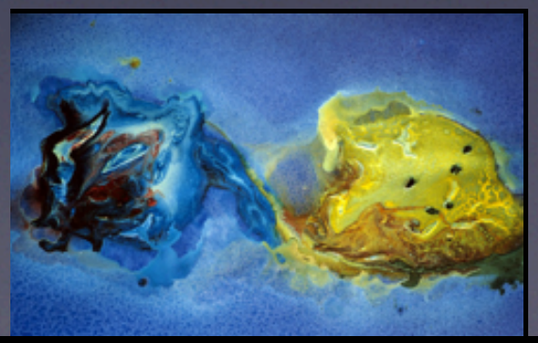
Heavy Quarkonium with Effective Field Theories



Nora Brambilla

Physik Department TUM
T30f

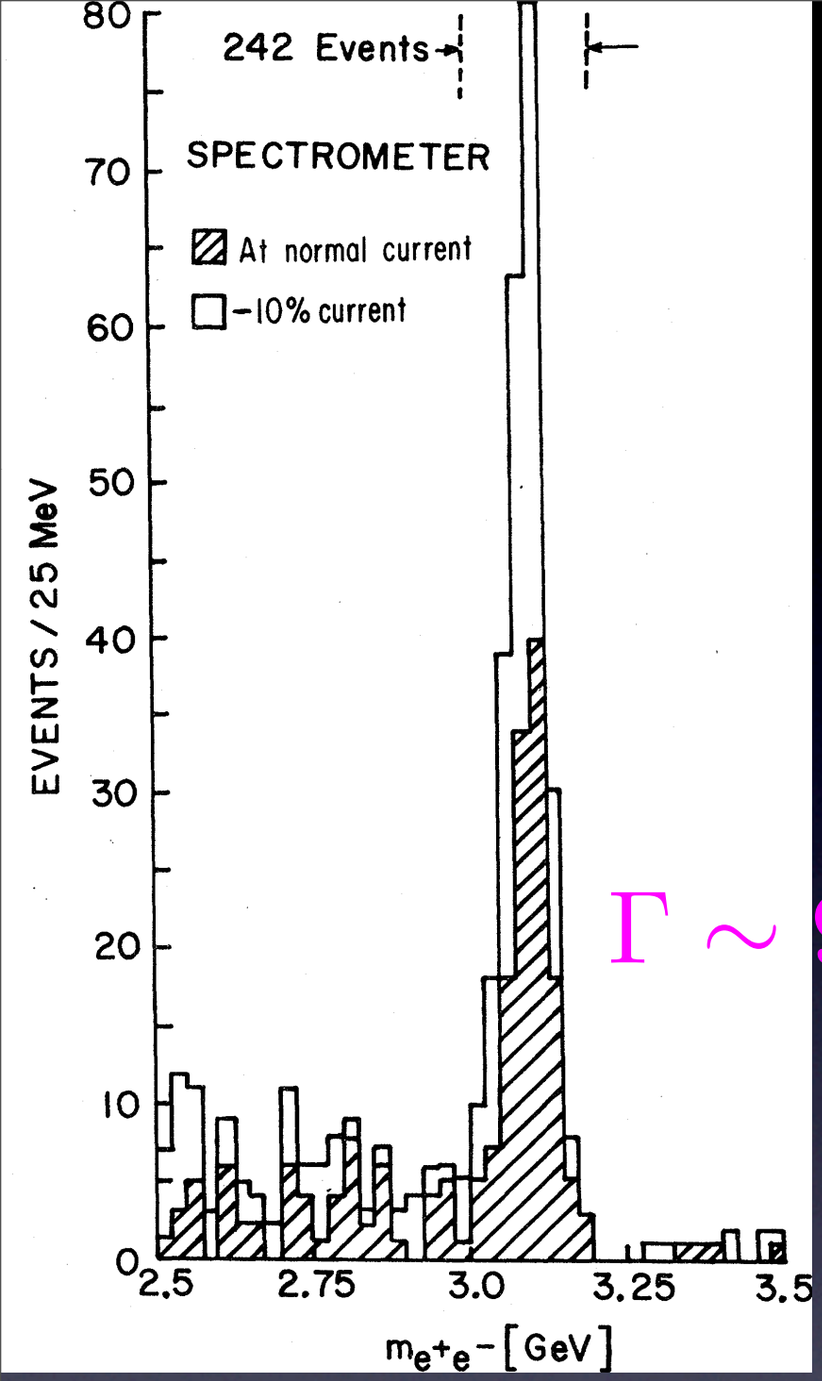
- the physics of quarkonium and its relevance to strong interactions and beyond

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

- experimental/theoretical challenges and opportunities

Quarkonium (=bound state of a heavy quark and a heavy antiquark) has been instrumental for the establishing of QCD, the theory of strong interaction, and the Standard Model of Particle

The November revolution in 1974: the J/ψ discovery



$\Gamma \sim 90\,\mathrm{KeV}$

Aubert et al. BNL 74

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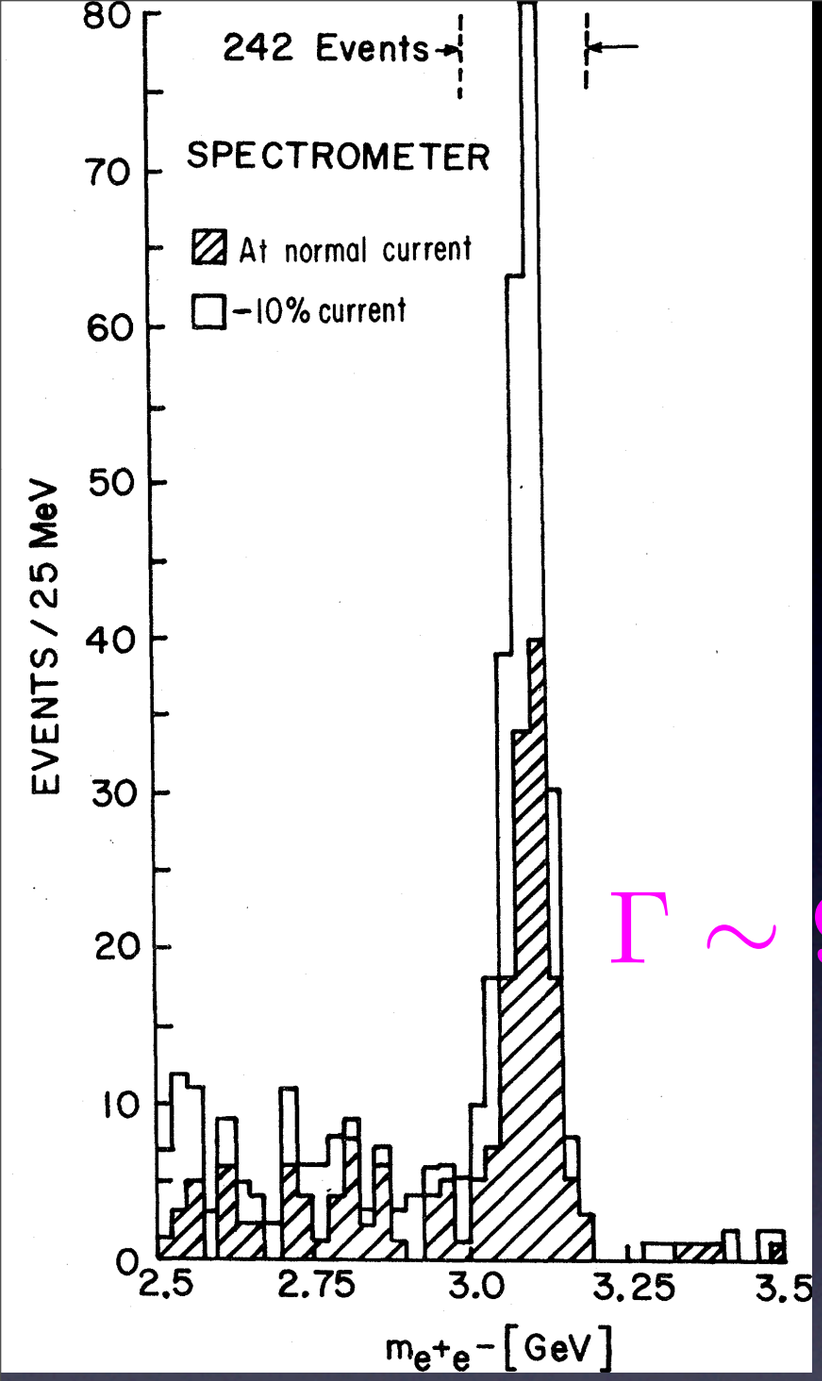

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Samuel Ting: "It is like to stumble on a village where people live 70000 years"

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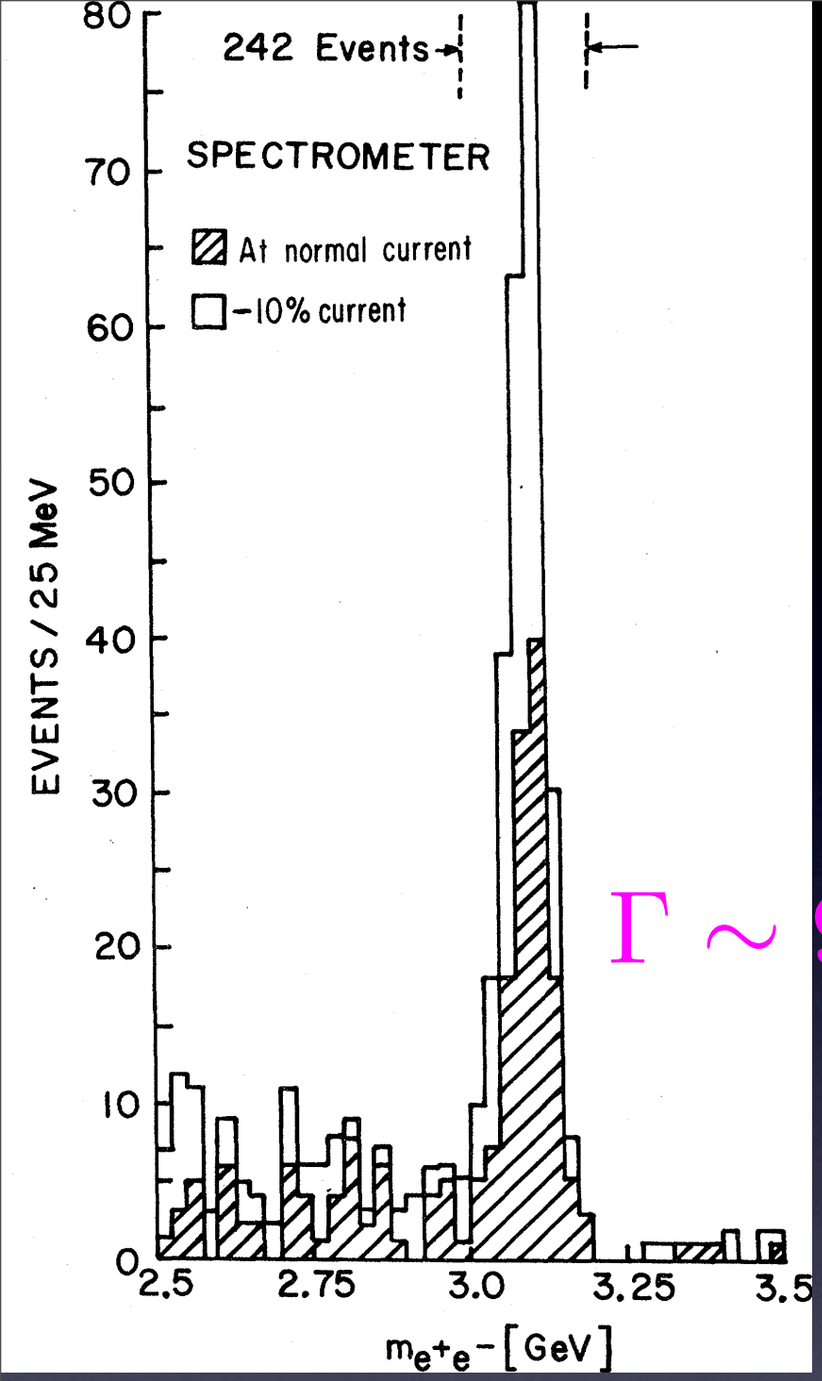

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Samuel Ting: "It is like to stumble on a village where people live 70000 years"

it has been the confirmation of the charm quark prediction and of QCD (strong int theory) foundations

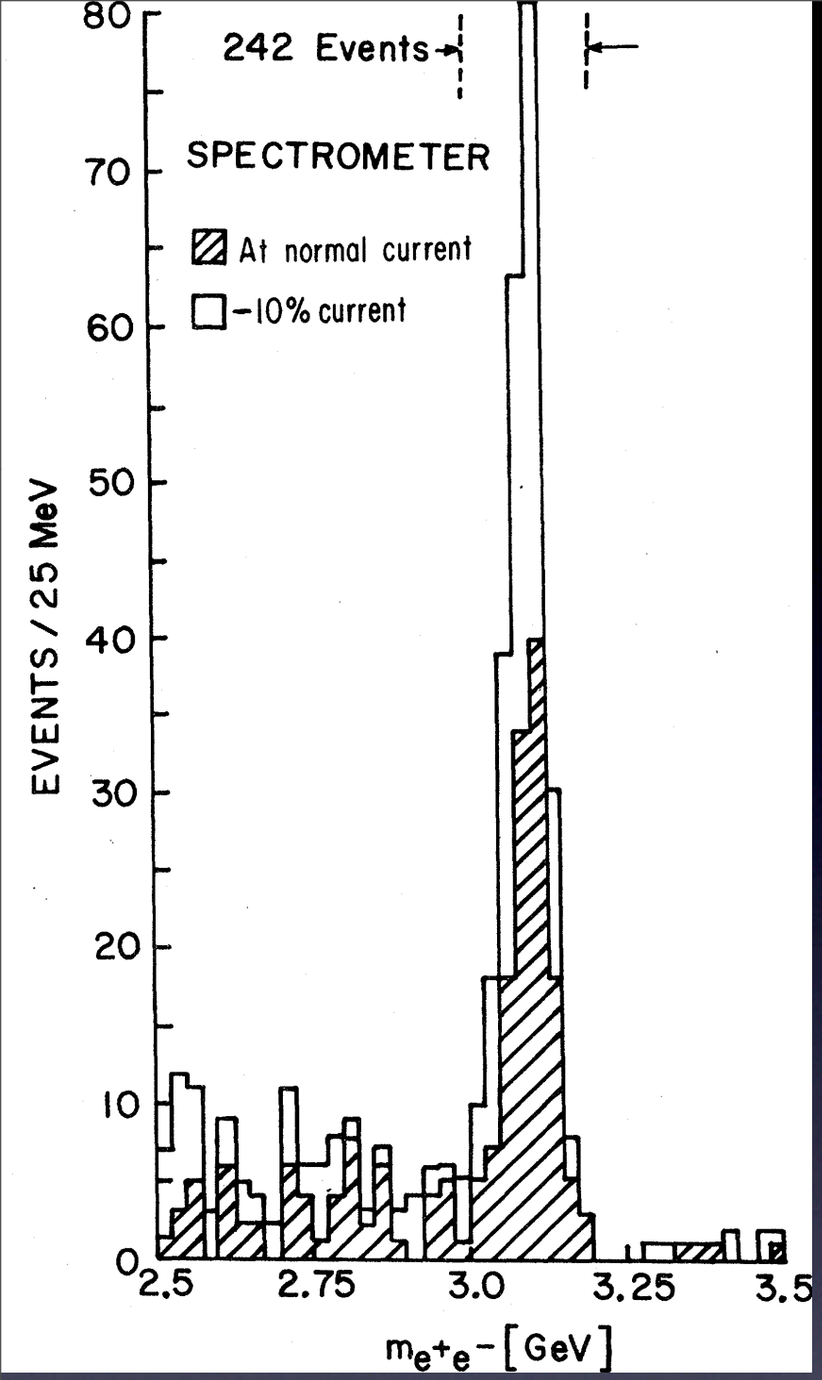
Aubert et al. BNL 74

narrow width and asymptotic freedom

annihilation at large scale controlled by small α_s

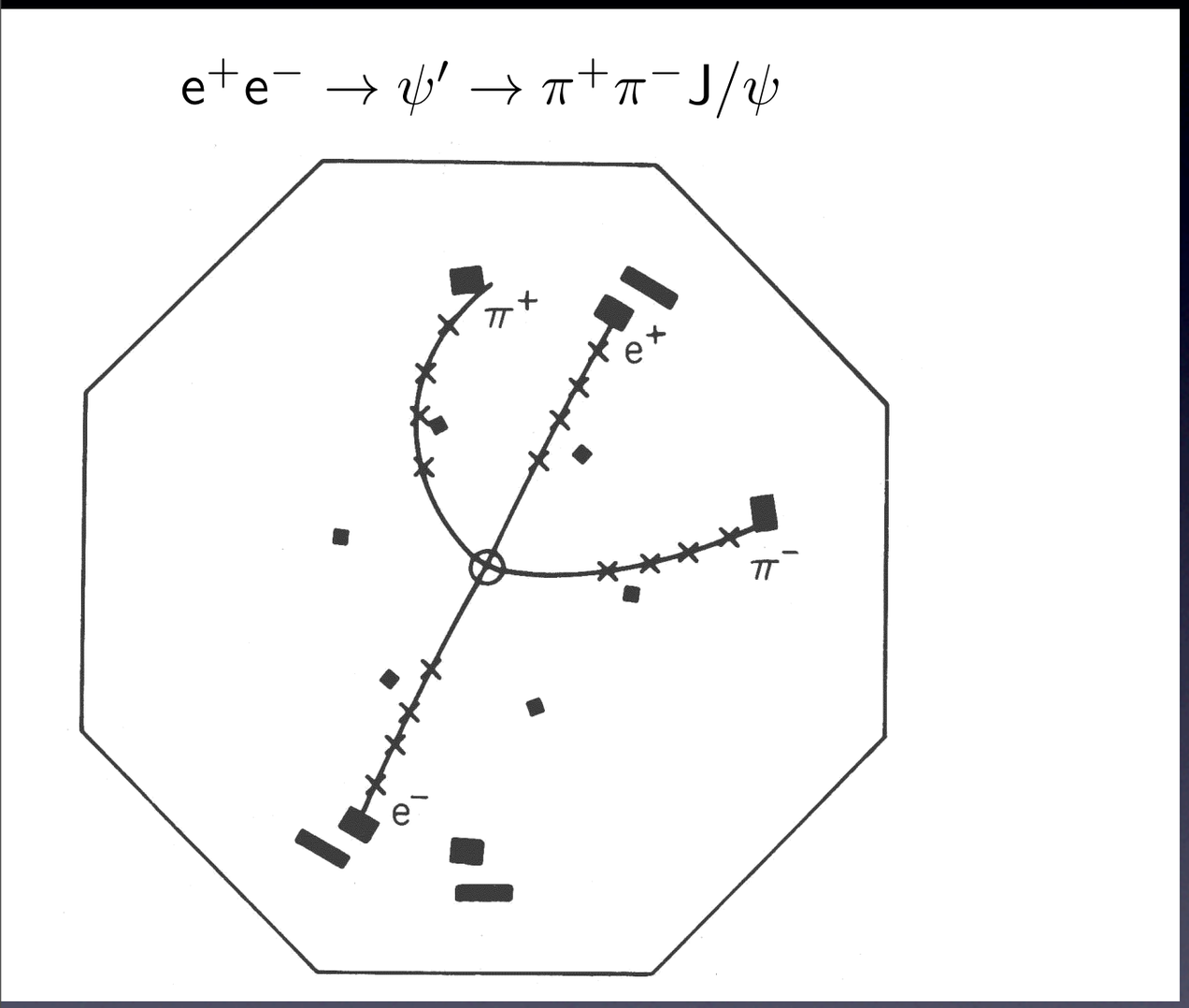
first discovery of a quark of large mass moving "slowly"

The November revolution in 1974: the J/ψ discovery



The Nobel Prize in Physics 1976 was awarded jointly to Burton Richter and Samuel Chao Chung Ting "for their pioneering work in the discovery of a heavy elementary particle of a new kind"

The November revolution in the '70s: more quarkonia

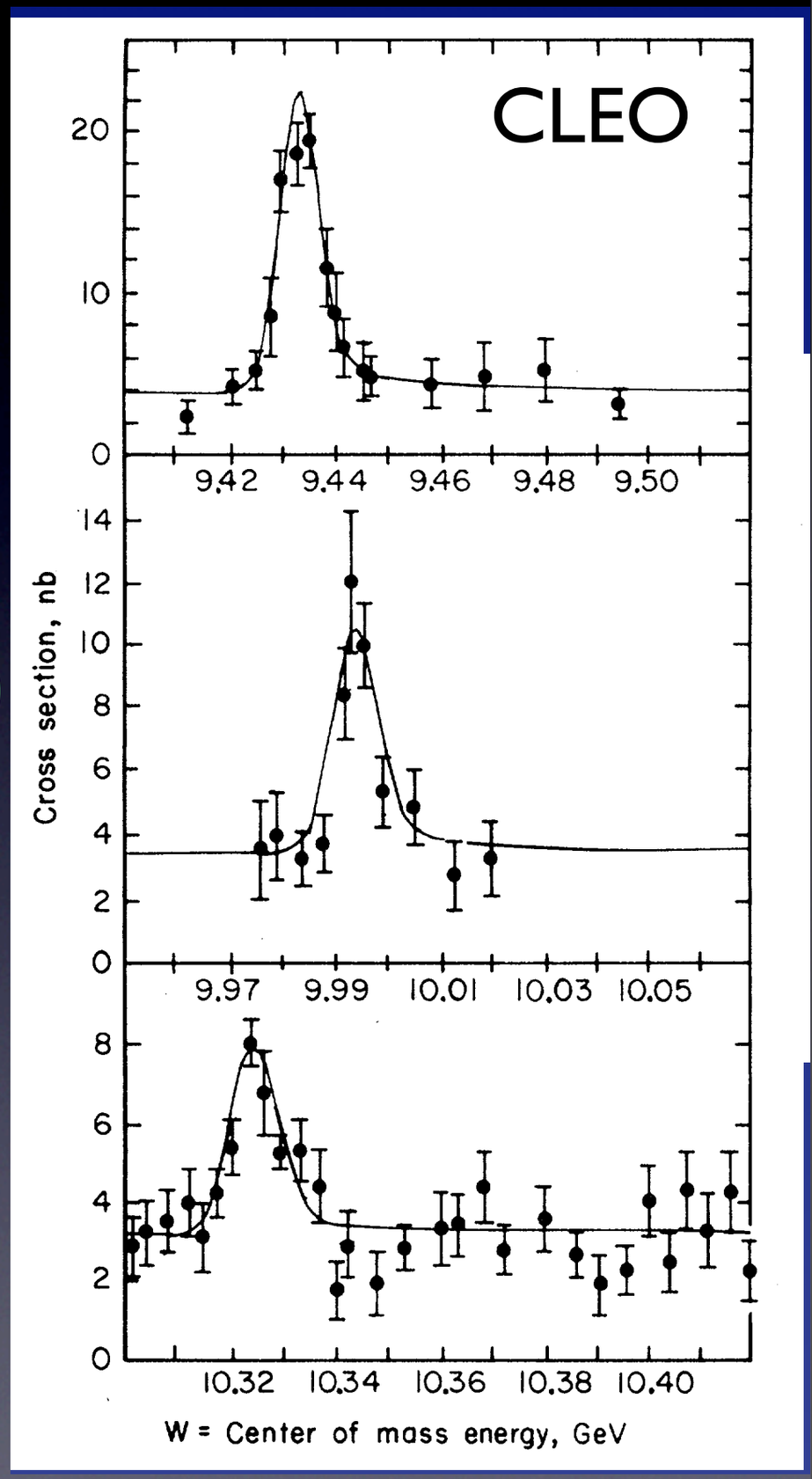


$\psi(2S)$

$\Upsilon(1S)$

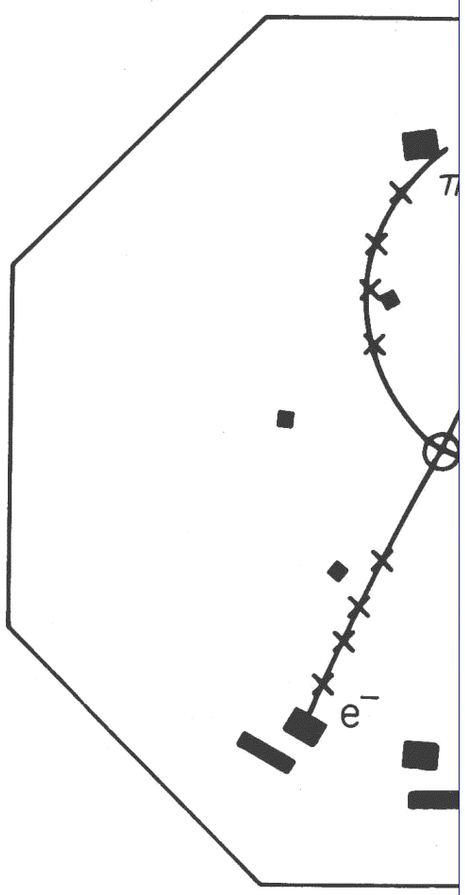
$\Upsilon(2S)$

$\Upsilon(3S)$



The Noven e quarkonia

$e^+e^- \to \psi' -$



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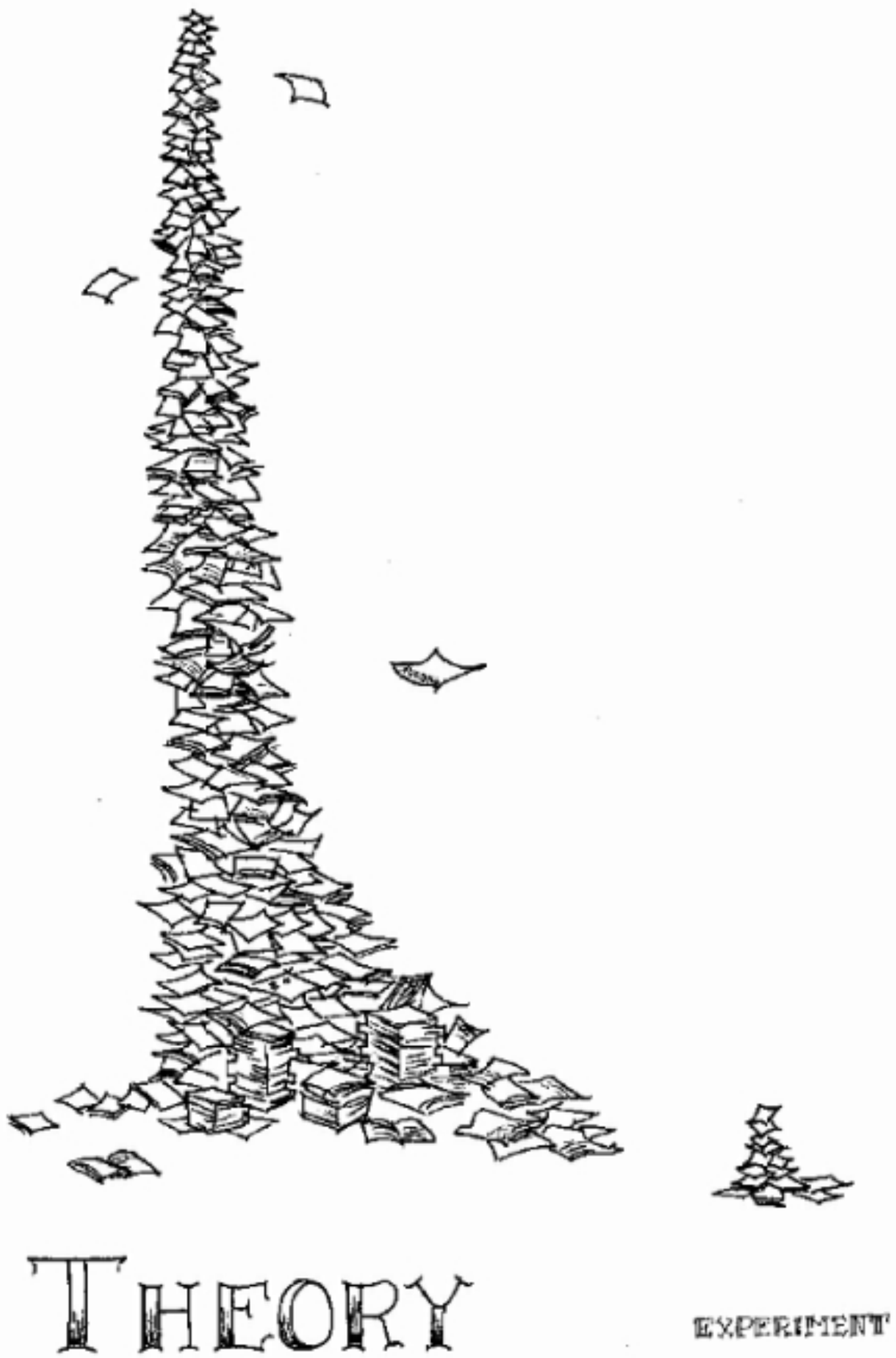

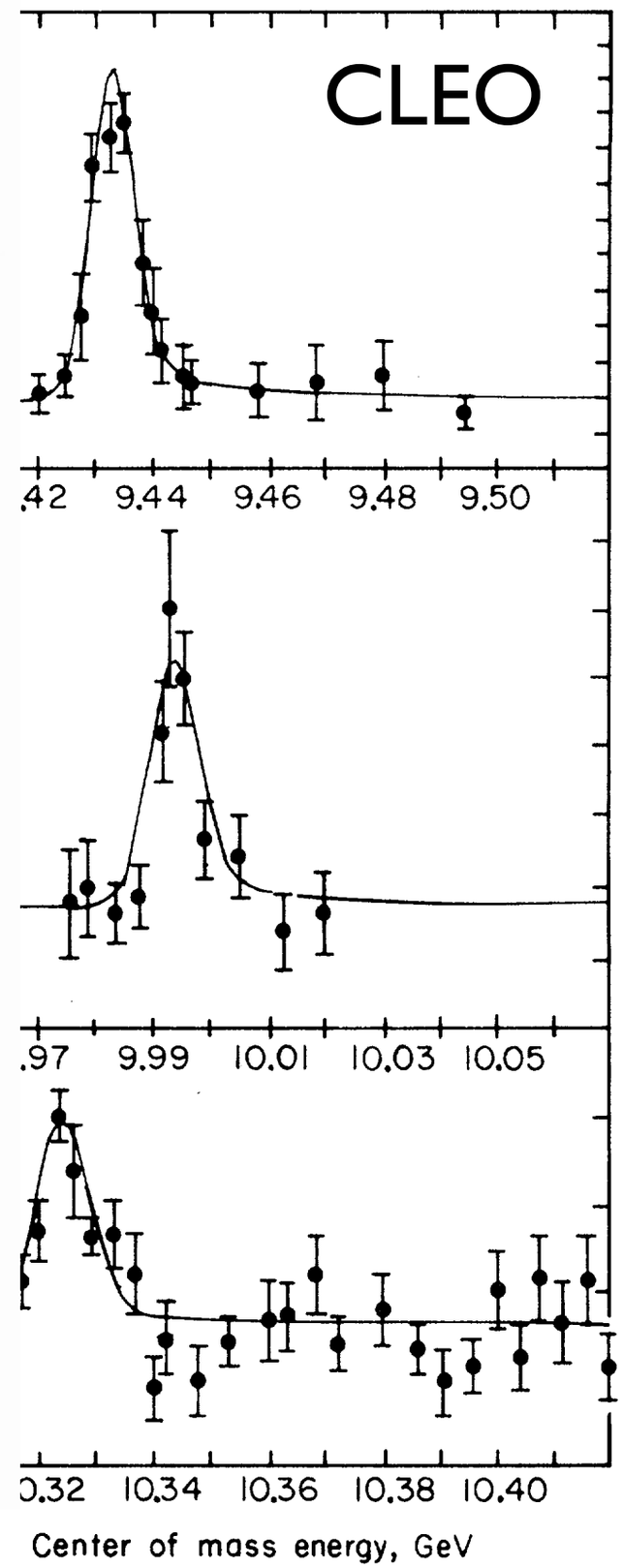

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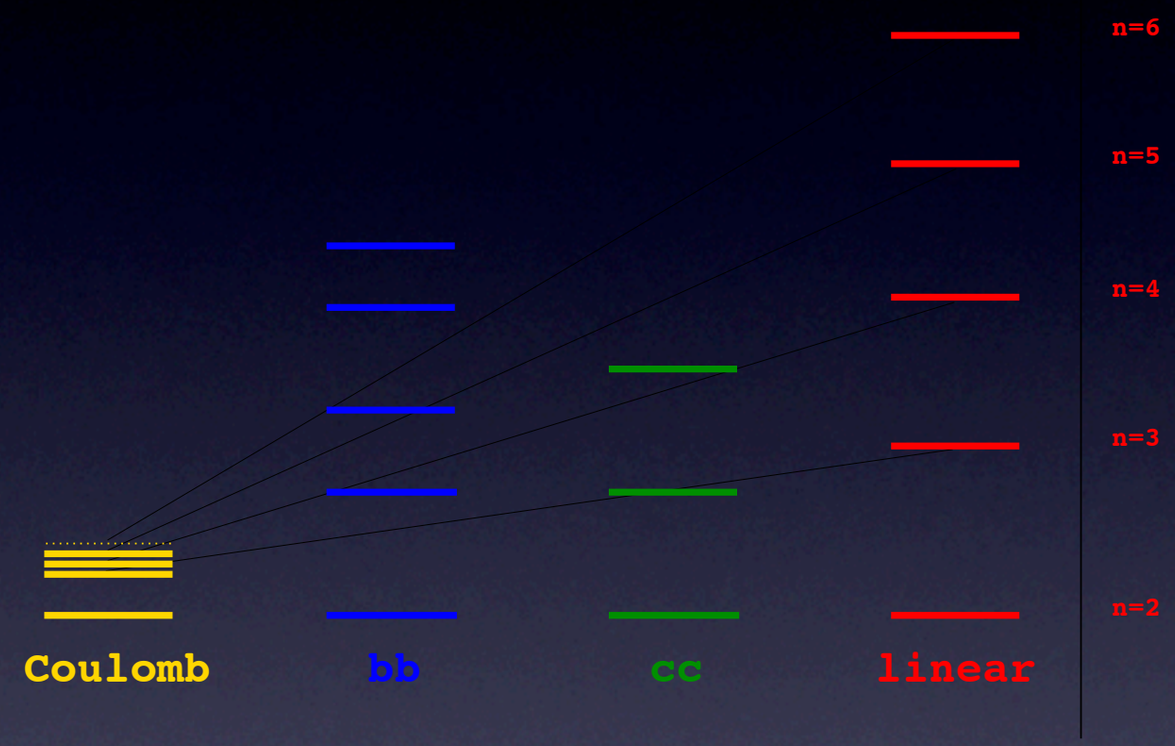

bbar and ccbar energy levels in comparison to
Coulomb and linear potential energy levels

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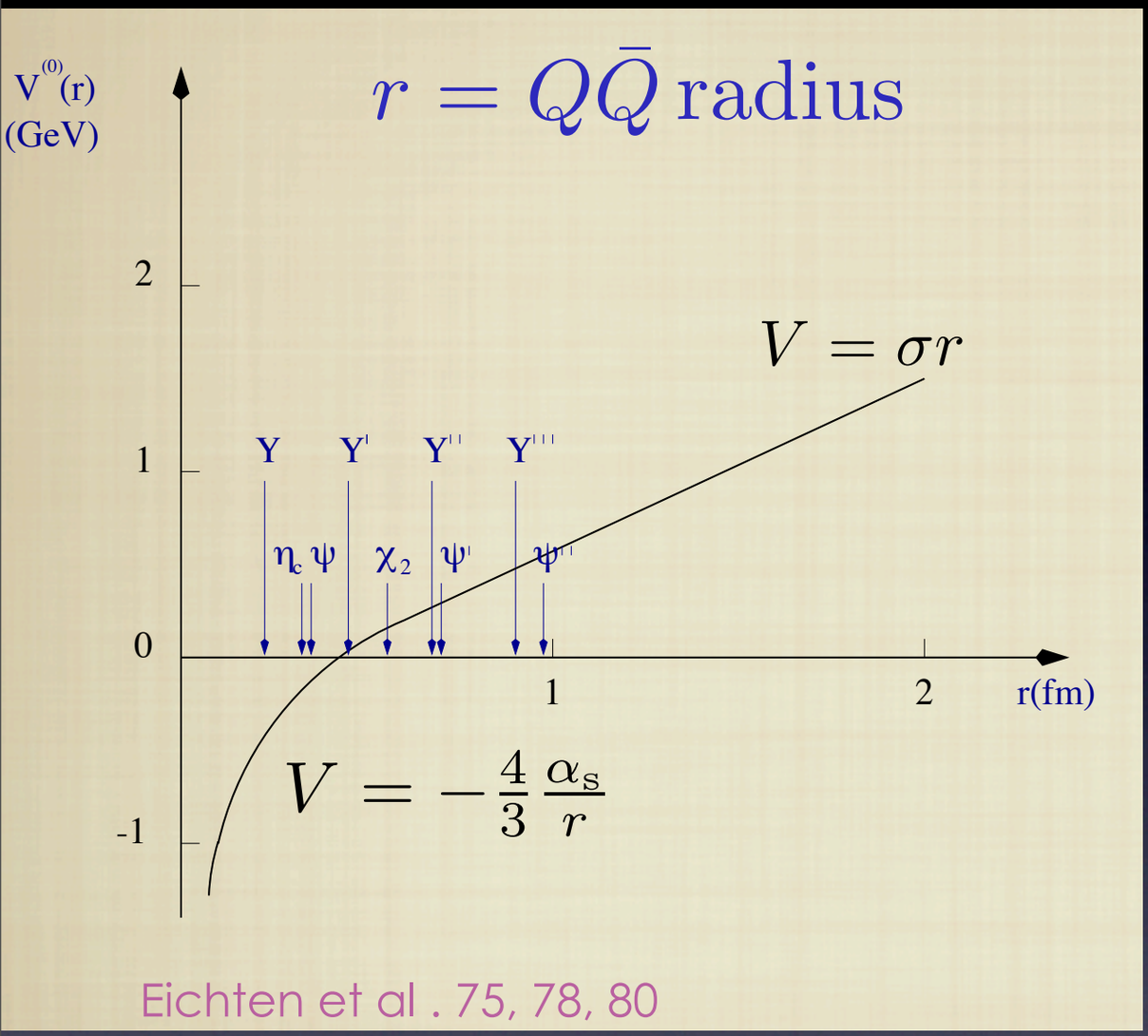
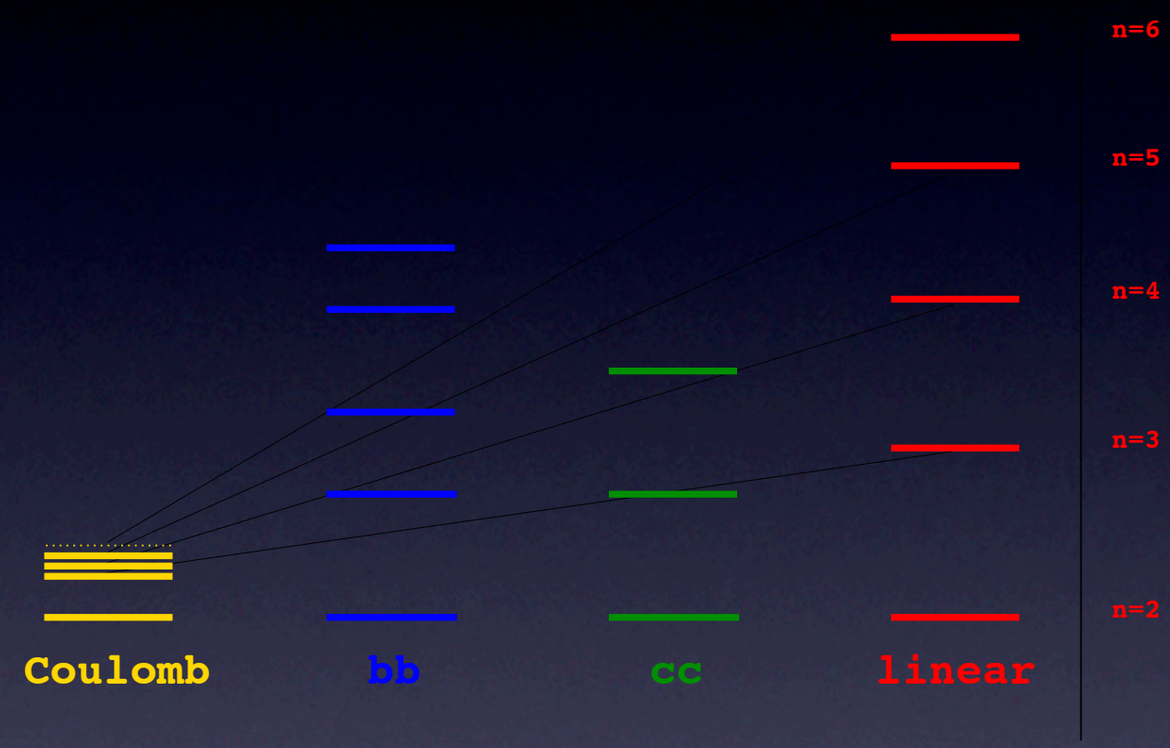


Eichten et al . 75, 78, 80



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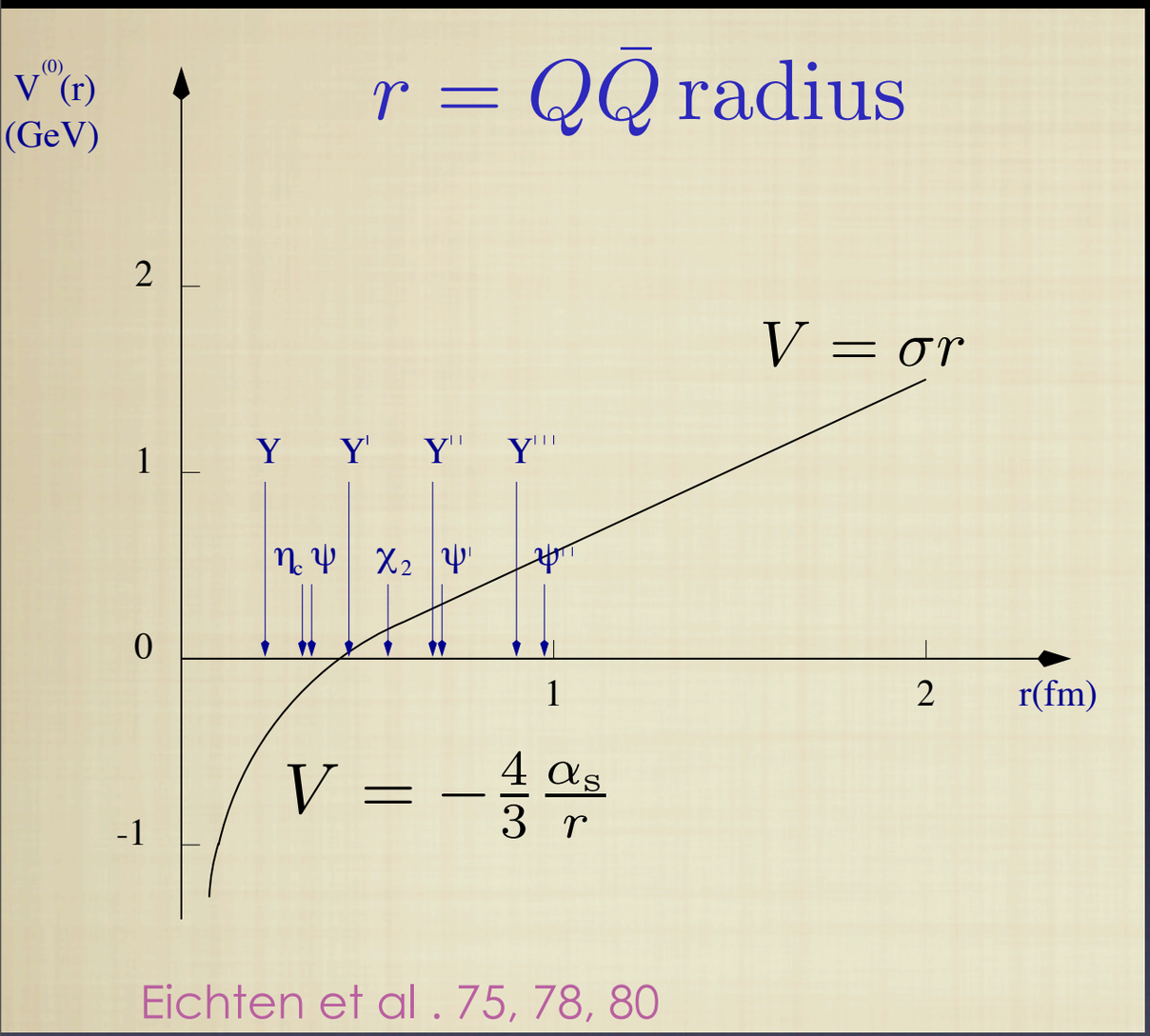

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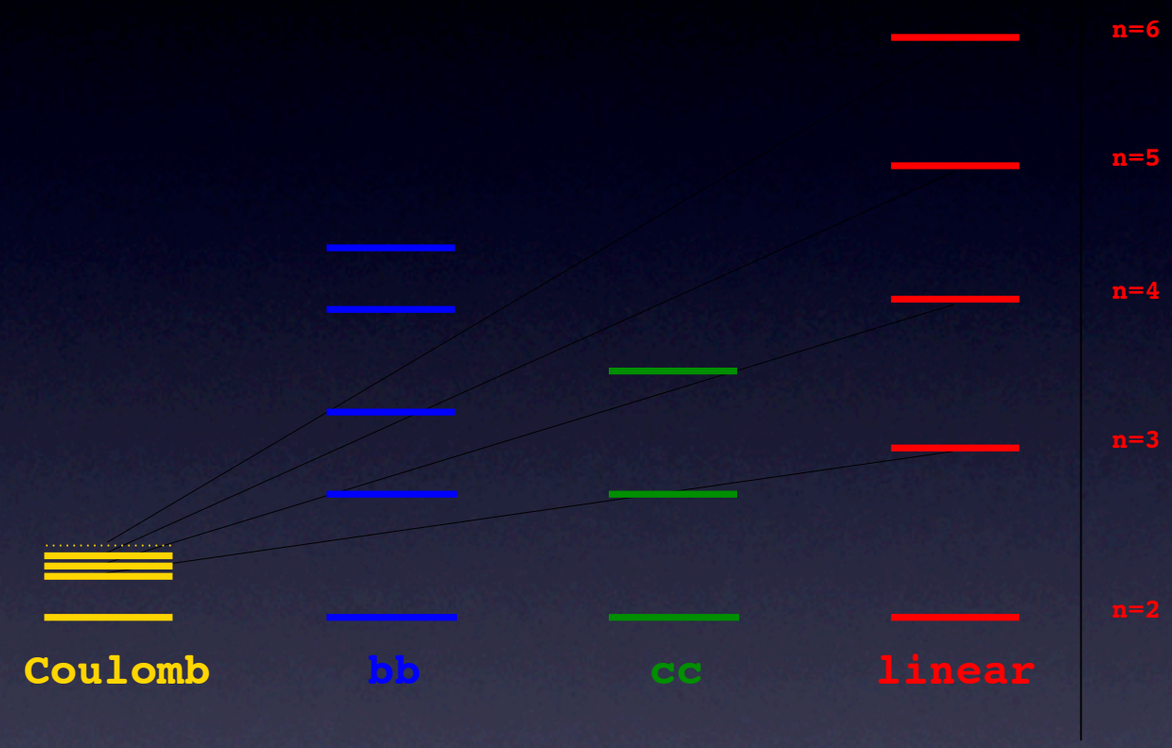


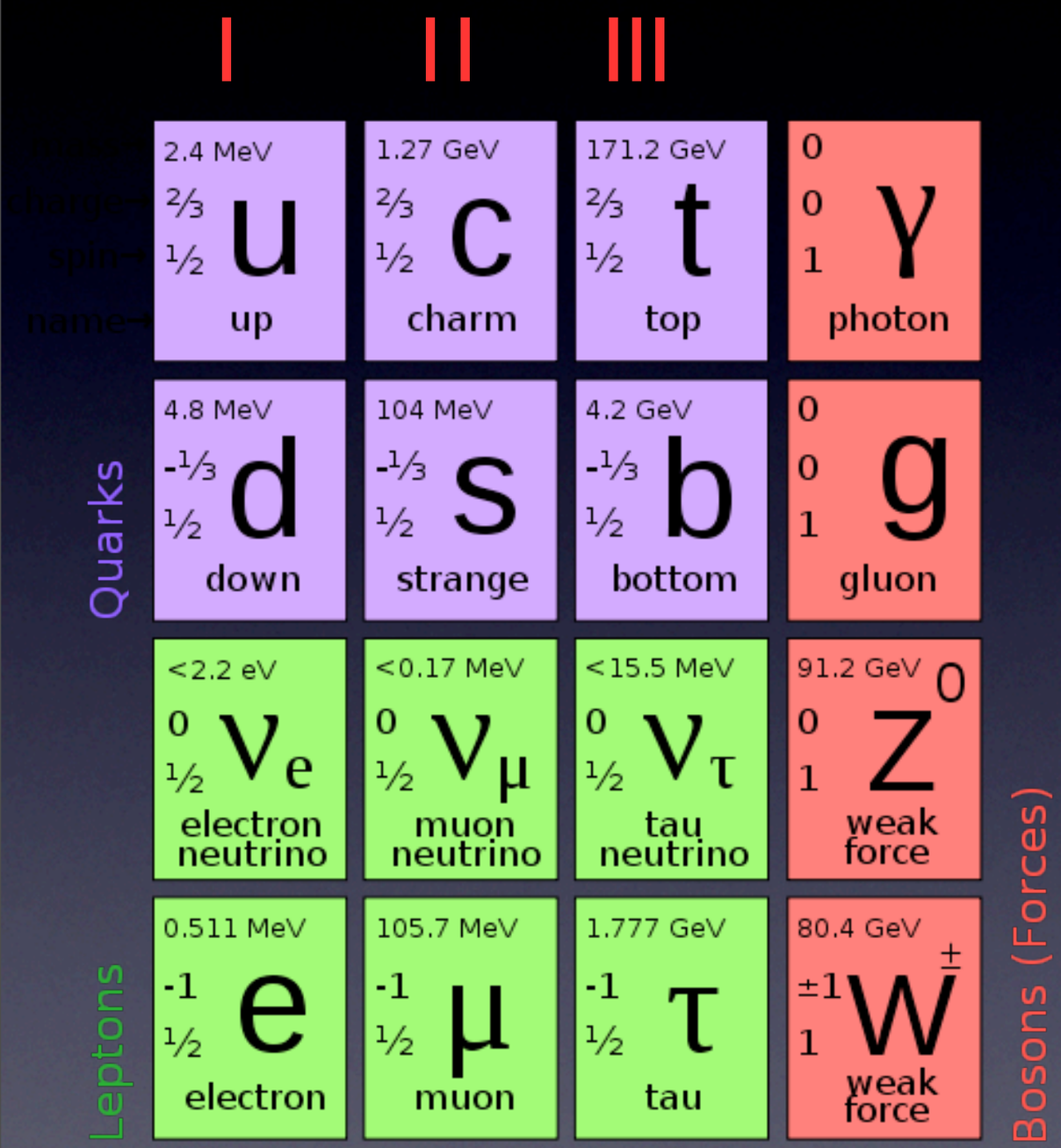
bbar and ccbar energy levels in comparison to Coulomb and linear potential energy levels

Variety of potential models used

Confinement and asymptotic freedom--> main properties of QCD

our present knowledge of particle physics is in

Standard model of Particle Physics



+ the Higgs boson

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Standard model of Particle Physics

A quantum field theory based on the gauge principle tested up to the Tev= 10^{12}eV and up to 10^{-19}m

	I	II	III	
mass→	2.4 MeV	1.27 GeV	171.2 GeV	0
charge→	⅔	⅔	⅔	0
spin→	½	½	½	1
name→	u up	c charm	t top	γ photon
Quarks	4.8 MeV, -⅓, ½, d down	104 MeV, -⅓, ½, s strange	4.2 GeV, -⅓, ½, b bottom	0, 0, 1, g gluon
Leptons	<2.2 eV, 0, ½, ν_e electron neutrino	<0.17 MeV, 0, ½, ν_μ muon neutrino	<15.5 MeV, 0, ½, ν_τ tau neutrino	91.2 GeV, 0, 1, Z^0 weak force
	0.511 MeV, -1, ½, e electron	105.7 MeV, -1, ½, μ muon	1.777 GeV, -1, ½, τ tau	80.4 GeV, ±1, 1, $W^\pm$ weak force

Bosons (Forces)

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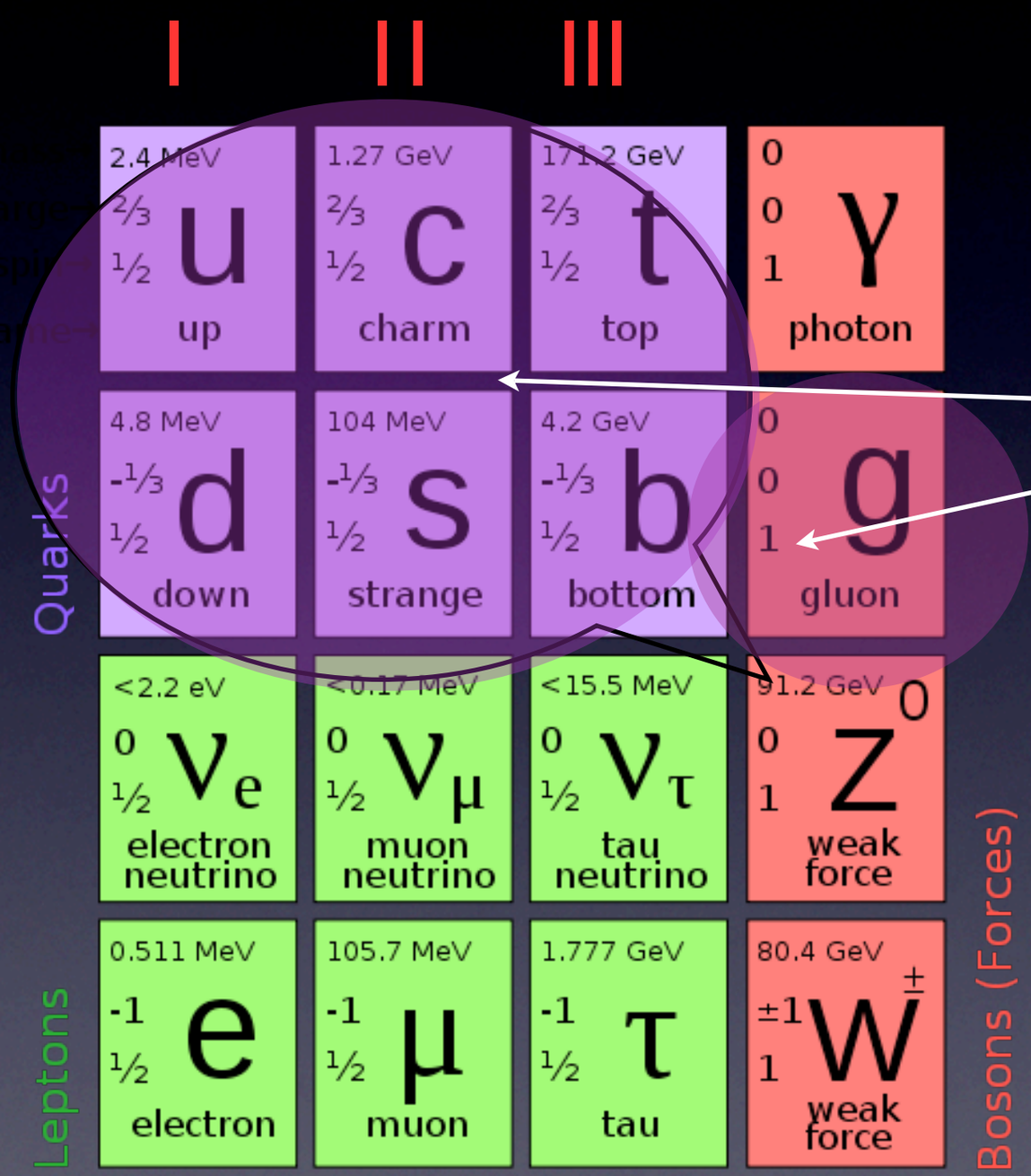

QCD

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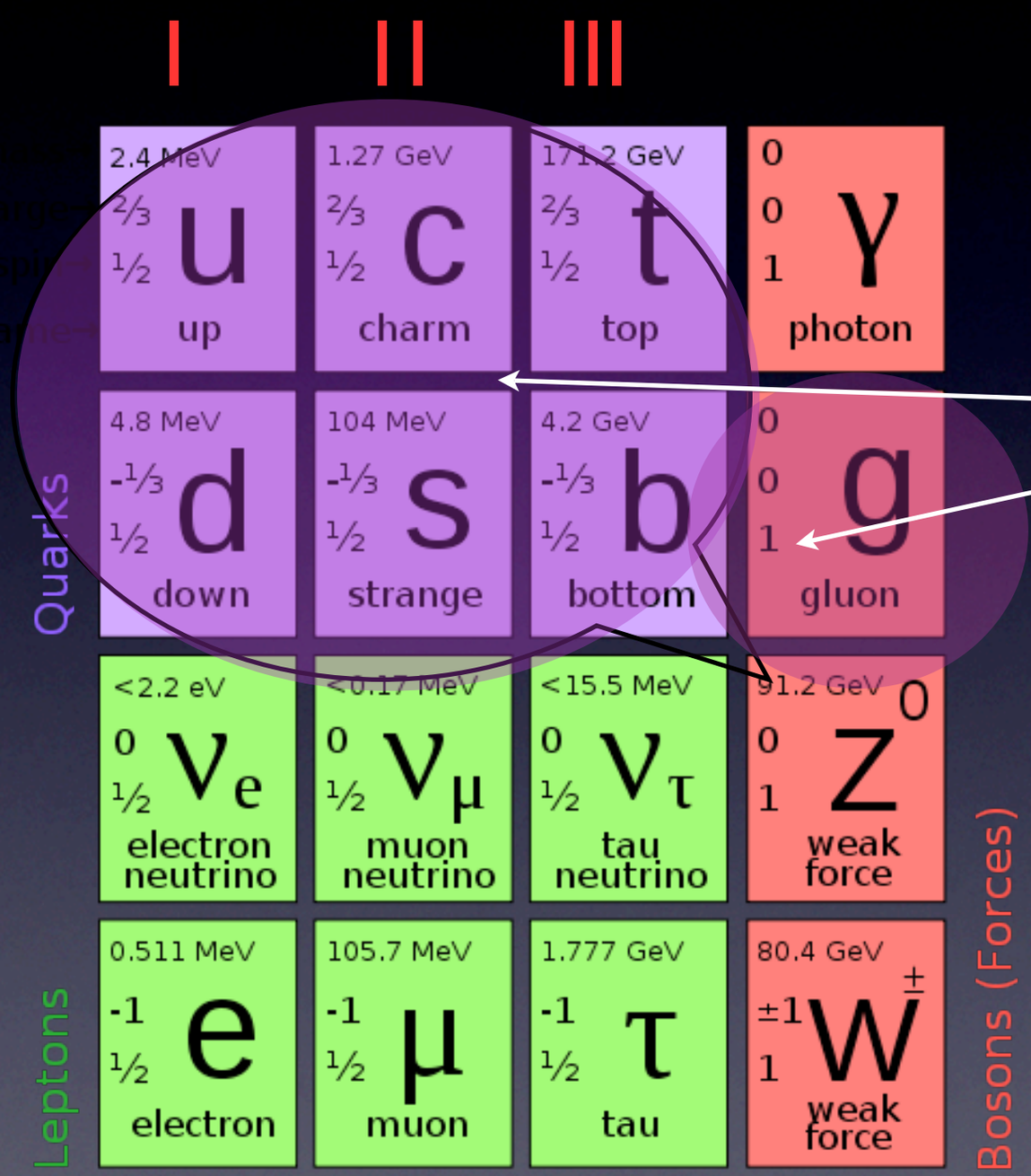

+ the Higgs boson

QCD

Differently from the other parts of the theory the low energy region of QCD cannot be studied by expanding in a small coupling constant, i.e. in perturbation theory. The non-perturbative nature of the QCD vacuum is a major difficulty that affects the determination of several observables in Particle Physics and some of the parameters of the Standard Model.

Quantum chromodynamics (QCD)

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4}\left(\partial_\mu A_\nu - \partial_\nu A_\mu - ig[A_\mu, A_\nu]\right)^2 + \bar{\psi}_f\left(i\partial\!\!\!/ - gA\!\!\!/ - m_f\right)\psi_f$$

$A^a_\mu, a = 1, 8$

Gluon field

$\psi^j{}_f, j = 1, 3, f = 1, 6$

Quark field

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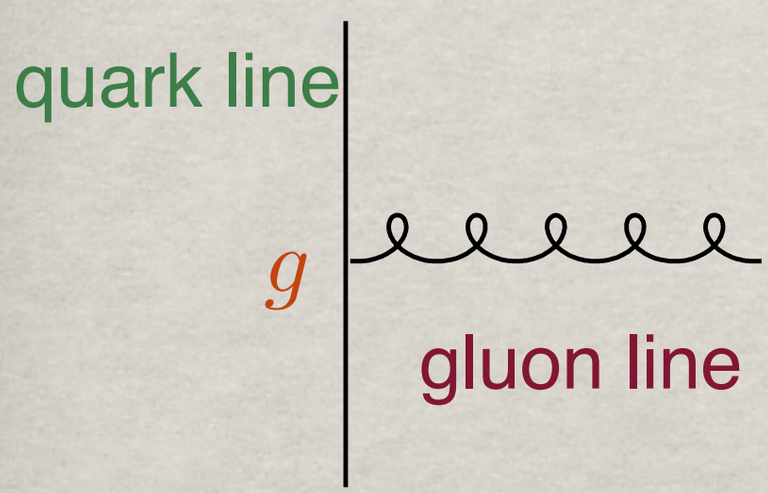
Quark field

Interaction vertices



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

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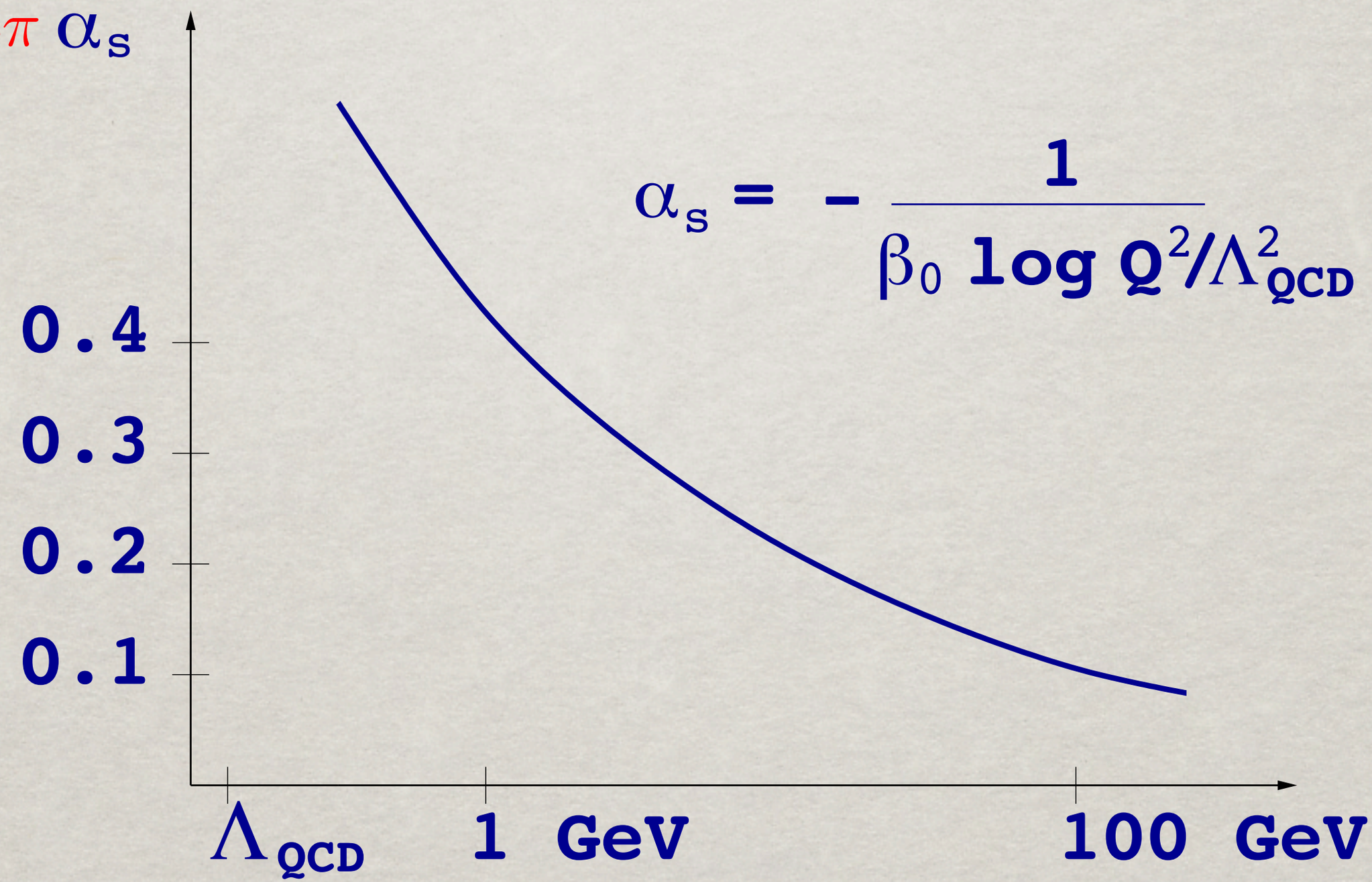

$$\alpha_s = -\frac{1}{\beta_0 \log Q^2/\Lambda^2_{QCD}}$$

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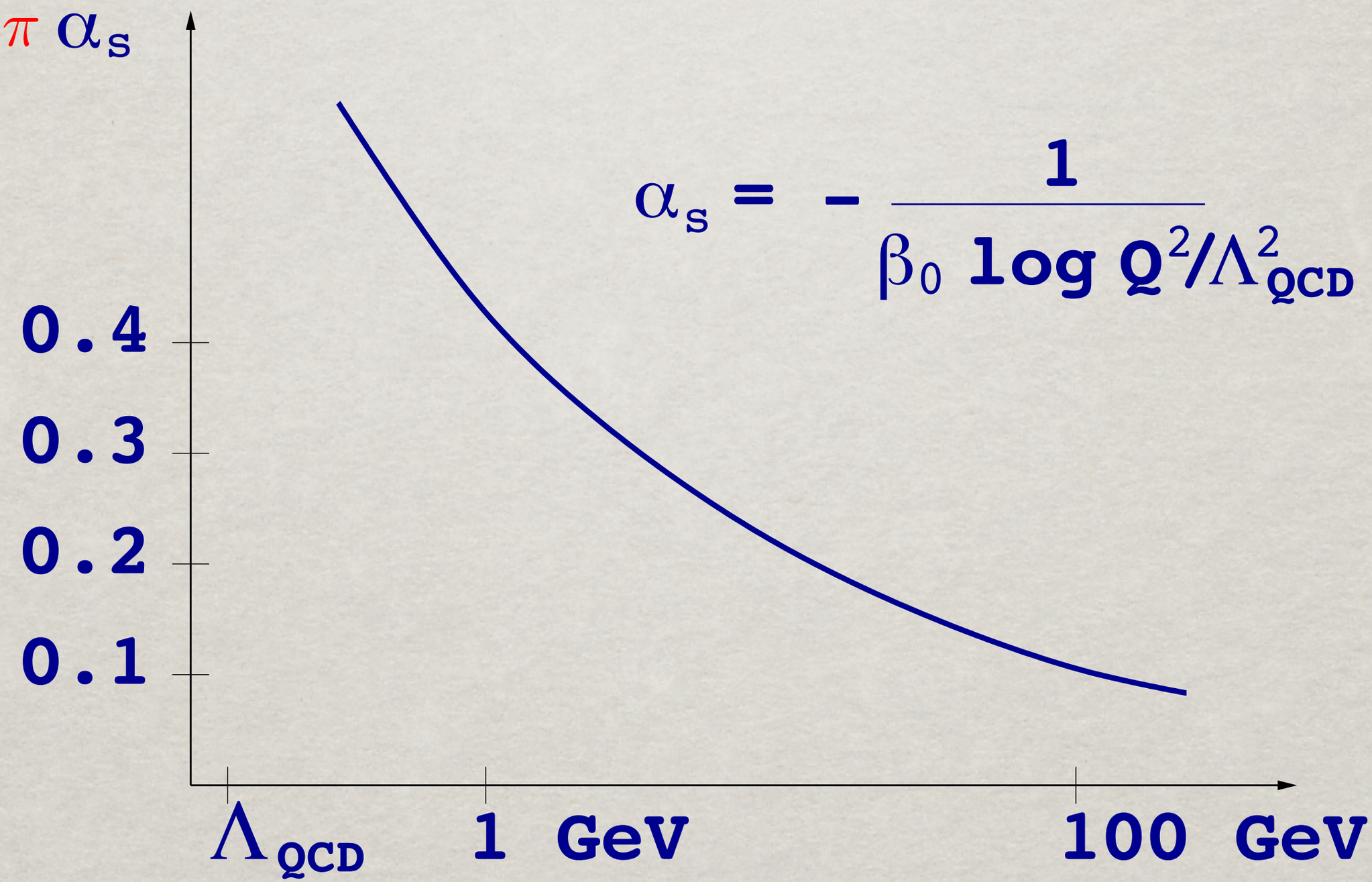

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Λ_{QCD} is the scale where nonperturbative effects dominate

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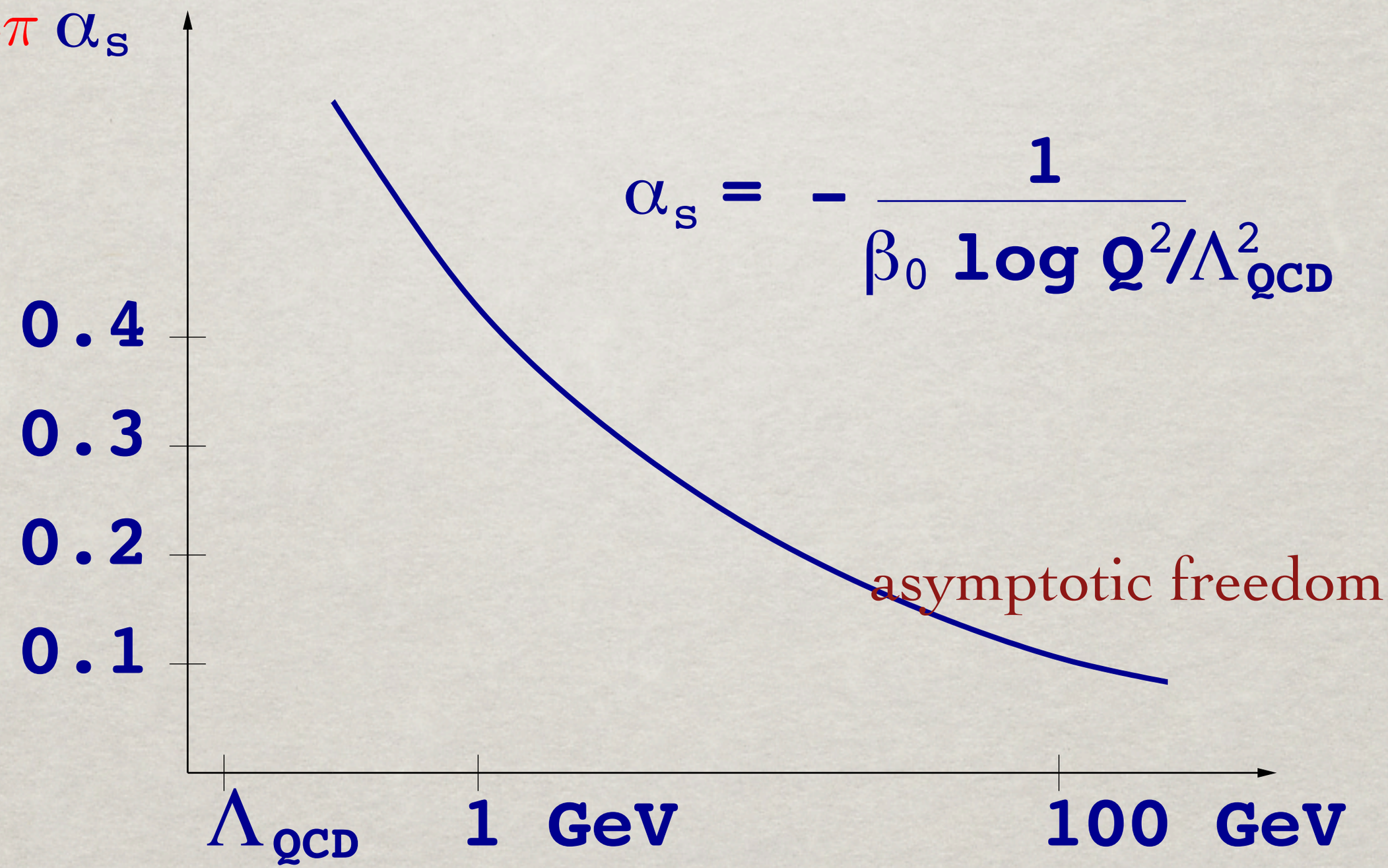

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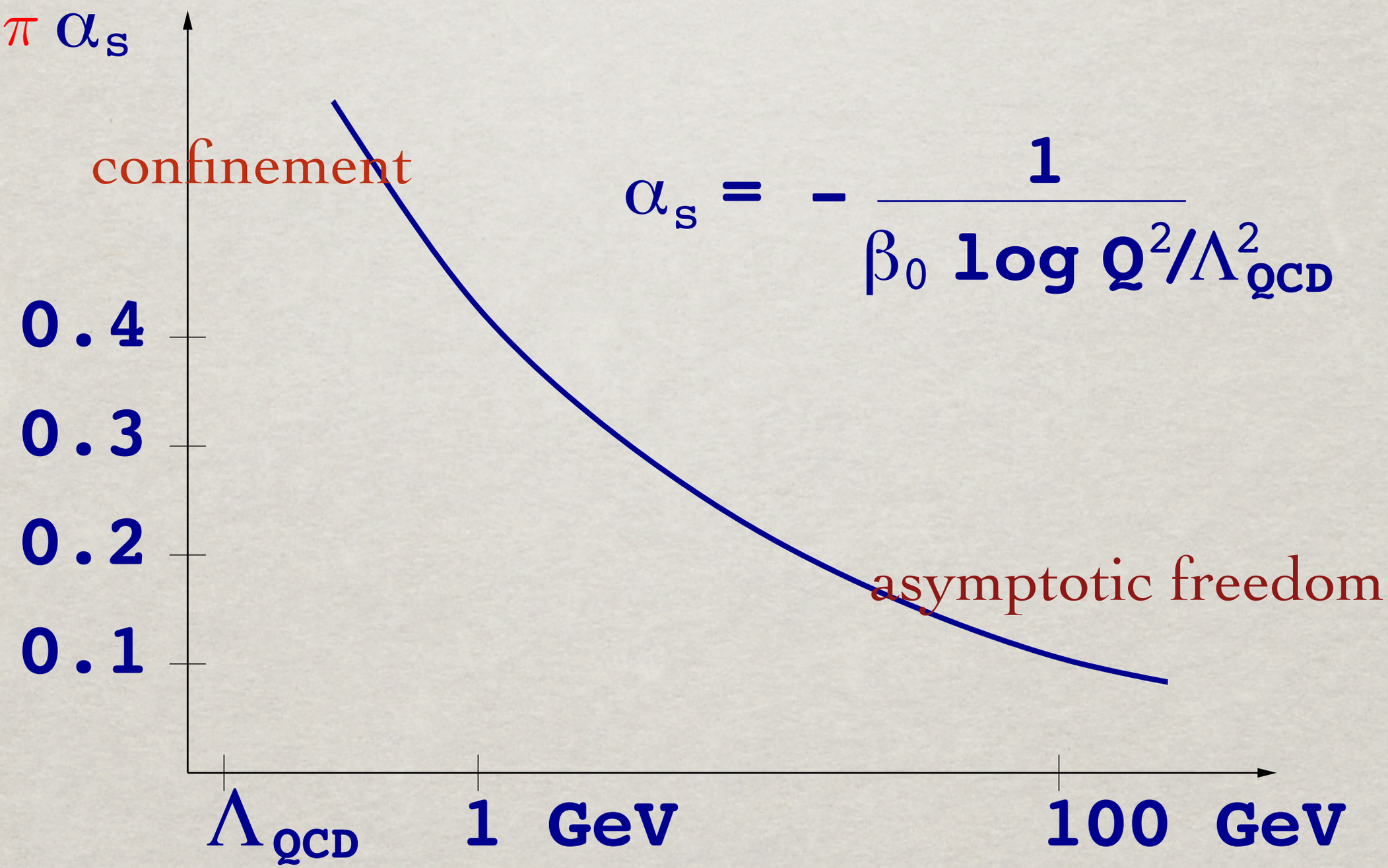

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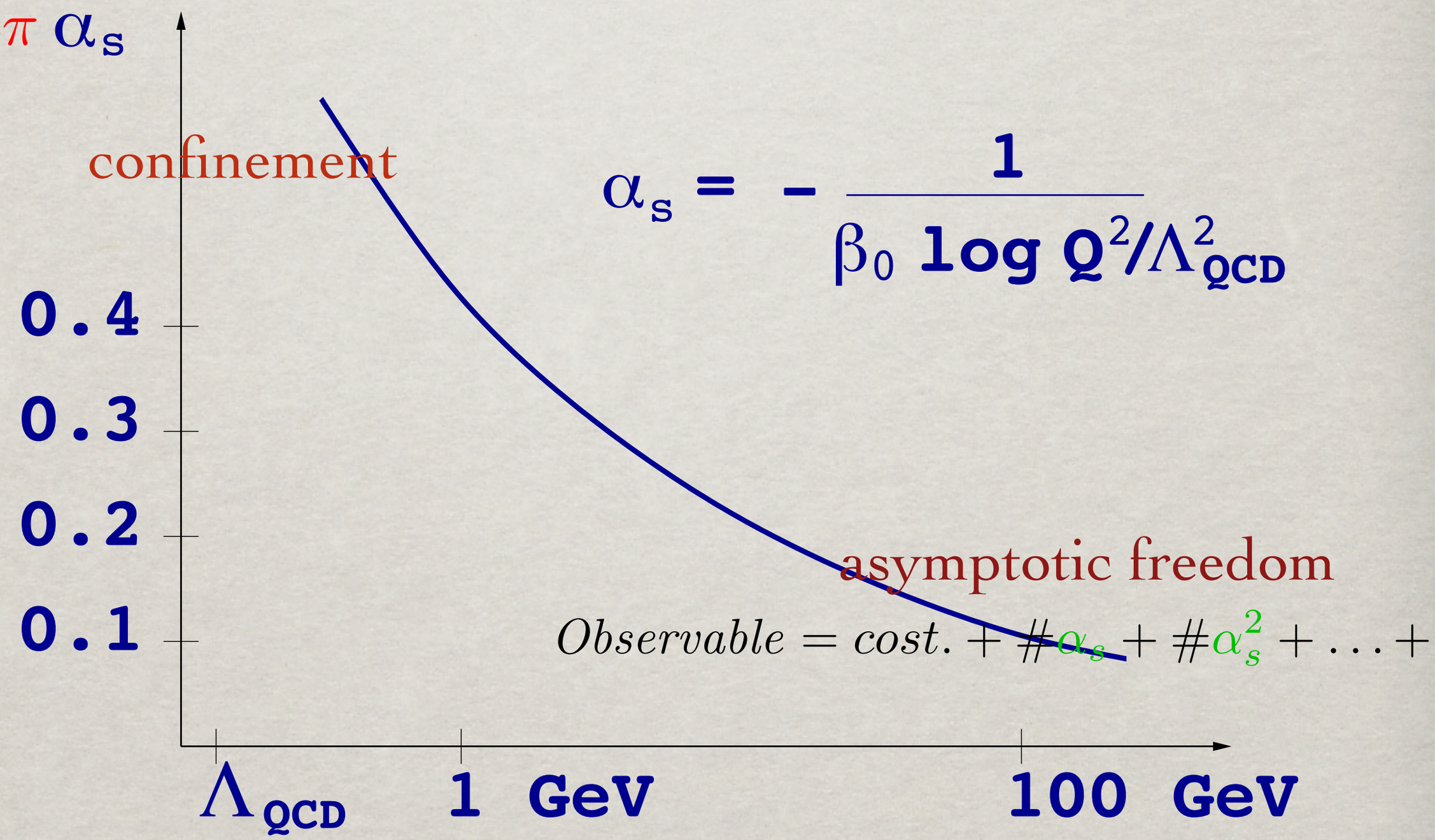

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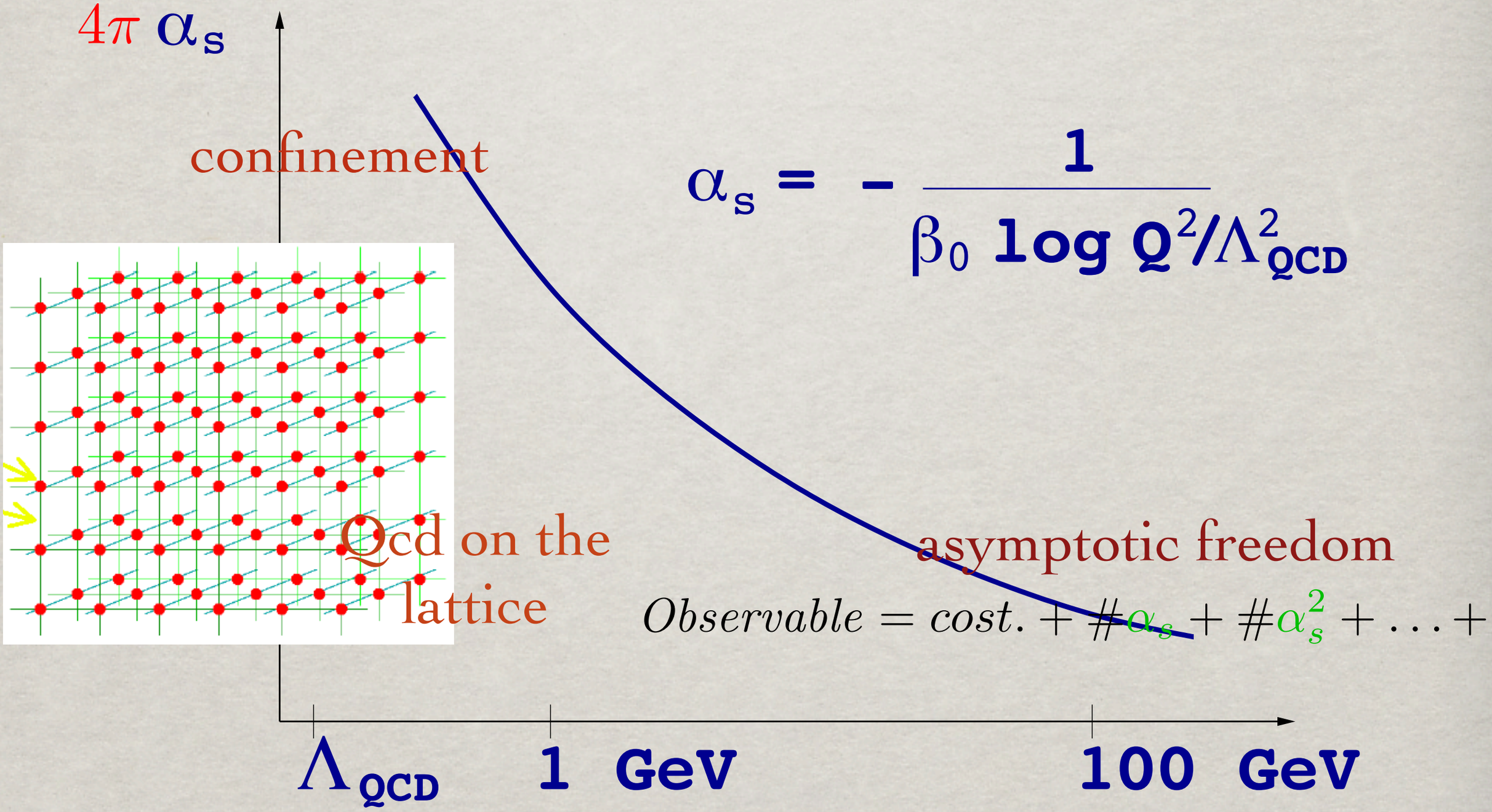


Λ_{QCD} is the scale where nonperturbative effects dominate

QCD contains a lot of physics : hadron masses

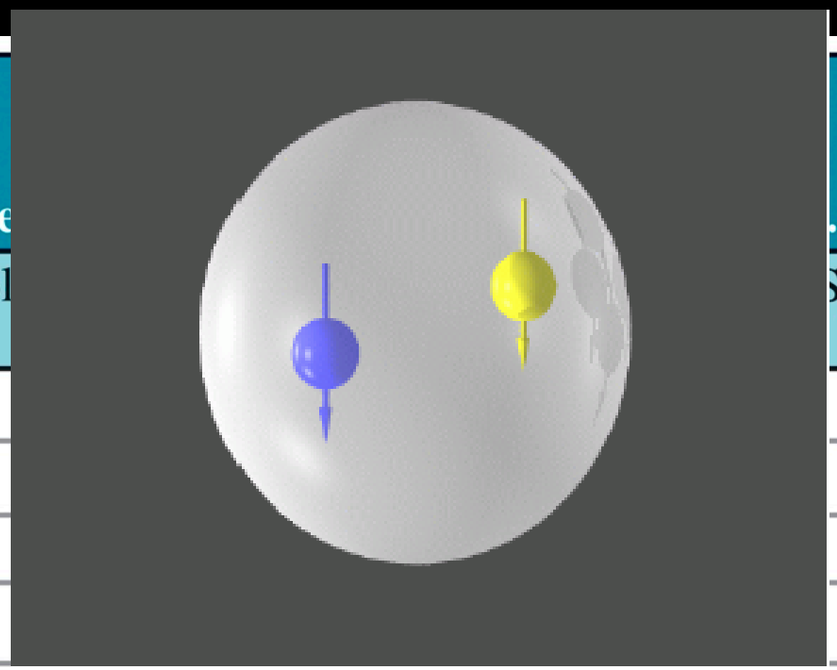
Mesons $q\bar{q}$
Mesons are bosonic hadrons
These are a few of the many types of mesons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

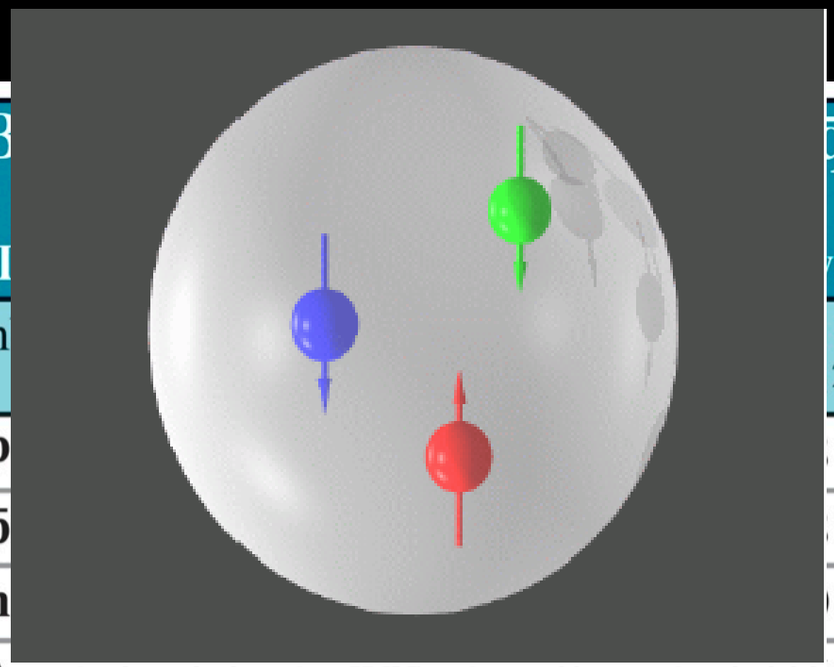
Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$
Baryons are fermionic hadrons.
These are a few of the many types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	antiproton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

QCD contains a lot of physics : hadron masses



Symbol					Spin
π^+					0
K^-					0
ρ^+					1
B^0					0
η_c	eta-c	$c\bar{c}$	0	2.980	0



Sym				2	Spin
p					1/2
$\bar{p}$					1/2
n					1/2
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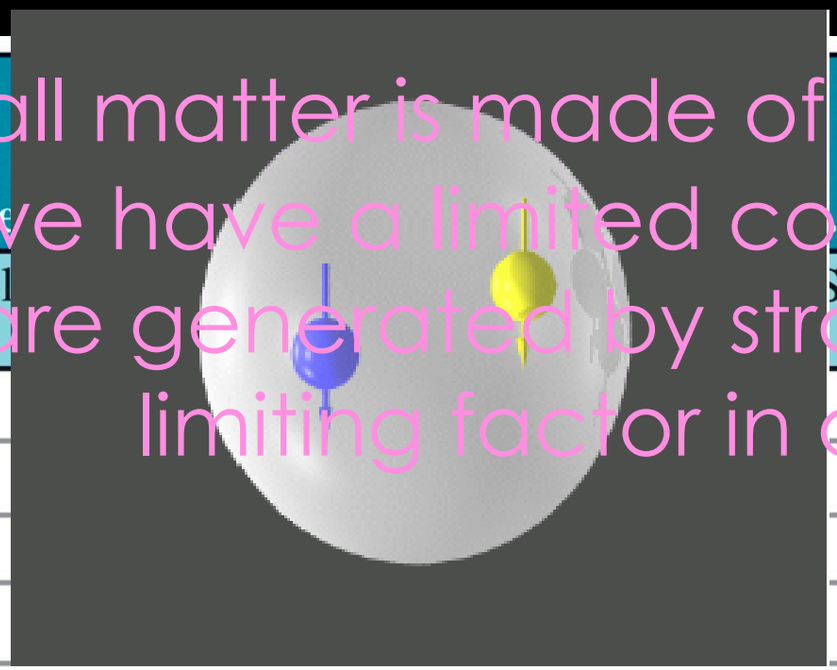

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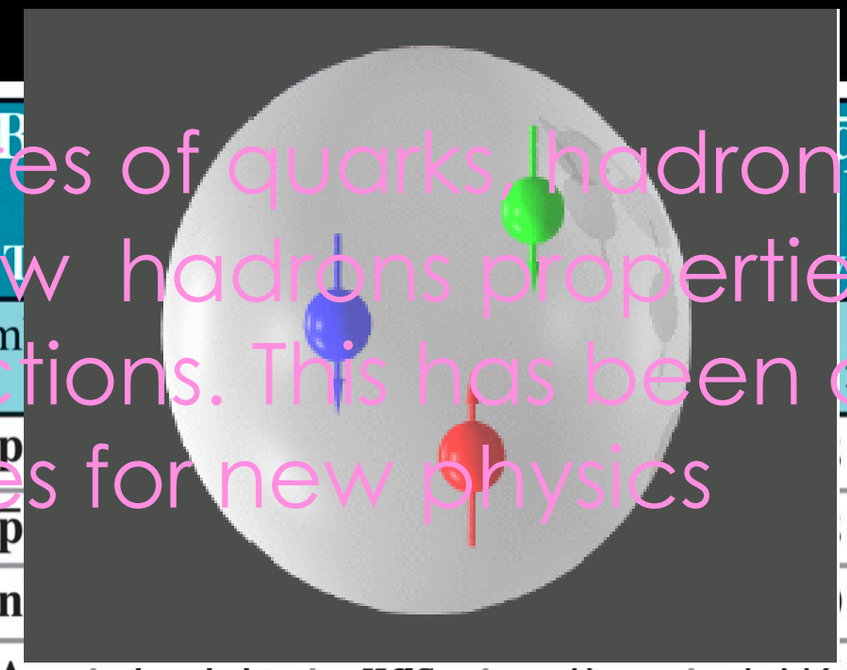

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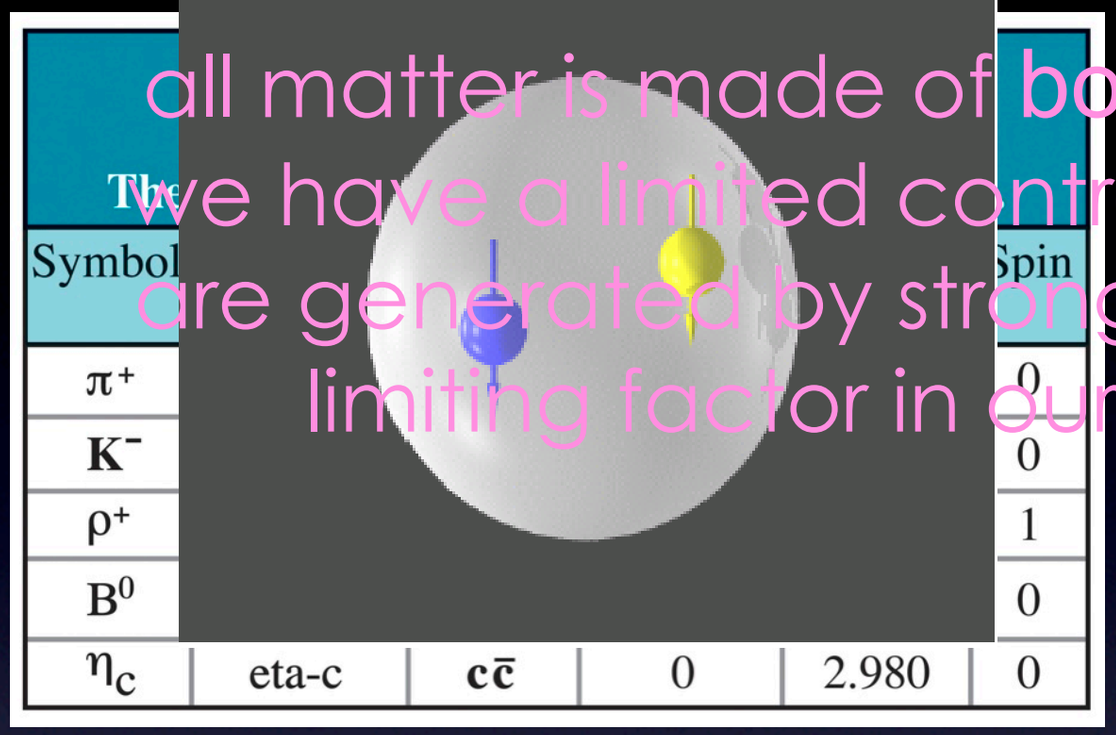
all matter is made of **bound** states of quarks, hadrons.
We have a limited control on how hadrons properties are generated by strong interactions. This has been a limiting factor in our searches for new physics

QCD contains a lot of physics : hadron masses



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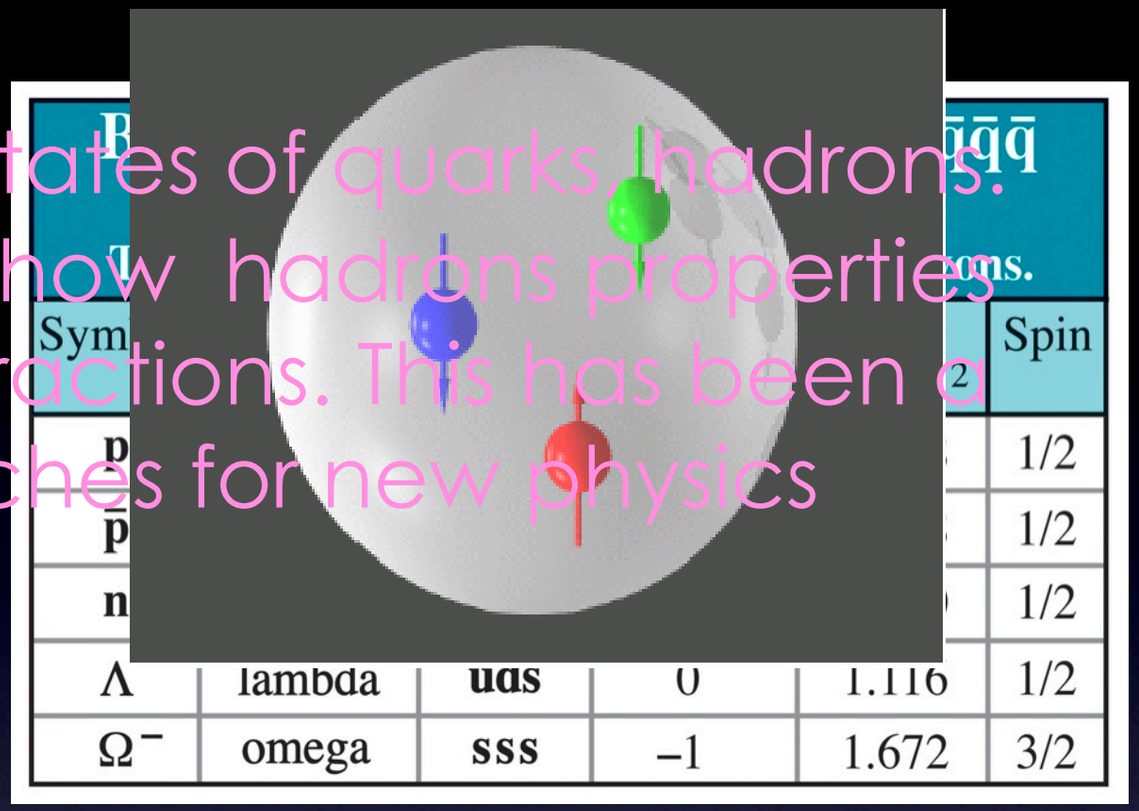

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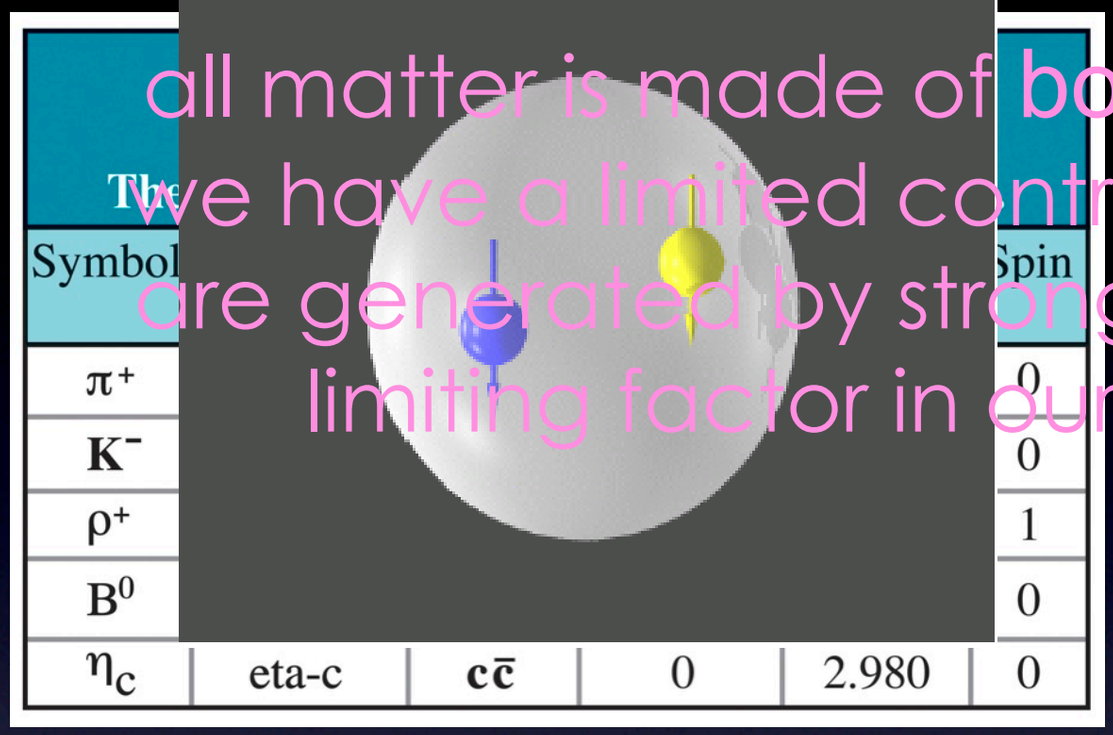
it is at the origin of all “observable” matter

QCD contains a lot of physics : hadron masses



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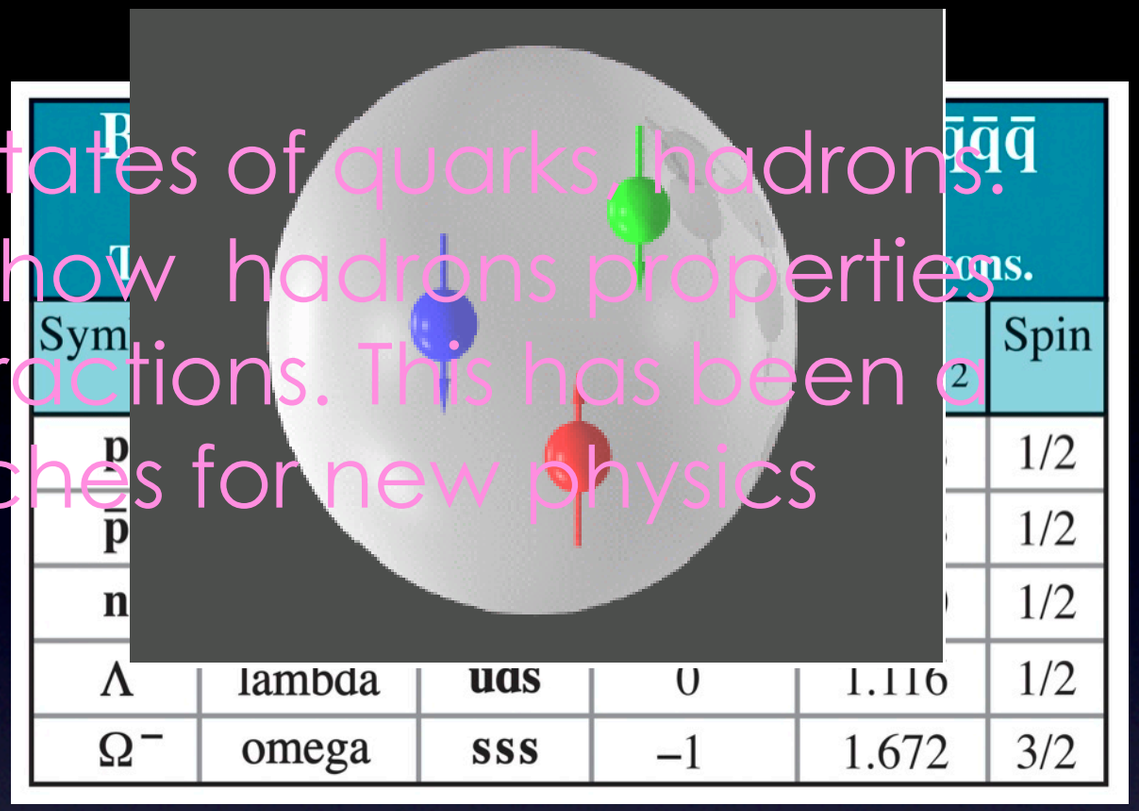

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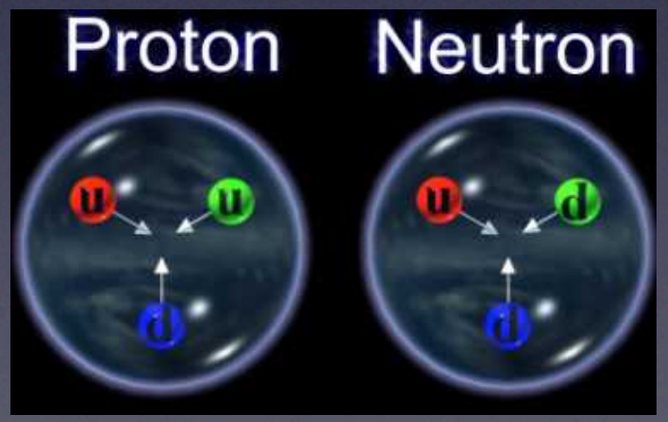
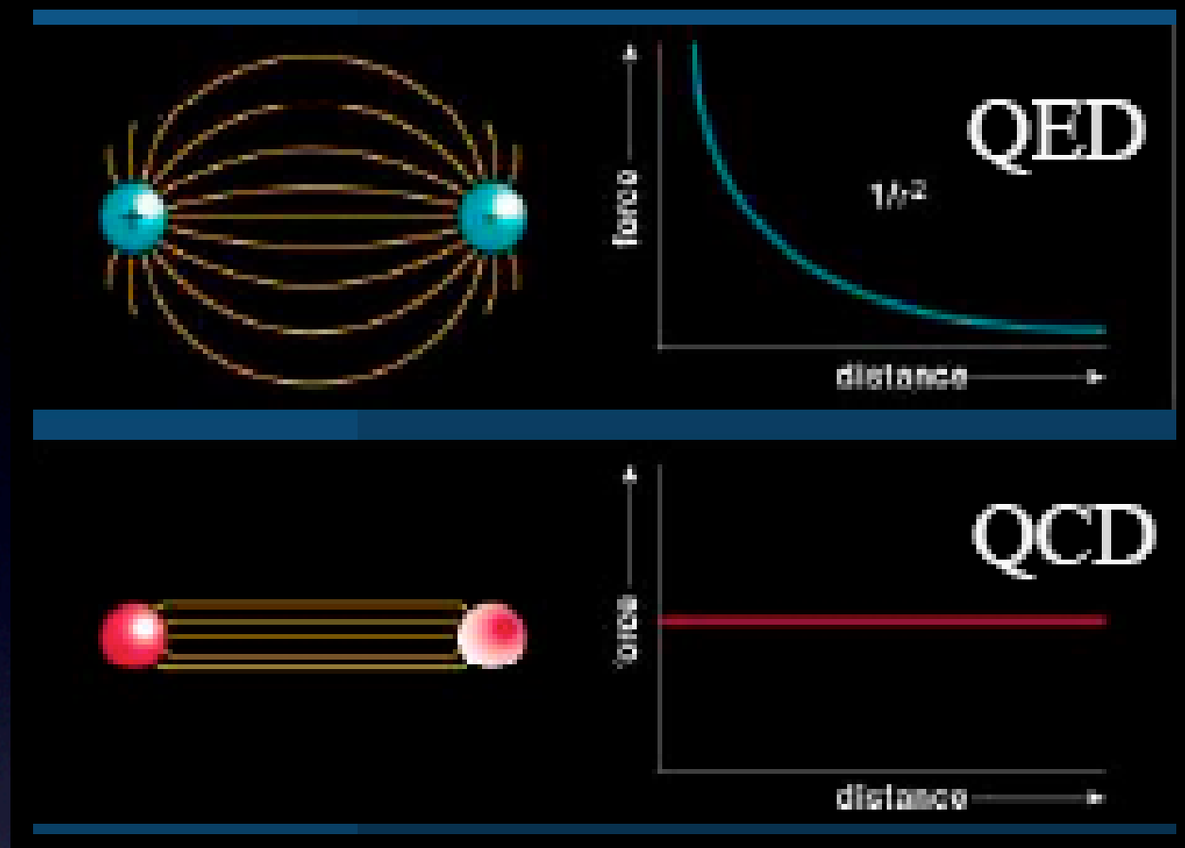
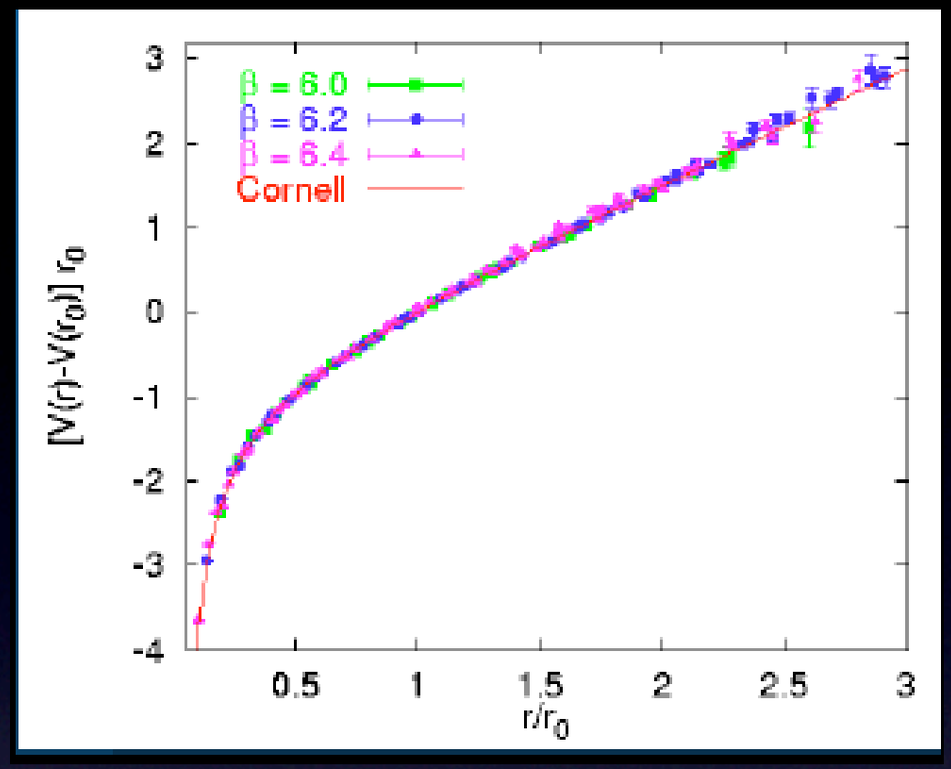
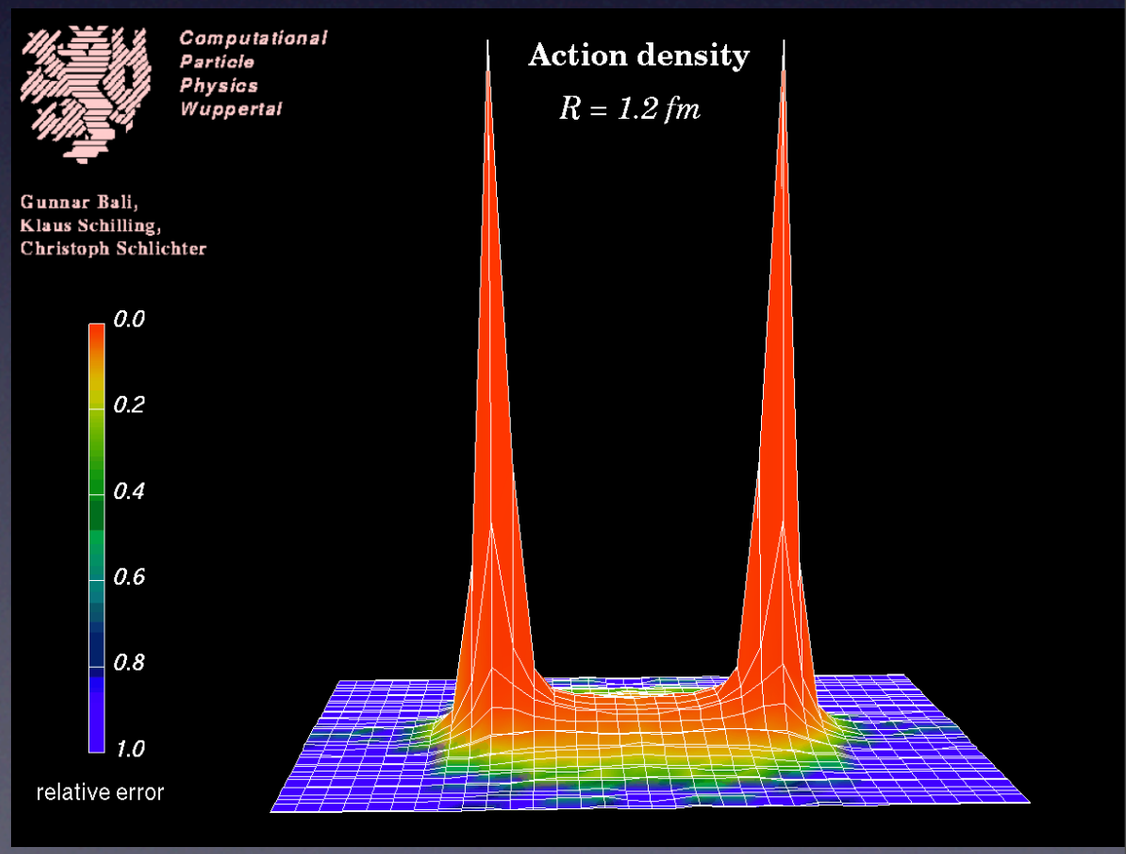


$$M \sim \Lambda_{QCD}$$

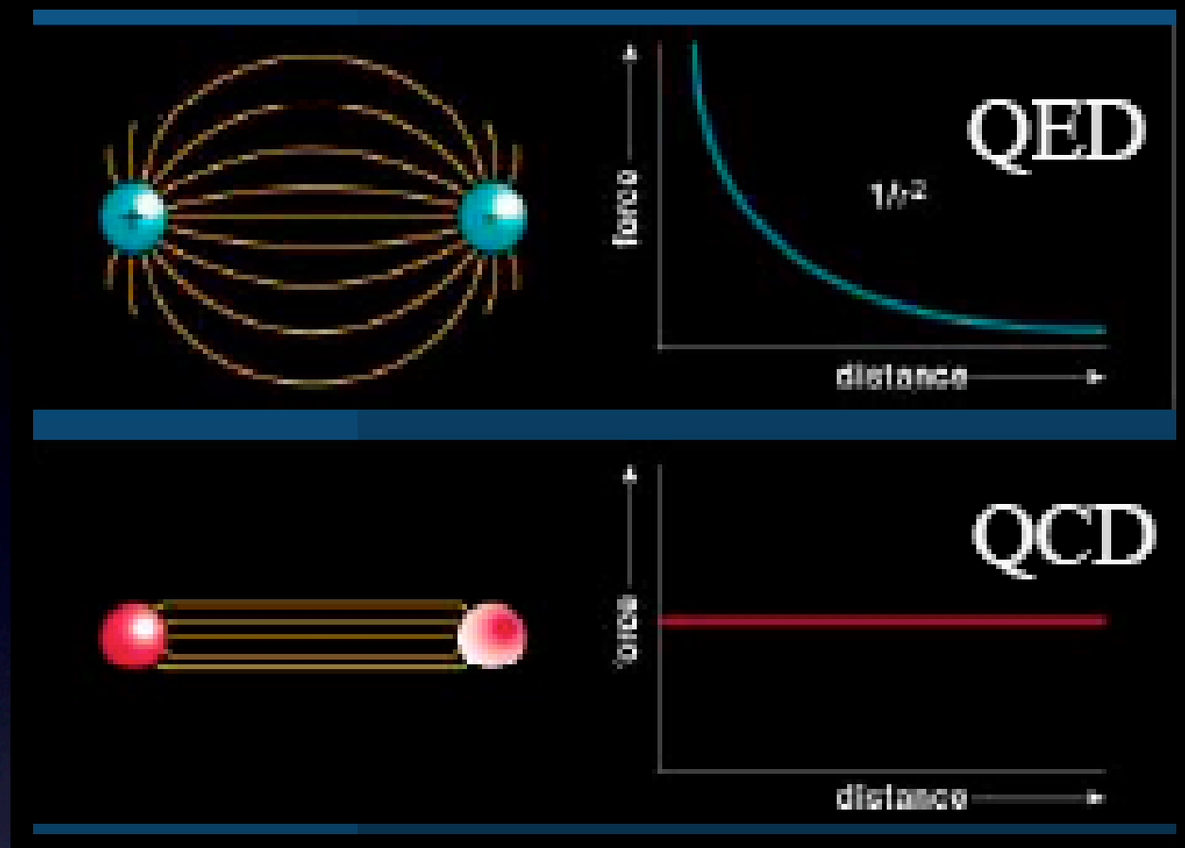
QCD contains a lot of physics : confinement

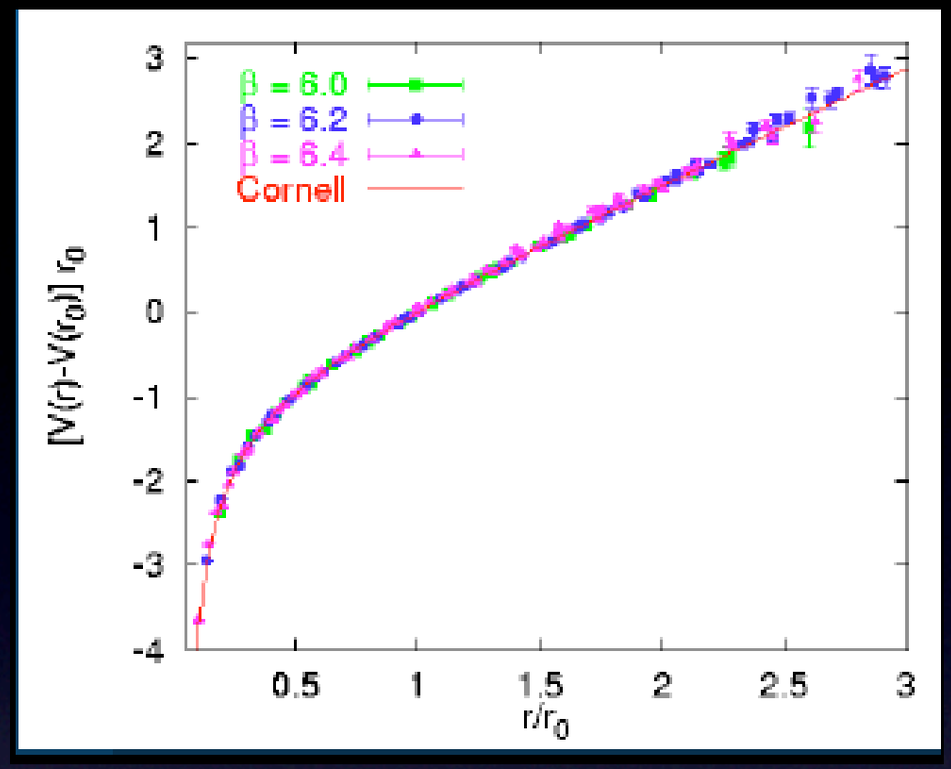






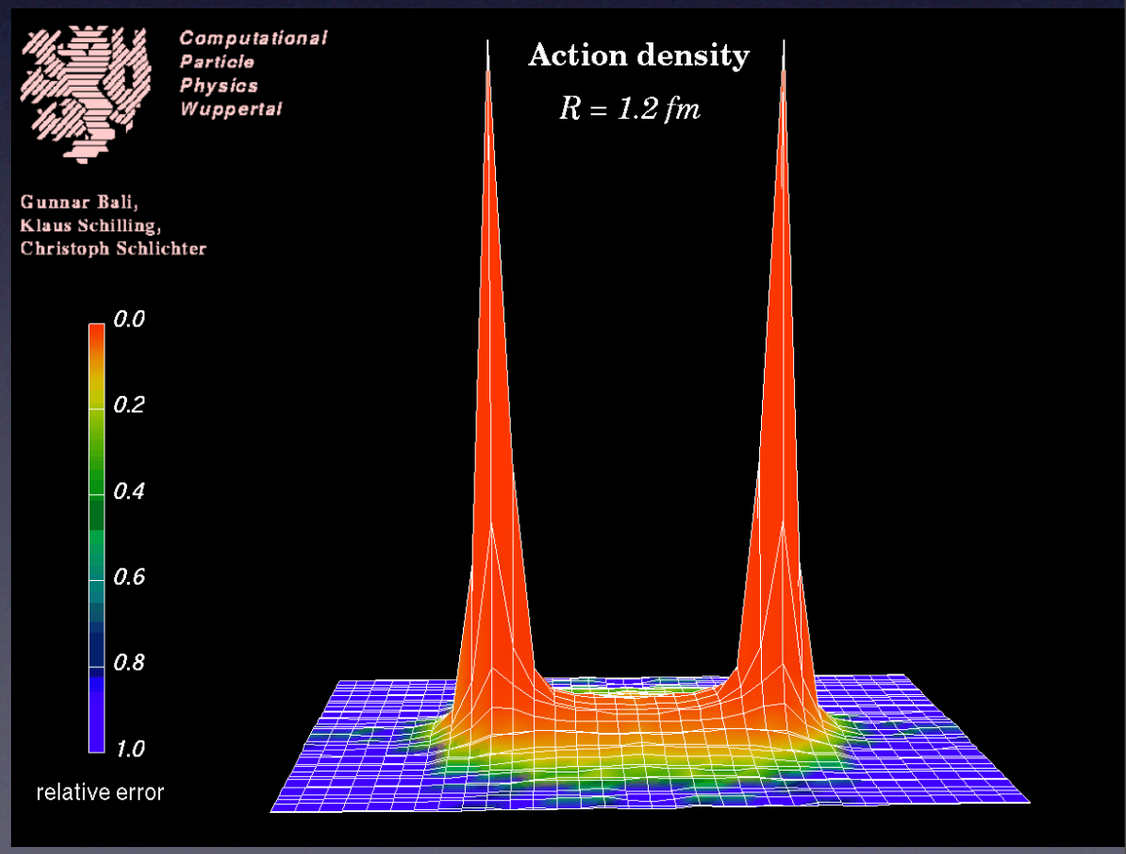
QCD contains a lot of physics : confinement



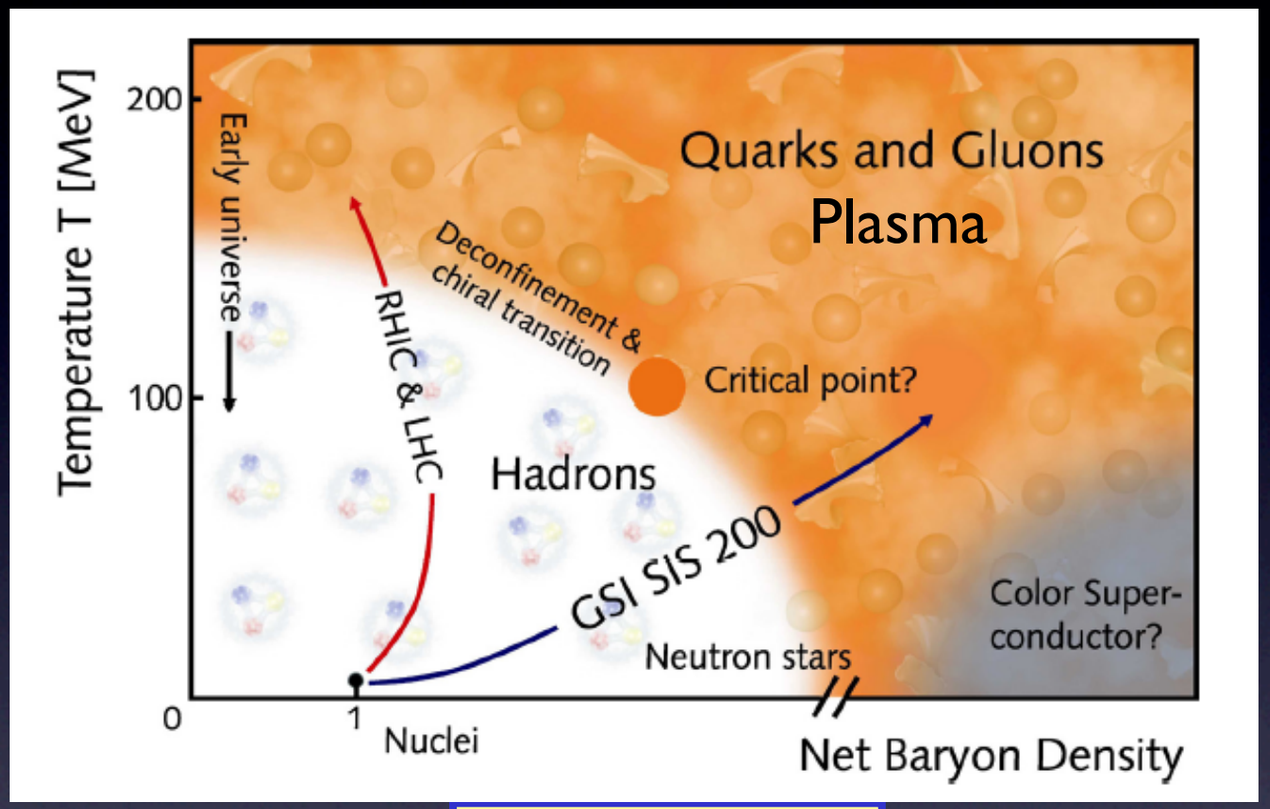


preferred benchmark field for Strings and SUSY theories

new sectors beyond the Standard Model can also be strongly coupled



QCD contains a lot of physics : deconfinement



Nuclear Matter

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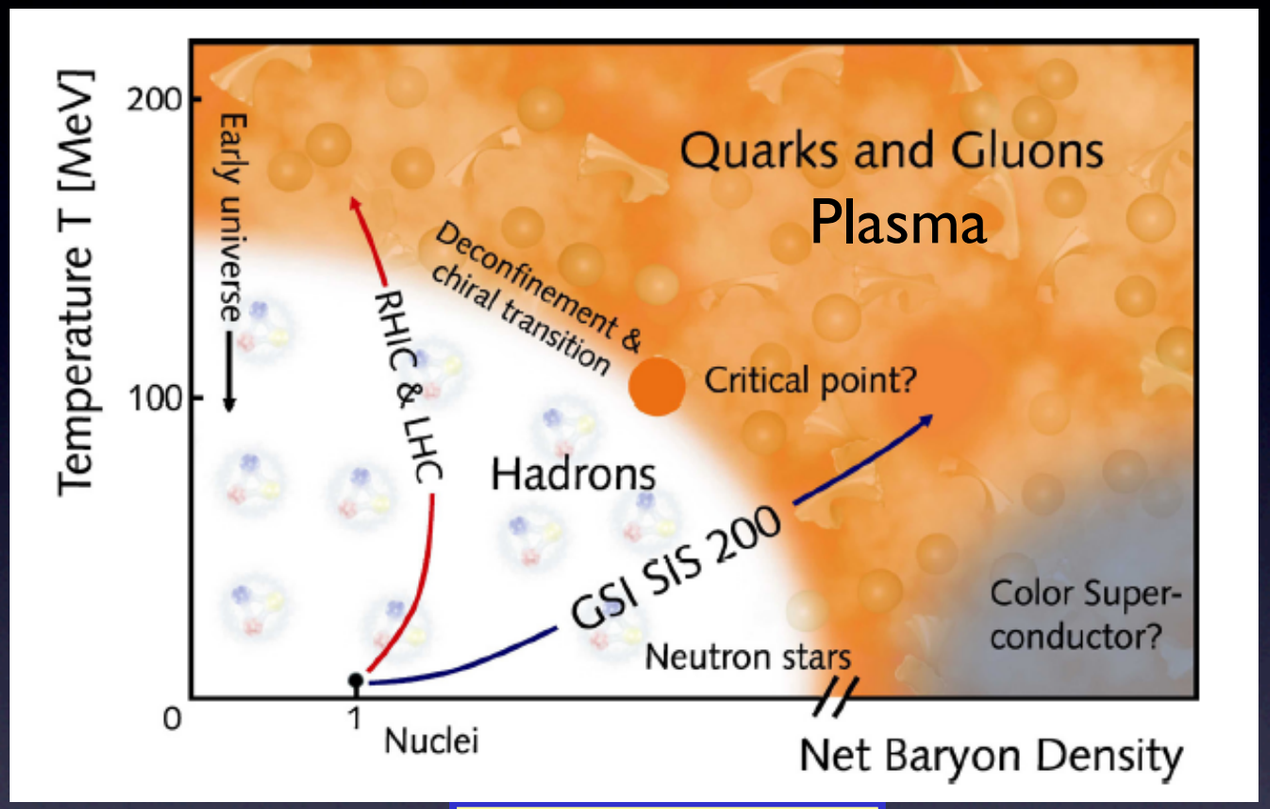

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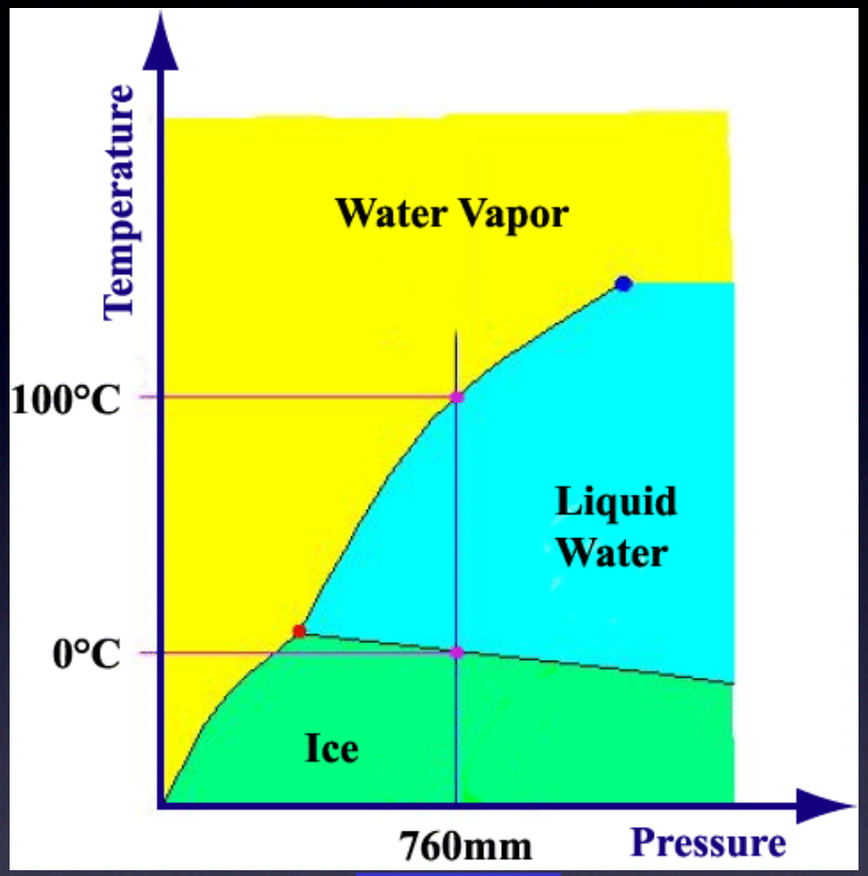

Water

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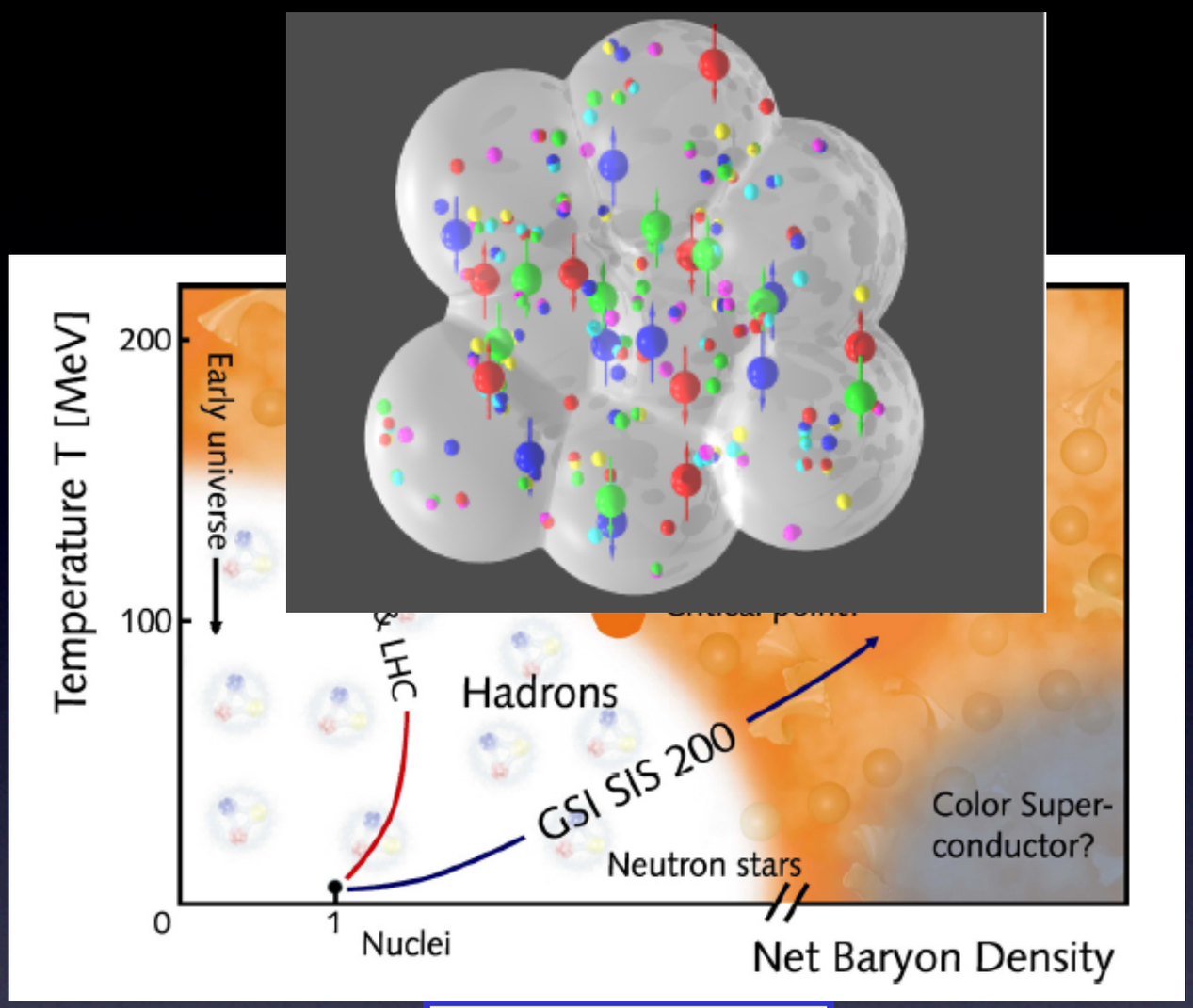

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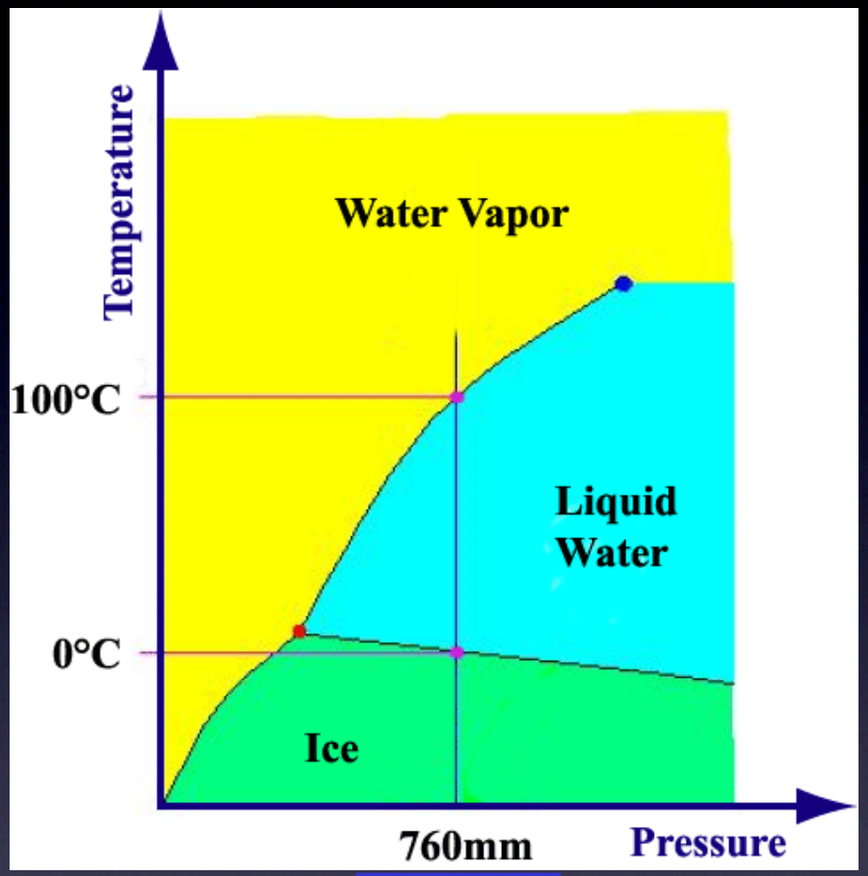
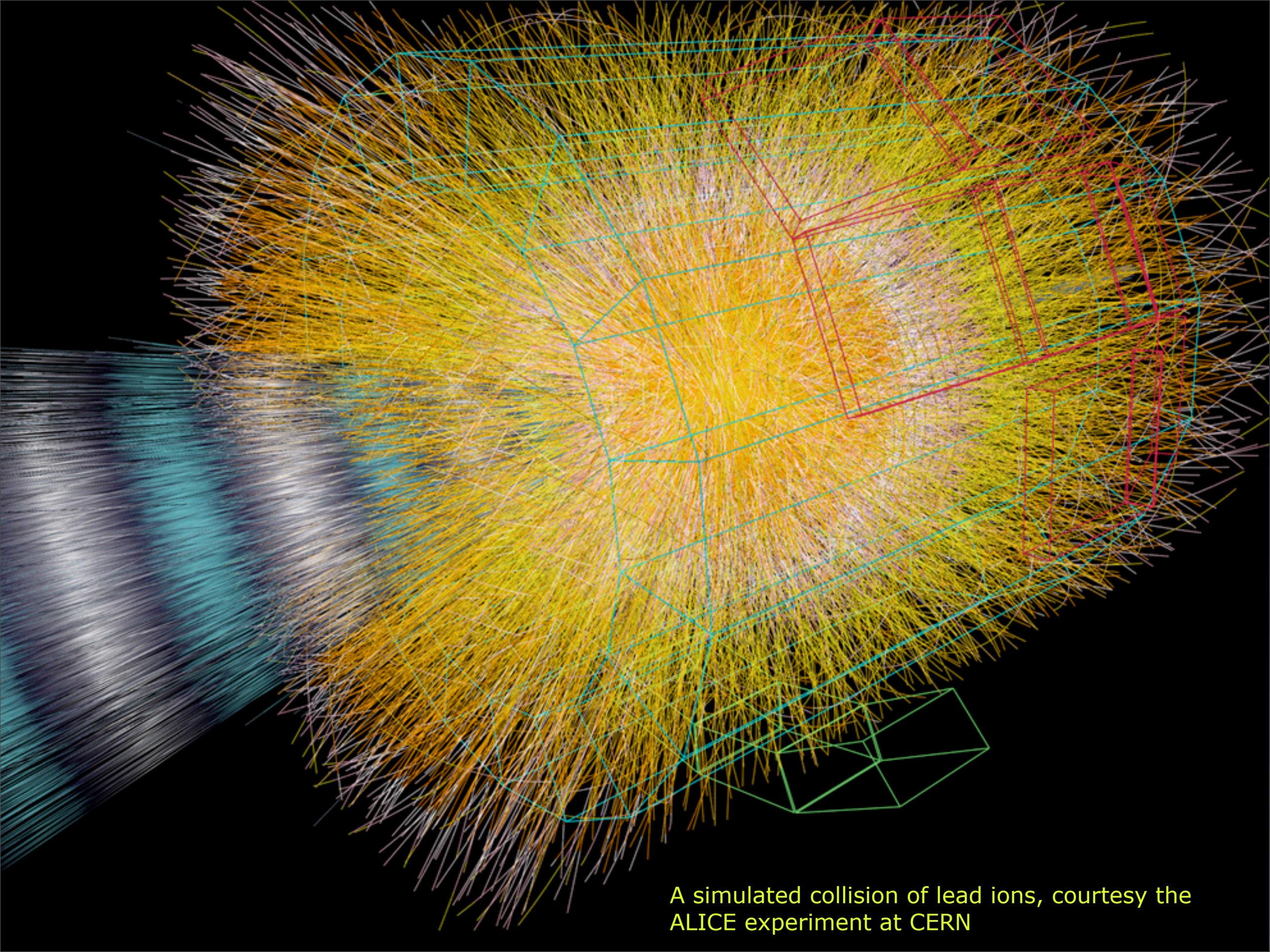
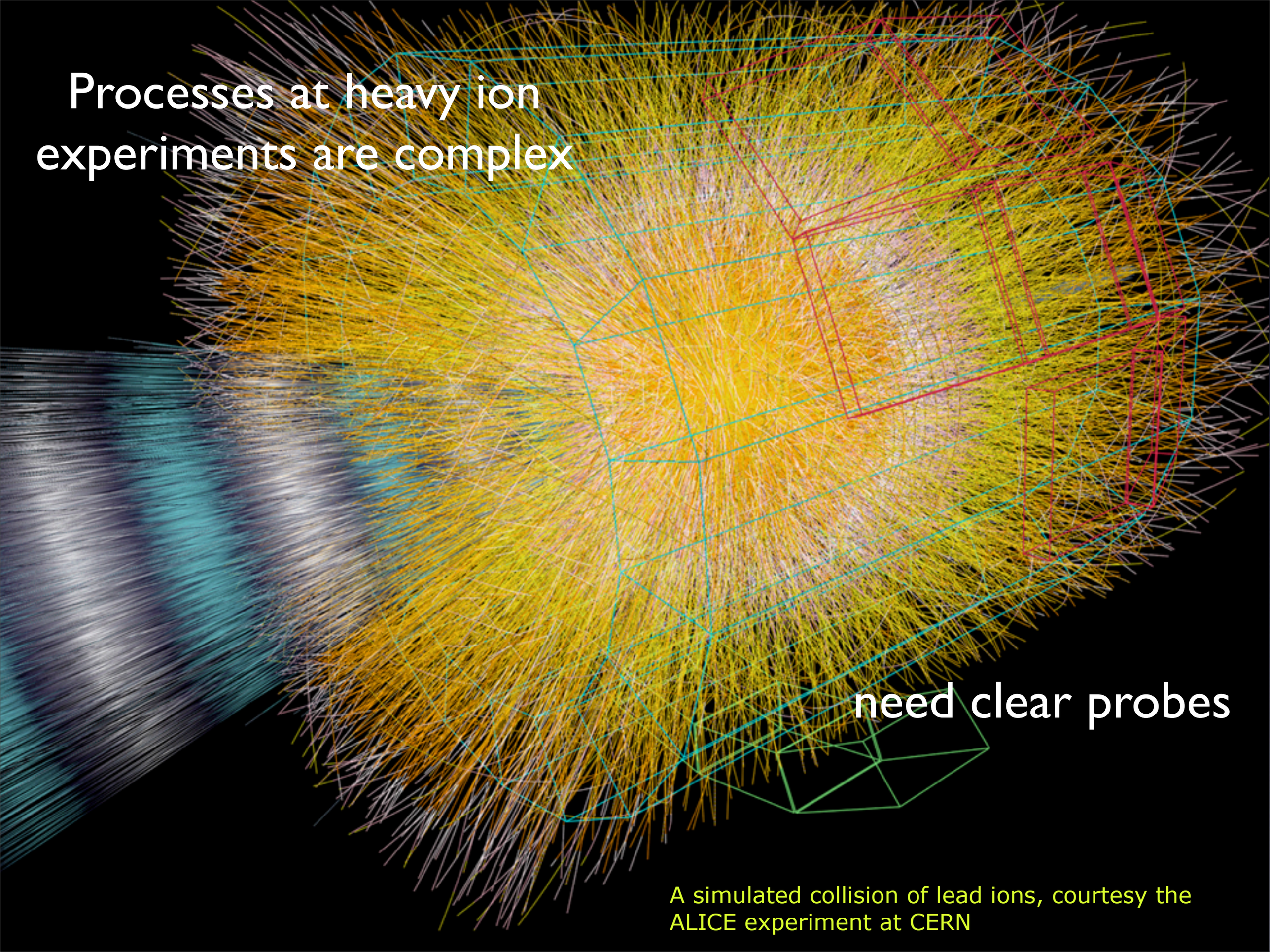


Water

nuclear matter
compressed/heated
T ~150 Mev $\sim 10^{12}\mathrm{K}$
Energy density
~1Gev/fm^3



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



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QCD and strongly coupled gauge theories: challenges and perspectives

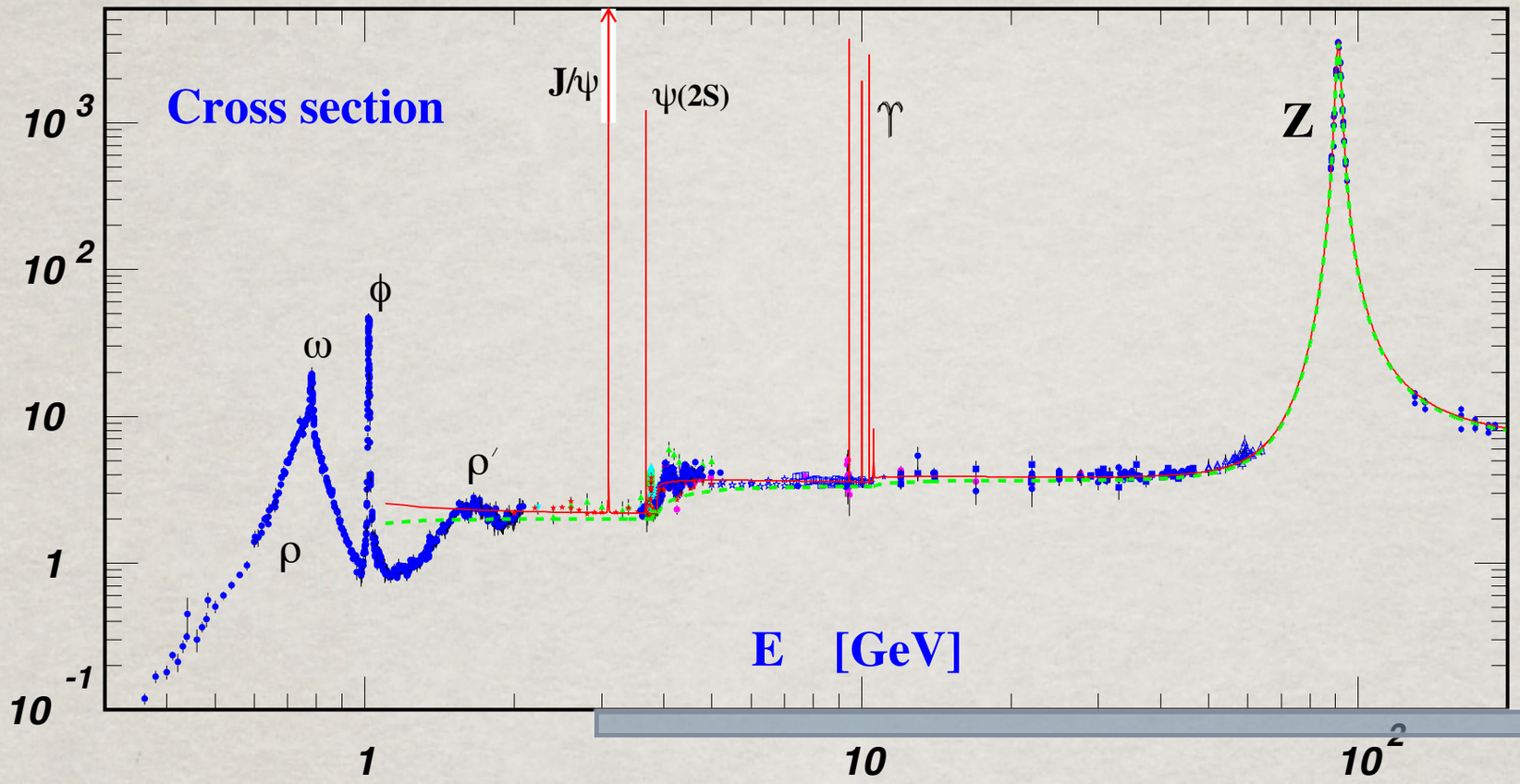
N. Brambilla*†,[1] S. Eidelman†,[2,3] P. Foka†‡,[4] S. Gardner†‡,[5] A.S. Kronfeld†,[6]
M.G. Alford‡,[7] R. Alkofer‡,[8] M. Butenschön‡,[9] T.D. Cohen‡,[10] J. Erdmenger‡,[11] L. Fabbietti‡,[12]
M. Faber‡,[13] J.L. Goity‡,[14,15] B. Ketzer‡§,[1] H.W. Lin‡,[16] F.J. Llanes-Estrada‡,[17]
H.B. Meyer‡,[18] 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] G. 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]

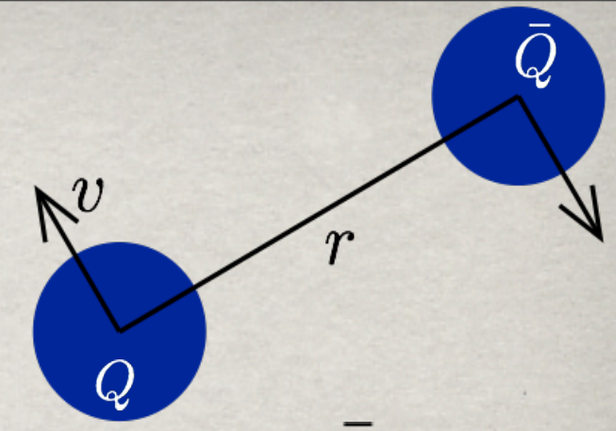
arXiv:1404.3723v1 [hep-ph] 14 Apr 2014

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 is a golden system to study strong interactions and to understand these QCD challenges

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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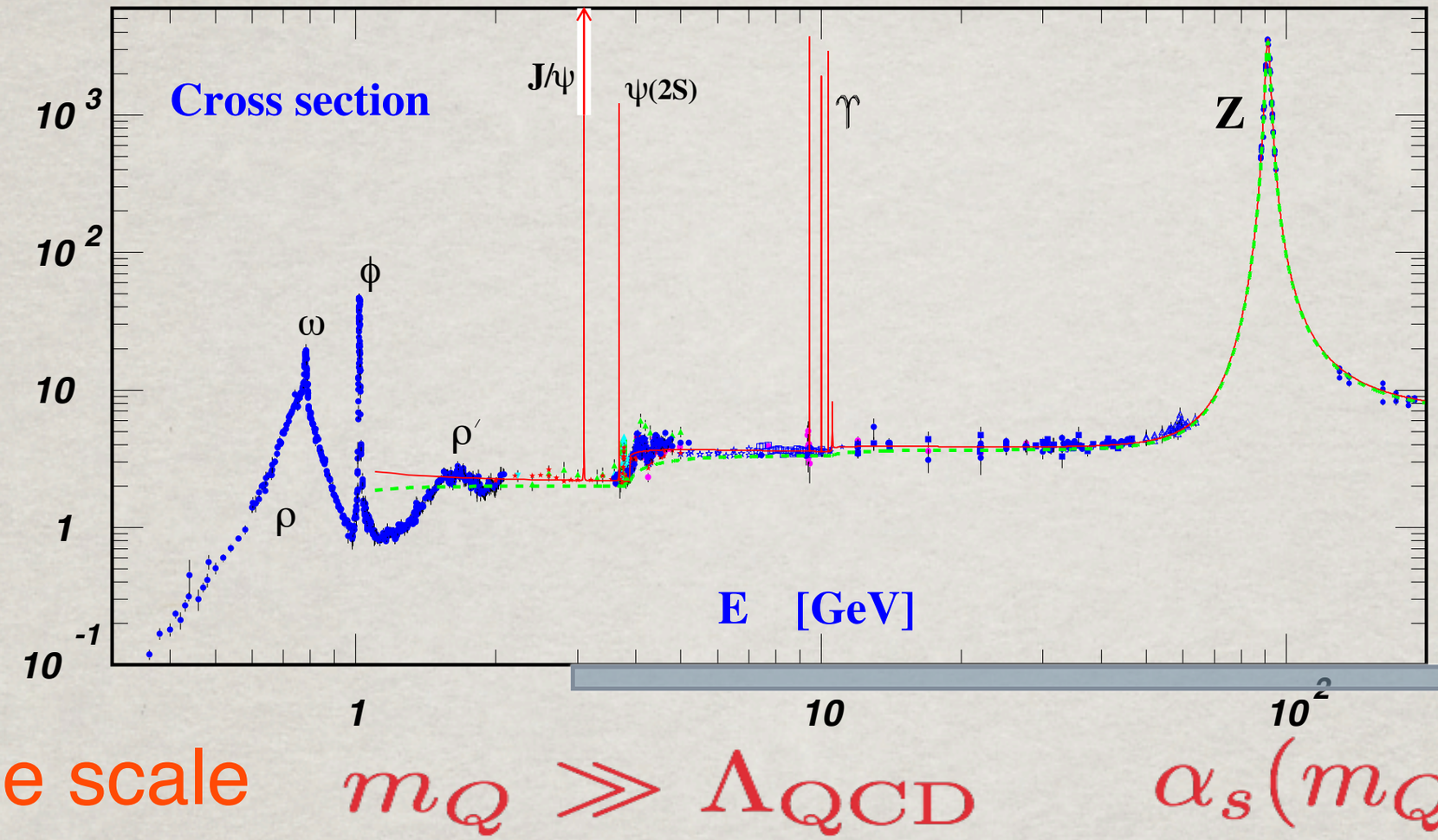

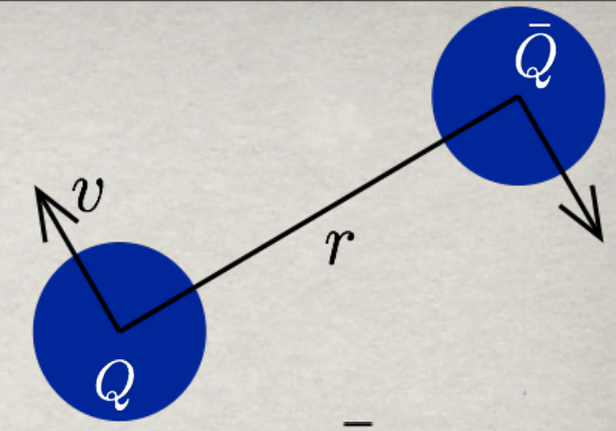

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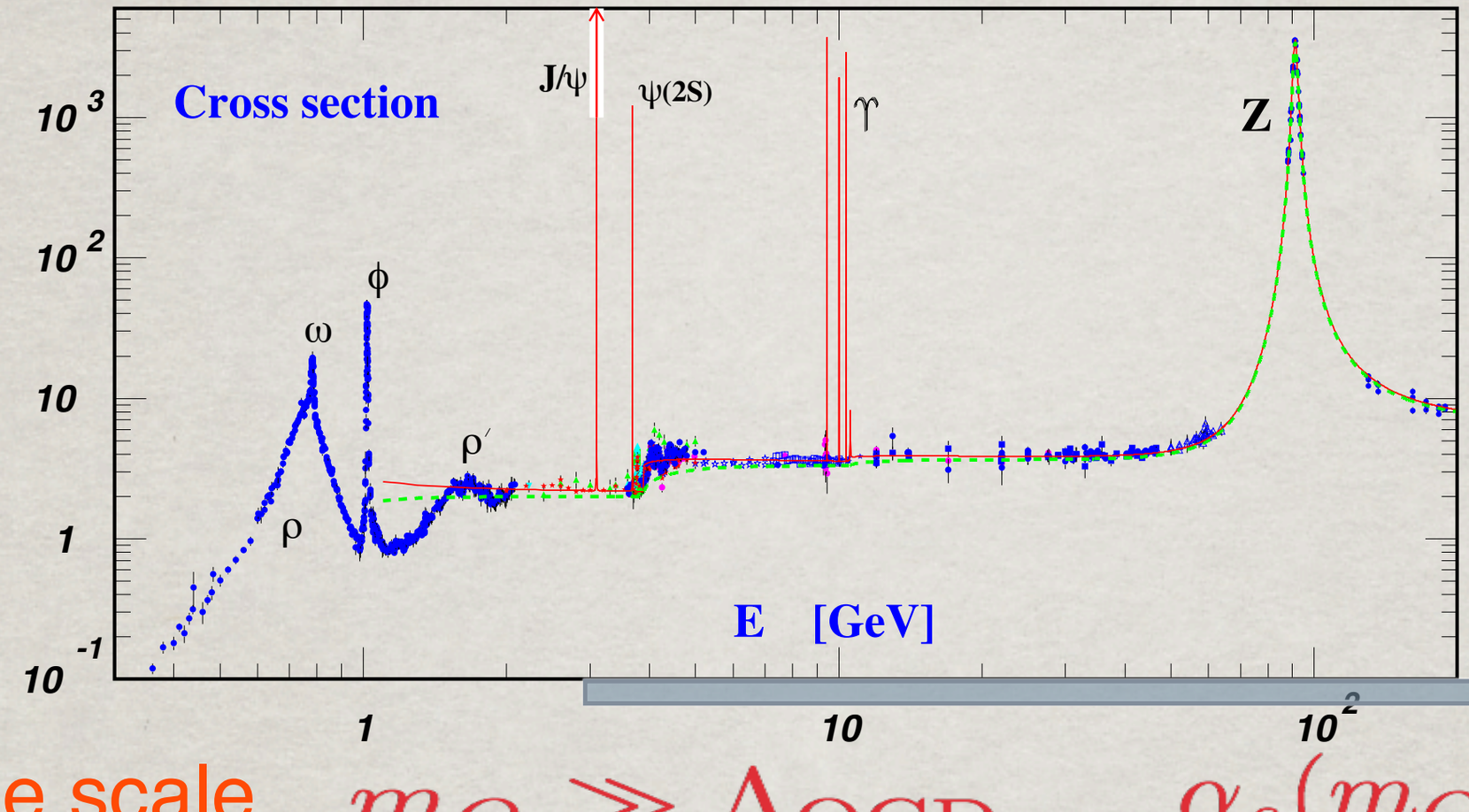

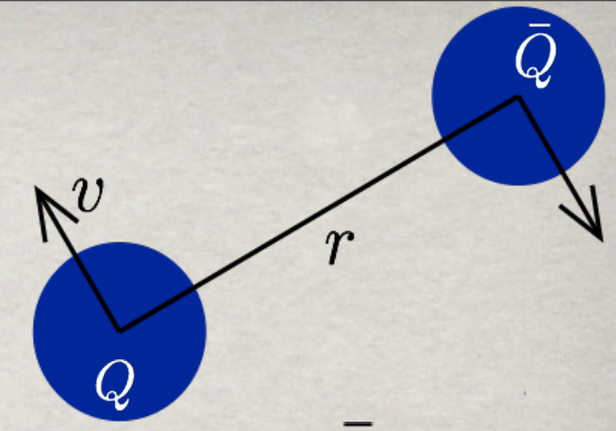

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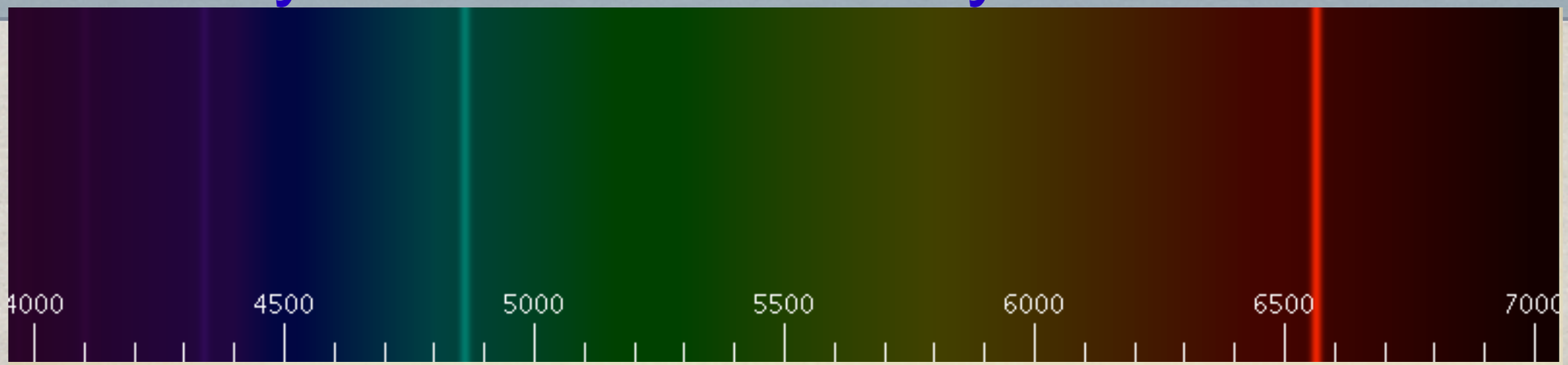
Heavy quarkonia are nonrelativistic bound systems: multiscale systems



Electromagnetic bound states: atoms, molecules,

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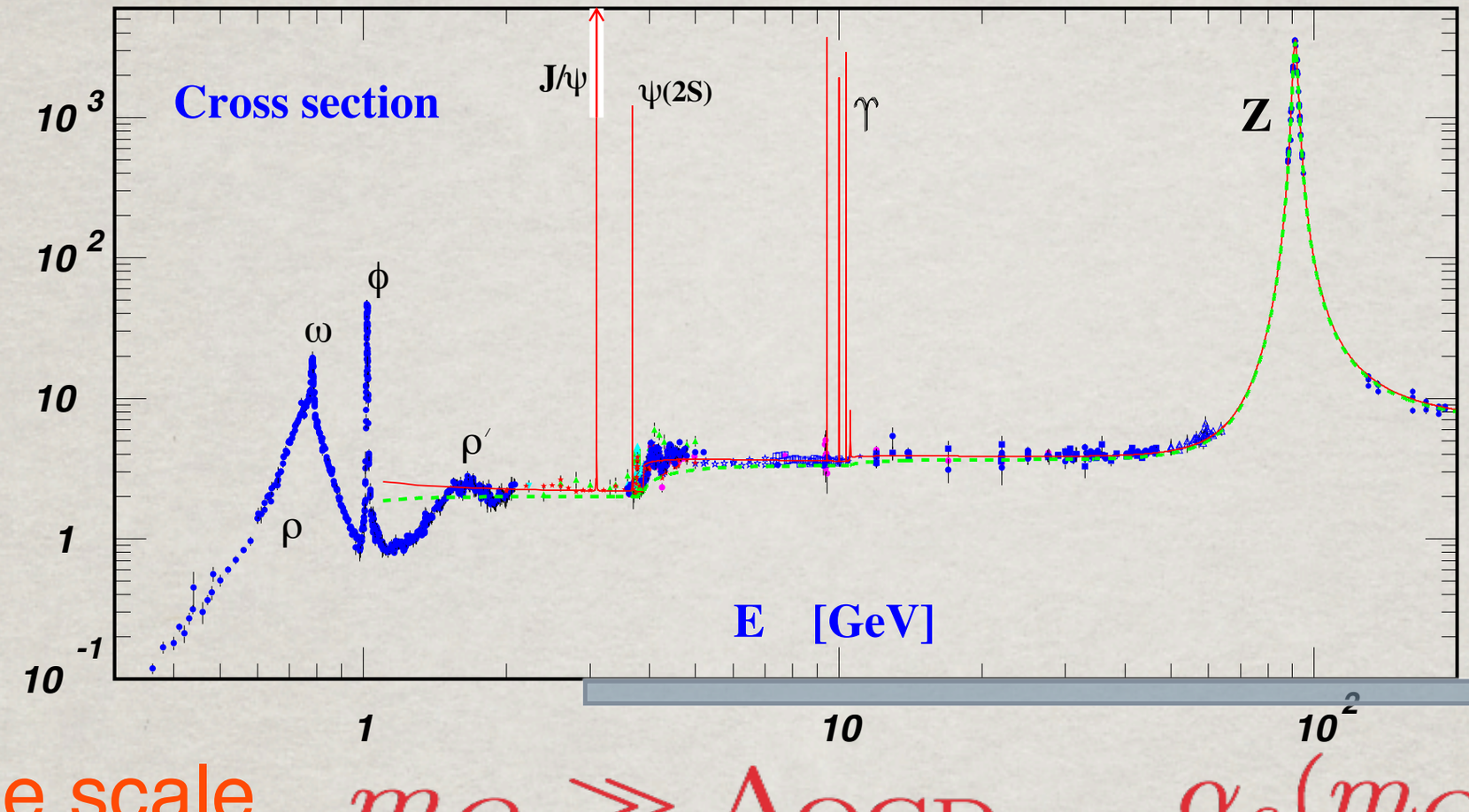

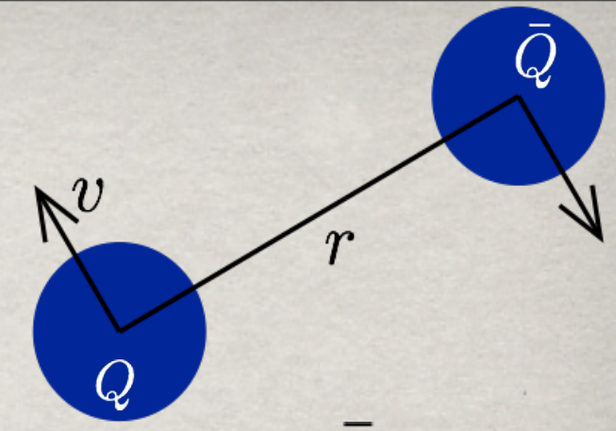

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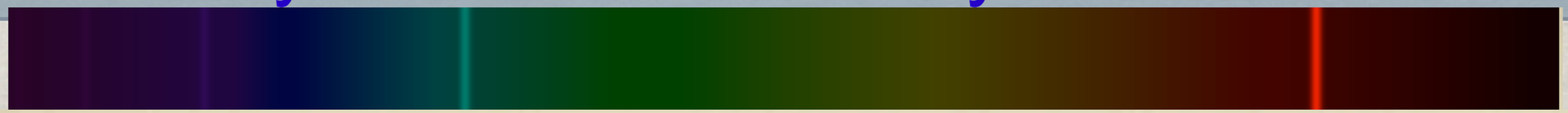
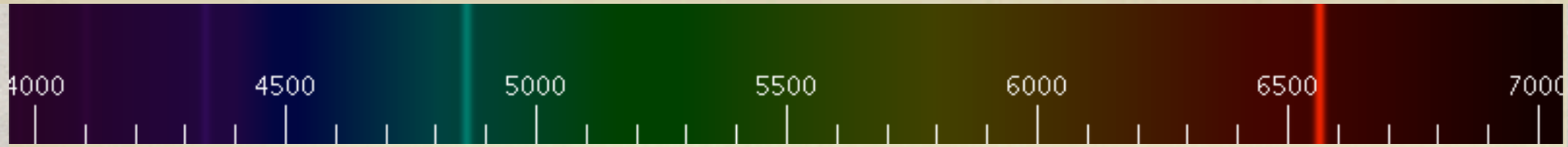


many scales: a challenge and an opportunity



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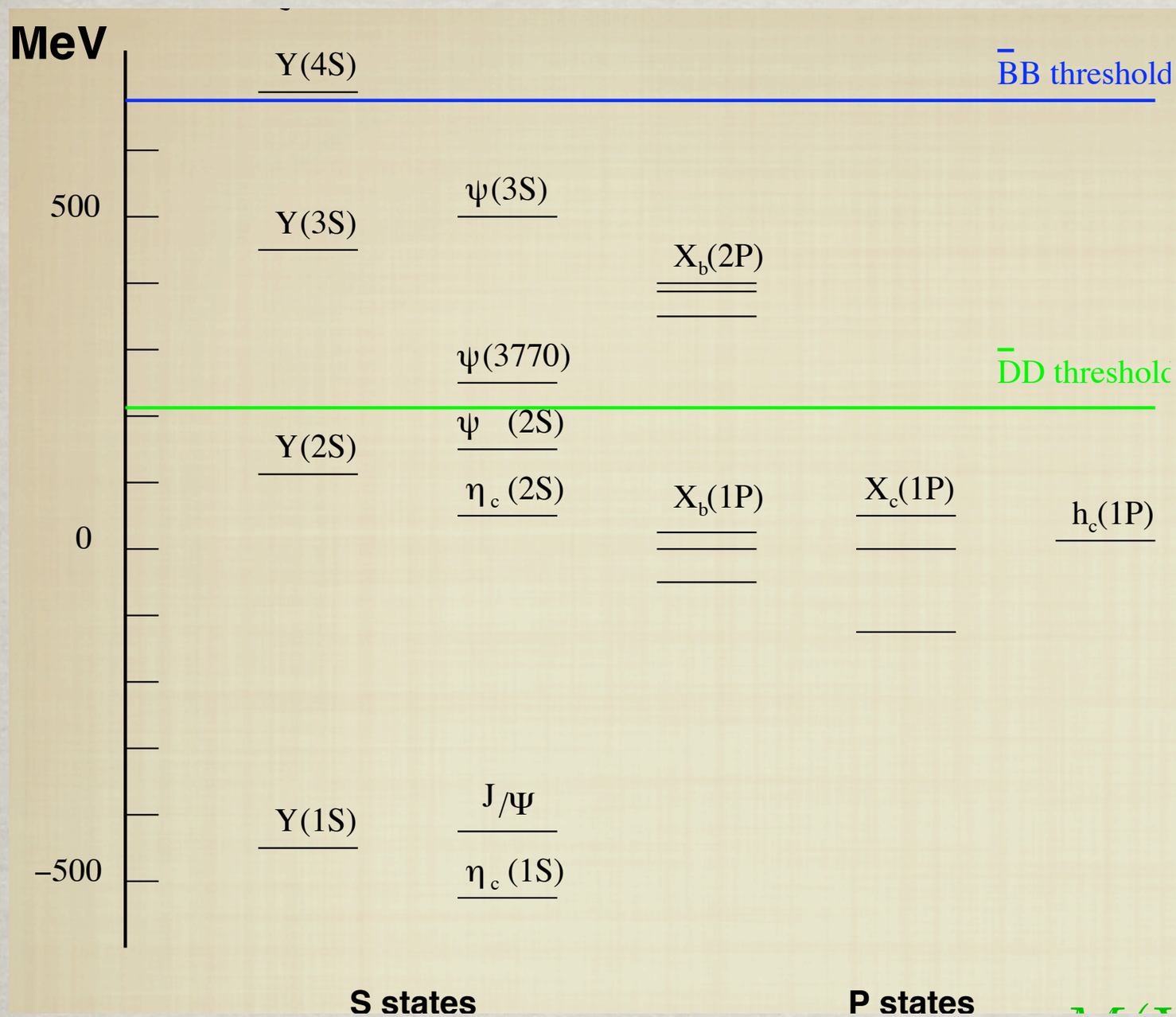
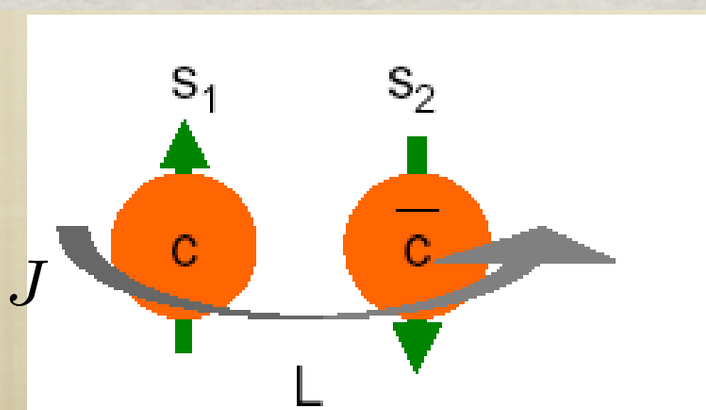
Quarkonium scales



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

$^{2S+1}L_J$



The mass scale is perturbative

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

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

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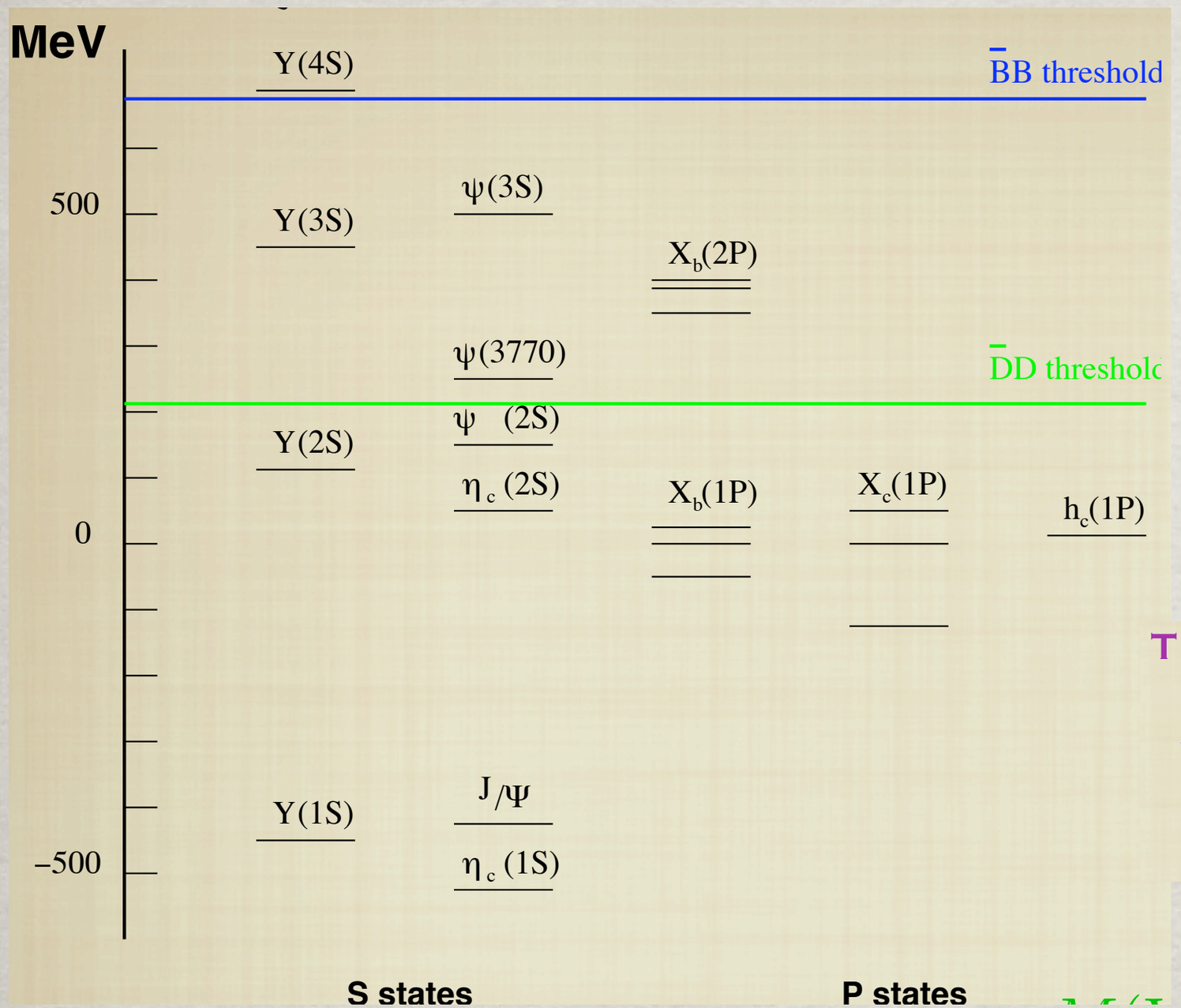

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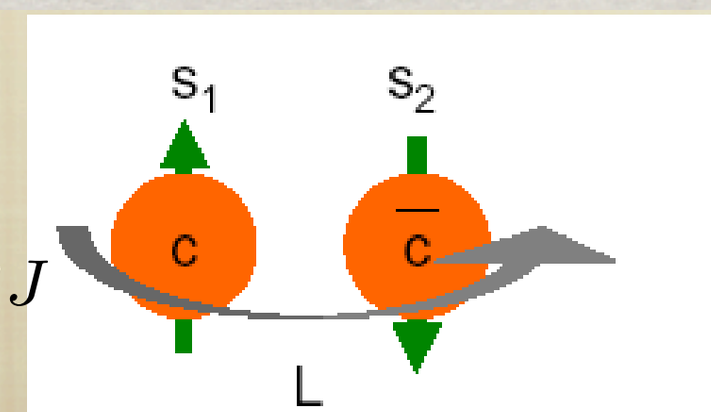

THE SYSTEM IS NONRELATIVISTIC(NR)

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

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

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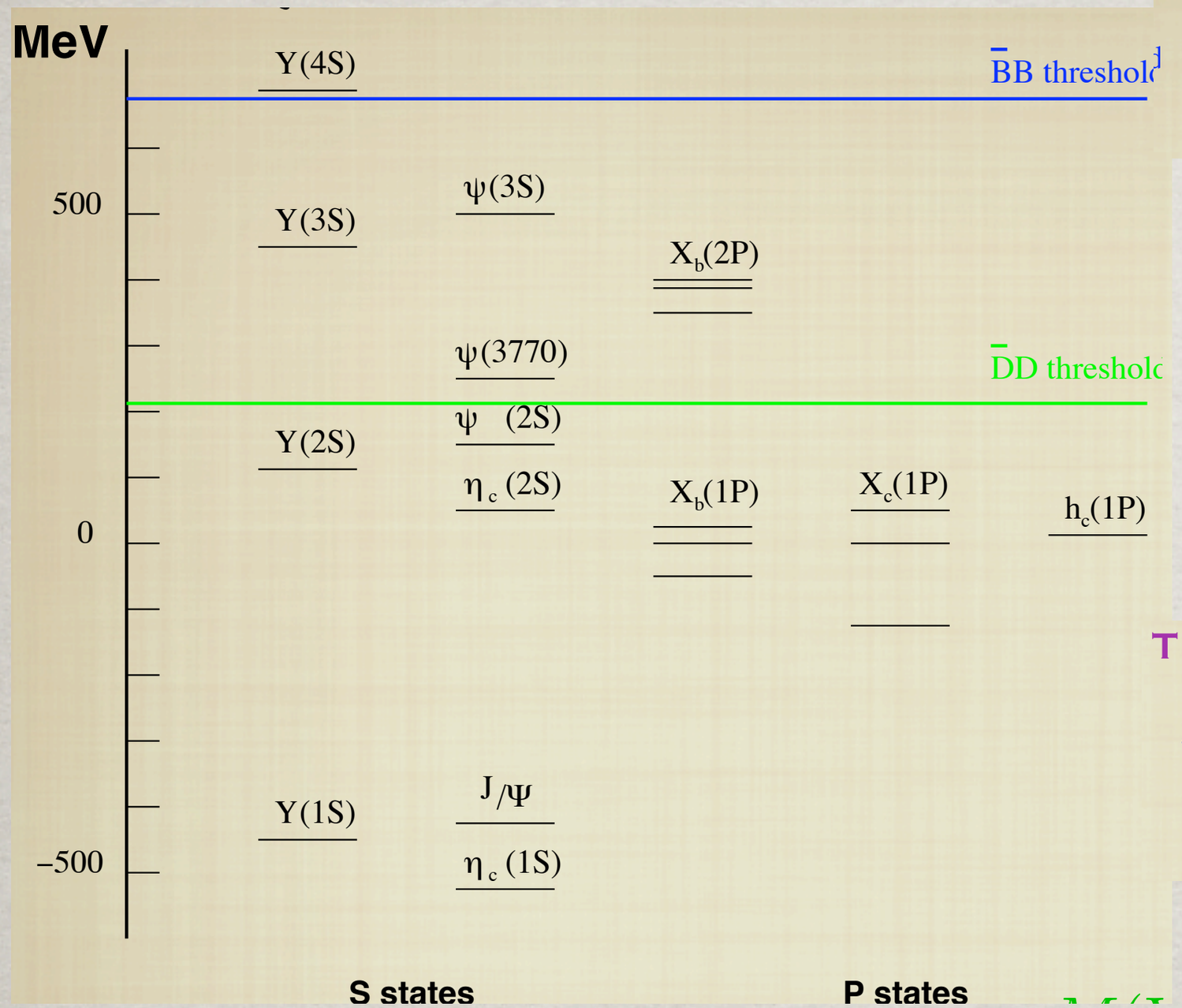

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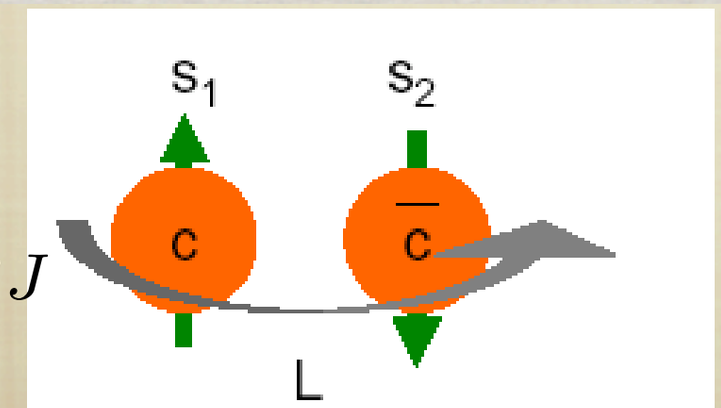

NR bound states have at least 3 scales

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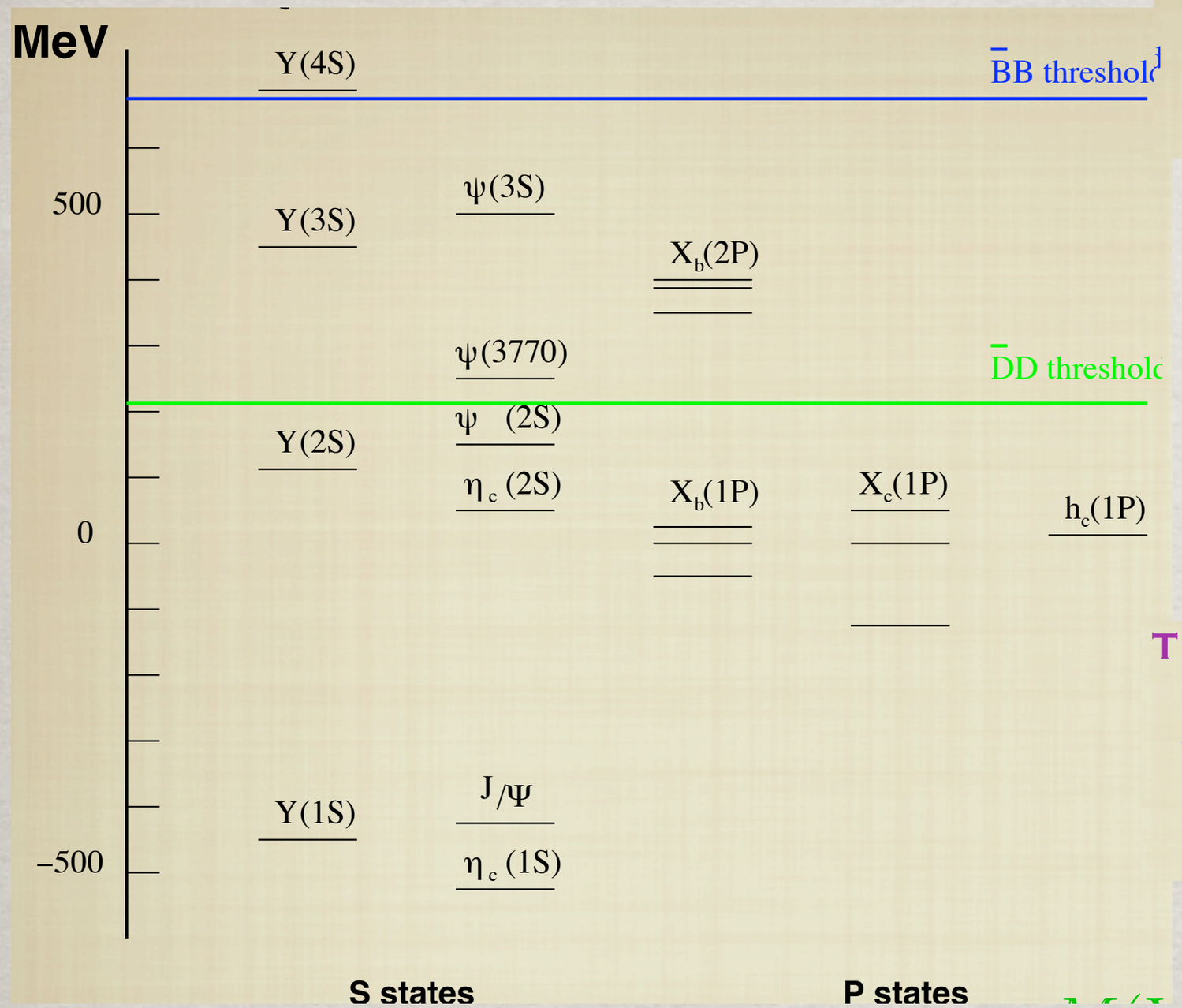

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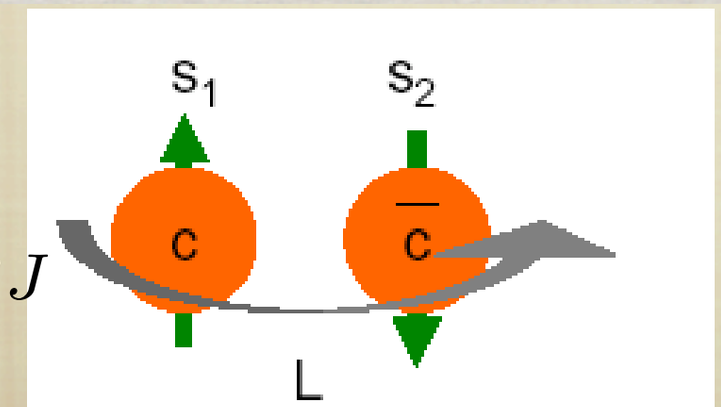

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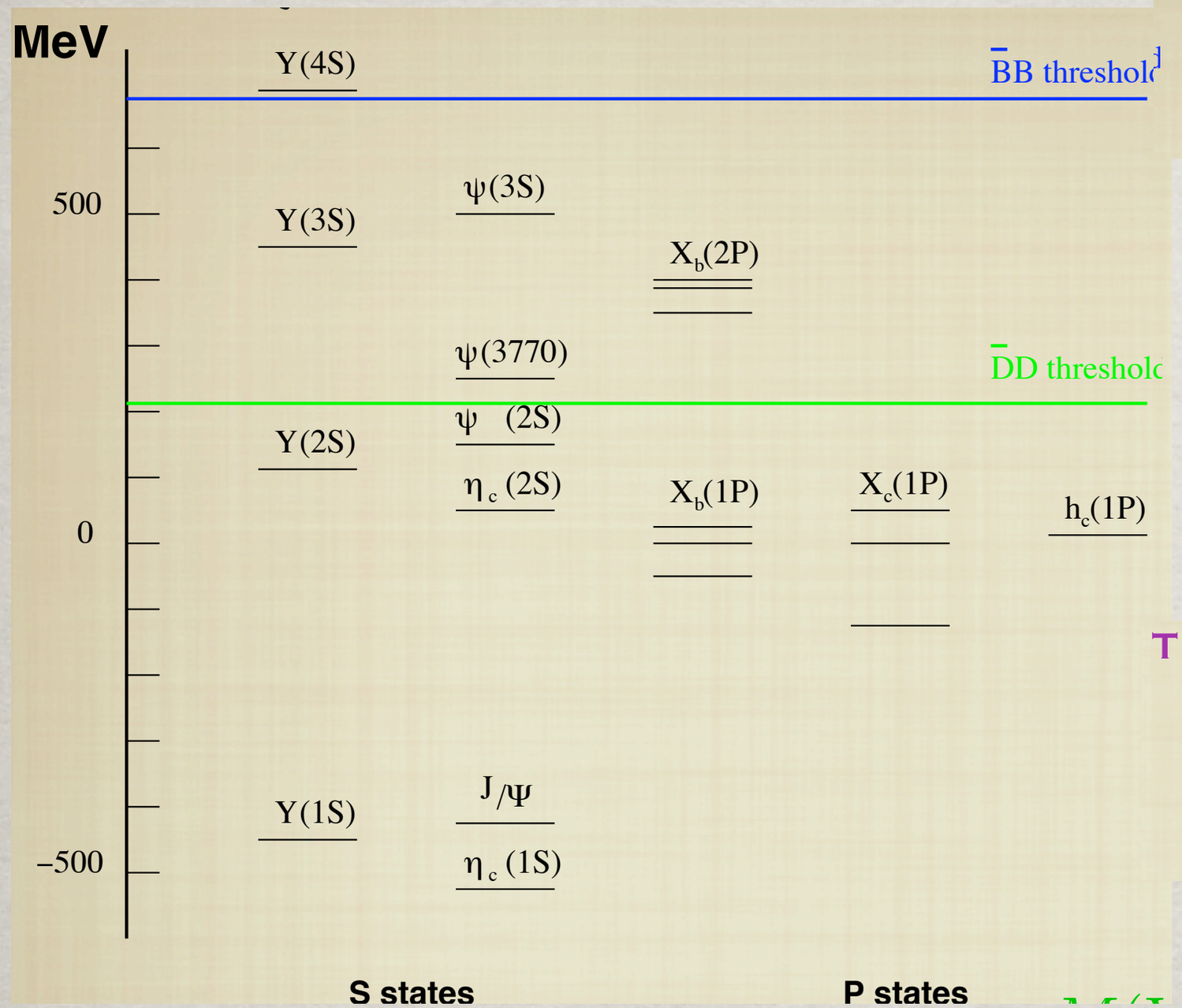

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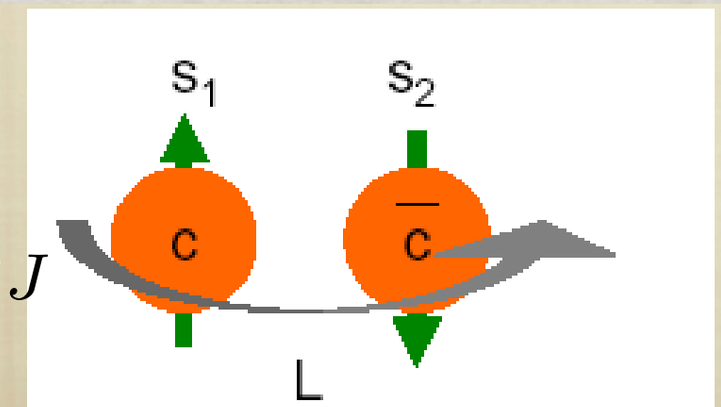

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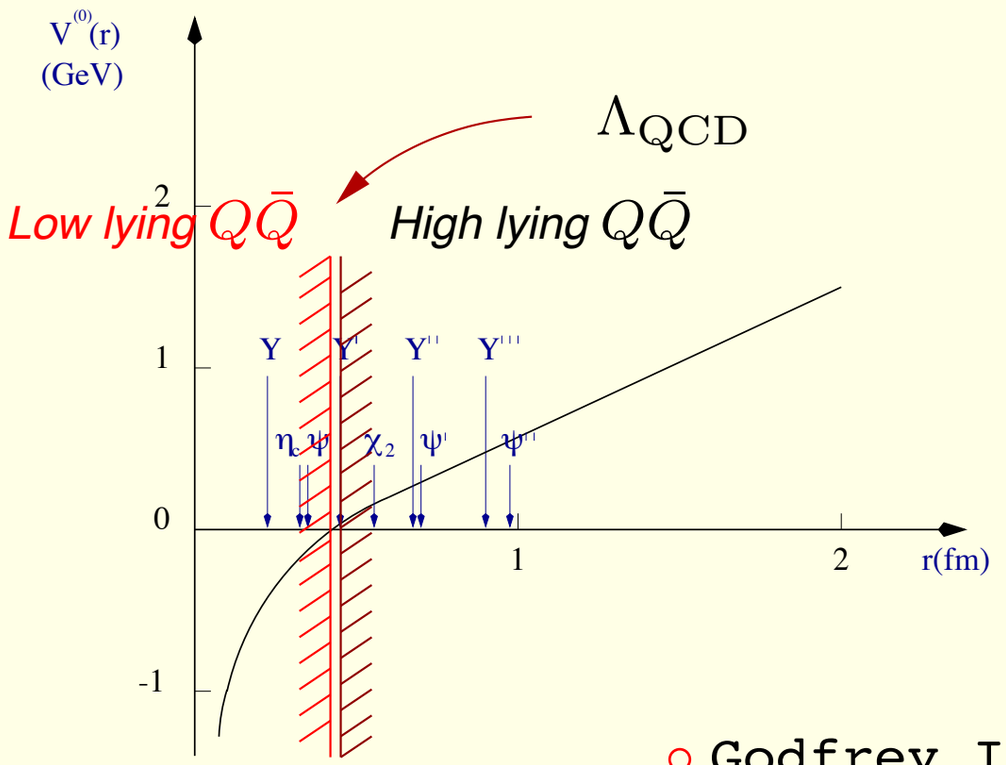
Quarkonium as a confinement and deconfinement probe

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.

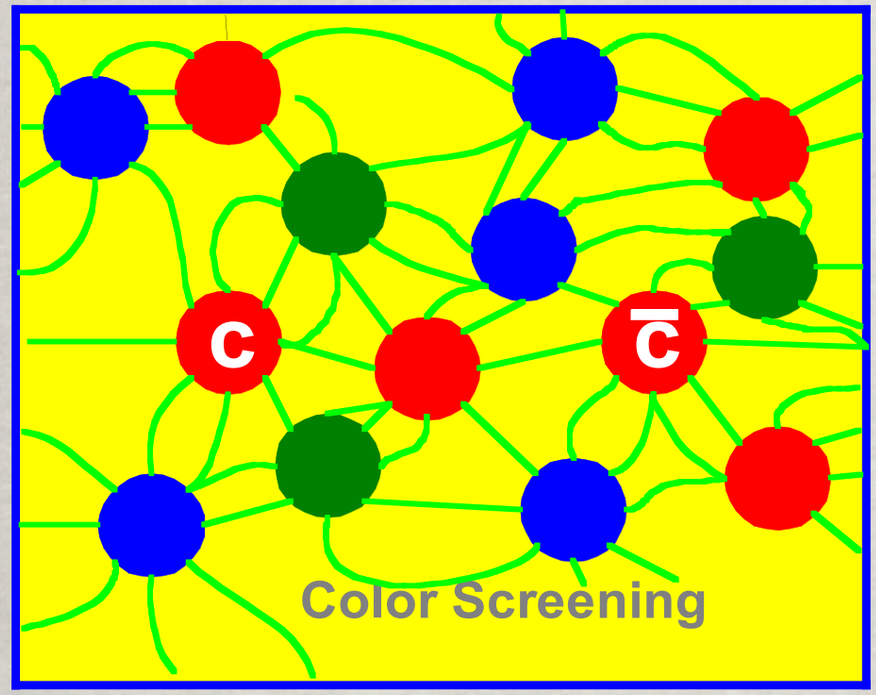


- Godfrey Isgur PRD 32(85)189

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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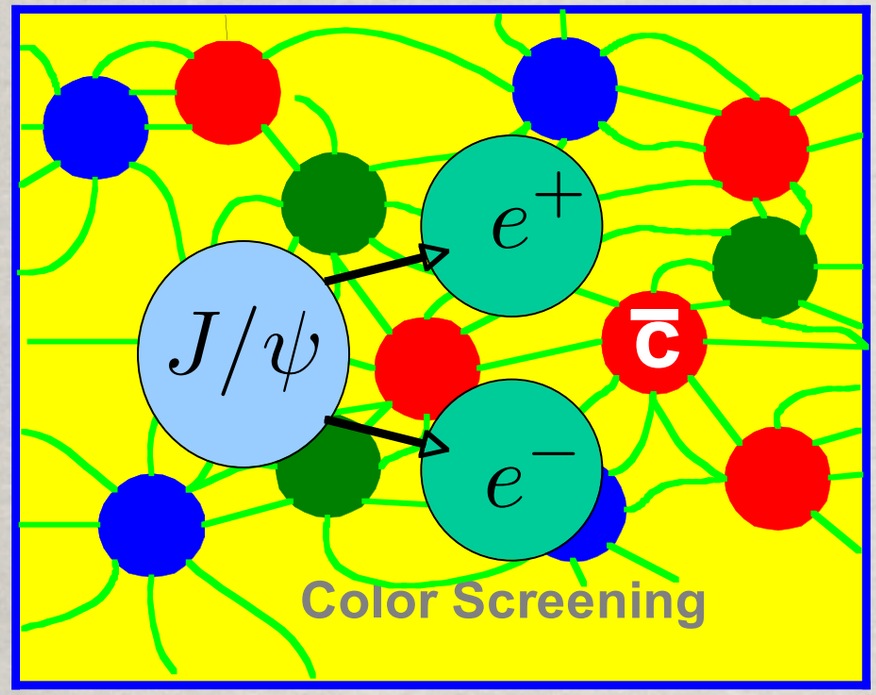

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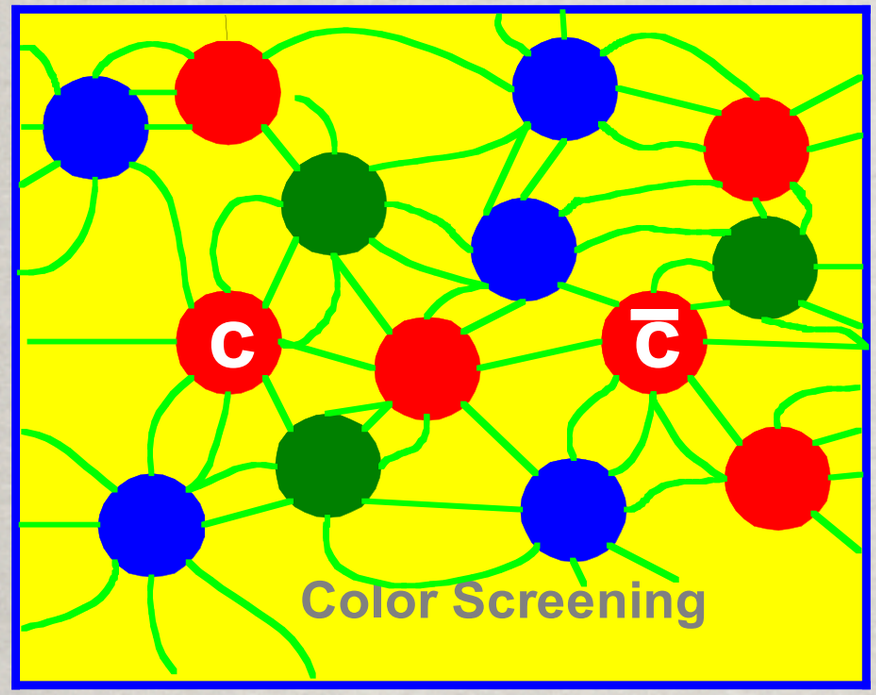

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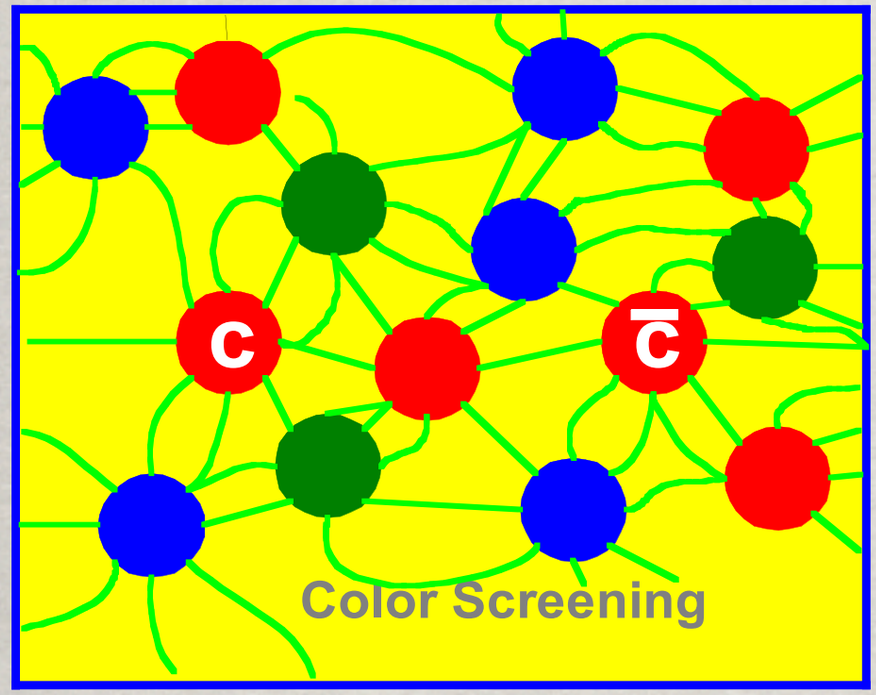

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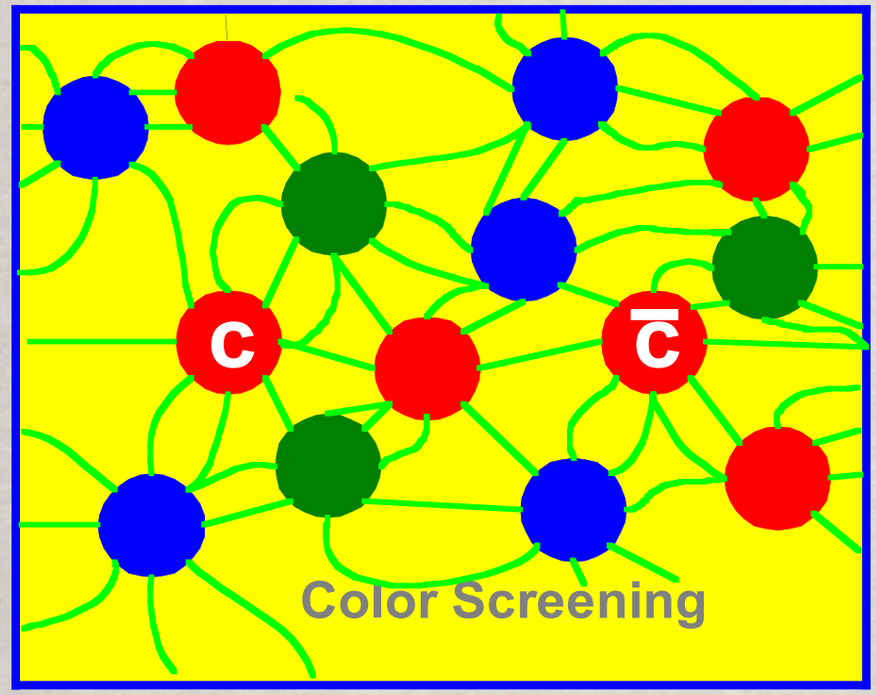

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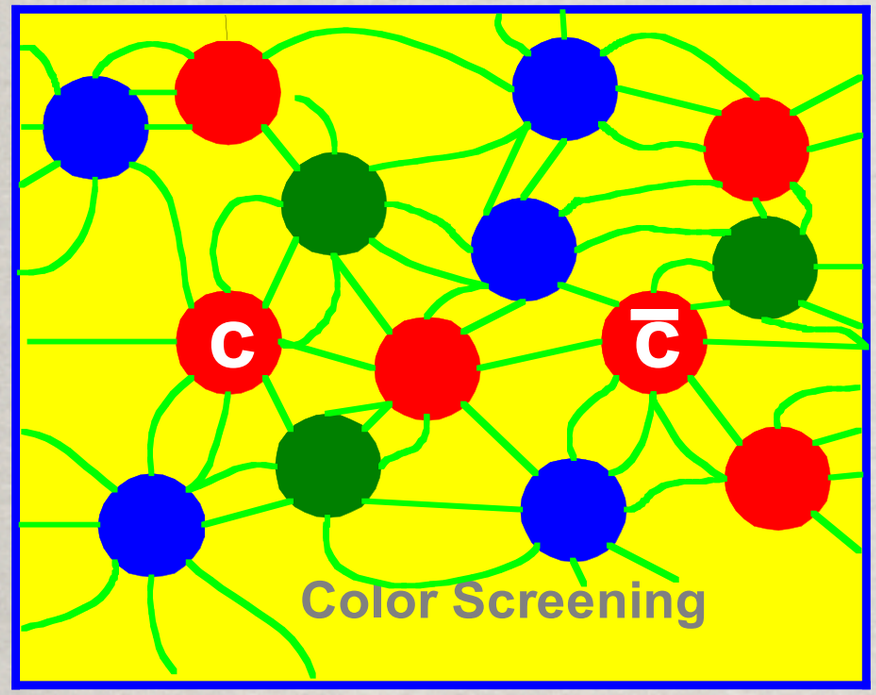

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Matsui Satz 1986

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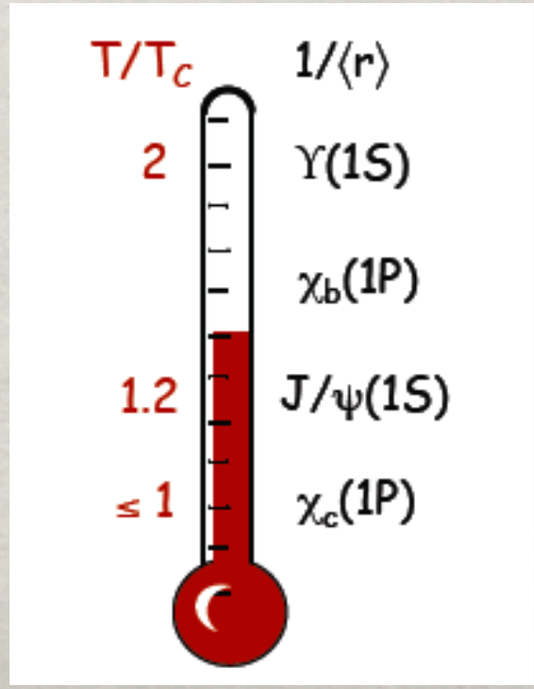

Quarkonium as an exploration tool of physics of Standard Model and beyond

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	$10^{-5} - 10^{-3}$

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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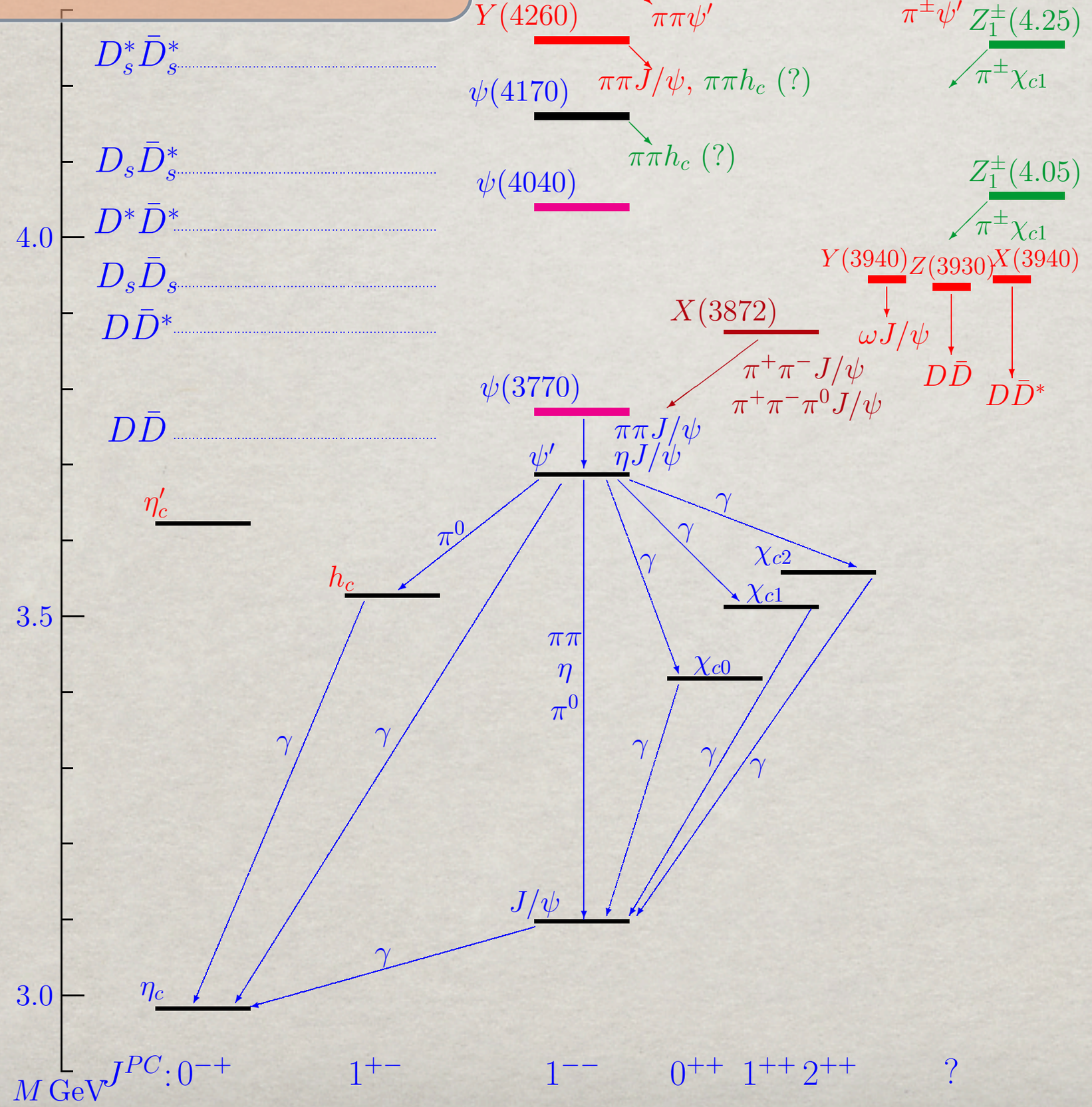
Charmonium
the present revolution



THE COLLIDER DETECTOR AT FERMILAB

DØ

BELLE

BABAR Collaboration Home Page

BES

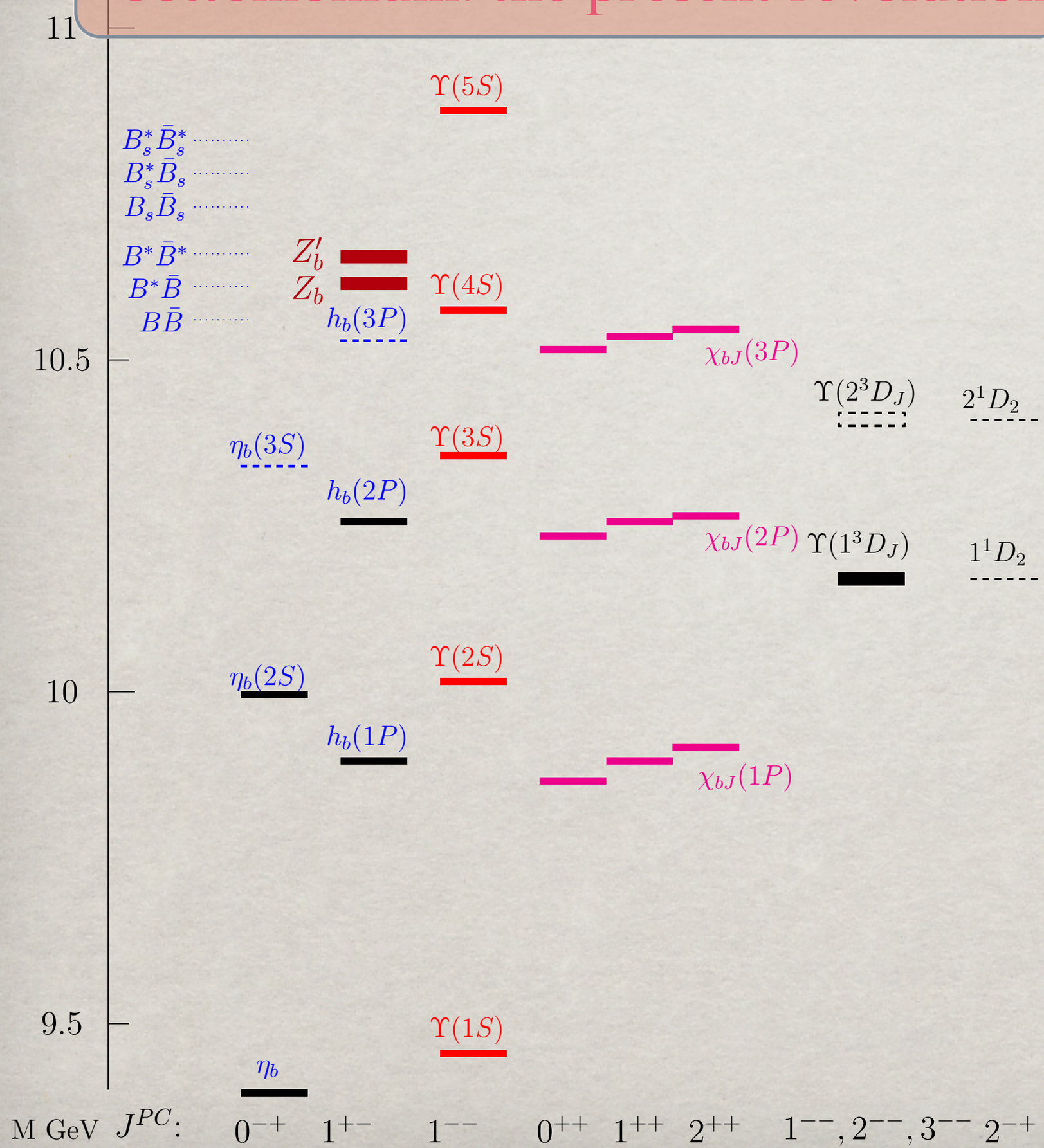
CLEO

ATLAS

CMS

LHCb

bottomonium: the present revolution



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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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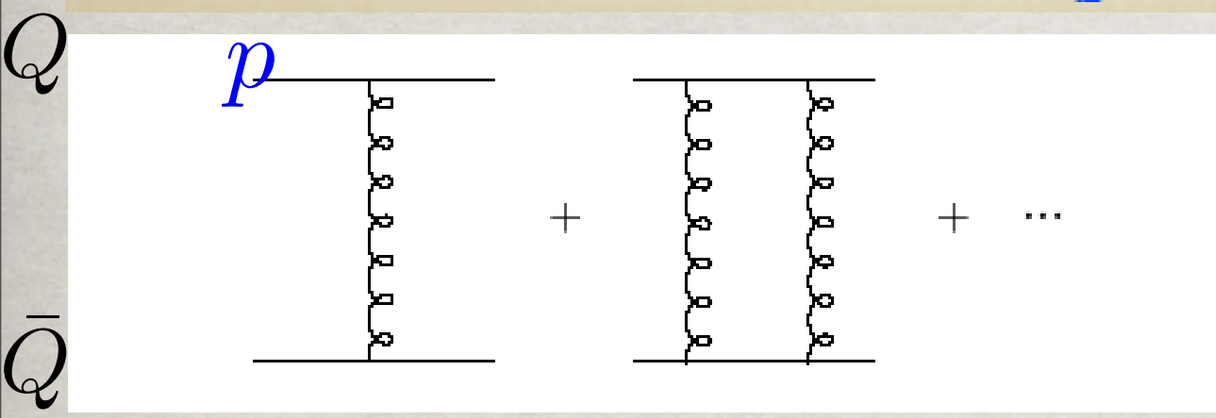

QCD theory of Quarkonium: a very hard problem

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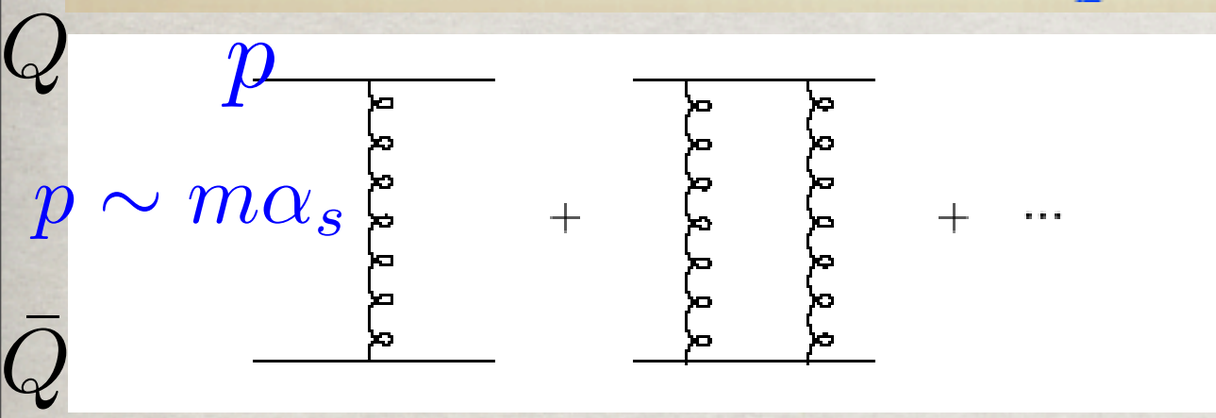

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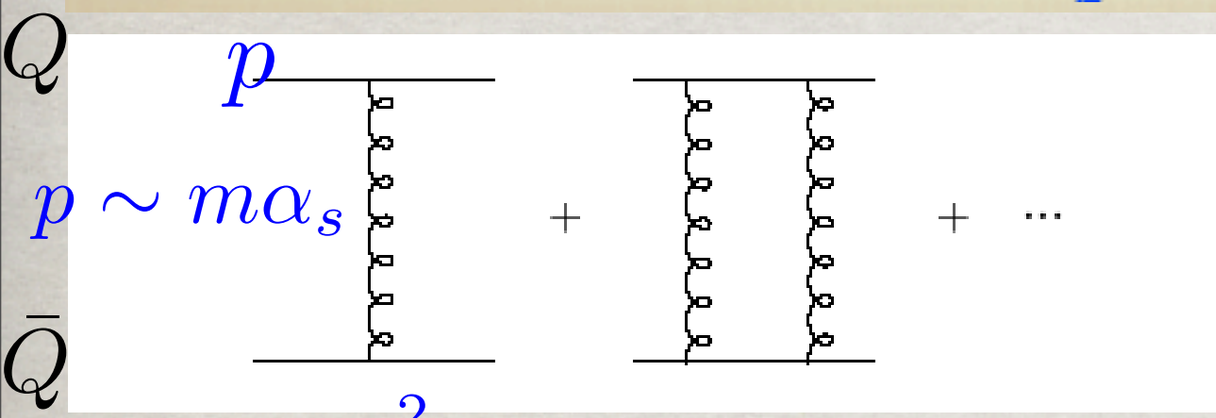

$$\frac{g^2}{p^2}\left(1 + \frac{m\alpha_s}{p}\right)$$

QCD theory of Quarkonium: a very hard problem

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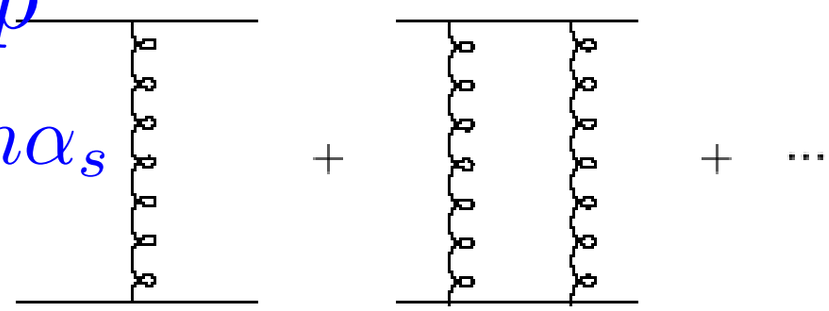
Q

p

$p \sim m\alpha_s$



$\bar{Q}$

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

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

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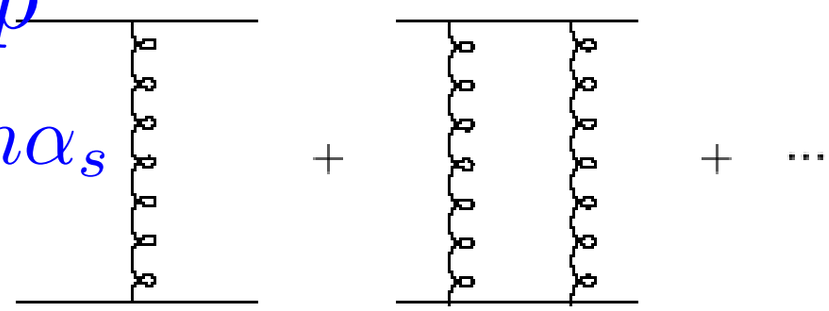

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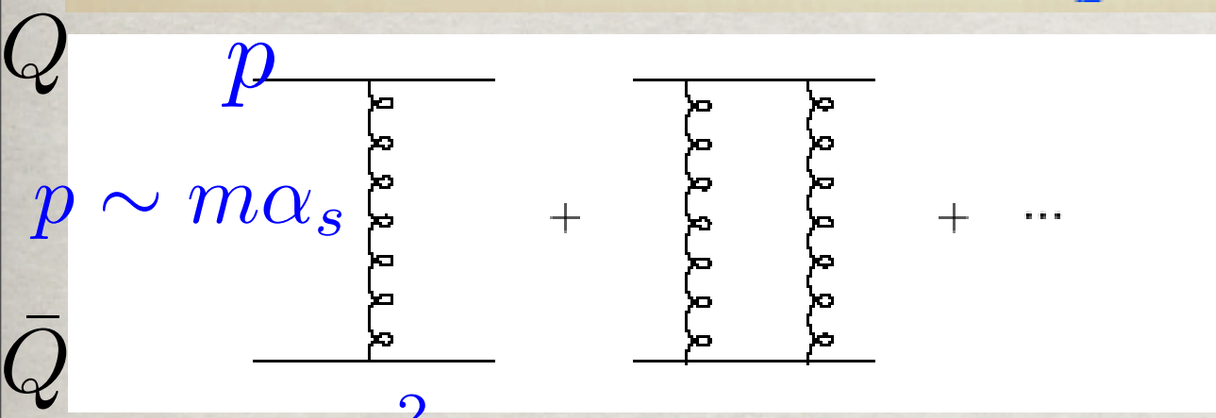

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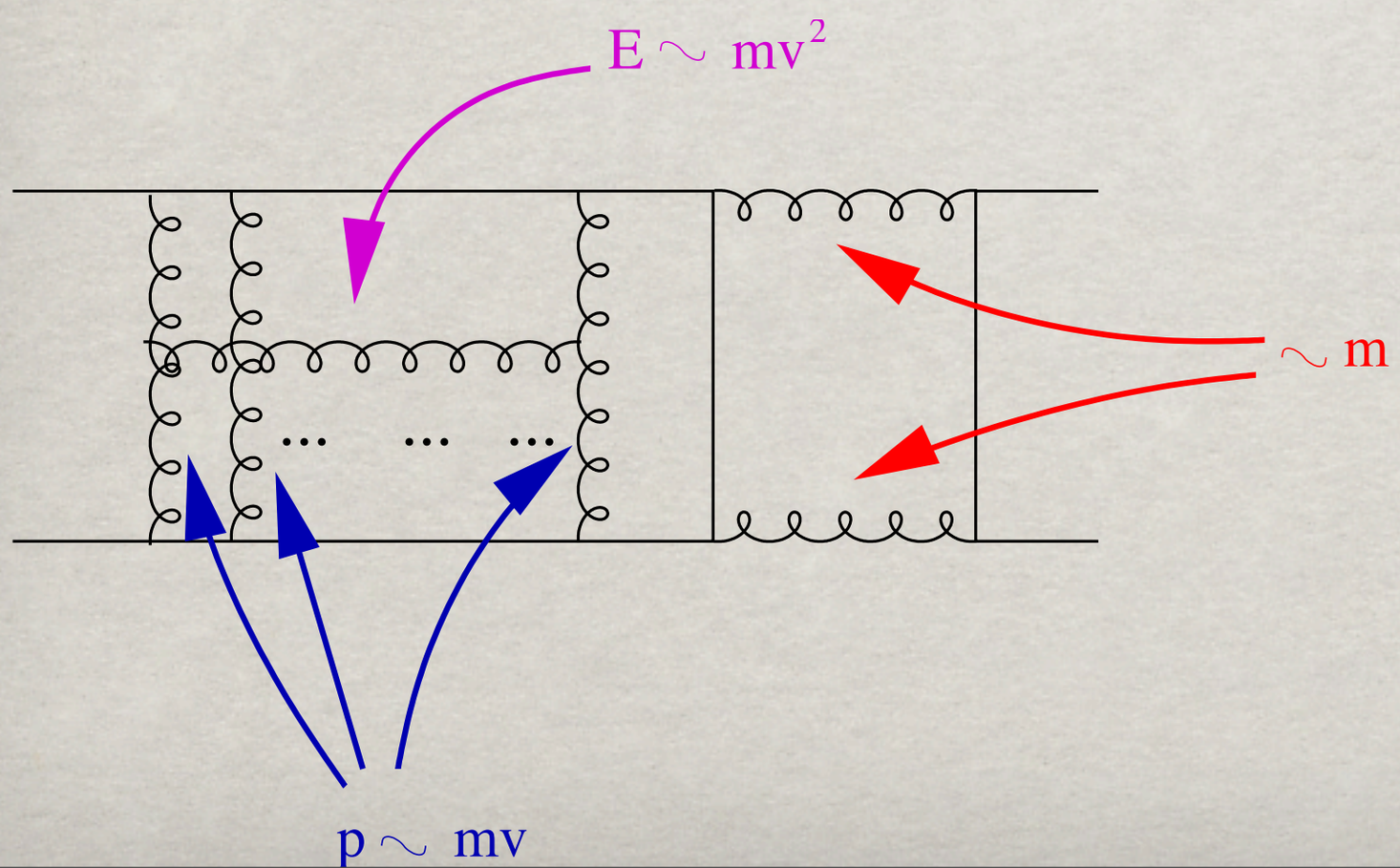

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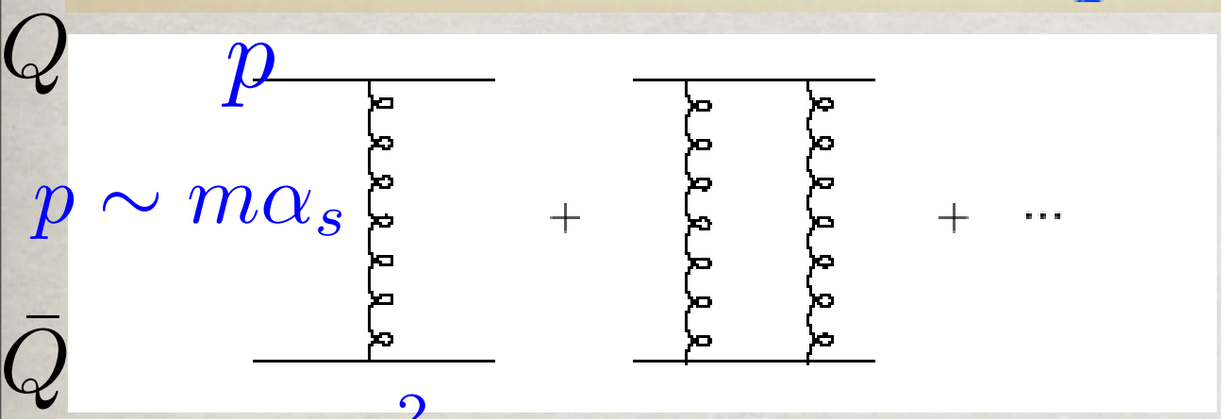

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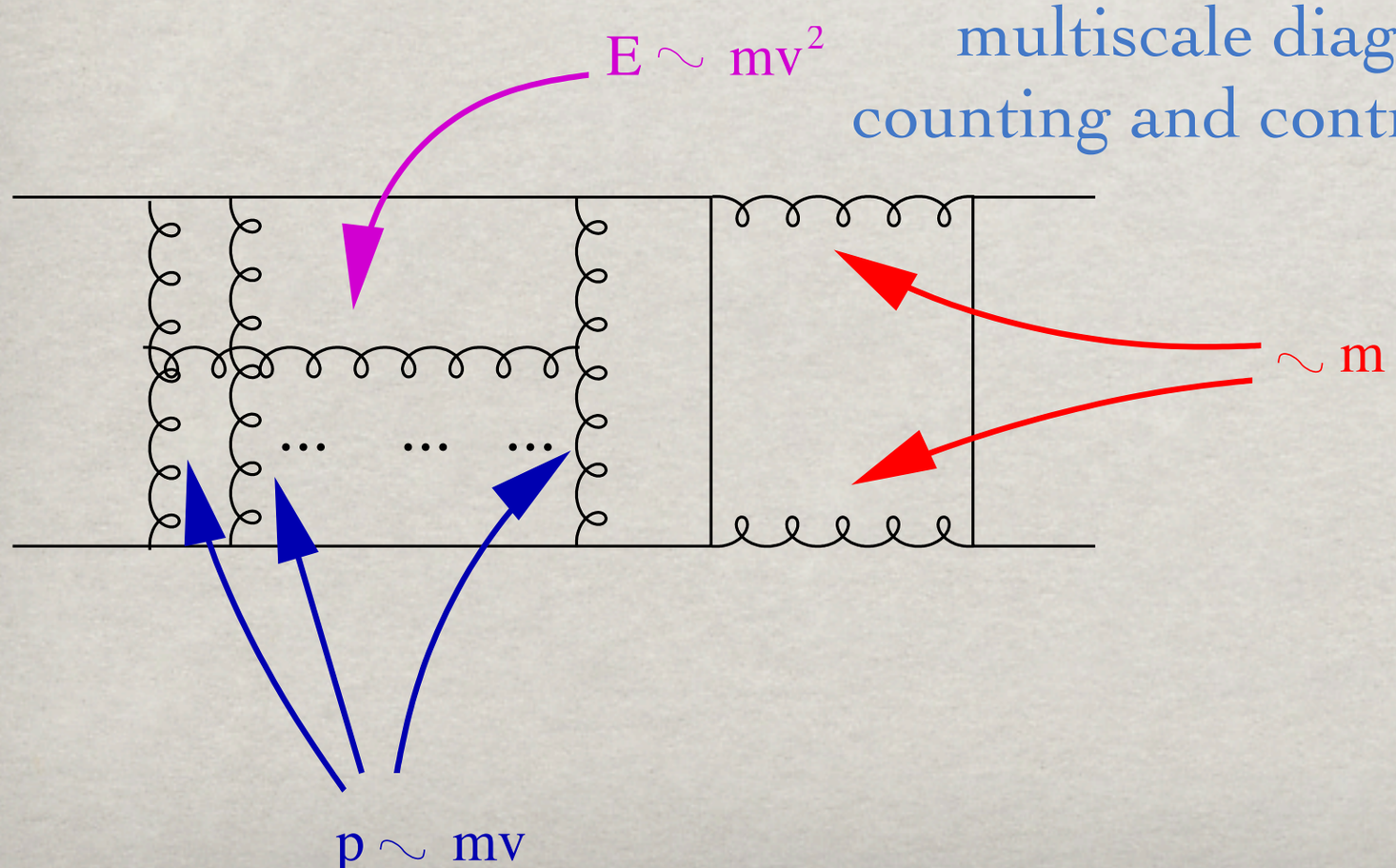
multiscale diagrams have a complicate power counting and contribute to all orders in the coupling



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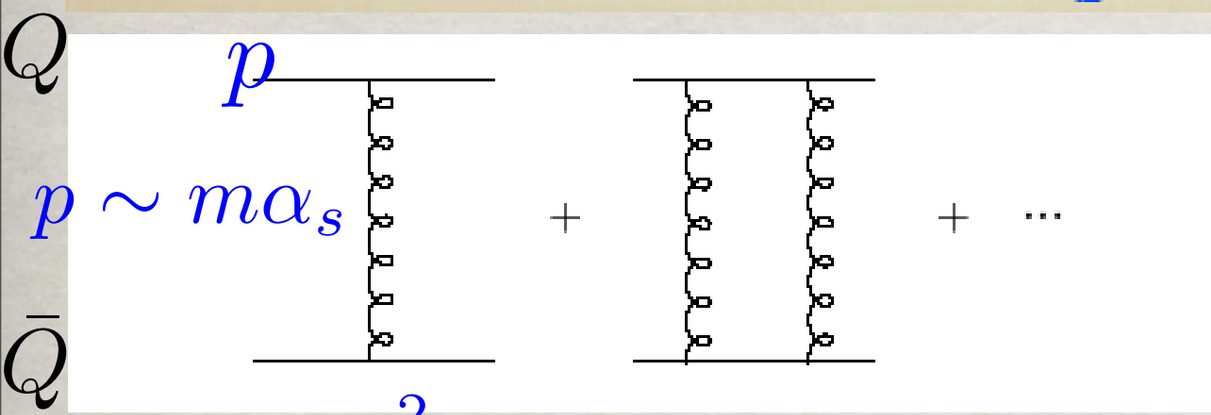

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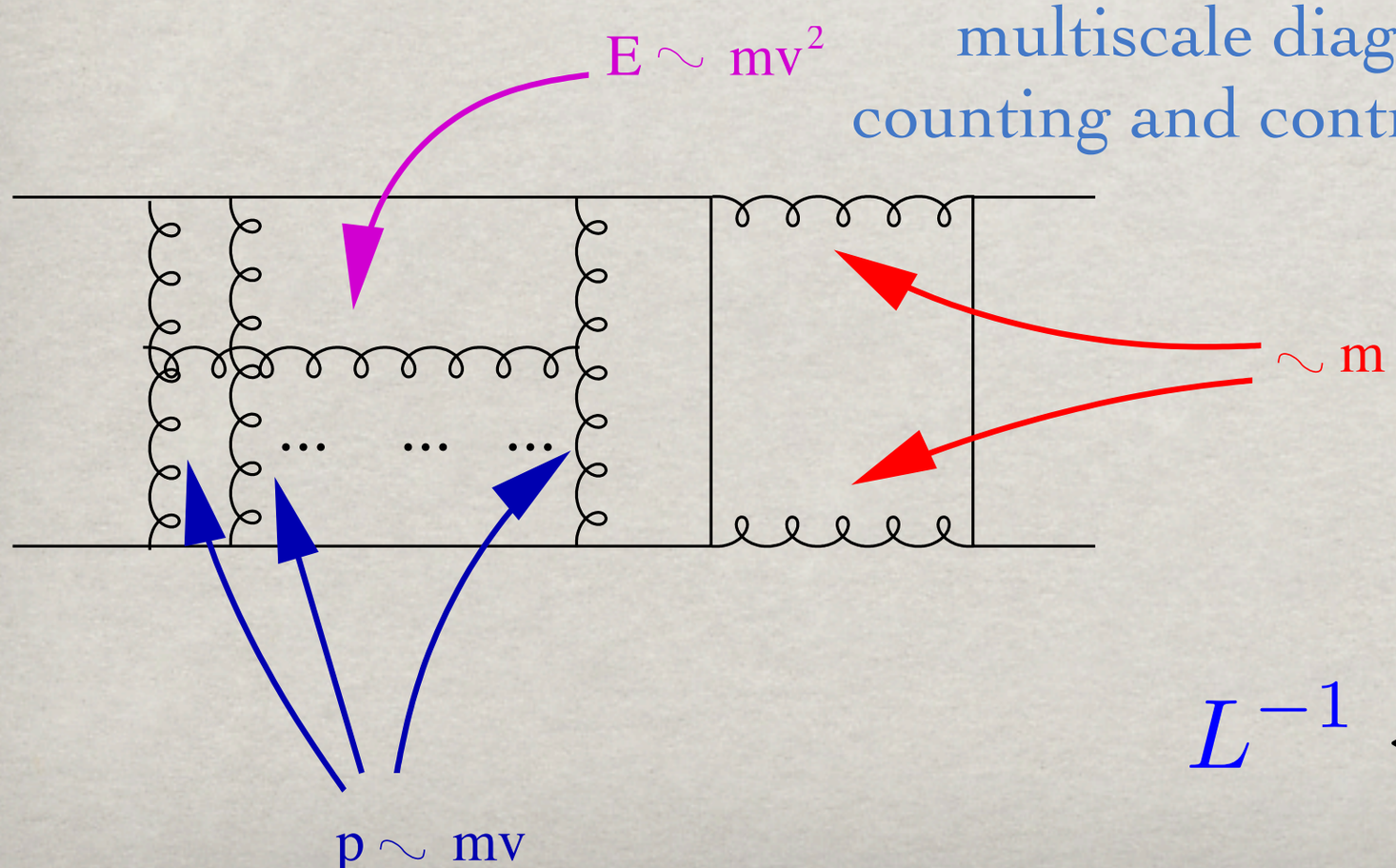
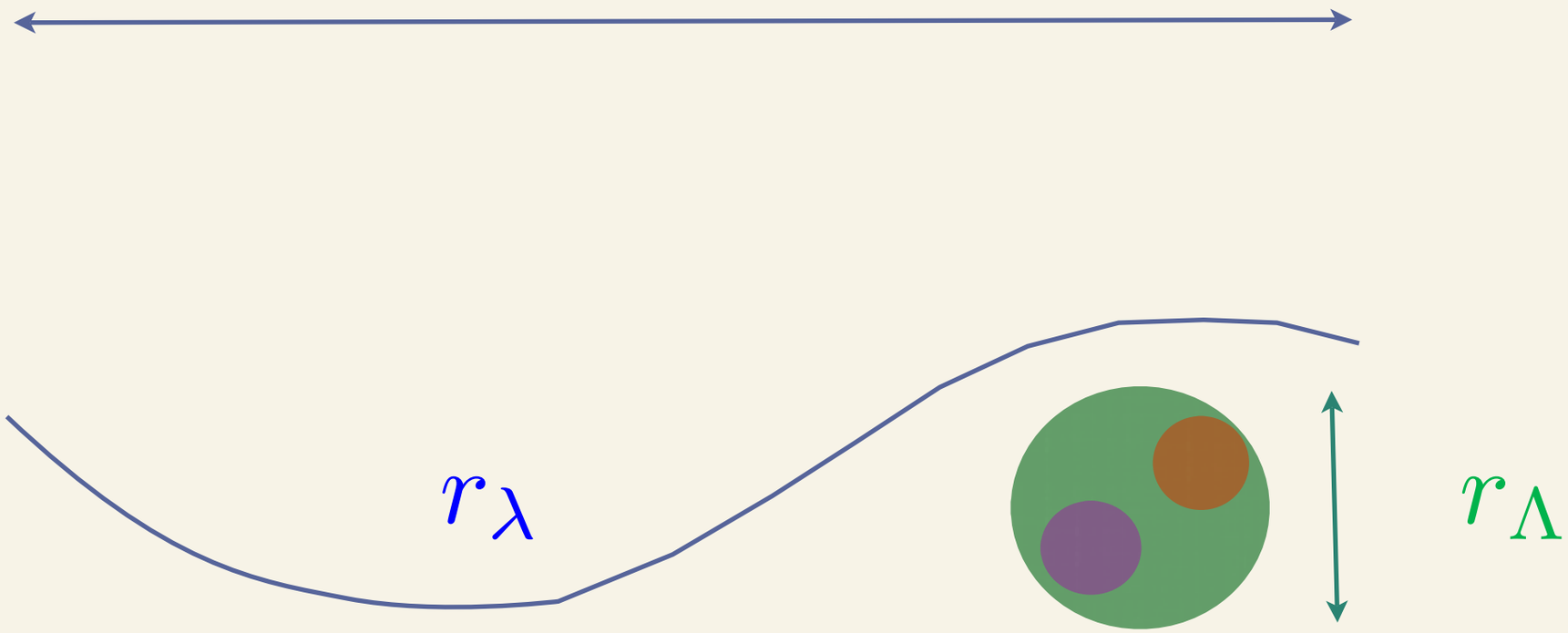


Difficult also for the lattice!

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

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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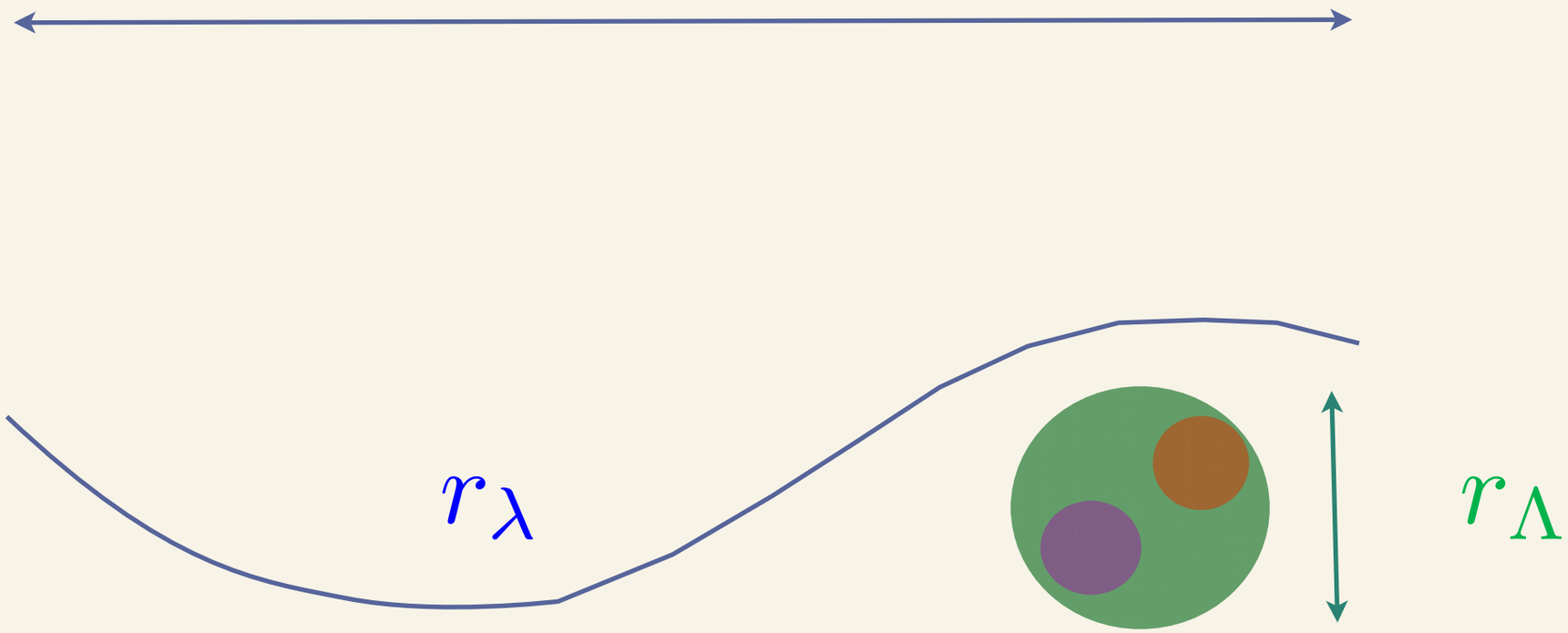

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The EFT Lagrangian, $\mathcal{L}_{\mathrm{EFT}}$, suitable to describe H at scales lower than Λ is defined by

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

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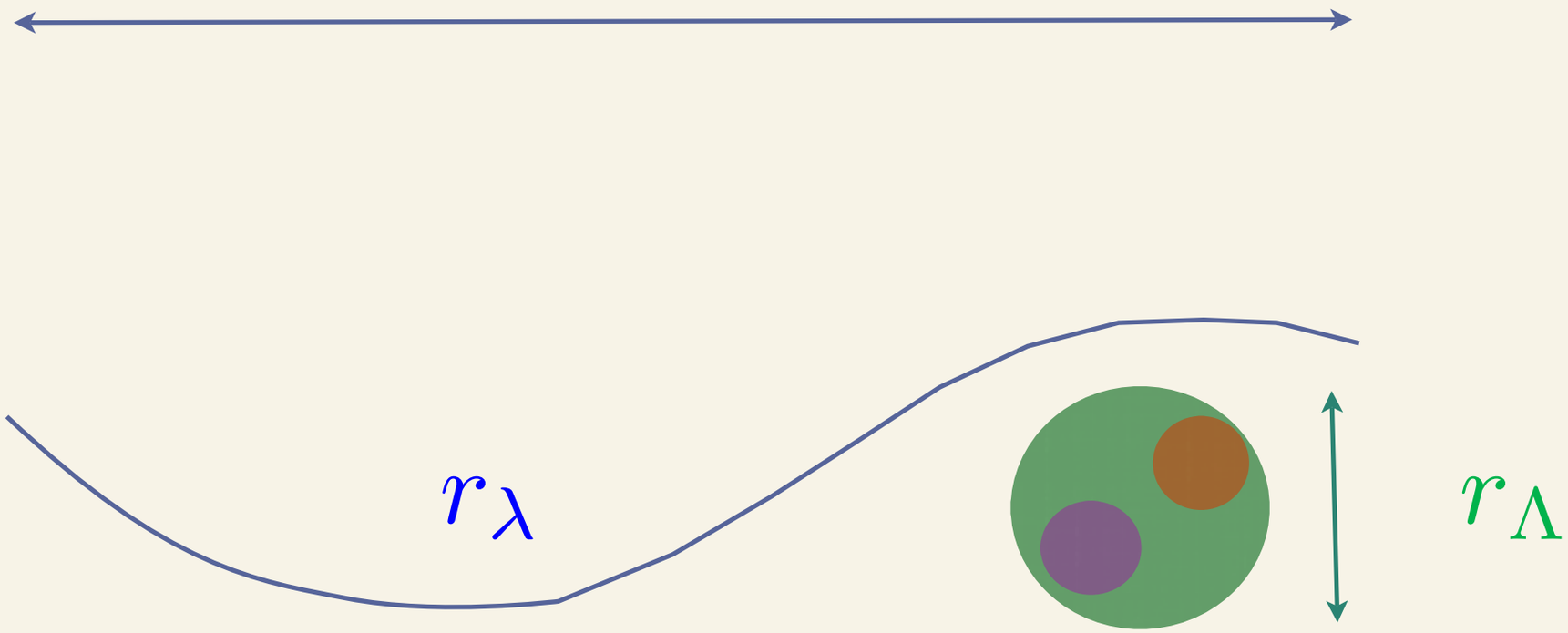

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RANGE OF VALIDITY OF THE EFT: ENERGY $< \mu$

$\Rightarrow$ $\mathcal{L}_{\rm EFT}$ 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

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

Effective Field Theories

low energy operator

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

Wilson coefficient

large scale

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- The matching coefficients $c_n(\Lambda/\mu)$ encode the non-analytic behaviour in Λ. They are calculated by imposing that $\mathcal{L}_{\rm EFT}$ and $\mathcal{L}$ describe the same physics at any finite order in the expansion: matching procedure.

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Matching

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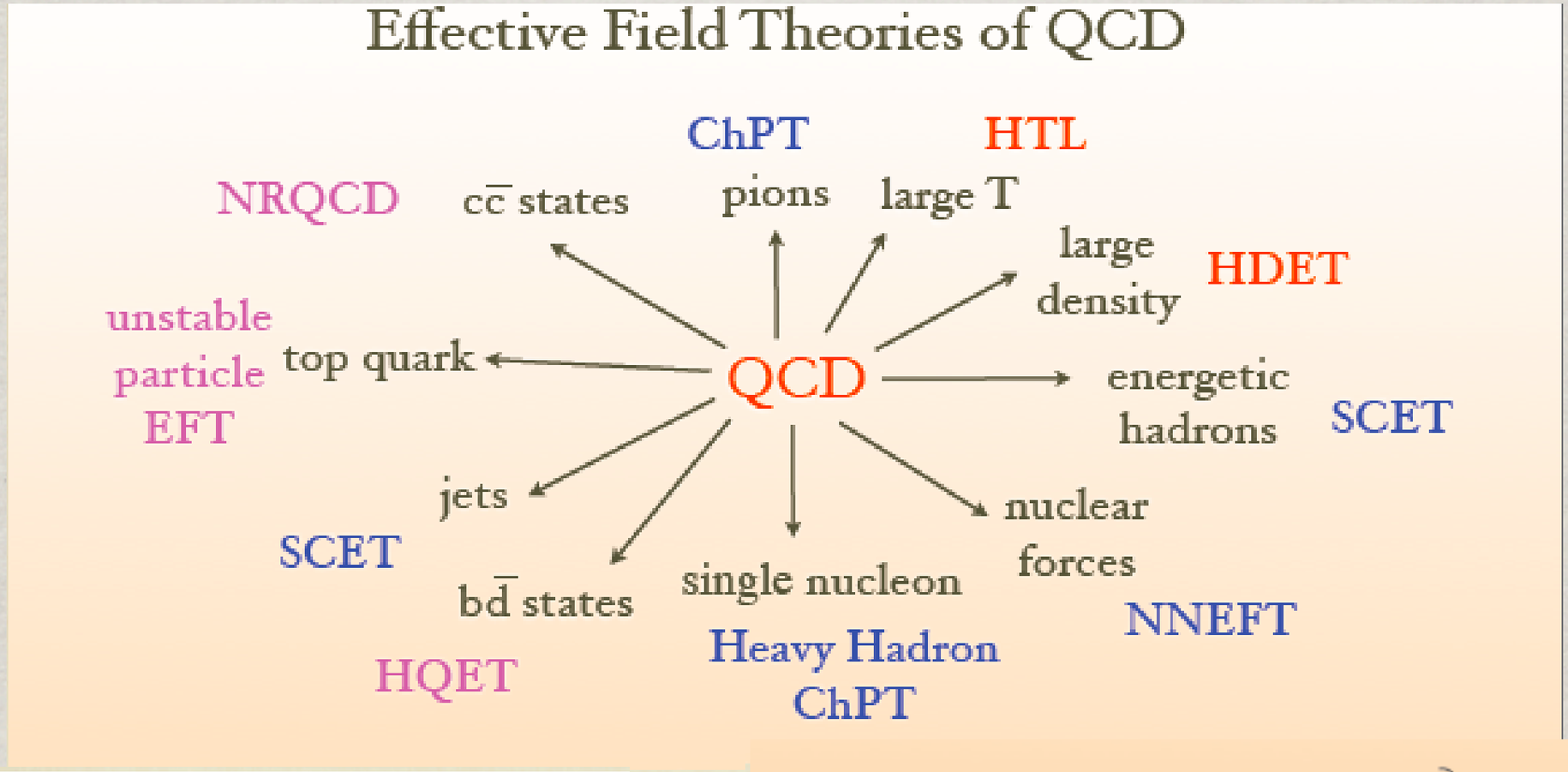
- Symmetries of the system become manifest;
- Large $\log(\Lambda/\lambda)$ can be resummed via RG. (Renormalization group)

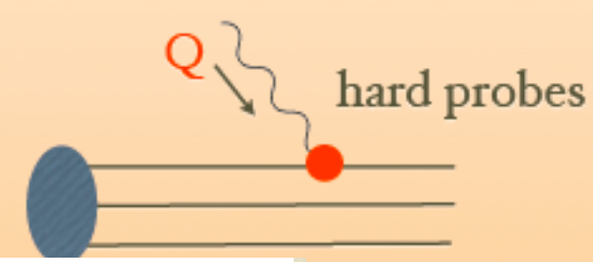
QCD Effective Field Theories

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



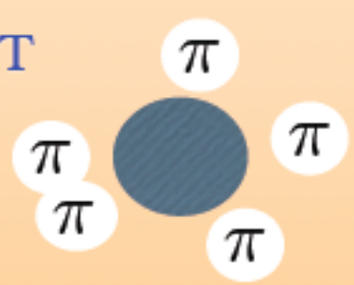
- Heavy quark effective theory (HQET): $\frac{\lambda}{\Lambda} = \frac{\Lambda_{QCD}}{m}$

Soft-Collinear Effective Theory (SCET)



$\frac{\Lambda}{Q} \ll$

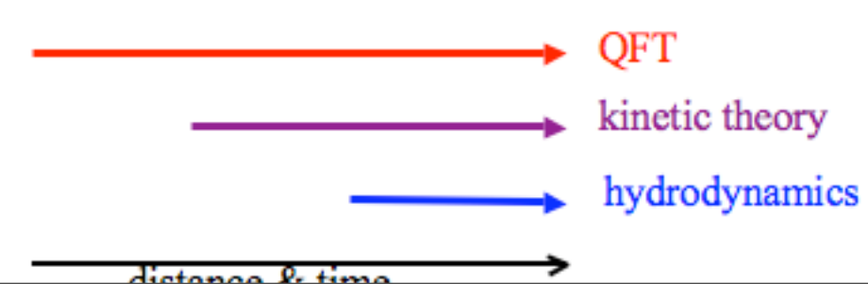
ChPT



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

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

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



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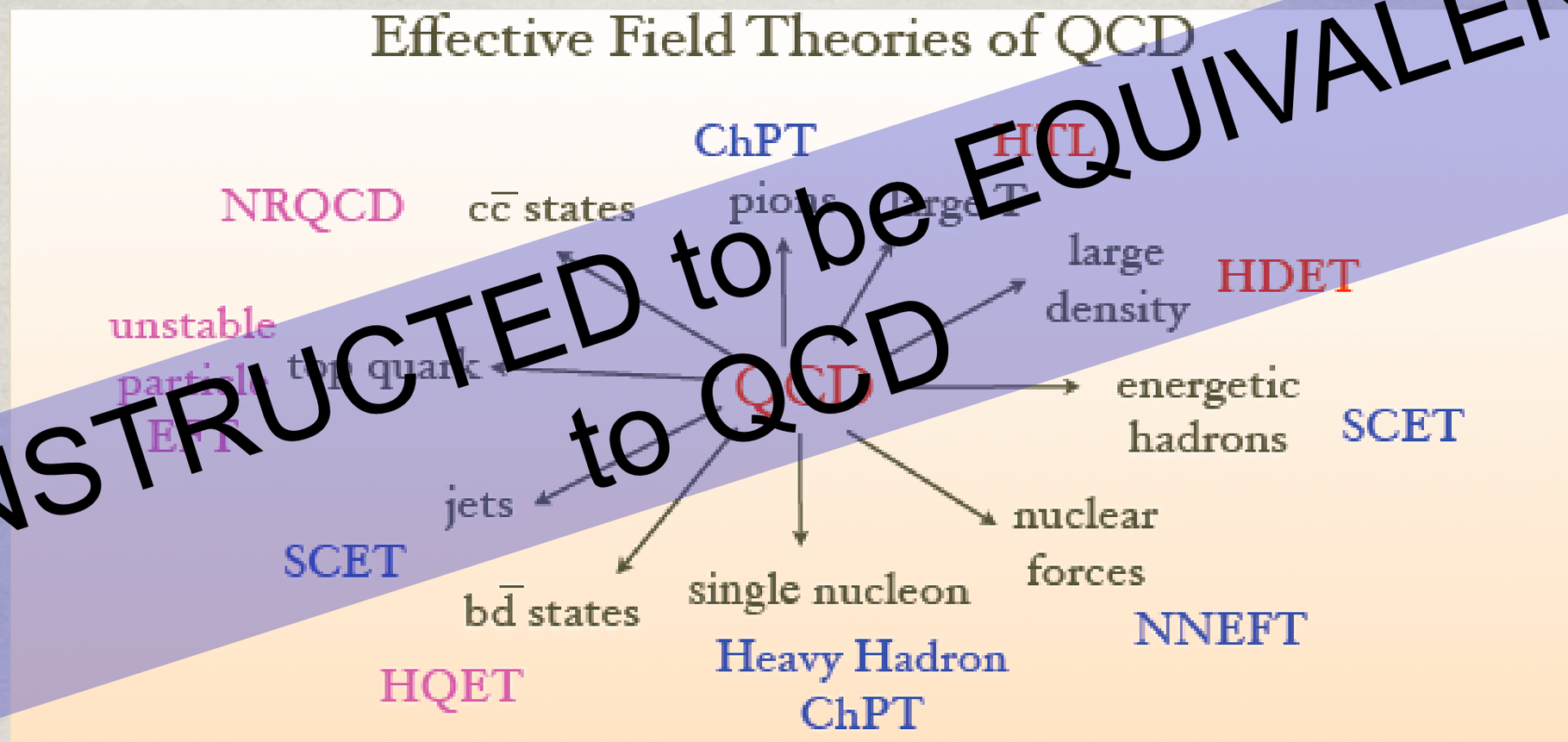
CONSTRUCTED to be EQUIVALENT to QCD



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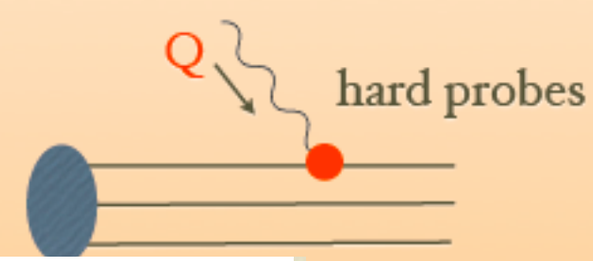
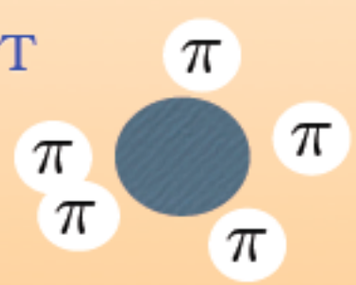


$\frac{\Lambda}{Q}$

ChPT



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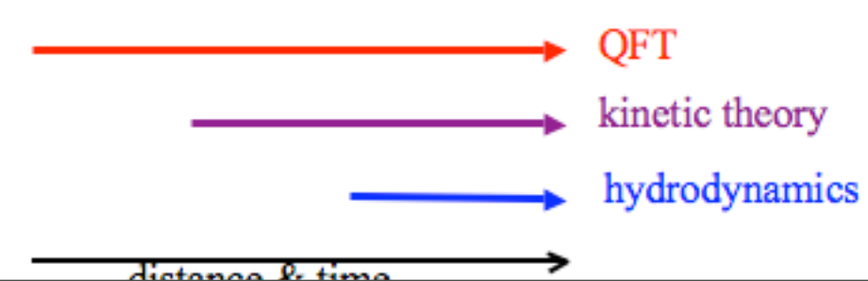
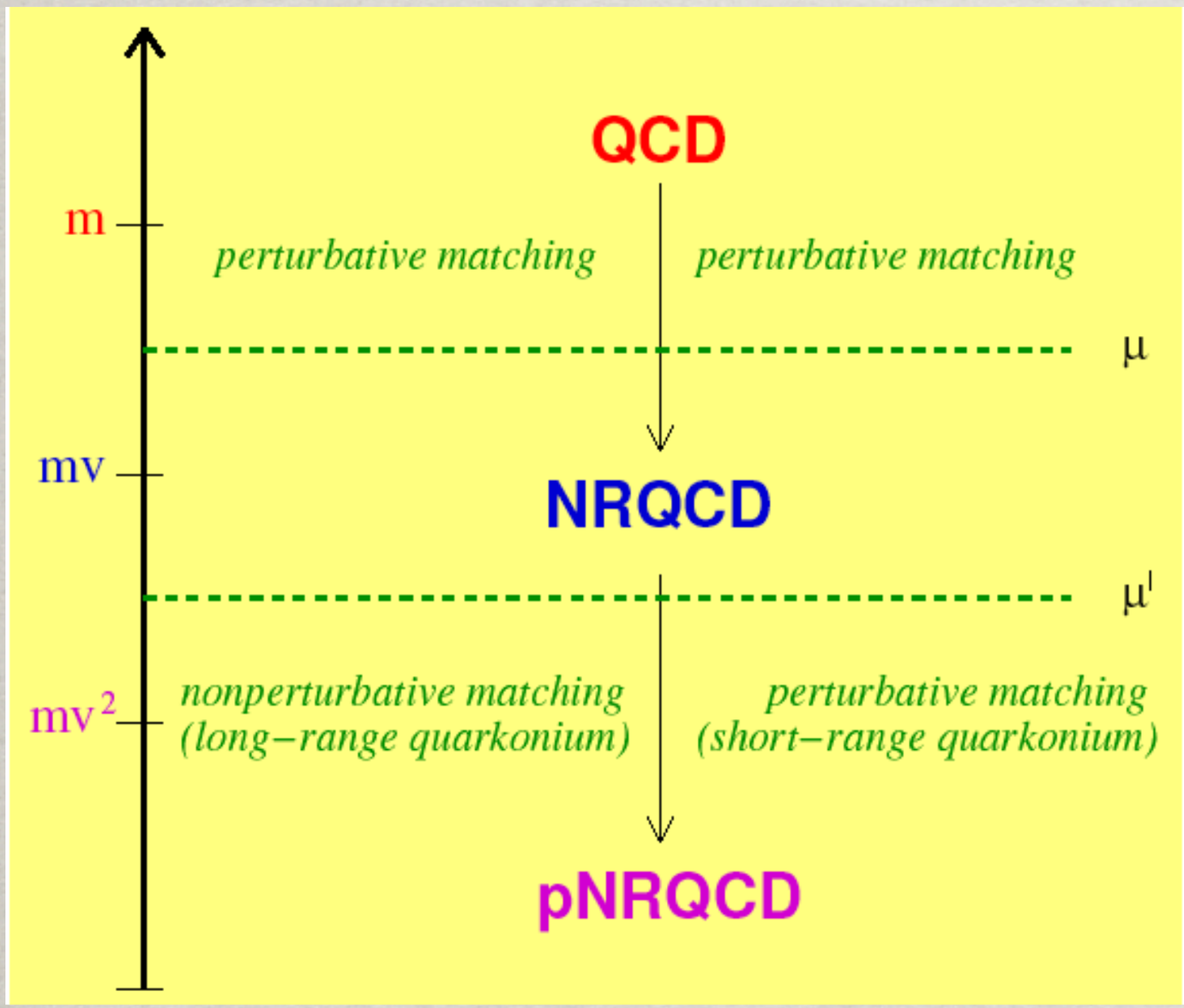


Quarkonium with NR EFT

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



Hard

Soft
(relative
momentum)

Ultrasoft
(binding energy)

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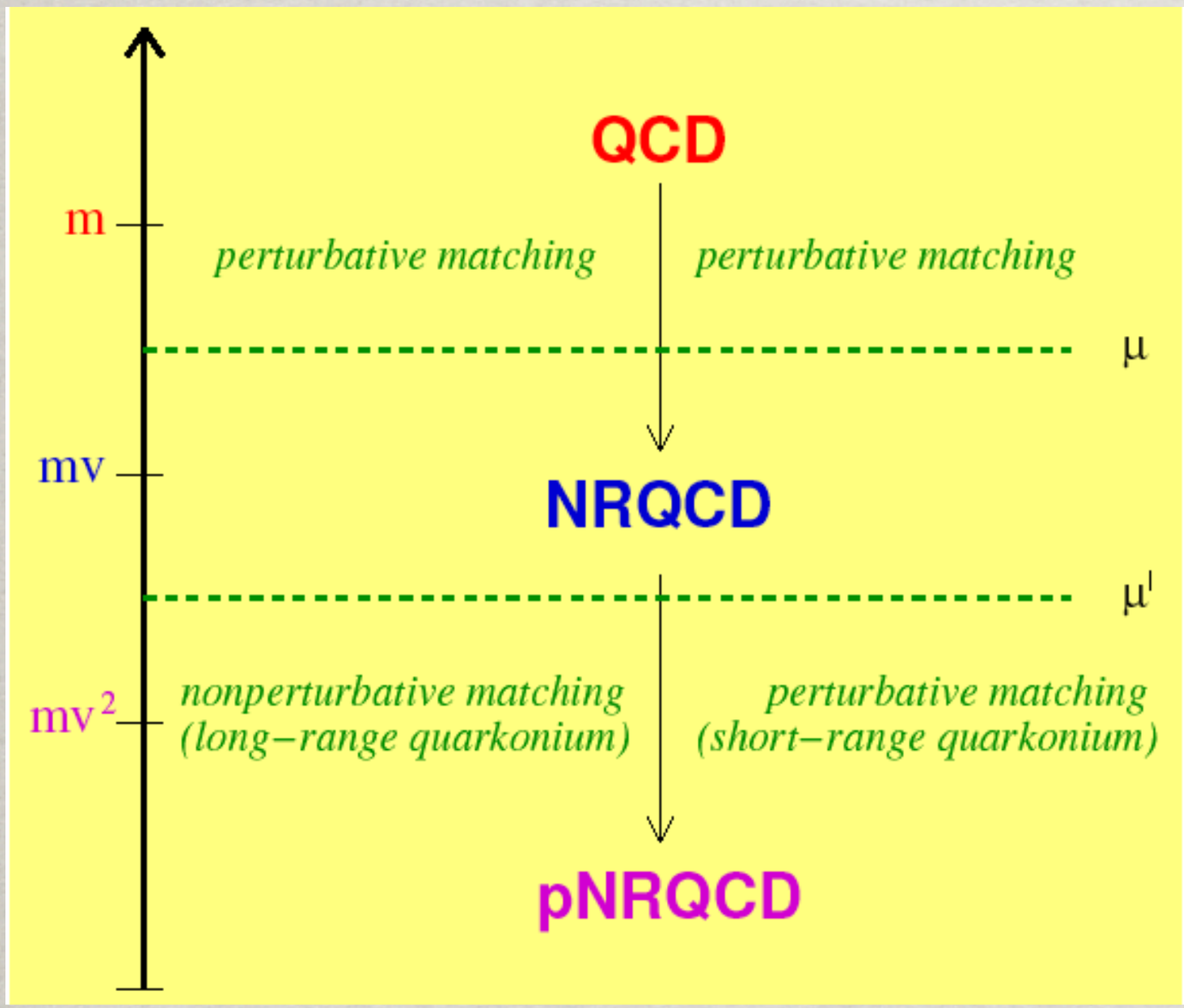

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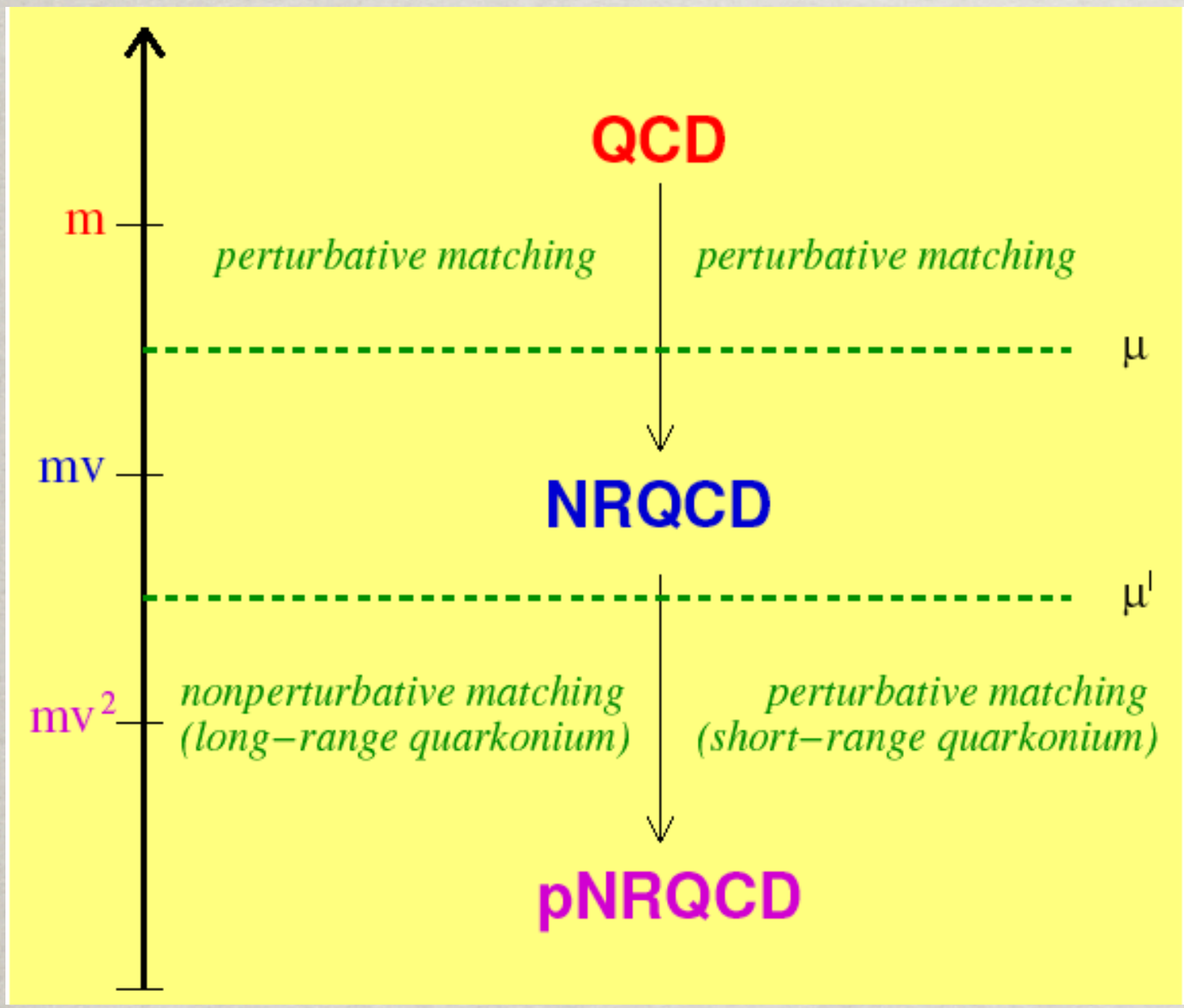

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$$\langle O_n \rangle \sim E_\lambda^n$$

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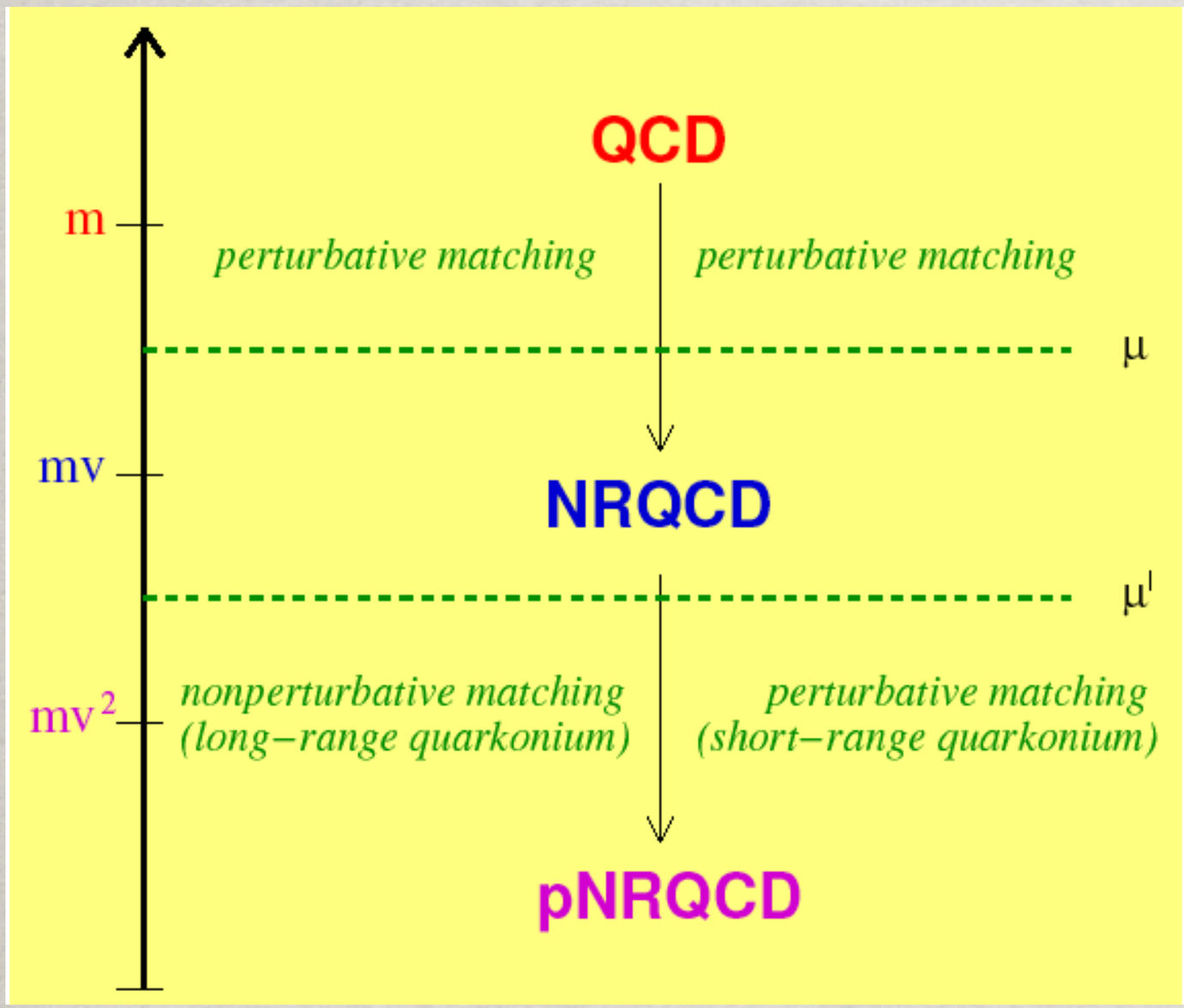

Hard

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

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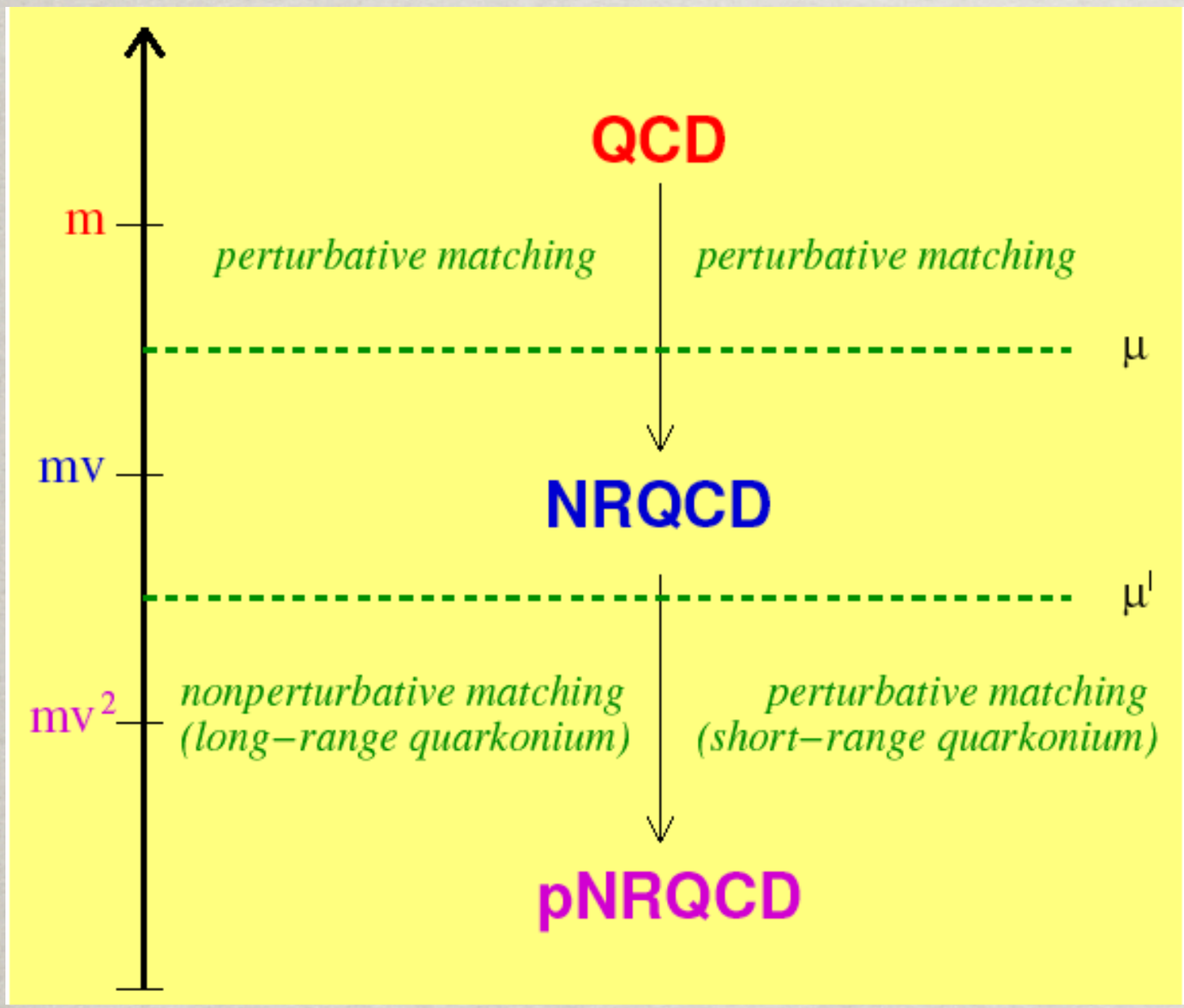
$$\mathcal{L}_{\rm EFT} = \sum_n c_n(E_\Lambda/\mu)\frac{O_n(\mu,\lambda)}{E_\Lambda}$$

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

Quarkonium with NR EFT

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



Hard

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

Soft
(relative
momentum)

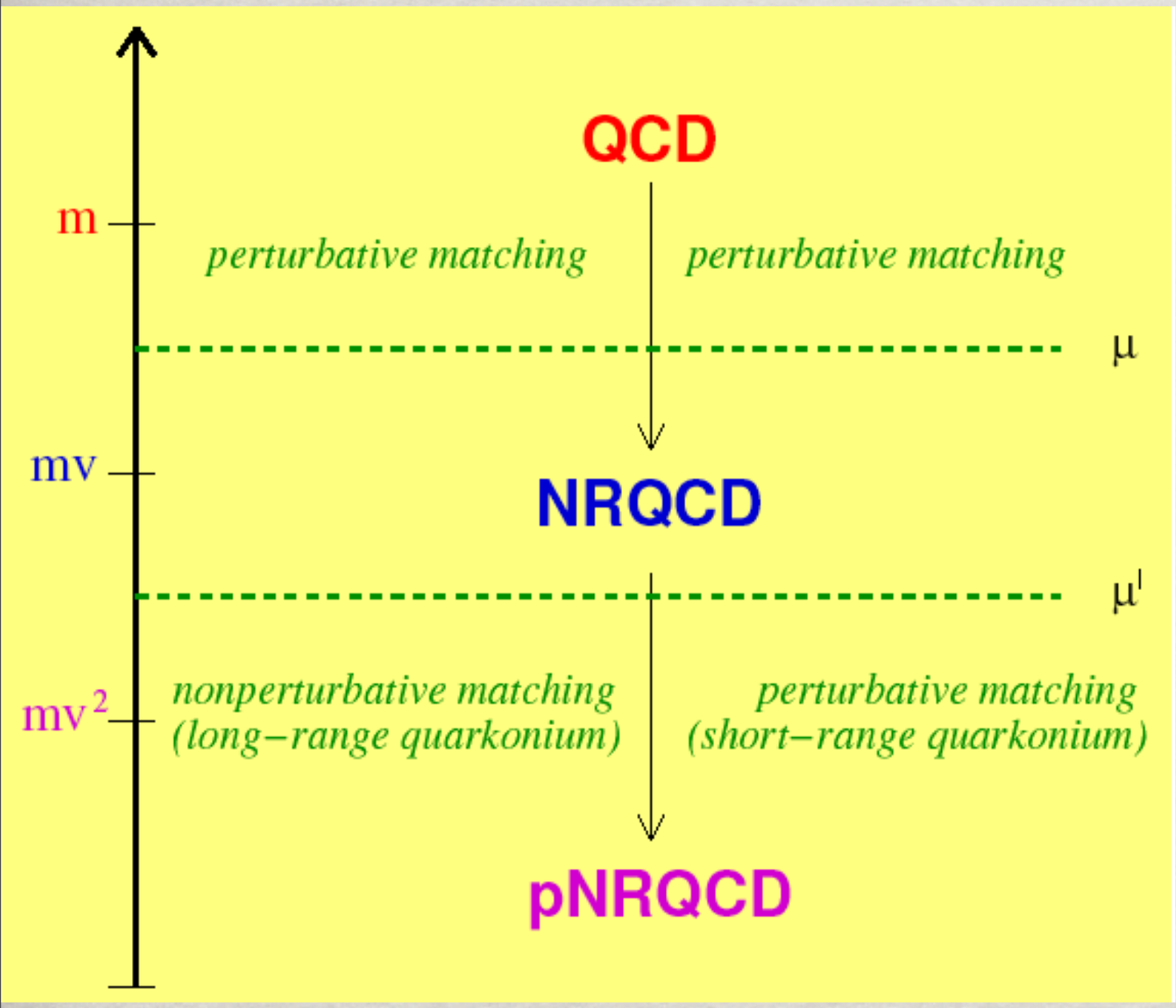
$$\frac{E_\lambda}{E_\Lambda} = \frac{mv^2}{mv}$$

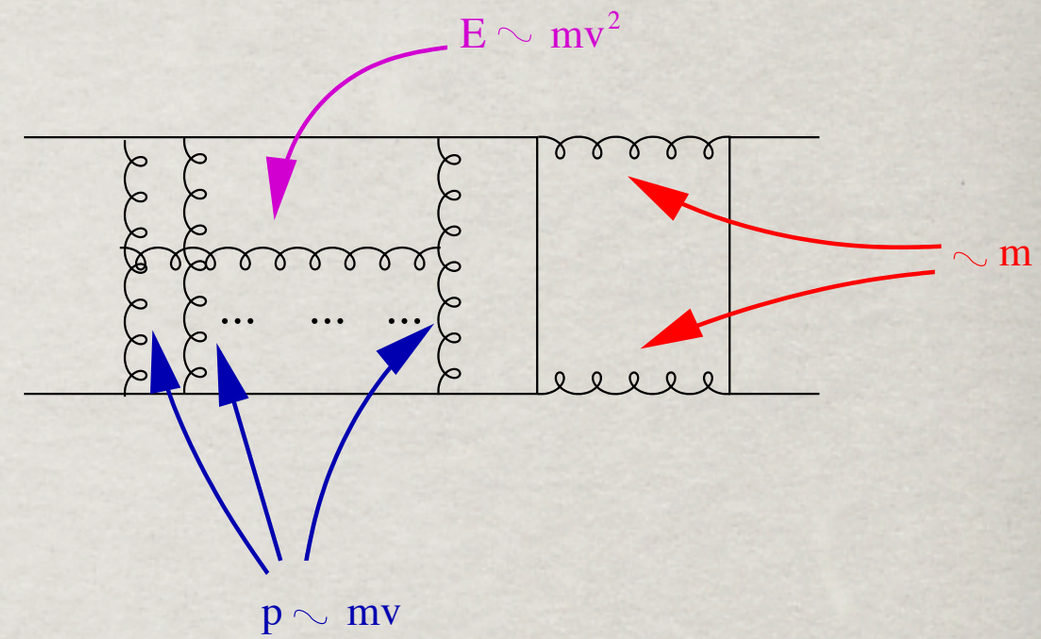
Ultrasoft
(binding energy)

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

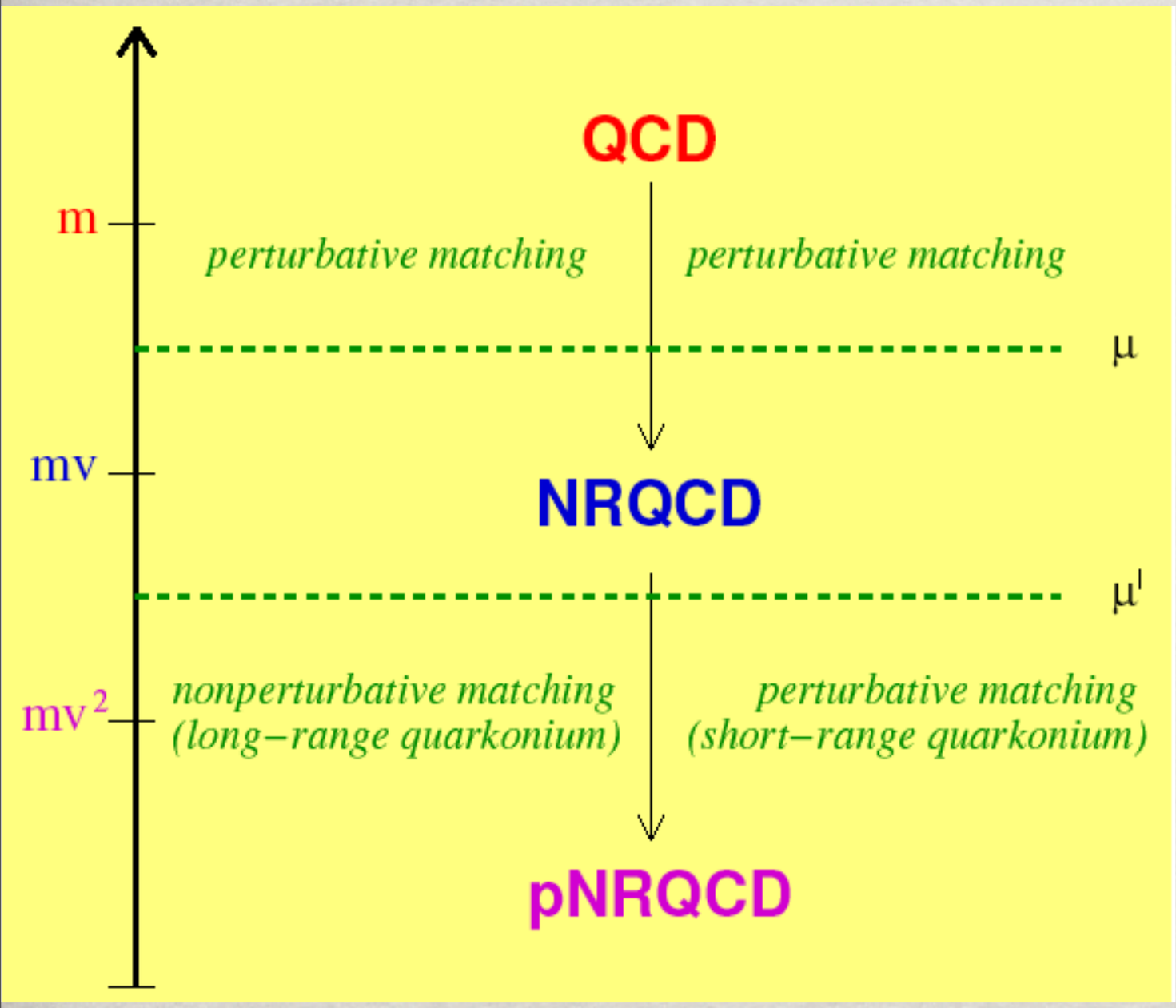
$$\langle O_n \rangle \sim E_\lambda^n$$

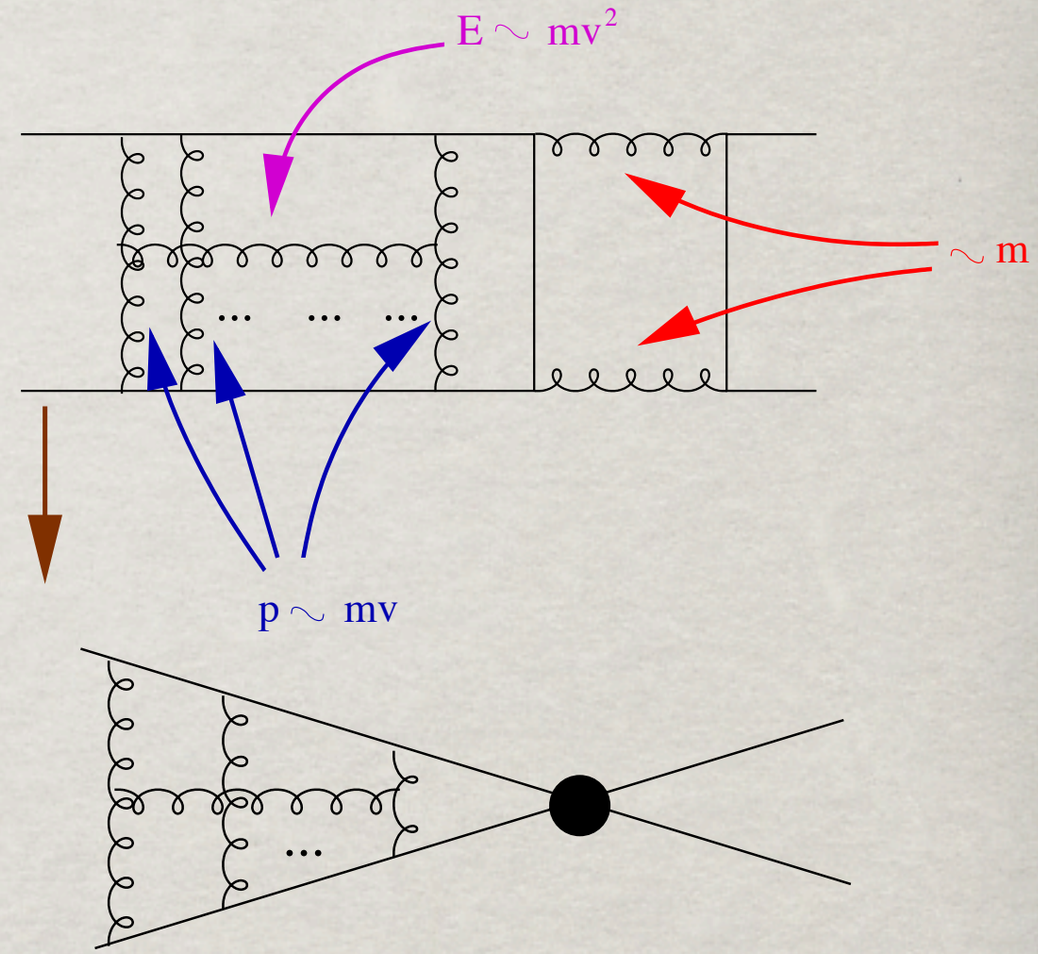
Quarkonium with NR EFT: Non Relativistic QCD (NRQCD)





Quarkonium with NR EFT: Non Relativistic QCD (NRQCD)





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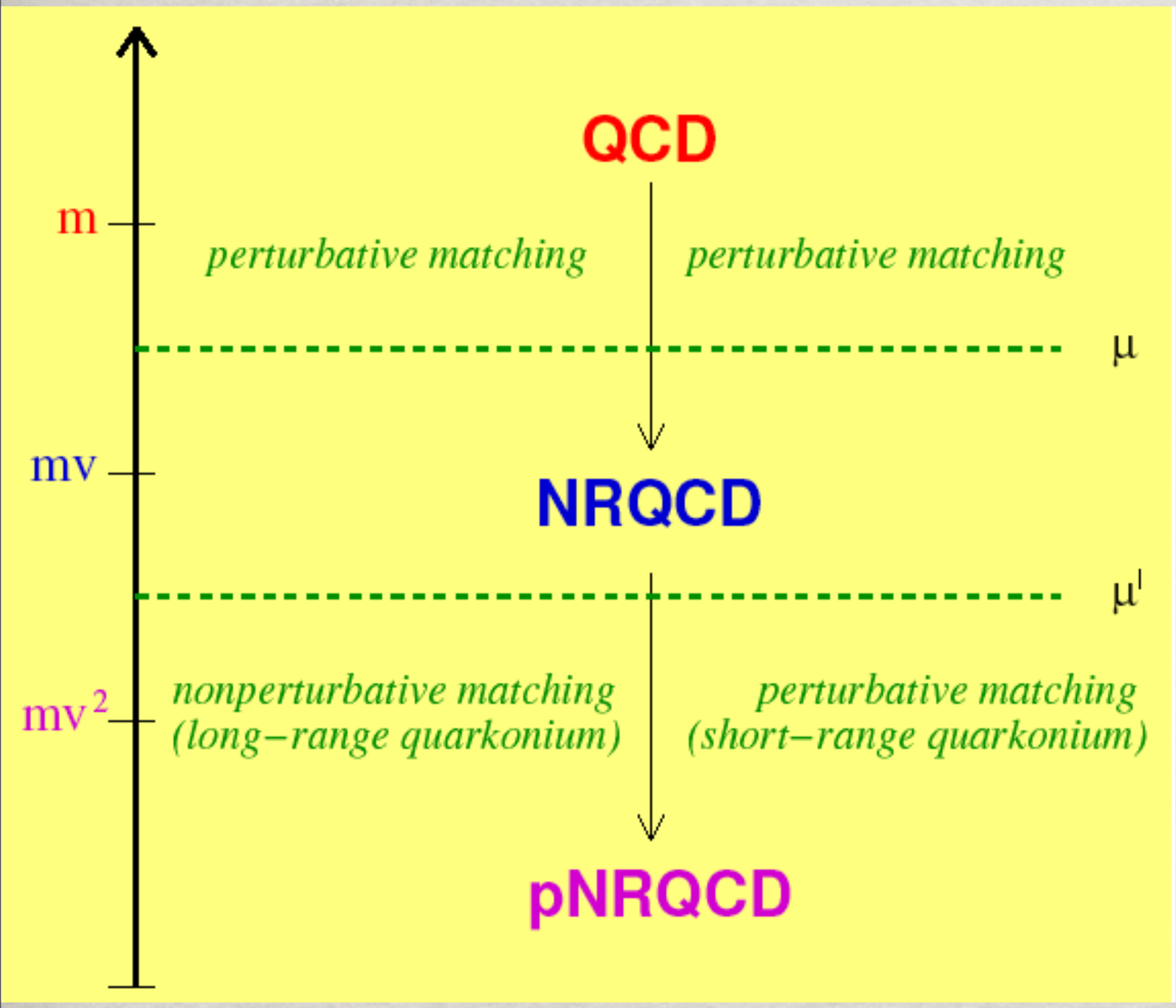
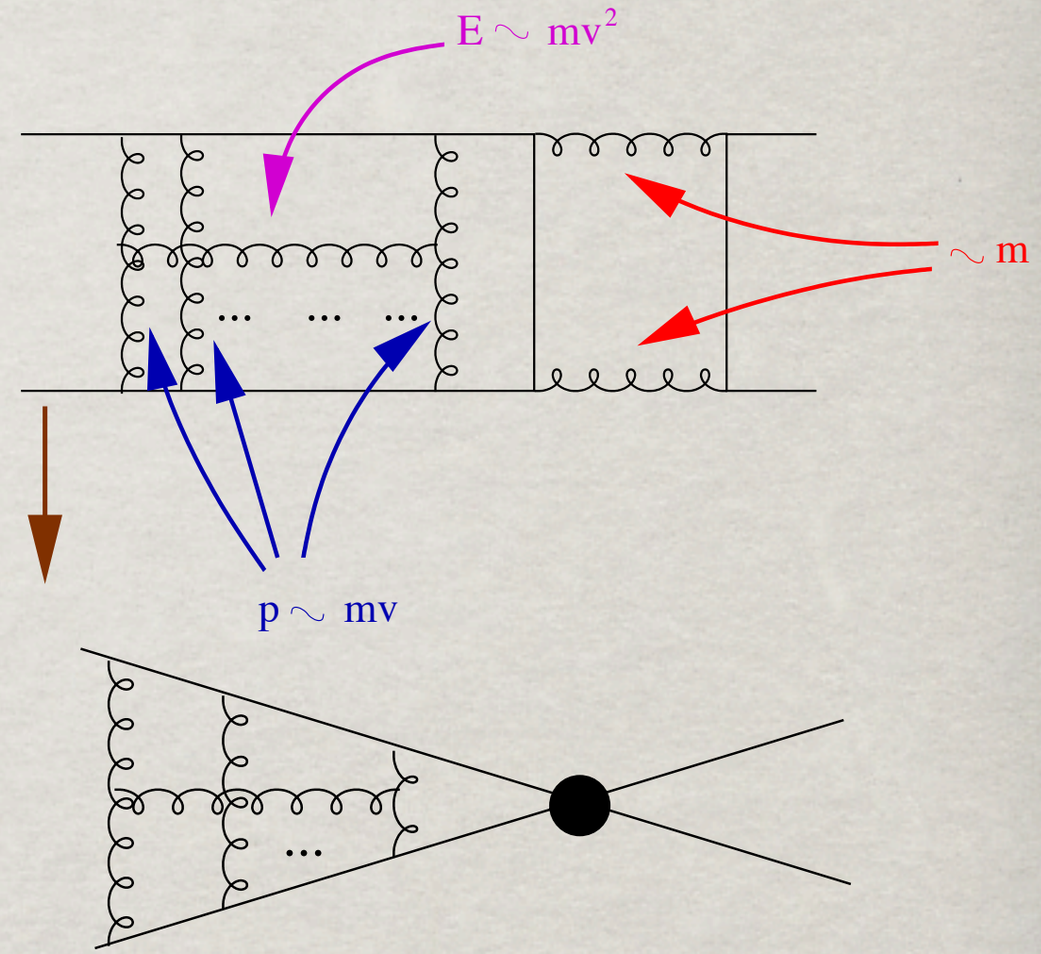
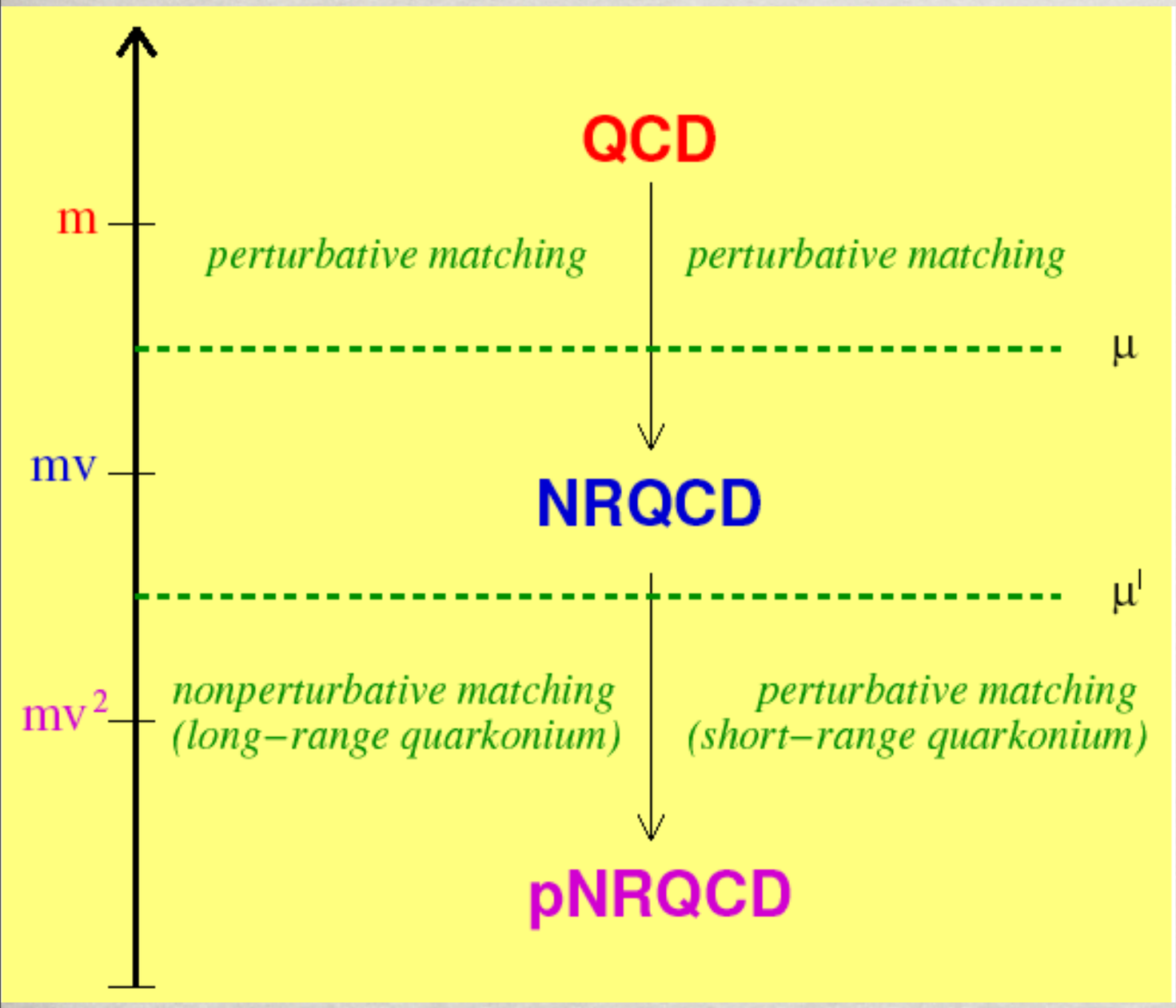
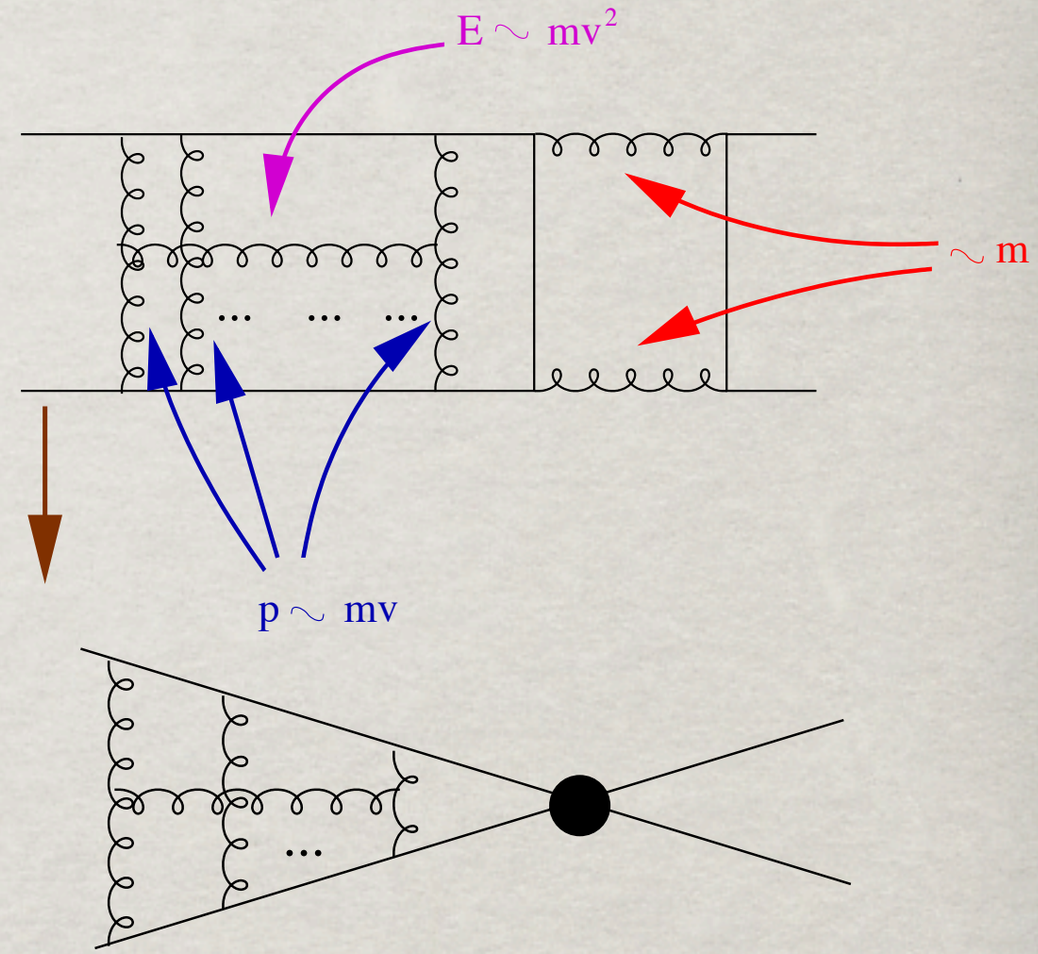




$$\mathcal{L}_{\mathrm{NRQCD}} = \sum_n c(\alpha_s(m/\mu)) \times \frac{O_n(\mu, \lambda)}{m^n}$$

Quarkonium with NR EFT: potential NonRelativistic QCD (pNRQCD)





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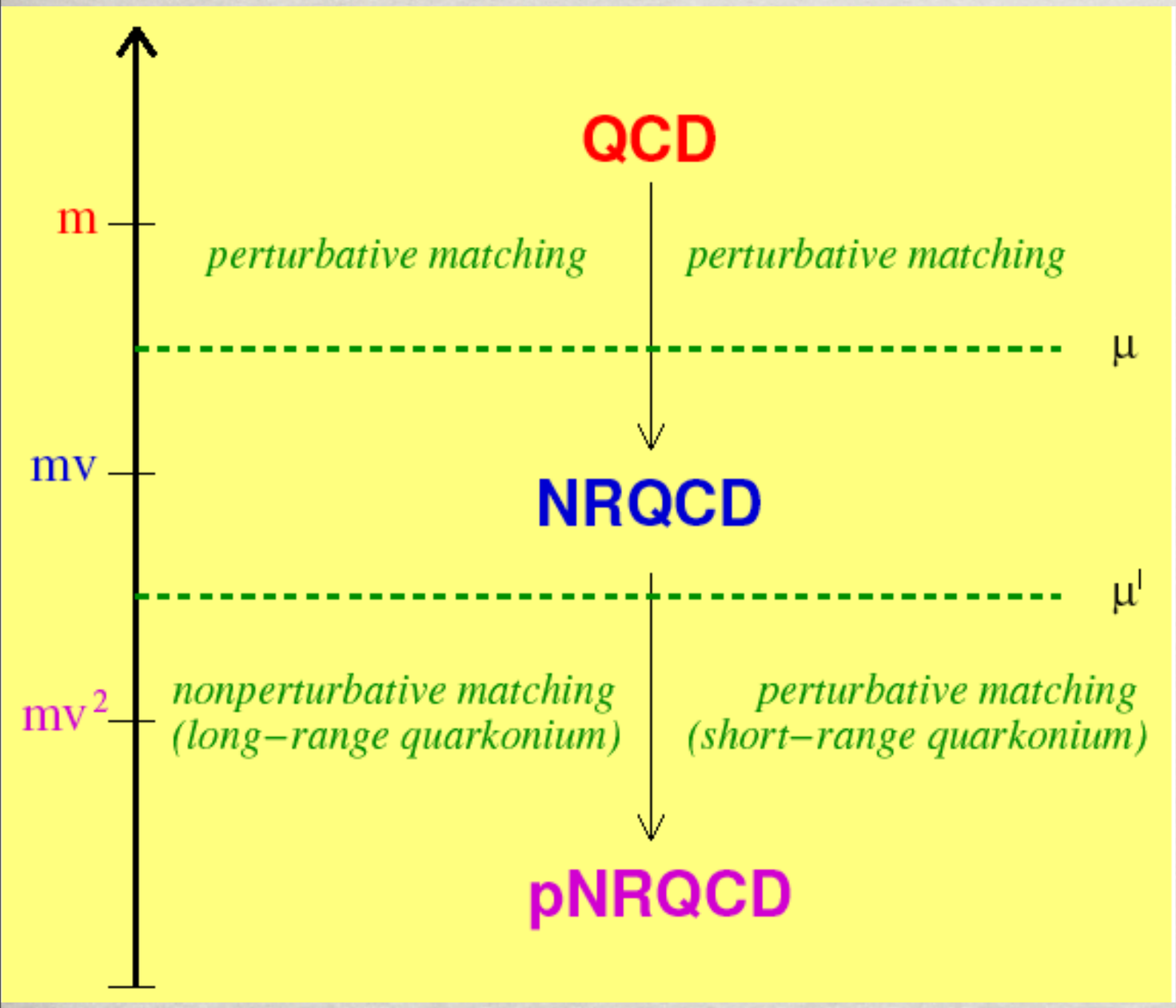

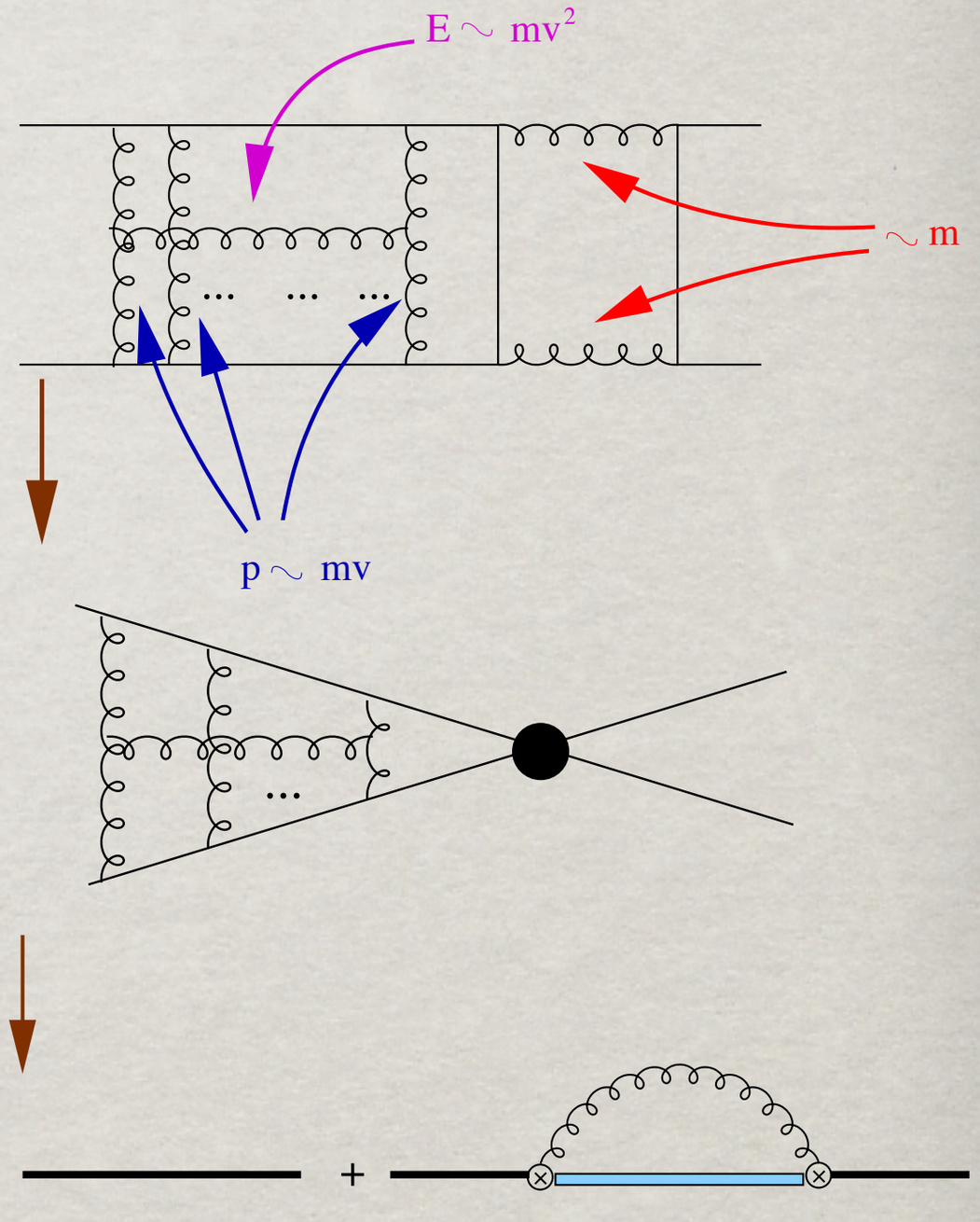

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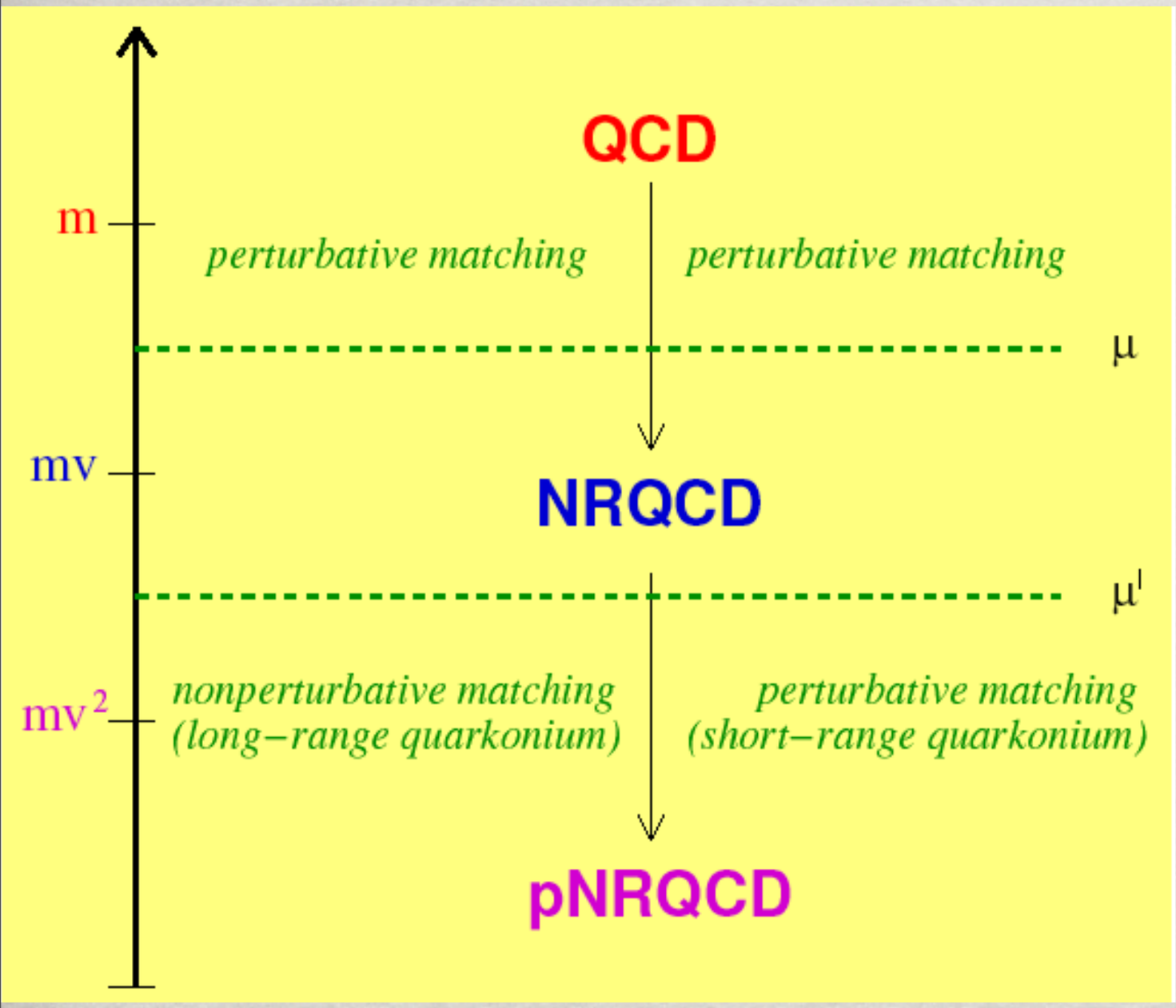
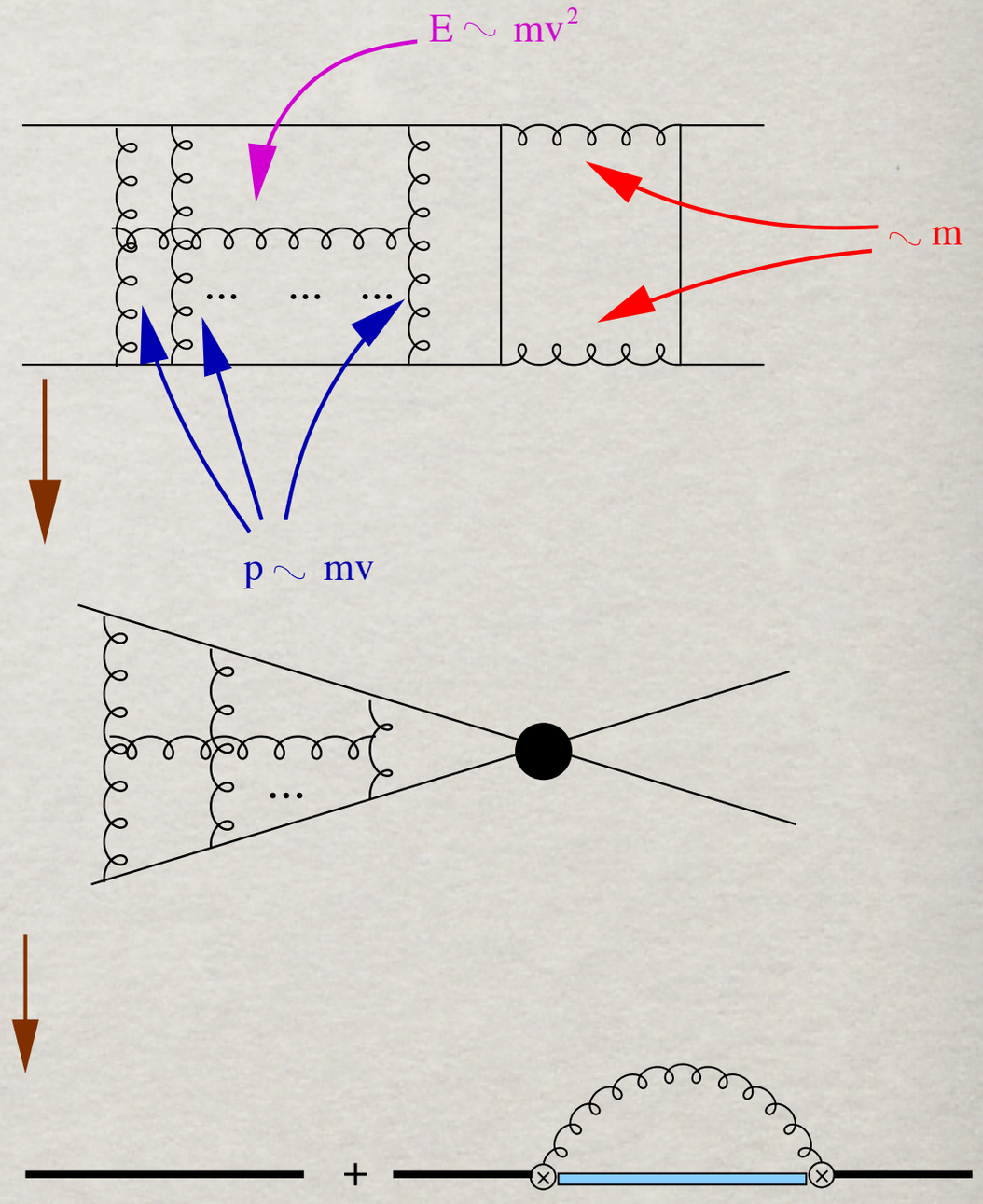
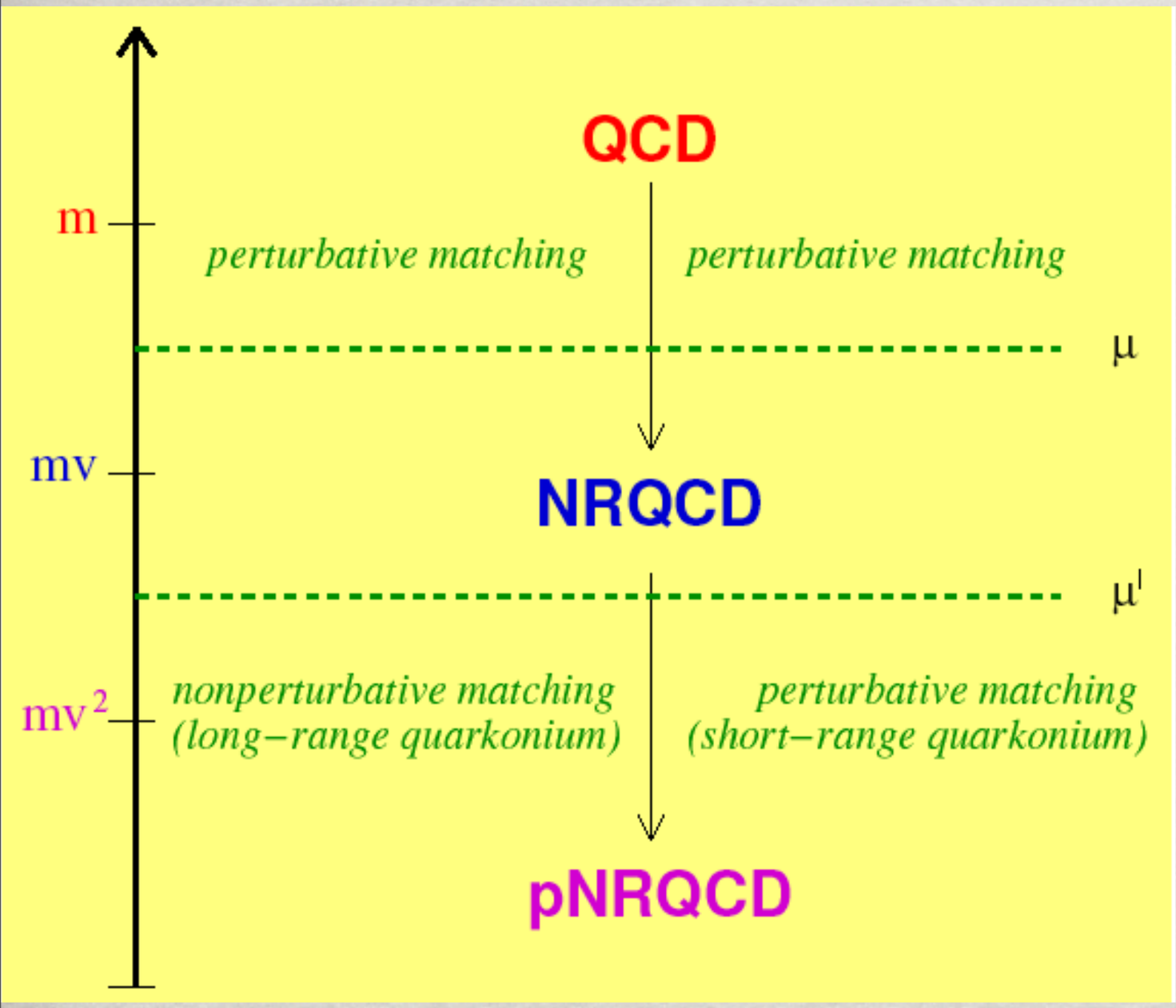
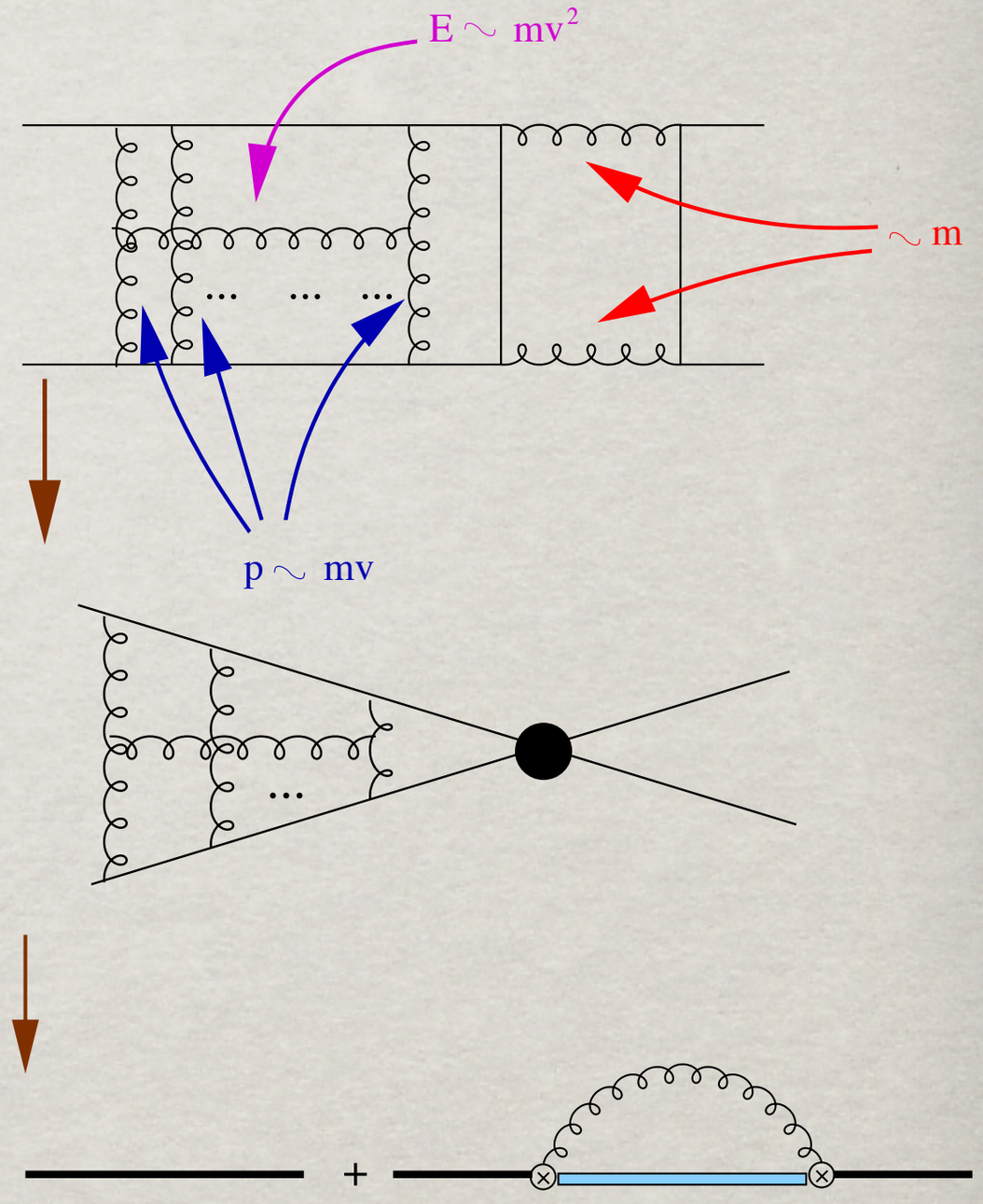




$$\mathcal{L}_{\rm pNRQCD} = \sum_k \sum_n \frac{1}{m^k} c_k(\alpha_{\rm s}(m/\mu)) \times V(r\mu', r\mu) \times O_n(\mu', \lambda)\, r^n$$

Quarkonium with NR EFT: potential NonRelativistic QCD (pNRQCD)





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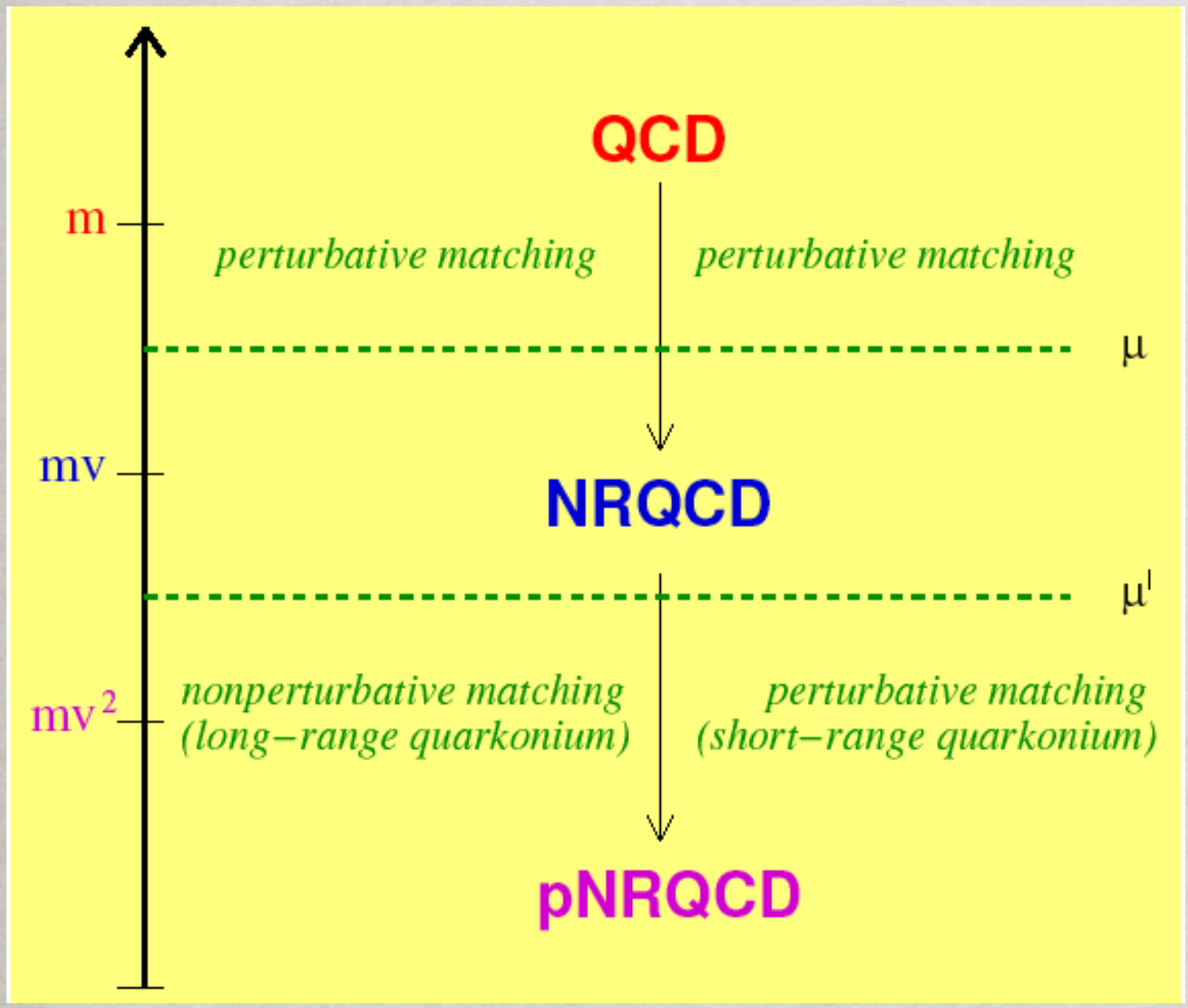
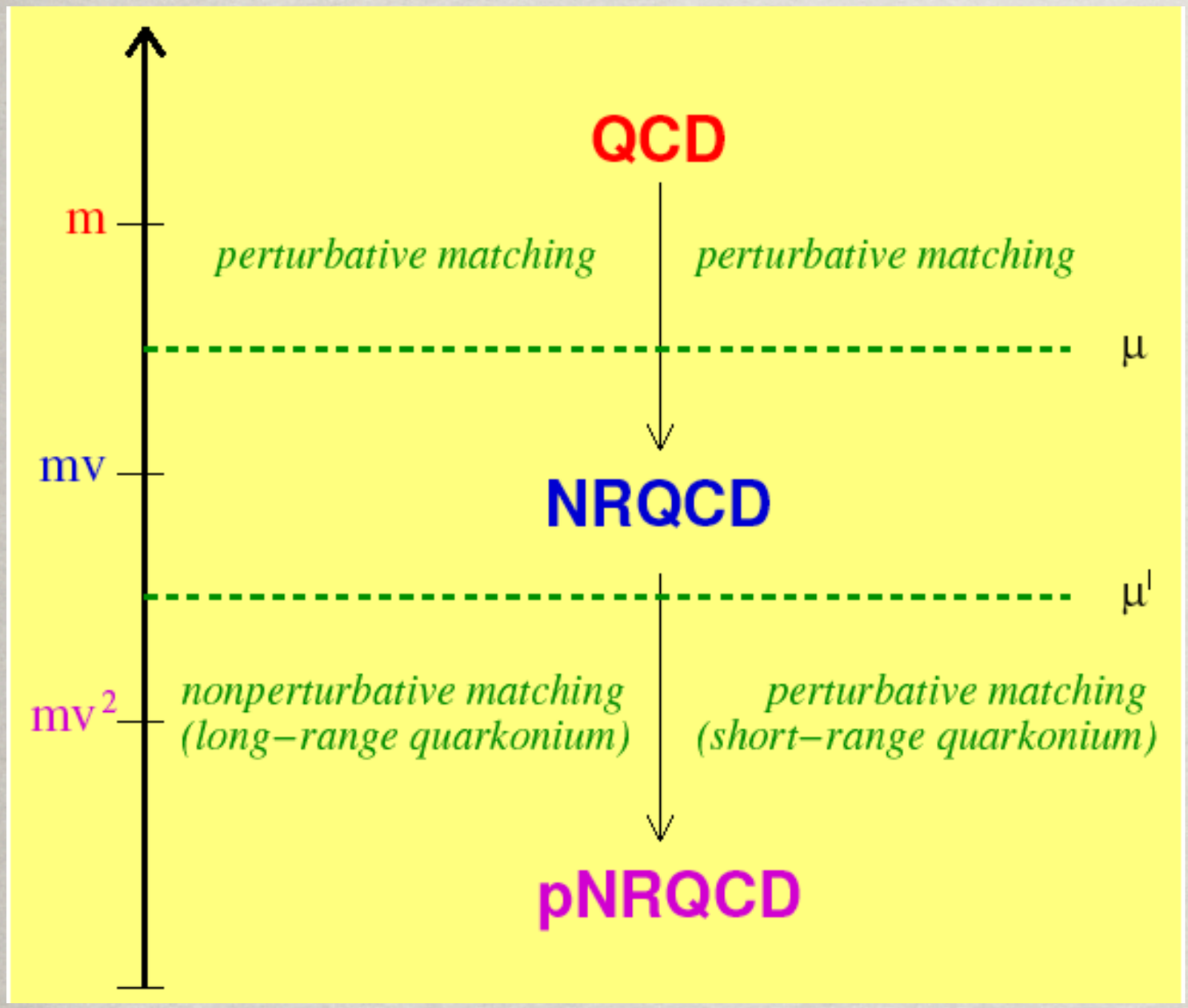
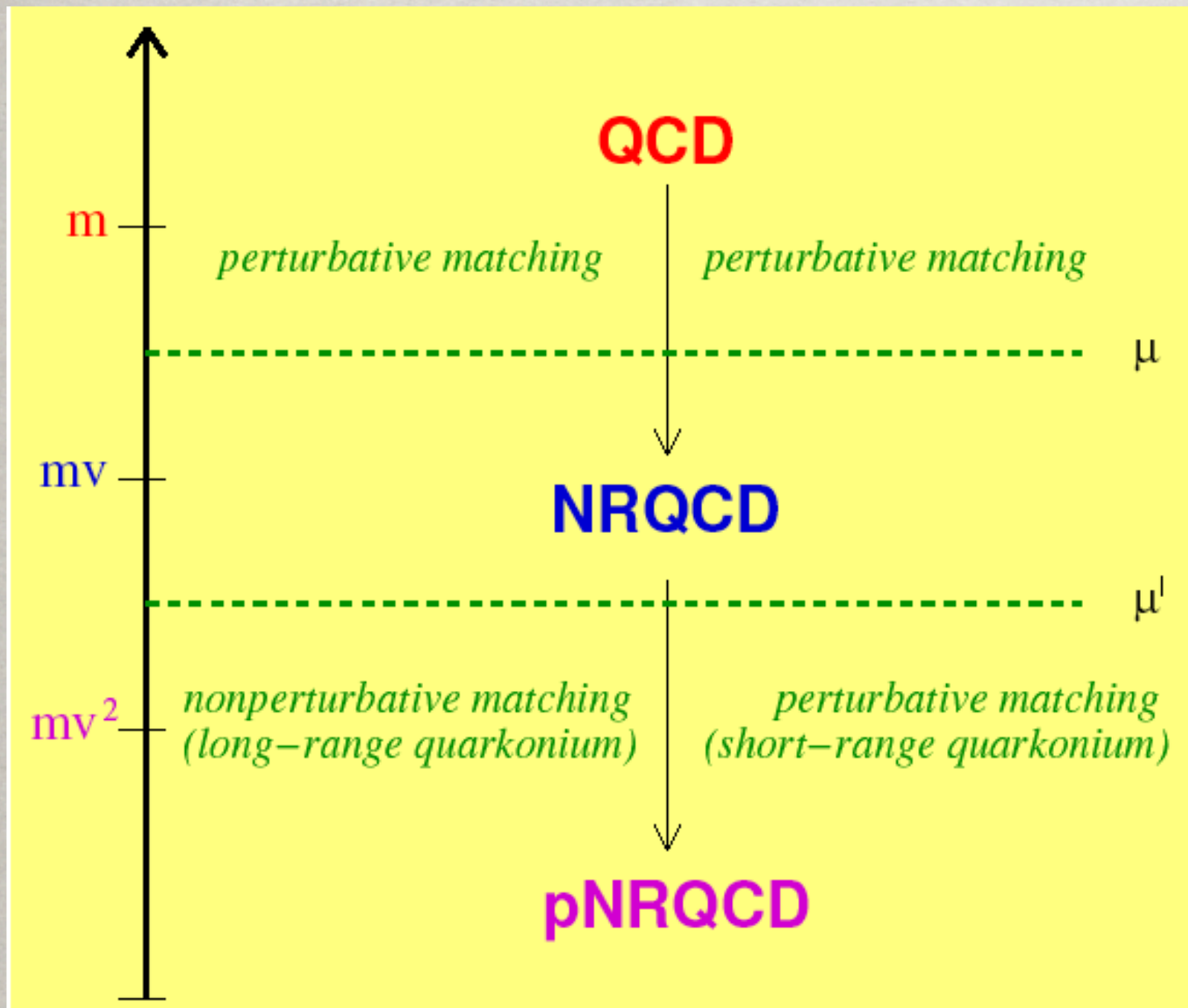


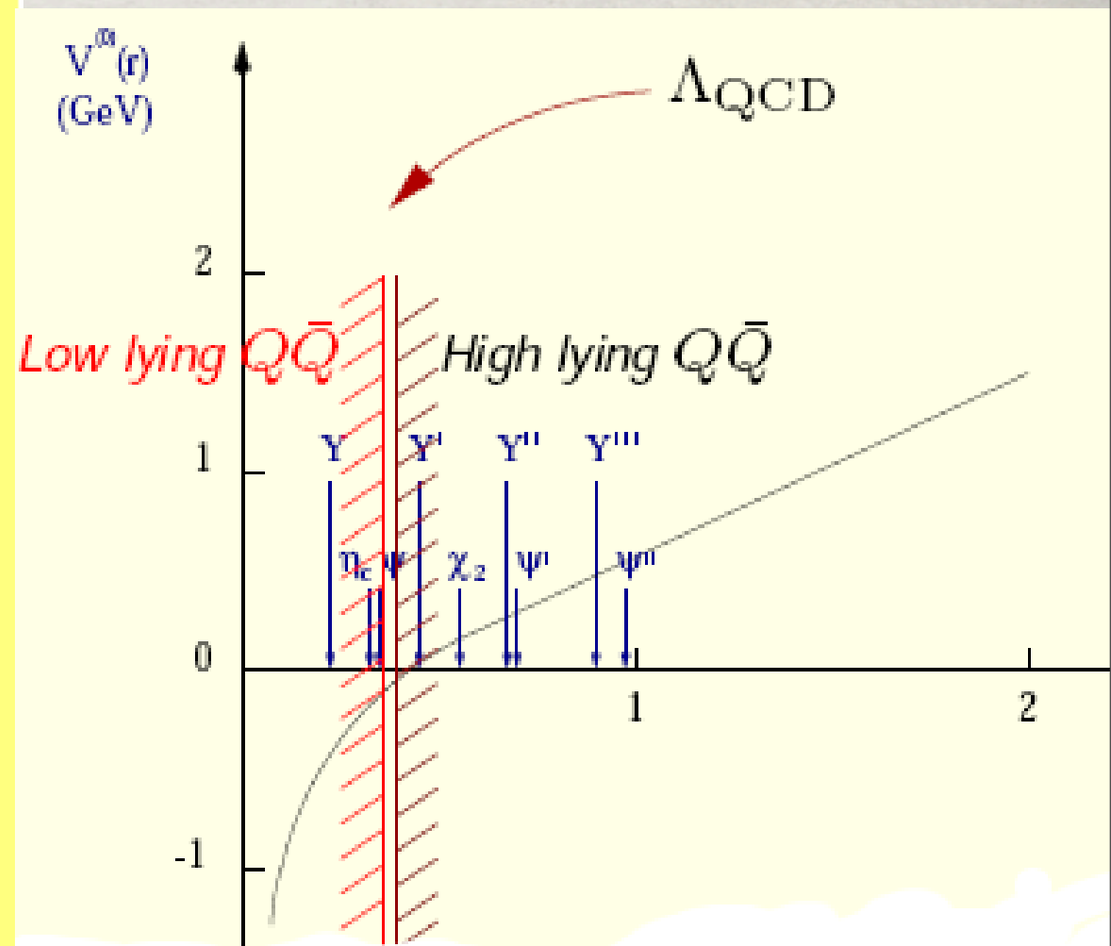
Quarkonium with NR EFT: pNRQCD



In QCD another scale is relevant Λ_{QCD}

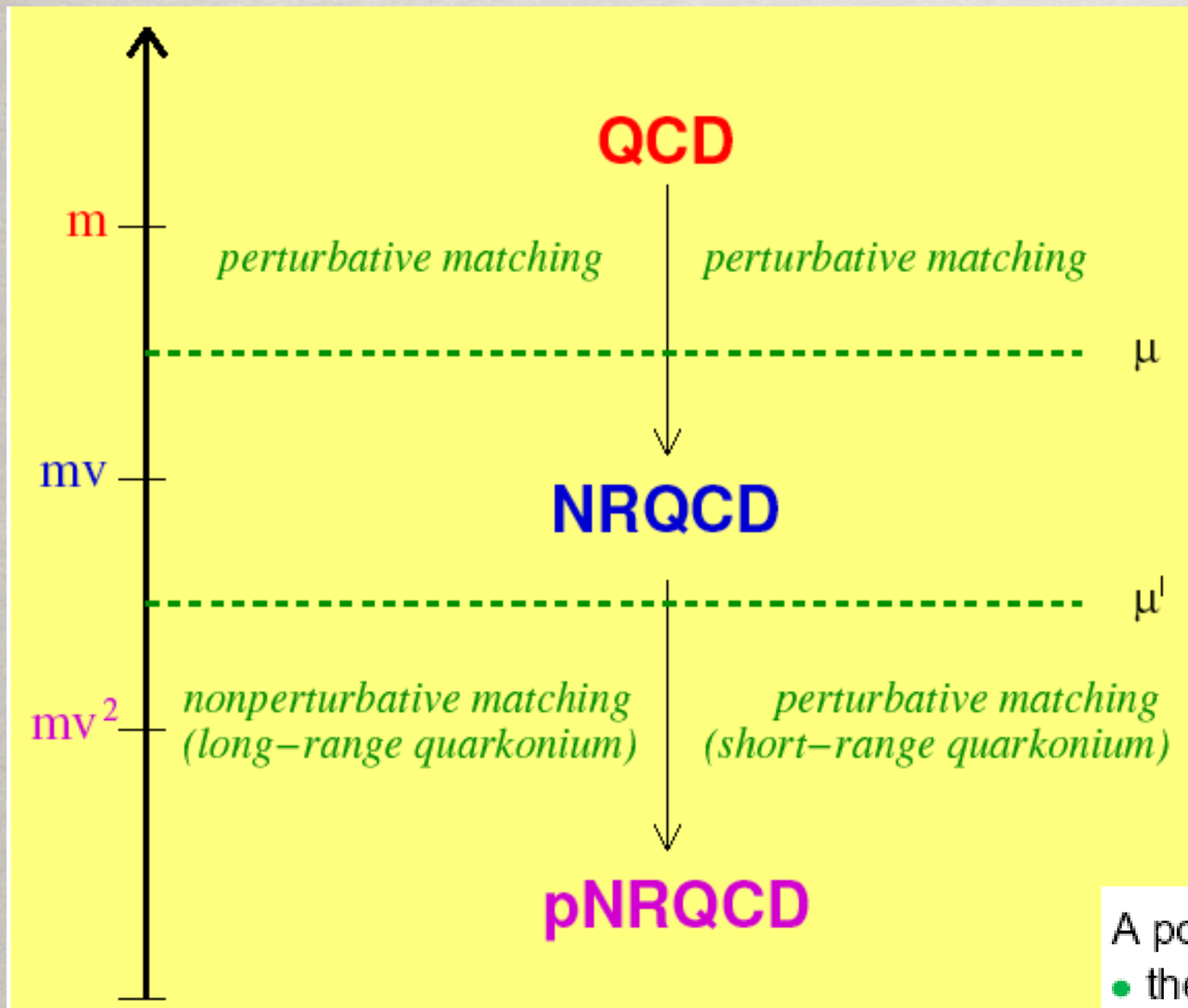
Quarkonium with NR EFT: pNRQCD

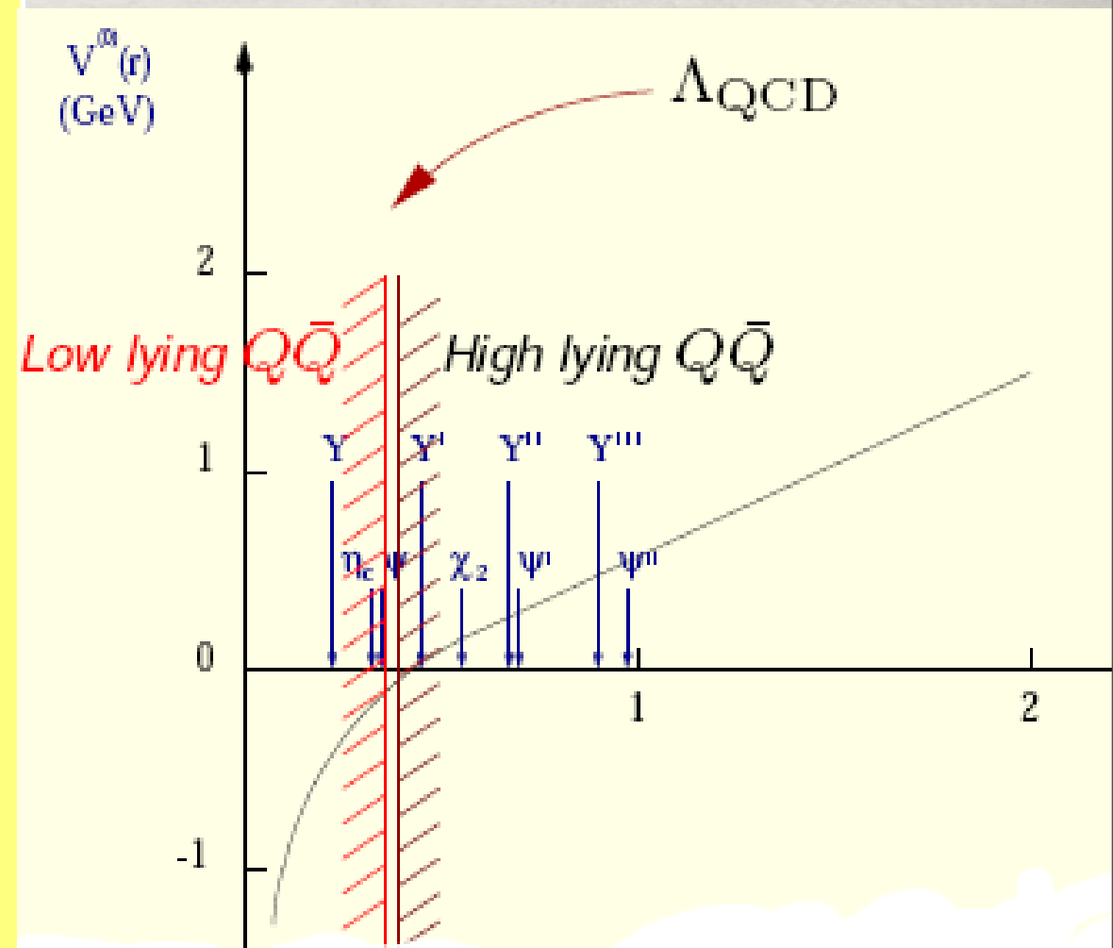




In QCD another scale is relevant $\Lambda_{\rm QCD}$

Quarkonium with NR EFT: pNRQCD



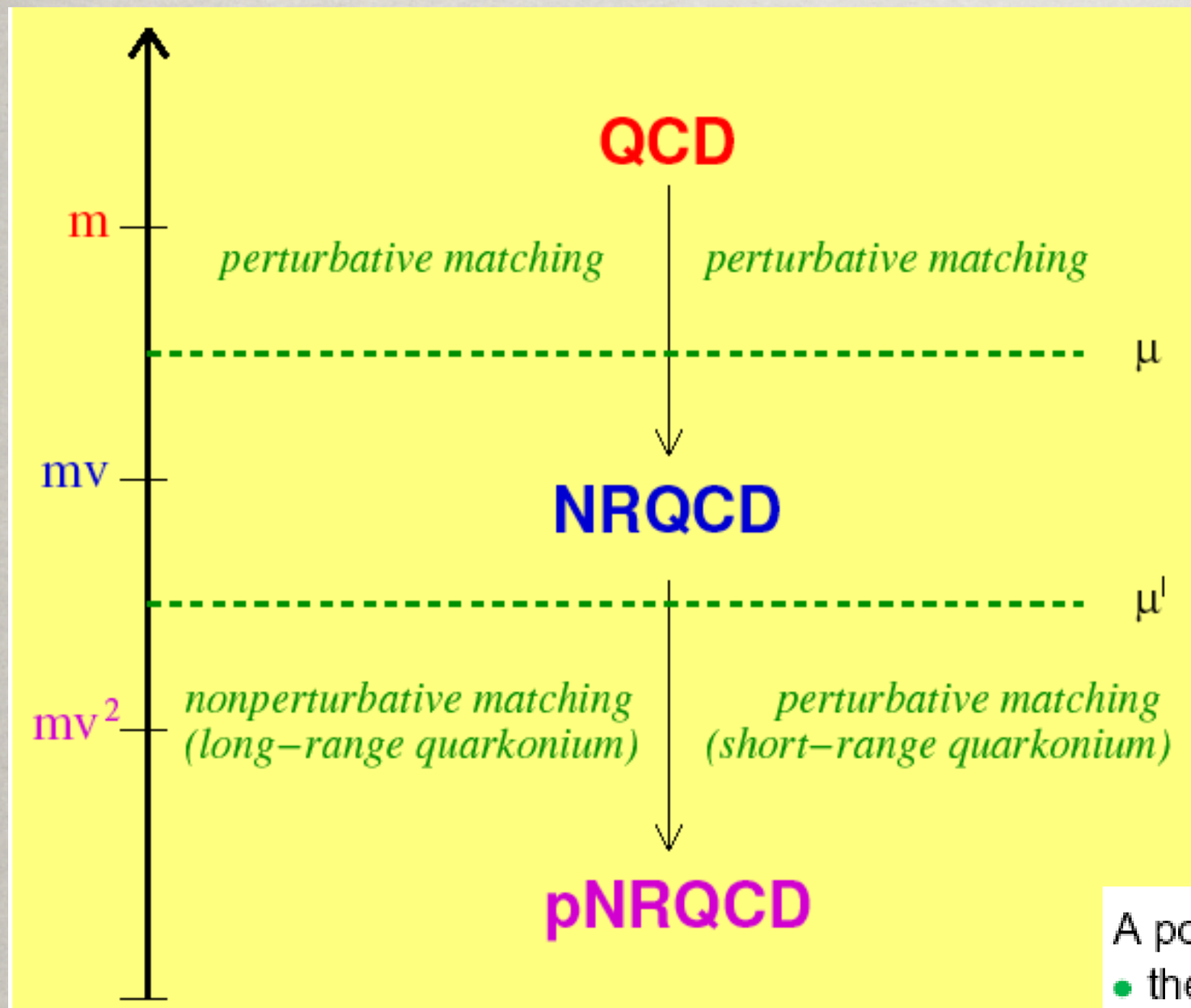


A potential picture arises at the level of pNRQCD:

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

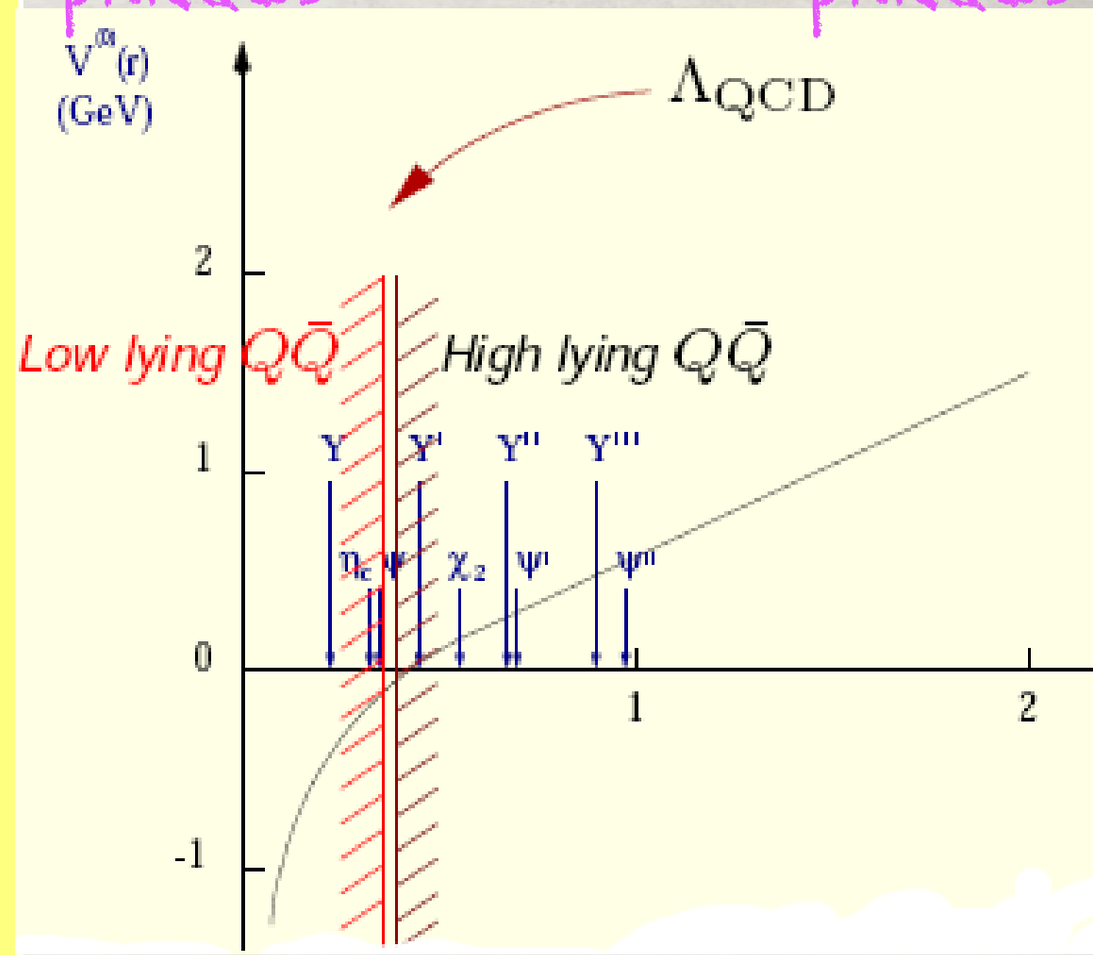
In QCD another scale is relevant $\Lambda_{\rm QCD}$

Quarkonium with NR EFT: pNRQCD



weakly coupled pNRQCD

strongly coupled pNRQCD



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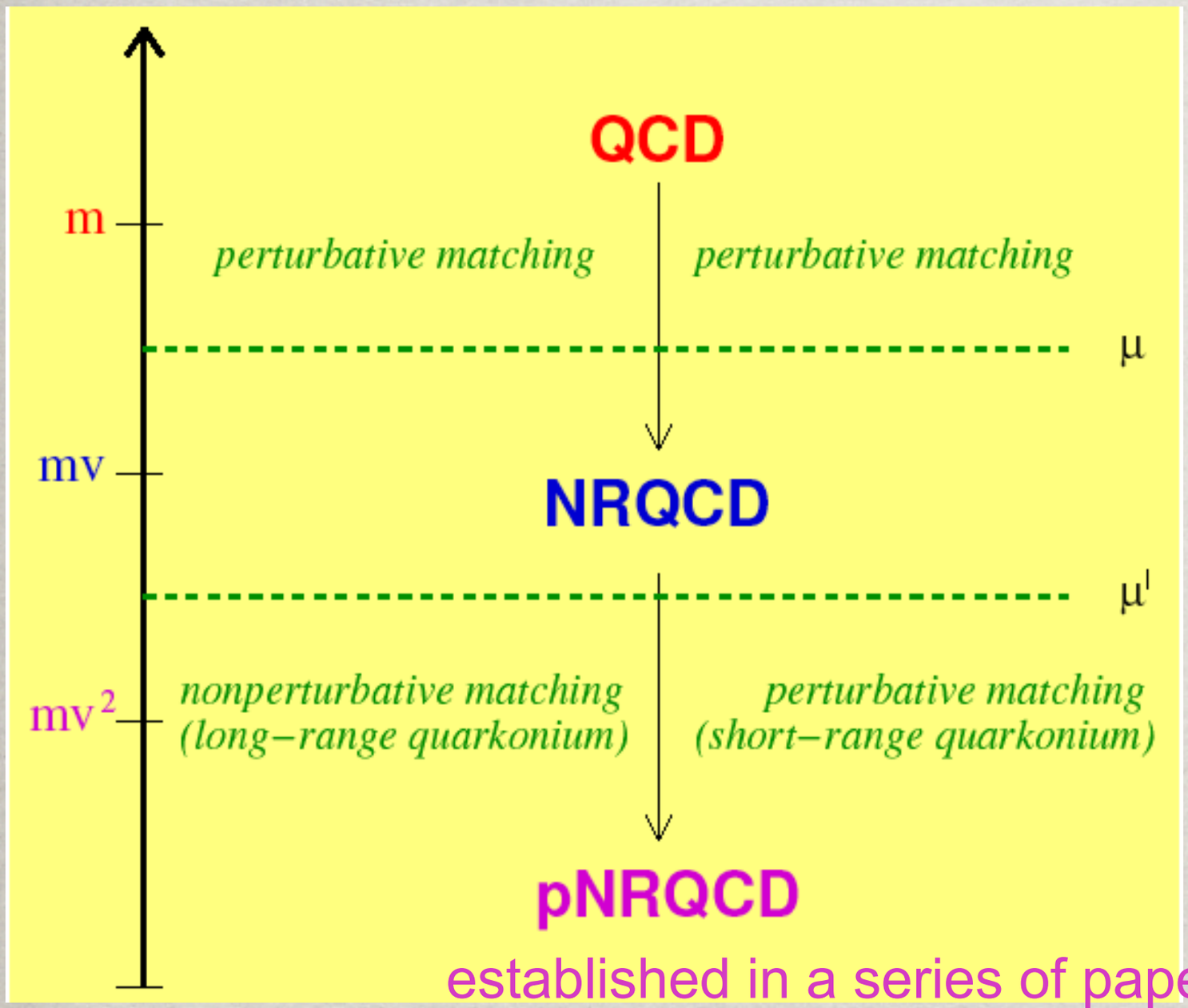
Quarkonium with EFT



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. Vairo, Pineda, Soto 00--014
N.B., Pineda, Soto, Vairo Review of Modern Physis 77(2005) 1423

Physics at the scale m : NRQCD quarkonium production and decays

NRQCD lattice calculations

Physics at the scale m : NRQCD quarkonium production and decays

Quarkonium production at Large Hadron Collider

Inclusive quarkonia decays

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

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

- Spectra

  high order perturbative calculations

- Decays

  Inclusive& seminclusive decays
  theory of M1 and E1 transitions
  Electromagnetic widths, Lines Shapes

- Doubly charmed baryons and QQQ
- Standard model parameters extraction

  c and b masses, alpha_s

- Gluelumps and Hybrids
- Threshold ttbar cross section (for the ILC)
- Nonperturbative potentials for the lattice
- Potential and spectra at finite Temperature

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

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The issue here is precision physics and the study of confinement

- Precise and systematic high order calculations allow the extraction of precise determinations of standard model parameters like the quark masses and alpha_s
- The eft has allowed to systematically factorize and to study the low energy nonperturbative contributions

pNRQCD and quarkonium Several cases for the physics at hand

The EFT is being constructed (Finite T) Laine et al, 2007, Escobedo, Soto 2007 N. B. et al. 2008

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

*Mass and width of quarkonium at m alpha^5(Y(1S) bbar at LHC) N. B. Escobedo, Ghiglieri, Vairo Soto, 2010-2014

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- The potential is neither the color singlet free energy nor the internal energy
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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

Let us focus on the calculation of the static quark-antiquark potential as a matching coefficient of pNRQCD in different physical situations

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$r \ll \frac{1}{\Lambda_{QCD}}$ lowest quarkonia states

$r \sim \frac{1}{\Lambda_{QCD}}$ excited quarkonia states

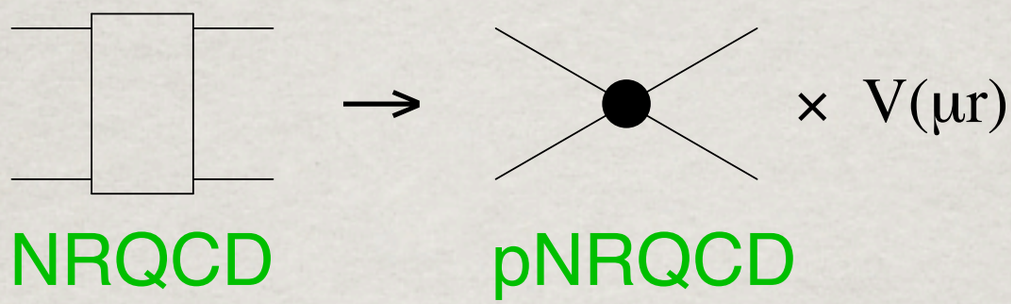
$r \ll \frac{1}{\Lambda_{QCD}}$ T quarkonia in a hot medium

$r \sim \frac{1}{\Lambda_{QCD}}$ quarkonia and exotics close and above threshold

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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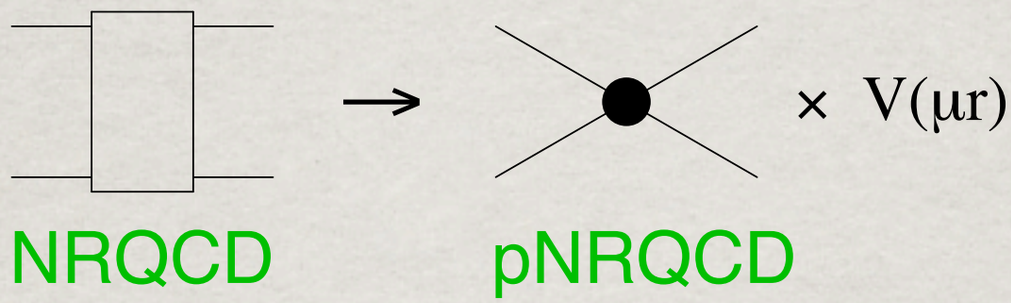


- If $mv \gg \Lambda_{\rm QCD}$, the matching is perturbative

- 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 $\rm S$ (ii) octet $\rm O$

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

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

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

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

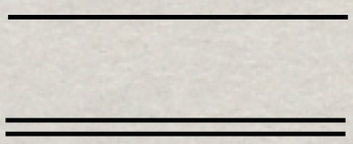
weak pNRQCD $r \ll \Lambda_{\rm QCD}^{-1}$

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

LO in r

S singlet field

O octet field



singlet propagator

octet propagator

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

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

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LO in r

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

NLO in r

S singlet field

O octet field

singlet propagator

octet propagator

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

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

Singlet static potential

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

LO in r

Octet static potential

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

NLO in r

S singlet field

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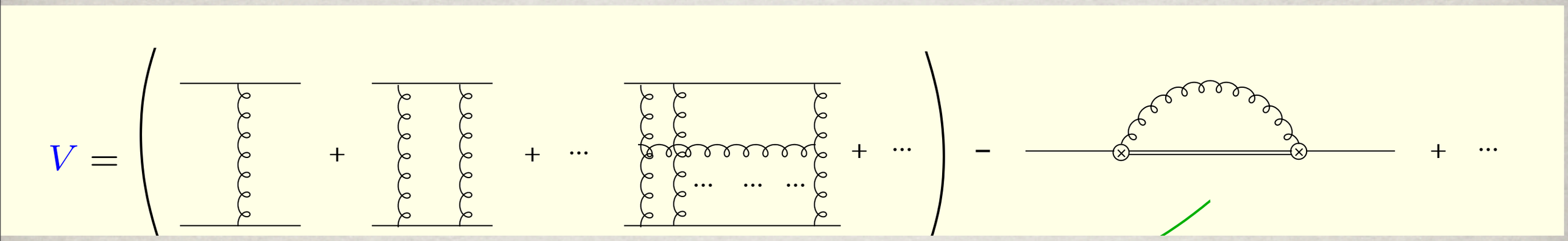
pNRQCD

- 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



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

Quarkonium singlet static potential at N^4LO

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

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

a_1 Billoire 80

a_2 Schroeder 99, Peter 97

coeff $lnr\mu$ 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

Quarkonium singlet static potential at N^4LO

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

a_1 Billoire 80

a_2 Schroeder 99, Peter 97

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

a_4^{L2}, a_4^L N.B., Garcia, Soto, Vairo 04

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3loops reduces to 1loop in the EFT

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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Two problems:

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The eft cures both:

1) Renormalon subtracted scheme

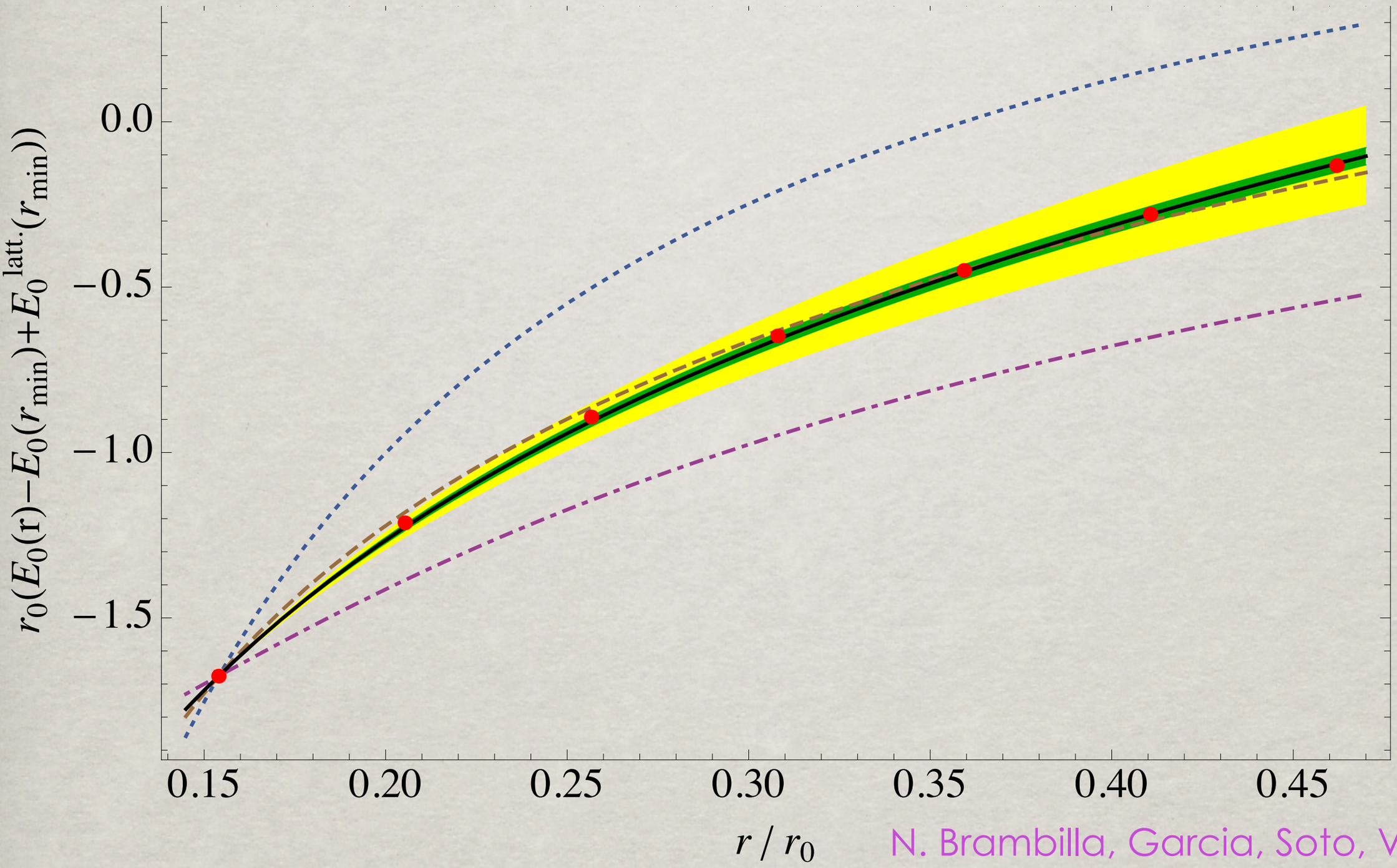
Beneke 98, Hoang, Lee 99, Pineda 01, N.B. Pineda Soto, Vairo 09

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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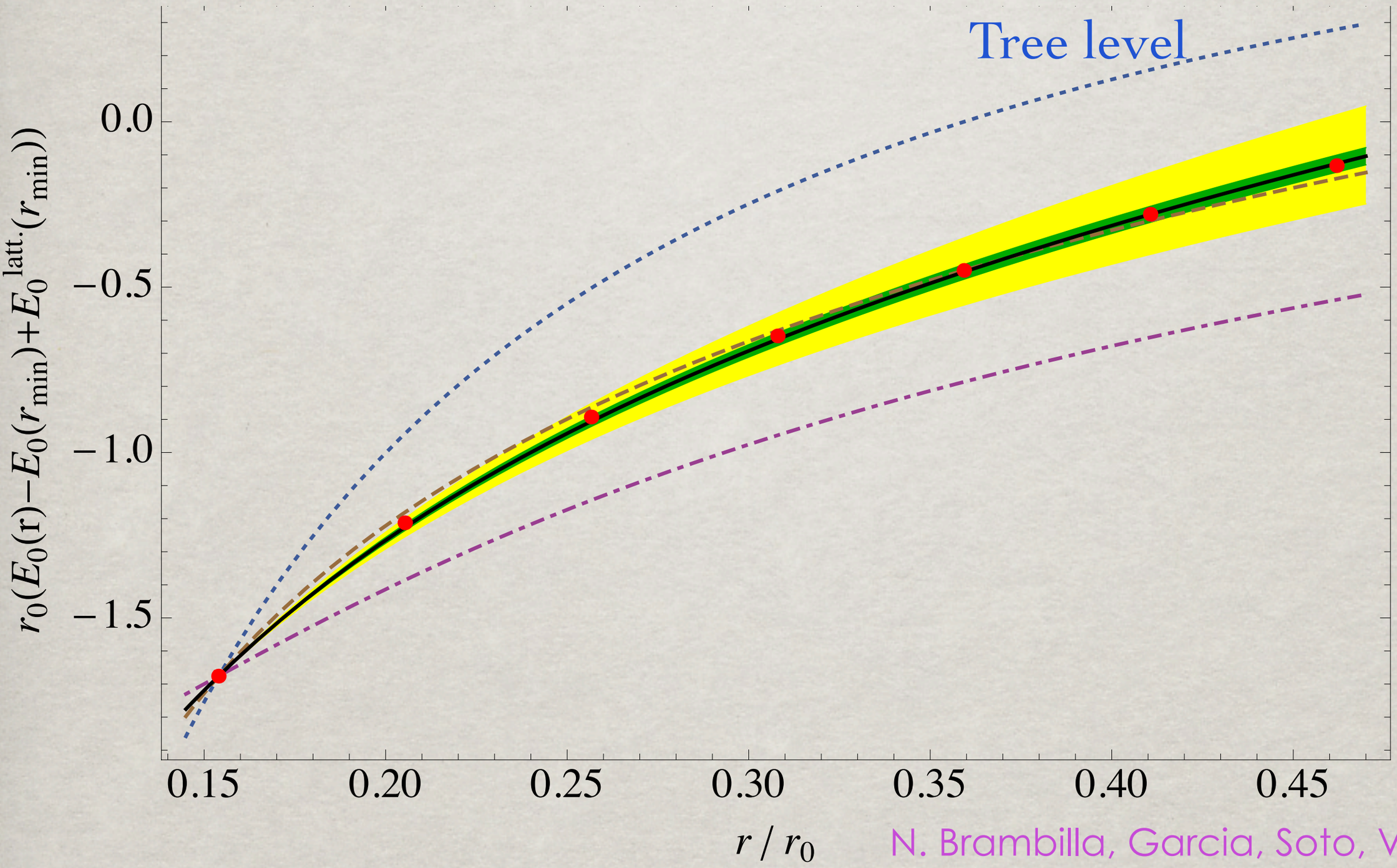

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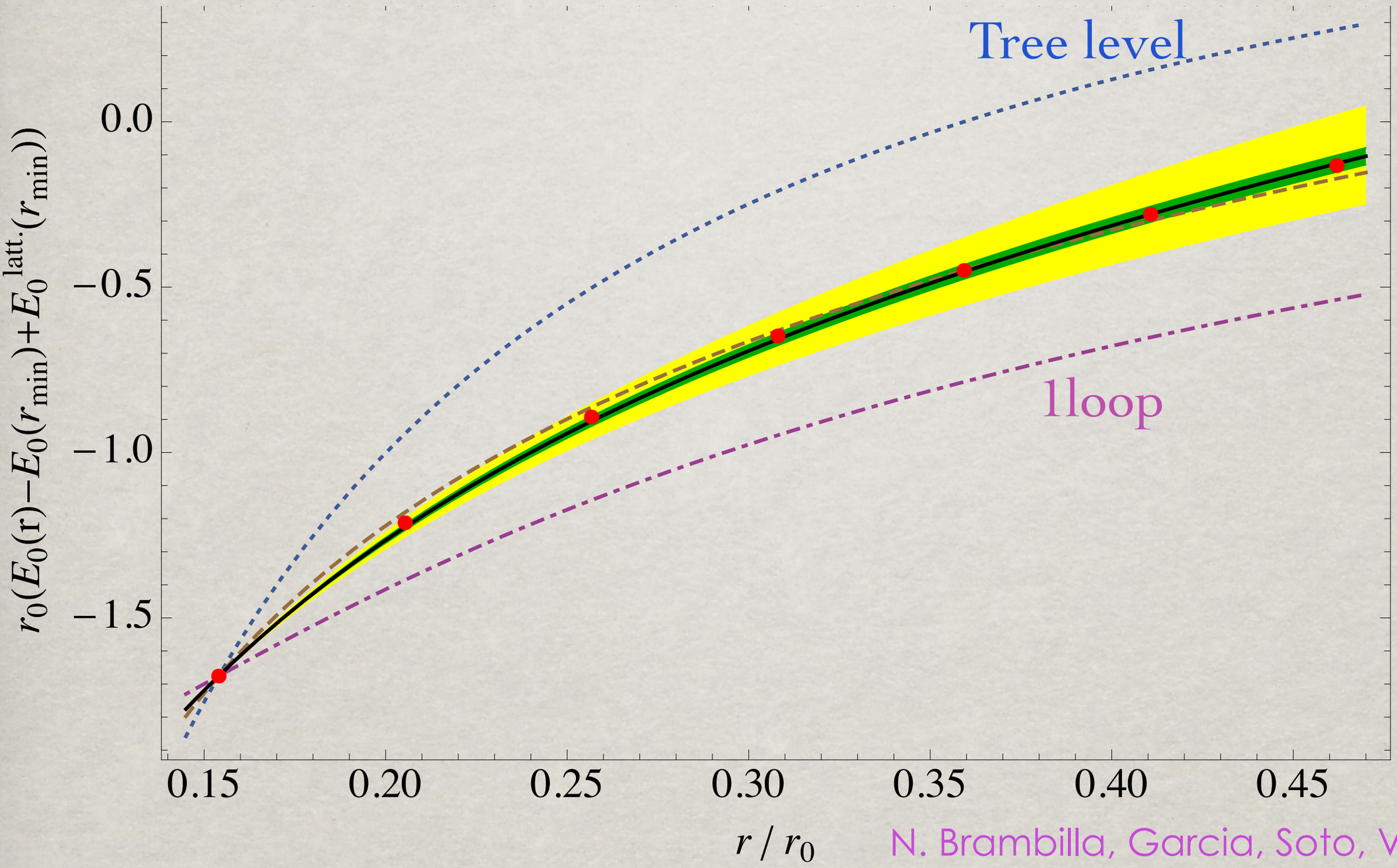

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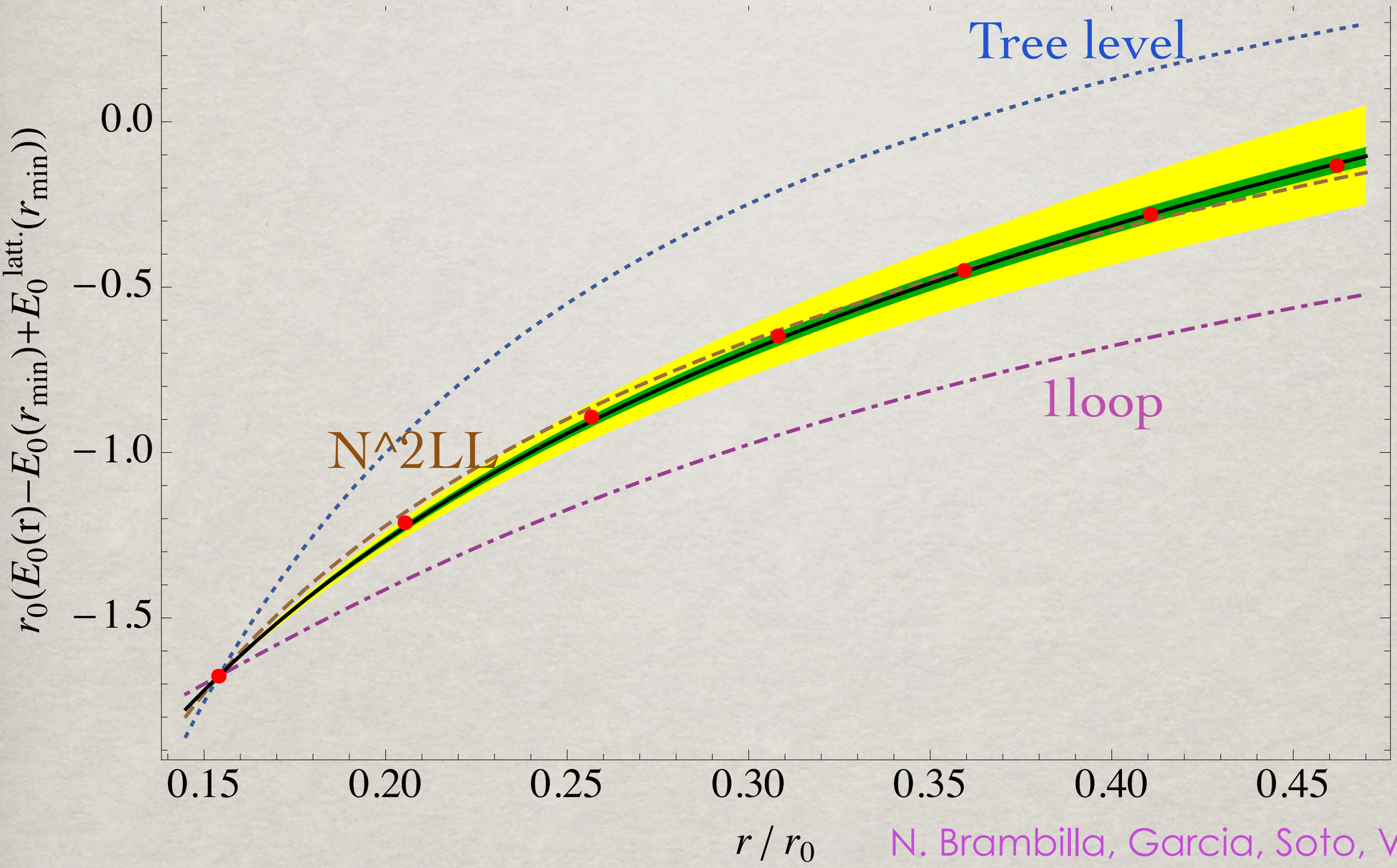

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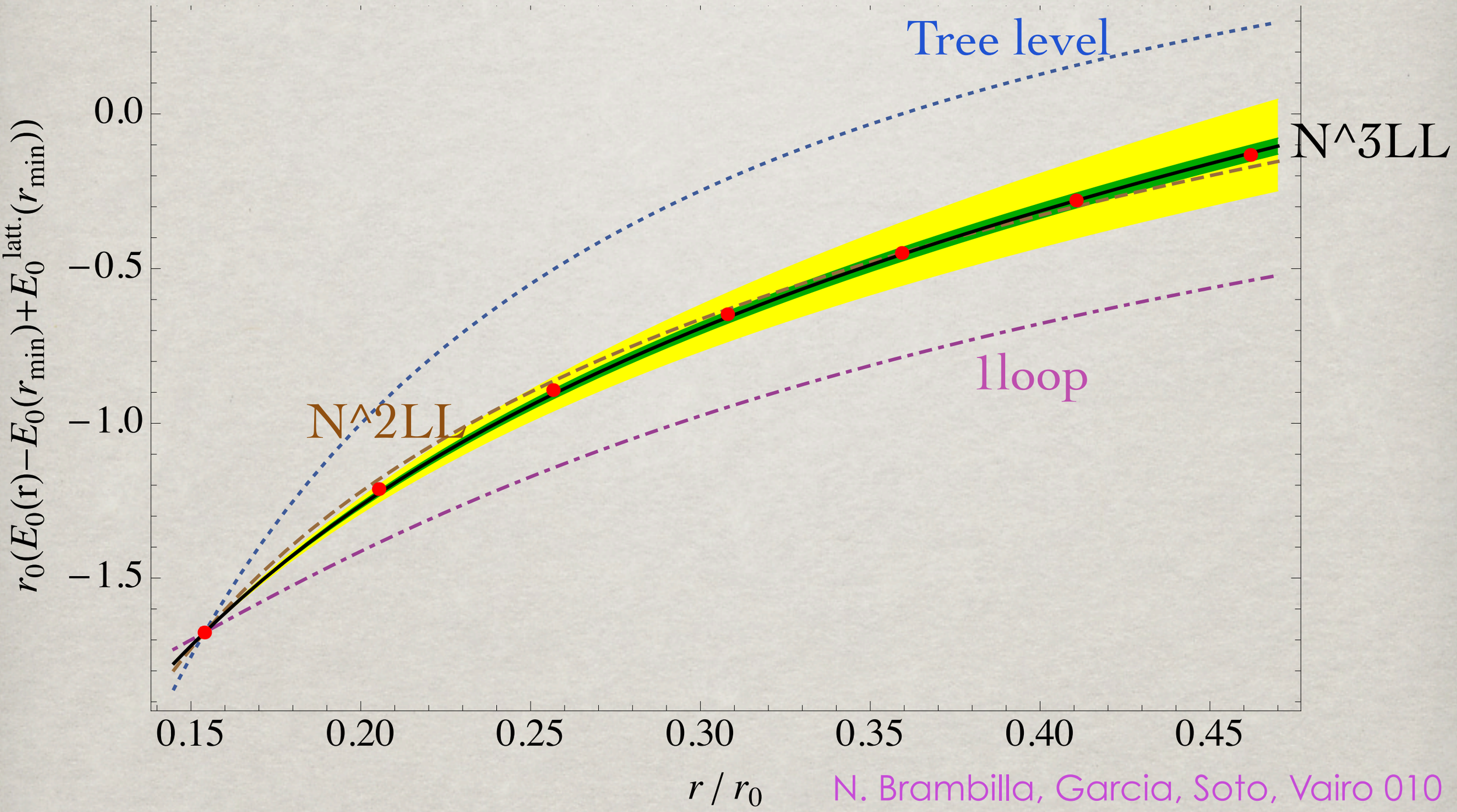

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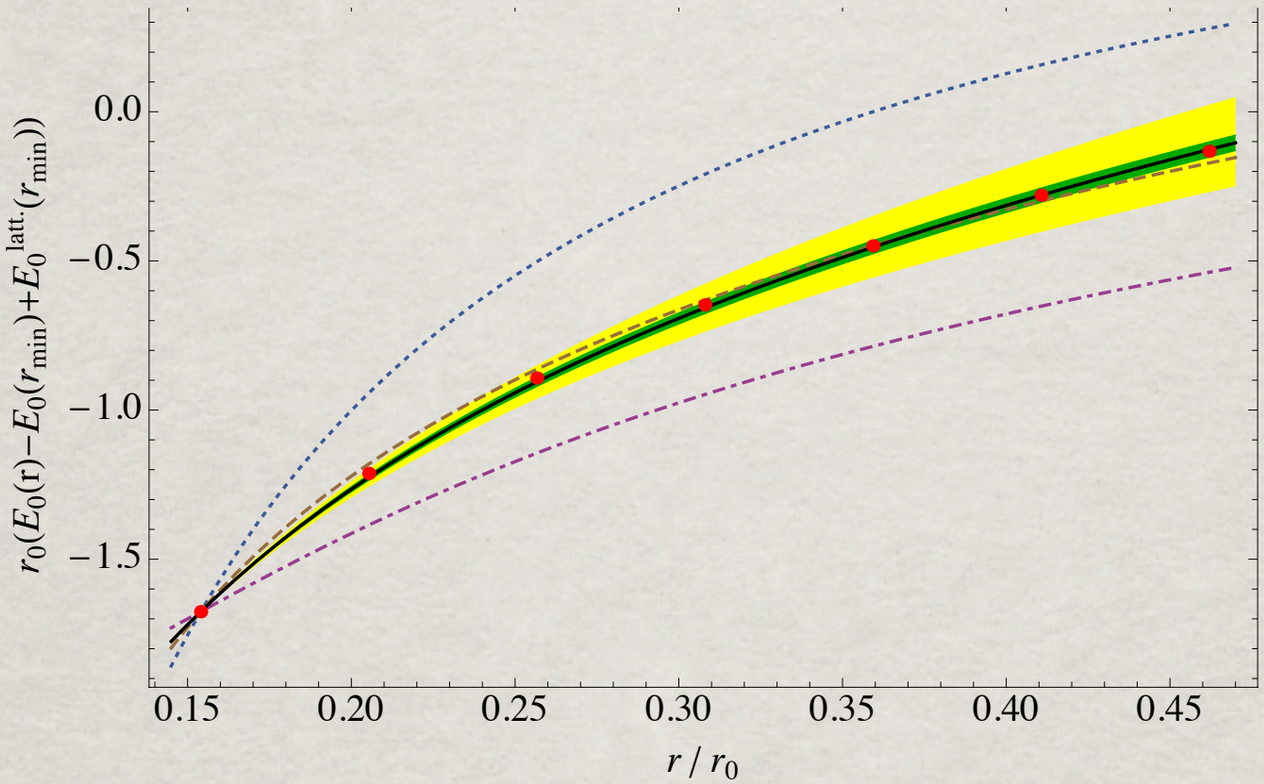

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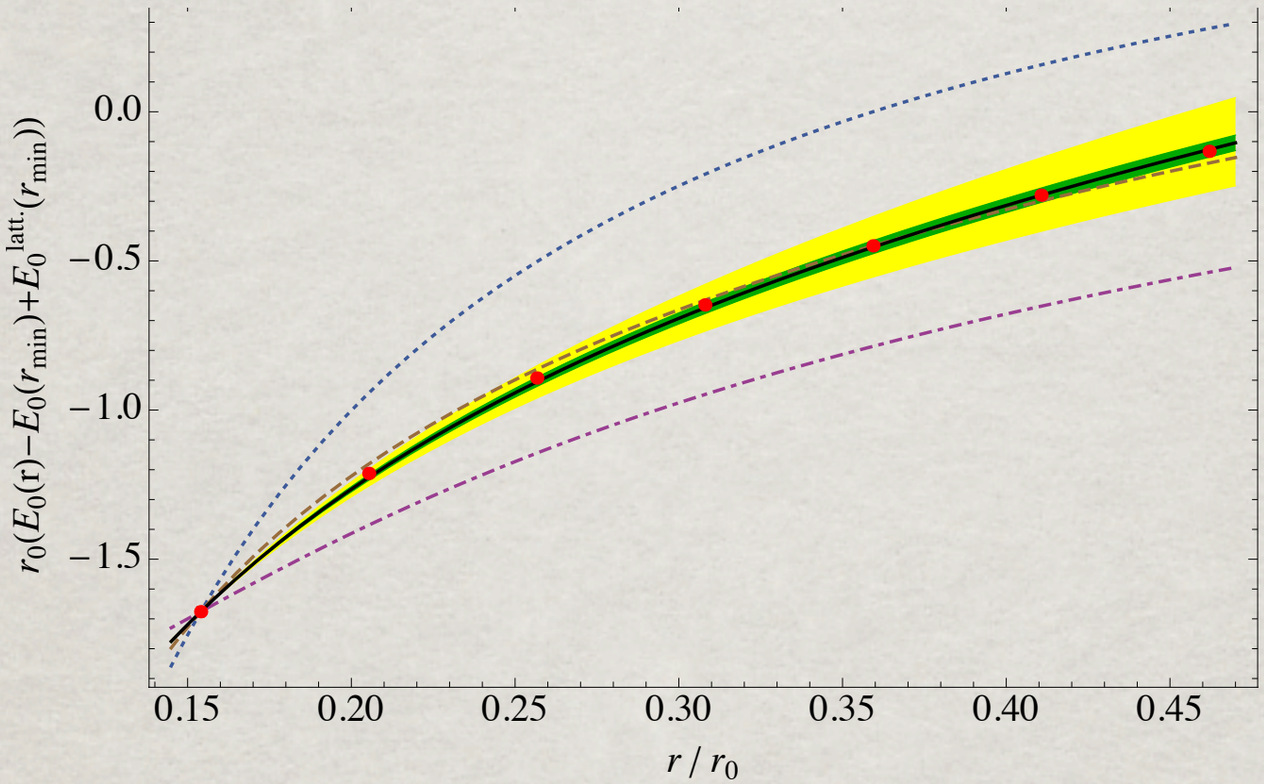

- Very good convergence of the QCD bound state perturbative series

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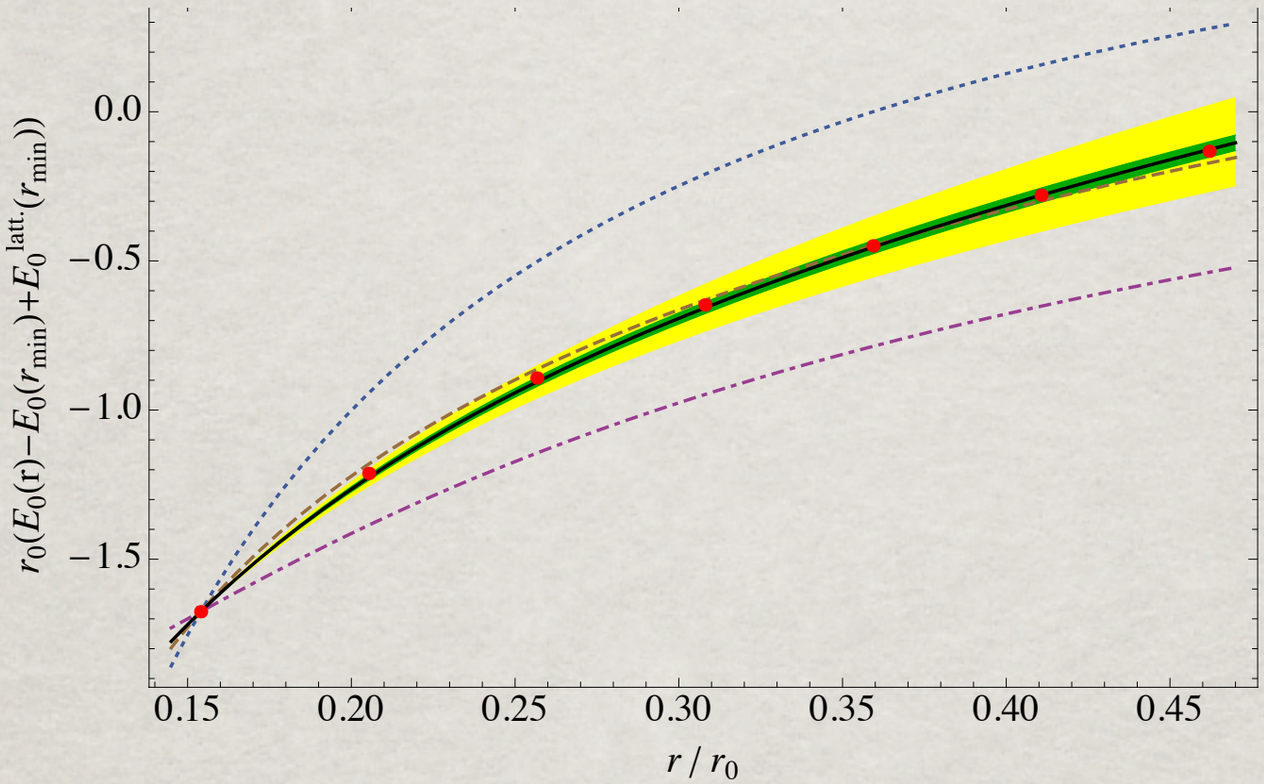

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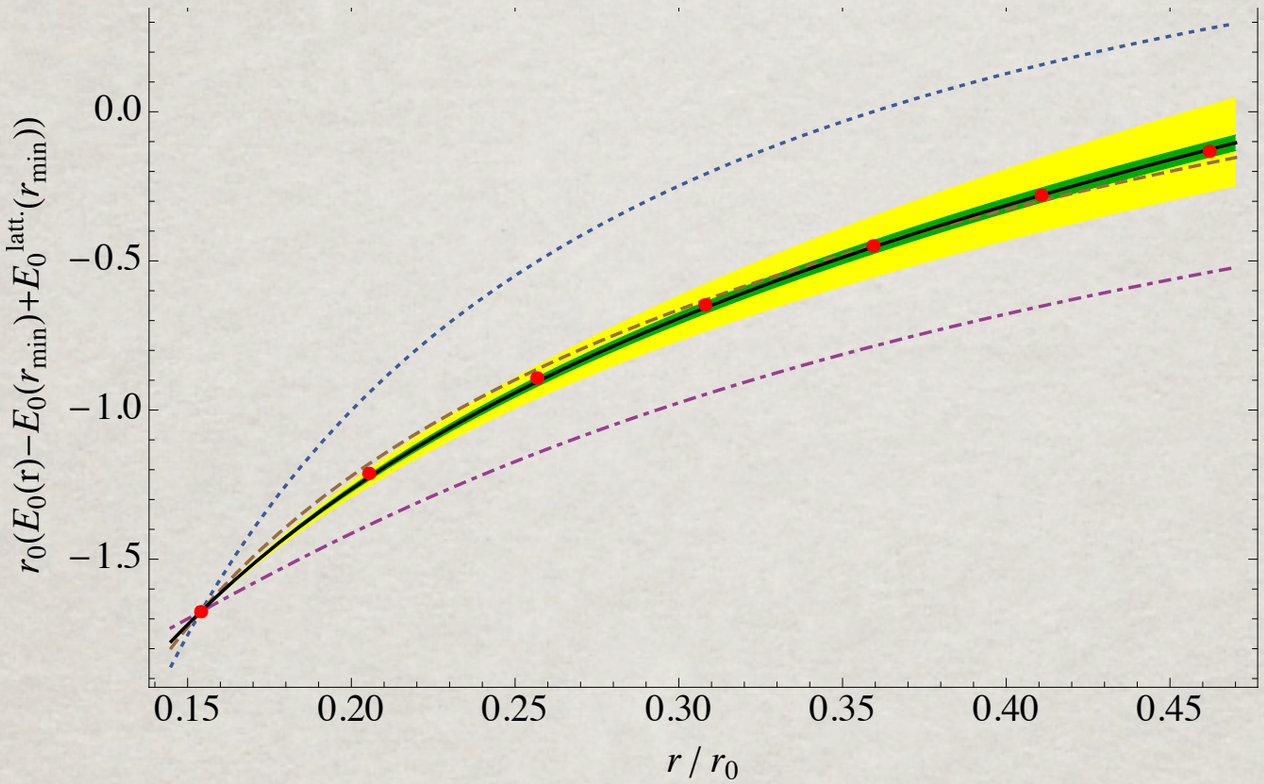

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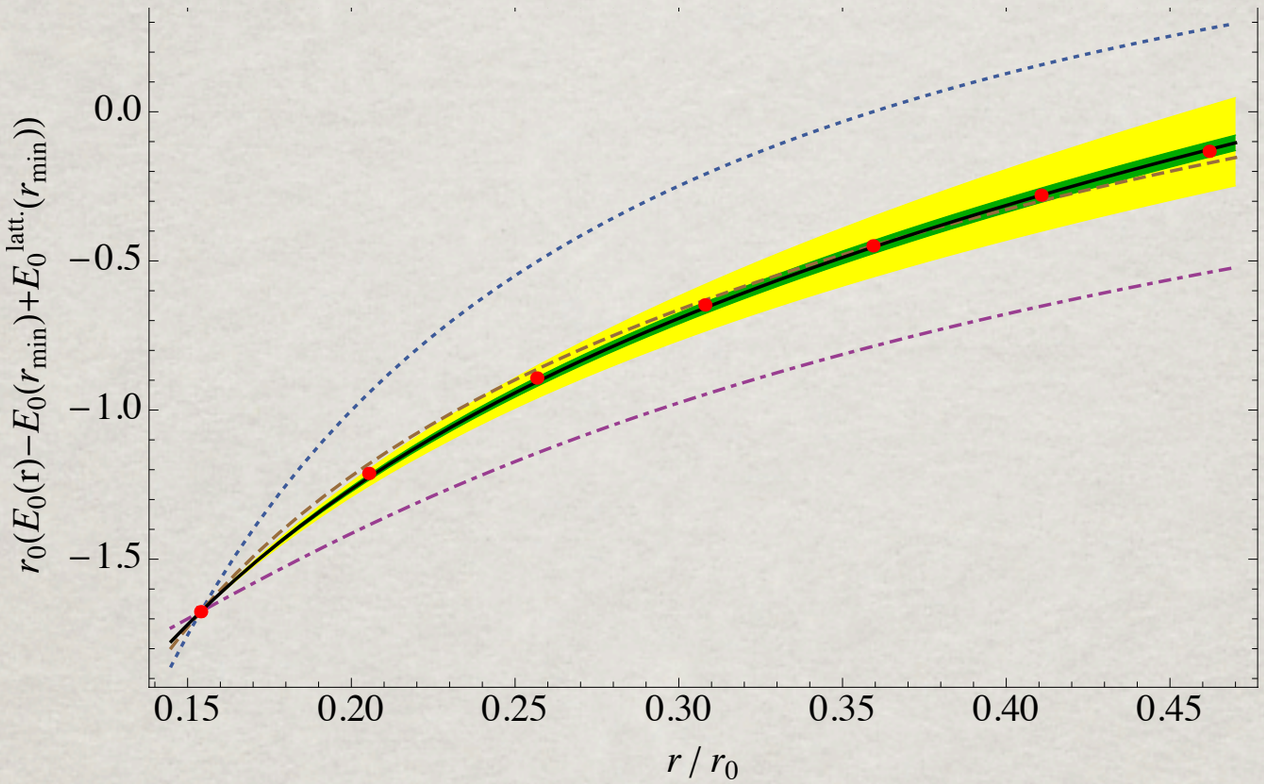

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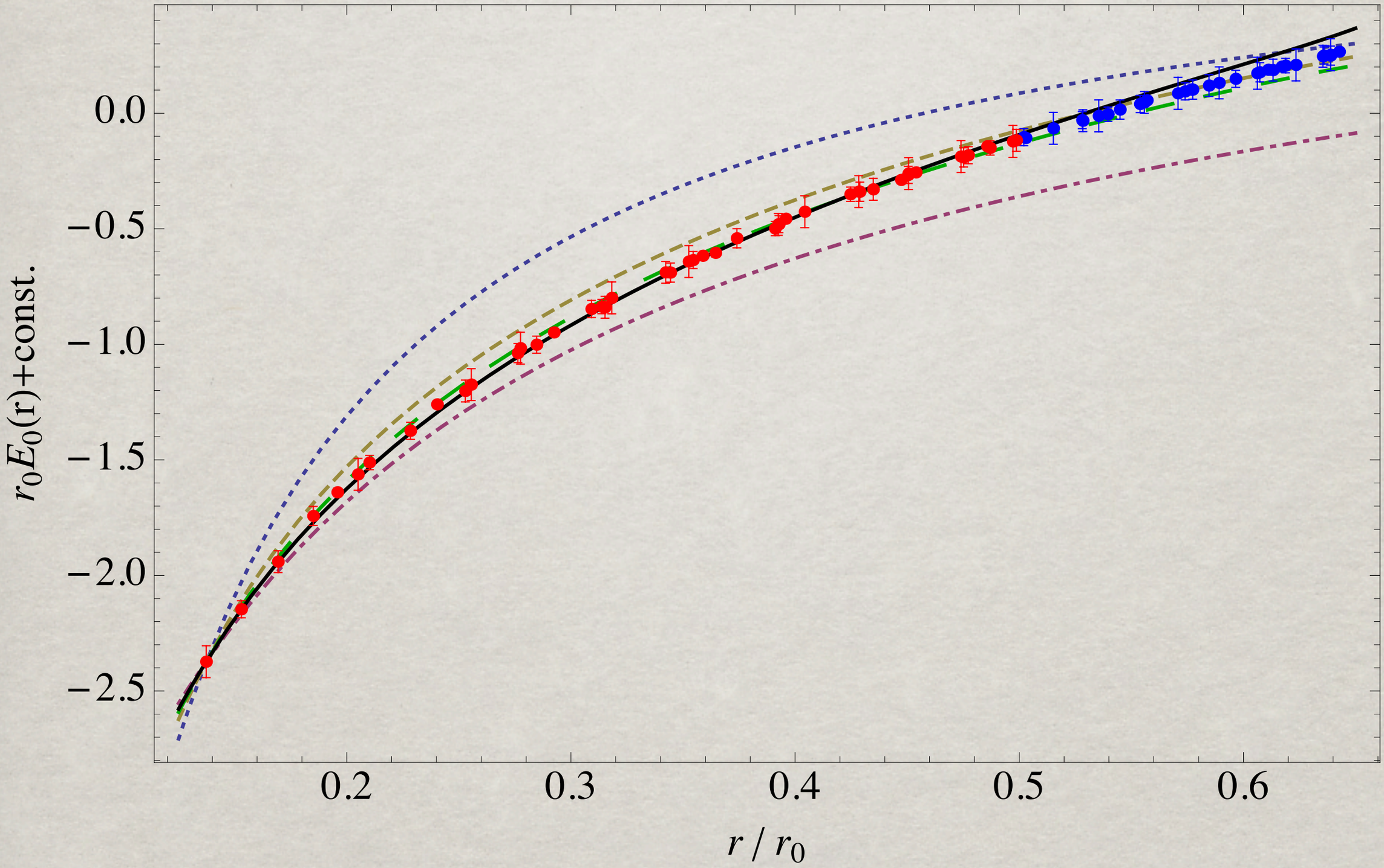
- Allows precise extraction of fundamental parameters of QCD

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

N. Brambilla, Garcia, Soto, Vairo 010)

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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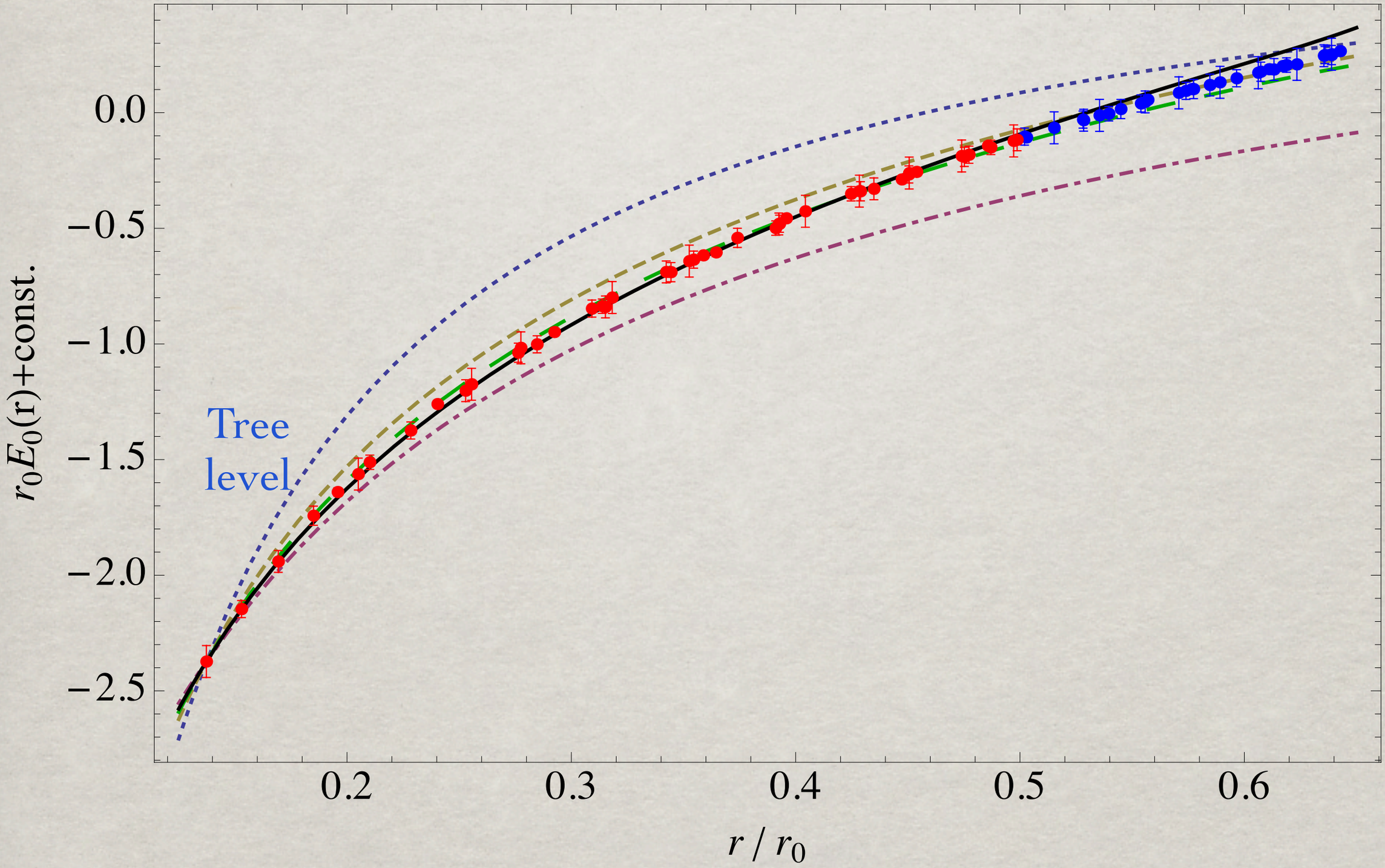

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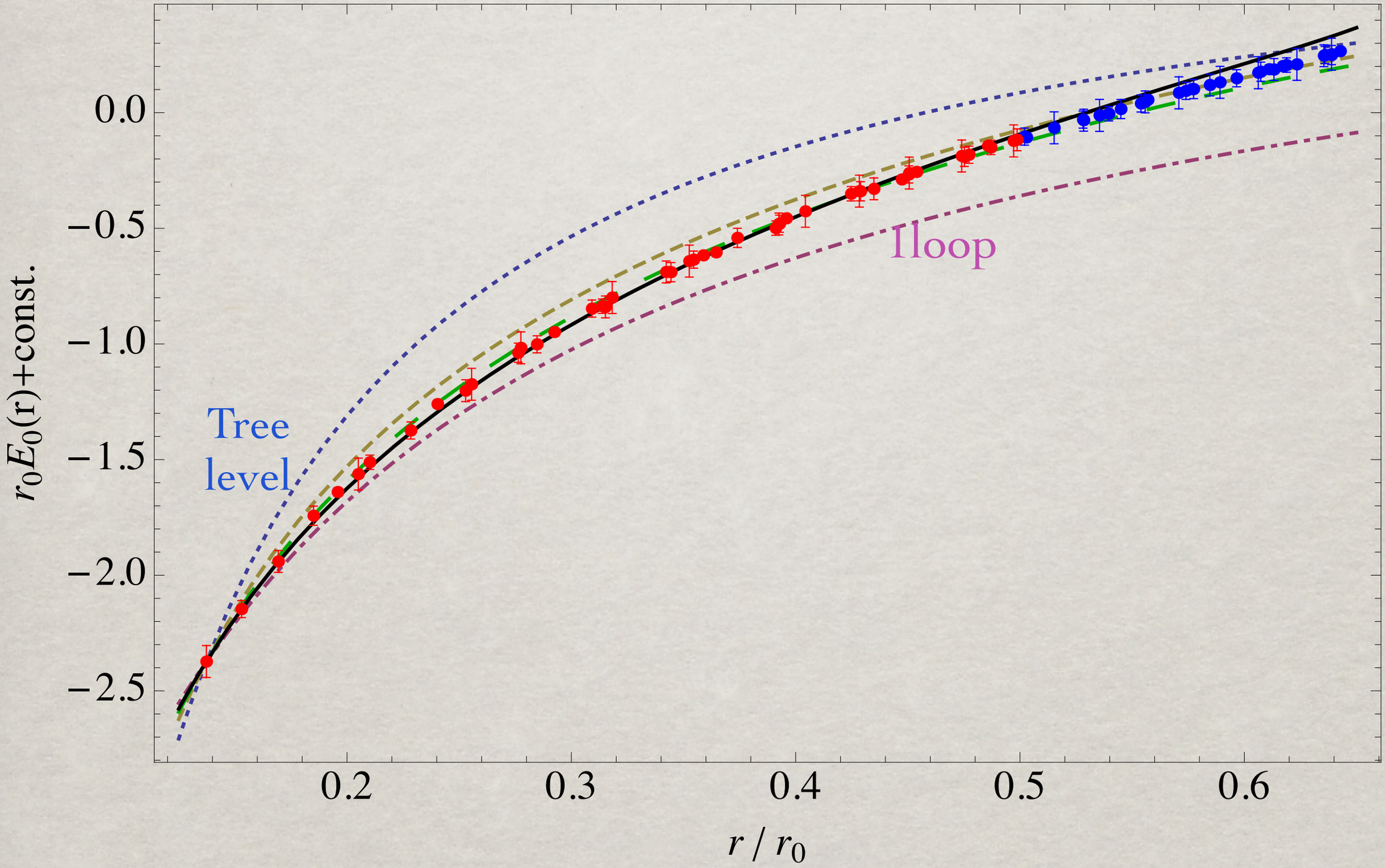

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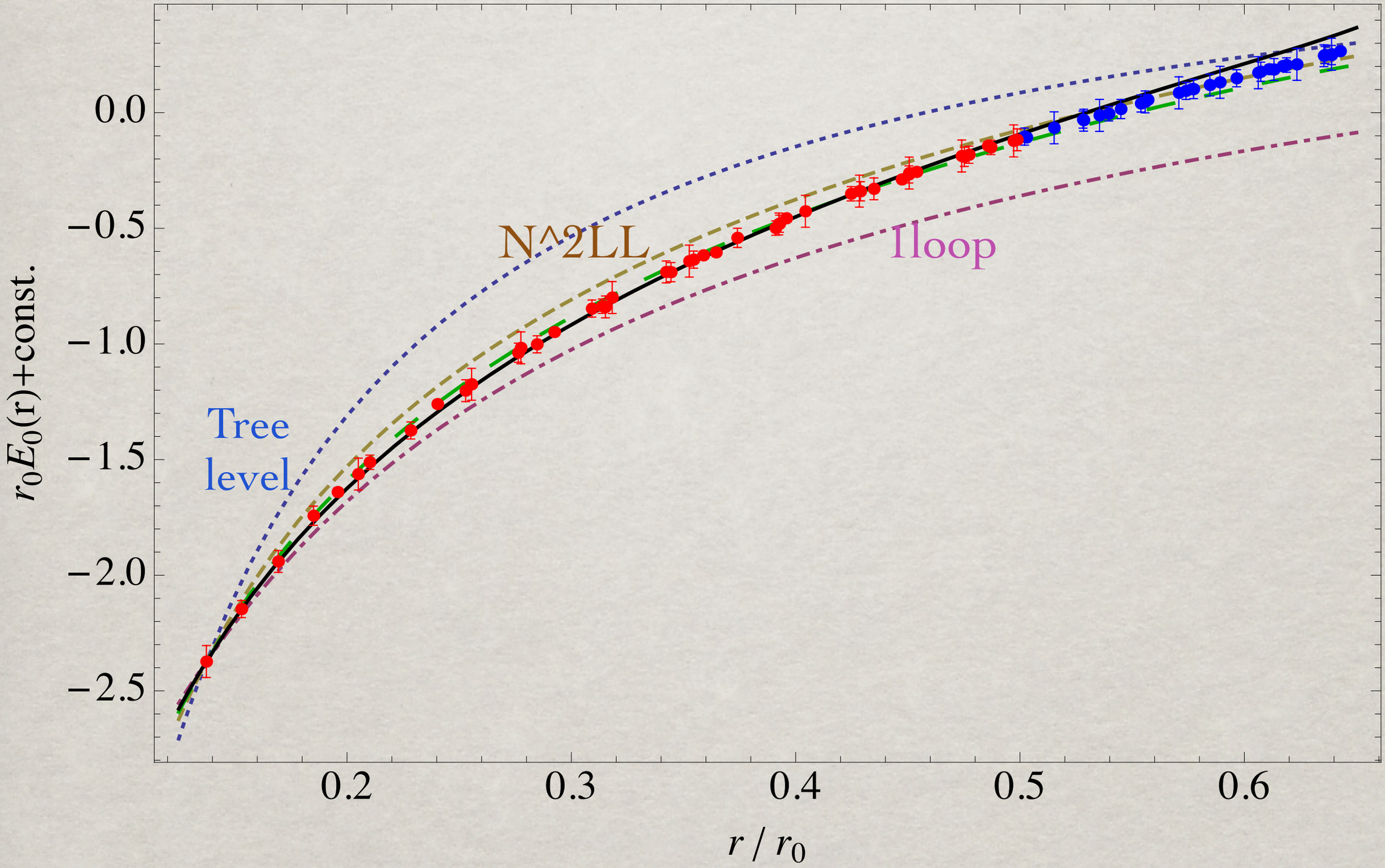

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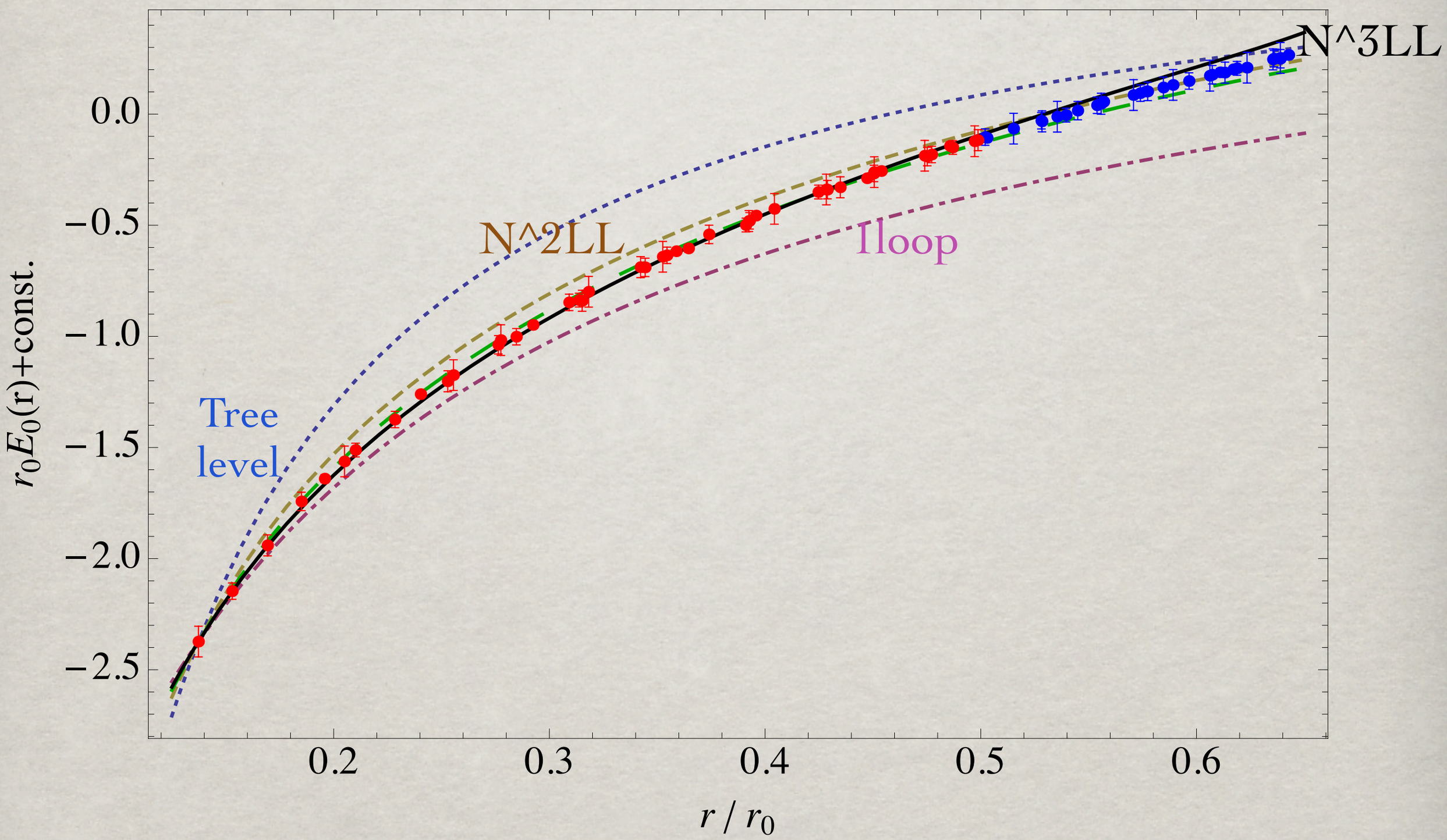

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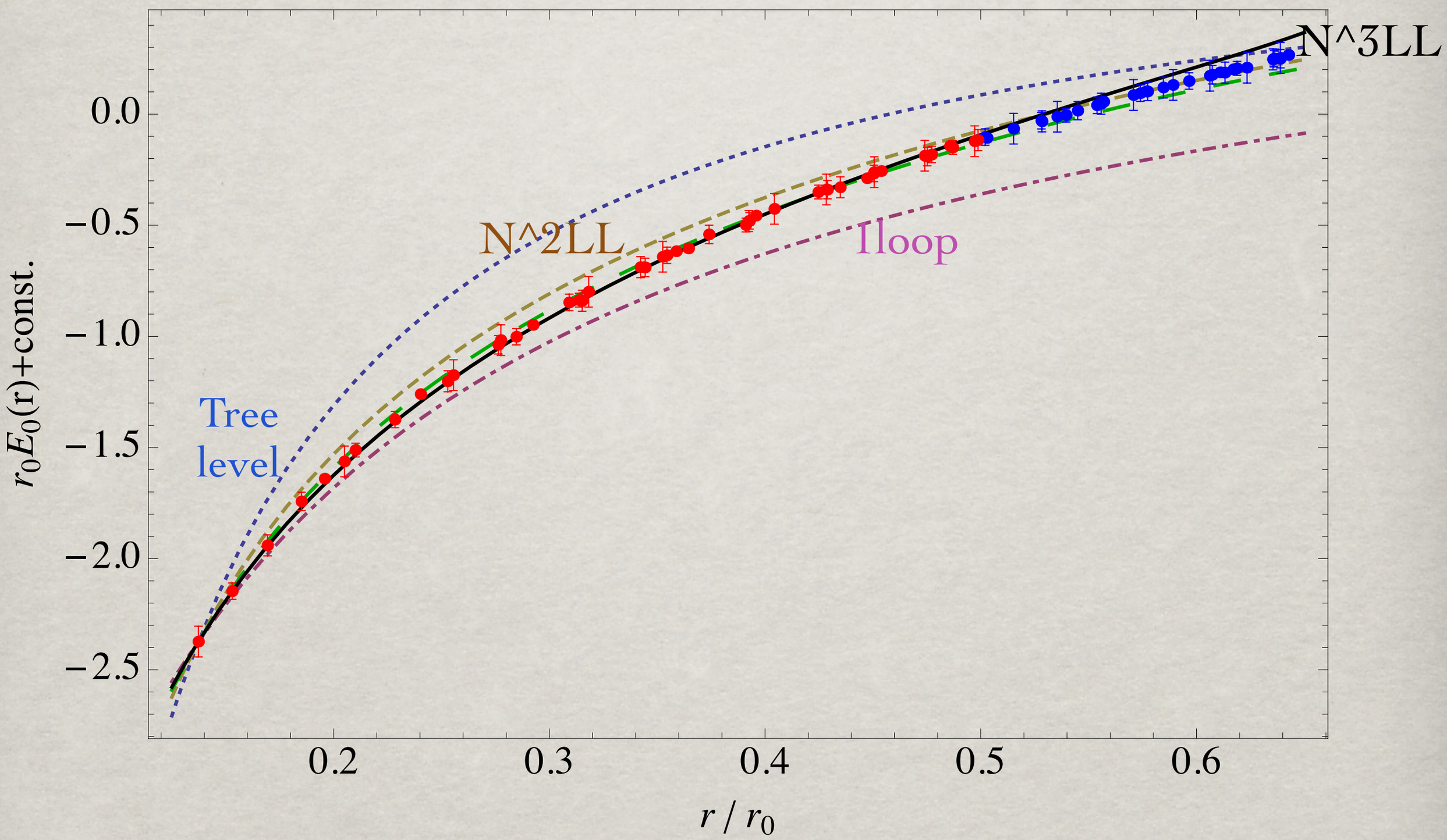

Good convergence to the lattice data

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

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

corresponding to

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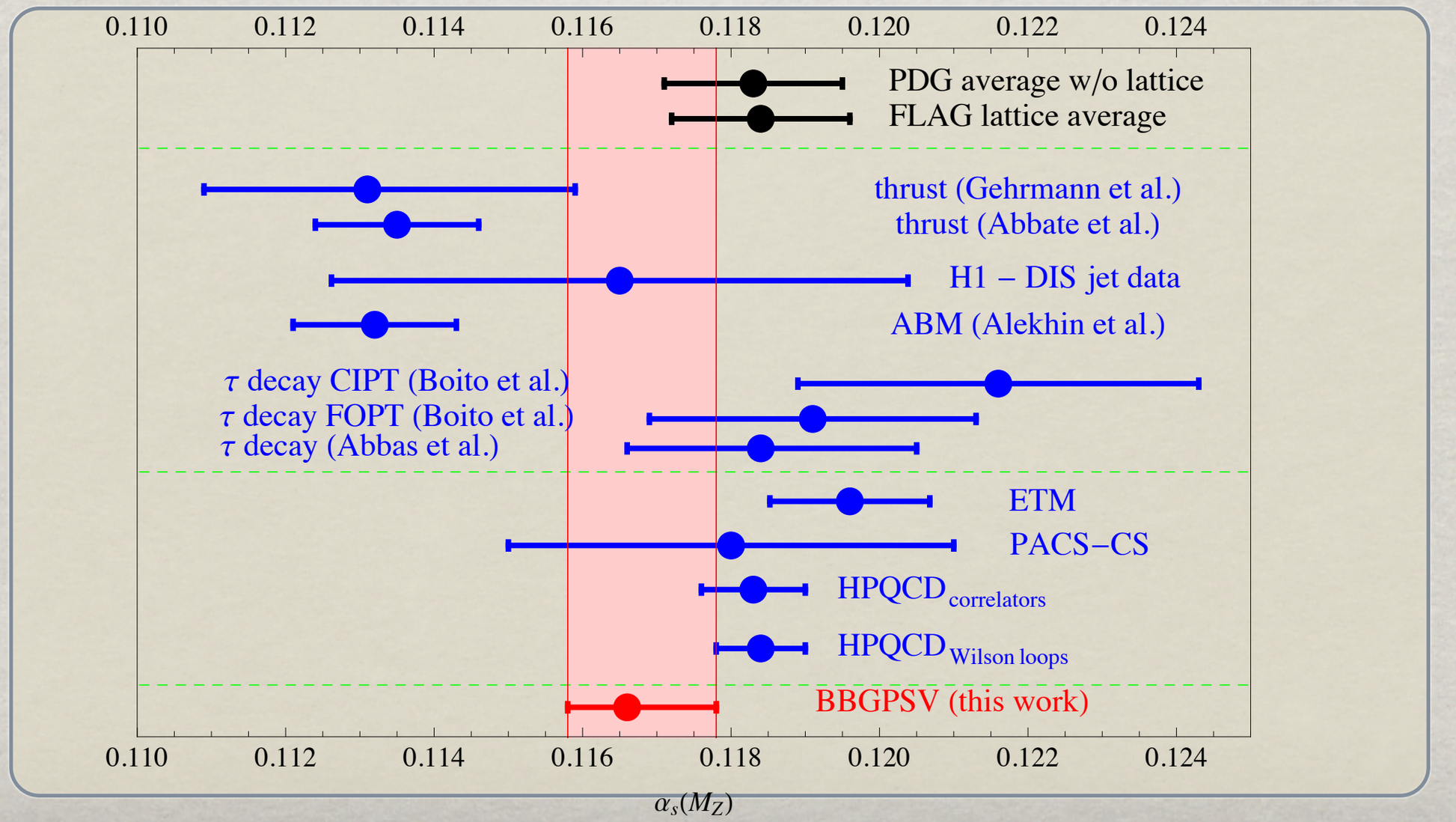

Applications to Quarkonium physics: systems with small radius

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 Λ_{QCD}

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

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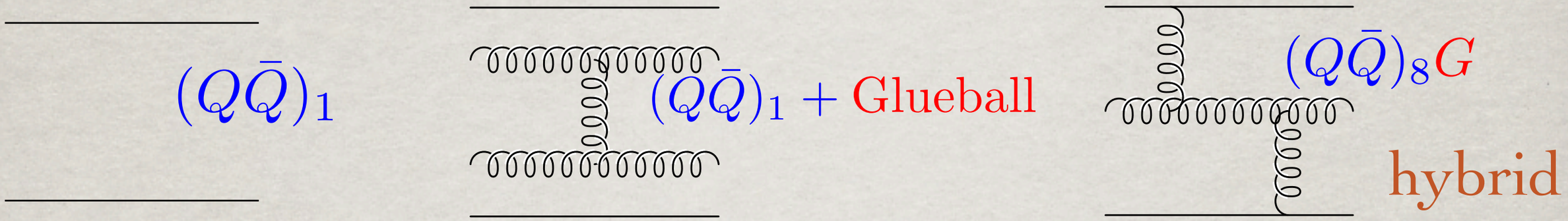
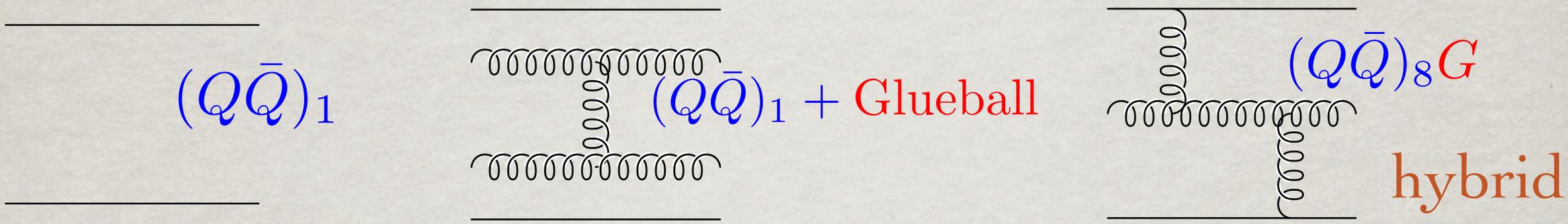
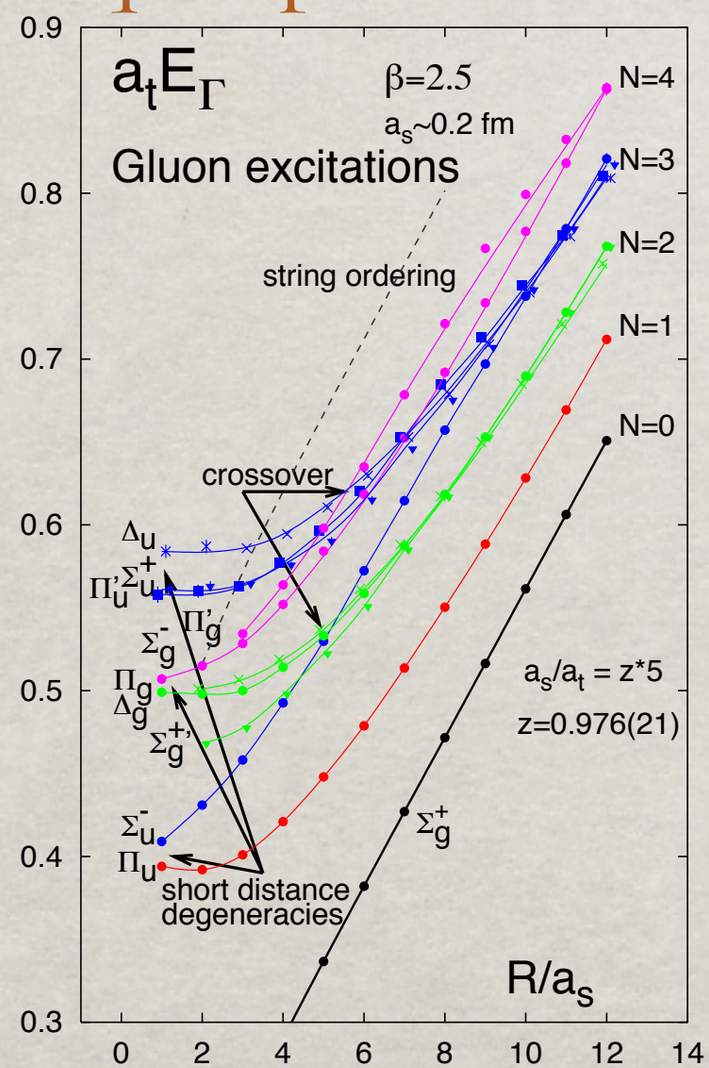


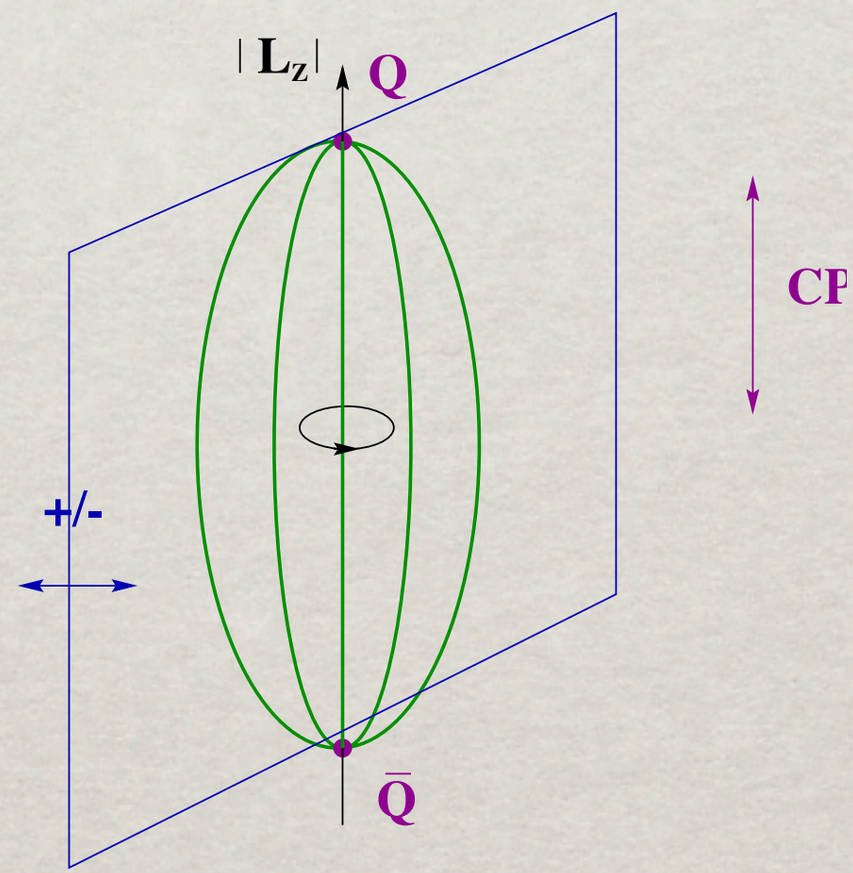
Hitting the scale $\Lambda_{\rm QCD}$ $r \sim \Lambda_{QCD}^{-1}$



Static qcd spectrum

Lattice





Symmetries of a diatomic molecule + C.C.

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

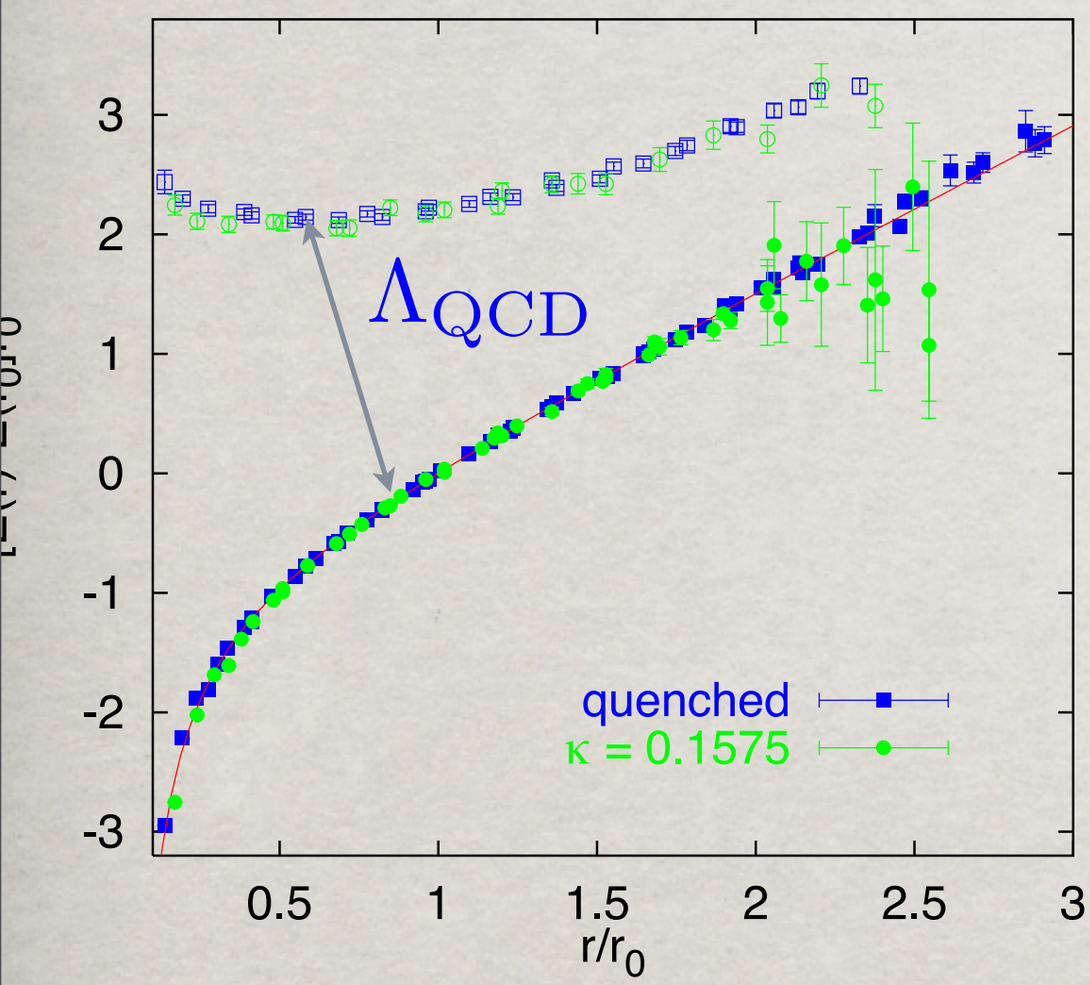
b) CP (u/g)

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
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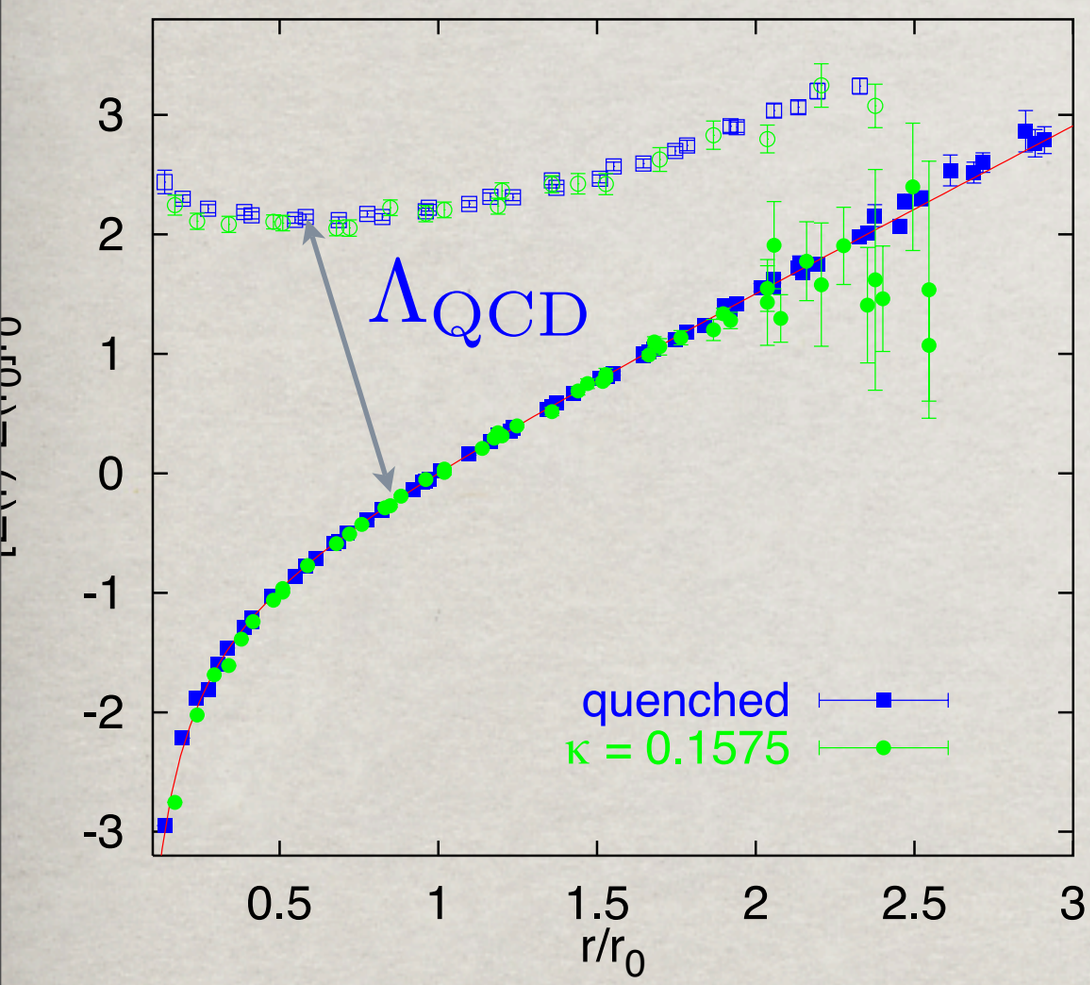
Bali et al. 98



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

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

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

Brambilla Pineda Soto Vairo 00

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Brambilla Pineda Soto Vairo 00

- A potential description emerges from the EFT
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- 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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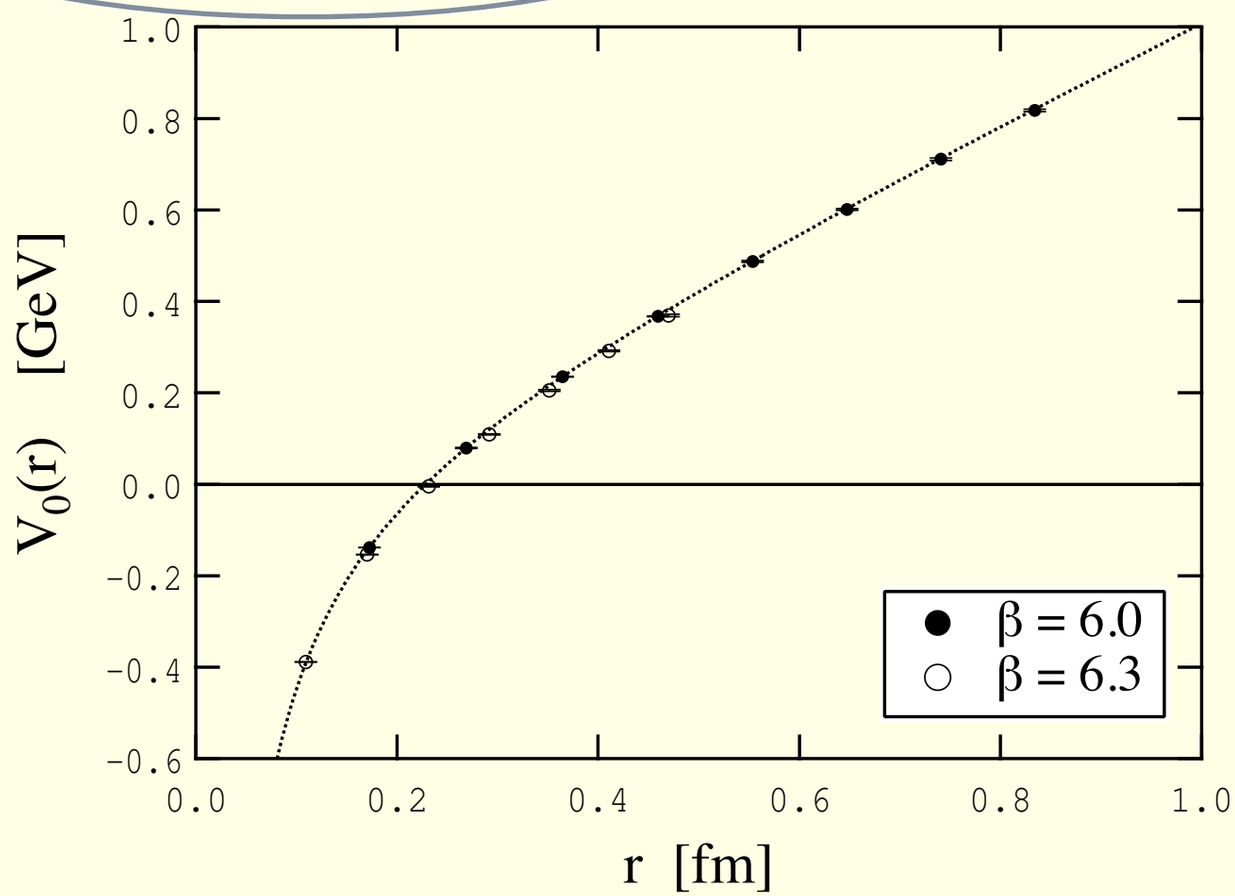
$$V_s^{(0)} = \lim_{T\to\infty} \frac{i}{T} \ln\langle W(r \times T)\rangle = \lim_{T\to\infty} \frac{i}{T} \ln \langle \square \rangle$$

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



○ Koma Koma NPB 769(07)79

Quarkonium singlet static potential

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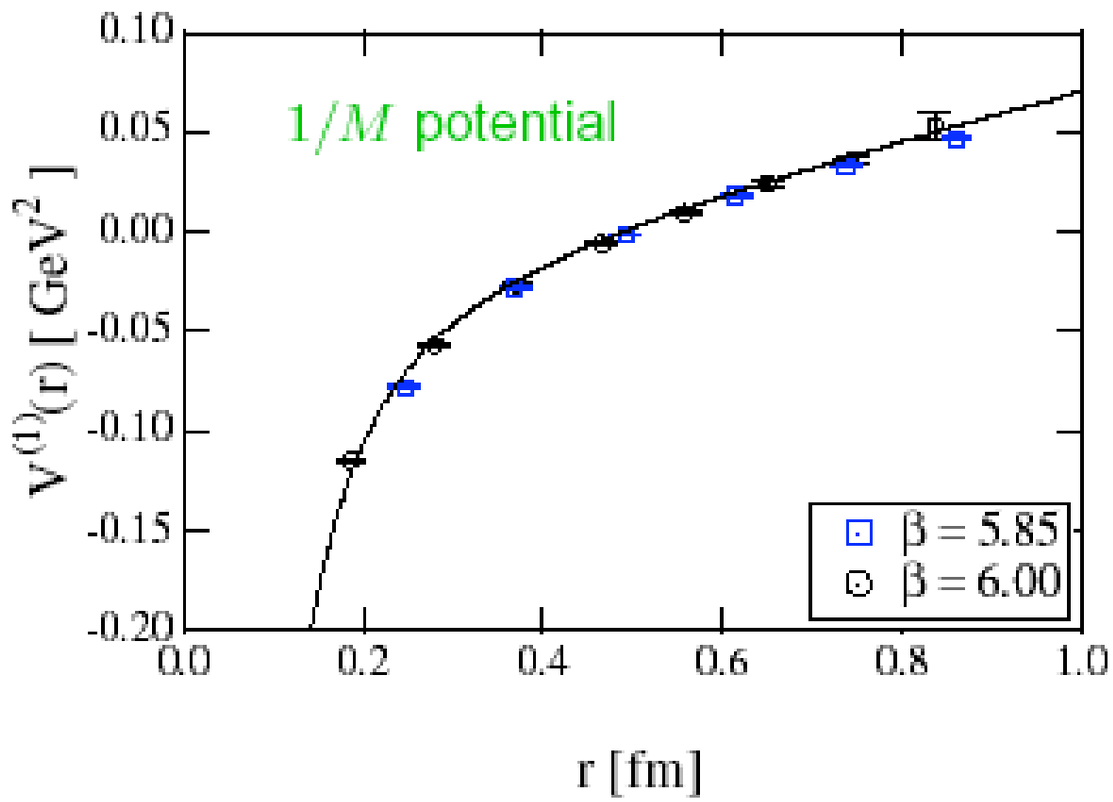
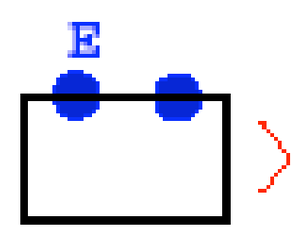


Koma Koma Wittig PoS LAT2007(07)111

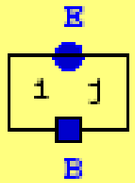
$$\frac{V_s^{(1)}}{m} = -\frac{1}{2m}\int_0^\infty dt\, t \langle$$

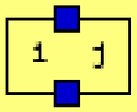
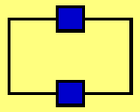


$\rangle$

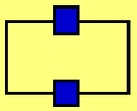
Brambilla et al 00

QCD Spin dependent potentials

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

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

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

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

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

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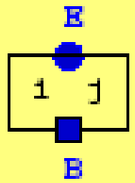

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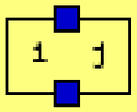

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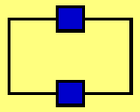

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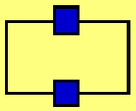

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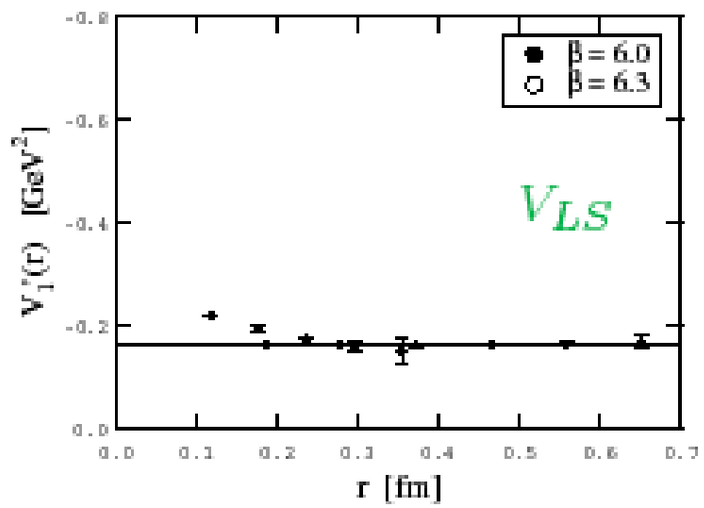
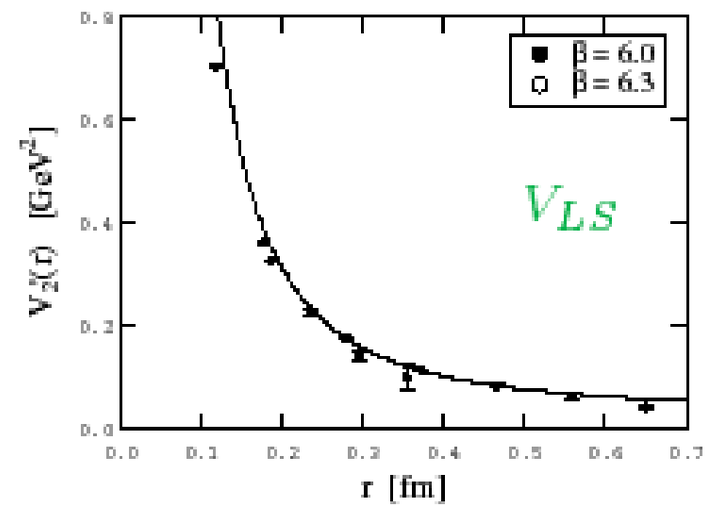
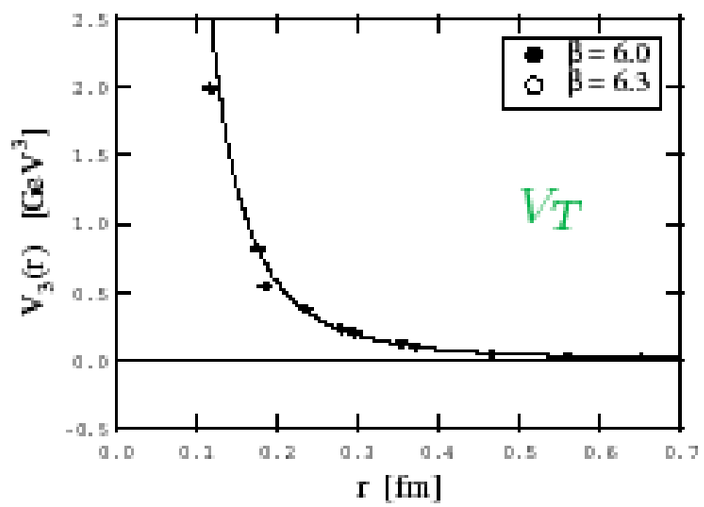
Eichten Feinberg 81, Gromes 84, Chen et al. 95 Brambilla Vairo 99 Pineda, Vairo 00

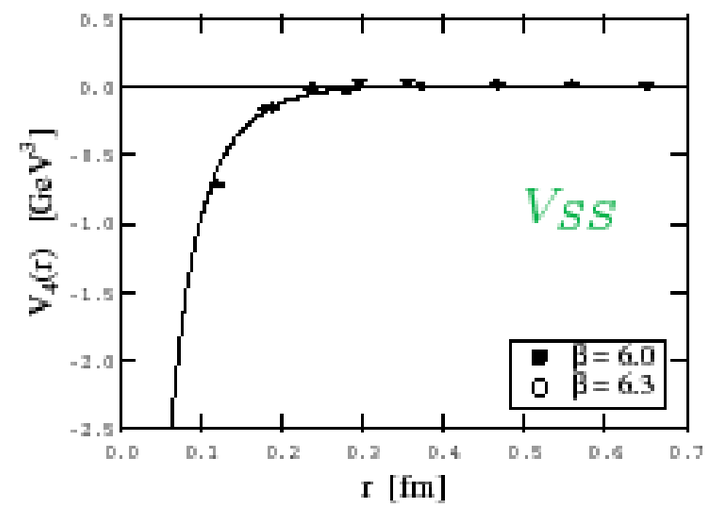
-factorization; power counting; QM divergences absorbed by NRQCD matching coefficients

Spin dependent potentials







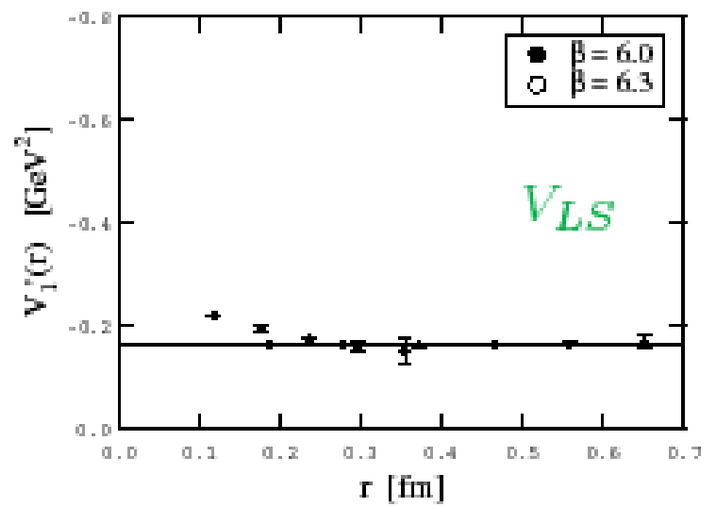


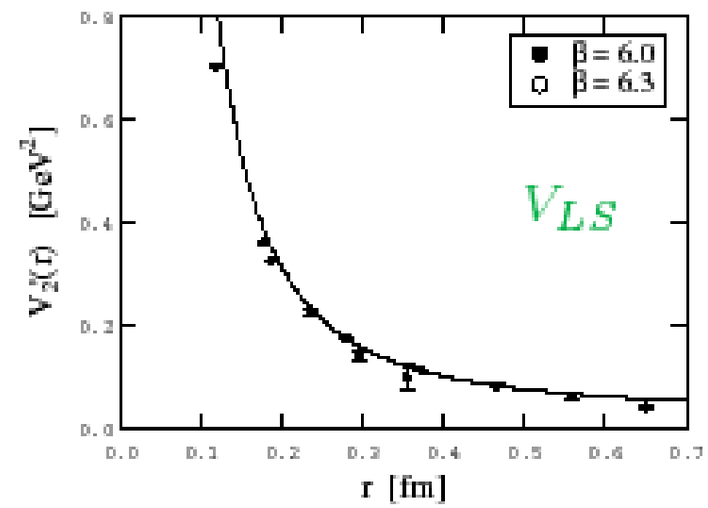
Koma Koma Wittig 05, Koma Koma 06

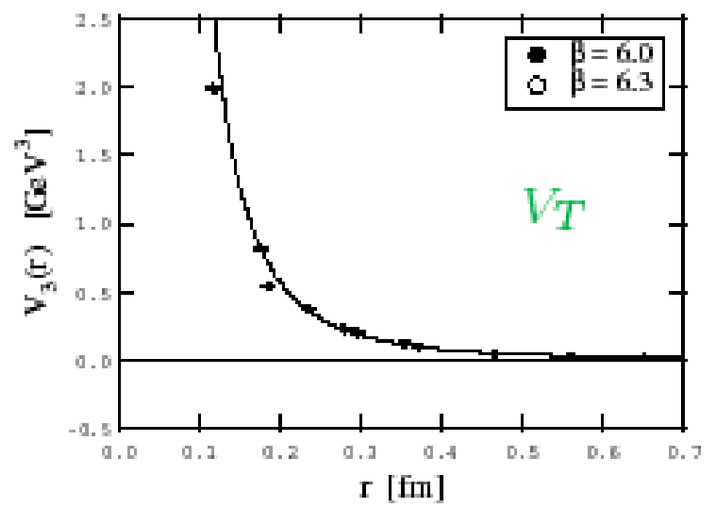
Terrific advance in the data precision with Lüscher multivel algorithm!

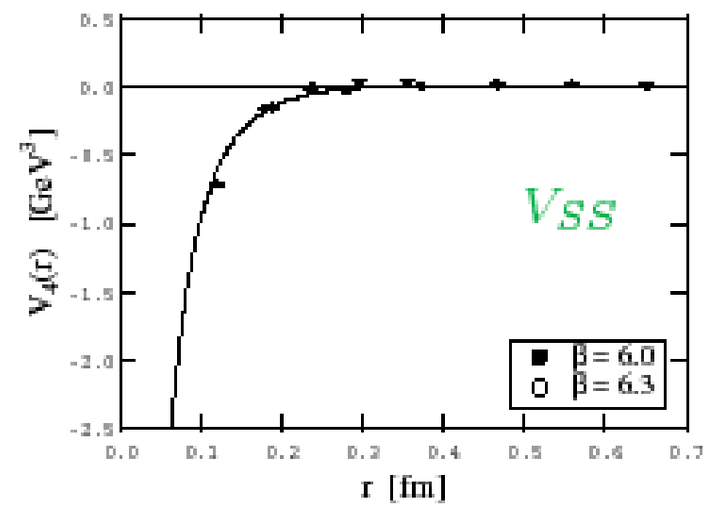
N. B., Martinez, vairo 2014

Spin dependent potentials









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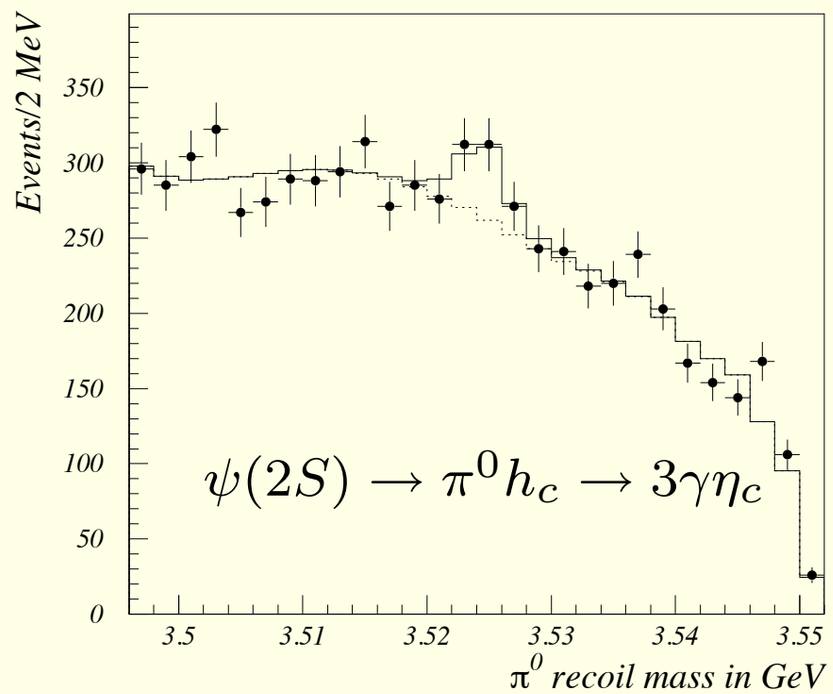
Terrific advance in the data precision with Lüscher multivel algorithm!

Such data can distinguish different models for the dynamics of low energy QCD 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 $M_{\text{c.o.g.}}(1P) = 3525.36 \pm 0.2 \pm 0.2$ MeV.

- Also

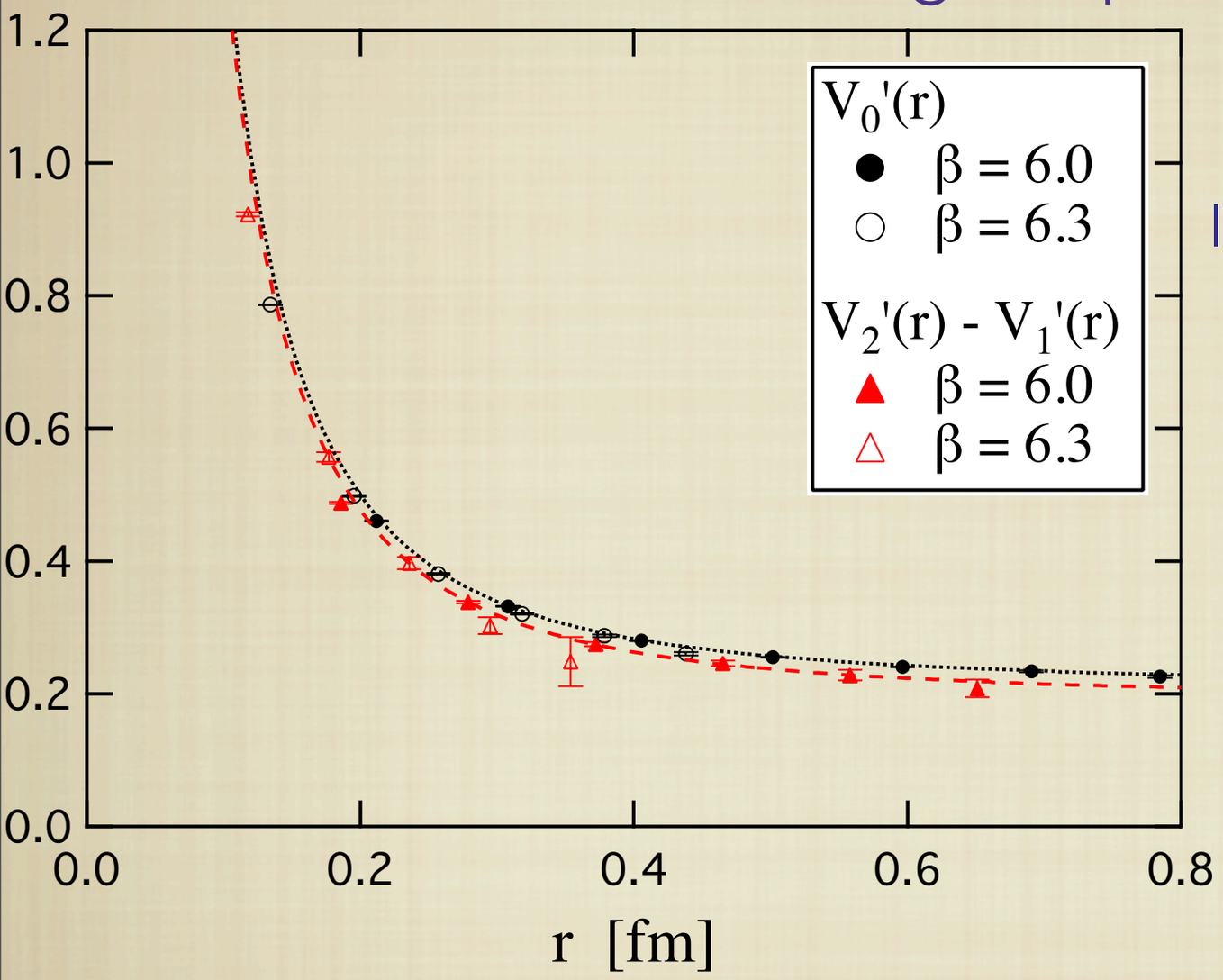
$M_{h_b} = 9902 \pm 4 \pm 1$ MeV ○ BABAR arXiv:1102.4565

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

Exact relations from Poincare' invariance

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

Koma and Koma 2006



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

Gromes relation

It is a check of the lattice calculation

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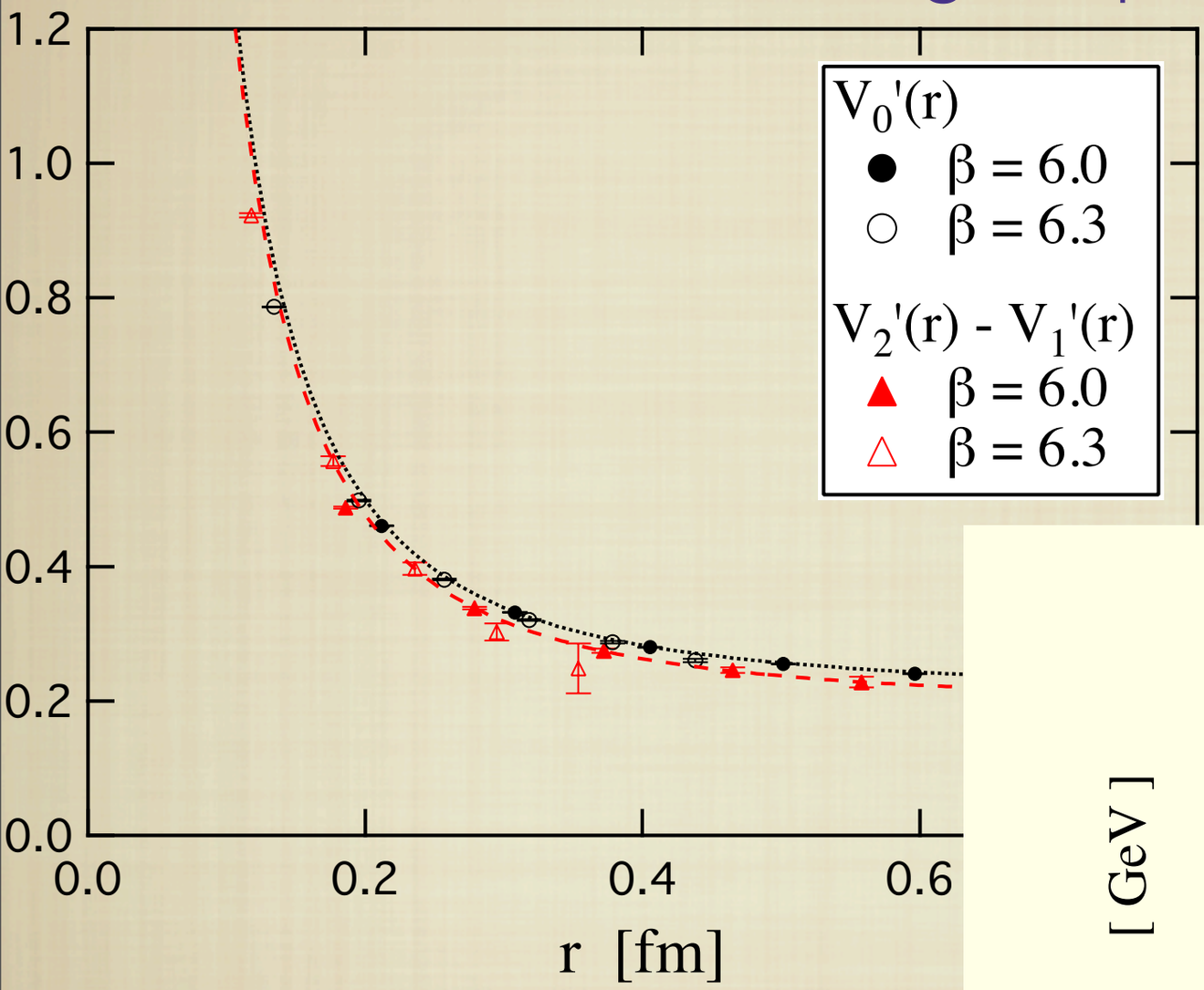

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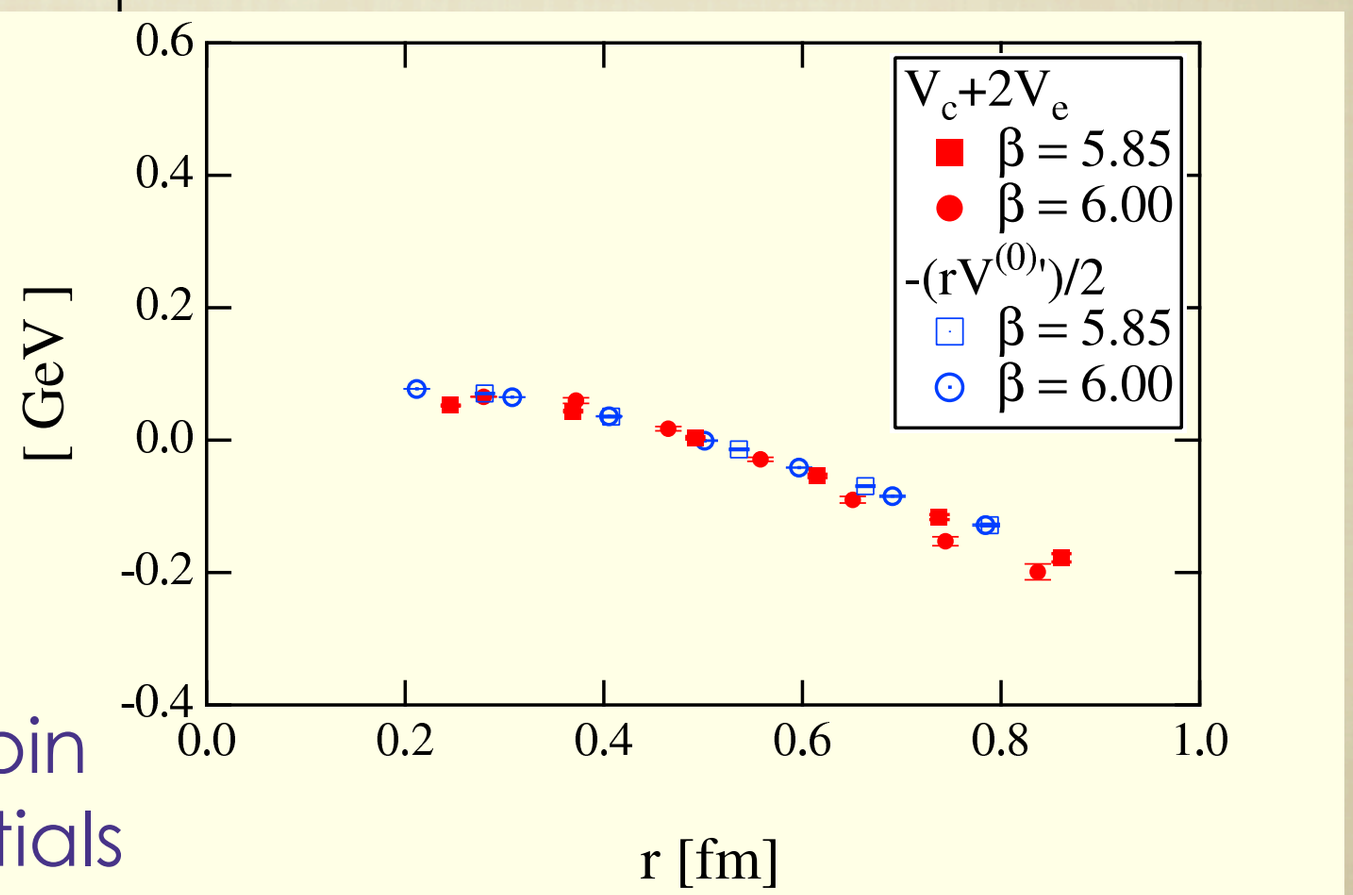
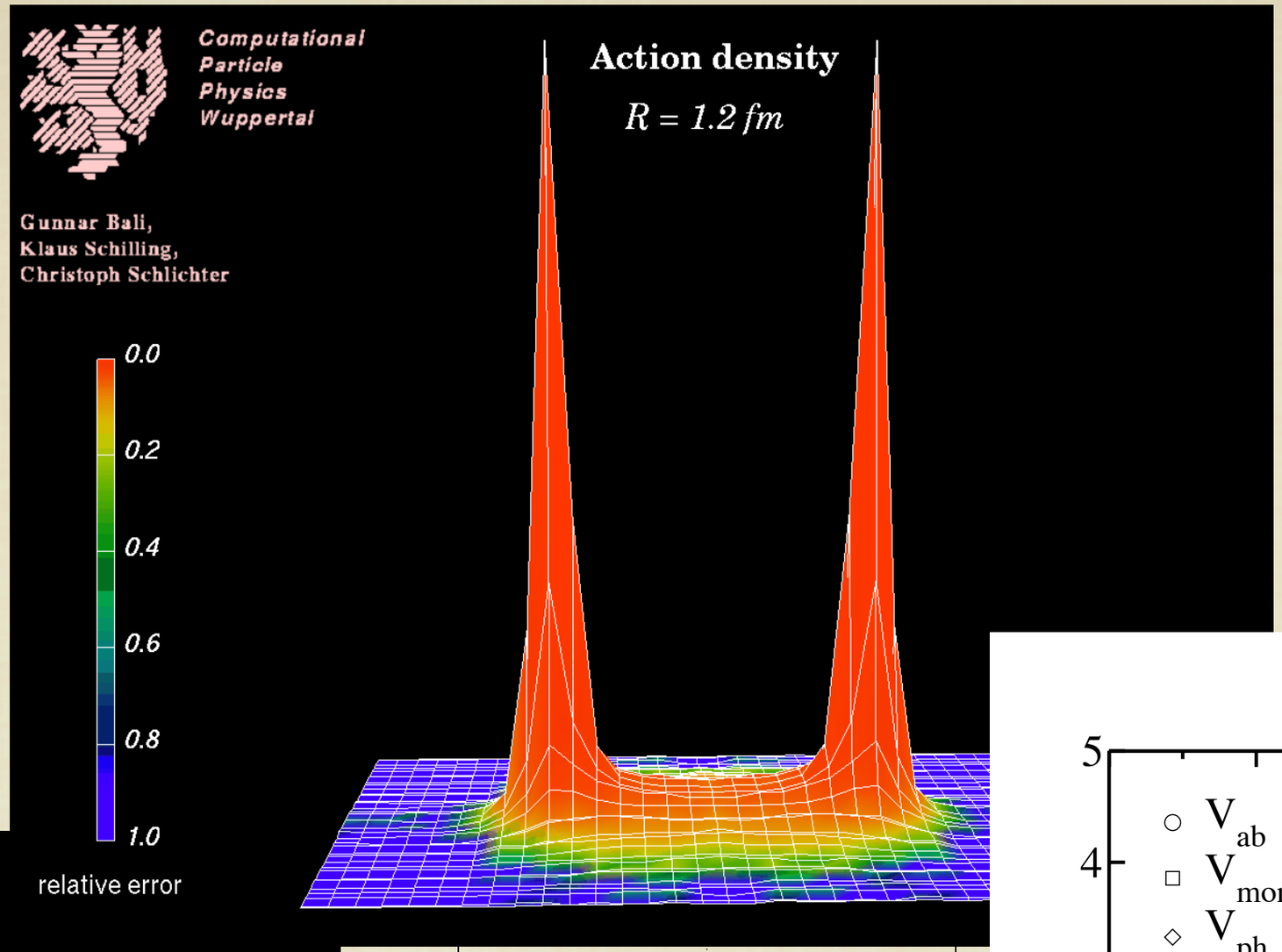


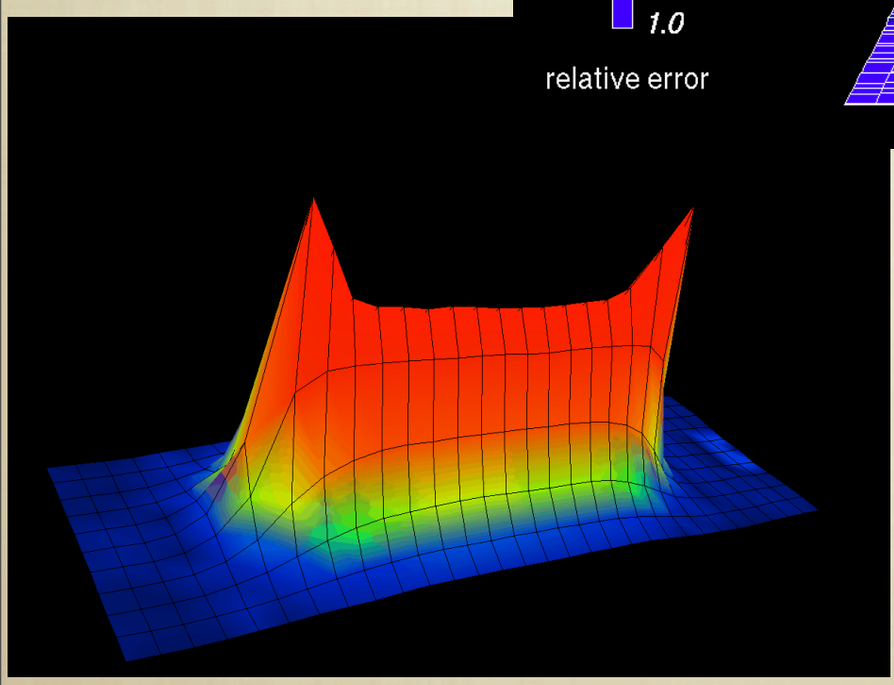
relations involving spin independent potentials

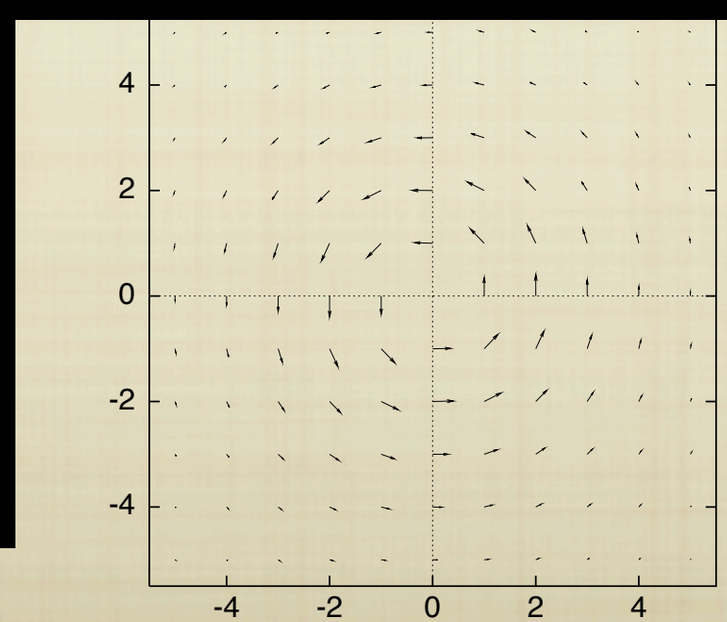
Koma Koma Wittig PoS LAT2007 (2007) 111

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

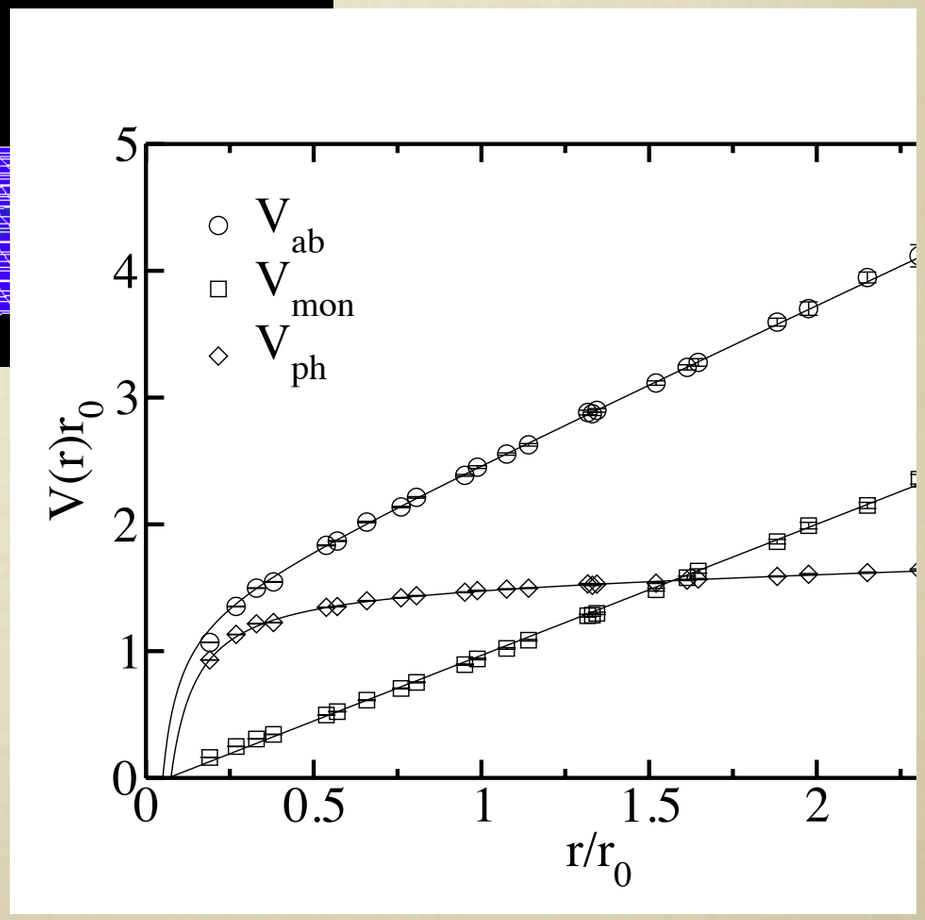
Bali et al







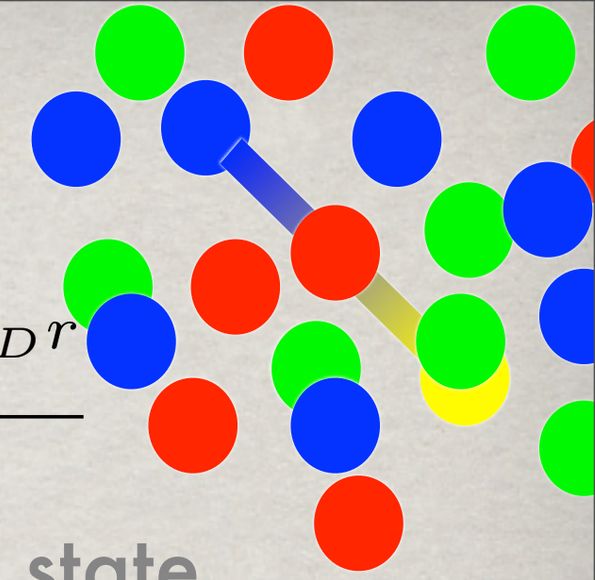
Boryakov et al. 04



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

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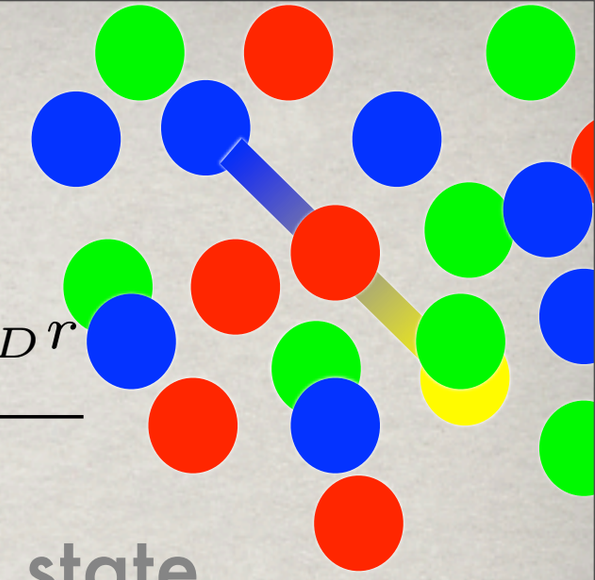

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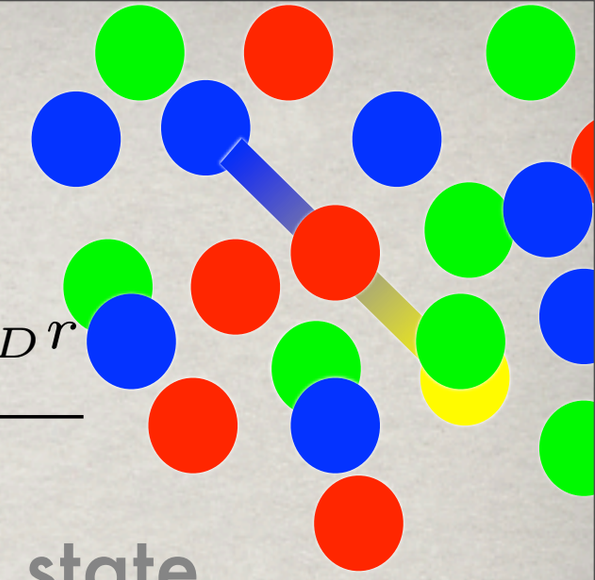

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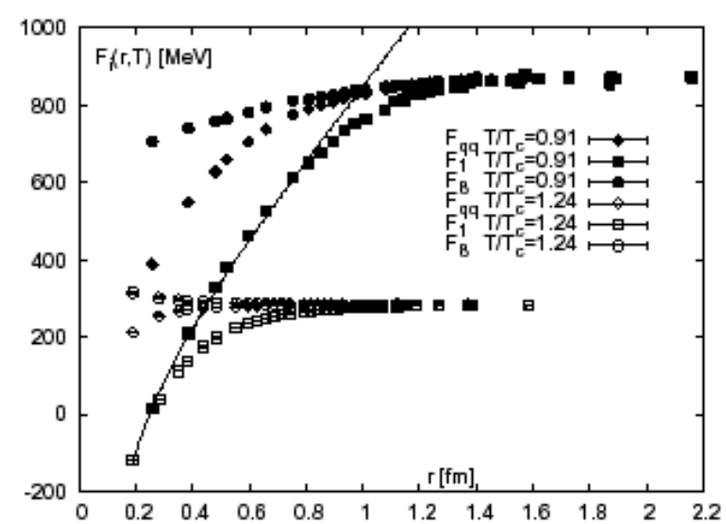
But what is the potential at finite T?

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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$m_D \sim gT$
Debye mass
Screening Scale

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Debye mass
Screening Scale

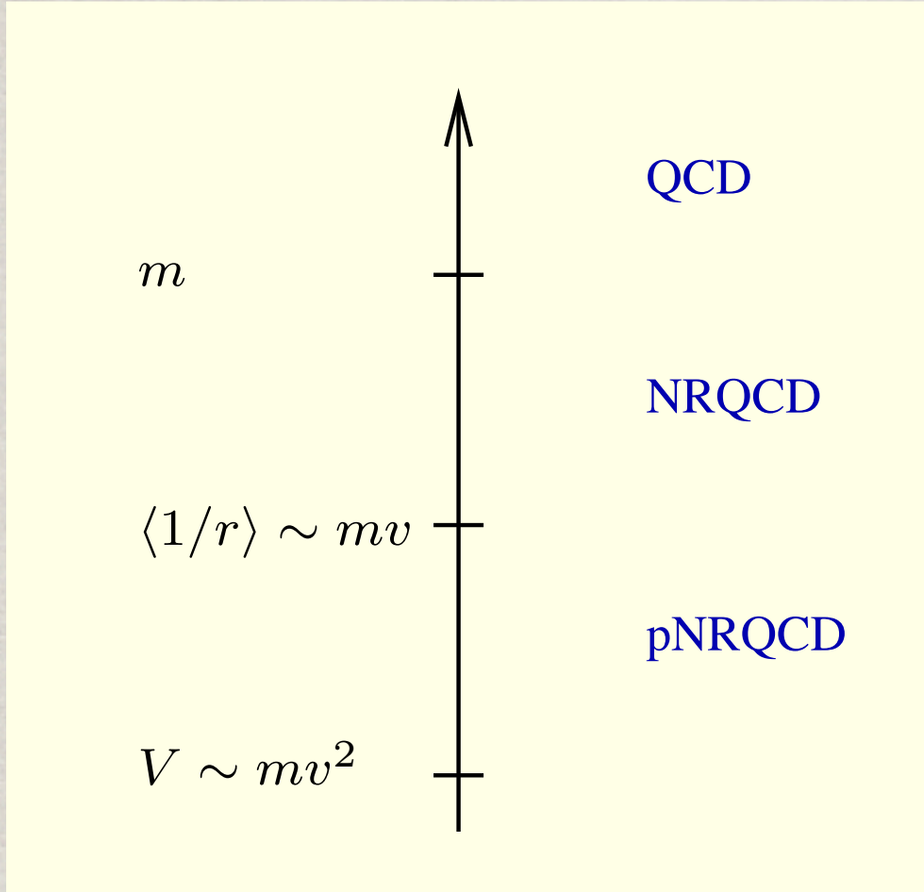
Without heavy quarks an EFT already exists that
mes from integrating out hard gluon of p \sim T:
Hard Thermal Loop EFT

Braaten Pisarski 90

-> obtain pNRQCD at finite T

Quarkonium at finite T with pNRQCD

N. B., Ghiglieri,Petreczky, Vairo 08



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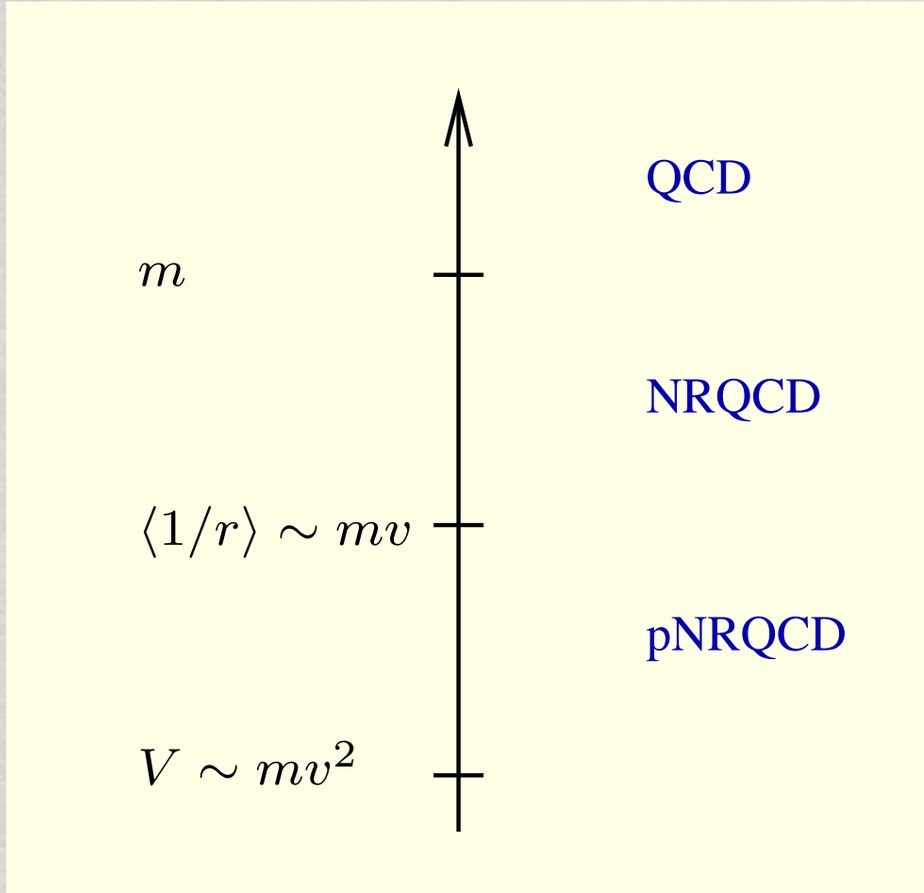

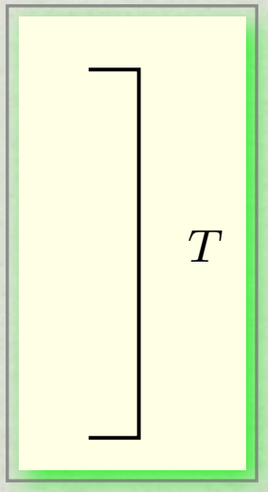

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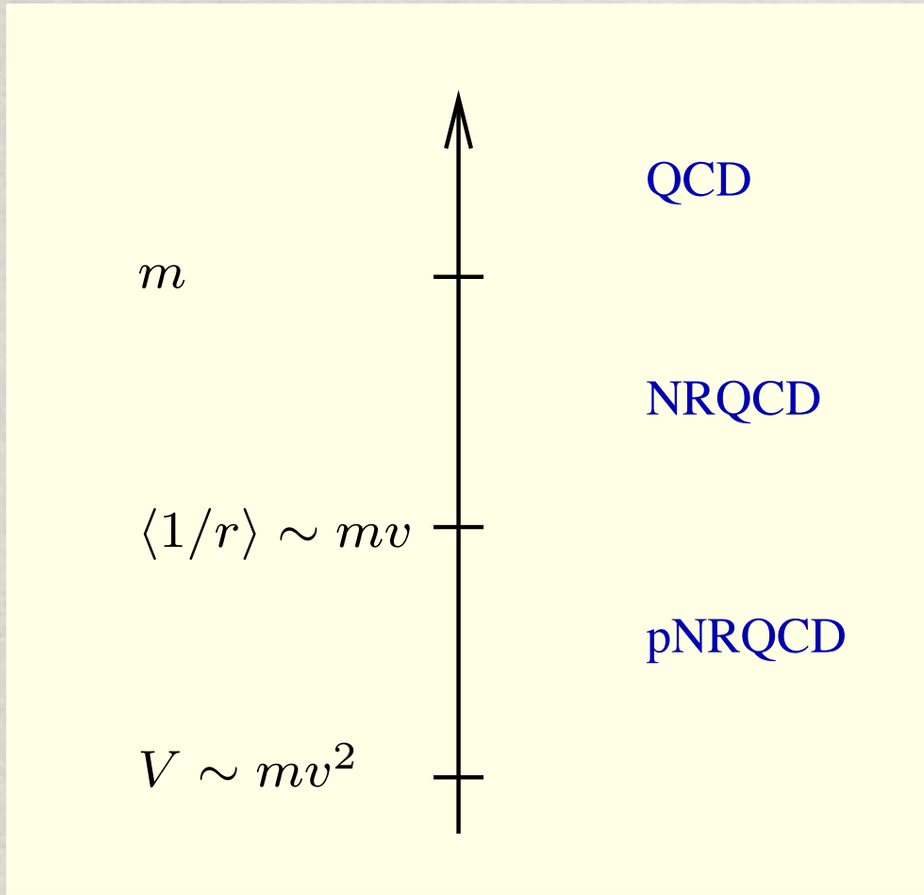
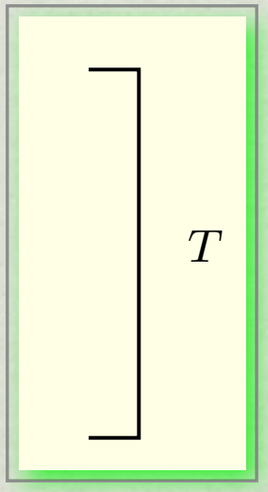


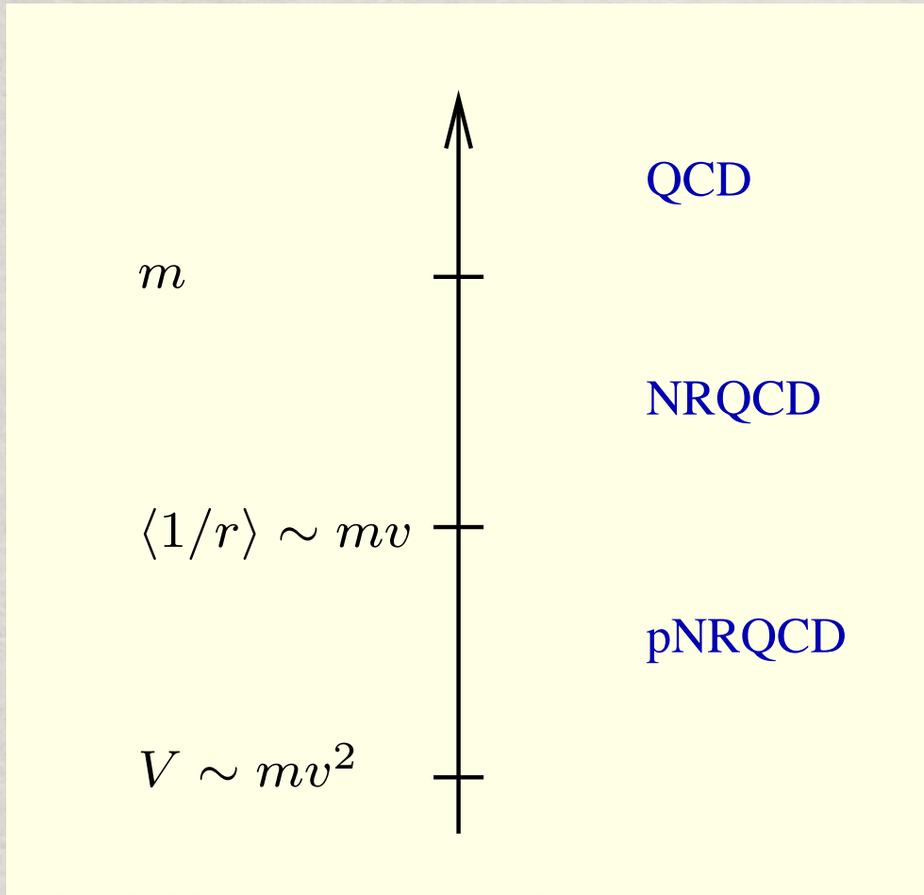


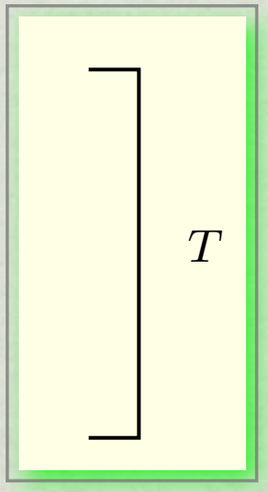
$\mathrm{NRQCD}_{\mathrm{HTL}}$

$\mathrm{pNRQCD}_{\mathrm{HTL}}$

Quarkonium at finite T with pNRQCD

N. B., Ghiglieri,Petreczky, Vairo 08





$\mathrm{NRQCD}_{\mathrm{HTL}}$

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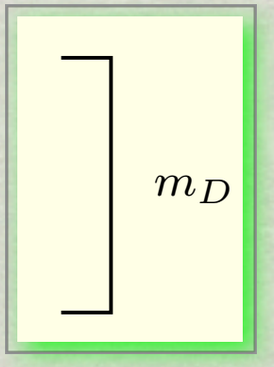
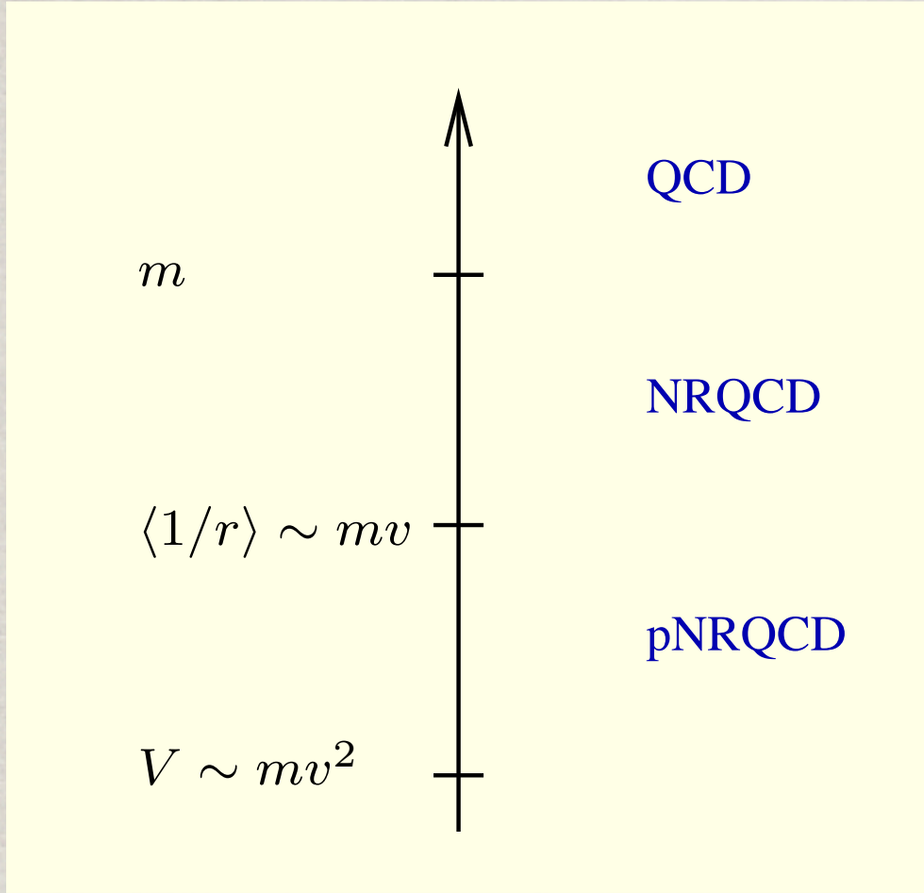
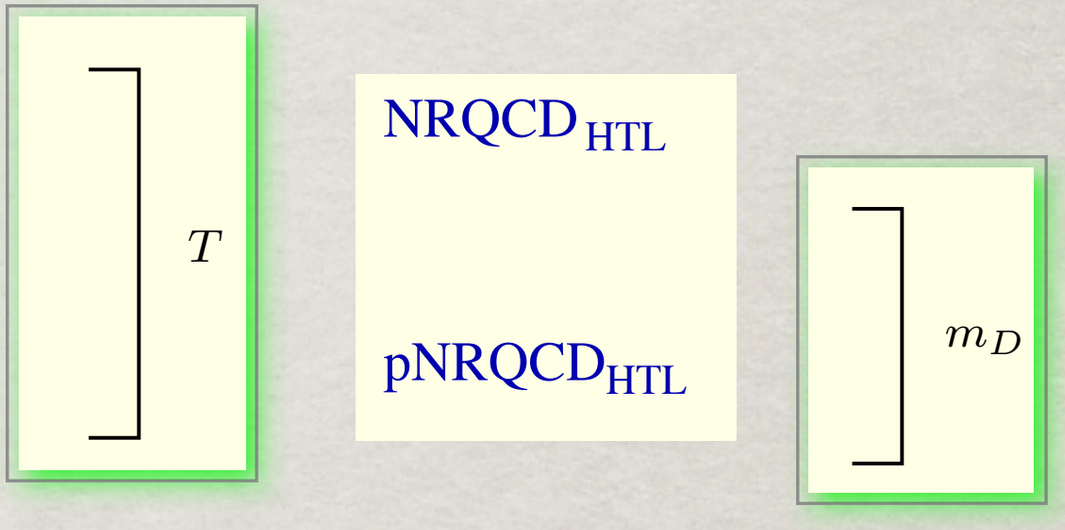


Quarkonium at finite T with pNRQCD

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.

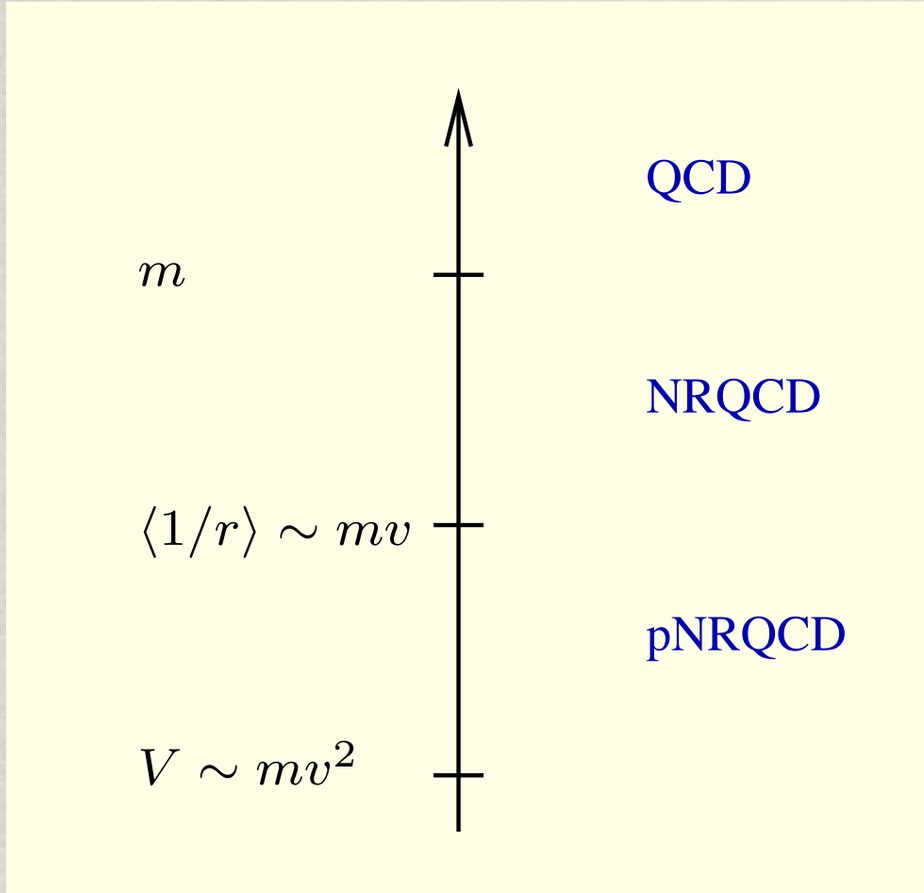
In the weak coupling regime:

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

Effects due to the scale $\Lambda_{\rm QCD}$ 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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- $T \gg gT \sim m_D$.

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

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

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

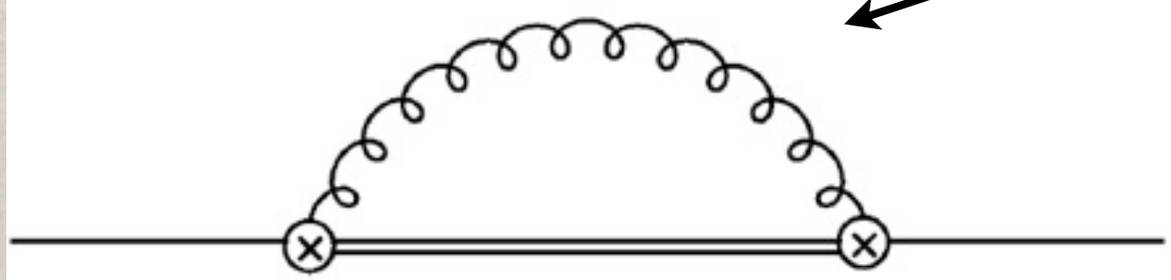
$\mathrm{Re}V_S(r,T)$

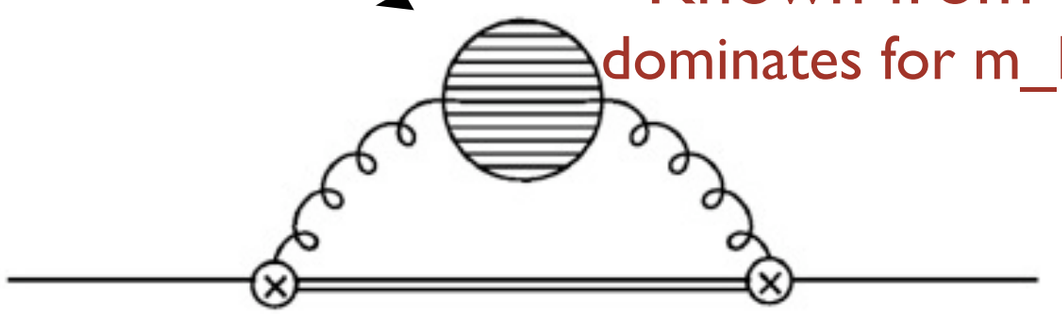
$\mathrm{Im}V_S(r,T)$

thermal width of $Q\bar{Q}$

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

Known from QED
dominates for m_D/E>>1





Singlet-to-octet

N.B Ghiglieri, Petreczky, Vairo 2008

Landau damping

Laine et al 07, Escobedo Soto 07

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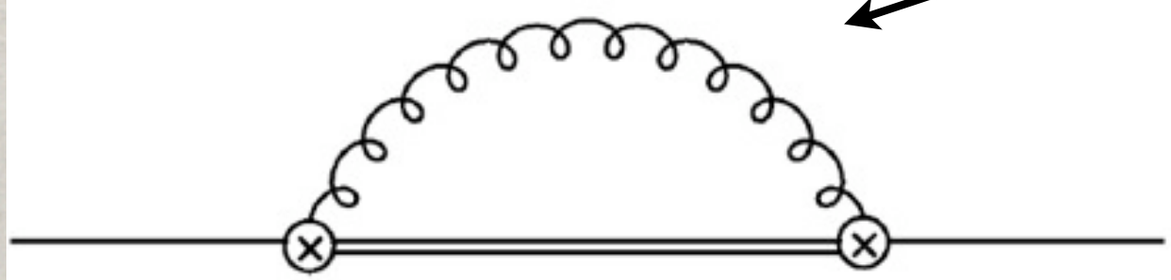

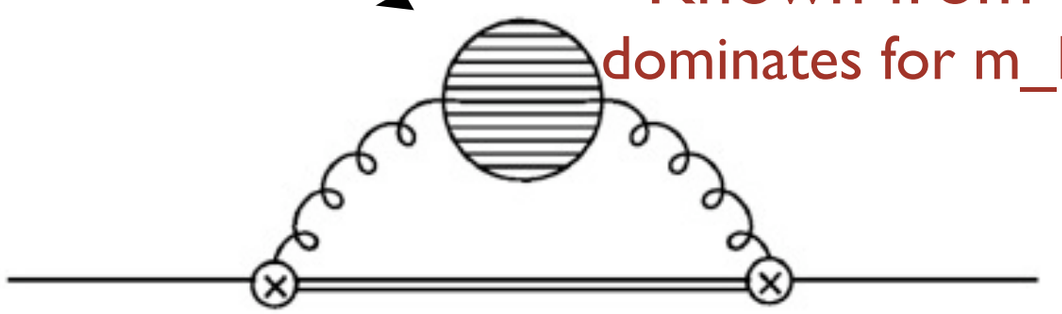

Singlet-to-octet

N.B Ghiglieri, Petreczky, Vairo 2008

(gluo dissociation)

N. B. Escobedo, Ghiglieri , Vairo 2011

Landau damping

Laine et al 07, Escobedo Soto 07

(inelastic parton scattering)

N. B. Escobedo, Ghiglieri , Vairo 2013

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

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$\mathrm{Re}V_S(r,T)$ differs from the free energy

N. B., Ghiglieri, Petreczky, Vairo 010

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

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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

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

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

- Escobedo Soto arXiv:0804.0691

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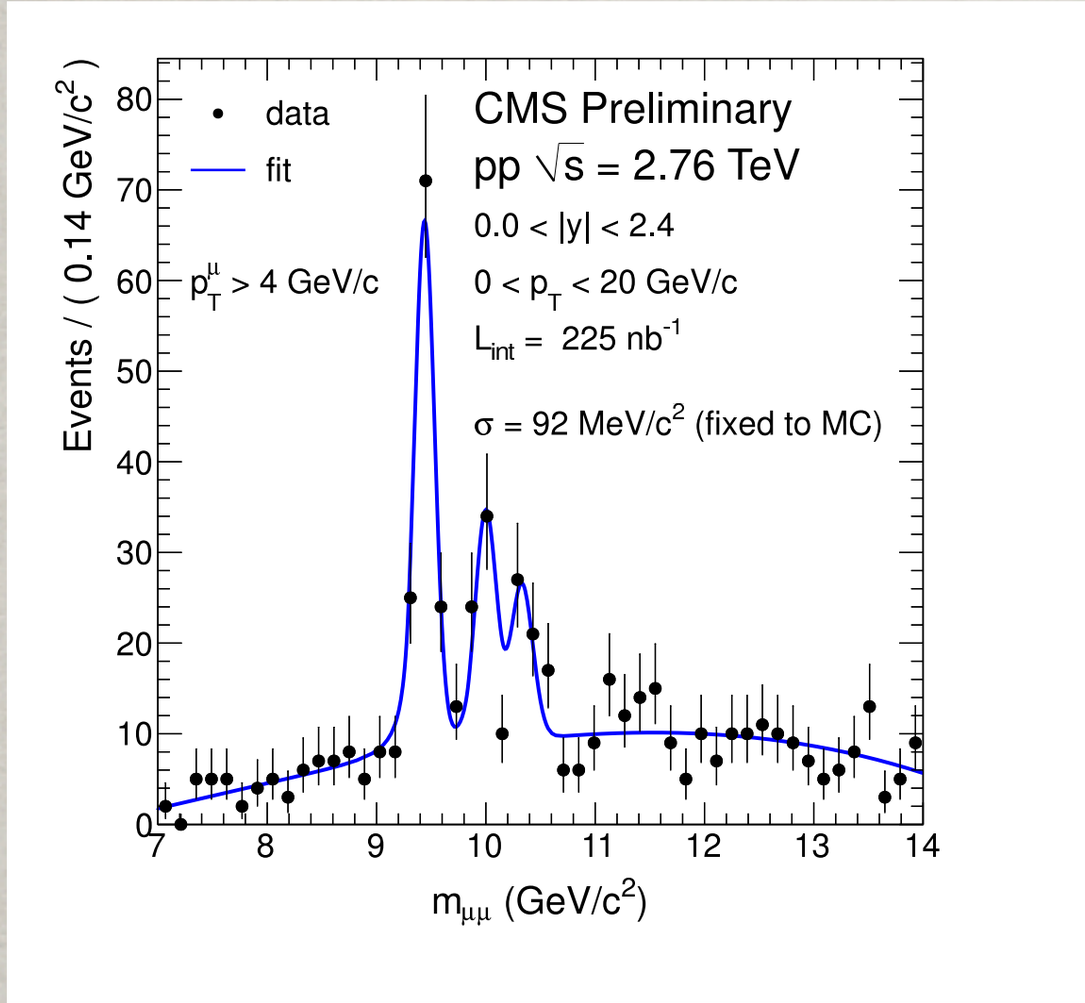
offer a systematic framework to do the calculation for the first time, inpired calculations in lattice, strings ..

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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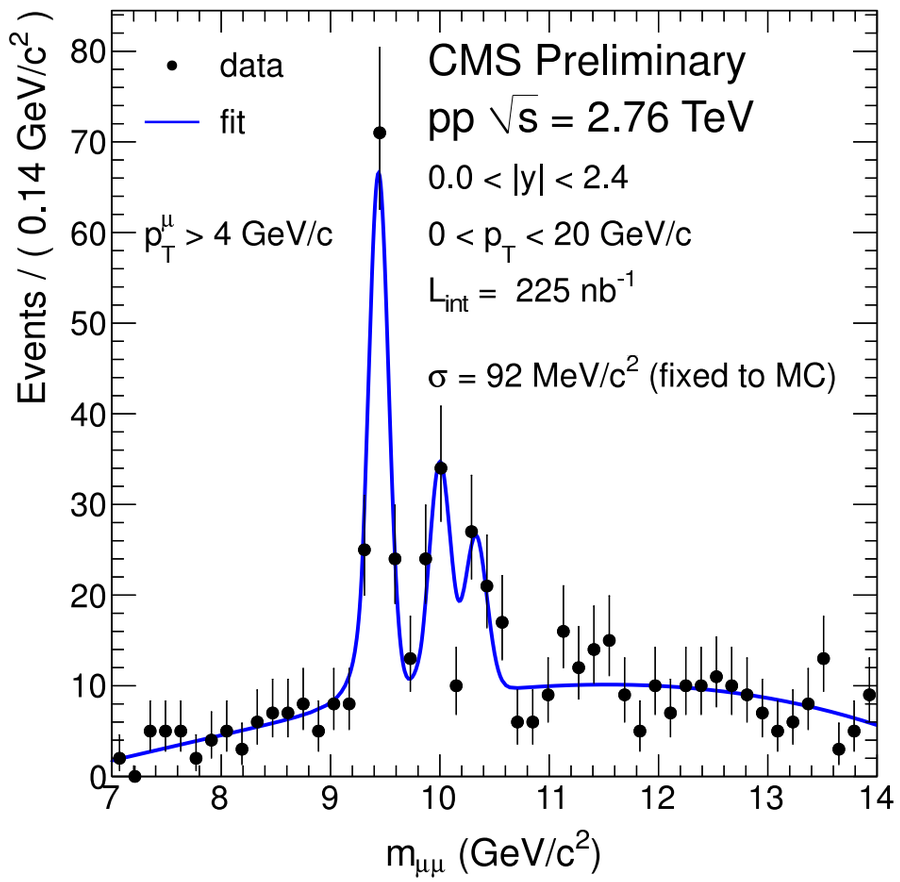

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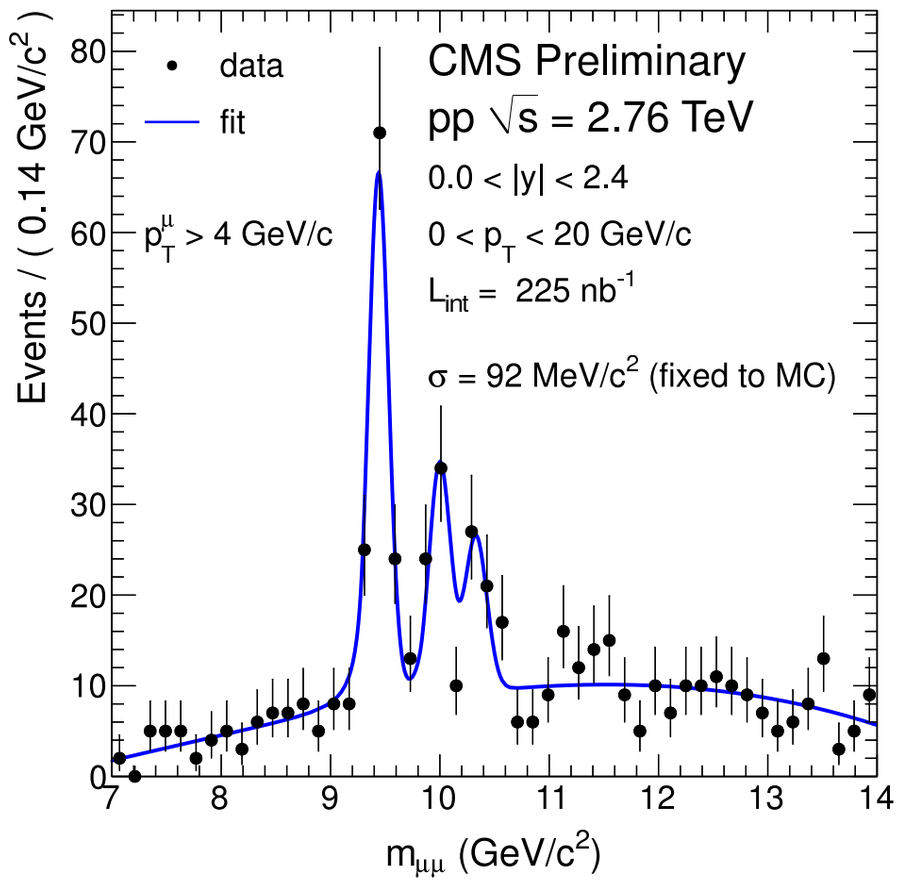

application to the study of Y(1S) in hot medium at LHC experiments

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

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

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

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

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

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

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

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

Consistent with 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

TABLE 10: Quarkonium-like states at the 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 (#σ)	Year	Status
$X(3872)$	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)	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!

arXiv:1404.3723v1

arXiv:1404.3723v1

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 (#σ)	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), LHCb [1062] (1.4), CMS [1063] (>5) D0 [1064] (3.1)	2009	NC!
$\psi(4160)$	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) Belle [1008, 1056] (15), BES III [1007] (np)	2005	Ok
				$e^+e^- \to (f_0(980)J/\psi)$	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), CMS [1063] (>3), D0 [1064] (np)	2011	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	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) LHCb [1077] (13.9)	2007	Ok
				$\bar{B}^0 \to K^-(\pi^+ J/\psi)$	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!

even the case without light quark is difficult

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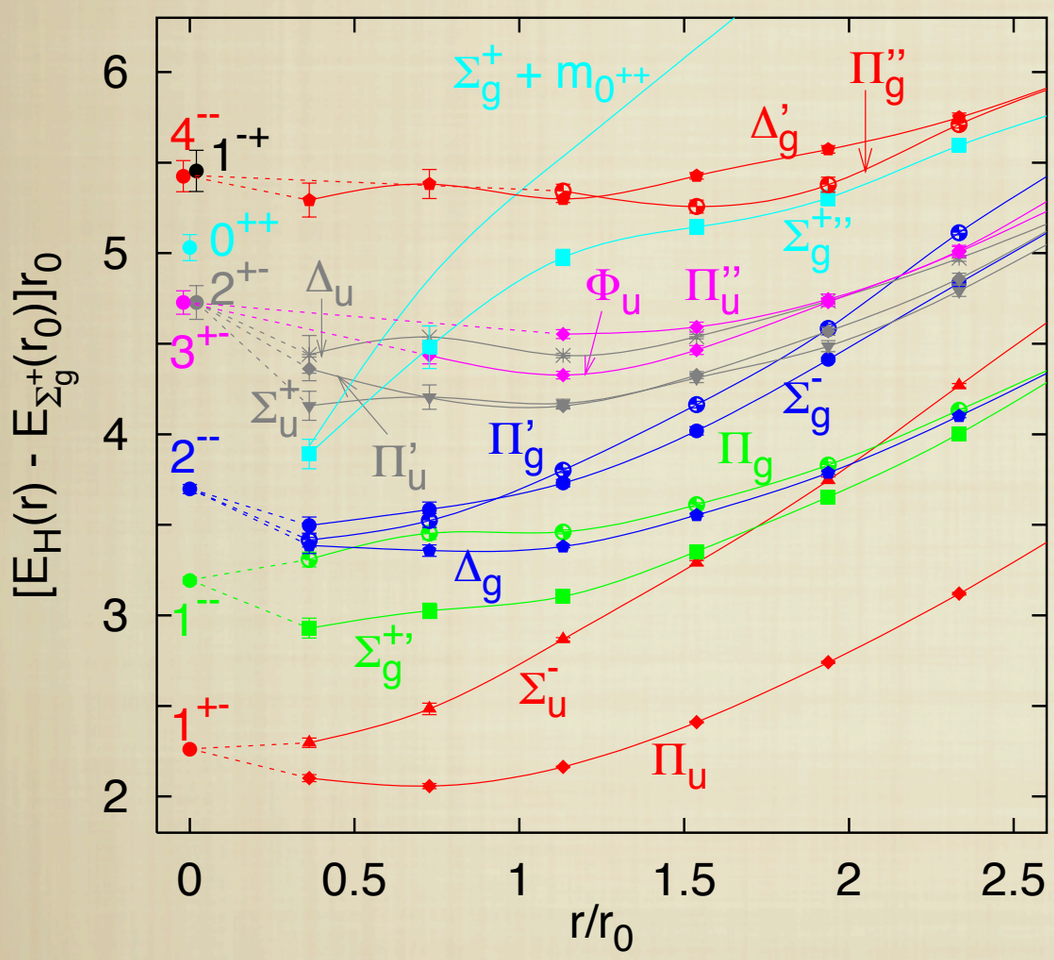
Gluonic excitations

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



Juge Kuti Morningstar 00 03

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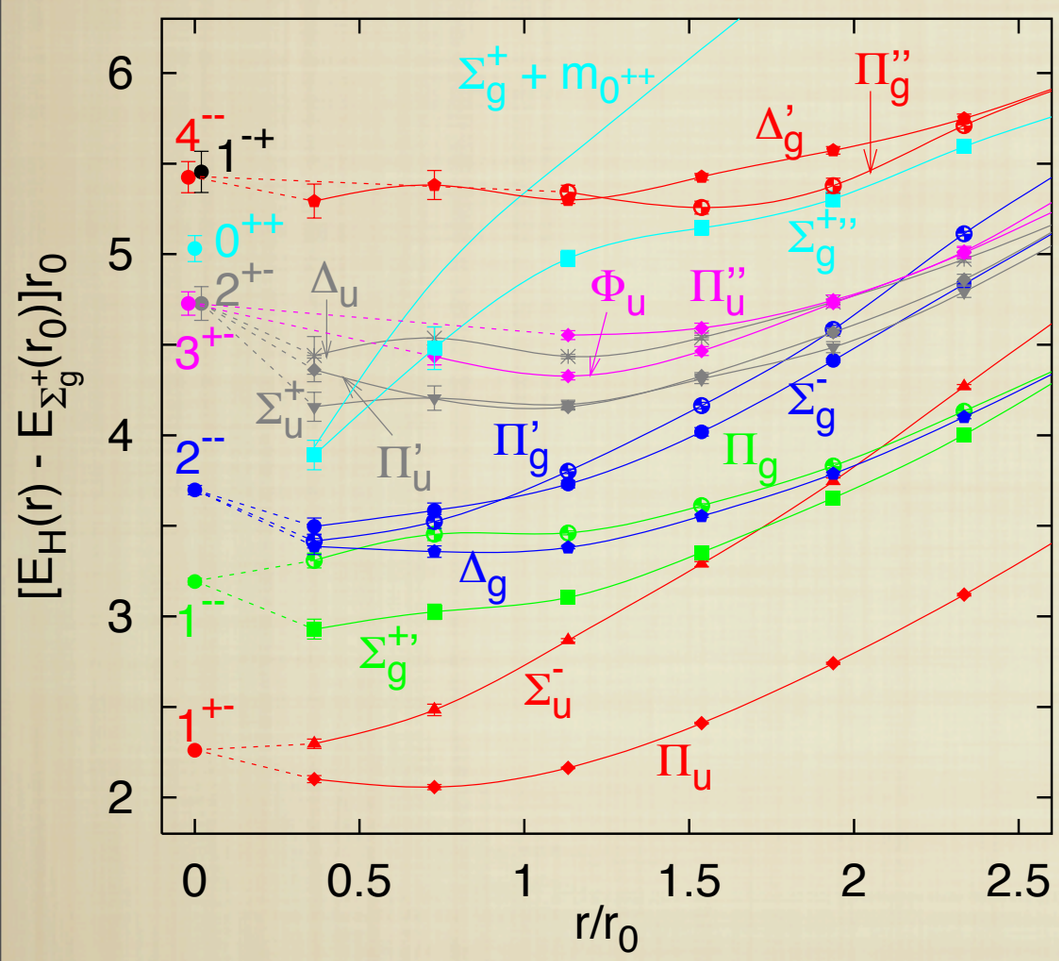
Gluelumps and hybrids in pNRQCD

more symmetry!



Juge Kuti Morningstar 00 03

	$L=1$	$L=2$
$\Sigma_g^{+\prime}$	$\mathbf{r}\cdot(\mathbf{E})$	
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'		$\mathbf{r}\times((\mathbf{r}\cdot\mathbf{D})\mathbf{E}+\mathbf{D}(\mathbf{r}\cdot\mathbf{E}))$
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Brambilla Pineda Soto Vairo 00

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

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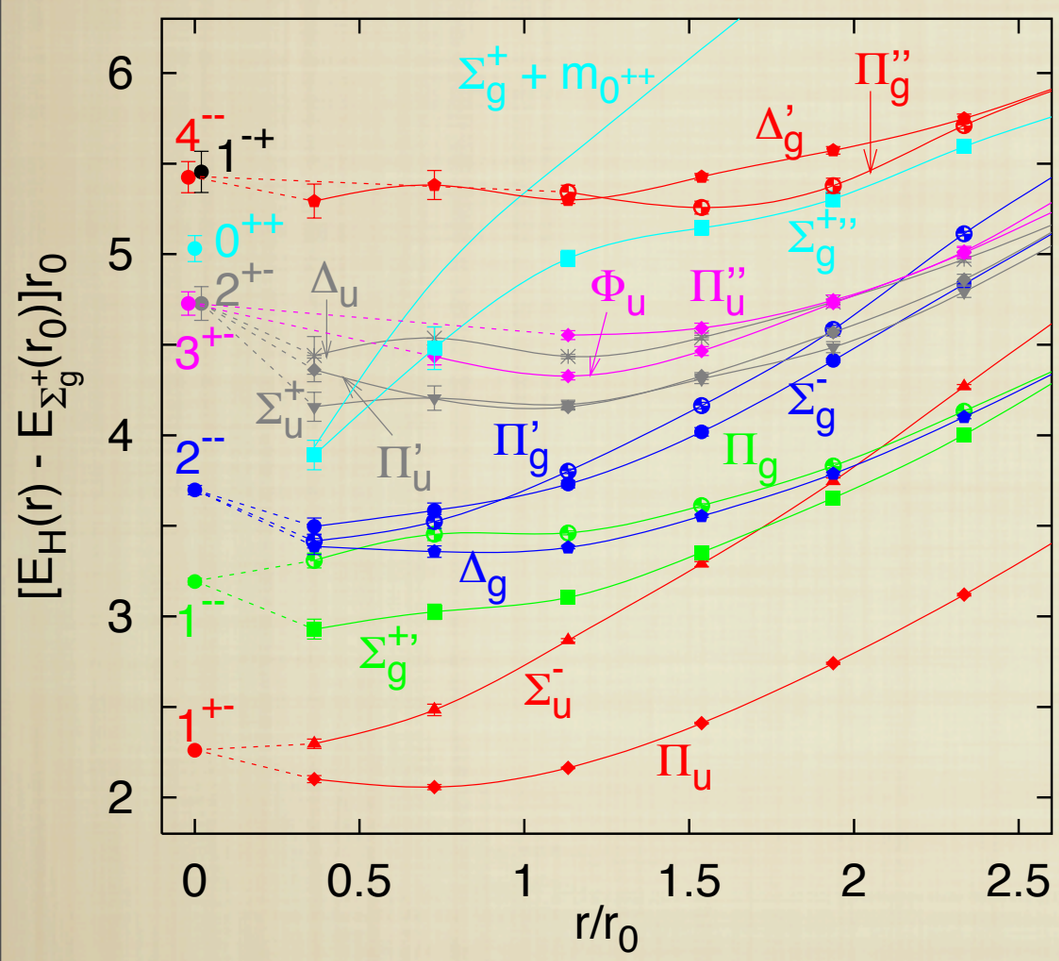

Juge Kuti Morningstar 00 03

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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		$(\mathbf{r}\times\mathbf{D})^i(\mathbf{r}\times\mathbf{E})^j+$ $+(\mathbf{r}\times\mathbf{D})^j(\mathbf{r}\times\mathbf{E})^i$

Brambilla Pineda Soto Vairo 00

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

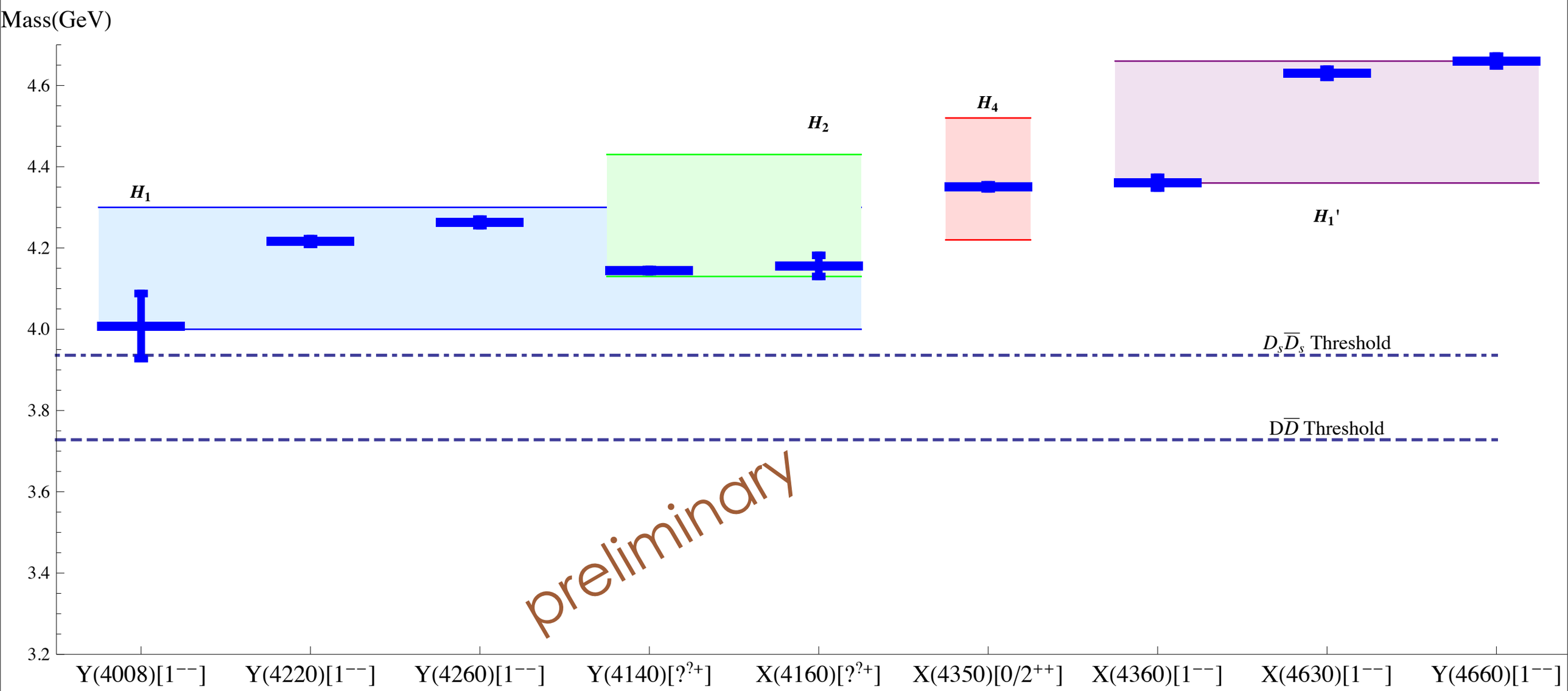
octet potential

hybrids static energy

$$E_H(r)=V_o(r)+\Lambda_H$$

gluelump mass

pNRQCD hybrids multiplets predictions



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

CLOSE TO THRES HOLD

The QCD spectrum with light quarks

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

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States made of two heavy and light quarks

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

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- In addition new states built using the light quark quantum numbers may form.
  - Soto NP PS 185(08)107

States made of two heavy and light quarks

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CLOSE TO THRES HOLD

The QCD spectrum with light quarks

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MAIANI, PICCININI, POLOSA ET AL. 2005--

  - Jaffe PRD 15(77)267
  - Ebert Faustov Galkin PLB 634(06)214

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Systems with a short-range interaction and a large scattering length have universal properties that may be exploited: in particular, production and decay amplitudes factorize in a short-range and a long-range part, where the latter depends only on one single parameter, the scattering length. An universal property that fits well with the observed large branching fraction of the $X(3872)$ *decaying into* $D^0\bar{D}^0\pi^0$ *is* $\mathcal{B}(X \to D^0\bar{D}^0\pi^0) \approx \mathcal{B}(D^{*\,0} \to D^0\pi^0) \approx 60\%$.

Pakvasa Suzuki 03, Voloshin 03, Braaten Kusunoki 03

Braaten Hammer 06

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

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

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

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

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

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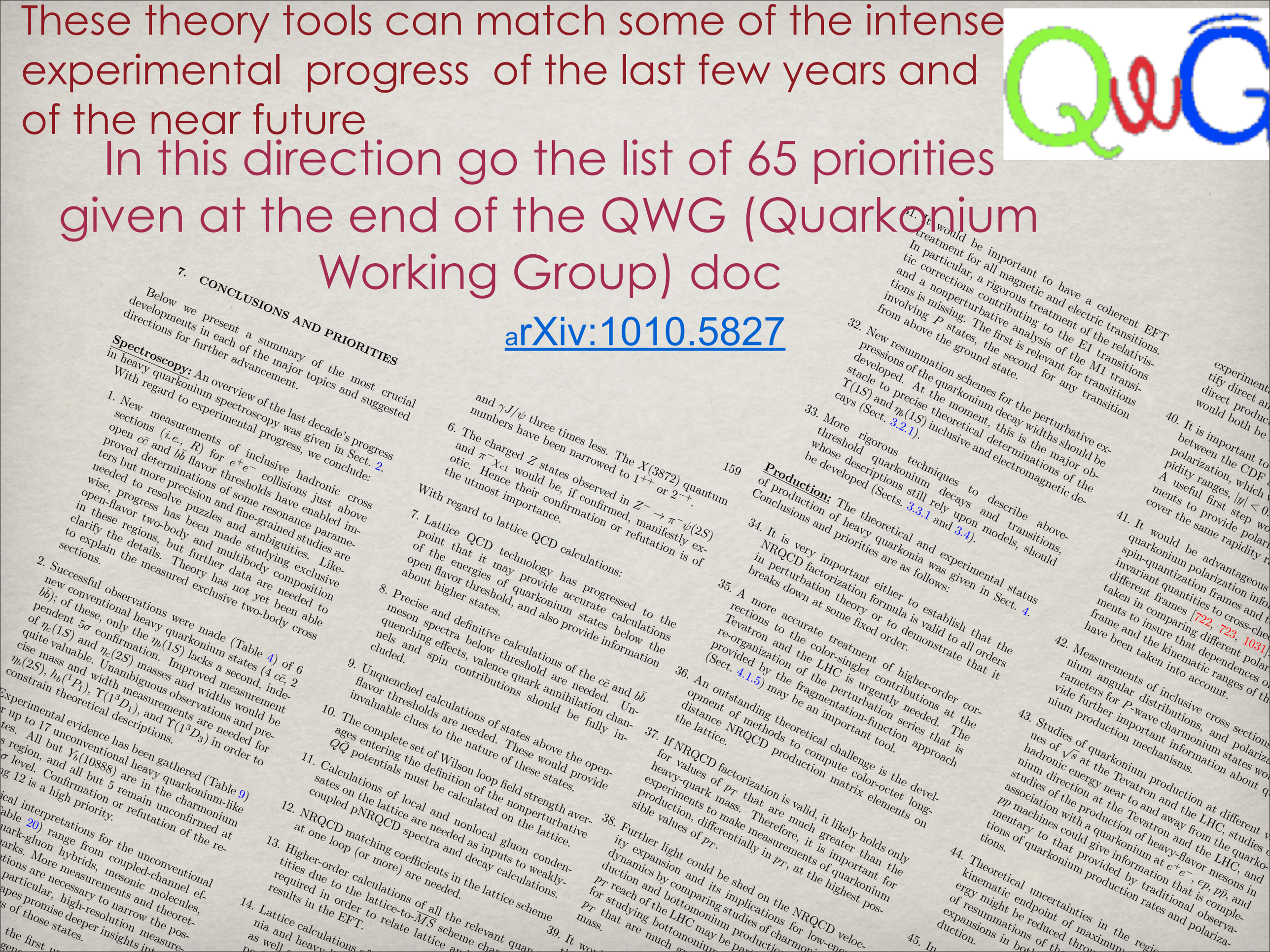
In this direction go the list of 65 priorities given at the end of the QWG (Quarkonium Working Group) doc

arXiv: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 just above open $c\bar{c}$ and $b\bar{b}$ flavor thresholds 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 and precise mass and width measurements 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) r up to 17 unconventional heavy quarkonium-like tes. All but $Y_b(10888)$ are in the charmonium s region, and all but 5 remain unconfirmed at σ level. Confirmation or refutation of the re- ng 12 is a high priority.

ical interpretations for the unconventional able 20) range from coupled-channel ef- uark-gluon hybrids, mesonic molecules, arks. More measurements and theoret- tions are necessary to narrow the pos- particular, high-resolution measure- apes promise deeper insights int s of those states.

the first m gene

159

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 $Z^- \to \pi^-\psi(2S)$ 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 quantities due to the lattice-to-$\overline{MS}$ scheme change are required in order to relate lattice and EFT results in the EFT.

14. Lattice calculations of nia and heavy as well

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 perturbation series that is 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 charmonium production and bottomonium production at the LHC may be par p_T reach of the LHC may be par for studying bottomonium p_T that are much g mass.

39. It wo

51. 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 E1 transitions and a nonperturbative analysis of the M1 transitions is missing. The first is relevant for 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).

experiment tify direct an direct produc would both be

40. It is important to between the CDF a 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 o 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 q nium production mechanisms.

43. Studies of quarkonium production at different w ues of $\sqrt{s}$ at the Tevatron and the LHC, studies o 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 at e^+e^-, ep, $p\bar{p}$, and pp machines could give information that is complementary to that provided by traditional observations of quarkonium production rates and polarizations.

44. Theoretical uncertainties in the regio kinematic endpoint of maximum ergy might be reduced throu of resummations of th expansions in bot duction.

45. In

Selected Outlook for future research

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

Alice, Rhic

Spectra/decays of quarkonia

Belle,BESIII, Panda, LHC exps

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

Belle,BESIII, Panda, LHC-b

Quarkonium-quarkonium van der Waals interaction; quarkonium on nuclei

Fair

Quarkonium production

CMS, Atlas, Alice, LHC-b

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CMS, Atlas, Alice, LHC-b

We are eagerly looking forward the new experimental data from LHC, BESIII, BELLEII ...

Backup SLIDES

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

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

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

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

Quarkonium production

NRQC

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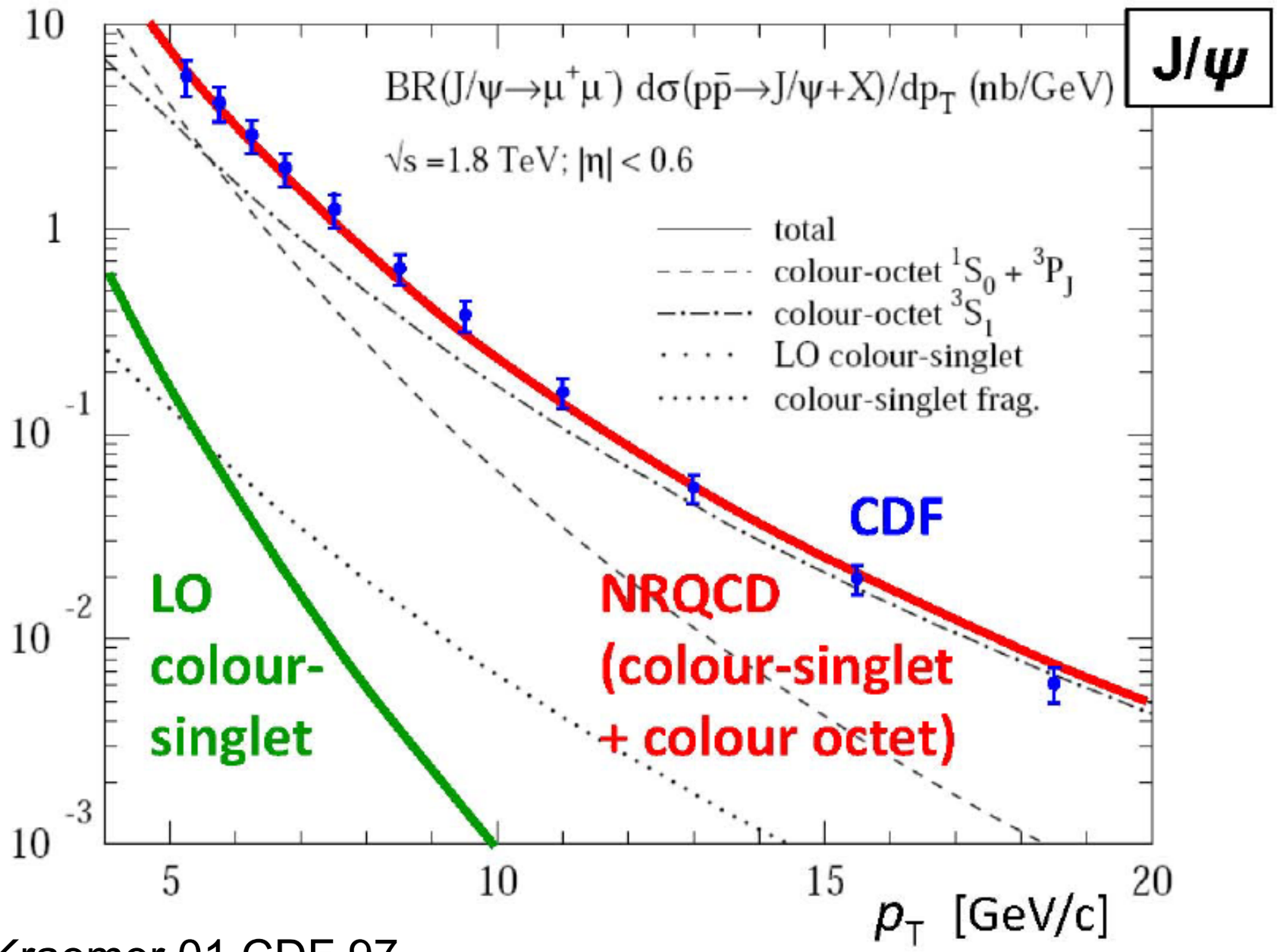

M. Kraemer 01 CDF 97

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

Quarkonium production

1995

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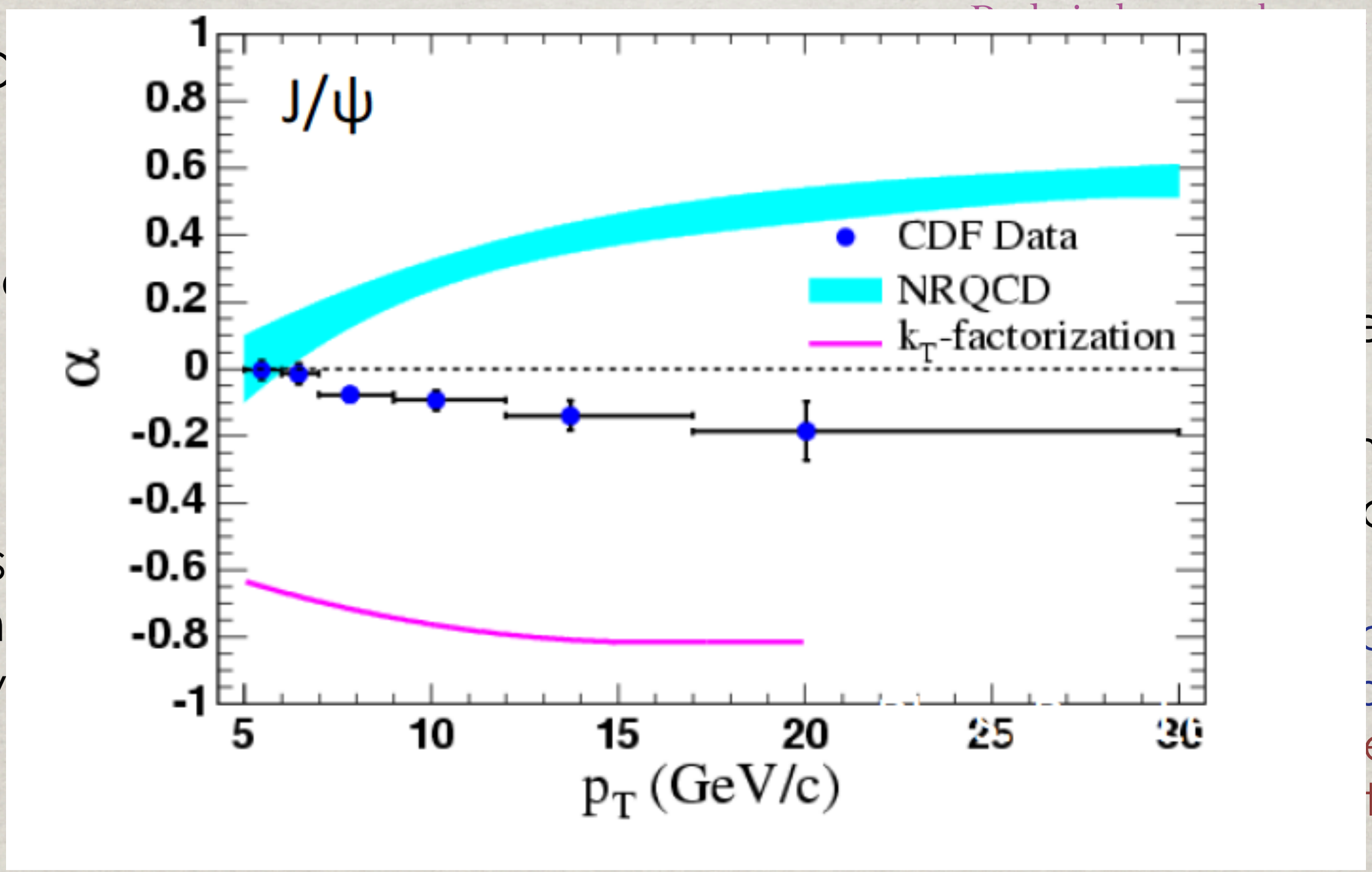

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Difficulties in explaining quarkonium polarization at Fermilab

Quarkonium production

Terrific progress in production in the last few years

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- Calculation of the differential singlet cross section at NLO and NNLO* — Gong, Wang 08 Artoisenet, Campbell,Lansberg, Maltoni, Tramontano 07
- Development of fragmentation function approach/ SCET approach — Qiu, Nayak, Sterman 050-014-S. Fleming et al 012-013
- 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
- Global fit of NRQCD color octet matrix elements at NLO — Kuang ta Chao et al 010, Butenschon Kniehl 011-015 Kuang ta Chao et al 011-015,
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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

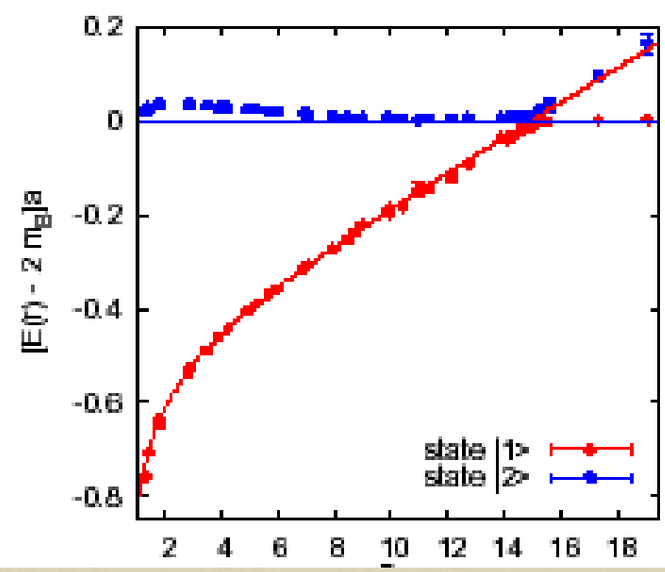
Coupled channels

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

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

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

Steps towards a lattice based approach have been undertaken



- SESAM PRD 71(05)114513

States near or above threshold:"exotics" !

hybrids, molecular states, tetraquarks

No systematic treatment is available; lattice calculations are inadequate

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

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

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Pakvasa Suzuki 03, Voloshin 03, Braaten Kusunoki 03 Braaten Hammer 06

Another example is the hybrids treatment in pNRQCD

M. Berwein, N. B., J. Tarrus, A. Vairo 014