Quarkonia:
a theoretical framework

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Energy scales

Why to study quarkonia?

Quarkonia are systems where low energy QCD may be studied in a systematic way (e.g. large order perturbation theory, non-perturbative matrix elements, QCD vacuum, exotica, confinement, deconfinement, ...).

This is because the quark mass M is the largest scale in the system:

- $M \gg p$
- $M \gg \Lambda_{\mathrm{QCD}}$

The non-relativistic expansion

- $M \gg p$ implies that quarkonia are non-relativistic and characterized by the hierarchy of scales typical of a non-relativistic bound state:

$$M \gg p \sim 1/r \sim Mv \gg E \sim Mv^2$$

Systematic expansions in the small heavy-quark velocity v may be implemented at the Lagrangian level by constructing suitable effective field theories (EFTs):

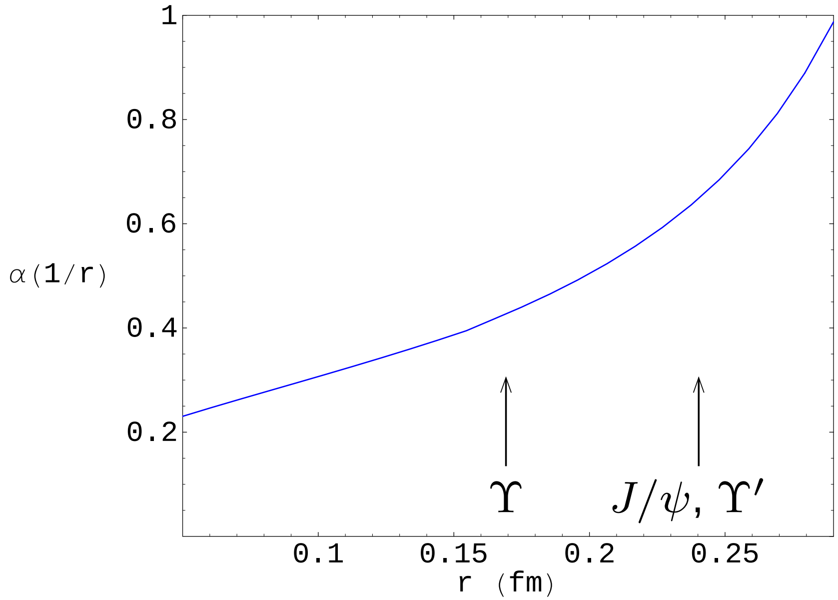
- expanding QCD in $p, E/M$ leads to NRQCD
  - `Bodwin Braaten Lepage PRD 51 (1995) 1125`
- expanding NRQCD in $E/p, 1/r$ leads to pNRQCD
  - `Brambilla Pineda Soto Vairo RMP 77 (2004) 1423`

The hierarchy of non-relativistic scales makes the very difference of quarkonia with heavy-light mesons, which are just characterized by the two scales M and $\Lambda_{\rm QCD}$.

The perturbative expansion

- $M \gg \Lambda_{\rm QCD}$ implies $\alpha_{\rm s}(M) \ll 1$: phenomena happening at the scale M may be treated perturbatively.

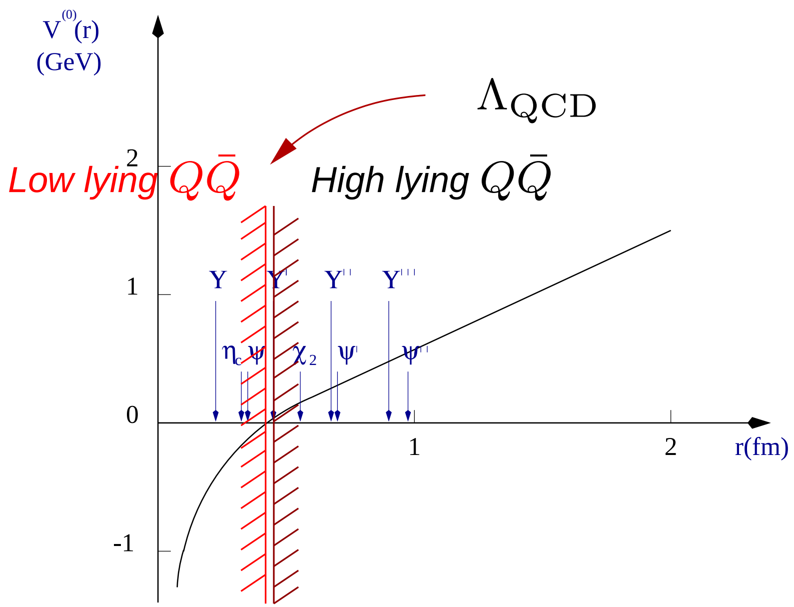
We may further have small couplings if $Mv \gg \Lambda_{\rm QCD}$ and $Mv^2 \gg \Lambda_{\rm QCD}$, in which case $\alpha_{\rm s}(Mv) \ll 1$ and $\alpha_{\rm s}(Mv^2) \ll 1$ respectively. This is likely to happen only for the lowest charmonium and bottomonium states.



Quarkonium as a confinement and deconfinement probe

It is precisely the rich structure of separated energy scales that makes quarkonium an ideal probe of confinement and deconfinement.

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

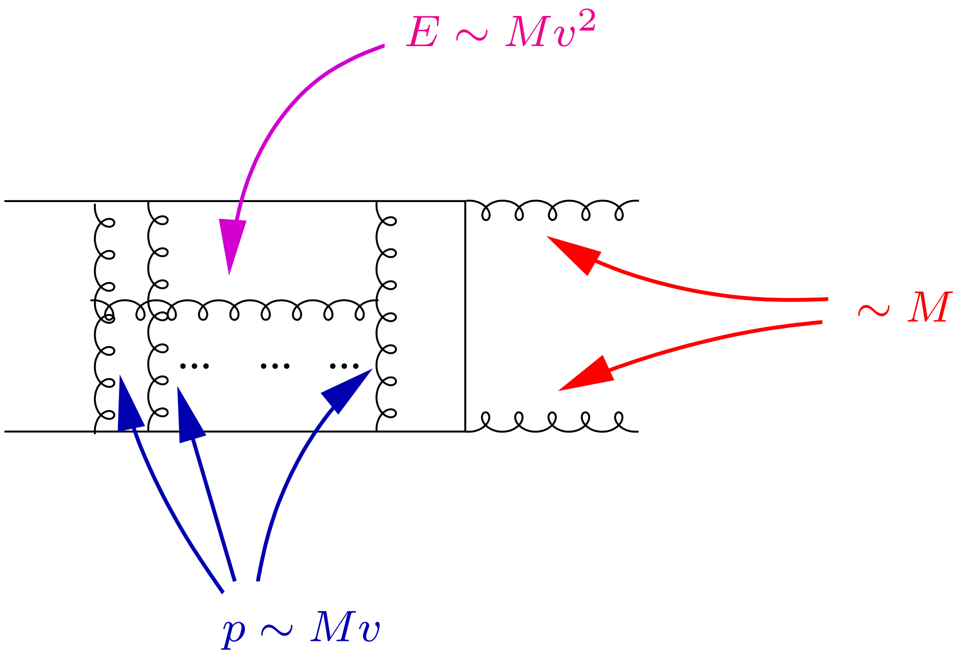


  - ○ `Godfrey Isgur PRD 32 (1985) 189`

- Different quarkonia will dissociate in a medium at different temperatures, providing a thermometer for the plasma.
  - ○ `Matsui Satz PLB 178 (1986) 416`

Quarkonium scales

Scales get entangled:

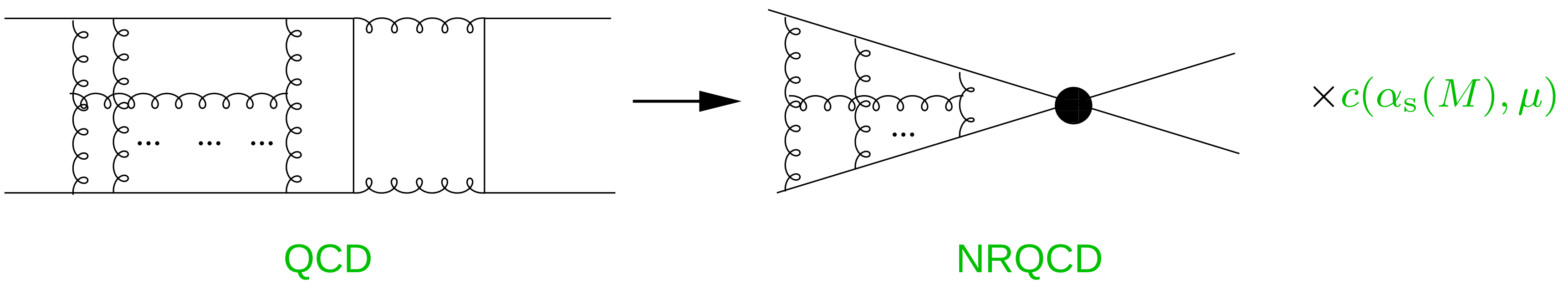


- Quarkonium production and annihilation happen at the scale M;
- Quarkonium binding happens at a scale Mv.

Physics at the scale M

Physics at the scale M: annihilation and production

Quarkonium annihilation and production happens at the scale M.
The suitable EFT is NRQCD.



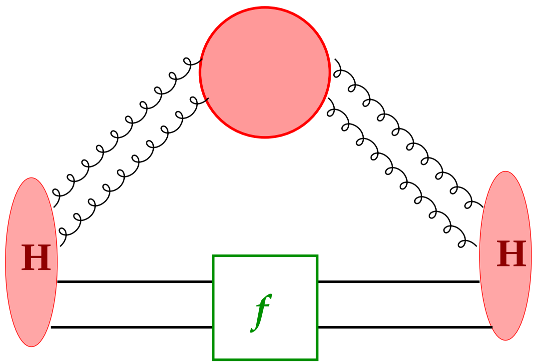
The effective Lagrangian is organized as an expansion in $1/M$ and $\alpha_s(M)$:

$$\mathcal{L}_{\rm NRQCD} = \sum_n \frac{c_n(\alpha_s(M),\mu)}{M^n} \times O_n(\mu, Mv, Mv^2, \ldots)$$

NRQCD: widths

The (all orders proved) NRQCD factorization formula reads

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



Progress has been made in

- the evaluation of the factorization formula at higher orders in v and $\alpha_s(M)$.
- the (lattice) evaluation of the matrix elements.

Progress has also been made in establishing a factorization formula for production.

∘ Nayak Qiu Sterman PLB 613 (2005) 45 ... Kang Qiu Sterman PRL 108 (2012) 102002, Kang Ma Qiu Sterman arXiv:1401.0923, Fleming Mehen Leibovich Rothstein PRD 86 (2012) 094012, D87 (2013) 074022

Charmonium P-wave decays

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

Ratio	QWG EPJ C71 (2011) 1534	PDG (2000)	LO	NLO
$\frac{\Gamma(\chi_{c0}\to\gamma\gamma)}{\Gamma(\chi_{c2}\to\gamma\gamma)}$	4.5±0.8	13±10	3.75	$\approx$ 5.43
$\frac{\Gamma(\chi_{c2}\to l.h.)-\Gamma(\chi_{c1}\to l.h.)}{\Gamma(\chi_{c0}\to\gamma\gamma)}$	450±100	270±200	$\approx$ 347	$\approx$ 383
$\frac{\Gamma(\chi_{c0}\to l.h.)-\Gamma(\chi_{c1}\to l.h.)}{\Gamma(\chi_{c0}\to\gamma\gamma)}$	4200±600	3500±2500	$\approx$ 1300	$\approx$ 2781
$\frac{\Gamma(\chi_{c0}\to l.h.)-\Gamma(\chi_{c2}\to l.h.)}{\Gamma(\chi_{c2}\to l.h.)-\Gamma(\chi_{c1}\to l.h.)}$	8.4±0.9	12.1±3.2	2.75	$\approx$ 6.63
$\frac{\Gamma(\chi_{c0}\to l.h.)-\Gamma(\chi_{c1}\to l.h.)}{\Gamma(\chi_{c2}\to l.h.)-\Gamma(\chi_{c1}\to l.h.)}$	9.4±1.1	13.1±3.3	3.75	$\approx$ 7.63

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

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

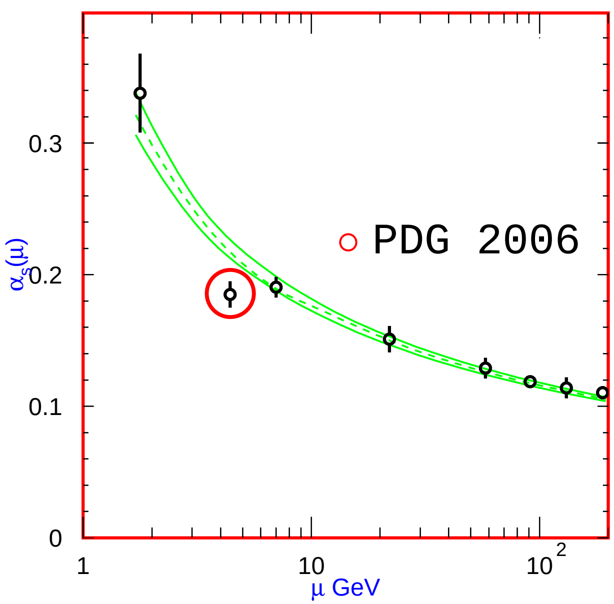
α_s from $\Upsilon(1S)$ decay

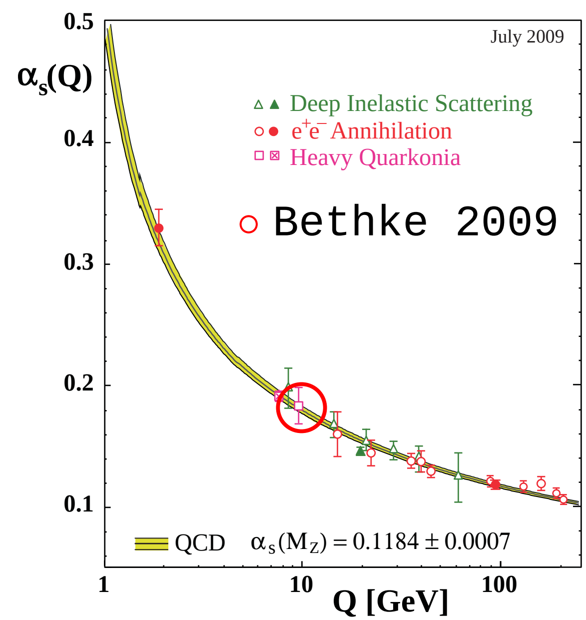
- CLEO data on $\Upsilon(1S) \to \gamma\, X$,
- theoretical determinations of $\Upsilon(1S) \to \gamma\, X$ and $\Upsilon(1S) \to X$,
- lattice determinations of NRQCD matrix elements,

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

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

○ Brambilla Garcia Soto Vairo PRD 75 (2007) 074014

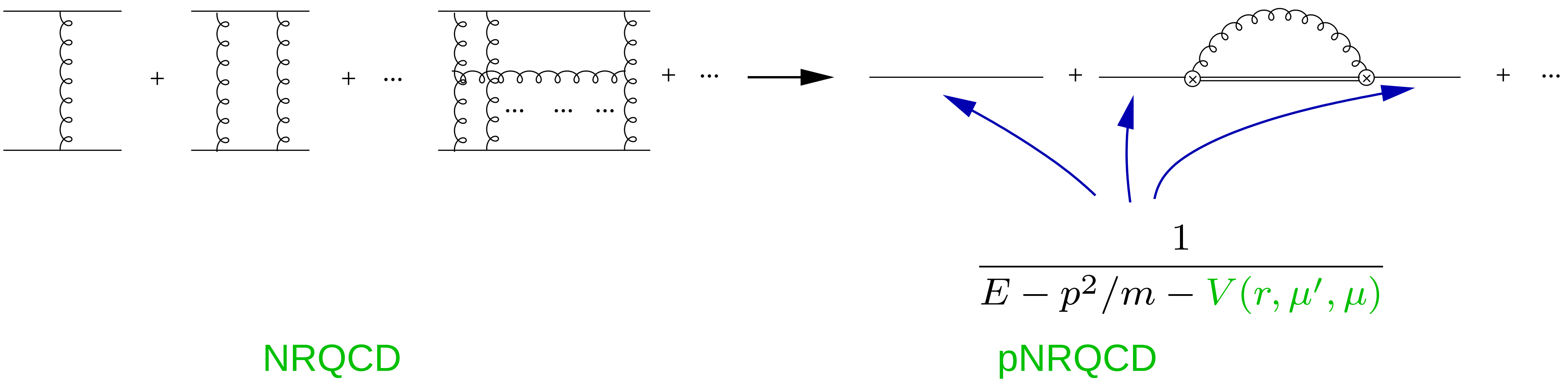




Physics at the scale Mv

Physics at the scale Mv: bound state formation

Quarkonium formation happens at the scale Mv. The suitable EFT is pNRQCD.



$$\frac{1}{E - p^2/m - V(r, \mu', \mu)}$$

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

$$\mathcal{L}_{\text{pNRQCD}} = \int d^3r \sum_n \sum_k \frac{c_n(\alpha_s(M), \mu)}{M^n} \times V_{n,k}(r, \mu', \mu)\, r^k \times O_k(\mu', Mv^2, \ldots)$$

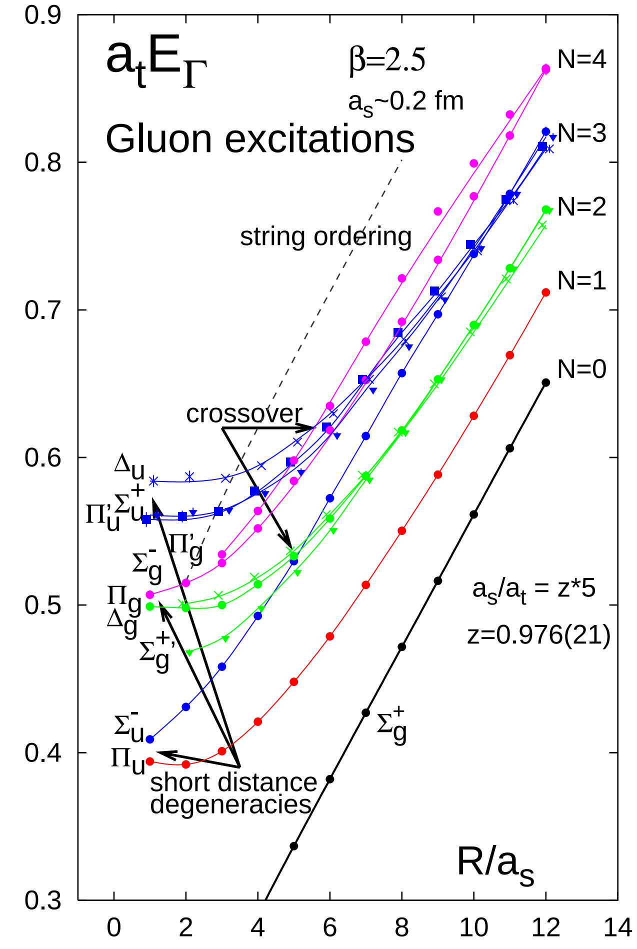
- $V_{n,0}$ are the potentials in the Schrödinger equation.
- $V_{n,k\neq 0}$ are the couplings with the low-energy degrees of freedom, which provide corrections to the potential picture.

The static QCD spectrum without light quarks

- At short distances, it is well described by the Coulomb potentials: $V_s = -4\alpha_s/3r$ and $V_o = \alpha_s/6r$.
- At large distances, the energies rise linearly with r.
- Higher excitations develop a mass gap $\sim \Lambda_{QCD}$ with respect to the lowest one.
- Introducing a finite heavy quark mass M:

  the spectrum of the Mv^2 fluctuations around the lowest state is the quarkonium spectrum;

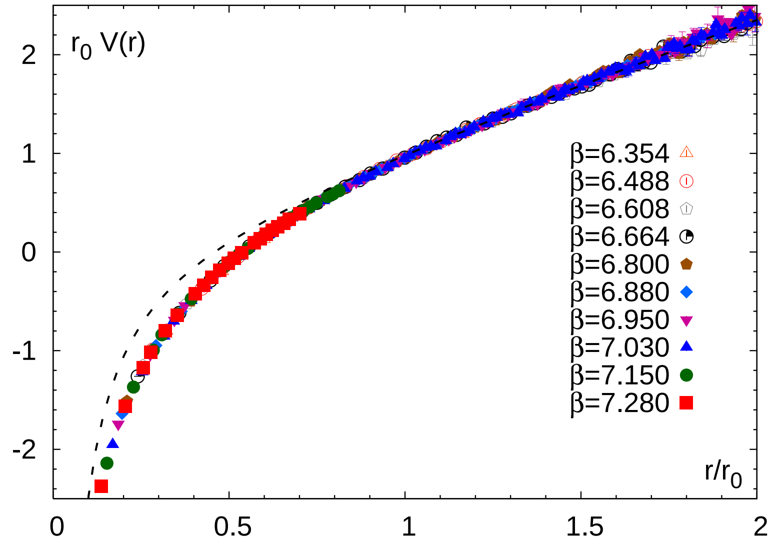
  the spectrum of the Mv^2 fluctuations around the higher excitations is the hybrid spectrum.



○ Juge Kuti Morningstar PRL 90 (2003) 161601

The quark-antiquark static energy

The energy of the lowest state is the quark-antiquark static energy.

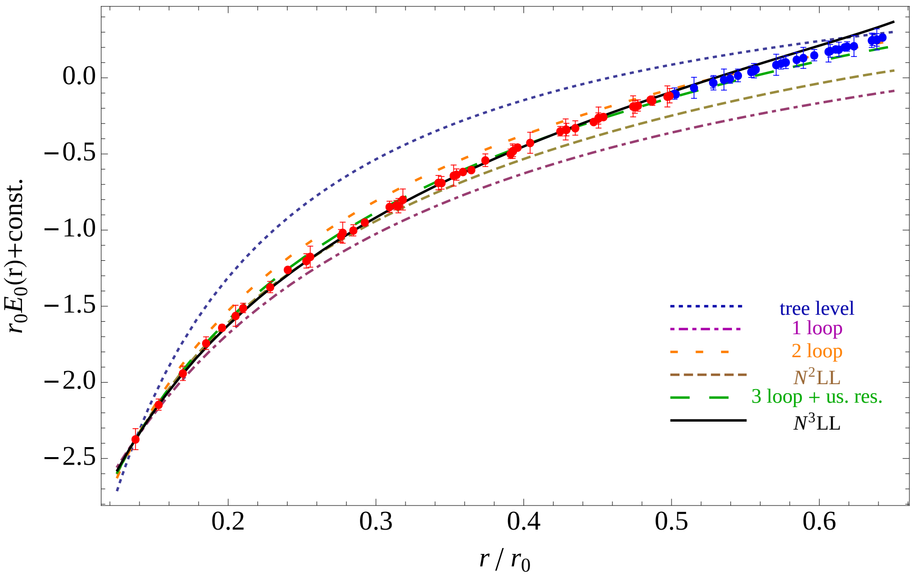


○ HotQCD coll. PRD 85 (2012) 054503

Low-lying quarkonia

Low-lying quarkonia

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

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 563 (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, ...;
- ...

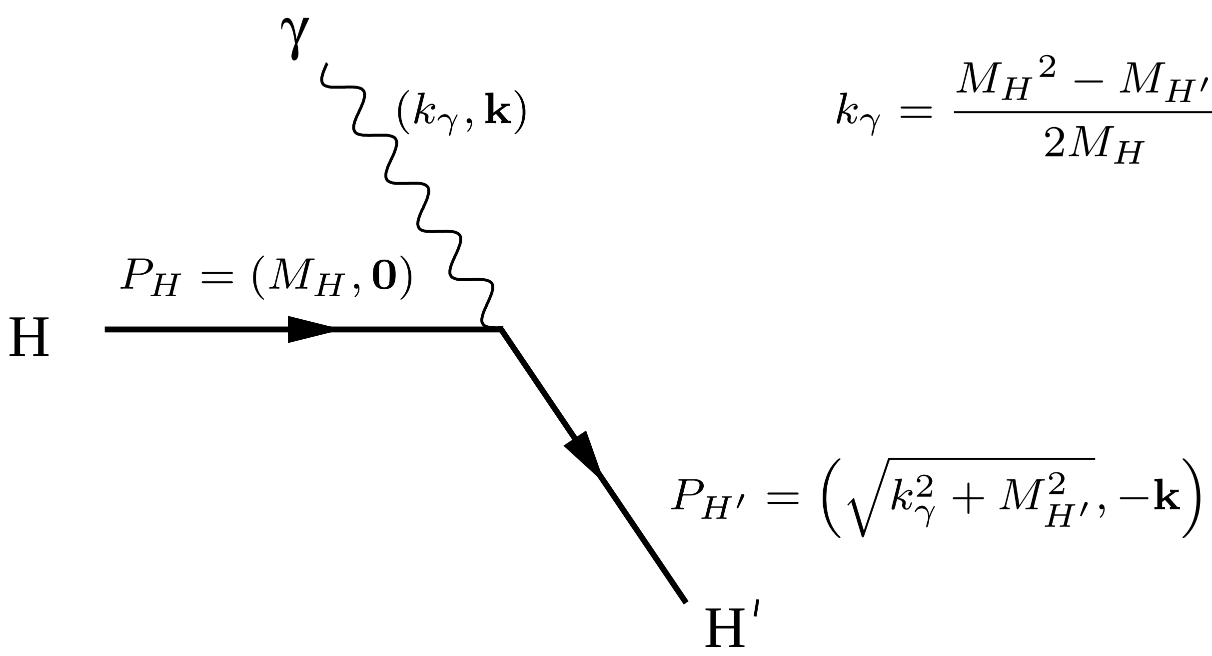
○ *for reviews* QWG *Heavy Quarkonium Physics* CERN Yellow Report CERN-2005-005
QWG EPJ C71 (2011) 1534
Vairo EPJ A31 (2007) 728, IJMP A22 (2007) 5481
Pineda PPNP 67 (2012) 735

Radiative transitions: M1 and E1

Two dominant single-photon-transition processes:

(1) magnetic dipole transitions (M1)

(2) electric dipole transitions (E1)



$$k_\gamma = \frac{{M_H}^2 - {M_{H'}}^2}{2M_H}$$

- for M1 transitions: Brambilla Jia Vairo PRD 73 (2006) 054005

  for E1 transitions Brambilla Pietrulewicz Vairo PRD 85 (2012) 094005

$J/\psi \to \eta_c \gamma$

Up to order v^2 the transition $J/\psi \to \eta_c\gamma$ is completely accessible by perturbation theory:

$$\Gamma_{J/\psi\to\eta_c\gamma} = \frac{16}{3}\alpha e_c^2 \frac{k_\gamma^3}{M_{J/\psi}^2}\left[1 + 4\frac{\alpha_s(M_{J/\psi}/2)}{3\,\pi} - \frac{32}{27}\alpha_s(p_{J/\psi})^2\right]$$

The normalization scale for the α_s inherited from the magnetic moment is the charm mass ($\alpha_s(M_{J/\psi}/2) \approx 0.35 \sim v^2$), and for the α_s, which comes from the Coulomb potential, is the typical momentum transfer $p_{J/\psi} \approx 2m\alpha_s(p_{J/\psi})/3 \approx 0.8$ GeV $\sim mv$

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

◦ `Brambilla Jia Vairo PRD 73 (2006) 054005`

or more recently using an improved perturbative counting scheme

$\Gamma_{J/\psi\to\eta_c\gamma} = (2.12 \pm 0.40)$ keV

◦ `Pineda Segovia PRD 87 (2013) 074024`

$\Gamma_{J/\psi\to\eta_c\gamma}$ as a probe of the J/ψ potential

$$\Gamma_{J/\psi\to\eta_c\gamma} = \frac{16}{3}\alpha e_c^2 \frac{k_\gamma^3}{M_{J/\Psi}^2}\left(1+\frac{4}{3}\frac{\alpha_s(M_{J/\Psi}/2)}{\pi} - \frac{2}{3}\frac{\langle 1|rV_s'|1\rangle}{M_{J/\Psi}} + 2\frac{\langle 1|V_s|1\rangle}{M_{J/\Psi}}\right)$$

- If $V_s = -\frac{4}{3}\frac{\alpha_s(\mu)}{r}$: $-\frac{2}{3}\frac{\langle 1|rV_s'|1\rangle}{M_{J/\Psi}} + 2\frac{\langle 1|V_s|1\rangle}{M_{J/\Psi}} = -\frac{32}{27}\alpha_s(\mu)^2 < 0$
- If $V_s = \sigma r$: $-\frac{2}{3}\frac{\langle 1|rV_s'|1\rangle}{M_{J/\Psi}} + 2\frac{\langle 1|V_s|1\rangle}{M_{J/\Psi}} = \frac{4}{3}\frac{\sigma}{M_{J/\Psi}}\langle 1|r|1\rangle > 0$

  A scalar interaction would add a negative contribution: $-2\langle 1|V^{\rm scalar}|1\rangle/M_{J/\Psi}$.

$J/\psi \to \eta_c\gamma$ (experimental status)

- Only one direct experimental measurement existed for long time:

  $\Gamma_{J/\psi\to\eta_c\gamma} = (1.14 \pm 0.23)$ keV

  ◦ `Crystal Ball coll. PRD 34 (1986) 711`

- The situation changed in the last few years:

  $\Gamma_{J/\psi\to\eta_c\gamma} = (1.85 \pm 0.08 \pm 0.28)$ keV

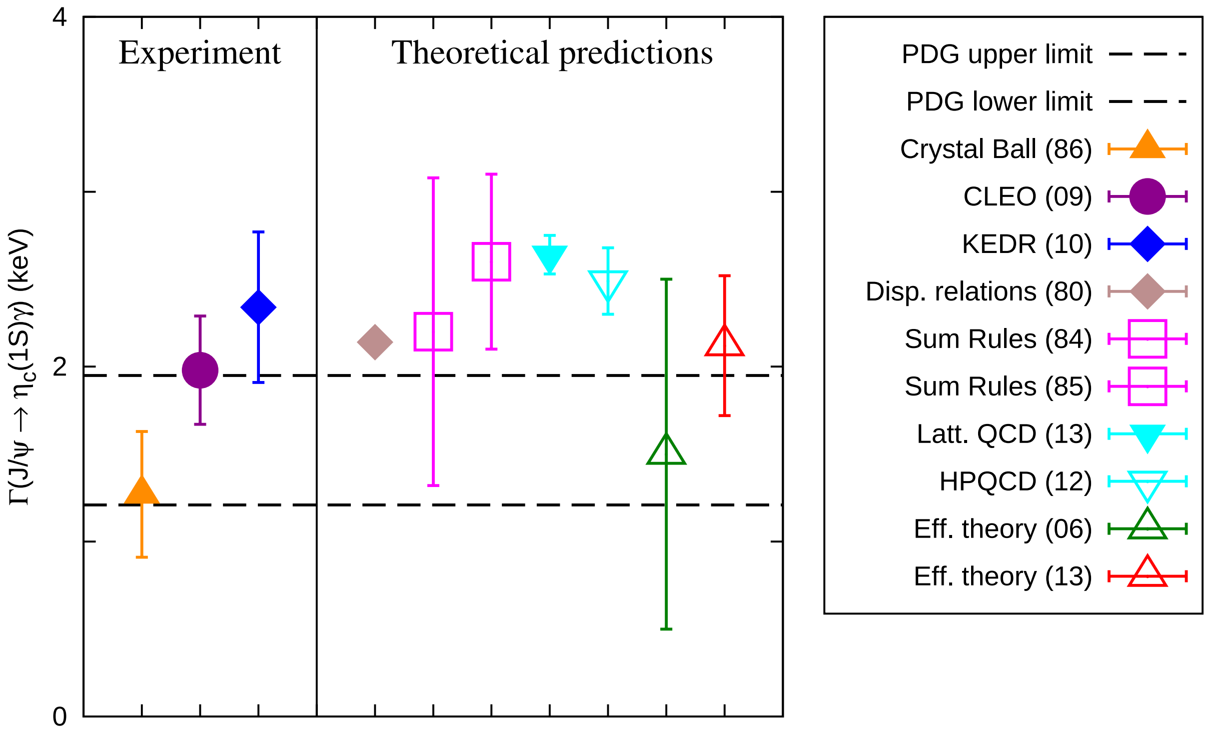
  ◦ `CLEO coll. PRL 102 (2009) 011801`

  $\Gamma_{J/\psi\to\eta_c\gamma} = (2.17 \pm 0.14 \pm 0.37)$ keV

  ◦ `KEDR coll. Chin. Phys. C34 (2010) 831`

Because the LO non-relativistic result is ≈ 2.83 keV, the data suggest that the J/ψ is a Coulombic bound state.

$J/\psi \to \eta_c\gamma$ (experimental & theoretical status)



- Pineda Segovia PRD 87 (2013) 074024

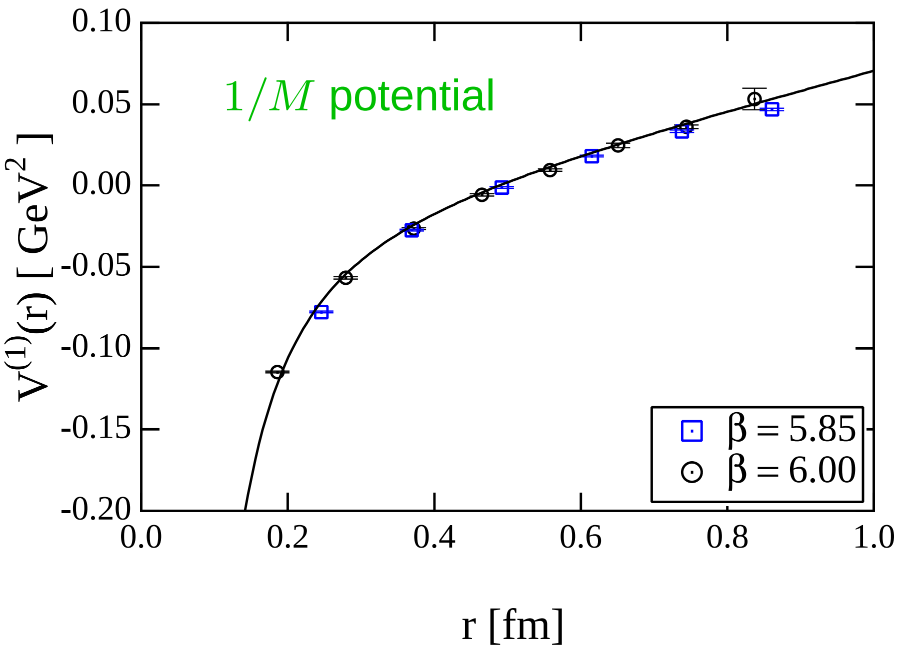
High-lying quarkonia

High-lying quarkonia: the $1/M$ potentials

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.

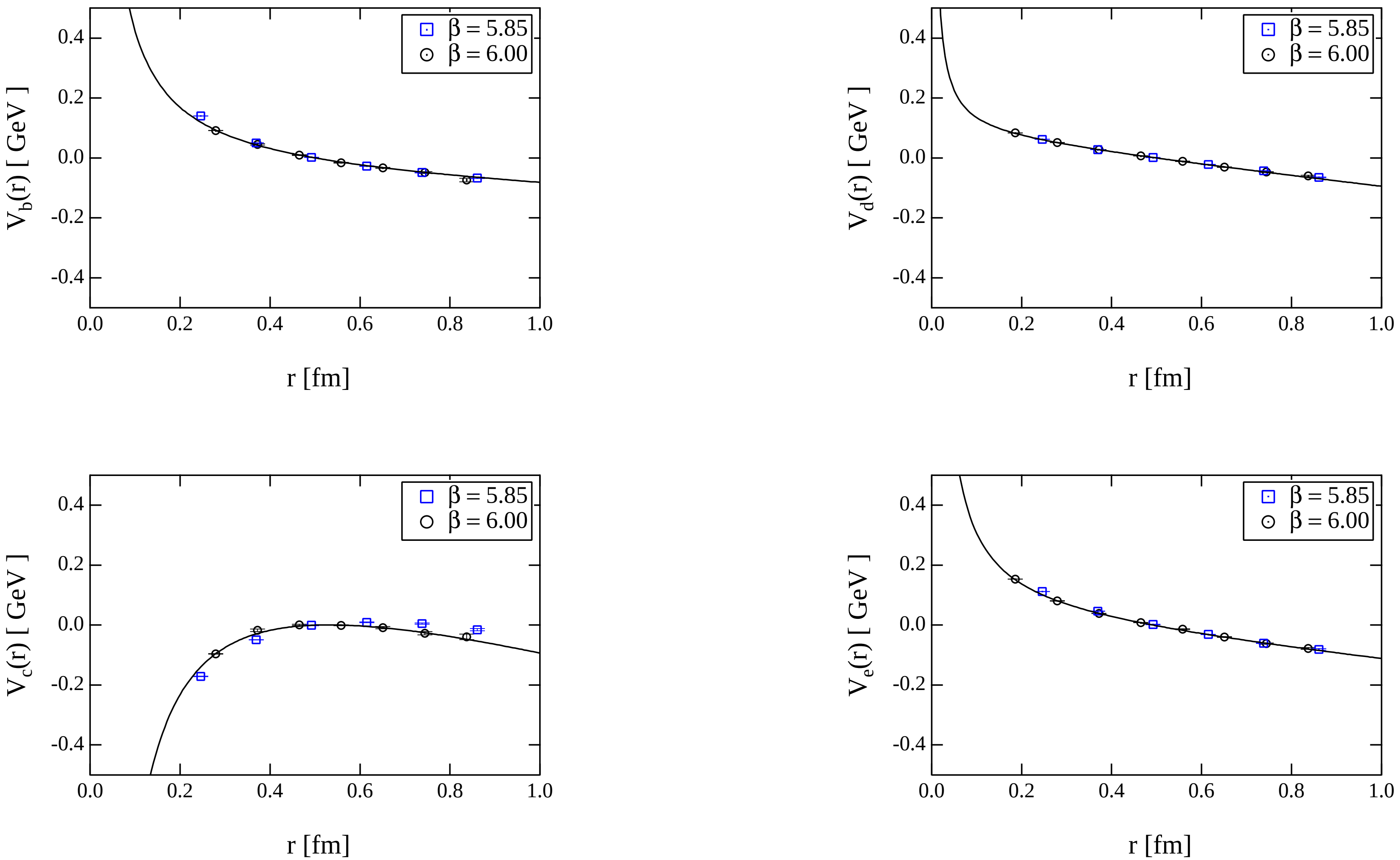
- `Brambilla Pineda Soto Vairo PRD 63 (2001) 014023`
- `Pineda Vairo PRD 63 (2001) 054007`

Lattice provides a non-perturbative determination of the potentials.



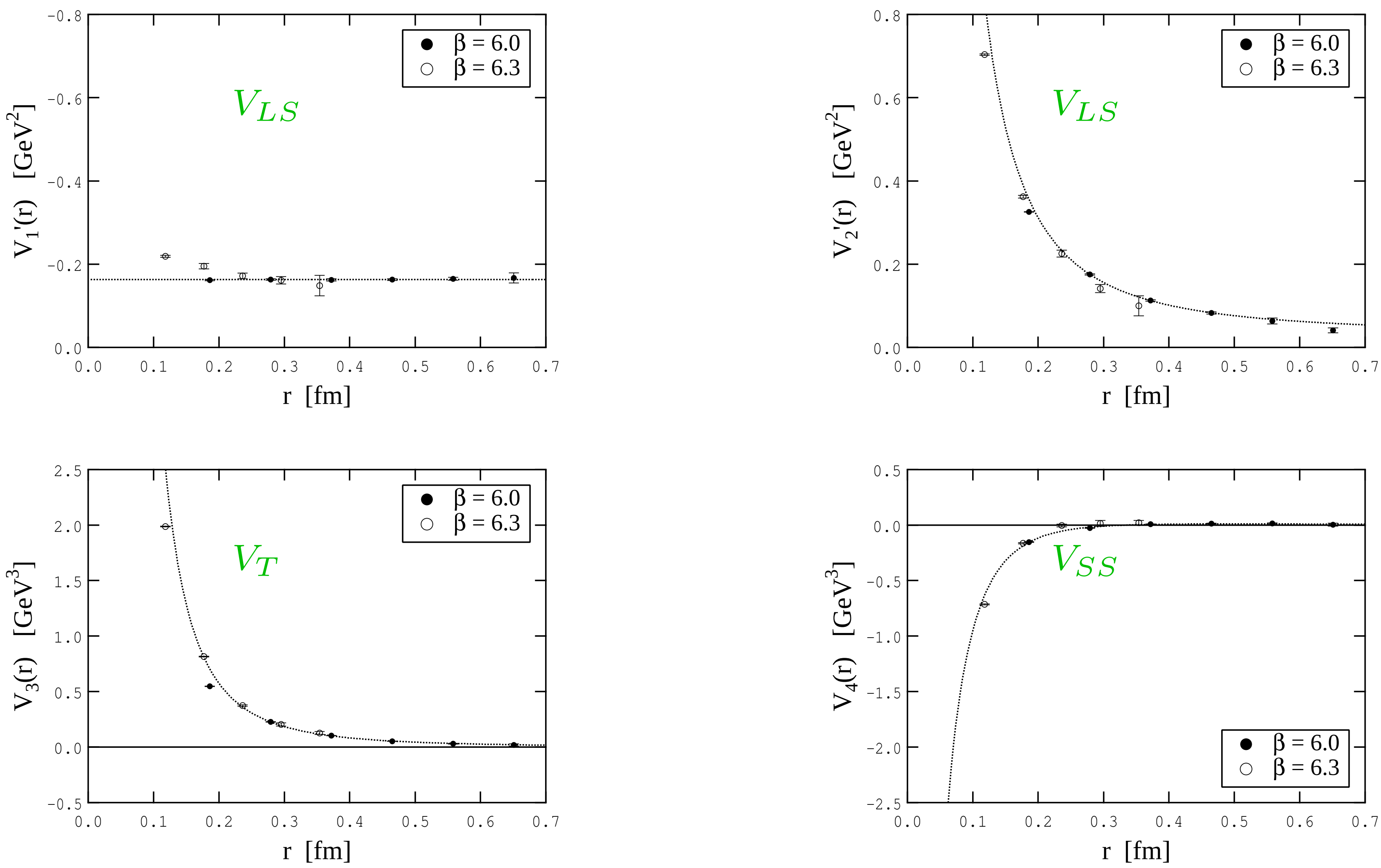
- `Koma Koma Wittig PoS LAT2007 (2007) 111`

Spin-independent p^2/M^2 potentials



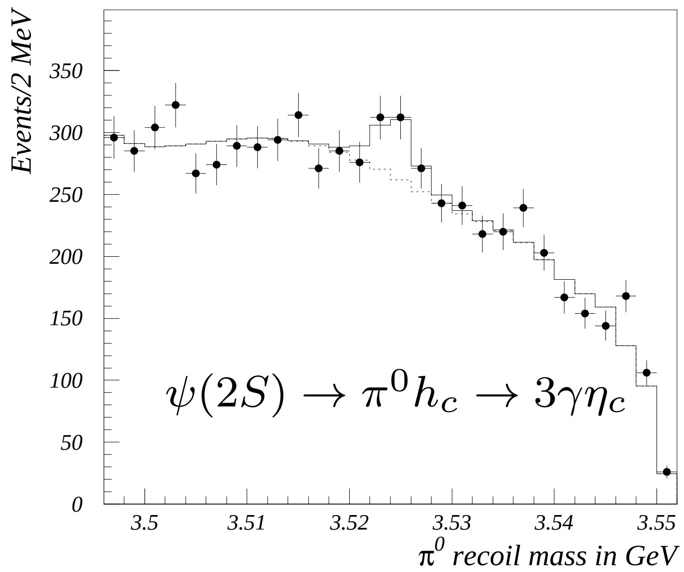
- Koma Koma Wittig PoS LAT2007 (2007) 111

Spin-dependent $1/M^2$ potentials



- Koma Koma NPB 769 (2007) 79

h_c



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

- CLEO PRL 95 (2005) 102003

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

- E835 PRD 72 (2005) 032001

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

- BES PRL 104 (2010) 132002

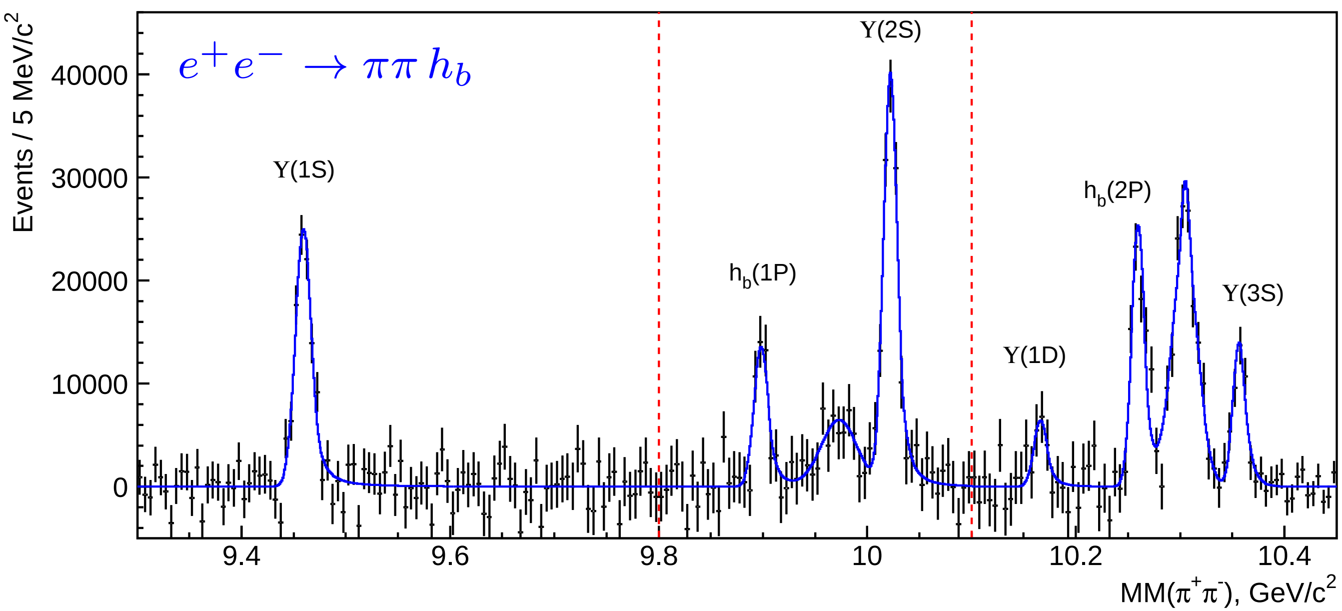
To be compared with $M_{\mathrm{c.o.g.}}(1P) = 3525.36 \pm 0.2 \pm 0.2$ MeV.

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

h_b



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

- BABAR PRD 84 (2011) 091101

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

- BELLE PRL 108 (2012) 032001

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

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

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.

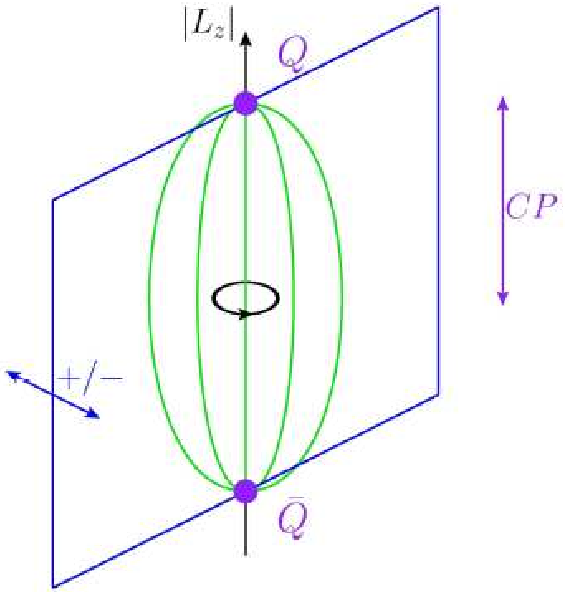
We may integrate out modes scaling like $1/r$ and $\Lambda_{\rm QCD}$ and describe hybrids as heavy quark-antiquark states bound by potentials that are the energies of the corresponding gluonic excitations between static sources $\rightarrow$ Born–Oppenheimer approximation.

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)



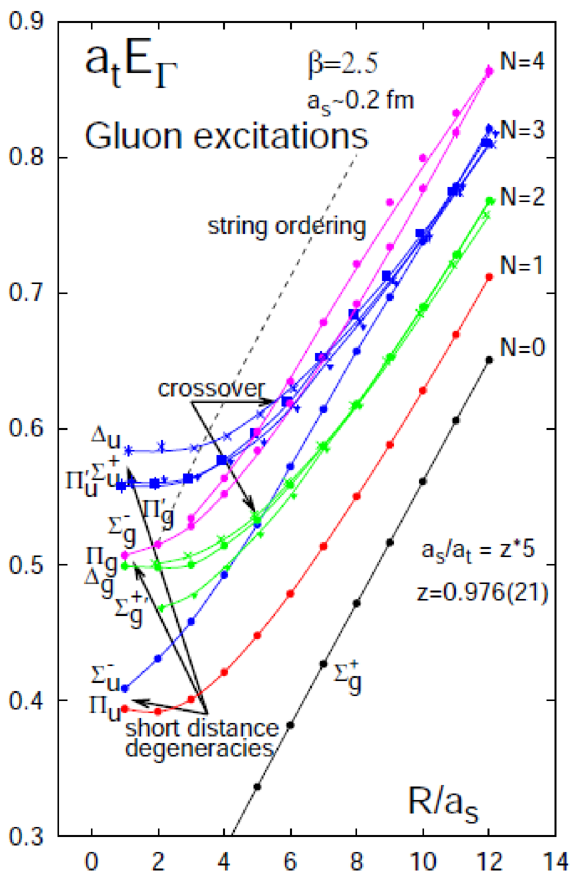
- The static energies correspond to the irreducible representations of $D_{\infty h}$.
- In general it can be more than one state for each irreducible representations of $D_{\infty h}$, usually denoted by primes, e.g. Π_u, Π_u', Π_u''...

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^{+-}.

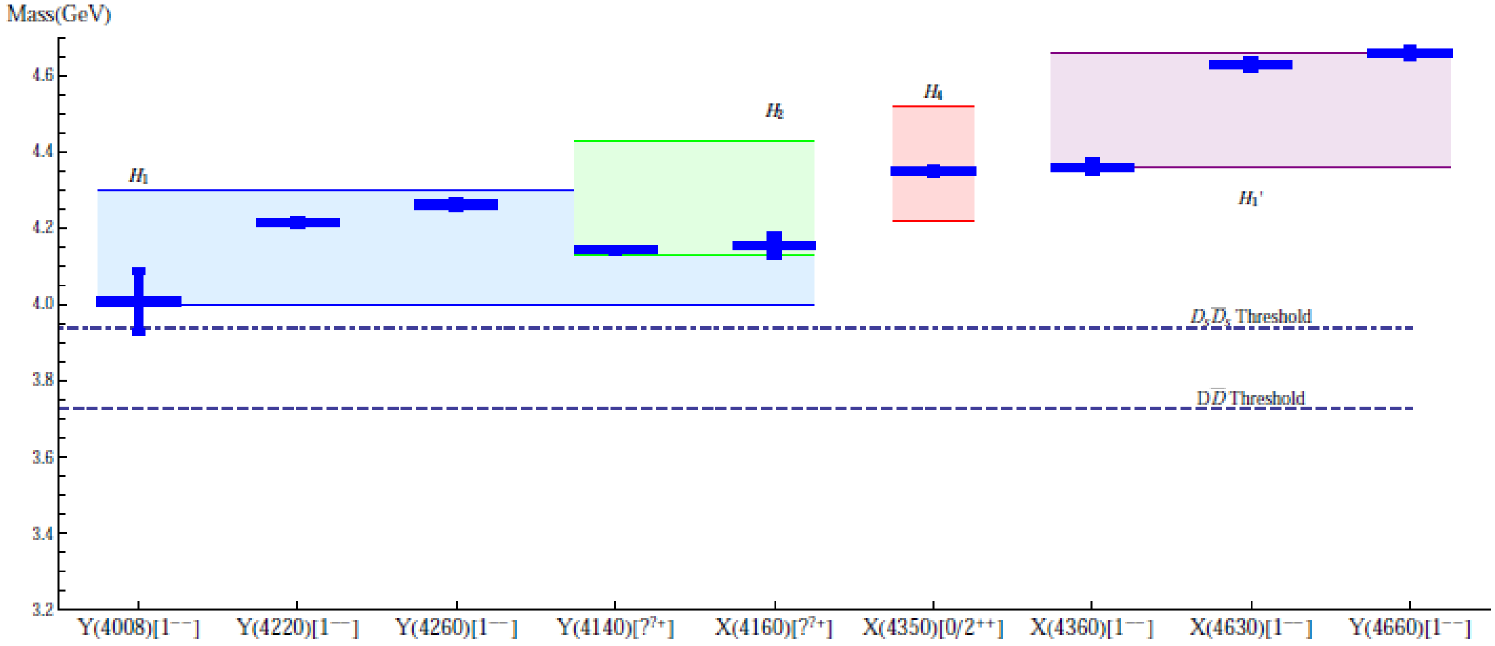
States are organized in spin multiplets.

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

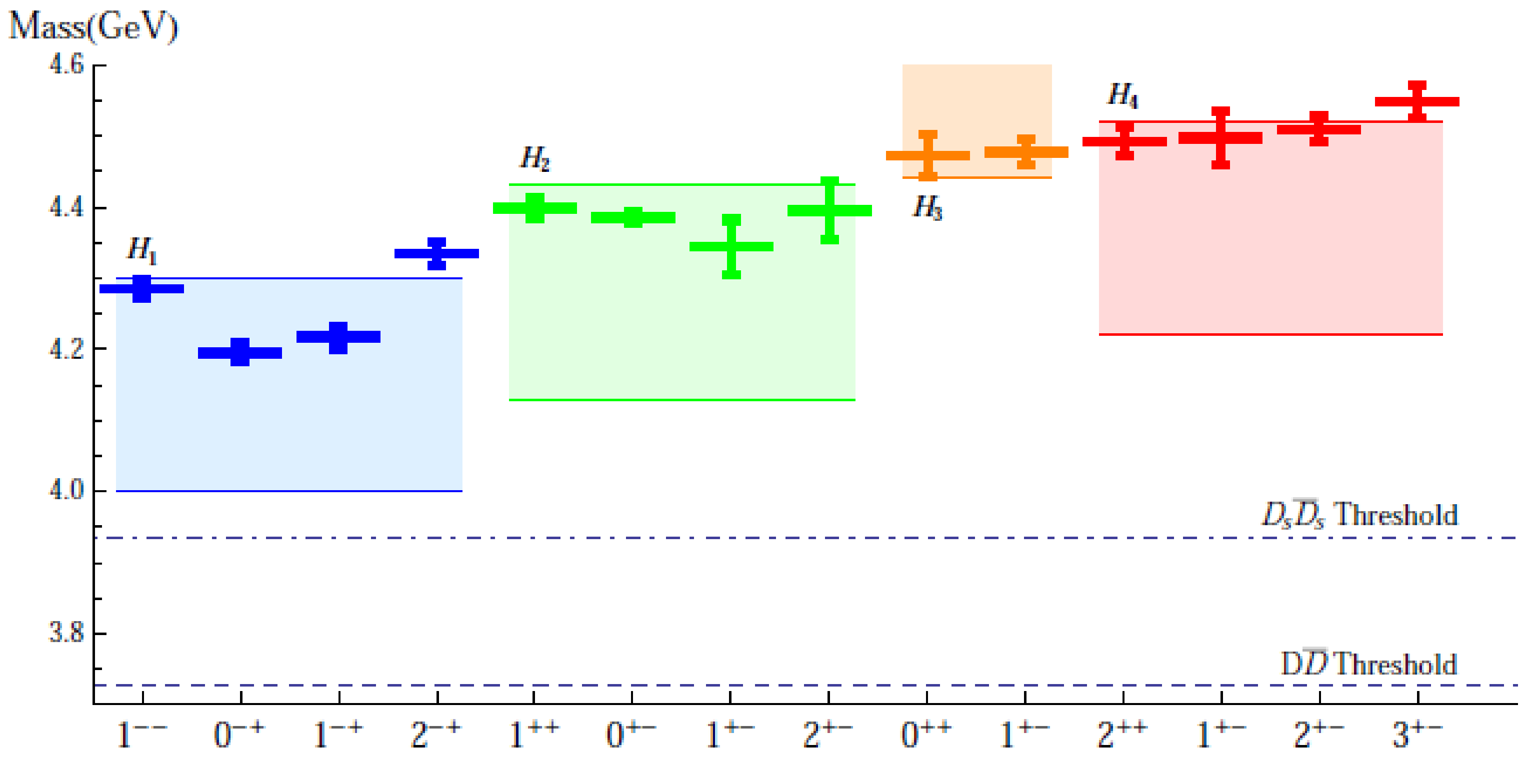
- Charmonium states (BELLE, CDF, BESIII, BABAR):



- 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:

- $J^{PC} = 1^{--}$
- $\dfrac{\mathcal{B}(Y \to D\bar{D})}{\mathcal{B}(Y \to J/\psi\pi^+\pi^-)} < 1.0$ $\quad$ (~ 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

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 $\Lambda_{\rm QCD}$ with respect to the former ones, then these new states may be absorbed into the definition of the potentials or of the (local or non-local) condensates.
  - `Brambilla Eiras Pineda Soto Vairo PRD 67 (2003) 034018`
- In addition new states built using the light quark quantum numbers may form.
  - `Soto NP PS 185 (2008) 107`

States made of two heavy and light quarks

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

- Molecular states, i.e. states built on the pair of heavy-light mesons.
  - Tornqvist PRL 67 (1991) 556

States made of two heavy and light quarks

- The usual quarkonium states, built on the static potential, may also give rise to molecular states through the interaction with light hadrons (hadro-quarkonium).
  - `Dubynskiy Voloshin PLB 666 (2008) 344`

States made of two heavy and light quarks

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

States made of two heavy and light quarks

- Tetraquark states.
  - Jaffe PRD 15 (1977) 267
  - Maiani Piccinini Polosa Riquer PRD 71 (2005) 014028
  - Ebert Faustov Galkin PLB 634 (2006) 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 investigations have started on the lattice.
  - Alexandrou et al. PRL 97 (2006) 222002
  - Fodor et al. PoS LAT2005 (2006) 310

- And likely many other states ...

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

New quarkonium-like states at threshold

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!

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

New quarkonium-like states above threshold

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

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Conclusions

Our understanding of how a theory of quarkonium should look like has dramatically improved over the last decade.

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).

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