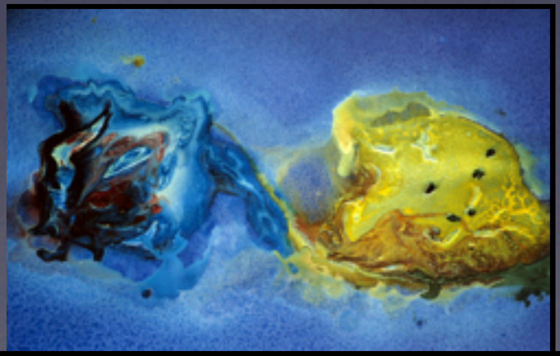
Heavy Quarkonium with Effective Field Theories

Nora Brambilla



Physik Department TUM
T30f

- the physics of quarkonium and its relevance to the physics of Standard Model and beyond

- the state of the art theory tools confronted to experimental data

- experimental/theoretical challenges and opportunities

QCD and strongly coupled gauge theories: challenges and perspectives

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H.B. Meyer‡,[18] P. Pakhlov‡,[19,20] E. Pallante‡,[21] M.I. Polikarpov‡,[19,20] H. Sazdjian‡,[22]
A. Schmitt‡,[23] W.M. Snow‡,[24] A. Vairo‡,[1] R. Vogt‡,[25,26] A. Vuorinen‡,[27] H. Wittig‡,[18]
P. Arnold,[28] P. Christakoglou,[29] P. Di Nezza,[30] Z. Fodor,[31,32,33] X. Garcia i Tormo,[34] R. Höllwieser,[13]
M.A. Janik,[35] A. Kalweit,[36] D. Keane,[37] E. Kiritsis,[38,39,40] A. Mischke,[41] R. Mizuk,[19,42]
G. Odyniec,[43] K. Papadodimas,[21] A. Pich,[44] R. Pittau,[45] J.-W. Qiu,[46,47] C. Ricciardi,[48,49]
C.A. Salgado,[50] K. Schwenzer,[7] N.G. Stefanis,[51] G.M. von Hippel,[18] and V.I. Zakharov[11,19]

We highlight the progress, current status, and open challenges of QCD-driven physics, in theory and in experiment. We discuss how the strong interaction is intimately connected to a broad sweep of physical problems, in settings ranging from astrophysics and cosmology to strongly-coupled, complex systems in particle and condensed-matter physics, as well as to searches for physics beyond the Standard Model. We also discuss how success in describing the strong interaction impacts other fields, and, in turn, how such subjects can impact studies of the strong interaction. In the course of the work we offer a perspective on the many research streams which flow into and out of QCD, as well as a vision for future developments.

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

In the near past data came from:

B-FACTORIES (Belle, BABAR): Heavy Mesons Factories

CLEO-c BES tau charm factories
CLEO-III bottomonium factory

Fermilab CDF, D0, E835

Hera RHIC (Star, Phenix), NA60

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

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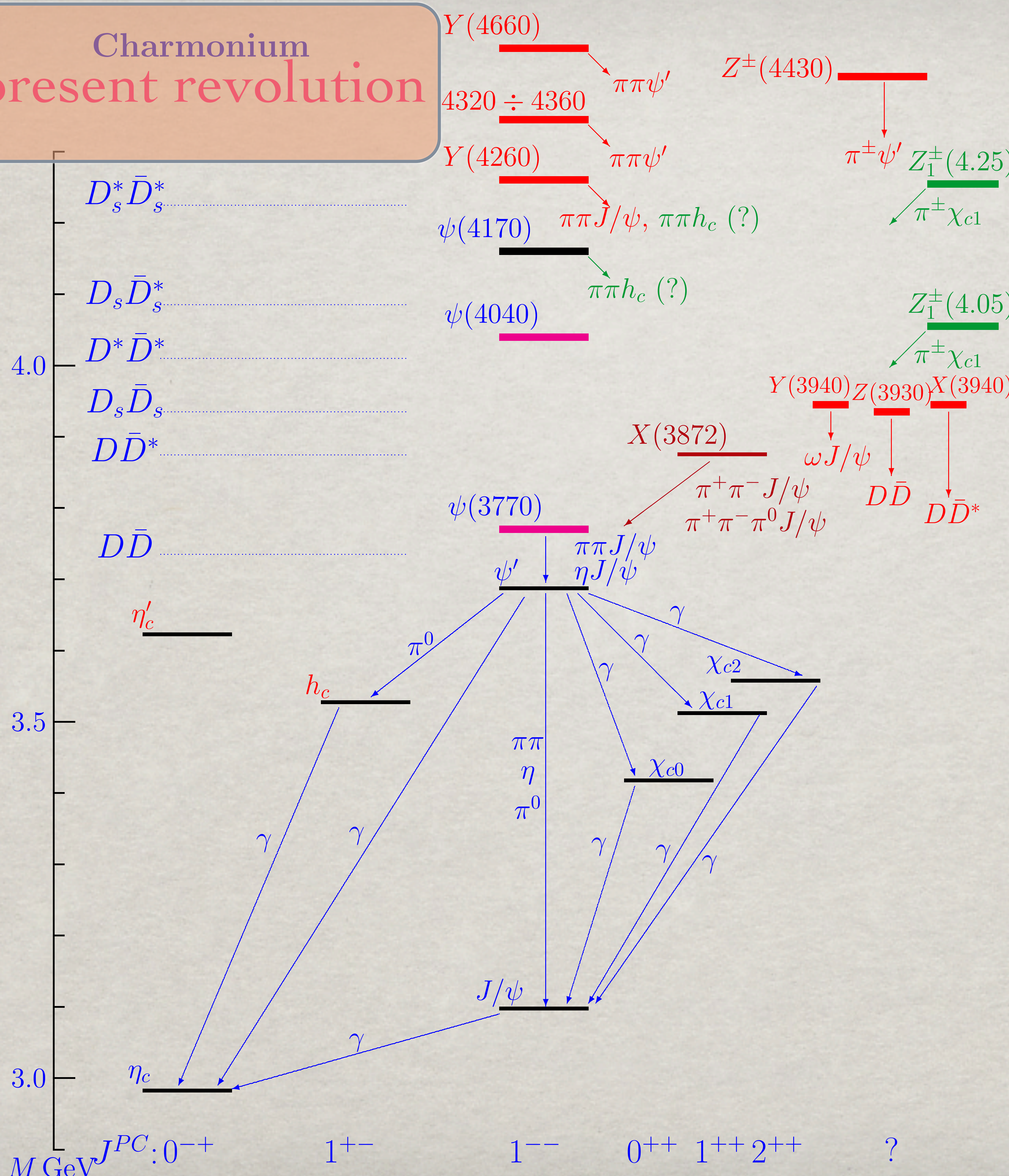
and in the future Belle II at SuperKEKB, PANDA at FAIR

Charmonium
the present revolution



THE COLLIDER DETECTOR AT FERMILAB

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BELLE

BABAR Collaboration Home Page

BES

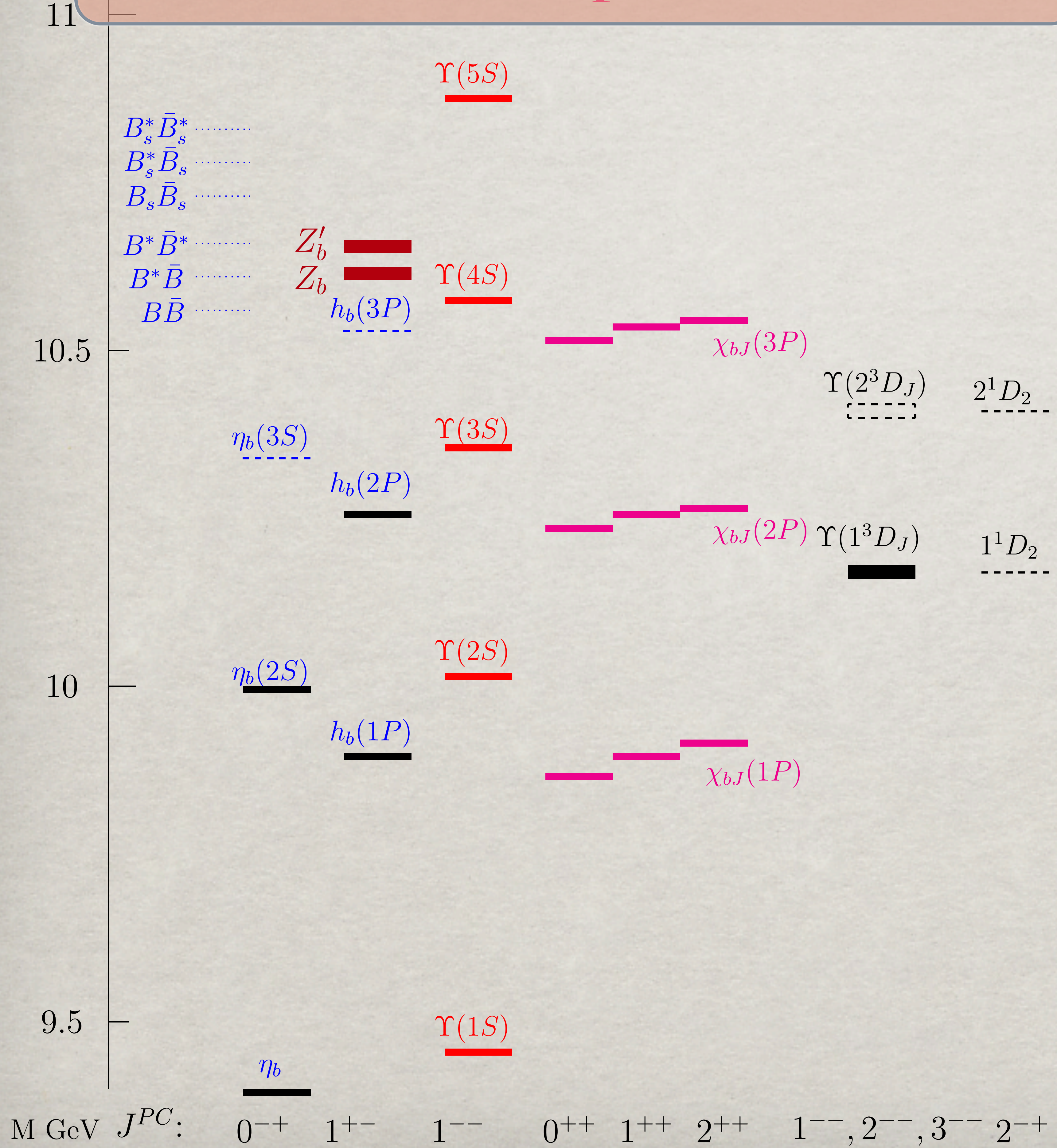
CLEO

ATLAS

CMS

LHCb

bottomonium: the present revolution



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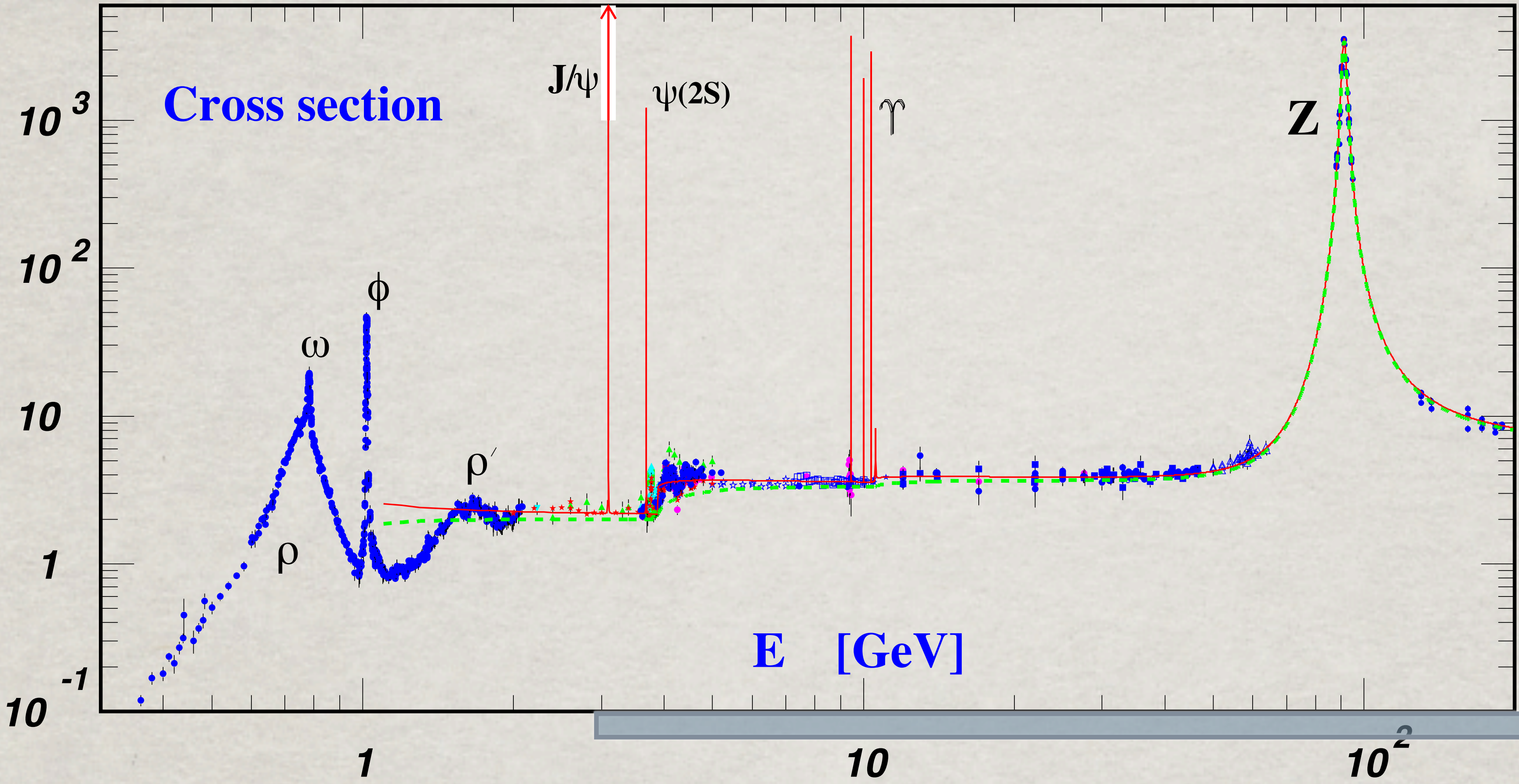
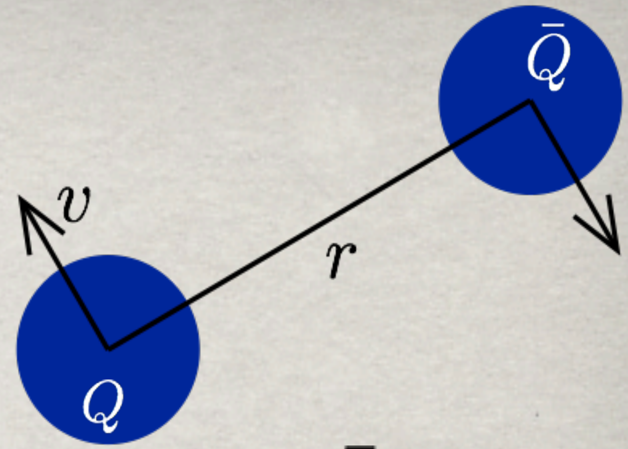
Heavy quarks offer a privileged access





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

$m_c \sim 1.5$GeV

$m_b \sim 5$GeV

$m_t \sim 170$GeV

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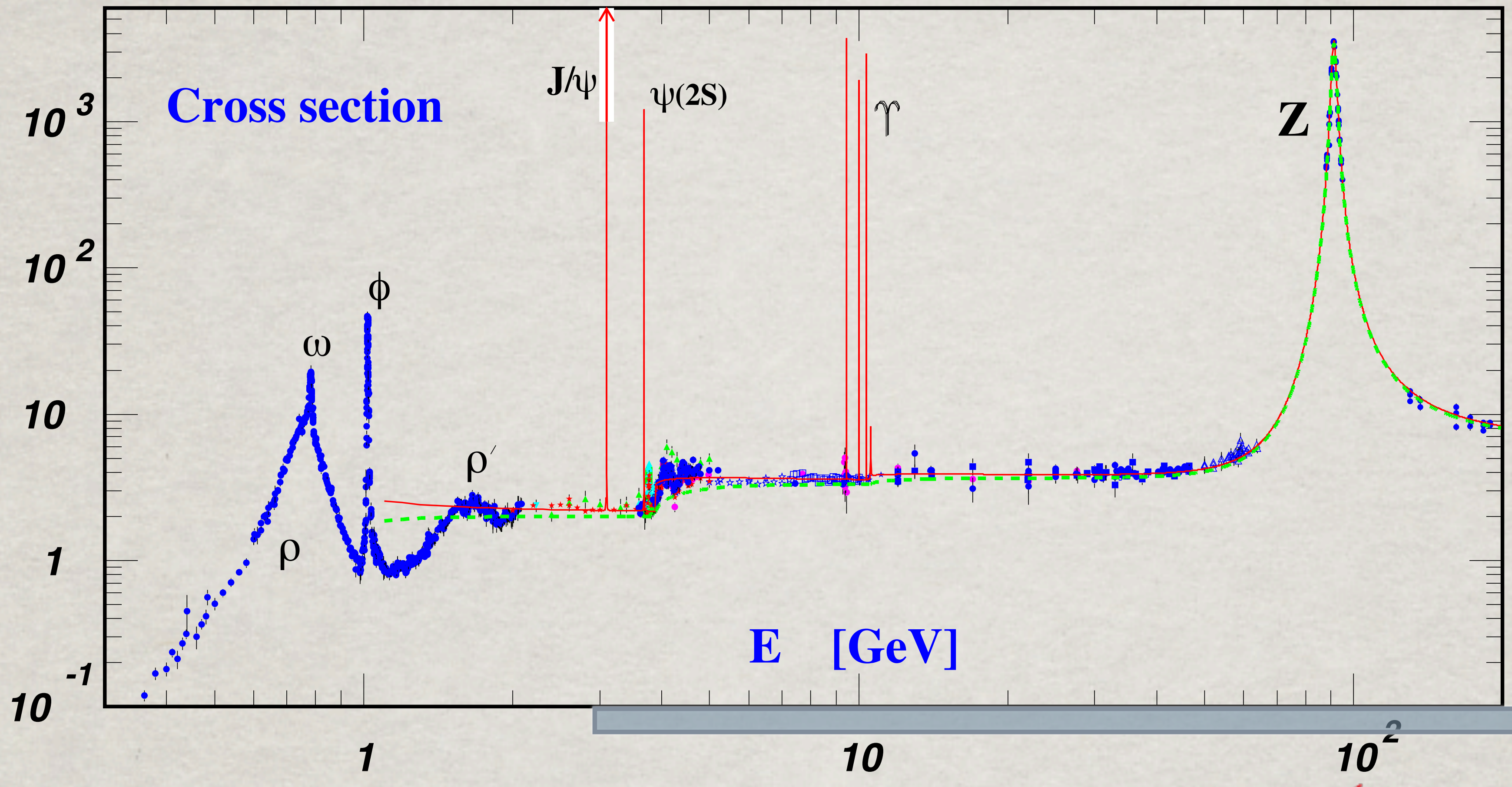

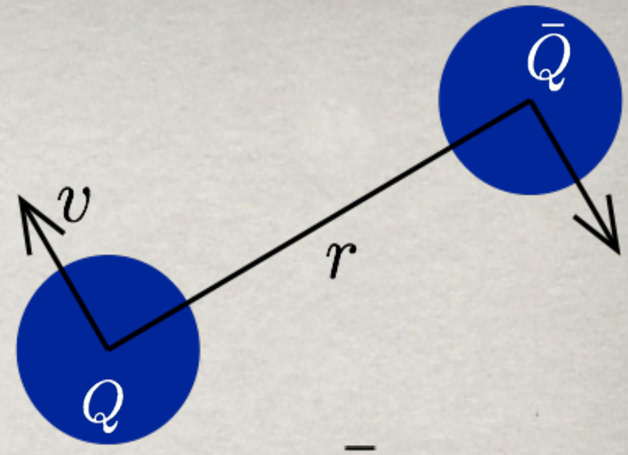

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A large scale $m_Q \gg \Lambda_{QCD}$ $\alpha_s(m_Q) \ll 1$

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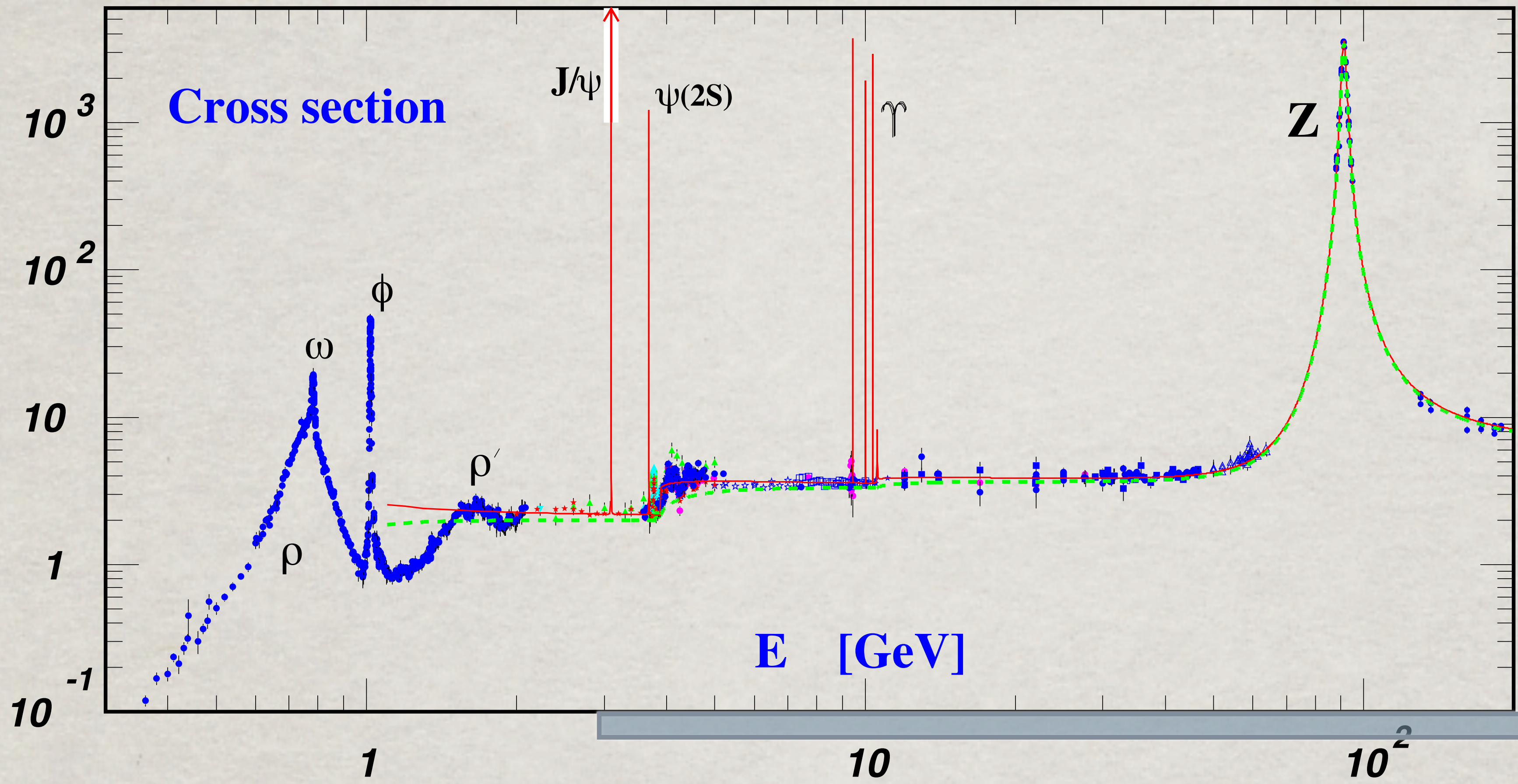

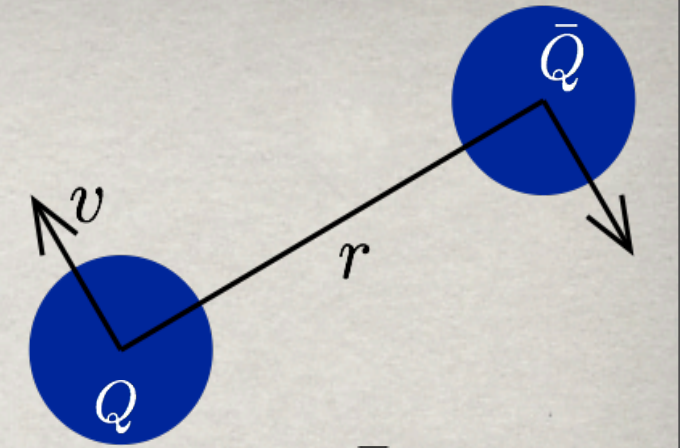

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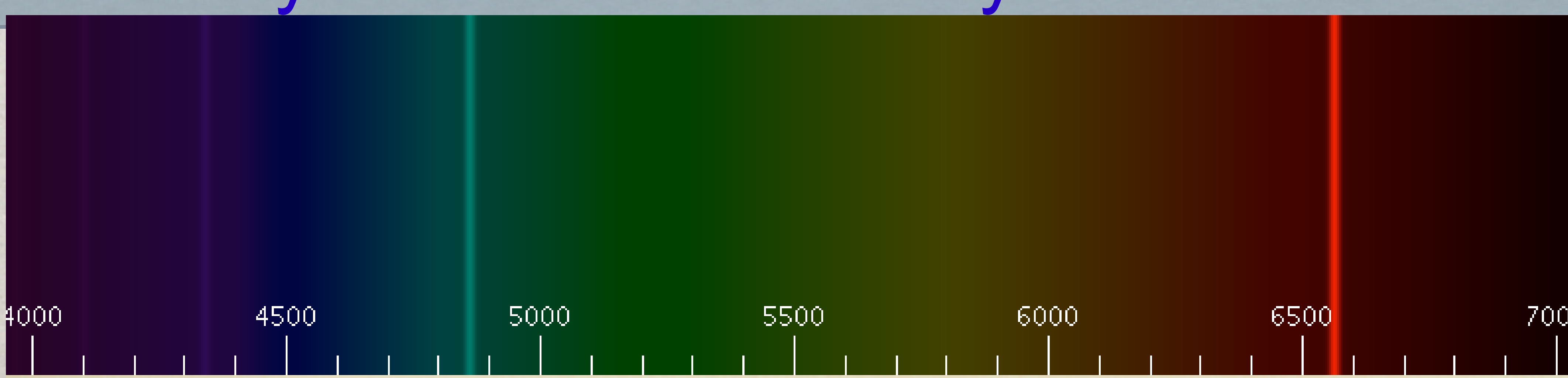
Heavy quarkonia are nonrelativistic bound systems: multiscale systems



Electromagnetic bound states: atoms, molecules,

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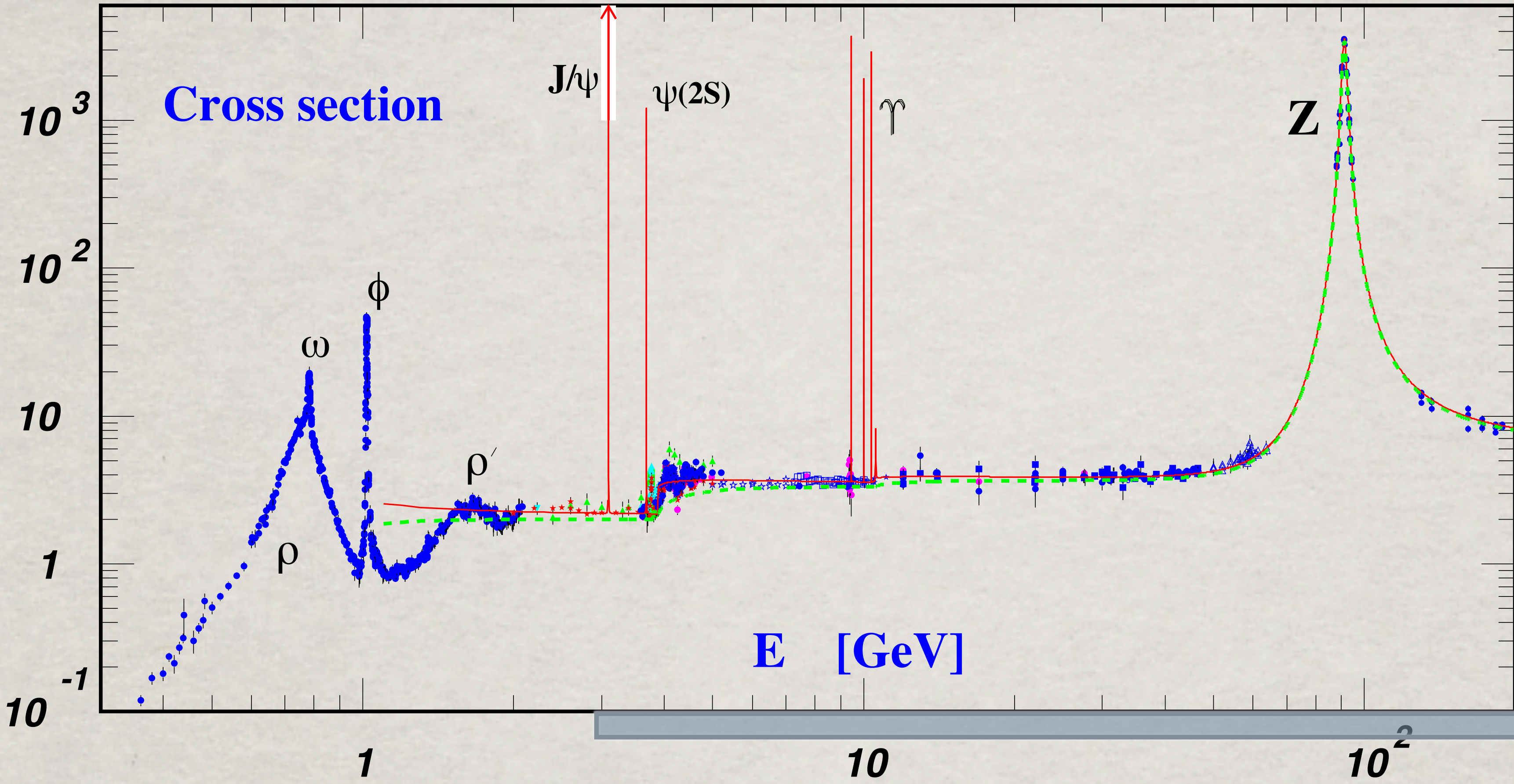

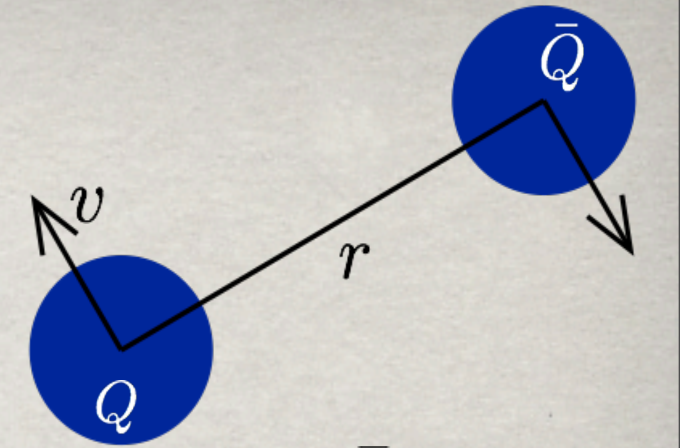

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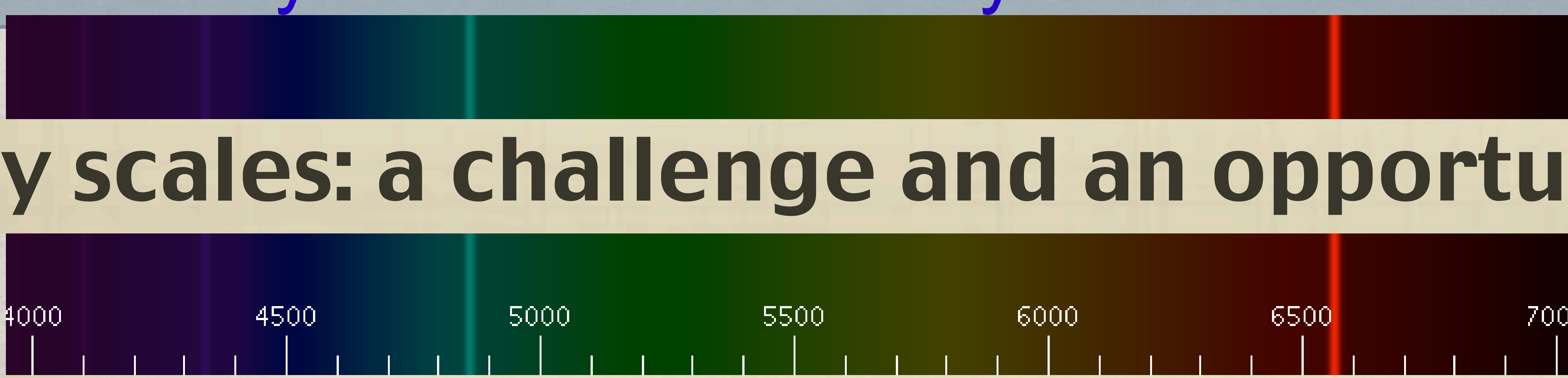
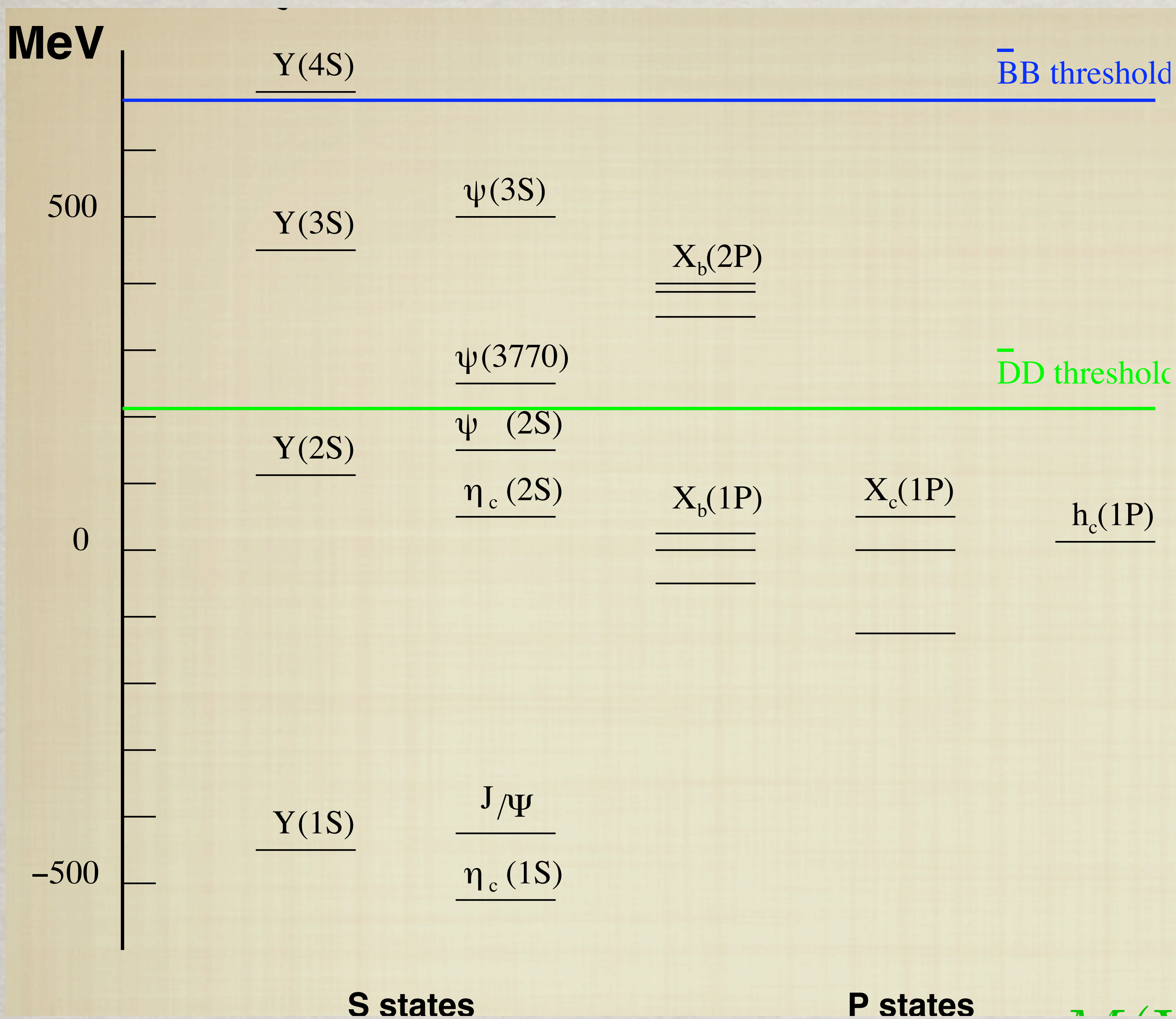


many scales: a challenge and an opportunity

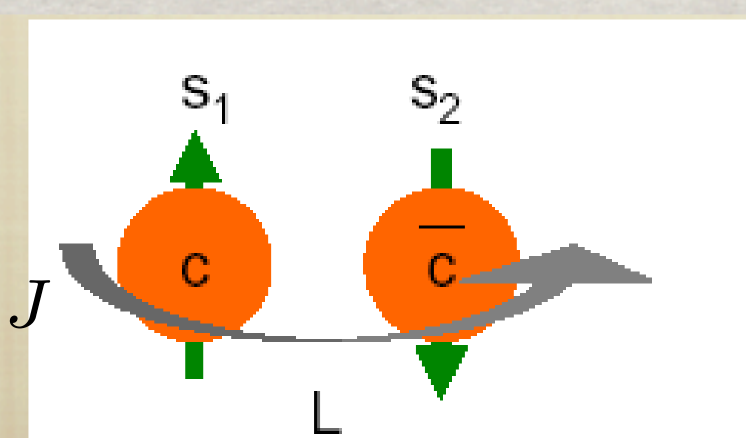
ELECTROMAGNETIC BOUND STATES: ATOMS, MOLECULES,

Quarkonium scales



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

$^{2S+1}L_J$

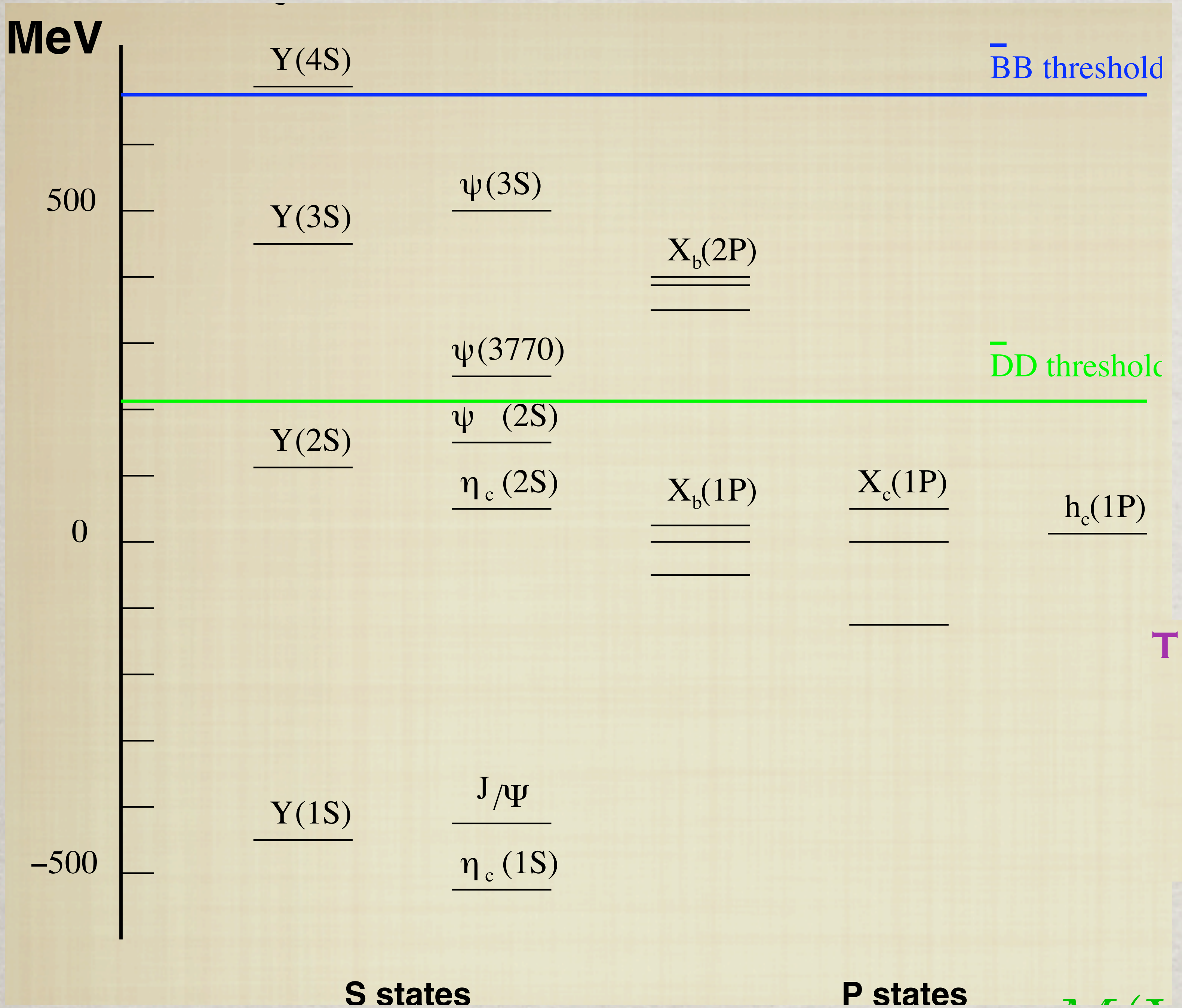


The mass scale is perturbative

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

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

Quarkonium scales



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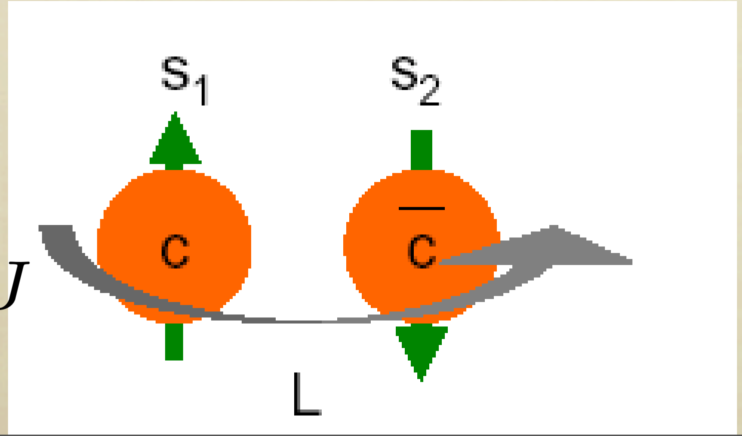

THE SYSTEM IS NONRELATIVISTIC(NR)

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

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

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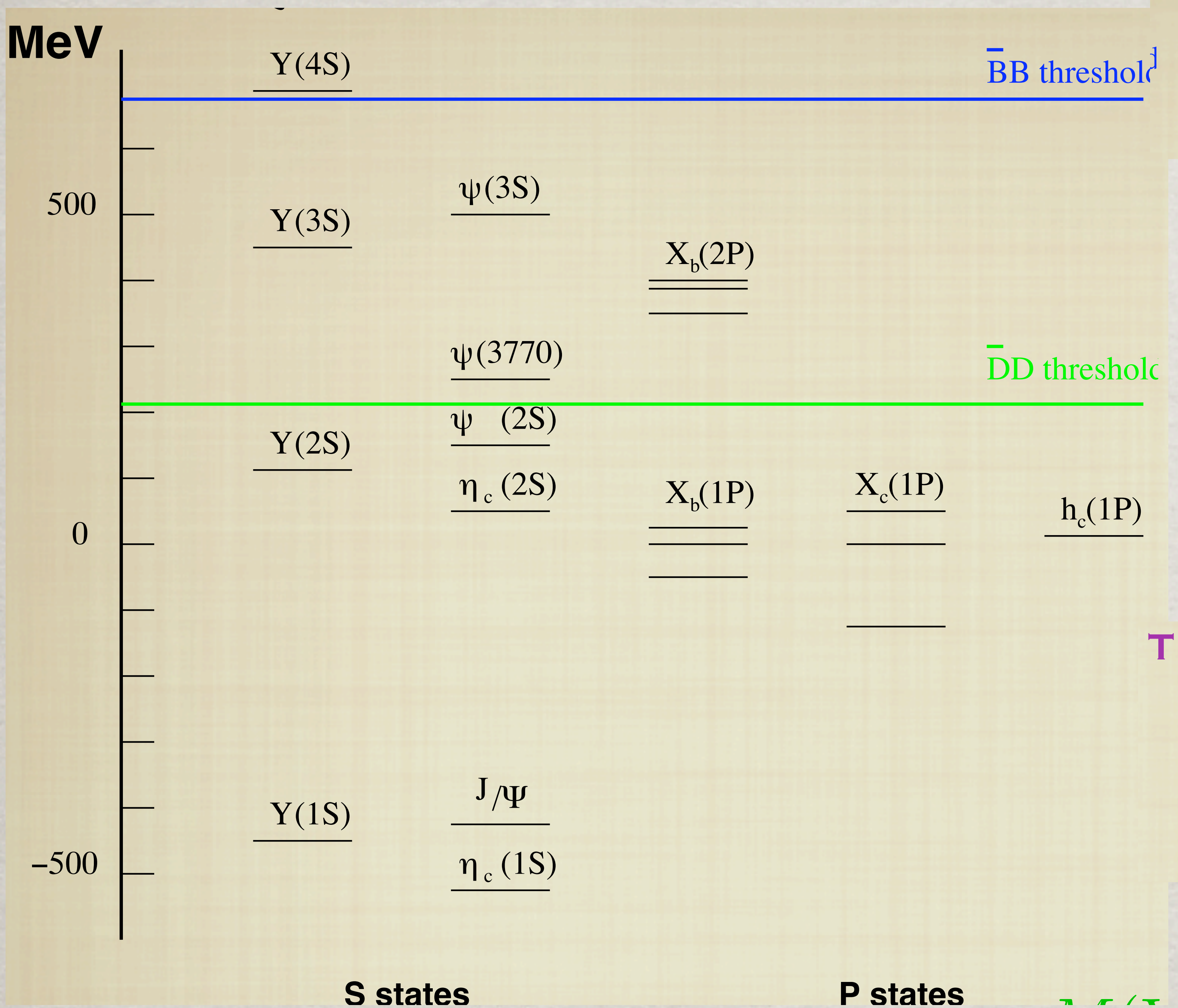

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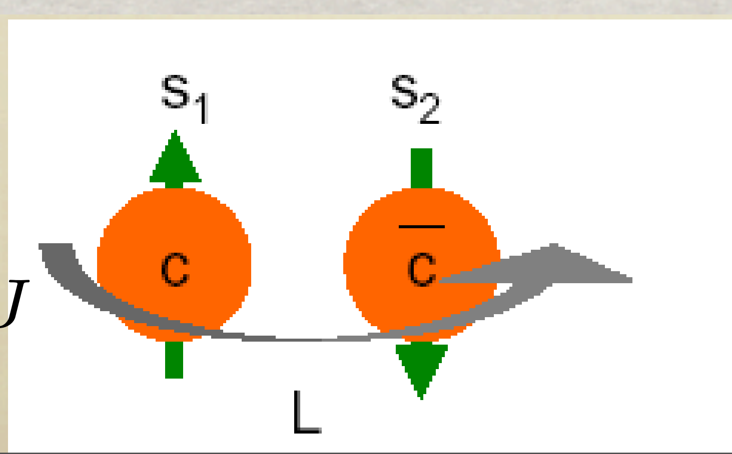

NR bound states have at least 3 scales

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

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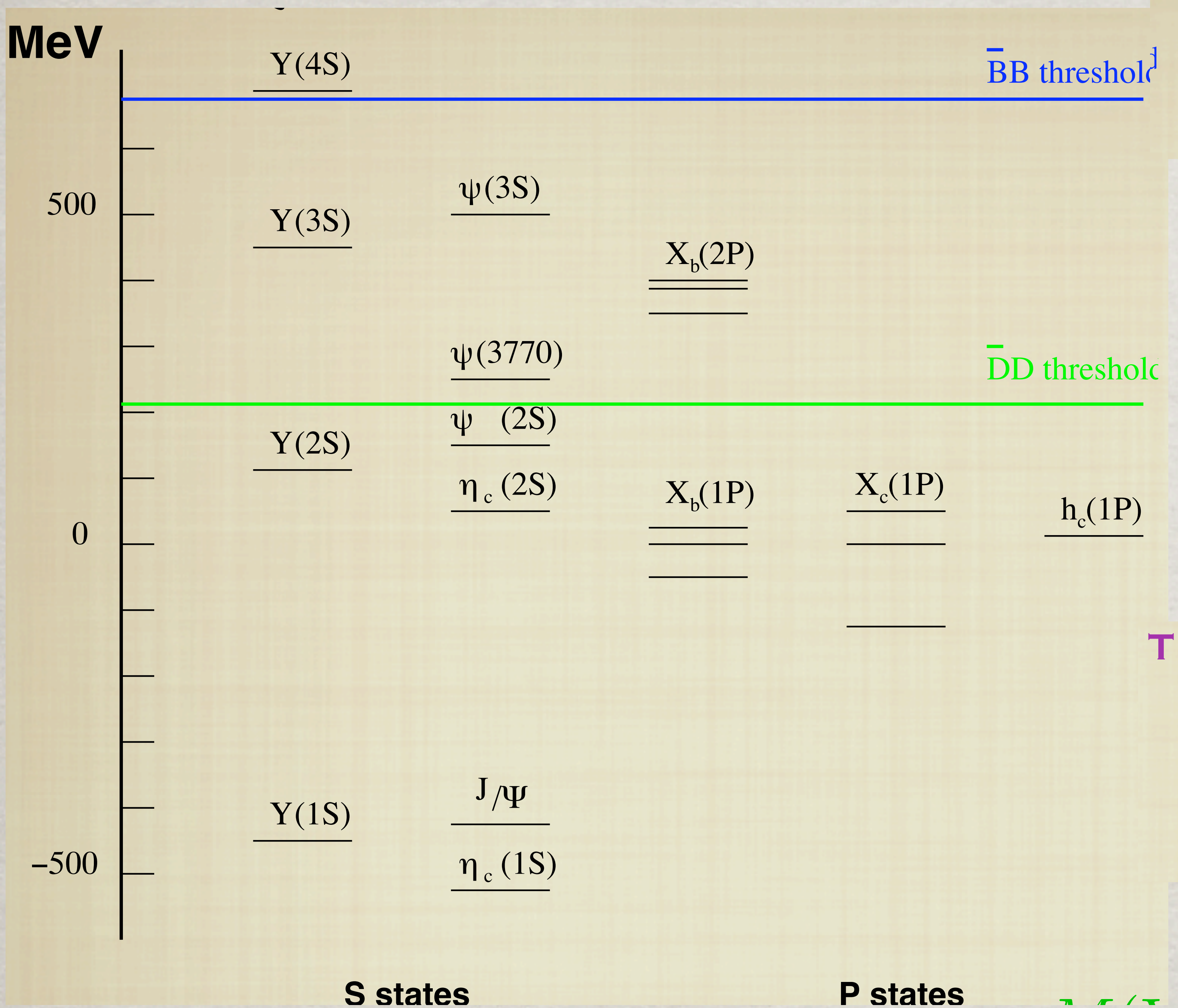

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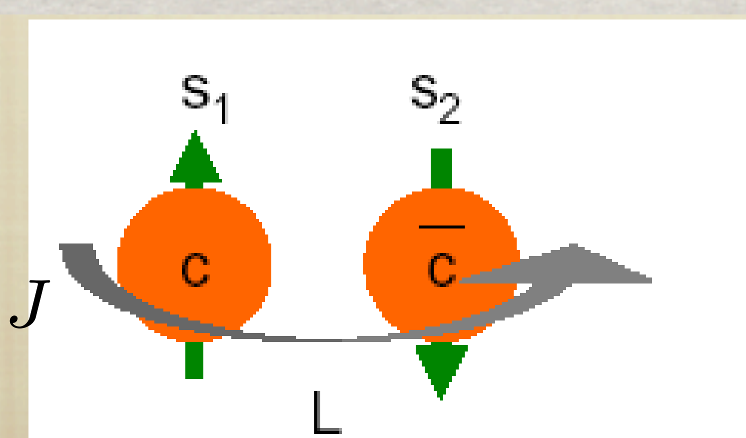

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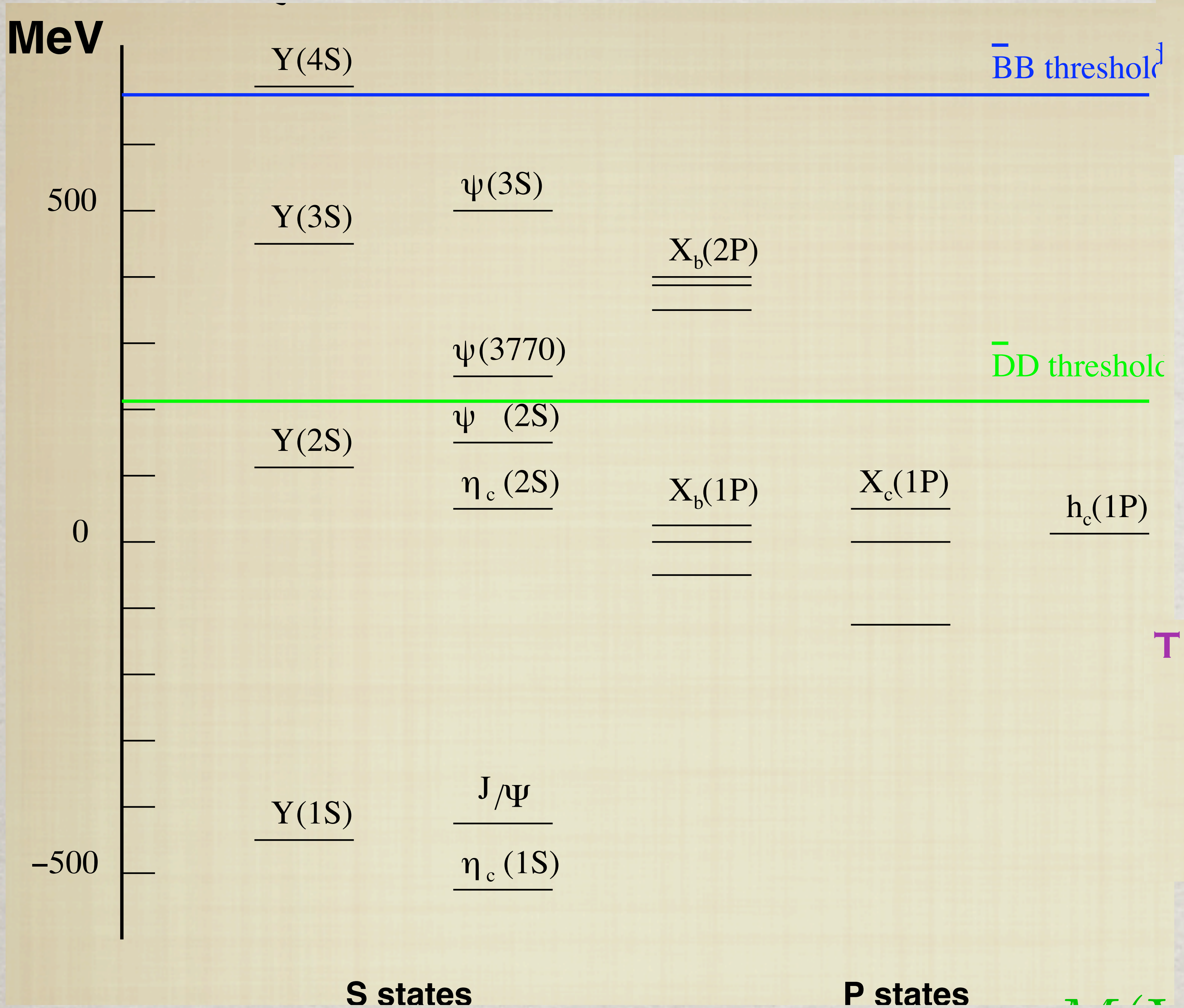

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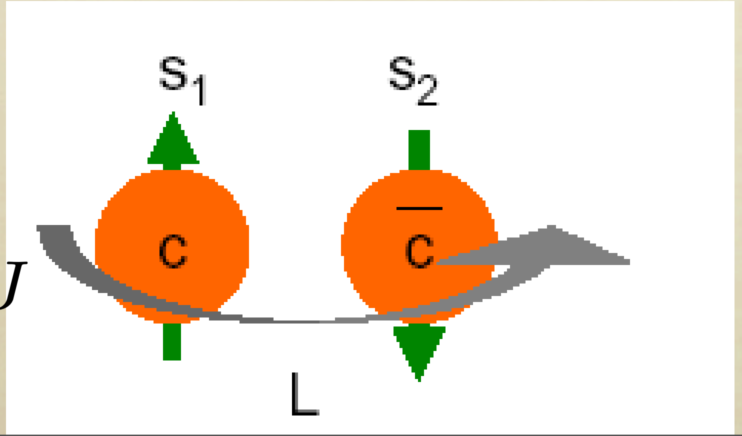

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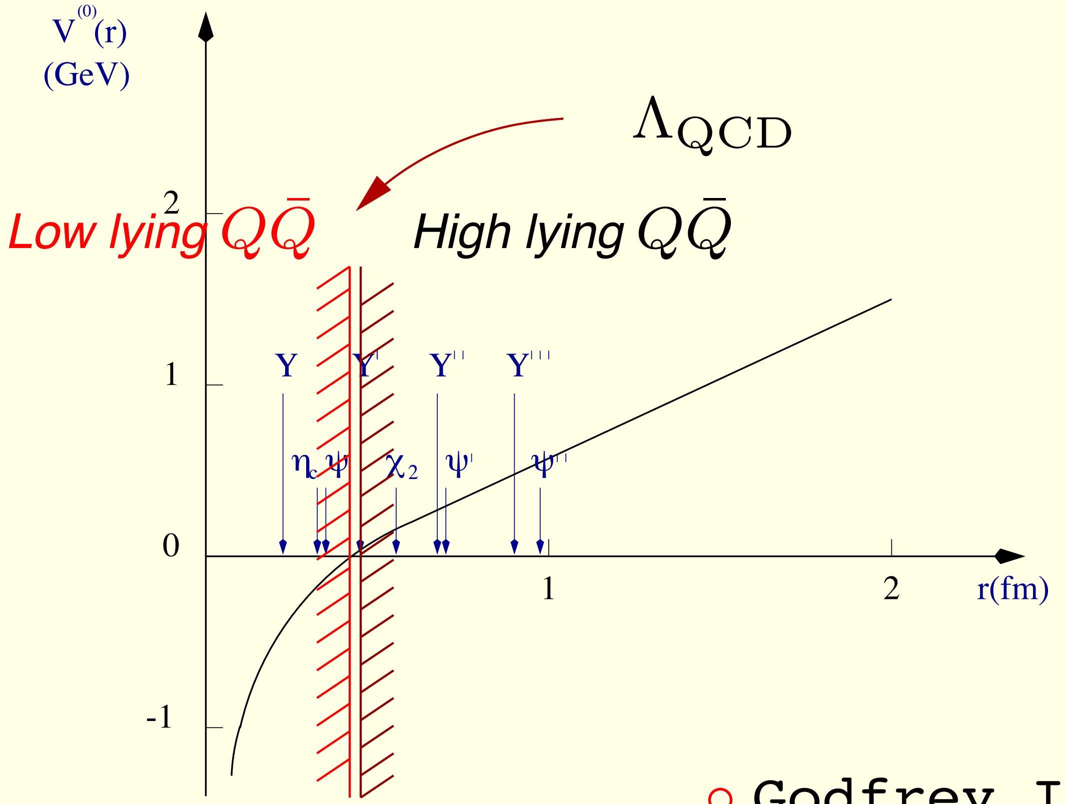
Quarkonium as a confinement and deconfinement probe

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

At zero temperature

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

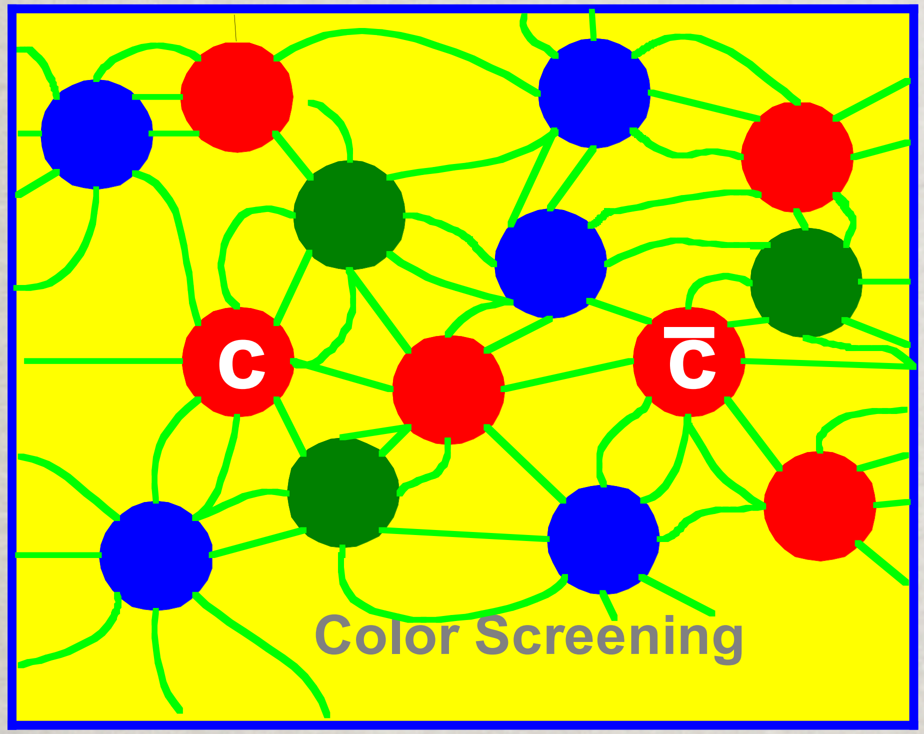


- Godfrey Isgur PRD 32(85)189

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

Quarkonium as a confinement and deconfinement probe

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



Debye charge screening $m_D \sim gT$

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

Matsui Satz 1986

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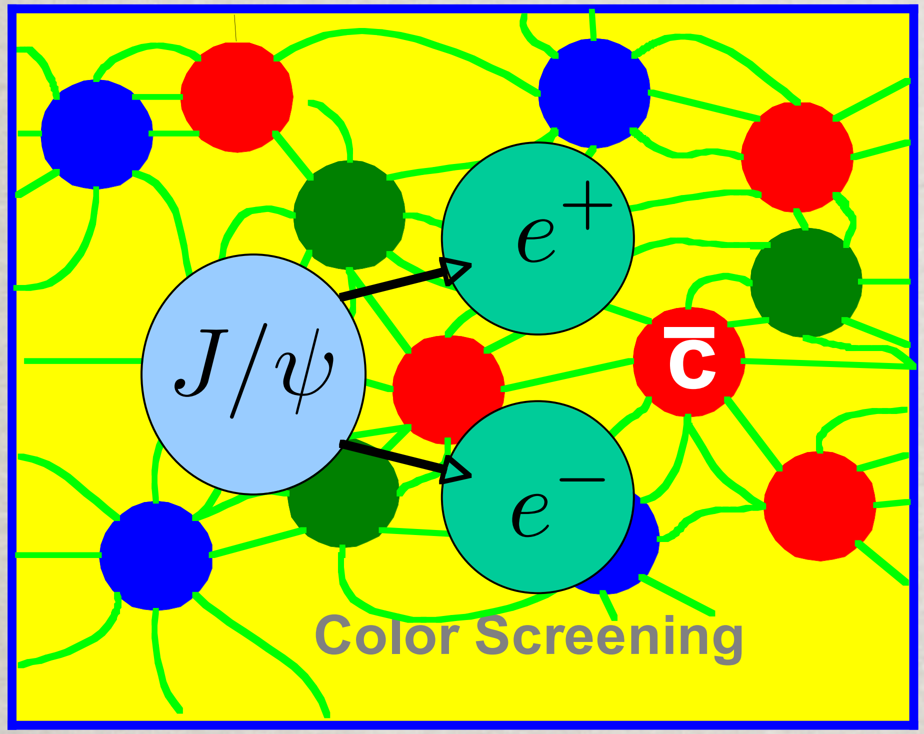

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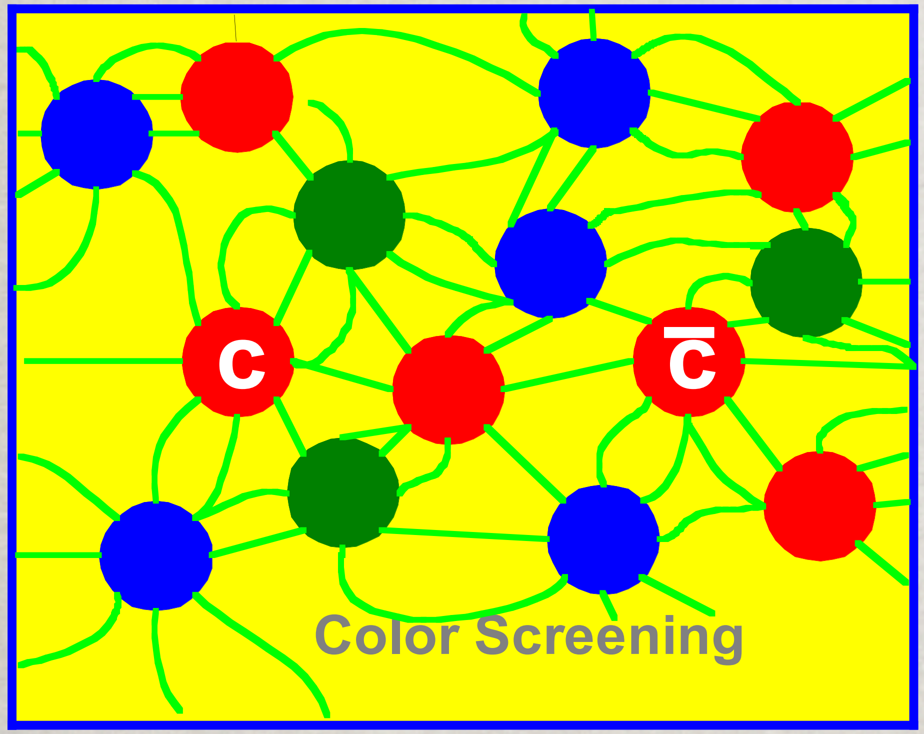

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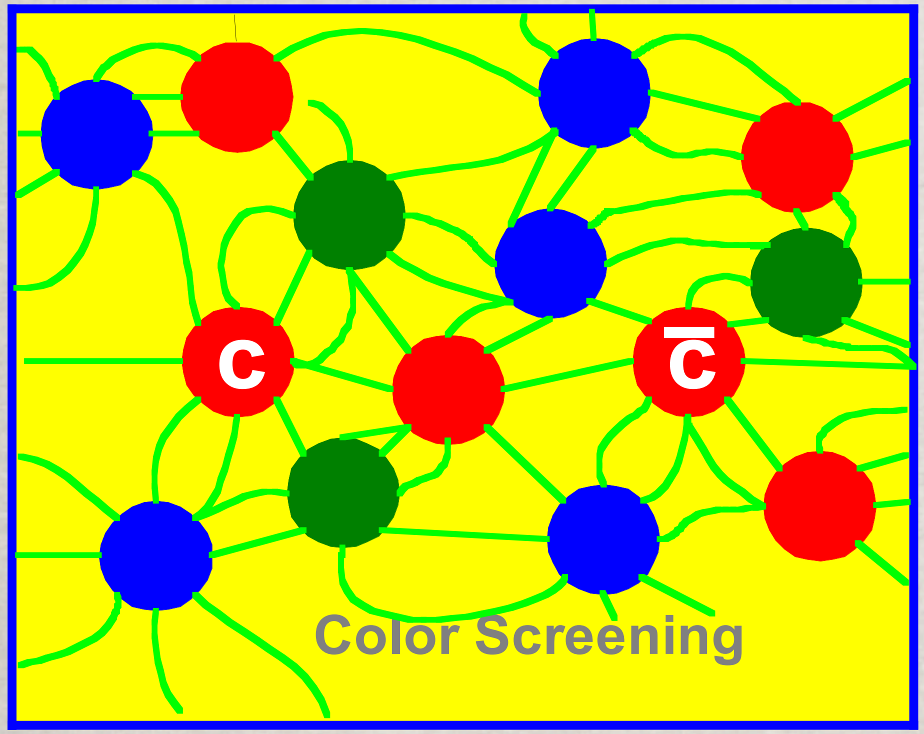

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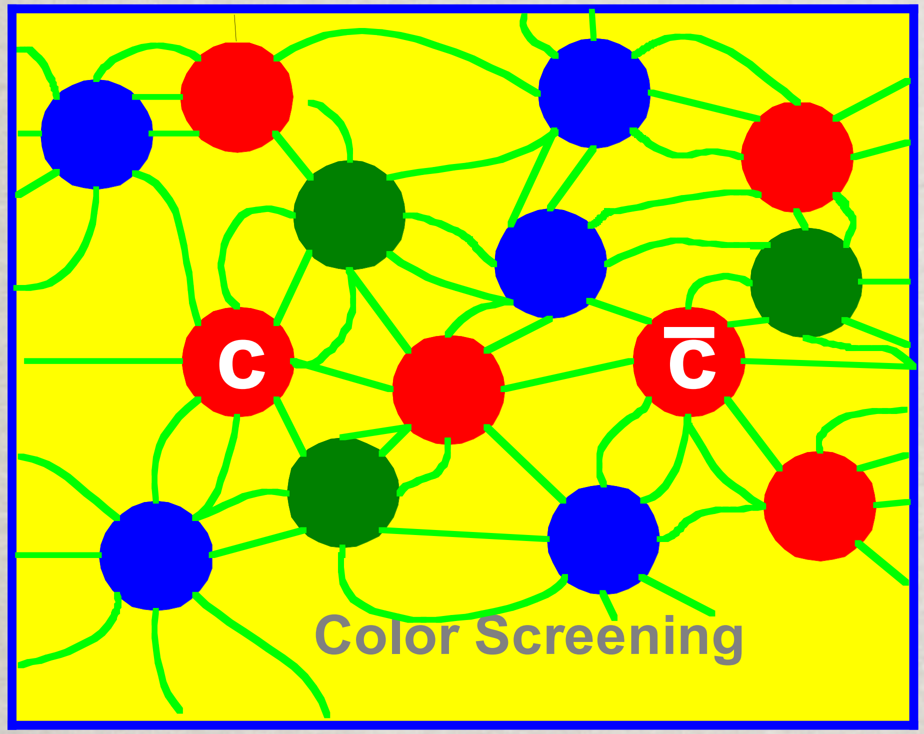

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Matsui Satz 1986

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

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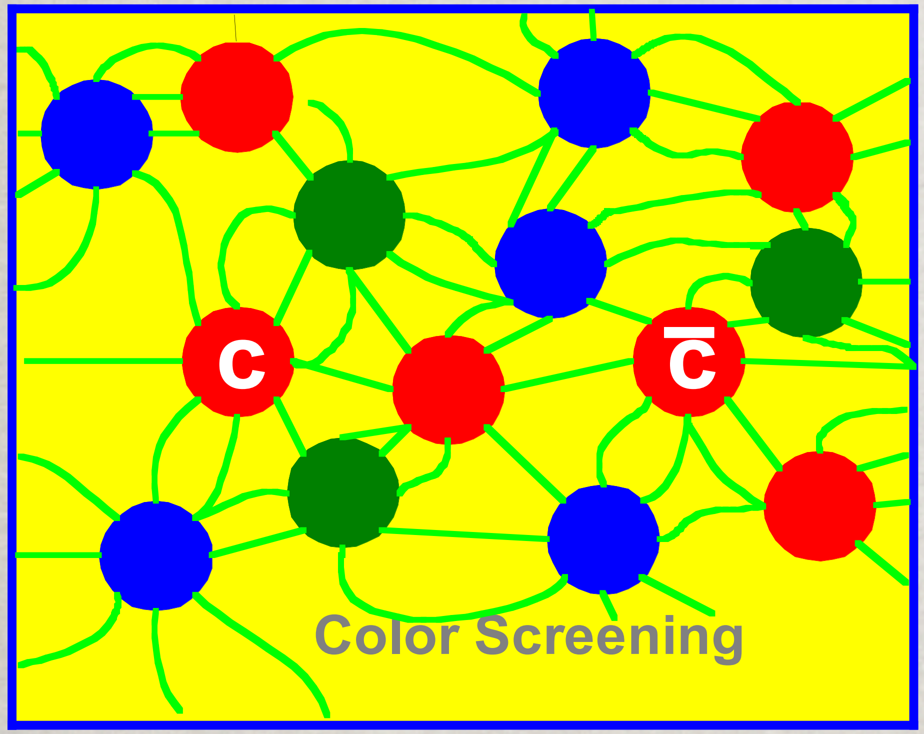

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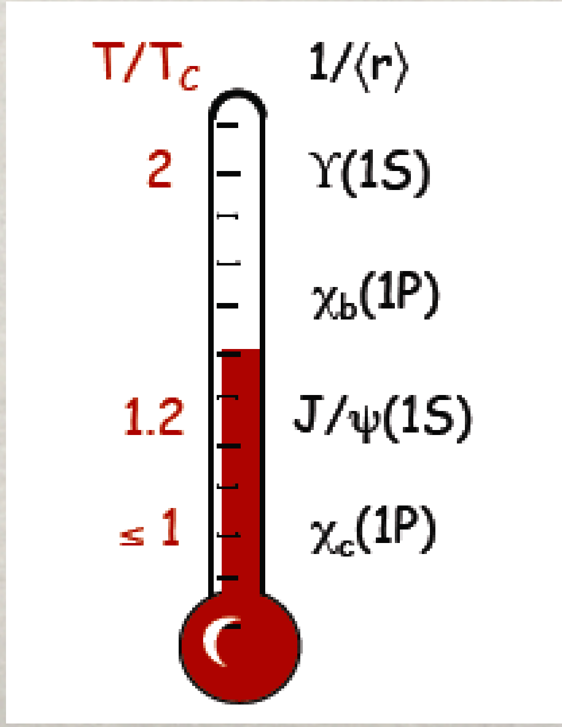

Quarkonium as an exploration tool of physics of Standard Model and beyond

Quarkonium can serve for the precise extraction of Standard Model parameters: heavy quark masses and strong coupling constant α_s

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The large mass makes quarkonium an ideal probe of new particles

BaBar light-Higgs & dark-photon searches

Mode	Mass range (GeV)	BF upper limit (90% CL)
$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to \mu^+\mu^-$	$0.21 < m_A < 9.3$	$(0.3 - 8.3) \times 10^{-6}$
$\Upsilon(3S) \to \gamma A^0, A^0 \to \tau^+\tau^-$	$4.0 < m_A < 10.1$	$(1.5 - 16) \times 10^{-5}$
$\Upsilon(2S,3S) \to \gamma A^0, A^0 \to$ hadrons	$0.3 < m_A < 7.0$	$(0.1 - 8) \times 10^{-5}$
$\Upsilon(1S) \to \gamma A^0, A^0 \to \chi\bar{\chi}$	$m_\chi < 4.5$ GeV	$(0.5 - 24) \times 10^{-5}$
$\Upsilon(1S) \to \gamma A^0, A^0 \to$ invisible	$m_A < 9.2$ GeV	$(1.9 - 37) \times 10^{-6}$
$\Upsilon(3S) \to \gamma A^0, A^0 \to$ invisible	$m_A < 9.2$ GeV	$(0.7 - 31) \times 10^{-6}$
$\Upsilon(1S) \to \gamma A^0, A^0 \to g\bar{g}$	$m_A < 9.0$ GeV	$10^{-6} - 10^{-2}$
$\Upsilon(1S) \to \gamma A^0, A^0 \to s\bar{s}$	$m_A < 9.0$ GeV	$10^{-5} - 10^{-3}$

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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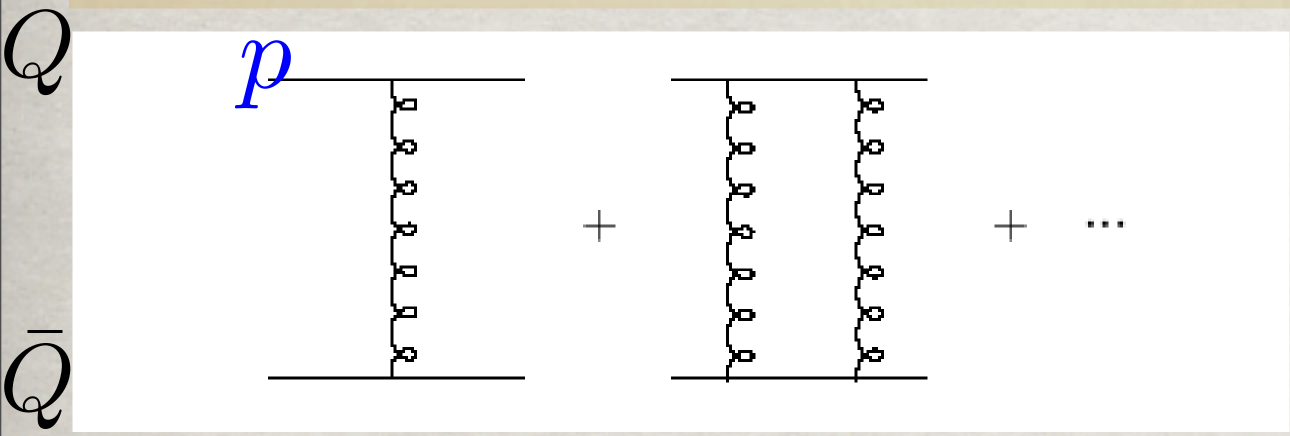

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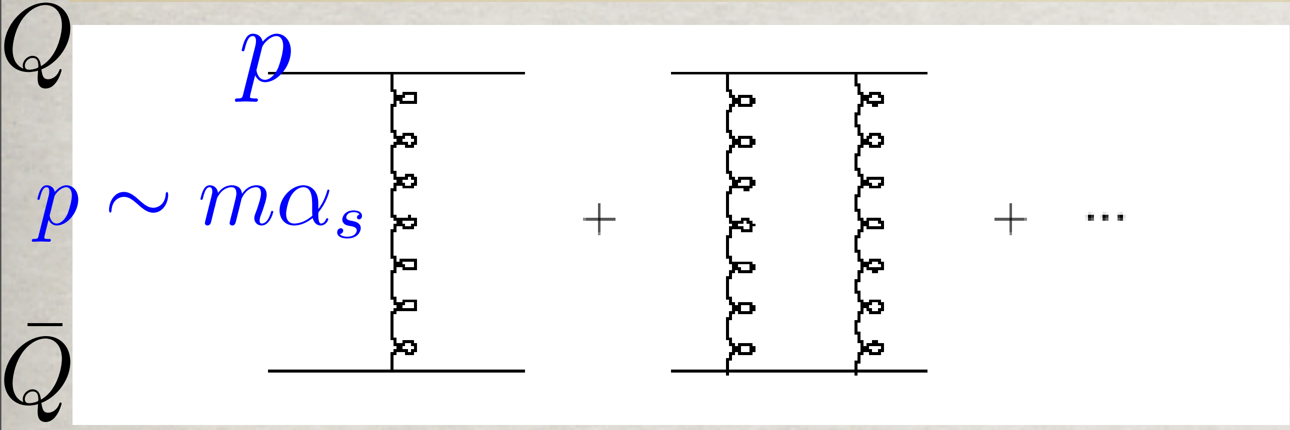

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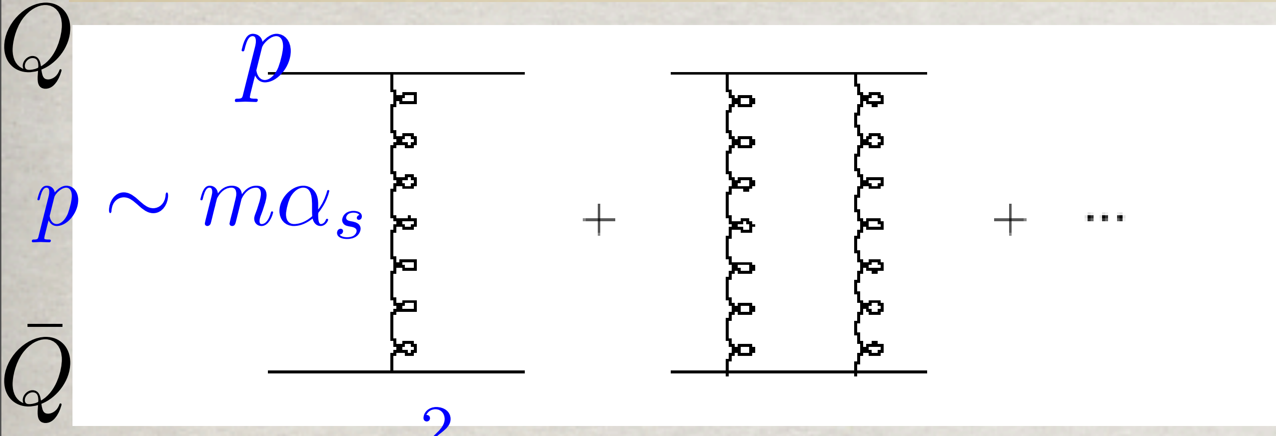

$$\frac{g^2}{p^2}\left(1 + \frac{m\alpha_s}{p}\right)$$

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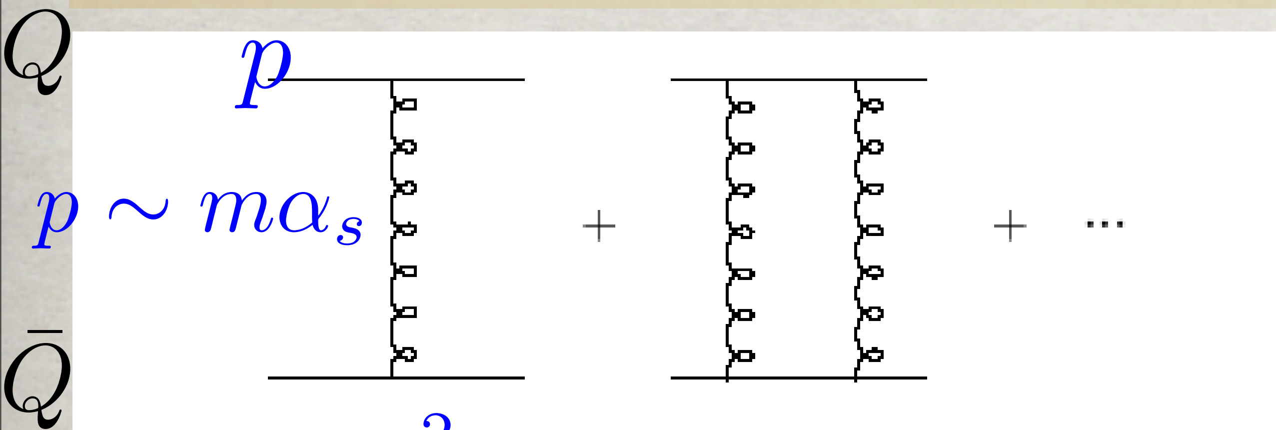

$$\frac{g^2}{p^2}\left(1 + \frac{m\alpha_s}{p}\right)$$

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

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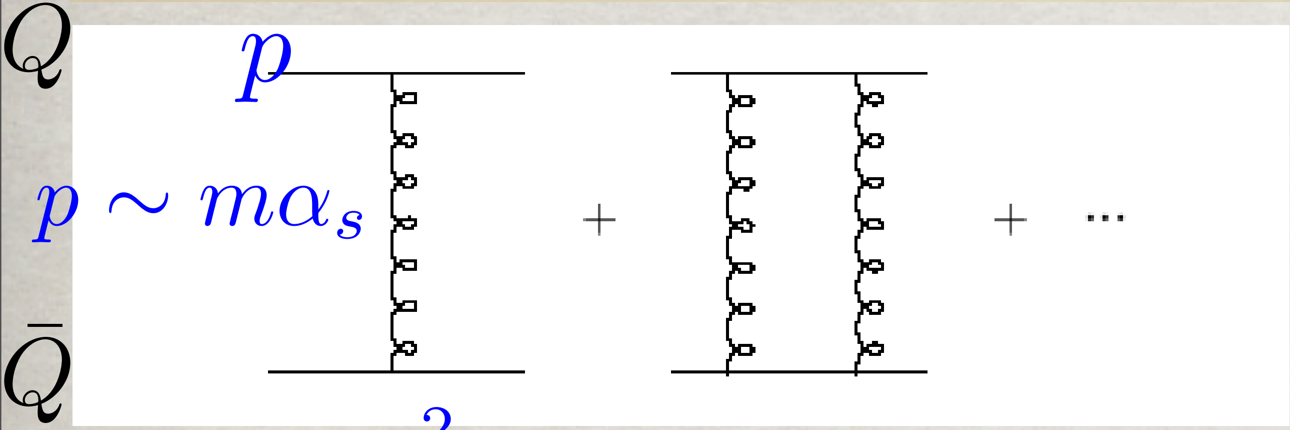

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- From $(\frac{p^2}{m} + V)\phi = E\phi \rightarrow p \sim mv$ and $E = \frac{p^2}{m} + V \sim mv^2$.

QCD theory of Quarkonium: a very hard problem

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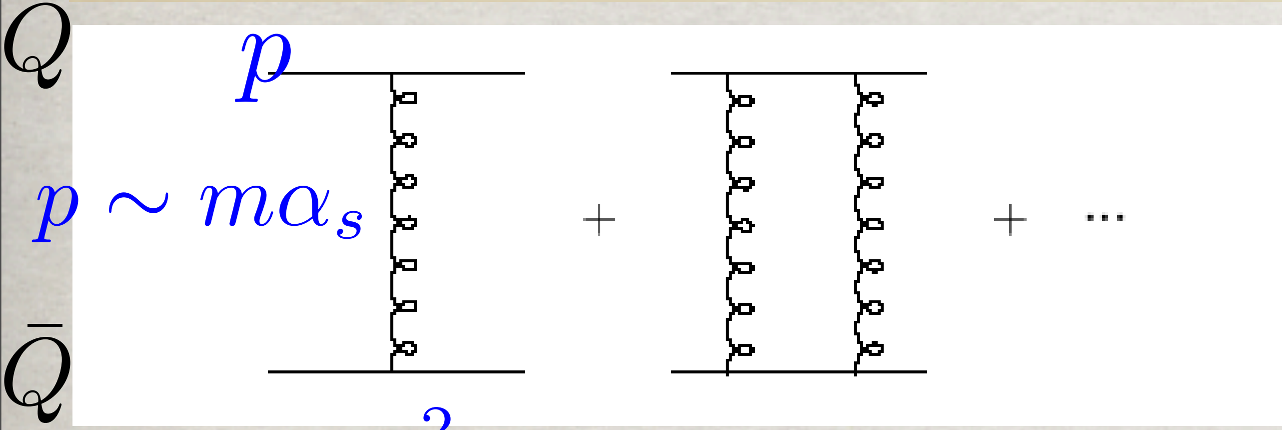
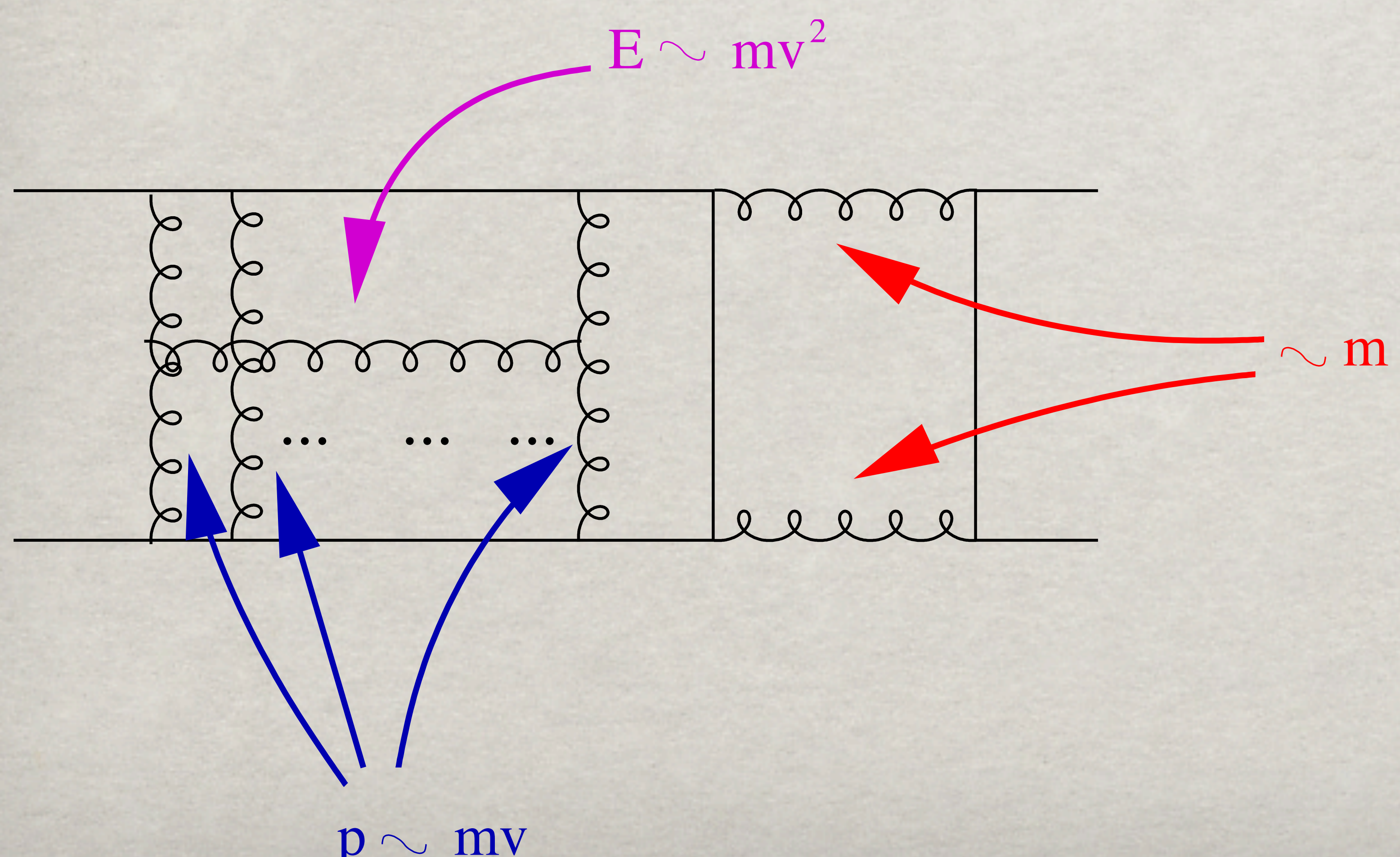


$$\frac{g^2}{p^2}\left(1+\frac{m\alpha_s}{p}\right)$$

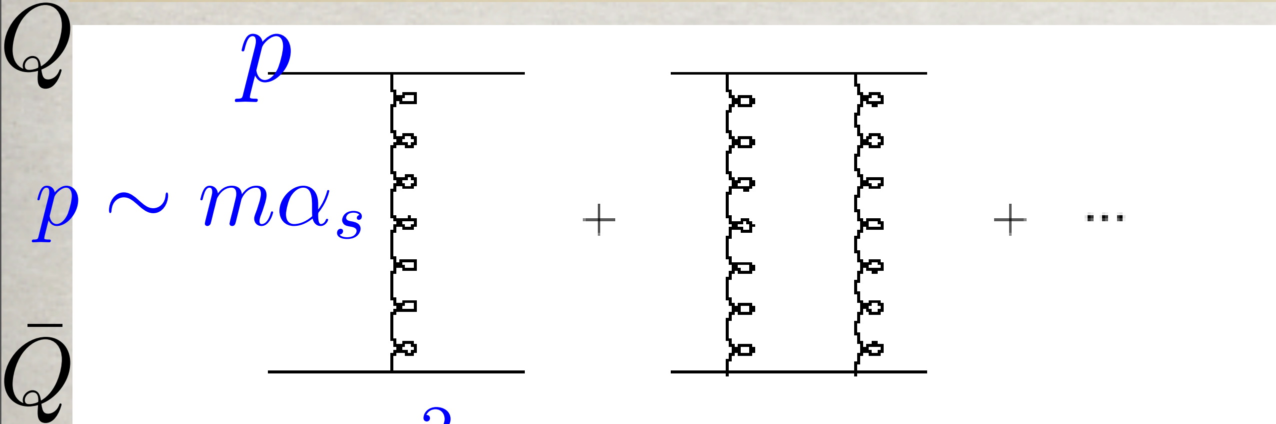
$$\sim \frac{1}{E-(\frac{p^2}{m}+V)}$$

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



QCD theory of Quarkonium: a very hard problem

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

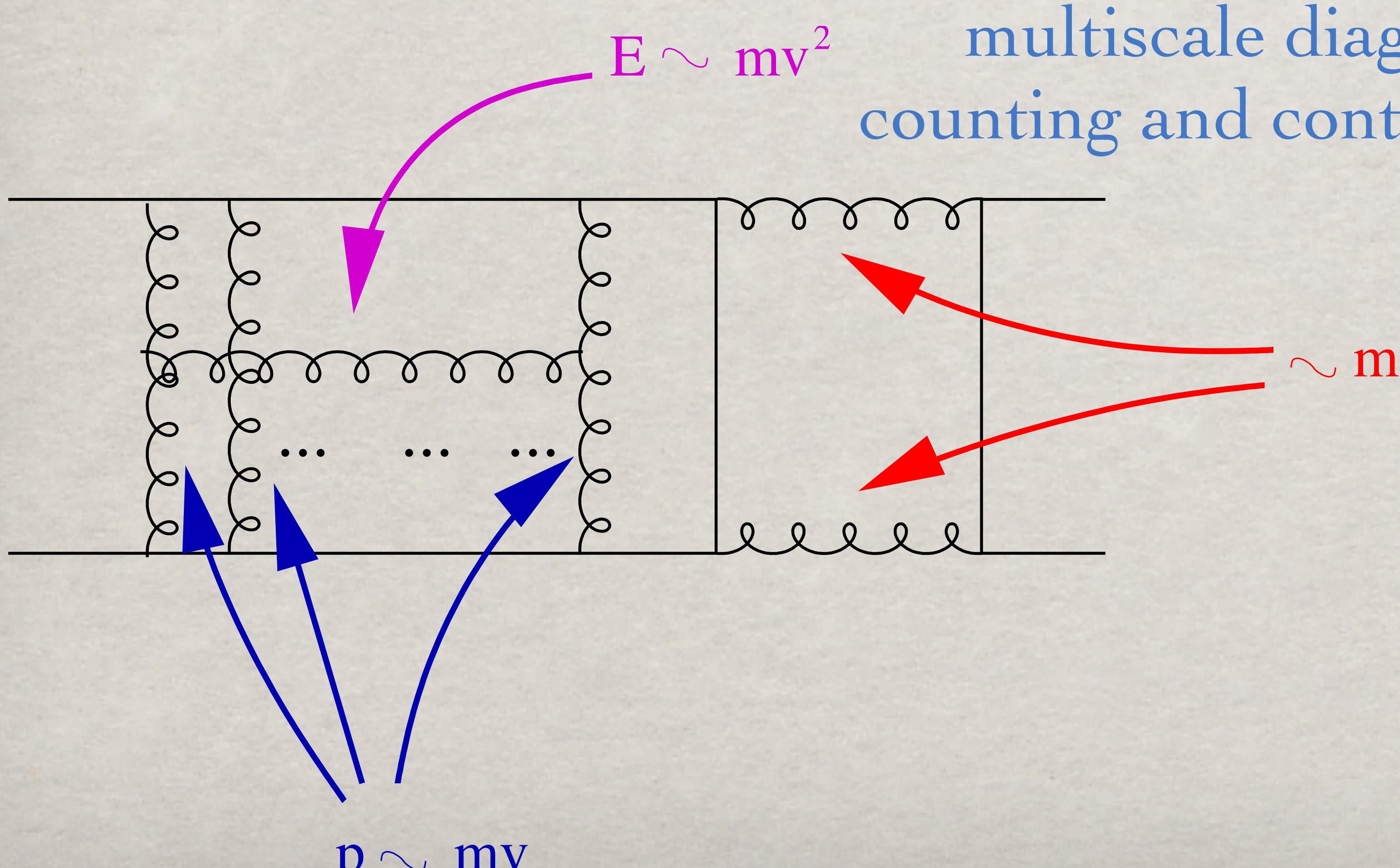


$$\frac{g^2}{p^2}\left(1 + \frac{m\alpha_s}{p}\right)$$

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

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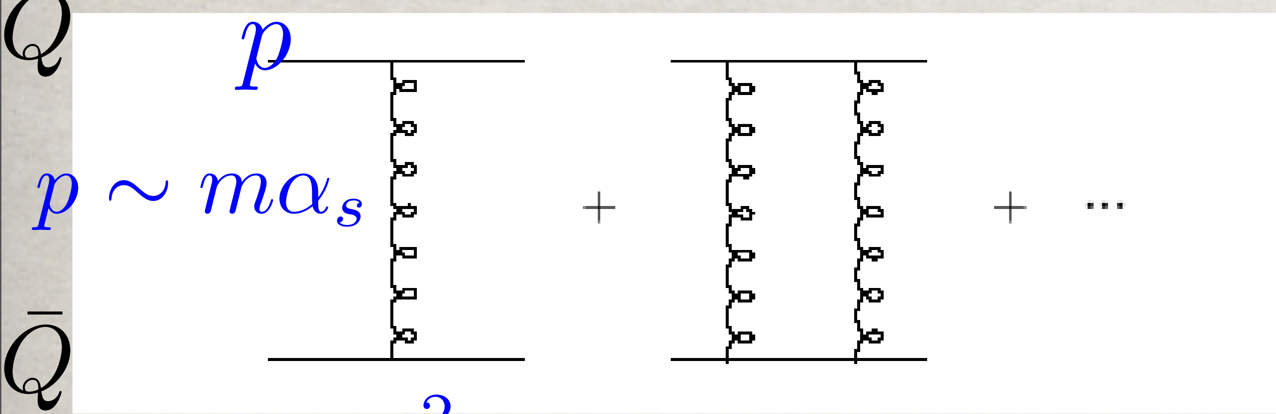

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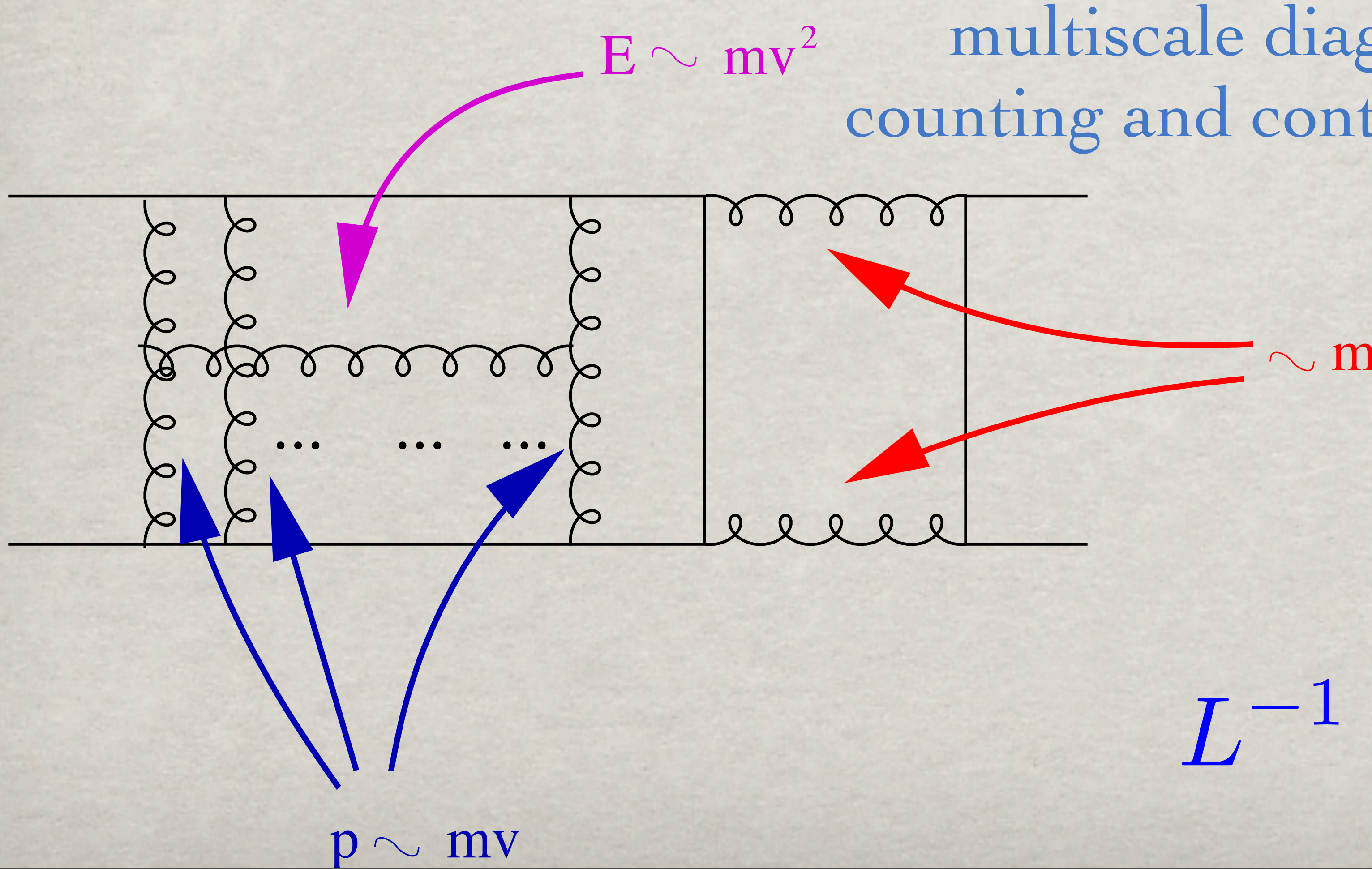
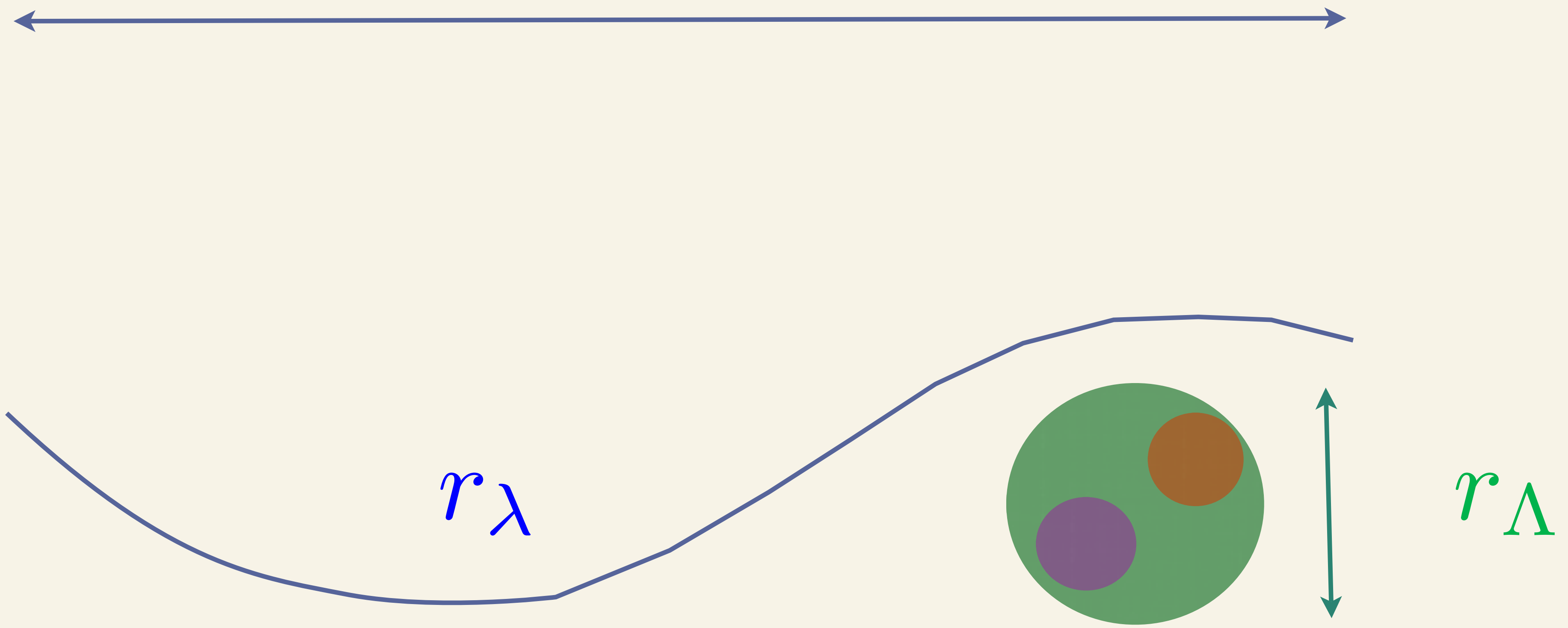


Difficult also for the lattice!

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

a hierarchy of EFTS can be formulated in correspondence to the hierarchy of scales



An effective field theory makes the expansion in λ/Λ explicit at the Lagrangian level.

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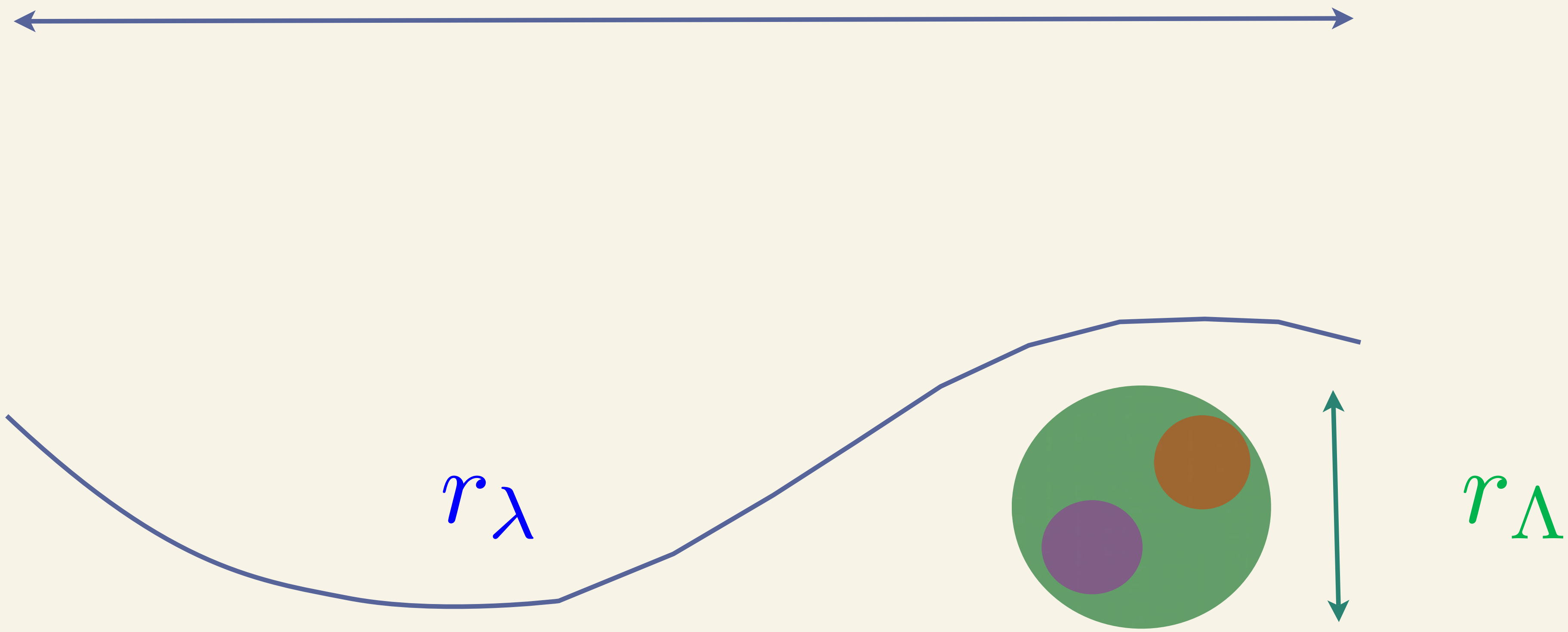

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The EFT Lagrangian, $\mathcal{L}_{\mathrm{EFT}}$, suitable to describe H at scales lower than Λ is defined by

(1) a cut off $\Lambda \gg \mu \gg \lambda$;

(2) by some degrees of freedom that exist at scales lower than μ

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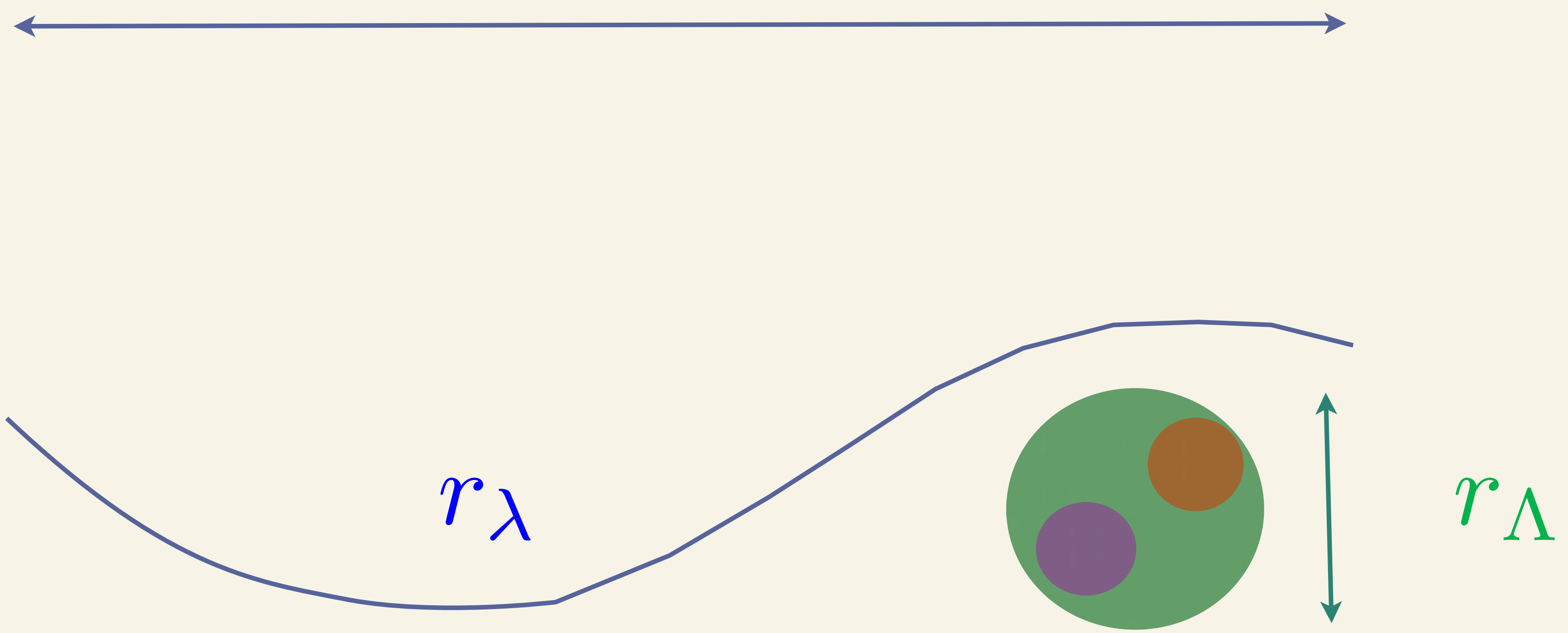

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RANGE OF VALIDITY OF THE EFT: ENERGY $< \mu$

$\Rightarrow$ $\mathcal{L}_{\text{EFT}}$ is made of all operators O_n that may be built from the effective degrees of freedom and are consistent with the symmetries of $\mathcal{L}$.

Effective Field Theories

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

Effective Field Theories

low energy operator

$$\mathcal{L}_{\text{EFT}} = \sum_n c_n(\Lambda, \mu) \frac{O_n(\mu, \lambda)}{\Lambda^n}$$

Wilson coefficient

large scale

Effective Field Theories

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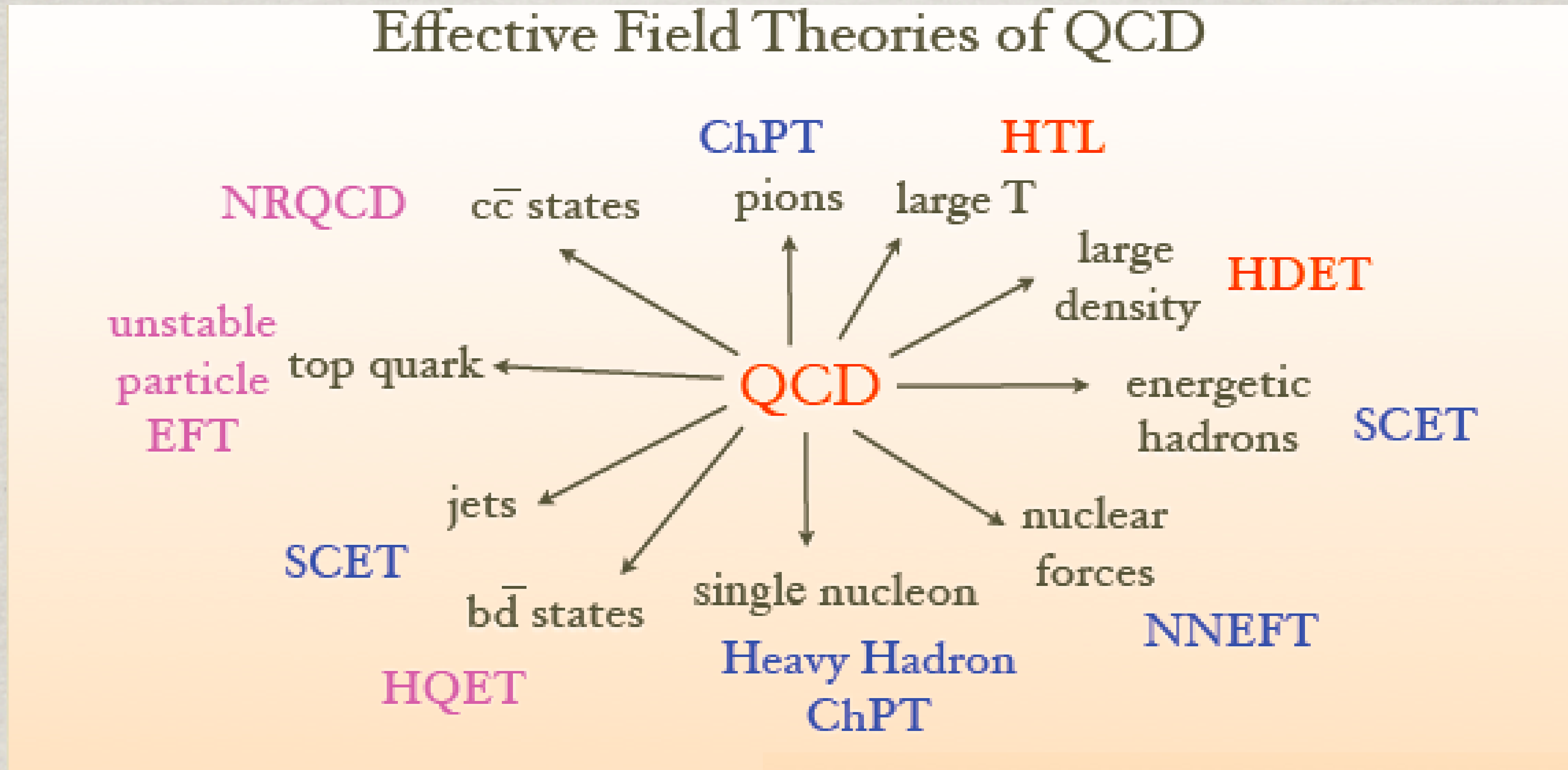
Matching

- If $\Lambda \gg \Lambda_{\rm QCD}$ then $c_n(\Lambda/\mu)$ may be calculated in perturbation theory.

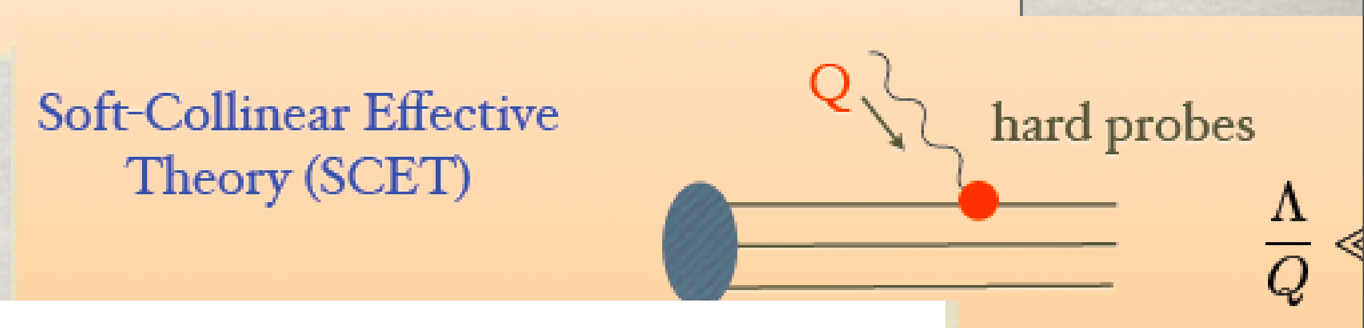
- Symmetries of the system become manifest;
- Large $\log(\Lambda/\lambda)$ can be resummed via RG. (Renormalization group)

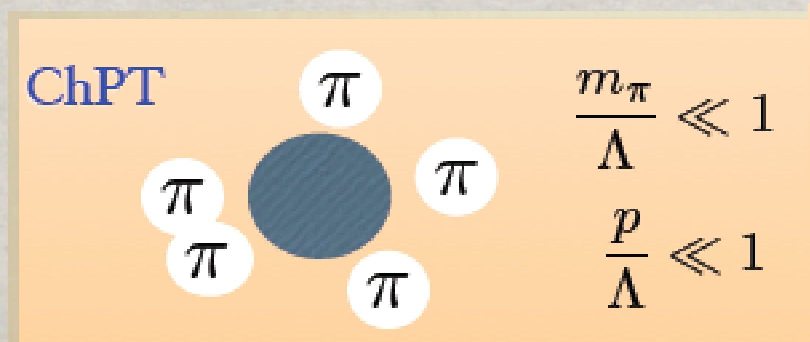
QCD Effective Field Theories

To address the research fronteer of strong interactions we need to construct effective field theories



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





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

QCD Effective Field Theories

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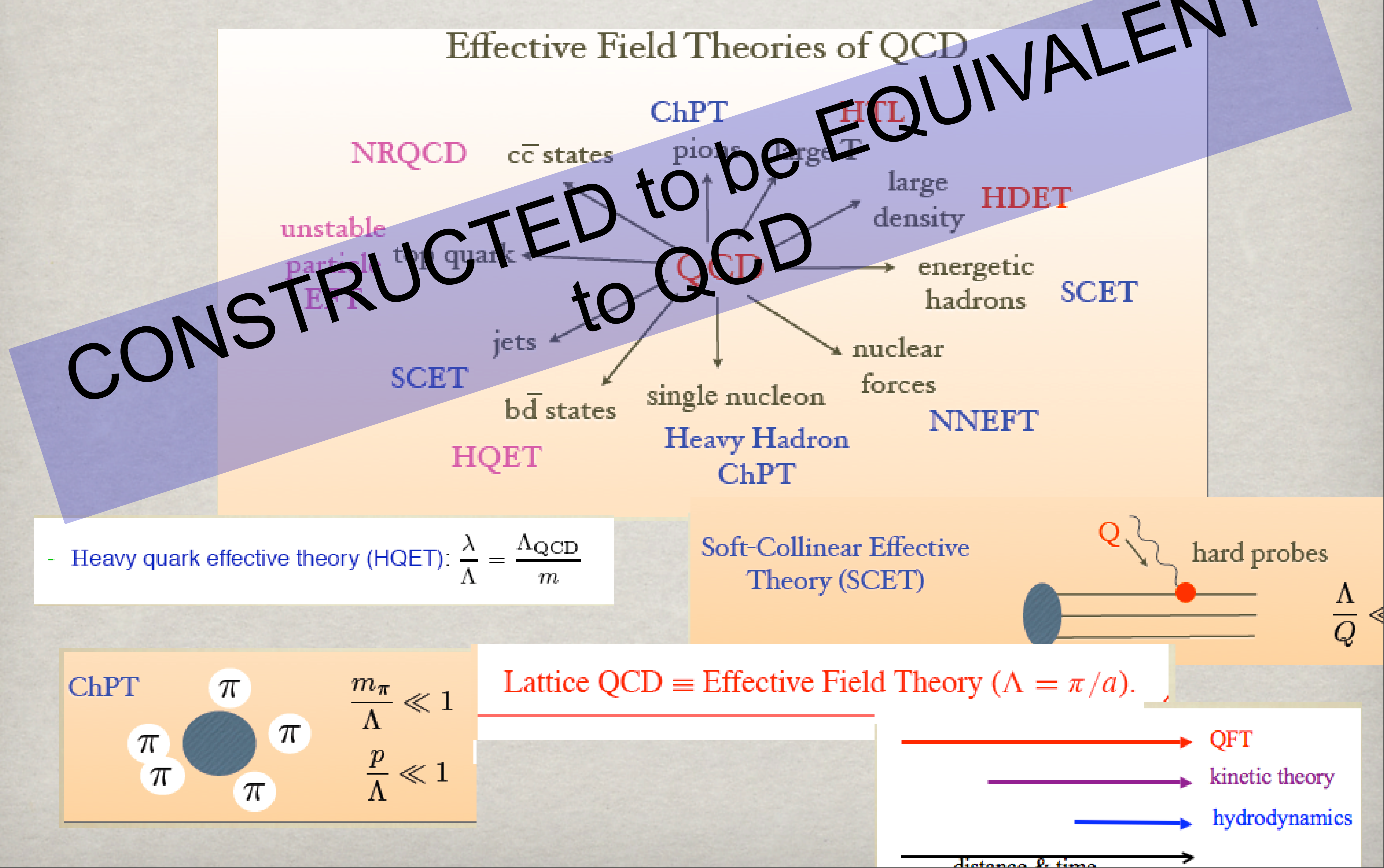
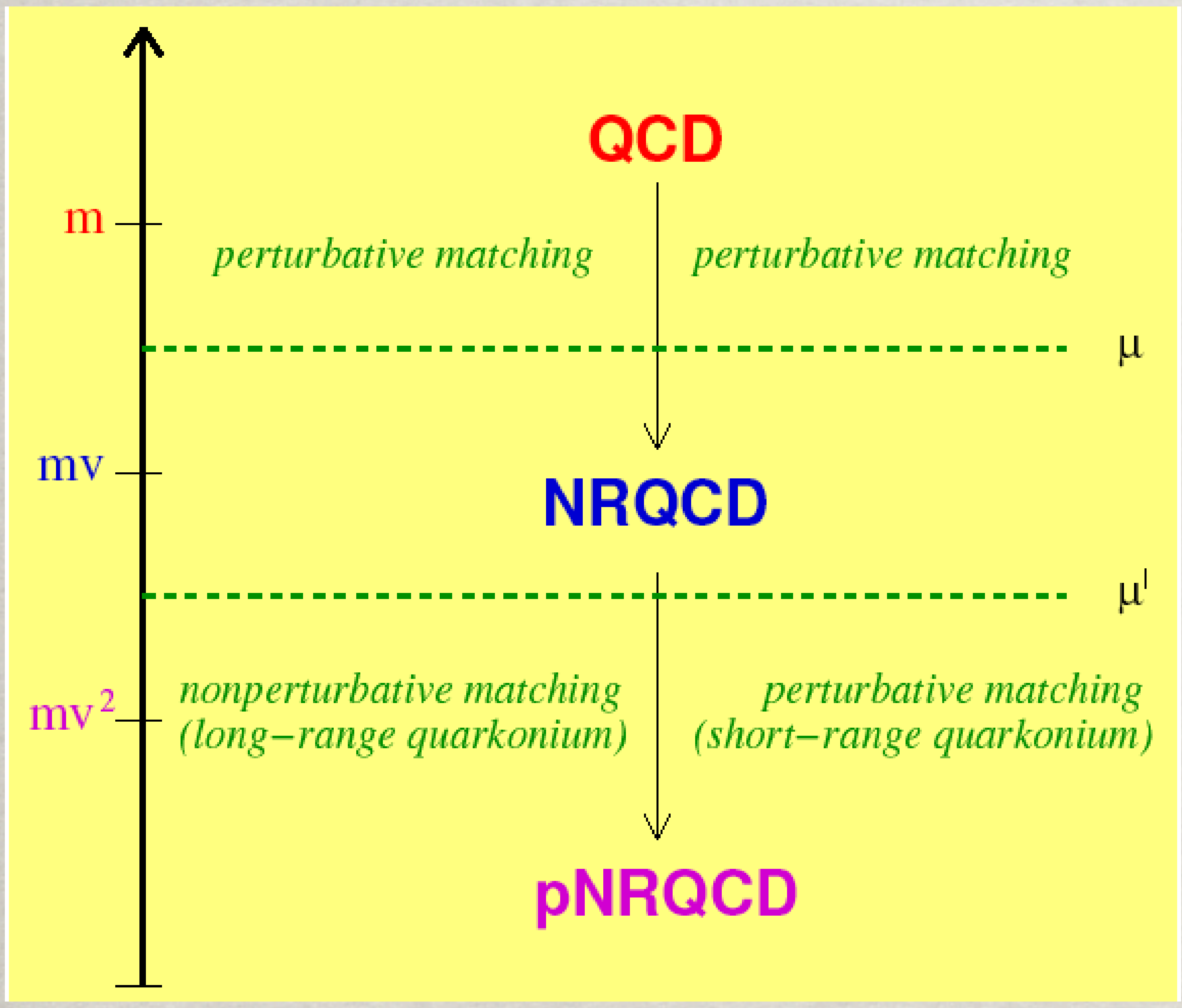


Quarkonium with NR EFT

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



Hard

Soft
(relative
momentum)

Ultrasoft
(binding energy)

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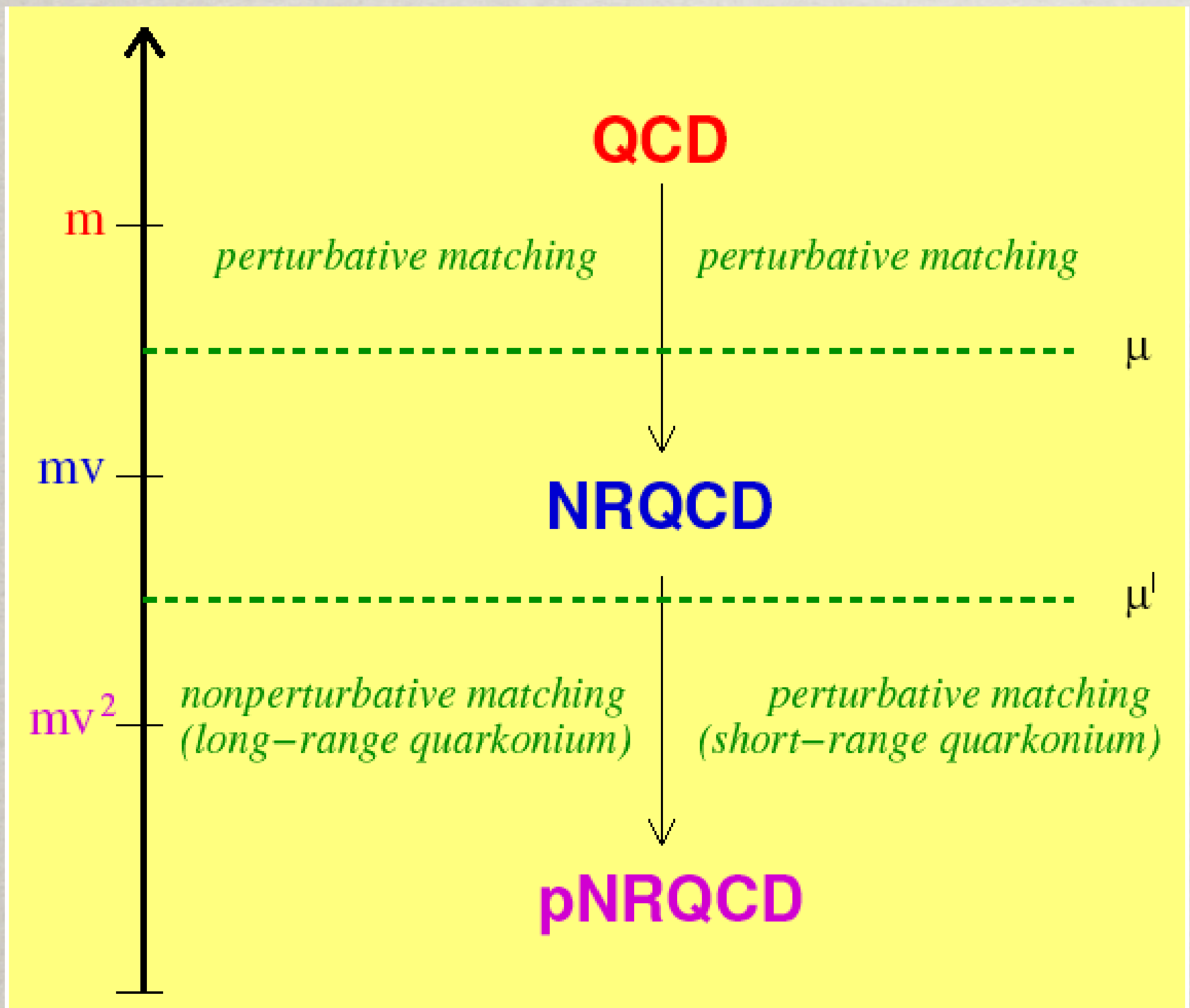

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$$\mathcal{L}_{\mathrm{EFT}} = \sum_n c_n(E_\Lambda/\mu)\frac{O_n(\mu,\lambda)}{E_\Lambda}$$

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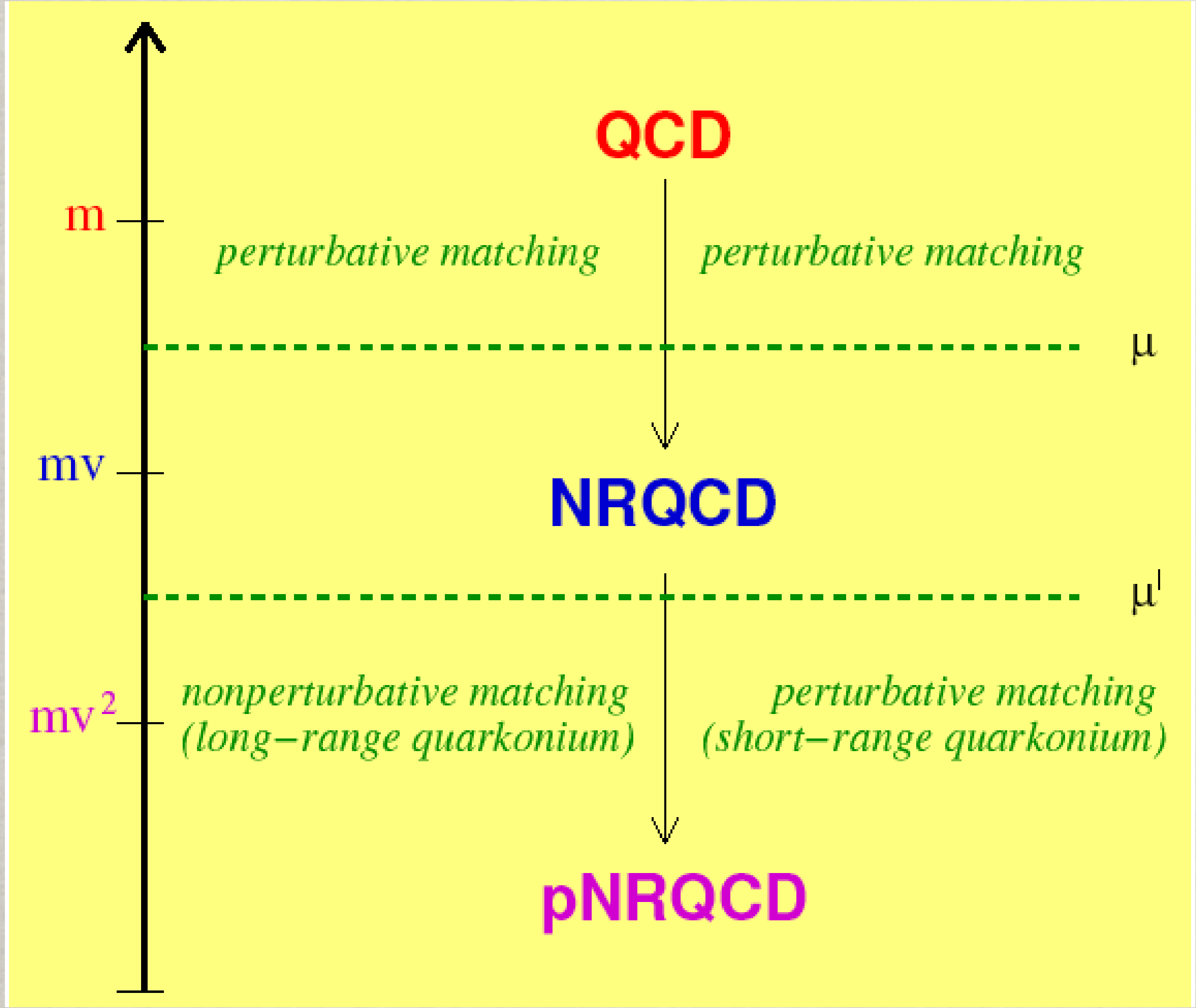

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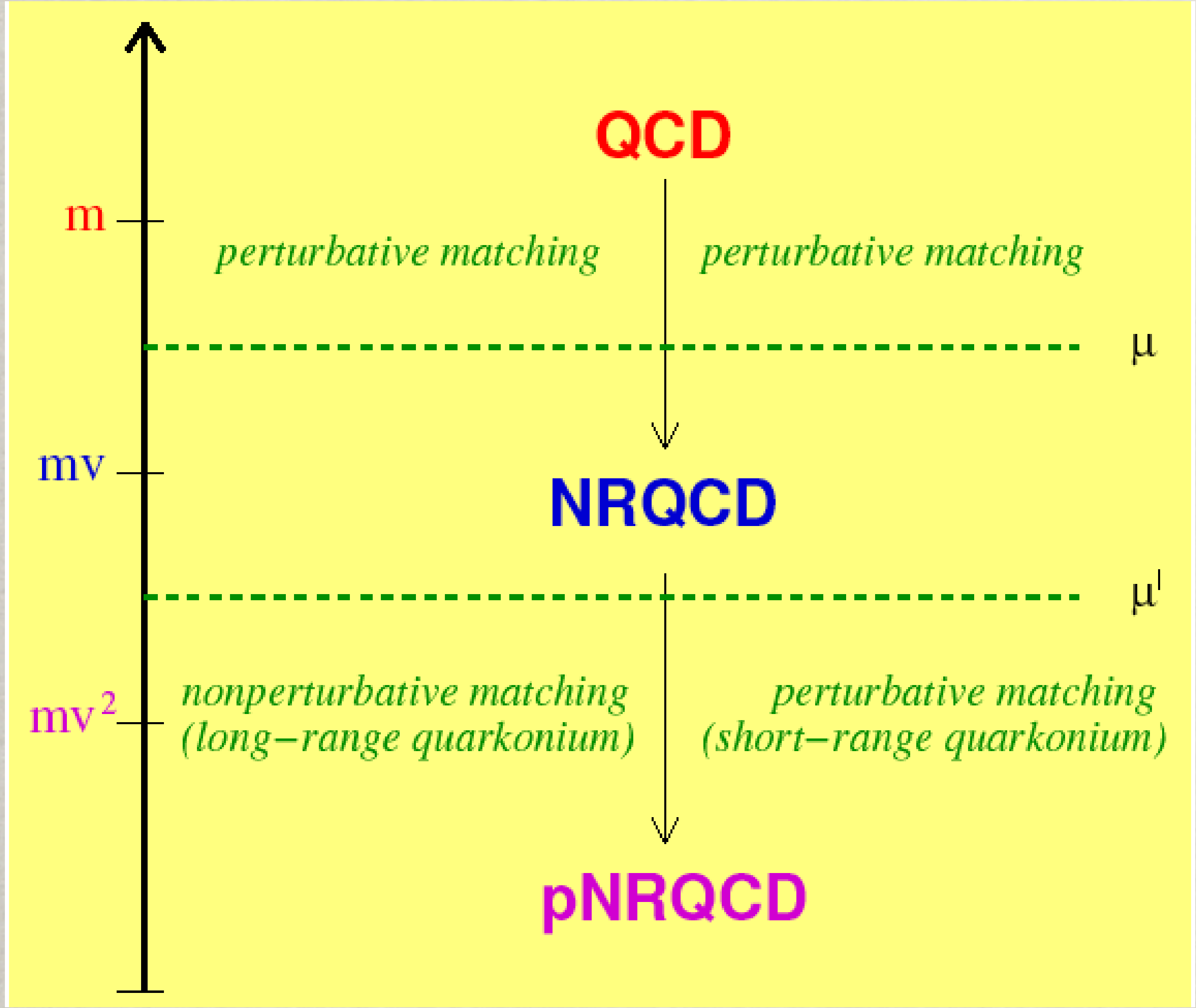

Hard

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

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Ultrasoft
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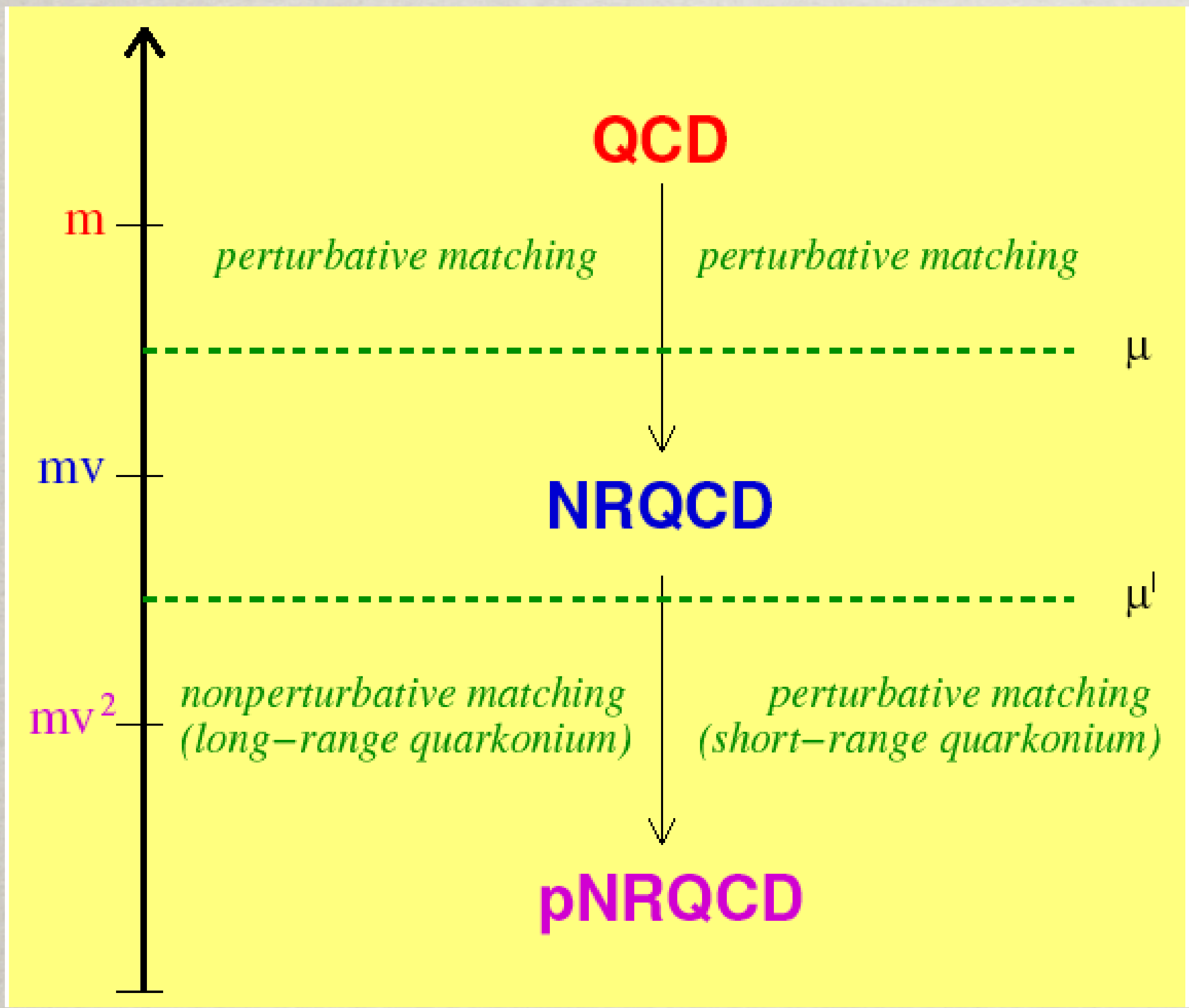


Hard

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

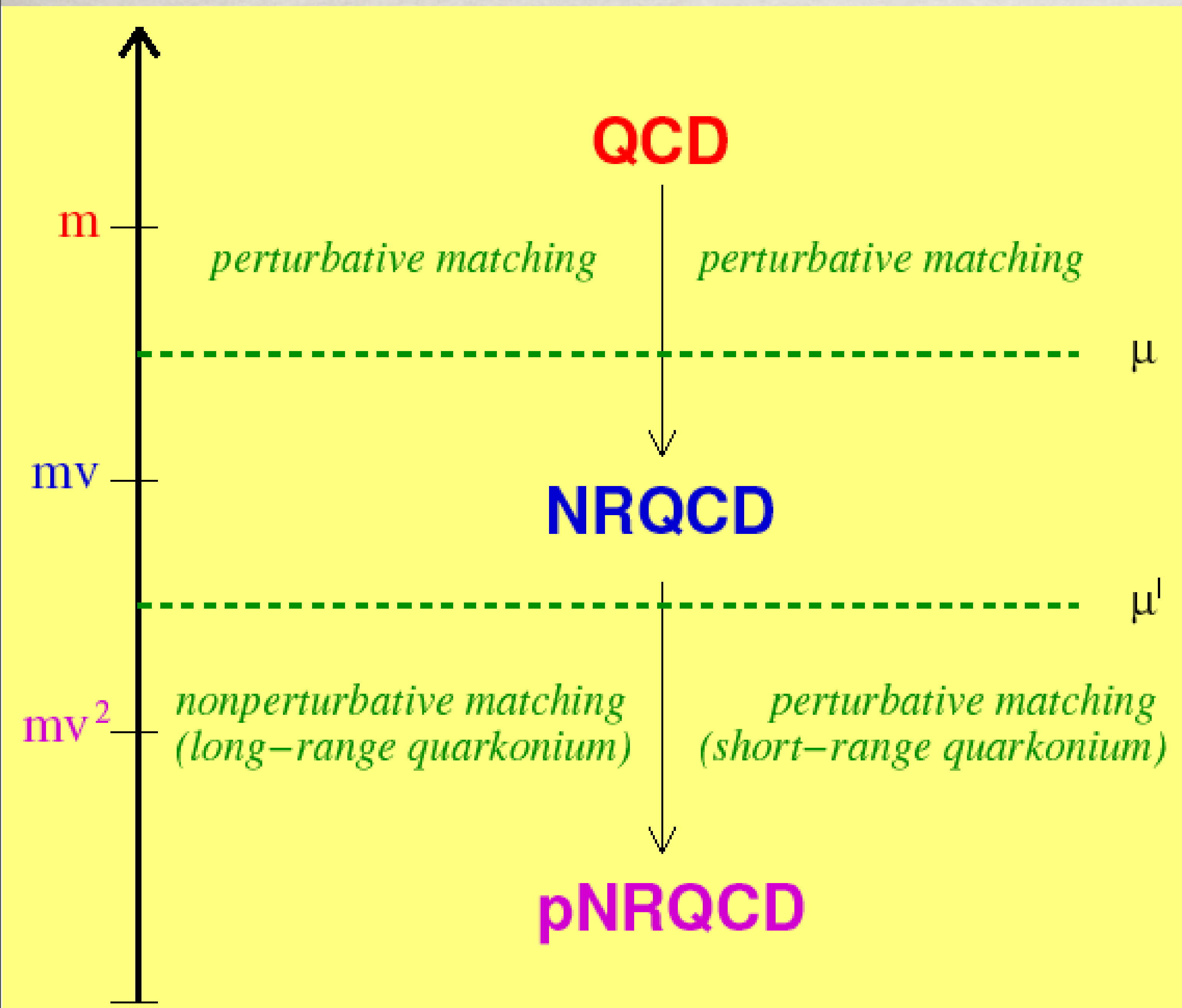
Soft (relative momentum)

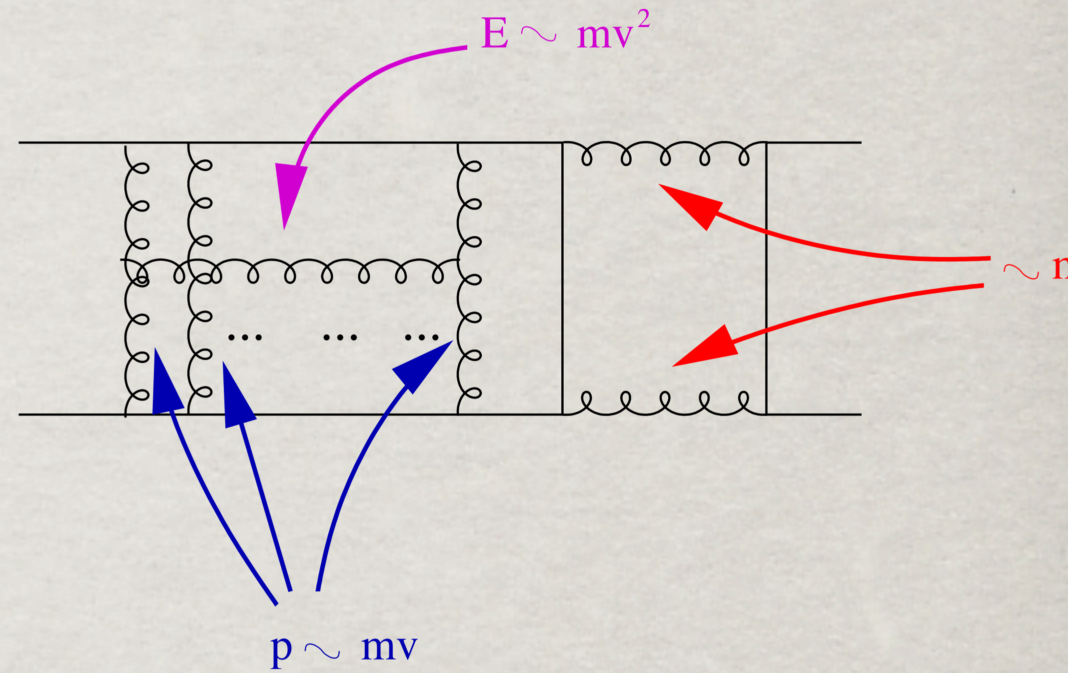
$$\frac{E_\lambda}{E_\Lambda} = \frac{mv^2}{mv}$$

Ultrasoft (binding energy)

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

Quarkonium with NR EFT: Non Relativistic QCD (NRQCD)





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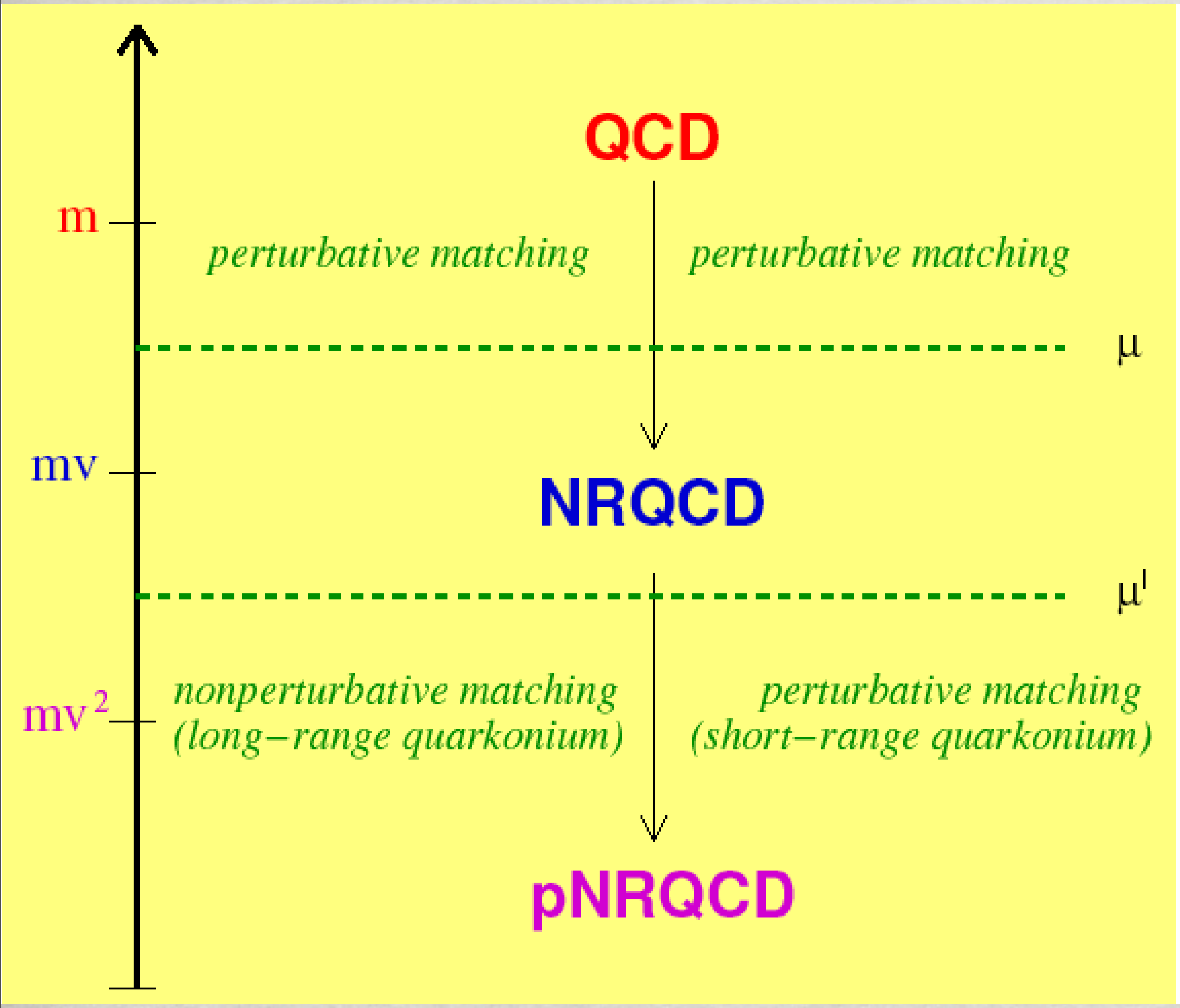

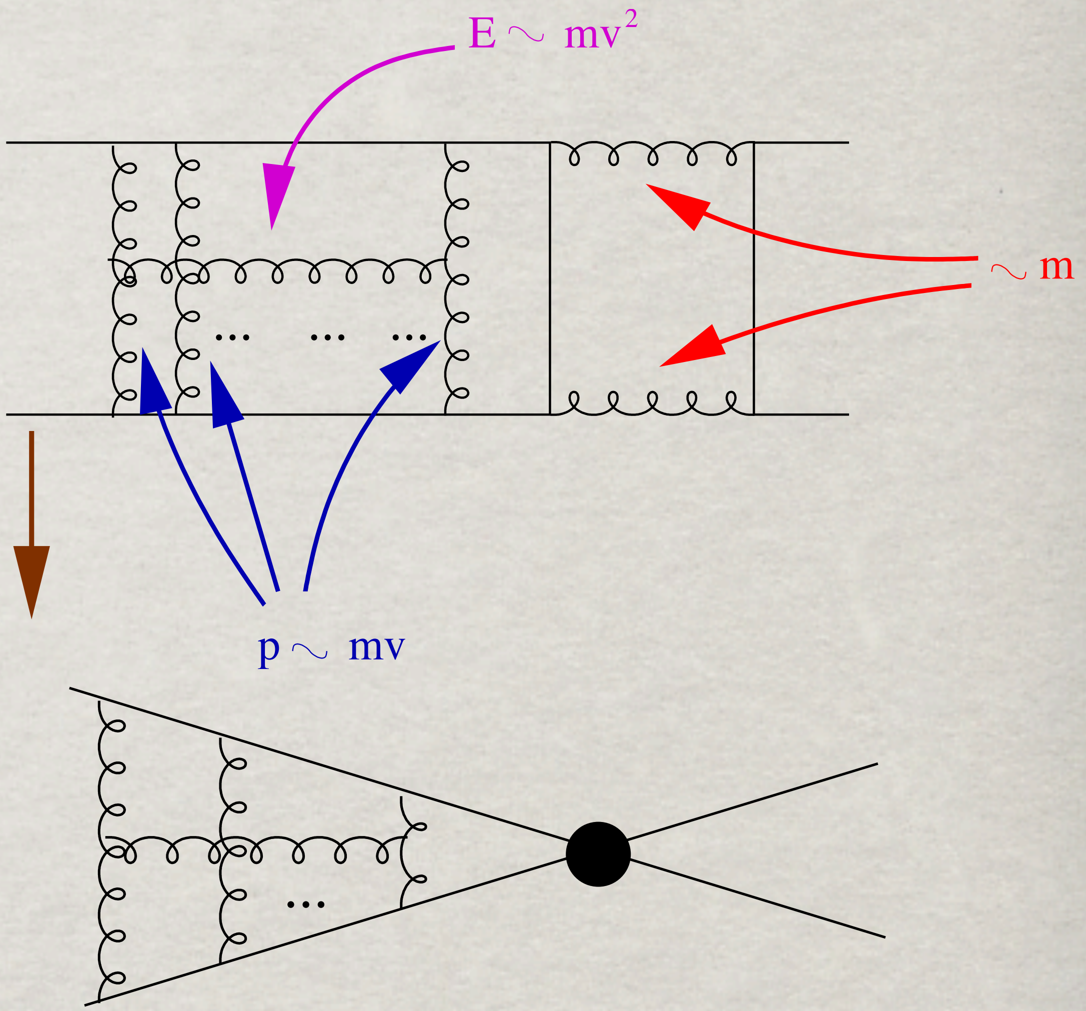

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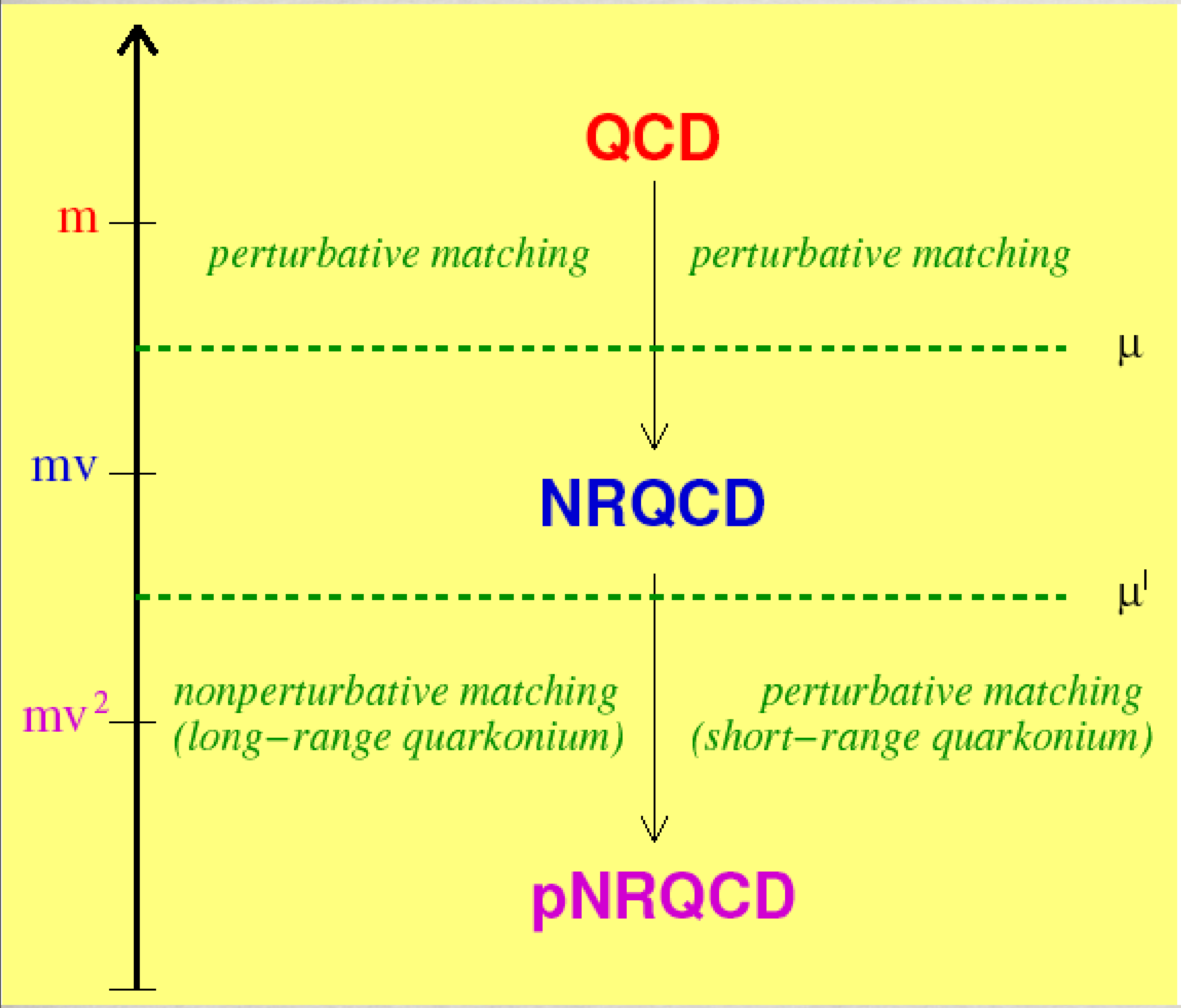
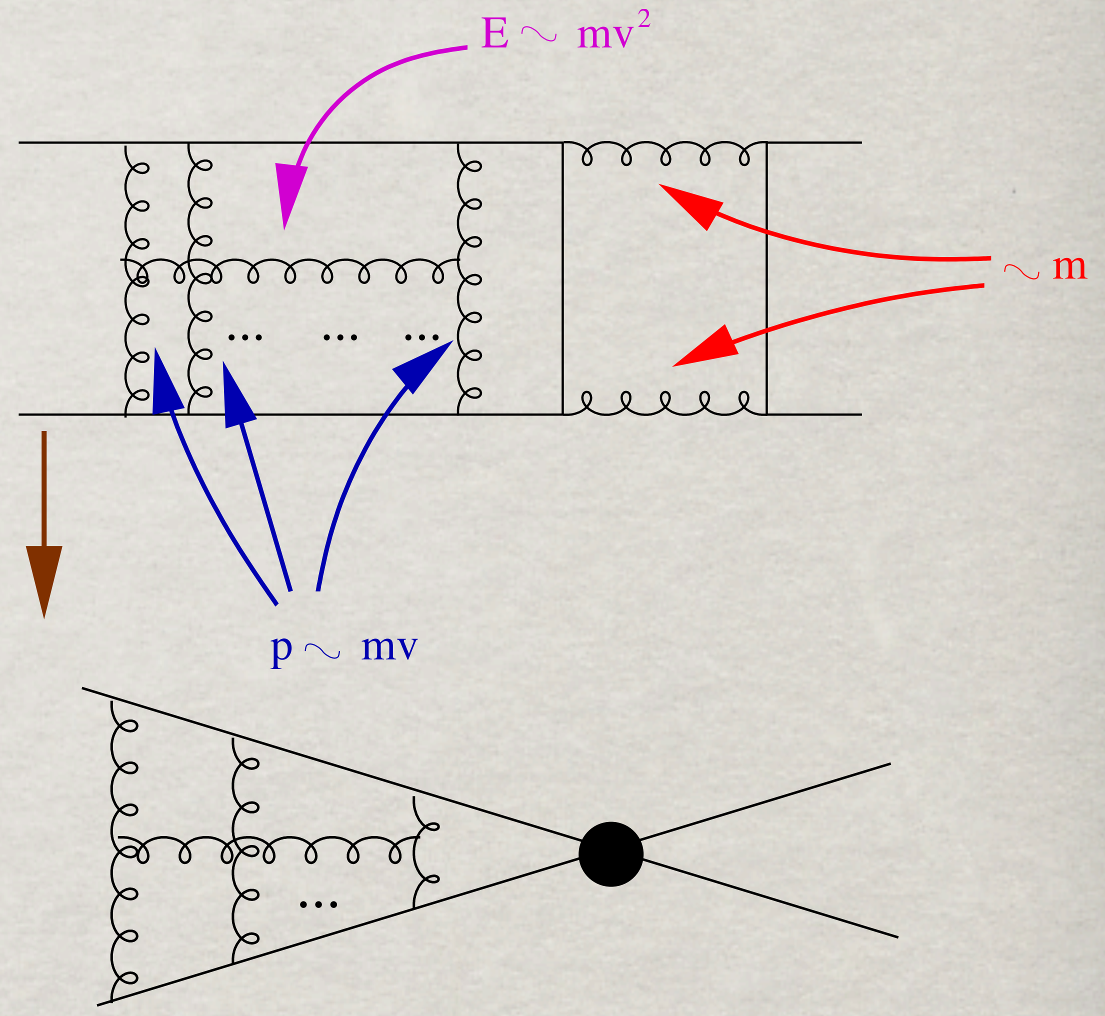
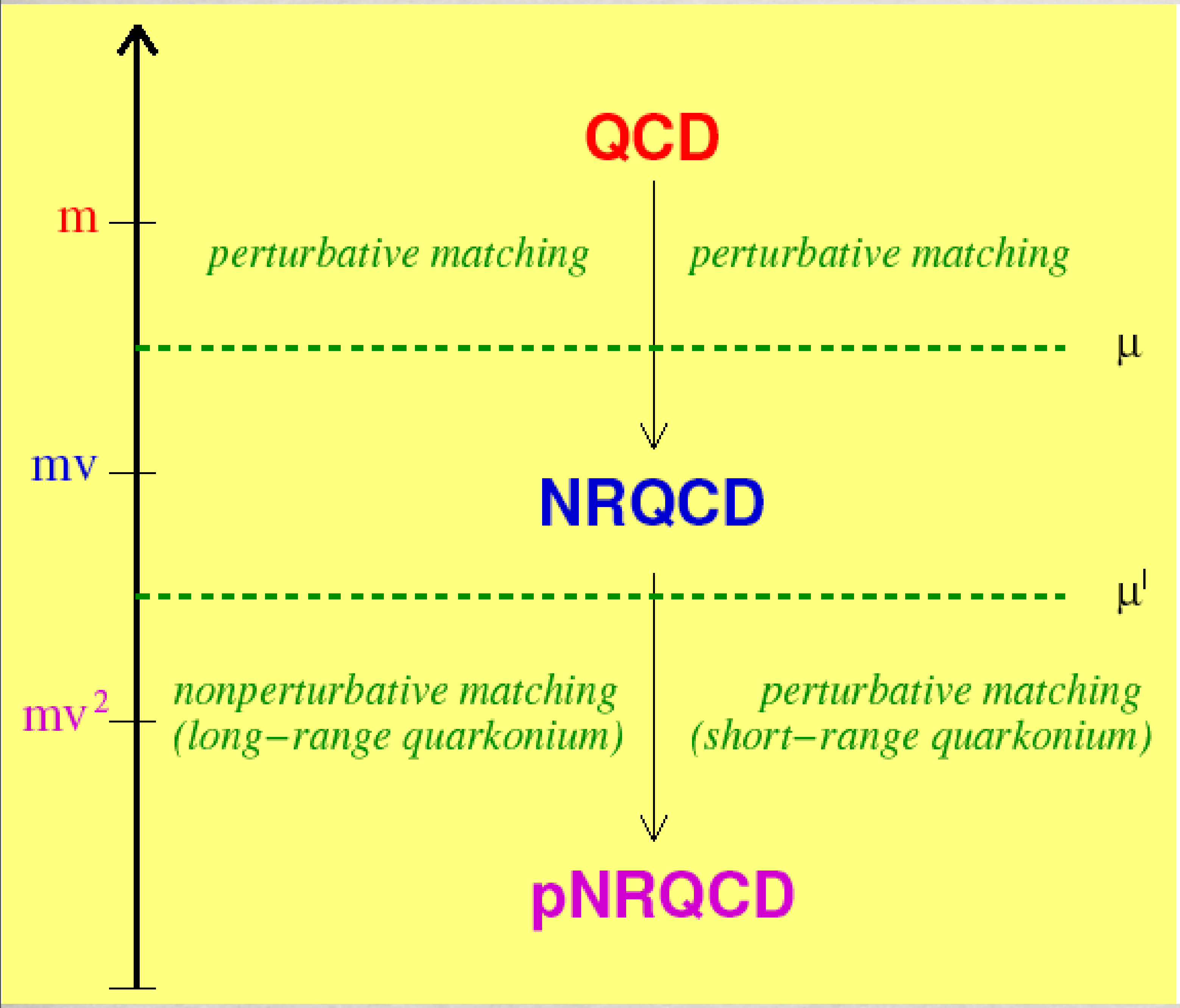
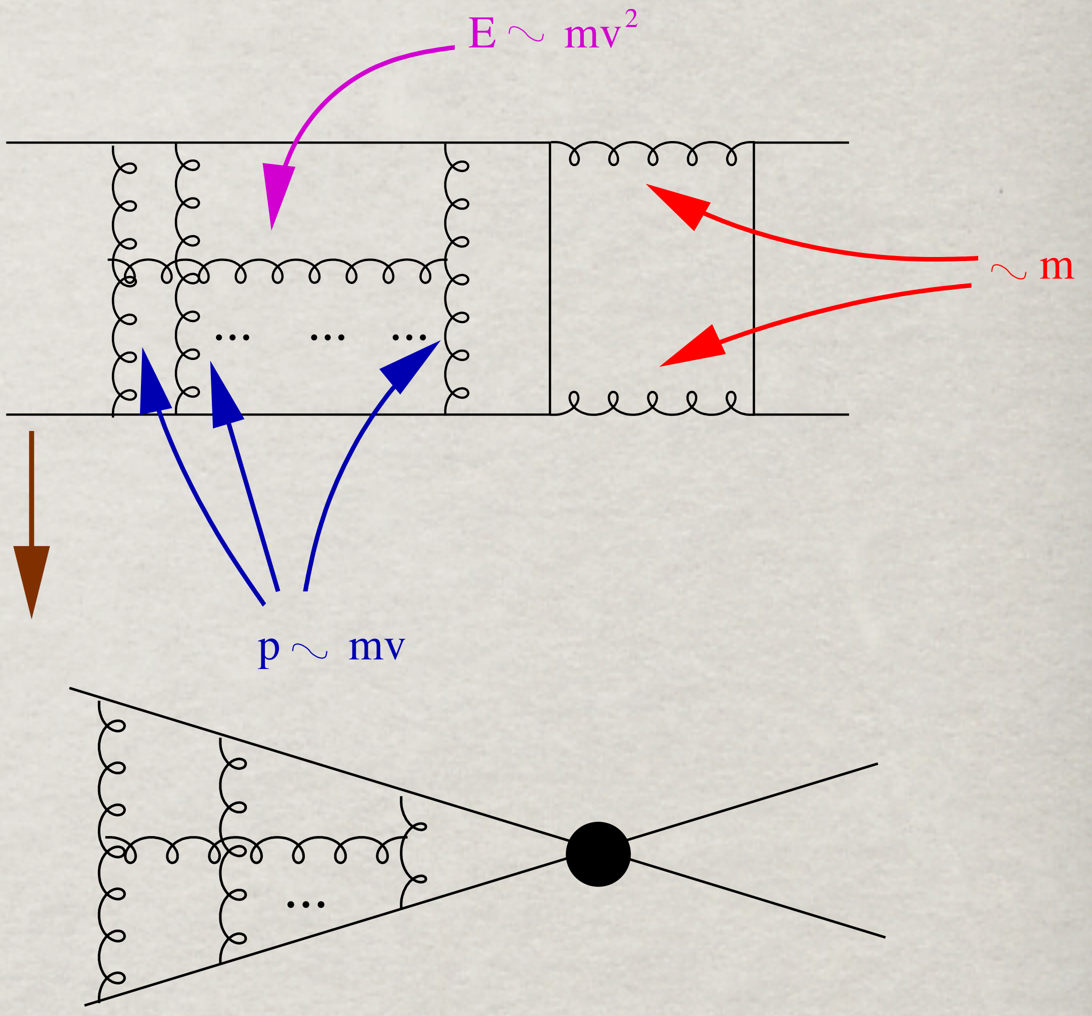




$$\mathcal{L}_{\mathrm{NRQCD}} = \sum_n c(\alpha_{\mathrm{s}}(m/\mu)) \times \frac{O_n(\mu,\lambda)}{m^n}$$

Quarkonium with NR EFT: potential NonRelativistic QCD (pNRQCD)





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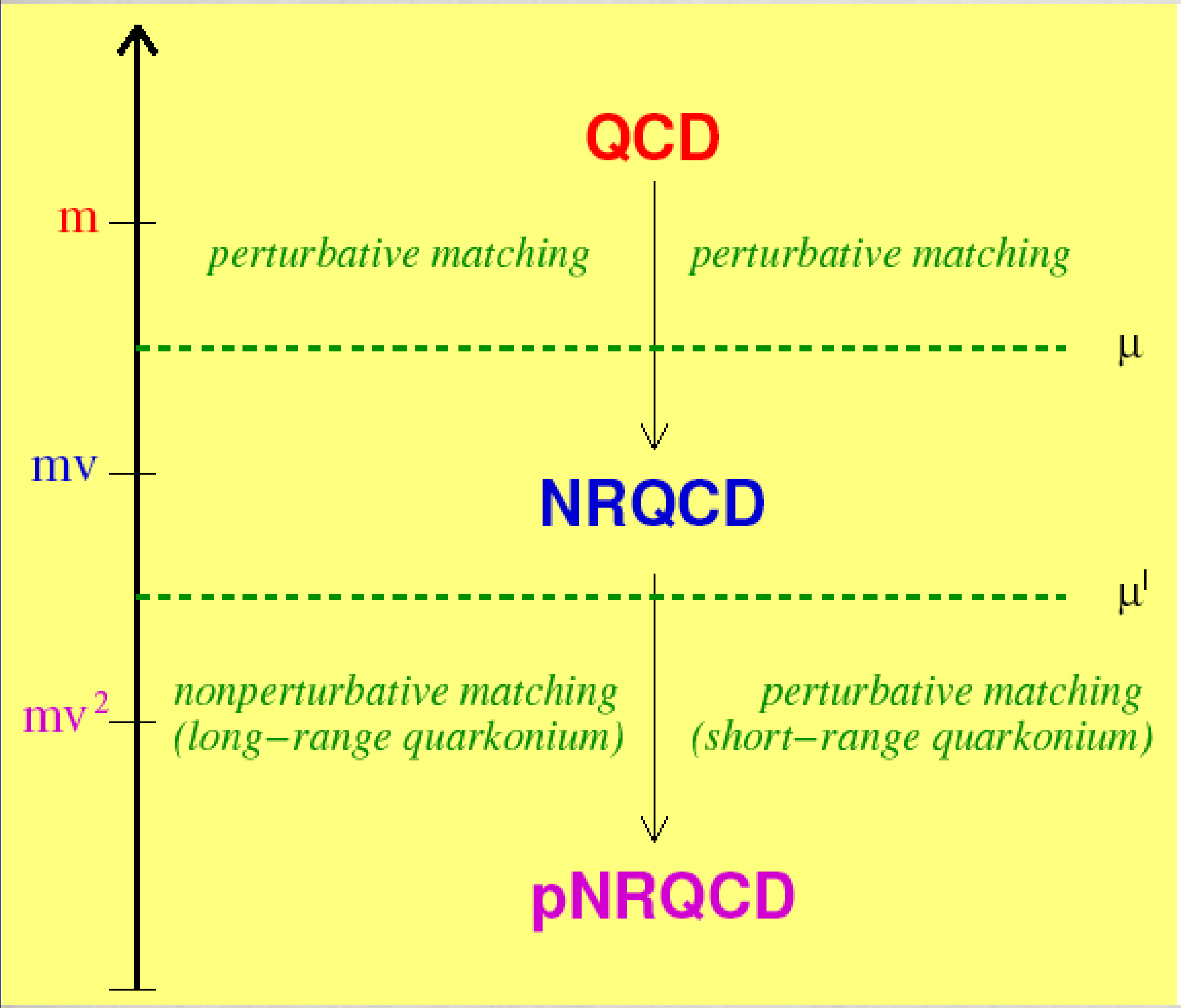

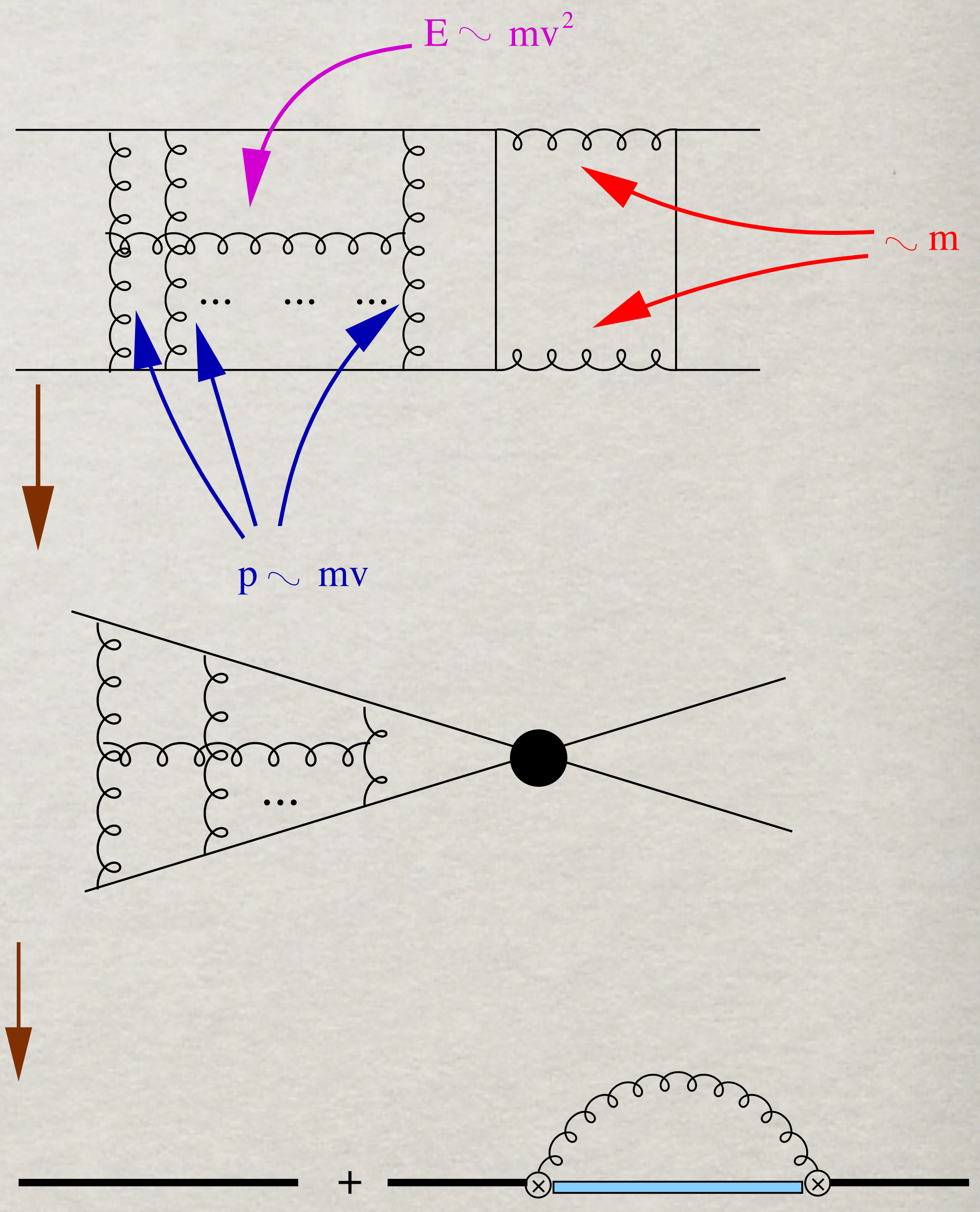

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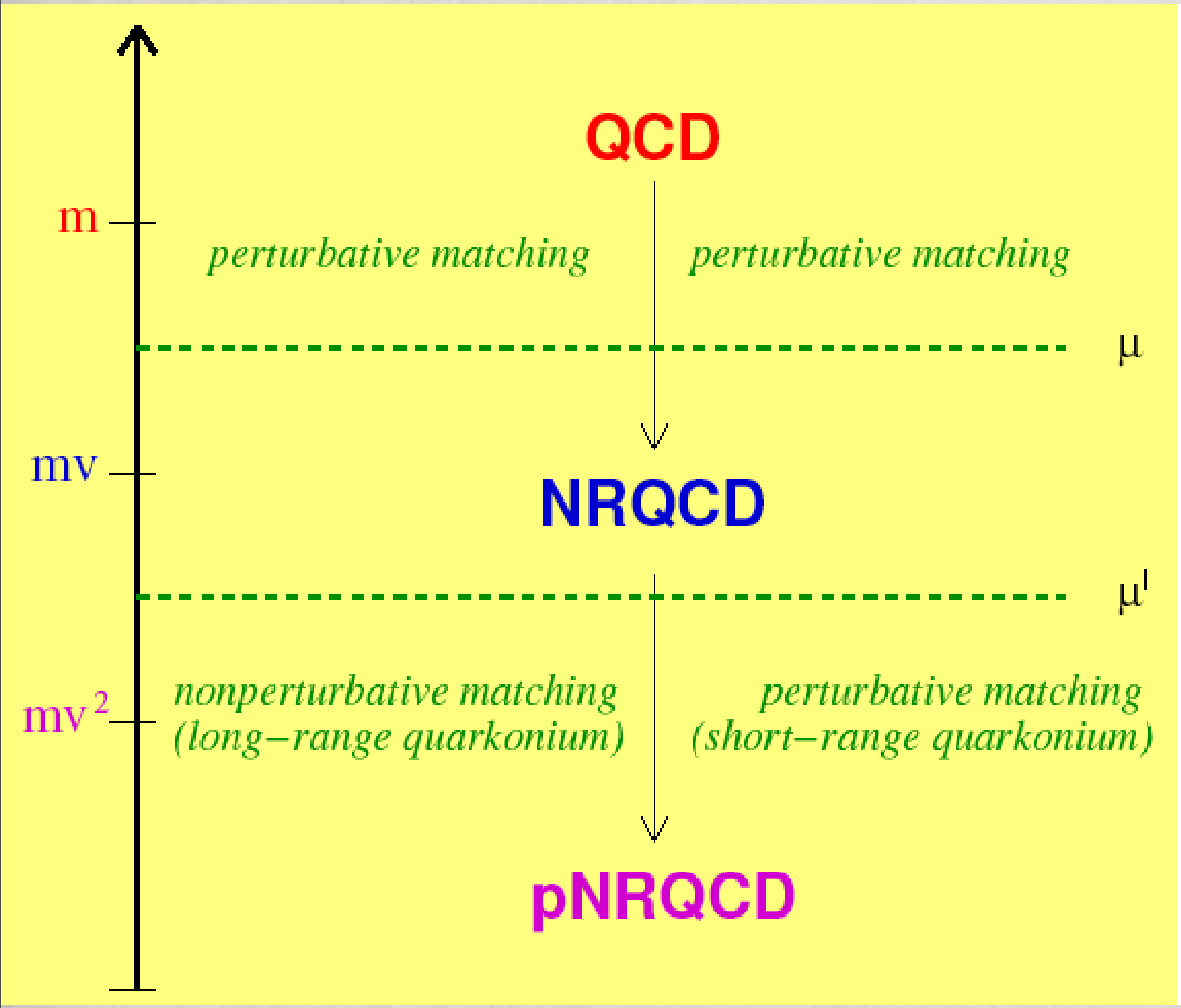
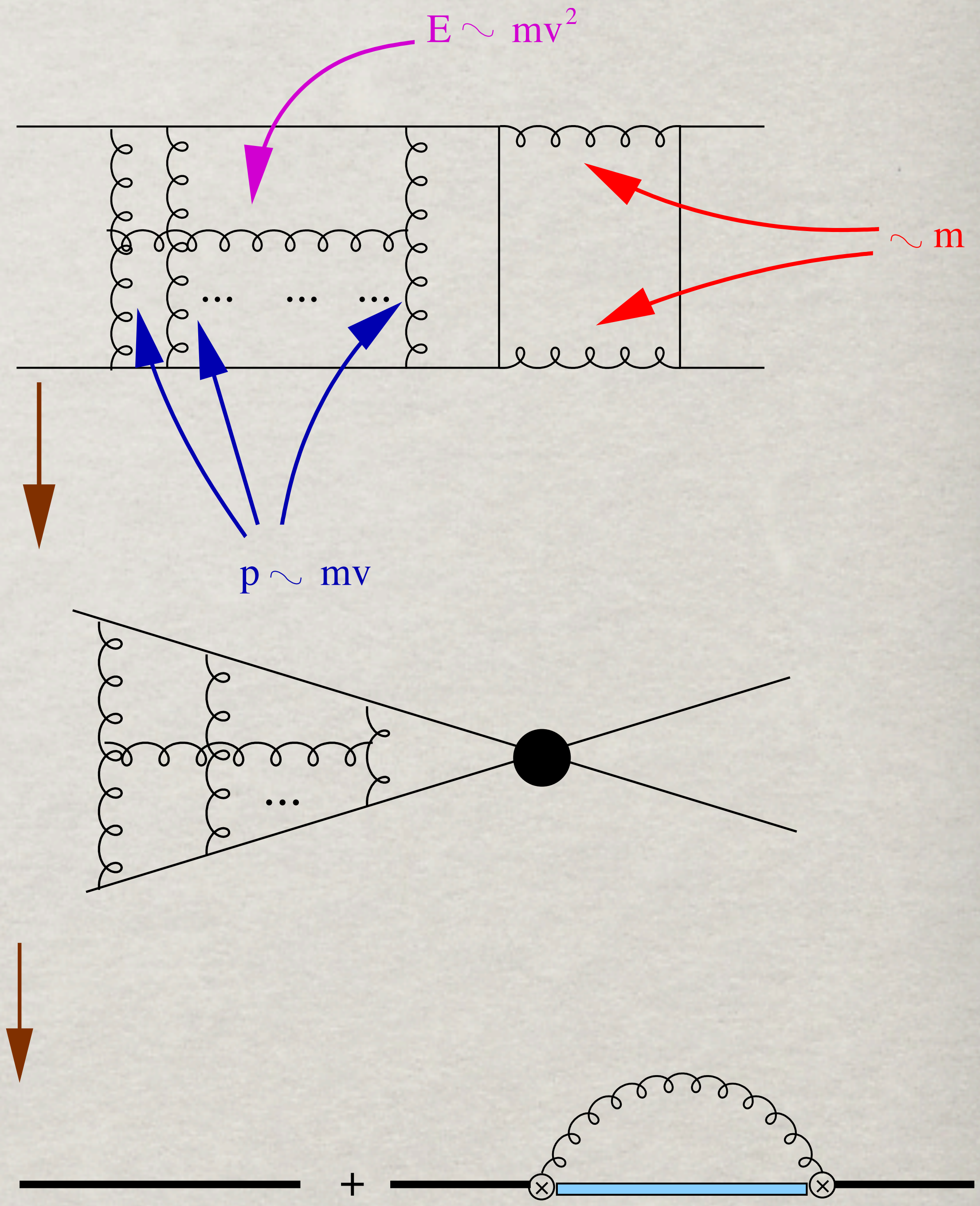
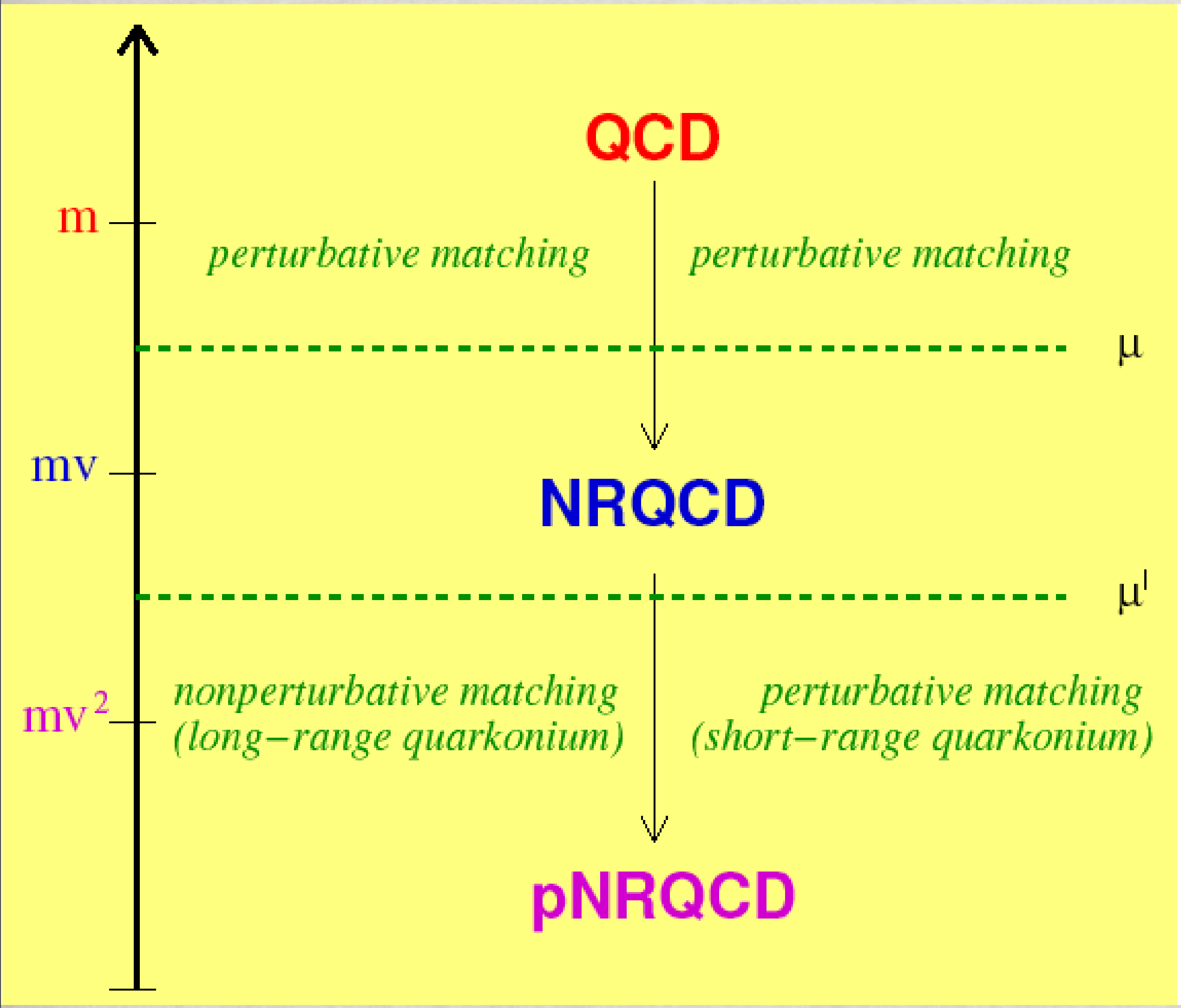
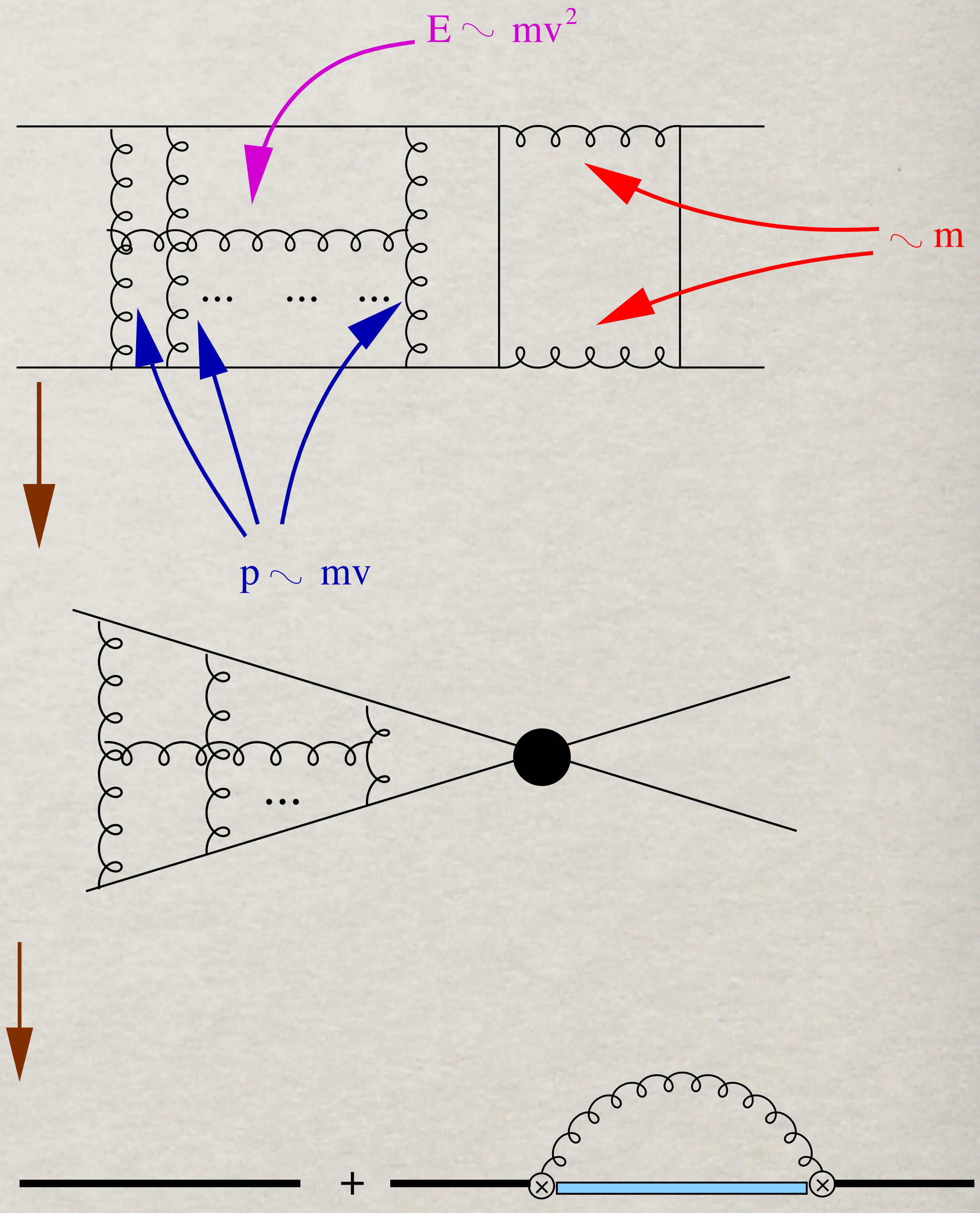




$$\mathcal{L}_{\rm pNRQCD} = \sum_k \sum_n \frac{1}{m^k} c_k(\alpha_{\rm s}(m/\mu)) \times V(r\mu', r\mu) \times O_n(\mu', \lambda)\, r^n$$

Quarkonium with NR EFT: potential NonRelativistic QCD (pNRQCD)





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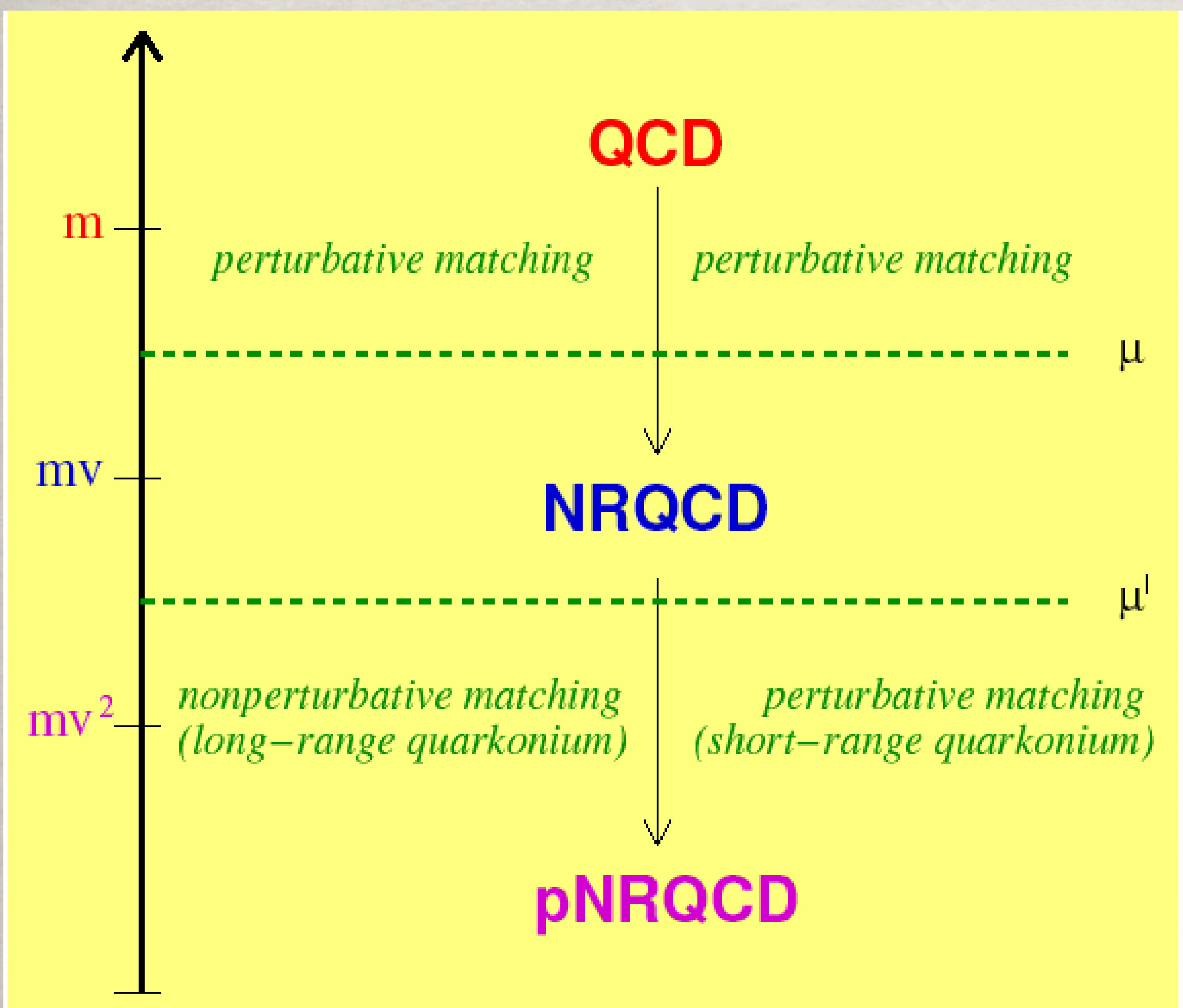

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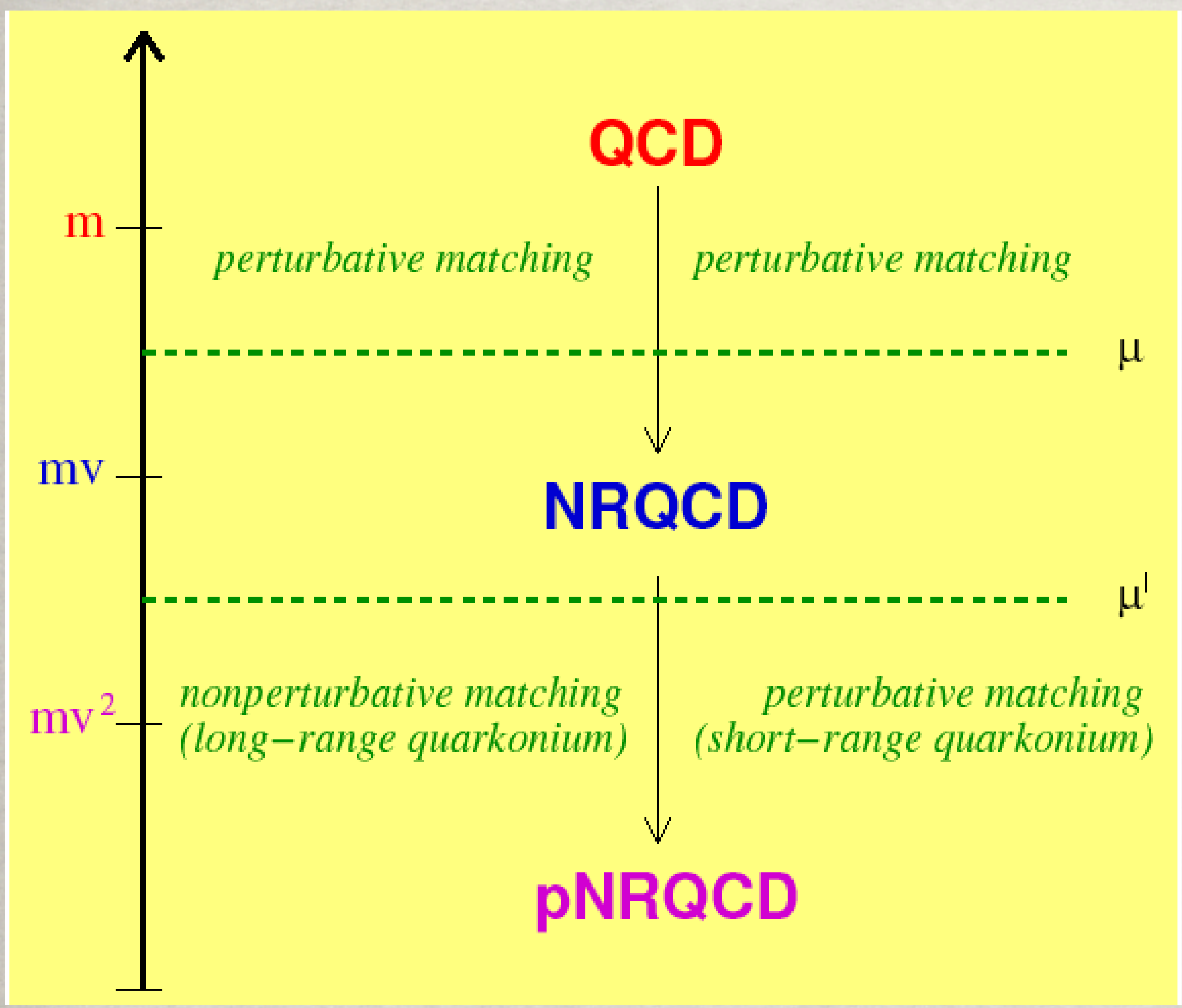
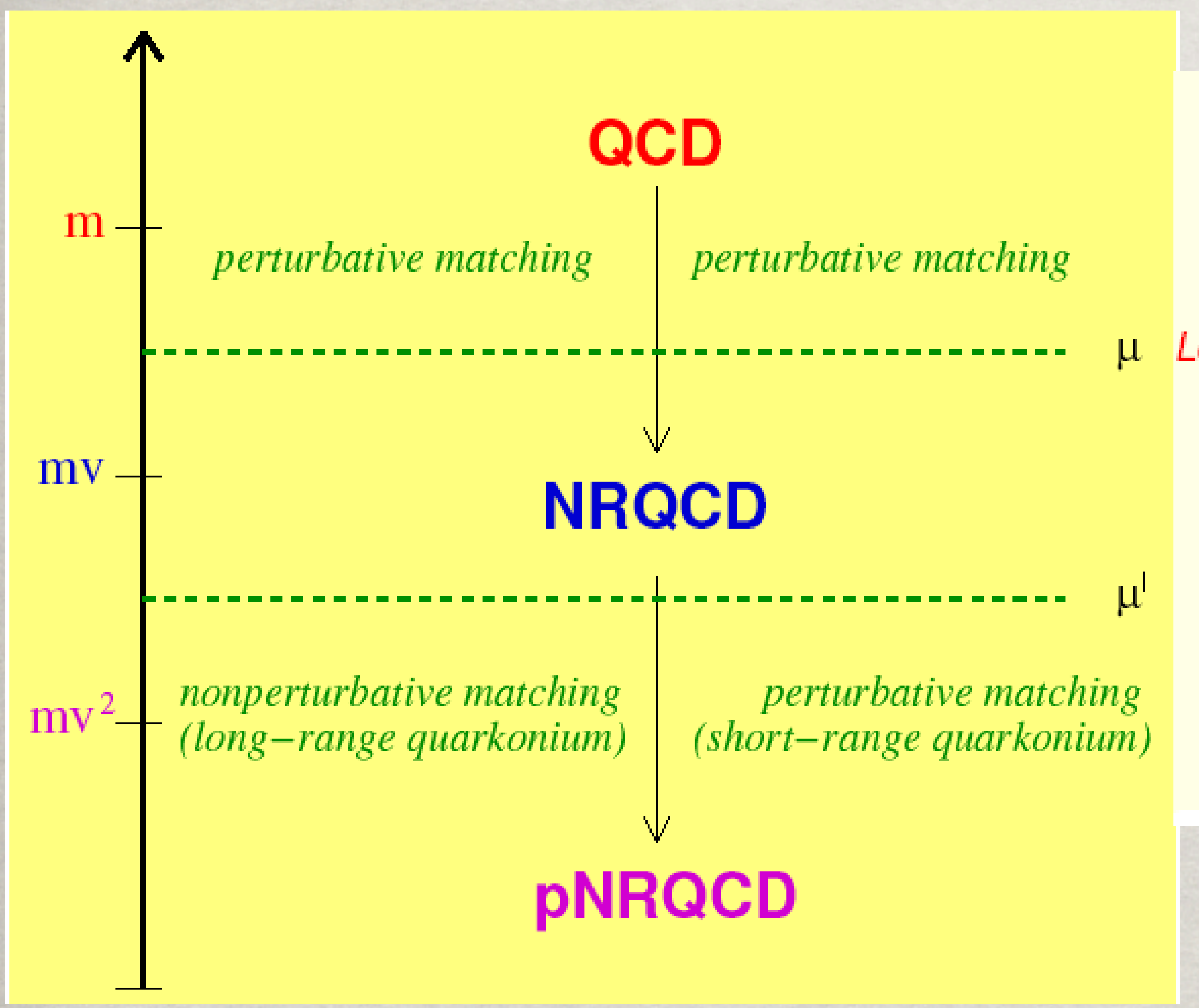
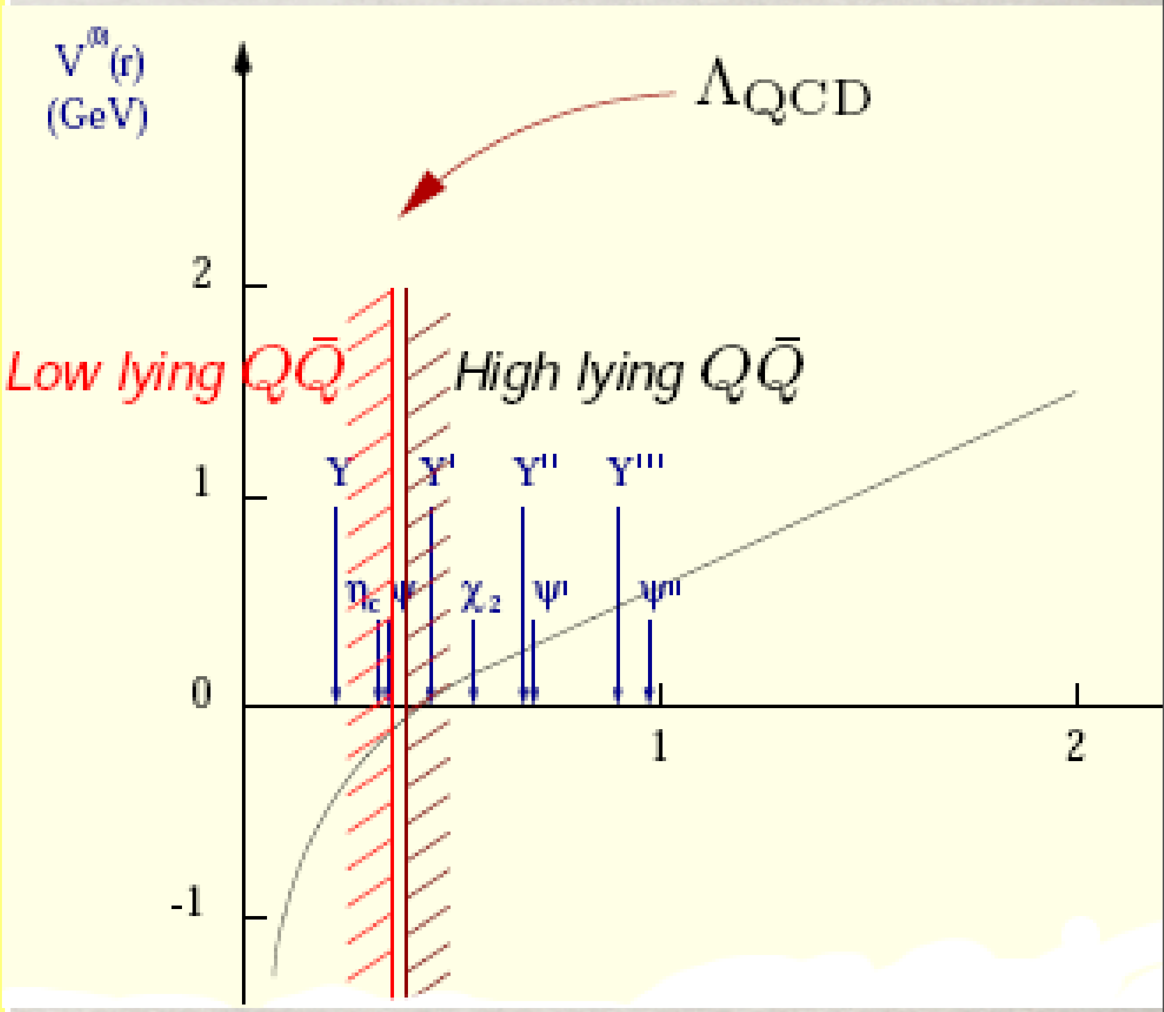


In QCD another scale is relevant Λ_{QCD}

Quarkonium with NR EFT: pNRQCD





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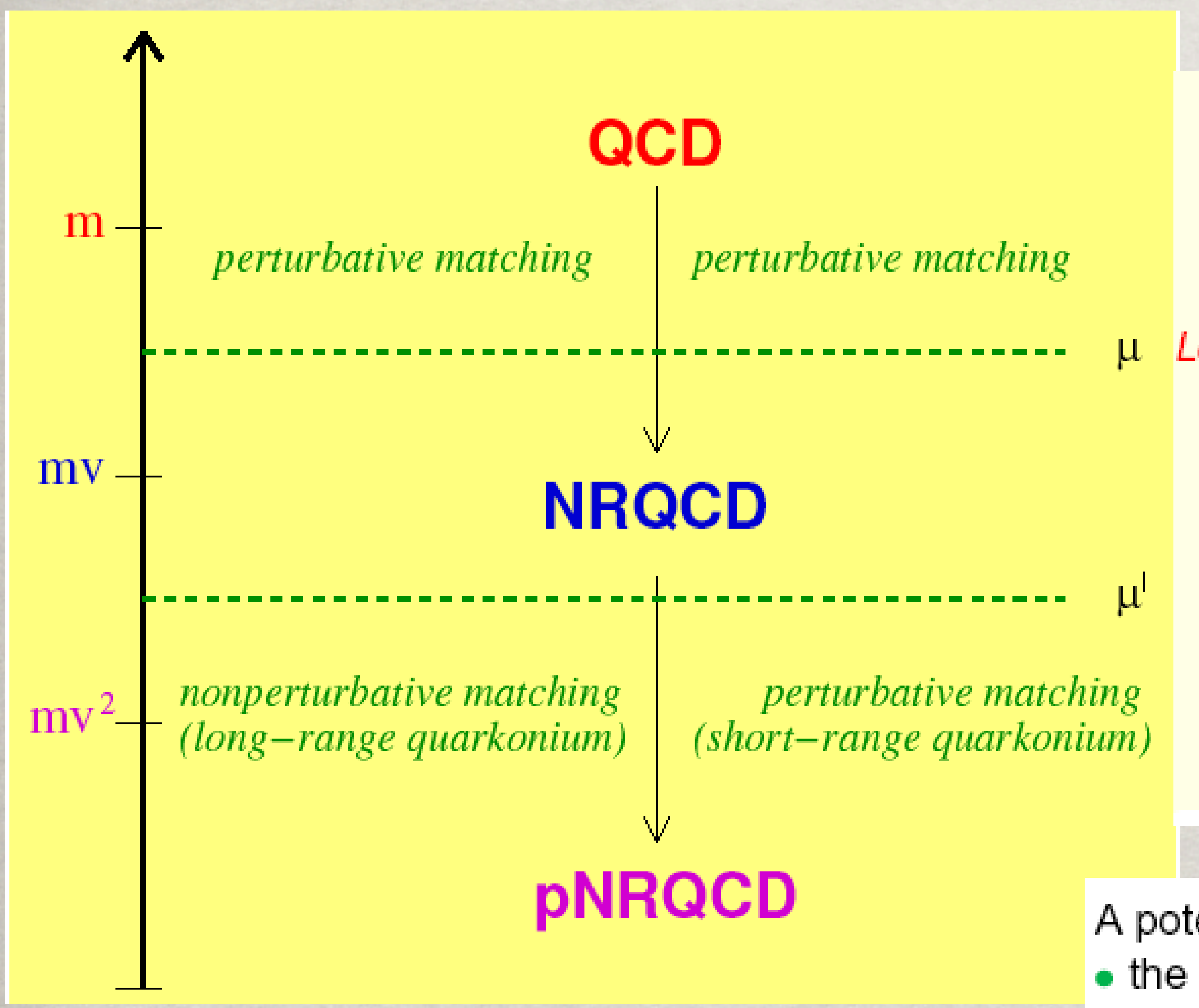
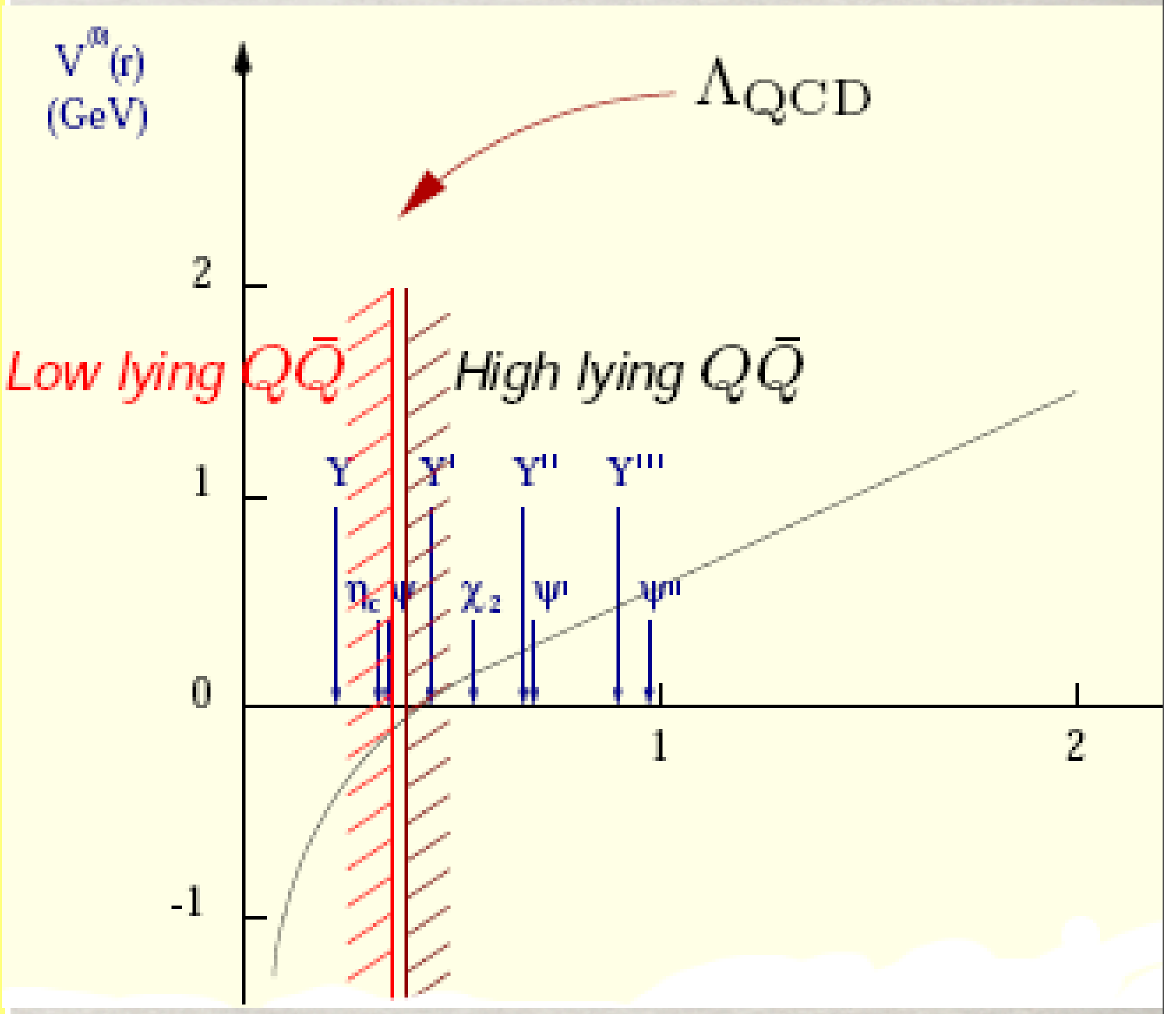


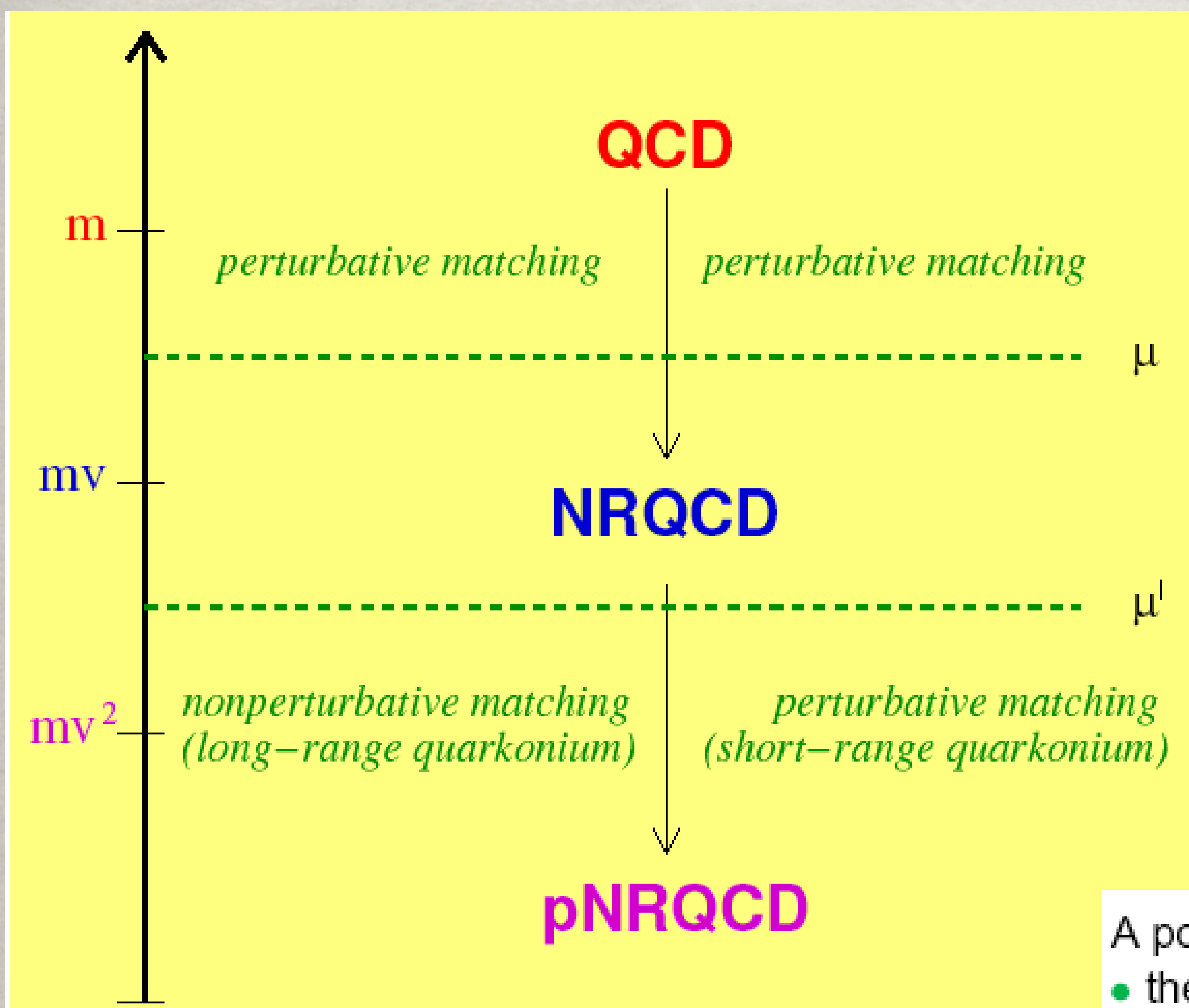


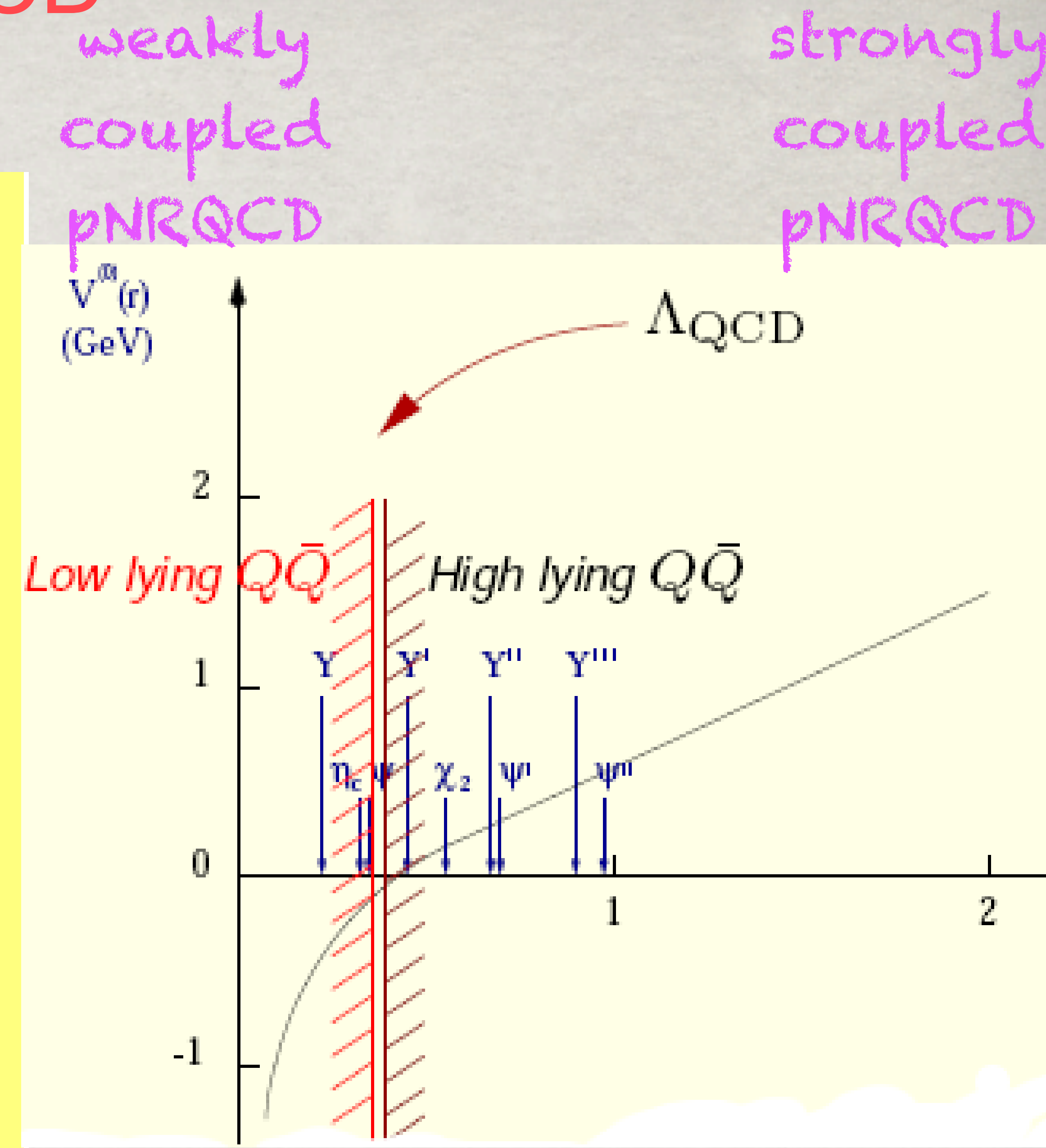
A potential picture arises at the level of pNRQCD:

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

In QCD another scale is relevant Λ_{QCD}

Quarkonium with NR EFT: pNRQCD





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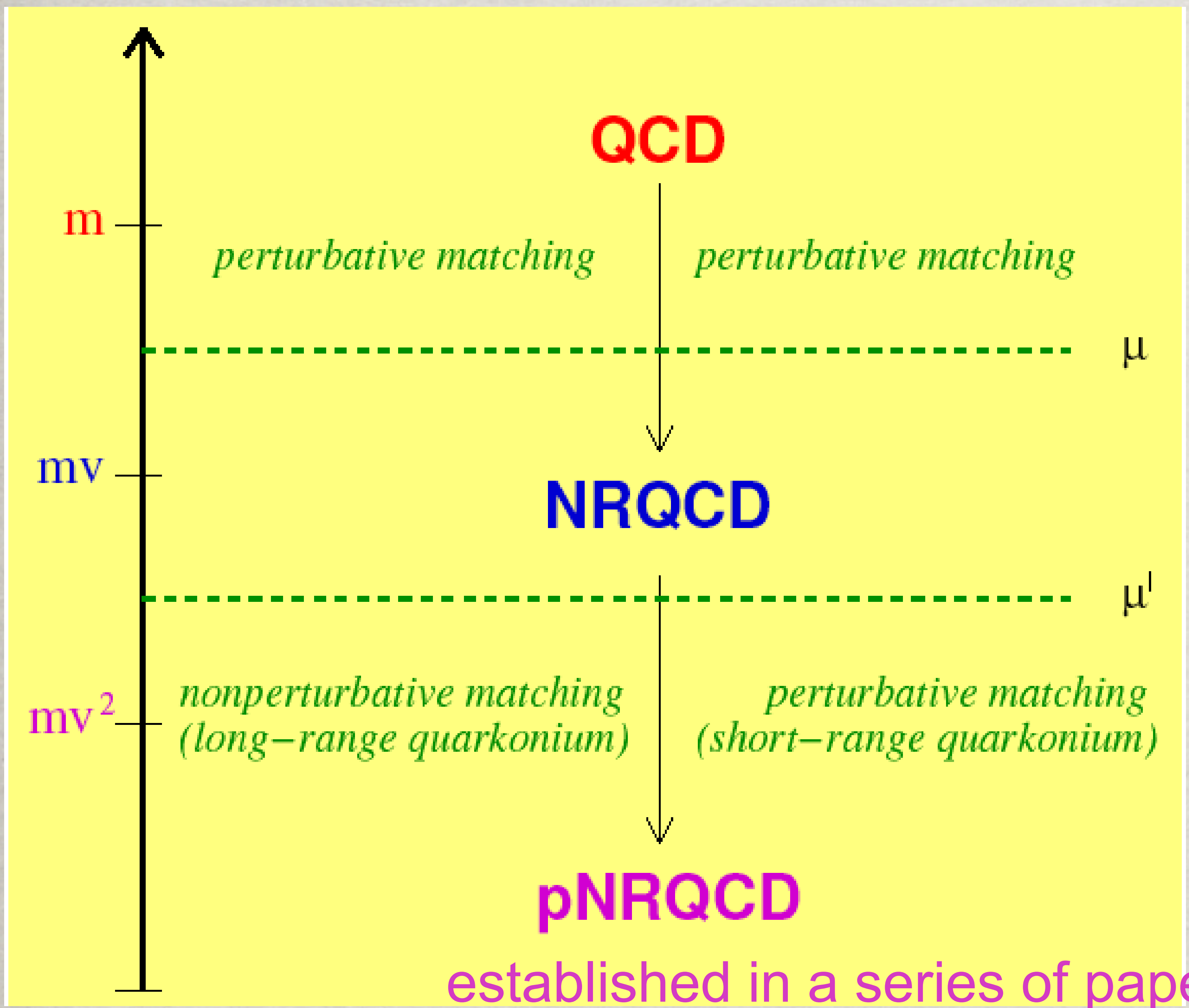
Quarkonium with EFT



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

established in a series of papers:
Pineda, Soto , N.B., Pineda, Soto, Vairo 97, 99
N.B. Vairo, Pineda, Soto 00--015
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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STUDIES of QUARKONIUM PRODUCTION IN VACUUM and in a MEDIUM are PROMINENT at the LARGE HADRON COLLIDER

Quarkonium production

Bodwin Braaten Lepage 1995

NRQCD factorization formula for quarkonium production valid for large p_T

$$\sigma(H) = \sum_n F_n \langle 0 | \mathcal{O}_n^H | 0 \rangle .$$

cross section

long distance matrix elements give the probability of a qqbar pair with certain quantum number to evolve into a final quarkonium H

short distance coefficients partonic hard scattering cross section convoluted with parton distribution

they are vacuum expectation values of four fermion operators and contain color singlet and color octet contribution

Quarkonium production

NRQC

age 1995

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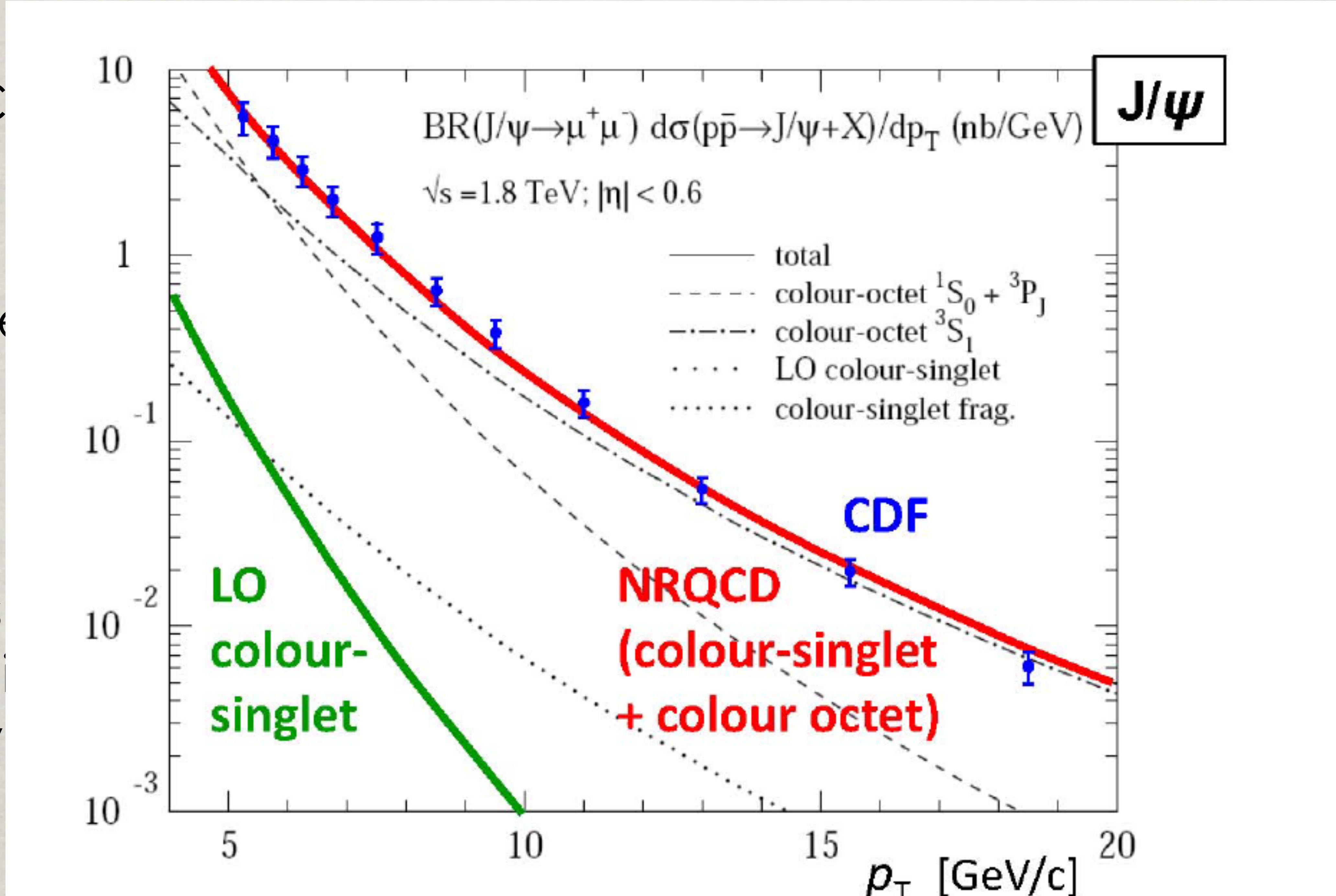

M. Kraemer 01 CDF 97

Explained the data at Fermilab on the cross section with the octet contribution (the singlet model failed)

Quarkonium production

1995

NRQC

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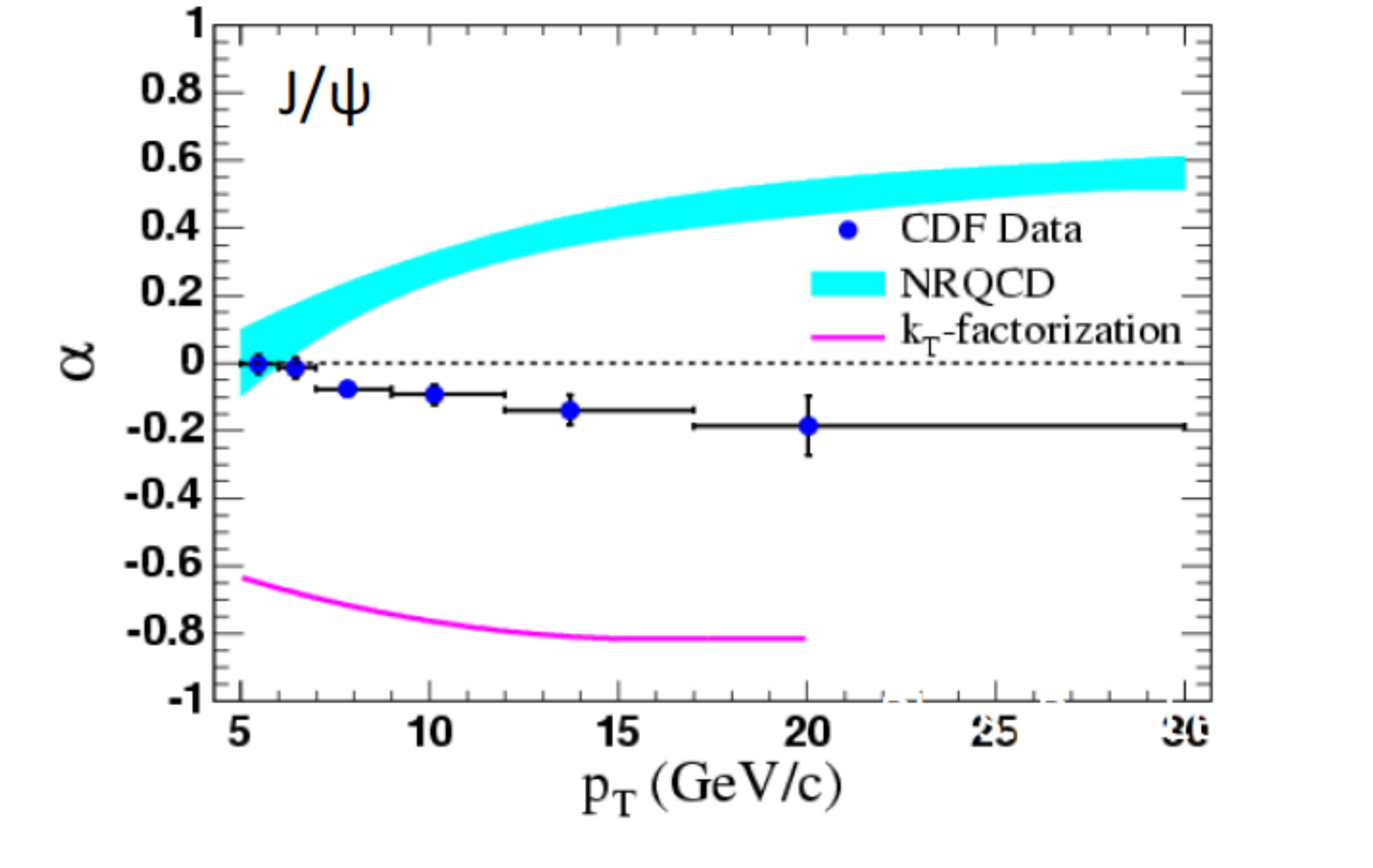

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Explained the data at Fermilab on the cross section with the octet contribution (the singlet model failed)

Difficulties in explaining quarkonium polarization at Fermilab

Quarkonium production

Terrific progress in production in the last few years

- Proof of NRQCD factorization at NNLO — Qiu, Nayak, Sterman 05-08
- Calculation of the differential singlet cross section at NLO and NNLO* — Gong, Wang 08 Artoisenet, Campbell,Lansberg, Maltoni, Tramontano 07
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- NLO calculation of J/psi photoproduction at HERA — Artoisenet, et al.09, Butenschon Kniehl 09
- Full NLO calculation of the direct J/psi hadroproduction in NRQCD — Butenschon Kniehl 010, Kuang ta Chao et al 010,
- Global fit of NRQCD color octet matrix elements at NLO — Butenschon Kniehl 011 Kuang ta Chao et al 011,
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a coherent picture in NRQCD for quarkonium production at Tevatron, Rhic, Hera is emerging and is being scrutinized at LHC

many more data are produced by LHC : polarizations (J/psi, psi(2s), Y(nS)), ratio of chi states, double quarkonium production, production of new states

NRQCD on the lattice for spectra calculations: many advances in the calculation of the matching coefficients in the lattice regularization and in considering higher order corrections in v^2: applications to bottomonium, hyperfine separation..... still a challenge the excited states

NRQCD for exclusive decays, implement collinear degrees of freedom with SCET

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

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bound state formation

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 the stong decay threshold)

*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

- 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 constructed (Finite T, small g)

Laine et al, 2007, Escobedo, Soto 2007 N. B., A. Vairo et al. 2008-2015

*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. Escobedo, Ghiglieri, Vairo Soto, 2010-2014

*Polyakov loop calculation N. B., Ghiglieri, Petreczky, Vairo 2010-2015

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

We have provided inspiration for other approaches: lattice, strings etc that now find imaginary parts in the finite T potential

pNRQCD and quarkonium Several cases for the physics at hand

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

*Degrees of freedom still to be identified

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

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Important to understand the X, Y, Z puzzles of the dozens of unexpected states showing up at the LHC and other collider experiments

Near theshold heavy-light mesons have to be included and many additional degrees of freedom considered

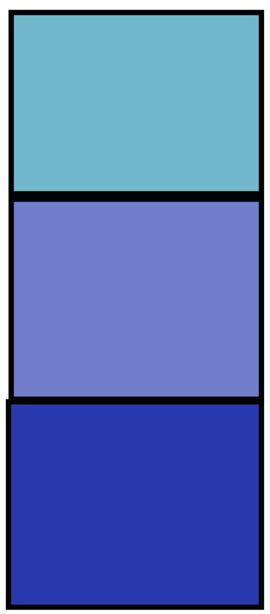
No systematic treatment is available; lattice calculations are also challenging and in the infancy state in this case

pNRQCD treatment available at the moment for the exotics states made by excited glue: HYBRIDS

N. B., M. Berwein, J. Tarrus, A. Vairo 2015

Low energy (nonperturbative) factorized effects depend on the size of the physical system

The EFT factorizes the low energy nonperturbative part.
Depending on the physical system:



The more extended the physical object, the more we probe the non-perturbative vacuum.

$$r \ll \frac{1}{\Lambda_{QCD}}$$

lowest quarkonia states

excited quarkonia states

$$r \sim \frac{1}{\Lambda_{QCD}}$$

quarkonia and exotics close and above threshold

$$r \sim \frac{1}{\Lambda_{QCD}}$$

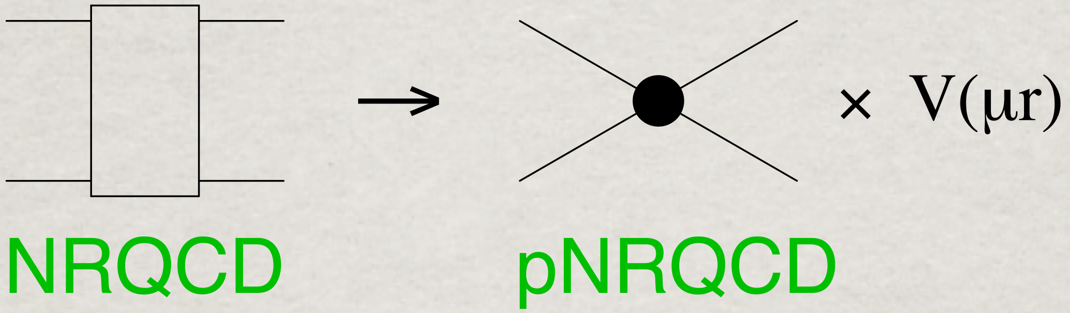
$$r \ll \frac{1}{\Lambda_{QCD}} \qquad T$$

quarkonia in a hot medium

Quarkonium systems with small radius $r \ll \Lambda_{\mathrm{QCD}}^{-1}$

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

Degrees of freedom that scale like mv are integrated out:



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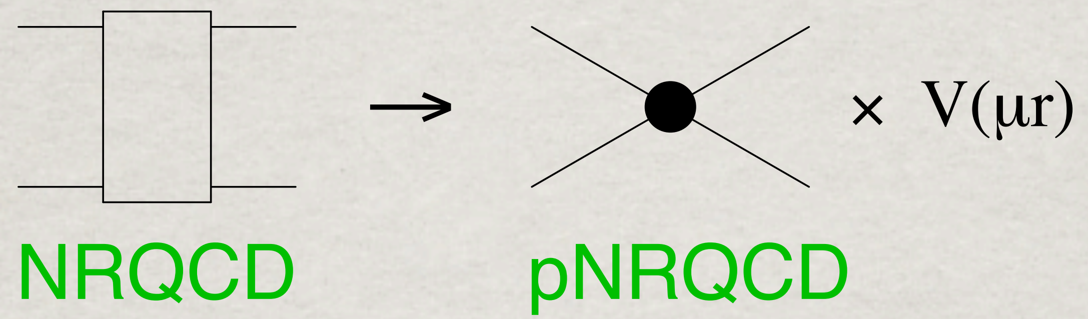

- If $mv \gg \Lambda_{\rm QCD}$, the matching is perturbative

- 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 $r \rightarrow$ matching coefficients V

weak 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-

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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

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Singlet static potential

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

LO in r

Octet static potential

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

——— singlet propagator

═══ octet propagator

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pNRQCD

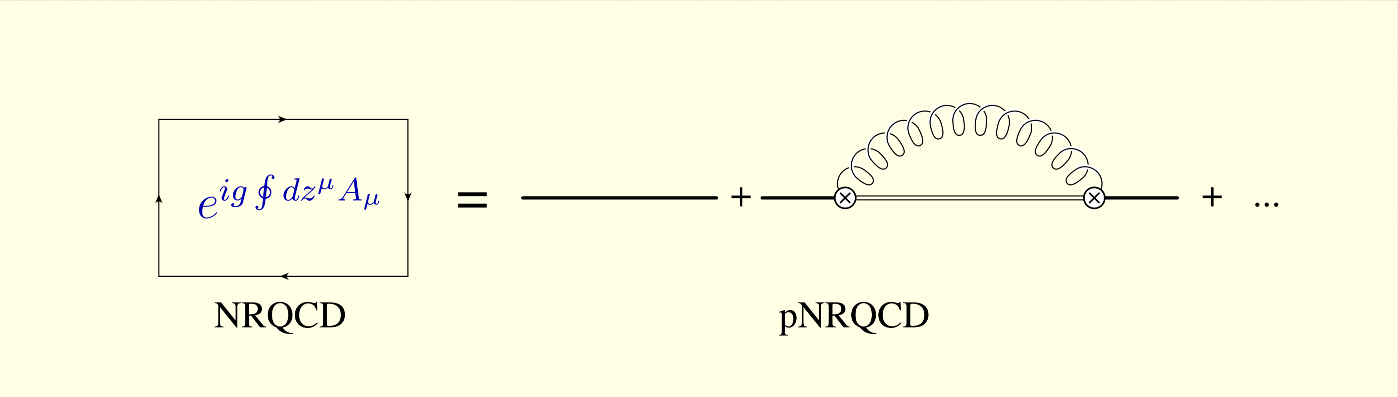
- pNRQCD provides a QM description from field theory: the Schroedinger equation and the potentials appear once all scales above the binding energy have been integrated out

- 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 and singlet static energy



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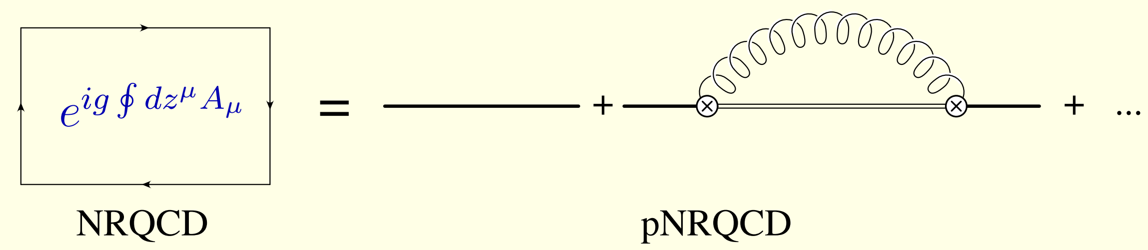


potential

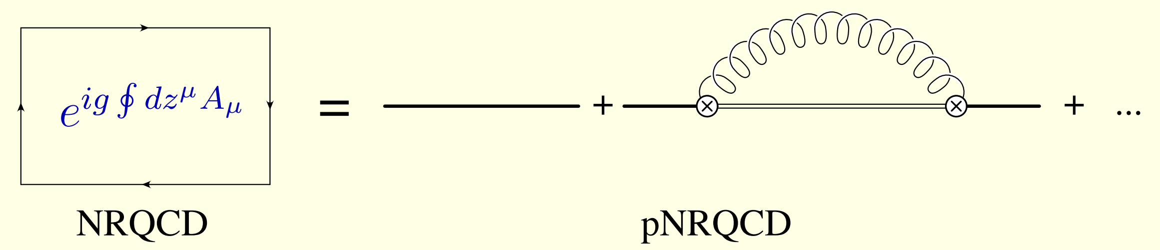
$$\lim_{T\to\infty} \frac{i}{T} \ln \langle \boxed{} \rangle = V_s(r,\mu) - i\frac{g^2}{N_c} V_A^2 \int_0^\infty dt\, e^{-it(V_o - V_s)} \langle \mathrm{Tr}(r\cdot E(t)\, r\cdot E(0)) \rangle(\mu) + \dots$$

static energy

ultrasoft contribution

contributes from 3 loops

QCD singlet static potential and singlet static energy



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

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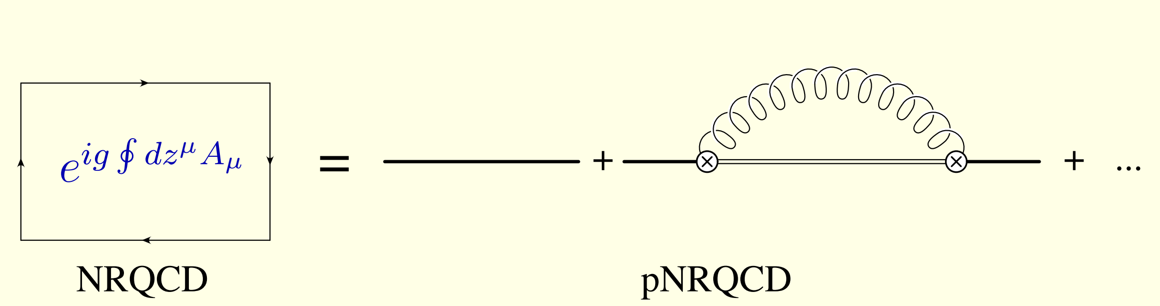

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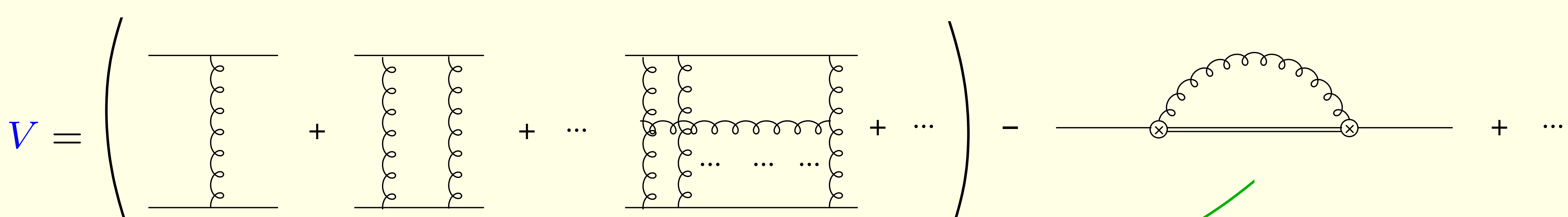

Quarkonium singlet static potential at N^4LO

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

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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, Soto…

4LOOPS REDUCES TO 2LOOPS IN THE EFT

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Two problems:

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

2) Large logs

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The eft cures both:

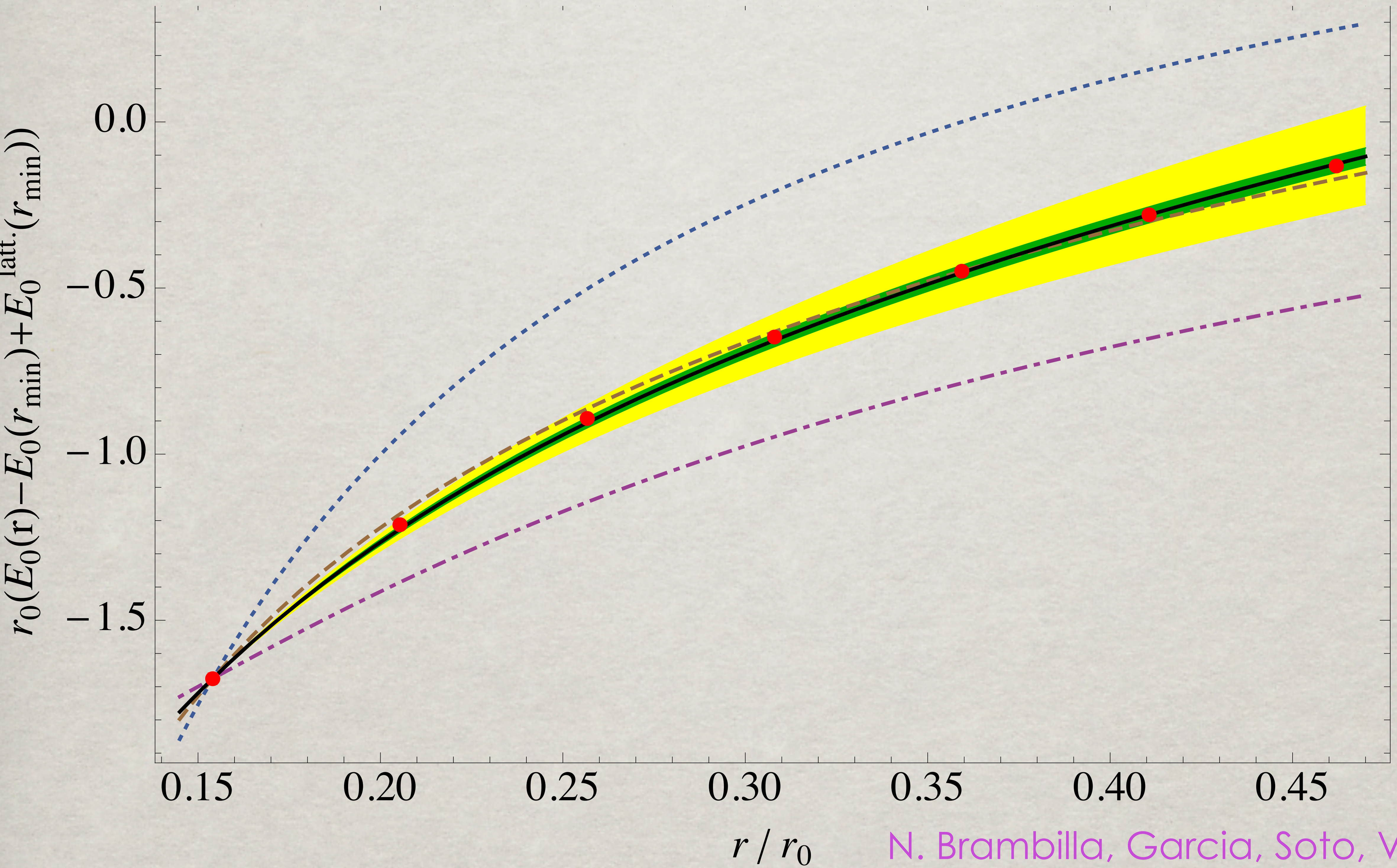
1) Renormalon subtracted scheme

Beneke 98, Hoang, Lee 99, Pineda 01, N.B. Pineda Soto, Vairo 09

2) Renormalization group summation of the logs

up to N^3LL $(\alpha_s^{4+n} \ln^n \alpha_s)$ N. B Garcia, Soto Vairo 2007, 2009, Pineda, Soto

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

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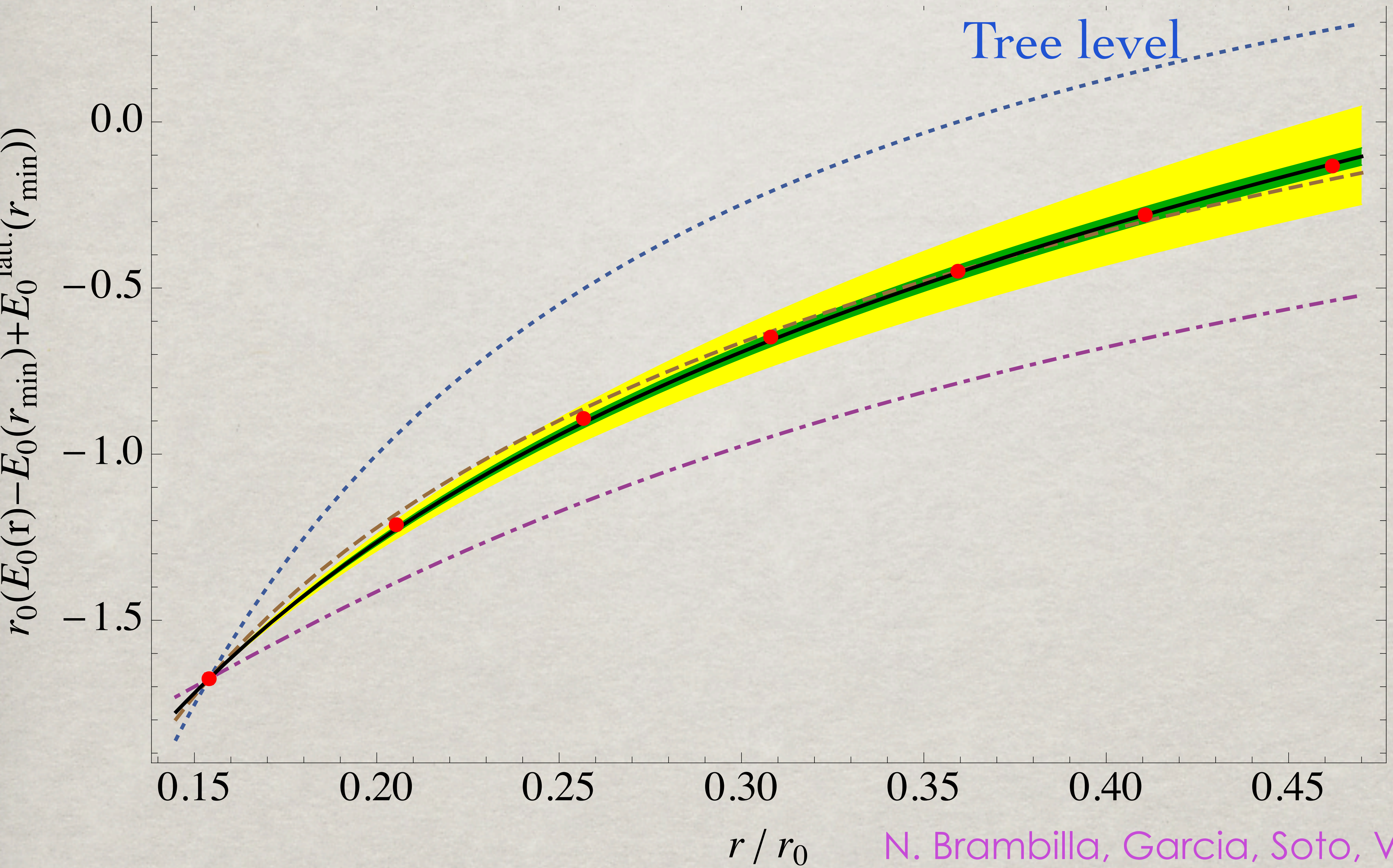

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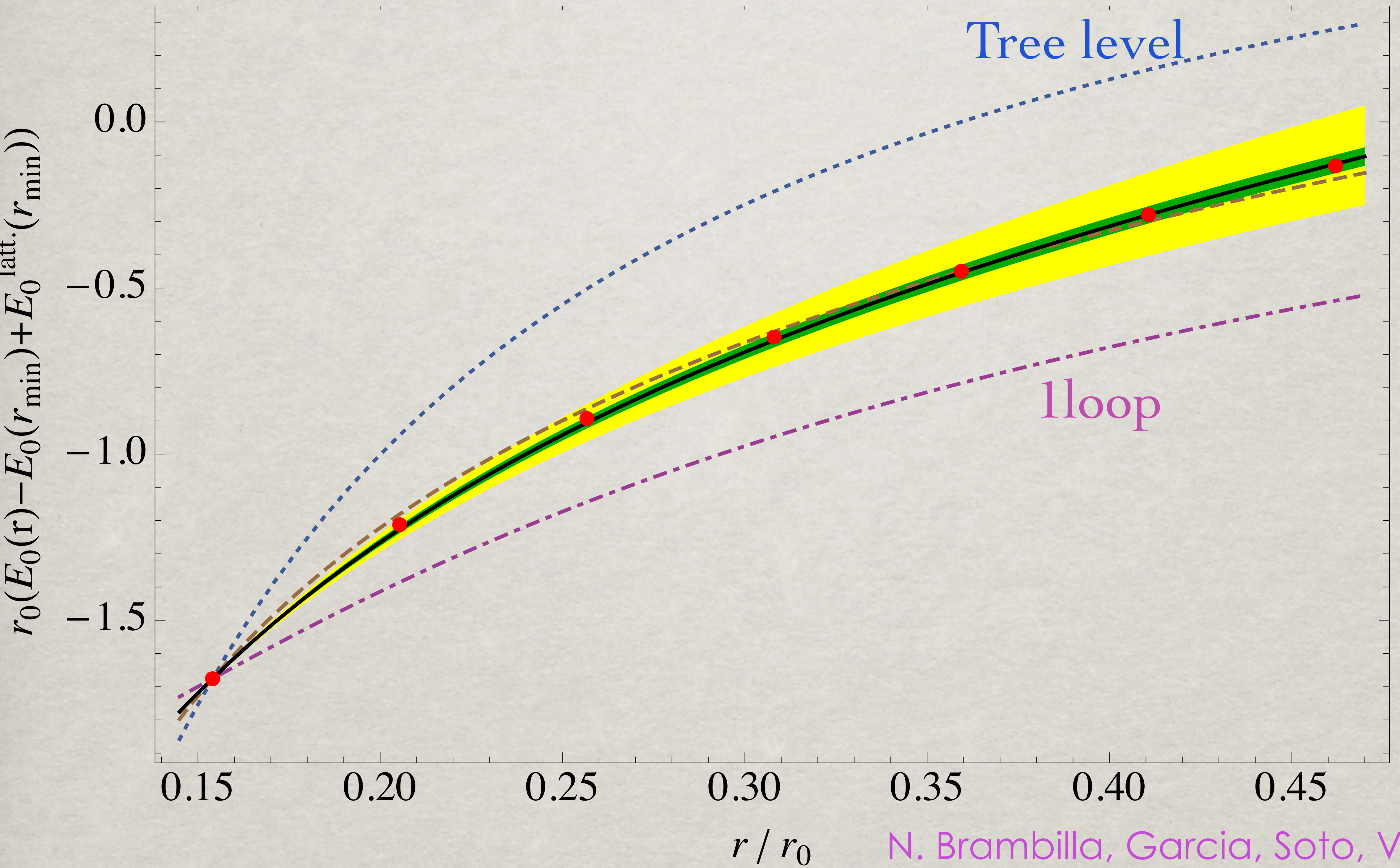

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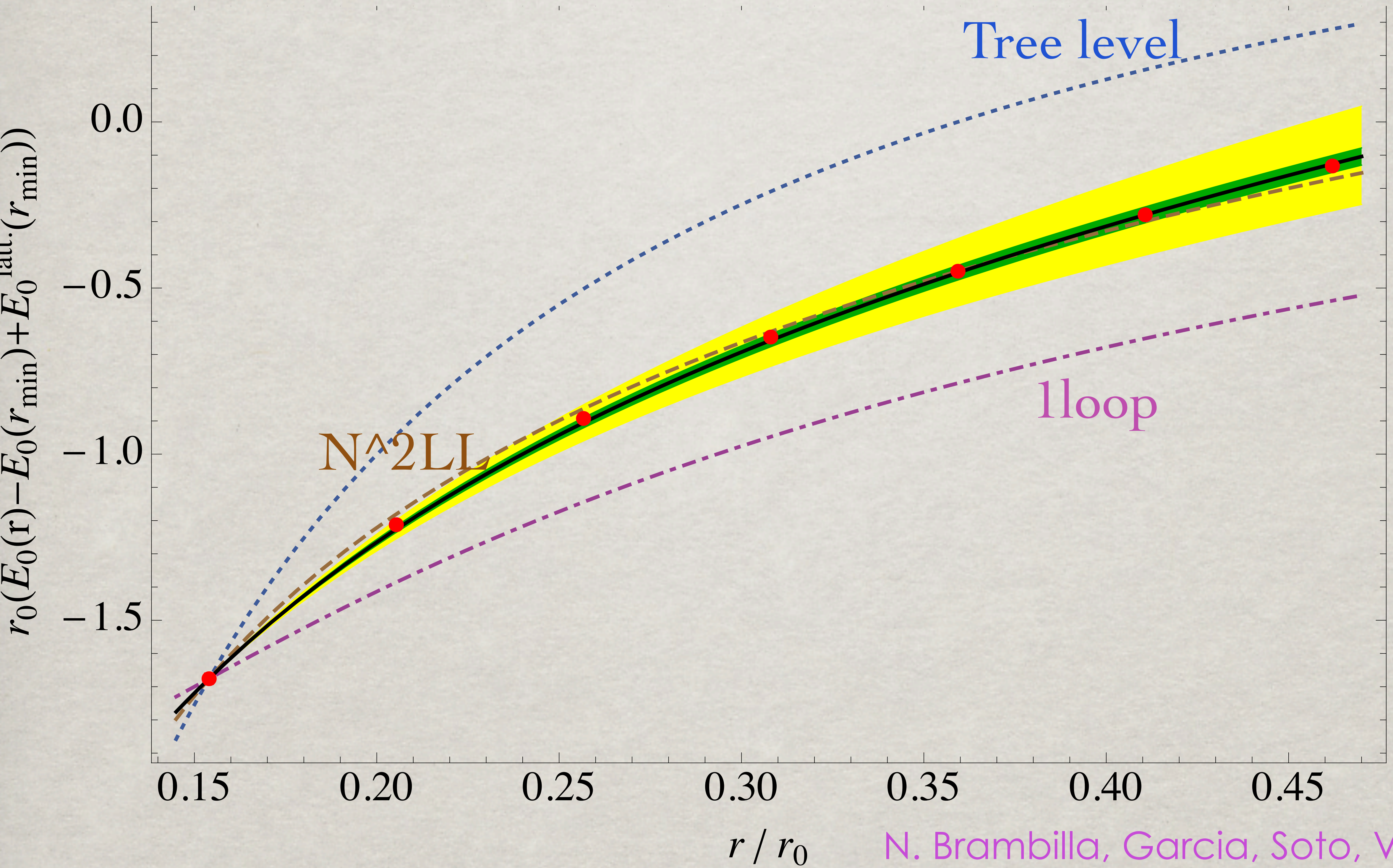

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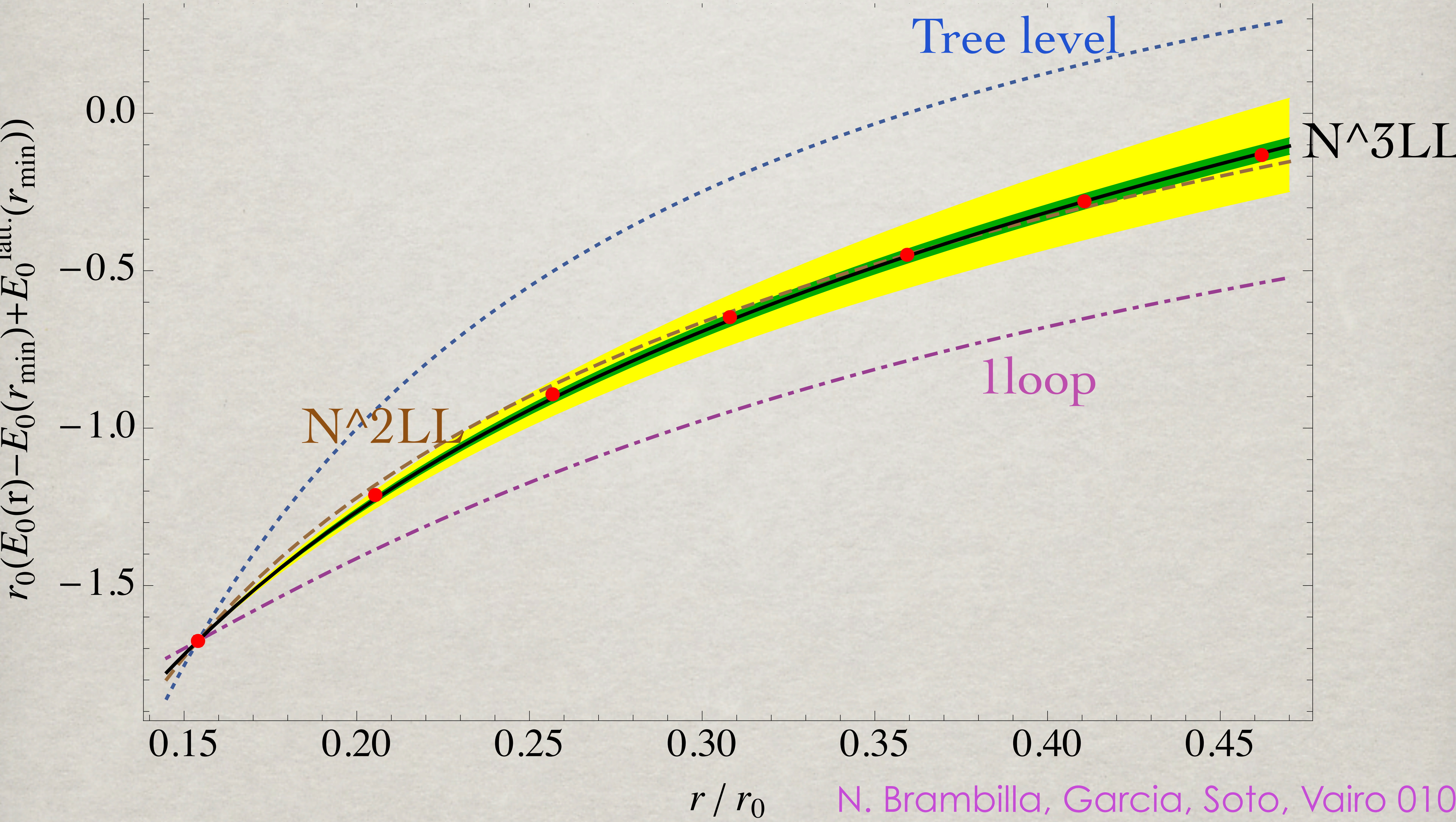

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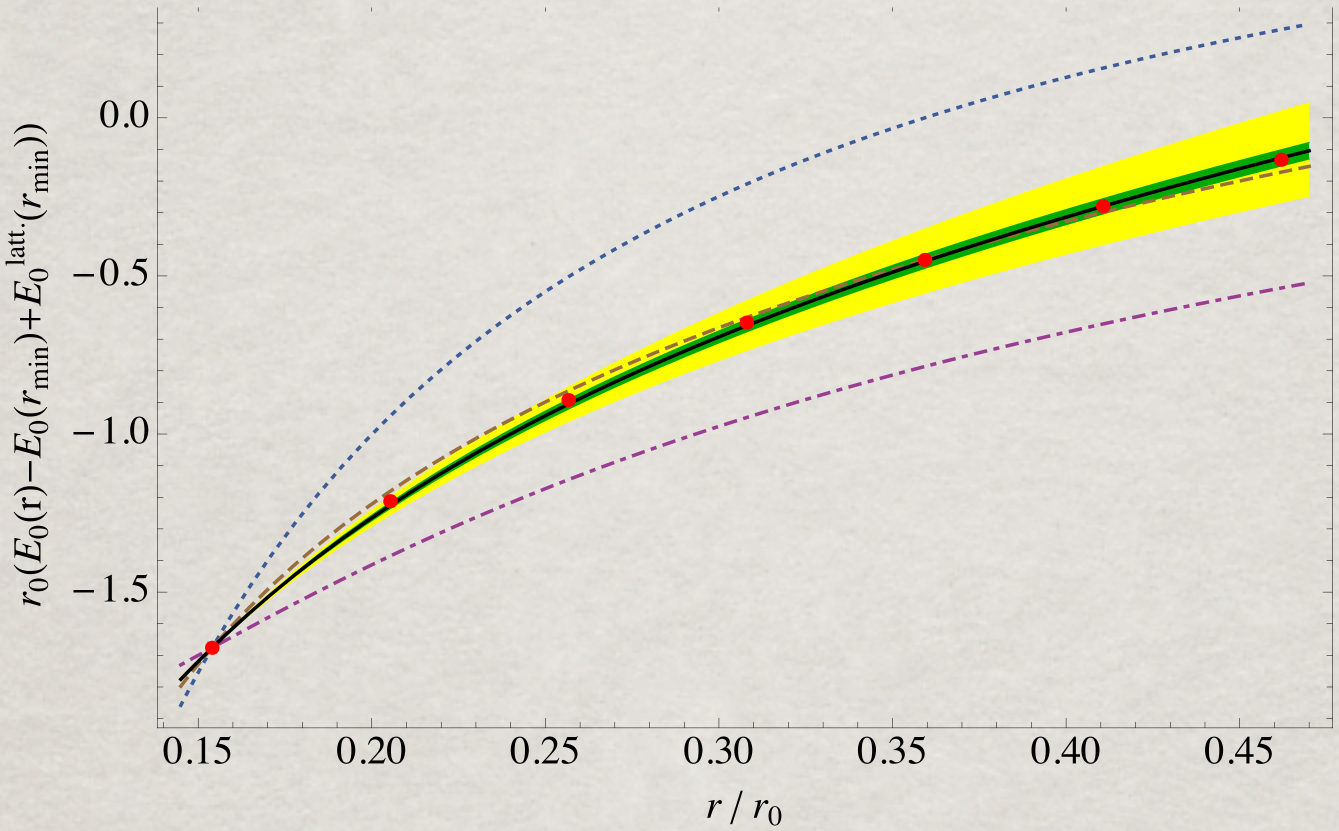

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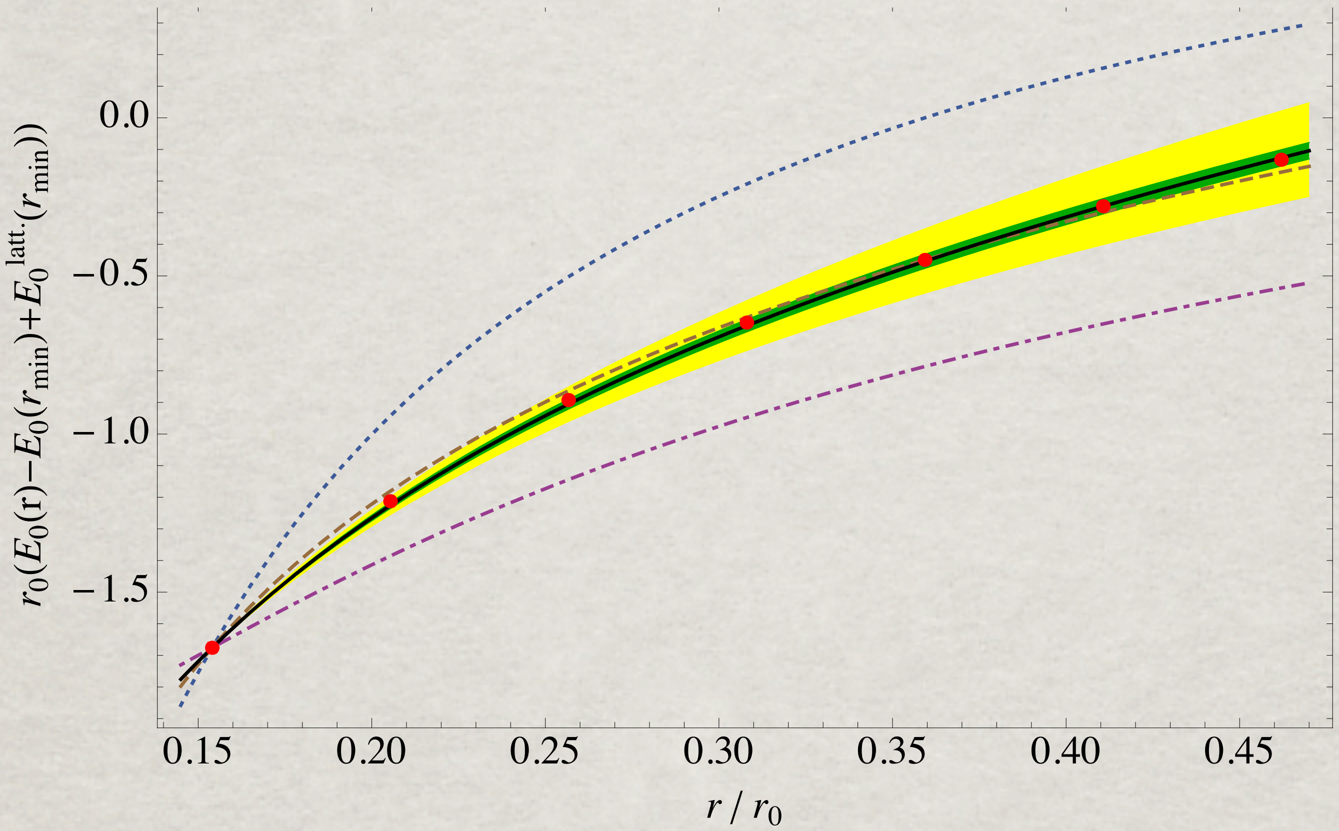

- Very good convergence of the QCD bound state perturbative series

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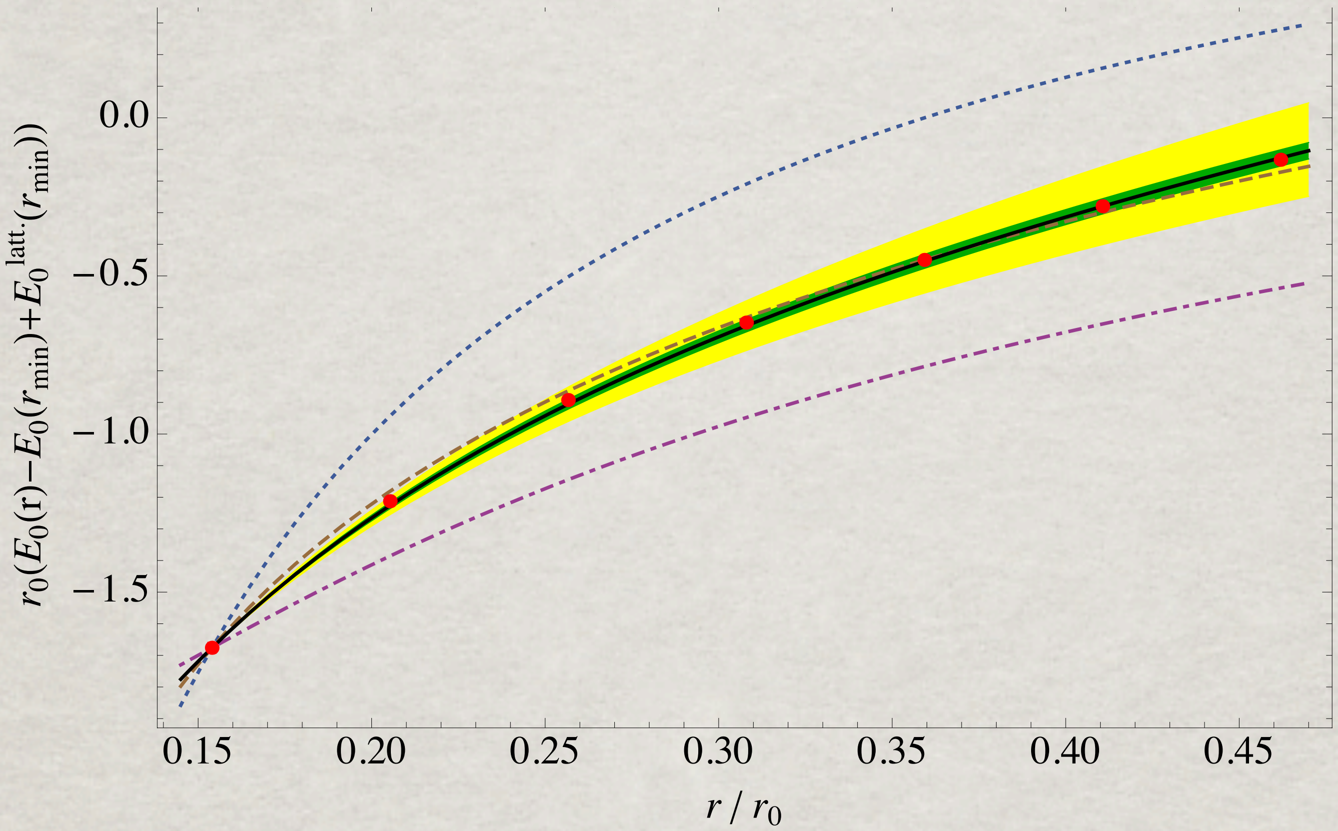

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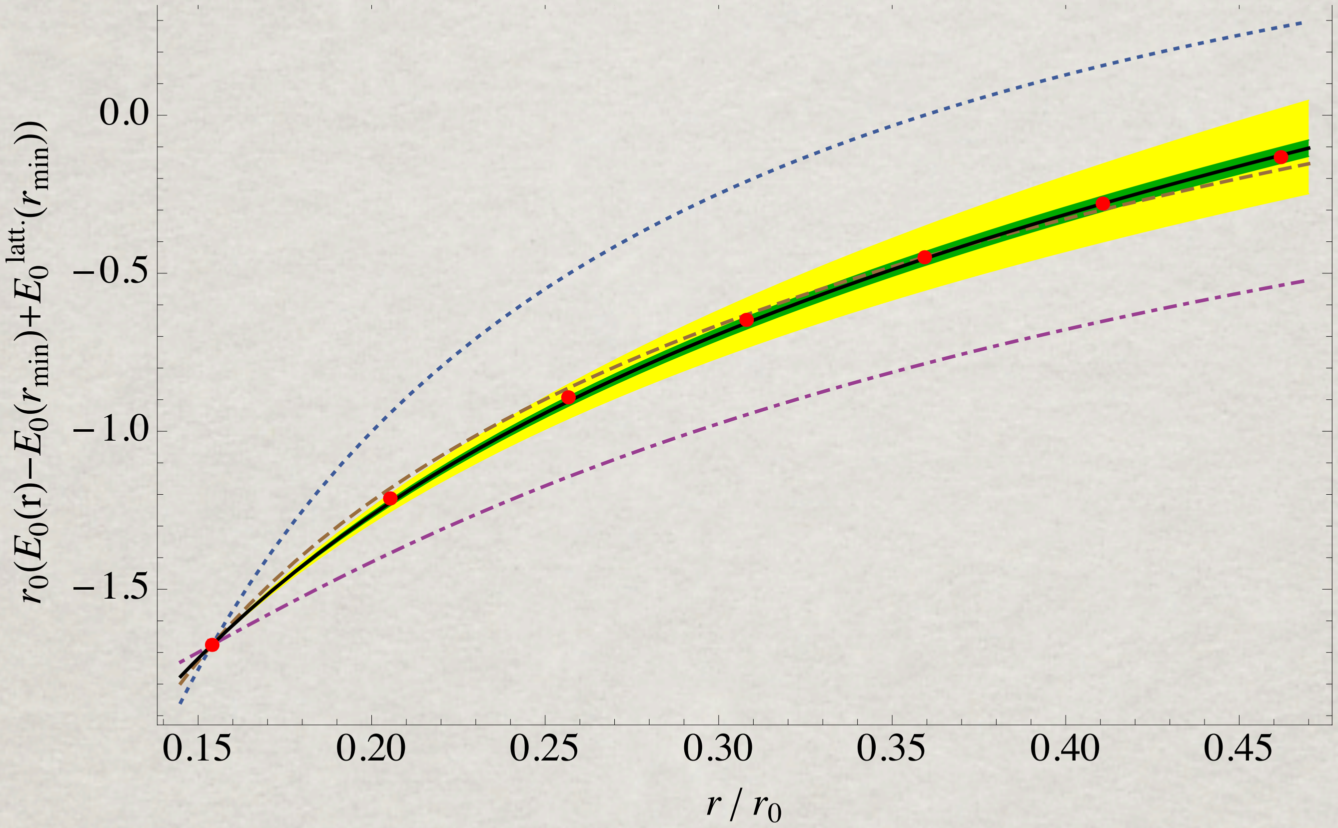

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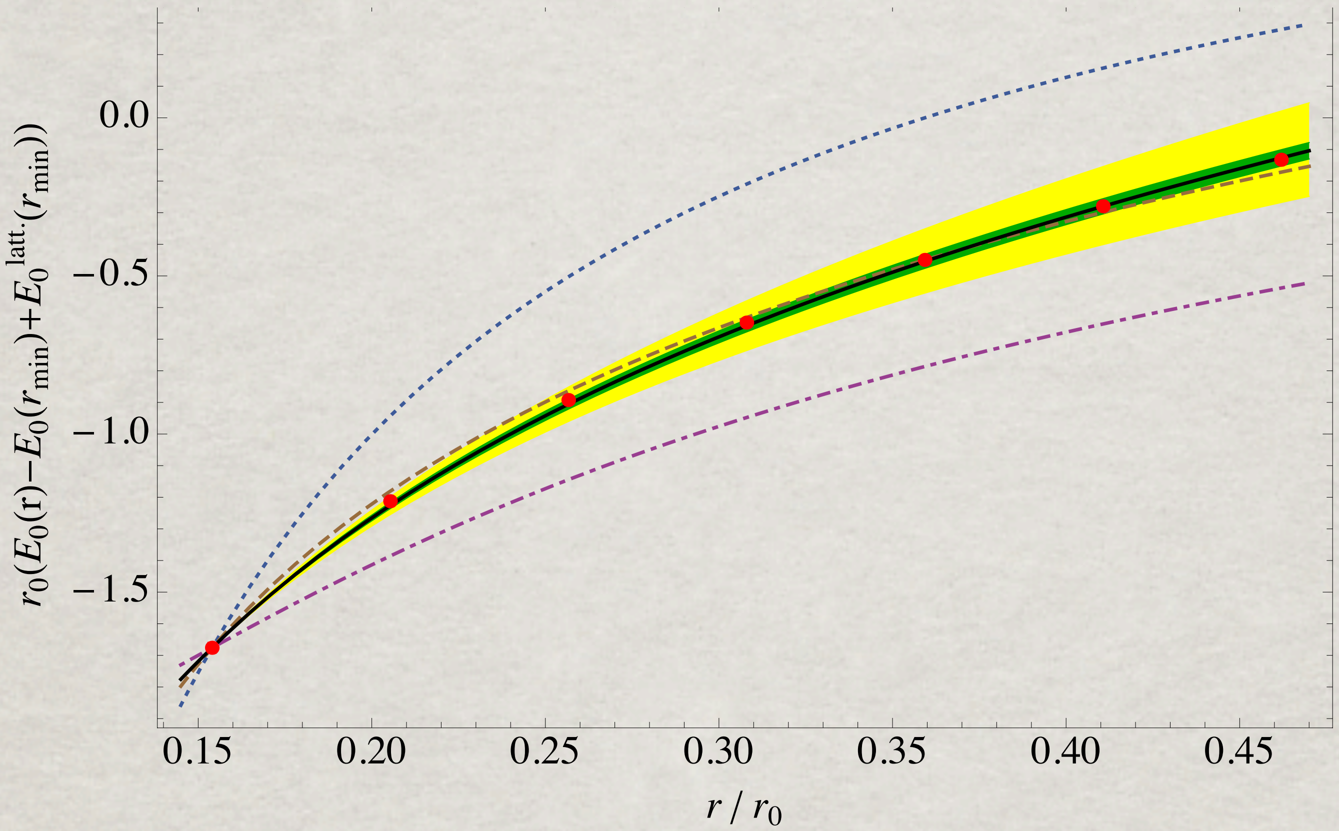

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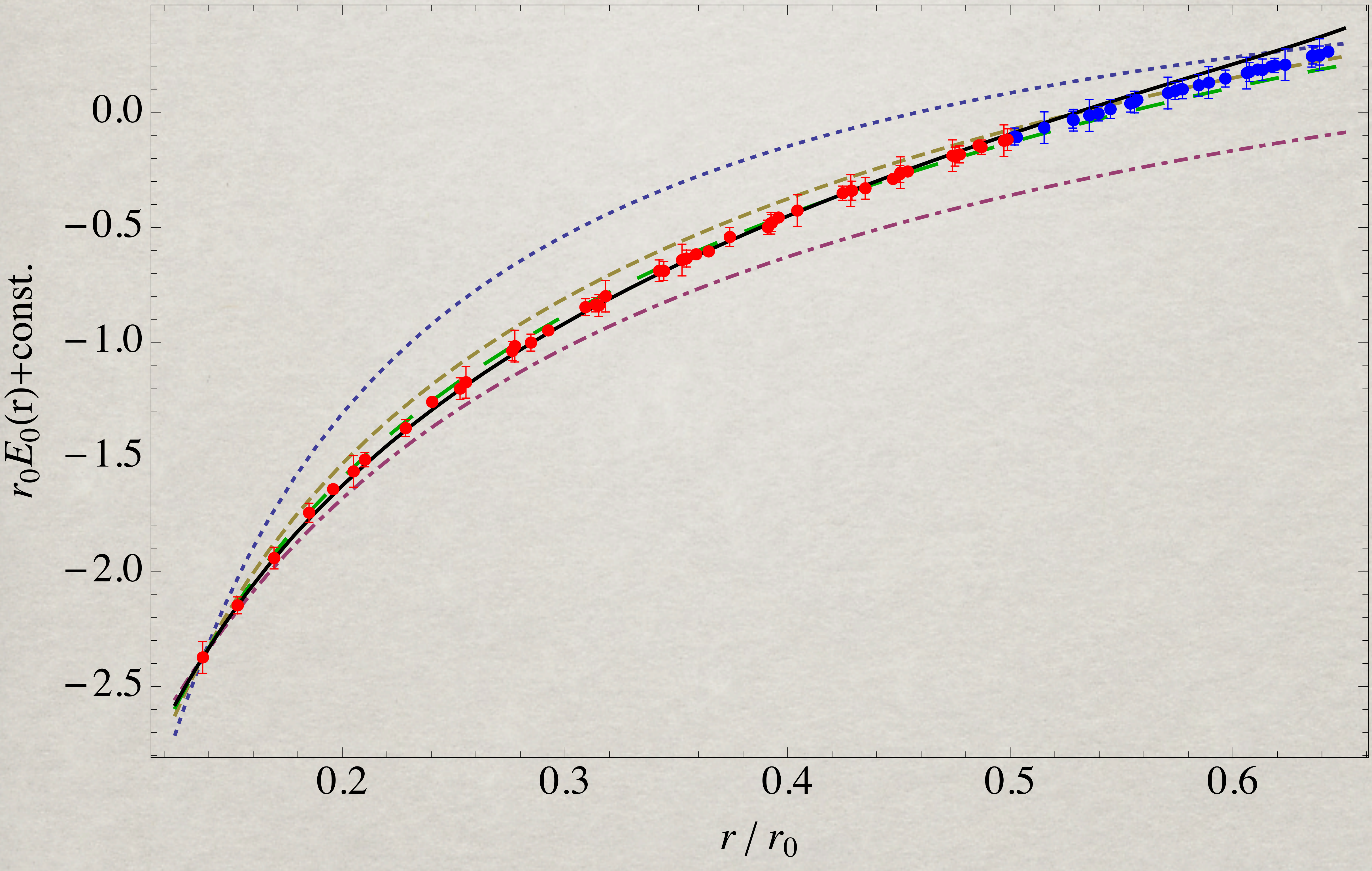
- Allows precise extraction of fundamental parameters of QCD

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

N. Brambilla, Garcia, Soto, Vairo 010)

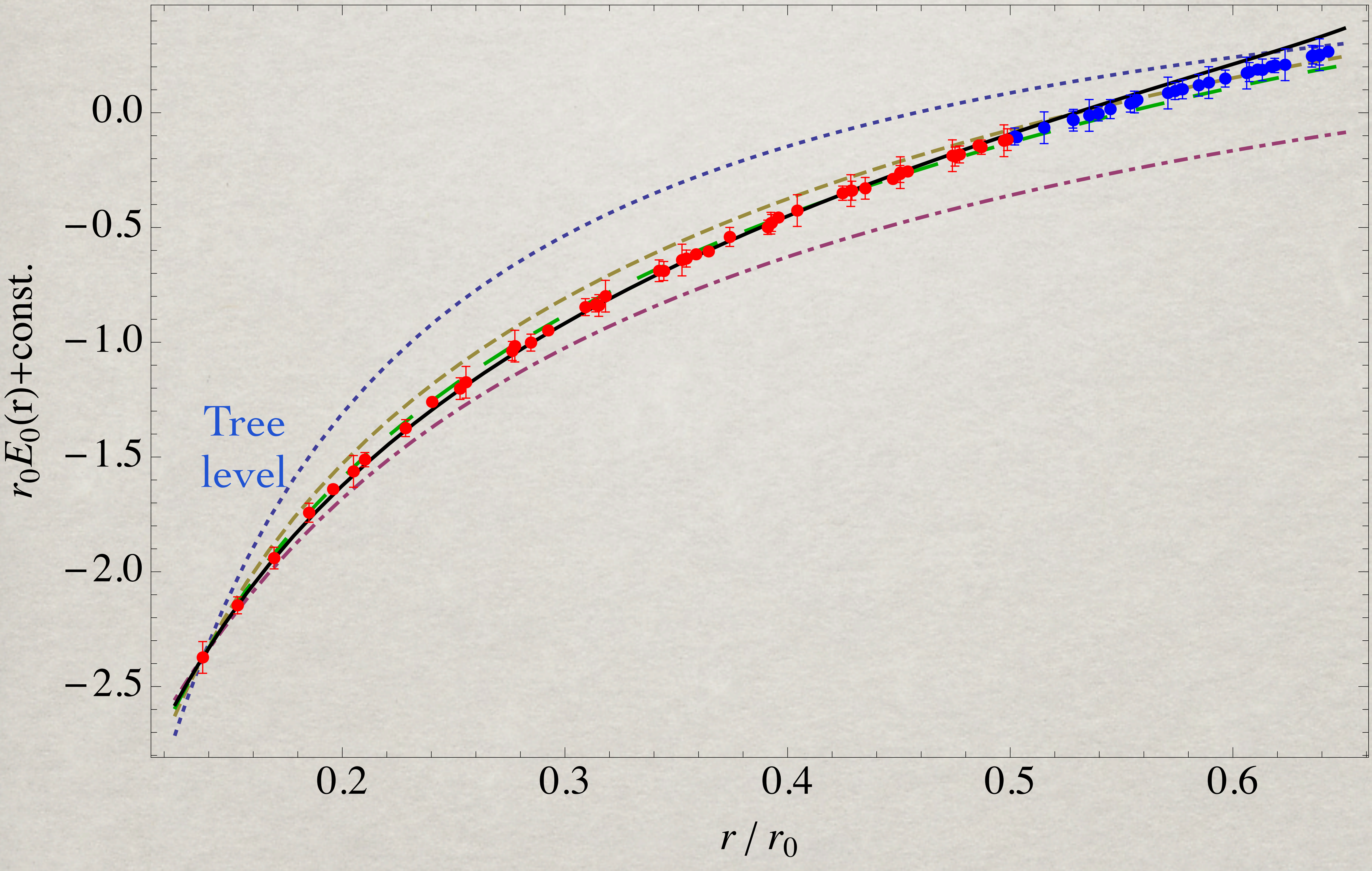
QQbar singlet static energy at N^3LL in comparison with unquenched (n_f=2+1) lattice data (red points,blue points)

Bazanov, N. B., Garcia, Petreczky, Soto, Vairo , 2012, 2014



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

Bazanov, N. B., Garcia, Petreczky, Soto, Vairo , 2012, 2014



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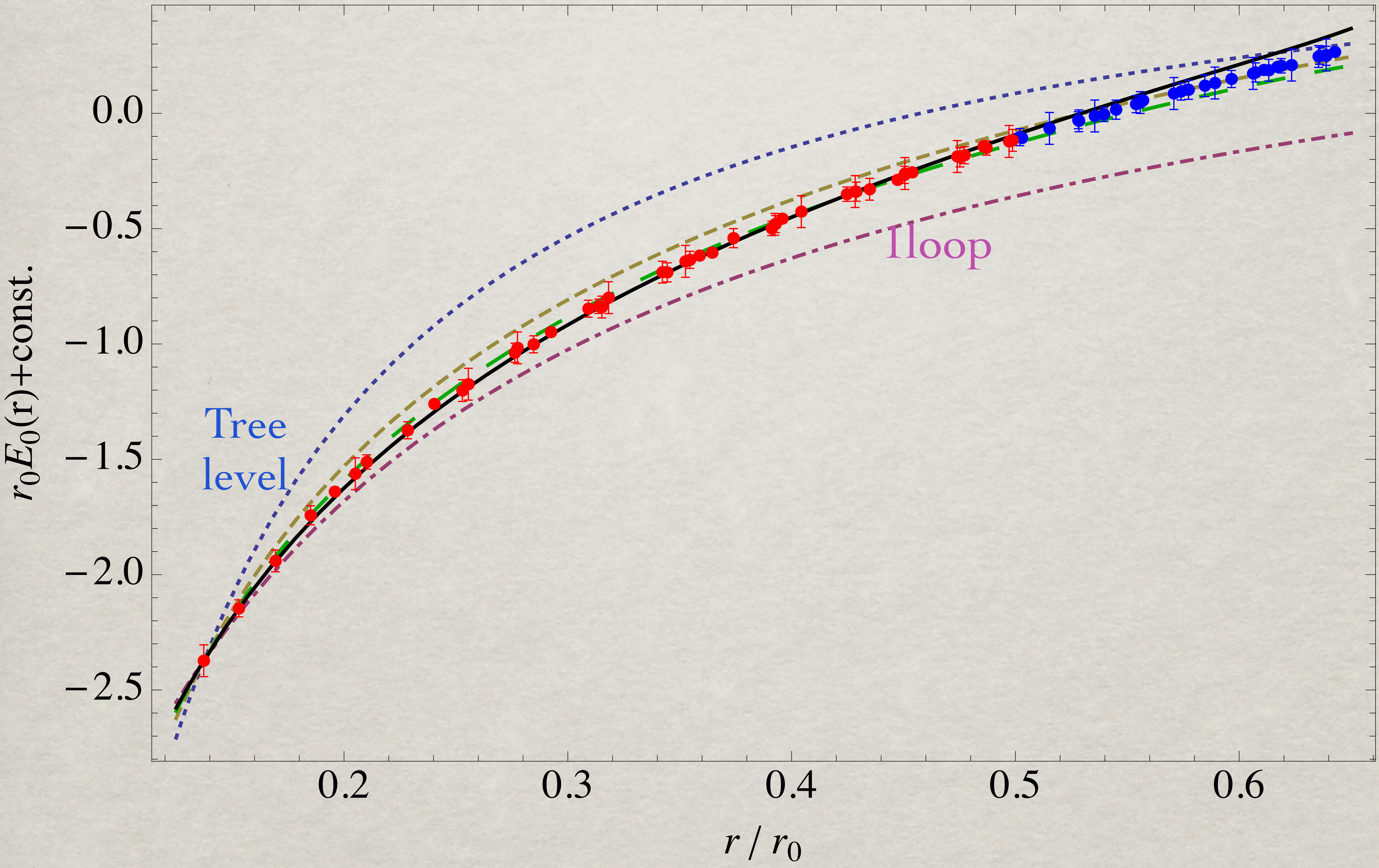
Bazanov, N. B., Garcia, Petreczky, Soto, Vairo , 2012, 2014



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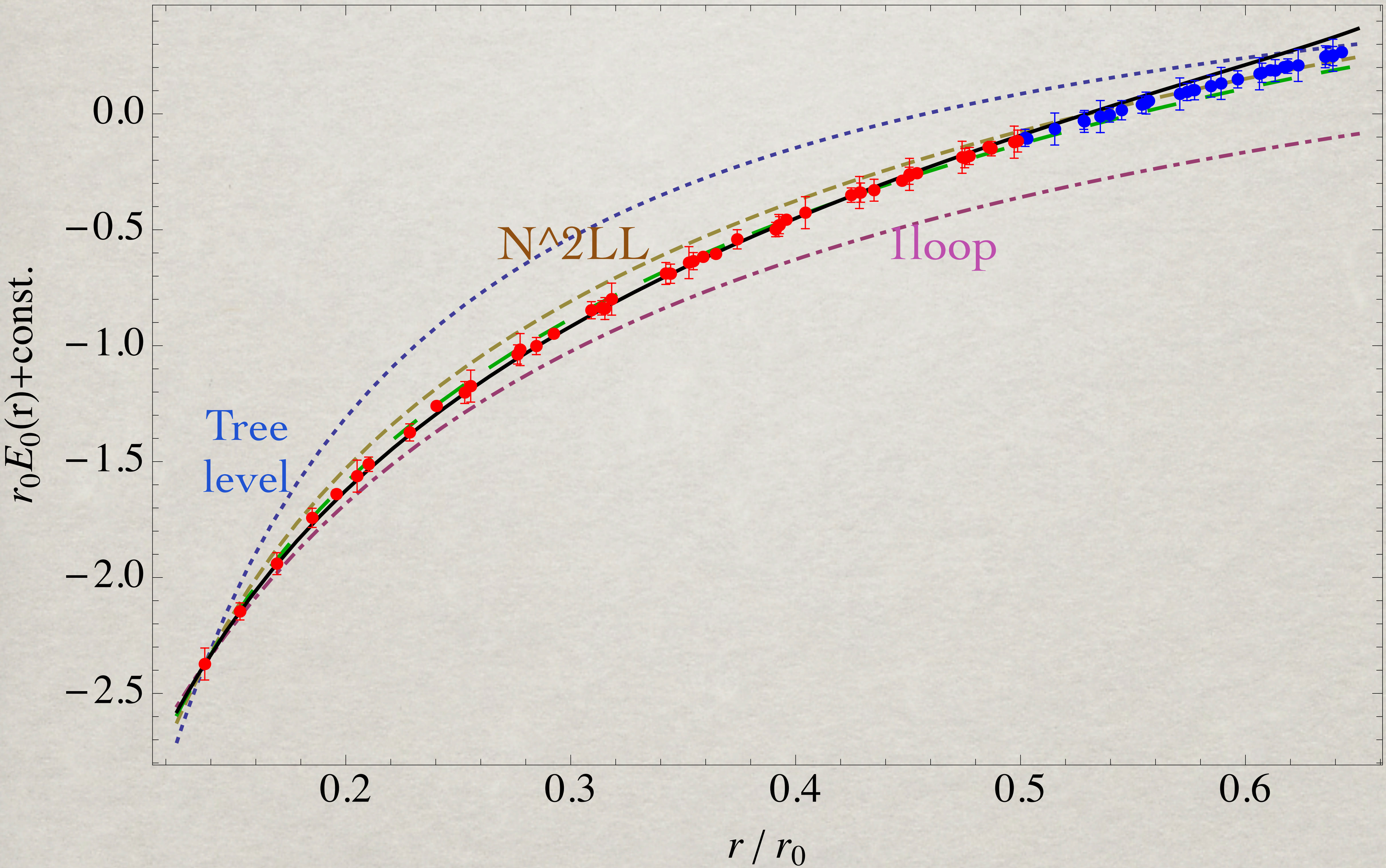

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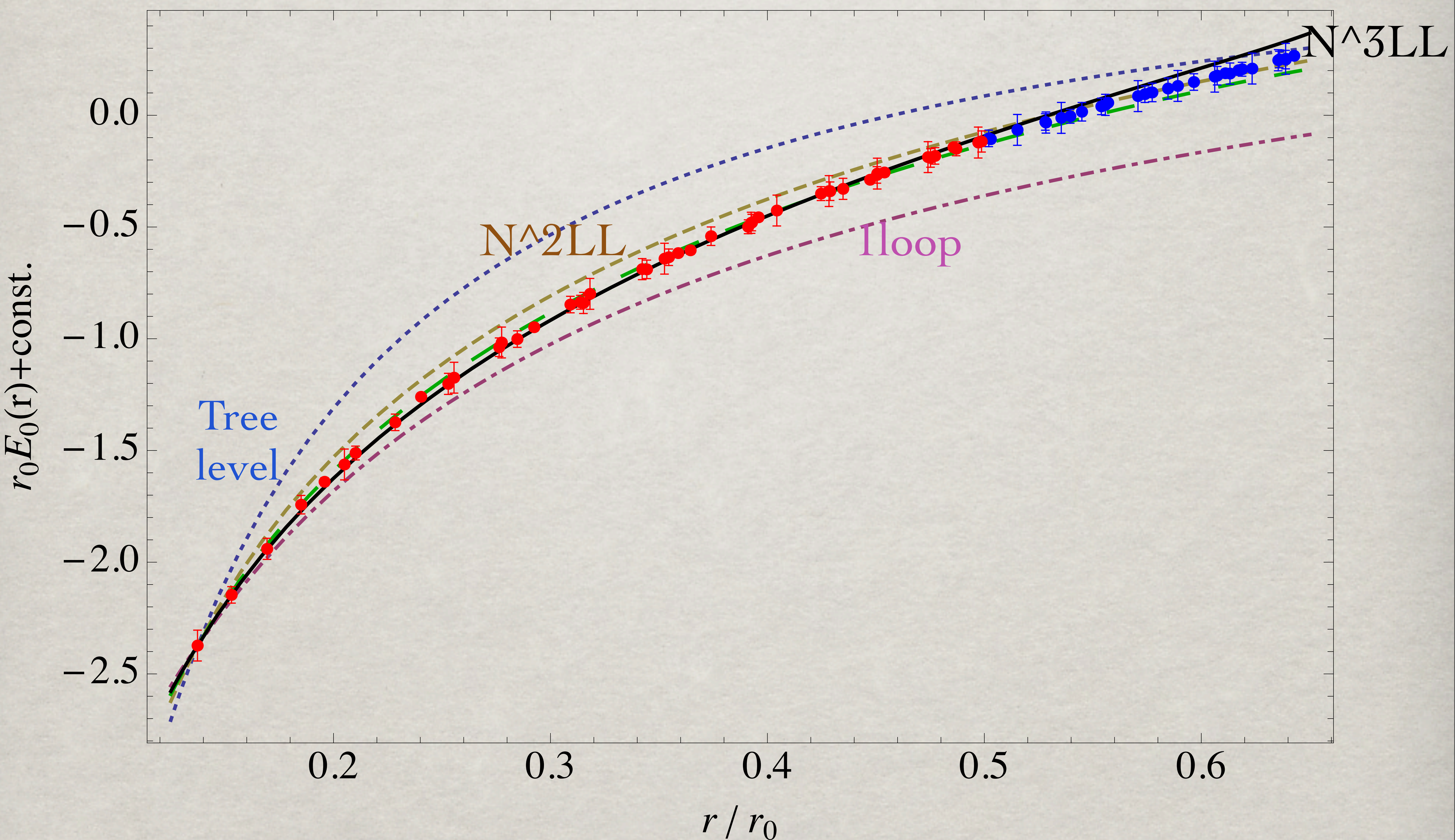

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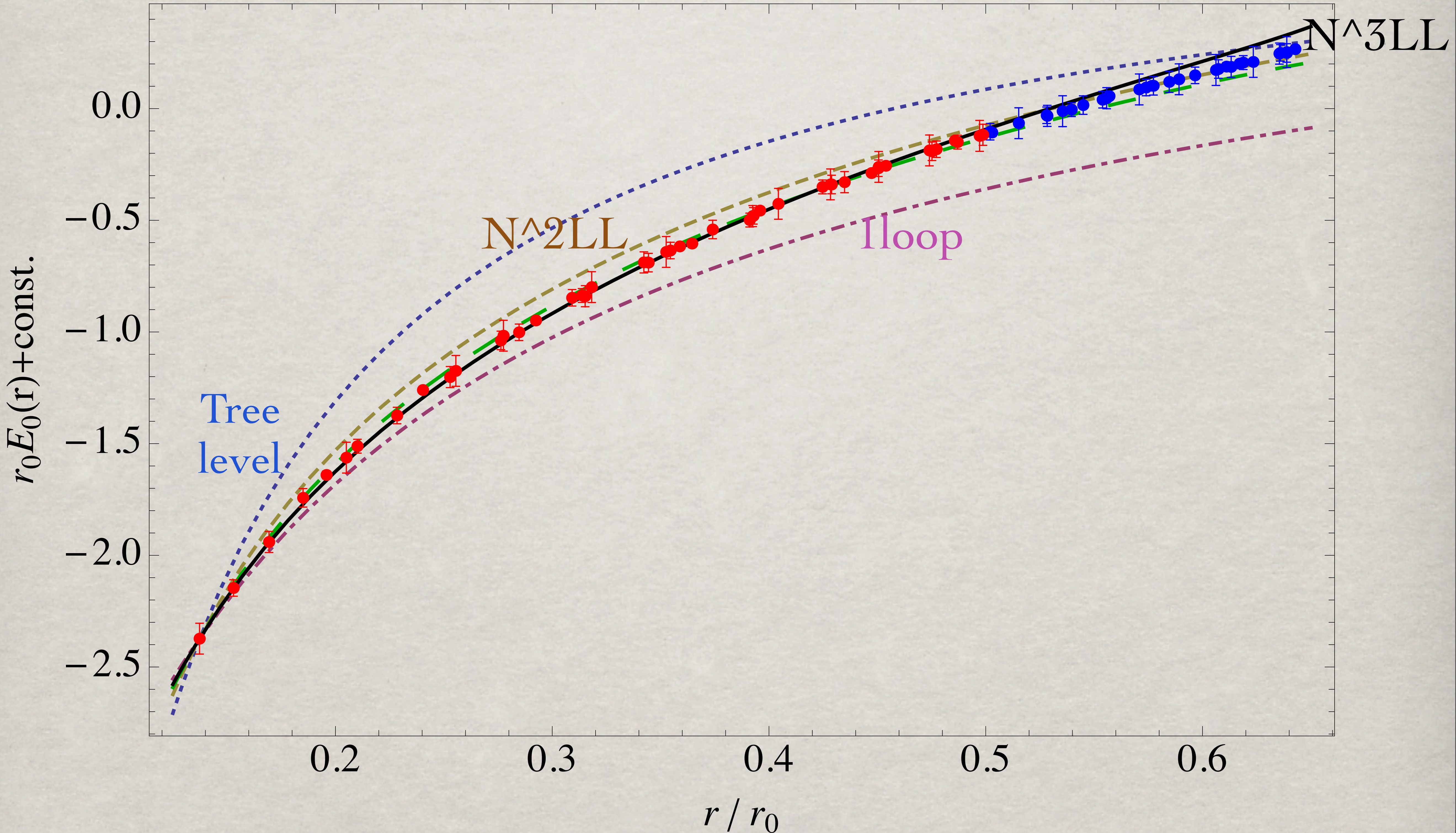

Good convergence to the lattice data

Lattice data less accurate in the unquenched case

α_s extraction

Bazanov, N. B., Garcia, Petreczky, Soto, Vairo , 2014

We obtain an extraction of alphas at N^3LO plus leading log resummation

$$\alpha_s(1.5\text{GeV}, n_f = 3) = 0.336^{+0.012}_{-0.008}$$

corresponding to

$$\alpha_s(M_z, n_f = 5) = 0.1166^{+0.0012}_{-0.0008}$$

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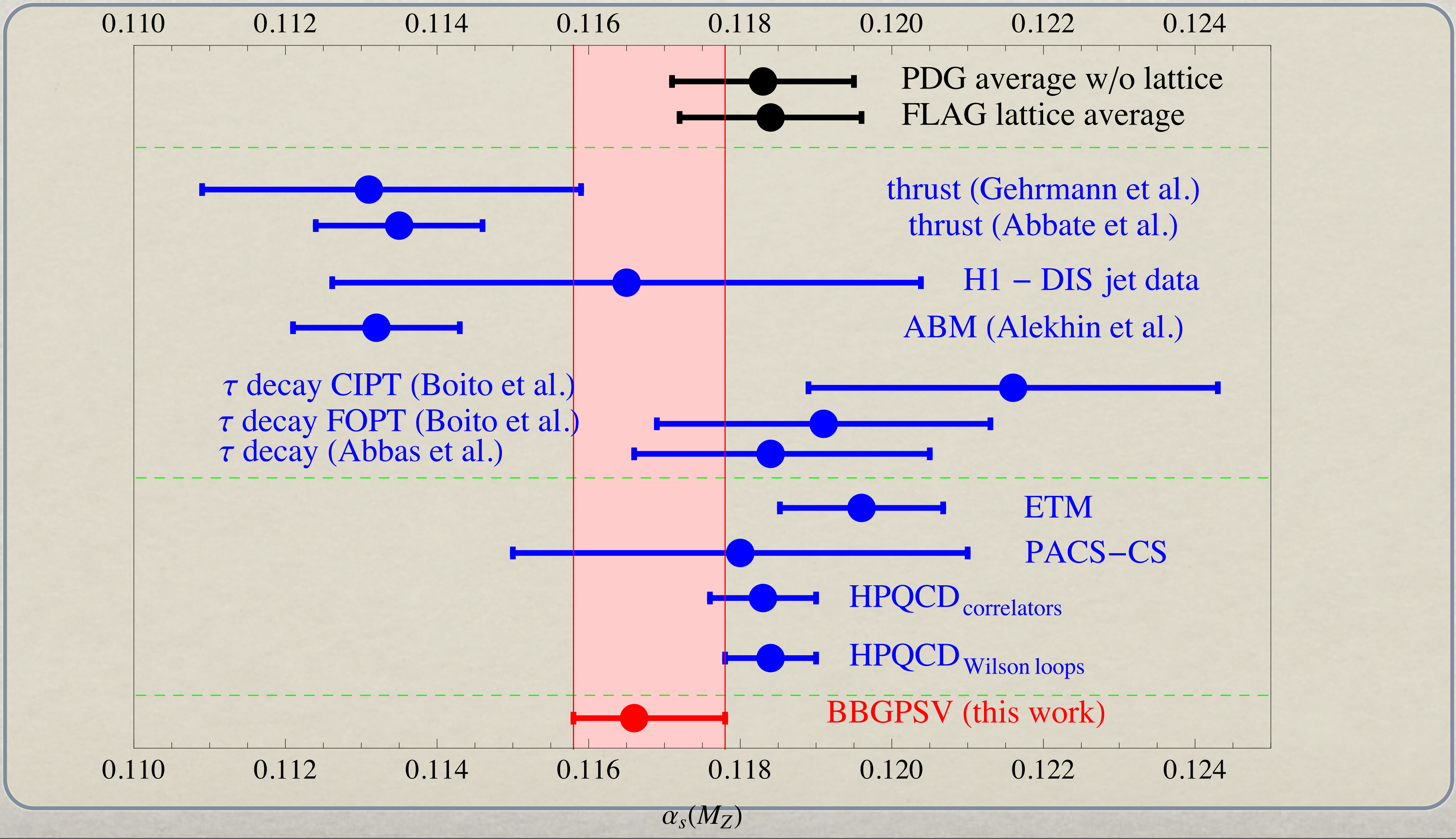

Low-lying quarkonia

Physical observables of the $\Upsilon(1S)$, η_b, B_c, J/ψ, η_c, ... may be understood in terms of PT.

E.g. the spectrum up to $\mathcal{O}(M\alpha_{\rm s}^5)$

$$E_n = \langle n|\frac{\mathbf{p}^2}{M} + V_s + ...|n\rangle - i\frac{g^2}{3N_c}\int_0^\infty dt\, \langle n|\mathbf{r}e^{it(E_n^{(0)}-H_o)}\mathbf{r}|n\rangle\ \langle \mathbf{E}(t)\,\mathbf{E}(0)\rangle$$

Non-perturbative corrections are small and encoded in (local or non-local) condensates.

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

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

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

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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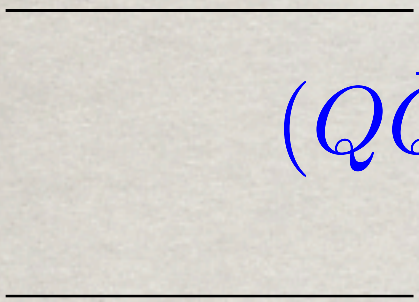
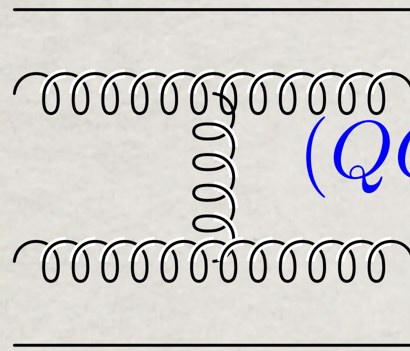
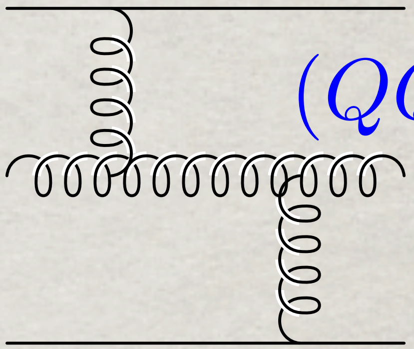


$(Q\bar{Q})_1$



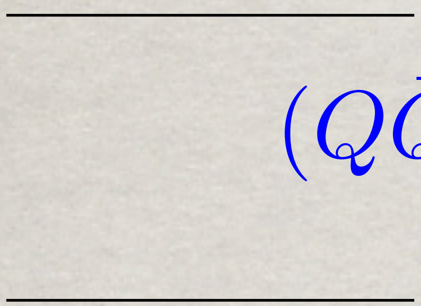
$(Q\bar{Q})_1$ + Glueball



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

hybrid

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



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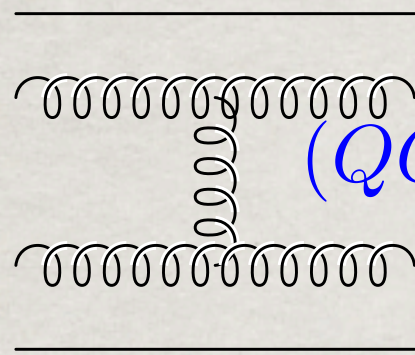
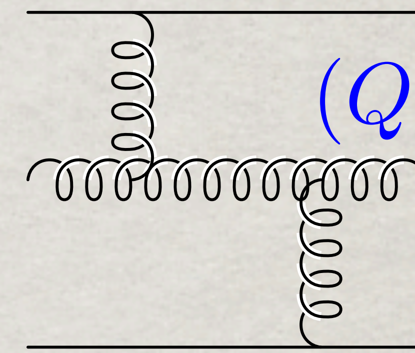


$(Q\bar{Q})_1 + \text{Glueball}$



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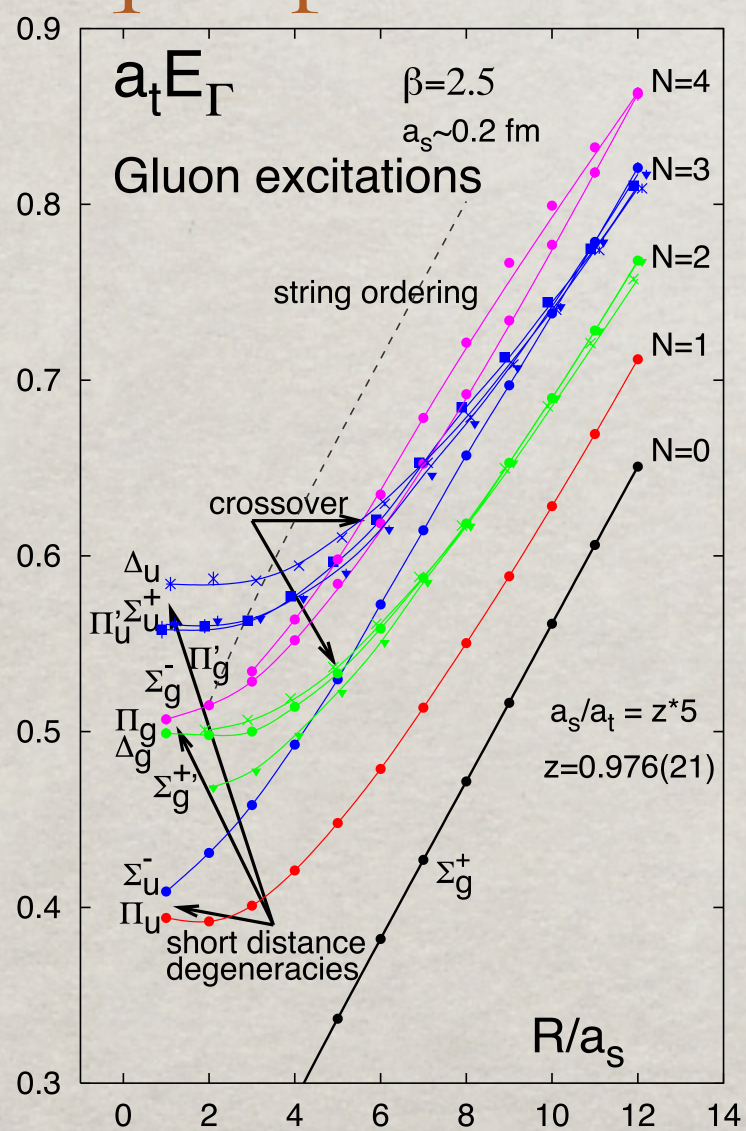
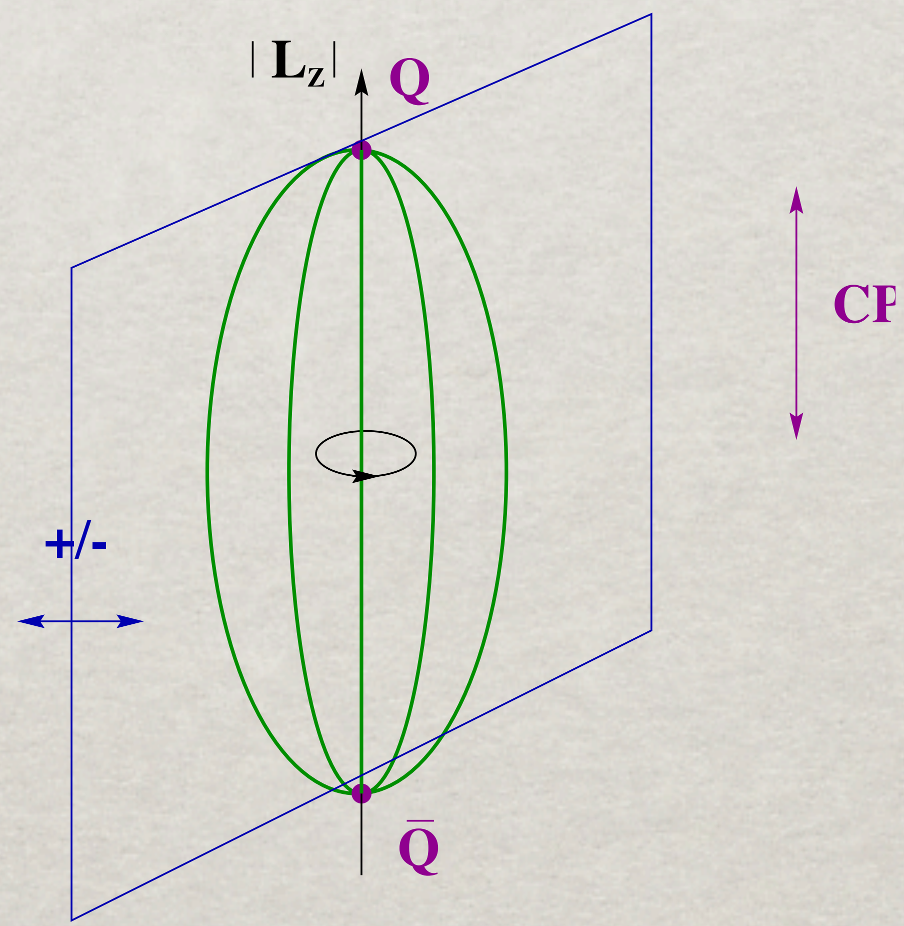
Static qcd spectrum

Lattice





Symmetries of a diatomic molecule + C.C.

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

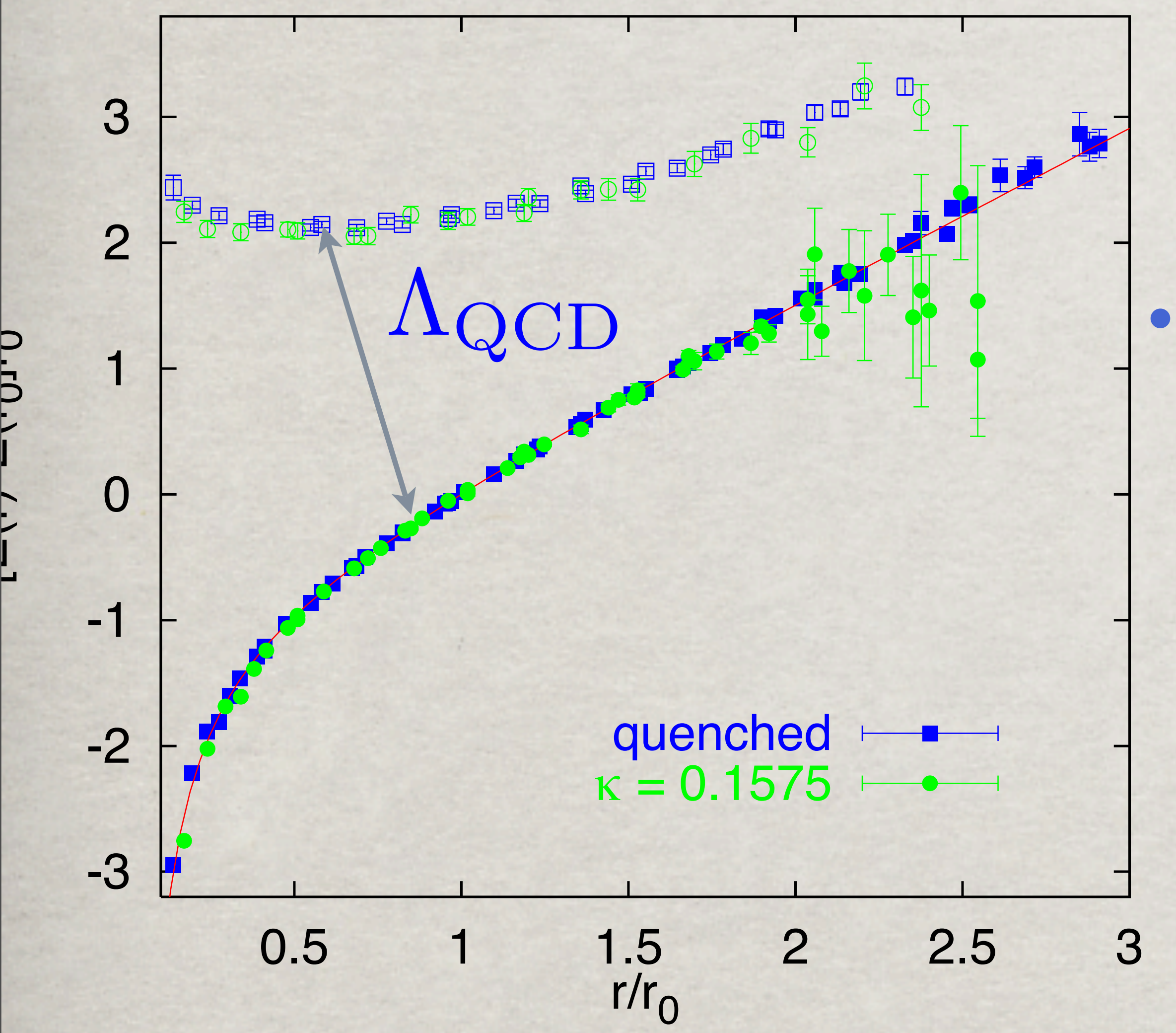
b) CP (u/g)

c) Reflection $(+/-)$
(for Σ only)

Juge Kuti Mornigstar 98-06 Static NRQCD

Quarkonium develops a gap to hybrids

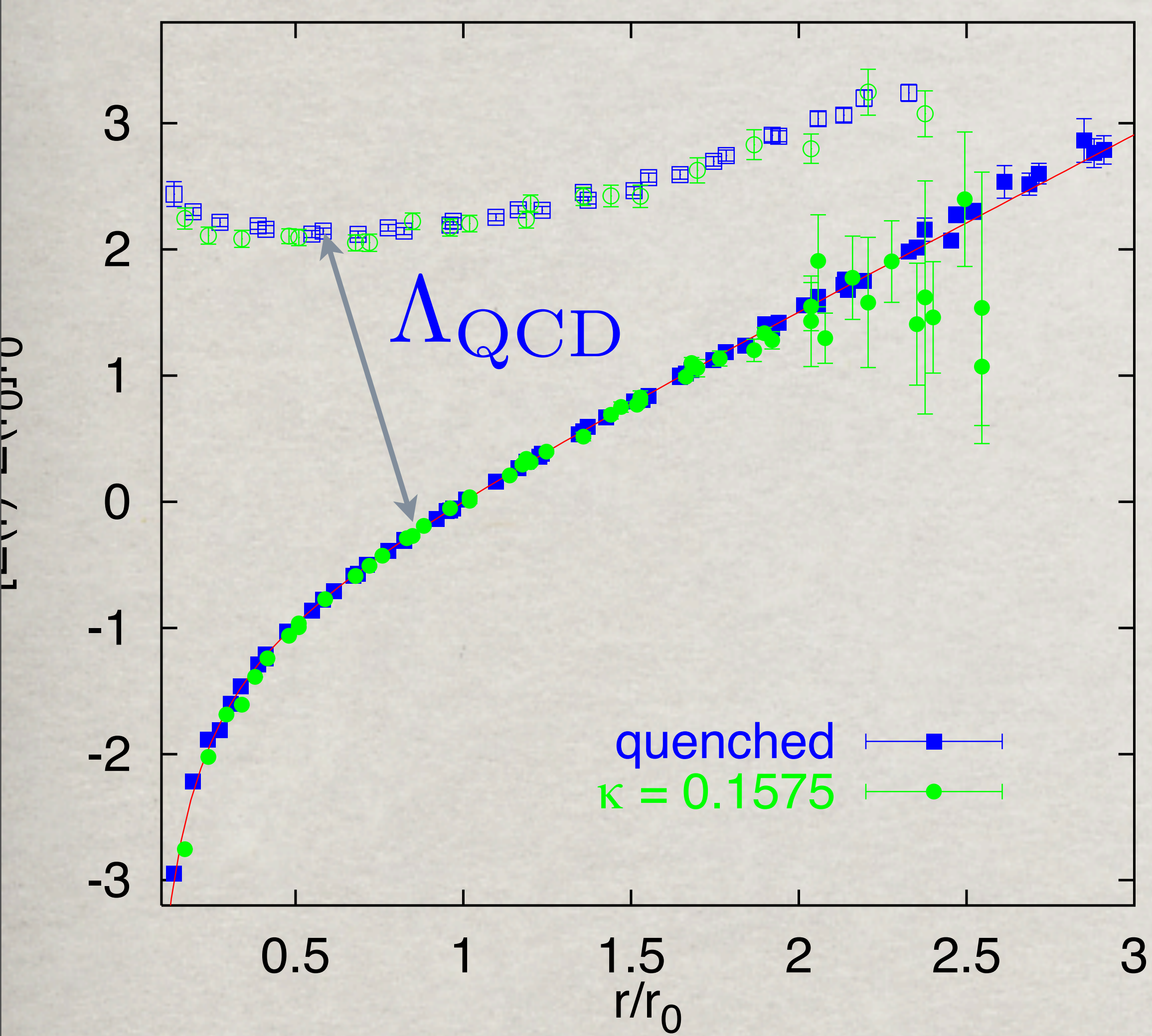
Bali et al. 98



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

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

⇒ 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).

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

Brambilla Pineda Soto Vairo 00

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Brambilla Pineda Soto Vairo 00

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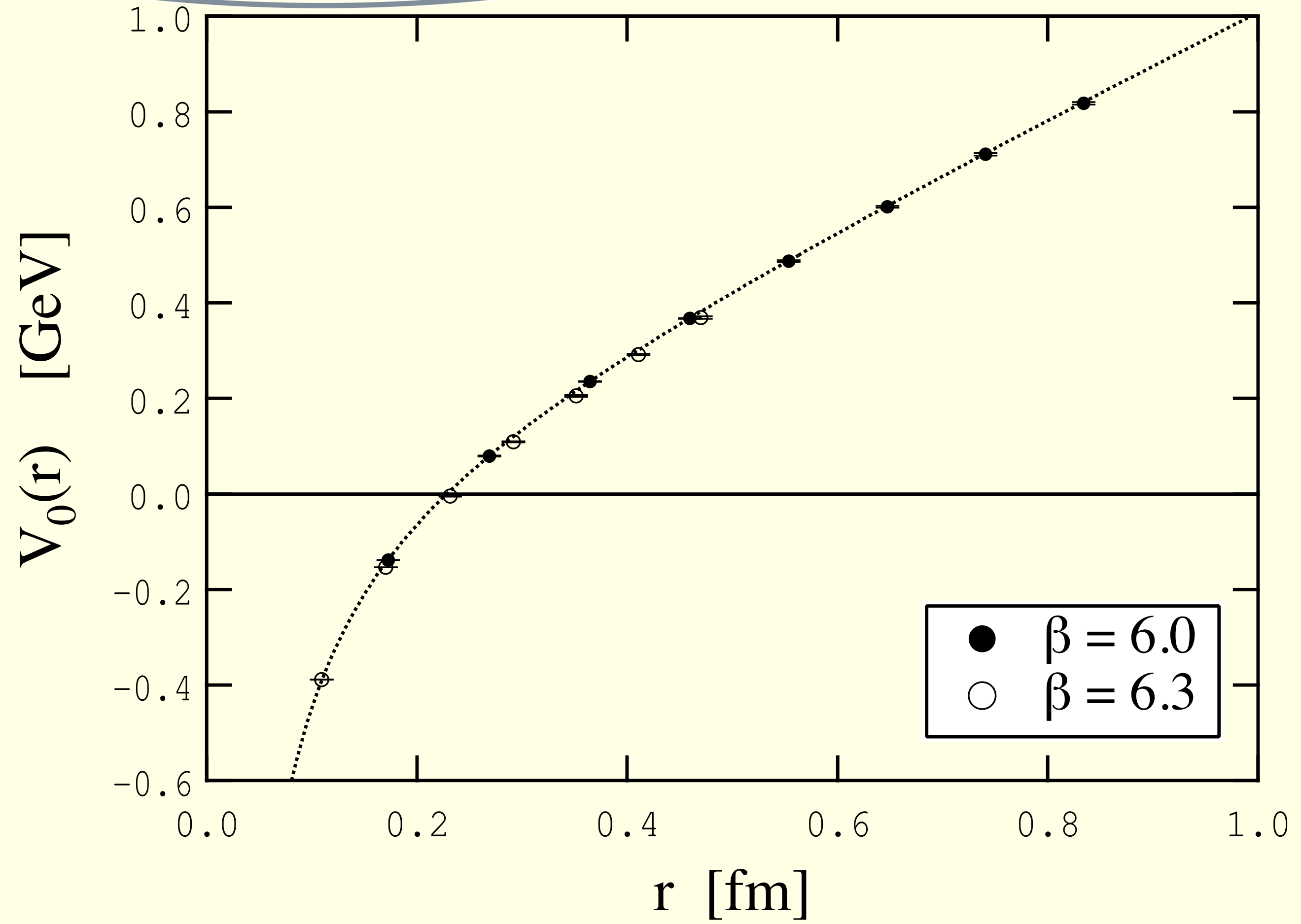
$$V_s^{(0)} = \lim_{T\to\infty}\frac{i}{T}\ln\langle W(r\times T)\rangle = \lim_{T\to\infty}\frac{i}{T}\ln\langle \square \rangle$$

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



○ 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

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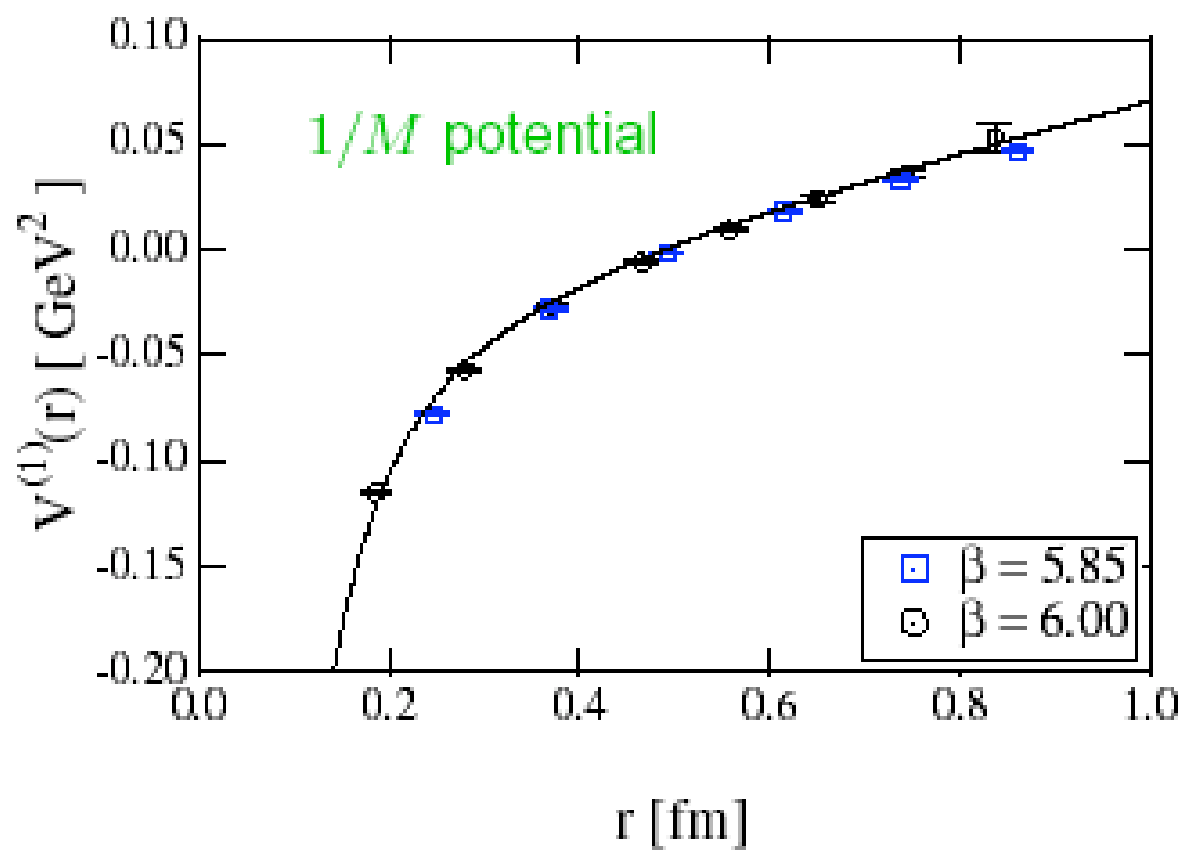
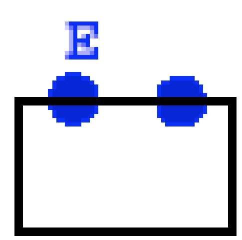
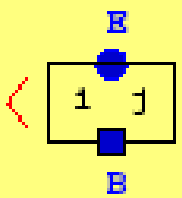


○ Koma Koma Wittig PoS LAT2007(07)111

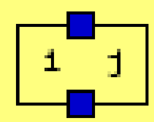
$$\frac{V_s^{(1)}}{m} = -\frac{1}{2m}\int_0^\infty dt\, t\, \langle$$  $$\rangle$$

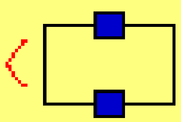
Brambilla et al 00

QCD Spin dependent potentials

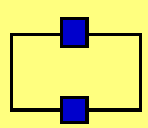
$V_{\mathrm{SD}}^{(2)} = \frac{1}{r}\Big(c_F \epsilon^{kij} \frac{2r^k}{r} i \int_0^\infty dt\, t \,\langle$ 

$\rangle - \frac{1}{2} V_s^{(0)\prime} \Big) (\mathbf{S}_1 + \mathbf{S}_2) \cdot \mathbf{L}$

$- {c_F}^2 \hat{r}_i \hat{r}_j i \int_0^\infty dt \Big(\langle$ 

$\rangle - \frac{\delta_{ij}}{3} \langle$  $\rangle \Big)$

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

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

Eichten Feinberg 81, Gromes 84, Chen et al. 95 Brambilla Vairo 99 Pineda, Vairo 00

QCD Spin dependent potentials

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

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

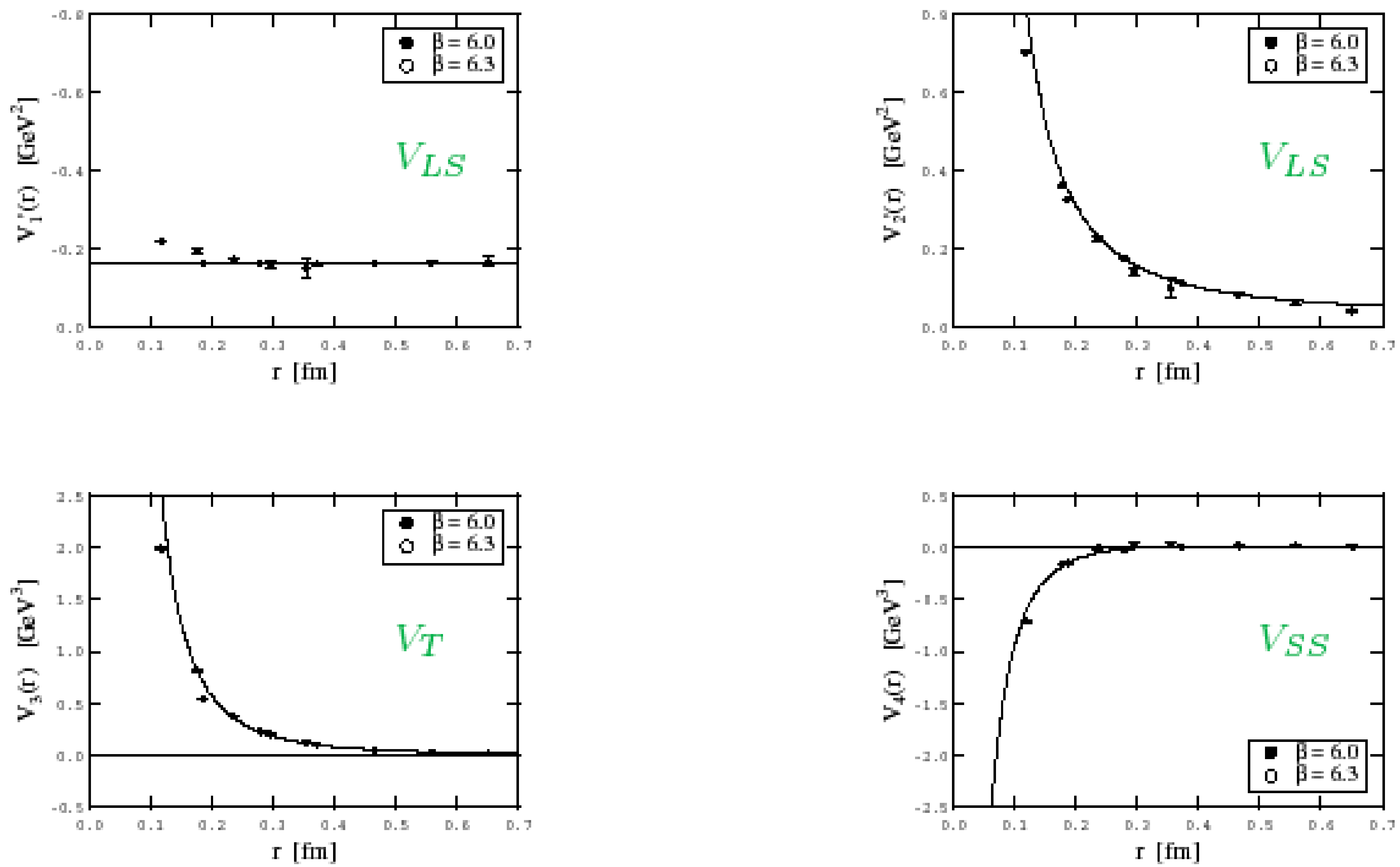
$$\times \left(\mathbf{S}_1 \cdot \mathbf{S}_2 - 3(\mathbf{S}_1 \cdot \hat{\mathbf{r}})(\mathbf{S}_2 \cdot \hat{\mathbf{r}}) \right)$$

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

Eichten Feinberg 81, Gromes 84, Chen et al. 95 Brambilla Vairo 99 Pineda, Vairo 00

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

Spin dependent potentials

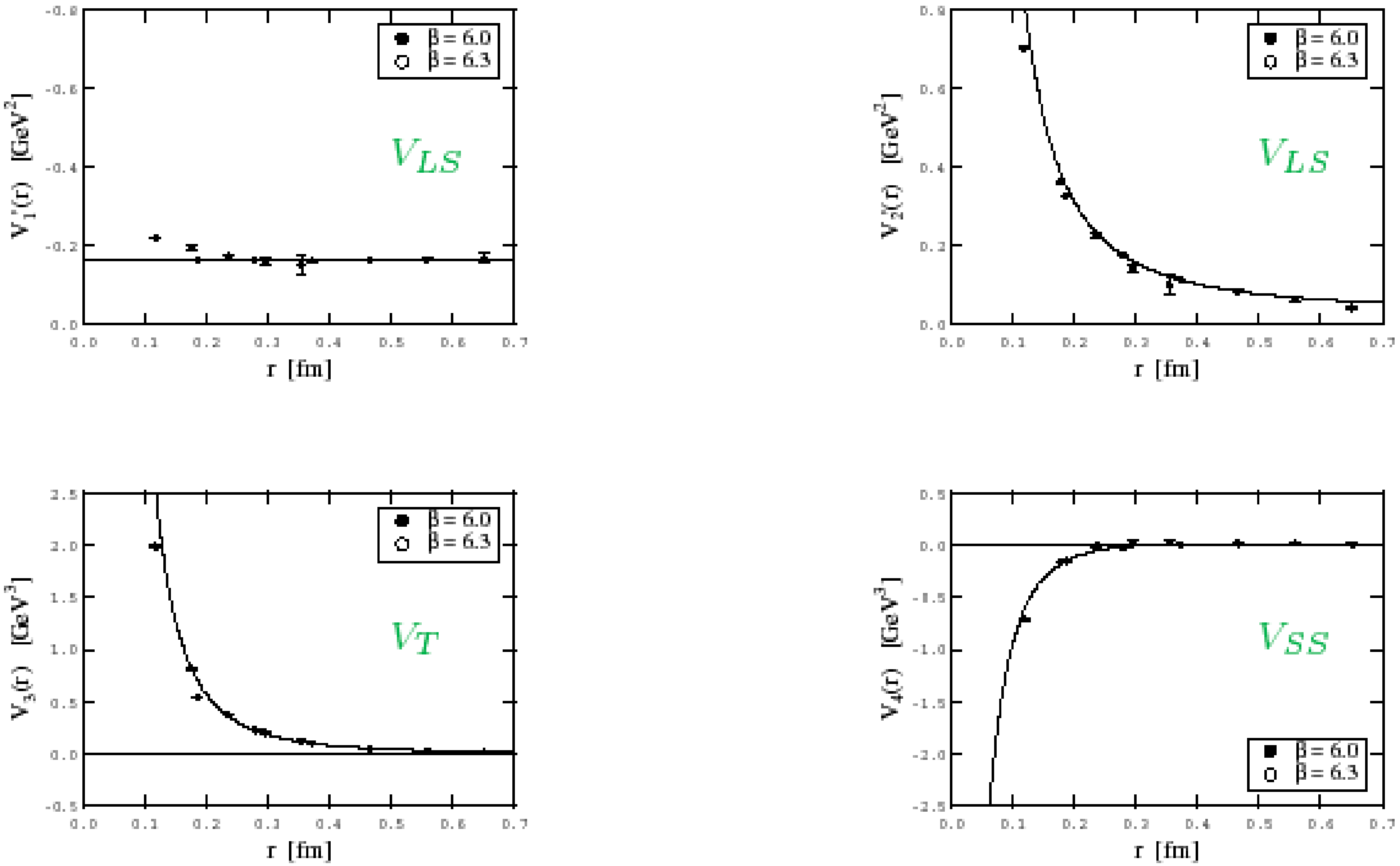


Koma Koma Wittig 05, Koma Koma 06

Terrific advance in the data precision with Lüscher multivel algorithm!

N. B., Martinez, Vairo 2014

Spin dependent potentials



Koma Koma Wittig 05, Koma Koma 06

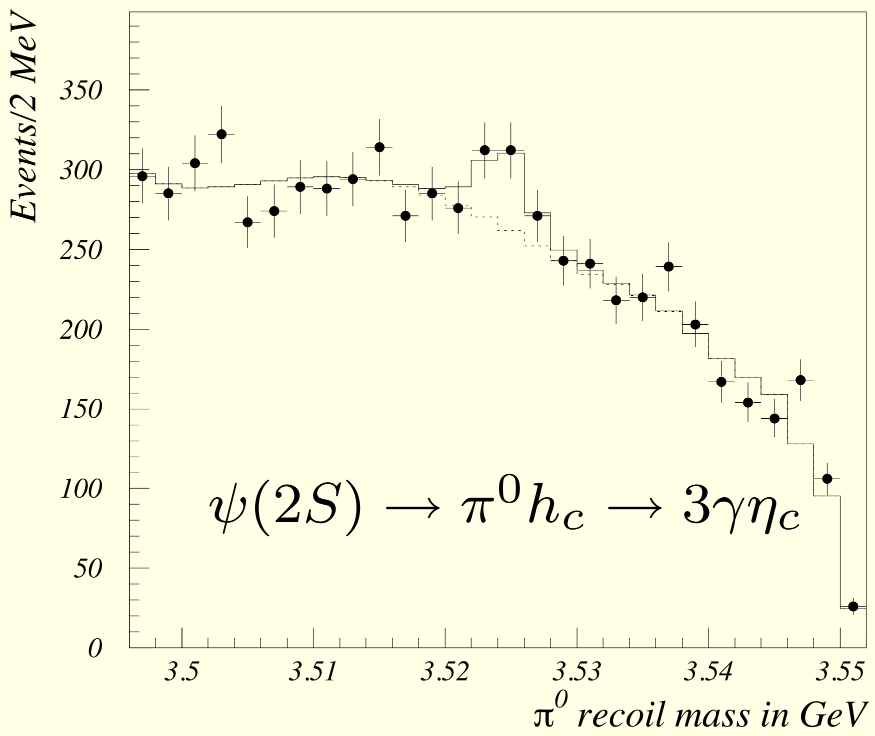
Terrific advance in the data precision with Lüscher multivel algorithm!

Such data can distinguish different models for the dynamics of low energy QCD e.g. effective string model

N. B., Martinez, Vairo 2014

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 $M_{\mathrm{c.o.g.}}(1P) = 3525.36 \pm 0.2 \pm 0.2$ MeV.

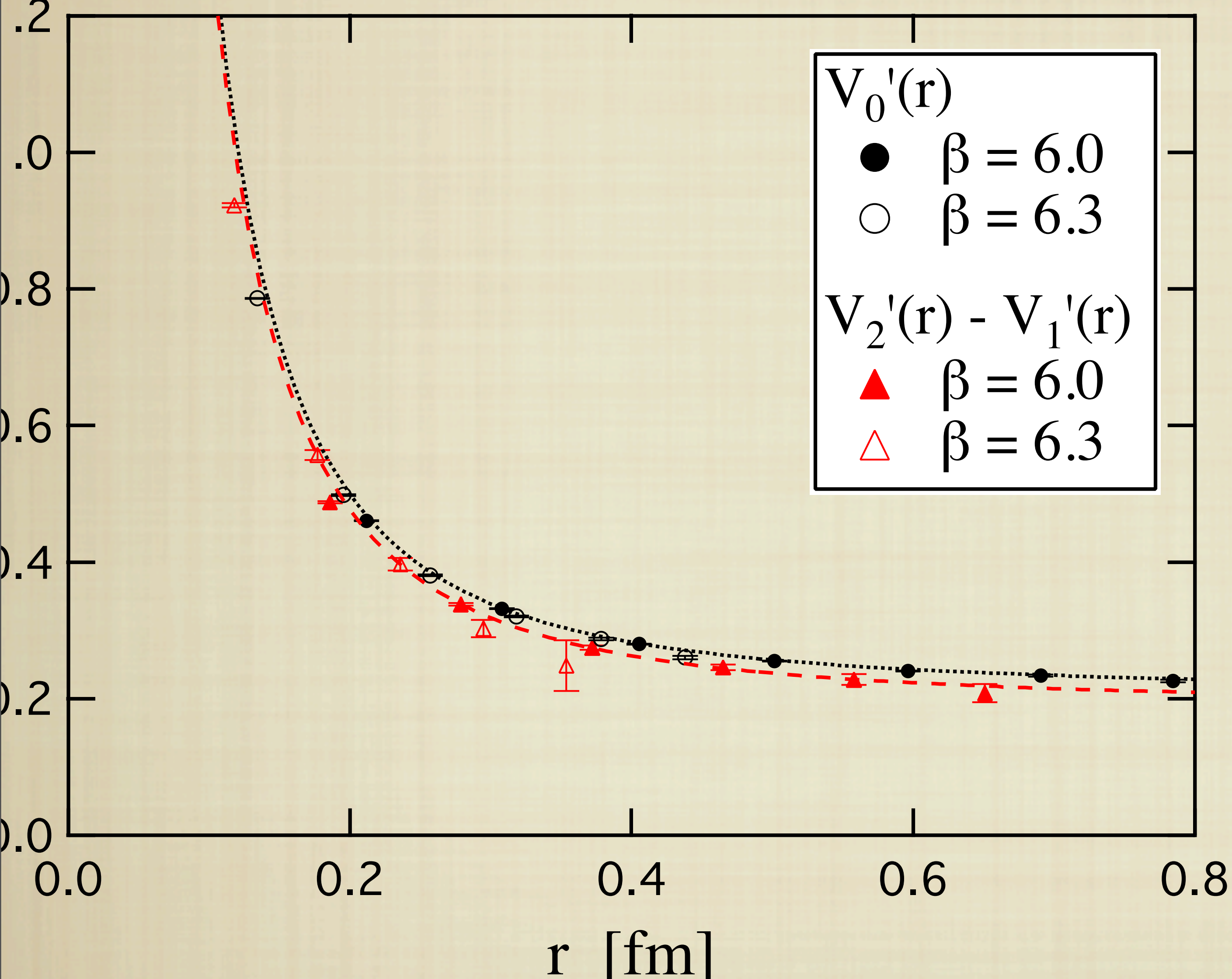
- Also

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

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

Exact relations from Poincare' invariance

The EFT is still Poincare' invariant-> this induces relations among the potentials (this corresponds to reparameterization invariance--> one can reformulate it with Poincare' algebra)



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

It can be used a check of the lattice calculation

many other relations among potentials in the EFT N. B, D. Gromes, A. Vairo

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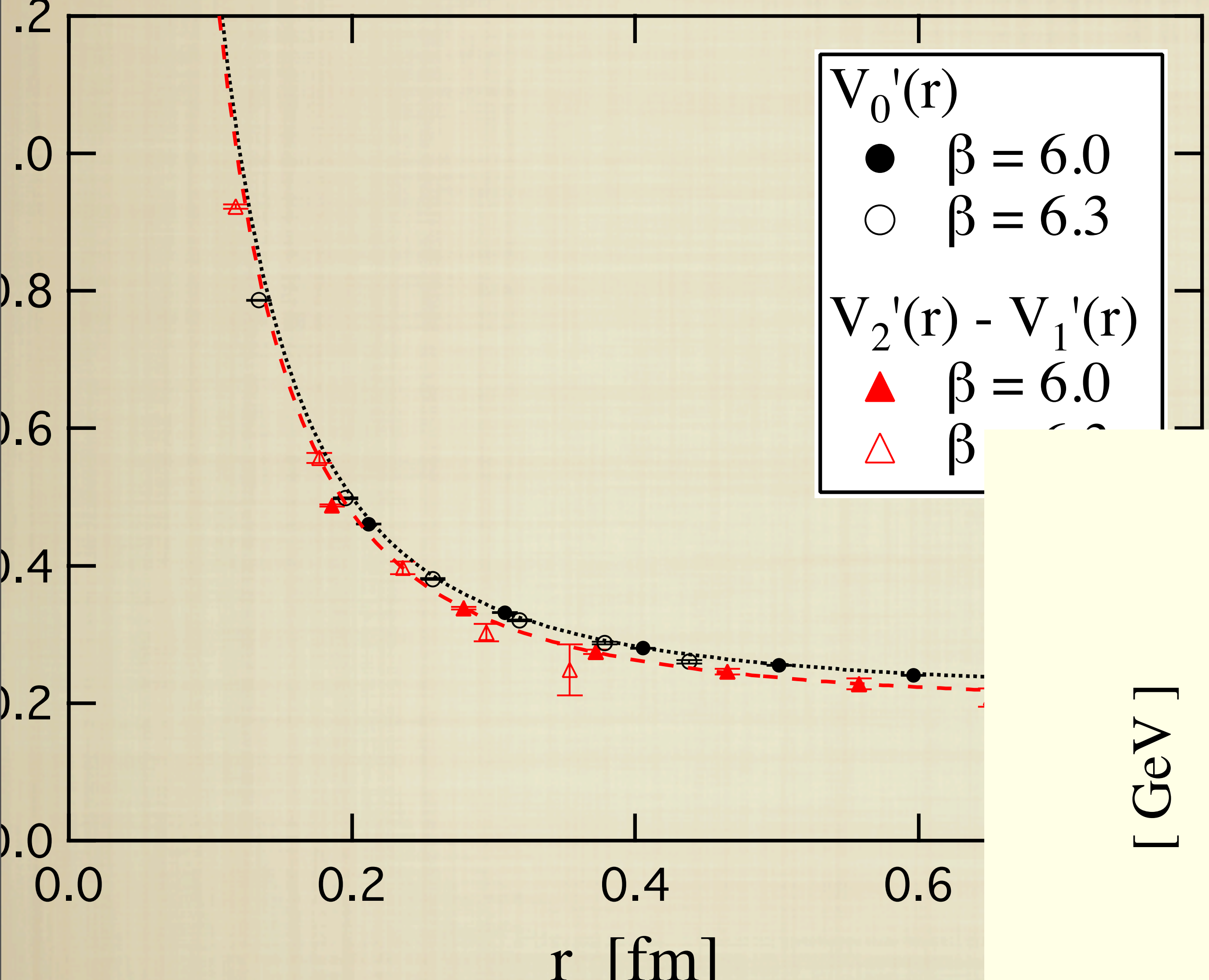

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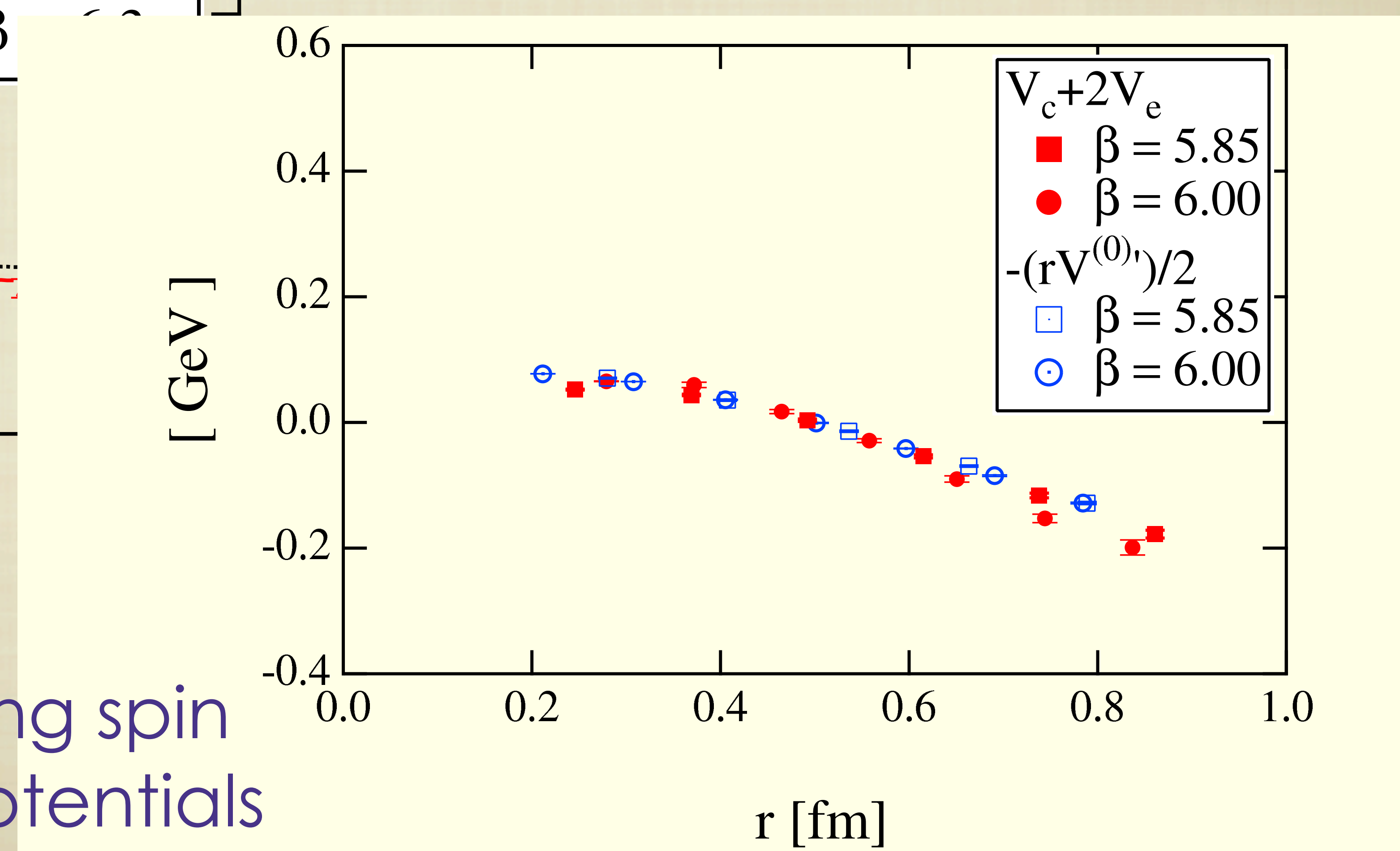
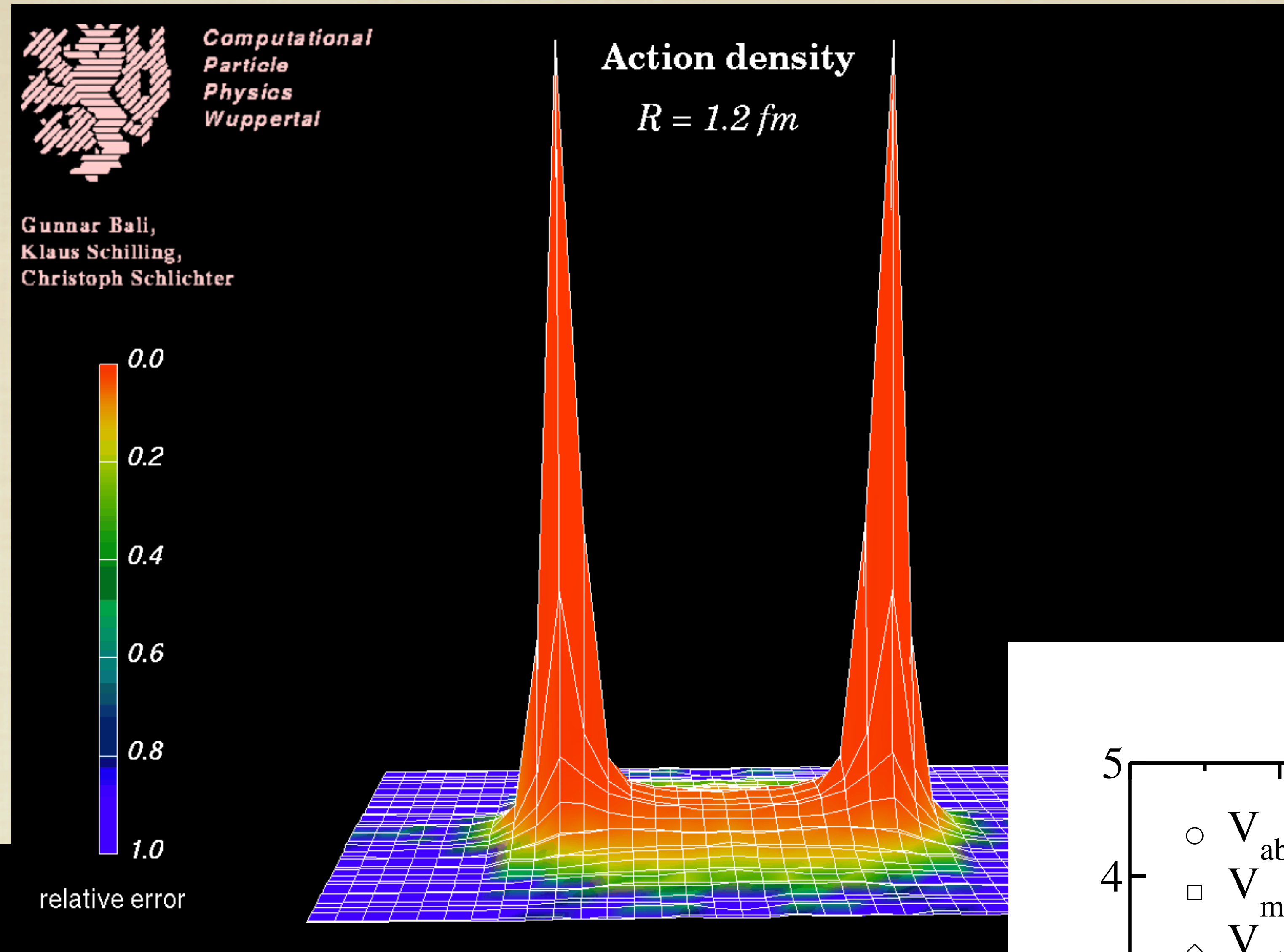


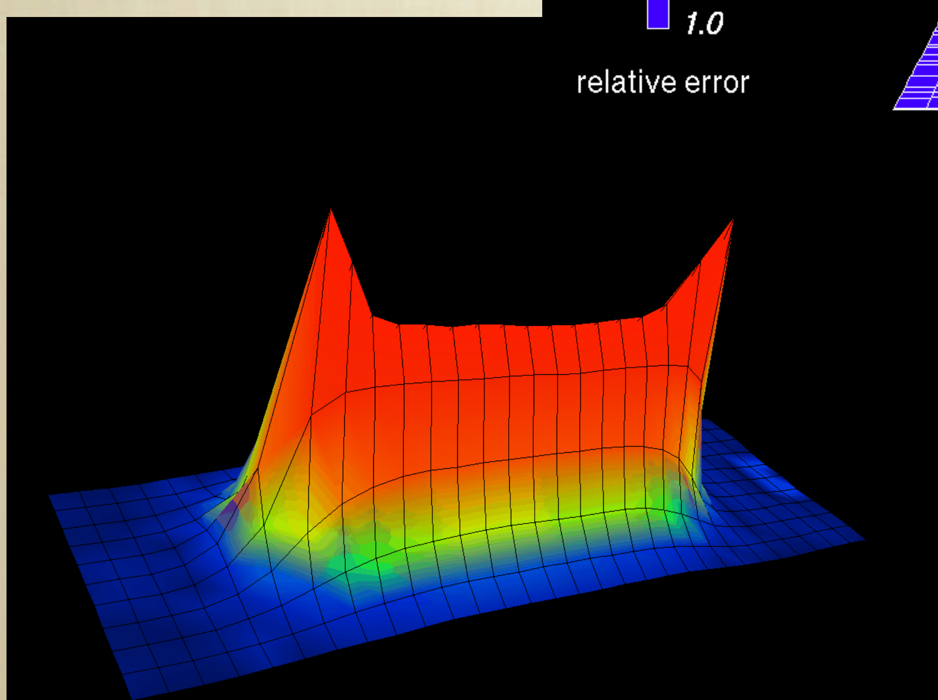
Koma Koma Wittig PoS LAT2007 (2007) 111

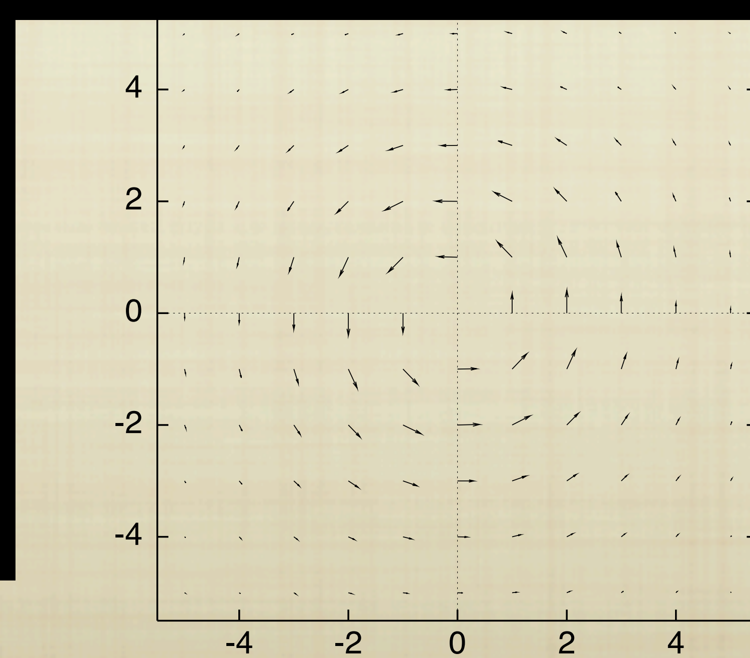
relations involving spin independent potentials

Low energy physics factorized in Wilson loops: can be used to probe the confinement mechanism

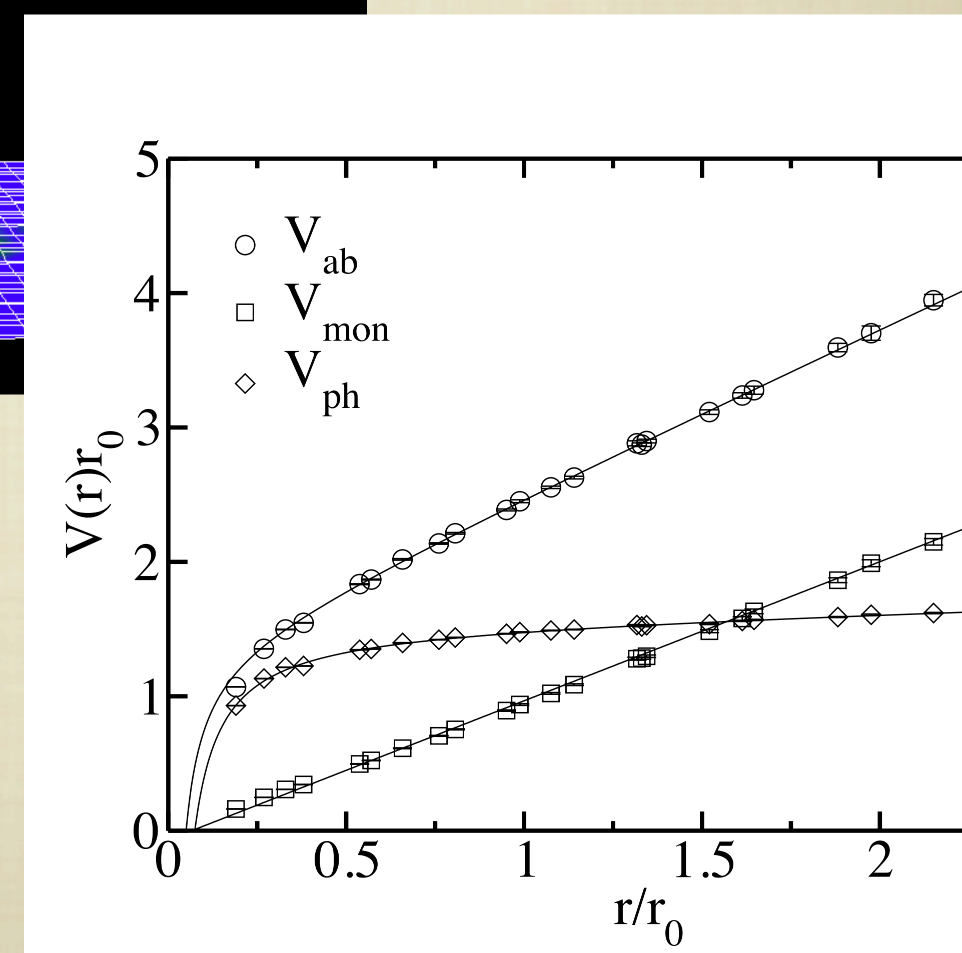
Bali et al







Boryakov et al. 04

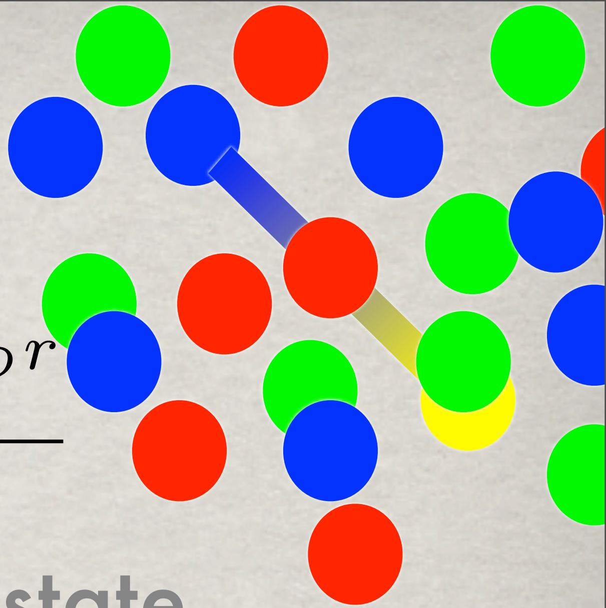


Heating quarkonium systems

$$T > 0$$

Quarkonium in a hot medium

Matsui Satz 86



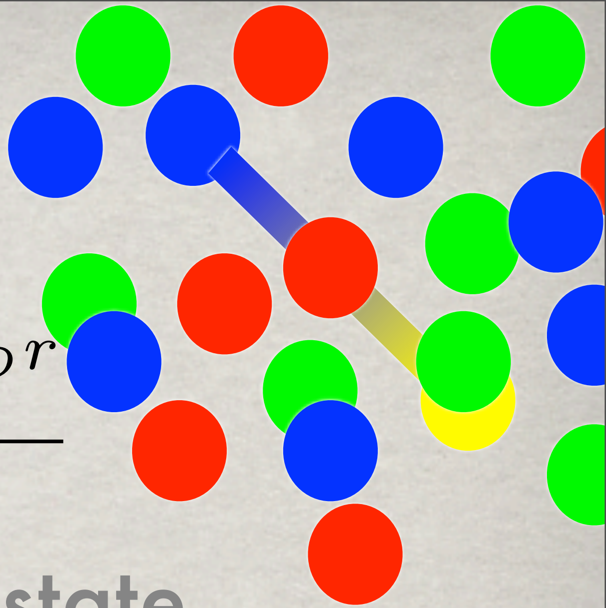
color screening of the potential originates quarkonium dissociation

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

Debye charge screening
(electromagnetic plasma)

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

Quarkonium in a hot medium



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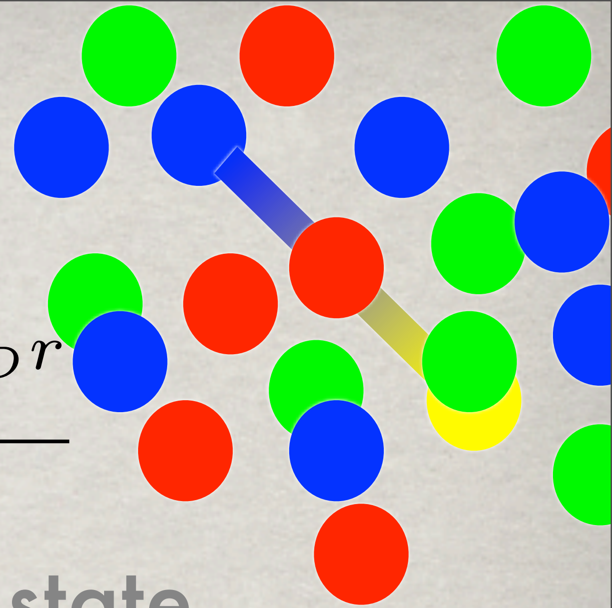
But what is the potential at finite T?

Quarkonium in a hot medium



Matsui Satz 86

color screening of the potential originates quarkonium dissociation

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

Debye charge screening (electromagnetic plasma)

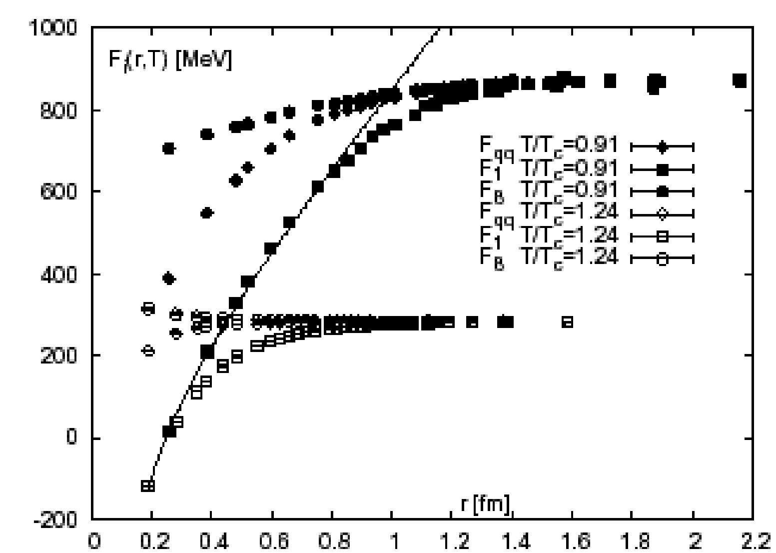
$$r \sim \frac{1}{m_D} \longrightarrow$$ Bound state dissolves

But what is the potential a finite T?

up to few years ago phenonological potentials used or hints from other observable calculted on the lattice

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) 11451

with the EFT one can define what is the quarkonium potential at finite T

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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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$?$ and $\Lambda_{\rm QCD}$

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$m_D \sim gT$
Debye mass
Screening Scale

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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

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

?

and Λ_{QCD}

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

$m_D \sim gT$
Debye mass
Screening Scale

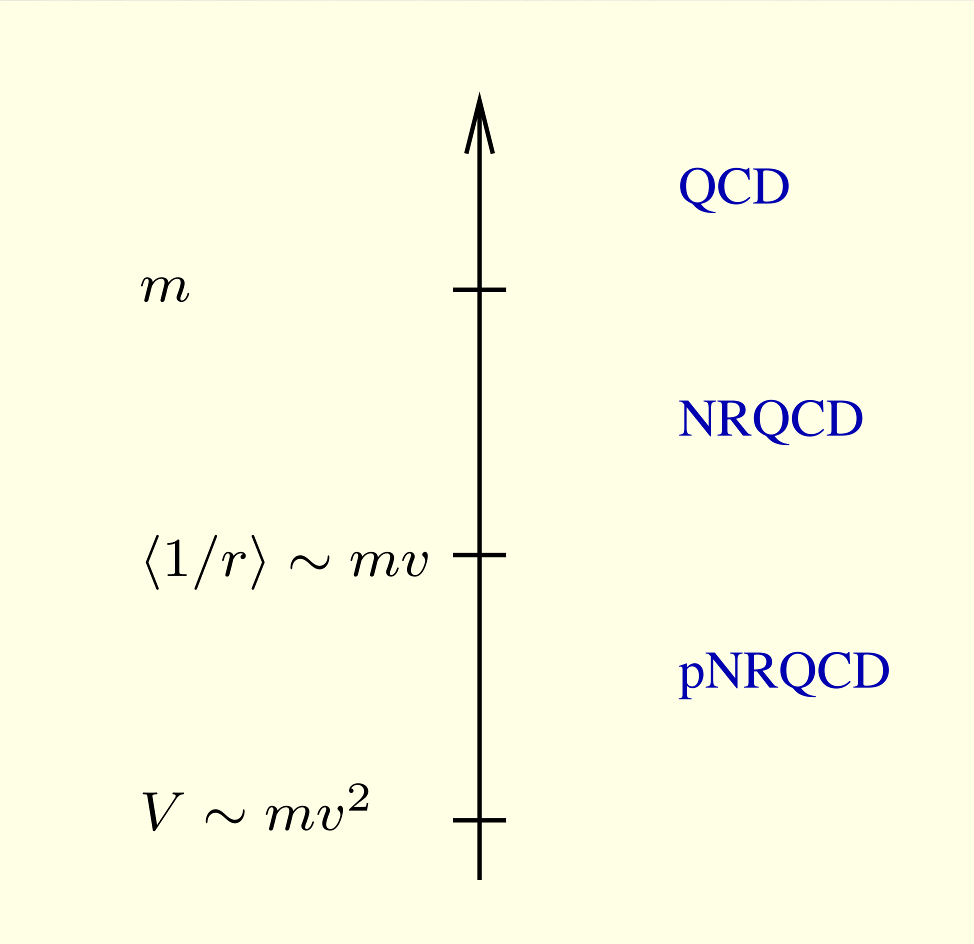
Vithout heavy quarks an EFT already exists that
mes from integrating out hard gluon of p \sim T:
Hard Thermal Loop EFT

Braaten Pisarski 90

-> obtain pNRQCD at finite T

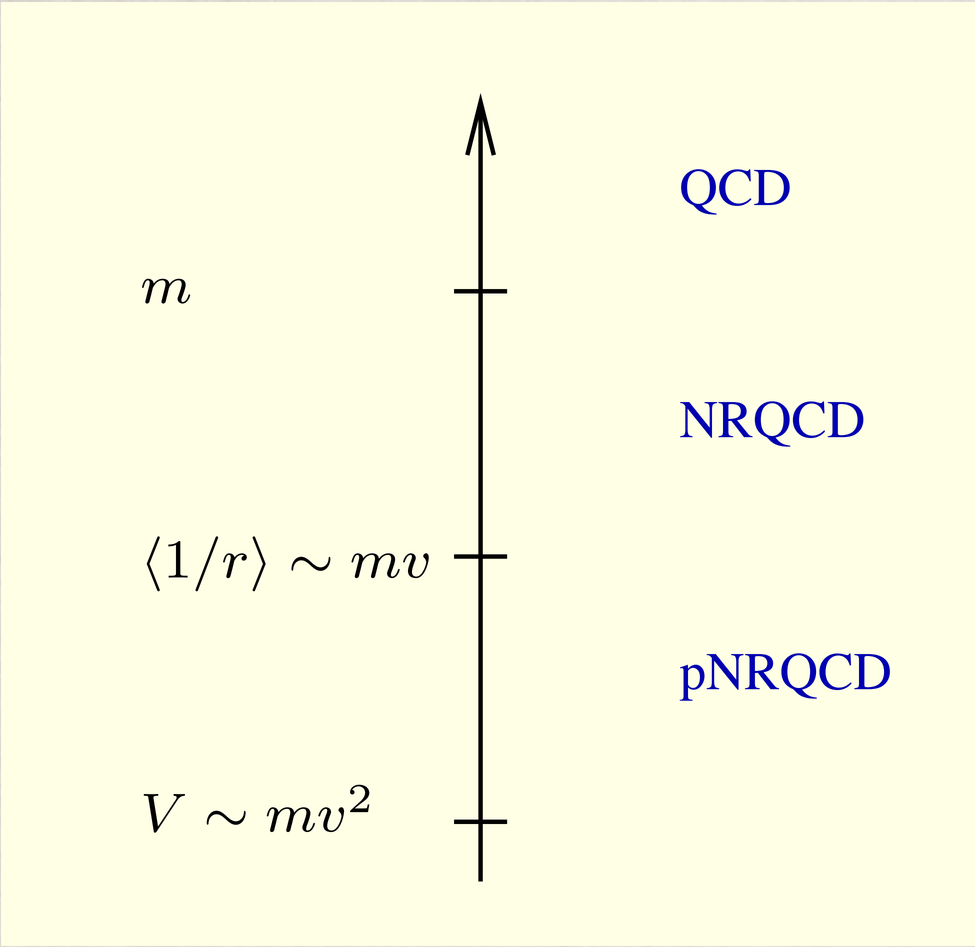
Quarkonium at finite T with pNRQCD

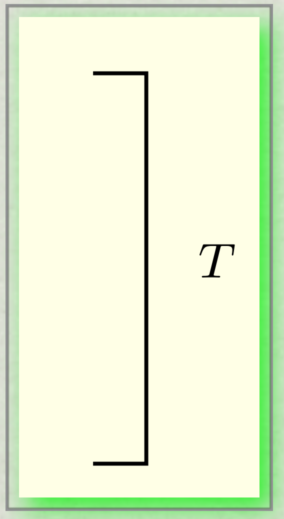
N. B., Ghiglieri,Petreczky, Vairo 08



Quarkonium at finite T with pNRQCD

N. B., Ghiglieri,Petreczky, Vairo 08





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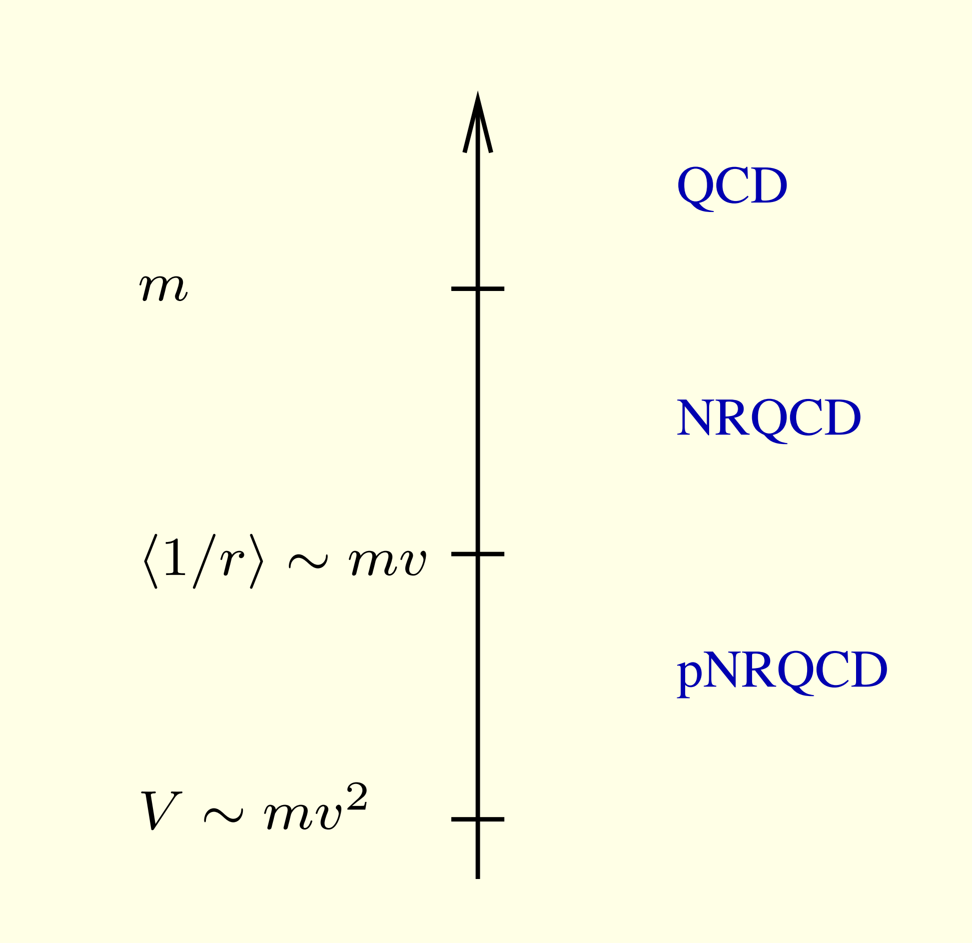
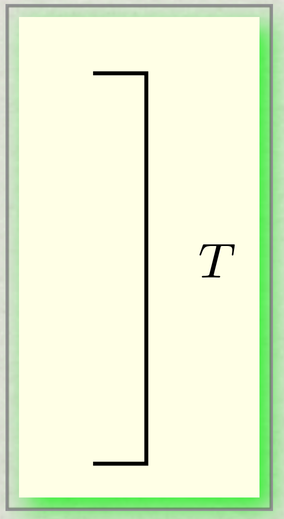


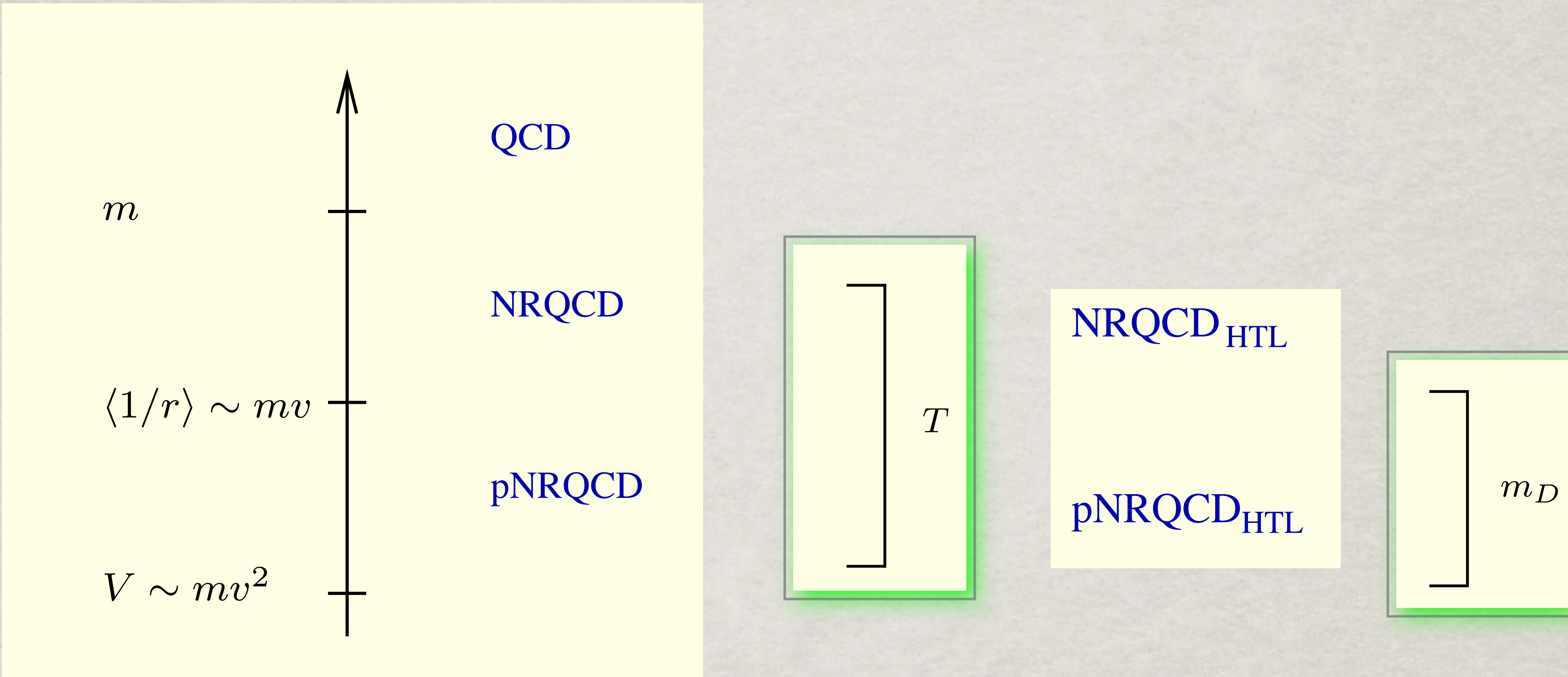


$NRQCD_{HTL}$

$pNRQCD_{HTL}$

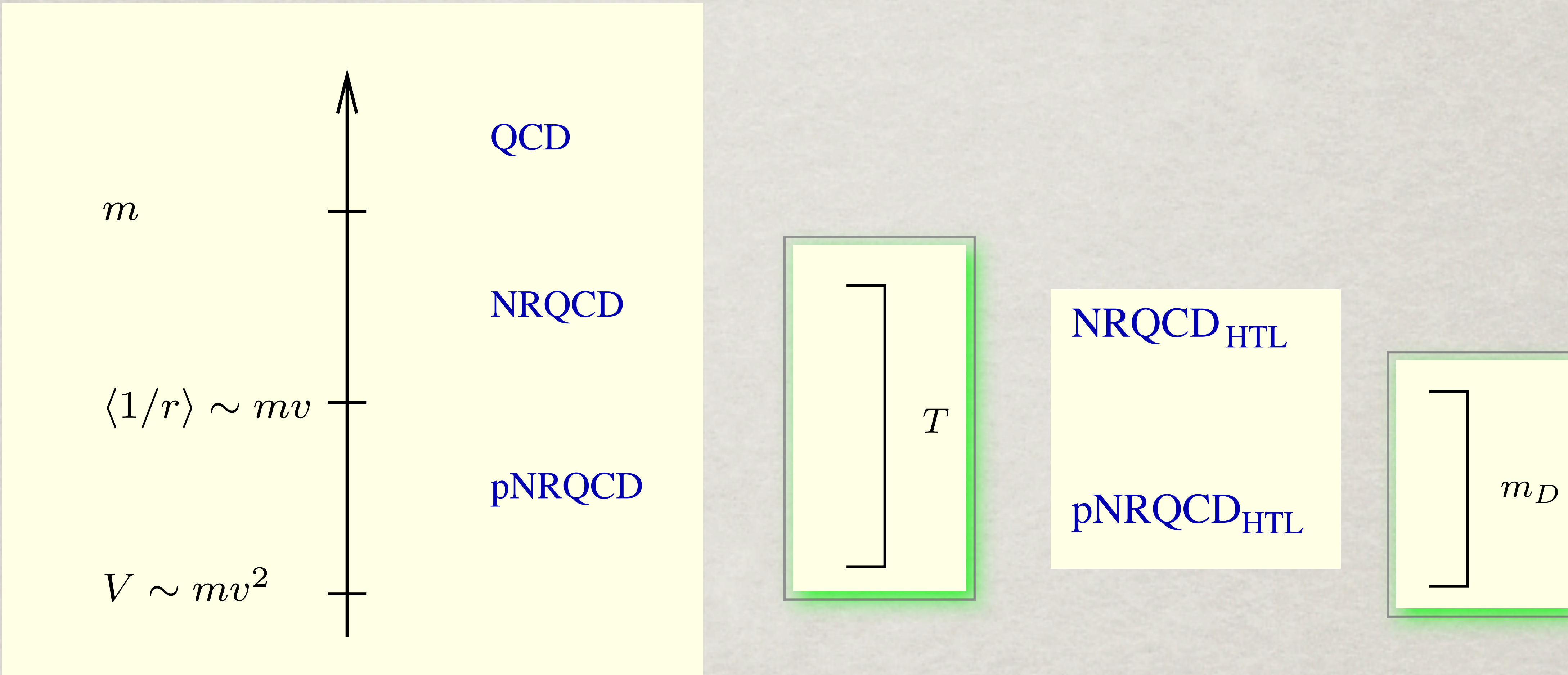
Quarkonium at finite T with pNRQCD

N. B., Ghiglieri,Petreczky, Vairo 08



Quarkonium at finite T with pNRQCD

N. B., Ghiglieri,Petreczky, Vairo 08



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.

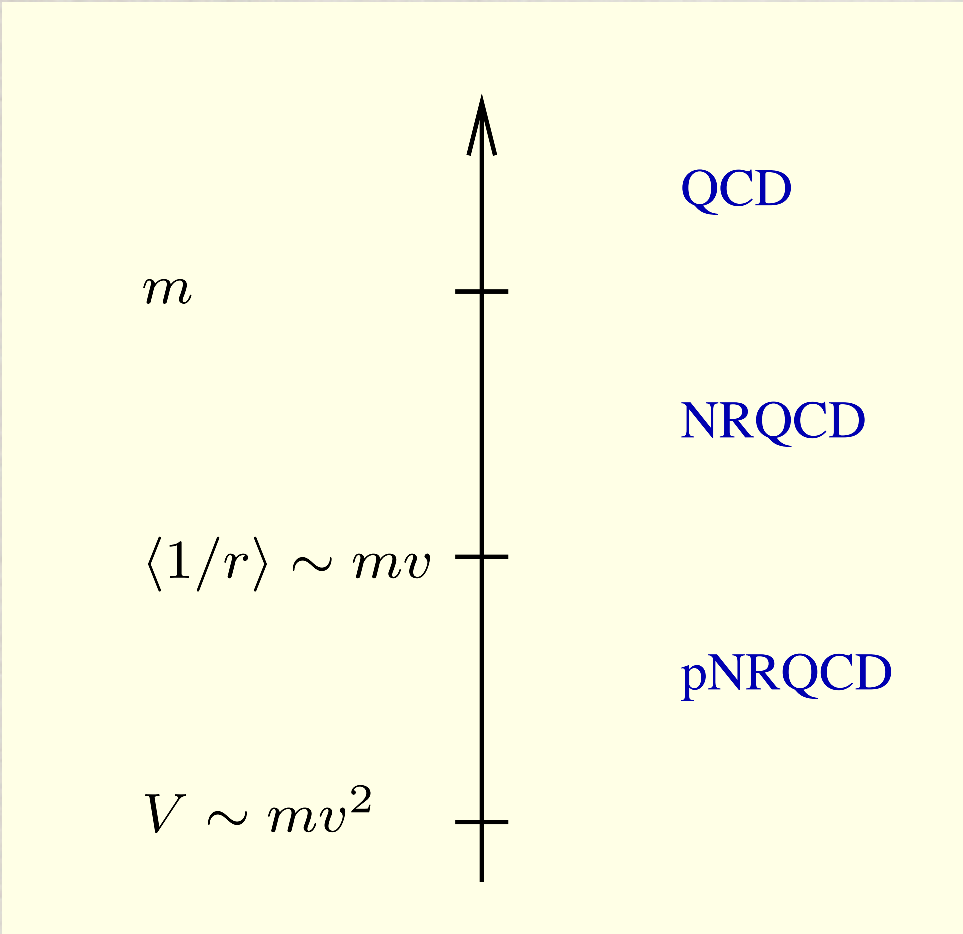
In the weak coupling regime:

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

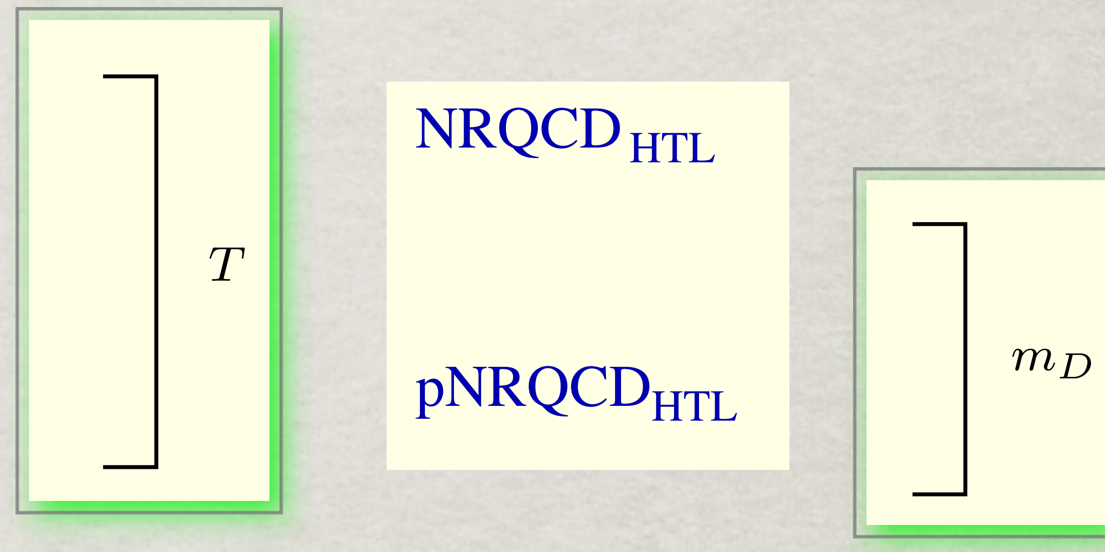
Effects due to the scale Λ_{QCD} will not be considered.

Quarkonium at finite T with pNRQCD

N. B., Ghiglieri,Petreczky, Vairo 08



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



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pNRQCD supply the potential (weak coupling regime T>>gT)

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

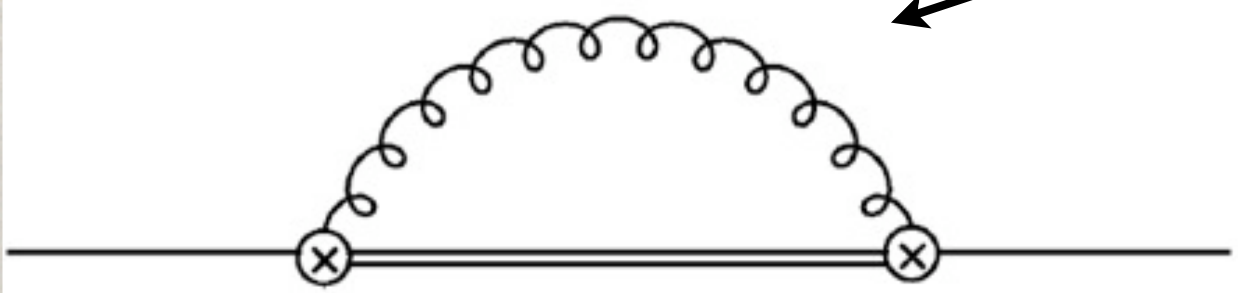
ReVs (r,T)

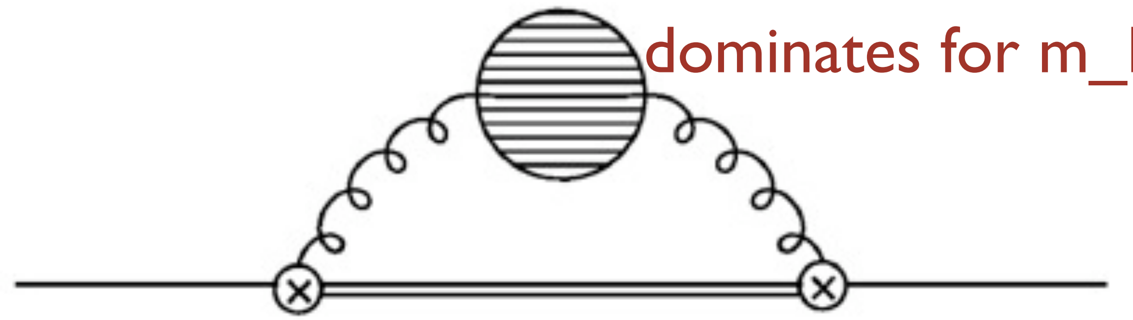
ImVs (r,T)

thermal width of $Q\bar{Q}$

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

Known from QED
dominates for m_D/E>>1





Singlet-to-octet
N.B Ghiglieri, Petreczky, Vairo 2008

Landau damping
Laine et al 07, Escobedo Soto 07

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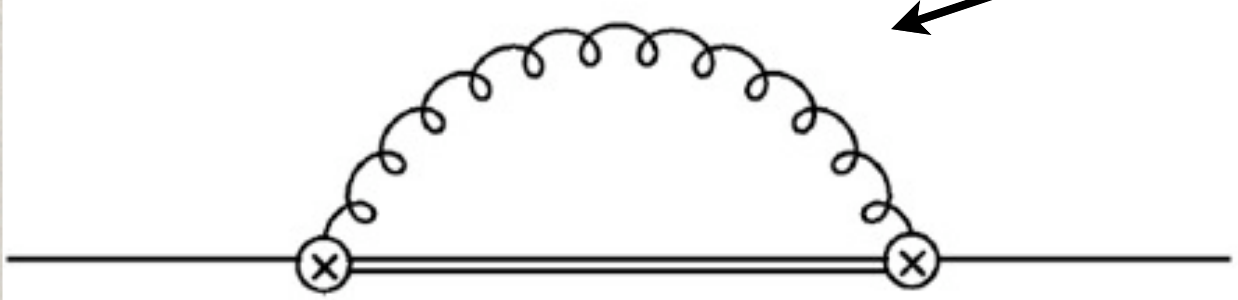

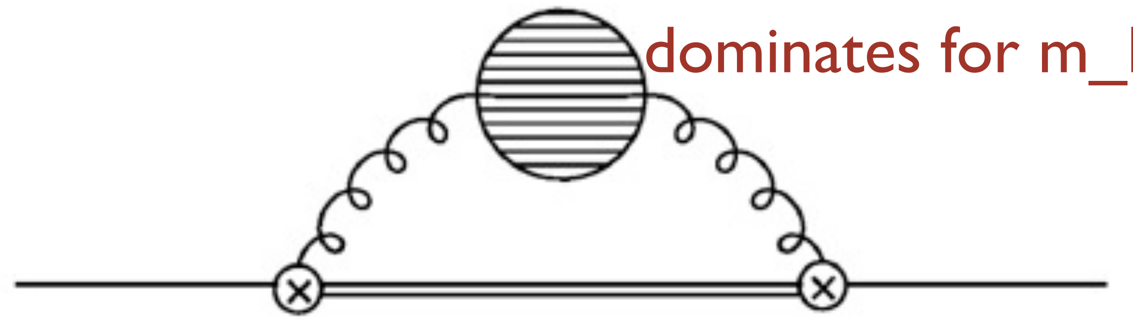

Singlet-to-octet

N.B Ghiglieri, Petreczky, Vairo 2008

(gluo dissociation)

N. B. Escobedo, Ghiglieri , Vairo 2011

Landau damping

Laine et al 07, Escobedo Soto 07

(inelastic parton scattering)

N. B. Escobedo, Ghiglieri , Vairo 2013

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ReVs (r,T) differs from the free energy

N. B., Ghiglieri, Petreczky, Vairo 010

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N.B Ghiglieri, Petreczky, Vairo 2008

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Laine et al 07, Escobedo Soto 07

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N. B. Escobedo, Ghiglieri , Vairo 2013

The singlet static potential and the static energy (pNRQCD)

- 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

We calculated the potential in the EFT for all the different scales hierarchies. There are preliminary lattice attempts to obtain the static potential

The singlet static potential and the static energy (pNRQCD)

We have calculated the potential for all the situations from T bigger than the inverse radius 1/r to smaller than the energy E

N.B., Ghiglieri, Petreczsky, Vairo

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

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

$$\pi T_{\mathrm{melting}} \sim m\, g^{4/3}$$

- Escobedo Soto arXiv:0804.0691
  Laine arXiv:0810.1112

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○ Escobedo Soto arXiv:0804.0691

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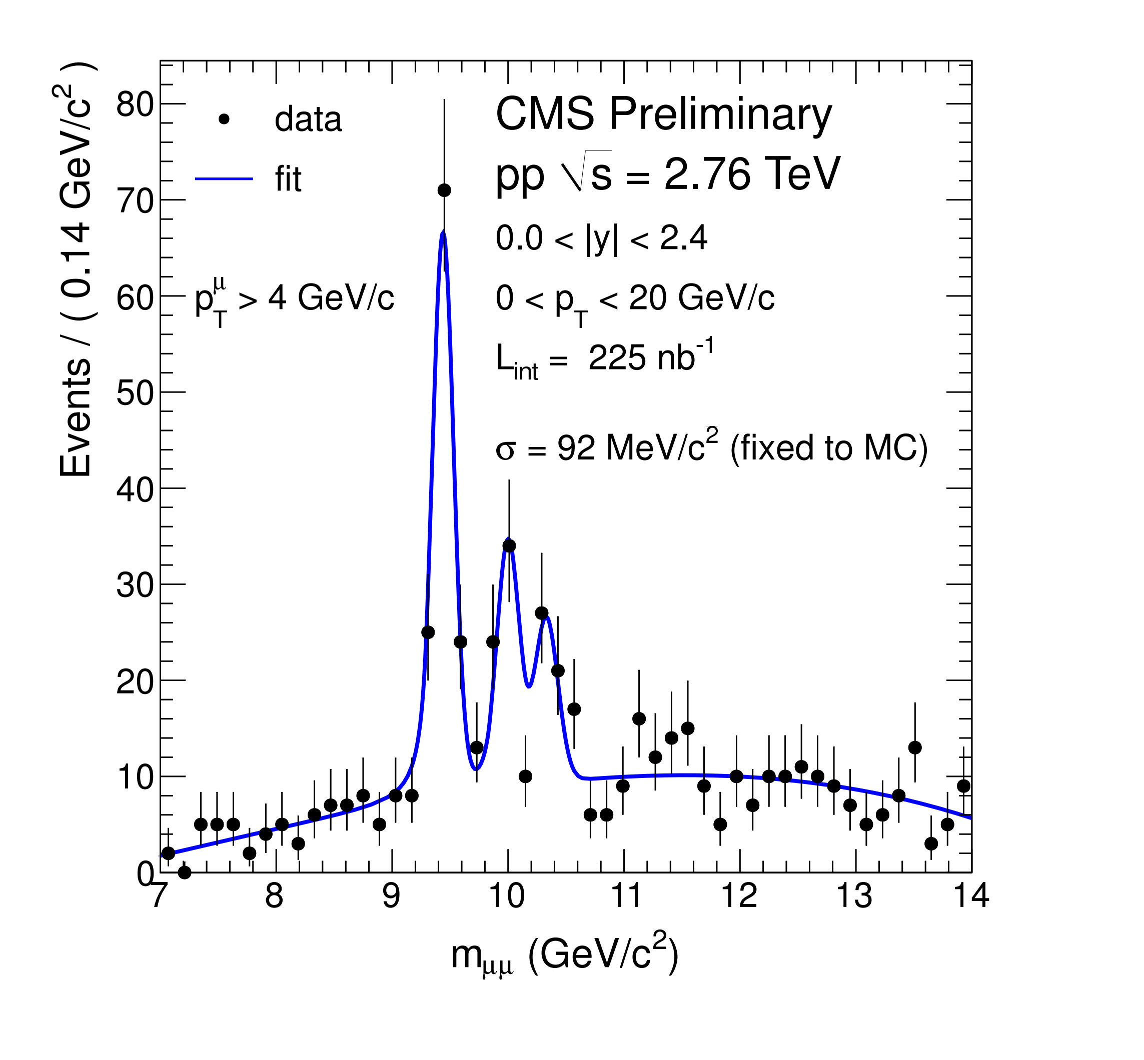
offer a systematic framework to do the calculation for the first time, inpired calculations in lattice, strings ..

The EFT supplies the potential and a scheme to calculate quarkonium energy levels at finite T



application to the study of
Y(1S) in hot medium at
LHC experiments

below the melting temperature T_d

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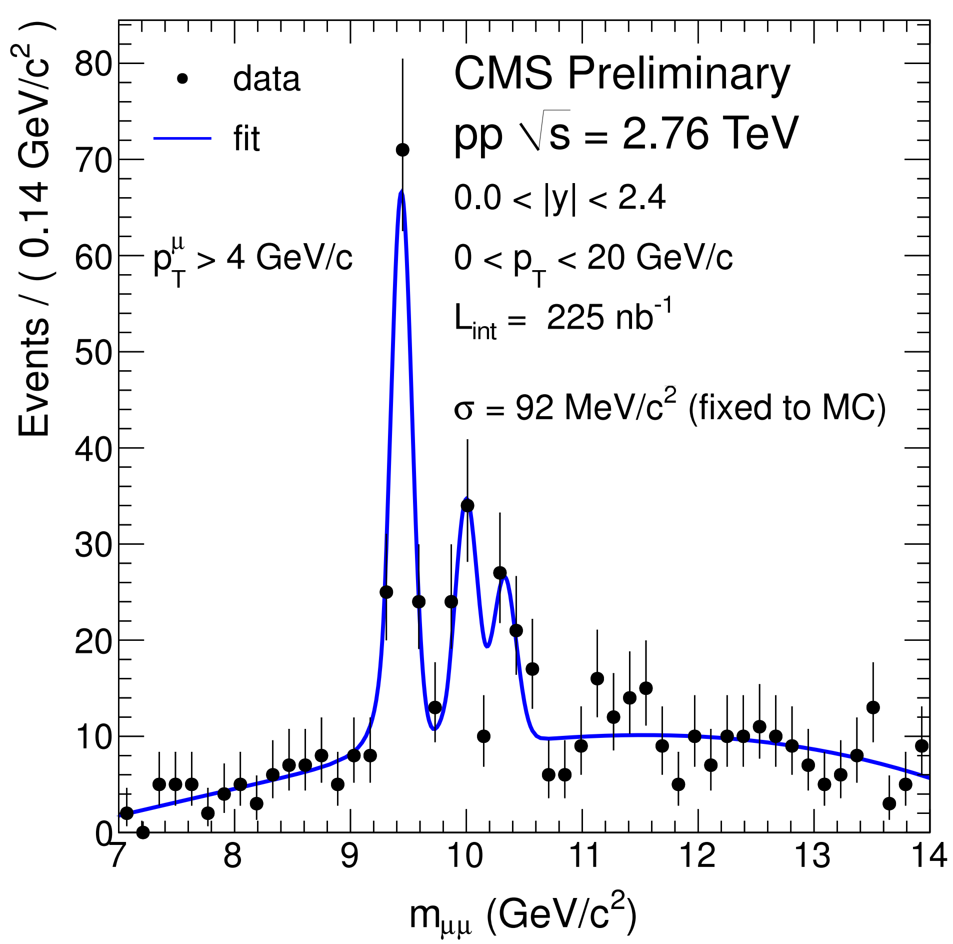

application to the study of Y(1S) in hot medium at LHC experiments

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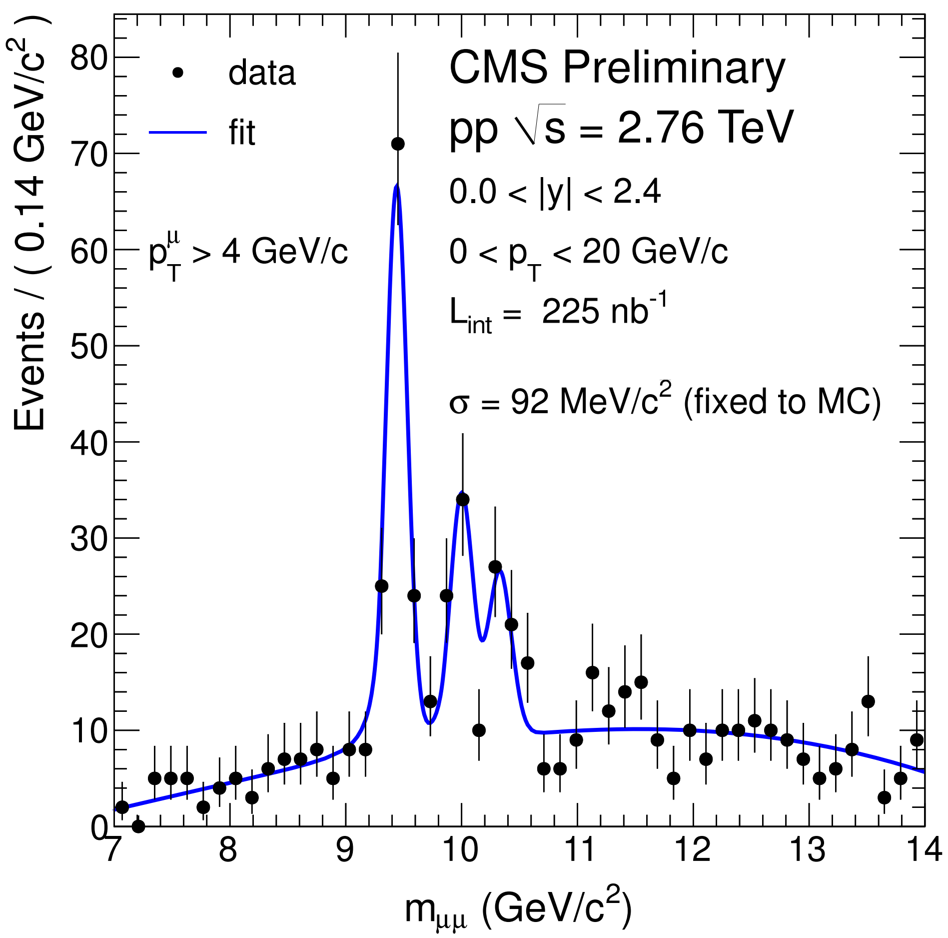
The relative size of non-relativistic and thermal scales depends on the medium and on the quarkonium state.

The EFT supplies the potential and a scheme to calculate quarkonium energy levels at finite T



application to the study of Y(1S) in hot medium at LHC experiments

below the melting temperature 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

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

case of interest for LHC: bottomonium 1S below the melting temperature T_d

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 lattice calculations of spectral functions

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

Quarkonium systems close or above

threshold

no Λ_{QCD} gap: close and above threshold

Quarkonium systems close or above

threshold

no gap: close and above threshold

Λ_{QCD}

Important to understand the X, Y, Z puzzles of the dozen of unexpected states showing up at the LHC and other collider experiments

TABLE 12: Quarkonium-like states above the corresponding open flavor thresholds. For charged states, the C-parity is given for the neutral members of the corresponding isotriplets.

State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment ($\#\sigma$)	Year	Status
$Y(3915)$	3918.4 ± 1.9	20 ± 5	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [1050] (8), BaBar [1000, 1051] (19)	2004	Ok
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [1052] (7.7), BaBar [1053] (7.6)	2009	Ok
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$e^+e^- \to e^+e^-(D\bar{D})$	Belle [1054] (5.3), BaBar [1055] (5.8)	2005	Ok
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi\,(D\bar{D}^*)$	Belle [1048, 1049] (6)	2005	NC!
$Y(4008)$	3891 ± 42	255 ± 42	1^{--}	$e^+e^- \to (\pi^+\pi^- J/\psi)$	Belle [1008, 1056] (7.4)	2007	NC!
$\psi(4040)$	4039 ± 1	80 ± 10	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)}(\pi))$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1057] (6.0)	2013	NC!
$Z(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1058] (5.0), BaBar [1059] (1.1)	2008	NC!
$Y(4140)$	4145.8 ± 2.6	18 ± 8	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1060] (5.0), Belle [1061] (1.9),	2009	NC!
					LHCb [1062] (1.4), CMS [1063] (>5)		
					D0 [1064] (3.1)		
$\psi(4160)$	4153 ± 3	103 ± 8	1^{--}	$e^+e^- \to (D^{(*)}\bar{D}^{(*)})$	PDG [1]	1978	Ok
				$e^+e^- \to (\eta J/\psi)$	Belle [1057] (6.5)	2013	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi\,(D^*\bar{D}^*)$	Belle [1049] (5.5)	2007	NC!
$Z(4200)^+$	4196^{+35}_{-30}	370^{+99}_{-110}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1065] (7.2)	2014	NC!
$Z(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	$?^{?+}$	$\bar{B}^0 \to K^-(\pi^+\chi_{c1})$	Belle [1058] (5.0), BaBar [1059] (2.0)	2008	NC!
$Y(4260)$	4250 ± 9	108 ± 12	1^{--}	$e^+e^- \to (\pi\pi J/\psi)$	BaBar [1066, 1067] (8), CLEO [1068, 1069] (11)	2005	Ok
					Belle [1008, 1056] (15), BES III [1007] (np)		
				$e^+e^- \to (f_0(980) J/\psi)$	BaBar [1067] (np), Belle [1008] (np)	2012	Ok
				$e^+e^- \to (\pi^- Z_c(3900)^+)$	BES III [1007] (8), Belle [1008] (5.2)	2013	Ok
				$e^+e^- \to (\gamma\, X(3872))$	BES III [1070] (5.3)	2013	NC!
$Y(4274)$	4293 ± 20	35 ± 16	$?^{?+}$	$B^+ \to K^+(\phi J/\psi)$	CDF [1060] (3.1), LHCb [1062] (1.0),	2011	NC!
					CMS [1063] (>3), D0 [1064] (np)		
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	13^{+18}_{-10}	$0/2^{?+}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [1071] (3.2)	2009	NC!
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1072] (8), BaBar [1073] (np)	2007	Ok
$Z(4430)^+$	4458 ± 15	166^{+37}_{-32}	1^{+-}	$\bar{B}^0 \to K^-(\pi^+\psi(2S))$	Belle [1074, 1075] (6.4), BaBar [1076] (2.4)	2007	Ok
					LHCb [1077] (13.9)		
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	Belle [1065] (4.0)	2014	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to (\Lambda_c^+\bar{\Lambda}_c^-)$	Belle [1078] (8.2)	2007	NC!
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$e^+e^- \to (\pi^+\pi^-\psi(2S))$	Belle [1072] (5.8), BaBar [1073] (5)	2007	Ok
$\Upsilon(10860)$	10876 ± 11	55 ± 28	1^{--}	$e^+e^- \to (B^{(*)}_{(s)}\bar{B}^{(*)}_{(s)}(\pi))$	PDG [1]	1985	Ok
				$e^+e^- \to (\pi\pi\Upsilon(1S, 2S, 3S))$	Belle [1013, 1014, 1079] (>10)	2007	Ok
				$e^+e^- \to (f_0(980)\Upsilon(1S))$	Belle [1013, 1014] (>5)	2011	Ok
				$e^+e^- \to (\pi Z_b(10610, 10650))$	Belle [1013, 1014] (>10)	2011	Ok
				$e^+e^- \to (\eta\Upsilon(1S, 2S))$	Belle [948] (10)	2012	Ok
				$e^+e^- \to (\pi^+\pi^-\Upsilon(1D))$	Belle [948] (9)	2012	Ok
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [1080] (2.3)	2008	NC!

TABLE 10: Quarkonium-like states at the open flavor thresholds. For charged states, the C-parity is given for the neutr
members of the corresponding isotriplets.

State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Statu
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [772, 992] (>10), BaBar [993] (8.6)	2003	Ok
				$p\bar{p} \to (\pi^+\pi^- J/\psi) ...$	CDF [994, 995] (11.6), D0 [996] (5.2)	2003	Ok
				$pp \to (\pi^+\pi^- J/\psi) ...$	LHCb [997, 998] (np)	2012	Ok
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	Belle [999] (4.3), BaBar [1000] (4.0)	2005	Ok
				$B \to K(\gamma J/\psi)$	Belle [1001] (5.5), BaBar [1002] (3.5)	2005	Ok
					LHCb [1003] (> 10)		
				$B \to K(\gamma \psi(2S))$	BaBar [1002] (3.6), Belle [1001] (0.2)	2008	NC!
					LHCb [1003] (4.4)		
				$B \to K(D\bar{D}^*)$	Belle [1004] (6.4), BaBar [1005] (4.9)	2006	Ok
$Z_c(3885)^+$	3883.9 ± 4.5	25 ± 12	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BES III [1006] (np)	2013	NC!
$Z_c(3900)^+$	3891.2 ± 3.3	40 ± 8	$?^{?-}$	$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BES III [1007] (8), Belle [1008] (5.2)	2013	Ok
					T. Xiao *et al.* [CLEO data] [1009] (>5)		
$Z_c(4020)^+$	4022.9 ± 2.8	7.9 ± 3.7	$?^{?-}$	$Y(4260, 4360) \to \pi^-(\pi^+ h_c)$	BES III [1010] (8.9)	2013	NC!
$Z_c(4025)^+$	4026.3 ± 4.5	24.8 ± 9.5	$?^{?-}$	$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BES III [1011] (10)	2013	NC!
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(10860) \to \pi(\pi\Upsilon(1S, 2S, 3S))$	Belle [1012–1014] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [1013] (16)	2011	Ok
				$\Upsilon(10860) \to \pi^-(B\bar{B}^*)^+$	Belle [1015] (8)	2012	NC!
$Z_b(10650)^+$	10652.2 ± 1.5	11.5 ± 2.2	1^{+-}	$\Upsilon(10860) \to \pi^-(\pi^+\Upsilon(1S, 2S, 3S))$	Belle [1012, 1013] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [1013] (16)	2011	Ok
				$\Upsilon(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle [1015] (6.8)	2012	NC!

TABLE 10: Quarkonium-like states at the open flavor thresholds. For charged states, the C-parity is given for the neutr
members of the corresponding isotriplets.

State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Statu
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [772, 992] (>10), BaBar [993] (8.6)	2003	Ok
				$p\bar{p} \to (\pi^+\pi^- J/\psi)\ldots$	CDF [994, 995] (11.6), D0 [996] (5.2)	2003	Ok
				$pp \to (\pi^+\pi^- J/\psi)\ldots$	LHCb [997, 998] (np)	2012	Ok
				$B \to K(\pi^+\pi^-\pi^0 J/\psi)$	Belle [999] (4.3), BaBar [1000] (4.0)	2005	Ok
				$B \to K(\gamma J/\psi)$	Belle [1001] (5.5), BaBar [1002] (3.5) LHCb [1003] (> 10)	2005	Ok
				$B \to K(\gamma \psi(2S))$	BaBar [1002] (3.6), Belle [1001] (0.2) LHCb [1003] (4.4)	2008	NC!
				$B \to K(D\bar{D}^*)$	Belle [1004] (6.4), BaBar [1005] (4.9)	2006	Ok
$Z_c(3885)^+$	3883.9 ± 4.5	25 ± 12	1^{+-}	$Y(4260) \to \pi^-(D\bar{D}^*)^+$	BES III [1006] (np)	2013	NC!
$Z_c(3900)^+$	3891.2 ± 3.3	40 ± 8	$?^{?-}$	$Y(4260) \to \pi^-(\pi^+ J/\psi)$	BES III [1007] (8), Belle [1008] (5.2) T. Xiao *et al.* [CLEO data] [1009] (>5)	2013	Ok
$Z_c(4020)^+$	4022.9 ± 2.8	7.9 ± 3.7	$?^{?-}$	$Y(4260, 4360) \to \pi^-(\pi^+ h_c)$	BES III [1010] (8.9)	2013	NC!
$Z_c(4025)^+$	4026.3 ± 4.5	24.8 ± 9.5	$?^{?-}$	$Y(4260) \to \pi^-(D^*\bar{D}^*)^+$	BES III [1011] (10)	2013	NC!
$Z_b(10610)^+$	10607.2 ± 2.0	18.4 ± 2.4	1^{+-}	$\Upsilon(10860) \to \pi(\pi\Upsilon(1S, 2S, 3S))$	Belle [1012–1014] (>10)	2011	Ok
				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [1013] (16)	2011	Ok
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				$\Upsilon(10860) \to \pi^-(\pi^+ h_b(1P, 2P))$	Belle [1013] (16)	2011	Ok
				$\Upsilon(10860) \to \pi^-(B^*\bar{B}^*)^+$	Belle [1015] (6.8)	2012	NC!

Near theshold heavy-light mesons have to be included and many additional degrees of freedom considered

No systematic treatment is available; lattice calculations are also challenging and in the infancy state in this case

We need a description of states close or above threshold from QCD

Already the case of QCD without light quark is very interesting. The degrees of freedom are heavy quarkonium, heavy hybrids and glueballs

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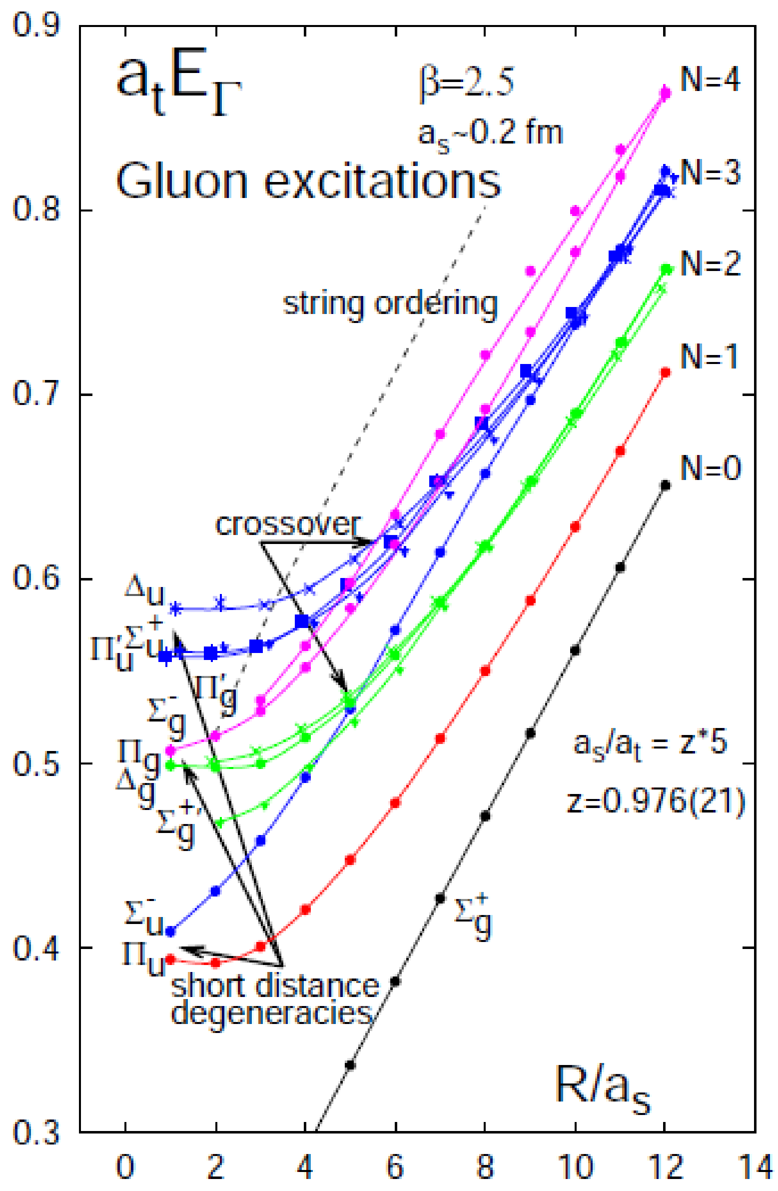
Static Lattice energies

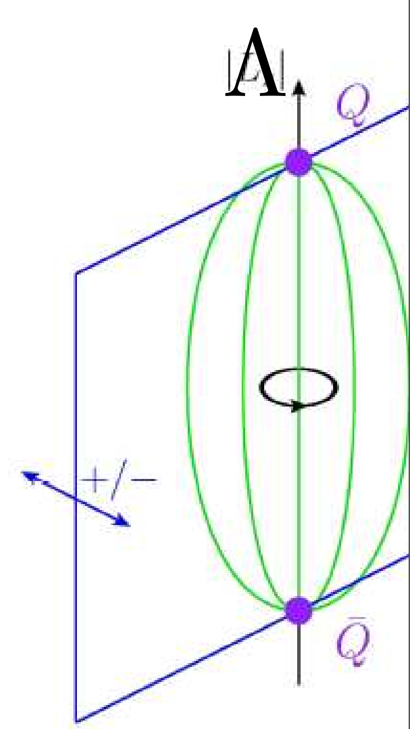
Juge Kuti Morningstar 2003



Symmetries

Static states classified by symmetry group $D_{\infty h}$
Representations labeled Λ^σ_η

- Λ rotational quantum number $|\hat{\mathbf{n}} \cdot \mathbf{K}| = 0, 1, 2 \ldots$ corresponds to $\Lambda = \Sigma, \Pi, \Delta \ldots$
- η eigenvalue of CP: $g \hat{=} +1$ (gerade), $u \hat{=} -1$ (ungerade)
- σ eigenvalue of reflections
- σ label only displayed on Σ states (others are degenerate)

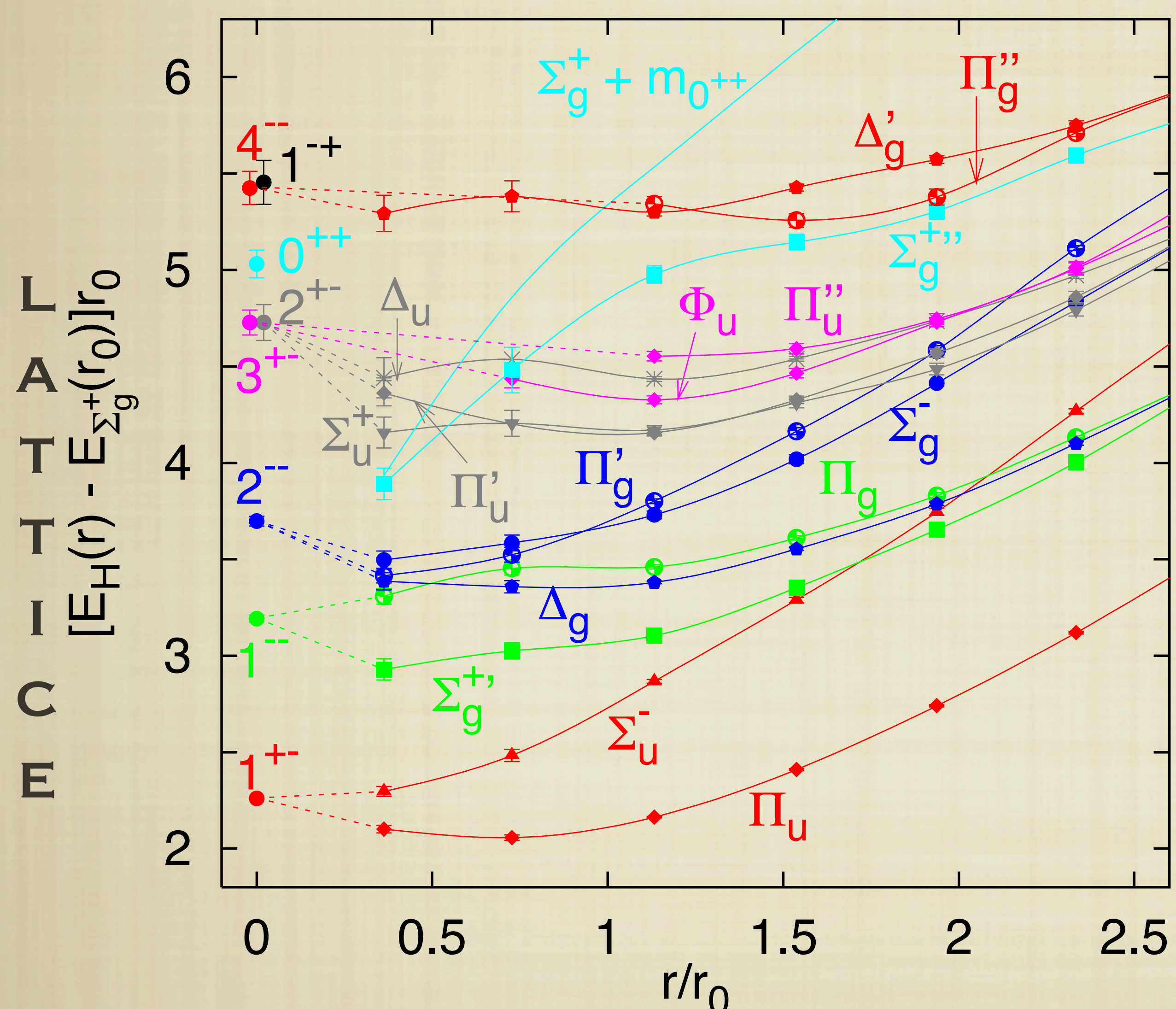


- The static energies correspond to the irreducible representations of D_{∞}
- In general it can be more than one state for each irreducible represent $D_{\infty h}$, usually denoted by primes, e.g. Π_u, Π'_u, Π''_u...

Gluonic excitations in pNRQCD:more symmetry!

In the limit $r \to 0$ more symmetry: $D_{\infty h} \to O(3) \times C$

- Several Λ_η^σ representations contained in one J^{PC} representation:
- Static energies in these multiplets have same $r \to 0$ limit.



	$L=1$	$L=2$
$\Sigma_g^{+\prime}$	$\mathbf{r}\cdot(\mathbf{E})$	
Σ_g^-		$(\mathbf{r}\cdot\mathbf{D})(\mathbf{r}\cdot\mathbf{B})$
Π_g	$\mathbf{r}\times(\mathbf{E})$	
Π_g'		$\mathbf{r}\times((\mathbf{r}\cdot\mathbf{D})\mathbf{B}+\mathbf{D}(\mathbf{r}\cdot\mathbf{B}))$
Δ_g		$(\mathbf{r}\times\mathbf{D})^i(\mathbf{r}\times\mathbf{B})^j+$ $+(\mathbf{r}\times\mathbf{D})^j(\mathbf{r}\times\mathbf{B})^i$
Σ_u^+		$(\mathbf{r}\cdot\mathbf{D})(\mathbf{r}\cdot\mathbf{E})$
Σ_u^-	$\mathbf{r}\cdot\mathbf{B}$	
Π_u	$\mathbf{r}\times\mathbf{B}$	
Π_u'		$\mathbf{r}\times((\mathbf{r}\cdot\mathbf{D})\mathbf{E}+\mathbf{D}(\mathbf{r}\cdot\mathbf{E}))$
Δ_u		$(\mathbf{r}\times\mathbf{D})^i(\mathbf{r}\times\mathbf{E})^j+$ $+(\mathbf{r}\times\mathbf{D})^j(\mathbf{r}\times\mathbf{E})^i$

pNRQCD predicts the structure of multiplets at short distance and the ordering

Brambilla Pineda Soto Vairo 0

We define symmetries and states in NRQCD

We match the energy and the states to pNRQCD at order 1/m in the expansion (but no spin for now) and identify coupled Schroedinger equations for Sigma_u and Pi_u

These are nonperturbative but would require lattice calculations of matrix elements

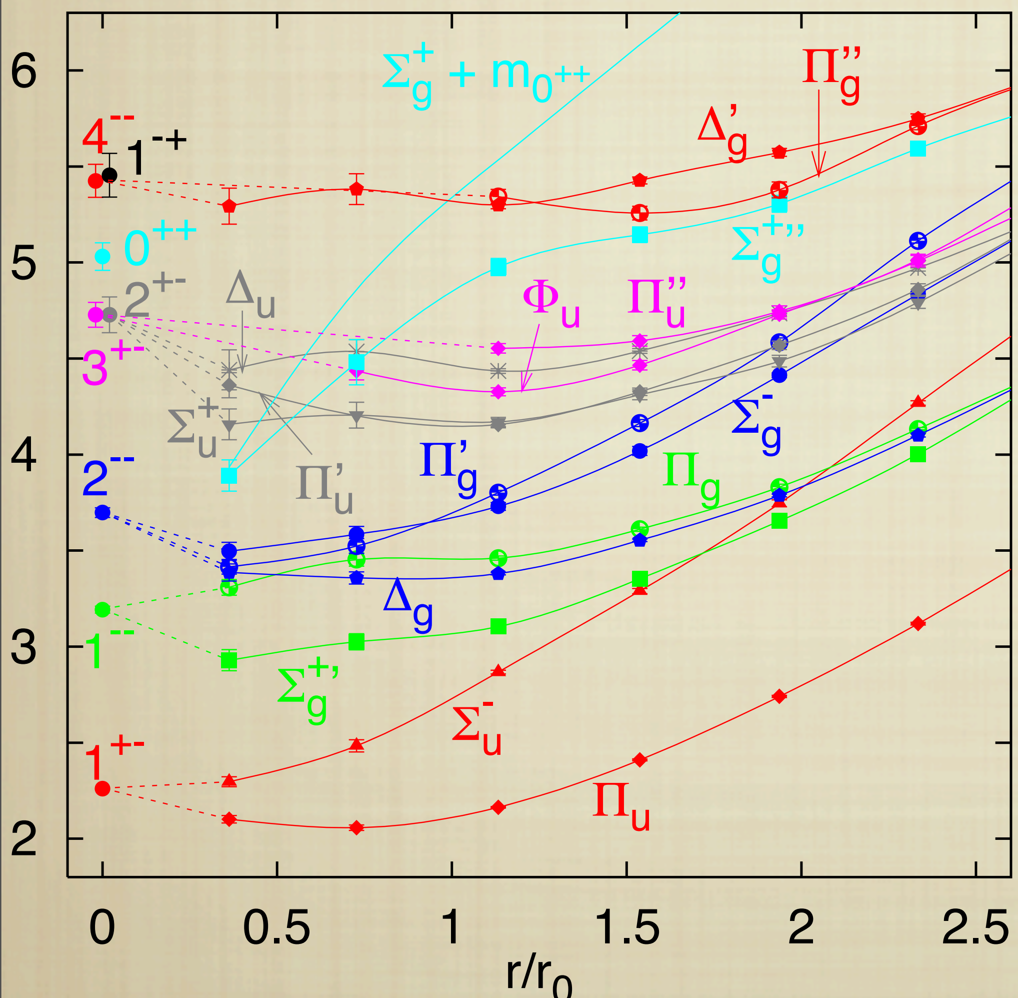
Lacking the lattice calculation, we identify the potentials with a multipole expansion in pNRQCD, solve the coupled equations and get the lowest ccbar, bbar and bcbar muliplets

Gluonic excitations in pNRQCD: one can determine the form of the potential

- *At lowest order in the multipole expansion, the singlet decouples while the octet is still coupled to gluons.*

- *Static hybrids at short distance are called gluelumps and are described by a static adjoint source (O) in the presence of a gluonic field (H):*

$$\mathrm{H}(R,r,t) = \mathrm{Tr}\{\mathrm{O}H\}$$



$$= e^{-iTE_H}$$

$$E_H = V_o + \frac{i}{T}\ln\langle H^a(\frac{T}{2})\phi_{ab}^{\mathrm{adj}}H^b(-\frac{T}{2})\rangle$$

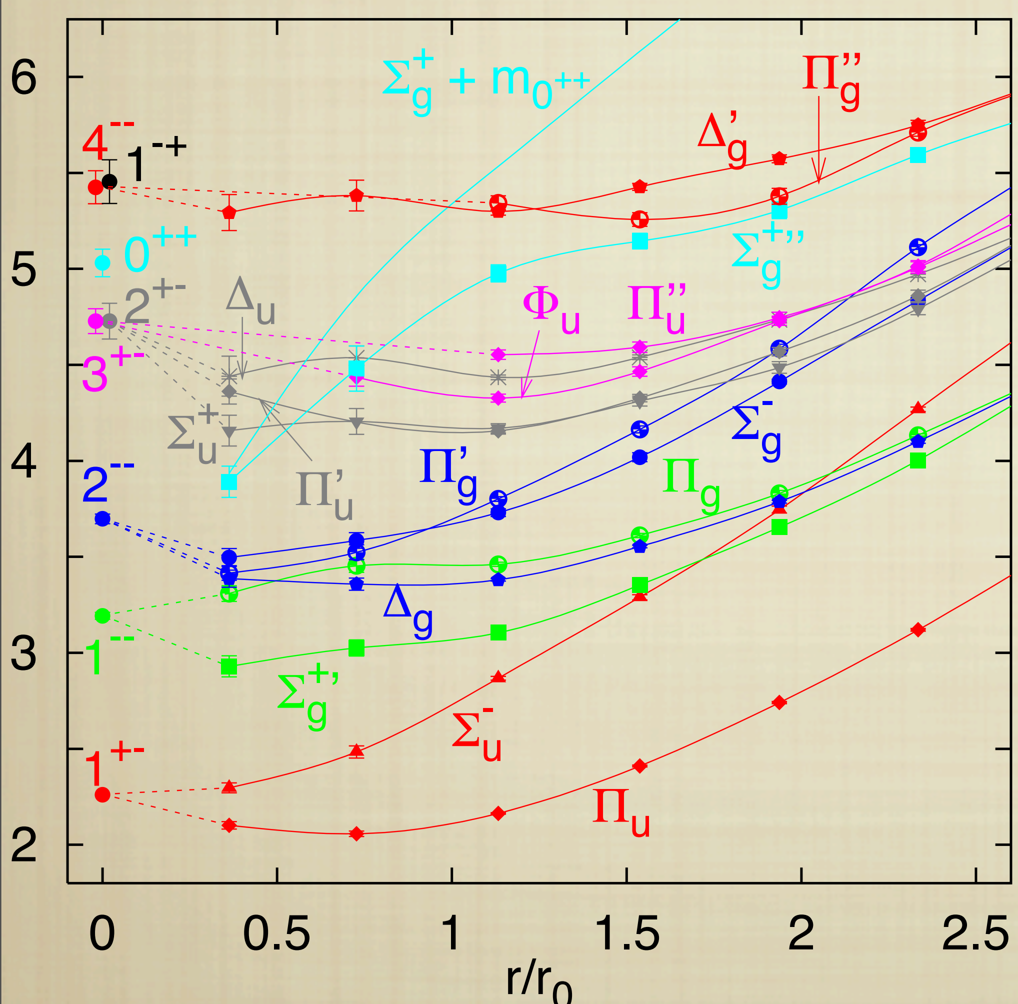
$$\langle H^a(\frac{T}{2})\phi_{ab}^{\mathrm{adj}}H^b(-\frac{T}{2})\rangle^{\mathrm{np}} \sim h\, e^{-iT\Lambda_H}$$

$$E_H(r) = V_o(r) + \Lambda_H + O(r^2)$$

Gluonic excitations in pNRQCD: one can determine the form of the potential

- *At lowest order in the multipole expansion, the singlet decouples while the octet is still coupled to gluons.*
- *Static hybrids at short distance are called gluelumps and are described by a static adjoint source* (O) *in the presence of a gluonic field* (H):

$$\mathrm{H}(R,r,t) = \mathrm{Tr}\{\mathrm{O}H\}$$



$$= e^{-iTE_H}$$

$$E_H = V_o + \frac{i}{T}\ln\langle H^a(\frac{T}{2})\phi^{\mathrm{adj}}_{ab}H^b(-\frac{T}{2})\rangle$$

$$\langle H^a(\frac{T}{2})\phi^{\mathrm{adj}}_{ab}H^b(-\frac{T}{2})\rangle^{\mathrm{np}} \sim h\, e^{-iT\Lambda_H}$$

$$E_H(r) = V_o(r) + \Lambda_H + O(r^2)$$

octet potential — gluelump mass — correction softly breaking the symmetry

Lowest energy multiplet Σ_u^-–Π_u

- The two lowest laying hybrid static energies are Π_u and Σ_u^-.
- They are generated by a gluelump with quantum numbers 1^{+-} and thus are degenerate at short distances.
- The kinetic operator mixes them but not with other multiplets.
- Well separated by a gap of ~ 1 GeV from the next multiplet with the same CP.

$$V_H = V_o + \Lambda_H + b_H r^2$$

Λ_H and b_H are nonperturbative and should be obtained from lattice calculations

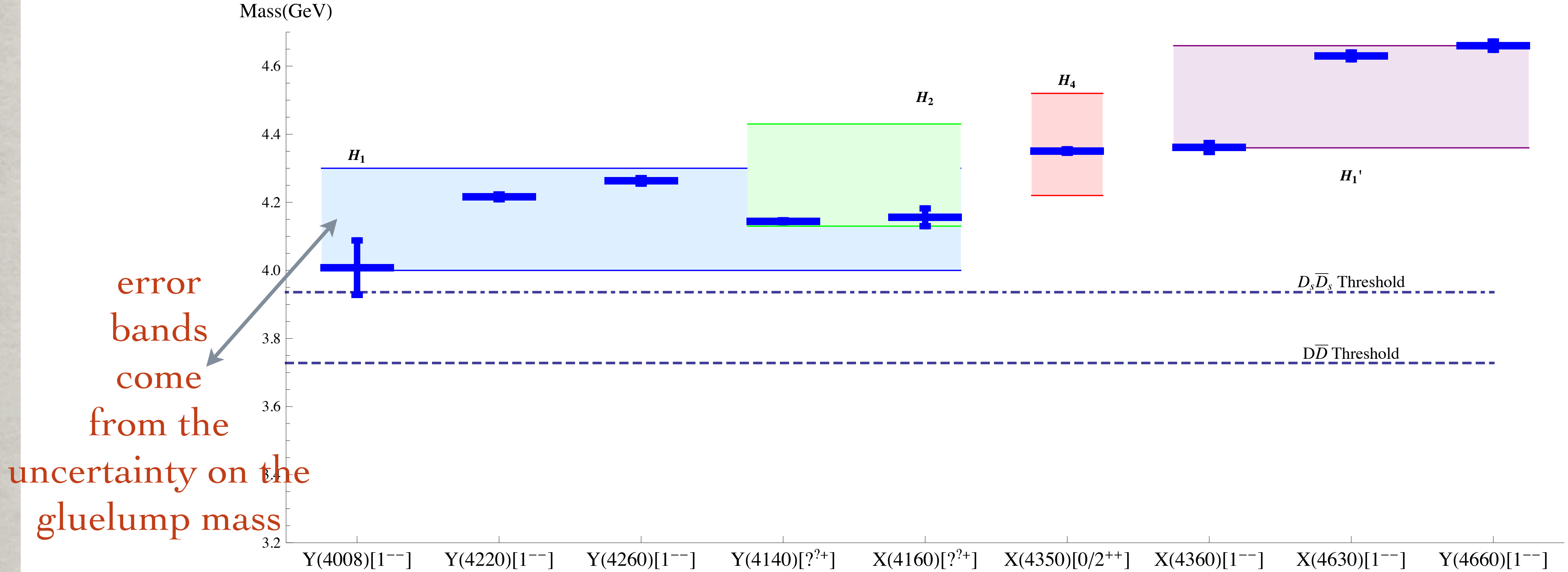
	l	$J^{PC}\{s=0, s=1\}$	$E_n^{(0)}$
H_1	1	$\{1^{--}, (0,1,2)^{-+}\}$	Σ_u^-, Π_u
H_2	1	$\{1^{++}, (0,1,2)^{+-}\}$	Π_u
H_3	0	$\{0^{++}, 1^{+-}\}$	Σ_u^-
H_4	2	$\{2^{++}, (1,2,3)^{+-}\}$	Σ_u^-, Π_u
H_5	2	$\{2^{--}, (1,2,3)^{-+}\}$	Π_u

TABLE II. J^{PC} multiplets with $l \leq 2$ for the Σ_u^- and Π_u gluonic states. We follow the naming notation H_i used in [20, 26], which orders the multiplets from lower to higher mass. The last column shows the gluonic static energies that appear in the Schrödinger equation of the respective multiplets.

Identification with experimental states

Most of the candidates have 1^{--} or $0^{++}/2^{++}$ since the main observation channels are production by e^+e^- or $\gamma\gamma$ annihilation respectively.

- Charmonium states (Belle, CDF, BESIII, Babar):



- Bottomonium states: $Y_b(10890)[1^{--}]$, $m = 10.8884 \pm 3.0$ (Belle). Possible H_1 candidate, $m_{H_1} = 10.79 \pm 0.15$.

However, except for $Y(4220)$, all other candidates observed decay modes violate Heavy Quark Spin Symmetry.

Berwein, N.B. , Tarrus, Vairo 2015

Comparison to direct lattice calculations

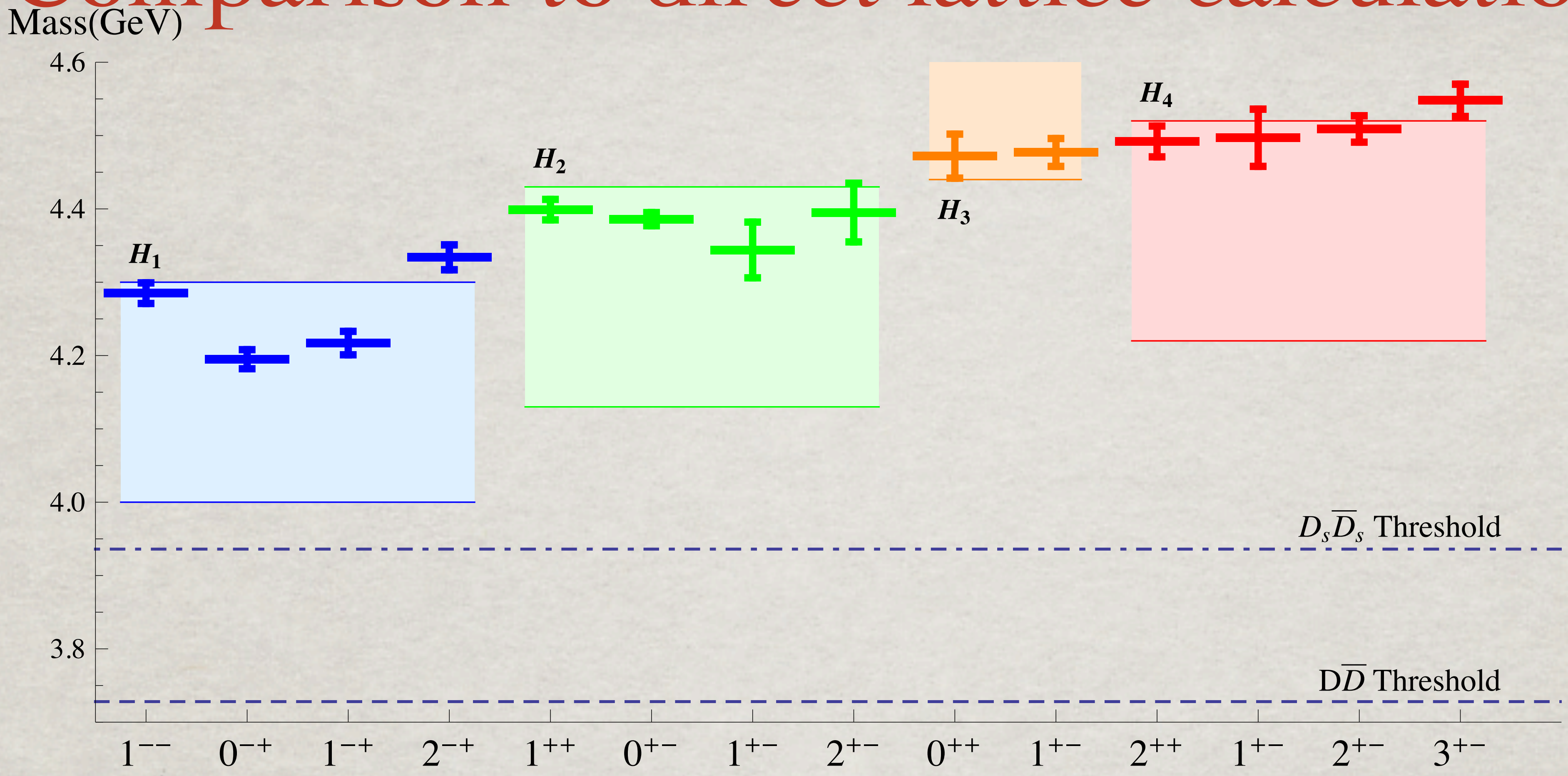


FIG. 5. Comparison of the results from direct lattice computations of the masses for charmonium hybrids [48] with our results using the $V^{(0.25)}$ potential. The direct lattice mass predictions are plotted in solid lines with error bars corresponding the mass uncertainties. Our results for the H_1, H_2, H_3, and H_4 multiplets have been plotted in error bands corresponding to the gluelump mass uncertainty of ± 0.15 GeV.

We observe the same Lambda-doubling pattern in lattice calculations, multiplets that receive mixed contributions from Sigma_u and Pi_u have lower masses then those that remain pure Pi_u states

L. Liu *et al.* [Hadron Spectrum Collaboration], JHEP **1207**, 126 (2012) [arXiv:1204.5425

Conclusions

Quarkonium is a golden system to study strong interactions

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

At T=0, away from threshold, EFTs 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.
Some lattice calculations are still needed (glue correlators, quenched and unquenched Wilson loops with field insertions).

At finite T allow us to give the appropriate definition and define a calculational scheme for quantities of huge phenomenological interest like the qqbar potential and energies 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

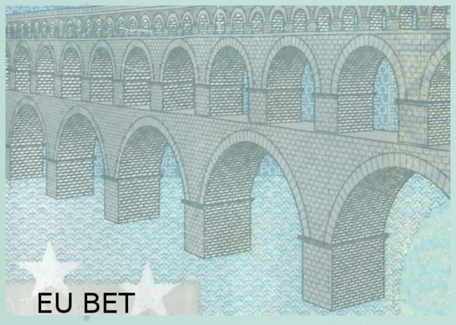
Outlook

the EFT gives us a definition of physical objects that can then be evaluated with other tools

the EFT gives us a factorization between high energy and low energy contributions: tools to evaluate the nonperturbative physics should be applied only to the low energy part

the EFT approach is very versatile and flexible can be applied to many different problems in

in quarkonium (the low energy part will be typically contained in some type of Wilson loops), in QCD, in QED, in atomic physics, condensed matter, etc..



EU BET
European Bridges with Effective Theories:
from high energy to condensed matter

The intended network brings together leading scientists in the fields of particle, nuclear, atomic, condensed-matter, quantum optics, and computational physics. The resulting group of researchers will have the capacity to address some of the most interesting open physics problems such as, for instance, the understanding of universal features in the equilibrium and transport properties of novel states of matter found in contexts as diverse as graphene, cold atom systems, and the quark-gluon plasma. It will develop needed novel numerical, analytic and computational tools,