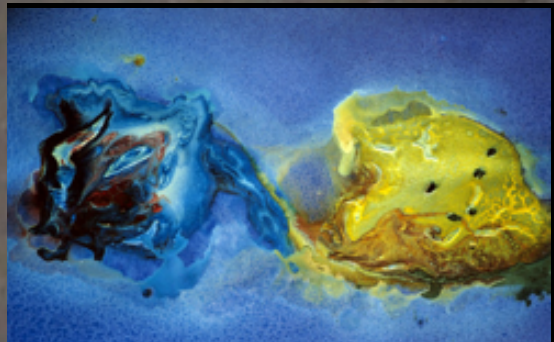


Heavy Quarkonium with Effective Field Theories

NORA BRAMBILLA

Talk dedicated to MISHA POLIKARPOV



- 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

$$\mathcal{L}_{\text{QCD}} = -\frac{1}{4} (\partial_\mu A_\nu - \partial_\nu A_\mu - i\textcolor{red}{g}[A_\mu, A_\nu])^2 + \bar{\psi}_f (i\not{\partial} - \textcolor{red}{g}\not{A} - m_f) \psi_f$$
$$\alpha_s = \frac{g^2}{4\pi}$$

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0.4

0.3

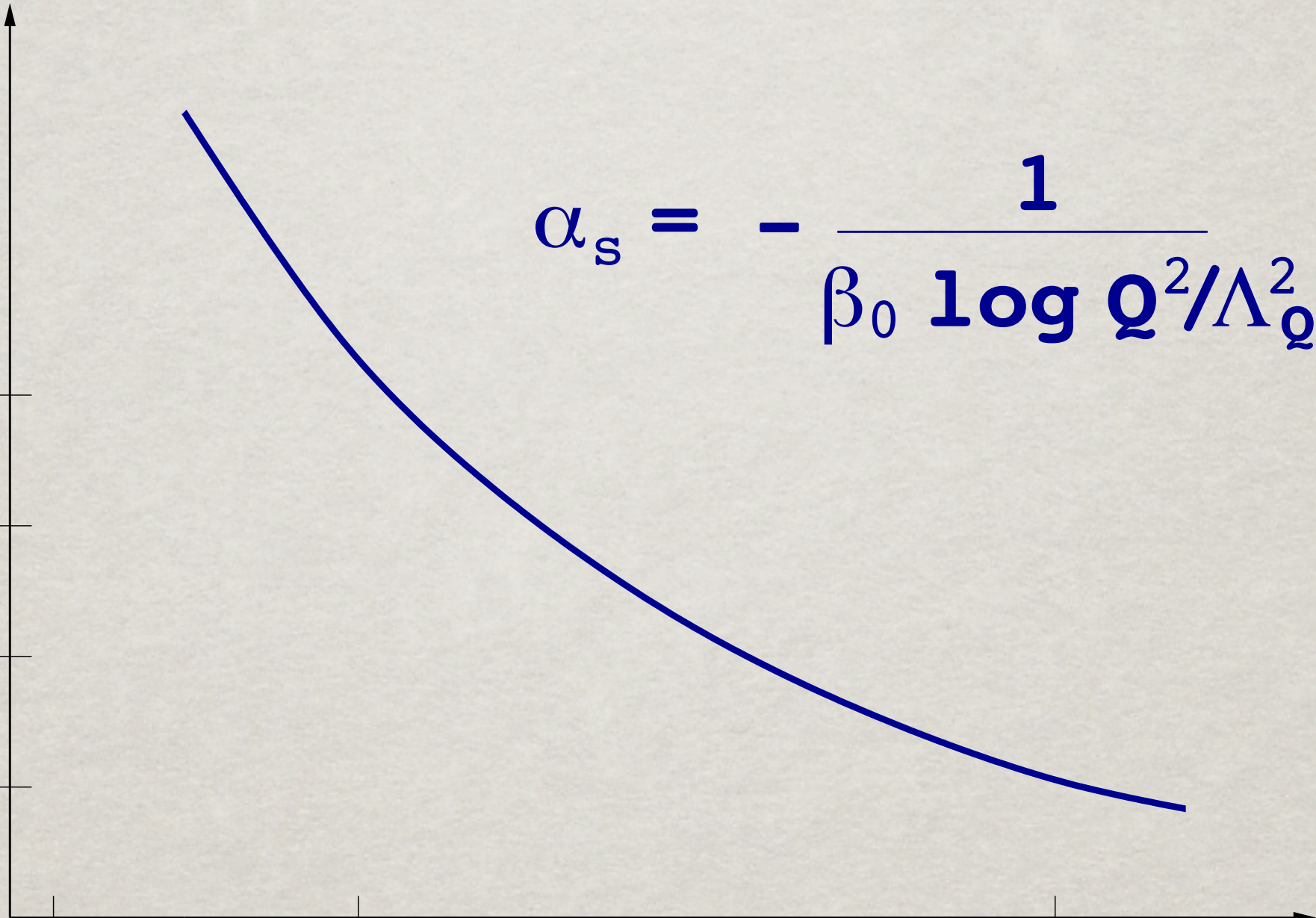
0.2

0.1

Λ_{QCD}

1 GeV

100 GeV



QCD and hadrons

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Λ_{QCD} is the scale where nonperturbative effects dominate

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asymptotic freedom

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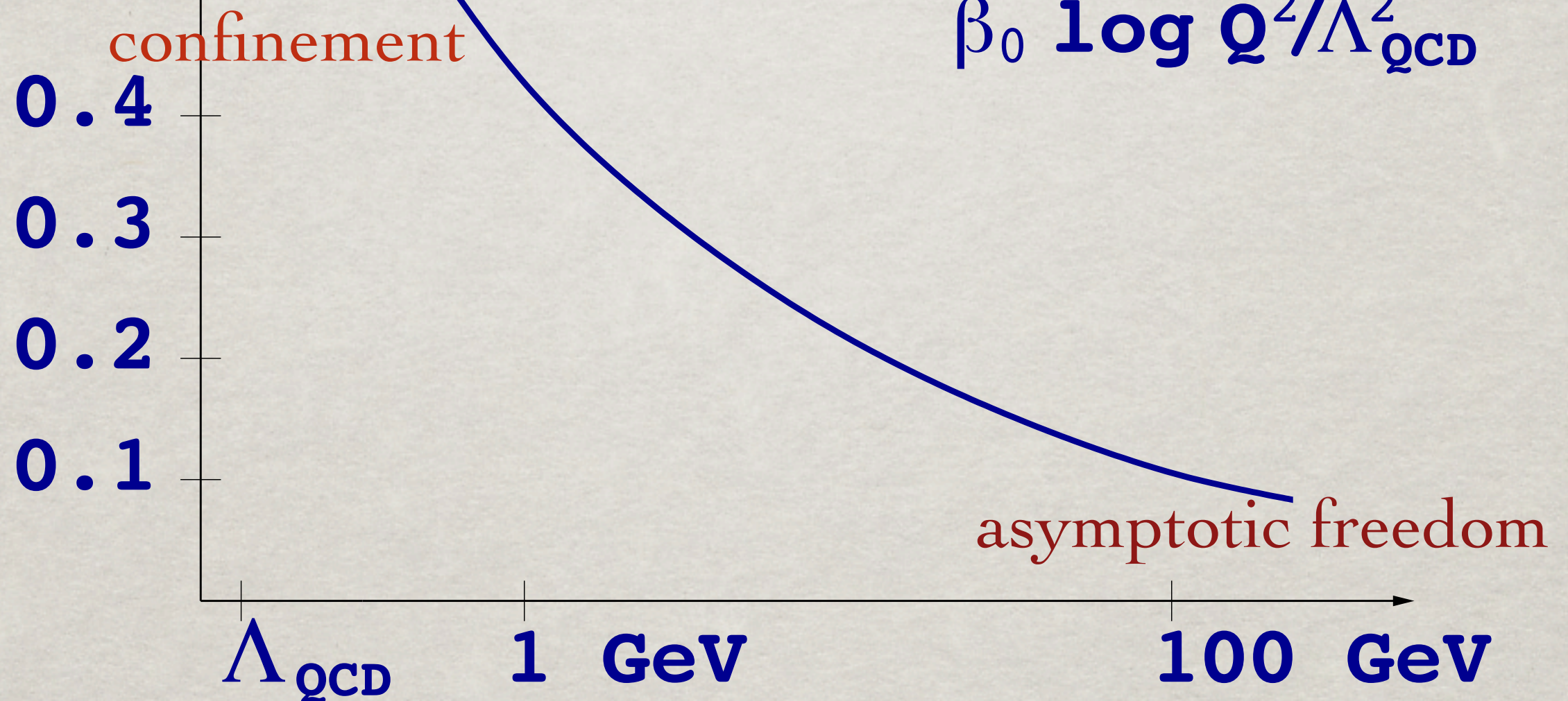
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confinement

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asymptotic freedom

$$\text{Observable} = \text{const.} + \# \alpha_s + \# \alpha_s^2 + \dots$$

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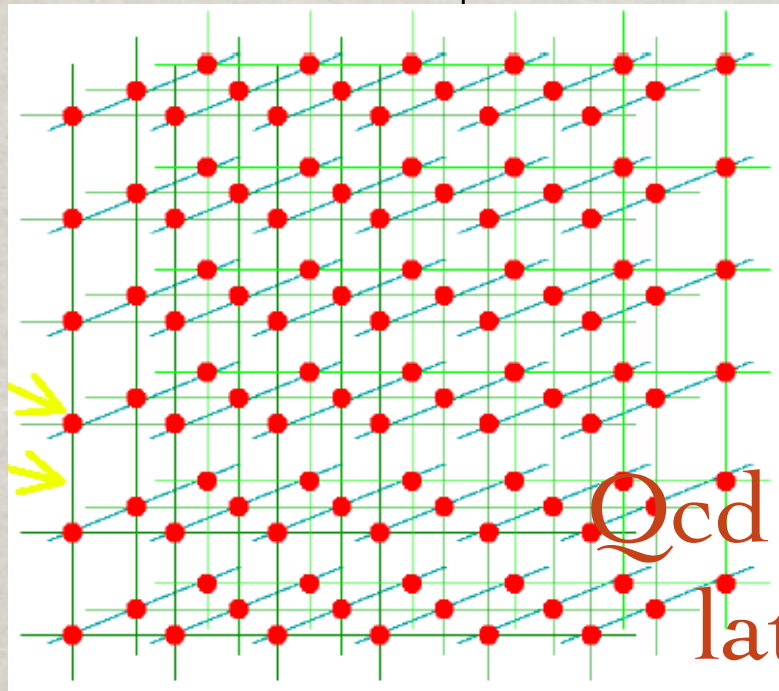
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Qcd on the
lattice

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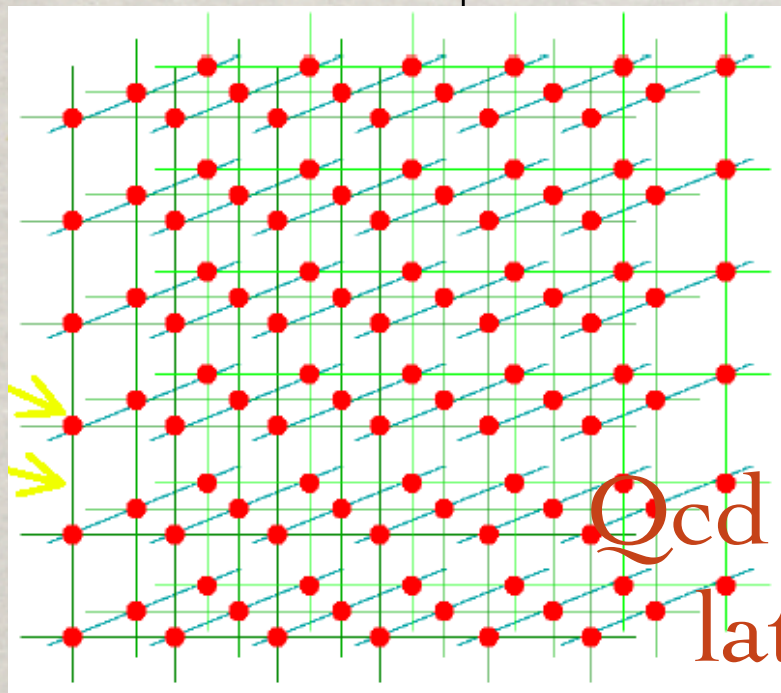
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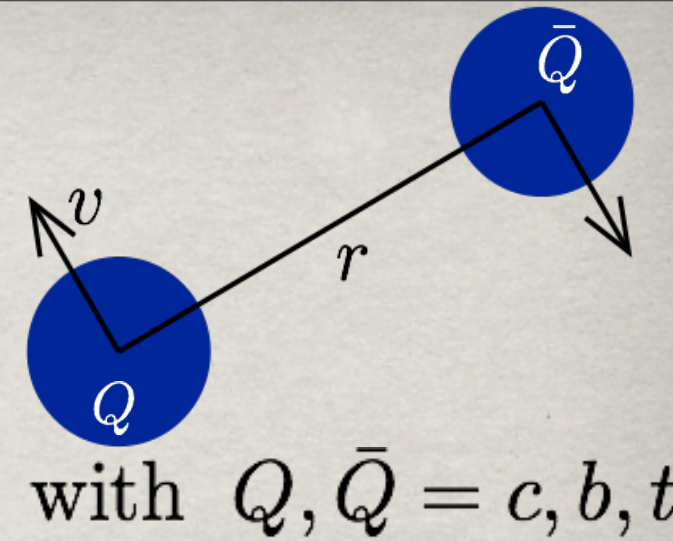
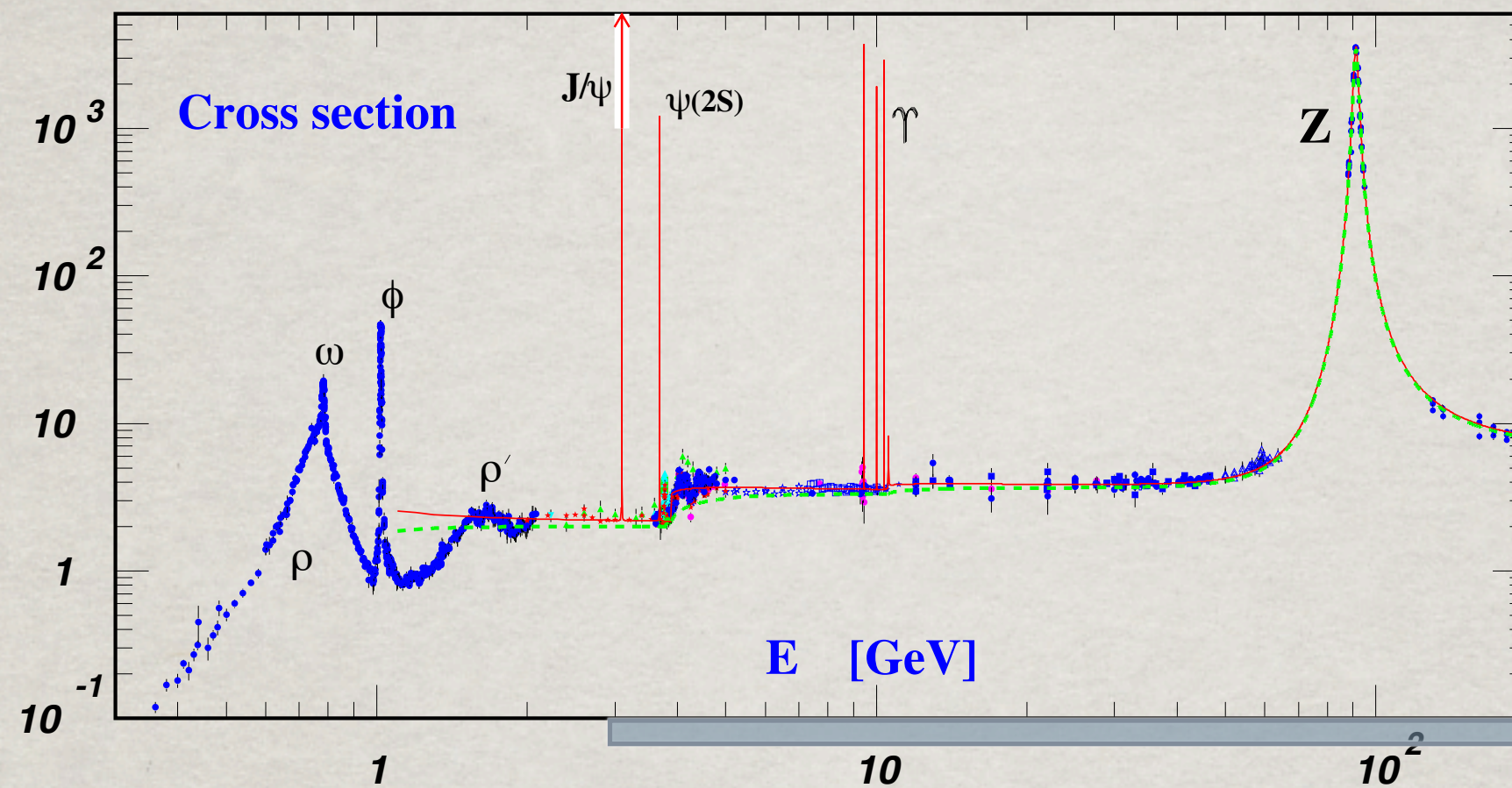
Λ_{QCD}

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

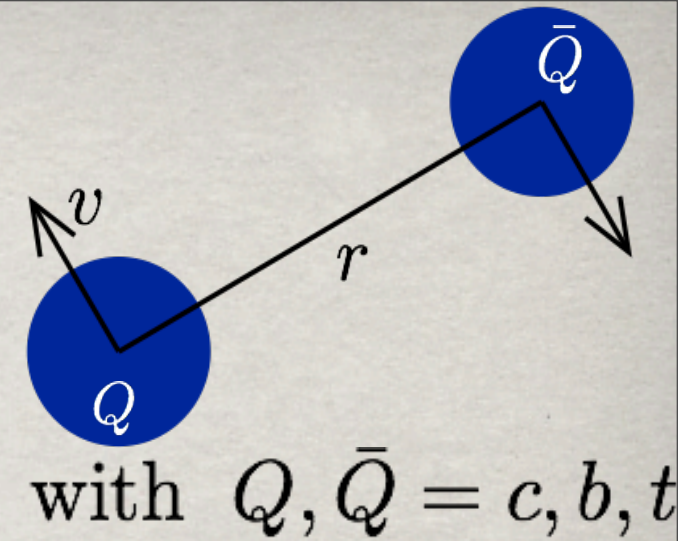
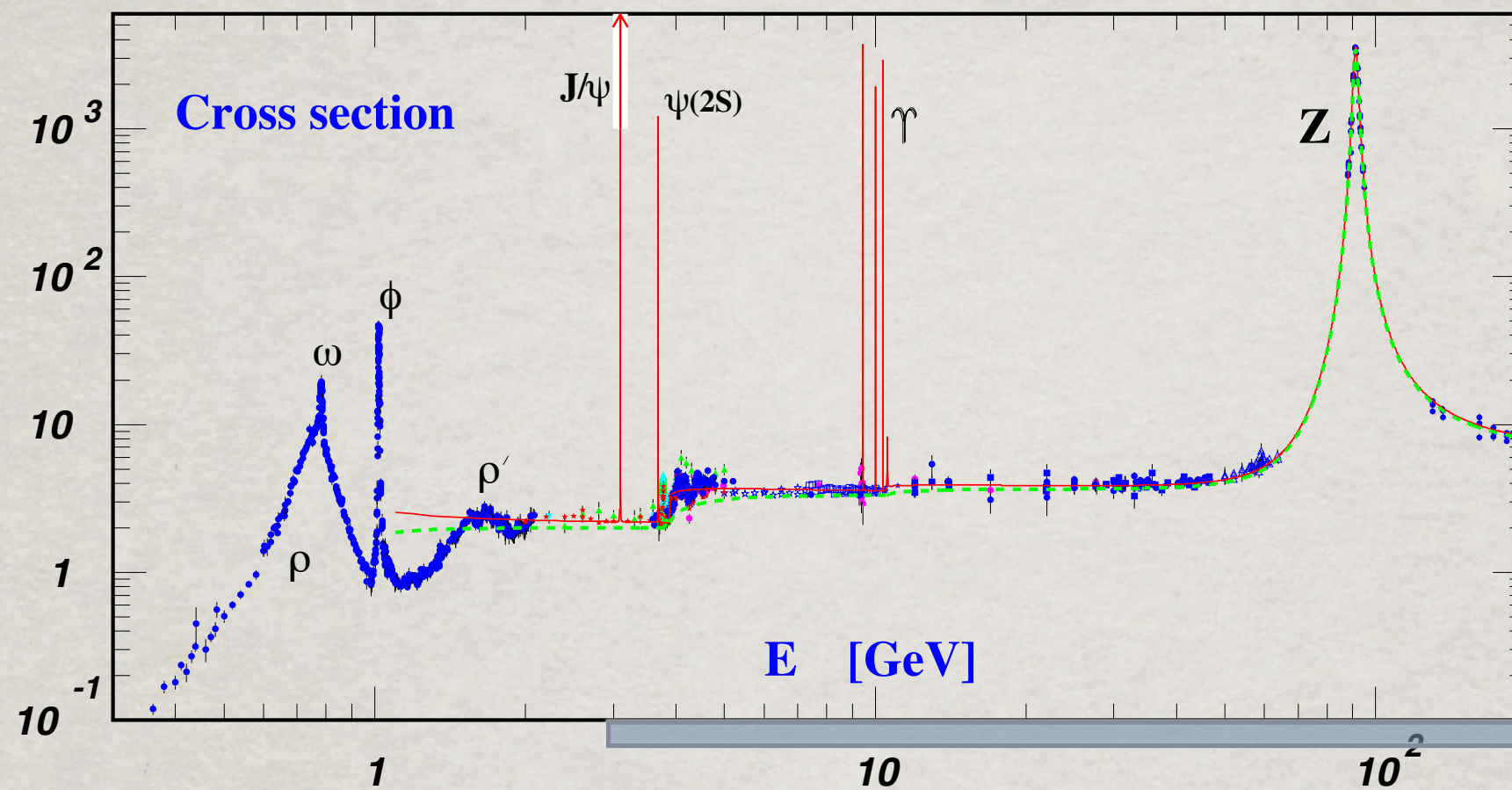


$m_c \sim 1.5 \text{ GeV}$

$m_b \sim 5 \text{ GeV}$

$m_t \sim 170 \text{ GeV}$

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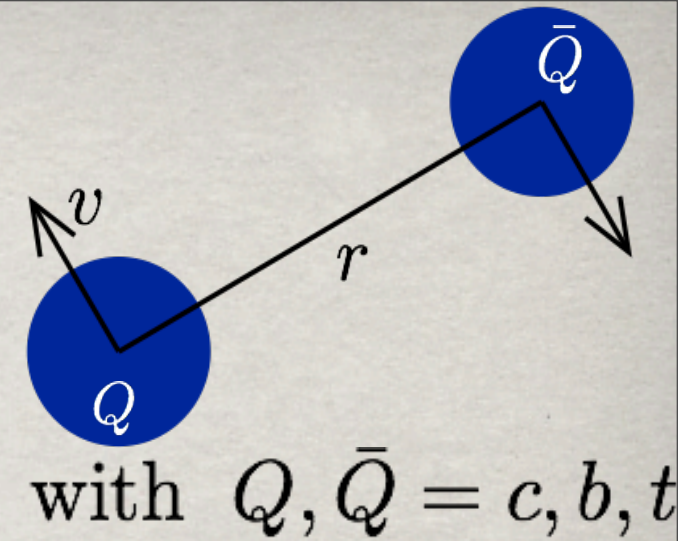
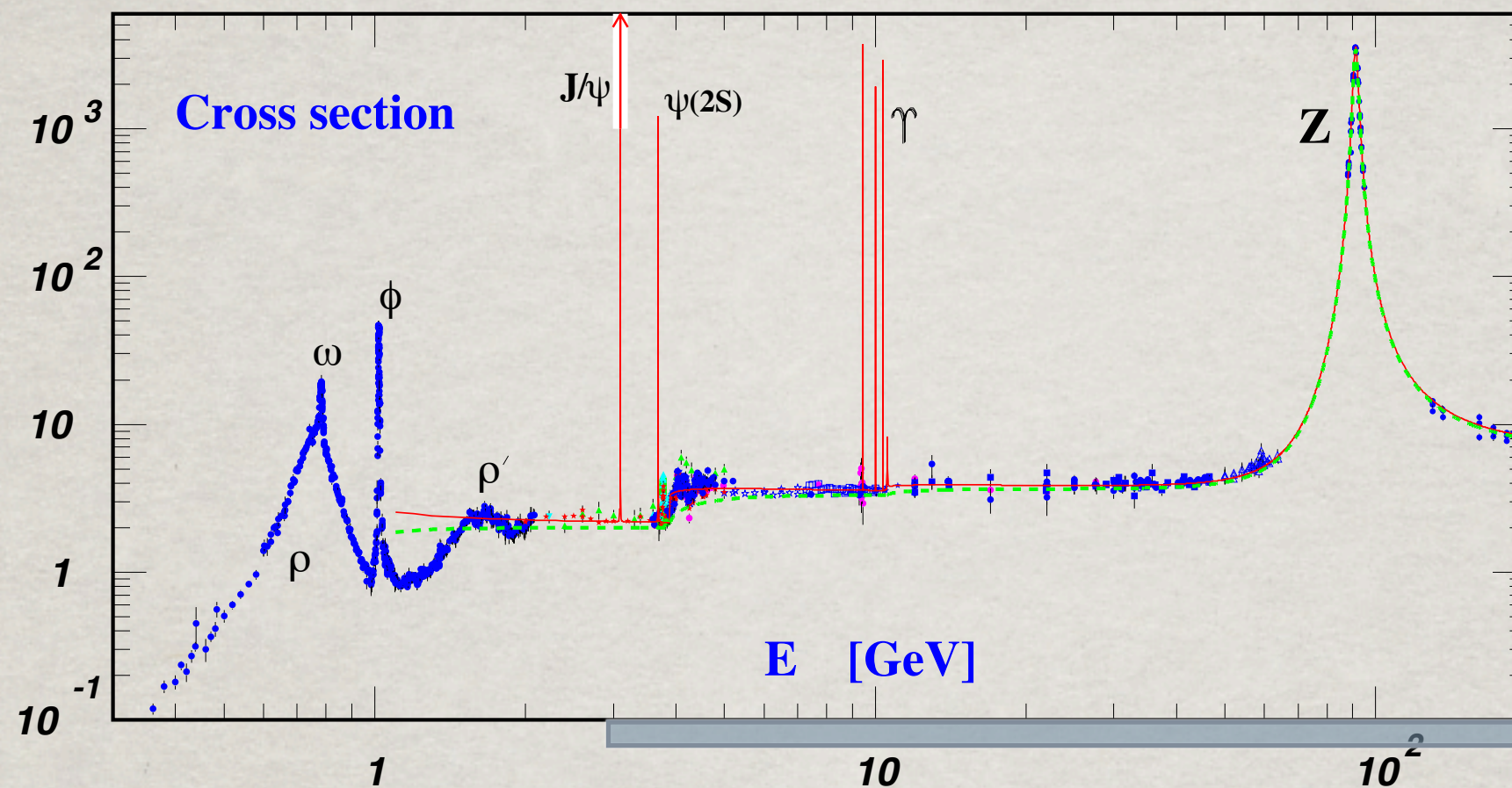
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A large scale

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

$$\alpha_s(m_Q) \ll 1$$

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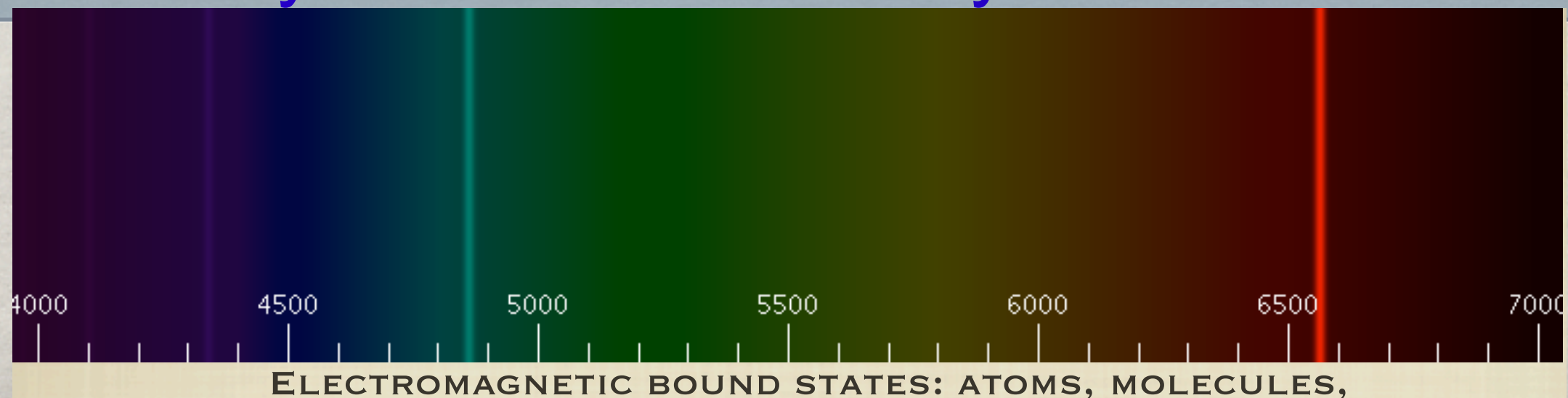
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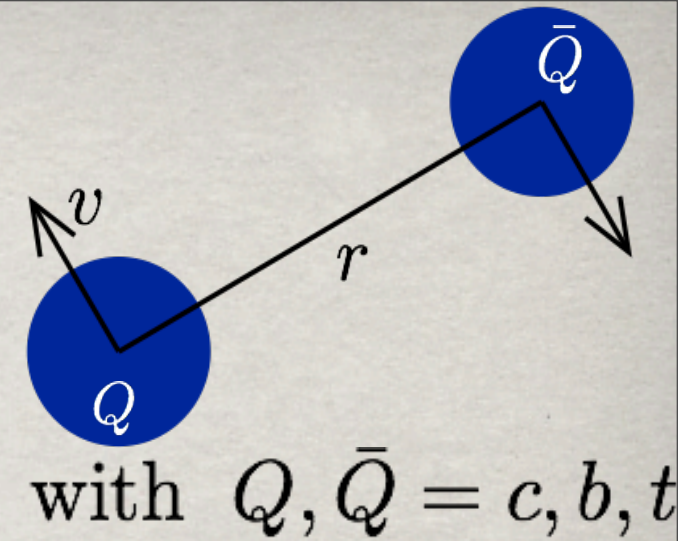
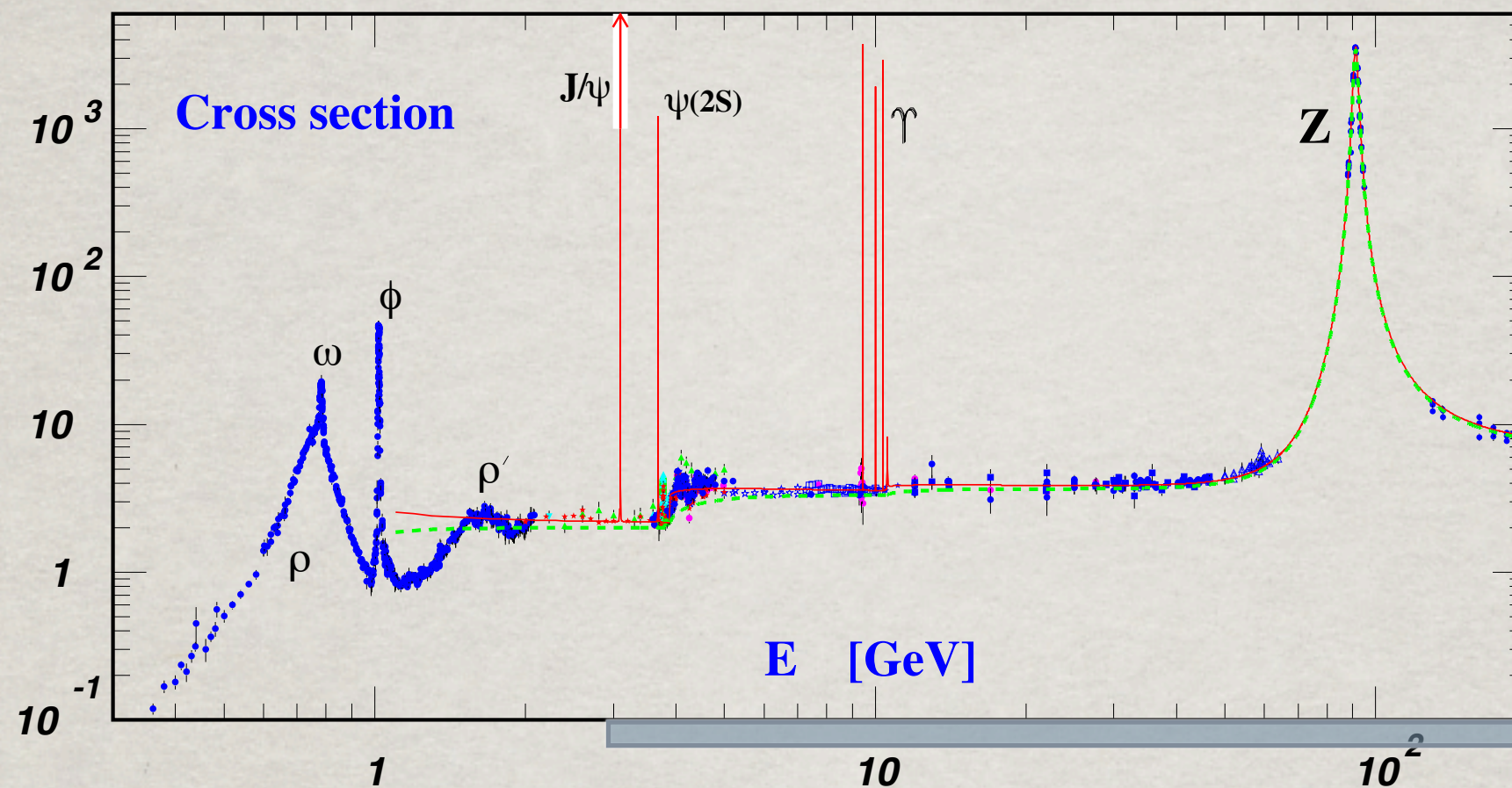
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Heavy quarkonia are nonrelativistic bound systems: multiscale systems



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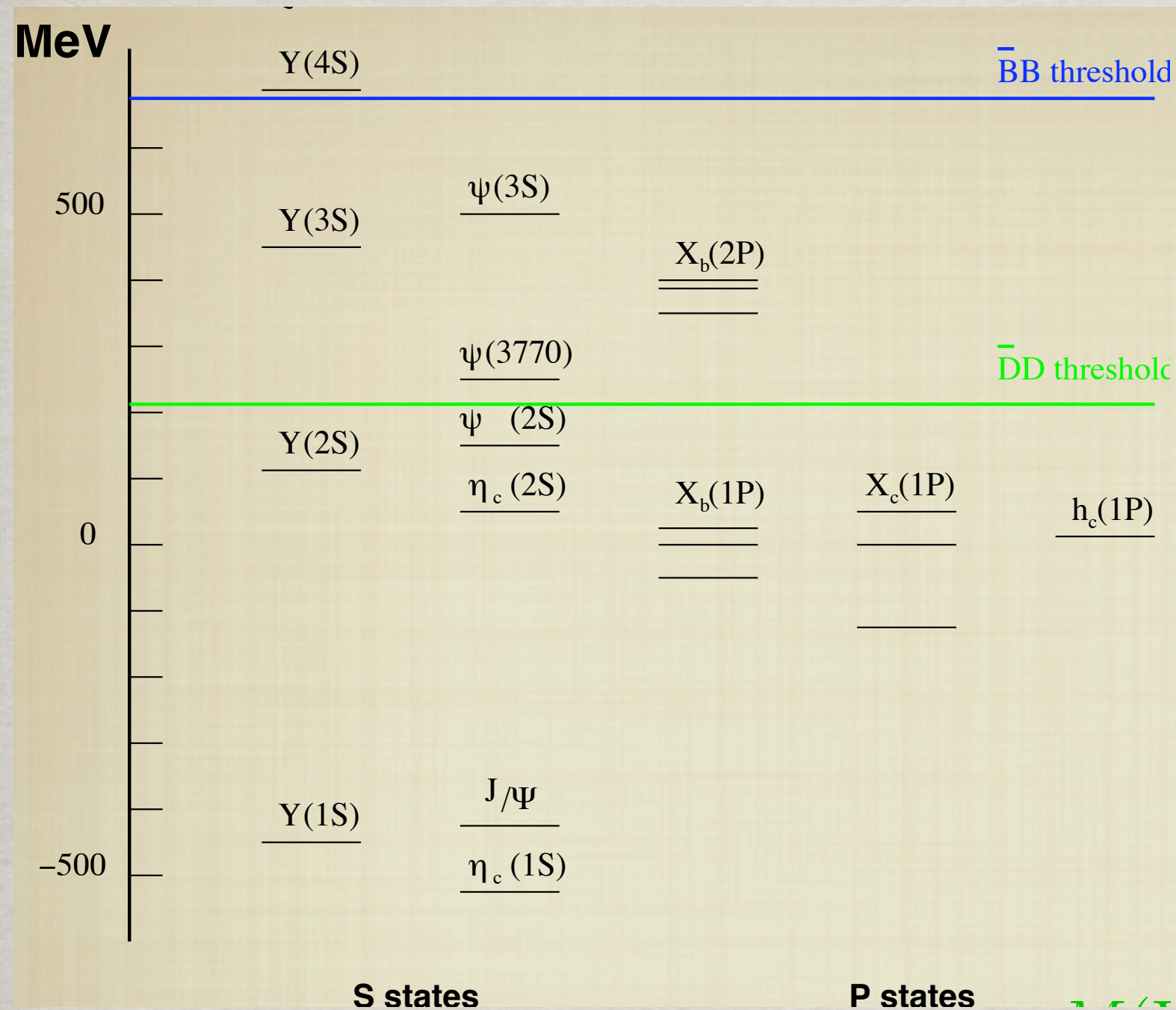
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many scales: a challenge and an opportunity

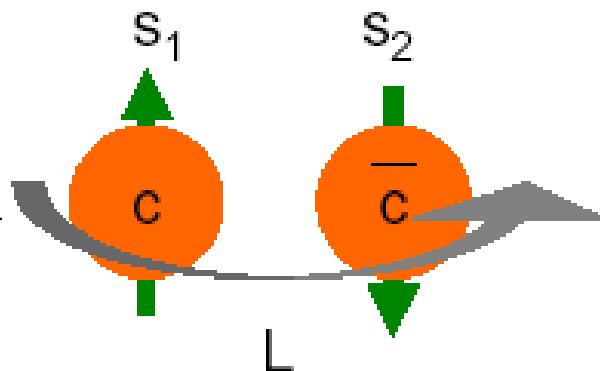


Quarkonium scales



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

$$2S+1 L_J$$

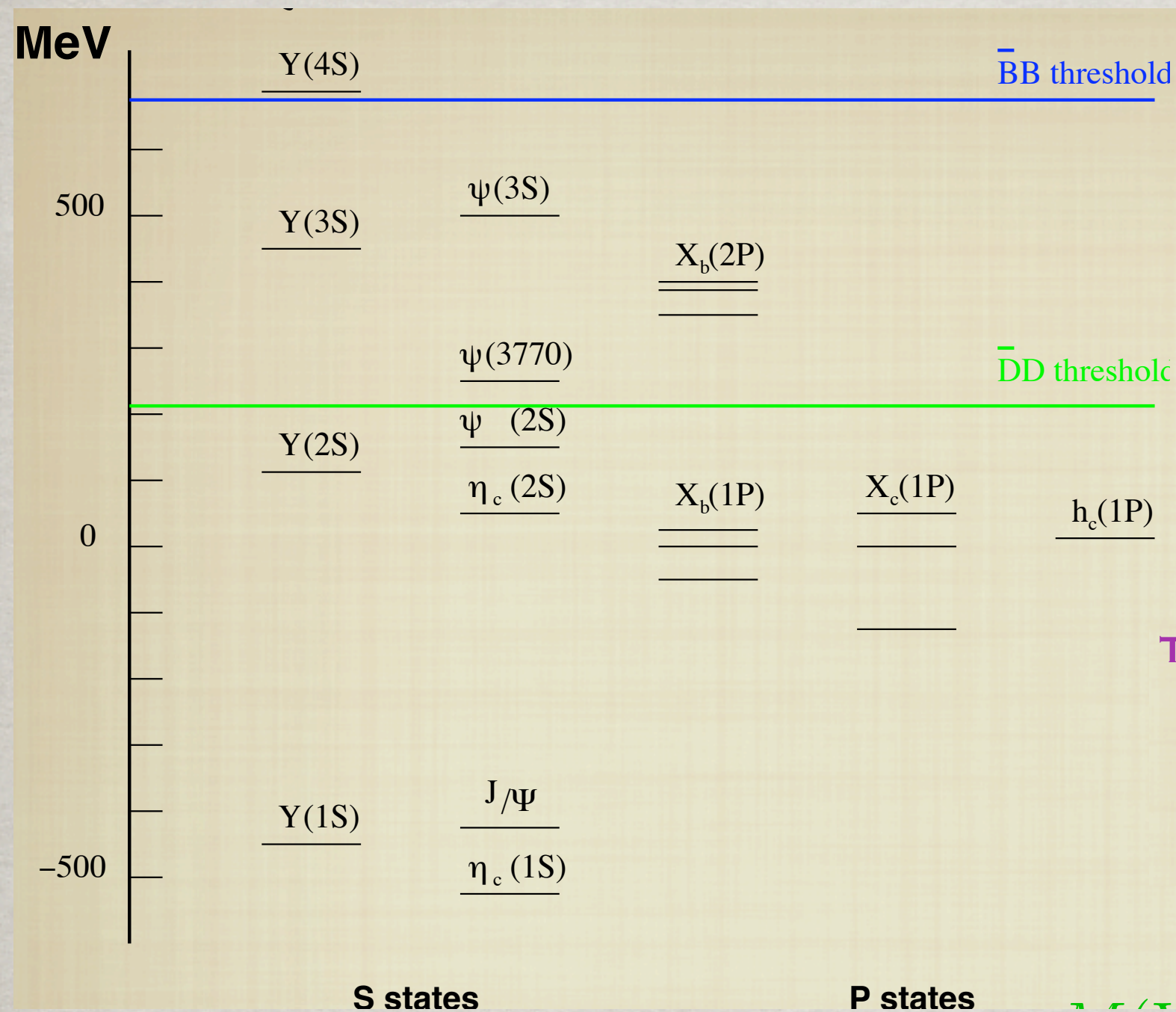


THE MASS SCALE IS PERTURBATIVE

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Quarkonium scales



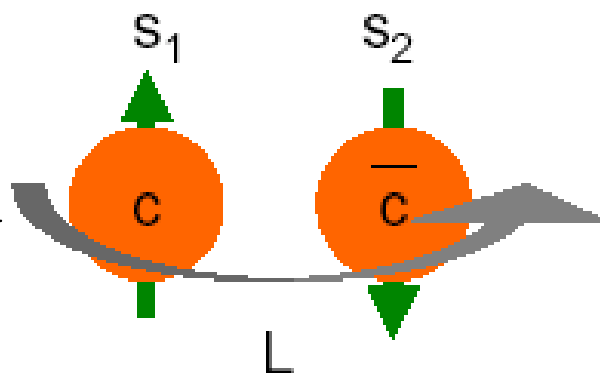
THE SYSTEM IS NONRELATIVISTIC(NR)

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

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

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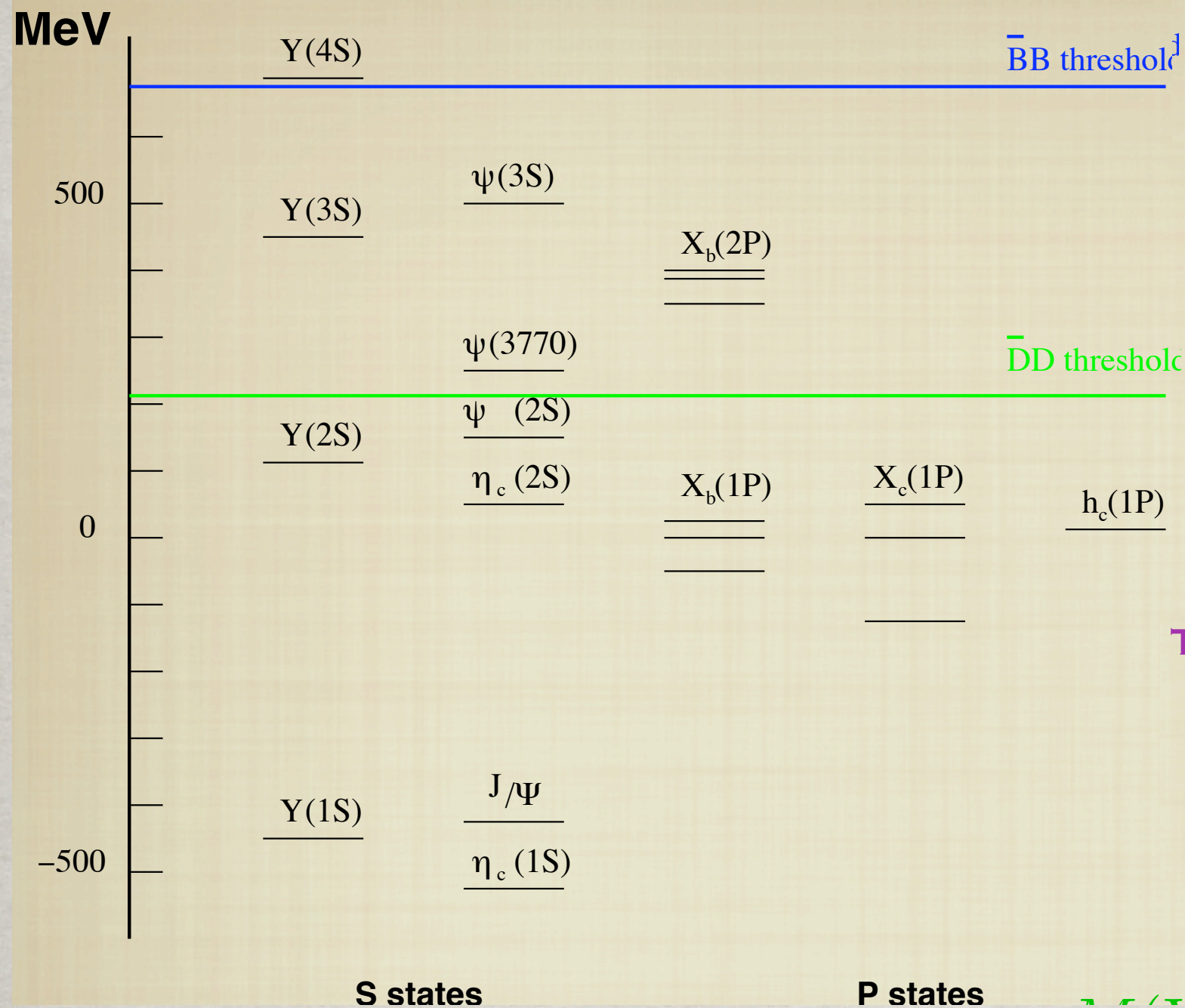


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NR BOUND STATES HAVE AT LEAST
3 SCALES

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

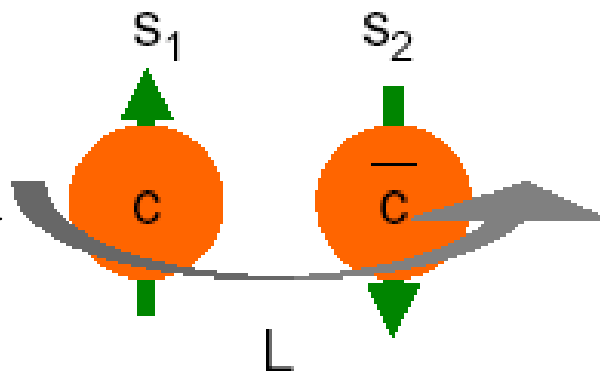
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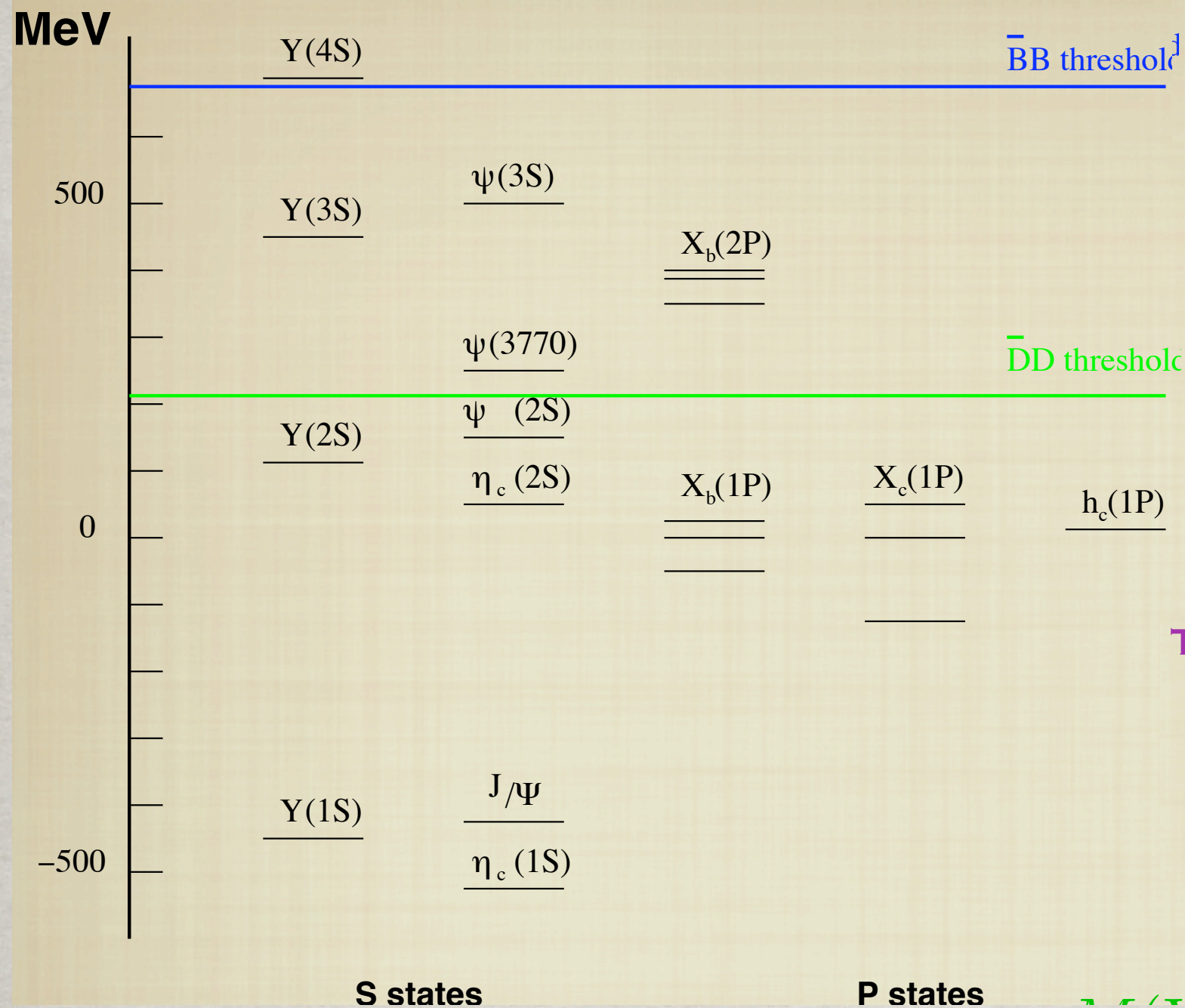


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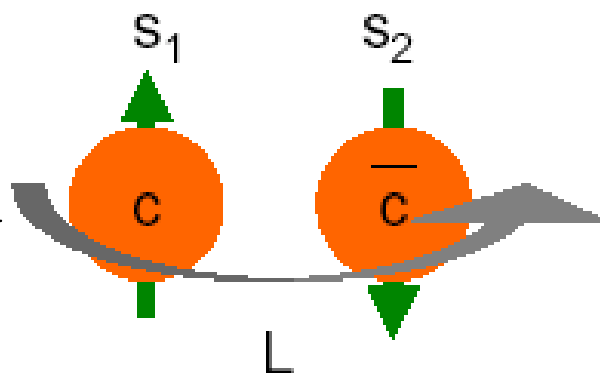
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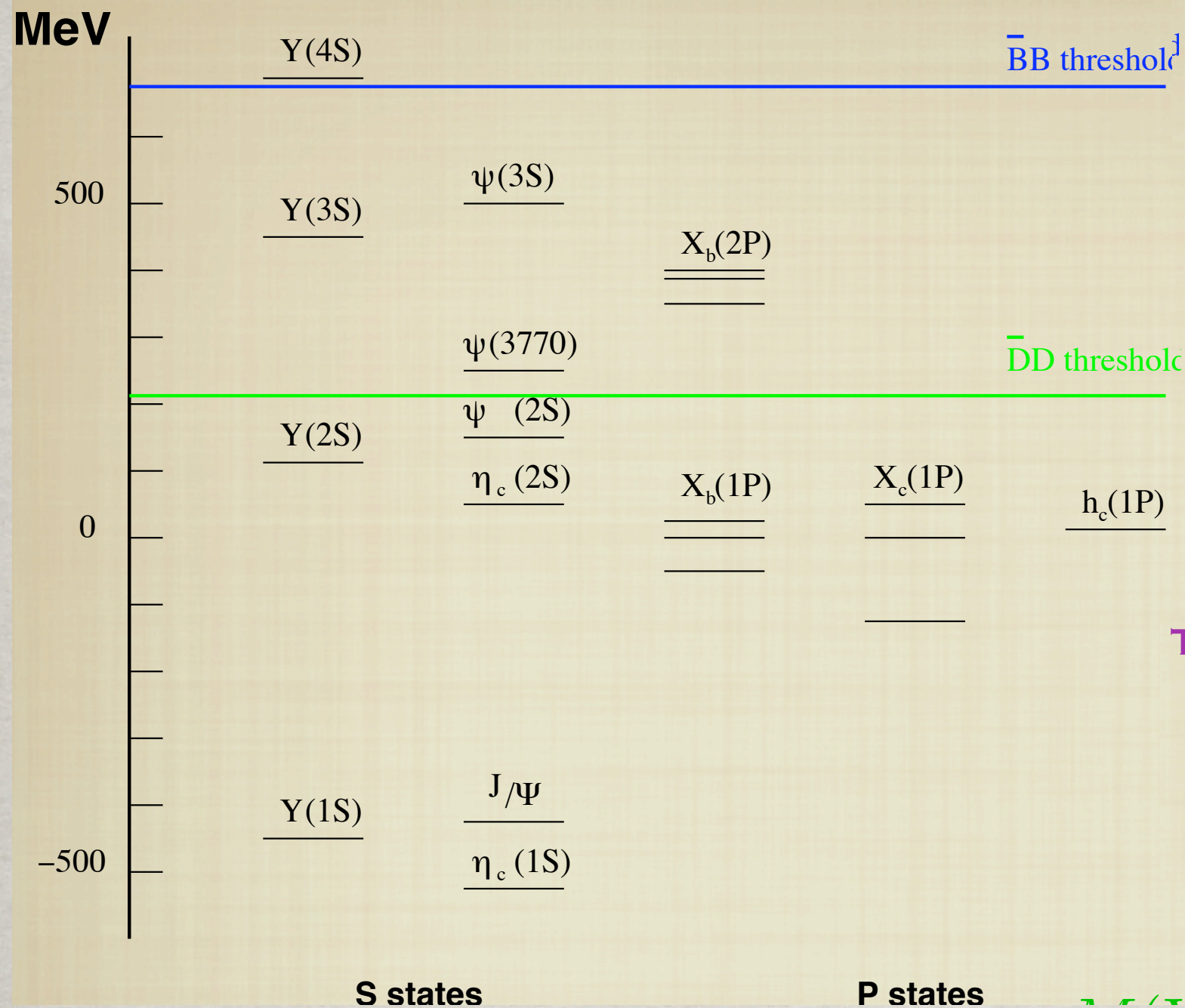
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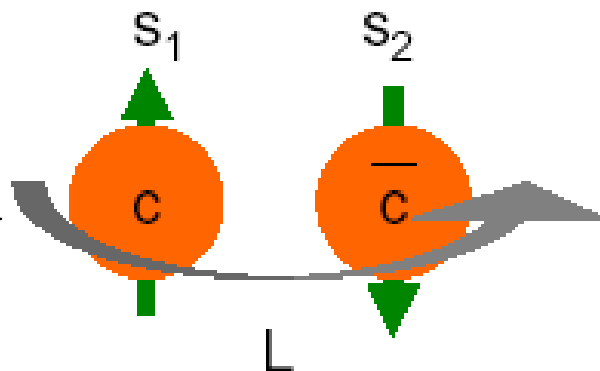
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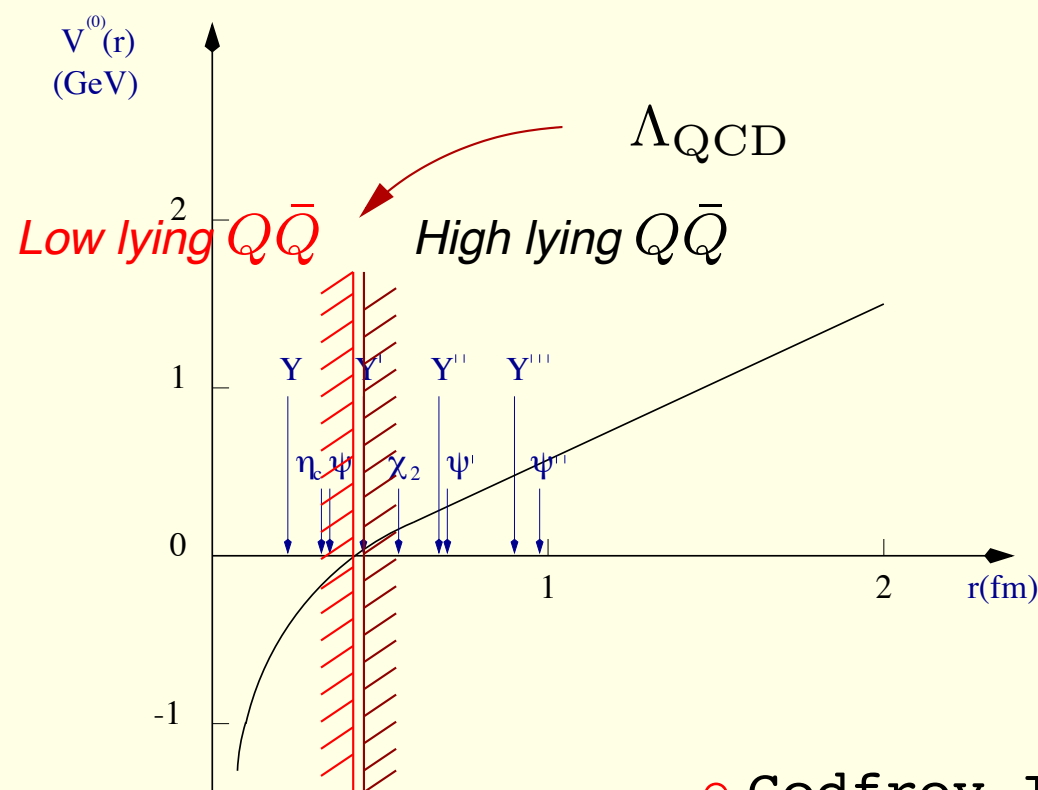
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The rich structure of separated energy scales makes quarkonium an ideal probe of confinement/deconfinement

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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.

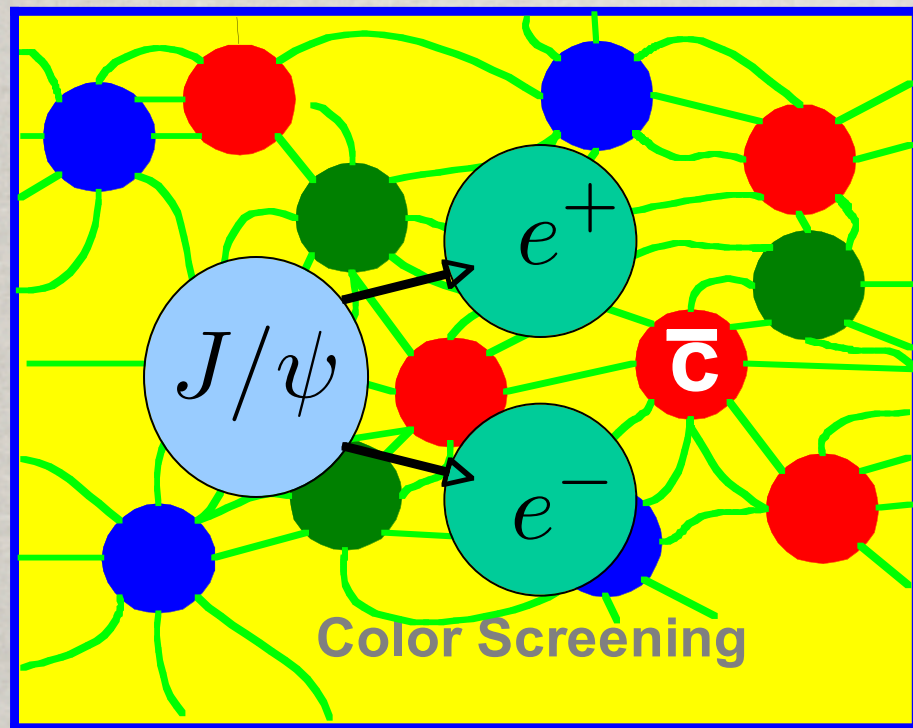


○ Godfrey Isgur PRD 32(85)189

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 $m_D \sim gT$

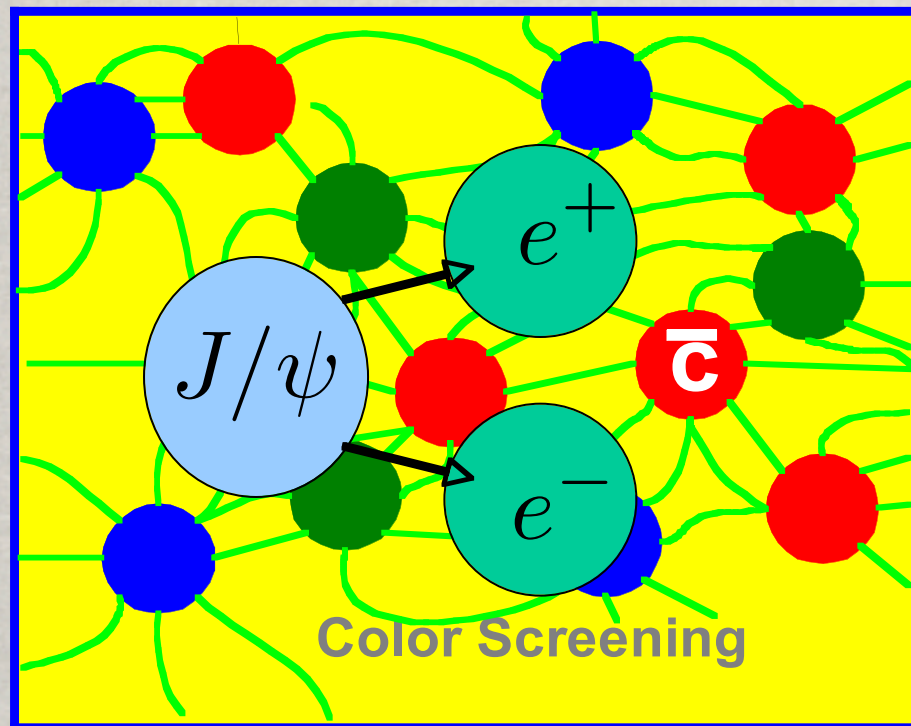
$$V(r) \sim -\alpha_s \frac{e^{-m_D r}}{r}$$

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

Matsui Satz 1986

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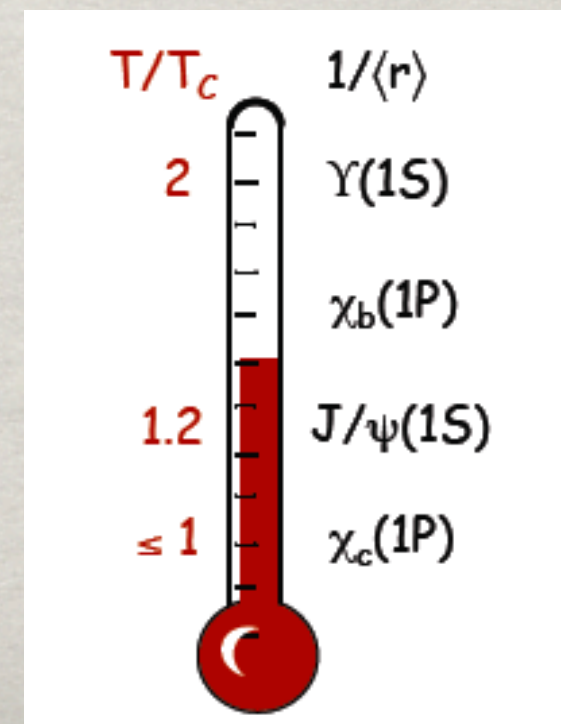
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quarkonia dissociate at different temperature in dependence of their radius: they are a Quark Gluon Plasma thermometer



Quarkonium Today is
a golden system to study strong interactions

Many experimental data and opportunities

Quarkonium Today is
a golden system to study strong interactions

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

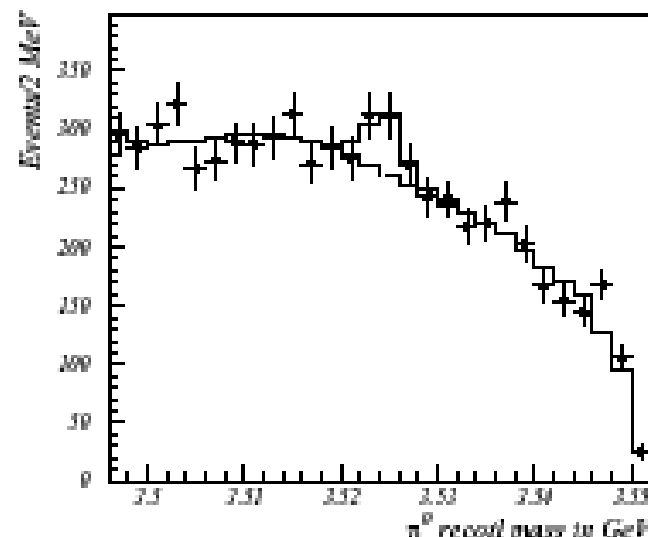
B-FACTORIES: Heavy Mesons Factories

CLEO, BESIII, charm factories

CLEO

Fermilab

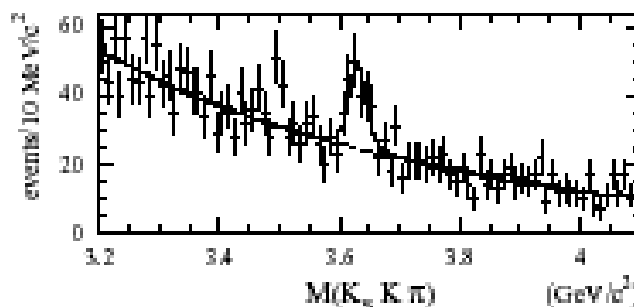
Herndon



$h_c(3523)$

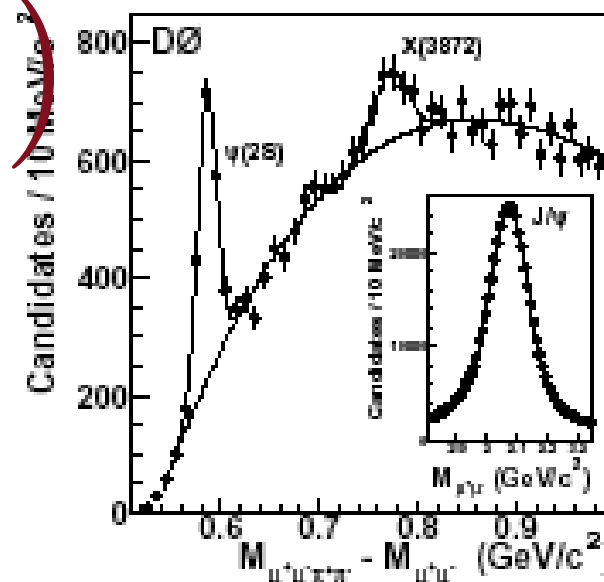
CLEO 05
E835 05

$Z_c(3900)$
BESIII 2013



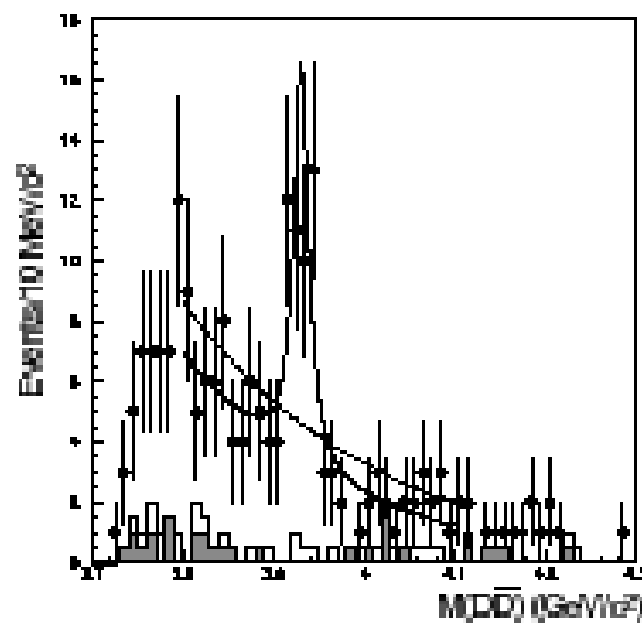
$\eta_c(2S)(3630)$

BaBar 04
CLEO 04
Belle 02



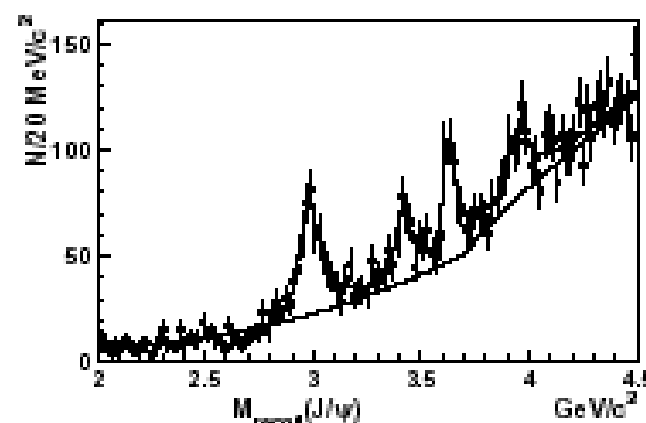
X(3872)

CDF D0/QWG 04
Belle 02
BaBar 05



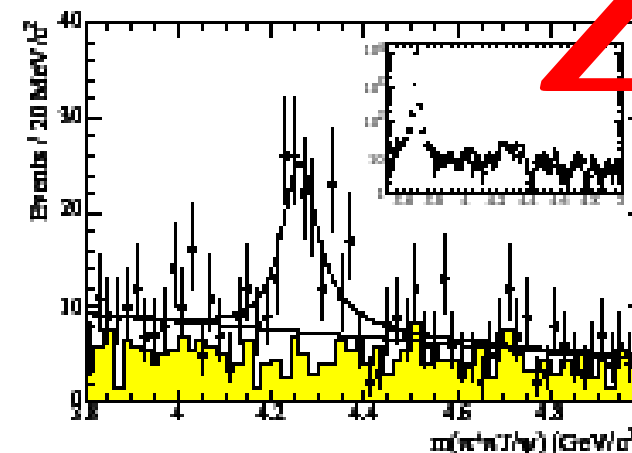
Z(3930)

Belle 05



X(3940)

Belle 05



Y(4260)

BaBar 05

η_b

BABAR
08

Z^+

BELLE
07-08

Today: new data

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

Today: new data

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BESIII

CMS ATLAS LHC-b

ALICE

and in the future PANDA, Belle2

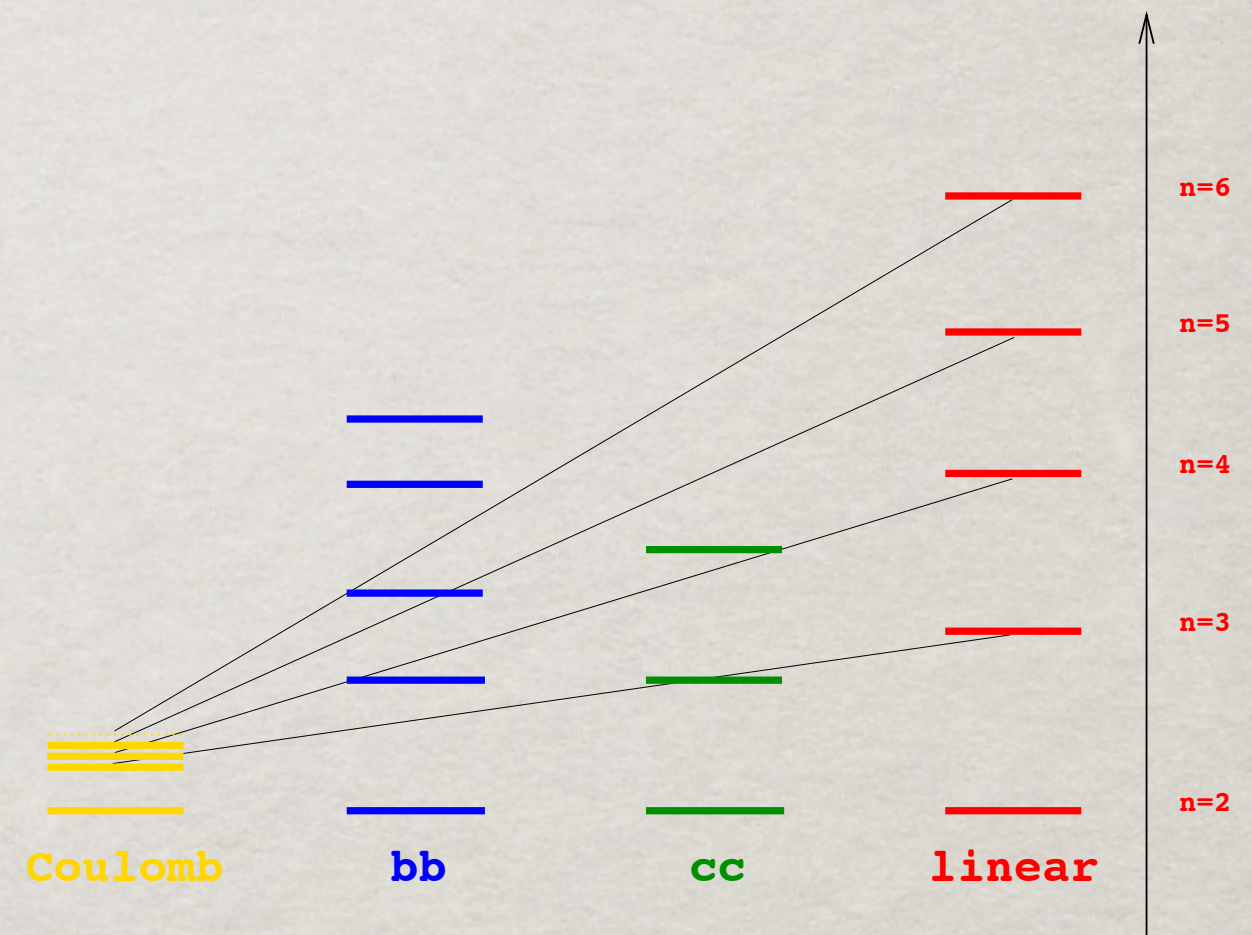
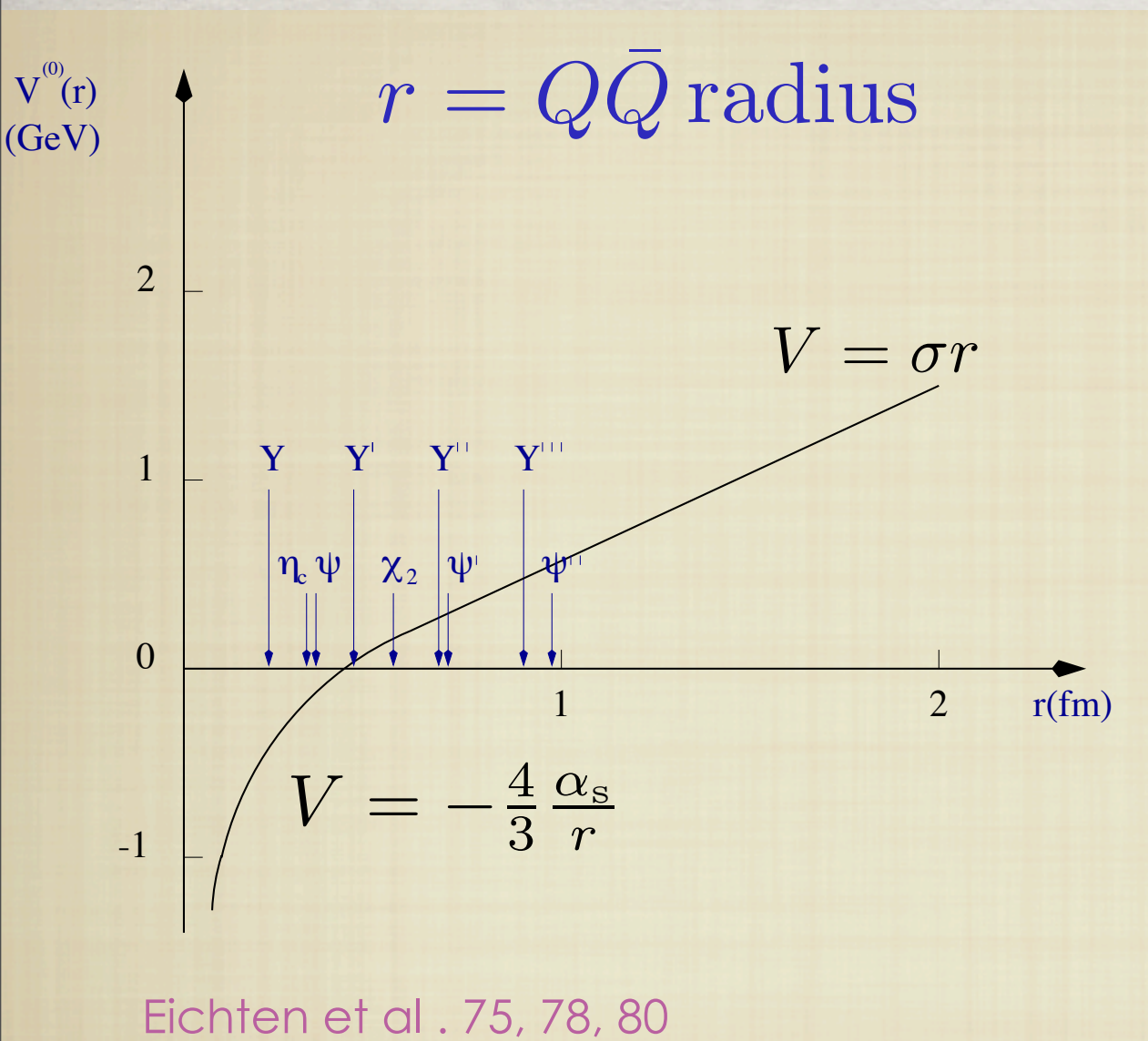
QCD theory of Quarkonium: a very hard problem

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

QCD theory of Quarkonium: a very hard problem

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



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

Variety of potential models used

Confinement and asymptotic freedom--> QCD

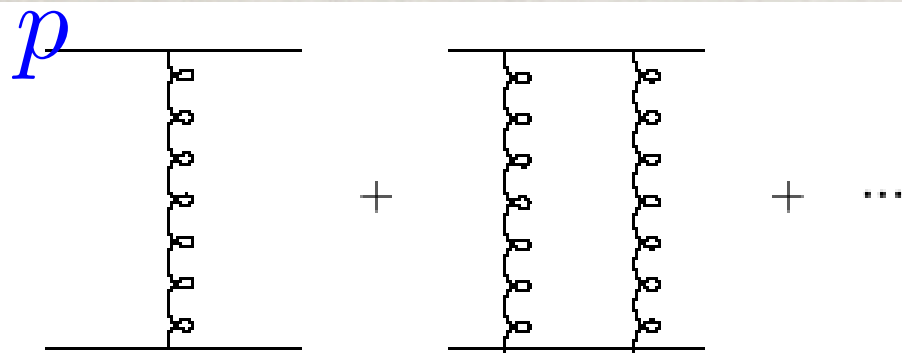
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Close to the bound state $\alpha_s \sim v$

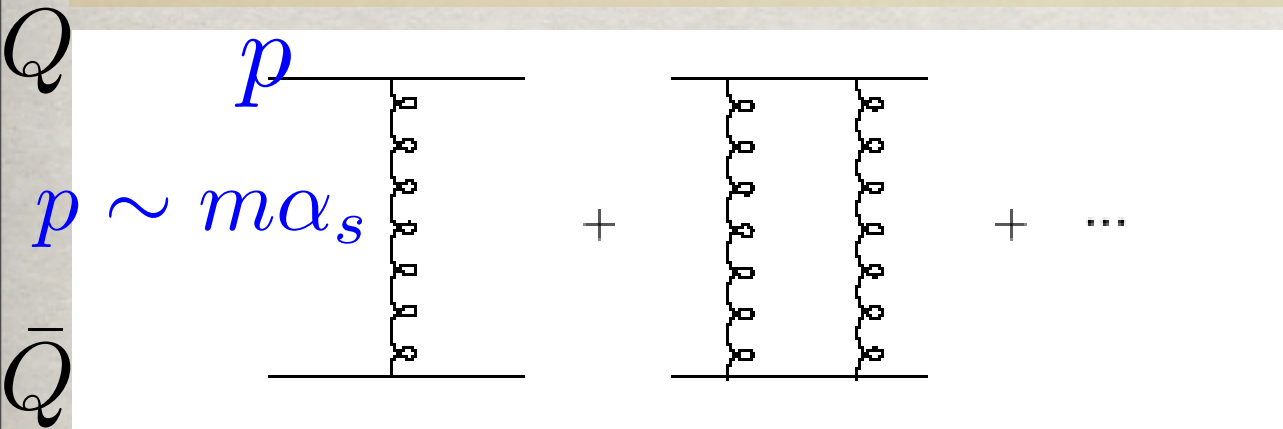
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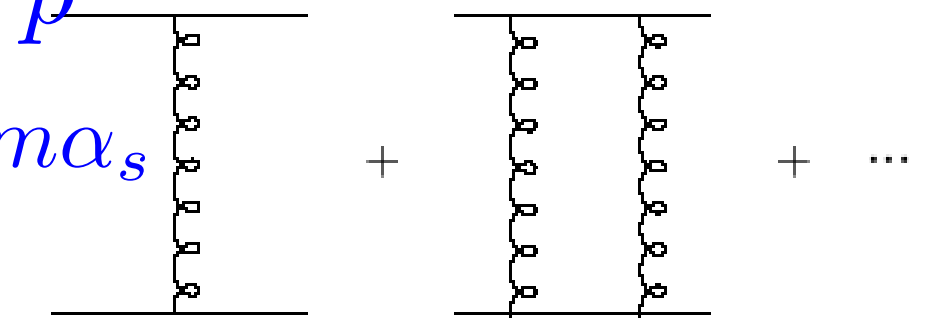
QCD theory of Quarkonium: a very hard problem

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

Q

$p \sim m\alpha_s$

Q



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

QCD theory of Quarkonium: a very hard problem

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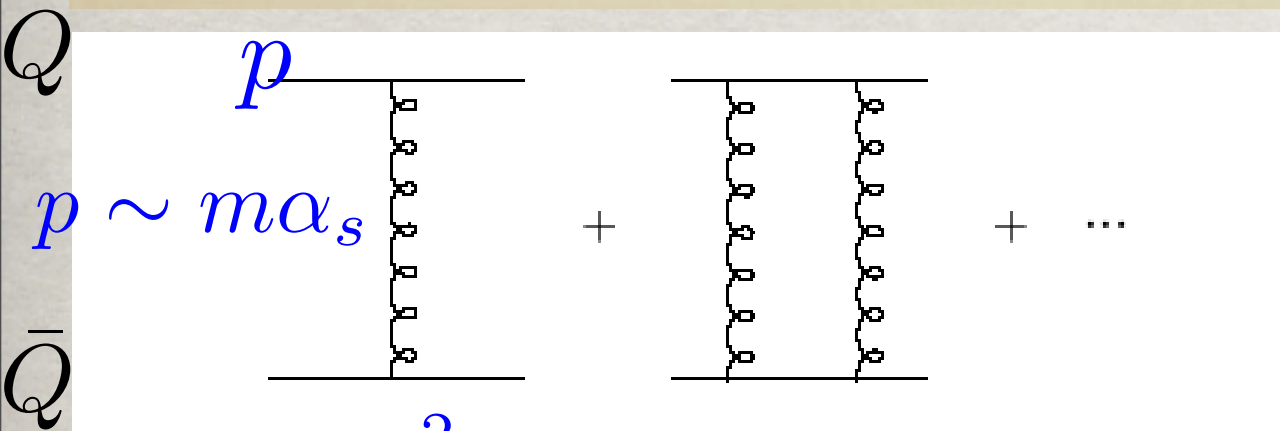
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$$\sim \frac{1}{E - \left(\frac{p^2}{m} + V \right)}$$

QCD theory of Quarkonium: a very hard problem

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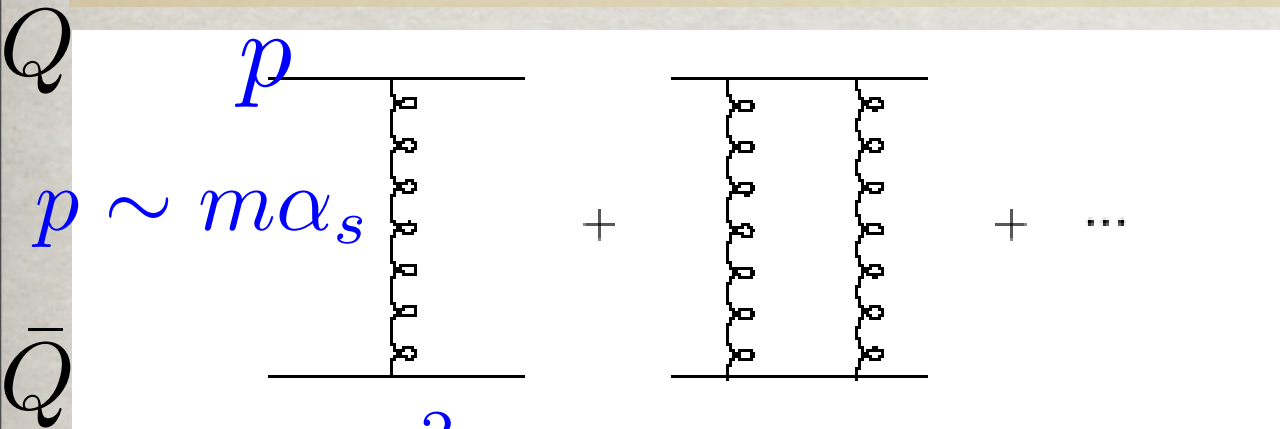
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- From $\left(\frac{p^2}{m} + V \right) \phi = E \phi \rightarrow p \sim m\alpha_s$ and $E = \frac{p^2}{m} + V \sim m\alpha_s^2$.

QCD theory of Quarkonium: a very hard problem

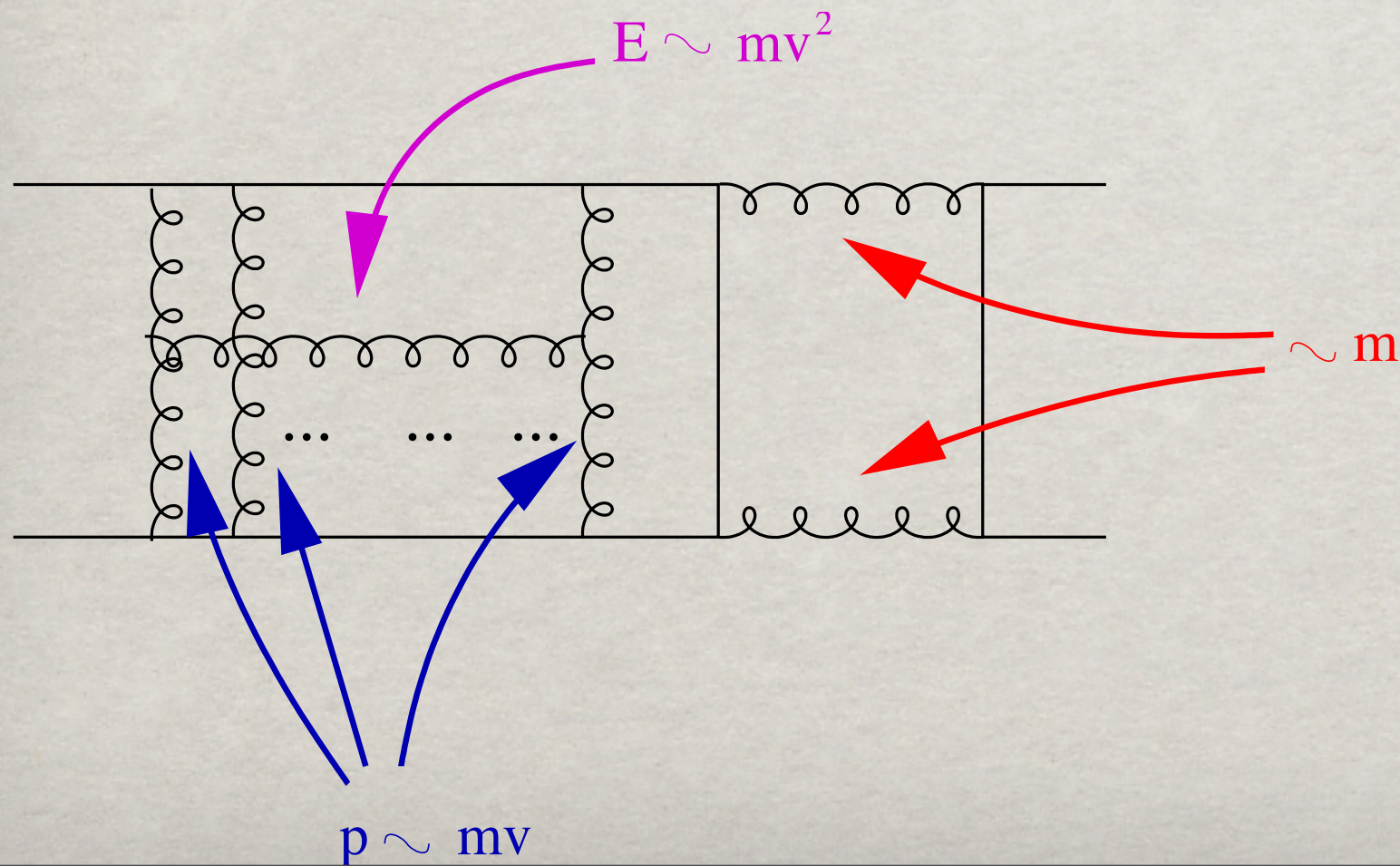
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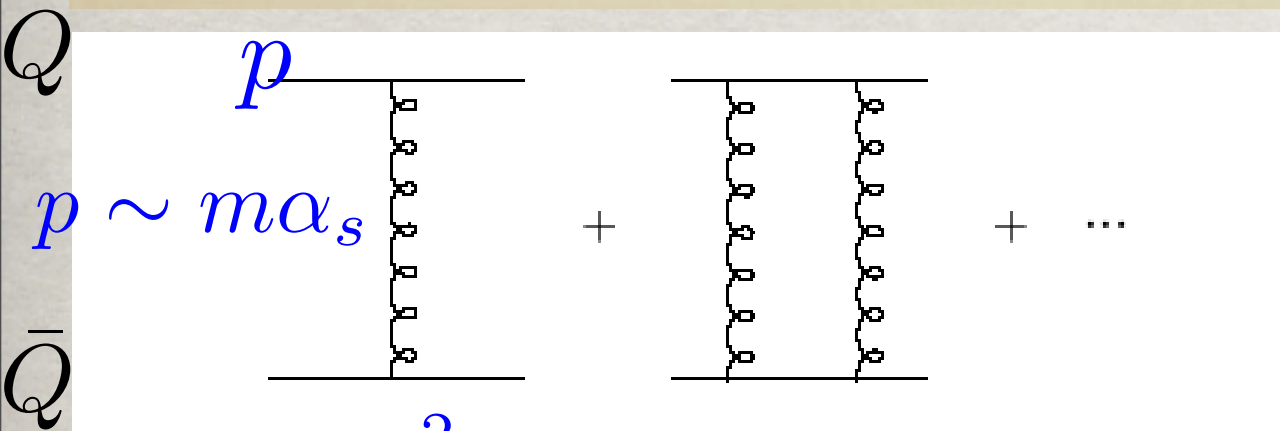
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- From $\left(\frac{p^2}{m} + V \right) \phi = E \phi \rightarrow p \sim mv$ and $E = \frac{p^2}{m} + V \sim mv^2$.



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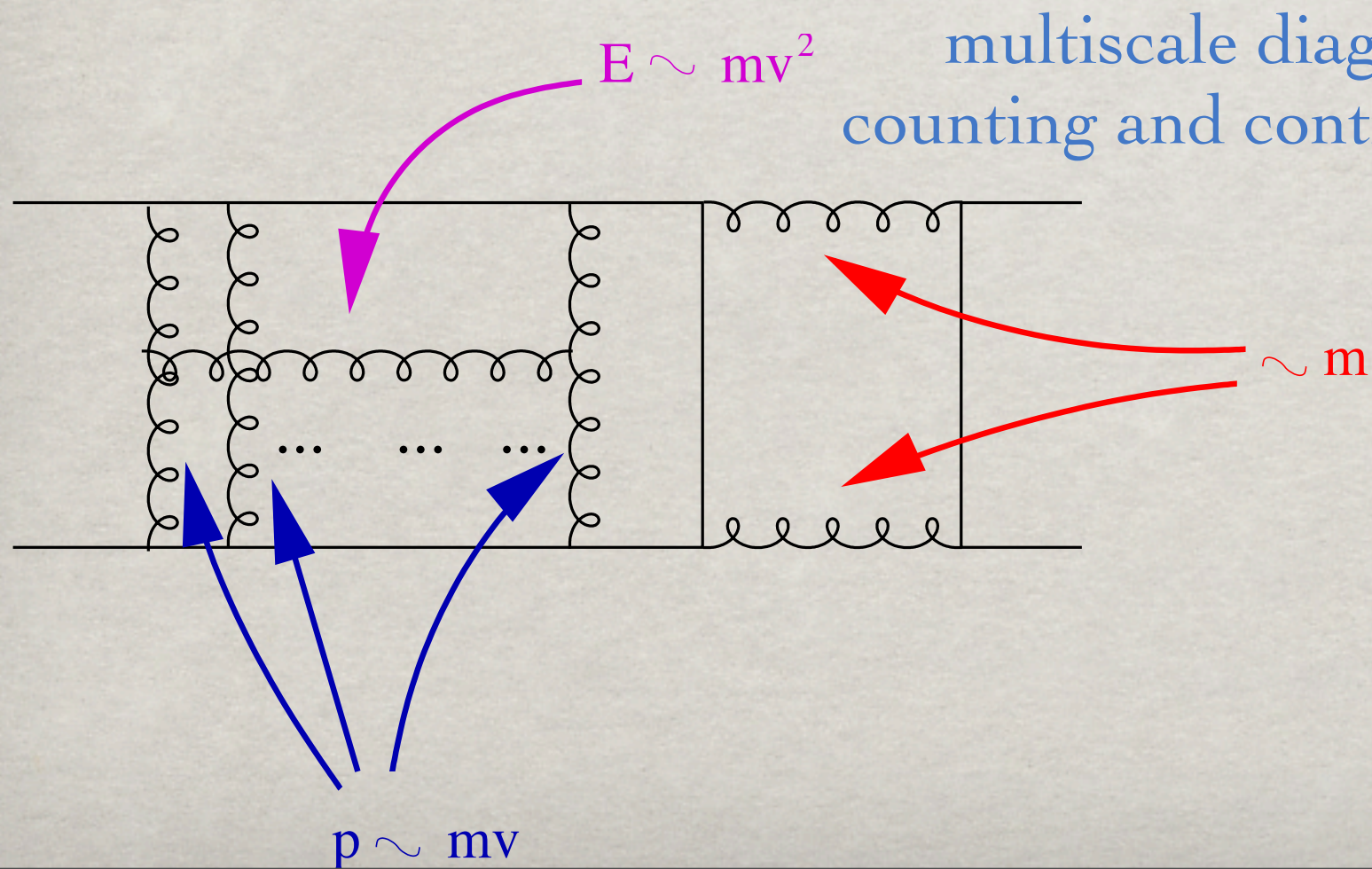
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$$\sim \frac{1}{E - \left(\frac{p^2}{m} + V\right)}$$

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

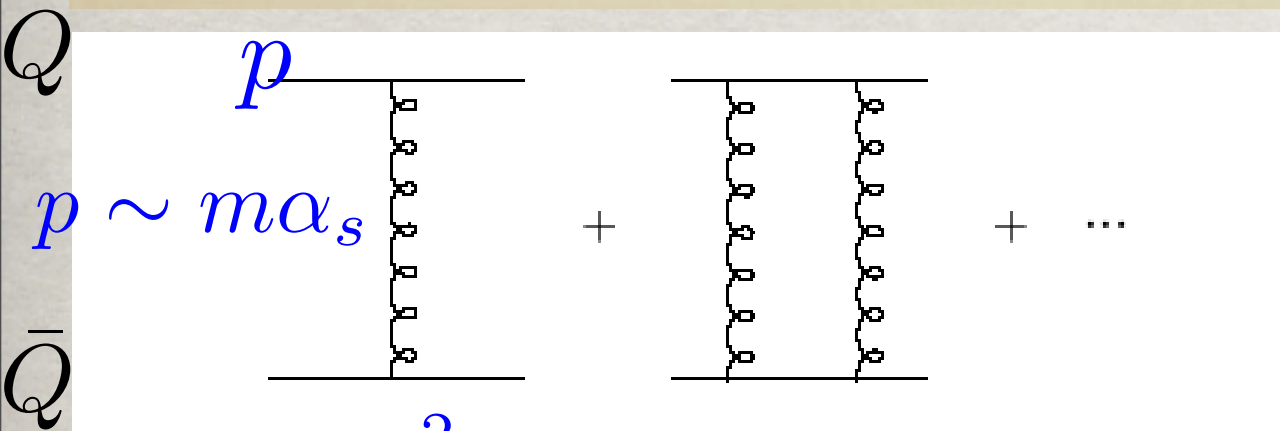
- From $\left(\frac{p^2}{m} + V\right)\phi = E\phi \rightarrow p \sim mv$ and $E = \frac{p^2}{m} + V \sim mv^2$.



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

QCD theory of Quarkonium: a very hard problem

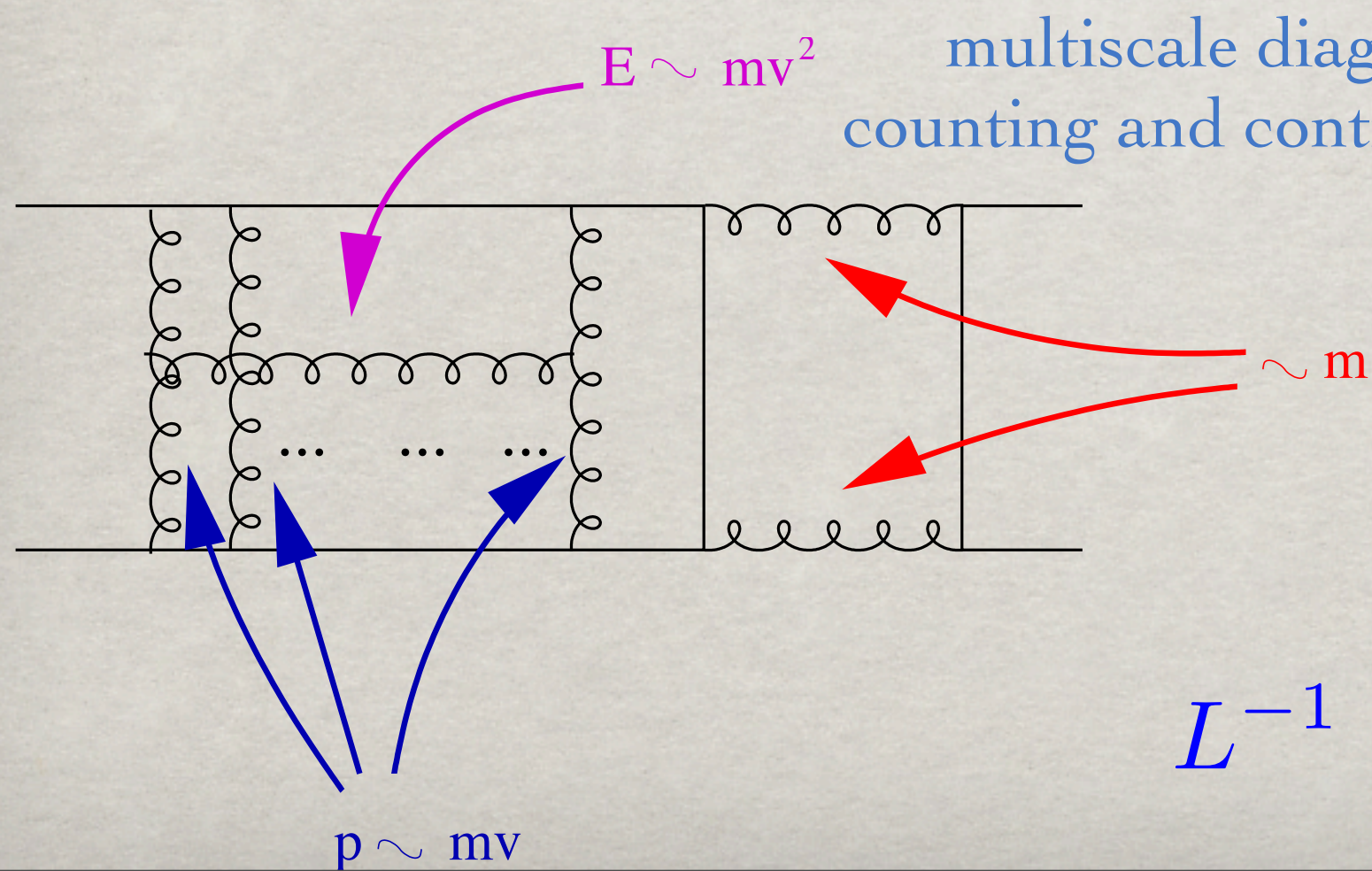
Close to the bound state $\alpha_s \sim v$



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

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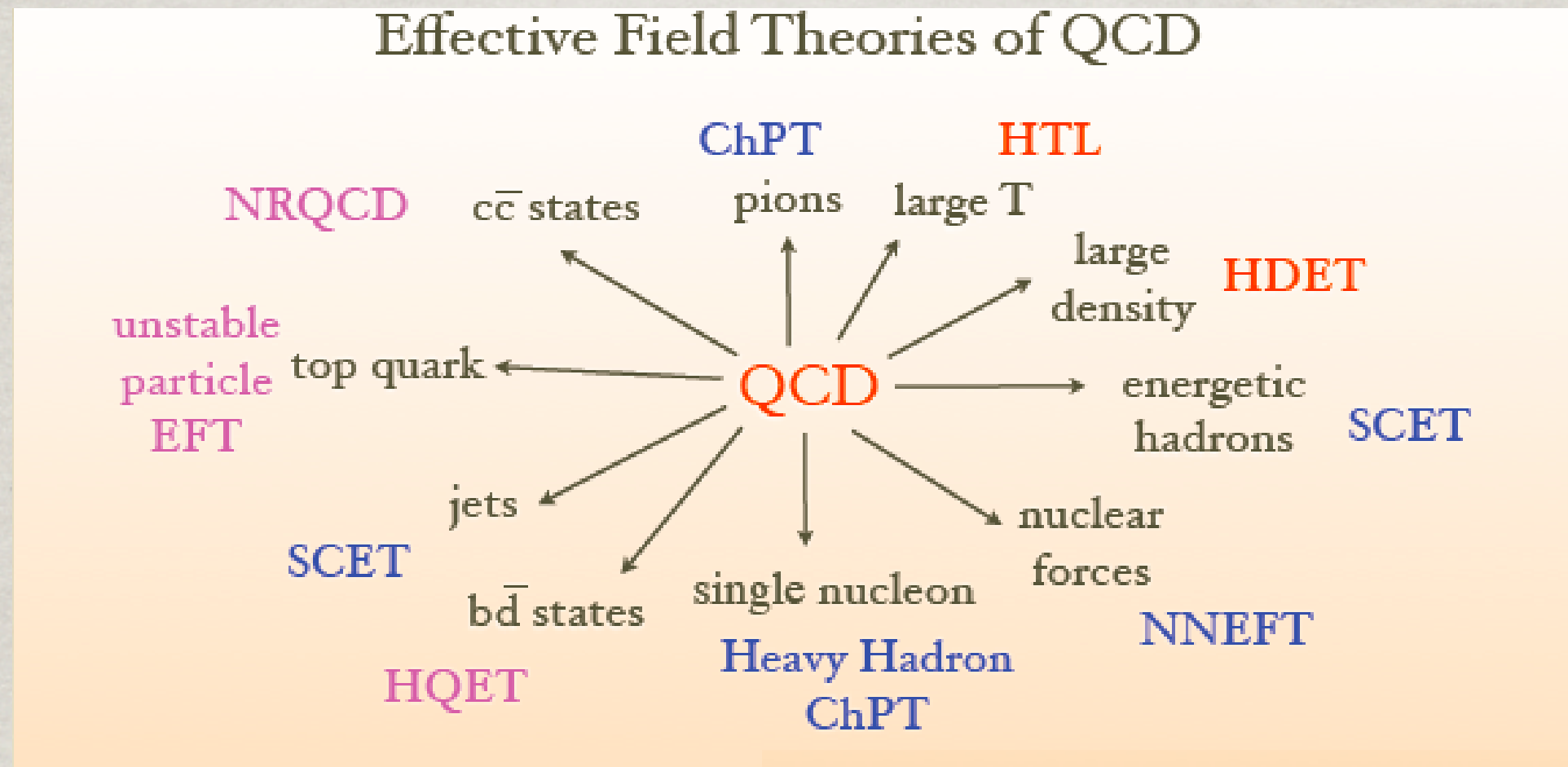
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Difficult also
for the lattice!

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

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

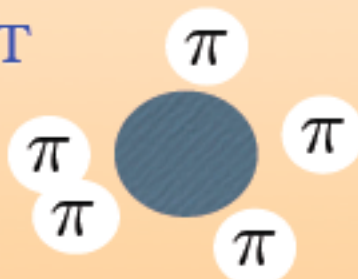


- Heavy quark effective theory (HQET): $\frac{\lambda}{\Lambda} = \frac{\Lambda_{\text{QCD}}}{m}$

Soft-Collinear Effective Theory (SCET)



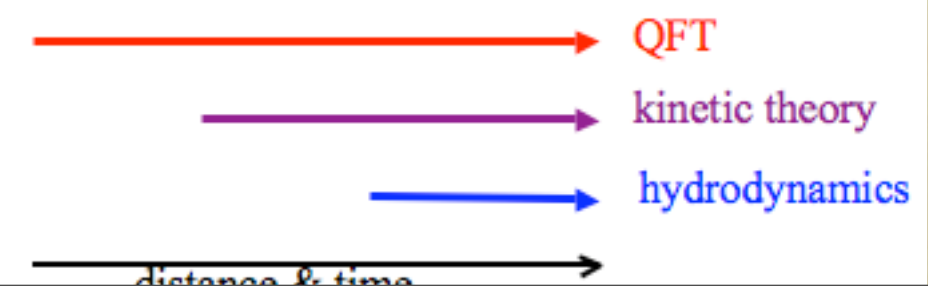
ChPT



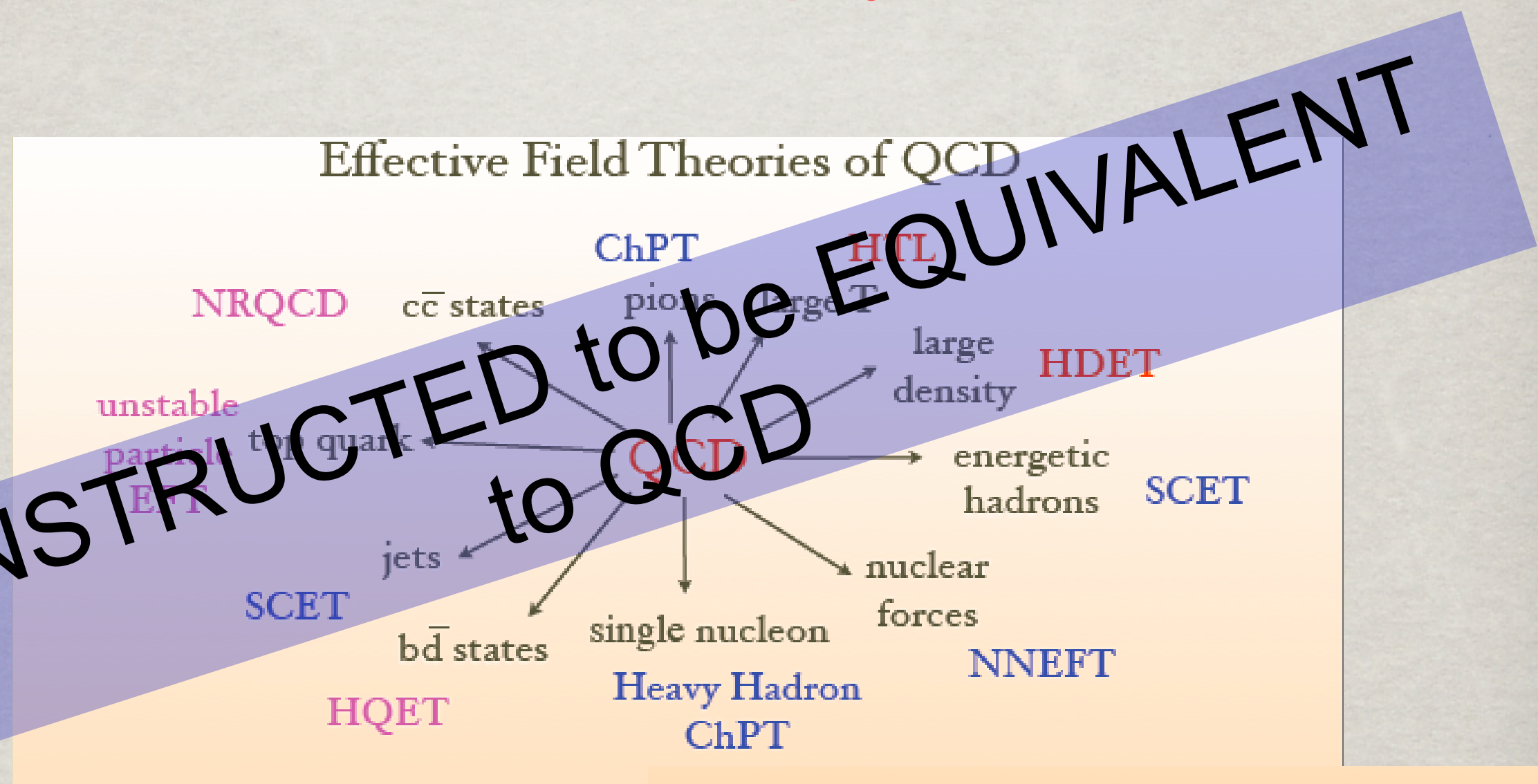
$$\frac{m_\pi}{\Lambda} \ll 1$$

$$\frac{p}{\Lambda} \ll 1$$

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

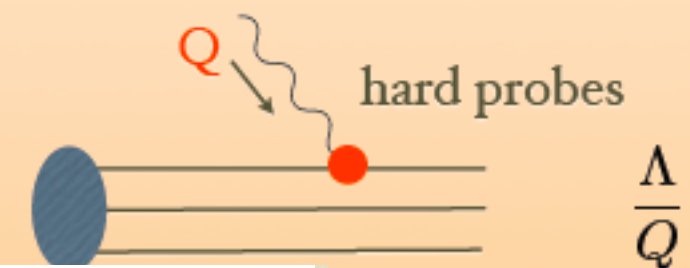


QCD Effective Field Theories to address the research frontier of hadronic physics

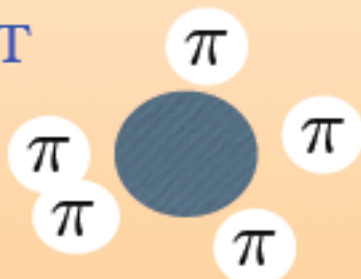


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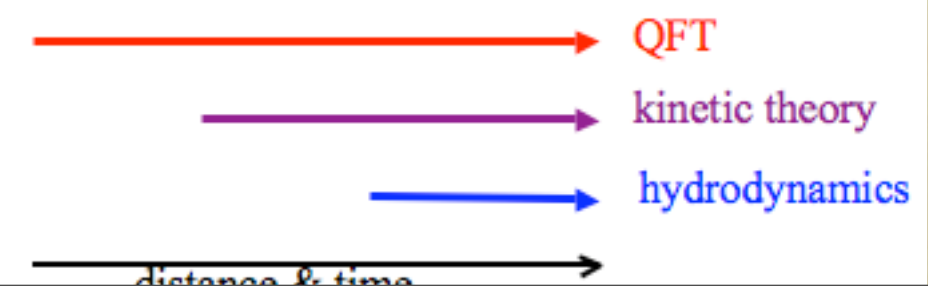
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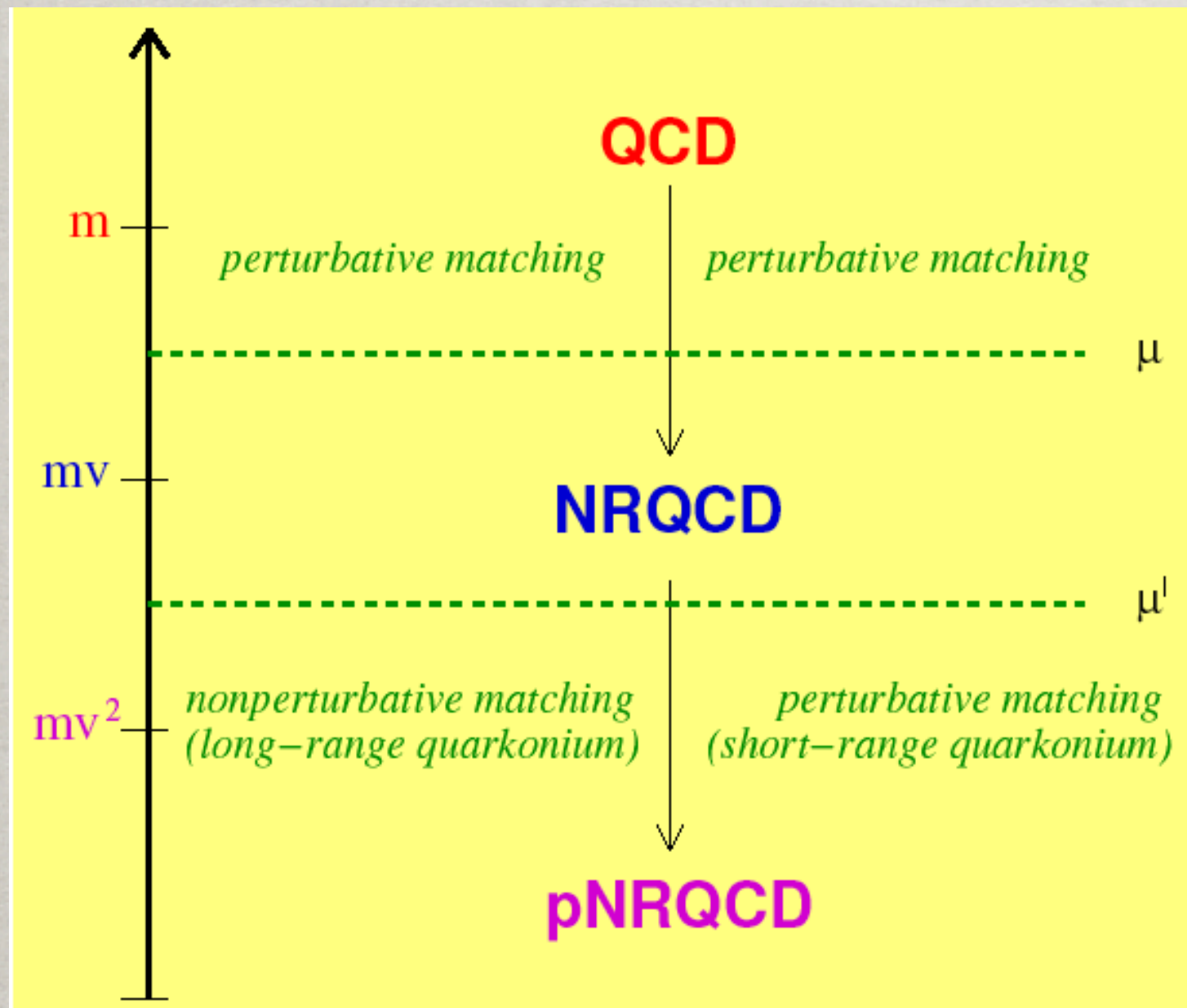
Quarkonium with Non Relativistic EFT

Color degrees of freedom
 $3 \times 3 = 1 + 8$
singlet and octet $Q\bar{Q}$

Hard

Soft
(relative momentum)

Ultrasoft
(binding energy)



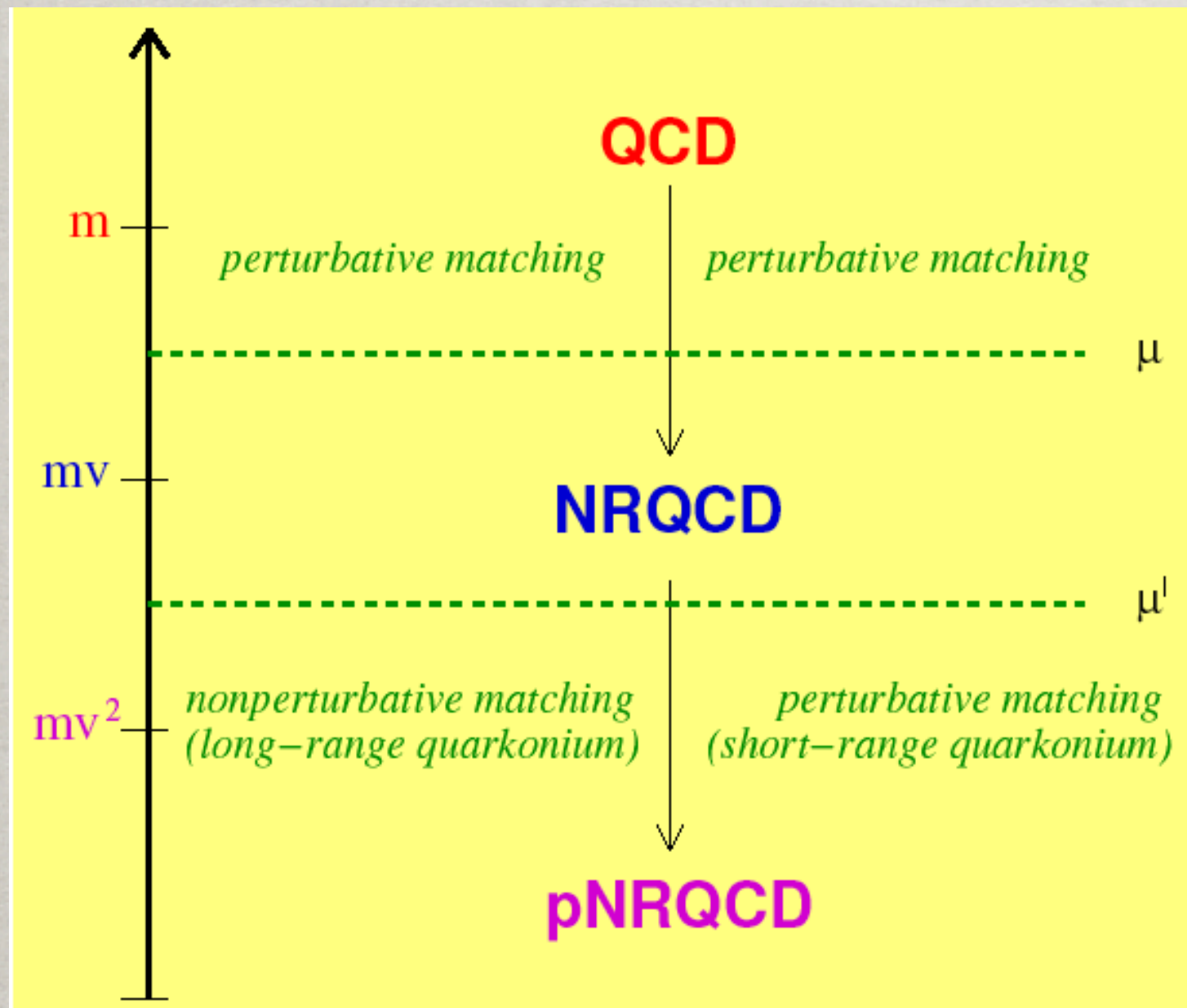
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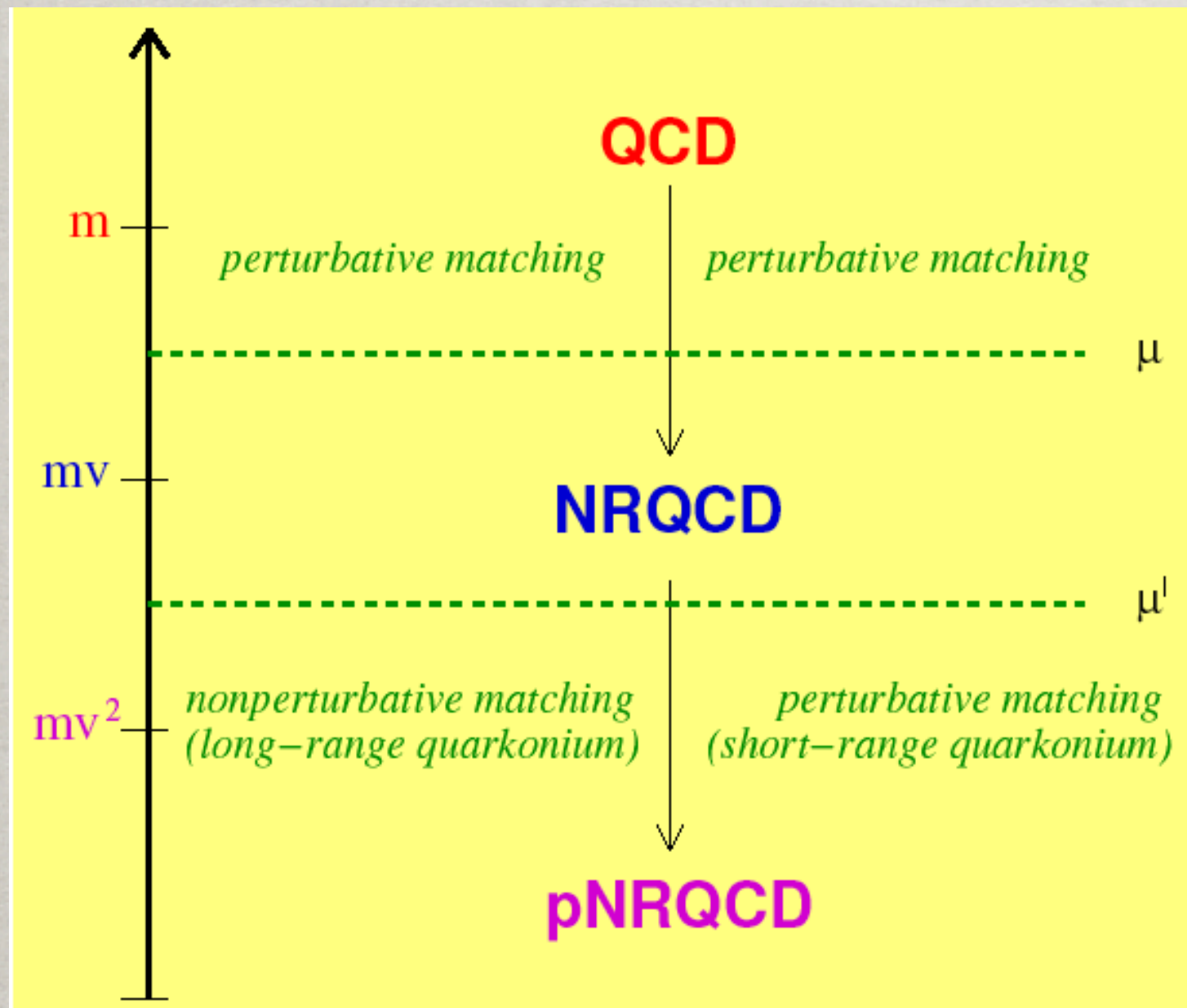
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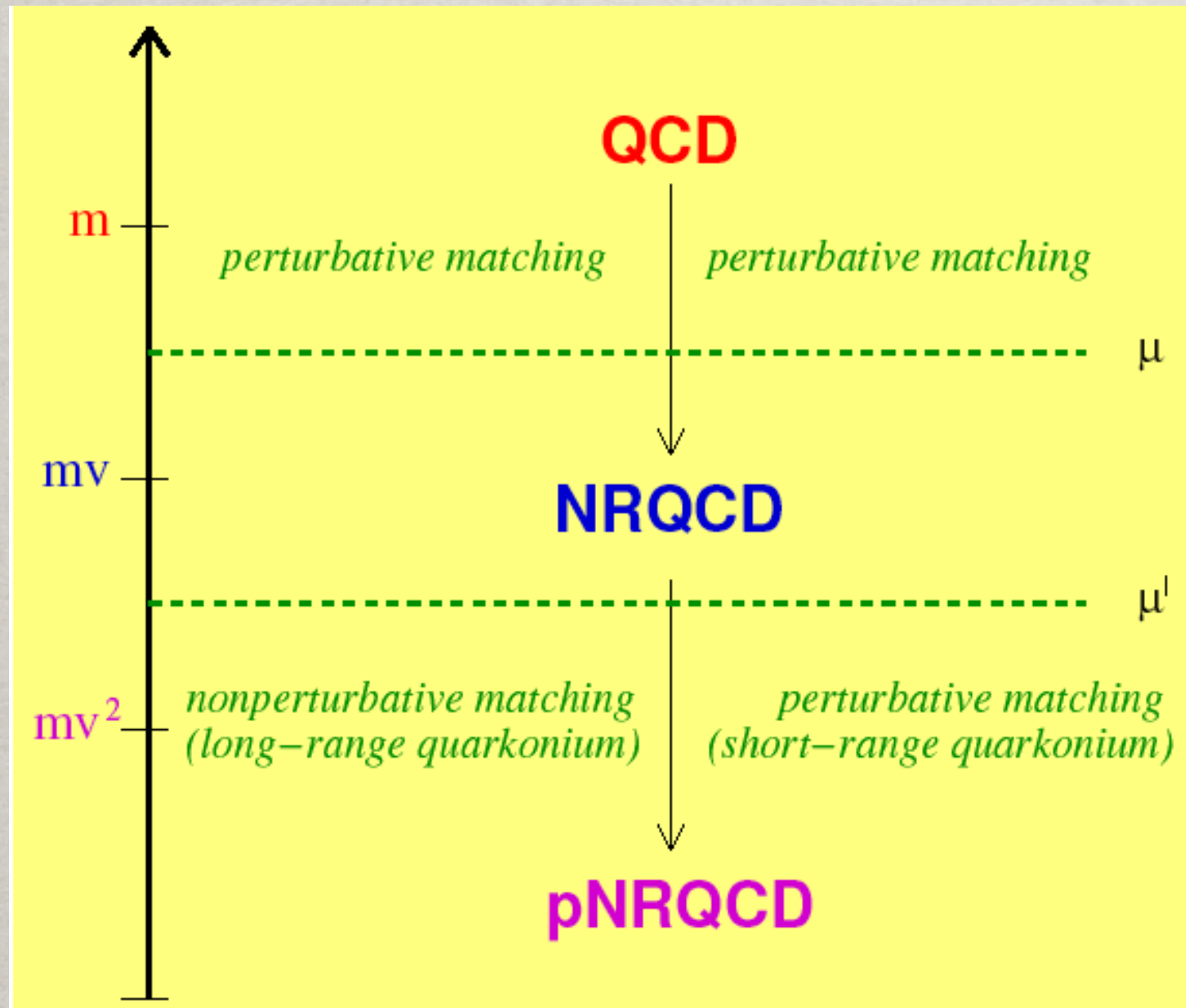
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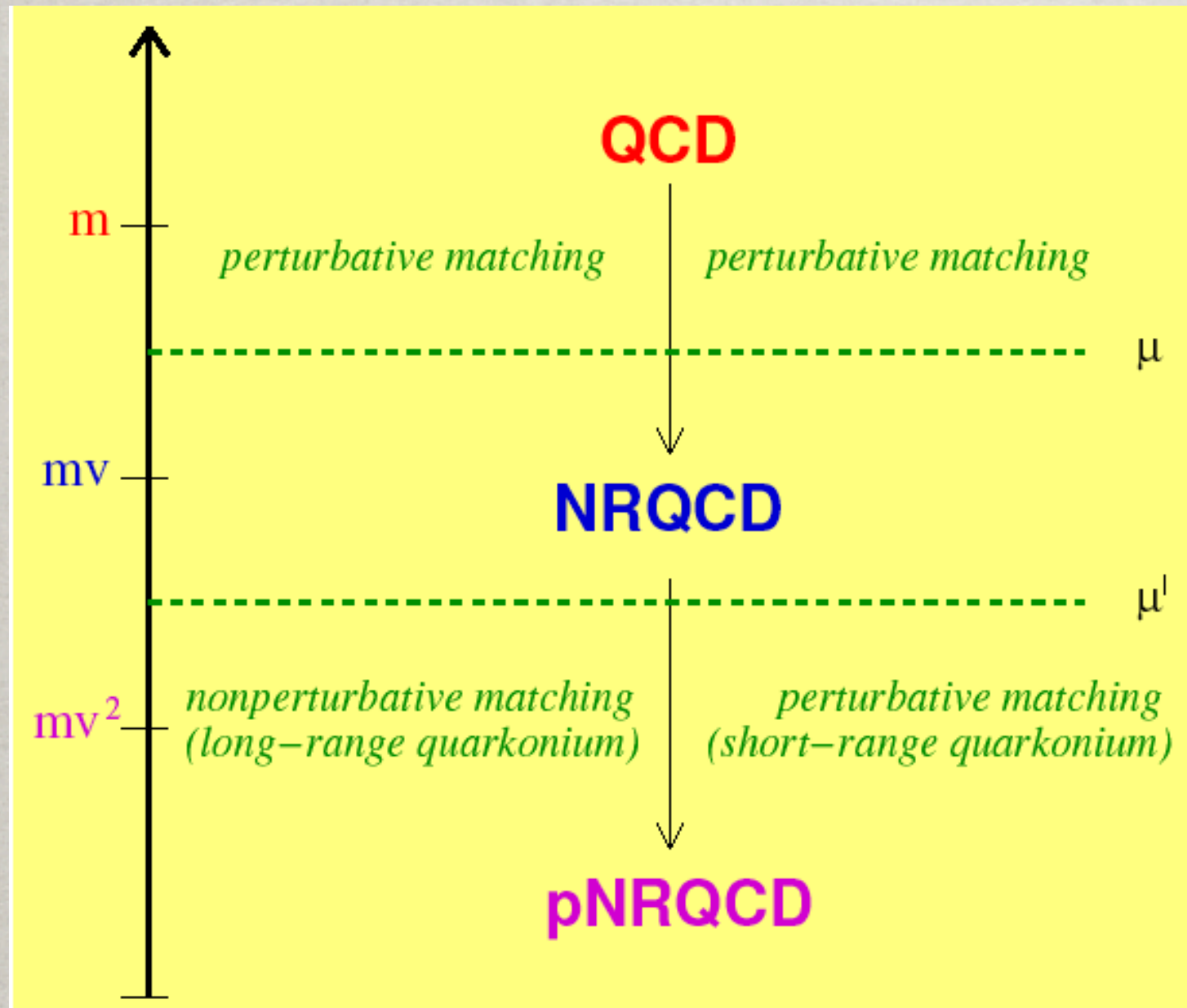
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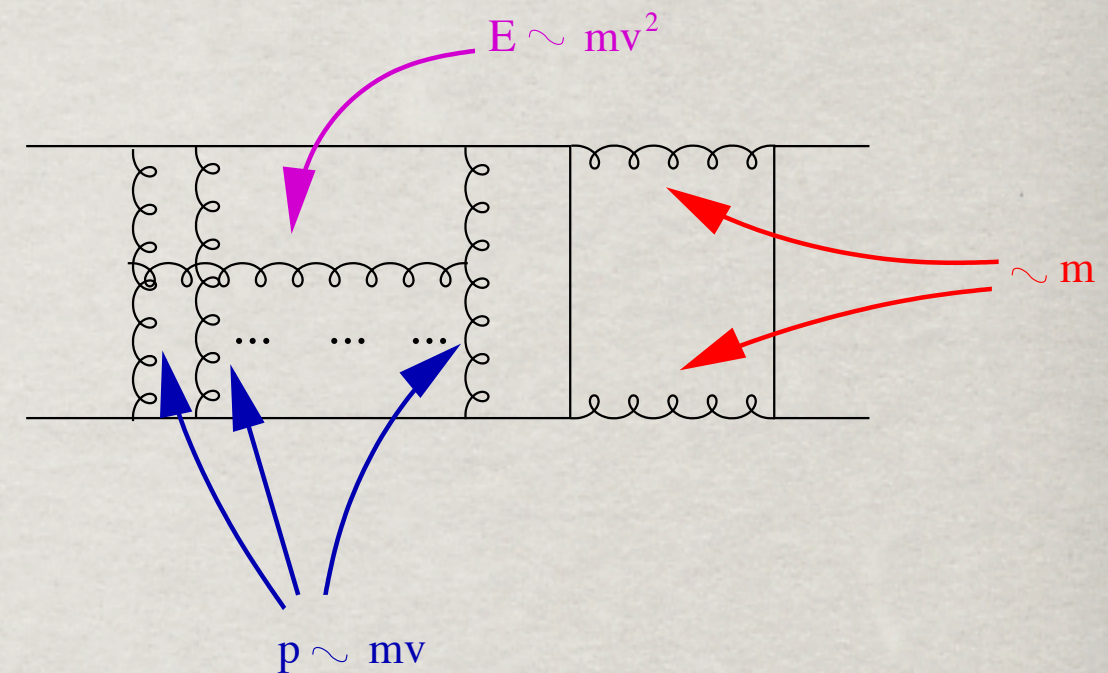
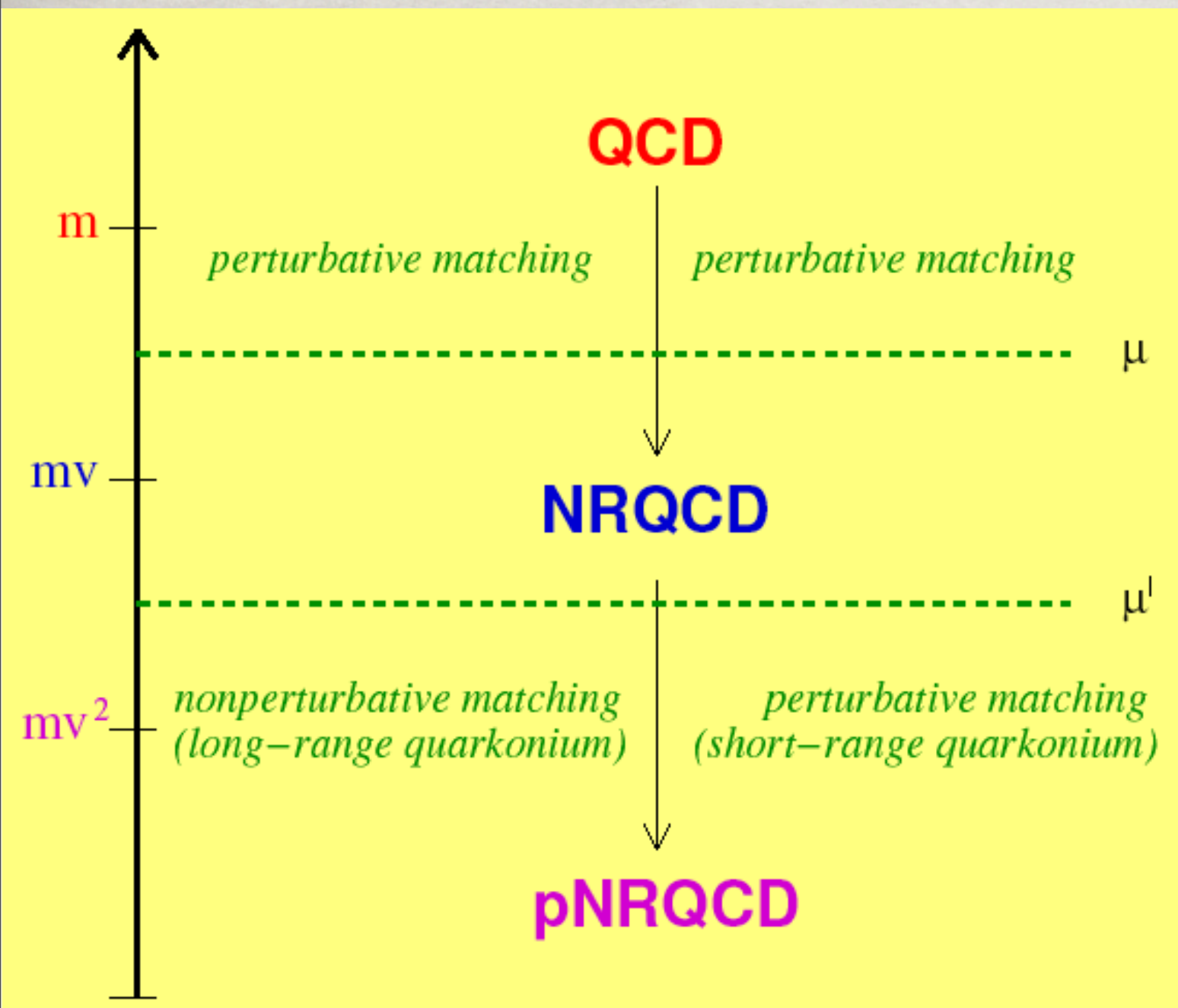
$$\frac{E_\lambda}{E_\Lambda} = \frac{mv^2}{mv}$$

Ultrasoft
 (binding energy)

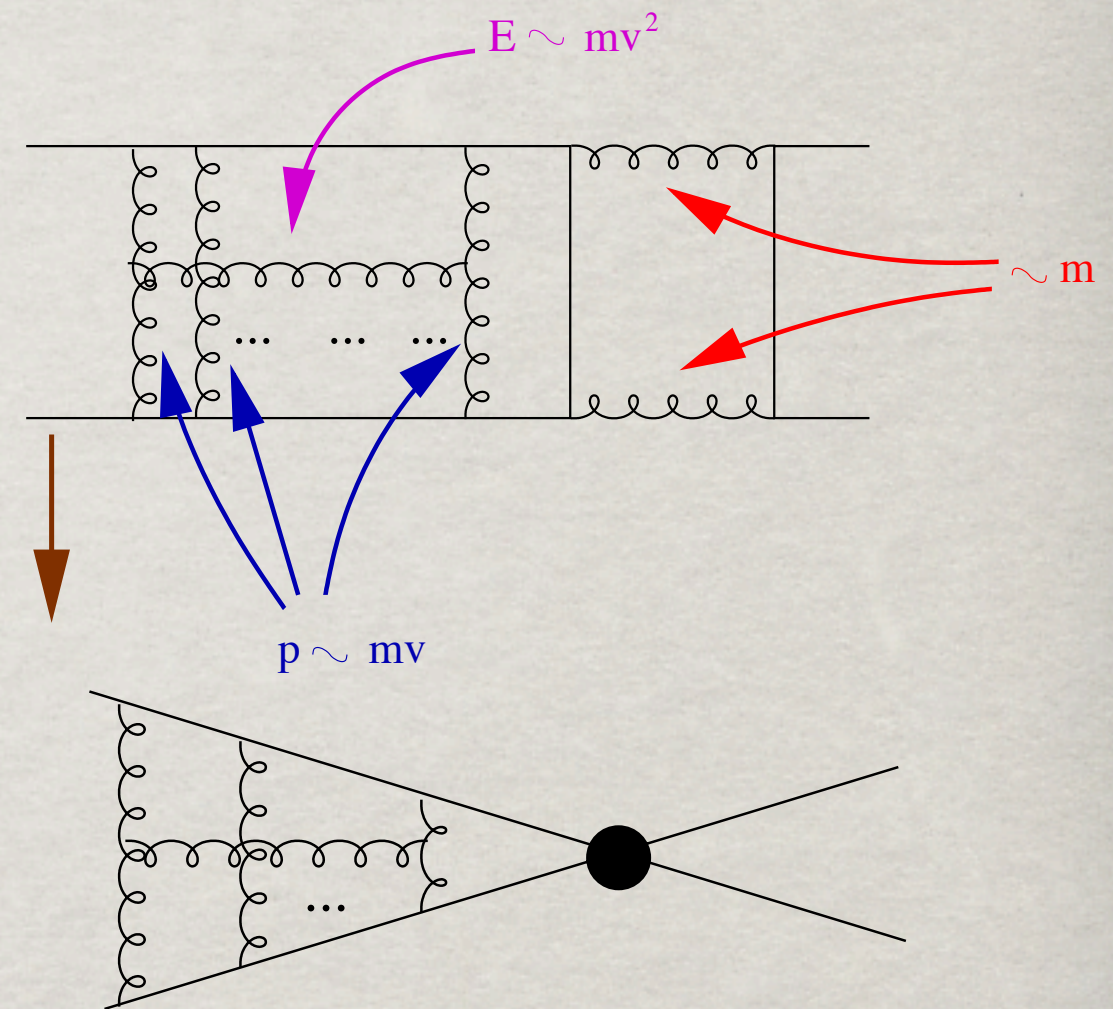
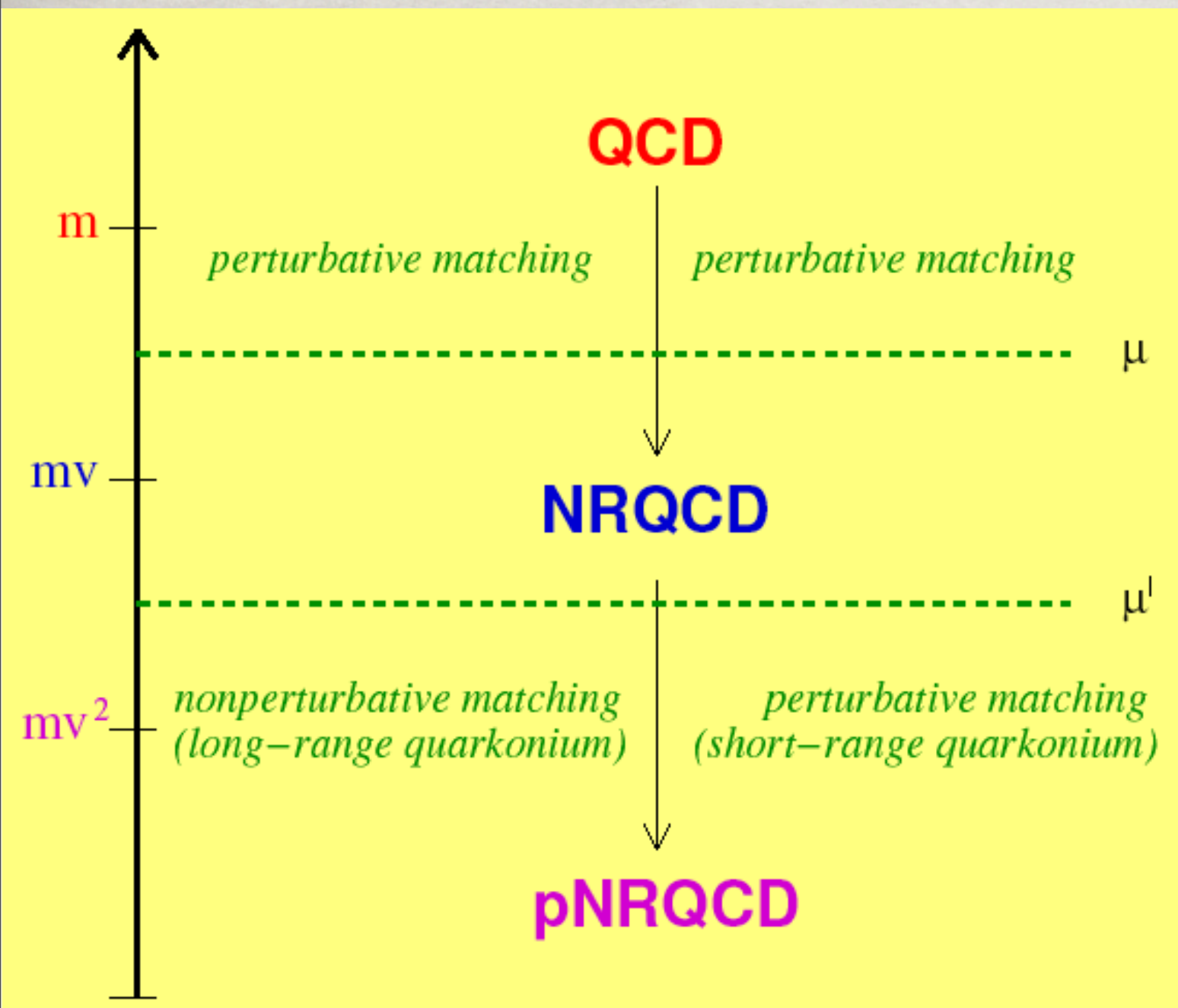
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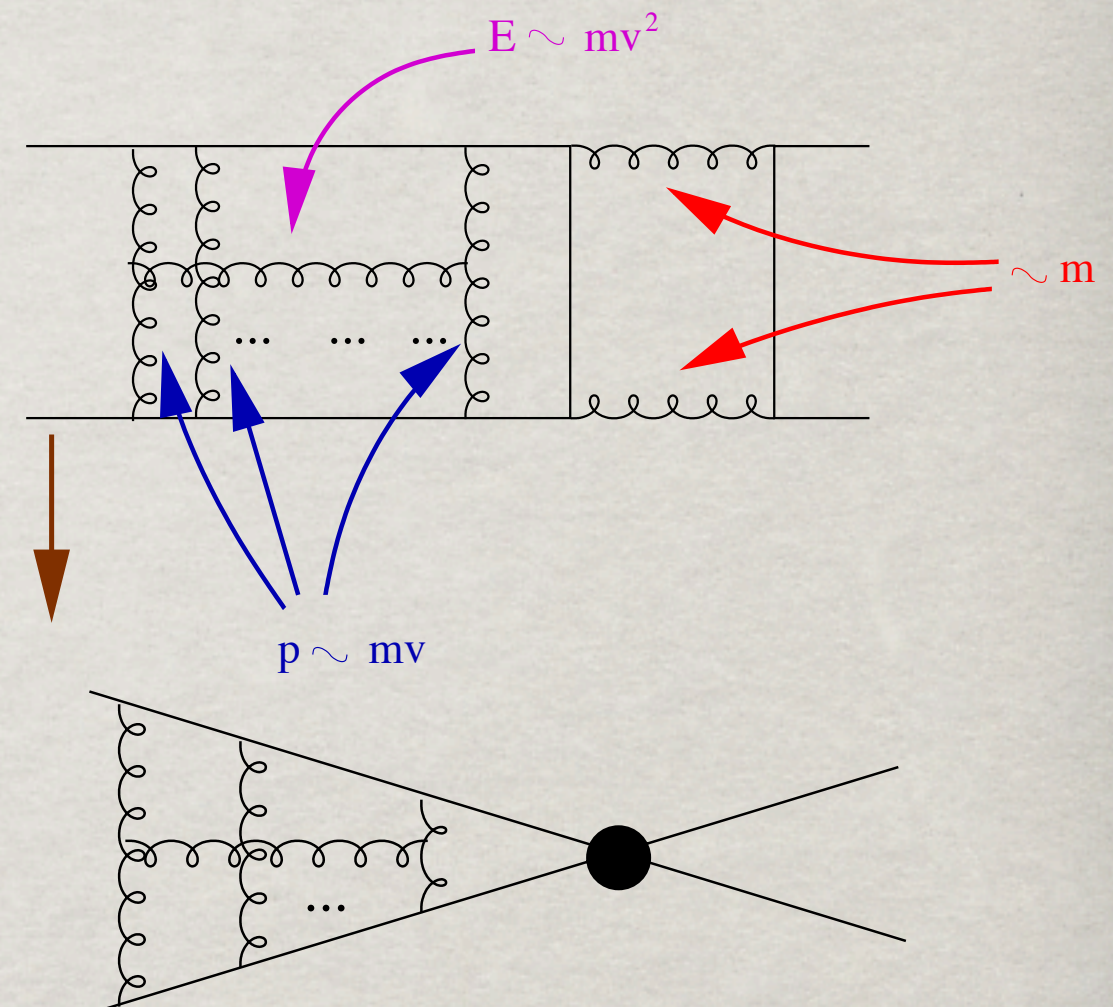
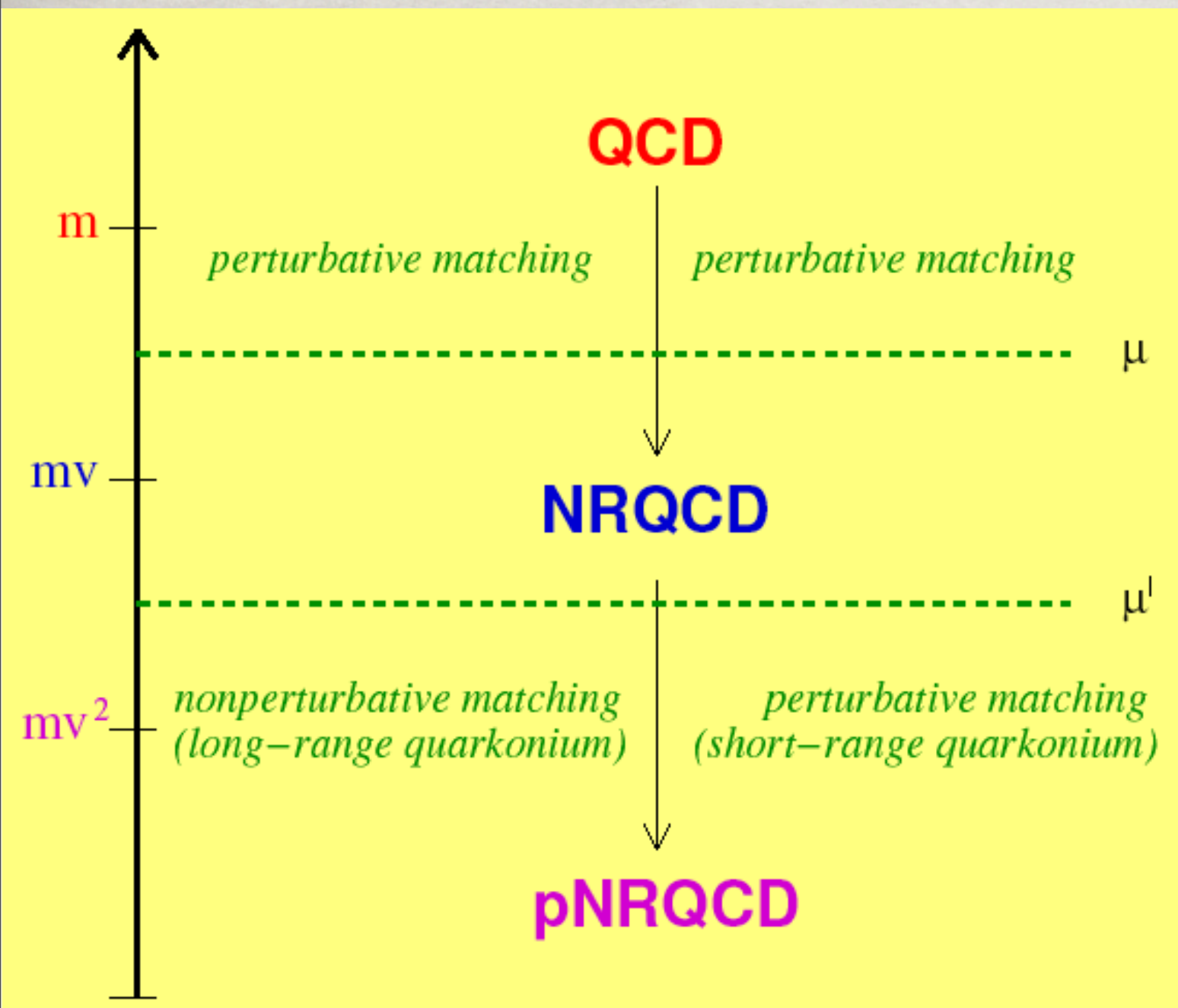
Quarkonium with NR EFT: Non Relativistic QCD (NRQCD)



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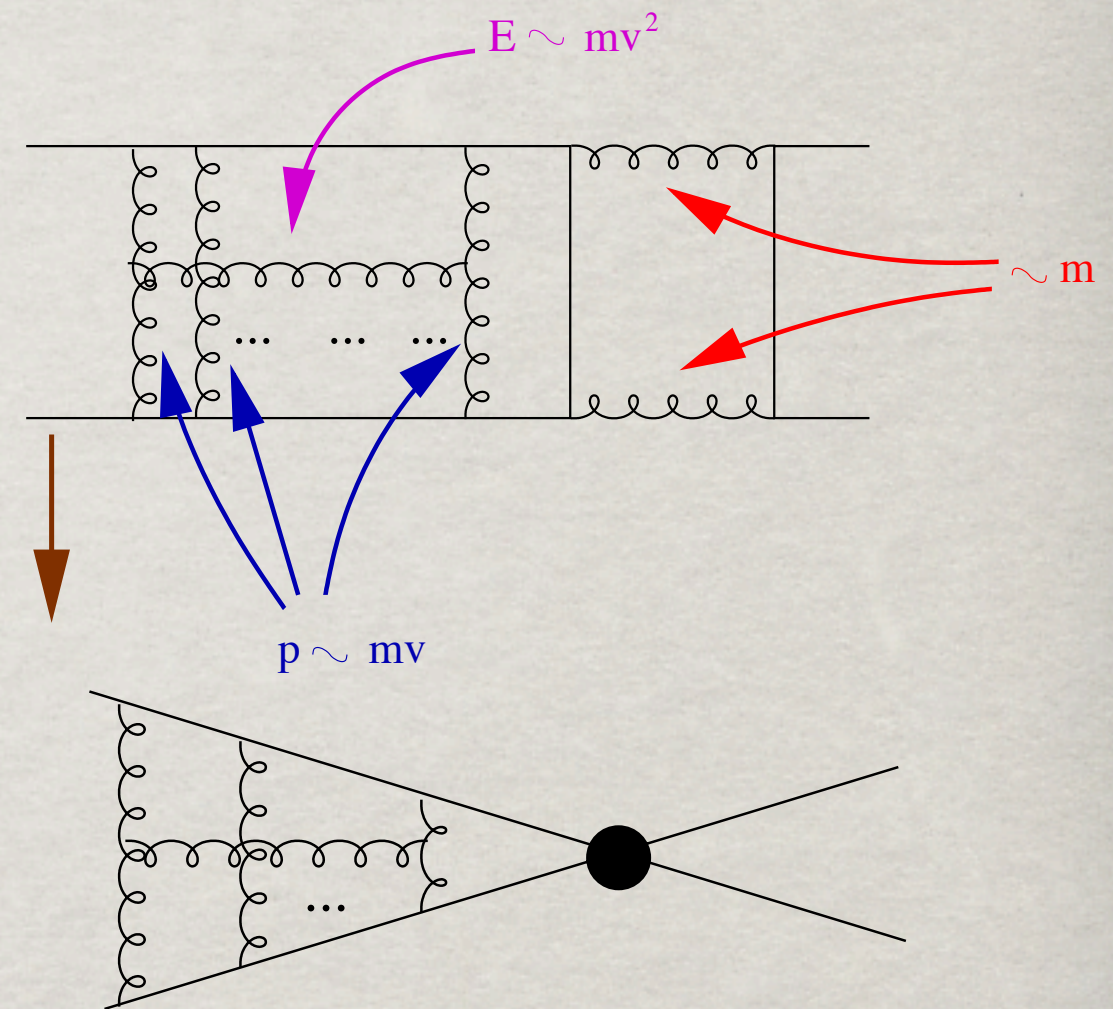
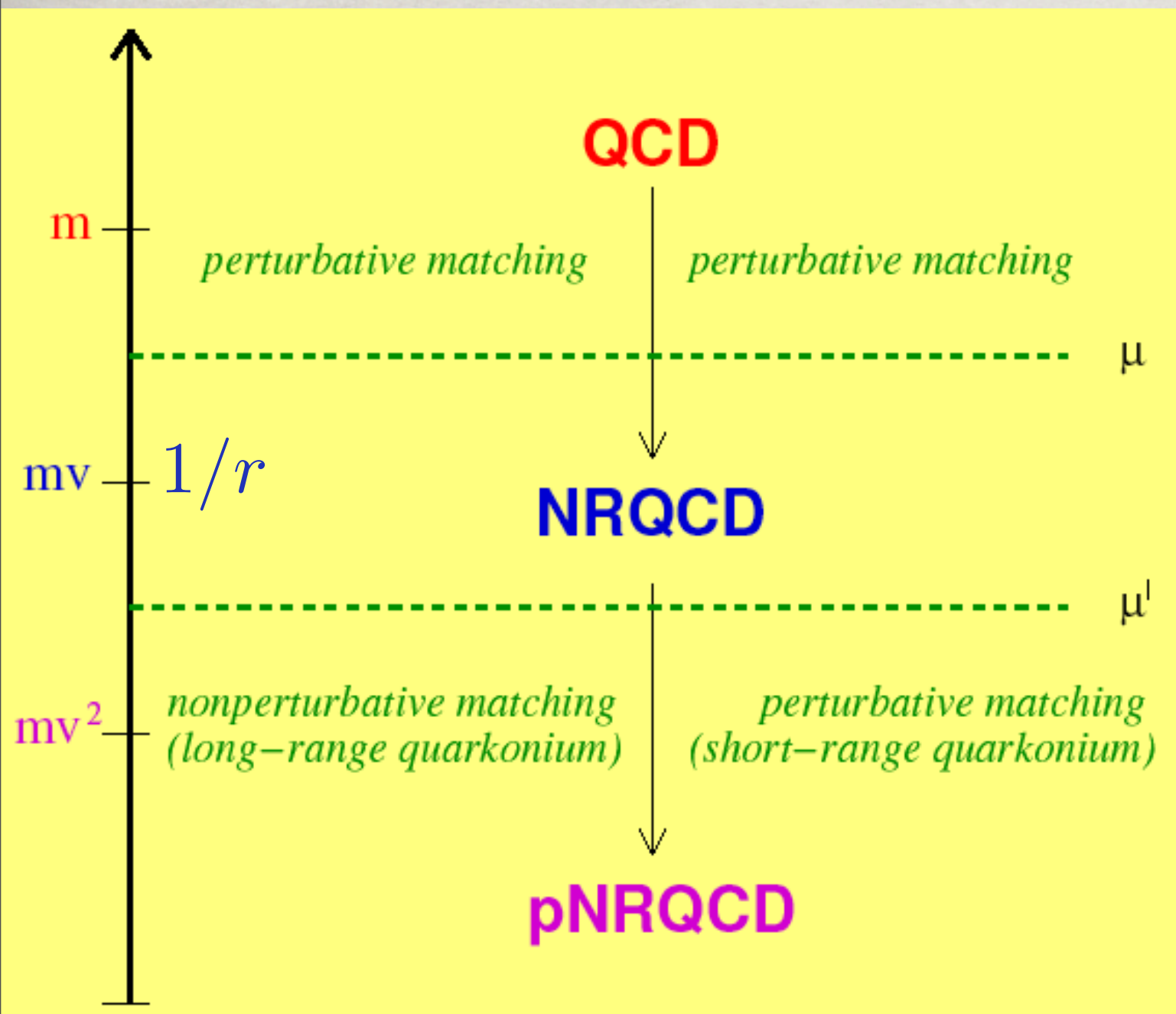


Quarkonium with NR EFT: Non Relativistic QCD (NRQCD)

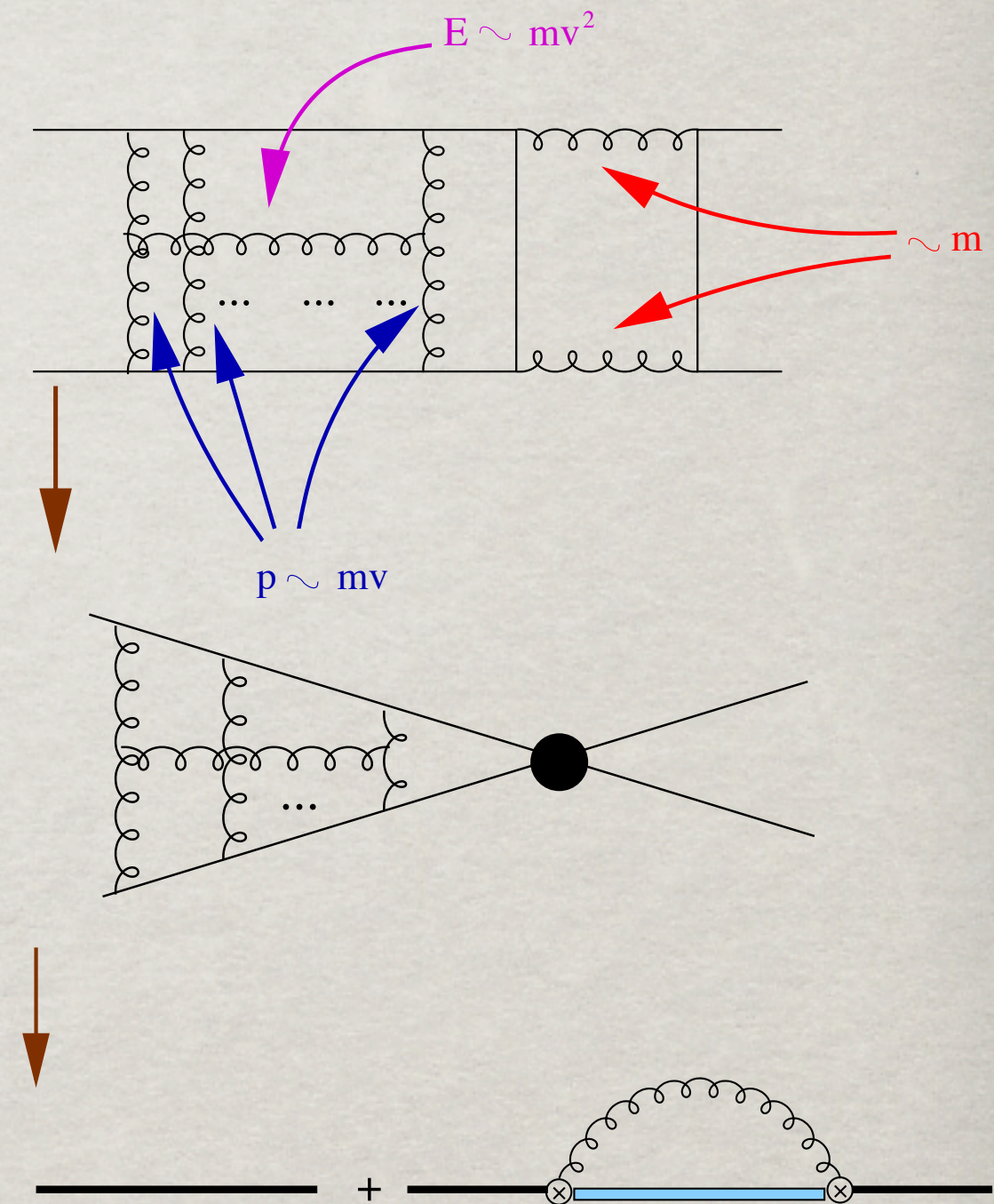
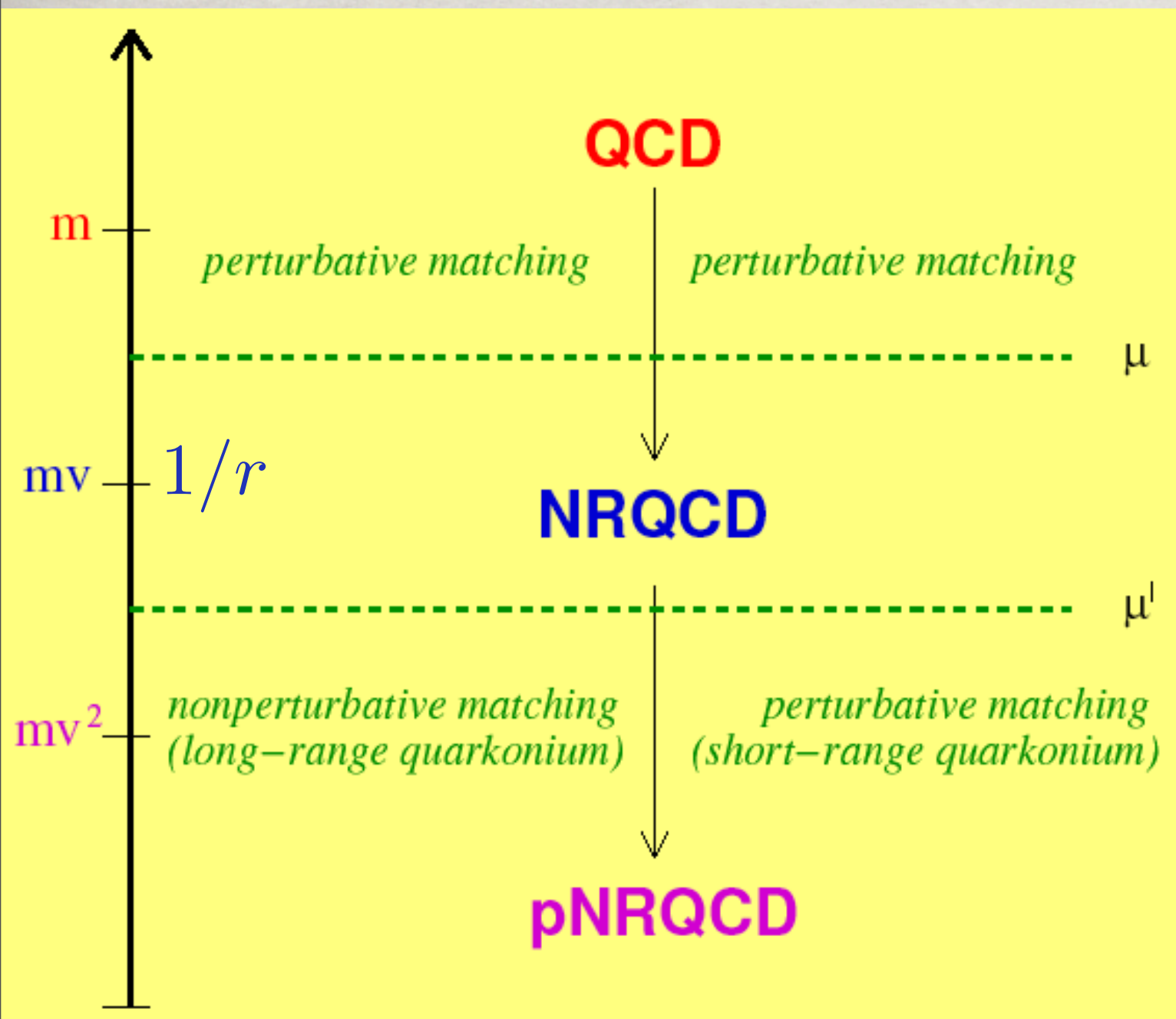


$$\mathcal{L}_{\text{NRQCD}} = \sum_n c(\alpha_s(m/\mu)) \times \frac{O_n(\mu, \lambda)}{m^n}$$

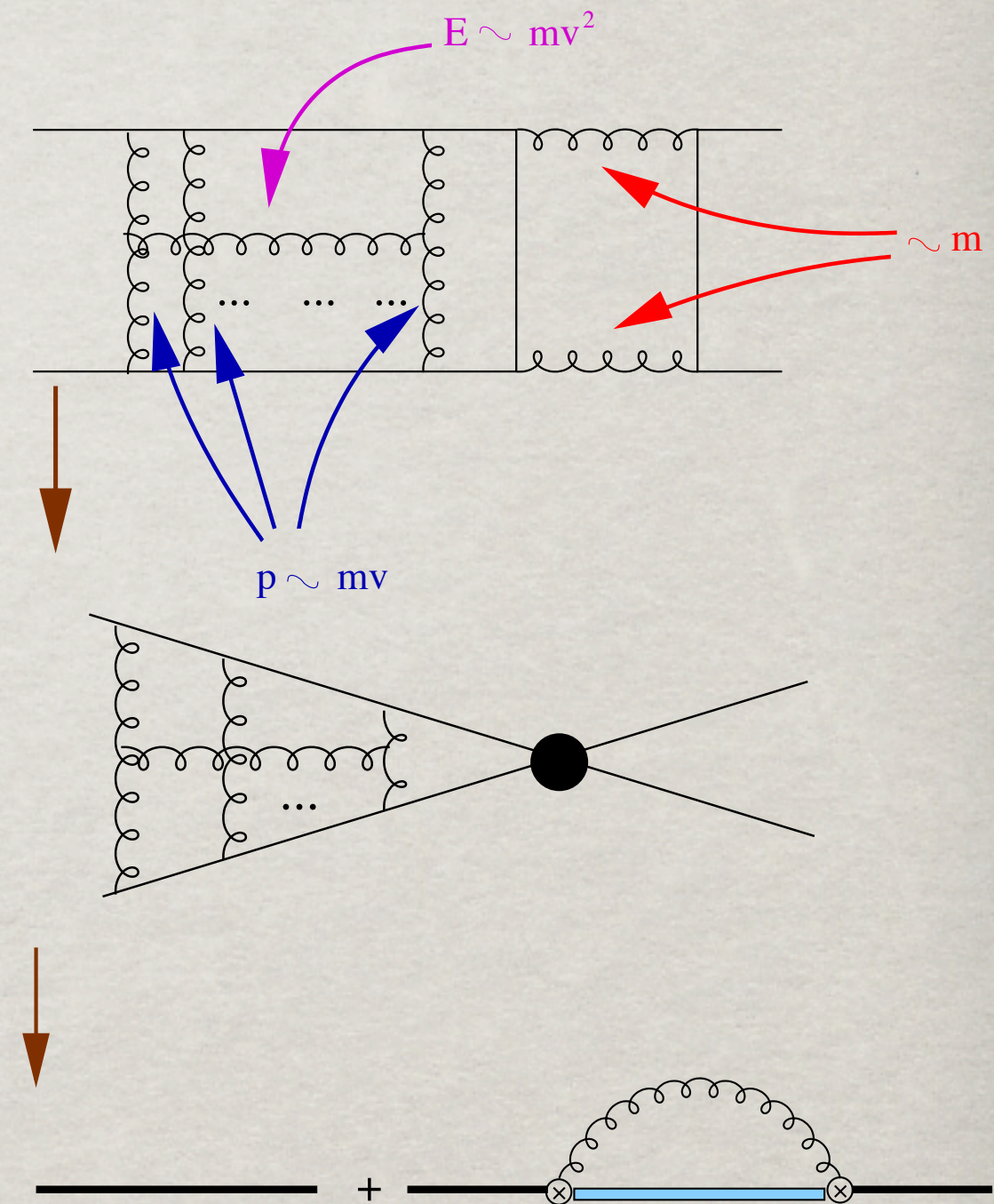
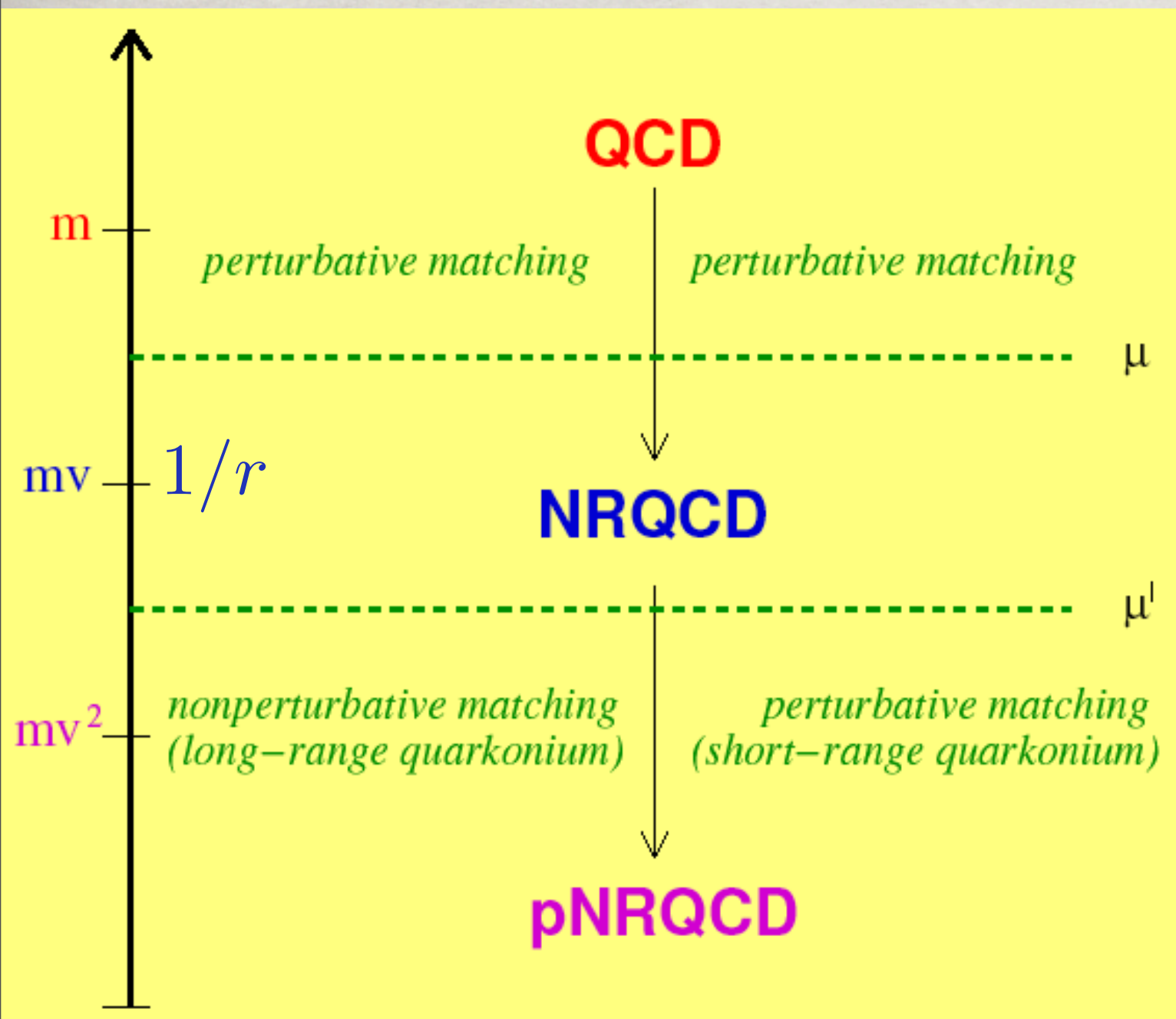
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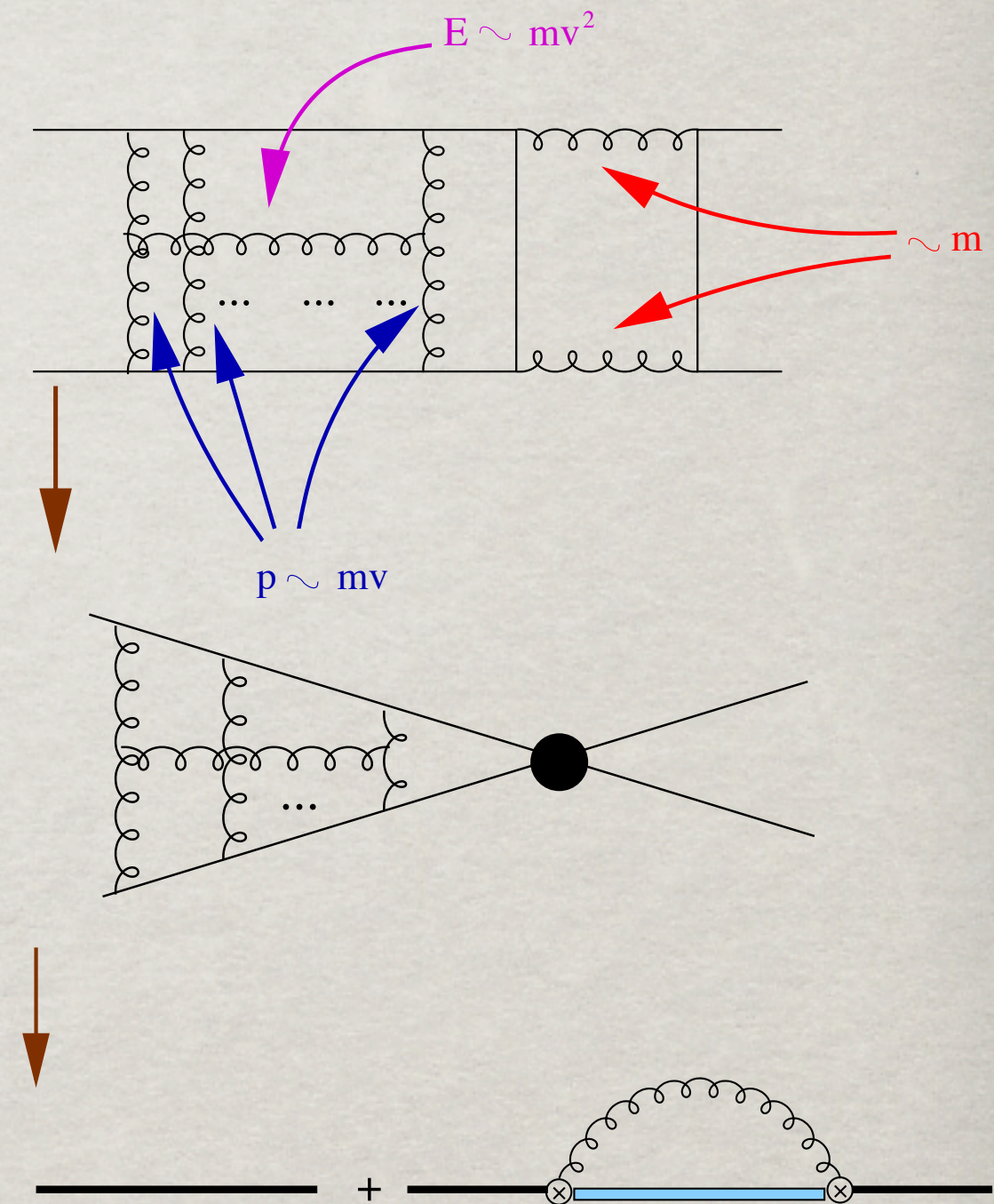
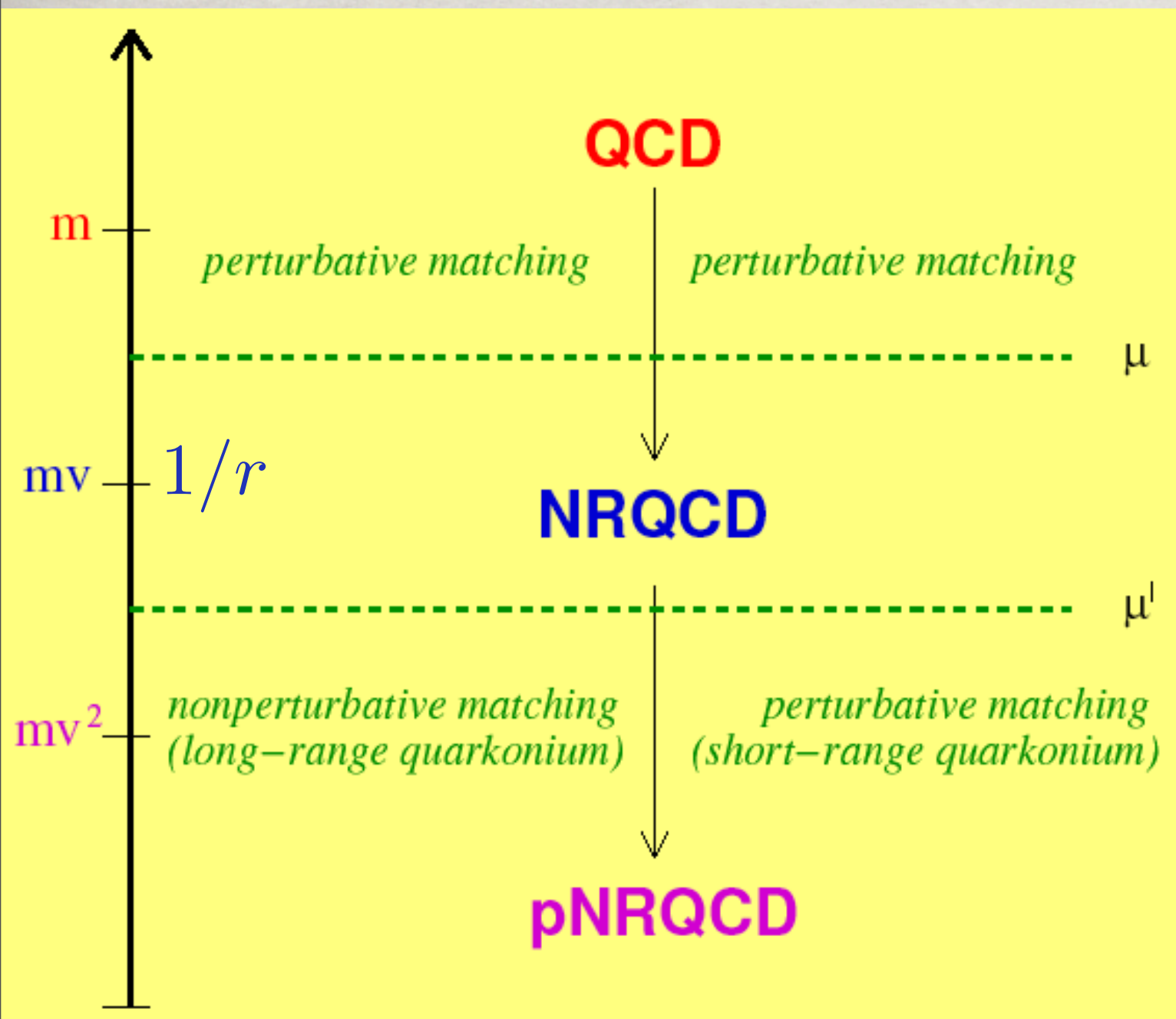


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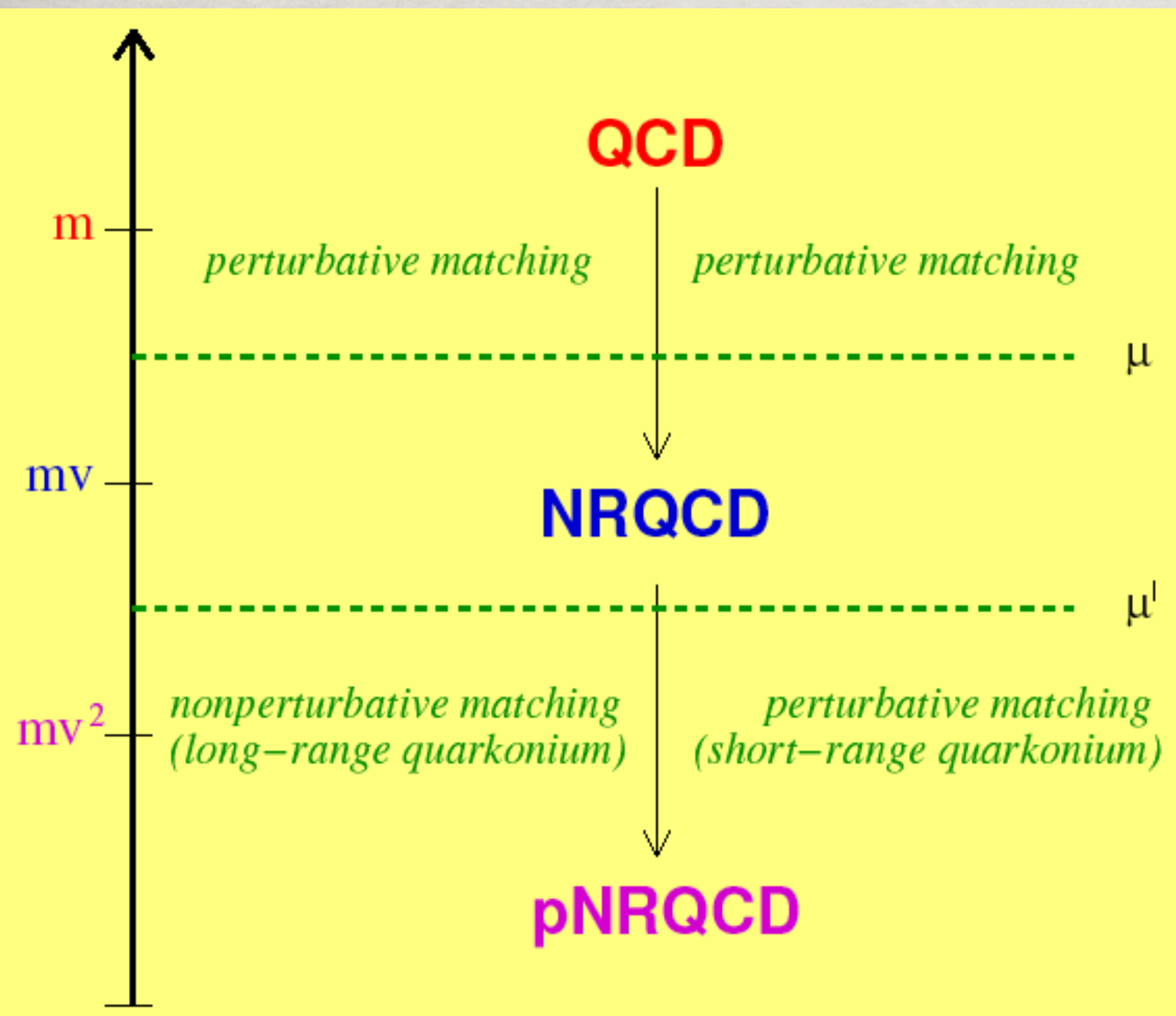
$$\mathcal{L}_{\text{pNRQCD}} = \sum_k \sum_n \frac{1}{m^k} c_k(\alpha_s(m/\mu)) \times V(r\mu', r\mu) \times O_n(\mu', \lambda) r^n$$

Quarkonium with NR EFT: potential NonRelativistic QCD (pNRQCD)



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

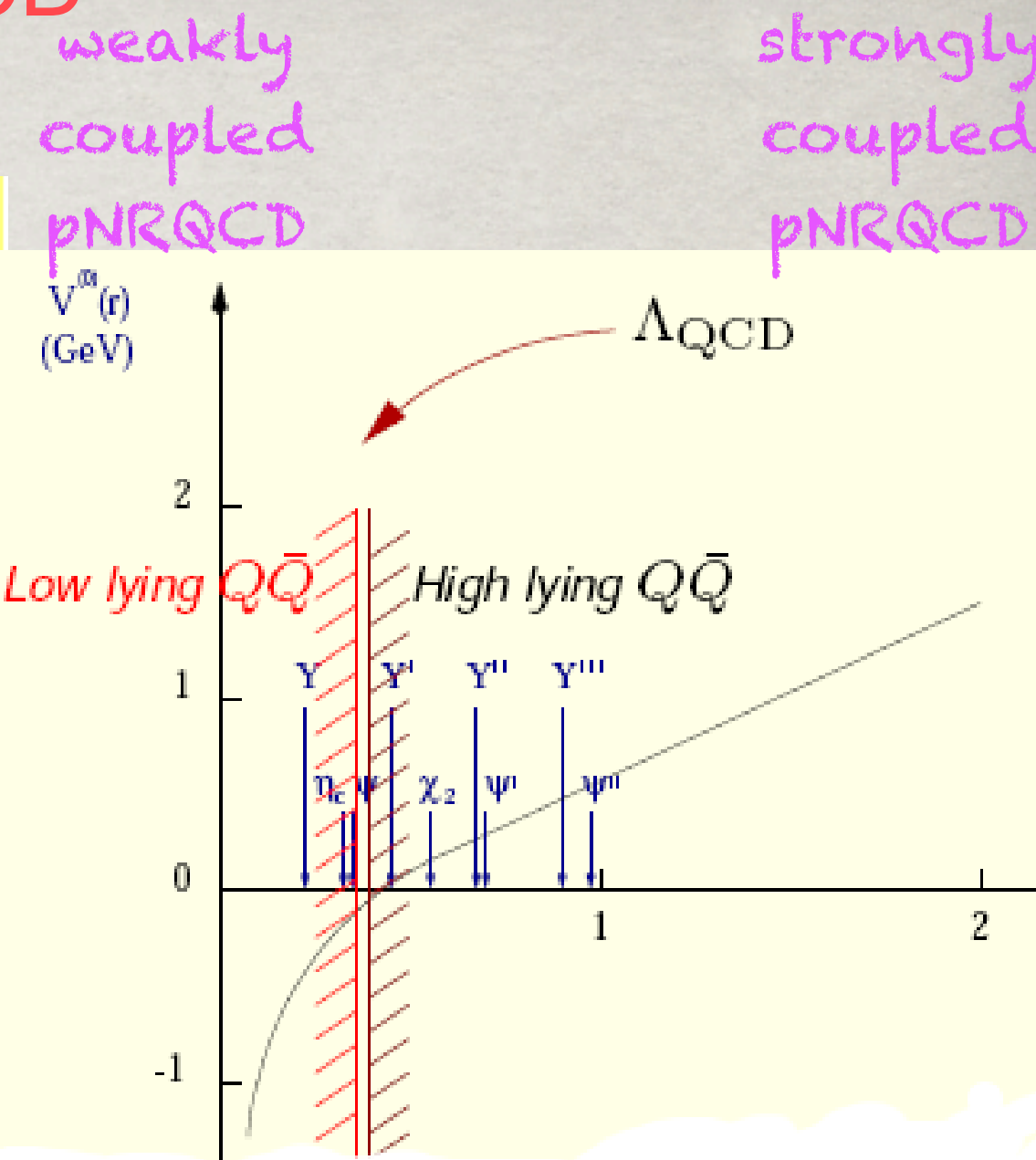
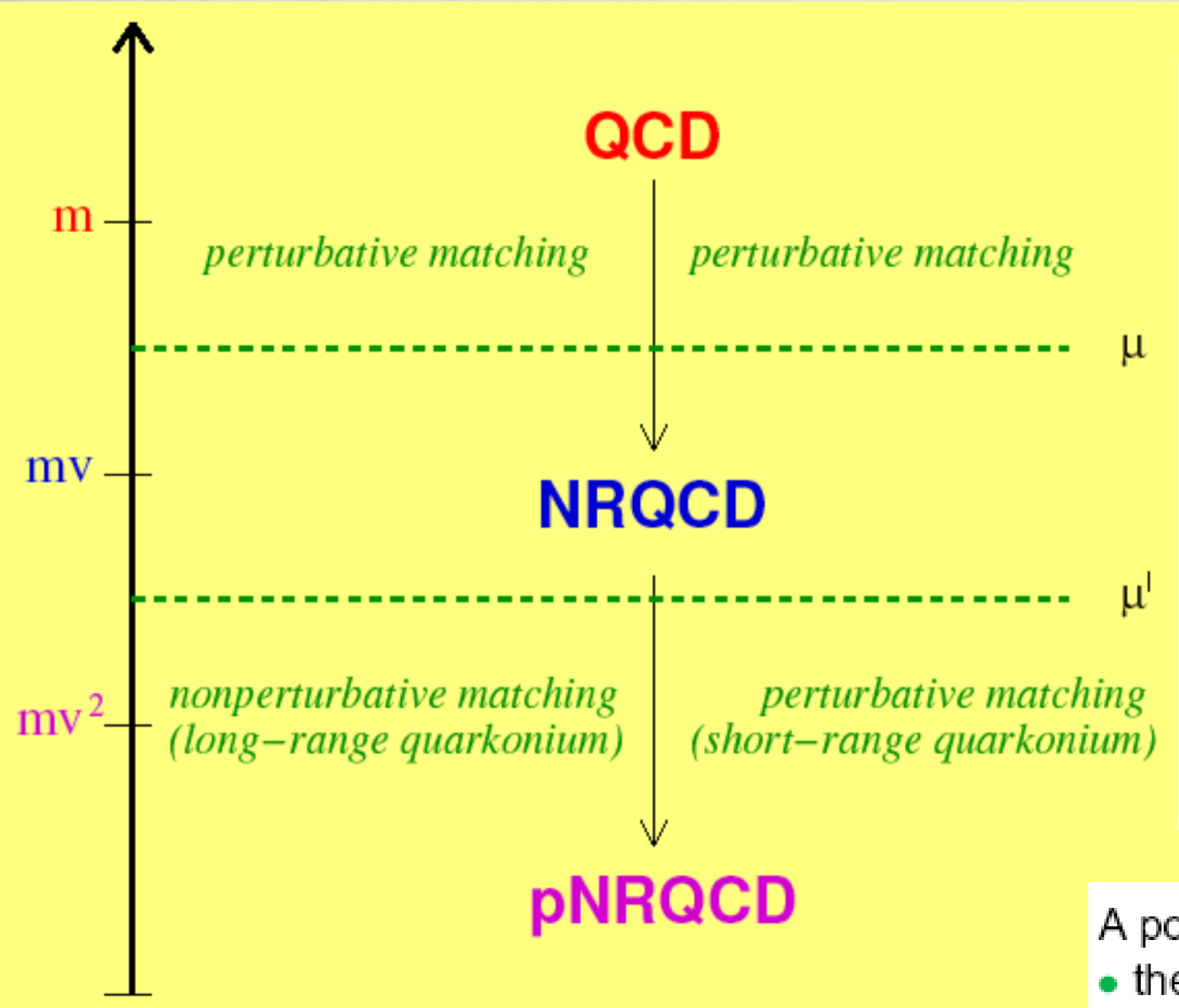
Quarkonium with NR EFT: pNRQCD



In QCD another scale is relevant

$$\Lambda_{\text{QCD}}$$

Quarkonium with NR EFT: pNRQCD

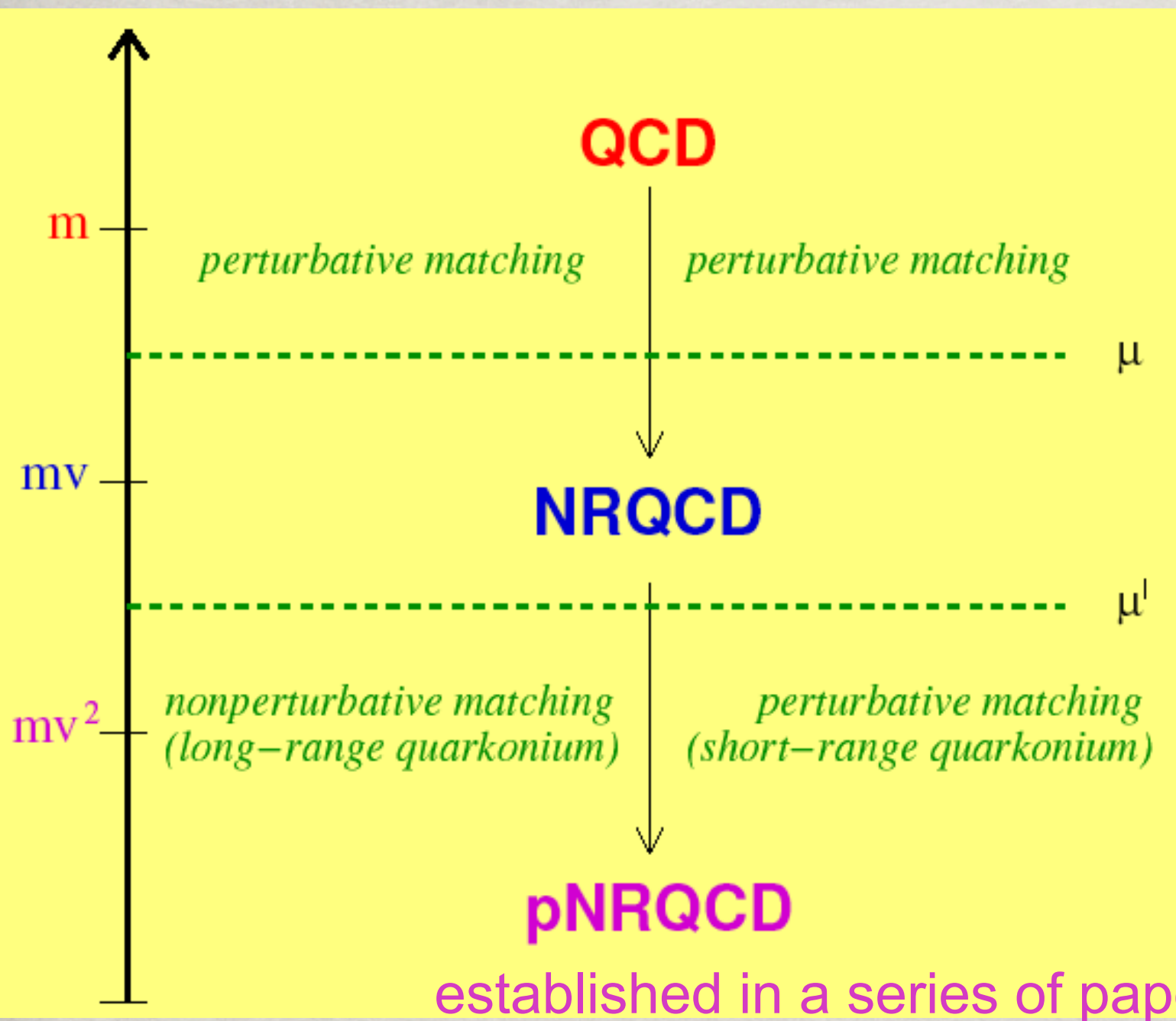


A potential picture arises at the level of pNRQCD:

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

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 Physics 77(2005)

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 threshold)

- *Work at calculating higher order perturbative corrections in v and α_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

- Precise and systematic high order calculations allow the extraction of precise determinations of standard model parameters like the quark masses and α_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 $m \alpha^5(Y(1S) \text{ bbar at LHC})$ N. B. et al. 2010

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- The quarkonium dissociation is a consequence of the appearance 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

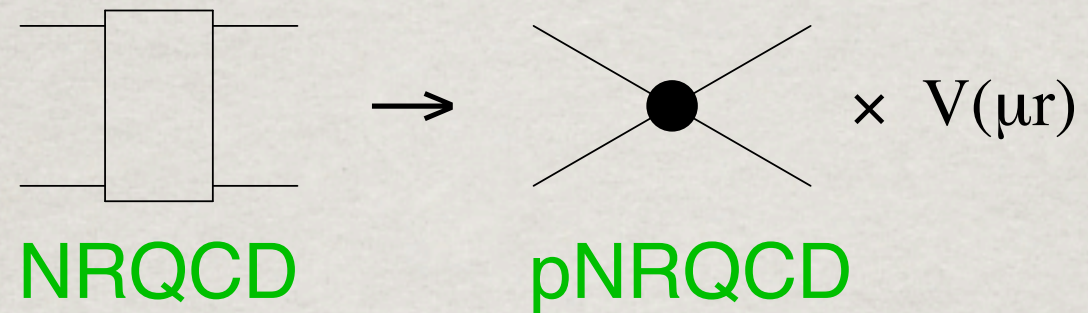
E. Braaten et al

Quarkonium systems with small radius

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

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

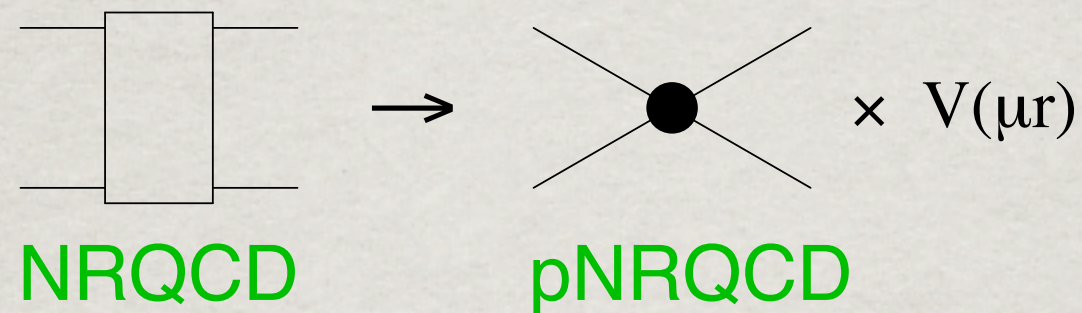
Degrees of freedom that **scale** like mv are integrated out:



pNRQCD for quarkonia with small radius

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

Degrees of freedom that **scale** like mv are integrated out:



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

- Degrees of freedom: **quarks** and **gluons**

Q - \bar{Q} states, with energy $\sim \Lambda_{\text{QCD}}$, mv^2 and momentum $\lesssim mv$

\Rightarrow (i) **singlet S** (ii) **octet O**

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

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

The gauge fields are **multipole expanded**:

$$A(R, r, t) = A(R, t) + \mathbf{r} \cdot \nabla A(R, t) + \dots$$

Non-analytic behaviour in $r \rightarrow$ **matching coefficients** V

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

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

LO in r

S singlet field

O octet field

————

=====

singlet propagator

octet propagator

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

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^a F^{\mu\nu a} + \text{Tr} \left\{ \textcolor{violet}{S}^\dagger \left(i\partial_0 - \frac{\mathbf{p}^2}{m} - \textcolor{teal}{V}_s \right) \textcolor{violet}{S} \right. \\ \left. + \textcolor{violet}{O}^\dagger \left(iD_0 - \frac{\mathbf{p}^2}{m} - \textcolor{teal}{V}_o \right) \textcolor{violet}{O} \right\}$$

LO in r

$$+ \textcolor{teal}{V}_A \text{Tr} \left\{ \textcolor{violet}{O}^\dagger \textcolor{teal}{r} \cdot g\mathbf{E} \textcolor{violet}{S} + \textcolor{violet}{S}^\dagger \textcolor{teal}{r} \cdot g\mathbf{E} \textcolor{violet}{O} \right\} \\ + \frac{\textcolor{teal}{V}_B}{2} \text{Tr} \left\{ \textcolor{violet}{O}^\dagger \textcolor{teal}{r} \cdot g\mathbf{E} \textcolor{violet}{O} + \textcolor{violet}{O}^\dagger \textcolor{violet}{O} \textcolor{teal}{r} \cdot g\mathbf{E} \right\} \\ + \dots$$

NLO in r

S singlet field

O octet field

————

=====

singlet propagator

octet propagator

weakly coupled pNRQCD

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

Singlet static potential

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

LO in r

Octet static potential

$$\begin{aligned} &+ V_A \text{Tr} \left\{ O^\dagger \mathbf{r} \cdot g\mathbf{E} S + S^\dagger \mathbf{r} \cdot g\mathbf{E} O \right\} \\ &+ \frac{V_B}{2} \text{Tr} \left\{ O^\dagger \mathbf{r} \cdot g\mathbf{E} O + O^\dagger O \mathbf{r} \cdot g\mathbf{E} \right\} \\ &+ \dots \end{aligned}$$

NLO in r

S singlet field

O octet field

—————

=====

singlet propagator

octet propagator

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

$$V = \left(\text{Diagram 1} + \text{Diagram 2} + \dots + \text{Diagram 3} + \dots \right) - \text{Diagram 4} + \dots$$

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 N⁴LO

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

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 & + \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 \\
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 \end{aligned}$$

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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 & + \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. + \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]
 \end{aligned}$$

a_1 Billoire 80

a_2 Schroeder 99, Peter 97

coeff $\ln r\mu$ N.B. Pineda, Soto, Vainshtein 99 **3LOOPS REDUCES TO 1 LOOP IN THE EFT**

a_4^{L2}, a_4^L N.B., Garcia, Soto, Vainshtein 99 **4LOOPS REDUCES TO 2LOOPS IN THE EFT**

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

Quarkonium singlet static potential at N⁴LO

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

Two problems:

- 1) Bad convergence of the series due to large β_0 terms
- 2) Large logs

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problem for any phenomenological application

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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

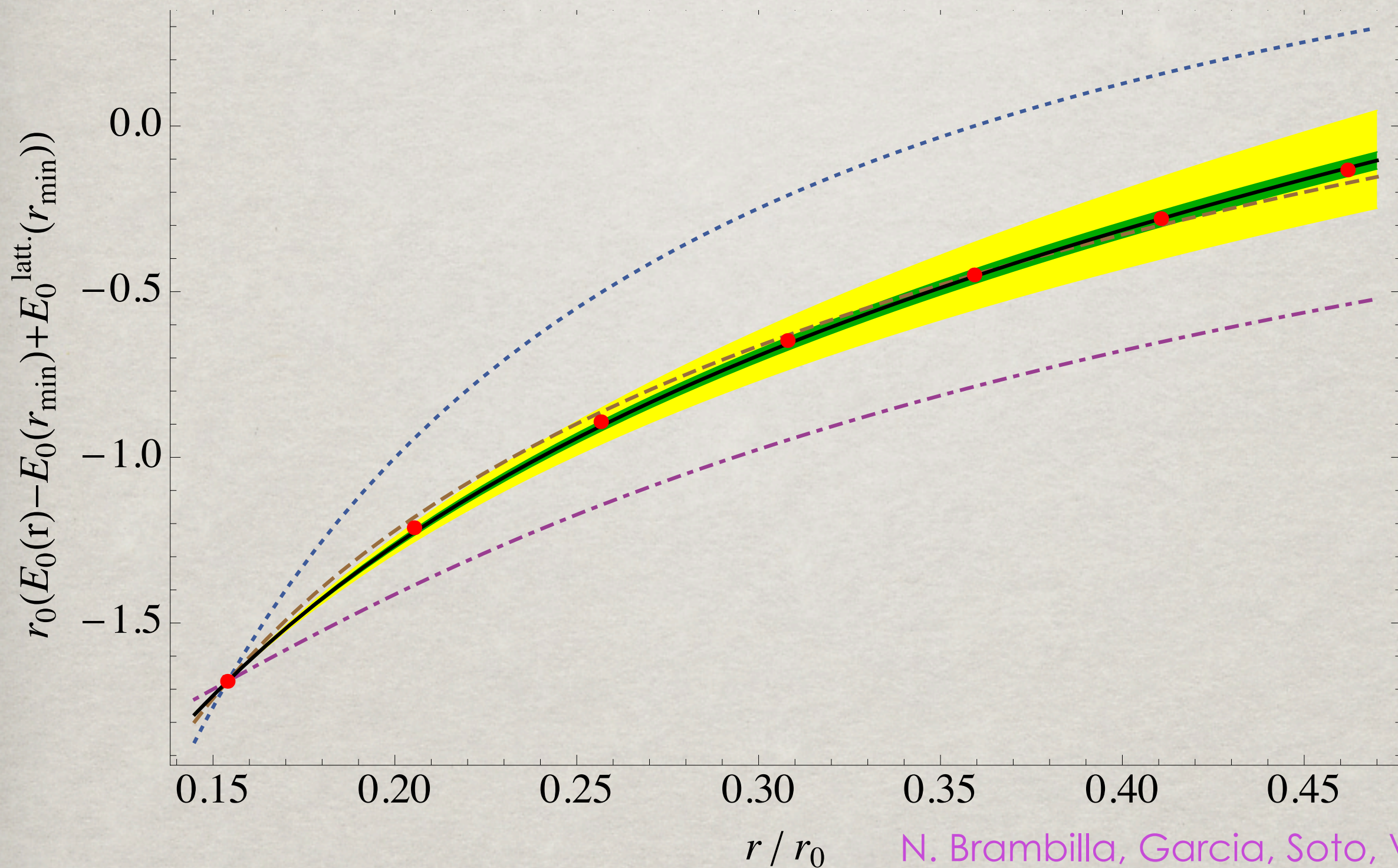
2) Renormalization group summation of the logs^{al 09}

up to N³LL $(\alpha_s^{4+n} \ln^n \alpha_s)$

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

Quarkonium singlet static energy at N³LI in comparison with lattice data (red points

Necco Sommer 2002)



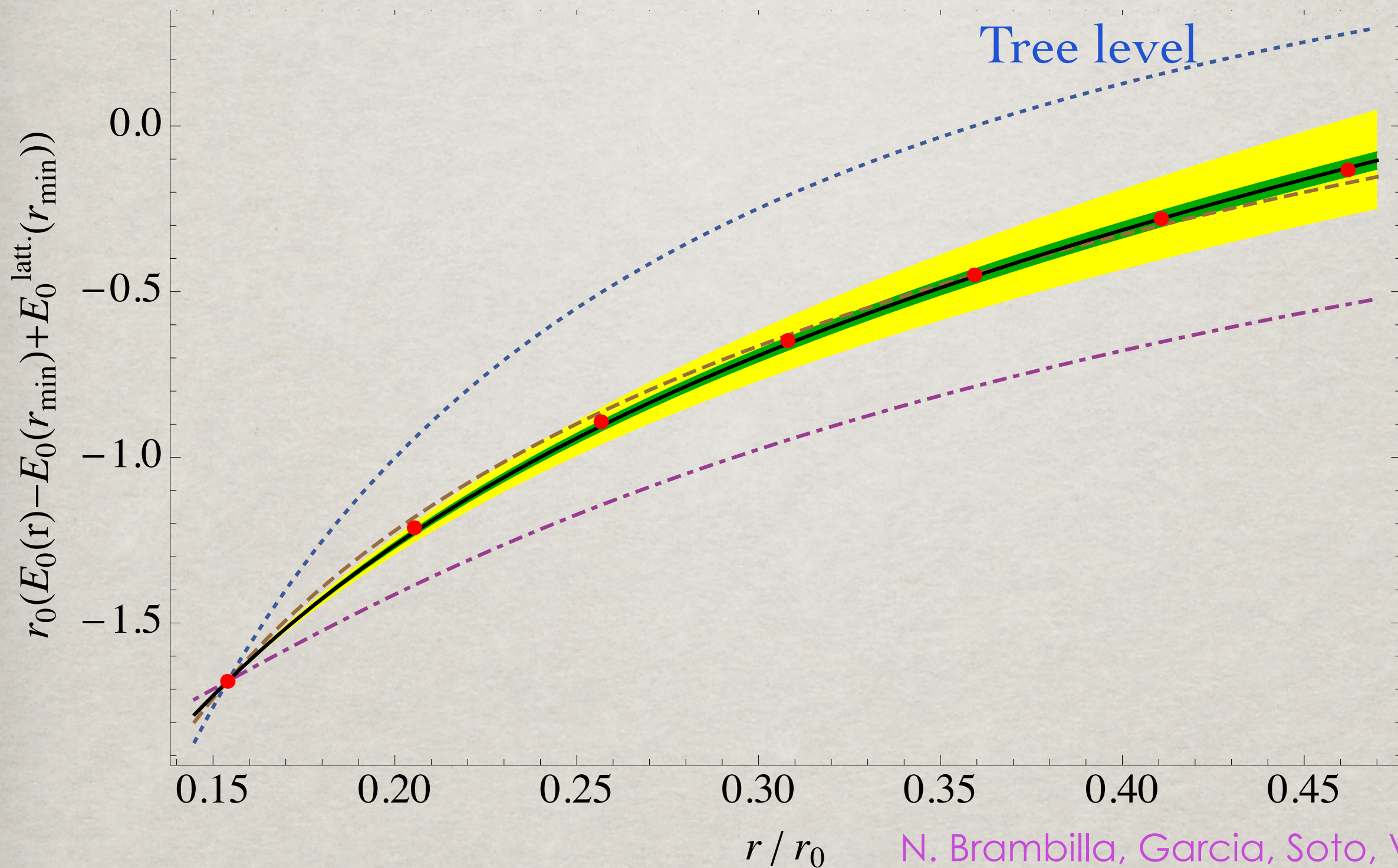
N. Brambilla, Garcia, Soto, Vairo 010

Yellow band : uncertainty in α_s ($r_0 \cdot \Lambda_{\text{QCD}}^{\overline{\text{MS}}}$)

Green band: uncertainty in higher order terms

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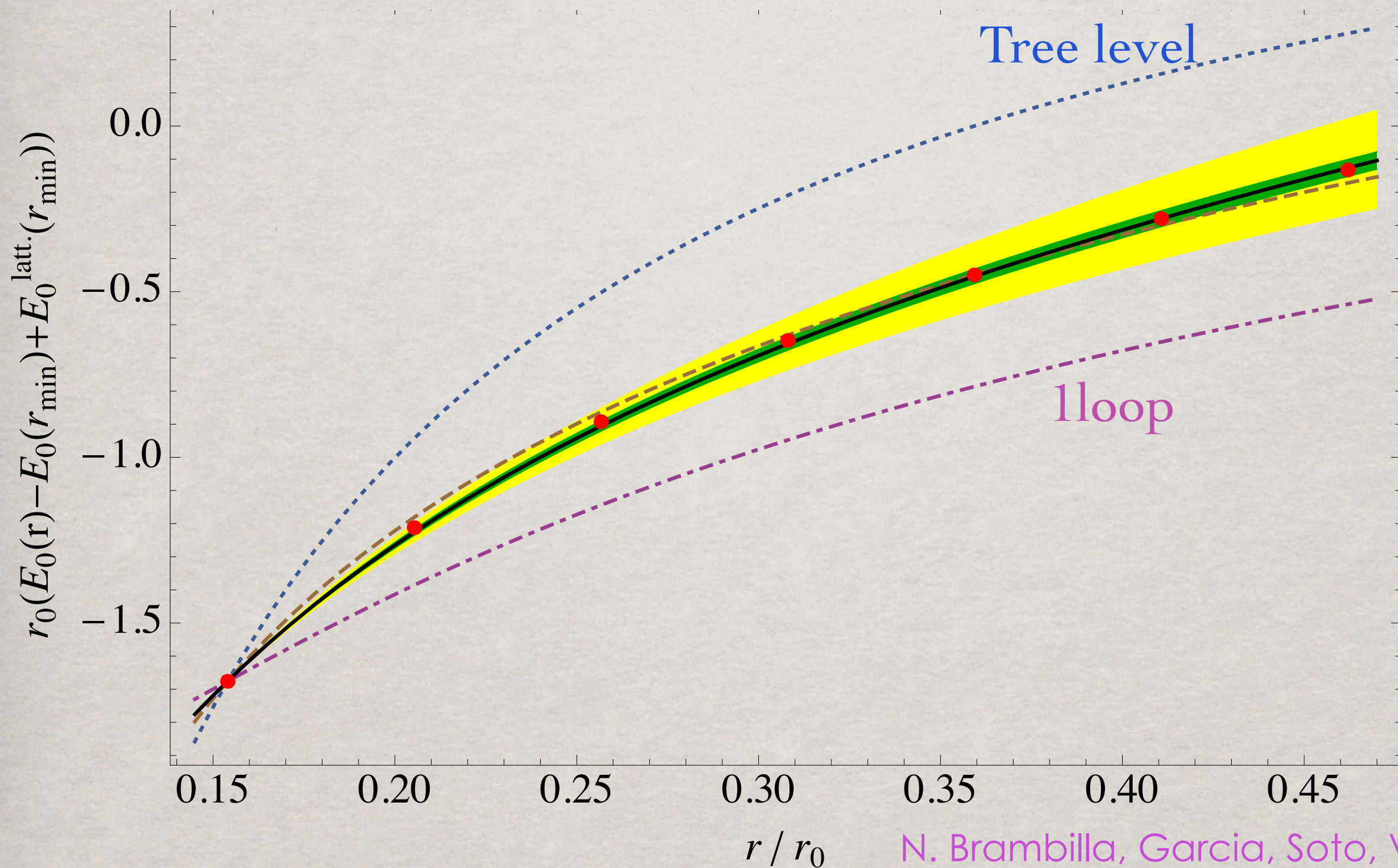


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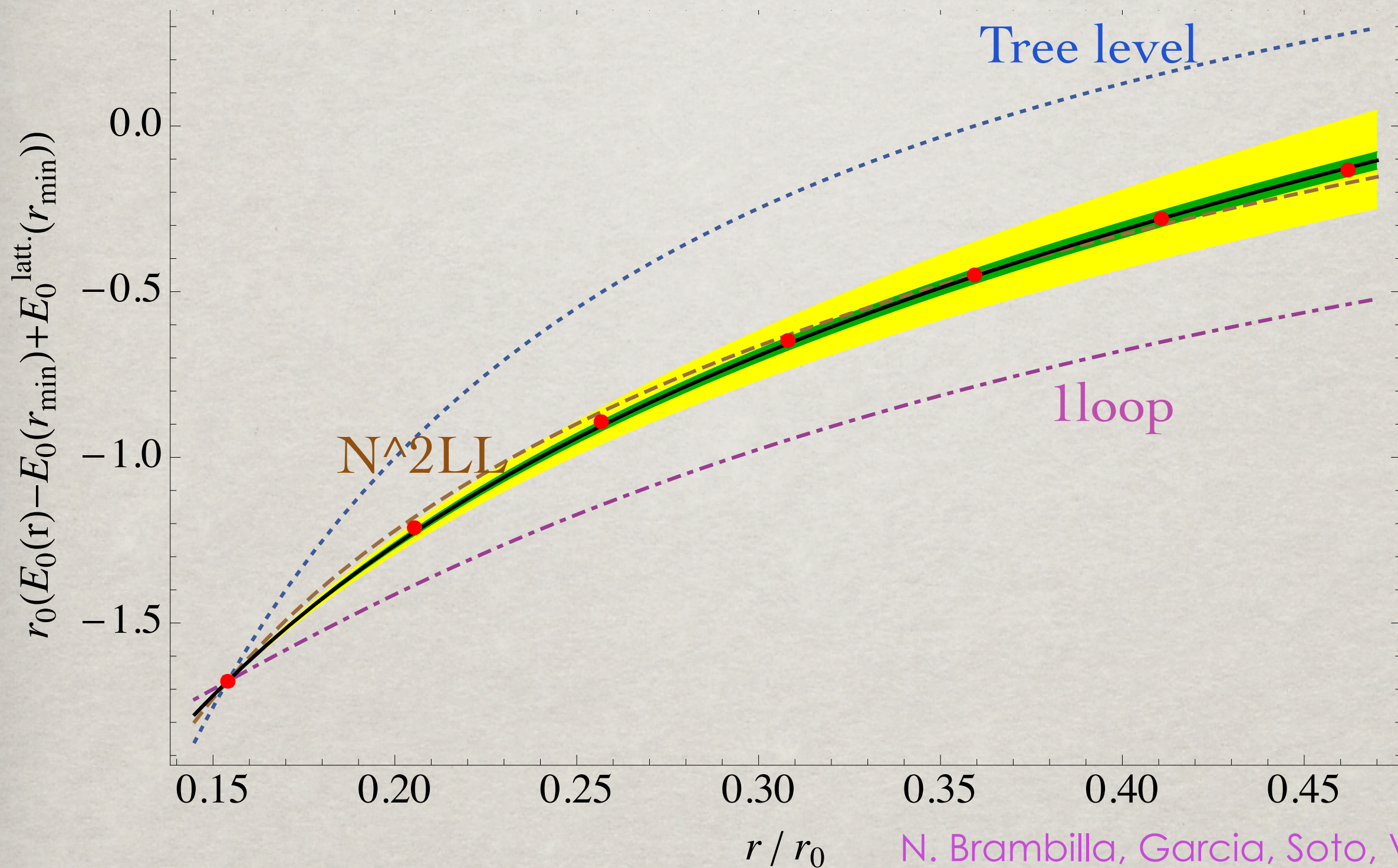
N. Brambilla, Garcia, Soto, Vairo 010

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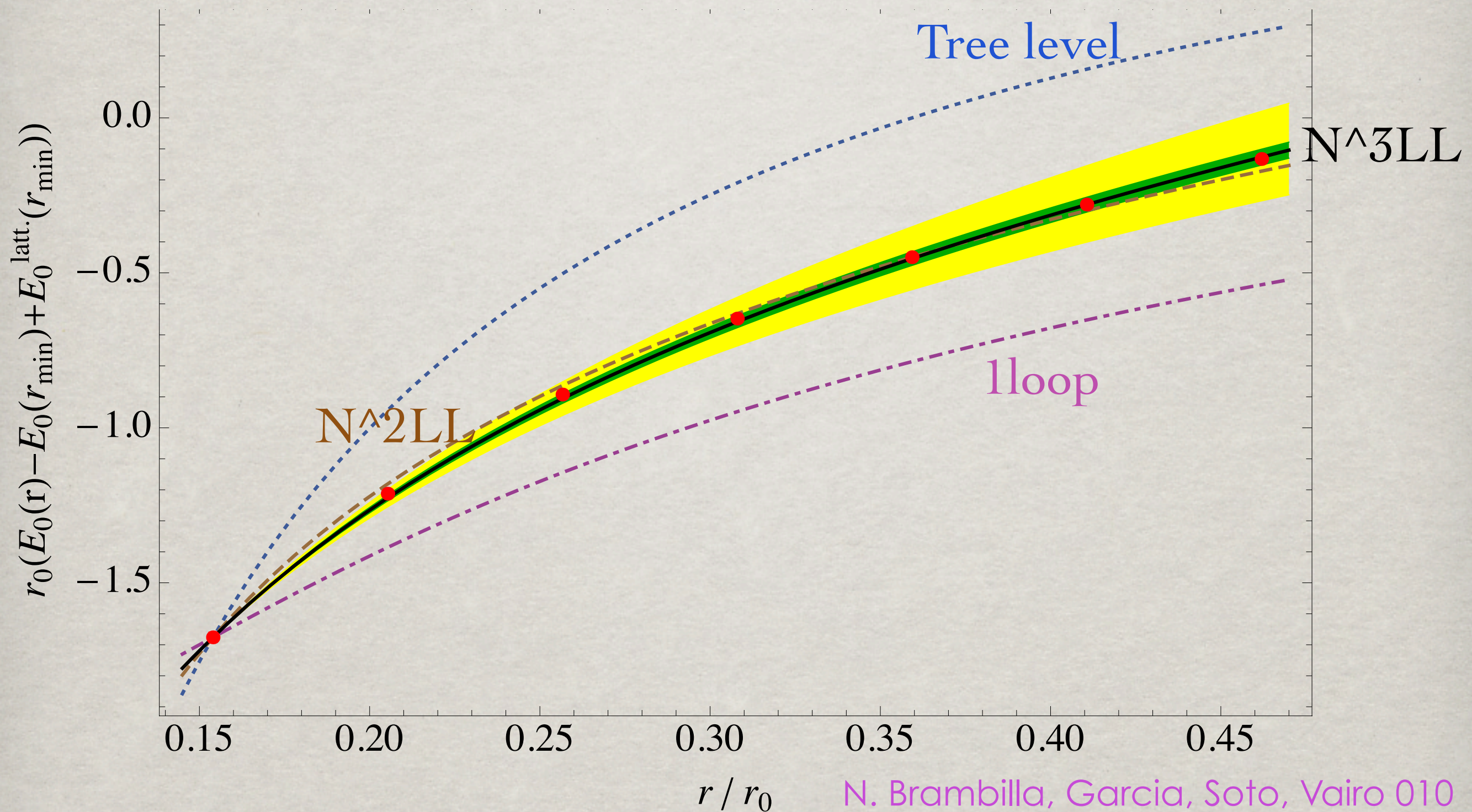
N. Brambilla, Garcia, Soto, Vairo 010

Yellow band : uncertainty in α_s ($r_0 \cdot \Lambda_{\text{QCD}}^{\overline{\text{MS}}}$)

Green band: uncertainty in higher order terms

Quarkonium singlet static energy at N³LL in comparison with lattice data (red points)

Necco Sommer 2002)

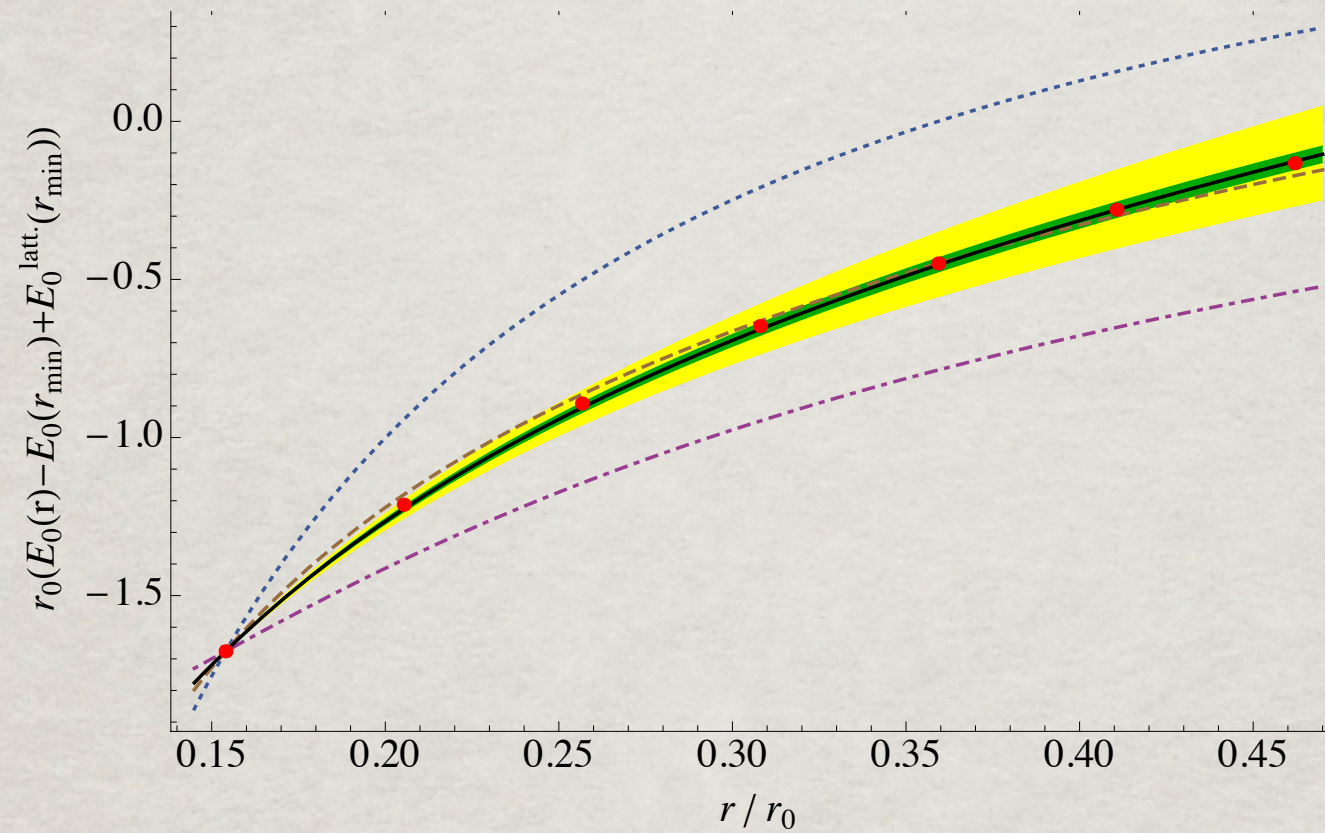


Yellow band : uncertainty in α_s ($r_0 \cdot \Lambda_{\text{QCD_MS}}$)

Green band: uncertainty in higher order terms

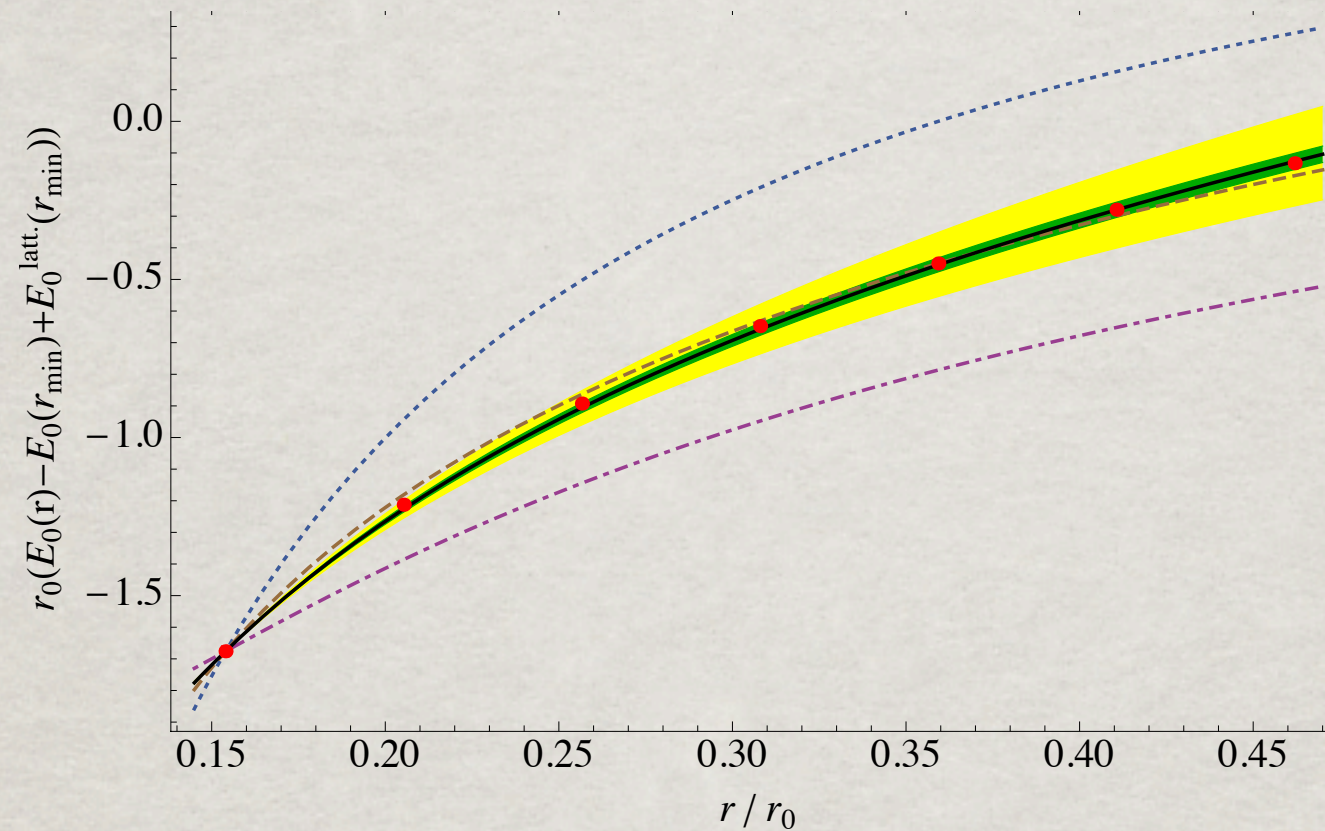
Quarkonium singlet static energy at N³LI in comparison with lattice data (red points)

Necco Sommer 2002)



Quarkonium singlet static energy at N³LI in comparison with lattice data (red points)

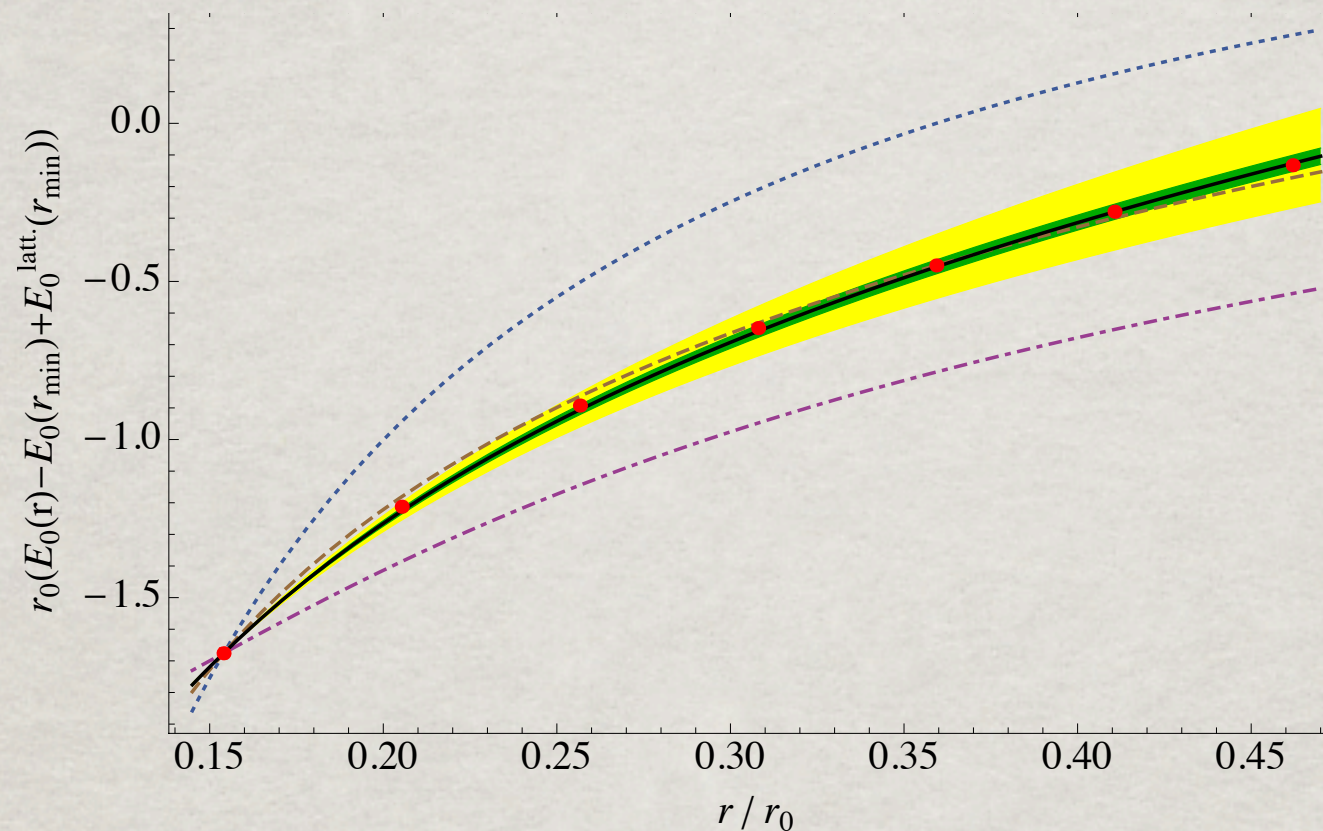
Necco Sommer 2002)



- Very good convergence of the QCD bound state perturbative series

Quarkonium singlet static energy at N³LI in comparison with lattice data (red points)

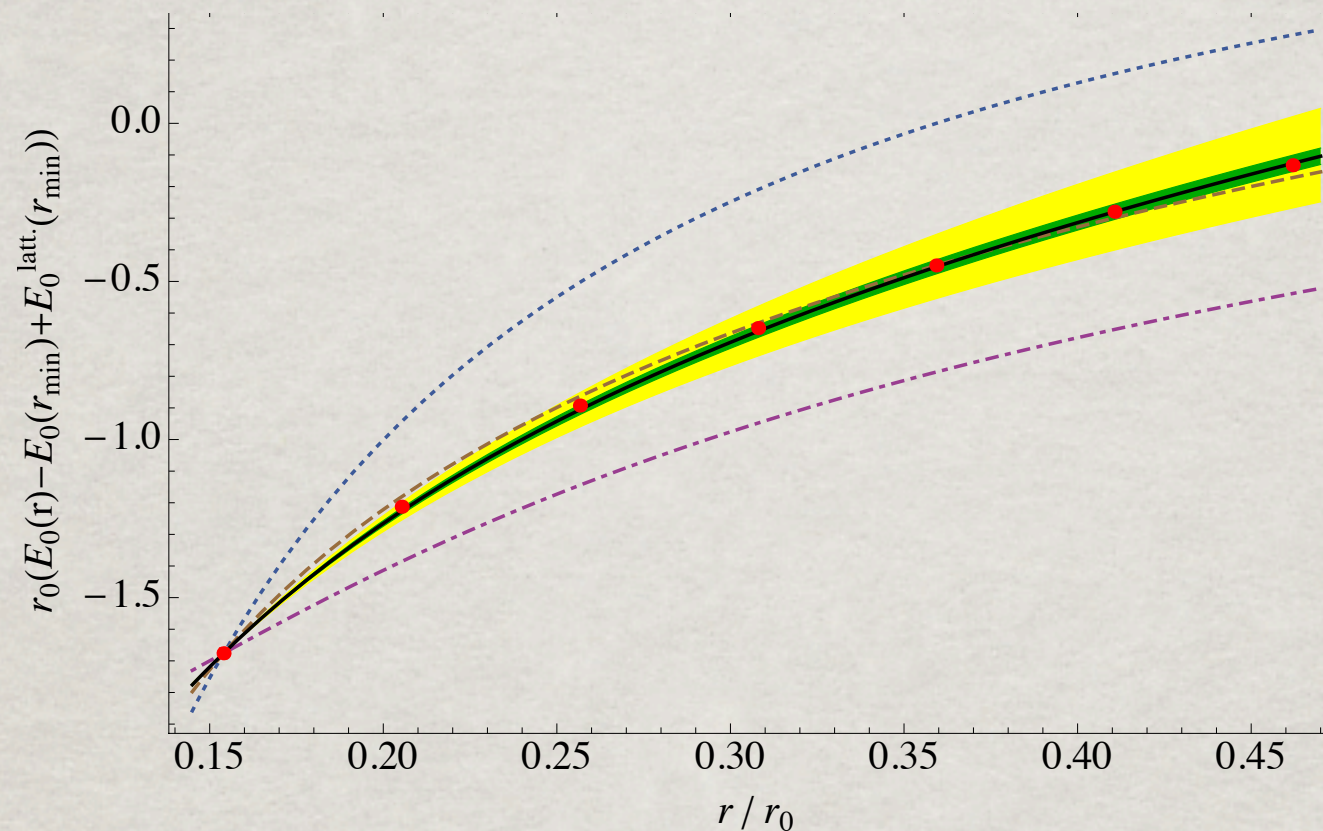
Necco Sommer 2002)



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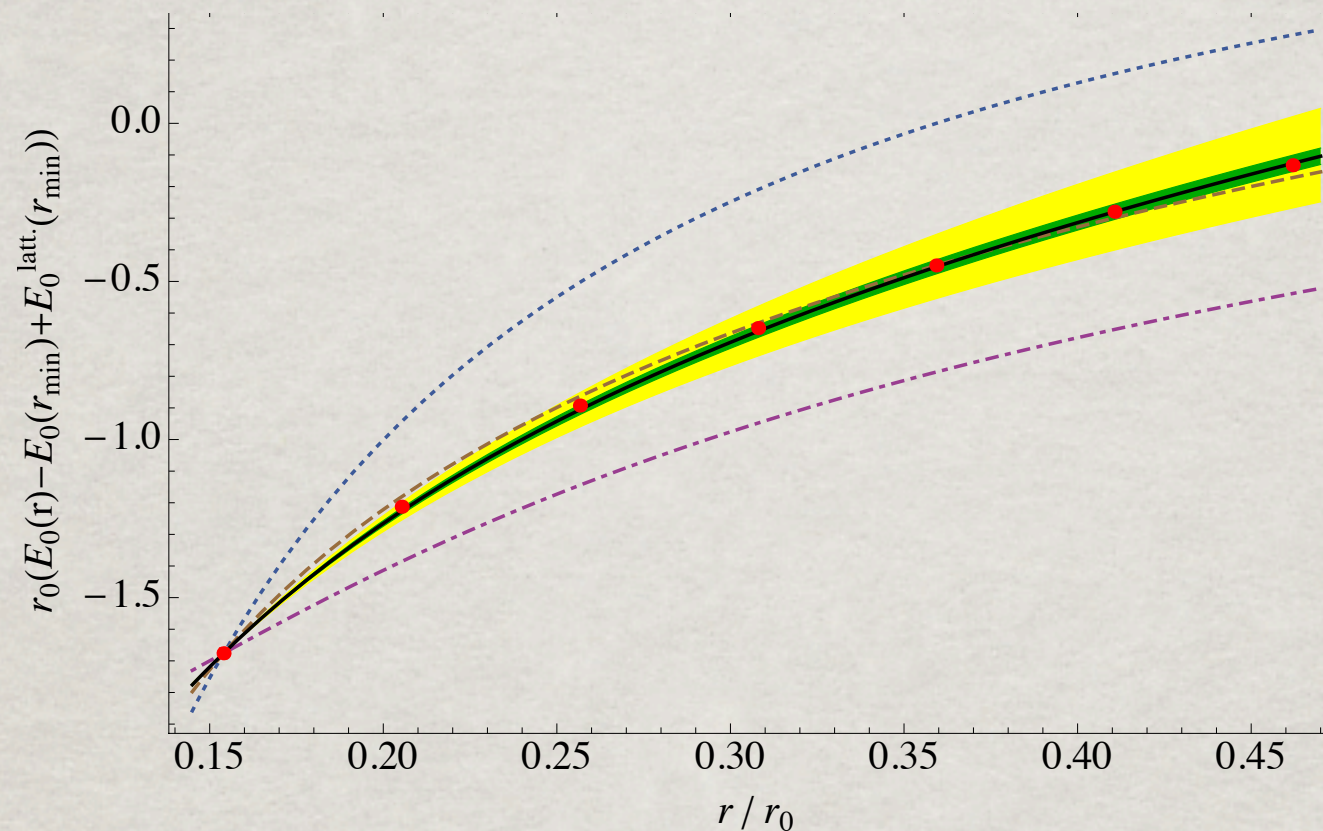
Necco Sommer 2002)



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Quarkonium singlet static energy at N³LI in comparison with lattice data (red points)

Necco Sommer 2002)



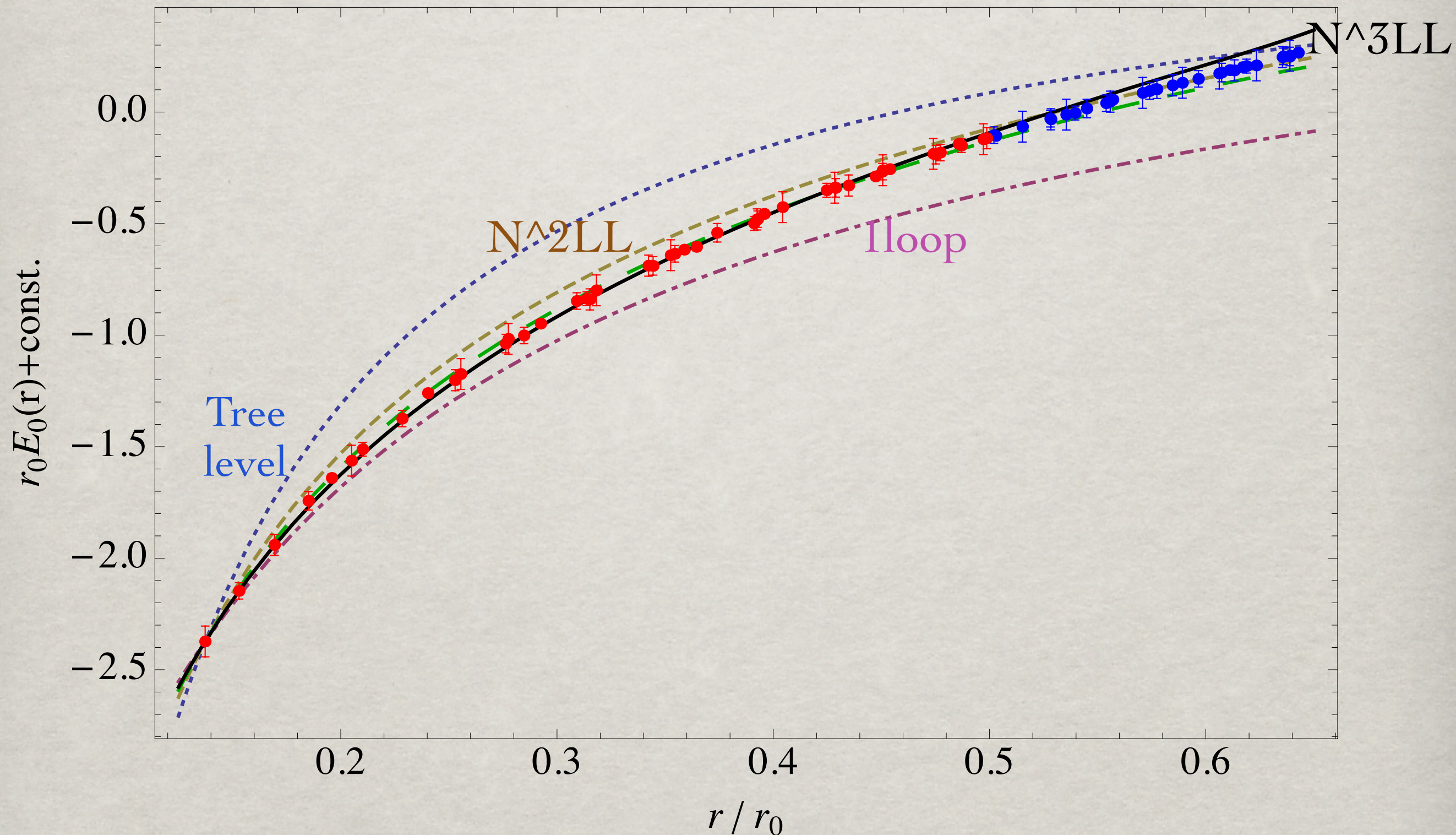
- Very good convergence of the QCD bound state perturbative series
- The lattice data are perfectly described from perturbation theory up to more than 0.2 fm
- Allows to rule out models: no string contribution at small r !
- Allows precise extraction of fundamental parameters of QCD

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

N. Brambilla, Garcia, Soto, Vairo 010)

QQbar singlet static energy at N³LL in comparison with unquenched (n_f=2+1) lattice data (red points, blue points)

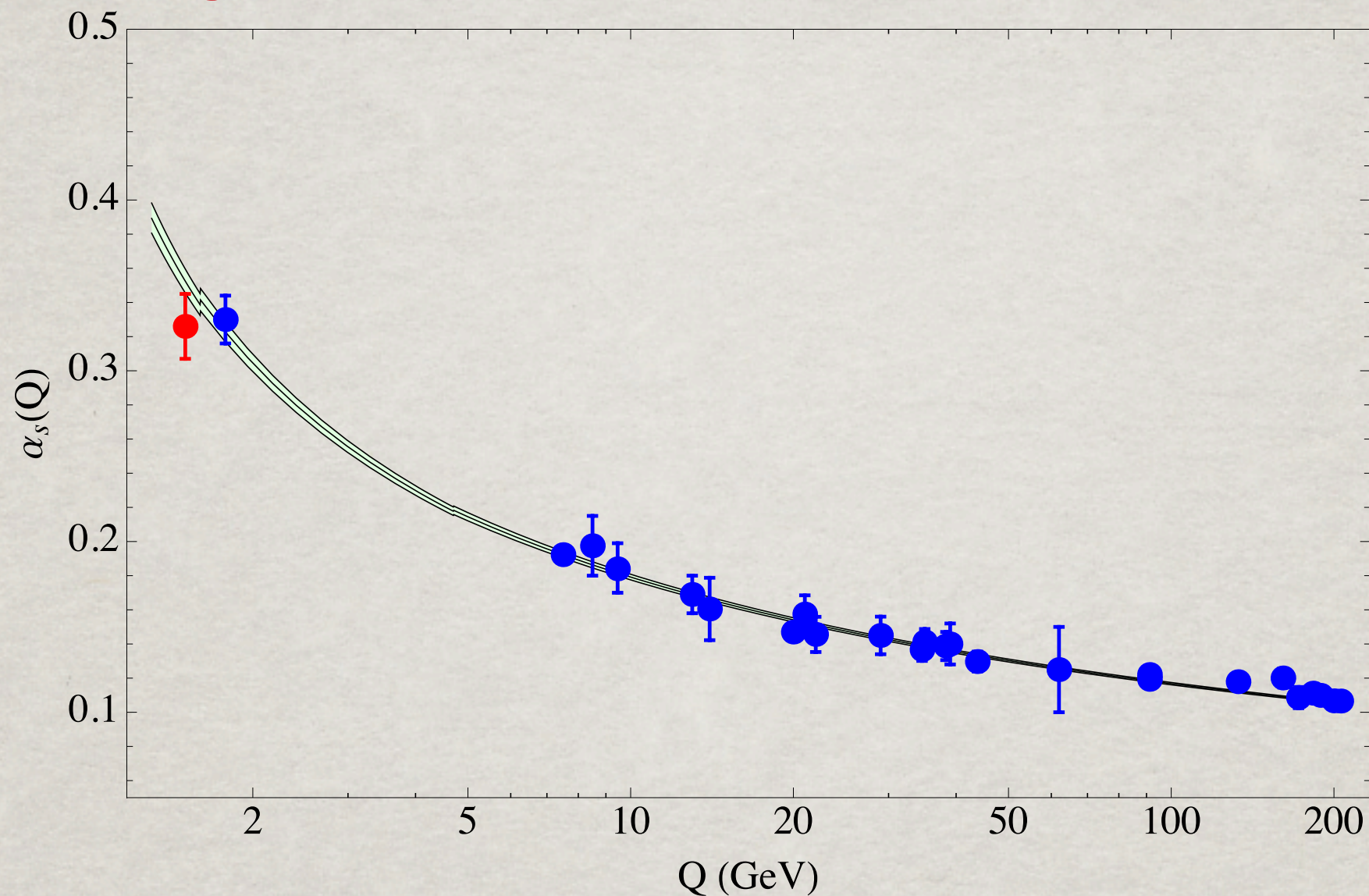
Bazanov, N. B., Garcia, Petreczky, Soto, Vairo , 2012



Good convergence to the lattice data

Lattice data less accurate in the unquenched case

α_s extraction



We obtain an extraction of alphas at **N³LO 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

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

Applications to Quarkonium physics: systems with small radius

for references see the QWG doc
[arXiv:1010.5827](https://arxiv.org/abs/1010.5827)

- c and b masses at NNLO, $N^3\text{LO}^*$, 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;
- $\Upsilon(1S) \rightarrow \gamma\eta_b$, $J/\psi \rightarrow \gamma\eta_c$ 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, ...;

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

N. B. Yu Jia A. Vairo 2005

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

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

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

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

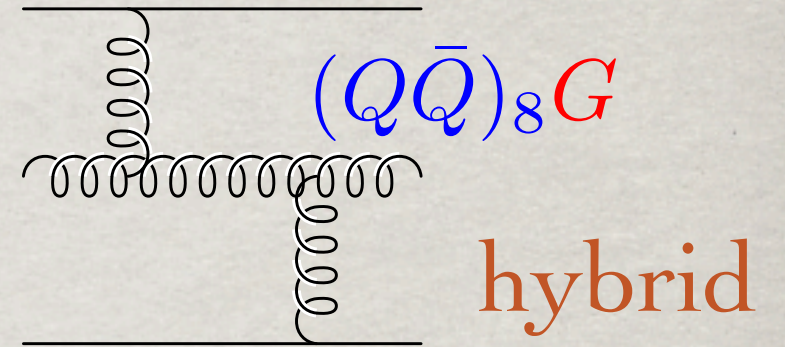
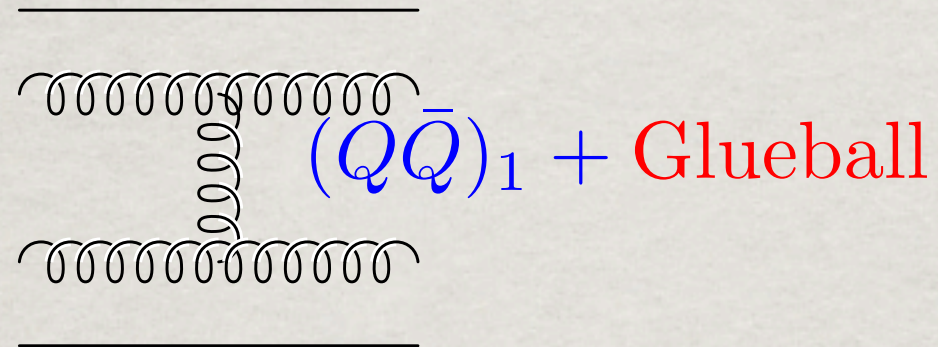
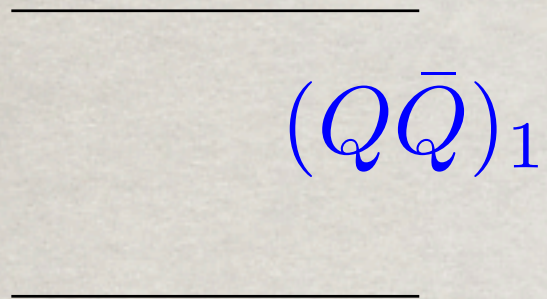
Quarkonium systems with large radius

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

— Hitting the scale Λ_{QCD} $r \sim \Lambda_{\text{QCD}}^{-1}$

— Hitting the scale Λ_{QCD}

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Hitting the scale Λ_{QCD}

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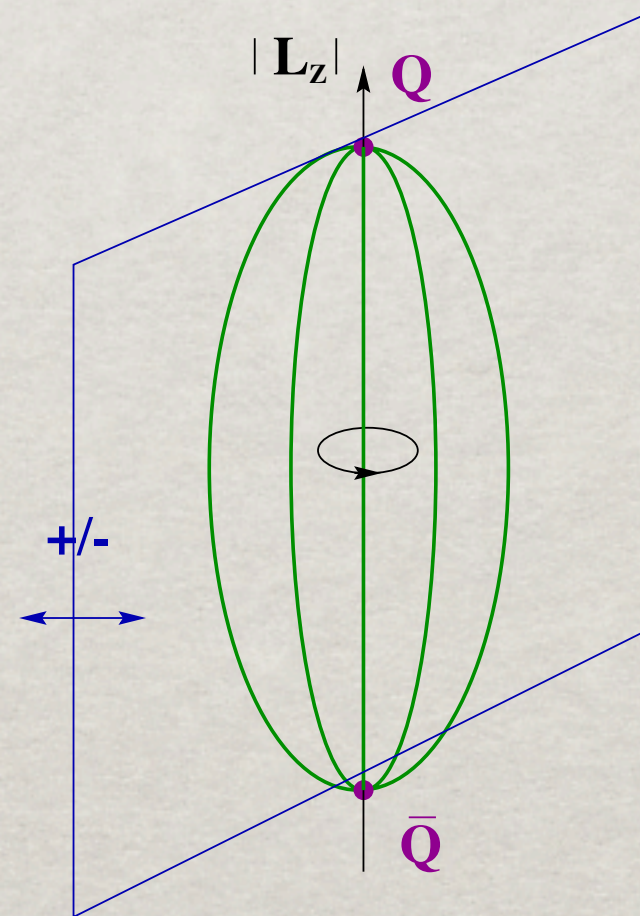
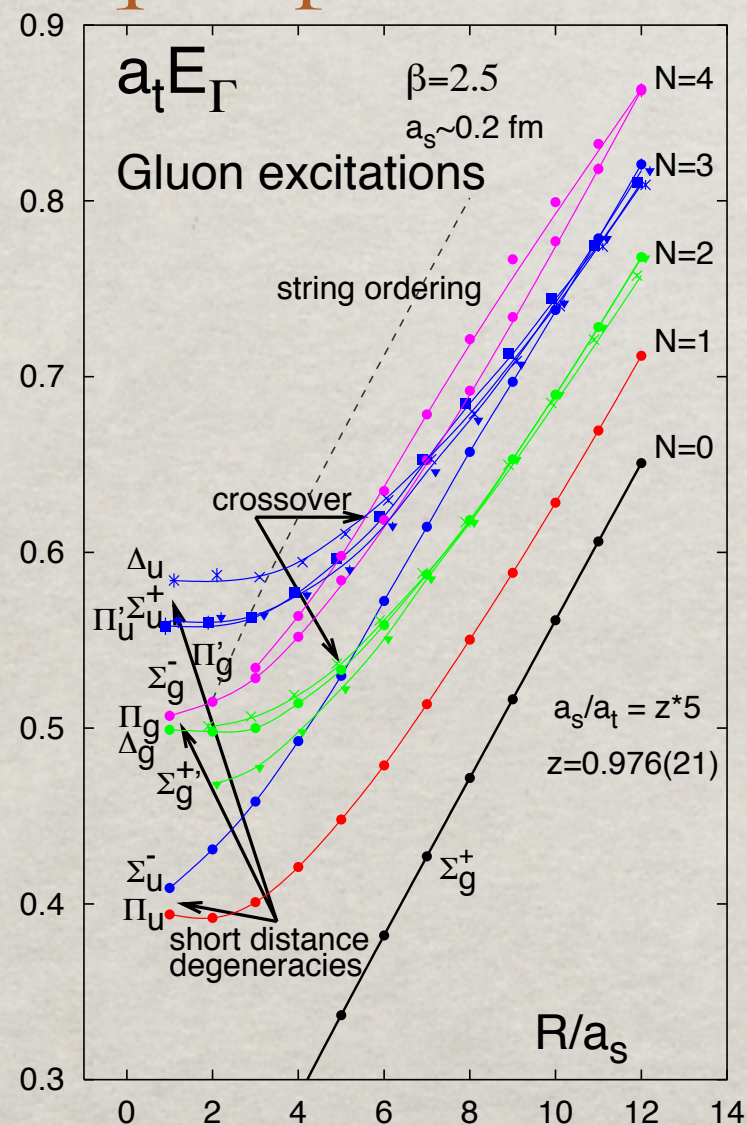
$(Q\bar{Q})_1$

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

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

Static qcd spectrum

L
a
t
t
i
c
e

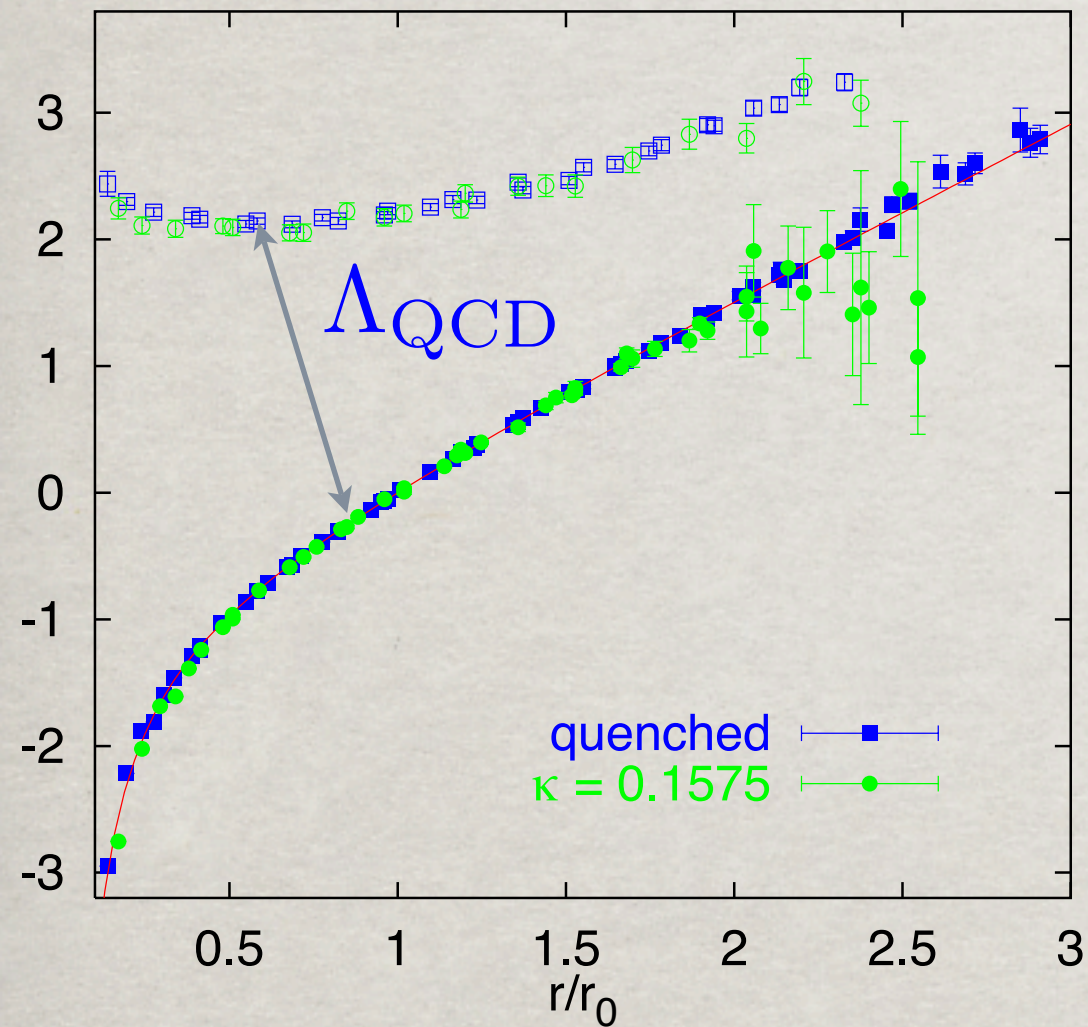


Symmetries of a diatomic molecule + C.C.

- a) $|L_z| = 0, 1, 2, \dots = \Sigma, \Pi, \Delta \dots$
- b) CP (u/g)
- c) Reflection (+/-) (for Σ only)

Quarkonium develops a gap to hybrids

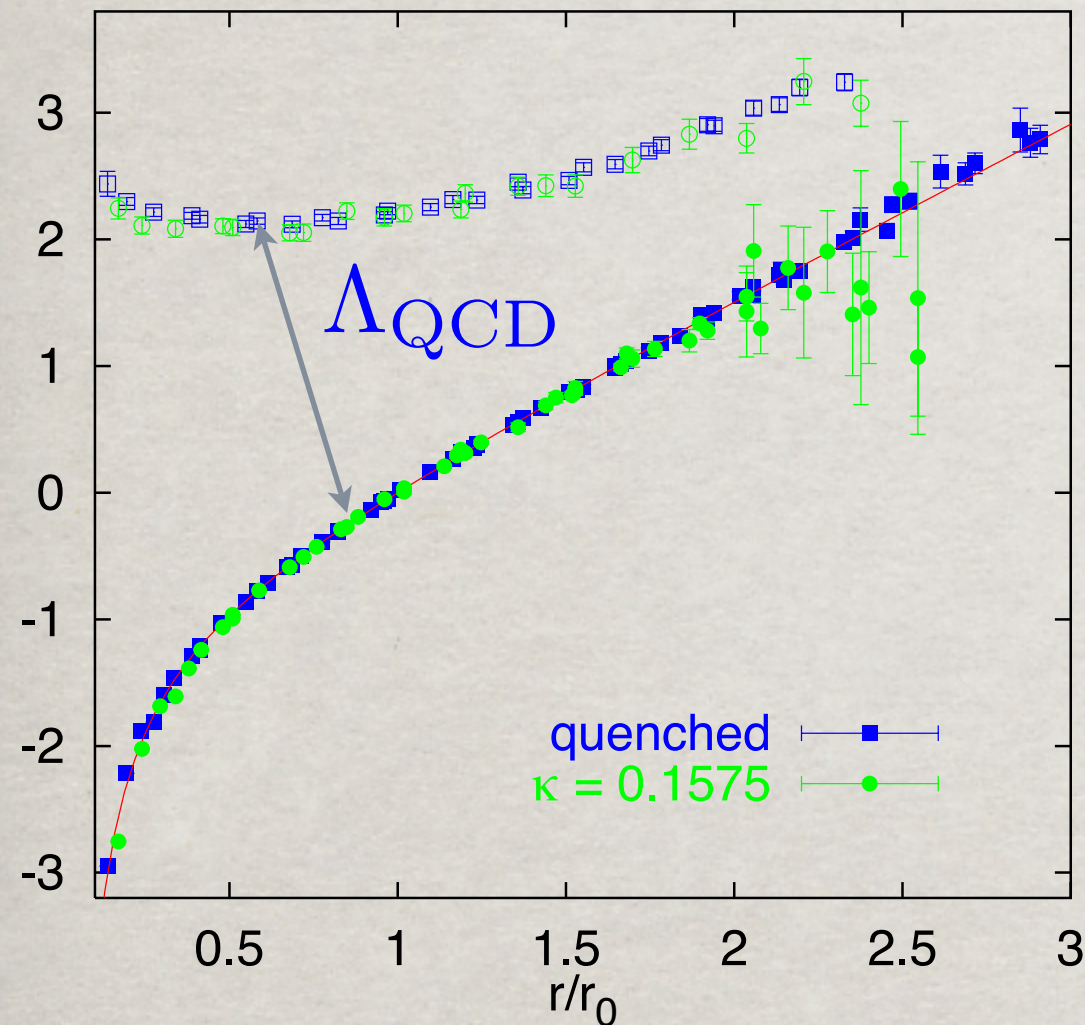
Bali et al. 98



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

Quarkonium develops a gap to hybrids

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

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Brambilla Pineda Soto Vairo 00

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Brambilla Pineda Soto Vairo 00

- A potential description emerges from the EFT
- The potentials $V = \text{Re}V + i\text{Im}V$ 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

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

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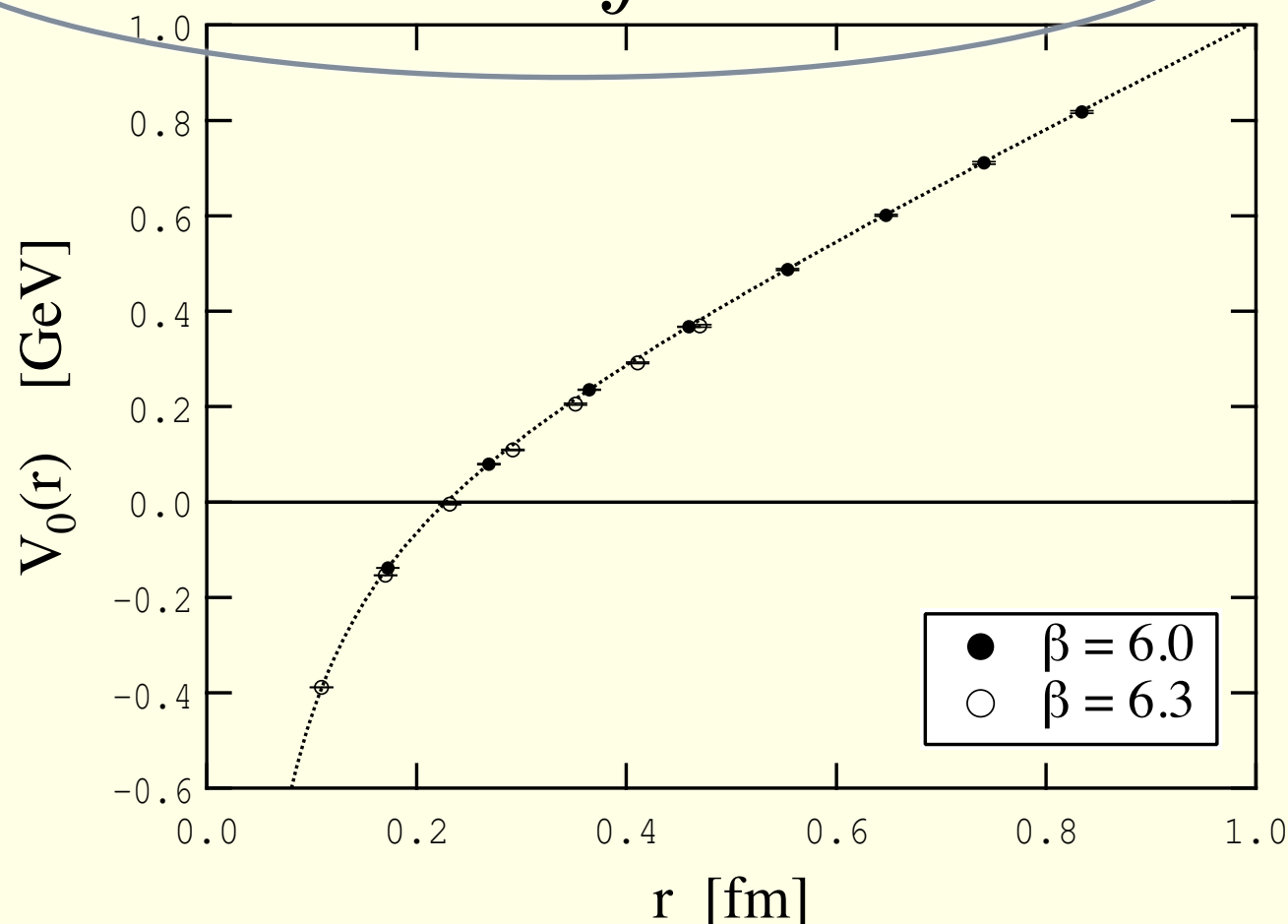
$$W = \langle \exp \{ i g \oint A^\mu dx_\mu \} \rangle$$

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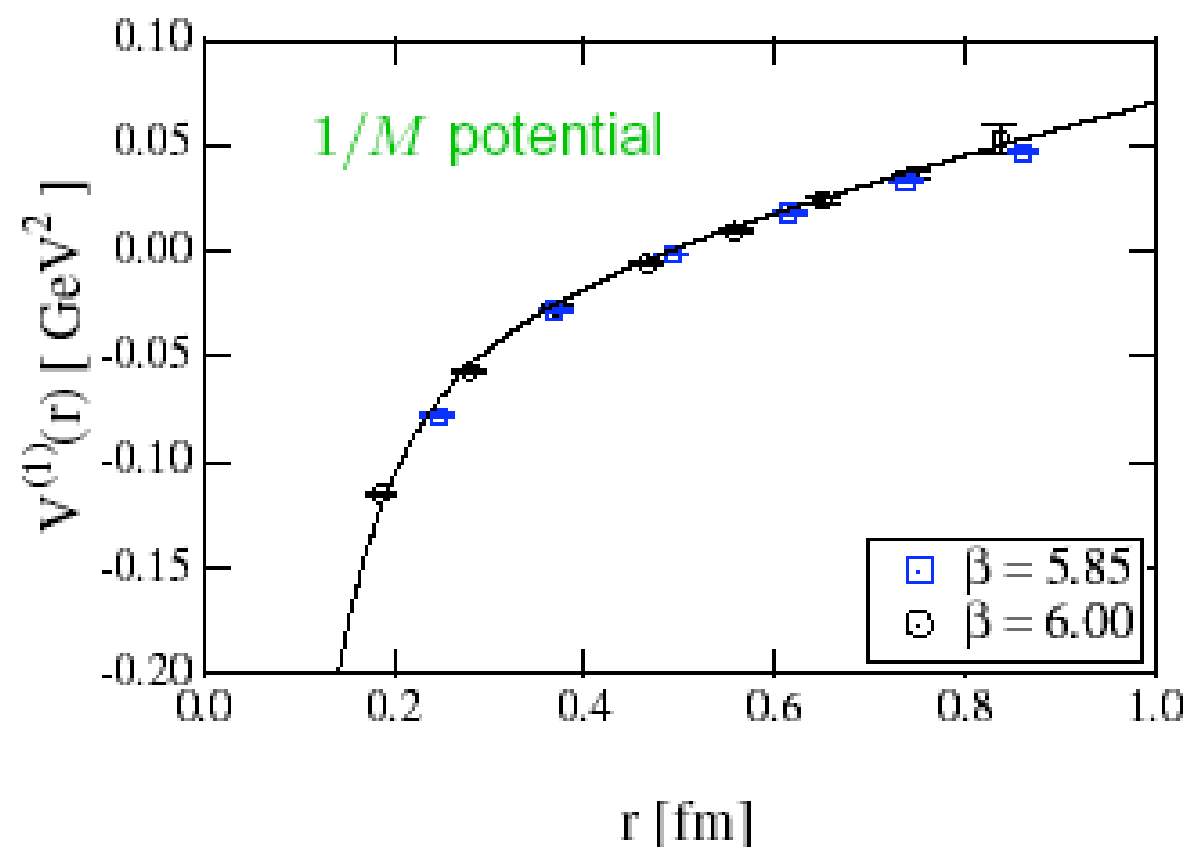
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Quarkonium singlet static potential

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

$$\frac{V_s^{(1)}}{m} = -\frac{1}{2m} \int_0^\infty dt t \langle \text{Wilson Loop with Electric Insertions} \rangle$$

QCD Spin dependent potentials

$$\begin{aligned}
 V_{\text{SD}}^{(2)} = & \frac{1}{r} \left(c_F \epsilon^{kij} \frac{2r^k}{r} i \int_0^\infty dt t \left\langle \begin{array}{c} \text{E} \\ \boxed{1 \quad j} \\ \text{B} \end{array} \right\rangle - \frac{1}{2} V_s^{(0)'} \right) (\mathbf{S}_1 + \mathbf{S}_2) \cdot \mathbf{L} \\
 & - c_F^2 \hat{r}_i \hat{r}_j i \int_0^\infty dt \left(\left\langle \begin{array}{c} \boxed{1 \quad j} \\ \text{---} \end{array} \right\rangle - \frac{\delta_{ij}}{3} \left\langle \begin{array}{c} \boxed{\quad \quad} \\ \text{---} \end{array} \right\rangle \right) \\
 & \quad \times \left(\mathbf{S}_1 \cdot \mathbf{S}_2 - 3(\mathbf{S}_1 \cdot \hat{\mathbf{r}})(\mathbf{S}_2 \cdot \hat{\mathbf{r}}) \right) \\
 & + \left(\frac{2}{3} c_F^2 i \int_0^\infty dt \left\langle \begin{array}{c} \boxed{\quad \quad} \\ \text{---} \end{array} \right\rangle - 4(d_2 + C_F d_4) \delta^{(3)}(\mathbf{r}) \right) \mathbf{S}_1 \cdot \mathbf{S}_2
 \end{aligned}$$

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

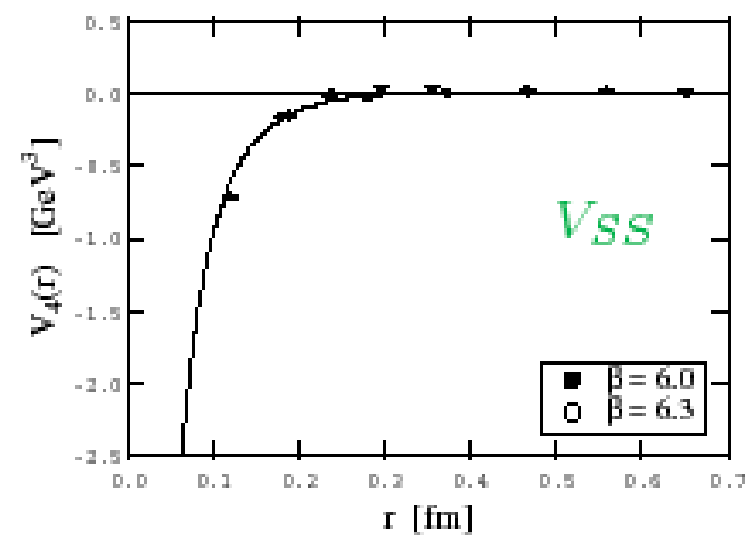
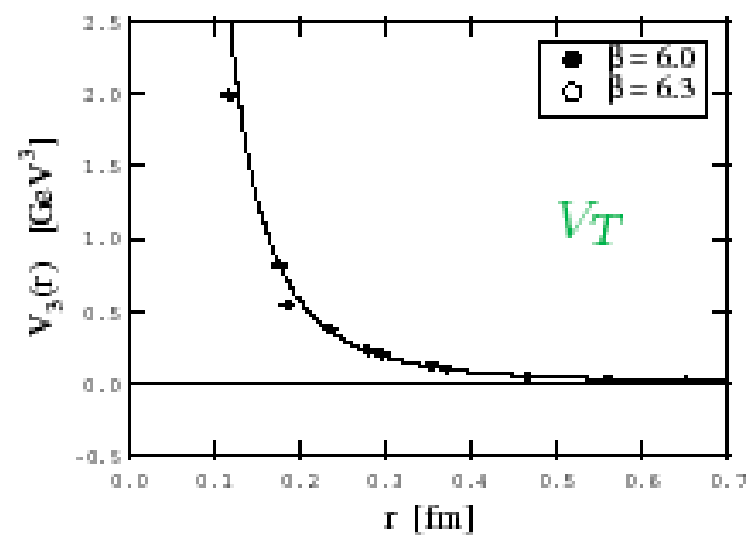
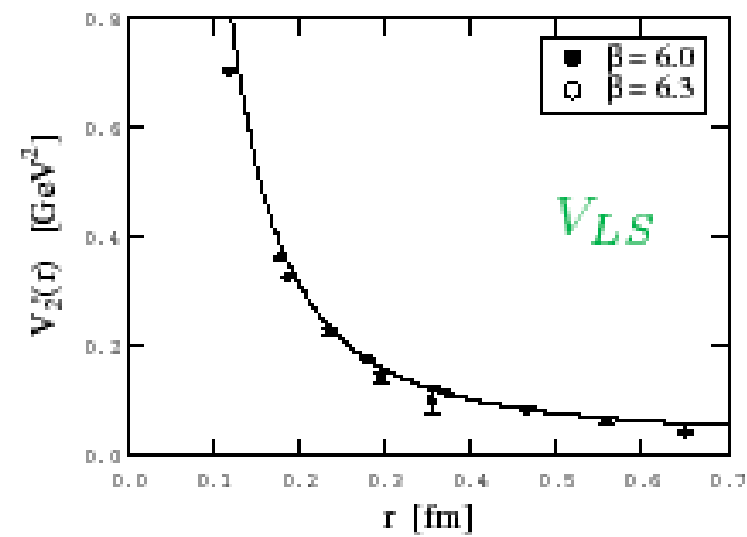
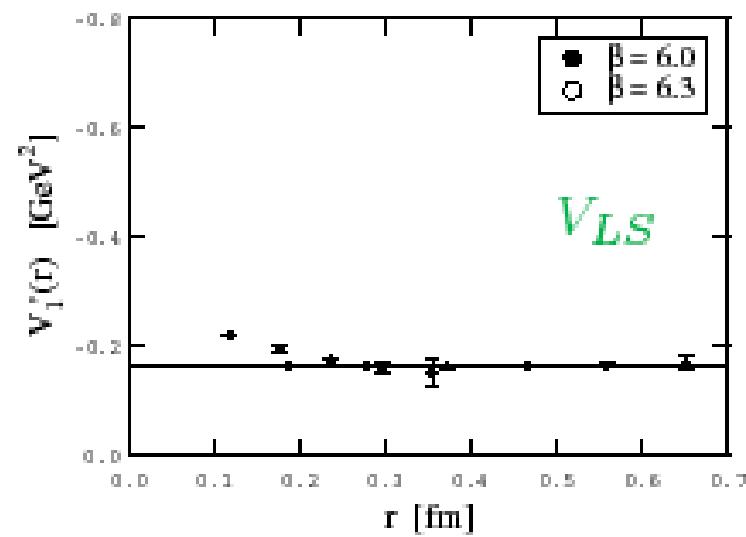
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 & - c_F^2 \hat{r}_i \hat{r}_j i \int_0^\infty dt \left(\left\langle \begin{array}{c} \boxed{\begin{array}{cc} 1 & j \\ \text{B} \end{array}} \right\rangle - \frac{\delta_{ij}}{3} \left\langle \begin{array}{c} \boxed{\text{B}} \end{array} \right\rangle \right) \\
 & \quad \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 \begin{array}{c} \boxed{\text{B}} \end{array} \right\rangle - 4(d_2 + C_F d_4) \delta^{(3)}(\mathbf{r}) \right) \mathbf{S}_1 \cdot \mathbf{S}_2
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Eichten Feinberg 81, Gromes 84, Chen et al. 95 Brambilla Vairo 99

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

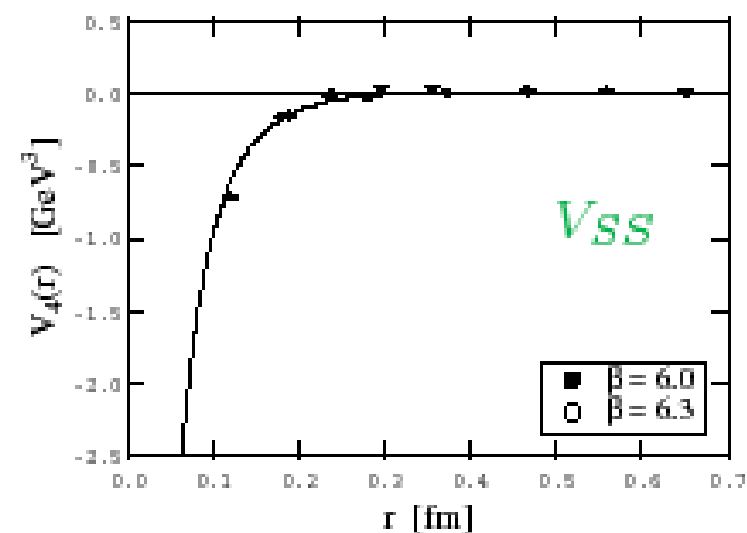
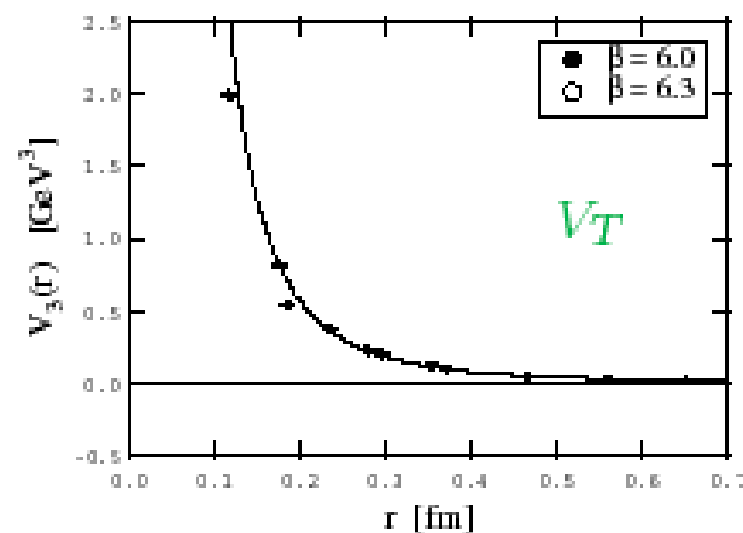
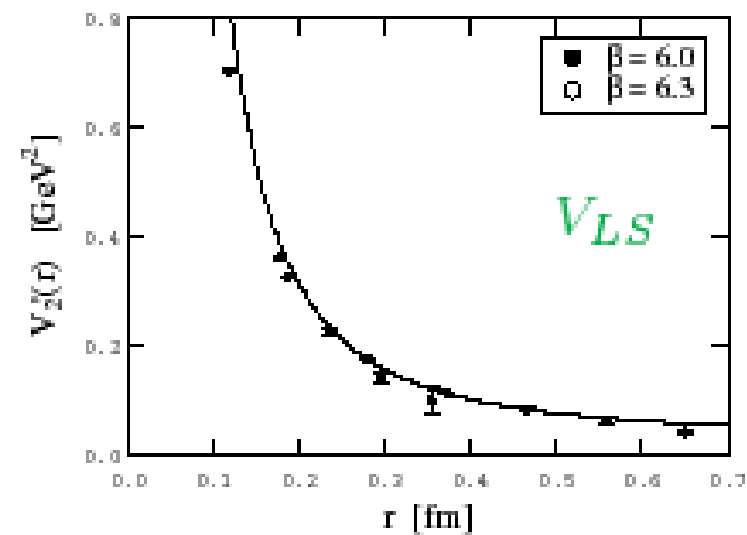
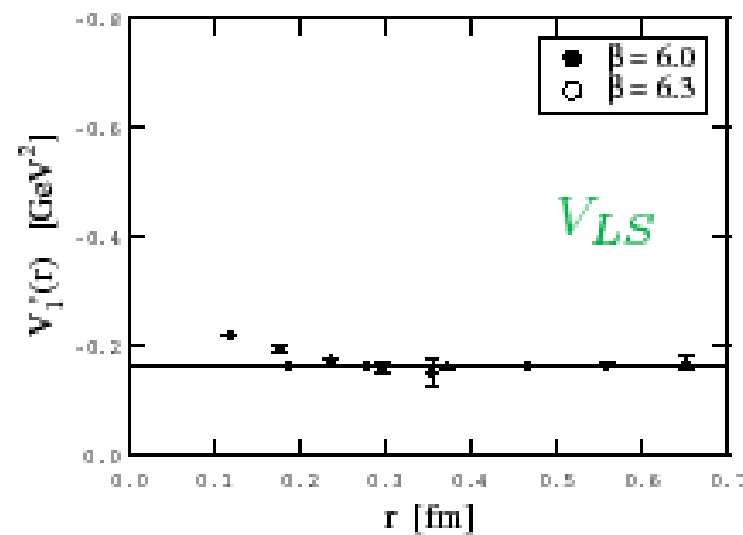
Spin dependent potentials



Koma Koma Wittig 05, Koma Koma 06

Terrific advance in the data precision with Lüscher multivel algorithm!

Spin dependent potentials



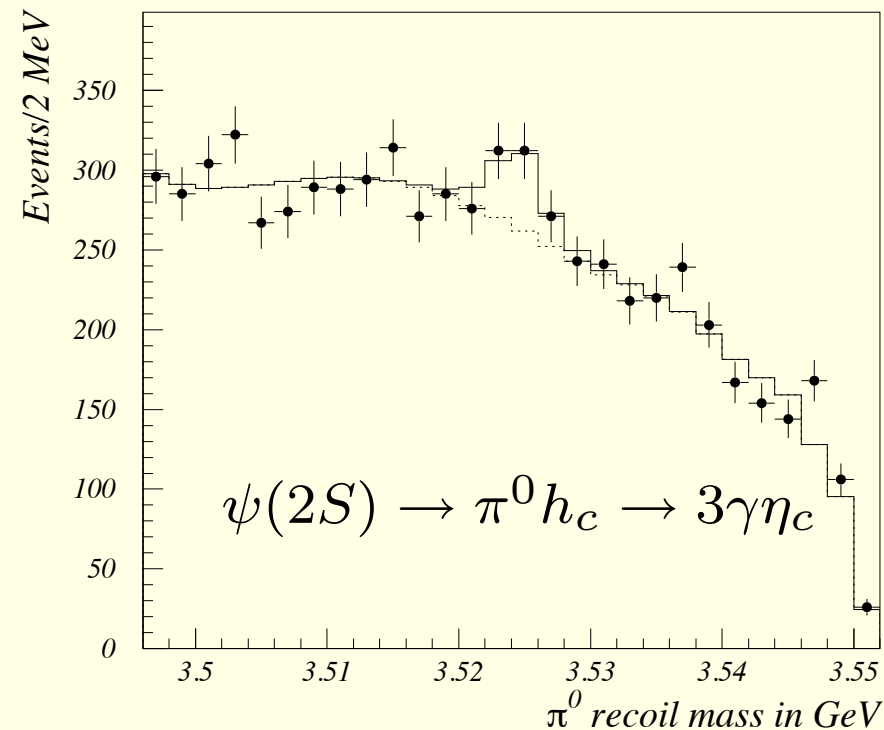
Koma Koma Wittig 05, Koma Koma 06

Terrific advance in the data precision with Lüscher multivell 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



$$M_{h_c} = 3524.4 \pm 0.6 \pm 0.4 \text{ MeV}$$

○ CLEO PRL 95 (2005) 102003

$$M_{h_c} = 3525.8 \pm 0.2 \pm 0.2 \text{ MeV},$$

$$\Gamma < 1 \text{ MeV}$$

○ E835 PRD 72 (2005) 032001

$$M_{h_c} = 3525.40 \pm 0.13 \pm 0.18 \text{ MeV},$$

$$\Gamma < 1.44 \text{ MeV}$$

○ BES PRL 104 (2010) 132002

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

● Also

$$M_{h_b} = 9902 \pm 4 \pm 1 \text{ MeV}$$

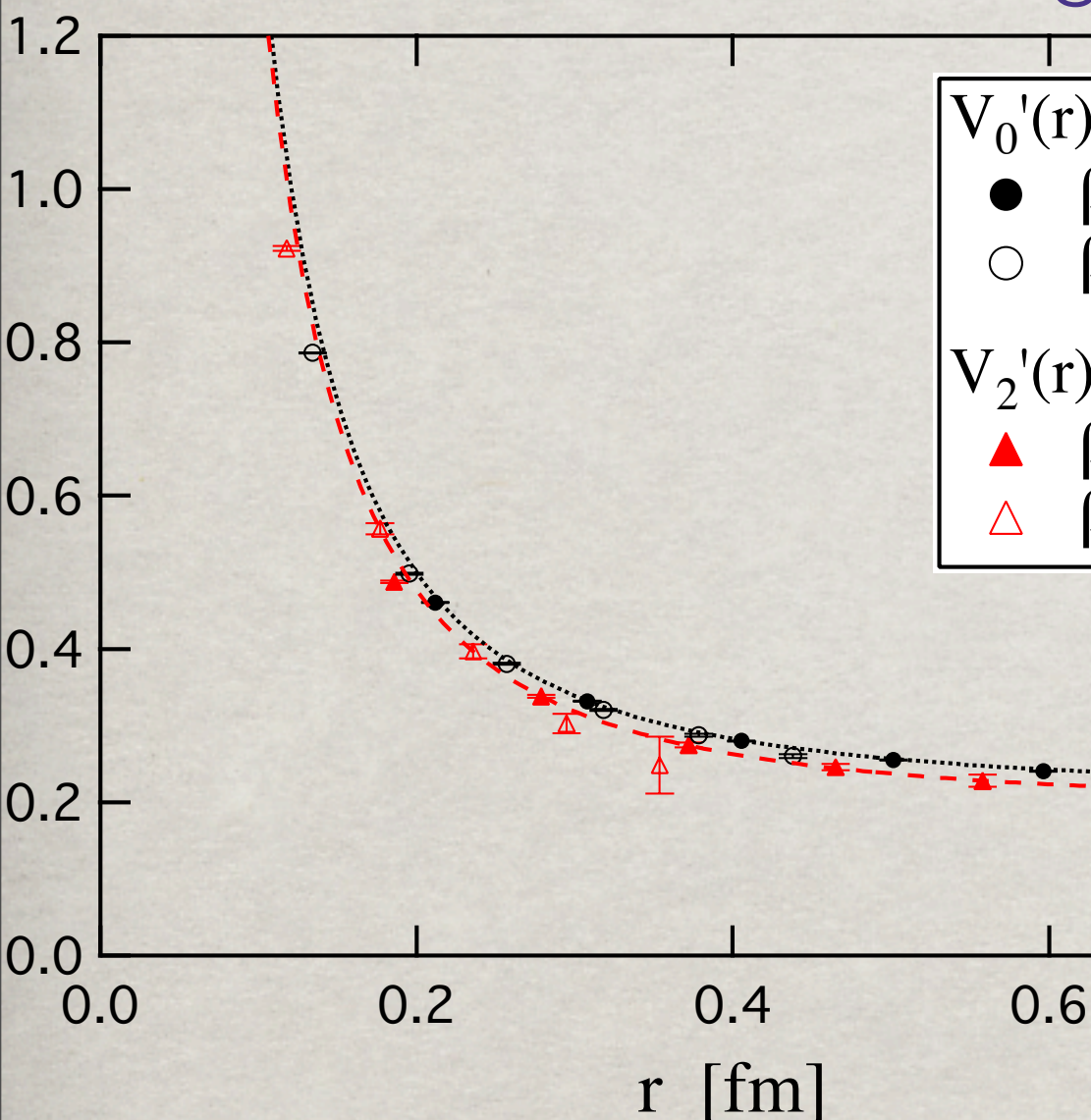
○ BABAR arXiv:1102.4565

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

Exact relations from Poincare' invariance

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

Koma and Koma 2006



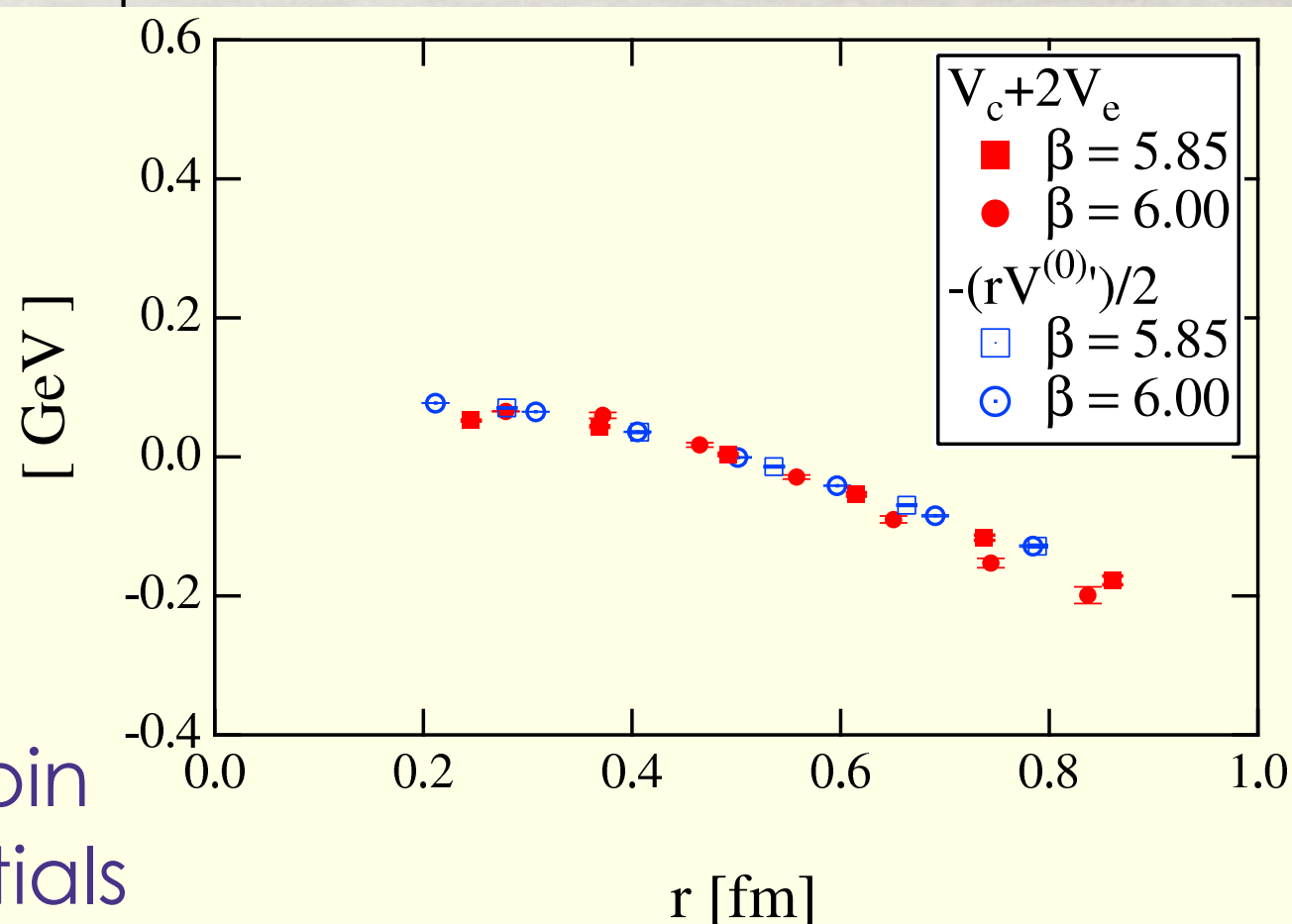
e. g. $V_0'(r) = V_2'(r) - V_1'(r)$

Gromes relation

It is a check of the lattice calculation

many other relations among potentials in the EFT

relations involving spin independent potentials



QCD Spin independent potentials

$$\begin{aligned}
 V_{\text{SI}}^{(2)} = & \textcolor{violet}{p}^i \left(i \int_0^\infty dt t^2 \langle \boxed{\textcolor{blue}{\bullet}_1 \textcolor{blue}{\bullet}_j} \rangle + \langle \boxed{\textcolor{blue}{\bullet}_1 \textcolor{blue}{\bullet}_j} \rangle \right) \textcolor{violet}{p}^j \\
 & - \frac{\textcolor{red}{c}_F^2}{2} i \int_0^\infty dt \langle \boxed{\textcolor{blue}{B} \textcolor{blue}{\bullet} \textcolor{blue}{\bullet}} \rangle + (\textcolor{red}{d}_1 + C_F \textcolor{red}{d}_3 + \pi C_F \alpha_s \textcolor{red}{c}_D) \delta^{(3)}(\mathbf{r}) \\
 & - i \int_0^\infty dt_1 \int_0^{t_1} dt_2 \int_0^{t_2} dt_3 (t_2 - t_3)^2 \left(\langle \boxed{\textcolor{blue}{\bullet} \textcolor{blue}{\bullet} \textcolor{blue}{\bullet} \textcolor{blue}{\bullet}} \rangle + \langle \boxed{\textcolor{blue}{\bullet} \textcolor{blue}{\bullet} \textcolor{blue}{\bullet} \textcolor{blue}{\bullet}} \rangle \right) \\
 & + \int_0^\infty dt_1 \int_0^{t_1} dt_2 (t_1 - t_2)^2 \nabla^i \\
 & \quad \times \left(\langle \boxed{\textcolor{blue}{\bullet}_1 \textcolor{blue}{\bullet} \textcolor{blue}{\bullet}} \rangle + \frac{1}{2} \langle \boxed{\textcolor{blue}{\bullet}_1 \textcolor{blue}{\bullet} \textcolor{blue}{\bullet}} \rangle + \frac{1}{2} \langle \boxed{\textcolor{blue}{\bullet}_1 \textcolor{blue}{\bullet} \textcolor{blue}{\bullet}} \rangle \right) \\
 & - 2 \textcolor{red}{b}_3 f_{abc} \int d^3 \mathbf{x} g \langle\langle \textcolor{blue}{G}_{\mu\nu}^a(\mathbf{x}) \textcolor{blue}{G}_{\mu\alpha}^b(\mathbf{x}) \textcolor{blue}{G}_{\nu\alpha}^c(\mathbf{x}) \rangle\rangle_{\square}^c
 \end{aligned}$$

QCD Spin independent potentials

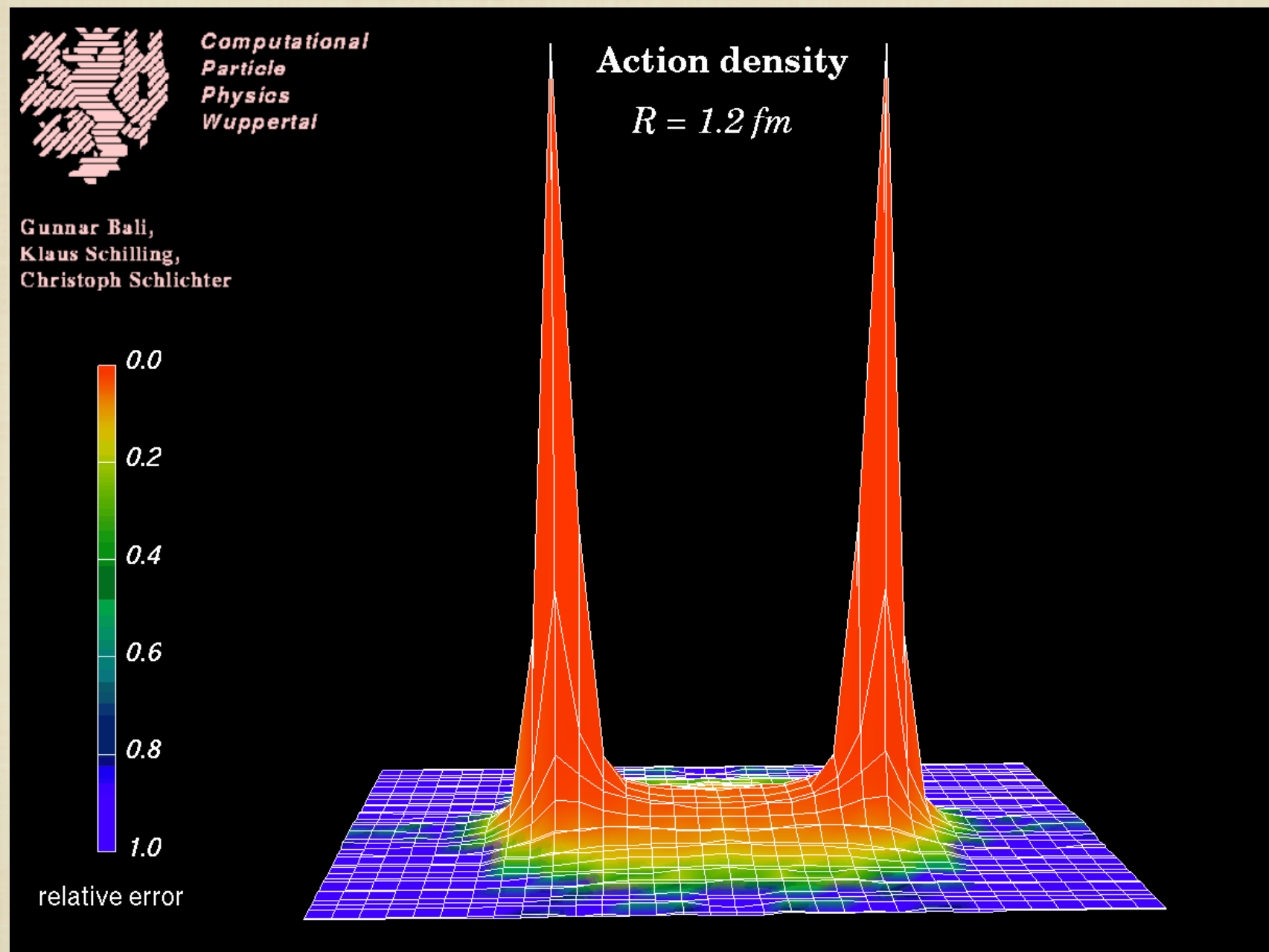
$$\begin{aligned}
 V_{\text{SI}}^{(2)} = & p^i \left(i \int_0^\infty dt t^2 \langle \boxed{\begin{smallmatrix} \bullet & \bullet \\ 1 & 2 \end{smallmatrix}} \rangle + \langle \boxed{\begin{smallmatrix} \bullet \\ 1 & 2 \\ \bullet \end{smallmatrix}} \rangle \right) p^j \\
 & - \frac{c_F^2}{2} i \int_0^\infty dt \langle \boxed{\begin{smallmatrix} \text{B} & \\ & \end{smallmatrix}} \rangle + (d_1 + C_F d_3 + \pi C_F \alpha_s c_D) \delta^{(3)}(\mathbf{r}) \\
 & - i \int_0^\infty dt_1 \int_0^{t_1} dt_2 \int_0^{t_2} dt_3 (t_2 - t_3)^2 \left(\langle \boxed{\begin{smallmatrix} \bullet & \bullet & \bullet & \bullet \\ & & & \end{smallmatrix}} \rangle + \langle \boxed{\begin{smallmatrix} \bullet & \bullet & & \\ & & \bullet & \bullet \end{smallmatrix}} \rangle \right) \\
 & + \int_0^\infty dt_1 \int_0^{t_1} dt_2 (t_1 - t_2)^2 \nabla^i \\
 & \quad \times \left(\langle \boxed{\begin{smallmatrix} \bullet & \bullet & \bullet \\ 1 & & \end{smallmatrix}} \rangle + \frac{1}{2} \langle \boxed{\begin{smallmatrix} \bullet & & \\ & \bullet & \bullet \end{smallmatrix}} \rangle + \frac{1}{2} \langle \boxed{\begin{smallmatrix} & \bullet & \bullet \\ \bullet & & \end{smallmatrix}} \rangle \right) \\
 & - 2b_3 f_{abc} \int d^3\mathbf{x} g \langle\langle G_{\mu\nu}^a(\mathbf{x}) G_{\mu\alpha}^b(\mathbf{x}) G_{\nu\alpha}^c(\mathbf{x}) \rangle\rangle_{\square}^c
 \end{aligned}$$

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

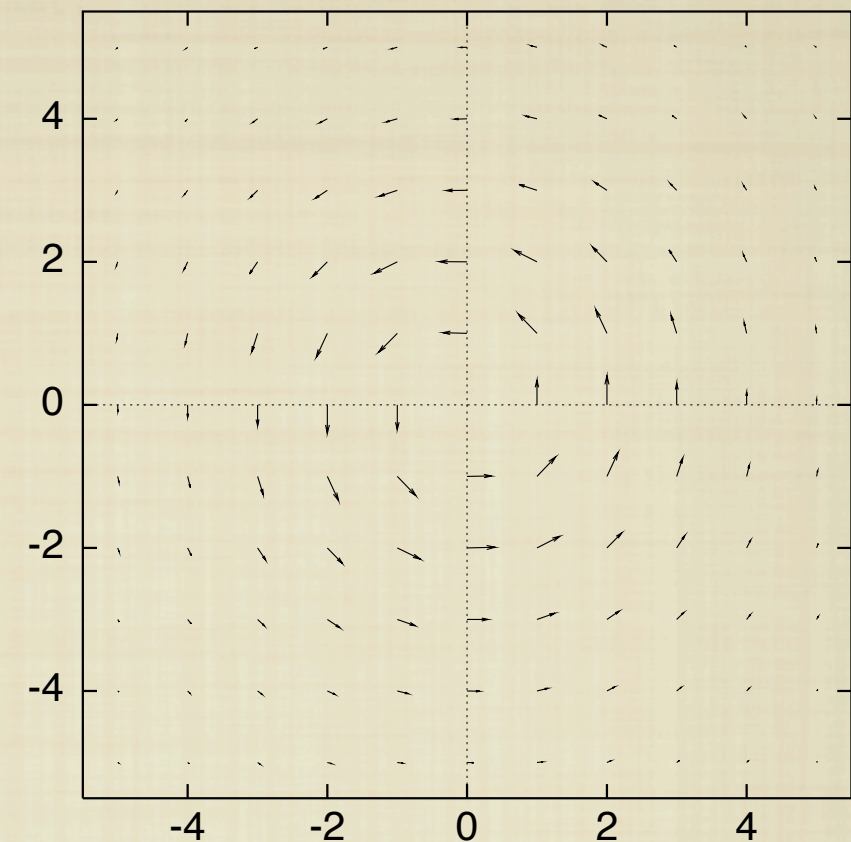
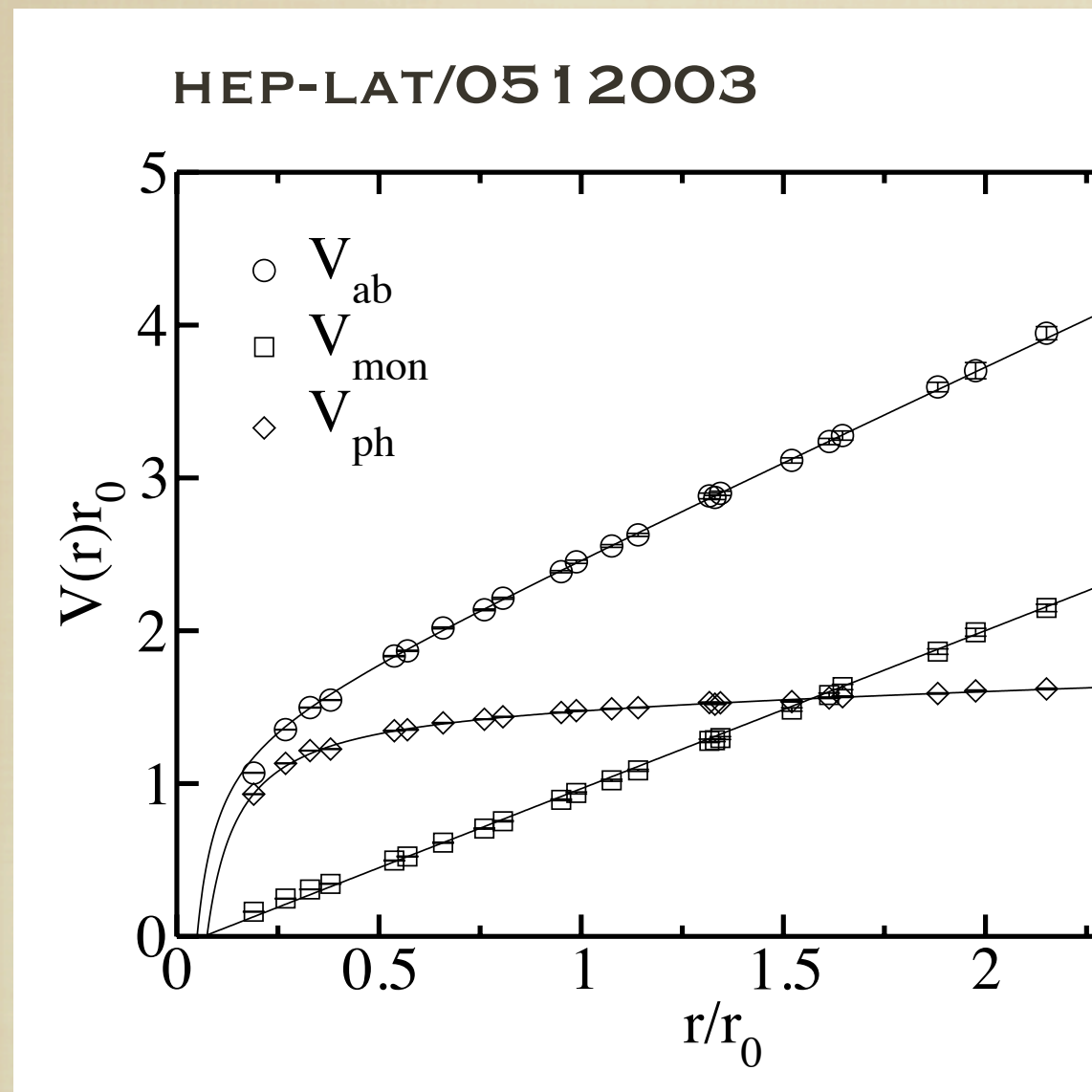
The low energy physics is now factorized in Wilson loops: they can be calculated on the lattice, in QCD vacuum models, in string theory they can be used to probe the confinement mechanism



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

The low energy physics is now factorized in Wilson loops:
they can be used to probe the confinement mechanism

many lattice investigations by Polikarpov and collaborators



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

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

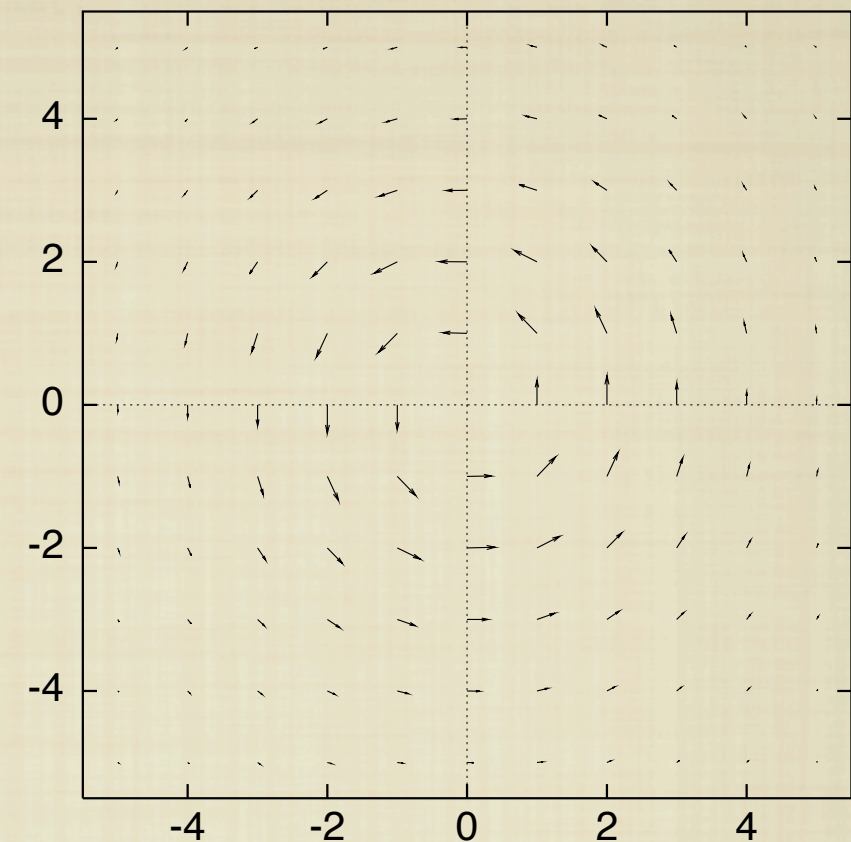
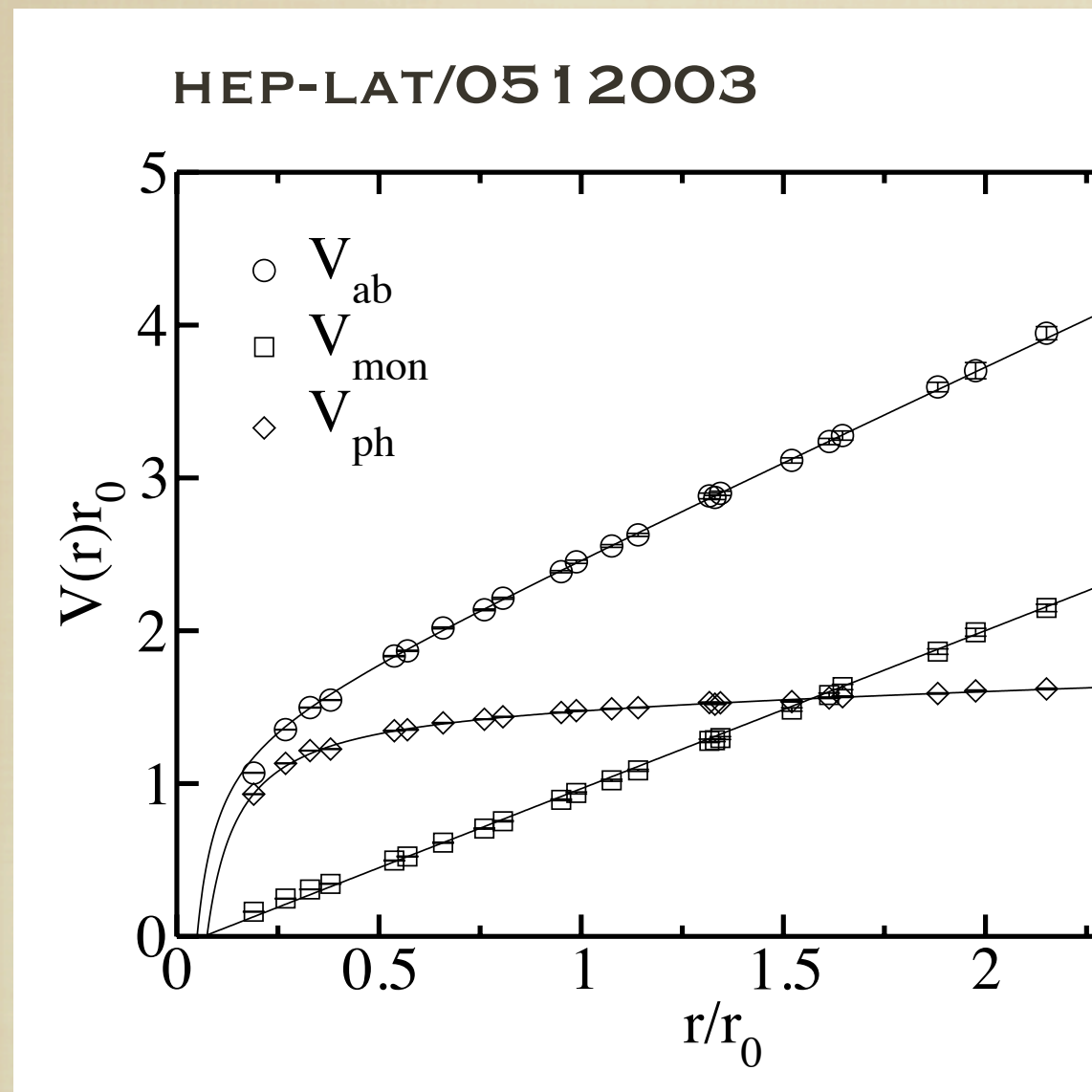
Abelian projections and monopoles

[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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uncountable important contributions
by Polikarpov and his group to the
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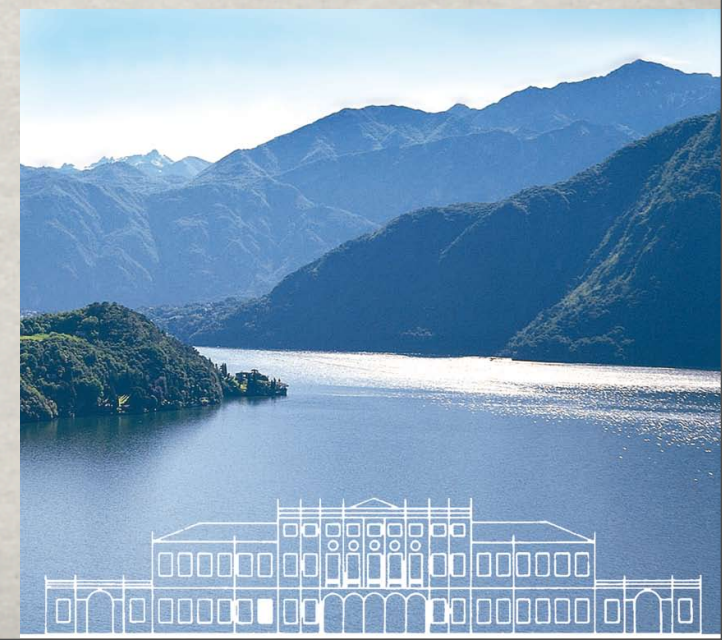
Published in In *Cambridge 1997, Confinement, duality, and nonperturbative aspects of QCD* 387-414



QUARK CONFINEMENT AND THE HADRON SPECTRUM I

Como

1994

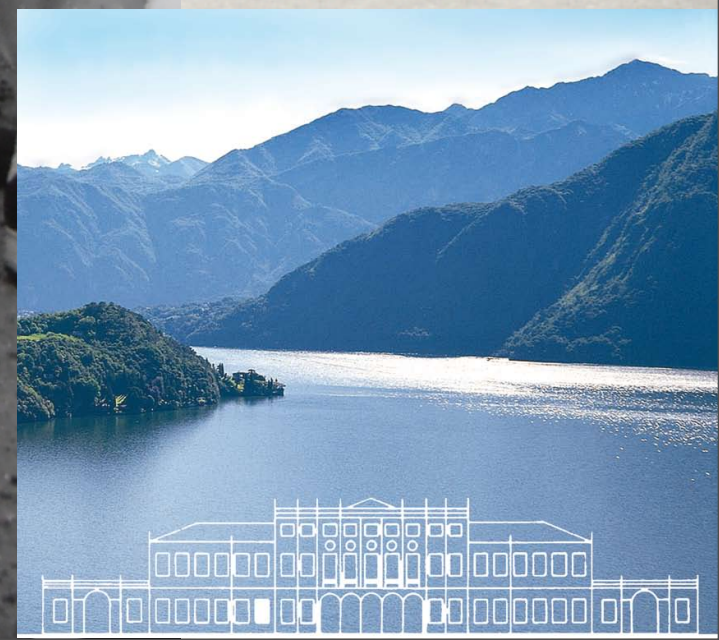




QUARK CONFINEMENT AND THE HADRON SPECTRUM I

Como

1994



Past Editions

Madrid (Spain) 2010

Mainz (Germany) 2008

Açores (Portugal) 2006

Sardinia (Italy) 2004

Gargnano (Italy) 2002

Vienna (Austria) 2000

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Xth Quark Confinement and the Hadron Spectrum

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

about 400 participants

Conference Sections

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 Mainz)

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](#) (University 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 University)

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

Two projects came out in collaboration with Misha



organized
by

Vladimir Andrianov
Gennady Kozlov,
Vladimir Shevchenko,
Nora Brambilla

dedicated to
Misha
Polikarpov

QCD driven Strongly Coupled Physics: challenges, scenarios and perspectives

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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}

QCD driven Strongly Coupled Physics: challenges, scenarios and perspectives

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The document about "QCD driven Strongly Coupled Physics: challenges, scenarios and perspectives" will be useful and impactful for the future developments in this field. The document will be organized in the confX topical sections, we are addressing the following issues for each topical section: **what have been the latest achievements/highlights in the field? **what are the most important open problems? **what are the most promising techniques/investigation avenues? **what do experiments need from theory and theory need from experiments?

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

QCD driven Strongly Coupled Physics: challenges, scenarios and perspectives

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Misha Polikarpov

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

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 unprecedented precision, where high order perturbative calculations are possible and to systematically factorize short from long range contributions where observables are sensitive 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 $q\bar{q}$ static energies and the $q\bar{q}$ 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](https://arxiv.org/abs/1010.5827)

7. CONCLUSIONS AND PRIORITIES

Below we present a summary of the most crucial developments in each of the major topics and suggested directions for further advancement.

Spectroscopy: An overview of the last decade's progress in heavy quarkonium spectroscopy was given in Sect. 2. With regard to experimental progress, we conclude:

1. New measurements of inclusive hadronic cross sections (*i.e.*, R) for e^+e^- collisions have enabled improved determinations of some resonance parameters but more precision and fine-grained studies are needed to resolve puzzles and ambiguities. Likewise, progress has been made studying exclusive open-flavor two-body and multibody composition in these regions, but further data are needed to clarify the details. Theory has not yet been able to explain the measured exclusive two-body cross sections.
2. Successful observations were made (Table 4) of 6 new conventional heavy quarkonium states ($4 c\bar{c}$, 2 $b\bar{b}$); of these, only the $\eta_b(1S)$ lacks a second, independent 5σ confirmation. Improved measurement of $\eta_c(1S)$ and $\eta_c(2S)$ masses and widths would be quite valuable. Unambiguous observations are needed for $\eta_b(2S)$, $h_b(1P_1)$, $\Upsilon(1^3D_1)$, and $\Upsilon(1^3D_3)$ in order to constrain theoretical descriptions.

Experimental evidence has been gathered (Table 9) up to 17 unconventional heavy quarkonium-like states. All but $Y_b(10888)$ are in the charmonium σ level, and all but 5 remain unconfirmed at 12σ level. Confirmation or refutation of the remaining 12 is a high priority.

Interpretations for the unconventional quark-gluon hybrids, mesonic molecules, and tetraquarks. More measurements and theoretical calculations are necessary to narrow the possibilities, particularly, high-resolution measurements promise deeper insights into the nature of those states.

the first

and $\gamma J/\psi$ three times less. The $X(3872)$ quantum numbers have been narrowed to 1^{++} or 2^{-+} .

6. The charged Z states observed in $Z^- \rightarrow \pi^- \psi(2S)$ and $\pi^- \chi_{c1}$ would be, if confirmed, manifestly exotic. Hence their confirmation or refutation is of the utmost importance.

With regard to lattice QCD calculations:

7. Lattice QCD technology has progressed to the point that it may provide accurate calculations of the energies of quarkonium states below the open flavor threshold, and also provide information about higher states.
8. Precise and definitive calculations of the $c\bar{c}$ and $b\bar{b}$ meson spectra below threshold are needed. Unquenching effects, valence quark annihilation channels and spin contributions should be fully included.
9. Unquenched calculations of states above the open-flavor thresholds are needed. These would provide invaluable clues to the nature of these states.
10. The complete set of Wilson loop field strength averages entering the definition of the nonperturbative $Q\bar{Q}$ potentials must be calculated on the lattice.
11. Calculations of local and nonlocal gluon condensates on the lattice are needed as inputs to weakly-coupled pNRQCD spectra and decay calculations.
12. NRQCD matching coefficients in the lattice scheme at one loop (or more) are needed.
13. Higher-order calculations of all the relevant quarkonium and heavy meson masses as well as their decay widths are needed.

39. It we

31. It would be important to have a coherent EFT treatment for all magnetic and electric transitions. In particular, a rigorous treatment of the relativistic corrections contributing to the M1 transitions and a nonperturbative analysis of the transitions involving P states, the second for any transition from above the ground state.

32. New resummation schemes for the perturbative expressions of the quarkonium decay widths should be developed. At the moment, this is the major obstacle to precise theoretical determinations of the $\Upsilon(1S)$ and $\eta_b(1S)$ inclusive and electromagnetic decays (Sect. 3.2.1).

33. More rigorous techniques to describe above-threshold quarkonium decays and transitions, whose descriptions still rely upon models, should be developed (Sects. 3.3.1 and 3.4).

Production: The theoretical and experimental status of production of heavy quarkonia was given in Sect. 4. Conclusions and priorities are as follows:

34. It is very important either to establish that the NRQCD factorization formula is valid to all orders in perturbation theory or to demonstrate that it breaks down at some fixed order.
35. A more accurate treatment of higher-order corrections to the color-singlet contributions at the Tevatron and the LHC is urgently needed. The re-organization of the fragmentation-function approach provided by the fragmentation-function approach (Sect. 4.1.5) may be an important tool.
36. An outstanding theoretical challenge is the development of methods to compute color-octet long-distance NRQCD production matrix elements on the lattice.
37. If NRQCD factorization is valid, it likely holds only for values of p_T that are much greater than the heavy-quark mass. Therefore, it is important for experiments to make measurements of quarkonium production, differentially in p_T , at the highest possible values of p_T .
38. Further light could be shed on the NRQCD velocity expansion and its implications for low-energy dynamics by comparing studies of quarkonium production and bottomonium production. The p_T reach of the LHC may be particularly useful for studying bottomonium production. p_T that are much greater than the heavy-quark mass.

45. In

experiment
tify direct an
direct produc
would both be

40. It is important to
between the CDF
polarization, which
pidity ranges, $|y| < 0$.
A useful first step wo
ments to provide polar
cover the same rapidity r

41. It would be advantageous
quarkonium polarization info
spin-quantization frames and t
invariant quantities to cross-che
different frames [722, 723, 1031].
taken in comparing different polar
ments to insure that dependences of
frame and the kinematic ranges of th
have been taken into account.

42. Measurements of inclusive cross sections
nium angular distributions, and polariza
rameters for P -wave charmonium states wo
vide further important information about qu
nium production mechanisms.

43. Studies of quarkonium production at different
ues of \sqrt{s} at the Tevatron and the LHC, and
hadronic energy near to and away from the quarko
nium direction at the Tevatron and the LHC, and
studies of the production of heavy-flavor mesons in
association with a quarkonium that is comple
 pp machines could give information that is comple
mentary to that provided by traditional observa
tions of quarkonium production rates and polariza

44. Theoretical uncertainties in the reg
kinematic endpoint of maximum
energy might be reduced thro
of resummations of th
expansions in bot
duction.

Selected Outlook for future research

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

*Alice, Rhic
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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EFT for states close to thresholds: X , Y , Z

Quarkonium-quarkonium van der Waals interaction; quarkonium on nuclei

Quarkonium production

Alice, Rhic
Belle, BESIII, Panda, LHC exps
Belle, BESIII, Panda, LHC-b
Fair
CMS, Atlas, Alice, LHC-b

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

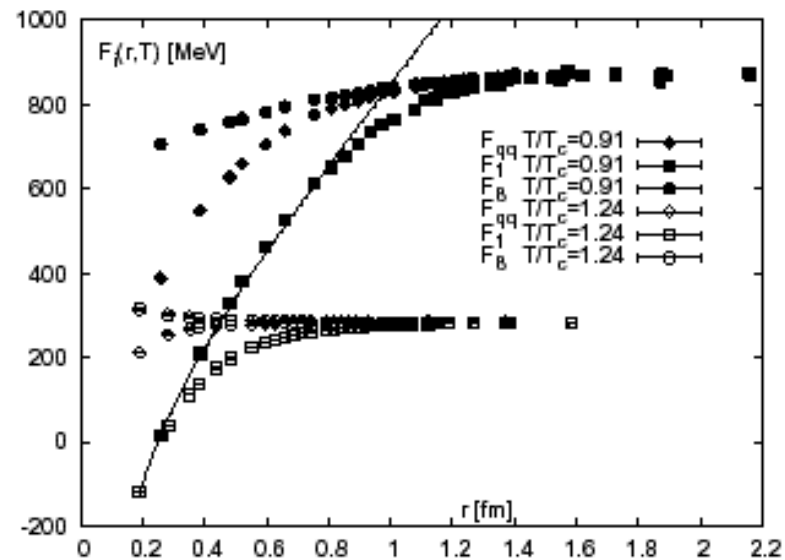
Heating quarkonium systems

$$T > 0$$

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 ($\sim \langle \text{Tr } L^\dagger(r) \text{Tr } L(0) \rangle$) is an overlap of singlet and octet quark-antiquark states, what is called the singlet ($\sim \langle \text{Tr } L^\dagger(r) L(0) \rangle$) and the octet ($\sim \langle \text{Tr } L^\dagger(r) \text{Tr } L(0) \rangle - 1/3 \langle \text{Tr } L^\dagger(r) L(0) \rangle$) free energy are gauge dependent;

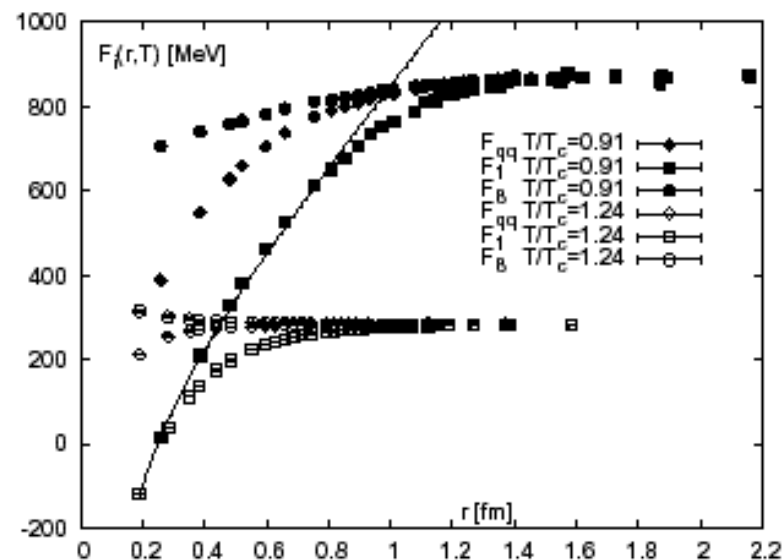


○ Kaczmarek Zantow PRD 71 (2005) 114510

Quarkonium in a hot medium: the interaction potential

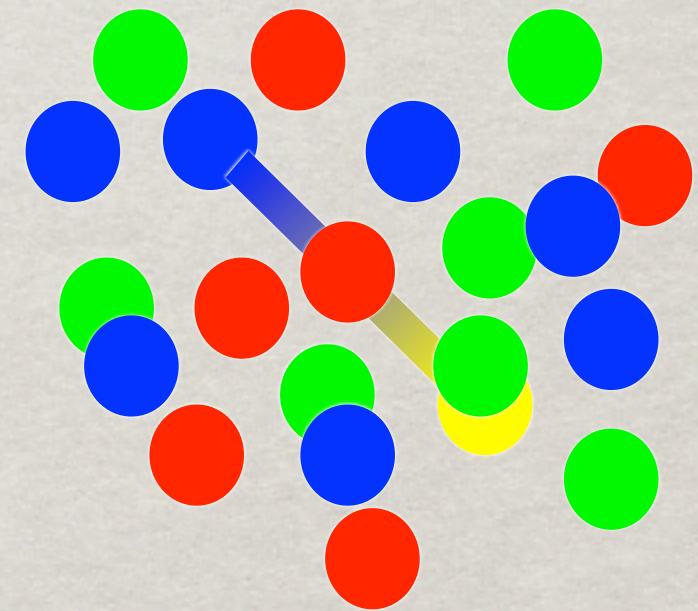
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○ Kaczmarek Zantow PRD 71 (2005) 114510

It was believed
that the color
screening
of the potential
originates quarkonium
dissociation
Matsui Satz 86



Debye charge screening
(electromagnetic plasma)

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

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

But, at finite temperature what is the quarkonium potential?

But, at finite temperature what is the quarkonium potential?

The potential $V(r,T)$ dictates through the Schrödinger equation the real time evolution of the $Q\bar{Q}$ pair in the medium \rightarrow use the EFT to define and calculate it

But, at finite temperature what is the quarkonium potential?

The potential $V(r,T)$ dictates through the Schrödinger equation the real time evolution of the $Q\bar{Q}$ pair in the medium \rightarrow use the EFT to define and calculate it

more scales

But, at finite temperature what is the quarkonium potential?

The potential $V(r,T)$ dictates through the Schroedinger equation the real time evolution of the $Q\bar{Q}$ pair in the medium \rightarrow use the EFT to define and calculate it

more scales

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

?

and Λ_{QCD}

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

$m_D \sim gT$
Debye mass
Screening Scale

But, at finite temperature what is the quarkonium potential?

The potential $V(r,T)$ dictates through the Schroedinger equation the real time evolution of the $Q\bar{Q}$ pair in the medium \rightarrow use the EFT to define and calculate it

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

?

and Λ_{QCD}

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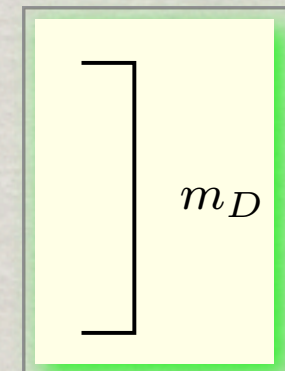
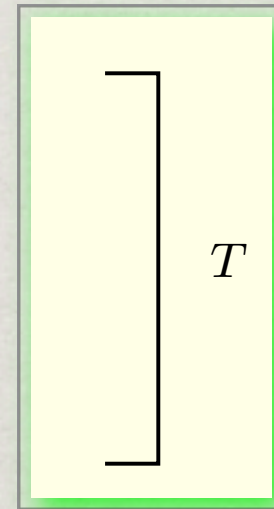
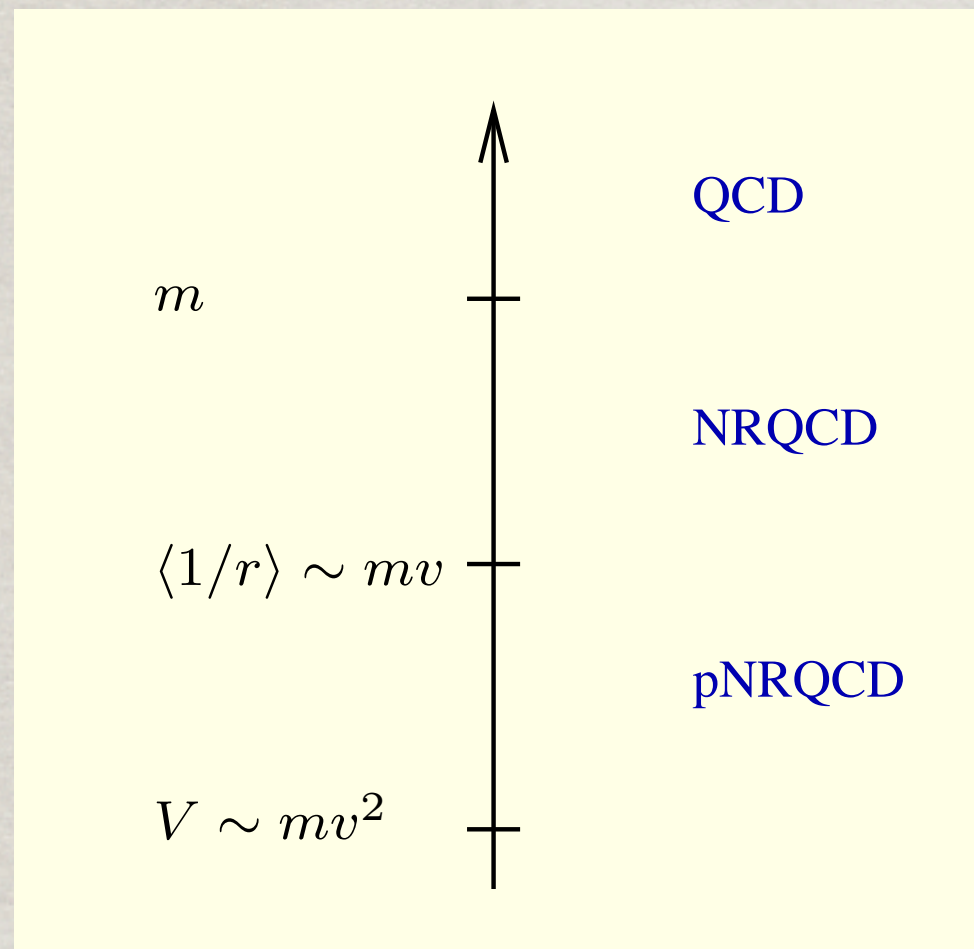
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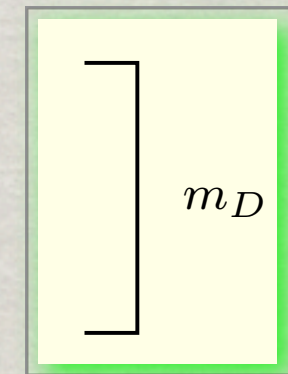
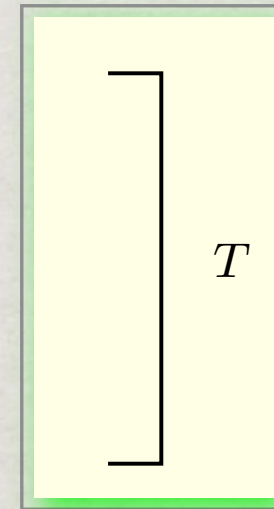
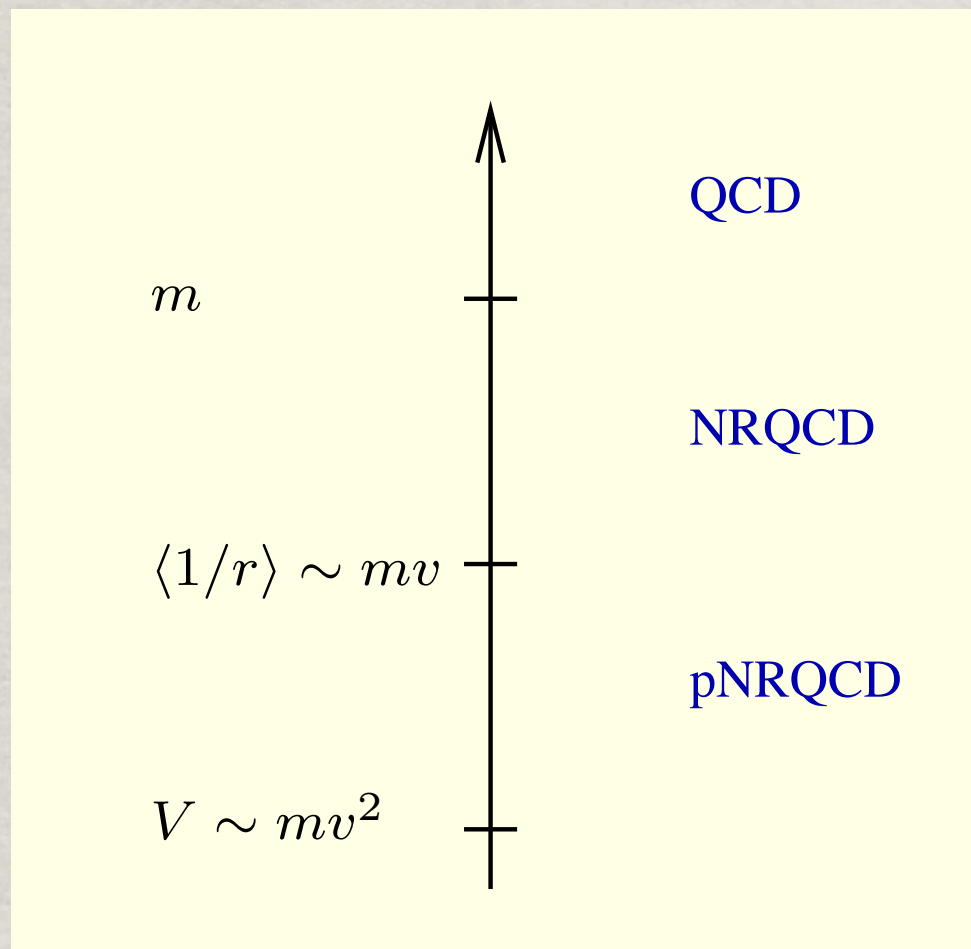
Without heavy quarks an EFT already exists that comes from integrating out hard gluon of $p \sim T$:

Hard Thermal Loop EFT

Quarkonium at finite T with pNRQCD

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





We work under the conditions:

We assume that bound states exist for

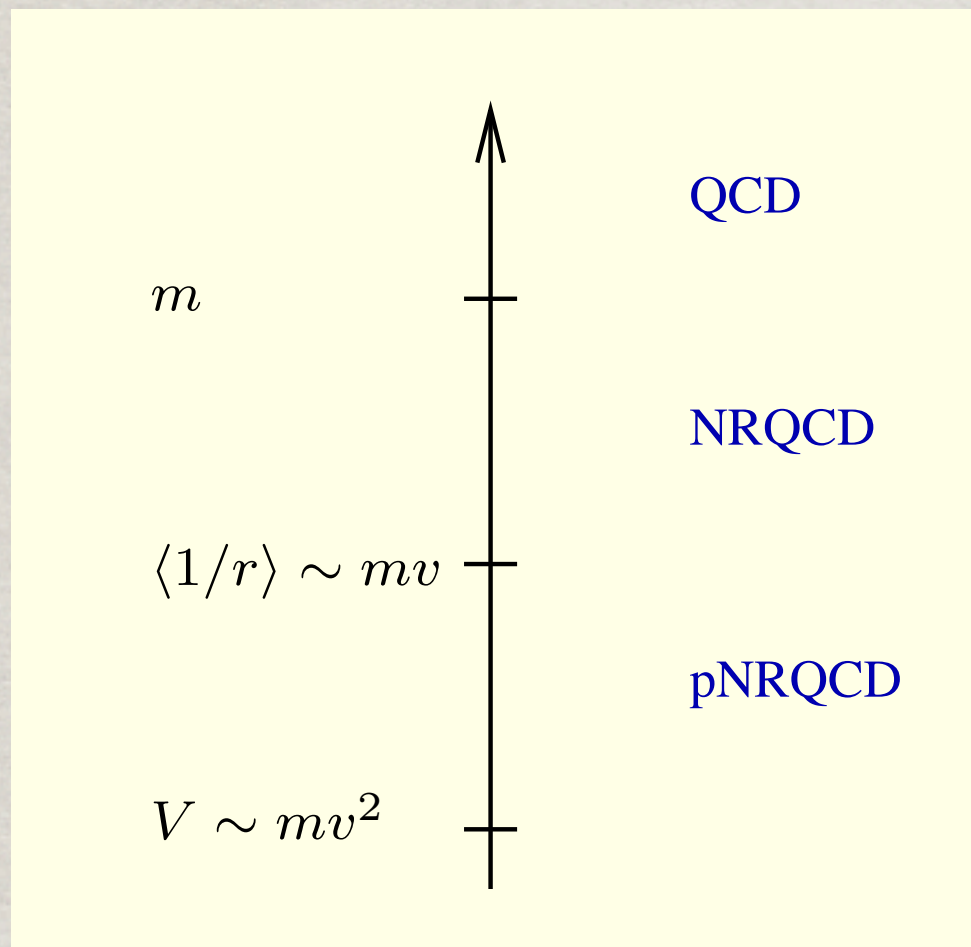
- $T \ll m$
- $\langle 1/r \rangle \sim mv \gtrsim m_D$

We neglect smaller thermodynamical scales.

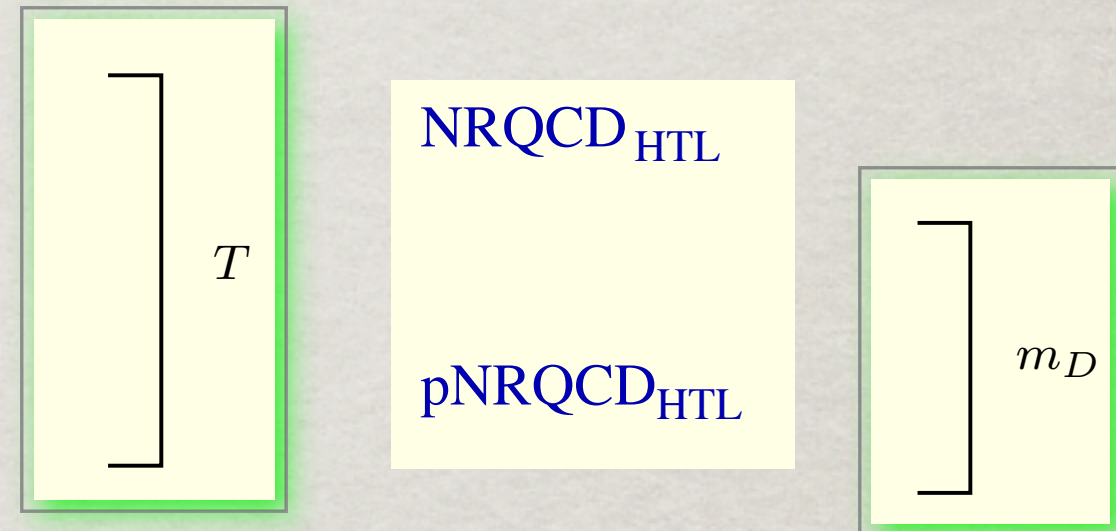
In the weak coupling regime:

- $v \sim \alpha_s \ll 1$; 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.



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

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

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

thermal width of $Q\bar{Q}$



N. B., Ghiglieri,
Petreczky, Vairo 2008 **Singlet-to-octet**
New effect, specific of QCD
dominates for $E/m_D \gg 1$
(gluo dissociation)

Landau damping Laine et al 2007
Known from QED
dominates for $m_D/E \gg 1$
(dissociation via inelastic
parton scattering)

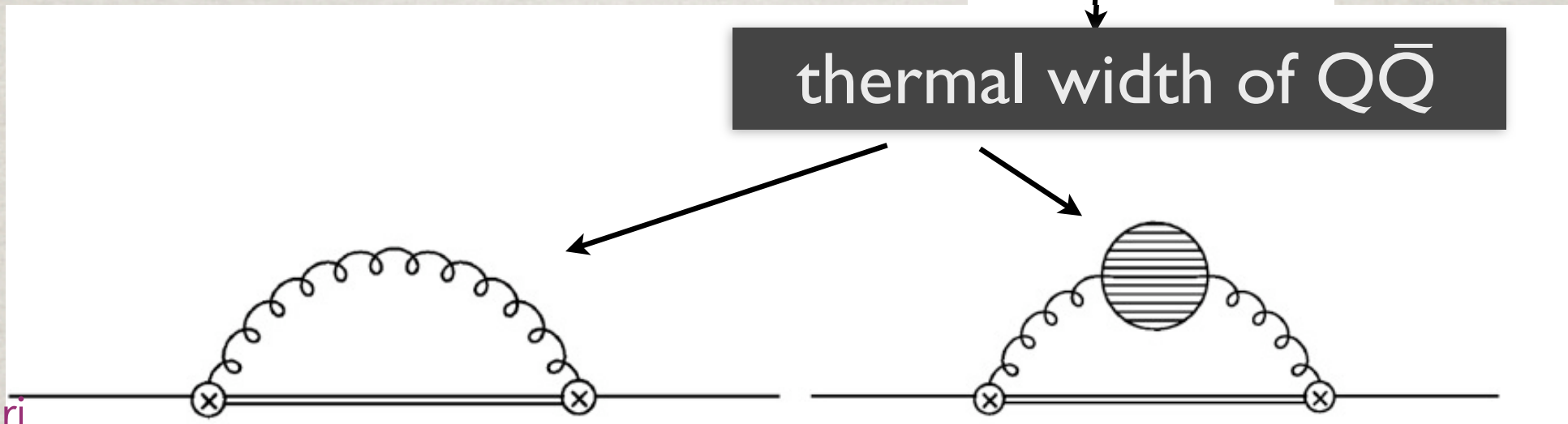
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N. B., Ghiglieri,

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Laine et al 2007

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(dissociation via inelastic
parton scattering)

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

->the imaginary part is responsible for $Q\bar{Q}$ dissociation !

$T \gg 1/r \gg m_D \gg V$: Quarkonium melts in the medium

Escobedo Soto arXiv:0804.0691

Laine arXiv:0810.1112

$E_{\text{binding}} \sim \Gamma$

The singlet static potential

- Temperature effects can be other than screening

The singlet static potential

- Temperature effects can be other than screening

$$T > 1/r \text{ and } 1/r \sim m_D \sim gT$$

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

$$T > 1/r \text{ and } 1/r > m_D \sim gT$$

no exponential screening but
power-like T corrections

$$T < E_{\text{bin}}$$

no corrections to the potential,
corrections to the energy

Y(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: $mv \sim m\alpha_s$, $mv^2 \sim m\alpha_s^2 \gtrsim \Lambda_{\text{QCD}}$, produced in the QCD medium of heavy-ion collisions at the LHC may possibly realize the hierarchy

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

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Y(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 $\mathcal{O}(m\alpha_s^5)$

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

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

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
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