Extraction of SM parameters

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Extraction of SM parameters from Onia

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- Onia and QCD
- Onia Scales and QCD Effective Field Theories
- Extraction of alpha_s and m_Q
- Other examples
- Open challenges in theory and experiments

QCD and the Onia

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

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Parameters:

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

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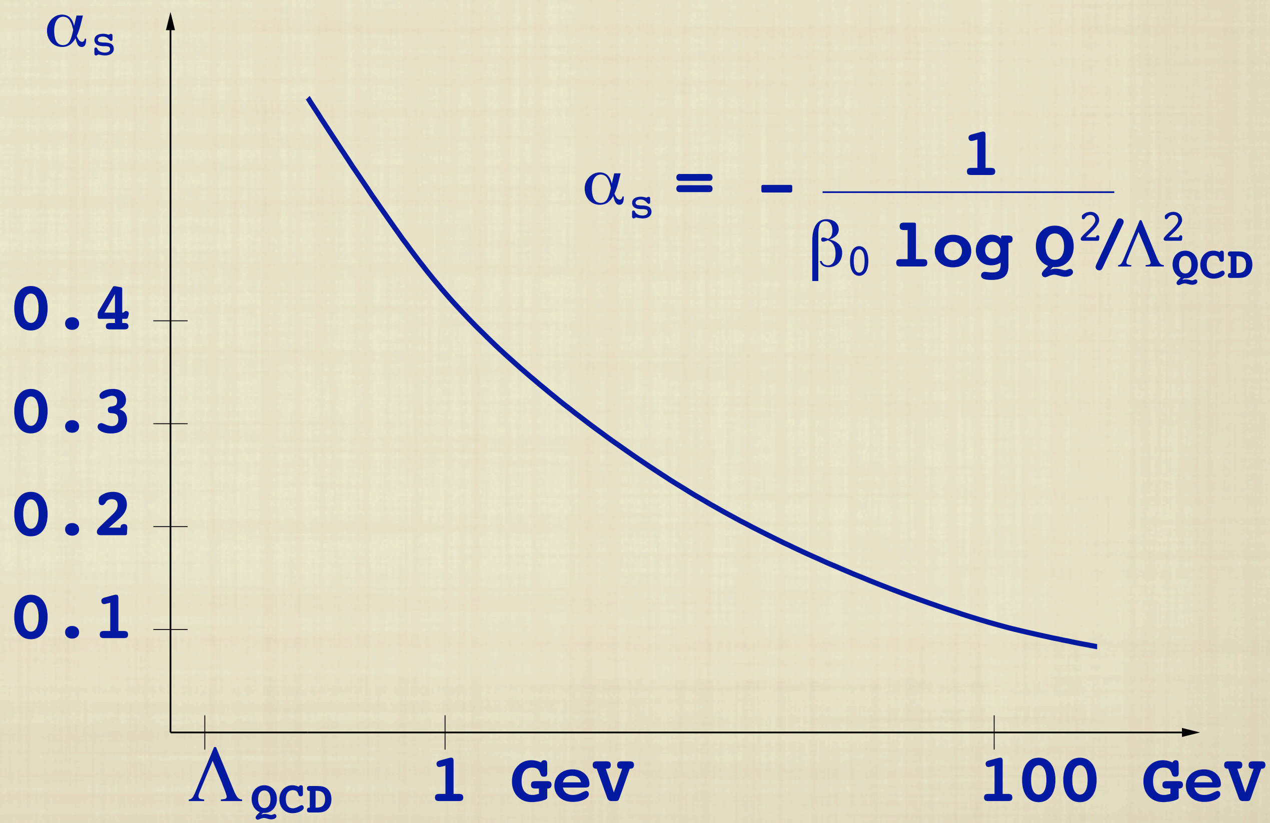

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in some scheme and at some scale

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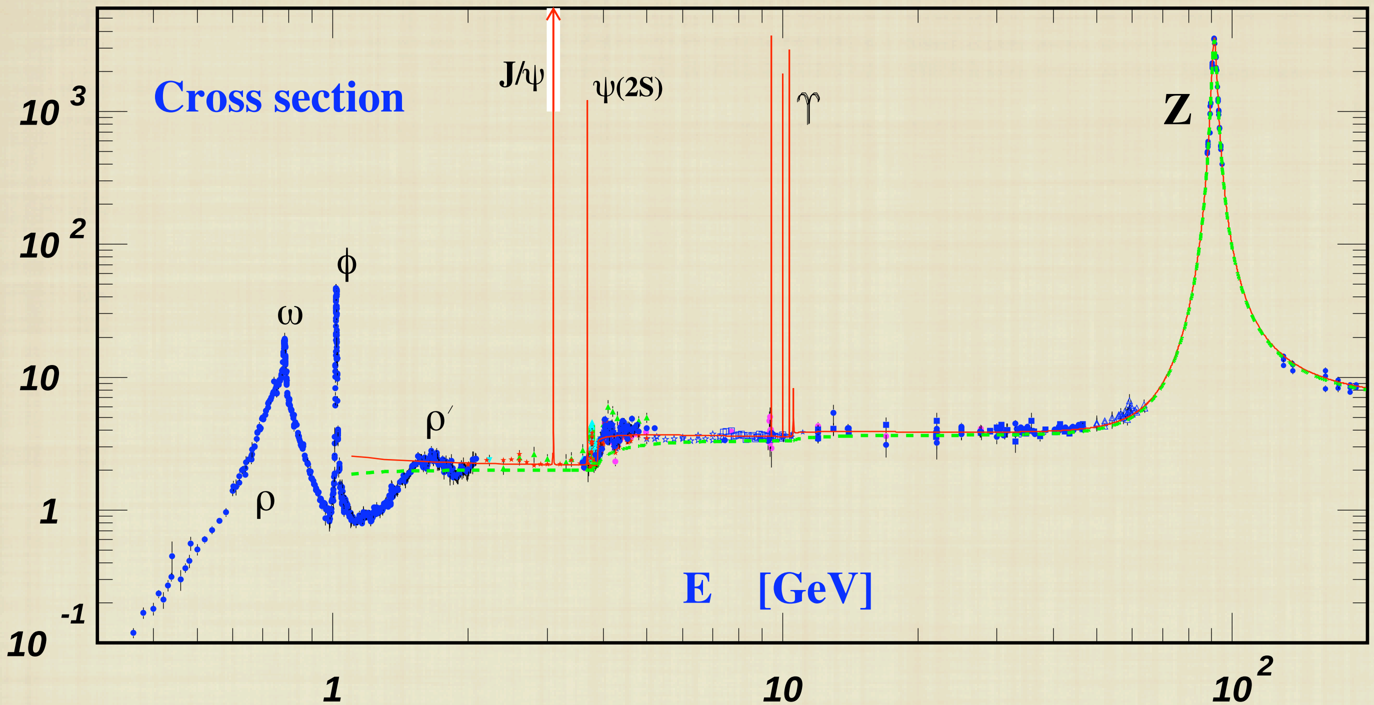

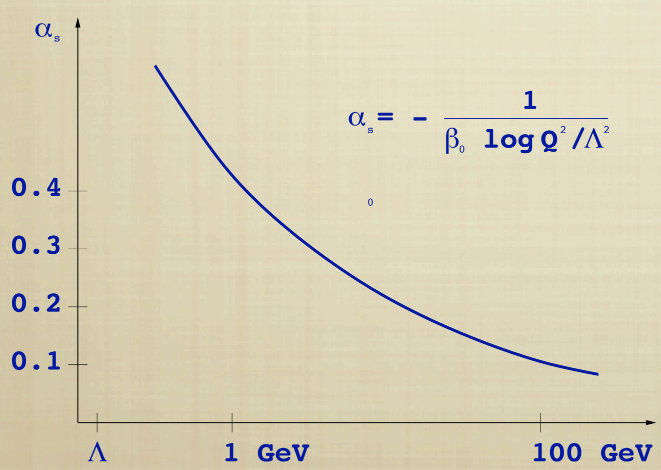

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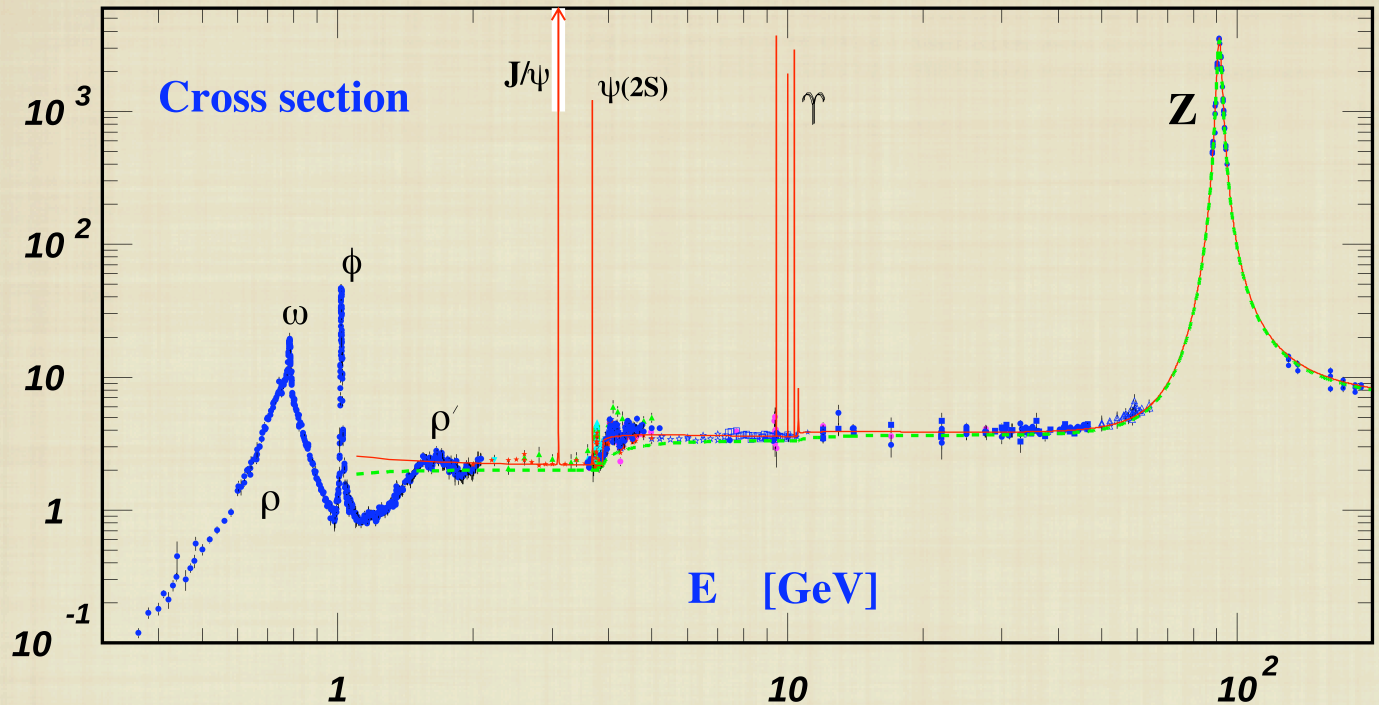

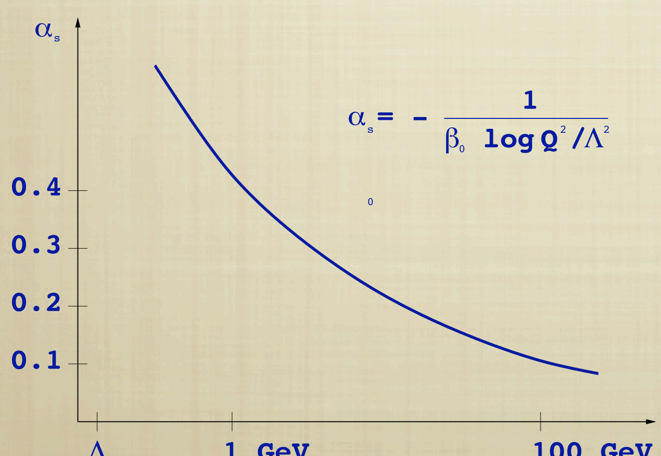

$$m_Q \gg \Lambda_{\mathrm{QCD}}$$

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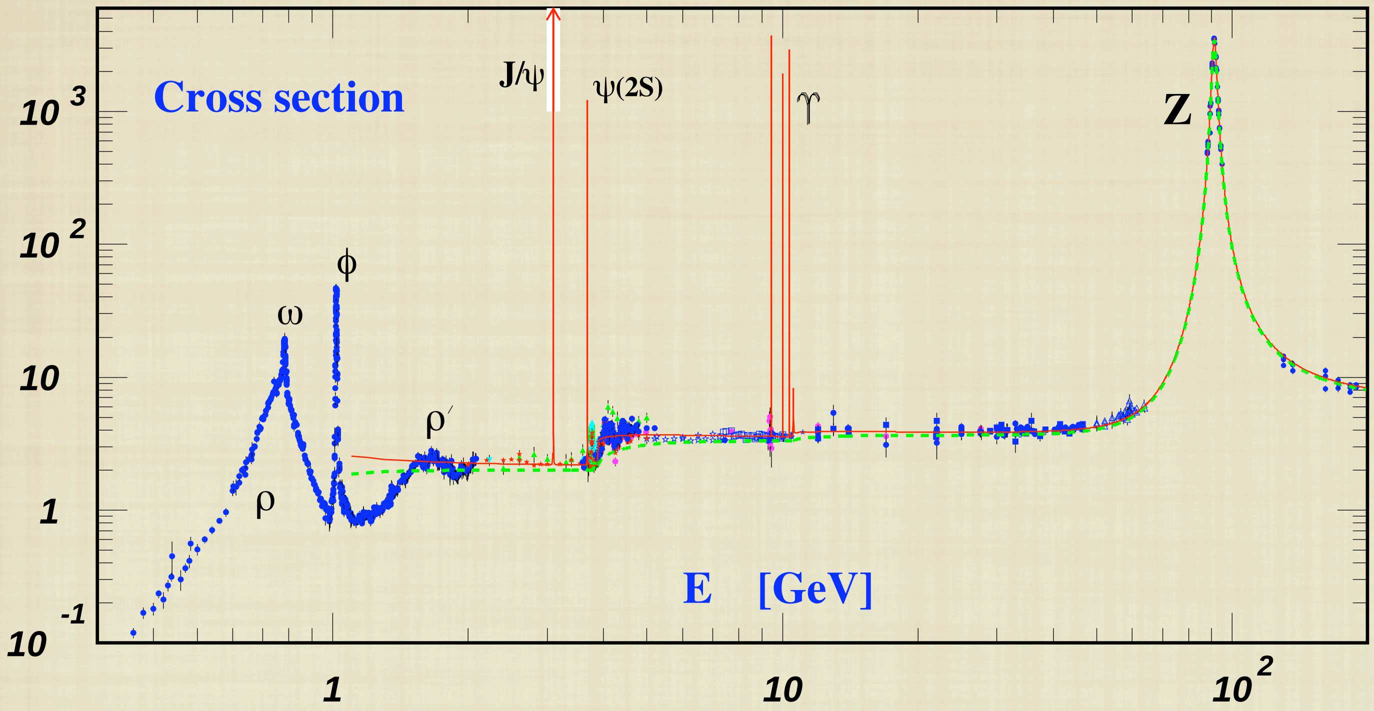
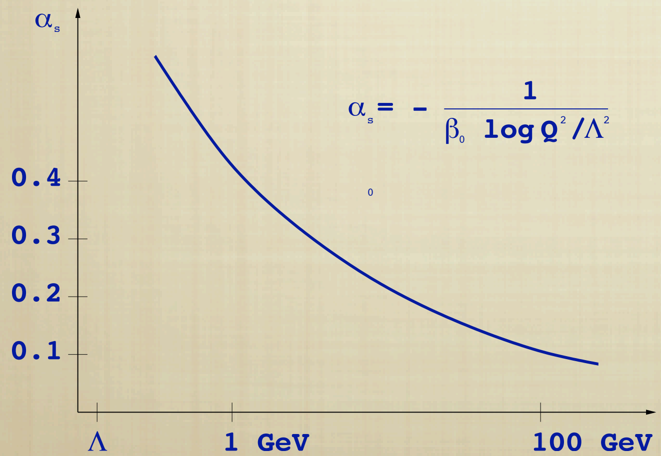
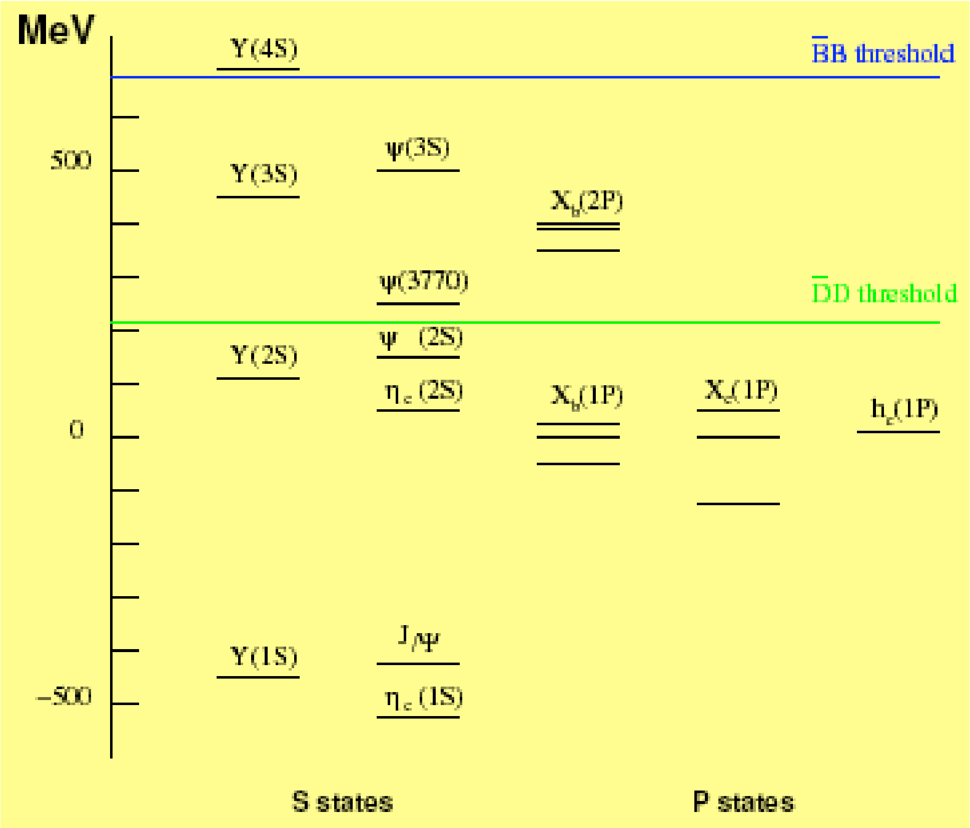




$$m_Q \gg \Lambda_{QCD}$$

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

QQ: a multiscale System



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

The mass scale is perturbative:

$m_b \simeq 5$ GeV, $m_c \simeq 1.5$ GeV

The system is non-relativistic:

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

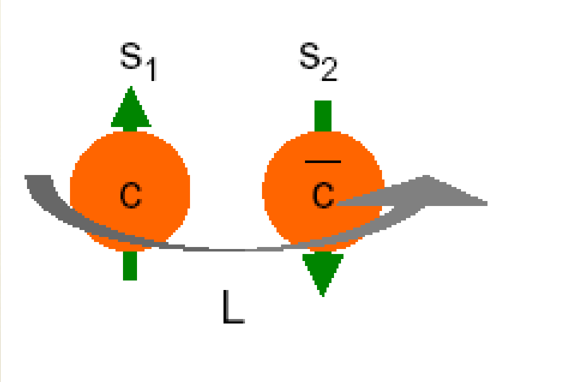
$v_b^2 \simeq 0.1$, $v_c^2 \simeq 0.3$

Non-relativistic bound states are characterized by at least three energy scales

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

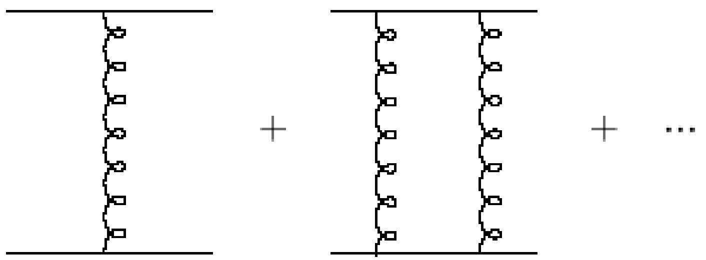
and $\Lambda_{\rm QCD}$

$^{2S+1}L_J$



Non-relativistic bound states

- Even if $\alpha_s \ll 1$
  on bound state the perturbative expansion breaks down when $\alpha_s \sim v$:



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

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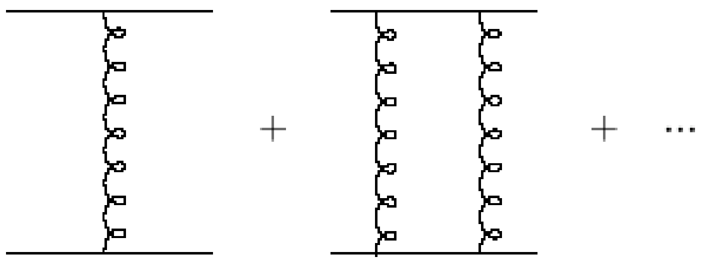

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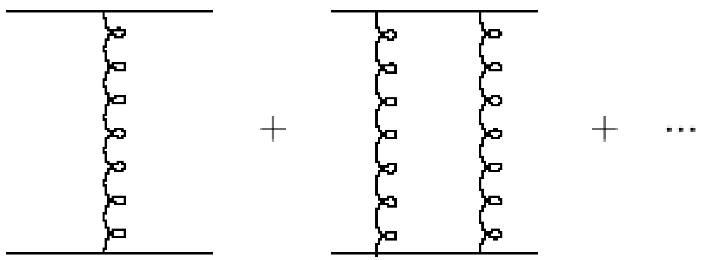

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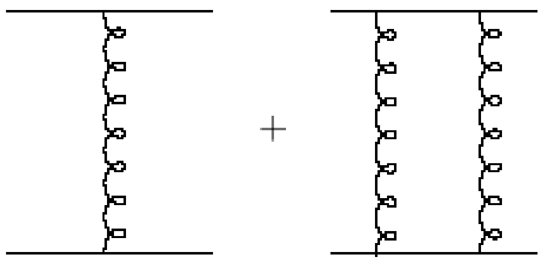

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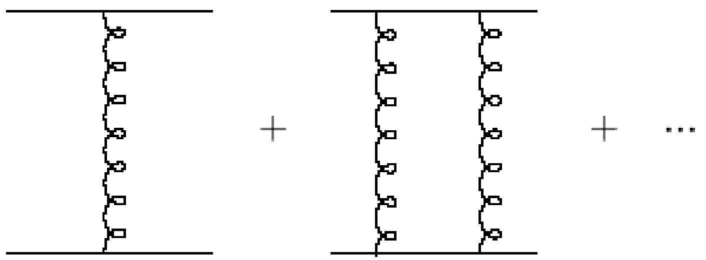

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- From $(\frac{p^2}{m} + V)\phi = E\phi \to p \sim mv$ and $E = \frac{p^2}{m} + V \sim mv^2$.

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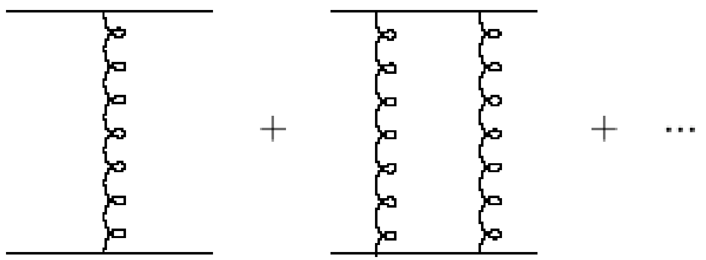

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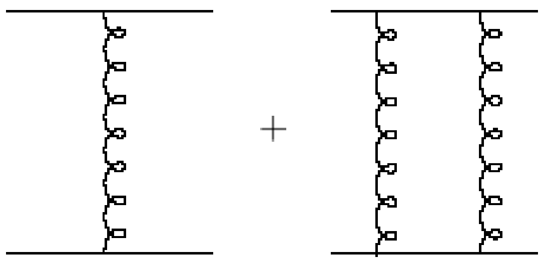

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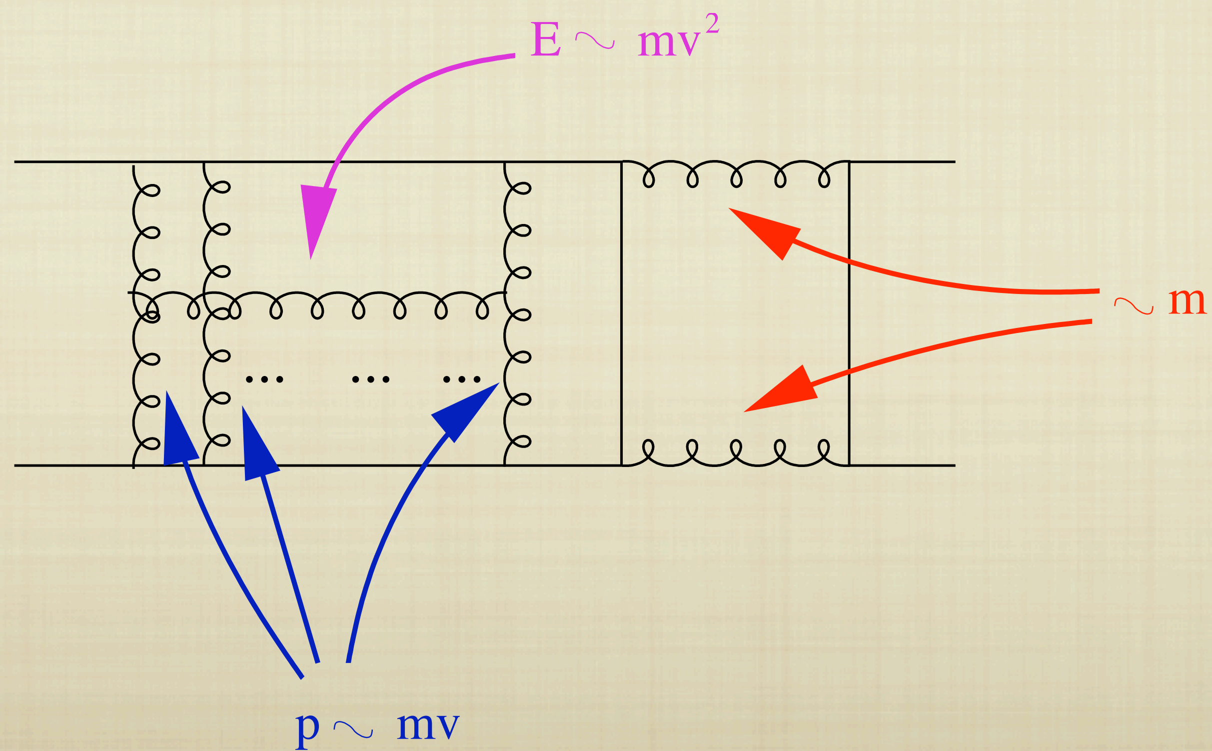

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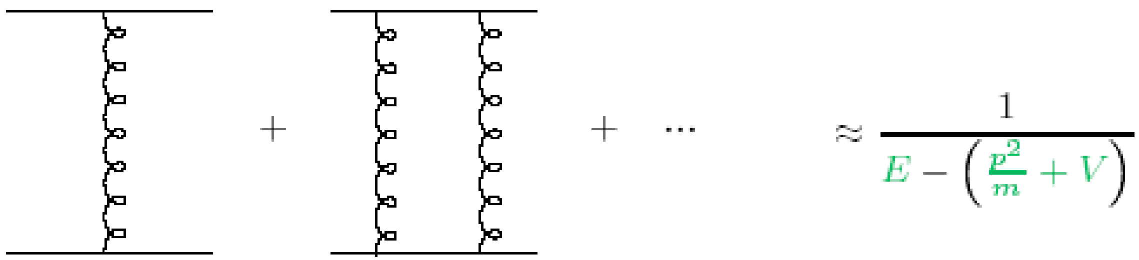
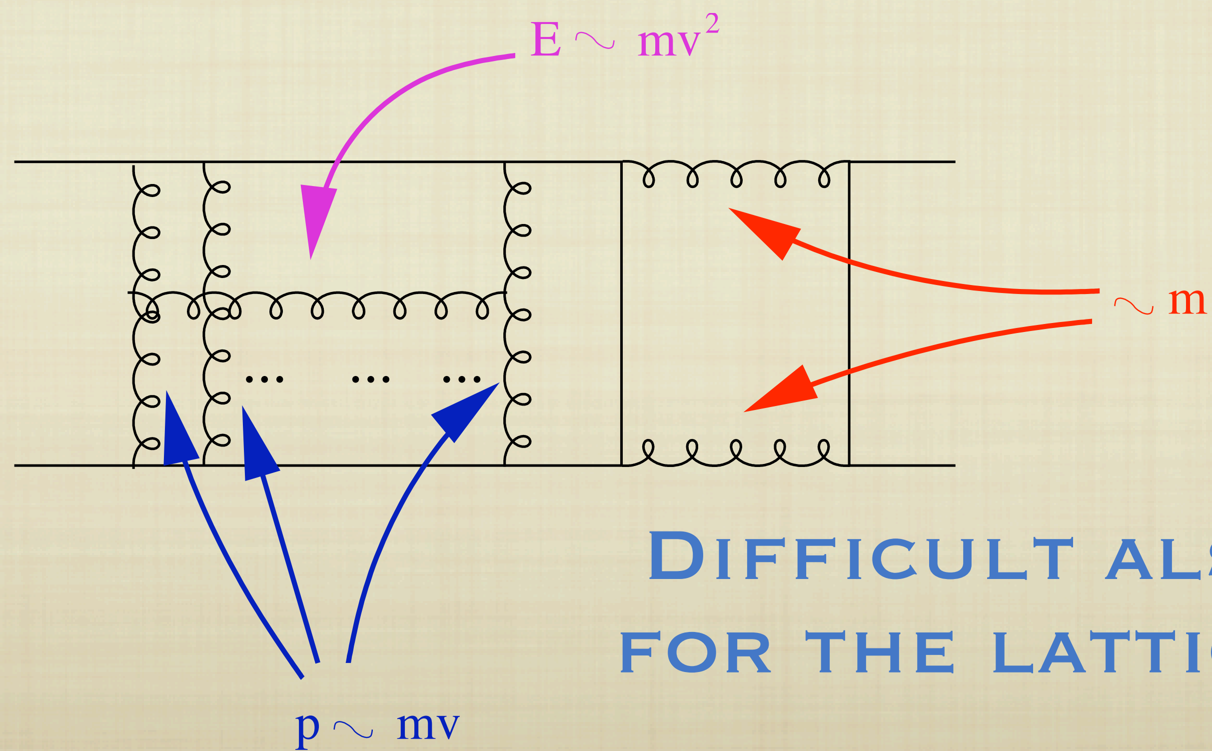
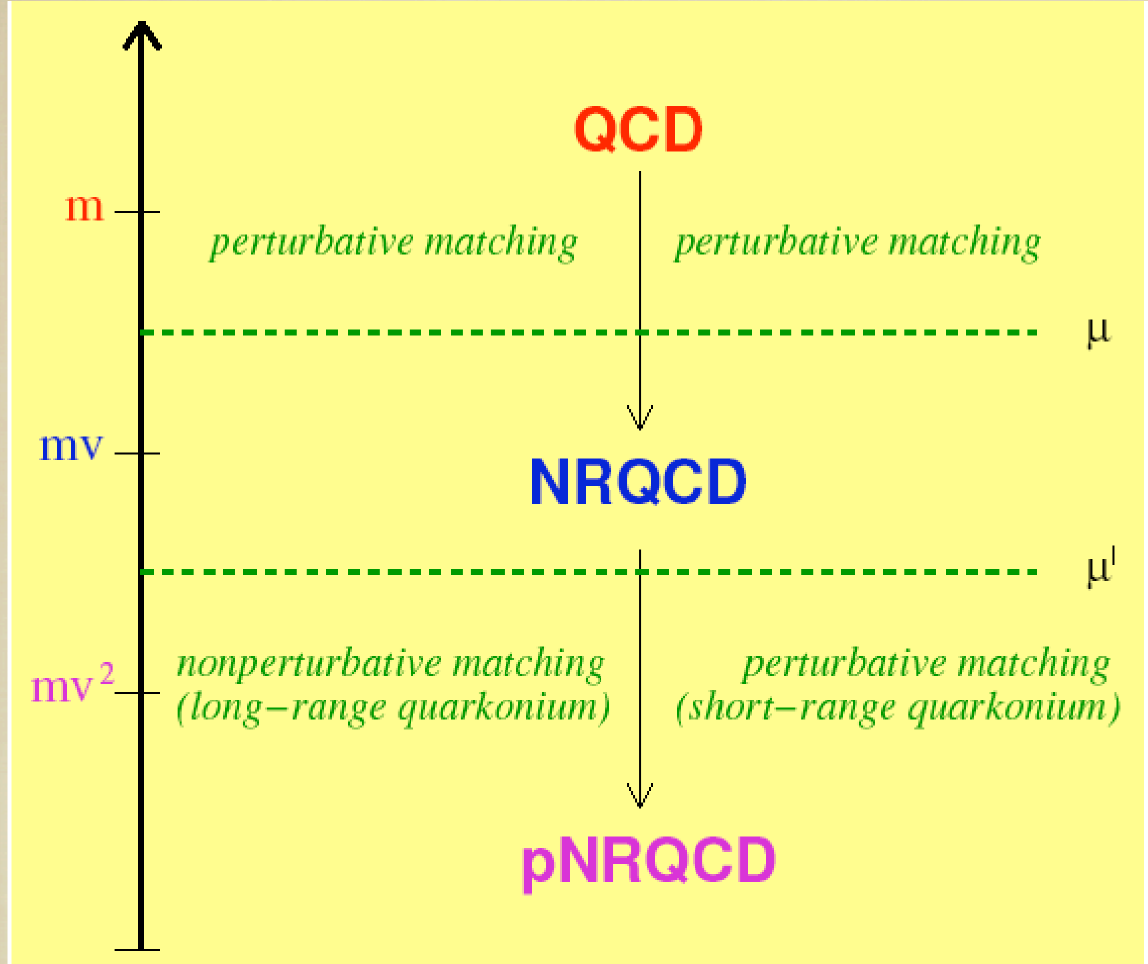


$$\frac{g^2}{p^2}(1 + \frac{m\alpha_s}{p})$$



DIFFICULT ALSO FOR THE LATTICE!

Disentangling scales with EFTs

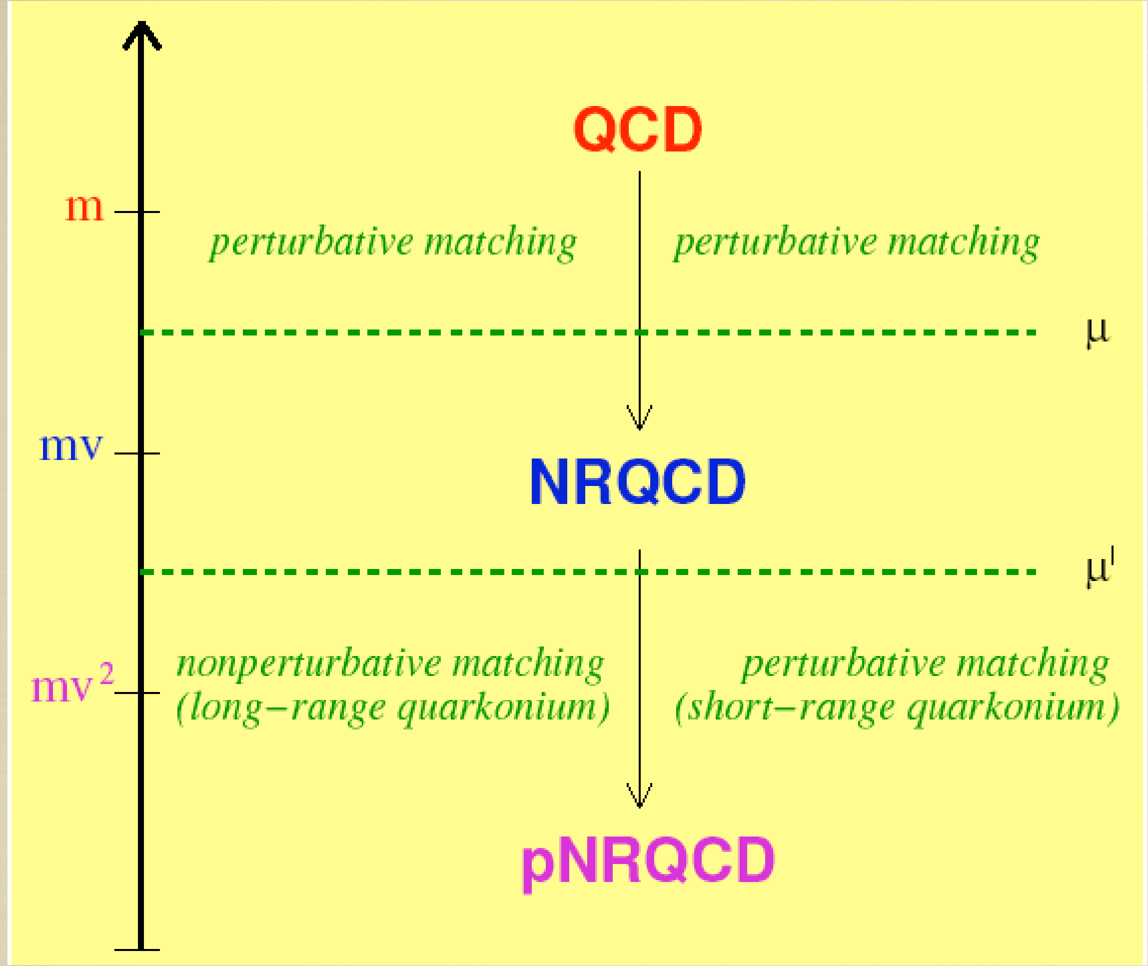


Hard

Soft
(relative
momentum)

Ultrasoft
(binding energy)

Disentangling scales with EFTs



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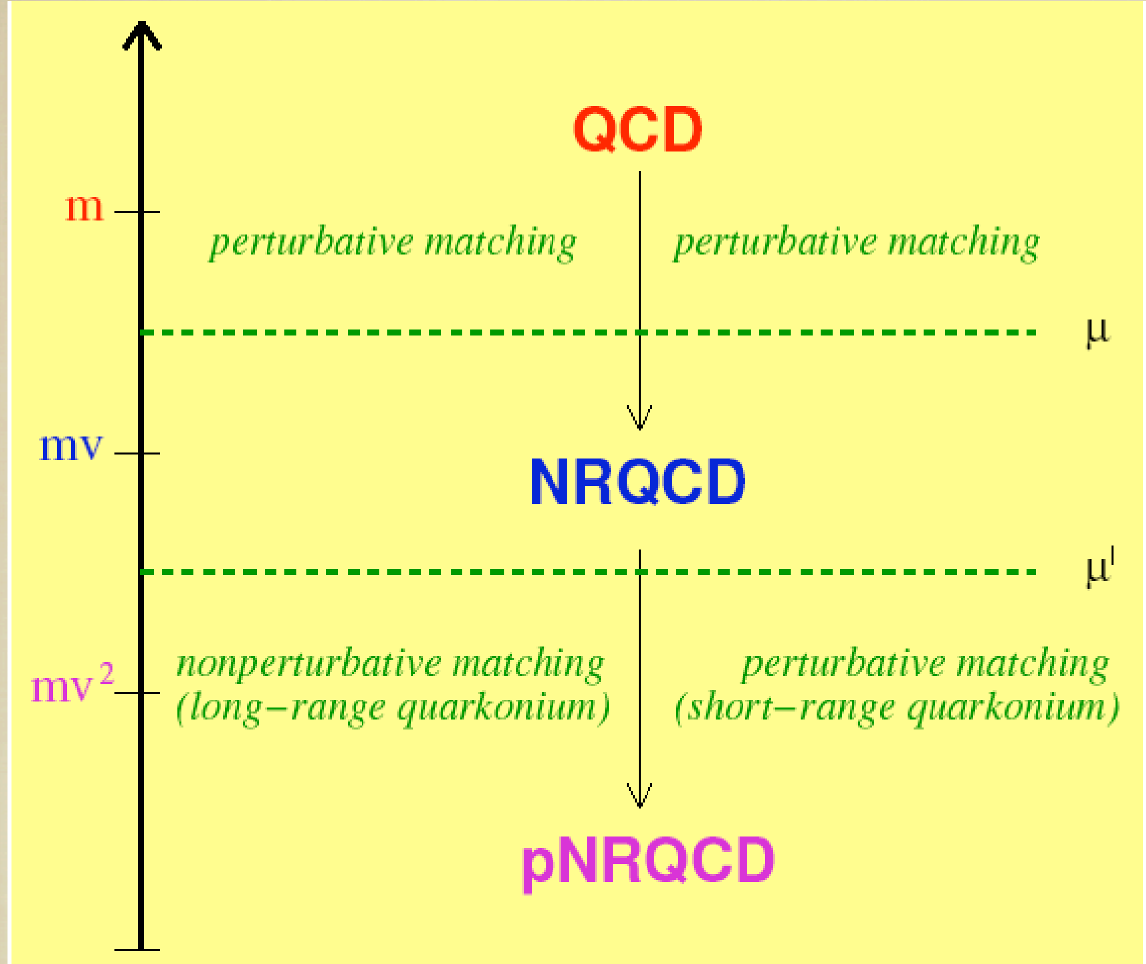

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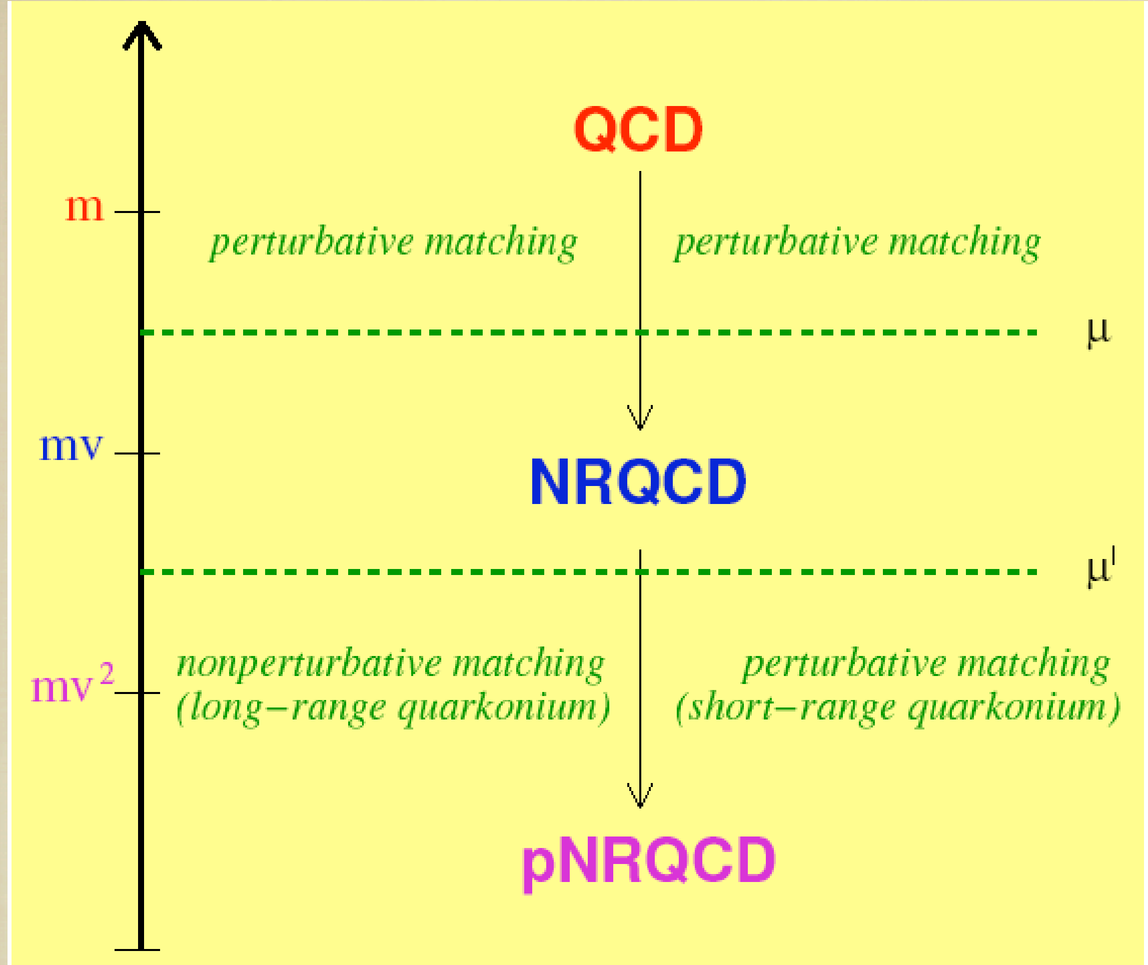

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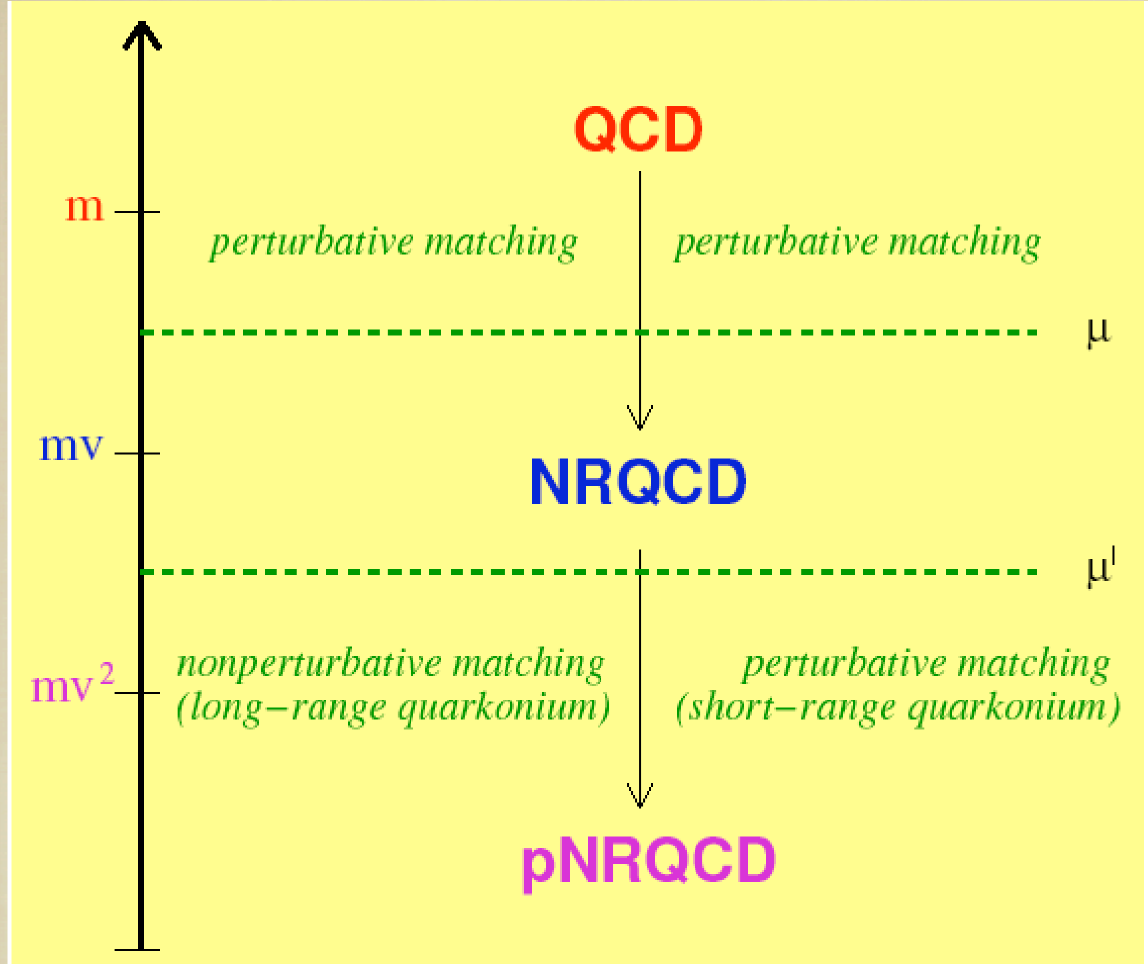

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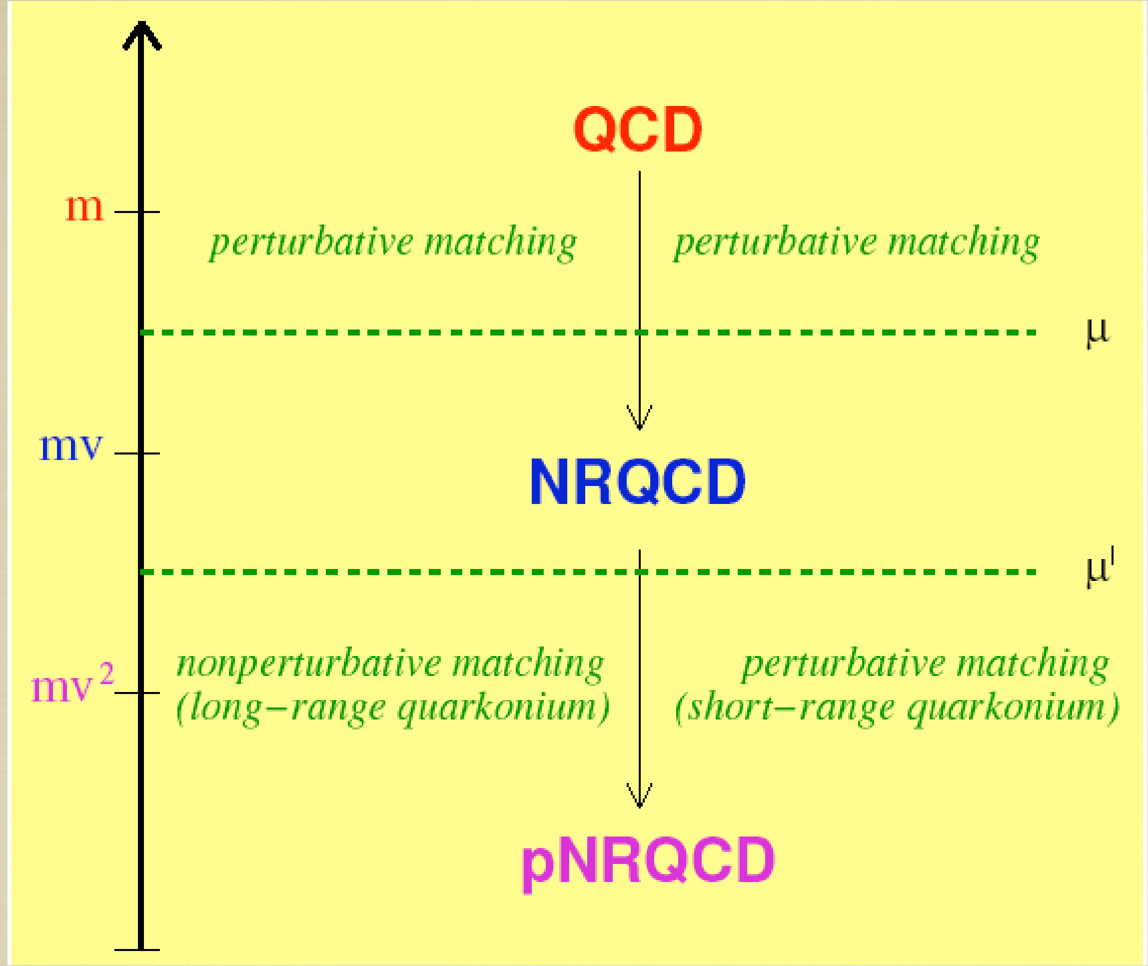

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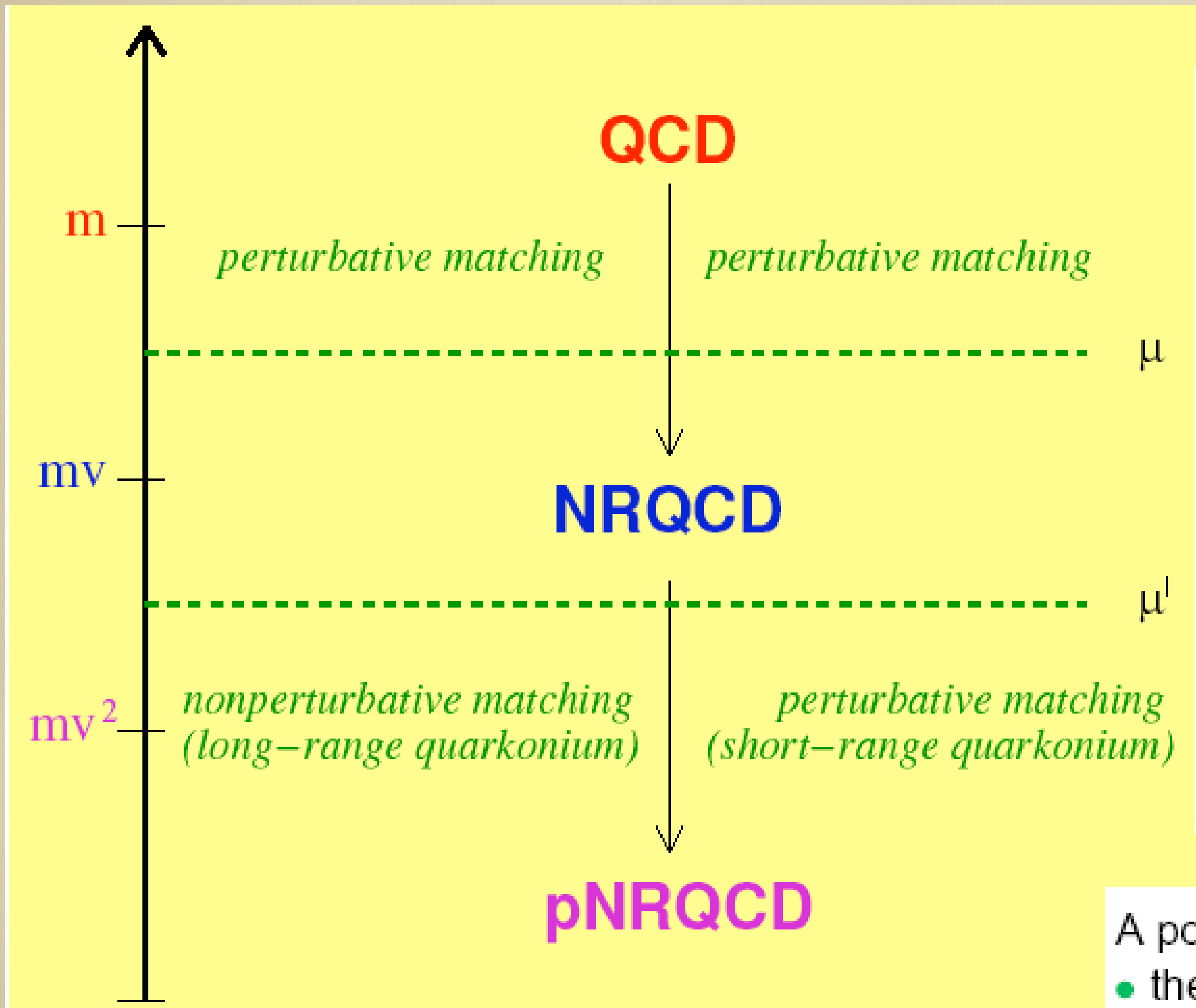
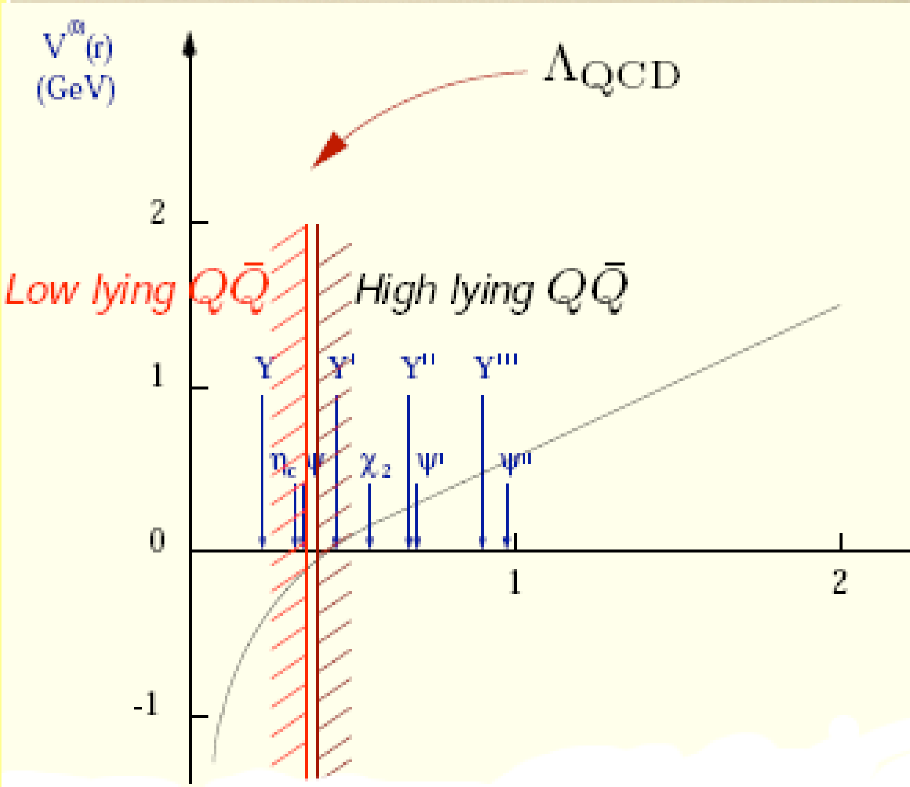
EFTs for Quarkonium



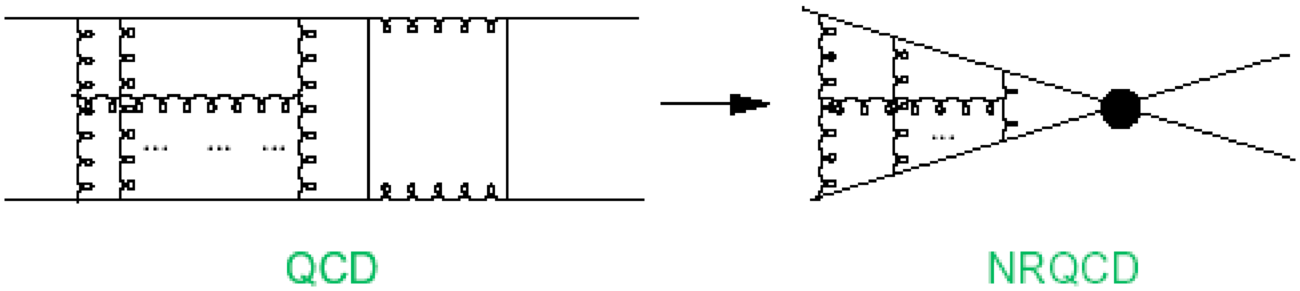


A potential picture arises at the level of pNRQCD:

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

NRQCD

NRQCD is the EFT that follows from QCD when $\Lambda = m$



$\times c(\mu/m)$

- The matching is perturbative.
- The Lagrangian is organized as an expansion in $1/m$ and $\alpha_s(m)$:

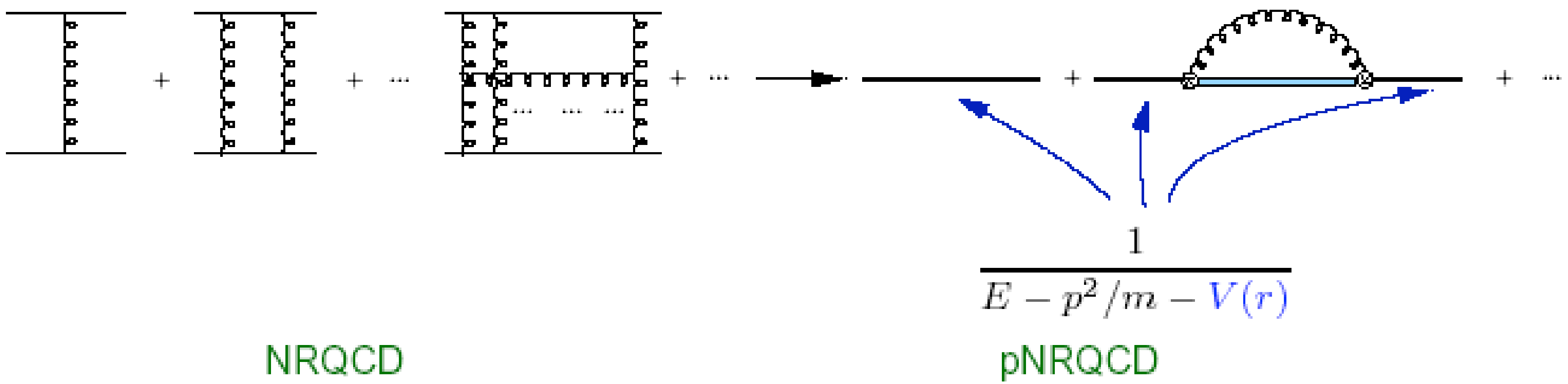
$$\mathcal{L}_{\rm NRQCD} = \sum_n c(\alpha_s(m/\mu)) \times O_n(\mu, \lambda)/m^n$$

Suitable to describe decay and production of quarkonium.

Caswell Lepage 86, Bodwin Braaten Lepage 95

Weakly coupled pNRQCD

pNRQCD is the EFT for heavy quarkonium that follows from NRQCD when $\Lambda = \frac{1}{r} \sim mv$



- The Lagrangian is organized as an expansion in $1/m$, r, and $\alpha_s(m)$:

$$\mathcal{L}_{\rm pNRQCD} = \sum_n c(\alpha_s(m/\mu)) \times V(r\mu', r\mu) \times O_n(\mu', \lambda)\, r^n$$

Pineda, Soto 97 Brambilla Pineda Soto Vairo 99

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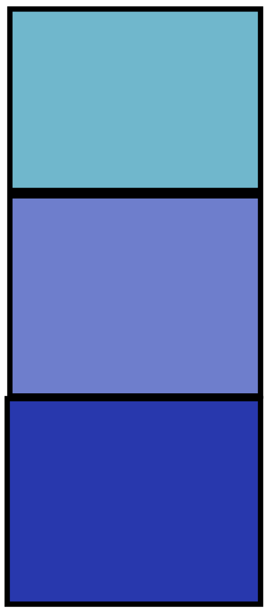
- Precision determinations of QCD parameters (of interest for SM and BSM physics)
- information on QCD vacuum and low energy properties (of interest for theories beyond QCD)
- information on the transition region from high energy to low energy (of interest for the behaviour of perturbative series)

Low energy (nonperturbative) effects always exist but their form depend on the size of the system

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



$\langle F^2(0) \rangle$ $\Upsilon(1S)$, ...

$\Lambda_{QCD} \sim t$ $\langle F(t)F(0) \rangle$ annihilations, short range $c\bar{c}$, $b\bar{b}$, gluelumps, ...

$\Lambda_{QCD} \sim loop$ $\langle e^{ig \oint dx A(x)} \rangle$ long range $c\bar{c}$, $b\bar{b}$, hybrids, glueballs, ...

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

To extract SM parameters

CONSIDER SYSTEMS OR OBSERVABLES WITH SUPPRESSED NONPERTURBATIVE EFFECTS (TYPICALLY QUARKONIA WITH SMALL RADIUS)

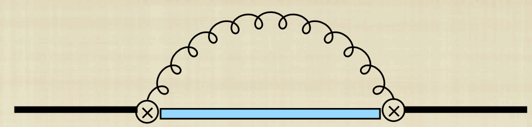
GET UNDER CONTROL THE PERTURBATIVE SERIES AND RESUM ALL LARGE CONTRIBUTIONS

Mass determination

Mass determination

Example: mass extraction from 1S energy level (e.g. Υ(1s))

Calculate QQ energies at best possible accuracy $m\alpha_s^5$

$E_n = 2m + \langle n | \frac{p^2}{m} + V_s | n \rangle + \langle n |$  $| n \rangle$

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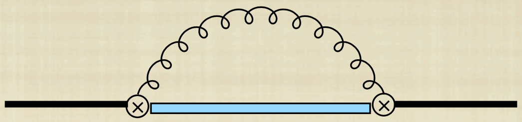
$$|n\rangle$$

perturbative singlet potential

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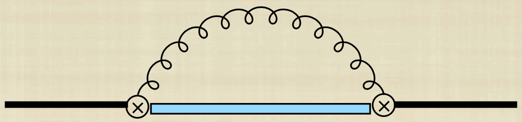

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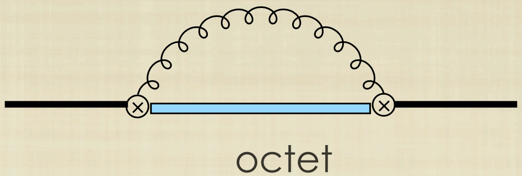
$$E_n = 2m + \langle n|\frac{p^2}{m} + V_s|n\rangle + \langle n|$$  $$|n\rangle$$

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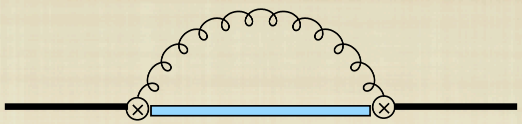

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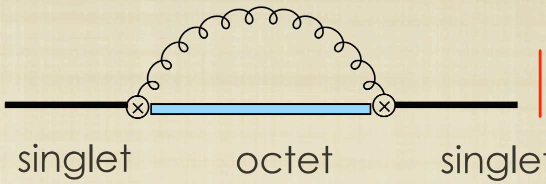

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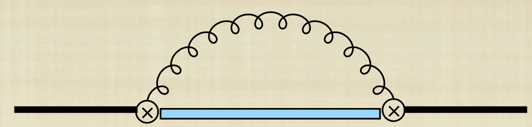

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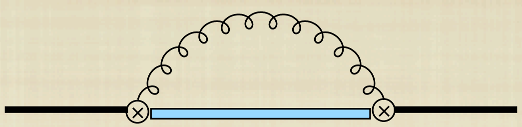

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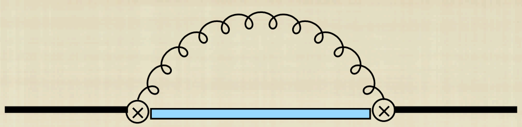
$$E_n = \langle n|H_s(\mu)|n\rangle - i\frac{g^2}{3N_c}\int_0^\infty dt\, \langle n|\mathbf{r}\, e^{it(E_n^{(0)}-H_o)}\mathbf{r}|n\rangle\, \langle \mathbf{E}(t)\,\mathbf{E}(0)\rangle(\mu)$$

Calculate QQ energies at best possible accuracy $m\alpha_s^5$

$$E_n = 2m + \langle n|\frac{p^2}{m} + V_s|n\rangle + \langle n|$$



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$$\sim e^{i\Lambda_{\rm QCD}t}$$

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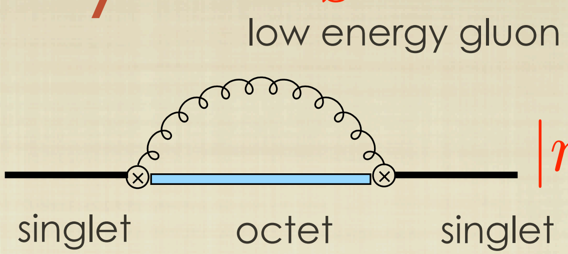
$$E_n = 2m + \langle n|\frac{p^2}{m} + V_s|n\rangle + \langle n|$$ 

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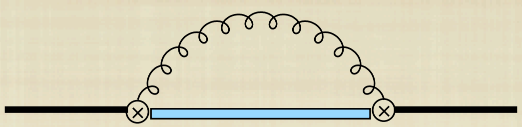

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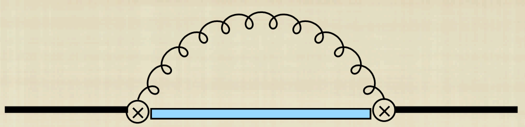

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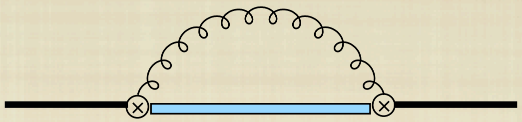

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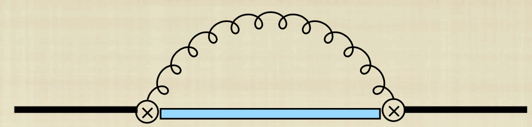

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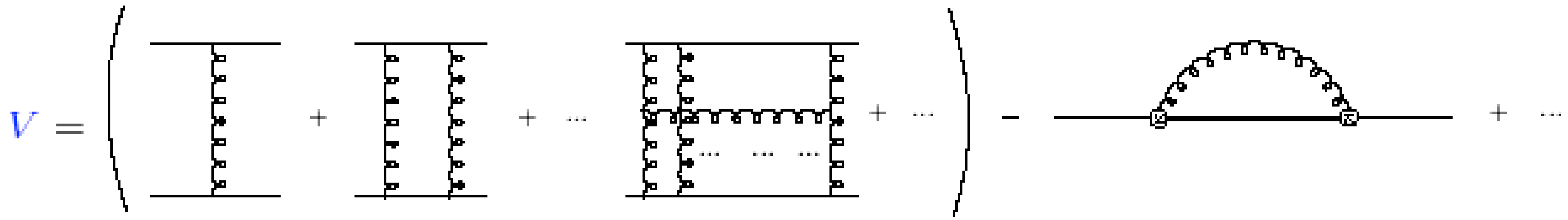
- 3) Deal with the nonperturbative corrections

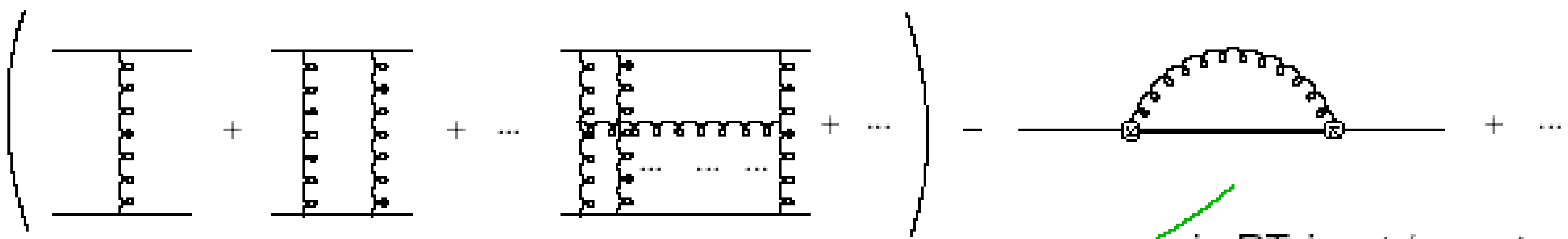
1)Bad behaviour of the perturbative series (the renormalon $O(\Lambda_{QCD})$)

Static singlet 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.

Static singlet potential

$V =$ 

in PT, i.e. $1/r \gg \Lambda_{\rm QCD}$

$$
\begin{aligned}
&= -\frac{4}{3}\frac{\alpha_s(1/r)}{r}\Bigg[1 + a_1\frac{\alpha_s(1/r)}{4\pi} + a_2\left(\frac{\alpha_s(1/r)}{4\pi}\right)^2 \\
&+ \left(144\,\pi^2\,\ln r\mu + a_3\right)\left(\frac{\alpha_s(1/r)}{4\pi}\right)^3 \\
&+ \left(a_4^{L2}\ln^2 r\mu + \left(a_4^L + 48\pi^2\,\beta_0(-5+6\ln 2)\right)\ln r\mu + a_4\right)\left(\frac{\alpha_s(1/r)}{4\pi}\right)^4 + \dots\Bigg]
\end{aligned}
$$

$$a_4^{L2} = -144\pi^2\,\beta_0$$

$$a_4^L = 432\pi^2\left[a_1 + 2\gamma_E\beta_0 + n_f\left(-\frac{20}{27} + \frac{4}{9}\ln 2\right) + \frac{149}{9} - \frac{22}{3}\ln 2 + \frac{4}{3}\pi^2\right]$$

Brambilla Pineda Soto Vairo 99, Brambilla Garcia Soto Vairo 06

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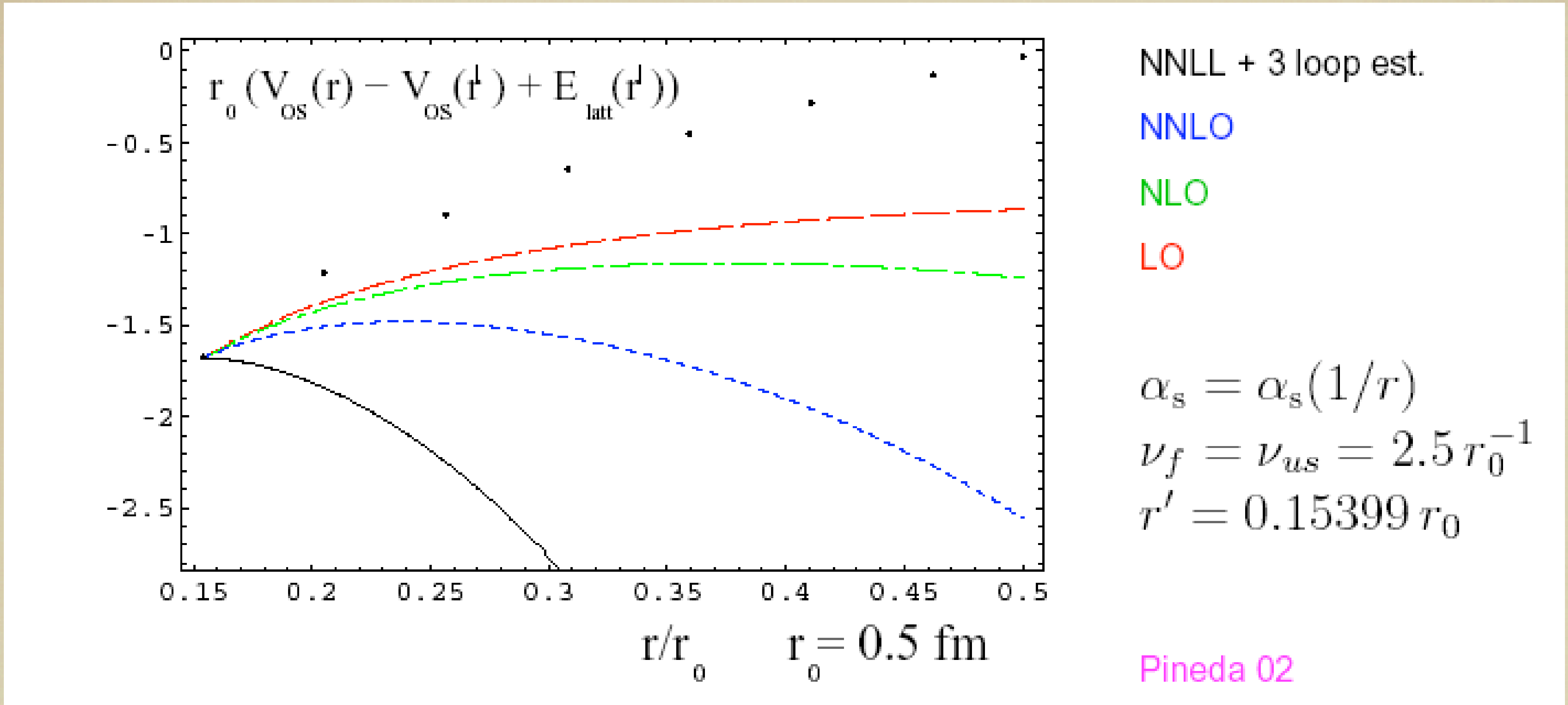

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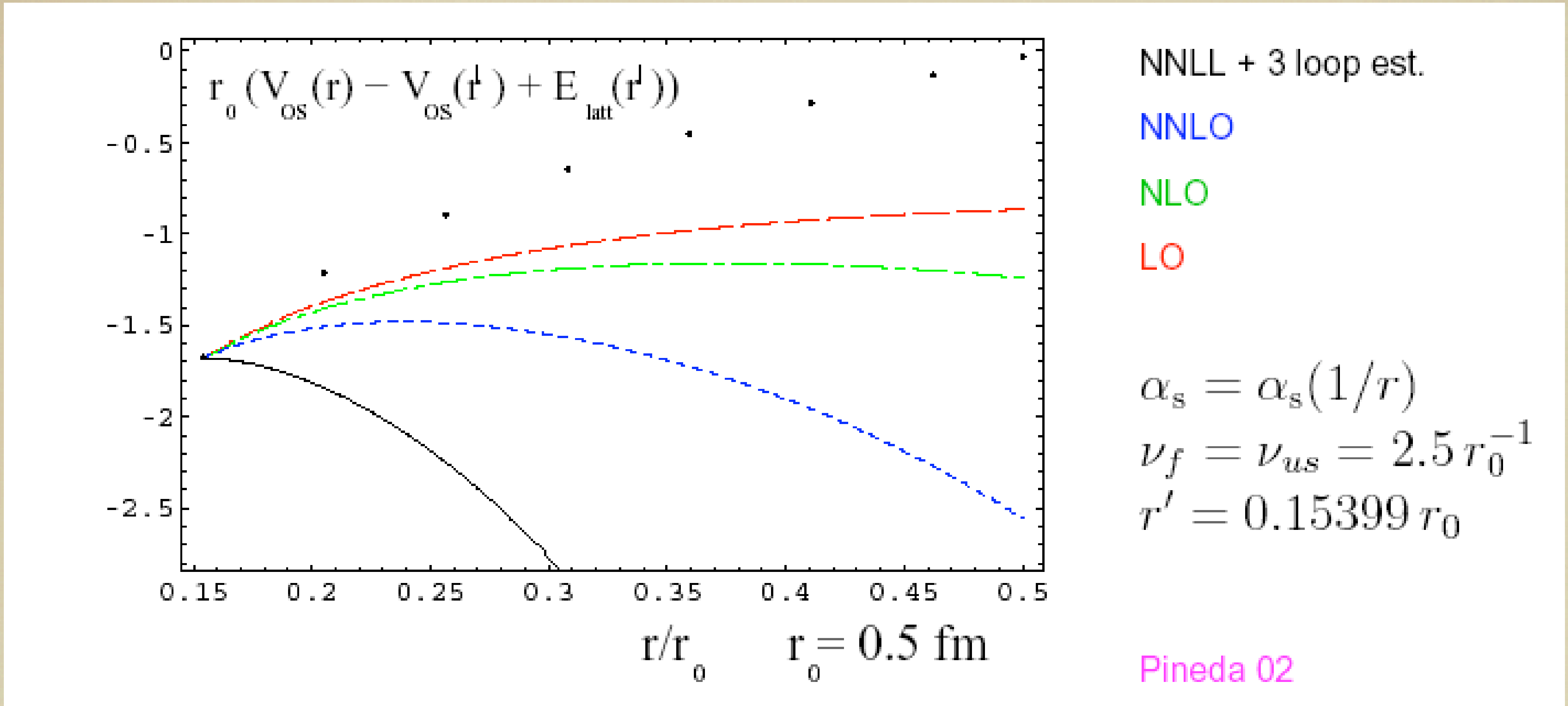

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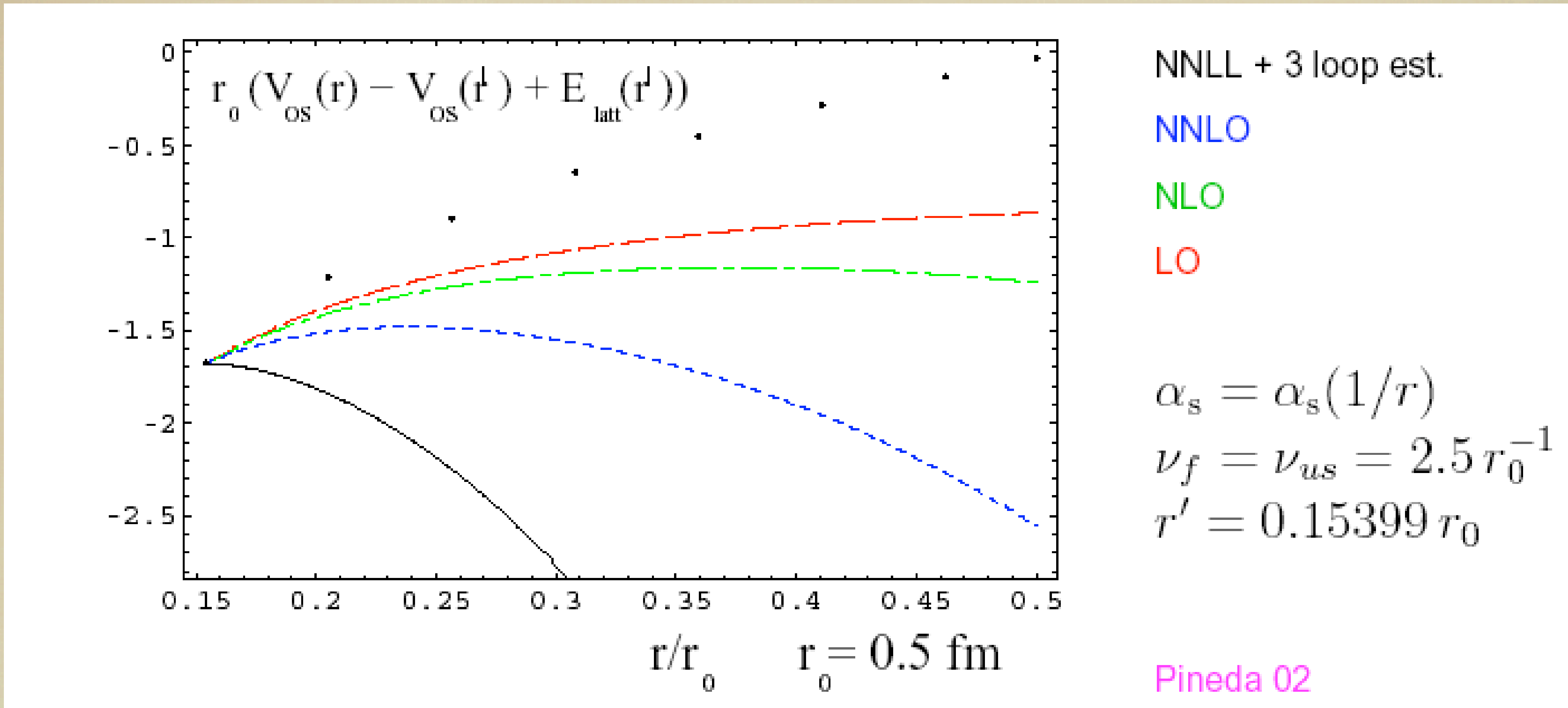

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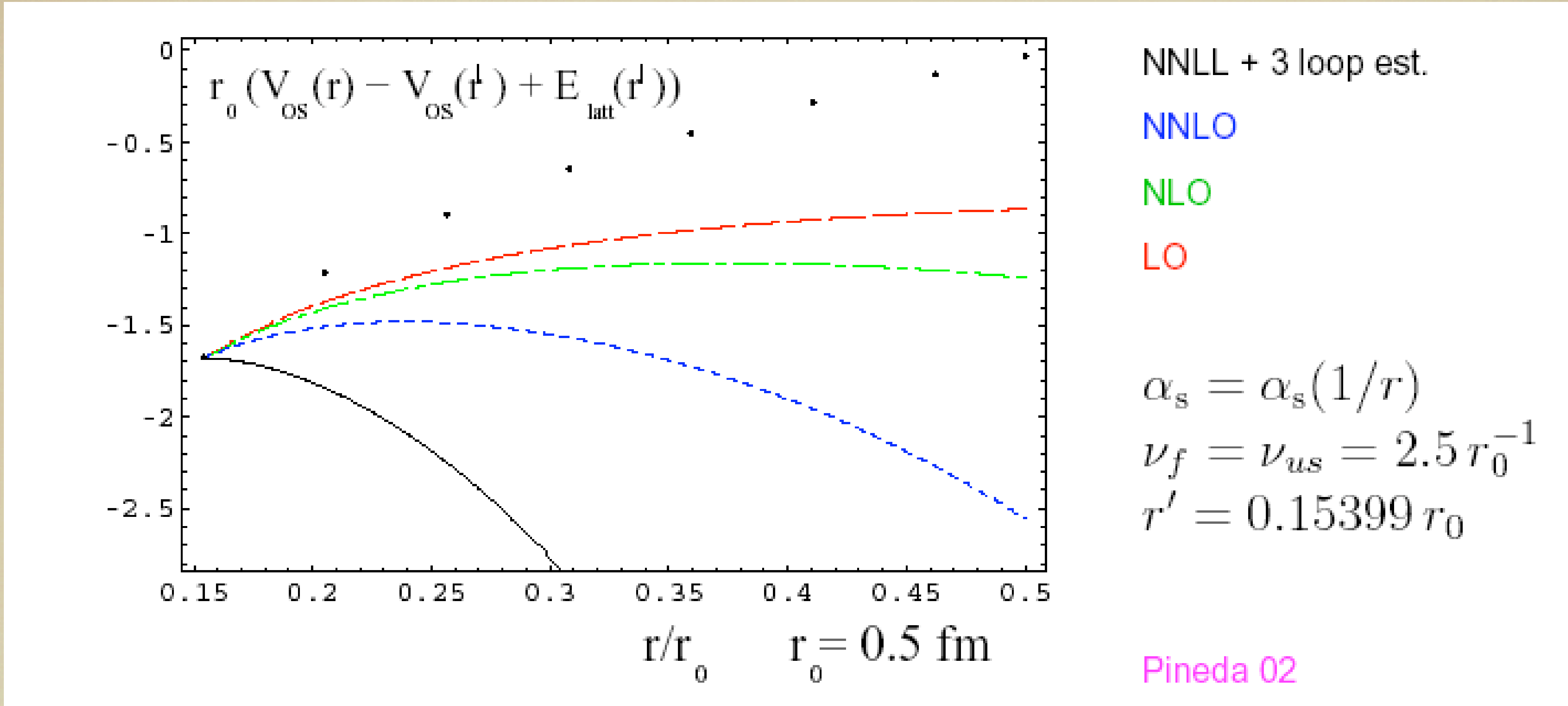

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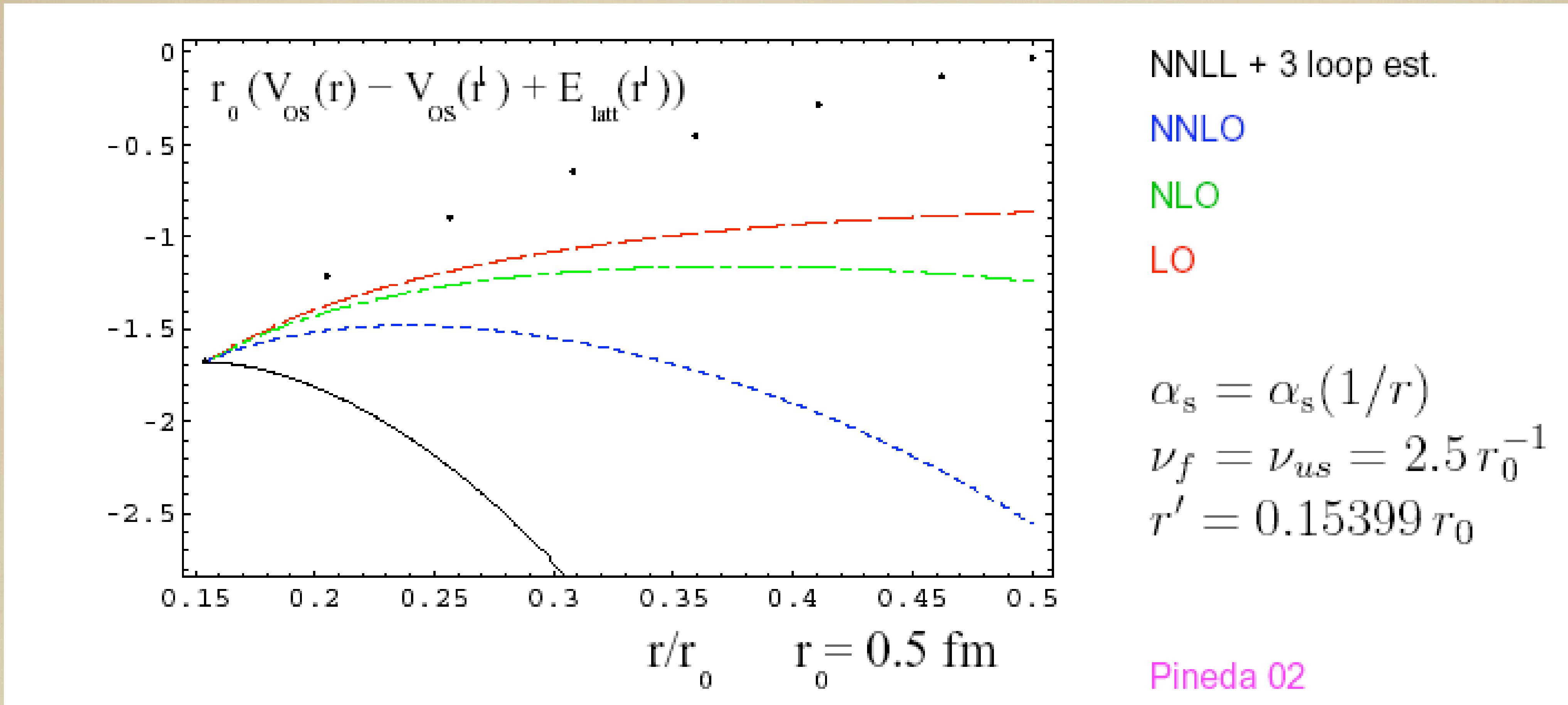

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Is well behaved (the renormalon cancels between the two when one eliminates m_pole in terms of msbar or threshold mass)

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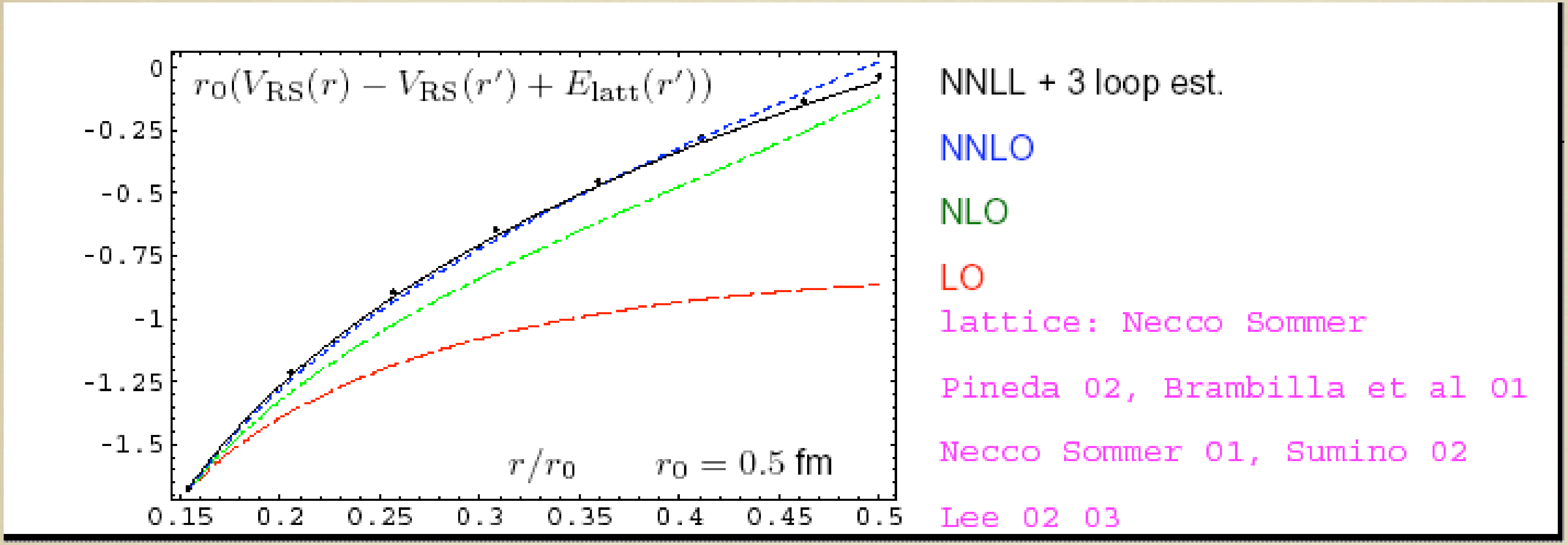

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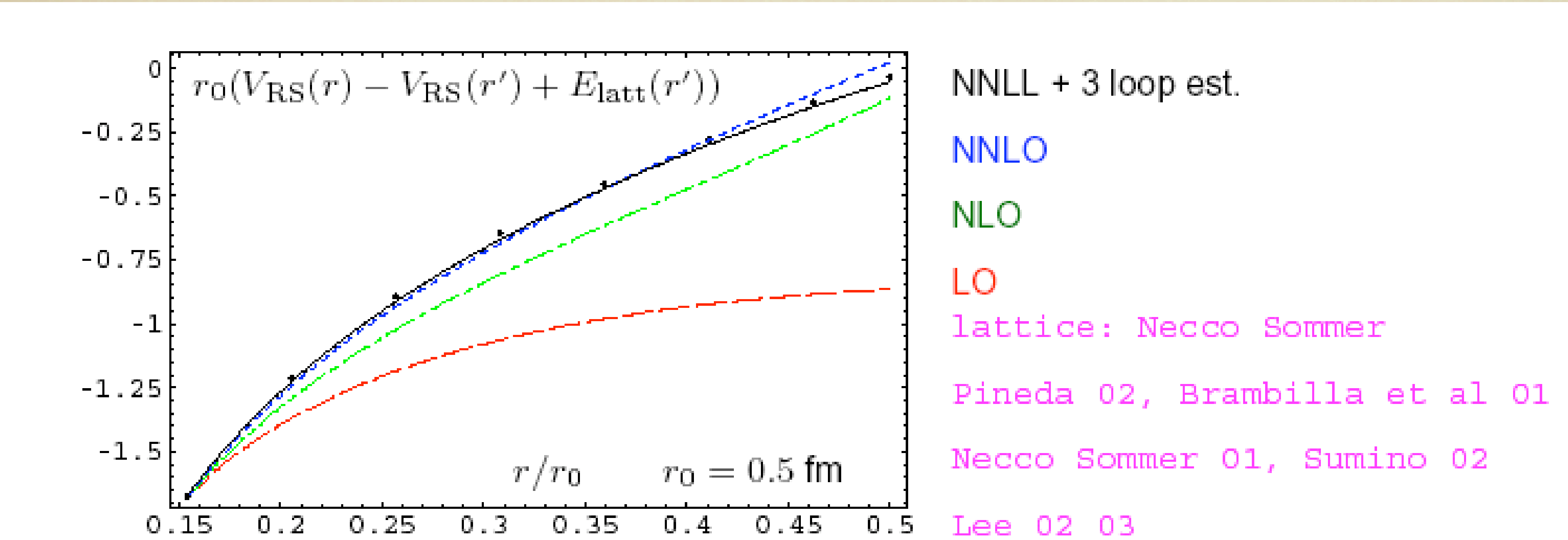

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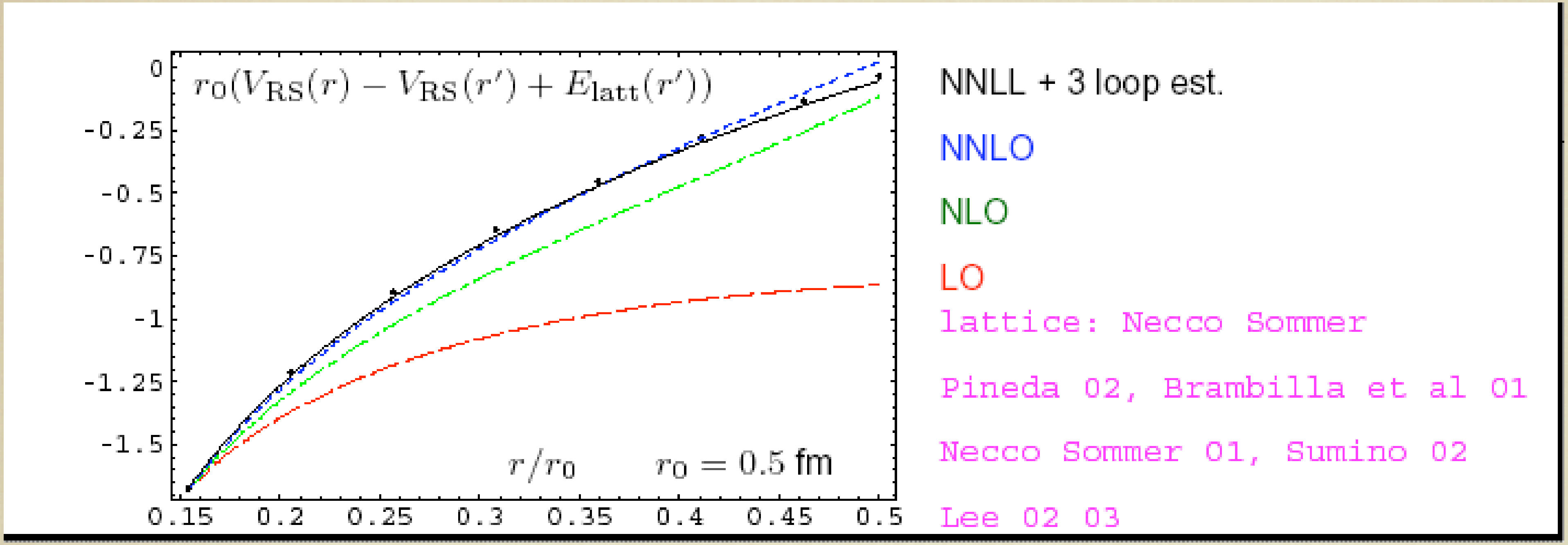

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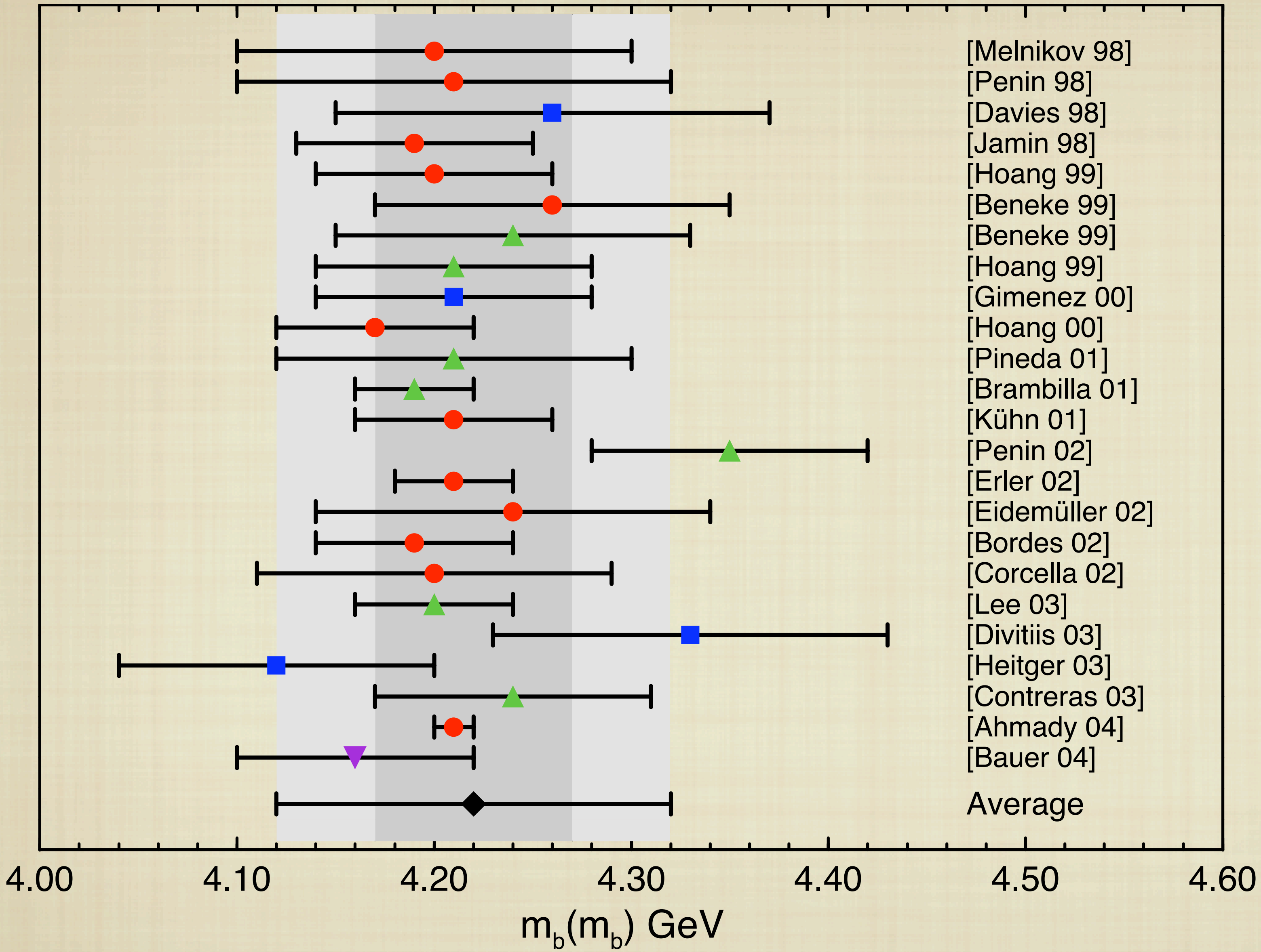
3)nonperturbative corrections are neglected (when suppressed)

Bottom mass extractions from Υ(1S), Sum rules, lattice

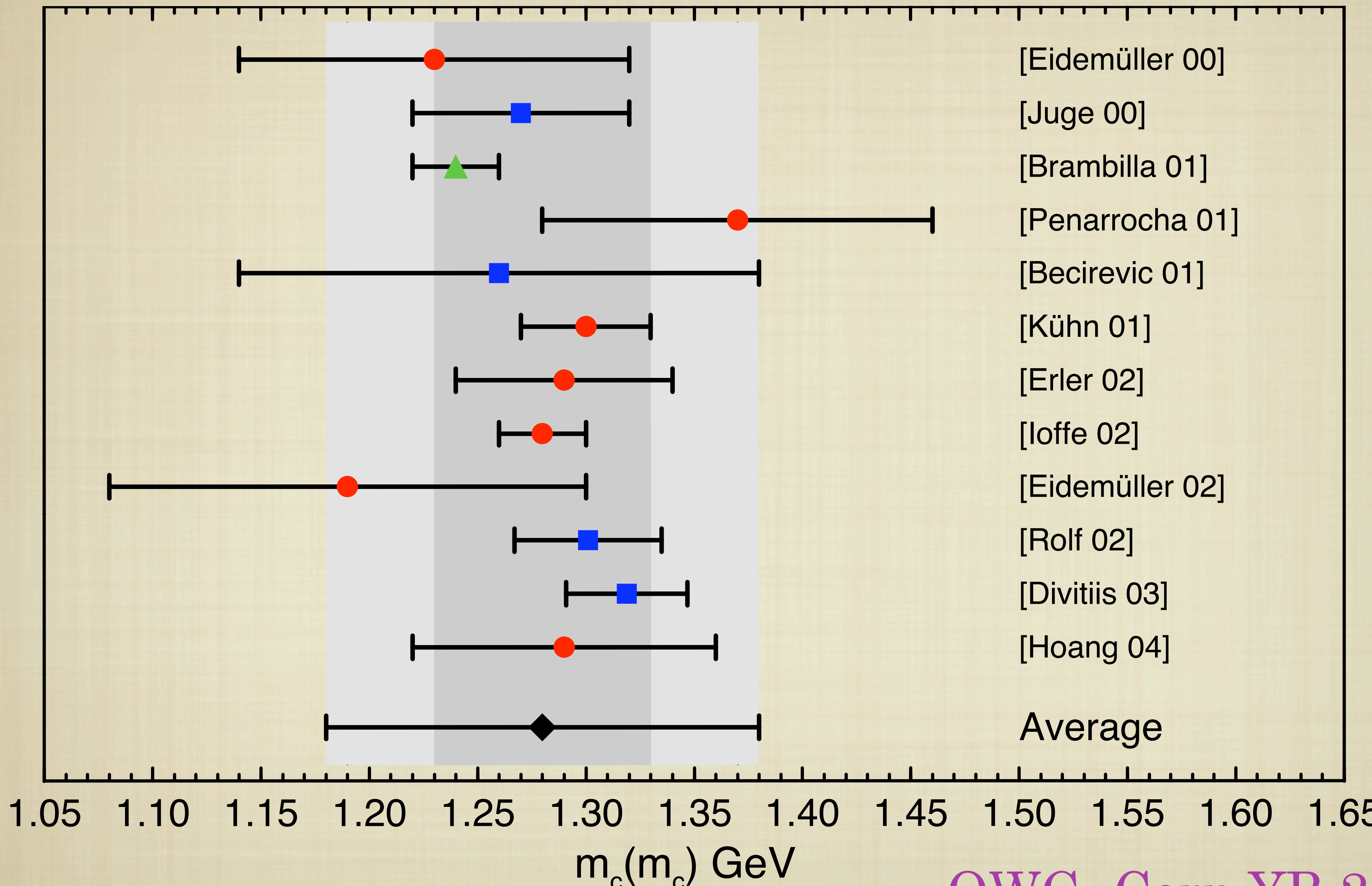


$$\overline{m}_b(\overline{m_b}) = 4.22 \pm 0.05\,\mathrm{GeV}$$

QWG Cern YR 2005

hep-ph/0412158

Charm mass extraction from J/psi, sum rules, lattice



$$\overline{m}_c(\overline{m}_c) = 1.28 \pm 0.05\,\mathrm{GeV}$$

QWG Cern YR 2005
hep-ph/0412158

More recent determinations:

NR Sum Rules (full NLL ,partial NNLL accuracy):

$$\overline{m}_b(\overline{m}_b) = 4.19 \pm 0.06\,\mathrm{GeV}$$

Pineda Signer 06

semileptonic B decays

$$\overline{m}_c(\overline{m}_c) = 1.224 \pm 0.017 \pm 0.054\,\mathrm{GeV}$$

Hoang Manohar 05

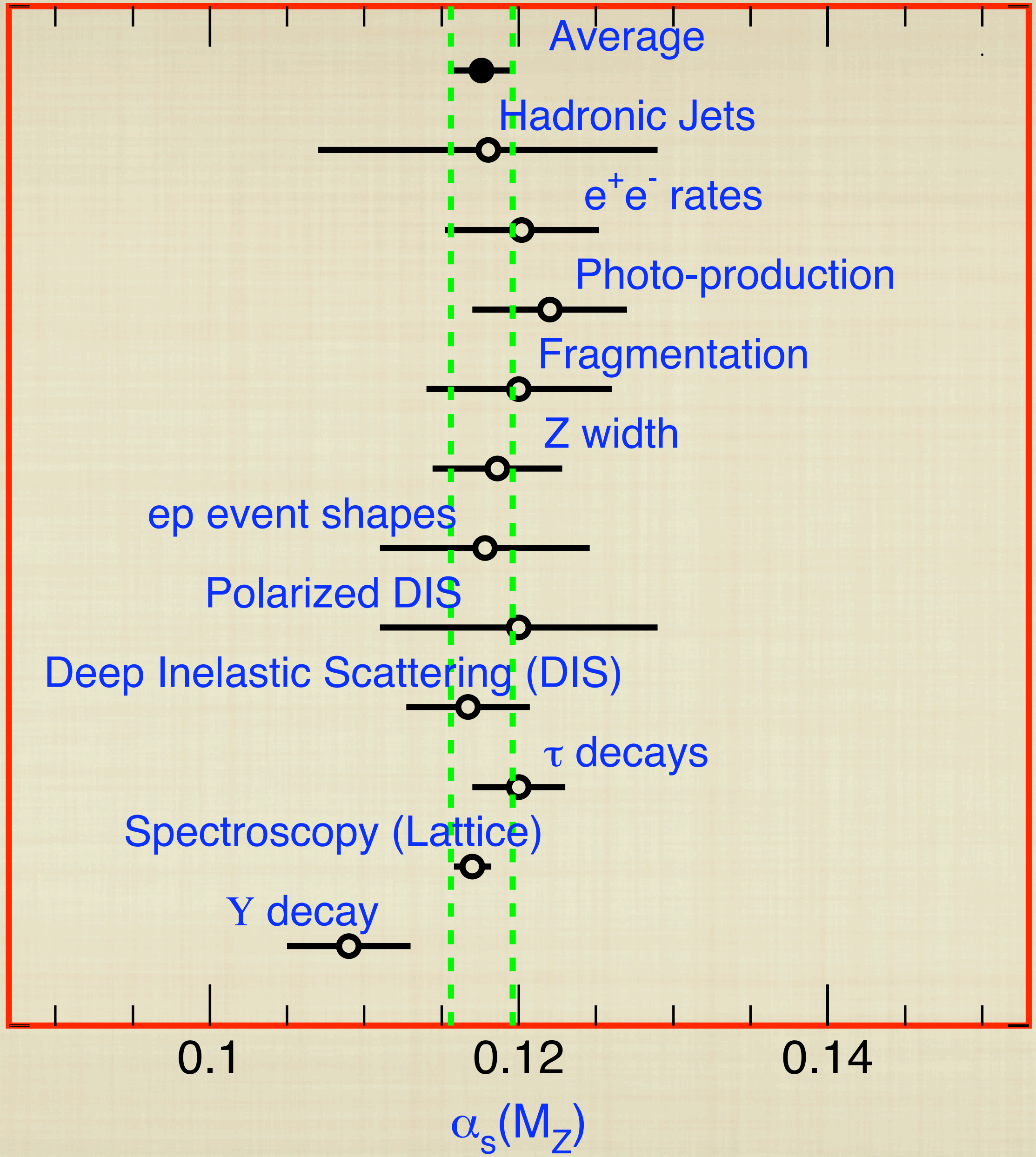
lattice (unquenched)

$$\overline{m}_b(\overline{m}_b) = 4.4 \pm 0.030\,\mathrm{GeV}$$

Gray et al 05

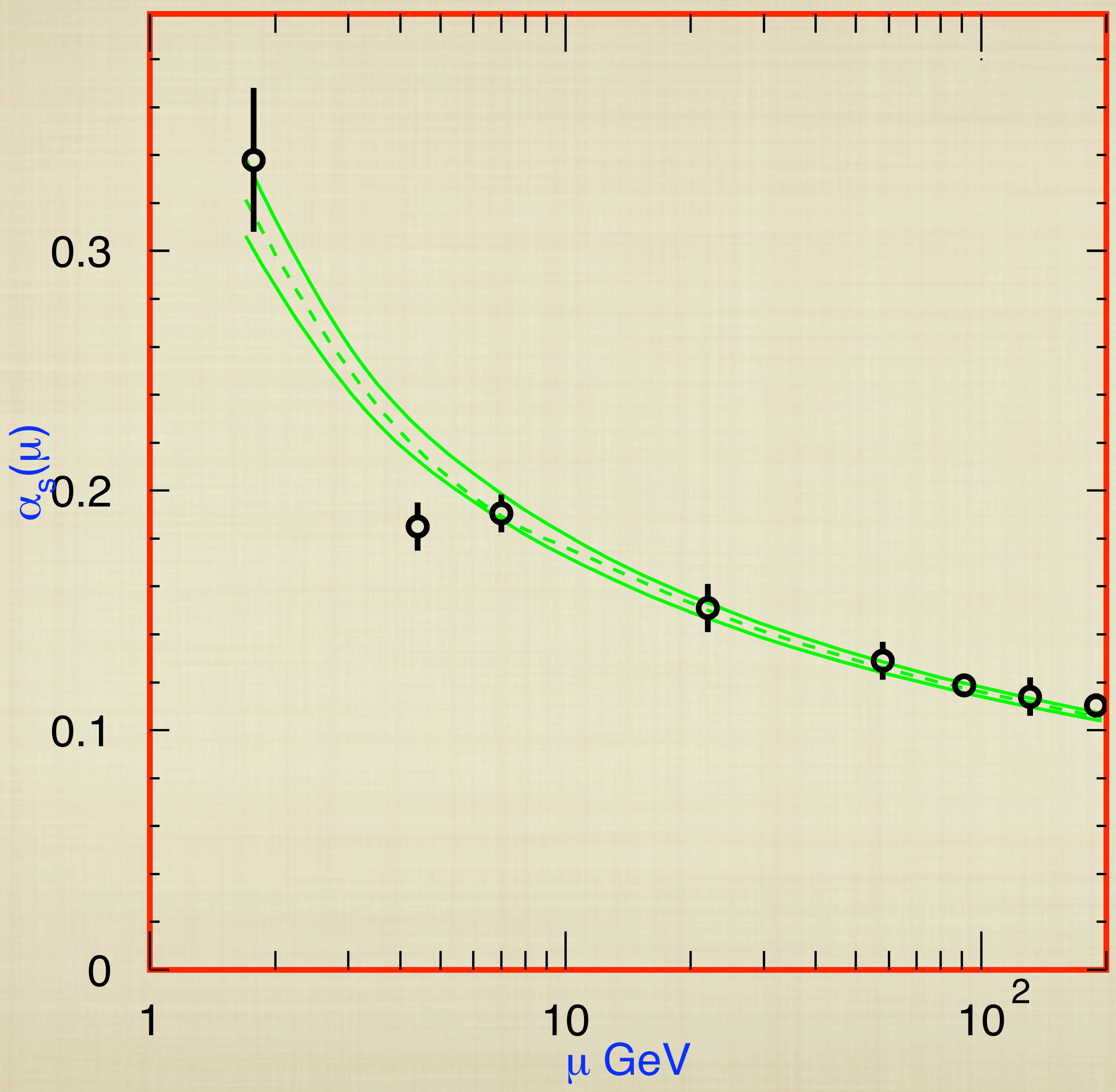
alpha_s determination

$\alpha_s(M_Z)$ FROM PDG06



$$\alpha_s(M_Z) = 0.1176 \pm 0.002$$

Running of α_s from PDG06



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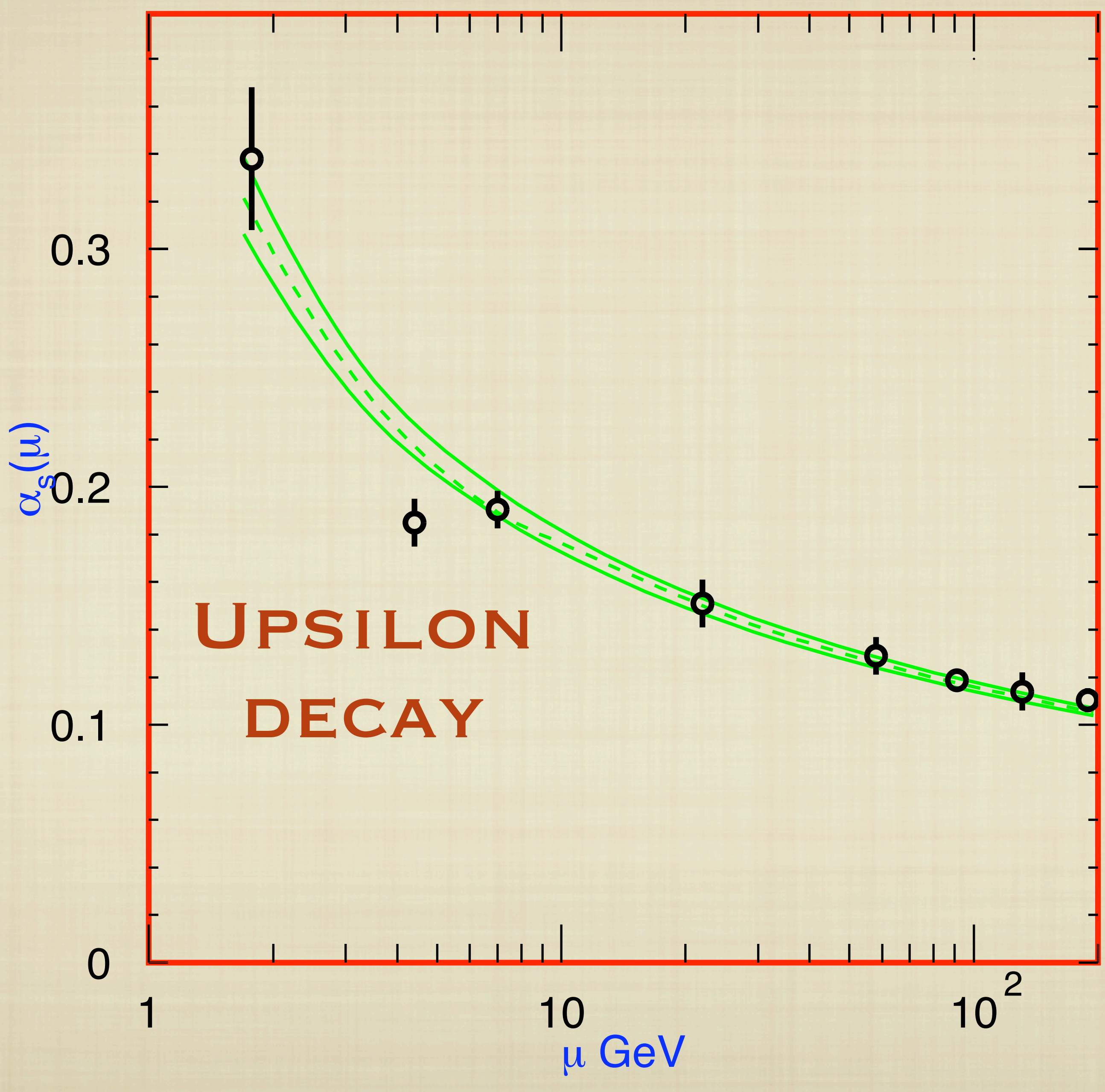

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$$R_\gamma \equiv \frac{\Gamma(\Upsilon(1S) \to \gamma X)}{\Gamma(\Upsilon(1S) \to X)}$$

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- ACCURATE ESTIMATES OF THE OCTET CONTRIBUTIONS FROM THE LATTICE (BODWIN, LEE, SINCLAIR 05) AND FROM CONTINUUM (GARCIA, SOTO 05)

Using NRQCD decay factorization:

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

Bodwin et al 95

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accurate at NLO in alpha_s and v

We obtain

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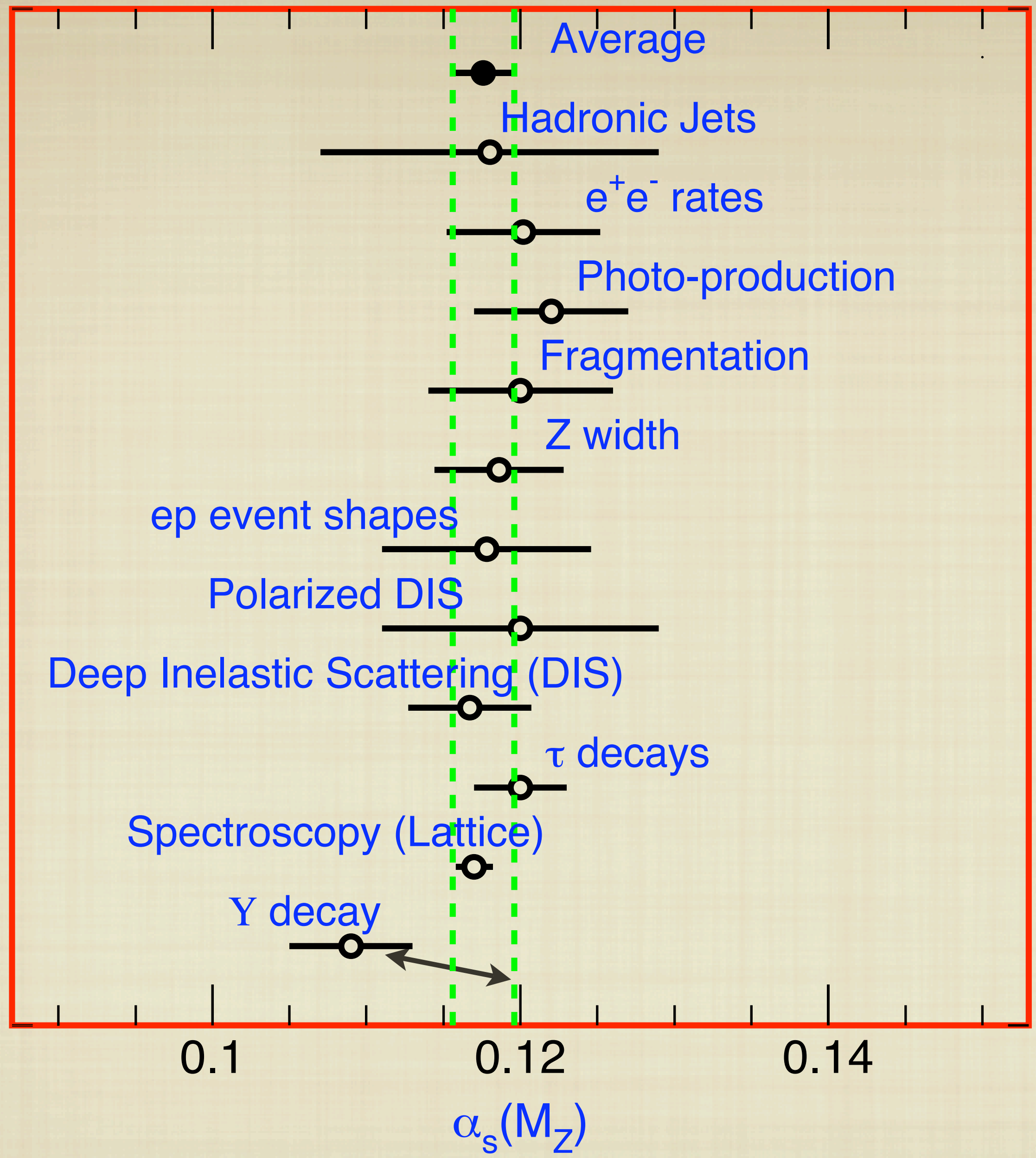
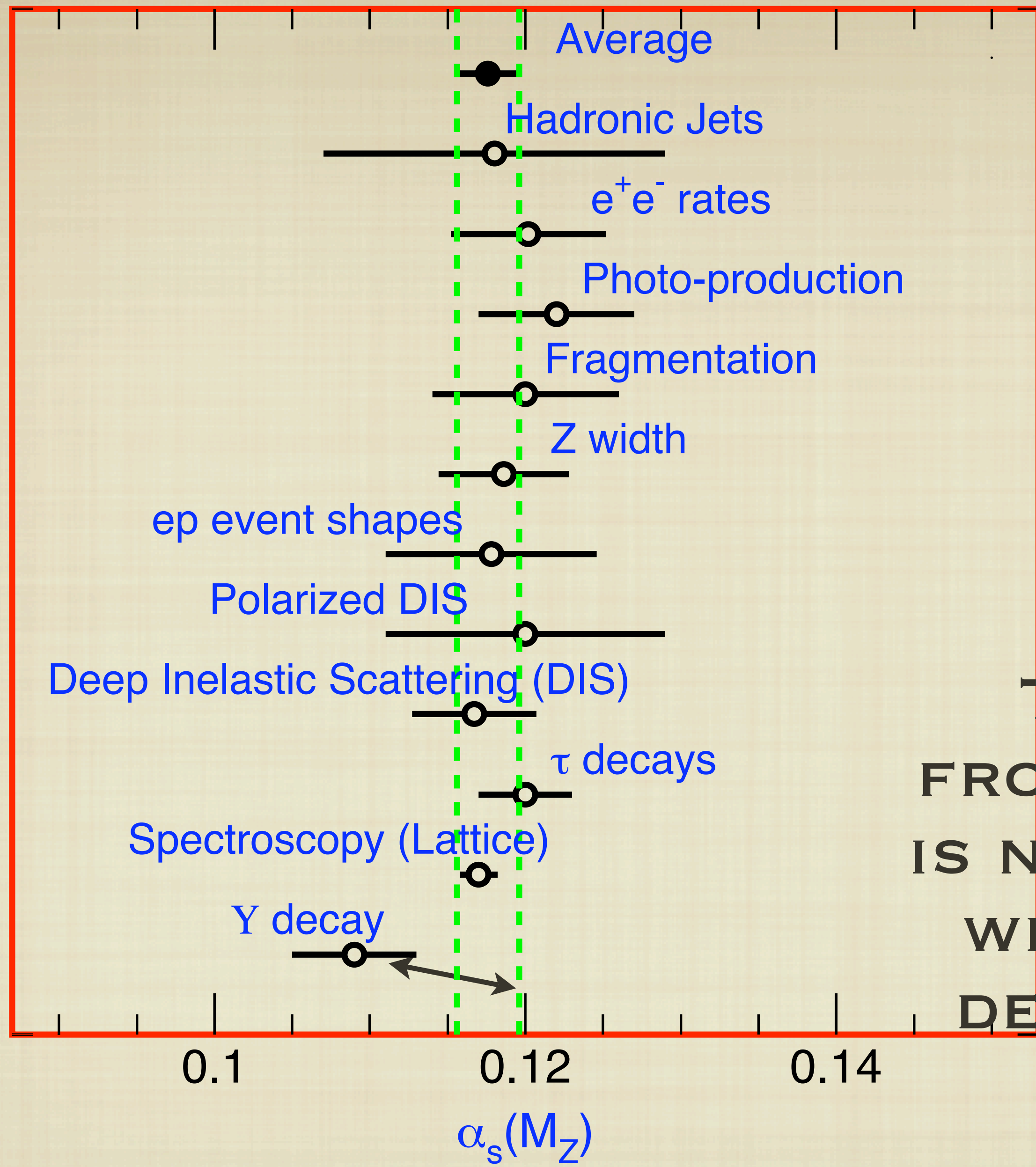
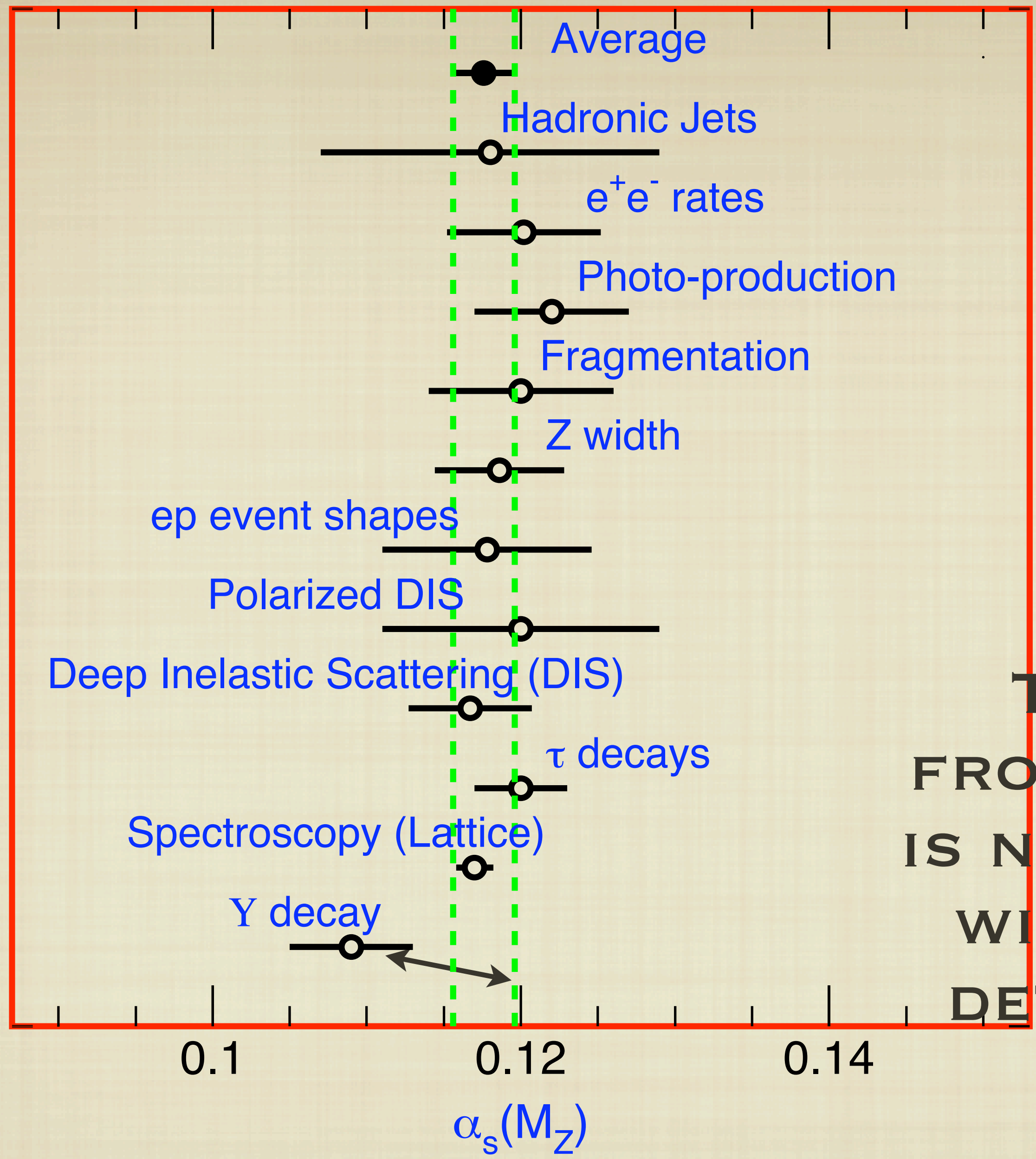
discussion of previous determinations CLEO/PDG


Average
Hadronic Jets
e+e- rates
Photo-production
Fragmentation
Z width
ep event shapes
Polarized DIS
Deep Inelastic Scattering (DIS)
τ decays
Spectroscopy (Lattice)
Υ decay
0.1
0.12
0.14
αs(MZ)



The alpha_s from quarkonium is now consistent with the other determinations



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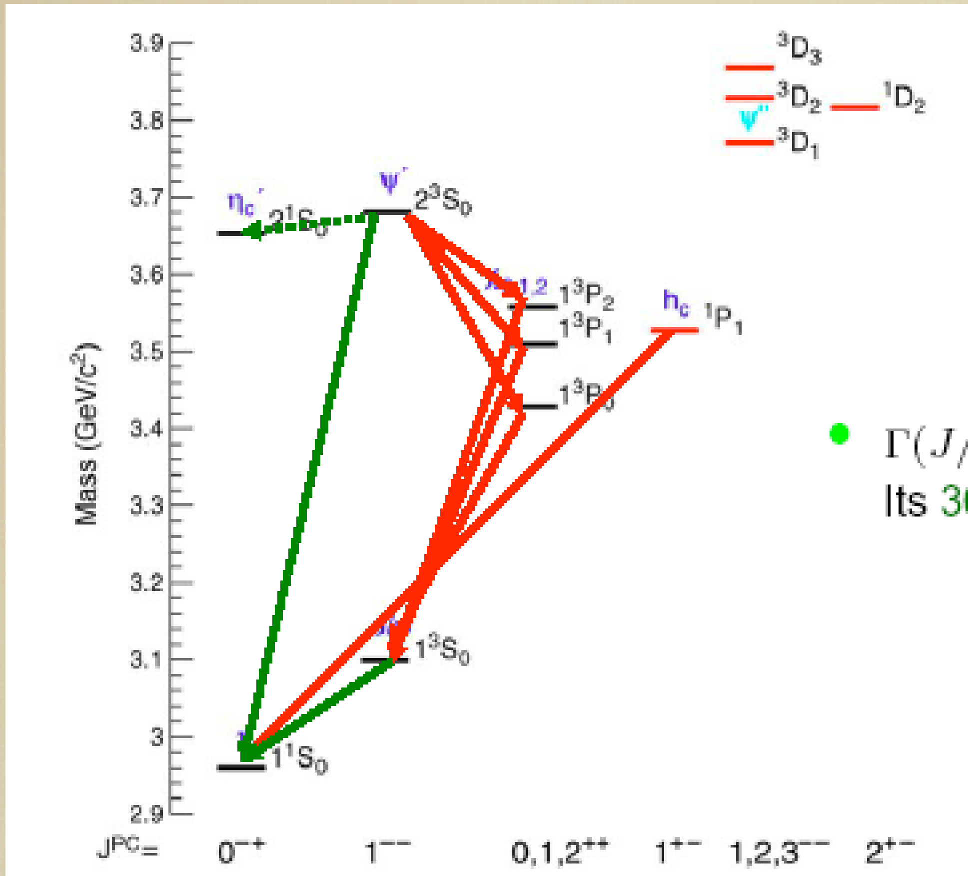
The new determination of alpha_s will move up the alpha_s average!

M1 Transitions

RADIATIVE TRANSITIONS



Magnetic Dipole transitions

$\Gamma(J/\psi \to \eta_c \gamma) = (1.18 \pm 0.36)\,\mathrm{keV}$ PDG 06

- $\Gamma(J/\psi \to \eta_c \gamma)$ enters into many charmonium BR. Its 30% 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

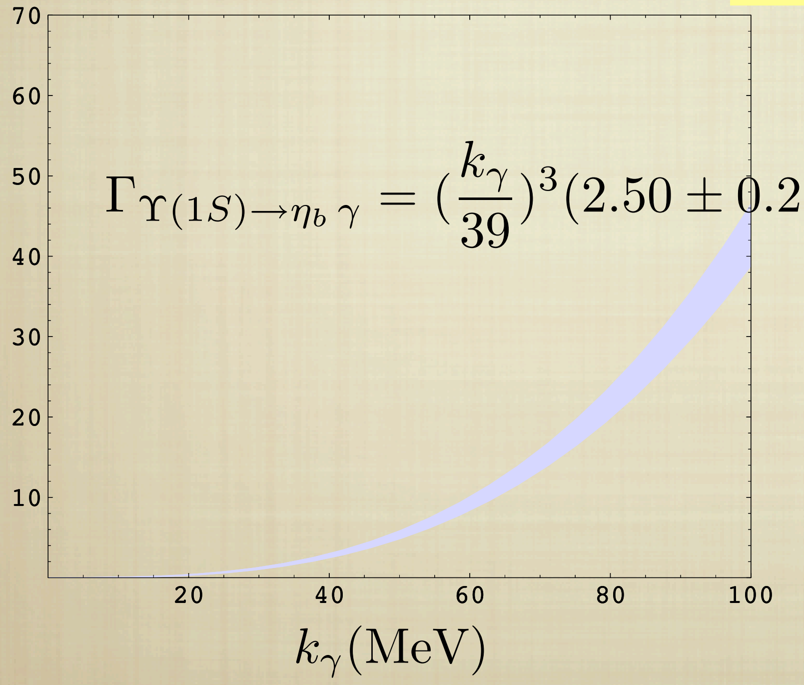
pNRQCD with singlet, octet, US gluons and photons

Brambilla, Jia, Vairo 05

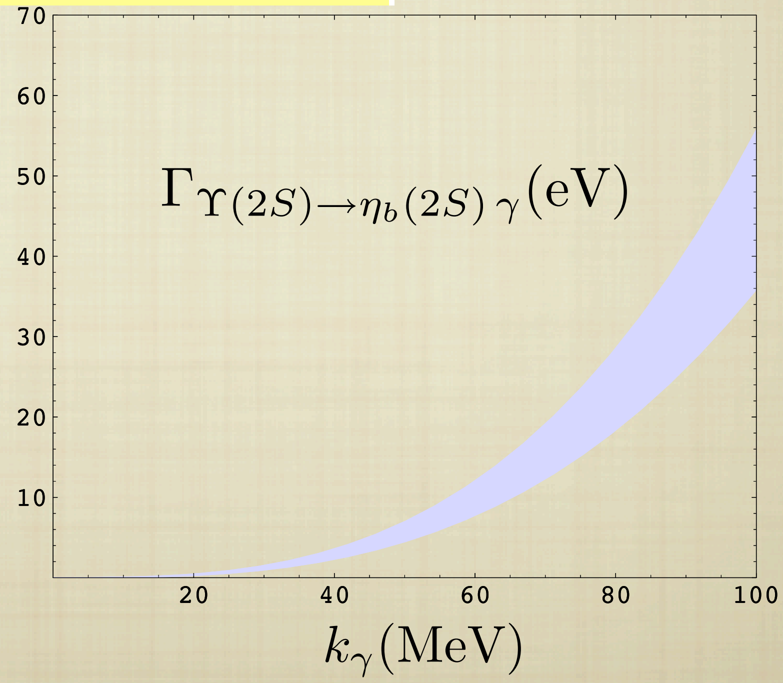
- No nonperturbative physics at order v^2
- Exact relations from Poincare invariance
- No large anomalous magnetic moment

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

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



$$\Gamma_{\Upsilon(1S)\to\eta_b\,\gamma} = (\frac{k_\gamma}{39})^3(2.50 \pm 0.25)\text{eV}$$



Outlook: bottom and charm masses

QWG extraction of c and b mass (2005)

$\overline{m_b}(\overline{m}_b) = 4.22 \pm 0.05\,\mathrm{GeV}$ $\overline{m}_c(\overline{m}_c) = 1.28 \pm 0.05\,\mathrm{GeV}$

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For lattice: th error in lattice -->MS conversion, need 2 loop matching in NRQCD and Fermilab; nonperturbative matching desirable

Outlook: top mass and alphas

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ttbar system: extraction of m_t at the ILC.
Present undetermination around 100 MeV.
Needed: complete NNLL and complete NNNLO;
EW and non fact.; EFT for unstable particles

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alphas da j/psi ->gamma X
need both theory calculations and
experimental measurement

Outlook

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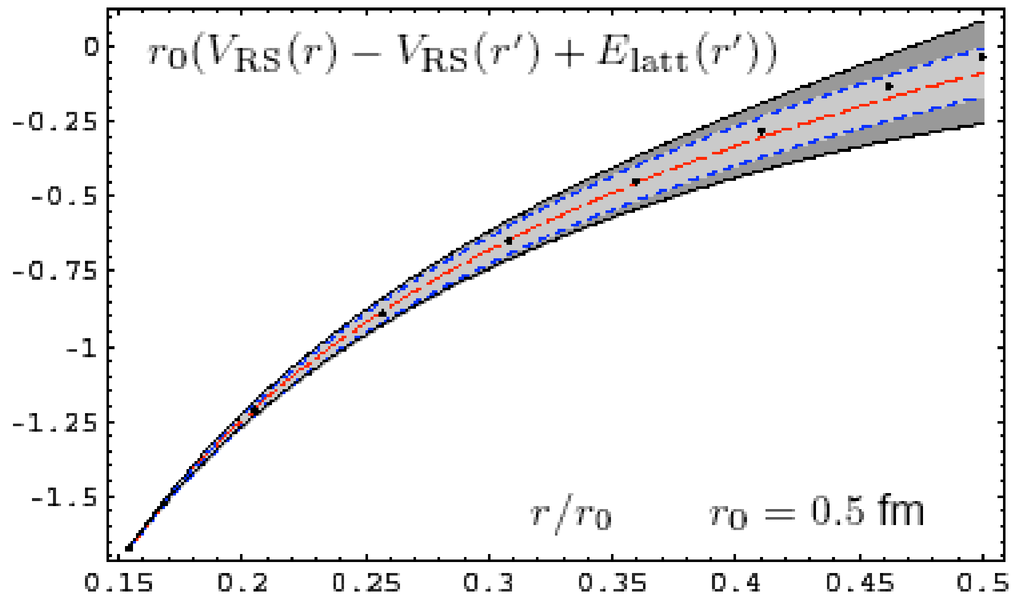
Heavy quark bound states are a unique lab for the study of the strong interactions from the high energy scales where precision studies can be made to the low energy region where confinement and nonperturbative physics are dominant

Fifth QWG meeting

DESY, October 17-20, 2007

http://www.qwg.to.infn.it

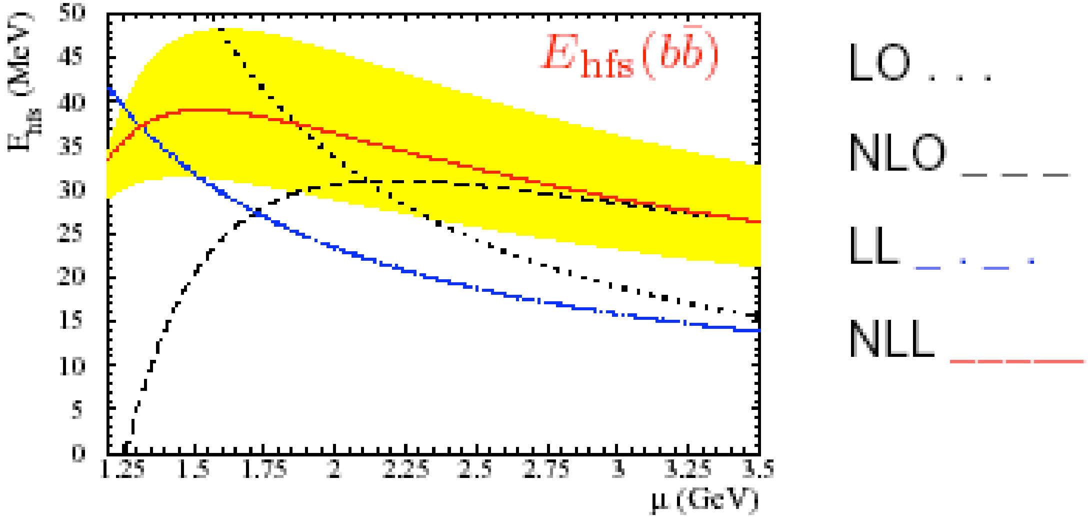
BACKUP SLIDES



$r_0(V_{\rm RS}(r) - V_{\rm RS}(r') + E_{\rm latt}(r'))$
0
-0.25
-0.5
-0.75
-1
-1.25
-1.5
r/r_0
$r_0 = 0.5$ fm
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0.5

Pineda 02

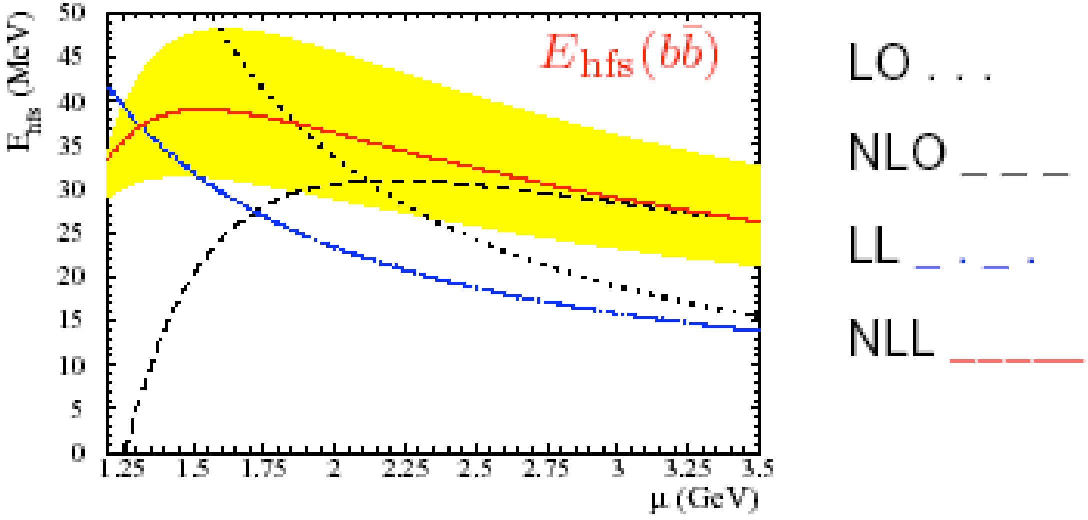
ETA_B



$$M(\eta_b) = 9421 \pm 10\,(\mathrm{th})\,{}^{+9}_{-8}\,(\delta\alpha_s)\ \mathrm{MeV}$$

Kniehl Penin Pineda Smirnov Steinhauser

ETA_B



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UNDER SEARCH AT FERMILAB AND CLEO