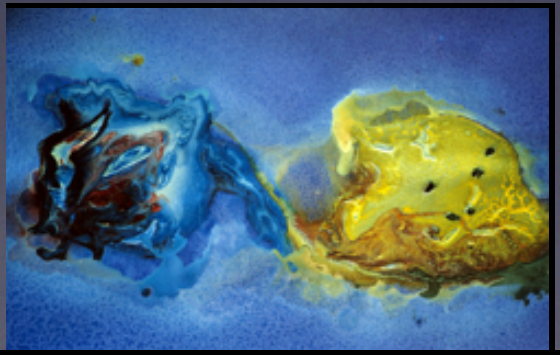
TECHNISCHE
UNIVERSITÄT
MÜNCHEN

Heavy Quarkonium Spectroscopy

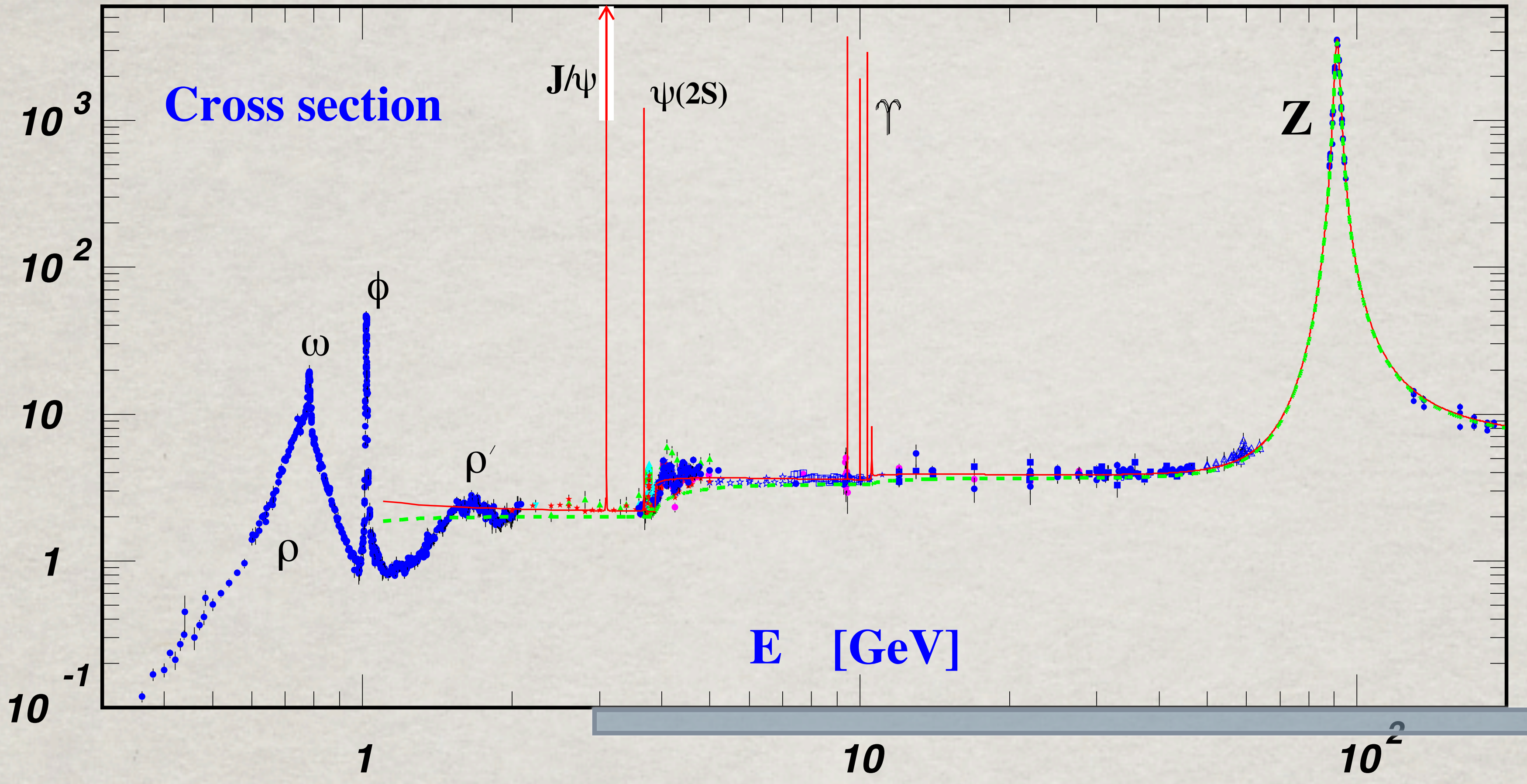
Nora Brambilla

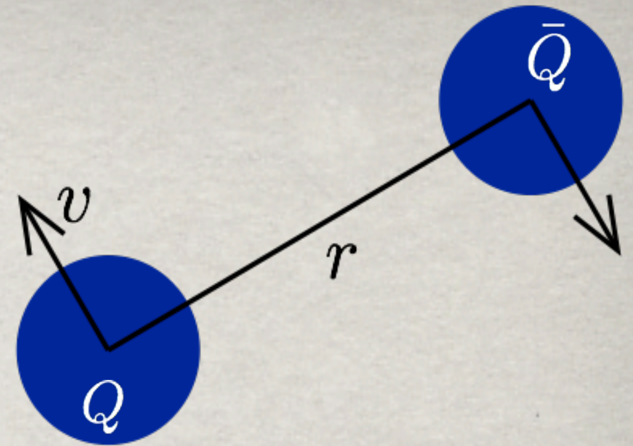


Physik Department TUM
T30f

- relevance of Quarkonium
  - state of the art of the theory tools and how they match the data
    - experimental/theoretical challenges and opportunities

Heavy quarks offer a privileged access





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

$m_c \sim 1.5\,\text{GeV}$

$m_b \sim 5\,\text{GeV}$

$m_t \sim 170\,\text{GeV}$

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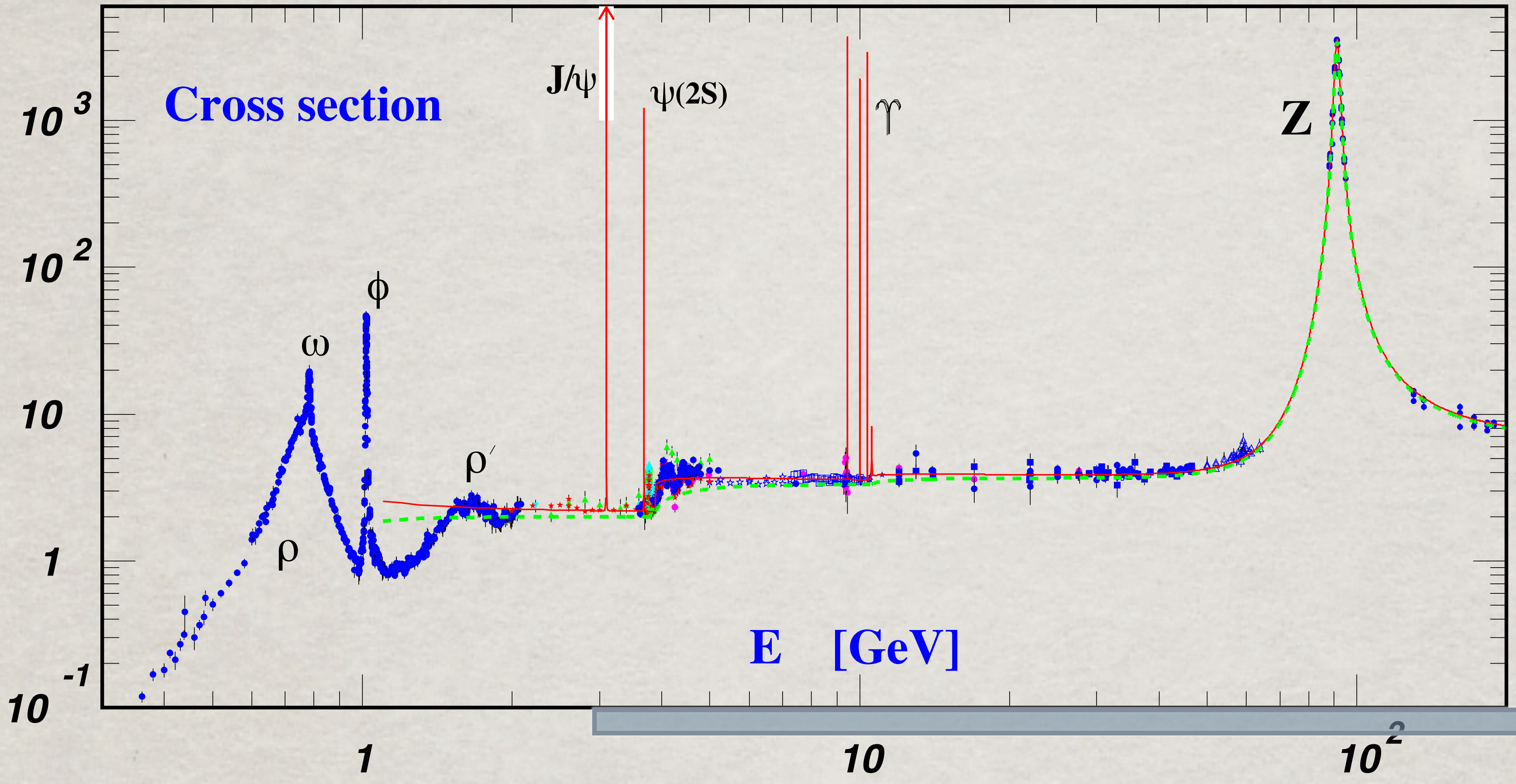

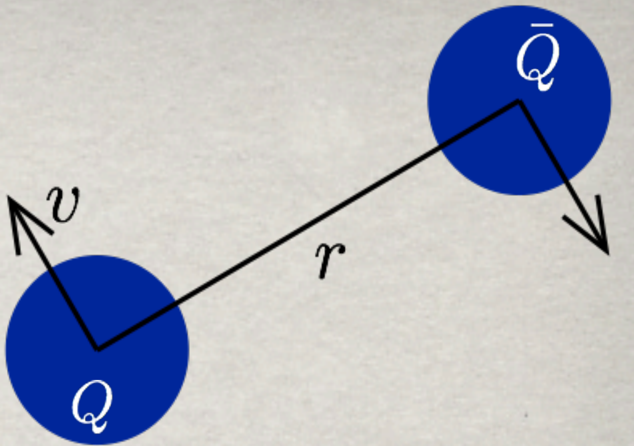

with $Q, \bar{Q} = c, b, t$

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

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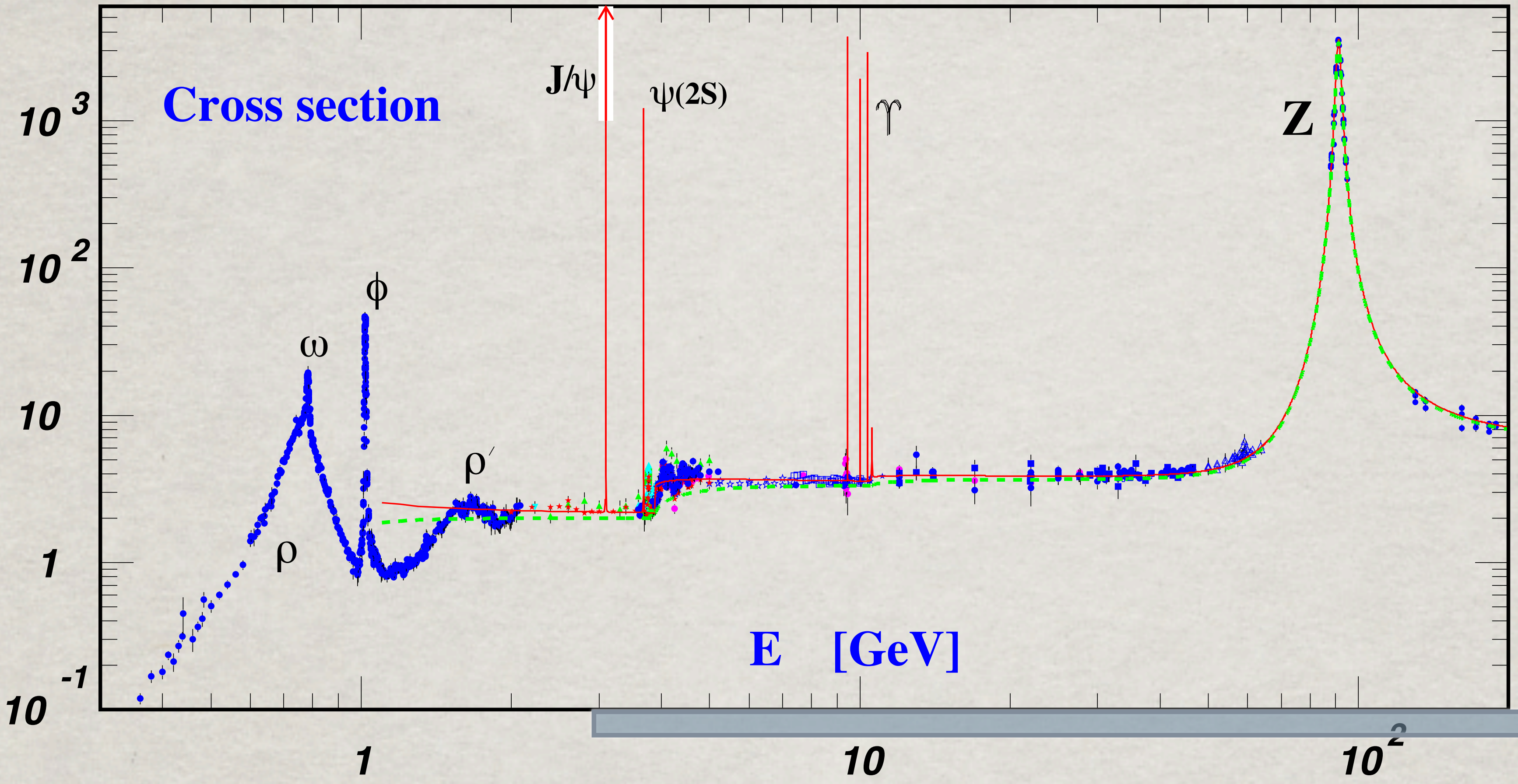

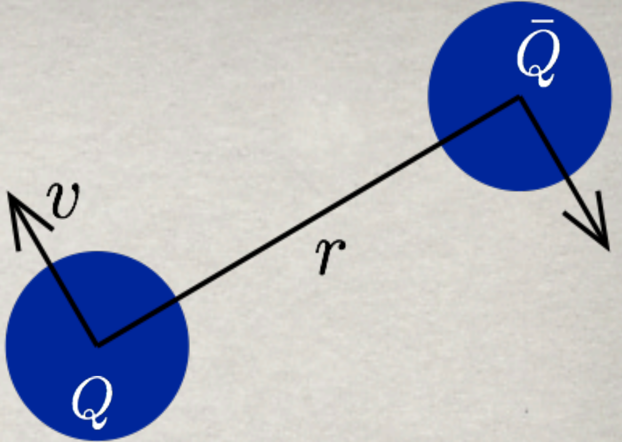

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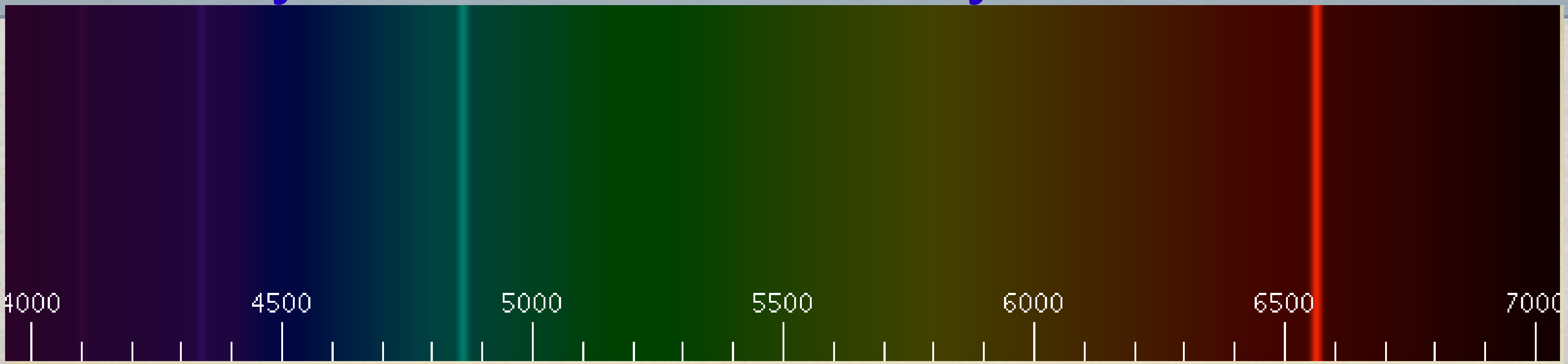
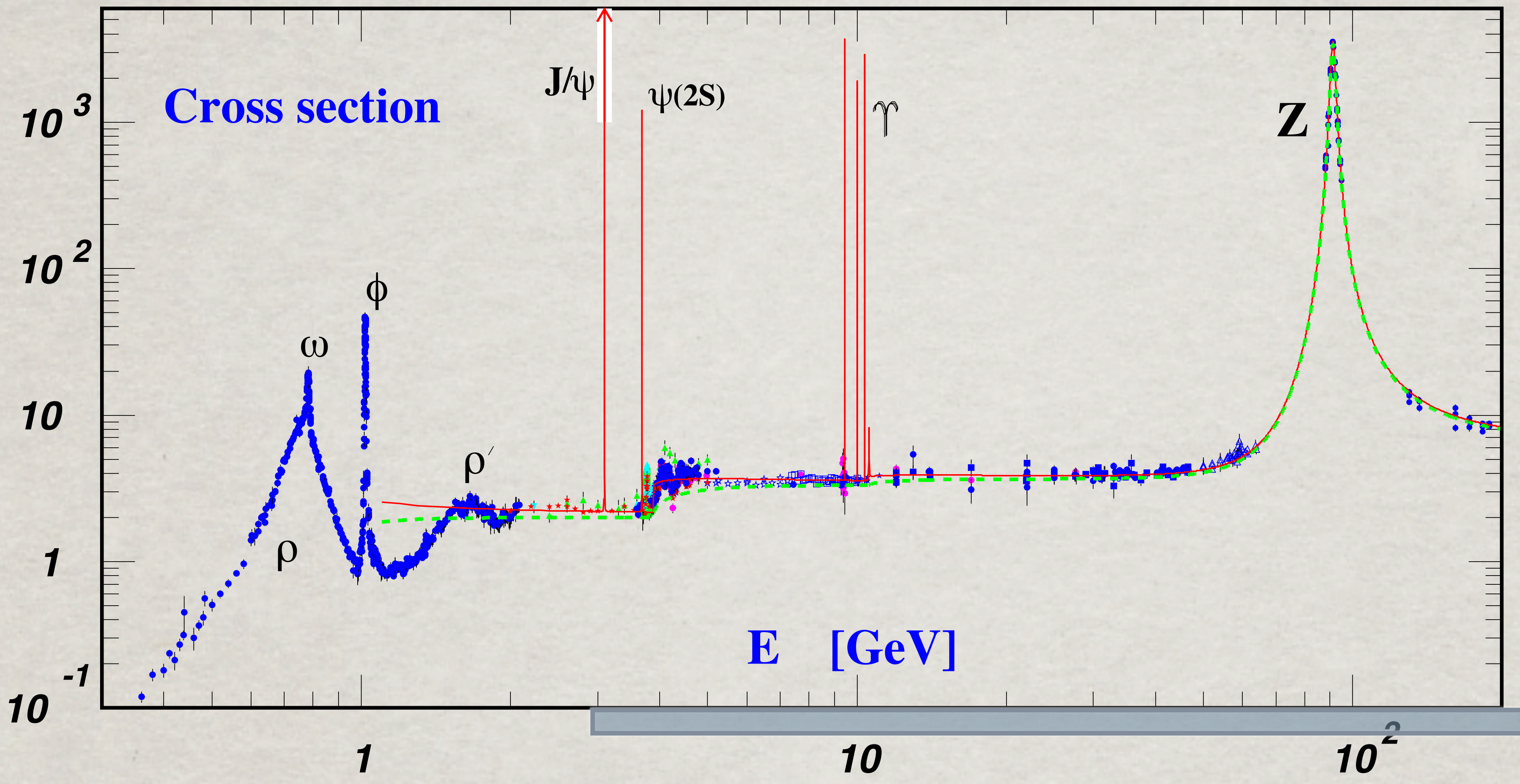
A large scale $m_Q \gg \Lambda_{QCD}$ $\alpha_s(m_Q) \ll 1$

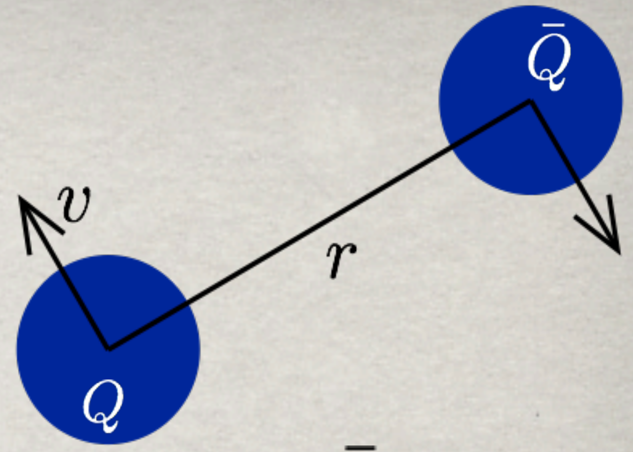
Heavy quarkonia are nonrelativistic bound systems: multiscale systems



Electromagnetic bound states: atoms, molecules,

Heavy quarks offer a privileged access





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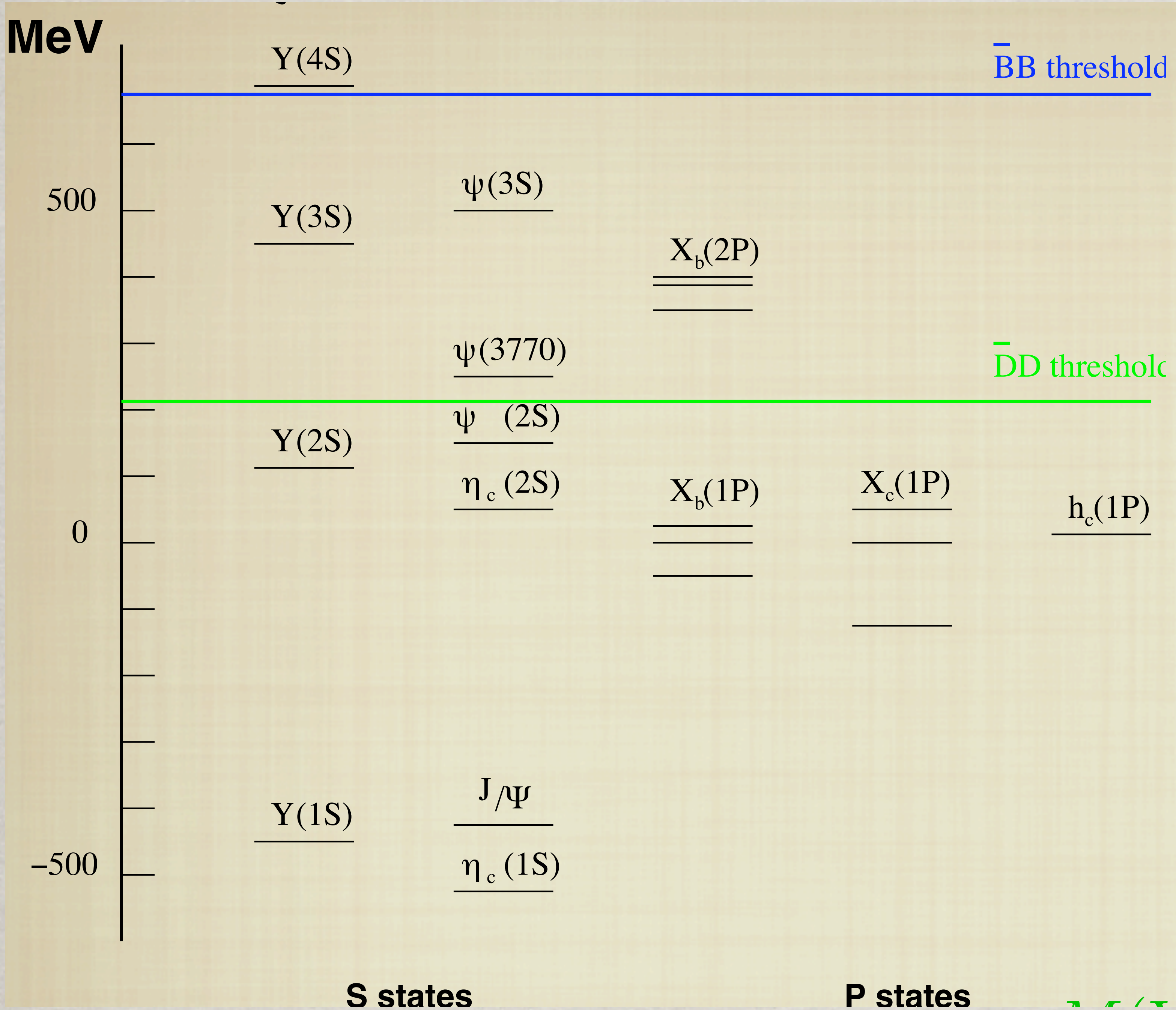
Heavy quarkonia are nonrelativistic bound systems: multiscale systems

many scales: a challenge and an opportunity

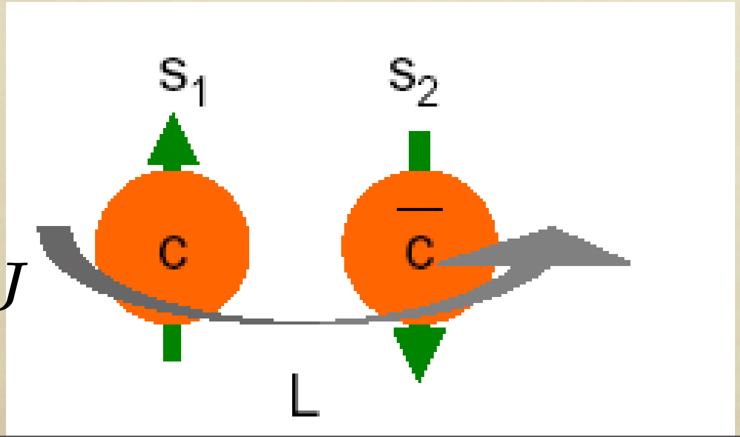
ELECTROMAGNETIC BOUND STATES: ATOMS, MOLECULES,

Quarkonium scales



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

$$^{2S+1}L_J$$

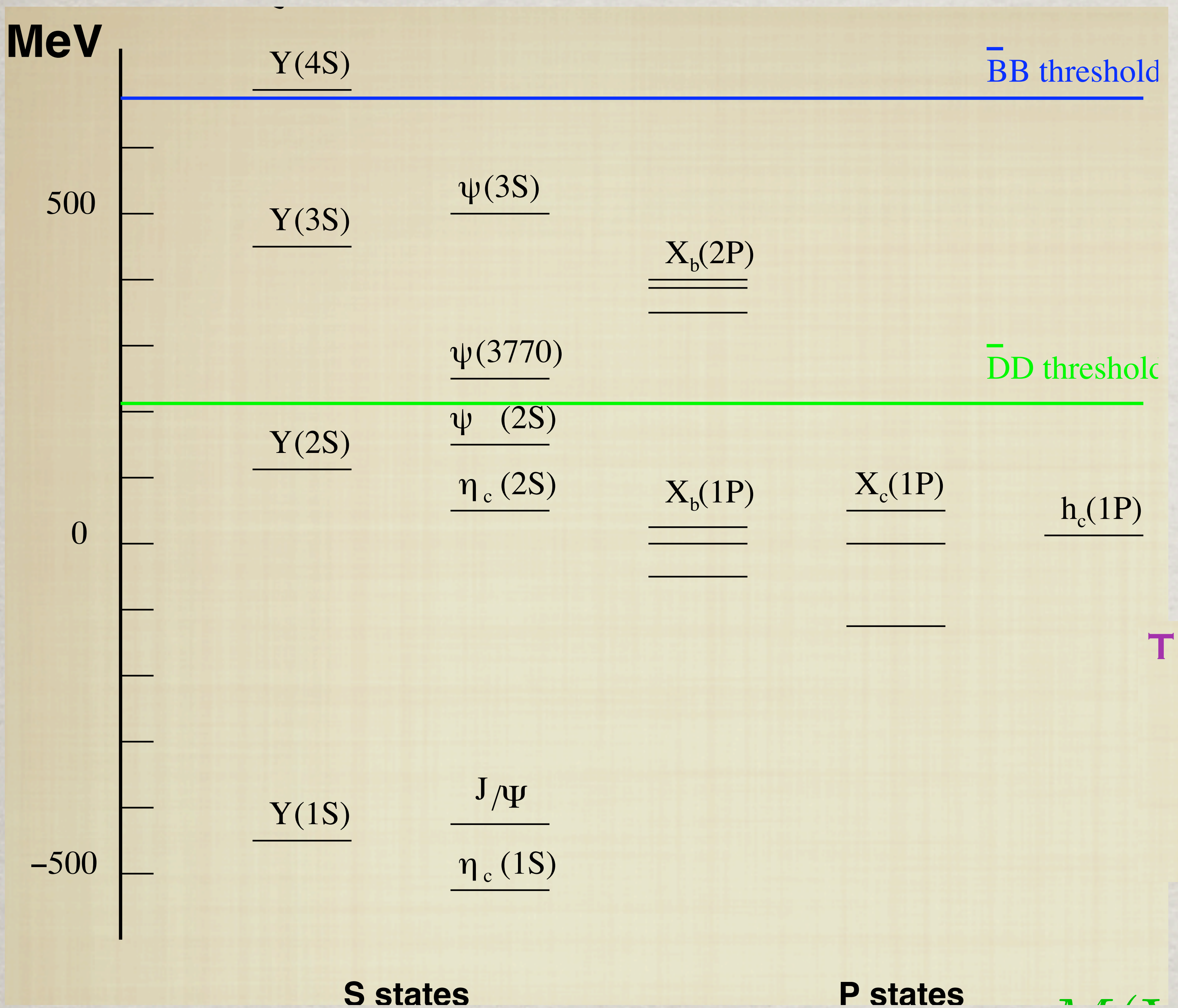


THE MASS SCALE IS PERTURBATIVE

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

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

Quarkonium scales



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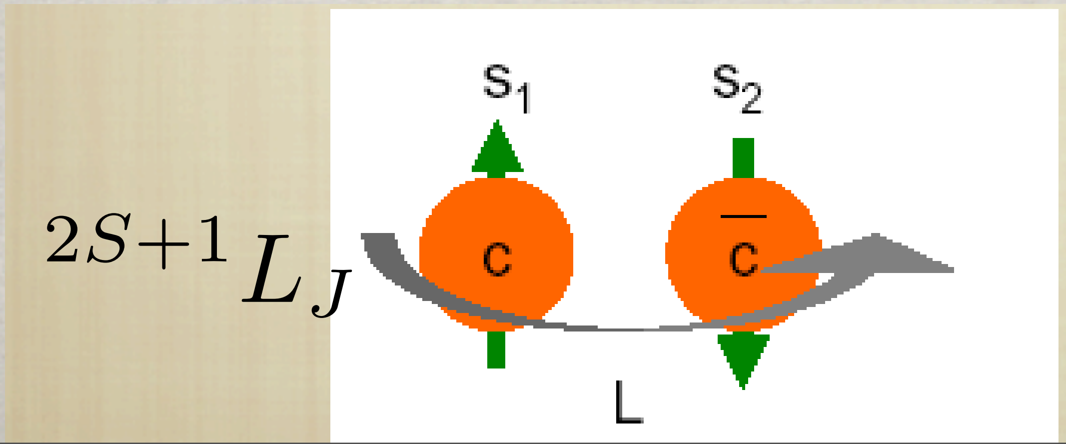

$$^{2S+1}L_J$$

THE SYSTEM IS NONRELATIVISTIC(NR)

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

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

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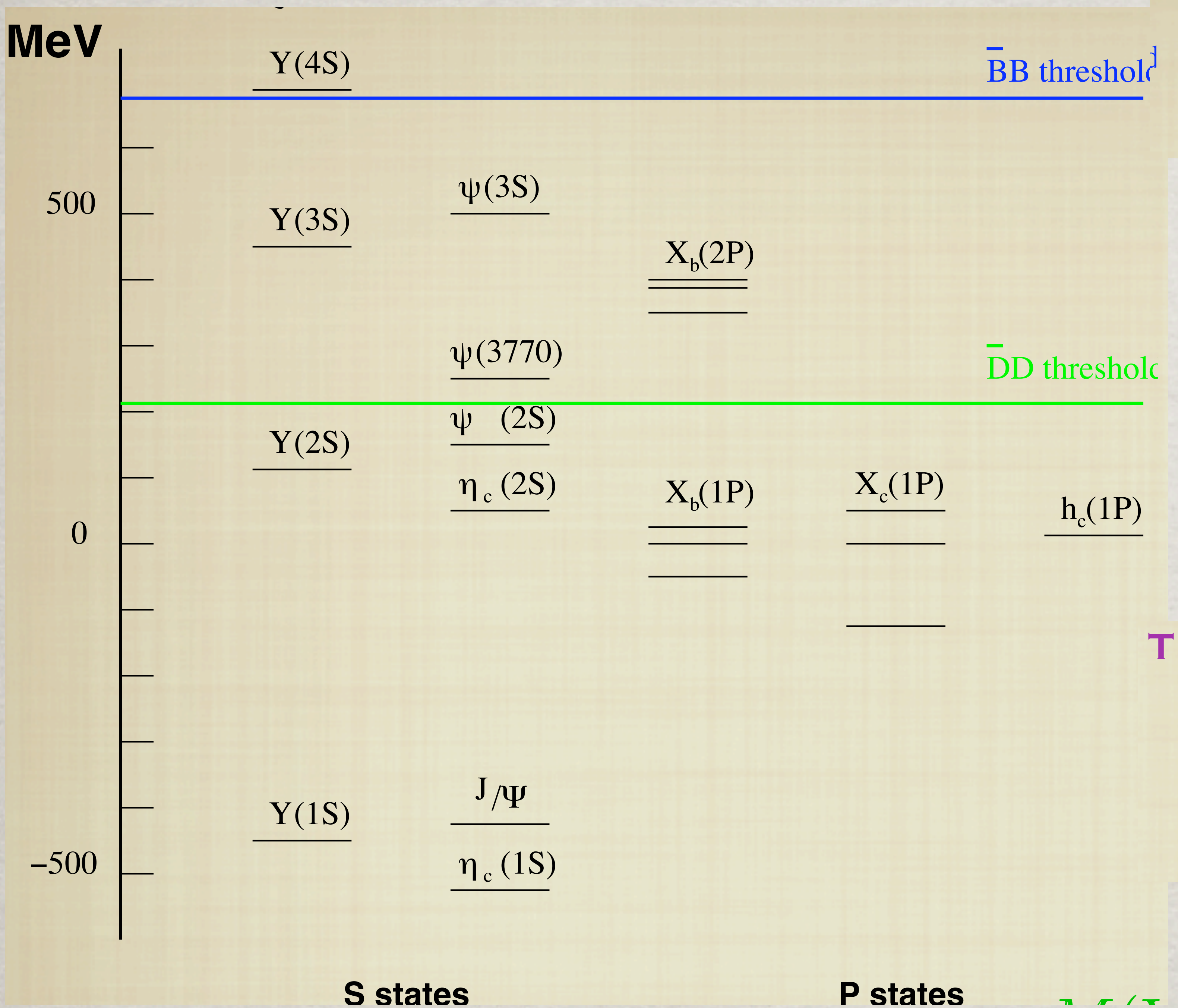

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NR bound states have at least 3 scales

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

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

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

The mass scale is perturbative

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

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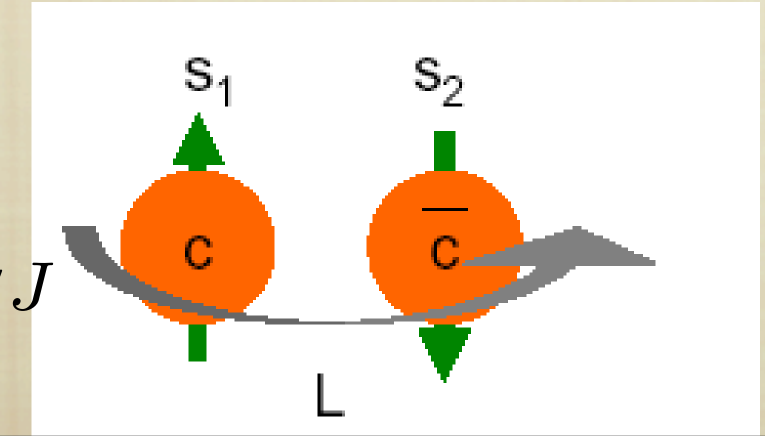
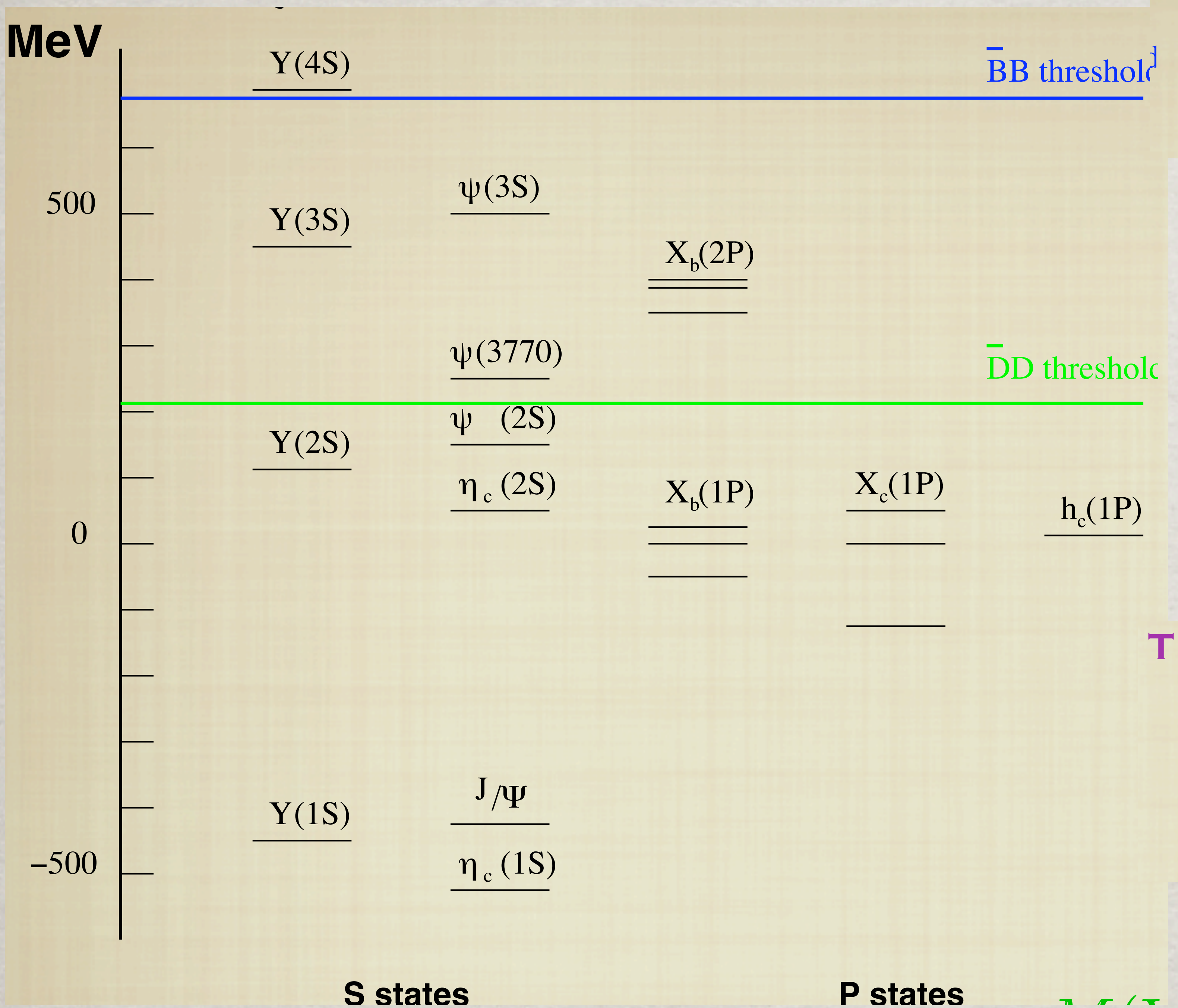


Quarkonium scales



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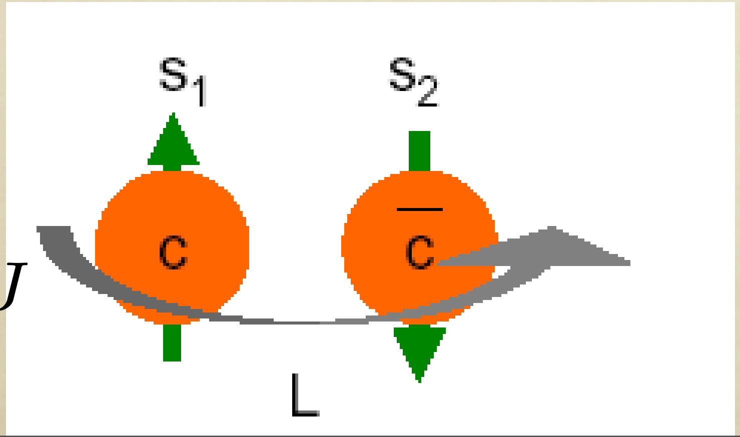

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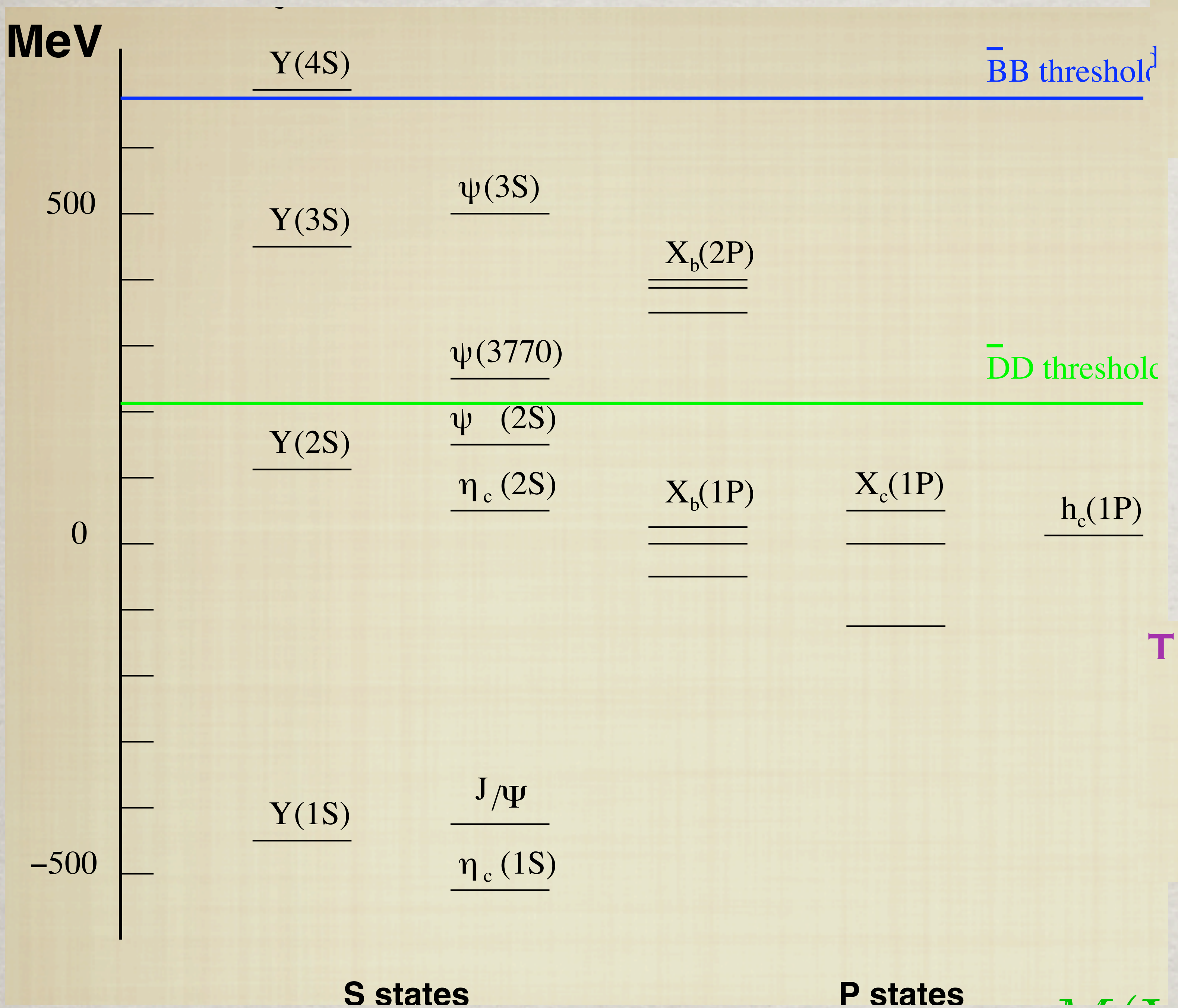
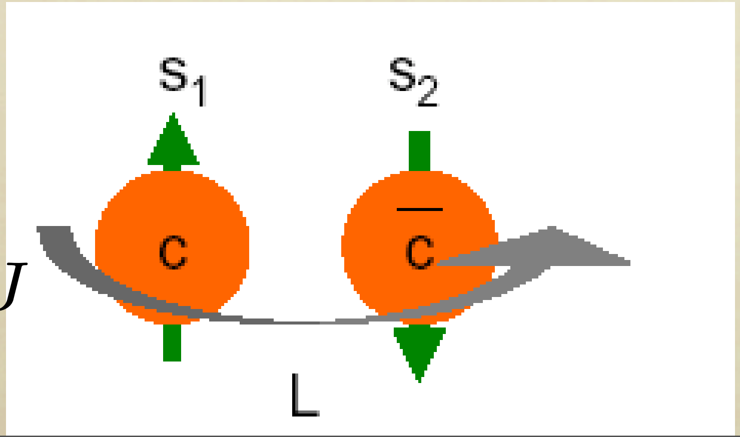


Normalized with respect to $\chi_b(1P)$ and $\chi_c(1P)$

$^{2S+1}L_J$



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and $\Lambda_{\rm QCD}$

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Quarkonium as a confinement and deconfinement probe

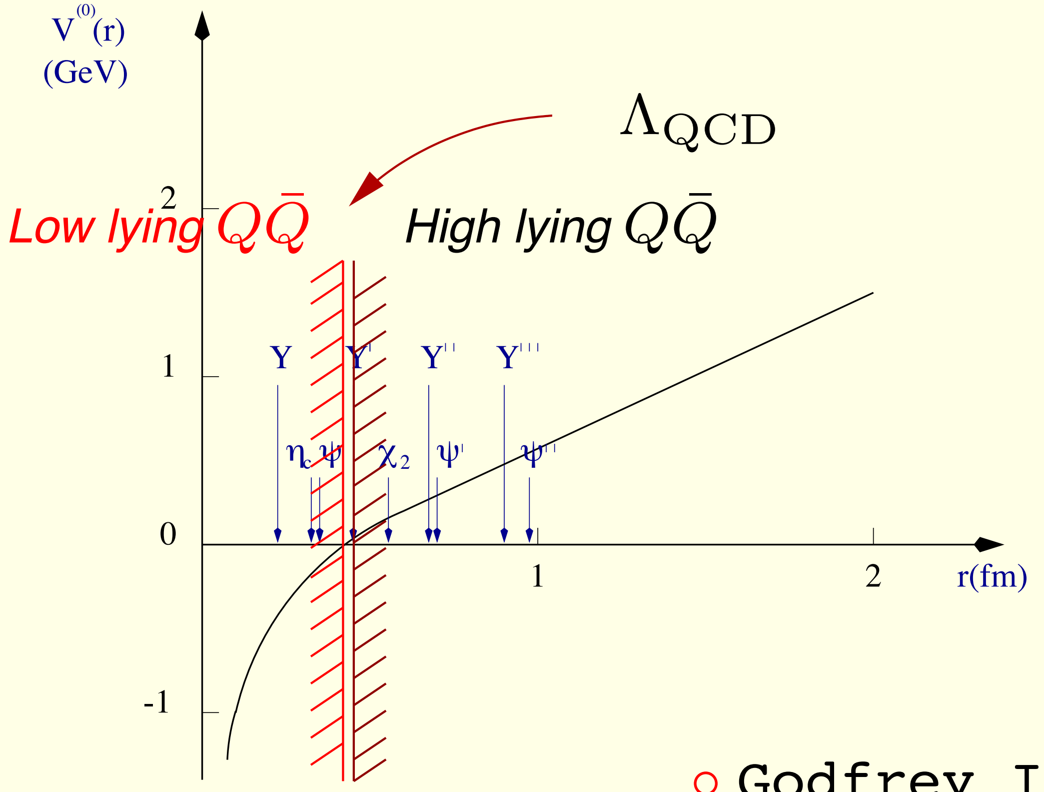
The rich structure of separated energy scales makes QQbar an ideal probe

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

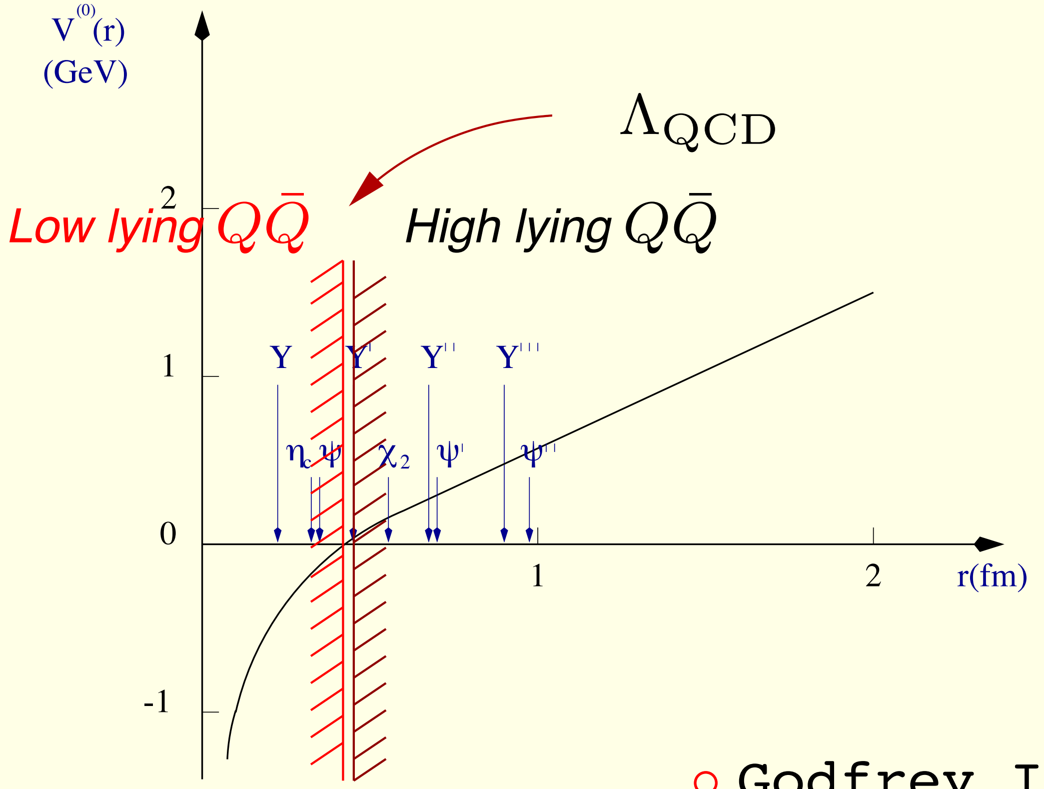
quarkonia probe the perturbative (high energy) and non perturbative region (low energy) as well as the transition region in dependence of their radius r

Quarkonium as a confinement and deconfinement probe

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

At finite temperature (in heavy ion collisions)

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



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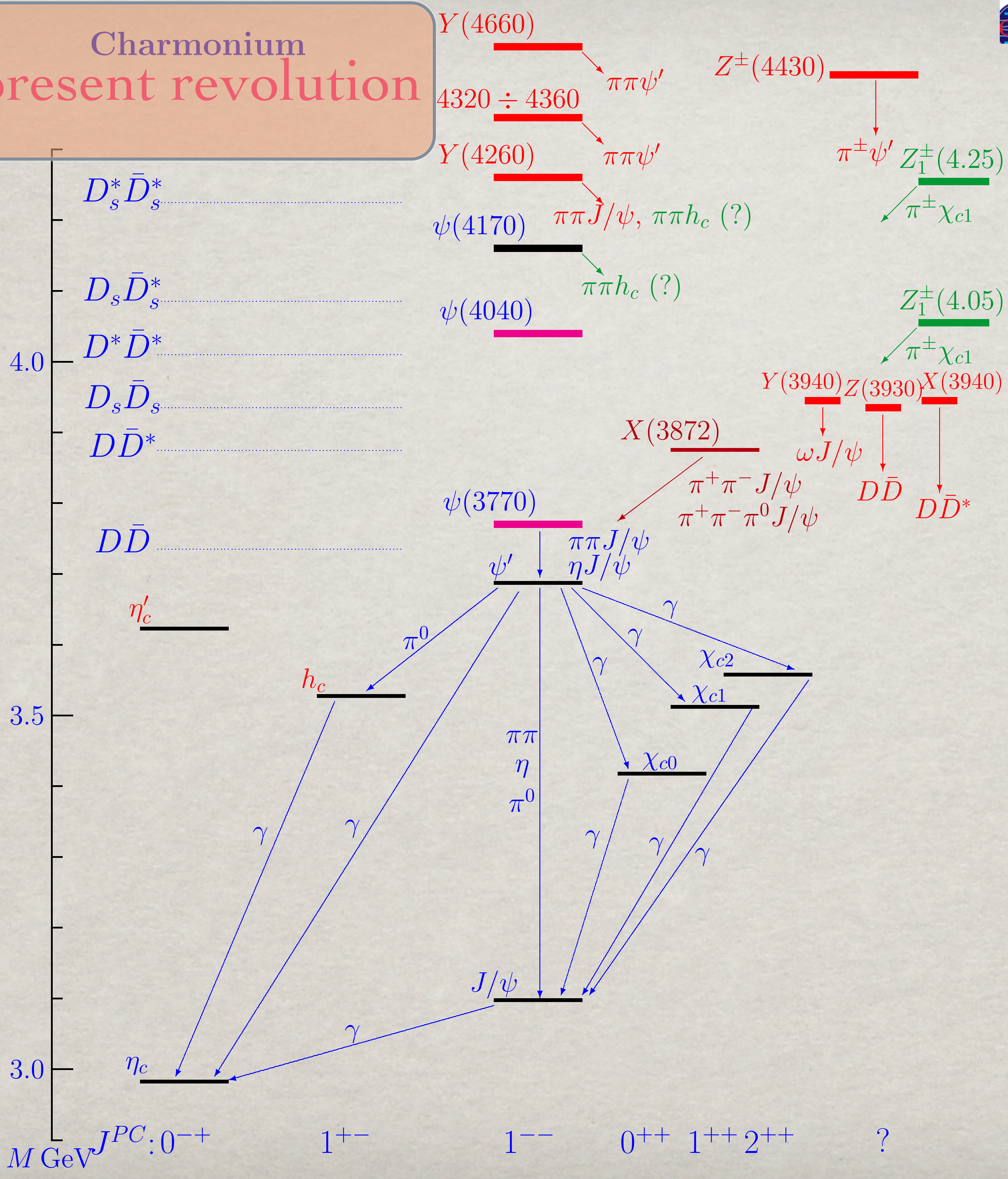
different quarkonia will dissociate in the medium at different temperatures providing a thermometer for the hot QCD plasma

Charmonium
the present revolution



THE COLLIDER DETECTOR AT FERMILAB

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BELLE

BABAR
Collaboration Home Page

BES

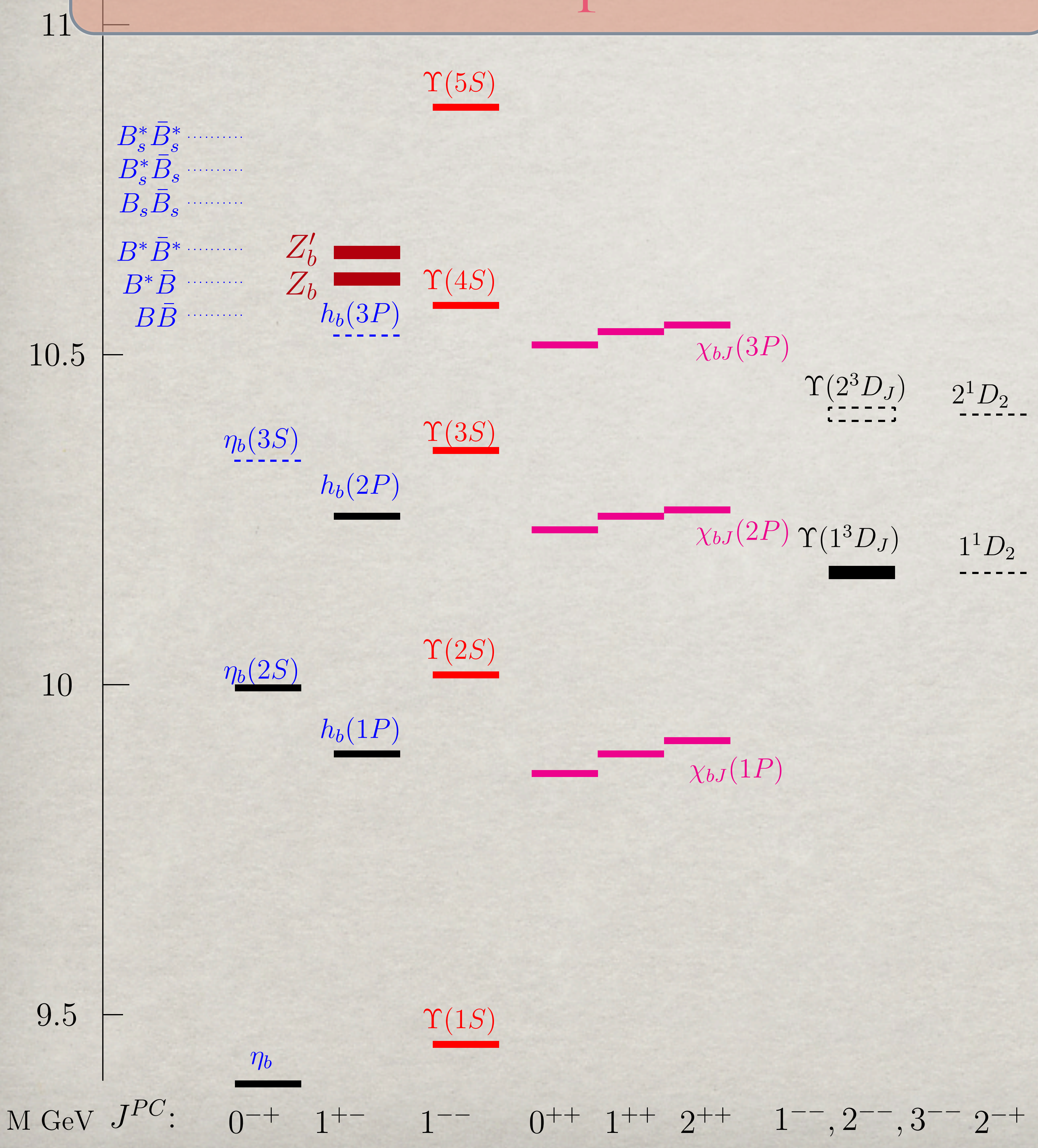
CLEO

ATLAS

CMS

LHCb

bottomonium: the present revolution



THE COLLIDER DETECTOR AT FERMILAB

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Quarkonium-like states at threshold

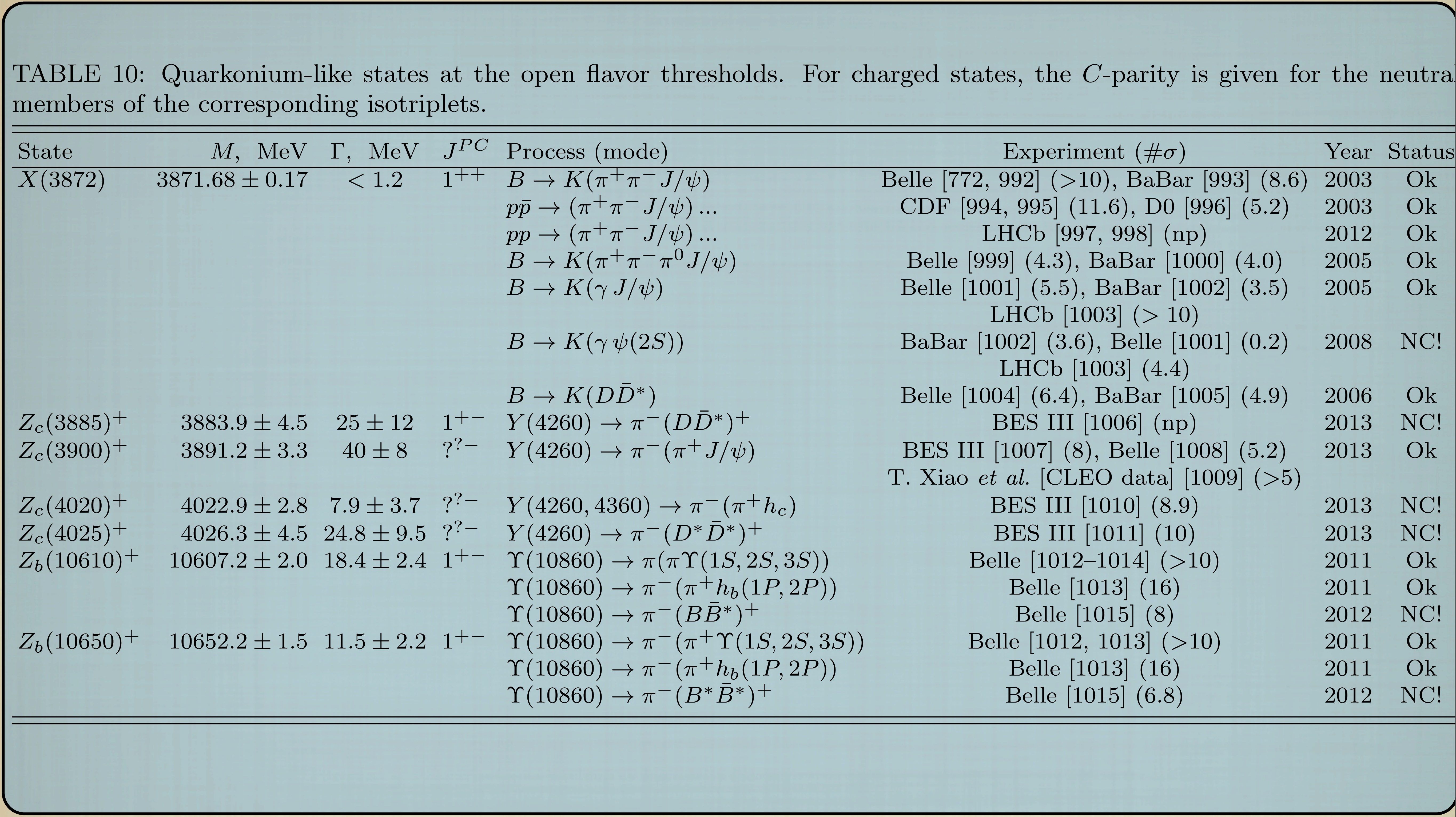

TABLE 10: Quarkonium-like states at the open flavor thresholds. For charged states, the C-parity is given for the neutra members of the corresponding isotriplets.

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

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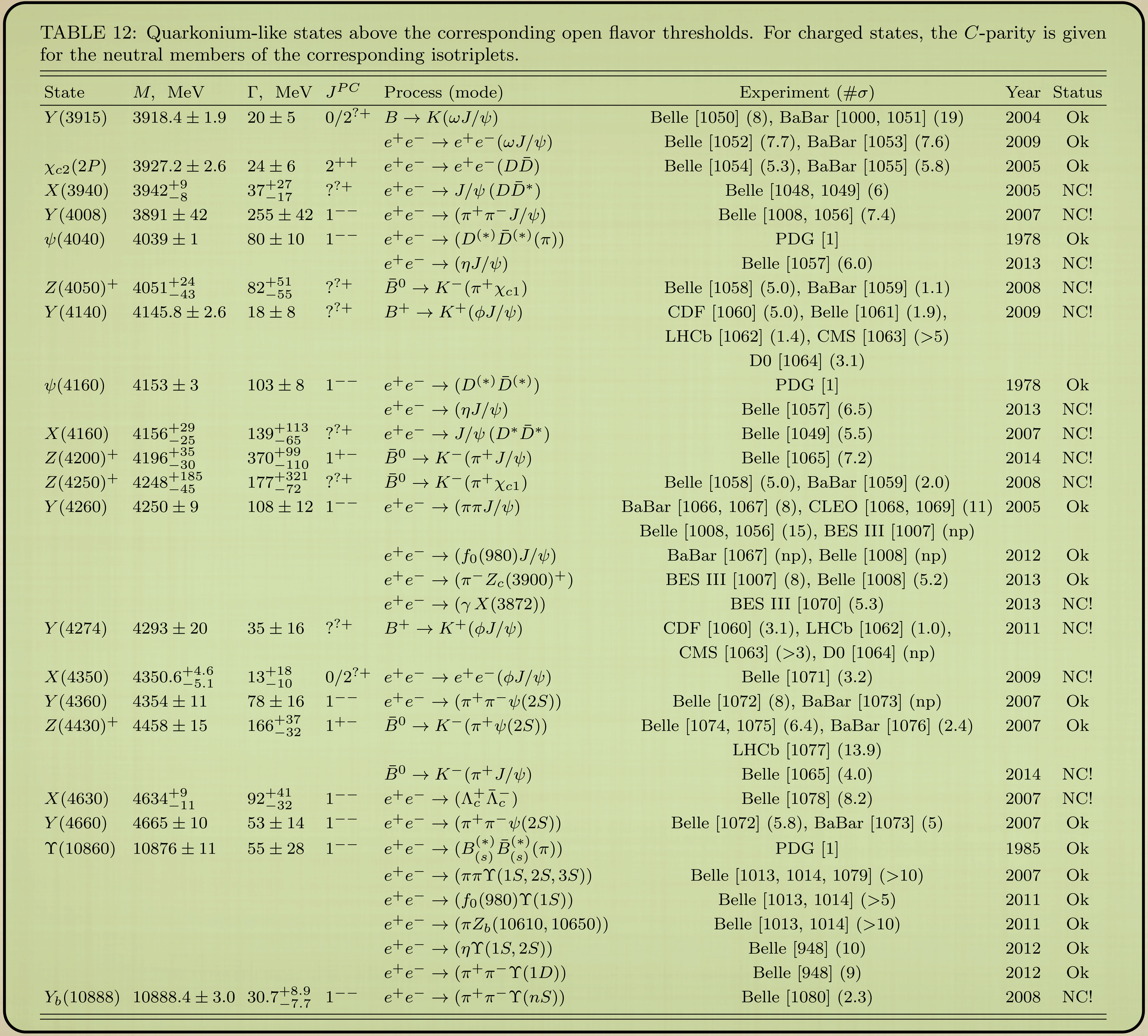

TABLE 12: Quarkonium-like states above the corresponding open flavor thresholds. For charged states, the C-parity is given for the neutral members of the corresponding isotriplets.

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

above threshold

QCD theory of Quarkonium: a very hard problem

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Close to the bound state $\alpha_{\mathrm{s}} \sim v$

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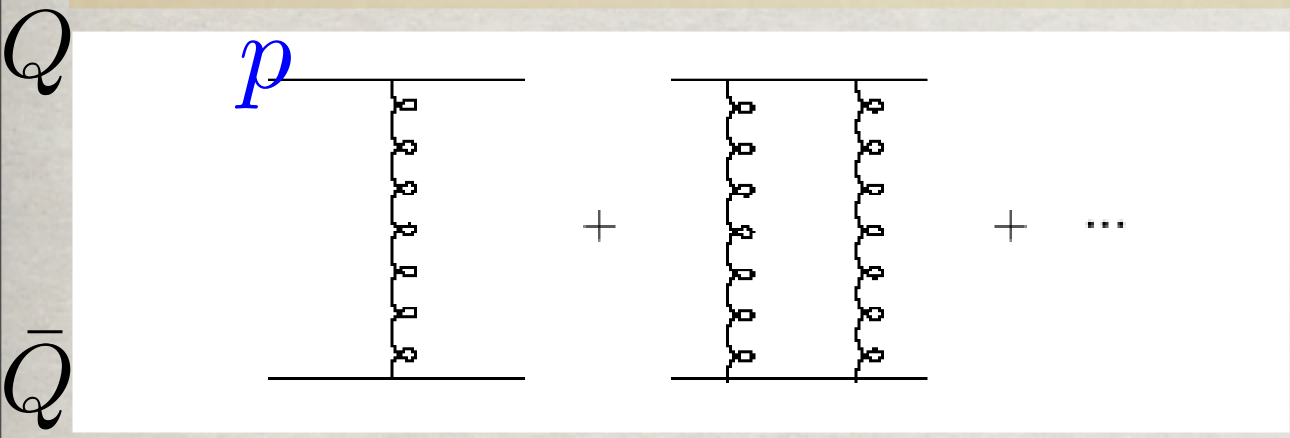

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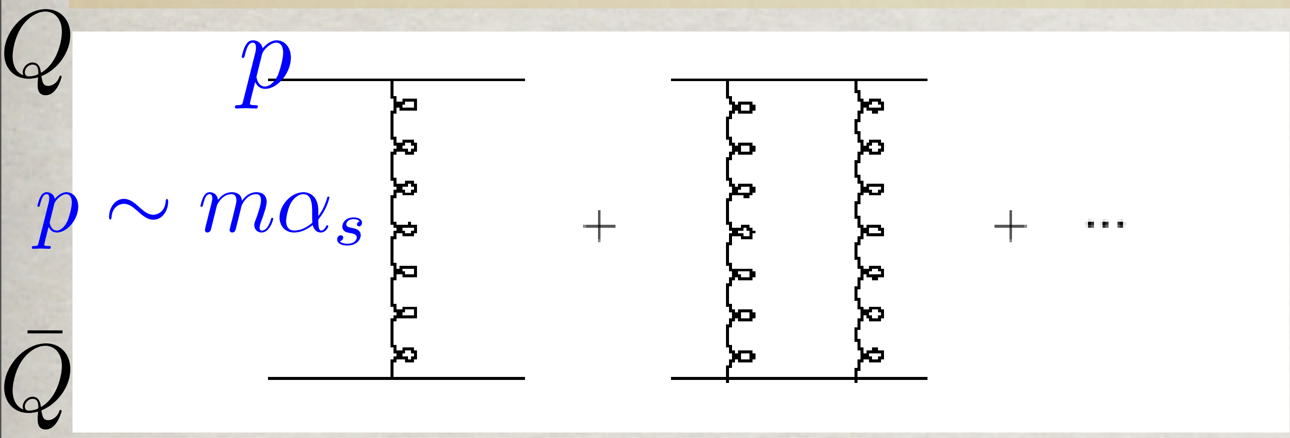

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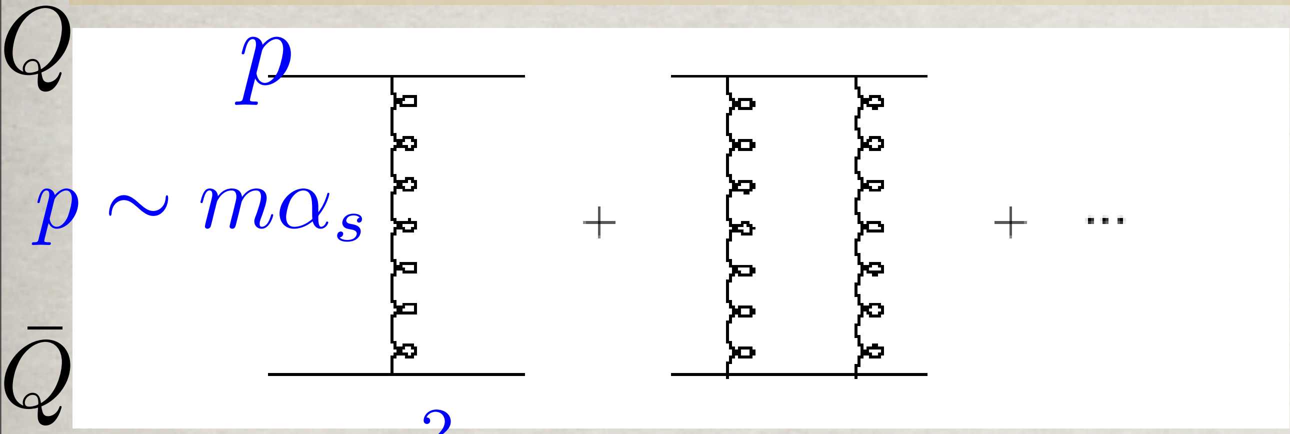

$$\frac{g^2}{p^2}\left(1+\frac{m\alpha_s}{p}\right)$$

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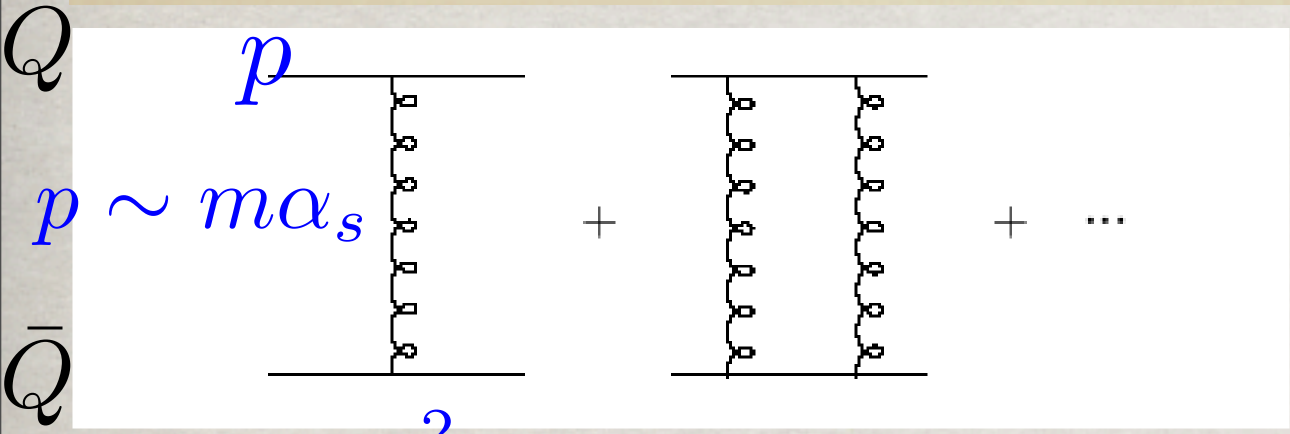
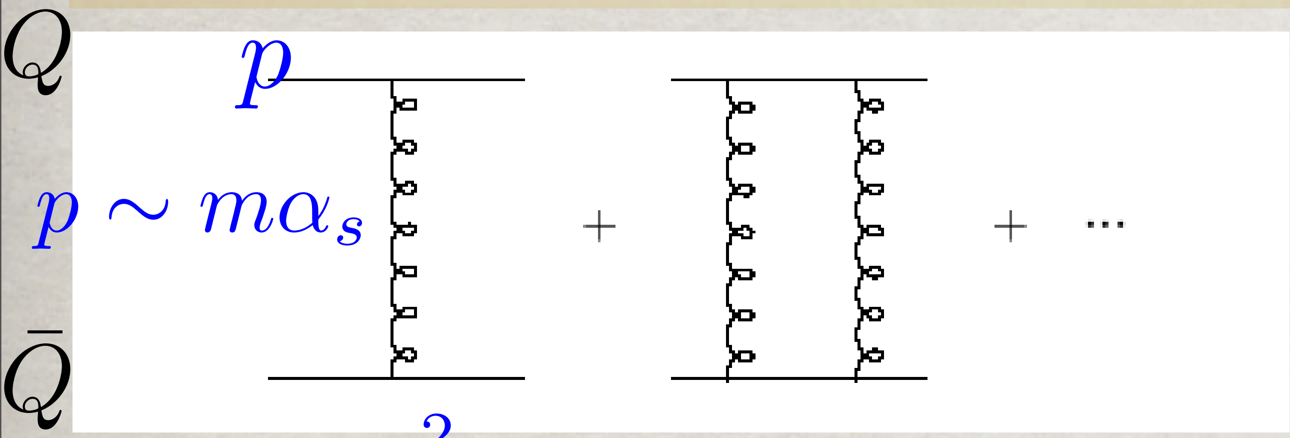


$$\frac{g^2}{p^2}\left(1+\frac{m\alpha_s}{p}\right)$$

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

QCD theory of Quarkonium: a very hard problem

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



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

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

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

QCD theory of Quarkonium: a very hard problem

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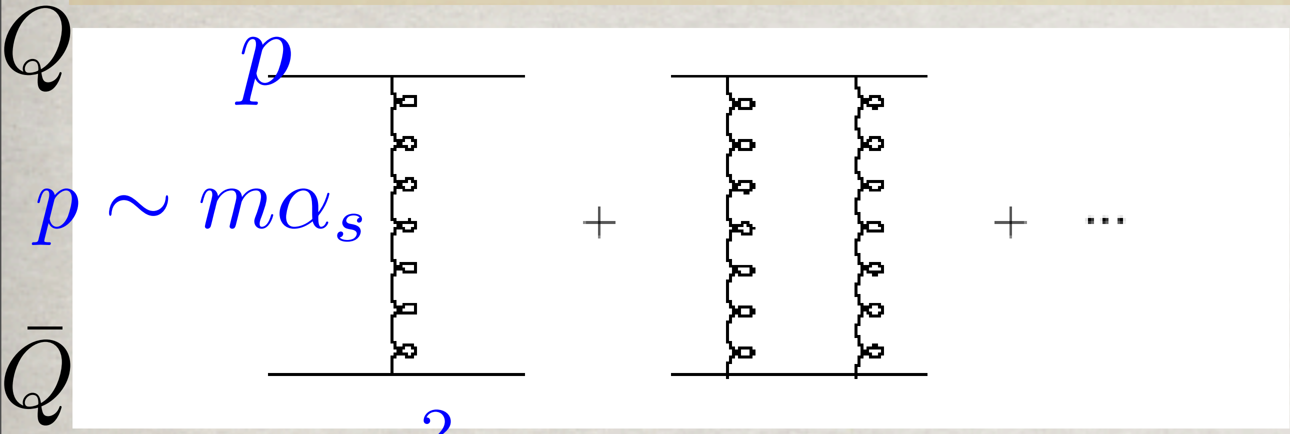

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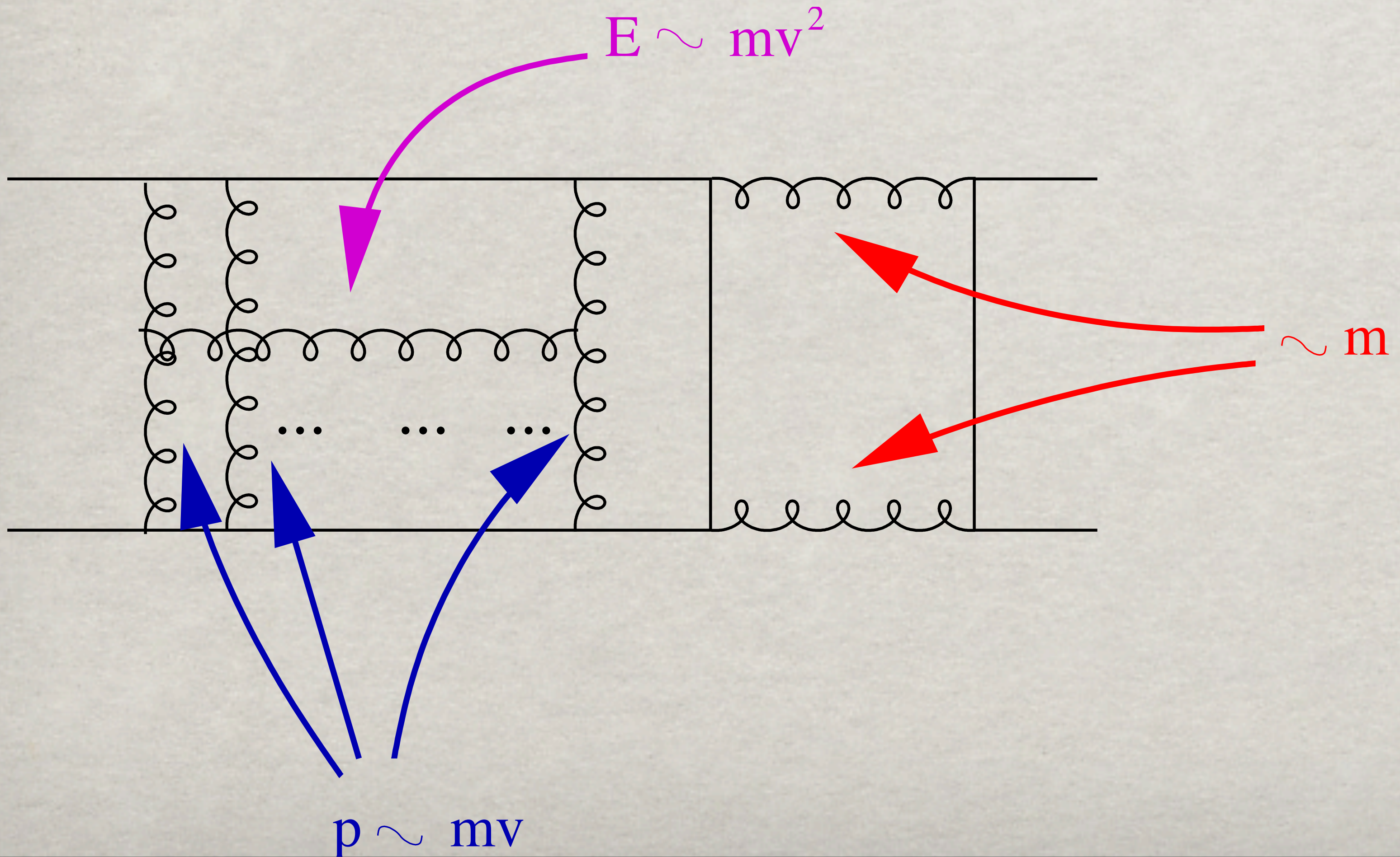

QCD theory of Quarkonium: a very hard problem

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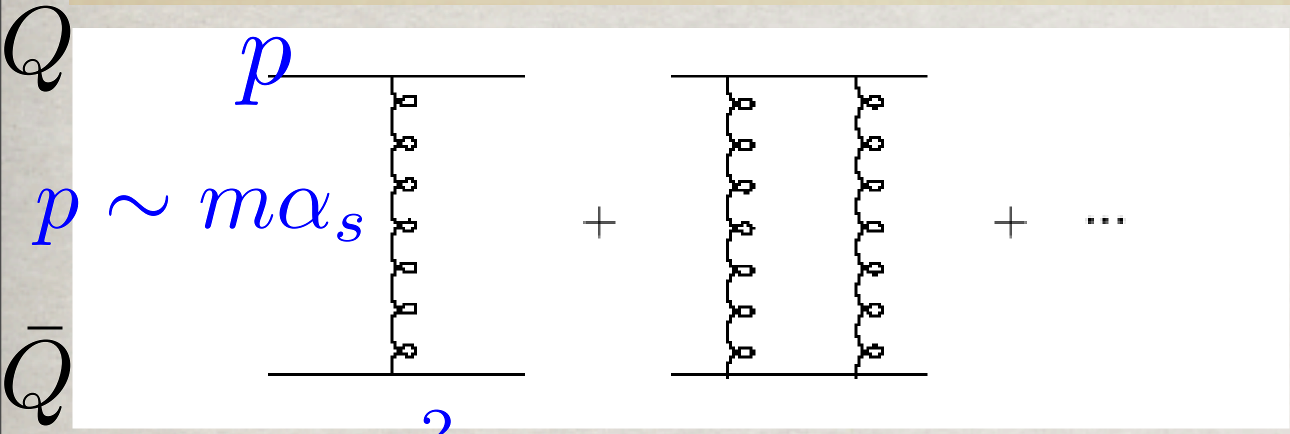
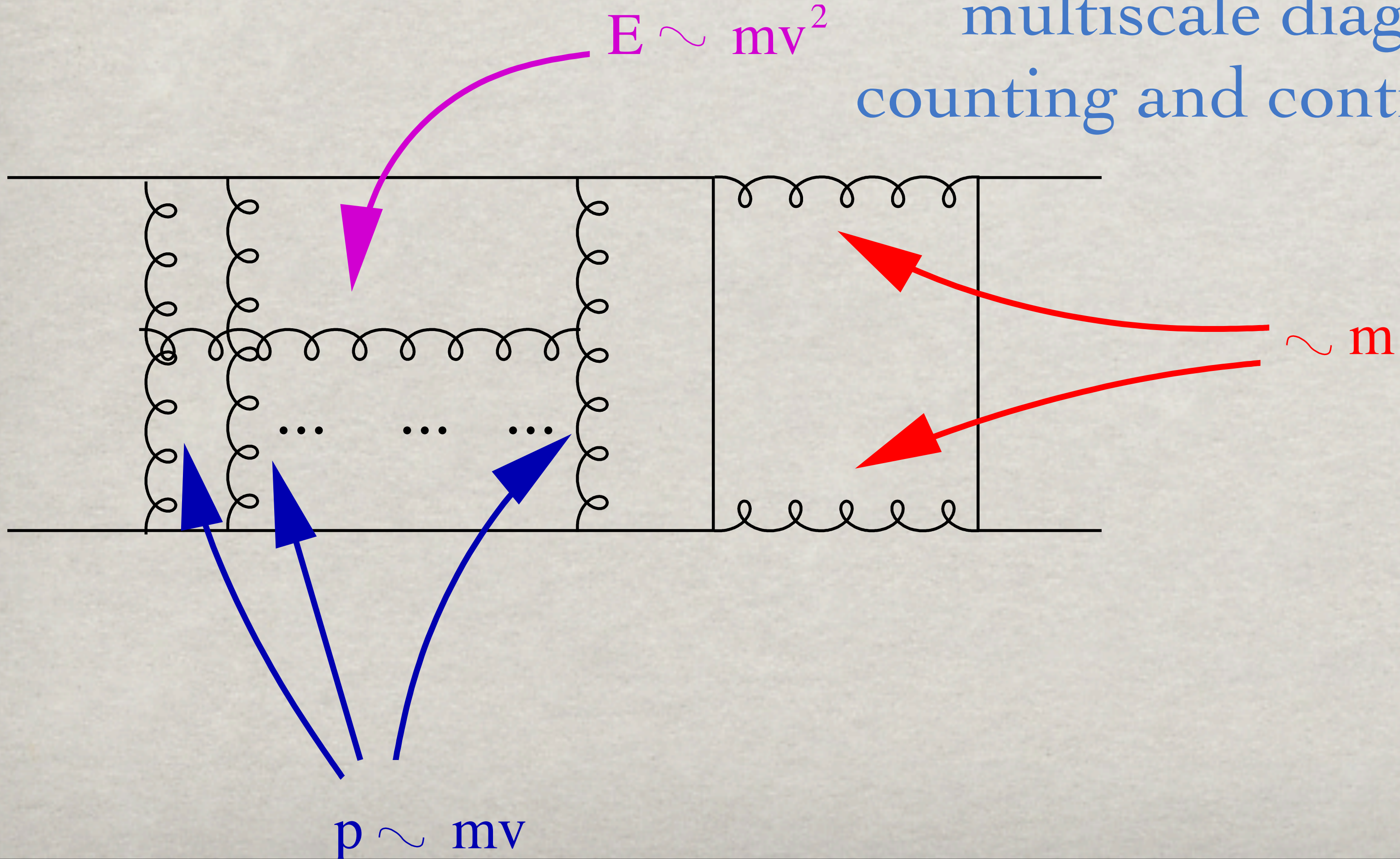


$$\frac{g^2}{p^2}\left(1 + \frac{m\alpha_s}{p}\right)$$

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

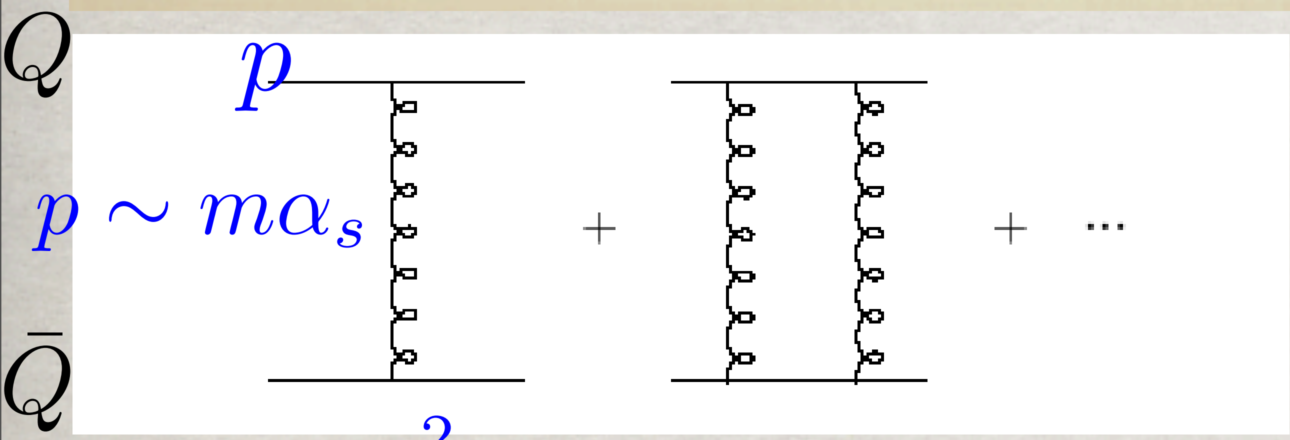
- From $(\frac{p^2}{m} + V)\phi = E\phi \to p \sim mv$ and $E = \frac{p^2}{m} + V \sim mv^2$.

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



QCD theory of Quarkonium: a very hard problem

Close to the bound state $\alpha_{s} \sim v$



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

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

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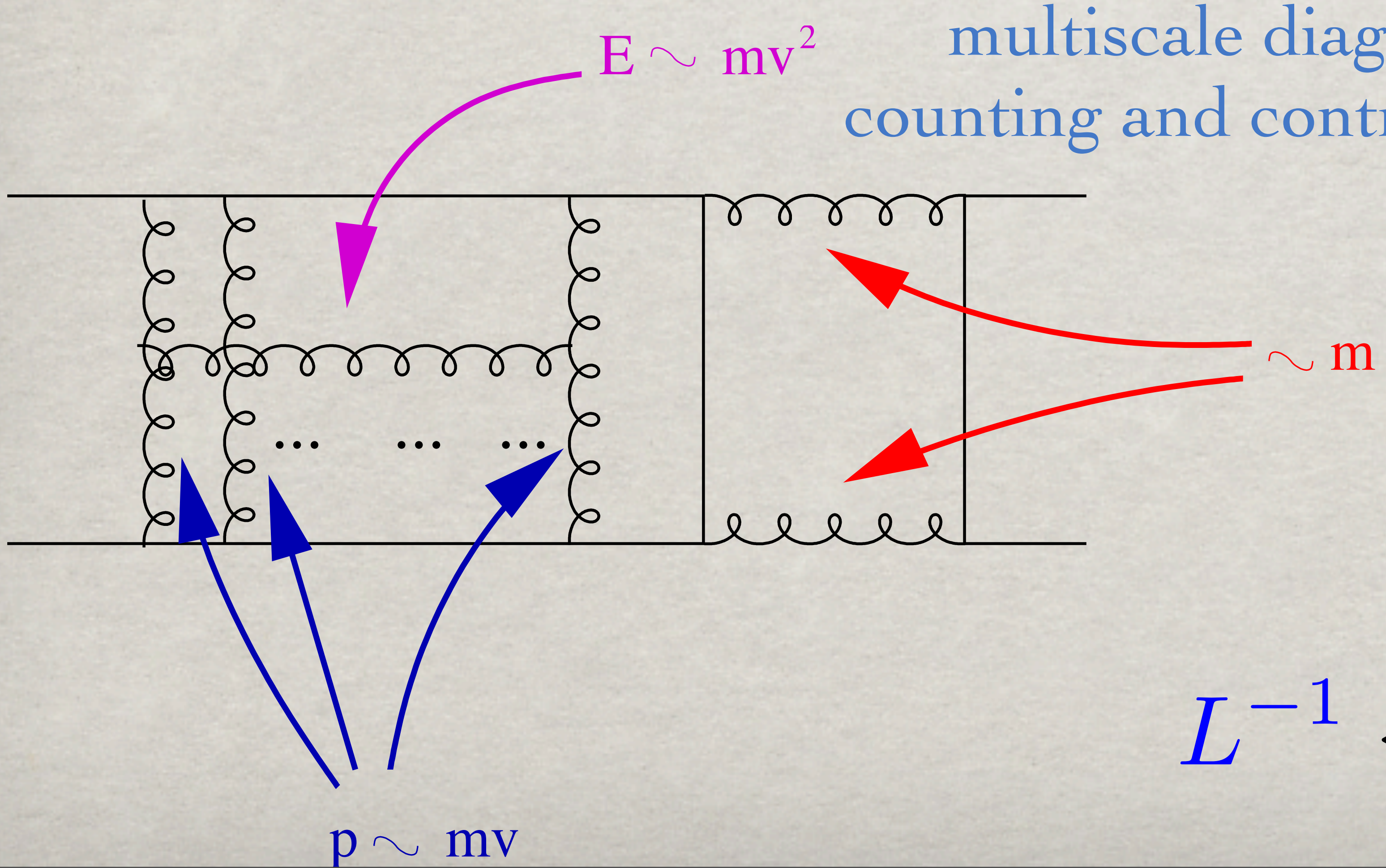


multiscale diagrams have a complicate power counting and contribute to all orders in the coupling

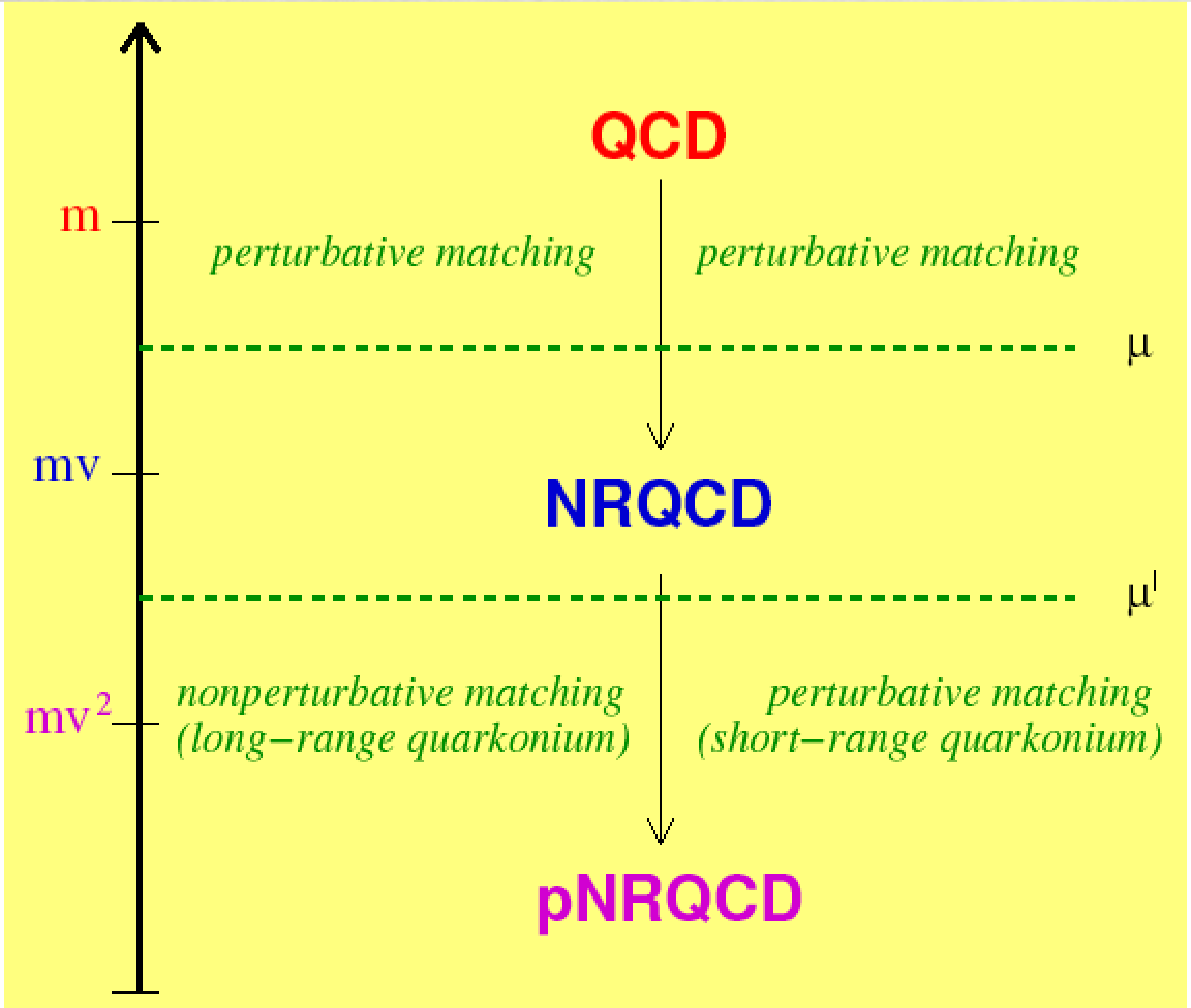
Difficult also
for the lattice!

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

Theory tools:effective field theories of QCD and lattice

Quarkonium with NR EFT

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



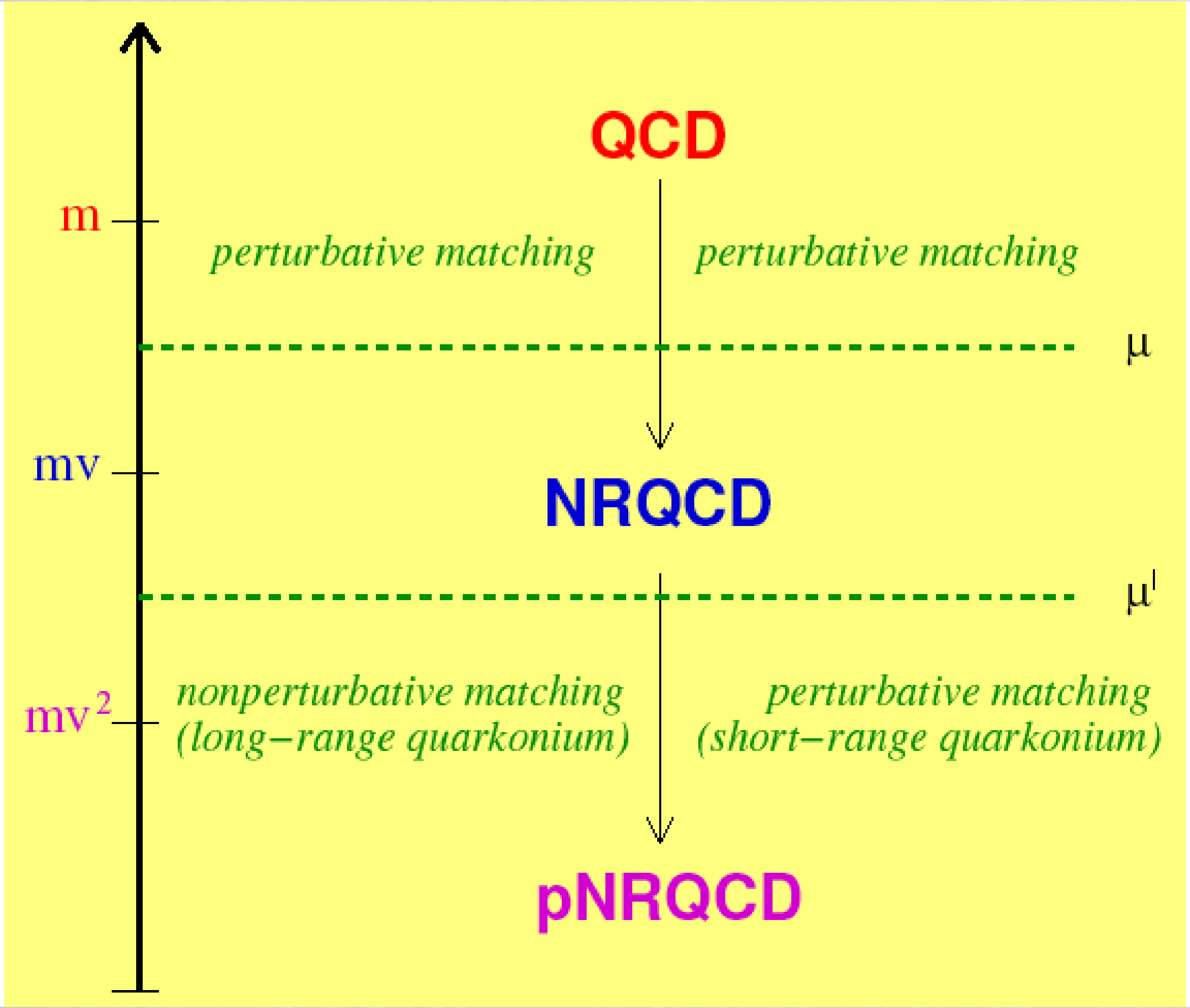
Hard

Soft
(relative
momentum)

Ultrasoft
(binding energy)

Quarkonium with NR EFT

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



Hard

Soft
(relative
momentum)

Ultrasoft
(binding energy)

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

Quarkonium with NR EFT

Color degrees of freedom
3X3=1+8
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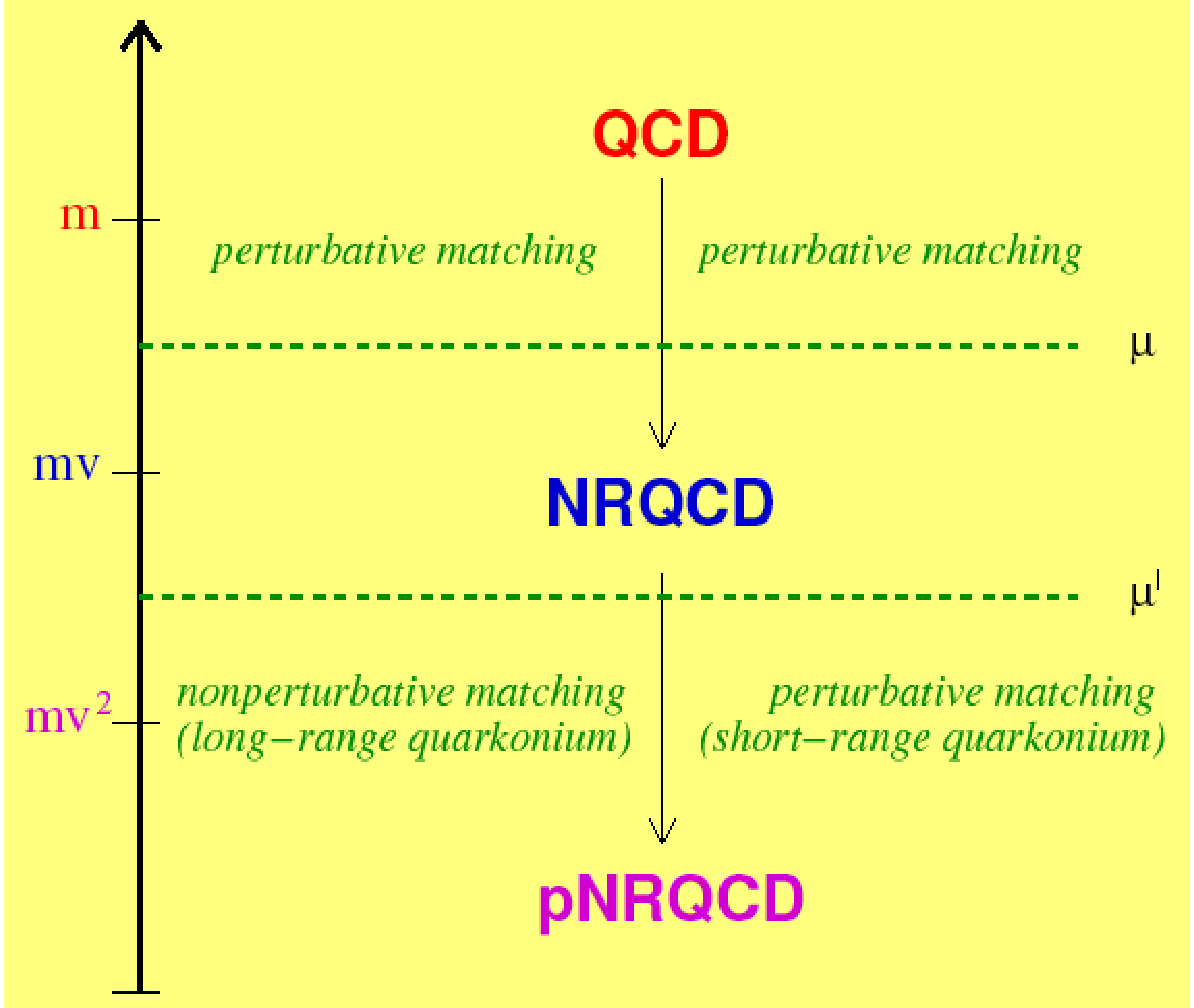

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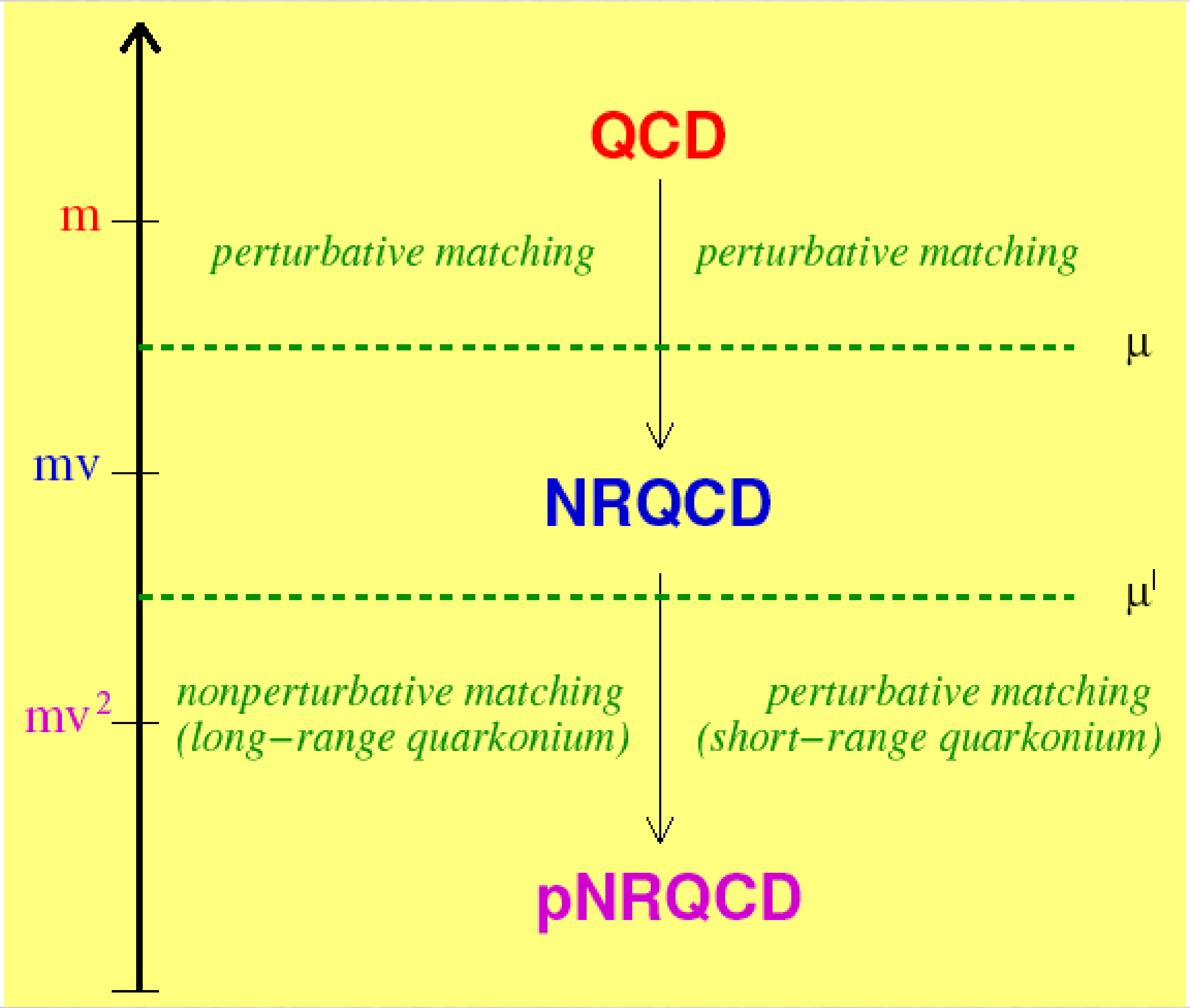

Hard

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

Soft
(relative
momentum)

Ultrasoft
(binding energy)

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

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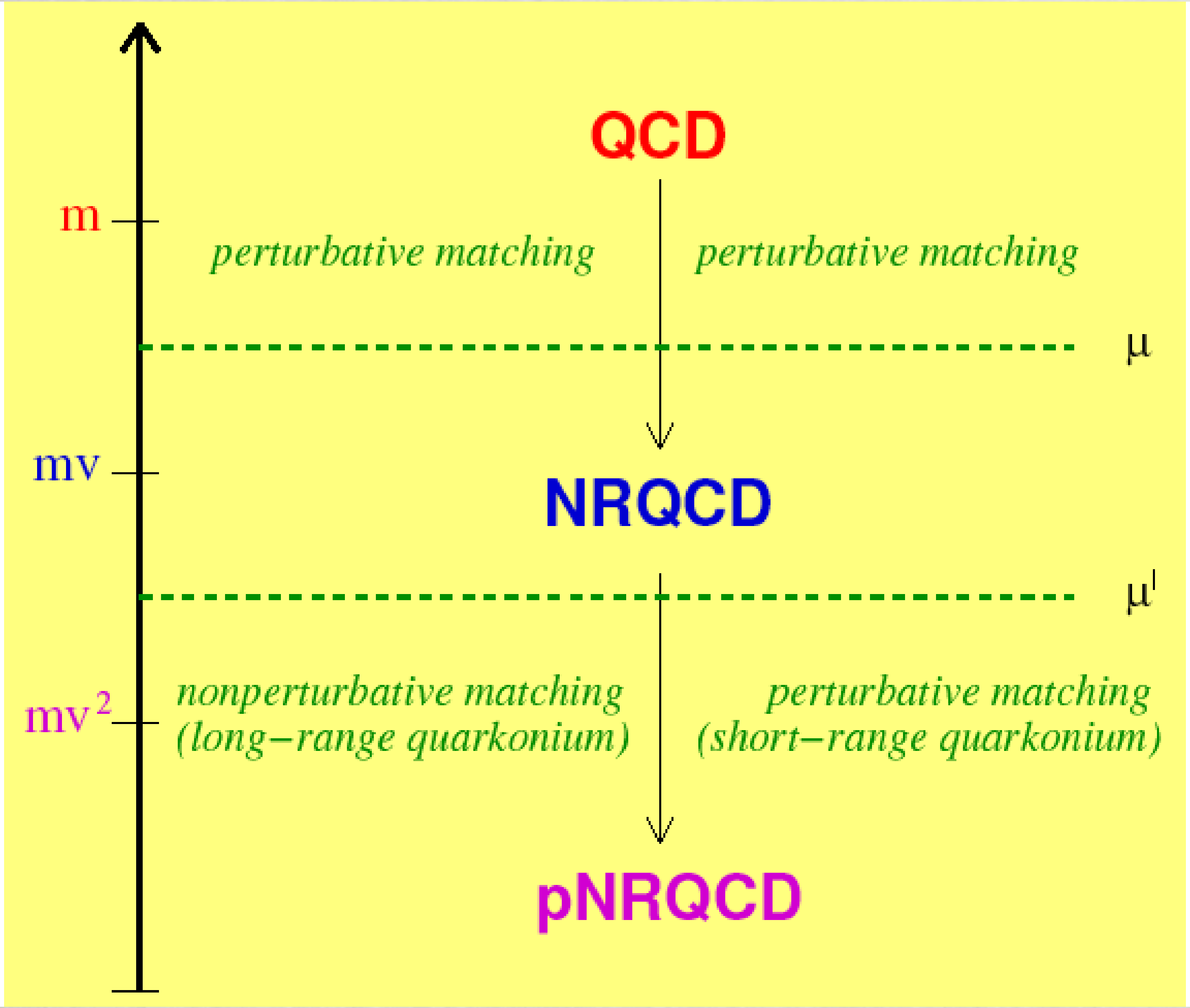


Hard

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

Soft
(relative
momentum)

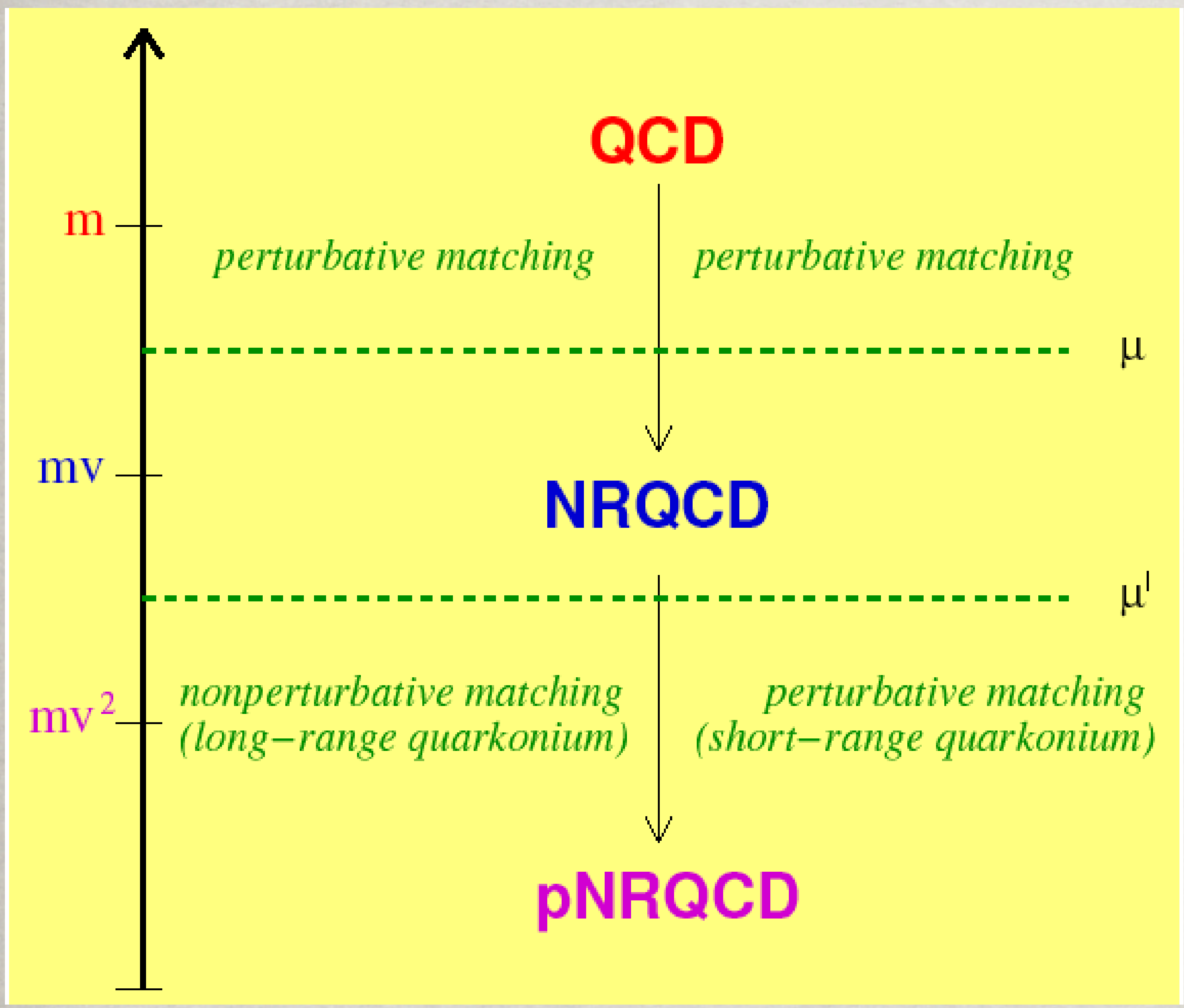
$$\frac{E_\lambda}{E_\Lambda} = \frac{mv^2}{mv}$$

Ultrasoft
(binding energy)

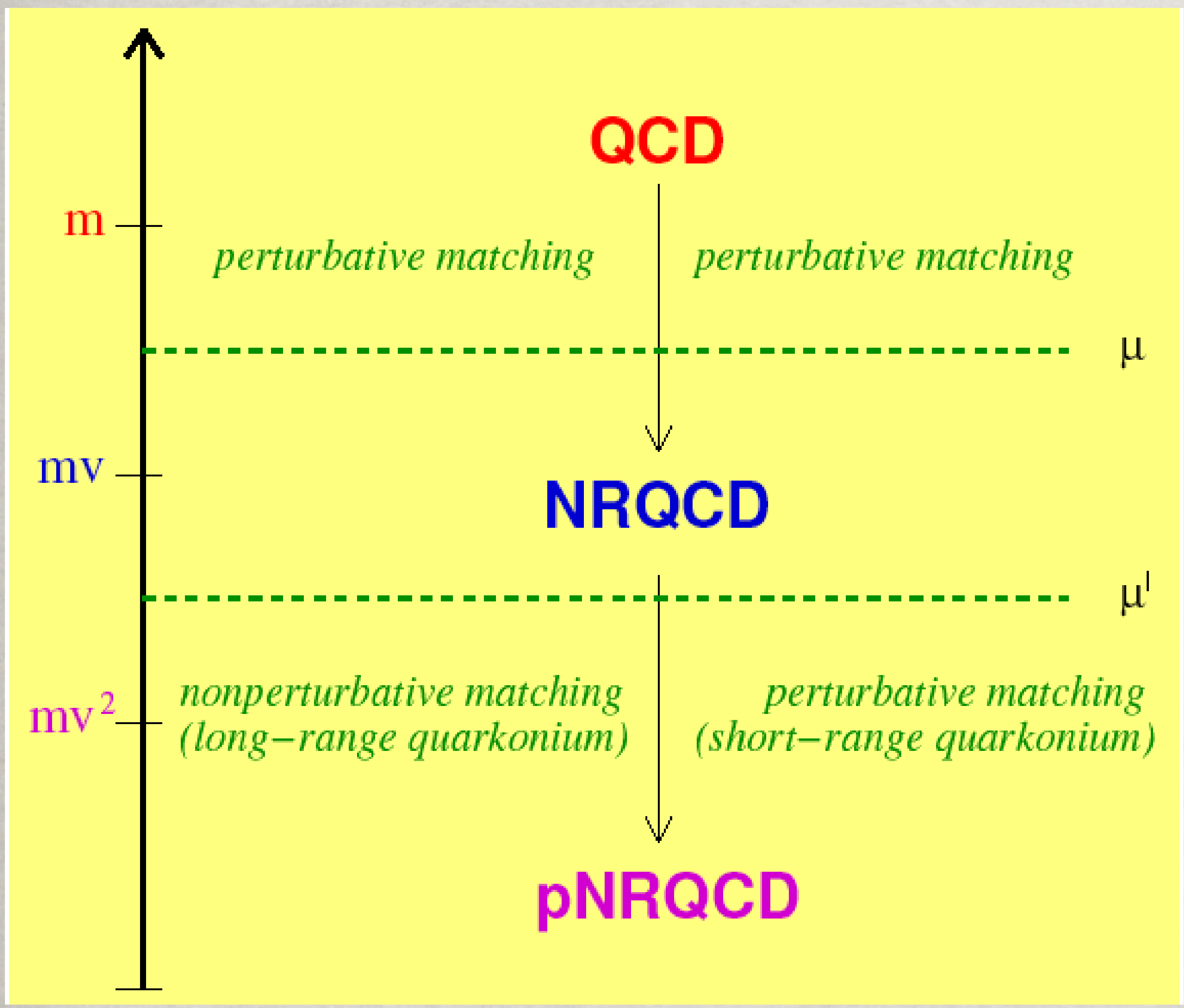
$$\mathcal{L}_{\mathrm{EFT}} = \sum_n c_n(E_\Lambda/\mu)\frac{O_n(\mu,\lambda)}{E_\Lambda}$$

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

Quarkonium with NR EFT: pNRQCD

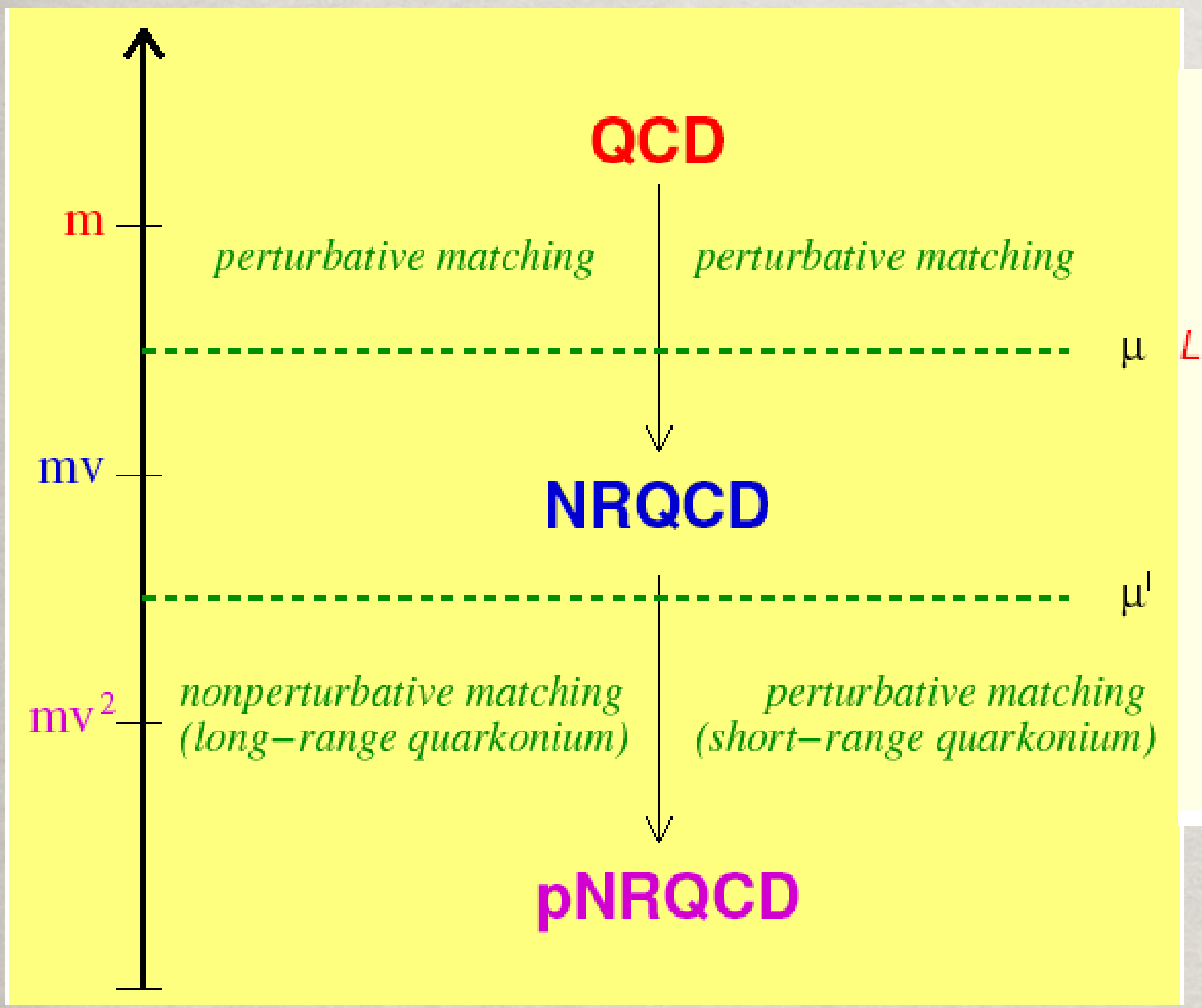


Quarkonium with NR EFT: pNRQCD



In QCD another scale is relevant Λ_{QCD}

Quarkonium with NR EFT: pNRQCD



QCD

m

perturbative matching *perturbative matching*

μ

mv

NRQCD

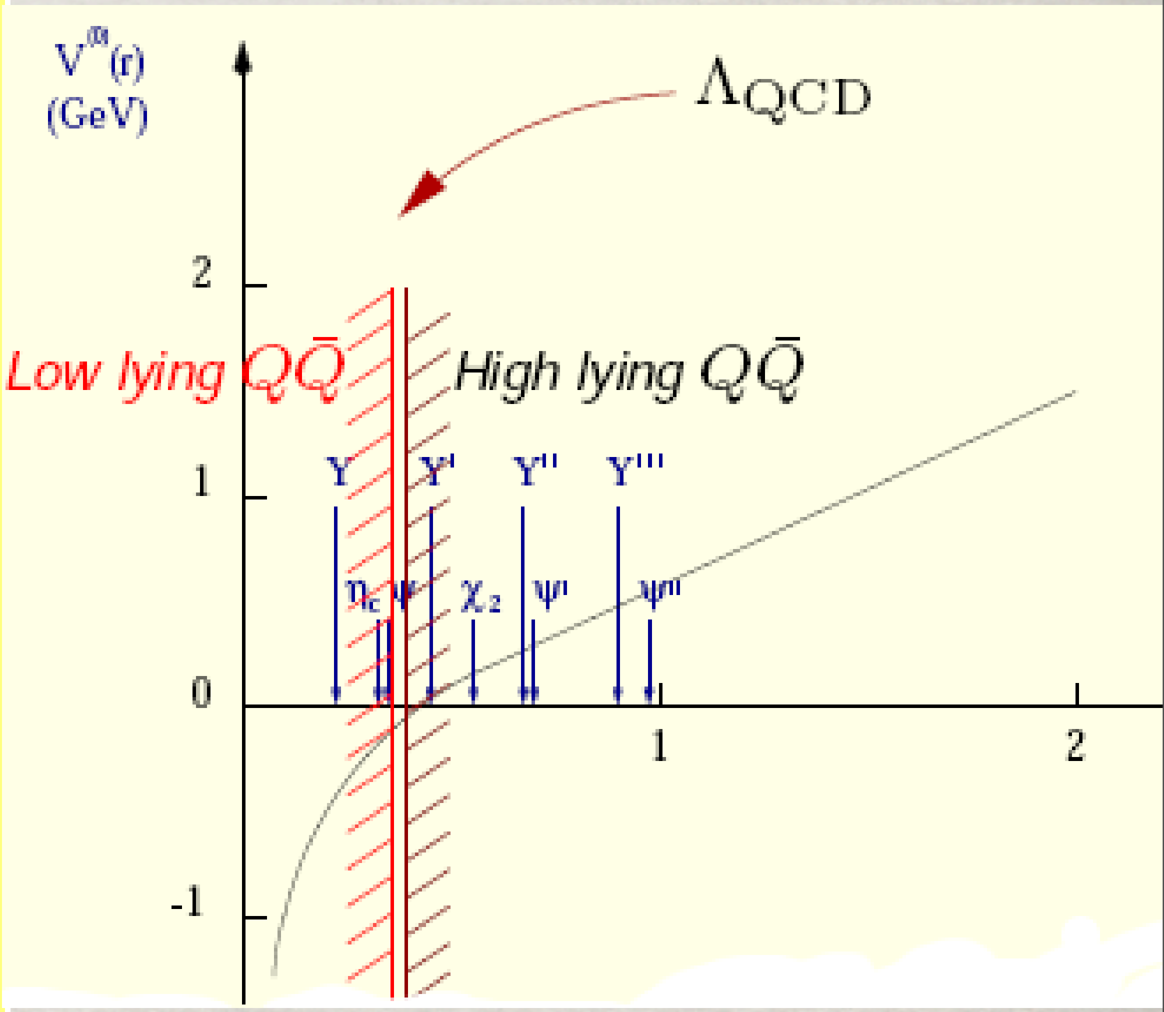
μ'

mv^2

nonperturbative matching (long–range quarkonium)

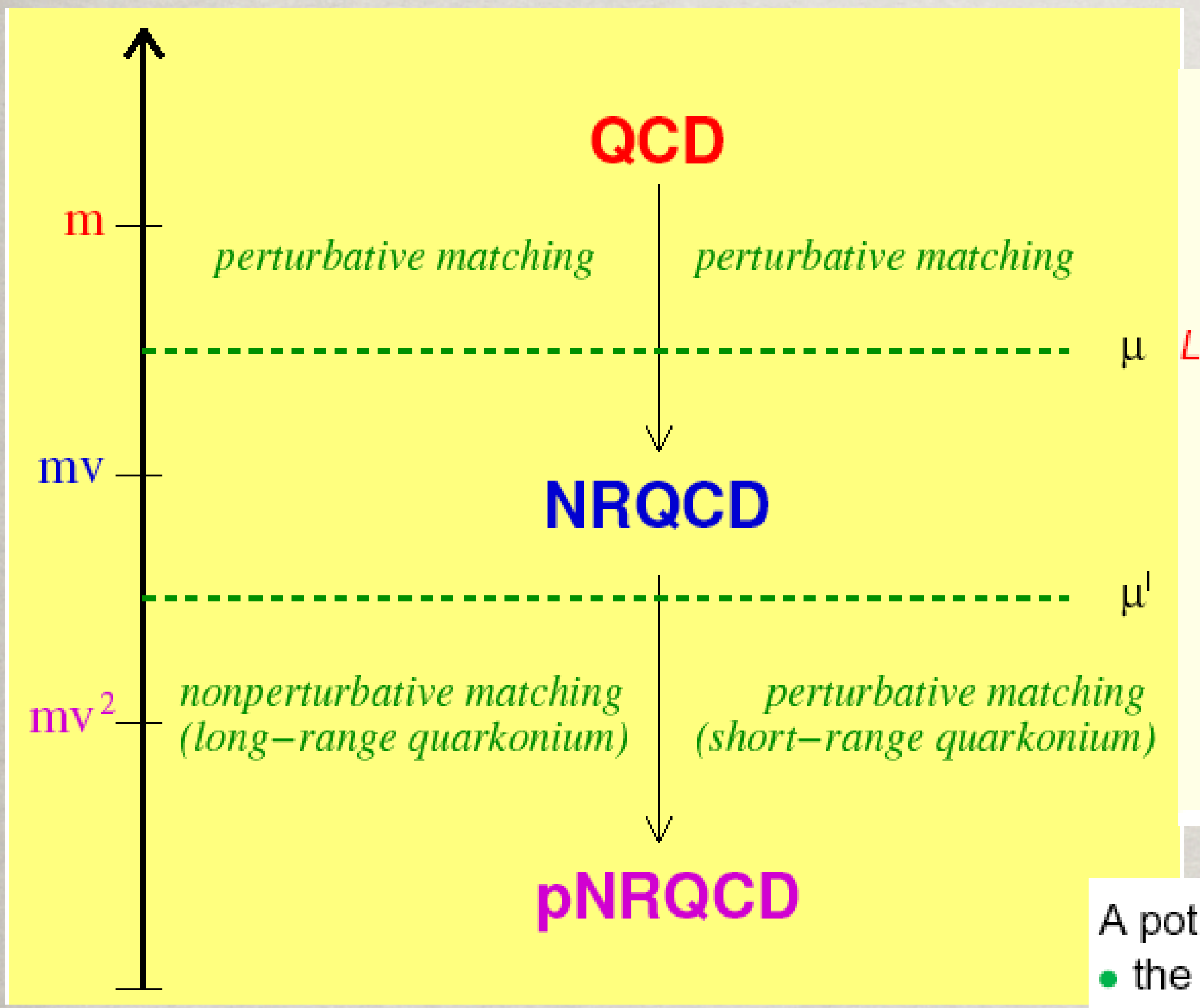
perturbative matching (short–range quarkonium)

pNRQCD



In QCD another scale is relevant Λ_{QCD}

Quarkonium with NR EFT: pNRQCD



QCD

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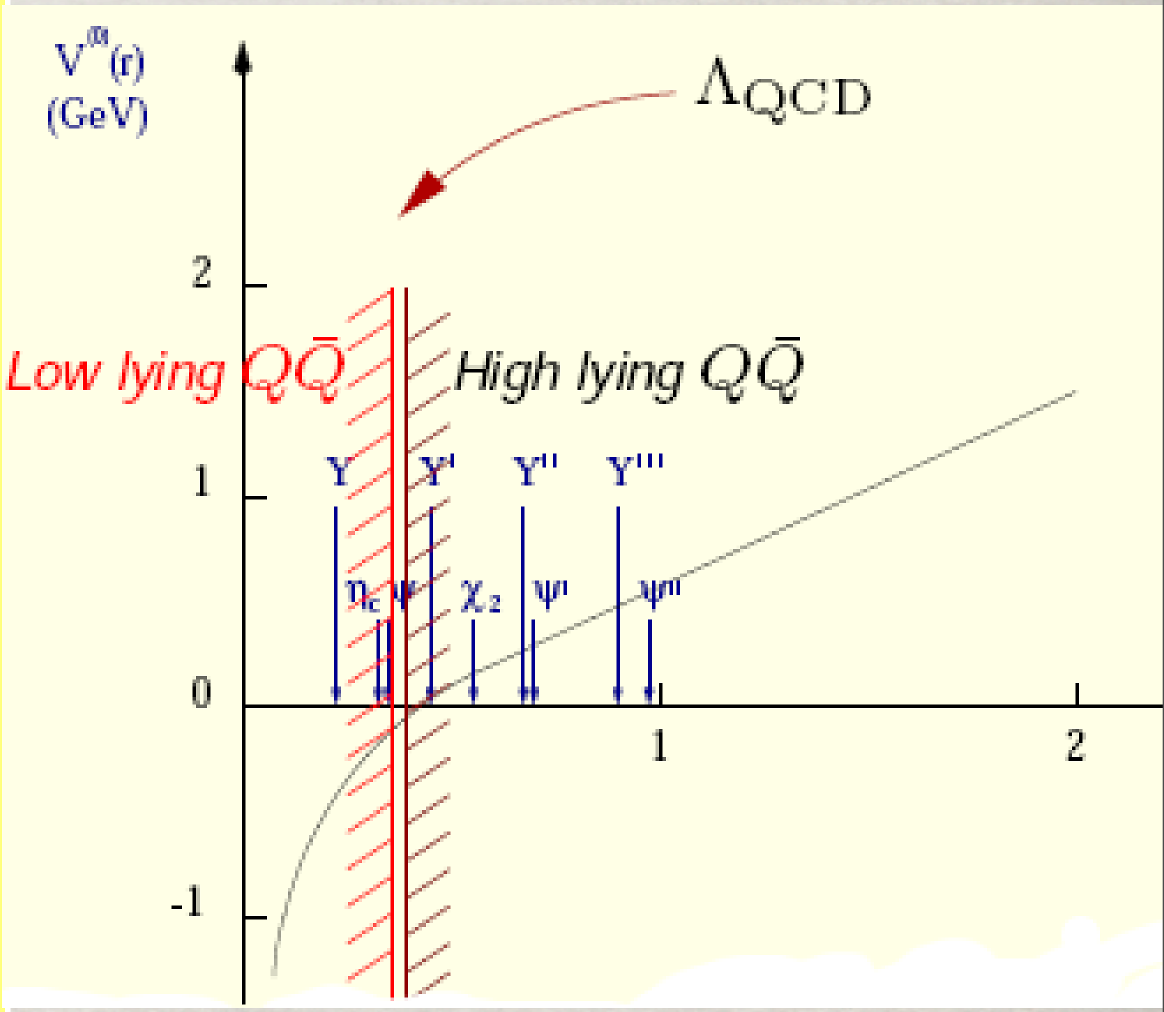
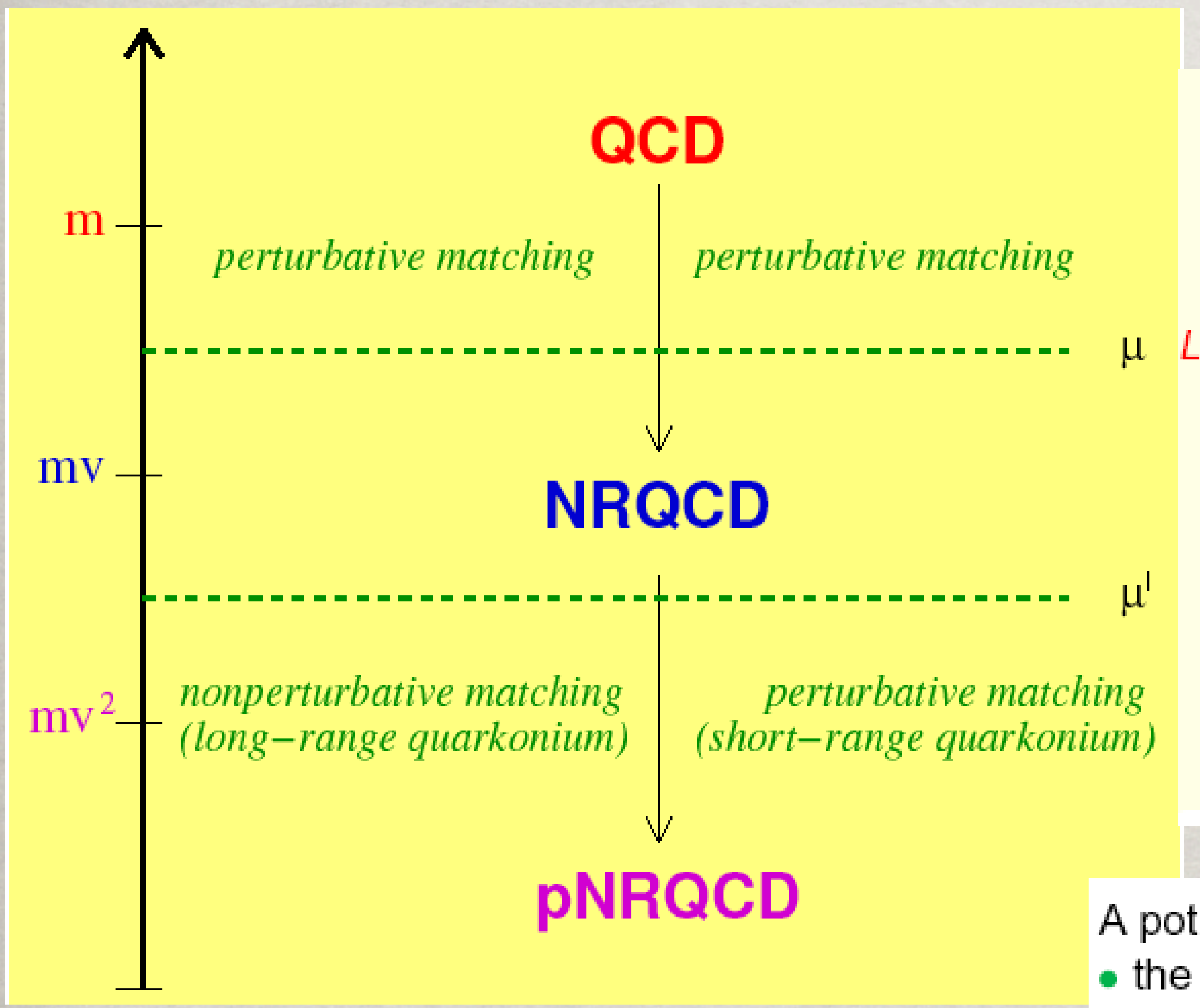


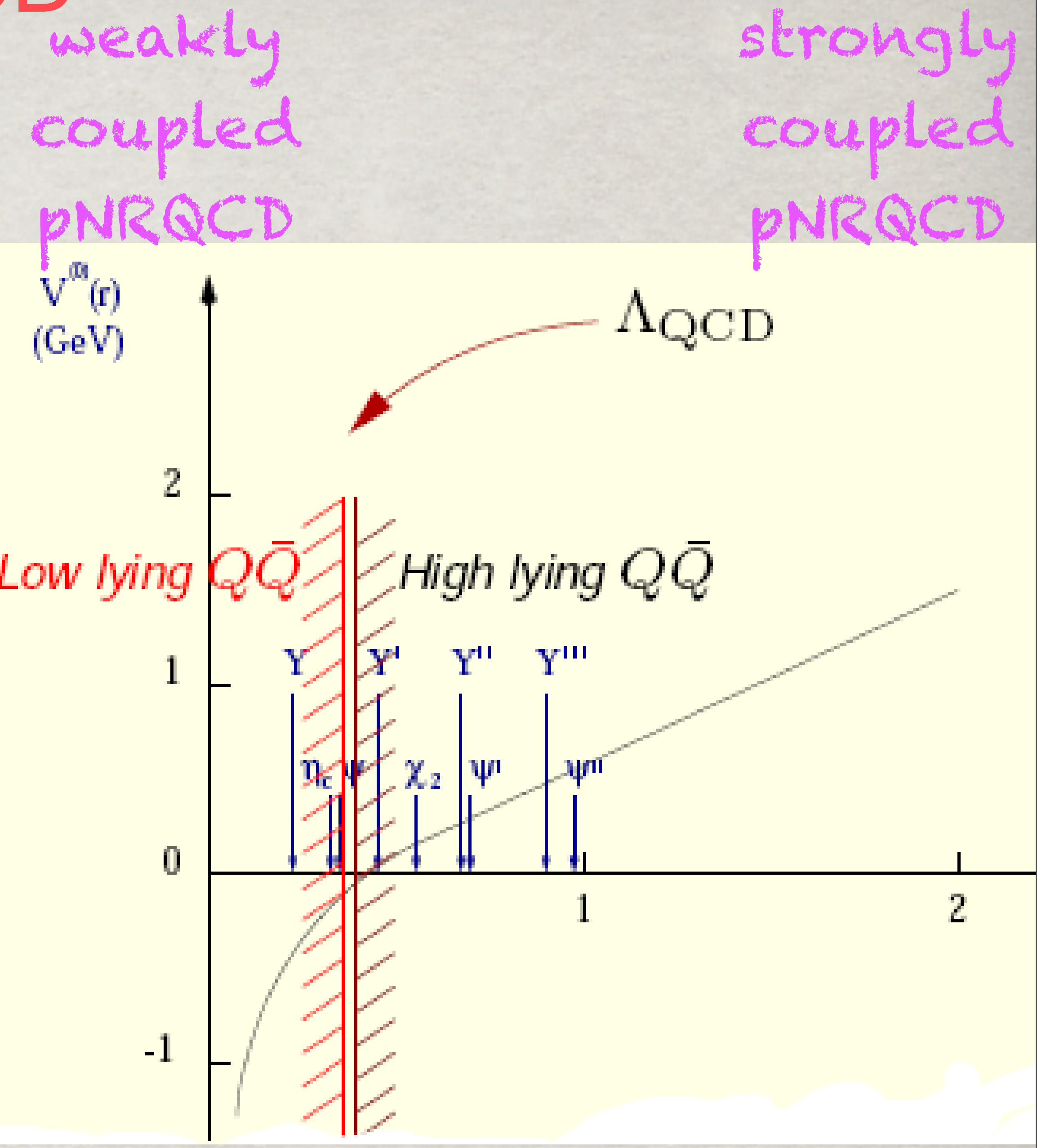
A potential picture arises at the level of pNRQCD:

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

In QCD another scale is relevant Λ_{QCD}

Quarkonium with NR EFT: pNRQCD





A potential picture arises at the level of pNRQCD:

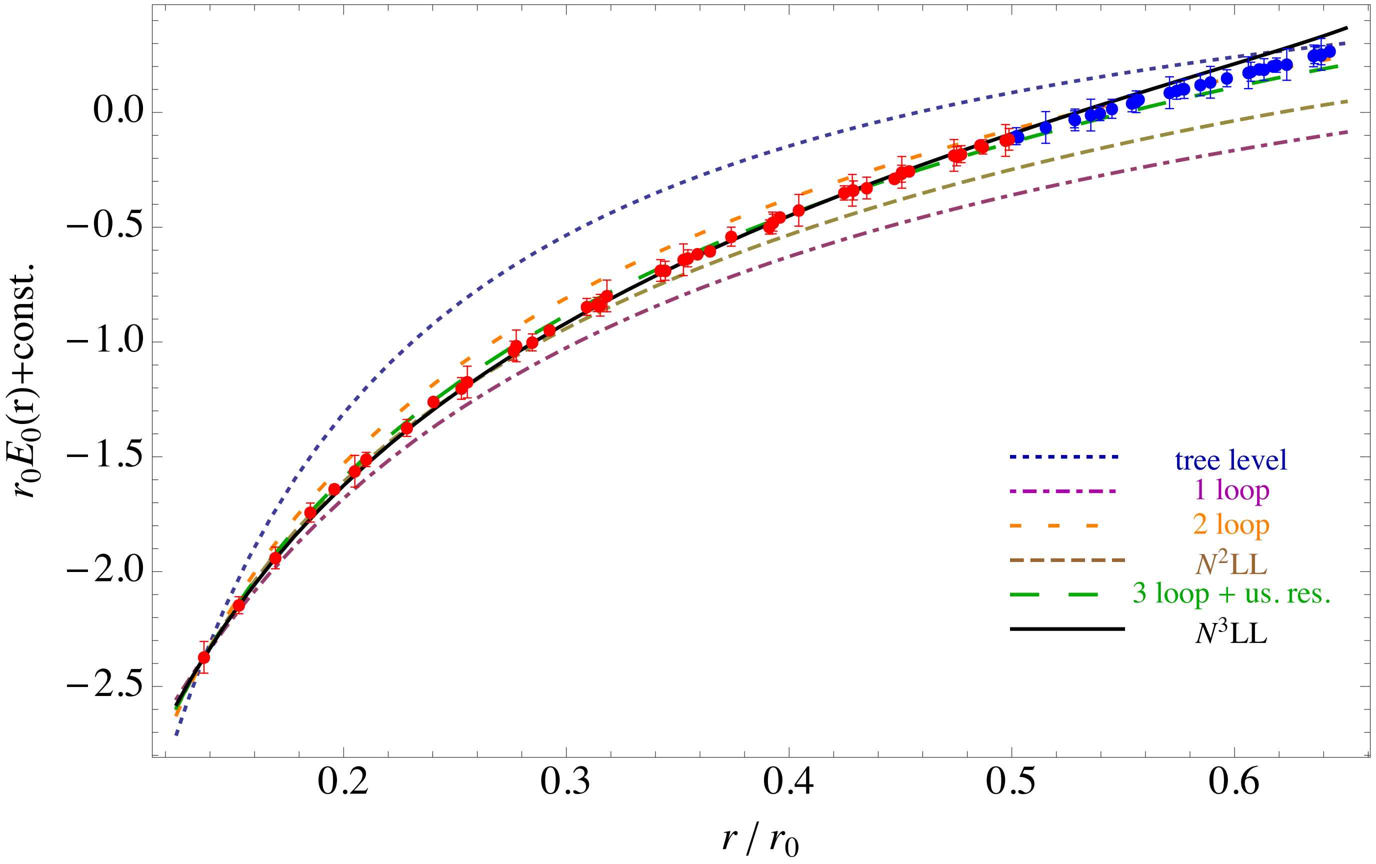
- the potential is perturbative if $mv \gg \Lambda_{QCD}$
- the potential is non-perturbative if $mv \sim \Lambda_{QCD}$

In QCD another scale is relevant Λ_{QCD}

Low-lying quarkonia (quarkonia with a small radius r<Lambda_QCD^-1)

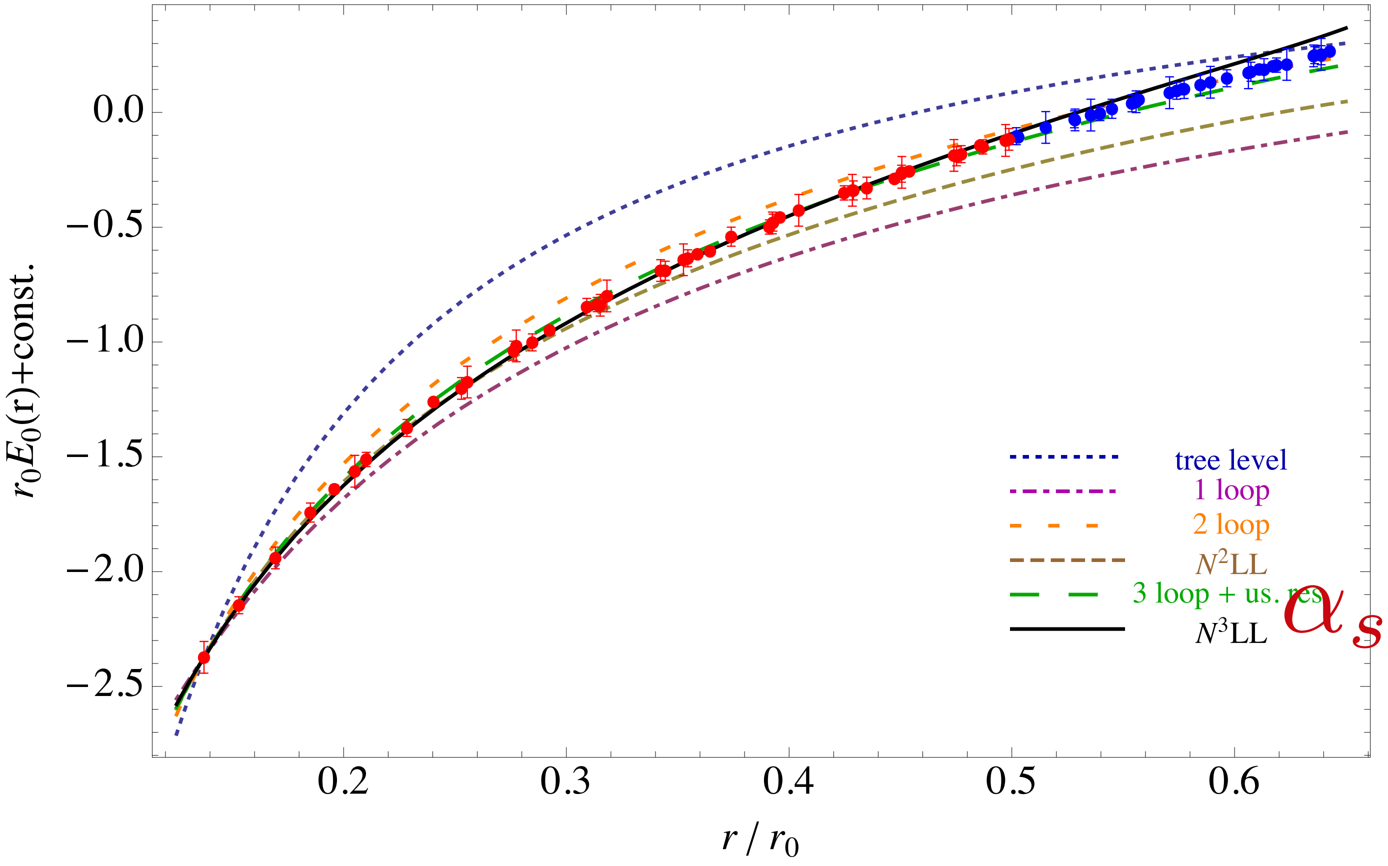
(weakly coupled pNRQCD)

At short distances the potential is well described by PT up to NNNLL accuracy.



- ○ Bazavov Brambilla Garcia i Tormo Petreczky Soto Vairo PRD 86 (2012) 114031

At short distances the potential is well described by PT up to NNNLL accuracy.



- Bazavov Brambilla Garcia i Tormo Petreczky Soto Vairo PRD 86 (2012) 114031

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

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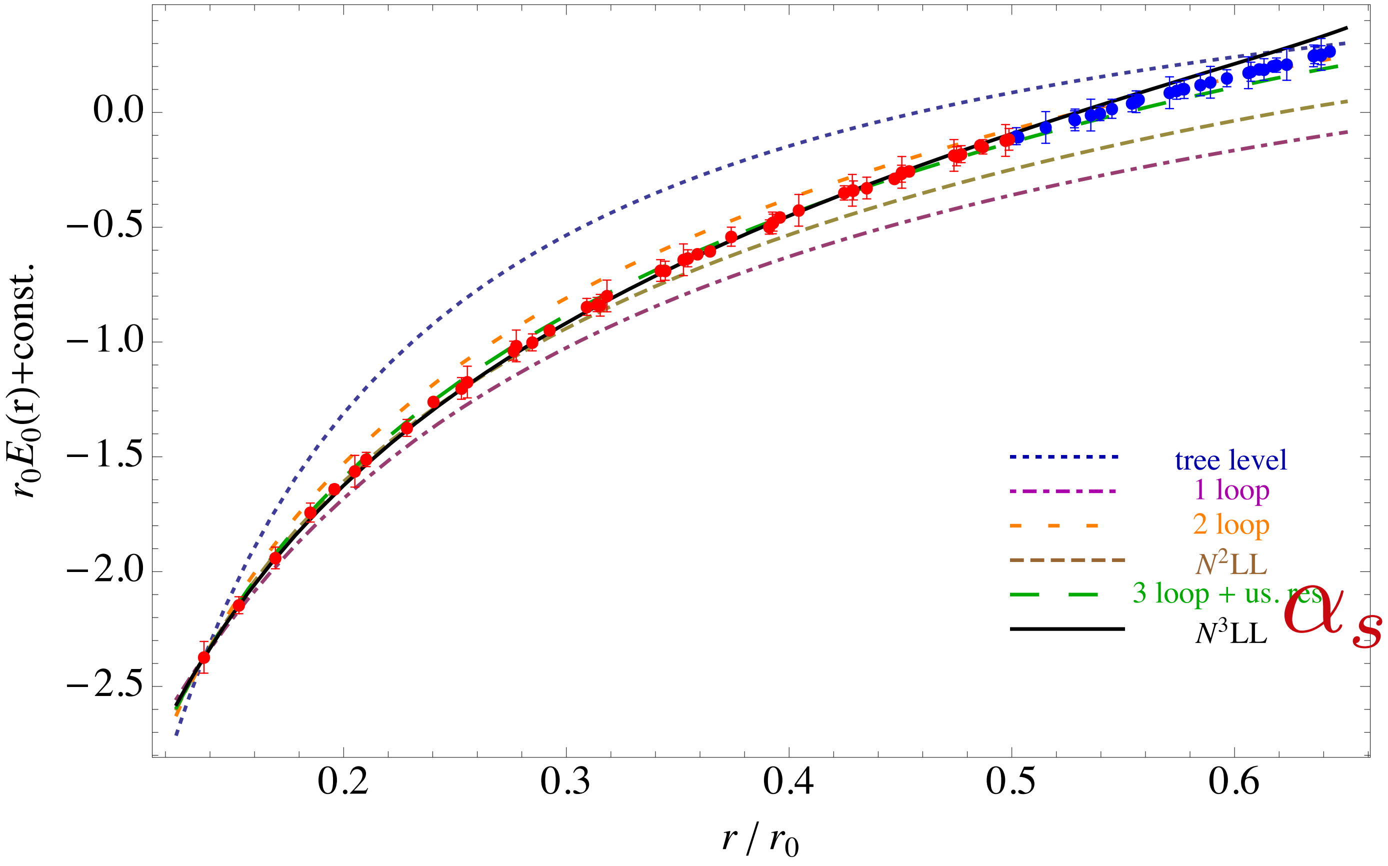


- Bazavov Brambilla Garcia i Tormo Petreczky Soto Vairo PRD 86 (2012) 114031

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

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

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

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

- Brambilla Pineda Soto Vairo PLB 470 (1999) 215 Kniehl Penin NPB 56 (1999) 200 Kniehl Penin Smirnov Steinhauser NPB 635 (2002) 357

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

Low-lying quarkonia

- c and b masses at NNLO, N^{3}LO*, NNLL*;
- B_c mass at NNLO;
- B_c^*, η_c, η_b masses at NLL;
- 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, ... ;
- Thermal effects on quarkonium in medium: potential, masses (at $m\alpha_{\rm s}^5$), widths, ...;
- ...

○ *for reviews* `QWG` *Heavy Quarkonium Physics* `CERN Yellow Report CERN-2005-005`
`QWG EPJ C71 (2011) 1534`
`Vairo EPJ A31 (2007) 728, IJMP A22 (2007) 5481`
`Pineda PPNP 67 (2012) 735`

high-lying quarkonia (quarkonia with a larger radius r>Lambda_QCD^-1)

(strongly coupled pNRQCD)

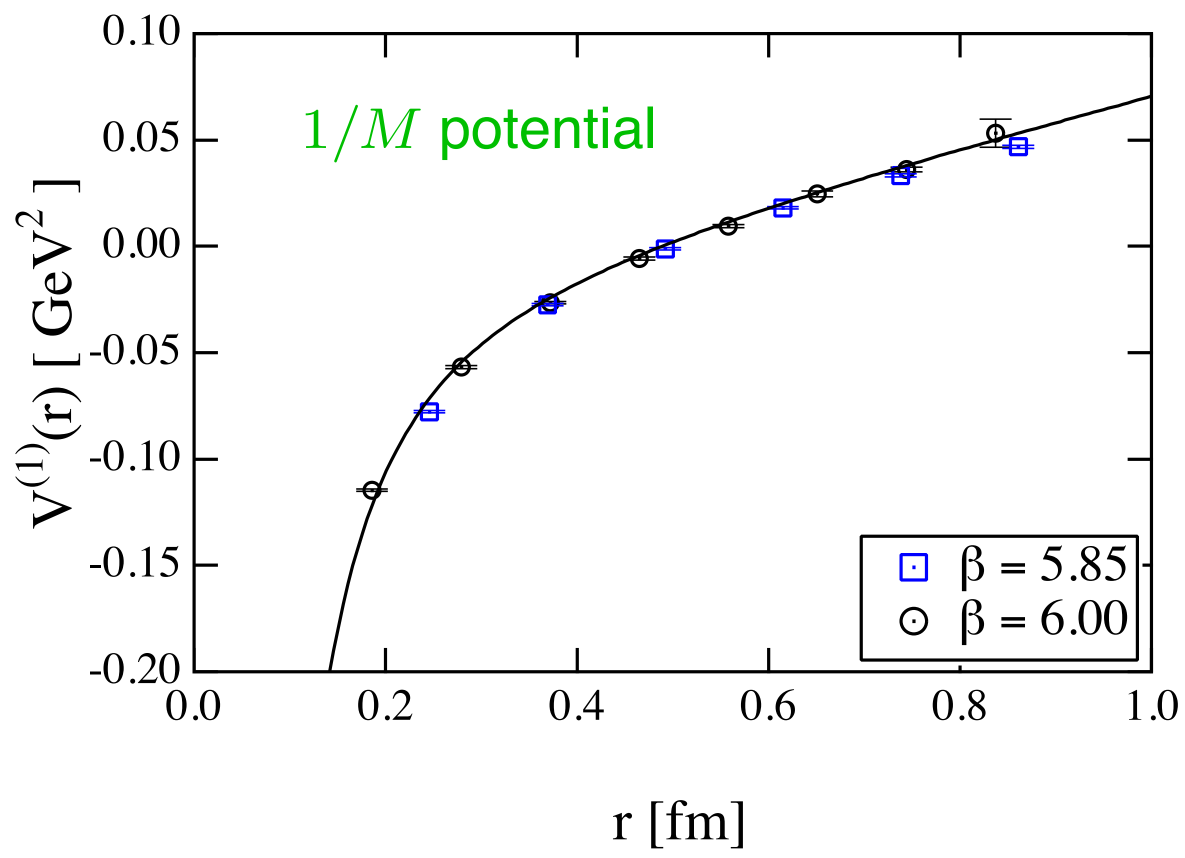
High-lying quarkonia:

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

The long range tail of the potential describes high-lying quarkonium resonances. $1/M$ and $1/M^2$ terms of the potential may be systematically included.

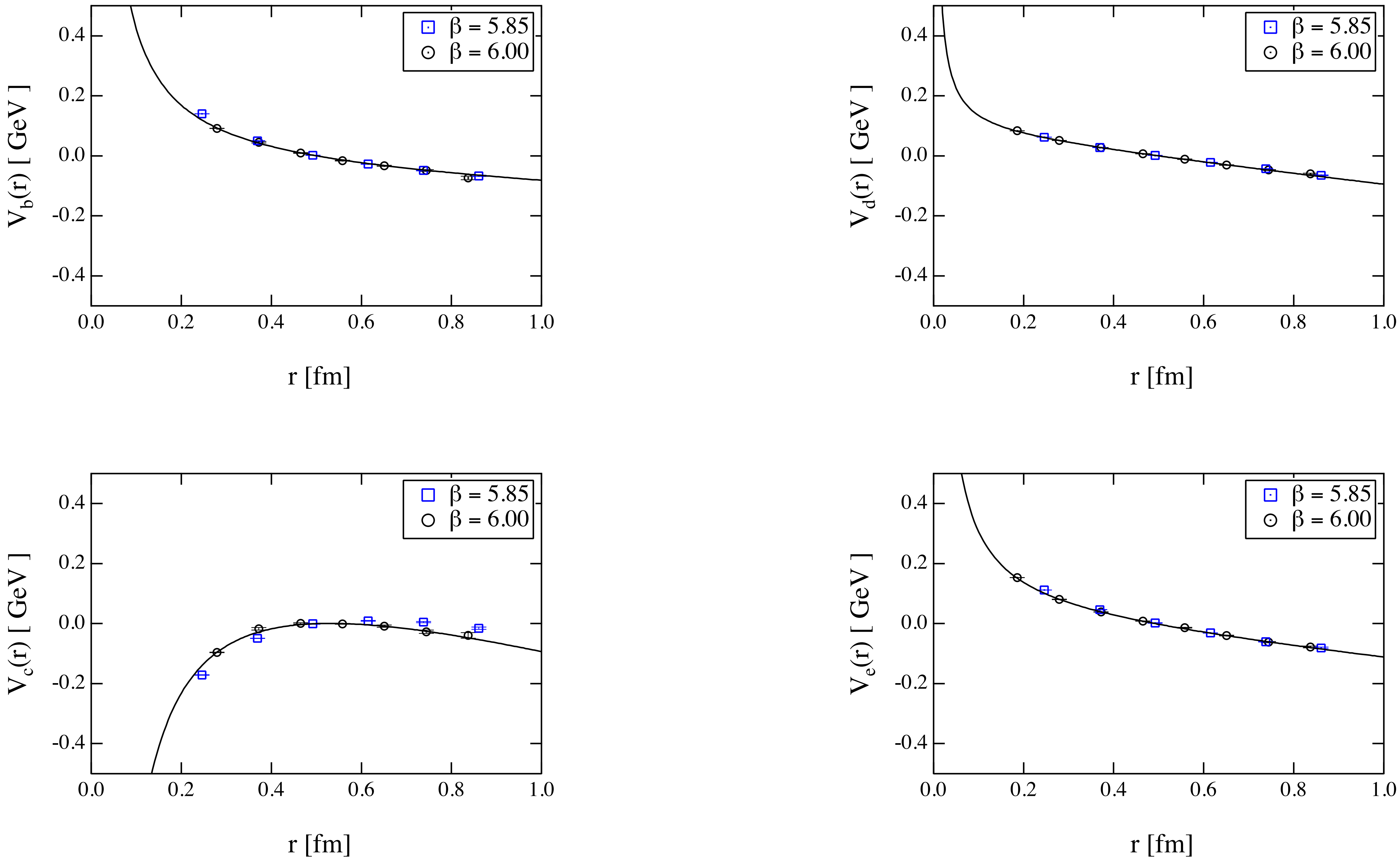
- ○ `Brambilla Pineda Soto Vairo PRD 63 (2001) 014023`
- ○ `Pineda Vairo PRD 63 (2001) 054007`

Lattice provides a non-perturbative determination of the potentials.



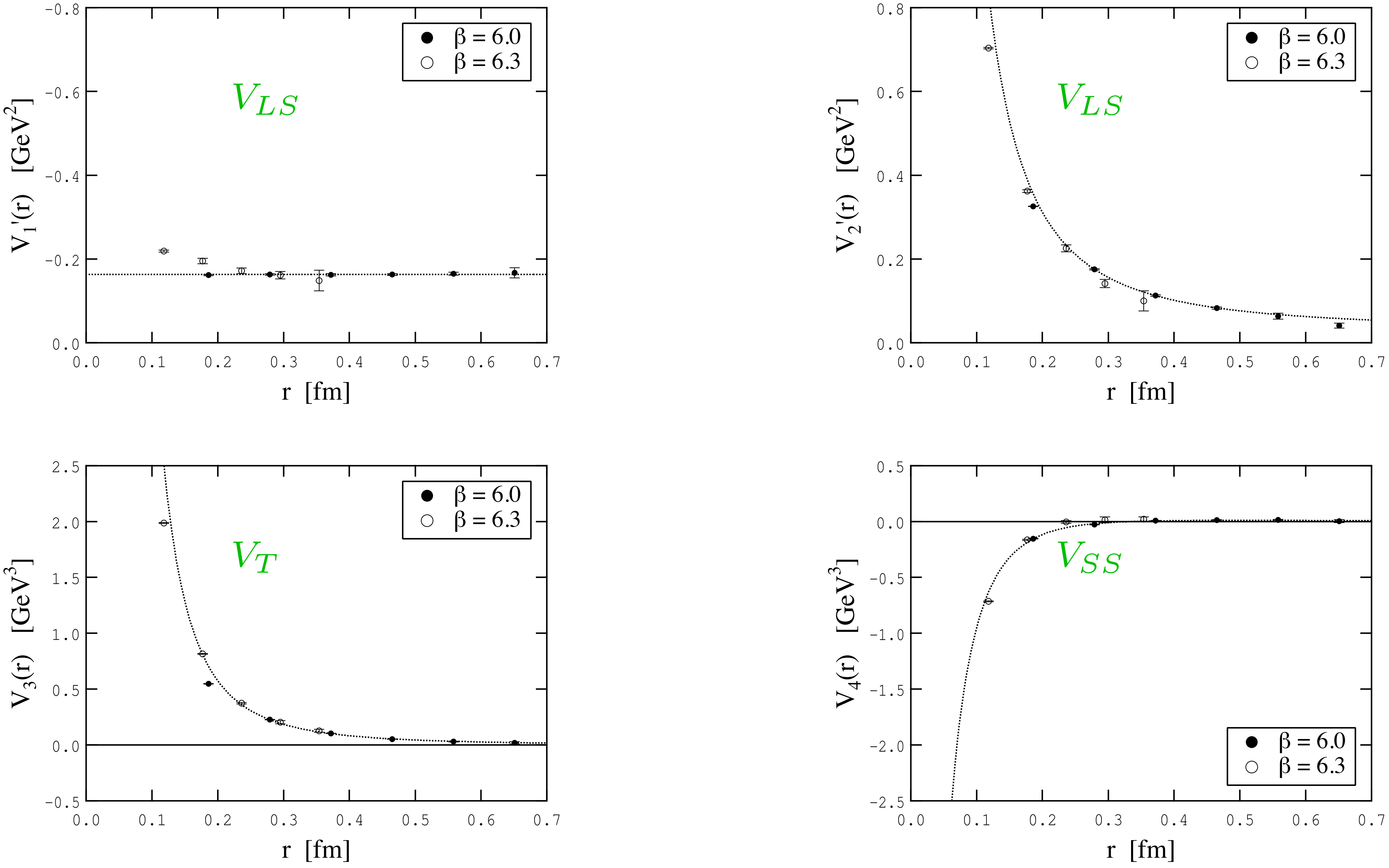
- ○ `Koma Koma Wittig PoS LAT2007 (2007) 111`

Spin-independent p^2/M^2 potentials



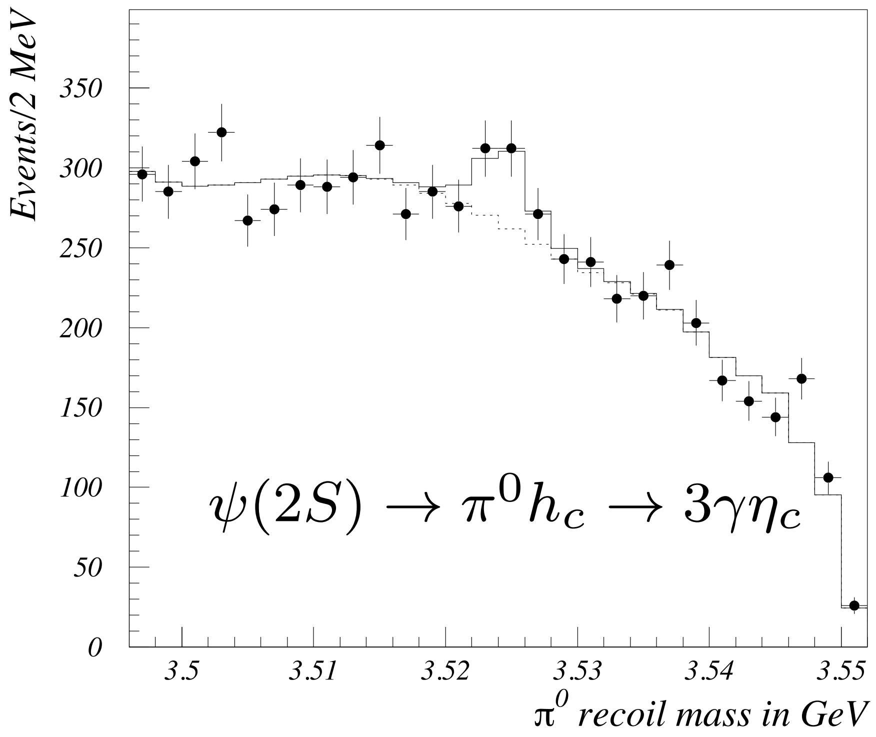
- Koma Koma Wittig PoS LAT2007 (2007) 111

Spin-dependent $1/M^2$ potentials



- `Koma Koma NPB 769 (2007) 79`

h_c



$$M_{h_c(1P)} = 3524.4 \pm 0.6 \pm 0.4 \text{ MeV}$$

○ CLEO PRL 95 (2005) 102003

$$M_{h_c(1P)} = 3525.8 \pm 0.2 \pm 0.2 \text{ MeV}, \qquad \Gamma < 1 \text{ MeV}$$

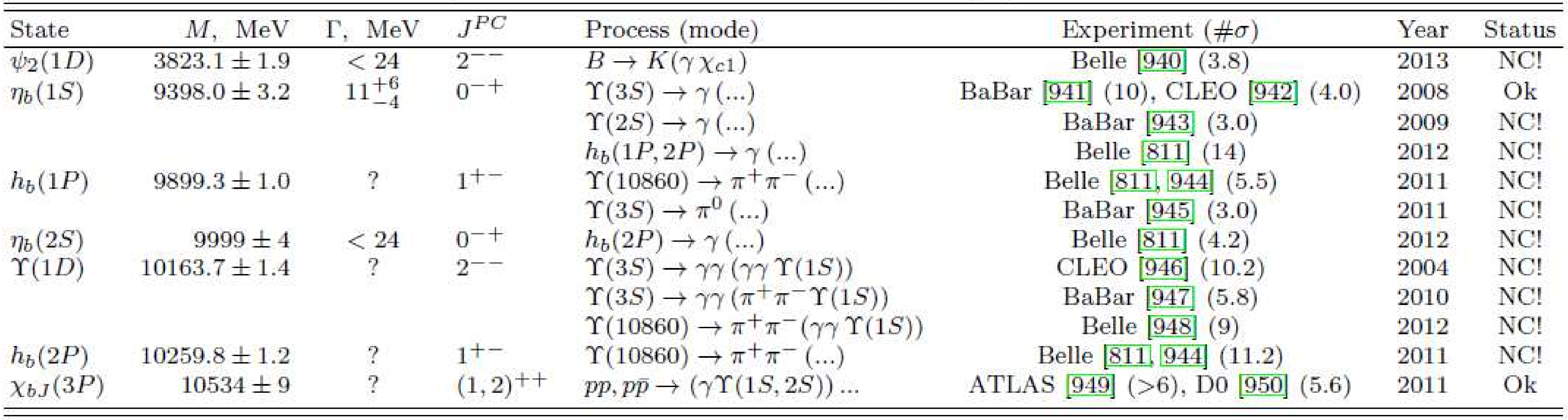
○ E835 PRD 72 (2005) 032001

$$M_{h_c(1P)} = 3525.40 \pm 0.13 \pm 0.18 \text{ MeV}, \qquad \Gamma < 1.44 \text{ MeV}$$

○ BES PRL 104 (2010) 132002

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

New quarkonium-like states below threshold



State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$\psi_2(1D)$	3823.1 ± 1.9	< 24	2^{--}	$B \to K(\gamma \chi_{c1})$	Belle [940] (3.8)	2013	NC!
$\eta_b(1S)$	9398.0 ± 3.2	11^{+6}_{-4}	0^{-+}	$\Upsilon(3S) \to \gamma\,(...)$	BaBar [941] (10), CLEO [942] (4.0)	2008	Ok
				$\Upsilon(2S) \to \gamma\,(...)$	BaBar [943] (3.0)	2009	NC!
				$h_b(1P, 2P) \to \gamma\,(...)$	Belle [811] (14)	2012	NC!
$h_b(1P)$	9899.3 ± 1.0	?	1^{+-}	$\Upsilon(10860) \to \pi^+\pi^-\,(...)$	Belle [811, 944] (5.5)	2011	NC!
				$\Upsilon(3S) \to \pi^0\,(...)$	BaBar [945] (3.0)	2011	NC!
$\eta_b(2S)$	9999 ± 4	< 24	0^{-+}	$h_b(2P) \to \gamma\,(...)$	Belle [811] (4.2)	2012	NC!
$\Upsilon(1D)$	10163.7 ± 1.4	?	2^{--}	$\Upsilon(3S) \to \gamma\gamma\,(\gamma\gamma\,\Upsilon(1S))$	CLEO [946] (10.2)	2004	NC!
				$\Upsilon(3S) \to \gamma\gamma\,(\pi^+\pi^-\,\Upsilon(1S))$	BaBar [947] (5.8)	2010	NC!
				$\Upsilon(10860) \to \pi^+\pi^-(\gamma\gamma\,\Upsilon(1S))$	Belle [948] (9)	2012	NC!
$h_b(2P)$	10259.8 ± 1.2	?	1^{+-}	$\Upsilon(10860) \to \pi^+\pi^-\,(...)$	Belle [811, 944] (11.2)	2011	NC!
$\chi_{bJ}(3P)$	10534 ± 9	?	$(1,2)^{++}$	$pp, p\bar{p} \to (\gamma\Upsilon(1S, 2S))\,...$	ATLAS [949] (>6), D0 [950] (5.6)	2011	Ok

- Brambilla et al *QCD and strongly coupled gauge theories* arXiv:1404.3723

New quarkonium-like states below threshold

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- `Brambilla et al` *QCD and strongly coupled gauge theories* `arXiv:1404.3723`

h_b

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

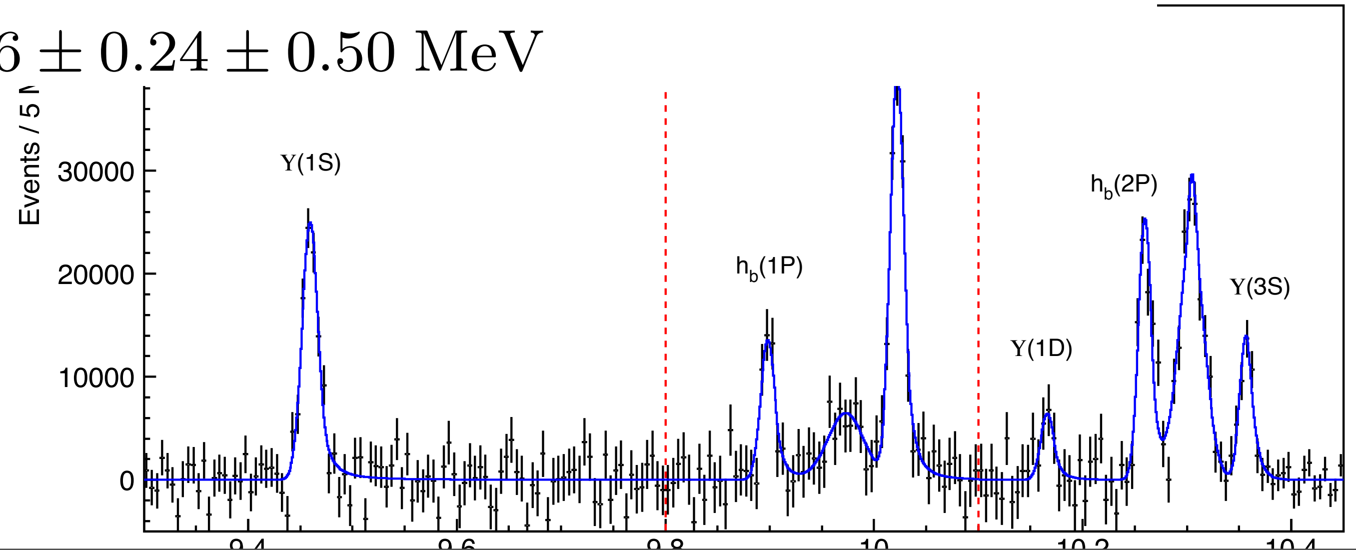
- `BABAR PRD 84 (2011) 091101`

$$M_{h_b(1P)} = 9898.25 \pm 1.06^{+1.03}_{-1.07} \text{ MeV} \qquad M_{h_b(2P)} = 10259.76 \pm 0.64^{+1.43}_{-1.03} \text{ MeV}$$

- `BELLE PRL 108 (2012) 032001`

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

$$M_{\text{c.o.g.}}(2P) = 10260.06 \pm 0.24 \pm 0.50 \text{ MeV}$$



close or above the threshold

close or above the threshold

gluonic excitations

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 $\rightarrow$ glueball + quark-antiquark.

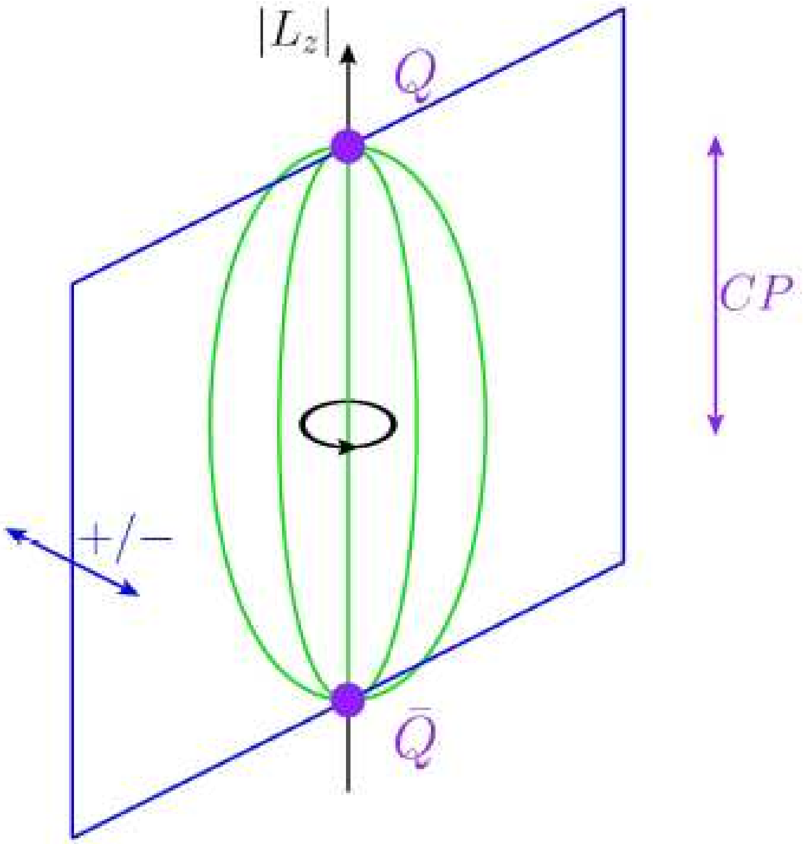
We may integrate out modes scaling like $1/r$ and $\Lambda_{\rm QCD}$ and describe hybrids as heavy quark-antiquark states bound by potentials that are the energies of the corresponding gluonic excitations between static sources $\rightarrow$ Born–Oppenheimer approximation.

If more states are nearly degenerate, then all of these need to be considered as effective low-energy degrees of freedom and mix.

Symmetries

Static states classified by symmetry group $D_{\infty\, h}$
Representations labeled Λ_η^σ

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



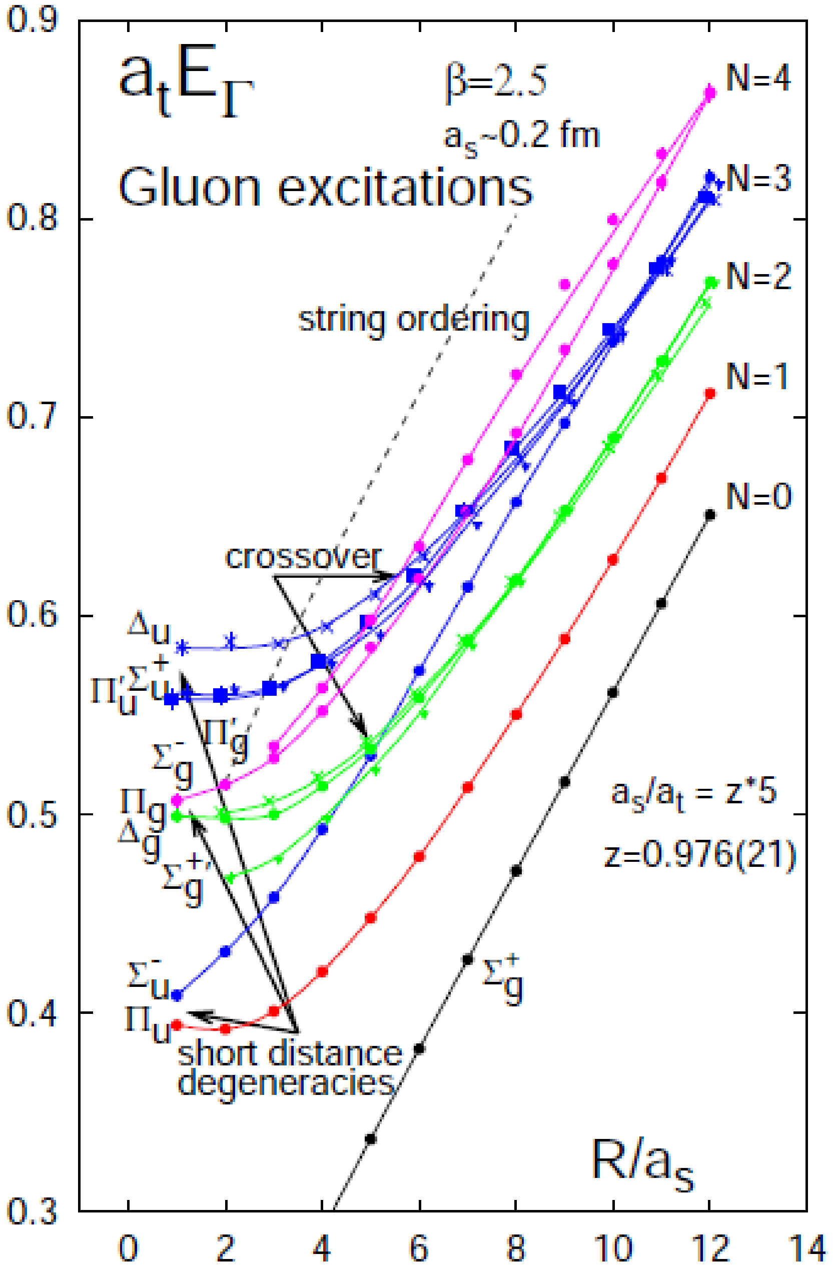
- The static energies correspond to the irreducible representations of $D_{\infty\, h}$.
- In general it can be more than one state for each irreducible representations of $D_{\infty\, h}$, usually denoted by primes, e.g. Π_u, Π'_u, $\Pi''_u\ldots$

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

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

○ Brambilla Pineda Soto Vairo NPB 566 (2000) 275

Lattice energies



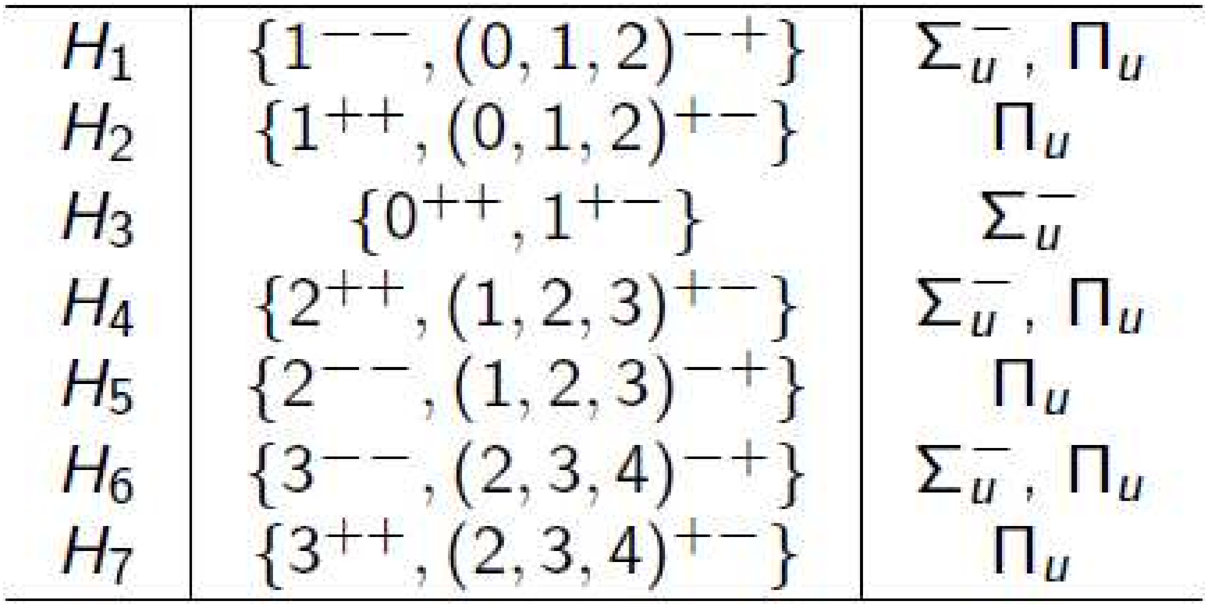
- Σ_g^+ is the ground state potential that generates the standard quarkonium states.
- The rest of the static energies correspond to excited gluonic states that generate hybrids.
- The two lowest hybrid static energies are Π_u and Σ_u^-, they are nearly degenerate at short distances.
- The static energies have been computed in quenched lattice QCD, the most recent data by Juge, Kuti, Morningstar, 2002 and Bali and Pineda 2003.
- Quenched and unquenched calculations for Σ_g^+ and Π_u were compared in Bali et al 2000 and good agreement was found below string breaking distance.

- Juge Kuti Morningstar PRL 90 (2003) 161601

State multiplets

We consider hybrid states that are excitations of the lowest lying static energies Π_u and Σ_u^-. In the $r \to 0$ limit Π_u and Σ_u^- are degenerate and correspond to a gluonic operator with quantum numbers 1^{+-}.

States are organized in spin multiplets.

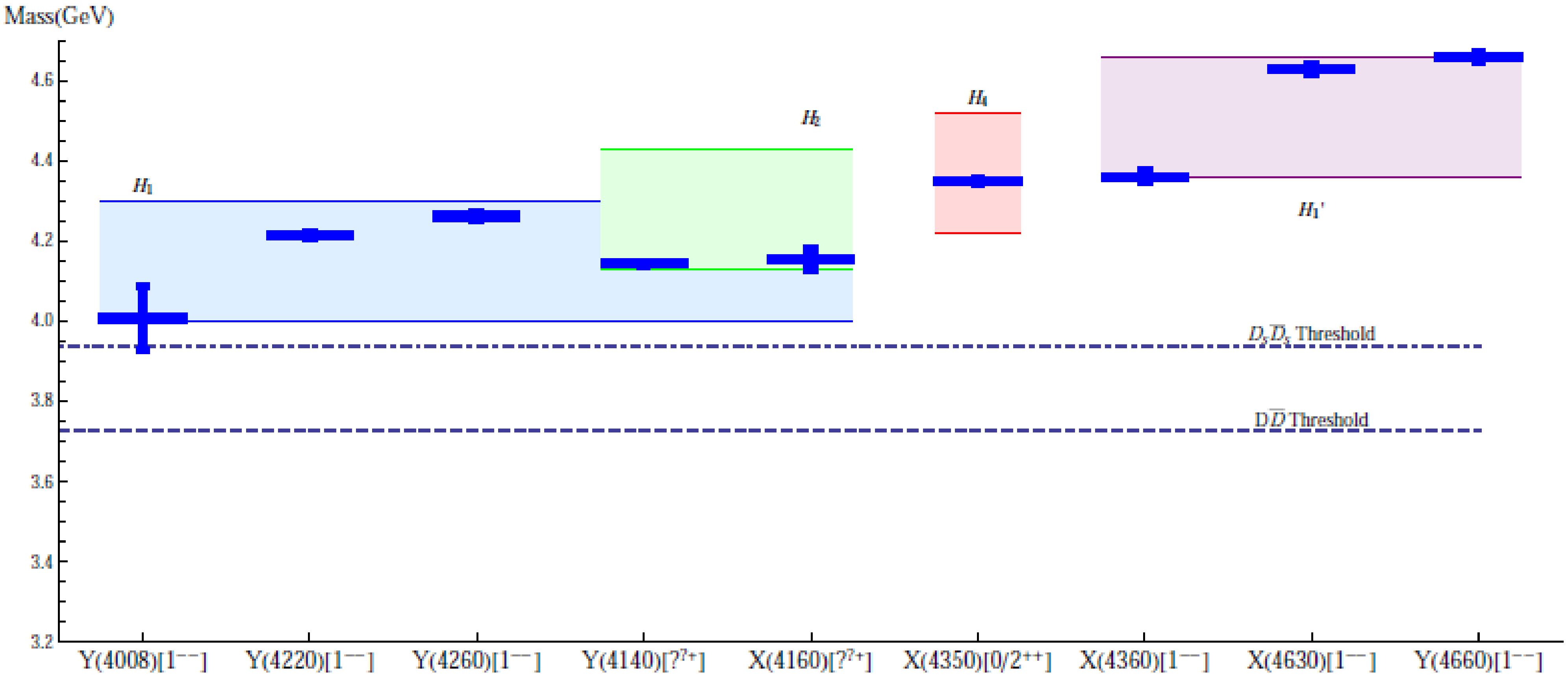


H_1	$\{1^{--}, (0,1,2)^{-+}\}$	Σ_u^-, Π_u
H_2	$\{1^{++}, (0,1,2)^{+-}\}$	Π_u
H_3	$\{0^{++}, 1^{+-}\}$	Σ_u^-
H_4	$\{2^{++}, (1,2,3)^{+-}\}$	Σ_u^-, Π_u
H_5	$\{2^{--}, (1,2,3)^{-+}\}$	Π_u
H_6	$\{3^{--}, (2,3,4)^{-+}\}$	Σ_u^-, Π_u
H_7	$\{3^{++}, (2,3,4)^{+-}\}$	Π_u

○ `Braaten PRL 111 (2013) 162003, Braaten Langmack Smith arXiv:1402.0438`

Charmonium hybrid states

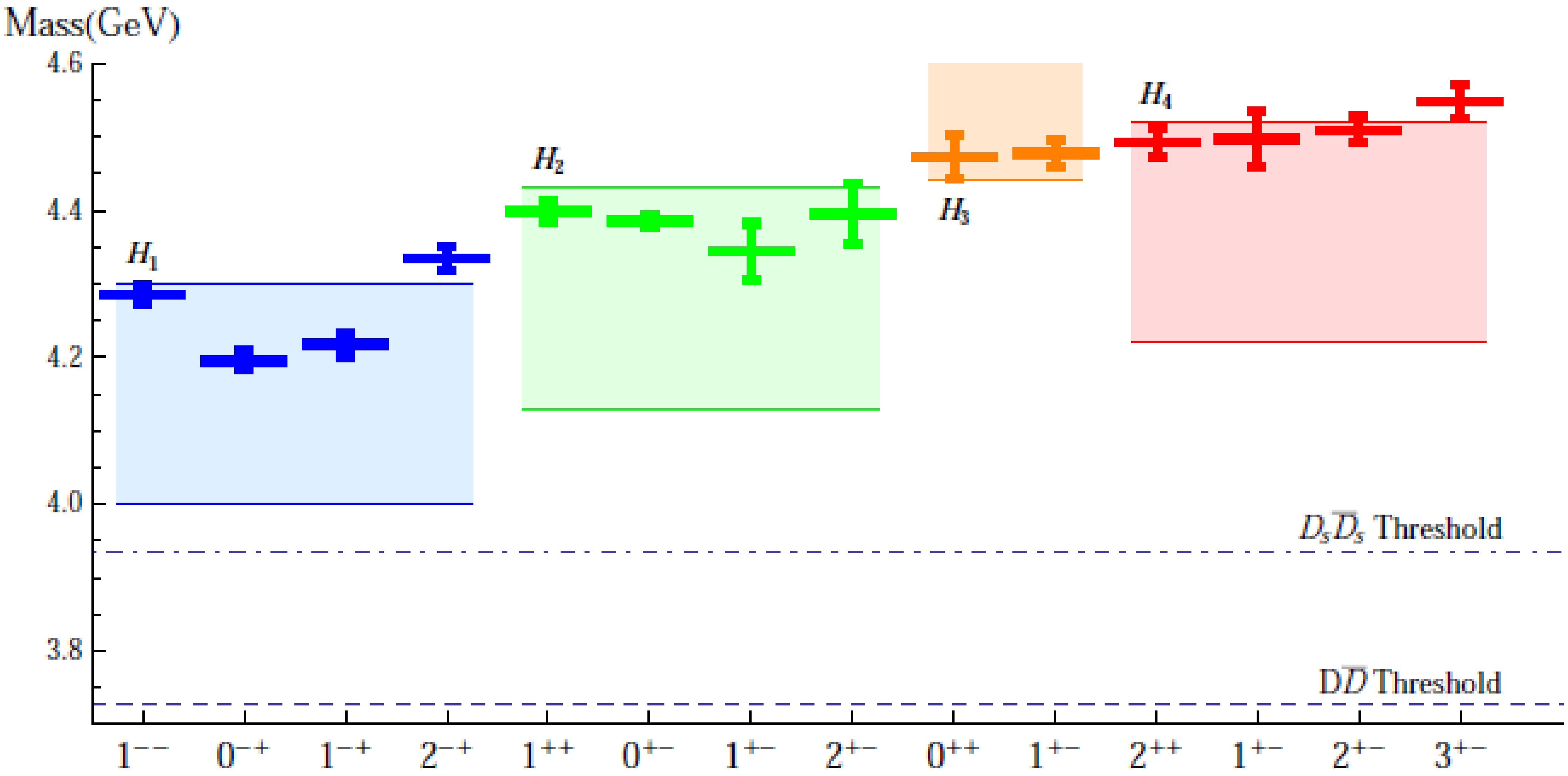
- Charmonium states (BELLE, CDF, BESIII, BABAR):



- Bottomonium states: $Y_b(10890)[1^{--}]$, $M_{Y_b} = (10.8884 \pm 3.0)$ GeV (BELLE). Possible H1 candidate, $M_{H1} = (10.79 \pm 0.15)$ GeV.

○ Berwein Brambilla Tarrus Castellà Vairo in preparation (2014)

Charmonium hybrid states: comparison with lattice



- Lattice data from Liu et al JHEP 1207 (2012) 126

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

Experimental facts:

- $J^{PC} = 1^{--}$
- $\dfrac{\mathcal{B}(Y \to D\bar{D})}{\mathcal{B}(Y \to J/\psi\pi^+\pi^-)} < 1.0$ (~ 500 for $\psi(3770)$)
- $\dfrac{\mathcal{B}(Y \to D^*\bar{D})}{\mathcal{B}(Y \to J/\psi\pi^+\pi^-)} < 34, \quad \dfrac{\mathcal{B}(Y \to D^*\bar{D}^*)}{\mathcal{B}(Y \to J/\psi\pi^+\pi^-)} < 40$

Possible intepretation:

- $Y(4260)$ as a 1^{--} state of the H_1 multiplet.
- Analogous conclusions in the constitutent gluon framework.
  $D^{(*)}\bar{D}^{(*)}$ decays are suppressed.
  - `Kou Pene PLB 631 (2005) 164`

close or above the threshold

tetraquarks

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.
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The QCD spectrum with light quarks

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States made of two heavy and light quarks

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- Tetraquark states.

MAIANI, PICCININI, POLOSA ET AL. 2005--

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

Having the spectrum of tetraquark potentials, like we have for the gluonic excitations, would allow us to build a plethora of states on each of the tetraquark potentials, many of them developing a width due to decays through pion (or other light hadrons) emission. Diquarks have been recently investigated on the lattice.

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

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States made of two heavy and light quarks

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- Pairs of heavy-light baryons.
  - `Qiao PLB 639 (2006) 263`
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MAIANI, PICCININI, POLOSA ET AL. 2005--

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(hadro-quarkonium). Voloshin

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Maiani, Piccinini, Polosa et al. 2005--

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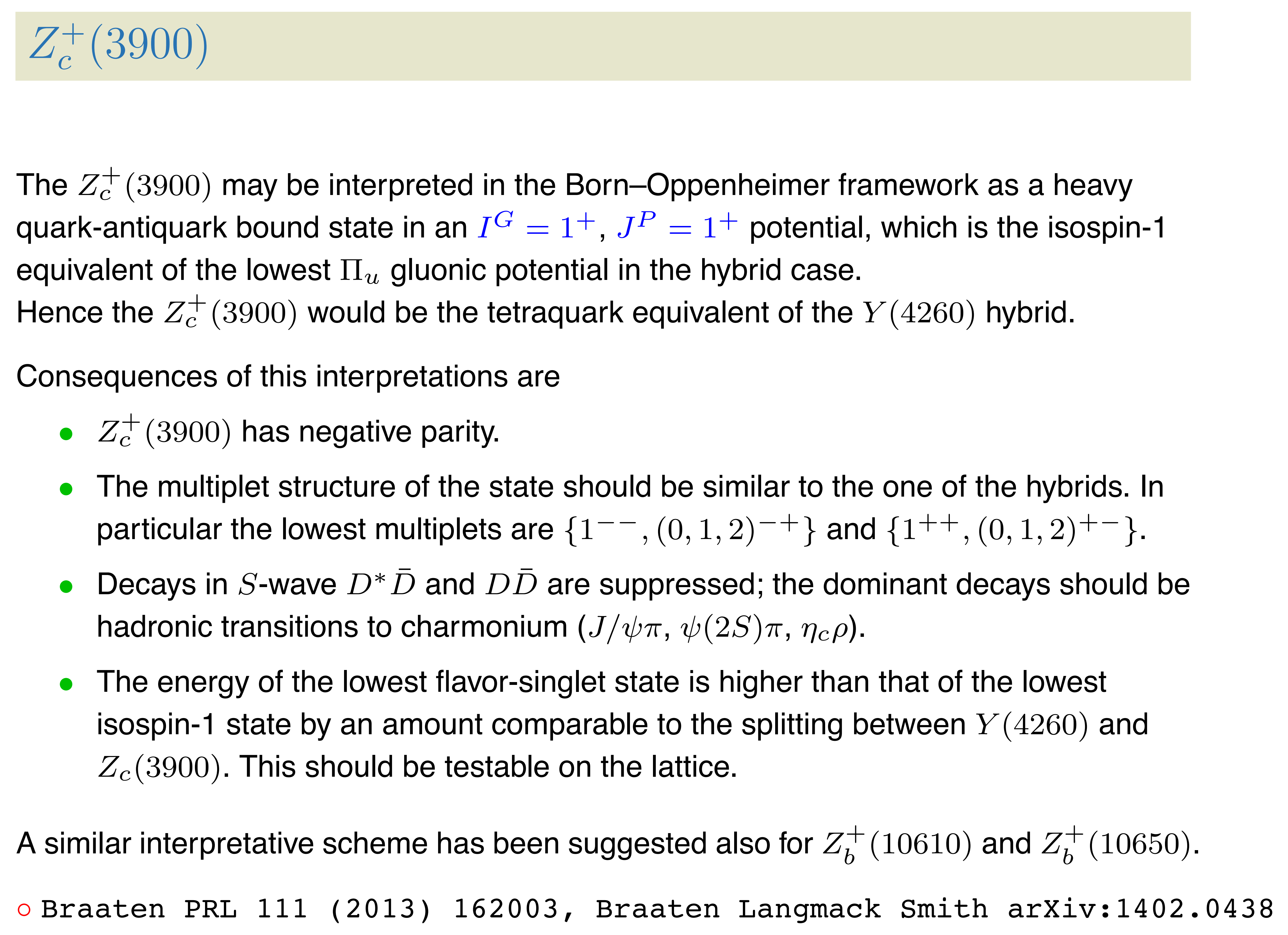
  - Alexandrou et al. PRL 97(06)222002
  - Fodor et al. PoS LAT2005(06)310

Experimental evidences of new states

- There is accumulating evidence that the $X(3872)$ is a four quark state.
  - `Pakvasa Suzuki PLB 579 (2004) 67`
  - `Voloshin PLB 579 (2004) 316, 598 (2004) 69`
  - `Braaten Kusunoki PRD 69 (2004) 074005, 72 (2005) 014012`
  - `Hanhart Kalashnikova Kudryavtsev Nefediev PRD 76 (2007) 034007`

- Clear evidence for four-quark states may be provided by charged resonances: $Z^+(4430)$, $Z_1^+(4050)$, $Z_2^+(4250)$ (seen by BELLE but unconfirmed), $Z_c^+(3900)$ (seen by BES, BELLE, CLEO$_c$), $Z_c^+(4025)$ (BES), $Z_b^+(10610)$, $Z_b^+(10650)$ (BELLE).



$Z_c^+(3900)$

The $Z_c^+(3900)$ may be interpreted in the Born–Oppenheimer framework as a heavy quark-antiquark bound state in an $I^G = 1^+$, $J^P = 1^+$ potential, which is the isospin-1 equivalent of the lowest Π_u gluonic potential in the hybrid case.
Hence the $Z_c^+(3900)$ would be the tetraquark equivalent of the $Y(4260)$ hybrid.

Consequences of this interpretations are

- $Z_c^+(3900)$ has negative parity.
- The multiplet structure of the state should be similar to the one of the hybrids. In particular the lowest multiplets are $\{1^{--}, (0,1,2)^{-+}\}$ and $\{1^{++}, (0,1,2)^{+-}\}$.
- Decays in S-wave $D^*\bar{D}$ and $D\bar{D}$ are suppressed; the dominant decays should be hadronic transitions to charmonium ($J/\psi\pi$, $\psi(2S)\pi$, $\eta_c\rho$).
- The energy of the lowest flavor-singlet state is higher than that of the lowest isospin-1 state by an amount comparable to the splitting between $Y(4260)$ and $Z_c(3900)$. This should be testable on the lattice.

A similar interpretative scheme has been suggested also for $Z_b^+(10610)$ and $Z_b^+(10650)$.

○ `Braaten PRL 111 (2013) 162003, Braaten Langmack Smith arXiv:1402.0438`

lattice is also devising ways to calculate this state

S. Prelovsek et al 1405.7623

Conclusions

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For states below threshold such a theory exists and allows for a systematic study of the quarkonium lowest resonances. Higher resonances may need to be supplemented by lattice data. High quality lattice data have become available in the last years for some fundamental quantities (e.g. potentials, decay matrix elements, ...).

● Precision physics is possible but also requires the accurate determination of some observables (e.g. χ_c widths).

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For states above threshold the picture appears less certain. Many degrees of freedom show up, and the absence of a clear systematics appears as an obstacle to an universal picture, although the EFT approach that leads to the Born–Oppenheimer approximation seems to provide a rather general and promising framework. In some other cases, descriptions have been found that suite specific families of states, the near threshold molecular states providing an example.

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- Fundamental experimental input (like confirmation, quantum numbers, widths and masses) is still crucially missing for some of these states.

QCD and strongly coupled gauge theories: challenges and perspectives

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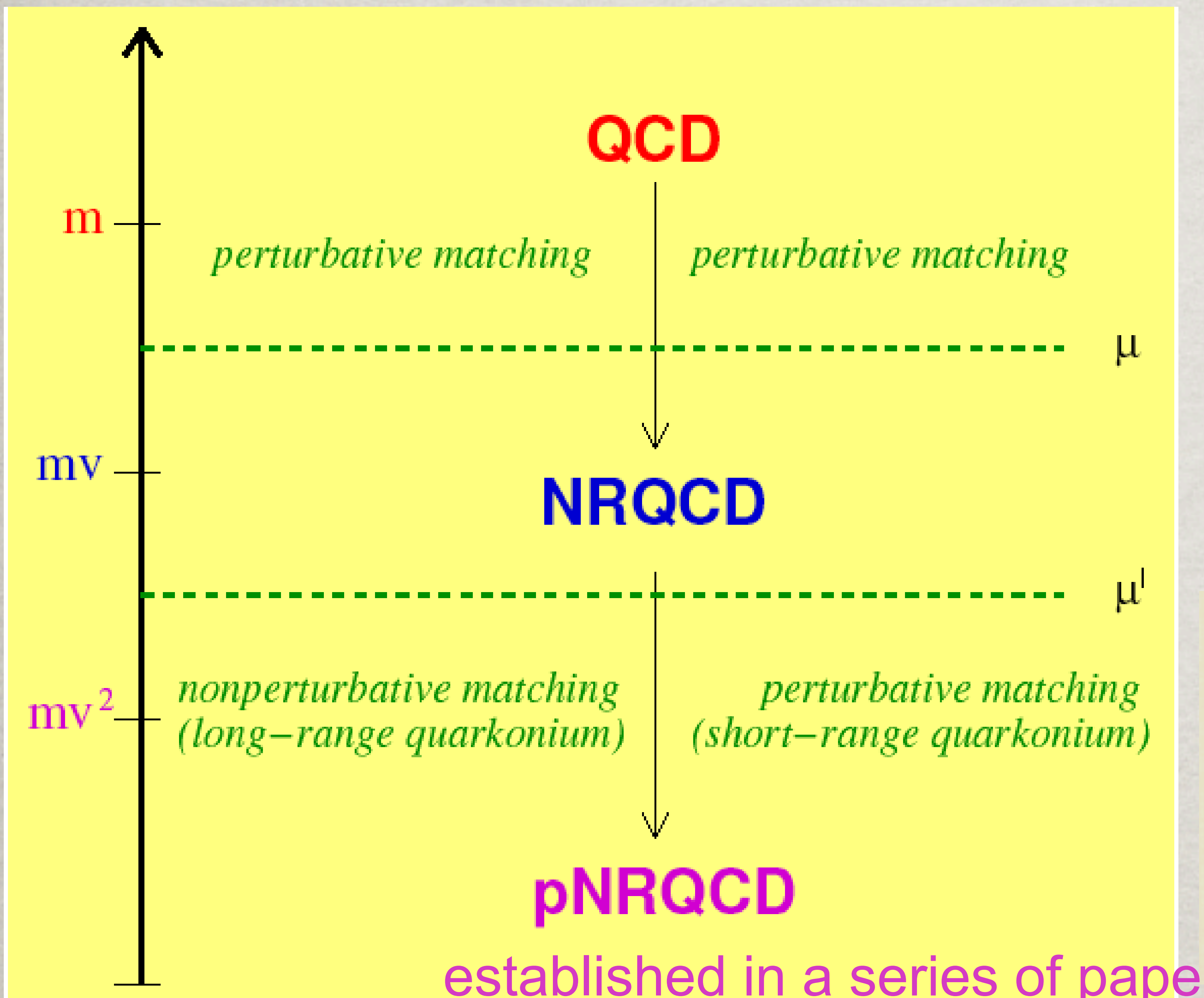
M. Faber[‡,13] J.L. Goity[‡,14,15] B. Ketzer[‡§,1] H.W. Lin[‡,16] F.J. Llanes-Estrada[‡,17]
H.B. Meyer[‡,18] P. Pakhlov[‡,19,20] E. Pallante[‡,21] M.I. Polikarpov[‡,19,20] H. Sazdjian[‡,22]
A. Schmitt[‡,23] W.M. Snow[‡,24] A. Vairo[‡,1] R. Vogt[‡,25,26] A. Vuorinen[‡,27] H. Wittig[‡,18]
P. Arnold,[28] P. Christakoglou,[29] P. Di Nezza,[30] Z. Fodor,[31,32,33] X. Garcia i Tormo,[34] R. Höllwieser,[13]
M.A. Janik,[35] A. Kalweit,[36] D. Keane,[37] E. Kiritsis,[38,39,40] A. Mischke,[41] R. Mizuk,[19,42]
G. Odyniec,[43] K. Papadodimas,[21] A. Pich,[44] R. Pittau,[45] J.-W. Qiu,[46,47] C. Ricciardi,[48,49]
C.A. Salgado,[50] K. Schwenzer,[7] N.G. Stefanis,[51] G.M. von Hippel,[18] and V.I. Zakharov[11,19]

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

Quarkonium with EFT



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

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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->

established in a series of papers:
Pineda, Soto 97, N.B., Pineda, Soto, Vairo 99
N.B. Vairo, Pineda, Soto 00--014
N.B., Pineda, Soto, Vairo Review of Modern Physis 77(2005) 1423