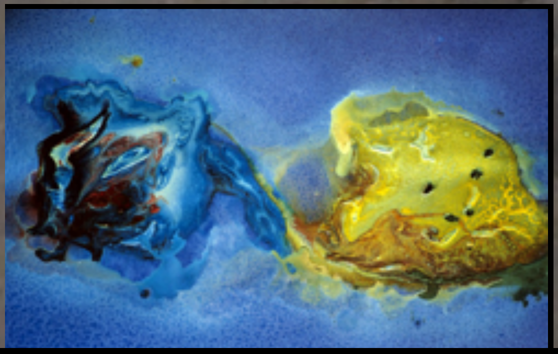
Heavy Quarkonium with Effective Field Theories

NORA BRAMBILLA

Talk dedicated to MISHA POLIKARPOV



PHYSIK DEPARTMENT TUM
T30F

- quarkonium and its relevance
  hadronic physics

  - the state of the art theory tools and
    their impact on hadronic physics

    - experimental/theoretical challenges
      and opportunities

QCD and hadrons

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4}\left(\partial_\mu A_\nu - \partial_\nu A_\mu - ig[A_\mu, A_\nu]\right)^2 + \bar{\psi}_f\left(i\not\partial - g\not A - m_f\right)\psi_f$$

$$\alpha_{\mathrm{s}} = \frac{g^2}{4\pi}$$

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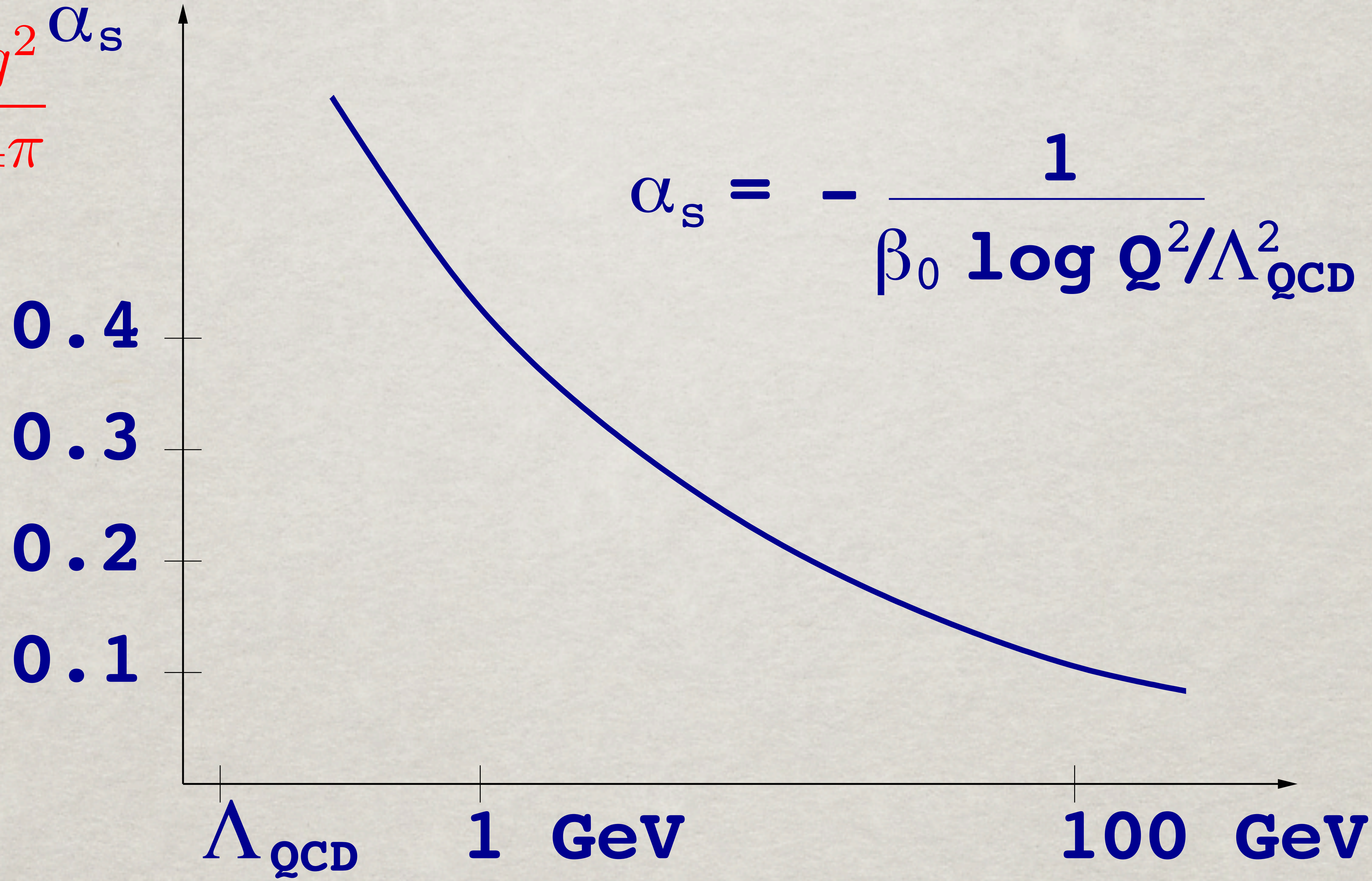

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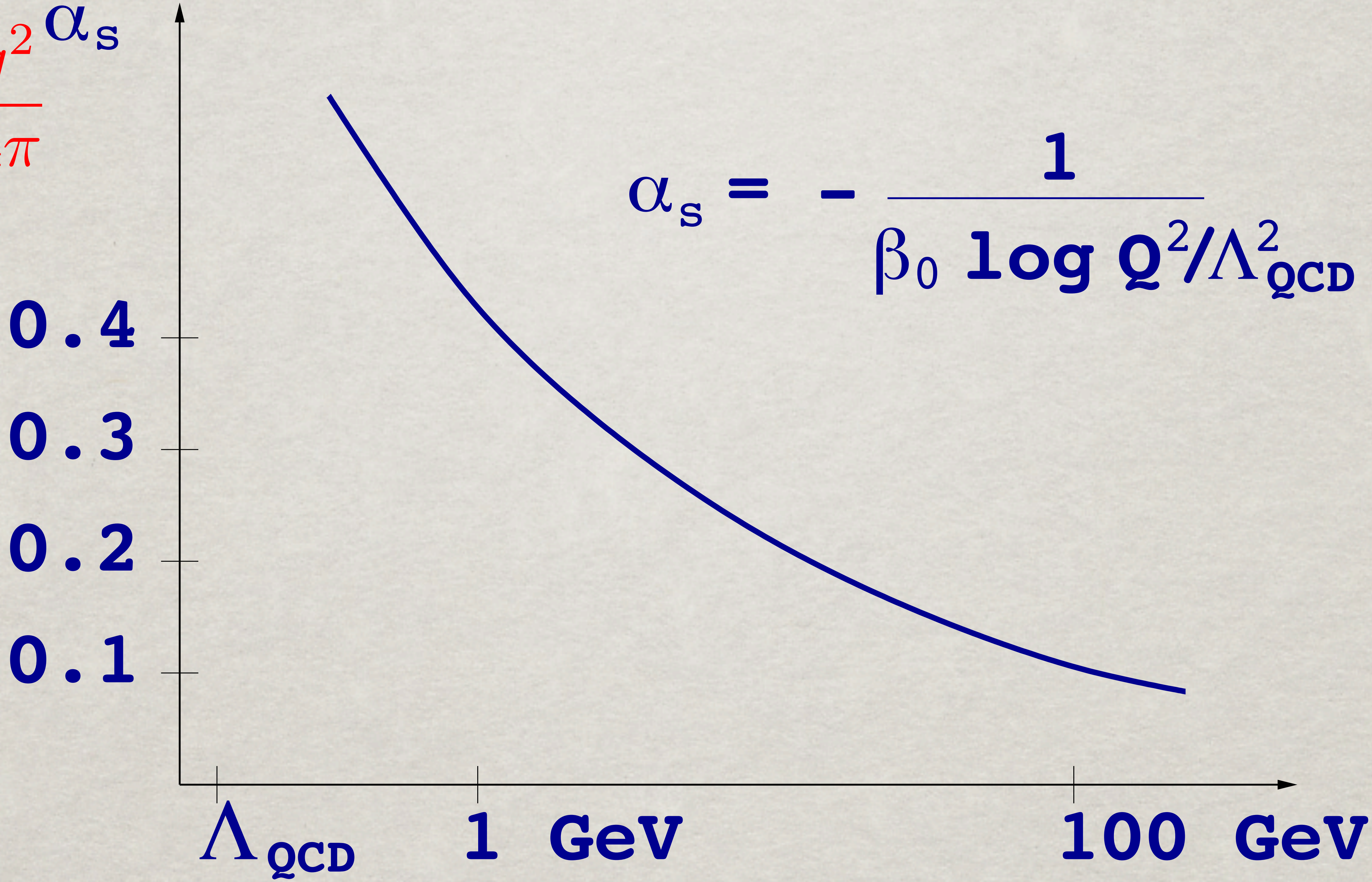

Λ_{QCD} is the scale where nonperturbative effects dominate

QCD and hadrons

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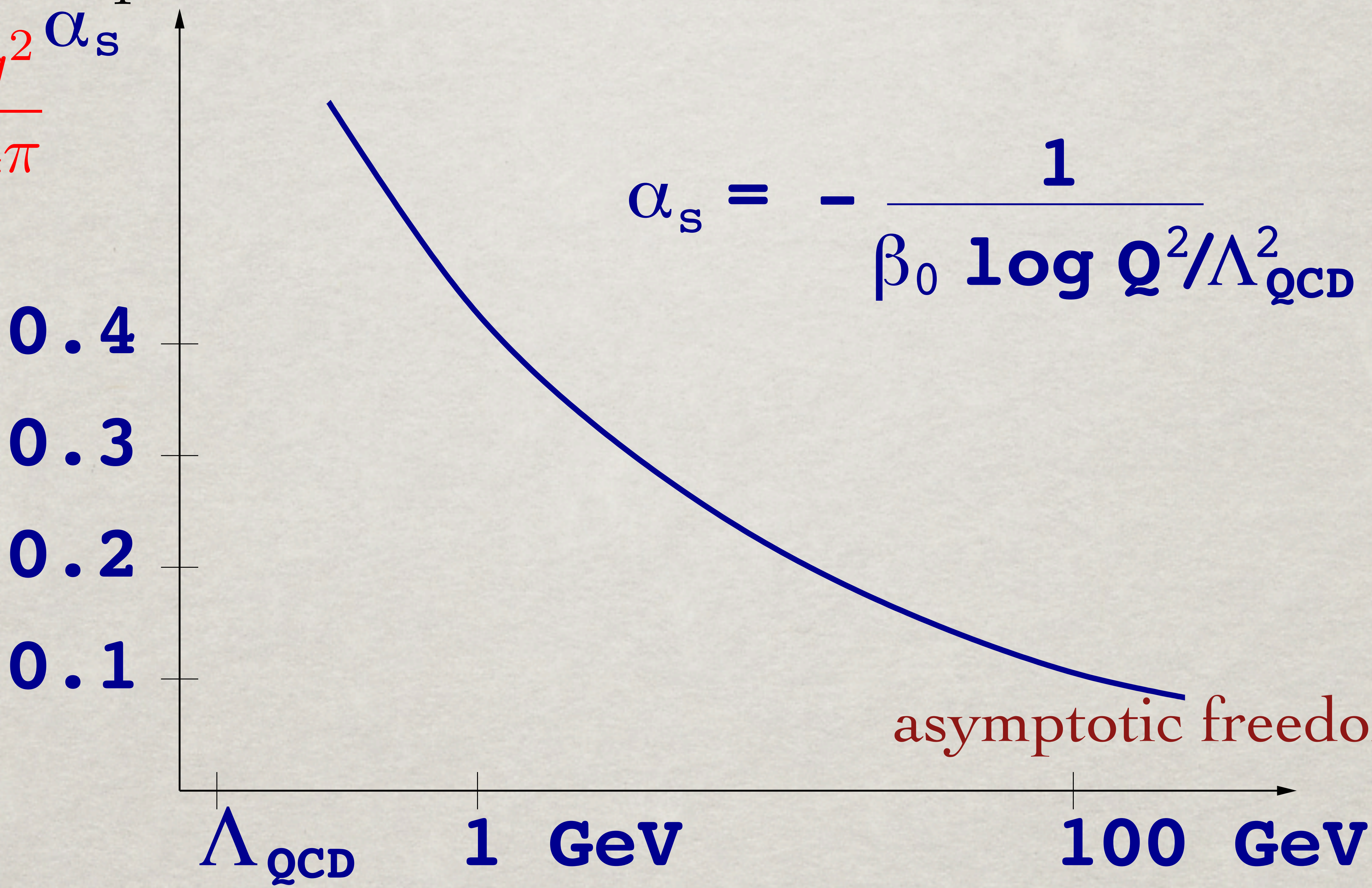

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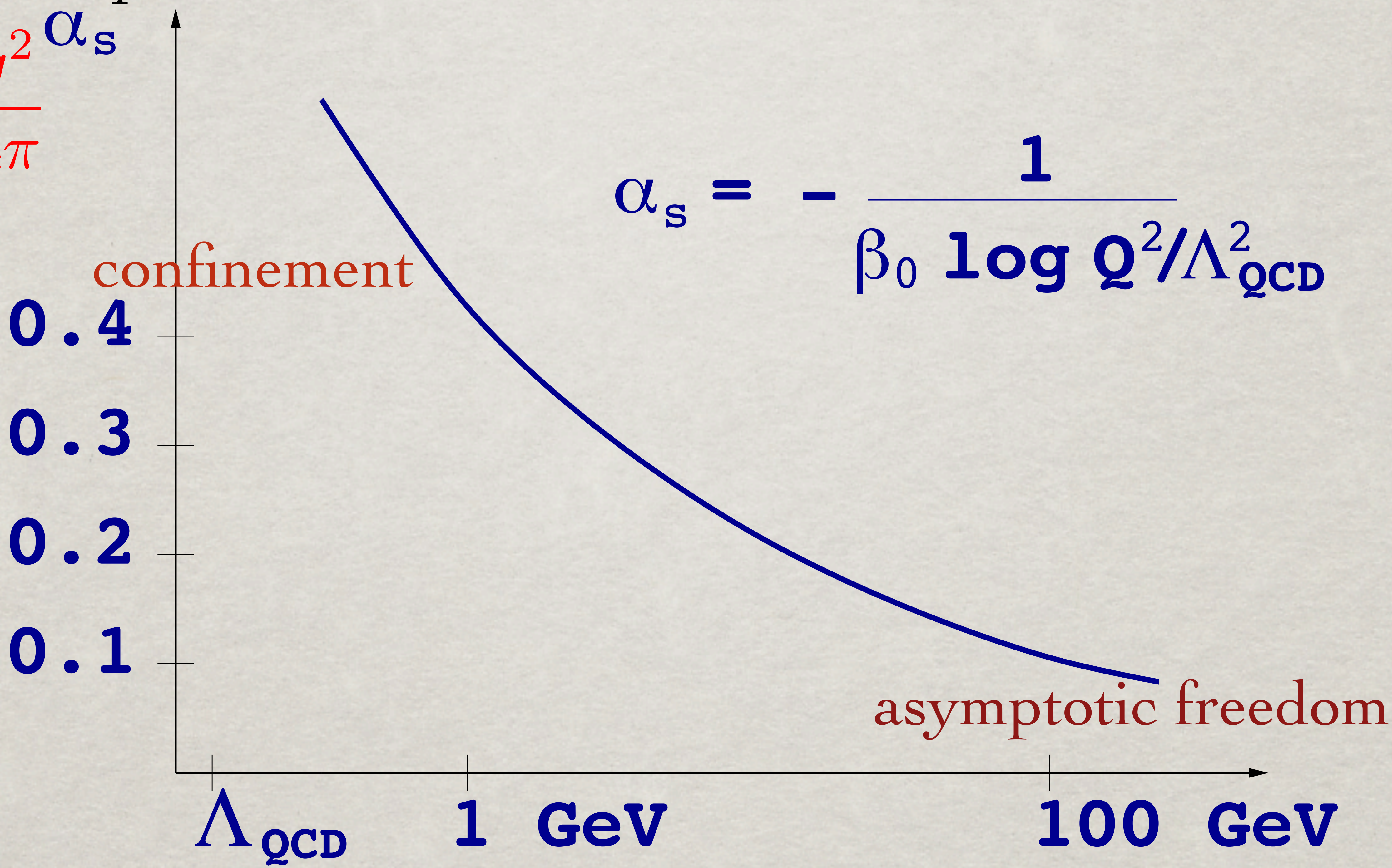

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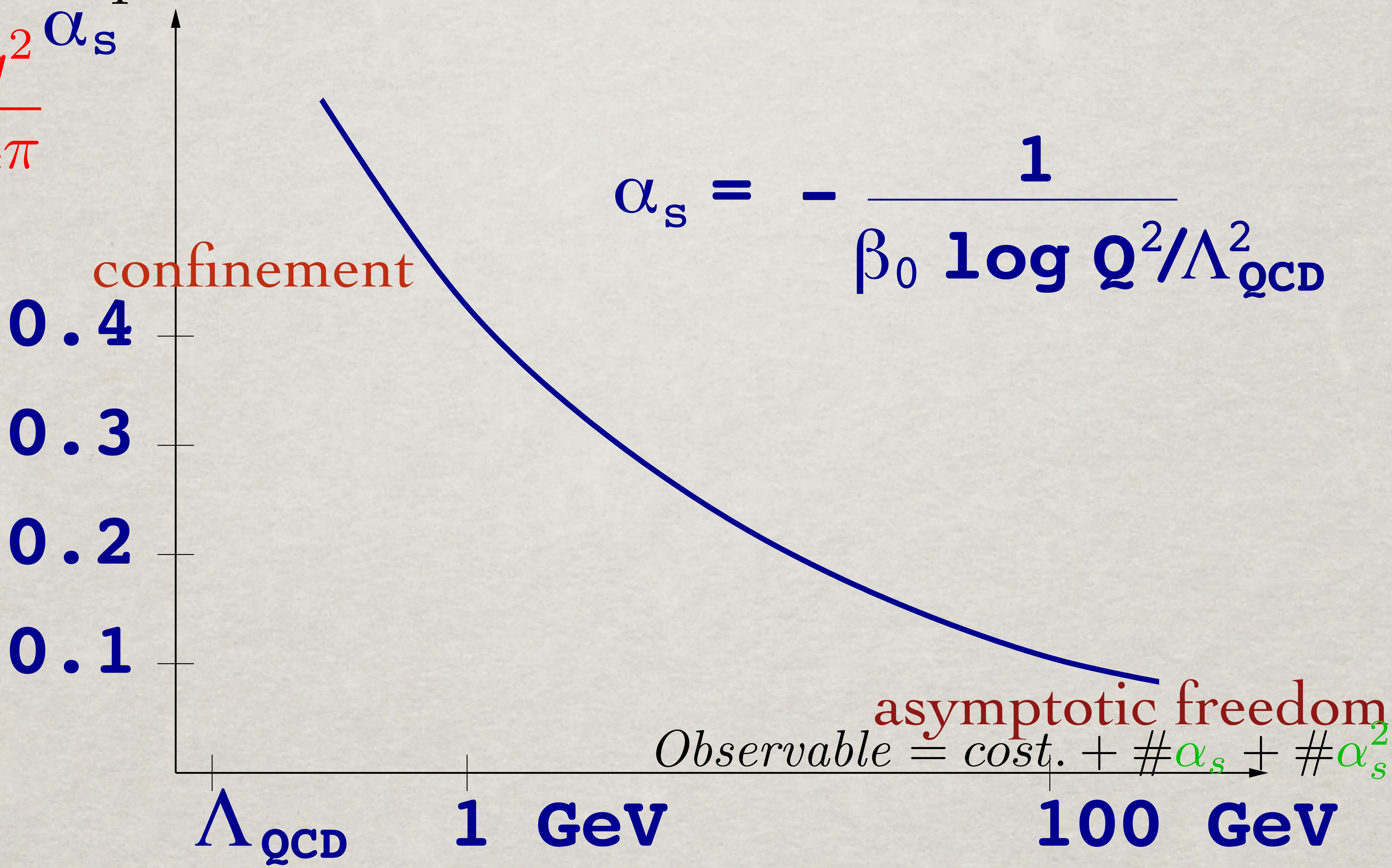

$$\alpha_s = -\frac{1}{\beta_0 \log Q^2/\Lambda^2_{QCD}}$$

$$Observable = cost. + \#\alpha_s + \#\alpha_s^2 + \ldots$$

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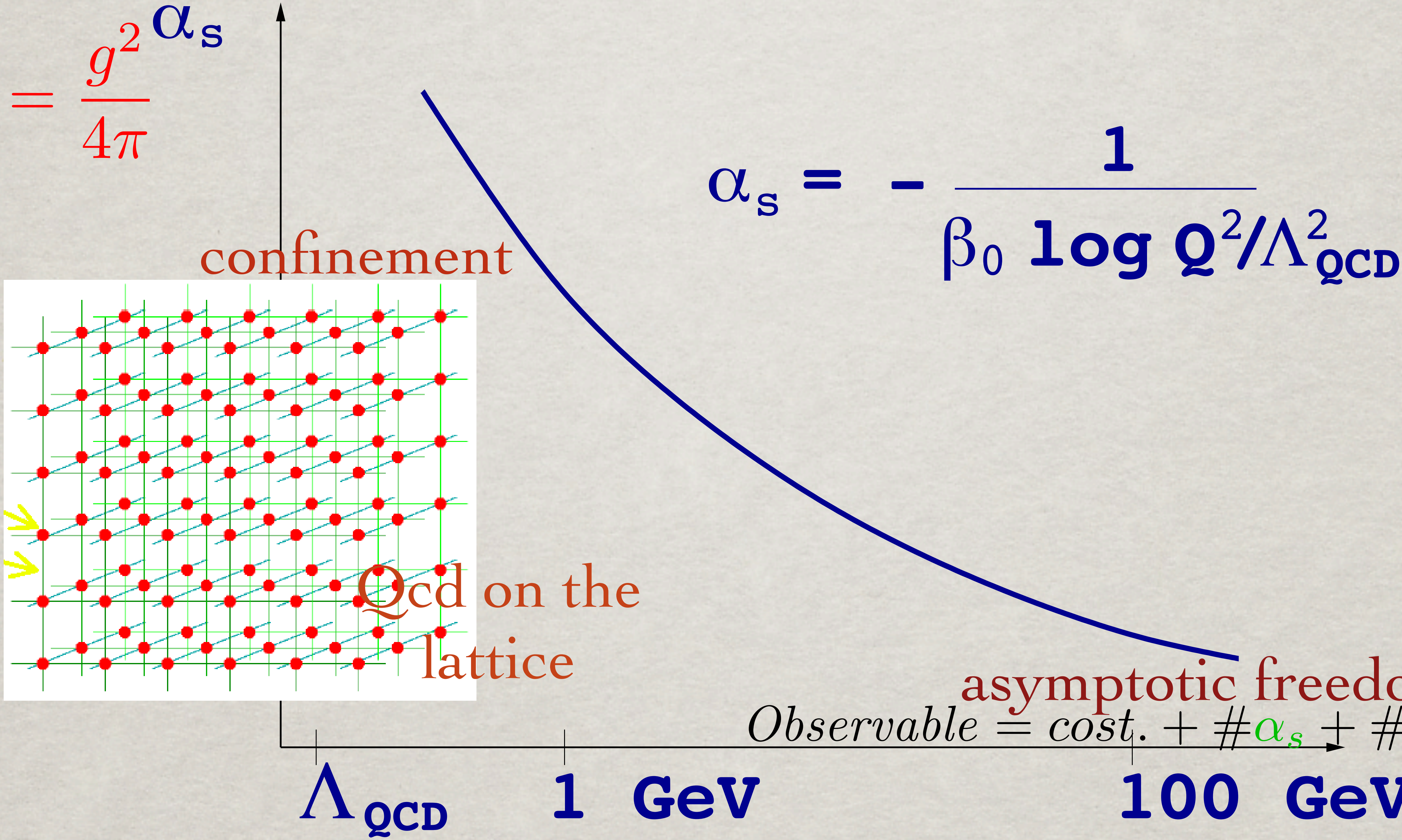

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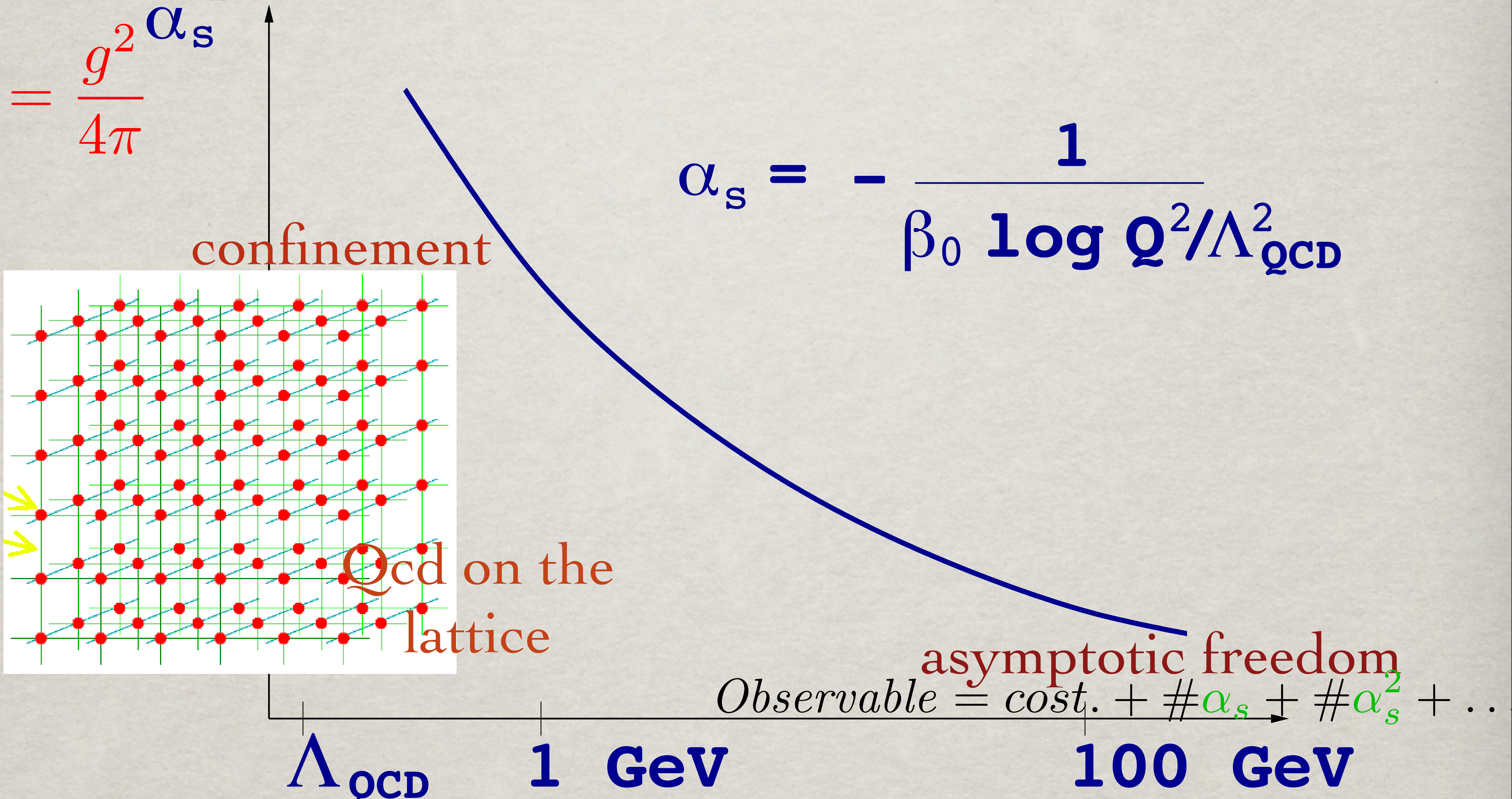
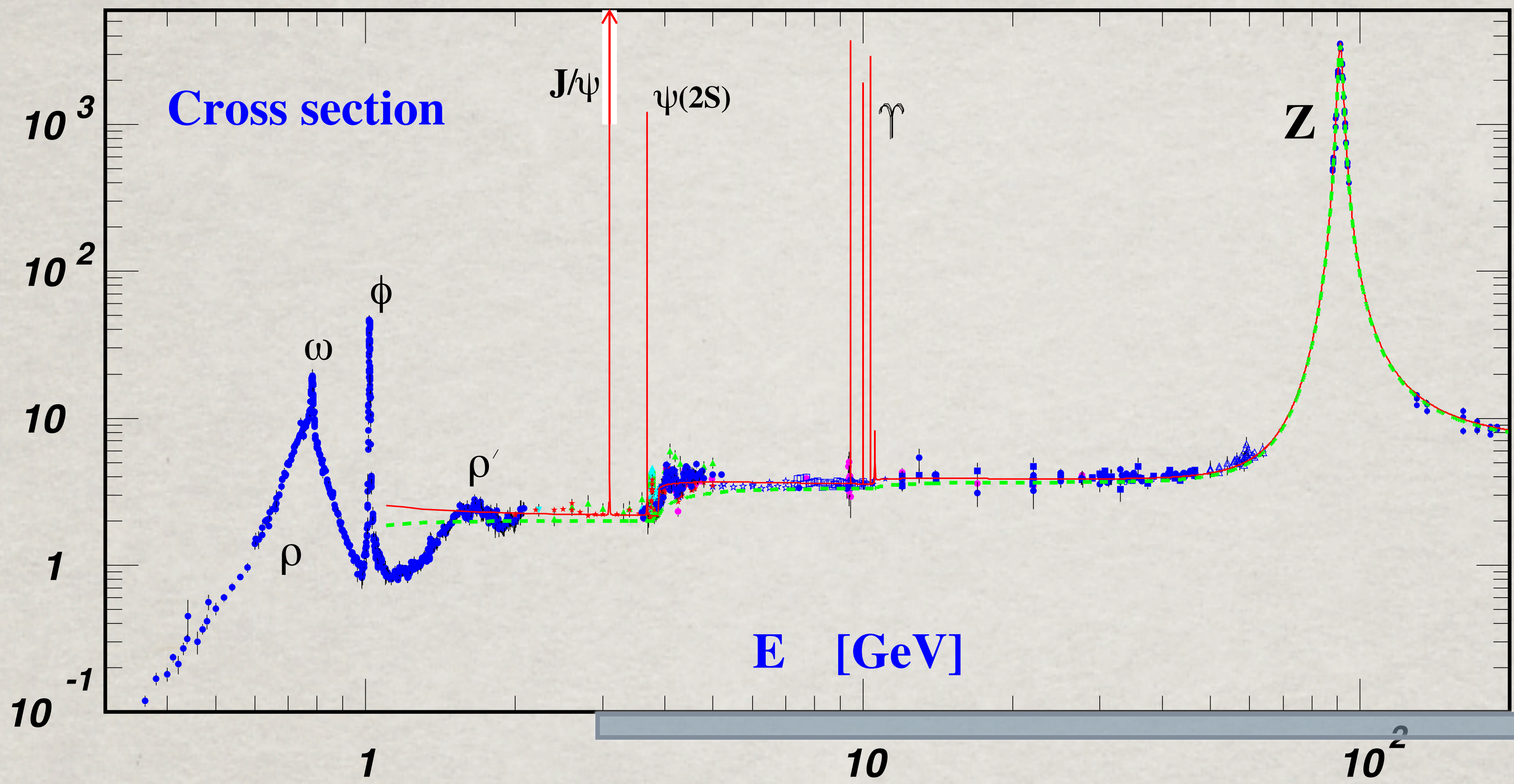


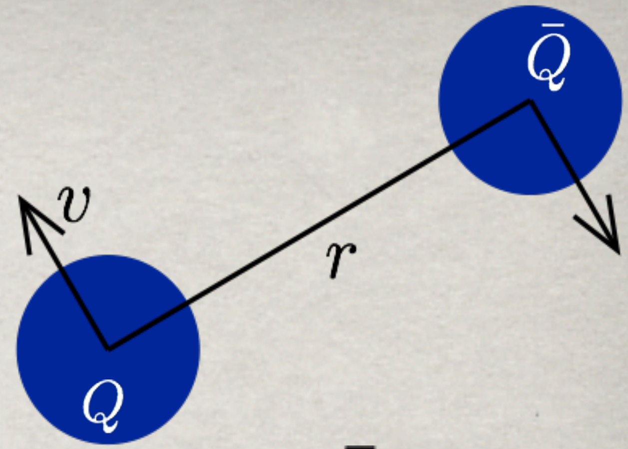
Λ_{QCD} is the scale where nonperturbative effects dominate

We have still a limited control on how hadronic properties are generated by QCD

Quarkonium is a privileged window over the hadronic world

Heavy quarks offer a privileged access





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

$m_c \sim 1.5\text{GeV}$

$m_b \sim 5\text{GeV}$

$m_t \sim 170\text{GeV}$

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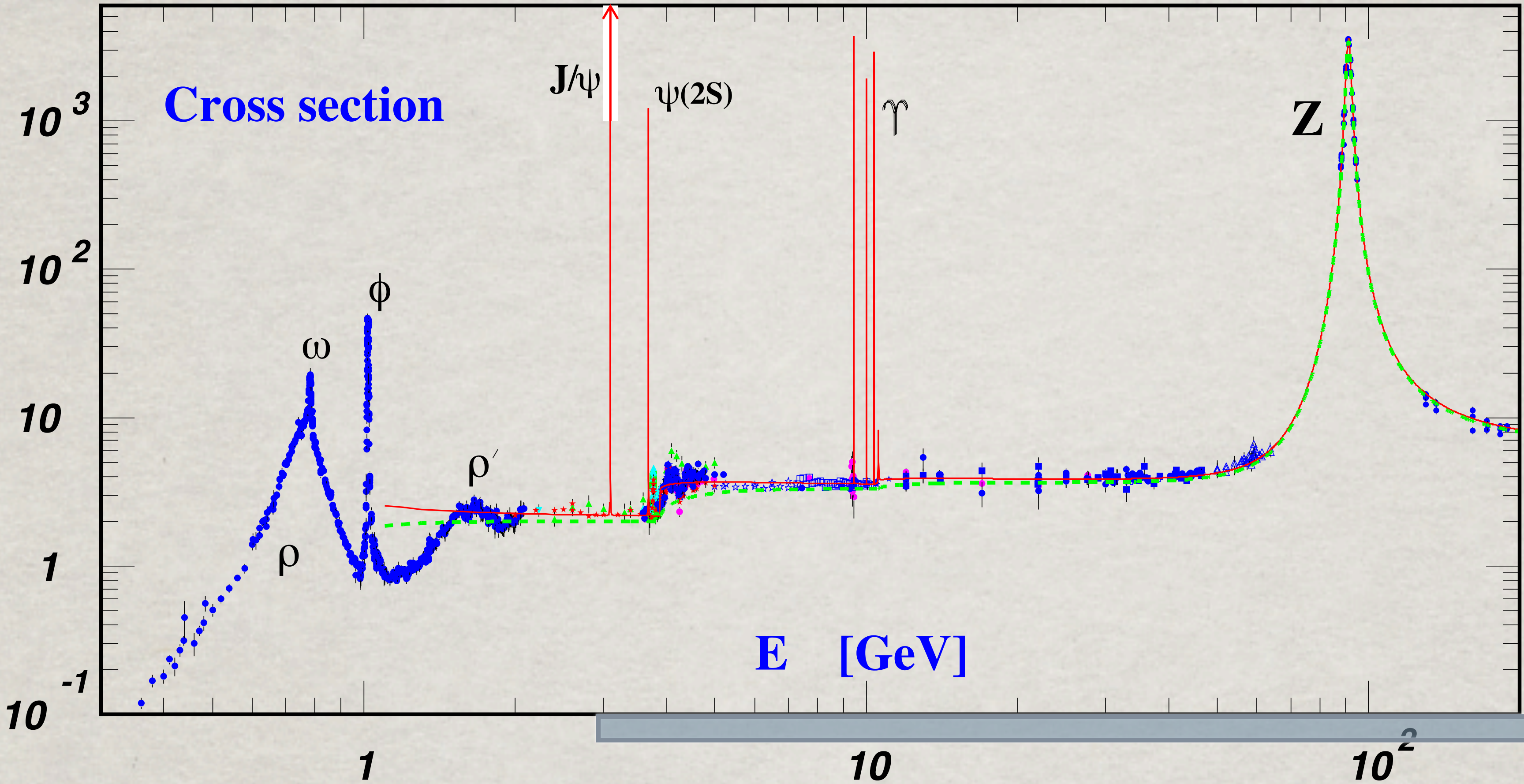

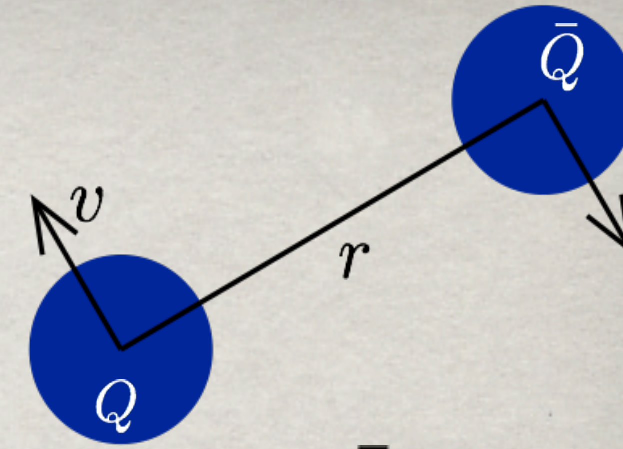

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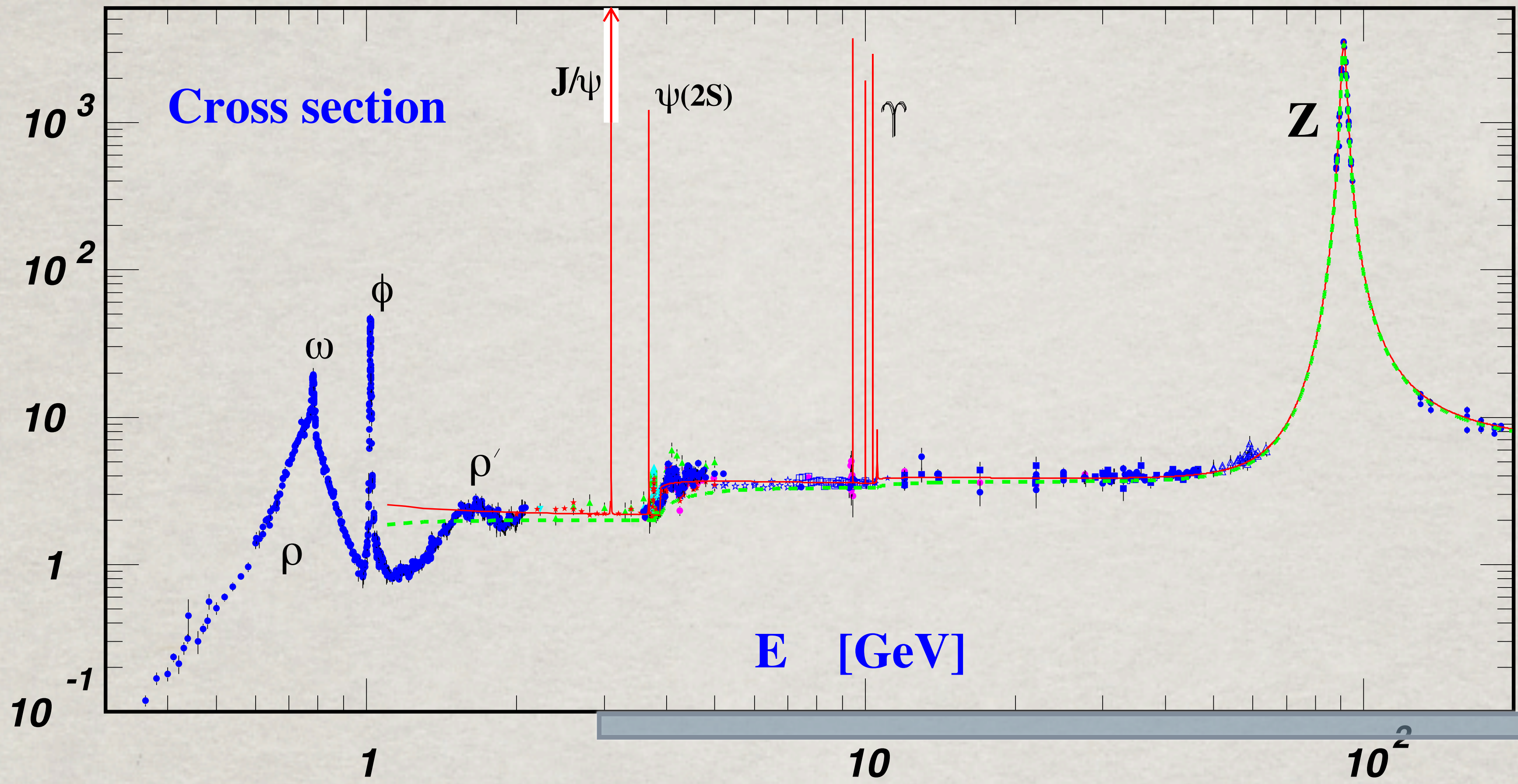

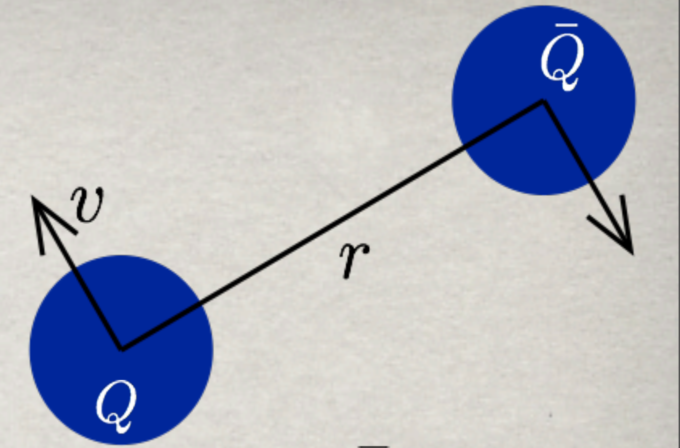

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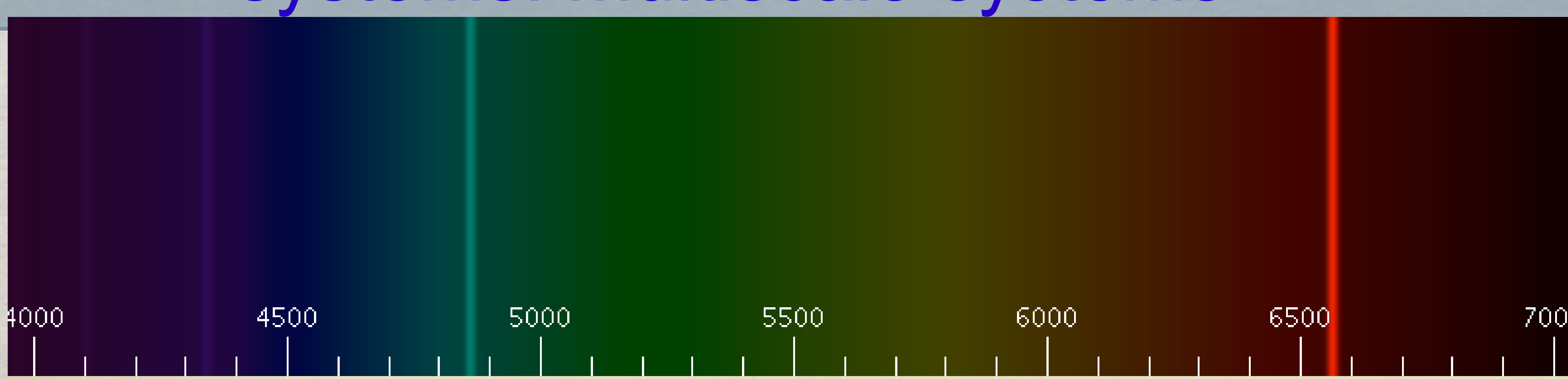
Heavy quarkonia are nonrelativistic bound systems: multiscale systems



Electromagnetic bound states: atoms, molecules,

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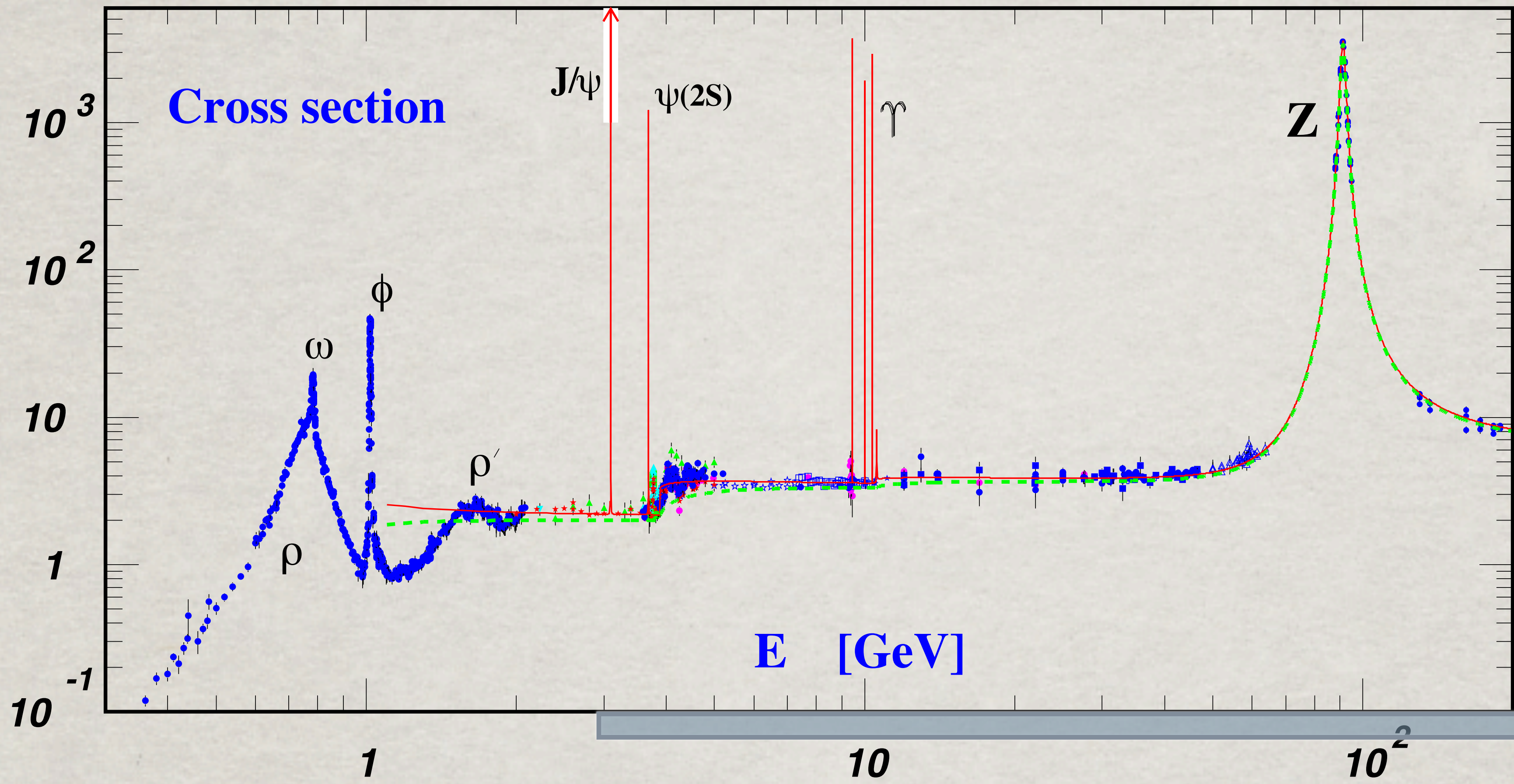

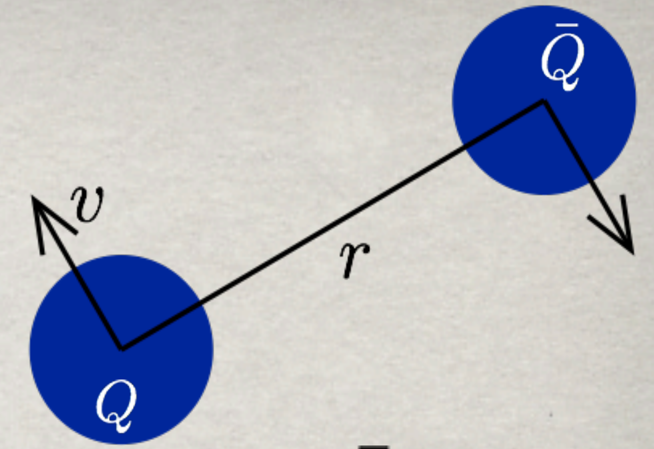

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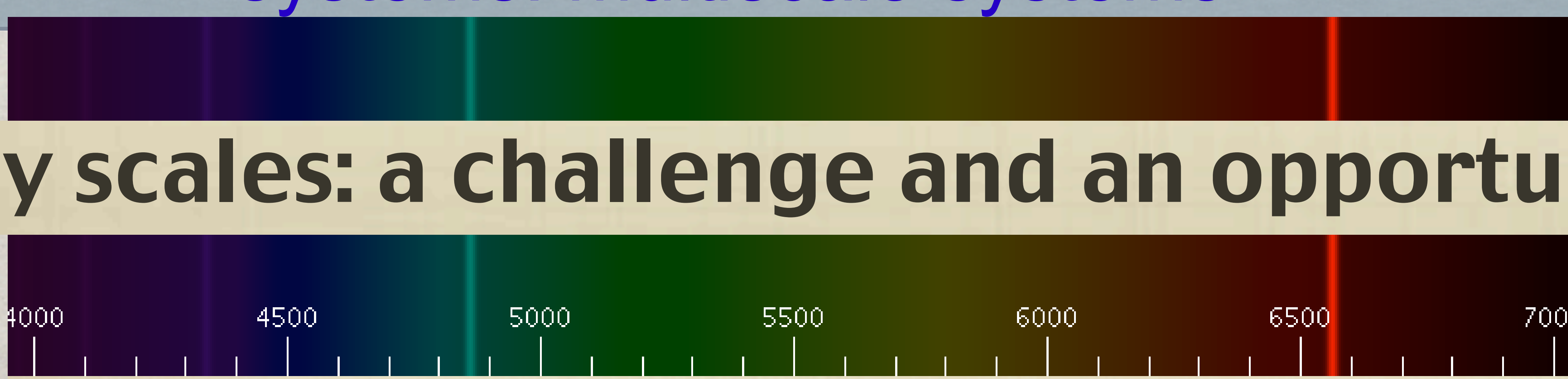
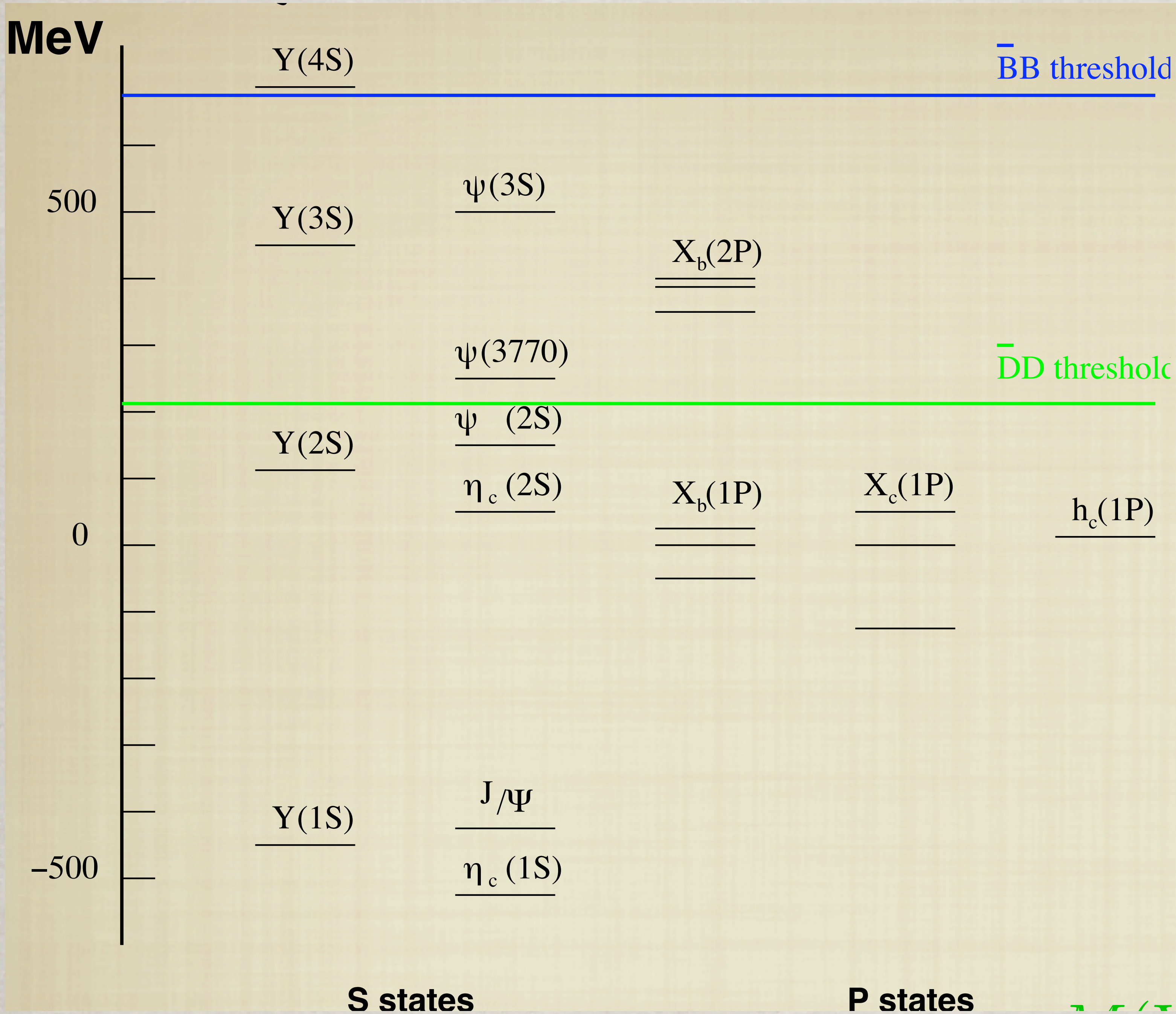


many scales: a challenge and an opportunity

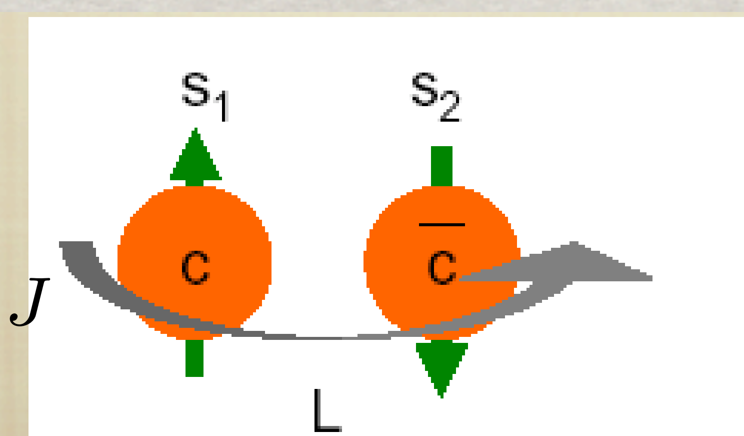
Electromagnetic bound states: atoms, molecules,

Quarkonium scales



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

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

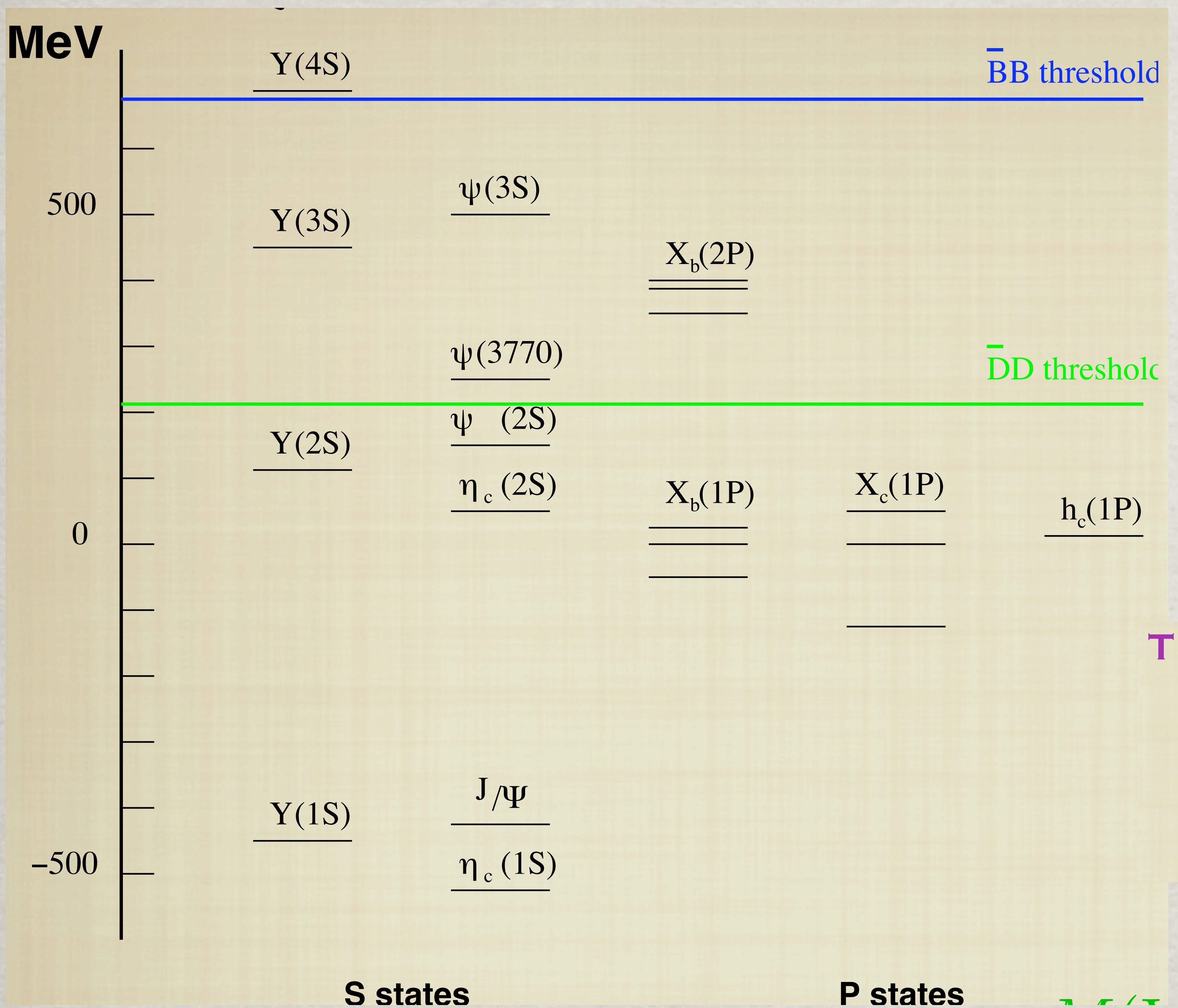


The mass scale is perturbative

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

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

Quarkonium scales



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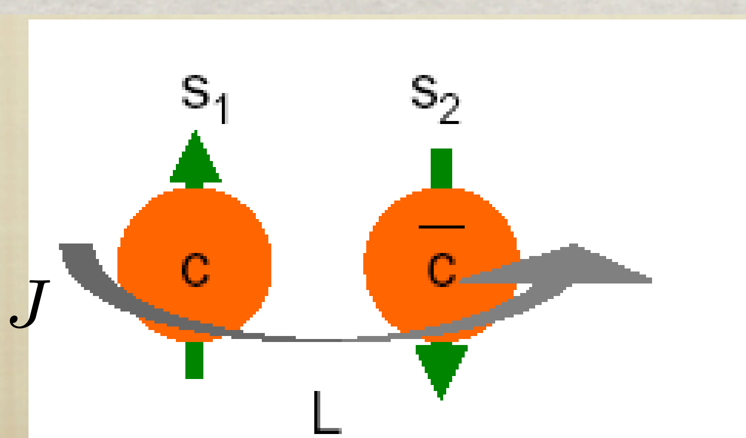

The system is nonrelativistic(NR)

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

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

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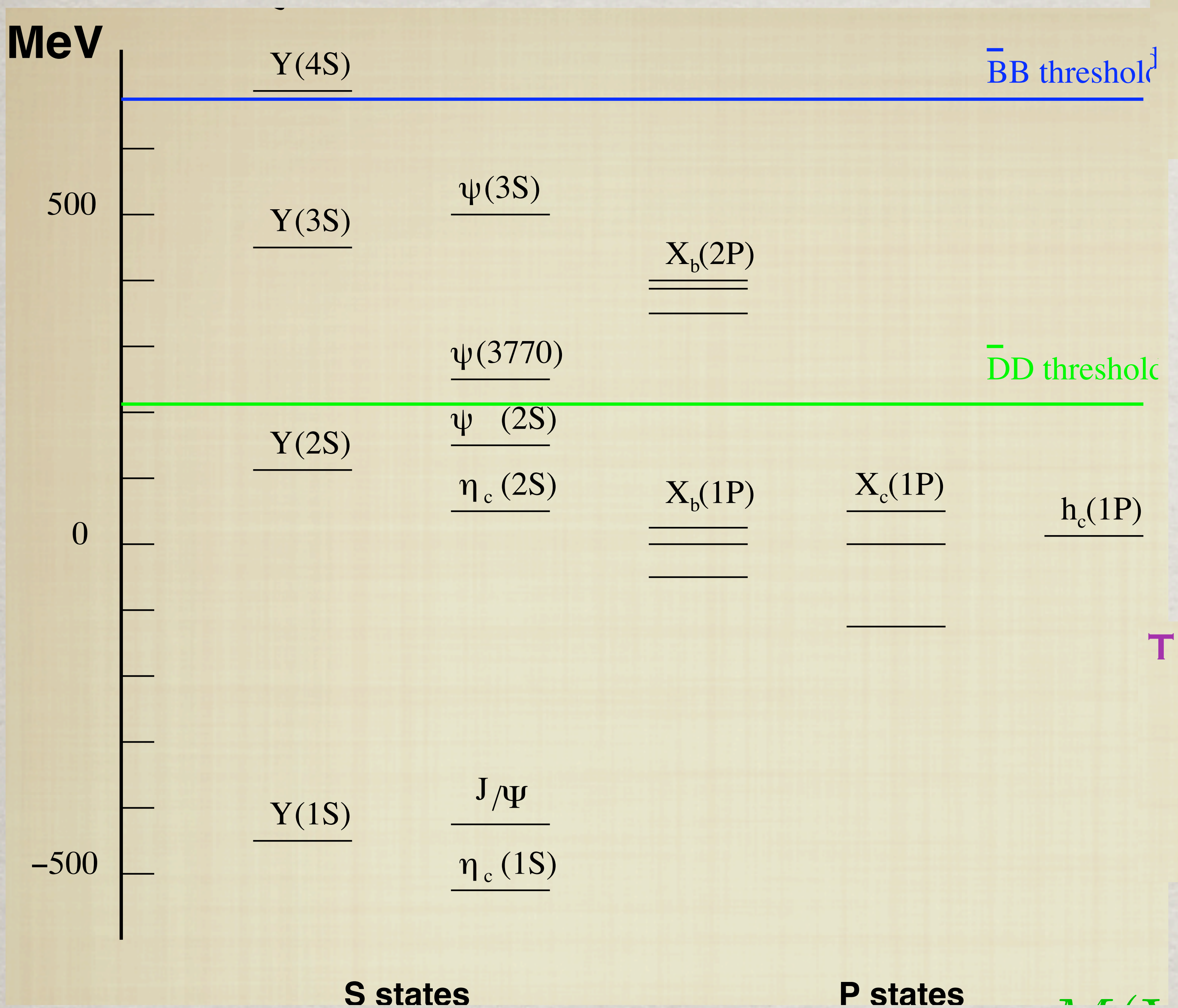

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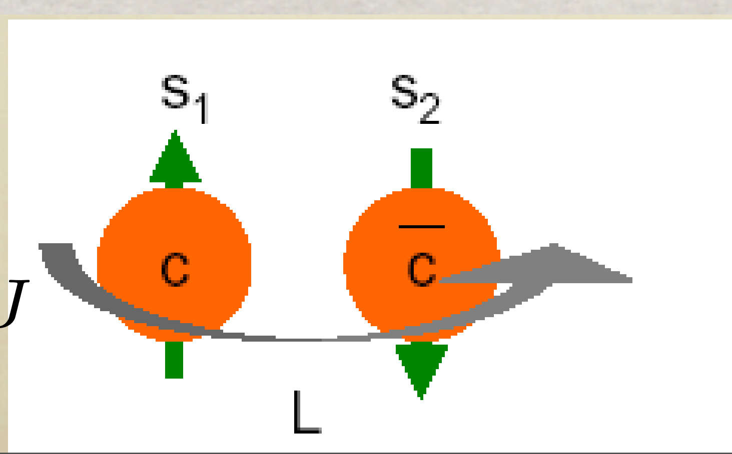

NR bound states have at least 3 scales

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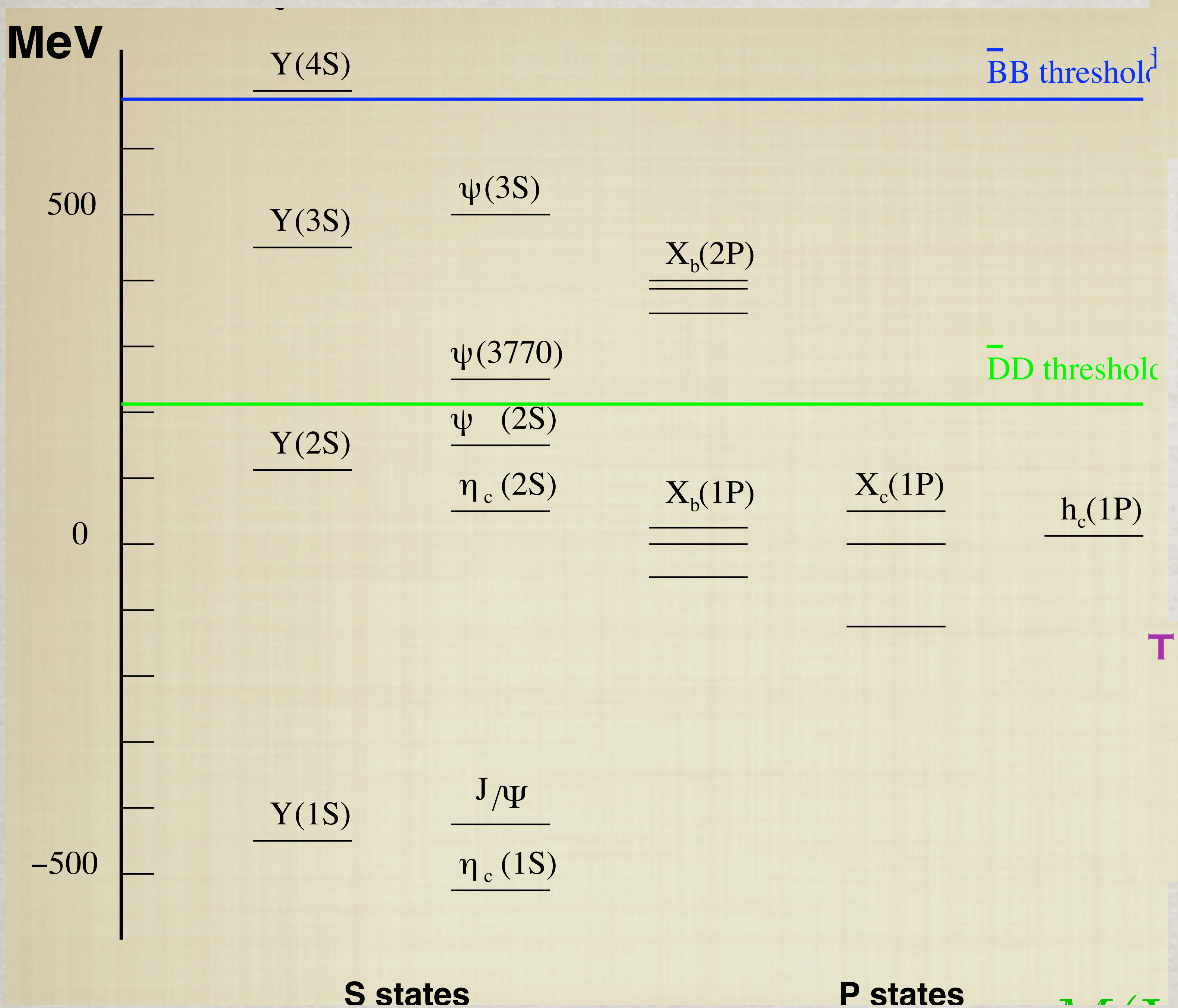

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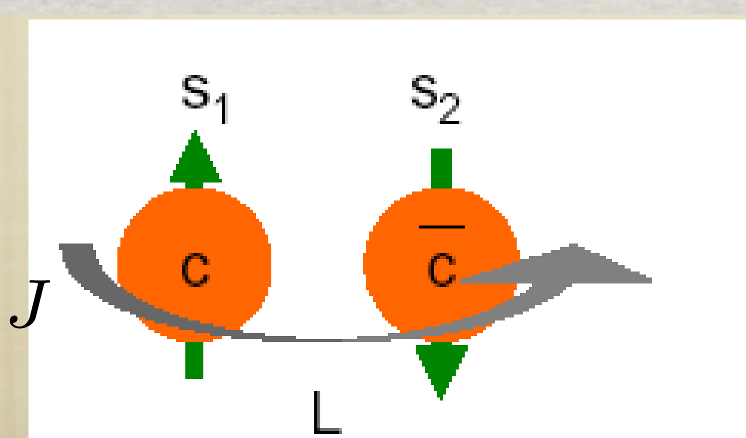

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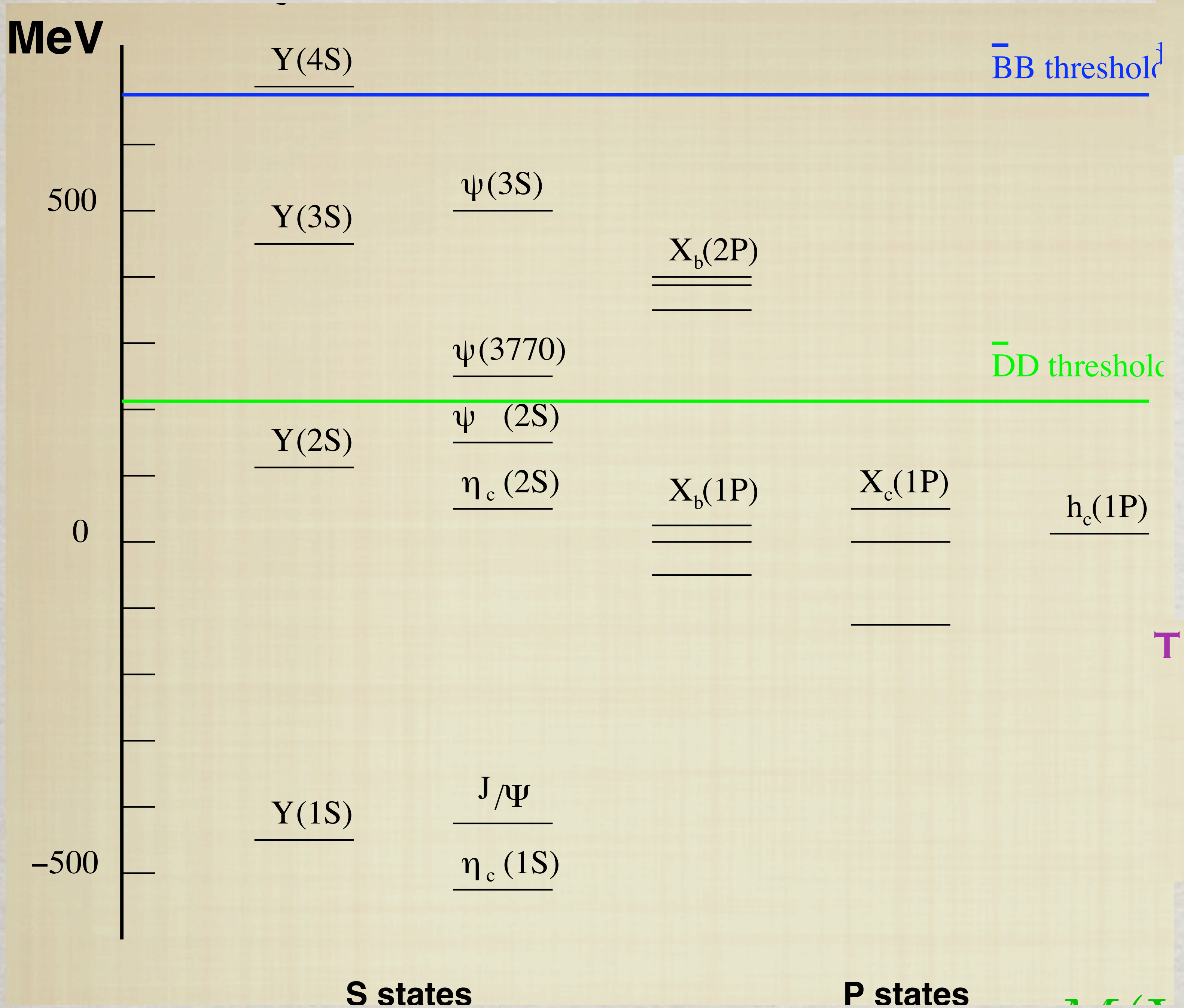

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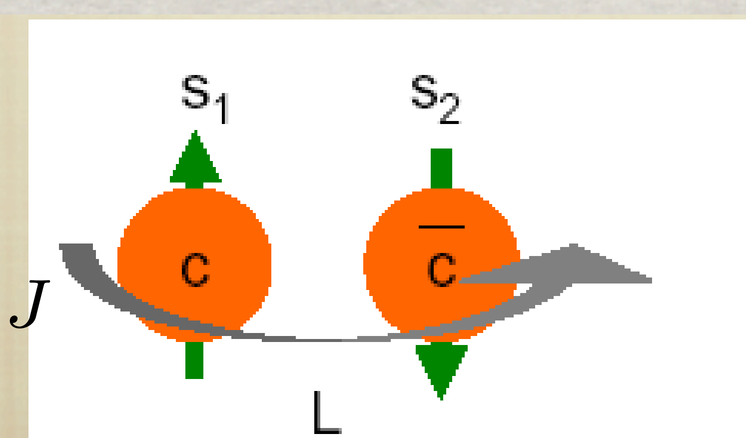

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The rich structure of separated energy scales makes quarkonium an ideal probe of confinement/deconfinement

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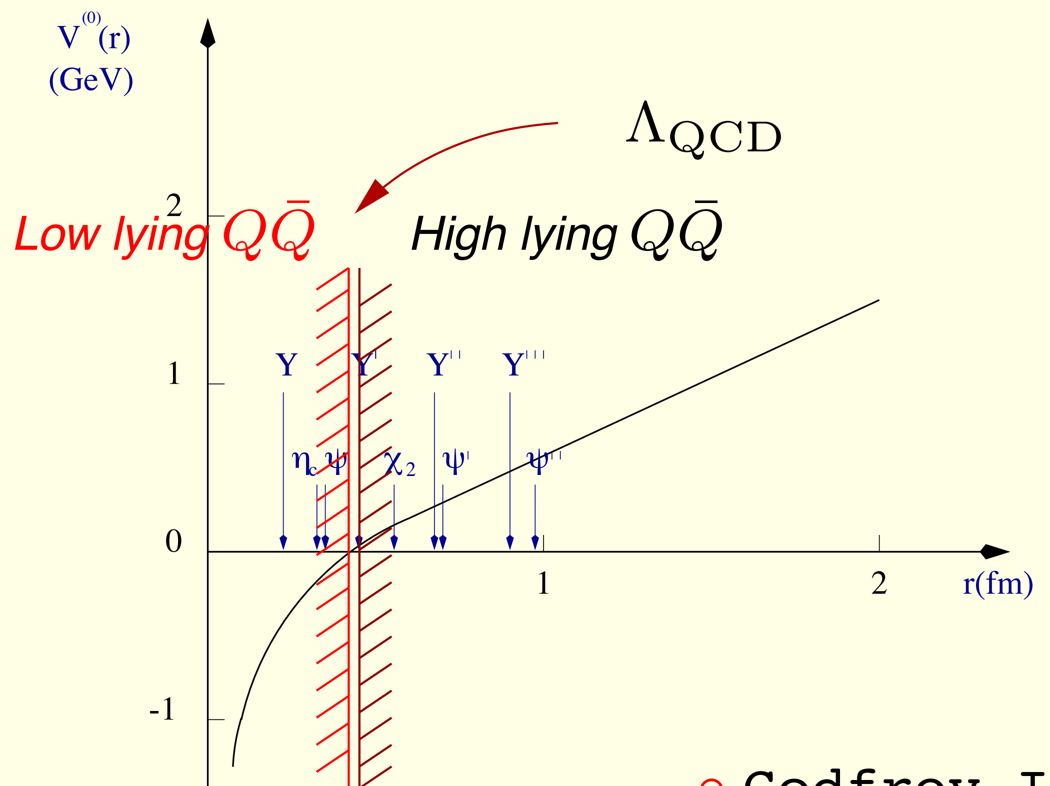
At zero temperature

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

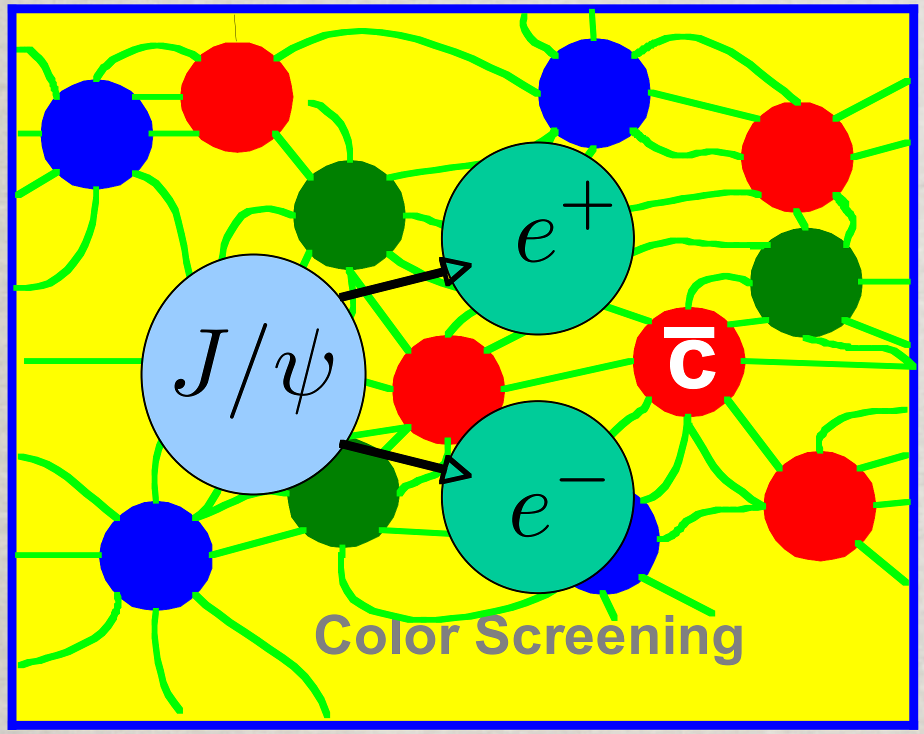


○ Godfrey Isgur PRD 32(85)189

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

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



Debye charge screening $m_D \sim gT$

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

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

Matsui Satz 1986

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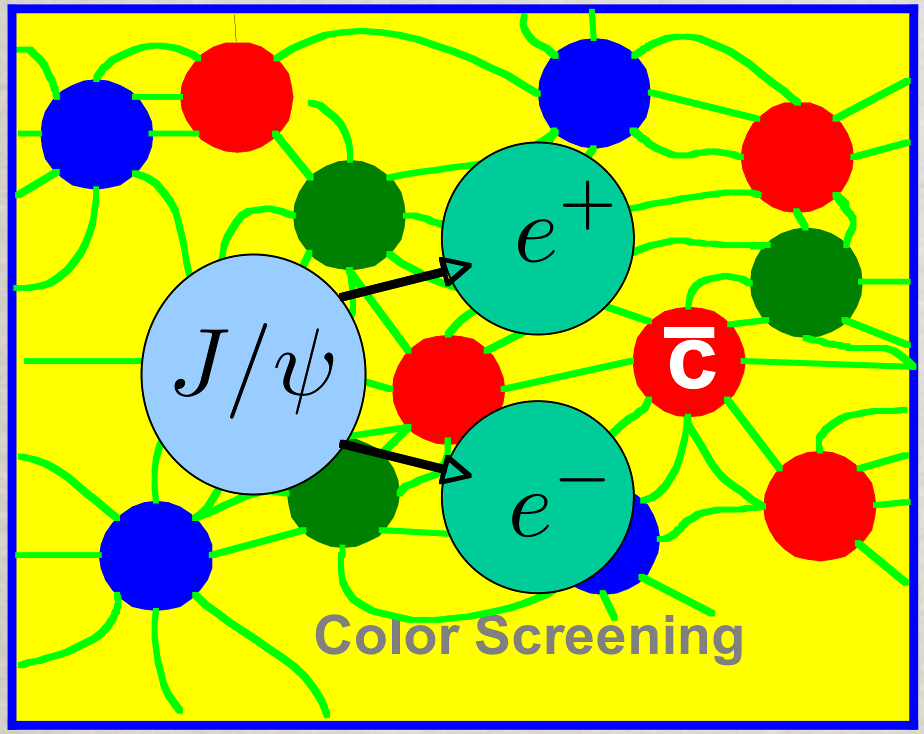

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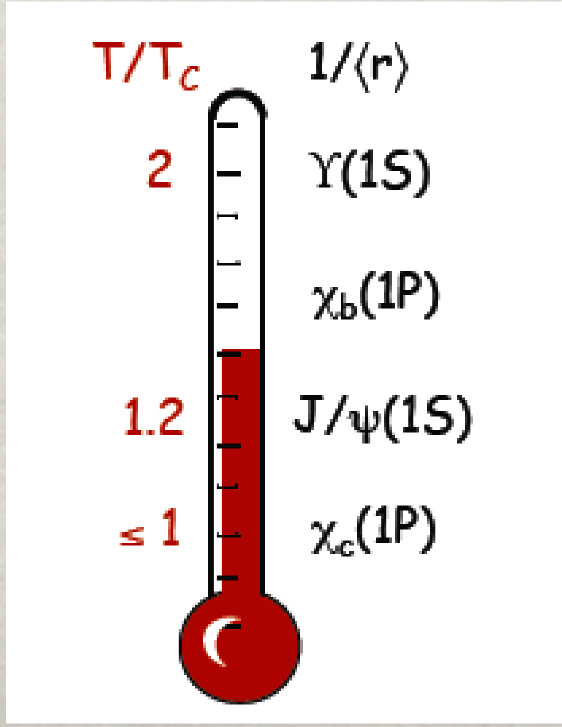
quarkonia dissociate at different temperature in dependence of their radius: they are a Quark Gluon Plasma thermometer



Quarkonium Today is
a golden system to study strong interactions

Many experimental data and opportunities

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New theoretical tools:
Effective Field Theories (EFTs) of QCD
and progress in lattice QCD

Today: new data

B-FACTORIES: Heavy Mesons Factories

CLEO-c BESII tau charm factories

CLEO-III bottomonium factory

Fermilab CDF, D0, E835

Hera RHIC (Star, Phenix), NA60

Today: new data

B-FACTORIES: Heavy Mesons Factories

CLEO-c BESII tau-charm factories

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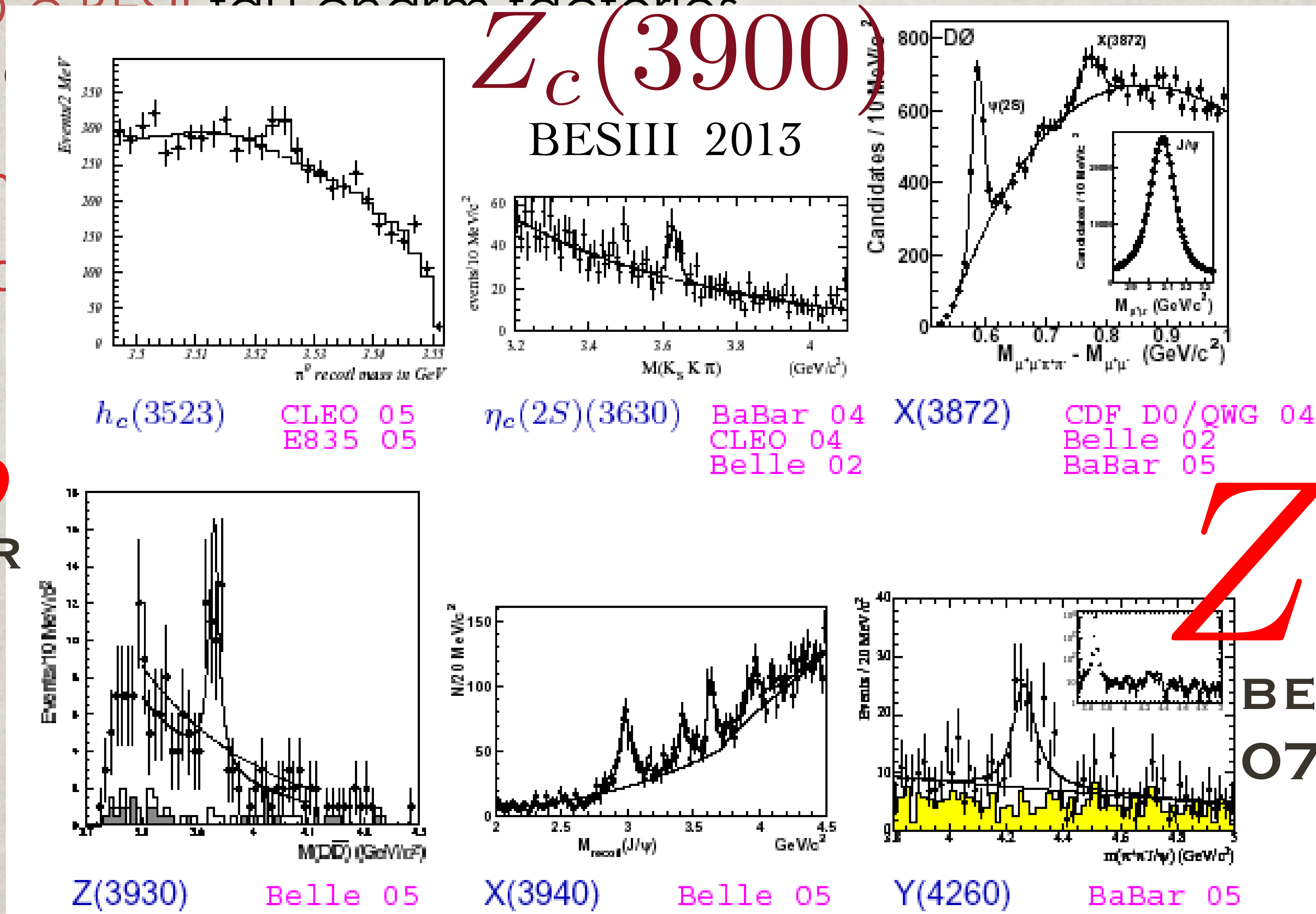

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Discovery of New States, New Production Mechanisms, Exotics, New decays and transitions, Precision and high statistics data

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BESIII

CMS ATLAS LHC-b

ALICE

and in the future PANDA, Belle2

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Initial phenomenological/model descriptions of the 70s,80s

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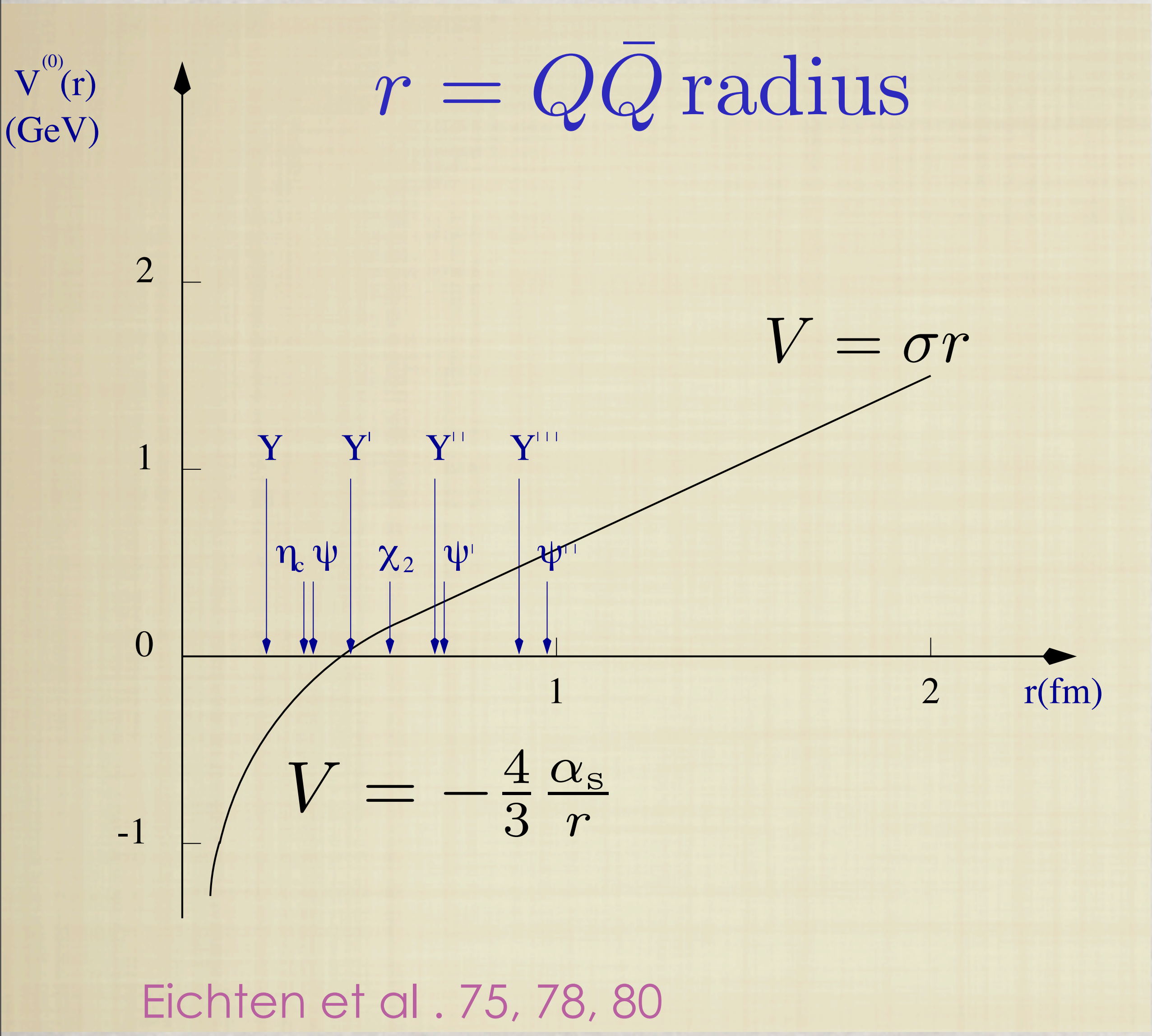

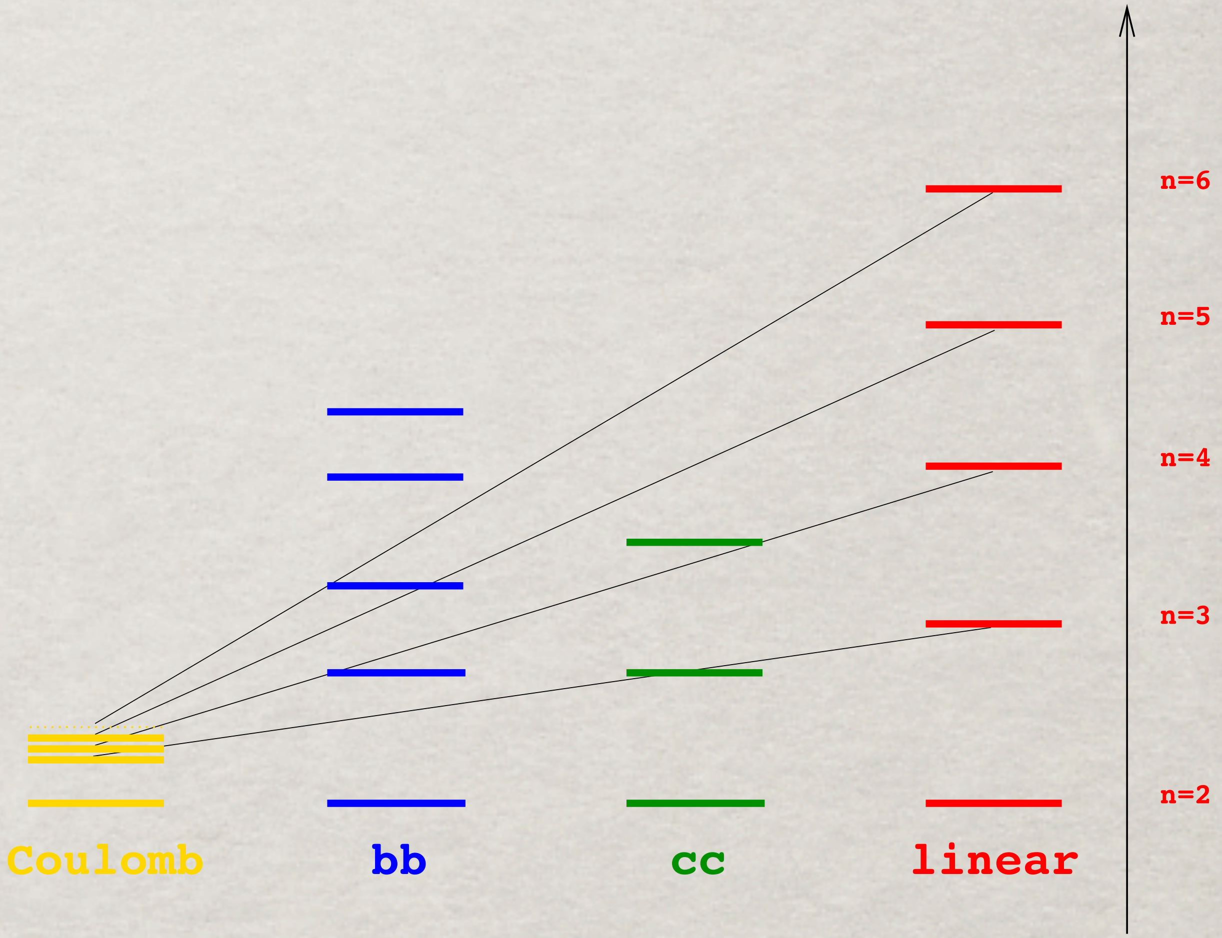

bbar and ccbar energy levels in comparison to Coulomb and linear potential energy levels

Variety of potential models used

Confinement and asymptotic freedom--> QCD

QCD theory of Quarkonium: a very hard problem

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

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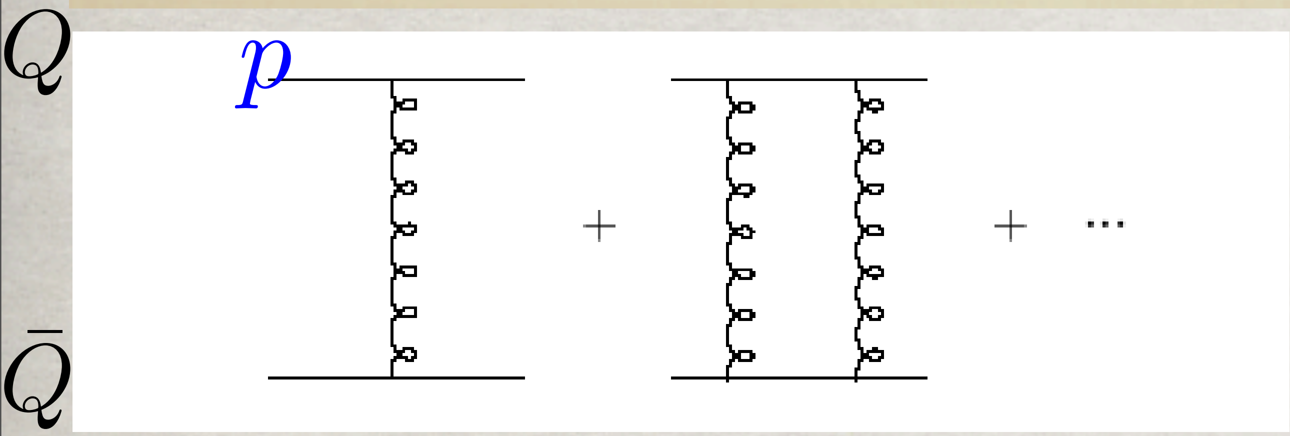

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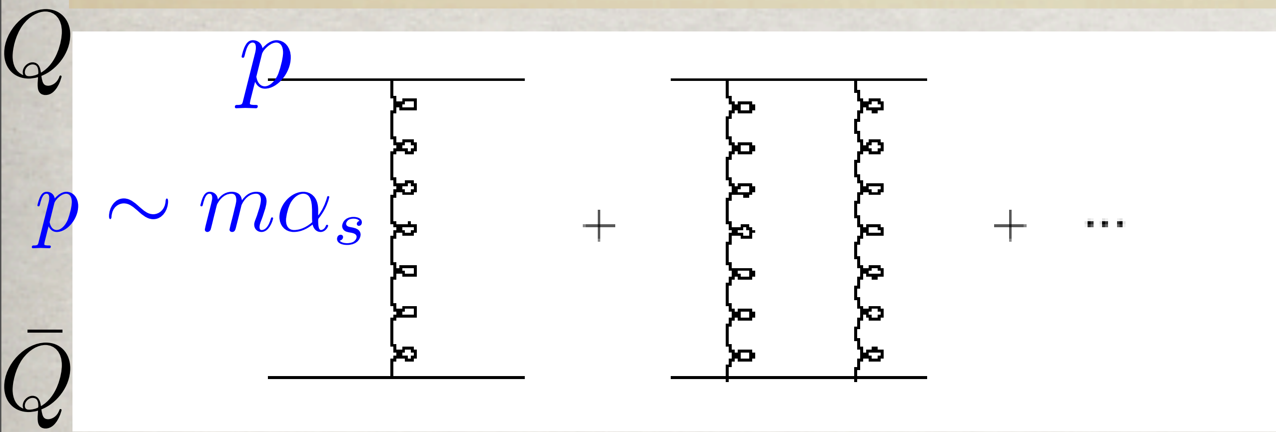

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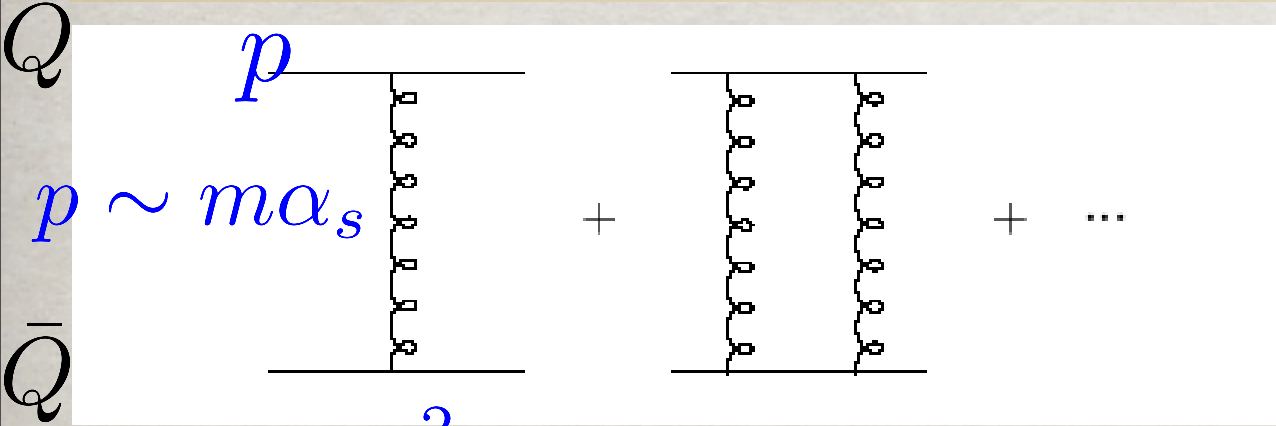

$$\frac{g^2}{p^2}\left(1 + \frac{m\alpha_s}{p}\right)$$

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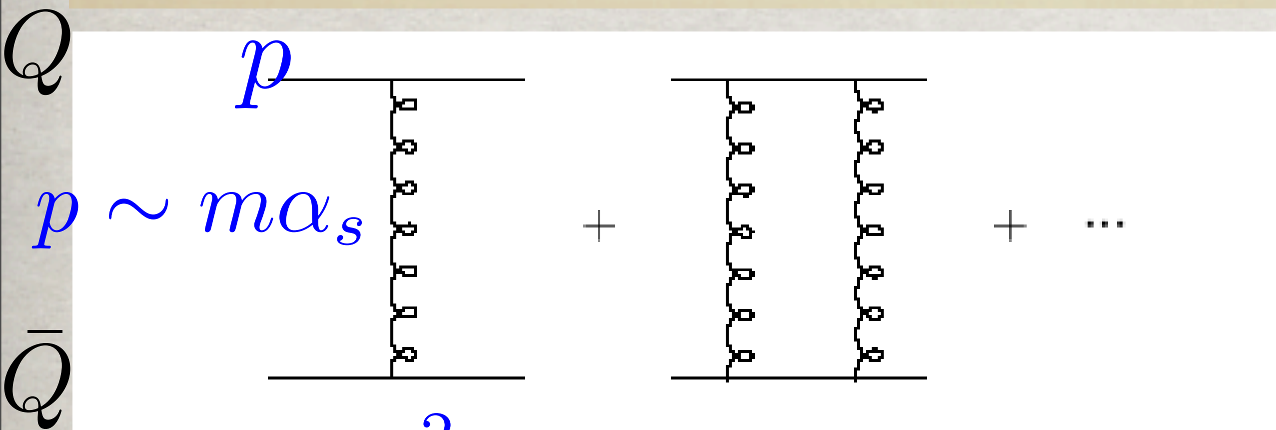

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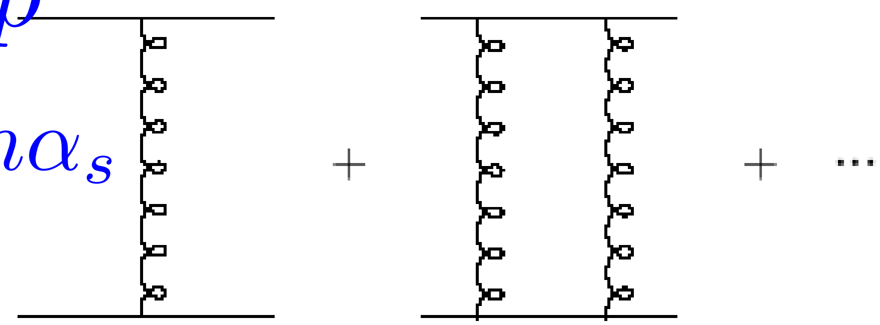

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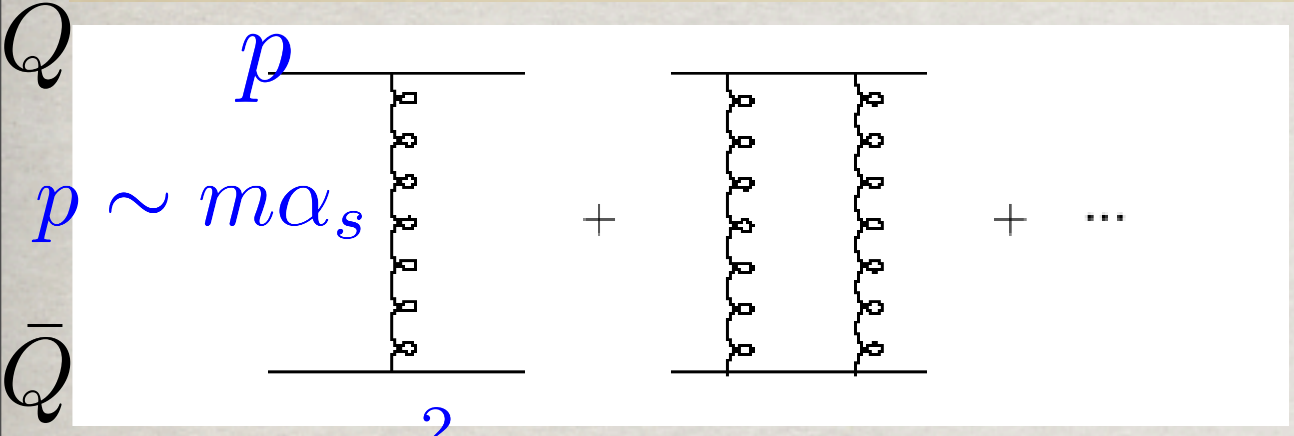

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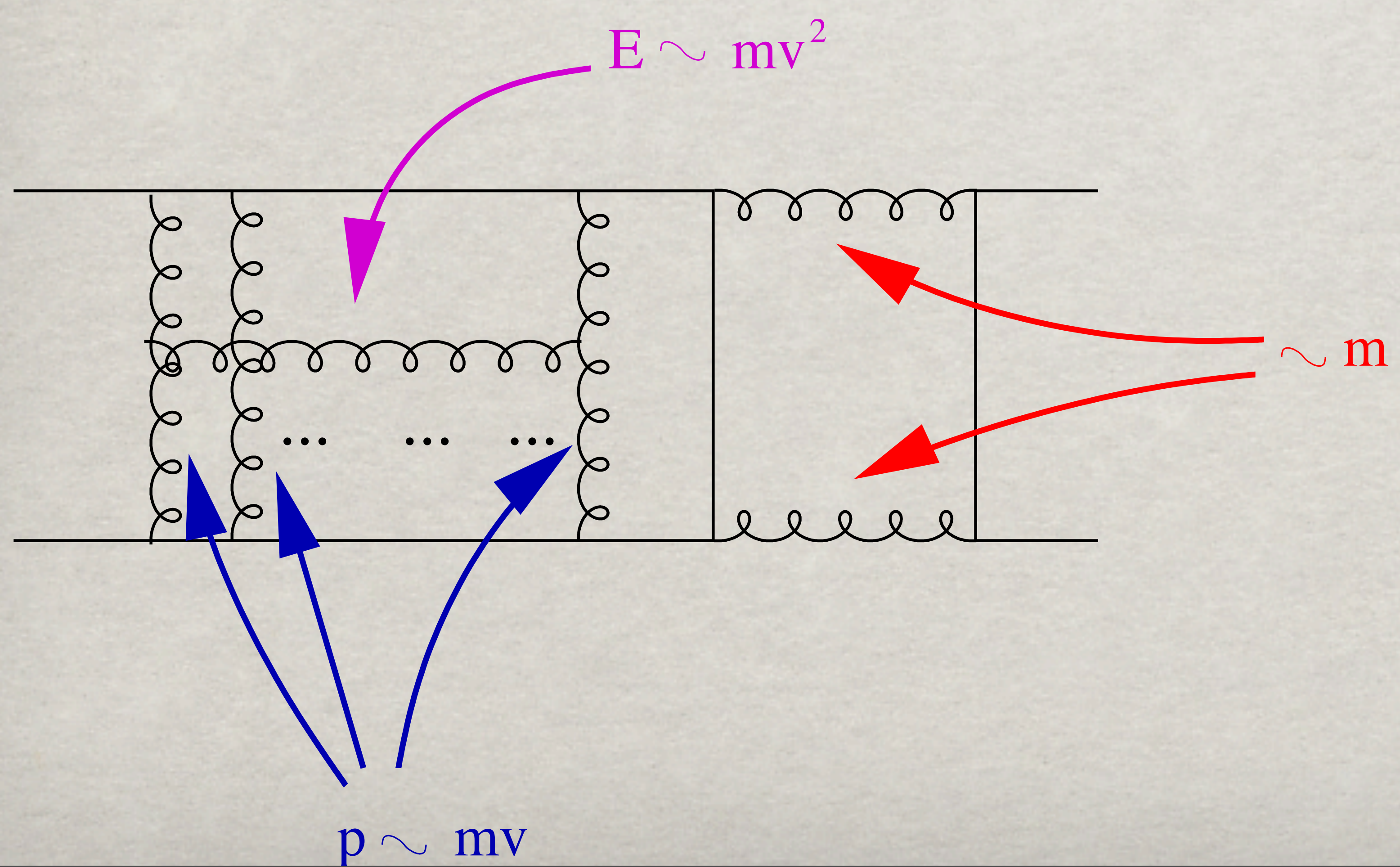
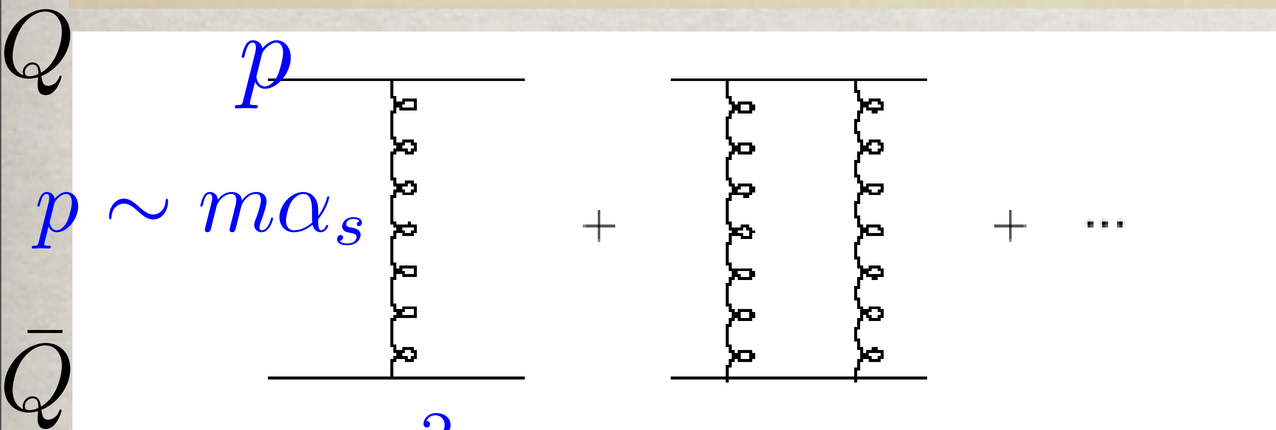
$$\sim \frac{1}{E - \left(\frac{p^2}{m} + V\right)}$$

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



QCD theory of Quarkonium: a very hard problem

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

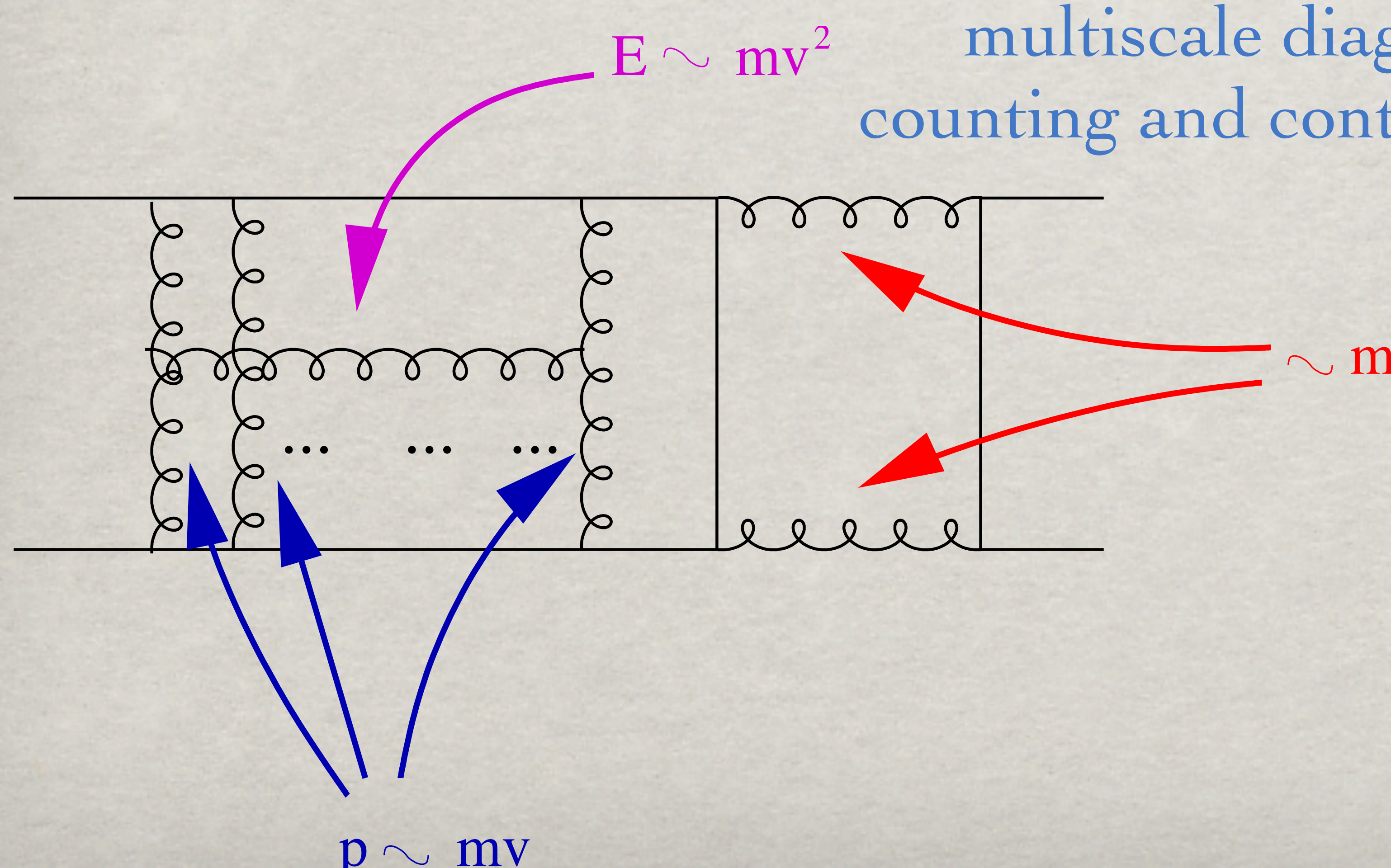


$$\frac{g^2}{p^2}\left(1 + \frac{m\alpha_s}{p}\right)$$

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

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

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



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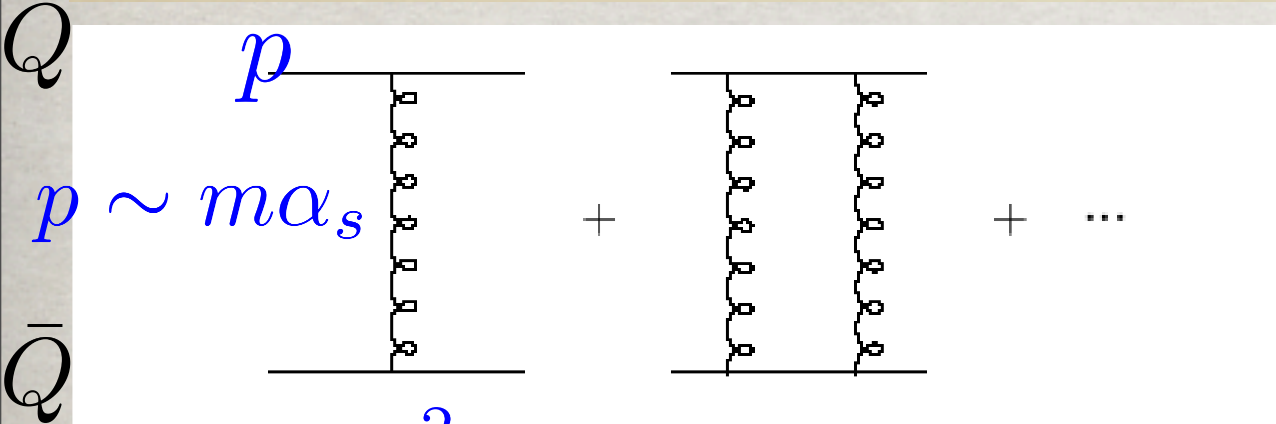

$$\sim \frac{1}{E - (\frac{p^2}{m} + V)}$$

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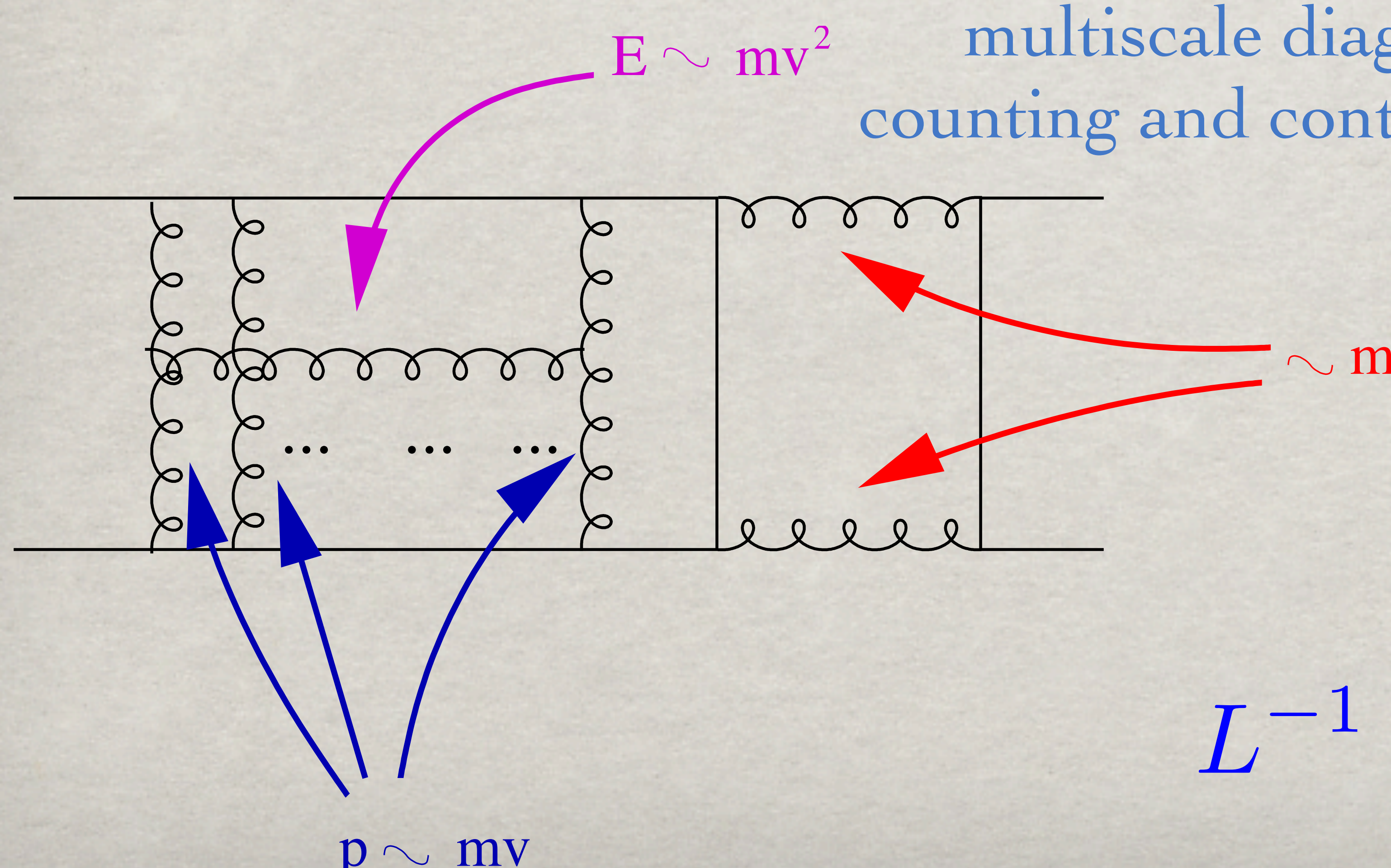
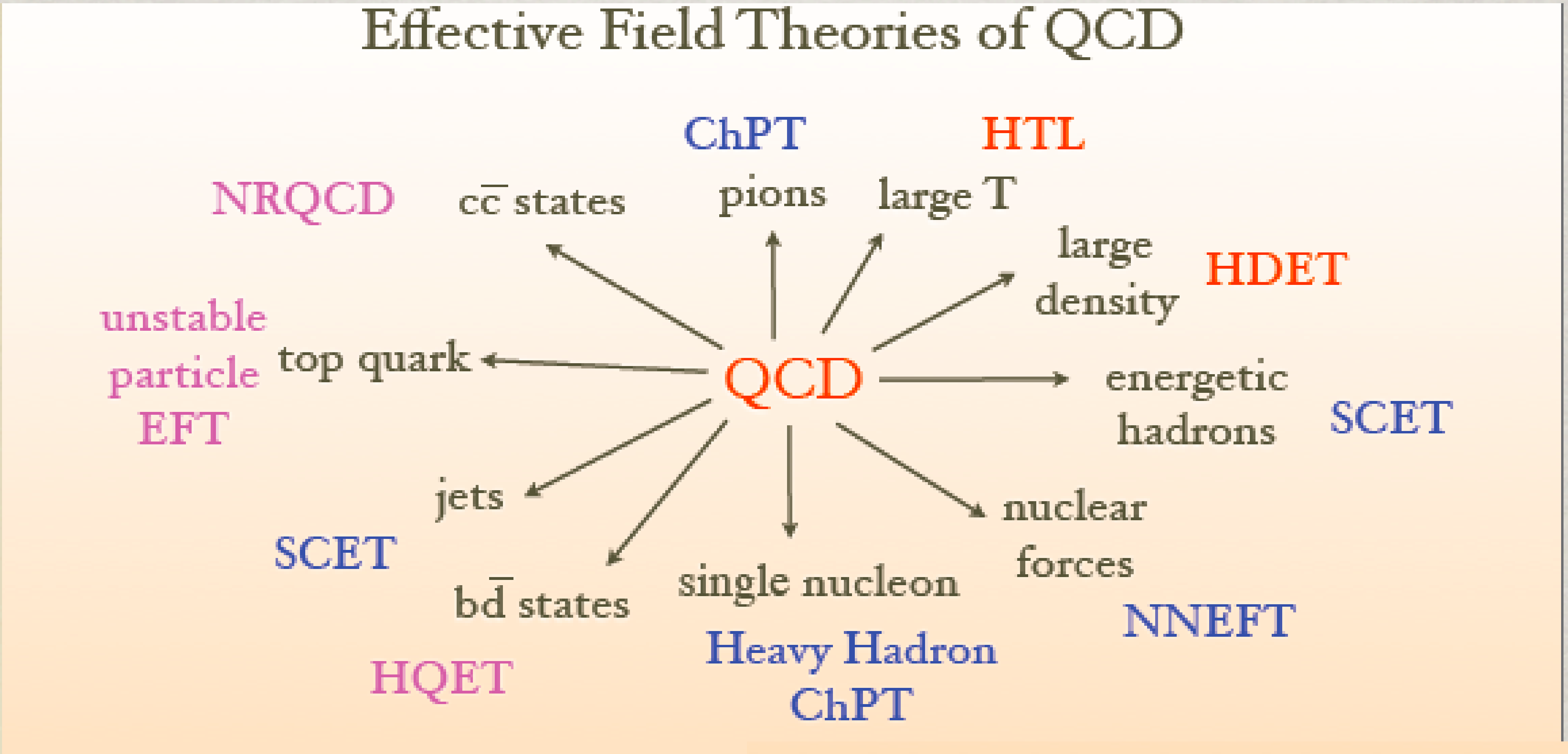


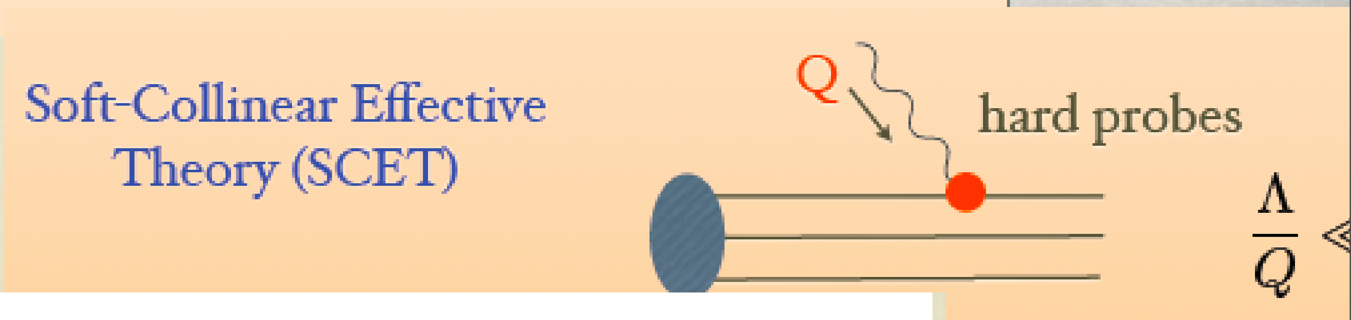
Difficult also for the lattice!

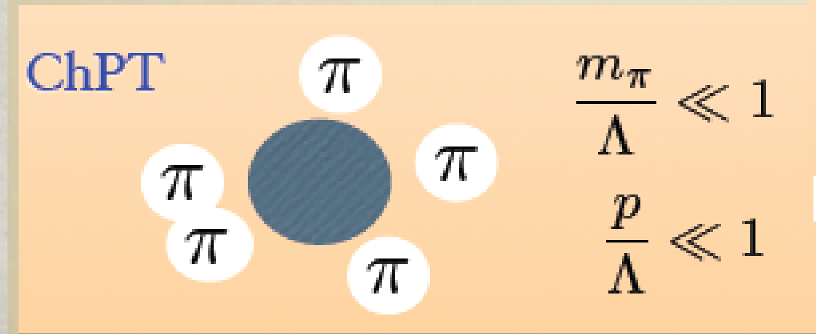
$$L^{-1} \ll \lambda \ll \Lambda \ll a^{-1}$$

QCD Effective Field Theories to address the research frontier of hadronic physics

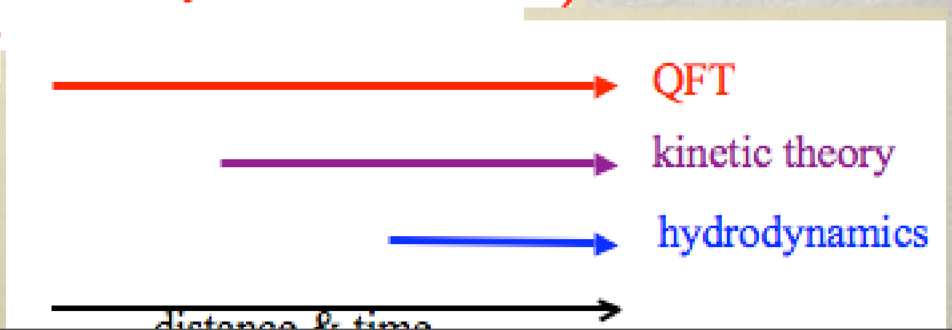


- Heavy quark effective theory (HQET): $\frac{\lambda}{\Lambda} = \frac{\Lambda_{QCD}}{m}$





Lattice QCD $\equiv$ Effective Field Theory ($\Lambda = \pi/a$).



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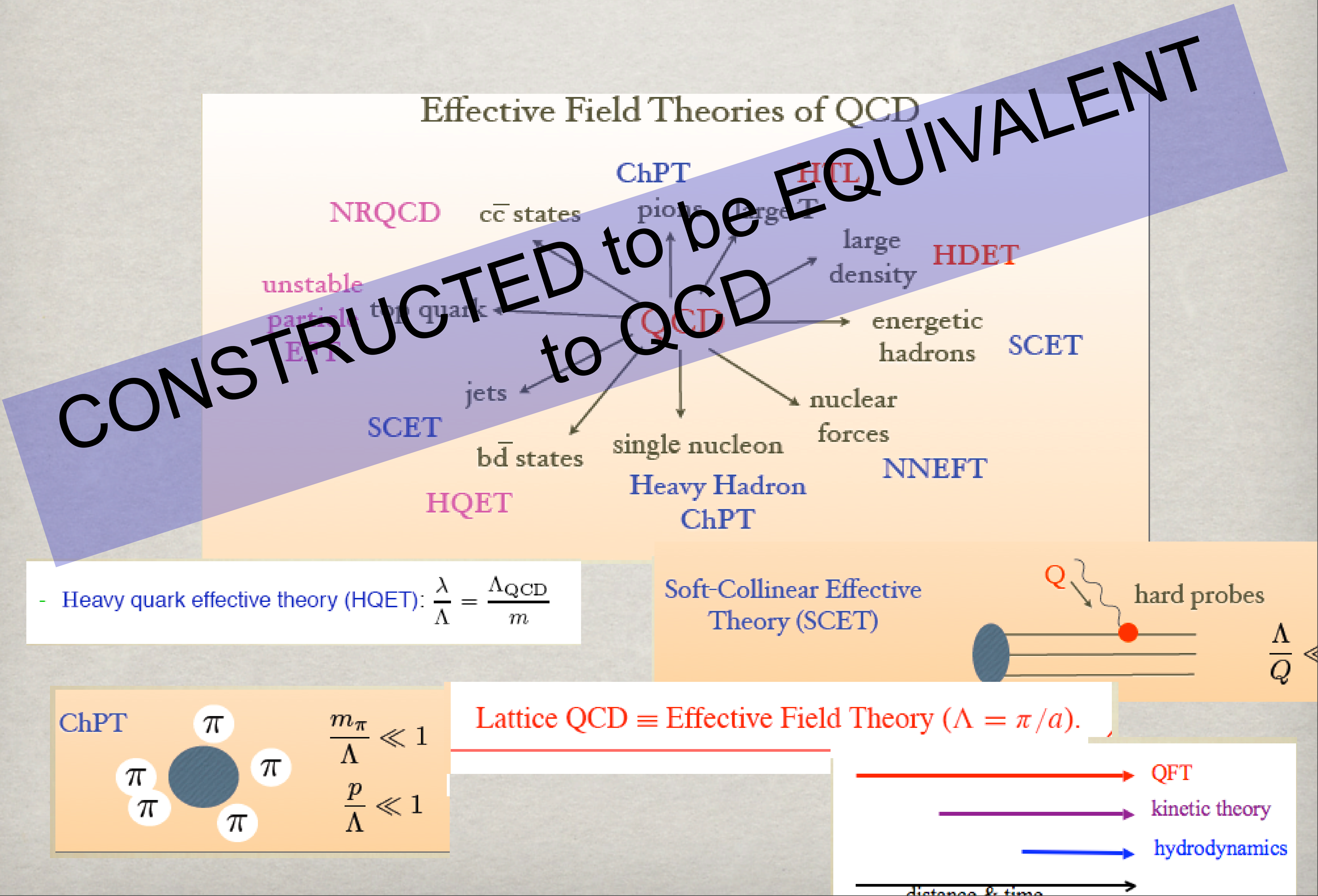
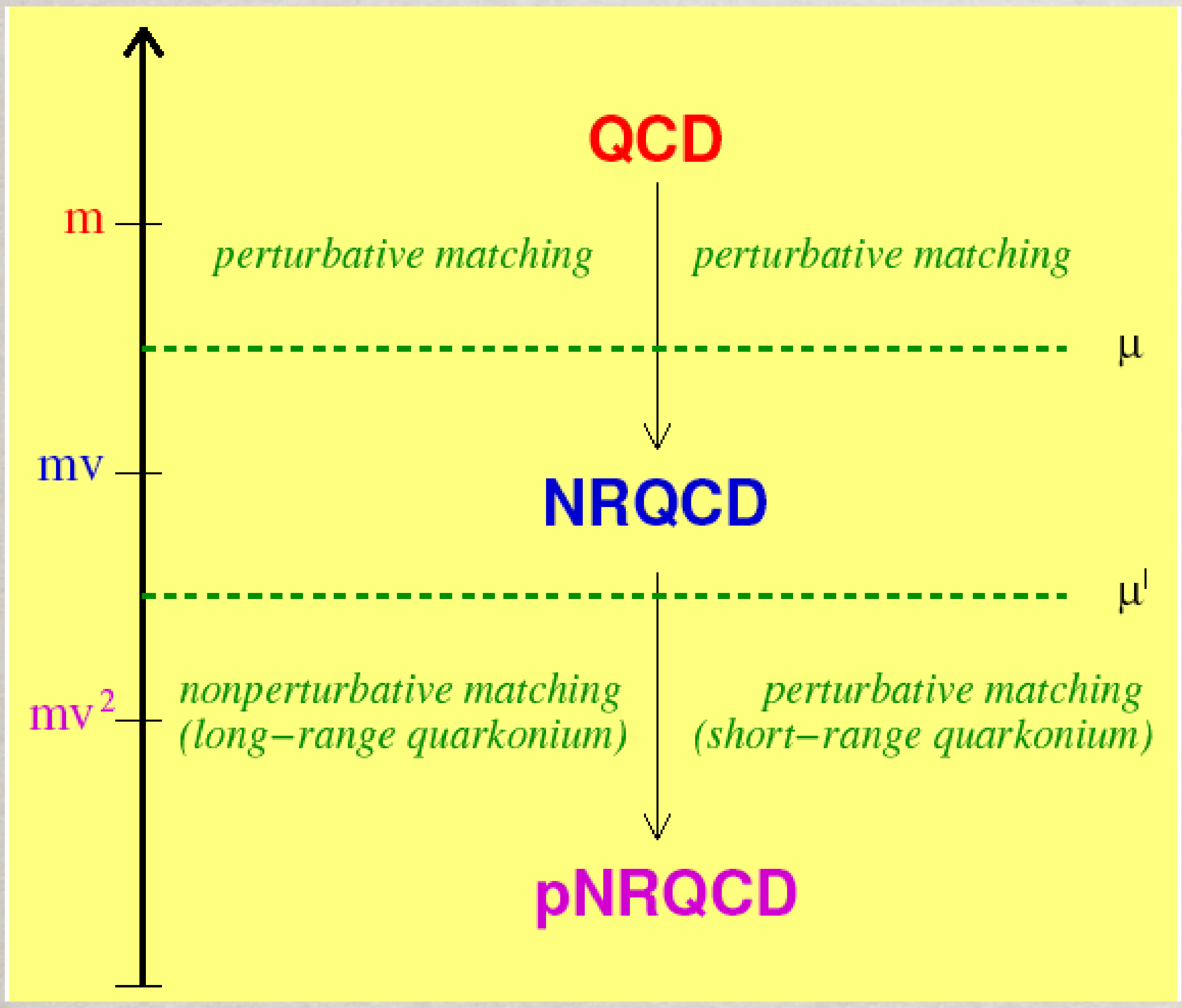


Quarkonium with Non Relativistic EFT

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



Hard

Soft
(relative
momentum)

Ultrasoft
(binding energy)

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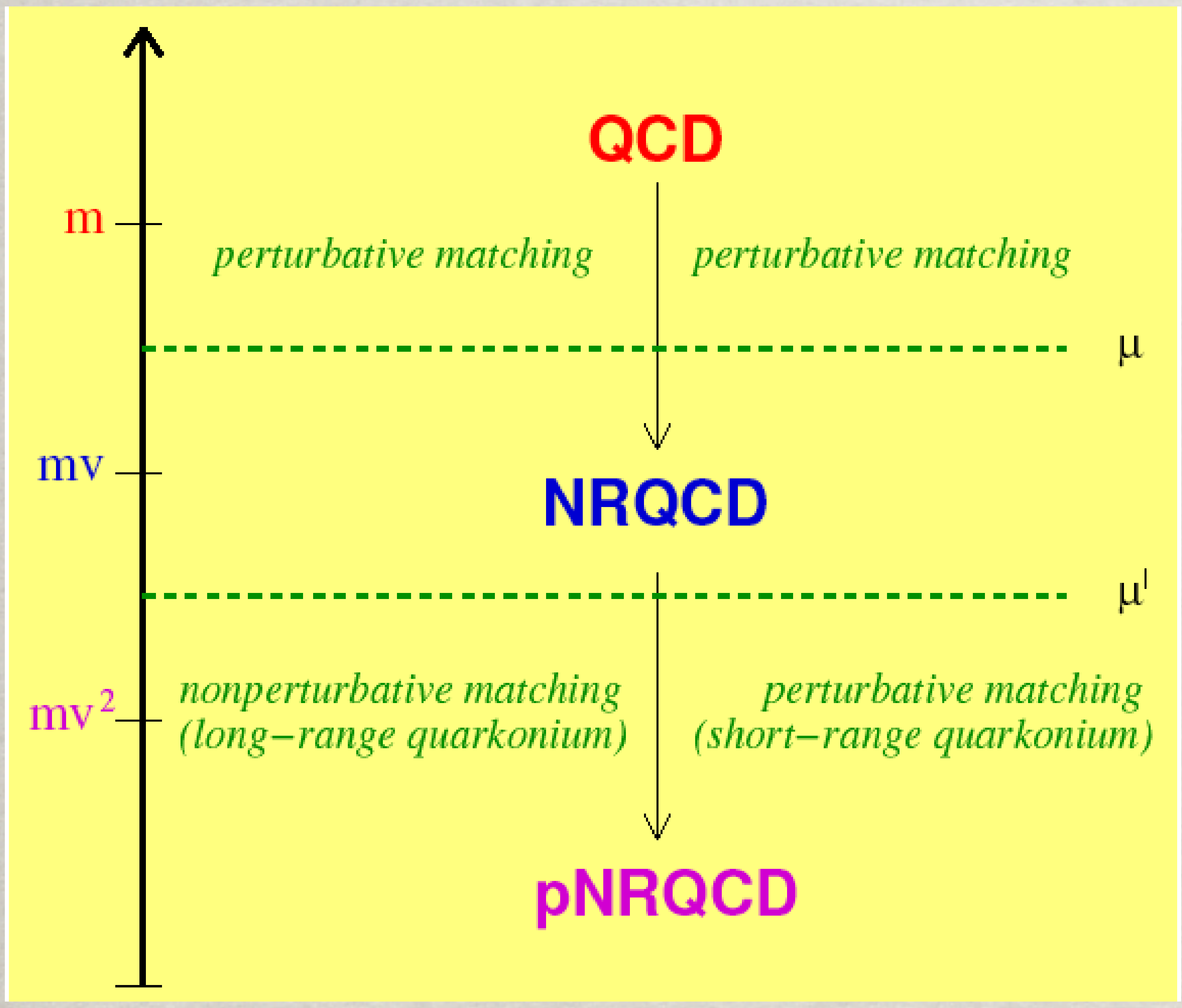

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$$\mathcal{L}_{\mathrm{EFT}} = \sum_n c_n(E_\Lambda/\mu)\frac{O_n(\mu,\lambda)}{E_\Lambda}$$

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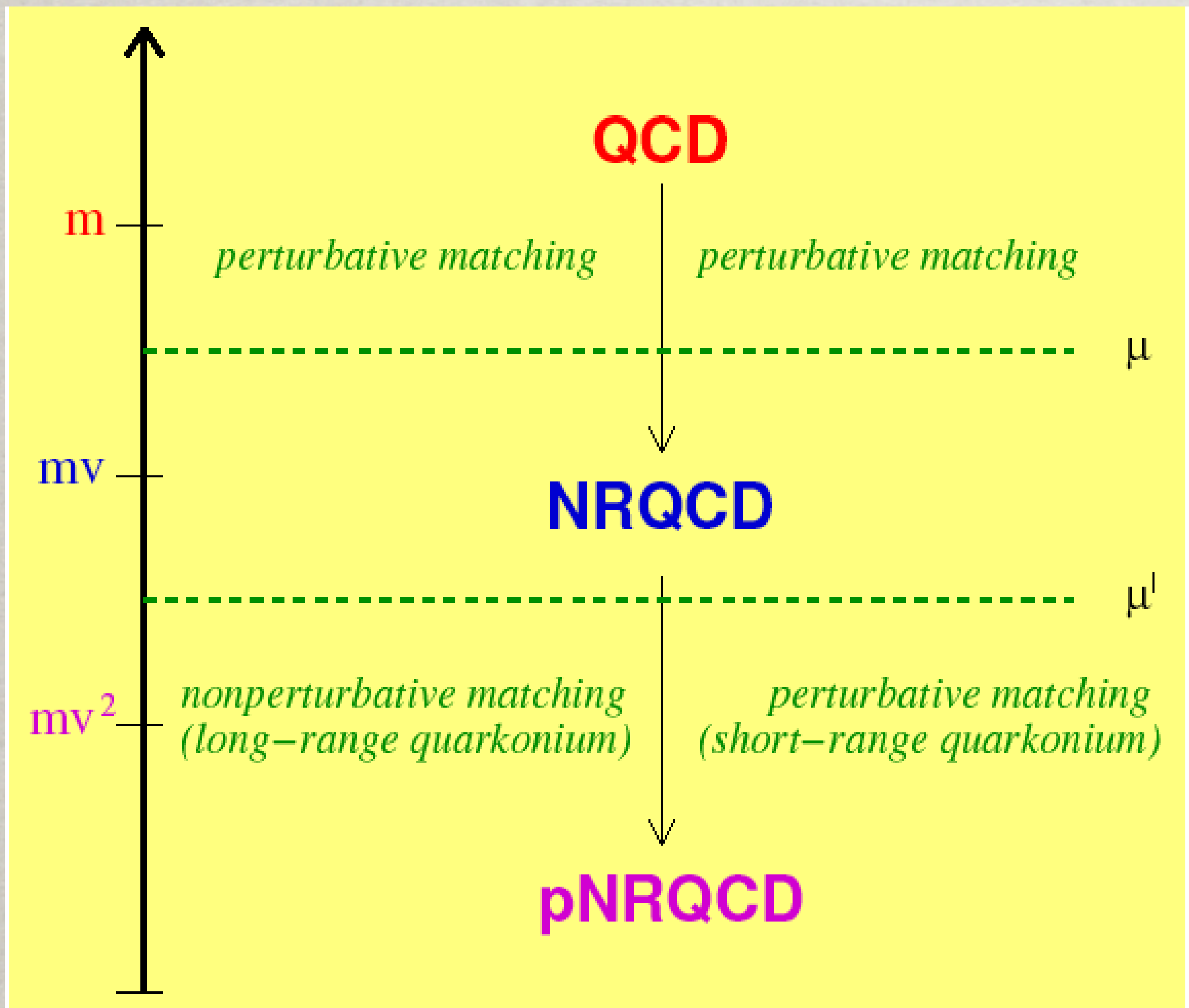

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$$\mathcal{L}_{\mathrm{EFT}} = \sum_n c_n(E_\Lambda/\mu) \frac{O_n(\mu, \lambda)}{E_\Lambda} \qquad \langle O_n \rangle \sim E_\lambda^n$$

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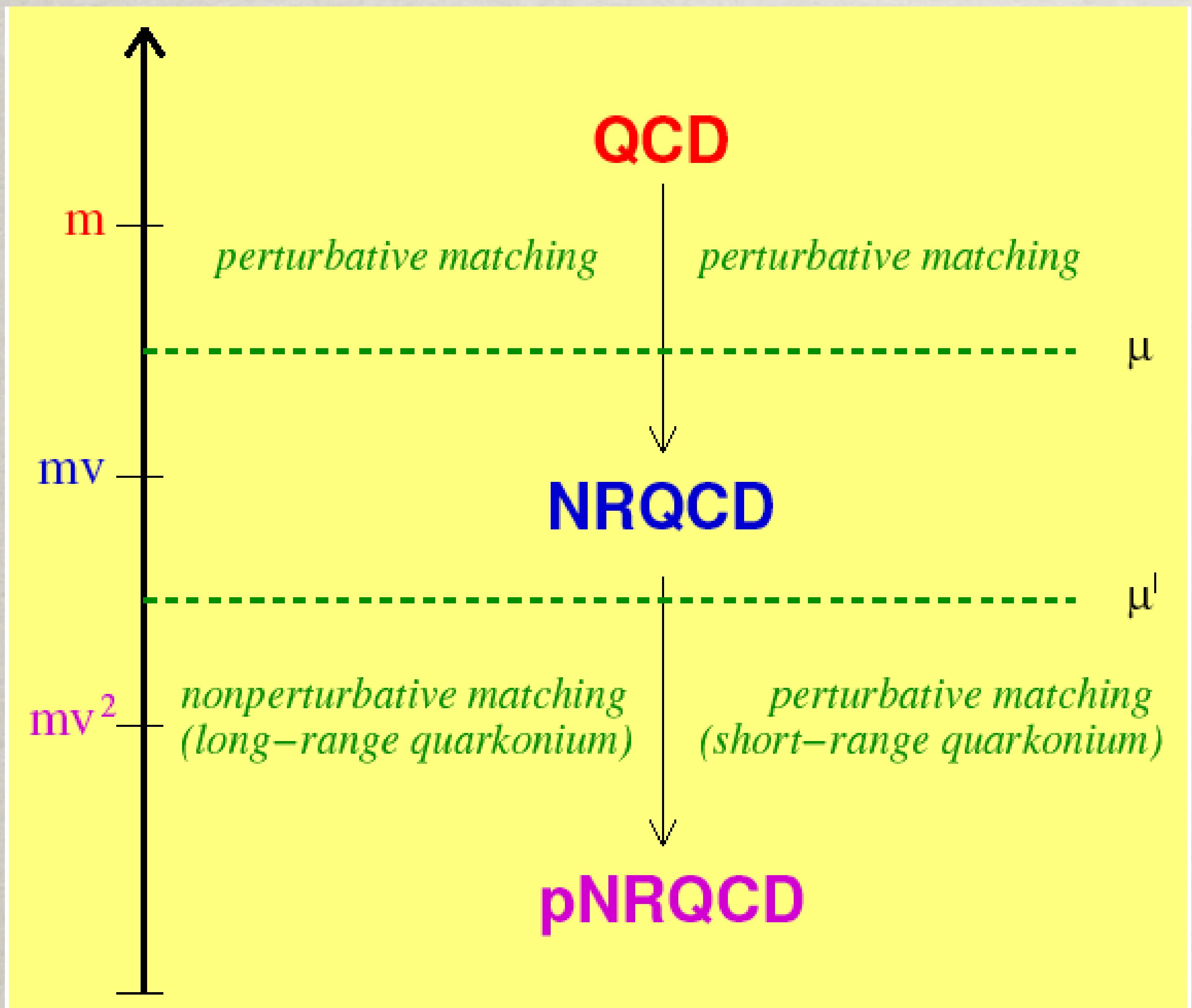

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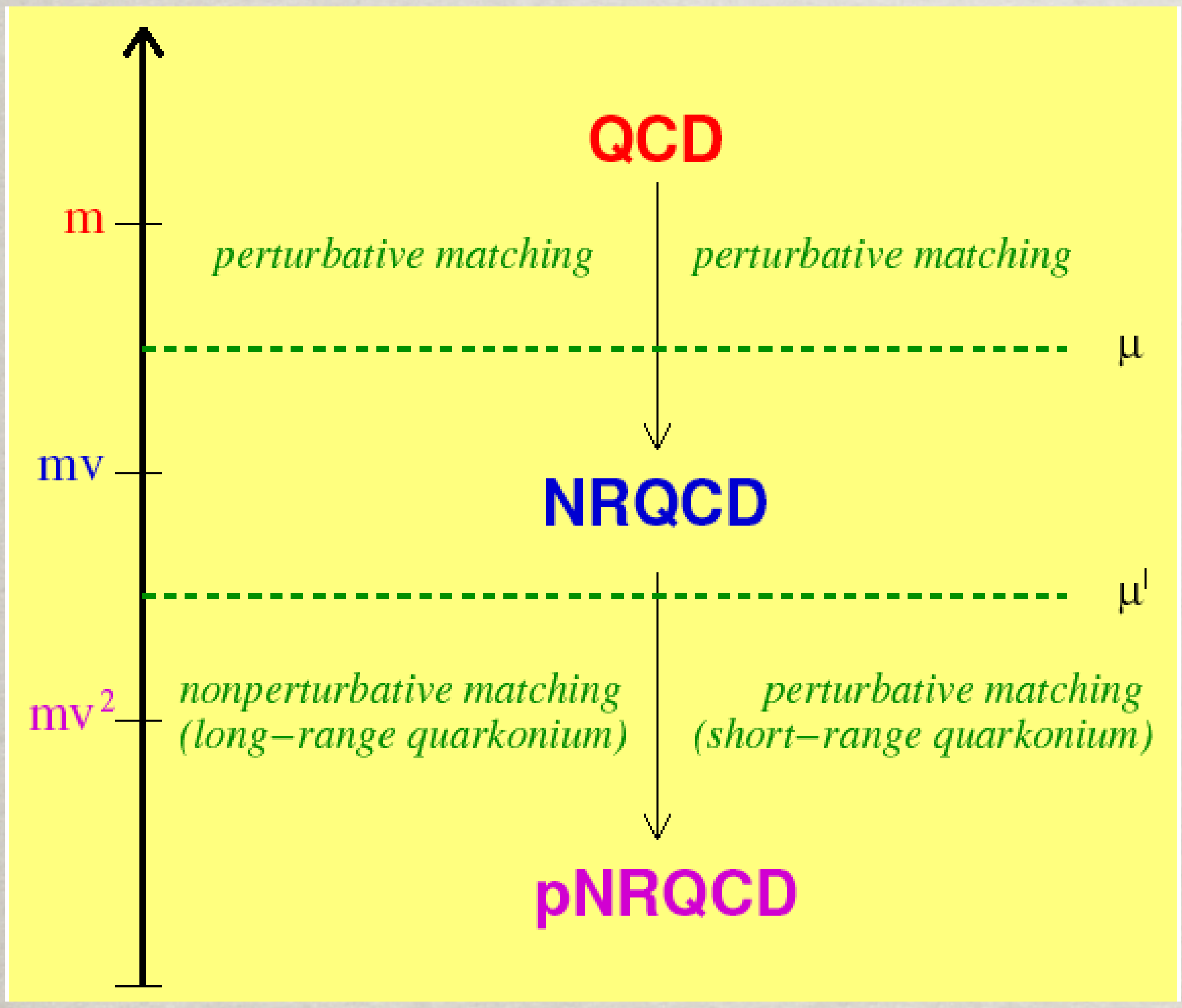

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momentum)

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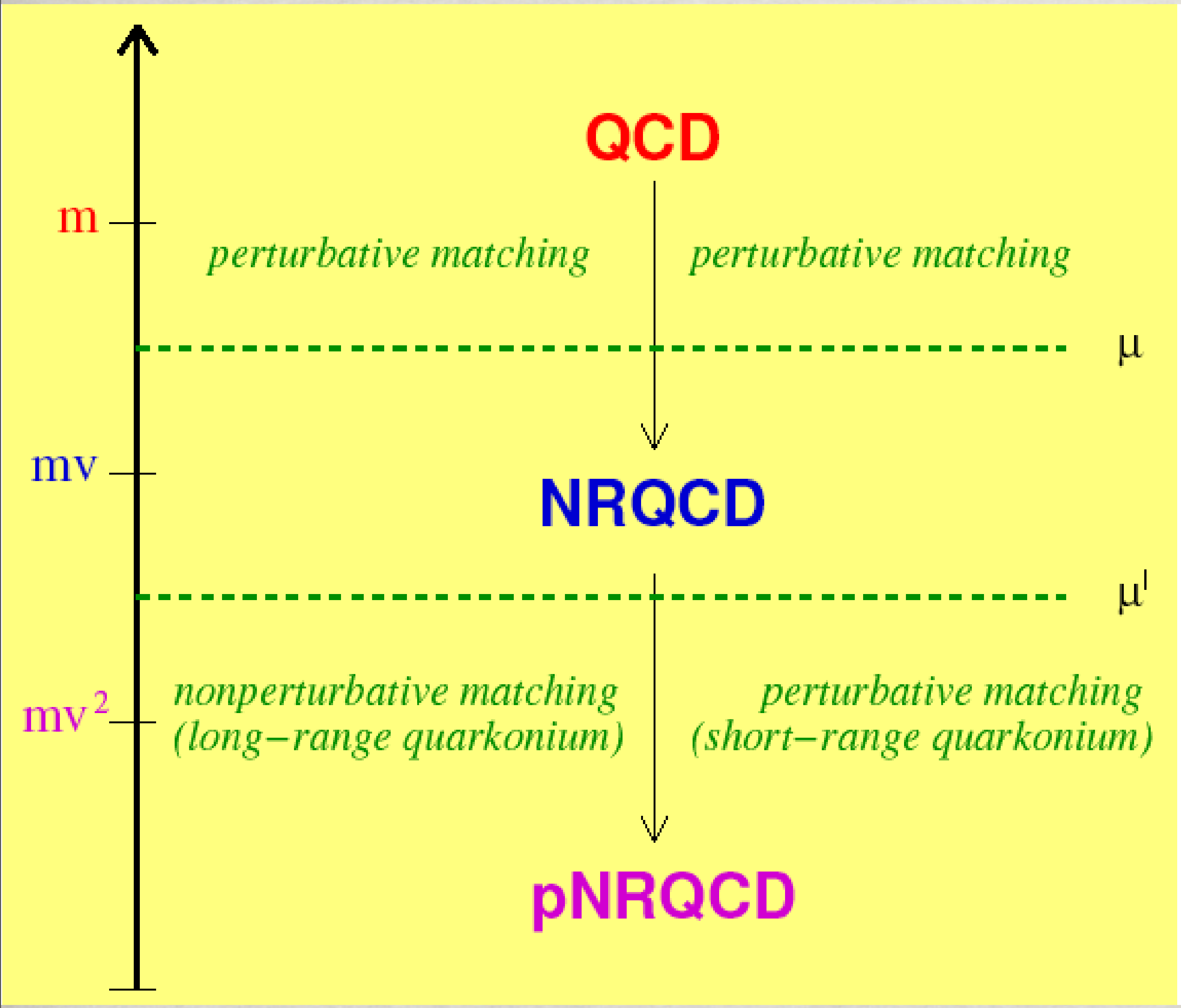
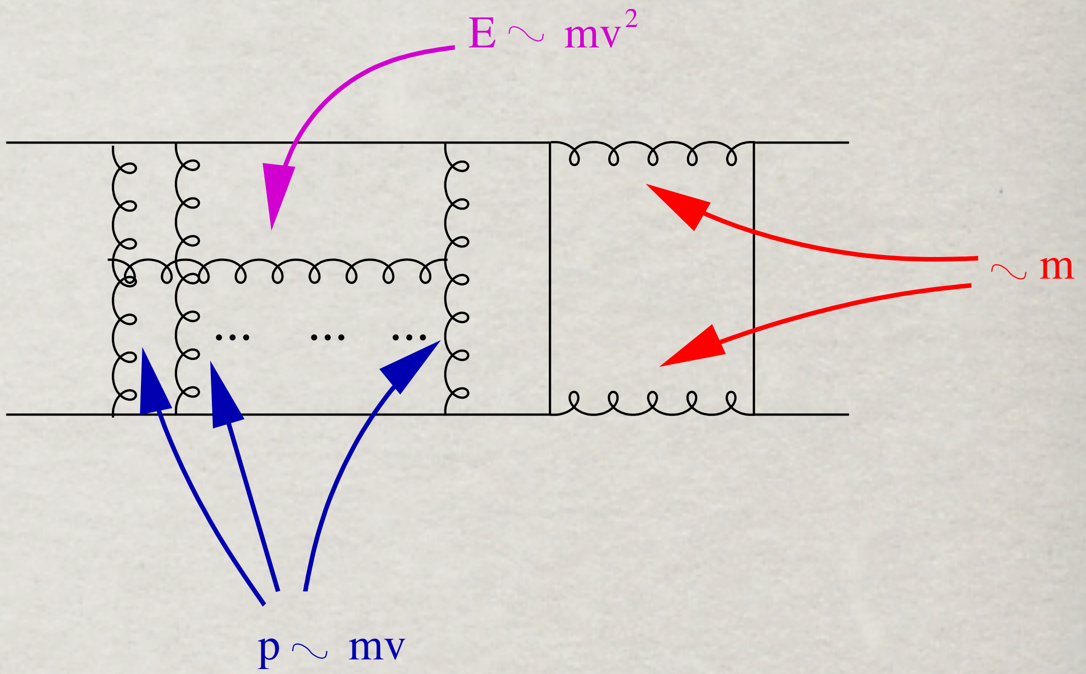
Ultrasoft
(binding energy)

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

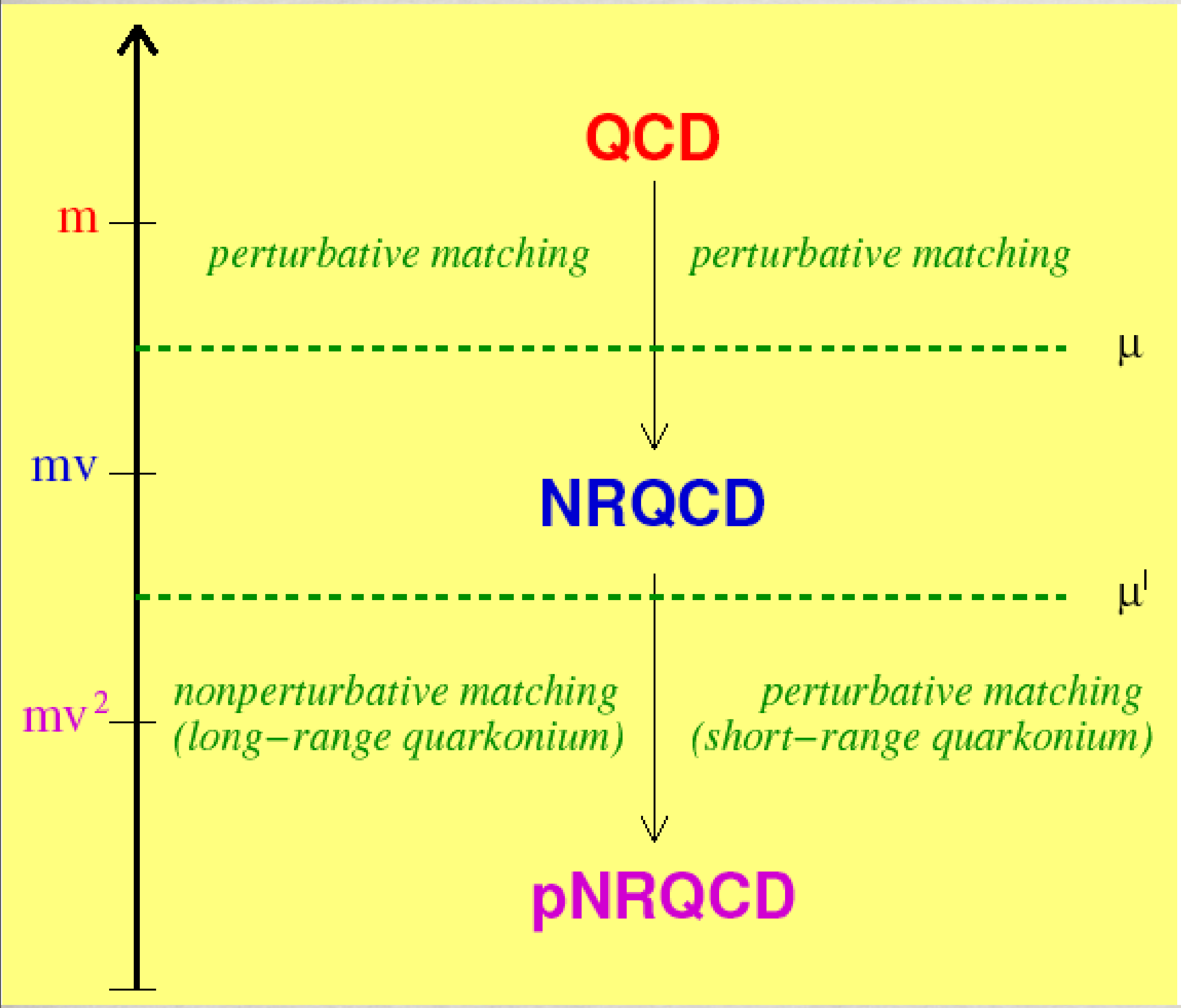
$$\langle O_n \rangle \sim E_\lambda^n$$

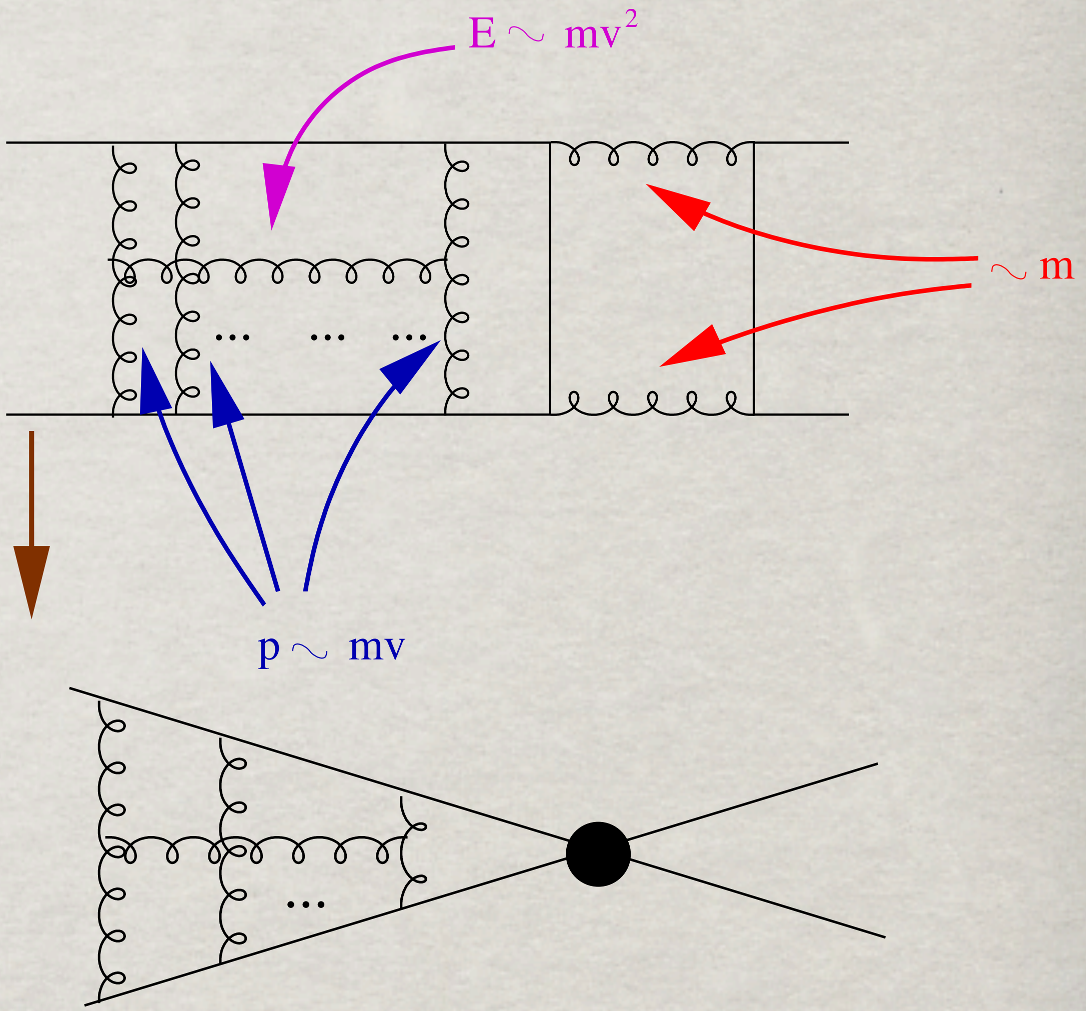
Quarkonium with NR EFT: Non Relativistic QCD (NRQCD)



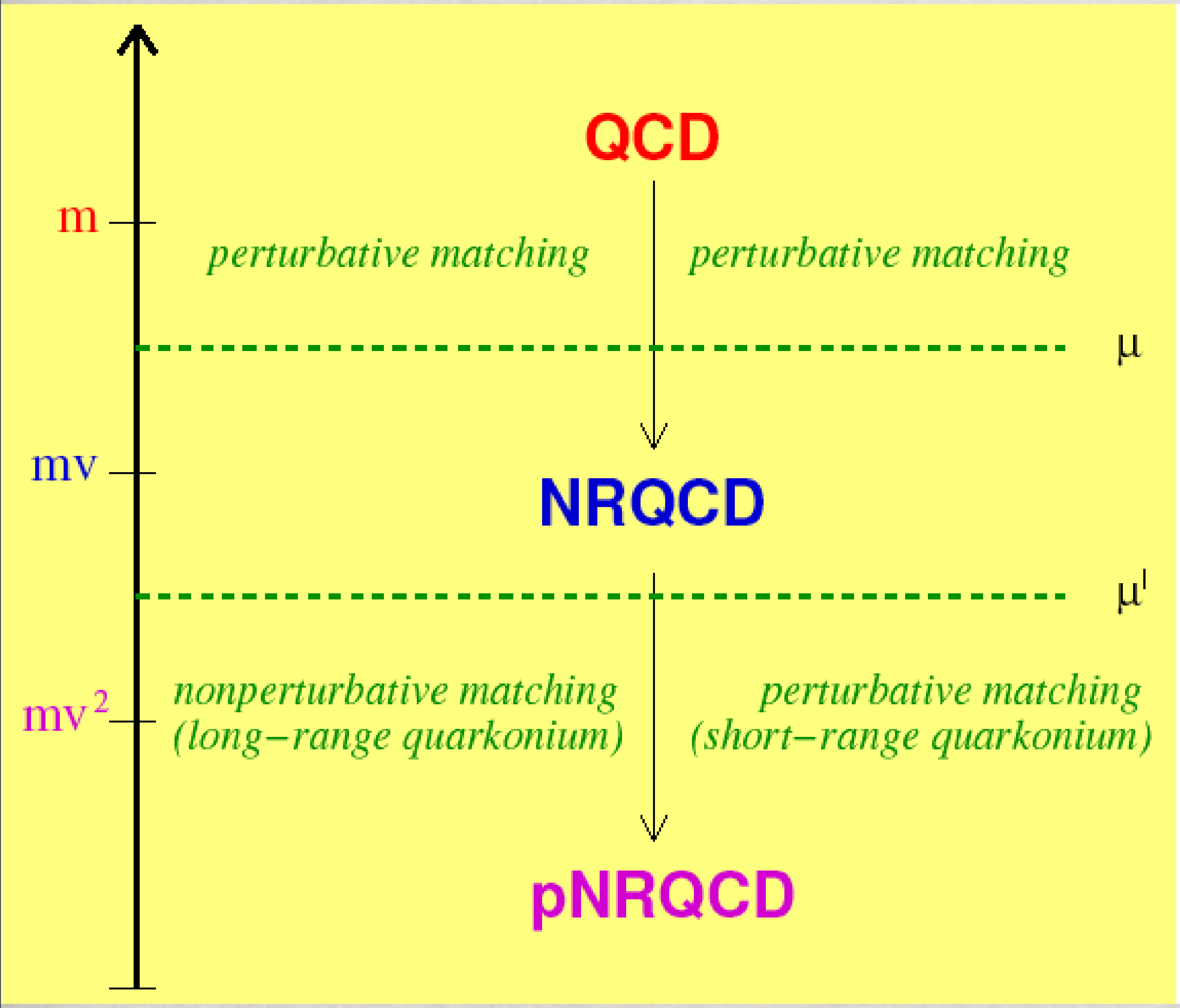


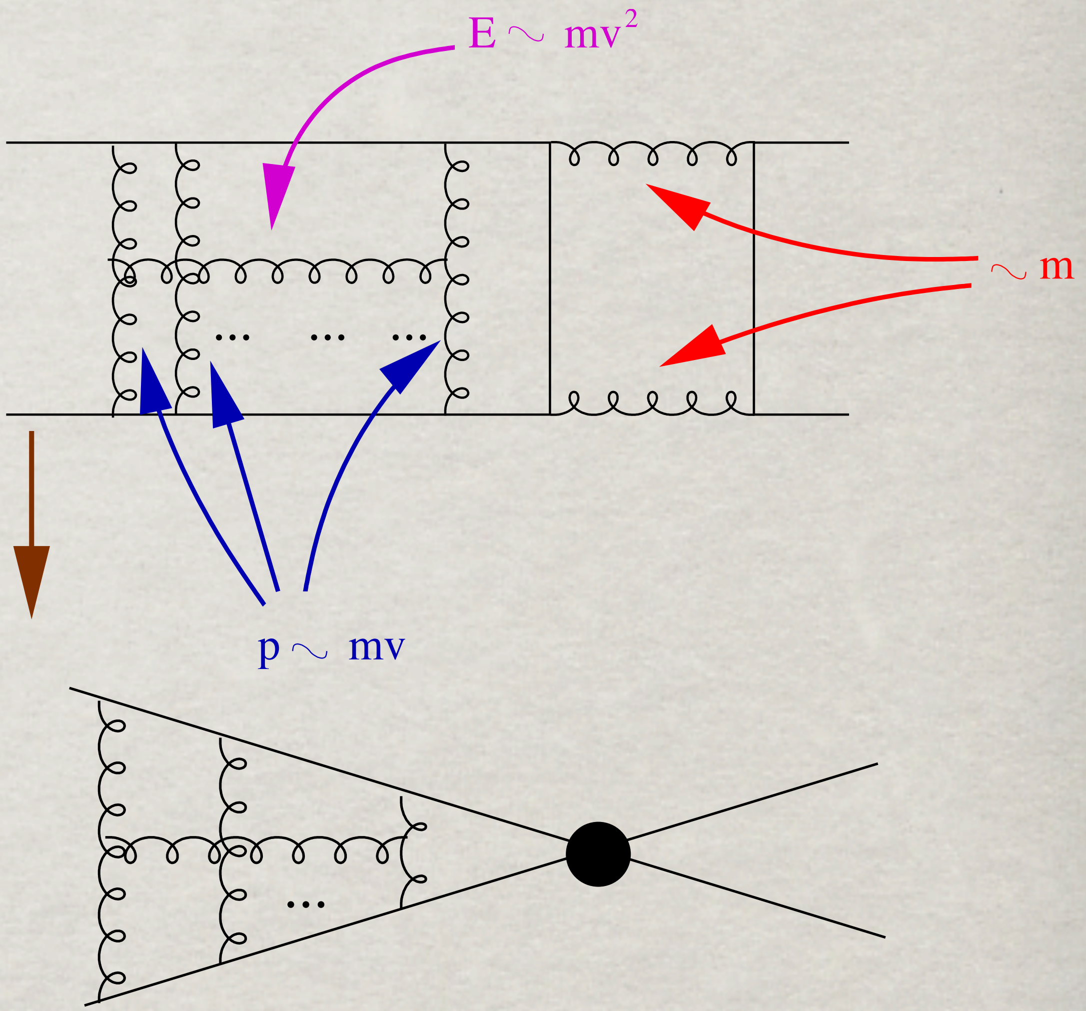
Quarkonium with NR EFT: Non Relativistic QCD (NRQCD)





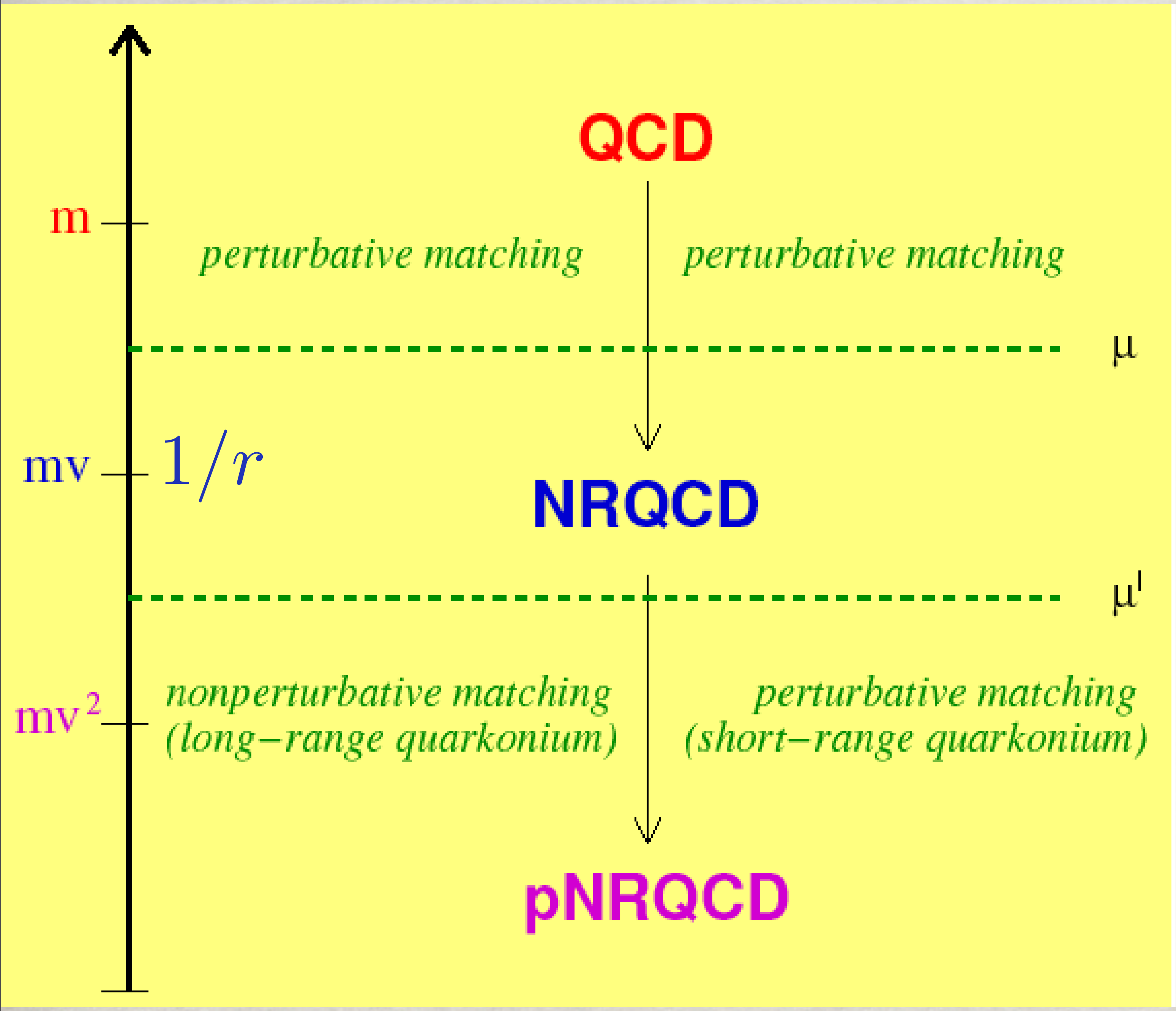
Quarkonium with NR EFT: Non Relativistic QCD (NRQCD)

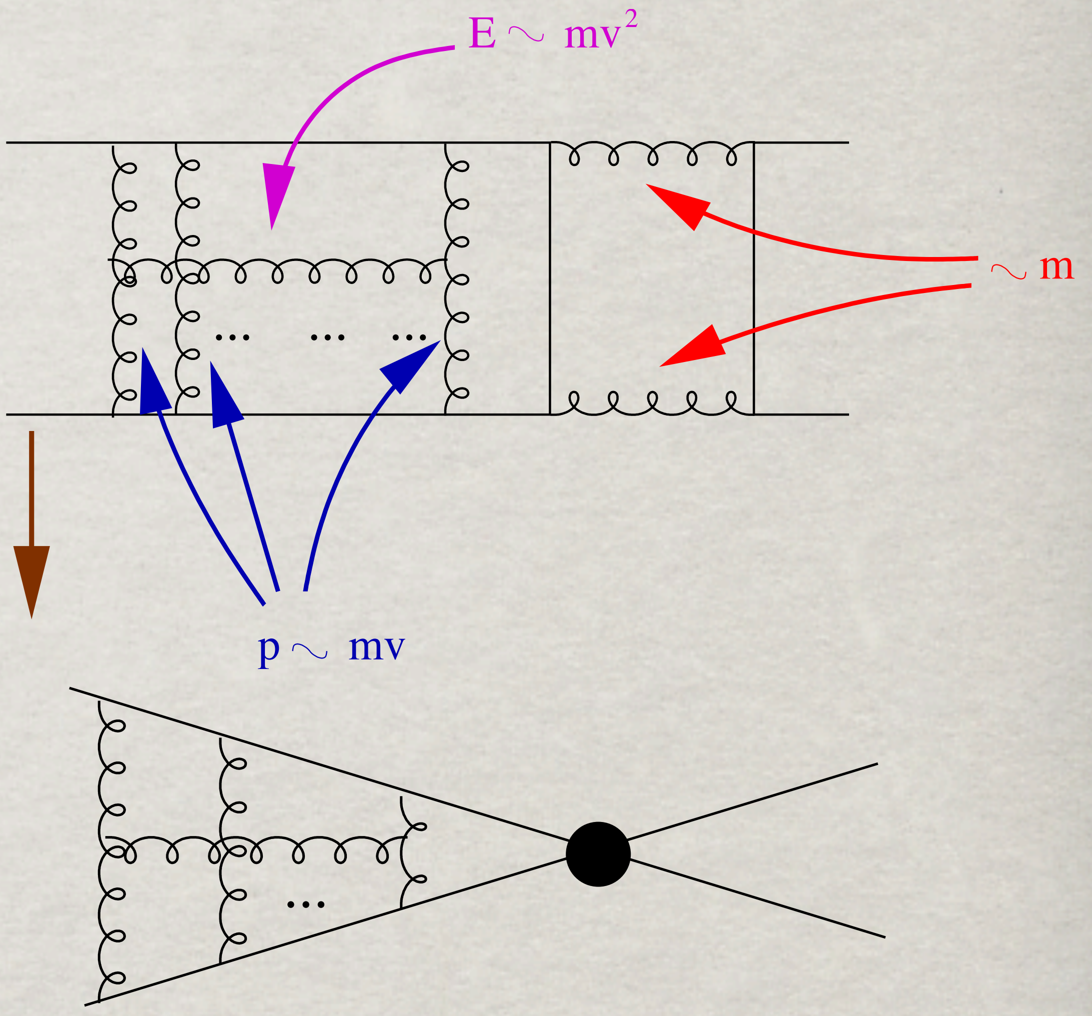




$$\mathcal{L}_{\rm NRQCD} = \sum_n c(\alpha_{\rm s}(m/\mu)) \times \frac{O_n(\mu,\lambda)}{m^n}$$

Quarkonium with NR EFT: potential NonRelativistic QCD (pNRQCD)





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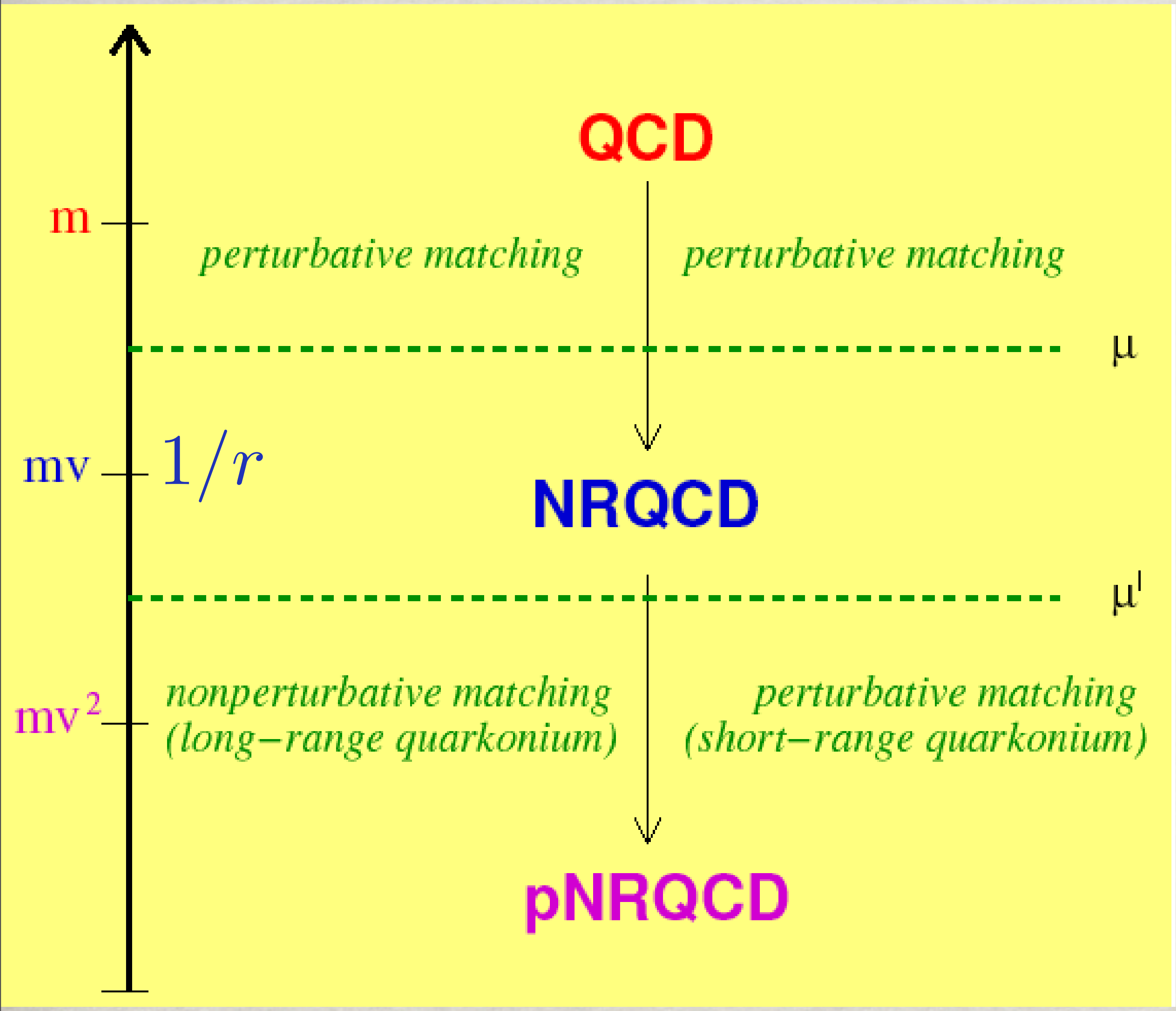
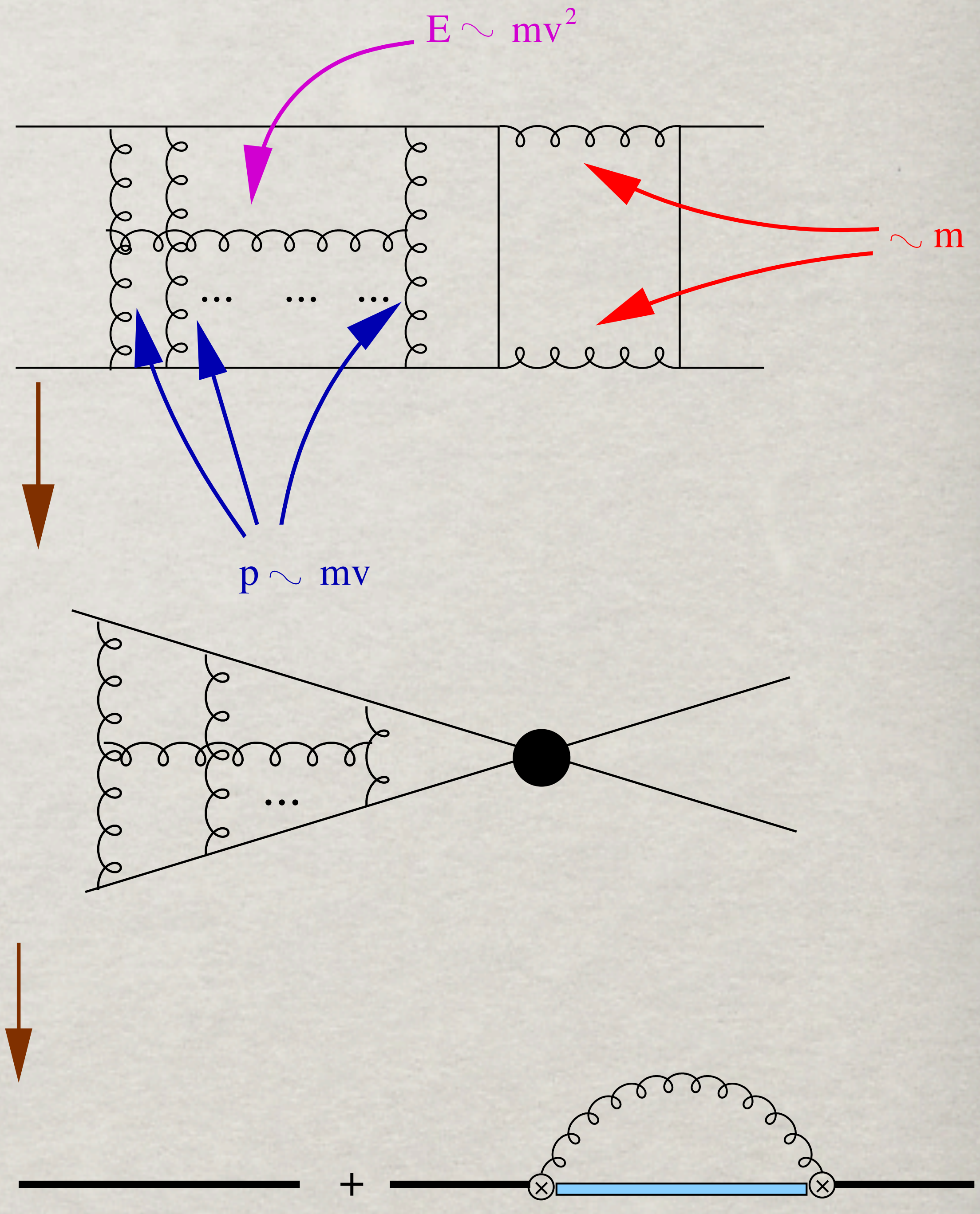
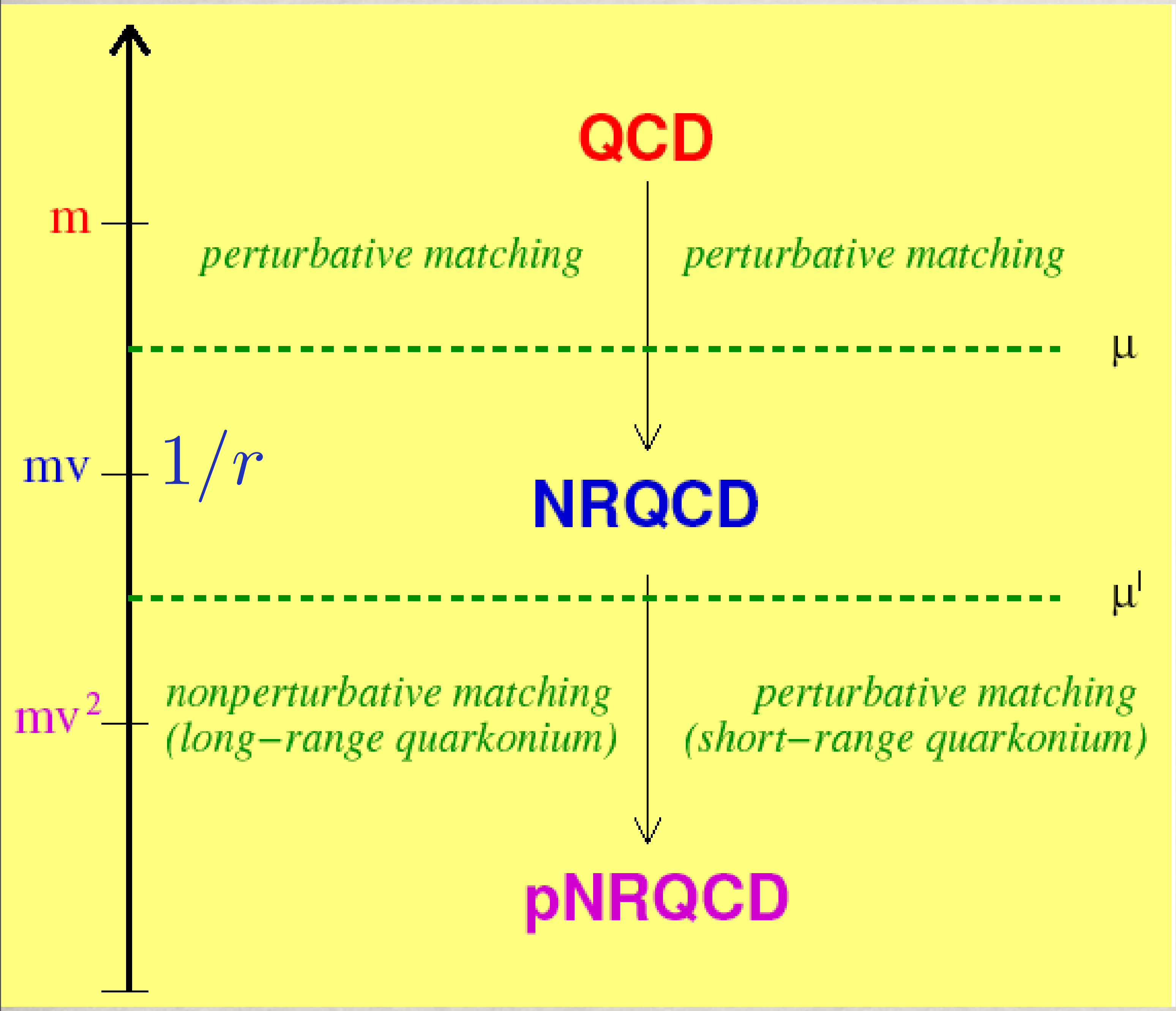
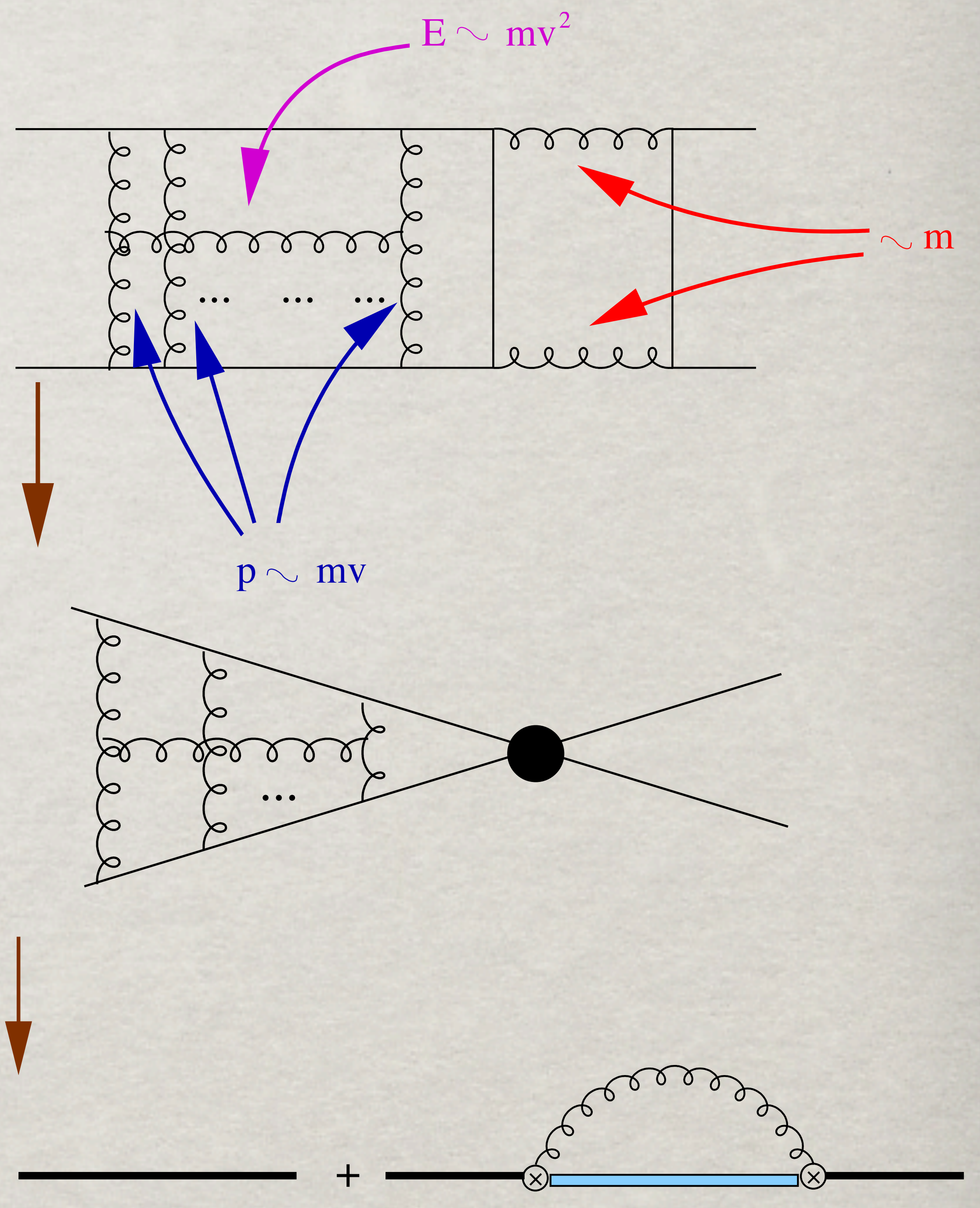




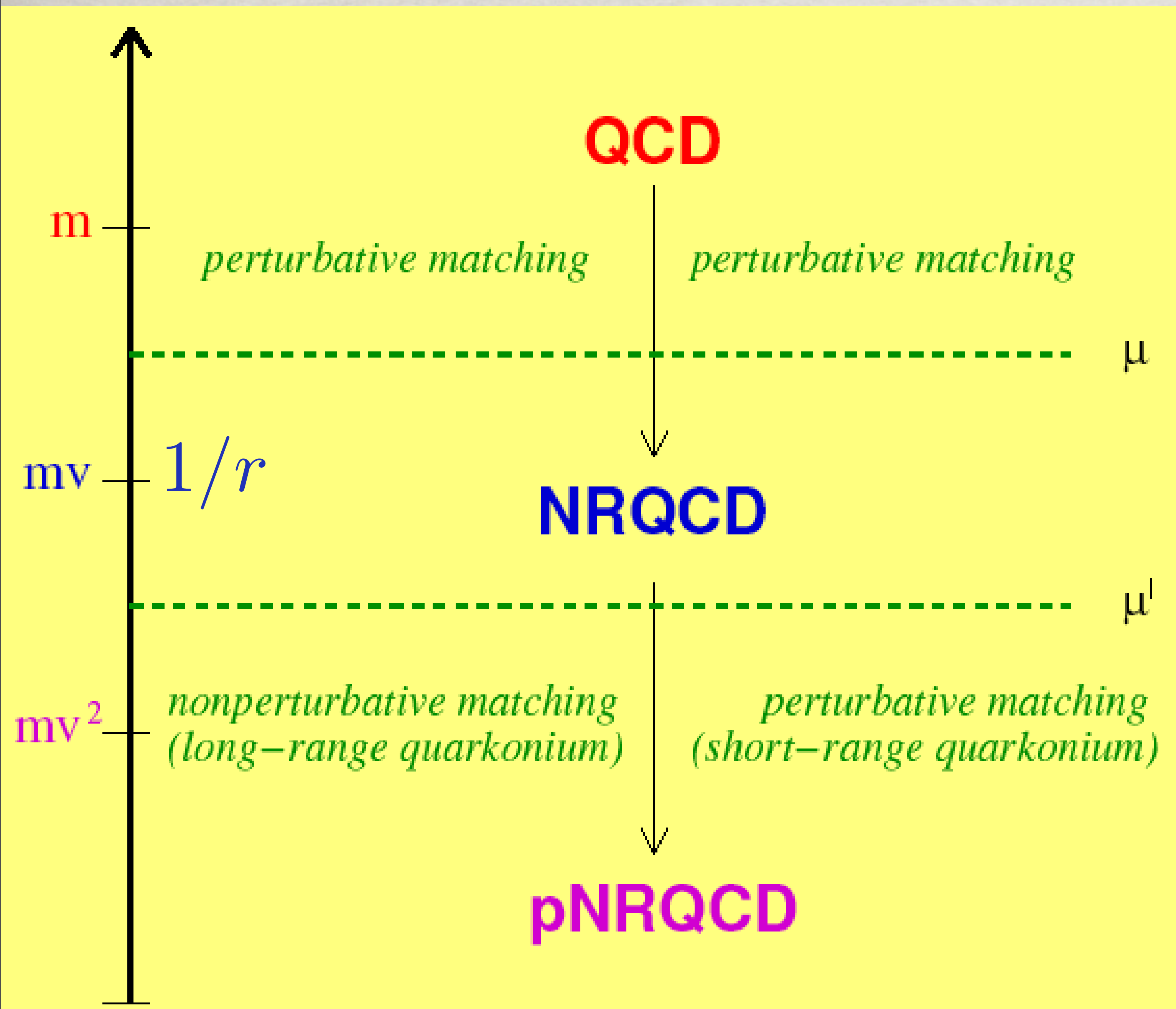
Quarkonium with NR EFT: potential NonRelativistic QCD (pNRQCD)

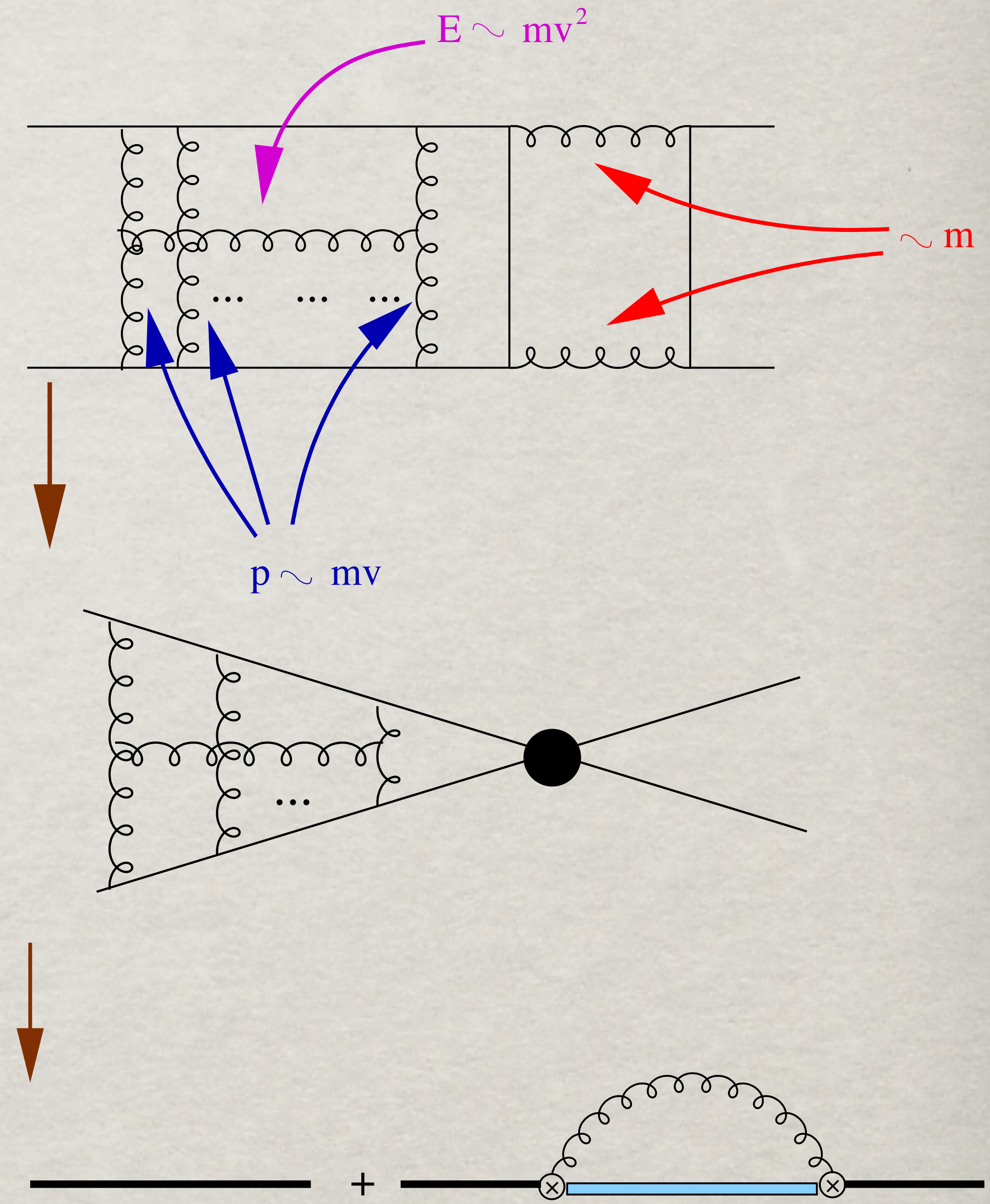




$$\mathcal{L}_{\text{pNRQCD}} = \sum_k \sum_n \frac{1}{m^k} c_k(\alpha_s(m/\mu)) \times V(r\mu', r\mu) \times O_n(\mu', \lambda)\, r^n$$

Quarkonium with NR EFT: potential NonRelativistic QCD (pNRQCD)





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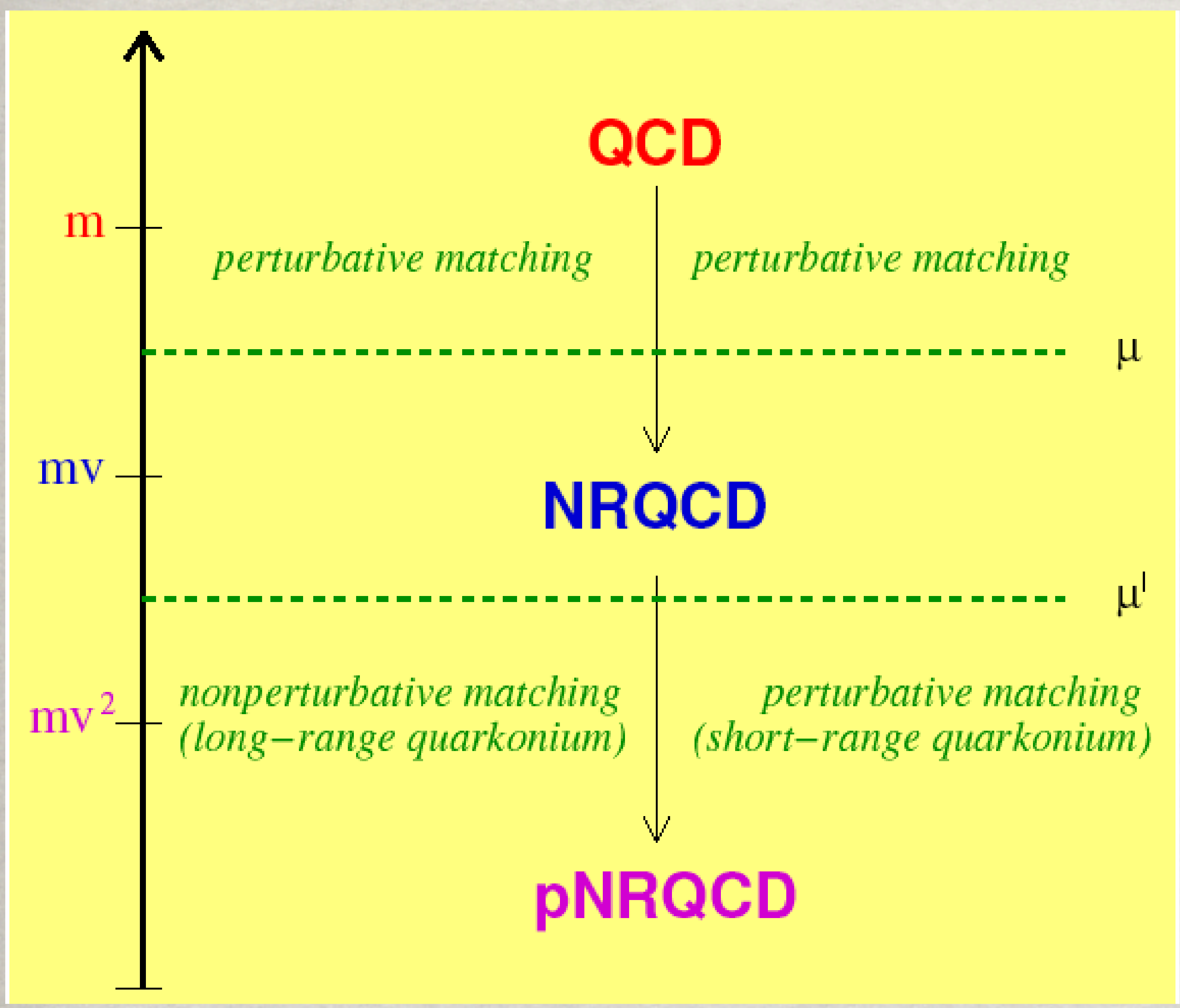
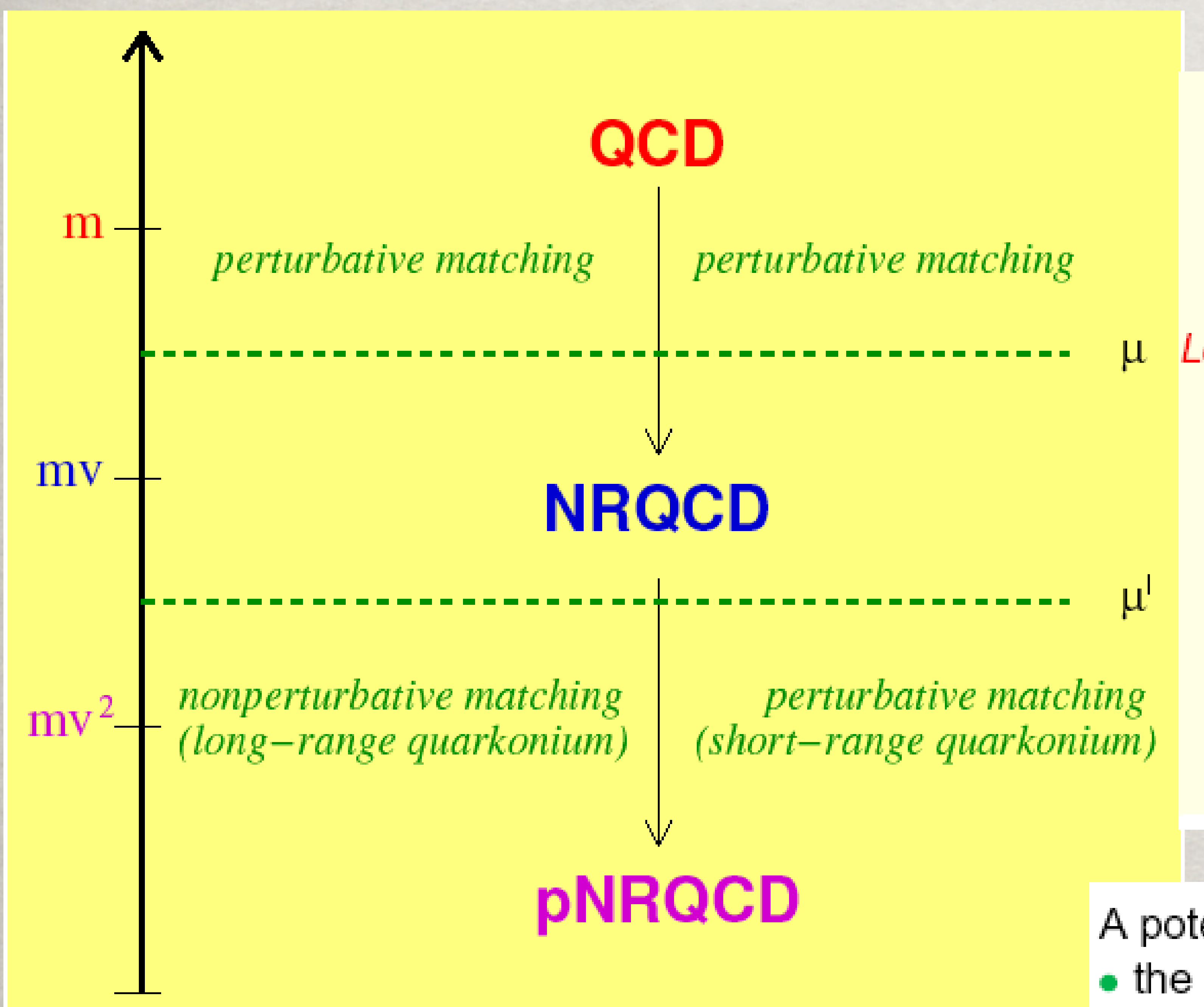
Quarkonium with NR EFT: pNRQCD



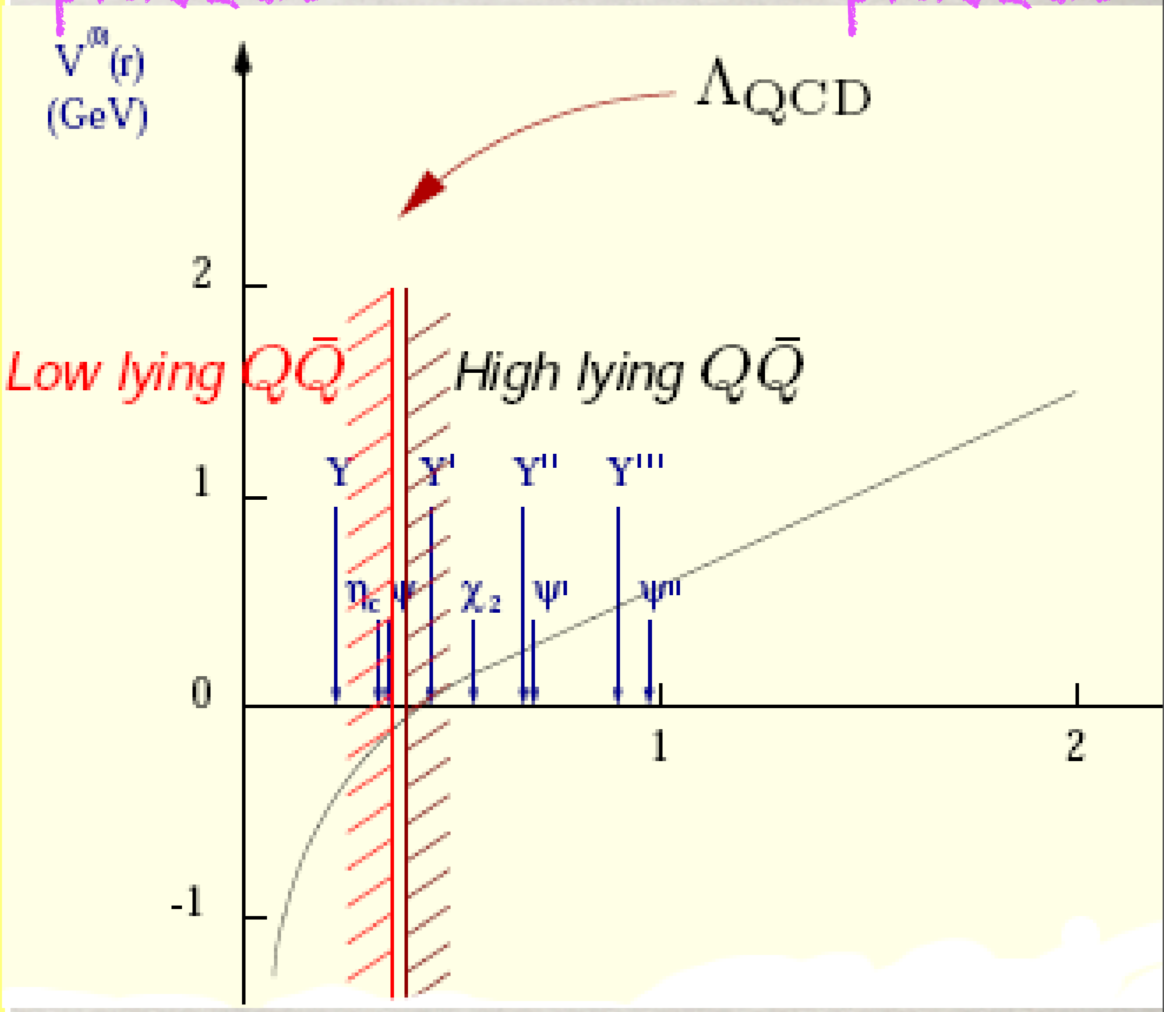
In QCD another scale is relevant $\Lambda_{\rm QCD}$

Quarkonium with NR EFT: pNRQCD



weakly coupled pNRQCD

strongly coupled pNRQCD

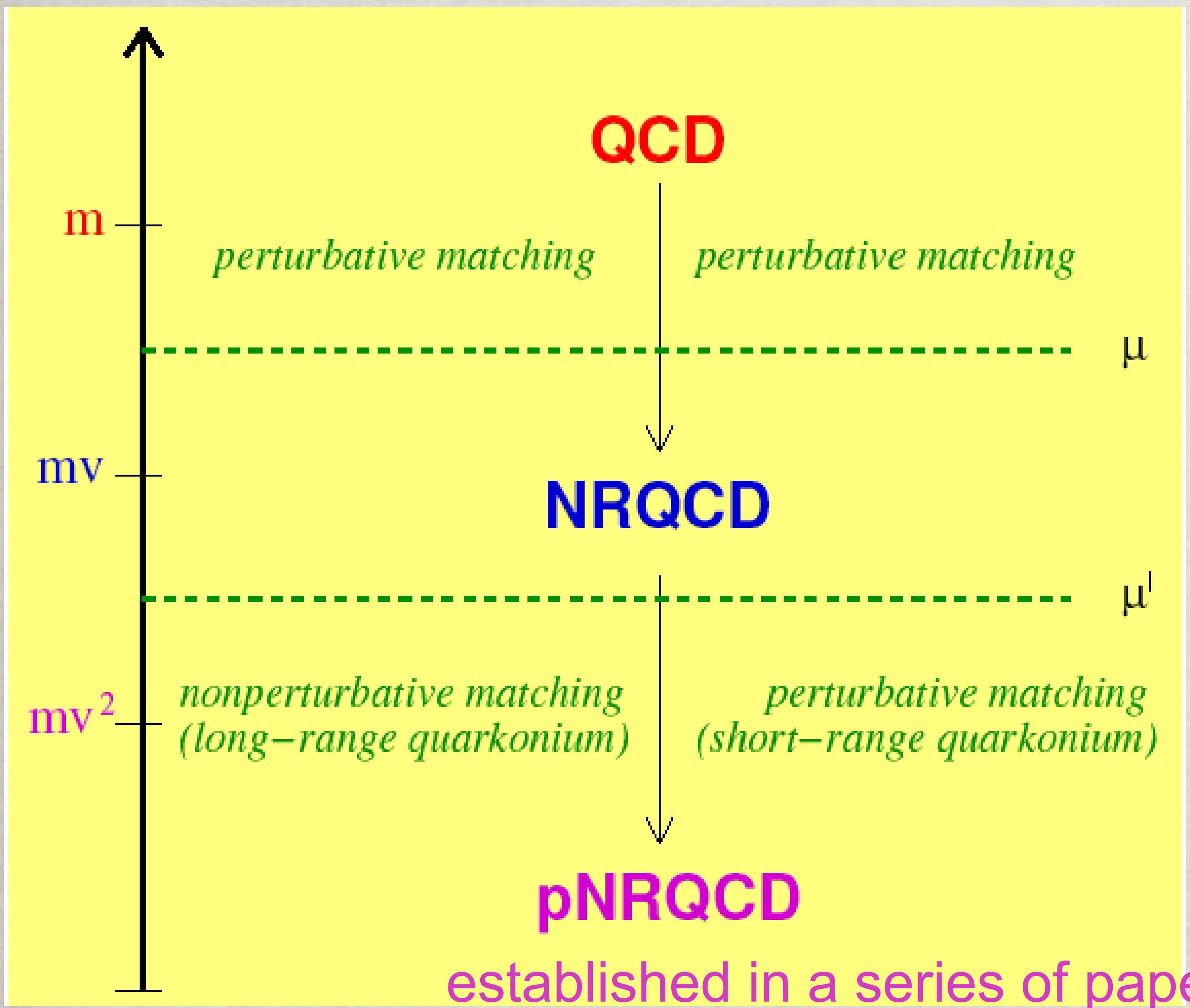


A potential picture arises at the level of pNRQCD:

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

In QCD another scale is relevant Λ_{QCD}

Quarkonium with EFT



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

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->

established in a series of papers:
Pineda, Soto 97, N.B., Pineda, Soto, Vairo 99
N.B. et al 00--013
N.B., Pineda, Soto, Vairo Review of Modern Physis 77(2005) 1423

Physics at the scale m : NRQCD
Quarkonium production and Decays

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Physics at the scale mv and mv^2 : pNRQCD
bound state formation

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

pNRQCD and quarkonium Several cases for the physics at hand

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The EFT has been constructed (away from theshold)

*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)

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The issue here is precision physics and the study of confinement

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The issue here is precision physics and the study of confinement

- Precise and systematic high order calculations allow the extraction of precise determinations of standard model parameters like the quark masses and alpha_s

- The eft has allowed to systematically factorize and to study the low energy nonperturbative contributions

pNRQCD and quarkonium Several cases for the physics at hand

The EFT is being constructed (Finite T) 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

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The eft allows us to discover new, unexpected and important facts:

- The potential is neither the color singlet free energy nor the internal energy
- The quarkonium dissociation is a consequence of the apparence of a thermal decay width rather than being due to the color screening of the real part of the potential

We have now a coherent and systematical setup to calculate masses and width of quarkonium at finite T for small coupling

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only in particular cases (X(3872)) a universal treatment is possible

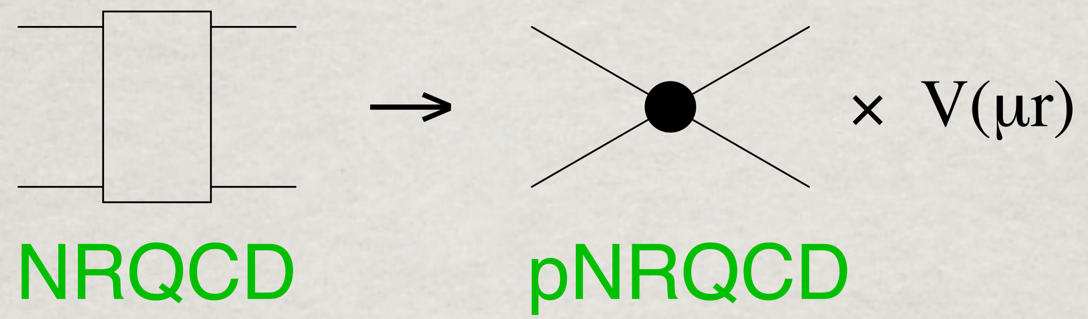
E. Braaten et al

Quarkonium systems with small radius

$$r \ll \Lambda_{\mathrm{QCD}}^{-1}$$

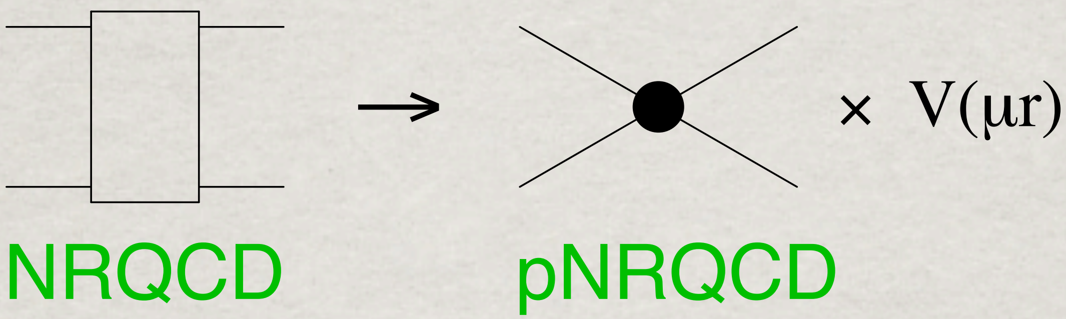
pNRQCD for quarkonia with small radius $\quad r \ll \Lambda_{\text{QCD}}^{-1}$

Degrees of freedom that scale like mv are integrated out:



pNRQCD for quarkonia with small radius $r \ll \Lambda_{\rm QCD}^{-1}$

Degrees of freedom that scale like mv are integrated out:



- If $mv \gg \Lambda_{\rm QCD}$, the matching is perturbative

- Degrees of freedom: quarks and gluons

  Q-$\bar{Q}$ states, with energy $\sim \Lambda_{\rm QCD}, mv^2$ and momentum $\lesssim mv$
  $\Rightarrow$ (i) singlet S (ii) octet O

  Gluons with energy and momentum $\sim \Lambda_{\rm QCD}, mv^2$

- Definite power counting: $r \sim \frac{1}{mv}$ and $t, R \sim \frac{1}{mv^2}, \frac{1}{\Lambda_{\rm QCD}}$

  The gauge fields are multipole expanded:
  $A(R, r, t) = A(R, t) + \mathbf{r} \cdot \boldsymbol{\nabla} A(R, t) + \ldots$

  Non-analytic behaviour in $r \to$ matching coefficients V

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

S singlet field

O octet field

singlet propagator

octet propagator

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

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

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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

S singlet field

O octet field

singlet propagator

octet propagator

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

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

Singlet static potential

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

LO in r

Octet static potential

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

NLO in r

S singlet field

O octet field

singlet propagator

octet propagator

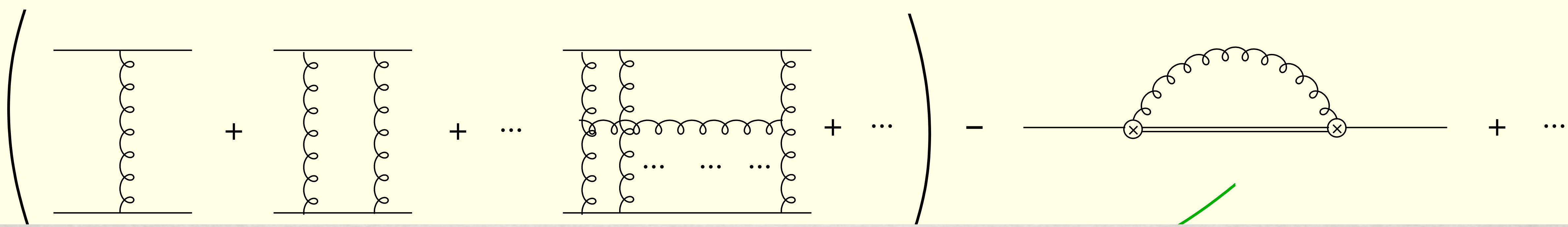
Pineda, Soto 97; Brambilla, Pineda, Soto, Vairo 99-

pNRQCD

- pNRQCD provides a QM description from field theory: the Schroedinger equation and the potentials appear once all scales above the binding energy have been integrated out
- The EFT accounts for non-potential terms as well. They provide loop corrections to the leading potential picture. Retardation effects are typically related to the nonperturbative physics
- The Quantum Mechanical divergences are cancelled by the NRQCD matching coefficients.
- Poincare’ invariance is intact and is realized via exact relations among the matching coefficients (potentials)

QCD singlet static potential

$V =$



The potential is a Wilson coefficient of an EFT.
In general, it undergoes renormalization, develops scale dependence and satisfies renormalization group equations, which allow to resum large logarithms.

Quarkonium singlet static potential at N^4LO

$$
\begin{aligned}
V_s(r,\mu) \quad = \quad & -C_F \frac{\alpha_s(1/r)}{r}\left[1 + a_1 \frac{\alpha_s(1/r)}{4\pi} + a_2 \left(\frac{\alpha_s(1/r)}{4\pi}\right)^2\right. \\
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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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Quarkonium singlet static potential at N^4LO

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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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3LOOPS REDUCES TO 1LOOP IN THE EFT

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

4LOOPS REDUCES TO 2LOOPS IN THE EFT

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

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\end{aligned}
$$

Two problems:

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

2) Large logs

Quarkonium singlet static potential at N^4LO

$$V_s(r,\mu) = -C_F \frac{\alpha_s(1/r)}{r}\left[1 + a_1 \frac{\alpha_s(1/r)}{4\pi} + a_2\left(\frac{\alpha_s(1/r)}{4\pi}\right)^2 + \left(\frac{16\,\pi^2}{3} C_A^3 \ln r\mu + a_3\right)\left(\frac{\alpha_s(1/r)}{4\pi}\right)^3 + \left(a_4^{L2}\ln^2 r\mu + \left(a_4^L + \frac{16}{9}\pi^2 C_A^3 \beta_0(-5+6\ln 2)\right)\ln r\mu + a_4\right)\left(\frac{\alpha_s(1/r)}{4\pi}\right)^4\right]$$

for long it was believed that such series was not convergent problem for any phenomenological application

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\end{aligned}
$$

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The eft cures both:

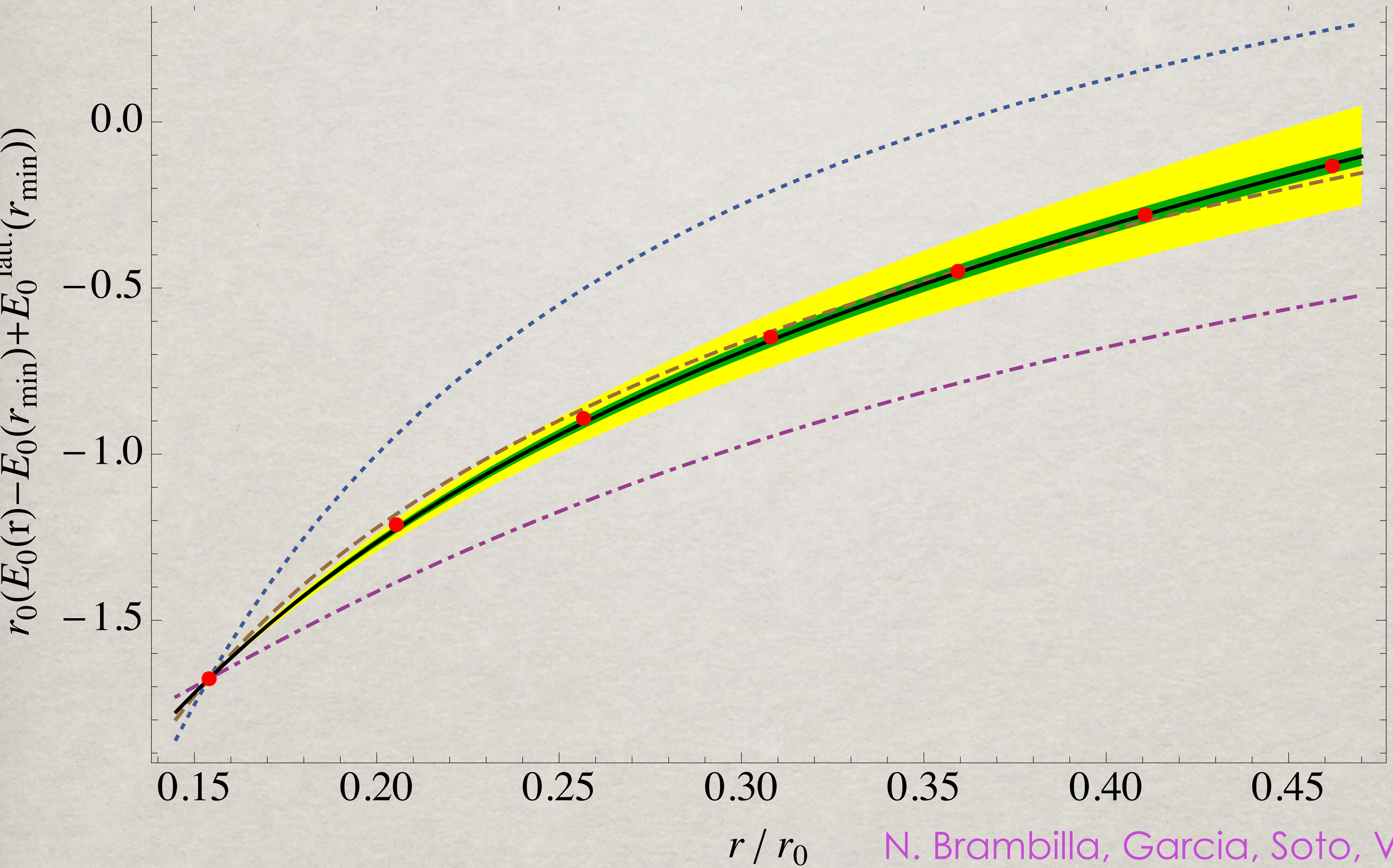
1) Renormalon subtracted scheme

Beneke 98, Hoang, Lee 99, Pineda 01, n.brambilla et al 09

2) Renormalization group summation of the logs up to N^3LL $(\alpha_s^{4+n} \ln^n \alpha_s)$

Pineda, Soto, N. B. , X. Garcia, Soto, Vairo . et al 2007, 2009

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

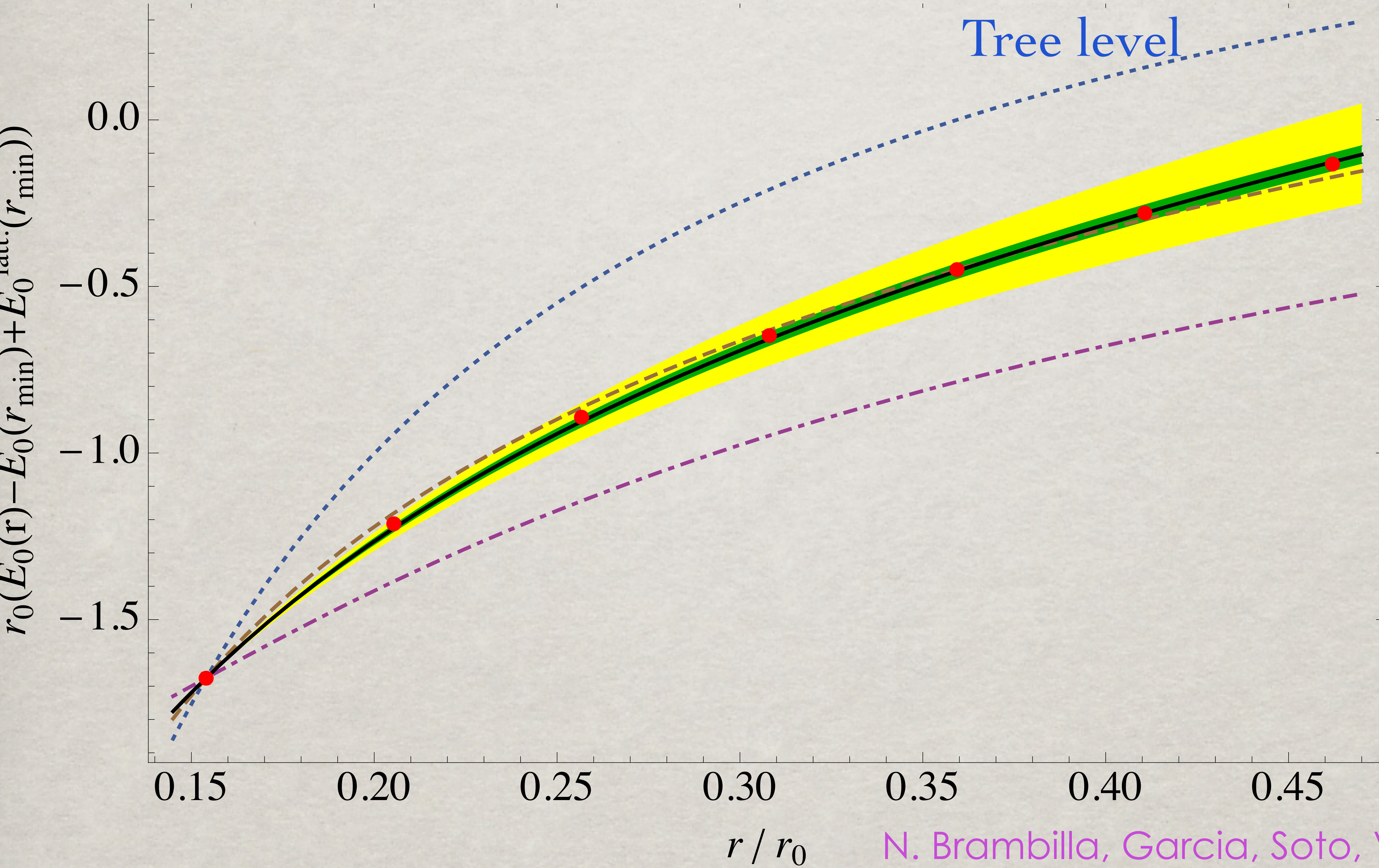


N. Brambilla, Garcia, Soto, Vairo 010

Yellow band : uncertainty in alpha_s (r_0*Lambda_QCD_MS)

Green band: uncertainty in higher order terms

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



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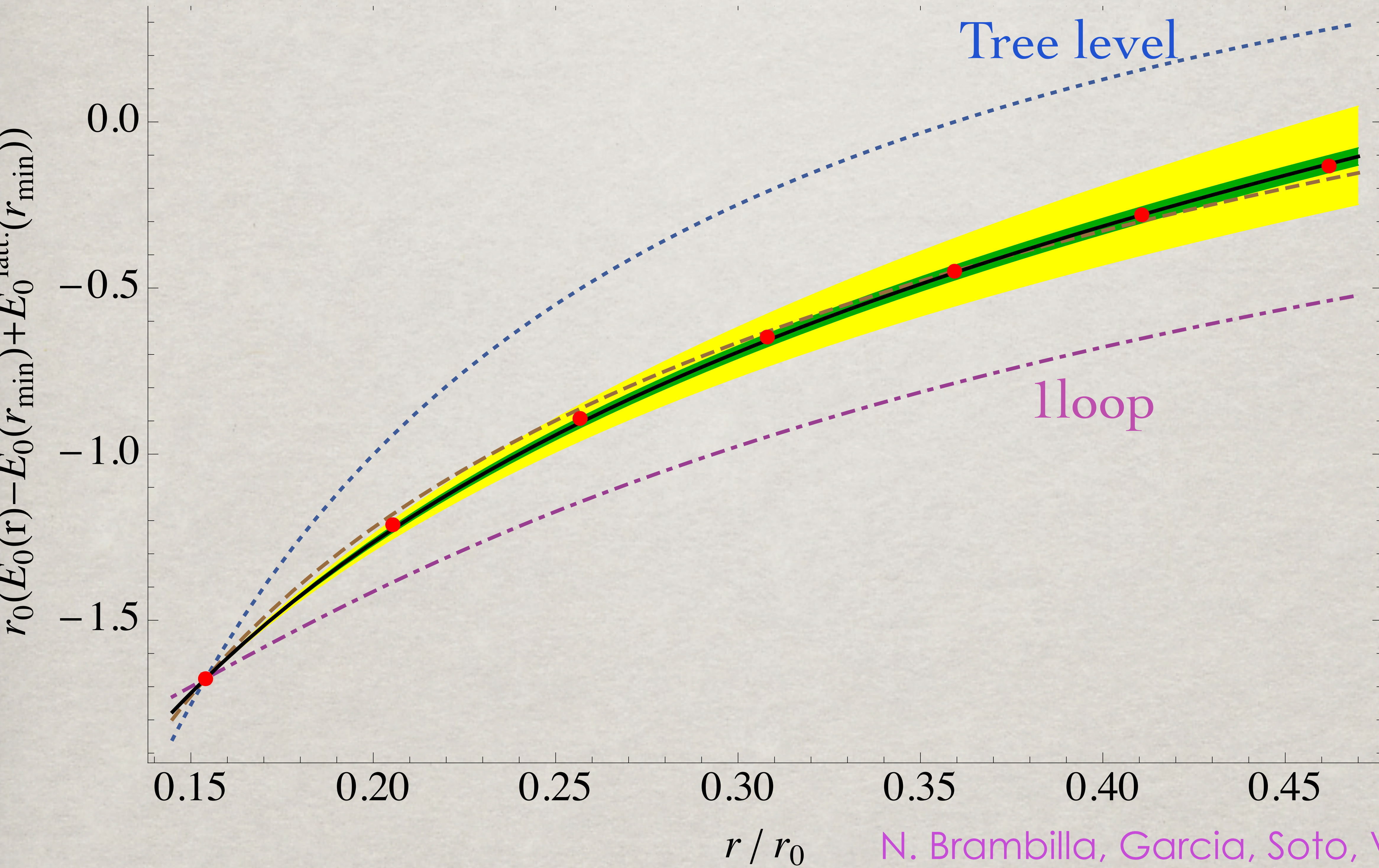

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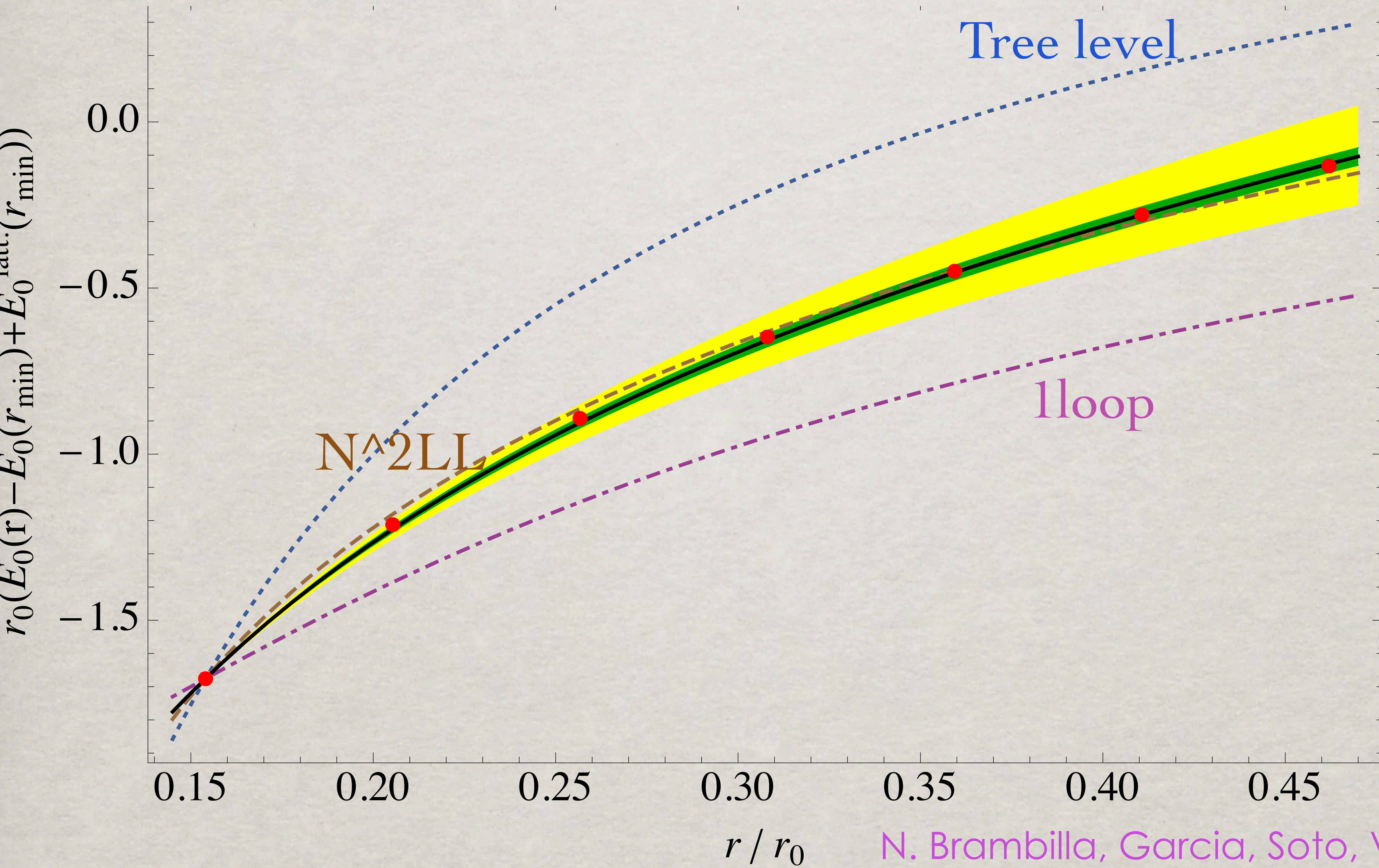

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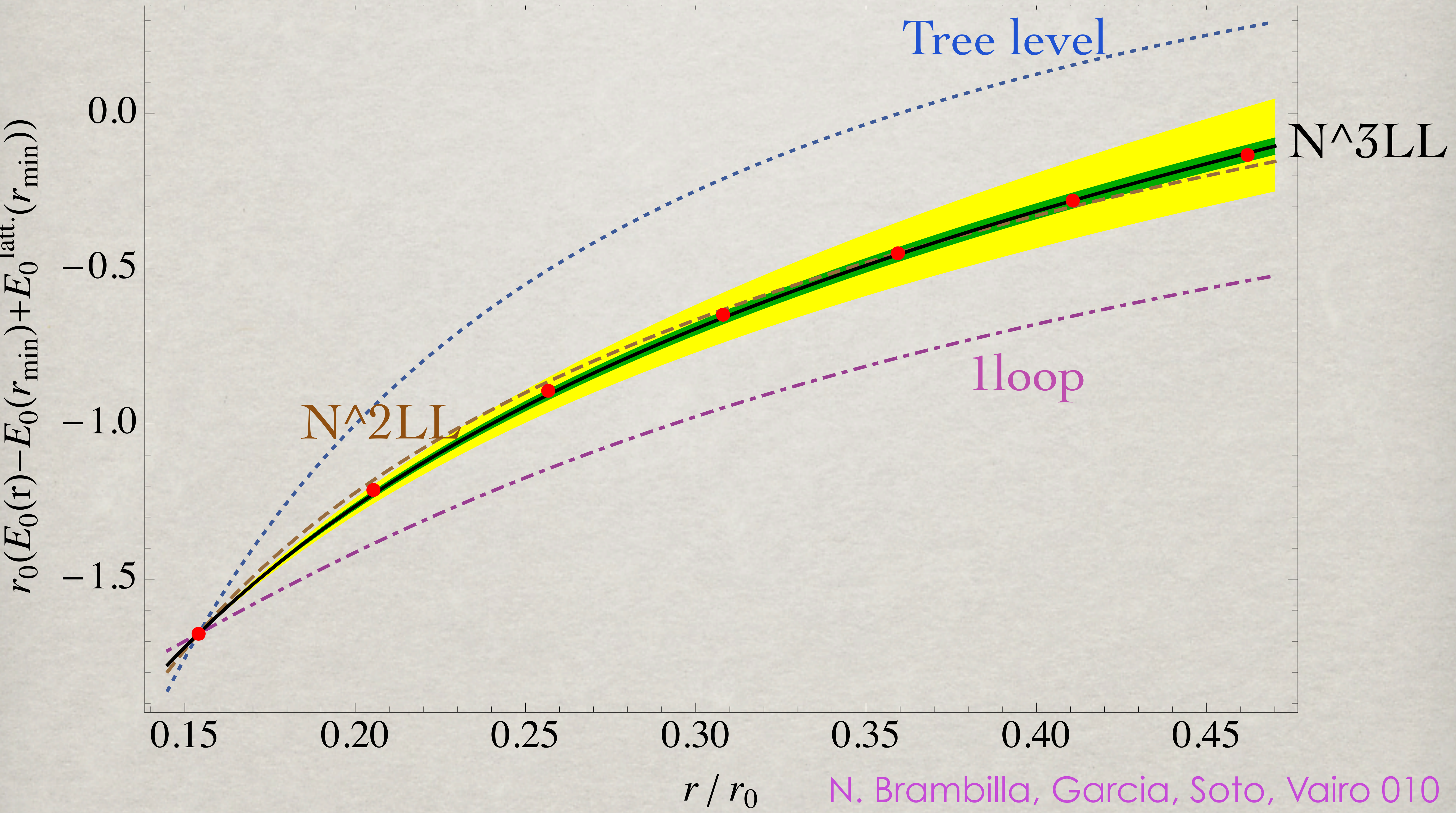

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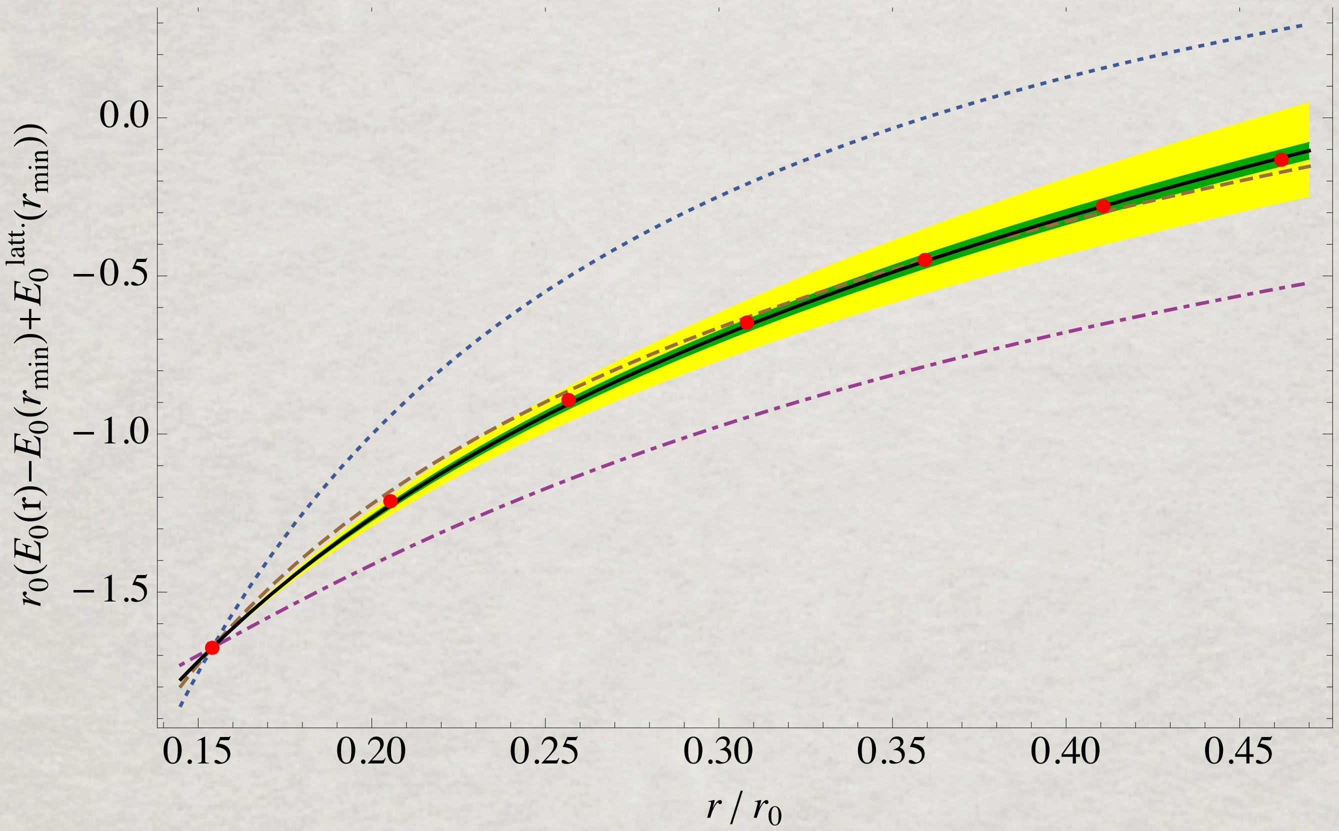

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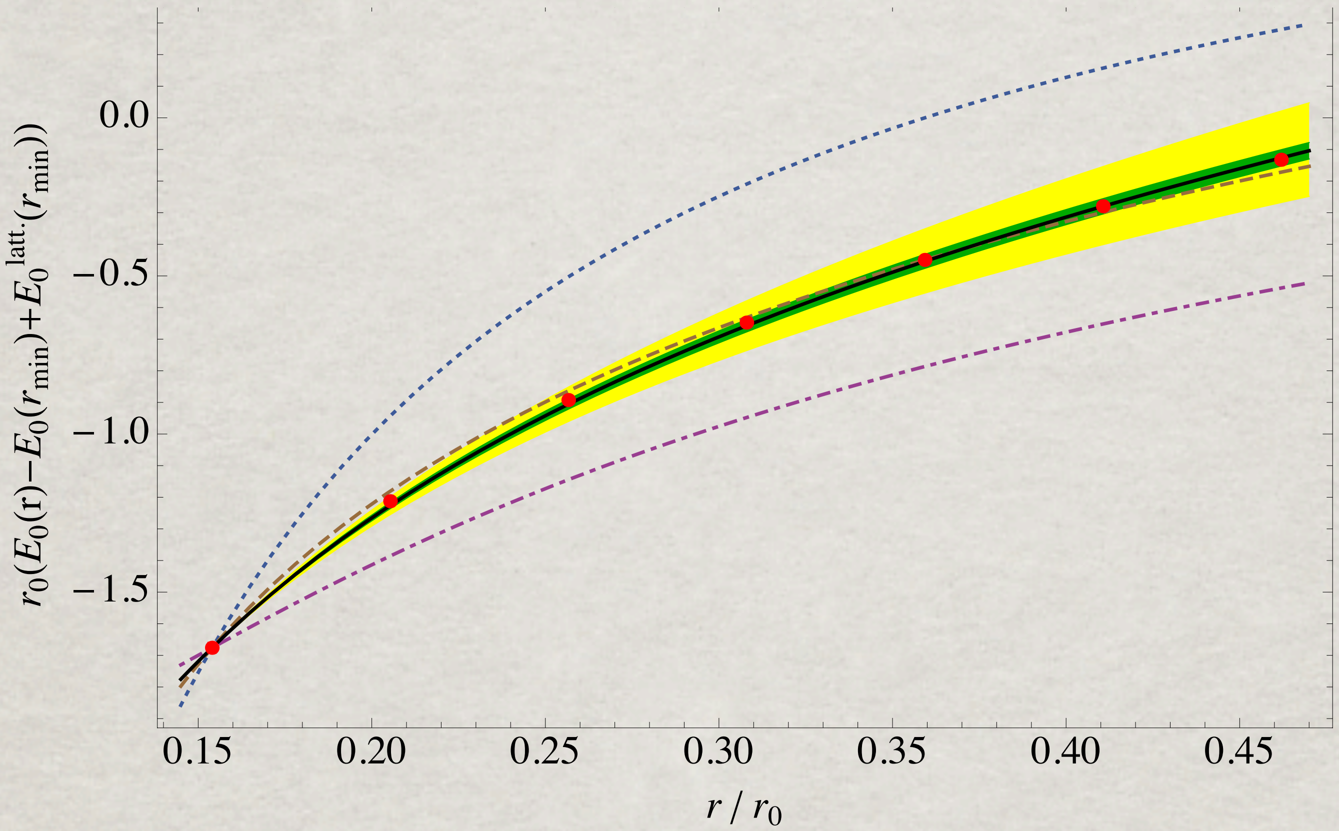
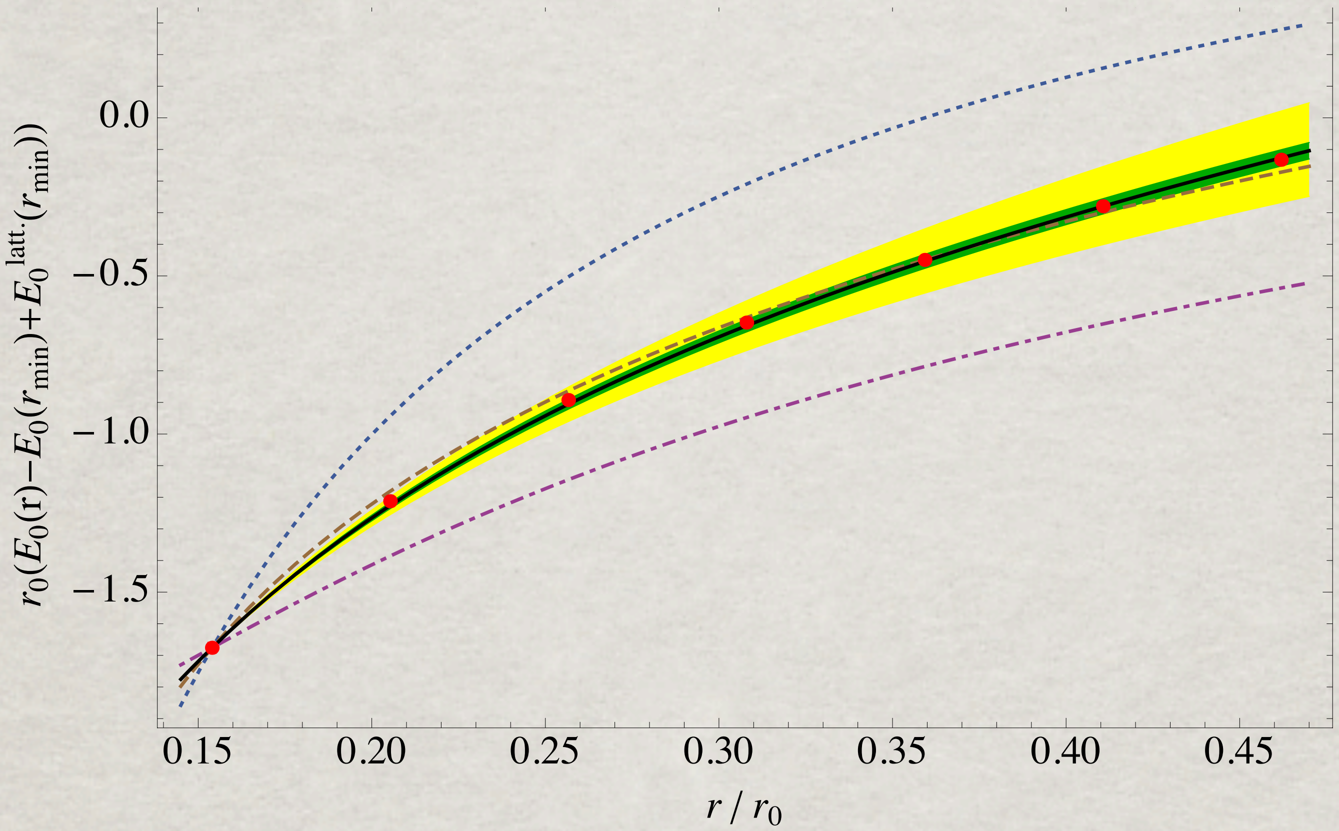


- Very good convergence of the QCD bound state perturbative series

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



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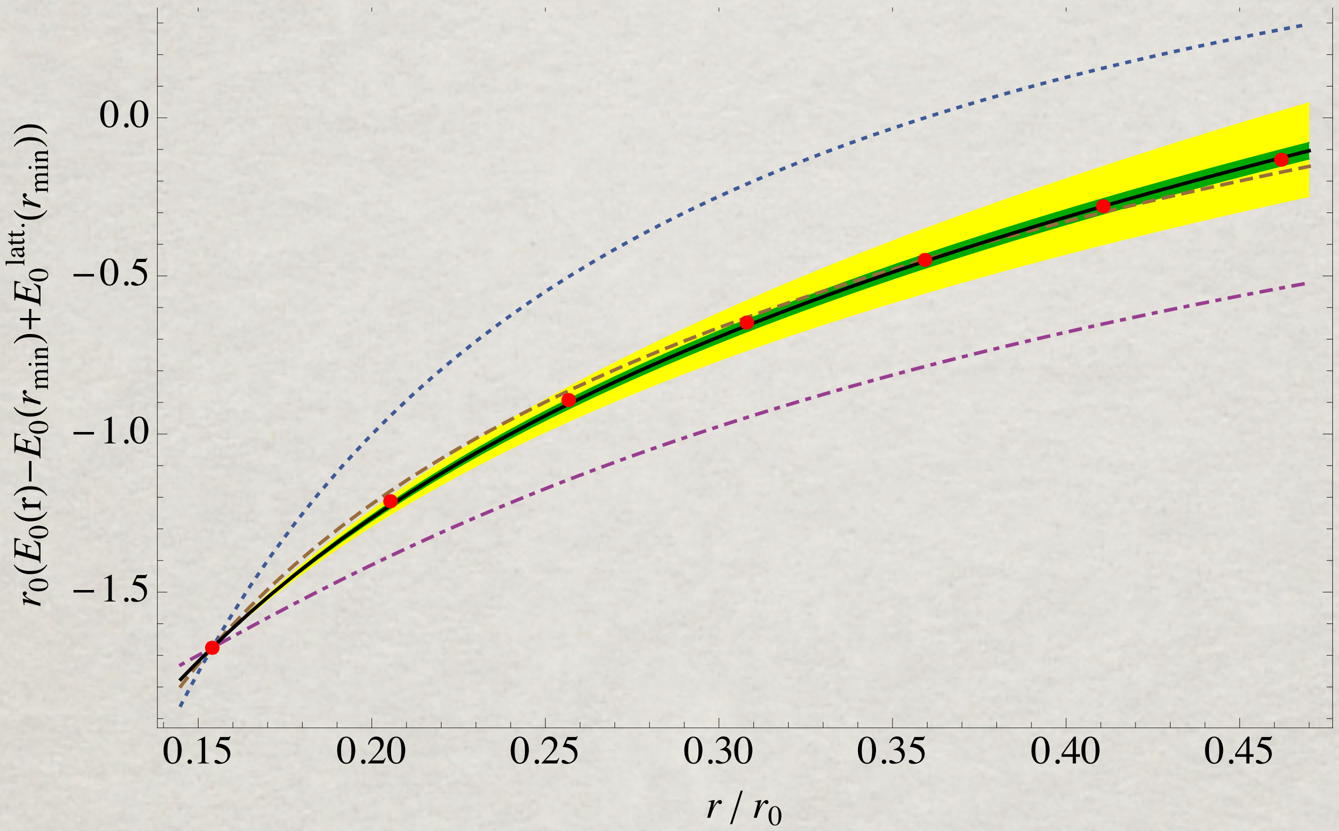

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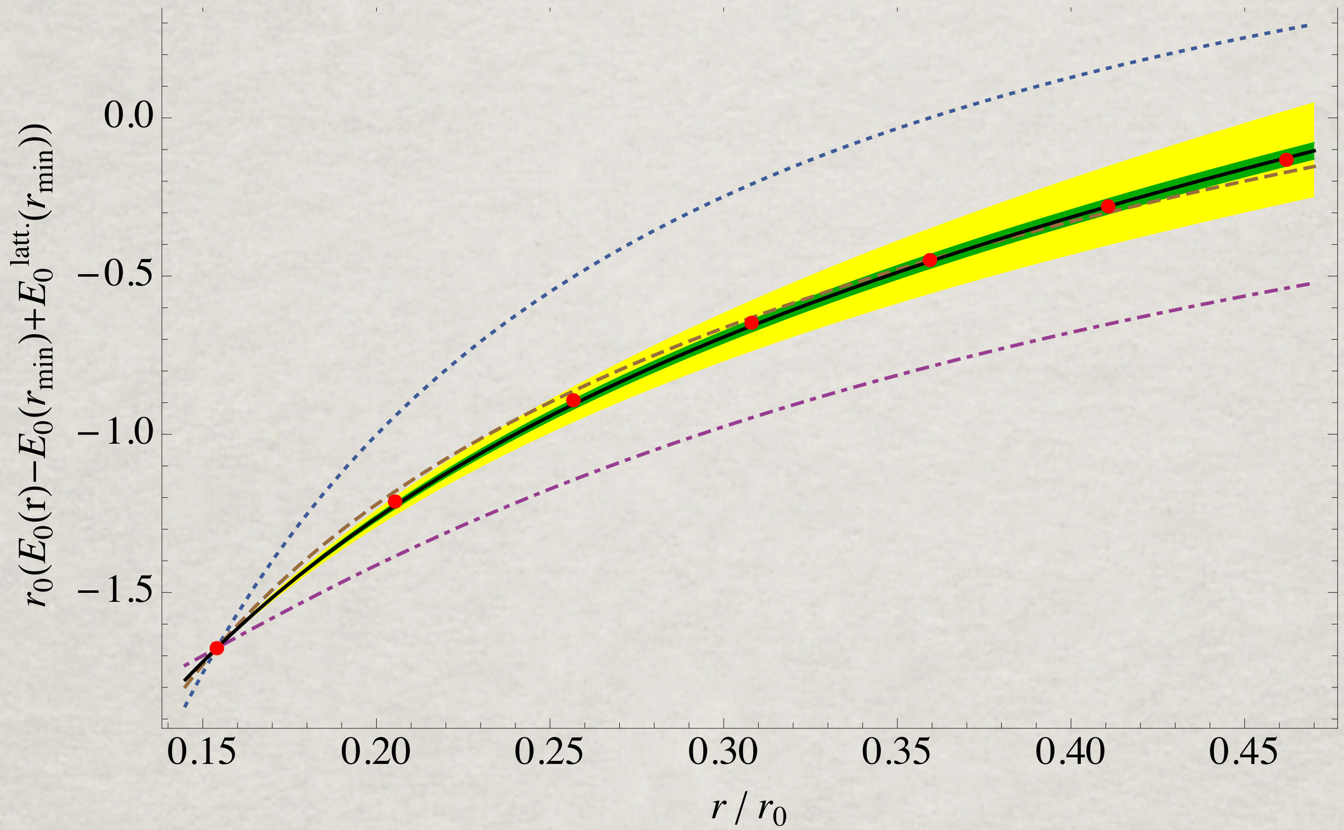
Necco Sommer 2002)



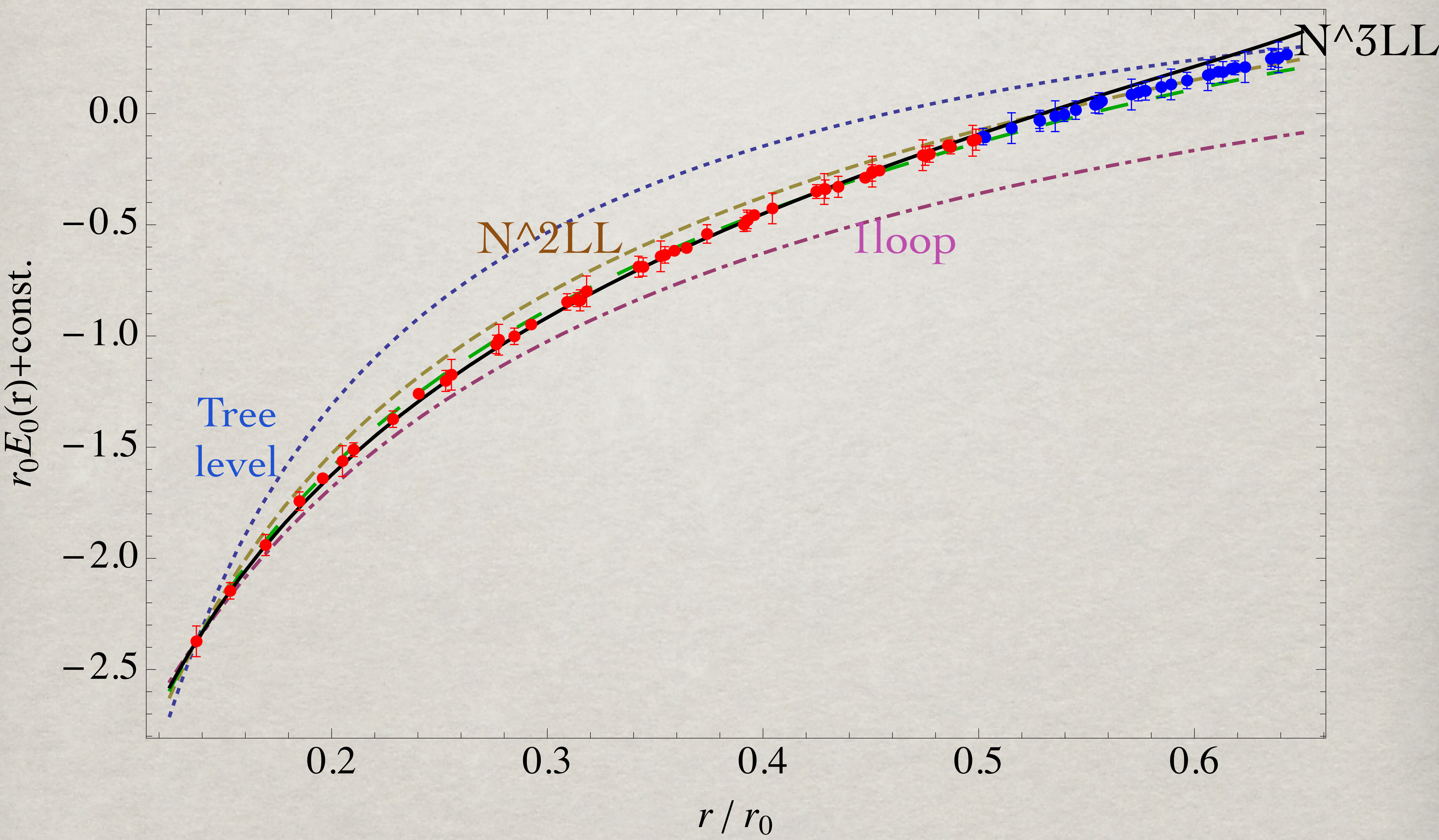
- Very good convergence of the QCD bound state perturbative series
- The lattice data are perfectly described from perturbation theory up to more than 0.2 fm
- Allows to rule out models: no string contribution at small r !
- Allows precise extraction of fundamental parameters of QCD

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

N. Brambilla, Garcia, Soto, Vairo 010)

QQbar singlet static energy at N^3Ll in comparison with unquenched (n_f=2+1) lattice data (red points,blue points)

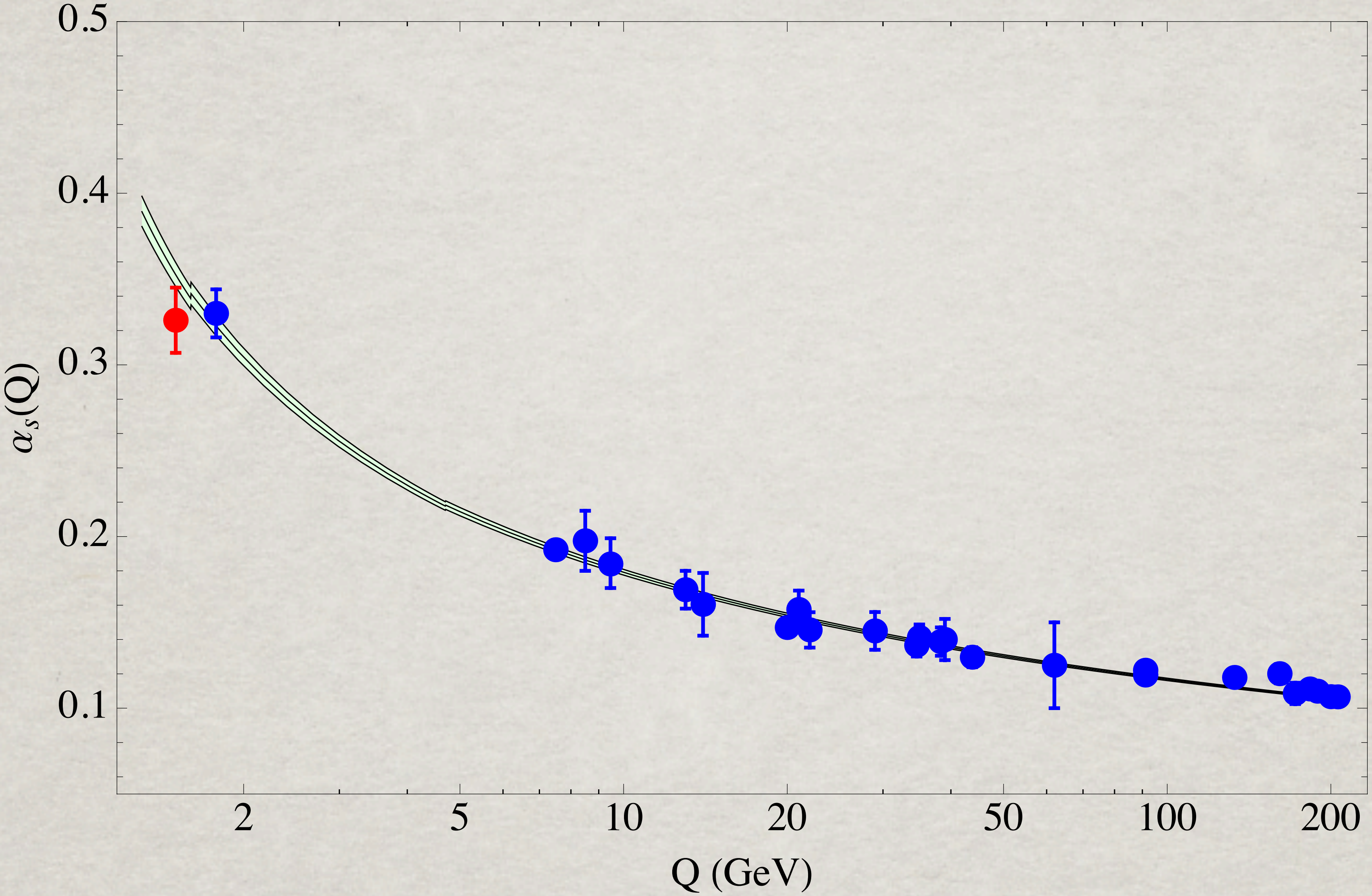
Bazanov, N. B., Garcia, Petreczky, Soto, Vairo , 2012



Good convergence to the lattice data

Lattice data less accurate in the unquenched case

α_s extraction



We obtain an extraction of alphas at N^3LO plus leading log resummation at the lowest energy scale (at the m_c mass)!

$$\alpha_s(\rho = 1.5\,\text{GeV}, n_f = 3) = 0.326 \pm 0.019$$

corresponding to

$$\alpha_s(M_z, n_f = 5) = 0.1156^{+0.0021}_{-0.0022}$$

Bazanov, N. B., Garcia, Petreczky, Soto, Vairo , 2012

$$\rho = 3.14 r_0^{-1}$$

Applications to Quarkonium physics: systems with small radius

for references see the QWG doc arXiv:1010.5827

- c and b masses at NNLO, N^{3}LO*, NNLL*;
- B_c mass at NNLO; Penin et al 04
- B_c^*, η_c, η_b masses at NLL; Kniehl et al 04
- 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;
- QQq and QQQ baryons: potentials at NNLO, masses, hyperfine splitting, ... ; N. B. et al 010
- Thermal effects on quarkonium in medium: potential, masses (at $m\alpha_s^5$), widths, ...;

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

$$\mathcal{B}(\Upsilon(1S) \to \gamma\eta_b(1S)) = (2.85 \pm 0.30) \times 10^{-4}$$

N. B. Yu Jia A. Vairo 2005

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

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

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

Quarkonium systems with large radius

$$r \sim \Lambda_{QCD}^{-1}$$

- Hitting the scale $\Lambda_{\rm QCD}$ $r \sim \Lambda_{QCD}^{-1}$

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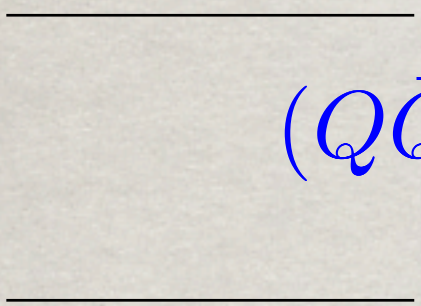
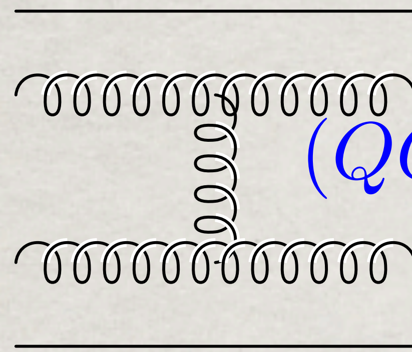
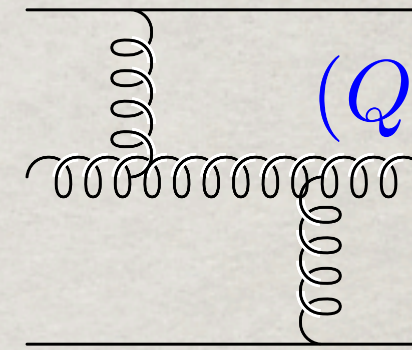


$(Q\bar{Q})_1$



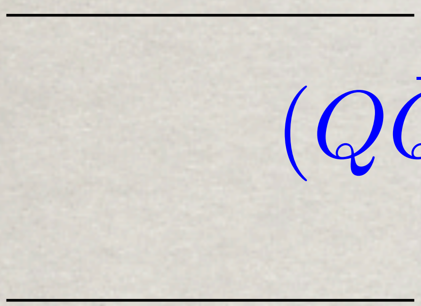
$(Q\bar{Q})_1 +$ Glueball



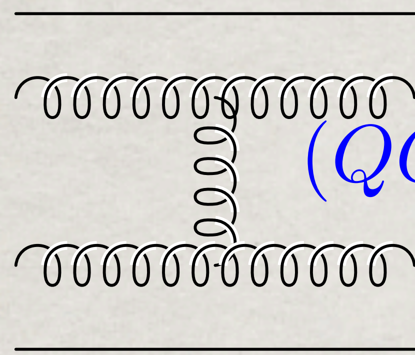
$(Q\bar{Q})_8 G$

hybrid

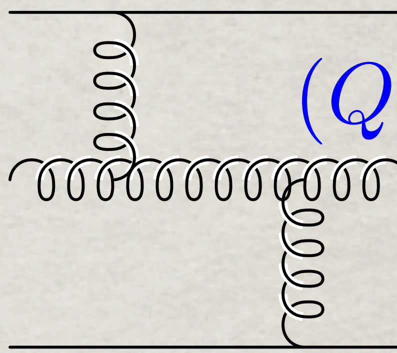
Hitting the scale $\Lambda_{\rm QCD}$ $\quad r \sim \Lambda_{QCD}^{-1}$



$(Q\bar{Q})_1$



$(Q\bar{Q})_1 + \text{Glueball}$

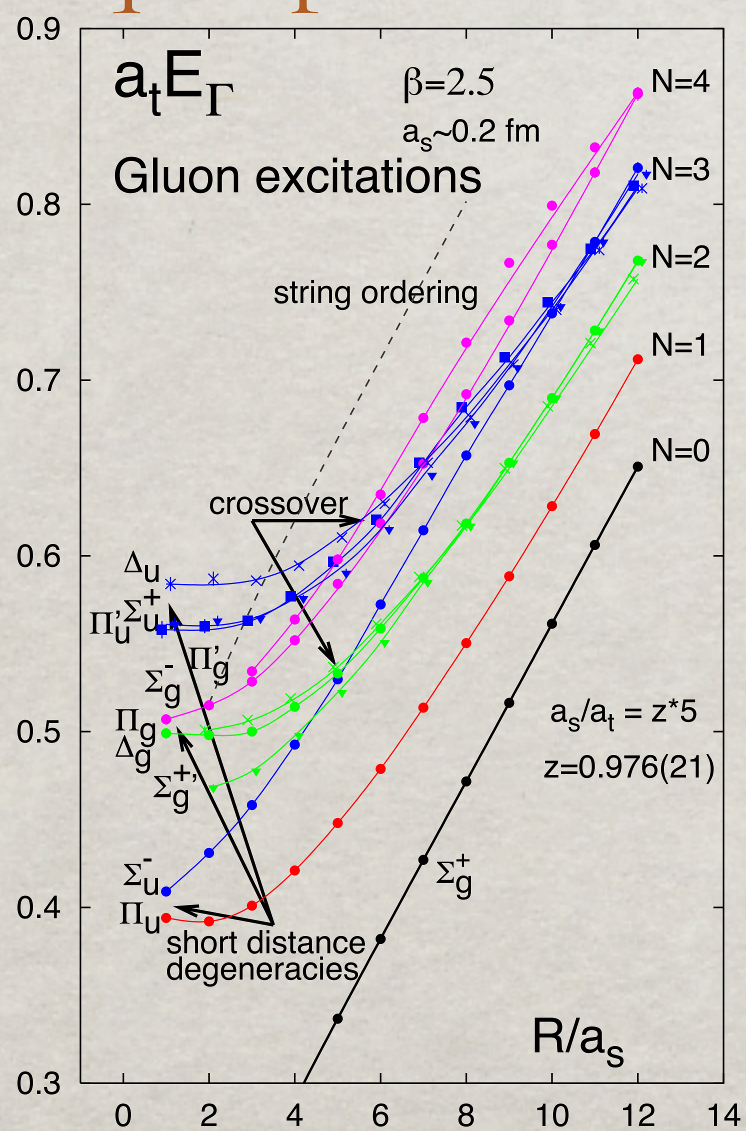


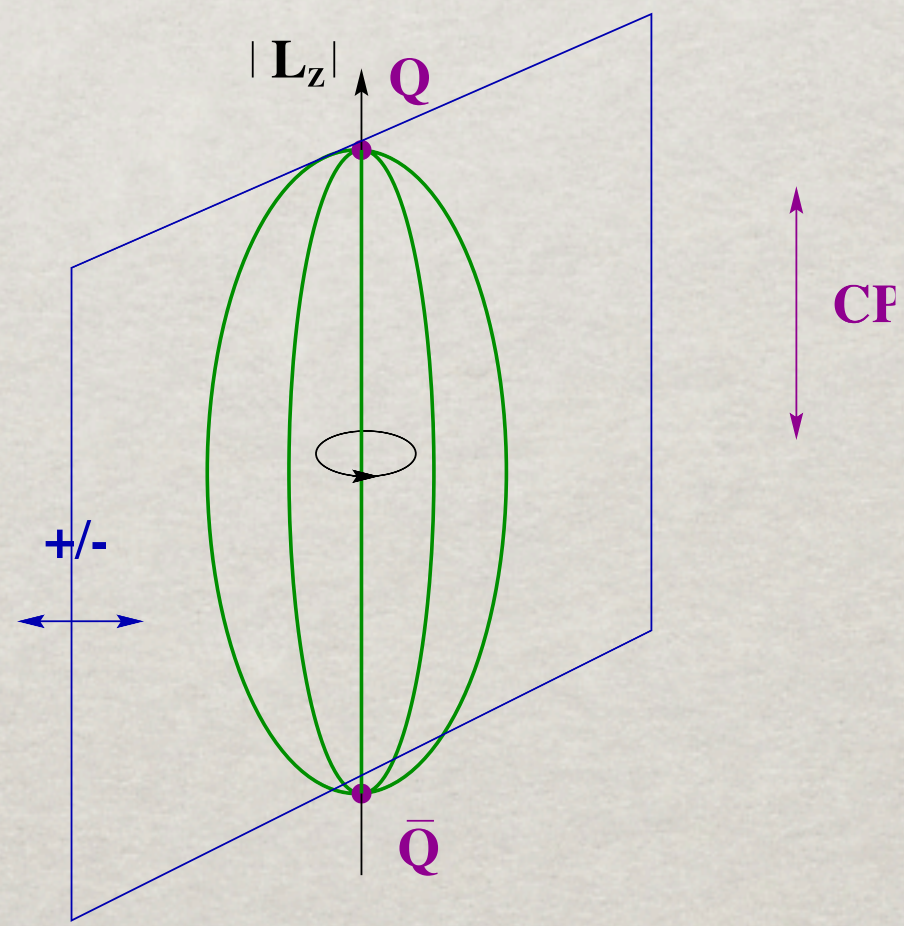
$(Q\bar{Q})_8 G$

hybrid

Static qcd spectrum

L
a
t
t
i
c
e





Symmetries of a diatomic molecule + C.C.

a) $|L_z| = 0, 1, 2, \ldots$
$= \Sigma, \Pi, \Delta \ldots$

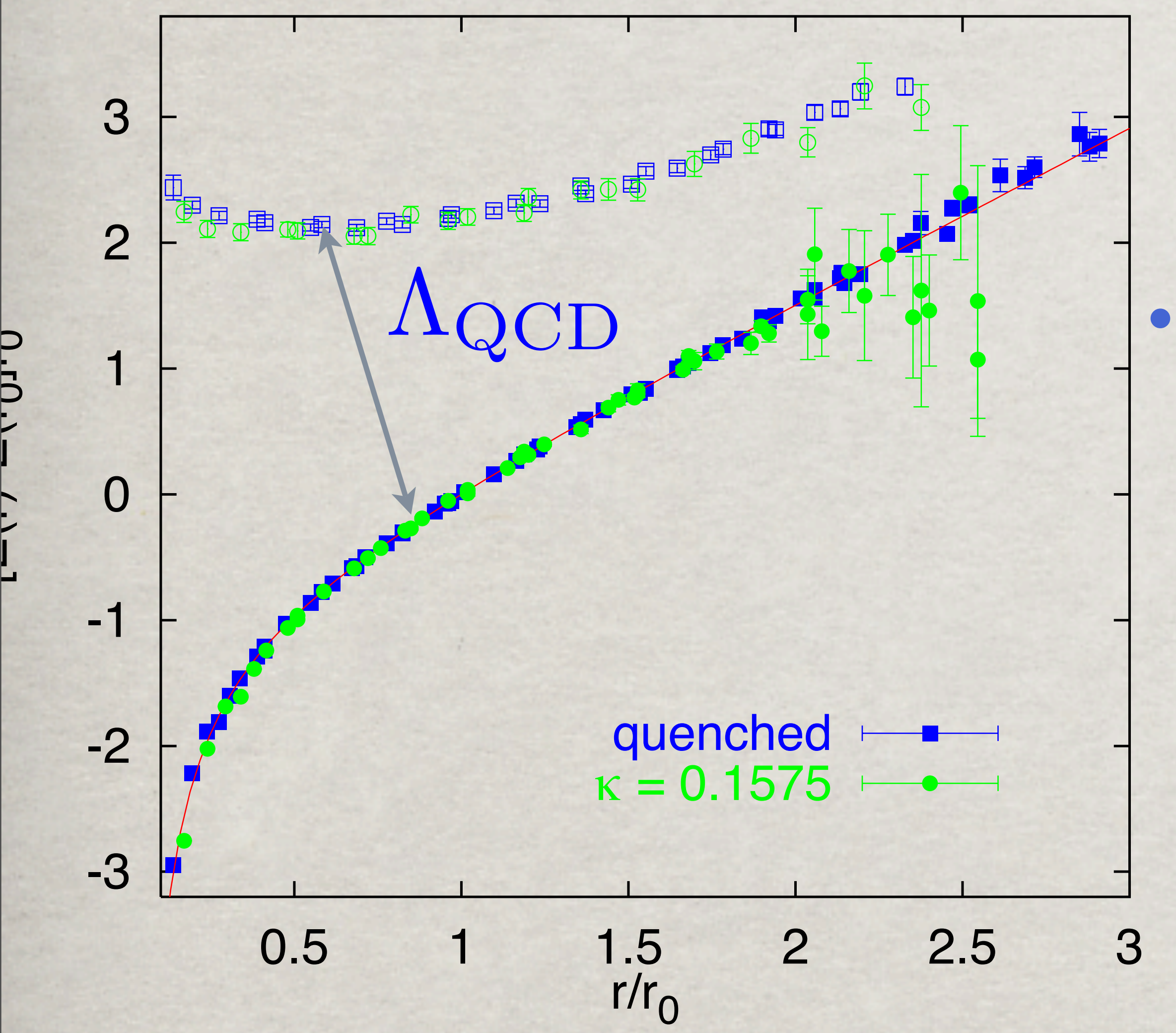
b) CP (u/g)

c) Reflection $(+/-)$
(for Σ only)

Juge Kuti Mornigstar 98-06 Static NRQCD

Quarkonium develops a gap to hybrids

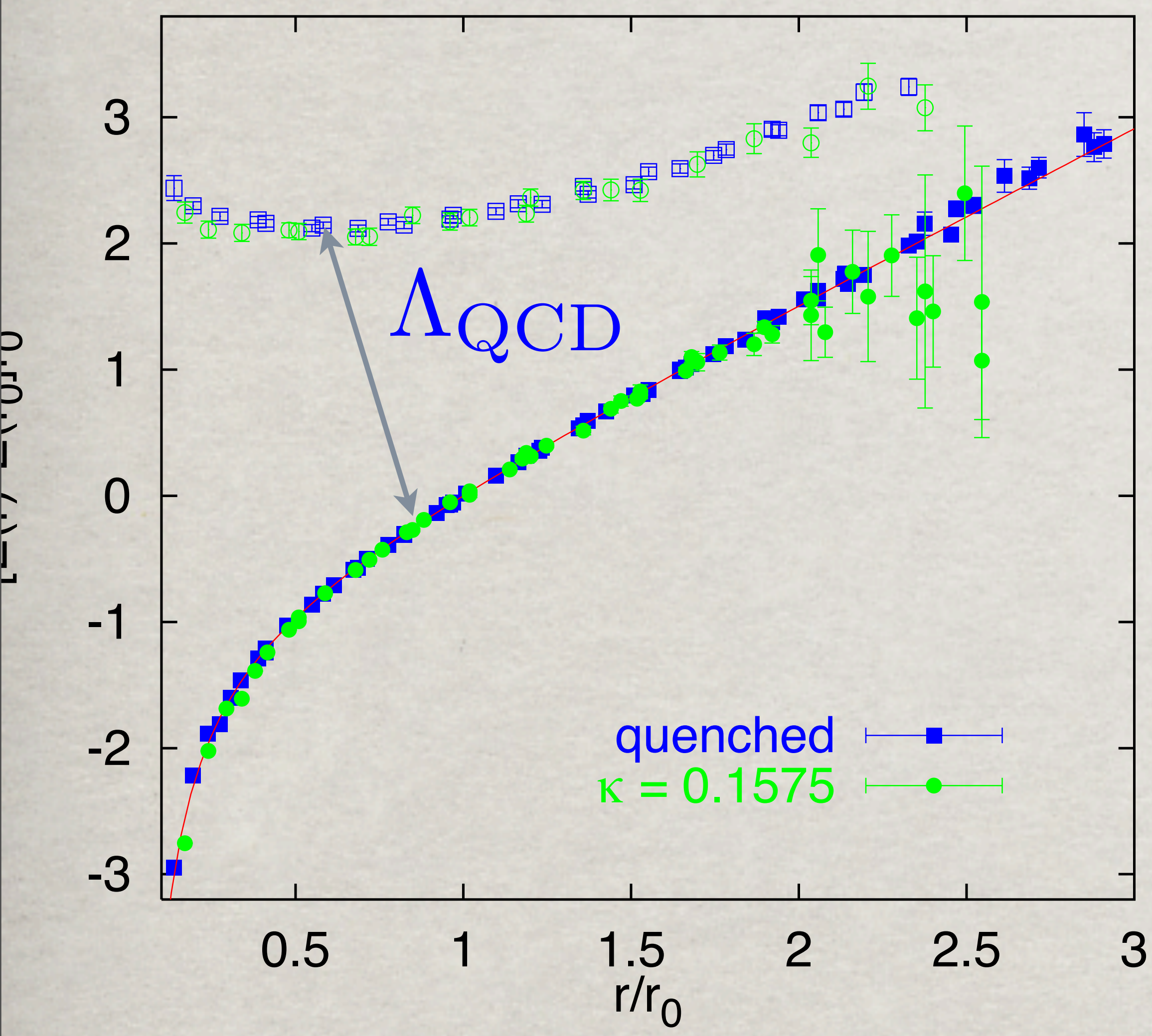
Bali et al. 98



- $mv \sim \Lambda_{QCD}$
- integrate out all scales above mv^2
- gluonic excitations develop a gap $\Lambda_{\rm QCD}$ and are integrated out

Quarkonium develops a gap to hybrids

Bali et al. 98



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$\Rightarrow$ The singlet quarkonium field S of energy mv^2 is the only the degree of freedom of pNRQCD (up to ultrasoft light quarks, e.g. pions).

strongly coupled pNRQCD $r \sim \Lambda_{QCD}^{-1}$

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$$\mathcal{L} = \mathrm{Tr}\left\{ \mathrm{S}^\dagger \left(i\partial_0 - \frac{\mathbf{p}^2}{m} - V_s \right) \mathrm{S} \right\}$$

Brambilla Pineda Soto Vairo 00

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Brambilla Pineda Soto Vairo 00

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Brambilla Pineda Soto Vairo 00

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- The potentials $V = \mathrm{Re}V + ImV$ from QCD in the matching:
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Brambilla Pineda Soto Vairo 00

- A potential description emerges from the EFT
- The potentials $V = \mathrm{Re}V + ImV$ from QCD in the matching: get spectra and decays
- V to be calculated on the lattice or in QCD vacuum models

Quarkonium singlet static potential

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

Quarkonium singlet static potential

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$$V_s^{(0)} = \lim_{T\to\infty} \frac{i}{T} \ln\langle W(r \times T)\rangle = \lim_{T\to\infty} \frac{i}{T} \ln \left\langle \boxed{} \right\rangle$$

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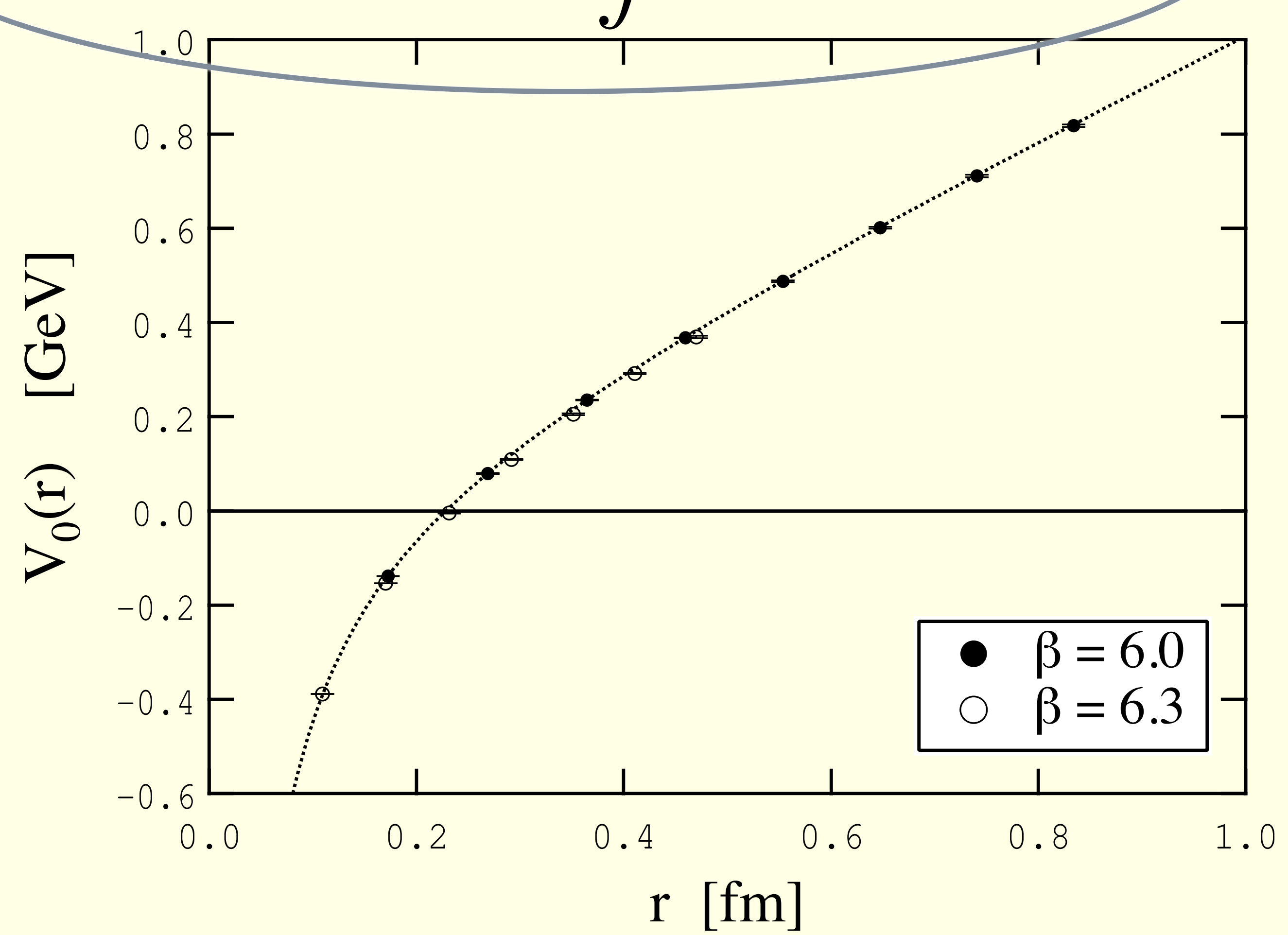
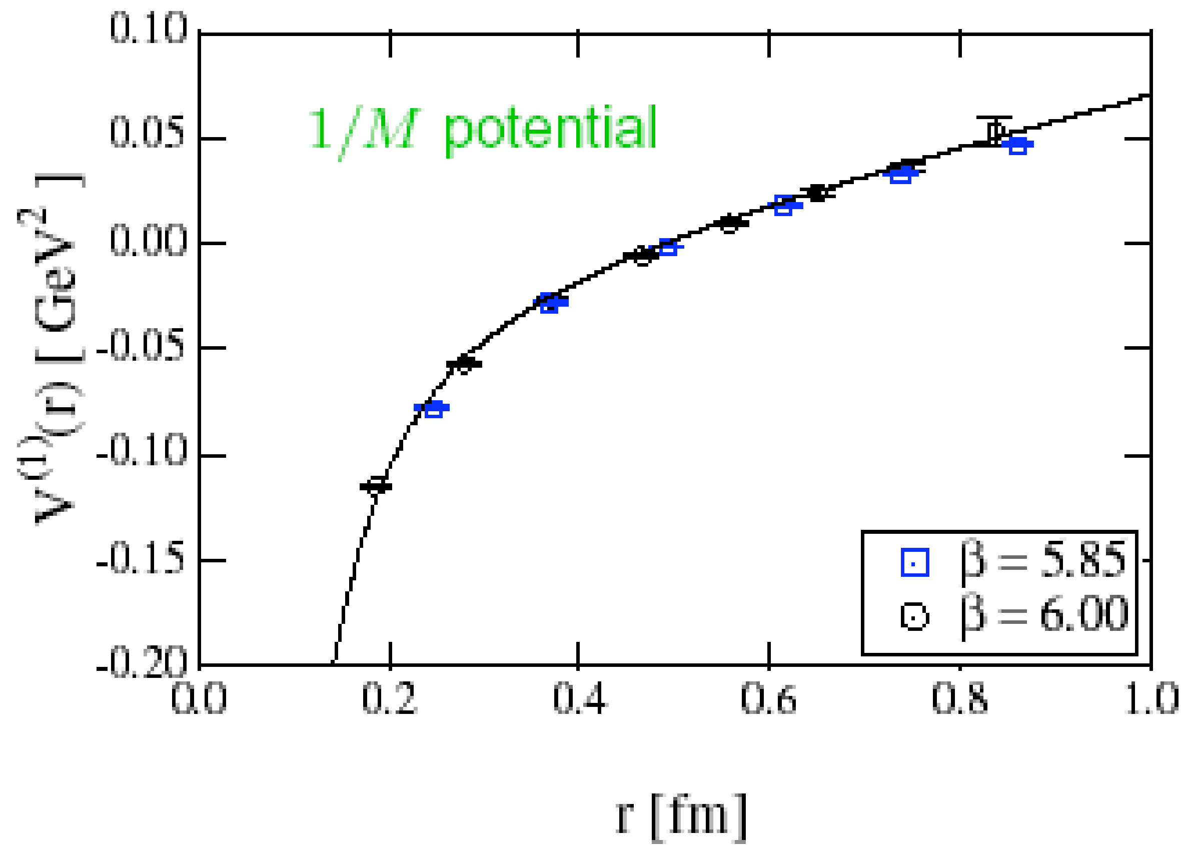


○ Koma Koma NPB 769(07)79

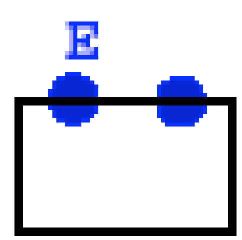
Quarkonium singlet static potential

Potentials are given in a factorized form as product of NRQCD matching coefficients and low energy terms. These are gauge invariant wilson loop with electric and magnetic insertions



∘ Koma Koma Wittig PoS LAT2007(07)111

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



Brambilla et al 00

QCD Spin dependent potentials

$$V_{\rm SD}^{(2)} = \frac{1}{r}\left(c_F \epsilon^{kij}\,\frac{2r^k}{r} i \int_0^\infty dt\, t\, \left\langle \overset{E}{\underset{B}{\boxed{\;i\quad j\;}}} \right\rangle - \frac{1}{2} V_s^{(0)\prime} \right) (\mathbf{S}_1 + \mathbf{S}_2)\cdot \mathbf{L}$$

$$- {c_F}^2 \hat{r}_i \hat{r}_j i \int_0^\infty dt \left(\left\langle \boxed{\;i\quad j\;} \right\rangle - \frac{\delta_{ij}}{3} \left\langle \boxed{\quad\quad} \right\rangle \right)$$

$$\times \left(\mathbf{S}_1 \cdot \mathbf{S}_2 - 3(\mathbf{S}_1 \cdot \hat{\mathbf{r}})(\mathbf{S}_2 \cdot \hat{\mathbf{r}}) \right)$$

$$+ \left(\frac{2}{3} {c_F}^2 i \int_0^\infty dt \left\langle \boxed{\quad\quad} \right\rangle - 4(d_2 + C_F d_4)\delta^{(3)}(\mathbf{r}) \right) \mathbf{S}_1 \cdot \mathbf{S}_2$$

Eichten Feinberg 81, Gromes 84, Chen et al. 95 Brambilla Vairo 99

QCD Spin dependent potentials

$$V_{\rm SD}^{(2)} = \frac{1}{r}\left(c_F \epsilon^{kij}\,\frac{2r^k}{r} i \int_0^\infty dt\, t\, \left\langle \overset{E}{\underset{B}{\boxed{i \quad j}}} \right\rangle - \frac{1}{2} V_s^{(0)\prime} \right)(\mathbf{S}_1 + \mathbf{S}_2)\cdot \mathbf{L}$$

$$- {c_F}^2 \hat{r}_i \hat{r}_j i \int_0^\infty dt \left(\left\langle \boxed{i \quad j} \right\rangle - \frac{\delta_{ij}}{3} \left\langle \boxed{} \right\rangle \right)$$

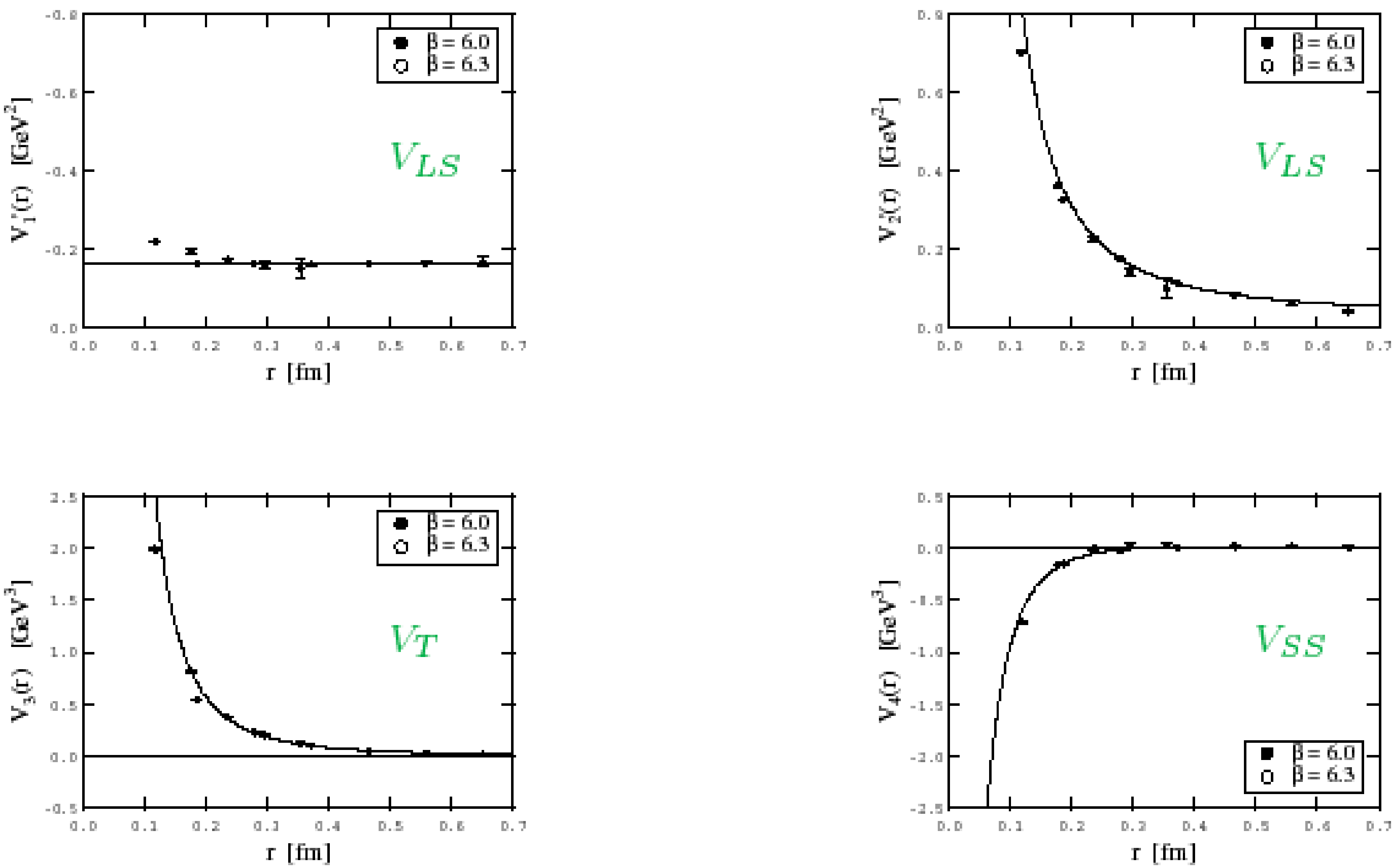
$$\times \left(\mathbf{S}_1 \cdot \mathbf{S}_2 - 3(\mathbf{S}_1 \cdot \hat{\mathbf{r}})(\mathbf{S}_2 \cdot \hat{\mathbf{r}}) \right)$$

$$+ \left(\frac{2}{3} {c_F}^2 i \int_0^\infty dt \left\langle \boxed{} \right\rangle - 4(d_2 + C_F d_4)\delta^{(3)}(\mathbf{r}) \right) \mathbf{S}_1 \cdot \mathbf{S}_2$$

Eichten Feinberg 81, Gromes 84, Chen et al. 95 Brambilla Vairo 99

-factorization; power counting; QM divergences absorbed by NRQCD matching coefficients

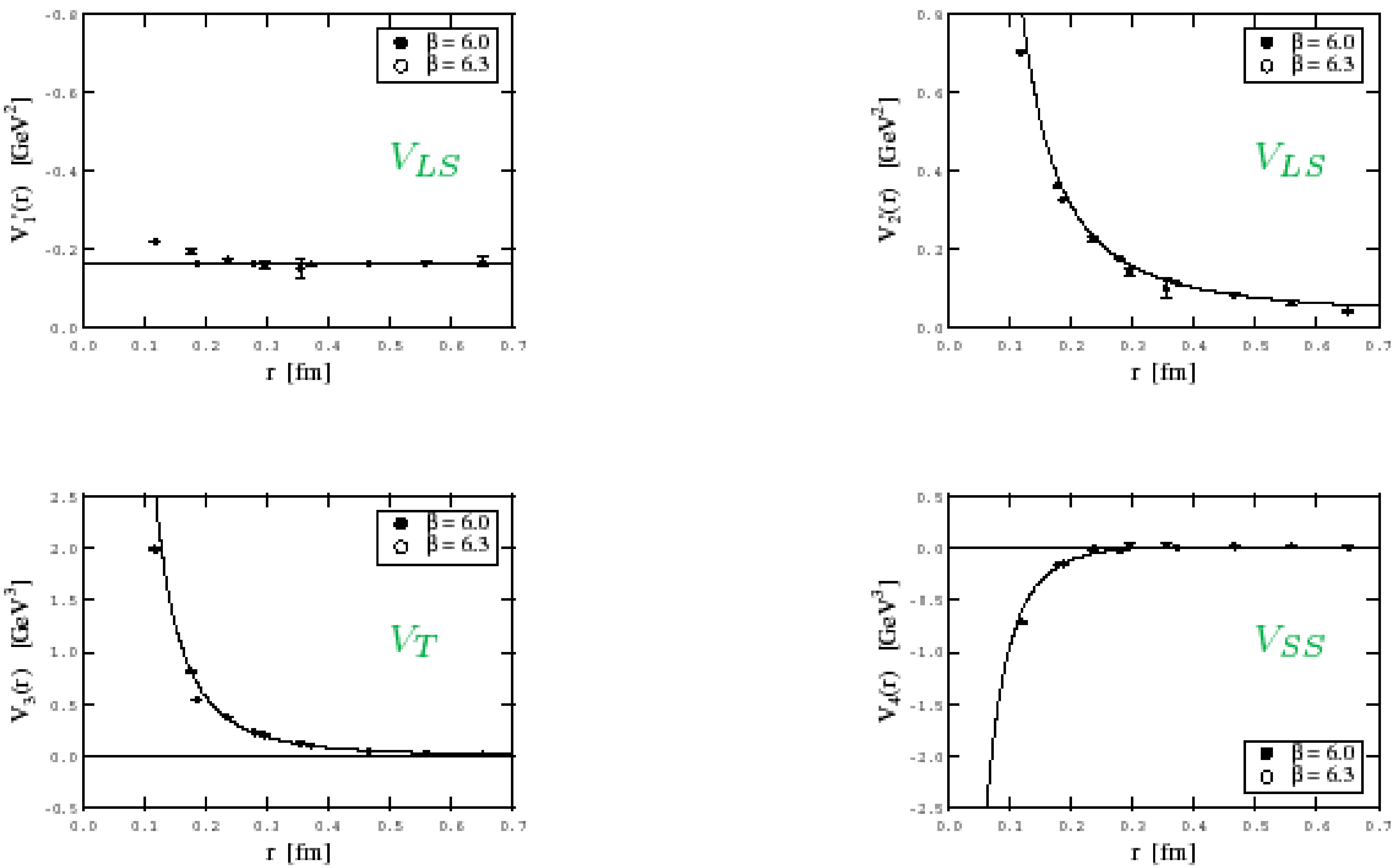
Spin dependent potentials



Koma Koma Wittig 05, Koma Koma 06

Terrific advance in the data precision with Lüscher multivel algorithm!

Spin dependent potentials



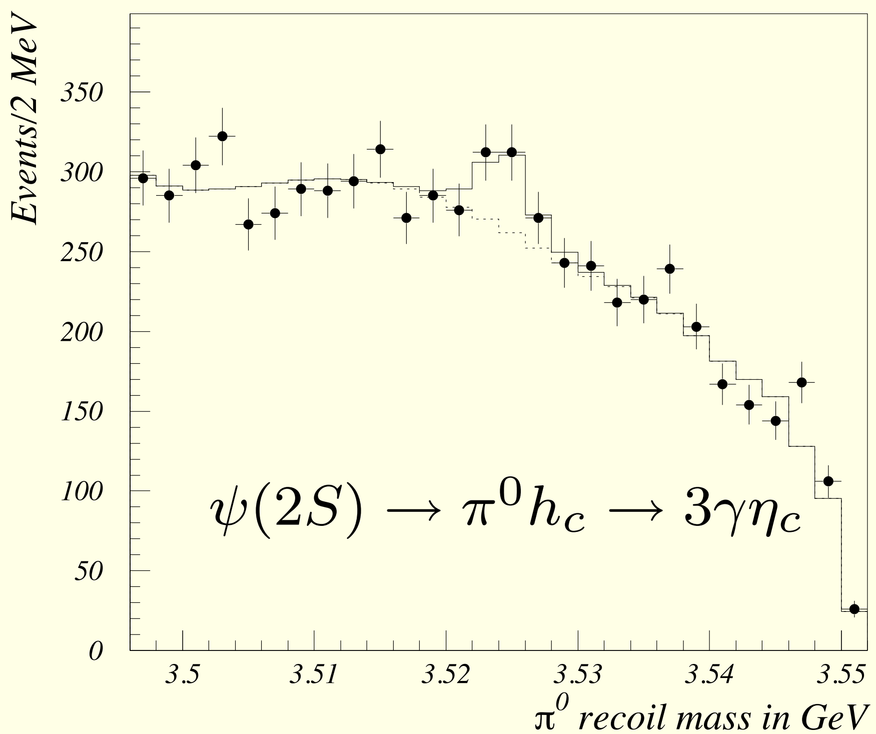
Koma Koma Wittig 05, Koma Koma 06

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

$$h_c, h_b$$



$M_{h_c} = 3524.4 \pm 0.6 \pm 0.4$ MeV ○ CLEO PRL 95 (2005) 102003

$M_{h_c} = 3525.8 \pm 0.2 \pm 0.2$ MeV, $\Gamma < 1$ MeV ○ E835 PRD 72 (2005) 032001

$M_{h_c} = 3525.40 \pm 0.13 \pm 0.18$ MeV, $\Gamma < 1.44$ MeV ○ BES PRL 104 (2010) 132002

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

- Also

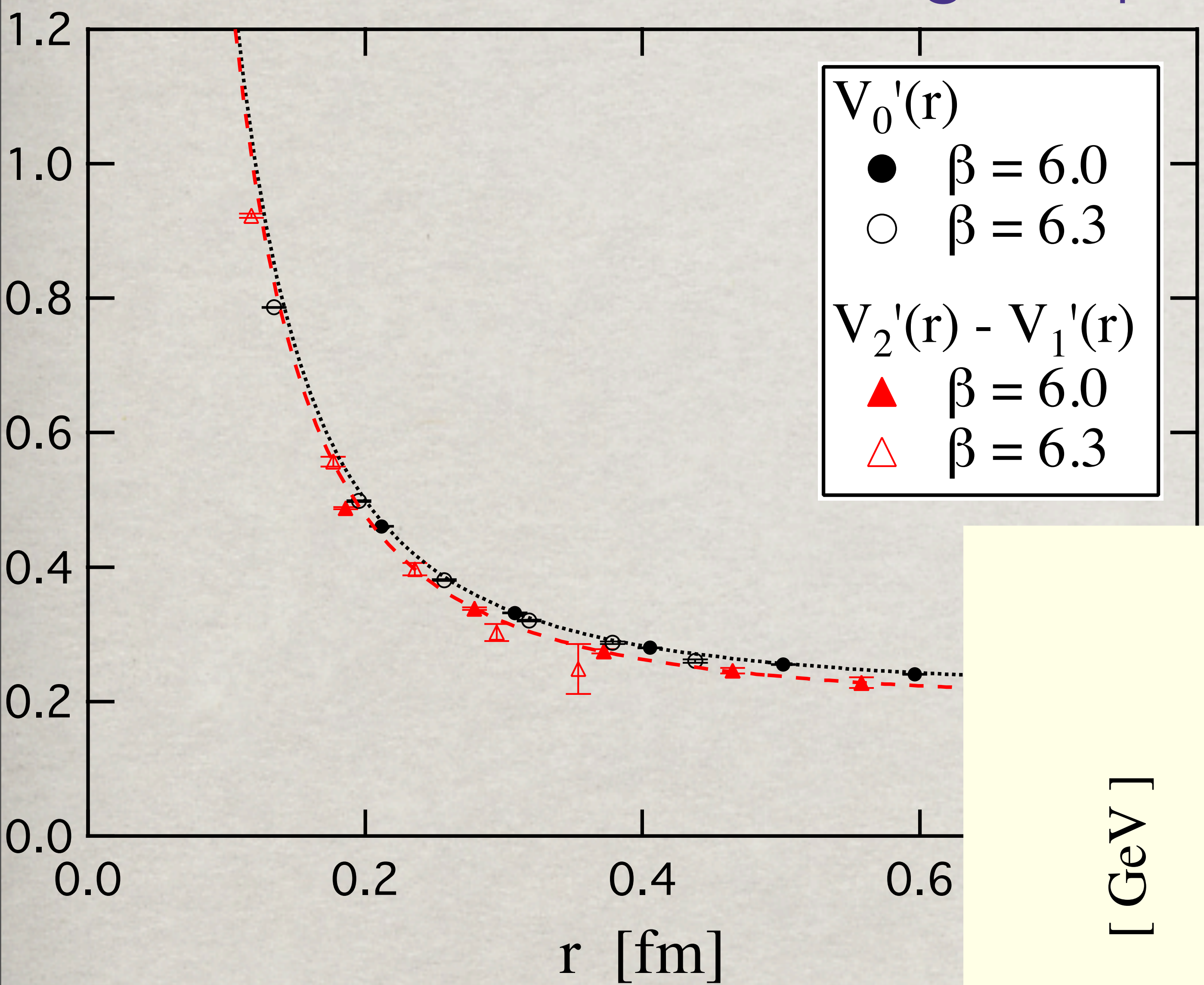
$M_{h_b} = 9902 \pm 4 \pm 1$ MeV ○ BABAR arXiv:1102.4565

To be compared with $M_{\rm c.o.g.}(1P) = 9899.87 \pm 0.28 \pm 0.31$ MeV.

Exact relations from Poincare' invariance

The EFT is still Poincare' invariant-> this induces relations among the potentials

Koma and Koma 2006

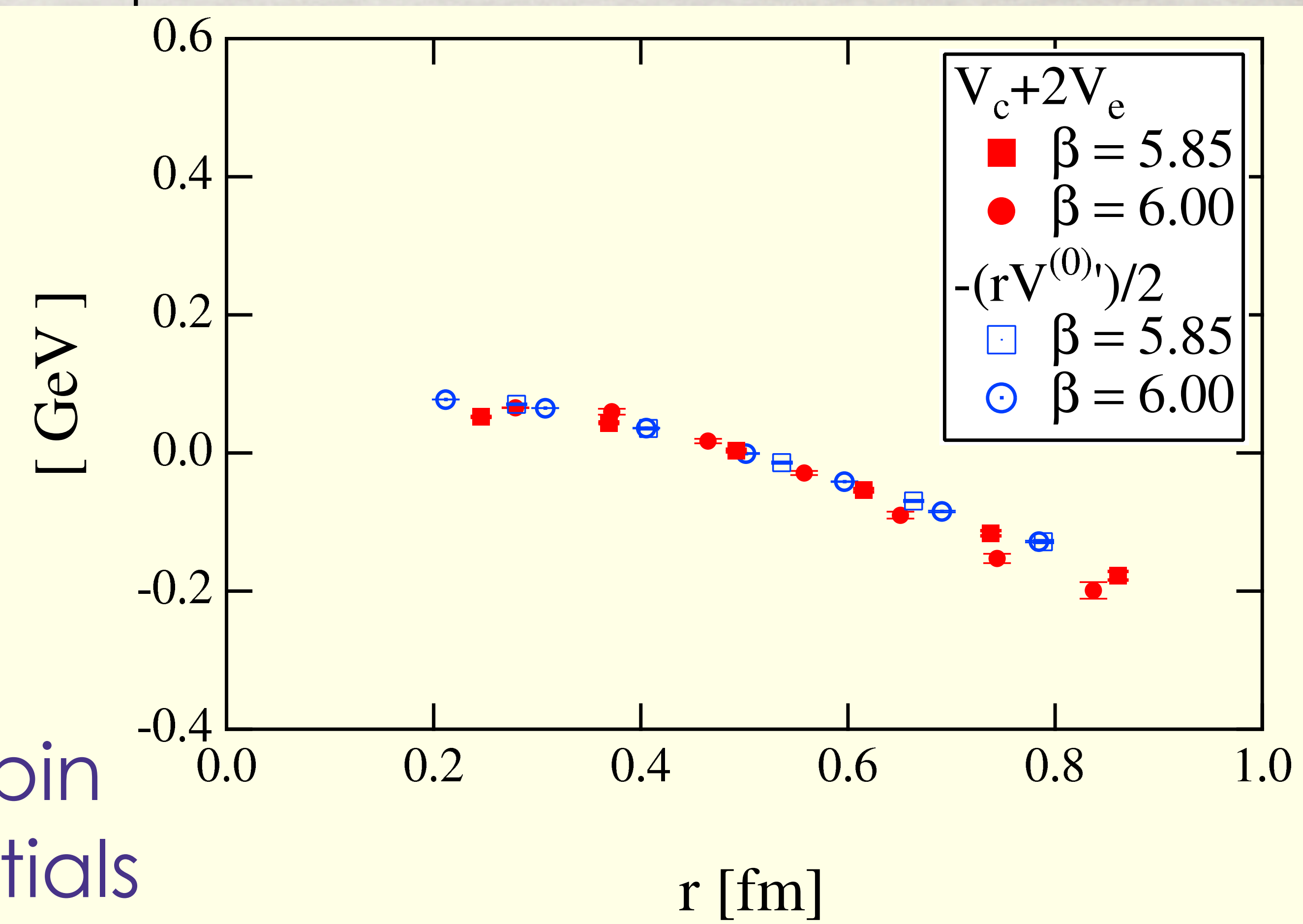


e. g. $$V_0'(r) = V_2'(r) - V_1'(r)$$

Gromes relation

It is a check of the lattice calculation

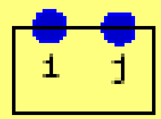
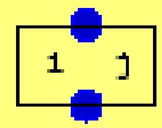
many other relations among potentials in the EFT

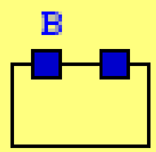


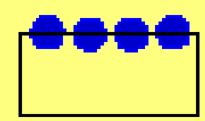
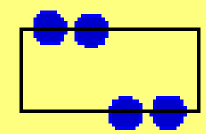
Koma Koma Wittig PoS LAT2007 (2007) 111

relations involving spin independent potentials

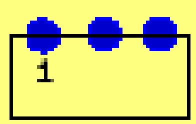
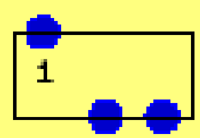
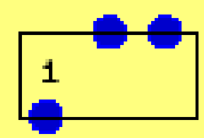
QCD Spin independent potentials

$V_{\rm SI}^{(2)} = p^i \Big(i \int_0^\infty dt\, t^2 \, \langle$  $\rangle + \langle$  $\rangle \Big) p^j$

$- \frac{c_F^2}{2} i \int_0^\infty dt \langle$  $\rangle + (d_1 + C_F d_3 + \pi C_F \alpha_{\rm s} c_D)\delta^{(3)}(\mathbf{r})$

$- i \int_0^\infty dt_1 \int_0^{t_1} dt_2 \int_0^{t_2} dt_3 (t_2 - t_3)^2 \Big(\langle$  $\rangle + \langle$  $\rangle \Big)$

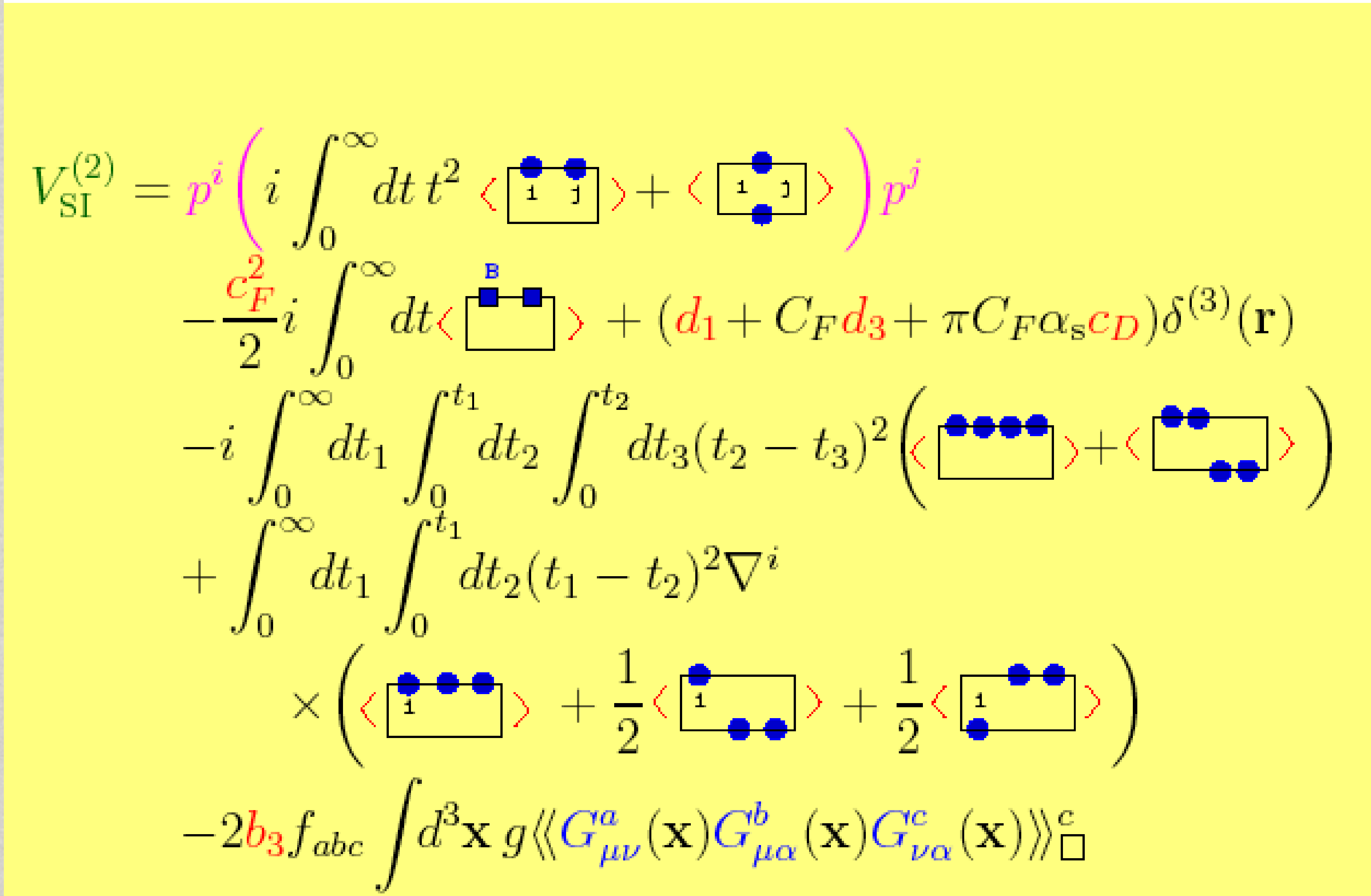
$+ \int_0^\infty dt_1 \int_0^{t_1} dt_2 (t_1 - t_2)^2 \nabla^i$

$\times \Big(\langle$  $\rangle + \frac{1}{2} \langle$  $\rangle + \frac{1}{2} \langle$  $\rangle \Big)$

$$-2 b_3 f_{abc} \int d^3\mathbf{x}\, g \langle\langle G^a_{\mu\nu}(\mathbf{x}) G^b_{\mu\alpha}(\mathbf{x}) G^c_{\nu\alpha}(\mathbf{x}) \rangle\rangle^c_\Box$$

Brambilla et al. 88 90, Pineda Vairo 00

QCD Spin independent potentials



$$V_{\rm SI}^{(2)} = p^i \left(i\int_0^\infty dt\, t^2 \langle\ \rangle + \langle\ \rangle \right) p^j$$
$$-\frac{c_F^2}{2} i \int_0^\infty dt \langle\ \rangle + (d_1 + C_F d_3 + \pi C_F \alpha_{\rm s} c_D)\delta^{(3)}(\mathbf{r})$$
$$-i\int_0^\infty dt_1 \int_0^{t_1} dt_2 \int_0^{t_2} dt_3 (t_2 - t_3)^2 \left(\langle\ \rangle + \langle\ \rangle \right)$$
$$+\int_0^\infty dt_1 \int_0^{t_1} dt_2 (t_1 - t_2)^2 \nabla^i$$
$$\times \left(\langle\ \rangle + \frac{1}{2}\langle\ \rangle + \frac{1}{2}\langle\ \rangle \right)$$
$$-2b_3 f_{abc} \int d^3\mathbf{x}\, g \langle\langle G^a_{\mu\nu}(\mathbf{x}) G^b_{\mu\alpha}(\mathbf{x}) G^c_{\nu\alpha}(\mathbf{x}) \rangle\rangle^c_\square$$

Brambilla et al. 88 90, Pineda Vairo 00

field strength insertions under calculation on the lattice
and in QCD vacuum models

The low energy physics is now factorized in Wilson loops: they can be calculated on the lattice, in QCD vacuum models, in string theory

they can be used to probe the confinement mechanism

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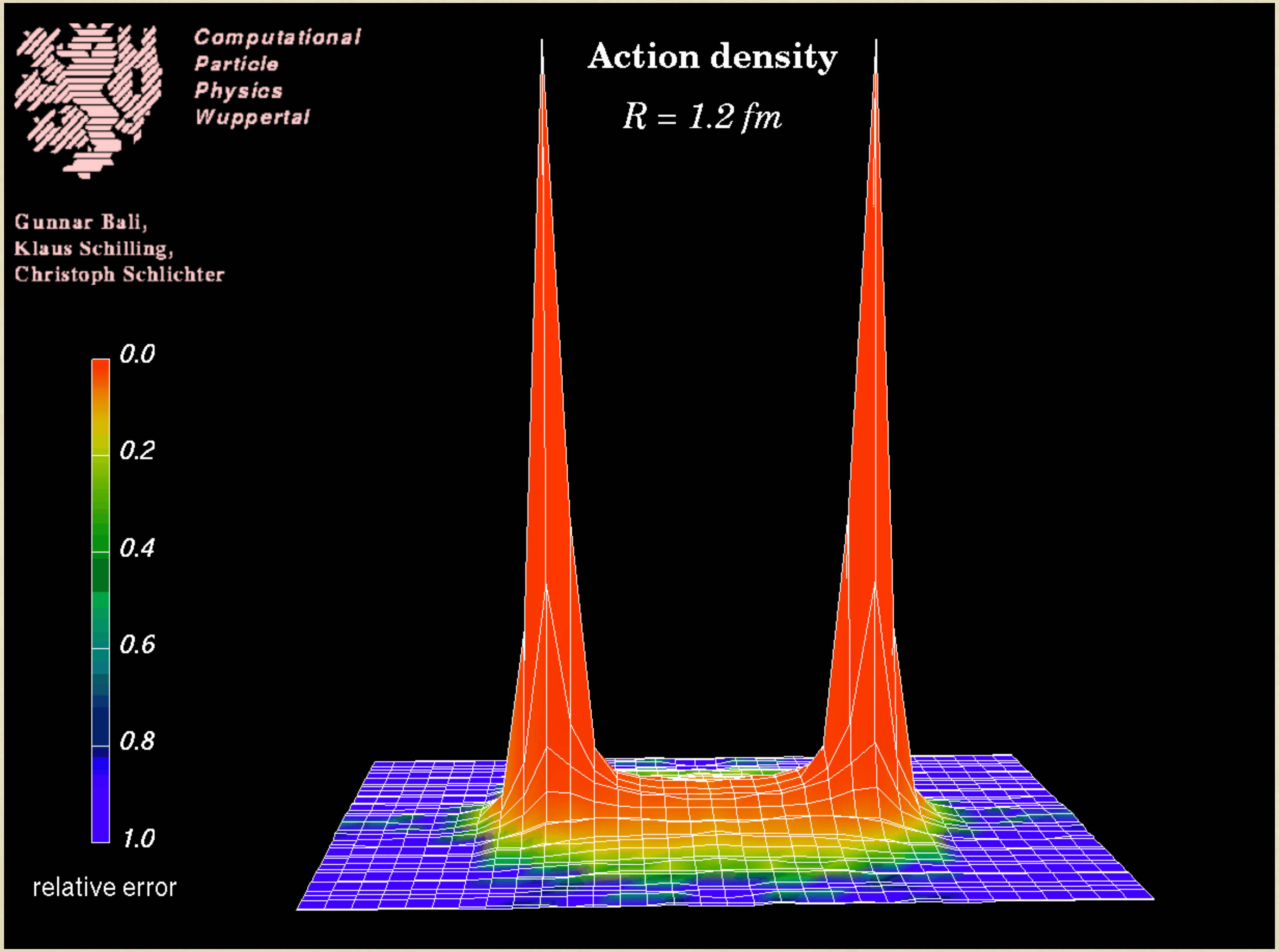

chromoelectric flux tube formation between the static quark-antiquark pair-> dual Meissner effect

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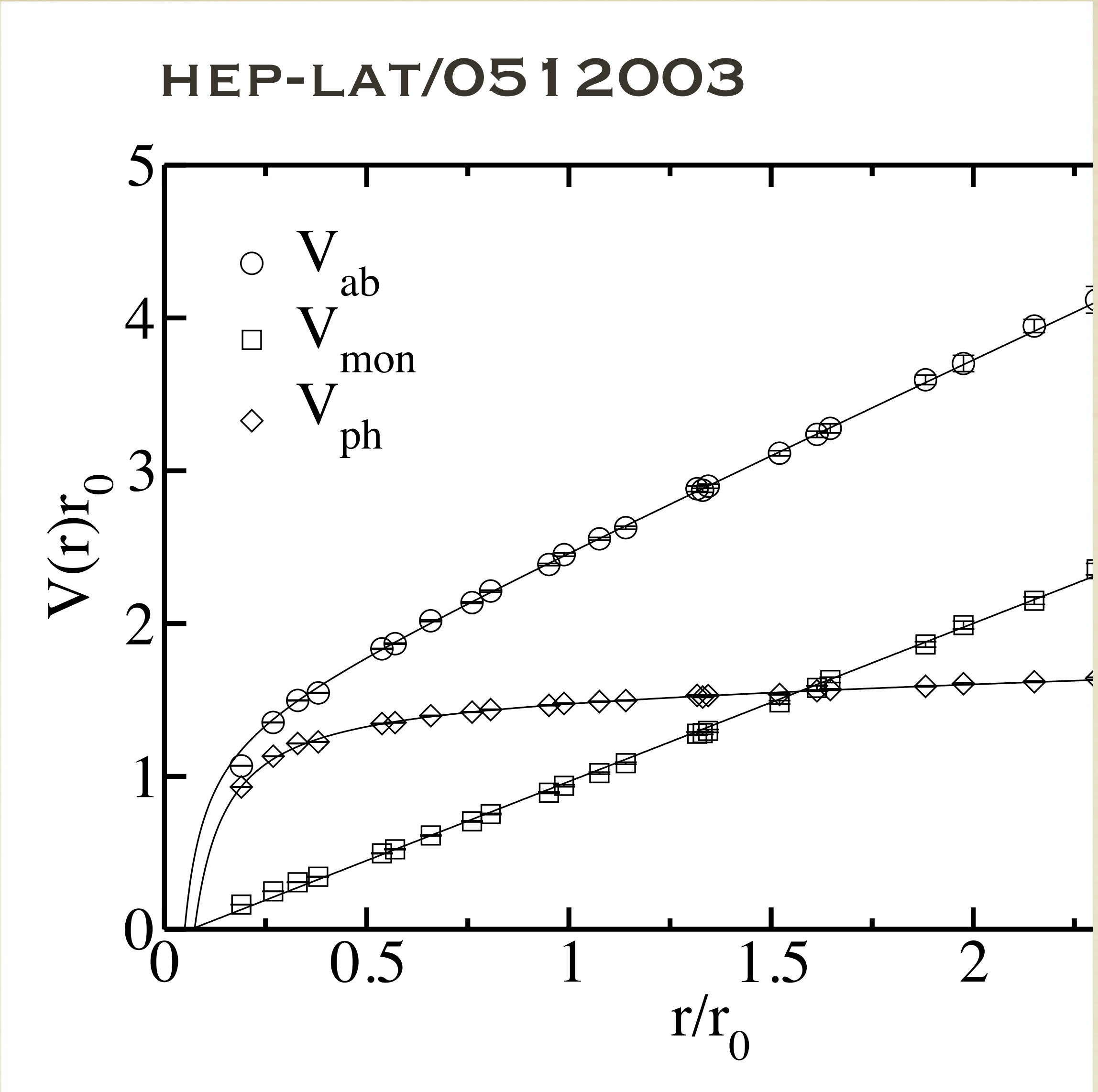
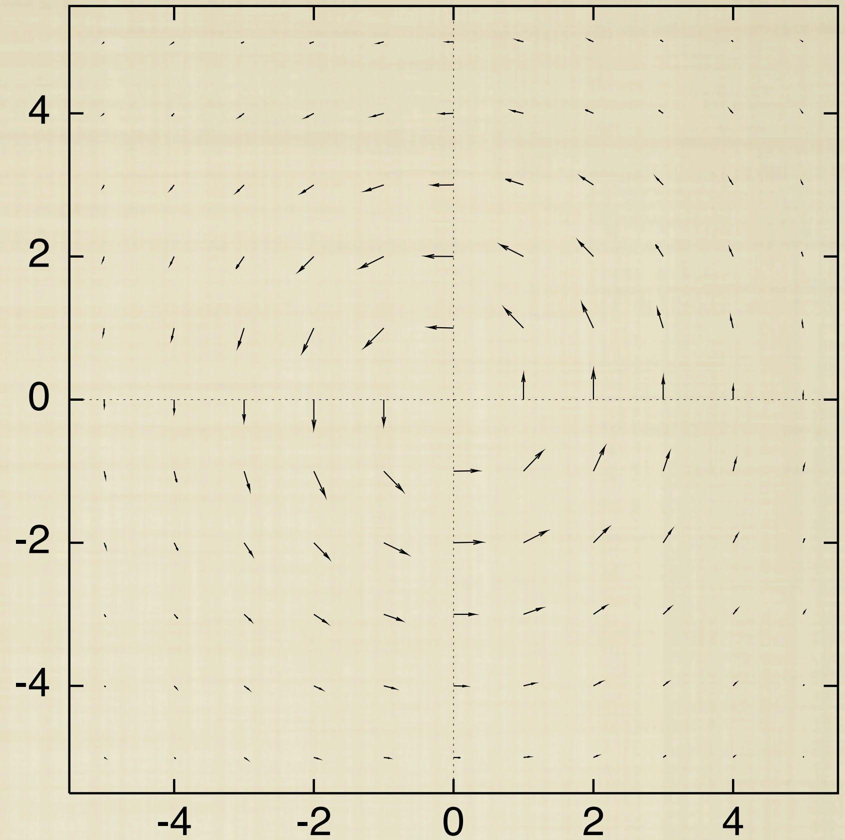
many lattice investigations by Polikarpov and collaborators



Static potential in maximal abelian projection: “photon” and monopole parts



monopole currents winding around the flux tube, studies of monopole condensation

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Abelian projections and monopoles
M.N. Chernodub, M.I. Polikarpov (Moscow, ITEP). Jun 1997. 34 pp.
Published in **In *Cambridge 1997, Confinement, duality, and nonperturbative aspects of QCD* 387-414**

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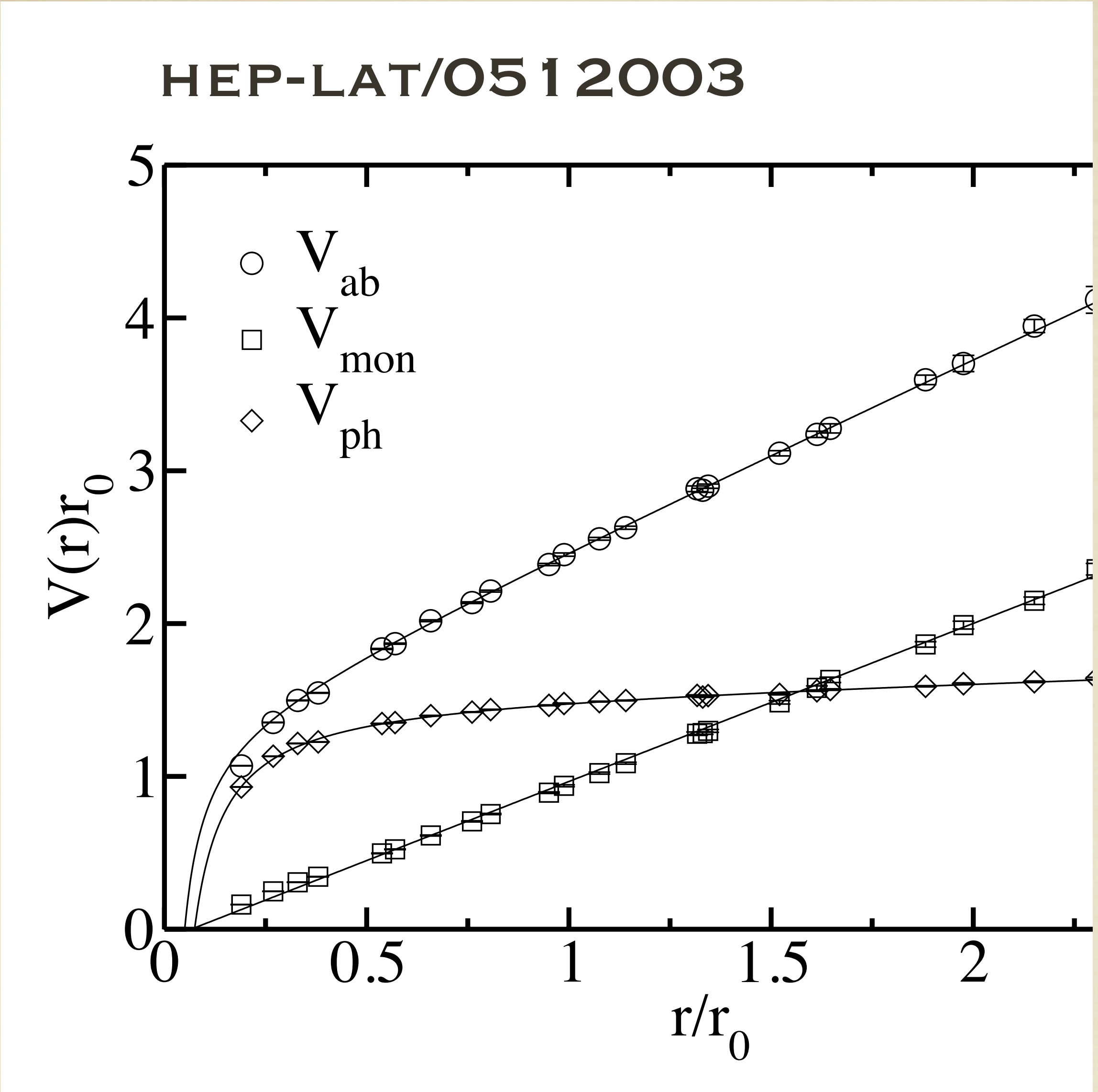

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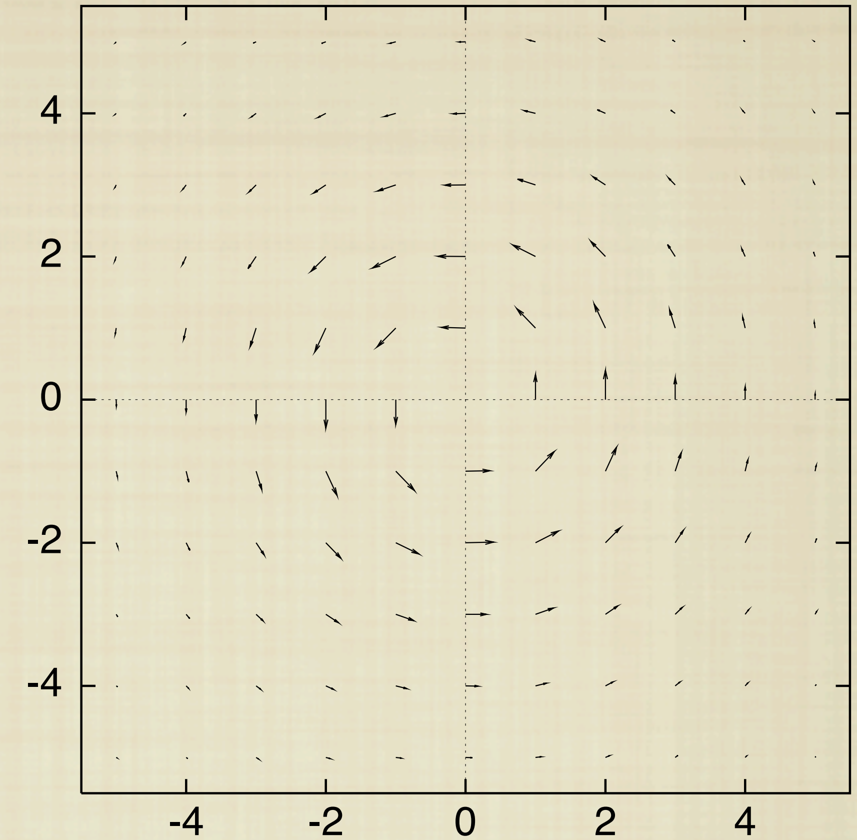

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uncountable important contributions by Polikarpov and his group to the understanding of the confinement mechanism

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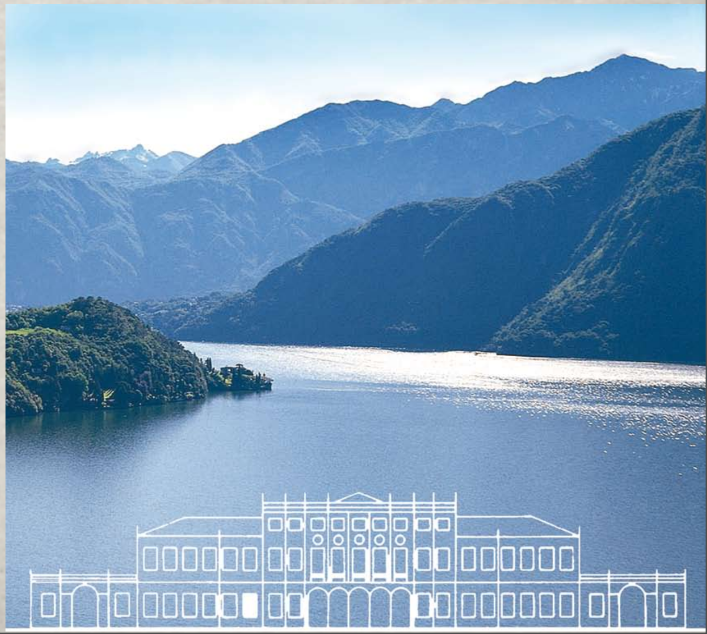
QUARK CONFINEMENT AND THE HADRON SPECTRUM I

Como 1994



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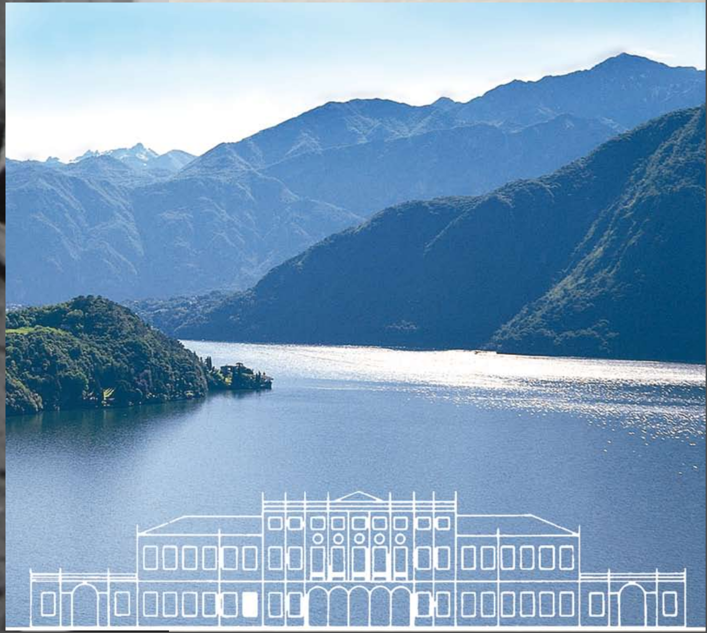

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Madrid (Spain) 2010

Mainz (Germany) 2008

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X$_{th}$ Quark Confinement and the Hadron Spectrum

7-12 October 2012 *TUM Department of Physics*
Europe/Berlin timezone

about 400 participants

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Section A: *Vacuum Structure and Confinement*

Conveners: M. Faber (TU Vienna), M. Polikarpov (ITEP, Moscow)

Section B: *Light Quarks*

Conveners: R. Alkofer (Univerität Graz), B. Ketzer (TU München), J. Goity (JLAB, Newport News), H. Sazdjian (IPN Orsay), H. Wittig (JGU Mai

Section C: *Heavy Quarks*

Conveners: G. Bodwin (Argonne National Lab), P. Pakhlov (ITEP, Moscow), J. Soto (University of Barcelona), A. Vairo (TU München)

Section D: *Deconfinement*

Conveners: P. Arnold (Univerity of Virginia), Y. Foka (GSI, Darmstadt), H. Meyer (JGU Mainz), J. Rafelski (University of Arizona)

Section E: *QCD and New Physics*

Conveners: S. Gardner (University of Kentucky), H. W. Lin (University of Washington), F. Llanes Estrada (UC Madrid), M. Snow (Indiana Univers

Section F: *Nuclear and Astroparticle Physics*

Conveners: M. Alford (Washington University in St. Louis), T. Cohen (University of Maryland), L. Fabbietti (TU München), A. Schmitt (TU Vienna

Section G: *Strongly Coupled Theories*

Conveners: J. Erdmenger (MPP Munich), E. Katz (Boston University), E. Pallante (University of Groningen), A. Szczepaniak (Indiana University

Two projects came out in collaboration with Misha

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organized by

Vladimir Andrianov
Gennady Kozlov,
Vladimir Shevchenko,
Nora Brambilla

dedicated to
Misha
Polikarpov

QCD driven Strongly Coupled Physics:challenges, scenarios and perspectives

N. Brambilla[*†,1] S. Eidelman[†,2] P. Foka[†‡,3] S. Gardner[†‡,4] A. S. Kronfeld[†,5] M.G. Alford[‡,6] R. Alkofer[‡,7] M. Butenschoen[‡,8] T.D. Cohen[‡,9] J. Erdmenger[‡,10] M. Faber[‡,11] L. Fabbietti[‡,12] J. L. Goity[‡,13] B. Ketzer[‡,14] H.W. Lin[‡,15] F. J. Llanes-Estrada[‡,16] H. Meyer[‡,17] E. Pallante[‡,18] P. Pakhlov[‡,19,20] M. I. Polikarpov[‡,21,22] H. Sazdjian[‡,23] A. Schmitt[‡,24] W. Michael Snow[‡,25] A. Vairo[‡,1] A. Vuorinen[‡,26] P. Arnold,[27] P. Christakoglou,[28] Z. Fodor,[29,30,31] R. Höllwieser,[11] D. Keane,[32] E. Kiritsis,[33] M. Laine,[3] R. Mizuk,[19,20] G. Odyniec,[34] A. Pich,[35] J.-W. Qiu,[36,37] G. Ricciardi,[38,39] K. Schwenzer,[6] X. Garcia. i Tormo,[40] G. M. v. Hippel,[41] and V. I . Zakharov[42,43]

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Vacuum Structure and Confinement; Heavy Quarks, Light Quarks; Deconfinement and QGP; Searching new Physics with Precision Experiments; Nuclear physics and dense QCD in colliders and compact stars; Strongly coupled theories and Conformal Symmetry

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Misha Polikarpov

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Conclusions

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 static energies 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

These theory tools can match some of the intense experimental progress of the last few years and of the near future

In this direction go the list of 65 priorities given at the end of the QWG (Quarkonium Working Group) doc

arXiv:1010.5827

Selected Outlook for future research

Alice, Rhic

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

Spectra/decays of quarkonia

Belle,BESIII, Panda, LHC exps

EFT for states close to thresholds: X, Y, Z

Belle,BESIII, Panda, LHC-b

Quarkonium-quarkonium van der Waals interaction; quarkonium on nuclei Fair

Quarkonium production

CMS, Atlas, Alice, LHC-b

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quarkonium on nuclei

CMS, Atlas, Alice, LHC-b

Quarkonium production

Invaluable effect of Spin-off of hadronic physics to other fields:

An example among many: EFTs developed at finite T and for heavy masses used in cosmology: calculation of thermal production of dark matter

Institute: "Jets, particle production and transport properties in collider and cosmological environments", MITP Mainz 2014

BACKUP

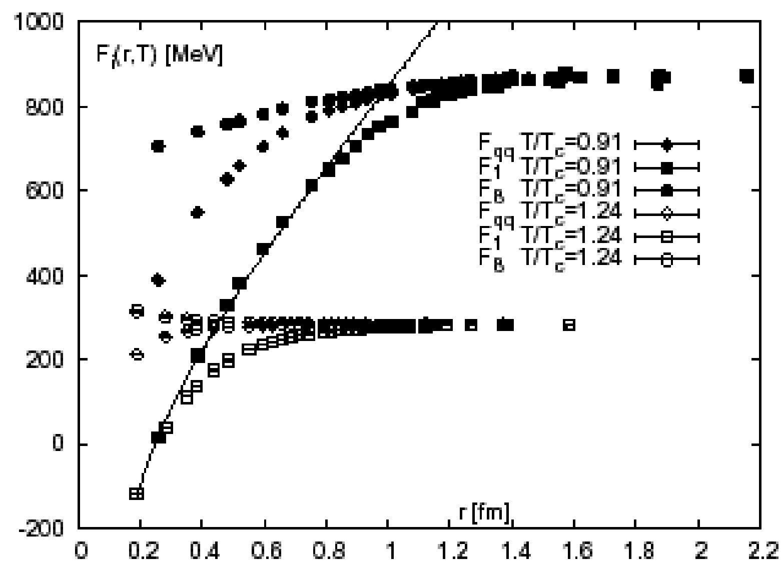
Heating quarkonium systems

$$T > 0$$

Quarkonium in a hot medium: the interaction potential

Free energy vs potential

- Either phenomenological potentials have been used so far or the free energy calculated on the lattice.
- The free energy is not the static potential: the average free energy ($\sim \langle \mathrm{Tr}\, L^\dagger(r) \mathrm{Tr}\, L(0) \rangle$) is an overlap of singlet and octet quark-antiquark states, what is called the singlet ($\sim \langle \mathrm{Tr}\, L^\dagger(r)\, L(0) \rangle$) and the octet ($\sim \langle \mathrm{Tr}\, L^\dagger(r) \mathrm{Tr}\, L(0) \rangle$ $-1/3\, \langle \mathrm{Tr}\, L^\dagger(r)\, L(0) \rangle$) free energy are gauge dependent;



- Kaczmarek Zantow PRD 71 (2005) 114510

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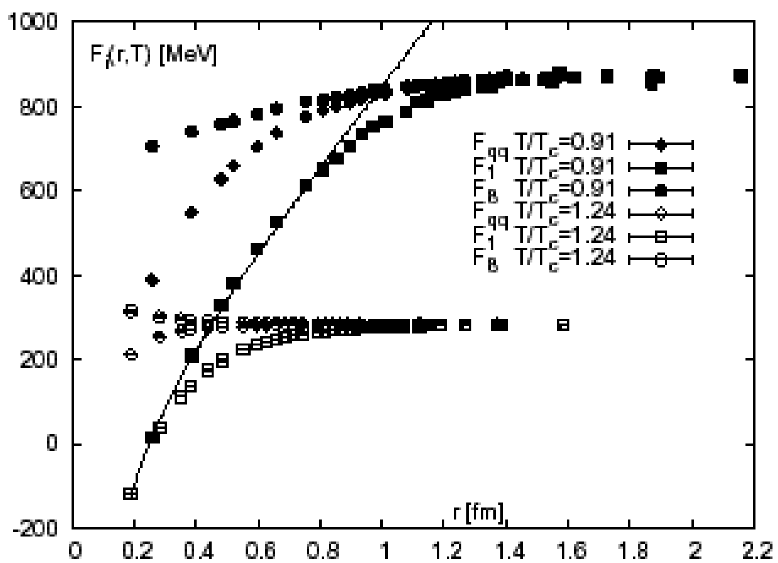
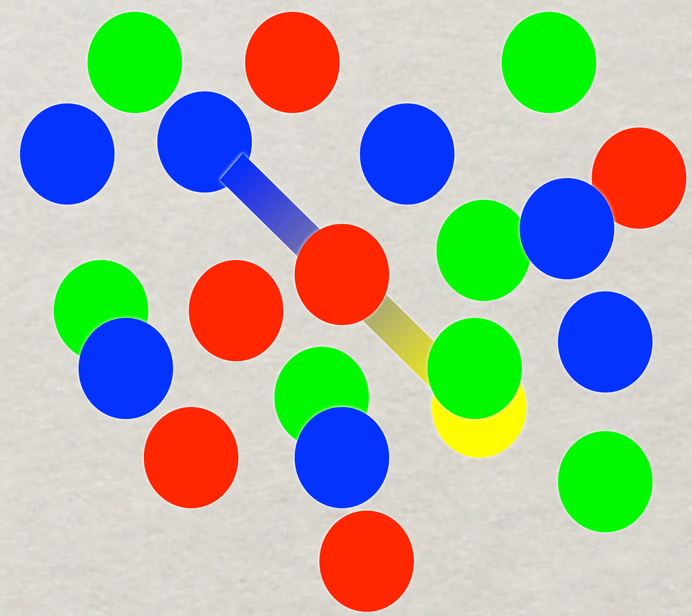


Kaczmarek Zantow PRD 71 (2005) 114510

It was believed that the color screening of the potential originates quarkonium dissociation

Matsui Satz 86



Debye charge screening (electromagnetic plasma)

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

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

But, at finite temperature what is the quarkonium potential?

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The potential $V(r,T)$ dictates throught the Schroedinger equation the real time evolution of the QQbar pair in the medium-> use the EFT to define and calculate it

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more scales

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more scales $$m \gg mv \gg mv^2$$

?

and Λ_{QCD}

$$T \gg gT \gg g^2T \ldots$$

$m_D \sim gT$
Debye mass
Screening Scale

But, at finite temperature what is the quarkonium potential?

The potential V(r,T) dictates throught the Schroedinger equation the real time evolution of the QQbar pair in the medium-> use the EFT to define and calculate it

more scales

$$m \gg mv \gg mv^2$$

?

and Λ_{QCD}

$$T \gg gT \gg g^2T \ldots$$

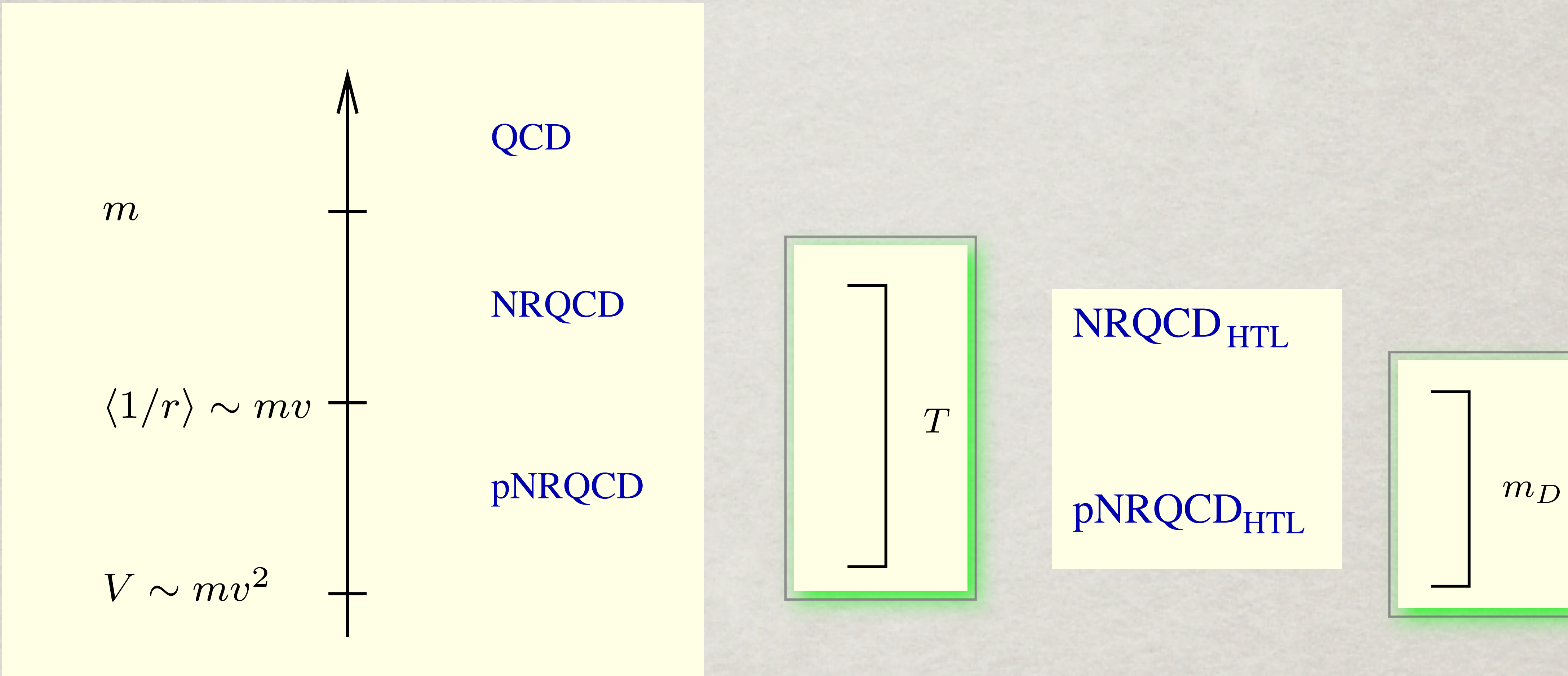
$m_D \sim gT$
Debye mass
Screening Scale

Without heavy quarks an EFT already exists that comes from integrating out hard gluon of p \sim T:
Hard Thermal Loop EFT

Braaten Pisarski 90

Quarkonium at finite T with pNRQCD

N. B. J. Ghiglieri, P. Petreczky, M. Escobedo, A. Vairo 08--013



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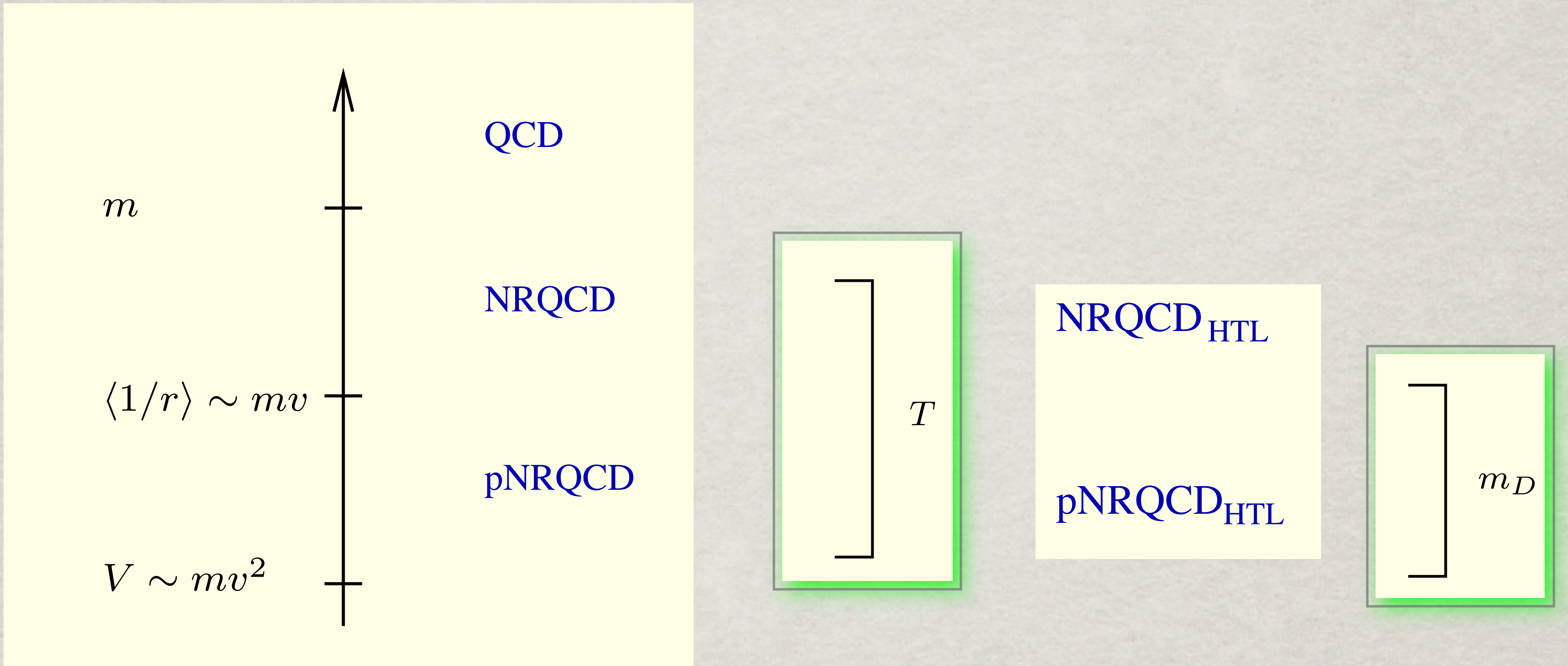

We work under the conditions:

We assume that bound states exist for

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

We neglect smaller thermodynamical scales.

In the weak coupling regime:

- $v \sim \alpha_s \ll 1$; valid for tightly bound states: $\Upsilon(1S)$, J/ψ, ...
- $T \gg gT \sim m_D$.

Effects due to the scale Λ_{QCD} will not be considered.

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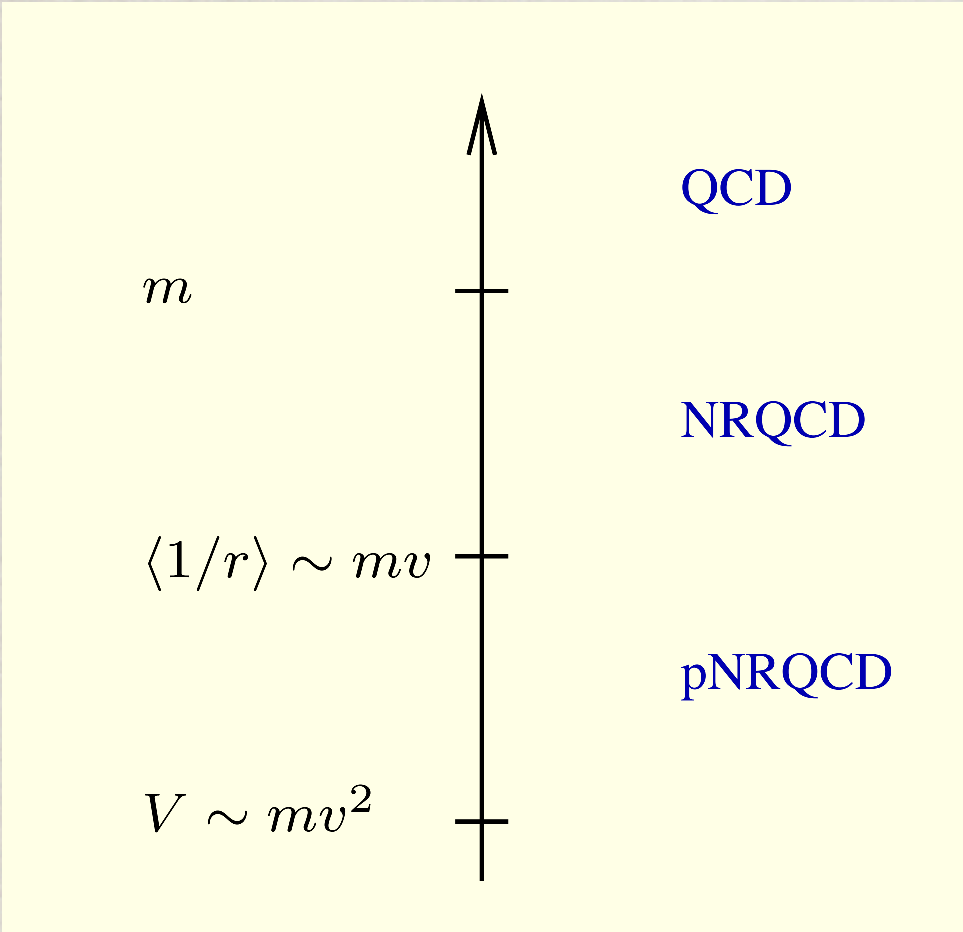

pNRQCD at finite T allows us to define the static QQbar potential in the medium in real time

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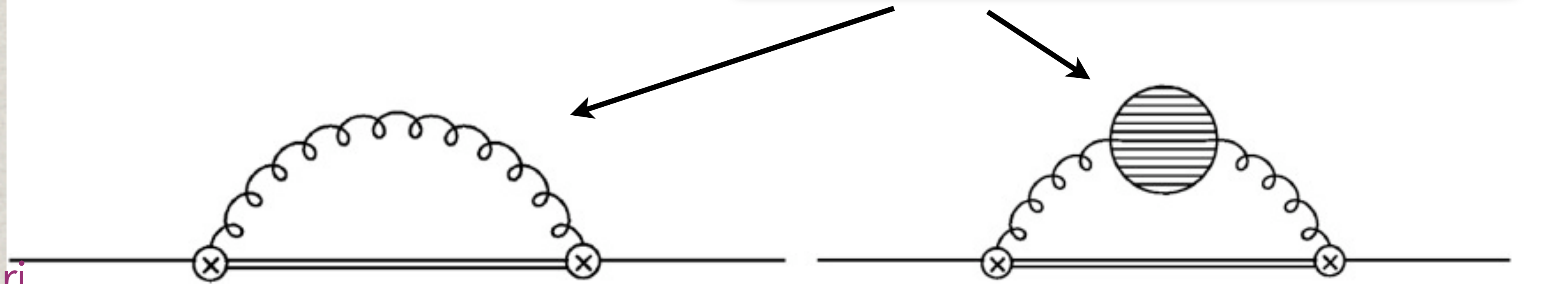
The singlet static potential

- 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 $Q\bar{Q}$



N. B., Ghiglieri, Petreczky, Vairo 2008

Singlet-to-octet

New effect, specific of QCD

dominates for E/m_D>>1

(gluo dissociation)

Landau damping Laine et al 2007

Known from QED

dominates for m_D/E>>1

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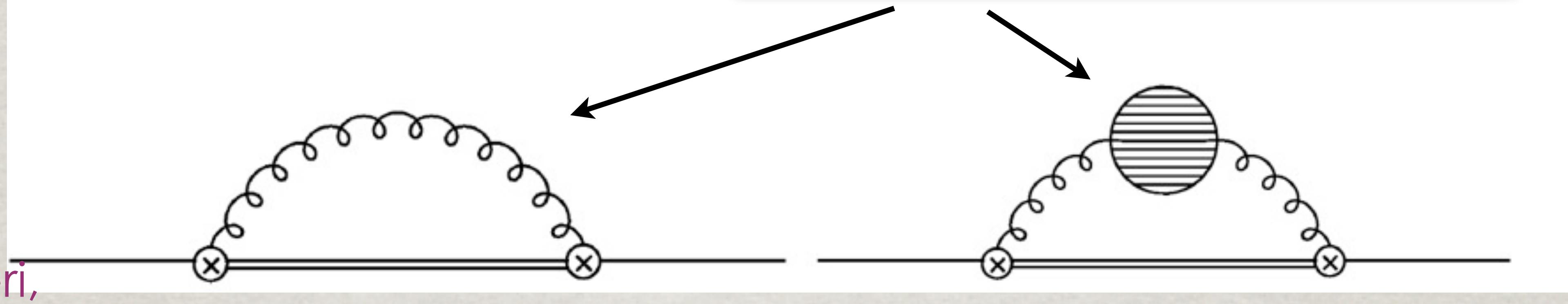

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- The imaginary part is bigger than the real part before the screening exp{-m_D r} sets in

->the imaginary part is responsible for QQbar dissociation !

$T \gg 1/r \gg m_D \gg V$:Quarkonium melts in the medium $E_{\text{binding}} \sim \Gamma$

- Escobedo Soto arXiv:0804.0691

Laine arXiv:0810.1112

The singlet static potential

- Temperature effects can be other than screening

The singlet static potential

- 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 $1/r > m_D \sim gT$

no exponential screening but
power-like T corrections

$T < E_{bin}$

no corrections to the potential,
corrections to the energy

Υ(1S) at LHC below T_d

The relative size of non-relativistic and thermal scales depends on the medium and on the quarkonium state.

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

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

Vairo AIP CP 1317 (2011) 241

N.B., Escobedo, Ghiglieri, Soto ,Vairo 010

Υ(1S)

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

Escobedo, Soto 010

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

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

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

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

Consistent with NRQCD lattice calculations of spectral functions

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