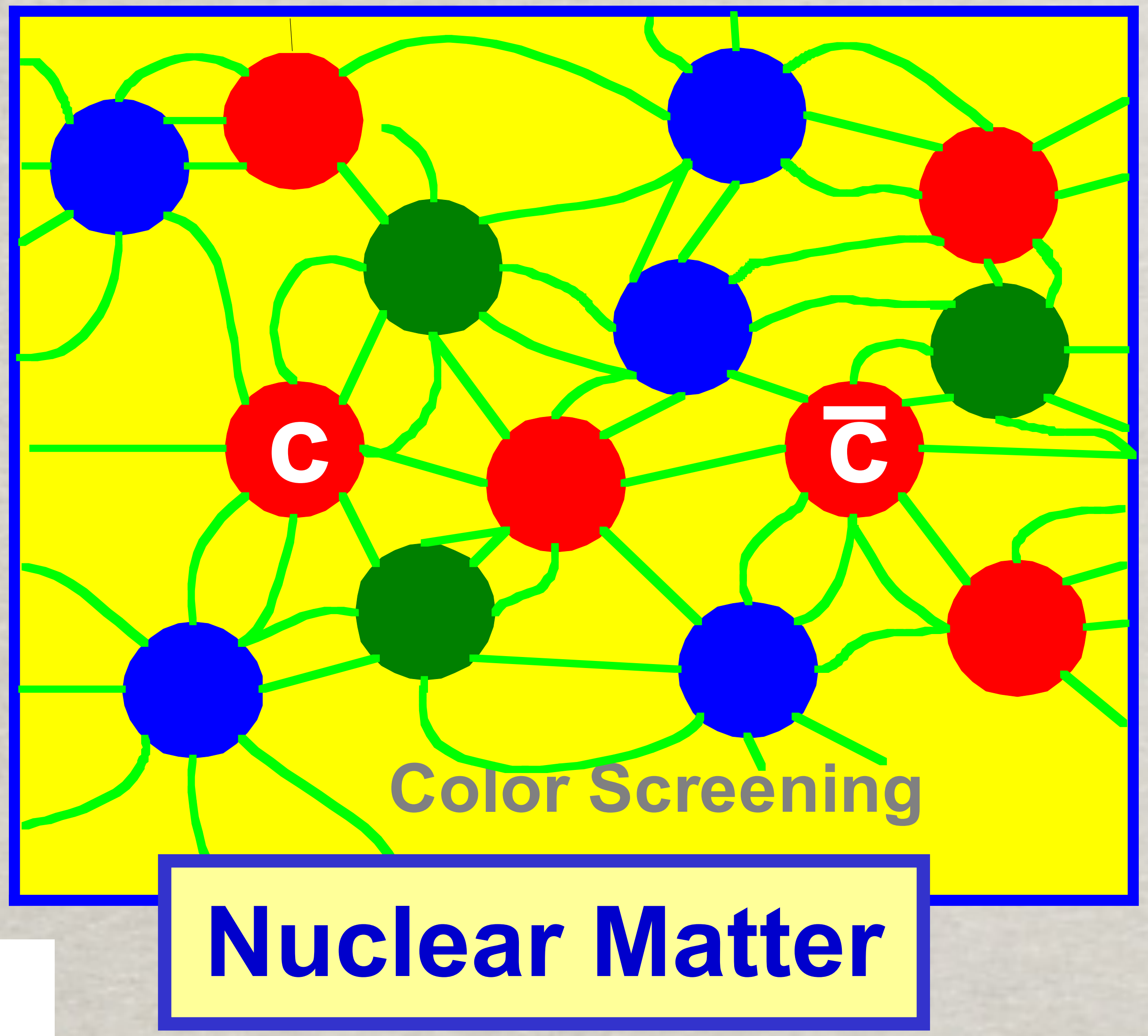

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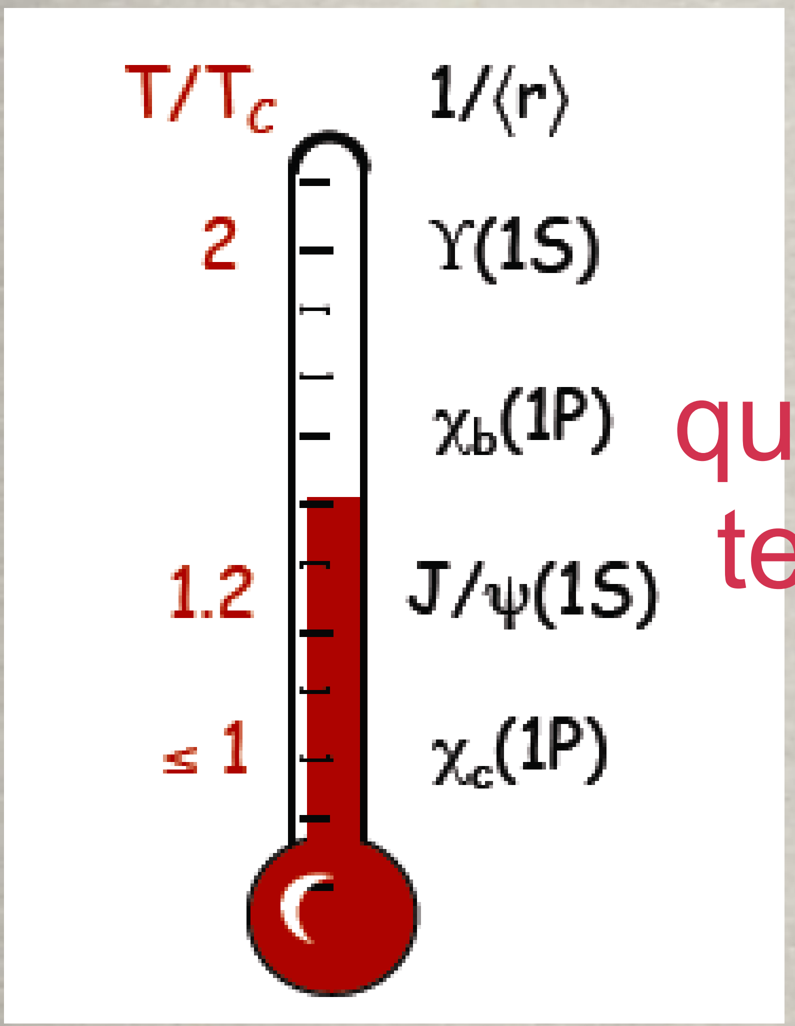

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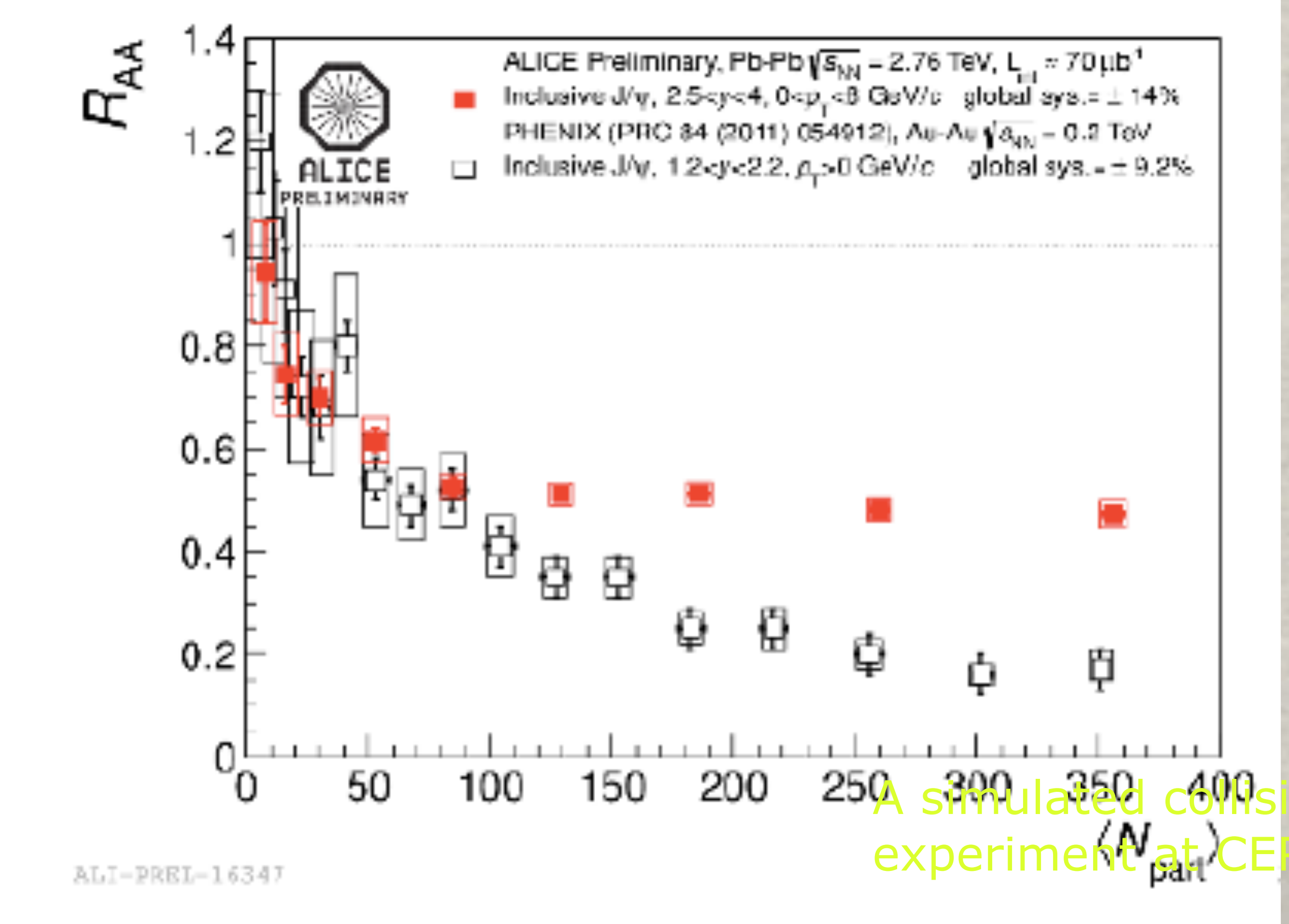
nuclear modificatio

$$R_{AA} = \frac{Yield^{q\bar{q}}_{AA}}{\langle N_{coll}\rangle \times Yield^{q\bar{q}}_{pp}}$$



A simulated collision of lead ions, courtesy the AL experiment at CERN

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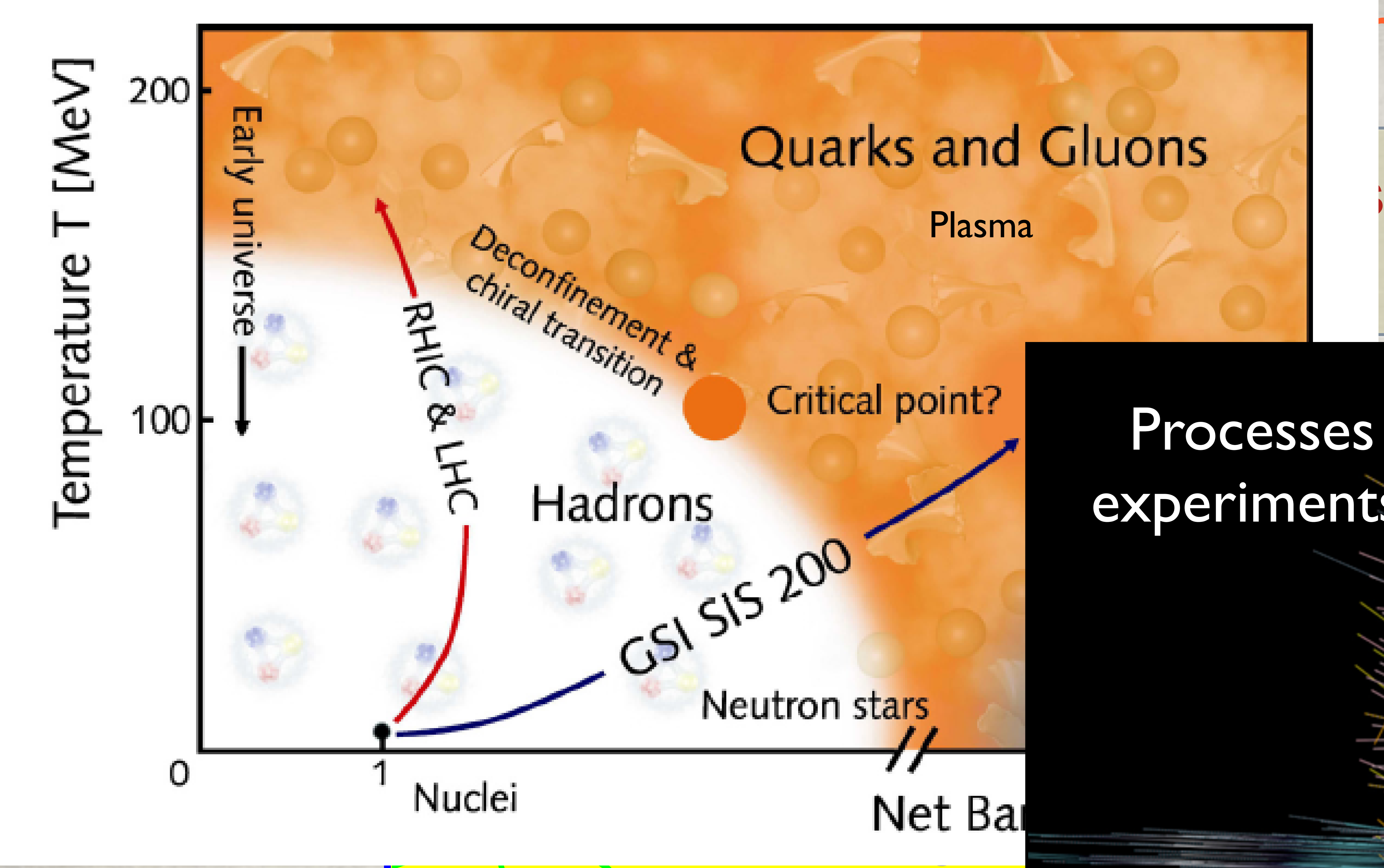

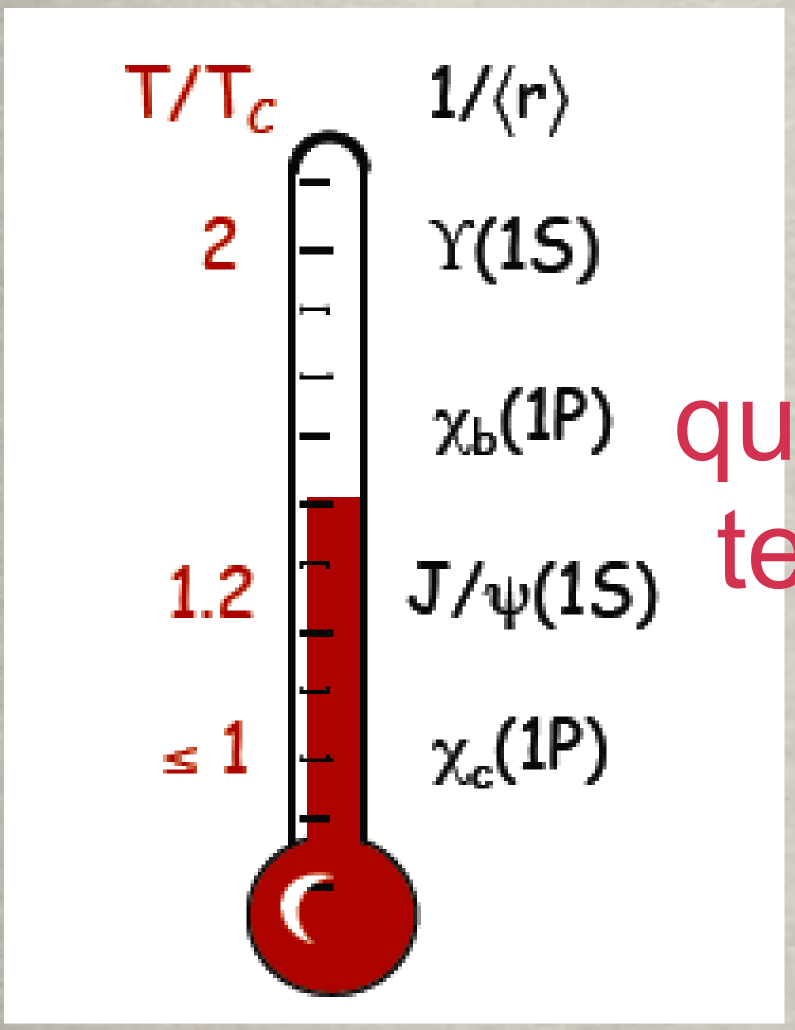

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are a Quark Gluon Pla...
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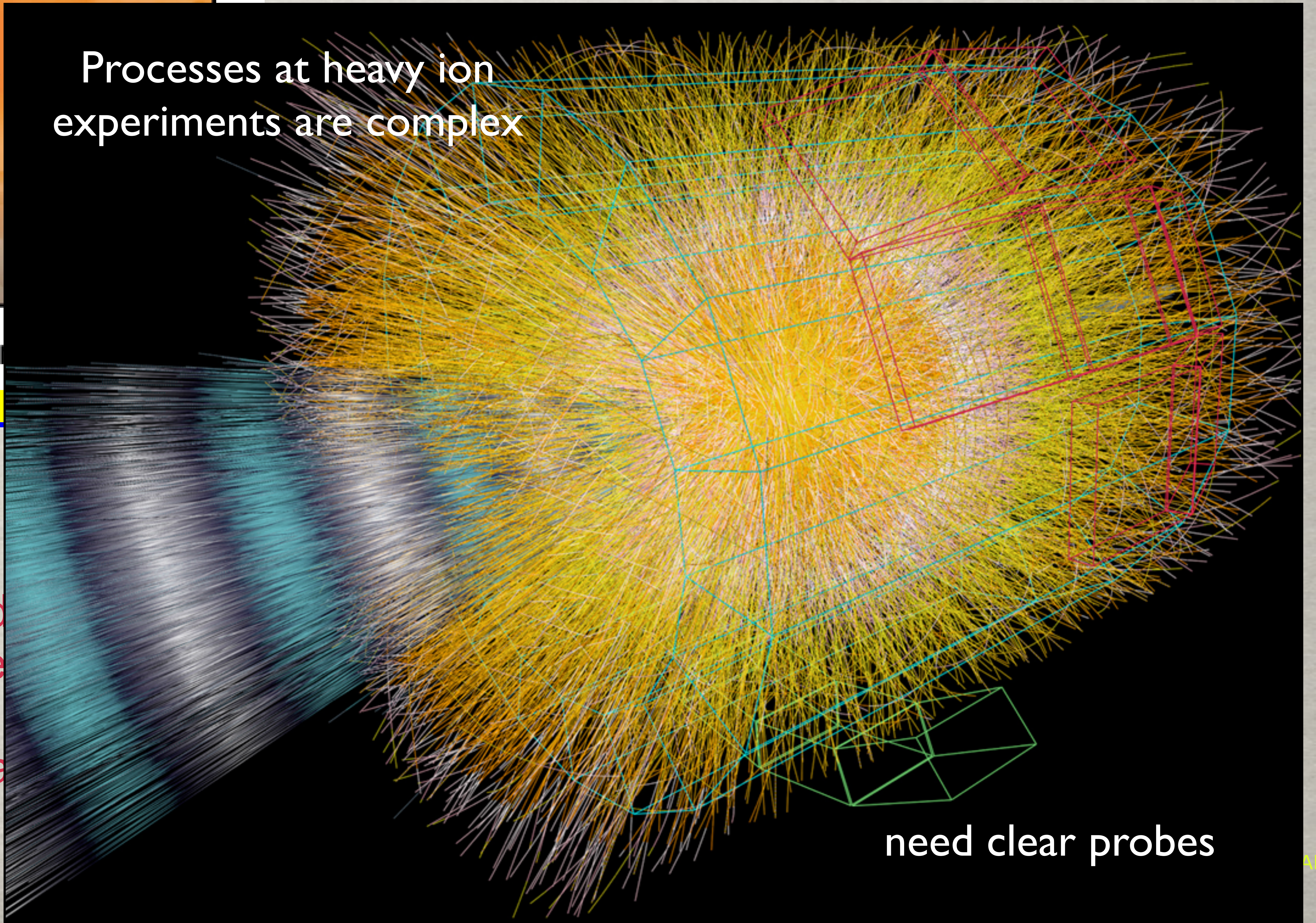

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Nonrelativistic Effective Field Theories (NREFTs) can give an answer to this
in particular potential Nonrelativistic QCD (pNRQCD)

QCD theory of Quarkonium: a very hard problem even at T=0

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Close to the bound state $\alpha_s \sim v$

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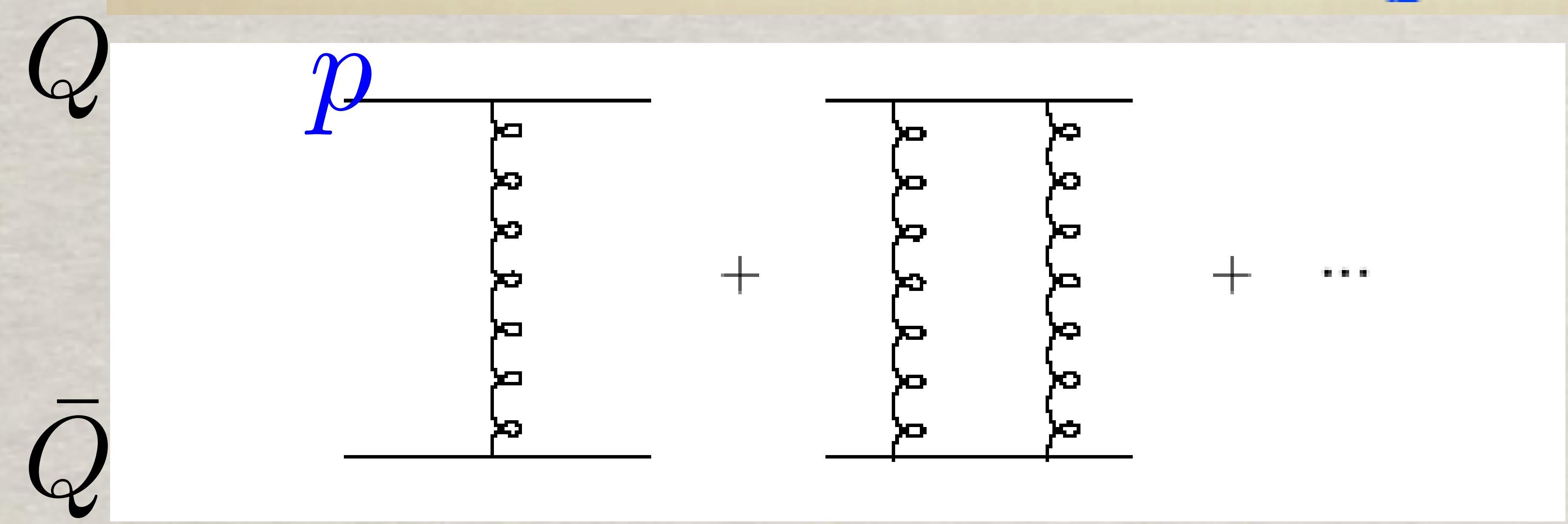

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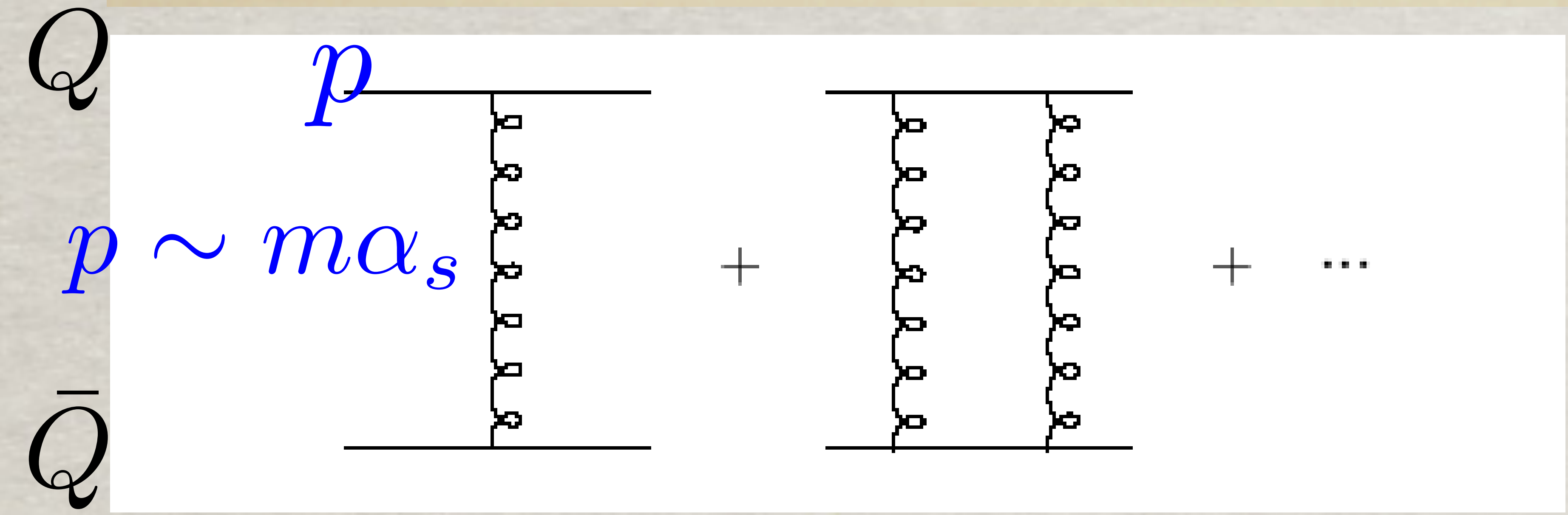

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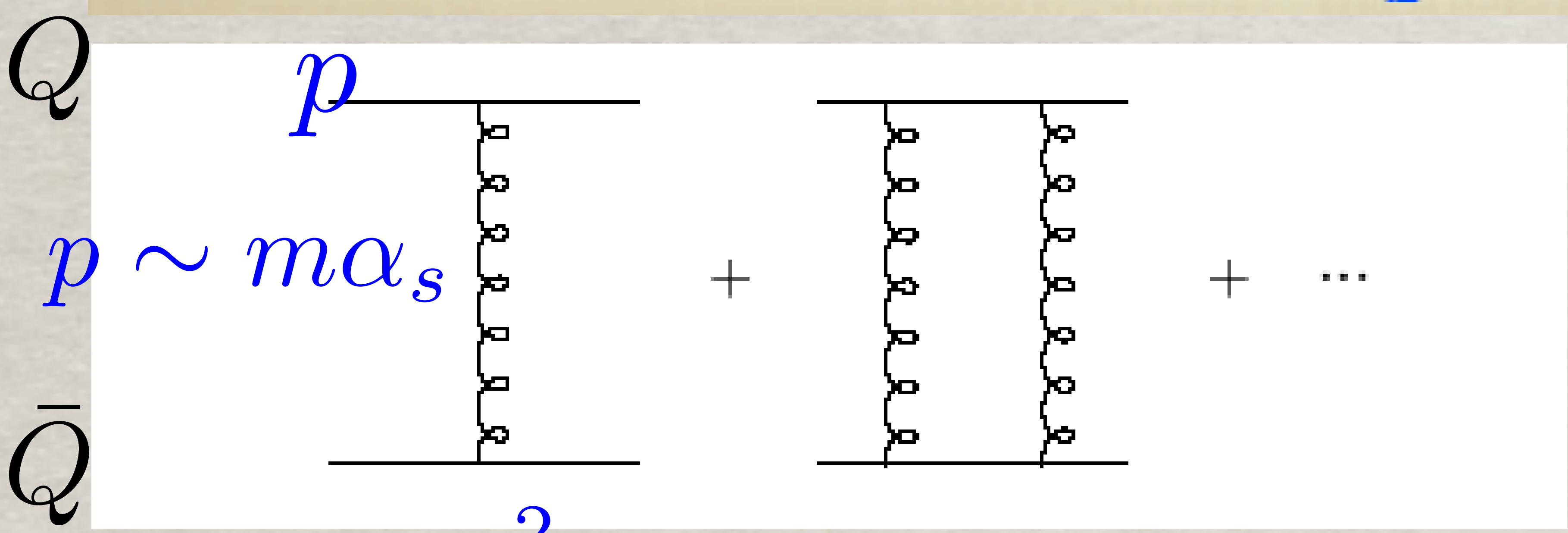

$$\frac{g^2}{p^2}\left(1 + \frac{m\alpha_s}{p}\right)$$

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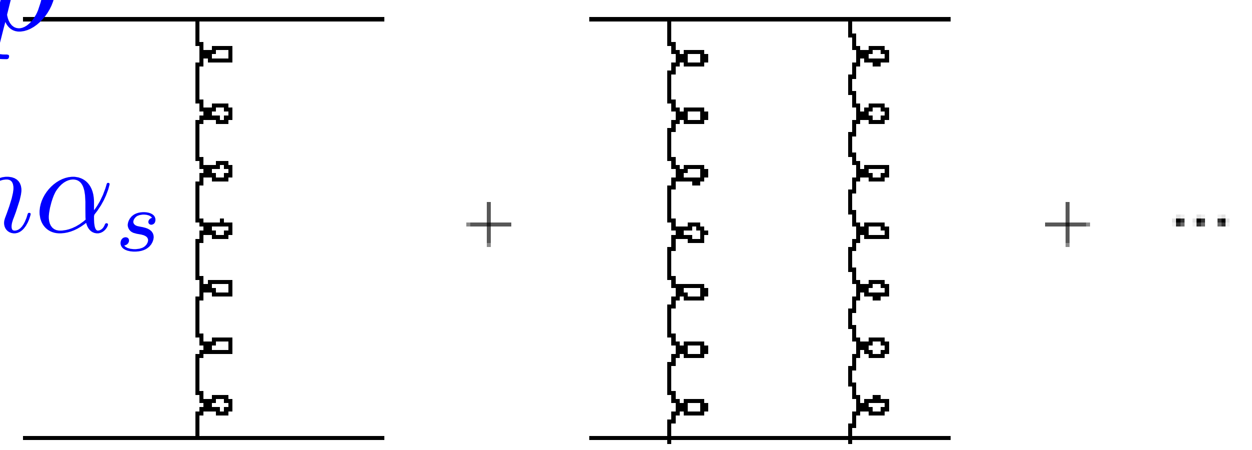
Q $\quad p$

$p \sim m\alpha_s$



$\bar{Q}$

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$$\sim \frac{1}{E-\left(\frac{p^2}{m}+V\right)}$$

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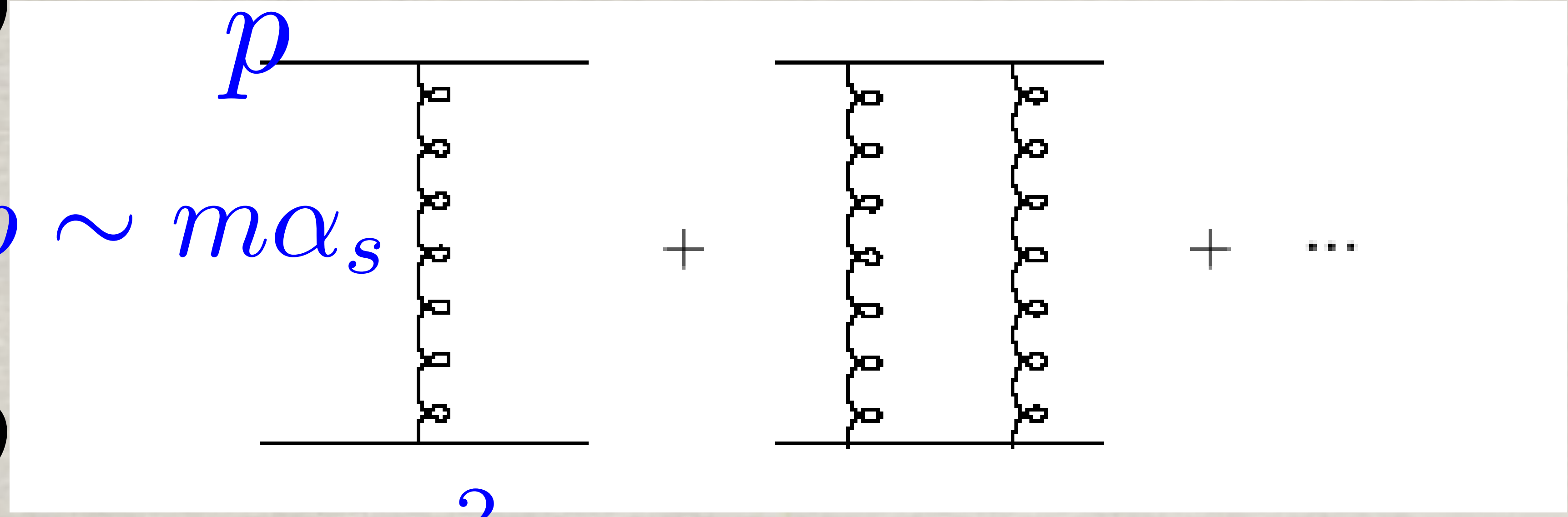

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$$\sim \frac{1}{E - (\frac{p^2}{m} + V)}$$

- From $(\frac{p^2}{m} + V)\phi = E\phi \to p \sim mv$ and $E = \frac{p^2}{m} + V \sim mv^2$.

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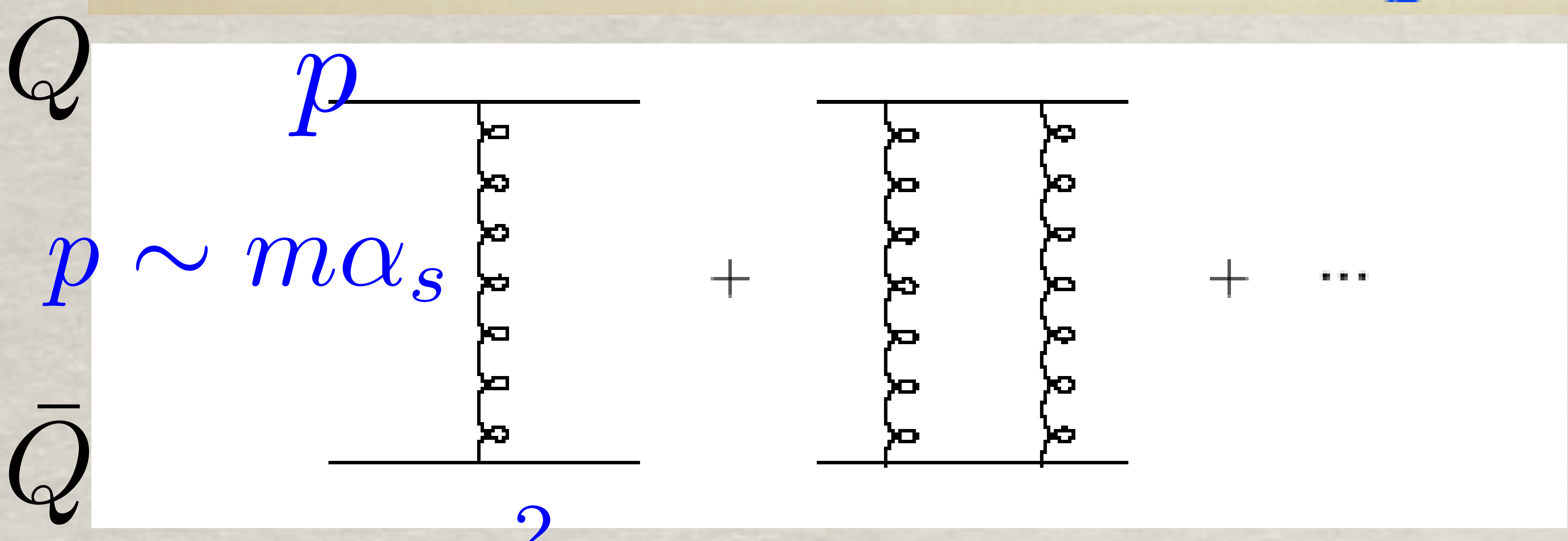

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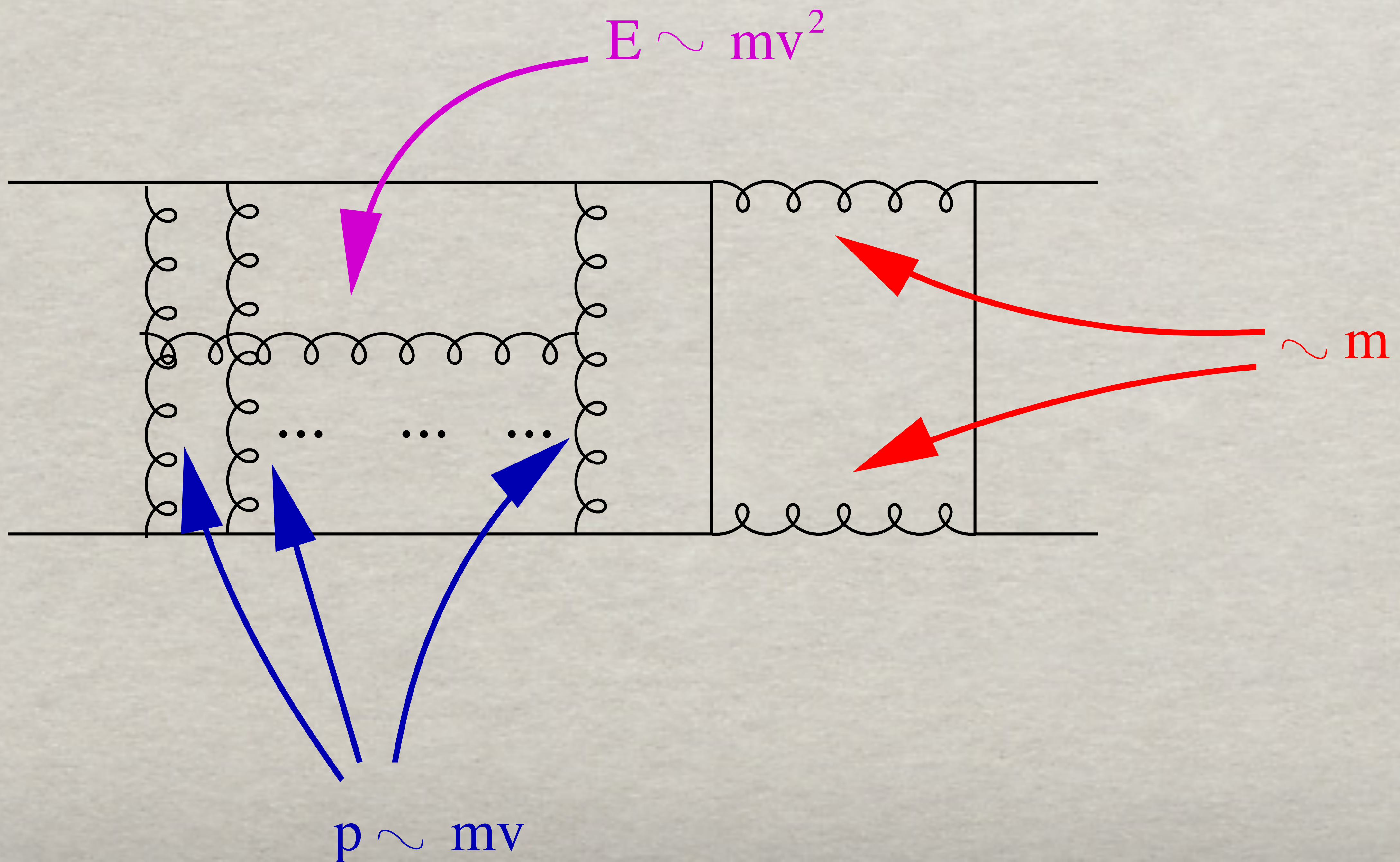
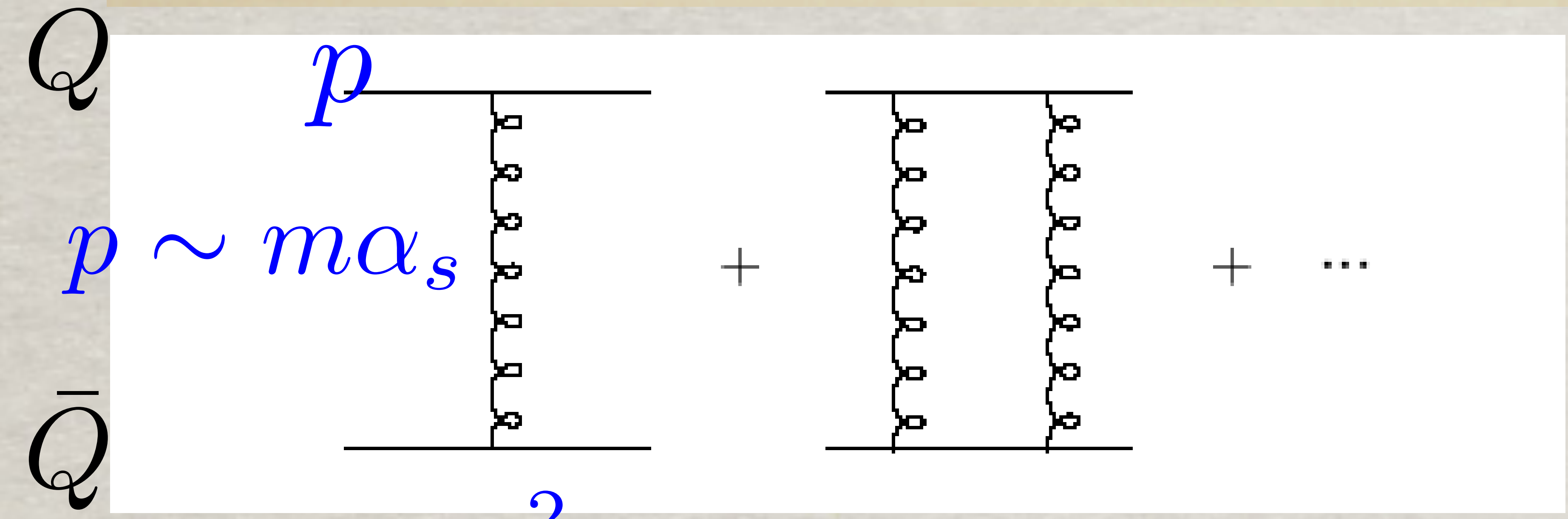
- From $(\frac{p^2}{m} + V)\phi = E\phi \rightarrow p \sim mv$ and $E = \frac{p^2}{m} + V \sim mv^2$.



QCD theory of Quarkonium: a very hard problem even at T=0

Close to the bound state $\alpha_s \sim v$



$$\frac{g^2}{p^2}\left(1+\frac{m\alpha_s}{p}\right)$$

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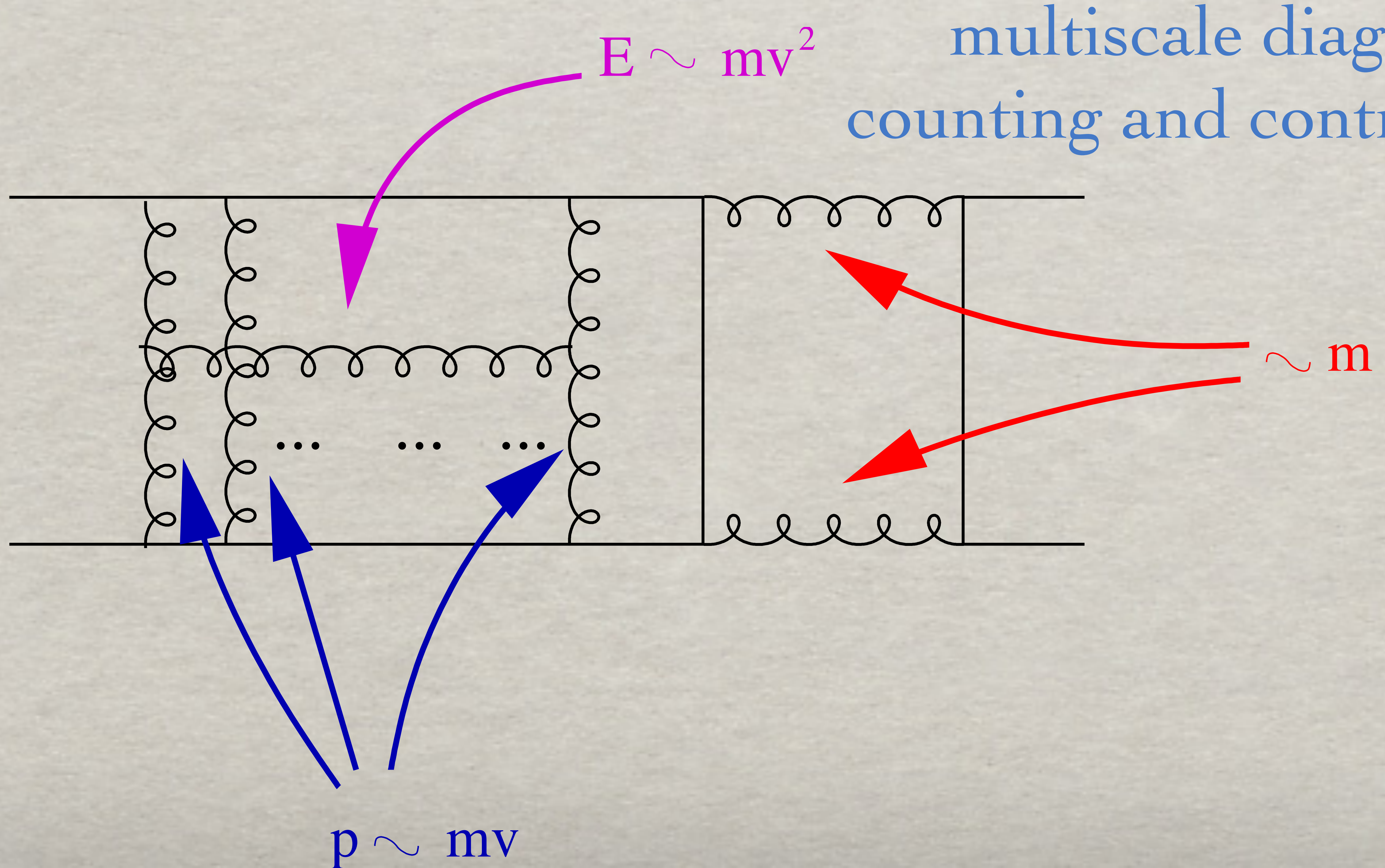
multiscale diagrams have a complicate power counting and contribute to all orders in the coupling



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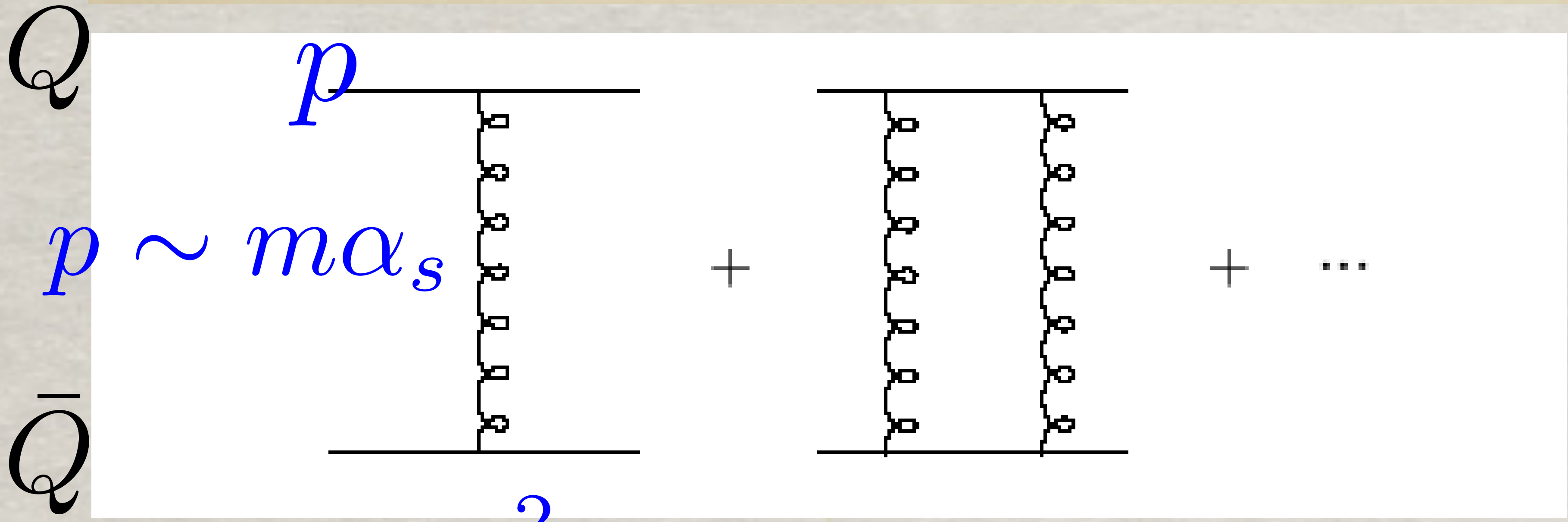

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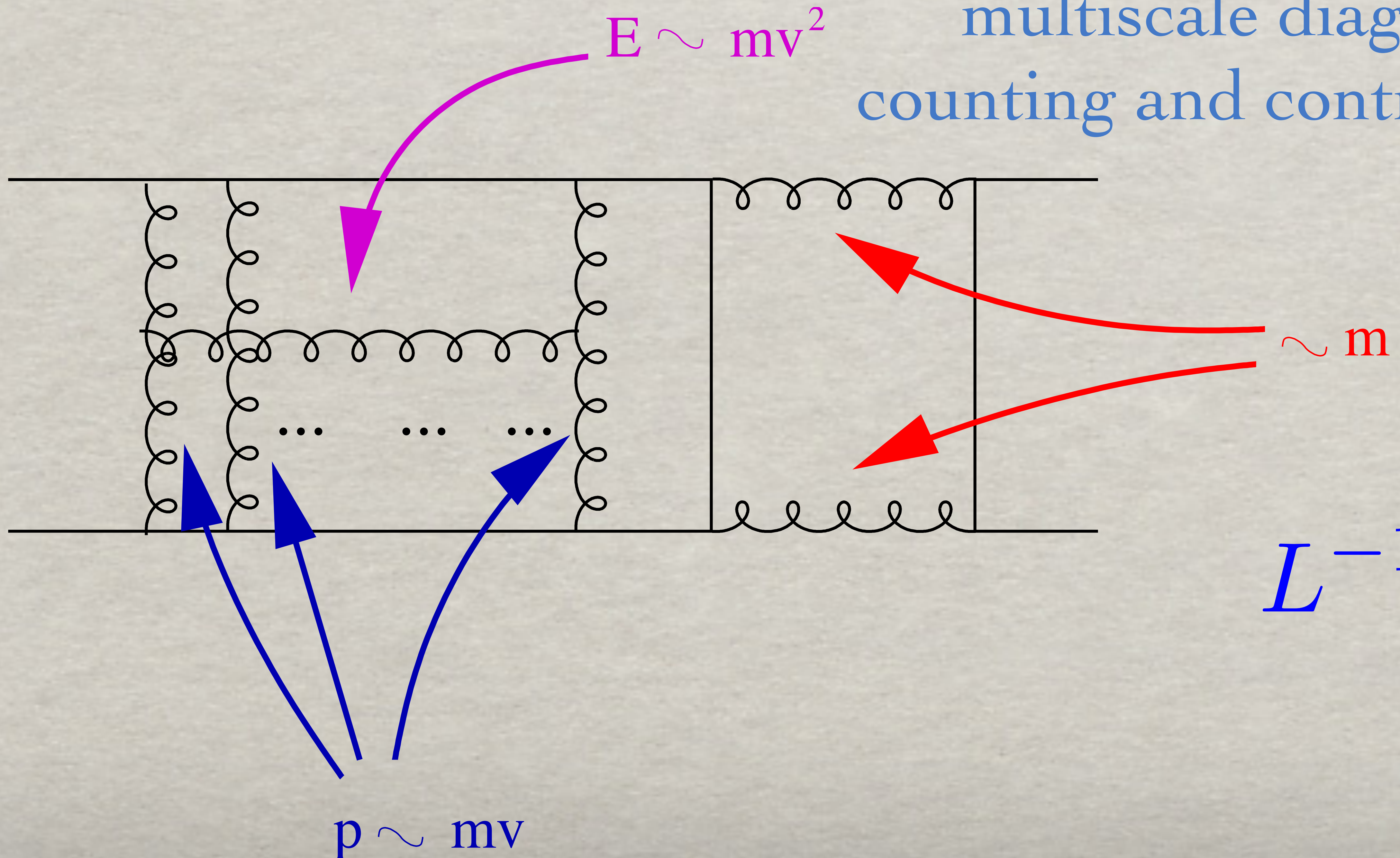

Difficult also for the lattice!

$$L^{-1} \ll \lambda \ll \Lambda \ll a^{-1}$$

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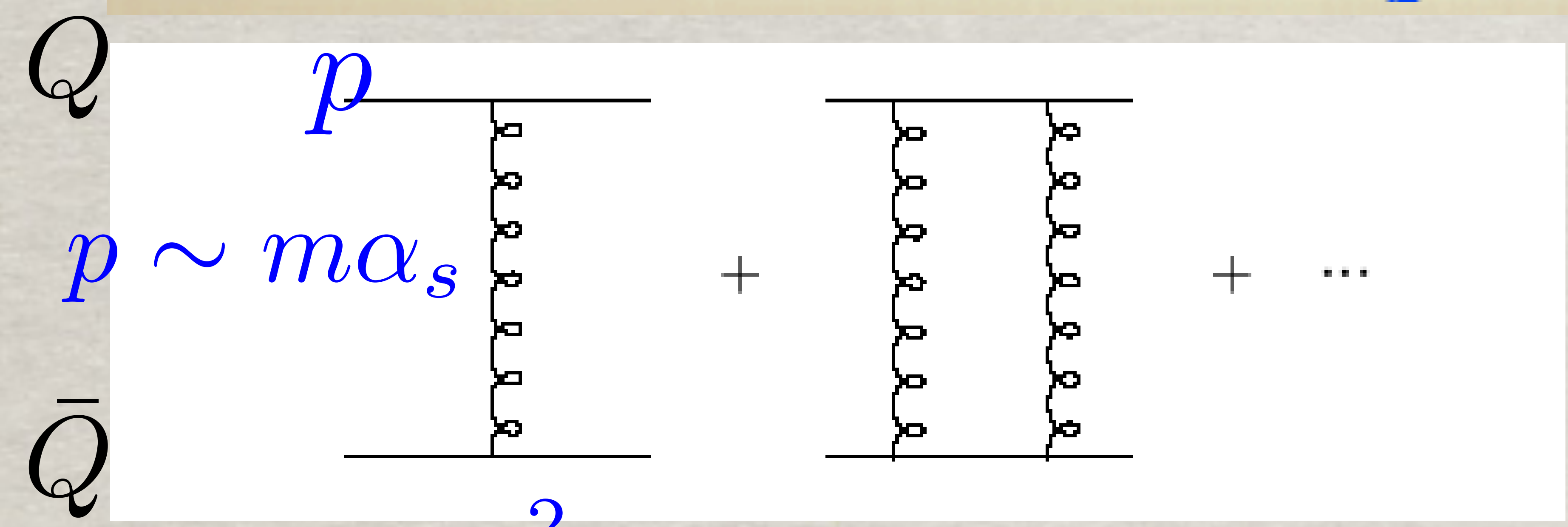

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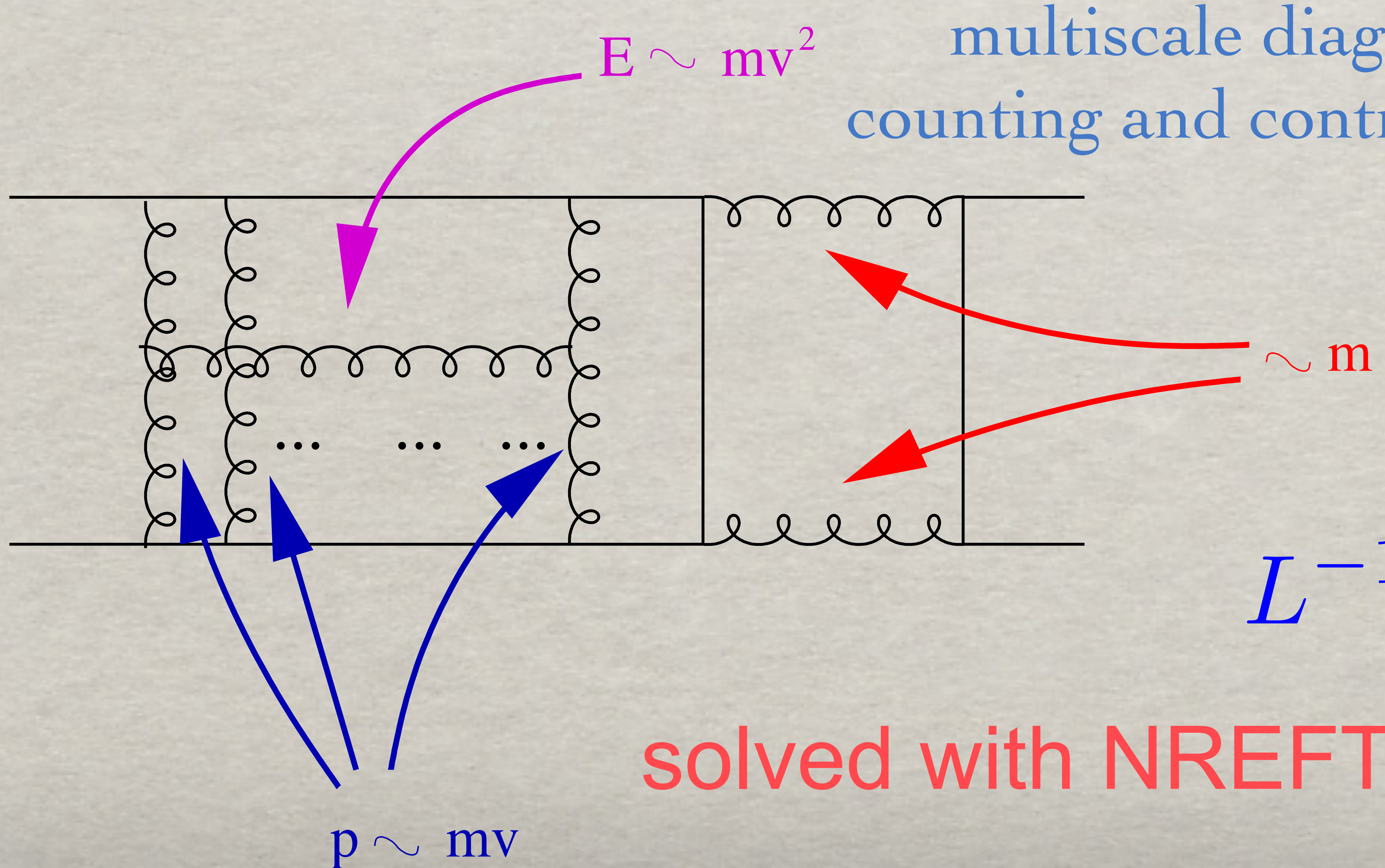

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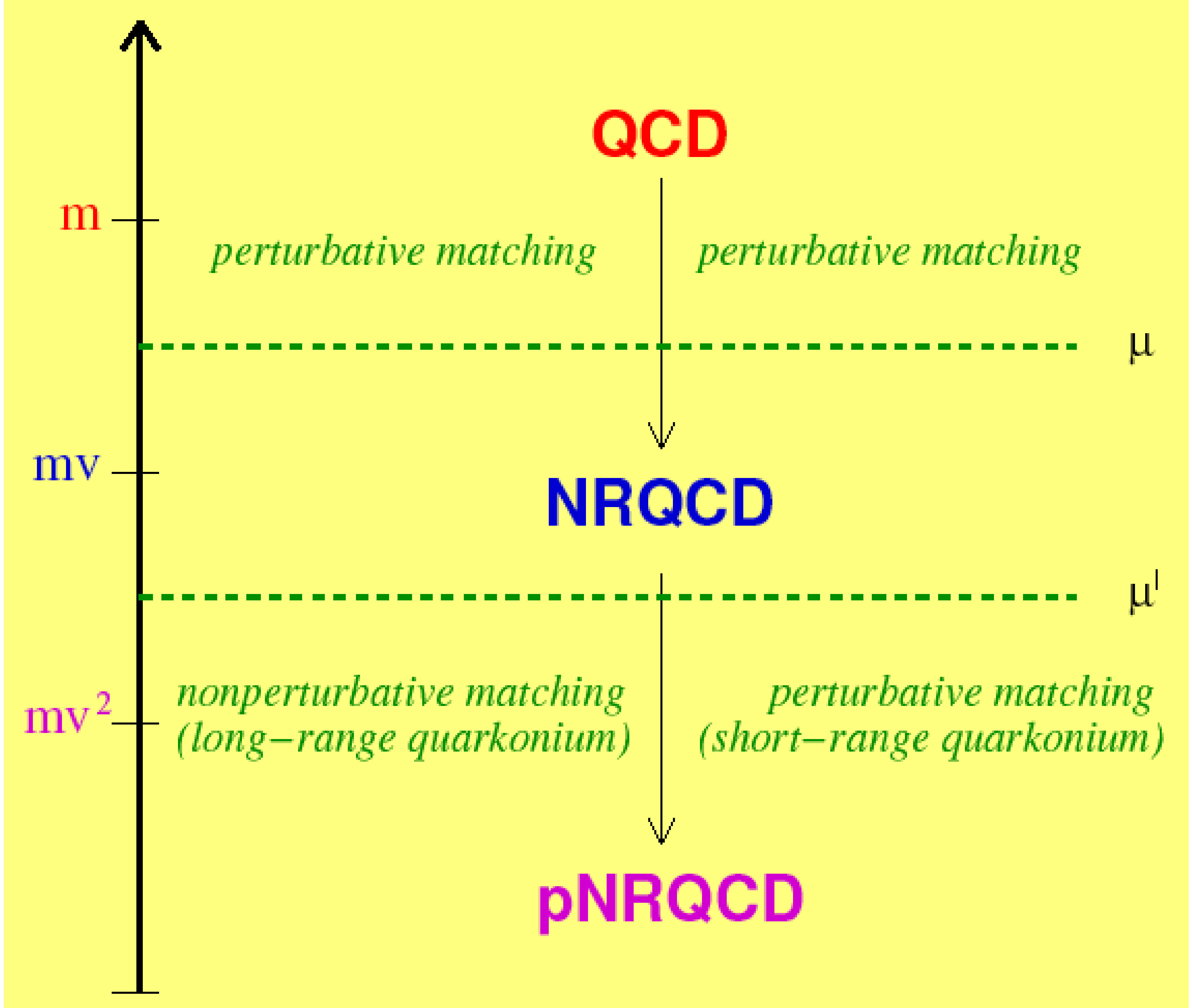
solved with NREFT

Quarkonium with NR EFT

Color degrees of freedom
3X3=1+8
singlet and octet QQbar



Hard

Soft
(relative
momentum)

Ultrasoft
(binding energy)

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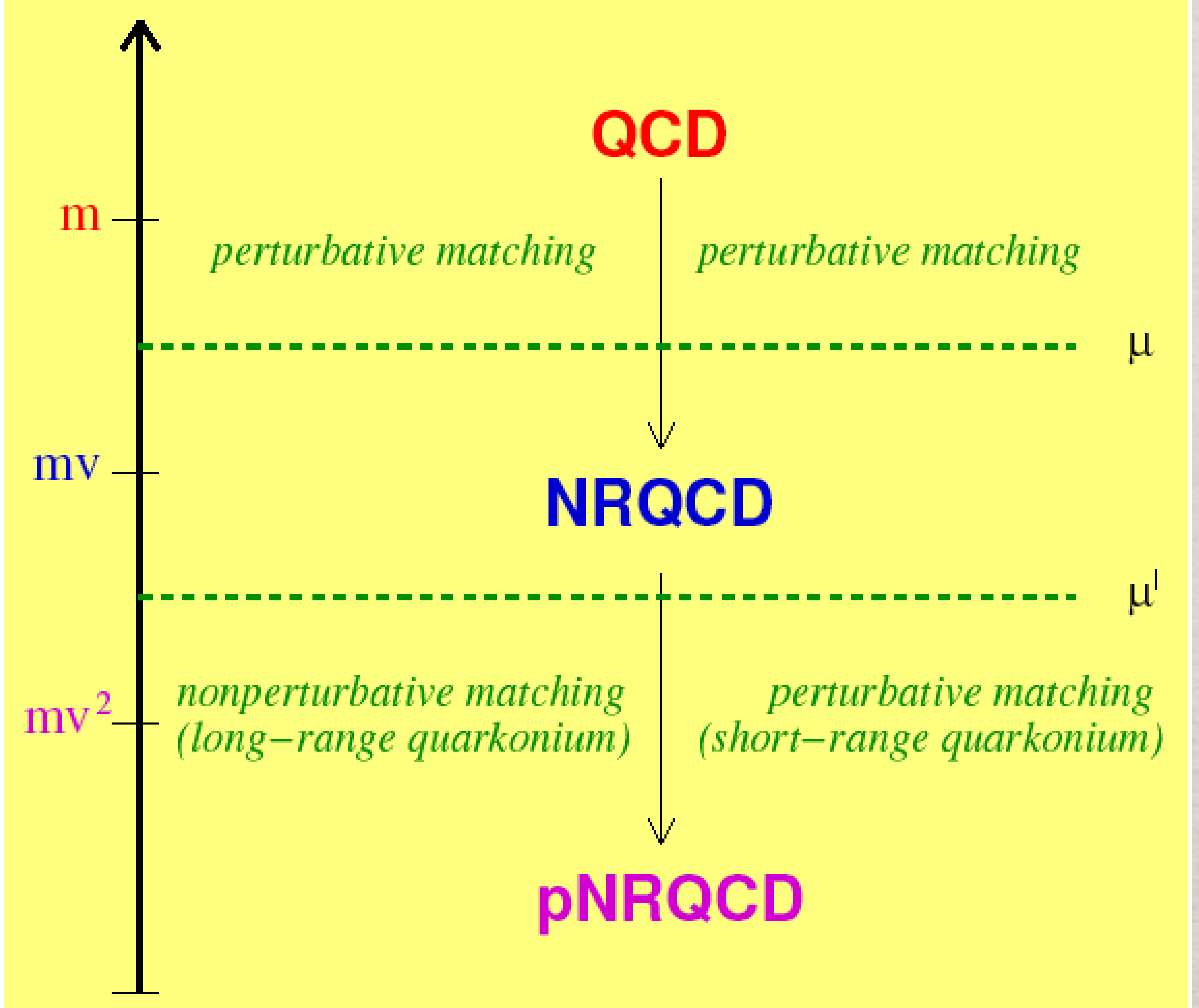

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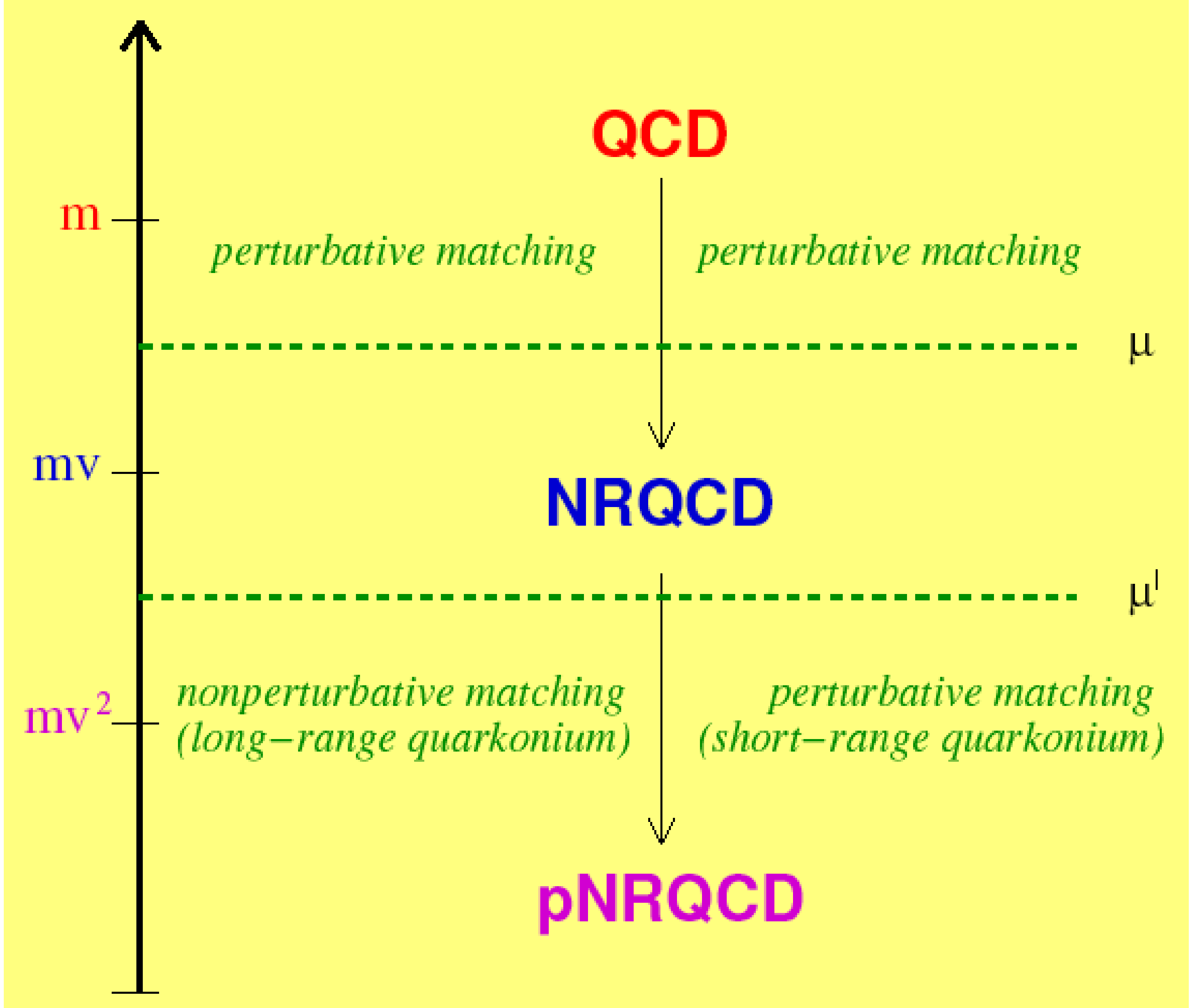

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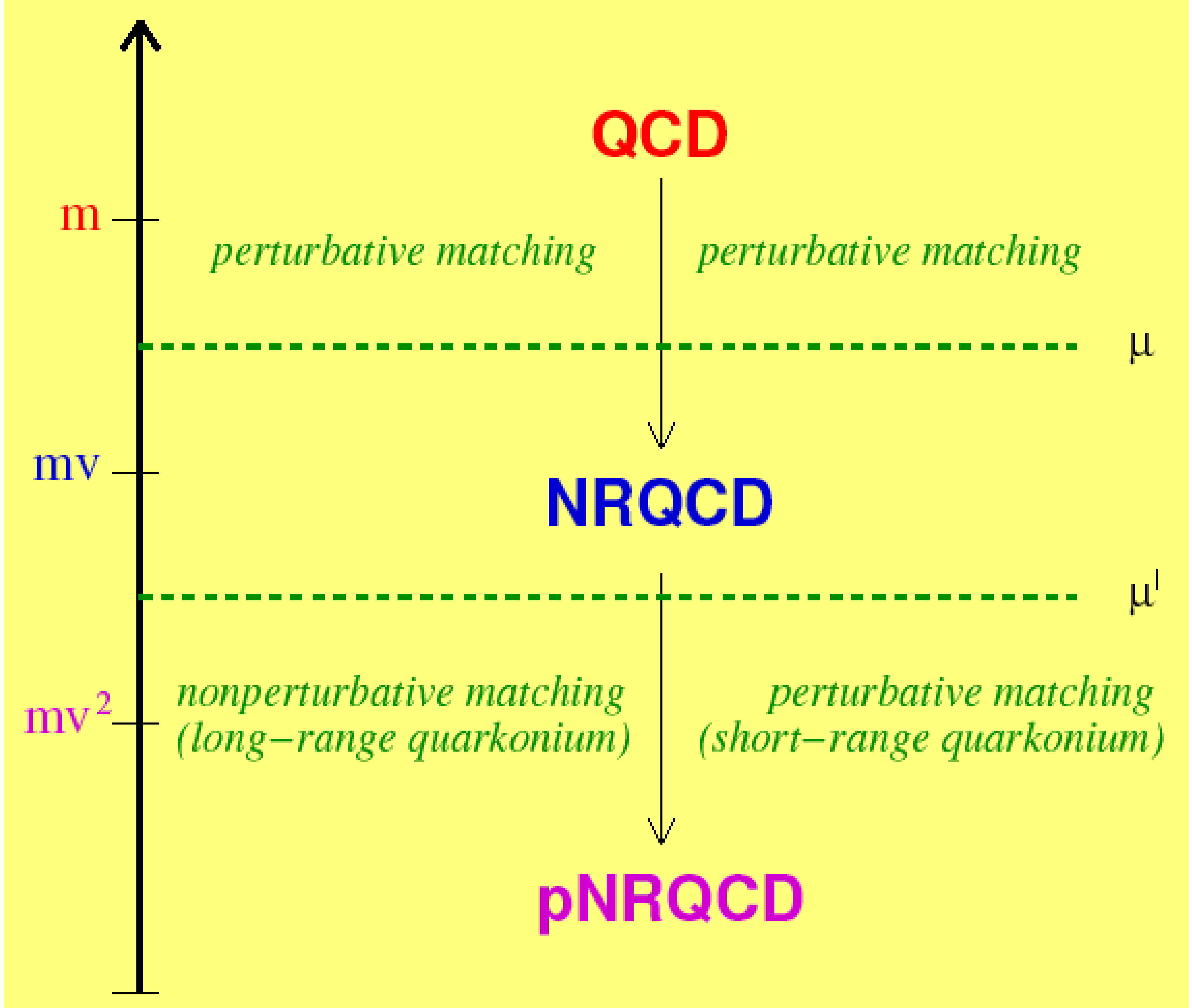

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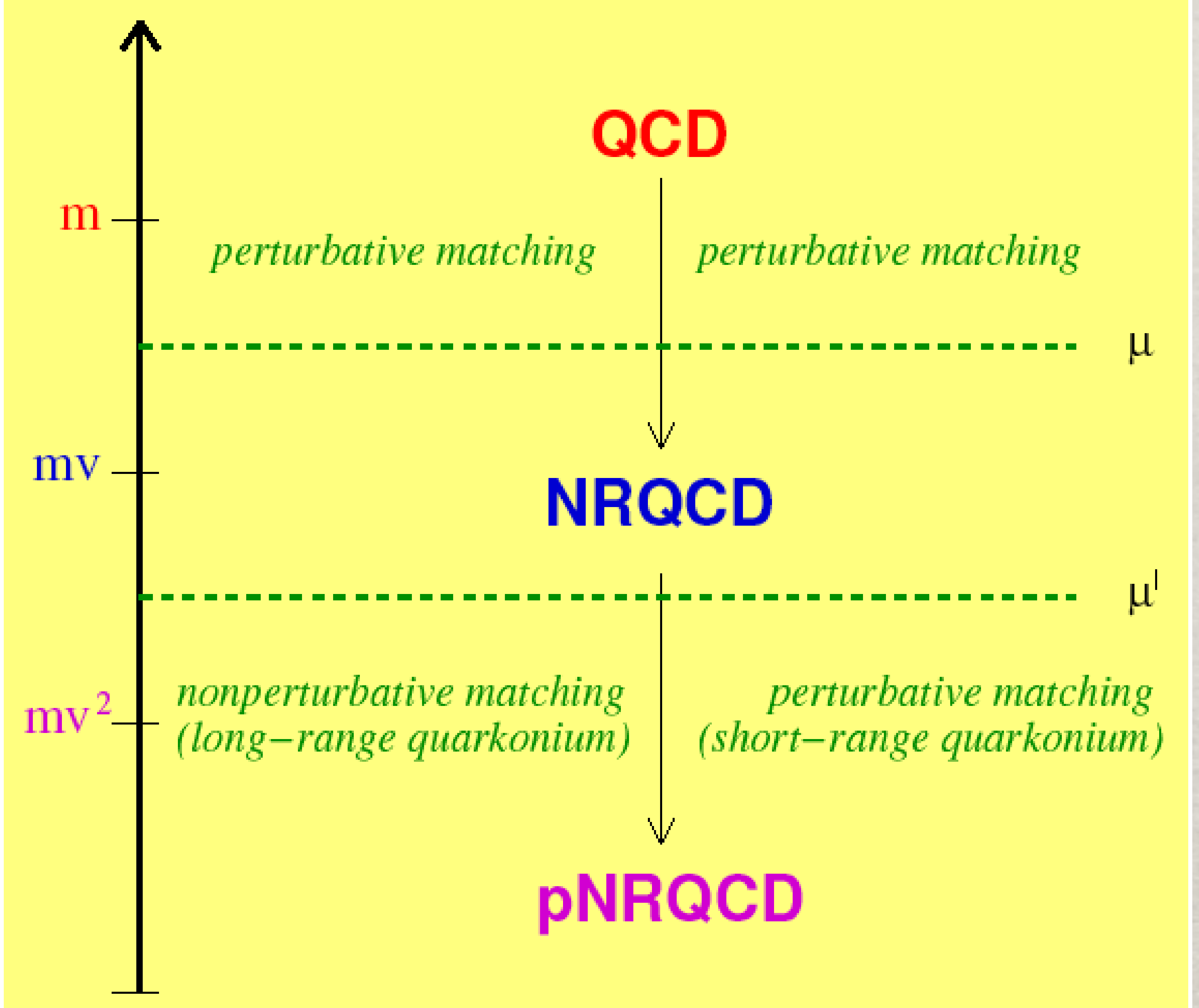

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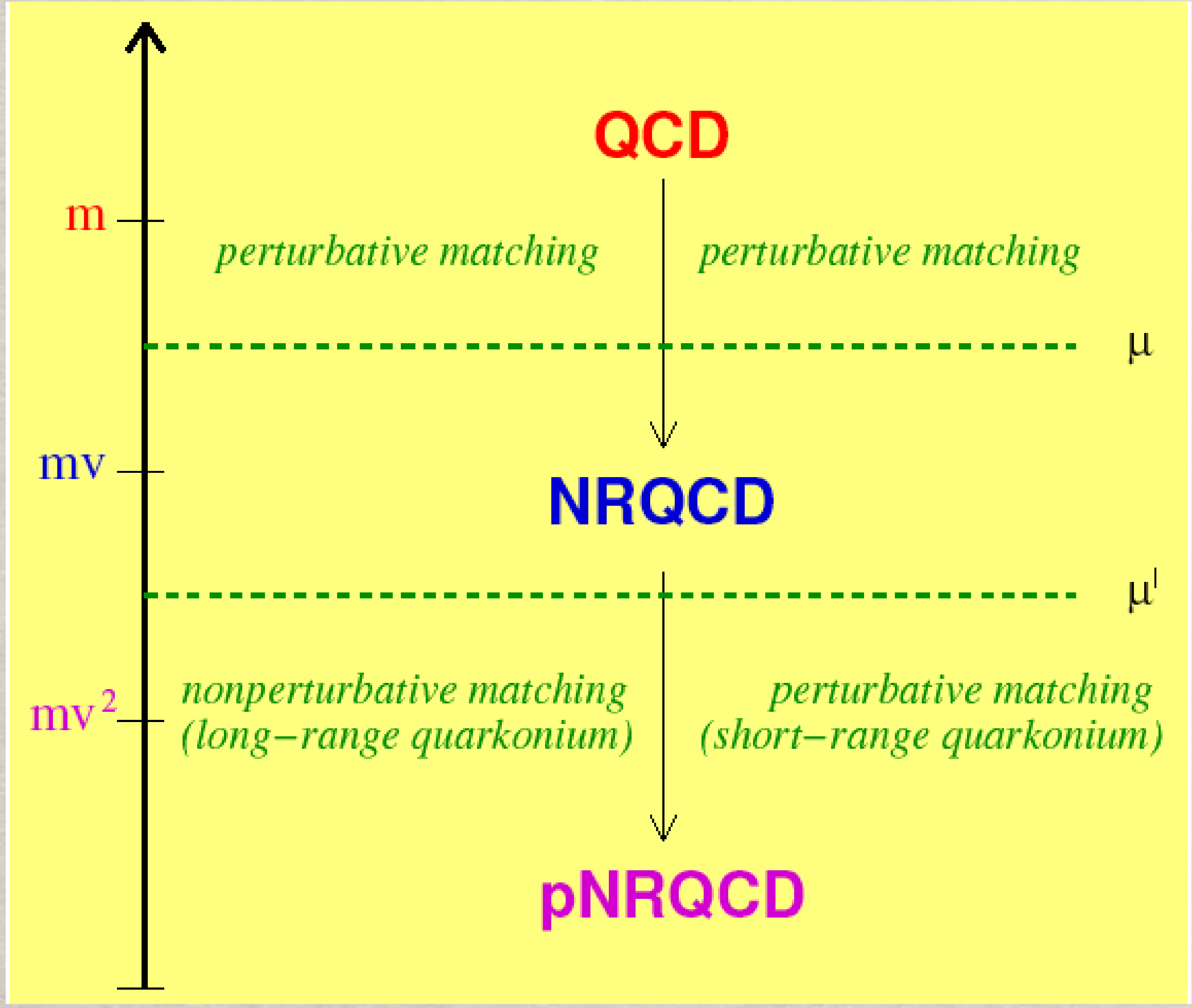
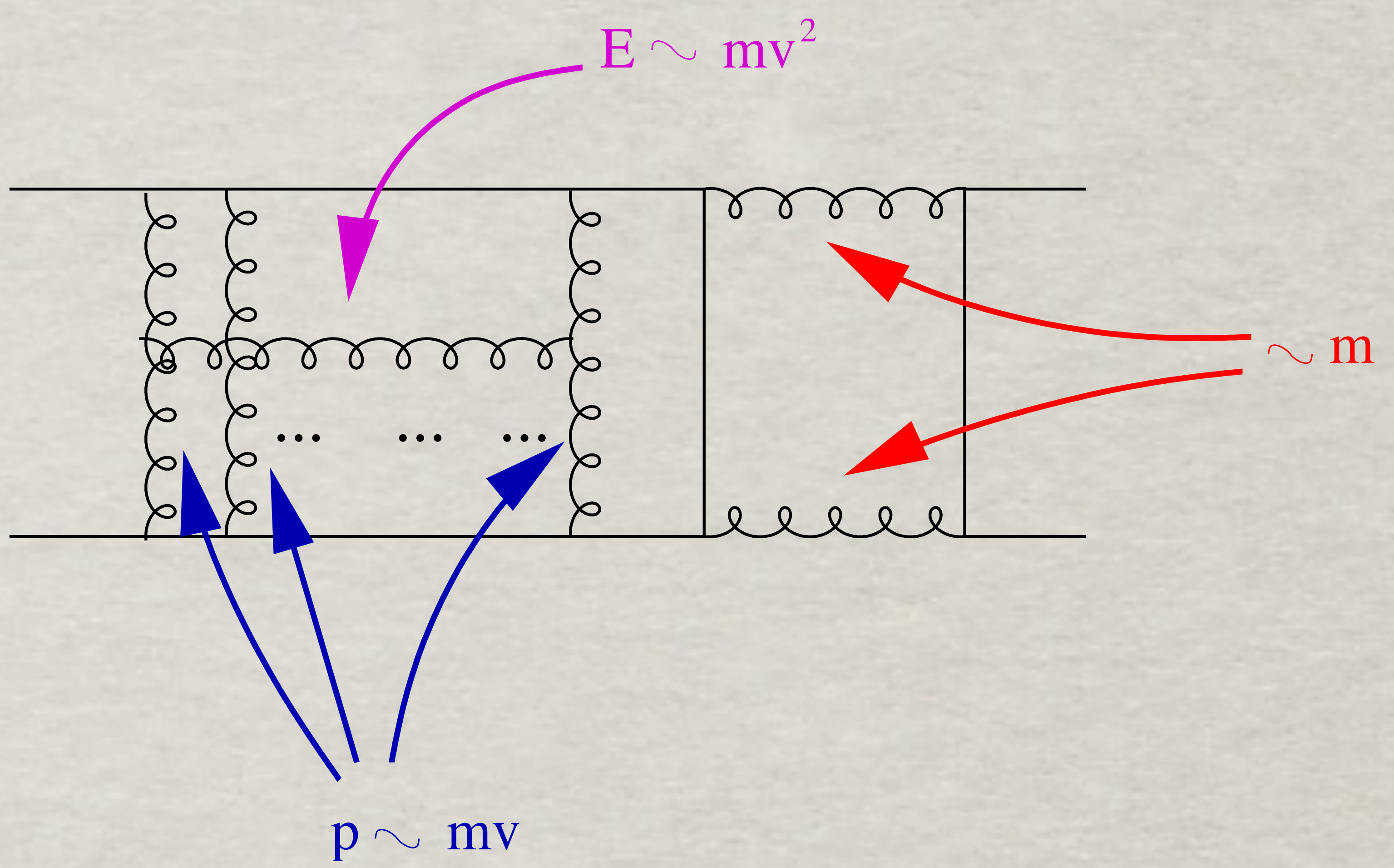
Quarkonium with NR EFT: Non Relativistic QCD (NRQCD)





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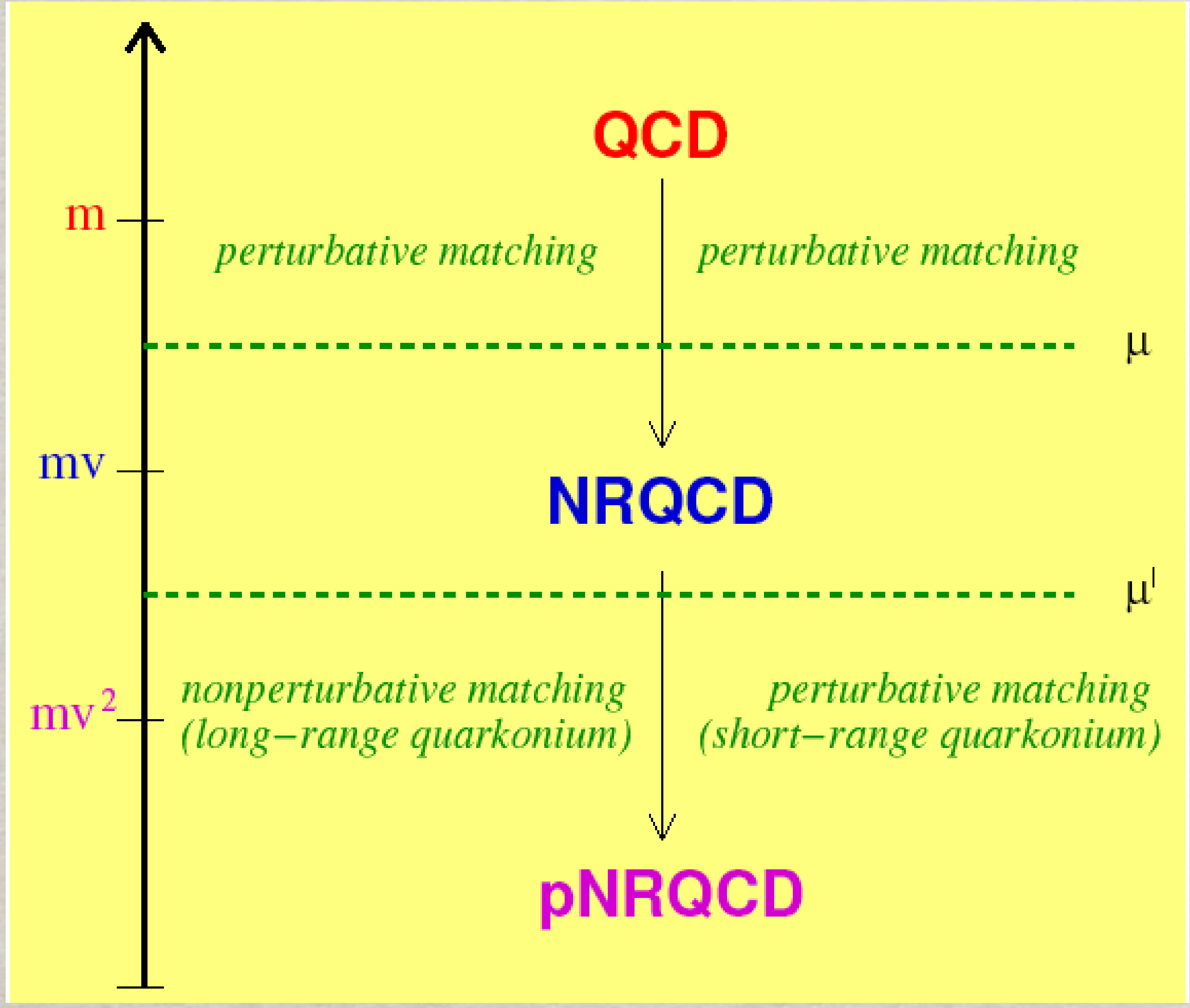

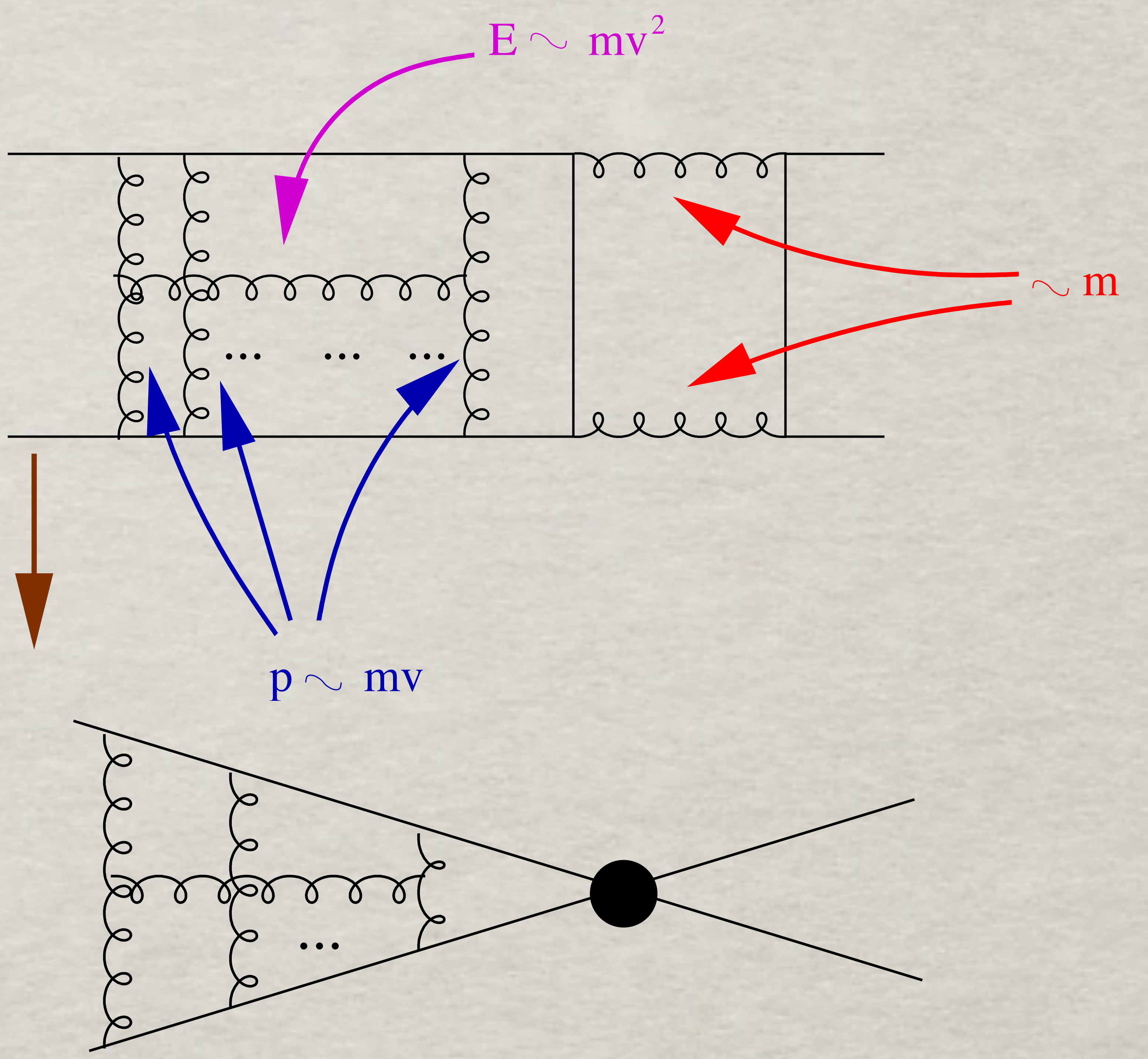

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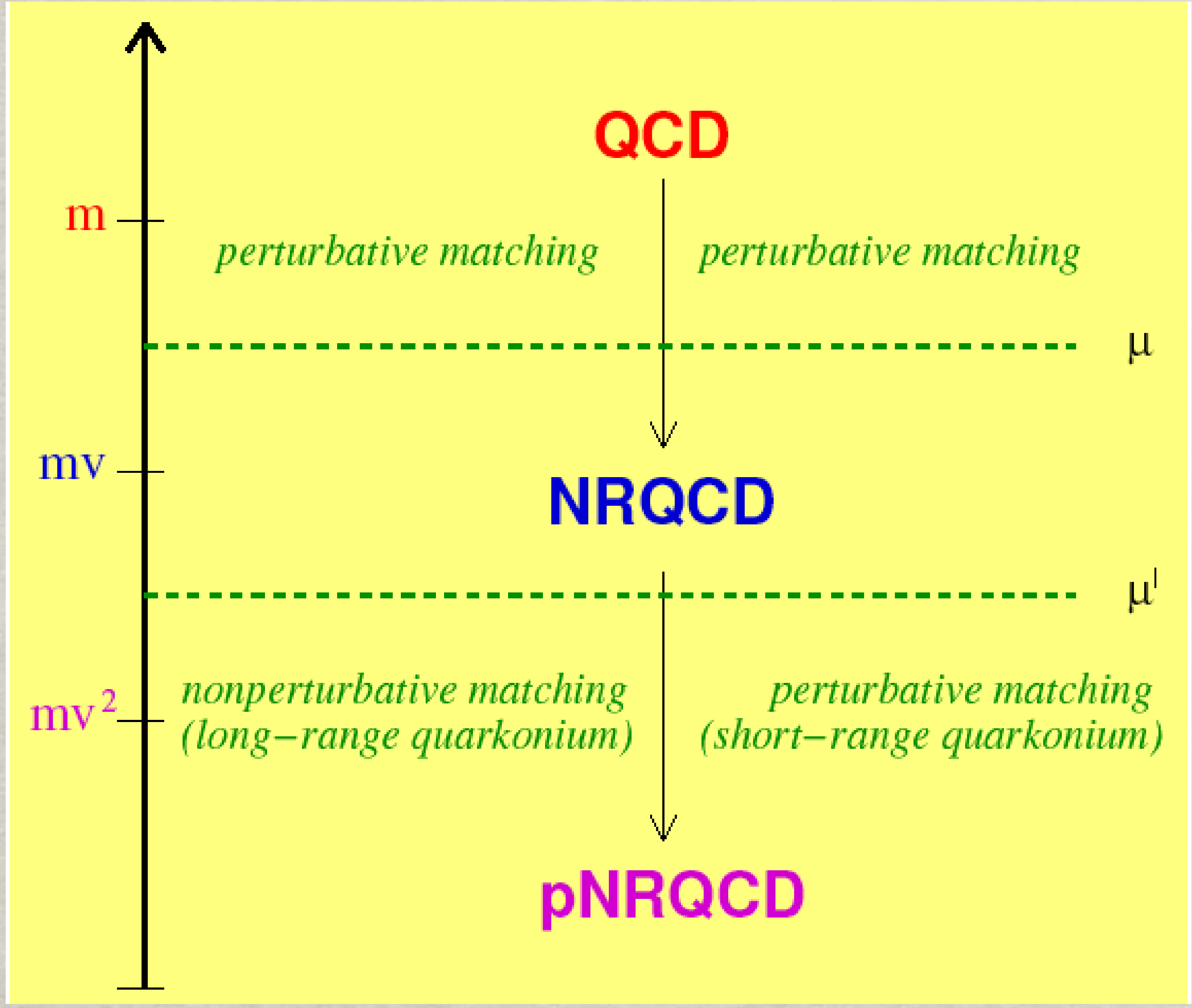
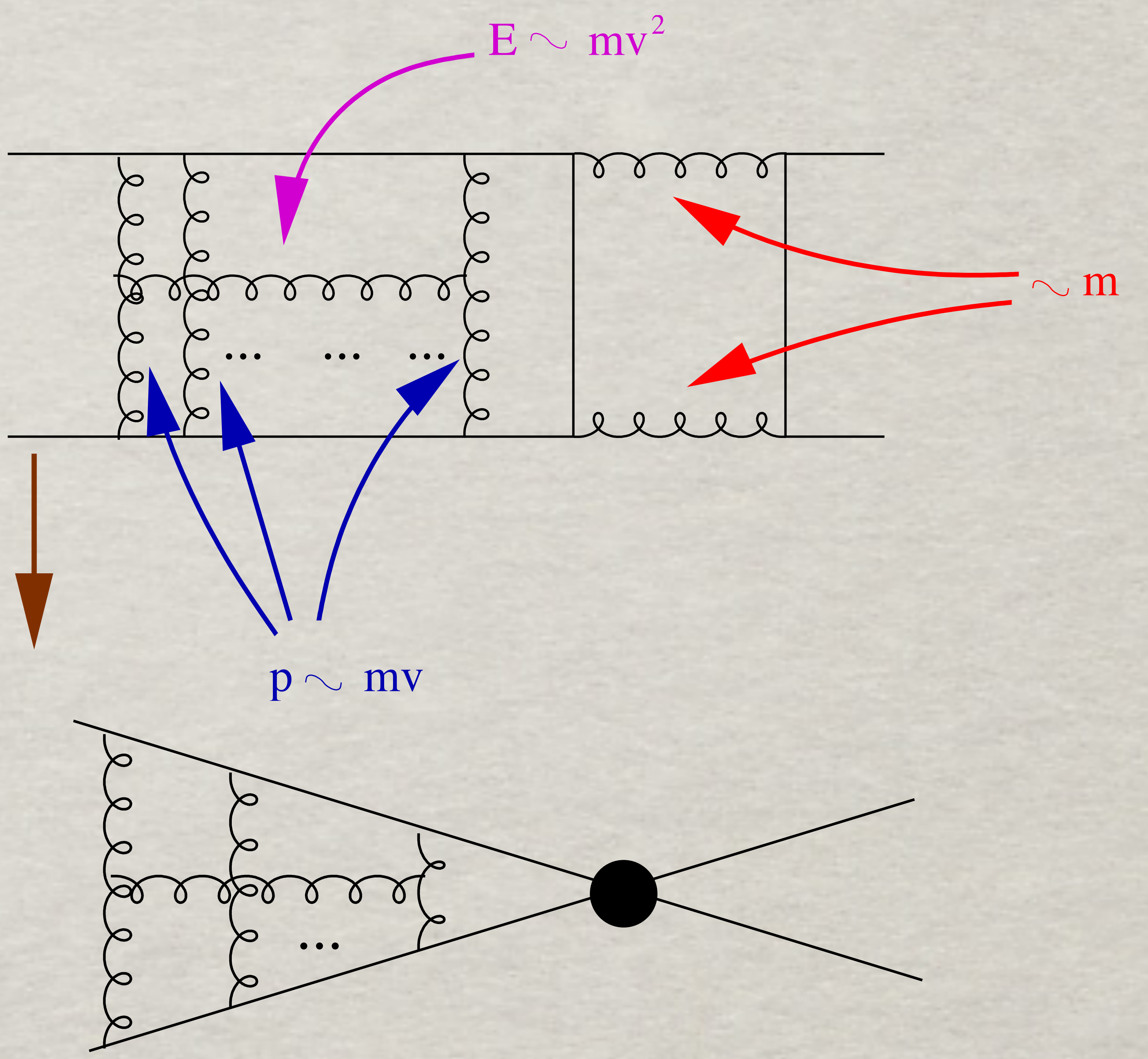
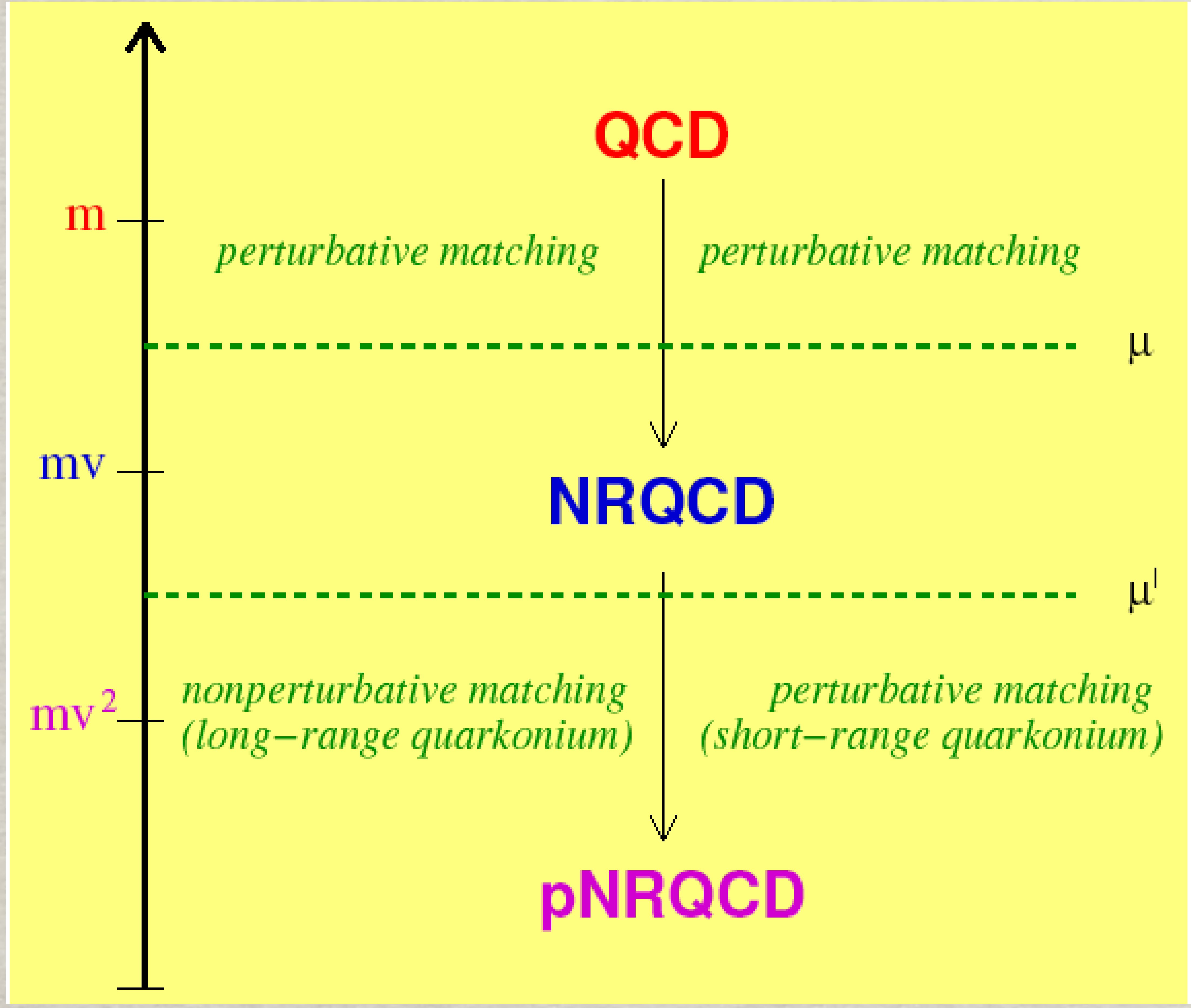
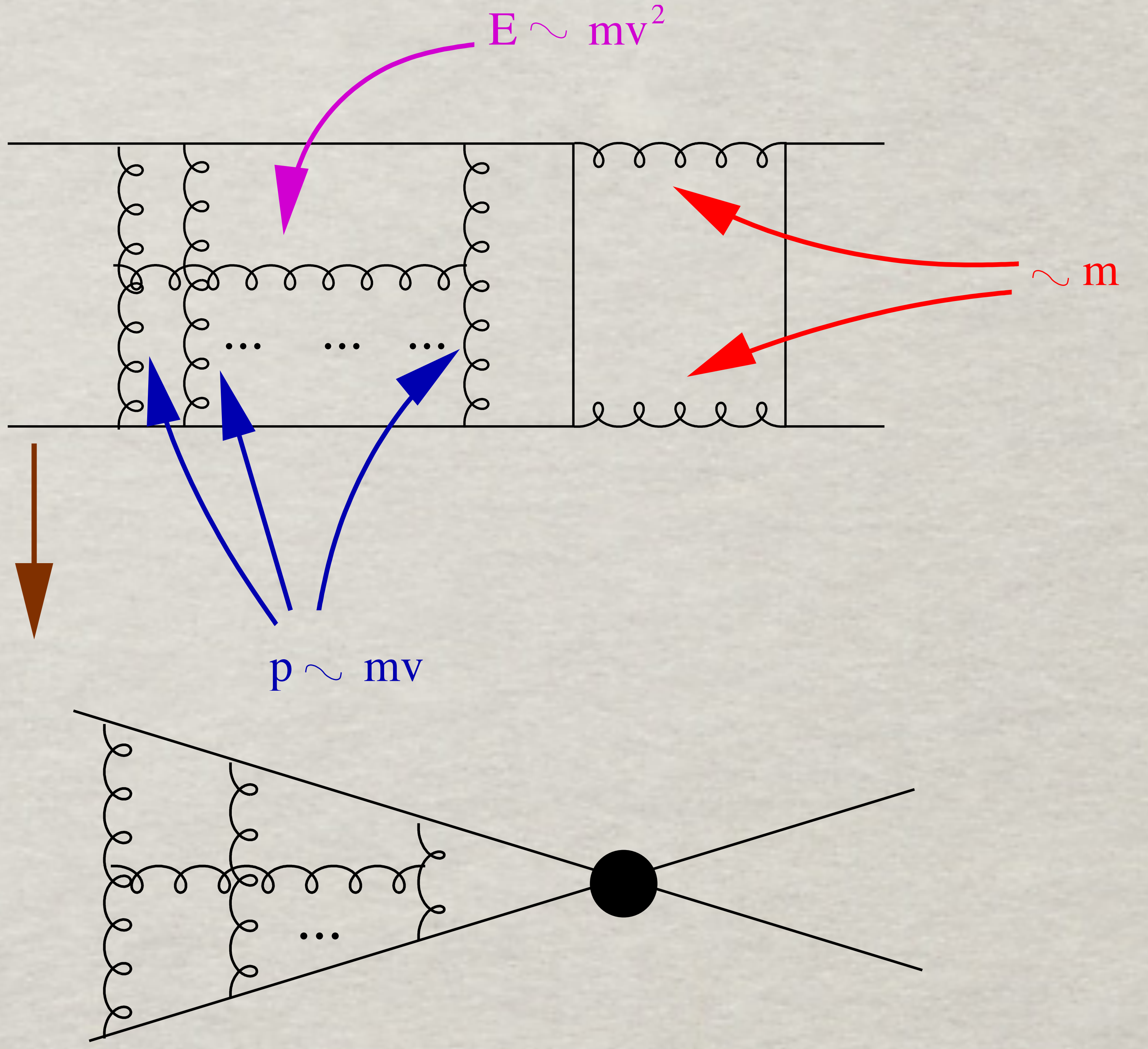




$$\mathcal{L}_{\rm NRQCD} = \sum_n c(\alpha_s(m/\mu)) \times \frac{O_n(\mu,\lambda)}{m^n}$$

Quarkonium with NR EFT: potential NonRelativistic QCD (pNRQCD)





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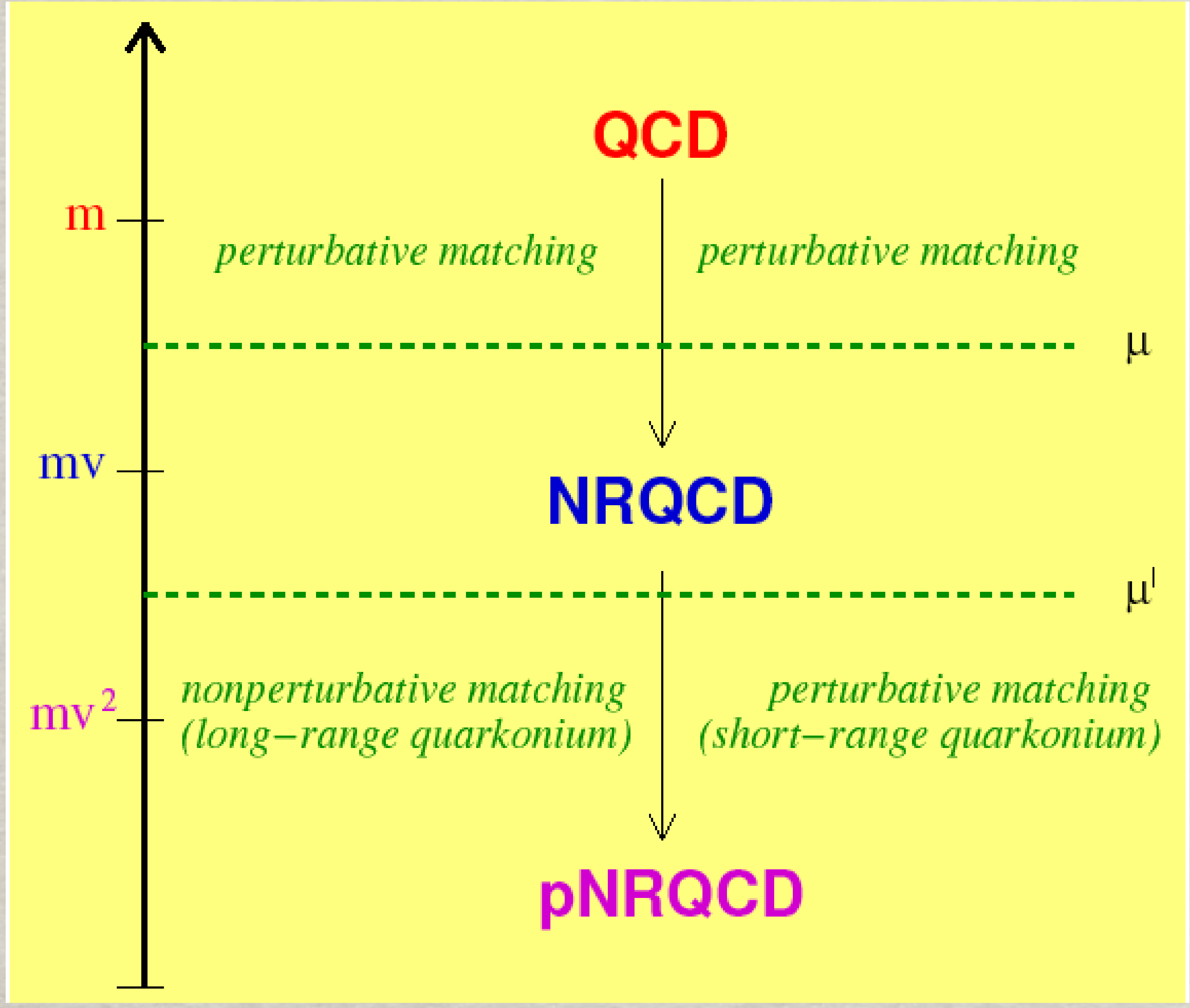

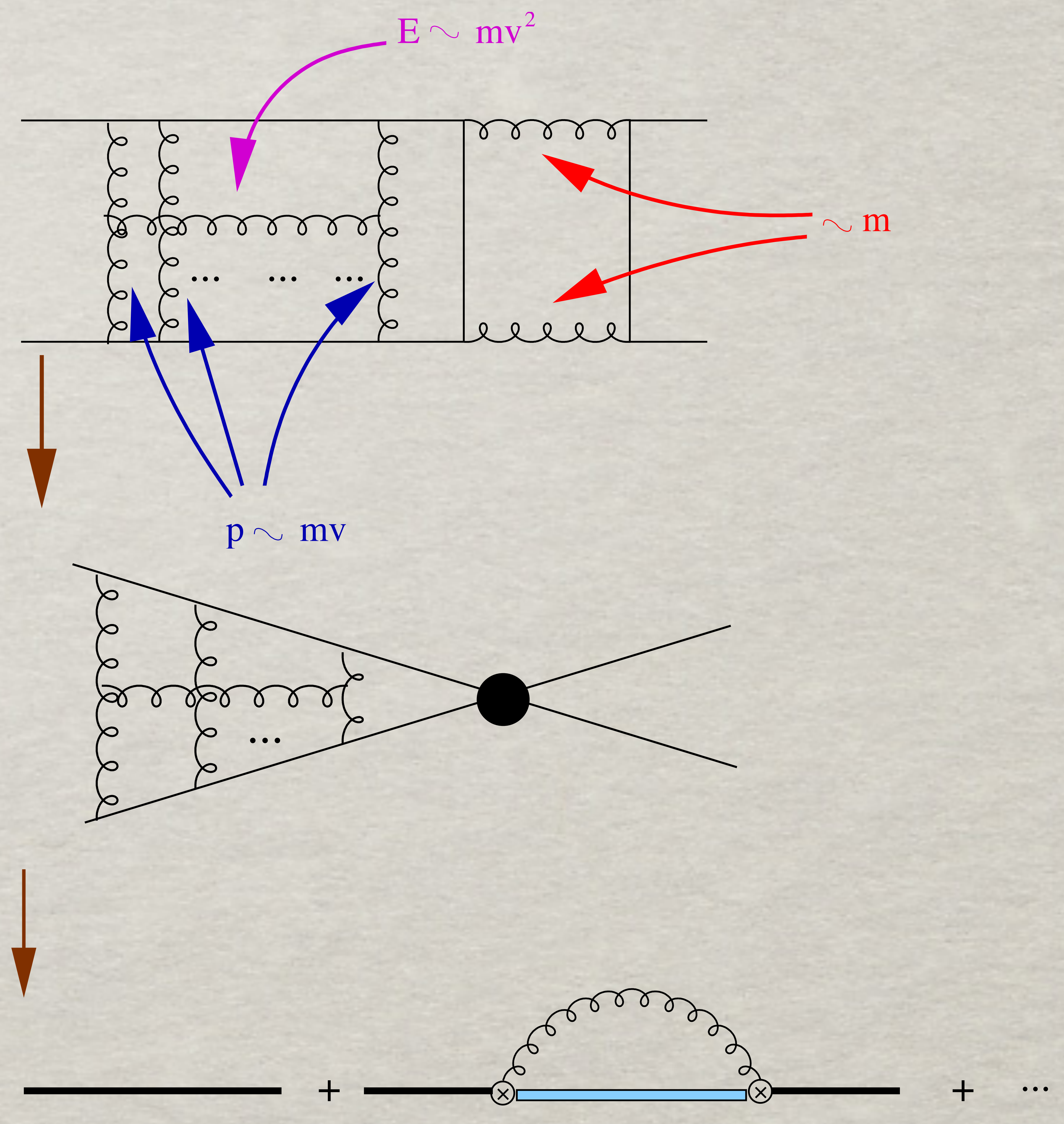

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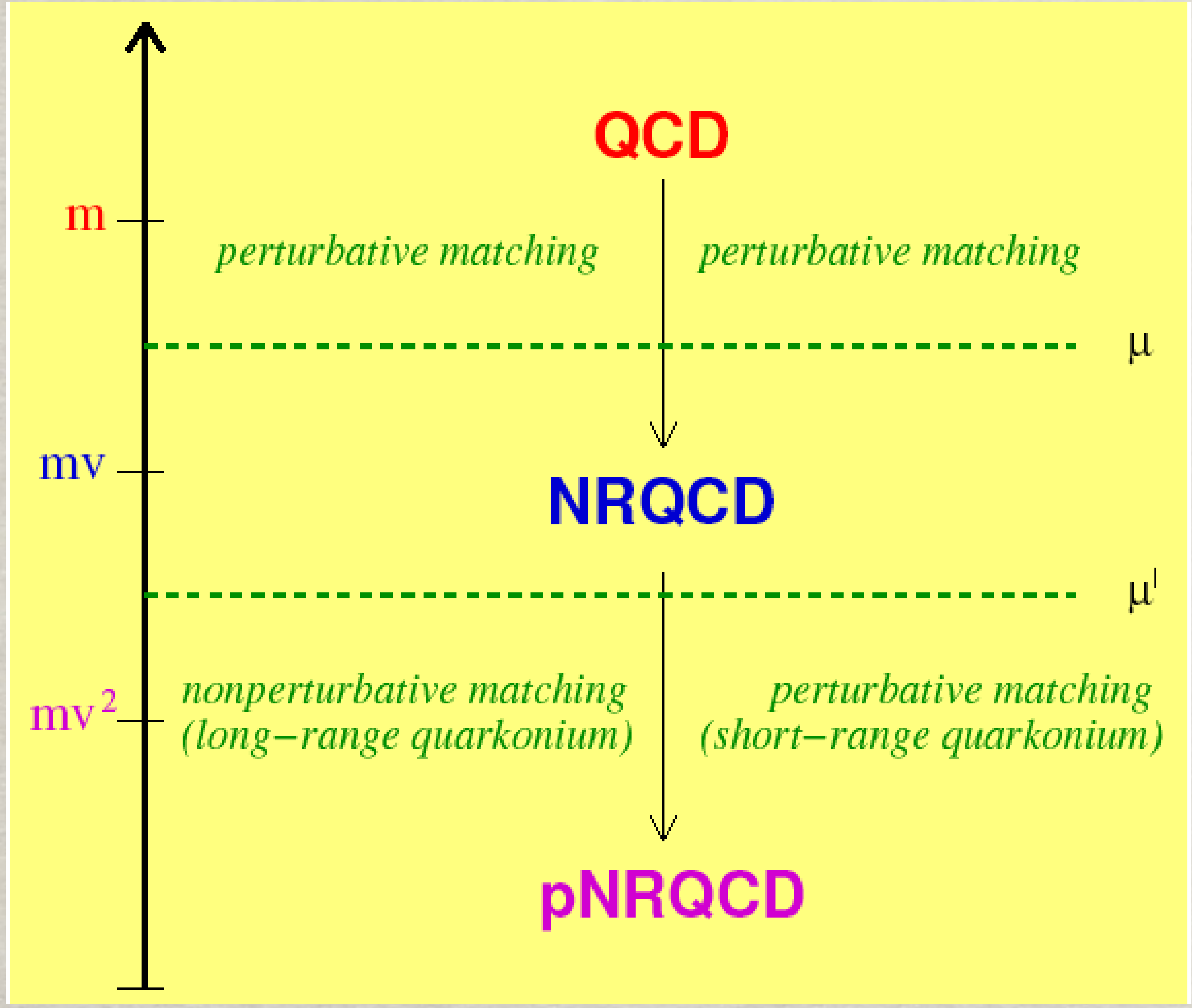

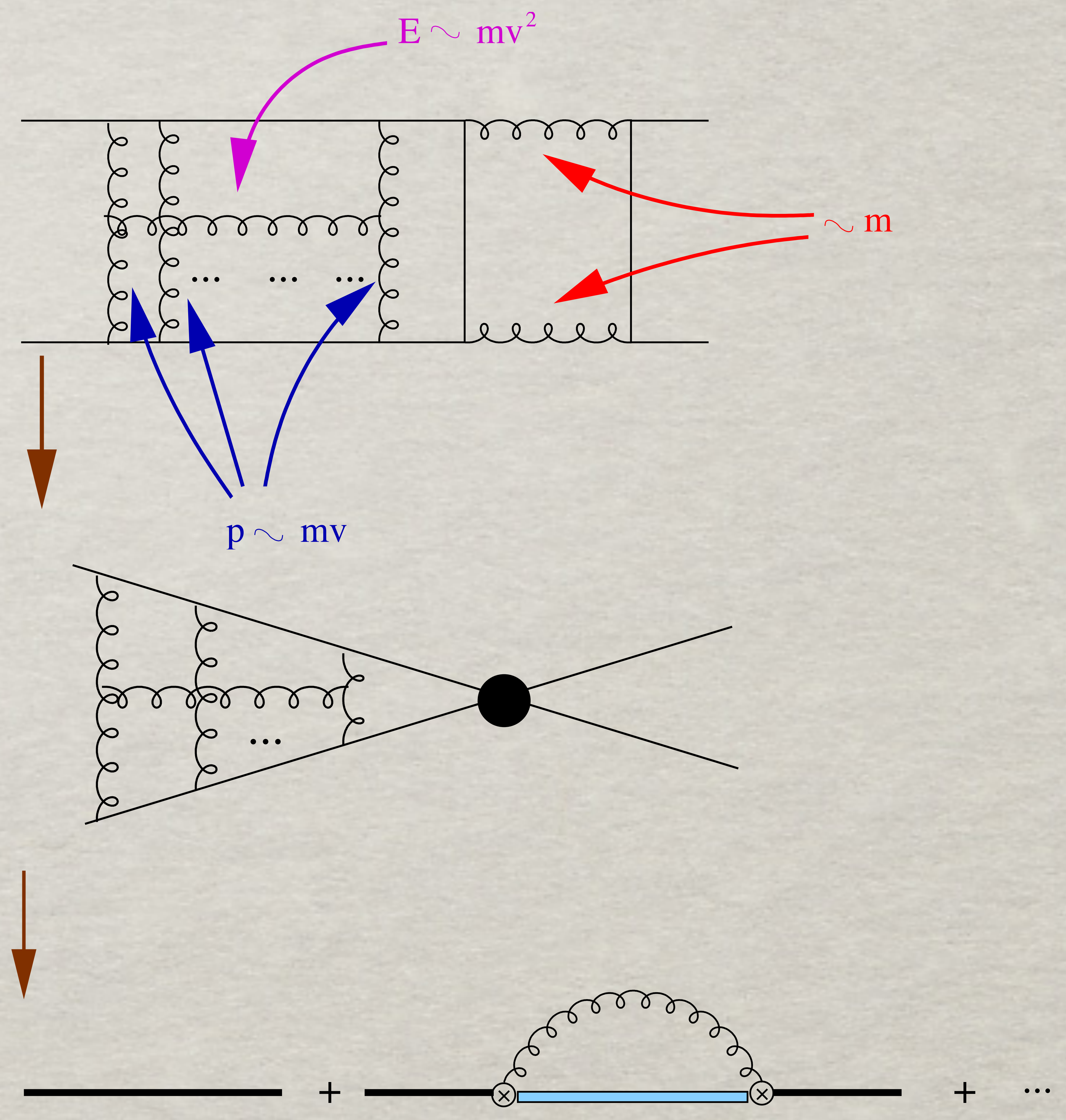

$$\mathcal{L}_{\rm pNRQCD} = \sum_k \sum_n \frac{1}{m^k} c_k(\alpha_{\rm s}(m/\mu)) \times V(r\mu', r\mu) \times O_n(\mu', \lambda)\, r^n$$

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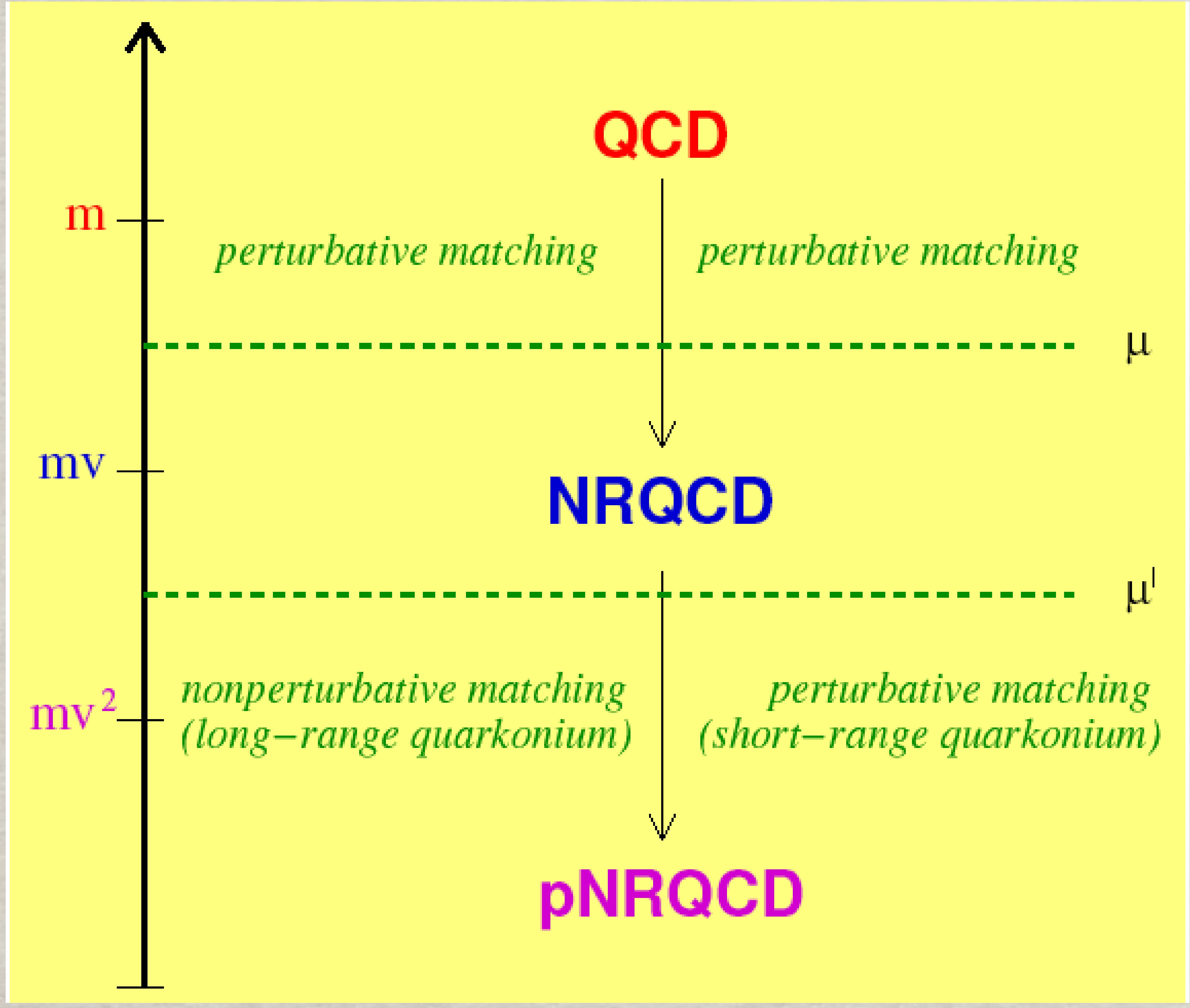

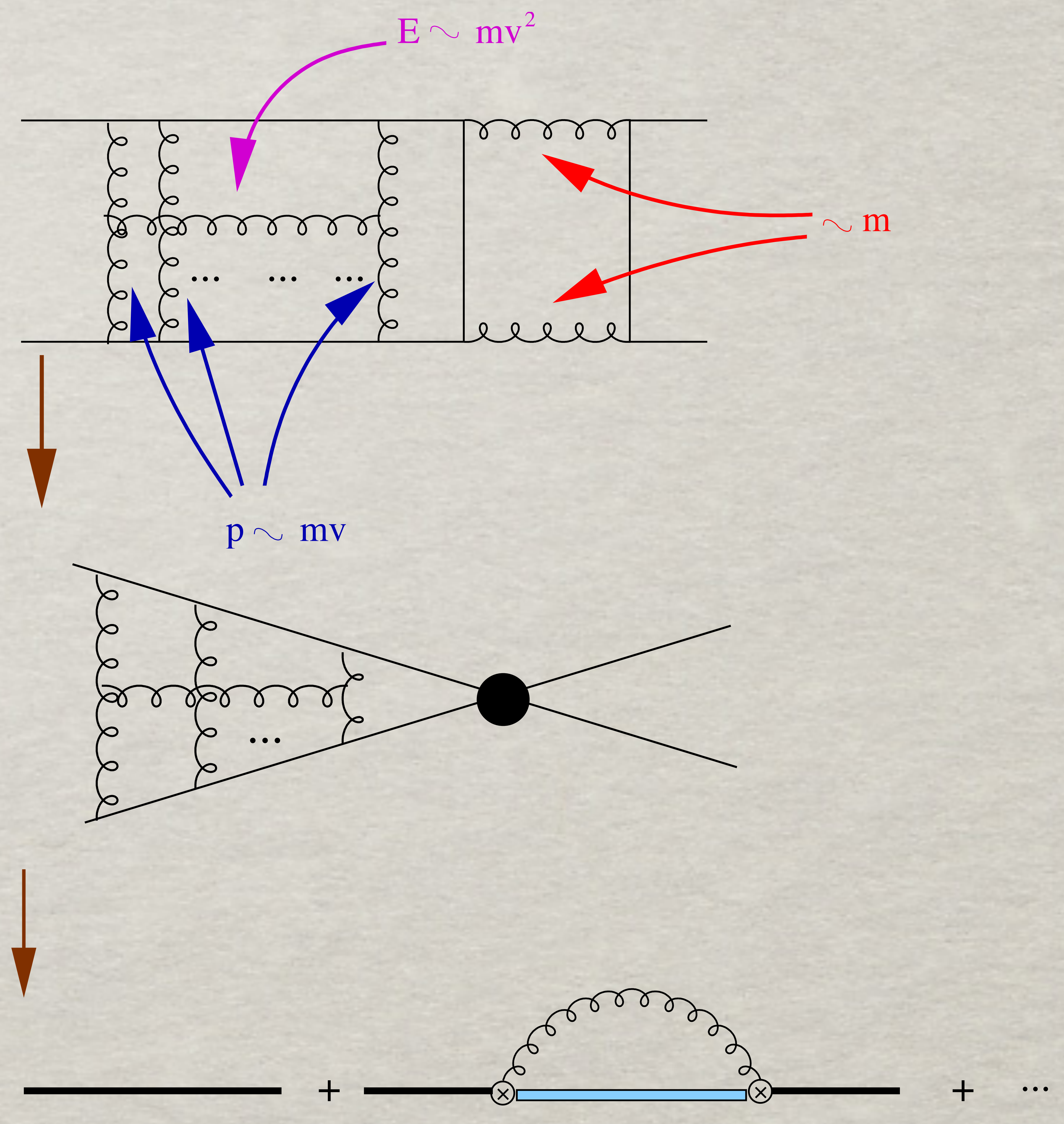

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pNRQCD (potential NonRelativistic QCD) EFT for quarkonium for r<< Lambda_QCD^-1

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu\, a} + \sum_{i=1}^{n_f} \bar{q}_i \, i \not{D} q_i + \int d^3r \mathrm{Tr} \left\{ \mathrm{S}^\dagger \left(i\partial_0 - h_s \right) \mathrm{S} + \mathrm{O}^\dagger \left(iD_0 - h_o \right) \mathrm{O} \right\}$$

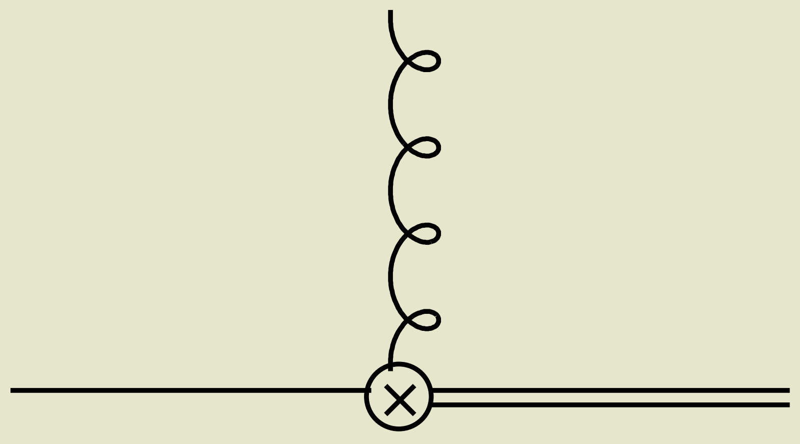
- LO in r

$\theta(T)\, e^{-iTh_s}$ $\qquad$ $\theta(T)\, e^{-iTh_o} \left(e^{-i\int dt\, A^{\mathrm{adj}}} \right)$

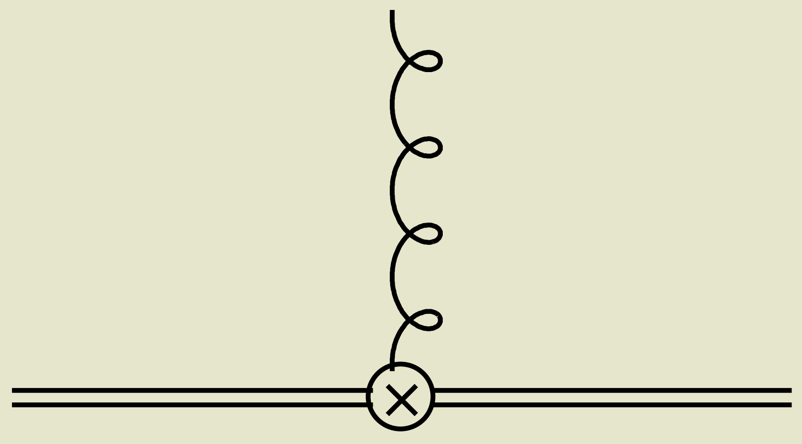
$$+V_A \mathrm{Tr} \left\{ \mathrm{O}^\dagger \mathbf{r} \cdot g\mathbf{E}\, \mathrm{S} + \mathrm{S}^\dagger \mathbf{r} \cdot g\mathbf{E}\, \mathrm{O} \right\} + \frac{V_B}{2} \mathrm{Tr} \left\{ \mathrm{O}^\dagger \mathbf{r} \cdot g\mathbf{E}\, \mathrm{O} + \mathrm{O}^\dagger \mathrm{O} \mathbf{r} \cdot g\mathbf{E} \right\}$$

$+\cdots$

- NLO in r



$O^\dagger \mathbf{r} \cdot g\mathbf{E}\, \mathrm{S}$



$O^\dagger \{ \mathbf{r} \cdot g\mathbf{E}, \, \mathrm{O} \}$

Degrees of freedom: colour singlet S and colour octet O and low energy gluons (multipole expanded)

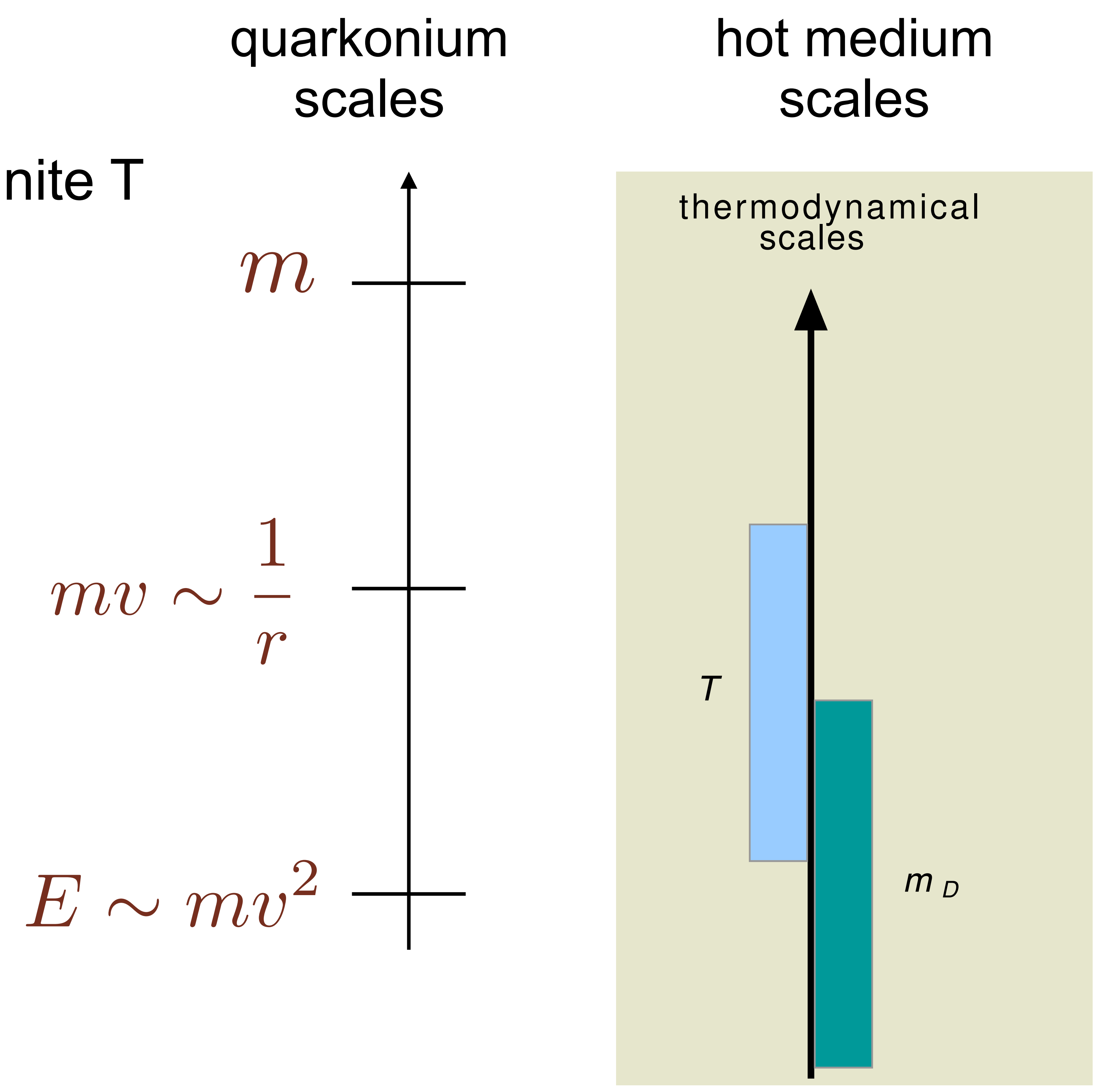
The potentials are the matching coefficients of pNRQCD : they are calculated via a well defined matching procedure

the finite T potential in equilibrium

the change of paradigm from the screening to the imaginary part of the potential

pNRQCD at finite T: the static potential

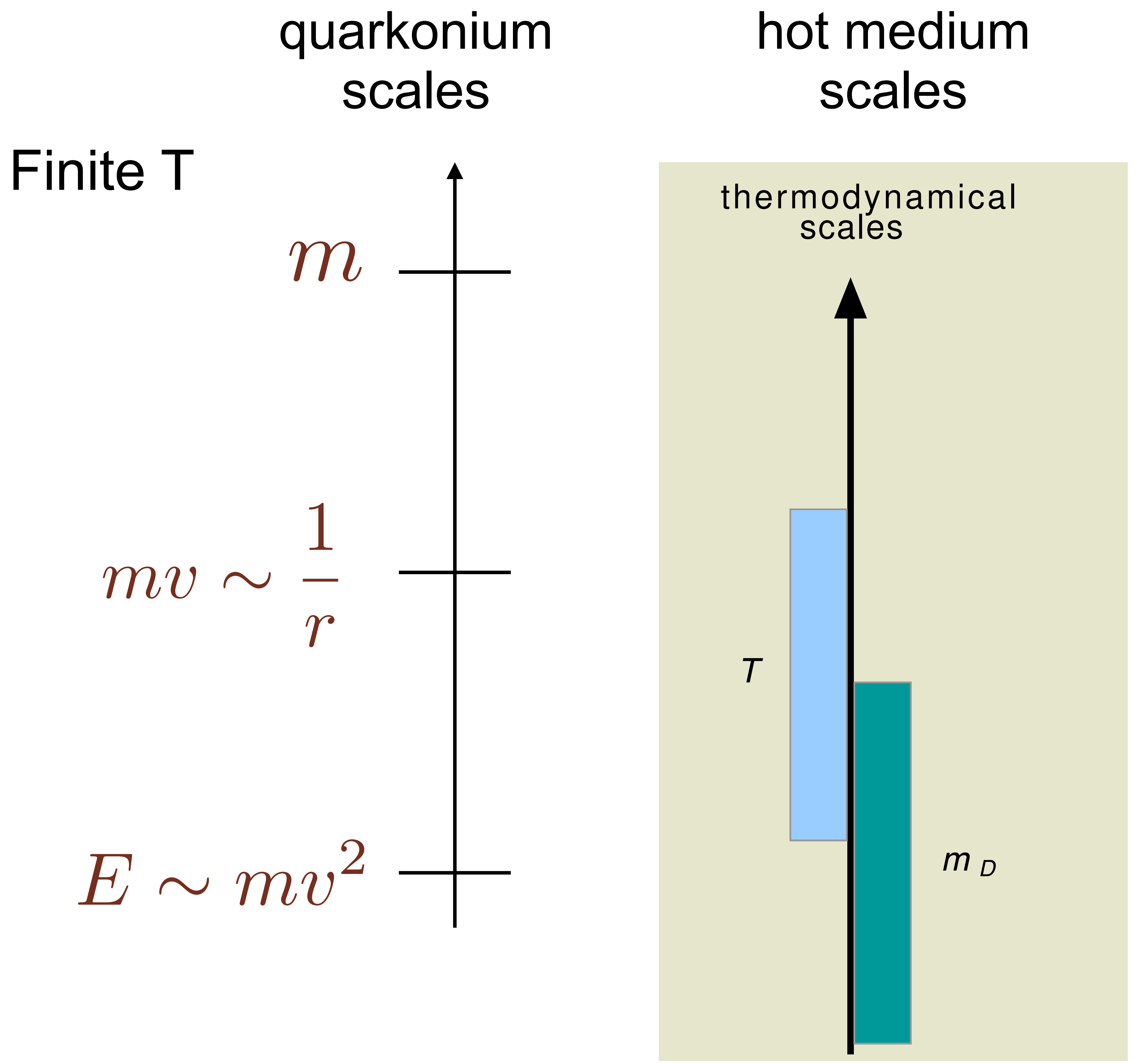
Finite T



$$m \gg \Lambda_{QCD}$$

pNRQCD at finite T: the static potential

in pNRQCD the potential has a clear definition: it a matching coefficient and comes from the integration of all scales from mv up to (and not included) the energy mv^2



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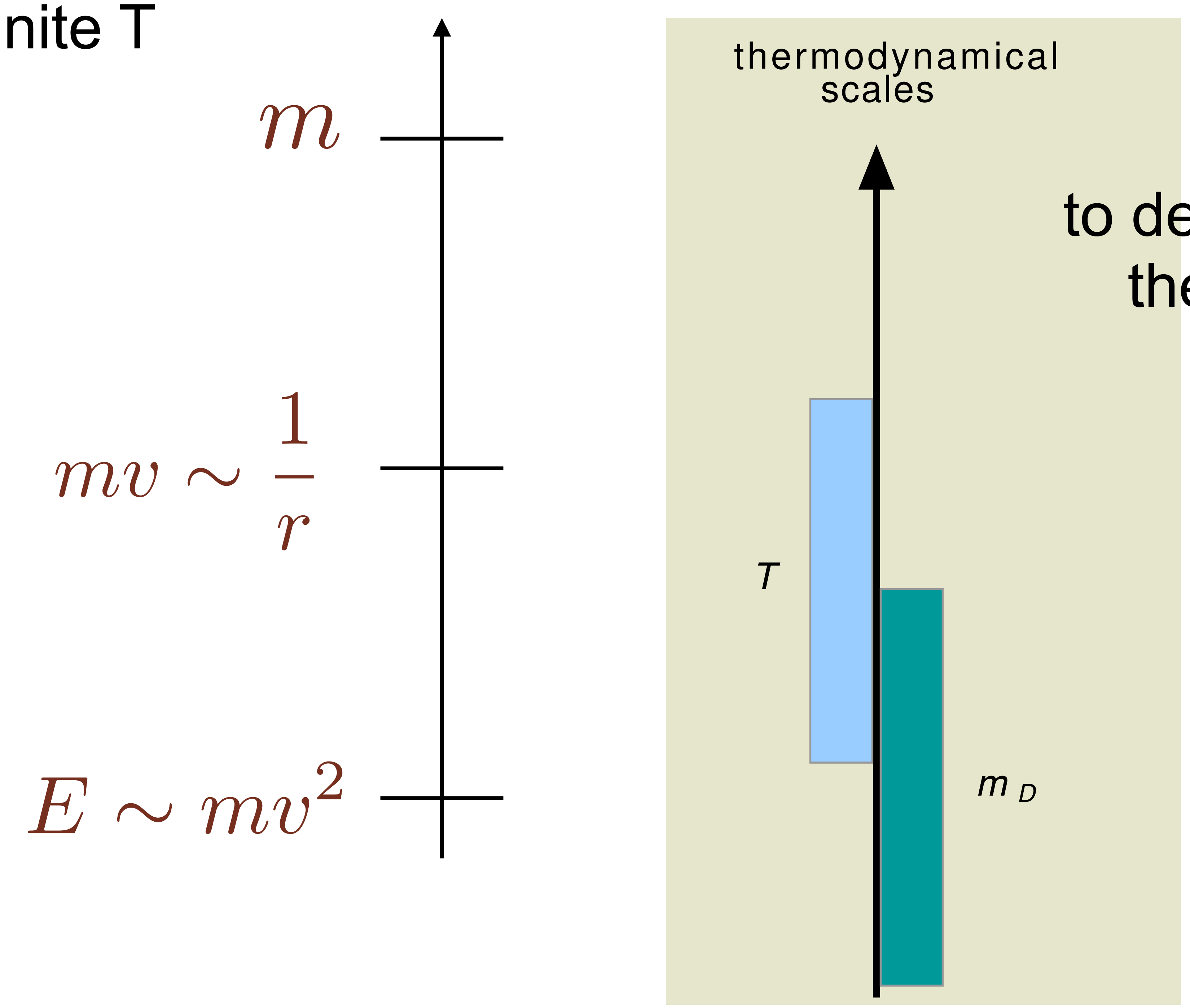
quarkonium scales

hot medium scales

Finite T



to define the potential we have to integrate out all the scales bigger than E including T and m_d

if T is of order E or less will give contribution to the energy and not to the potential

$$m \gg \Lambda_{QCD}$$

Notice:

The potential V(r,T) dictates through the Schroedinger equation the real time evolution of the QQbar in the medium

The finite T potential: how to obtain it

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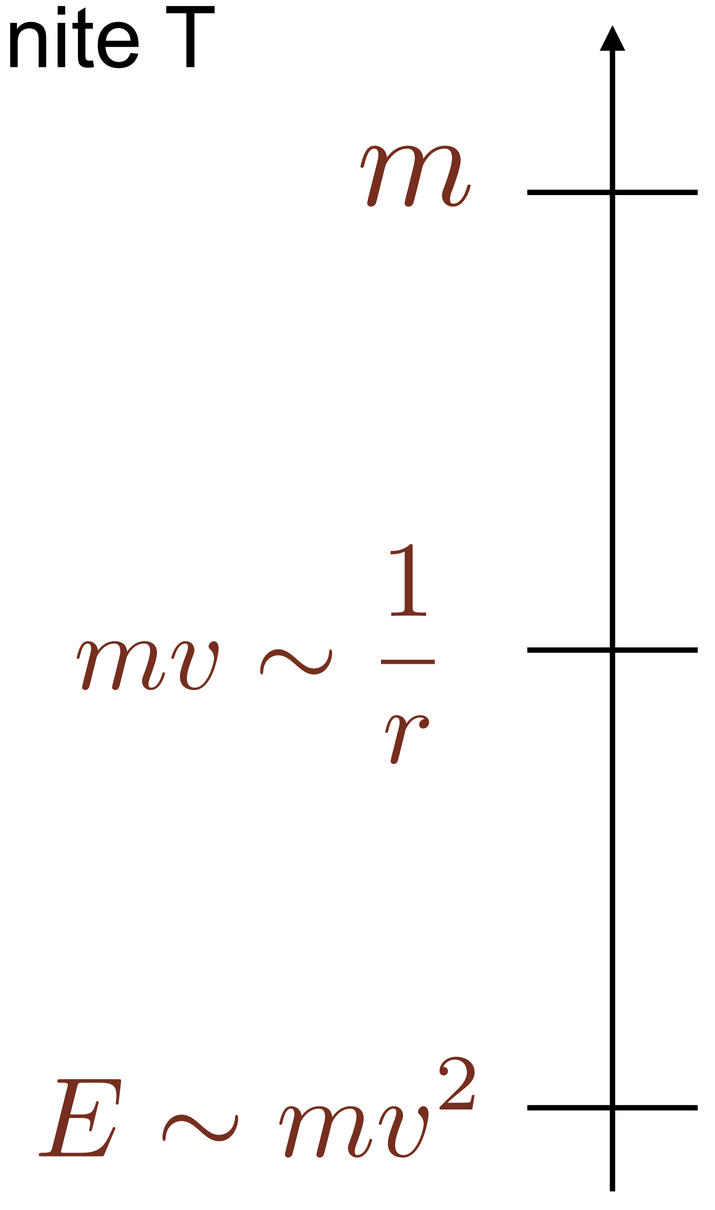
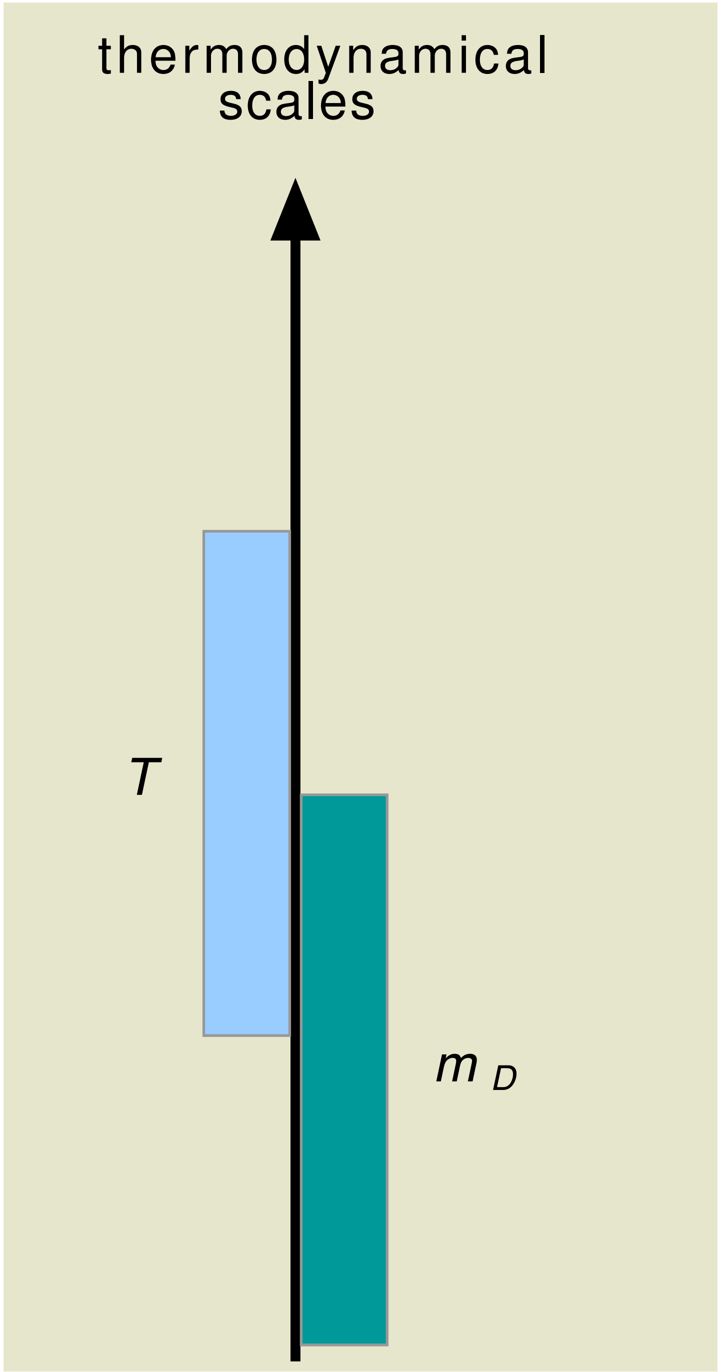
Finite T





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We assume that bound states exist for

- $T \ll m$
- $1/r \sim mv \gtrsim m_D$

We neglect smaller thermodynamical scales.

Inside these constraints we consider all the possible scales hierarchies

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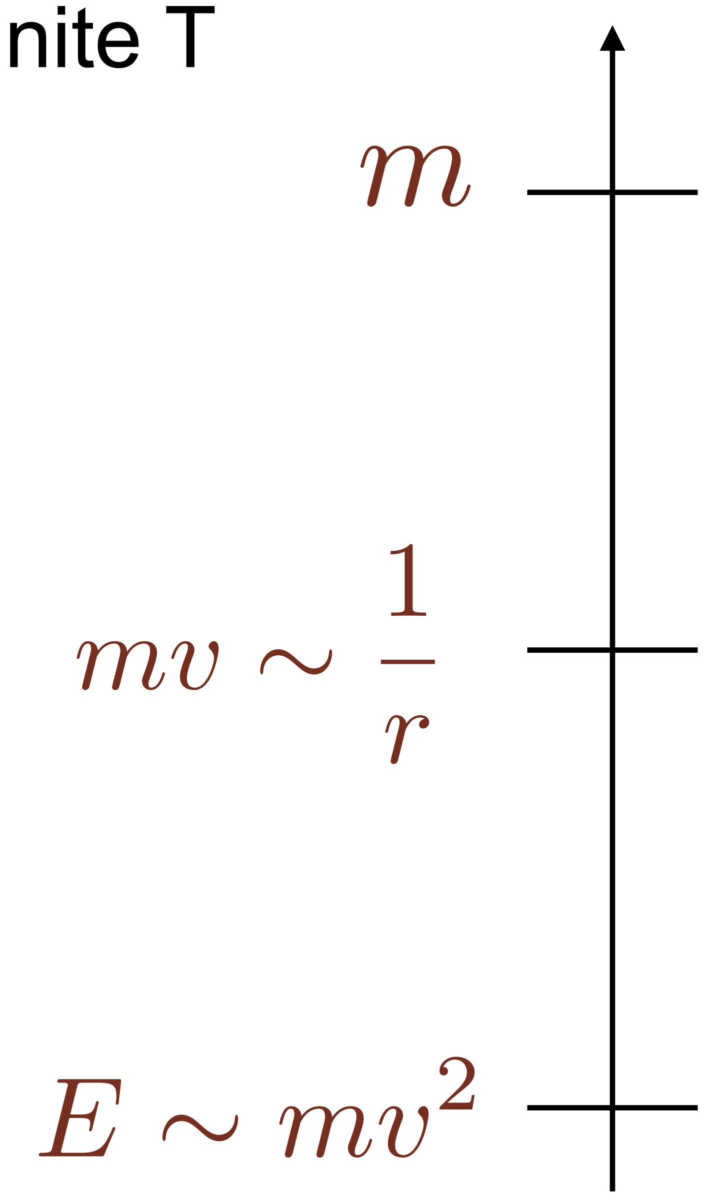

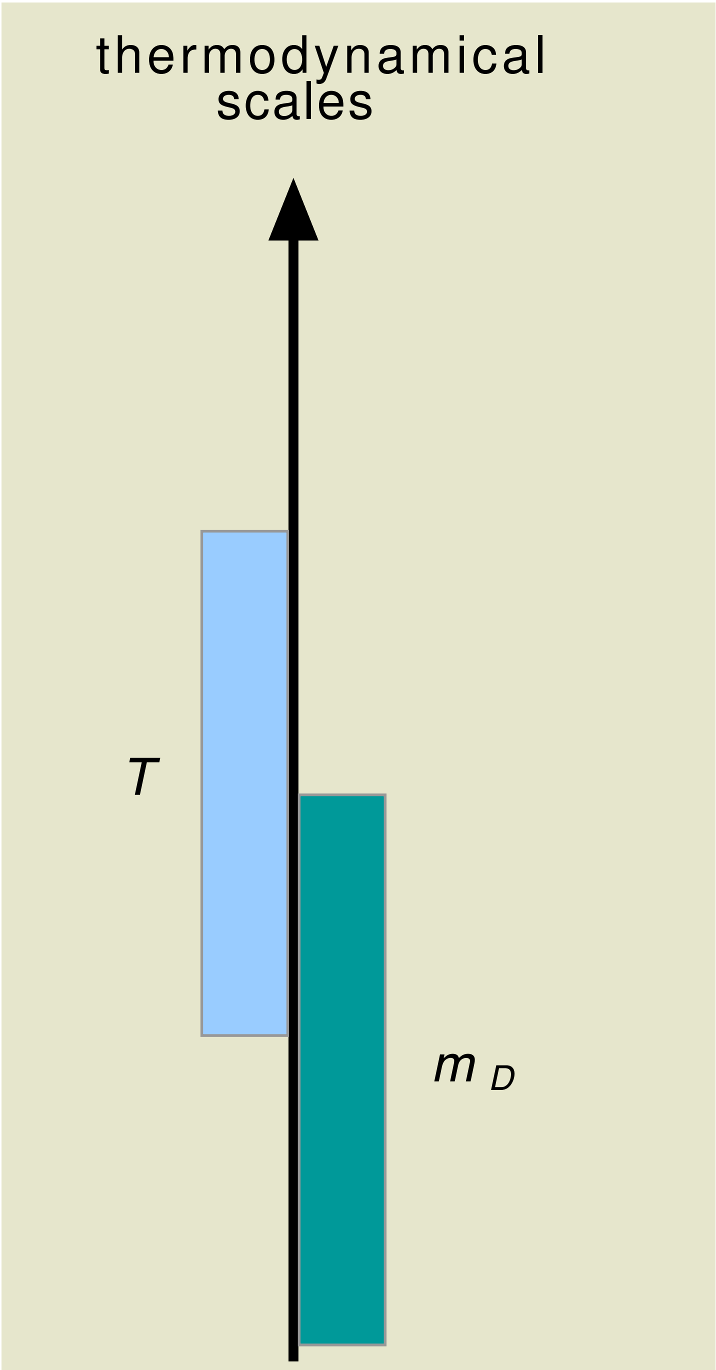

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we work in the weak coupling regime

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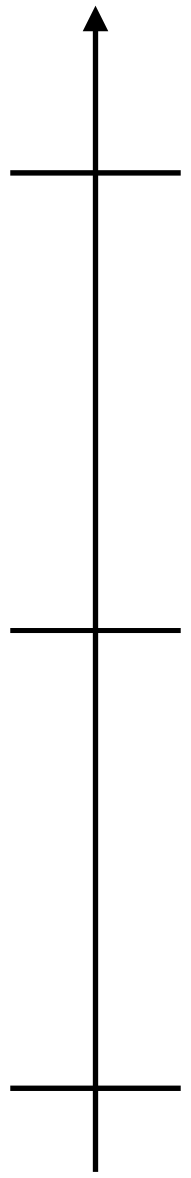
Finite T

m

$mv \sim \frac{1}{r}$

$E \sim mv^2$



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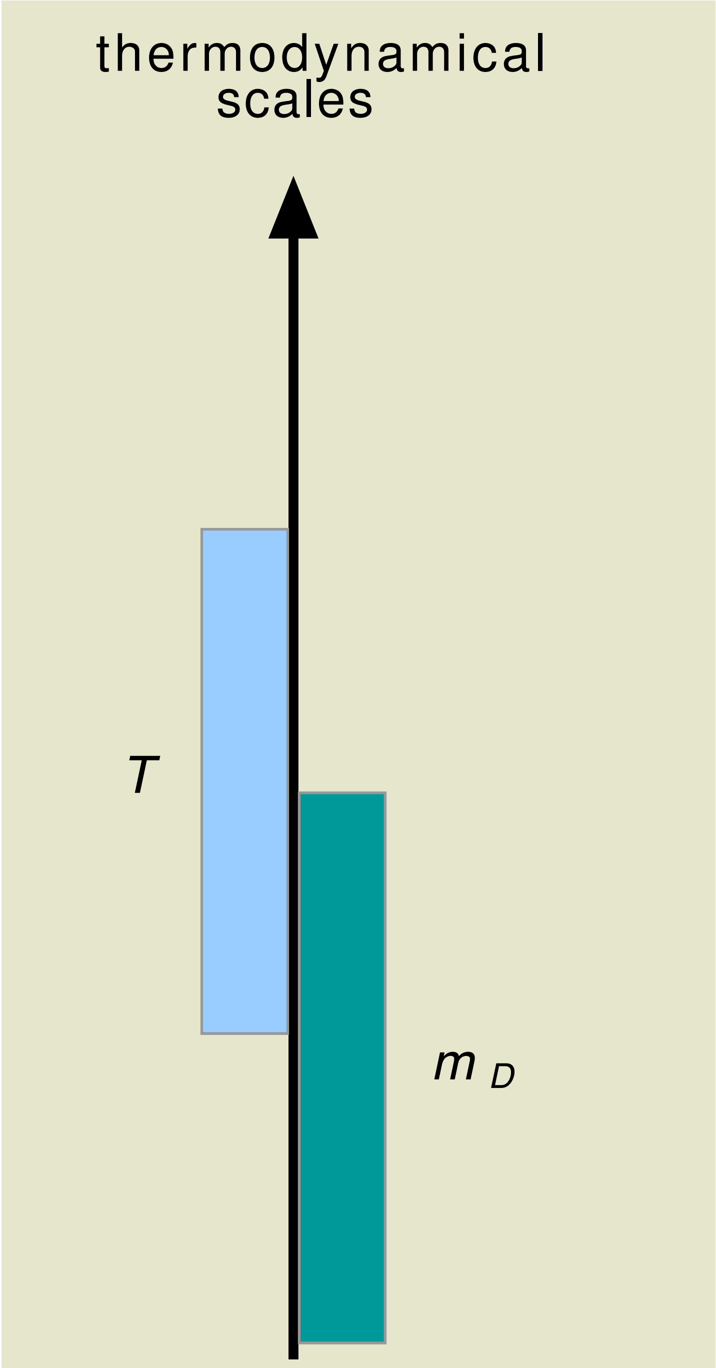

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for the nonperturbative regime -> lattice calculation of the Wilson loop

The thermal part of the potential has a real and an imaginary part

$\mathrm{Re}V_s\,(r,T)$

$\mathrm{Im}V_s\,(r,T)$

thermal width of $Q\bar{Q}$

New effect, specific of QCD
dominates for E/m_D>>1

Known from QED
dominates for m_D/E>>1

Singlet-to-octet

N.B Ghiglieri, Petreczky, Vairo 2008

Landau damping

Laine et al 07, Escobedo Soto 07

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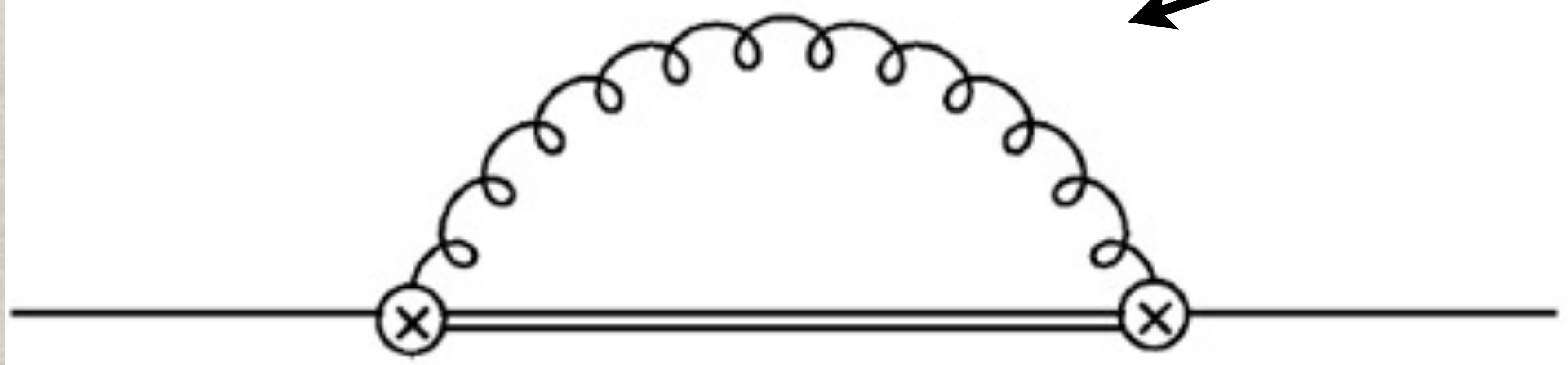

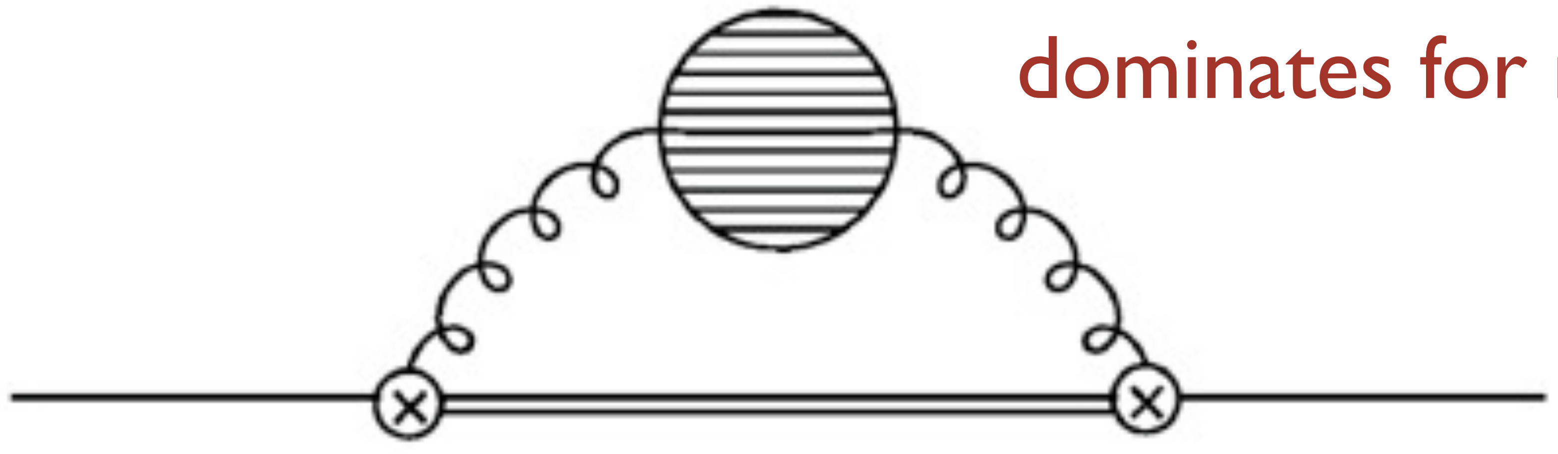

Singlet-to-octet

N.B Ghiglieri, Petreczky, Vairo 2008

(gluo dissociation)

N. B. Escobedo, Ghiglieri , Vairo 2011

Landau damping

Laine et al 07, Escobedo Soto 07

(inelastic parton scattering)

N. B. Escobedo, Ghiglieri , Vairo 2013

The singlet static potential and the static energy

you always have a real and an imaginary part

- Temperature effects can be other than screening

$T > 1/r$ and $1/r \sim m_D \sim gT$

exponential screening but $\mathrm{Im}V \gg \mathrm{Re}V$

$T > 1/r$ and $1/r > m_D \sim gT$ or $\frac{1}{r} \gg T \gg E$

no exponential screening but power-like T corrections

$T < E_{bin}$

no corrections to the potential, corrections to the energy

for the detailed form of the potentials in each regime see: N.B Ghiglieri, Petreczky, Vairo Phys.Rev. D78 (2008) 014017

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imaginary parts in the potential have subsequently been found also for a strongly coupled plasma on the lattice (A. Rothkopf et al, Petreczky, Weber..) and in strings calculations

Change in the paradigm of dissociation

- The imaginary part is bigger than the real part before the screening exp{-m_D r} sets in

->the imaginary part is responsible for QQbar dissociation

$$T \gg 1/r \gg m_D \gg V$$

- Quarkonium dissociates at a temperature such that $\mathrm{Im}\, V_s(r) \sim \mathrm{Re}\, V_s(r) \sim \alpha_s/r$:

E binding

$$\pi T_{\text{dissociation}} \sim m g^{4/3}$$

Escobedo Soto arXiv:0804.0691

Laine arXiv:0810.1112

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the EFT offers a systematic framework to do the calculations of the energy and width in a hot medium

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E binding

Escobedo Soto arXiv:0804.0691
Laine arXiv:0810.1112

- The interaction is screened when $\langle 1/r \rangle \sim m_D$, hence

$$\pi T_{\text{screening}} \sim m g \gg \pi T_{\text{dissociation}}$$

the EFT offers a systematic framework to do the calculations of the energy and width in a hot medium

The bottomonium ground state , which is a weakly coupled non-relativistic bound state: $mv \sim m\alpha_s$, $mv^2 \sim m\alpha_s^2 \gtrsim \Lambda_{QCD}$, produced in the QCD medium of heavy-ion collisions at the LHC may possibly realize the hierarchy

$$m \approx 5 \text{ GeV} > m\alpha_s \approx 1.5 \text{ GeV} > \pi T \approx 1 \text{ GeV} > m\alpha_s^2 \approx 0.5 \text{ GeV} \gtrsim m_D, \Lambda_{QCD}$$

T_dissociation in the $\Upsilon(1S)$ case is about 450 MeV.

bottomonium 1S below the melting temperature T_d

The complete mass and width up to $\mathcal{O}(m\alpha_s^5)$

$$\delta E_{1S}^{(\mathrm{thermal})} = \frac{34\pi}{27}\alpha_s^2\,T^2 a_0 + \frac{7225}{324}\frac{E_1\alpha_s^3}{\pi}\left[\ln\left(\frac{2\pi T}{E_1}\right)^2 - 2\gamma_E\right] + \frac{128E_1\alpha_s^3}{81\pi}L_{1,0} - 3a_0^2\left\{\left[\frac{6}{\pi}\zeta(3)+\frac{4\pi}{3}\right]\alpha_s\,T\,m_D^2 - \frac{8}{3}\zeta(3)\,\alpha_s^2\,T^3\right\}$$

$$\Gamma_{1S}^{(\mathrm{thermal})} = \frac{1156}{81}\alpha_s^3 T + \frac{7225}{162}E_1\alpha_s^3 + \frac{32}{9}\alpha_s\,Tm_D^2\,a_0^2\,I_{1,0} - \left[\frac{4}{3}\alpha_s T m_D^2\left(\ln\frac{E_1^2}{T^2} + 2\gamma_E - 3 - \ln 4 - 2\frac{\zeta'(2)}{\zeta(2)}\right) + \frac{32\pi}{3}\ln 2\,\alpha_s^2\,T^3\right]a_0^2$$

where $E_1 = -\frac{4m\alpha_s^2}{9}$, $a_0 = \frac{3}{2m\alpha_s}$ and $L_{1,0}$ (similar $I_{1,0}$) is the Bethe logarithm.

- Brambilla Escobedo Ghiglieri Soto Vairo JHEP 1009 (2010) 038

first systematic calculation of the thermal contributions to quarkonium mass and width

Consistent with lattice calculations of spectral functions

Aarts Allton Kim Lombardo Oktay Ryan Sinclair Skullerud JHEP 1111 (2011) 103

To describe quarkonium in QGP we should account for: screening,
dissociation effects (singlet to octet, inelastic parton scattering),
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—->The non equilibrium evolution of quarkonium in QGP

Using pNRQCD and Open Quantum Systems (OQS) we could use bottomonium as a probe of a strongly coupled QGP and obtain master equations for the singlet and octet matrix density evolution

The equations are quantum, nonabelian and conserve the number of heavy quarks

Quarkonium in the fireball

- After the heavy-ion collisions, heavy quark-antiquarks propagate freely up to 0.6 fm.
- From 0.6 fm to the freeze-out time t_F they propagate in the medium.
- We assume the medium infinite, homogeneous and isotropic.
- We assume the heavy quarks comoving with the medium.
- We assume the medium to be locally in thermal equilibrium,

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Quarkonium as a small radius probe: bottomonium

Hierarchy of scales:

$$m \gg 1/r \sim m\alpha_s \gg T \sim gT \gg E$$

Coulombic bound state:

quark-antiquark color singlet Hamiltonian $$h_s = \frac{\mathbf{p}^2}{m} - \frac{4}{3}\frac{\alpha_s}{r}$$

quark-antiquark color octet Hamiltonian $$h_o = \frac{\mathbf{p}^2}{m} + \frac{1}{6}\frac{\alpha_s}{r}$$

The octet potential describes an unbound quark-antiquark pair.

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Open Quantum system

- Subsystem: heavy quarks/quarkonium
- Environment: quark gluon plasma

N.B., J. Soto, M. Escobedo, A. Vairo 2016, 2018 (1612.07248, 1711.04515)

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We may define a density matrix in pNRQCD for the heavy quark-antiquark pair in a singlet and octet configuration:

$$\langle \mathbf{r}', \mathbf{R}' | \rho_s(t';t) | \mathbf{r}, \mathbf{R} \rangle \equiv \mathrm{Tr}\{\rho_{\mathrm{full}}(t_0)\, S^\dagger(t, \mathbf{r}, \mathbf{R}) S(t', \mathbf{r}', \mathbf{R}')\}$$

$$\langle \mathbf{r}', \mathbf{R}' | \rho_o(t';t) | \mathbf{r}, \mathbf{R} \rangle \frac{\delta^{ab}}{8} \equiv \mathrm{Tr}\{\rho_{\mathrm{full}}(t_0)\, O^{a\dagger}(t, \mathbf{r}, \mathbf{R}) O^b(t', \mathbf{r}', \mathbf{R}')\}$$

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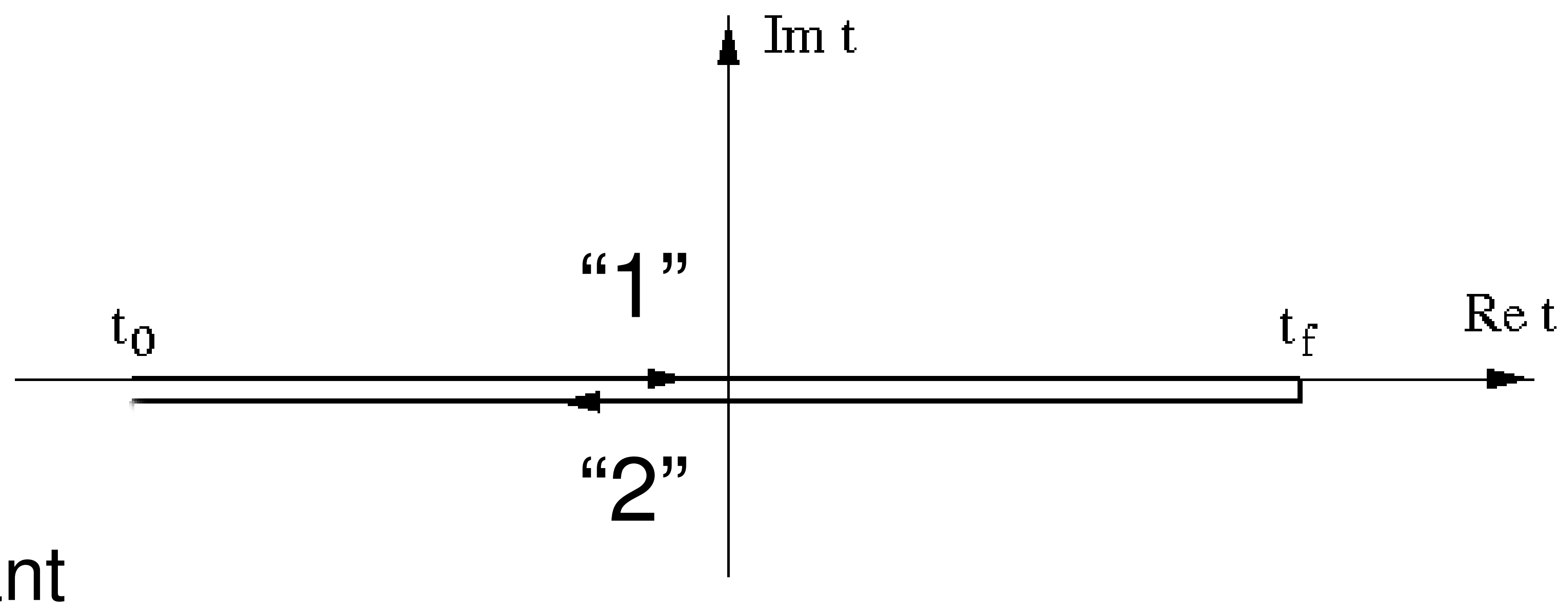
The system is in non-equilibrium because through interaction with the environment (quark gluon plasma) singlet and octet quark-antiquark states continuously transform in each other although the number of heavy quarks is conserved: $\mathrm{Tr}\{\rho_s\} + \mathrm{Tr}\{\rho_o\} = 1$.

Closed time path formalism

In the closed-time path formalism we can represent the density matrices as 12 propagators on a closed time path:

$$\langle \mathbf{r}', \mathbf{R}' | \rho_s(t';t) | \mathbf{r}, \mathbf{R} \rangle = \langle S_1(t', \mathbf{r}', \mathbf{R}') S_2^\dagger(t, \mathbf{r}, \mathbf{R}) \rangle$$

$$\langle \mathbf{r}', \mathbf{R}' | \rho_o(t';t) | \mathbf{r}, \mathbf{R} \rangle \frac{\delta^{ab}}{8} = \langle O_1^b(t', \mathbf{r}', \mathbf{R}') O_2^{a\dagger}(t, \mathbf{r}, \mathbf{R}) \rangle$$



Differently from the thermal equilibrium case 12 propagators are relevant (in thermal equilibrium they are exponentially suppressed).

12 propagators are not time ordered, while 11 and 22 operators select the forward time direction $\propto \theta(t - t')$, $\theta(t' - t)$.

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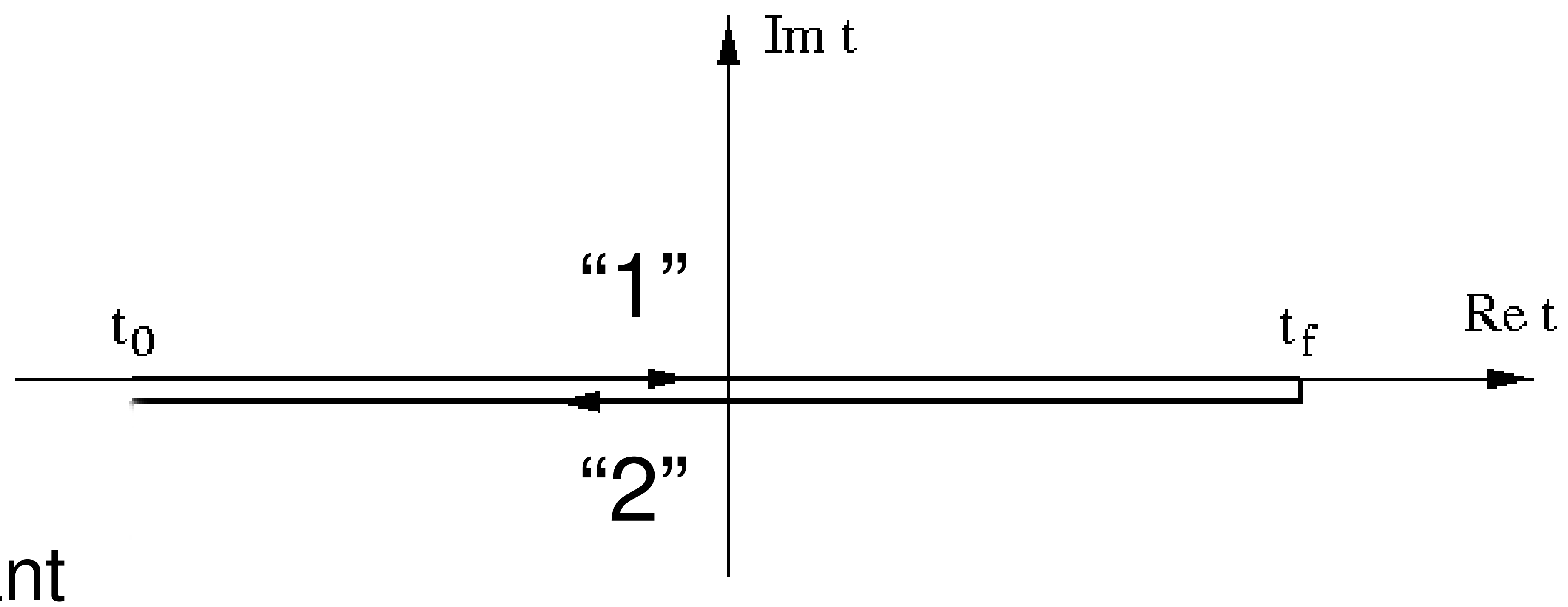

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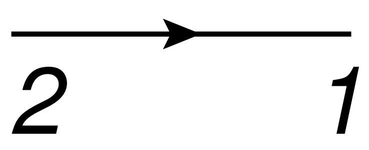
Expansions

- The density of heavy quarks is much smaller than the one of light quarks: we expand at first order in the heavy quark-antiquark density.
- We consider T much smaller than the Bohr radius of the quarkonium: we expand up to order r^2 in the multipole expansion.

LO and NLO evolution

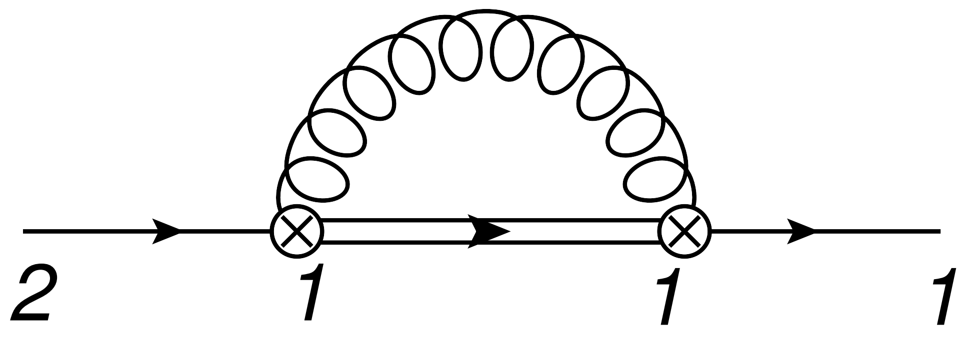
For $t > t_0$, the LO singlet density matrix is



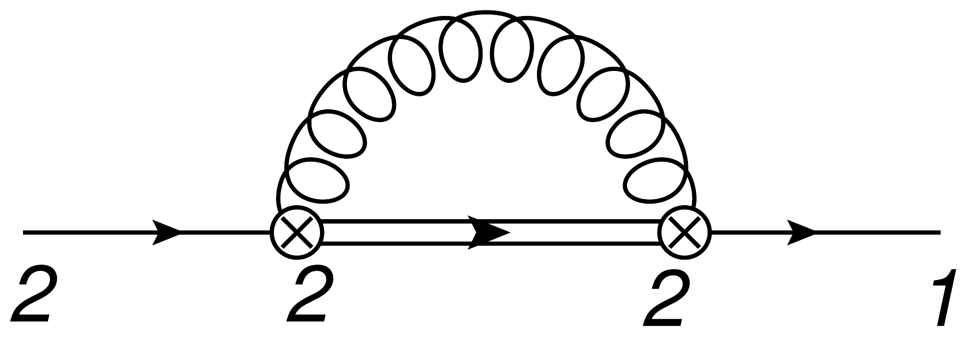
$$= e^{-ih_s(t-t_0)}\rho_s(t_0;t_0)e^{ih_s(t-t_0)}$$

($h_{s,o}$ = singlet/octet pNRQCD Hamiltonian = $V_{s,o}$ in the static limit)

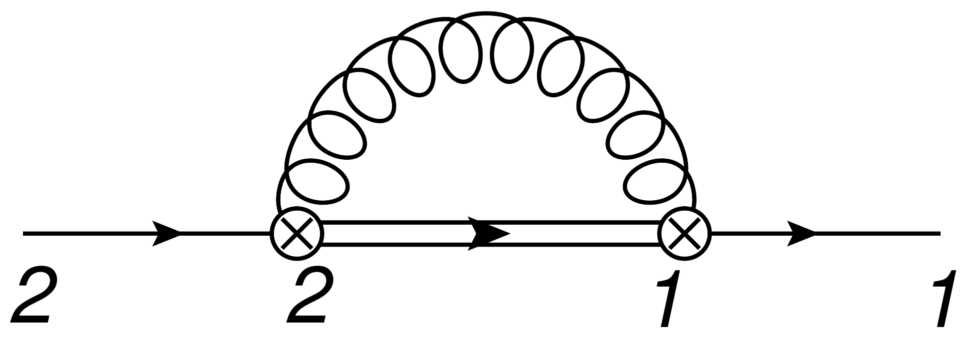
and the NLO (in the multipole expansion) corrections are at first order in the density



$$= -\int_{t_0}^{t} dt_1\, e^{-ih_s(t-t_1)}\,\Sigma_s(t_1)\, e^{-ih_s(t_1-t_0)}\,\rho_s(t_0;t_0)\, e^{ih_s(t-t_0)}$$



$$= -\int_{t_0}^{t} dt_1\, e^{-ih_s(t-t_0)}\,\rho_s(t_0;t_0)\, e^{ih_s(t_1-t_0)}\,\Sigma_s^\dagger(t_1)\, e^{ih_s(t-t_1)}$$



$$= \int_{t_0}^{t} dt_1\, e^{-ih_s(t-t_1)}\,\Xi_{so}(\rho_o(t_0;t_0),t_1)\, e^{ih_s(t-t_1)}$$

and similar for the octet

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

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$$\Xi_{so}(\rho_o(t_0;t_0),t) = \frac{g^2}{2N_c(N_c^2-1)}\int_{t_0}^{t} dt_2\, \Big[r^i\, e^{-ih_o(t-t_0)}\, \rho_o(t_0;t_0)\, e^{ih_o(t_2-t_0)} \times r^j\, e^{ih_s(t-t_2)}\, \langle E^{a,j}(t_2,\mathbf{0})E^{a,i}(t,\mathbf{0})\rangle + \text{H.c.}\Big]$$

A Wilson line in the adjoint representation is understood in the chromoelectric correlators.

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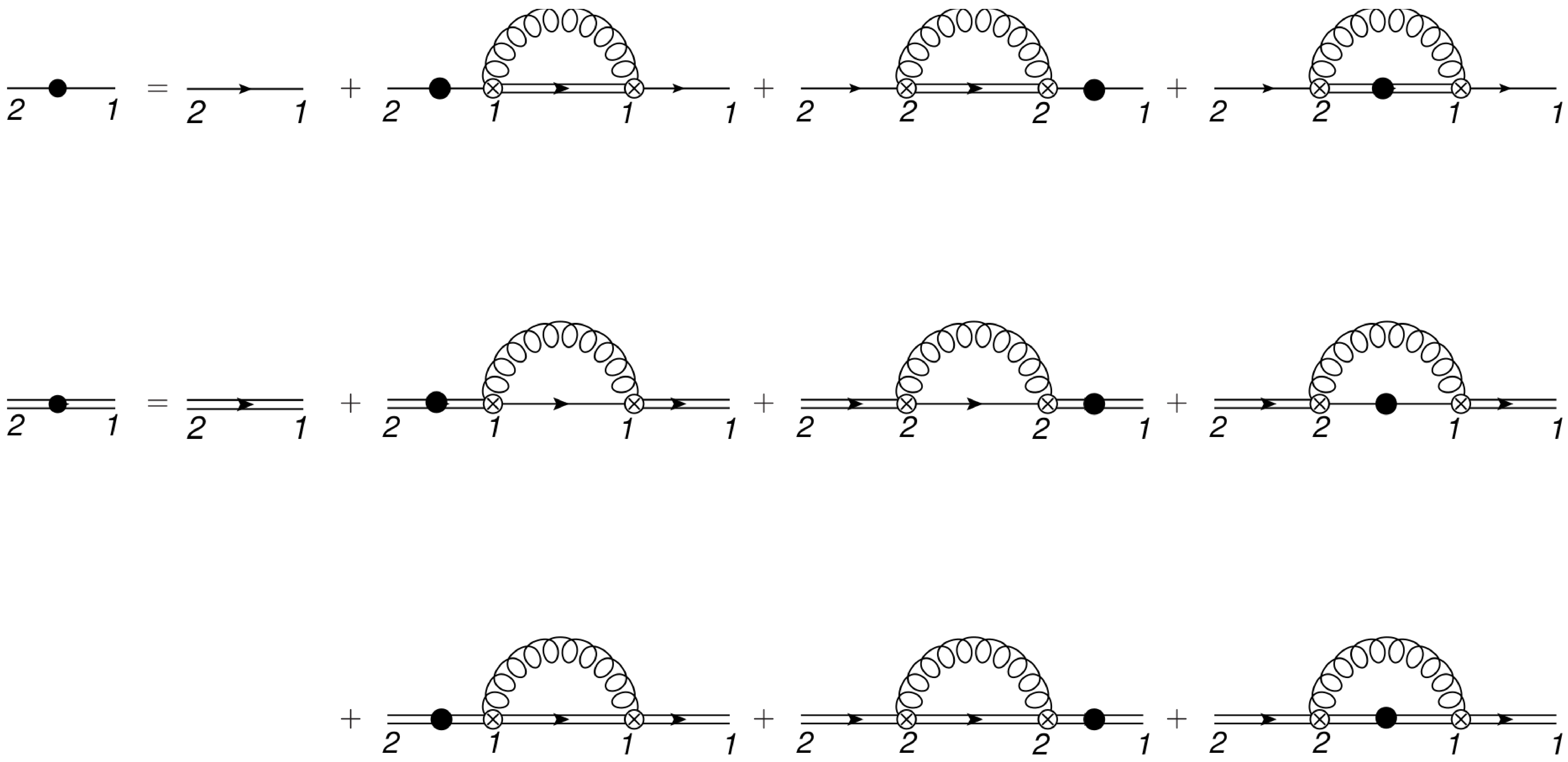
Diagrams and resummation

Resumming $(t-t_0)\times$ self-energy contributions à la Schwinger–Dyson ...



Singlet and octet density matrix evolution equations

... and differentiating over time we obtain the coupled evolution equations:

$$\frac{d\rho_s(t;t)}{dt} = -i[h_s, \rho_s(t;t)] - \Sigma_s(t)\rho_s(t;t) - \rho_s(t;t)\Sigma_s^\dagger(t) + \Xi_{so}(\rho_o(t;t), t)$$

$$\frac{d\rho_o(t;t)}{dt} = -i[h_o, \rho_o(t;t)] - \Sigma_o(t)\rho_o(t;t) - \rho_o(t;t)\Sigma_o^\dagger(t) + \Xi_{os}(\rho_s(t;t), t) + \Xi_{oo}(\rho_o(t;t), t)$$

The evolution equations are Markovian.

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The evolution equations are Markovian.

Interpretation

- The self energies Σ_s and Σ_o provide the in-medium induced mass shifts, $\delta m_{s,o}$, and widths, $\Gamma_{s,o}$, for the color-singlet and color-octet heavy quark-antiquark systems respectively:

$$-i\Sigma_{s,o}(t) + i\Sigma^\dagger_{s,o}(t) = 2\,\mathrm{Re}\,(-i\Sigma_{s,o}(t)) = 2\delta m_{s,o}(t)$$

$$\Sigma_{s,o}(t) + \Sigma^\dagger_{s,o}(t) = -2\,\mathrm{Im}\,(-i\Sigma_{s,o}(t)) = \Gamma_{s,o}(t)$$

- Ξ_{so} accounts for the production of singlets through the decay of octets, and Ξ_{os} and Ξ_{oo} account for the production of octets through the decays of singlets and octets respectively. There are two octet production mechanisms/octet chromoelectric dipole vertices in the pNRQCD Lagrangian.

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The conservation of the trace of the sum of the densities, i.e., the conservation of the number of heavy quarks, follows from

$$\begin{aligned}
\mathrm{Tr}\left\{\rho_s(t;t)\left(\Sigma_s(t)+\Sigma_s^\dagger(t)\right)\right\} &= \mathrm{Tr}\left\{\Xi_{os}(\rho_s(t;t),t)\right\} \\
\mathrm{Tr}\left\{\rho_o(t;t)\left(\Sigma_o(t)+\Sigma_o^\dagger(t)\right)\right\} &= \mathrm{Tr}\left\{\Xi_{so}(\rho_o(t;t),t)+\Xi_{oo}(\rho_o(t;t),t)\right\}
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Time scales

Environment correlation time: $\tau_E \sim \frac{1}{T}$

System intrinsic time scale: $\tau_S \sim \frac{1}{E}$

a_0=r

System relaxation time: $\tau_R \sim \frac{1}{\text{self-energy}} \sim \frac{1}{\alpha_s a_0^2 \Lambda^3}$

$a_0 =$ Bohr radius, $\Lambda = T, E$

- Because we have assumed $1/a_0 \gg \Lambda$, it follows $\tau_R \gg \tau_S, \tau_E$ which, after resummation, qualifies the system as Markovian.
  - Akamatsu PRD 91 (2015) 056002
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From the evolution equations to the Linblad equations

Under the Markovian

$$\tau_R \gg \tau_S, \tau_E \quad \text{or} \quad \frac{1}{a_0} \gg E, T$$

and quantum Brownian motion condition

$$\tau_S \gg \tau_E \quad \text{or} \quad T \gg E$$

at least at LO in E/T the evolution equations can be written in the Lindblad form.

nonequilibrium evolution of quarkonium: Linblad equations

If $E \ll T \sim m_D$ the Lindblad equation for a strongly coupled plasma reads

$$\rho = \begin{pmatrix} \rho_s & 0 \\ 0 & \rho_o \end{pmatrix}$$

$$\frac{d\rho}{dt} = -i[H,\rho] + \sum_i \left(C_i \rho C_i^\dagger - \frac{1}{2}\{C_i^\dagger C_i, \rho\}\right)$$

C collapse operators

$$H = \begin{pmatrix} h_s & 0 \\ 0 & h_o \end{pmatrix} + \frac{r^2}{2}\gamma(t) \begin{pmatrix} 1 & 0 \\ 0 & \frac{7}{16} \end{pmatrix},$$

$$C_i^0 = \sqrt{\frac{\kappa(t)}{8}}\, r^i \begin{pmatrix} 0 & 1 \\ \sqrt{8} & 0 \end{pmatrix}, \qquad C_i^1 = \sqrt{\frac{5\kappa(t)}{16}}\, r^i \begin{pmatrix} 0 & 0 \\ 0 & 1 \end{pmatrix}$$

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the sQGP is characterised by two nonperturbative parameters (transport coefficients) kappa and gamma that must be calculated on the lattice

κ is the heavy-quark momentum diffusion coefficient:

$$\kappa = \frac{g^2}{18}\,\mathrm{Re}\int_{-\infty}^{+\infty} ds\,\langle \mathrm{T}\, E^{a,i}(s,\mathbf{0})\,\phi^{ab}(s,0)\,E^{b,i}(0,\mathbf{0})\rangle$$

$$\gamma = \frac{g^2}{18}\,\mathrm{Im}\int_{-\infty}^{+\infty} ds\,\langle \mathrm{T}\, E^{a,i}(s,\mathbf{0})\,\phi^{ab}(s,0)\,E^{b,i}(0,\mathbf{0})\rangle$$

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the EFT allows to use lattice QCD equilibrium calculation to study the non equilibrium evolution! EFT is intermediate layer to non equilibrium

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on two transport coefficients kappa and gamma that inside
pNRQCD acquire a field theoretical definition
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How to calculate these nonperturbative
transport coefficients?

use lattice QCD

The heavy quark diffusion coefficient

Langevin dynamics of the heavy quark in the med

$$\frac{dp_i}{dt} = -\eta_D p_i + \xi_i(t)$$

$$\eta_D = \frac{\kappa}{2MT}$$

$$\langle \xi(t)\xi(t') \rangle = \kappa\delta(t-t')$$

$$< x^2(t) >= 6Dt$$

$$D = \frac{2T^2}{\kappa}$$

D in real space, related to κ in momentum space

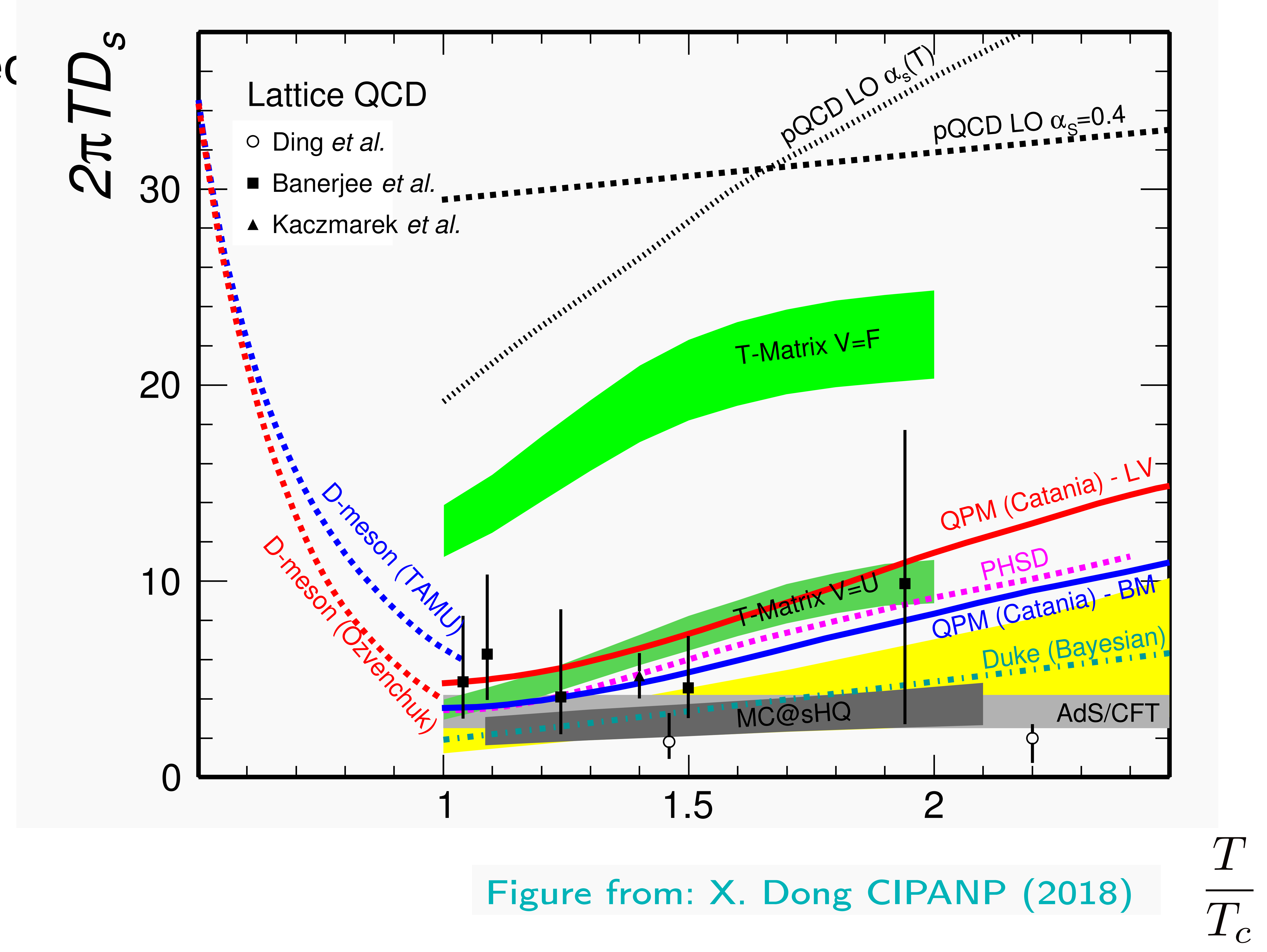

Figure from: X. Dong CIPANP (2018)

The heavy quark diffusion coefficient

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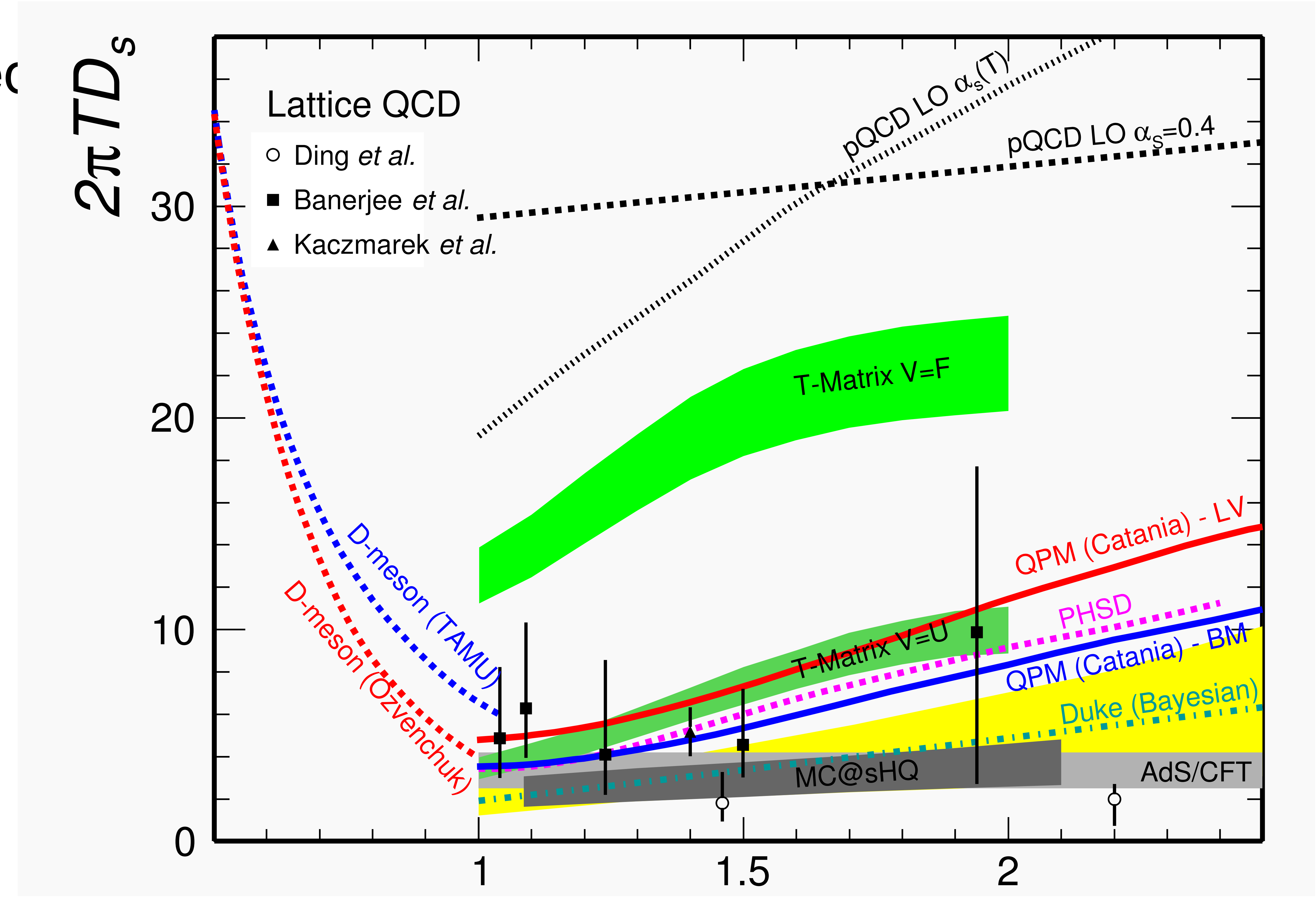
$$\eta_D = \frac{\kappa}{2MT}$$

$$D = \frac{2T^2}{\kappa}$$

$$< x^2(t) >= 6Dt$$



X. Dong CIPANP (2018)

$$\frac{T}{T_c}$$

in the limit in which the mass M of the heavy quark is the biggest scale one can integrate it out non relativistic effective field theory and from the current current correlator obtain

$$\kappa = \frac{g^2}{18}\,\mathrm{Re}\int_{-\infty}^{+\infty} ds\,\langle\, \mathrm{T}\, E^{a,i}(s,\mathbf{0})\,\phi^{ab}(s,0)\,E^{b,i}(0,\mathbf{0})\rangle$$

which is the same transport coefficient kappa that we found studying the non equilibrium evolution of quarkonium in the QGP!

1903.08063

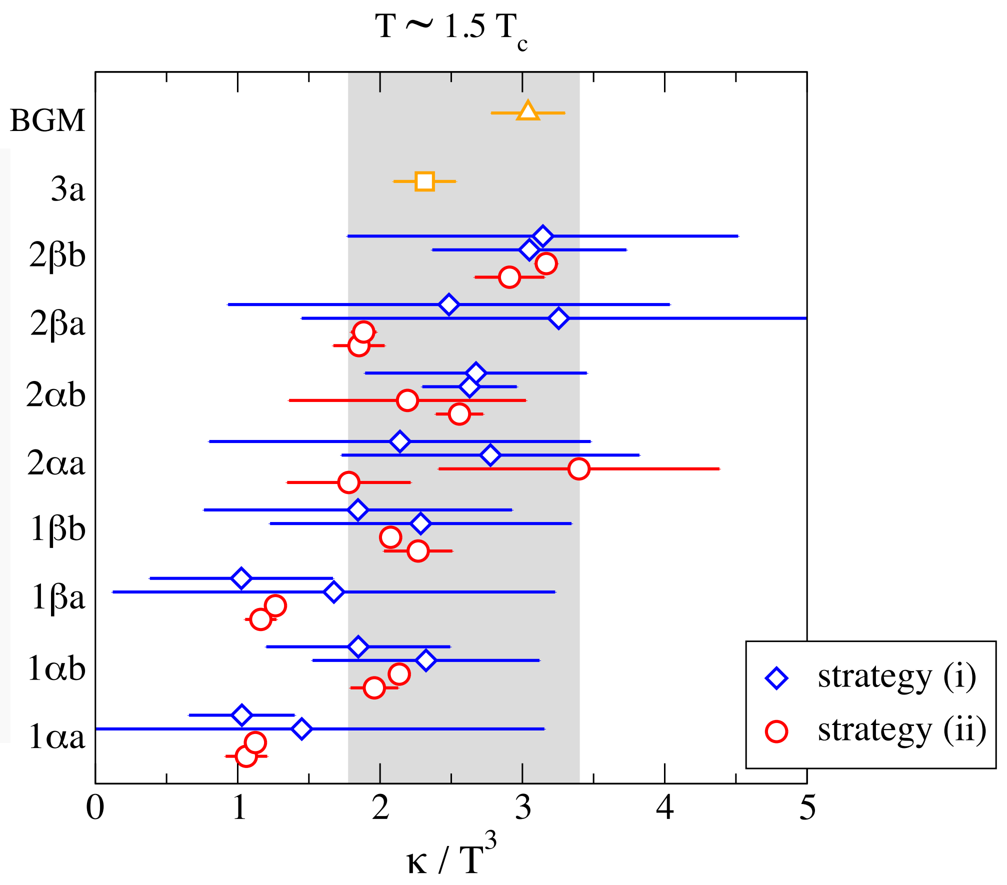
this object was already studied on quenched lattice

Meyer NJP13 (2011),

Ding *et.al.*JPG38 (2011),

Banarjee *et.al.* PRD85 (2012),

Francis *et.al.* PRD92 (2015)



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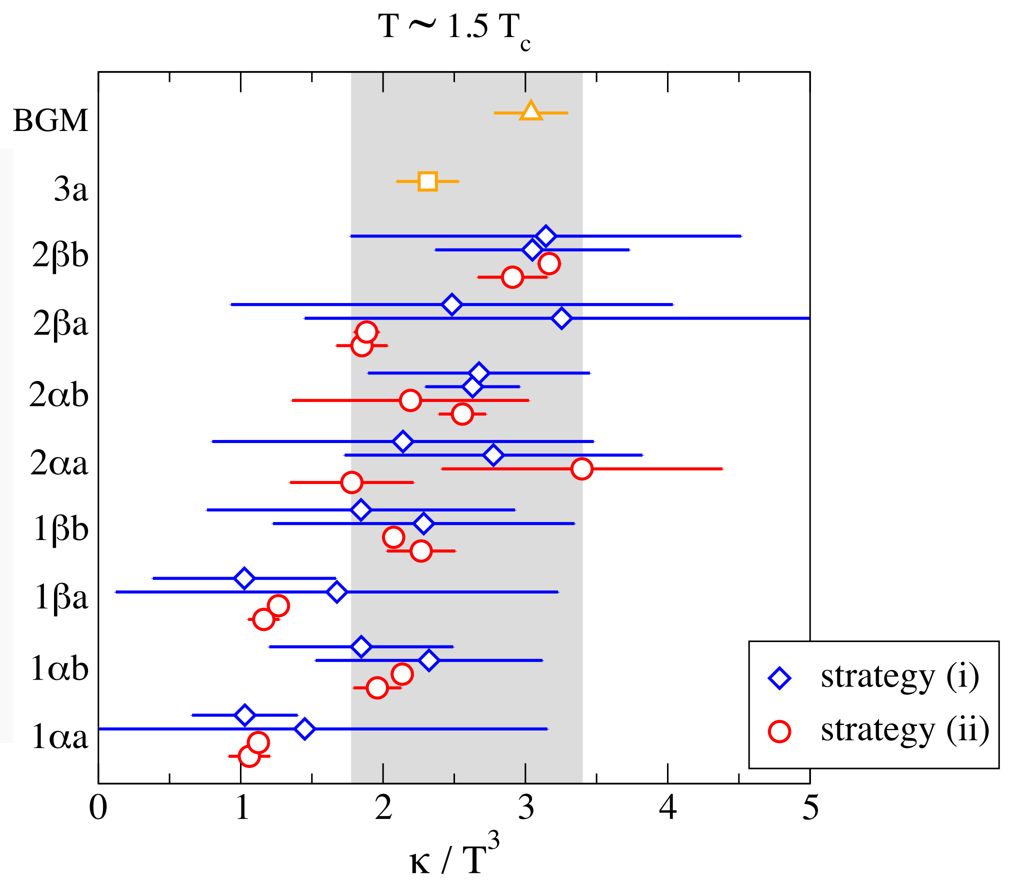

$$1.91 < \frac{\kappa}{T^3} < 5.4 \text{ for } T = 1.1\,T_c\,,$$

$$1.31 < \frac{\kappa}{T^3} < 3.64 \text{ for } T = 1.5\,T_c\,,$$

$$0.63 < \frac{\kappa}{T^3} < 2.20 \text{ for } T = 3\,T_c\,,$$

$$0.43 < \frac{\kappa}{T^3} < 1.05 \text{ for } T = 6\,T_c\,,$$

$$0 < \frac{\kappa}{T^3} < 0.72 \text{ for } T = 10\,T_c\,,$$

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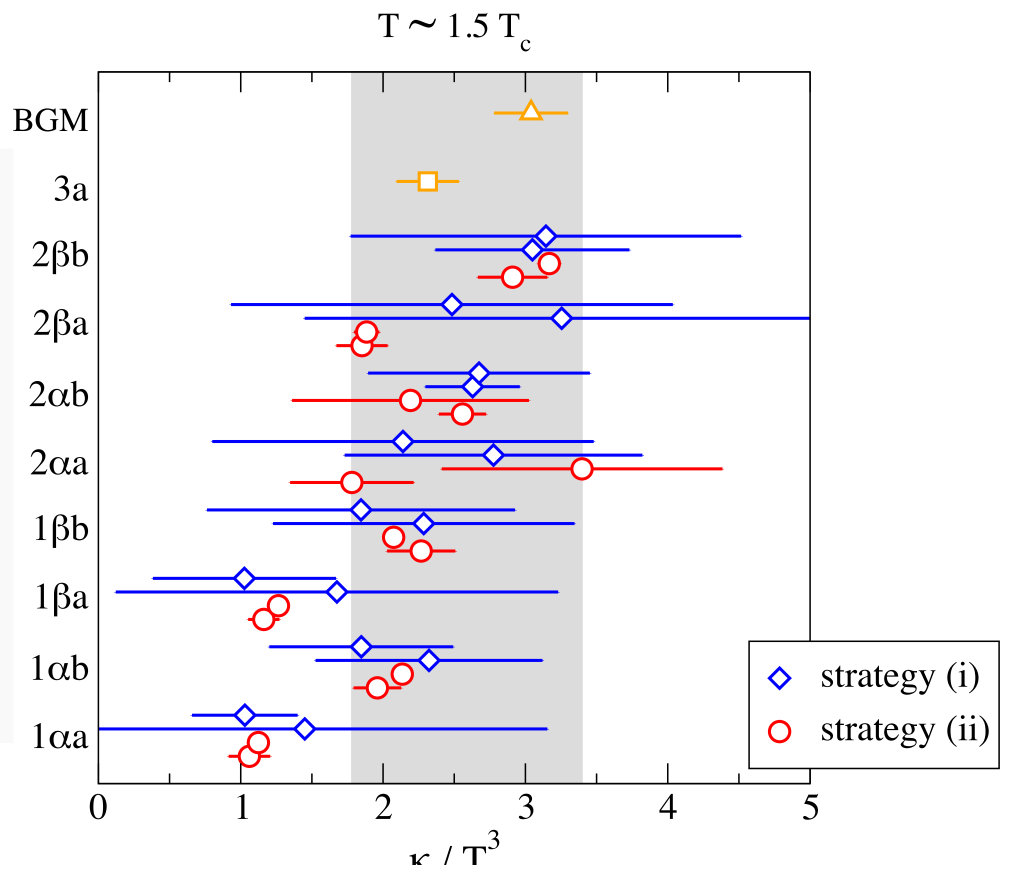
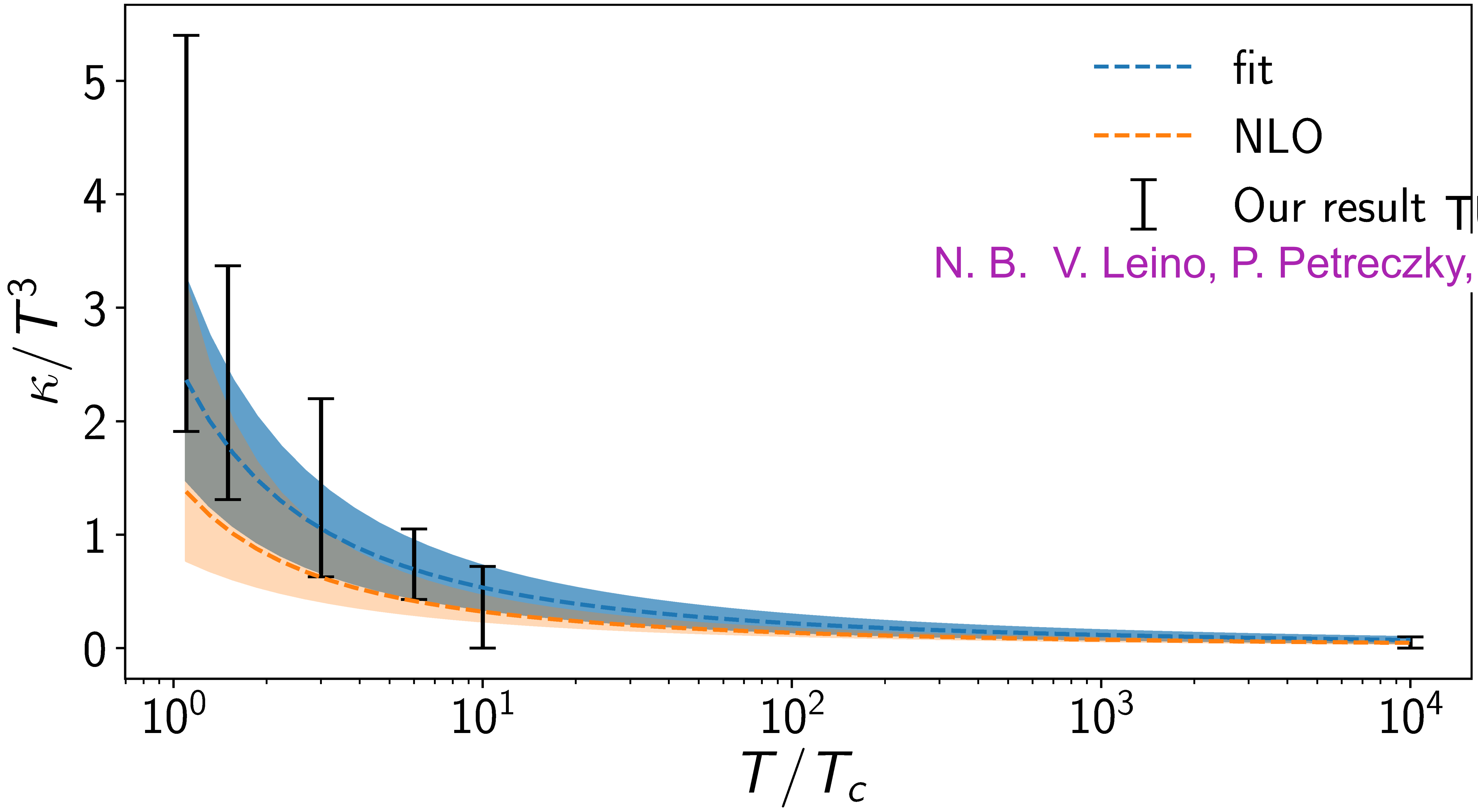


in TUMQCD we studied kappa on quenched latticed with the multilevel algorithm

in a window of T never attempted before

-> we get the T dependence of kappa



TUMQCD

N. B. V. Leino, P. Petreczky, A. Vairo 2020

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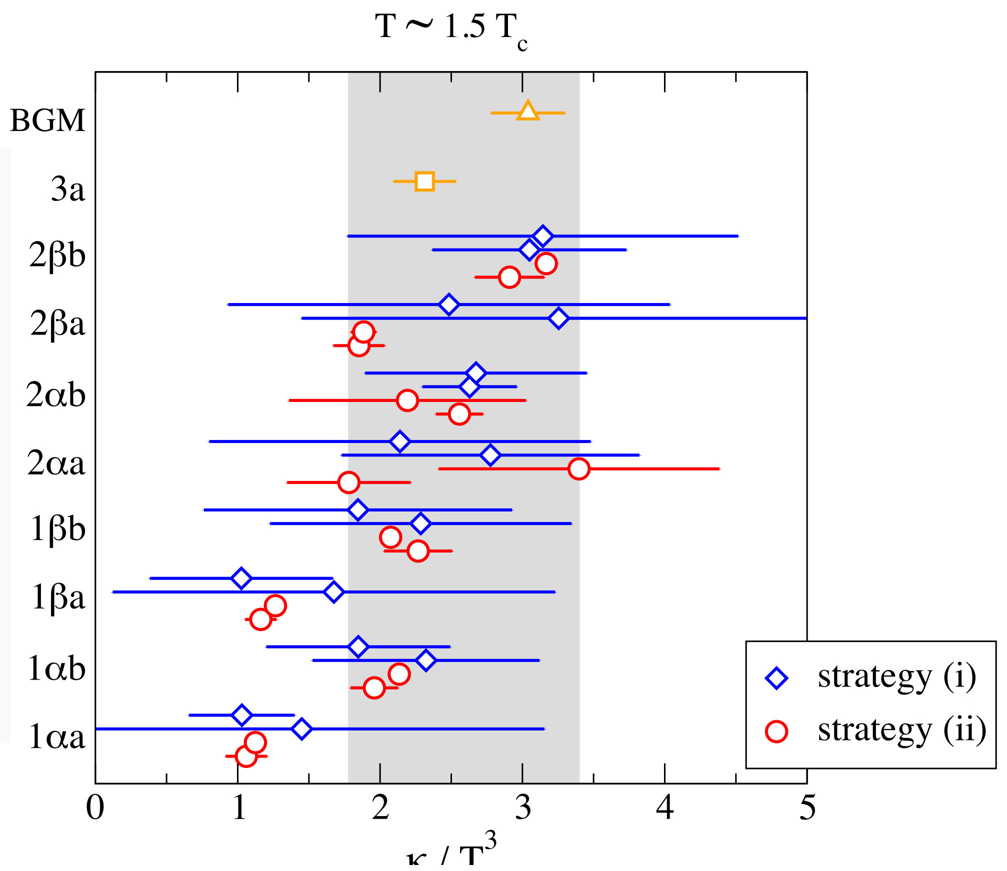

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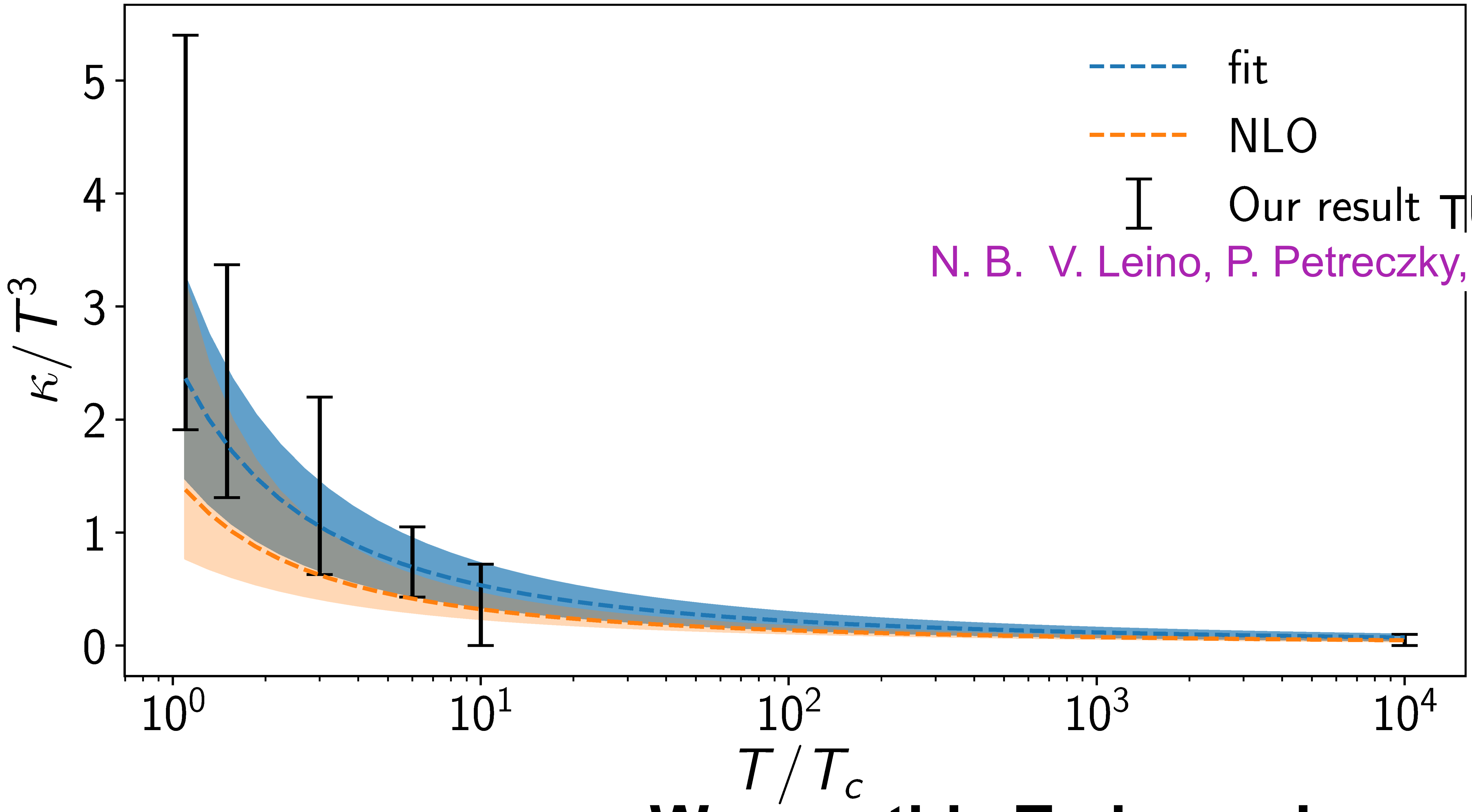

TUMQCD

N. B. V. Leino, P. Petreczky, A. Vairo 2020

We use this T dependence of kappa in our Linblad equation

within the errors the lattice results are compatible with the next-to-leading order perturbative results

Use the EFT to relate kappa (and gamma) to observables: quarkonium thermal mass shift and thermal widths

N.B., M. Escobedo, A. Vairo, P. vander Griend Phys.Rev. D100 (2019) no.5, 054025

kappa is related to the thermal decay width of quarkonium

in the hierarchy $\frac{1}{r} \gg T \gg E$ pNRQCD predicts for 1S states

$$\Gamma(1S) = -2\langle \mathrm{Im}\,(-i\Sigma_s)\rangle = 3 < r^2 > \kappa$$

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Therefore we can use unquenched lattice data on quarkonium thermal mass shift and widths to get unquenched determination of these transport coefficients

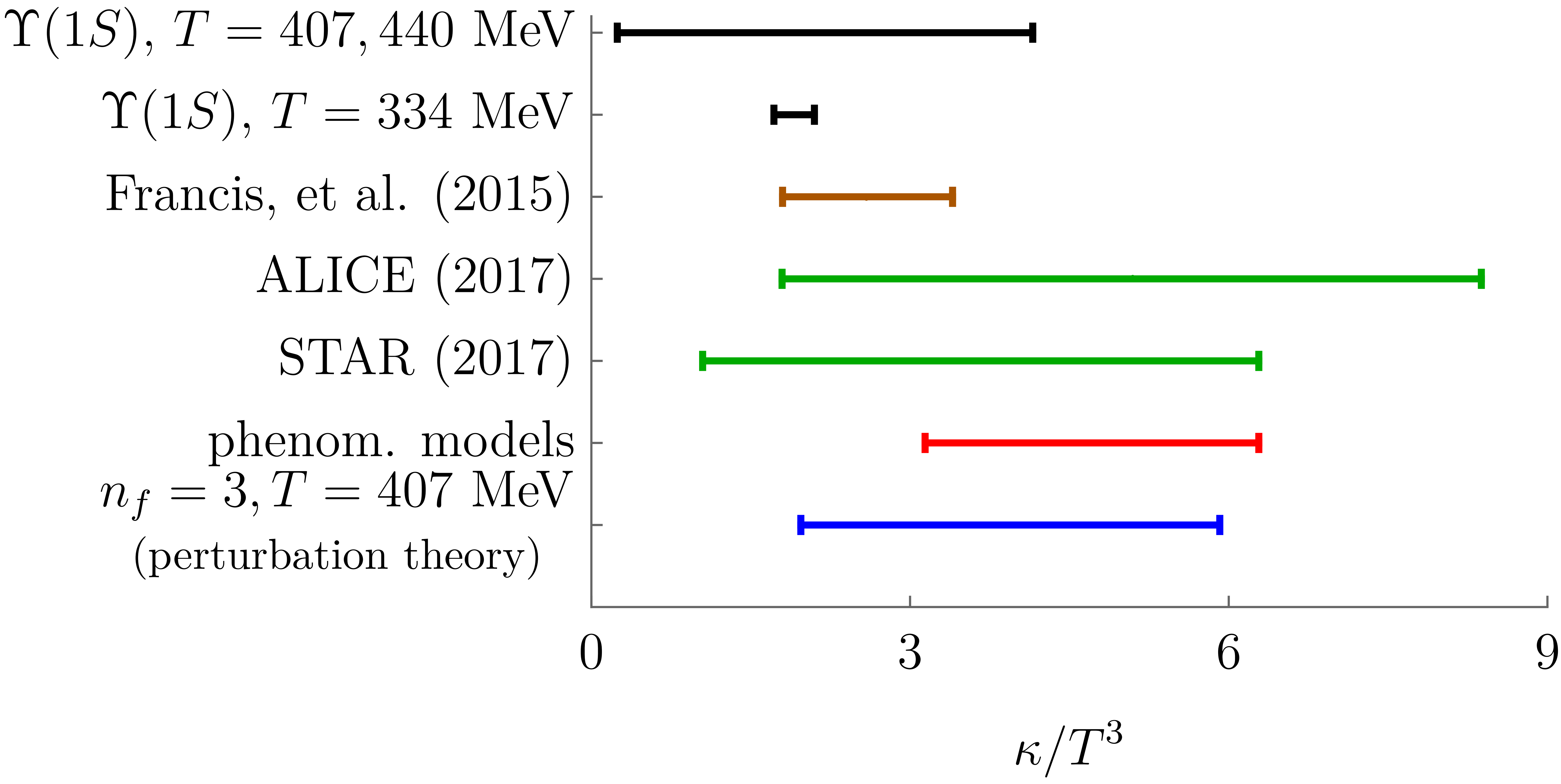
Use lattice data from Aarts, Allton, Kim, Lombardo, Oktay, Ryan, Sinclair and Skullerud (2011) and Kim, Petreczky and Rothkopf (2018). Unquenched.

and the new data from R. Larsen, S. Meinel, S. Mukherjee, P. Petreczy 2019, 2020

Unquenched determinations of kappa and gamma

N.B., M. Escobedo, A. Vairo, P. vander Griend
Phys.Rev. D100 (2019) no.5, 054025

Extraction of kappa from unquenched lattice data for the thermal width of the Y(1S) (black lines) in comparison to a quenched lattice determination (brown), determinations from the D meson v2 from Alice and Star data (green), model compilation from 1903.07709) (red) and the perturbative calculation (truncated g^5) (blue)



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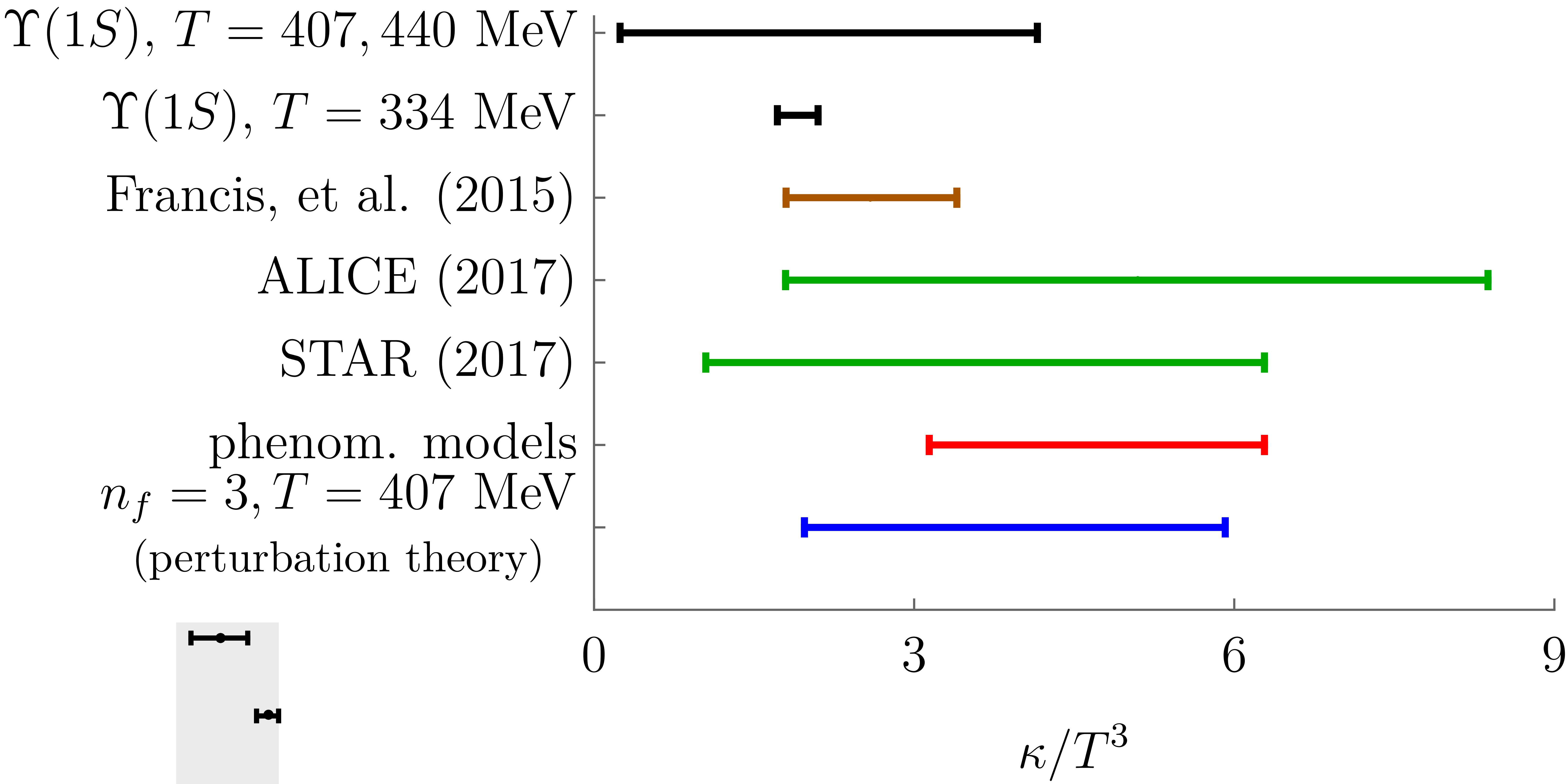

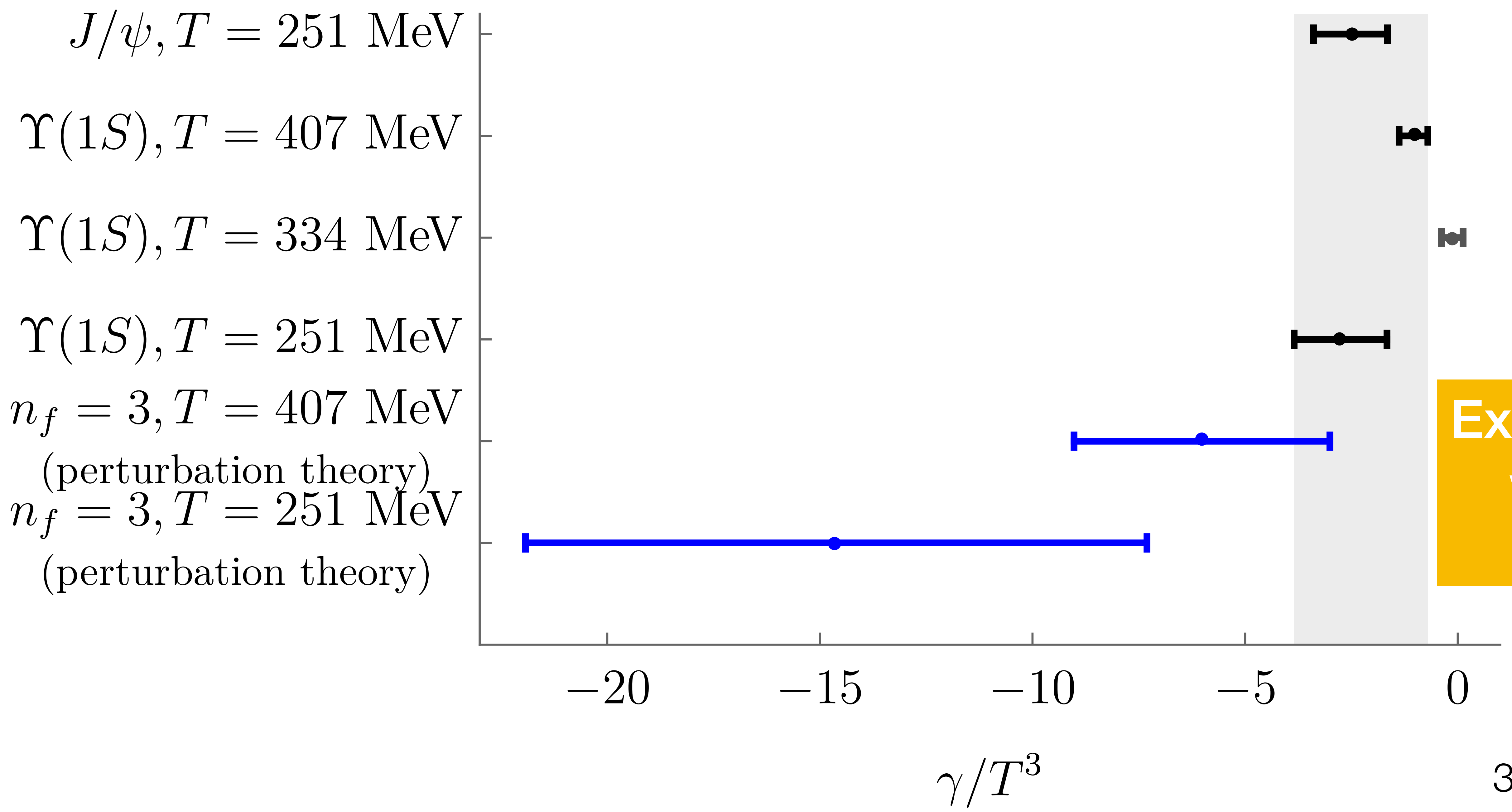

Extraction of gamma from unquenched lattice data for the thermal width of the Y(1S) and J/psi (black lines)n comparison to NLO order perturbation theory at two different T

Solving the Linblad equation

Initial conditions

- The production of singlets is α_s suppressed compared to that of octets.
  - Cho Leibovich PRD 53 (1996) 6203

$$\rho_s = N|\mathbf{0}\rangle\langle\mathbf{0}|, \qquad \rho_o = \frac{1}{\alpha_s}\rho_s$$

N is fixed by $\mathrm{Tr}\{\rho_s\} + \mathrm{Tr}\{\rho_o\} = 1$

evolve in QGP from t_0 =0.6 fm up T= 250 MeV

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a pretty challenging tasks

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Brambilla Escobedo Soto Vairo PRD 96 (2017) 034021

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Brambilla Escobedo Soto Vairo PRD 96 (2017) 034021

Recently **thanks to the collaboration with Mike Strickland** we developed a much more efficient (embarassingly parallel) program based on the quantum trajectory algorithm (Qtraj) and we coupled this to the hydrodynamical evolution of the QGP using a 3+1D dissipative hydrodynamics code (aHydro3p1)

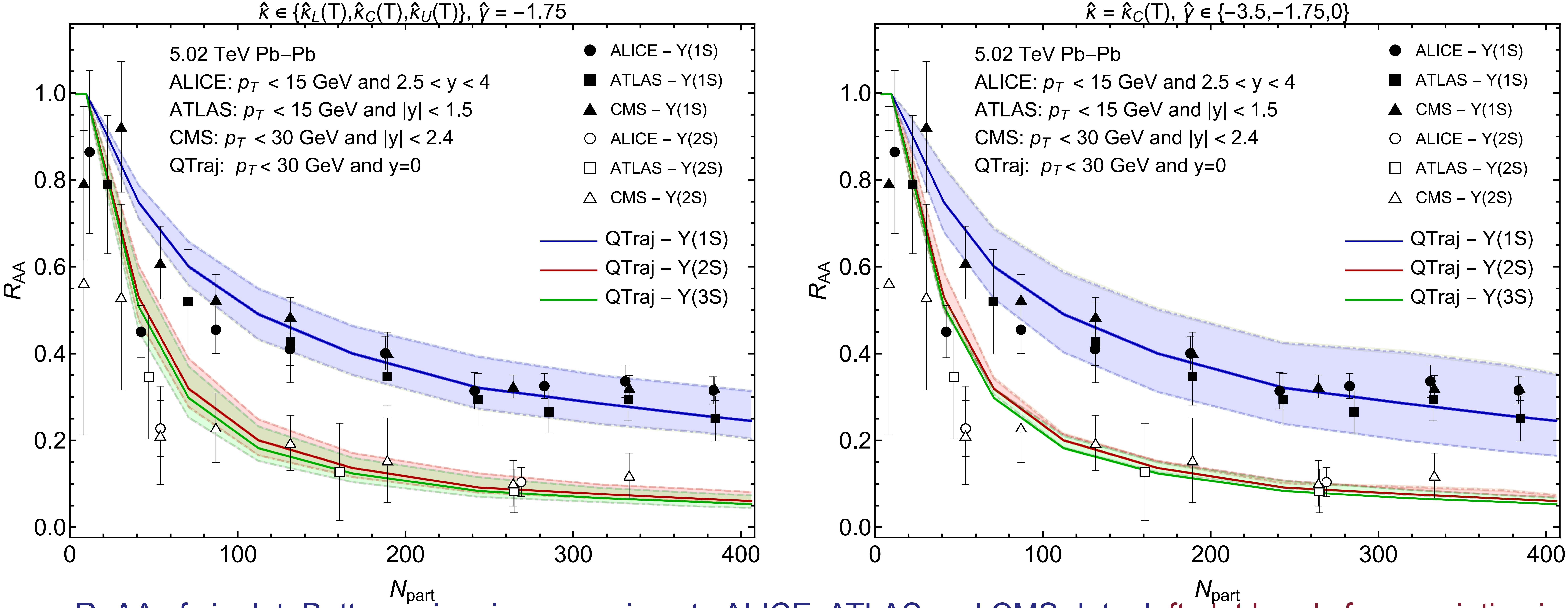
N.B. Escobedo , Strickland, Vairo, Vander Griend, Weber, 2012.01240

nonequilibrium evolution of quarkonium in medium: nuclear modification factor R_AA

We compute the nuclear modification factor R_{AA}:

$$R_{AA}(nS) = \frac{\langle n, \mathbf{q} | \rho_s(t_F; t_F) | n, \mathbf{q} \rangle}{\langle n, \mathbf{q} | \rho_s(0; 0) | n, \mathbf{q} \rangle}$$

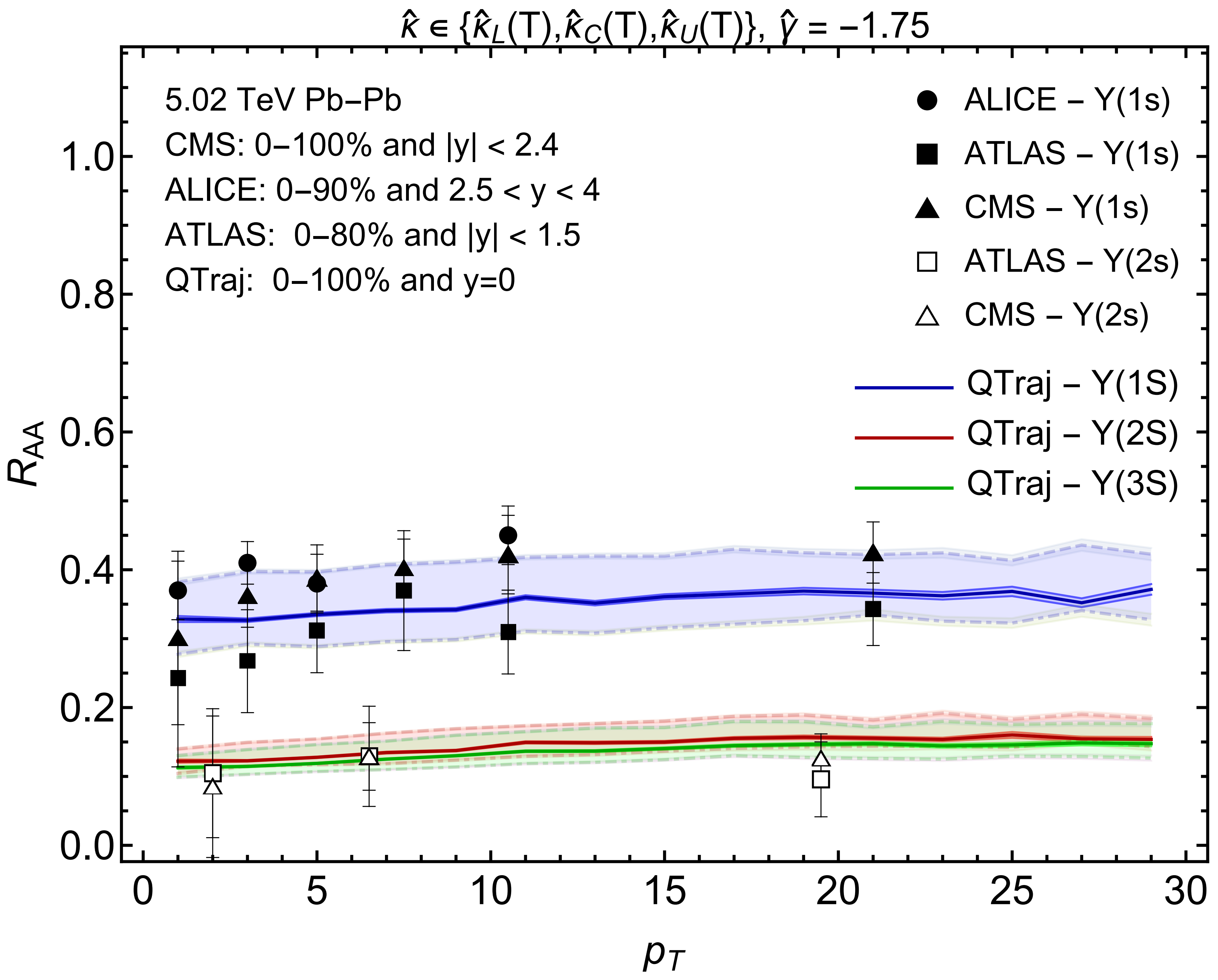
calculation with no free parameters, results depends on kappa function of T (calculated on the lattice) and gamma (extracted from the lattice)

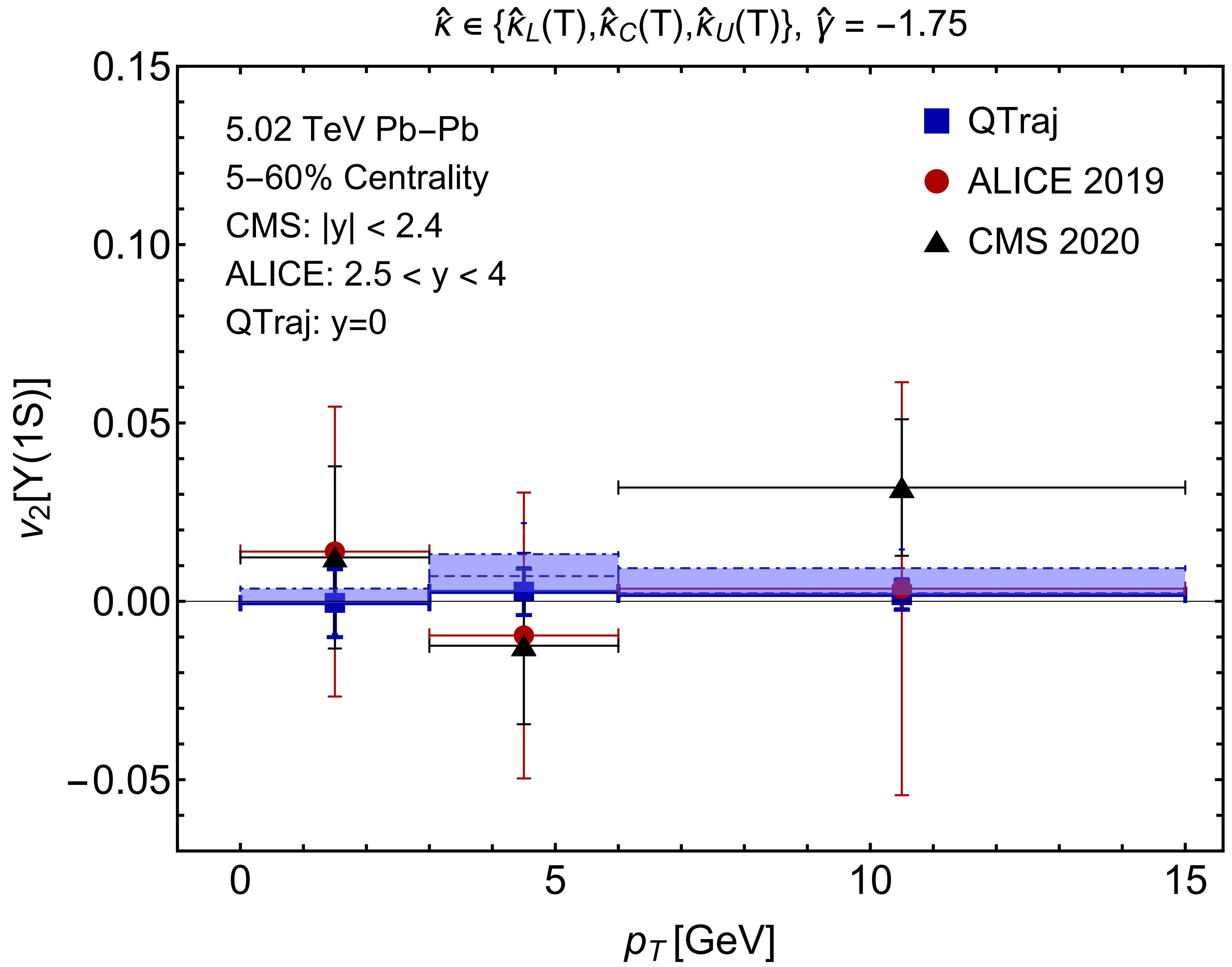


R_AA of singlet Bottomonium in comparison to ALICE, ATLAS and CMS data, left plot bands from variation in kappa, right plot variation in gamma —> we can use R_AA to learn about the QGP!

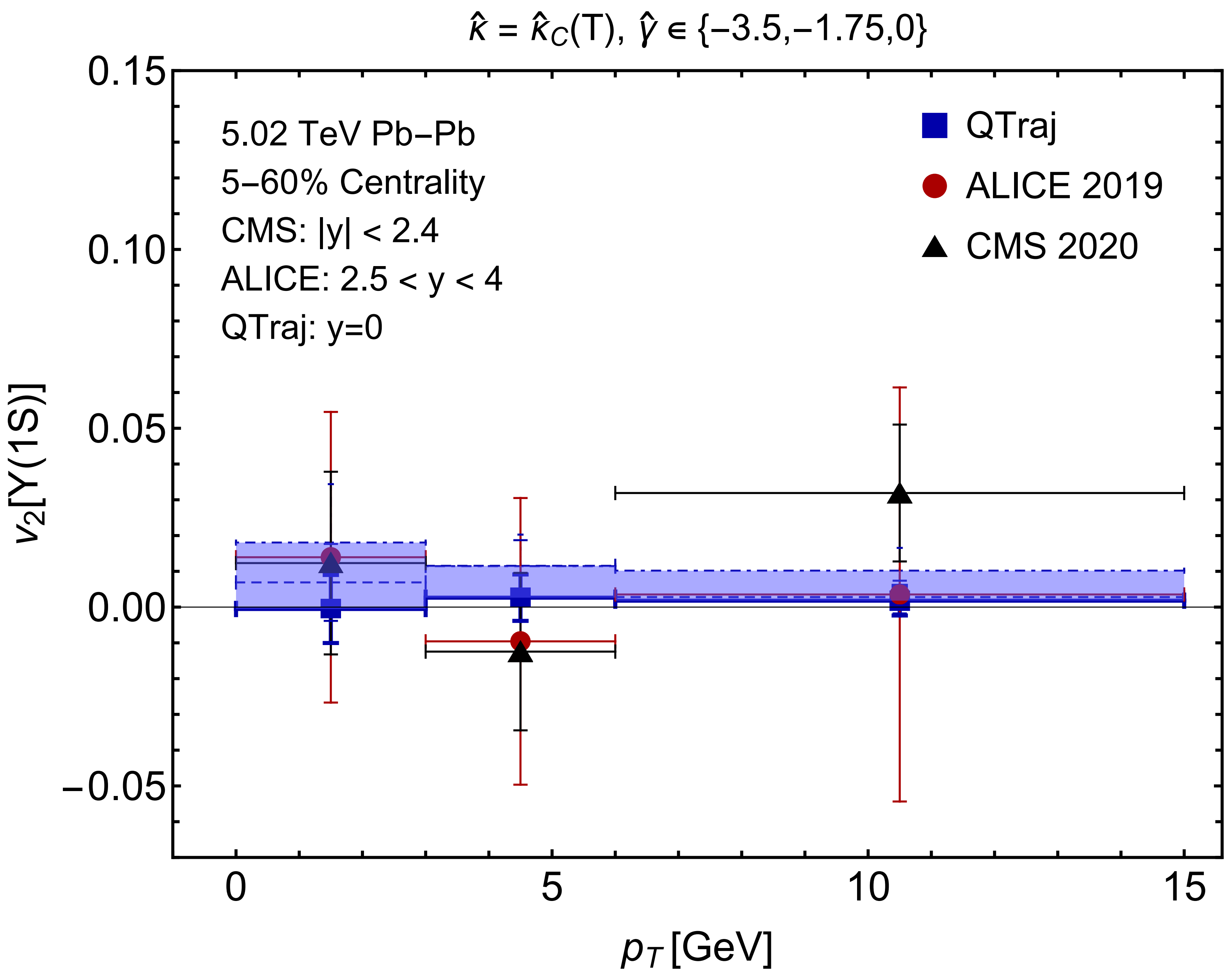
N.B. Escobedo , Strickland, Vairo, Vander Griend, Weber, 2012.01240

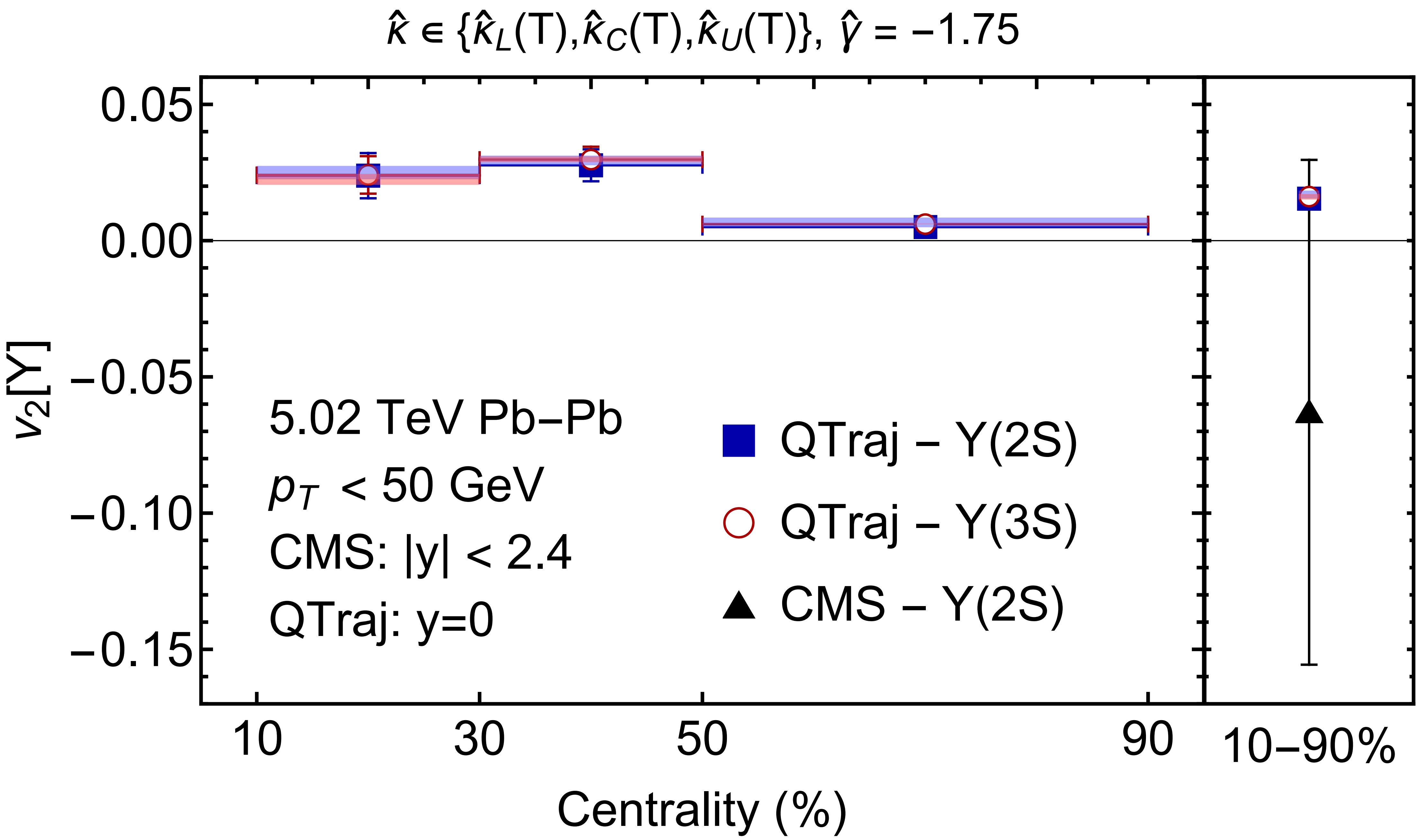
Differential quantities





Full diagnostic of the medium in terms of objects with a proper field theoretical definition, evaluated on the lattice





- This calculation with no free parameter can reproduce *inside errors* all the experimental data on bottomonia 1S 2S 3S:

- The band in our prediction depends on the indetermination on the transport coefficients

- Recombination is there but it is small for Y(1S) bottomonium

- The evolution equations we obtained do not make any special assumption on the medium

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  - Ratios of R_AA, v_2
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They could be used far from equilibrium or for a medium with a scale different from T-> use different methods to evaluate kappa and gamma (kinetic theory, classical simulations)

Conclusions

We have shown a realistic particle physics example where a complex full system made out of a multiscale subsystem (quarkonium) interacting with a rich and inherently non-perturbative environment (the quark-gluon plasma) could be studied in its out-of-equilibrium evolution with the methods of

- effective field theories, to factorize contributions coming from different energy scales. Contributions coming from high-energy scales (mass, ...) can be computed in perturbation theory.
- lattice QCD, to compute numerically on a space-time lattice low-energy non-perturbative contributions.
- open quantum systems, to compute the out-of-equilibrium evolution of the subsystem and its non-trivial interaction with the environment (production, dissociation and recombination of quarkonium).

As a result the study describes for the first time quarkonium dissociation taking into account the conservation of the total number of heavy quarks, the non-Abelian nature of QCD, without any classical approximation.

which is fundamental to obtain recombination!

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which is fundamental to obtain recombination!

- Quarkonium suppression may be systematically studied with the use of **effective field theories** and **lattice QCD**
- **In equilibrium** properties like **dissociation width, cross section, mass shift...** have been computed as expansions in the small parameters of the system.
- **Out of equilibrium** properties, like octet recombination, can be studied by treating quarkonium as an open quantum system. Lattice input is crucial.

The evolution equations follow from assuming the inverse size of the quark-antiquark system to be larger than any other scale of the medium and from being accurate at first non-trivial order in the multipole expansion and at first order in the heavy-quark density.

Under some conditions (large time, quasistatic evolution, temperature much larger than the inverse evolution time of the quarkonium) the evolution equations are of the Lindblad form. Their numerical solution provides $R_{AA}(nS)$ close to experimental data.

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Outlook

- We need precise and unquenched determinations of the kappa and gamma transport coefficients
- Recombination effects are small for bottomonium for not for charmonium: we should go beyond the linear density approximation in that case
- We should investigate the effect of quarkonium moving with respect to the QGP and the anisotropy
- We should investigate the full master equations farther out of equilibrium: all the calculations holds if T is substituted by a generic scale
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Inside EFT and OQS and with the help of the lattice quarkonium holds the promise to be a golden probe of QGP!