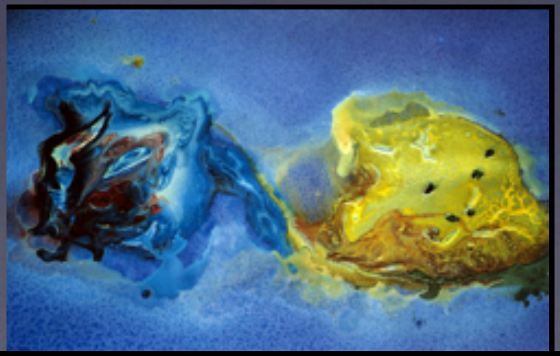
TECHNISCHE
UNIVERSITÄT
MÜNCHEN

HEAVY EXOTICS STATES with Effective Field Theories

NORA BRAMBILLA



PHYSIK DEPARTMENT TUM
T30F

- definition, importance, occurrence of heavy exotic states

- the state of the art theory tools

- Calculation of hybrids masses

QCD and strongly coupled gauge theories: challenges and perspectives

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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.

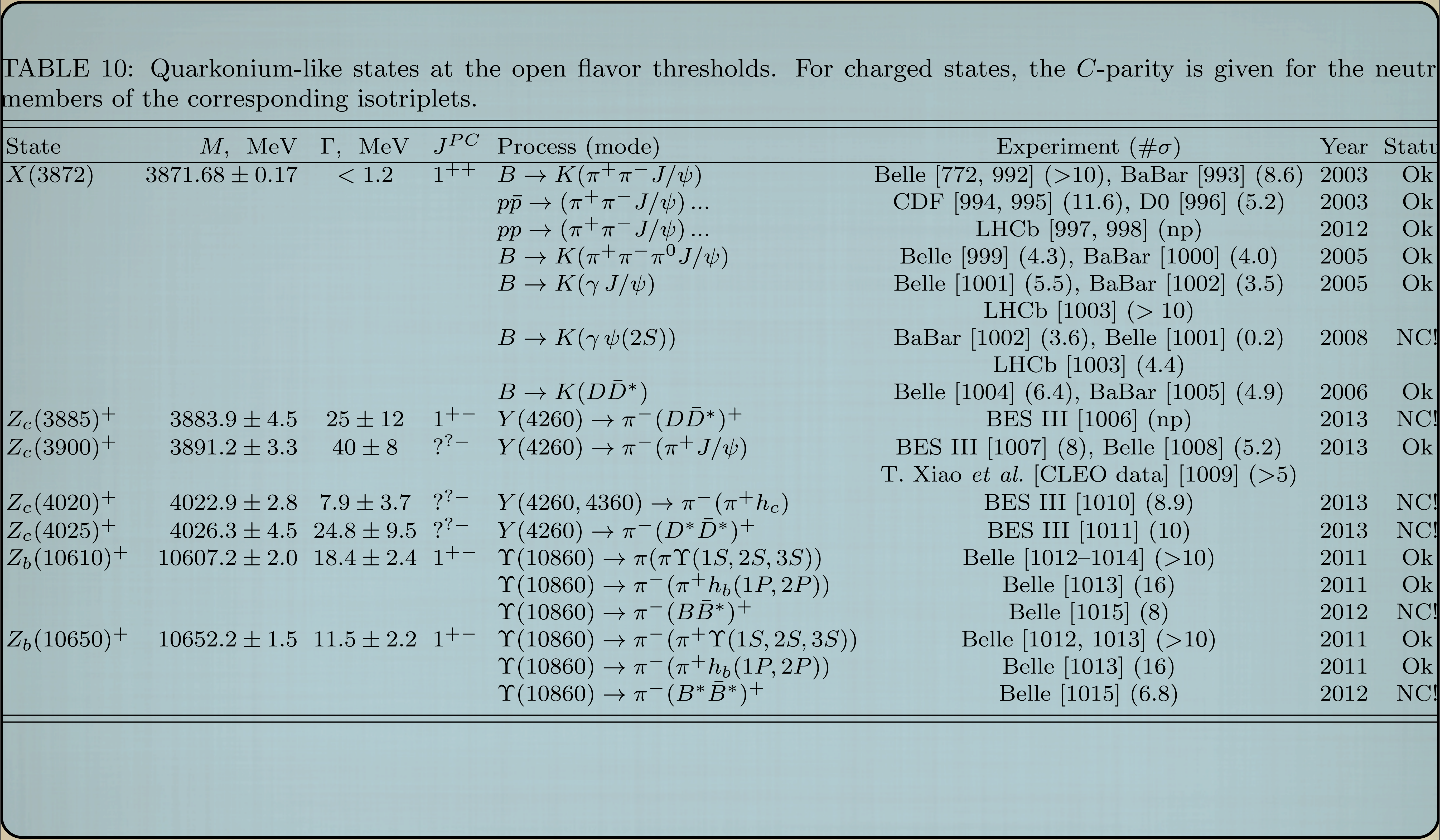


TABLE 10: Quarkonium-like states at the open flavor thresholds. For charged states, the C-parity is given for the neutr
members of the corresponding isotriplets.

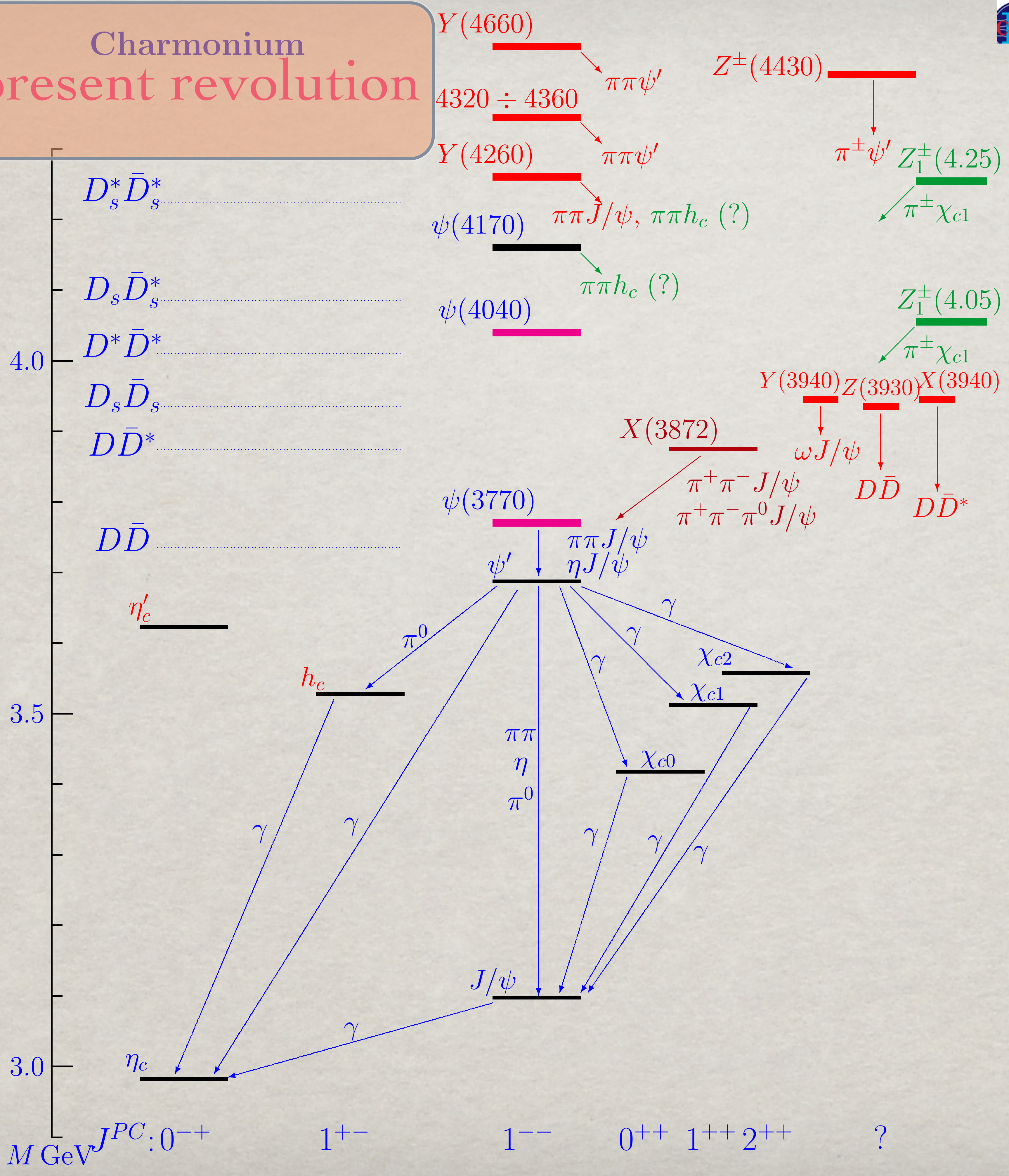
State	M, MeV	Γ, MeV	J^{PC}	Process (mode)	Experiment (#σ)	Year	Statu
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$B \to K(\pi^+\pi^- J/\psi)$	Belle [772, 992] (>10), BaBar [993] (8.6)	2003	Ok
				$p\bar{p} \to (\pi^+\pi^- J/\psi) \ldots$	CDF [994, 995] (11.6), D0 [996] (5.2)	2003	Ok
				$pp \to (\pi^+\pi^-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

arXiv:1404.3723v1

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!

Charmonium
the present revolution



THE COLLIDER DETECTOR AT FERMILAB

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Collaboration Home Page

BES

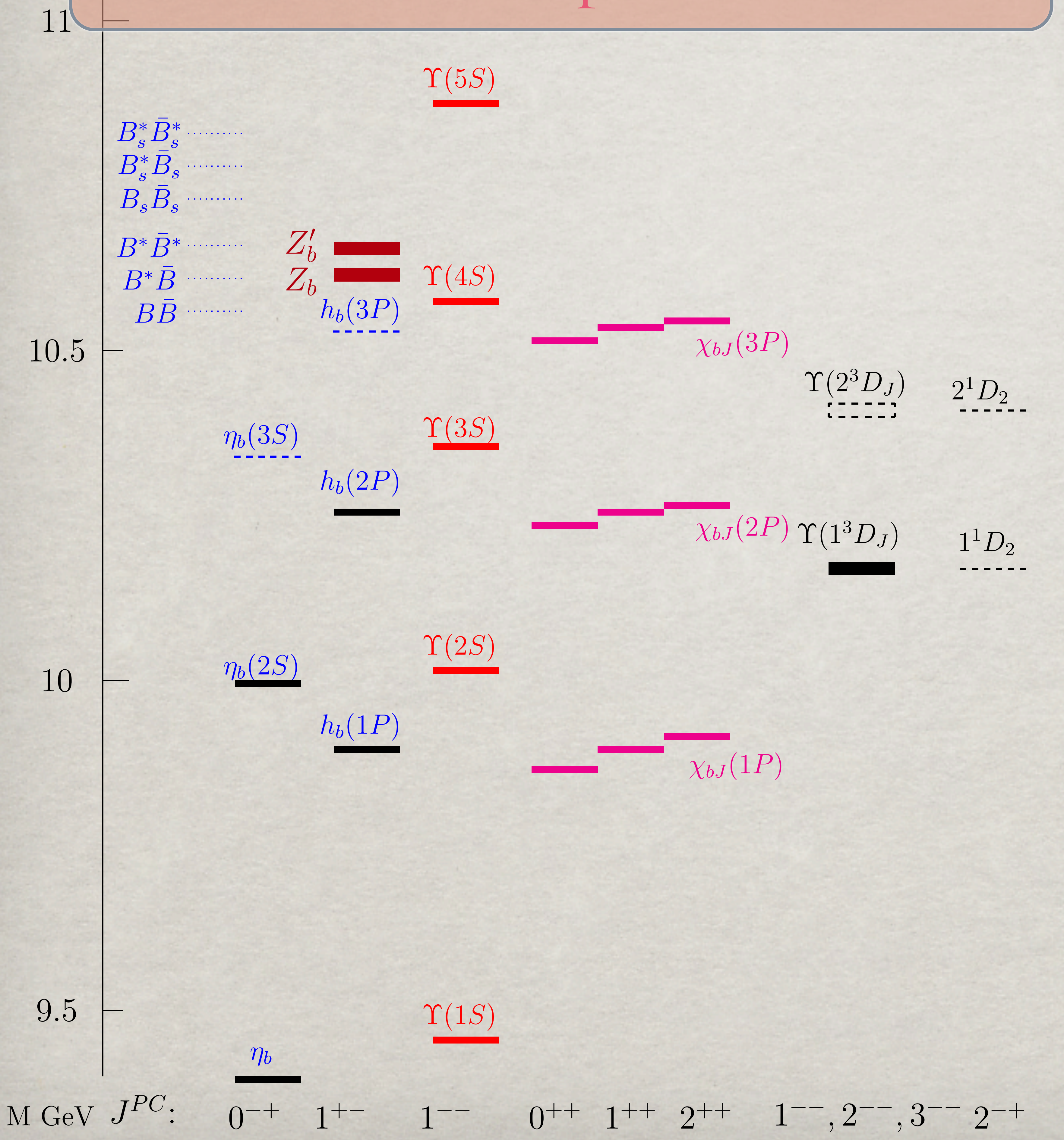
CLEO

ATLAS

CMS

LHCb

bottomonium: the present revolution



THE COLLIDER DETECTOR AT FERMILAB

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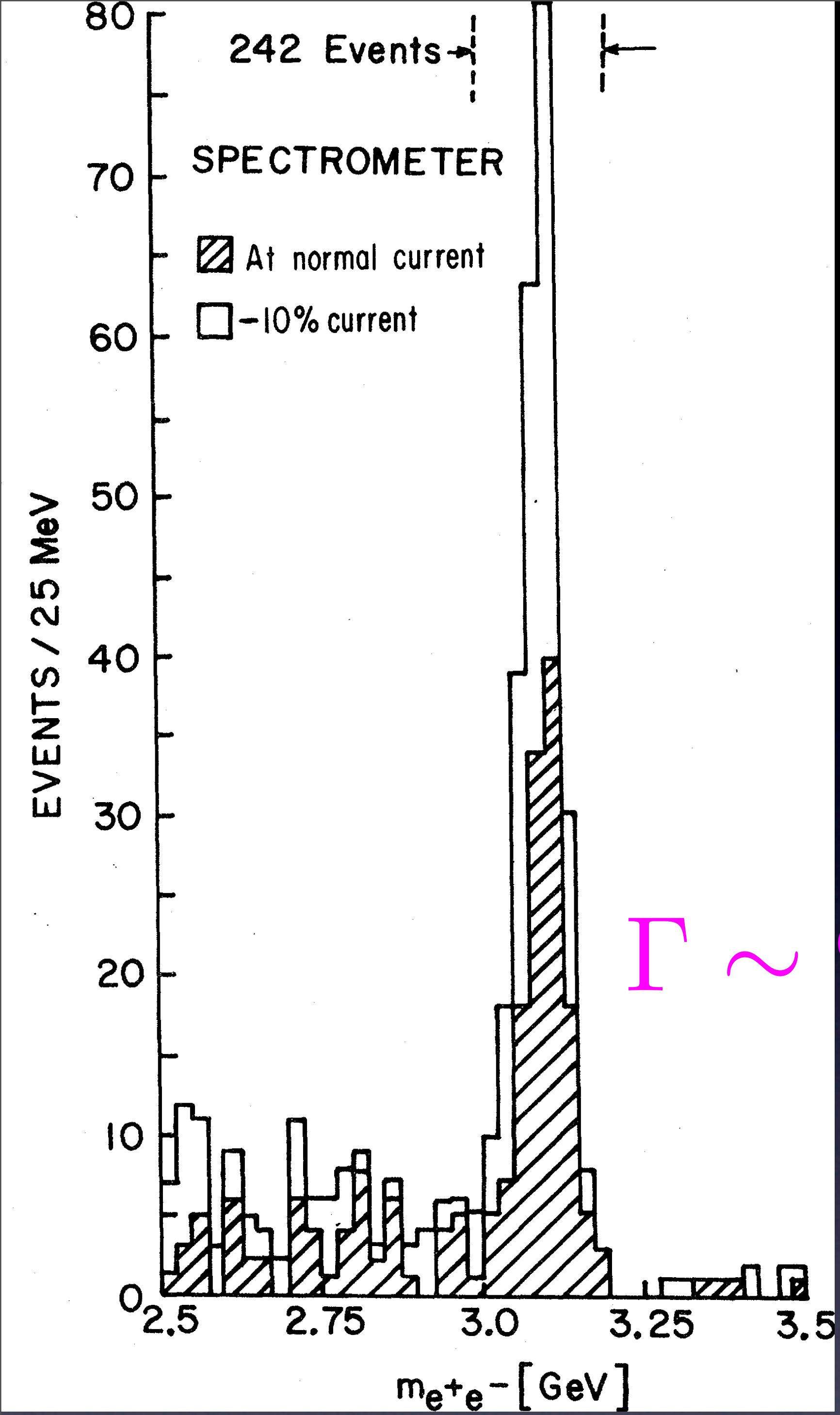
Quarkonium (=bound state of a heavy quark and a heavy antiquark) has been instrumental for the establishing of QCD, the theory of strong interaction, and the Standard Model of Particle

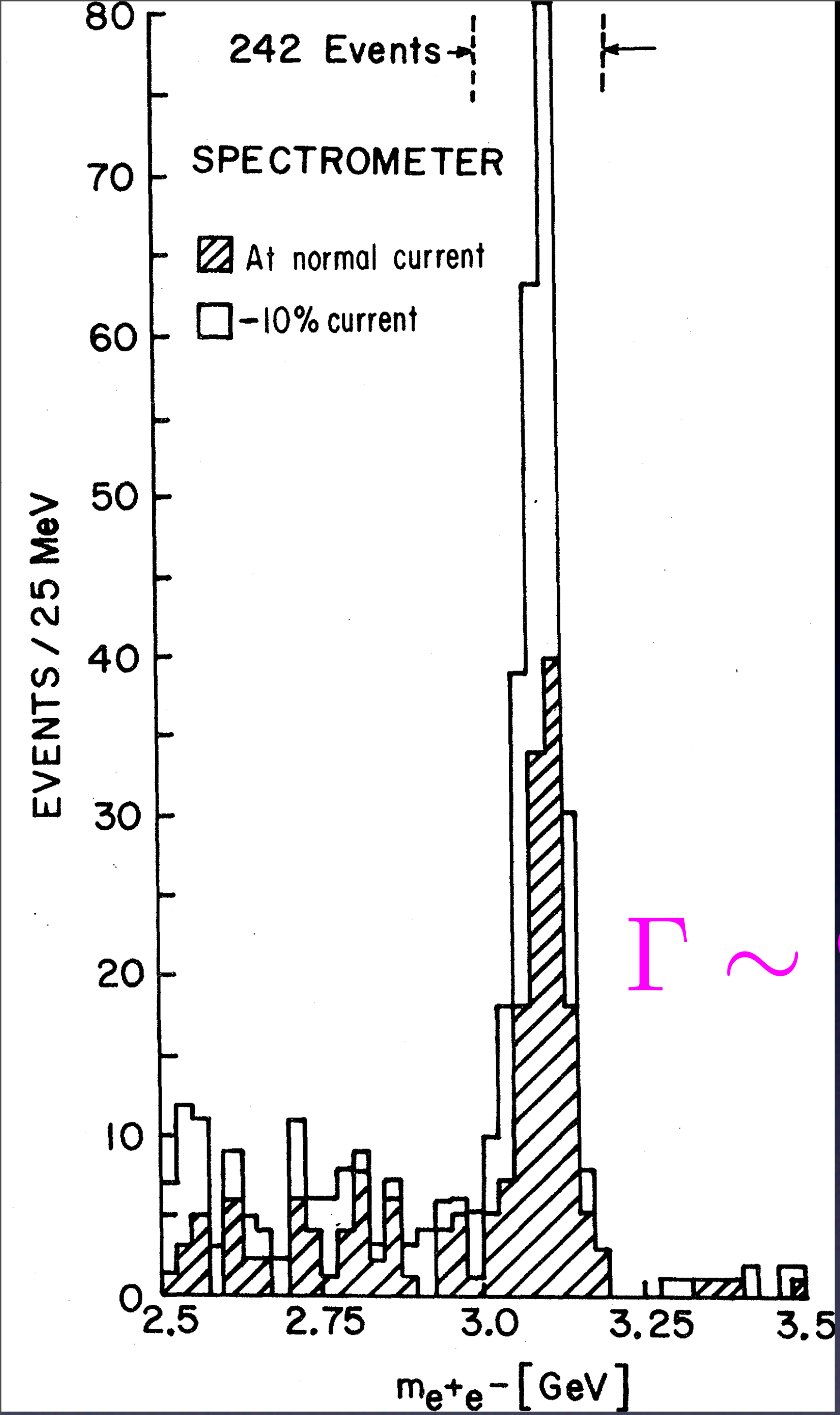
The November revolution in 1974: the J/ψ discovery



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

Aubert et al. BNL 74

The November revolution in 1974: the J/ψ discovery



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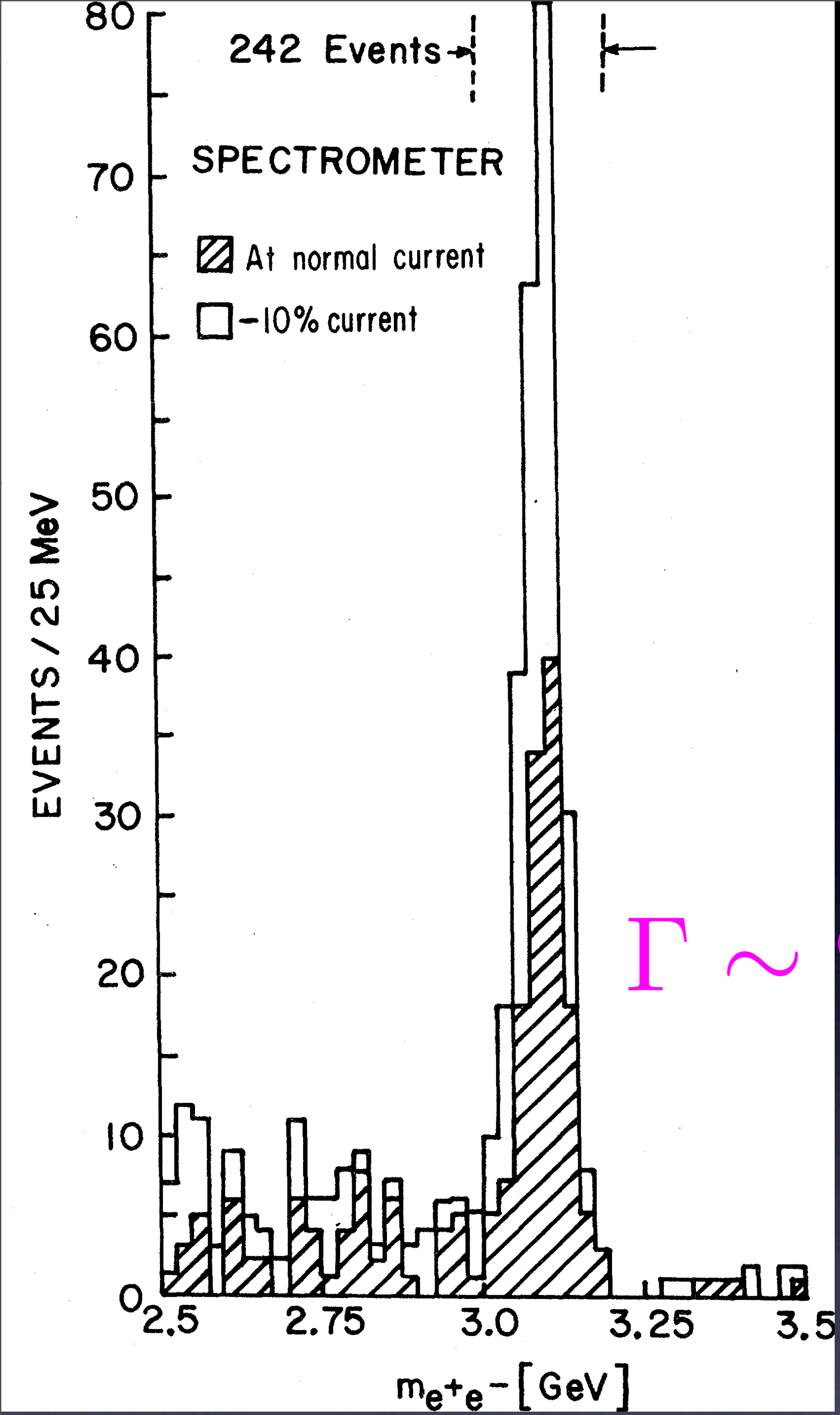
Aubert et al. BNL 74

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

The November revolution in 1974: the J/ψ discovery



Aubert et al. BNL 74

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

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

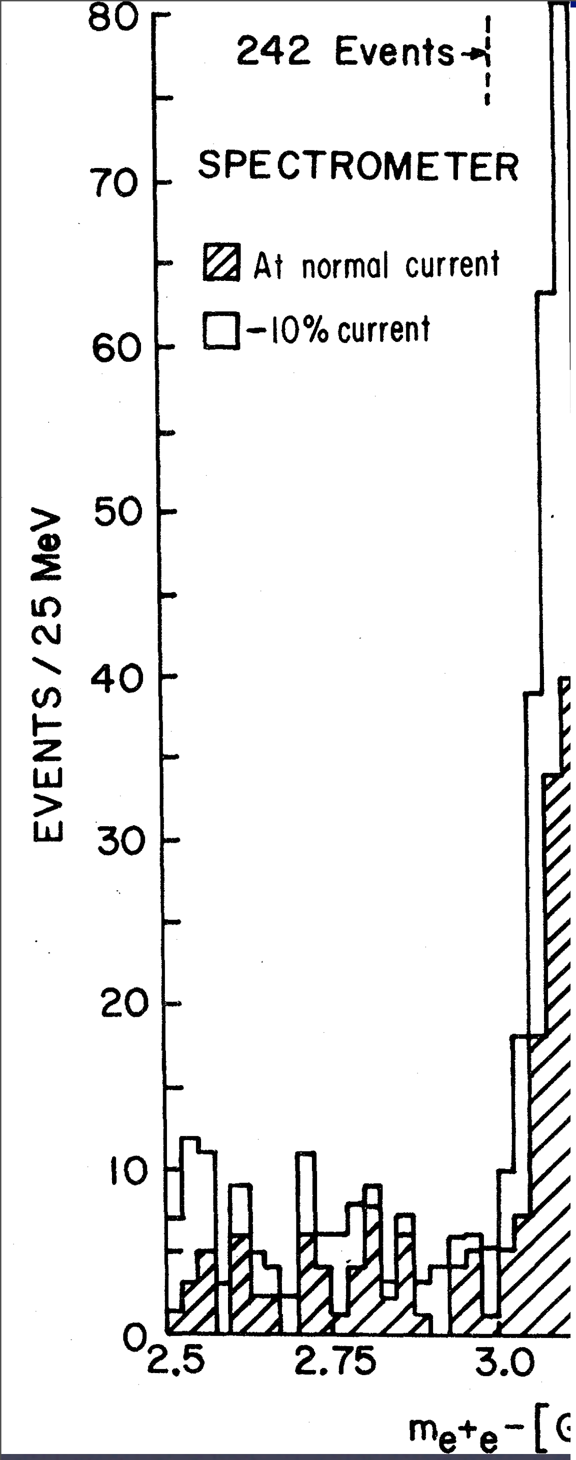
it has been the confirmation of the charm quark prediction and of QCD (strong int theory) foundations

narrow width and asymptotic freedom

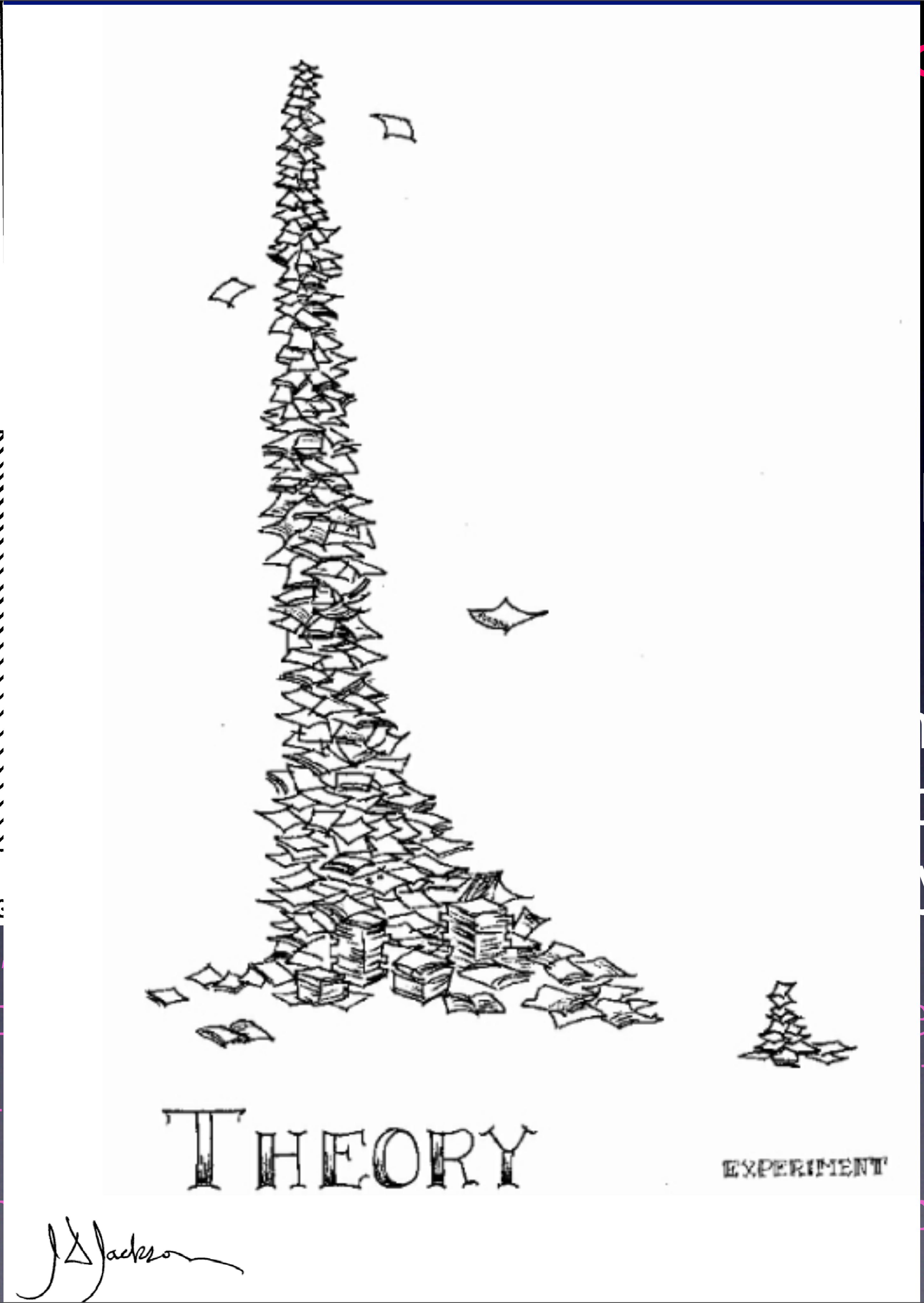
annihilation at large scale controlled by small α_s

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

on in 1974:



Aubert et al. BNL '



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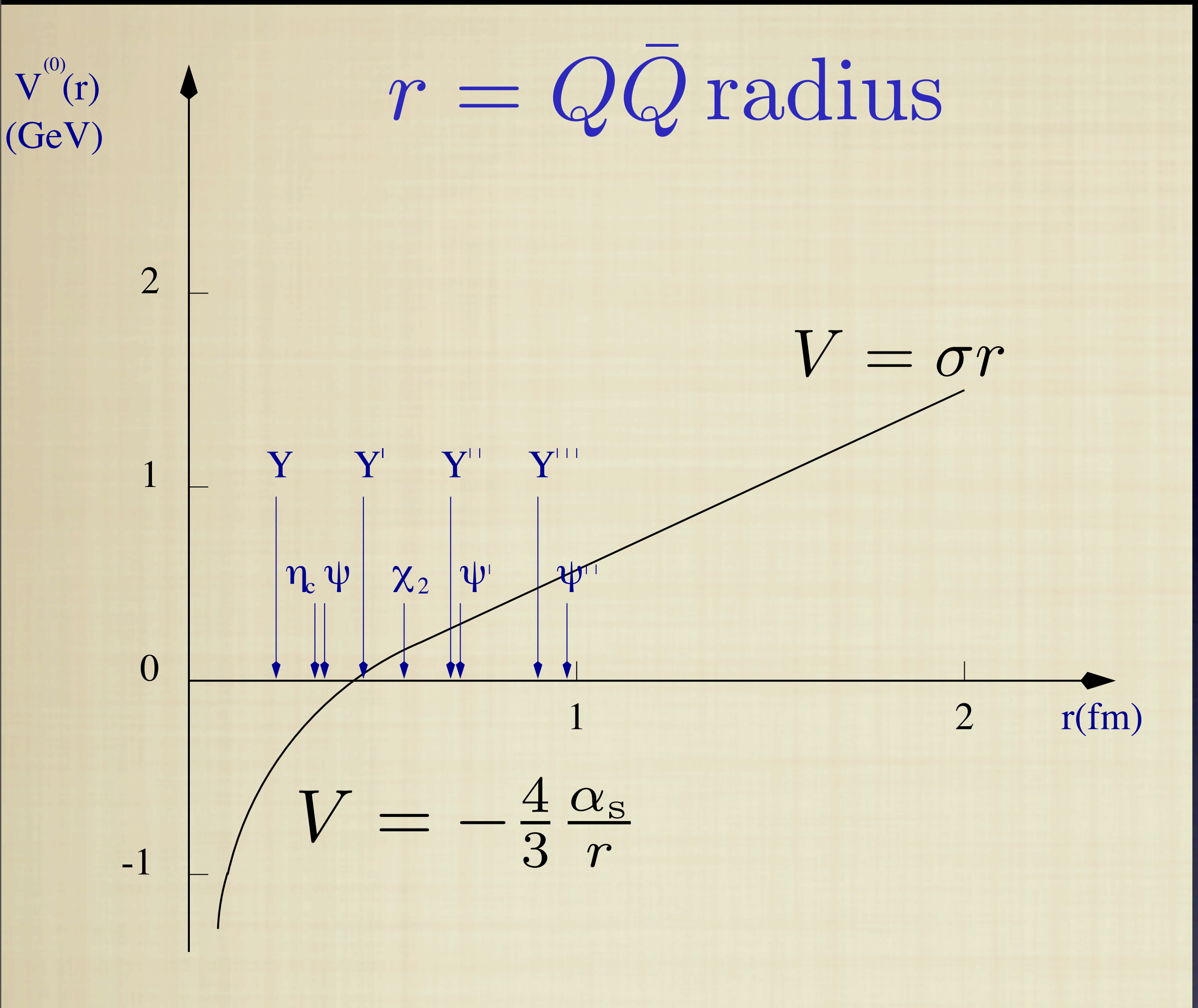
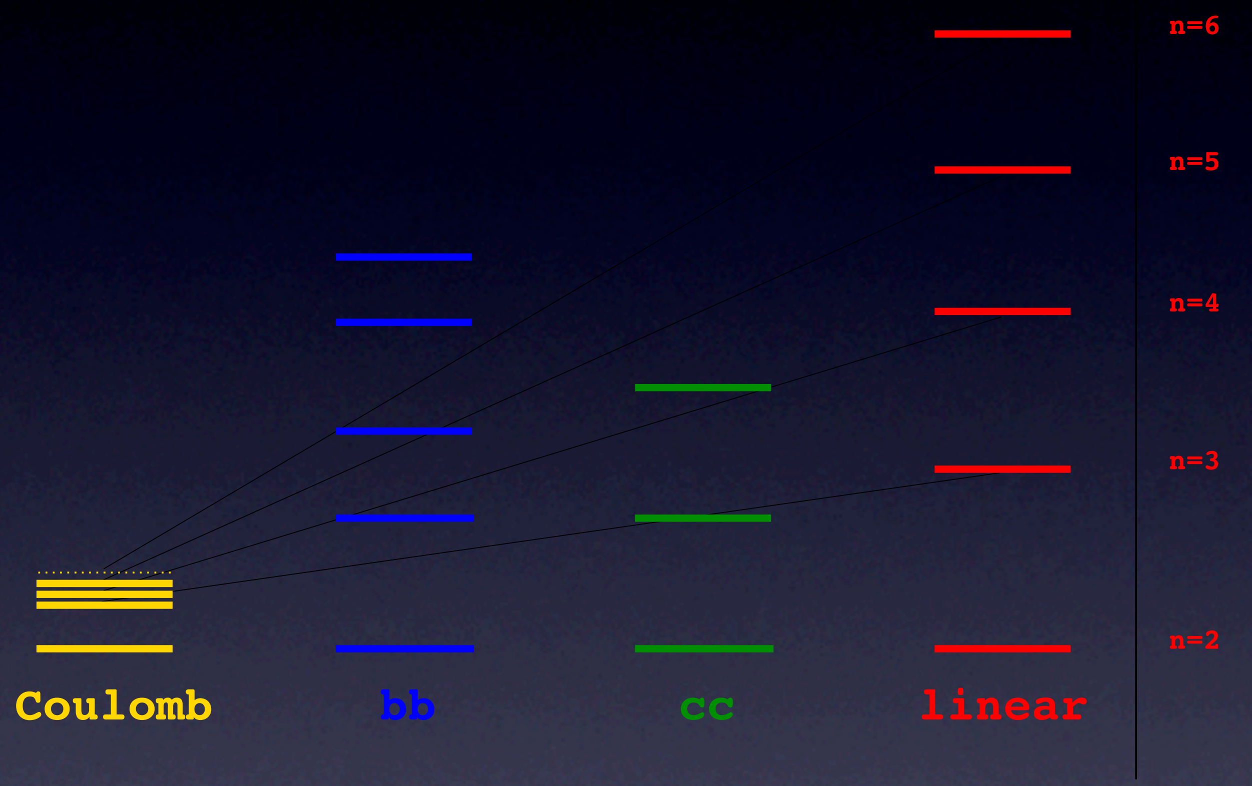
The November revolution in the '70s: more quarkonia



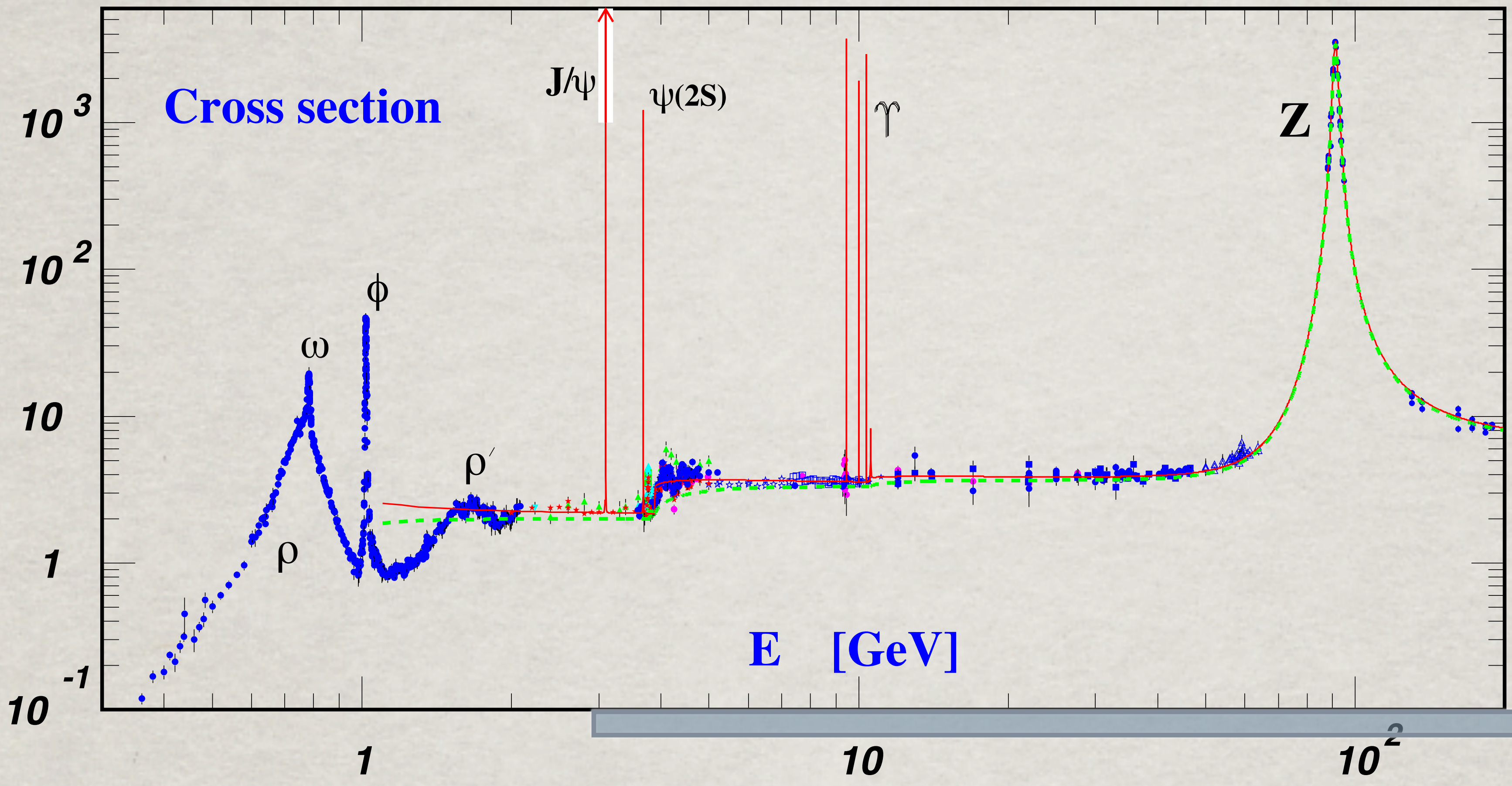
Eichten et al . 75, 78, 80

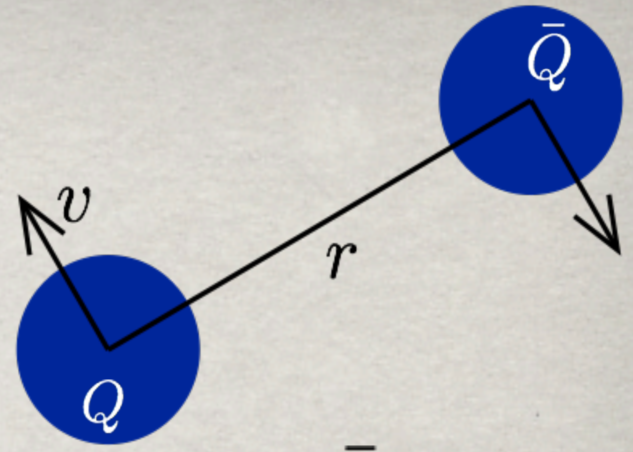


bbar and ccbar energy levels in comparison to
Coulomb and linear potential energy levels

Variety of potential models used
Confinement and asymptotic freedom--> main properties of QCD

Heavy quarks offer a privileged access





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

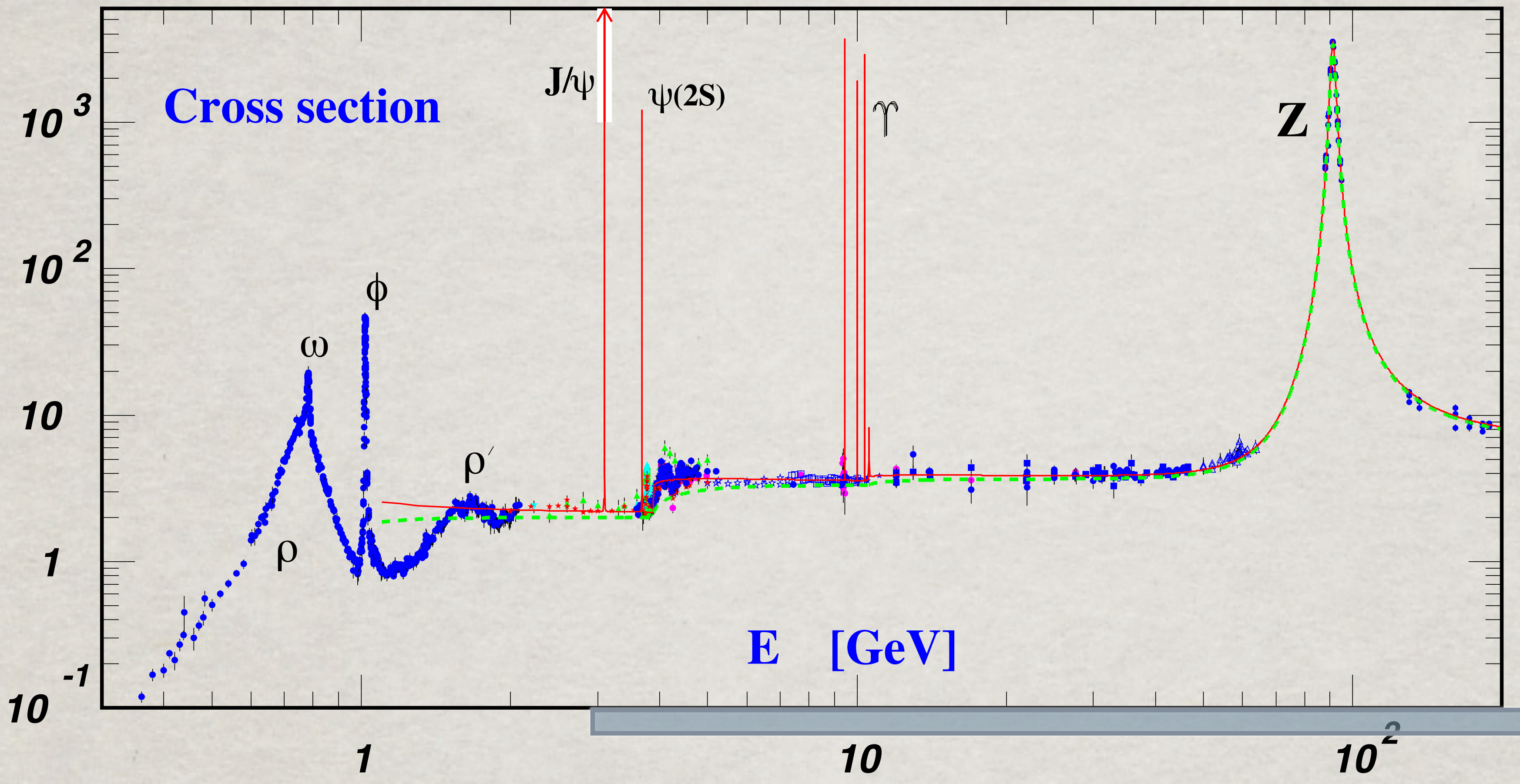
$m_c \sim 1.5$GeV

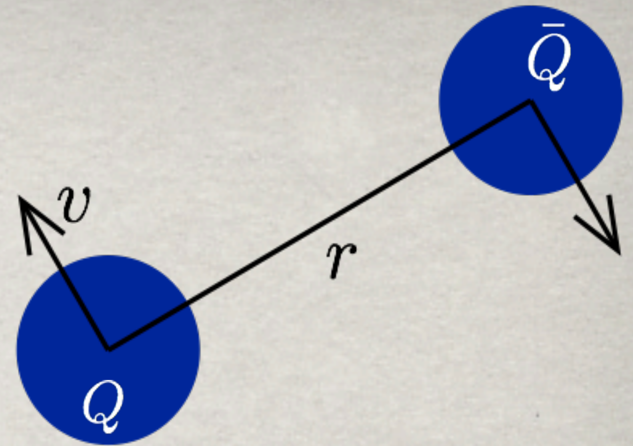
$m_b \sim 5$GeV

$m_t \sim 170$GeV

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

Heavy quarks offer a privileged access





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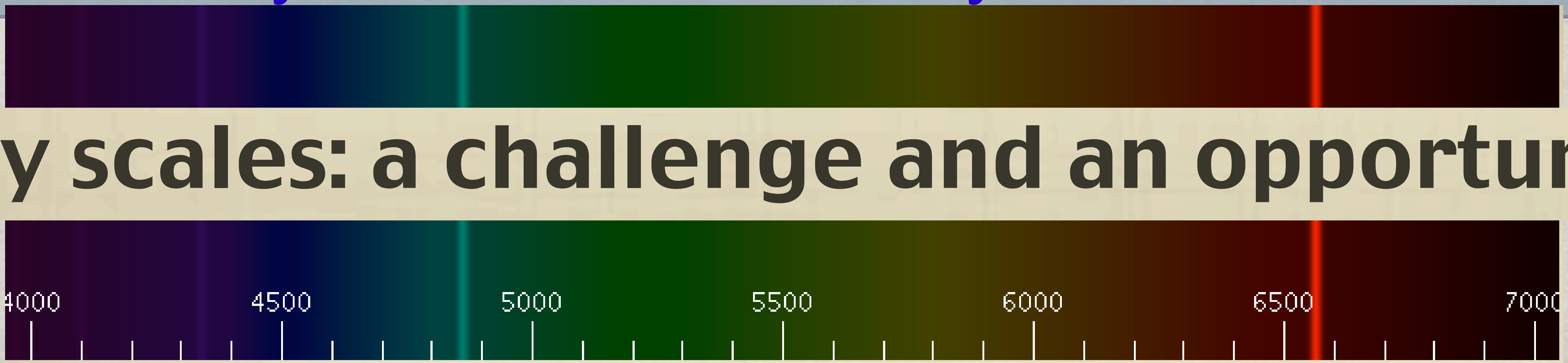
A large scale $m_Q \gg \Lambda_{QCD}$ $\alpha_s(m_Q) \ll 1$

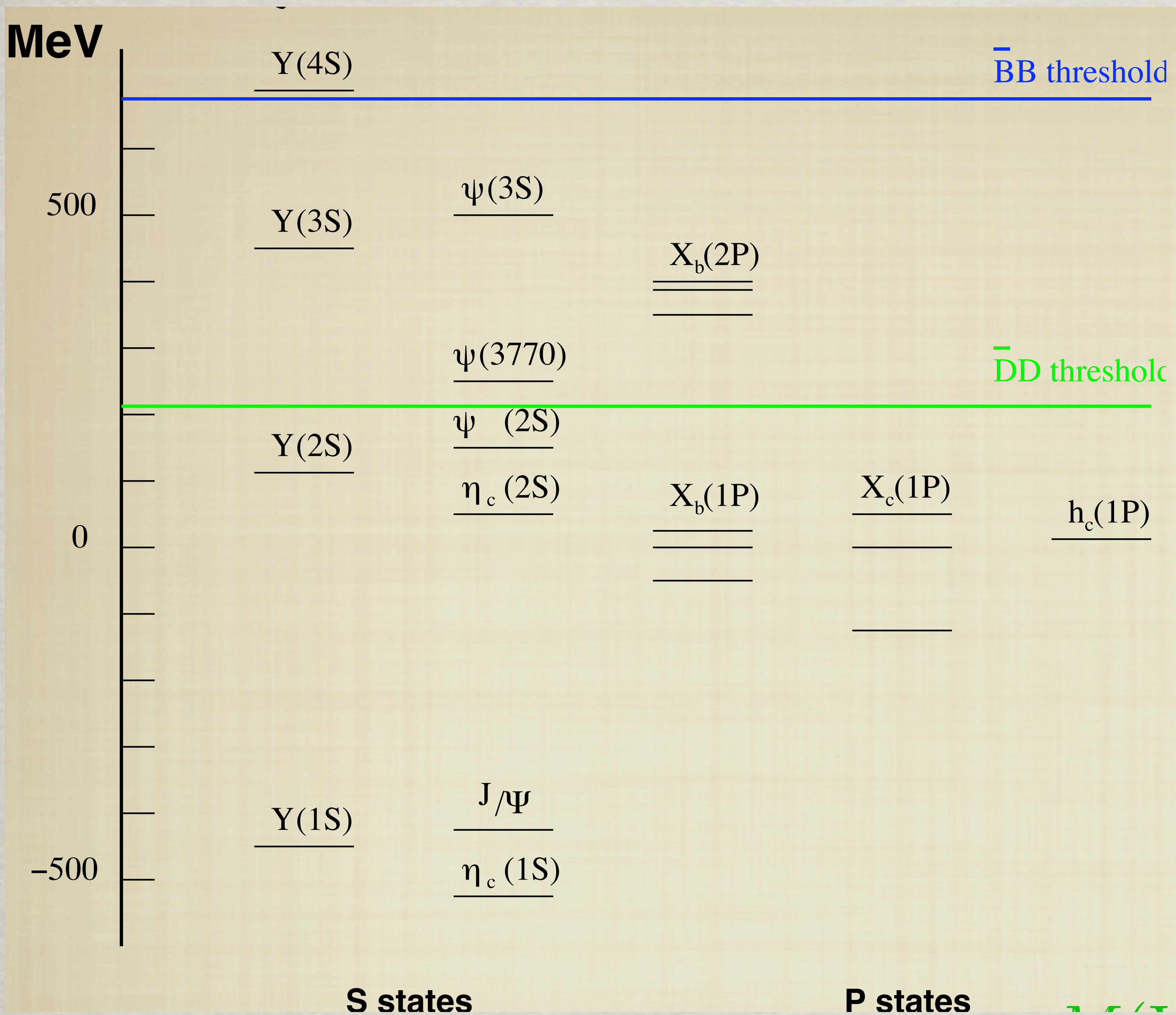
Heavy quarkonia are nonrelativistic bound systems: multiscale systems



many scales: a challenge and an opportunity

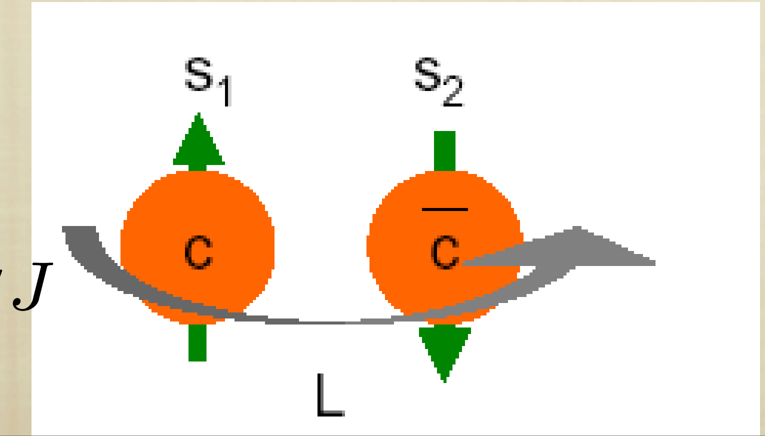
ELECTROMAGNETIC BOUND STATES: ATOMS, MOLECULES,

Quarkonium scales

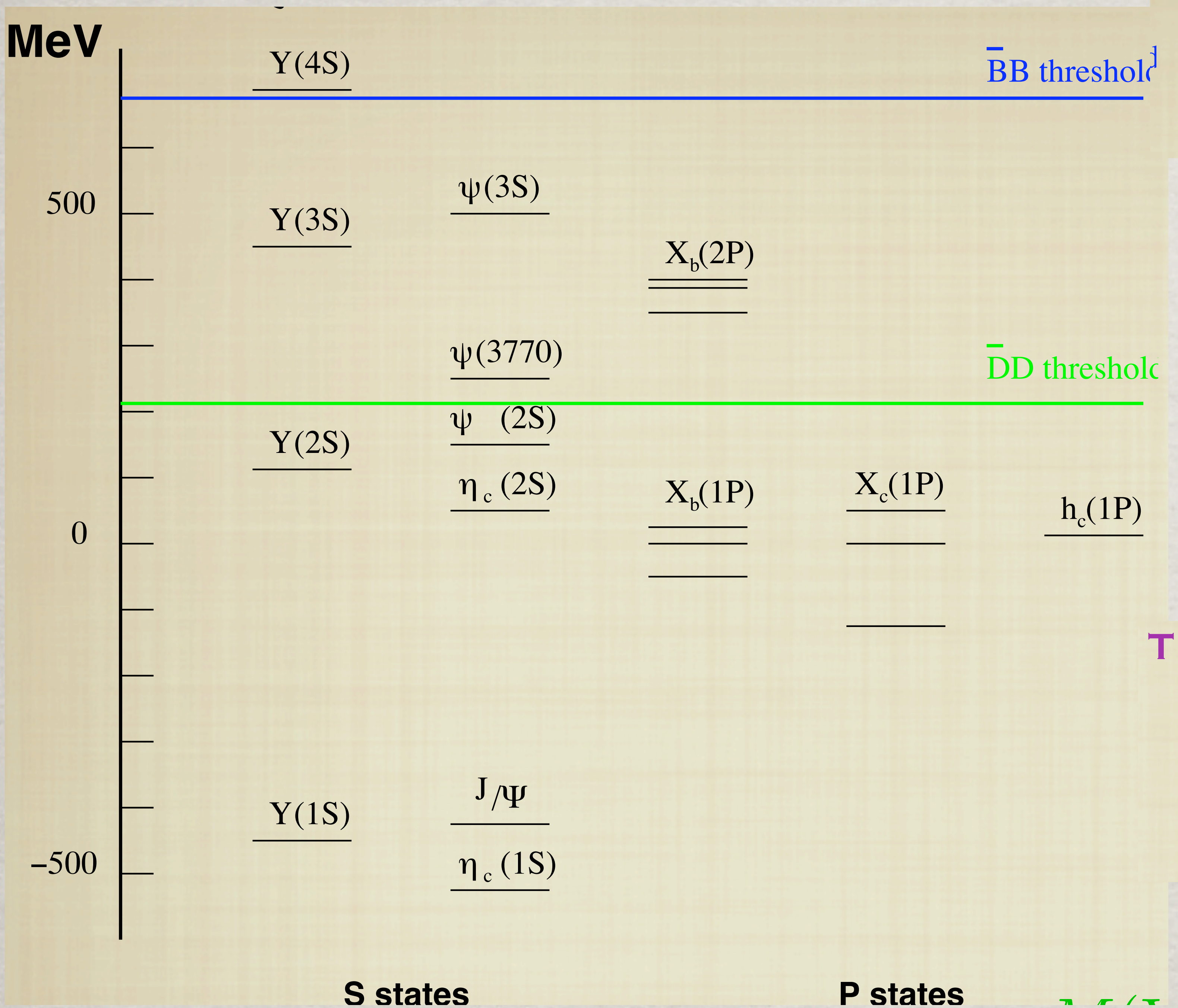


Normalized with respect to $\chi_b(1P)$ and $\chi_c(1P)$

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



Quarkonium scales



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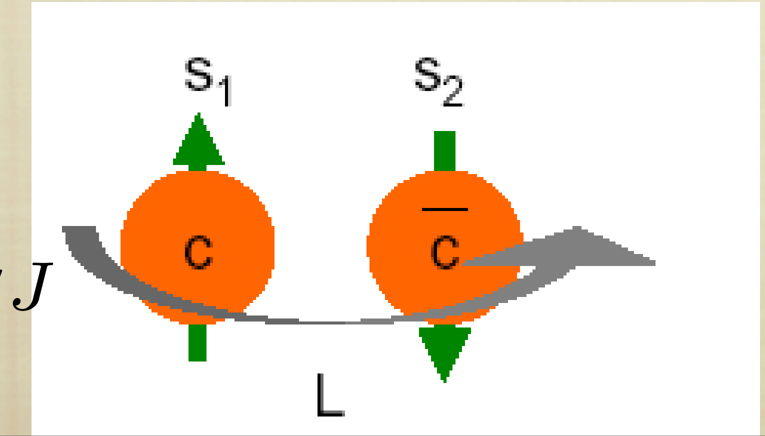


NR BOUND STATES HAVE AT LEAST 3 SCALES

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

$$mv \sim r^{-1}$$

and $\Lambda_{\rm QCD}$

THE SYSTEM IS NONRELATIVISTIC(NR)

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

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

THE MASS SCALE IS PERTURBATIVE

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

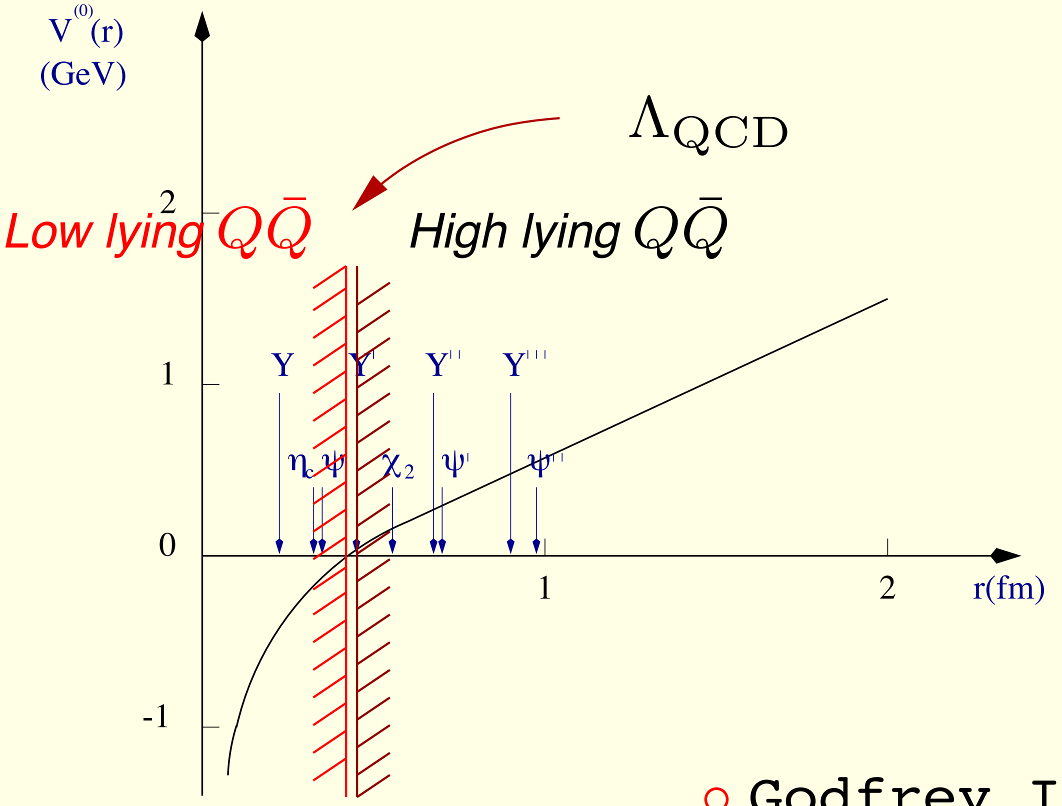
$$m_b \simeq 5\,{\rm GeV}; m_c \simeq 1.5\,{\rm GeV}$$

Quarkonium 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.

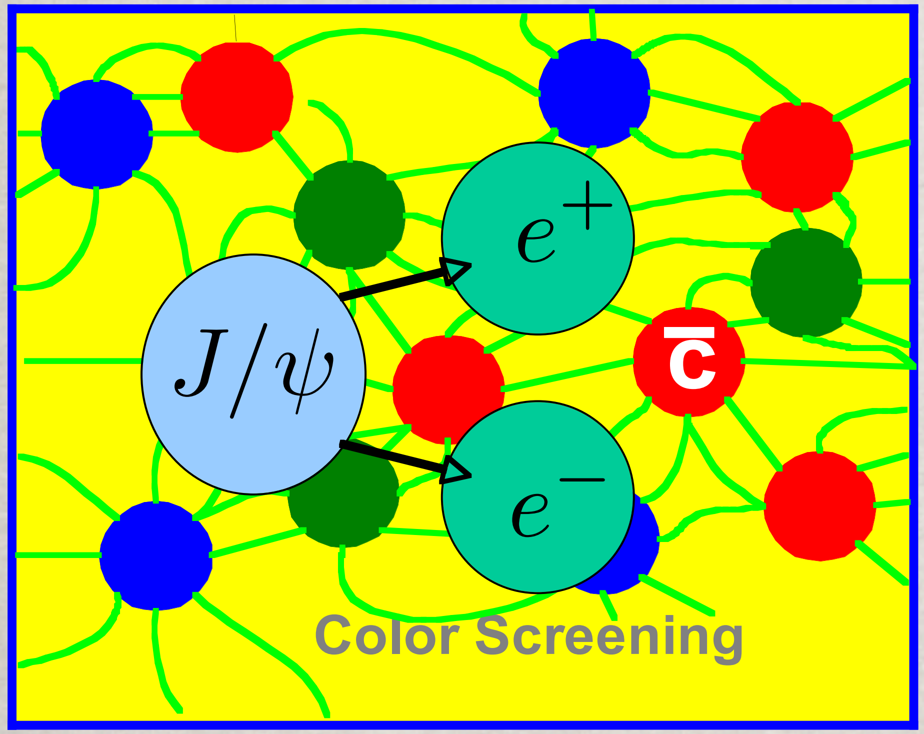


○ Godfrey Isgur PRD 32(85)189

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 $m_D \sim gT$

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

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

Matsui Satz 1986

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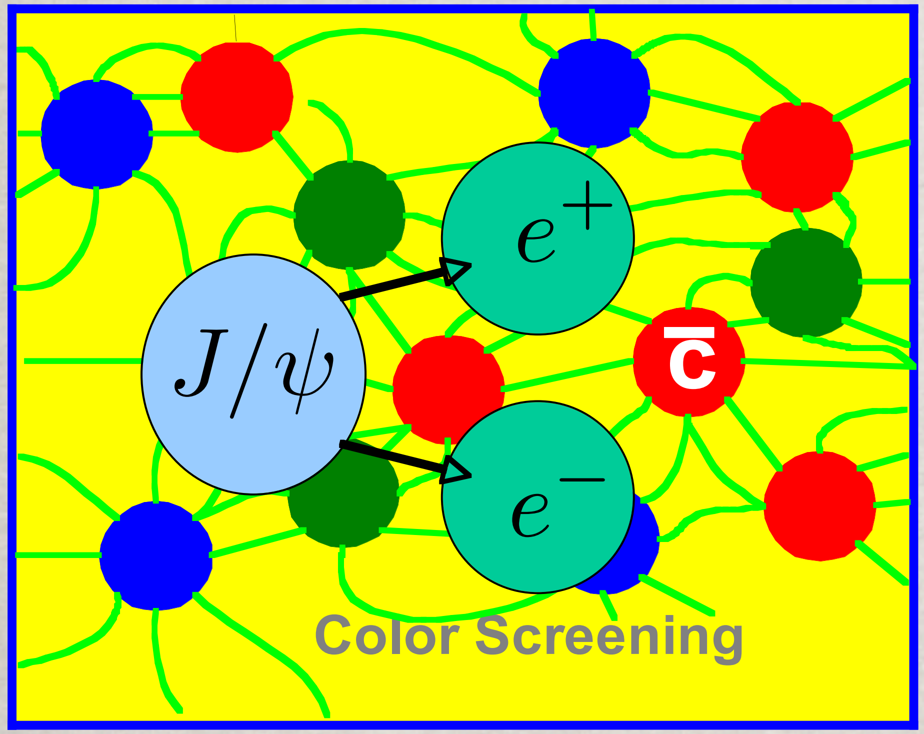

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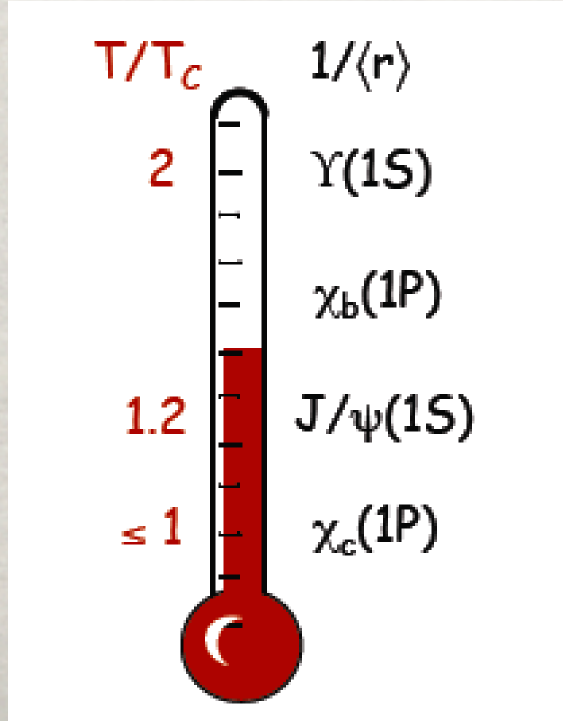
$$V(r) \sim -\alpha_s \frac{e^{-m_D r}}{r}$$

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

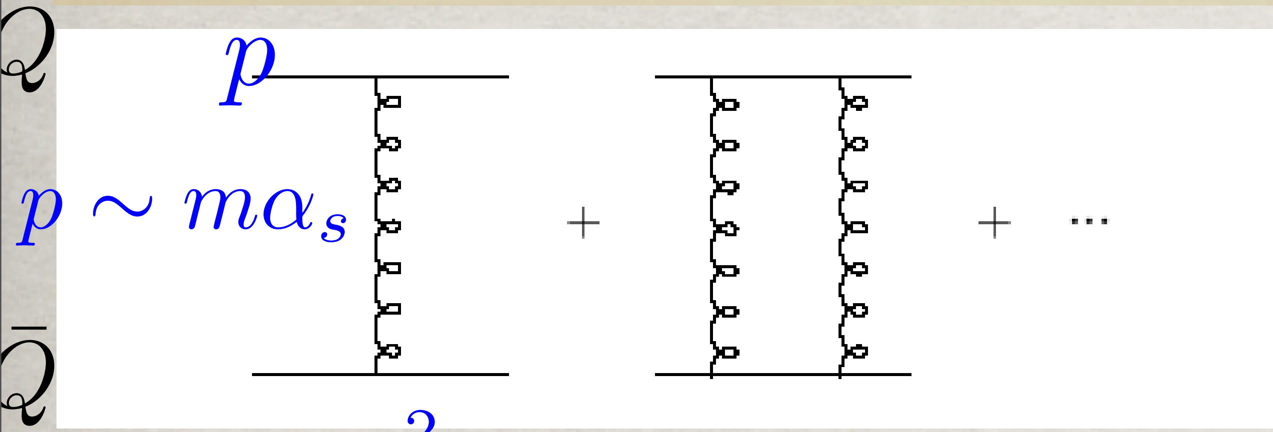
Matsui Satz 1986

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



QCD theory of Quarkonium: a very hard problem

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

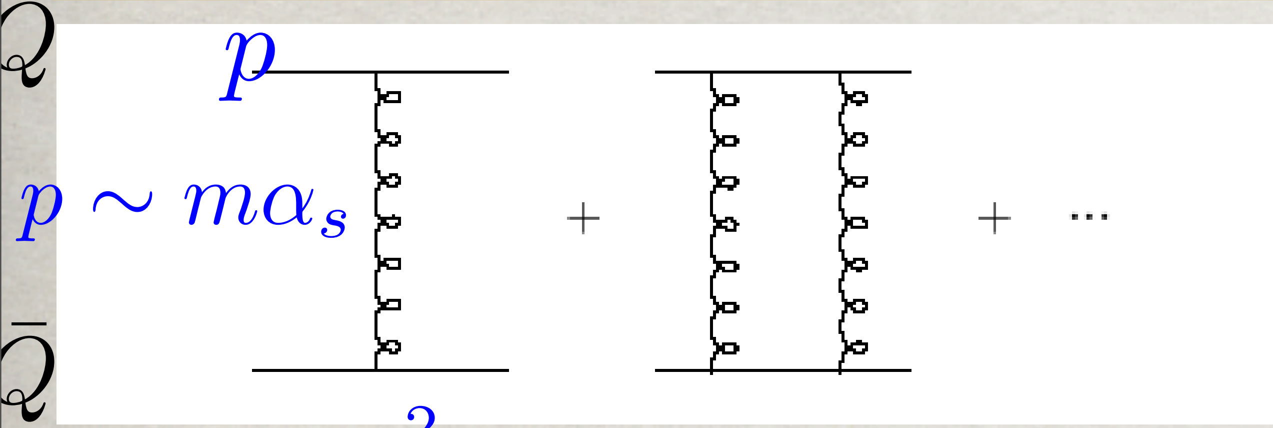


$$\frac{g^2}{p^2}\left(1 + \frac{m\alpha_s}{p}\right)$$

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

QCD theory of Quarkonium: a very hard problem

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



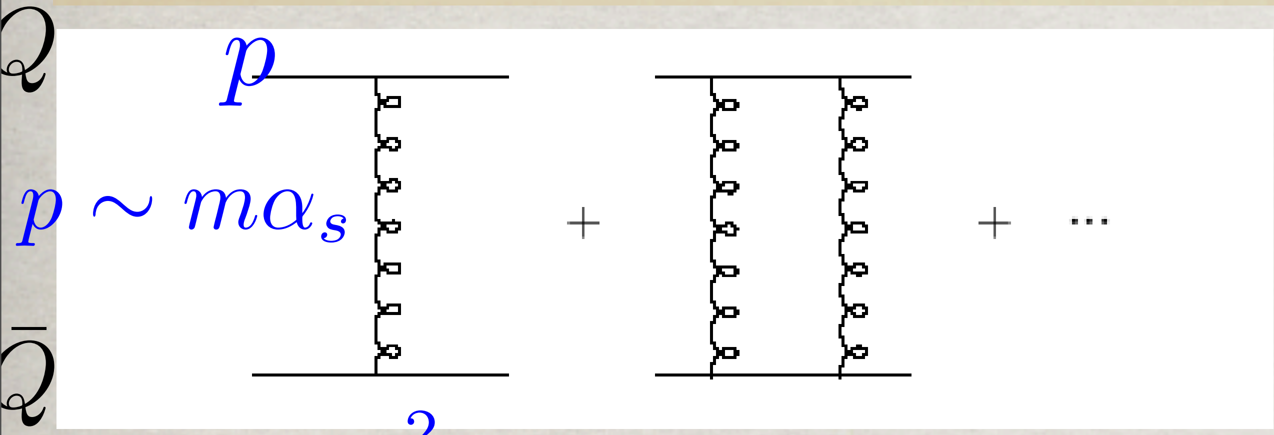
$$\frac{g^2}{p^2}\left(1 + \frac{m\alpha_s}{p}\right)$$

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

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

QCD theory of Quarkonium: a very hard problem

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

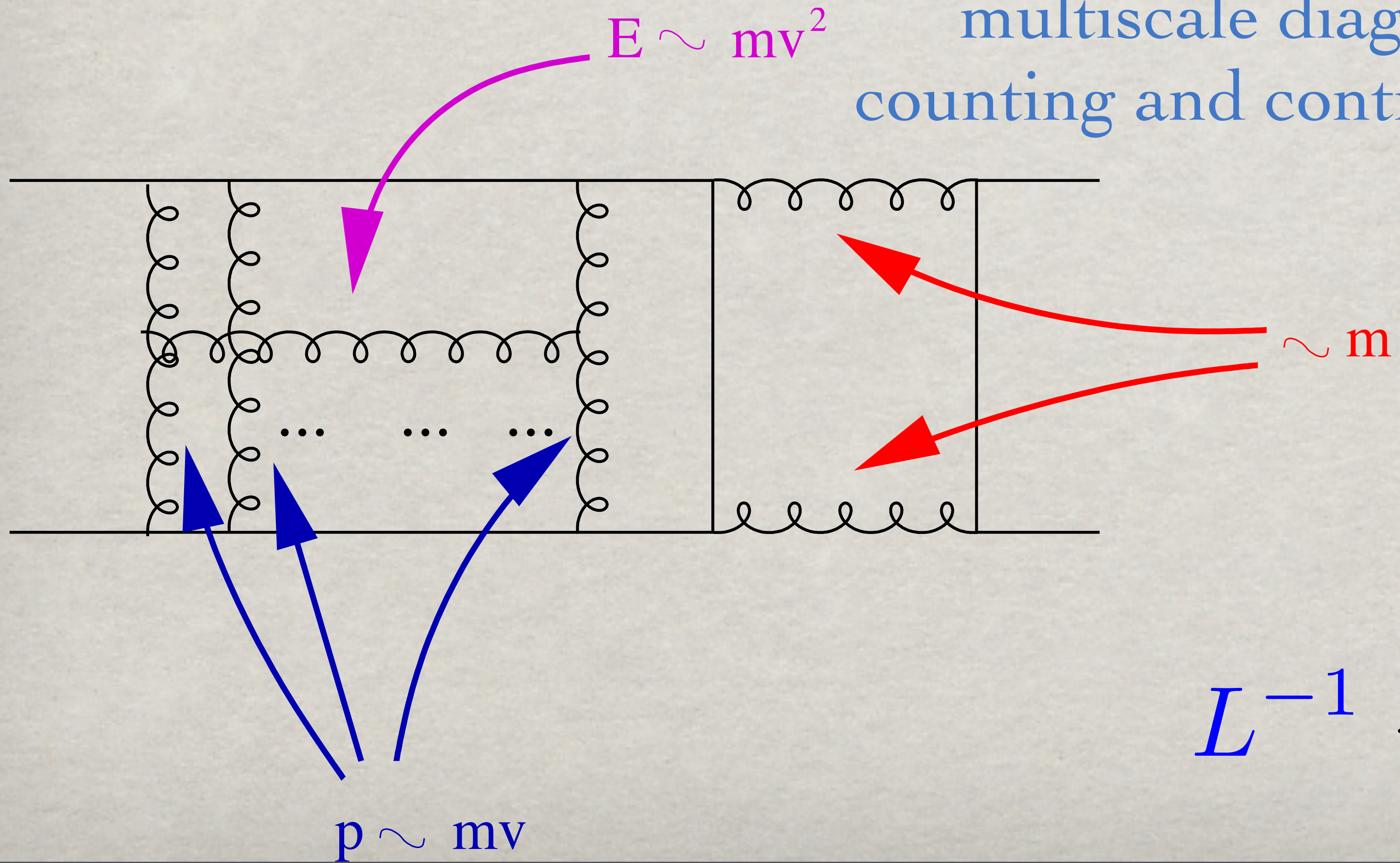


$$\frac{g^2}{p^2}\left(1 + \frac{m\alpha_s}{p}\right)$$

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

- 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

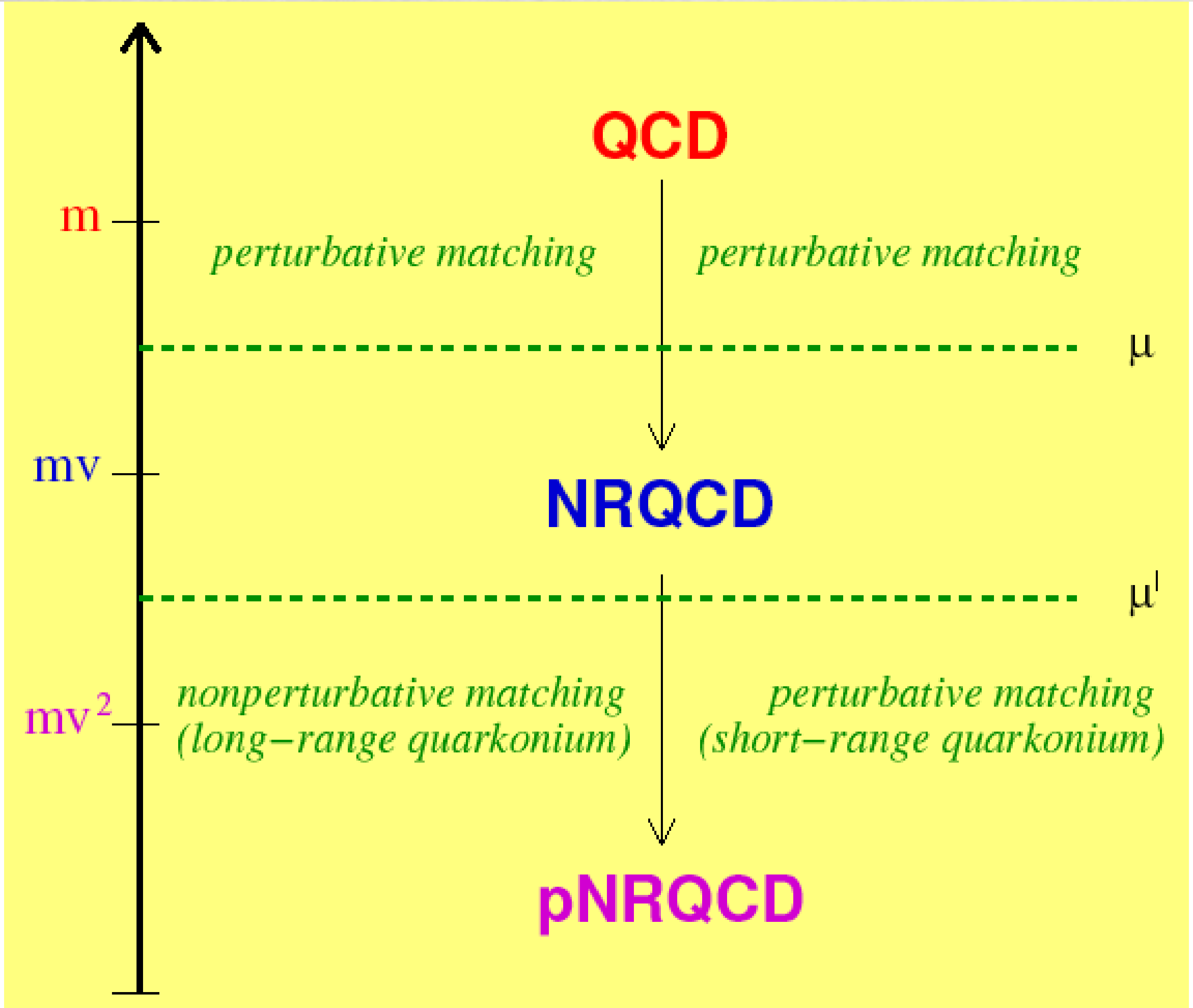


Difficult also
for the lattice!

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

Quarkonium with Non relativistic Effective Field Theories

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



QCD

m

perturbative matching *perturbative matching*

μ

mv

NRQCD

μ'

mv^2

nonperturbative matching
(long–range quarkonium)

perturbative matching
(short–range quarkonium)

pNRQCD

Hard

Soft
(relative
momentum)

Ultrasoft
(binding energy)

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

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

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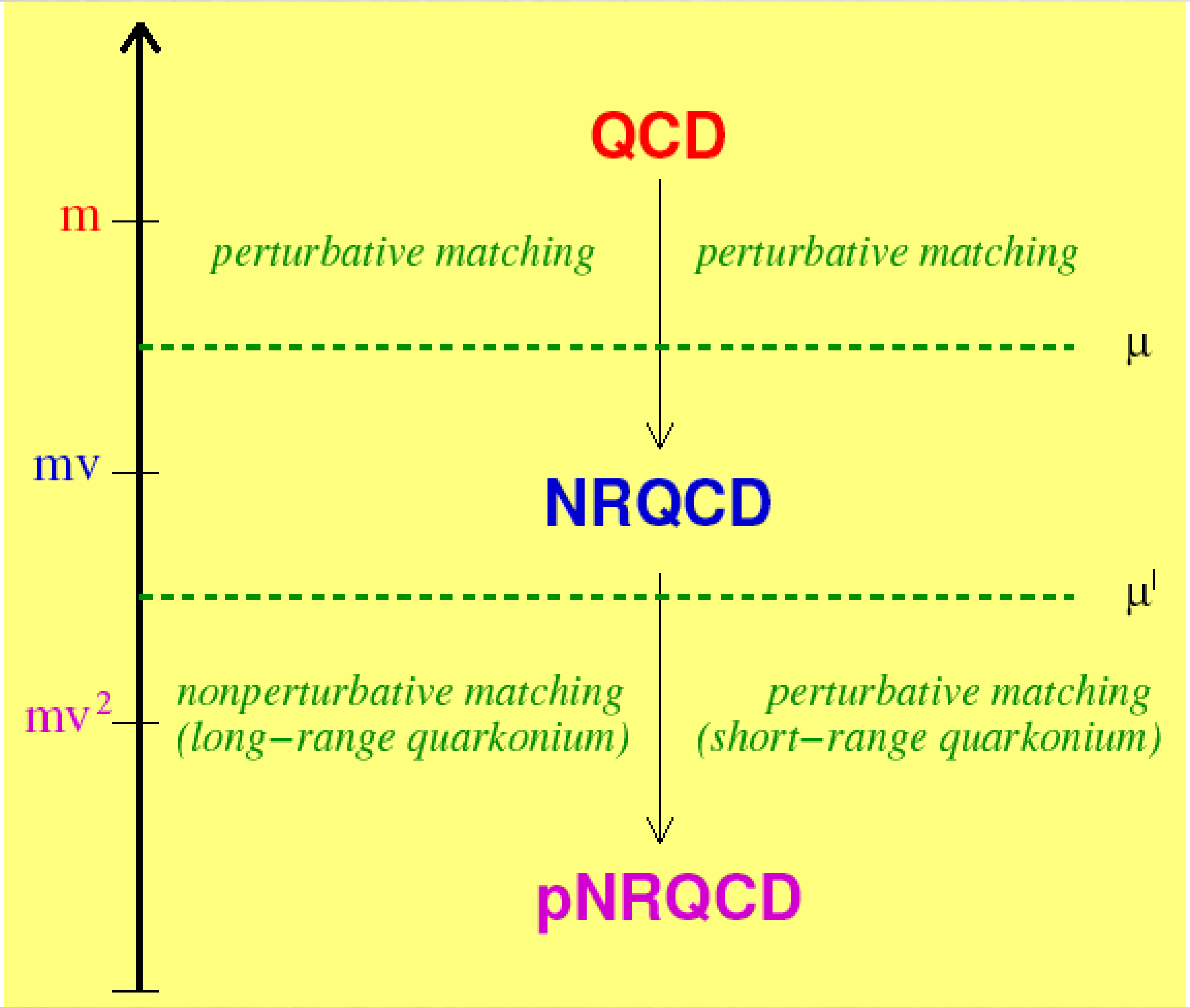

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$$\frac{E_\lambda}{E_\Lambda} = \frac{mv}{m}$$

Soft
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Ultrasoft
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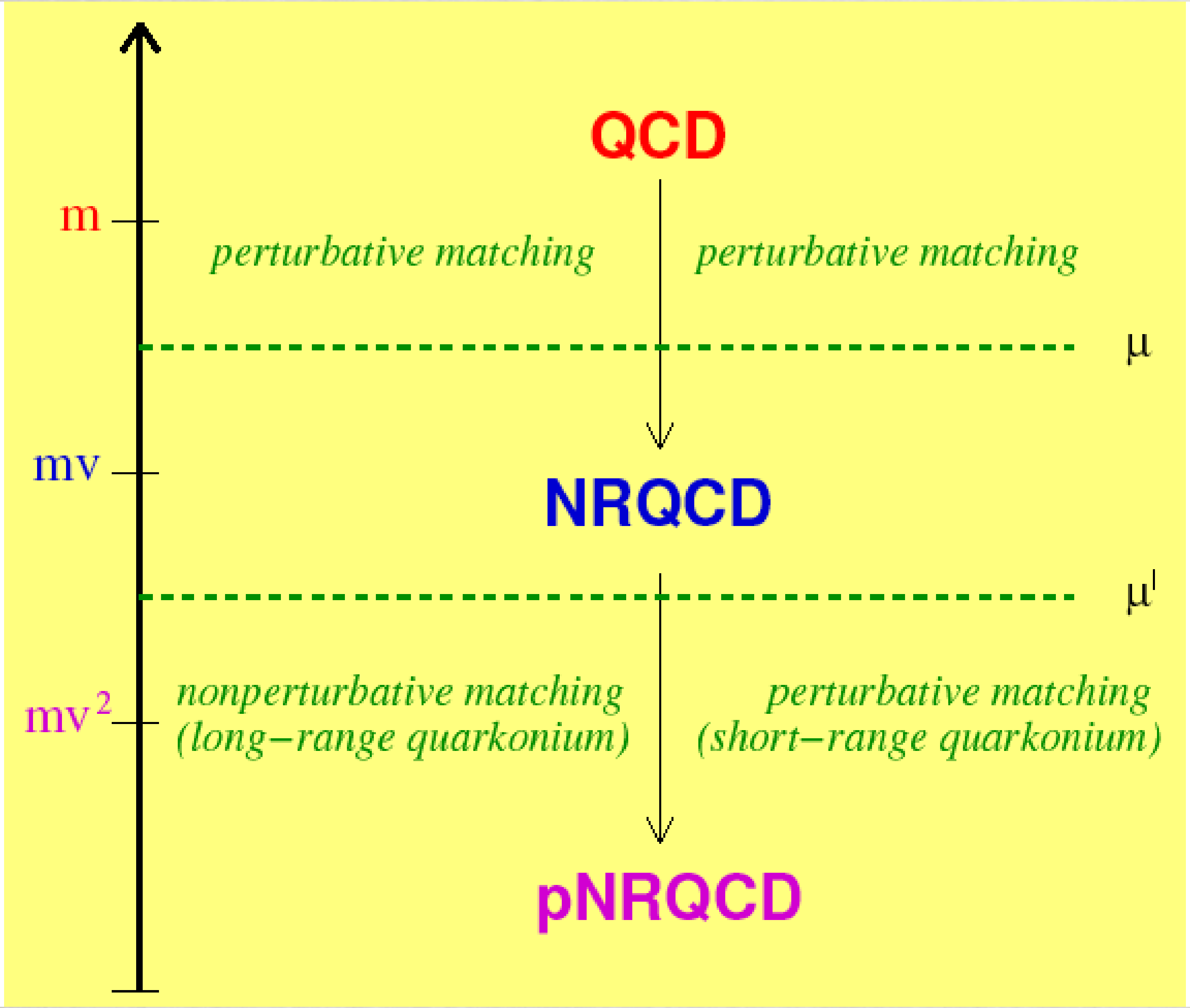

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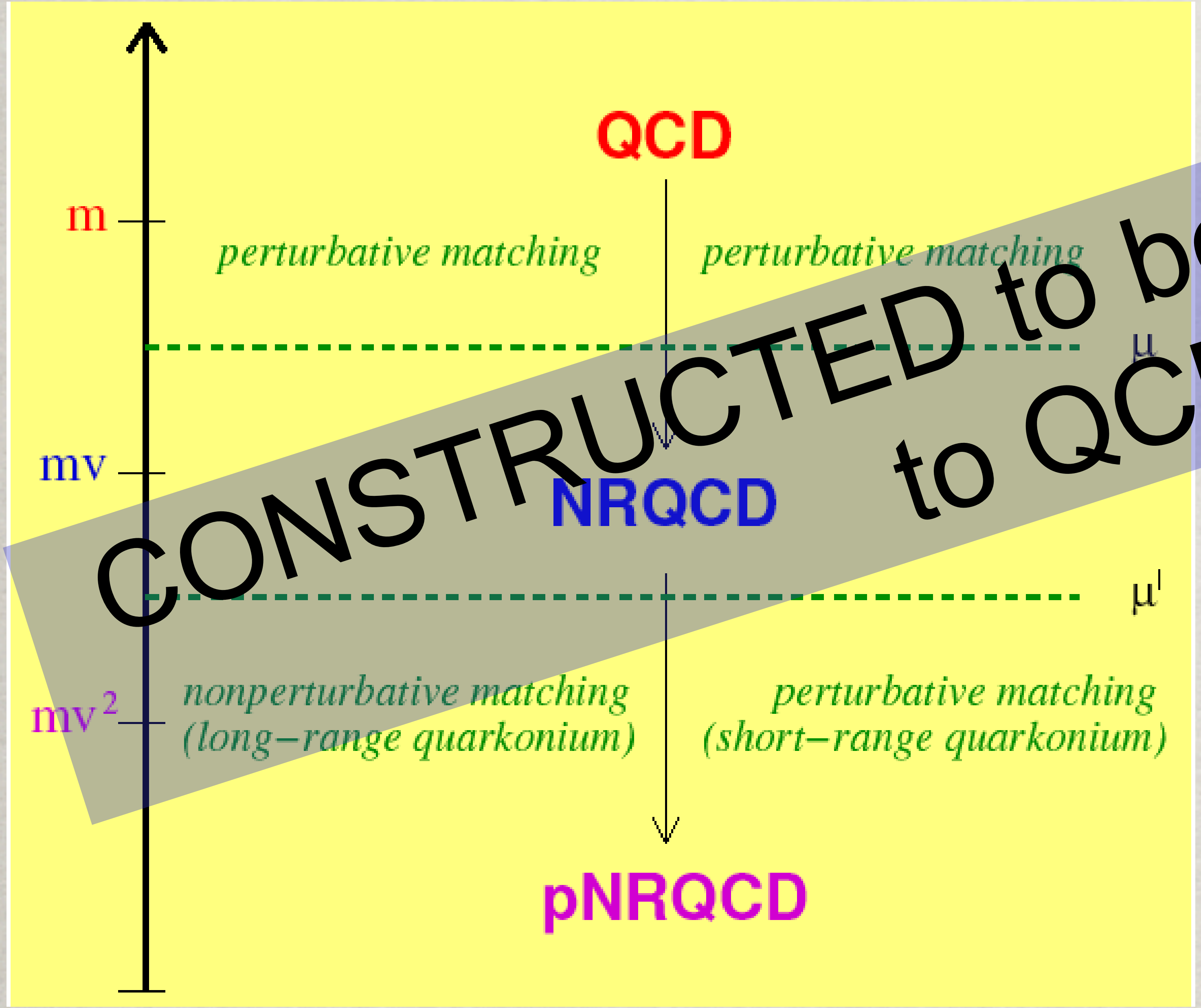

CONSTRUCTED to be EQUIVALENT to QCD

Hard

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

Soft
(relative
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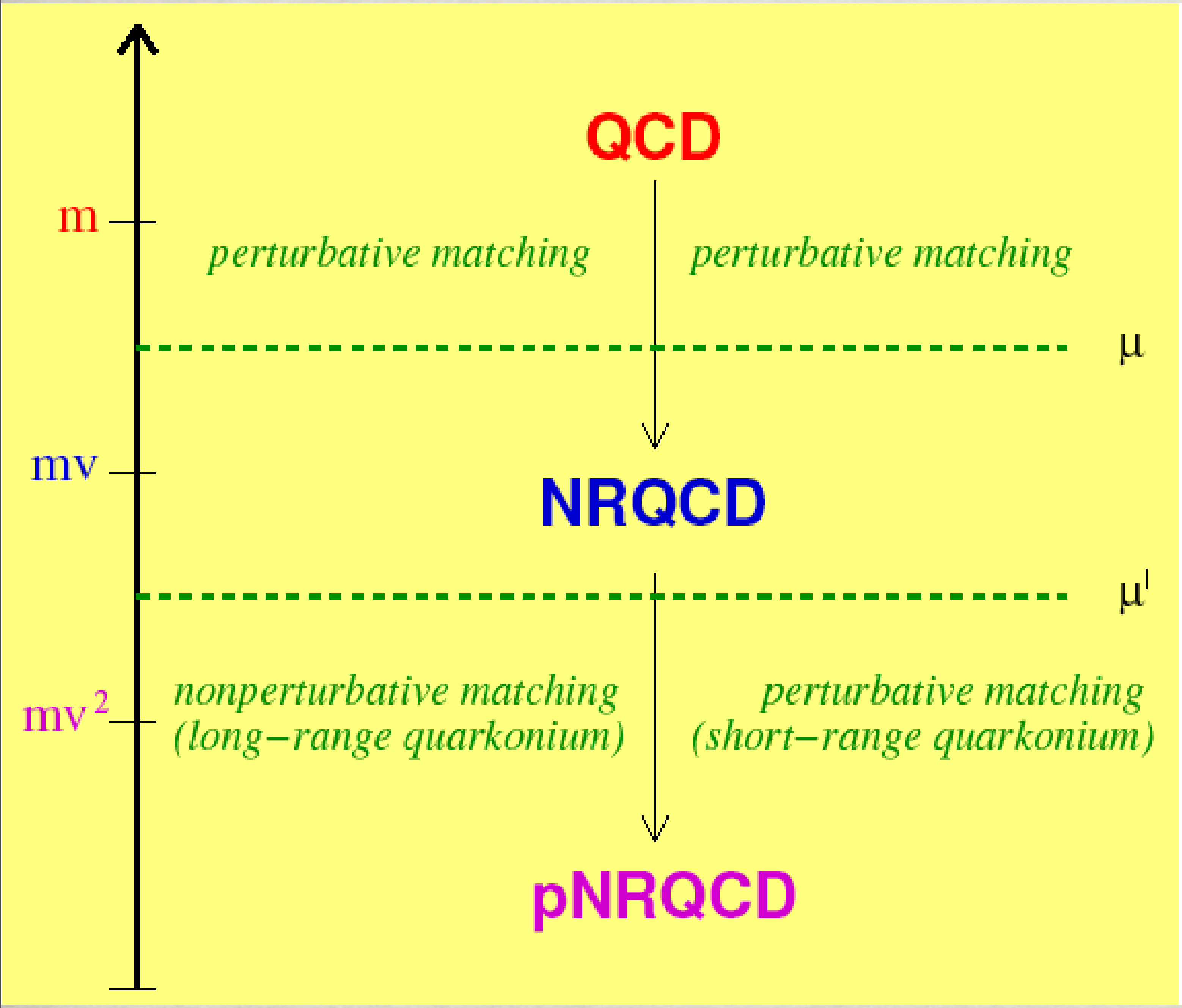
Quarkonium with NR EFT: Non Relativistic QCD (NRQCD)



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perturbative matching   *perturbative matching*

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NRQCD

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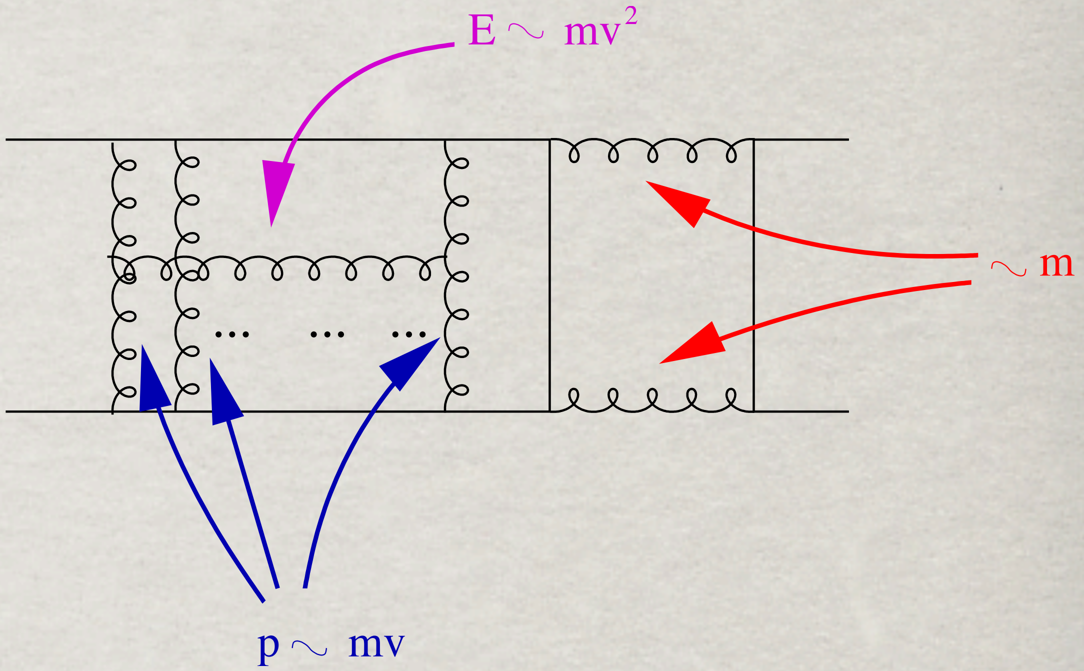
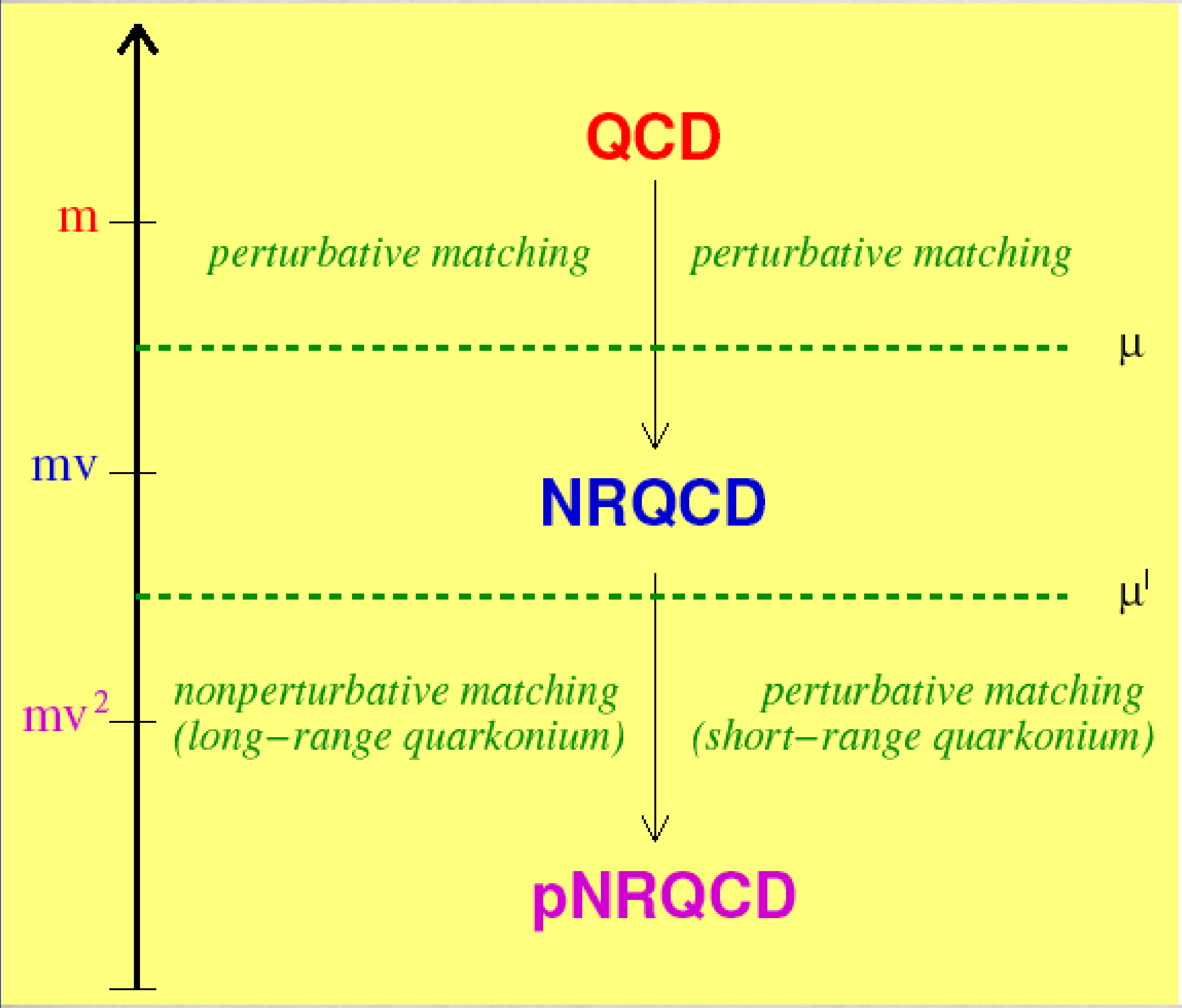
(long−range quarkonium)

perturbative matching
(short−range quarkonium)

pNRQCD



Quarkonium with NR EFT: Non Relativistic QCD (NRQCD)



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perturbative matching | *perturbative matching*

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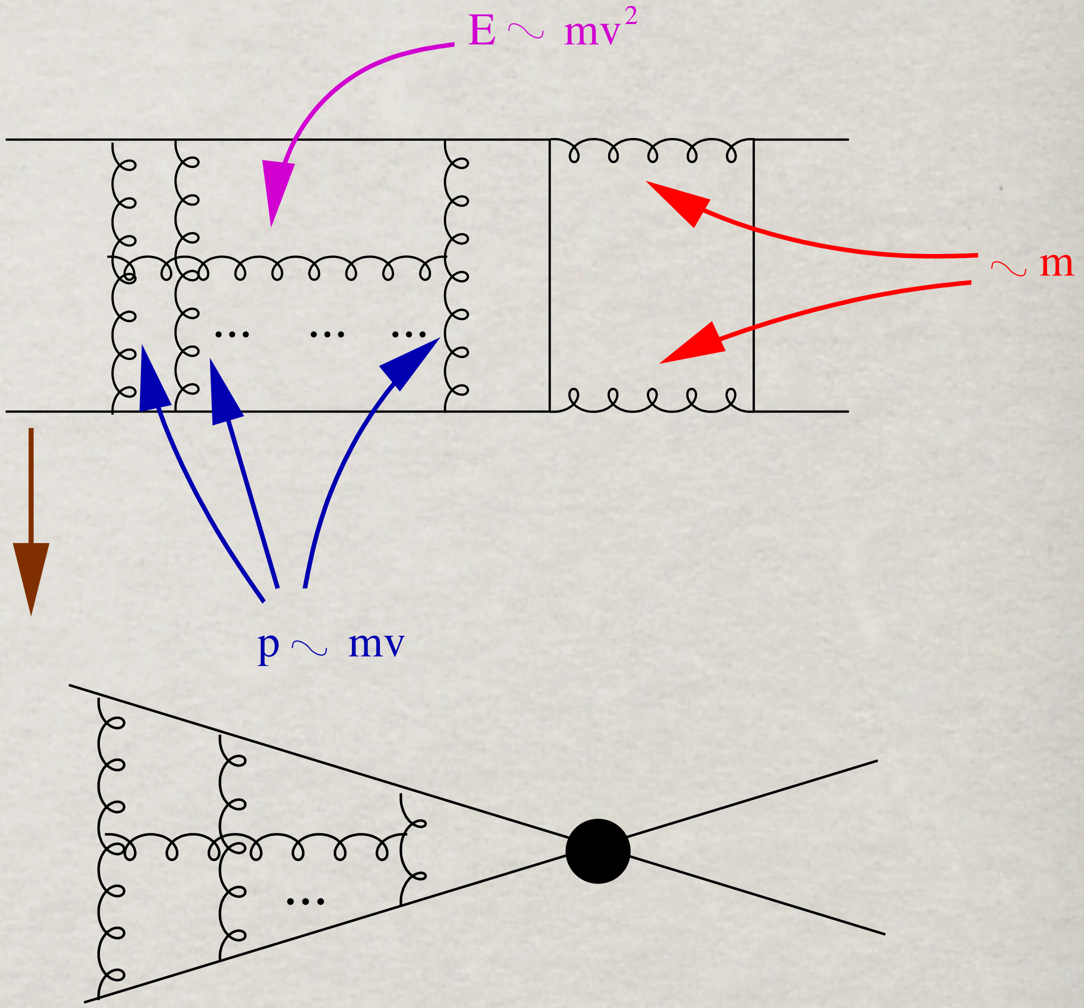
pNRQCD



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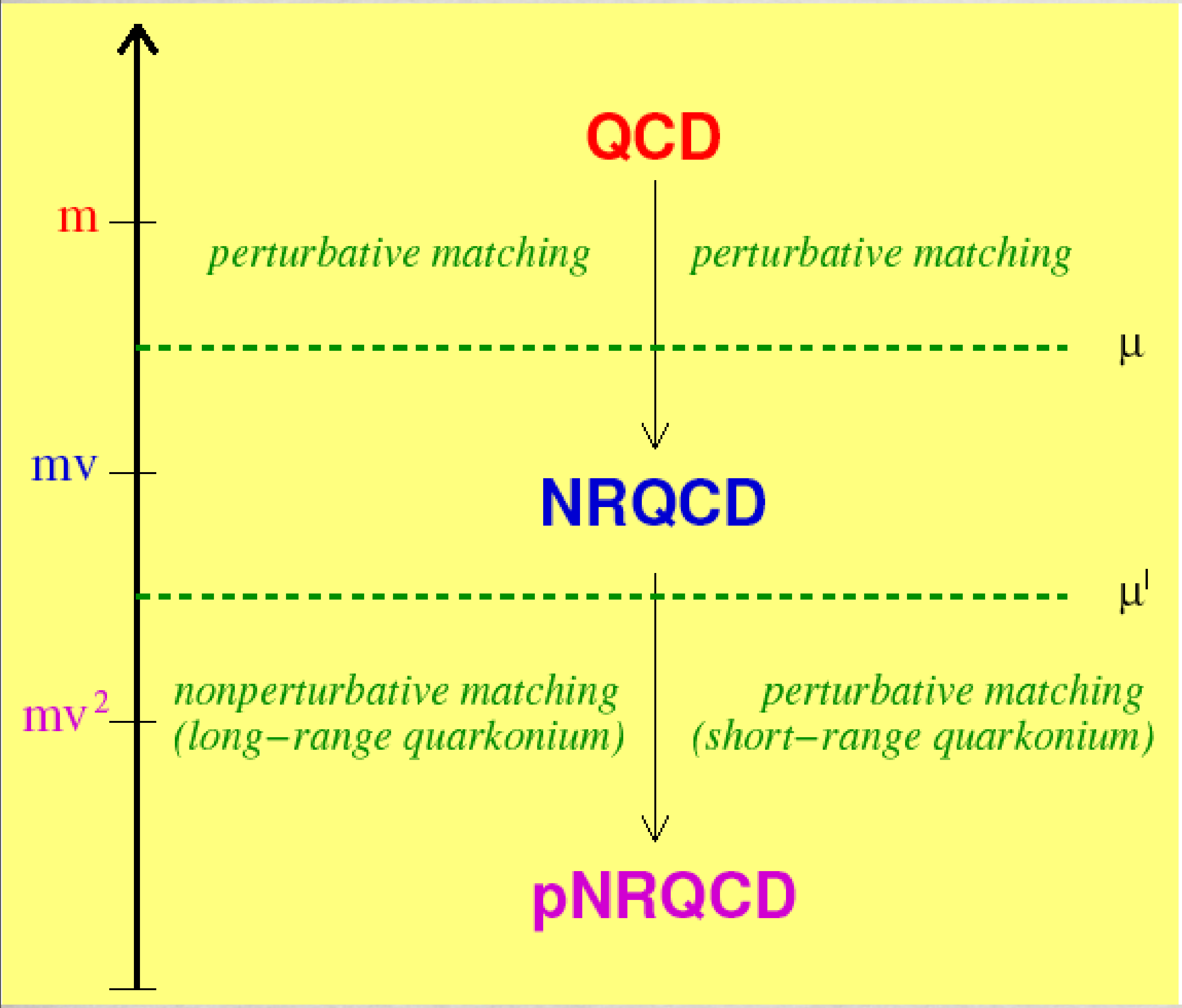

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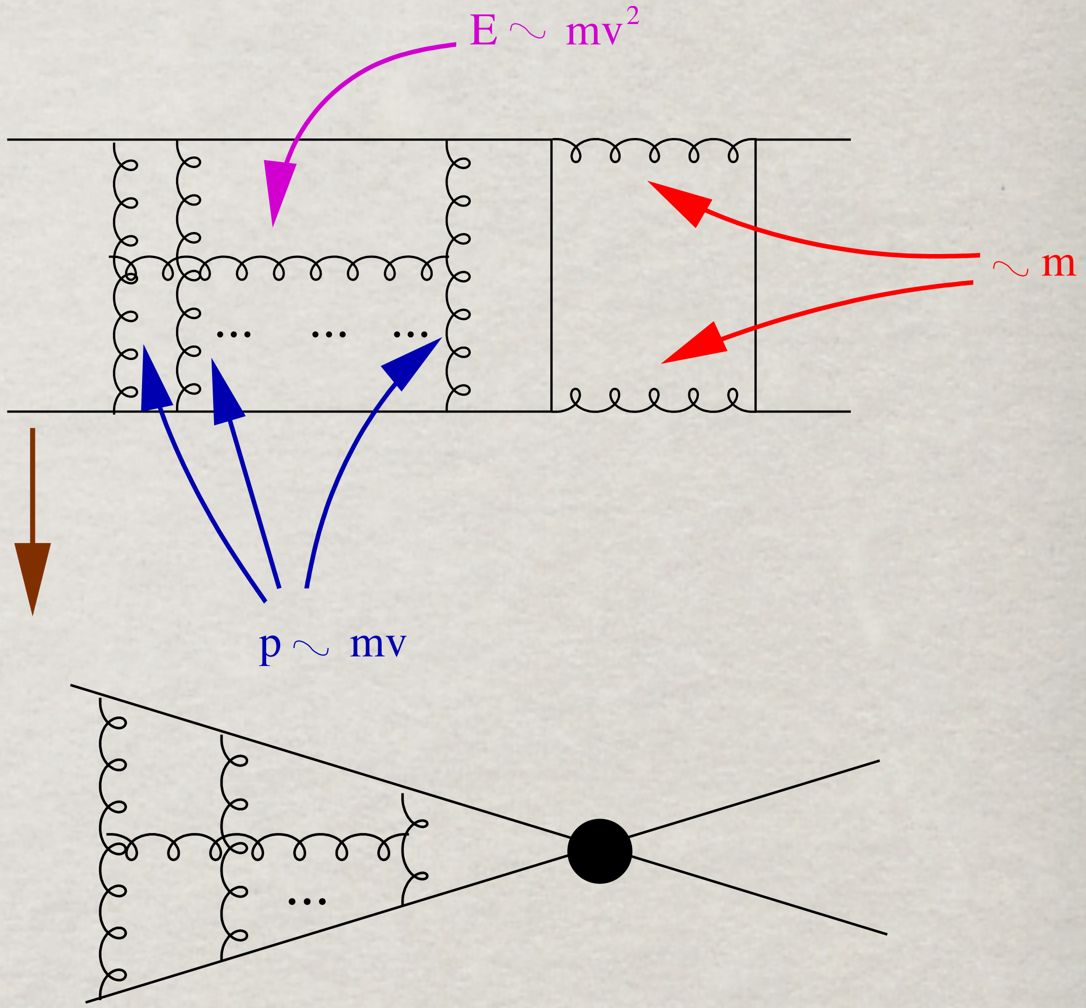
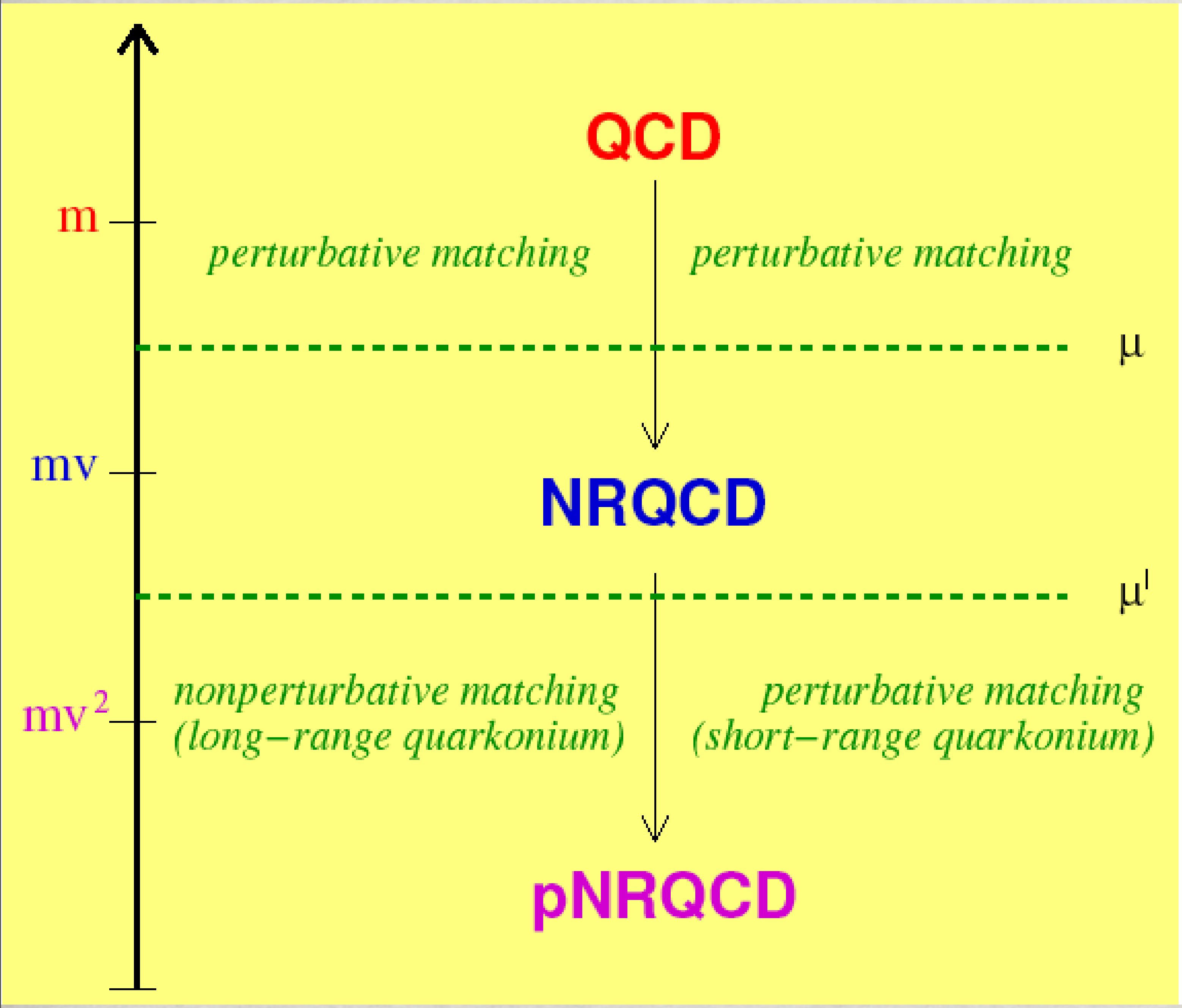
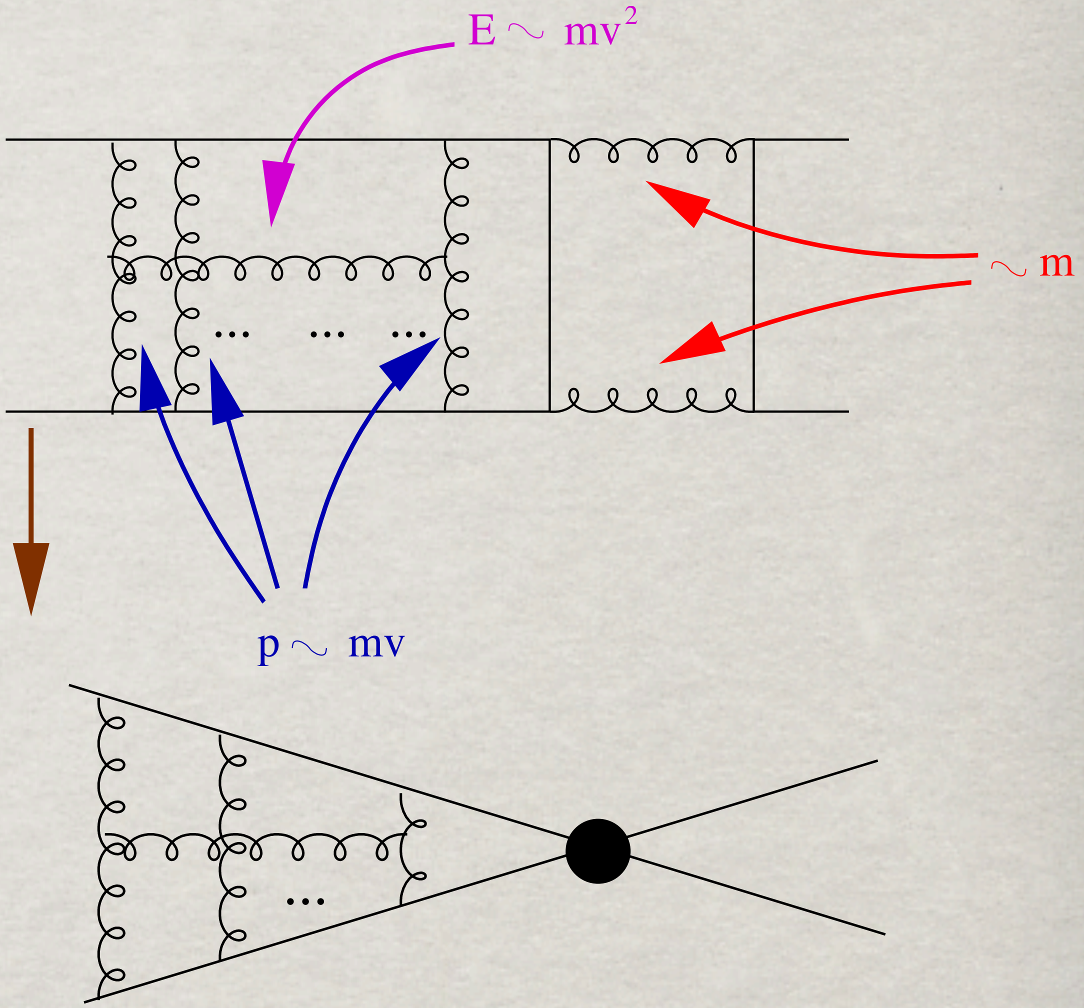


$$\mathcal{L}_{\mathrm{NRQCD}} = \sum_n c(\alpha_{\mathrm{s}}(m/\mu)) \times \frac{O_n(\mu,\lambda)}{m^n}$$

Quarkonium with NR EFT: potential NonRelativistic QCD (pNRQCD)





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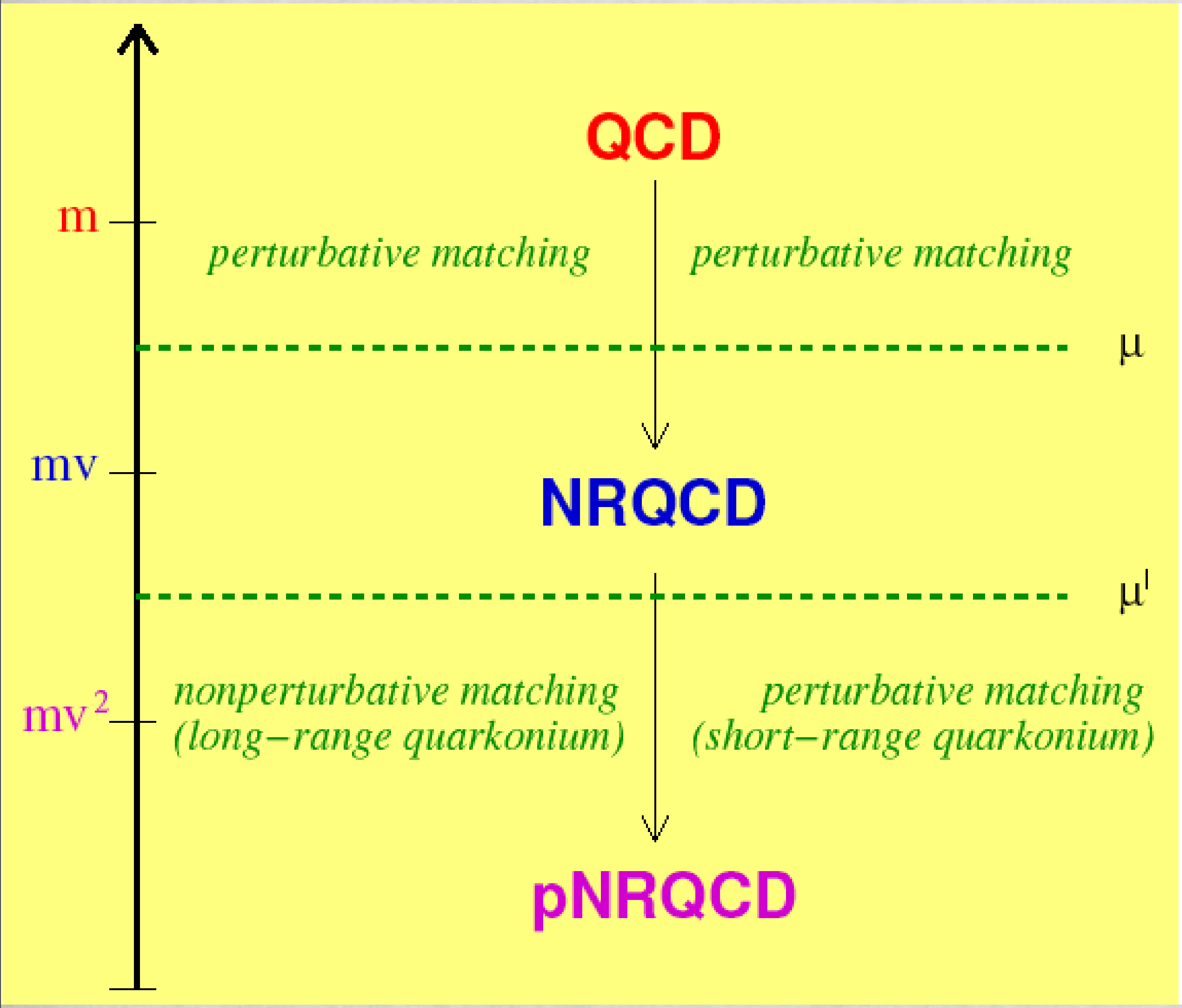

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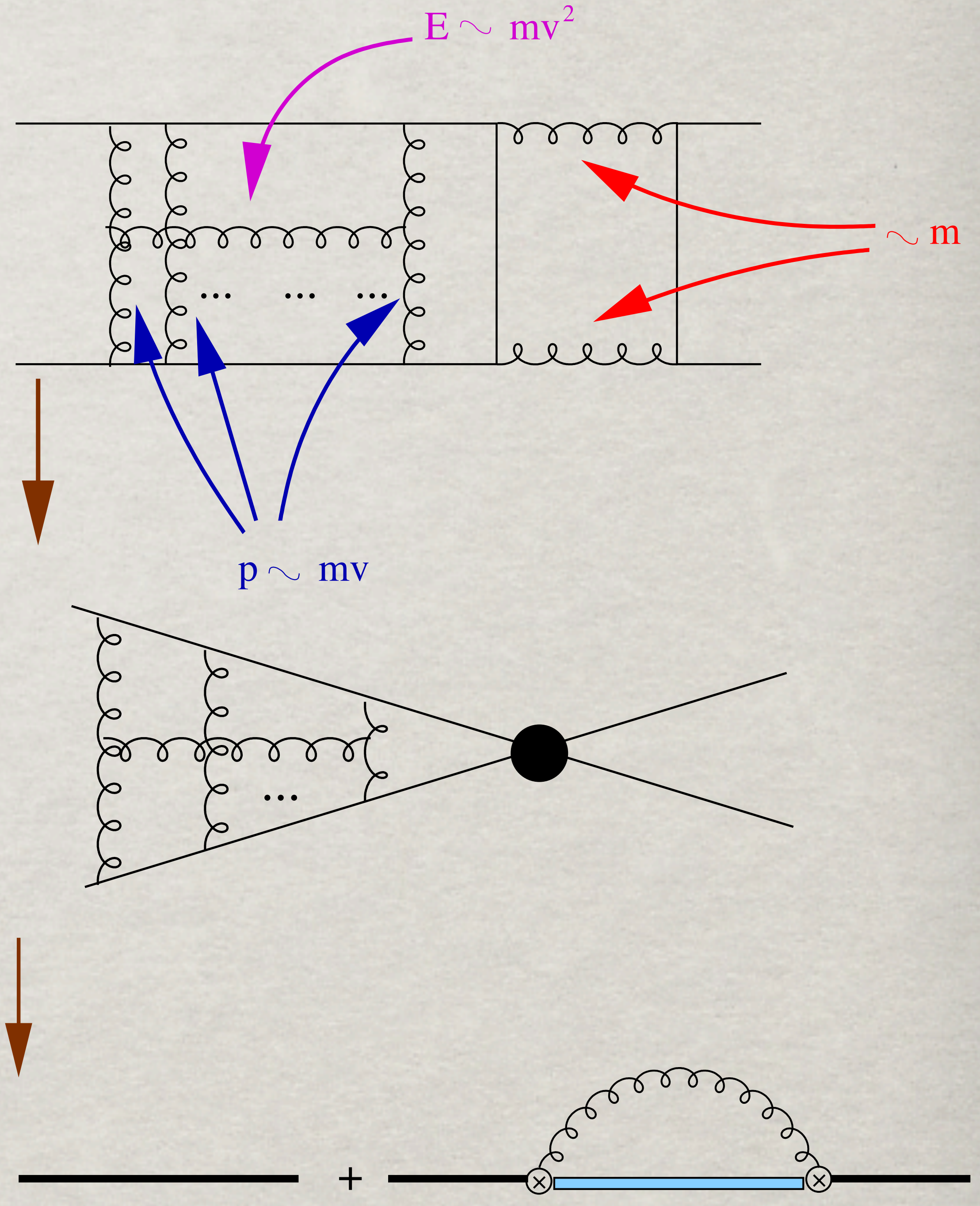

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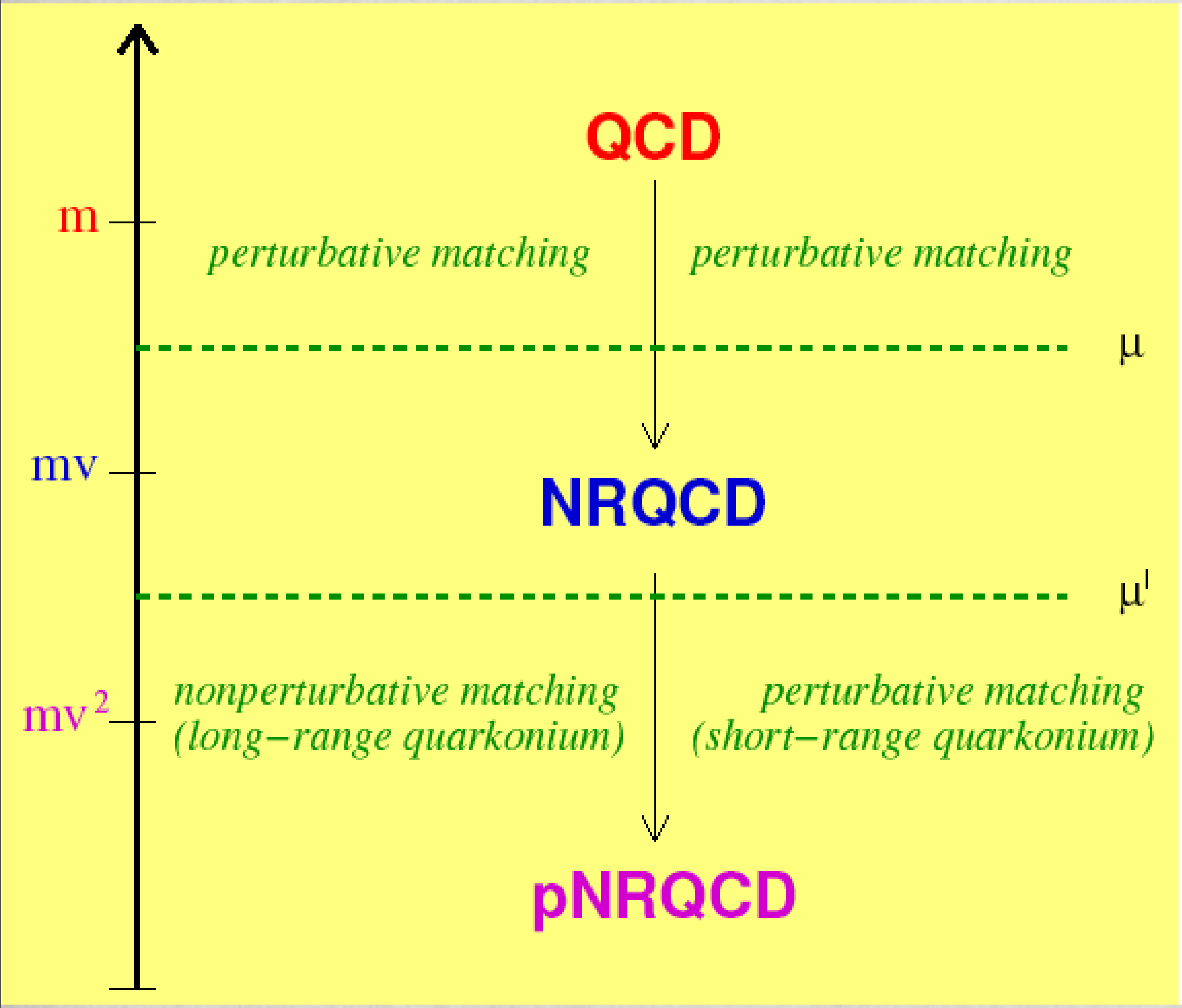

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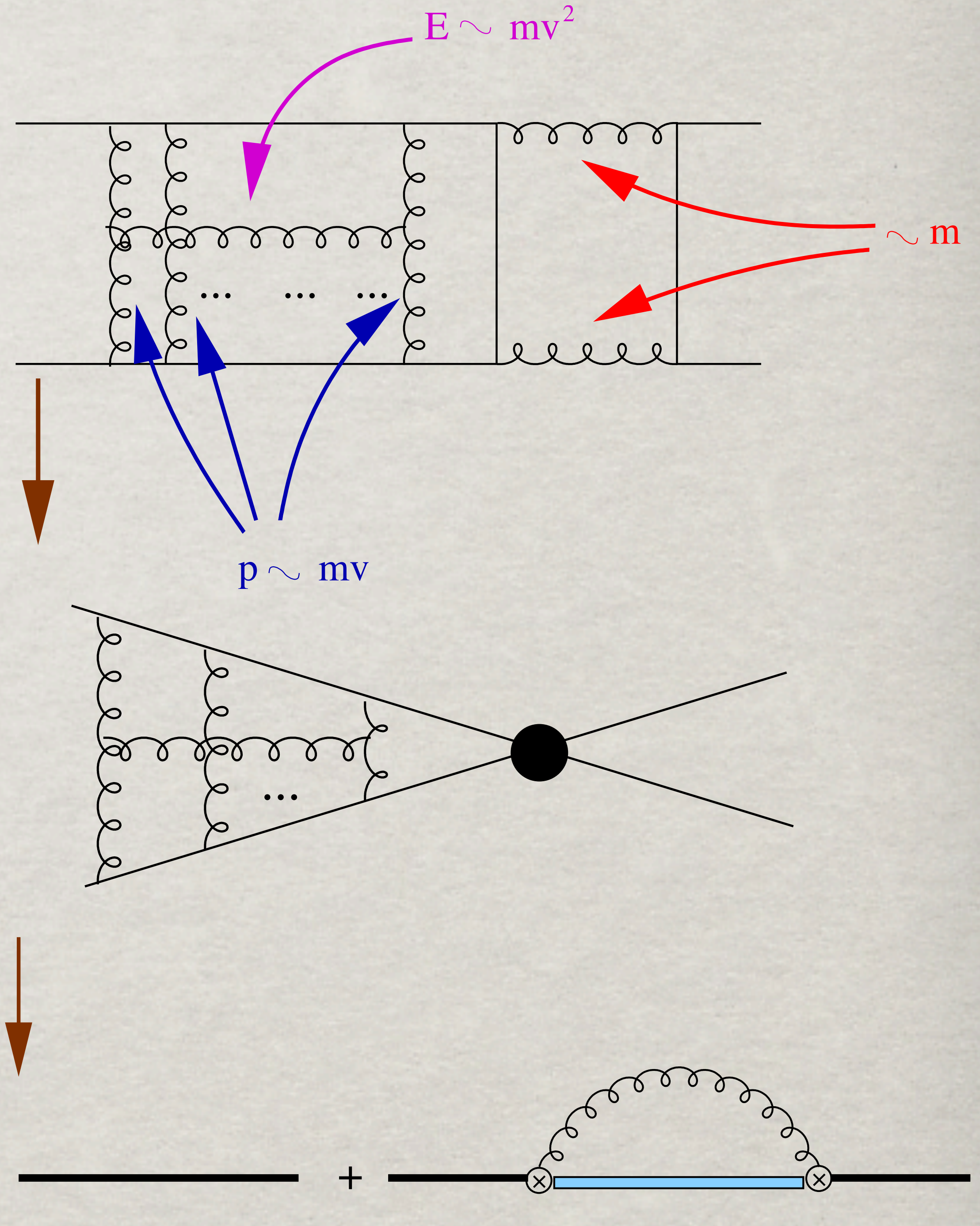
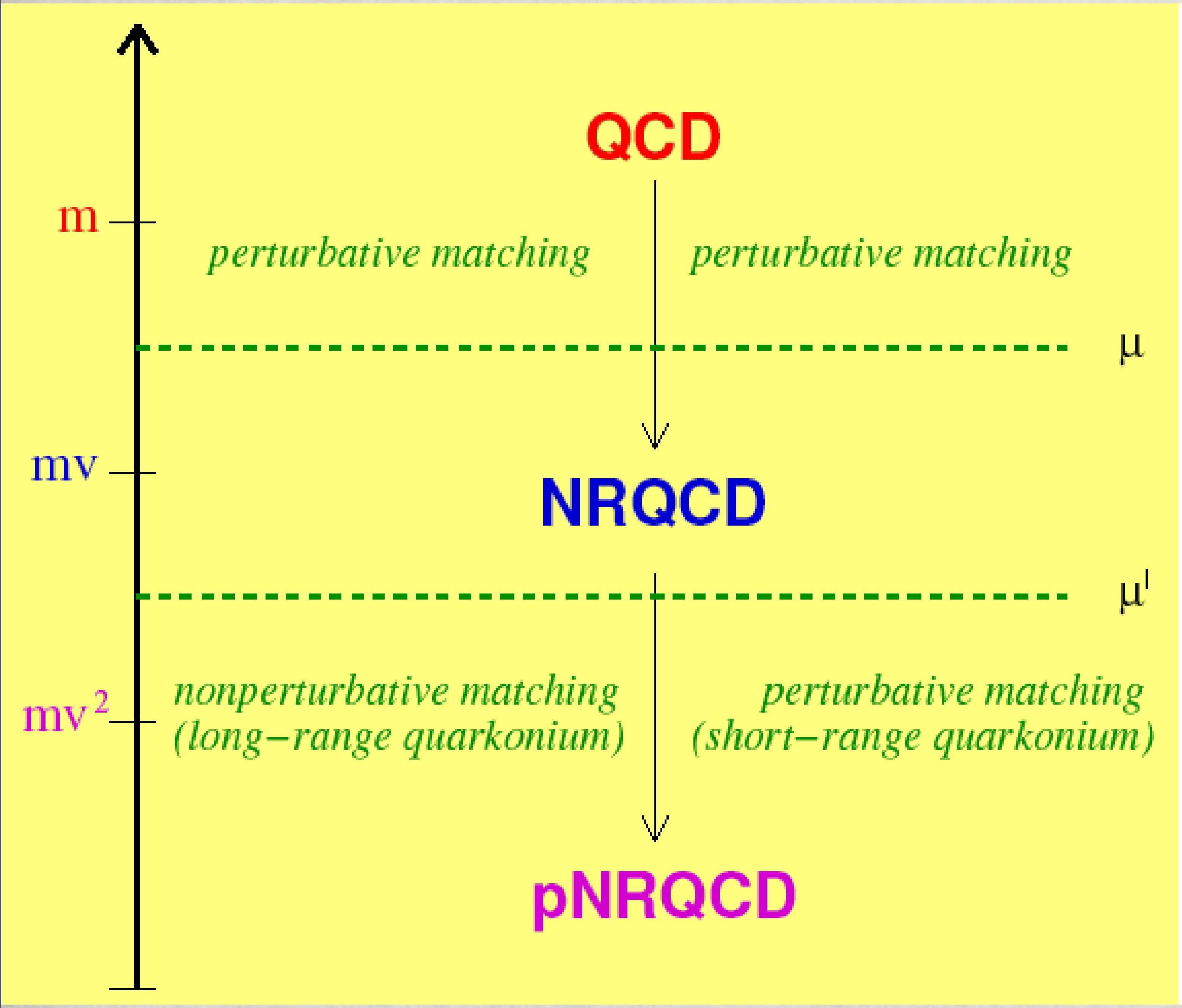


$$\mathcal{L}_{\mathrm{pNRQCD}} = \sum_k \sum_n \frac{1}{m^k} c_k(\alpha_{\mathrm{s}}(m/\mu)) \times V(r\mu', r\mu) \times O_n(\mu', \lambda)\, r^n$$

Quarkonium with NR EFT: potential NonRelativistic QCD (pNRQCD)



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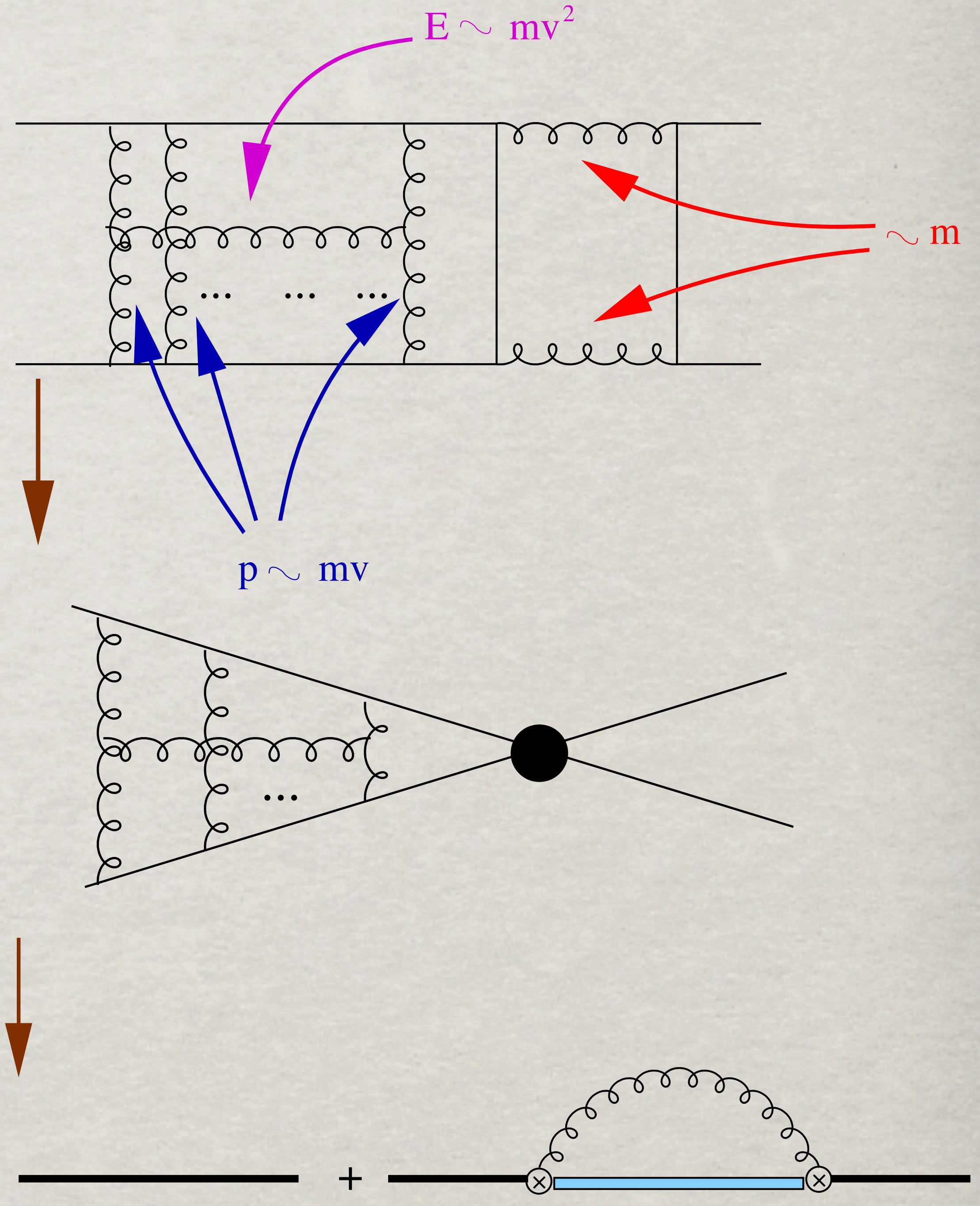

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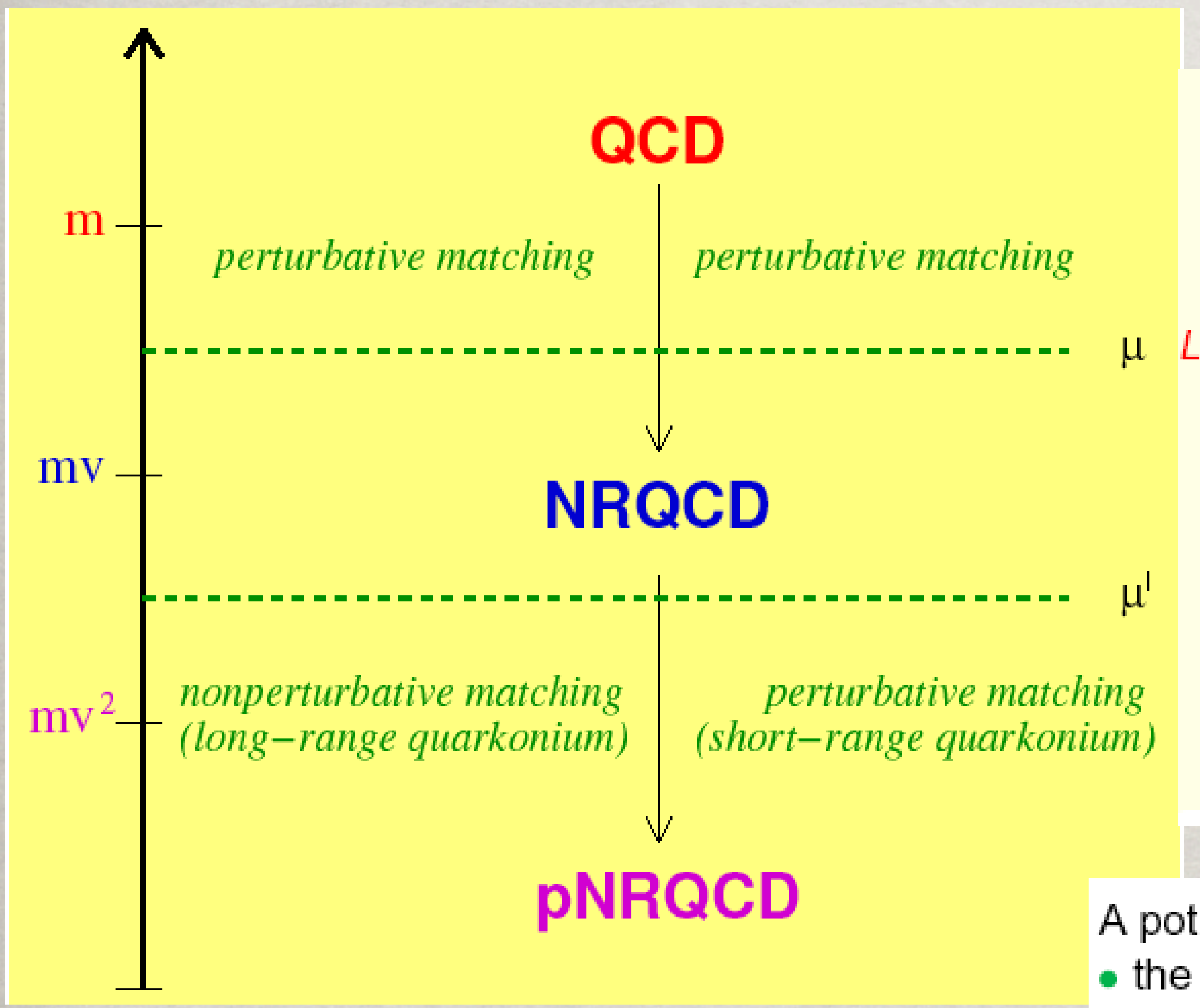
Quarkonium with NR EFT: pNRQCD



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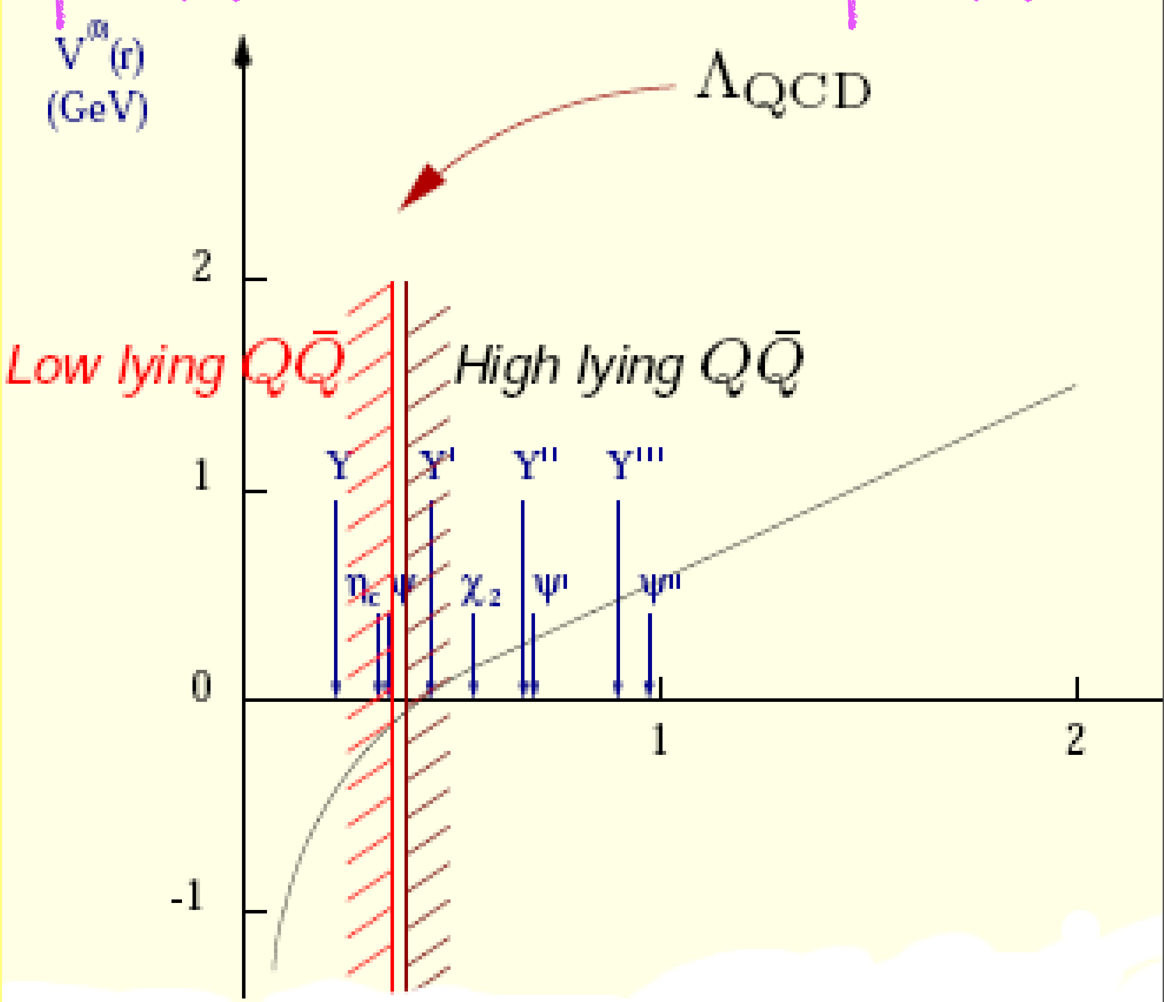
pNRQCD

weakly coupled pNRQCD

strongly coupled 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}

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

weakly coupled 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-

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

$\Rightarrow$ 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).

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

Brambilla Pineda Soto Vairo 00

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Brambilla Pineda Soto Vairo 00

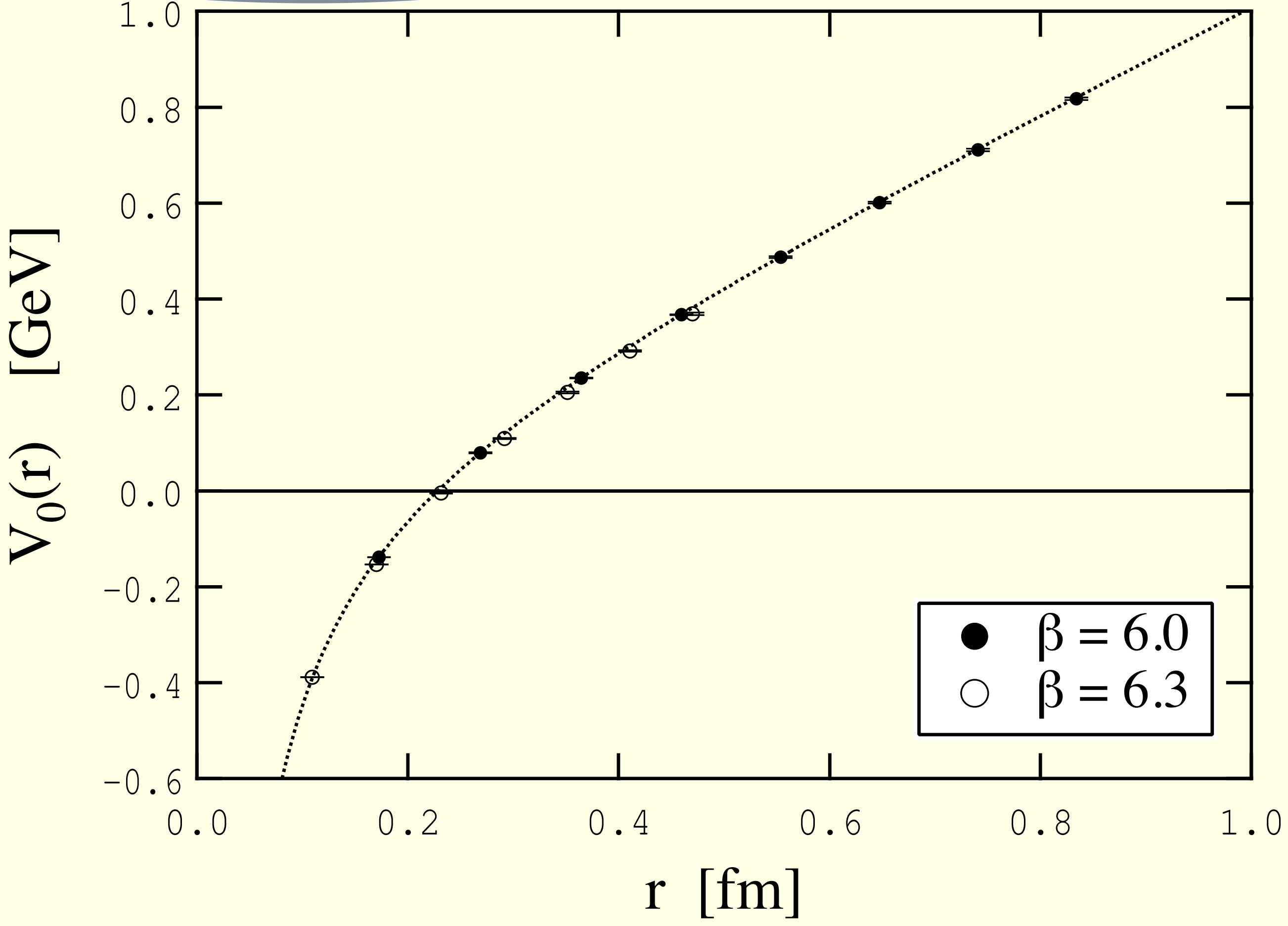
- A potential description emerges from the EFT
- The potentials $V = \mathrm{Re}V + ImV$ from QCD in the matching: get spectra and decays
- V to be calculated on the lattice or in QCD vacuum models

Quarkonium singlet static potential

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

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

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



○ Koma Koma NPB 769(07)79

many experimental data and opportunities

Quarkonium today is
a golden system to study strong interactions

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

pNRQCD and quarkonium (away from the stong decay threshold)

The EFT has been constructed

*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)

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 (at finite temperature T)

The EFT is being constructed (at small coupling) Laine et al, 2007, Escobedo, Sot
2007 N. B. et al. 2008

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

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

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

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 deca width rather than being due to the color screening of the real part of the potentia

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

pNRQCD and quarkonium (close or above the strong decay threshold

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

*Degrees of freedom still to be identified

Near theshold heavy-light mesons have to be included

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

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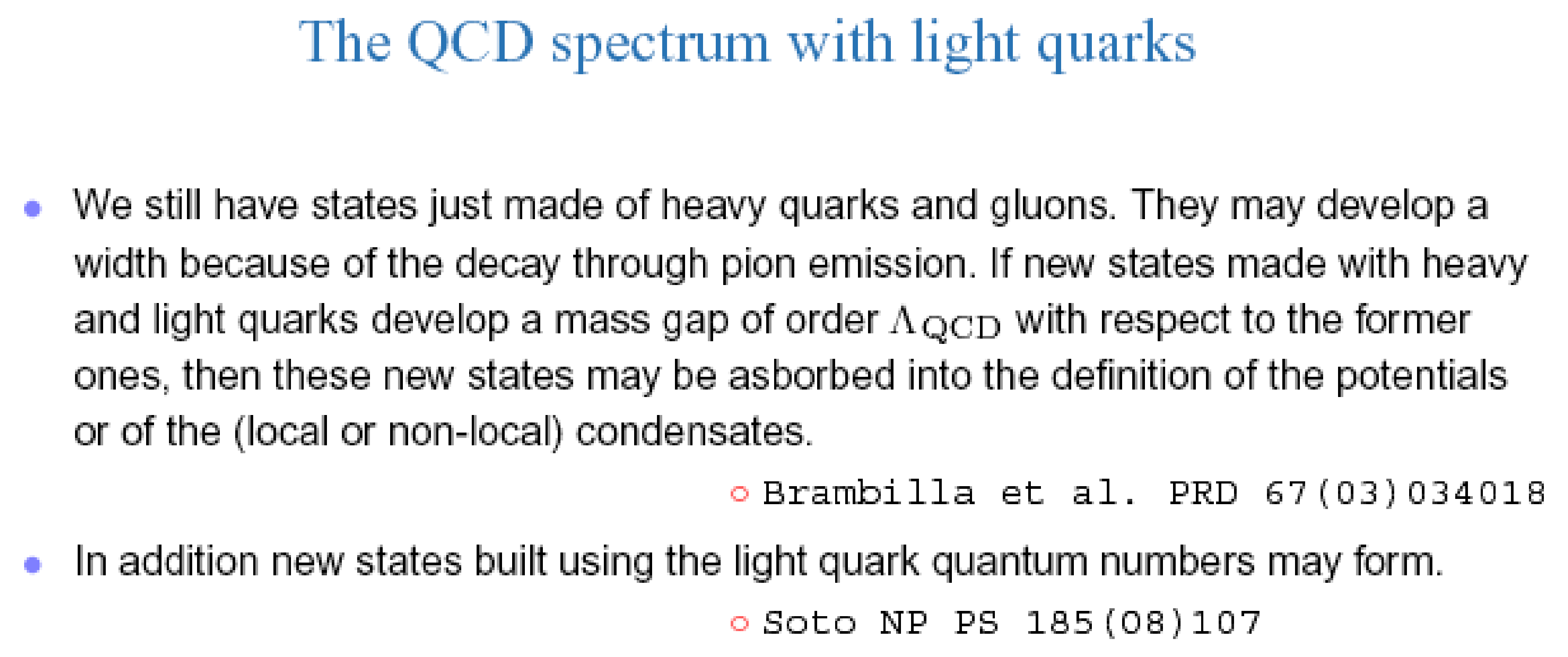

The QCD spectrum with light quarks

- 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

States made of two heavy and light quarks

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

- Pairs of heavy-light baryons.
  - Qiao PLB 639 (2006) 263

- Molecular states, i.e. states built on the pair of heavy-light mesons.
  - Tornqvist PRL 67(91)556

- Tetraquark states. MAIANI, PICCININI, POLOSA ET AL. 2005--
  - Jaffe PRD 15(77)267
  - Ebert Faustov Galkin PLB 634(06)214

(hadro-quarkonium). Voloshin

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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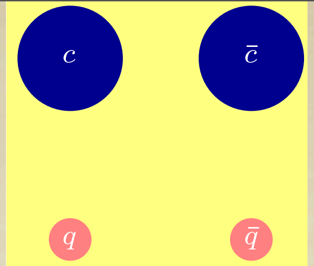
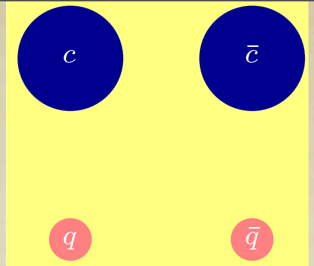
choosing one of these degrees of freedom and an interaction originates a model for exotics.

$X(3872)$: interpretations



4-quark state with $J^{PC} = 1^{++}$

$X(3872)$: interpretations



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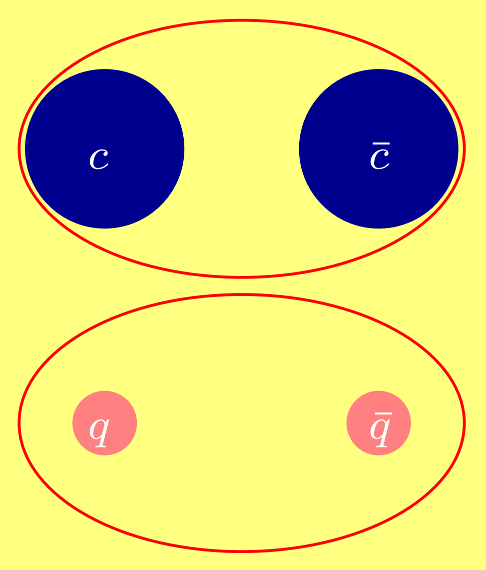
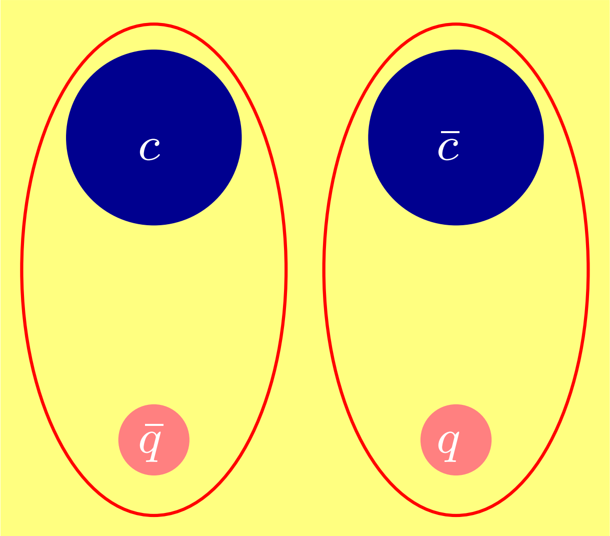


`Høgassen et al 05`

$$X \sim (c\bar{c})^8_{S=1} \otimes (q\bar{q})^8_{S=1}$$
$$\sim (c\bar{q})^1_{S=0} \otimes (q\bar{c})^1_{S=1} + (c\bar{q})^1_{S=1} \otimes (q\bar{c})^1_{S=0}$$

Molecular model

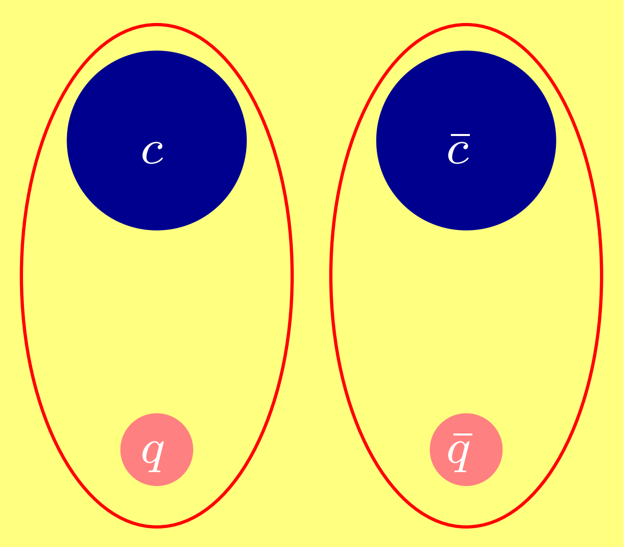
Predictions based on the phenomenological $H = -\sum_{ij} C_{ij}\, T^a \otimes T^a\, \boldsymbol{\sigma} \otimes \boldsymbol{\sigma}$;



`Törnqvist 93, Swanson 04`

$$X \sim (c\bar{q})^1_{S=0} \otimes (q\bar{c})^1_{S=1} + (c\bar{q})^1_{S=1} \otimes (q\bar{c})^1_{S=0}$$
$$\sim D\,\bar{D}^* + D^*\,\bar{D}$$

This is assumed to be the dominant long-range Fock component; short-range components of the type $(c\bar{c})^1_{S=1} \otimes (q\bar{q})^1_{S=1}$ $\sim J/\psi\ \rho, \omega$ *are assumed as well.*



`Maiani et al 04`

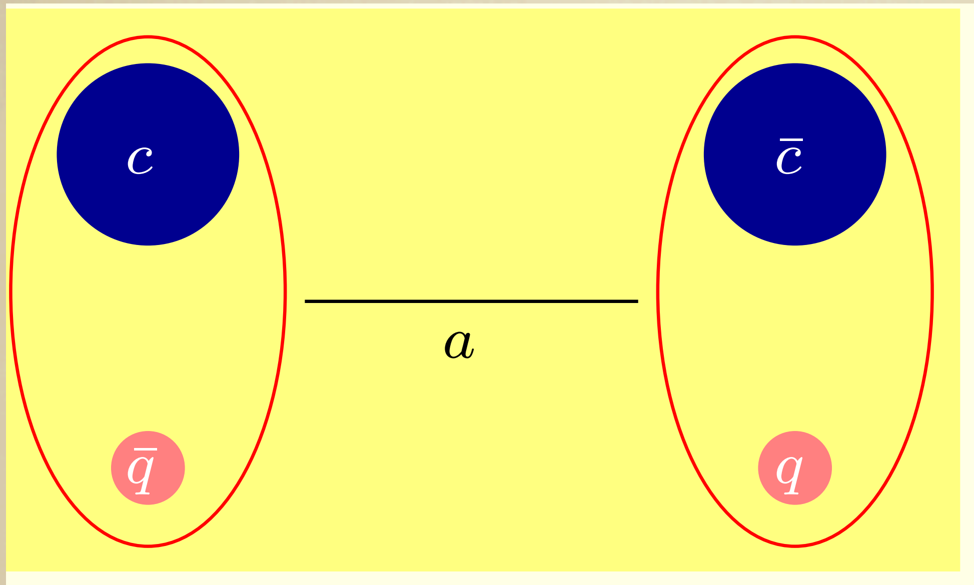
$$X \sim (cq)^{\bar{3}}_{S=1} \otimes (\bar{c}\bar{q})^3_{S=0} + (cq)^{\bar{3}}_{S=0} \otimes (\bar{c}\bar{q})^3_{S=1}$$

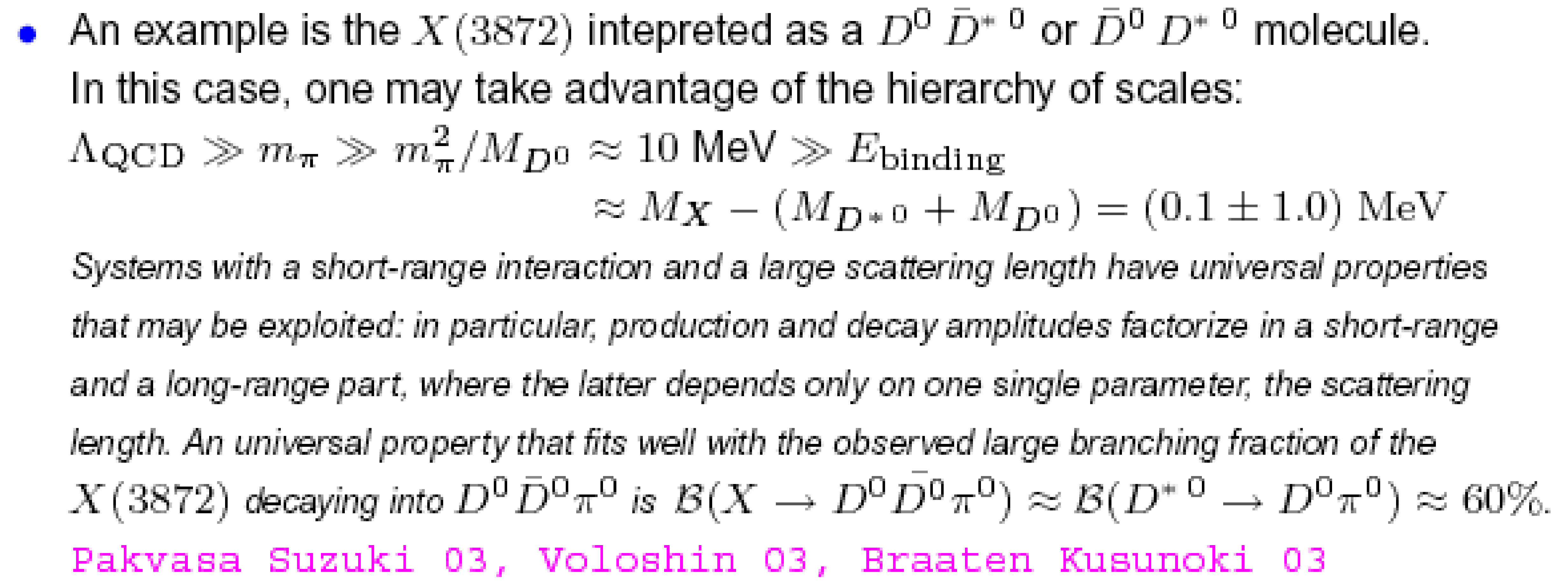
the dynamical assumption (there is no scale separation like in the doubly heavy baryons) is that quark pair cluster in tightly bound color triplet diquarks (see 1-gluon exchange); the difficulty in breaking the system explains the narrow width.

Tetraquark model

Predictions based on the phenomenological Hamiltonian: $H = \sum_{ij} \kappa_{ij}\, \boldsymbol{\sigma} \otimes \boldsymbol{\sigma}$; the

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

even the case without light quark is difficult:

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.

even the case without light quark is difficult:

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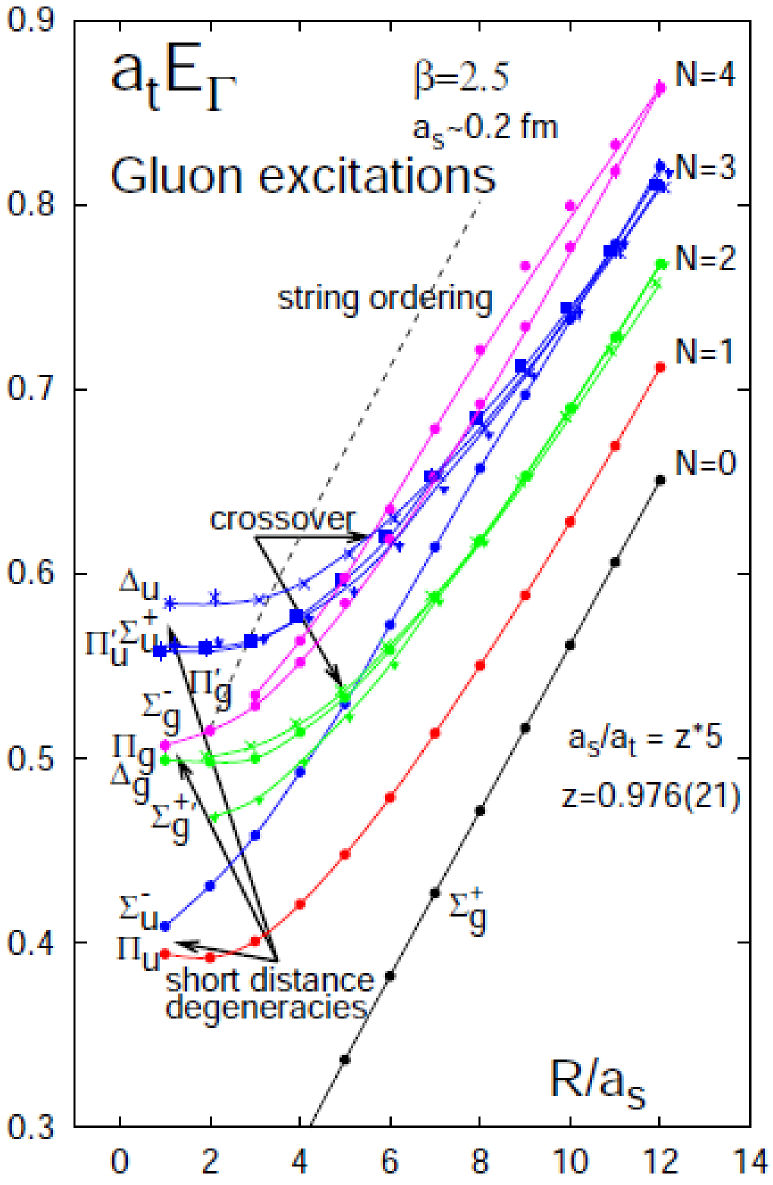
If more states are nearly degenerate, then all of these need to be considered as effective low-energy degrees of freedom and mix.

We have obtained an EFT description of hybrids matching the NRQCD static energies to pNRQCD potential in the short range

even the case without light quark is difficult

static

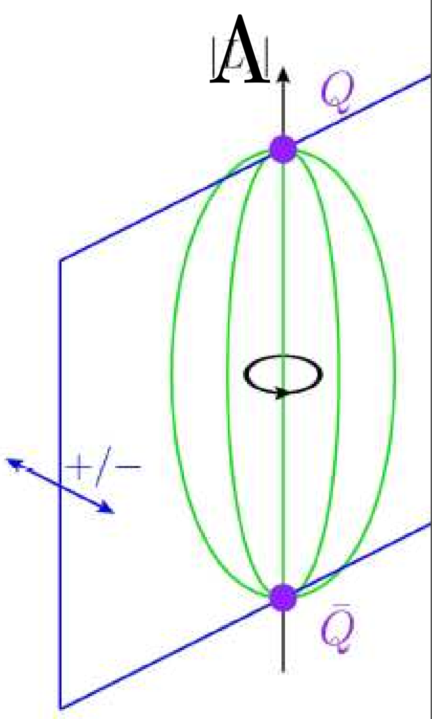
Lattice energies



Symmetries

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

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



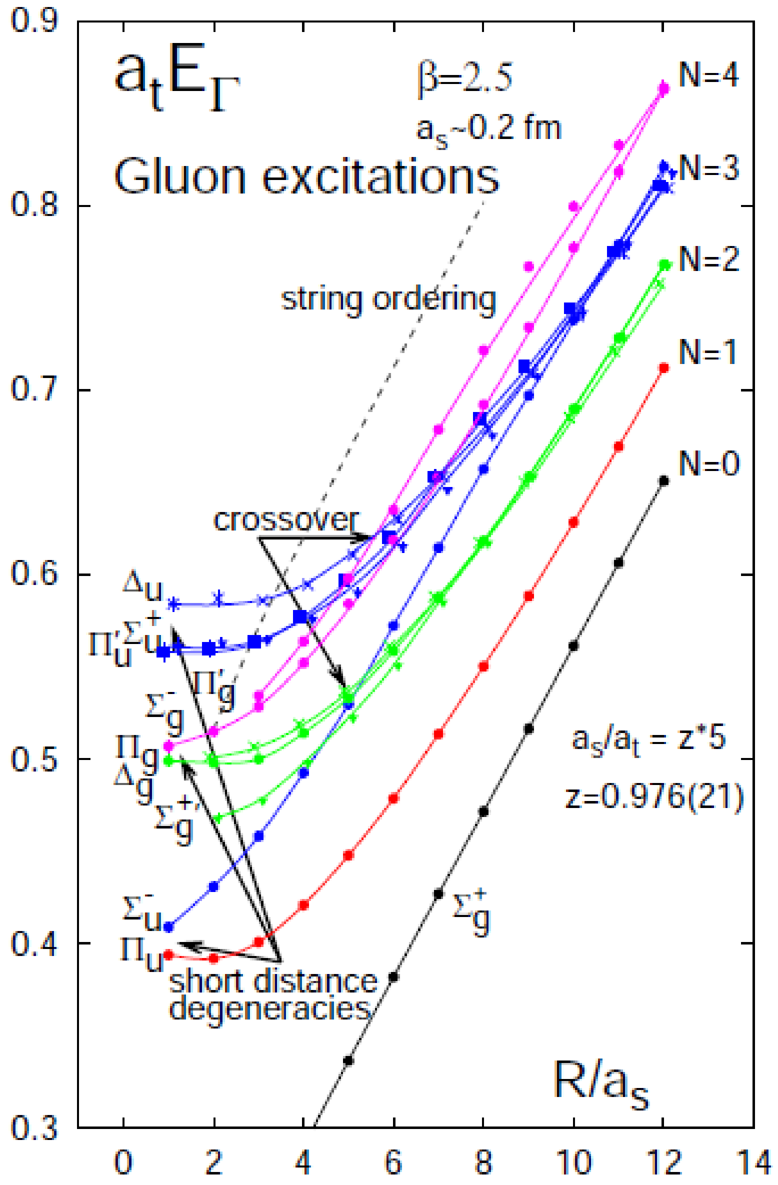
- The static energies correspond to the irreducible representations of D_∞
- In general it can be more than one state for each irreducible representat $D_{\infty\, h}$, usually denoted by primes, e.g. Π_u, Π'_u, $\Pi''_u \ldots$

○ Juge Kuti Morningstar PRL 90 (2003) 161601

even the case without light quark is difficult

static

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.

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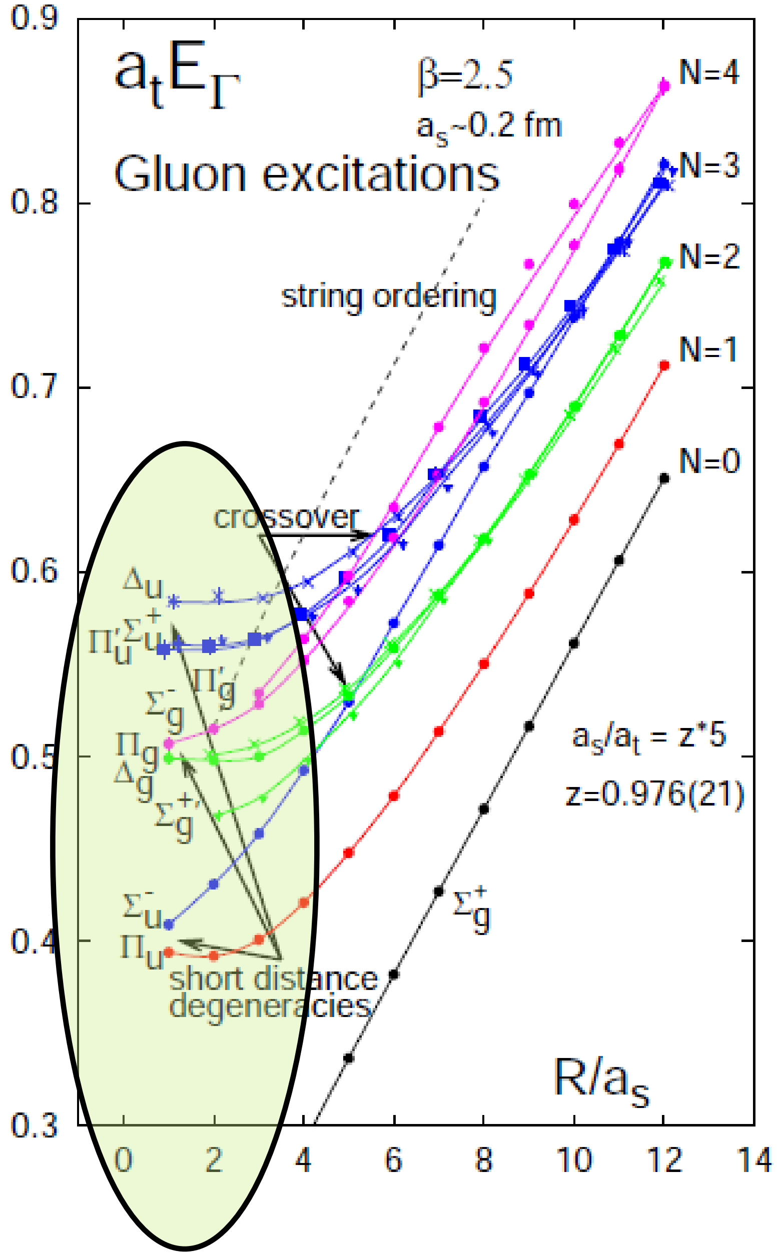

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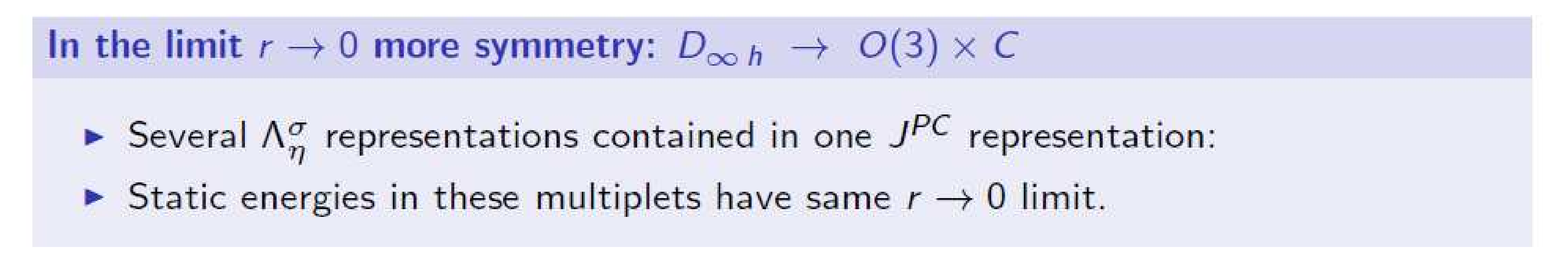
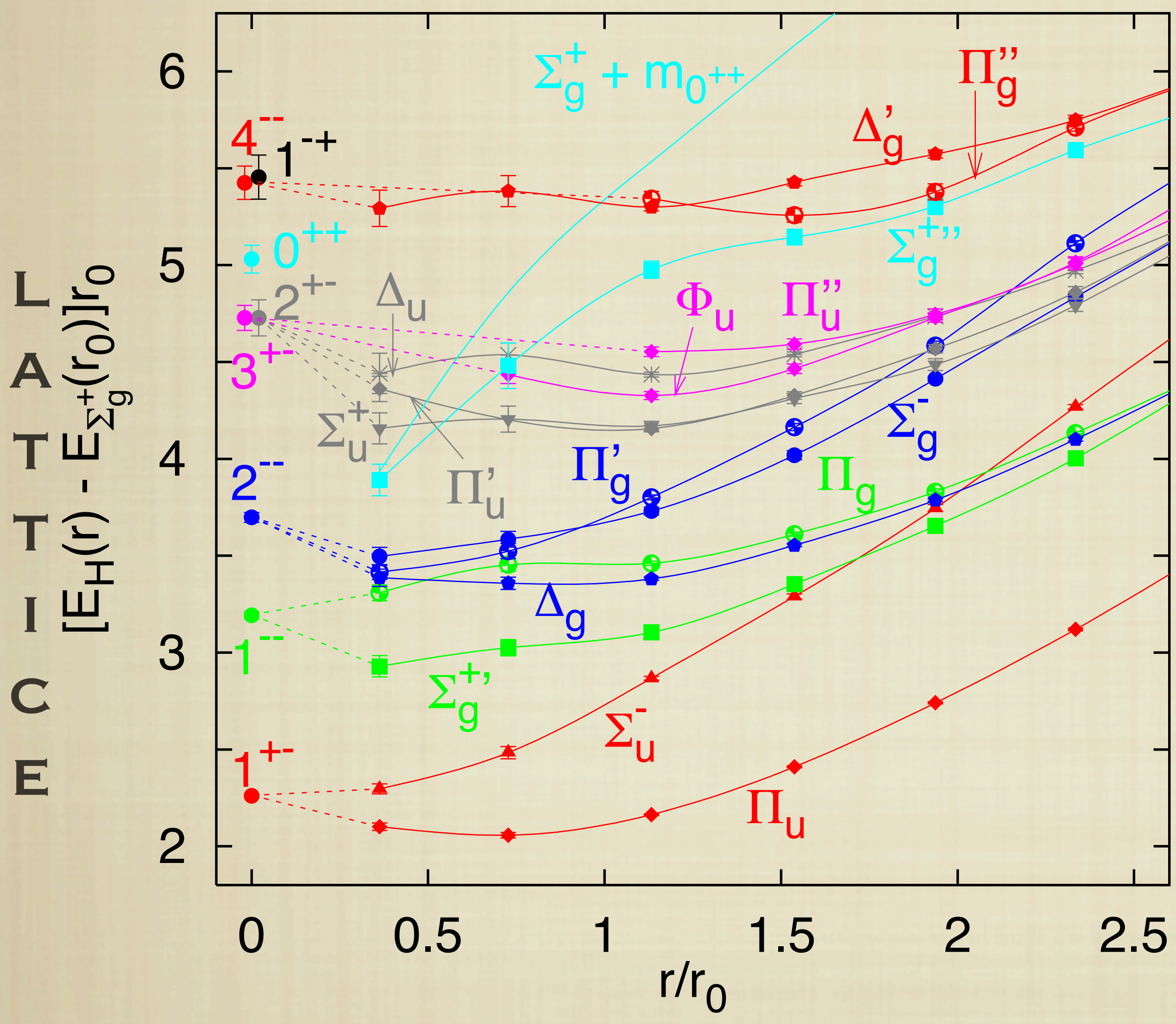
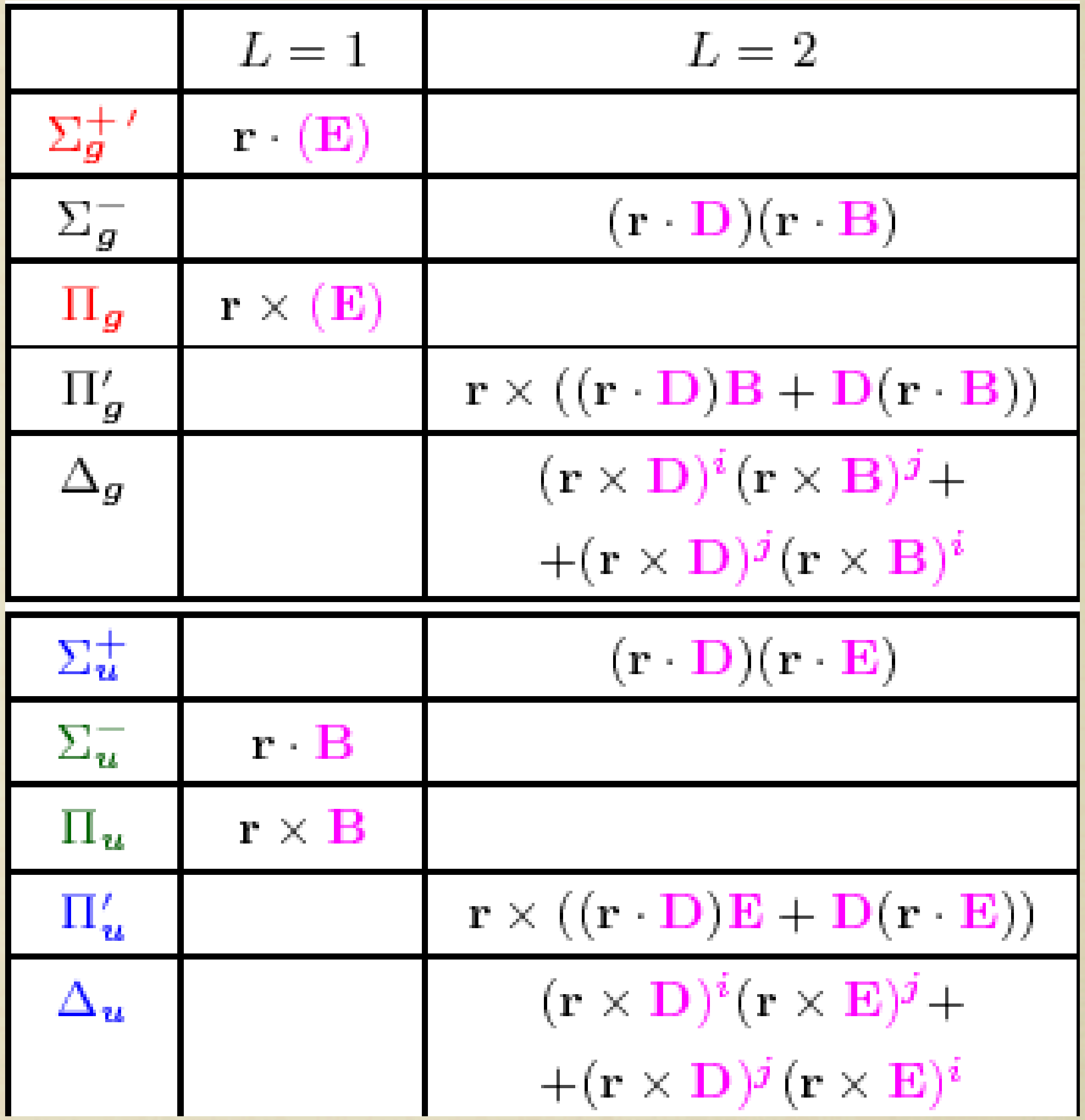
Gluonic excitations in pNRQCD:more symmetry!



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

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





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

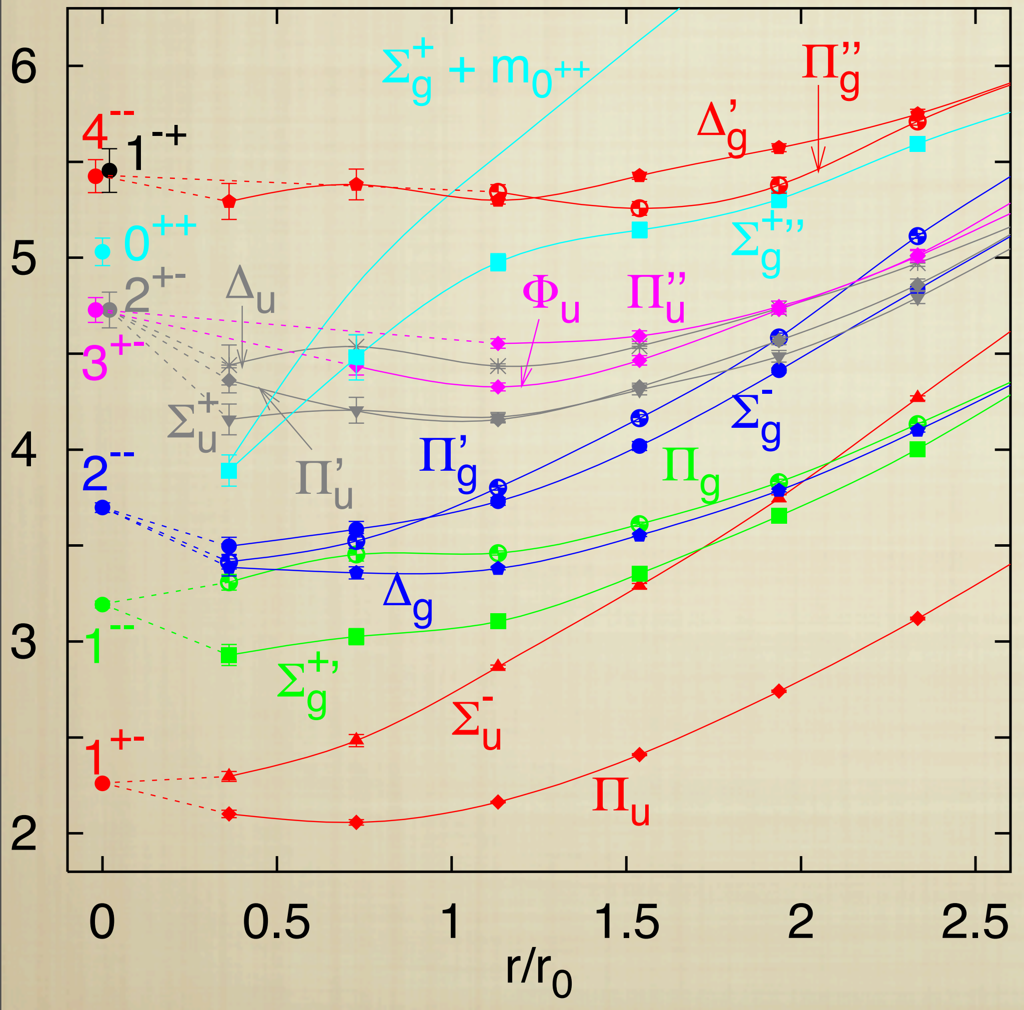
pNRQCD predicts the structure of multiplets at short distance and the ordering

Brambilla Pineda Soto Vairo 0

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

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

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



$$= e^{-iTE_H}$$

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

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

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

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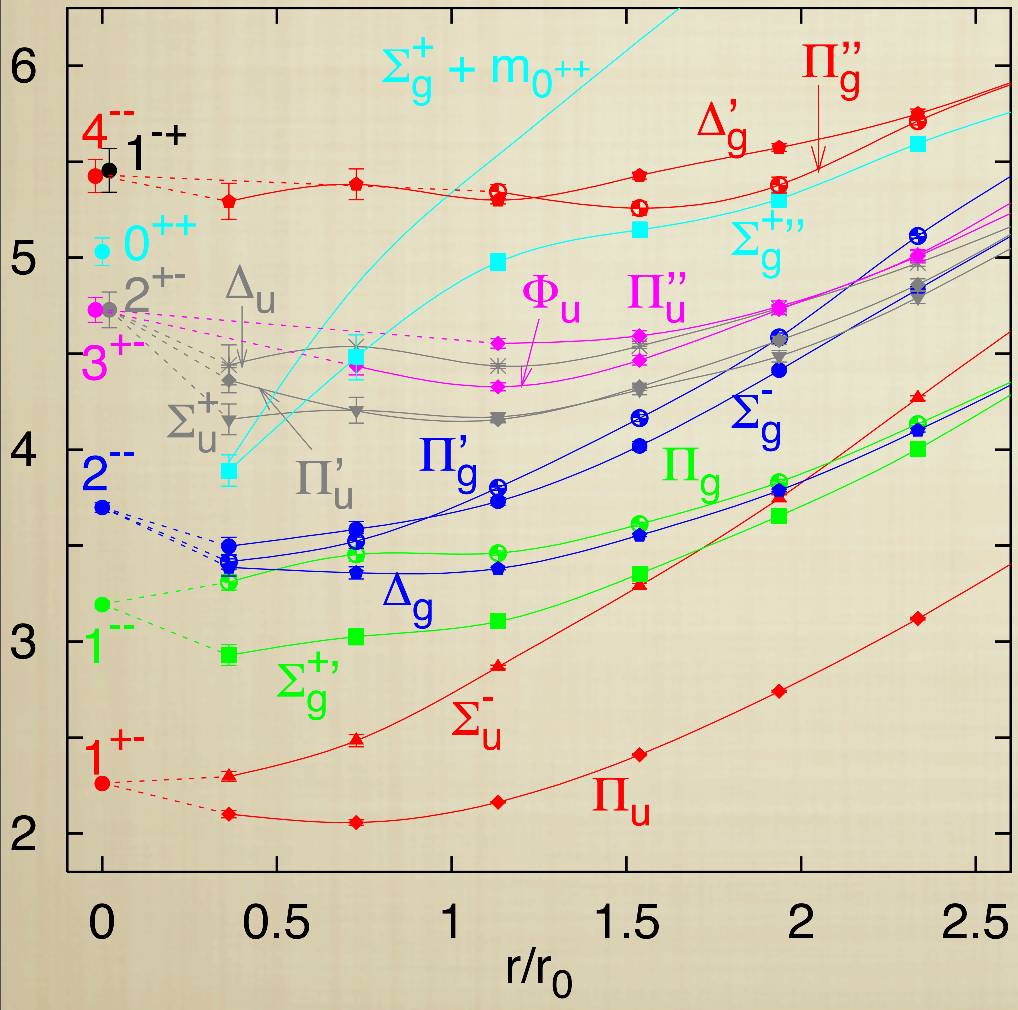

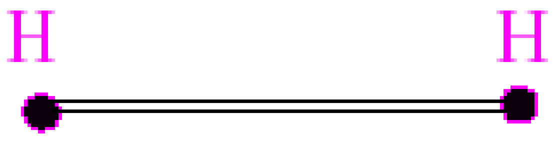

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$$E_H(r) = V_o(r) + \Lambda_H + O(r^2)$$

octet potential

gluelump mass

correction softly breaki
the symmetry

Hybrid Static energies

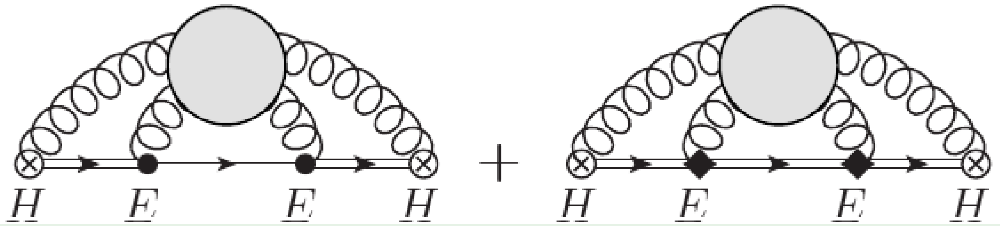
Λ_H

- It is a non-perturbative quantity.
- It depends on the particular operator H^a, however it is the same for operators corresponding to different projections of the same gluonic operators.
- The gluelump masses have been determined in the lattice. Foster *et all* 1999; Bali, Pineda 2004; Marsh Lewis 2014

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

b_H

- It is a non-perturbative quantity.



- Proportional to r^2 due to rotational invariance and the multipole expansion.
- We are going to fix it through a fit to the static energies lattice data.
- Breaks the degeneracy of the potentials.

Hybrids masses

calculated by using the potential $V_H = V_o + \Lambda_H + b_H r^2$
in the Schrodinger equation for heavy quarks obtained
from the matching between NRQCD and pNRQCD

with V_0 calculated in perturbation theory ,

Λ_H from the lattice=gluelump mass, in RS scheme =0.87\pm 0.15 GeV

most of the uncertainty comes from this error

b_H fit from the lattice data

and the mixing inside the multiplet taken into account with the coupled Schroedinger equations obtained in the matching

Berwein,N.B. , Tarrus, Vairo 2015, see also E. Braaten et al 2013, 2014

the spin is not included at this order of the matching

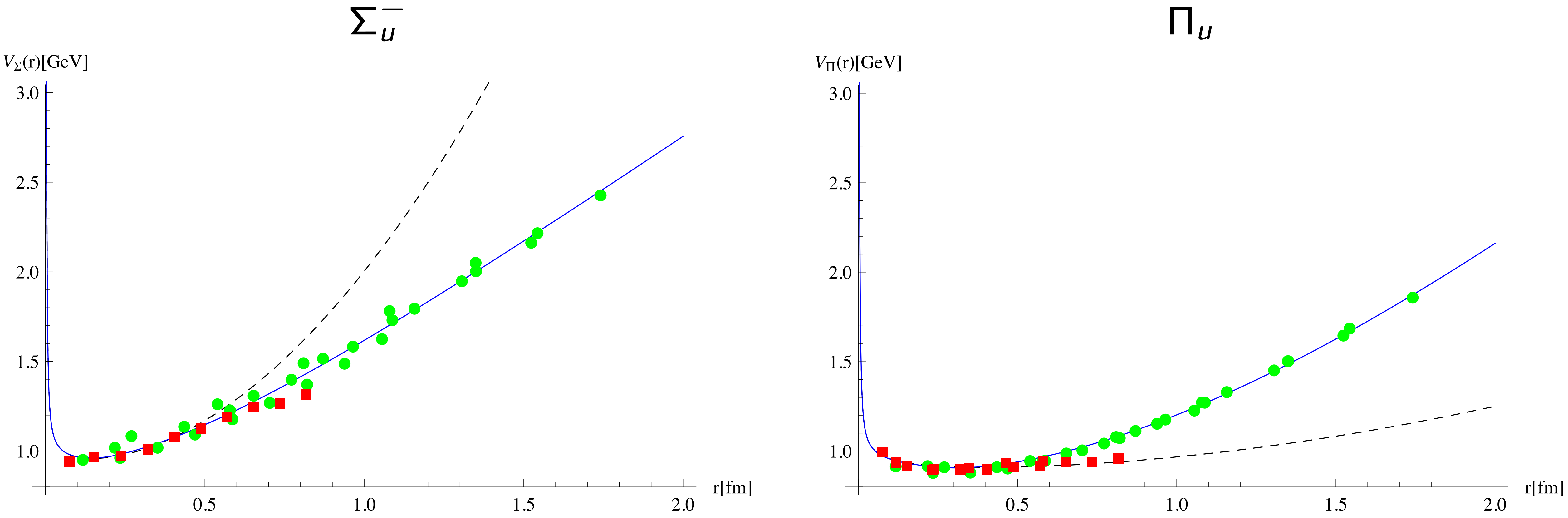
Lowest energy multiplet Σ_u^-–Π_u

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

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

Λ_H and b_H

are nonperturbative and should be obtained from lattice calculations



Lattice data:Bali, Pineda 2004; Juge, Kuti, Morningstar 2003, dashed line $V^{(0.5)}$, solid line $V^{(0.25)}$

$V^{(0.25)}$

- $r \leq 0.25$ fm: pNRQCD potential.
  - Lattice data fitted for the $r = 0 - 0.25$ fm range with the same energy offsets as in $V^{(0.5)}$.

$$b_\Sigma^{(0.25)} = 1.246\,\mathrm{GeV/fm}^2, \qquad b_\Pi^{(0.25)} = 0.000\,\mathrm{GeV/fm}^2 .$$

- $r > 0.25$ fm: phenomenological potential.
  - $\mathcal{V}'(r) = \frac{a_1}{r} + \sqrt{a_2 r^2 + a_3} + a_4$.
  - Same energy offsets as in $V^{(0.25)}$.
  - *Constraint:* Continuity up to first derivatives.

Hybrid state masses from $V^{(0.25)}$

Solving the coupled Schrödinger equations we obtain

GeV	$c\bar{c}$				$b\bar{c}$				$b\bar{b}$			
	m_H	$\langle 1/r \rangle$	E_{kin}	P_Π	m_H	$\langle 1/r \rangle$	E_{kin}	P_Π	m_H	$\langle 1/r \rangle$	E_{kin}	P_Π
H_1	4.15	0.42	0.16	0.82	7.48	0.46	0.13	0.83	10.79	0.53	0.09	0.86
H_1'	4.51	0.34	0.34	0.87	7.76	0.38	0.27	0.87	10.98	0.47	0.19	0.87
H_2	4.28	0.28	0.24	1.00	7.58	0.31	0.19	1.00	10.84	0.37	0.13	1.00
H_2'	4.67	0.25	0.42	1.00	7.89	0.28	0.34	1.00	11.06	0.34	0.23	1.00
H_3	4.59	0.32	0.32	0.00	7.85	0.37	0.27	0.00	11.06	0.46	0.19	0.00
H_4	4.37	0.28	0.27	0.83	7.65	0.31	0.22	0.84	10.90	0.37	0.15	0.87
H_5	4.48	0.23	0.33	1.00	7.73	0.25	0.27	1.00	10.95	0.30	0.18	1.00
H_6	4.57	0.22	0.37	0.85	7.82	0.25	0.30	0.87	11.01	0.30	0.20	0.89
H_7	4.67	0.19	0.43	1.00	7.89	0.22	0.35	1.00	11.05	0.26	0.24	1.00

Consistency test:

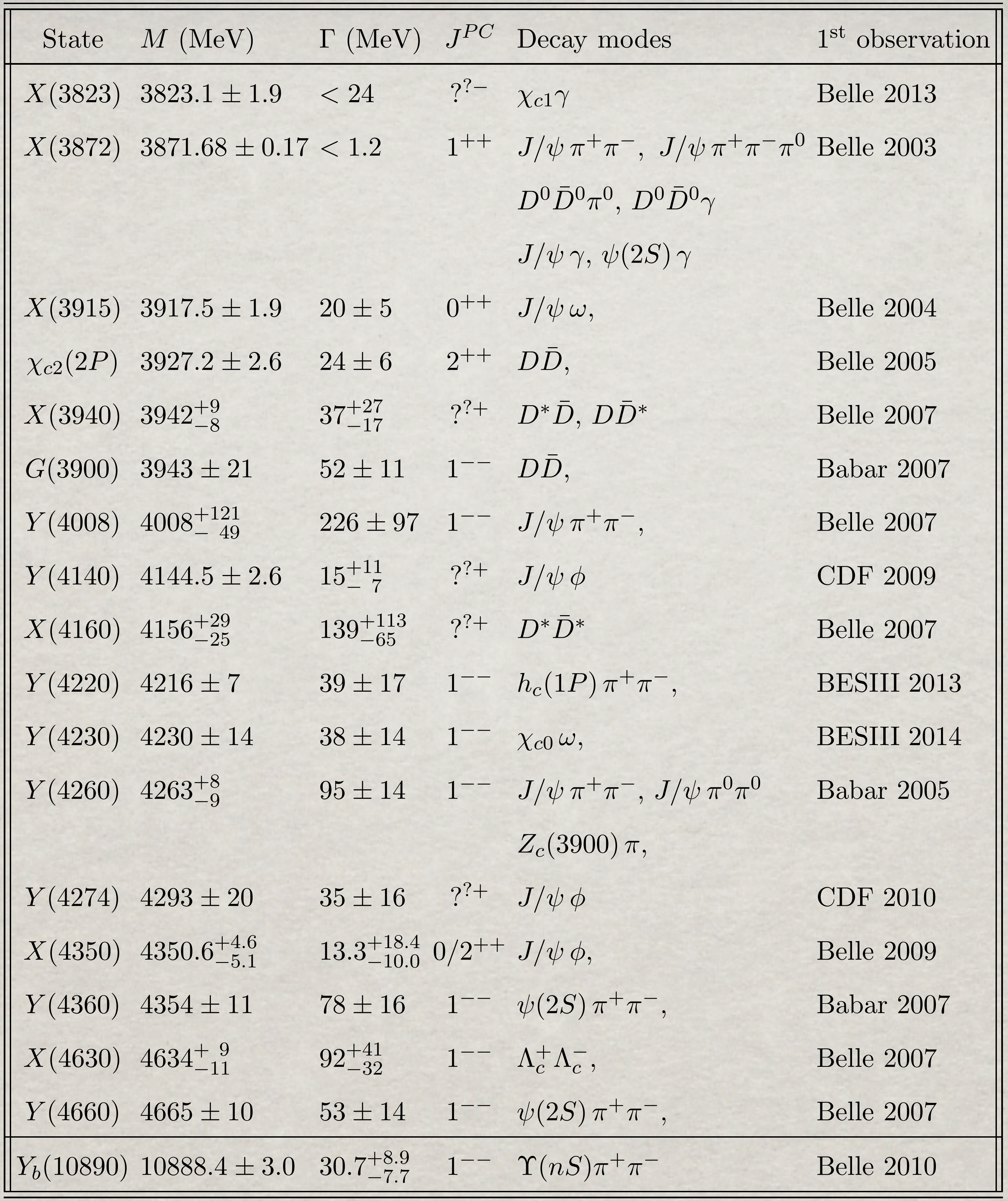
1. The multipole expansion requires $\langle 1/r \rangle > E_{kin}$.

- As expected the our approach works better in bottomonium than charmonium

- Spin symmetry 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

Experimental candidates for hybrids



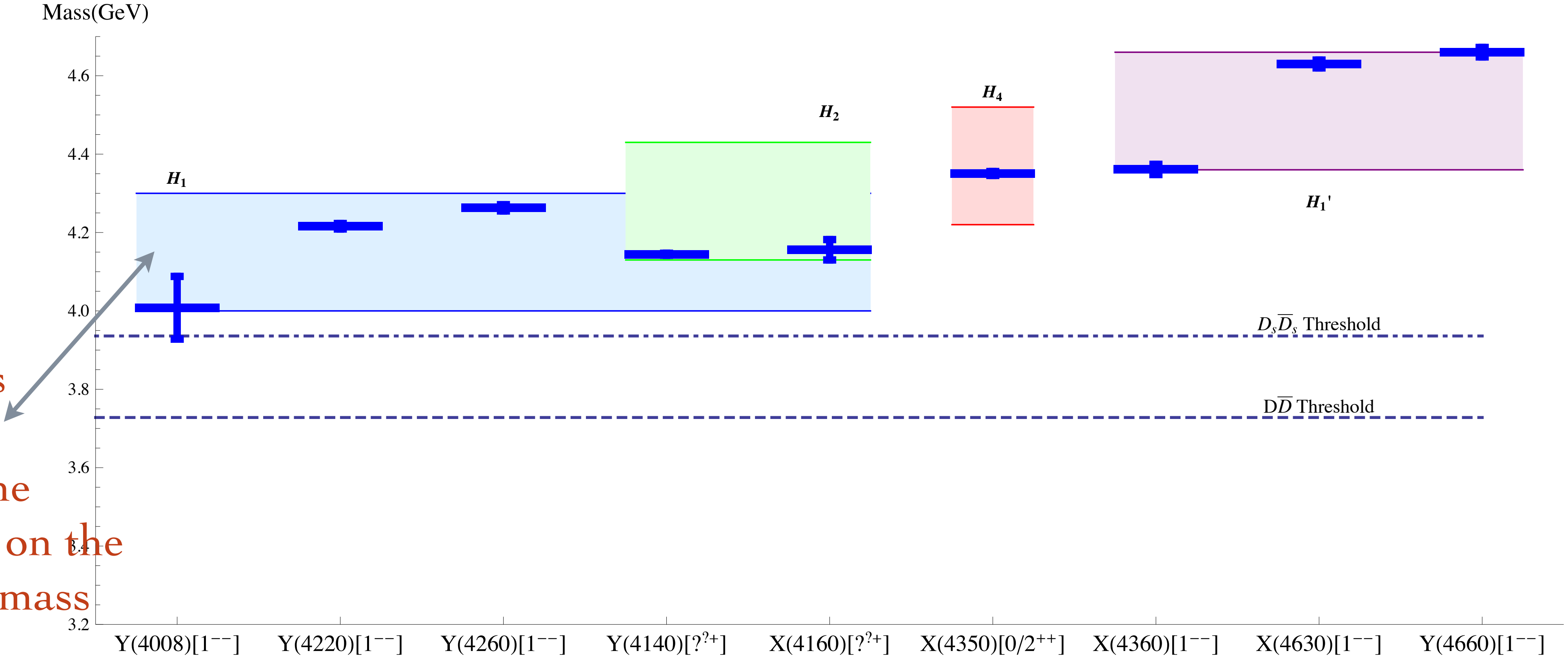
State	M (MeV)	Γ (MeV)	J^{PC}	Decay modes	1st observation
$X(3823)$	3823.1 ± 1.9	< 24	$?^{?-}$	$\chi_{c1}\gamma$	Belle 2013
$X(3872)$	3871.68 ± 0.17	< 1.2	1^{++}	$J/\psi\,\pi^+\pi^-,\ J/\psi\,\pi^+\pi^-\pi^0$ $D^0\bar{D}^0\pi^0,\ D^0\bar{D}^0\gamma$ $J/\psi\,\gamma,\ \psi(2S)\,\gamma$	Belle 2003
$X(3915)$	3917.5 ± 1.9	20 ± 5	0^{++}	$J/\psi\,\omega,$	Belle 2004
$\chi_{c2}(2P)$	3927.2 ± 2.6	24 ± 6	2^{++}	$D\bar{D},$	Belle 2005
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$D^*\bar{D},\ D\bar{D}^*$	Belle 2007
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$D\bar{D},$	Babar 2007
$Y(4008)$	$4008^{+121}_{-\ 49}$	226 ± 97	1^{--}	$J/\psi\,\pi^+\pi^-,$	Belle 2007
$Y(4140)$	4144.5 ± 2.6	$15^{+11}_{-\ 7}$	$?^{?+}$	$J/\psi\,\phi$	CDF 2009
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$D^*\bar{D}^*$	Belle 2007
$Y(4220)$	4216 ± 7	39 ± 17	1^{--}	$h_c(1P)\,\pi^+\pi^-,$	BESIII 2013
$Y(4230)$	4230 ± 14	38 ± 14	1^{--}	$\chi_{c0}\,\omega,$	BESIII 2014
$Y(4260)$	4263^{+8}_{-9}	95 ± 14	1^{--}	$J/\psi\,\pi^+\pi^-,\ J/\psi\,\pi^0\pi^0$ $Z_c(3900)\,\pi,$	Babar 2005
$Y(4274)$	4293 ± 20	35 ± 16	$?^{?+}$	$J/\psi\,\phi$	CDF 2010
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0/2^{++}$	$J/\psi\,\phi,$	Belle 2009
$Y(4360)$	4354 ± 11	78 ± 16	1^{--}	$\psi(2S)\,\pi^+\pi^-,$	Babar 2007
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-,$	Belle 2007
$Y(4660)$	4665 ± 10	53 ± 14	1^{--}	$\psi(2S)\,\pi^+\pi^-,$	Belle 2007
$Y_b(10890)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$\Upsilon(nS)\pi^+\pi^-$	Belle 2010

TABLE V: Neutral mesons above open flavor threshold excluding isospin partners of charged states.

Identification with experimental states

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

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



error bands come from the uncertainty on the gluelump mass

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

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

Berwein, N.B. , Tarrus, Vairo 2015,

Conclusions

Quarkonium is a golden system to study strong interactions

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

At T=0, away from threshold, EFTs allow us to make calculations with unprecented precision, where high order perturbative calculations are possible and to systematically factorize short from long range contributions where observables are sentitive to the nonperturbative dynamics of QCD.

Some lattice calculations are still needed (glue correlators, quenched and unquenched Wilson loops with field insertions).

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

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

Conclusions

For states close or above the strong decay threshold the situation is much more complicated.

Many degrees of freedom show up and the absence of a clear systematic is an obstacle to a universal picture

We have presented results obtained for the hybrid masses in pNRQCD that show a very rich structure of multiplets.

These results are promising but need to be complemented by decay and transitions calculations. A version of strongly coupled pNRQCD including hybrids should be eventually obtained in this framework and the inclusion of the operators carring the synamics light quark degrees of freedom should be realized.

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

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

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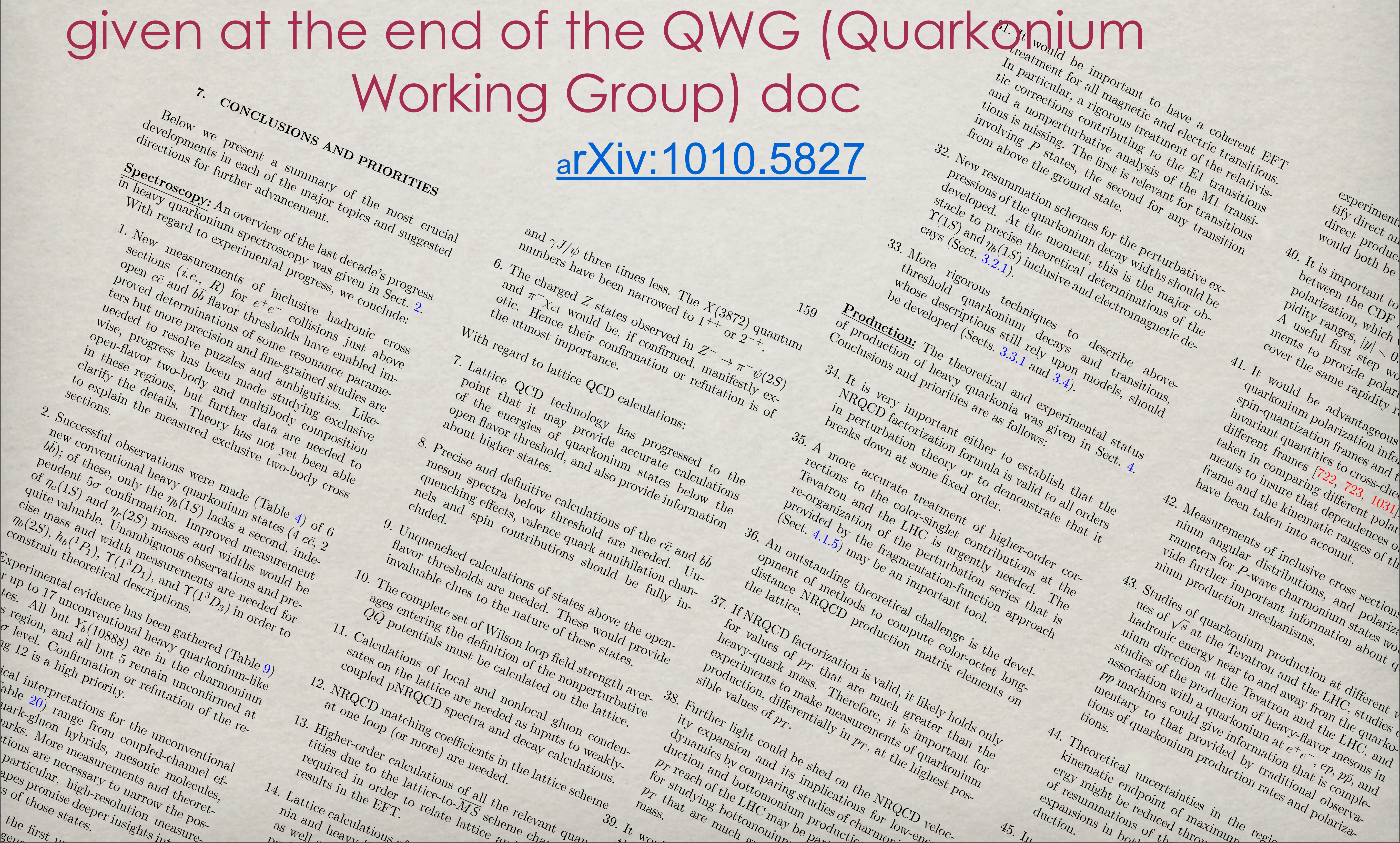
In this direction go the list of 65 priorities given at the end of the QWG (Quarkonium Working Group) doc

arXiv:1010.5827



7. CONCLUSIONS AND PRIORITIES

Below we present a summary of the most crucial developments in each of the major topics and suggested directions for further advancement.

Spectroscopy: An overview of the last decade's progress in heavy quarkonium spectroscopy was given in Sect. 2. With regard to experimental progress, we conclude:

1. New measurements of inclusive hadronic cross sections (*i.e.*, R) for e^+e^- collisions just above open $c\bar{c}$ and $b\bar{b}$ flavor thresholds have enabled improved determinations of some resonance parameters but more precision and fine-grained studies are needed to resolve puzzles and ambiguities. Likewise, progress has been made studying exclusive open-flavor two-body and multibody composition in these regions, but further data are needed to clarify the details. Theory has not yet been able to explain the measured exclusive two-body cross sections.
2. Successful observations were made (Table 4) of 6 new conventional heavy quarkonium states (4 $c\bar{c}$, 2 $b\bar{b}$); of these, only the $\eta_b(1S)$ lacks a second, independent 5σ confirmation. Improved measurement of $\eta_c(1S)$ and $\eta_c(2S)$ masses and widths would be quite valuable. Unambiguous observations and precise mass and width measurements are needed for $\eta_b(2S)$, $h_b(^1P_1)$, $\Upsilon(1^3D_1)$, and $\Upsilon(1^3D_3)$ in order to constrain theoretical descriptions.

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

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

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 quan
tities due to the lattice-to-$\overline{MS}$ scheme cha
required in order to relate lattice an
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 veloc-
ity expansion and its implications for low-ene
dynamics by comparing studies of charmon
duction and bottomonium productio
p_T reach of the LHC may be par
for studying bottomonium
p_T that are much g
mass.
39. It wo

experiment
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 polar
cover the same rapidity r
41. It would be advantageous
quarkonium polarization infor
spin-quantization frames and t
invariant quantities to cross-chec
different frames [722, 723, 1031].
taken in comparing different polar
ments to insure that dependences o
frame and the kinematic ranges of th
have been taken into account.
42. Measurements of inclusive cross sections
nium angular distributions, and polariza
rameters for P-wave charmonium states wou
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 comple-
mentary to that provided by traditional observa-
tions of quarkonium production rates and polariza-
tions.
44. Theoretical uncertainties in the regi
kinematic endpoint of maximum
ergy might be reduced thro
of resummations of th
expansions in bot
duction.
45. In

QUARK CONFINEMENT AND THE HADRON SPECTRUM XII

from 29 August 2016 to 2 September 2016
Ioannis Vellidis conference centre,
THESSALONIKI

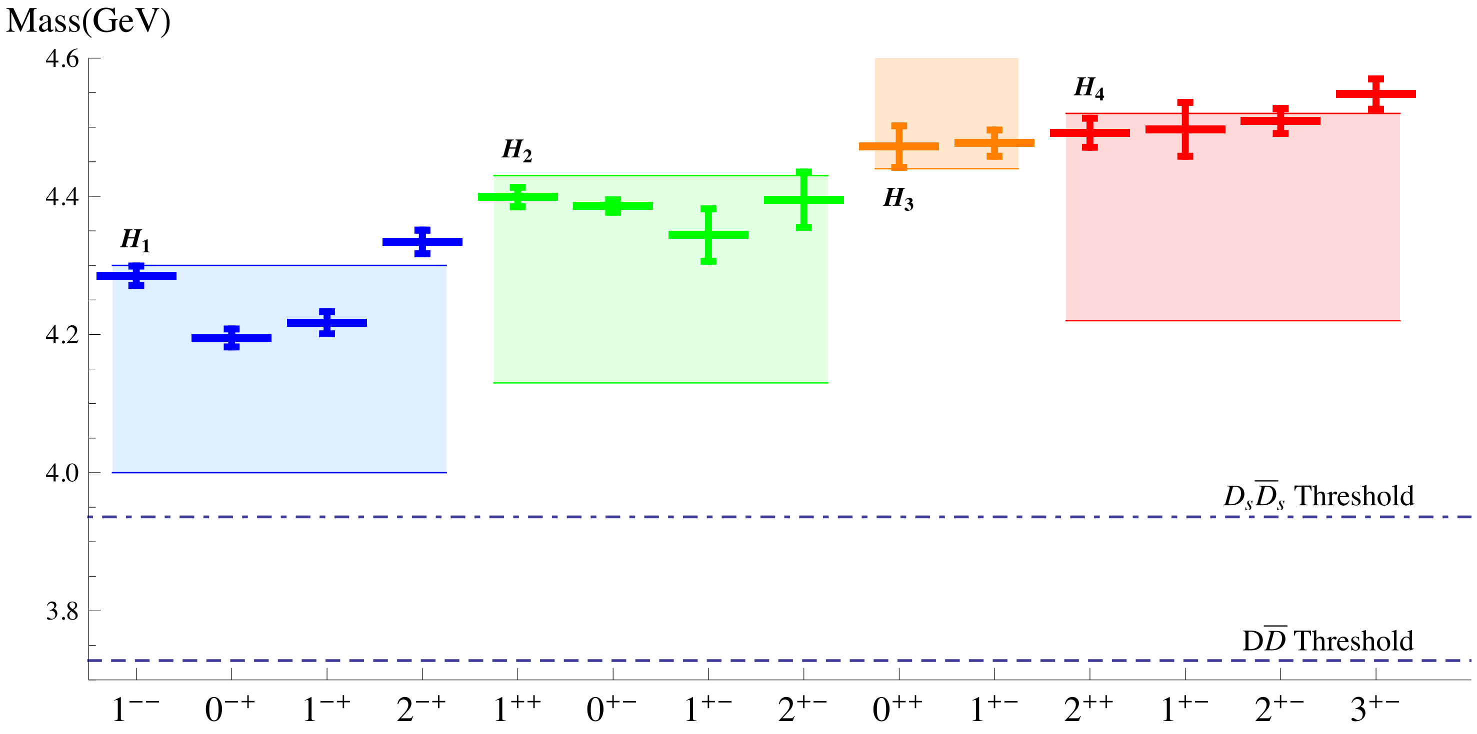
ORGANIZED
BY YIOTA FOKA

BACKUP

Comparison with direct lattice computations

Charmonium sector

- Calculations done by the Hadron Spectrum Collaboration using unquenched lattice QCD with a pion mass of 400 MeV. Liu *et all* 2012
- They worked in the constituent gluon picture, which consider the multiplets H_2, H_3, H_4 as part of the same multiplet.
- Their results are given with the η_c mass subtracted.



Error bands take into account the uncertainty on the gluelump mass ±0.15 GeV

Split (GeV)	Liu	$V^{(0.25)}$
$\delta m_{H_2-H_1}$	0.10	0.13
$\delta m_{H_4-H_1}$	0.24	0.22
$\delta m_{H_4-H_2}$	0.13	0.09
$\delta m_{H_3-H_1}$	0.20	0.44
$\delta m_{H_3-H_2}$	0.09	0.31

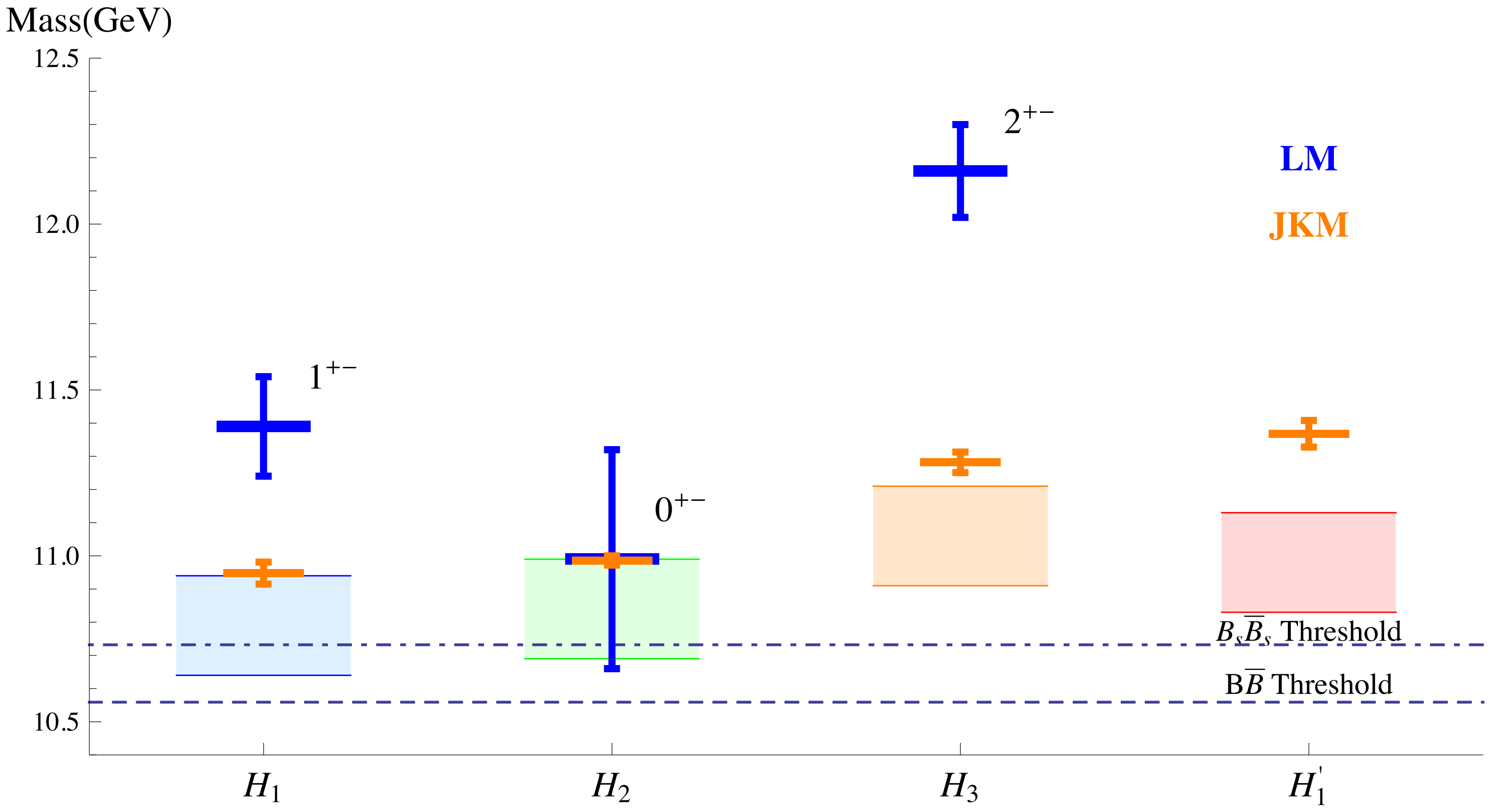
- Our masses are 0.1 – 0.14 GeV lower except the for the H_3 multiplet, which is the only one dominated by Σ_u^-.
- Good agreement with the mass gaps between multiplets, in particular the Λ-doubling effect ($\delta m_{H_2-H_1}$).

Berwein,N.B. , Tarrus, Vairo 2014,

Comparison with direct lattice computations

Bottomonium sector

- Calculations done by Juge, Kuti, Morningstar 1999 and Liao, Manke 2002 using quenched lattice QCD.
- Juge, Kuti, Morningstar 1999 included no spin or relativistic effects.
- Liao, Manke 2002 calculations are fully relativistic.



Error bands take into account the uncertainty on the gluelump mass ±0.15 GeV

Split (GeV)	JKM	$V^{(0.25)}$
$\delta m_{H_2-H_1}$	0.04	0.05
$\delta m_{H_3-H_1}$	0.33	0.27
$\delta m_{H_3-H_2}$	0.30	0.22
$\delta m_{H_1'-H_1}$	0.42	0.19

- Our masses are $0.15-0.25$ GeV lower except the for the H_1' multiplet, which is larger by 0.36 GeV.
- Good agreement with the mass gaps between multiplets, in particular the Λ-doubling effect ($\delta m_{H_2-H_1}$).

Berwein,N.B. , Tarrus, Vairo 2014,

- We have computed the heavy hybrid masses using a QCD analog of the Born-Oppenheimer approximation including the Λ–doubling terms by using coupled Schröringer equations.
- The static energies have been obtained combining pNRQCD for short distances and lattice data for long distances.
- A large set of masses for spin symmetry multiplets for $c\bar{c}$, $b\bar{c}$ and $b\bar{b}$ has been obtained.
- Λ–doubling effect lowers the mass of the multiplets generated by a mix of static energies, the same pattern is observed in direct lattice calculations and QCD sum rules.
- Mass gaps between multiplets in good agreement with direct lattice computations, but the absolute values are shifted.
- Several experimental candidates for Charmonium hybrids belonging to the H_1, H_2, H_4 and H_1' multiplets.
- One experimental candidate to the bottomonium H_1 multiplet.

Coupled radial equations for Σ_u^-–Π_u

$$\left[-\frac{\partial_r^2}{m}+\frac{1}{mr^2}\begin{pmatrix} l(l+1)+2 & 2\sqrt{l(l+1)} \\ 2\sqrt{l(l+1)} & l(l+1)\end{pmatrix}+\begin{pmatrix} E_\Sigma^{(0)} & 0 \\ 0 & E_\Pi^{(0)}\end{pmatrix}\right]\begin{pmatrix}\Psi_{\epsilon,\,\Sigma^N} \\ \psi^N_{\epsilon,\,\Pi}\end{pmatrix}=\mathcal{E}_N\begin{pmatrix}\Psi^N_{\epsilon,\,\Sigma} \\ \Psi^N_{\epsilon,\,\Pi}\end{pmatrix}$$

$$\left[-\frac{\partial_r^2}{m}+\frac{l(l+1)}{mr^2}+E_\Pi^{(0)}\right]\psi^{(N)}_{-\epsilon,\,\Pi}=\mathcal{E}_N\psi^{(N)}_{-\epsilon,\,\Pi}\,.$$

- The coupled Schrödinger equations can be solved numerically.