NORA BRAMBILLA

Recent developments in heavy quarkonium theory:

Nora Brambilla

Recent developments in heavy quarkonium theory: an Effective Field Theory Perspective

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Heavy quarkonium: progress, puzzles, and opportunities

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P. Senger,[23] F. Simon,[29,51] S. Stracka,[41,52] Y. Sumino,[53] M. Voloshin,[54] C. Weiss,[31] H. K. Wöhri,[35] and C.-Z. Yuan[49]

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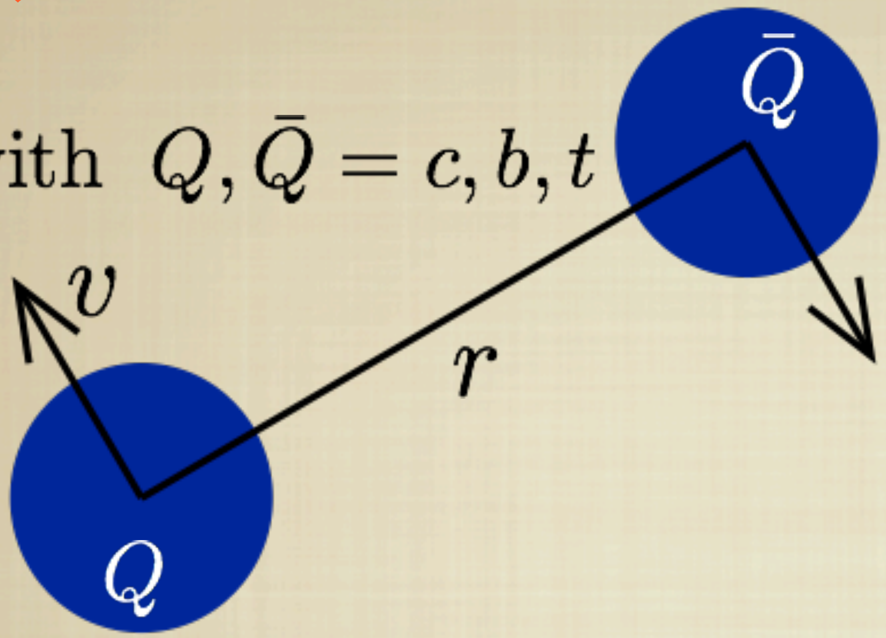
it contains:

Spectroscopy,
Decay,
Production,
Quarkonium in media,
Beyond the standard model

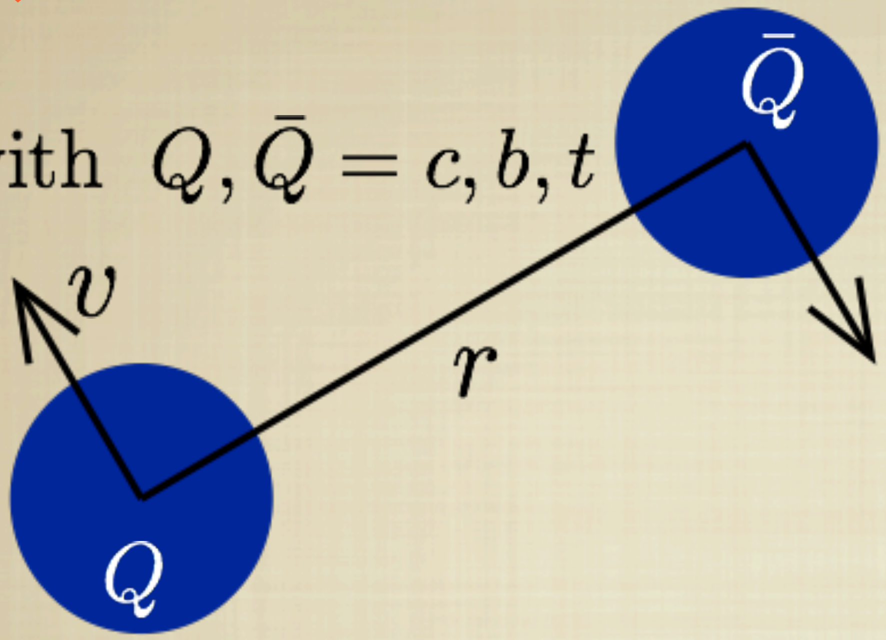
Quarkonium

with $Q, \bar{Q} = c, b, t$



Quarkonium is an ideal system to study strong interactions

with $Q, \bar{Q} = c, b, t$



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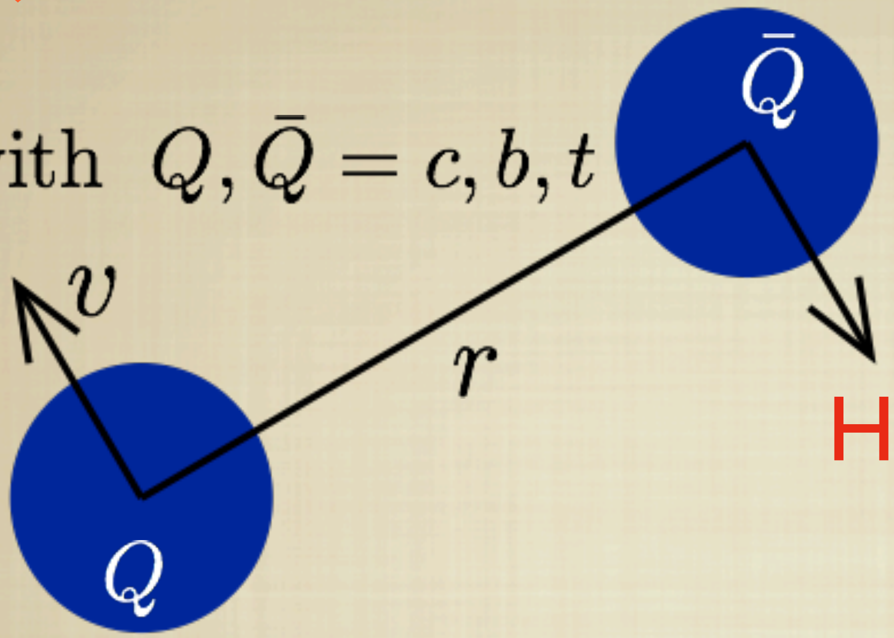

Heavy quarks offer a privileged access

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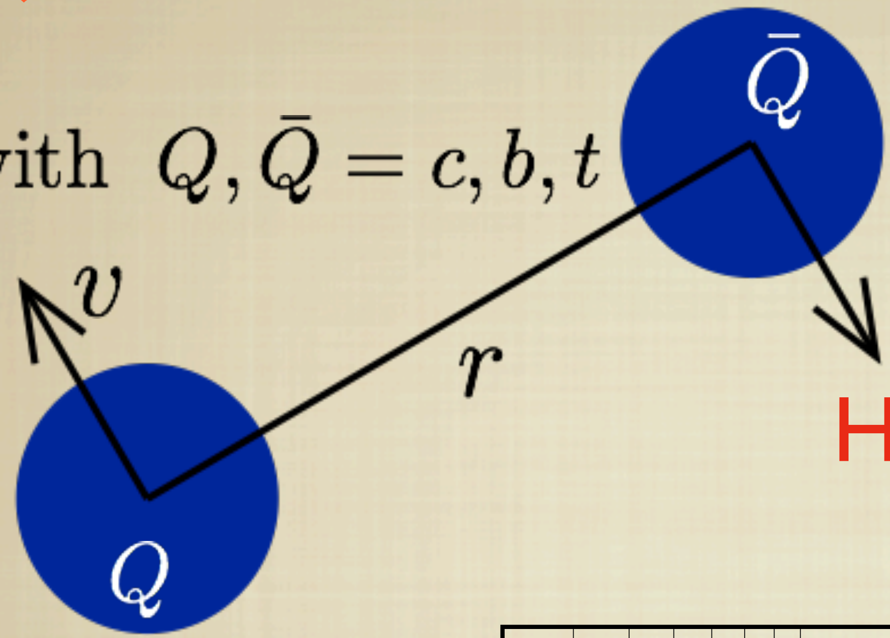

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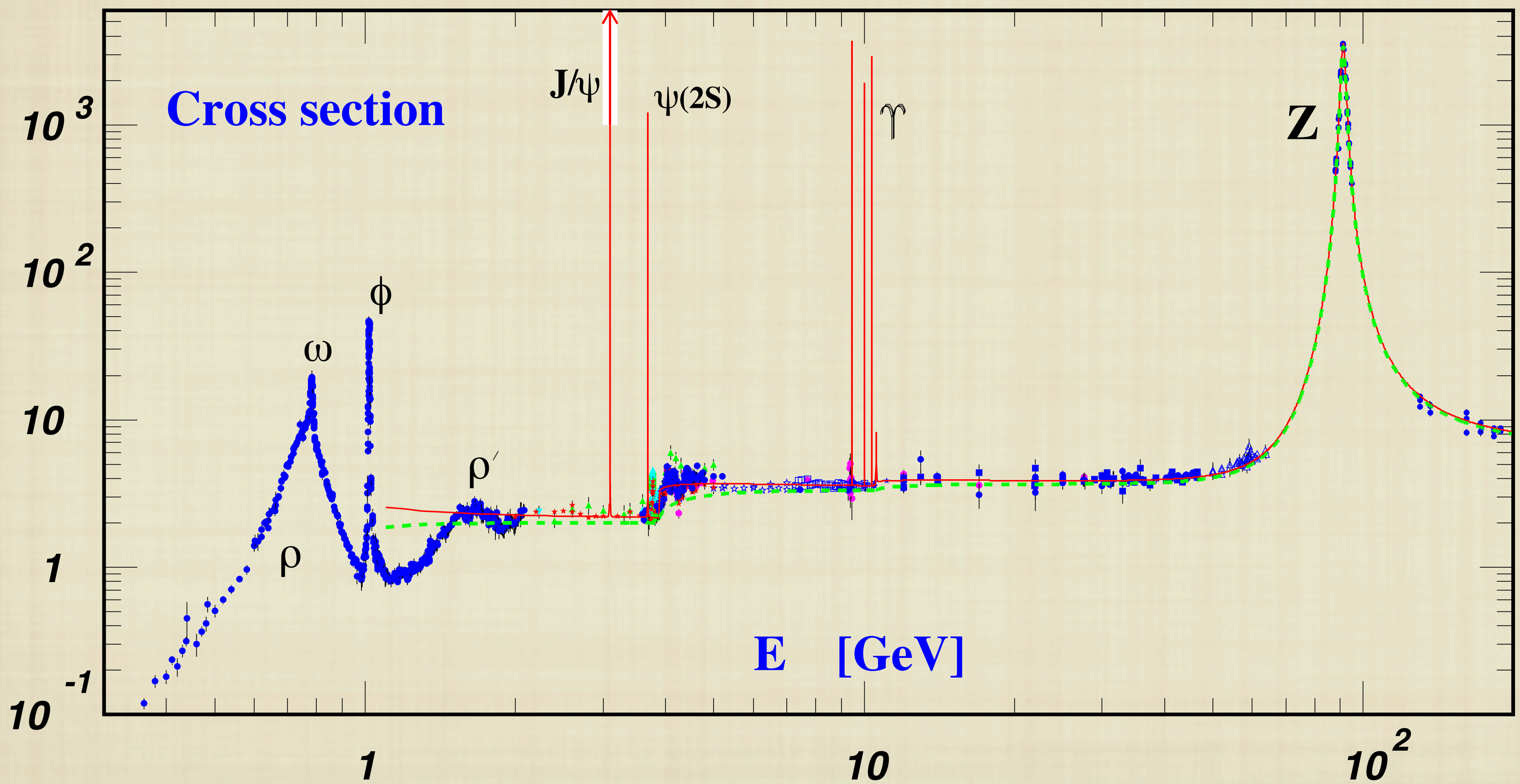

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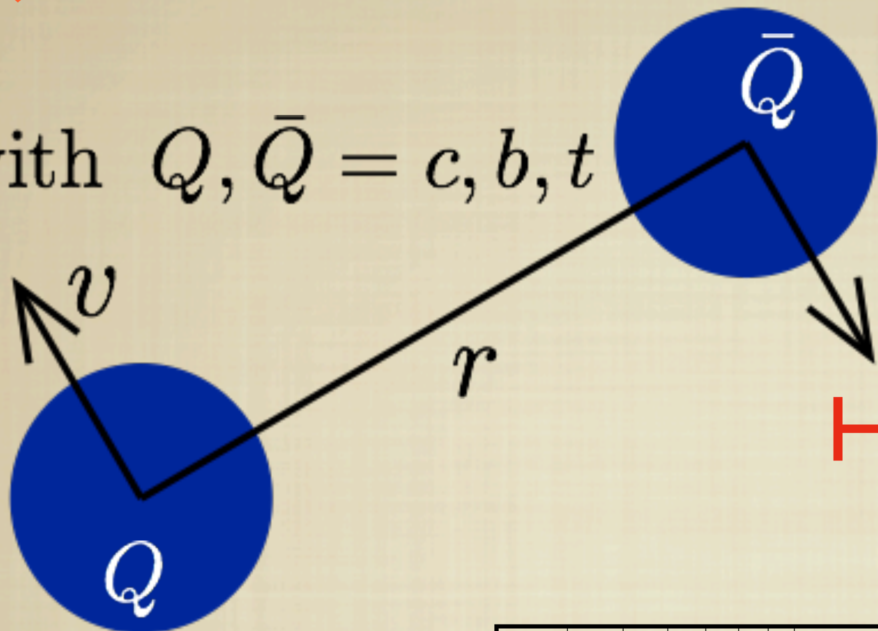

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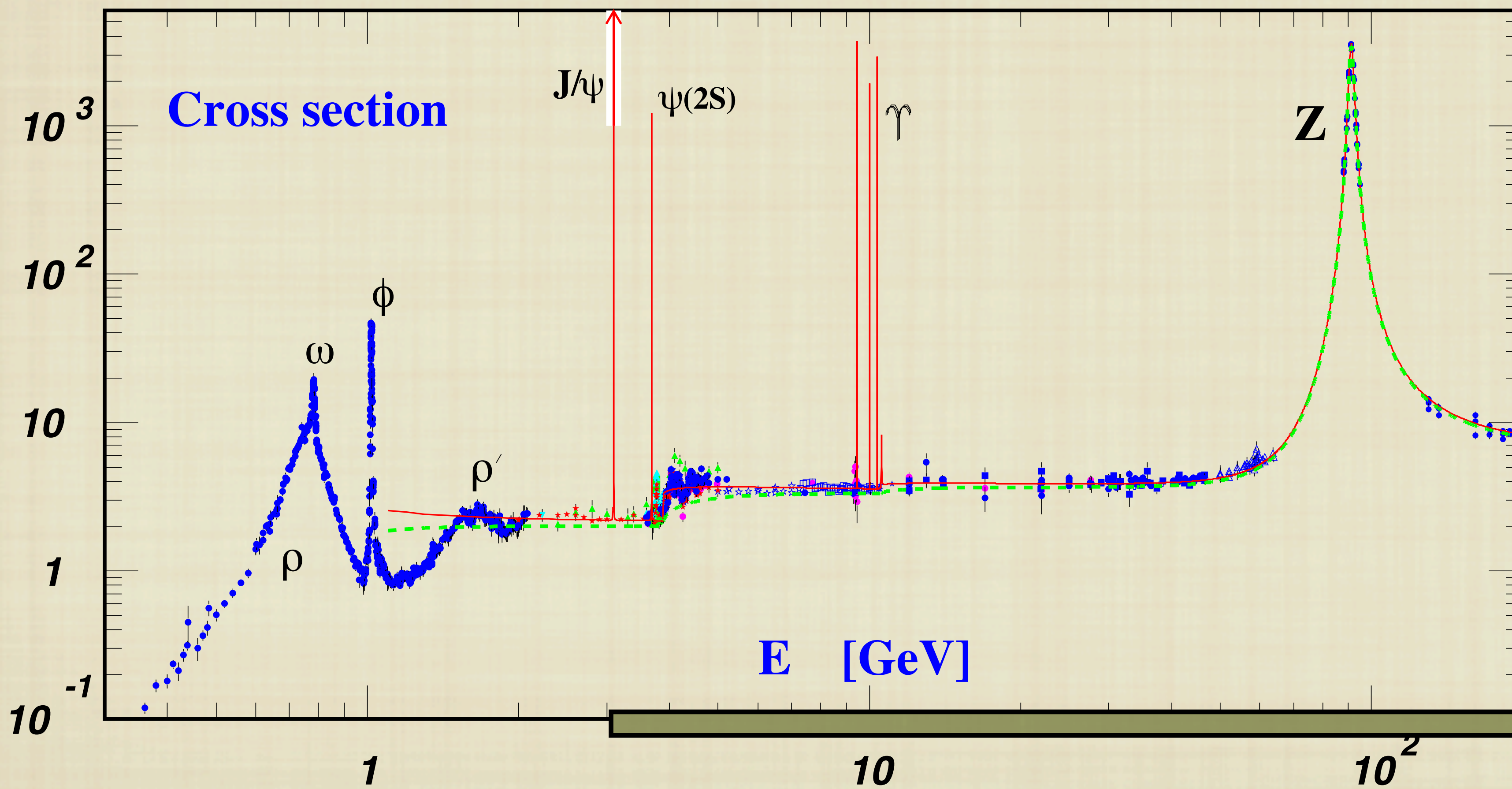

$m_c \sim 1.5\text{GeV}$

$m_b \sim 5\text{GeV}$

$m_t \sim 170\text{GeV}$

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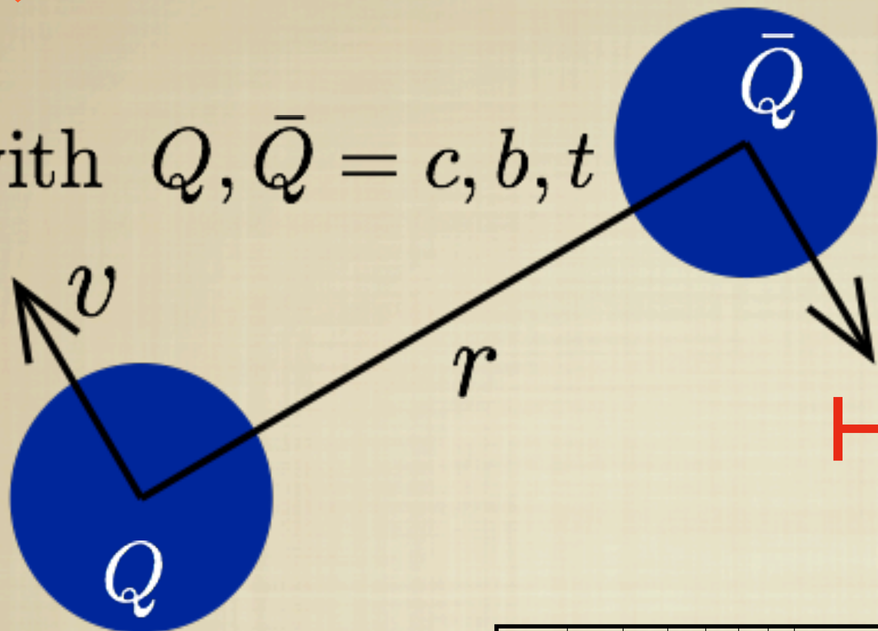

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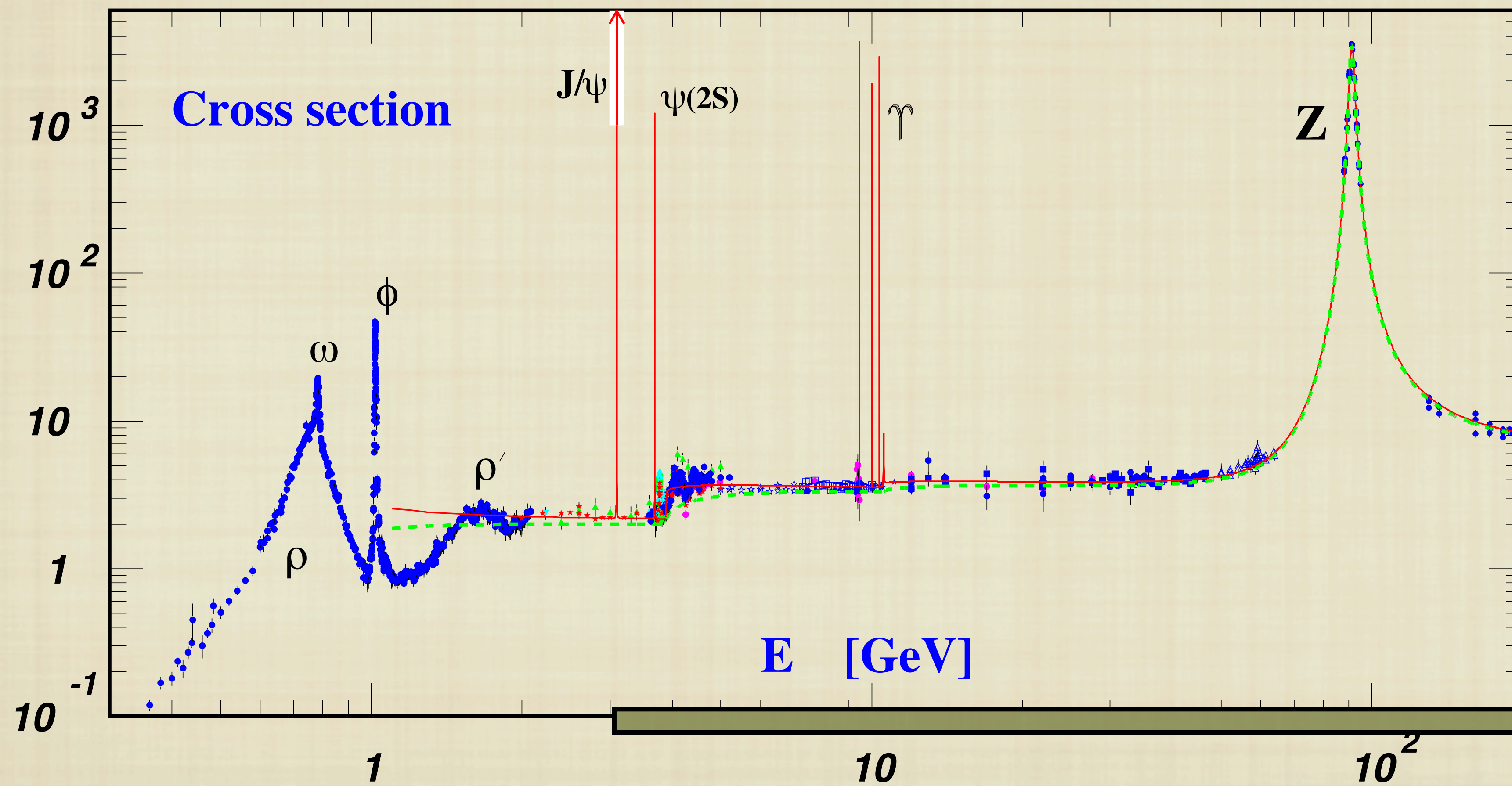
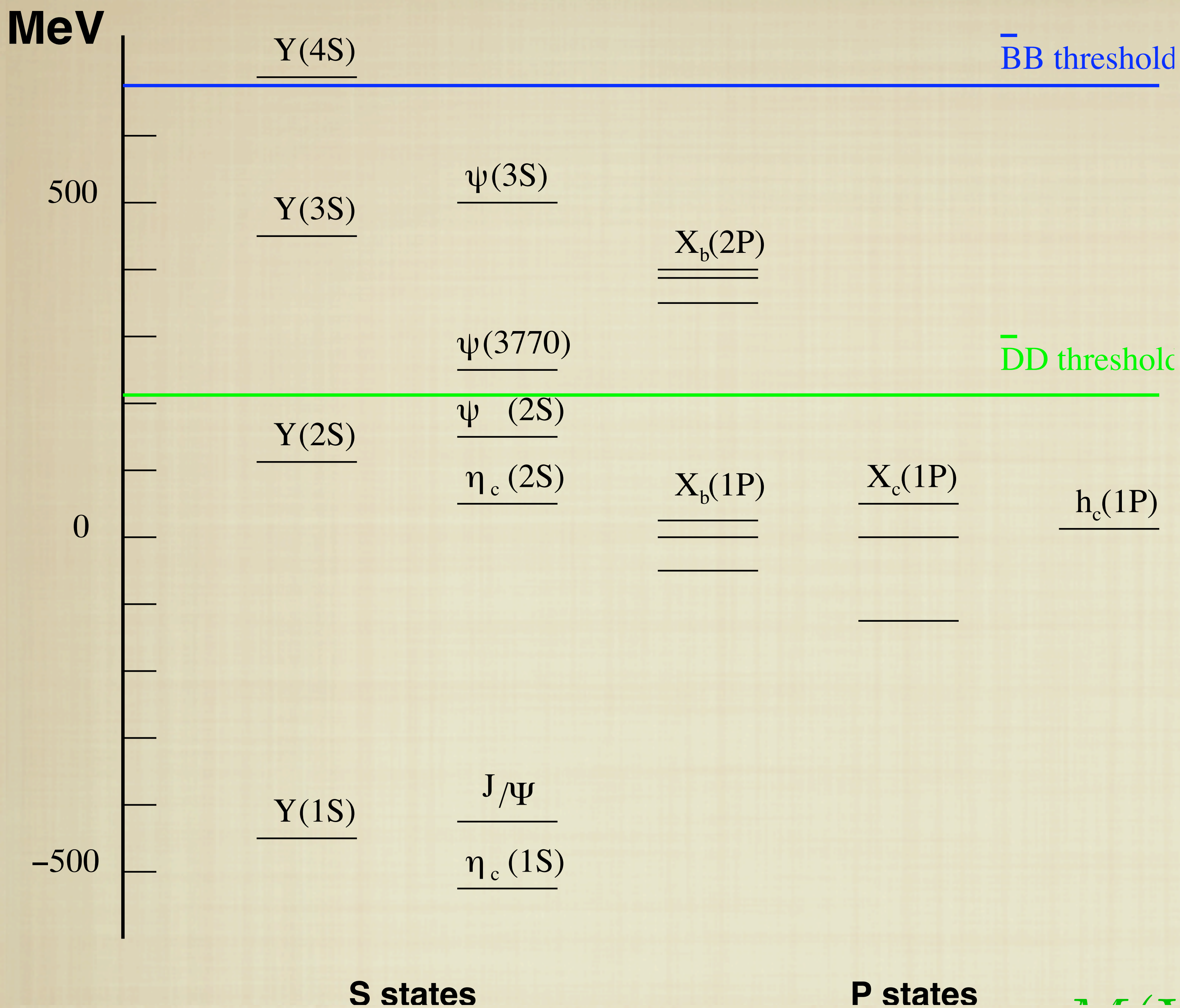


$m_c \sim 1.5$GeV
$m_b \sim 5$GeV
$m_t \sim 170$GeV

A large scale $m_Q \gg \Lambda_{QCD}$ $\alpha_s(m_Q) \ll 1$

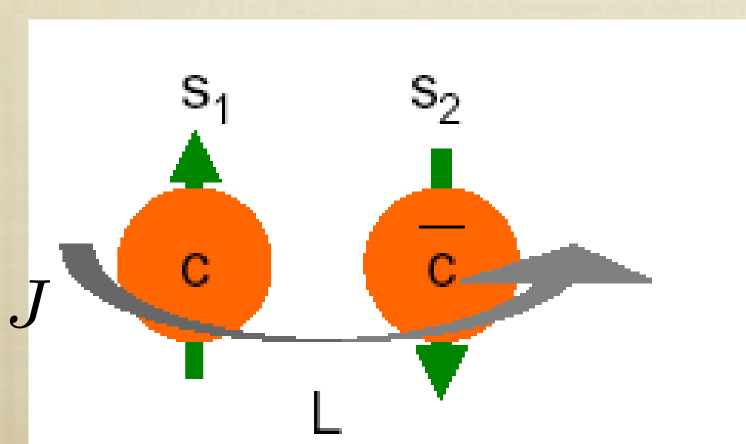
Quarkonium scales



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

$$M(Y(1S)) = 9460\,\mathrm{GeV}$$
$$M(J/\Psi) = 3097\,\mathrm{GeV}$$

$^{2S+1}L_J$



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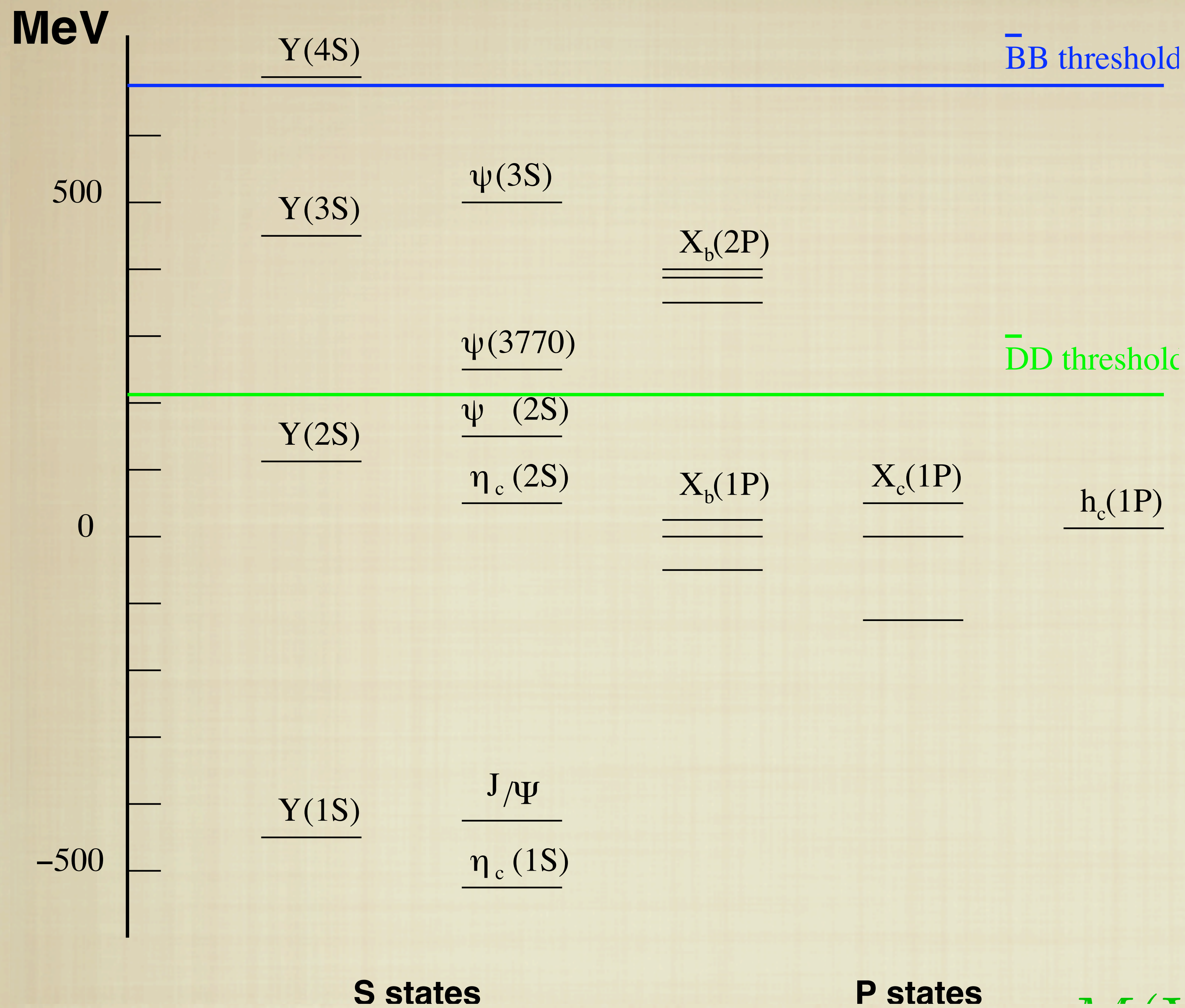

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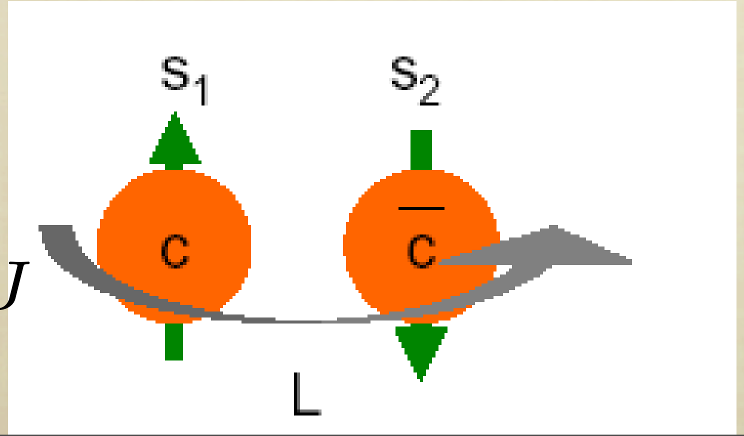
$$^{2S+1}L_J$$



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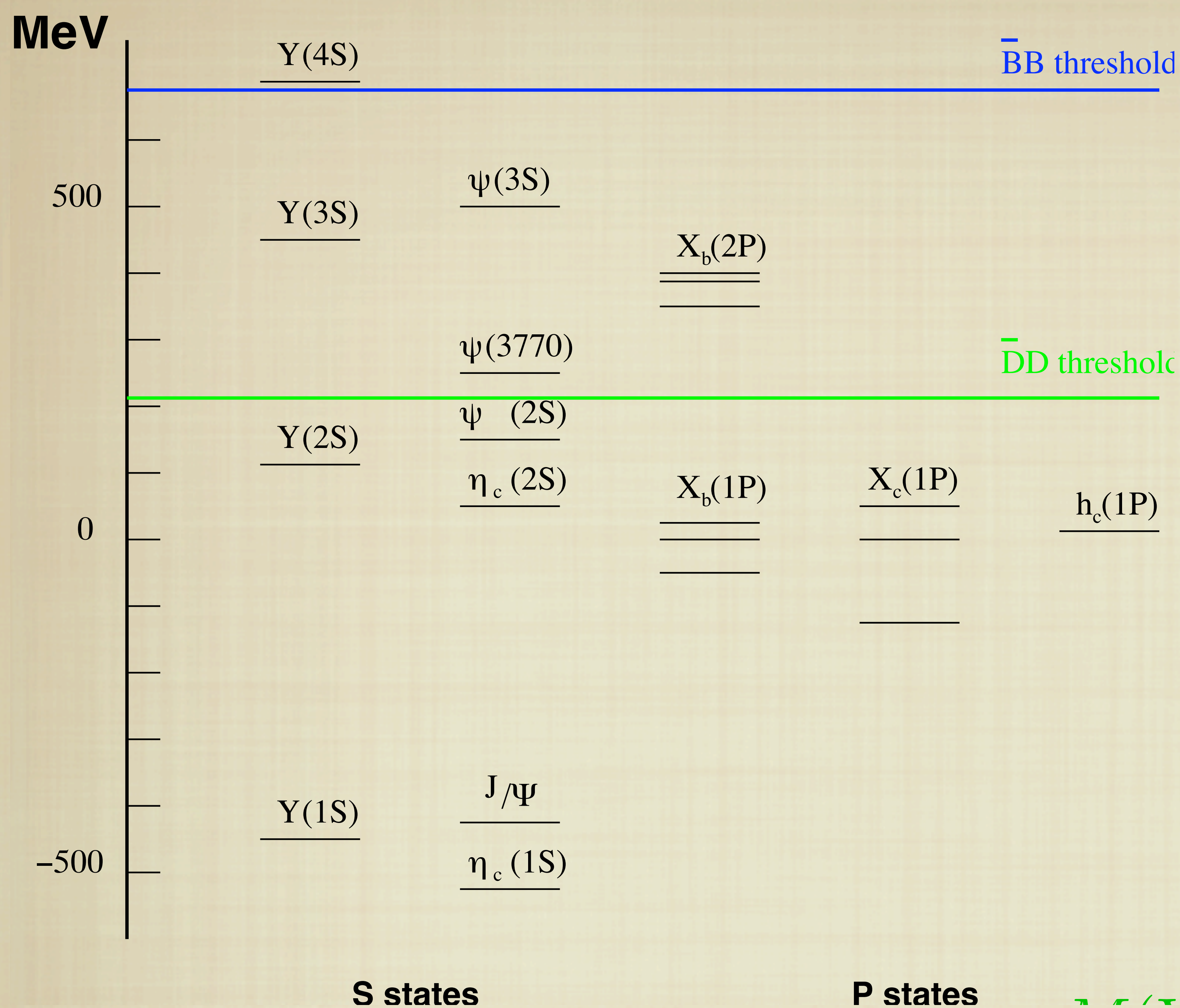

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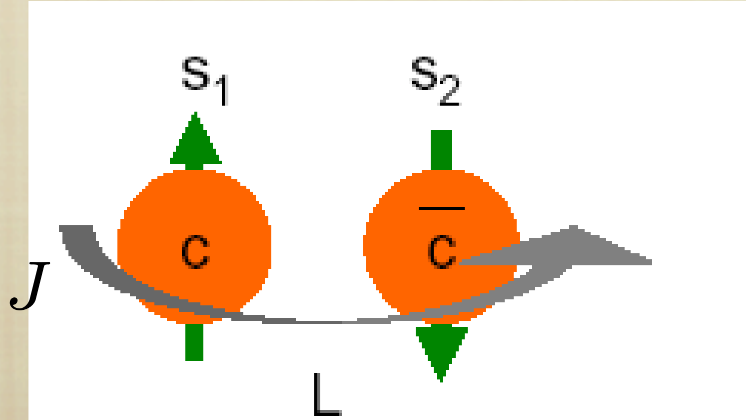
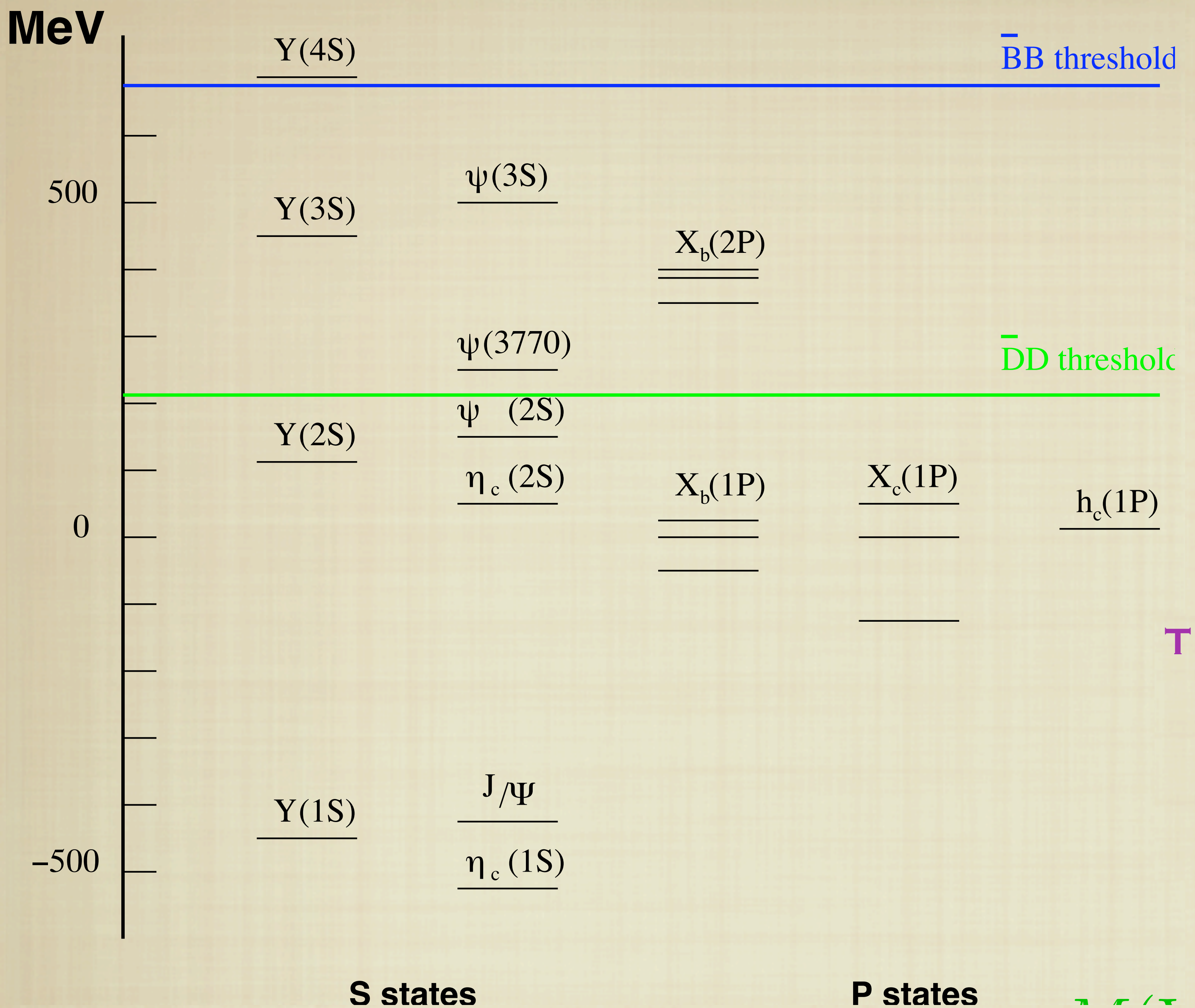


The mass scale is perturbative

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

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

Quarkonium scales



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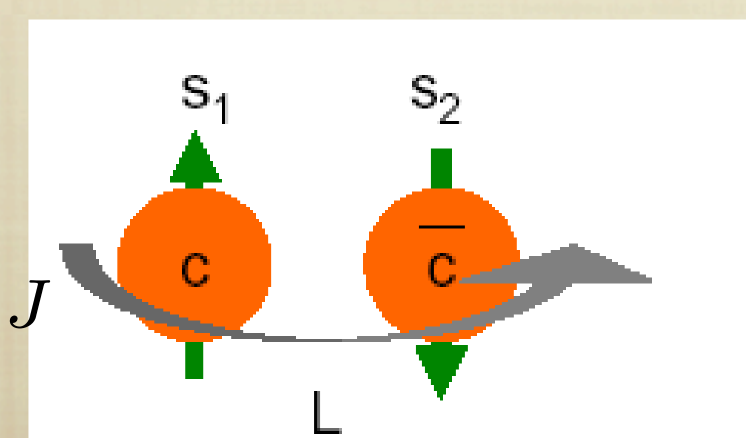


THE SYSTEM IS NONRELATIVISTIC(NR)

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

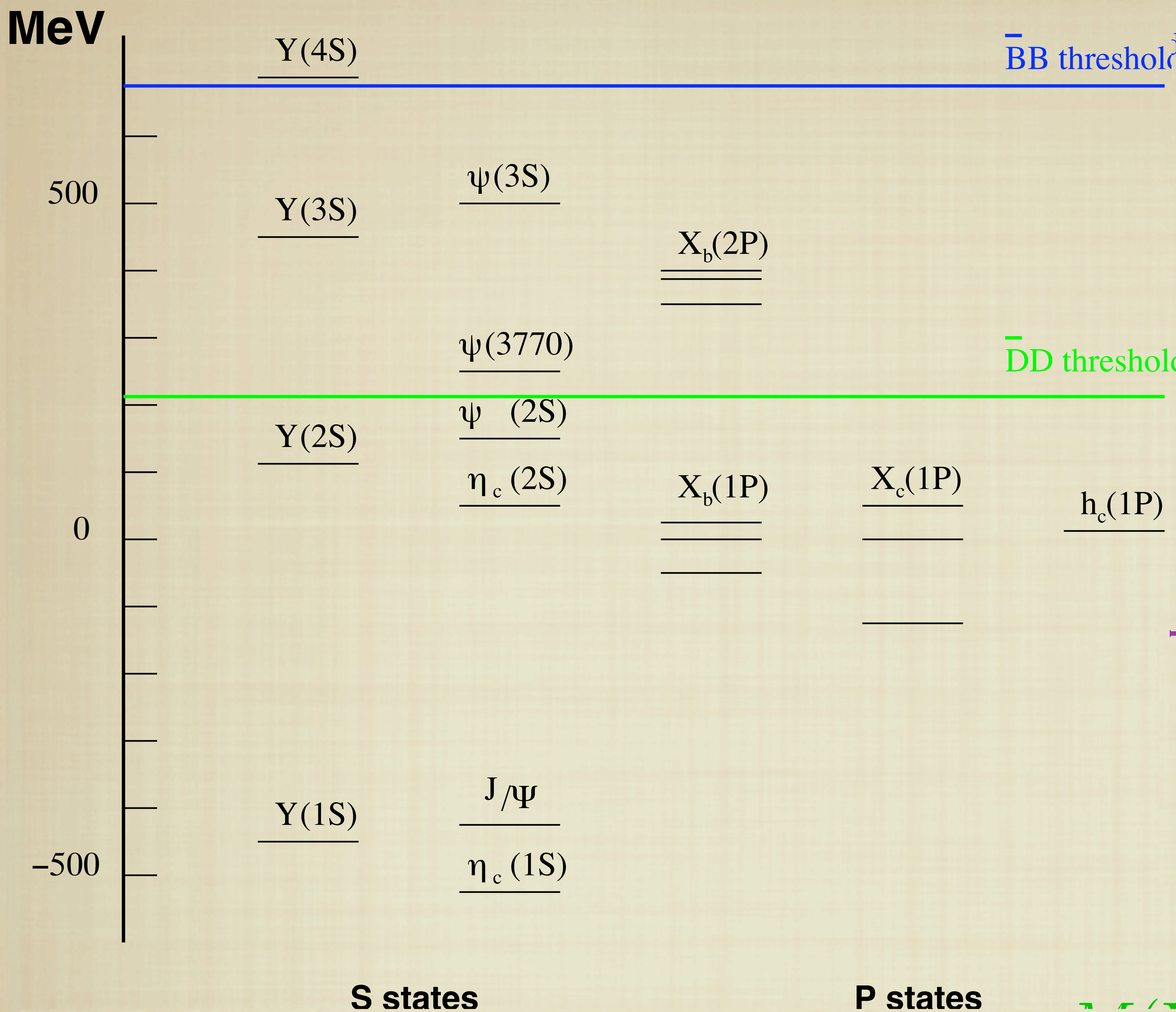
$$v_b^2 \sim 0.1, v_c^2 \sim 0.3$$

THE MASS SCALE IS PERTURBATIVE

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

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

Quarkonium scales



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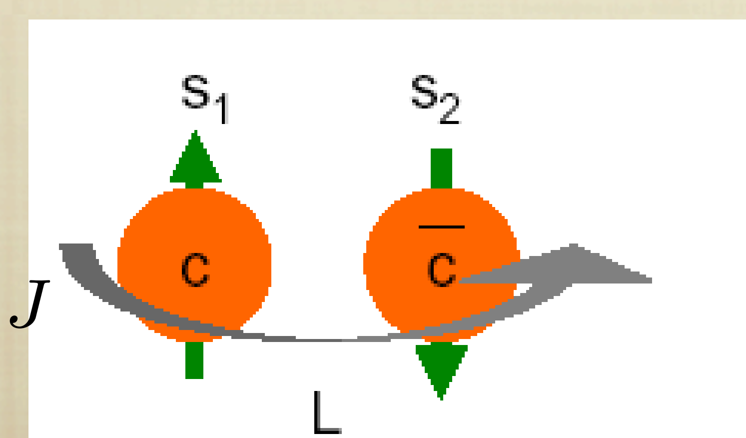

NR bound states have at least 3 scales

$$m \gg mv \gg mv^2 \quad v \ll 1$$

The system is nonrelativistic(NR)

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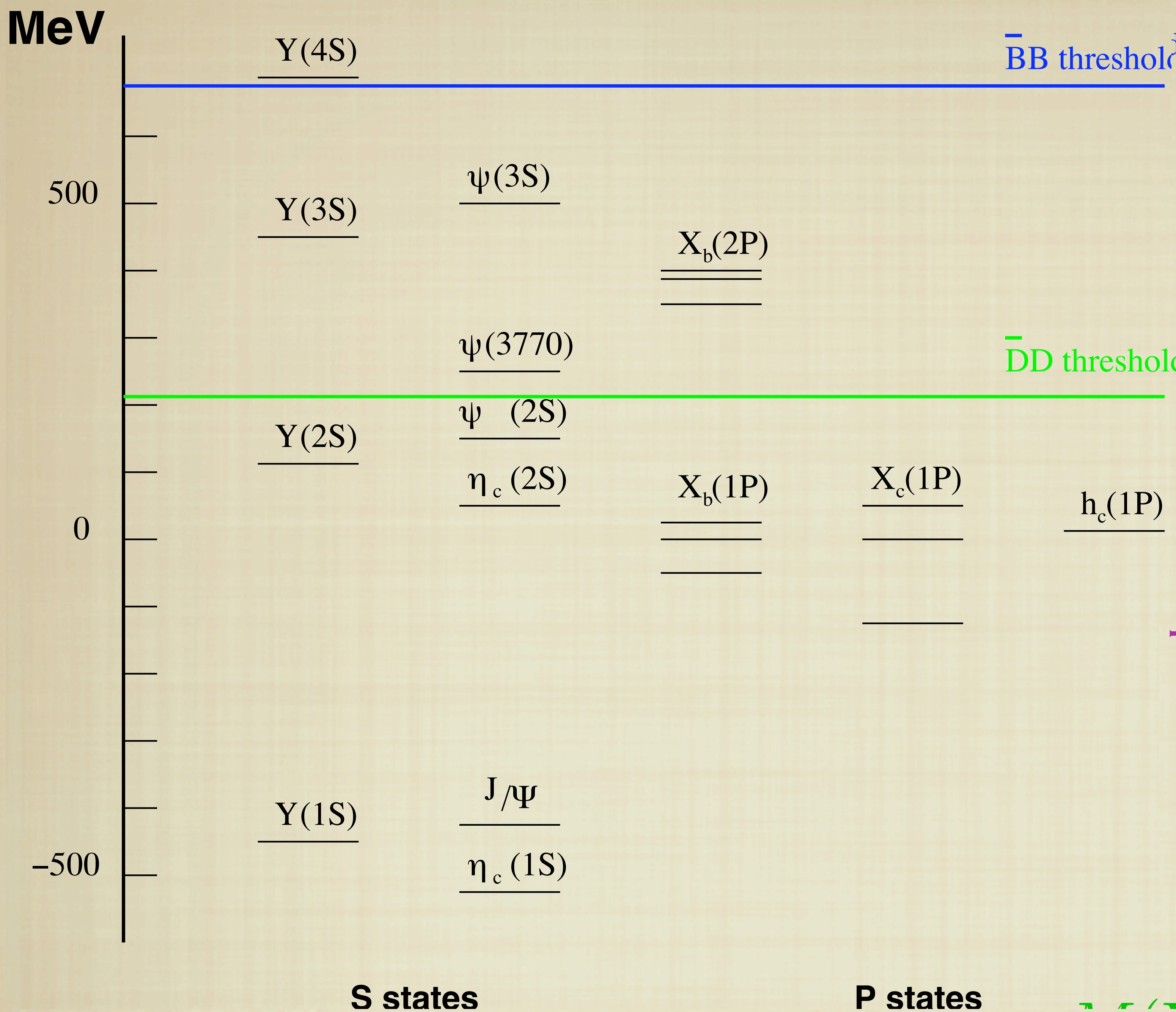

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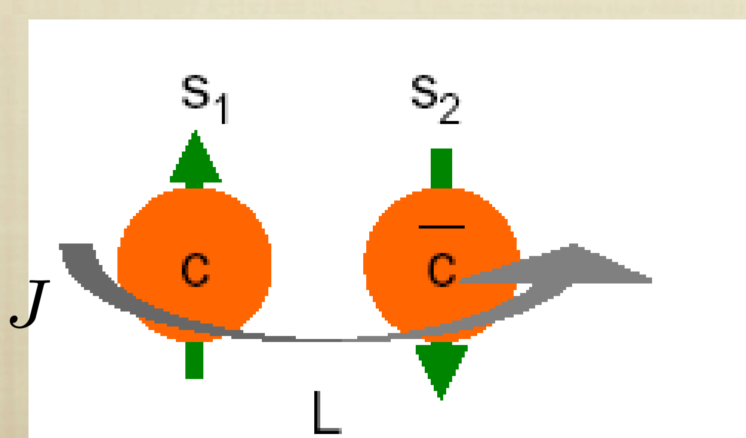

NR bound states have at least 3 scales

$$m \gg mv \gg mv^2 \quad v \ll 1$$

$$mv \sim r^{-1}$$

The system is nonrelativistic(NR)

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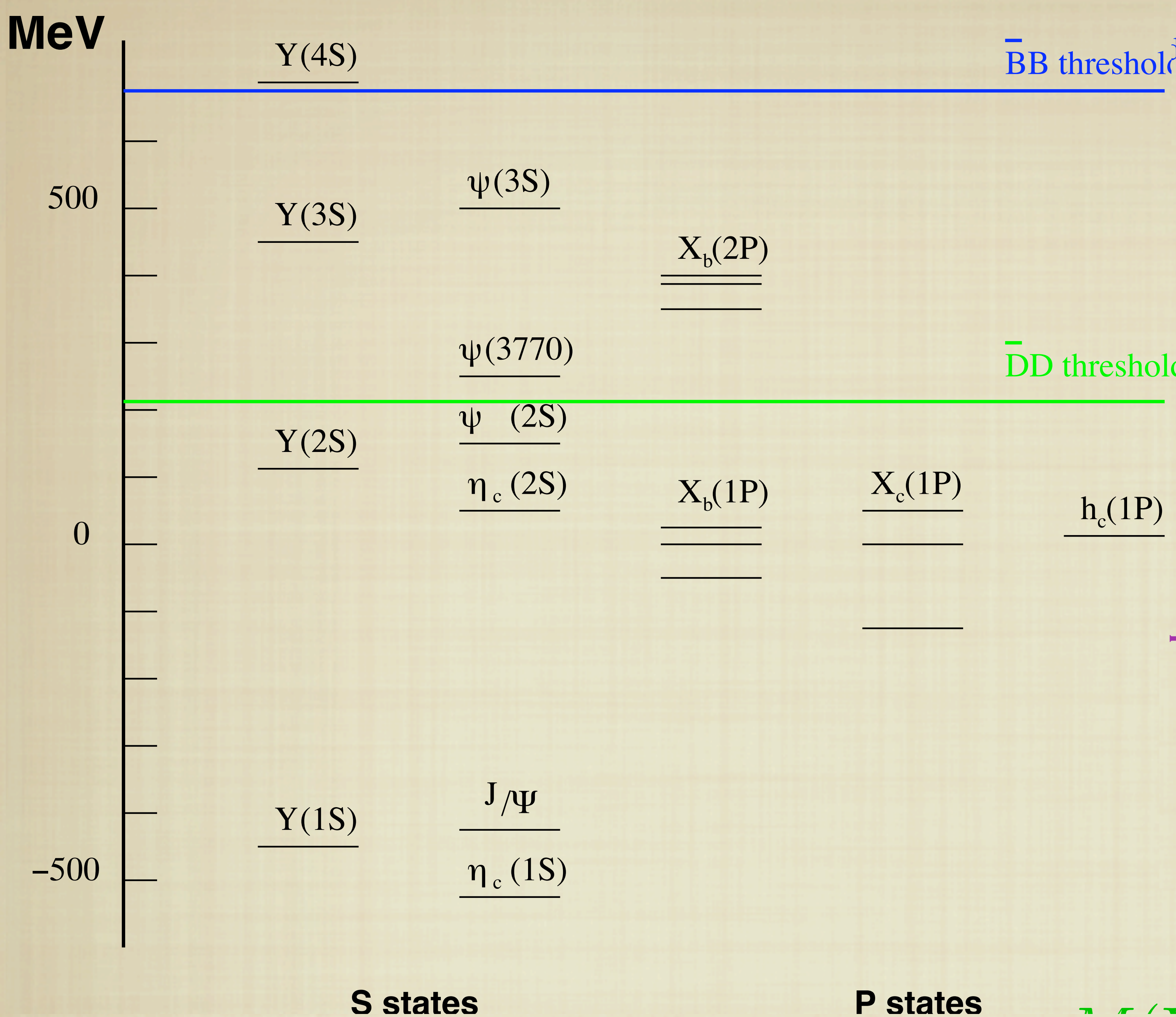

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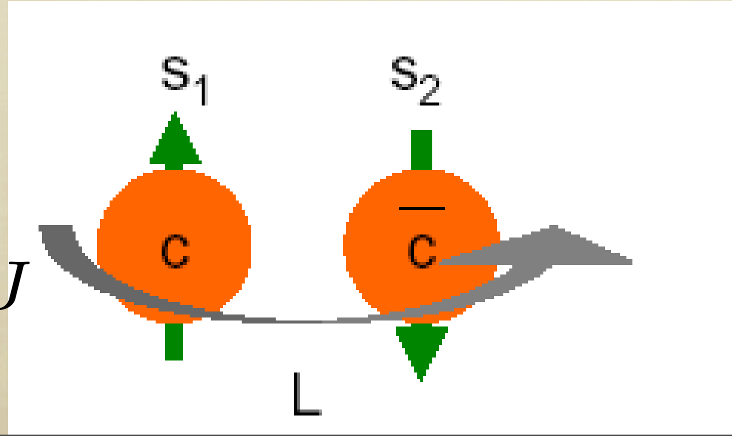

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$$m \gg mv \gg mv^2 \quad v \ll 1$$

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and $\Lambda_{\rm QCD}$

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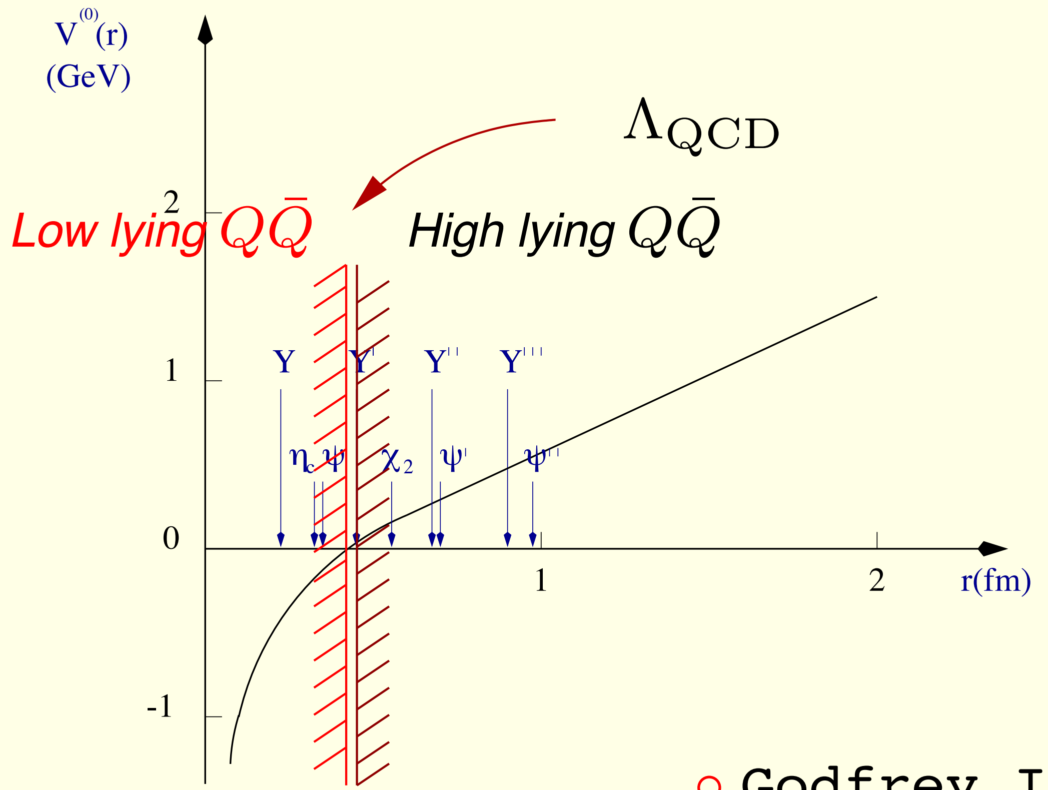
Quarkonium as a confinement and deconfinement probe

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

Quarkonium as a confinement and deconfinement probe

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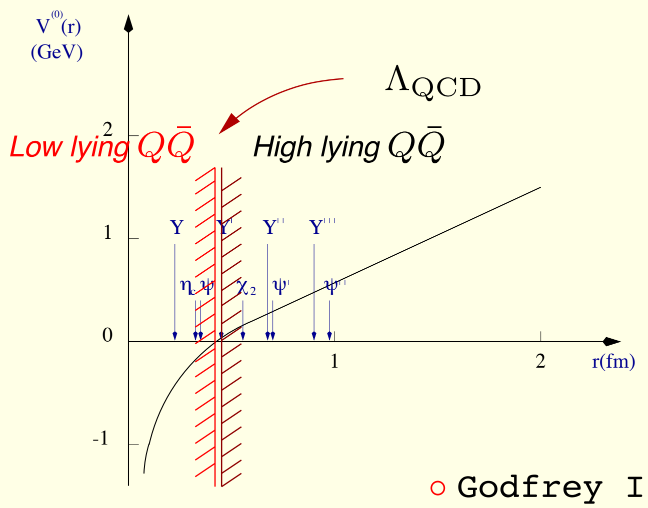

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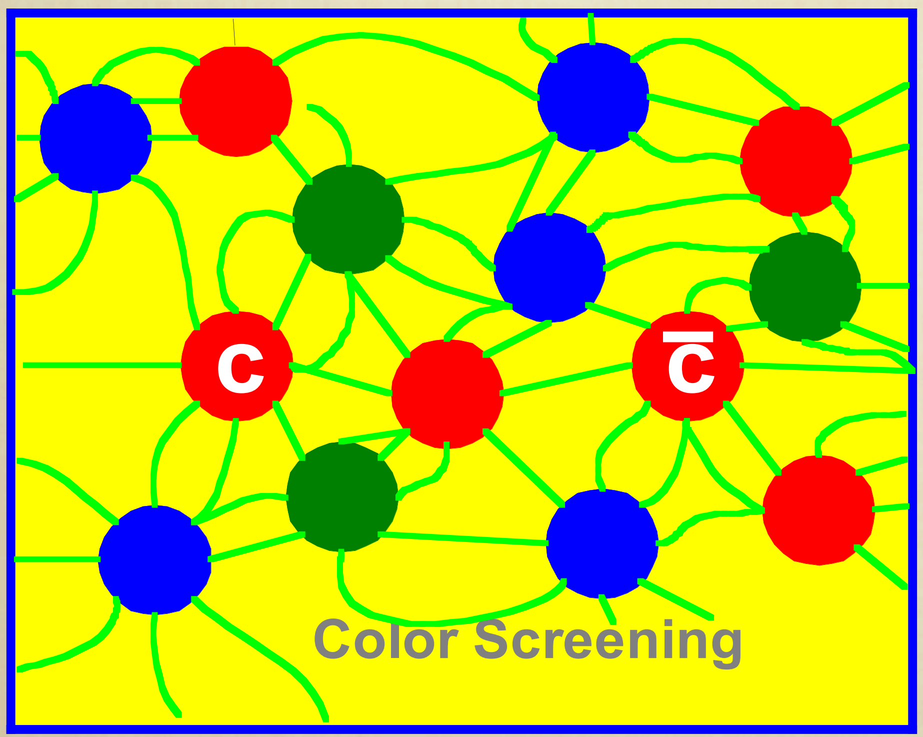

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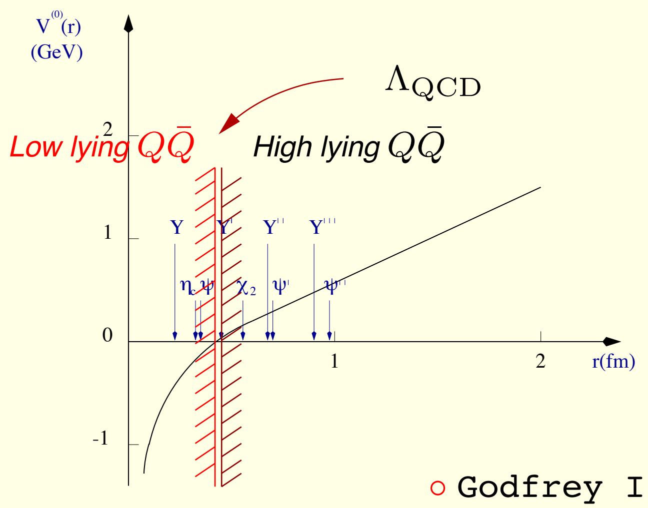

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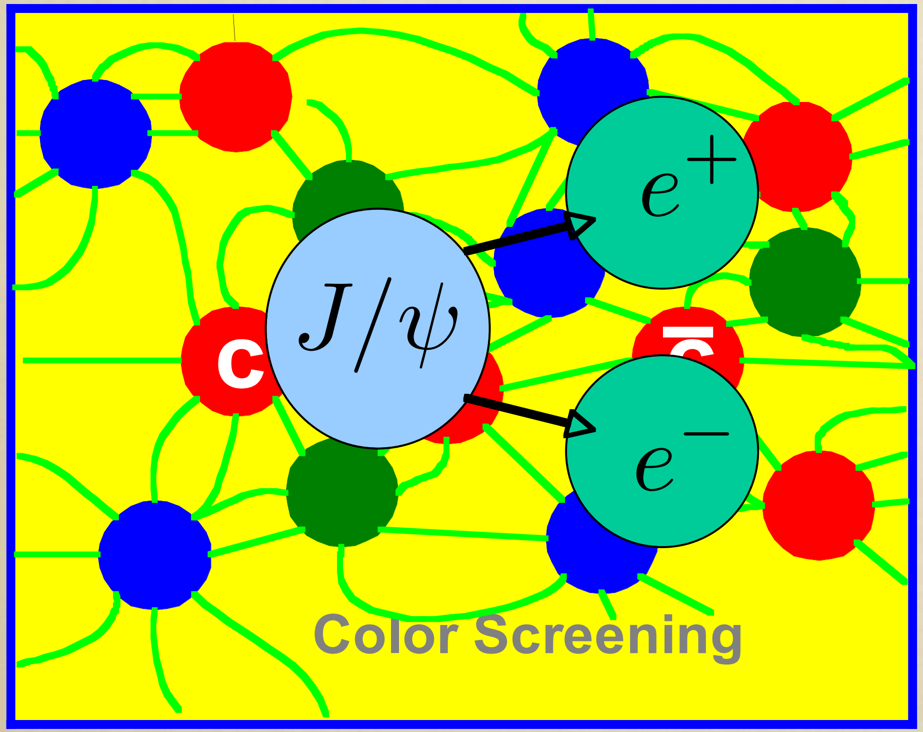

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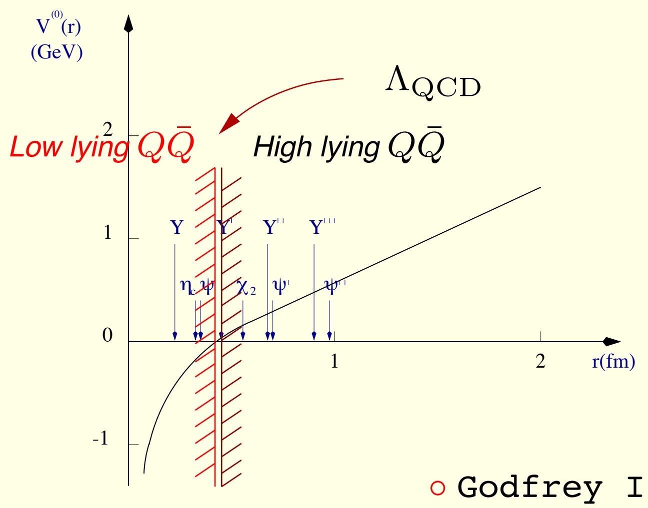

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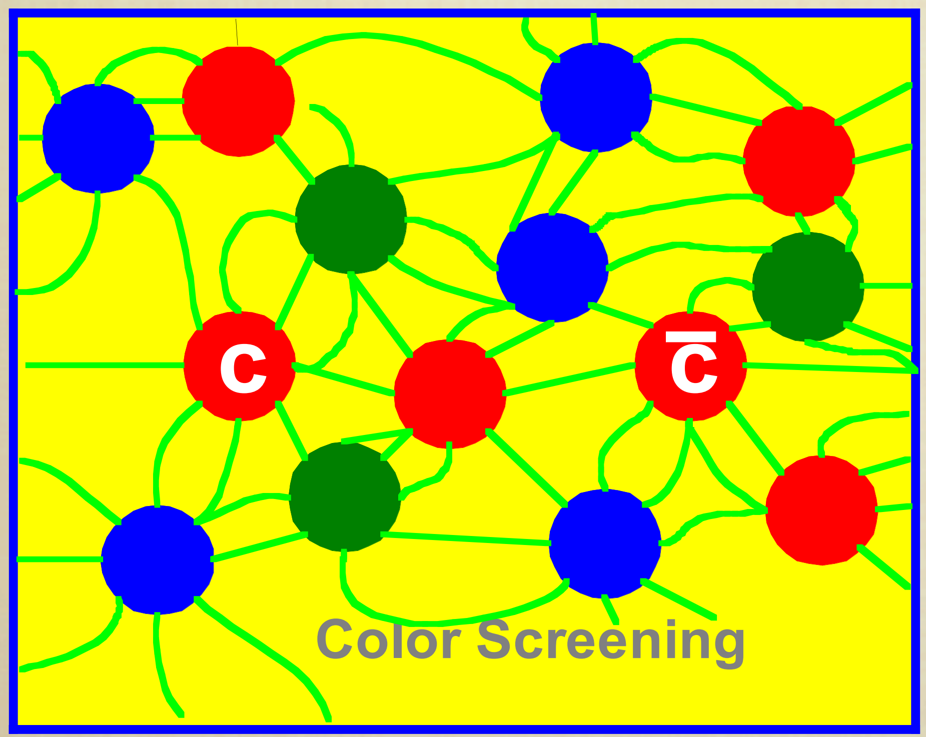

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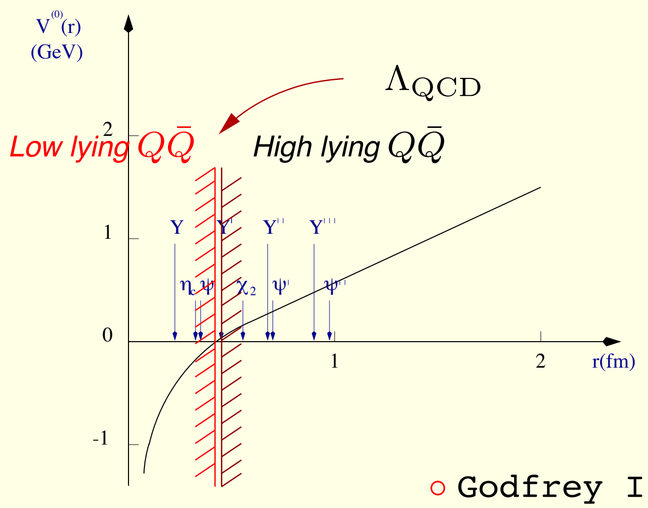

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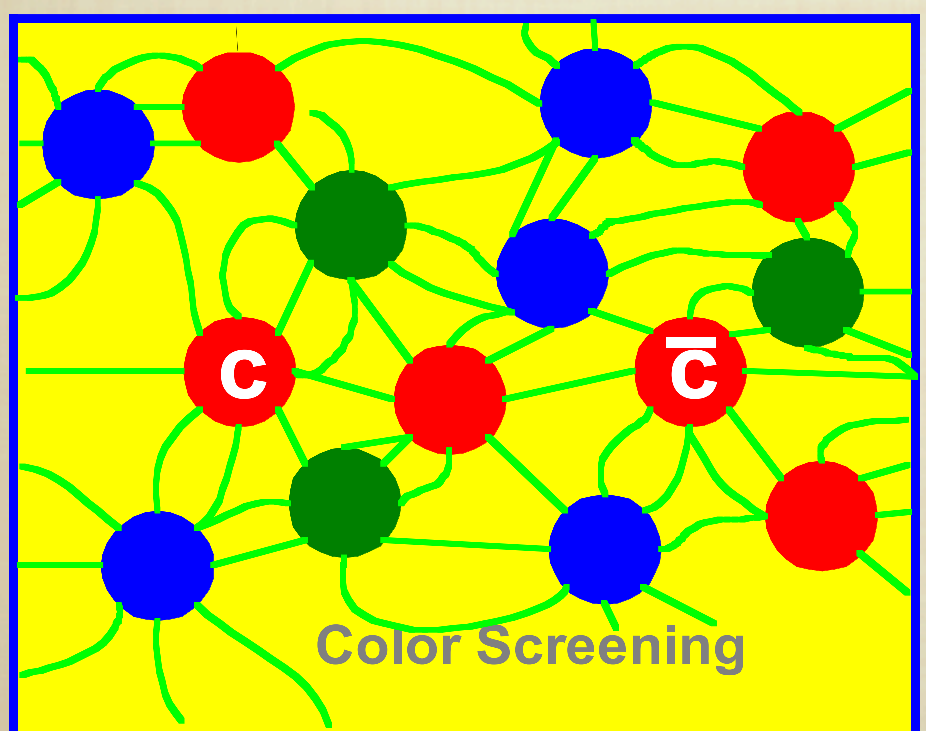

quarkonia dissociate at different temperature in dependence of their radius: they are a Quark Gluon Plasma thermometer

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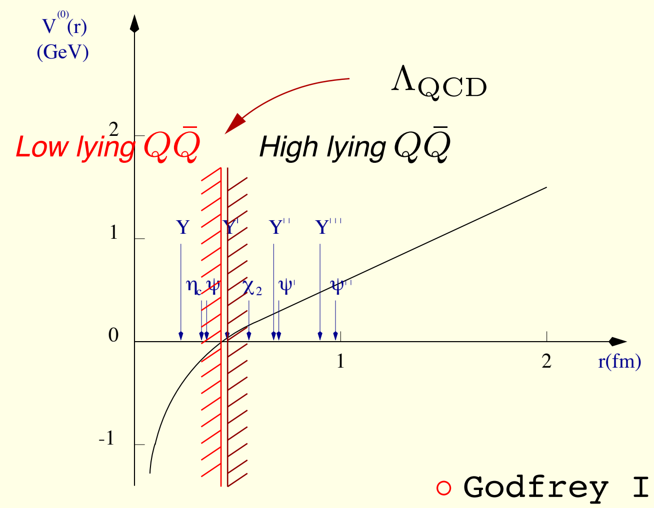

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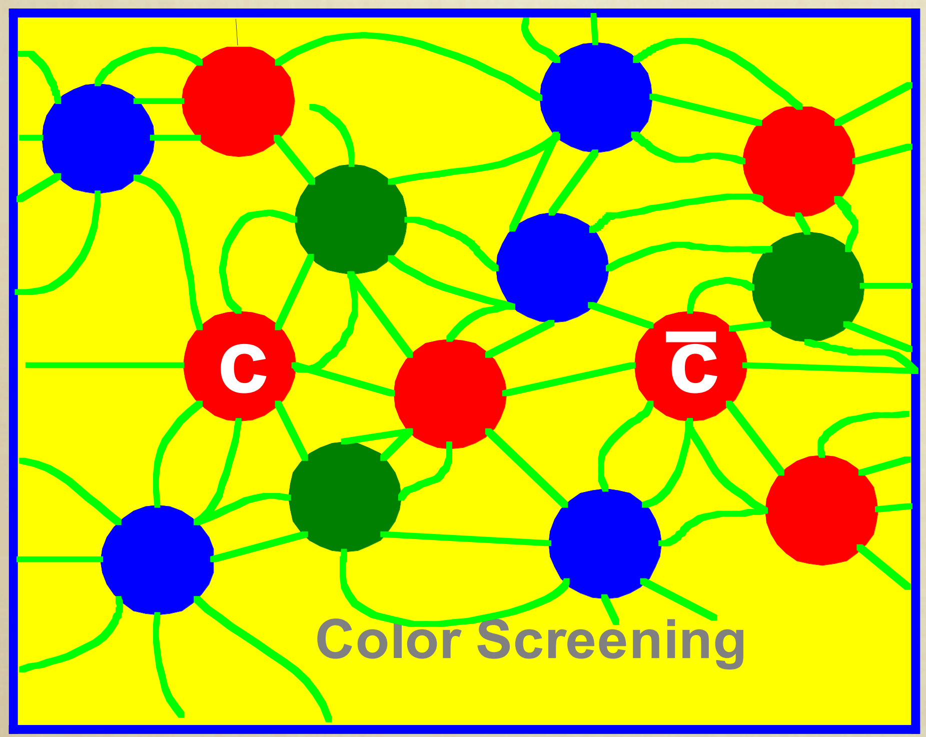

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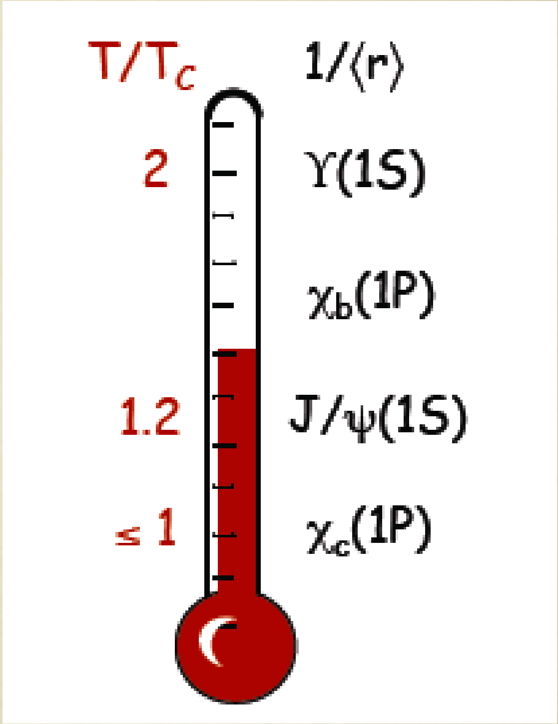

Quarkonium and experiments

B-FACTORIES: Heavy Mesons Factories

CLEO-c BESII tau charm factories

CLEO-III bottomonium factory

Fermilab CDF, D0, E835

Hera RHIC (Star, Phenix), NA60

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Discovery of New States, New Production Mechanisms, Exotics, New decays and transitions, Precision and high statistics data

More is expected in the future

BESIII, LHC-b

qqbar production at CMS and Atlas

Alice

Panda

Super B, ILC

Quarkonium in QCD : a very hard problem

Close to the bound state $\alpha_{\mathrm{s}} \sim v$

Quarkonium in QCD : a very hard problem

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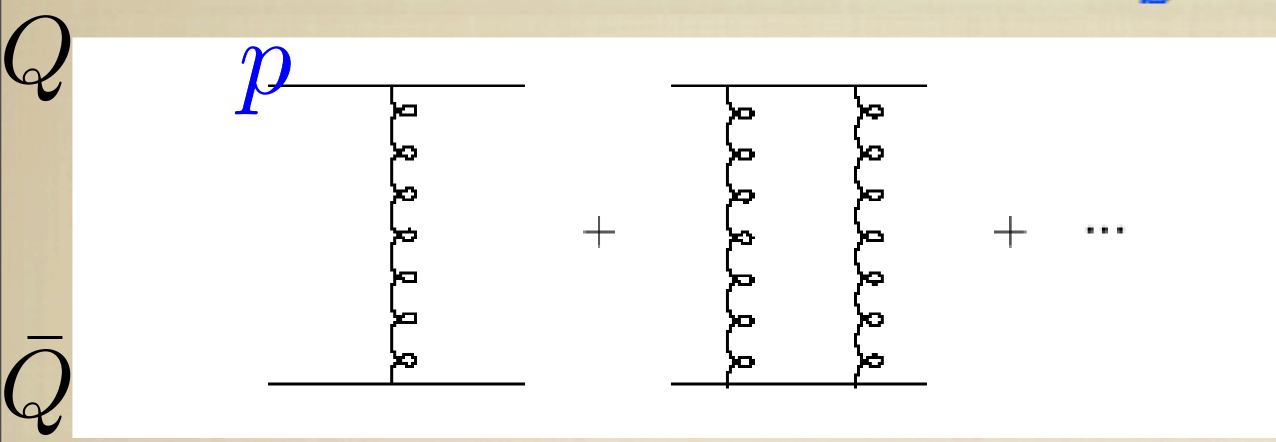

Quarkonium in QCD : a very hard problem

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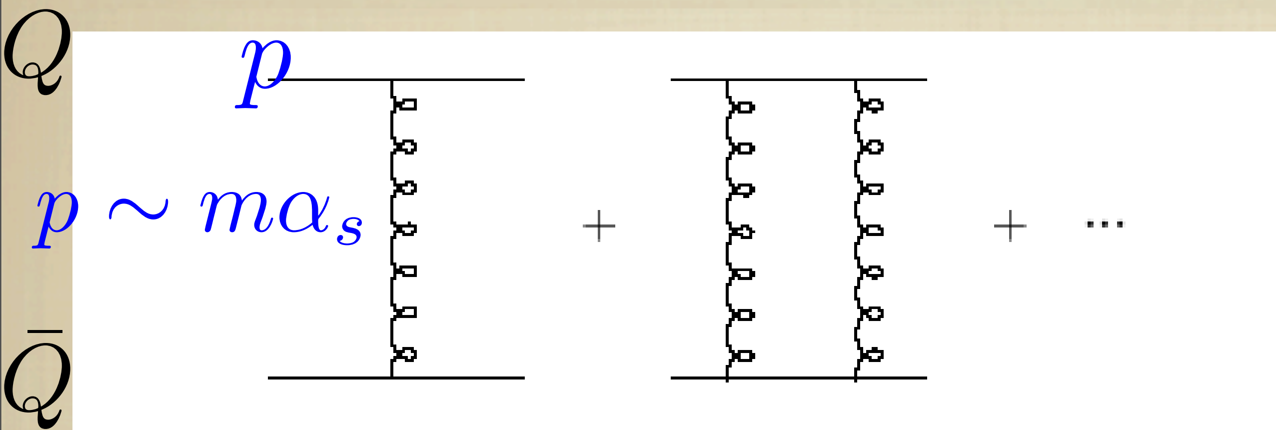

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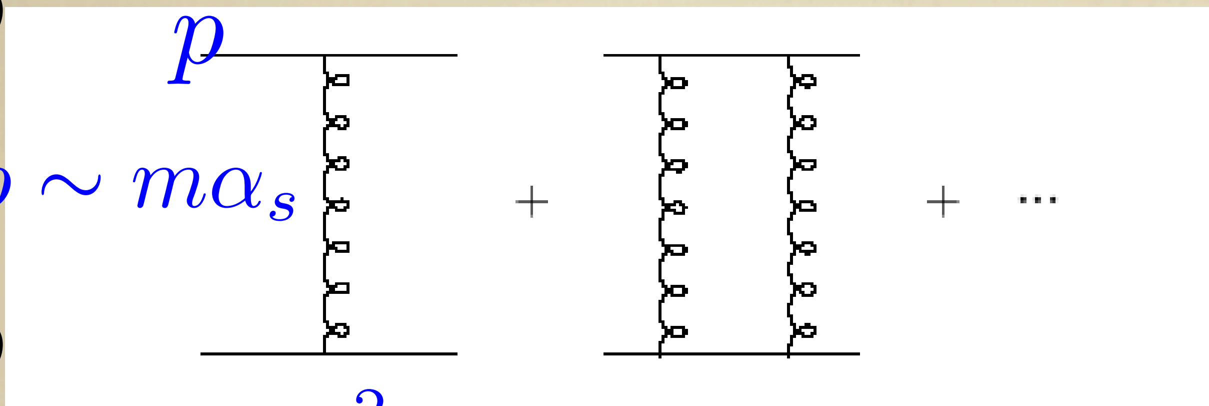
Q p

$p \sim m\alpha_s$



$\bar{Q}$

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

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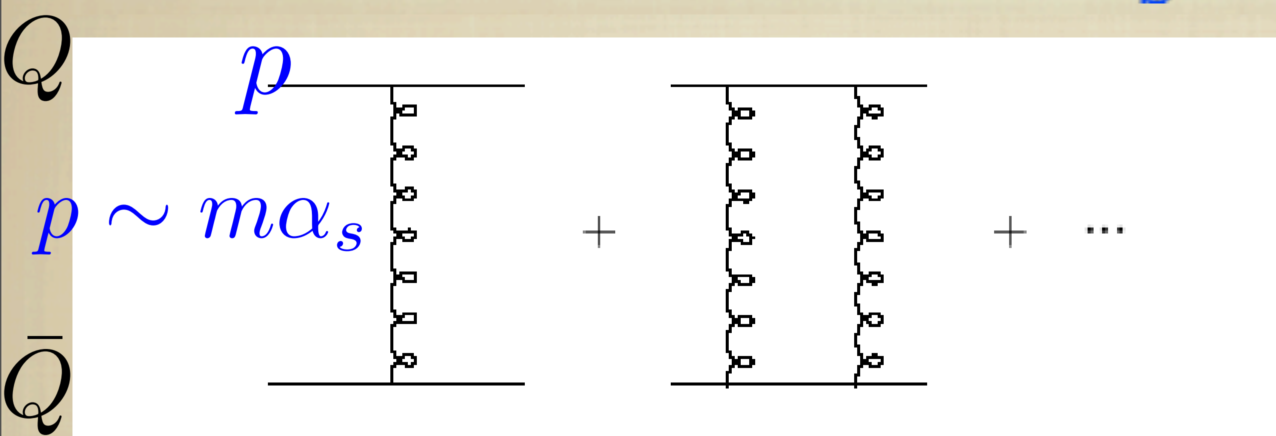

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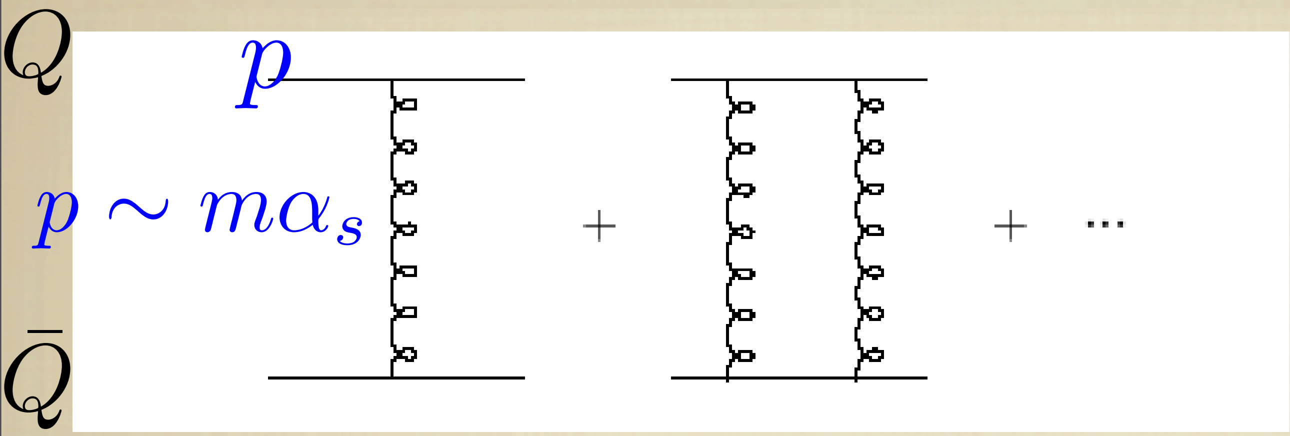

$$\sim \frac{1}{E - (\frac{p^2}{m} + V)}$$

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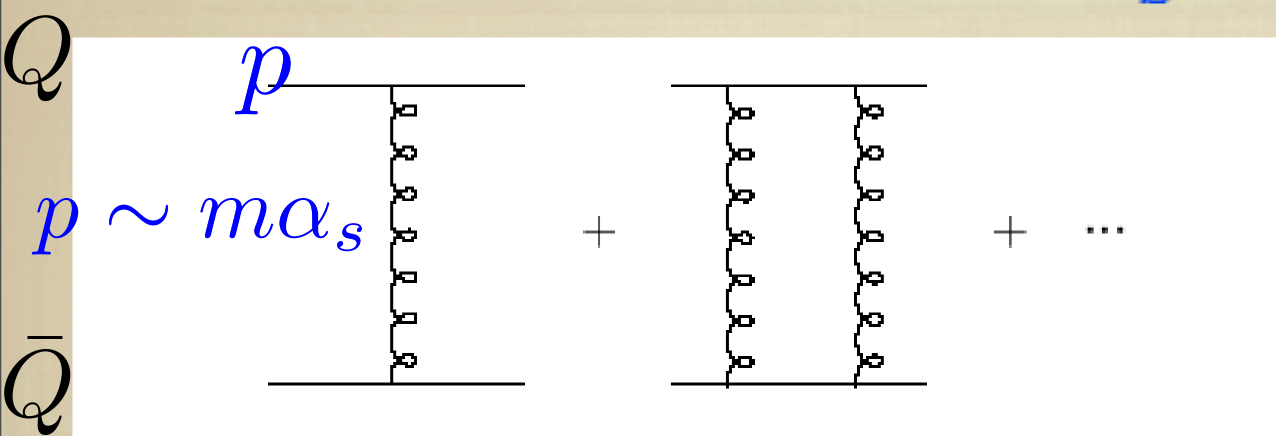

$$\sim \frac{1}{E - (\frac{p^2}{m} + V)}$$

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

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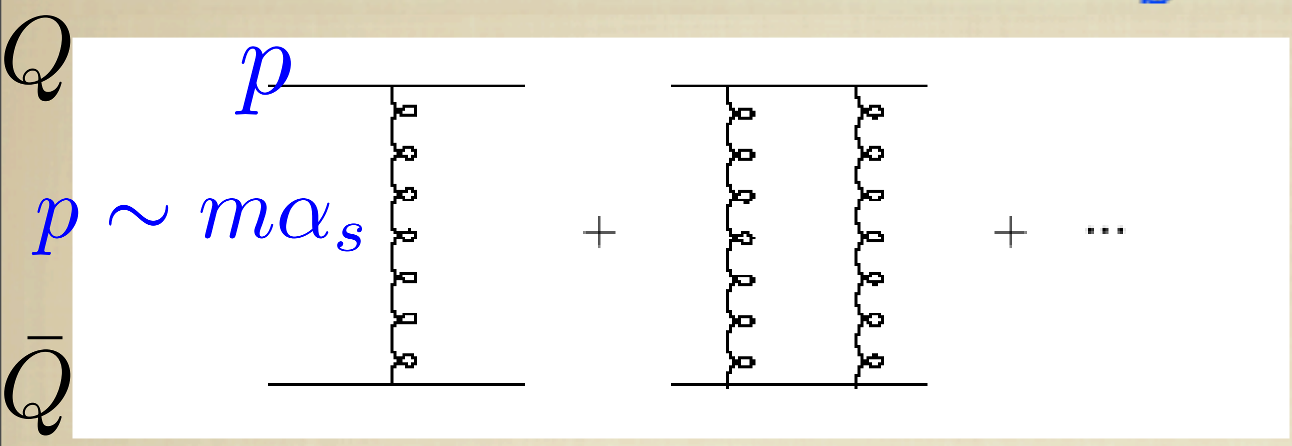

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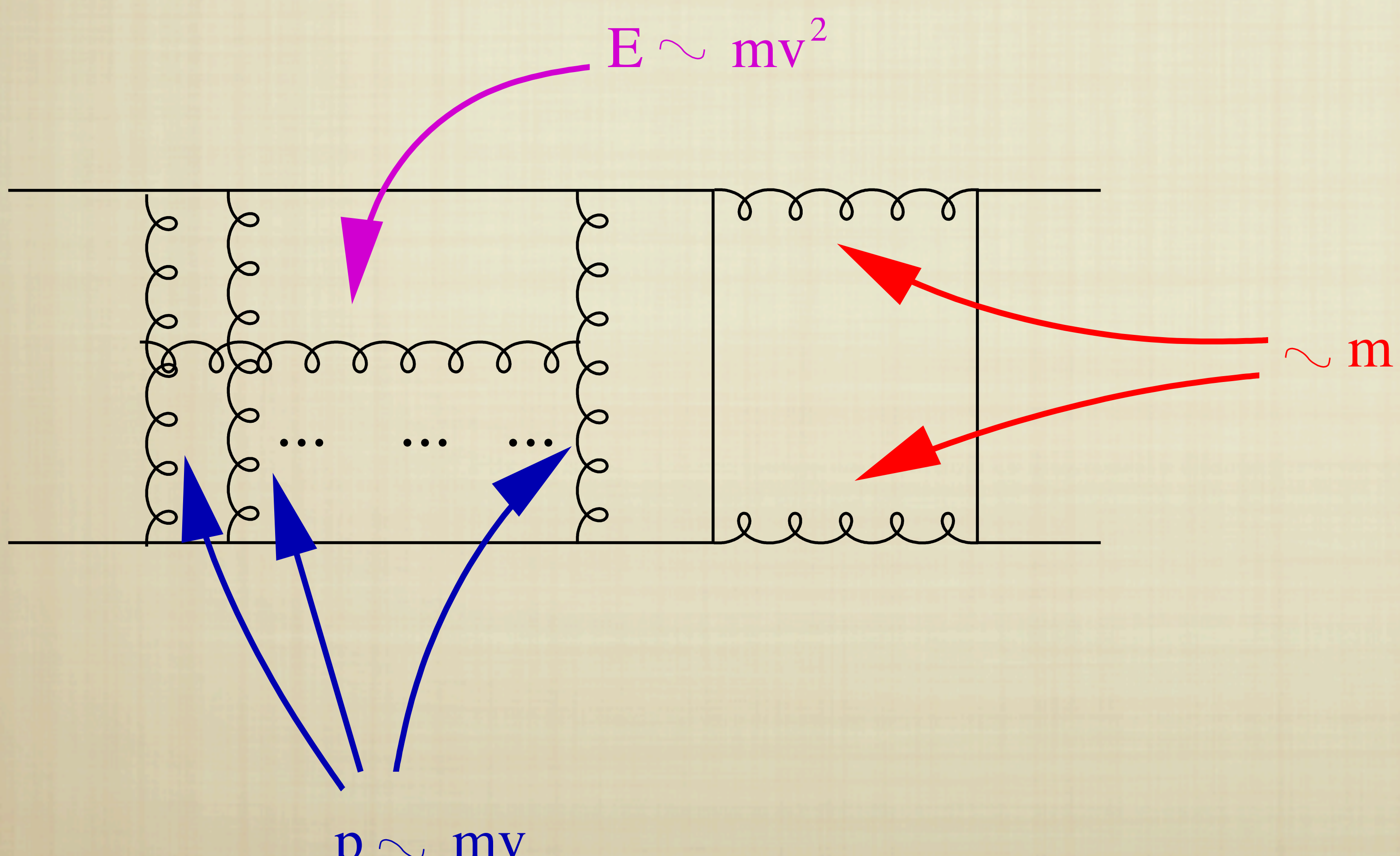

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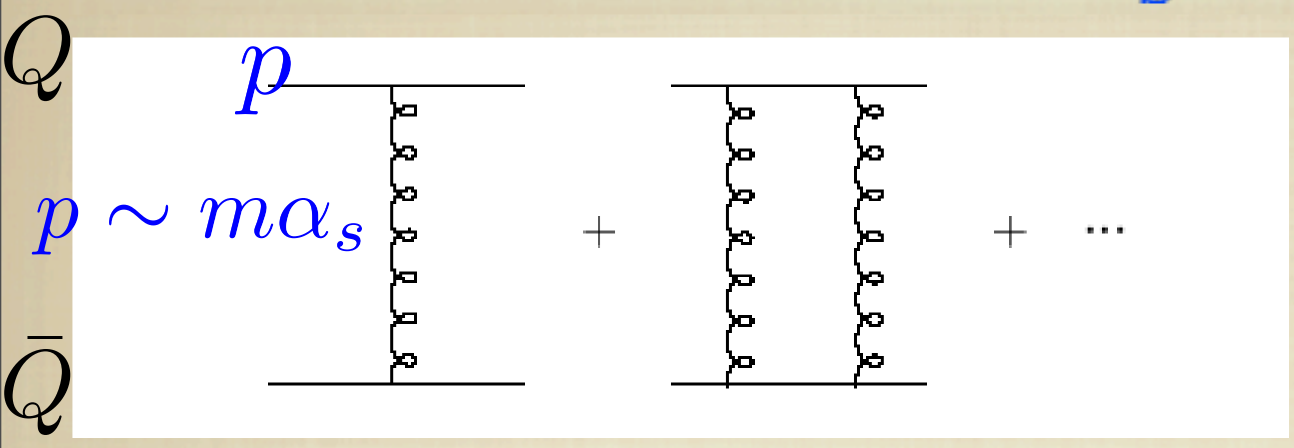

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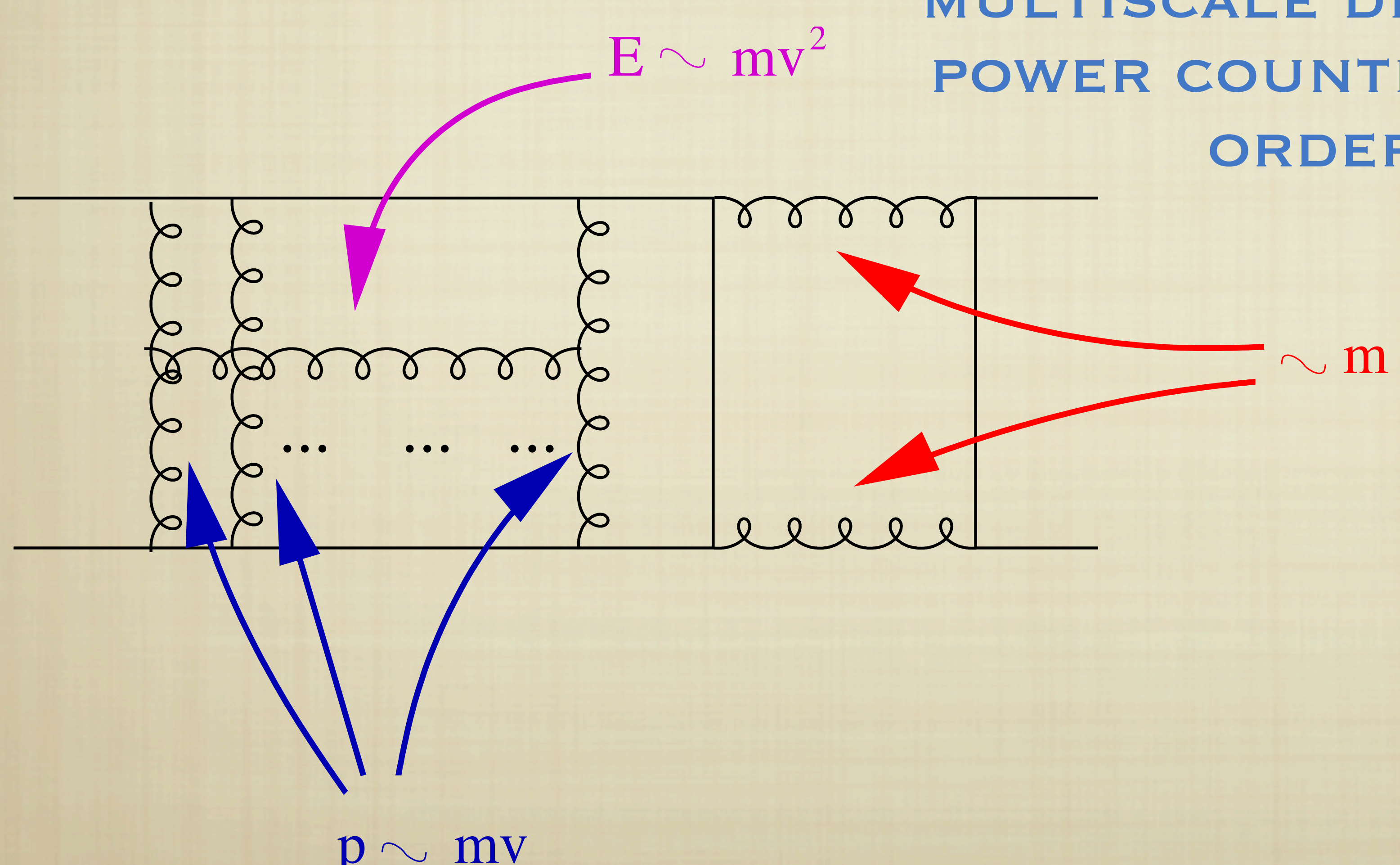
MULTISCALE DIAGRAMS HAVE A COMPLICATE POWER COUNTING AND CONTRIBUTE TO ALL ORDERS IN THE COUPLING



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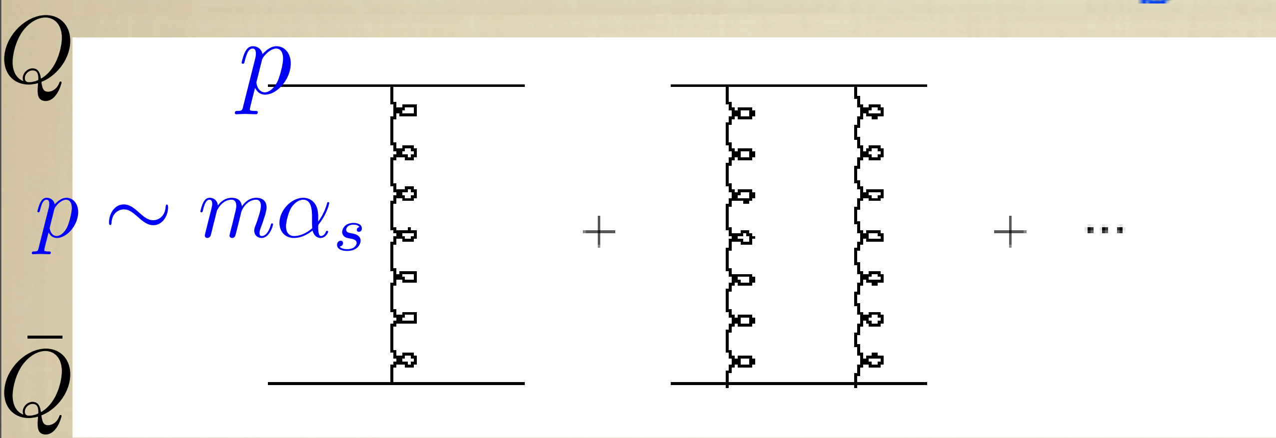

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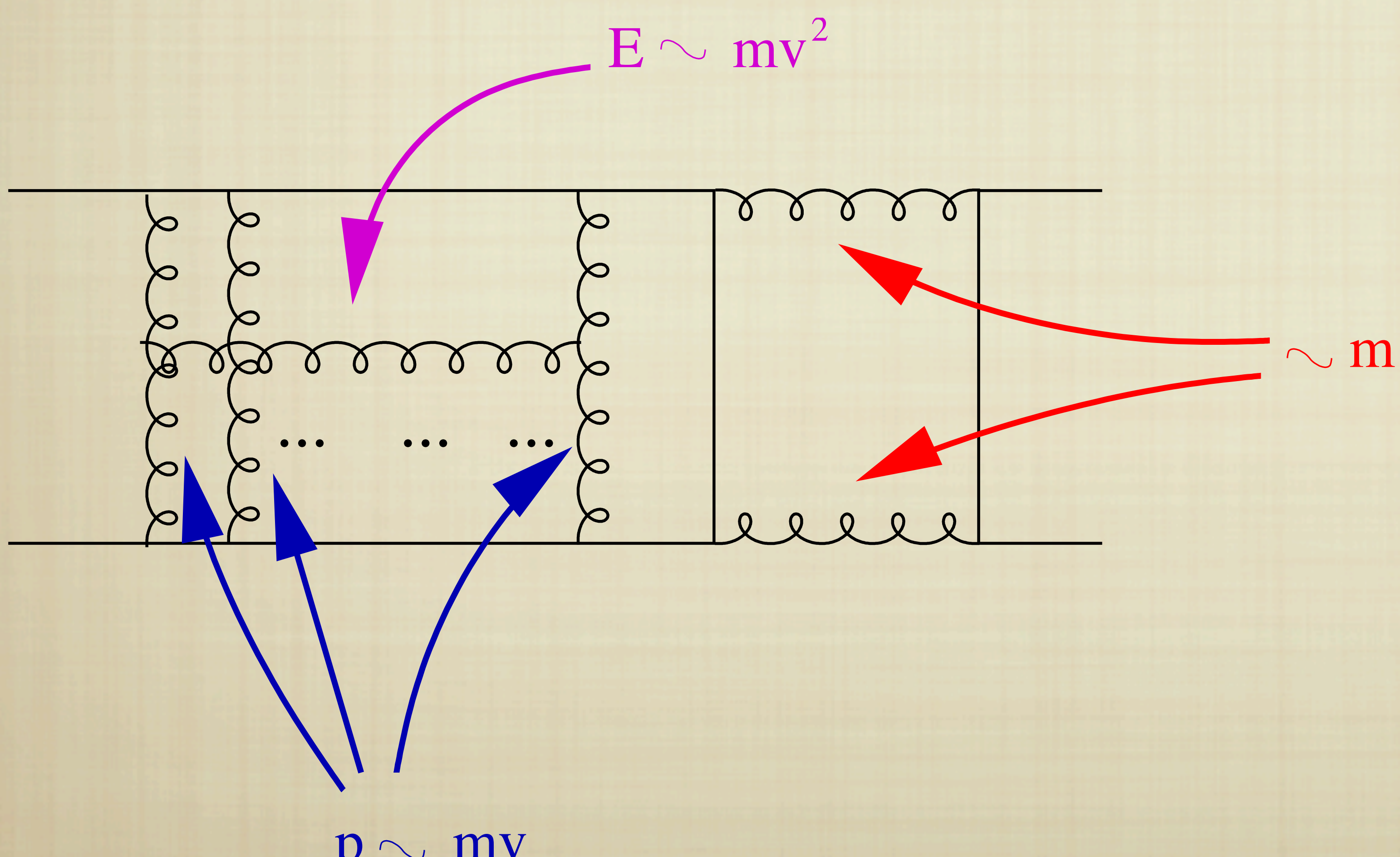

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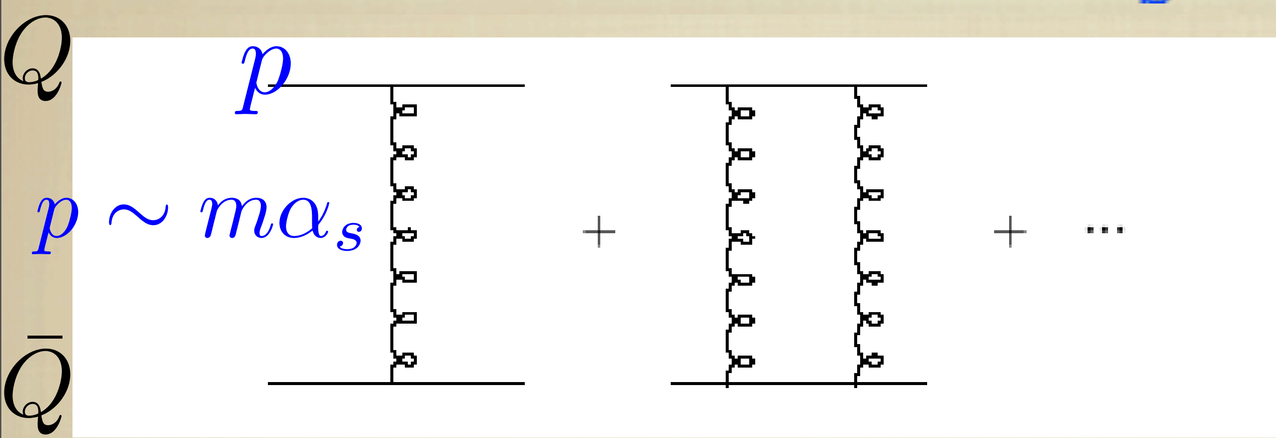

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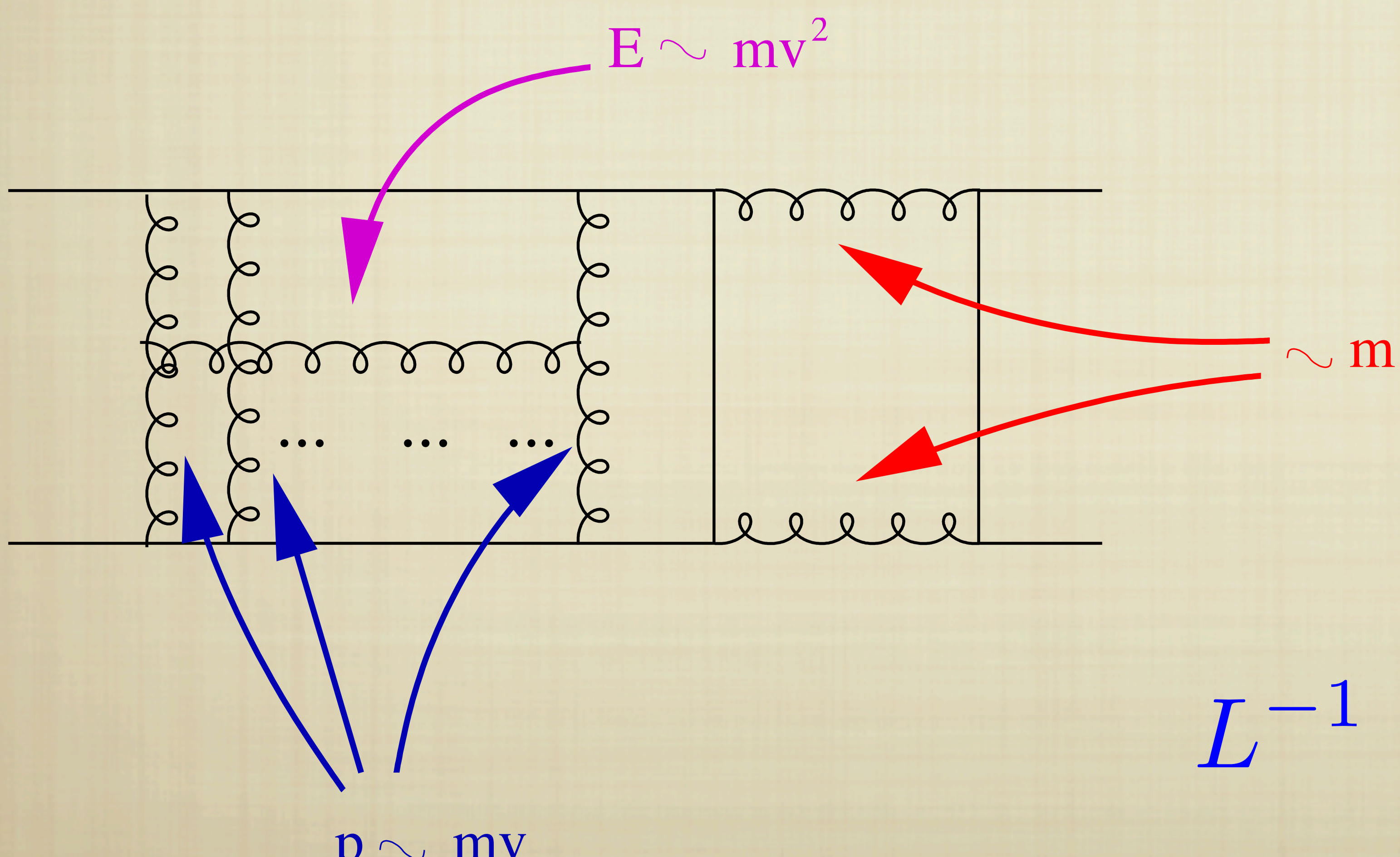


Difficult also for the lattice!

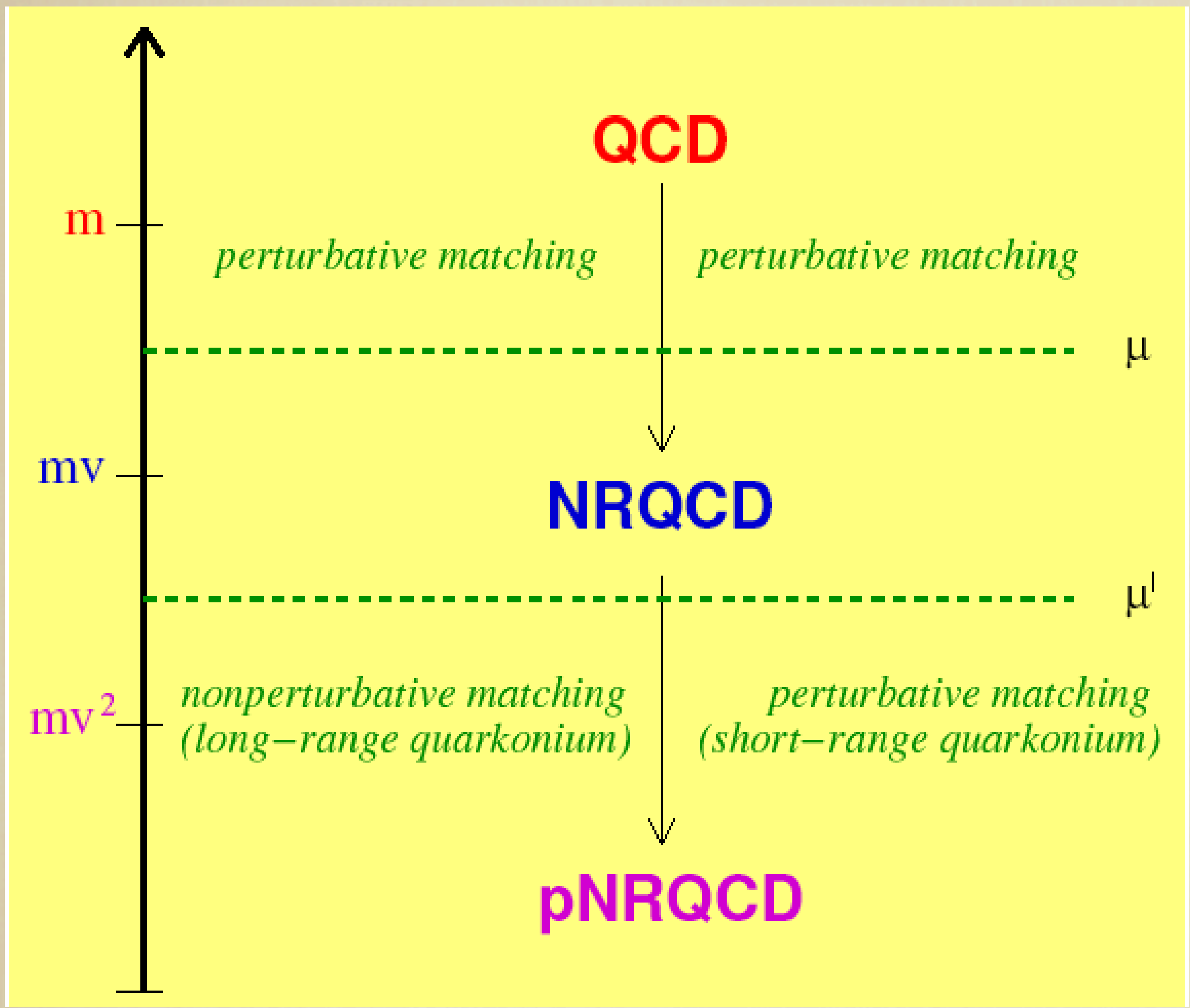
$$L^{-1} \ll \lambda \ll \Lambda \ll a^{-1}$$

Quarkonium with EFT

Color degrees of freedom

3X3=1+8

singlet and octet QQbar



Hard

Soft
(relative momentum)

Ultrasoft
(binding energy)

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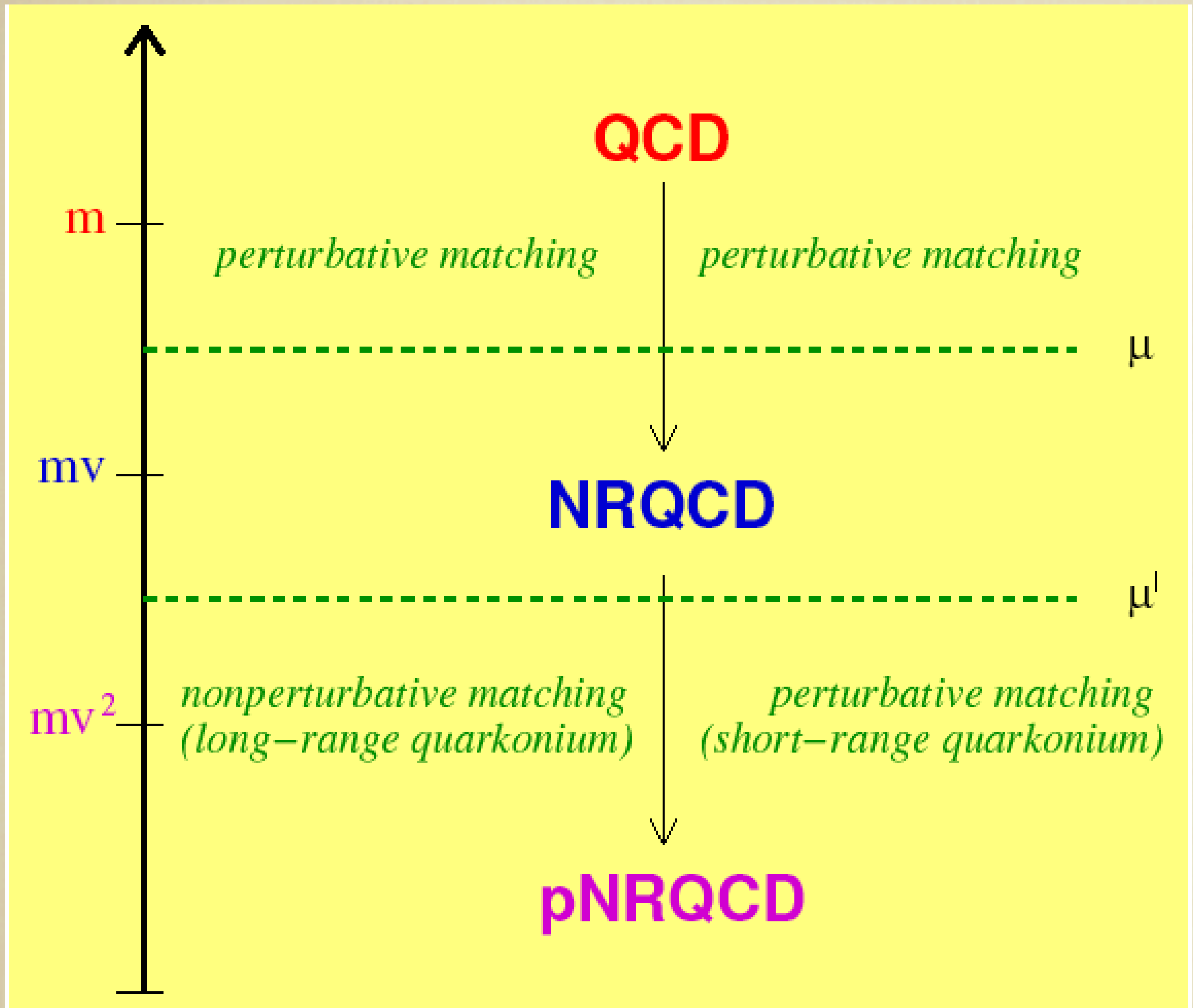

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$$\mathcal{L}_{\rm EFT} = \sum_n c_n(E_\Lambda/\mu)\frac{O_n(\mu,\lambda)}{E_\Lambda}$$

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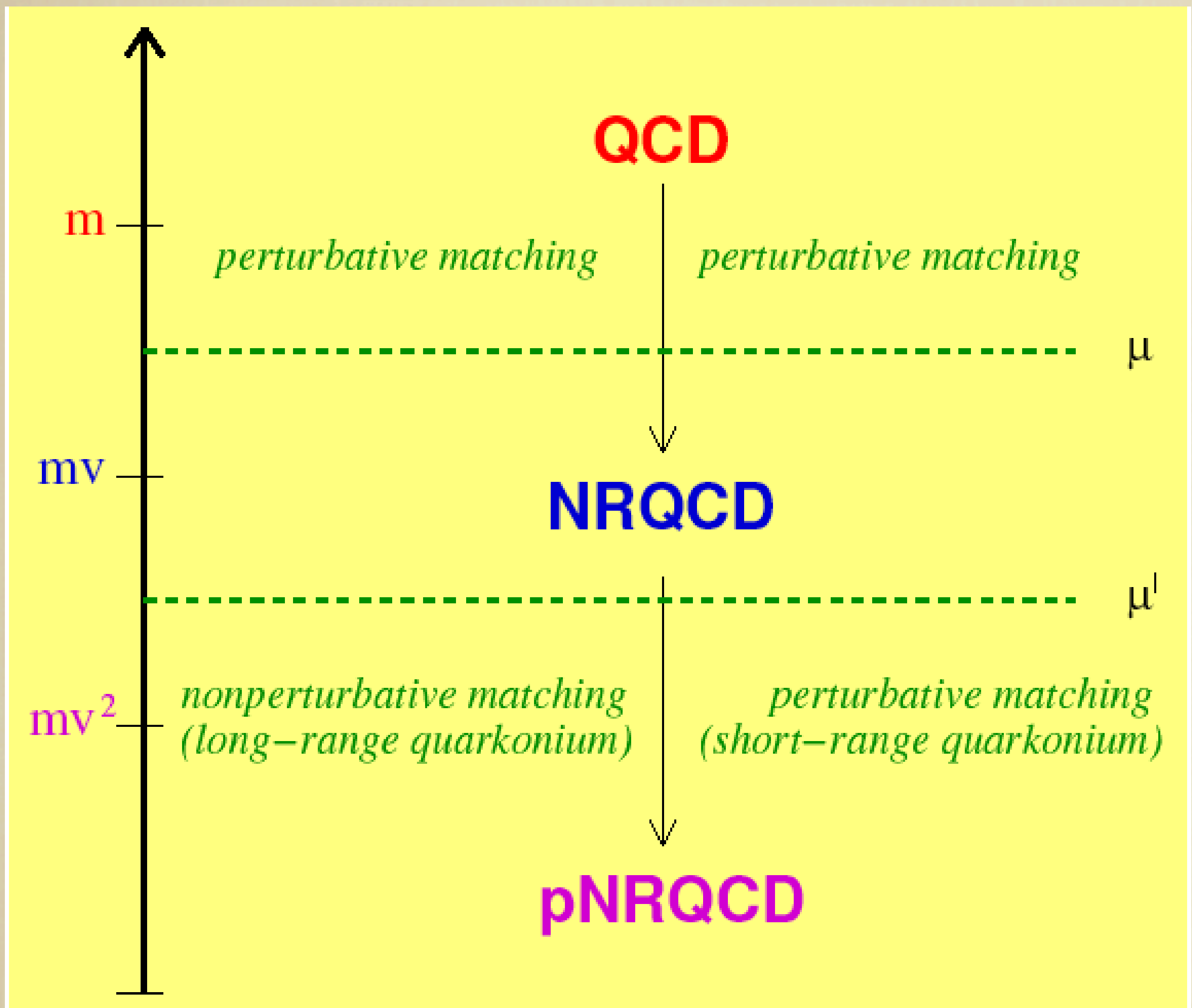

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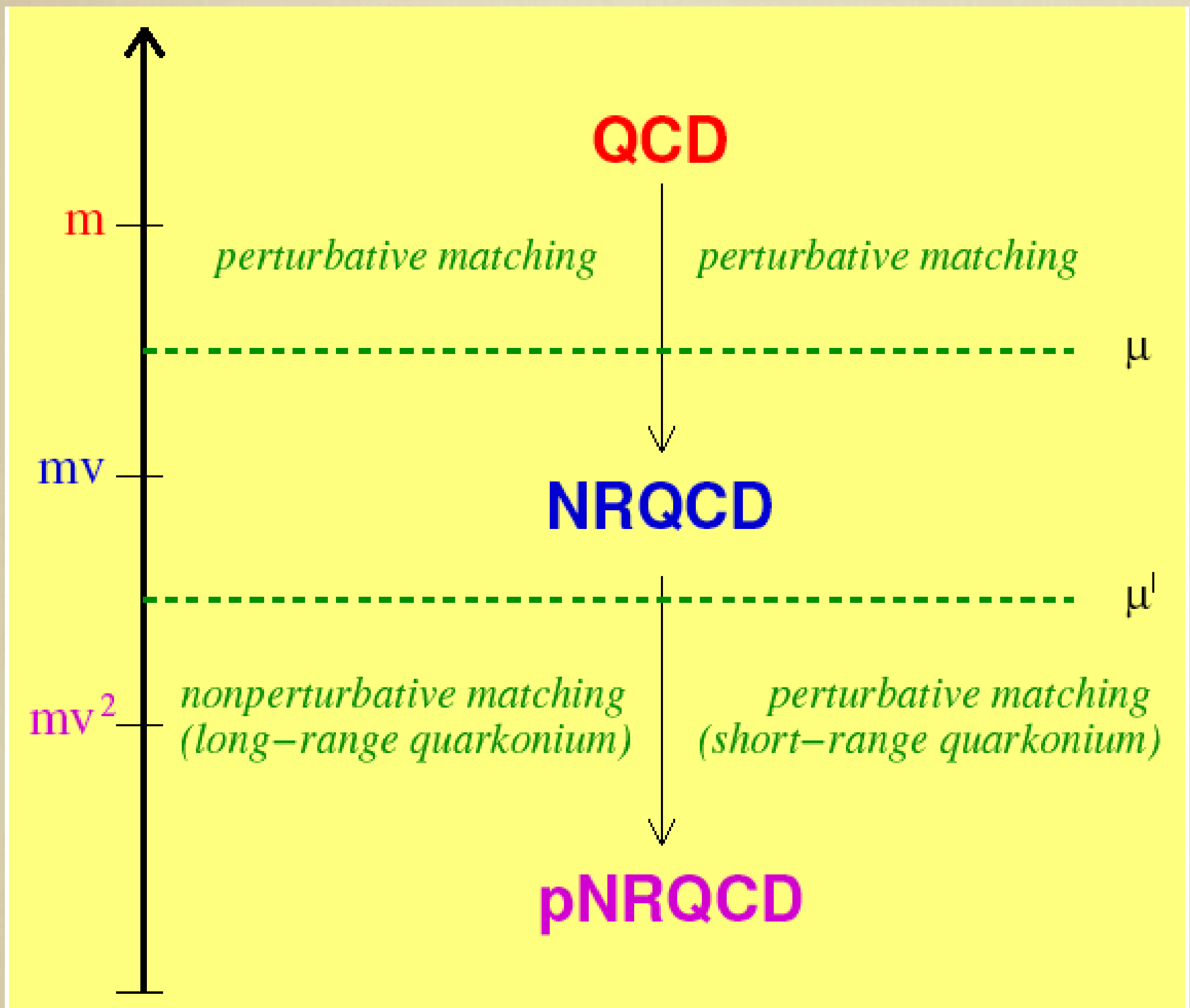

Hard

$$\frac{E_\lambda}{E_\Lambda} = \frac{mv}{m}$$

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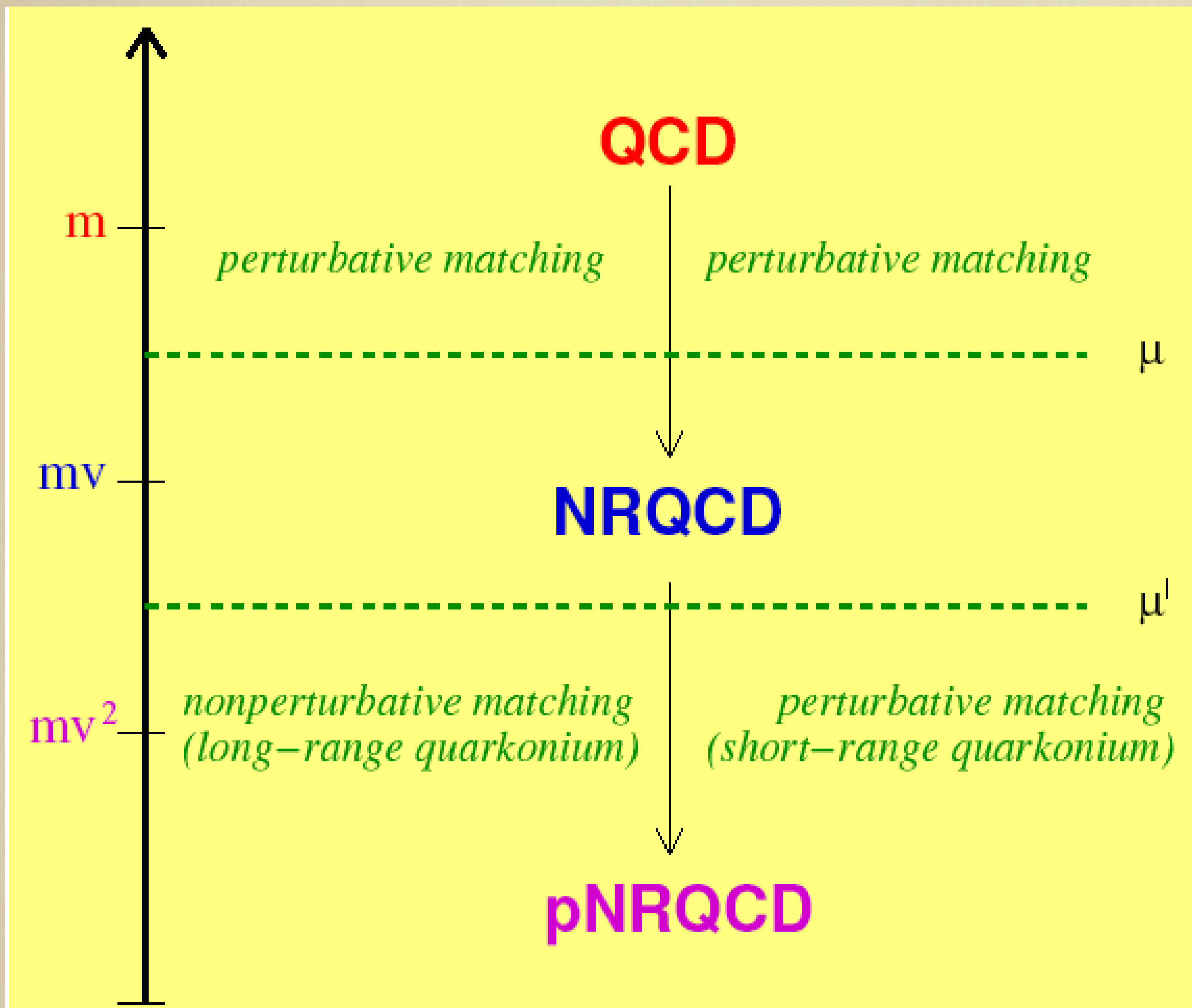

Hard

$$\frac{E_\lambda}{E_\Lambda} = \frac{mv}{m}$$

Soft (relative momentum)

$$\frac{E_\lambda}{E_\Lambda} = \frac{mv^2}{mv}$$

Ultrasoft (binding energy)

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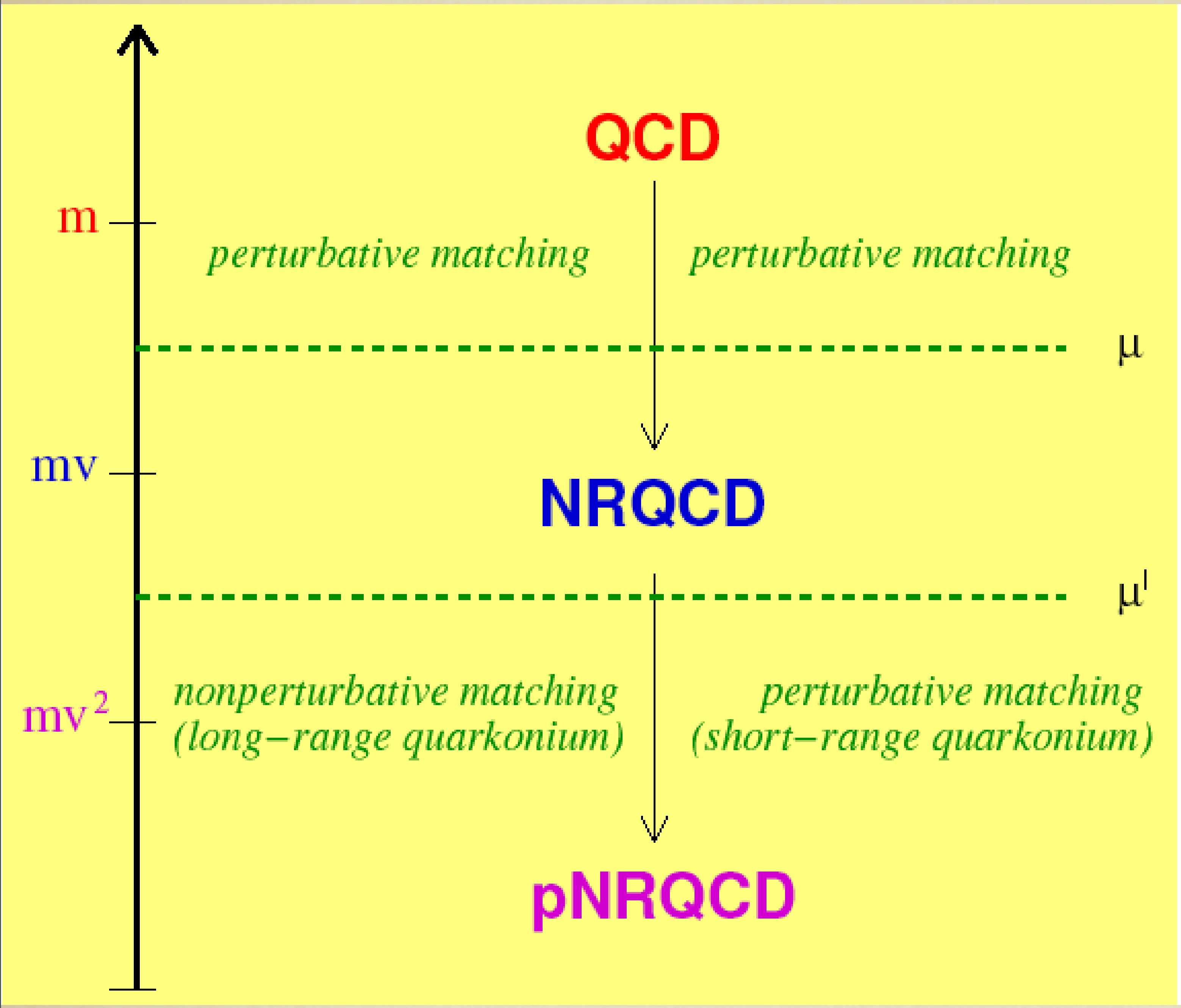
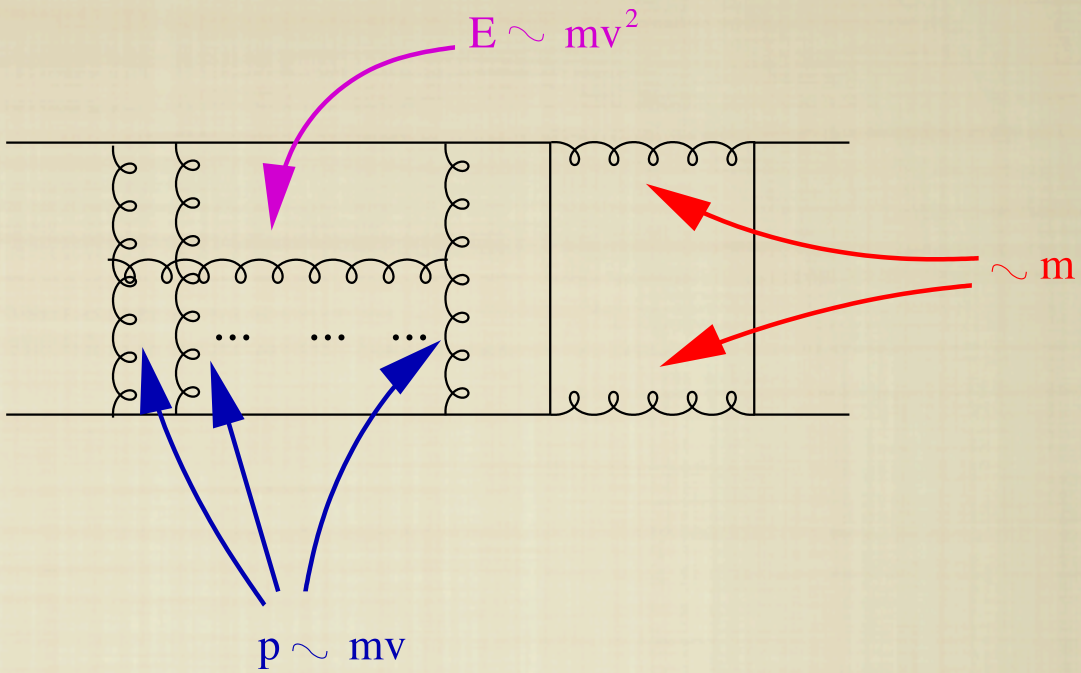
$$\langle O_n \rangle \sim E_\lambda^n$$

Quarkonium with EFT: Non Relativistic QCD (NRQCD)





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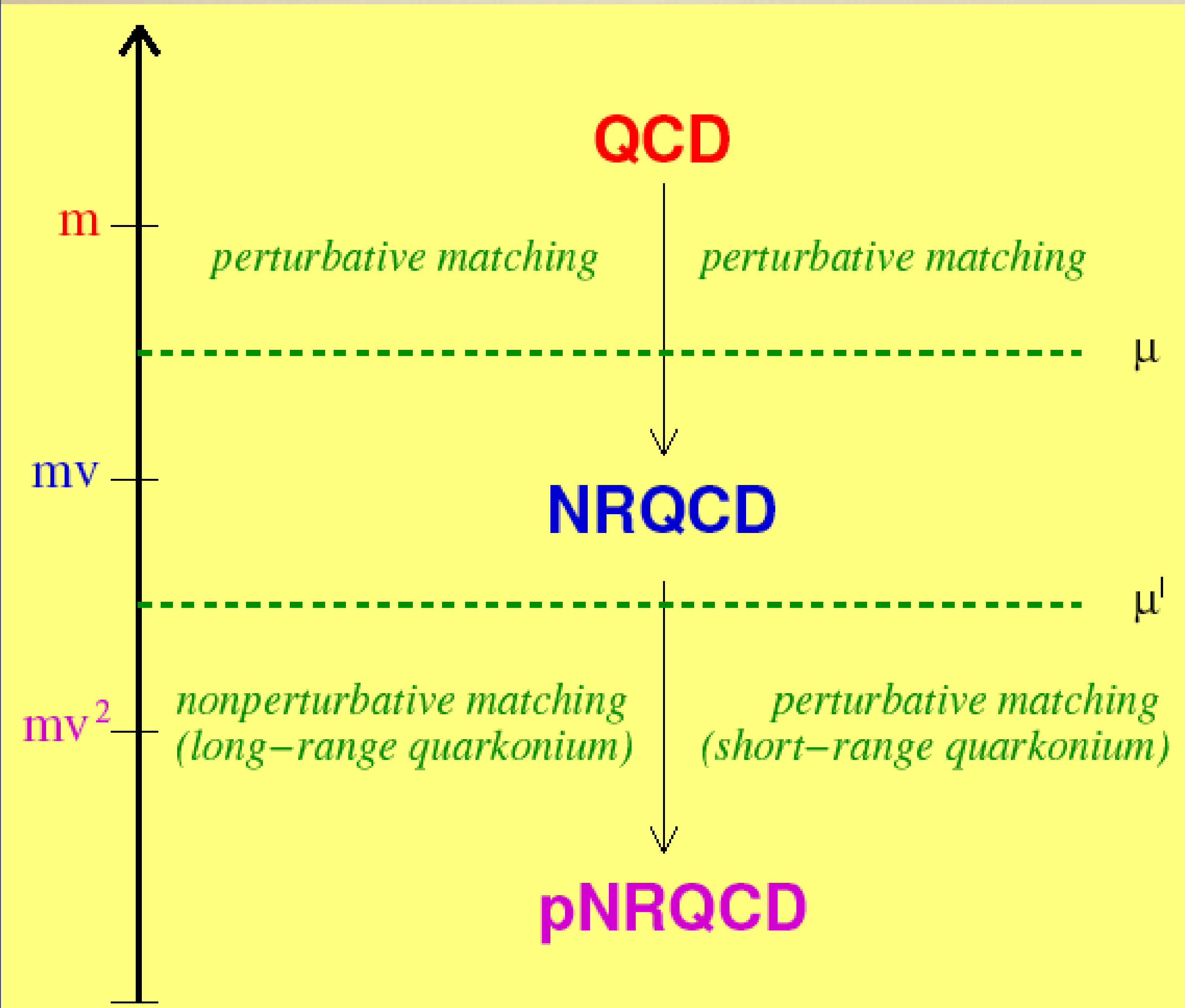

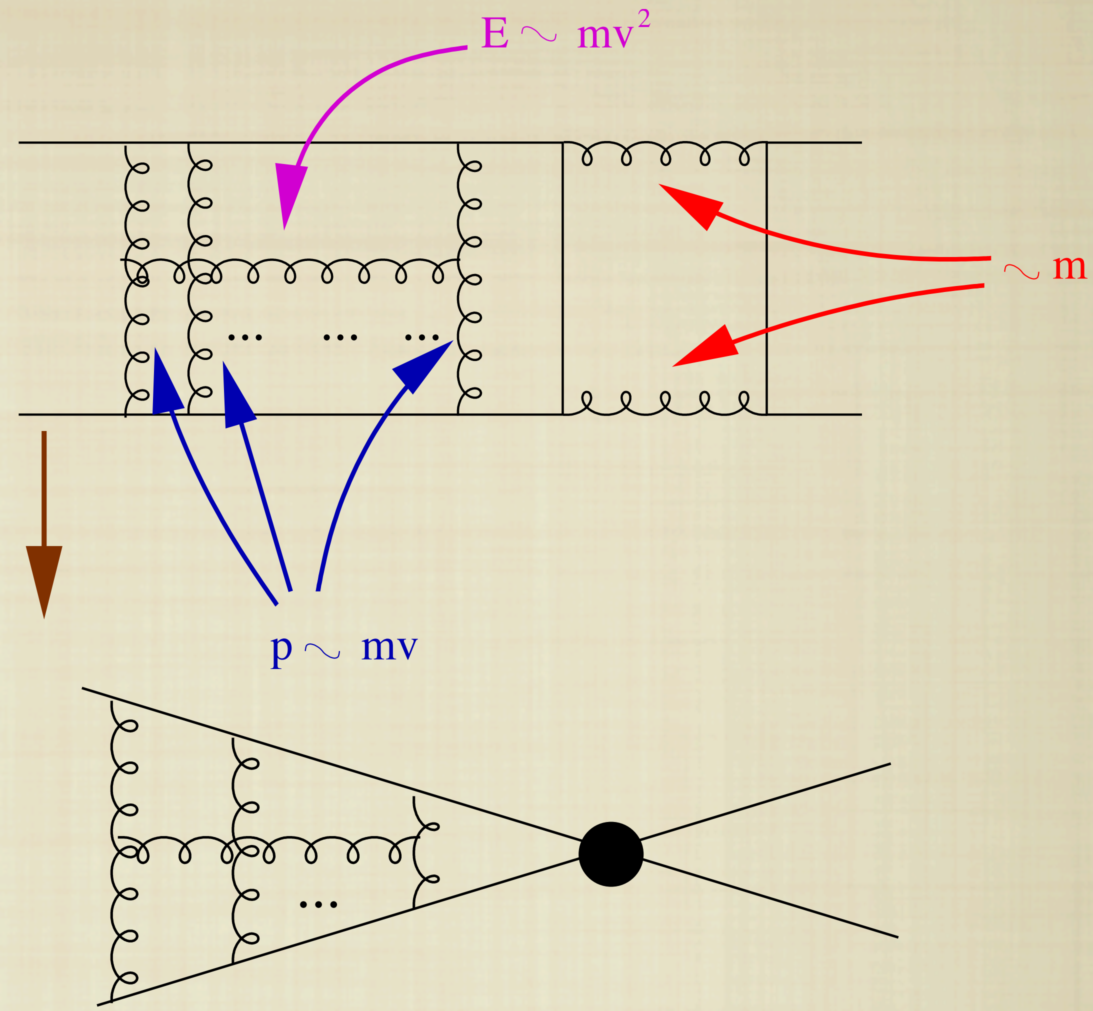

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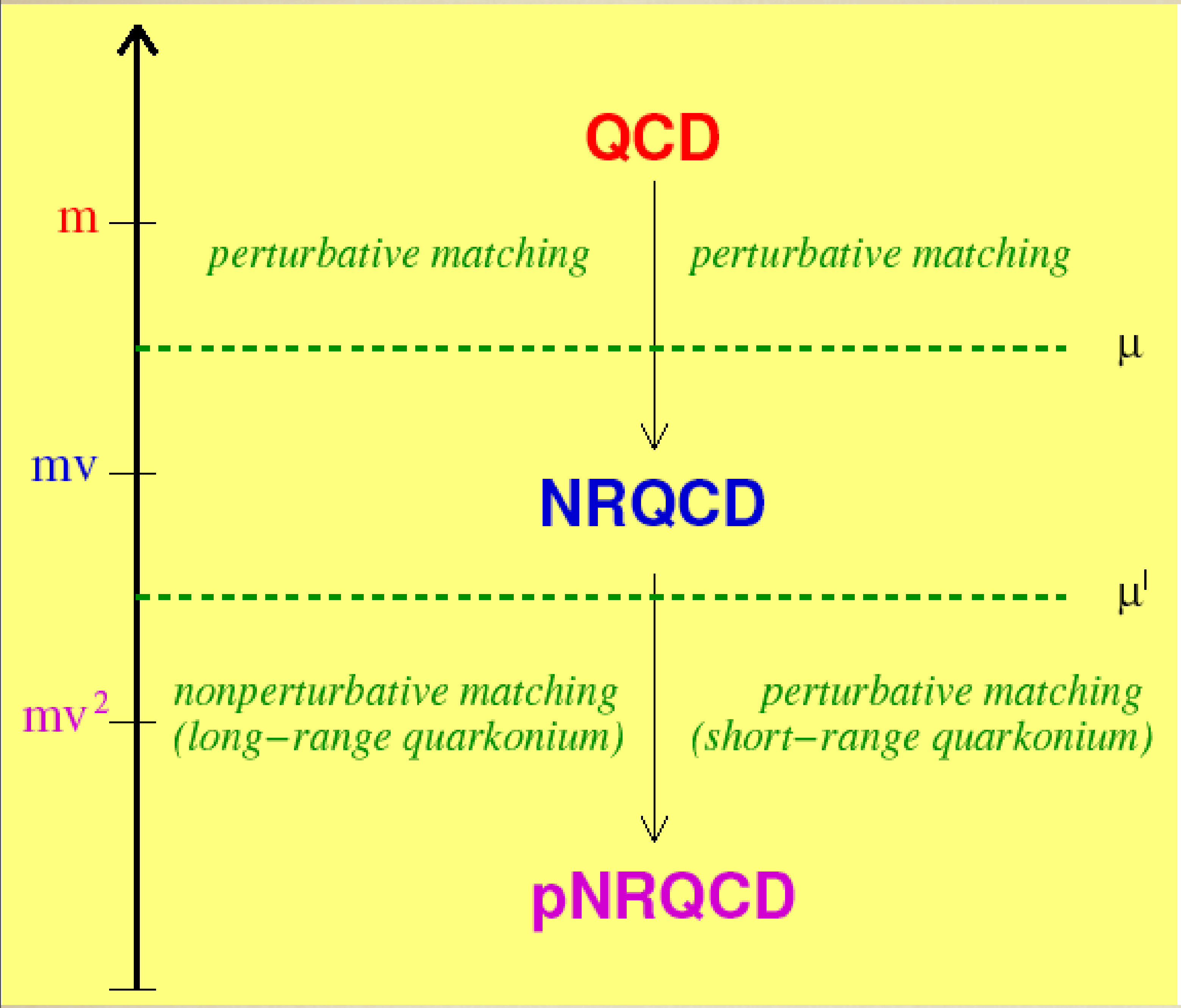
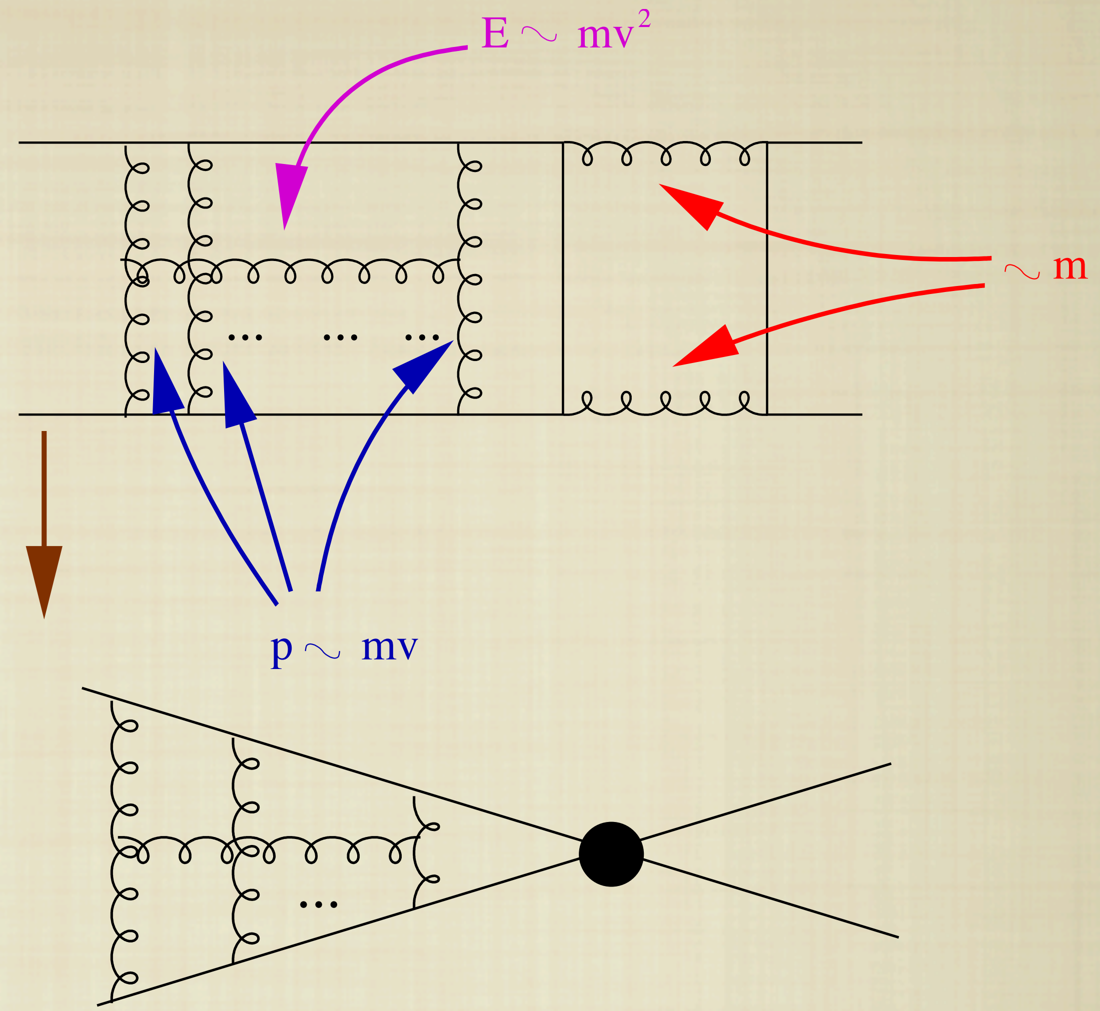
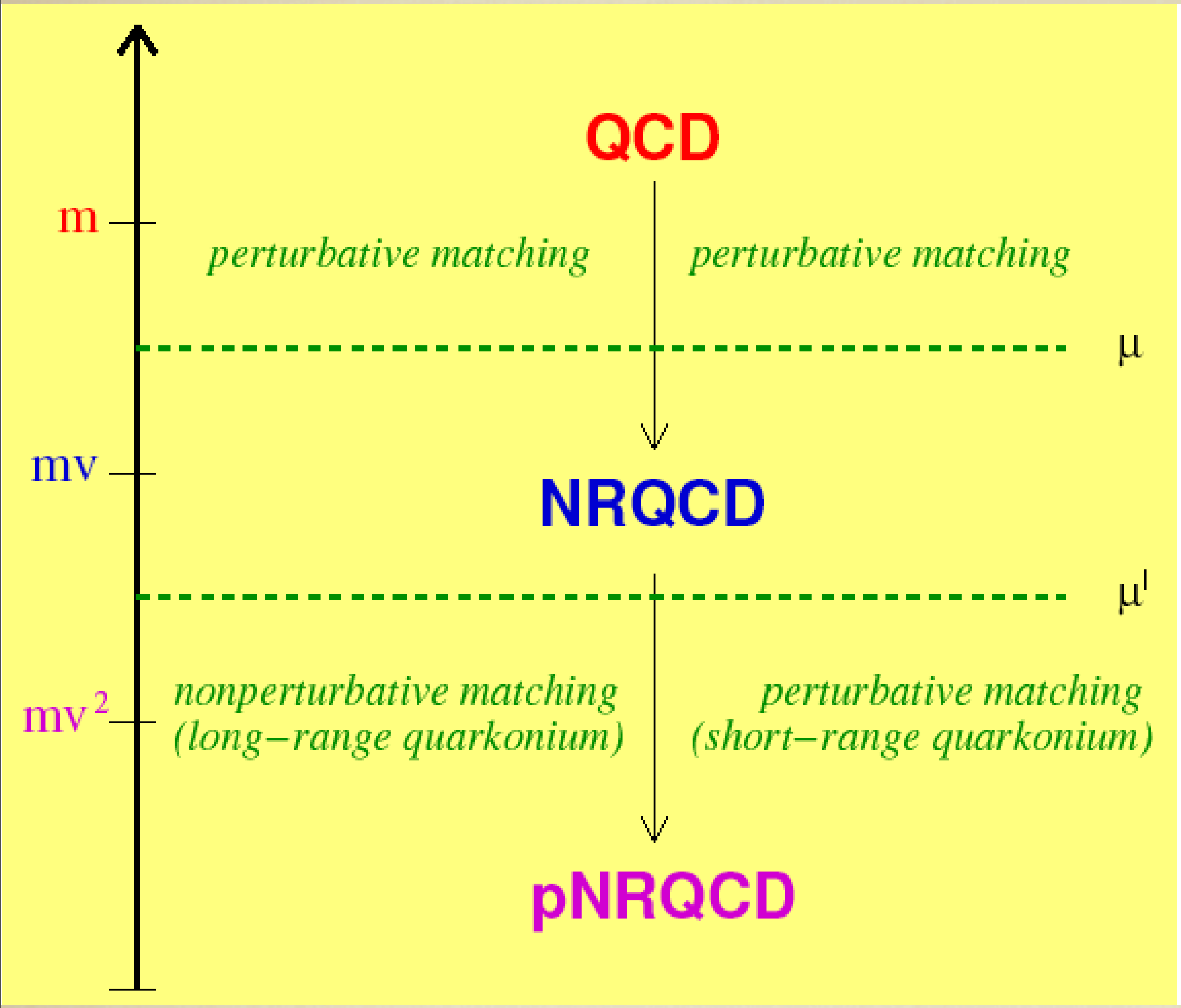
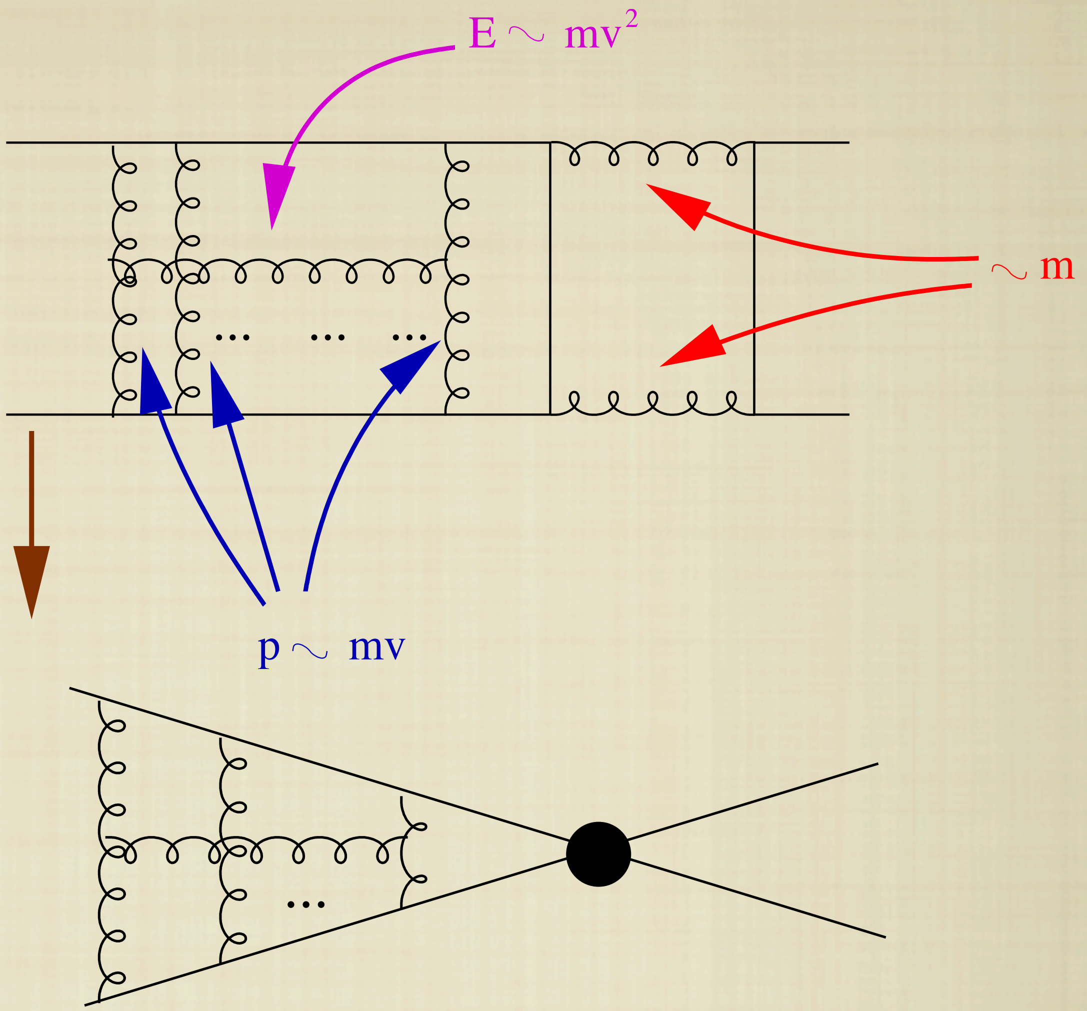




$$\mathcal{L}_{\mathrm{NRQCD}} = \sum_n c(\alpha_{\mathrm{s}}(m/\mu)) \times \frac{O_n(\mu,\lambda)}{m^n}$$

Quarkonium with EFT: potential NonRelativistic QCD (pNRQCD)





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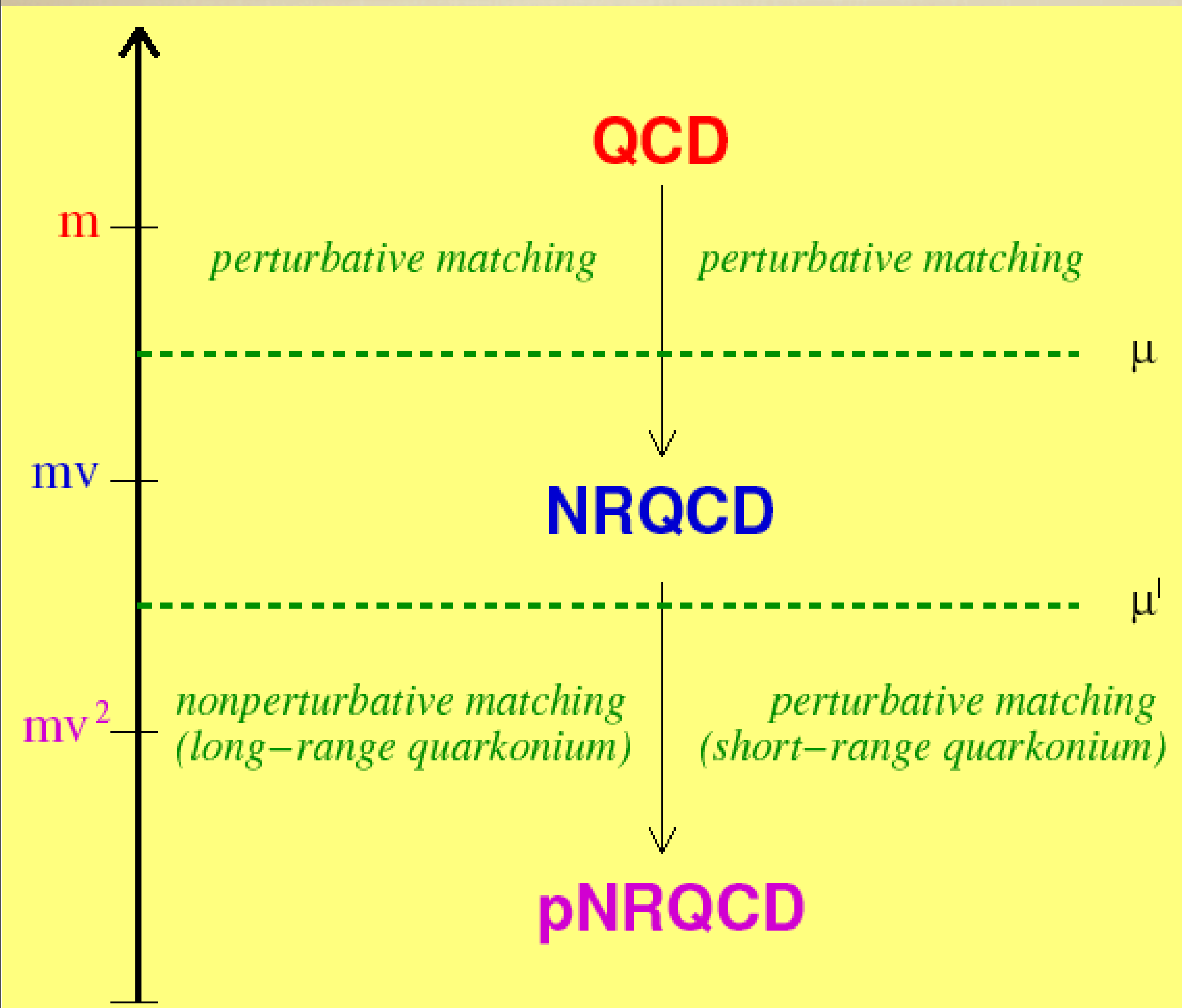

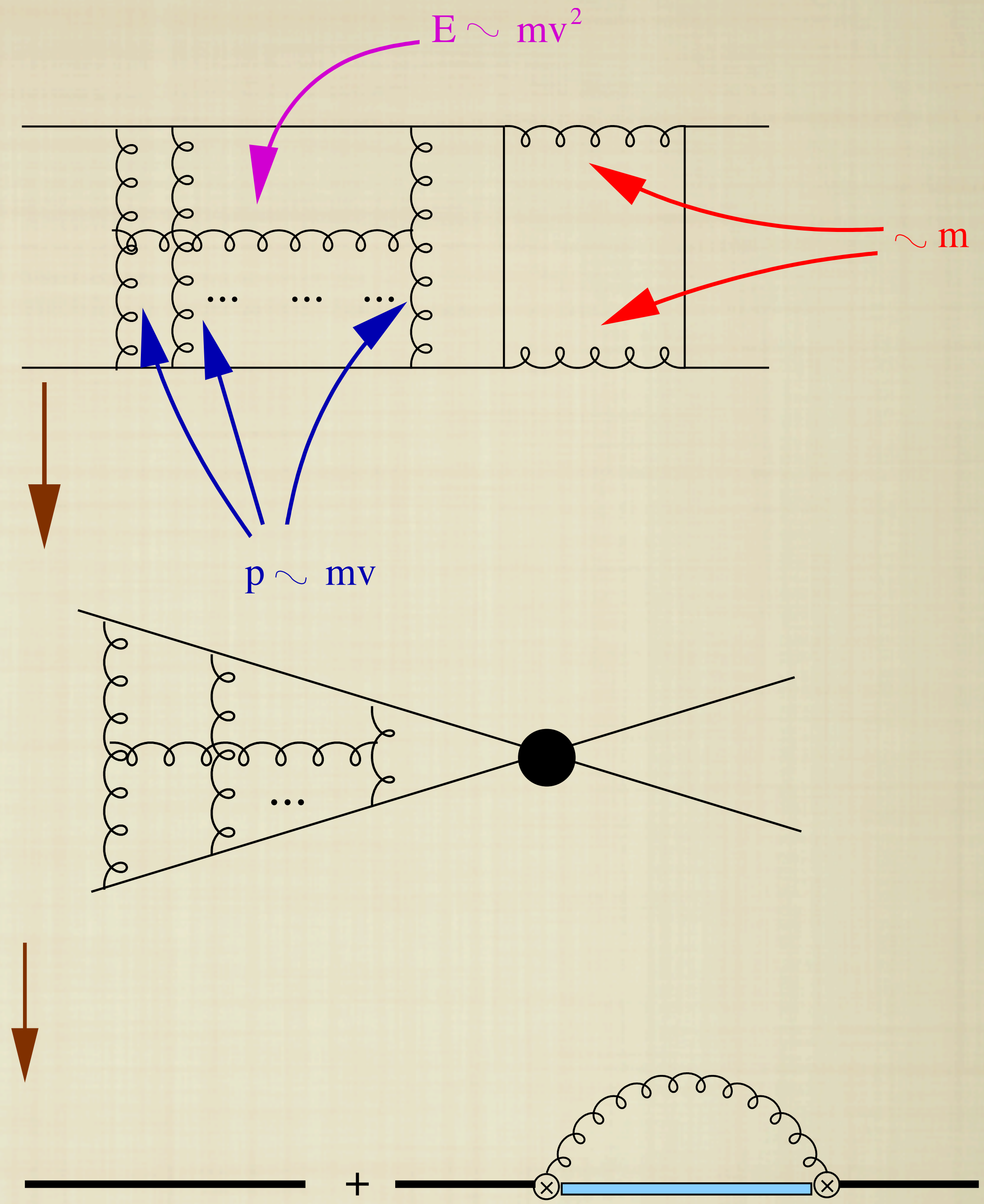

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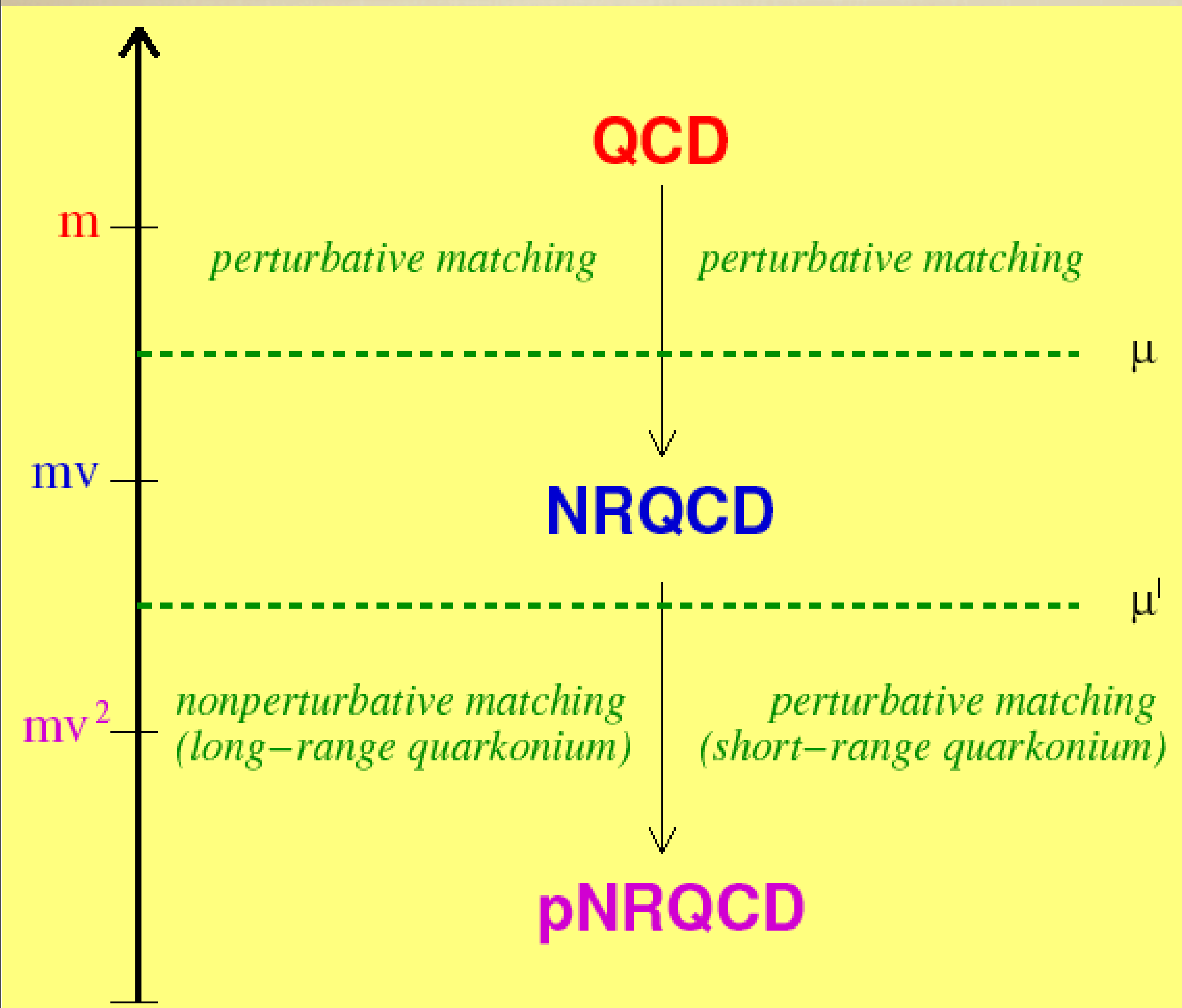

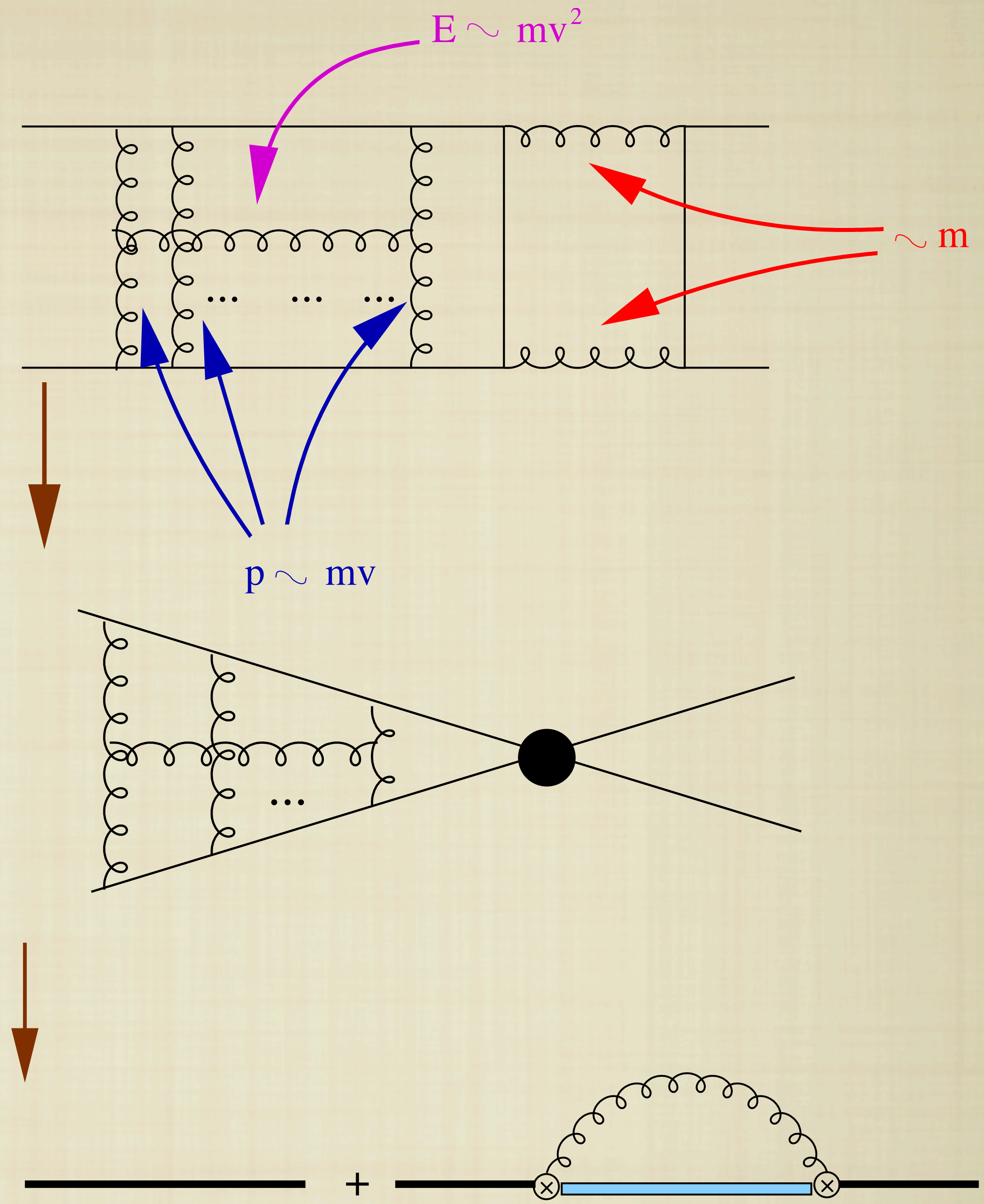

$$\mathcal{L}_{\rm pNRQCD} = \sum_k \sum_n \frac{1}{m^k} c_k(\alpha_{\rm s}(m/\mu)) \times V(r\mu', r\mu) \times O_n(\mu', \lambda)\, r^n$$

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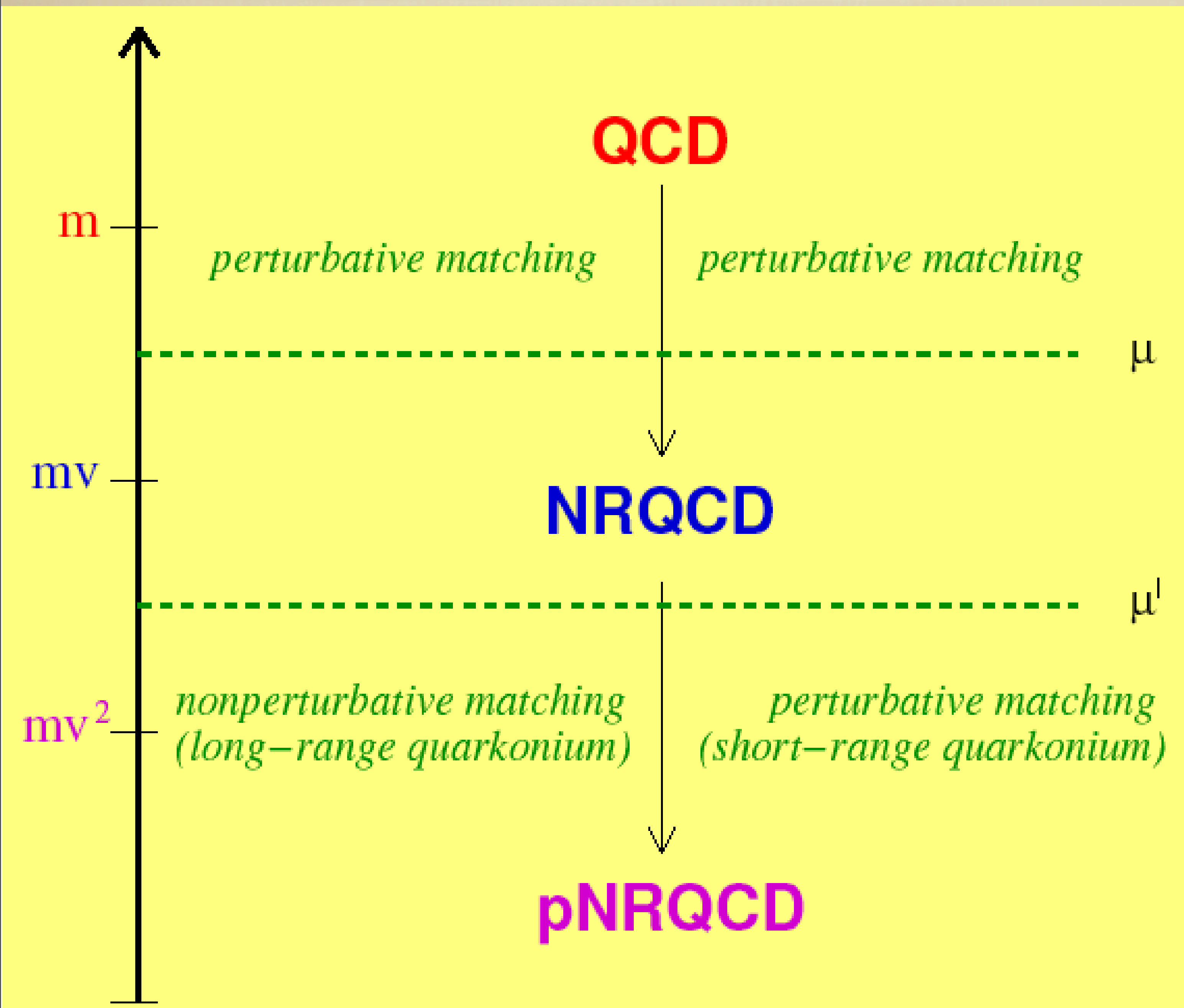

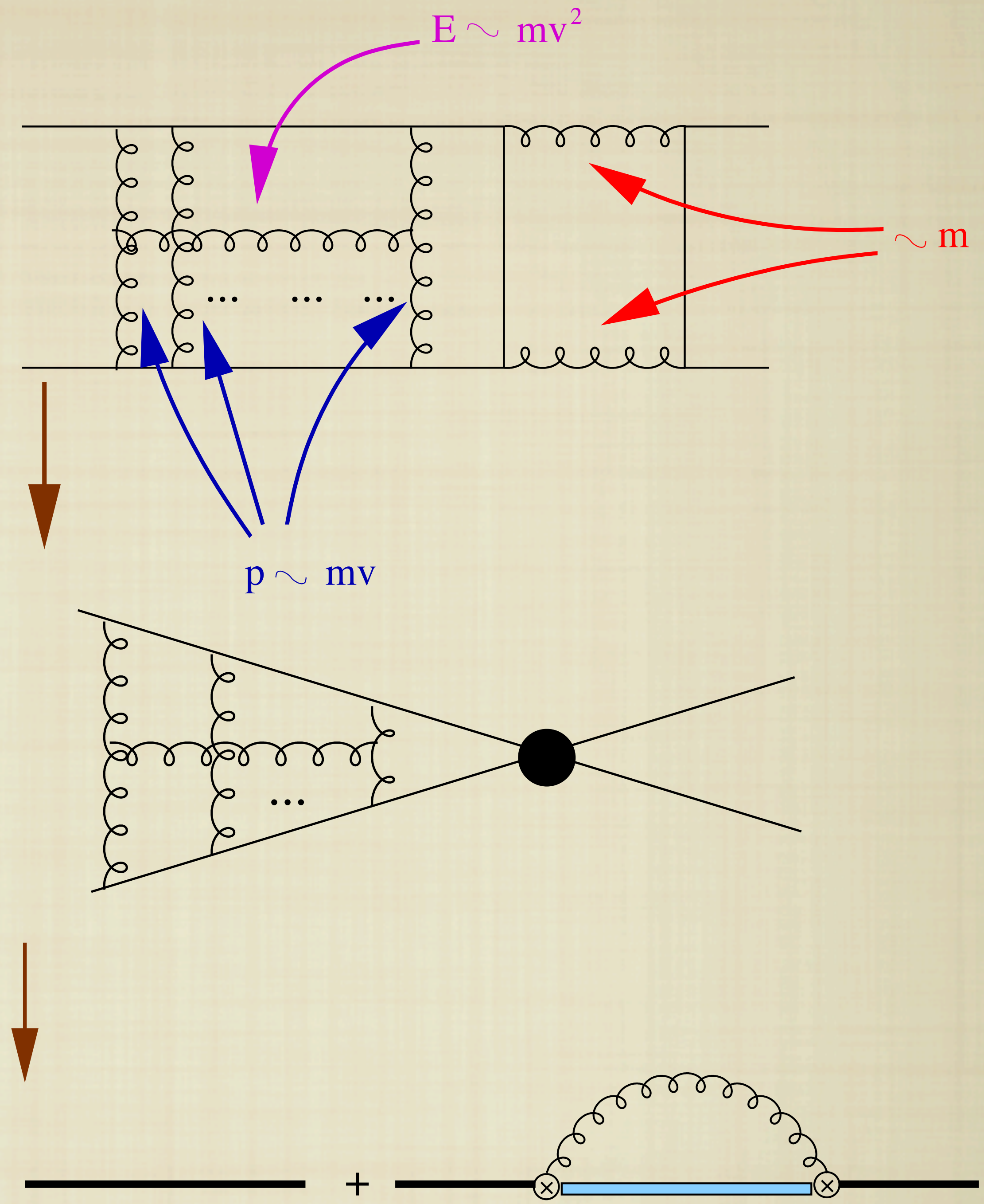

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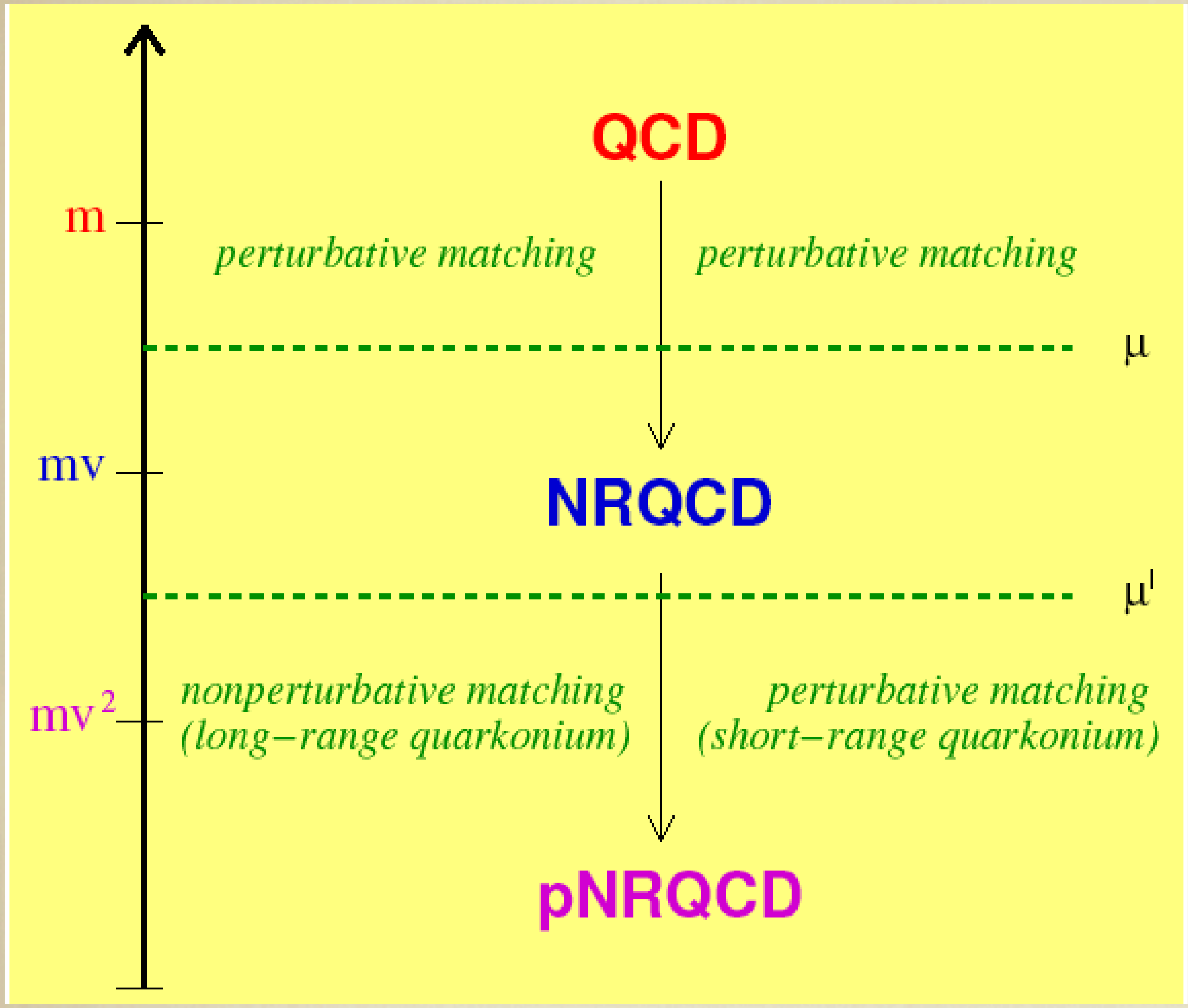

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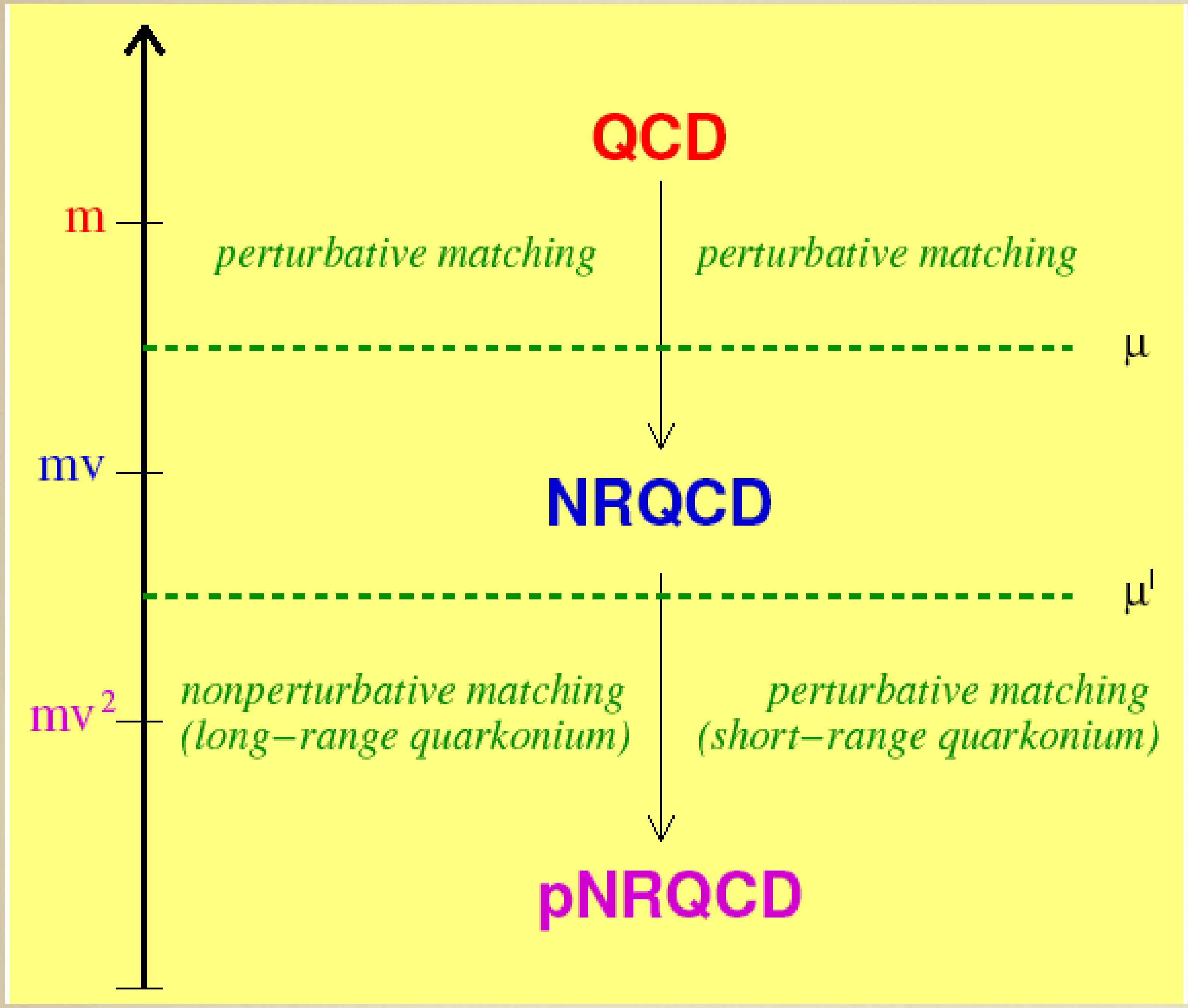
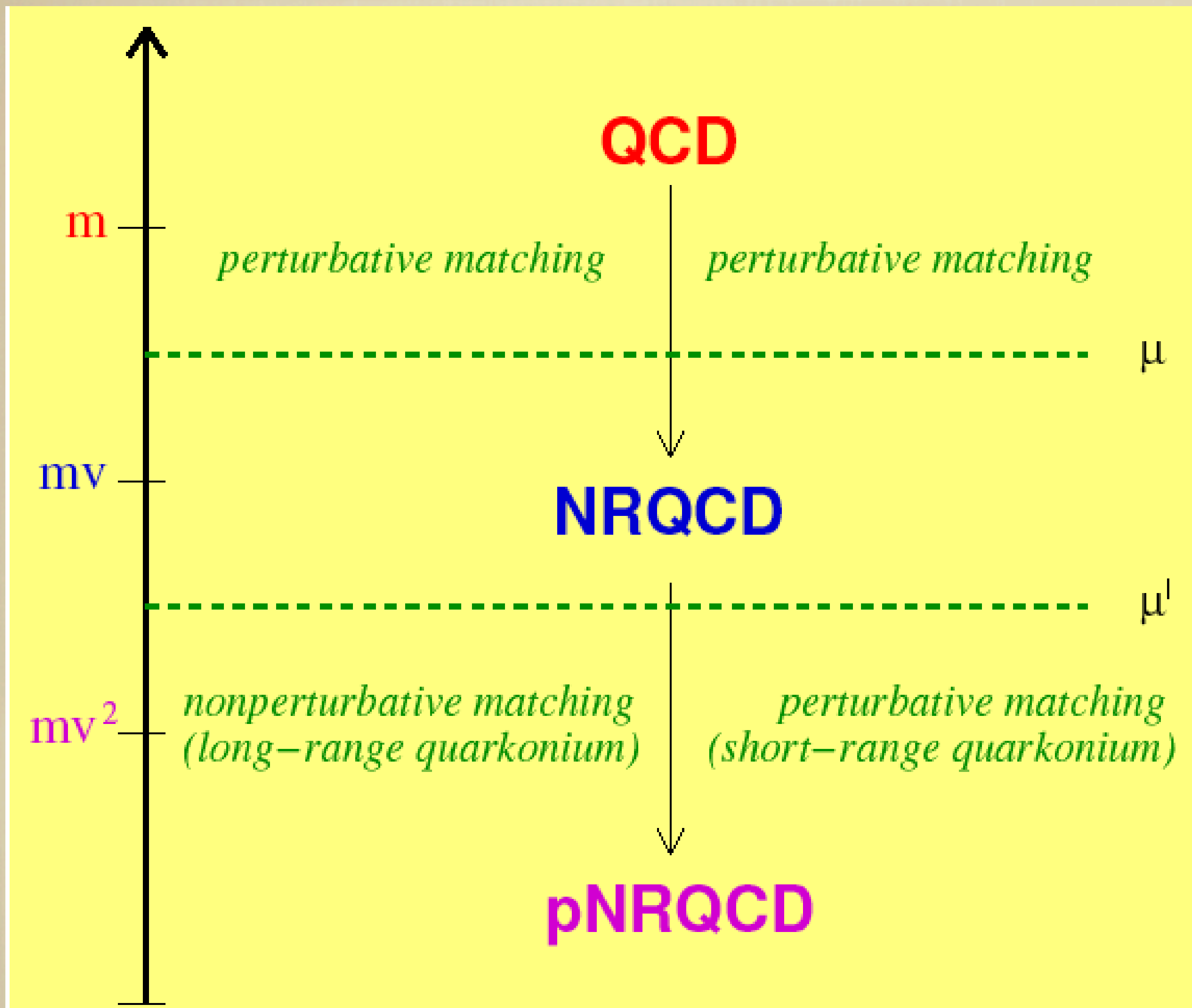
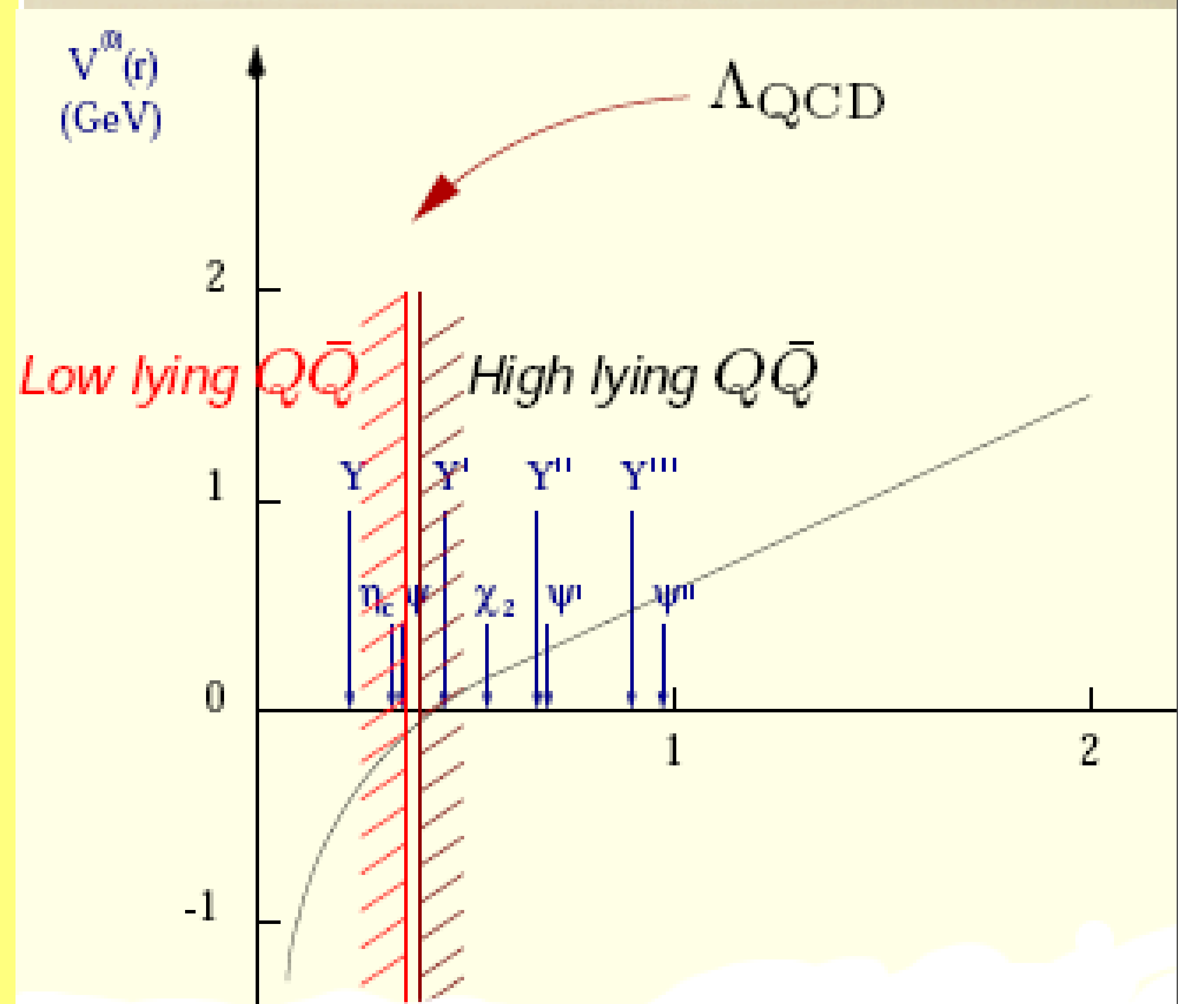


In QCD another scale is relevant Λ_{QCD}

Quarkonium with EFT: pNRQCD





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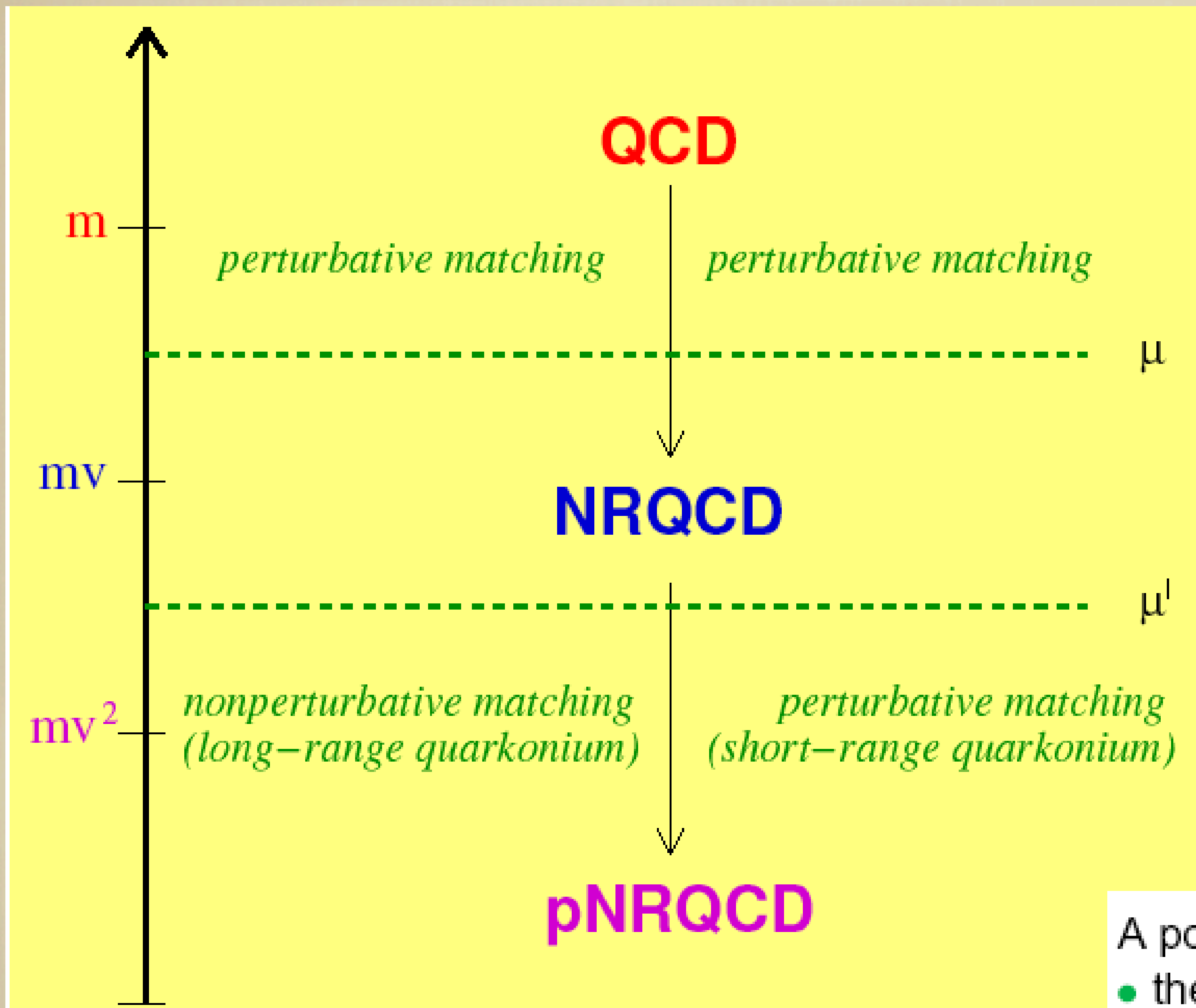

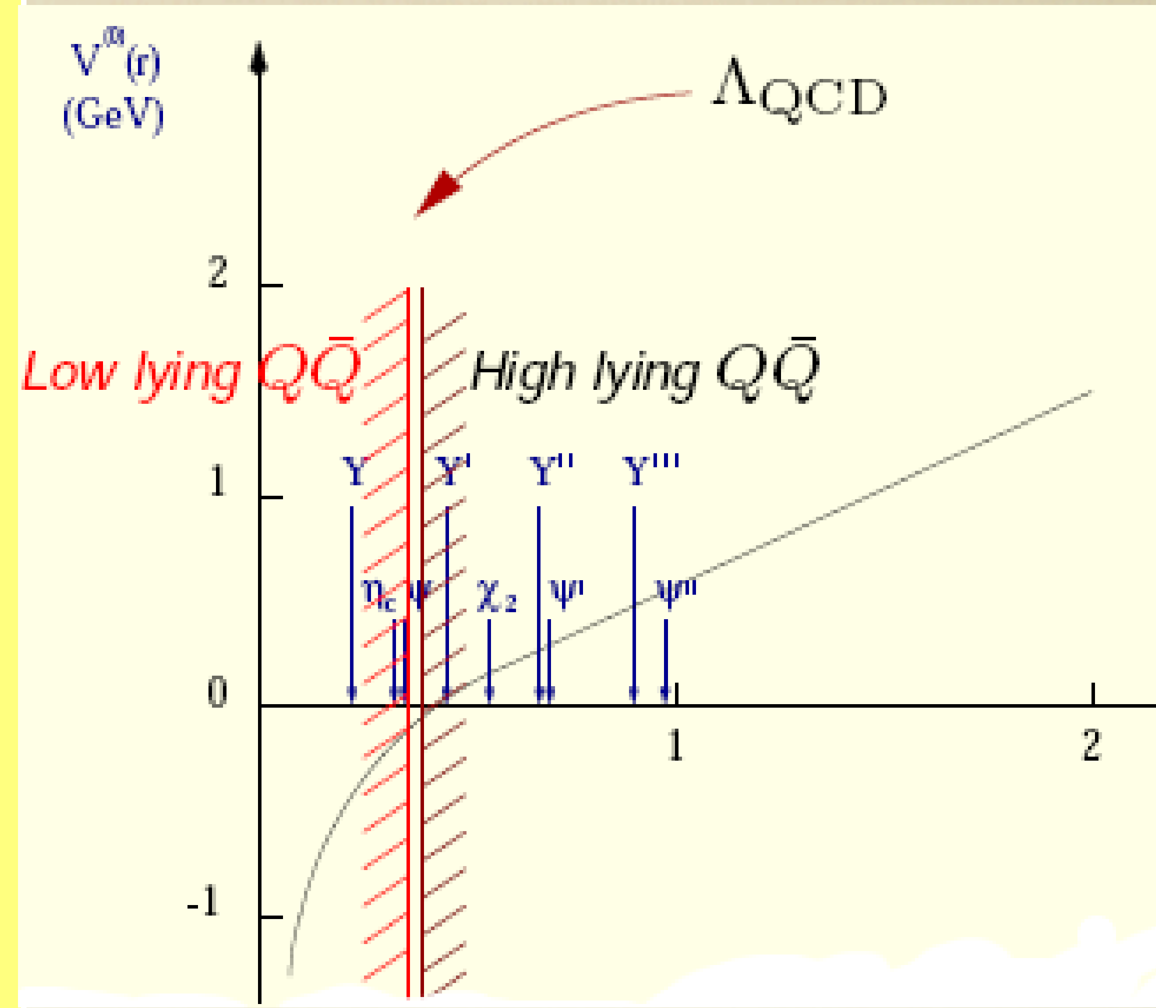

A potential picture arises at the level of pNRQCD:

- the potential is perturbative if $mv \gg \Lambda_{QCD}$
- the potential is non-perturbative if $mv \sim \Lambda_{QCD}$

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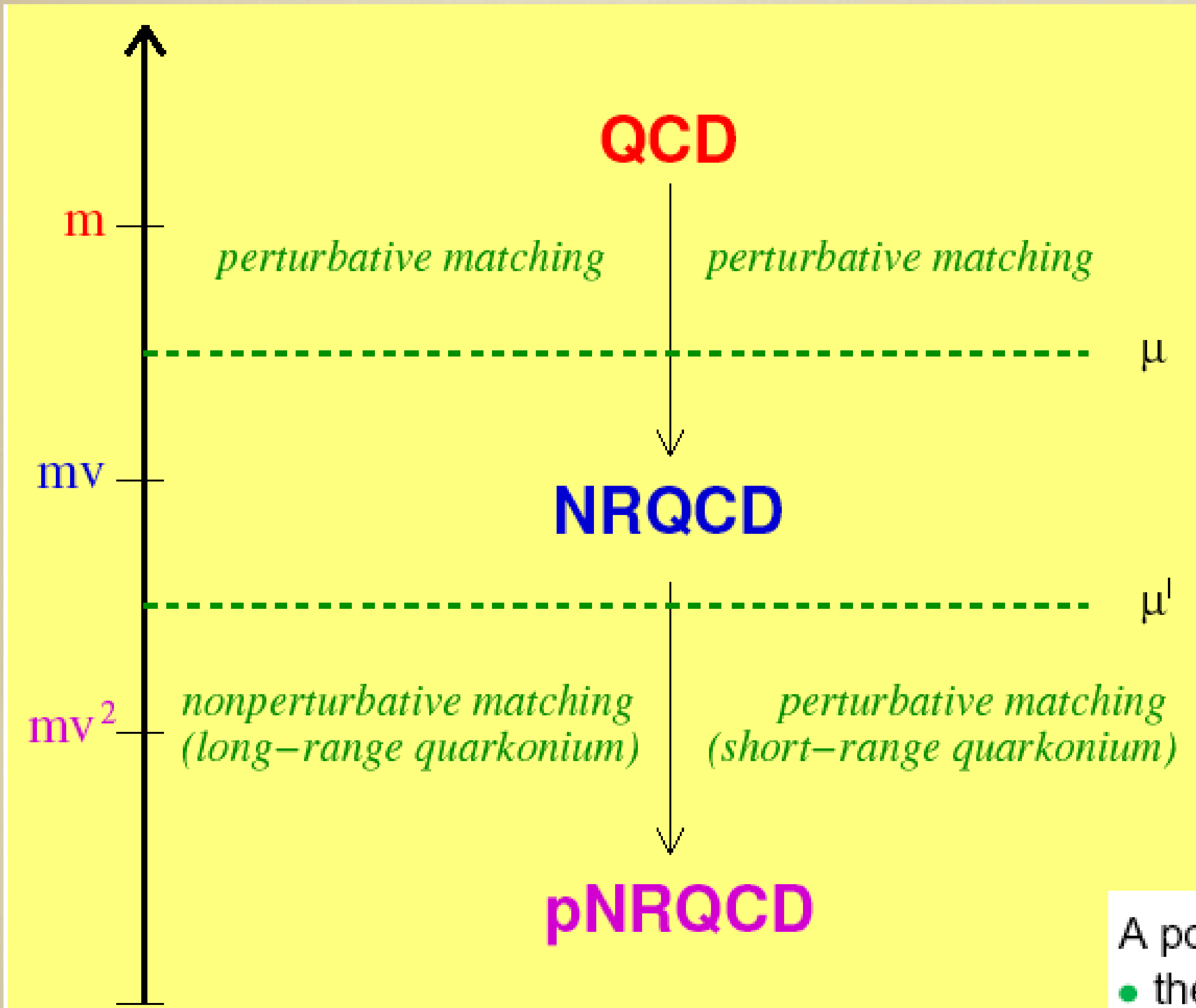
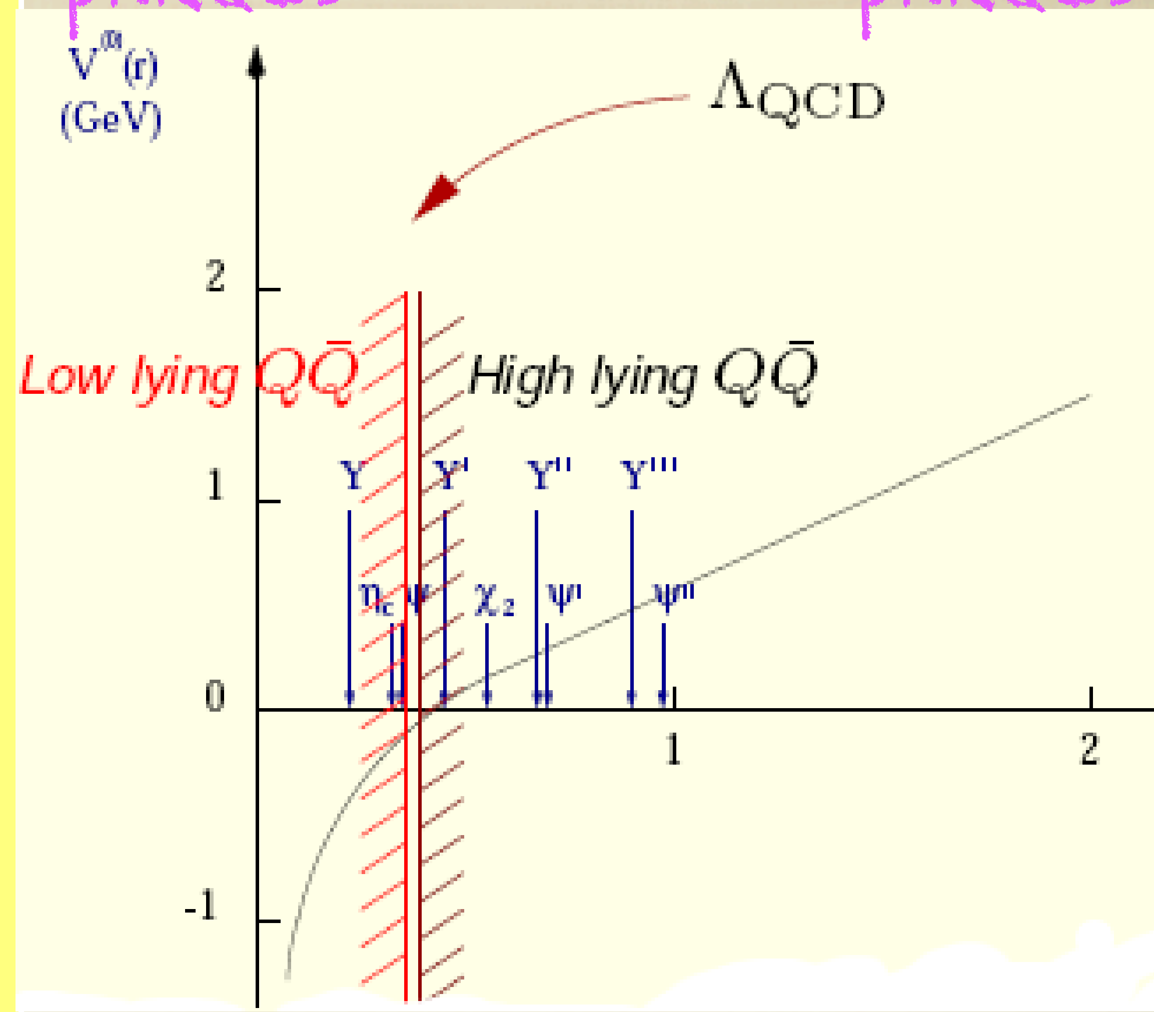
Quarkonium with EFT: pNRQCD



weakly coupled pNRQCD

strongly coupled pNRQCD



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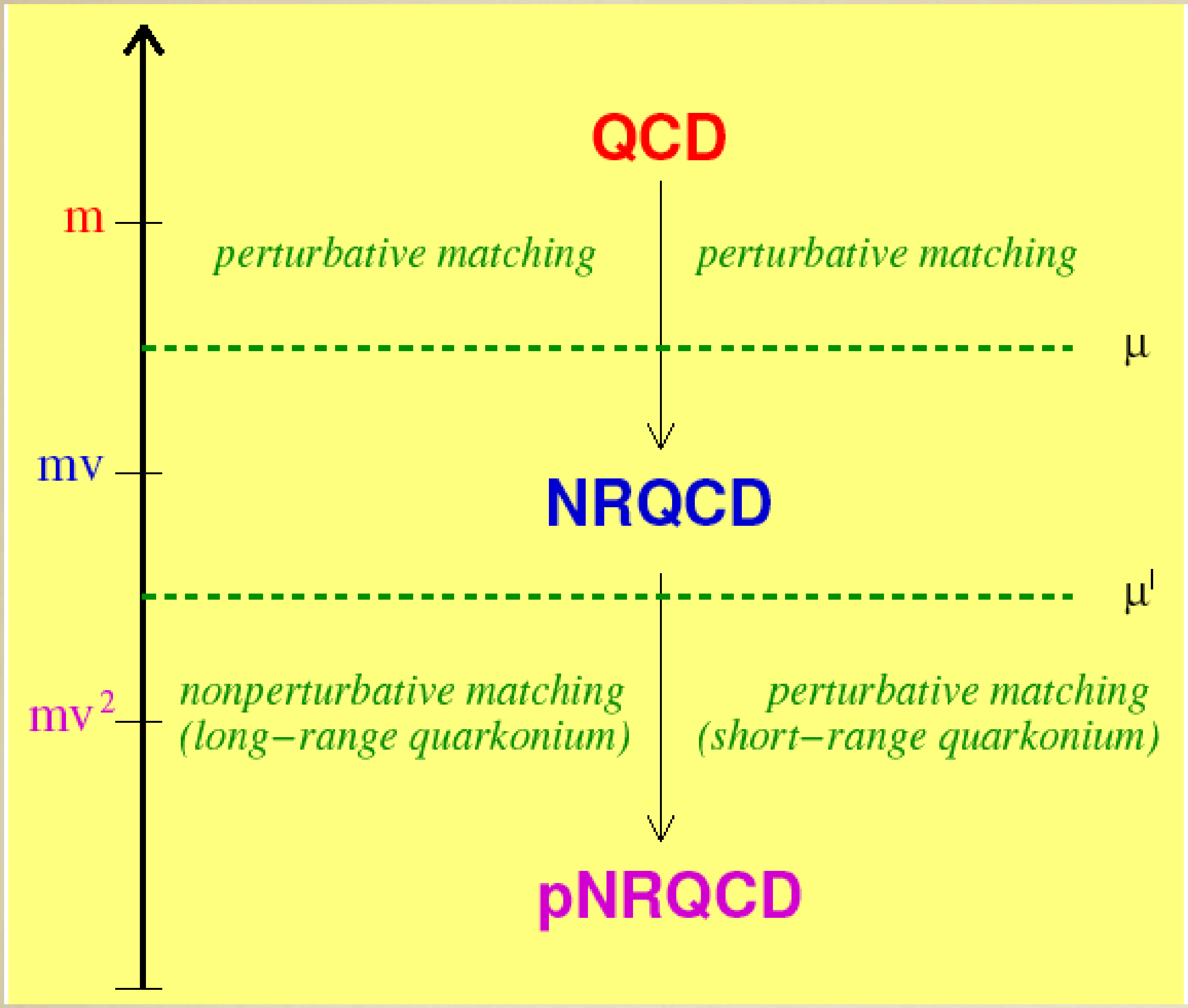

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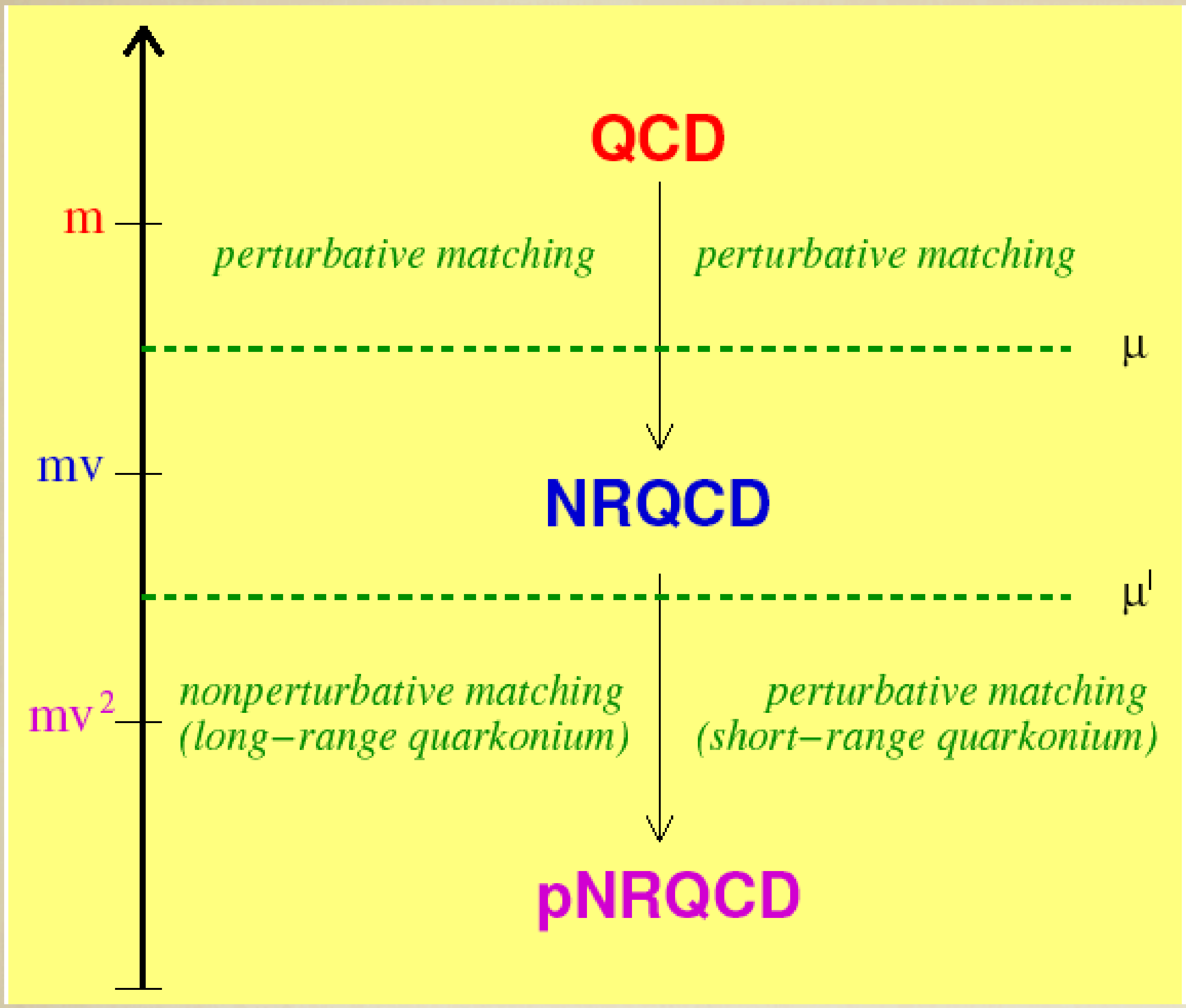
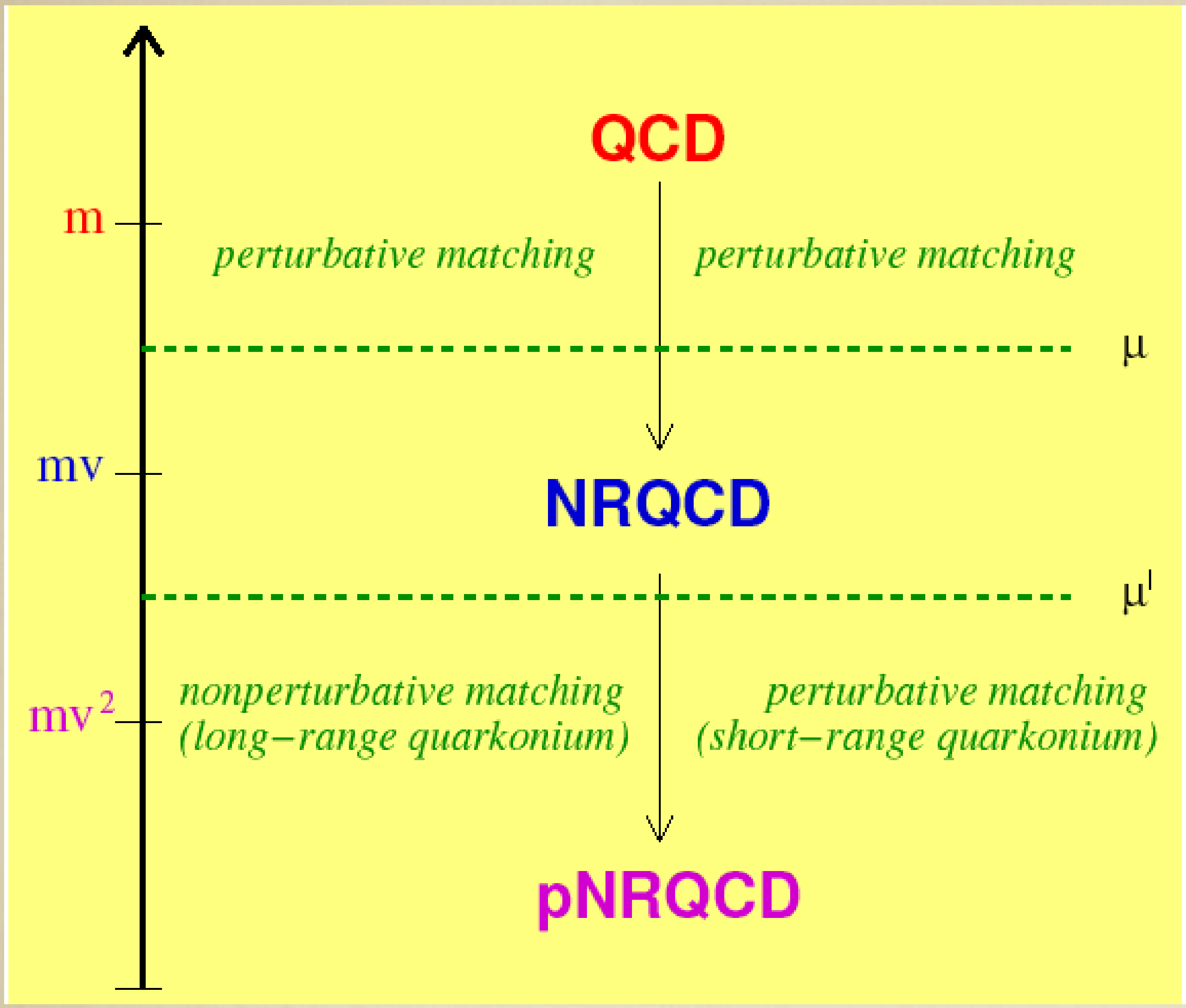


Caswell, Lepage 86,
Lepage, Thacker 88
Bodwin, Braaten, Lepage 95......

Quarkonium with EFT



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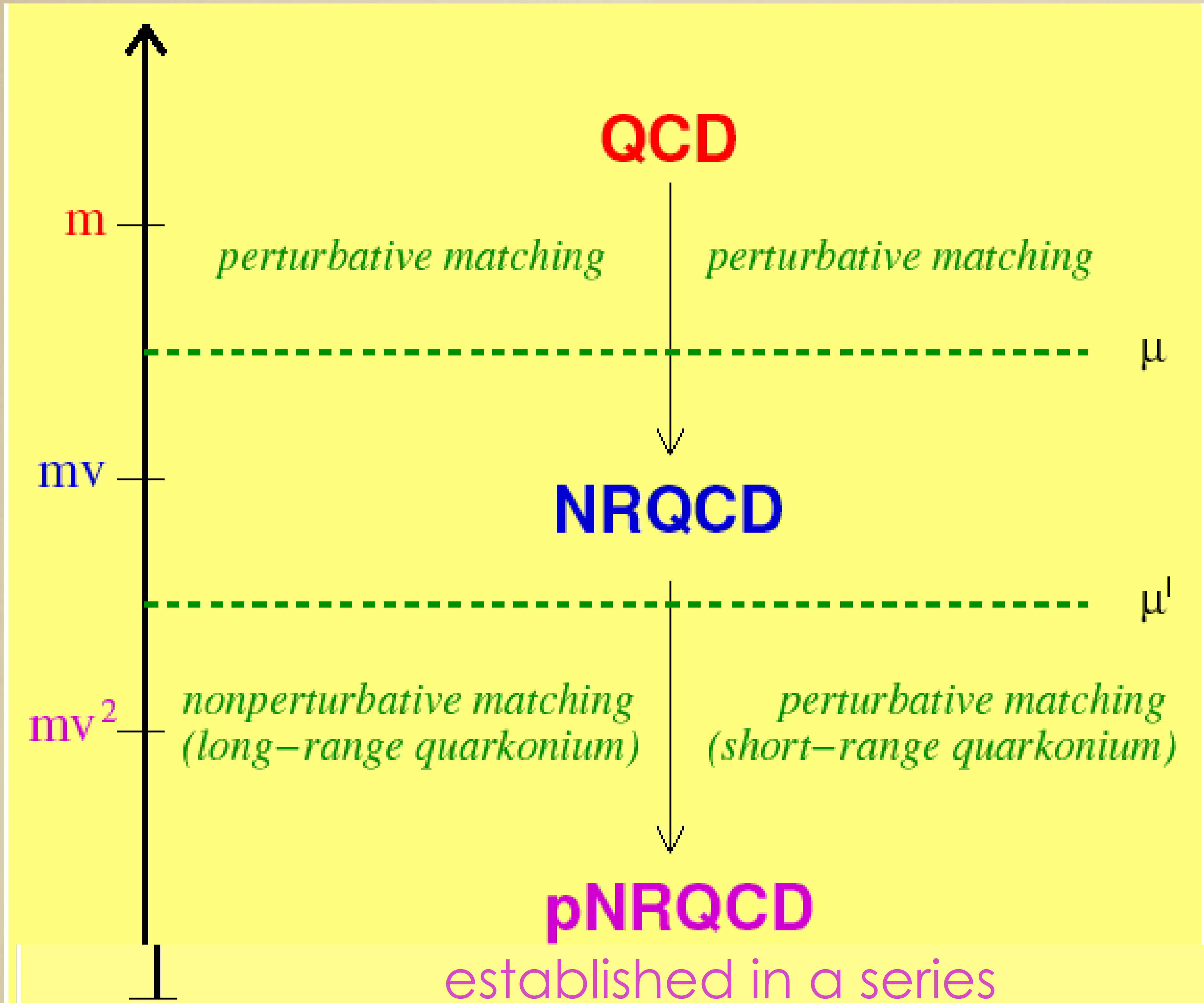
Pineda, Soto 97, N.B. et al, 99,00,
Luke Manohar 97, Luke Savage 98,
Beneke Smirnov 98, Labelle 98
Labelle 98, Grinstein Rothstein 98
Kniehl, Penin 99, Griesshammer 00,
Manohar Stewart 00, Luke et al 00,
Hoang et al 01, 03->

Quarkonium with EFT



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al 01, 03->

established in a series of papers: Pineda, Soto 97, N. Brambilla , Pineda, Soto, Vairo, 99, N. Brambilla et al. 00-09

N.B, Pineda, Soto, Vairo Review of Modern Physics 04

Physics at the scale m : NRQCD
Quarkonium production and decays

terrific progress in production in the last few years

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Quarkonium production and decays

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- Proof of NRQCD factorization at NNLO — QIU, NAYAK, STERMAN 05-08
- Calculation of the differential singlet cross section at NLO and NNLO* — Gong, Wang 08 Artoisenet, Campbell,Lansberg, Maltoni, Tramontano 07
- Development of fragmentation function approach — QIU, NAYAK, STERMAN 05--
- New calculation of the NLO color singlet channel in ep at HERA — Artoisenet, et al.09, Butenschon Kniehl 09
- Full NLO calculation of the direct J/psi hadroproduction in NRQCD — Kuang ta Chao et al 010, Butenschon Kniehl 010

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a coherent picture in NRQCD for quarkonium production at Tevatron, Rhic, Hera is emerging -> to be scrutinized at LHC!

Inclusive decays

- Annihilation: the NRQCD factorization formula reads

$$\Gamma(H \to l.h.) = \sum_n \frac{2\,\mathrm{Im}\, f^{(n)}}{M^{d_{O_n}-4}} \langle H | O_n^{4-\mathrm{fermion}} | H \rangle$$

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Progress has been made in

- the evaluation of the factorization formula at order v^7;
  - Brambilla Mereghetti Vairo JHEP 0608(06)039
    PRD 79(09)074002
- the (lattice) evaluation of the matrix elements.
  - Bodwin Lee Sinclair PRD 72(05)014009

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- ... and in the experimental data. E.g.

Ratio	PDG010	PDG00	LO	NLO
$\frac{\Gamma(\chi_{c0}\to\gamma\gamma)}{\Gamma(\chi_{c2}\to\gamma\gamma)}$	4.9±0.8	13±10	3.75	$\approx$ 5.43
$\frac{\Gamma(\chi_{c2}\to l.h.)-\Gamma(\chi_{c1}\to l.h.)}{\Gamma(\chi_{c0}\to\gamma\gamma)}$	440±100	270±200	$\approx$ 347	$\approx$ 383
$\frac{\Gamma(\chi_{c0}\to l.h.)-\Gamma(\chi_{c1}\to l.h.)}{\Gamma(\chi_{c0}\to\gamma\gamma)}$	4000±600	3500±2500	$\approx$ 1300	$\approx$ 2781
$\frac{\Gamma(\chi_{c0}\to l.h.)-\Gamma(\chi_{c2}\to l.h.)}{\Gamma(\chi_{c2}\to l.h.)-\Gamma(\chi_{c1}\to l.h.)}$	8.0±0.9	12.1±3.2	2.75	$\approx$ 6.63
$\frac{\Gamma(\chi_{c0}\to l.h.)-\Gamma(\chi_{c1}\to l.h.)}{\Gamma(\chi_{c2}\to l.h.)-\Gamma(\chi_{c1}\to l.h.)}$	9.0±1.1	13.1±3.3	3.75	$\approx$ 7.63

$m_c = 1.5$ GeV $\quad \alpha_s(2m_c) = 0.245$
in NLO, v^7 terms are not included

The table clearly shows that the data are sensitive to NLO corrections in the Wilson coefficients $f^{(n)}$ (and perhaps also to relativistic corrections).

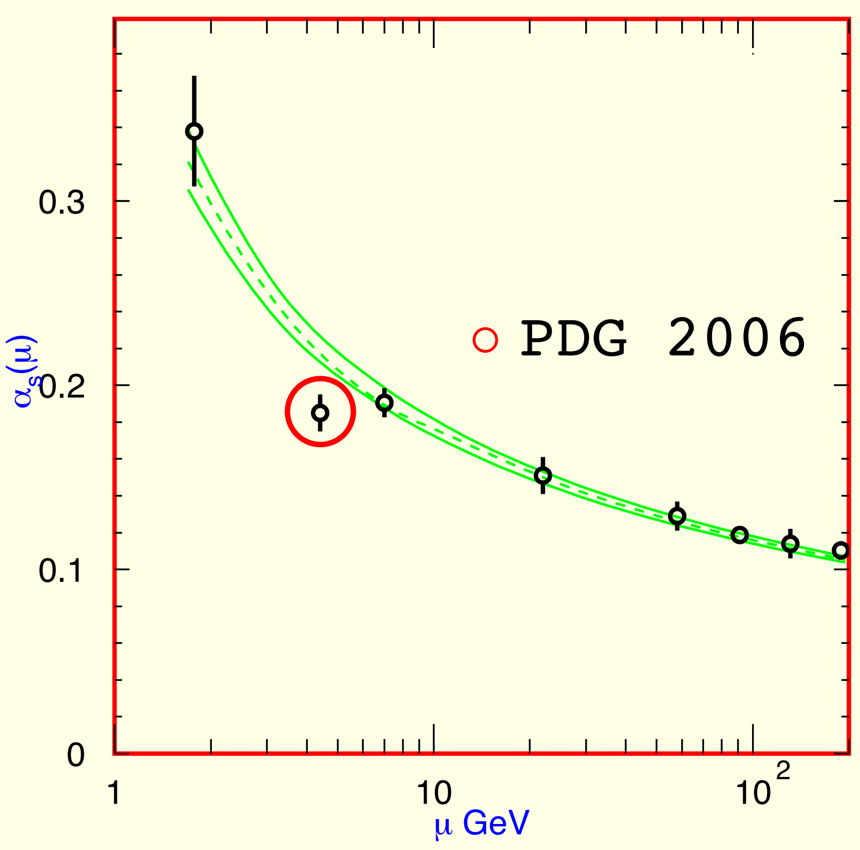
α_s from $\Upsilon(1S)$ decay

- New CLEO data on $\Upsilon(1S) \to \gamma X$,
- new lattice determinations of NRQCD matrix elements,

have led to an improved NLO analysis of $\Gamma(\Upsilon(1S) \to \gamma X)/\Gamma(\Upsilon(1S) \to X)$ and to an improved determination of α_s at the Υ-mass scale:

$$\alpha_s(M_{\Upsilon(1S)}) = 0.184^{+0.015}_{-0.014}, \qquad \alpha_s(M_Z) = 0.119^{+0.006}_{-0.005}$$

○ Brambilla Garcia Soto Vairo PRD 75(07)074014



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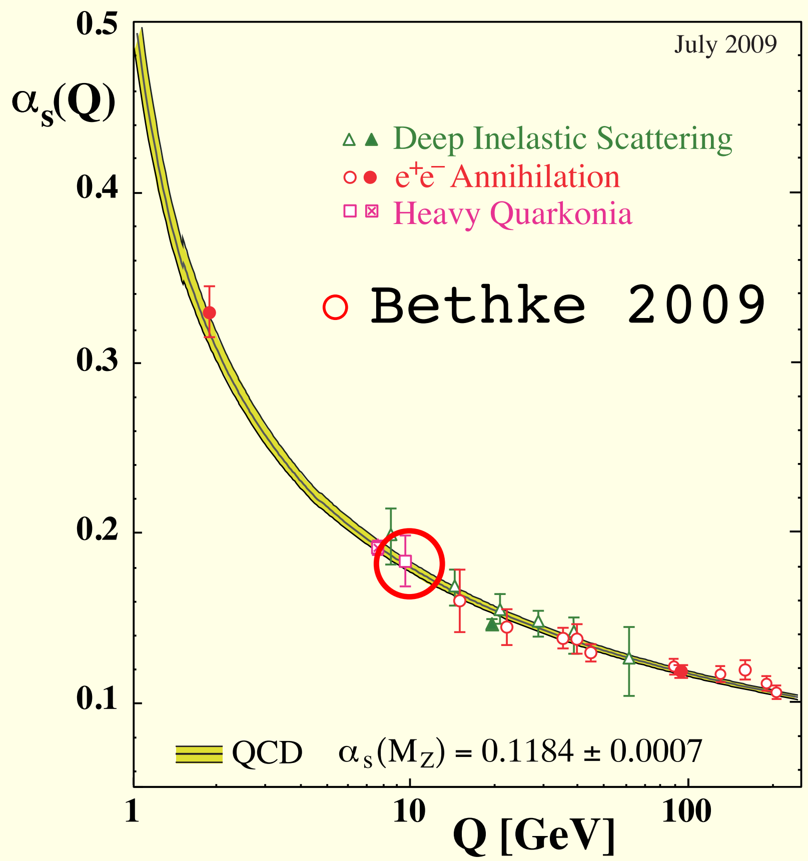

Physics at the scale mv and mv^2 : pNRQCD

Physics at the scale mv and mv^2 : pNRQCD

pNRQCD is today the theory used to address quarkonium bound states properties

- Spectra

  high order perturbative calculations
  Resonances

- Decays

  Inclusive& seminclusive decays
  M1and E1 transitions
  Electromagnetic widths, Lines Shapes

- Doubly charmed baryons and QQQ
- Standard model parameters extraction

  c and b masses, alpha_s

- Gluelumps and Hybrids
- Threshold ttbar cross section (for the ILC)
- Nonperturbative potentials for the lattice
- General features of the NR EFTs

pNRQCD and quarkonium Several cases for the physics at hand

The EFT has been constructed

*Work at calculating higher order perturbative corrections in v and alpha_s
*Resumming the log
*Calculating/extracting nonperturbatively the low energy quantities
*Extending the theory (electromagnetic effect, 3 bodies)

pNRQCD and quarkonium

Several cases for the physics at hand

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The issue here is precision physics and the study of confinement

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Laine et al, 2007, Escobedo, Soto 2007 N. B. et al. 2008

*Results on the static potential hint at a new physical picture of dissociation

*Mass and width of quarkonium at m alpha^5(Y(1S) bbar at LHC) N. B. et al. 2010

*Polyakov loop calculation N. B. et al. 2010

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The EFT has not yet been constructed (Exotics close to threshold)

*Degrees of freedom still to be identified

Weakly coupled pNRQCD $r \ll \Lambda_{\rm QCD}^{-1}$

Pineda, soto 97; Brambilla, Pineda, soto, Vairo 99-

Weakly coupled pNRQCD $r \ll \Lambda_{\rm QCD}^{-1}$

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu\, a} + \mathrm{Tr}\left\{ \mathrm{S}^\dagger \left(i\partial_0 - \frac{\mathbf{p}^2}{m} - V_s \right) \mathrm{S} + \mathrm{O}^\dagger \left(iD_0 - \frac{\mathbf{p}^2}{m} - V_o \right) \mathrm{O} \right\}$$

LO in r

PINEDA, SOTO 97; BRAMBILLA, PINEDA, SOTO, VAIRO 99-

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LO in r

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

NLO in r

Pineda, Soto 97; Brambilla, Pineda, Soto, Vairo 99-

Weakly coupled pNRQCD $r \ll \Lambda_{QCD}^{-1}$

Singlet static potential

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu\, a} + \mathrm{Tr}\left\{ \mathrm{S}^\dagger \left(i\partial_0 - \frac{\mathbf{p}^2}{m} - V_s \right) \mathrm{S} + \mathrm{O}^\dagger \left(iD_0 - \frac{\mathbf{p}^2}{m} - V_o \right) \mathrm{O} \right\}$$

LO in r

Octet static potential

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$$+ \cdots$$

NLO in r

PINEDA, SOTO 97; BRAMBILLA, PINEDA, SOTO, VAIRO 99-

Quarkonium singlet static potential at N^4LO

$$V_s(r,\mu) \;=\; -C_F\,\frac{\alpha_{\rm s}(1/r)}{r}\left[1+a_1\,\frac{\alpha_{\rm s}(1/r)}{4\pi}+a_2\left(\frac{\alpha_{\rm s}(1/r)}{4\pi}\right)^2\right.$$

$$+\left(\frac{16\,\pi^2}{3}C_A^3\,\ln r\mu+a_3\right)\left(\frac{\alpha_{\rm s}(1/r)}{4\pi}\right)^3$$

$$\left.+\left(a_4^{L2}\ln^2 r\mu+\left(a_4^L+\frac{16}{9}\pi^2\,C_A^3\beta_0(-5+6\ln 2)\right)\ln r\mu+a_4\right)\left(\frac{\alpha_{\rm s}(1/r)}{4\pi}\right)^4\right]$$

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a_1 Billoire 80

a_2 Schroeder 99, Peter 97

coeff $ln r\mu$ N.B. Pineda, Soto, Vairo 99

$a_4^{L2},\, a_4^L$ N.B., Garcia, Soto, Vairo 06

a_3 Anzai, Kiyo, Sumino 09, Smirnov, Smirnov, Steinhauser 09

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a_4^{L2}, a_4^L N.B., Garcia, Sot

3LOOPS REDUCES TO 1LOOP IN THE EFT

4LOOPS REDUCES TO 2LOOPS IN THE EFT

a_3 Anzai, Kiyo, Sumino 09, Smirnov, Smirnov, Steinhauser 09

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& \left. + \left(a_4^{L2} \ln^2 r\mu + \left(a_4^L + \frac{16}{9}\pi^2 \, C_A^3 \beta_0 (-5 + 6\ln 2) \right) \ln r\mu + a_4 \right) \left(\frac{\alpha_s(1/r)}{4\pi} \right)^4 \right]
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Two problems:

1)Bad convergence of the series due to large beta_0 terms

2) Large logs

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2) Large logs

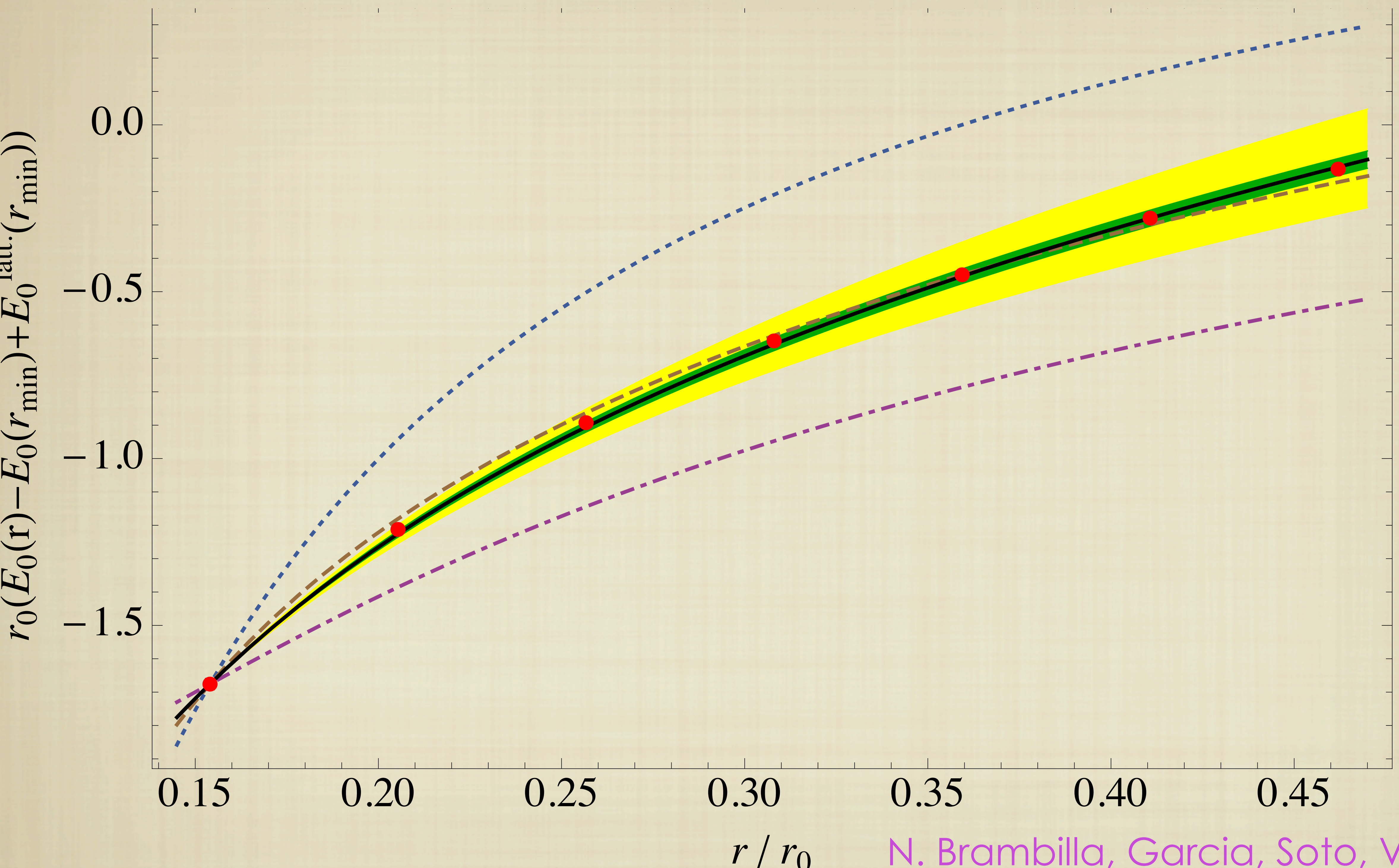
The eft cures both:

1) Renormalon subtracted scheme

BENEKE 98, HOANG, LEE 99, PINEDA 01, N.BRAMBILLA ET AL 09

2) Renormalization group summation of the logs up to N^3LL $(\alpha_s^{4+n} \ln^n \alpha_s)$ N. BRAMBILLA. ET AL 2007, 2009

Quarkonium singlet static energy at N^3LL in comparison with lattice data (red points NECCO SOMMER 2002)



N. Brambilla, Garcia, Soto, Vairo 010

Yellow band : uncertainty in alpha_s (r_0*Lambda_QCD_MS)

Green band: uncertainty in higher order terms

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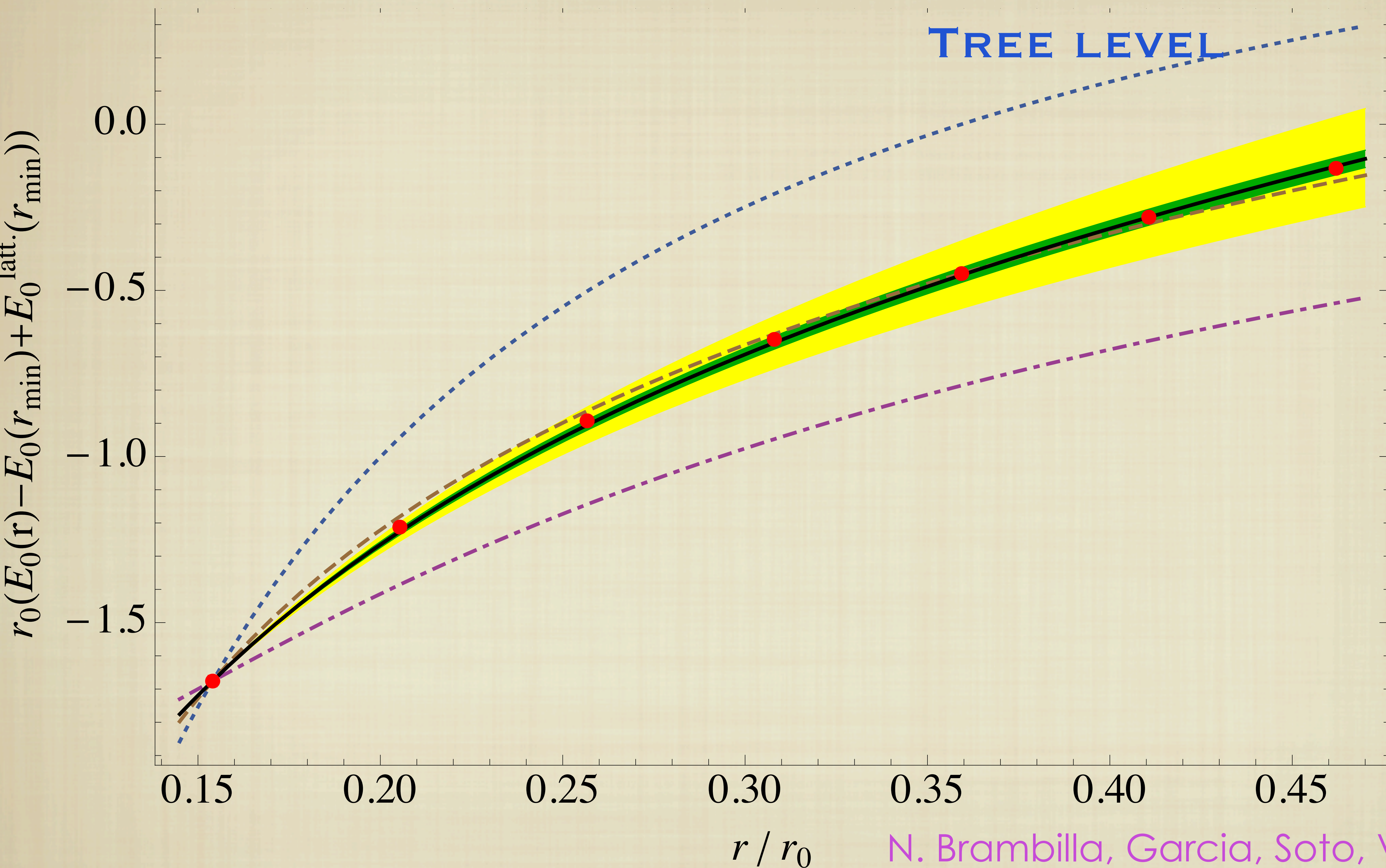

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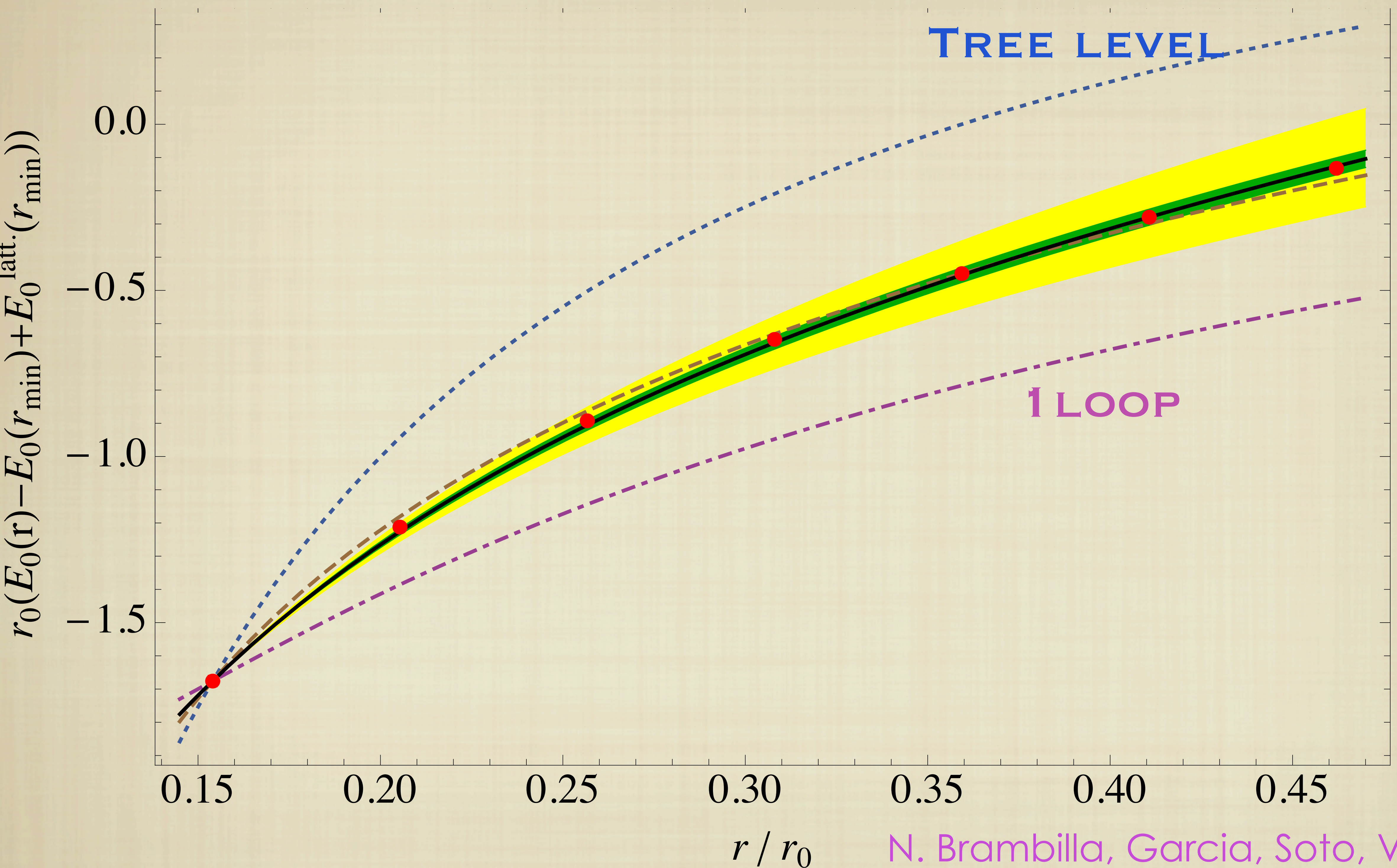

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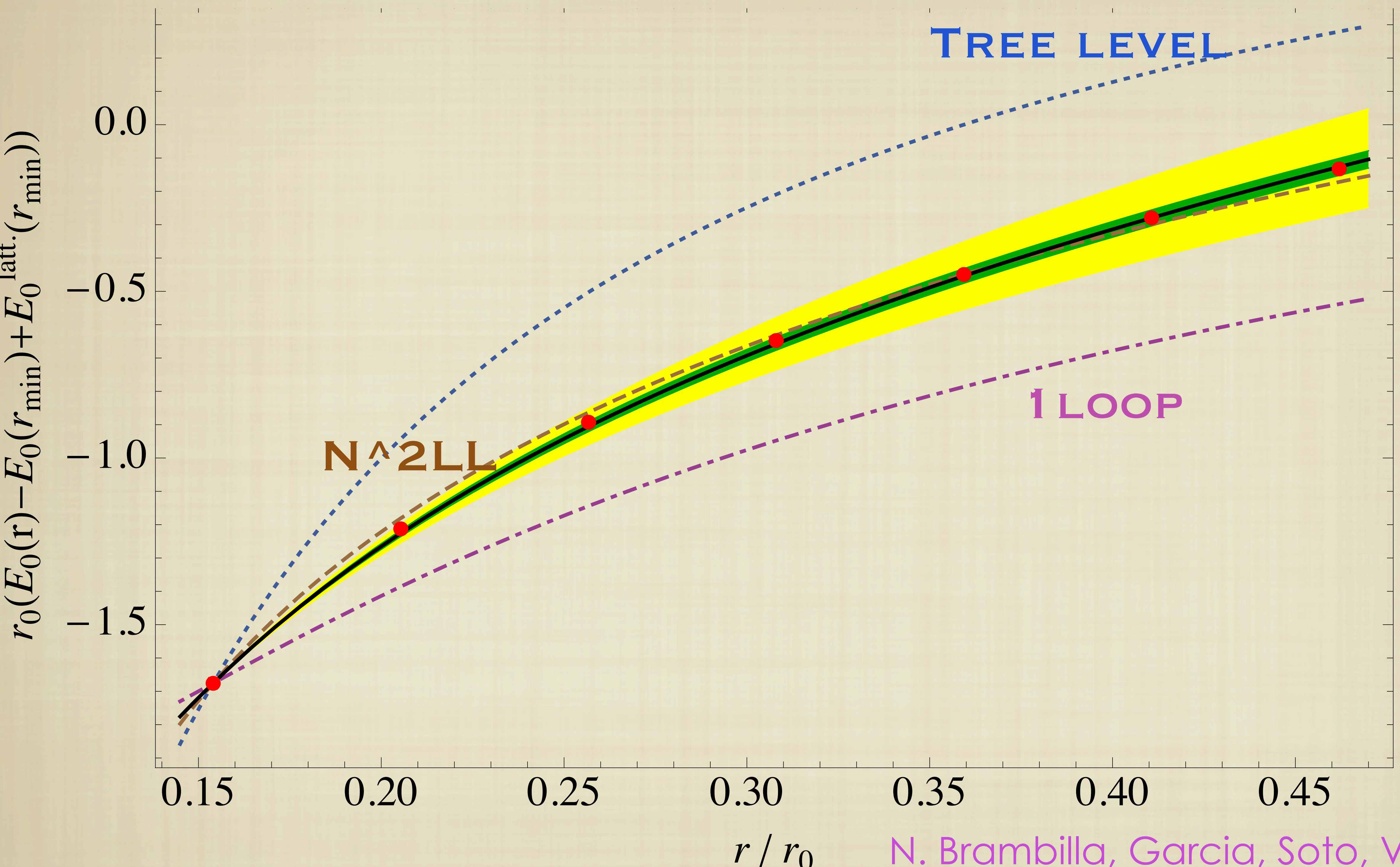

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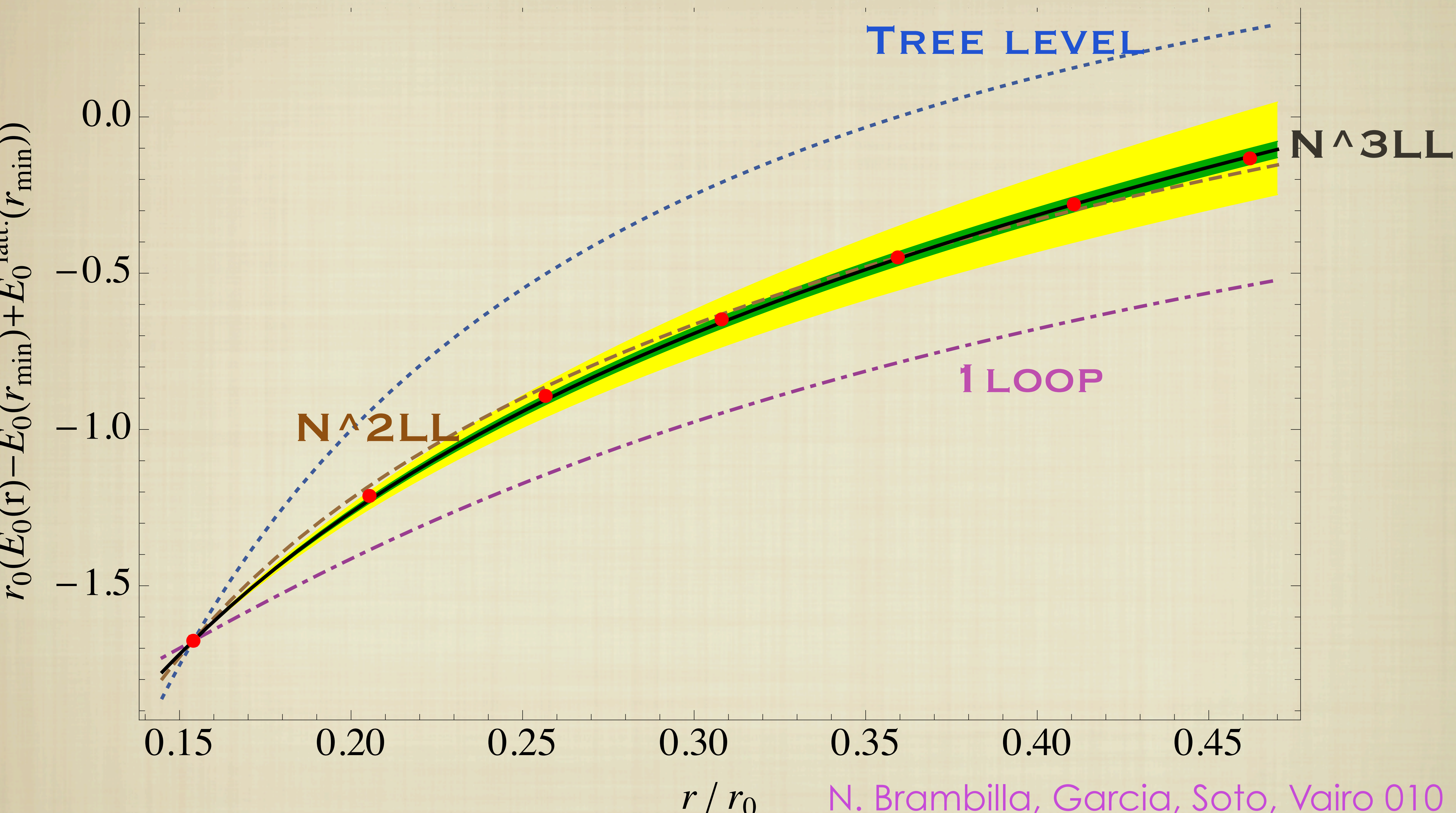

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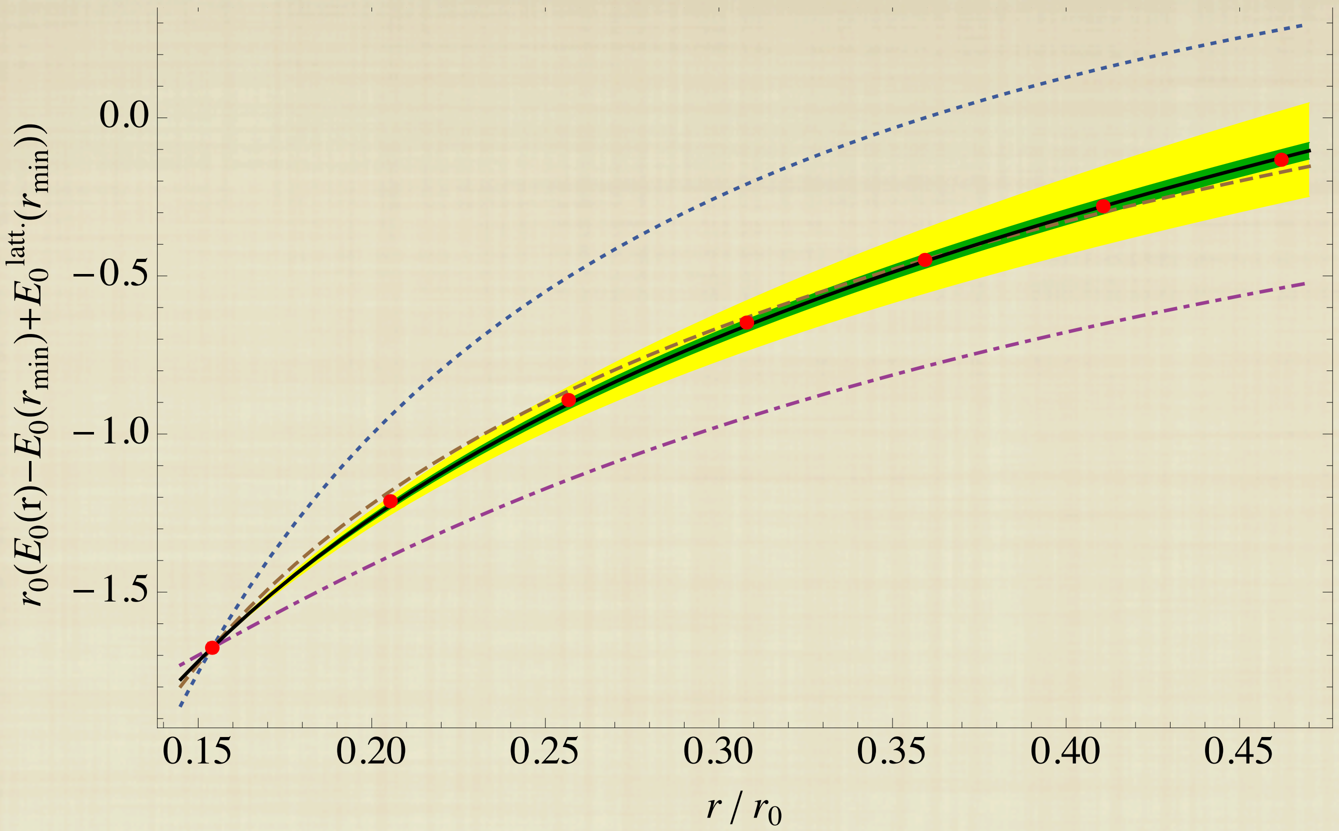

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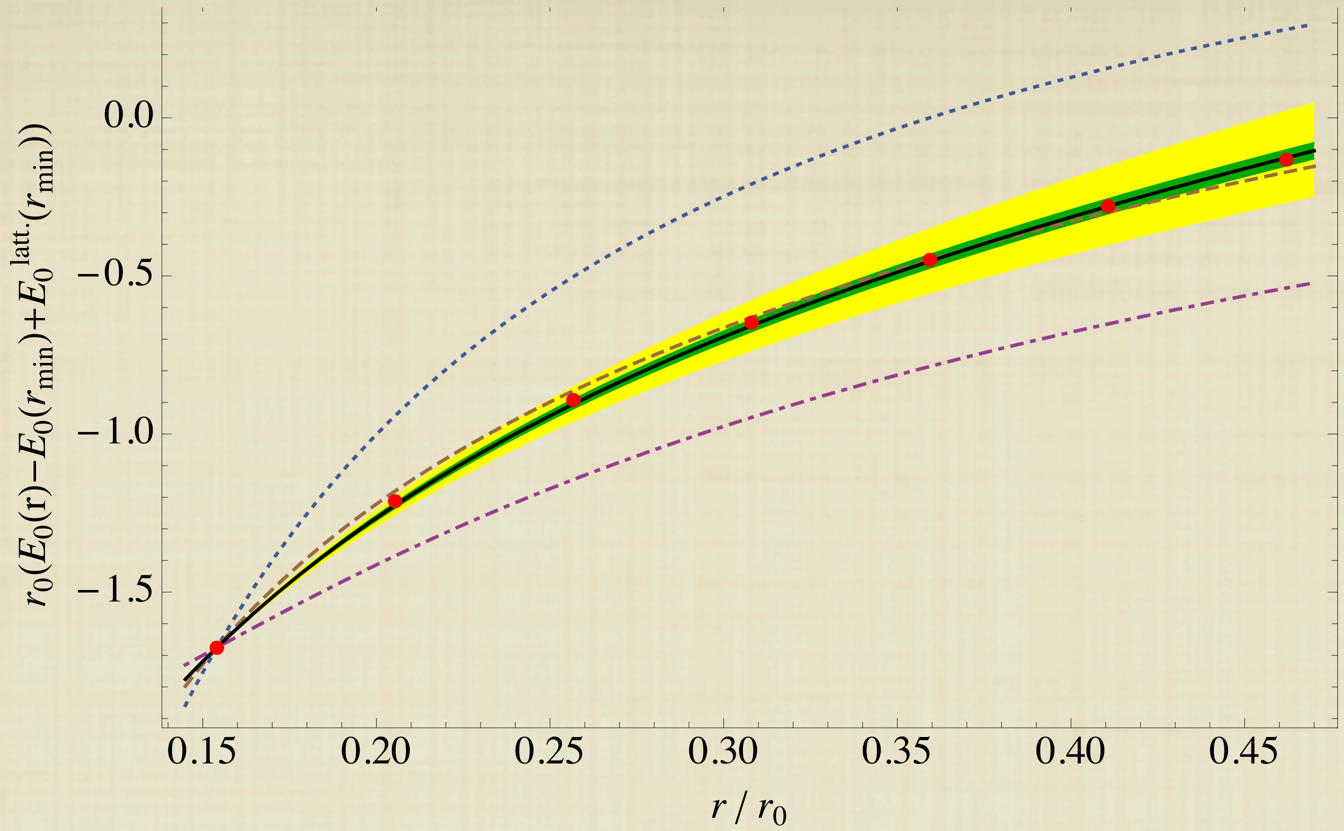
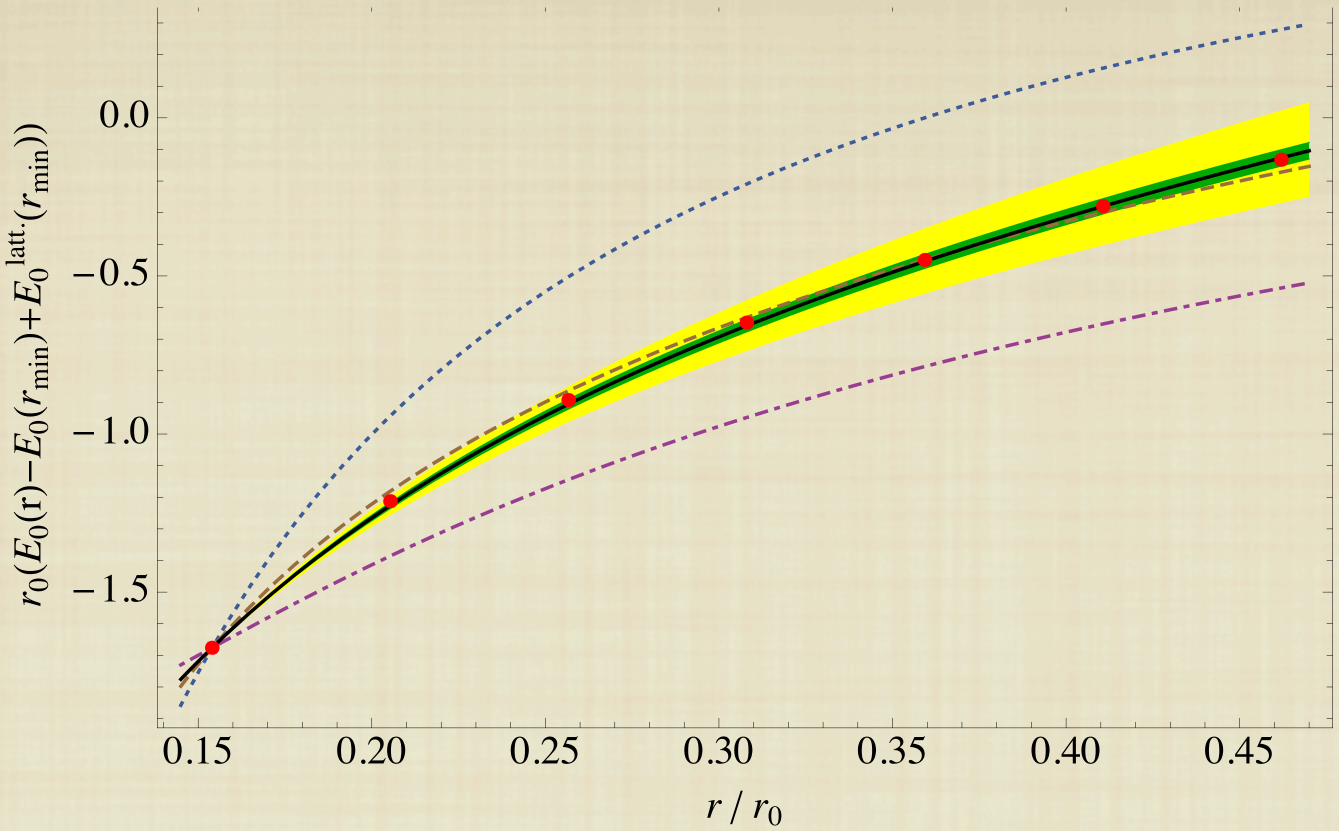


- Very good convergence of the QCD bound state perturbative series

Quarkonium singlet static energy at N^3LL in comparison with lattice data (red points Necco Sommer 2002)



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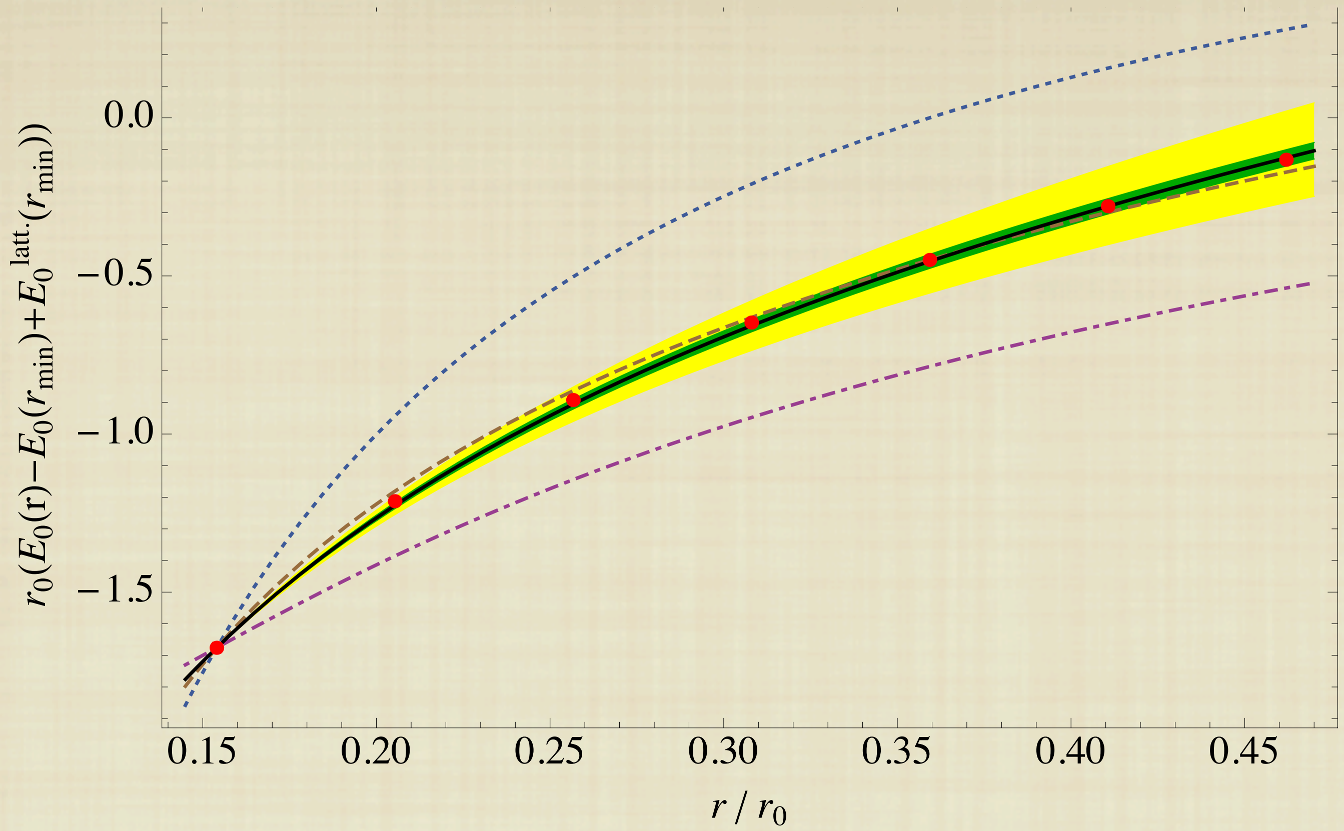

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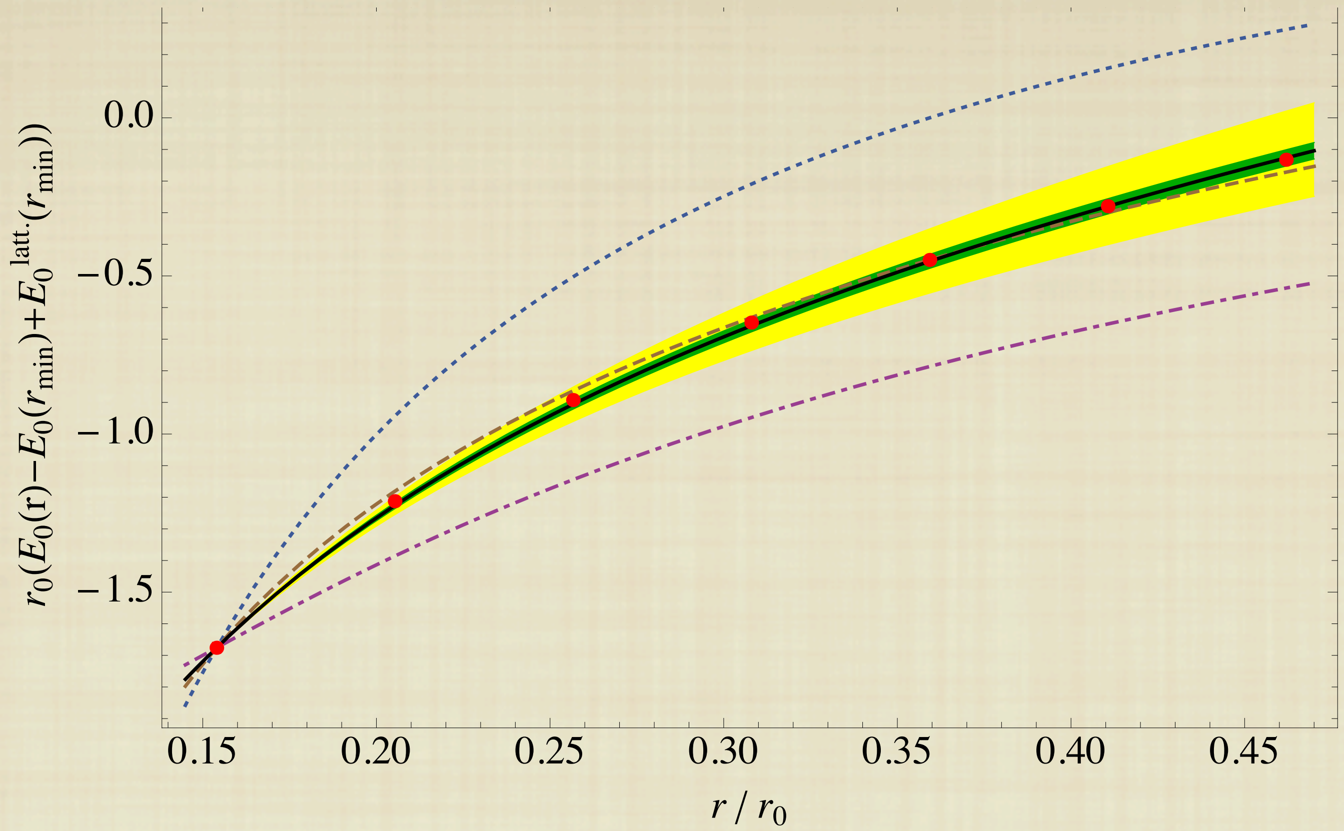

- Very good convergence of the QCD bound state perturbative series
- The lattice data are perfectly described from perturbation theory up to more than 0.2 fm
- Allows to rule out models: no string contribution at small r !
- Allows precise extraction of fundamental parameters of QCD

$$r_0 \Lambda_{\bar{M}S} = 0.622^{+0.019}_{-0.015}$$

(N. Brambilla, Garcia, Soto, Vairo 010)

several high order calculations of matching coefficients, spectra, decay have recently appeared

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e.g. QQQ static singlet potential at N^2LO

BRAMBILLA GHIGLIERI VAIR 2010

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& +\left(\frac{\alpha_s(1/|\mathbf{r}_q|)}{4\pi}\right)^2\left[+66\zeta(3)+484\gamma_E^2+\frac{1976}{3}\gamma_E+\frac{3}{4}\pi^4+\frac{121}{3}\pi^2+\frac{4343}{18}\right. \\
& -\left(\frac{52}{3}\zeta(3)+\frac{176}{3}\gamma_E^2+\frac{916}{9}\gamma_E+\frac{44}{9}\pi^2+\frac{1229}{27}\right)n_f \\
& \left.\left.+\left(\frac{16}{9}\gamma_E^2+\frac{80}{27}\gamma_E+\frac{4}{27}\pi^2+\frac{100}{81}\right)n_f^2\right]\right\} \\
& -\alpha_s\left(\frac{\alpha_s}{4\pi}\right)^2\left[v_{\mathcal{H}}(\mathbf{r}_2,\mathbf{r}_3)+v_{\mathcal{H}}(\mathbf{r}_1,-\mathbf{r}_3)+v_{\mathcal{H}}(-\mathbf{r}_2,-\mathbf{r}_1)\right]
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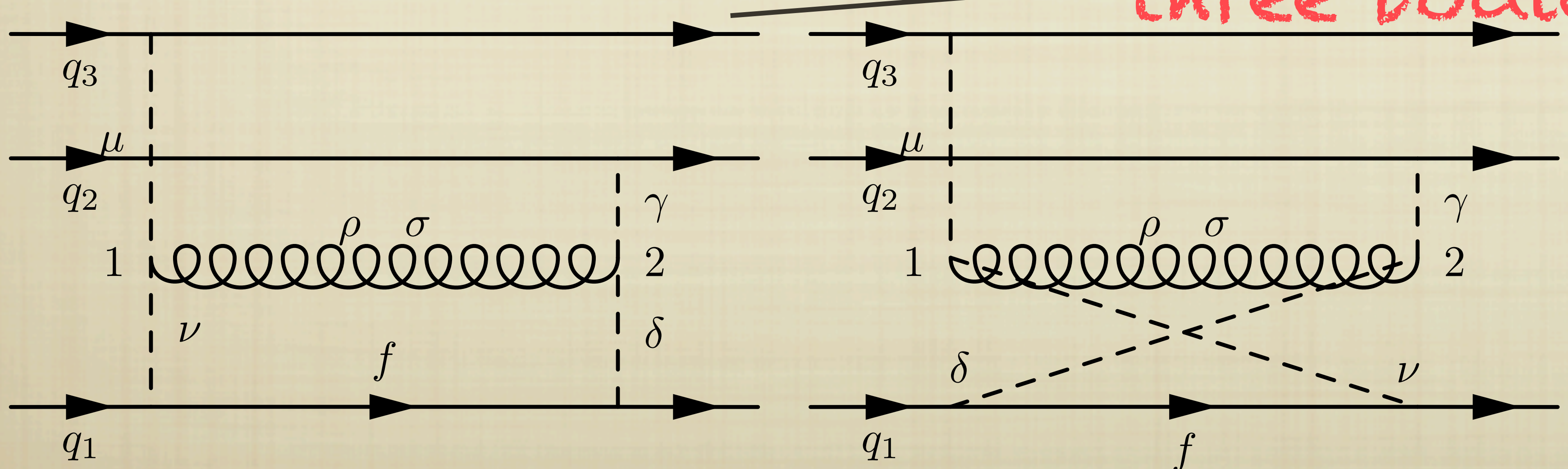
three bodies contributions



for references see the QWG doc

Applications to Quarkonium physics

for references see the QWG doc

Applications to Quarkonium physics

- c and b masses at NNLO, N^{3}LO*, NNLL*;
- B_c mass at NNLO;
- B_c^*, η_c, η_b masses at NLL;
- Quarkonium 1P fine splittings at NLO;
- $\Upsilon(1S)$, η_b electromagnetic decays at NNLL;
- $\Upsilon(1S)$ and J/ψ radiative decays at NLO;
- $\Upsilon(1S) \to \gamma\eta_b$, $J/\psi \to \gamma\eta_c$ at NNLO;
- $t\bar{t}$ cross section at NNLL*;

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$$\mathcal{B}(J/\psi \to \gamma\eta_c(1S)) = (1.6 \pm 1.1)\%$$

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N. B. Yu Jia A. Vairo 2005

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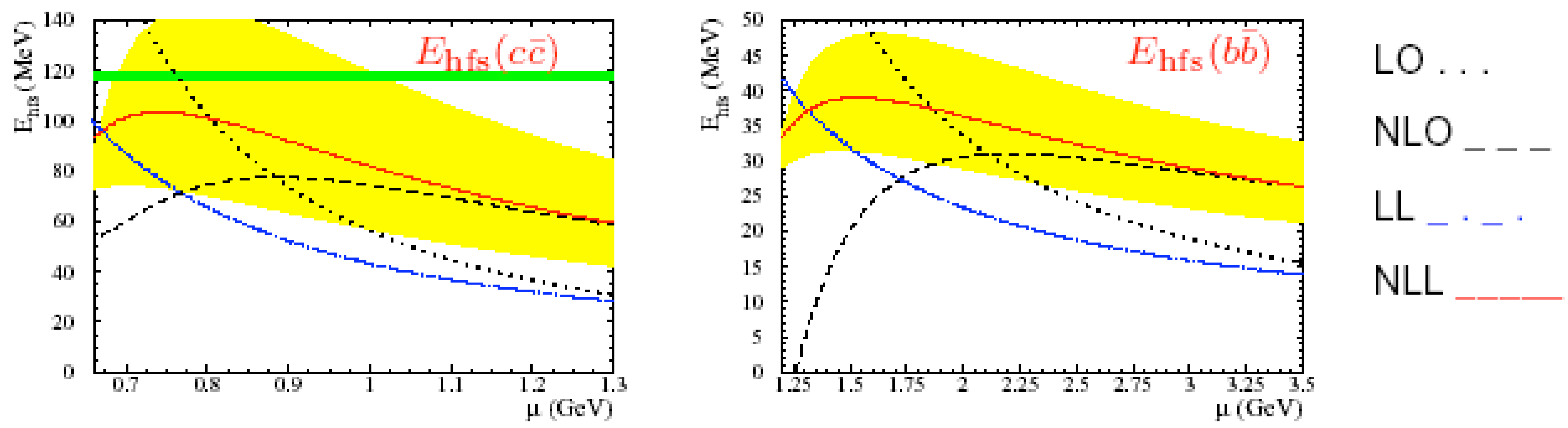
N. B. Yu Jia A. Vairo 2005

$$\Gamma(\eta_b(1S) \to \gamma\gamma) = 0.54 \pm 0.15 \text{ keV} .$$

$$\Gamma(\eta_b(1S) \to \text{ LH}) = 7\text{-}16 \text{ MeV}$$

Y. Kiyo, A. Pineda, A. Signer 2010

Predictions for η_b



$$M_{\eta_b} = 9419 \pm 11(th)^{+9}_{8}(\delta\alpha_s)\,\mathrm{MeV}$$

Kniehl et al 03

BABAR 08, 09

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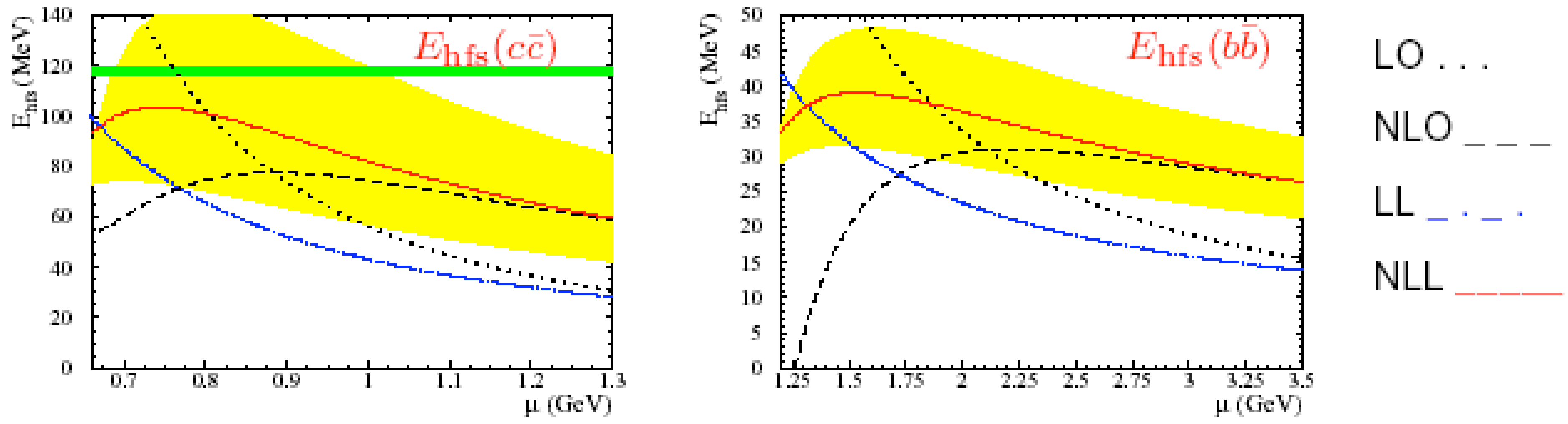

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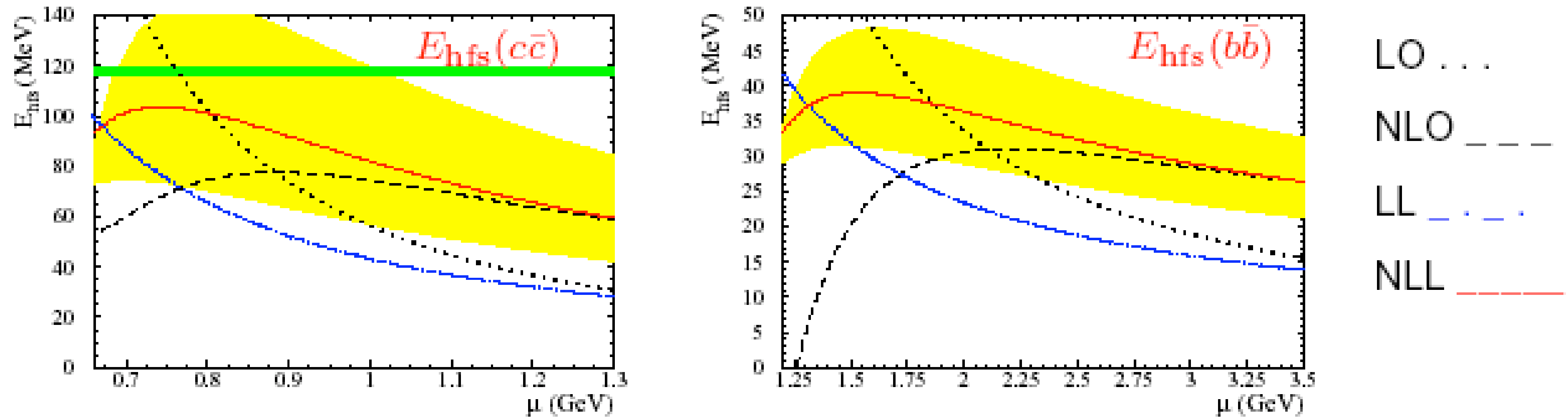

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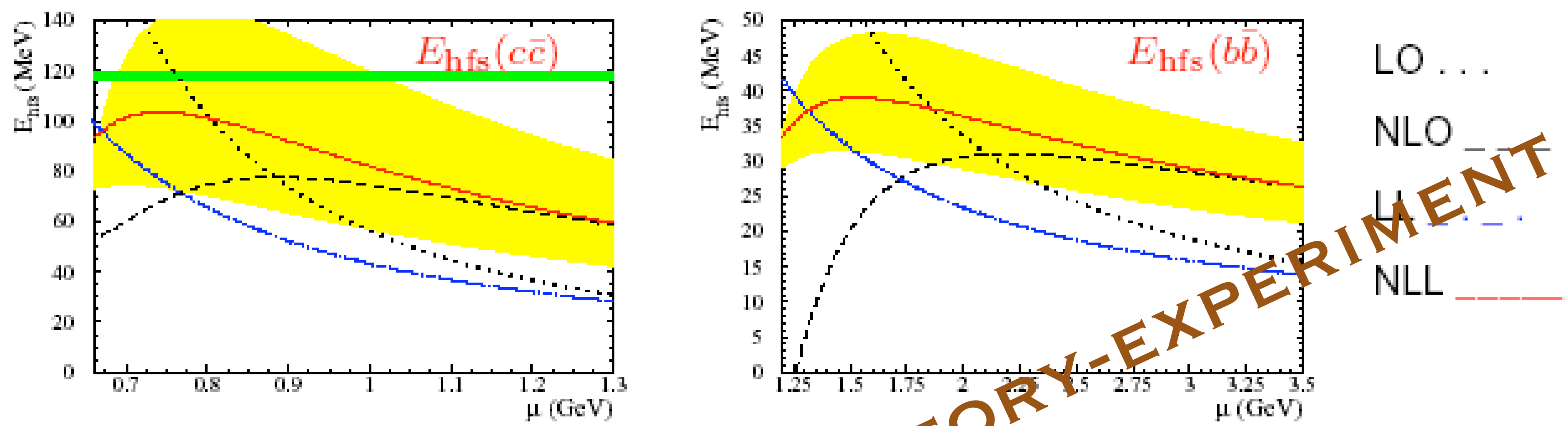

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2 SIGMA DISCREPANCY THEORY-EXPERIMENT

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Brambilla Pineda Soto Vairo 00

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Calculate once for ever the potential and get the full charmonium specroscopy

$$V = V_0 + \frac{1}{m} V_1 + \frac{1}{m^2} (V_{SD} + V_{VD})$$

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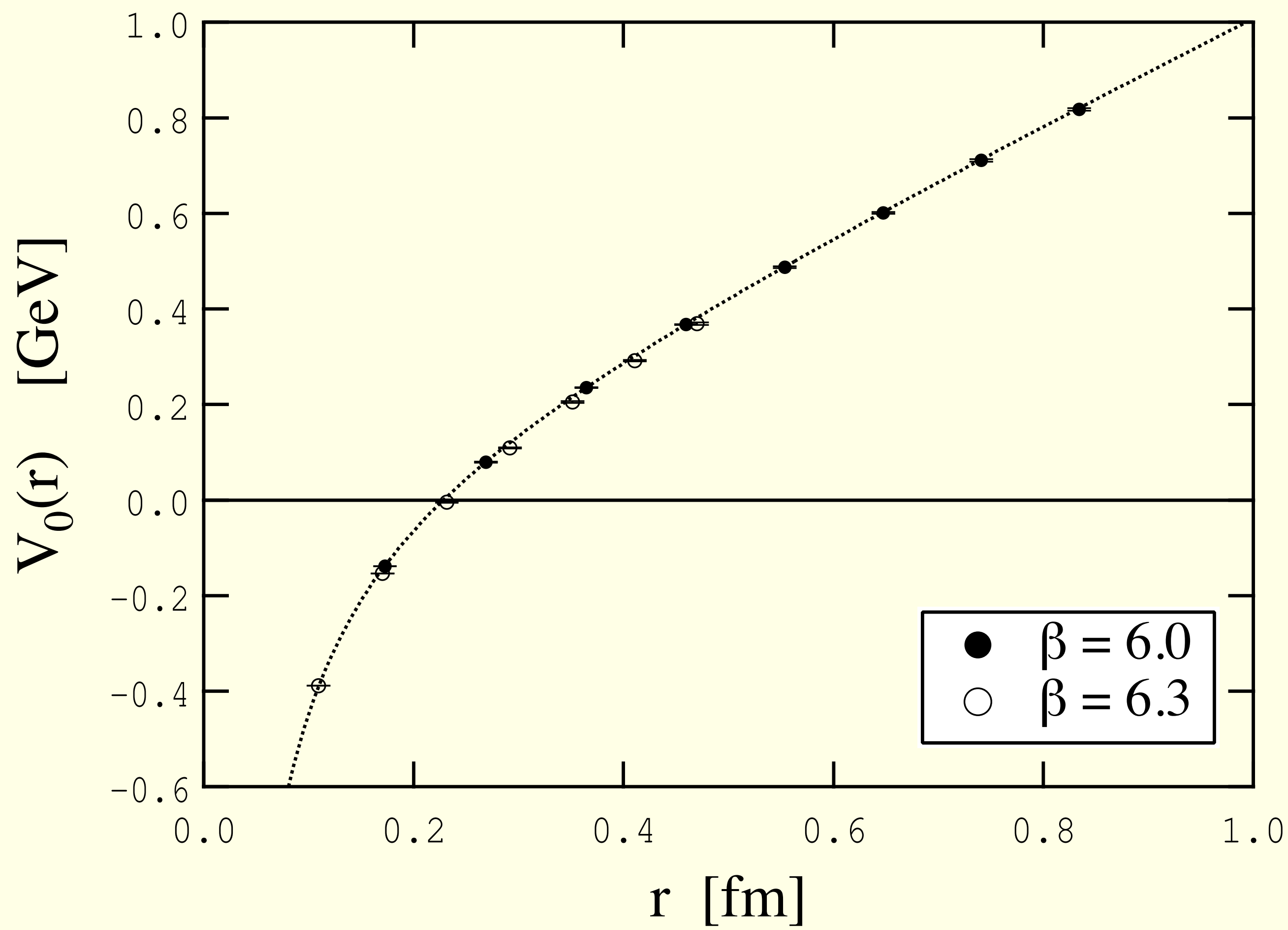
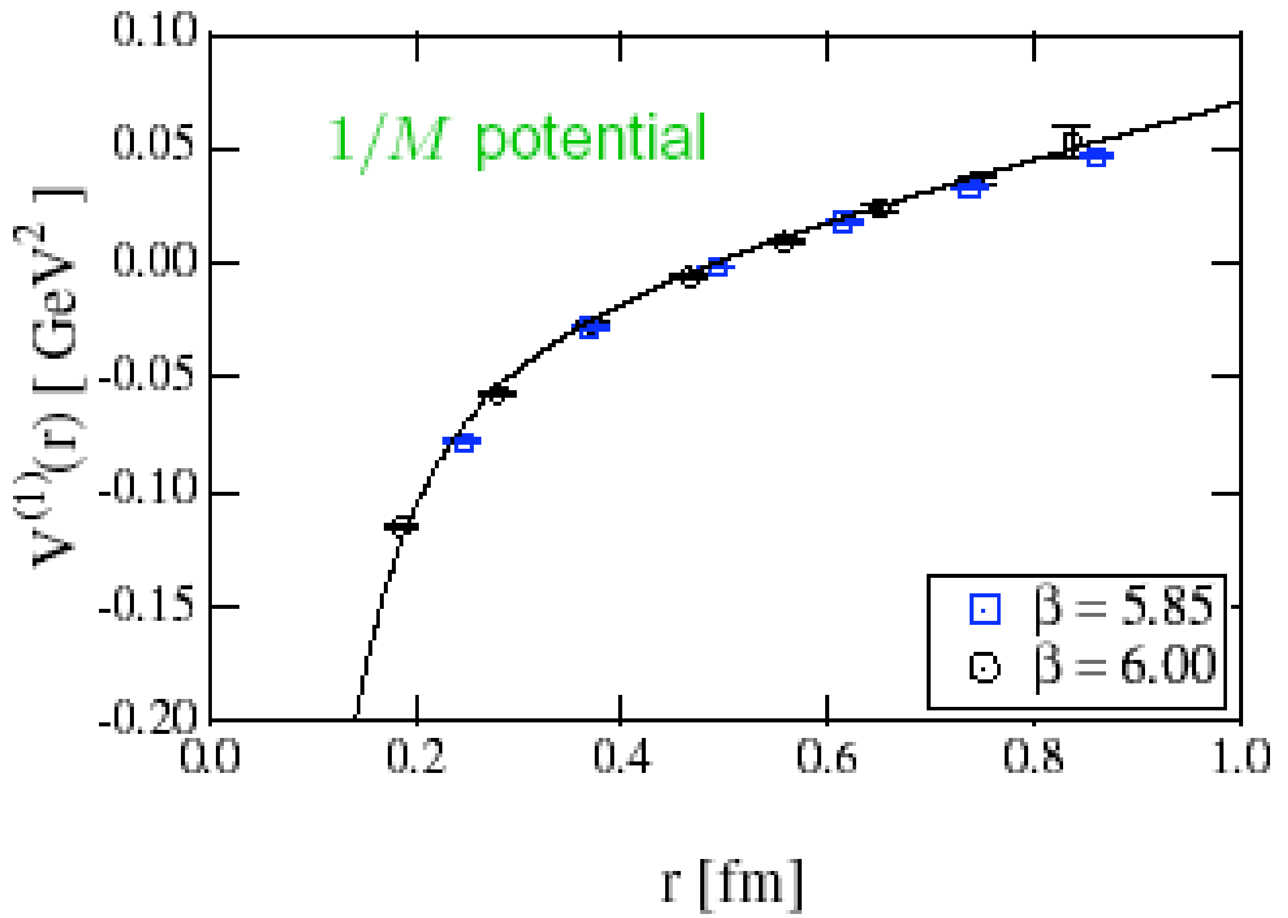
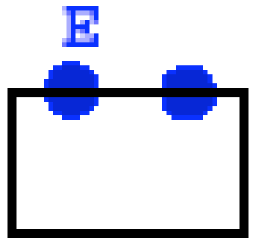


○ Koma Koma NPB 769(07)79

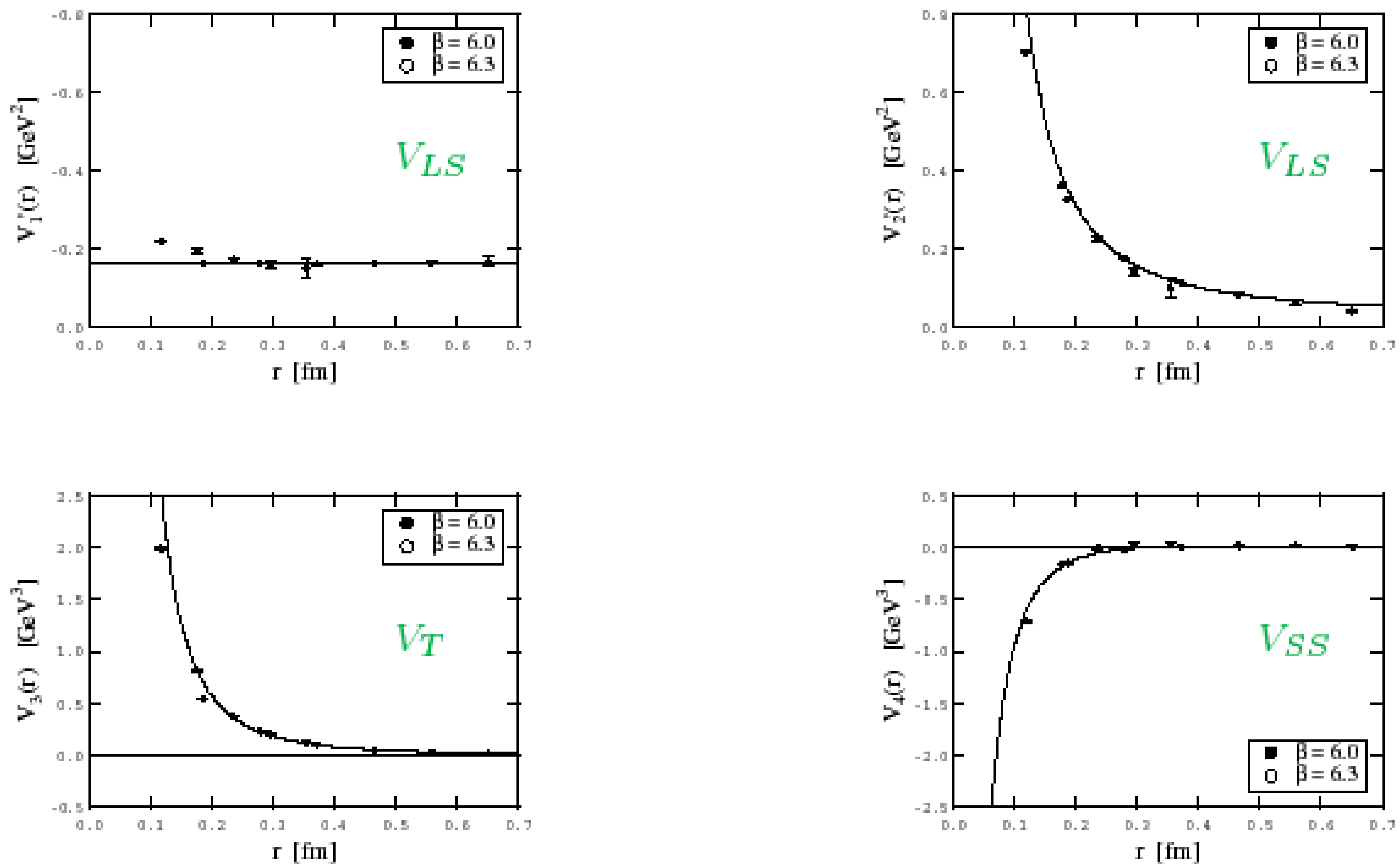


- Koma Koma Wittig PoS LAT2007(07)111

$$\frac{V_s^{(1)}}{m} = -\frac{1}{2m}\int_0^\infty dt\, t \,\Big\langle$$  $$\Big\rangle$$

Brambilla et al 00

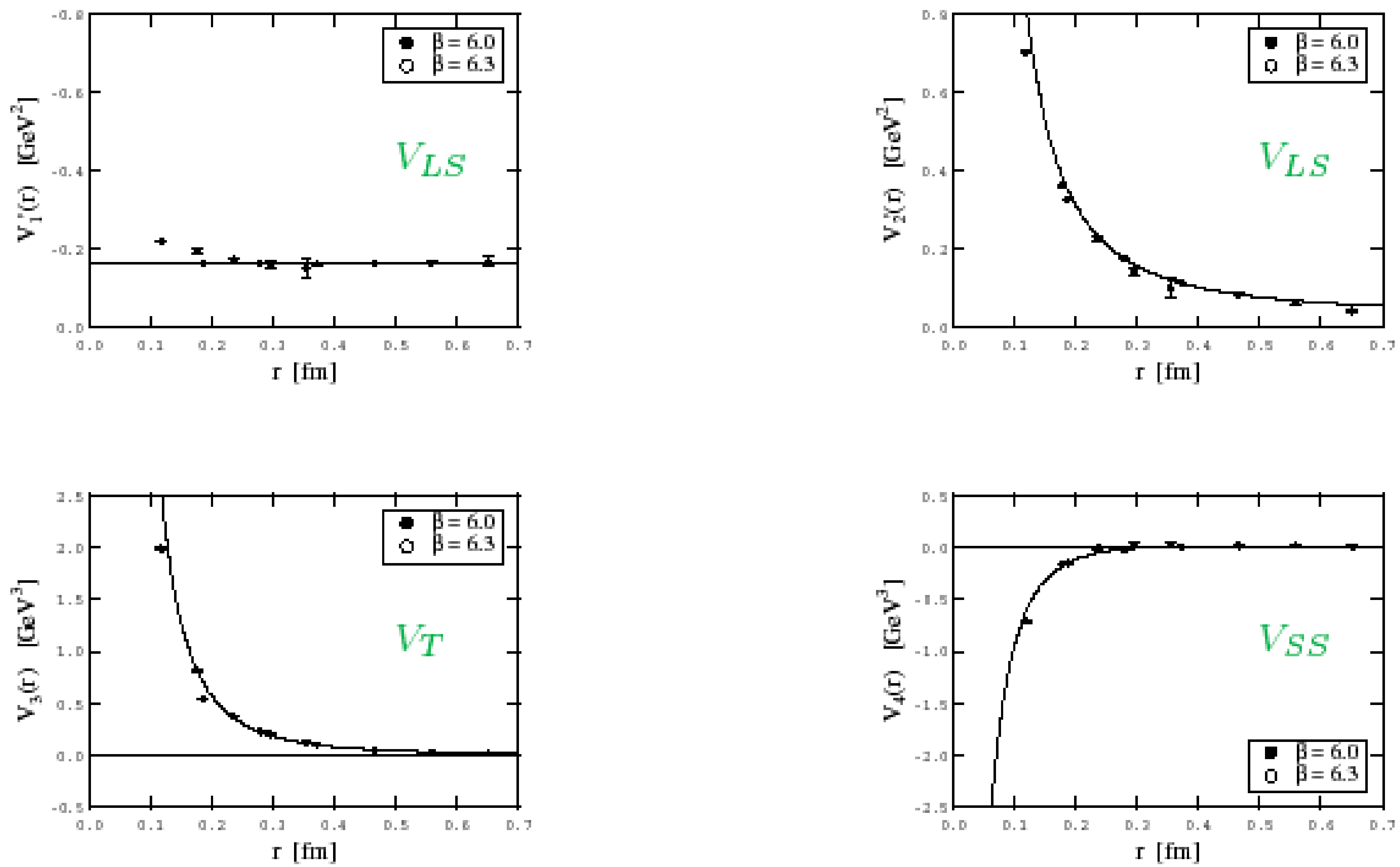
Spin dependent potentials



Koma Koma Wittig 05, Koma Koma 06

Terrific advance in the data precision with Lüscher multivel algorithm!

Spin dependent potentials



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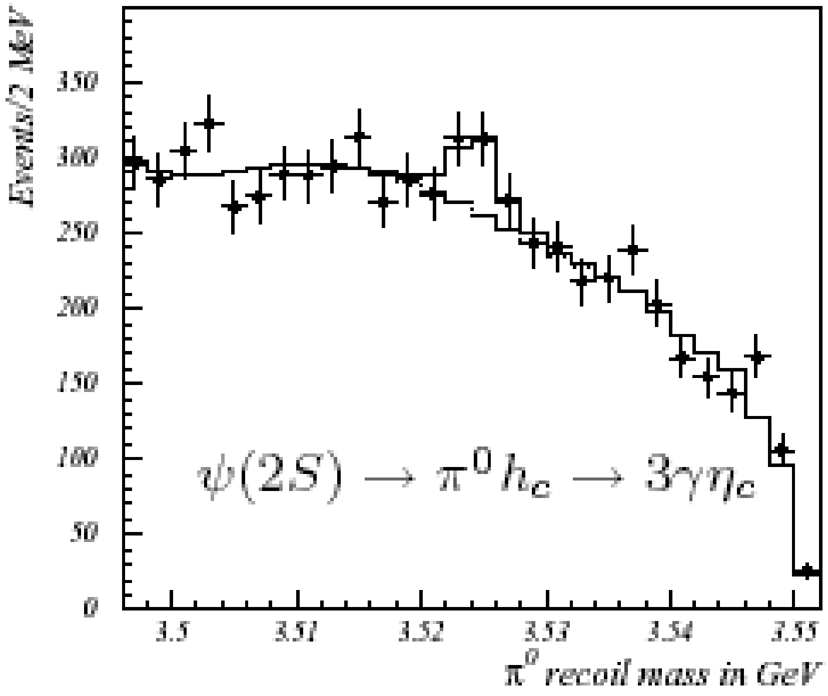
Terrific advance in the data precision with Lüscher multivel algorithm!

Such data can distinguish different models for the dynamics of low energy QCD

Confirmed in the spectrum, e.g. no long range spin-spin interaction

h_c



$$M = 3524.4 \pm 0.6 \pm 0.4 \text{ MeV}$$

CLEO 05

Also

$$M = 3525.8 \pm 0.2 \pm 0.2 \text{ MeV}, \qquad \Gamma < 1 \text{ MeV}$$

E835 05

- To be compared with $M_{\text{c.o.g.}}(1P) = 3525.36 \pm 0.2 \pm 0.2$ MeV.

no Λ_{QCD} gap: close and above threshold

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Gluonic excitations

A plethora of states built on each of the hybrid potentials is expected. These states typically develop a width also without including light quarks, since they may decay into lower states, e.g. like hybrid $\longrightarrow$ glueball + quark-antiquark.

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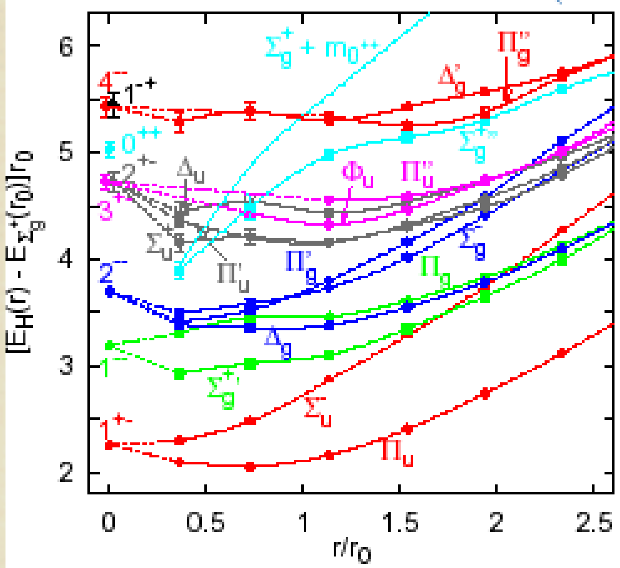
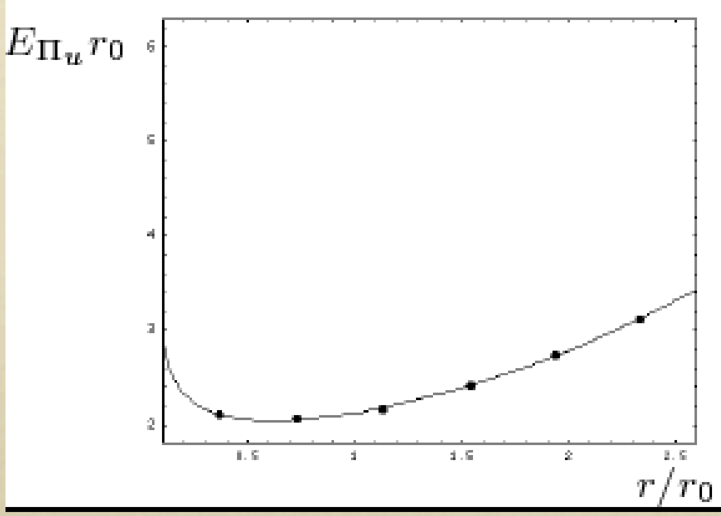
$Y(4260)$: a $c\bar{c}$ hybrid candidate



J^{PC}	H	$\Lambda_H^{RS} r_0$	Λ_H^{RS}/GeV
1^{+-}	B_i	2.25(39)	0.87(15)
1^{--}	E_i	3.18(41)	1.25(16)
2^{--}	$D_{\{i}B_{j\}}$	3.69(42)	1.45(17)
2^{+-}	$D_{\{i}E_{j\}}$	4.72(48)	1.86(19)
3^{+-}	$D_{\{i}D_j B_{k\}}$	4.72(45)	1.86(18)
0^{++}	$\mathbf{B}^2$	5.02(46)	1.98(18)
4^{--}	$D_{\{i}D_j D_k B_{l\}}$	5.41(46)	2.13(18)
1^{-+}	$(\mathbf{B} \wedge \mathbf{E})_i$	5.45(51)	2.15(20)

- Foster Michael PRD 59(99)094509
- Bali Pineda PRD 69(04)094001



Fitting the Π_u curve, $E_{\Pi_u} = (0.87 + 0.11/r + 0.24\, r^2)$ GeV and solving the Schrödinger equation, one gets

$$M(Y) = 2 \times 1.48 + 0.87 + 0.53 = 4.36 \quad \text{GeV}$$

- Vairo IJMP A22(07)5481

The QCD spectrum with light quarks

- We still have states just made of heavy quarks and gluons. They may develop a width because of the decay through pion emission. If new states made with heavy and light quarks develop a mass gap of order Λ_{QCD} with respect to the former ones, then these new states may be asborbed into the definition of the potentials or of the (local or non-local) condensates.
  - Brambilla et al. PRD 67(03)034018
- In addition new states built using the light quark quantum numbers may form.
  - Soto NP PS 185(08)107

States made of two heavy and light quarks

- Pairs of heavy-light mesons: $D\bar{D}$, $B\bar{B}$, ...

- Molecular states, i.e. states built on the pair of heavy-light mesons.
  - Tornqvist PRL 67(91)556

- Tetraquark states.

MAIANI, PICCININI, POLOSA ET AL. 2005--

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Having the spectrum of tetraquark potentials, like we have for the gluonic excitations, would allow us to build a plethora of states on each of the tetraquark potentials, many of them developing a width due to decays through pion (or other light hadrons) emission. Diquarks have been recently investigated on the lattice.

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Coupled channels

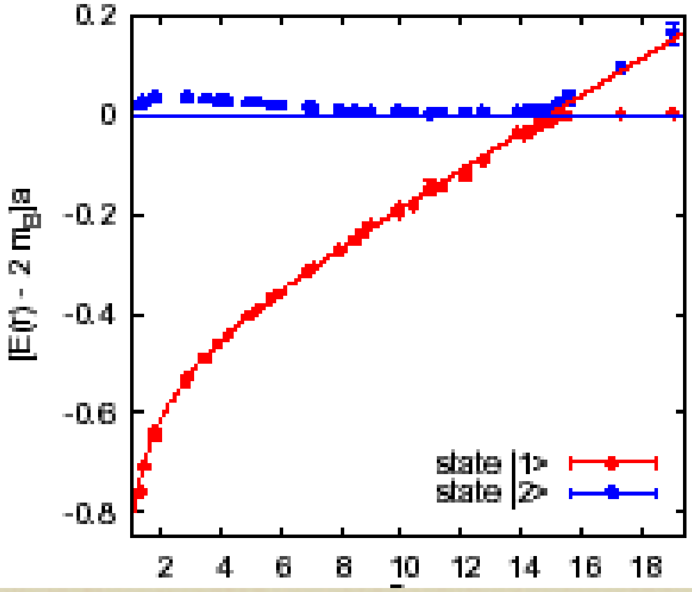
An important (and unsolved) issue is how all the different kind of states (with and without light quarks) interact with each other.

A systematic treatment does not exist so far. For the coupling with two-meson states, most of the existing analyses rely on two models, which are now more than 30 years old:

- the Cornell coupled-channel model;
  - `Eichten et al. PRD 17(78)3090, 21(80)313`
  - `Eichten et al. PRD 69(04)094019, 73(06)014014, 73(06)079903`
- and the ${}^3P_0$ model.
  - `Le Yaouanc et al. PRD 8(73)2223`
  - `Kalashnikova PRD 72(05)034010`

Steps towards a lattice based approach have been undertaken

- `SESAM PRD 71(05)114513`



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hybrids, molecular states, tetraquarks

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In some cases it is possible to develop an EFT owing to special dynamical condition

- An example is the $X(3872)$ intepreted as a $D^0\,\bar{D}^{*\,0}$ or $\bar{D}^0\,D^{*\,0}$ molecule.
  In this case, one may take advantage of the hierarchy of scales:

$$\Lambda_{\rm QCD} \gg m_\pi \gg m_\pi^2/M_{D^0} \approx 10 \text{ MeV} \gg E_{\rm binding}$$
$$\approx M_X - (M_{D^{*0}} + M_{D^0}) = (0.1 \pm 1.0)\ {\rm MeV}$$

Systems with a short-range interaction and a large scattering length have universal properties that may be exploited: in particular, production and decay amplitudes factorize in a short-range and a long-range part, where the latter depends only on one single parameter, the scattering length

Braaten Hammer 06

Pakvasa Suzuki 03, Voloshin 03, Braaten Kusunoki 03

Conclusions

Effective field theories gives us invaluable tools to investigate strong interactions

Nonrelativistic Effective Field Theories provide a systematic tool to investigate a wide range of heavy quarkonium observables in the realm of QCD

Allow us to make calculations with unprecented precision, where high order perturbative calculations are possible and to systematically factorize short from long range contributions where observables are sentitive to the nonperturbative dynamics of QCD

They allow us to give the appropriate definition and define a calculational scheme for quantities of huge phenomenological interest like the qqbar interaction, spectra, decays ... and the qqbar potential at finite T

in the EFT framework heavy quark bound states become a unique laboratory for the study of strong interaction from the high energy to the low energy scales

Outlook1: future research

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Finite T : masses, width of quarkonia states, impact of anisotropy of the medium, transport coefficients of heavy quarks, viscosity

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ALICE, RHIC

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BELLE,BESIII, PANDA, LHC-B

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Quarkonium-quarkonium van der Waals interaction

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Quarkonium-quarkonium van der Waals interaction FAIR

Quarkonium production

Outlook1: future research

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Spectra/decays of quarkonia BELLE,BESIII, PANDA, LHC-B

EFT for states close to thresholds: X, Y, Z BELLE,BESIII, PANDA, LHC-B

Quarkonium-quarkonium van der Waals interaction FAIR

Quarkonium production CMS, ATLAS