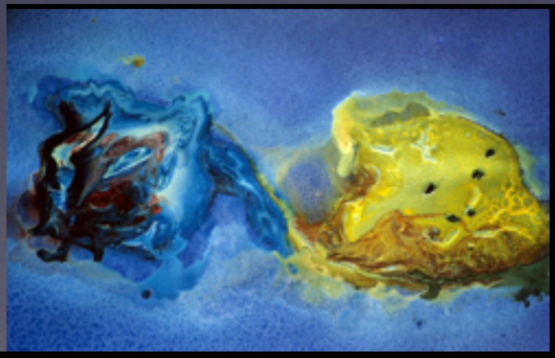
Quarkonium with Effective Field Theories

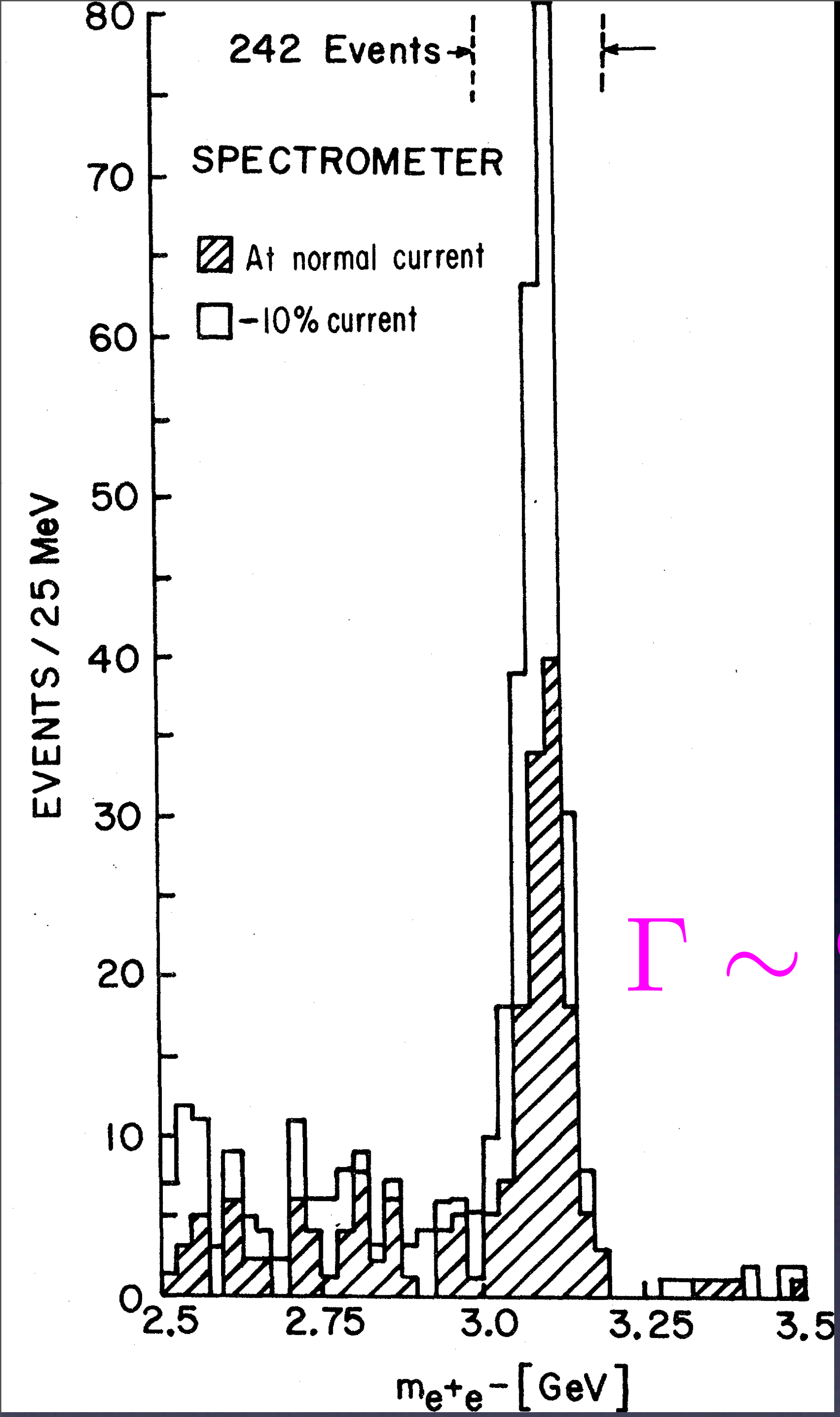
NORA BRAMBILLA



PHYSIK DEPARTMENT TUM
T30F

- the physics of quarkonium and its relevance
- the state of the art theory tools
- experimental challenges and opportunities

The November revolution in 1974: the J/ψ discovery



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

Aubert et al. BNL 74

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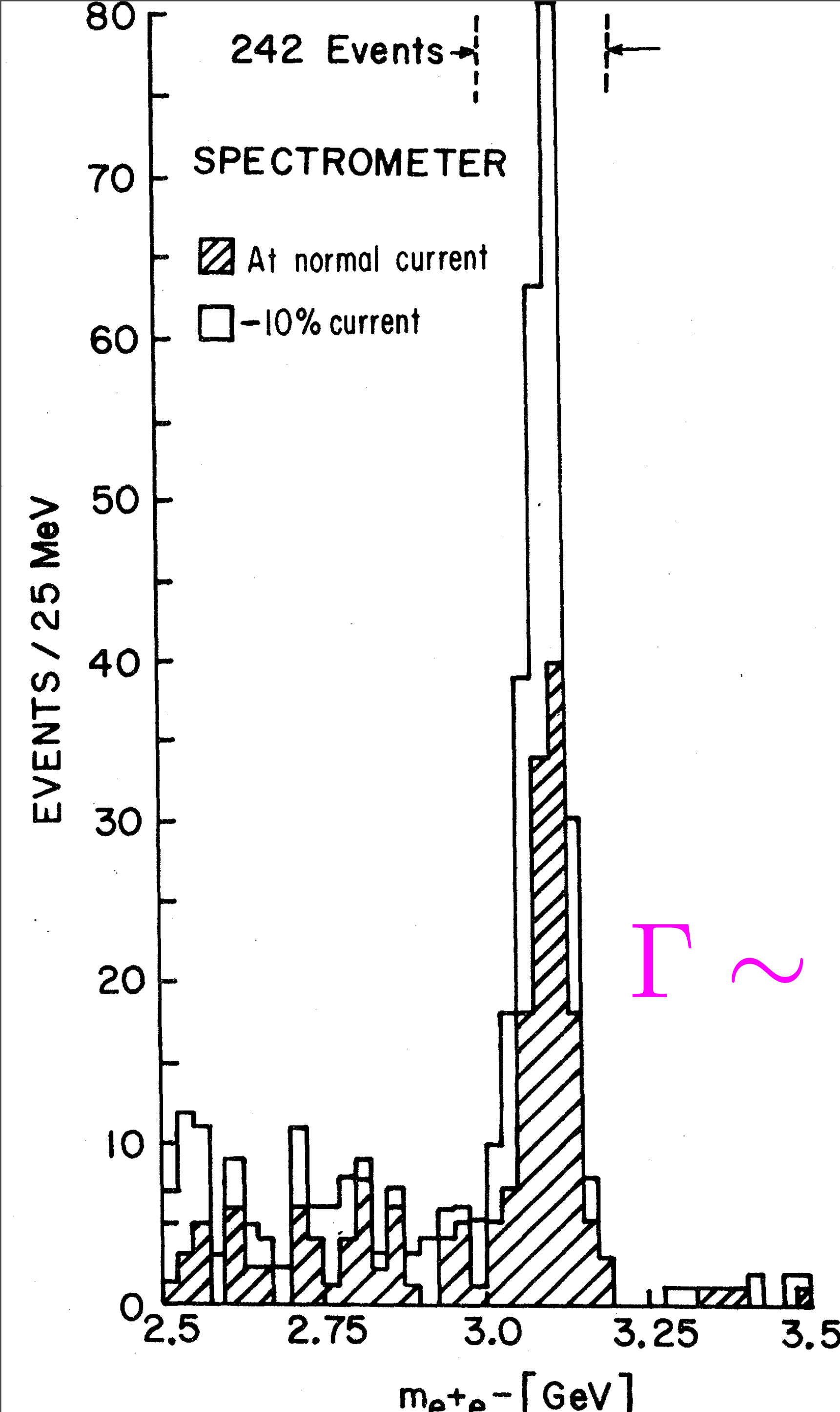

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Samuel Ting: "It is like to stumble on a village where people live 70000 years"

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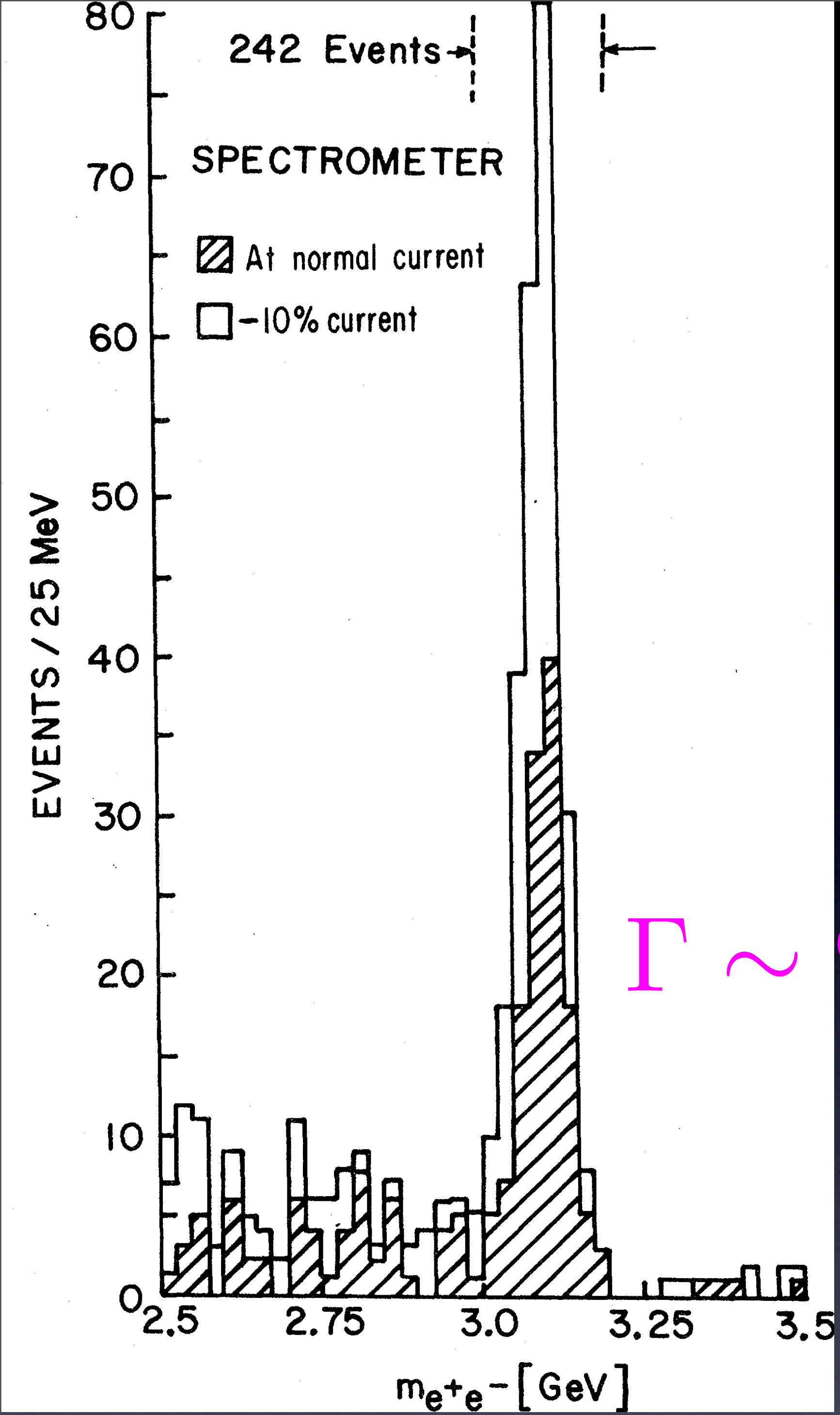

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Aubert et al. BNL 74

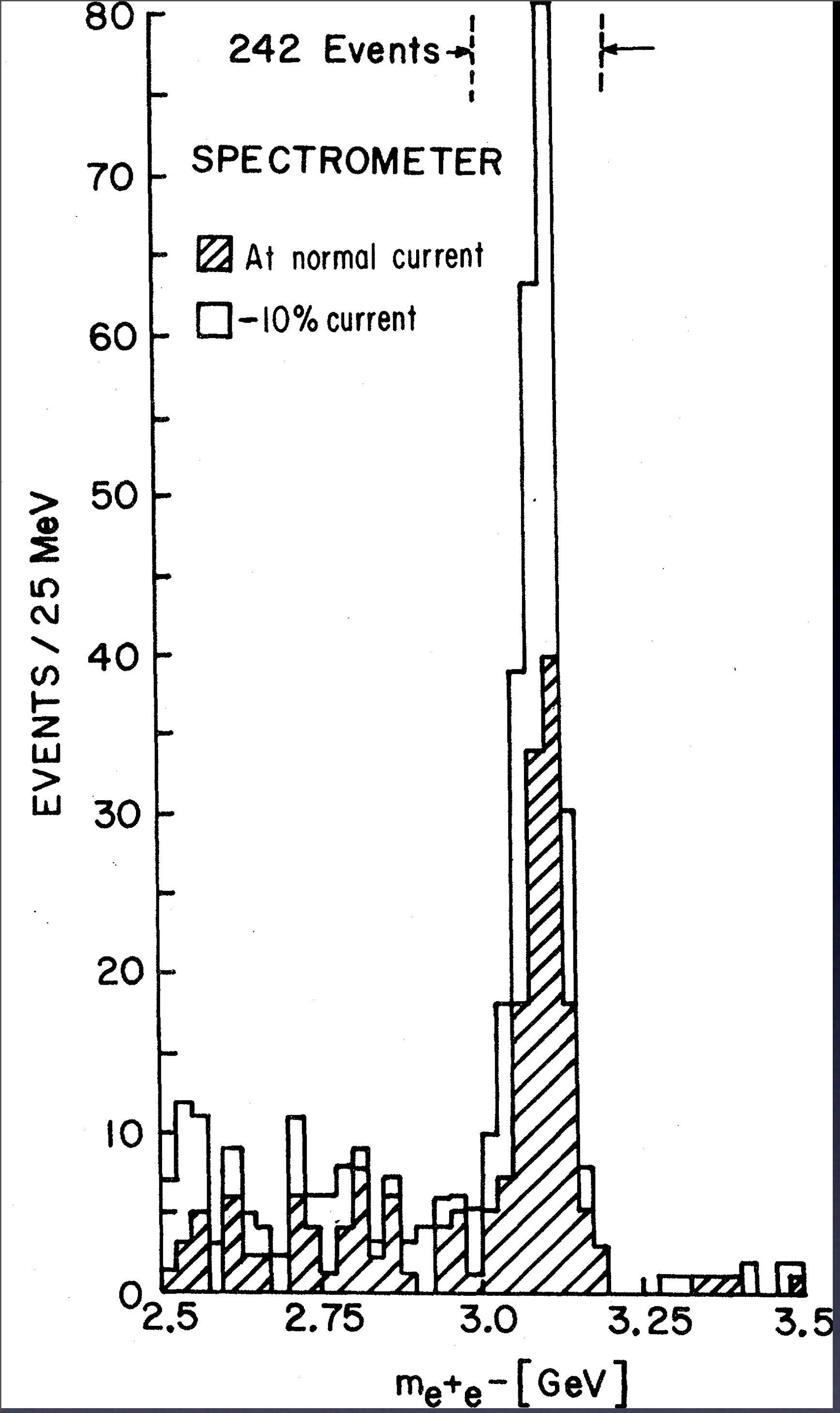
Samuel Ting: "It is like to stumble on a village where people live 70000 years"

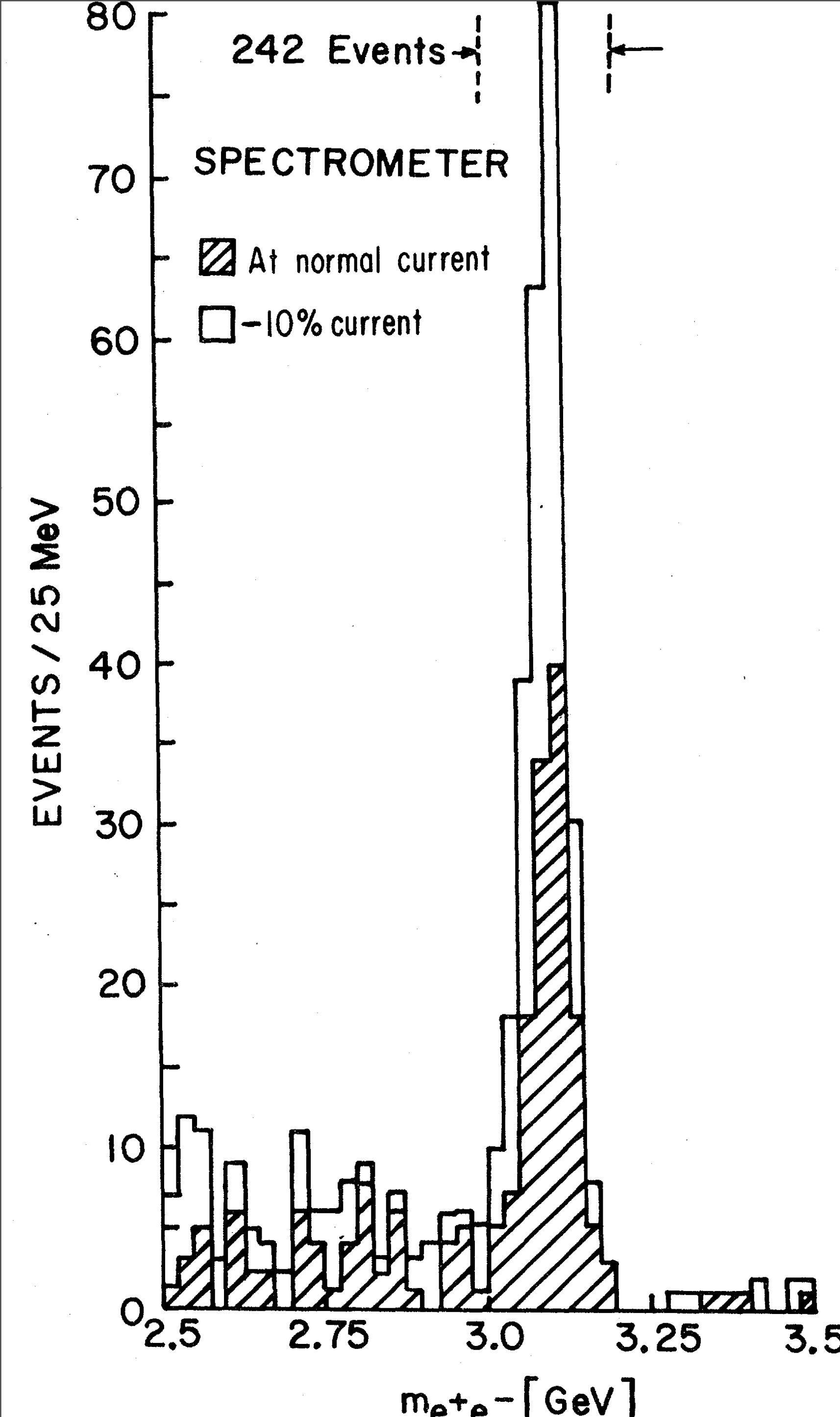
it has been the confirmation of the charm quark prediction and the foundation of QCD

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





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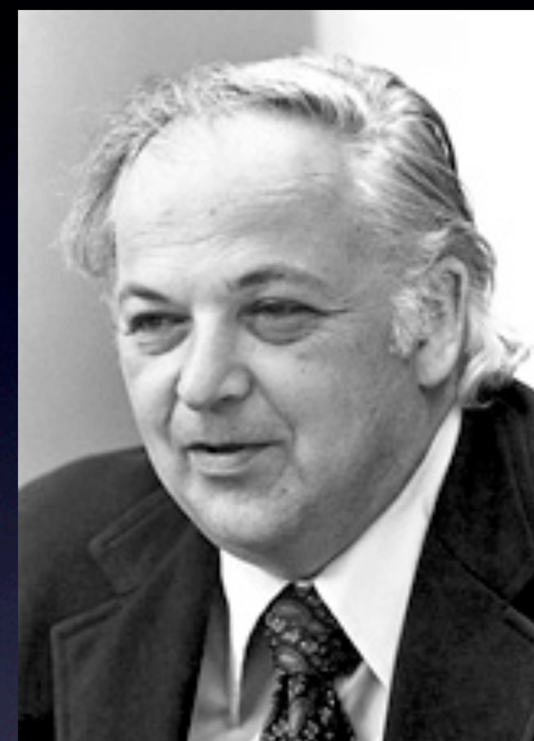
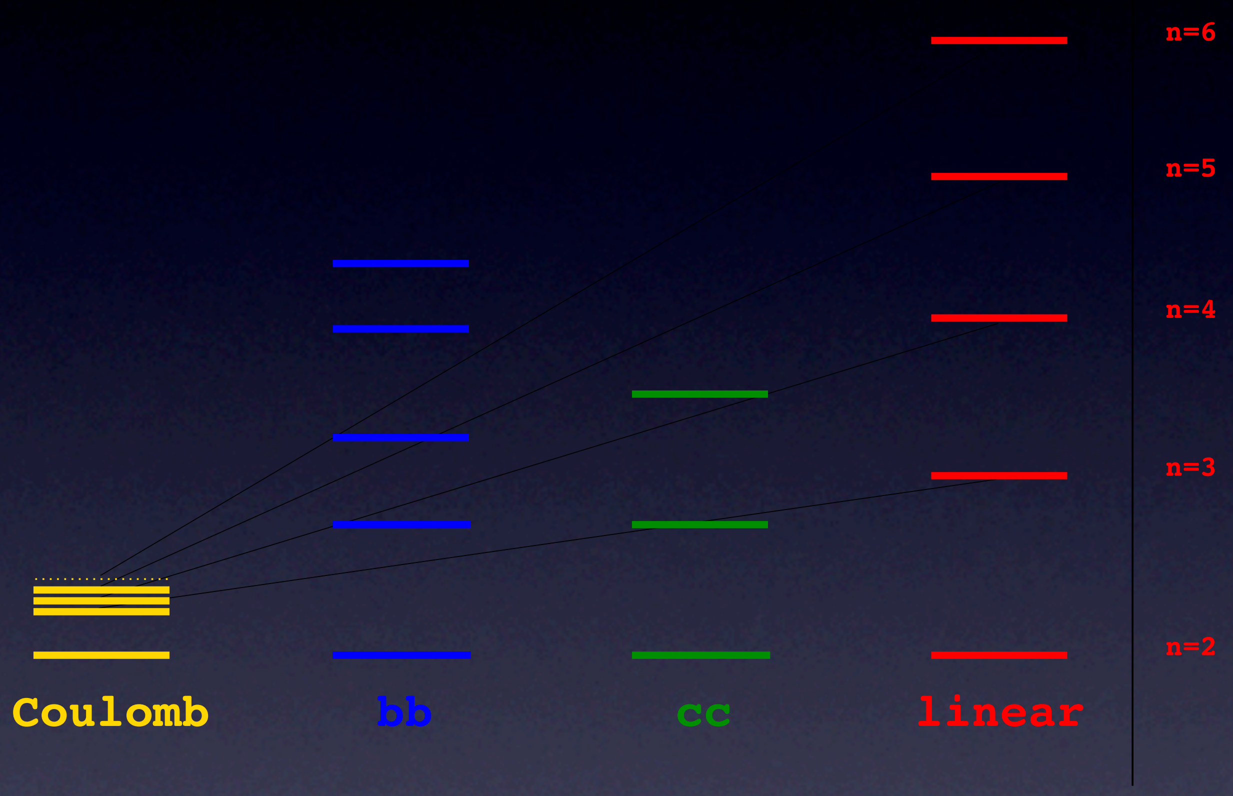


The Nobel Prize in Physics 1976 was awarded jointly to Burton Richter and Samuel Chao Chung Ting "for their pioneering work in the discovery of a heavy elementary particle of a new kind"

The November revolution in the '70s: more quarkonia



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

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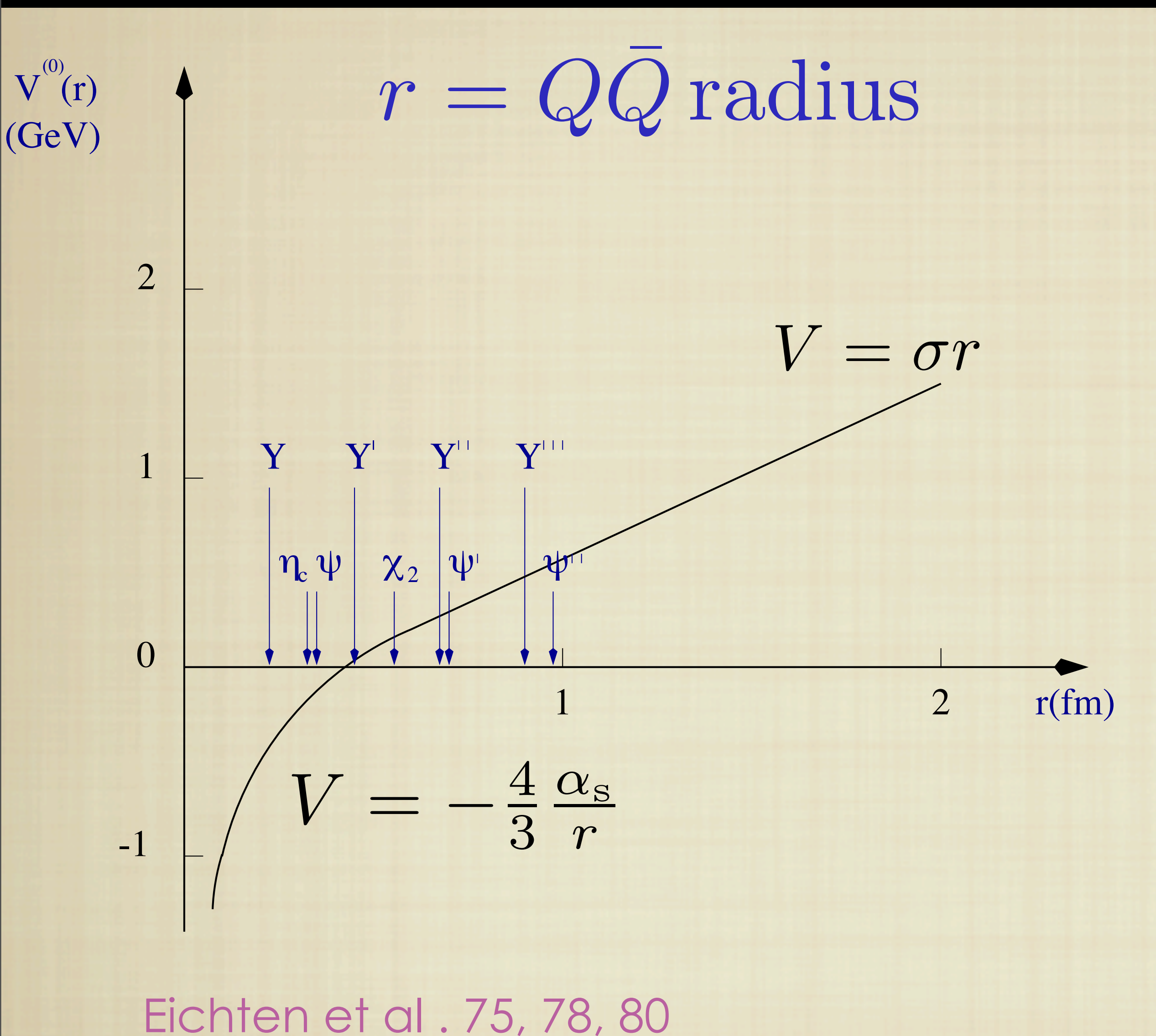

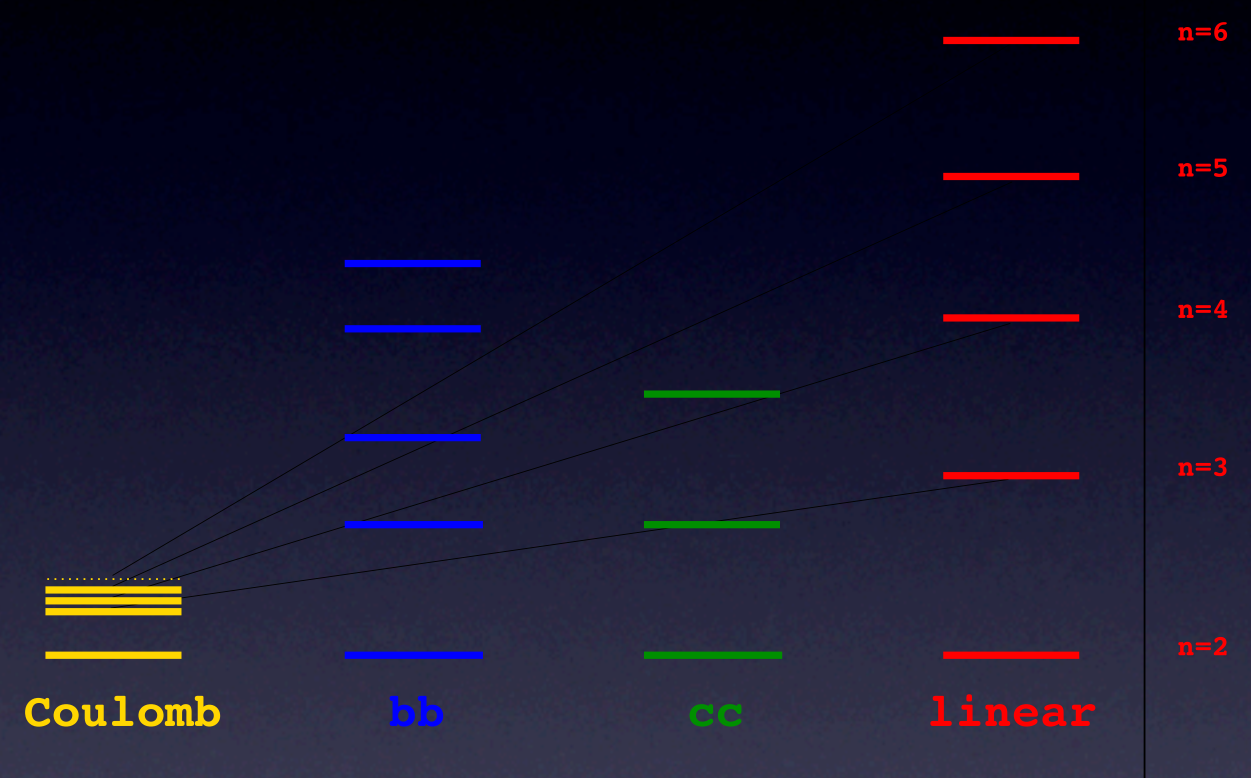

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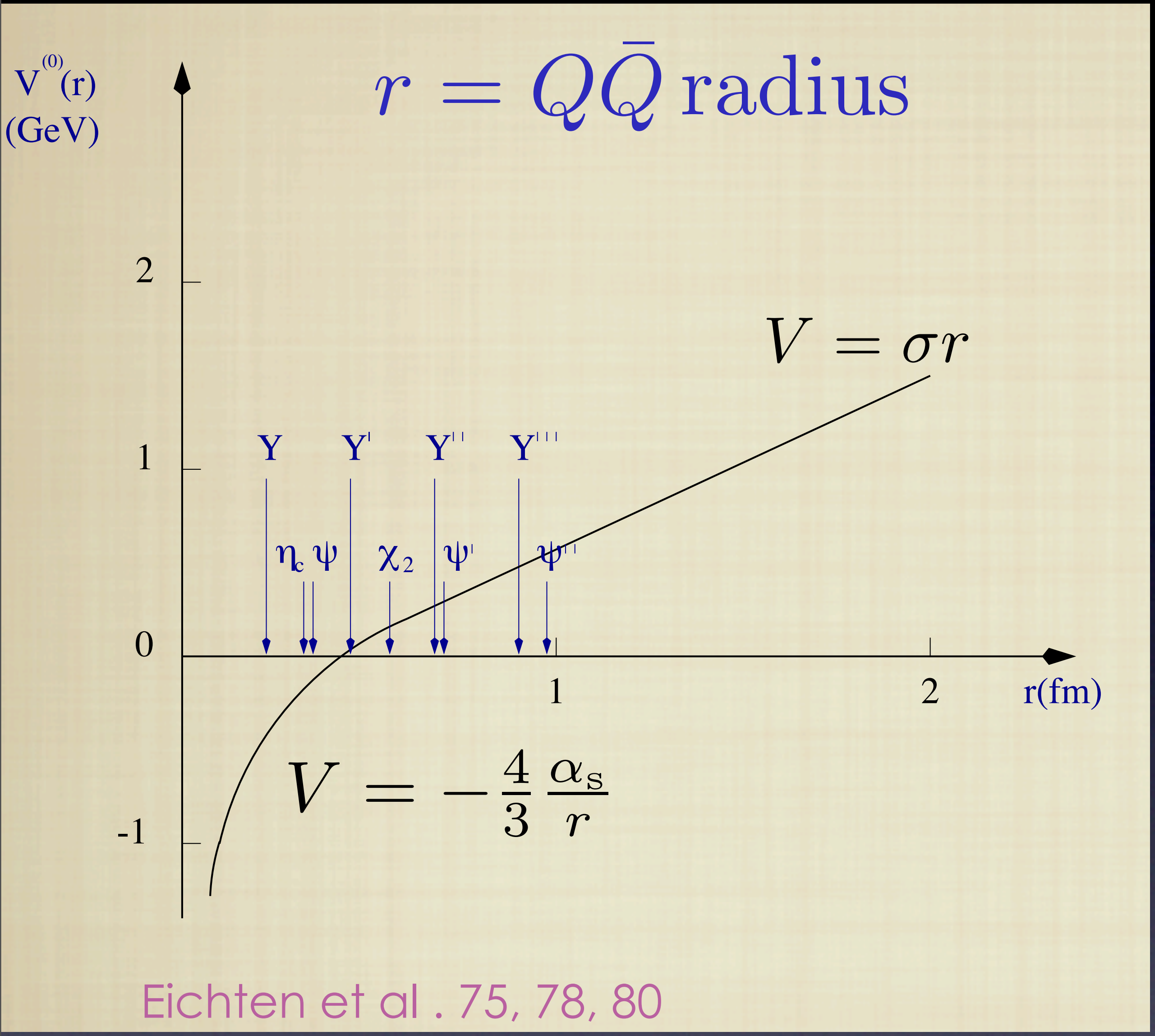
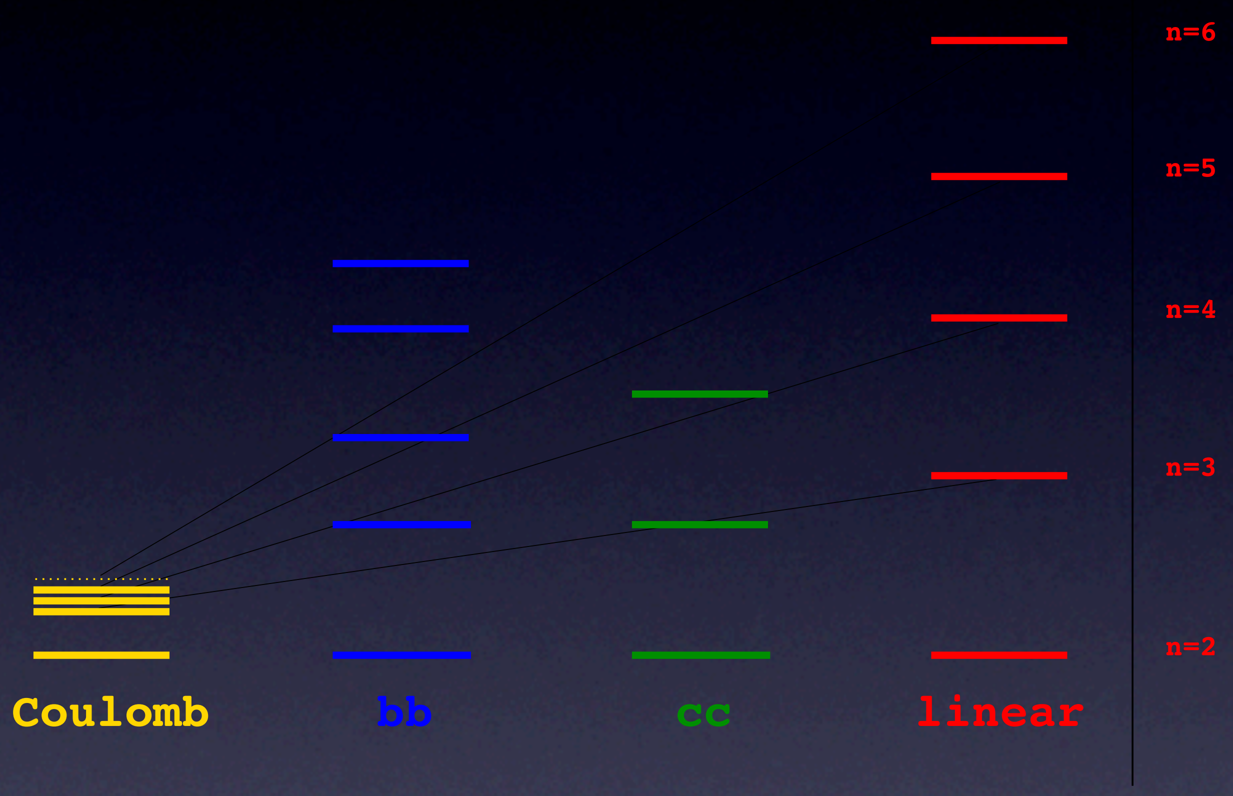




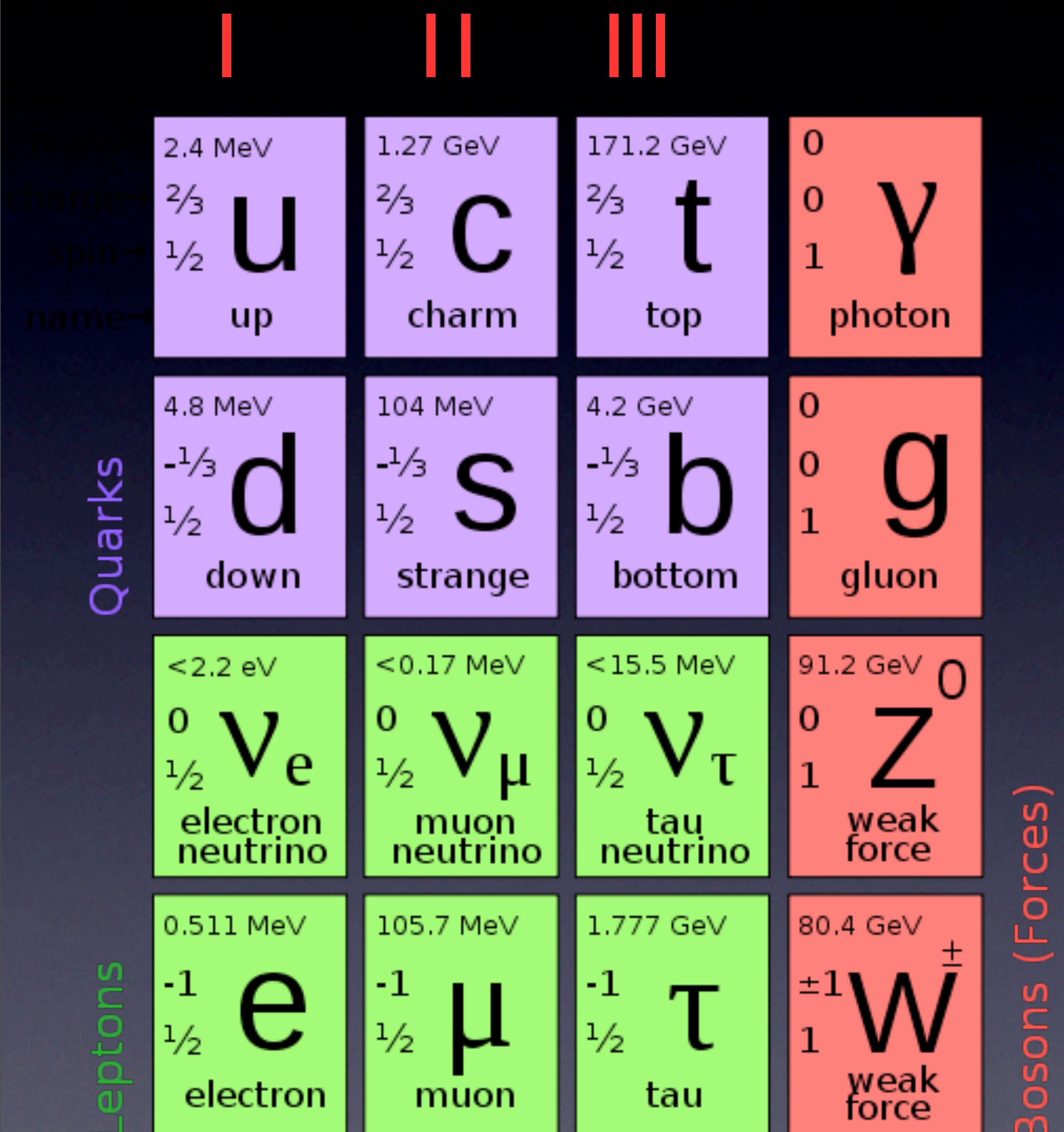
bbar and ccbar energy levels in comparison to
Coulomb and linear potential energy levels

Variety of potential models used

Confinement and asymptotic freedom--> QCD

our present knowledge of particle physics is in

Standard model of Particle Physics



+ the Higgs boson

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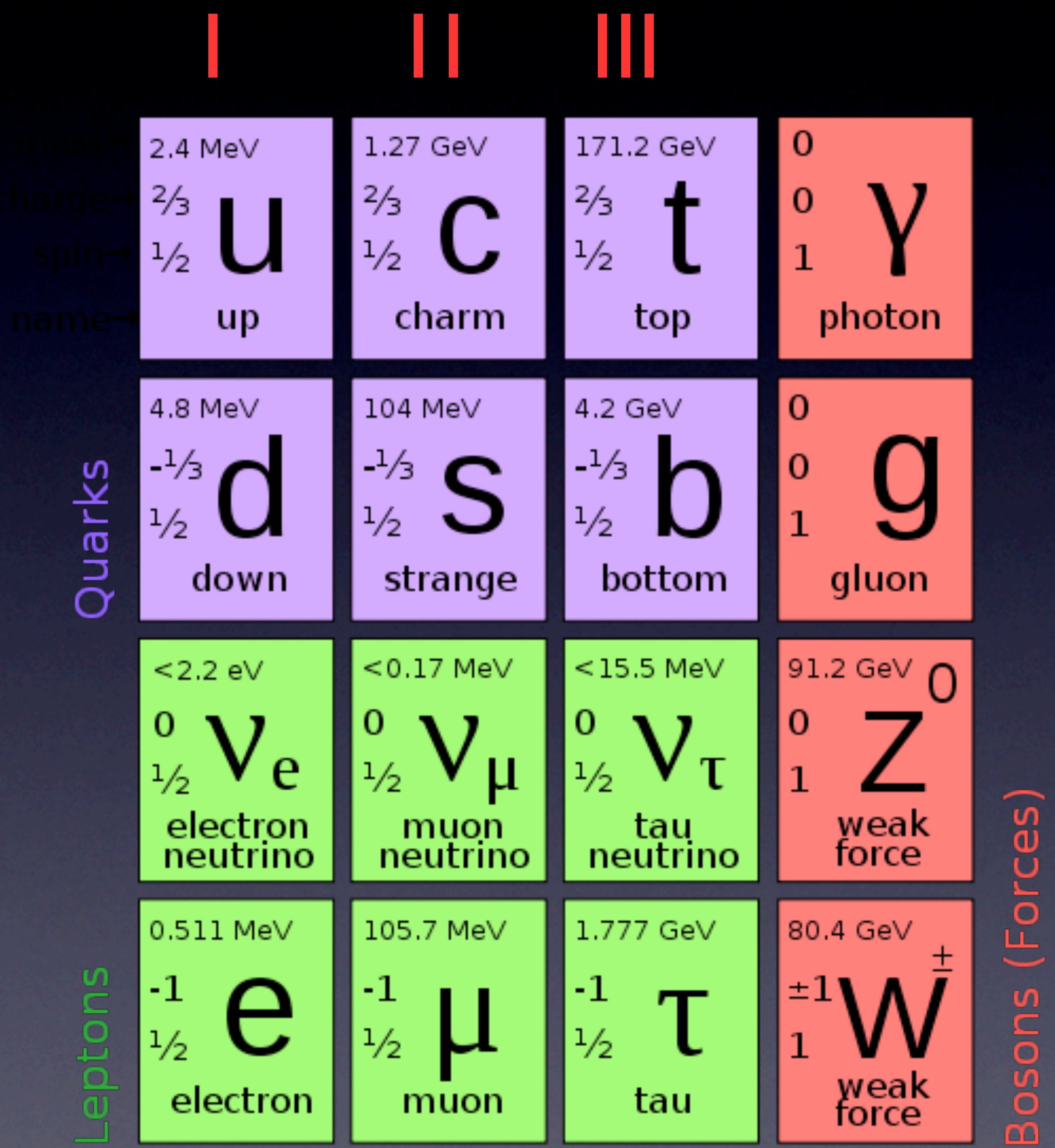
A quantum field theory based on the gauge principle tested up to the Tev= 10^{12}eV and up to 10^{-19}m



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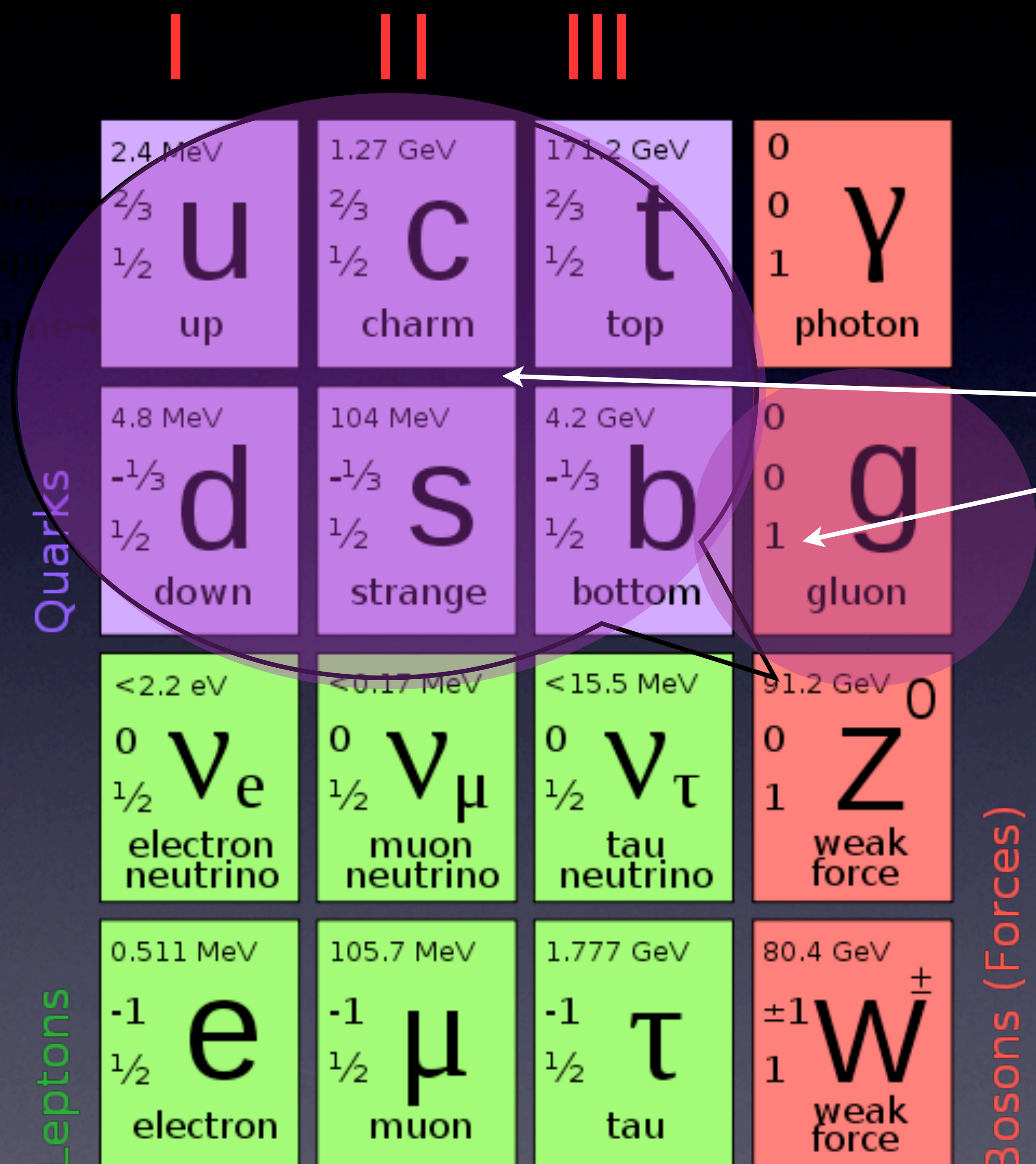

QCD

+ the Higgs boson

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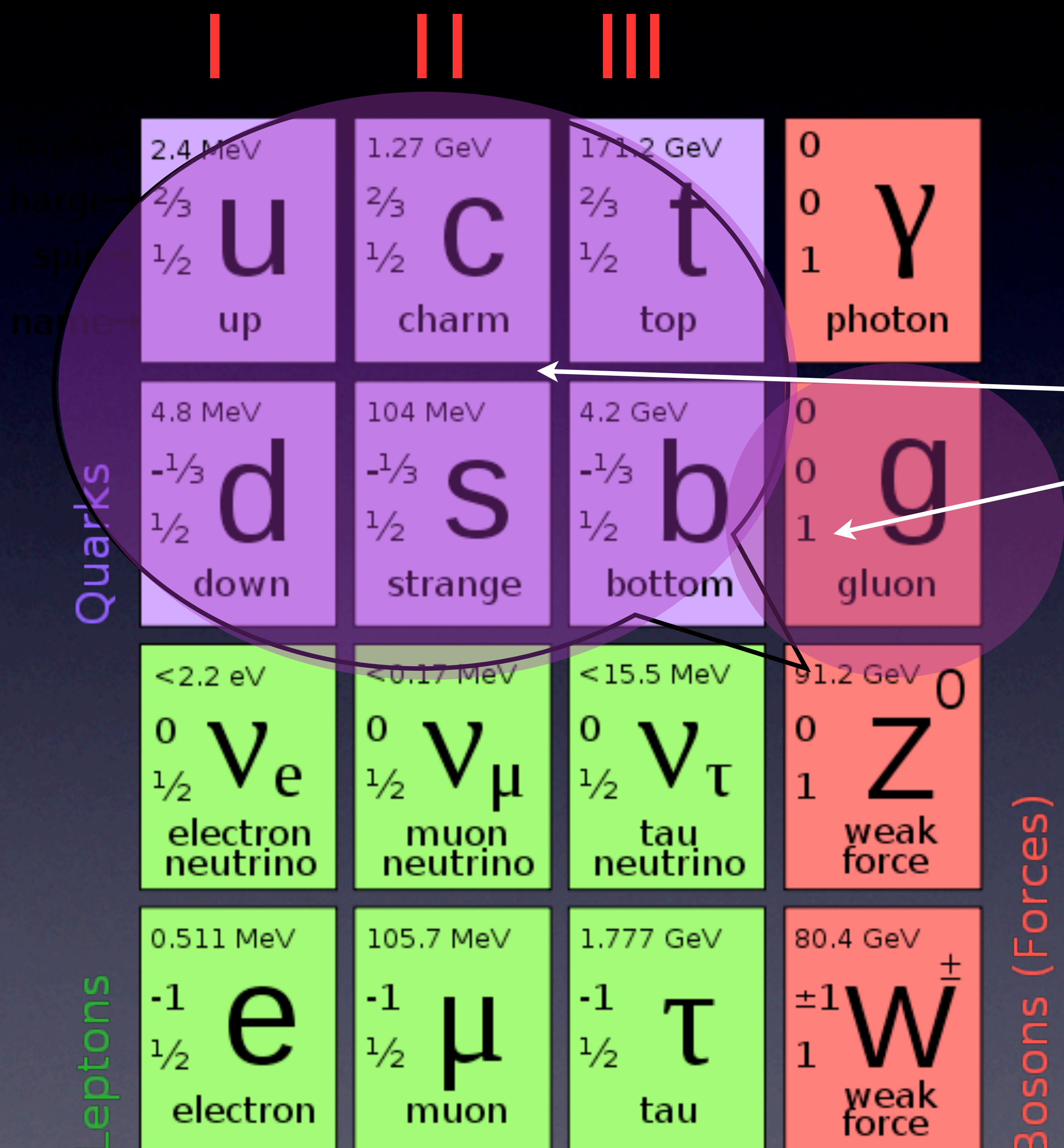

QCD

+ the Higgs boson

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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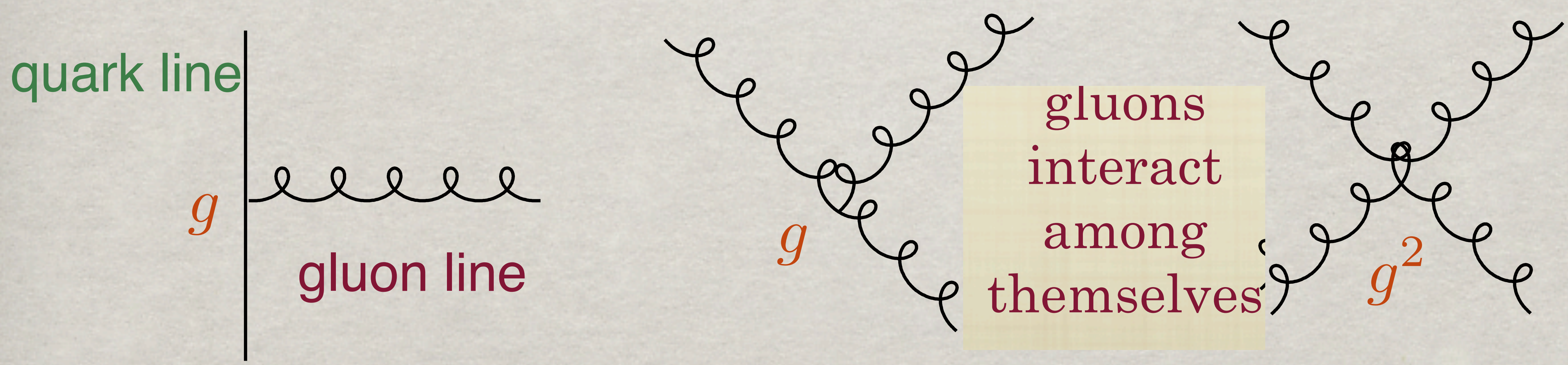
Quark field

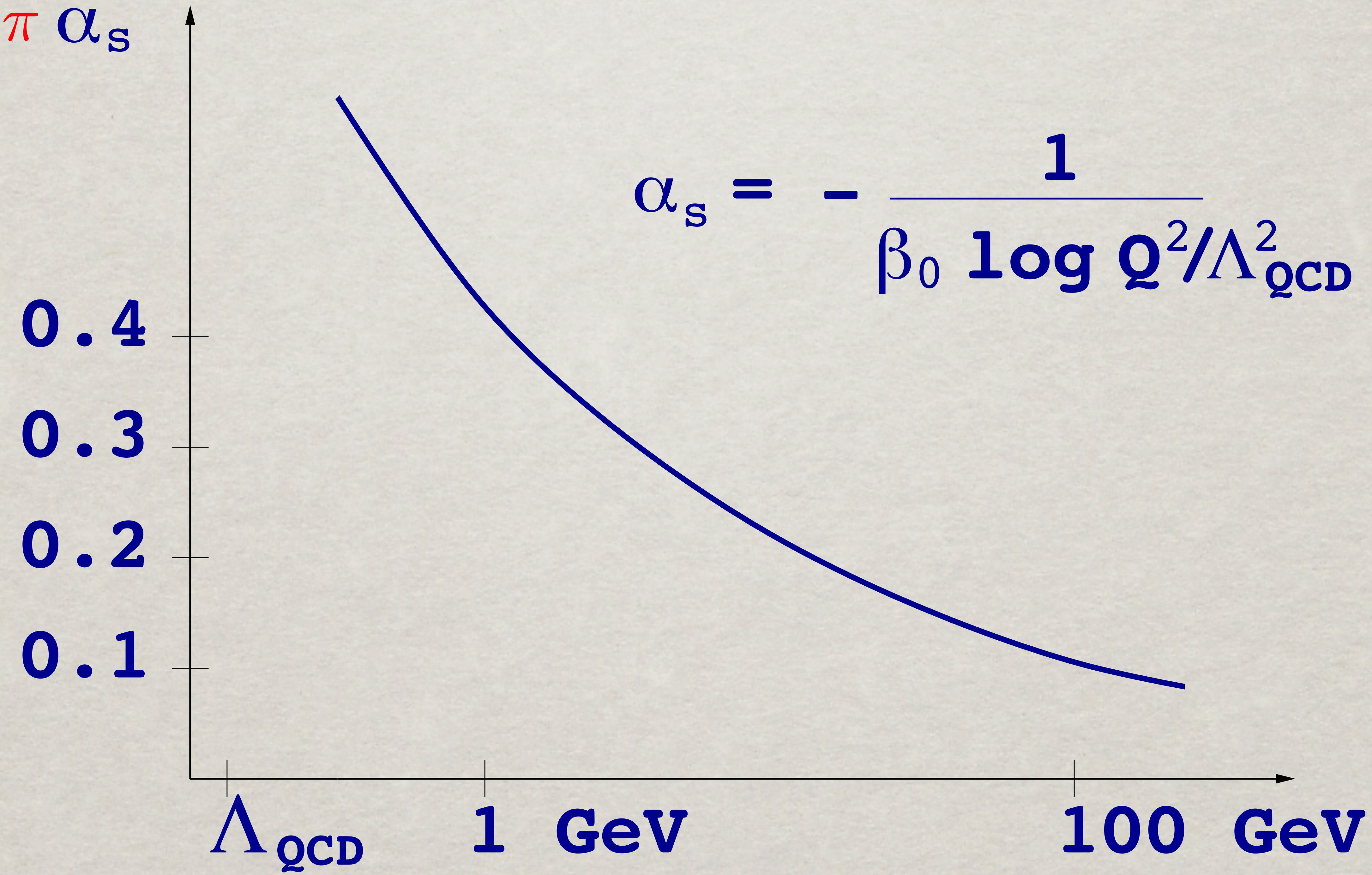
Interaction vertices



QCD

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

$$\alpha_s = \frac{g^2}{4\pi}$$



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

QCD

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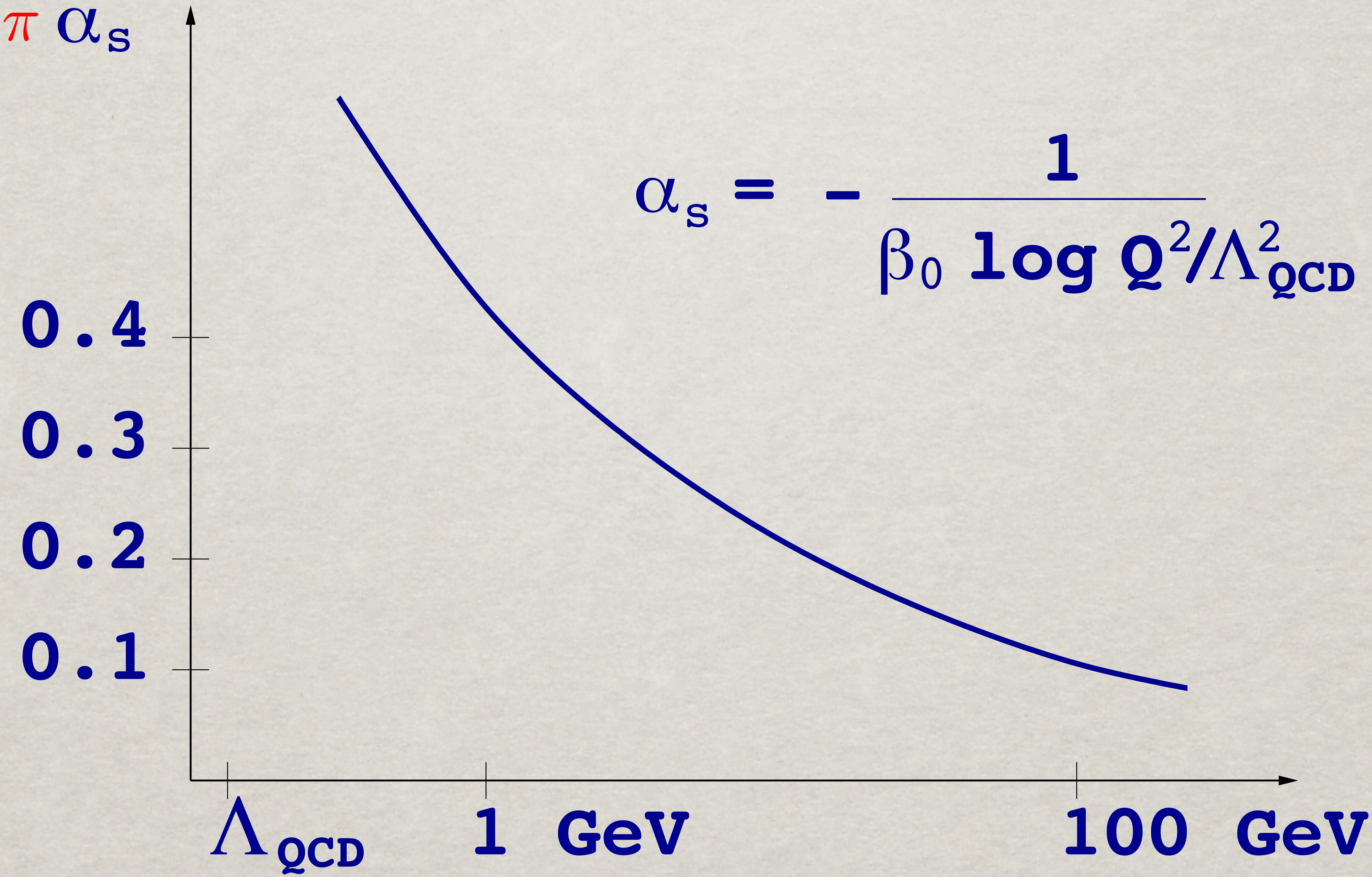

Λ_{QCD} is the scale where nonperturbative effects dominate

QCD

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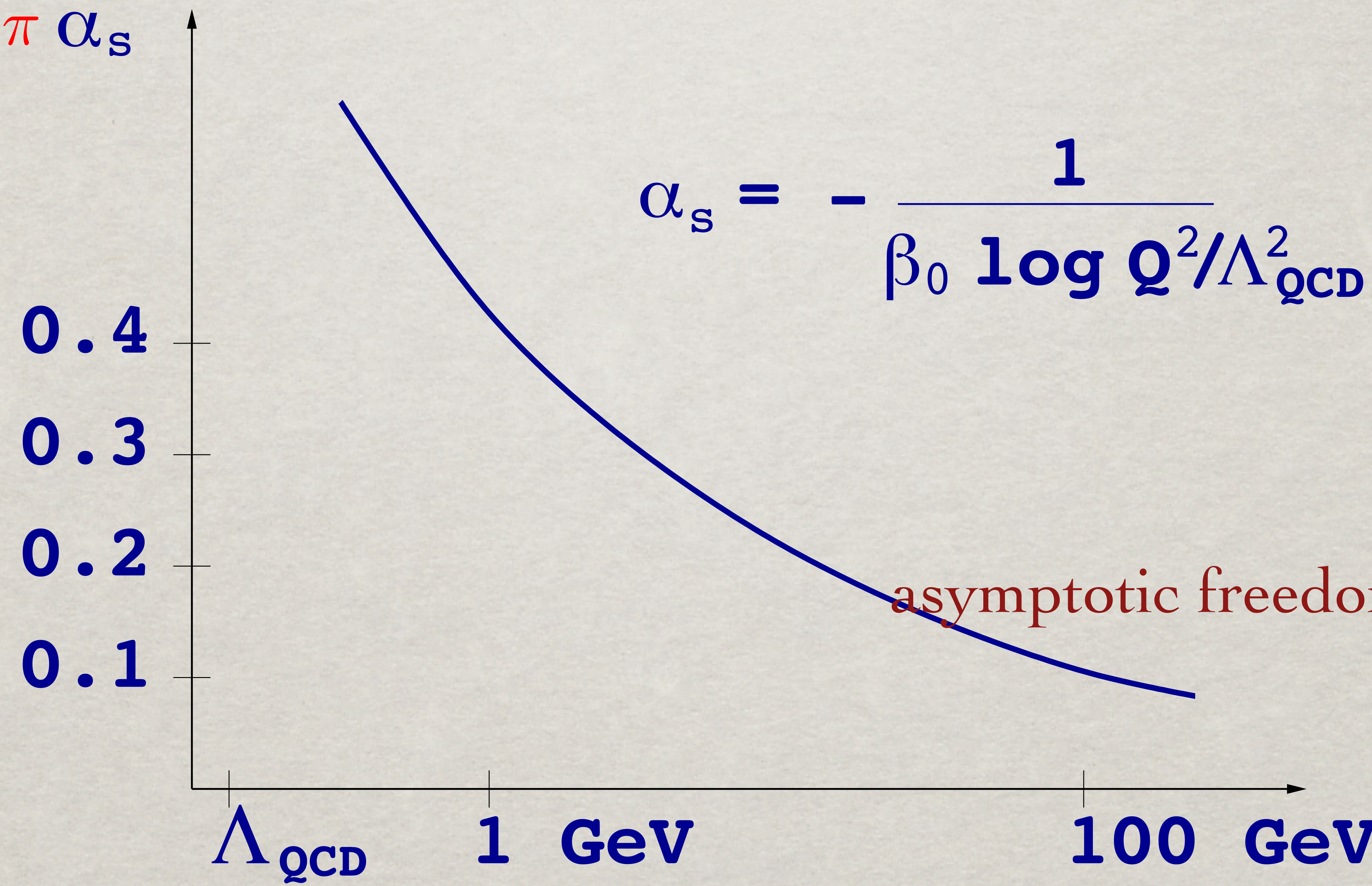

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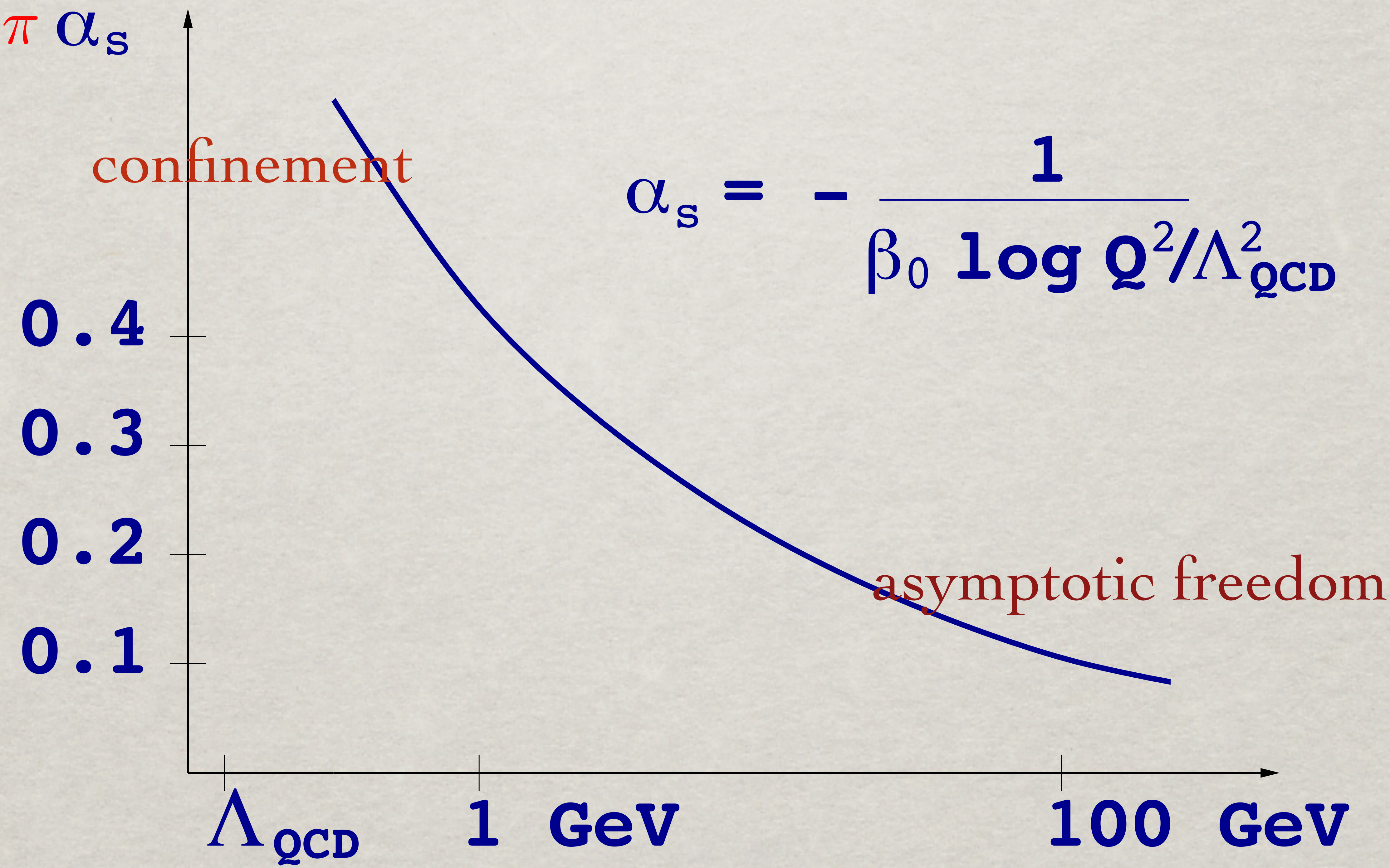

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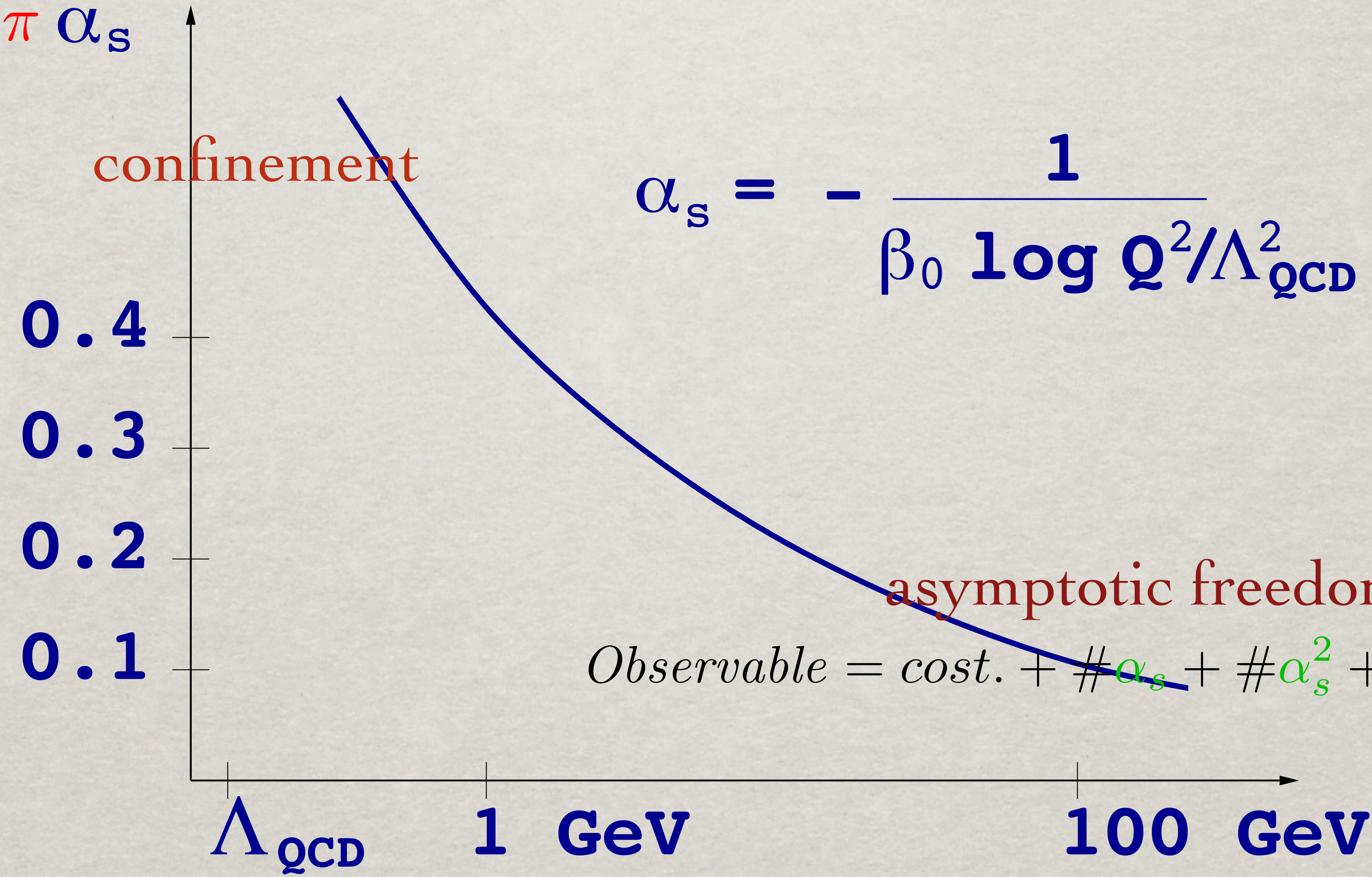

$$Observable = cost. + \#\alpha_s + \#\alpha_s^2 + \ldots +$$

$\Lambda_{\rm QCD}$ is the scale where nonperturbative effects dominate

QCD

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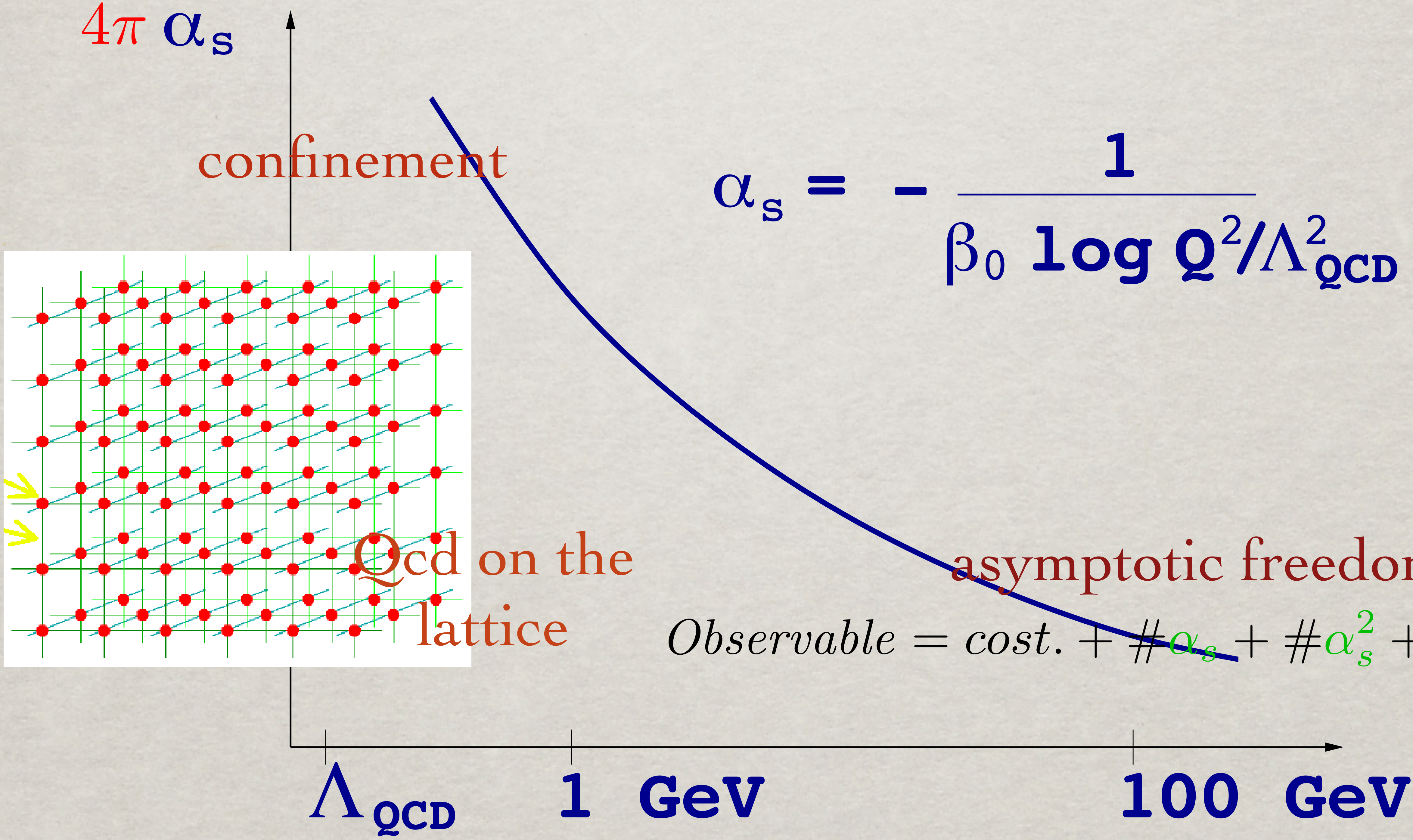


Λ_{QCD} is the scale where nonperturbative effects dominate

QCD contains a lot of physics : hadron masses

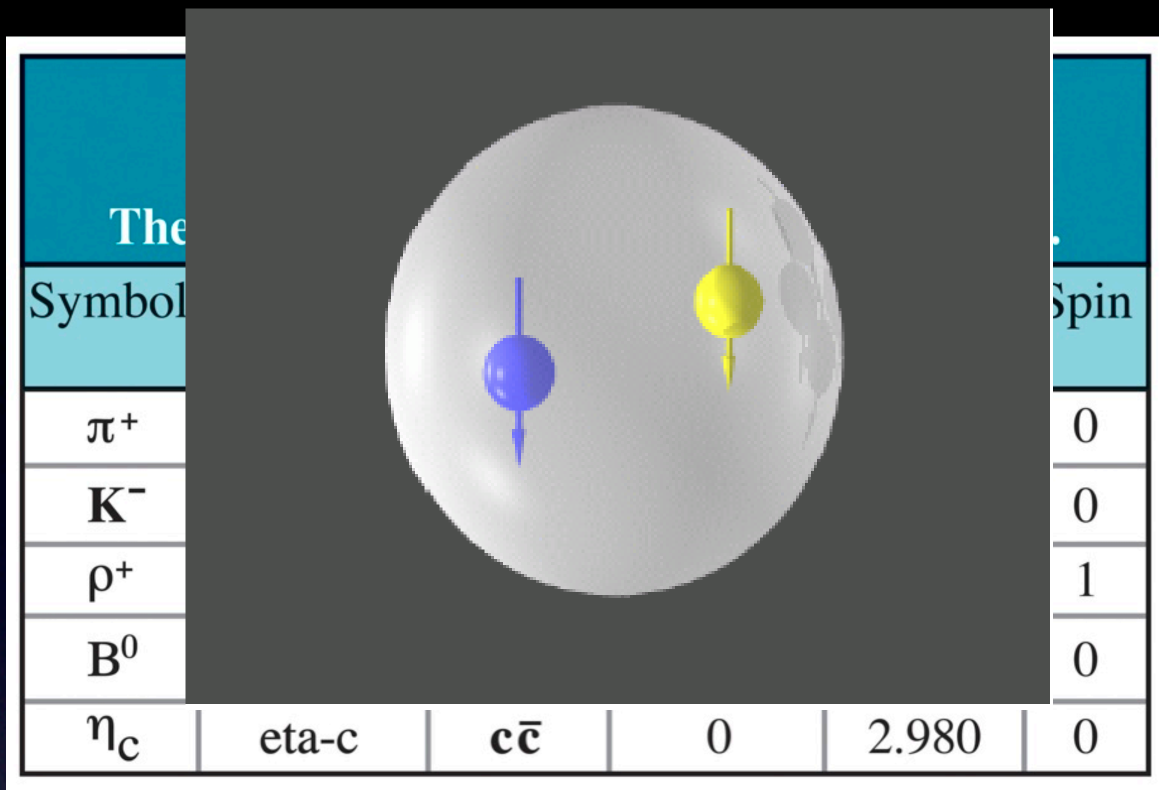
Mesons $q\bar{q}$
Mesons are bosonic hadrons
These are a few of the many types of mesons.

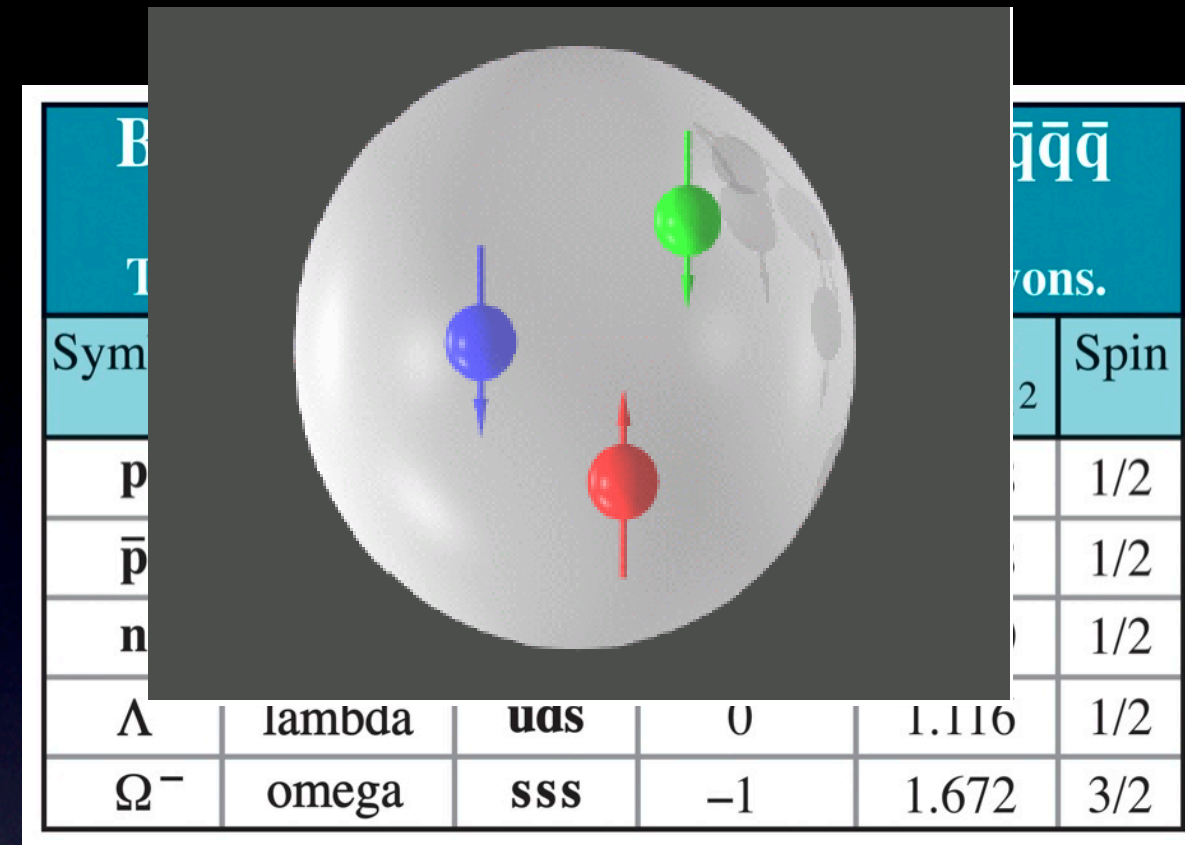
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.776	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2.980	0

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





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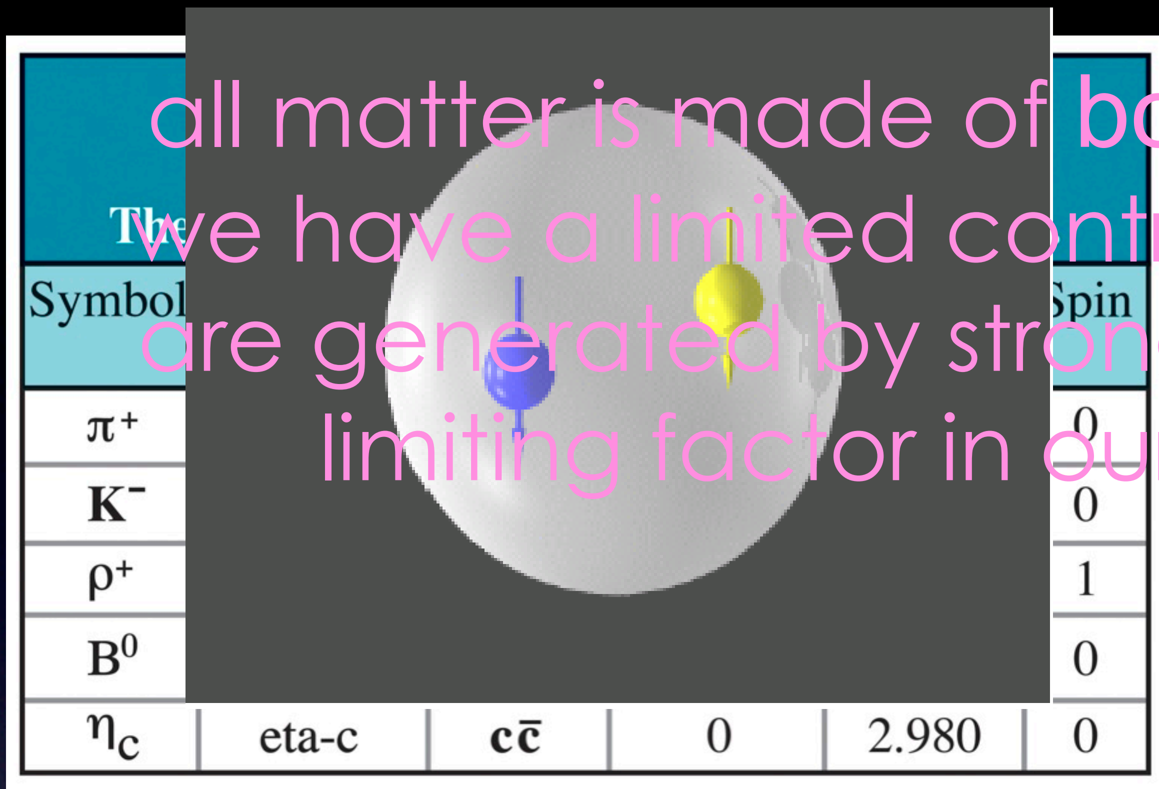
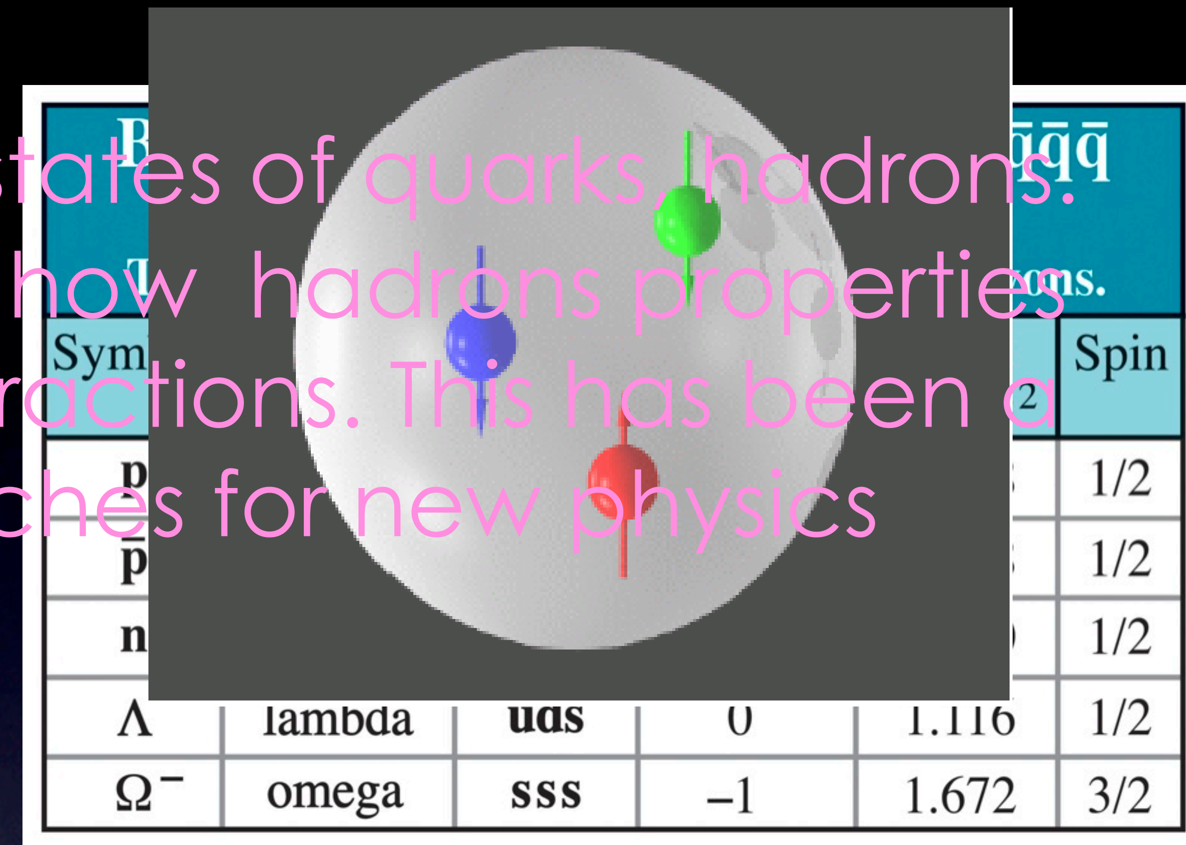
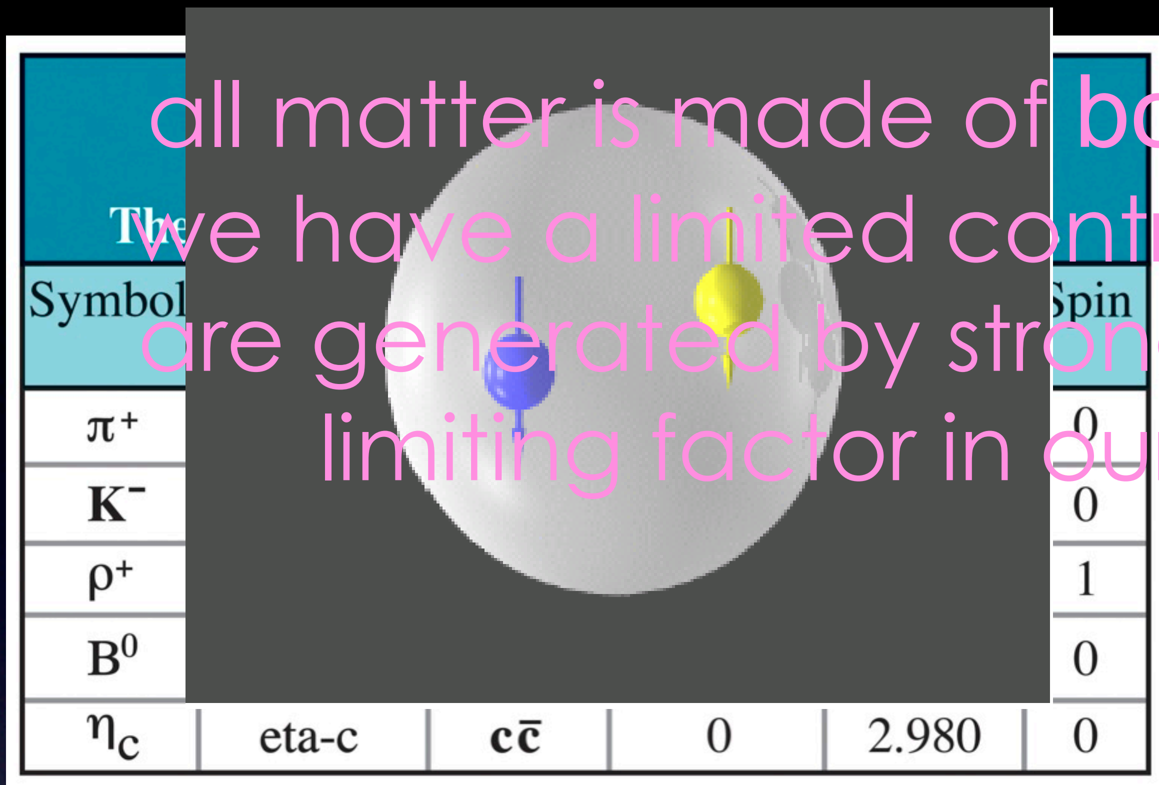
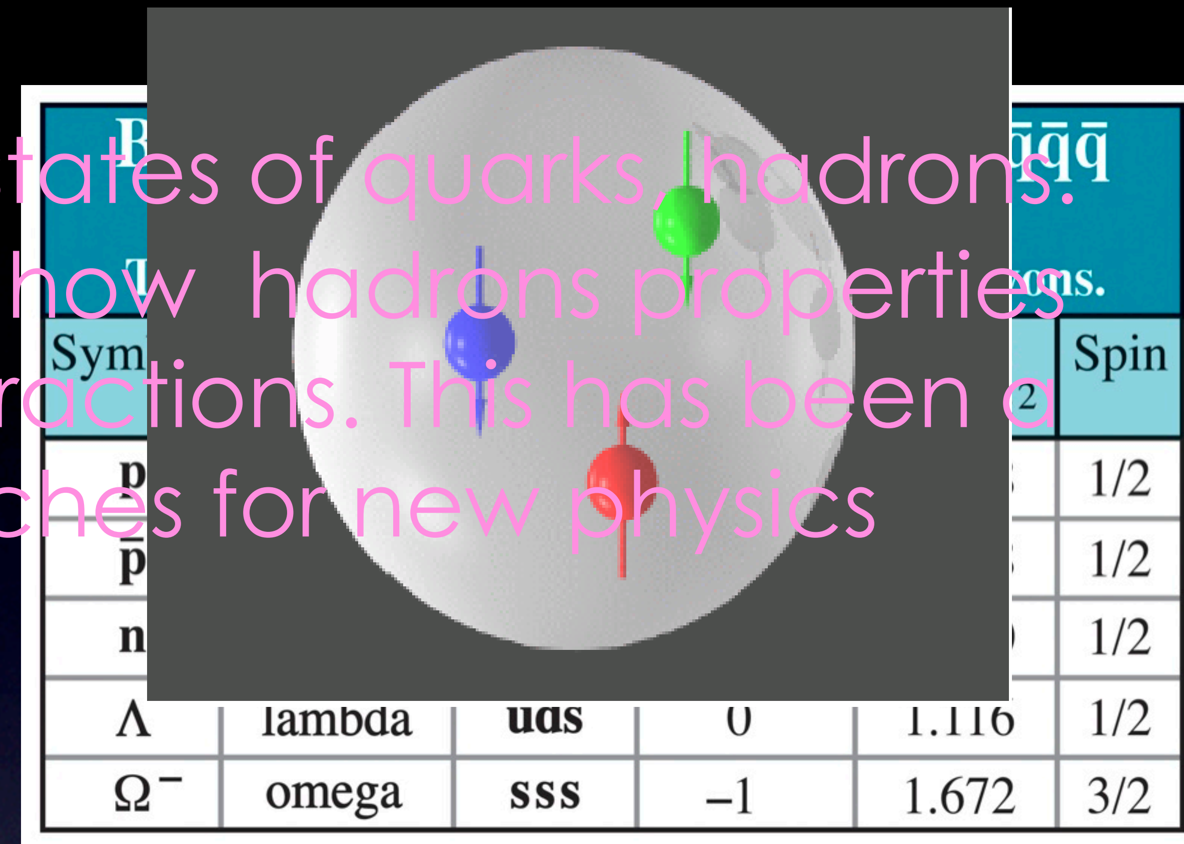




all matter is made of **bound** states of quarks, hadrons.
we have a limited control on how hadrons properties are generated by strong interactions. This has been a limiting factor in our searches for new physics

QCD contains a lot of physics : hadron masses





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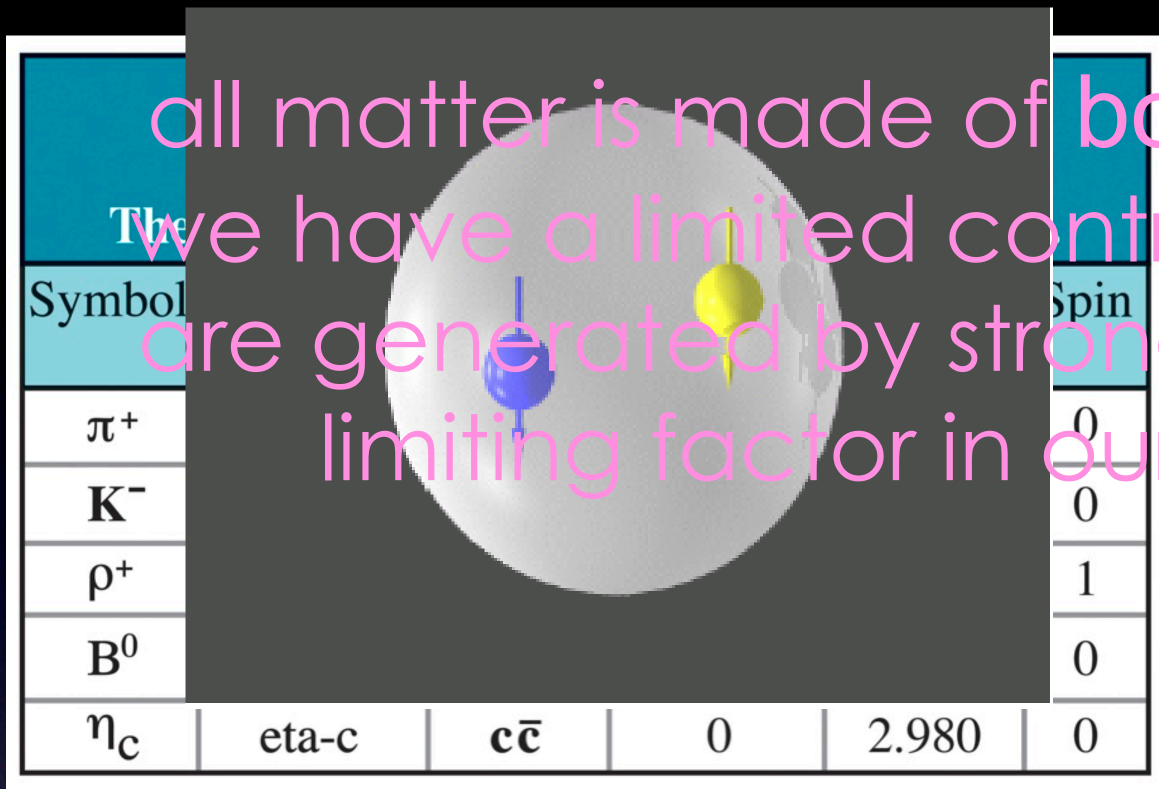
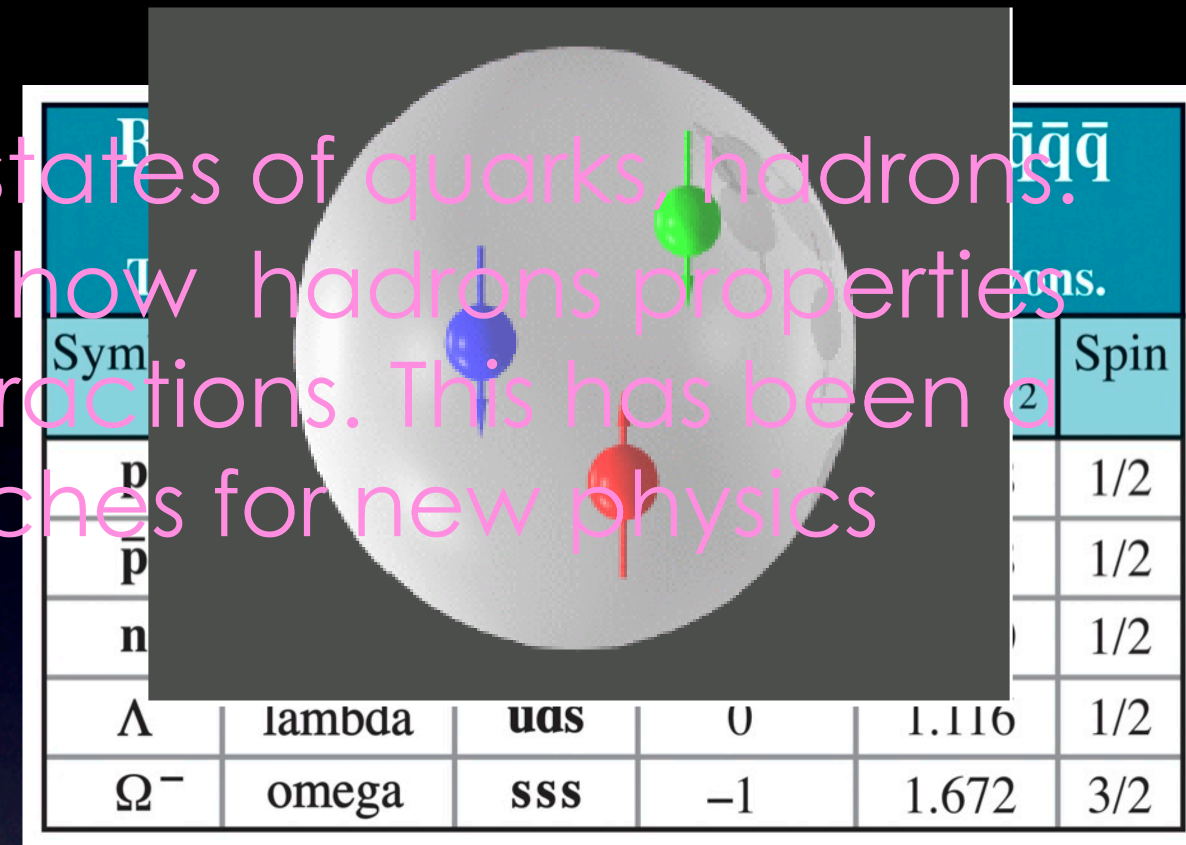
it is at the origin of all "observable" matter

QCD contains a lot of physics : hadron masses





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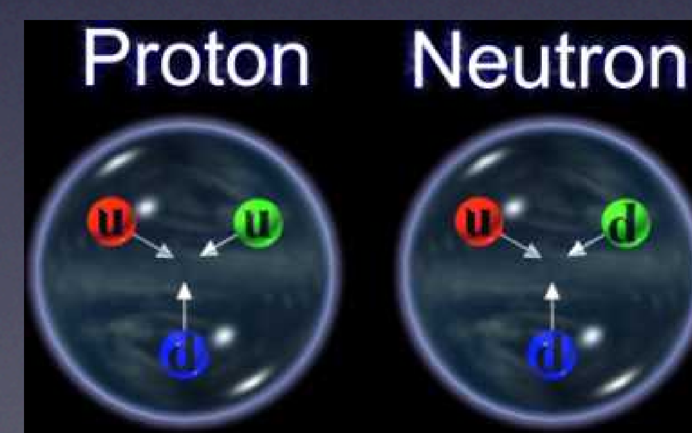
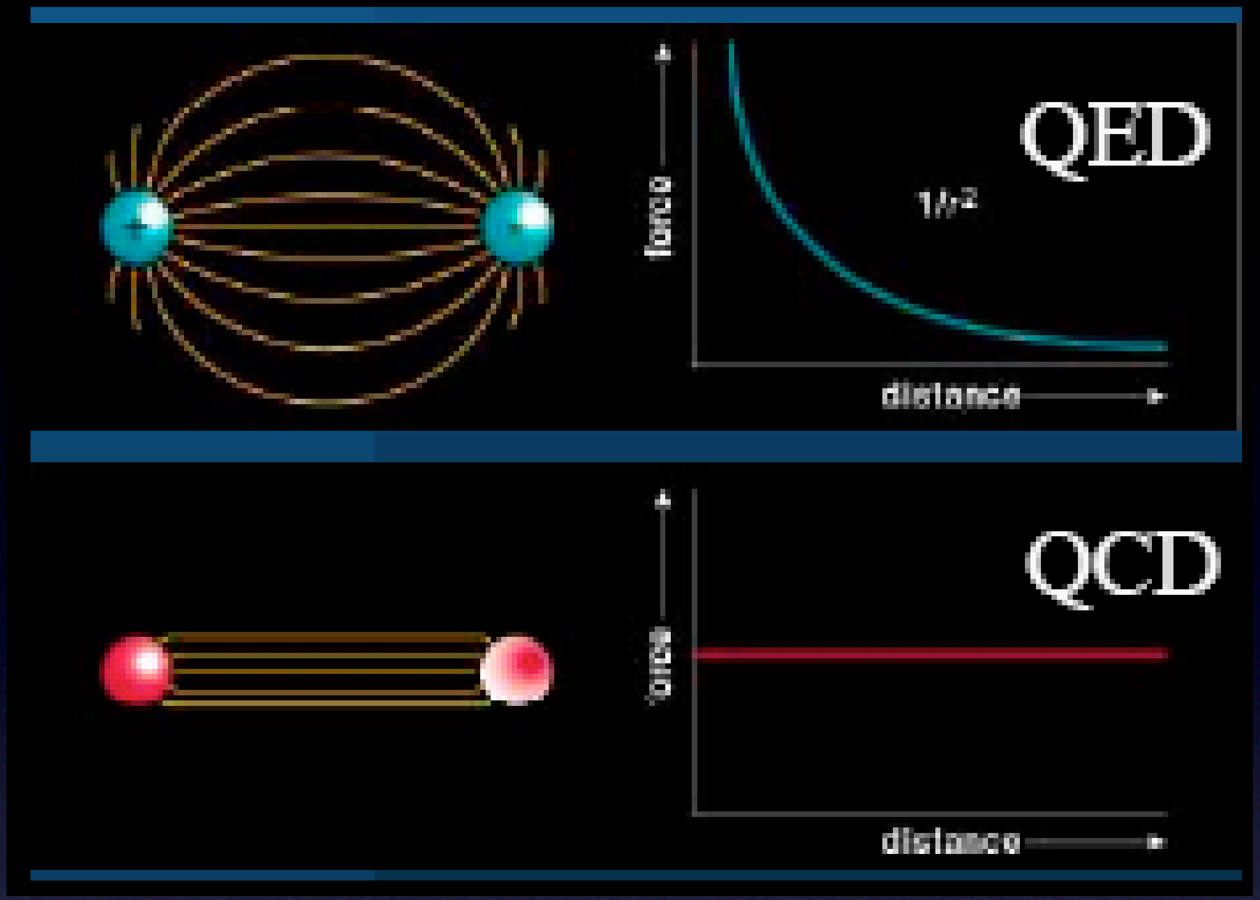
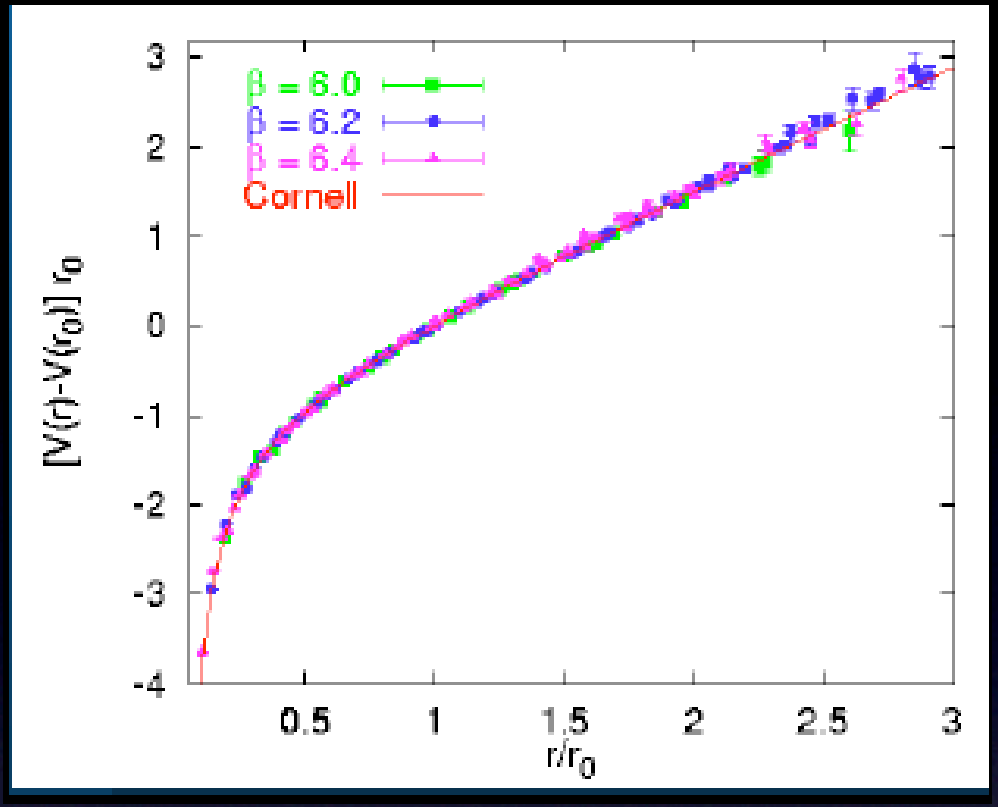
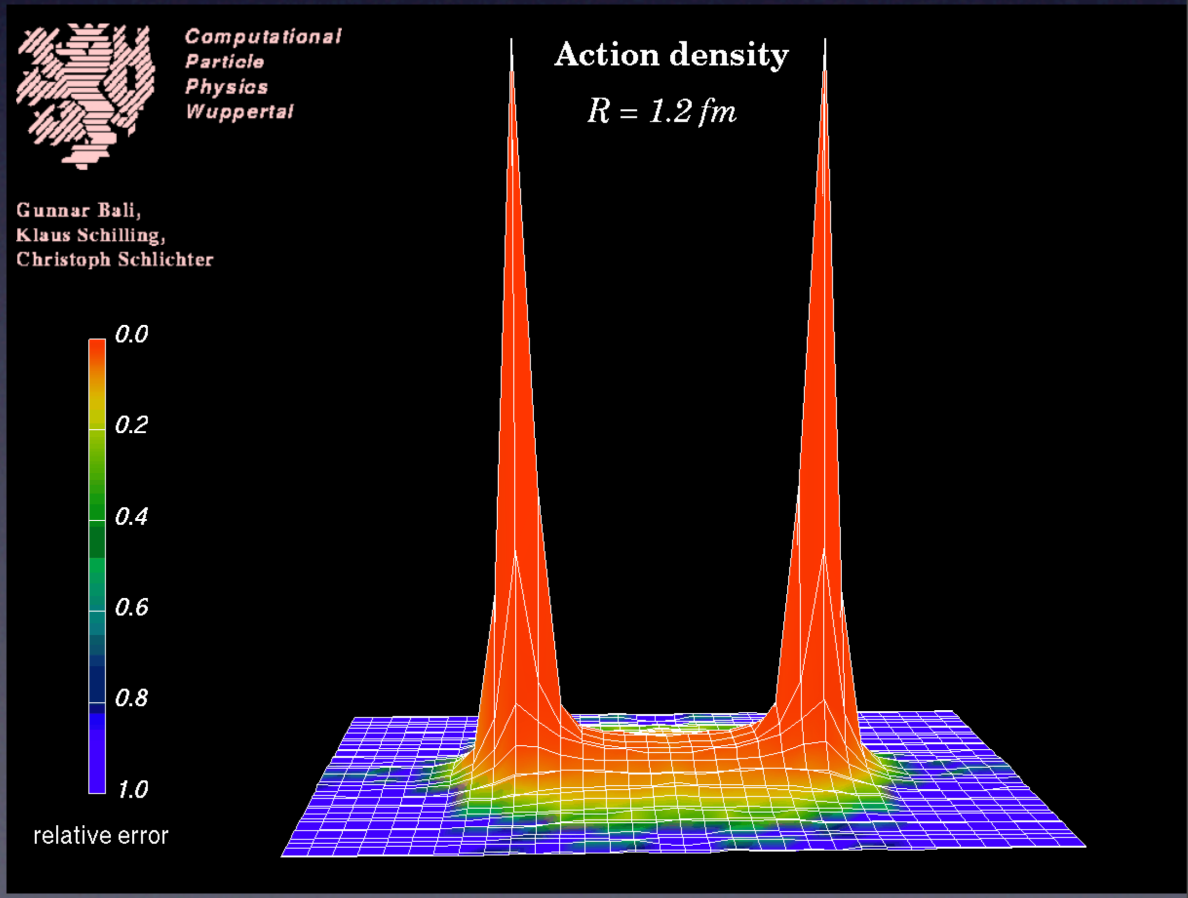


$$M \sim \Lambda_{QCD}$$

QCD contains a lot of physics : confinement







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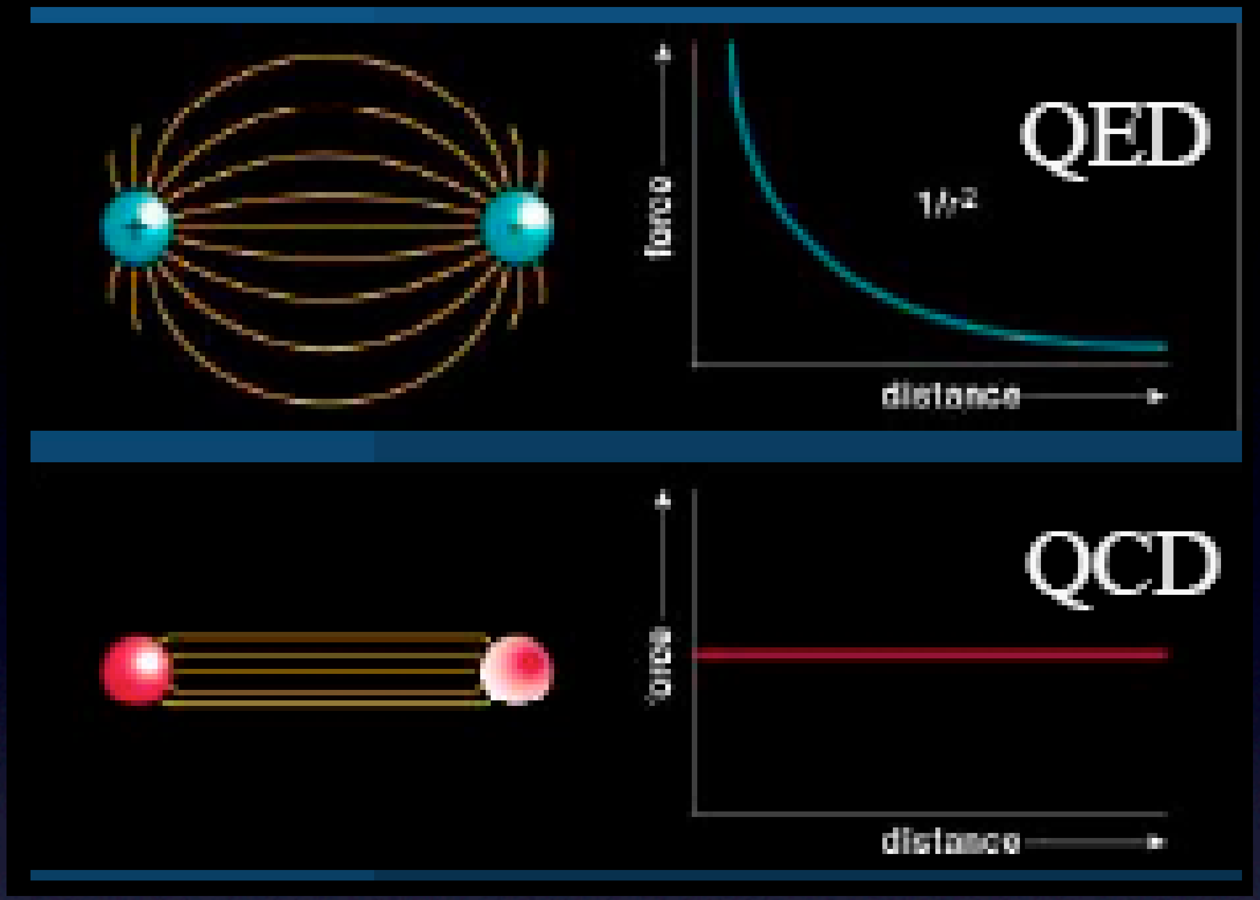
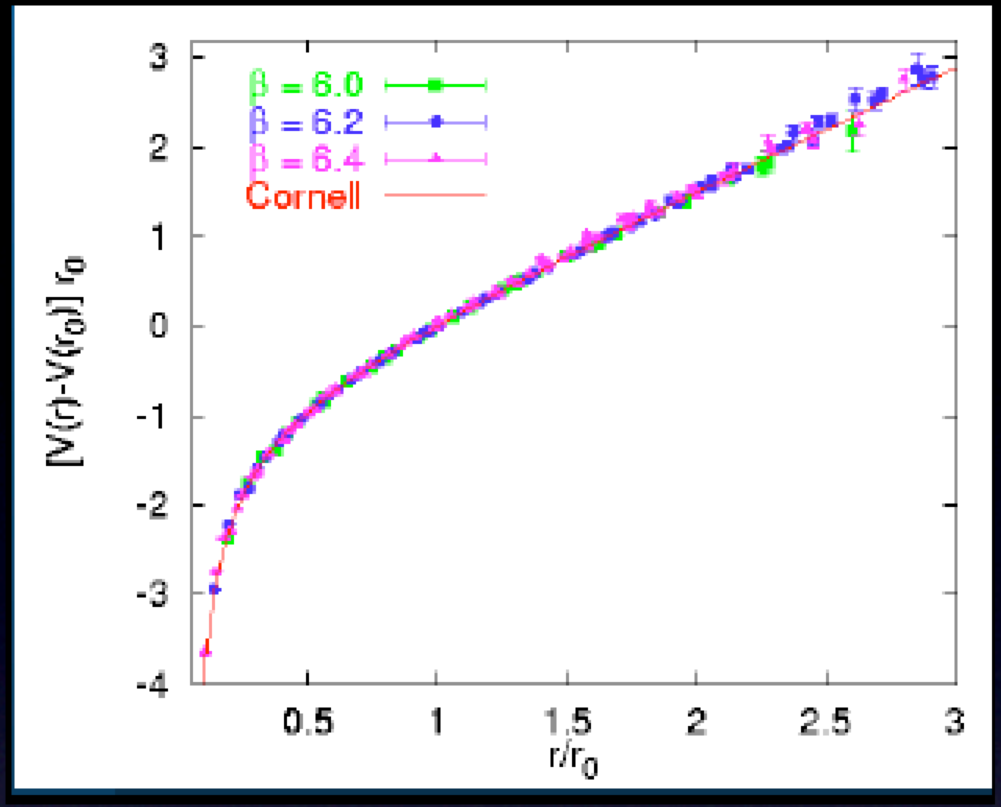
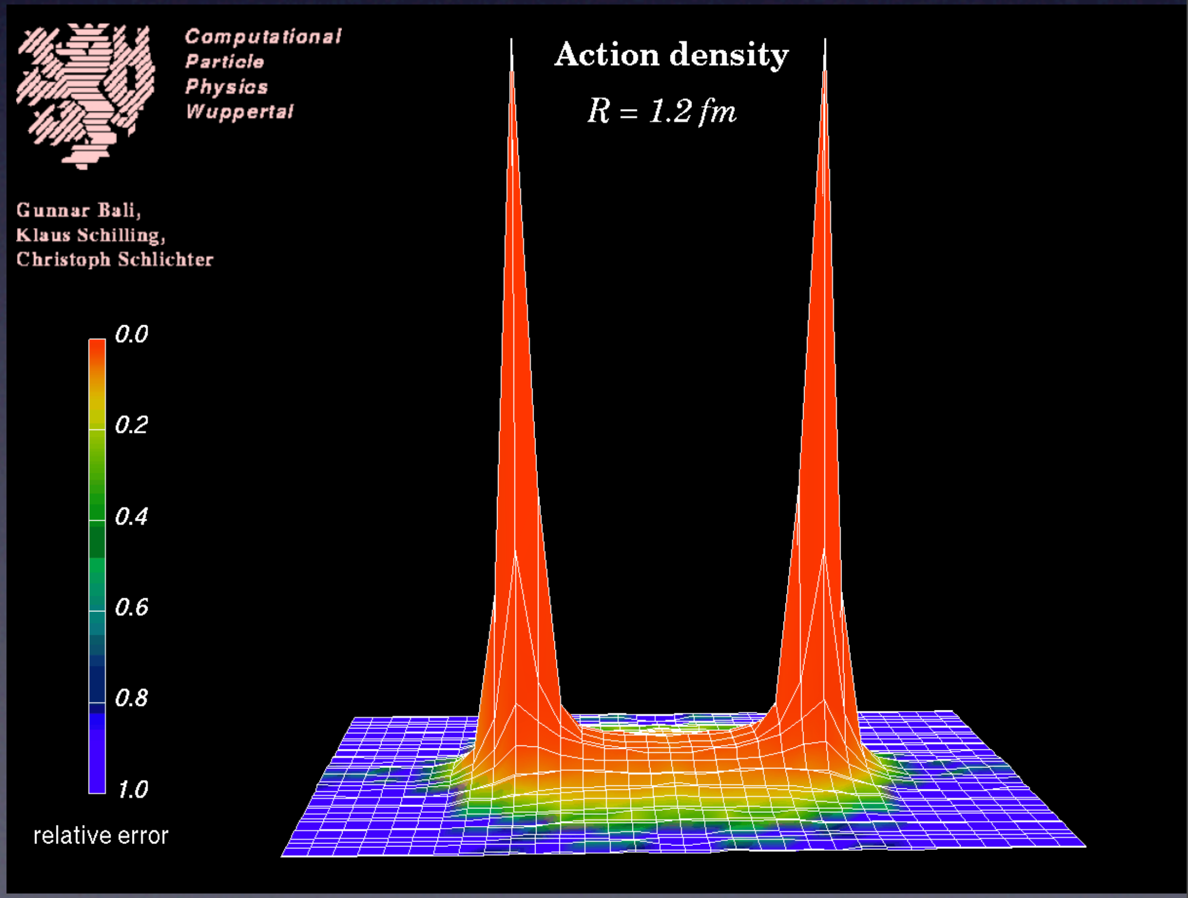




preferred benchmark field for
Strings and SUSY theories



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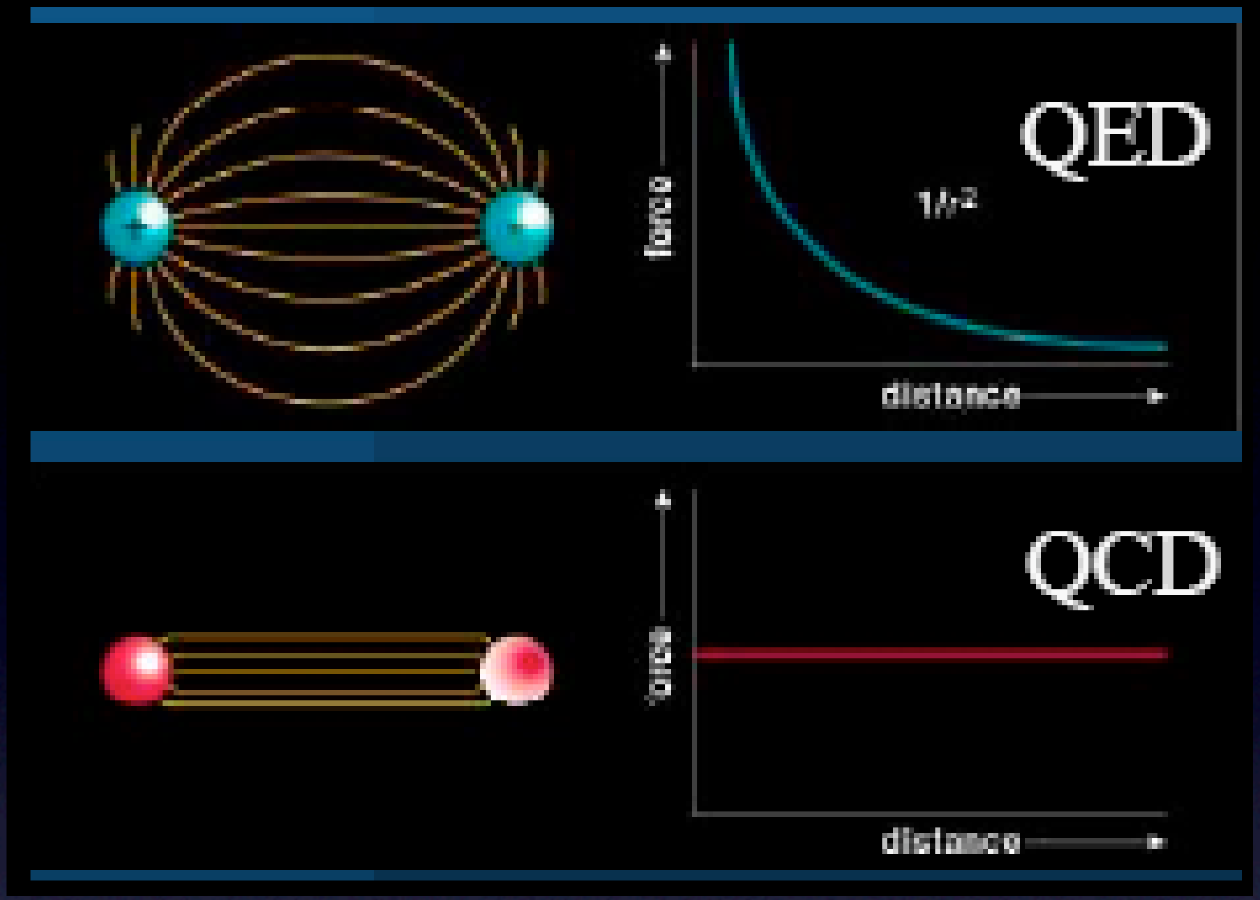

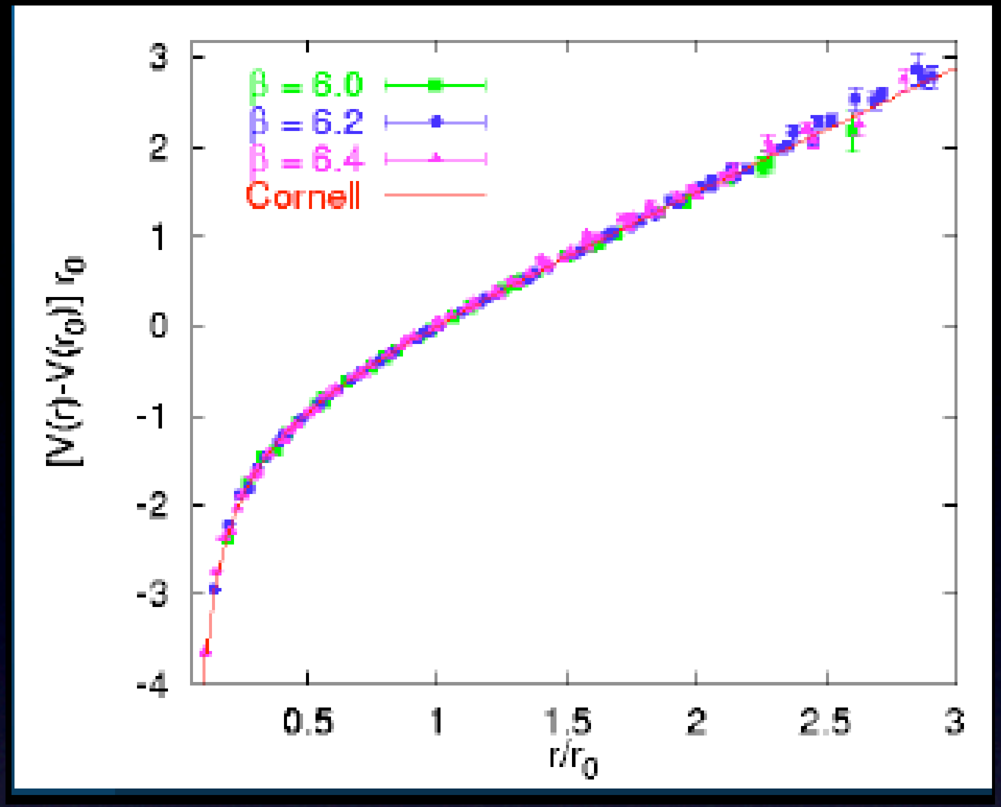

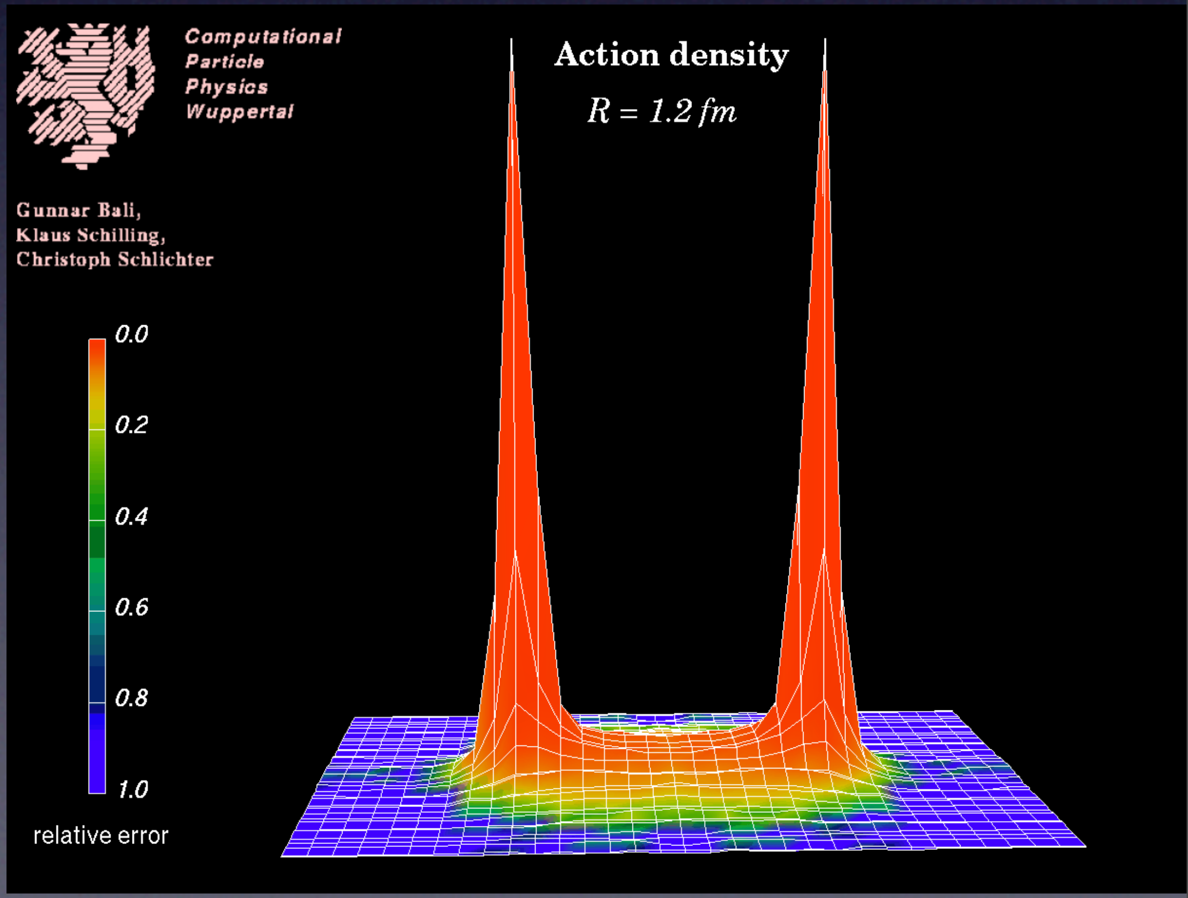

preferred benchmark field for Strings and SUSY theories

new sectors beyond the Standard Model can also be strongly coupled

QCD contains a lot of physics : deconfinement

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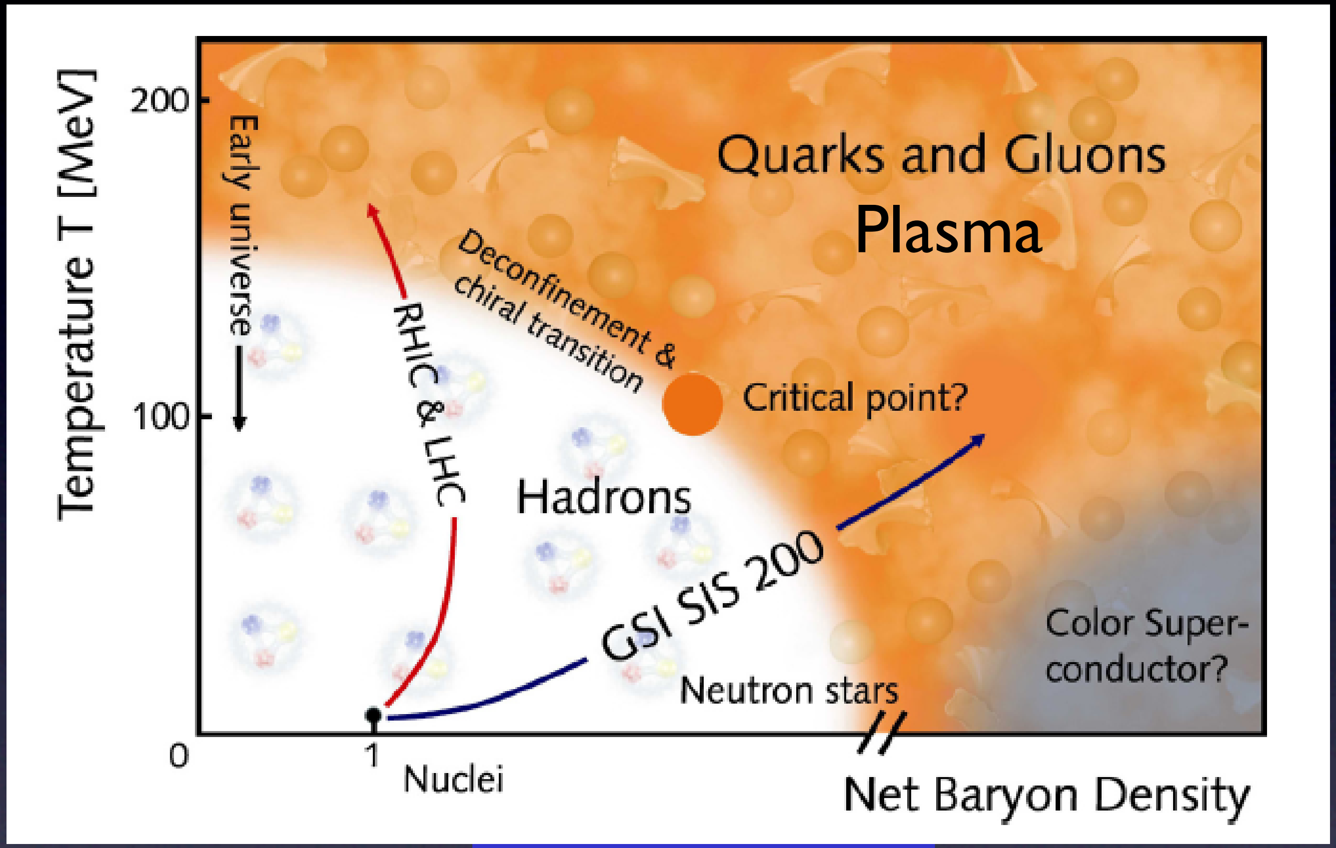
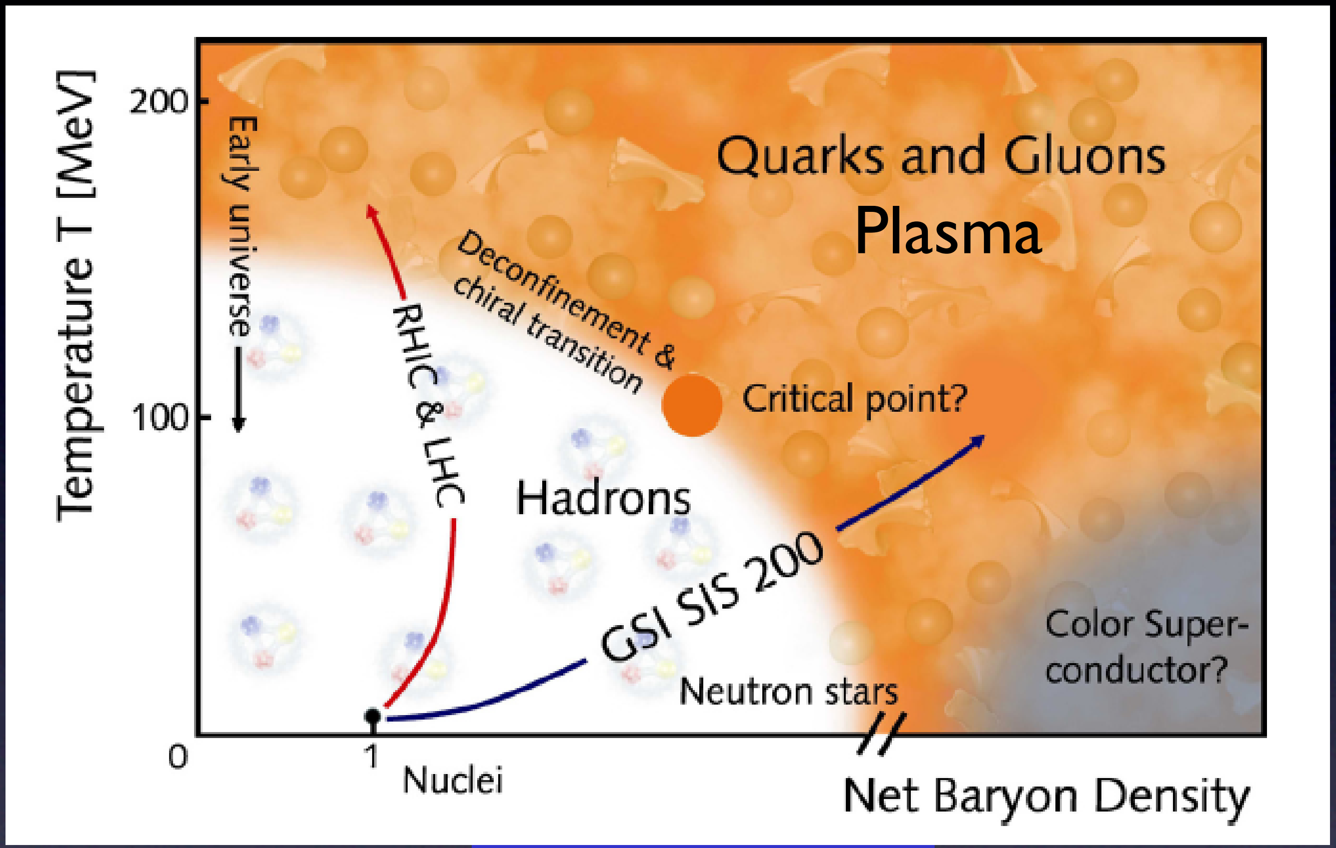
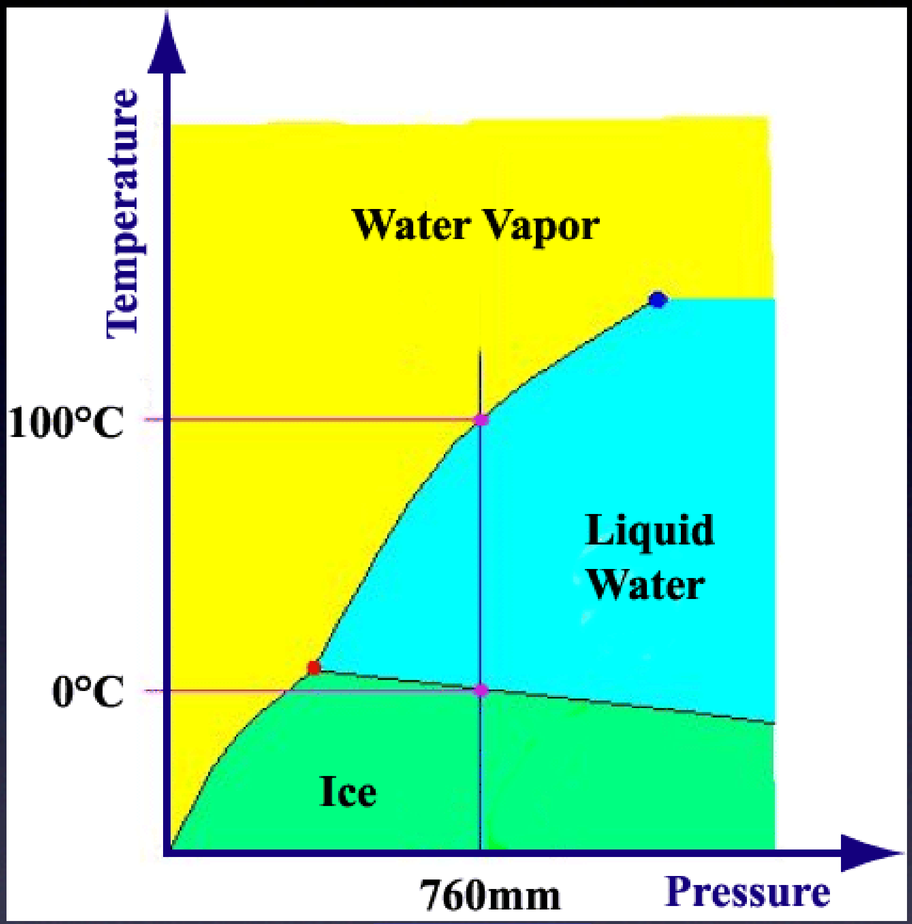


Nuclear Matter

QCD contains a lot of physics : deconfinement

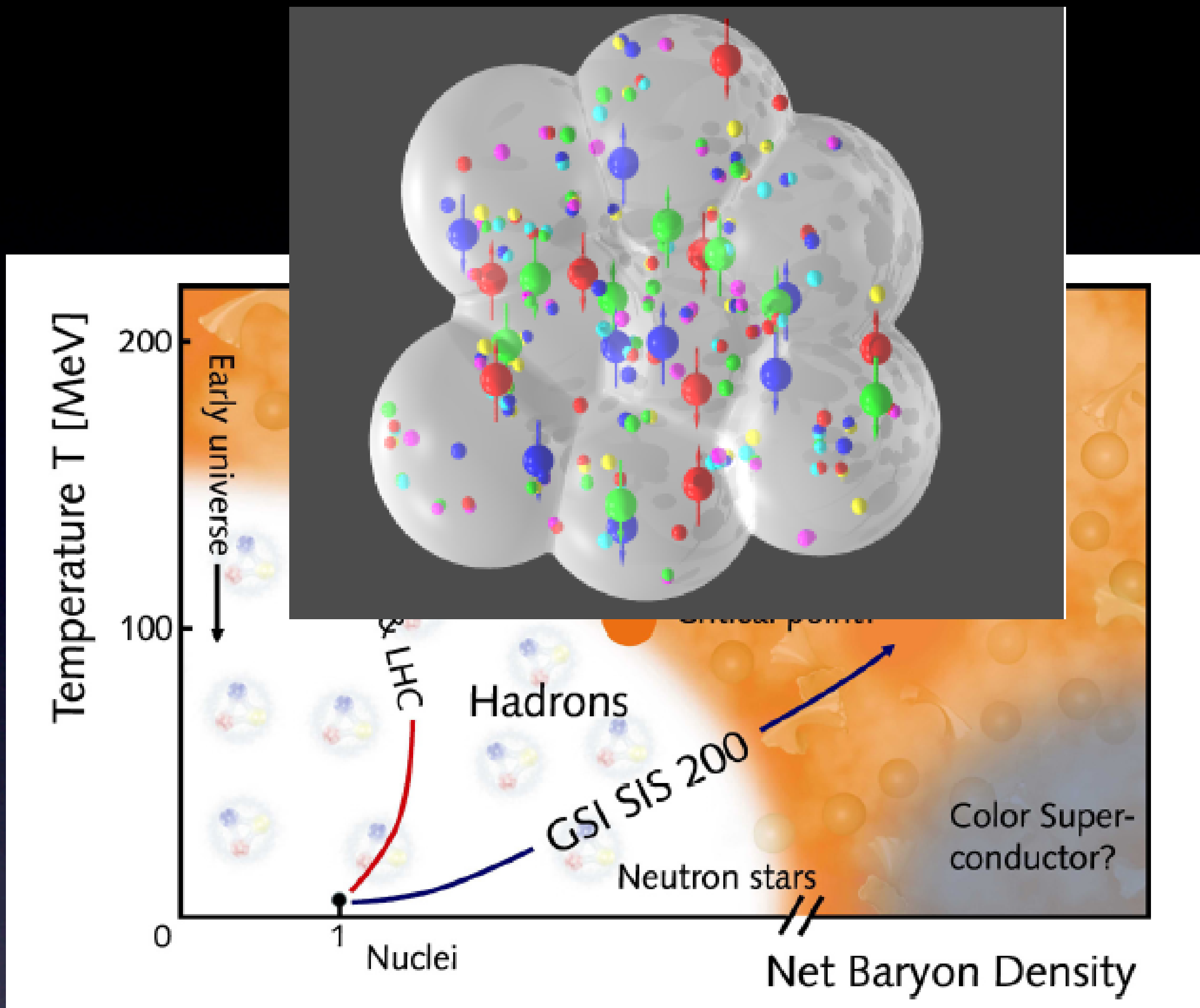


Nuclear Matter

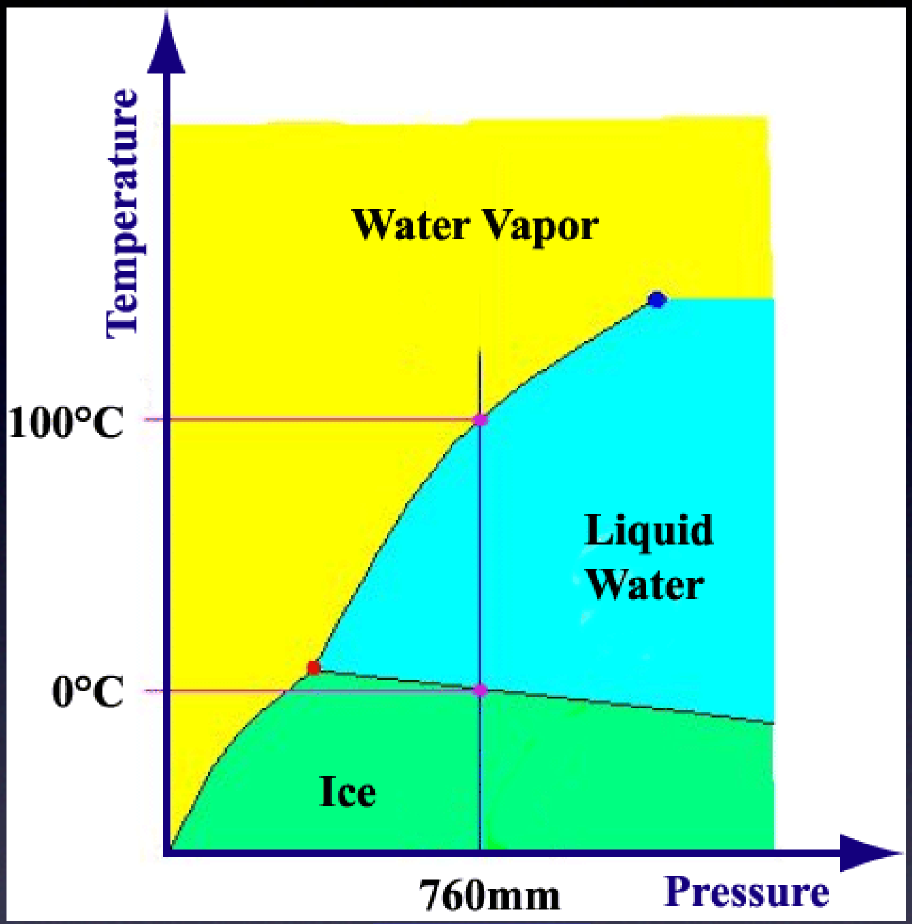


Water

QCD contains a lot of physics : deconfinement

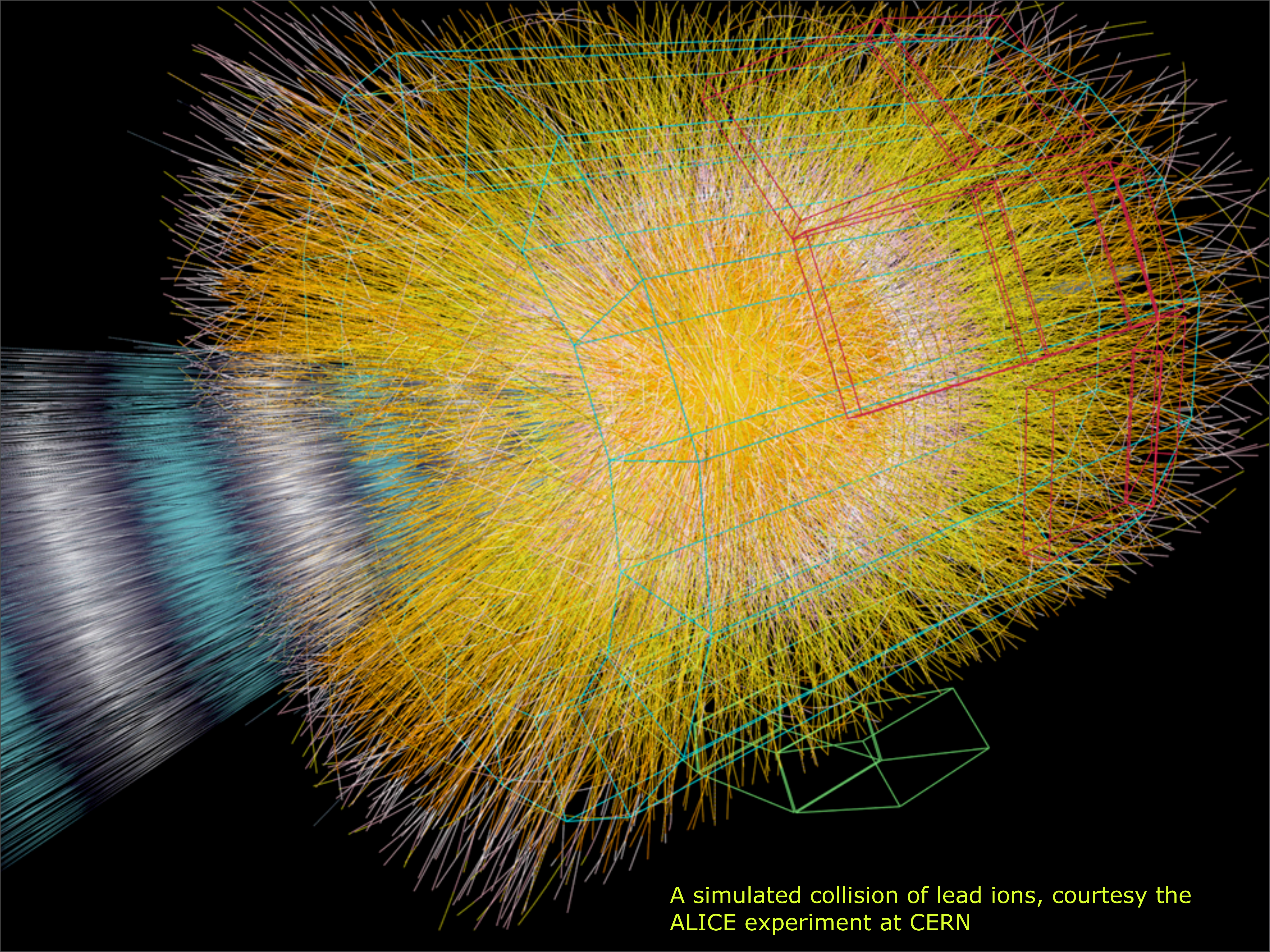


Nuclear Matter



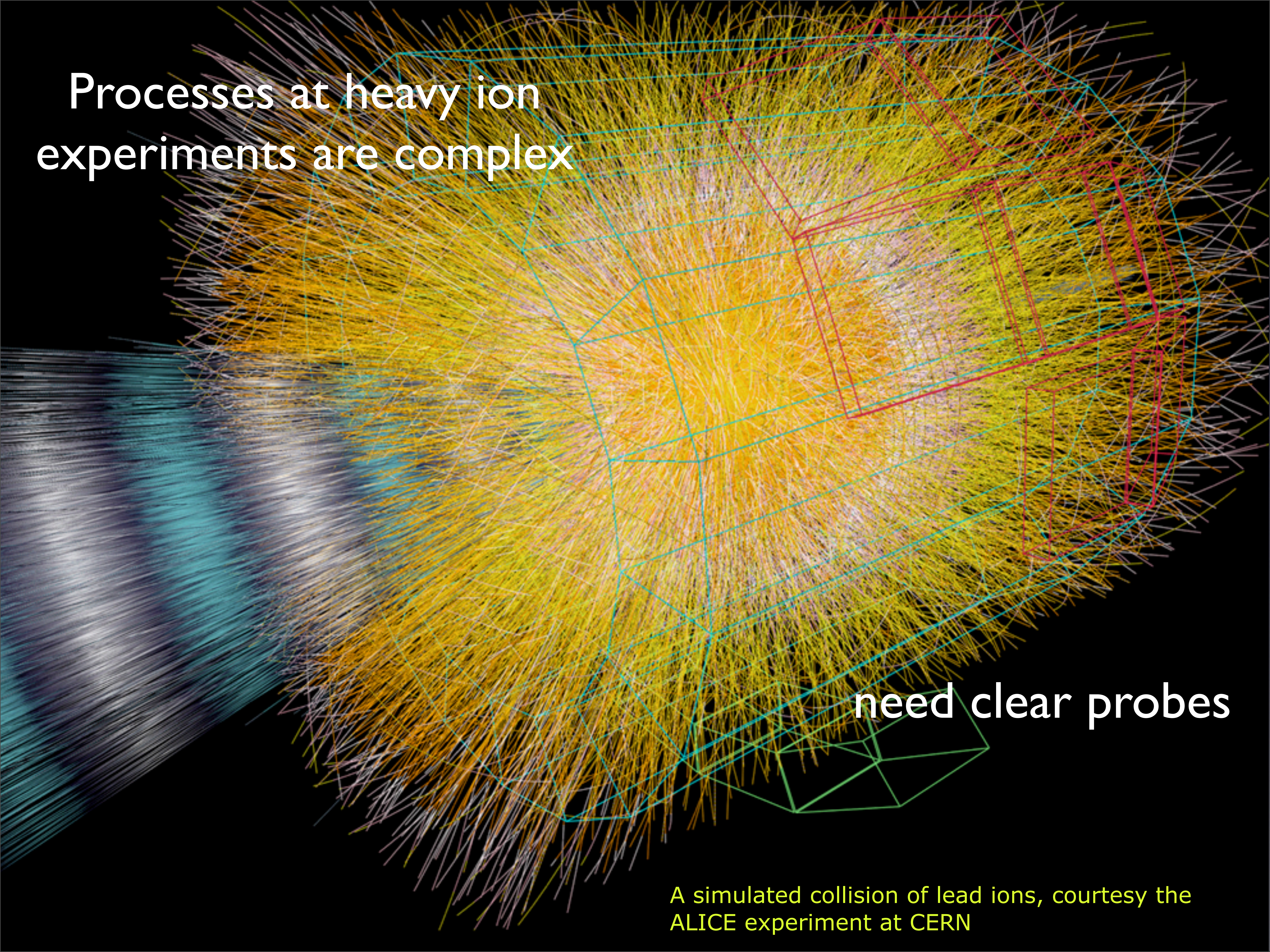
Water

nuclear matter
compressed/heated
T ~170 Mev $\sim 10^{12}\mathrm{K}$
Energy density
~1Gev/fm^3



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

Processes at heavy ion experiments are complex

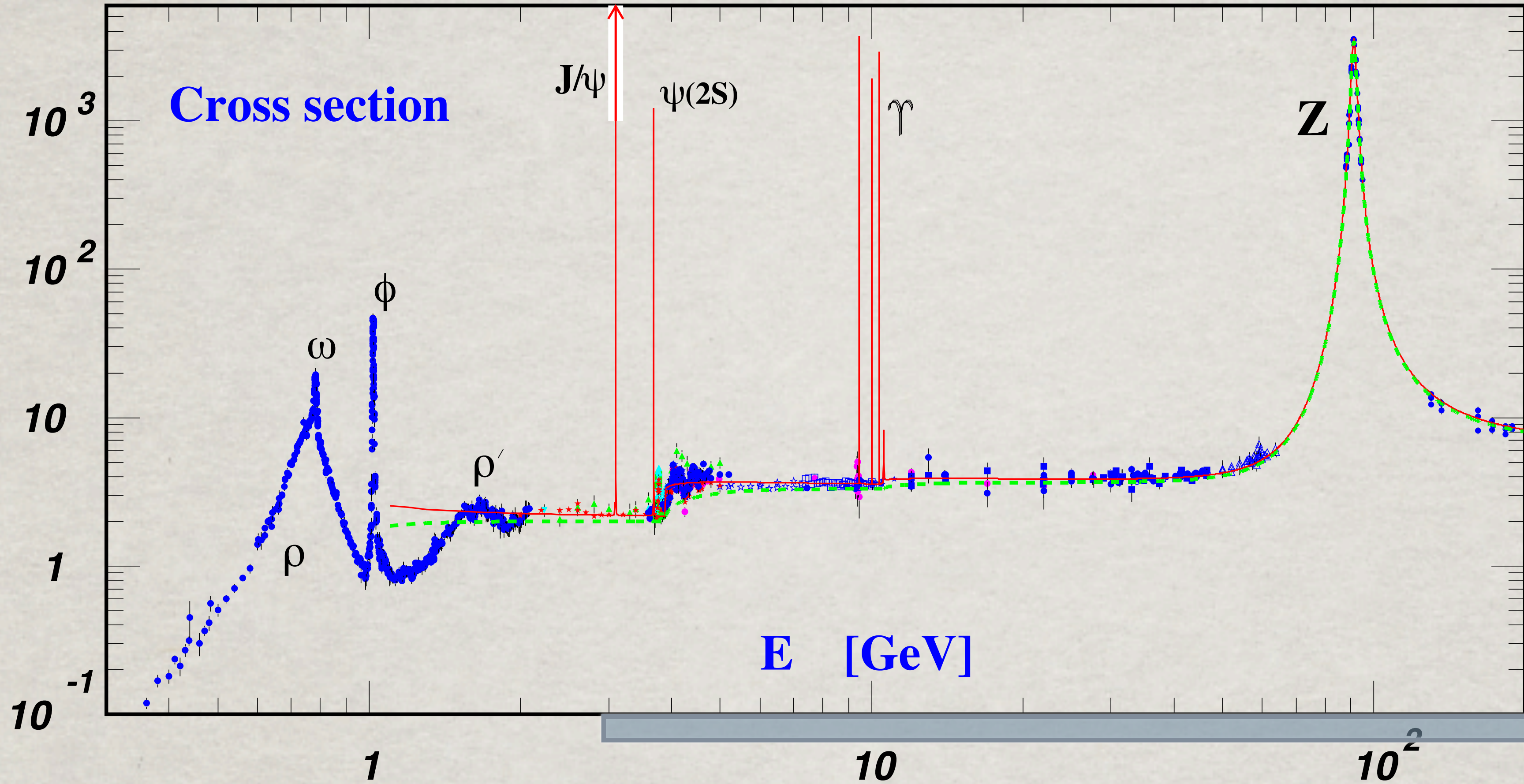


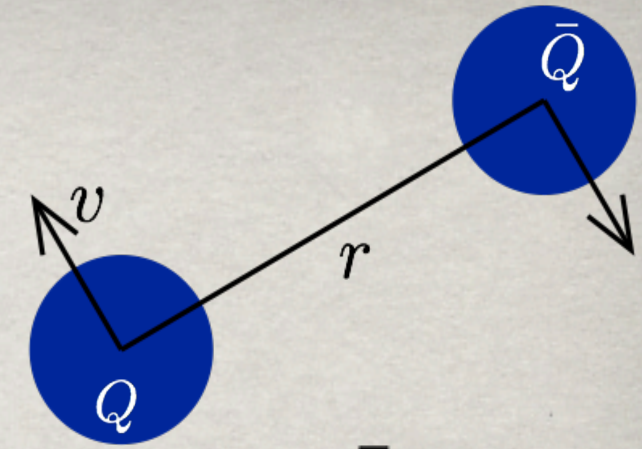
need clear probes

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

quarkonium is
a golden system to study strong interactions

Heavy quarks offer a privileged access





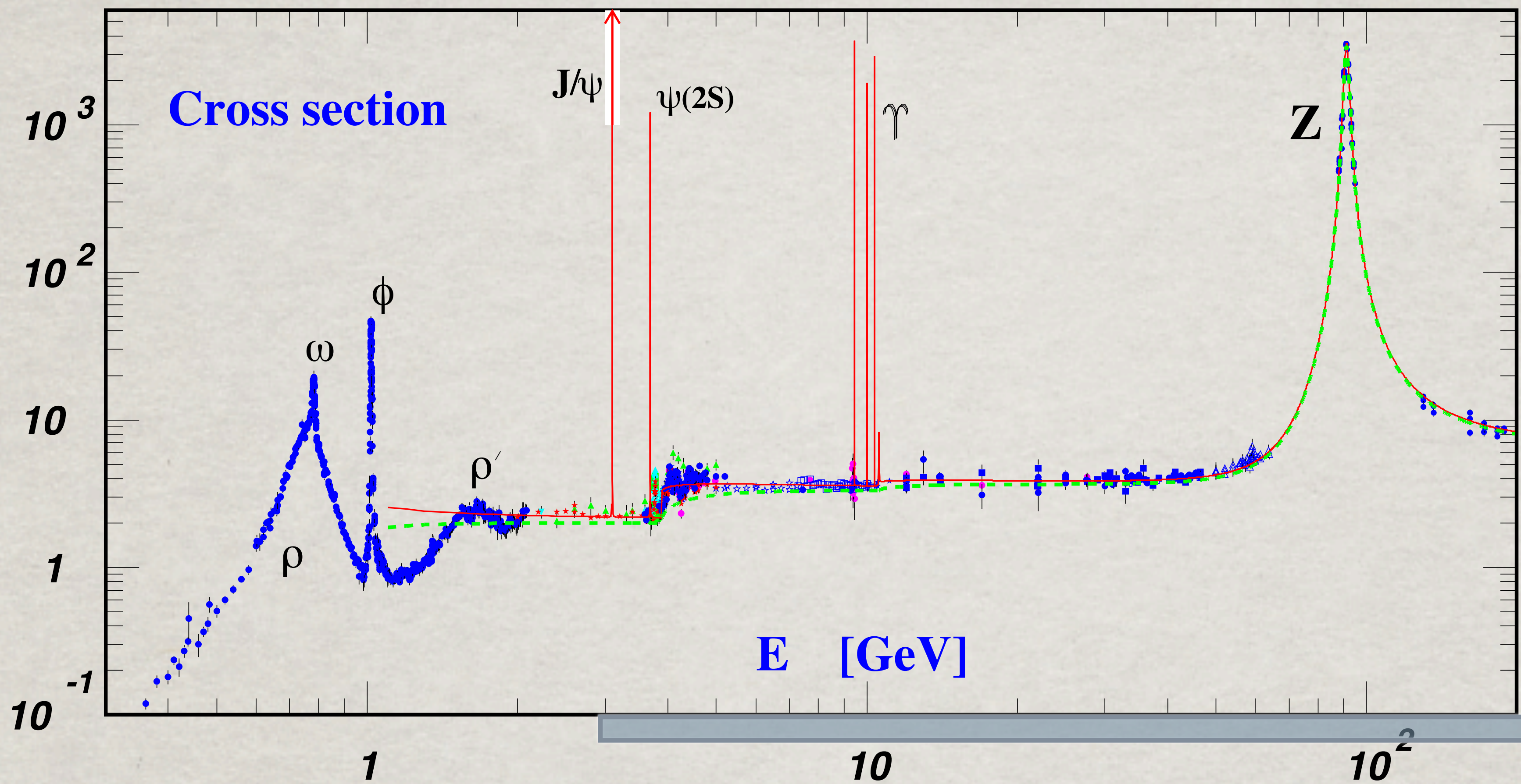
with $Q, \bar{Q} = c, b, t$

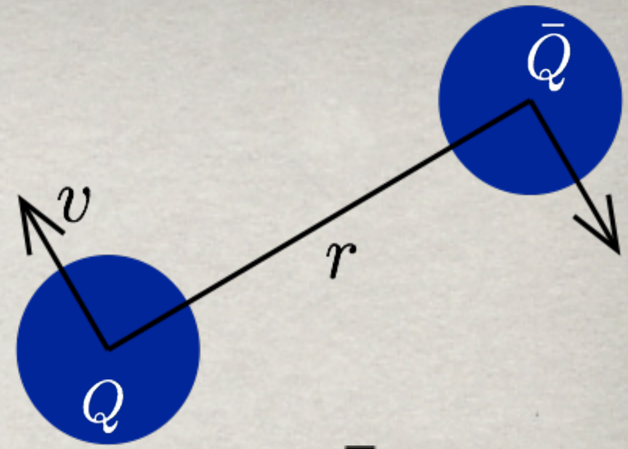
$m_c \sim 1.5$GeV

$m_b \sim 5$GeV

$m_t \sim 170$GeV

Heavy quarks offer a privileged access





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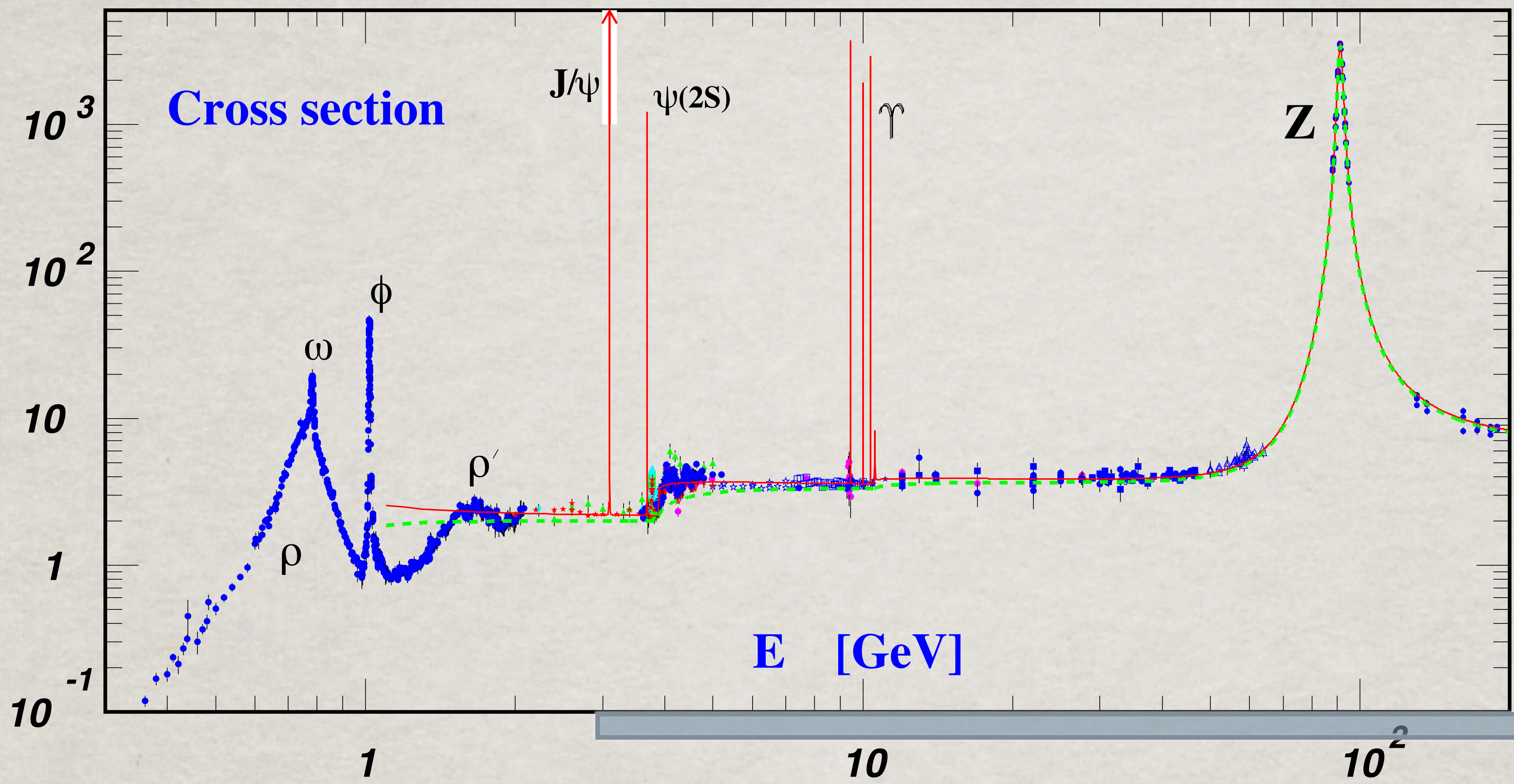
m_c ~1.5GeV

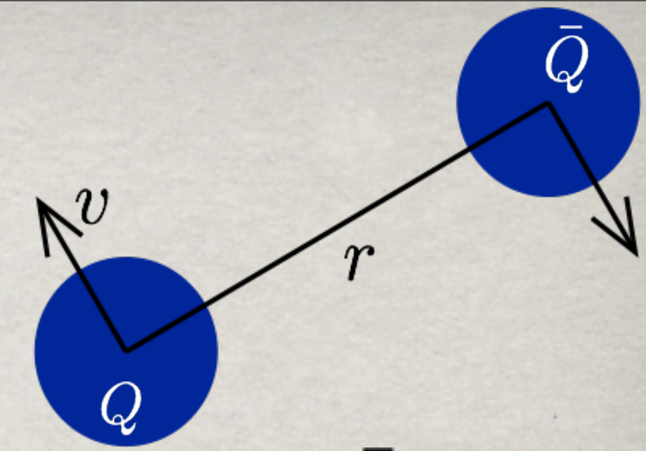
m_b ~5GeV

m_t ~170GeV

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

Heavy quarks offer a privileged access





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

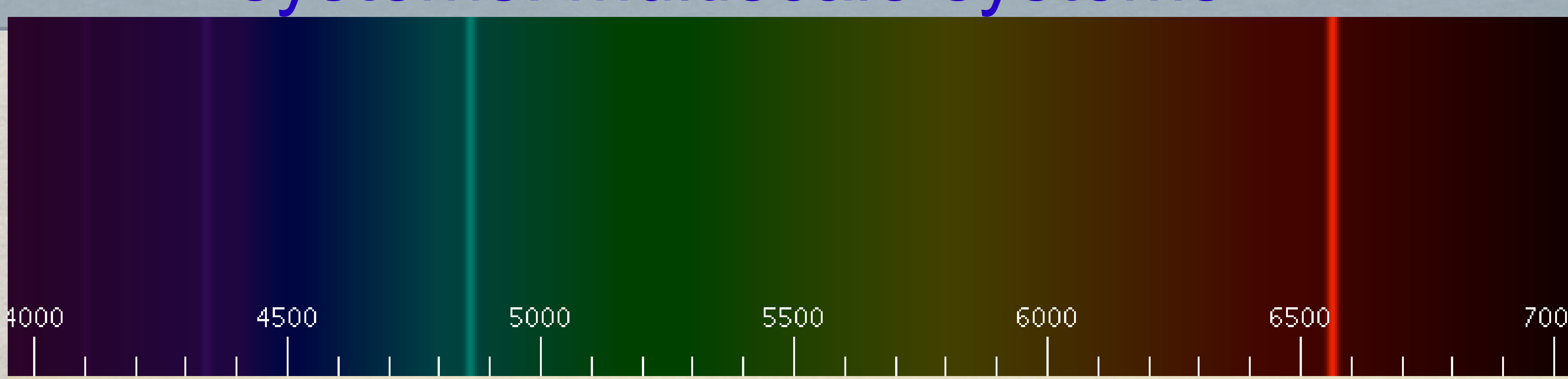
$m_c \sim 1.5\text{GeV}$

$m_b \sim 5\text{GeV}$

$m_t \sim 170\text{GeV}$

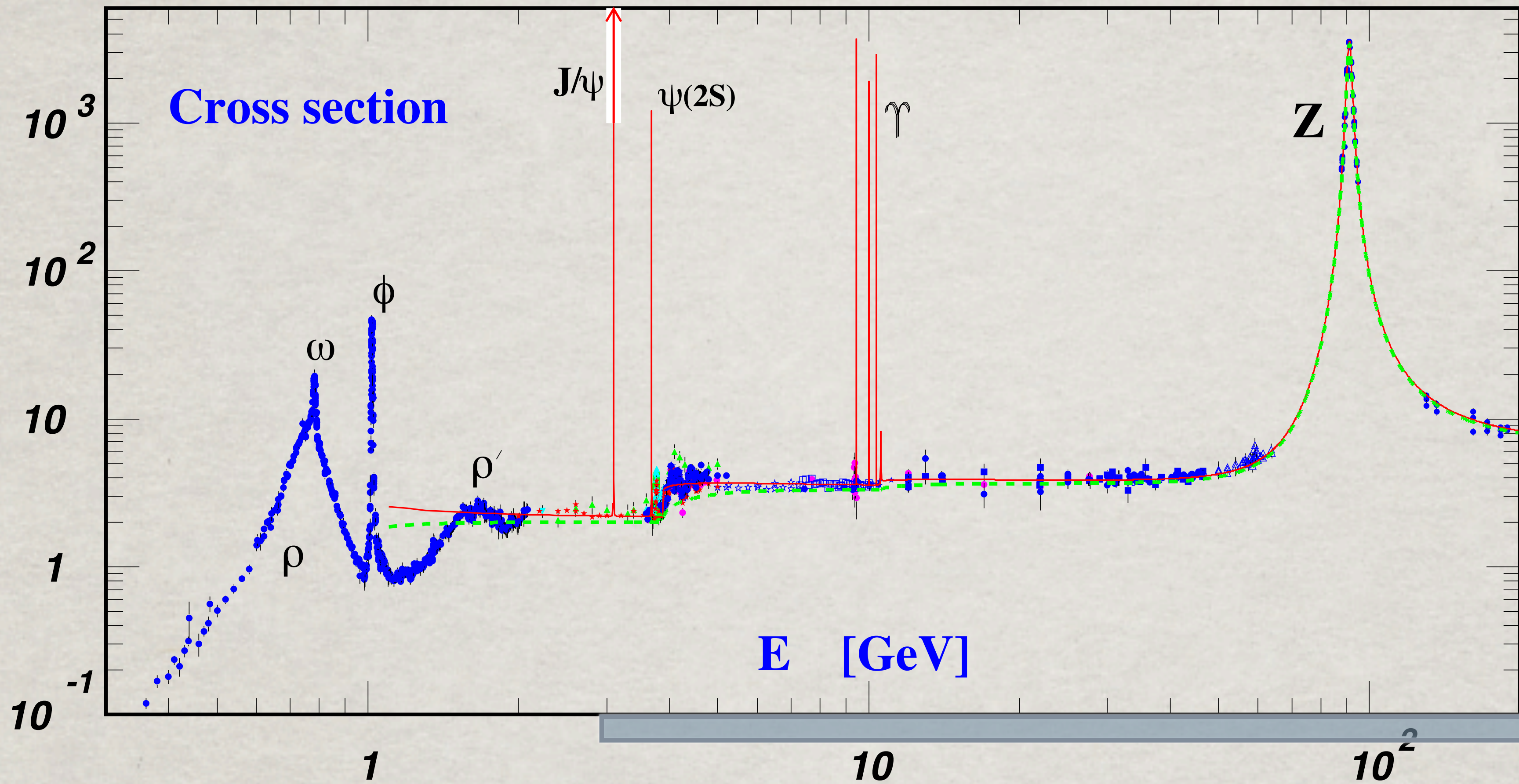
A large scale $m_Q \gg \Lambda_{QCD}$ $\alpha_s(m_Q) \ll 1$

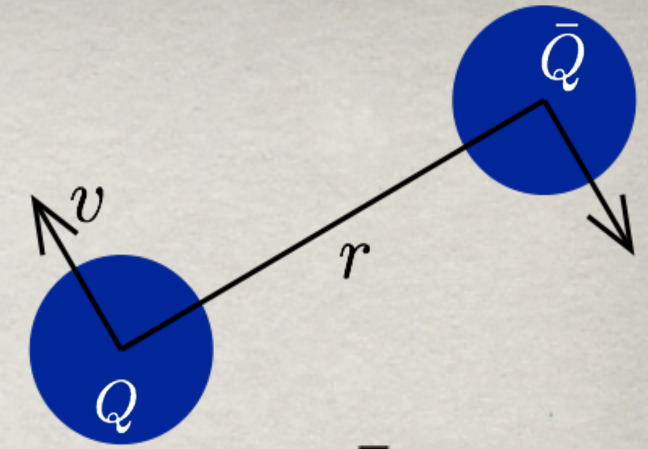
Heavy quarkonia are nonrelativistic bound systems: multiscale systems



ELECTROMAGNETIC BOUND STATES: ATOMS, MOLECULES,

Heavy quarks offer a privileged access





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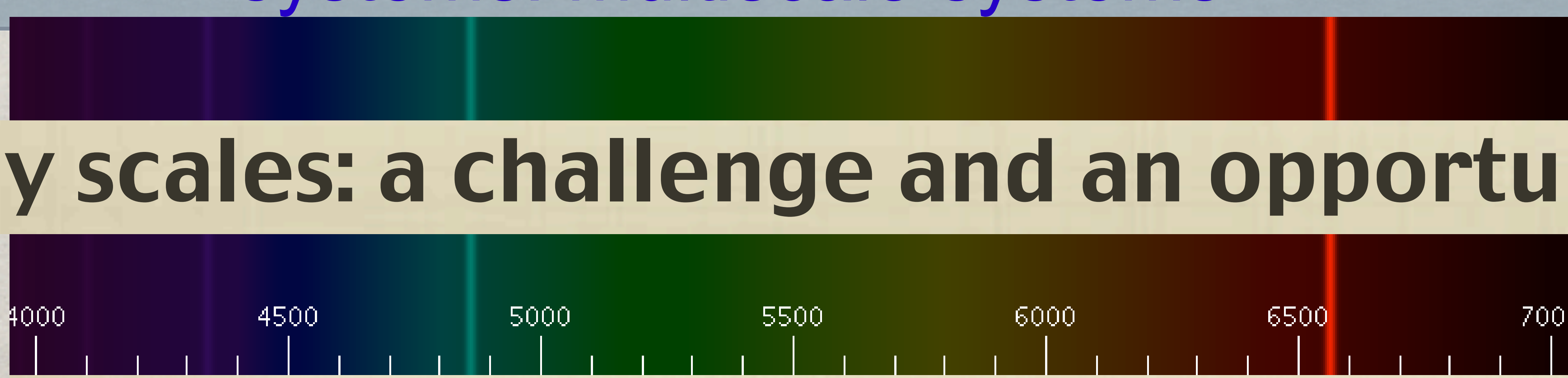
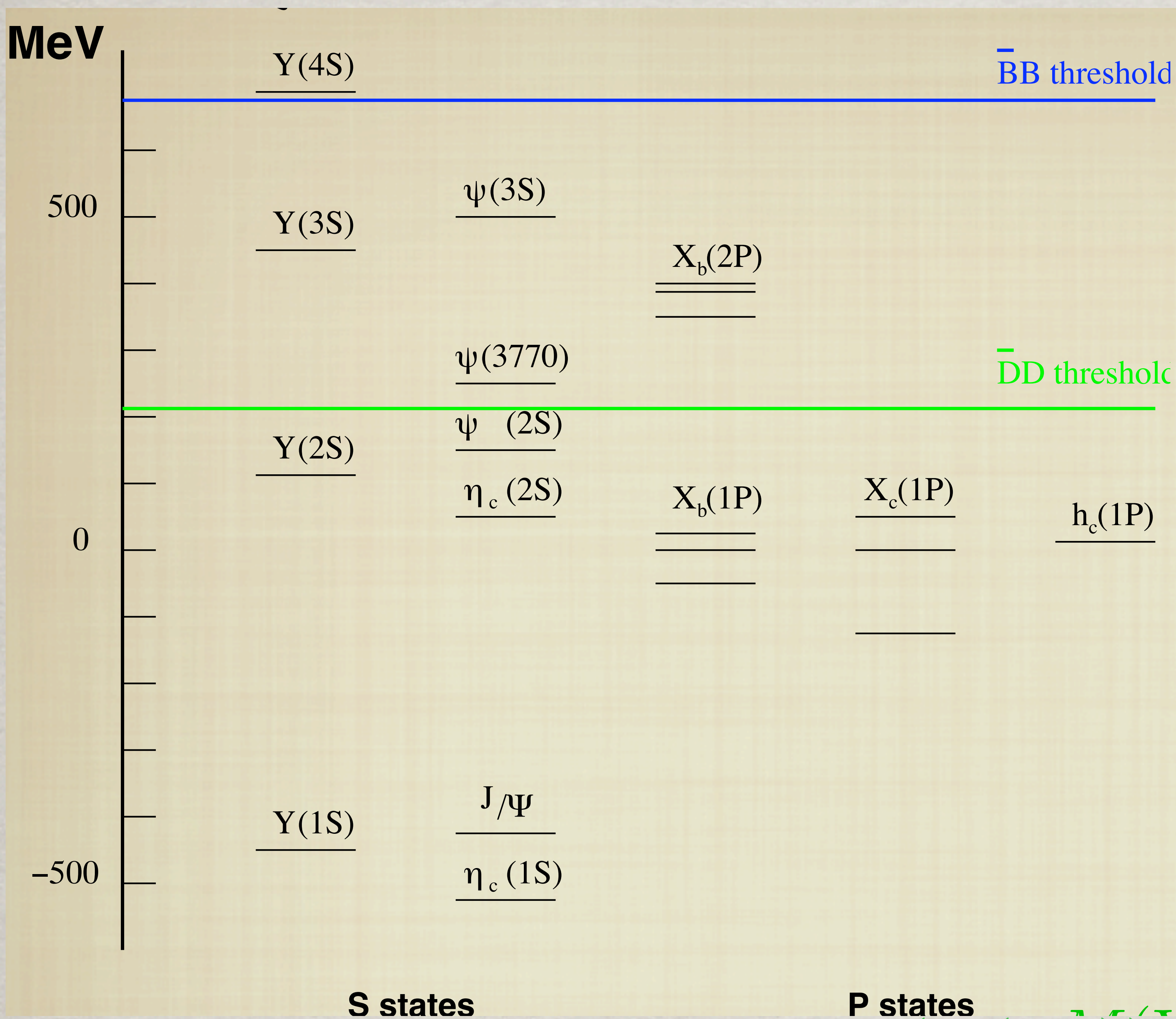


many scales: a challenge and an opportunity

ELECTROMAGNETIC BOUND STATES: ATOMS, MOLECULES,

Quarkonium scales

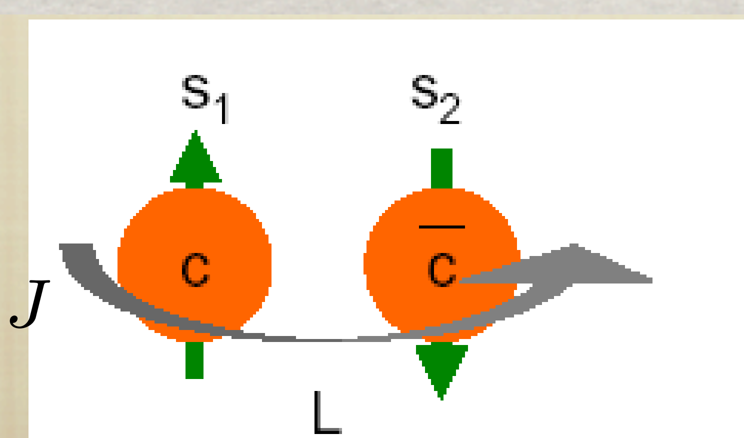


Normalized with respect to $\chi_b(1P)$ and $\chi_c(1P)$

$$M(\Upsilon(1S)) = 9460\,\mathrm{MeV}$$

$$M(J/\psi) = 3097\,\mathrm{MeV}$$

$^{2S+1}L_J$



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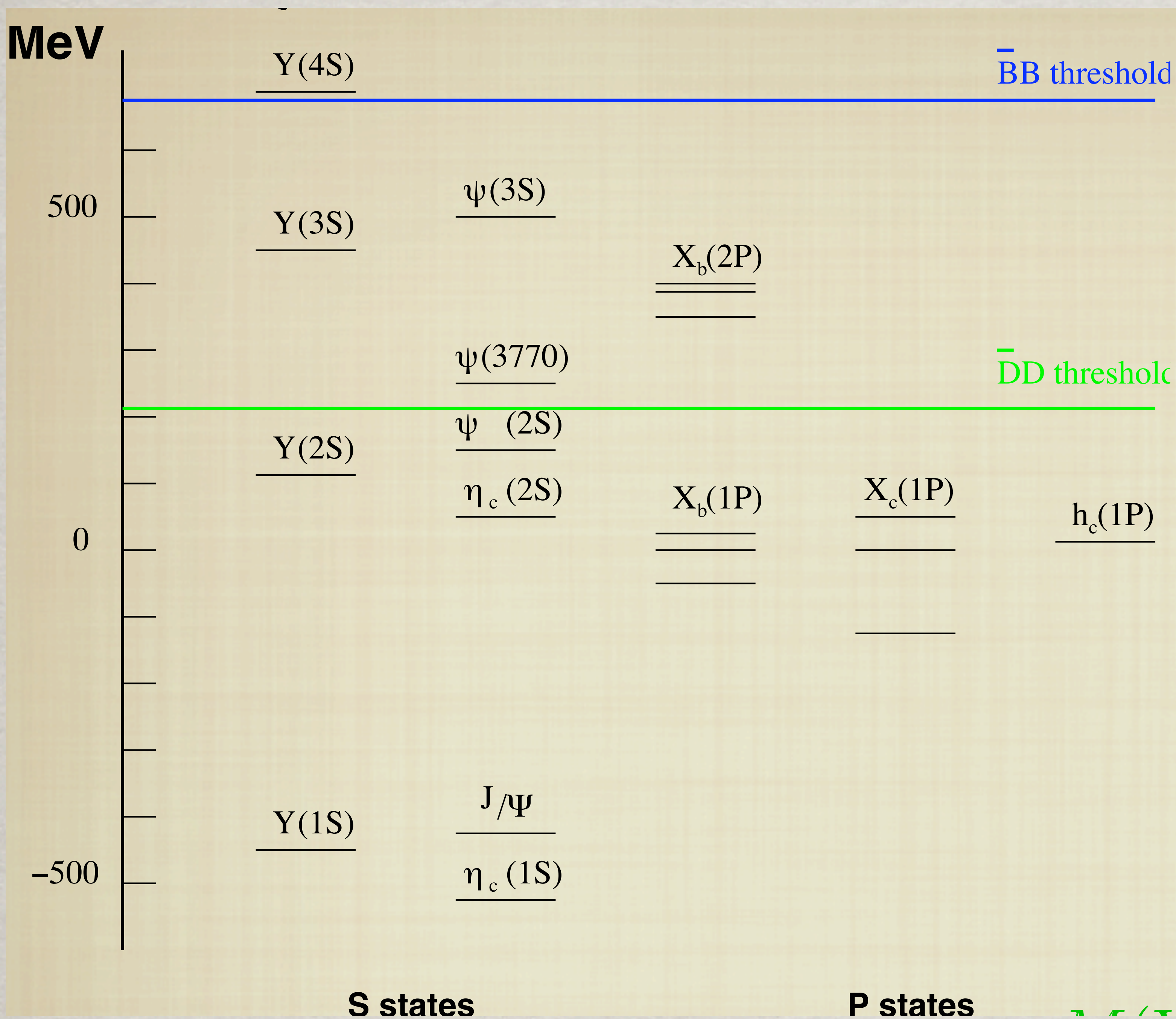

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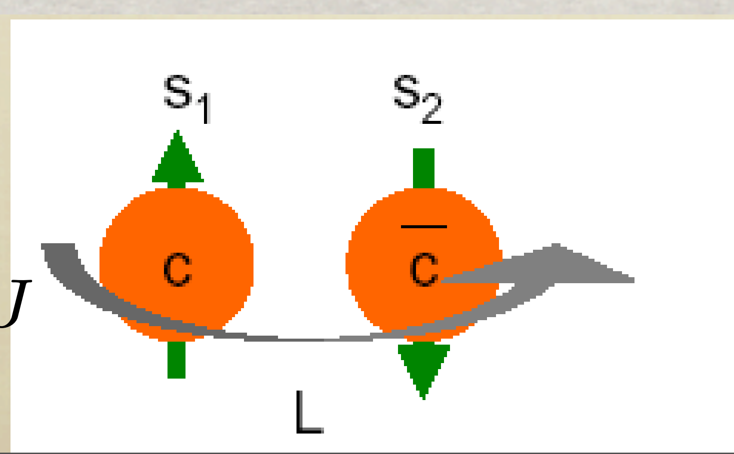

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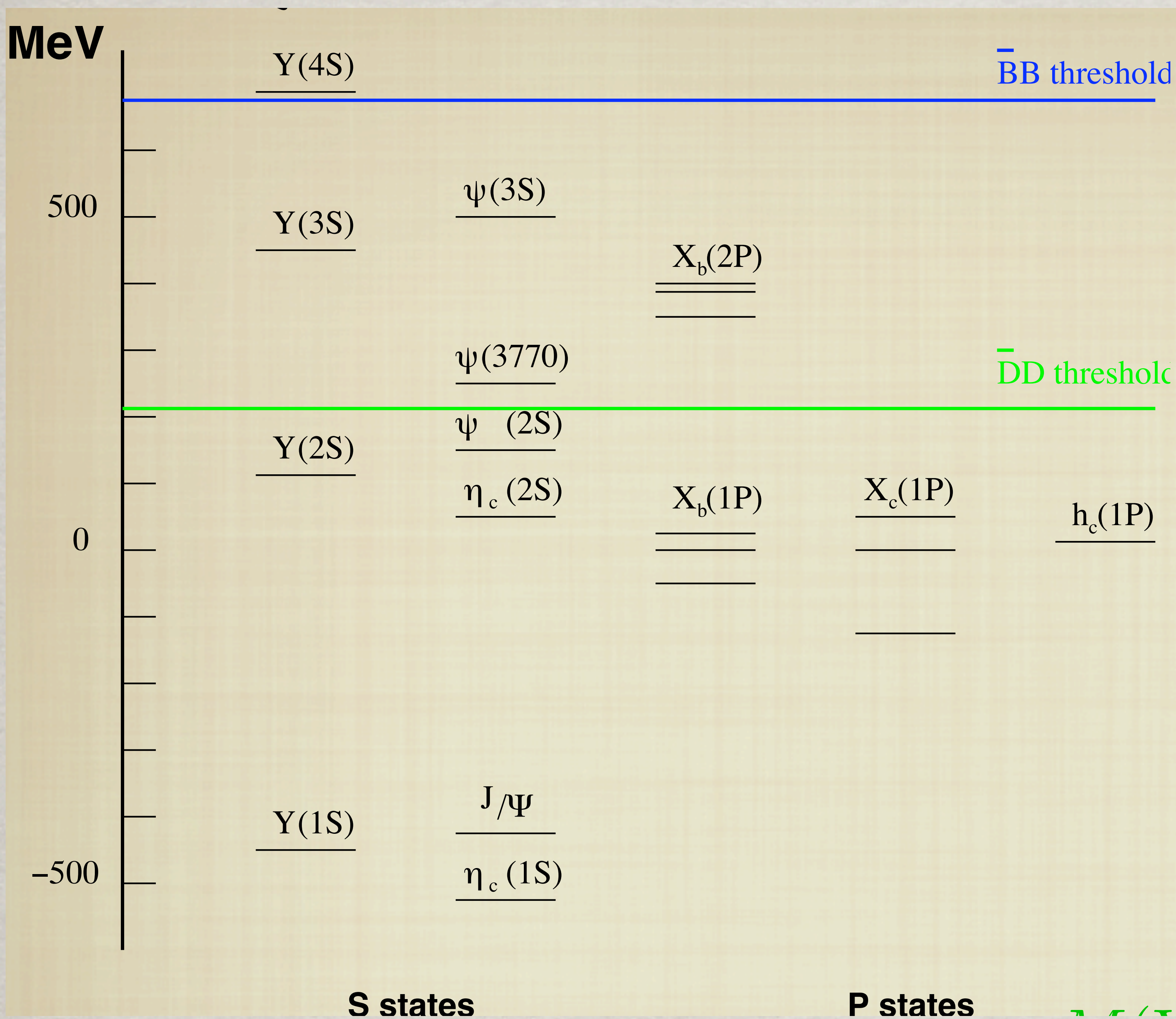

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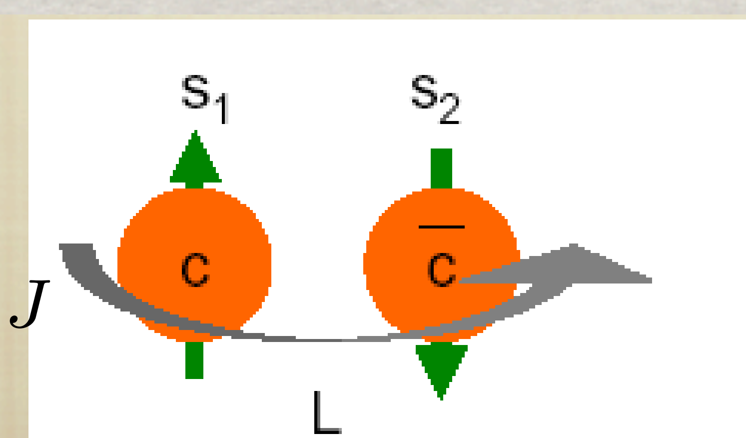
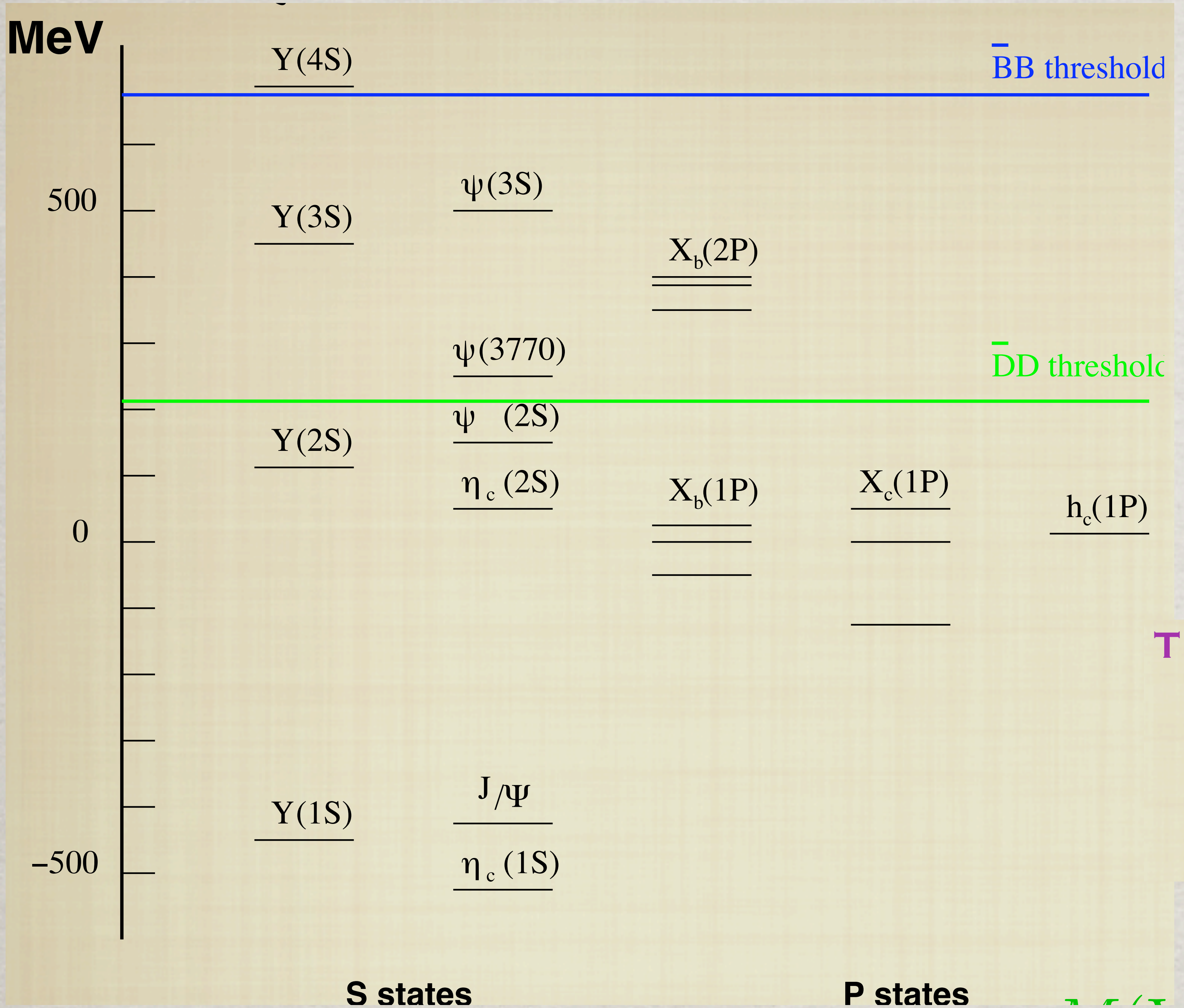


The mass scale is perturbative

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

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

Quarkonium scales



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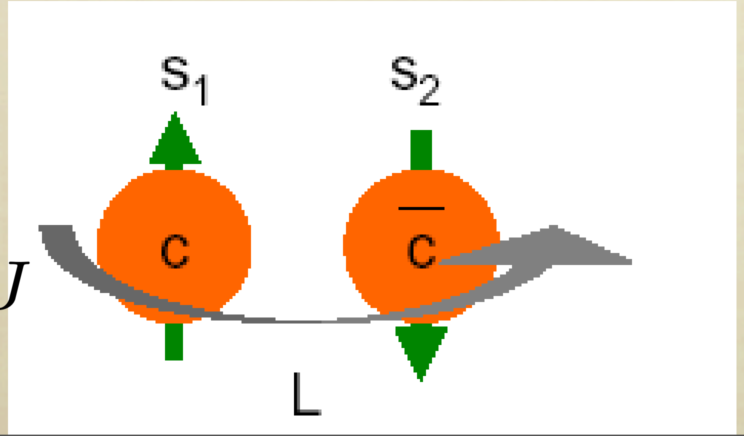

The system is nonrelativistic(NR)

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

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

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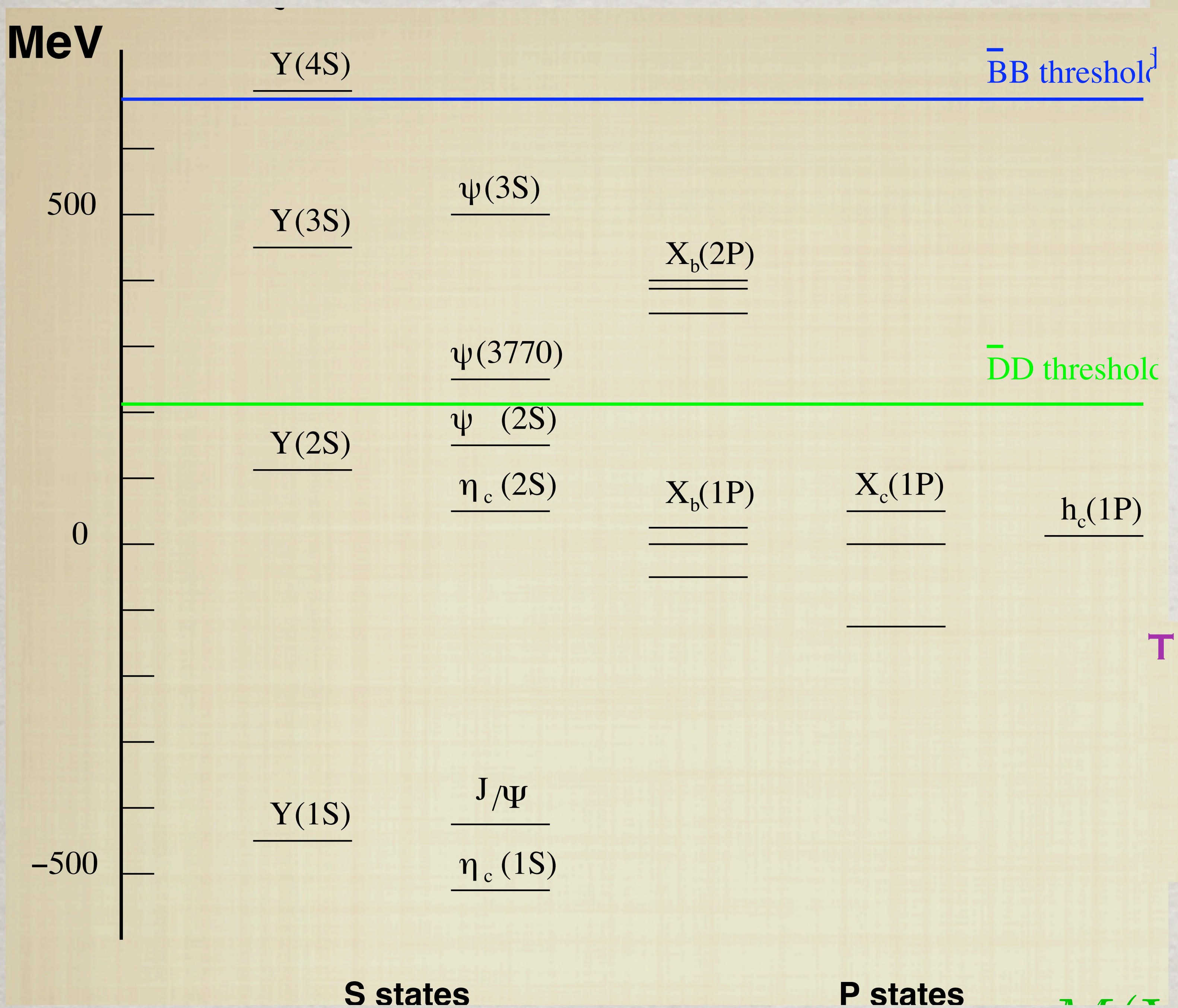
Quarkonium scales



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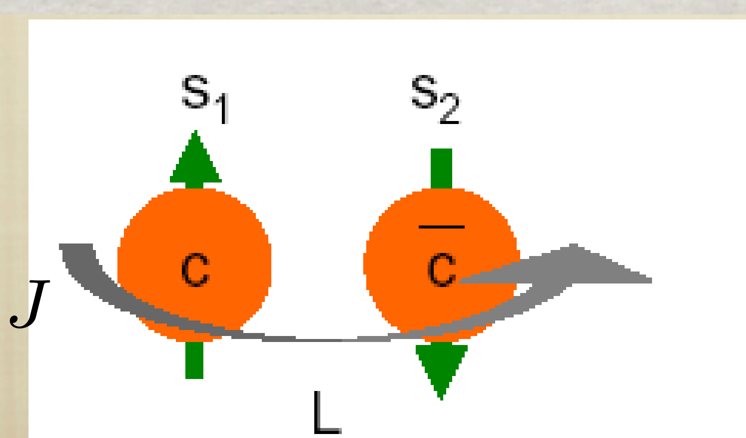

NR bound states have at least 3 scales

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

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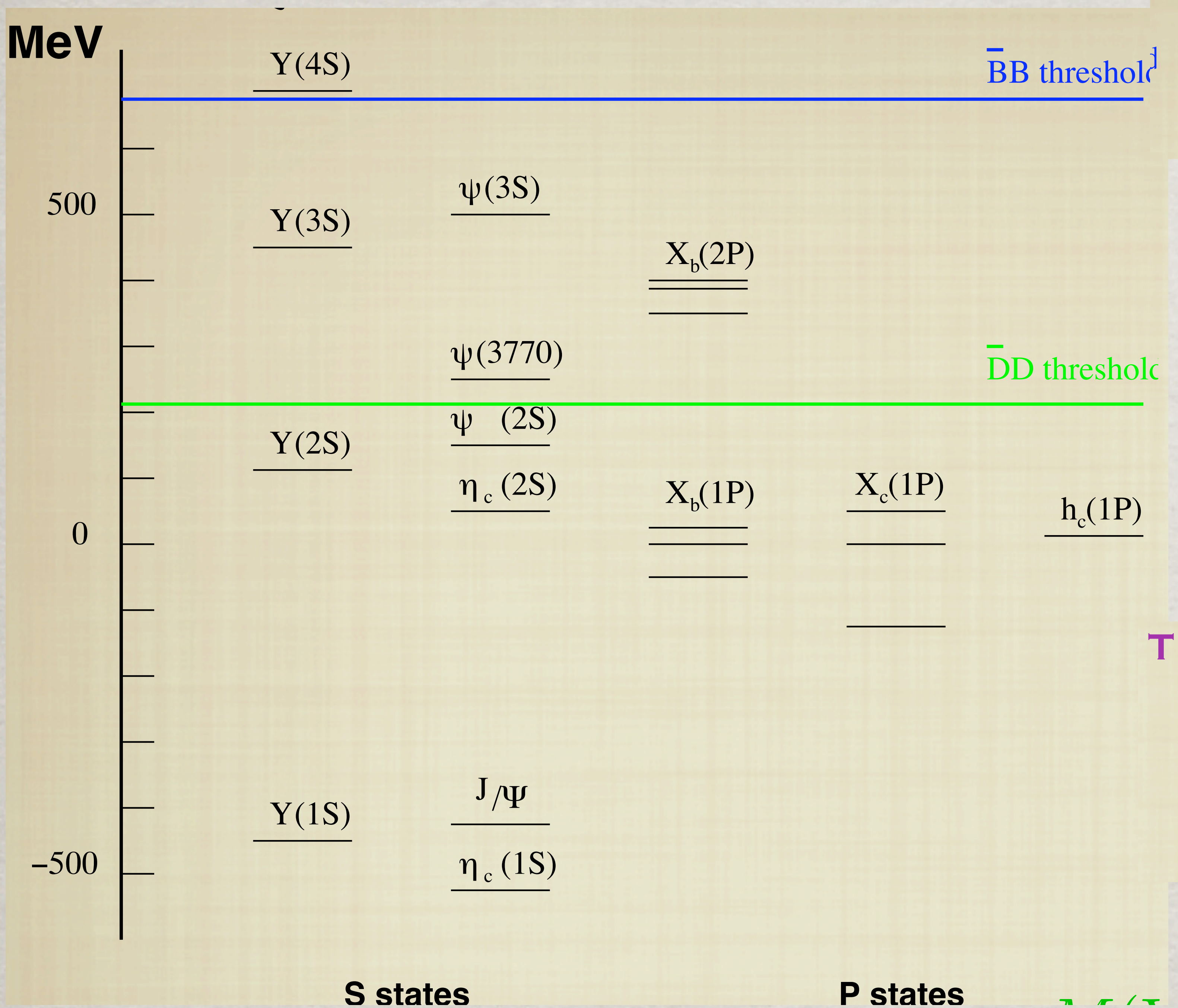

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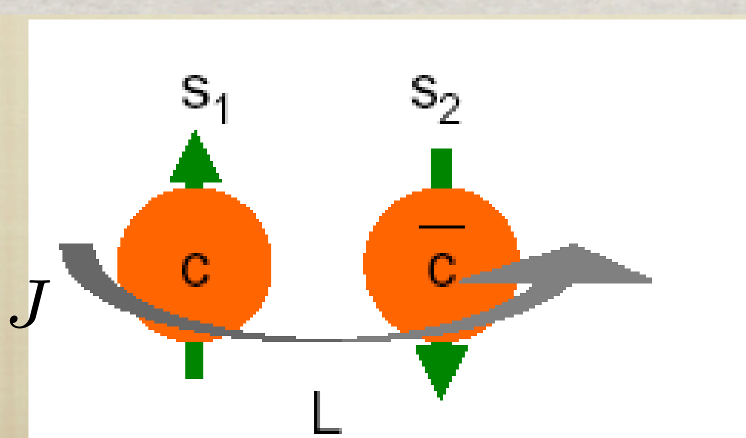

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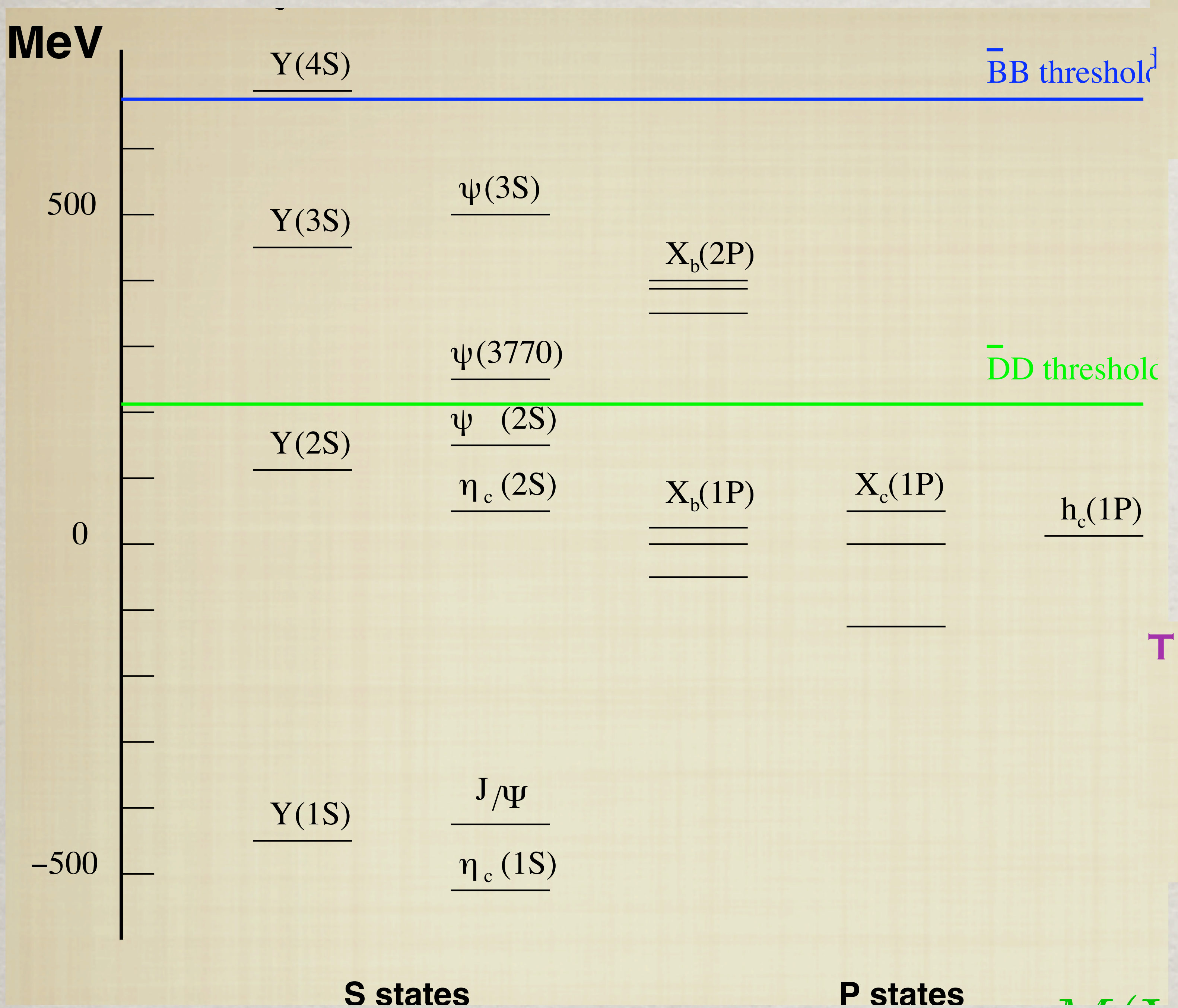

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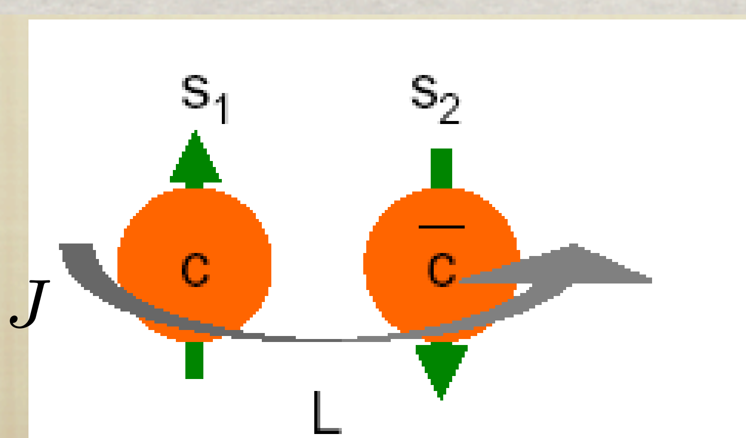

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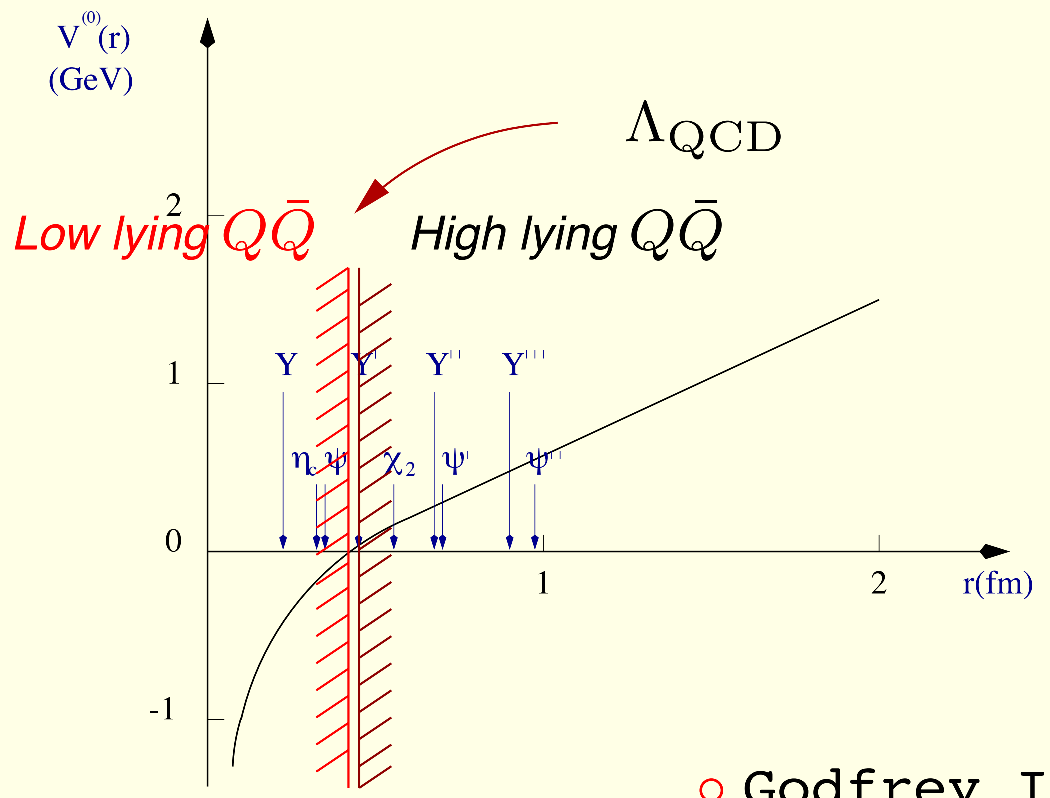
Quarkonium as a confinement and deconfinement probe

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

At zero temperature

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

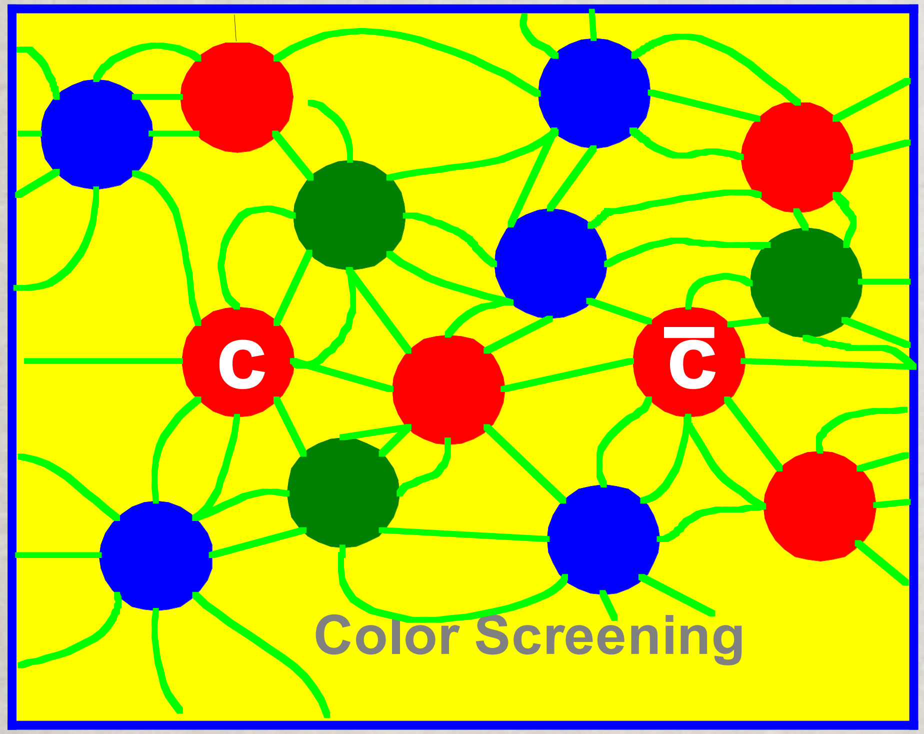


○ Godfrey Isgur PRD 32(85)189

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

Quarkonium as a confinement and deconfinement probe

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



Debye charge screening $m_D \sim gT$

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

Matsui Satz 1986

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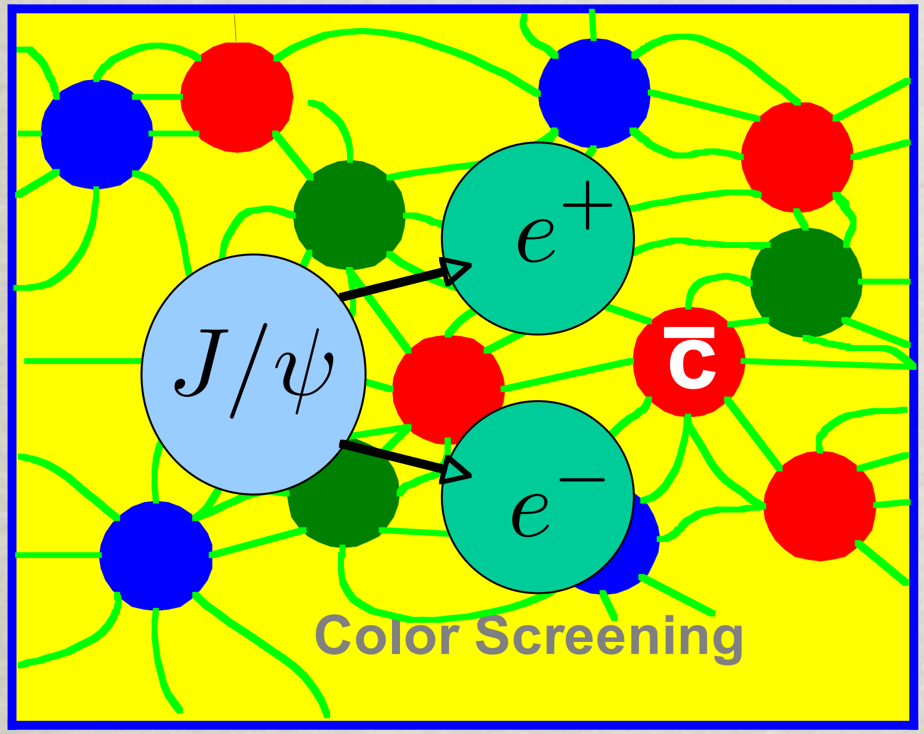

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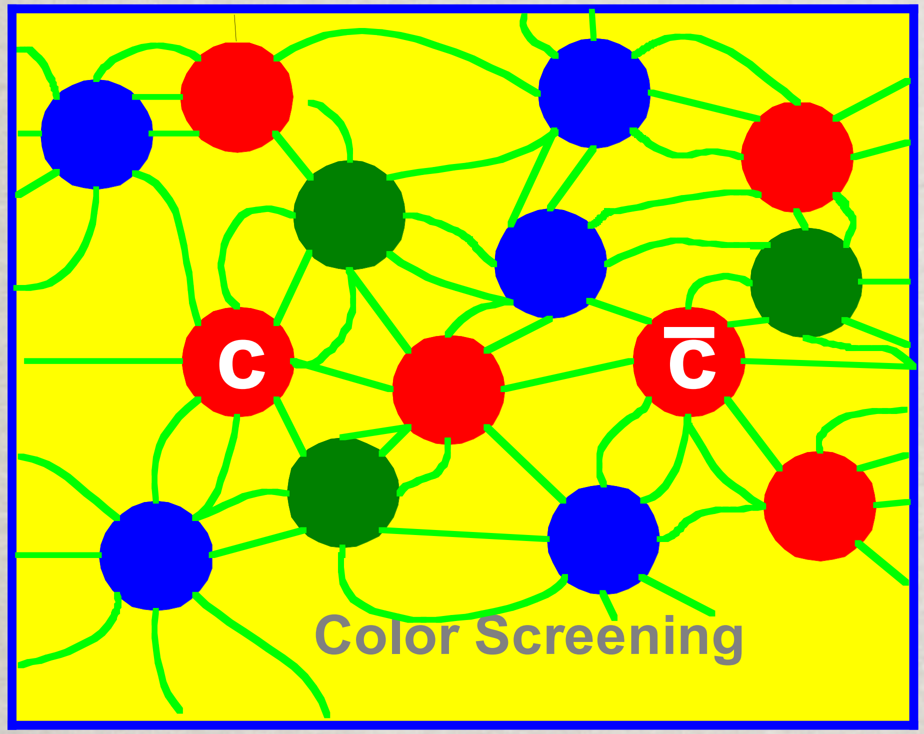

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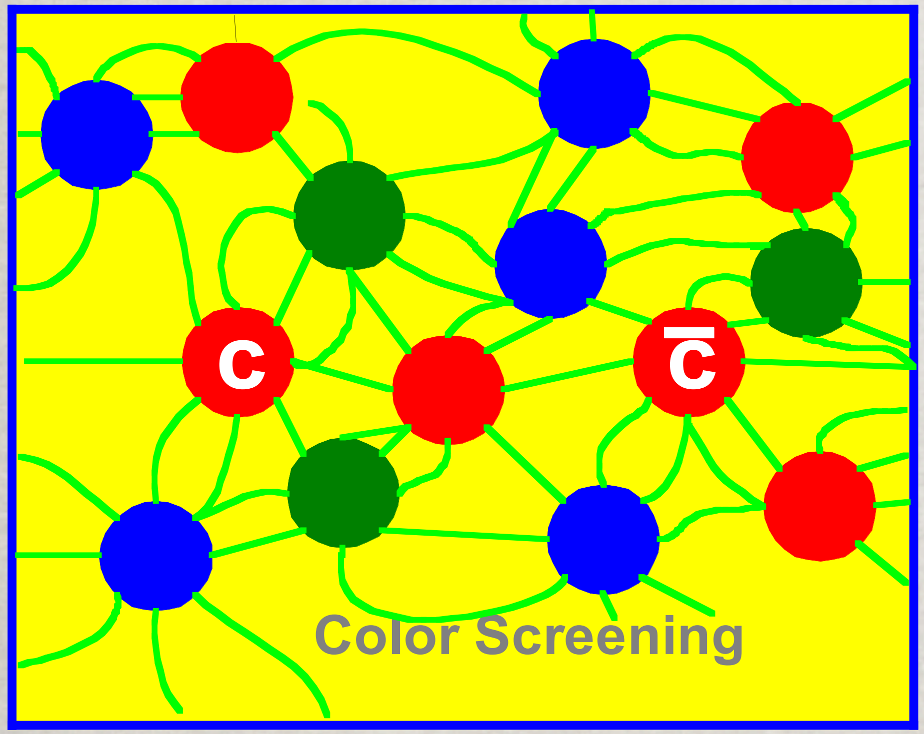

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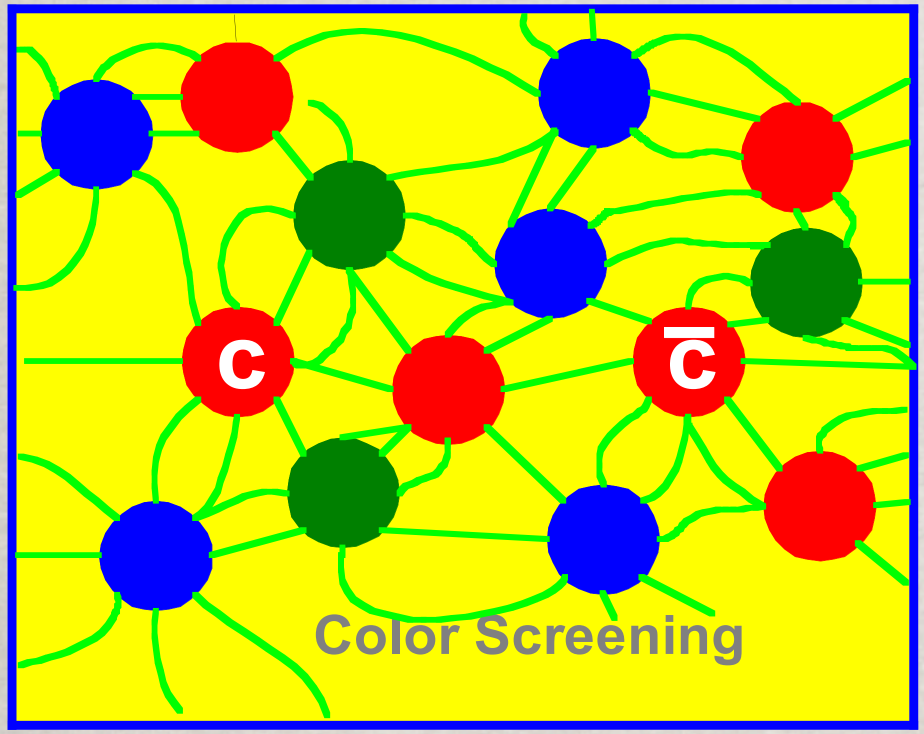

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quarkonia dissociate at different temperature in dependence of their radius: they are a Quark Gluon Plasma thermometer

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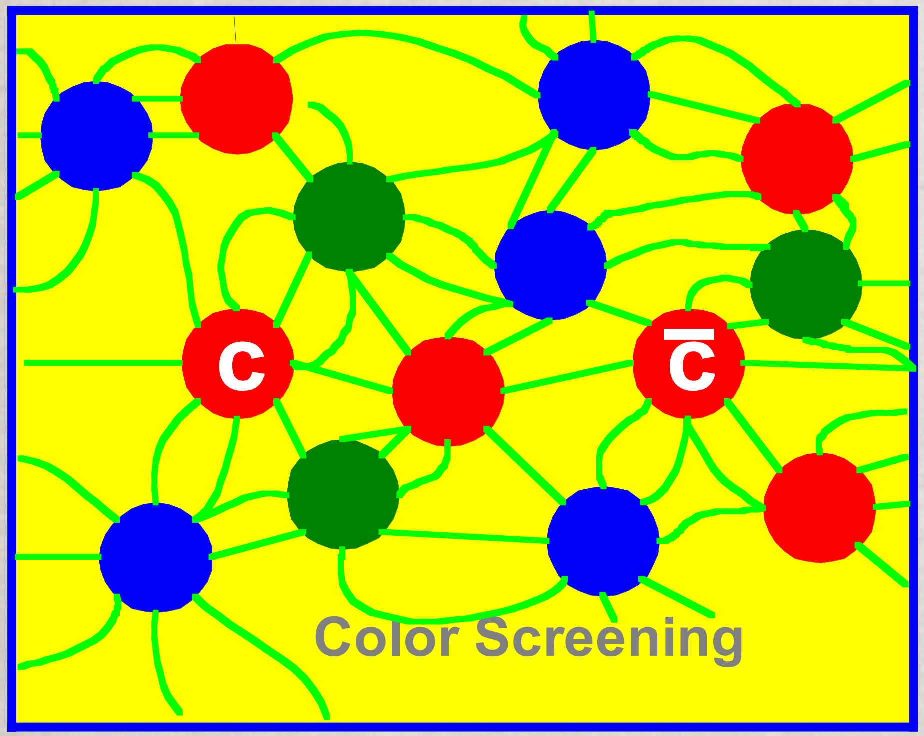

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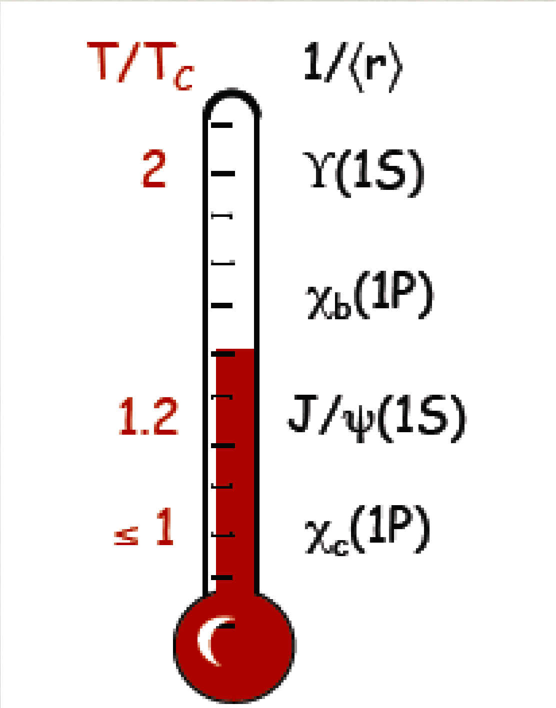

Quarkonium Today is
a golden system to study strong interactions

many experimental data and opportunities

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a golden system to study strong interactions

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

Today: new data

B-FACTORIES: Heavy Mesons Factories

CLEO-c BESII tau charm factories

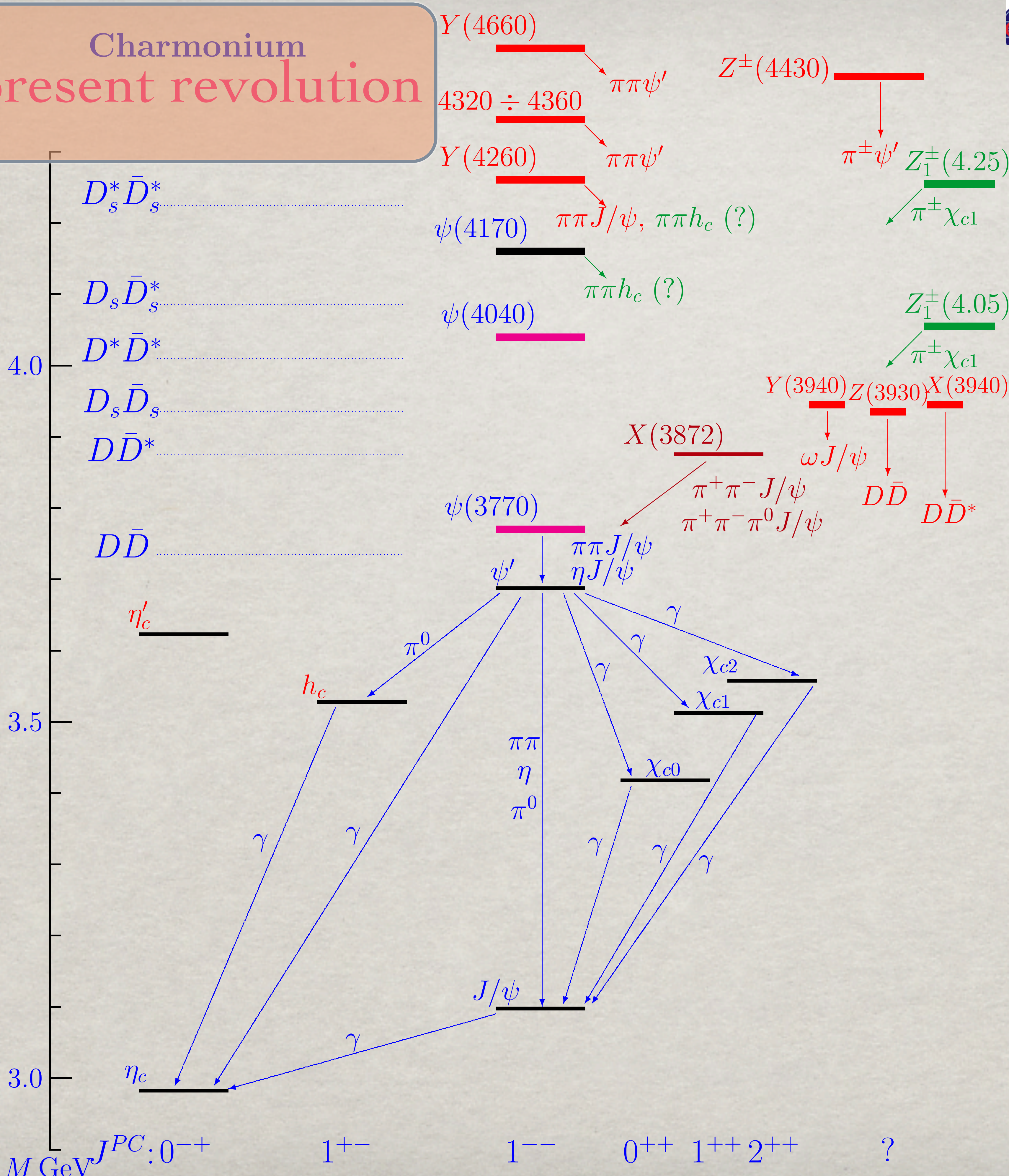
CLEO-III bottomonium factory

Fermilab CDF, D0, E835

Hera RHIC (Star, Phenix), NA60

Charmonium

the present revolution



THE COLLIDER DETECTOR AT FERMILAB

DØ

BELLE

BABAR

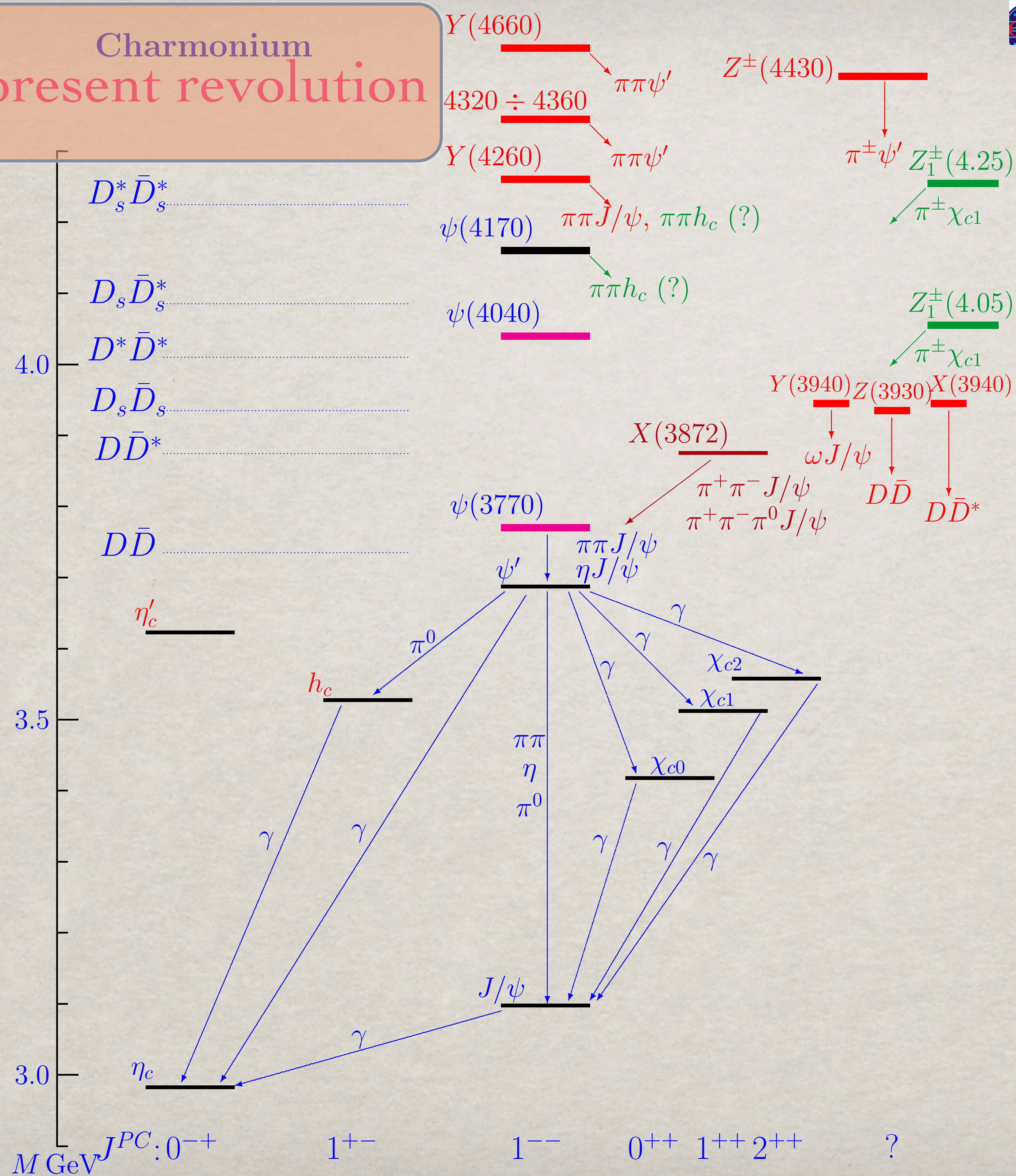
Collaboration Home Page

BES

CLEO

Charmonium

the present revolution



THE COLLIDER DETECTOR AT FERMILAB

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BELLE

BABAR Collaboration Home Page

BES

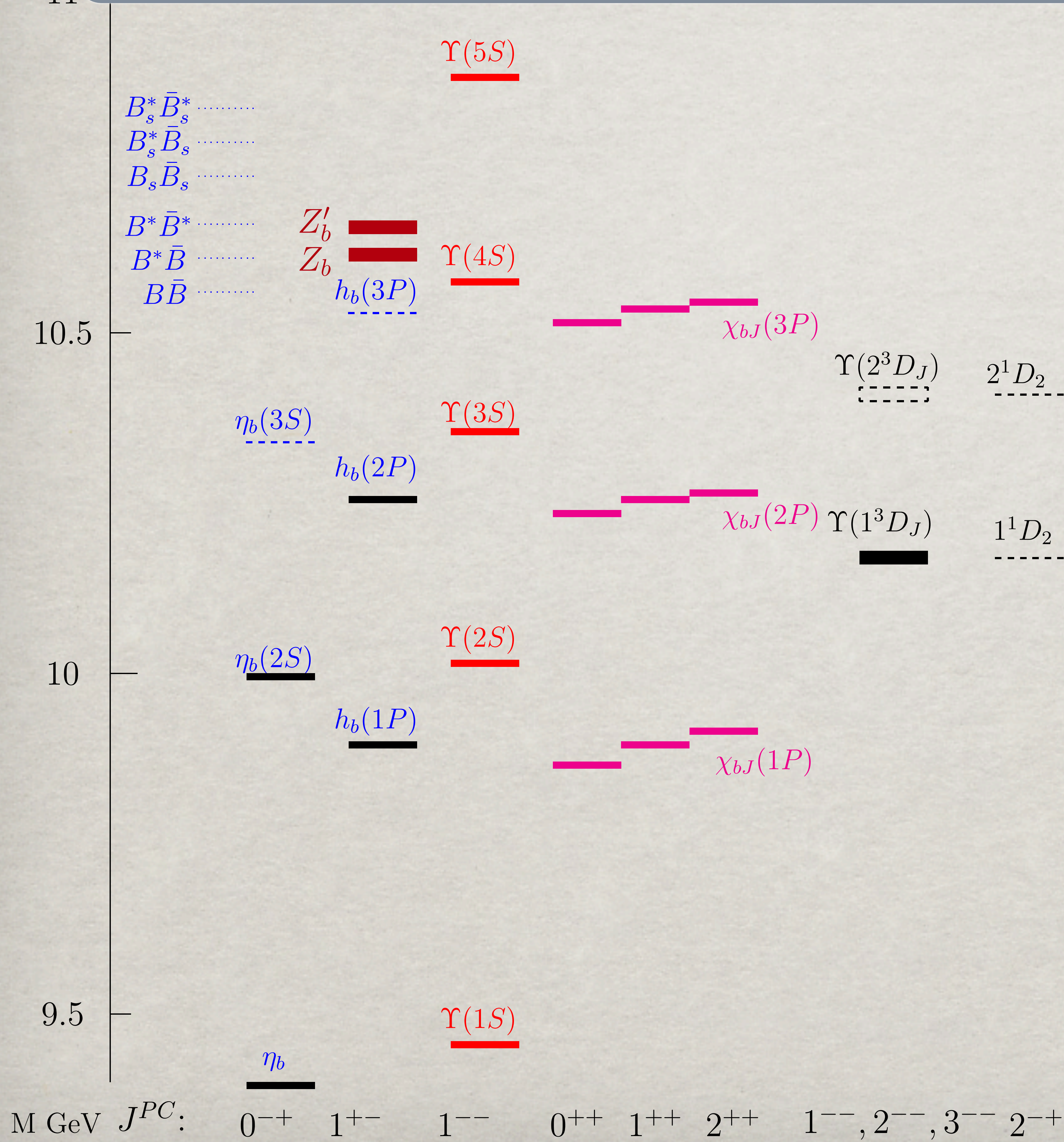
CLEO

ATLAS

CMS

LHCb

bottomonium: the present revolution



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BELLE

BABAR Collaboration Home Page

BES

CLEO

ATLAS

CMS Compact Muon Solenoid

LHCb

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

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BESIII

CMS ATLAS

ALICE

and in the future PANDA, Belle2, SuperB

B-factories: most famous papers

Belle:

Belle S.K. Choi Gyeongsang Natl. U. *et al.*

Detailed record - Cited by 702 records

Belle K. Abe *et al.*

Published in **Phys.Rev.Lett. 87 (2001) 091802**
e-Print: **hep-ex/0107061**

Detailed record - Cited by 581 records

BaBar:

Observation of a narrow meson decaying to $D^+_s\pi^0$ at a mass of 2.32-GeV
BABAR Collaboration (Bernard Aubert (Annecy, LAPP) *et al.*). Apr 2003. 7 pp. hep-ex/0304021,SLAC-PUB-9711,BABAR-PUB-03-011.
Published in **Phys.Rev.Lett. 90 (2003) 242001**
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Detailed record - Cited by 605 records

2.**Observation of CP violation in the B^0 meson system.**
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hep-ex/0107013,SLAC-PUB-8904,BABAR-PUB-01-18.
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First Discovery at LHC:

Observation of a new χ_b state in radiative transitions to $\Upsilon(1S)$ and $\Upsilon(2S)$ at ATLAS.
ATLAS Collaboration (Georges Aad *et al.*). Dec 2011. 4 pp.
CERN-PH-EP-2011-225.
Published in **Phys. Rev. Lett. 108 (2012) 152001**
e-Print: **arXiv:1112.5154 [hep-ex]**

$$\chi_b(3P)$$

QCD theory of Quarkonium: a very hard problem

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

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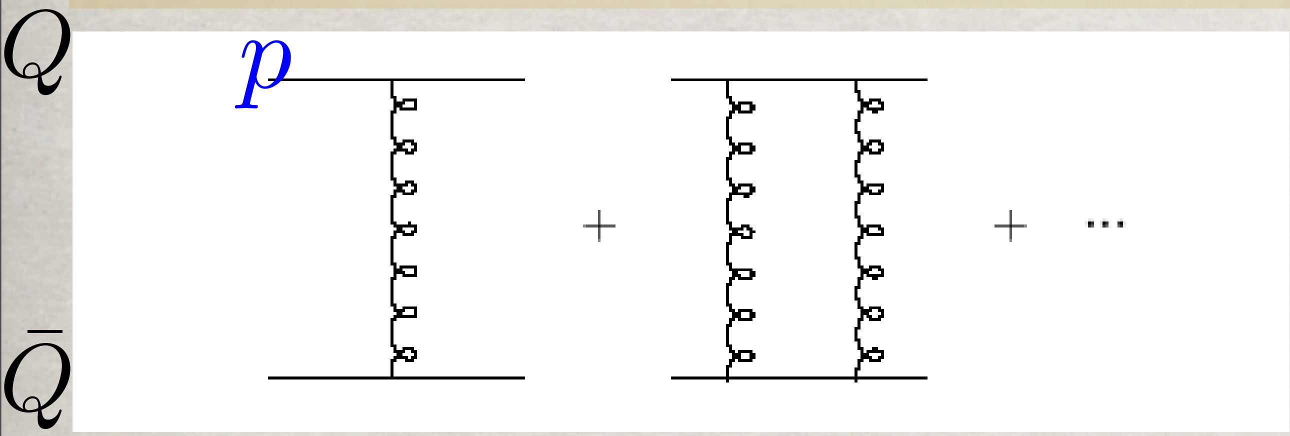

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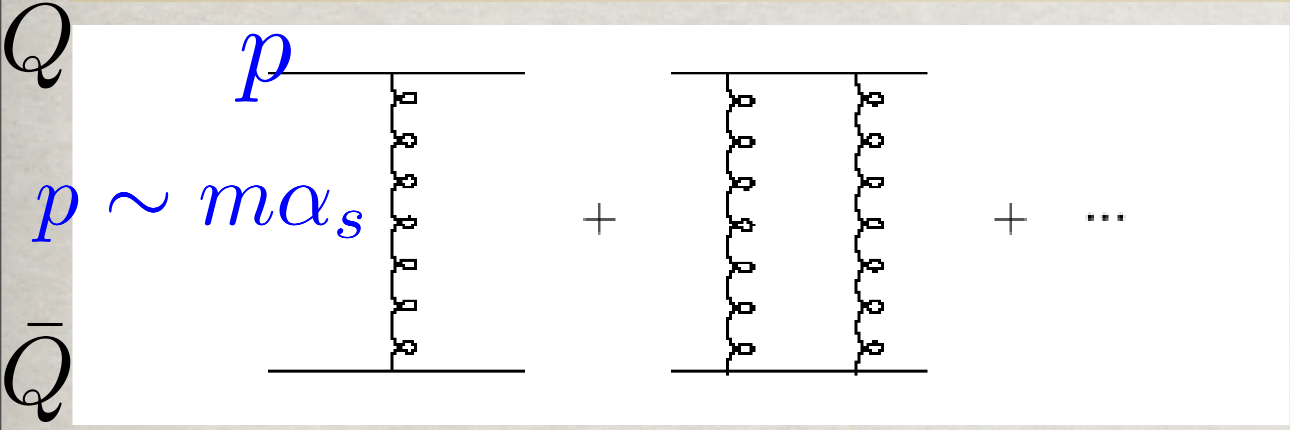

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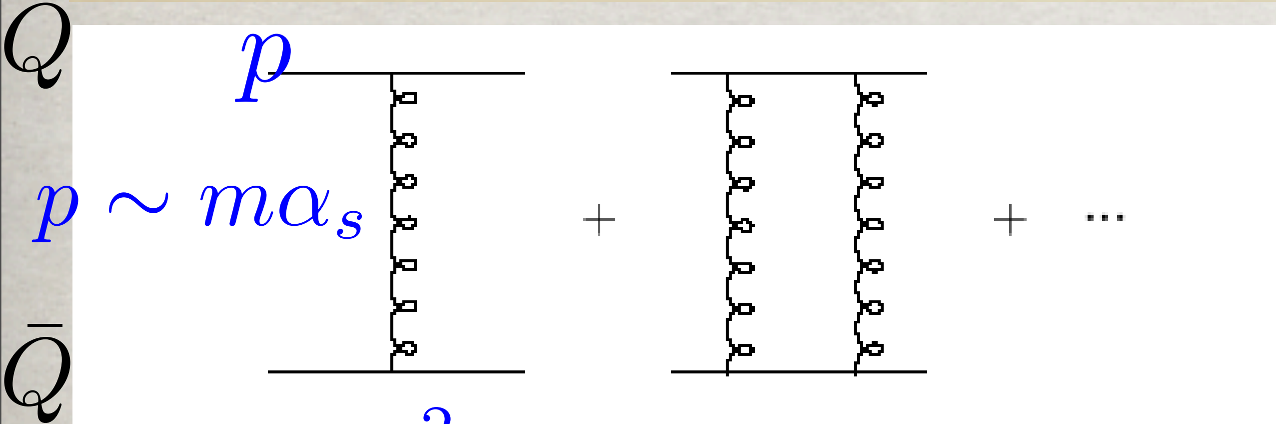


$$\frac{g^2}{p^2}\left(1 + \frac{m\alpha_s}{p}\right)$$

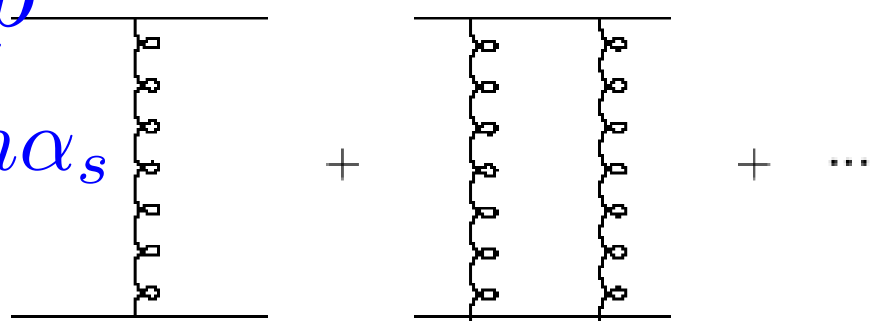
QCD theory of Quarkonium: a very hard problem

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

Q p

$p \sim m\alpha_s$

$\bar{Q}$



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

QCD theory of Quarkonium: a very hard problem

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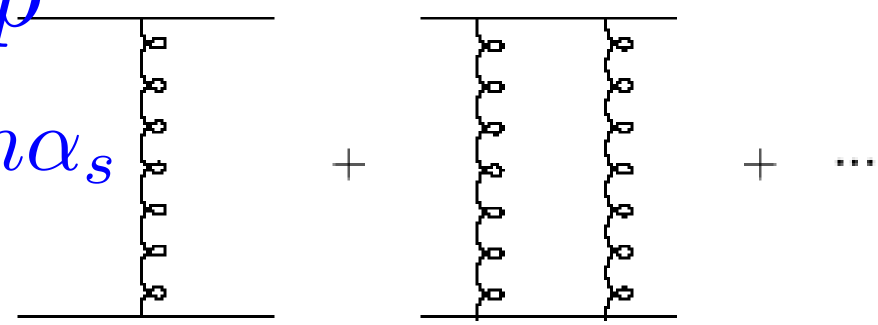
Q $\quad p$

$p \sim m\alpha_s$

$\bar{Q}$



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

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

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

QCD theory of Quarkonium: a very hard problem

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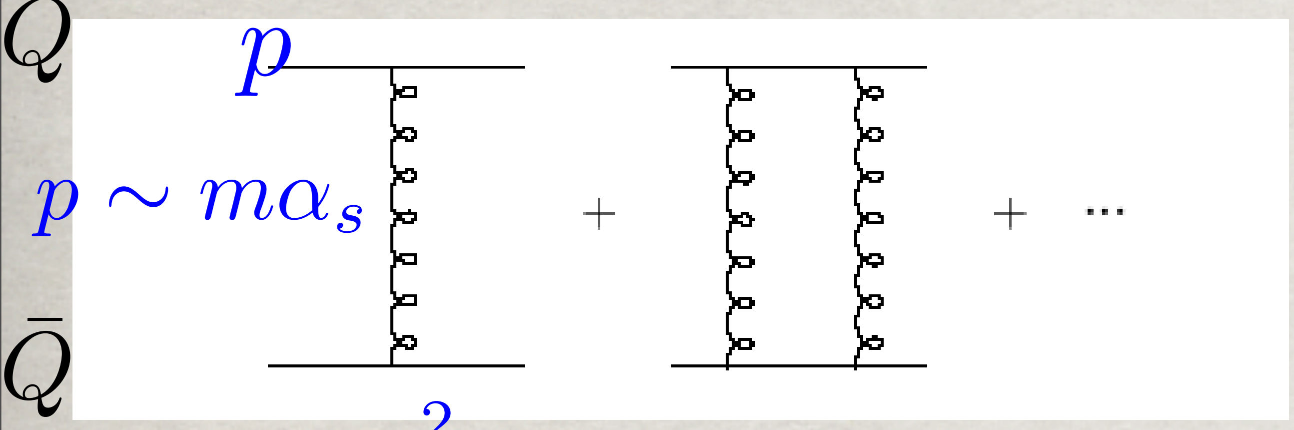

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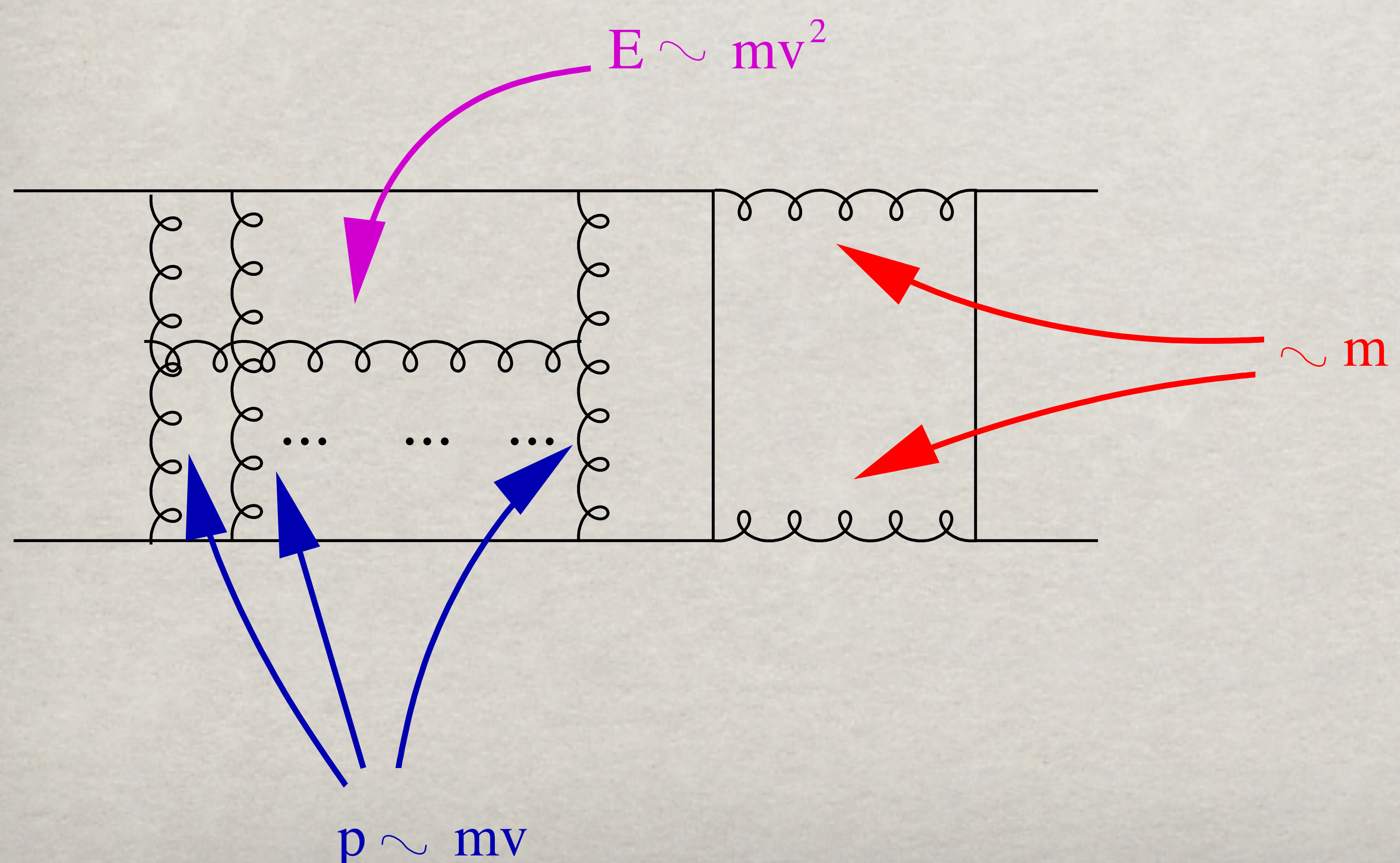
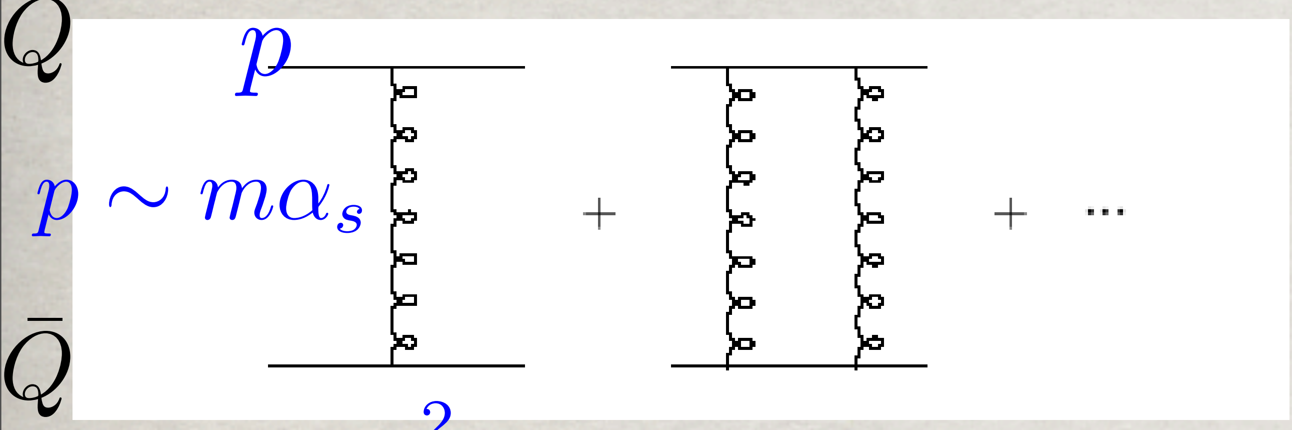
- From $(\frac{p^2}{m} + V)\phi = E\phi \rightarrow p \sim mv$ and $E = \frac{p^2}{m} + V \sim mv^2$.



QCD theory of Quarkonium: a very hard problem

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



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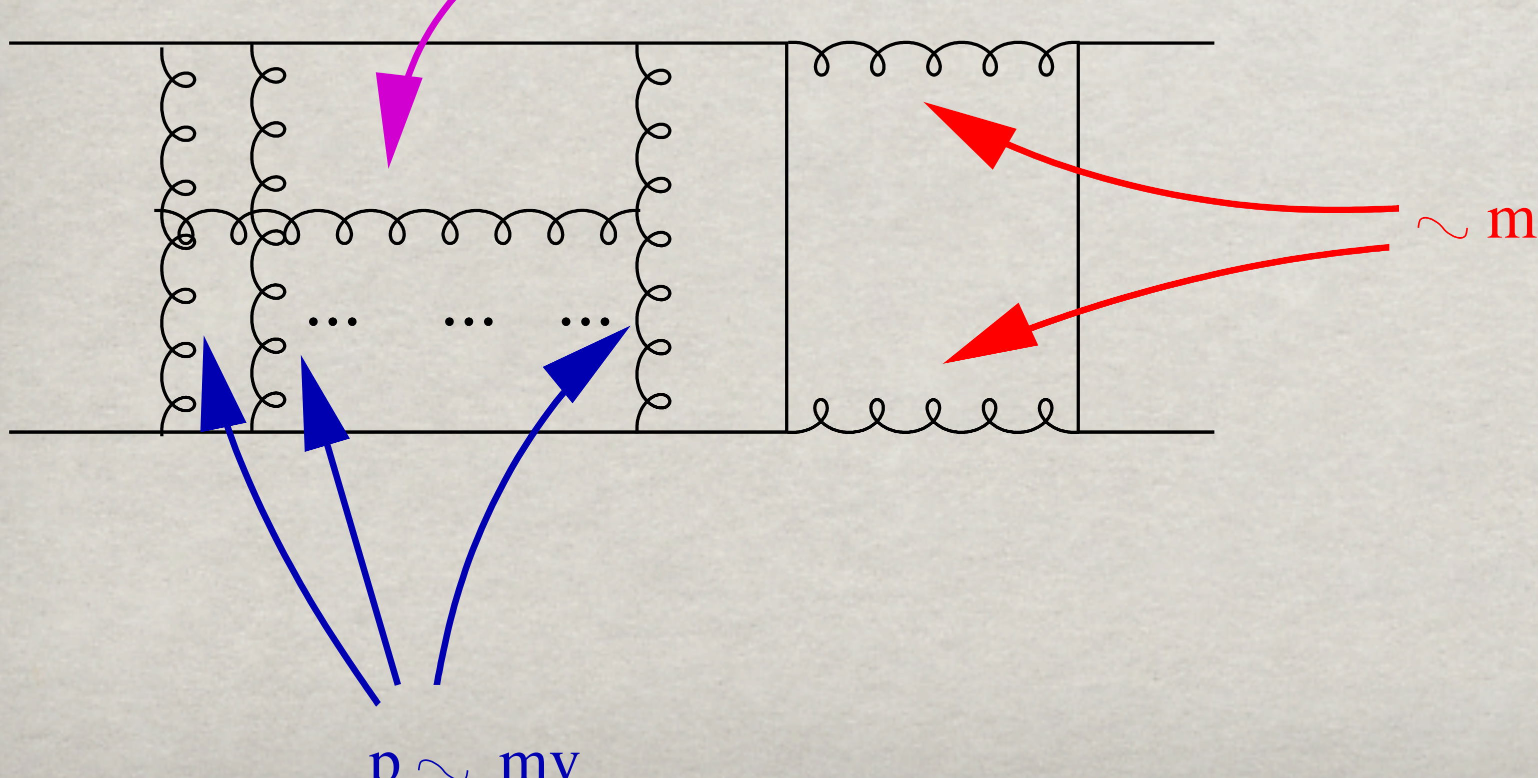
multiscale diagrams have a complicate power counting and contribute to all orders in the coupling



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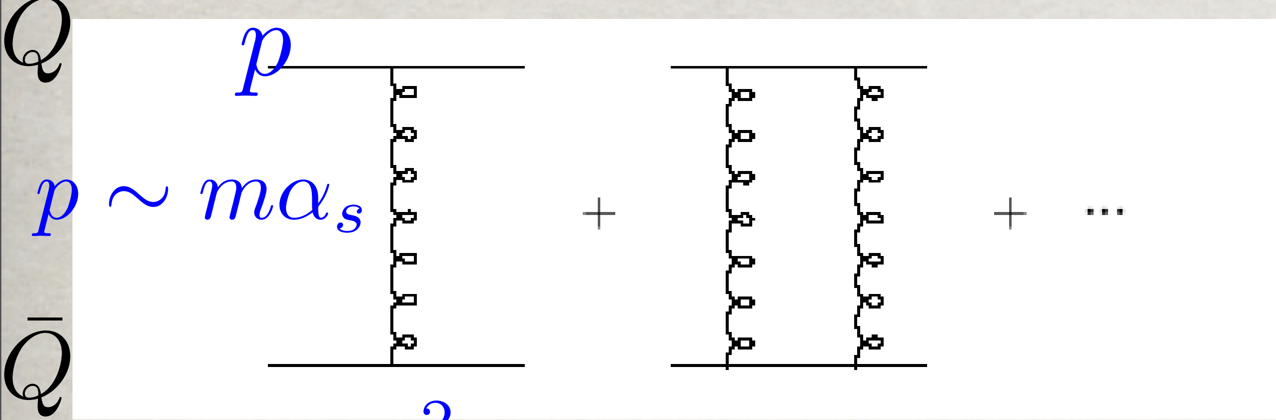

$$\sim \frac{1}{E - (\frac{p^2}{m} + V)}$$

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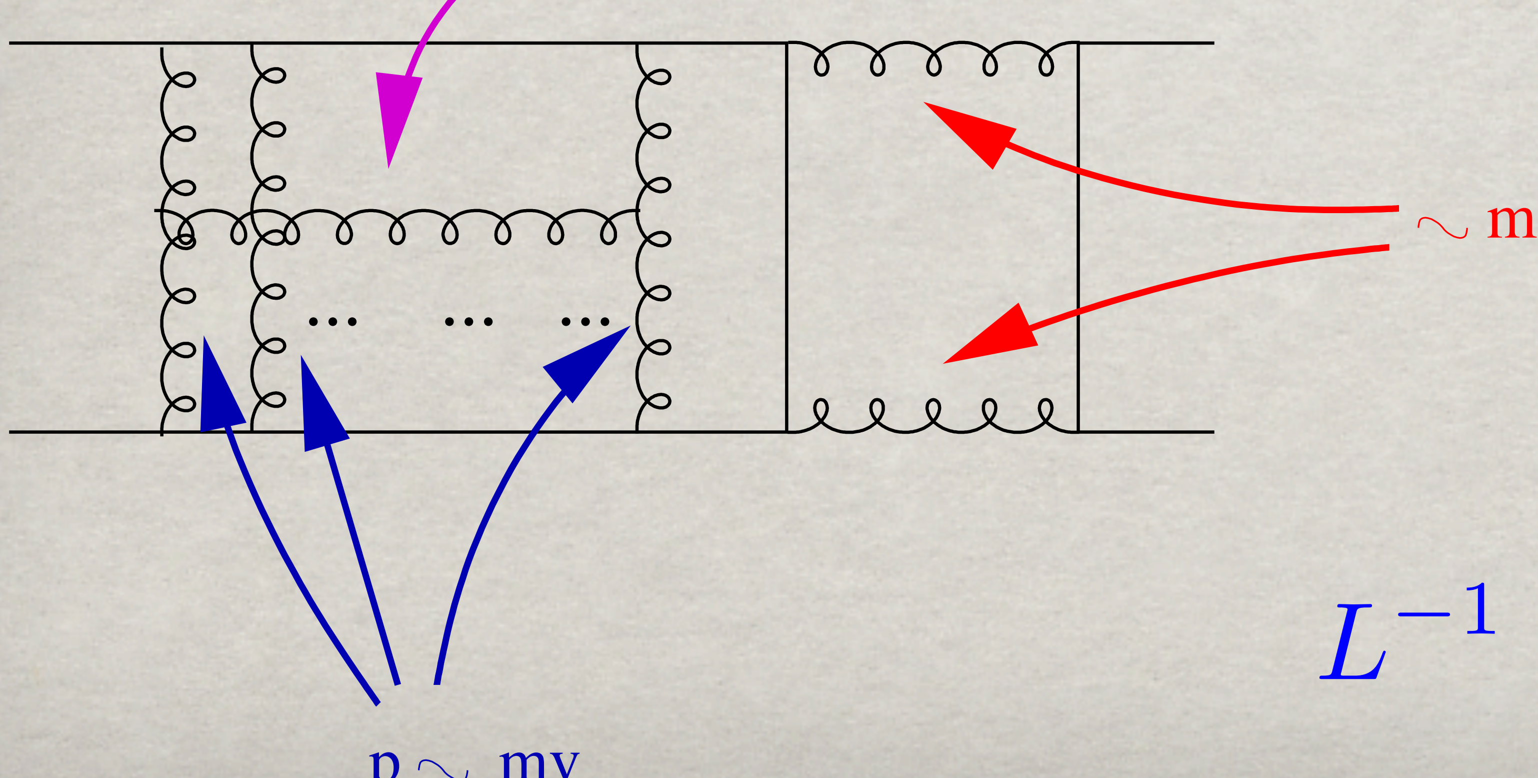
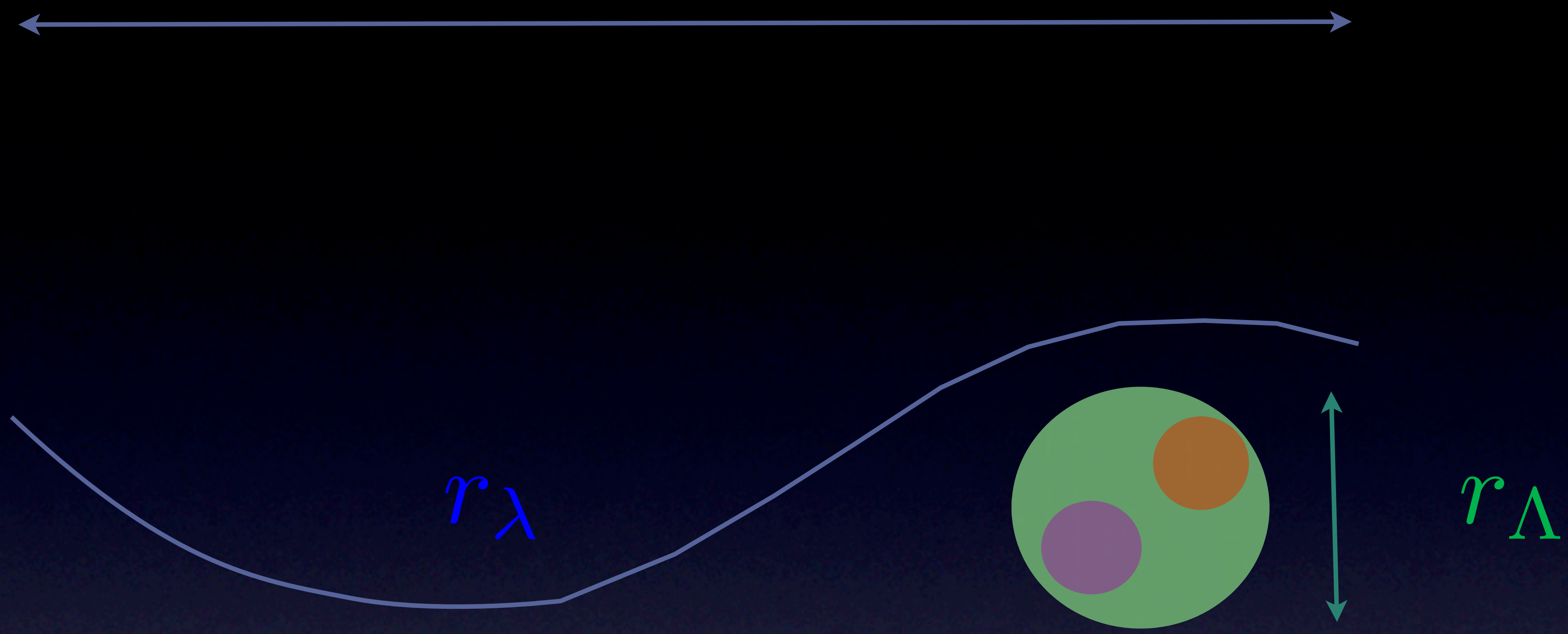


Difficult also for the lattice!

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

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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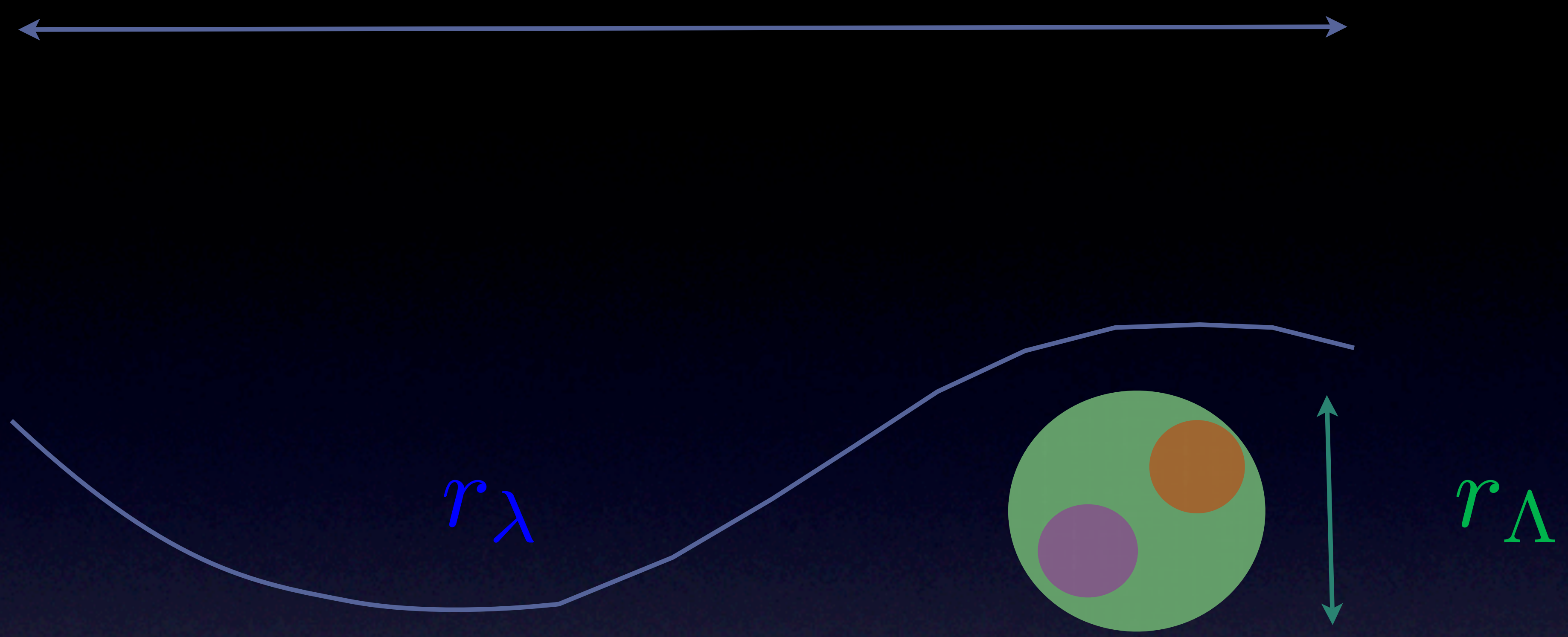

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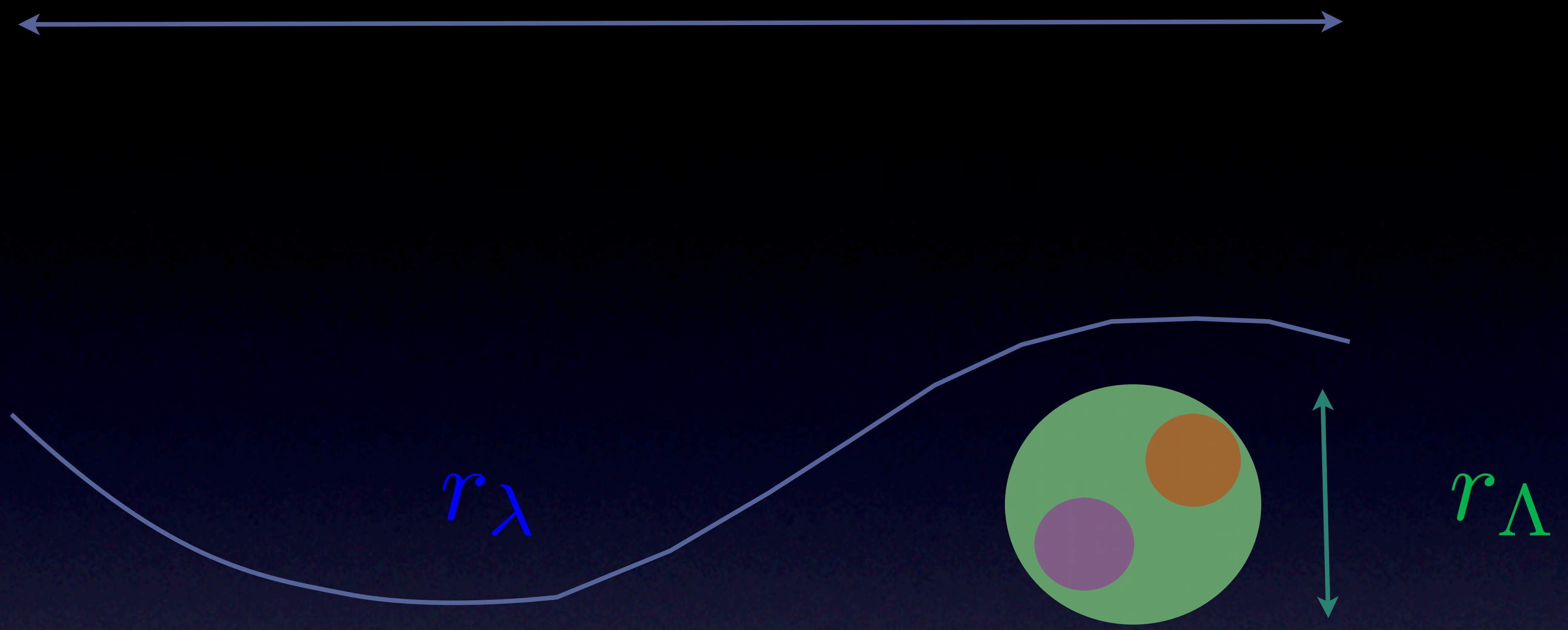

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RANGE OF VALIDITY OF THE EFT: ENERGY $< \mu$

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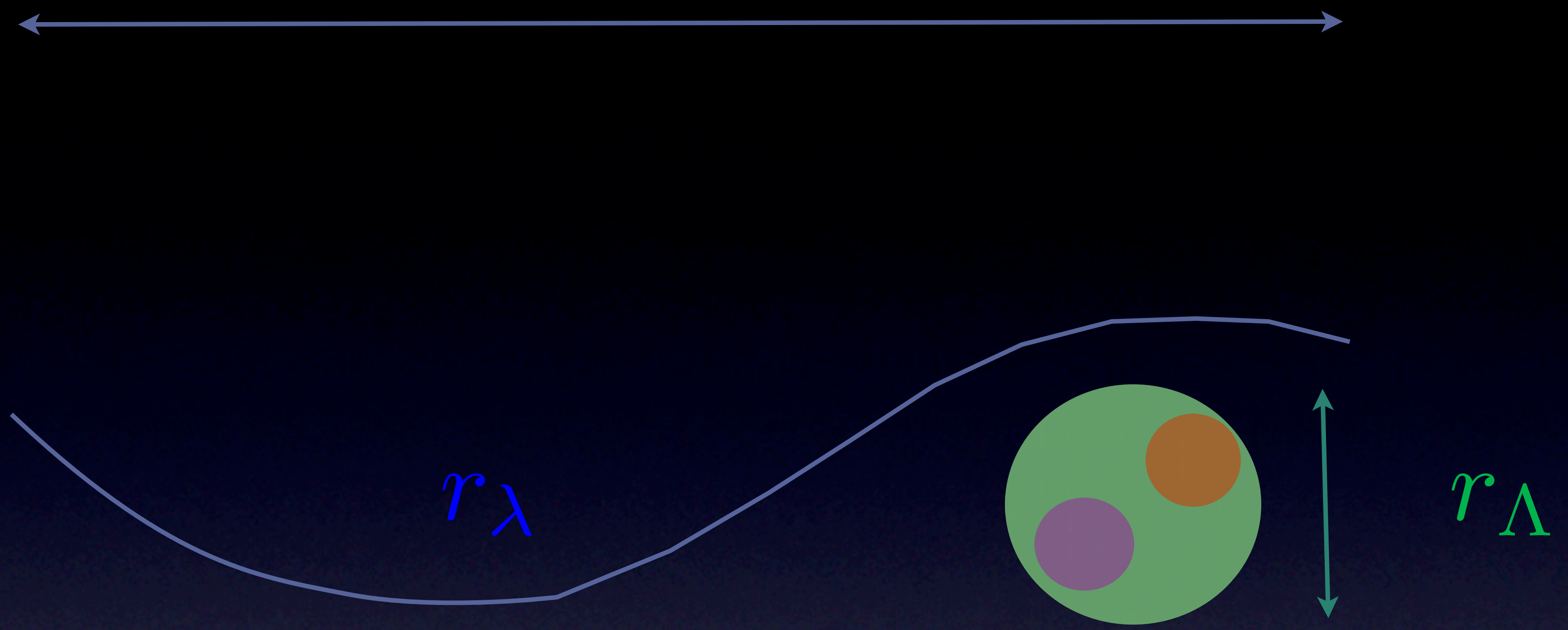

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RANGE OF VALIDITY OF THE EFT: ENERGY $< \mu$

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

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

Wilson coefficient

large scale

Effective Field Theories

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- 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

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

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

QCD Effective Field Theories

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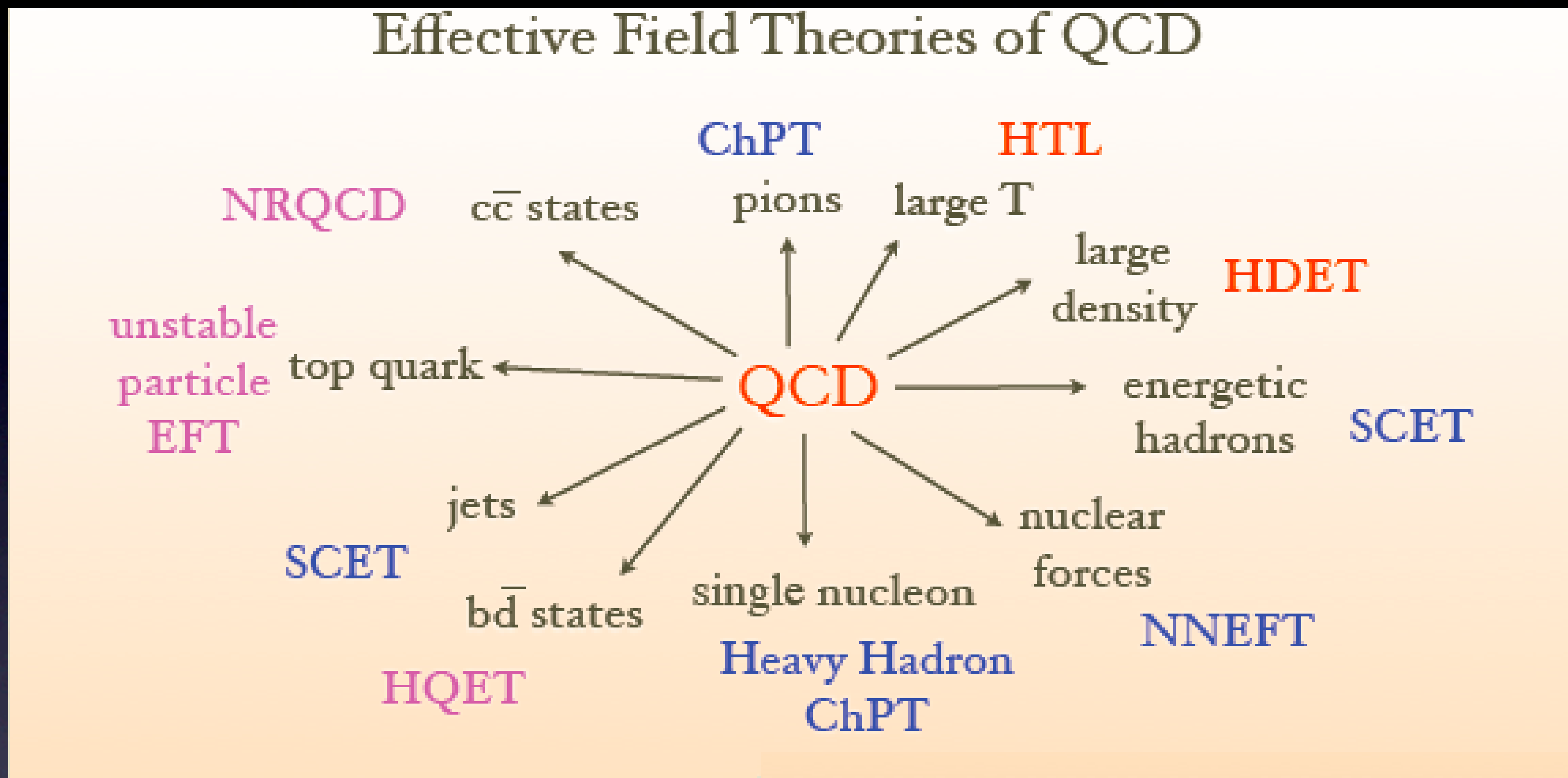
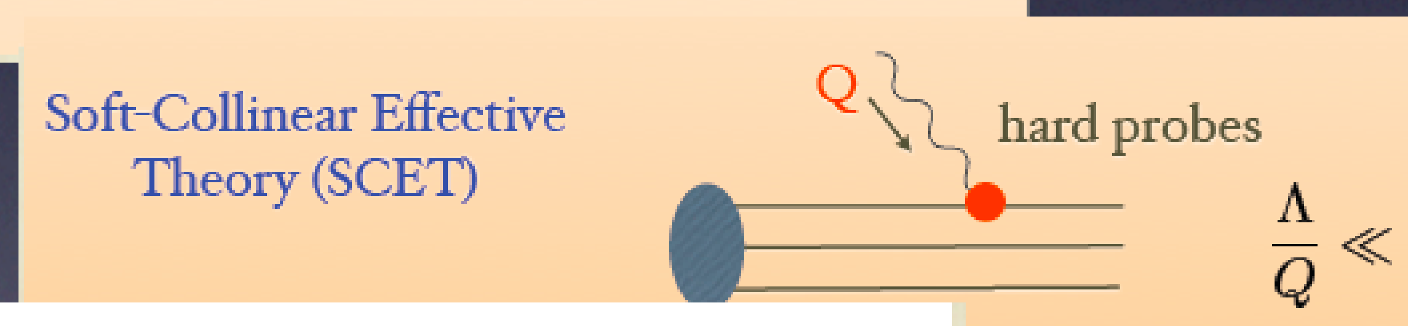
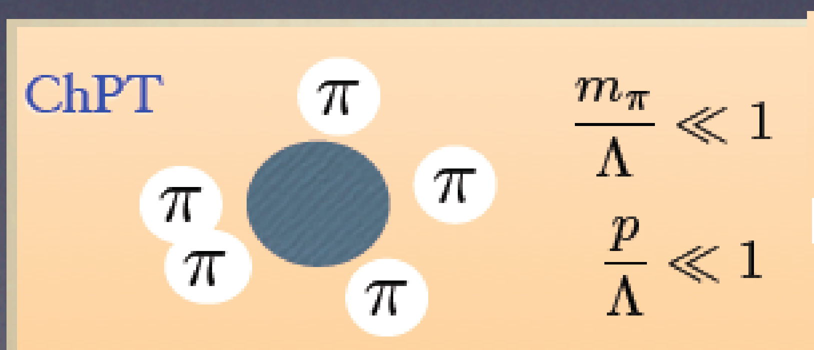
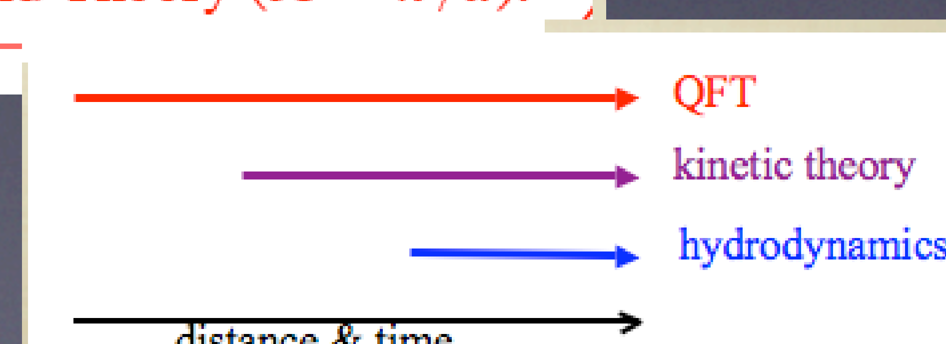


- Heavy quark effective theory (HQET): $\frac{\lambda}{\Lambda} = \frac{\Lambda_{QCD}}{m}$



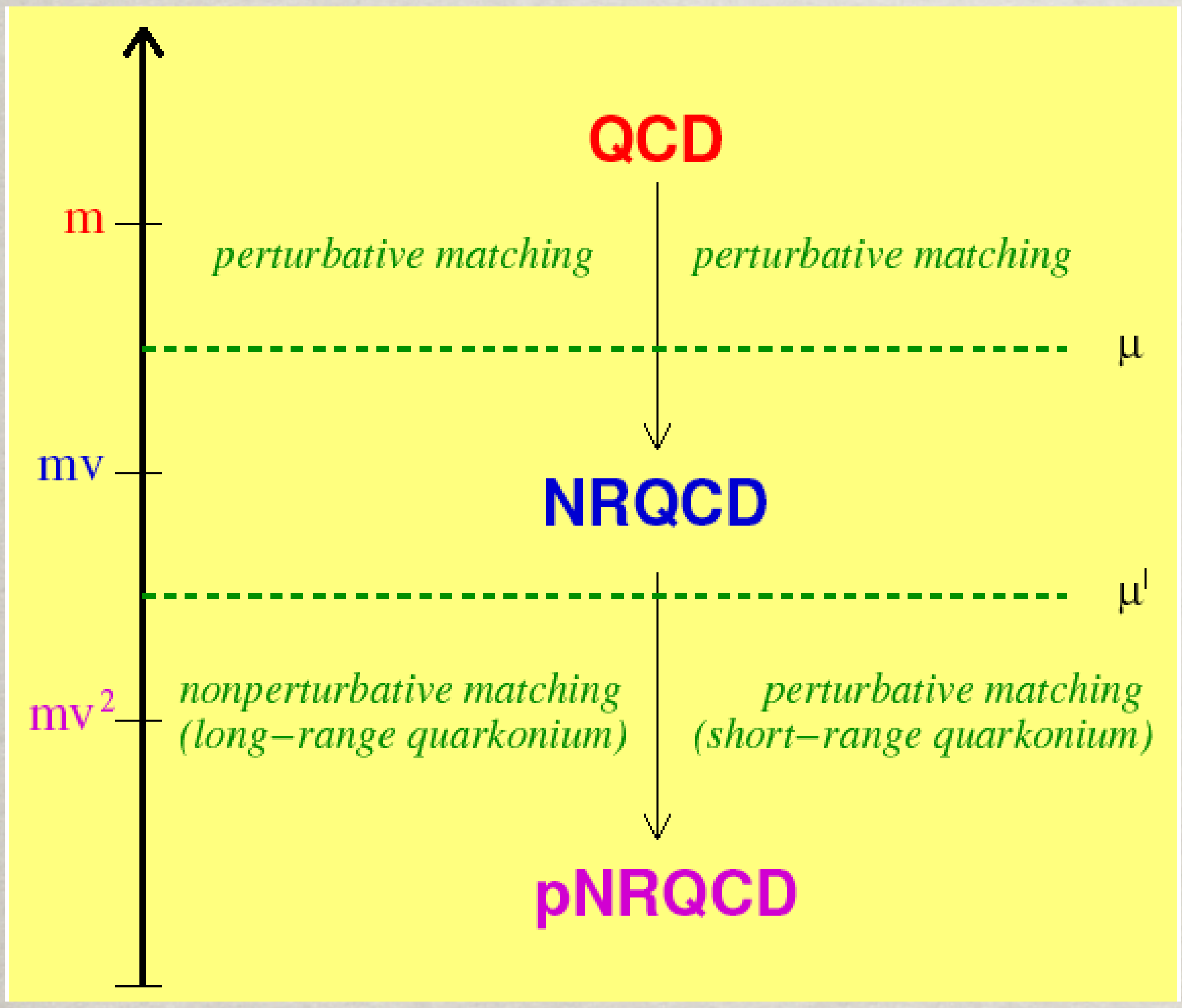


Lattice QCD $\equiv$ Effective Field Theory ($\Lambda = \pi/a$).



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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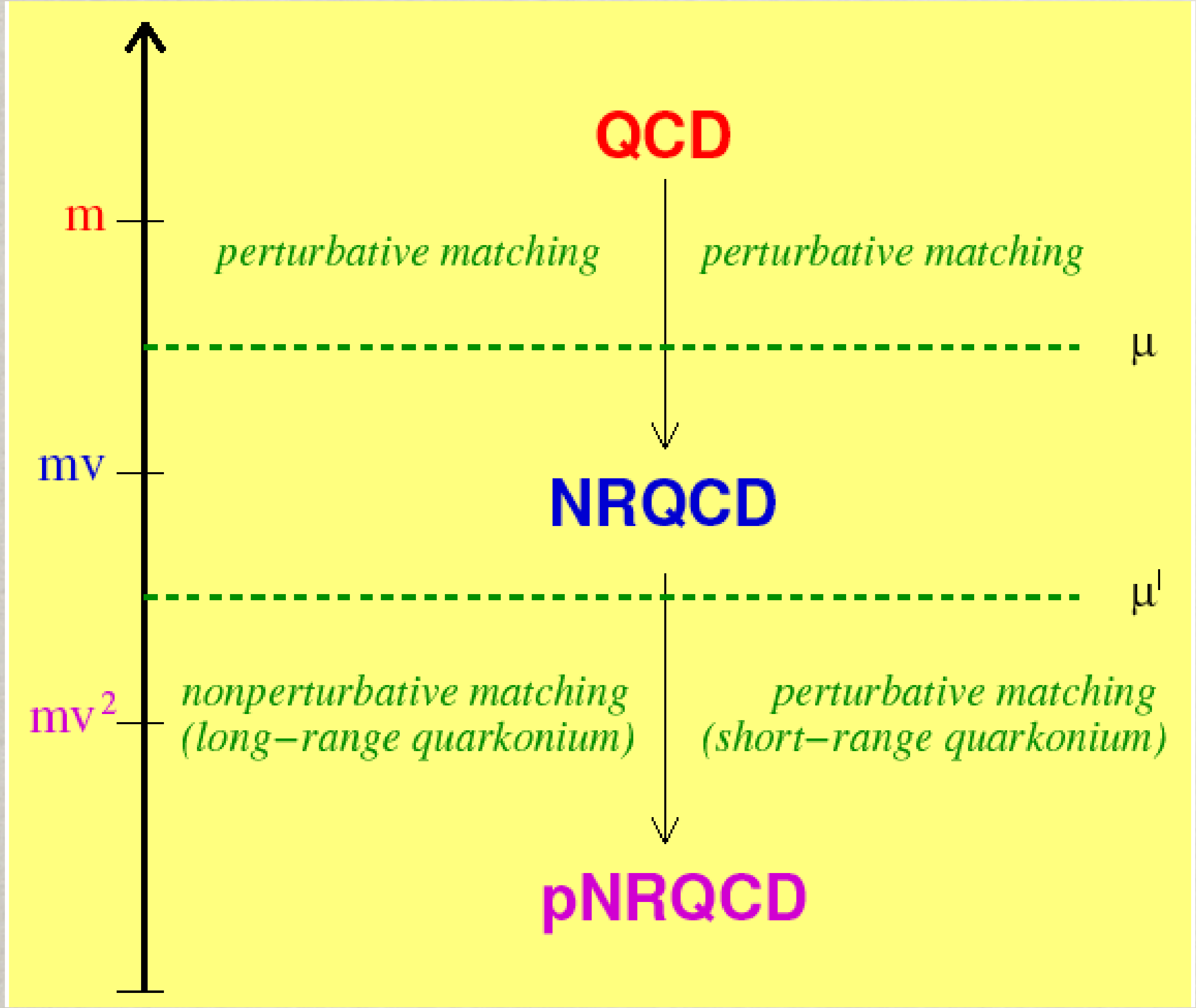

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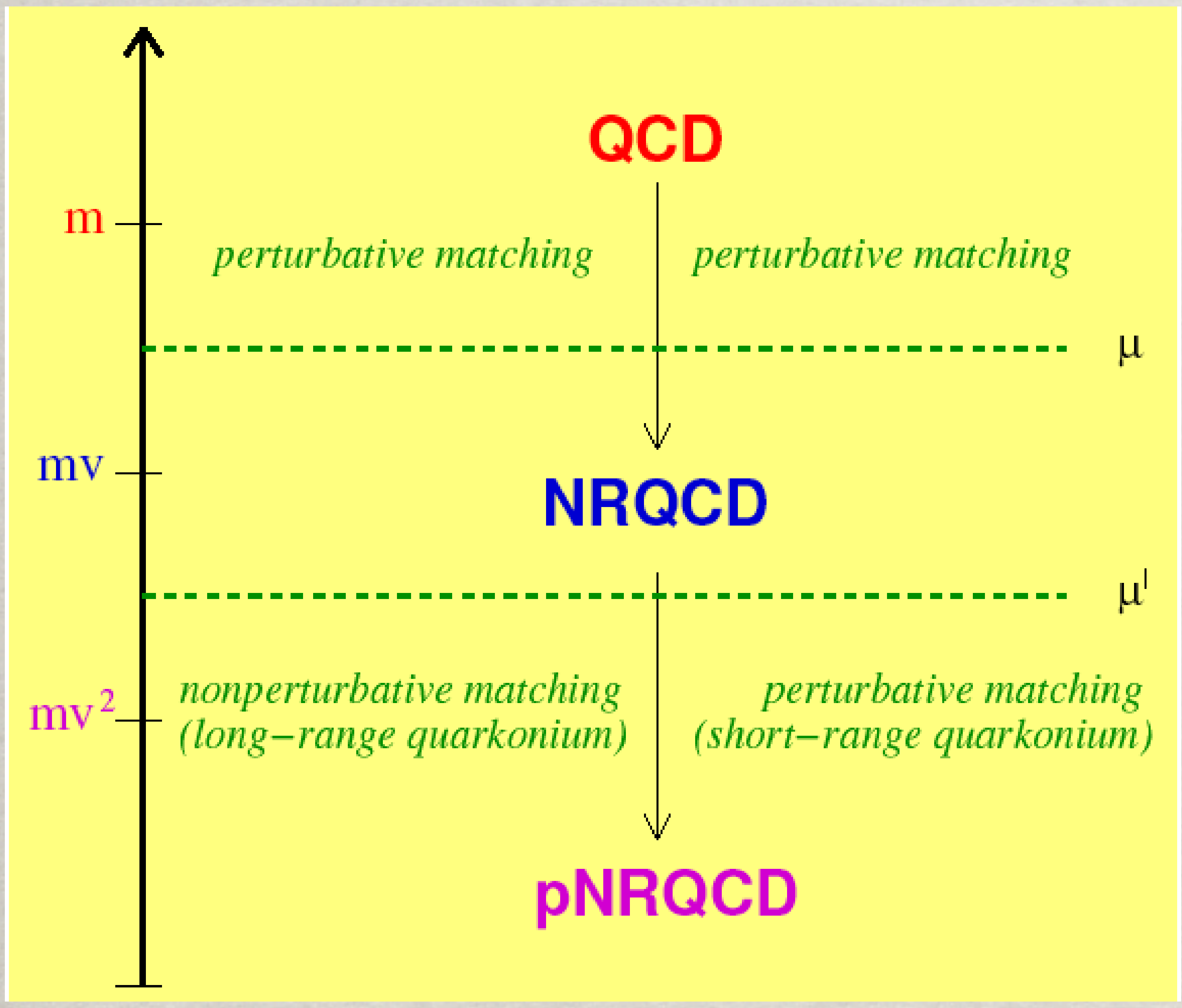

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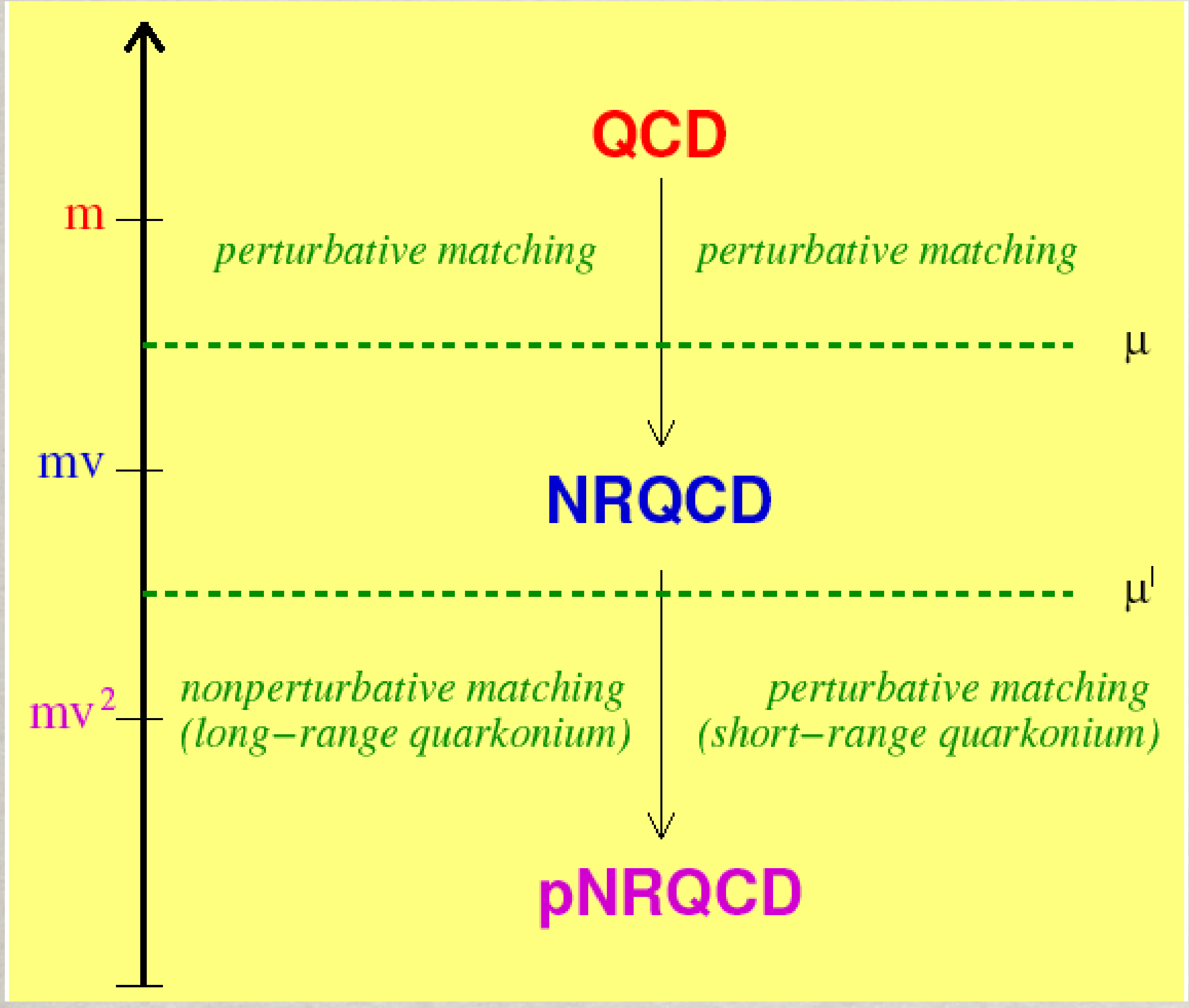

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$$\frac{E_\lambda}{E_\Lambda} = \frac{mv}{m}$$

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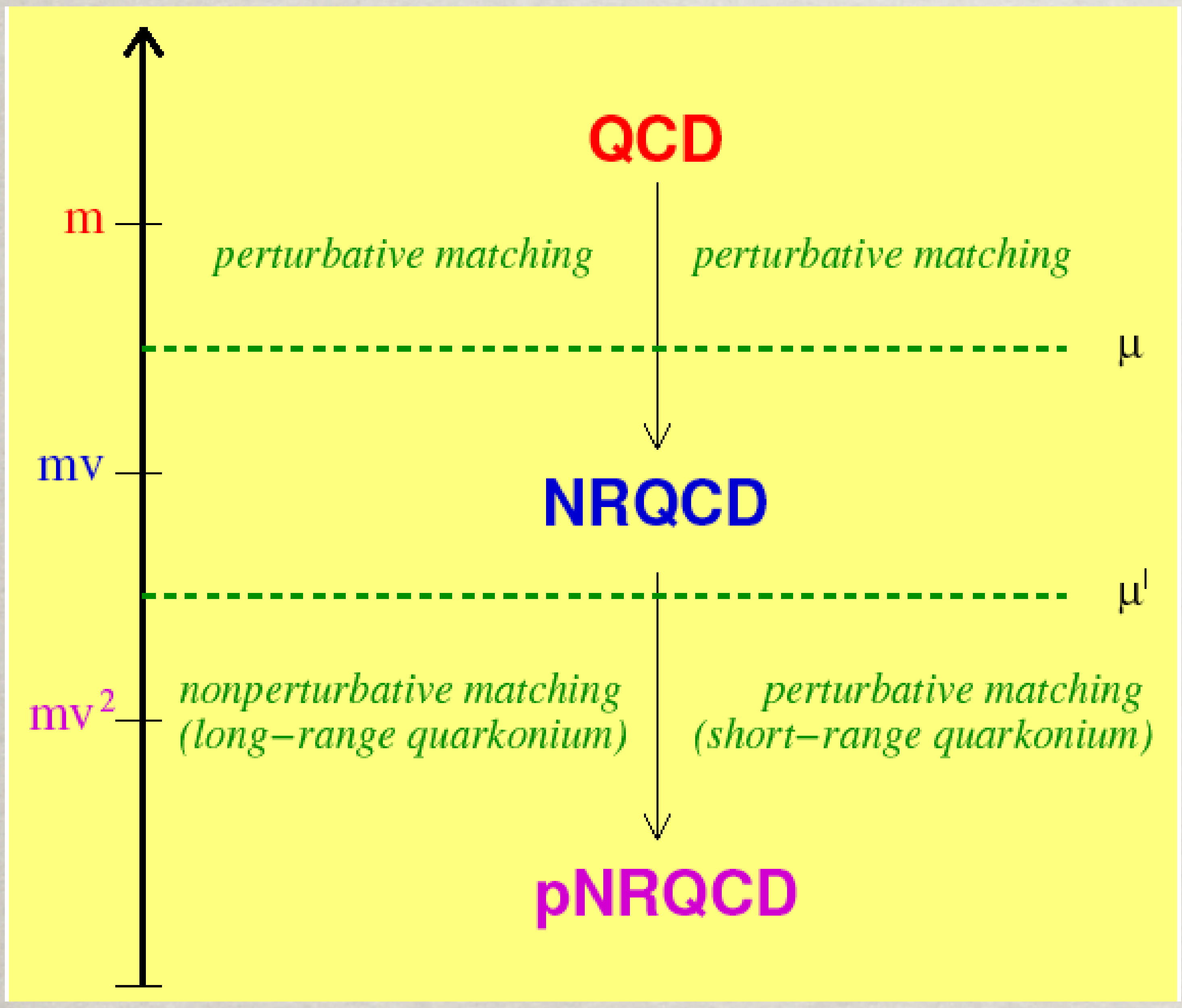

Hard

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

Soft
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momentum)

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

Ultrasoft
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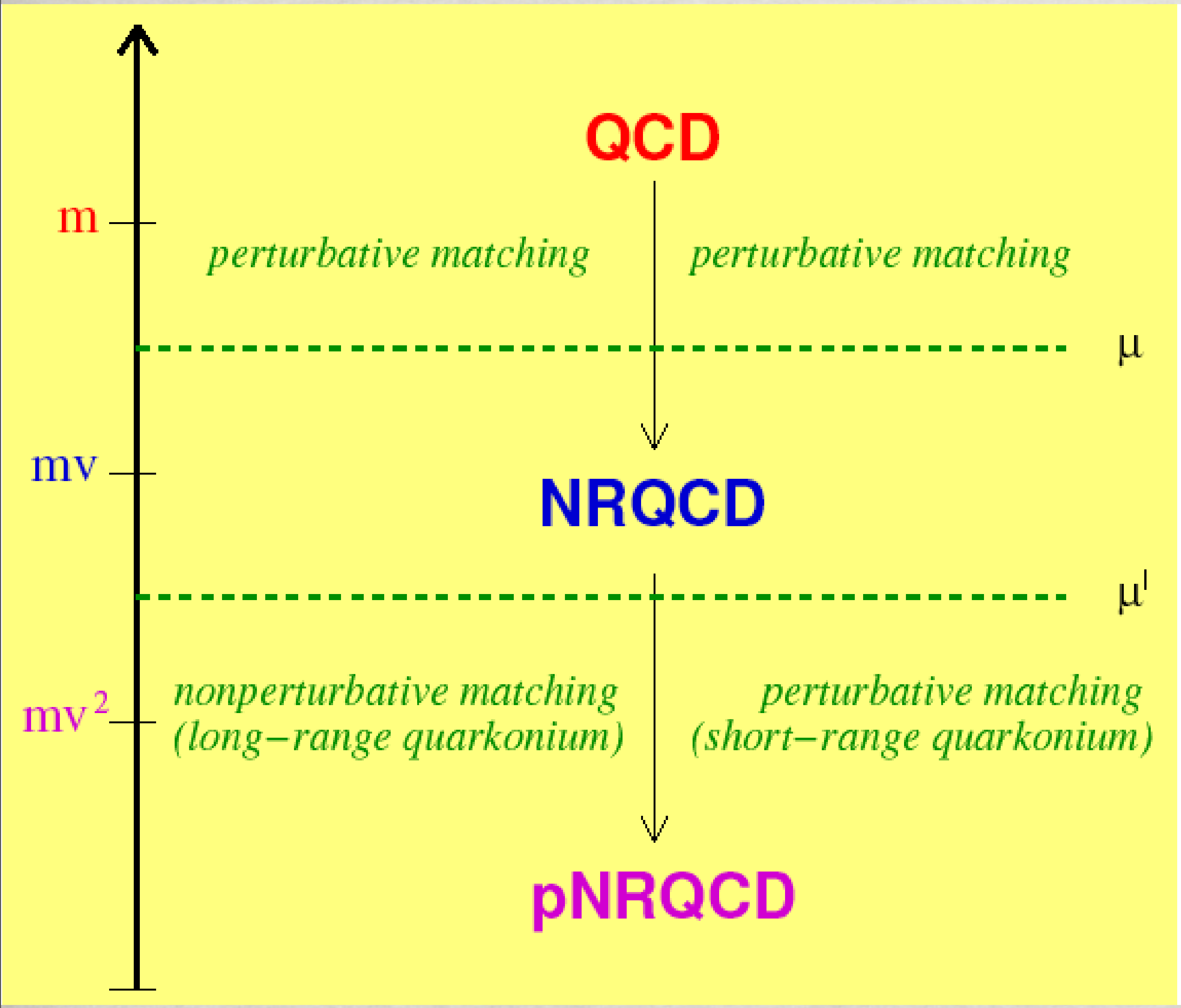
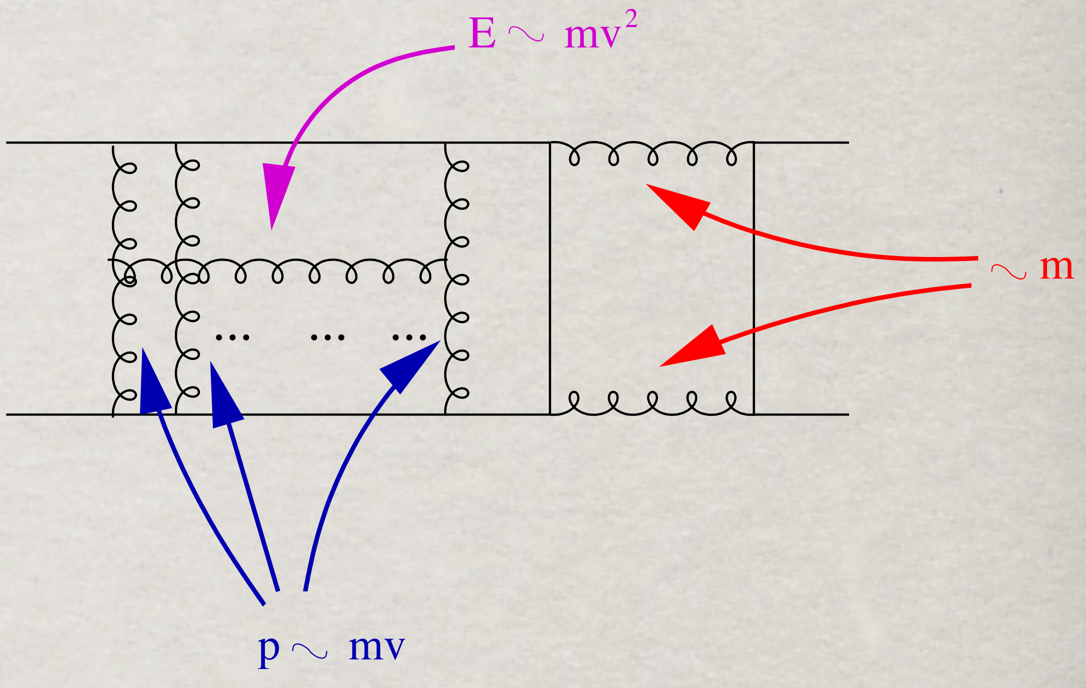
Quarkonium with NR EFT: Non Relativistic QCD (NRQCD)





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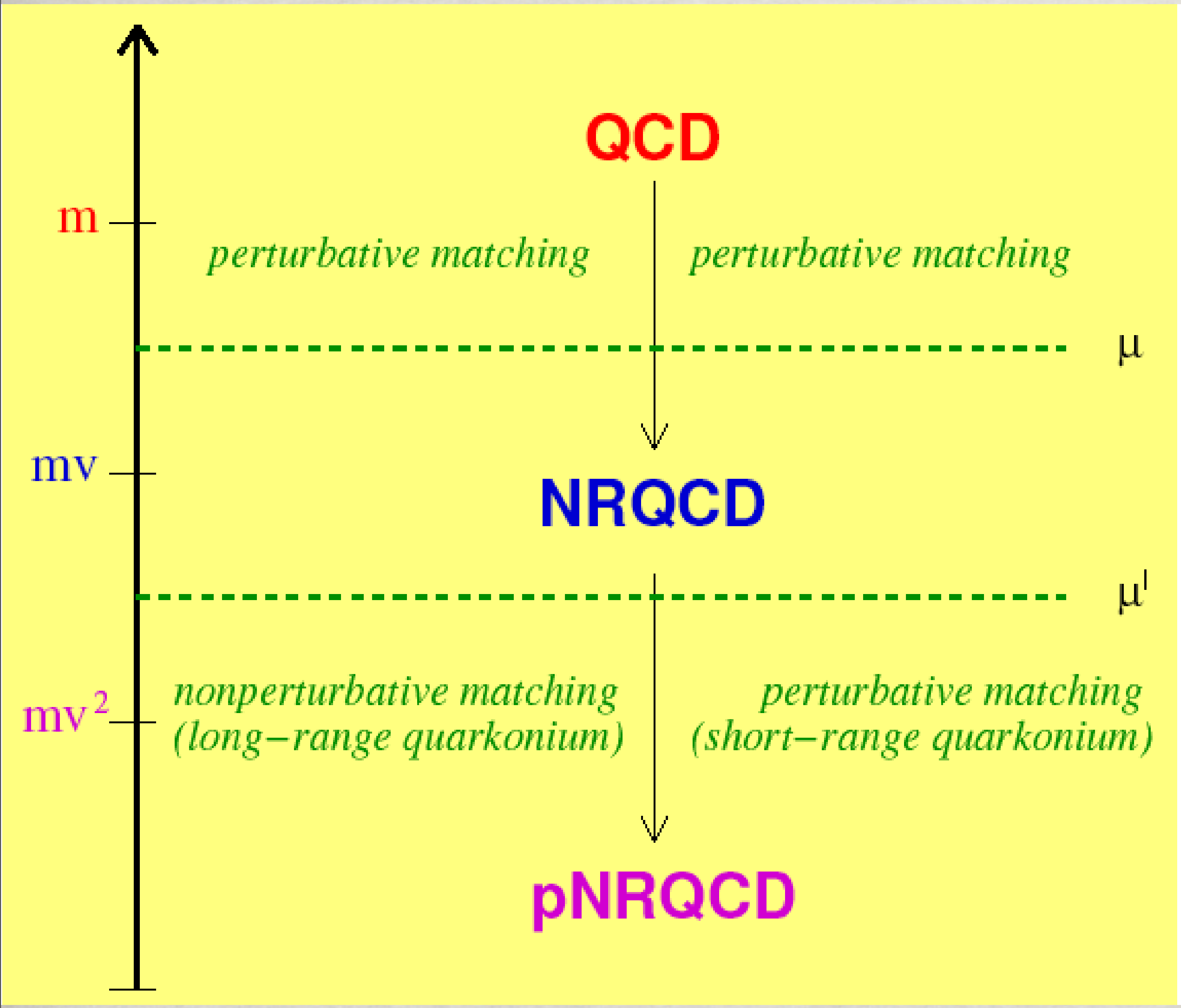

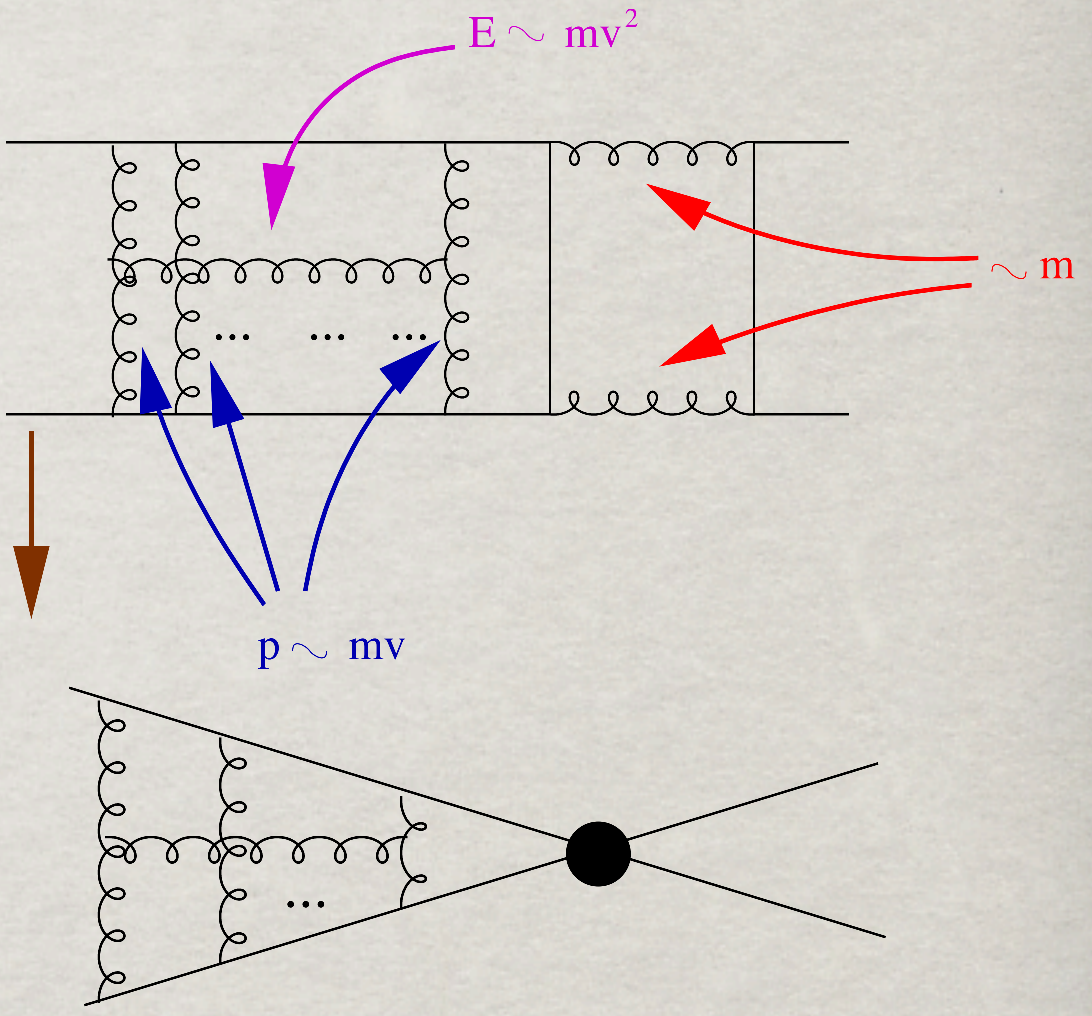

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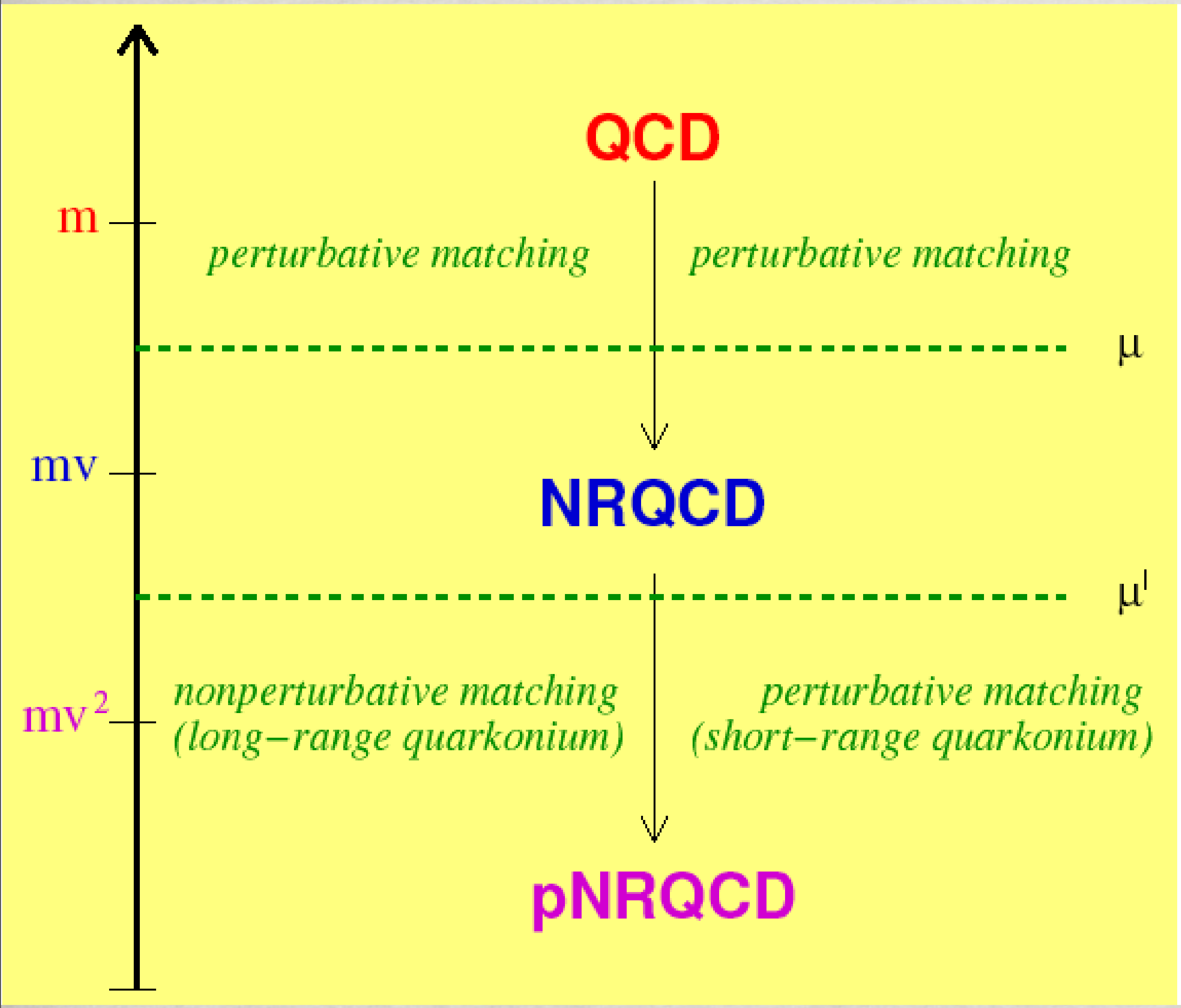
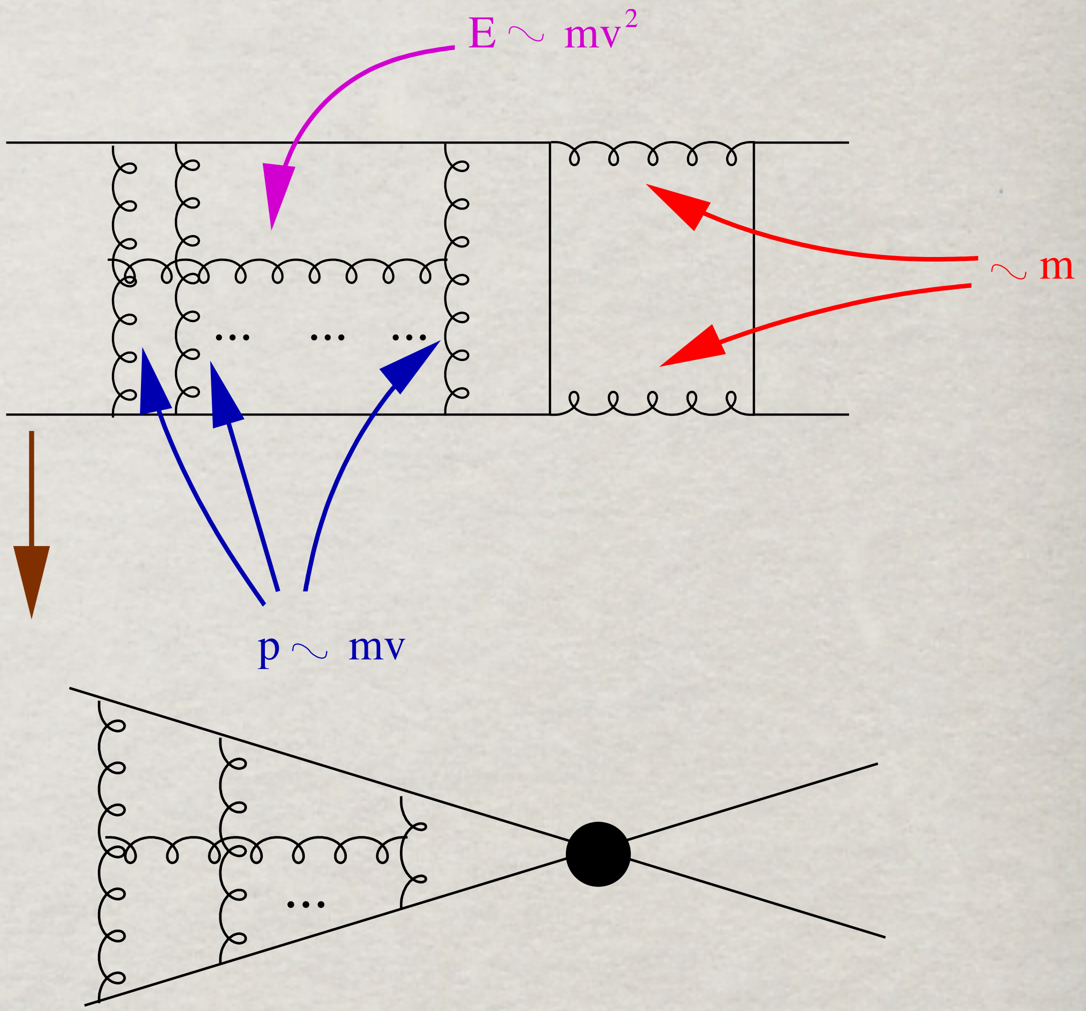
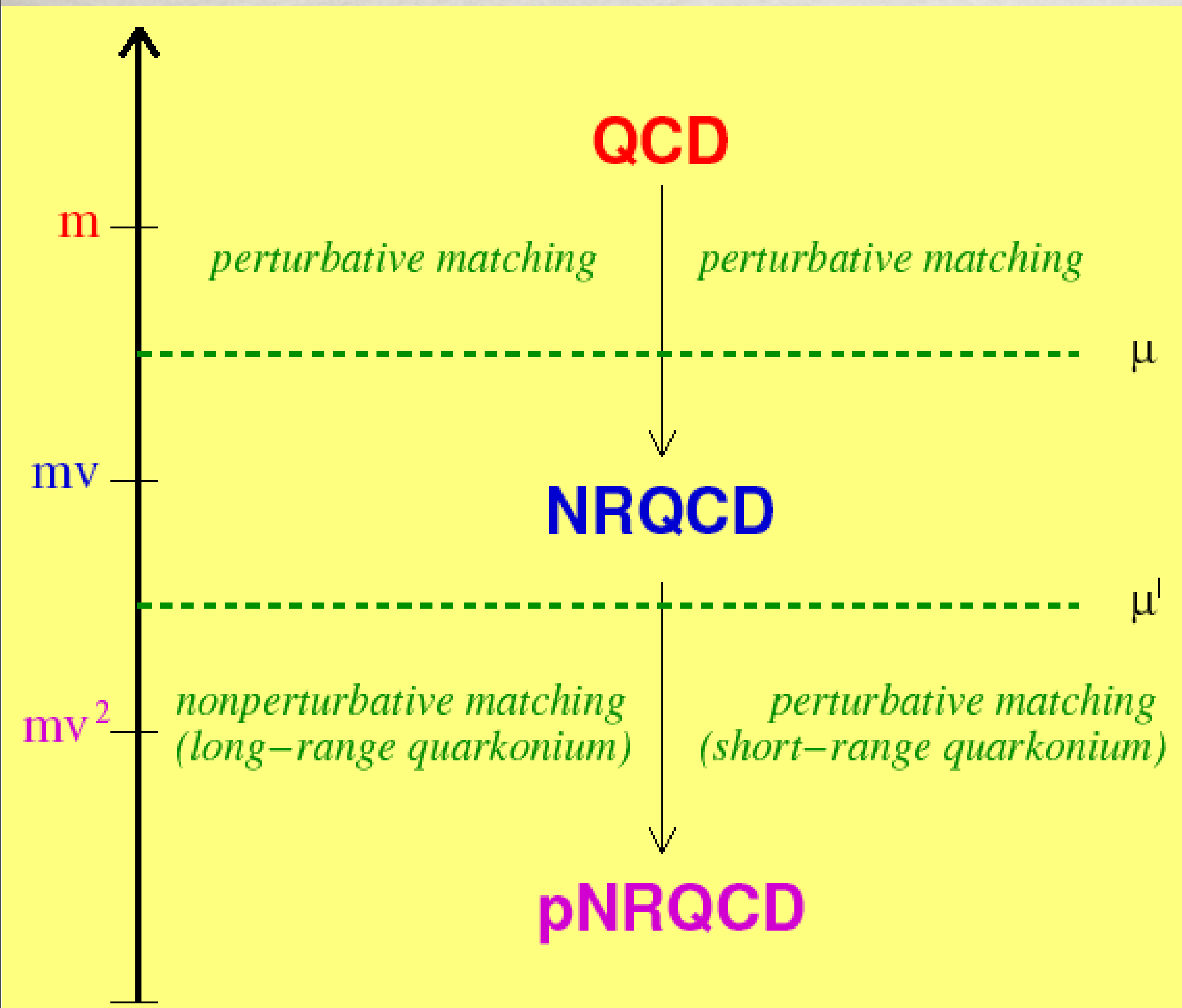
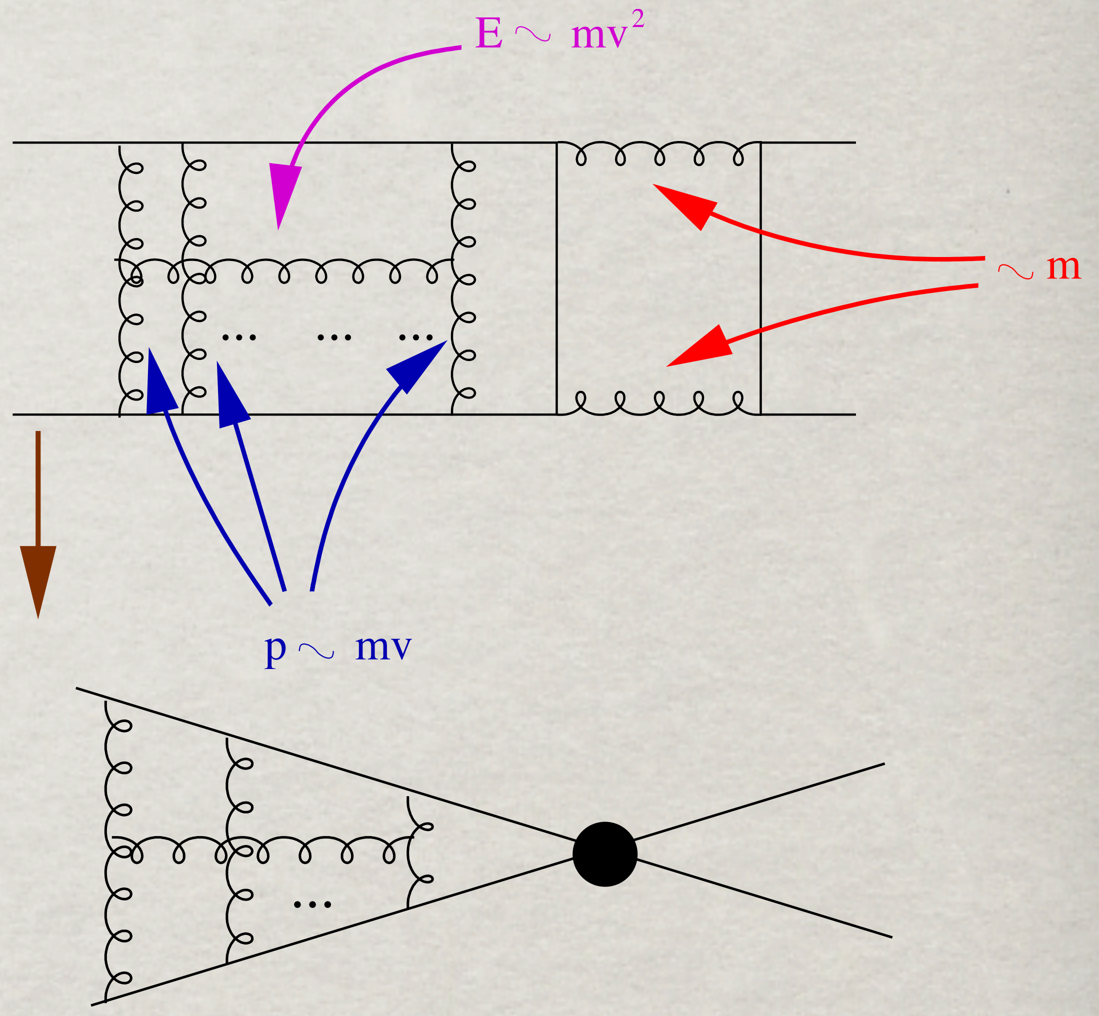




$$\mathcal{L}_{\mathrm{NRQCD}} = \sum_n c(\alpha_s(m/\mu)) \times \frac{O_n(\mu, \lambda)}{m^n}$$

Quarkonium with NR EFT: potential NonRelativistic QCD (pNRQCD)





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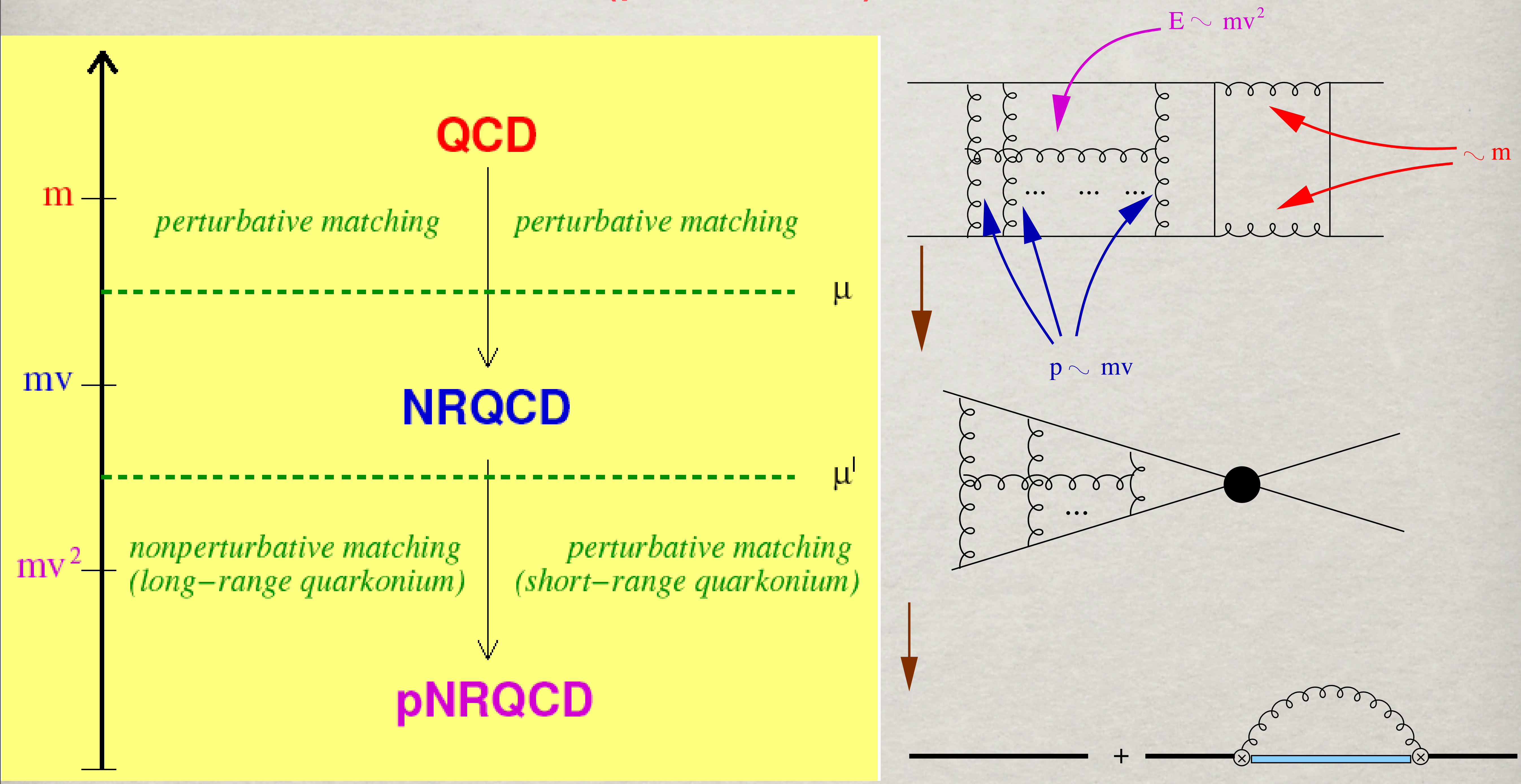

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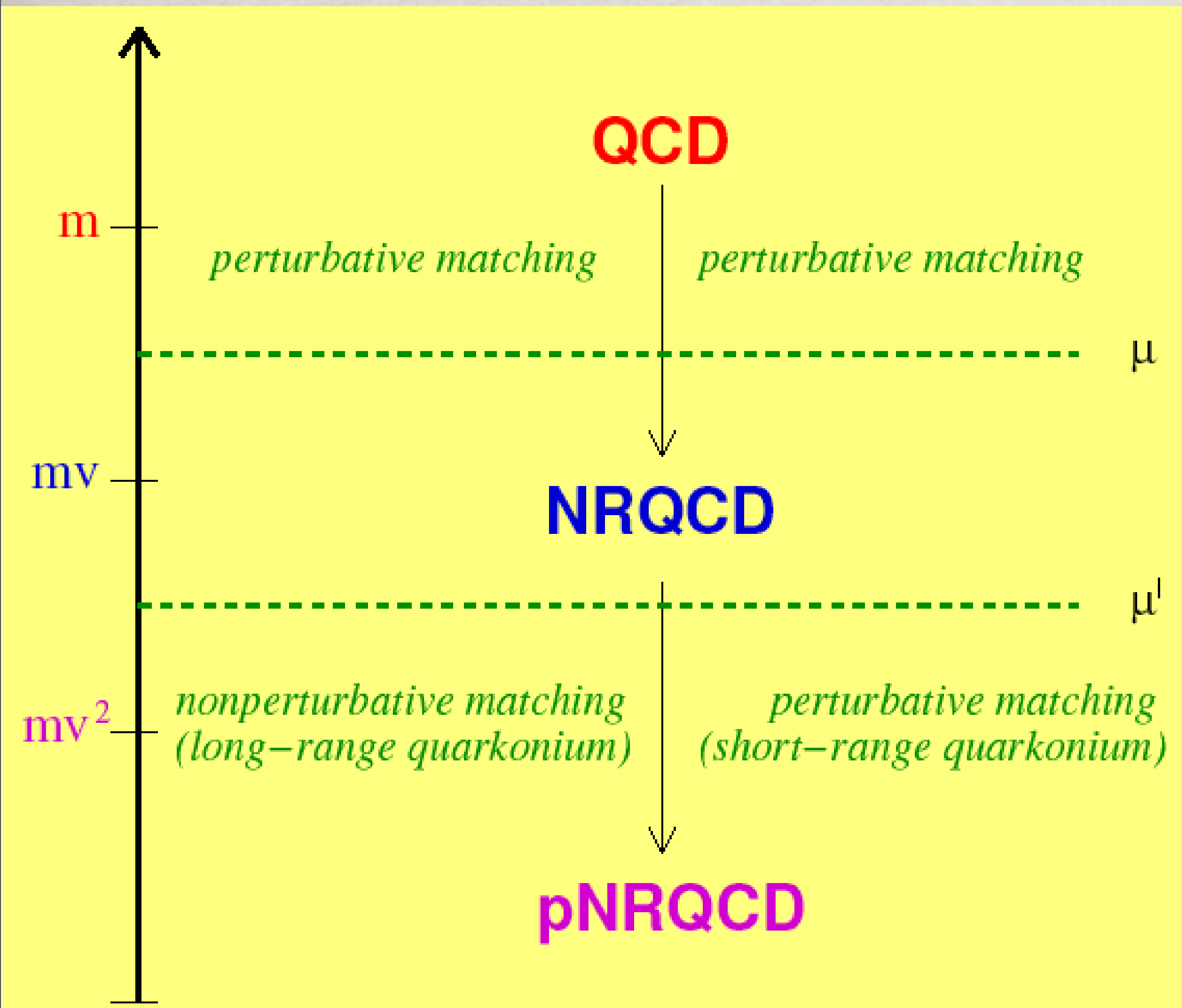

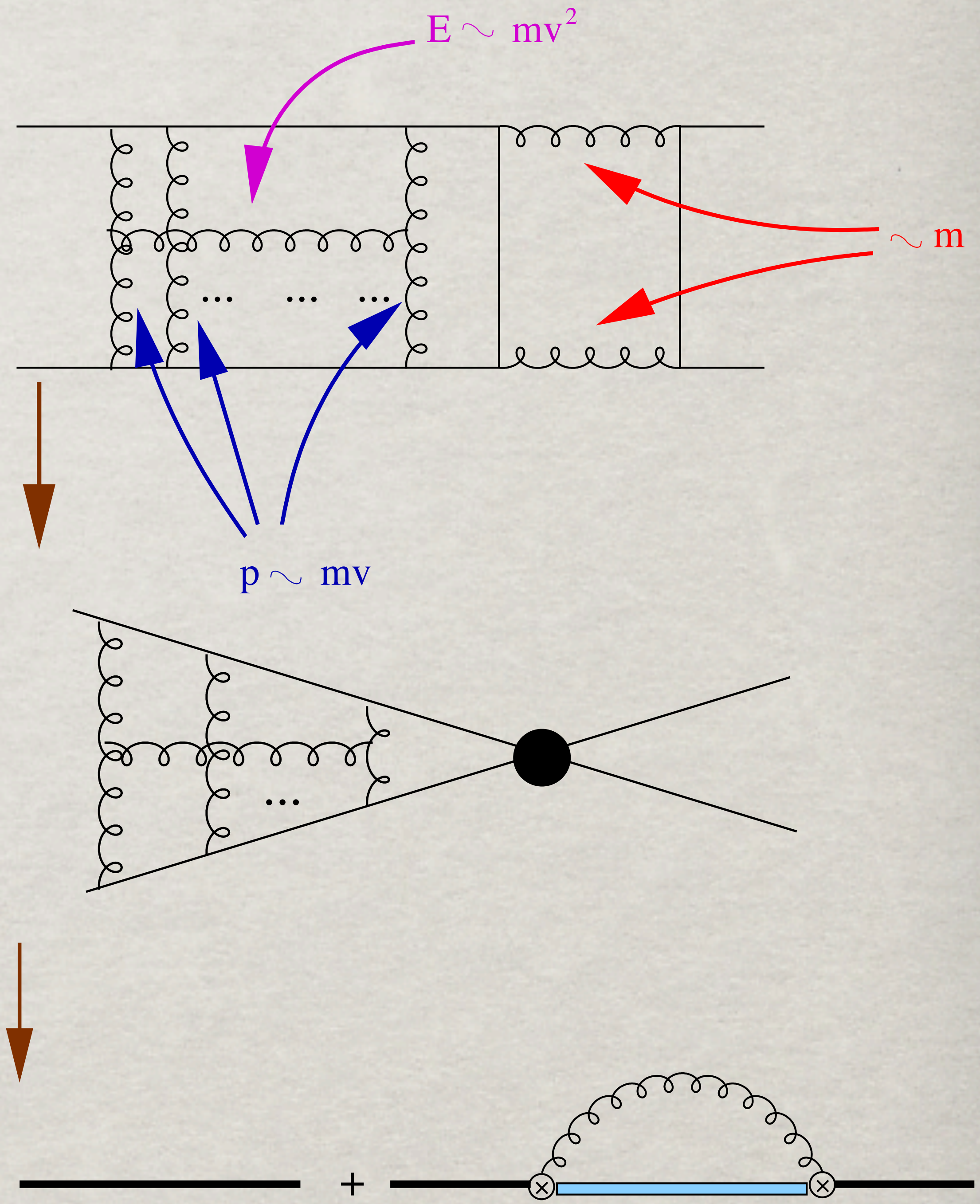

$$\mathcal{L}_{\mathrm{pNRQCD}} = \sum_k \sum_n \frac{1}{m^k} c_k(\alpha_{\mathrm{s}}(m/\mu)) \times V(r\mu', r\mu) \times O_n(\mu', \lambda)\, r^n$$

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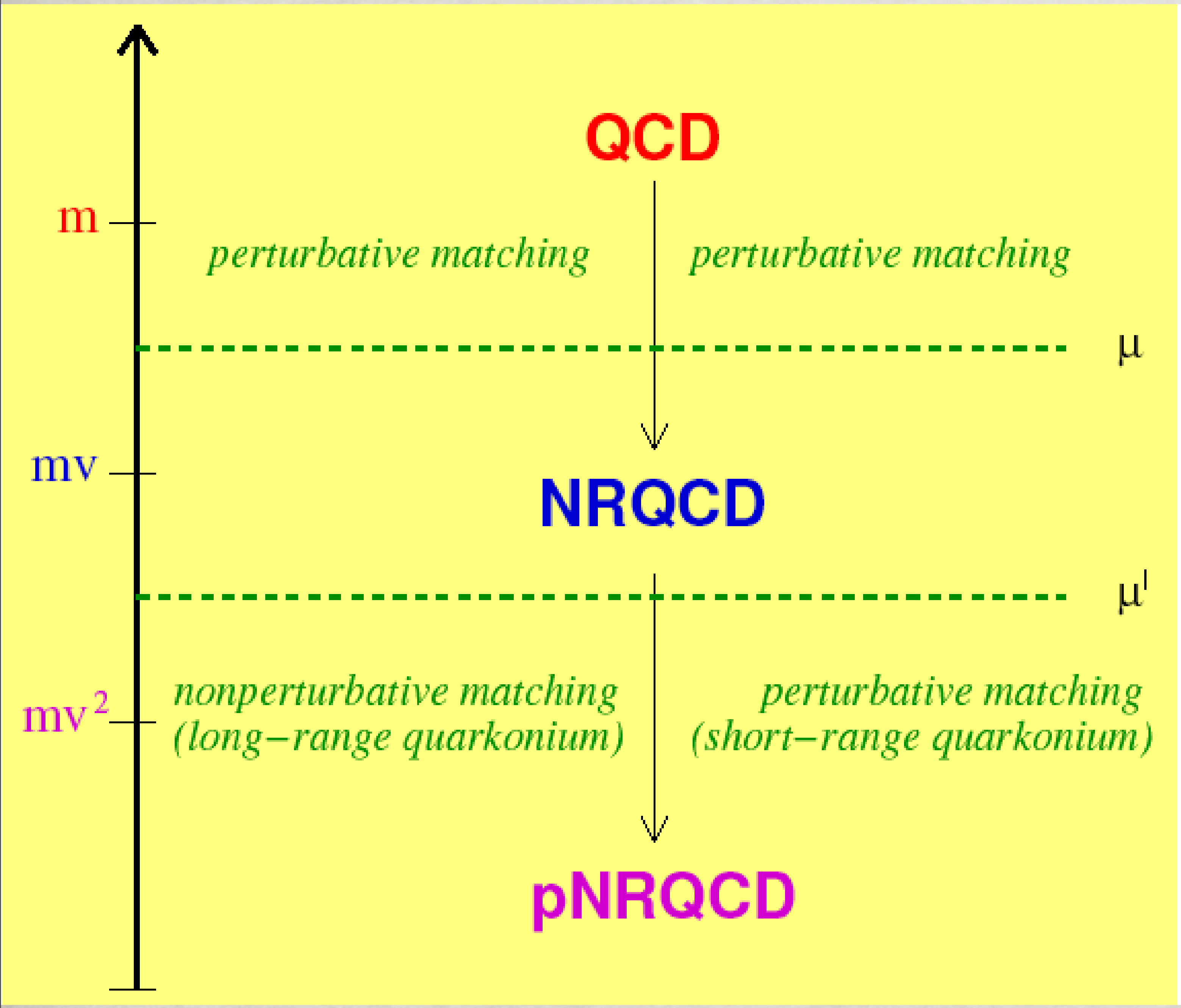

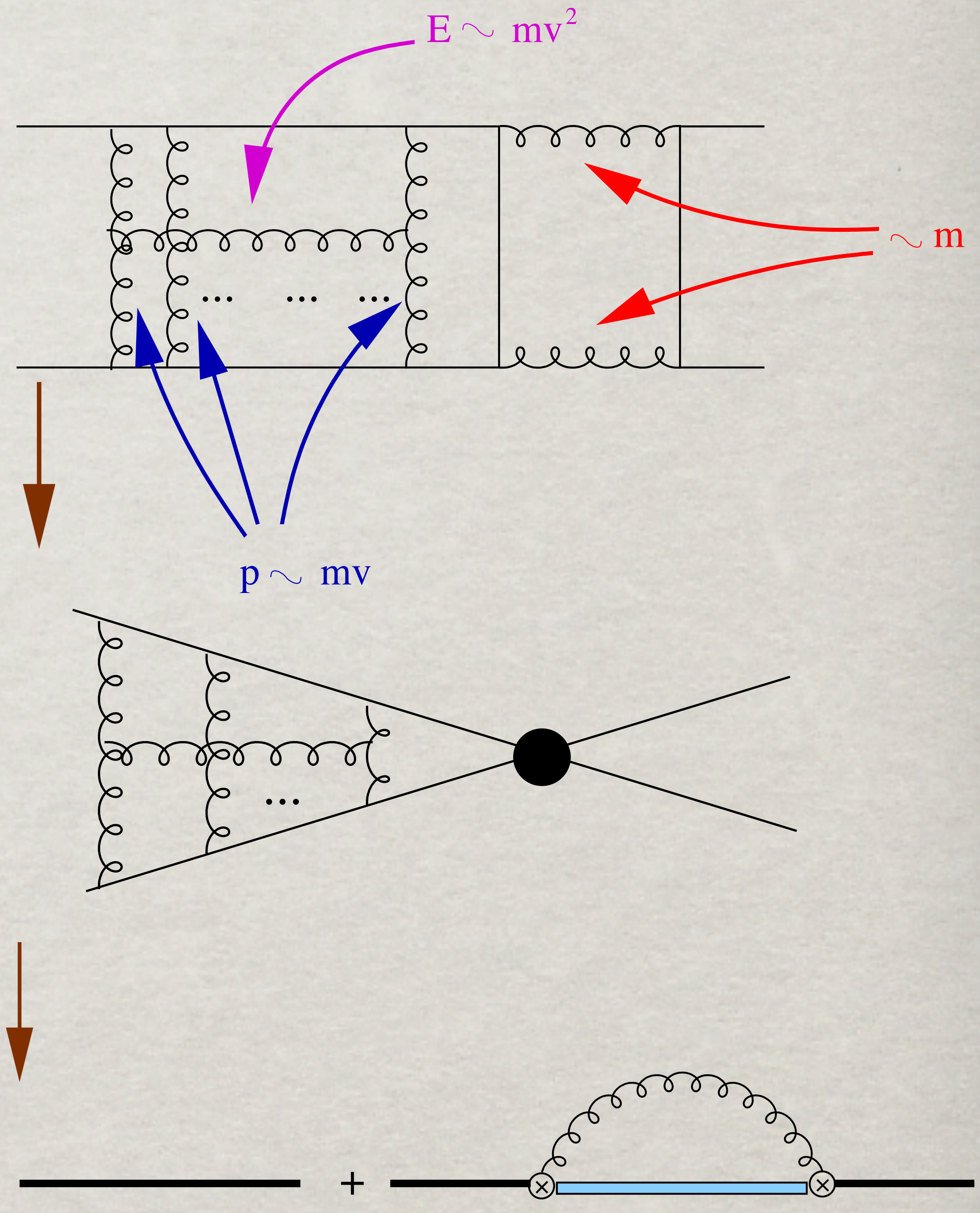

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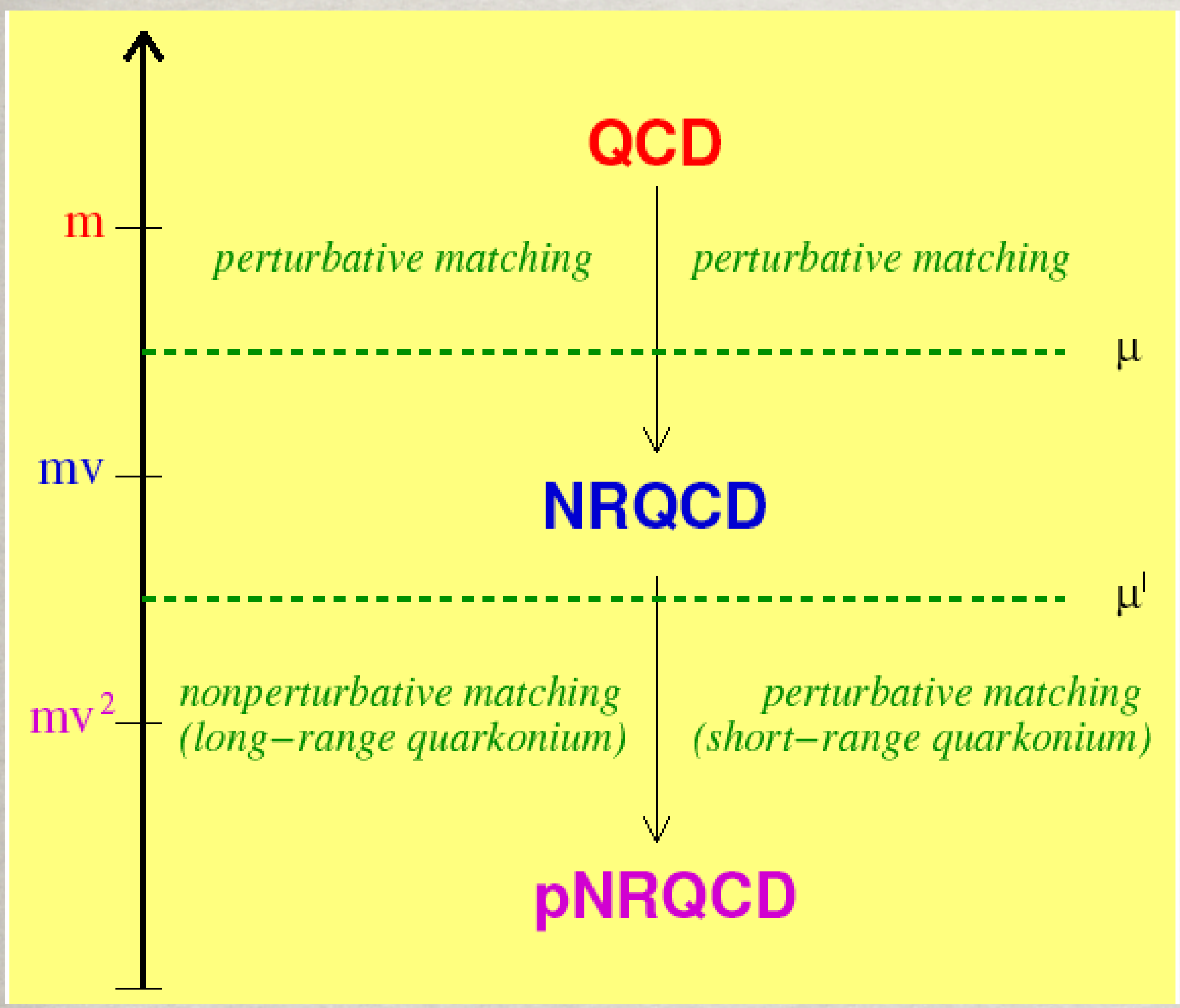

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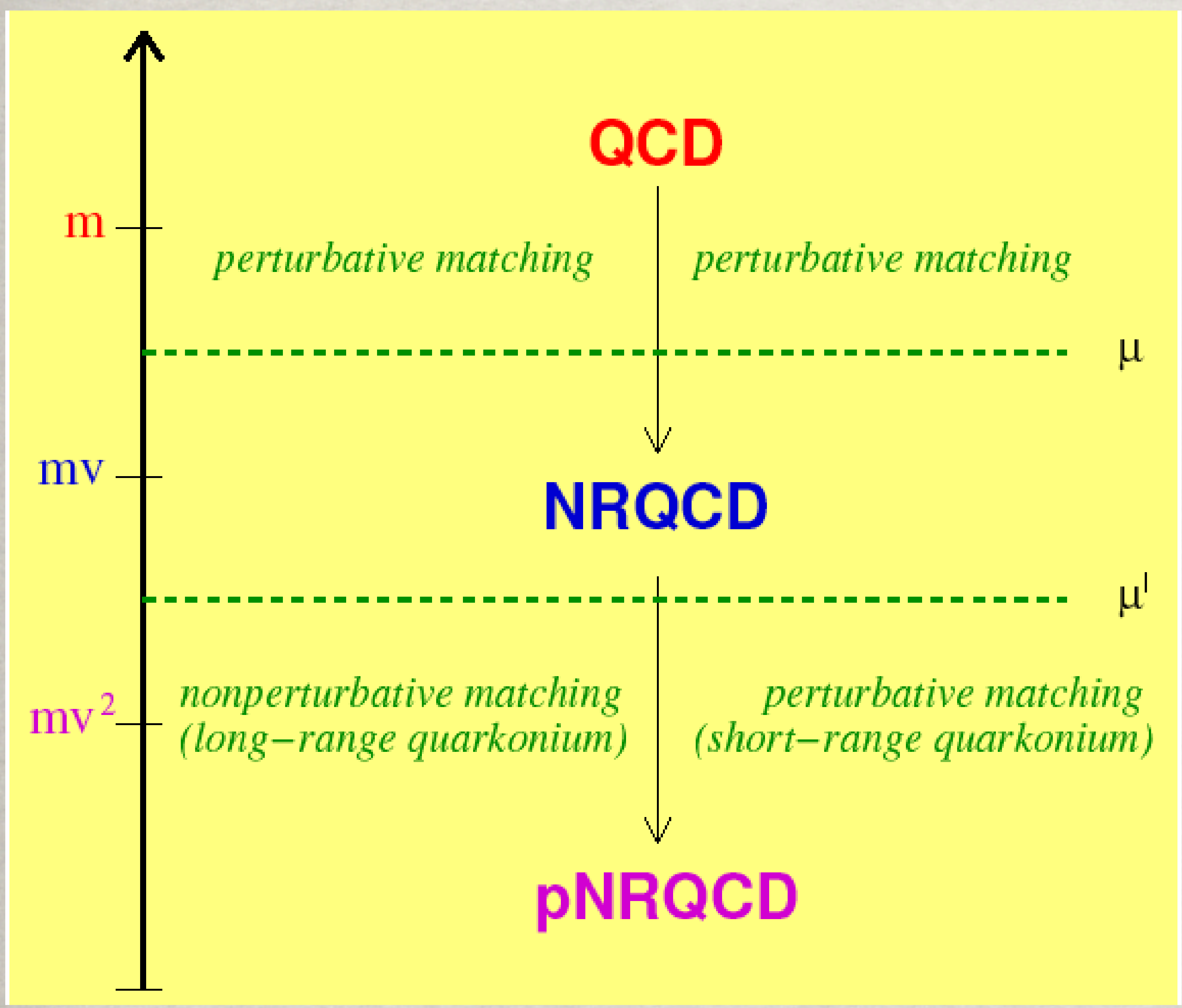
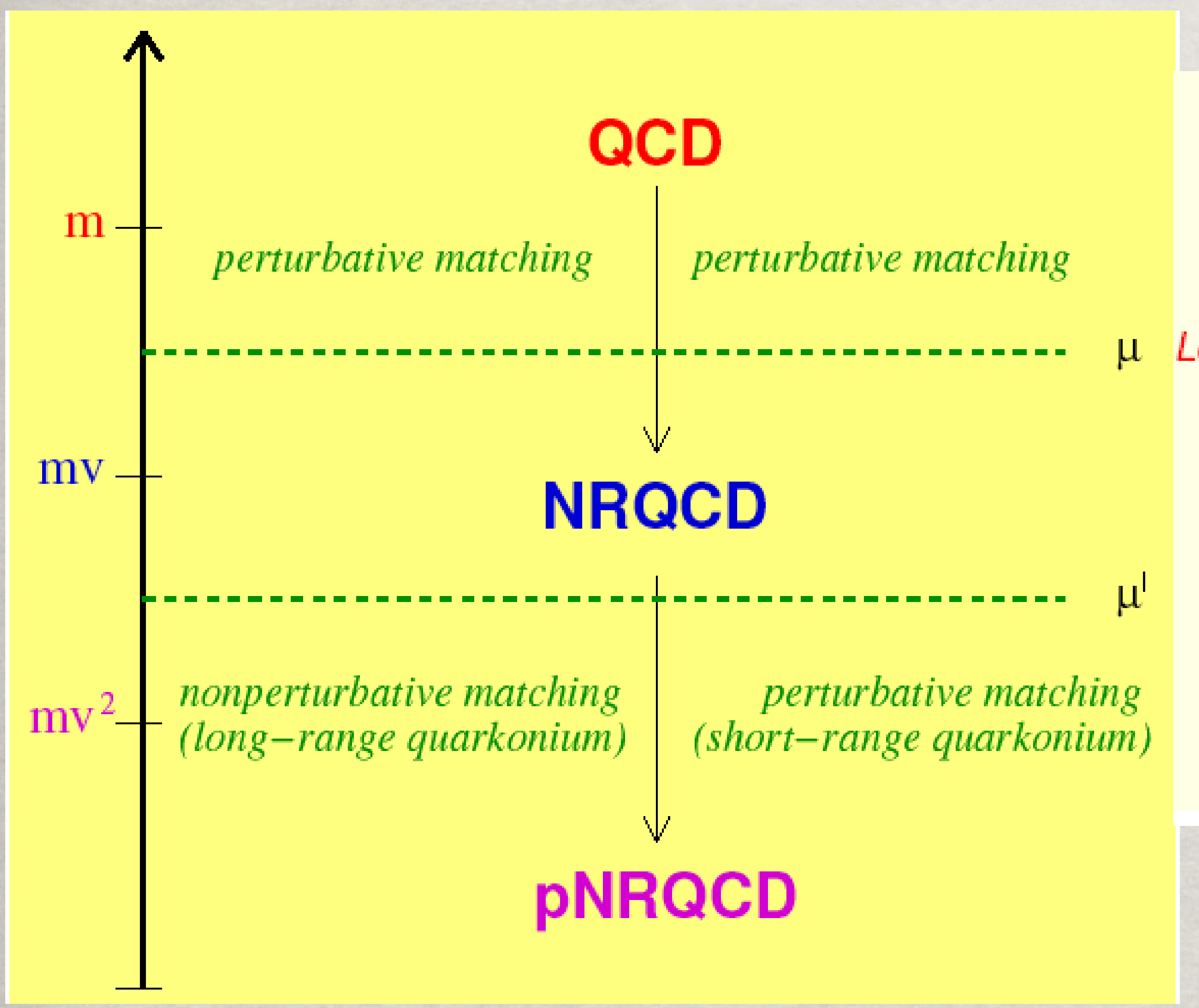
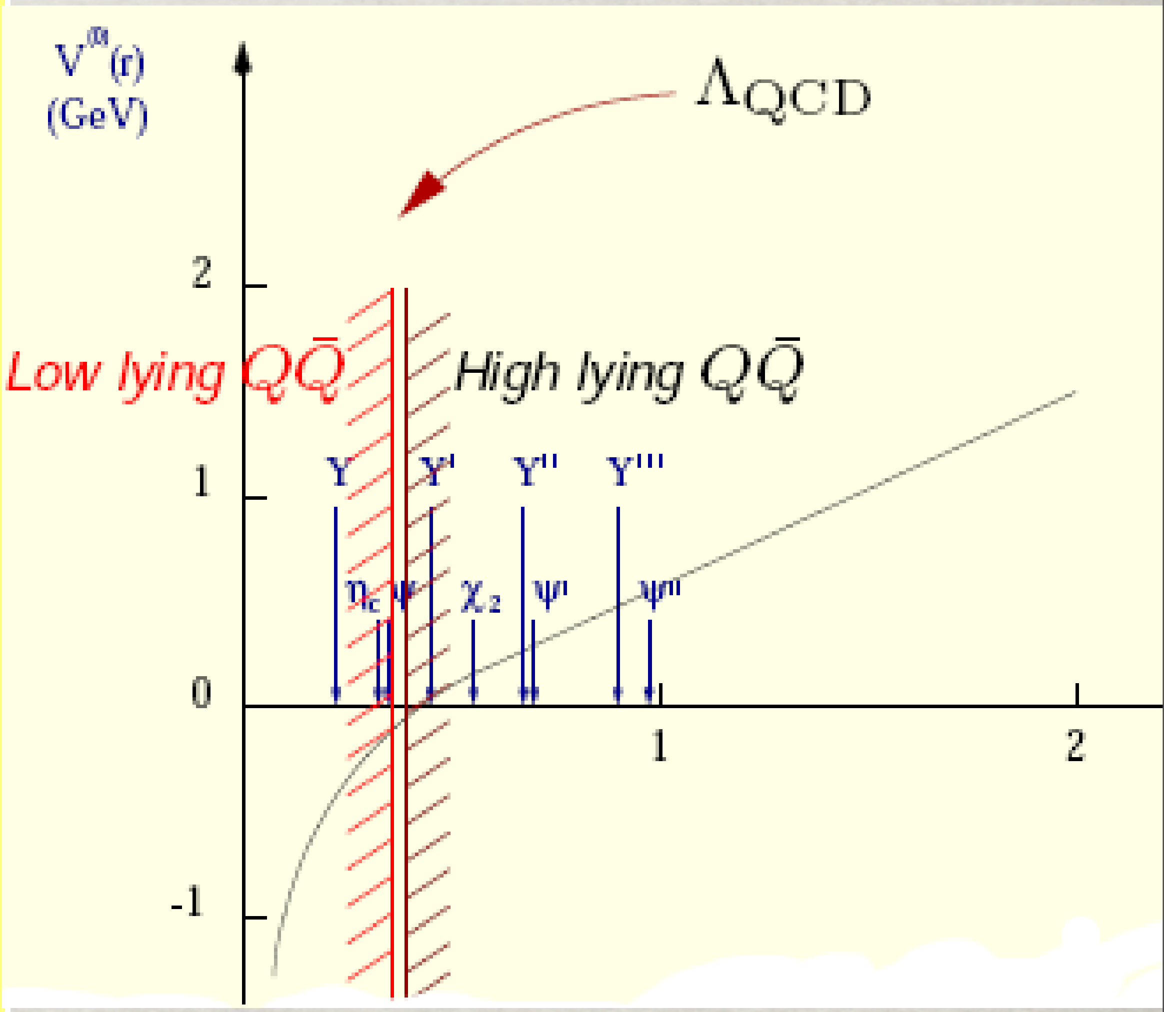


In QCD another scale is relevant Λ_{QCD}

Quarkonium with NR EFT: pNRQCD





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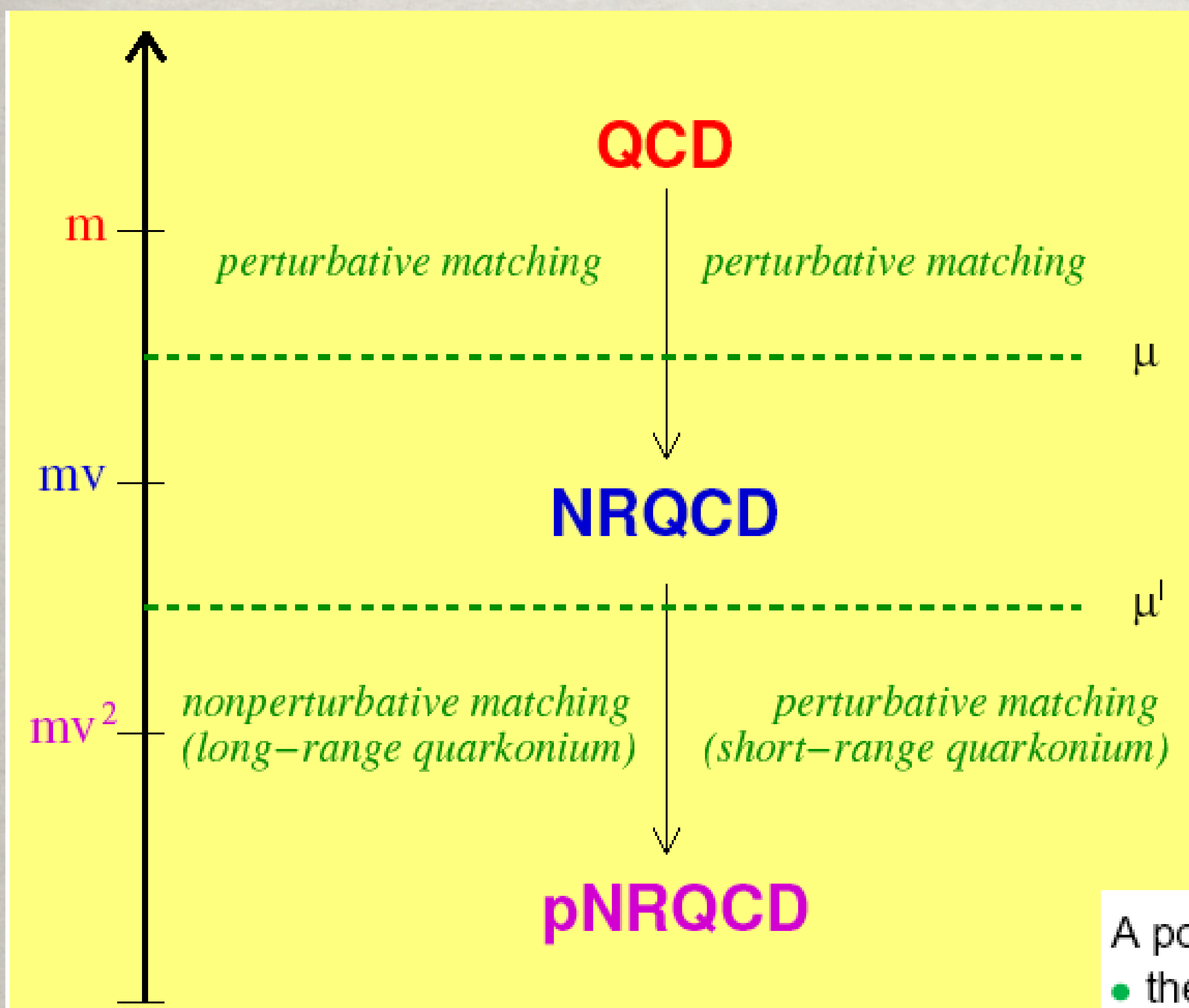

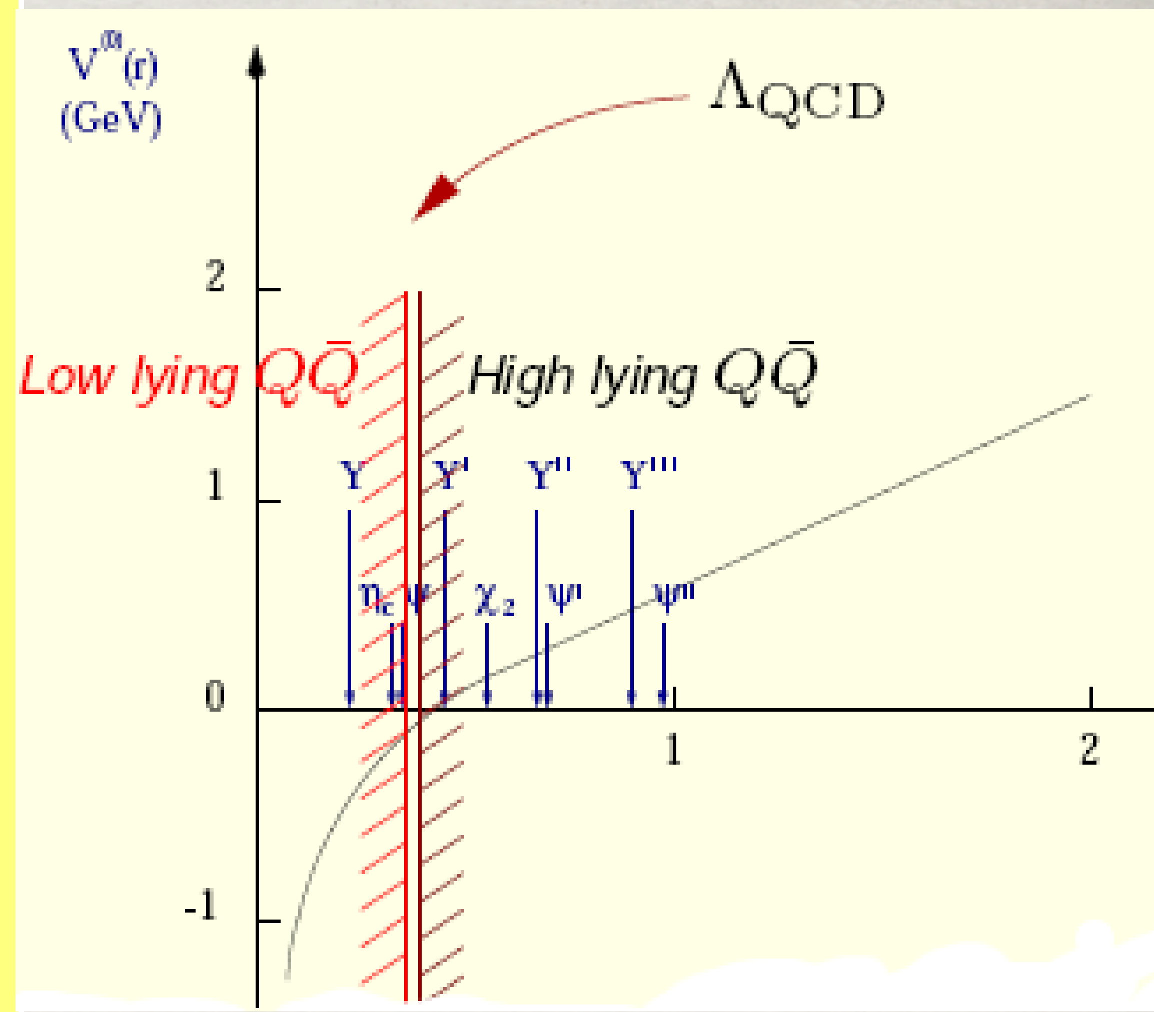

A potential picture arises at the level of pNRQCD:

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

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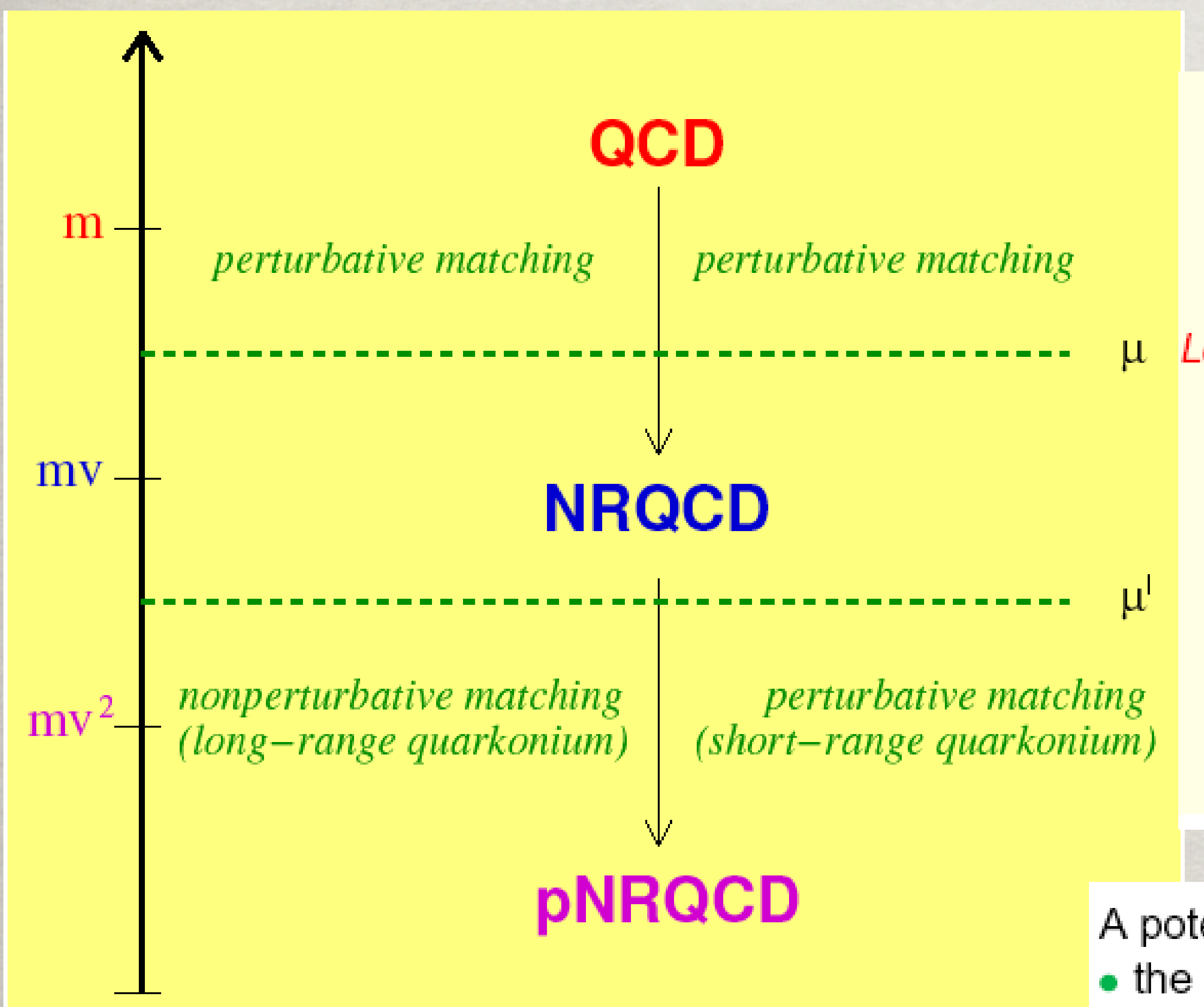

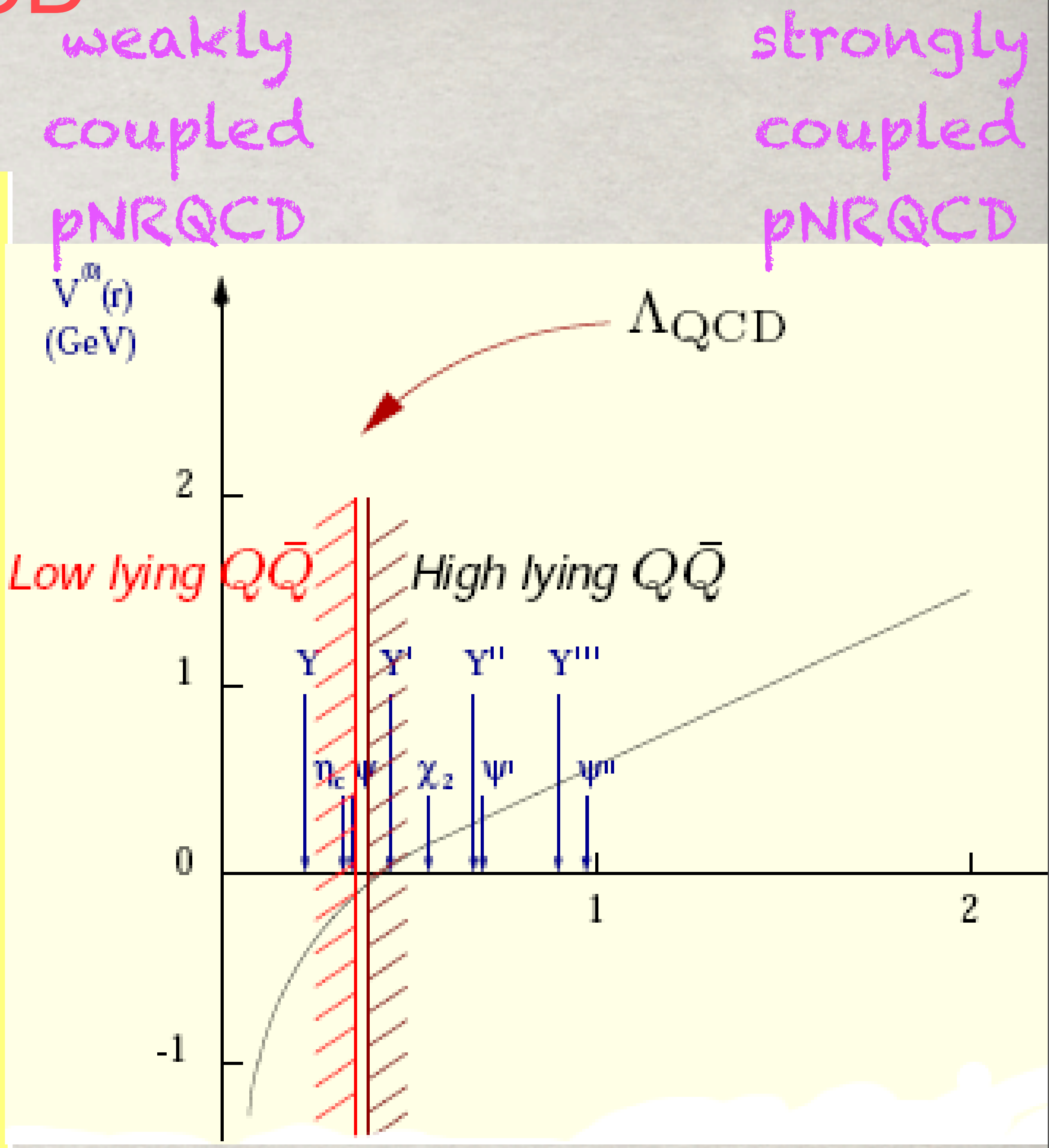

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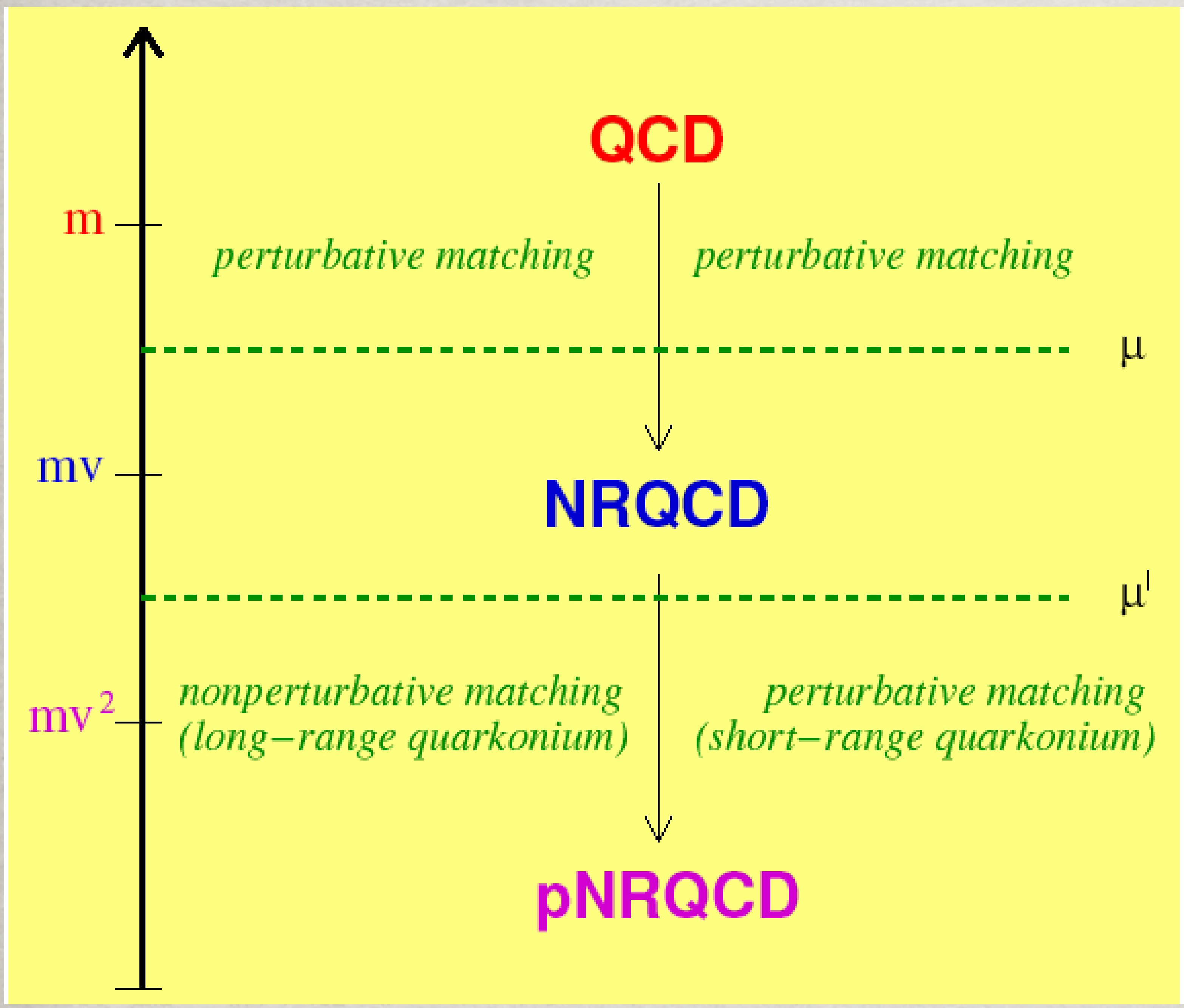
Quarkonium with EFT



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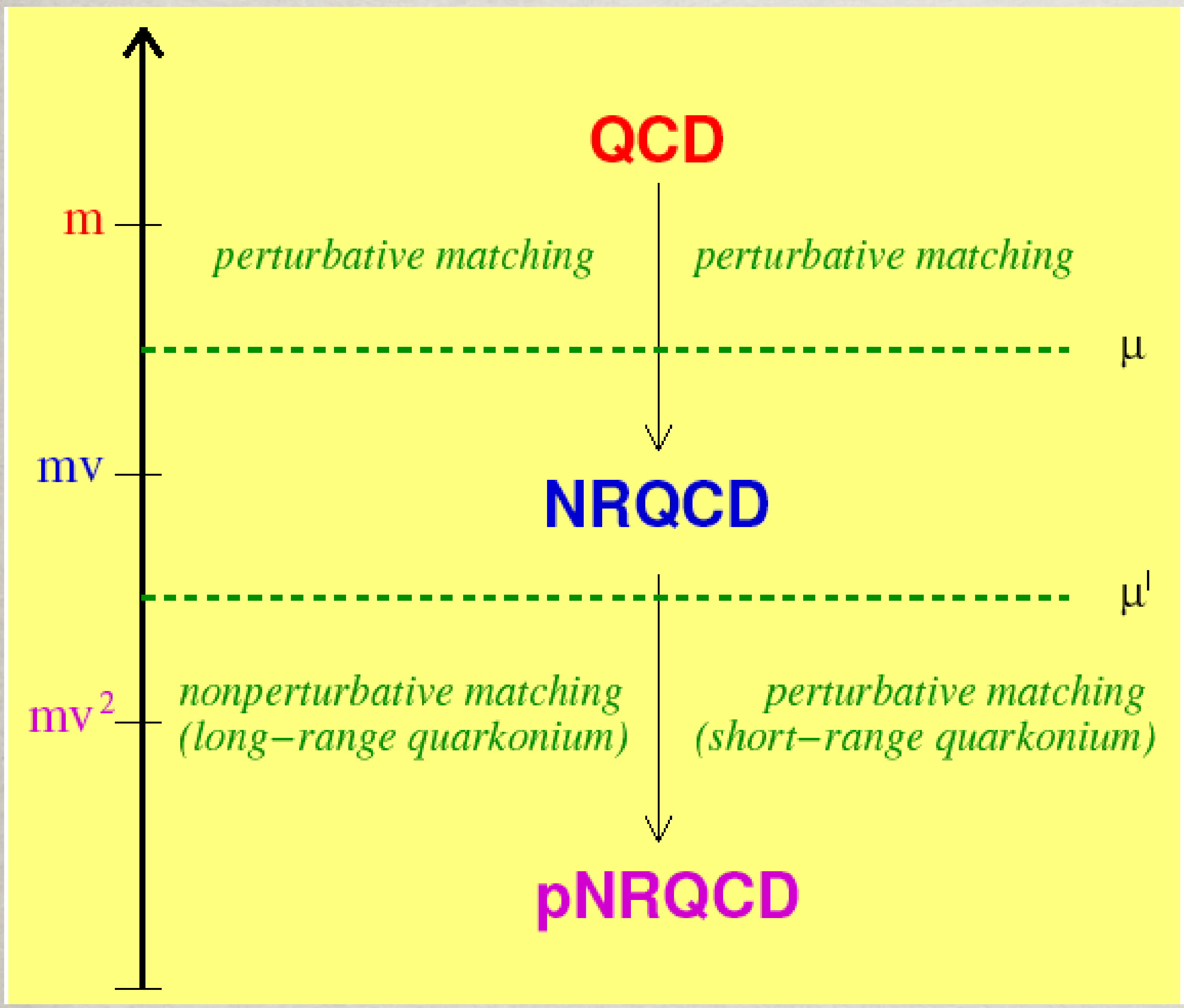
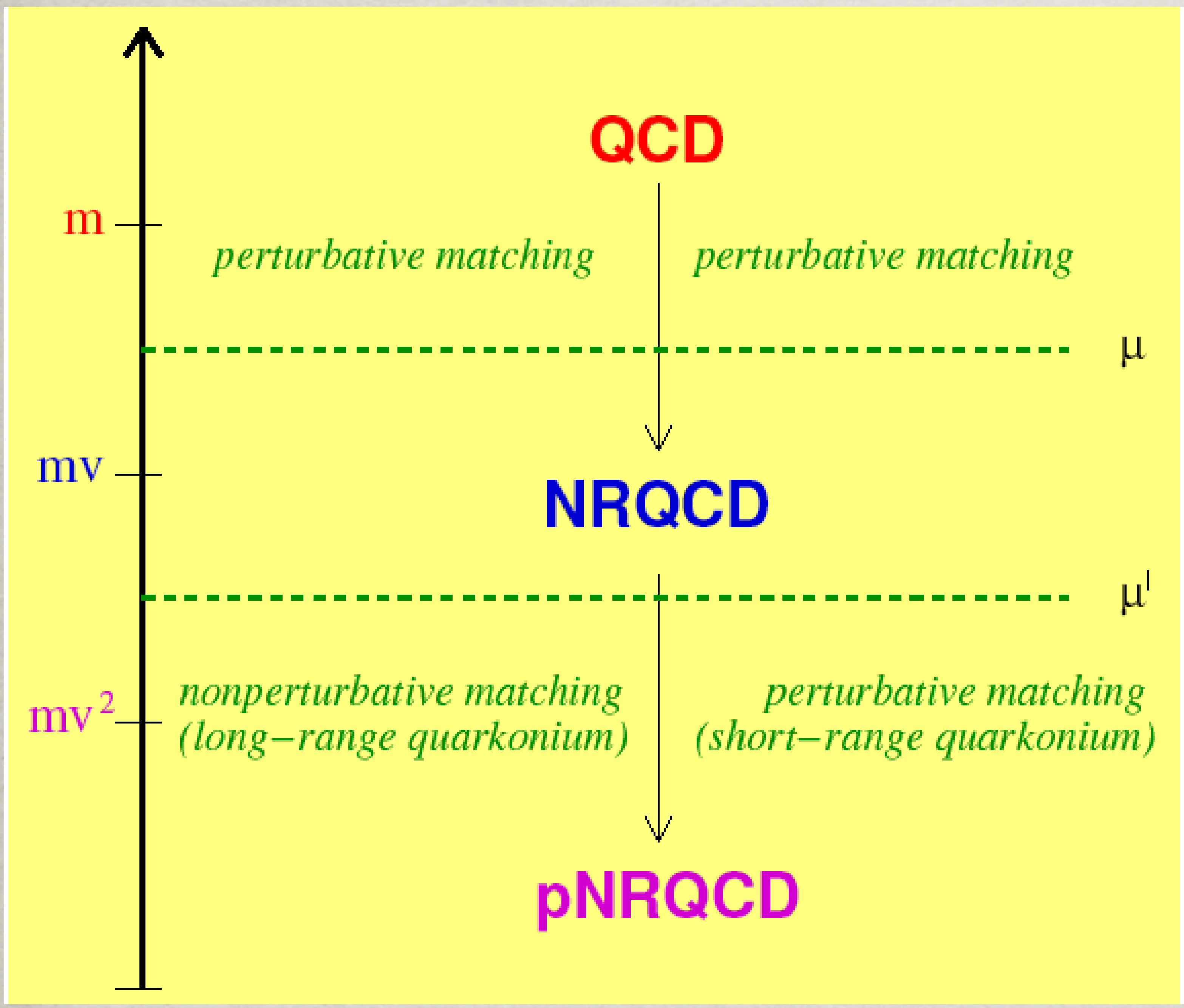


Caswell, Lepage 86,
Lepage, Thacker 88
Bodwin, Braaten, Lepage 95......

Quarkonium with EFT



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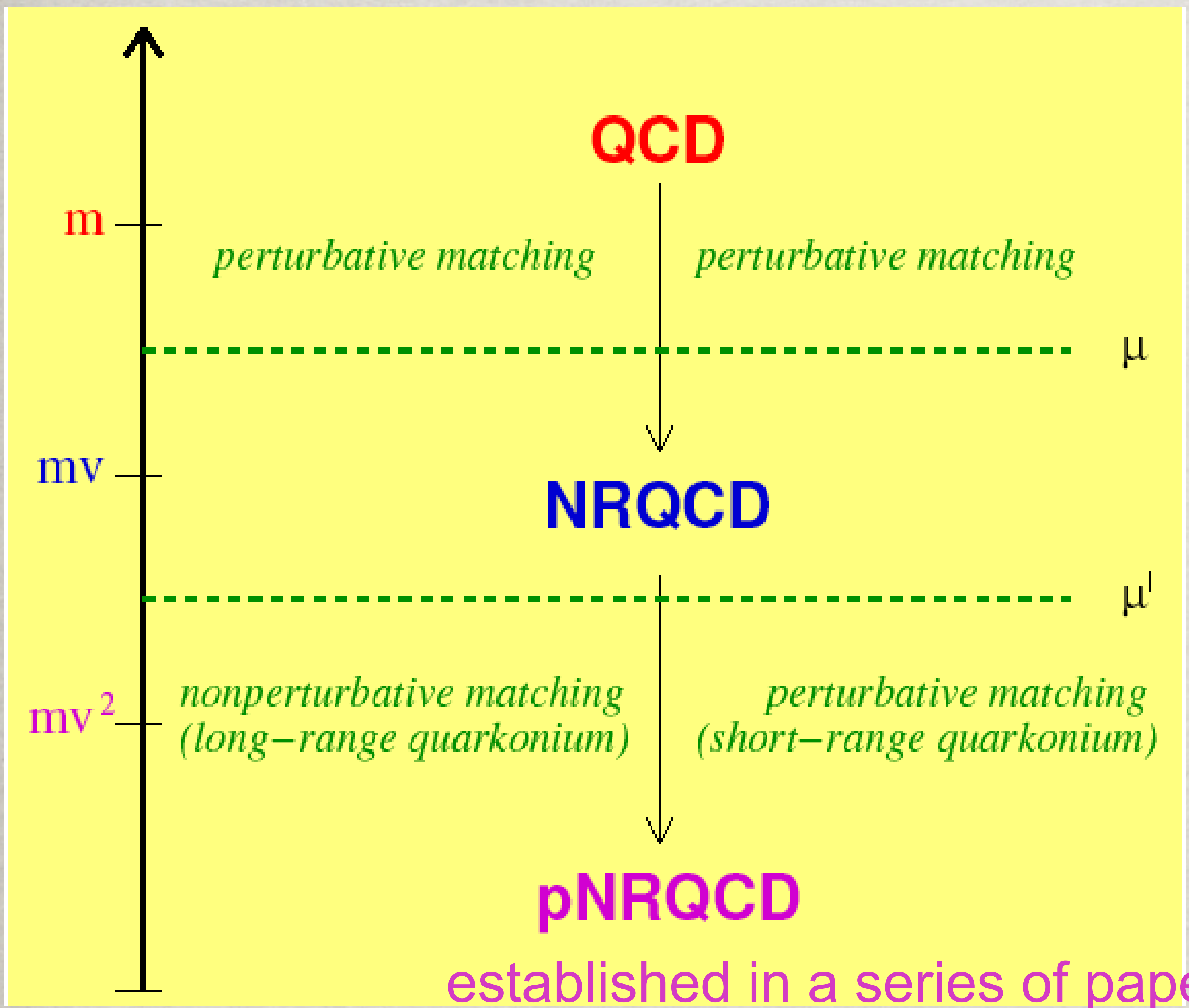
Luke Manohar 97, Luke Savage 98,
Beneke Smirnov 98, Labelle 98
Labelle 98, Grinstein Rothstein 98
Kniehl, Penin 99, Griesshammer 00,
Manohar Stewart 00, Luke et al 00,
Hoang et al 01, 03->

Quarkonium with EFT



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

established in a series of papers:
Pineda, Soto 97, N.B., Pineda, Soto, Vairo 99
N.B. et al 00--012
N.B., Pineda, Soto, Vairo Review of Modern Physis 77(2005) 1423

Physics at the scale m : NRQCD
quarkonium production and decays

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
convolved 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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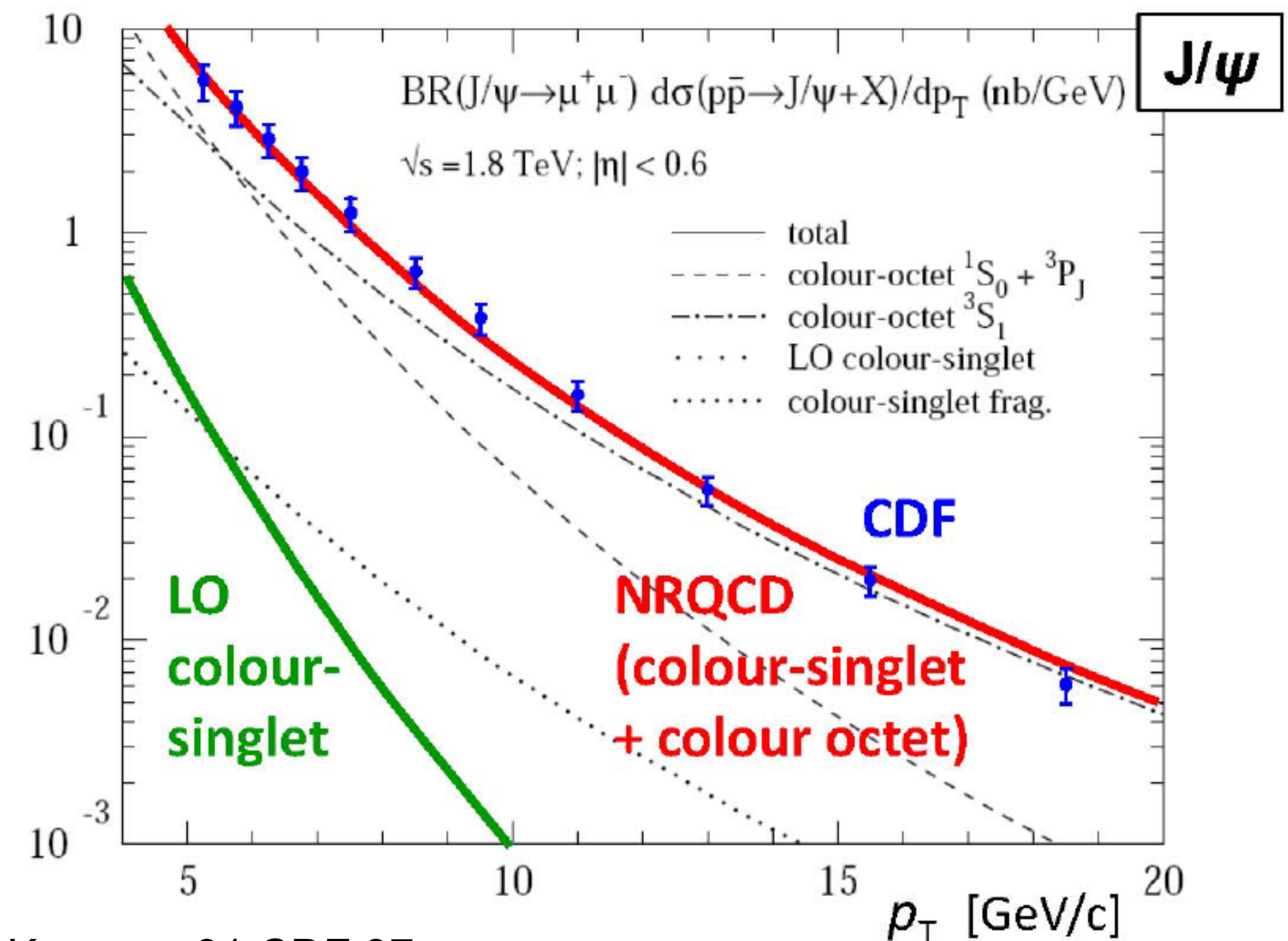

M. Kraemer 01 CDF 97

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

Quarkonium production

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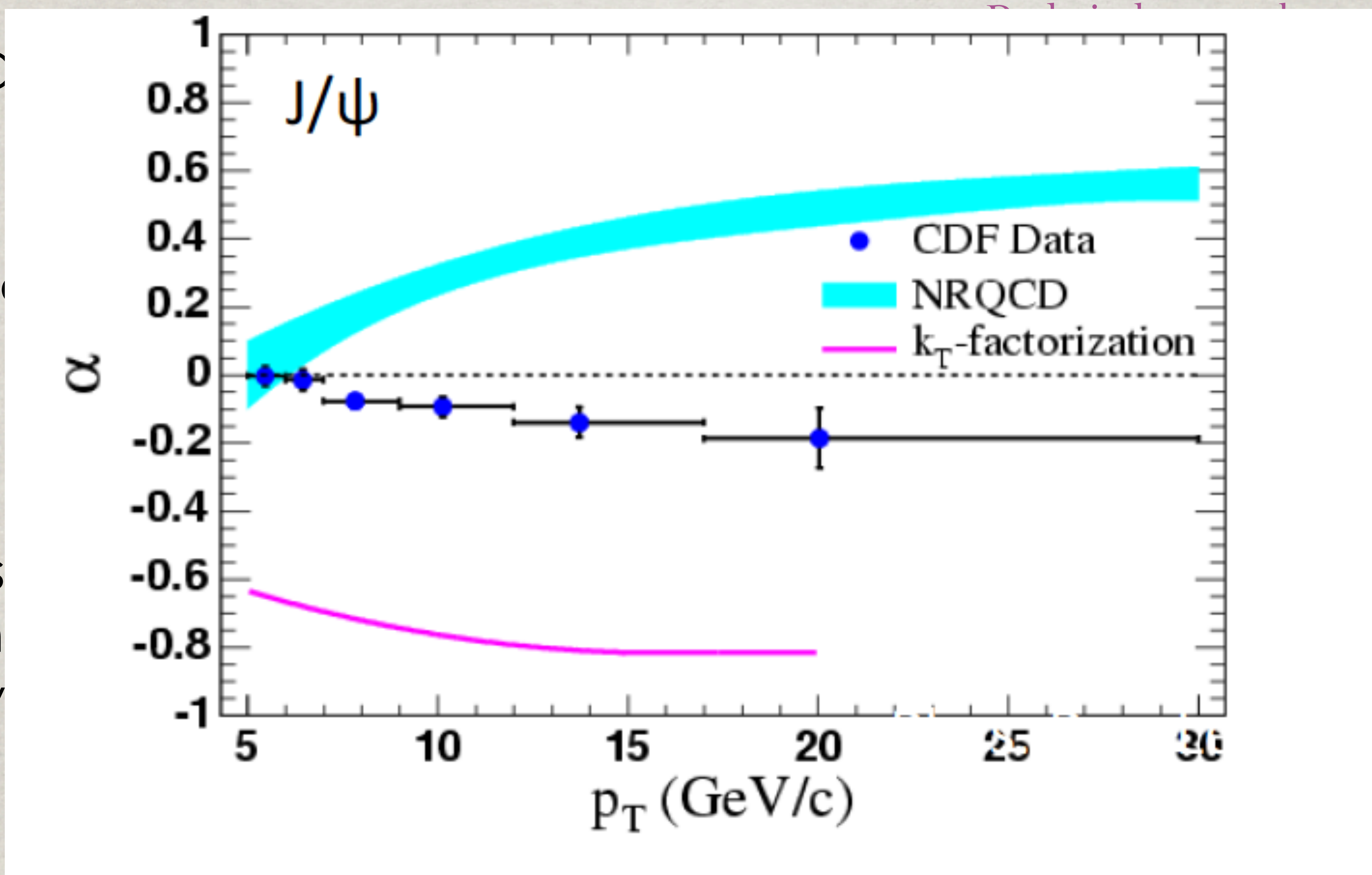

Explained the data at Fermilab on the cross section with the octet contribution (the singlet model failed)

Difficulties in explaining quarkonium polarization at Fermilab

Quarkonium production

Terrific progress in production in the last few years

- Proof of NRQCD factorization at NNLO — Qiu, Nayak, Sterman 05-08
- Calculation of the differential singlet cross section at NLO and NNLO* — Gong, Wang 08 Artoisenet, Campbell, Lansberg, Maltoni, Tramontano 07
- Development of fragmentation function approach — Qiu, Nayak, Sterman 05--S. Fleming et al 012
- NLO calculation of J/psi photoproduction at HERA — Artoisenet, et al.09, Butenschon Kniehl 09
- Full NLO calculation of the direct J/psi hadroproduction in NRQCD — Butenschon Kniehl 010, Kuang ta Chao et al 010,
- Global fit of NRQCD color octet matrix elements at NLO — Butenschon Kniehl 011 Kuang ta Chao et al 011,
- Polarization in hadroproduction at NLO — Butenschon Kniehl 012, Chao et al 012,Gong et al 012

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

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

Inclusive decays

- Annihilation: the NRQCD factorization formula reads

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

Inclusive decays

expansion in v

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expansion in alphas

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expansion in alphas

Progress has been made in

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

the calculation of matching coefficients at higher order in perturbation theory

Yu Jia et al 2011, Guo et al 2011

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with the order of the expansion in v the number of nonperturbative matrix elements increases ..

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

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

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

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

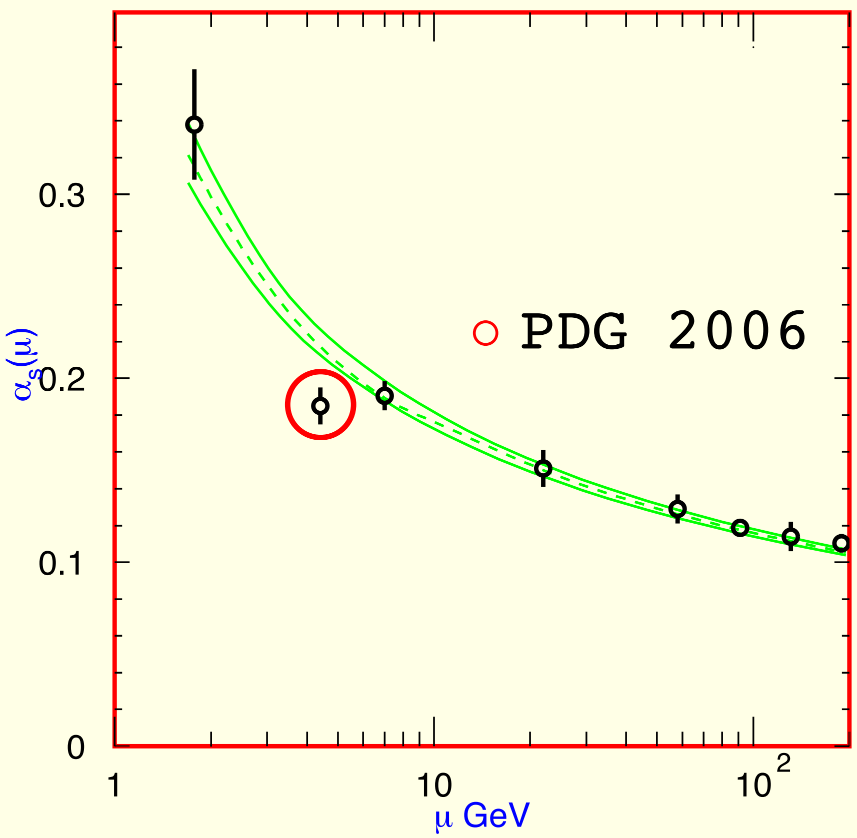
α_s from $\Upsilon(1S)$ decay

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

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

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

○ Brambilla Garcia Soto Vairo PRD 75(07)074014



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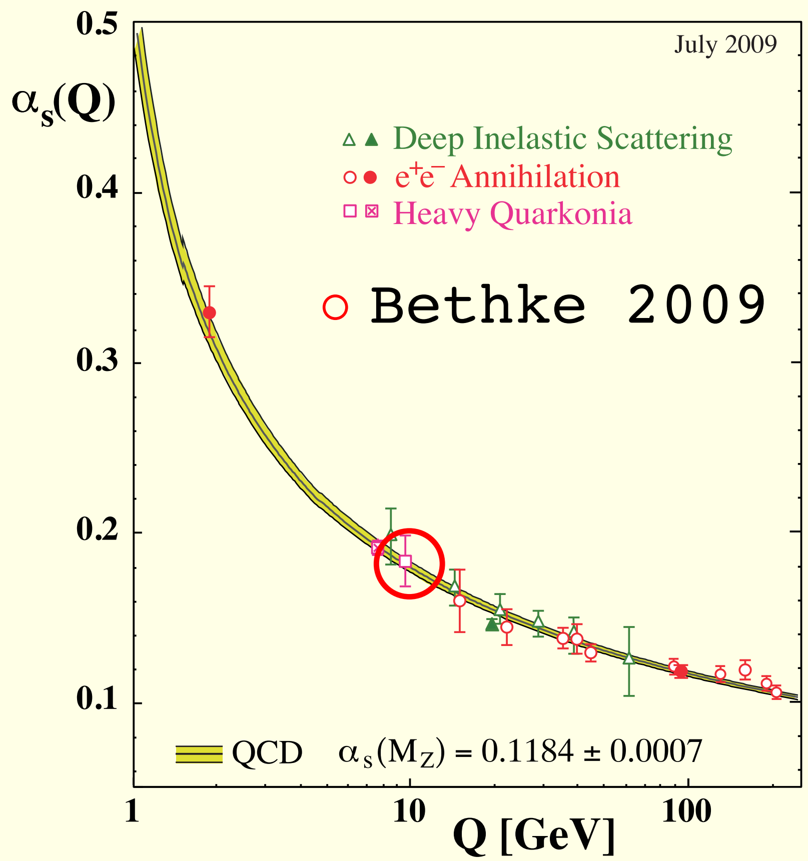

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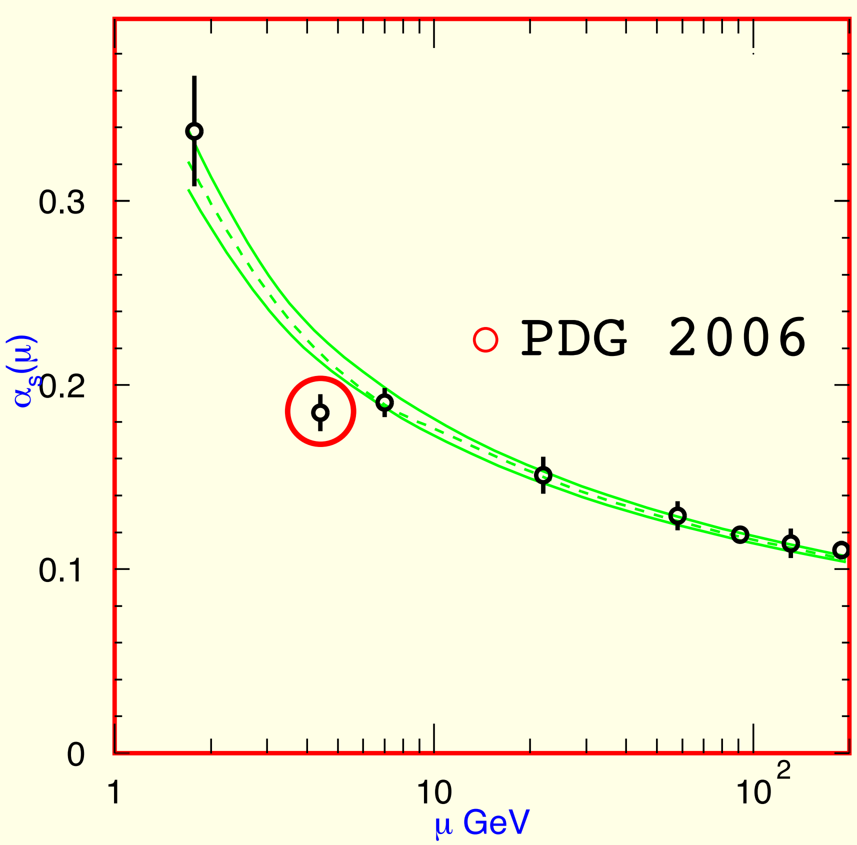

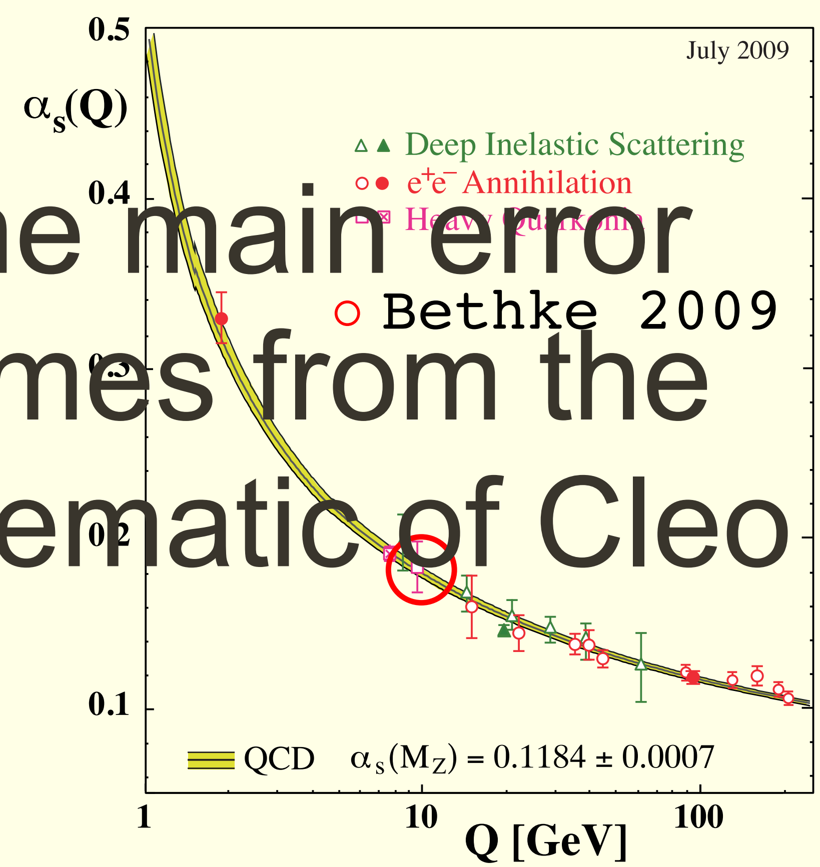

The main error comes from the systematic of Cleo

NRQCD on the lattice for spectra calculations: still problems for bottomonium, hyperfine separation, excited states...

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

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

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

- Spectra
  - high order perturbative calculations
  - Resonances
- 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 T

pNRQCD and quarkonium Several cases for the physics at hand

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The EFT has been constructed (away from theshold)

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

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The issue here is precision physics and the study of confinement

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

pNRQCD and quarkonium Several cases for the physics at hand

The EFT is being constructed (Finite T)

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

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

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

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

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

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

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*Degrees of freedom still to be identified

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

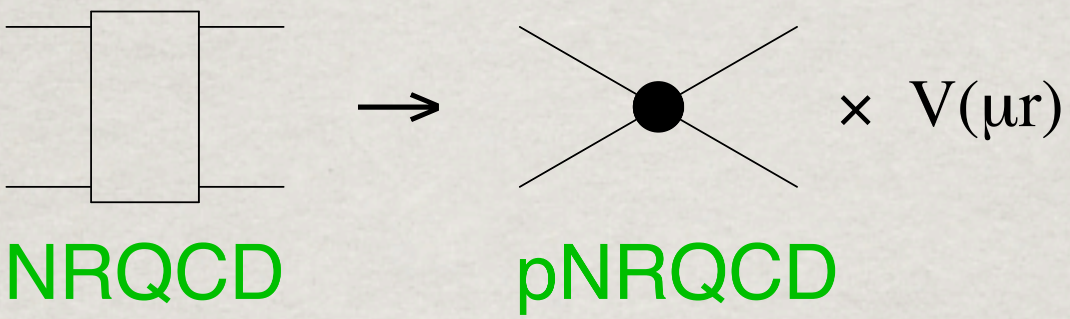
E. Braaten et al

Quarkonium systems with small radius

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

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

Degrees of freedom that scale like mv are integrated out:



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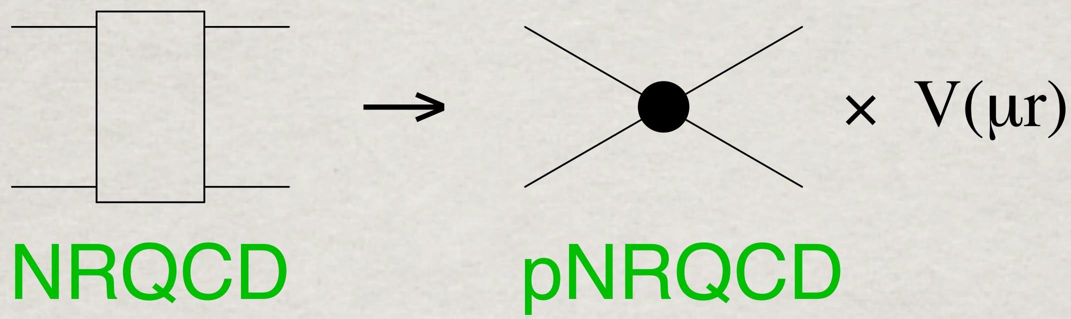

- If $mv \gg \Lambda_{\rm QCD}$, the matching is perturbative

- Degrees of freedom: quarks and gluons

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

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

- Definite power counting: $r \sim \dfrac{1}{mv}$ 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 $\quad r \ll \Lambda_{\mathrm{QCD}}^{-1}$

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

LO in r

S singlet field

O octet field

singlet propagator

octet propagator

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

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LO in r

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

NLO in r

S singlet field — singlet propagator

O octet field — octet propagator

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

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

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

O octet field

singlet propagator

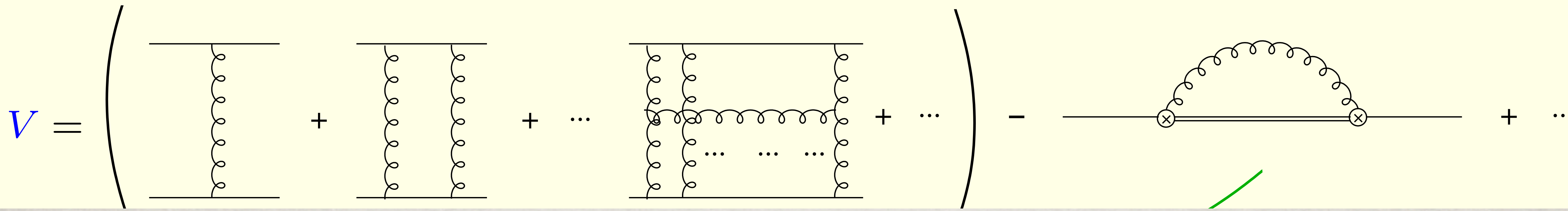
octet propagator

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

pNRQCD

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

QCD singlet static potential



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

Quarkonium singlet static potential at N^4LO

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

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

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

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

a_1 Billoire 80

a_2 Schroeder 99, Peter 97

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

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

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

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coeff $ln r\mu$ N.B. Pineda, Soto, V…

3LOOPS REDUCES TO 1LOOP IN THE EFT

a_4^{L2}, a_4^{L} N.B., Garcia, Sot…

4LOOPS REDUCES TO 2LOOPS IN THE EFT

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

Quarkonium singlet static potential at N^4LO

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

Quarkonium singlet static potential at N^4LO

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

Two problems:

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

2) Large logs

Quarkonium singlet static potential at N^4LO

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\end{aligned}
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for long it was believed that such series was not convergent problem for any phenomenological application

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

2) Large logs

Quarkonium singlet static potential at N^4LO

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

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

Two problems:

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

2) Large logs

The eft cures both:

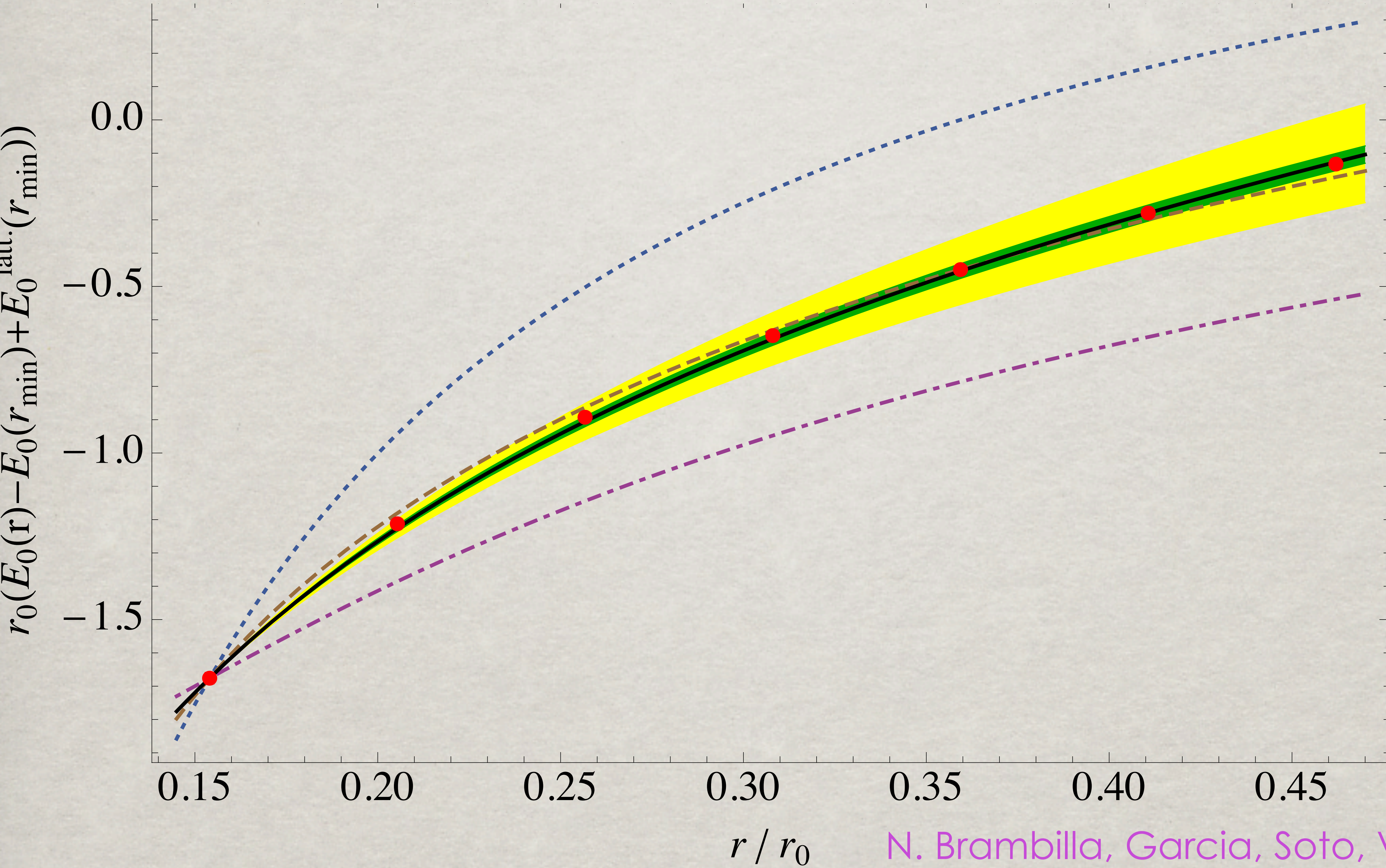
1) Renormalon subtracted scheme

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

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

N. Brambilla. et al 2007, 2009

Quarkonium singlet static energy at N^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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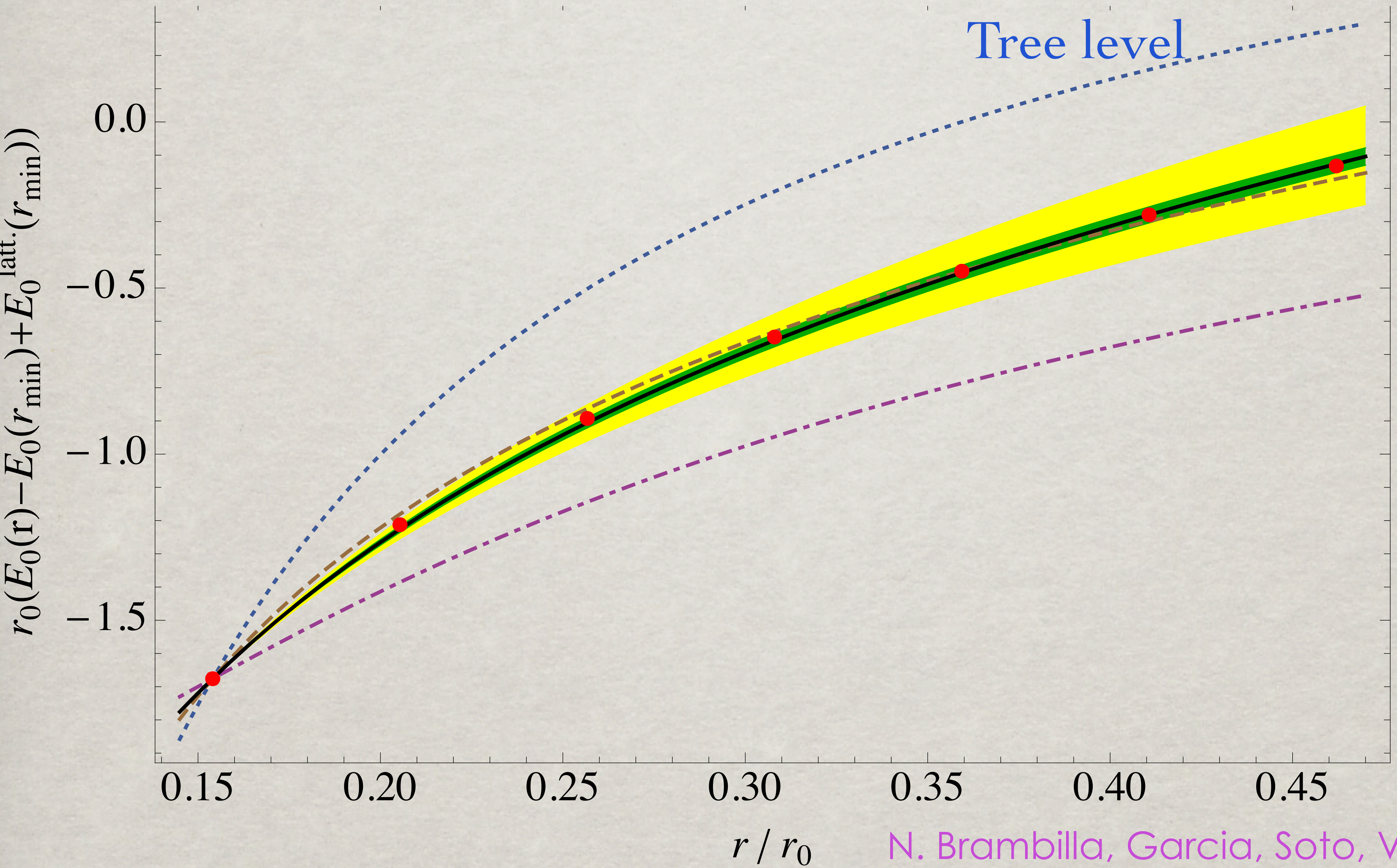

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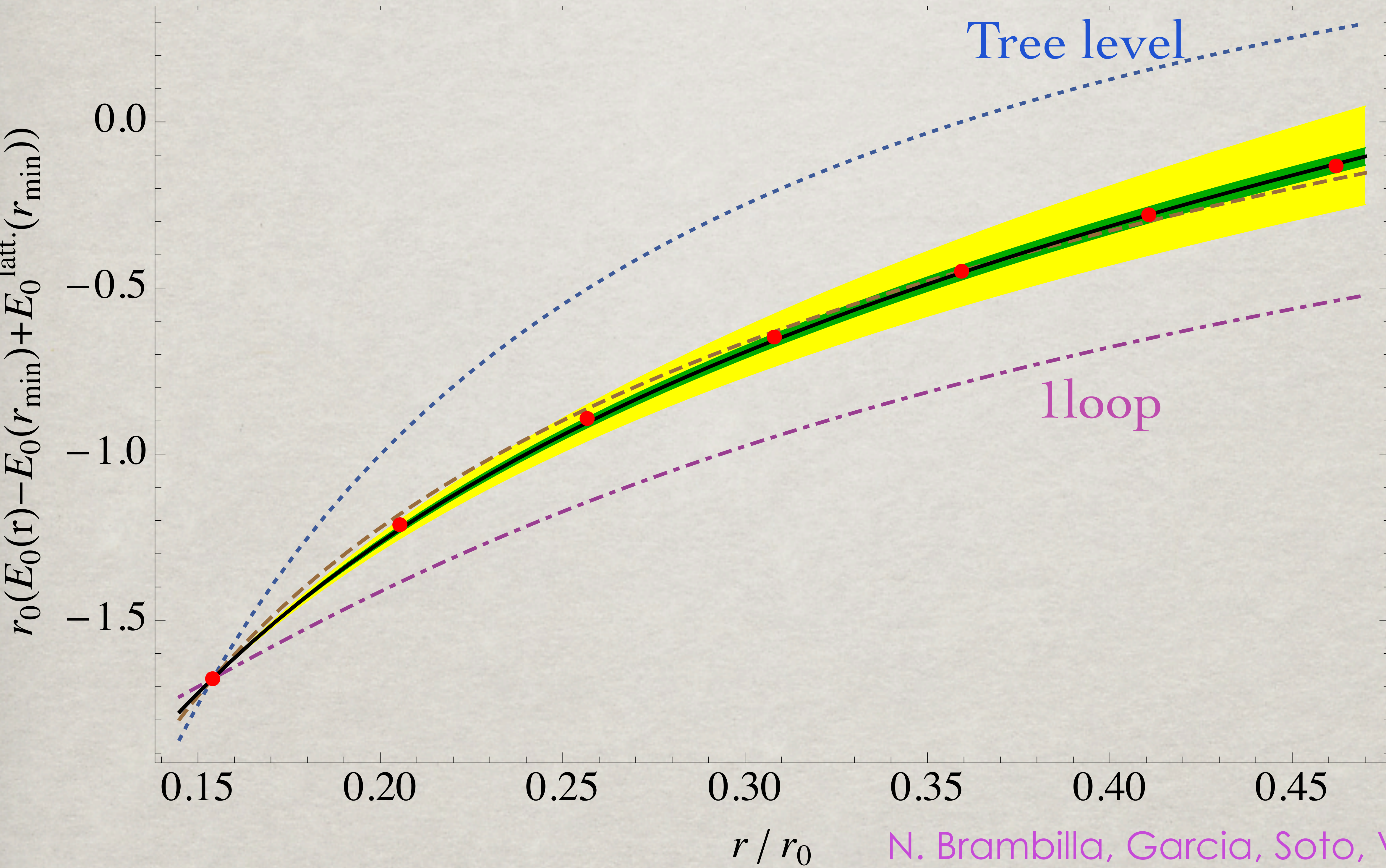

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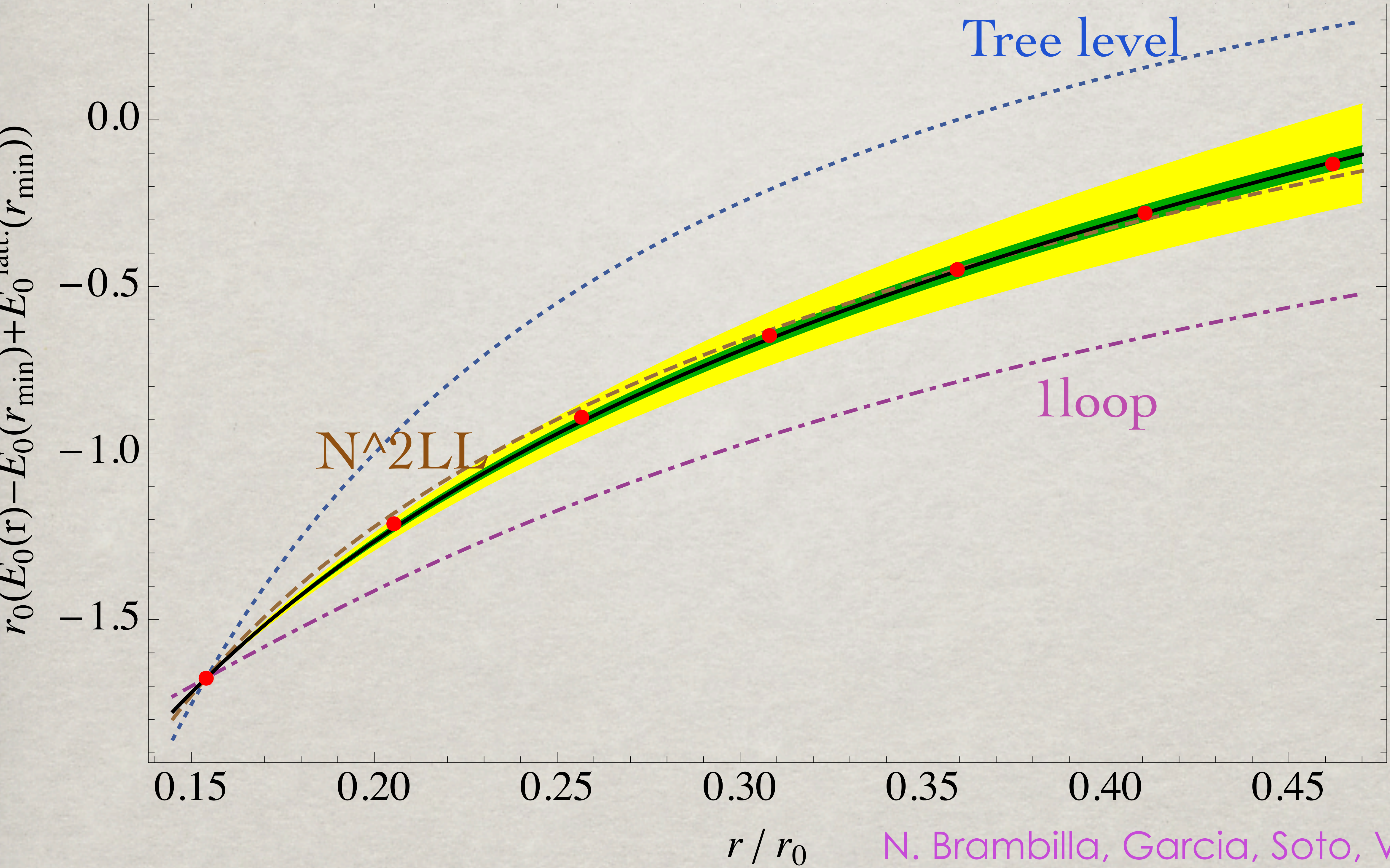

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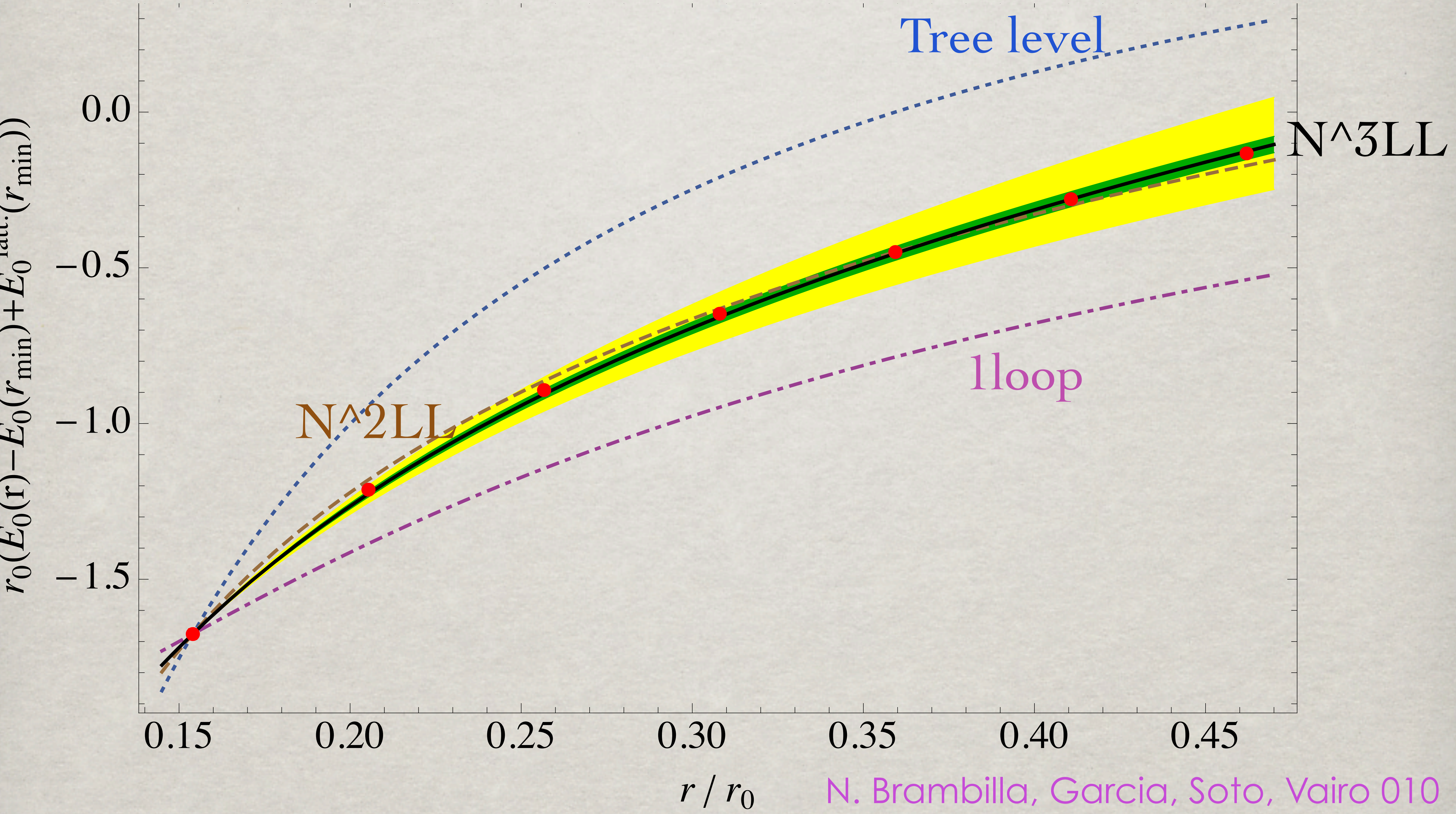

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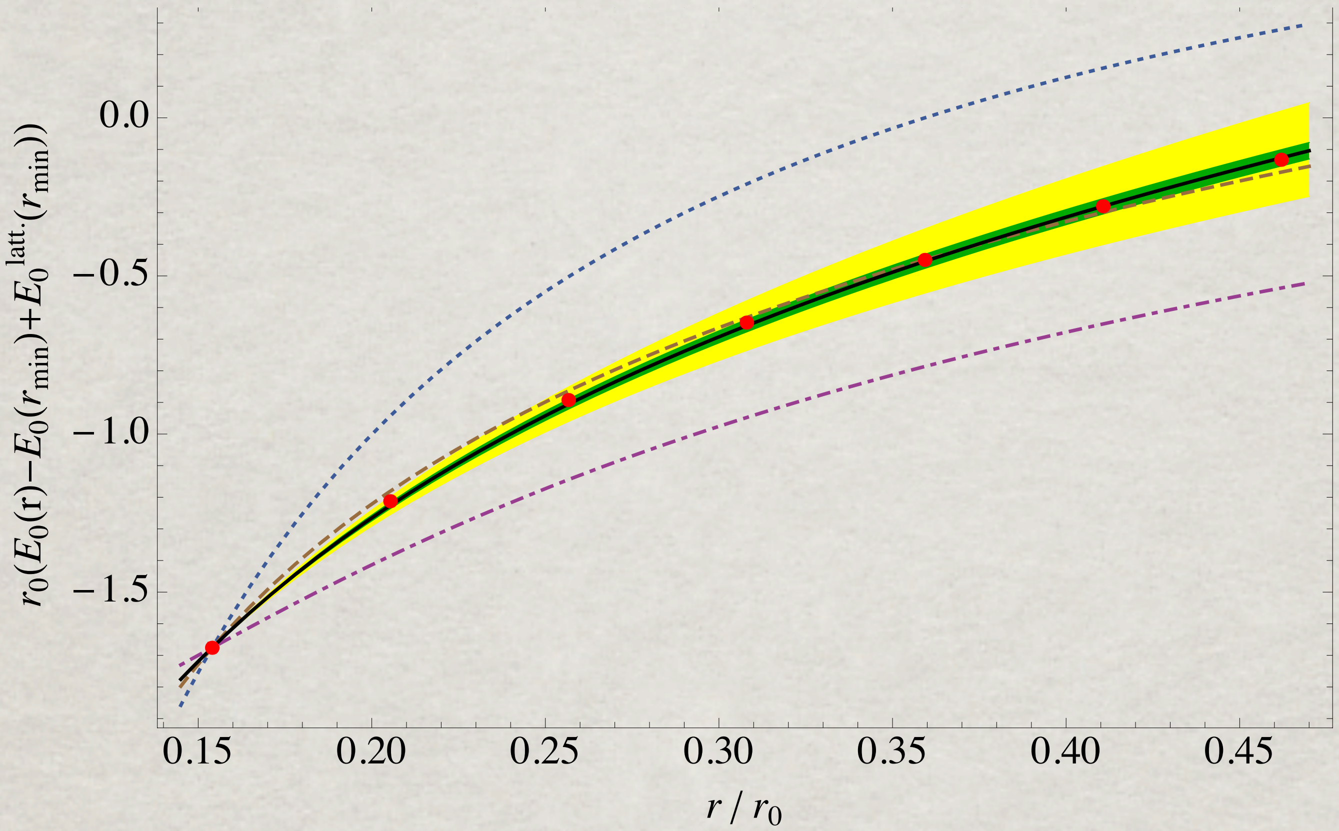

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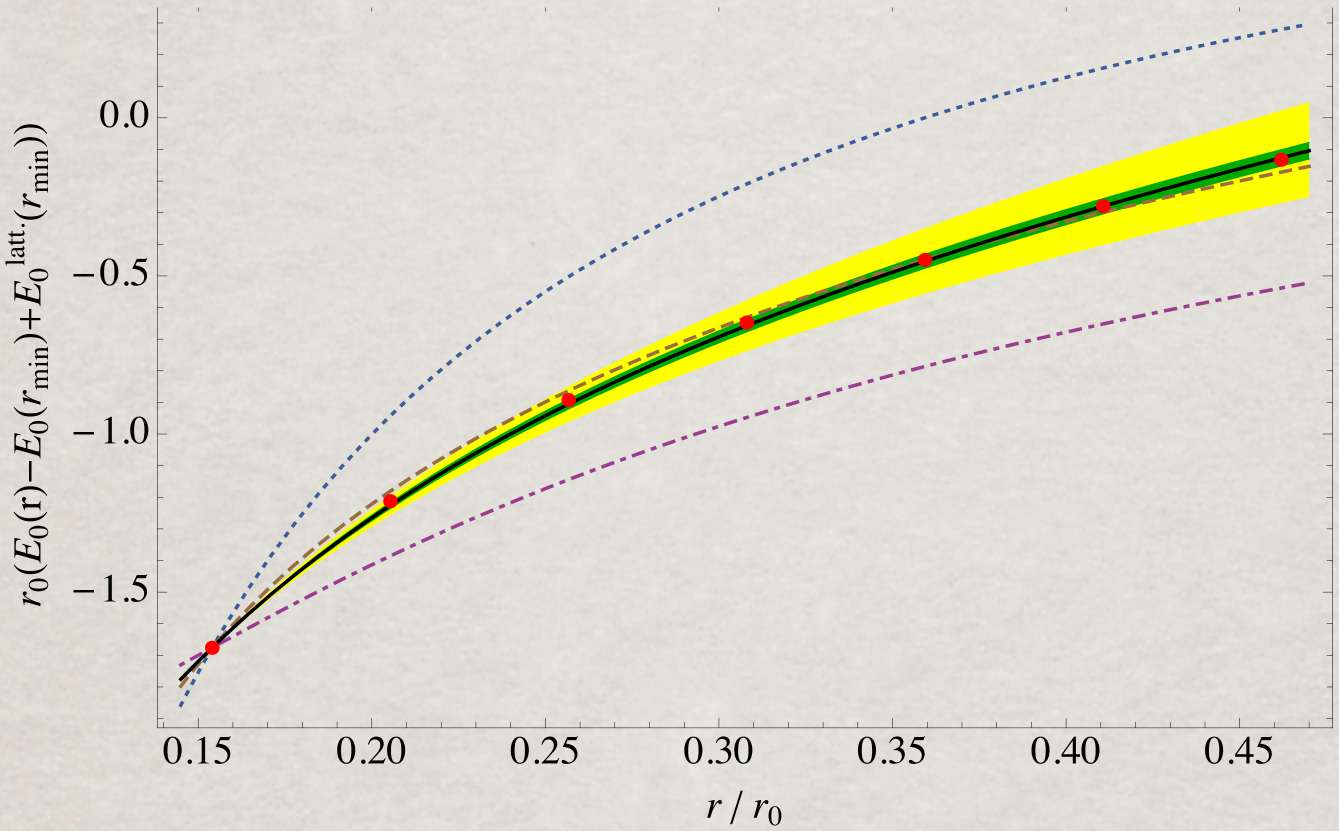
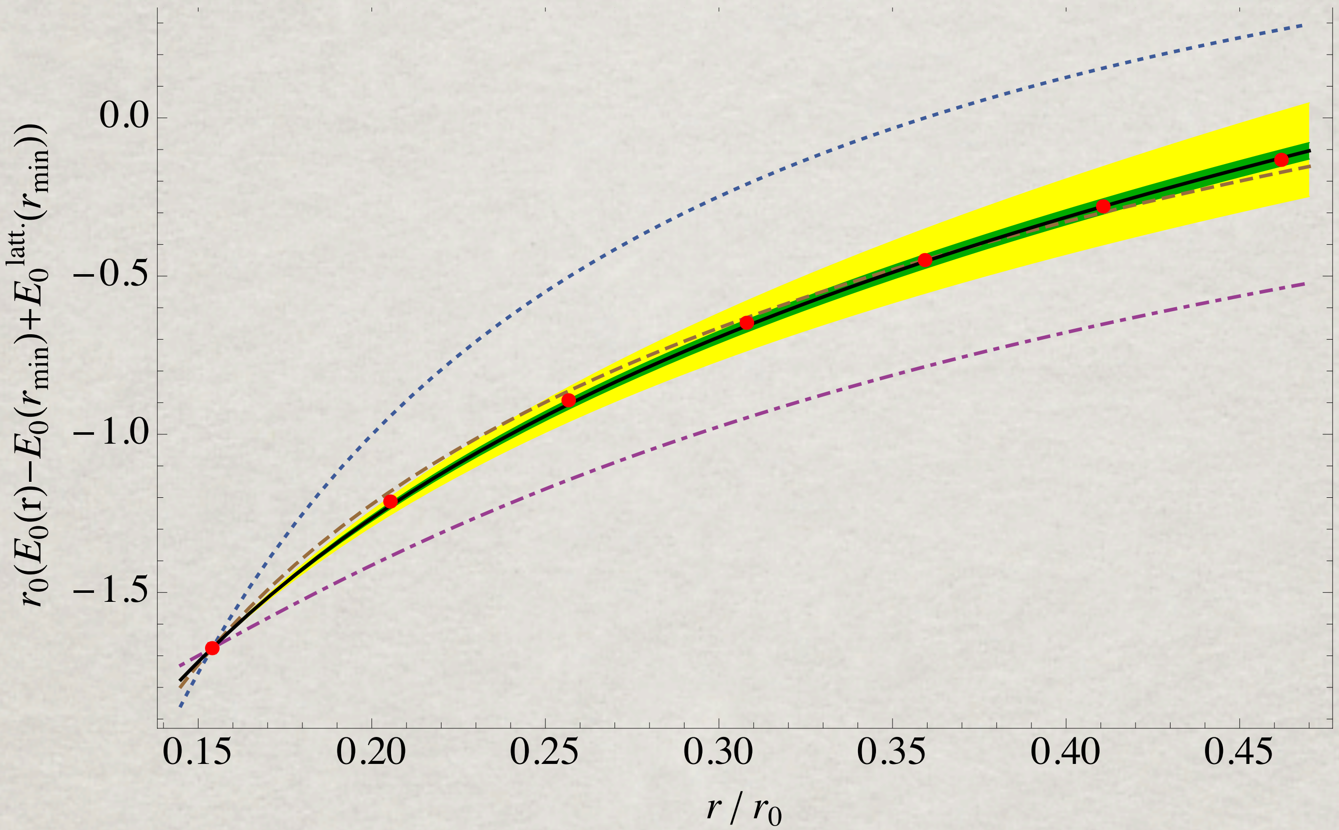


- Very good convergence of the QCD bound state perturbative series

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



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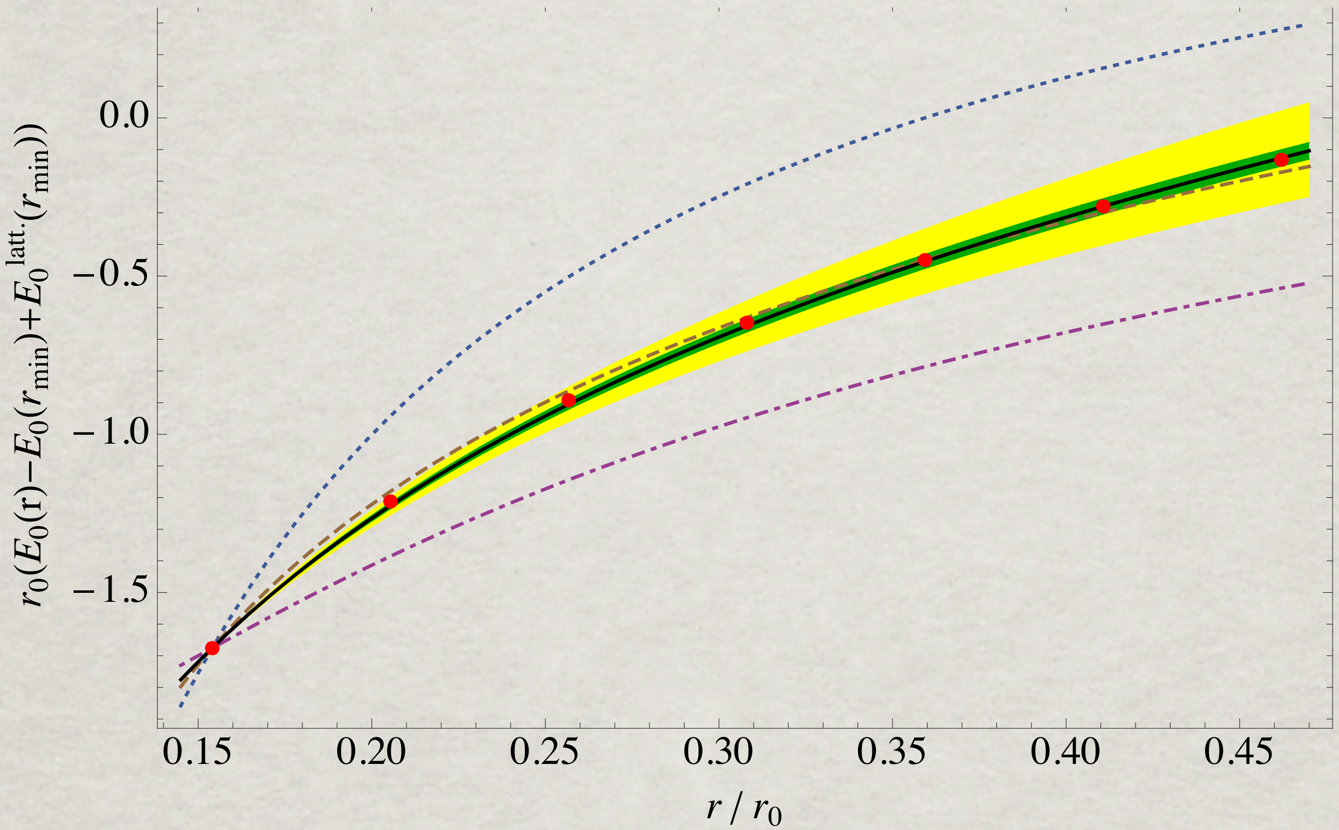

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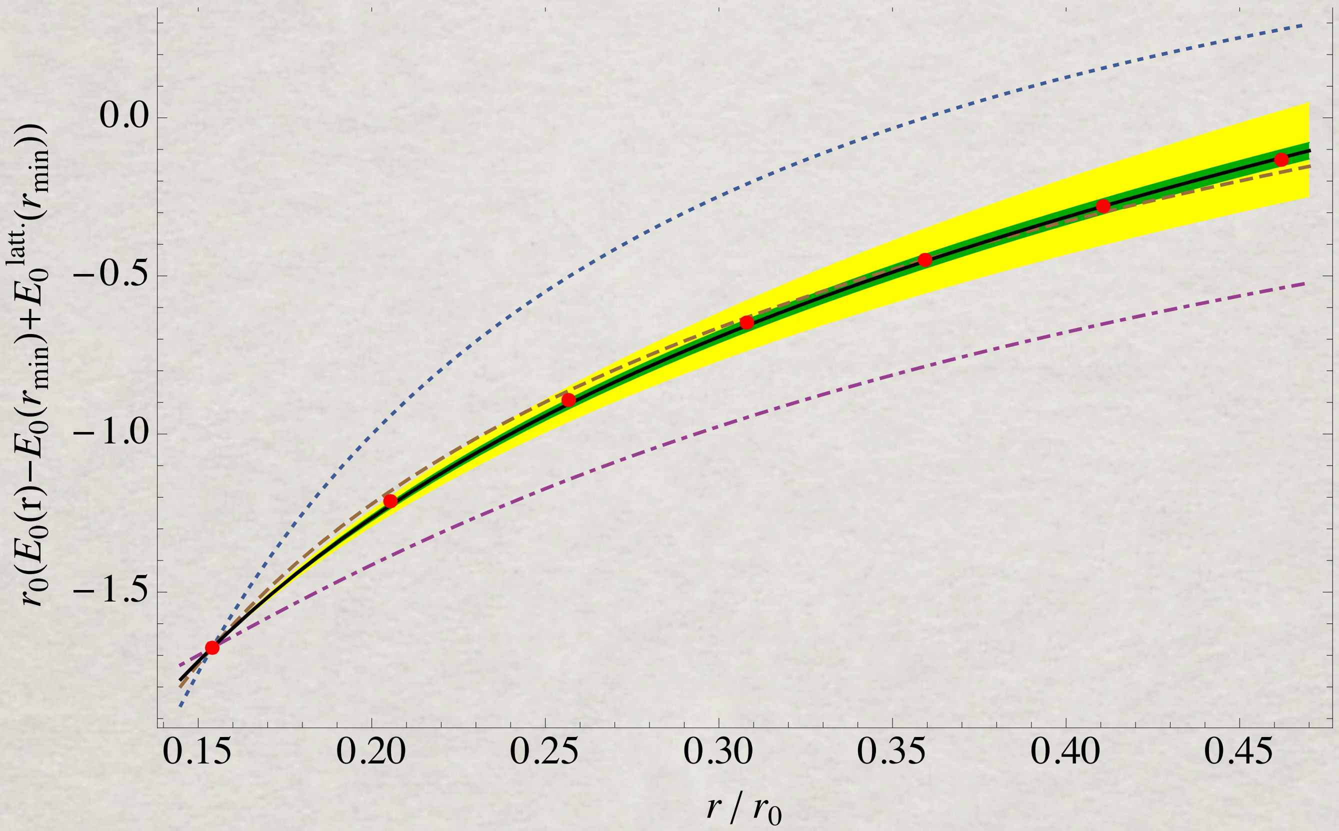


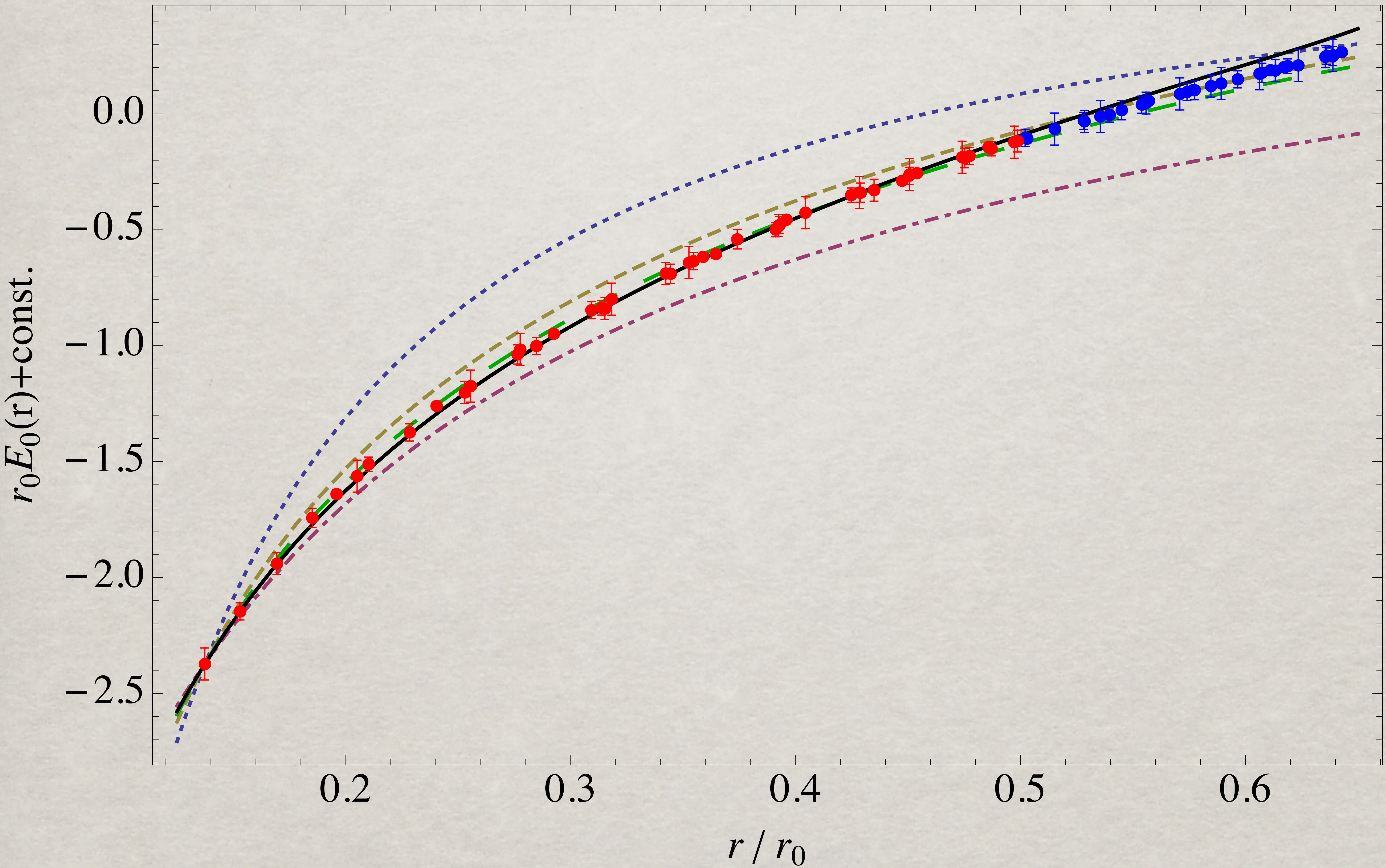
- Very good convergence of the QCD bound state perturbative series
- The lattice data are perfectly described from perturbation theory up to more than 0.2 fm
- Allows to rule out models: no string contribution at small r !
- Allows precise extraction of fundamental parameters of QCD

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

N. Brambilla, Garcia, Soto, Vairo 010)

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



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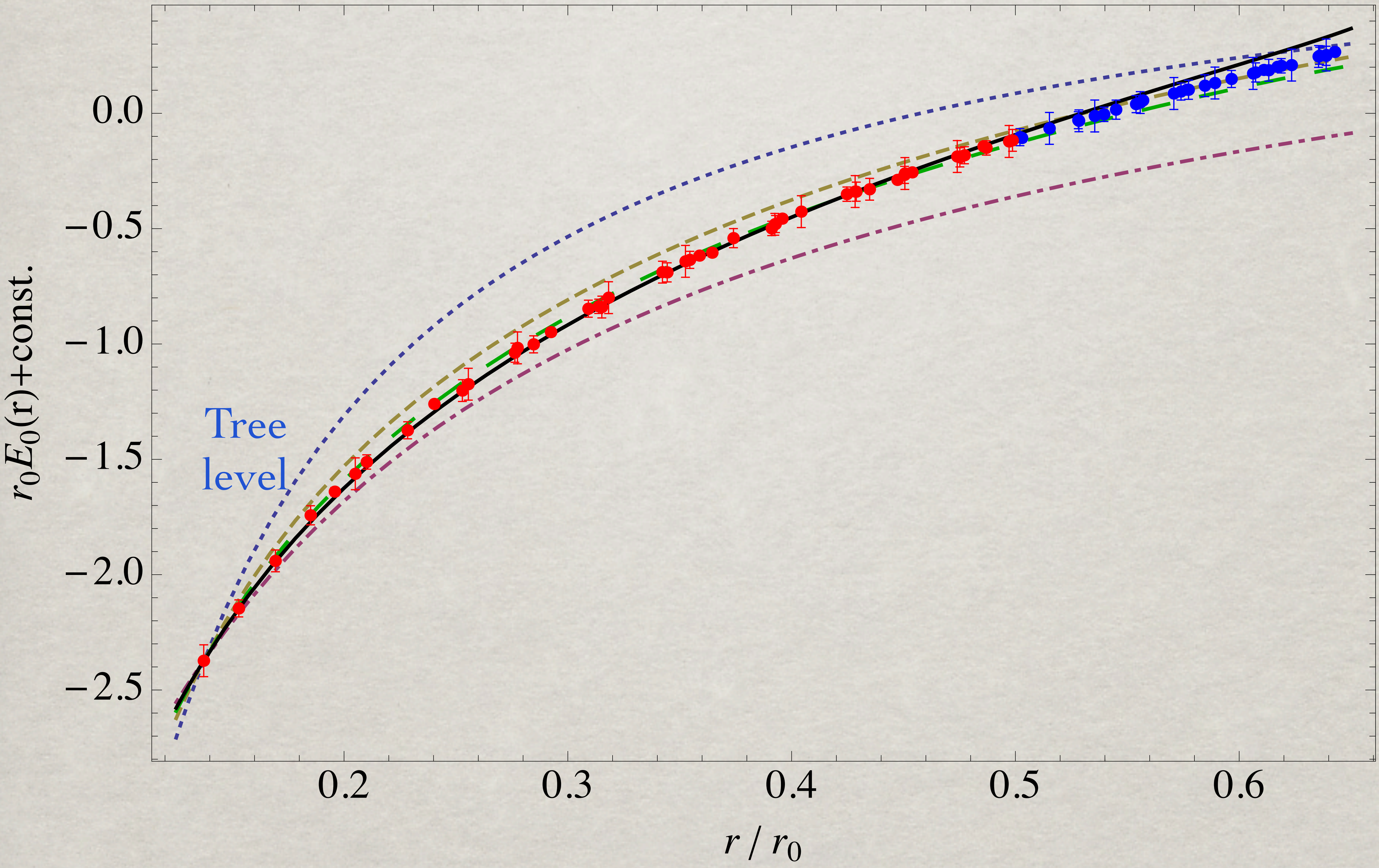

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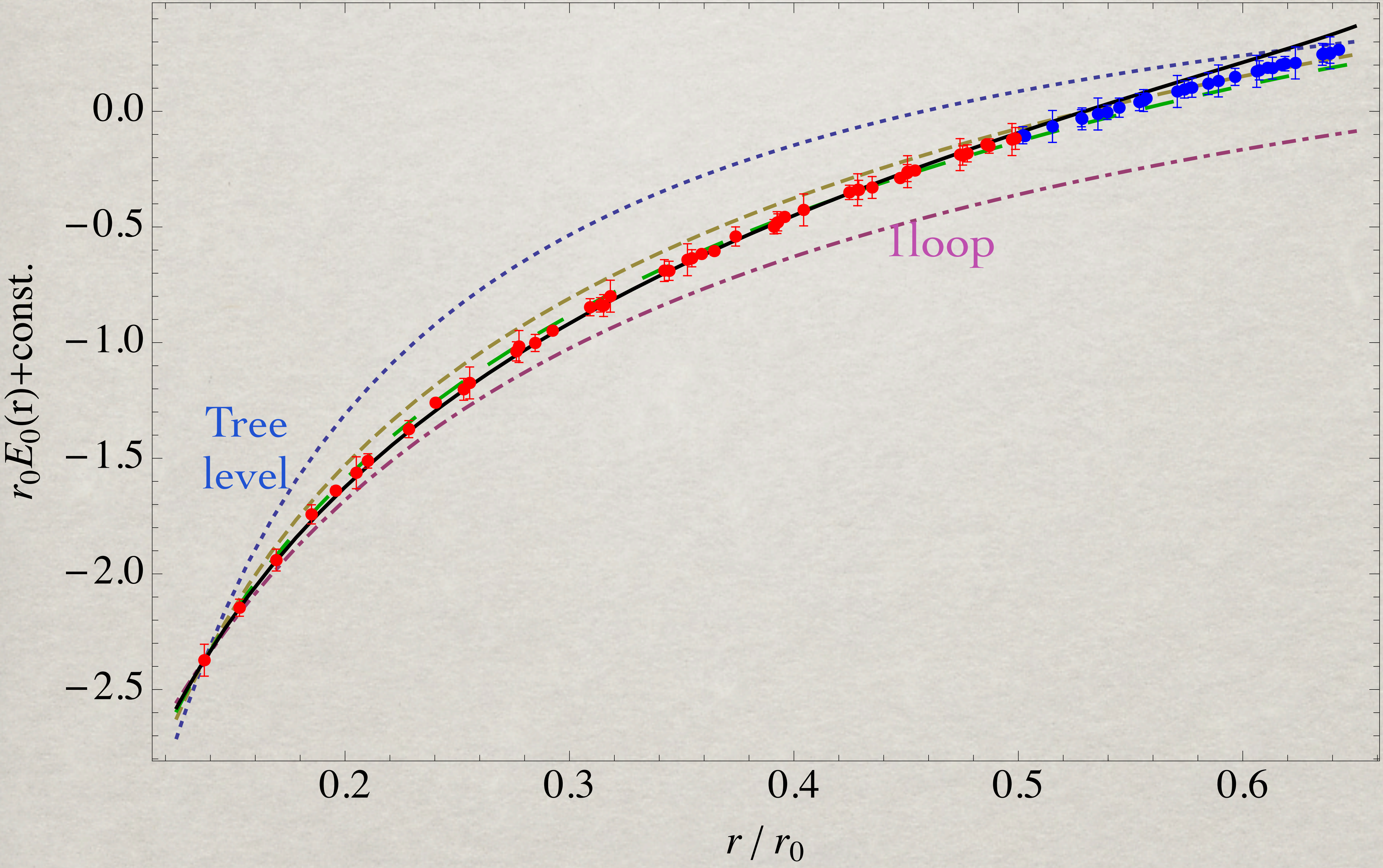

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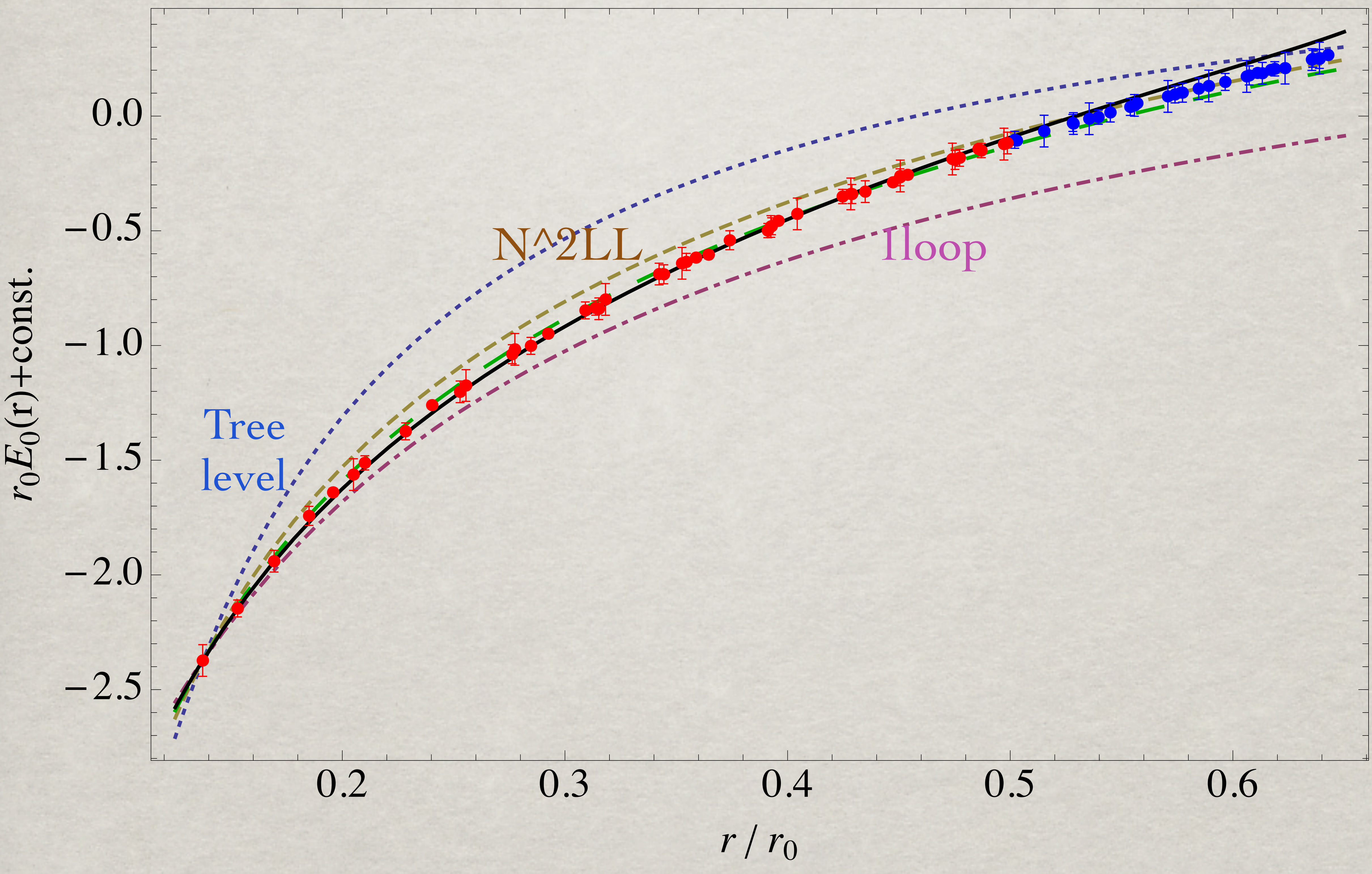

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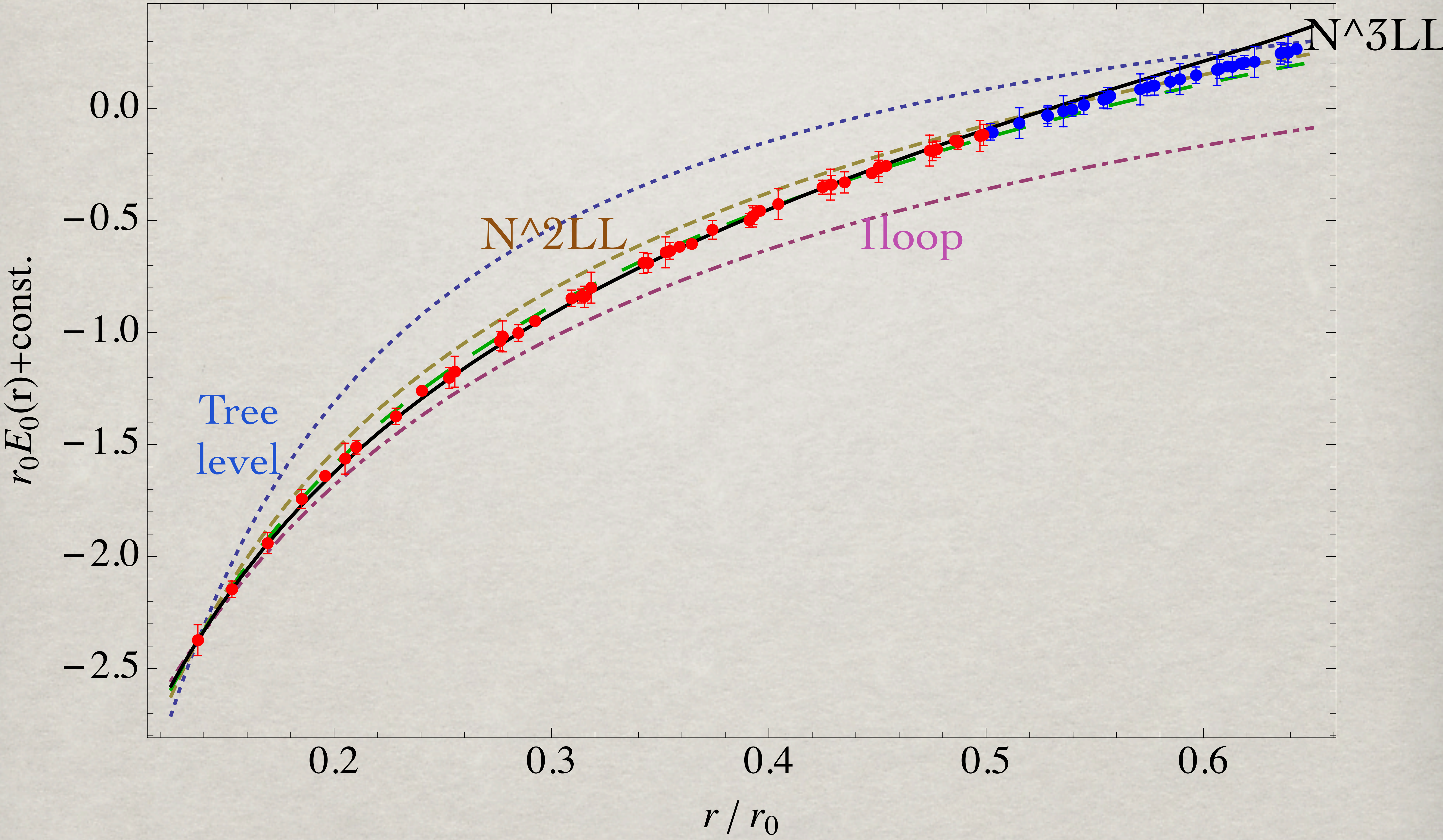

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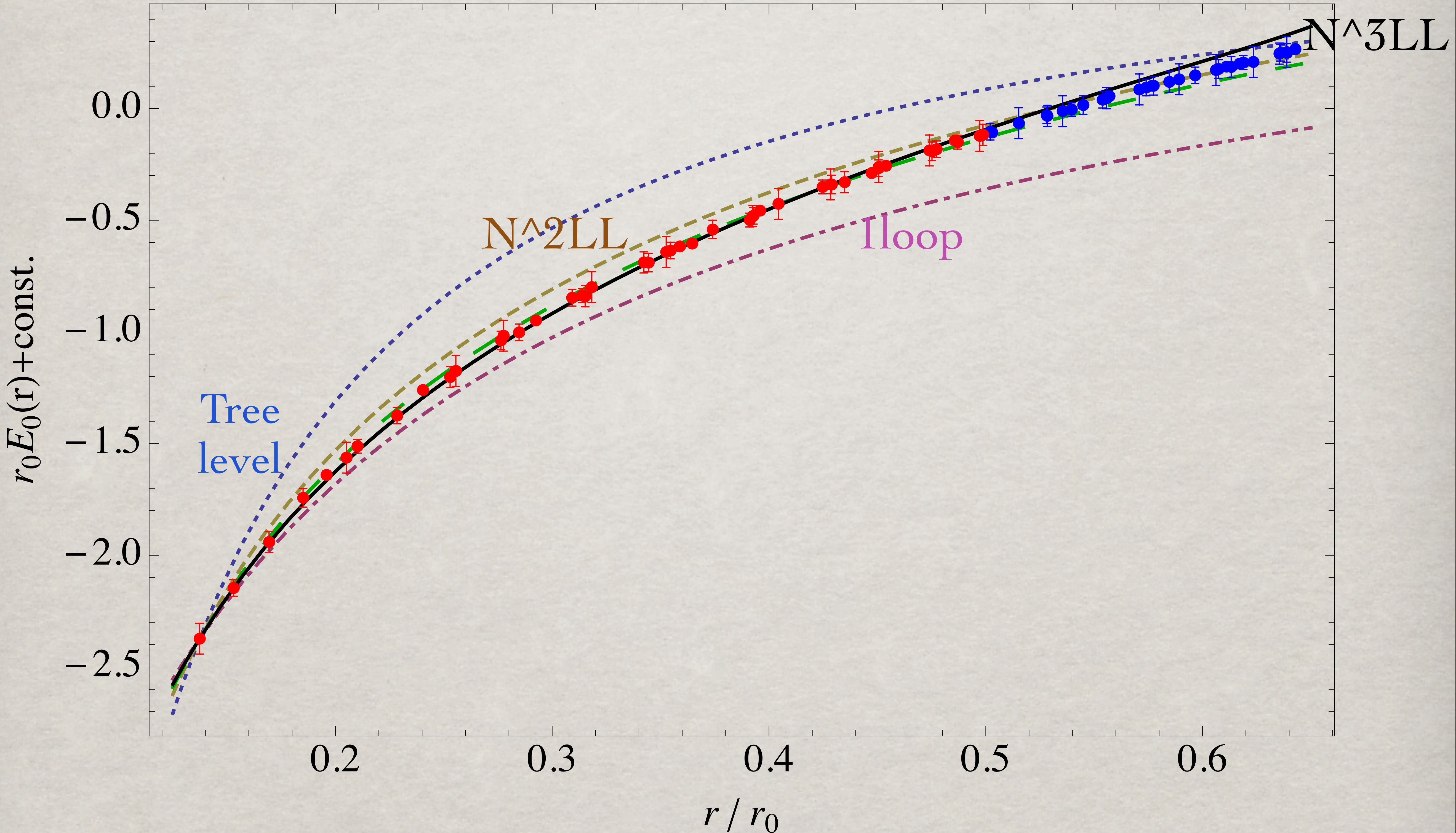
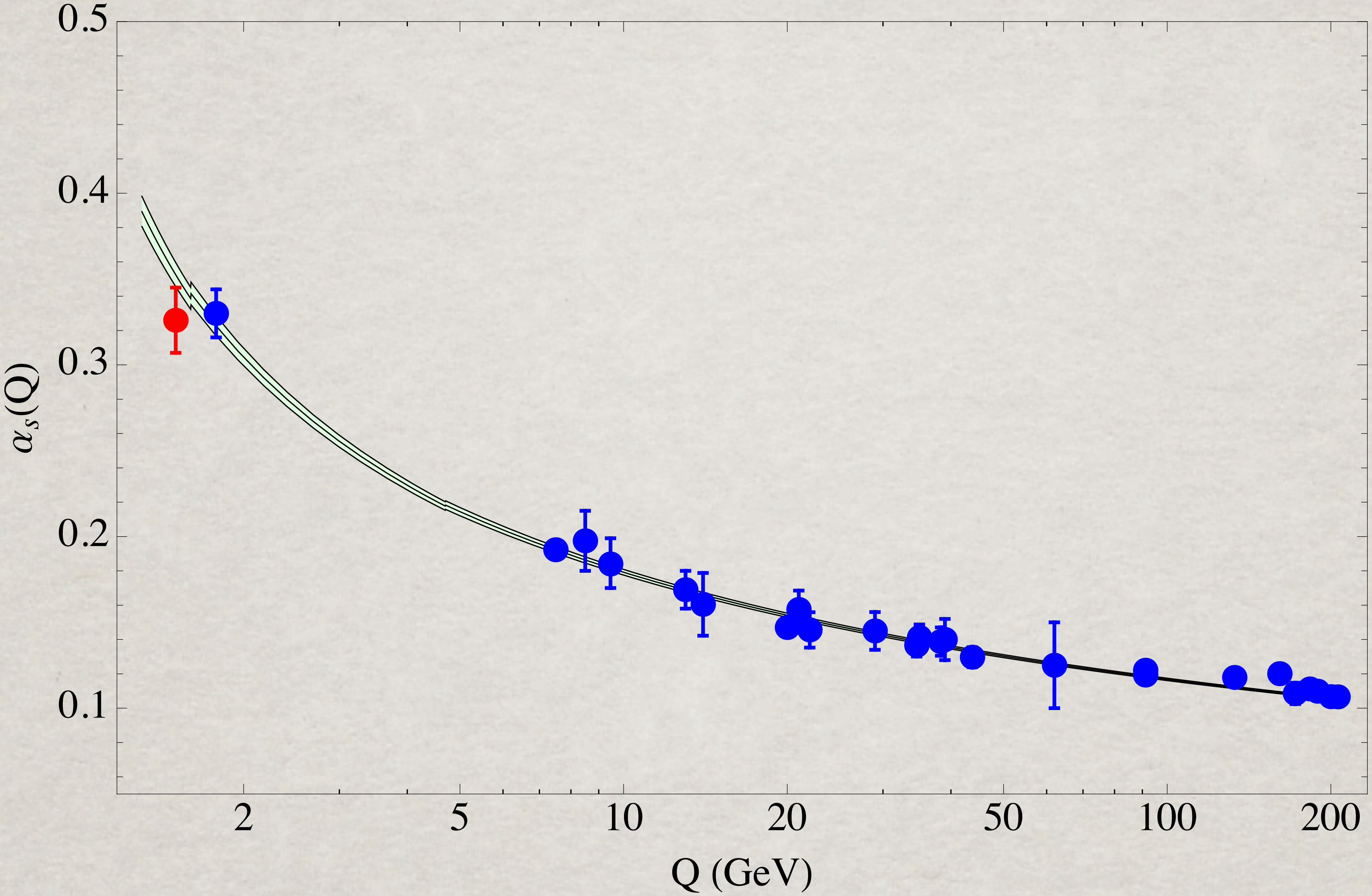


Good convergence to the lattice data

Lattice data less accurate in the unquenched case

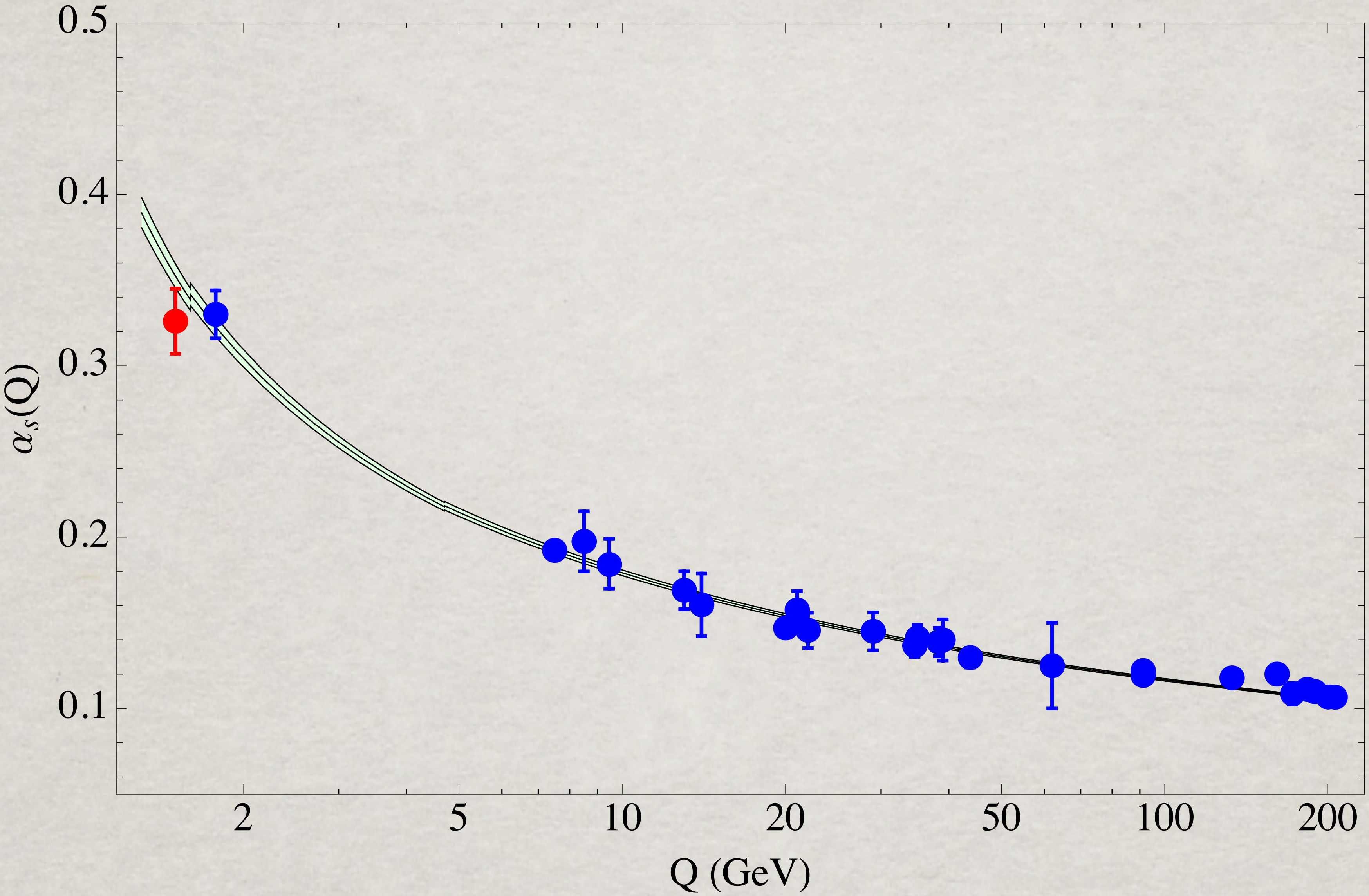
α_s extraction



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

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

α_s extraction



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

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

corresponding to

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

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

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

Applications to Quarkonium physics: systems with small radius

for references see the QWG doc arXiv:1010.5827

- c and b masses at NNLO, N^{3}LO*, NNLL*;
- B_c mass at NNLO; Penin et al 04
- B_c^*, η_c, η_b masses at NLL; Kniehl et al 04
- Quarkonium 1P fine splittings at NLO;
- $\Upsilon(1S)$, η_b electromagnetic decays at NNLL;
- $\Upsilon(1S)$ and J/ψ radiative decays at NLO;
- $\Upsilon(1S) \to \gamma\eta_b$, $J/\psi \to \gamma\eta_c$ at NNLO;
- $t\bar{t}$ cross section at NNLL;
- QQq and QQQ baryons: potentials at NNLO, masses, hyperfine splitting, ... ; N. B. et al 010
- Thermal effects on quarkonium in medium: potential, masses (at $m\alpha_s^5$), widths, ...;

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

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

N. B. Yu Jia A. Vairo 2005

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

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

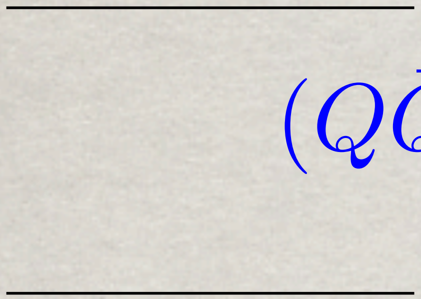
Y. Kiyo, A. Pineda, A. Signer 2010

Quarkonium systems with large radius

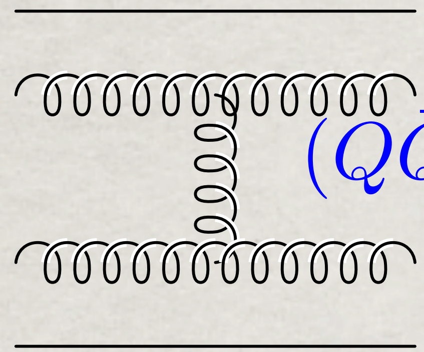
$$r \sim \Lambda_{QCD}^{-1}$$

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

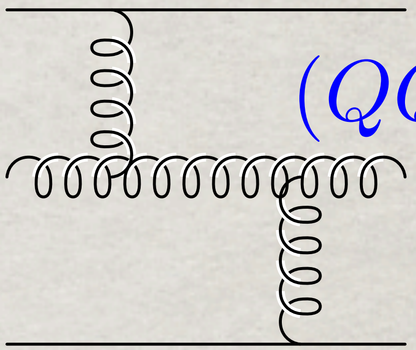
— Hitting the scale $\Lambda_{\rm QCD}$ $\quad r \sim \Lambda_{QCD}^{-1}$



$(Q\bar{Q})_1$



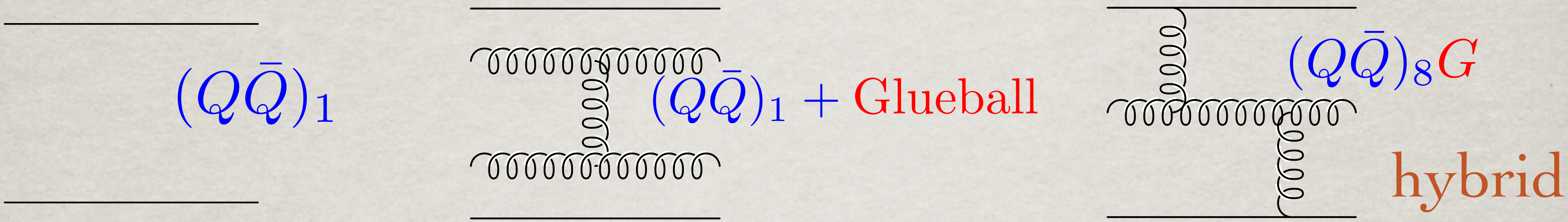
$(Q\bar{Q})_1$ + Glueball



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

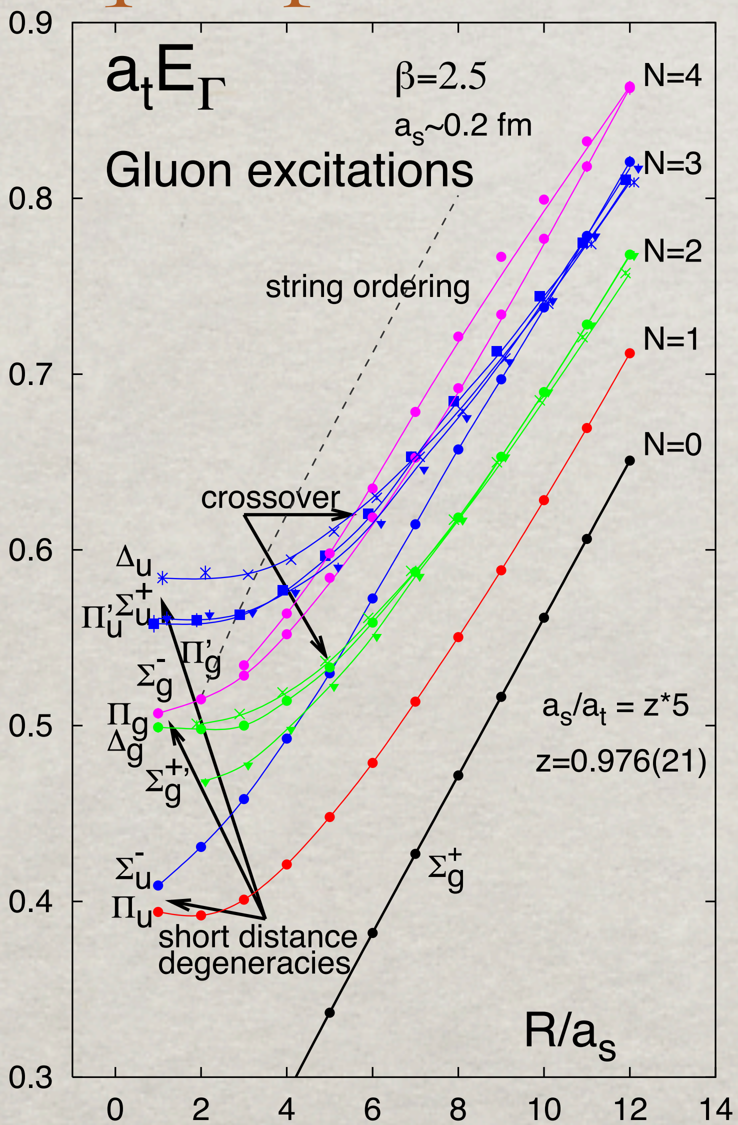
hybrid

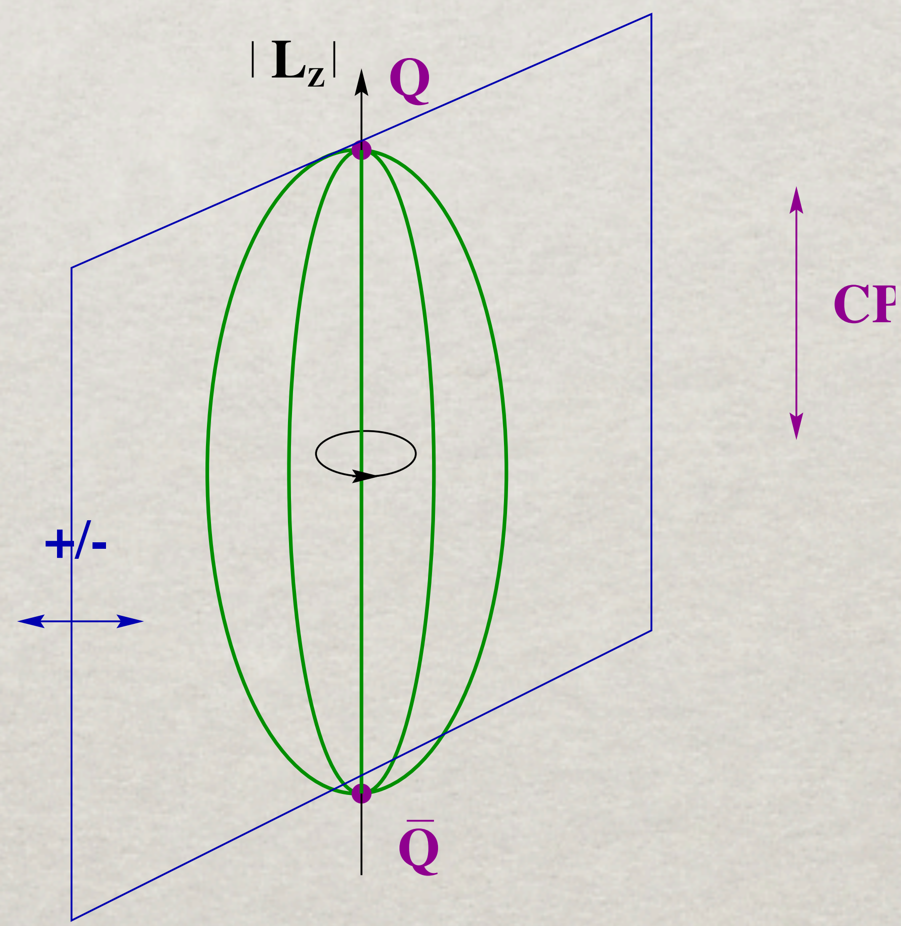
Hitting the scale $\Lambda_{\rm QCD}$ $r \sim \Lambda_{QCD}^{-1}$



Static qcd spectrum

Lattice





Symmetries of a diatomic molecule + C.C.

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

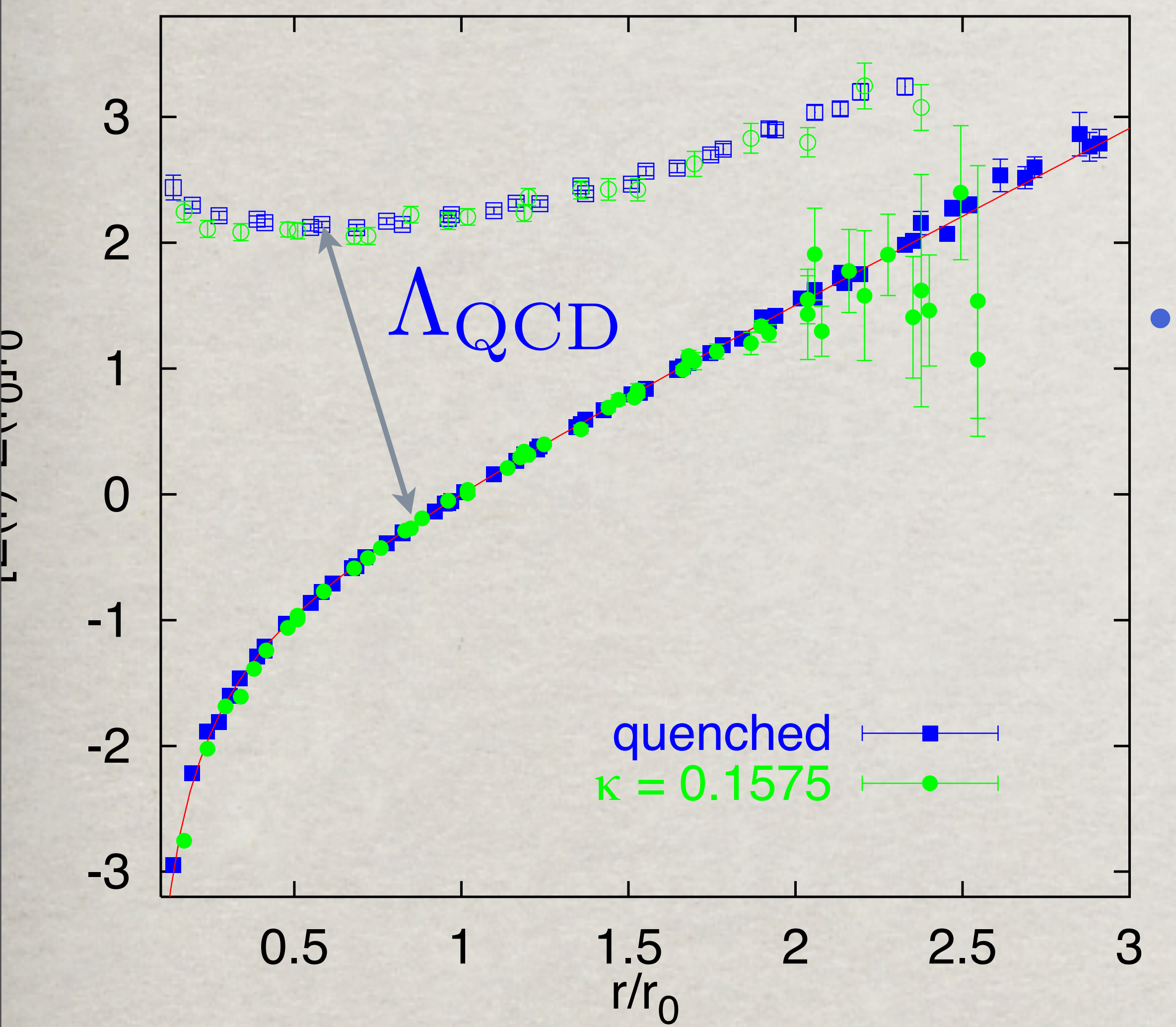
b) CP (u/g)

c) Reflection $(+/-)$
(for Σ only)

Juge Kuti Mornigstar 98-06 Static NRQCD

Quarkonium develops a gap to hybrids

Bali et al. 98



- $mv \sim \Lambda_{QCD}$
- integrate out all scales above mv^2
- gluonic excitations develop a gap $\Lambda_{\rm QCD}$
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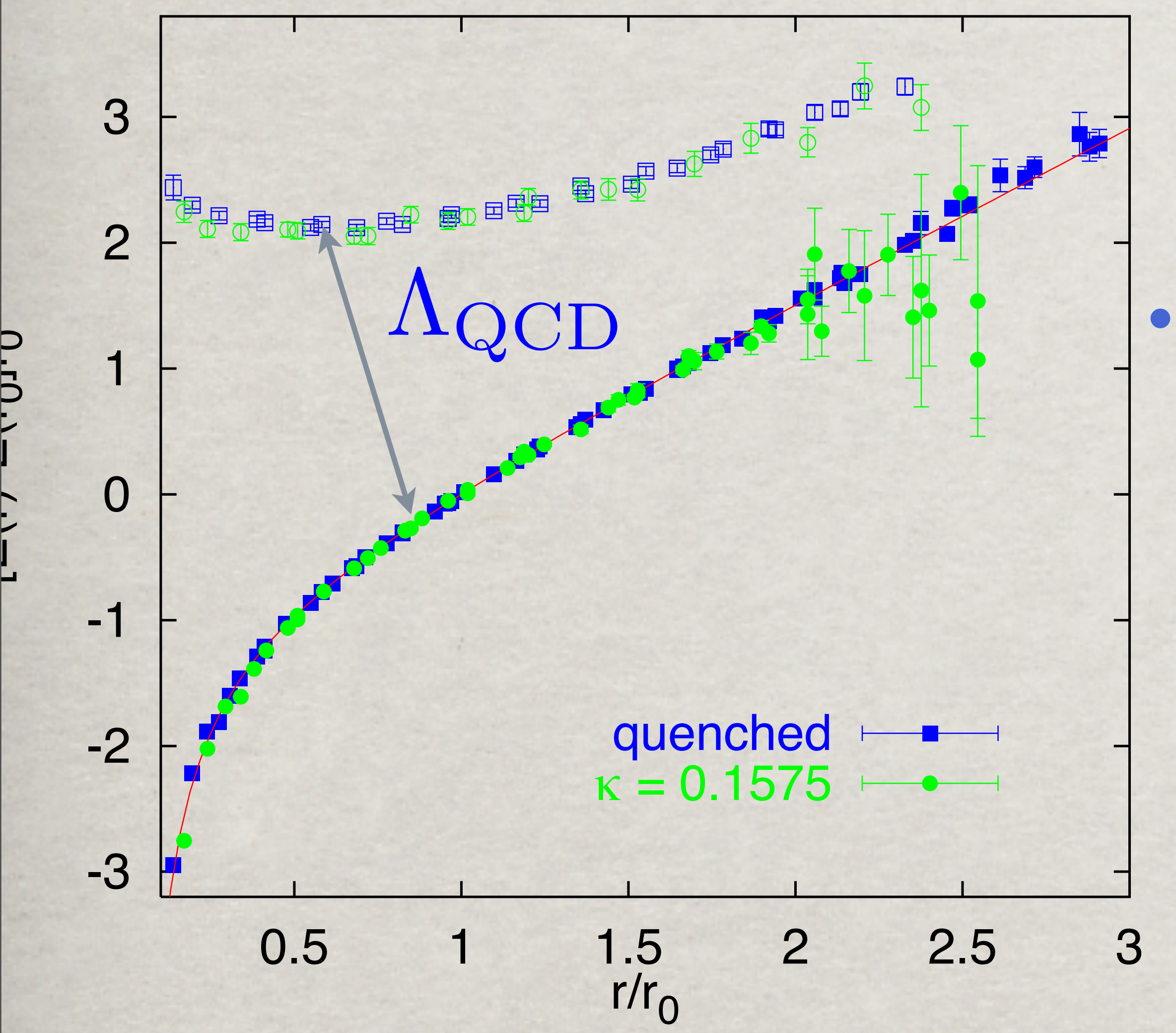
Quarkonium develops a gap to hybrids

Bali et al. 98



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

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

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

Brambilla Pineda Soto Vairo 00

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Brambilla Pineda Soto Vairo 00

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

Quarkonium singlet static potential

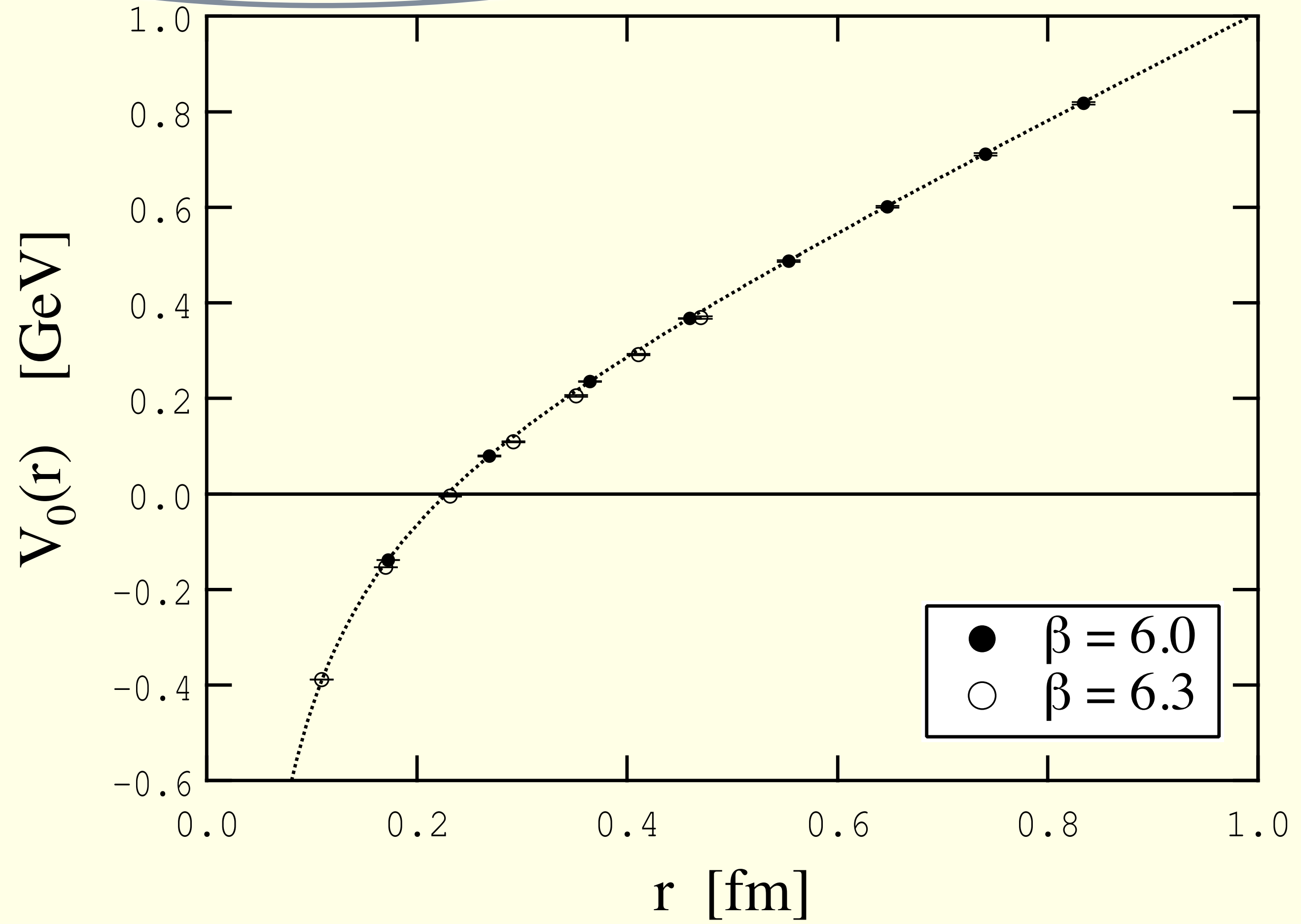
$$V = V_0 + \frac{1}{m} V_1 + \frac{1}{m^2}(V_{SD} + V_{VD})$$

Quarkonium singlet static potential

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

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

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



○ Koma Koma NPB 769(07)79

Quarkonium singlet static potential

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

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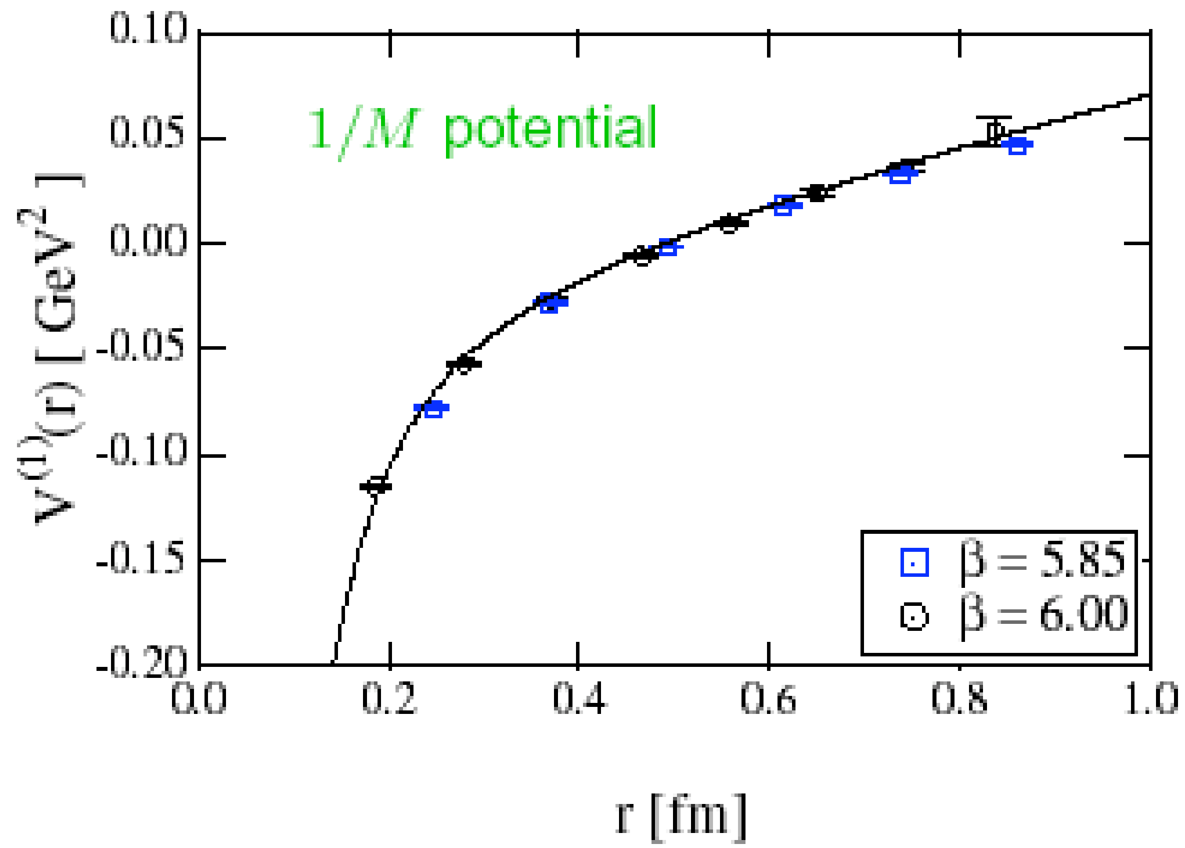
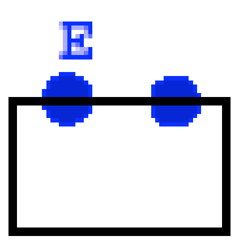


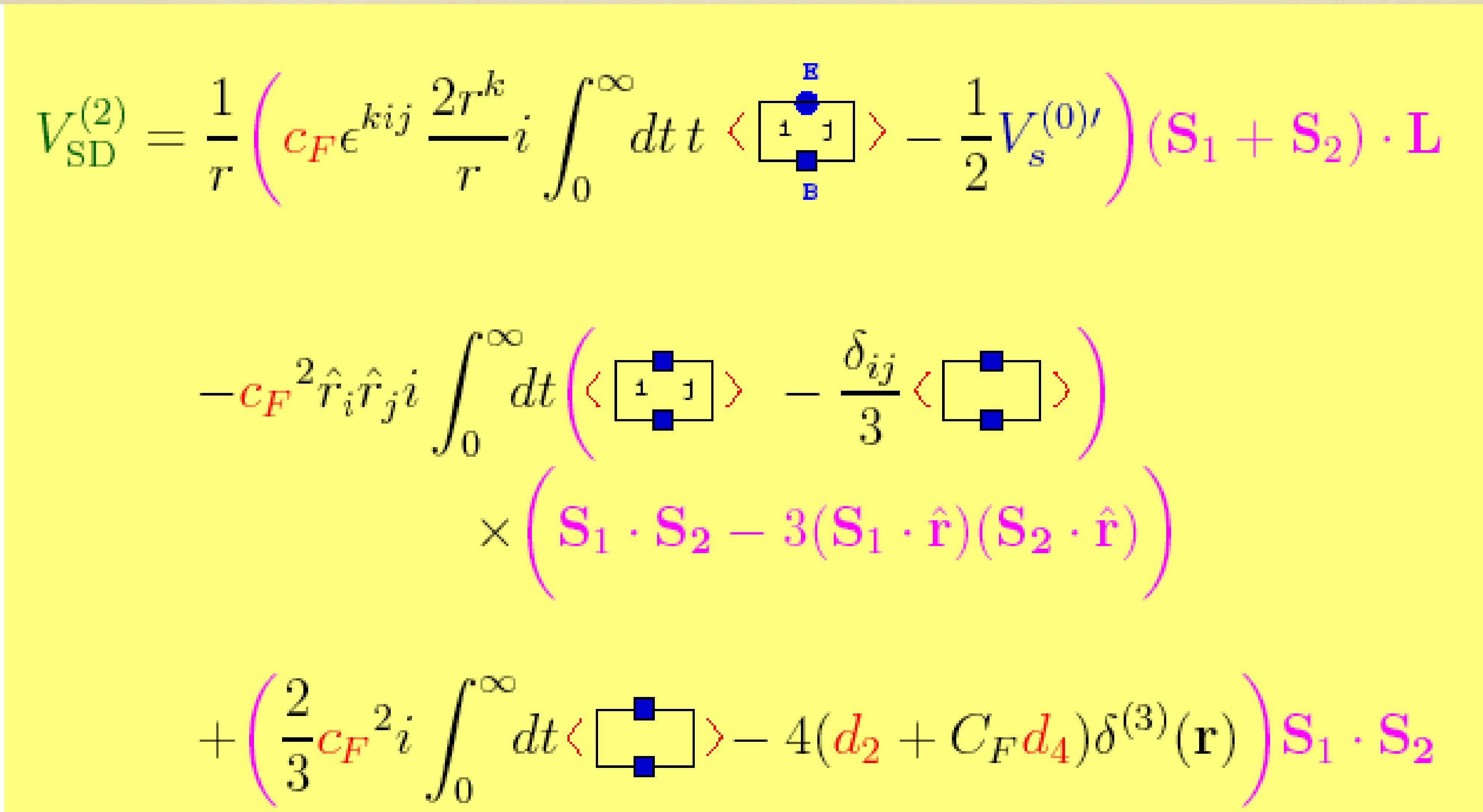
○ Koma Koma Wittig PoS LAT2007(07)111

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



Brambilla et al 00

QCD Spin dependent potentials



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

QCD Spin dependent potentials

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

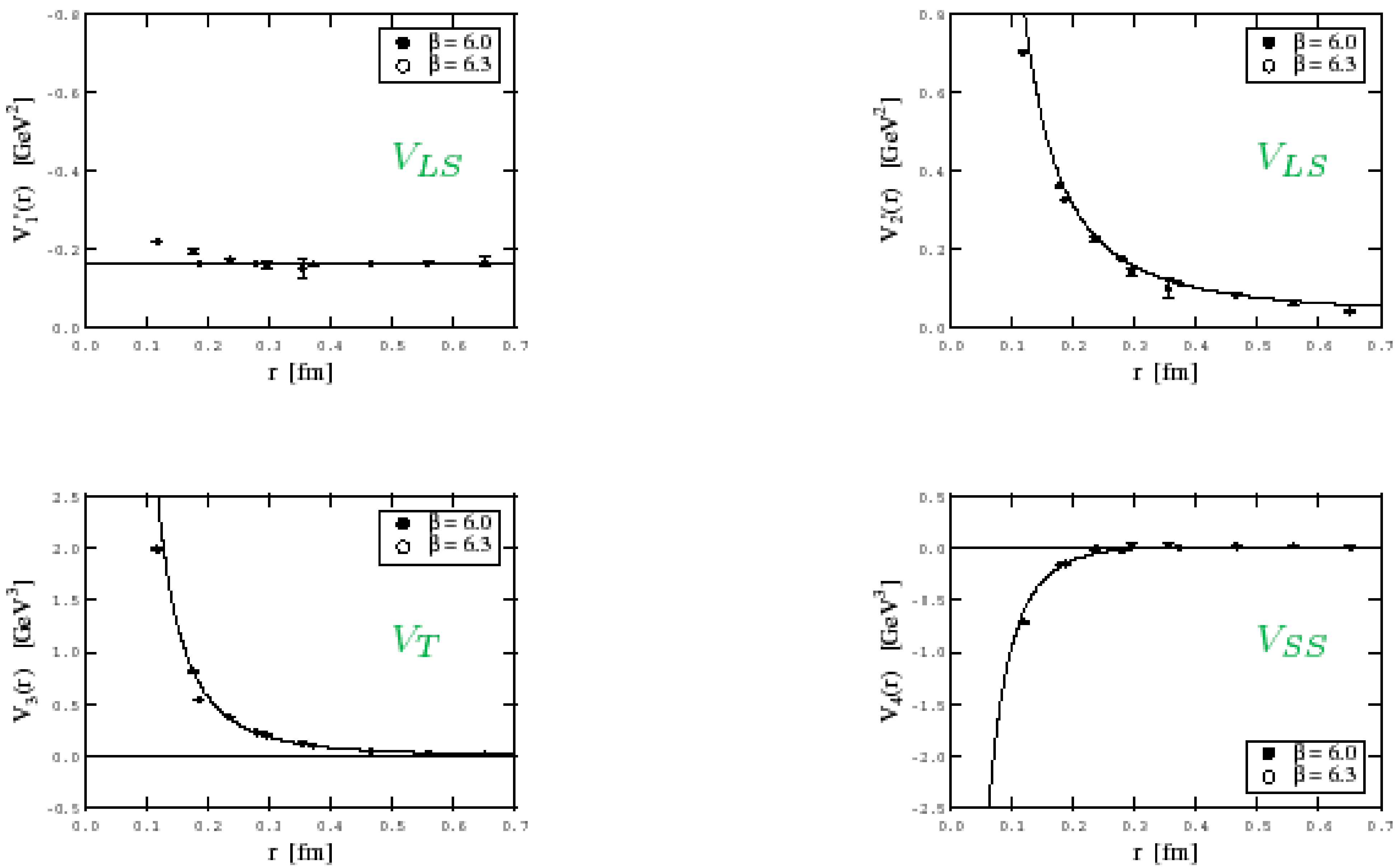
$$-{c_F}^2 \hat{r}_i \hat{r}_j i \int_0^\infty dt \left(\langle \boxed{i \;\; j} \rangle - \frac{\delta_{ij}}{3} \langle \boxed{} \rangle \right) \times \left(\mathbf{S}_1\cdot\mathbf{S}_2 - 3(\mathbf{S}_1\cdot\hat{\mathbf{r}})(\mathbf{S}_2\cdot\hat{\mathbf{r}}) \right)$$

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

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

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

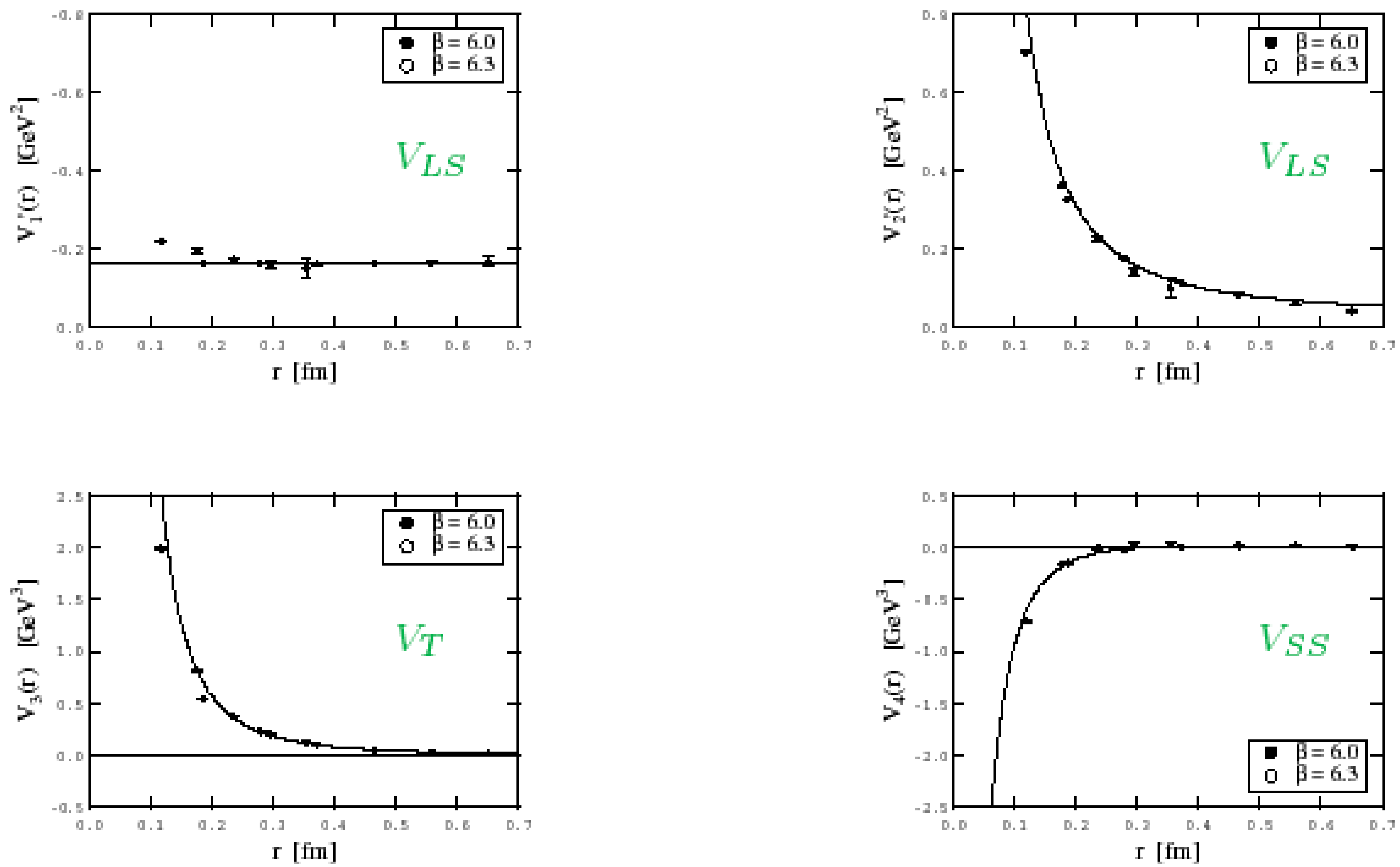
Spin dependent potentials



Koma Koma Wittig 05, Koma Koma 06

Terrific advance in the data precision with Lüscher multivel algorithm!

Spin dependent potentials



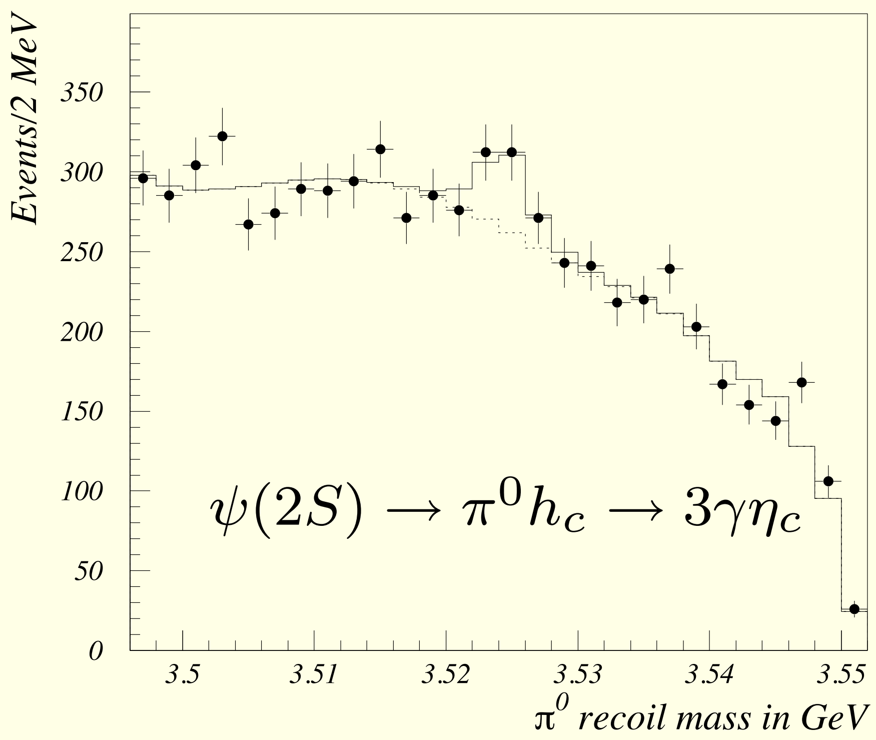
Koma Koma Wittig 05, Koma Koma 06

Terrific advance in the data precision with Lüscher multivel algorithm!

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

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

h_c, h_b



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

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

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

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

- Also

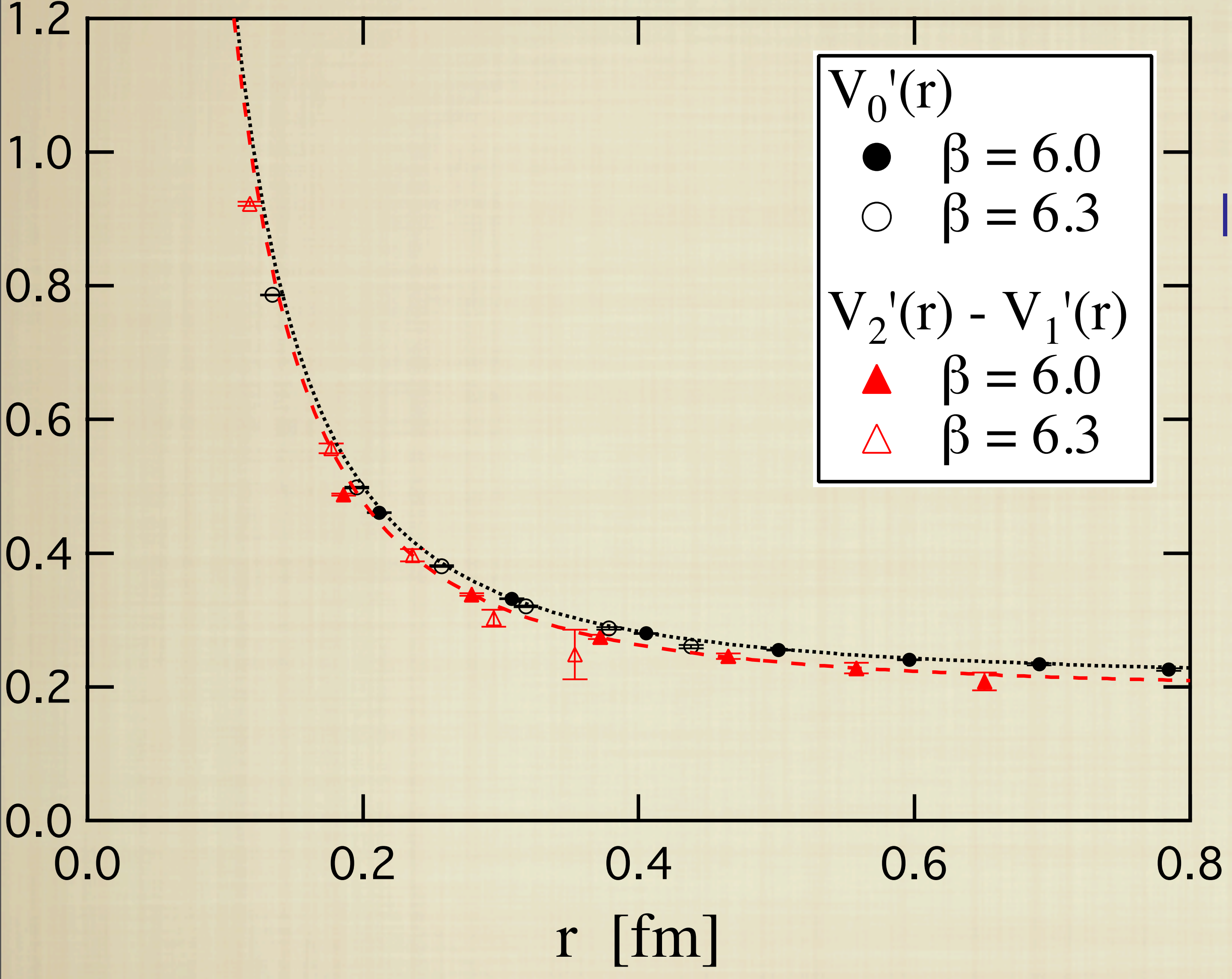
$M_{h_b} = 9902 \pm 4 \pm 1$ MeV ○ BABAR arXiv:1102.4565

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

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many other relations among potentials in the EFT

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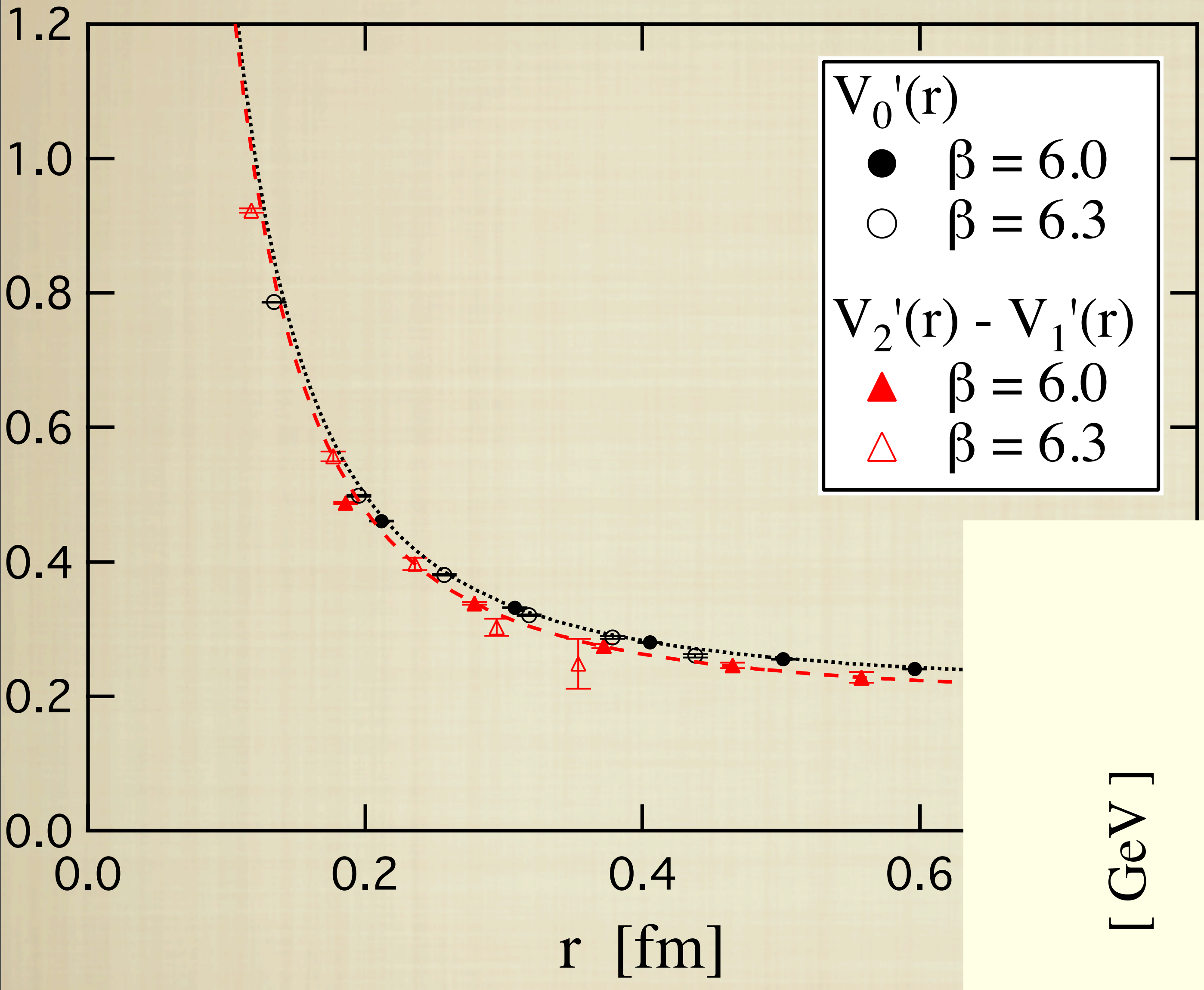

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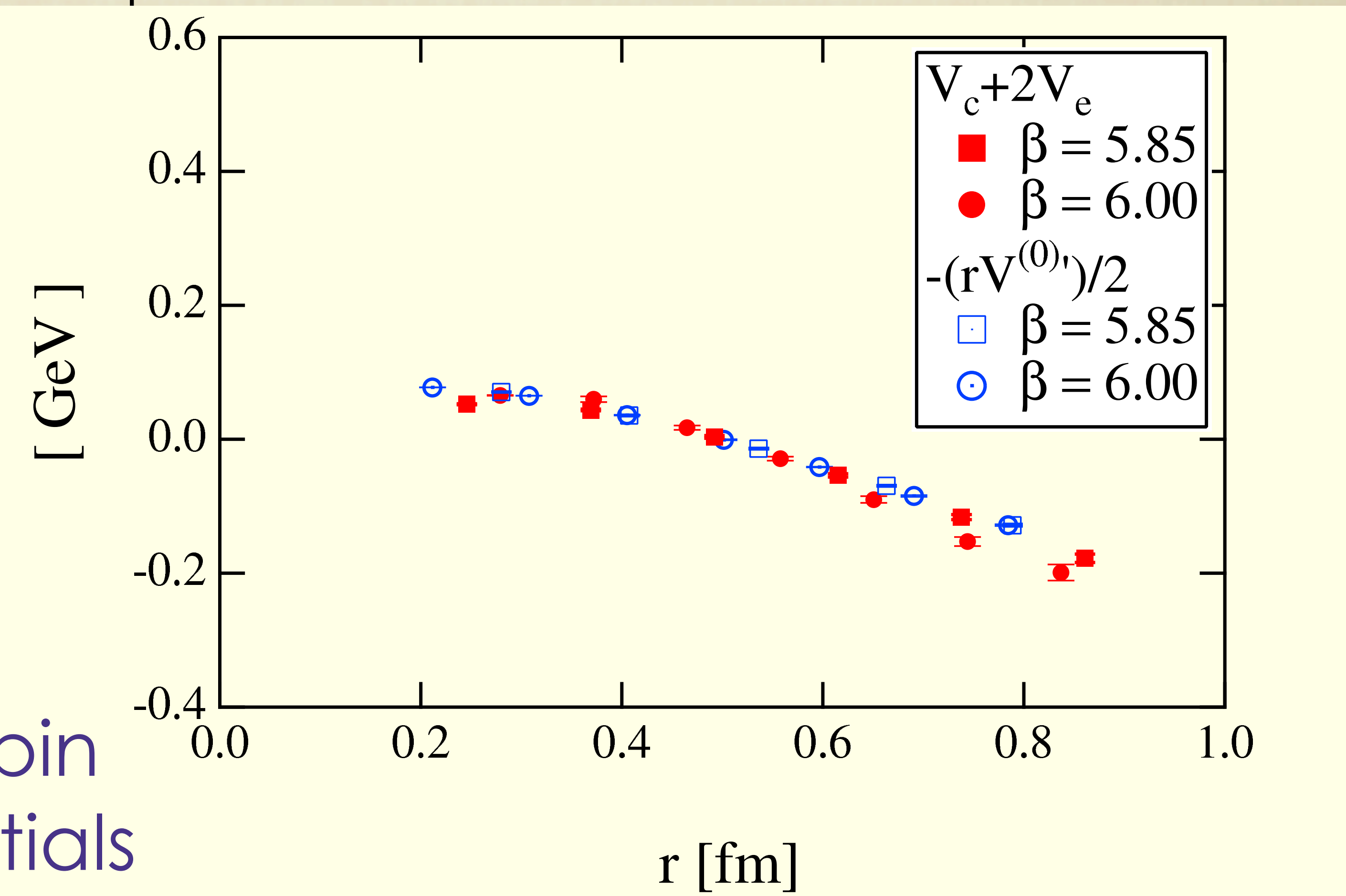
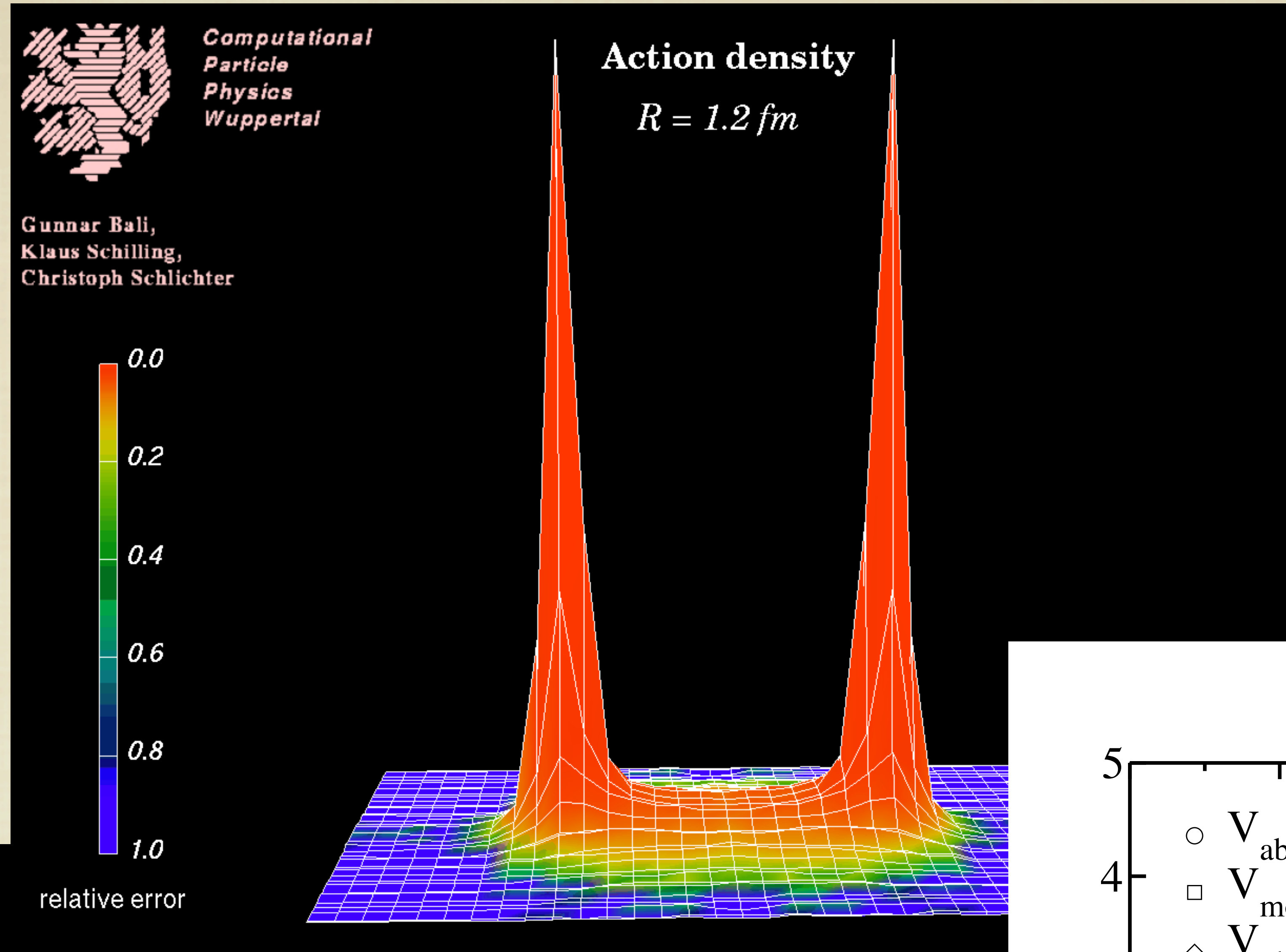


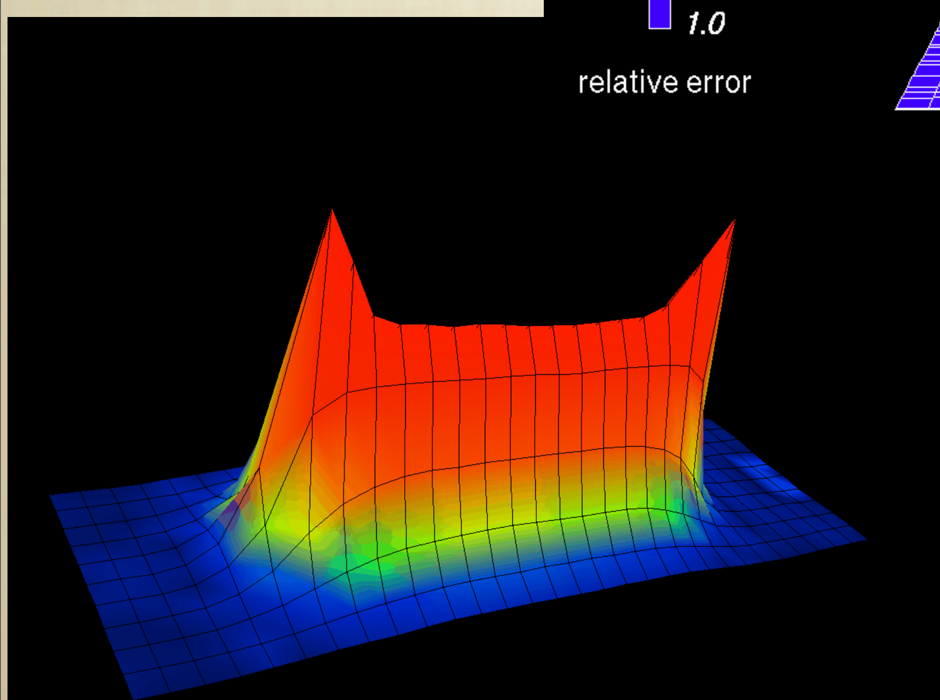
Koma Koma Wittig PoS LAT2007 (2007) 111

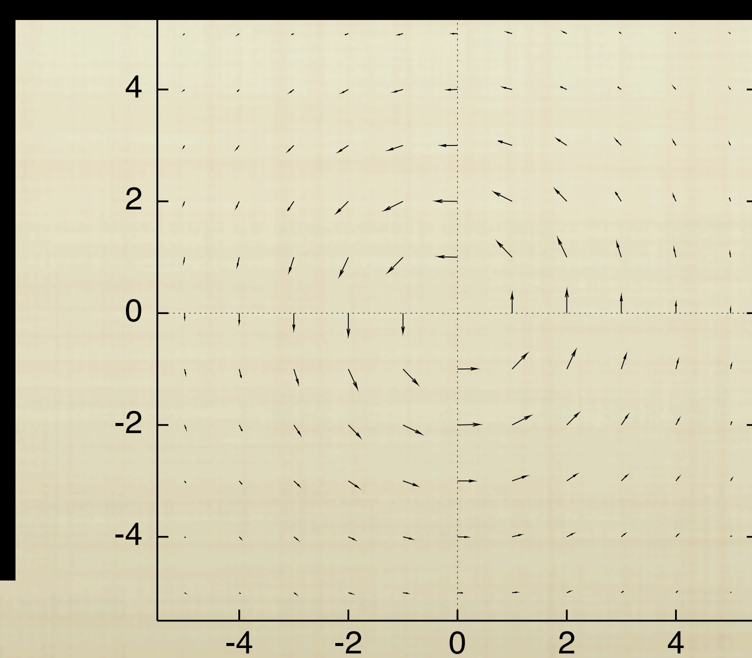
relations involving spin independent potentials

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

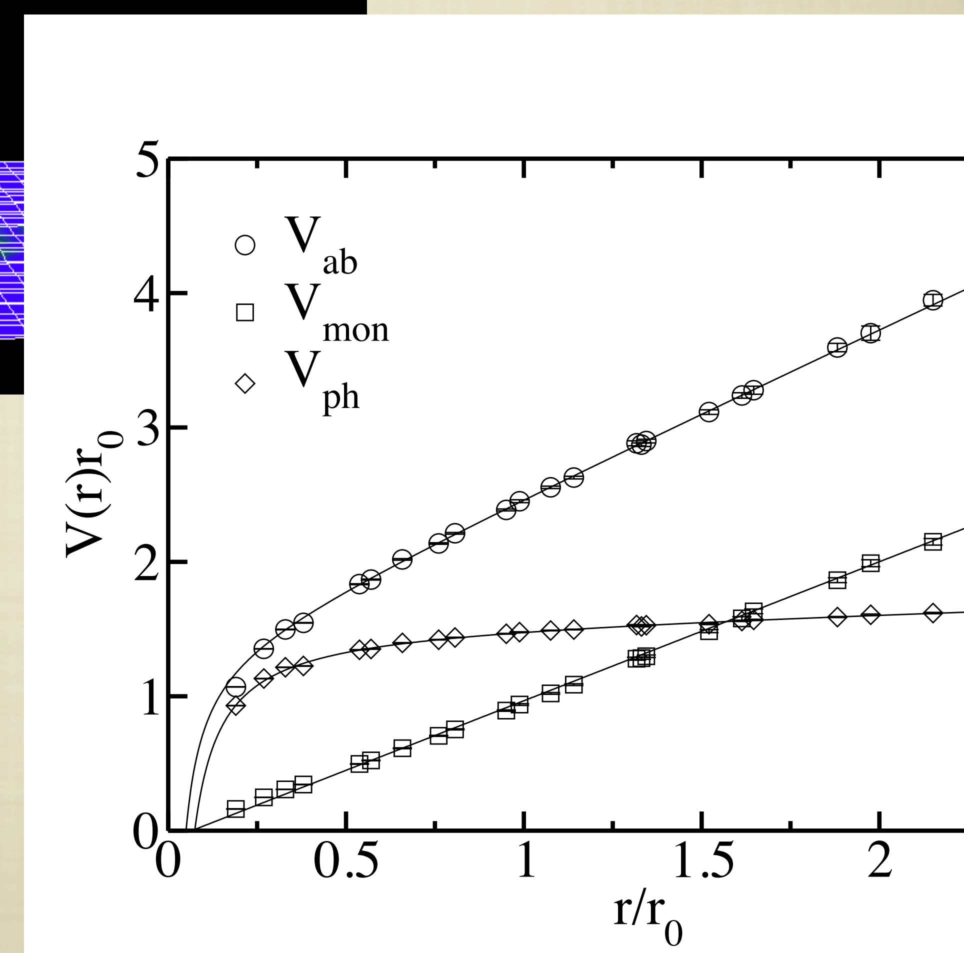
Bali et al







Boryakov et al. 04



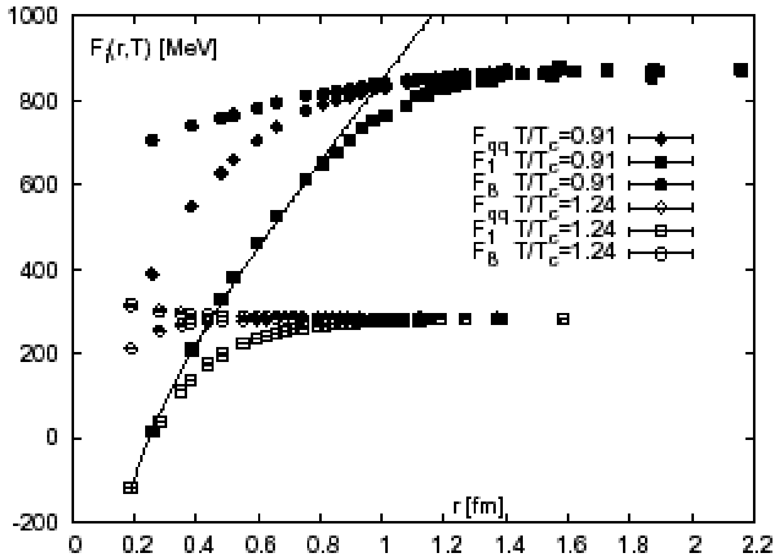
Heating quarkonium systems

$$T > 0$$

Quarkonium in a hot medium: the interaction potential

Free energy vs potential

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



- Kaczmarek Zantow PRD 71 (2005) 11451(

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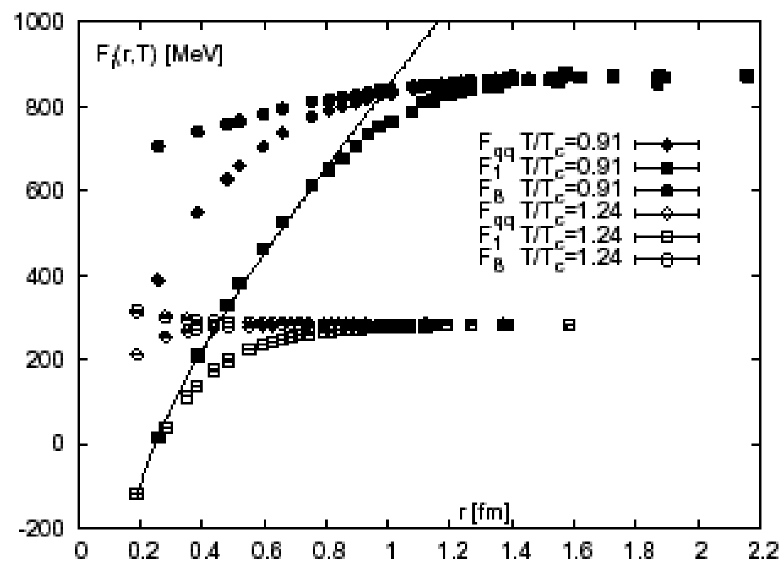

○ Kaczmarek Zantow PRD 71 (2005) 114510

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

Matsui Satz 86

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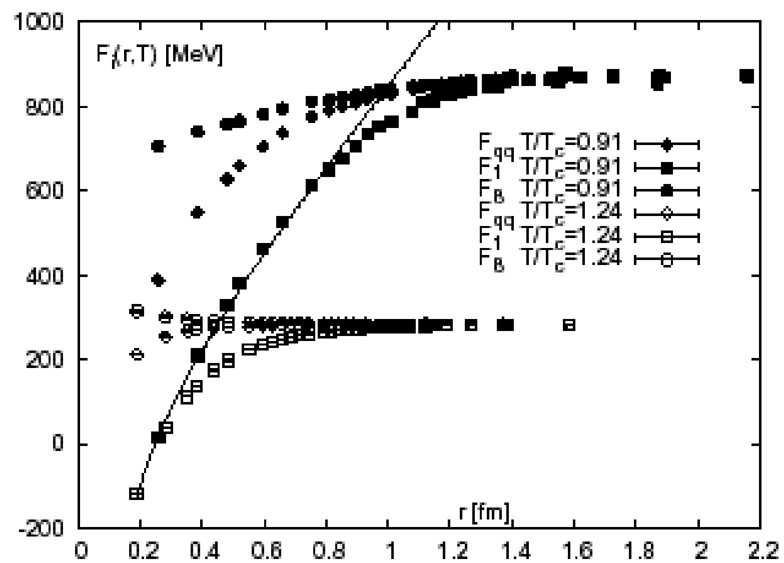

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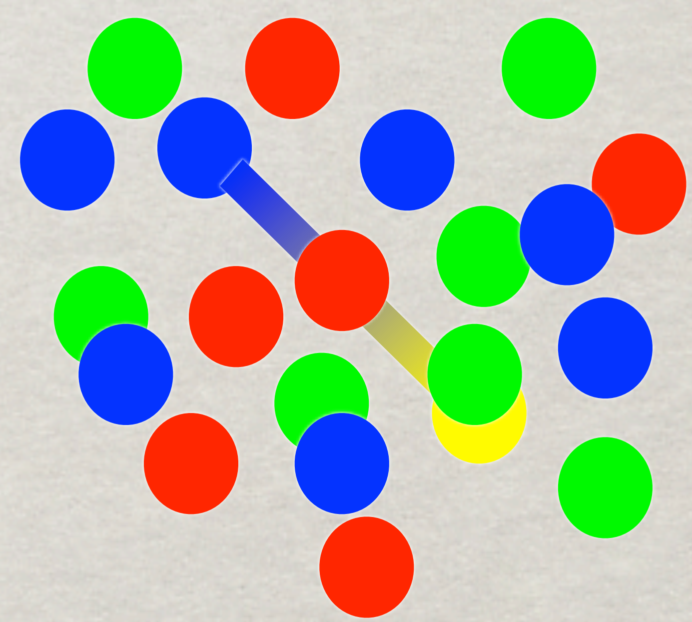

Debye charge screening (electromagnetic plasma)

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

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

But, at finite temperature what is the quarkonium potential?

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

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more scales

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$m_D \sim gT$
Debye mass
Screening Scale

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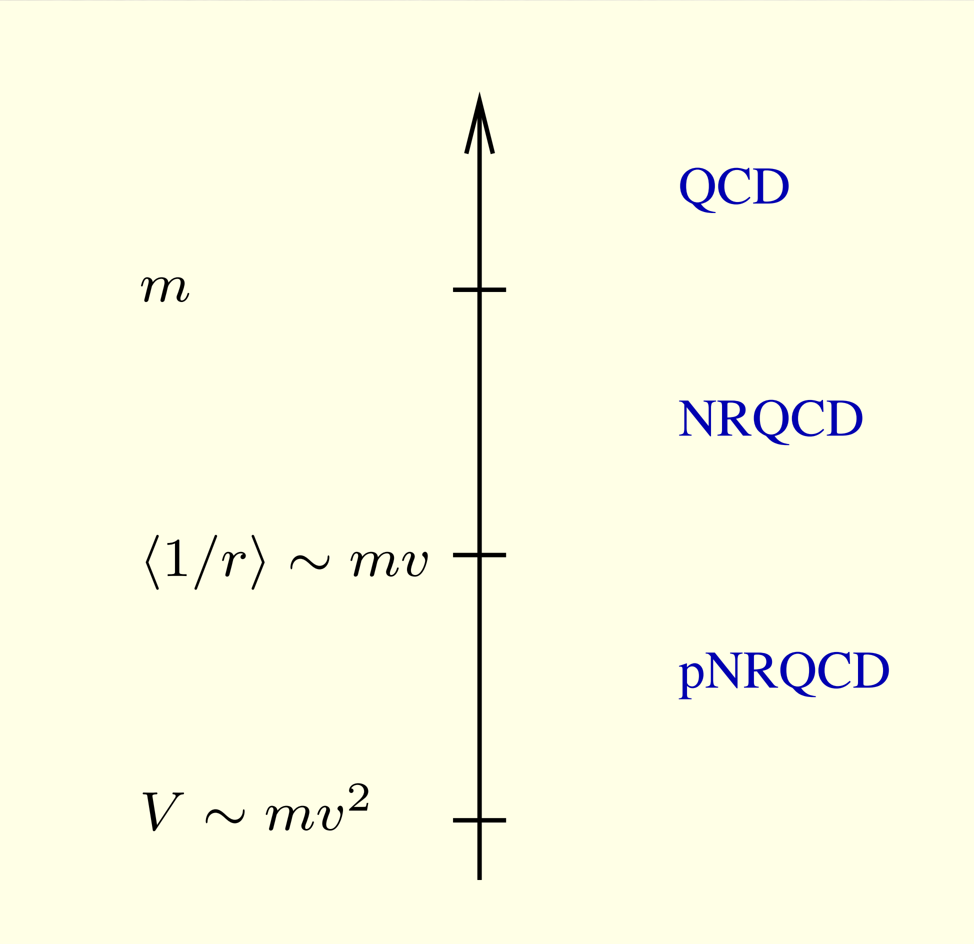
$m_D \sim gT$
Debye mass
Screening Scale

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

Braaten Pisarski 90

Quarkonium at finite T with pNRQCD

N. Brambilla et al 08



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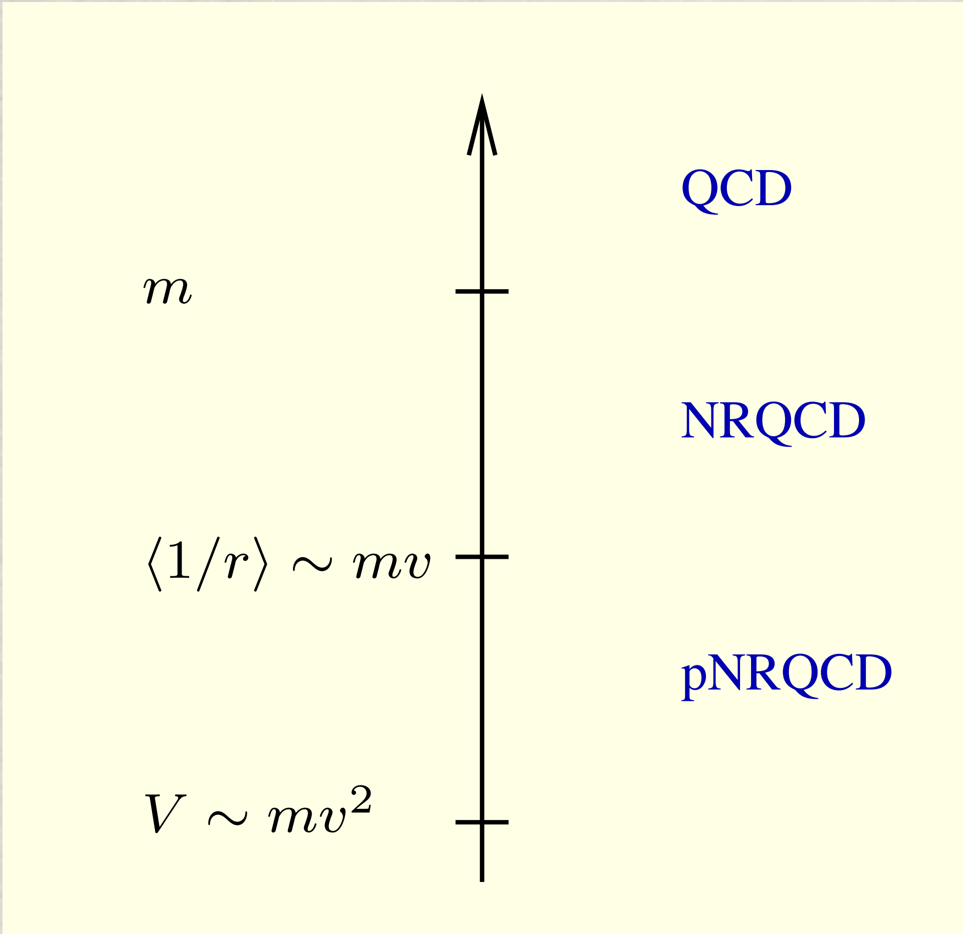

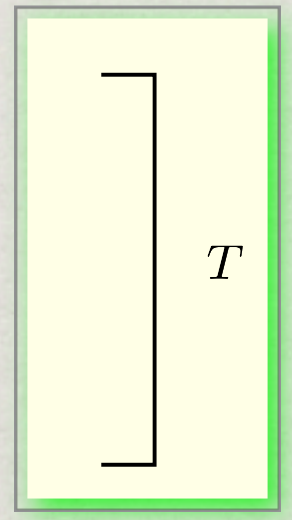

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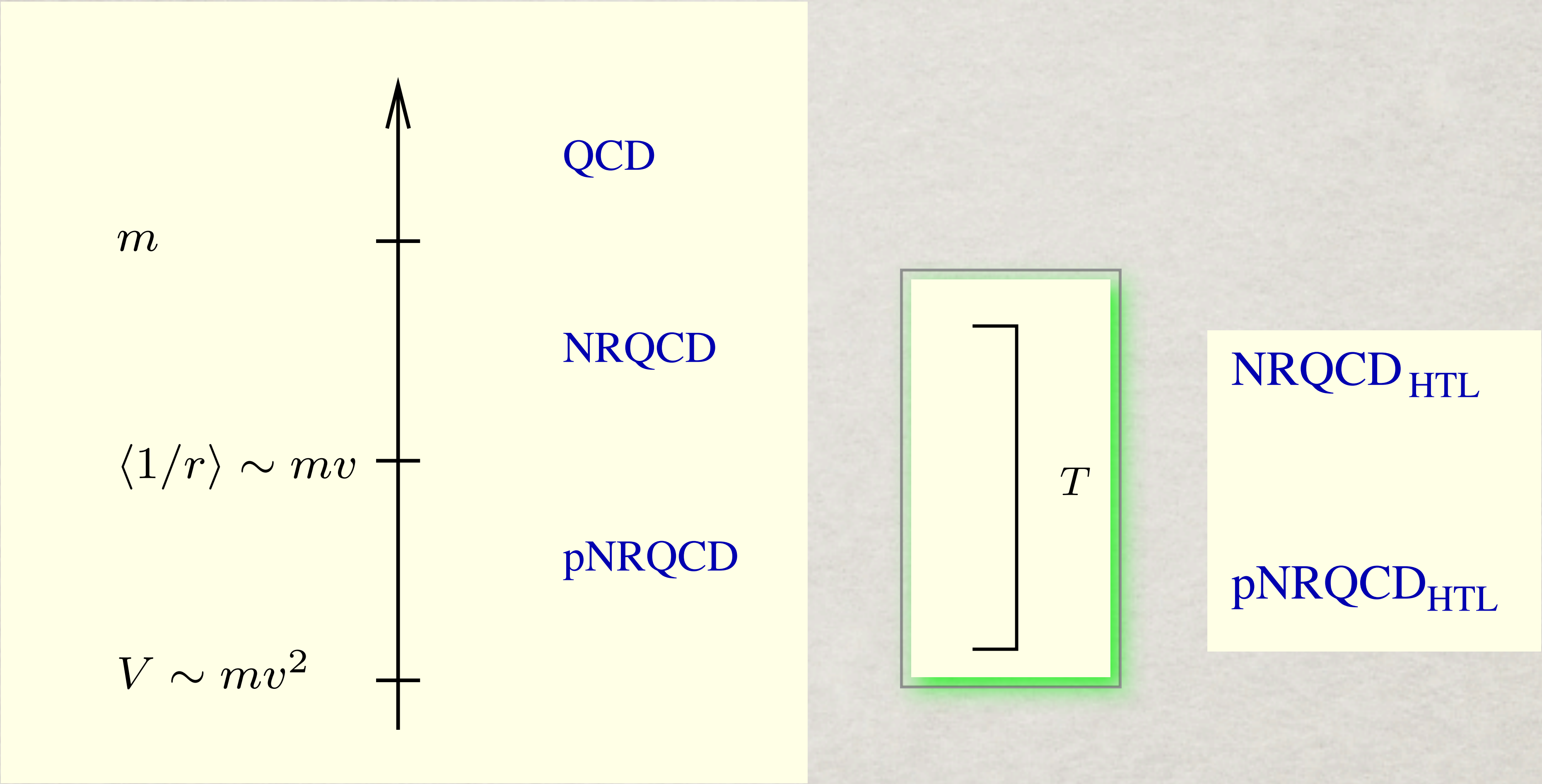
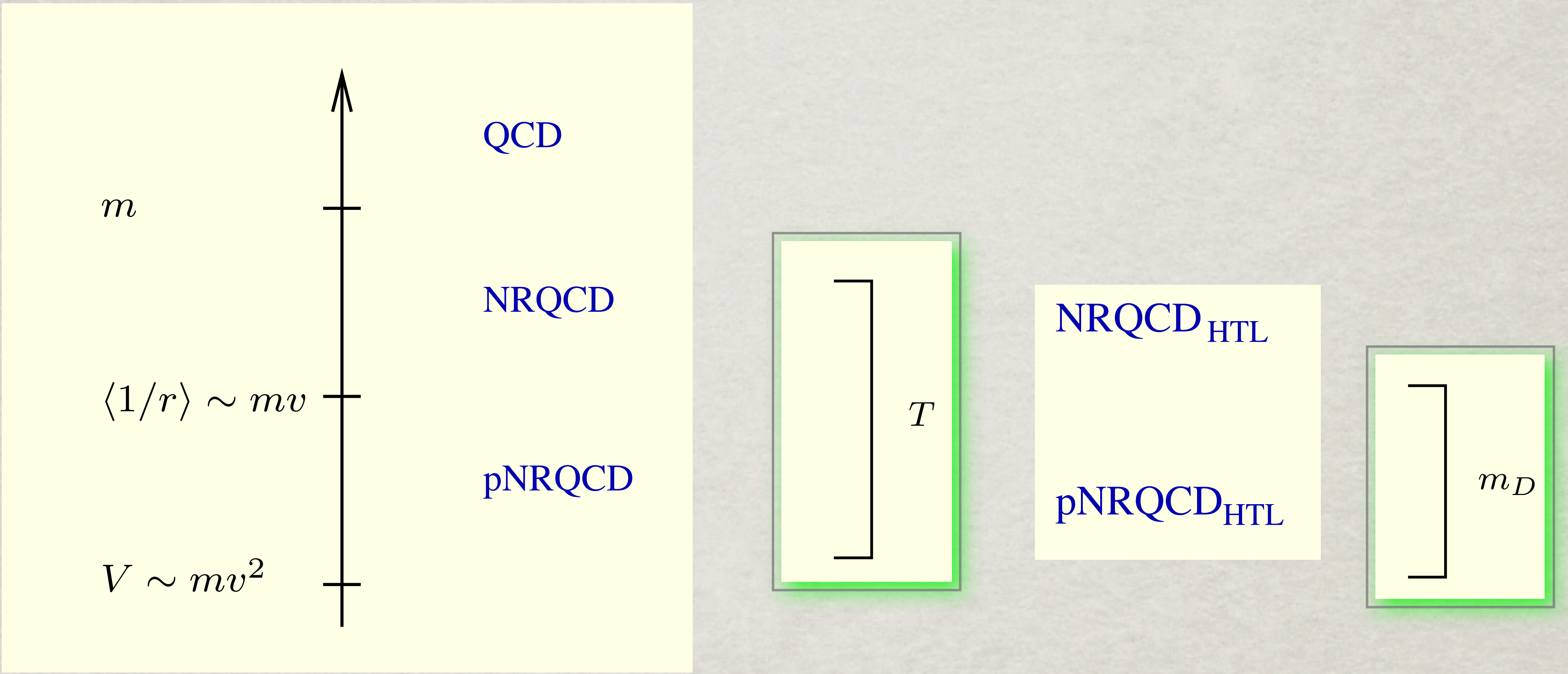


Quarkonium at finite T with pNRQCD

N. Brambilla et al 08



Quarkonium at finite T with pNRQCD

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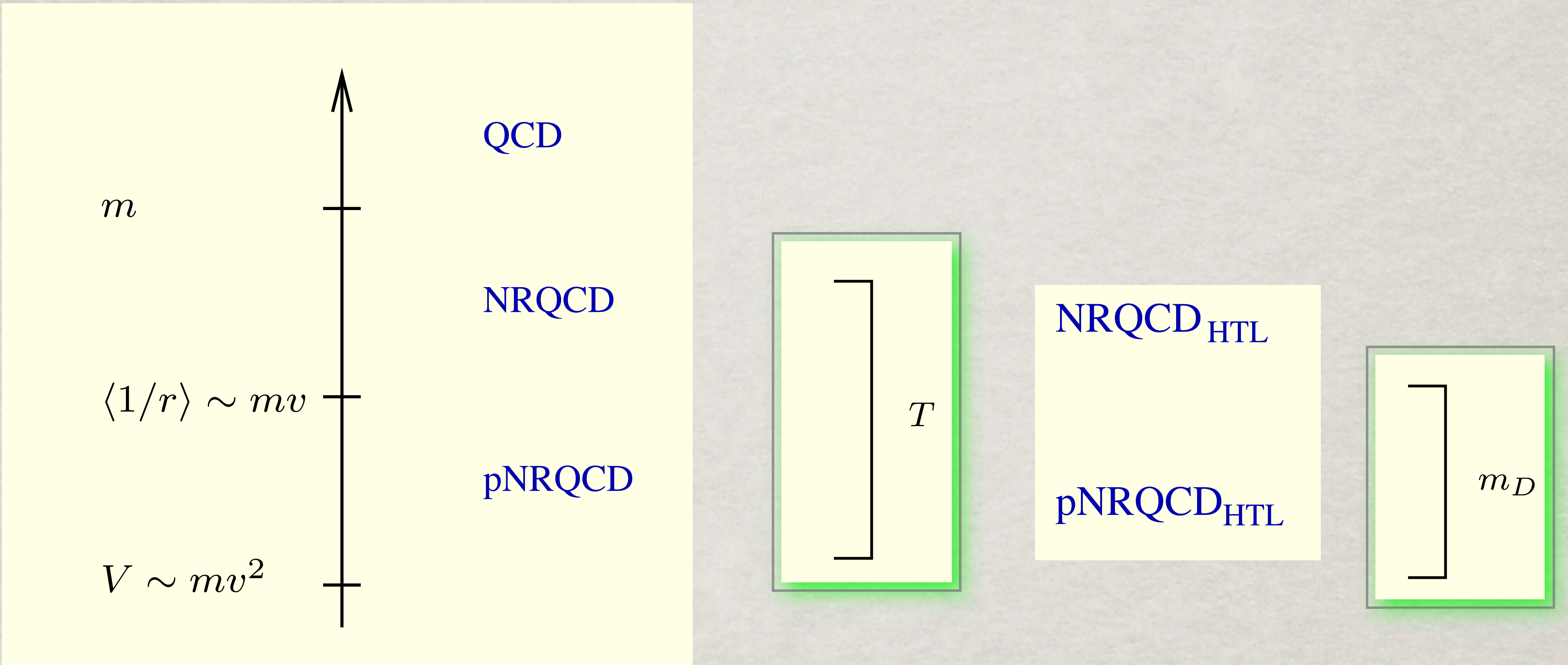


We work under the conditions:

We assume that bound states exist for

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

We neglect smaller thermodynamical scales.

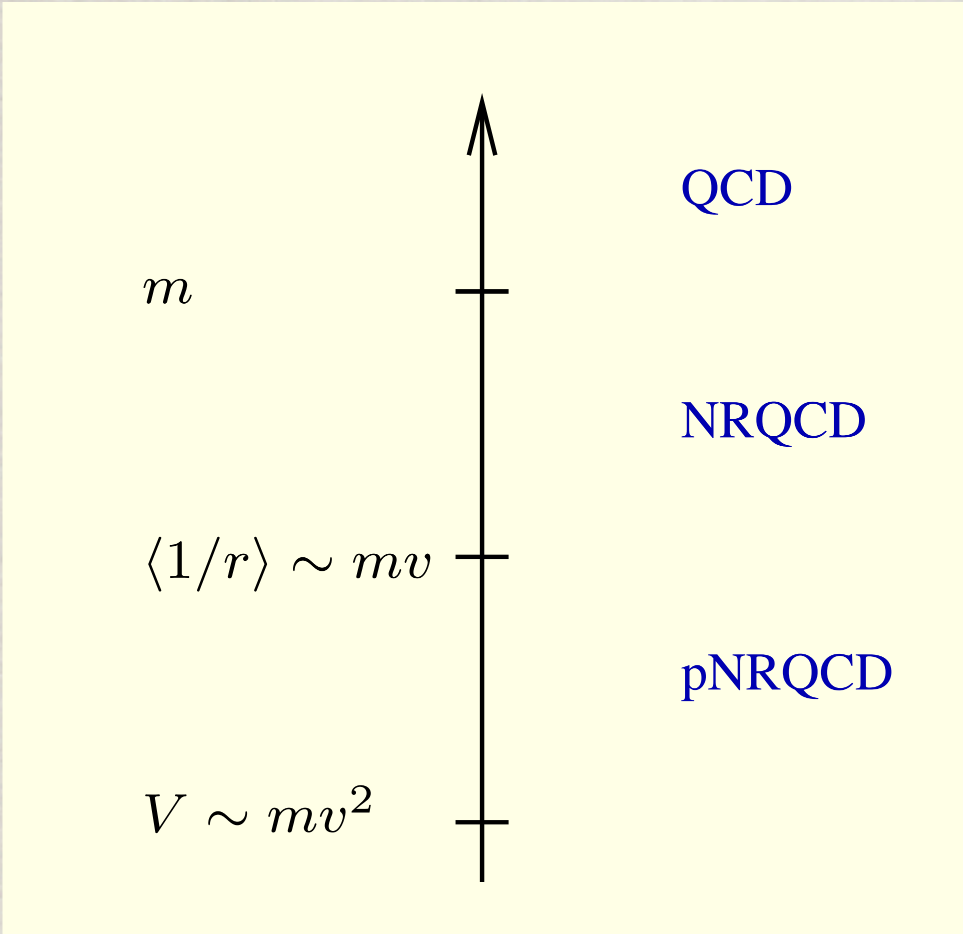
In the weak coupling regime:

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

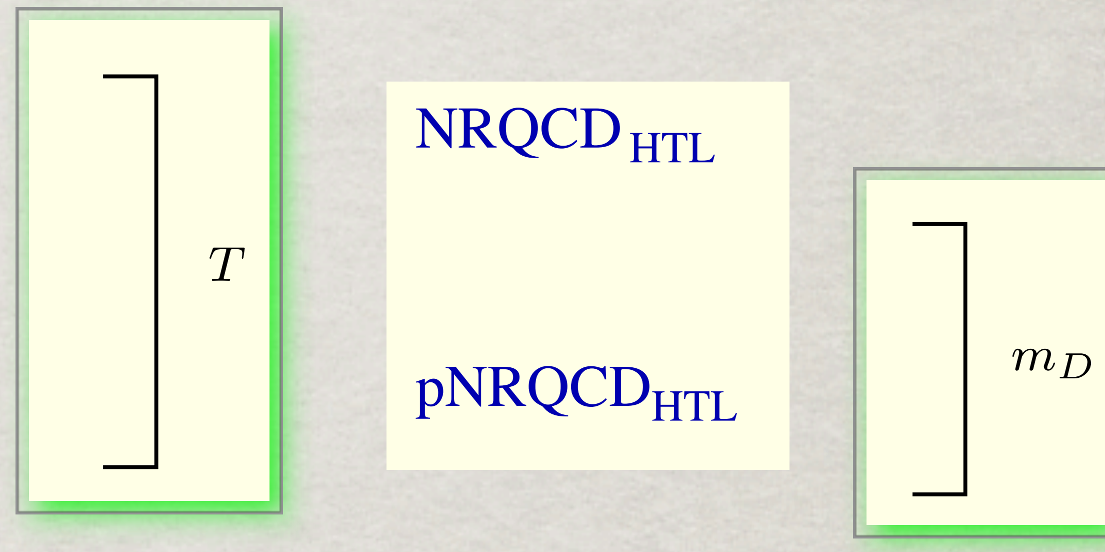
Effects due to the scale $\Lambda_{\rm QCD}$ will not be considered.

Quarkonium at finite T with pNRQCD

N. Brambilla et al 08



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



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

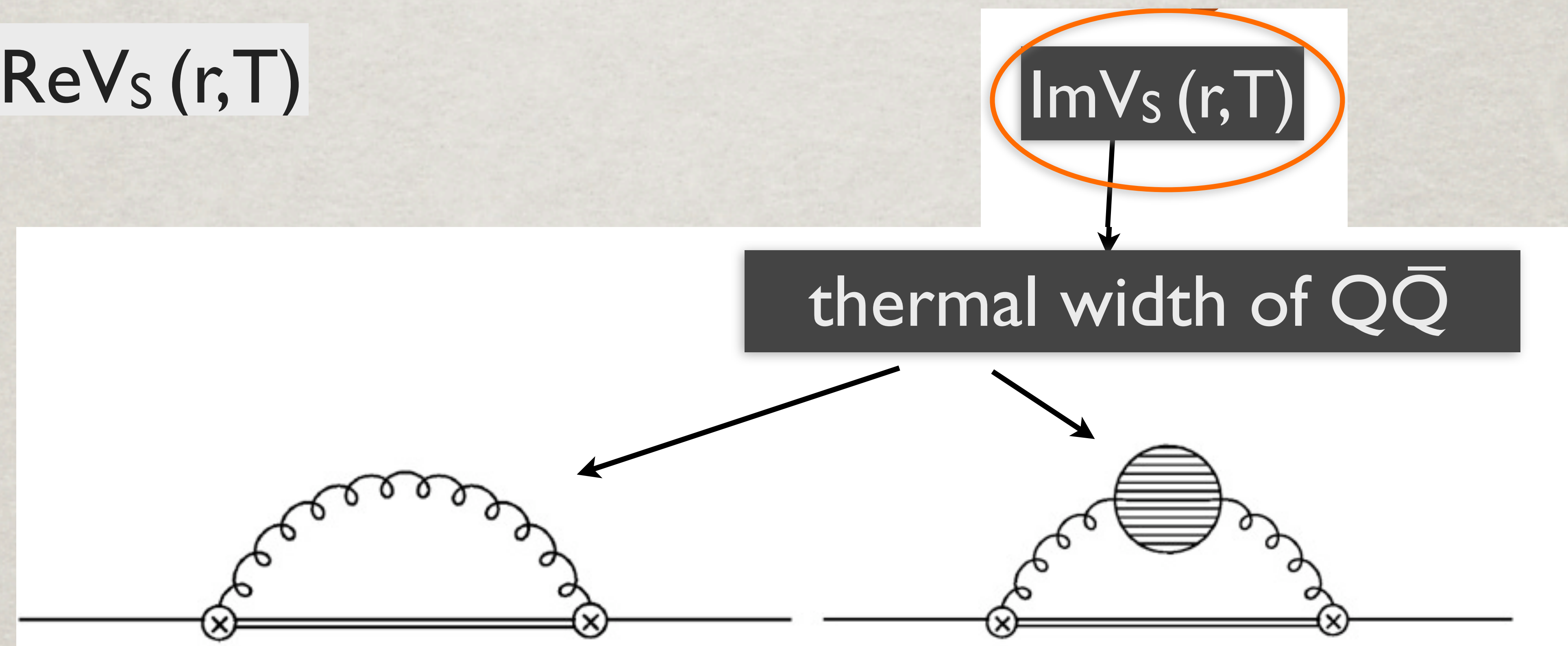
The singlet static potential and the static energy (pNRQCD)

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

N.B., Ghiglieri, Petreczsky, Vairo

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

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



Singlet-to-octet

New effect, specific of QCD

dominates for E/m_D>>1

(gluo dissociation)

Landau damping

Known from QED

dominates for m_D/E>>1

(quasi free dissociation)

N. B., Ghiglieri, Petreczky, Vairo 2008

Laine et al 2007

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

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

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

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

○ Escobedo Soto arXiv:0804.0691
Laine arXiv:0810.1112

- The quarkonium dissociation is a consequence of the apparence of a thermal decay width rather than being due to the color screening of the real part of the potential

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

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

The bottomonium ground state , which is a weakly coupled non-relativistic bound state: $mv \sim m\alpha_s$, $mv^2 \sim m\alpha_s^2 \gtrsim \Lambda_{QCD}$, produced in the QCD medium of heavy-ion collisions at the LHC may possibly realize the hierarchy

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

Vairo AIP CP 1317 (2011) 241

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

thermal contributions to the levels calculated at order malpha^5

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

Conclusions

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

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

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

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

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

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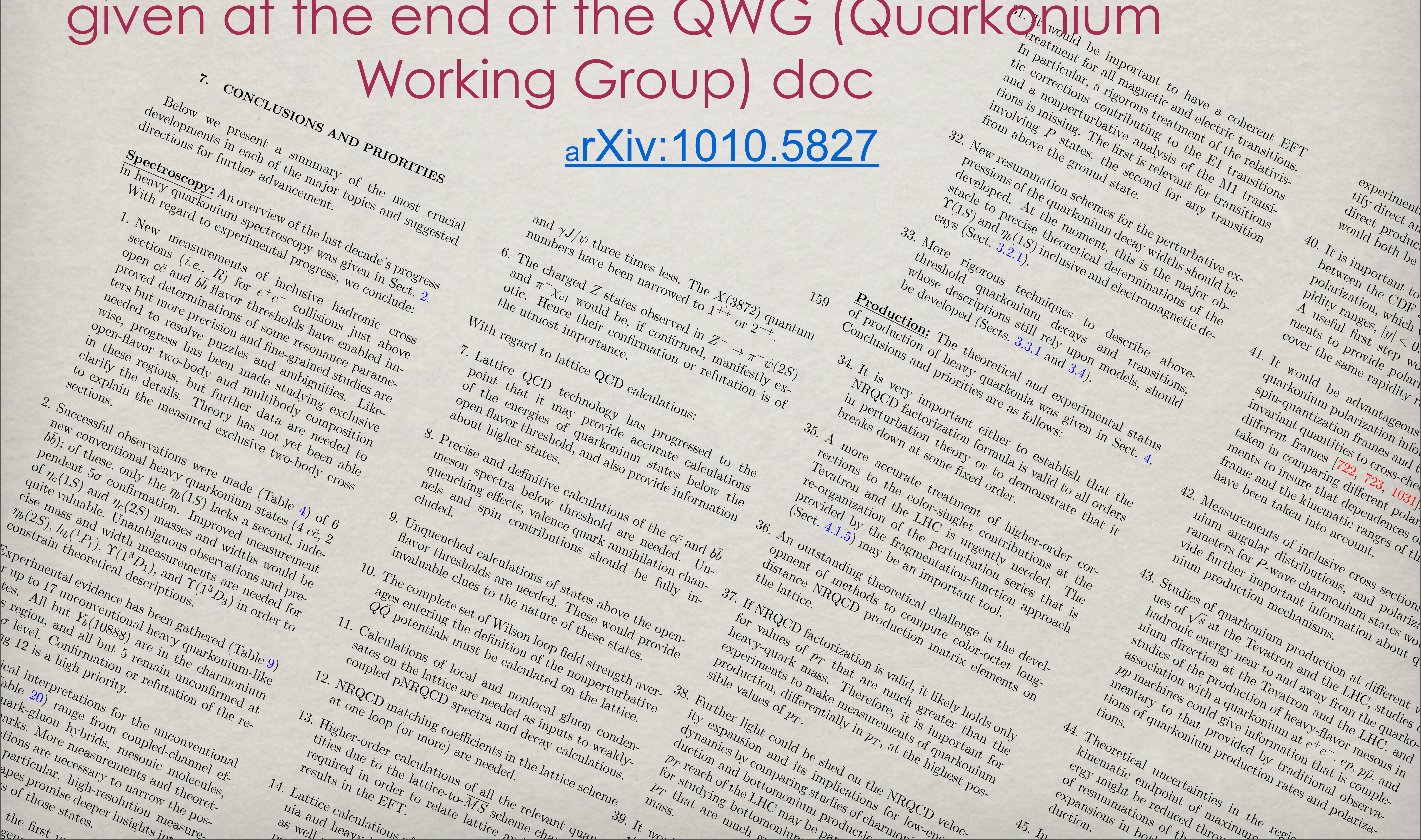
In this direction go the list of 65 priorities given at the end of the QWG (Quarkonium Working Group) doc

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 $\eta_b(2S)$, $h_b(^1P_1)$, $\Upsilon(1^3D_J)$, and $\Upsilon(1^3D_3)$ in order to constrain theoretical descriptions.

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

...ical interpretations for the unconventional ... Table 20) range from coupled-channel ef... quark-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.

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 cha... required in order to relate lattice a... results in the EFT.

14. Lattice calculations ... nia and heavy ... as well ...

159

31. It would be important to have a coherent EFT treatment for all magnetic and electric transitions. In particular, a rigorous treatment of the relativistic corrections contributing to the 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).

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-en... dynamics by comparing studies of charmon... duction and bottomonium productio... p_T reach of the LHC may be par... for studying bottomoniu... p_T that are much g... mass.

39. It wo...

experimenta... tify direct an... direct produc... would both be ...

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

41. It would be advantageous ... quarkonium polarization infor... 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 polariz... rameters for P-wave charmonium states wo... vide further important information about q... nium production mechanisms.

43. Studies of quarkonium production at different v... 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 regi... kinematic endpoint of maximum ... ergy might be reduced throu... of resummations of th... expansions in both ... 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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Quarkonium-quarkonium van der Waals interaction; quarkonium on nuclei

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Quarkonium production

CMS, Atlas, Alice, LHC-b

We are eagerly looking forward the new experimental data from LHC, BESIII, Panda and hopefully a Super B and ILC

Backup SLIDES

c and b masses

reference	order	$\overline{M}_b(\overline{M}_b)$ (GeV)
Brambilla et al. 01	NNLO +charm ($\Upsilon(1S)$)	$4.190 \pm 0.020 \pm 0.025$
Penin Steinhauser 02	NNNLO* ($\Upsilon(1S)$)	4.346 ± 0.070
Lee 03	NNNLO* ($\Upsilon(1S)$)	4.20 ± 0.04
Contreras et al. 03	NNNLO* ($\Upsilon(1S)$)	4.241 ± 0.070
Pineda Signer 06	NNLL* high moments SR	4.19 ± 0.06

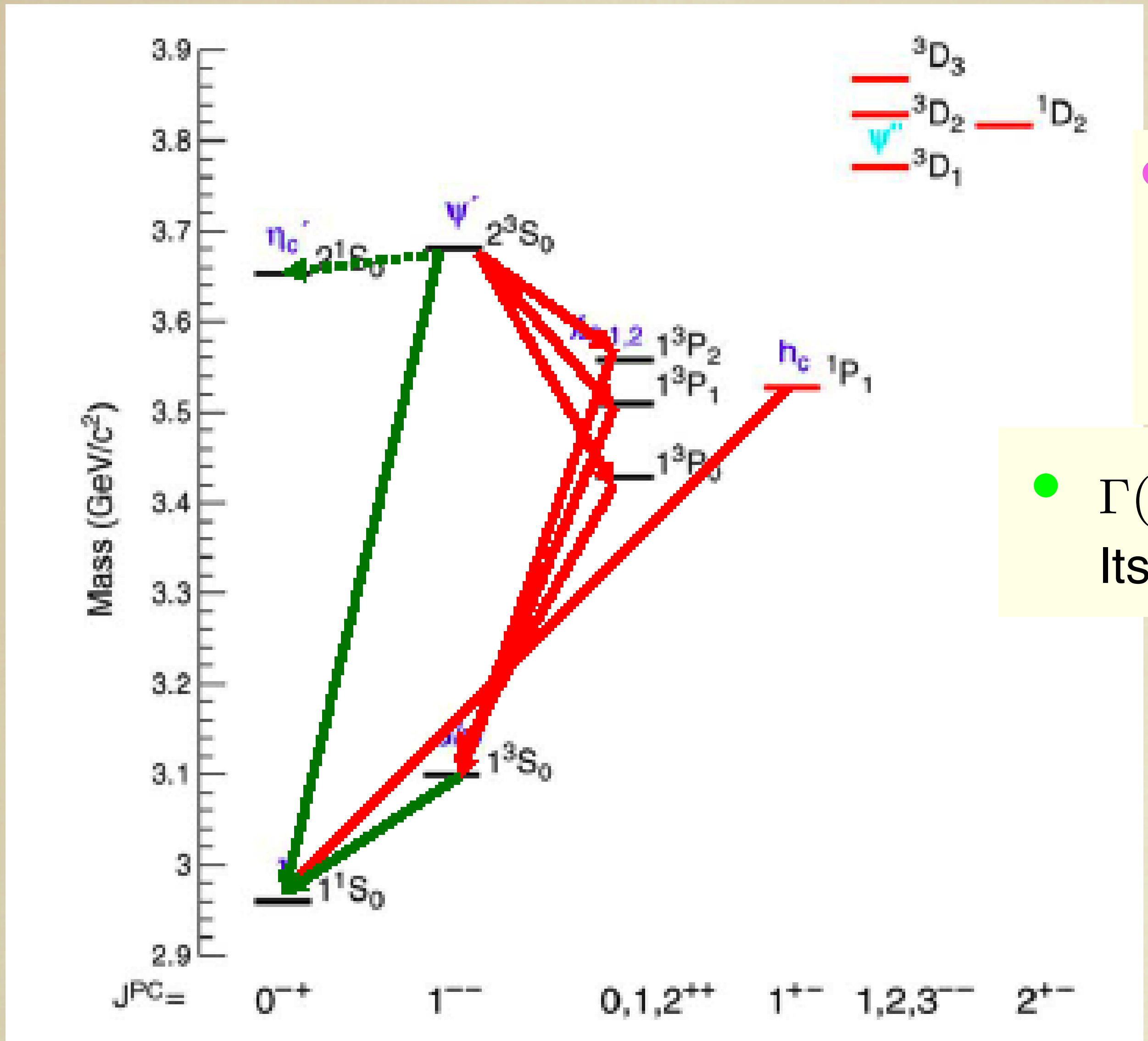
reference	order	$\overline{M}_c(\overline{M}_c)$ (GeV)
Brambilla et al. 01	NNLO (J/ψ)	1.24 ± 0.02
Eidemüller 02	NNLO high moments SR	1.19 ± 0.11

They compare well with the most precise available determinations:

$\overline{M}_b(\overline{M}_b) = 4163 \pm 16$ MeV ◦ Chetyrkin et al. arXiv:1010.6157

$\overline{M}_c(\overline{M}_c) = 1277 \pm 26$ MeV ◦ Dehnadi Hoang Mateu Zebarjad arXiv:1102.2264

Radiative transitions



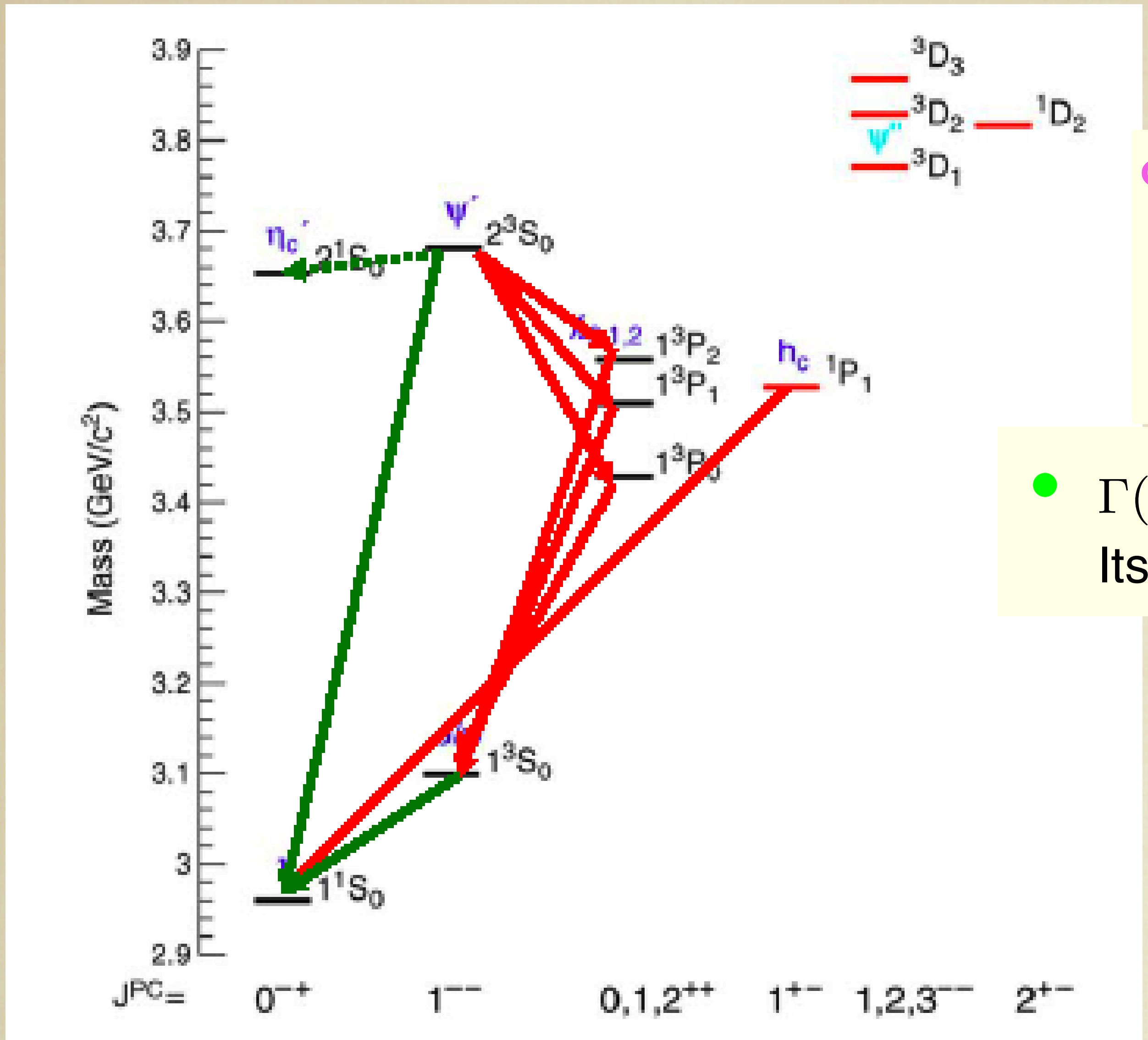
Magnetic Dipole transitions

Crystal Ball 86 + Belle 03 + Cleo 08

$$\Gamma(J/\psi \to \eta_c \gamma) = (1.44 \pm 0.18)\,\text{keV}$$

- $\Gamma(J/\psi \to \eta_c \gamma)$ enters into many charmonium BR. Its 12.5% uncertainty sets typically their experimental errors.

RADIATIVE TRANSITIONS



Magnetic Dipole transitions

CRYSTAL BALL 86 + BELLE 03 + CLEO 08

$$\Gamma(J/\psi \to \eta_c\gamma) = (1.44 \pm 0.18)\,\text{keV}$$

- $\Gamma(J/\psi \to \eta_c\gamma)$ enters into many charmonium BR.
  Its 12.5% uncertainty sets typically their experimental errors.

In potential models

At leading order $\Gamma(J/\psi \to \eta_c\gamma) \sim 2.83\,\mathrm{KeV}$

this implies:

- large value of the charm mass
- large anomalous magnetic moment of the quark
- large relativistic corrections to the S-state wave functions

Eichten QWG 02

EFTheory of radiative transitions

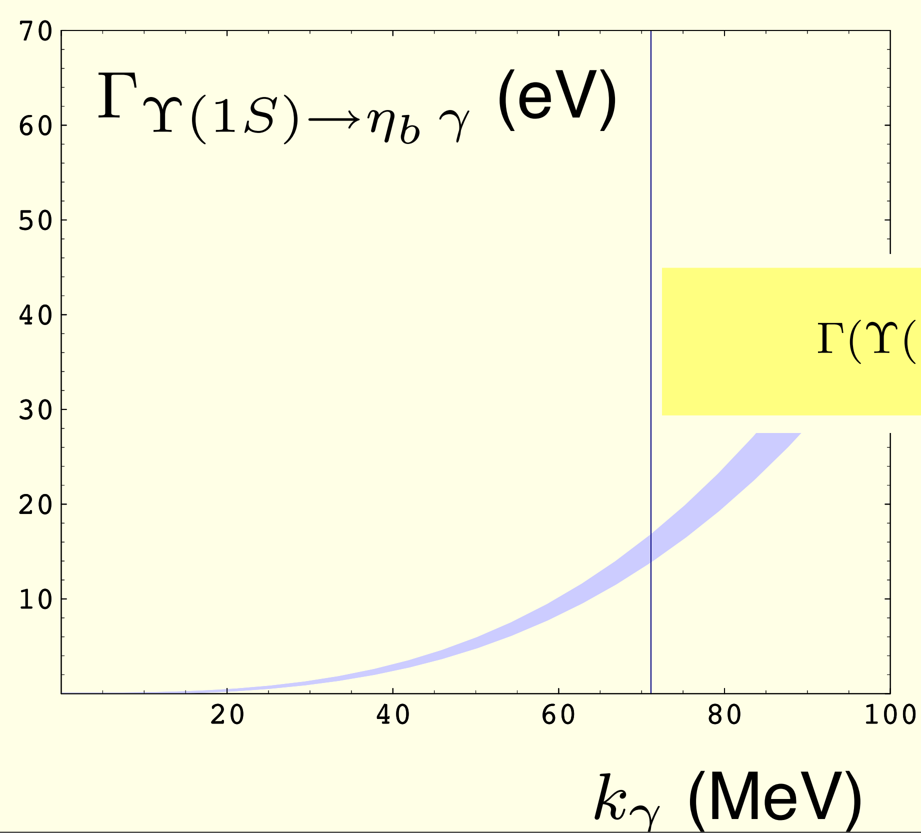
pNRQCD with singlet, octet, US gluons and photons

Brambilla, Jia, Vairo 05

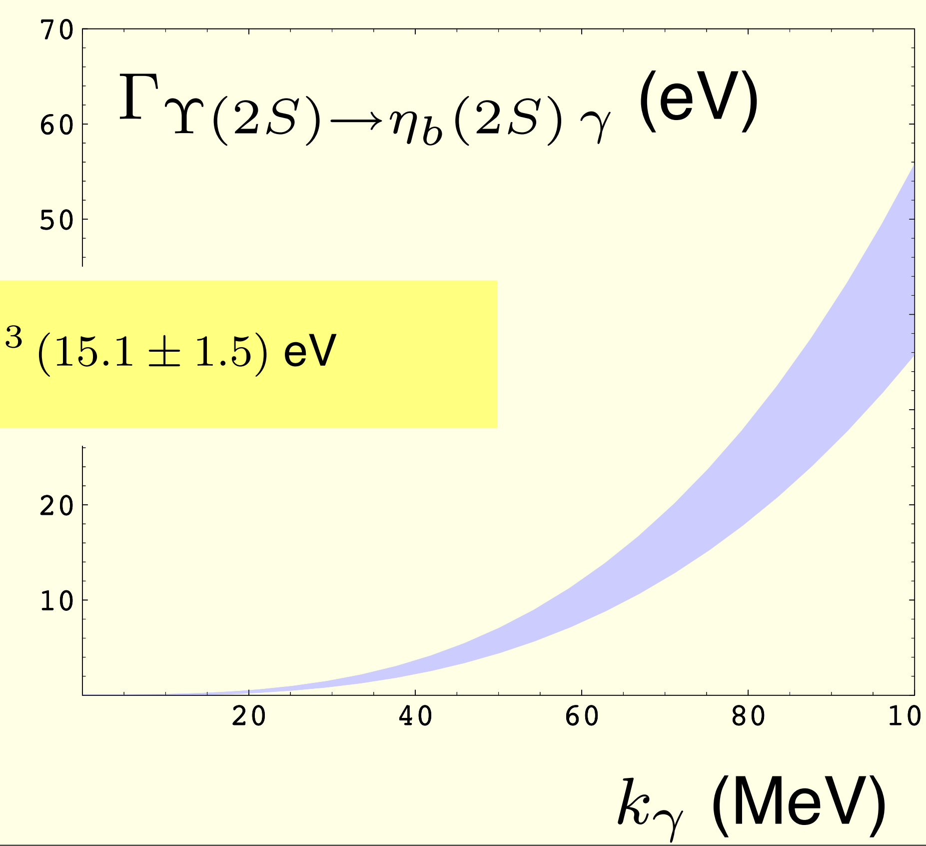
- No nonperturbative physics at order v^2
- Exact relations from Poincare invariance-> no scalar interaction
- No large anomalous magnetic moment

$$\Gamma(J/\psi \to \gamma\eta_c) = \frac{16}{3}\alpha e_c^2 \frac{k_\gamma^3}{M_{J/\psi}^2}\left[1 + C_F\frac{\alpha_s(M_{J/\psi}/2)}{\pi} - \frac{2}{3}(C_F\alpha_s(p_{J/\psi}))^2\right]$$

$$\Gamma(J/\psi \to \eta_c\gamma) = (1.5 \pm 1.0)\ \text{keV}.$$



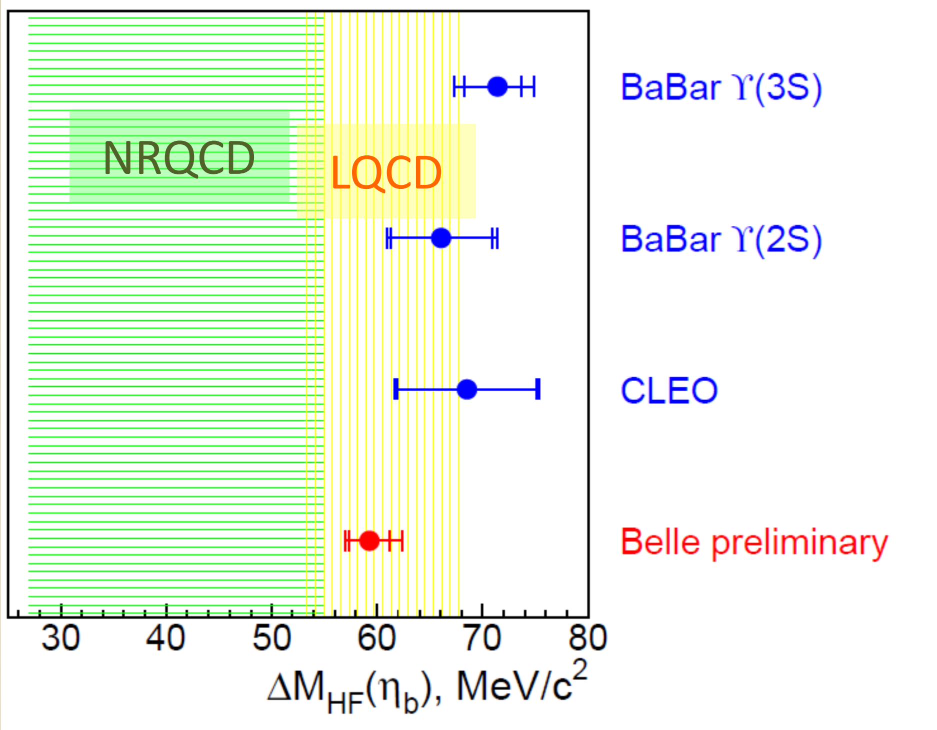
$$\Gamma(\Upsilon(1S) \to \gamma\,\eta_b) = (k_\gamma/71\ \text{MeV})^3\ (15.1 \pm 1.5)\ \text{eV}$$



Spectroscopy and Decays examples

$\eta_b(1S)$

Expt	$\Delta M_{hfs}(1S)$ (MeV)
BaBar	$66.1^{+4.9}_{-4.8} \pm 2.0$
CLEO	$68.5 \pm 6.6 \pm 2.0$
Belle	$59.3 \pm 1.9^{+2.4}_{-1.4}$



$\eta_b(2S)$

$\Delta M_{hfs}(2S) = 24.3 \pm 3.5^{+2.8}_{-1.9}$ MeV

$M[\eta_b(2S)] = 9999.0 \pm 3.5^{+2.8}_{-1.9}$ MeV

$Bf[h_b(2P) \rightarrow \gamma\eta_b(2S)] = 47.5 \pm 10.5^{+6.6}_{-7.7}$ %

preliminary

Belle, from S. Olsen, IWHSS 2012

Expt	$\Delta M_{hfs}(2S)$ (MeV)
CLEO	48.7 ± 2.7
Belle	24.3 ± 4.3

≈5σ discrepancy

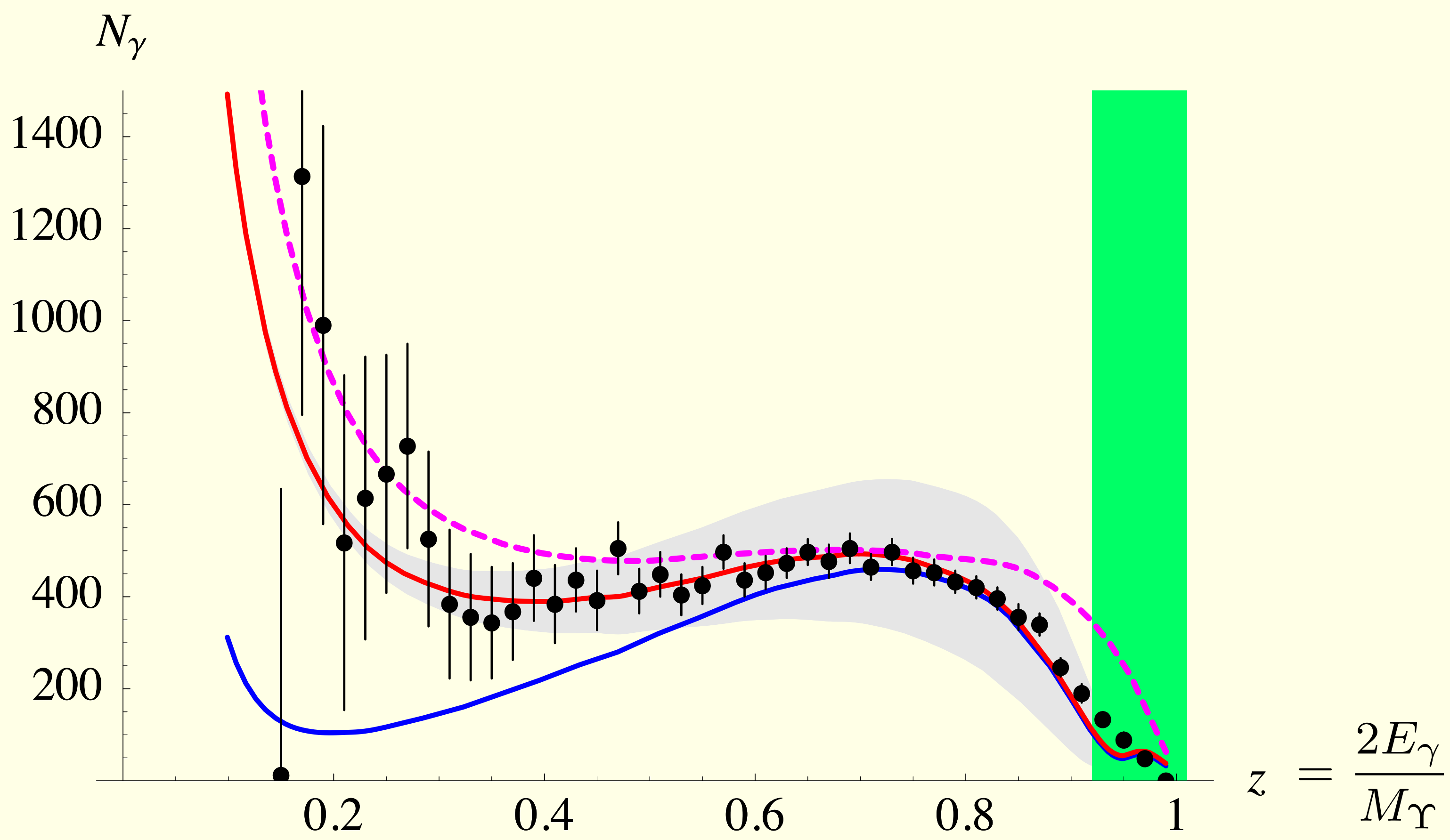
arXiv:1204.4205

$$\Upsilon(2S) \rightarrow \gamma\eta_b(2S), \eta_b(2S) \rightarrow \text{Hadrons}$$

$$M(\eta_b(2S)) = 9974.6 \pm 2.3(\text{stat}) \pm 2.1(\text{syst})\text{MeV}$$

Seminclusive decays

$$\Upsilon(1S) \to \gamma\, X$$



Photon spectrum at NLO (continuous lines, pNRQCD + SCET) vs CLEO data

- Garcia Soto PRD 72 (2005) 054014, Fleming Leibovich PRD 67 (2003) 074035

No Gap to threshold

New states

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.52±0.20	1.3±0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), *BABAR* [87] (8.6)	2003	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF [88–90] (np), DØ [91] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), *BABAR* [93] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), *BABAR* [96] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [92] (4.0), *BABAR* [97, 98] (3.6)		
				$B \to K(\gamma\psi(2S))$	*BABAR* [98] (3.5), Belle [99] (0.4)		
$X(3915)$	3915.6 ± 3.1	28±10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), *BABAR* [101] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\ (...)$	Belle [54] (5.0)		
$G(3900)$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	*BABAR* [27] (np), Belle [21] (np)	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226±97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4260)$	4263 ± 5	108±14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	*BABAR* [108, 109] (8.0)	2005	OK
					CLEO [110] (5.4)		
					Belle [104] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [111] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [107] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [112] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96±42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	*BABAR* [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
$Y(4660)$	4664±12	48±15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [114] (5.8)	2007	NC!
$Y_b(10888)$	10888.4±3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [37, 117] (3.2)	2010	NC!

- QWG EPJ C71 (2011) 1534

no Λ_{QCD} gap: close and above threshold

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Gluonic excitations

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

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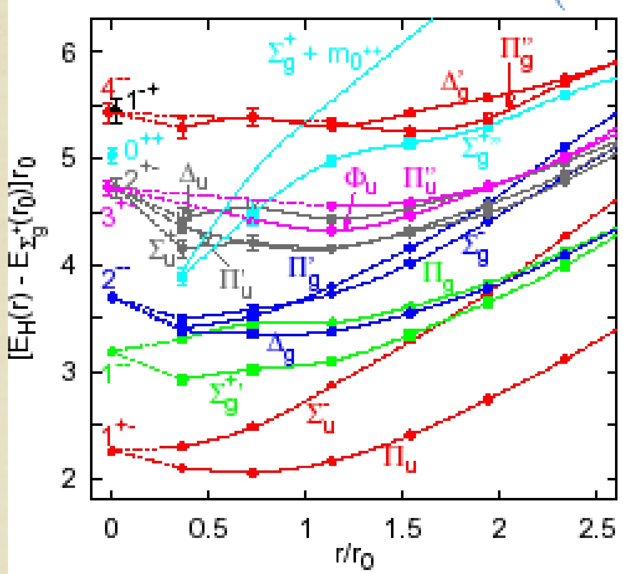
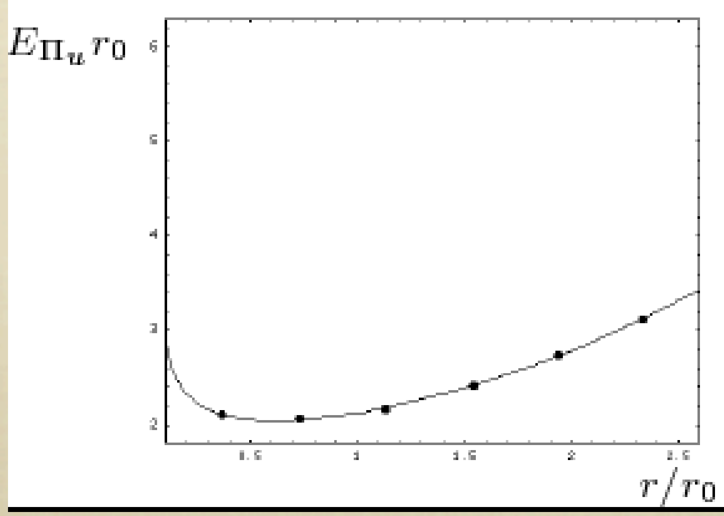
$Y(4260)$: a $c\bar{c}$ hybrid candidate



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

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



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

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

- Vairo IJMP A22(07)5481

CLOSE TO THRESHOLD

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

Text

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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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- Alexandrou et al. PRL 97(06)222002
- Fodor et al. PoS LAT2005(06)310

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  - Qiao PLB 639 (2006) 263
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(hadro-quarkonium). Voloshin

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Coupled channels

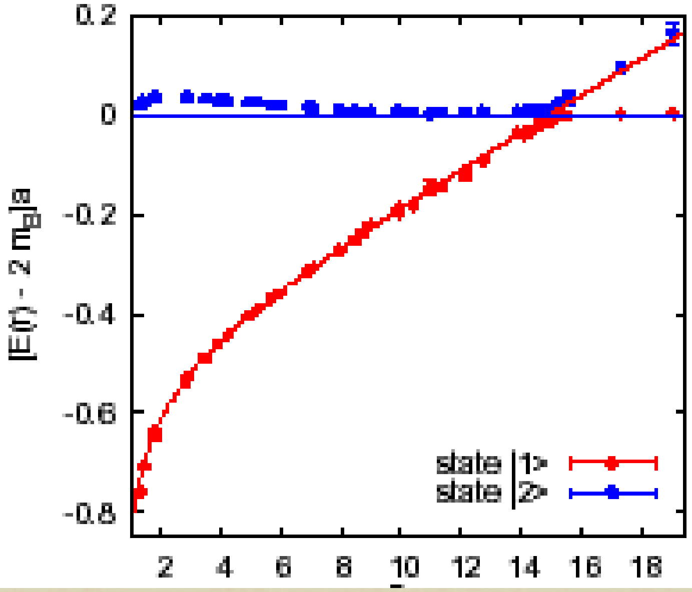
An important (and unsolved) issue is how all the different kind of states (with and without light quarks) interact with each other.

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

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

Steps towards a lattice based approach have been undertaken

- SESAM PRD 71(05)114513



States near or above threshold:"exotics" !

hybrids, molecular states, tetraquarks

Many new states from experiments: Xs, Ys, Zs

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

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

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

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