Effective Field Theory Investigations of the XYZ Puzzle

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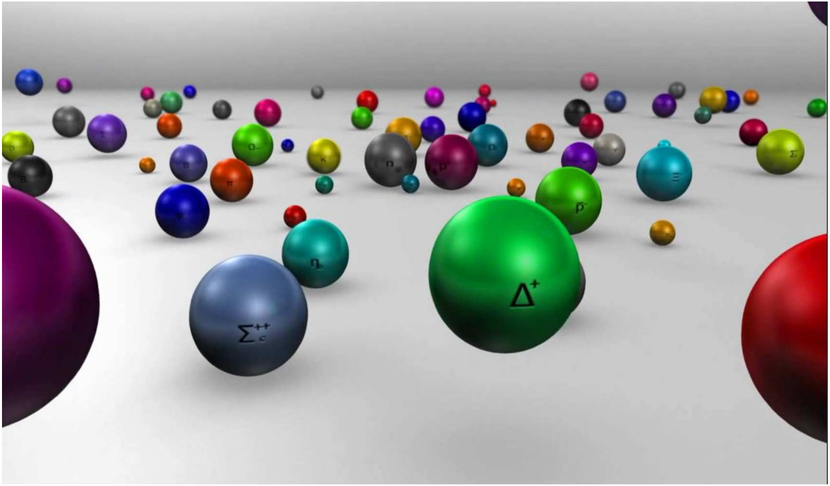
Main collaborators:

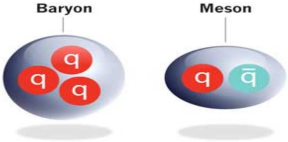
Matthias Berwein, Nora Brambilla, Jaume Tarrus-Castella and Antonio Vairo.

With the advent of the first particle accelerators, a large number of (lighter) hadrons were discovered in the 1950s and 1960s



- ☞ **Wolfgang Pauli:** "Had I foreseen that, I would have gone into botany".
- ☞ **Enrico Fermi:** "If I'd remember the names of these particles, I'd have been a botanist".

☞ A classification scheme for hadrons in terms of their valence quarks and antiquarks:

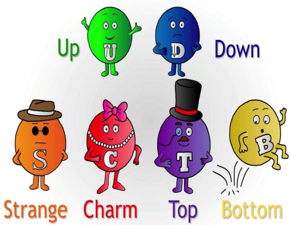


Murray Gell-Mann

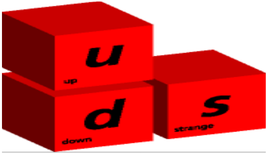
George Zweig

☞ The quarks and antiquarks give rise the quantum numbers of the hadrons:

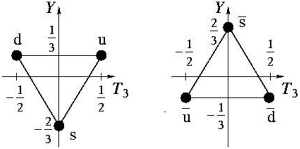
	d	u	s	c	b	t
Q - Electric charge	-1/3	+2/3	-1/3	+2/3	-1/3	+2/3
I - Isospin	+1/2	+1/2	0	0	0	0
I_z - Isospin z-component	-1/2	+1/2	0	0	0	0
S – strangeness	0	0	-1	0	0	0
C – charm	0	0	0	+1	0	0
B – Bottomness	0	0	0	0	-1	0
T – Topness	0	0	0	0	0	+1



☞ Underlies "flavor SU(3)" symmetry

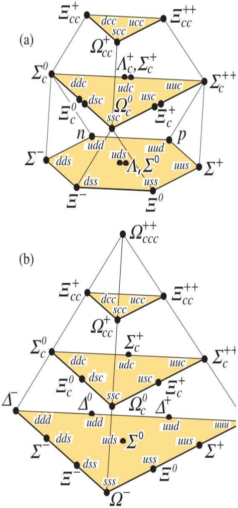


3 and $\bar{3}$ representations

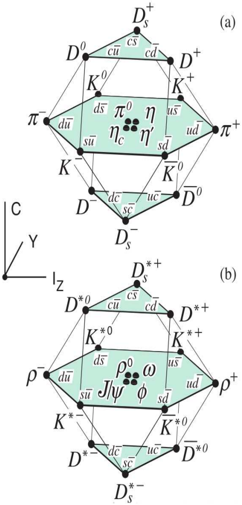


Successful classification scheme organizing the large number of **conventional hadrons**

Baryons

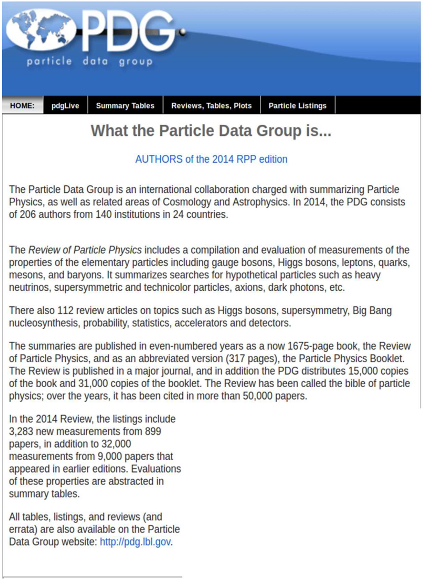


Mesons



$3 \otimes 3 \otimes 3 = 10_S \oplus 8_M \oplus 8_M \oplus 1_A$

$3 \otimes \bar{3} = 8 \oplus 1$



particle data group

HOME: | pdgLive | Summary Tables | Reviews, Tables, Plots | Particle Listings

What the Particle Data Group is...

AUTHORS of the 2014 RPP edition

The Particle Data Group is an international collaboration charged with summarizing Particle Physics, as well as related areas of Cosmology and Astrophysics. In 2014, the PDG consists of 206 authors from 140 institutions in 24 countries.

The *Review of Particle Physics* includes a compilation and evaluation of measurements of the properties of the elementary particles including gauge bosons, Higgs bosons, leptons, quarks, mesons, and baryons. It summarizes searches for hypothetical particles such as heavy neutrinos, supersymmetric and technicolor particles, axions, dark photons, etc.

There also 112 review articles on topics such as Higgs bosons, supersymmetry, Big Bang nucleosynthesis, probability, statistics, accelerators and detectors.

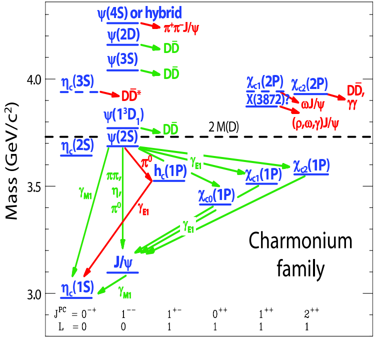
The summaries are published in even-numbered years as a now 1675-page book, the Review of Particle Physics, and as an abbreviated version (317 pages), the Particle Physics Booklet. The Review is published in a major journal, and in addition the PDG distributes 15,000 copies of the book and 31,000 copies of the booklet. The Review has been called the bible of particle physics; over the years, it has been cited in more than 50,000 papers.

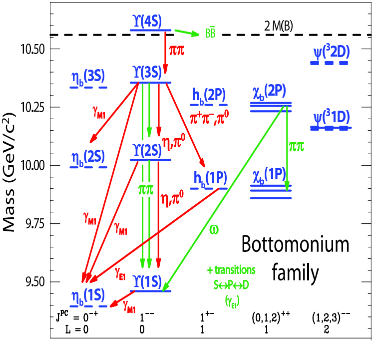
In the 2014 Review, the listings include 3,283 new measurements from 899 papers, in addition to 32,000 measurements from 9,000 papers that appeared in earlier editions. Evaluations of these properties are abstracted in summary tables.

All tables, listings, and reviews (and errata) are also available on the Particle Data Group website: http://pdg.lbl.gov.

The heavy quarkonia before 2003

Charmonium and bottomonium states were discovered in the 1970s.
Experimentally clear spectrum of narrow states below the open-flavor threshold



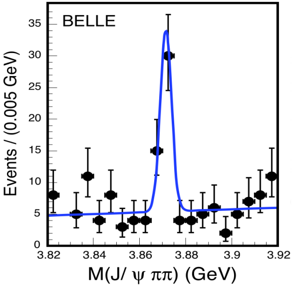


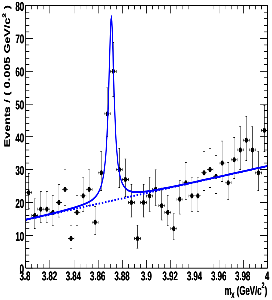
Eichten *et al.*, Rev. Mod. Phys. 80, 1161 (2008)

- Heavy quarkonia are bound states made of a heavy quark and its antiquark ($c\bar{c}$ charmonium and $b\bar{b}$ bottomonium).
- They can be classified in terms of the quantum numbers of a nonrelativistic bound state $\rightarrow$ Reminds positronium [(e^+e^-)-bound state] in QED.
- Heavy quarkonium is a very well established multiscale system which can serve as an ideal laboratory for testing all regimes of QCD.

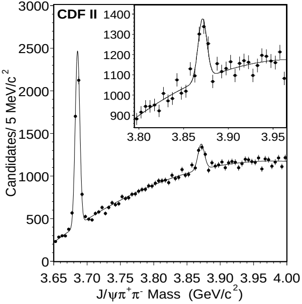
- In 2003, Belle observed an unexpected enhancement in the $\pi^+\pi^- J/\psi$ invariant mass spectrum while studying $B^+ \to K^+\pi^+\pi^- J/\psi$.
- It was later confirmed by BaBar in B-decays and by both CDF and D0 at Tevatron in prompt production from $p\bar{p}$ collisions.
- Its quantum numbers, mass, and decay patterns make it an unlikely conventional charmonium candidate.

PRL 91, 262001 (2003)

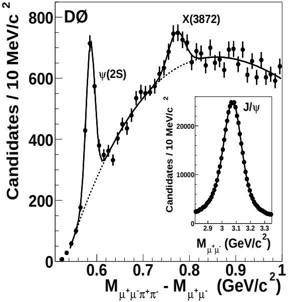




BaBar; PRD 77, 111101 (2008)



CDF; PRL 93, 072001 (2004)

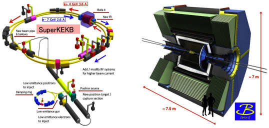


D0; PRL 93, 162002 (2004)

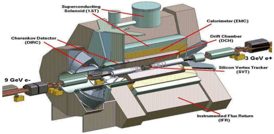
Many experiments around the world

The scientific community has witnessed an explosion of related experimental activity

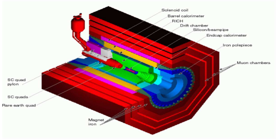
BELLE@KEK (Japan)



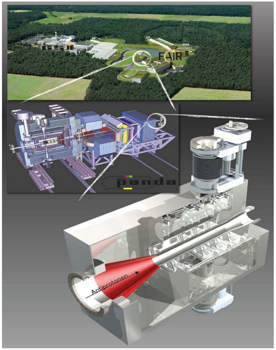
BABAR@SLAC (USA)



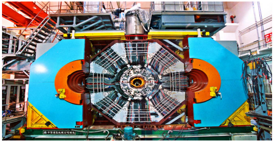
CLEO@CORNELL (USA)



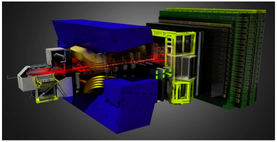
PANDA@GSI (Germany)



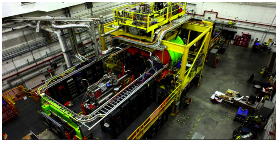
BES@IHEP (China)



LHCb@CERN (Switzerland)



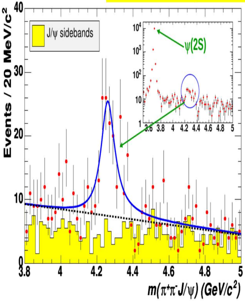
GLUEX@JLAB (USA)



The XYZ particles – A new particle zoo?

PRL95, 142001 (2005)

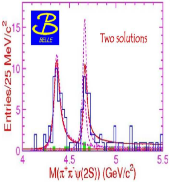
$\pi^+\pi^- J/\psi$ Mass



BaBar: 232 fb^{-1}

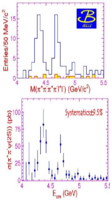
>8σ significance structure called Y(4260)

M(J/ψππ) of ψ(2S) with J/ψ constrain is well described b Cauchy shape func



Parameters	Solution one	Solution two
$M(Y(4360))$	$4361 \pm 9 \pm 9$	
$\Gamma_{tot}(Y(4360))$	$74 \pm 15 \pm 10$	
$\mathcal{B}\cdot\Gamma_{e^+e^-}(Y(4360))$	$10.4 \pm 1.7 \pm 1.5$	$11.8 \pm 1.8 \pm 1.4$
$M(Y(4660))$	$4664 \pm 11 \pm 5$	
$\Gamma_{tot}(Y(4660))$	$48 \pm 15 \pm 3$	
$\mathcal{B}\cdot\Gamma_{e^+e^-}(Y(4660))$	$3.0 \pm 0.9 \pm 0.3$	$7.6 \pm 1.8 \pm 0.8$
ϕ	$39 \pm 30 \pm 22$	$-79 \pm 17 \pm 20$

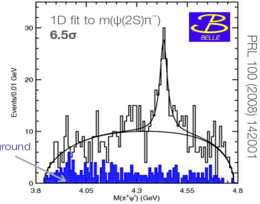
Belle: X. L. Wang *et al.*, PRL99,142002(2007)



- $Y(4360)$ - confirmed for the first time with much better resonance parameters.
- $Y(4660)$ - A 5.8σ narrow stat discovered.

Two solutions: constructive and destructive interference.

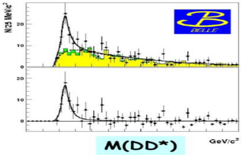
- Belle observed $Z(4430)^-$ from sample of ~2k $B^0 \to \psi(2S)K^{+,0}\pi^-$
- Charged state ⇒ minimal quark content of $c\bar{c}u\bar{d}$



$$M = 4433 \pm 4 \pm 2 \text{ MeV}/c^2$$
$$\Gamma = 45^{+18+30}_{-13-13} \text{ MeV}/c^2$$

not seen in $\omega J/\psi$ — probably different — not seen in DD^* — Probably the χ_{c2}'

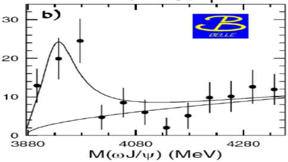
X(3940): $e^+e^- \to J/\psi\ DD^*$



$M = 3942\ ^{+7}_{-6} \pm 6$ MeV
$\Gamma_{tot} = 37\ ^{+26}_{-15} \pm 12$ MeV

693/fb, PRL 100, 202001

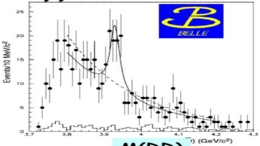
Y(3940): $B \to K\ \omega J/\psi$



$M \approx 3943 \pm 11 \pm 13$ MeV
$\Gamma_{tot} \approx 87 \pm 22 \pm 26$ MeV

253/fb, PRL 94, 182002

Z(3930): $\gamma\gamma \to DD$



$M = 3929 \pm 5 \pm 2$ MeV
$\Gamma_{tot} = 29 \pm 10 \pm 2$ MeV

395/fb, PRL 96, 082003

Summary table of the XYZ particles

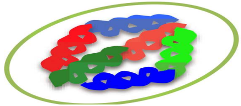
"Heavy quarkonium: progress, puzzles, and opportunities"
Brambilla *et al.*, Eur. Phys. J. C71 (2011) 1534; pages: 181 citations: 894

State	M (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment (#σ)	Year	Status
$X(3872)$	3871.52 ± 0.20	1.3 ± 0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [1, 10] (12.8), BABAR [11] (8.6)	2003	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + \ldots$	CDF [12–14] (np), DØ [15] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [16] (4.3), BABAR [17] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [18, 19] (6.4), BABAR [20] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [16] (4.0), BABAR [21, 22] (3.6)		
				$B \to K(\gamma\psi(2S))$	BABAR [22] (3.5)		
$X(3915)$	3915.6 ± 3.1	28 ± 10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [23] (8.1), BABAR [24] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [25] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [26] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\ (\ldots)$	Belle [27] (5.0)		
$G(3900)$	3943 ± 21	52 ± 11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	BABAR [28] (np), Belle [29] (np)	2007	OK
$Y(4008)$	4008^{+121}_{-49}	226 ± 97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [30] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [31] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	15^{+11}_{-7}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [32, 33] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [26] (5.5)	2007	NC!
$Z_2(4250)^+$	4248^{+185}_{-45}	177^{+321}_{-72}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [31] (5.0)	2008	NC!
$Y(4260)$	4263 ± 5	108 ± 14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	BABAR [34, 35] (8.0)	2005	OK
					CLEO [36] (5.4)		
					Belle [37] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [38] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [38] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [33] (3.1)	2010	NC!
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0,2^{++}$	$e^+e^- \to e^+e^-(\phi J/\psi)$	Belle [39] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96 ± 42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	BABAR [40] (np), Belle [41] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	107^{+113}_{-71}	?	$B \to K(\pi^+\psi(2S))$	Belle [42, 43] (6.4)	2007	NC!
$X(4630)$	4634^{+9}_{-11}	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [44] (8.2)	2007	NC!
$Y(4660)$	4664 ± 12	48 ± 15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [41] (5.8)	2007	NC!
$Y_b(10888)$	10888.4 ± 3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$e^+e^- \to (\pi^+\pi^-\Upsilon(nS))$	Belle [45, 46] (3.2)	2010	NC!

Exotic matter

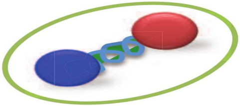
The states that do not fit into the quark model are called Exotics

(Keep in mind that QCD allows new forms of matter beyond qqq and $q\bar{q}$)



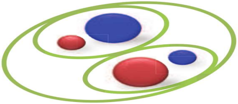
☞ Glueballs (only gluons)

An hypothetical composite particle which consists solely of gluon particles, without valence quarks.



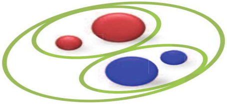
☞ Hybrids ($Q\bar{Q}g$)

Exotic properties are due to gluonic excitations.



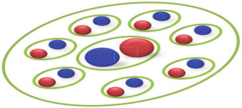
☞ Molecules ($Q\bar{q} - \bar{Q}q$)

Shallow bound states of heavy mesons analogous to the deuteron.



☞ Diquarkonium ($Qq - \bar{Q}\bar{q}$)

The constituent quarks are assumed to be clustered into color triplet diquarks.



☞ Hadroquarkonium ($Q\bar{Q} - q\bar{q}$)

A compact core that is a color-singlet $Q\bar{Q}$ surrounded by light mesons.

Possible theoretical approaches

☞ Phenomenological models: based on the choice of some relevant degrees of freedom and a phenomenological Hamiltonian that dictates their dynamics.

- Among its advantages:
  - i) Simple computational method which gives an idea of the mechanism under study.
  - ii) Very flexible allowing to develop new ideas in an easy way.
- Among its disadvantages:
  - i) A limited approach when you try to connect it to QCD.
  - ii) It is not clear how to improve the description.

☞ Lattice gauge theories: QCD is formulated on a grid of points in space and time with quarks placed on sites and gluons on the links between sites.

- Among its advantages:
  - i) Allows nonperturbative computations in a systematic and model independent way.
  - ii) QCD is recovered by taking the limits $a \to 0$, $L \to \infty$, and $m_\pi \to 140\,\mathrm{MeV}$.
- Among its disadvantages:
  - i) Do not take advantage of the XYZ features: NR systems, hierarchy of scales...
  - ii) Excited and scattering states are still challenging and computationally expensive.

☞ Effective field theories: Only for particular states like the $X(3872)$; prediction of universal properties based on its small binding energy and its large scattering length.

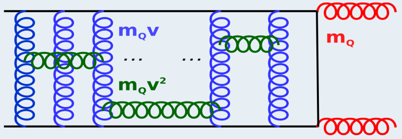
☞ Heavy quarkonium is a nonrelativistic system:

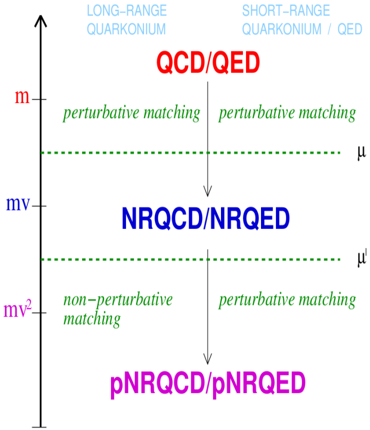
$$v_c \sim 0.55 \quad v_b \sim 0.32 \quad (v_{\mathrm{light}} = 1.0)$$

☞ Heavy quarkonium is a multiscale system:

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

☞ Scales are entangled in full QCD

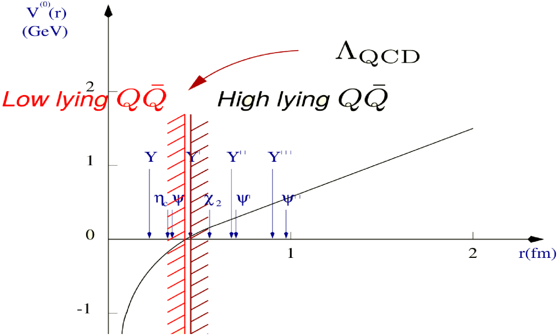


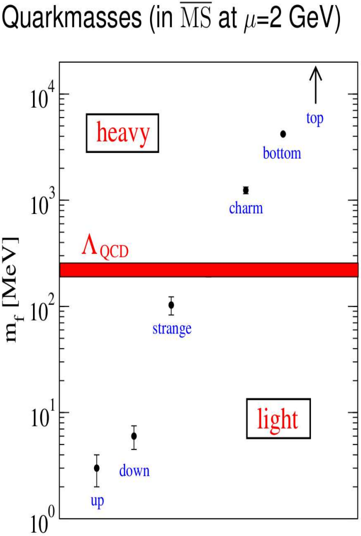


☞ Systematic expansions in the small heavy-quark velocity v may be implemented at the Lagrangian level by constructing suitable effective field theories (EFTs):

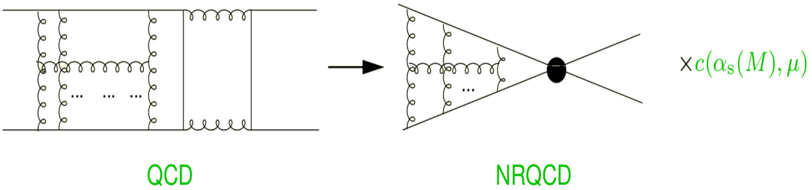
- Expanding QCD in p/M, E/M leads to **NRQCD.**
  Caswell and Lepage PLB 167 (1986) 437; Bodwin, Braaten and Lepage PRD 51 (1995) 1125.
- Expanding NRQCD in E/p leads to **pNRQCD.**
  Brambilla, Pineda, Soto and Vairo NPB 566 (2000) 275.

- The matching of QCD to NRQCD
  - $M \gg \Lambda_{\rm QCD} \to$ Perturbative matching.
- The matching of NRQCD to pNRQCD
  - $p \sim 1/r \gg \Lambda_{\rm QCD} \to$ Perturbative matching.
  - $p \sim 1/r \gtrsim \Lambda_{\rm QCD} \to$ Nonperturbative matching.





☞ Physics at the scale M: Quarkonium annihilation and production.



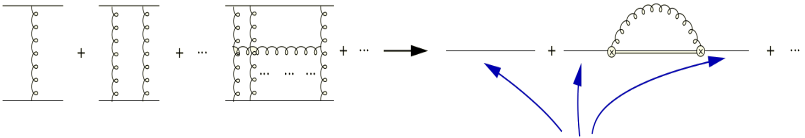
☞ The effective Lagrangian is organized as an expansion in $1/M$ and $\alpha_s(M)$:

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

- $\mathcal{L}_{\rm NRQCD}$ is made of all low-energy operators $\mathcal{O}_n$ that may be built from the effective degrees of freedom and are consistent with the symmetries of $\mathcal{L}_{\rm QCD}$.
- The Wilson coefficients c_n encode the high energy physics. They are calculated by imposing that $\mathcal{L}_{\rm NRQCD}$ and $\mathcal{L}_{\rm QCD}$ describe the same physics at $\mu = M$.

EFTs: pNRQCD at weak coupling (I)

- Physics at the scale Mv: Quarkonium formation.



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

NRQCD pNRQCD

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

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

where a multipole expansion of the gluon field has been performed.

- The Wilson coefficients of pNRQCD depends on the distance r (and scales μ, μ'):
  - $V_{n,0}$ 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.

EFTs: pNRQCD at weak coupling (II)

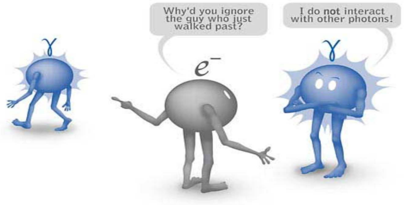
In summary...

- Provides a QM description from FT: the matching coefficients are the interaction potentials and the leading order dynamical equation is of the Schrödinger type.
- The degrees of freedom in pNRQCD (at weak coupling) are color singlet and octet fields and ultrasoft gluon fields.
- Account for non-potential terms as well. Singlet to Octet transitions vie ultrasoft gluons provide loop corrections to the leading potential picture.
- The Quantum Mechanical divergences are canceled by the NRQCD matching coefficients.
- Poincaré invariance is realized via exact relations between different matching coefficients.

pNRQCD is today the theory used to address Quarkonium bound state properties

- Conventional meson spectrum: higher order perturbative corrections in v and α_s.
- Inclusive and semi-inclusive decays, E1 and M1 transitions, EM line-shapes.
- Doubly- and triply-heavy baryons.
- Precise extraction of Standard Model parameters: m_c, m_b, α_s, ...
- **Exotic states**, in particular, Gluelumps and Hybrids.
- Nonperturbative potentials in terms of Wilson loops.
- Properties of Quarkonium systems at finite temperature.

Quantum Electrodynamics (QED)

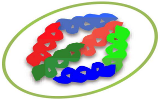


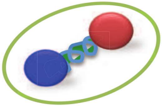
Quantum Chromodynamics (QCD)

- Theory of the electroweak interaction.
- d.o.f: electrons and photons.
- No Photon self-interactions.

- Theory of the strong interaction.
- d.o.f.: quarks and gluons.
- **GLUON SELF-INTERACTIONS.**

Origin of confinement, DCSB, ...? How does glue manifest itself in low energy regime?





- ☞ Possible clues looking at hadrons with explicit gluonic d.o.f. **Same role played by gluons and quarks in making matter!!**
- ☞ Hybrid mesons with a heavy-quark pair are the most amenable to theoretical treatment.
- ☞ Amongst the PANDA's experiment goals is the exploration of charmonium hybrids.

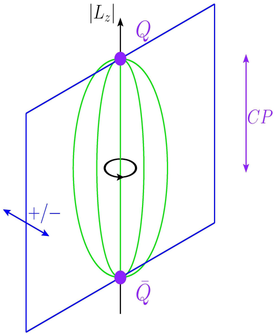
In static NRQCD: The gluonic excitations between static quarks have the same symmetries as the diatomic molecule.

☞ The static energies correspond to the irreducible representations of $D_{\infty h}$.

☞ Representations labeled by Λ_η^ϵ:

- Λ: rotational quantum number $|\hat{r}\cdot\vec{J}\,| = 0, 1, 2, \ldots$ corresponds to $\Lambda = \Sigma, \Pi, \Delta, \ldots$
- η: eigenvalue of CP: $g \equiv +1$ and $u \equiv -1$.
- ϵ: eigenvalue of reflections. Only displayed in Σ states (others are degenerated).

☞ There can be more than one state for each irreducible representation of $D_{\infty h}$, usually denoted by Π_u, Π'_u, Π''_u, ...

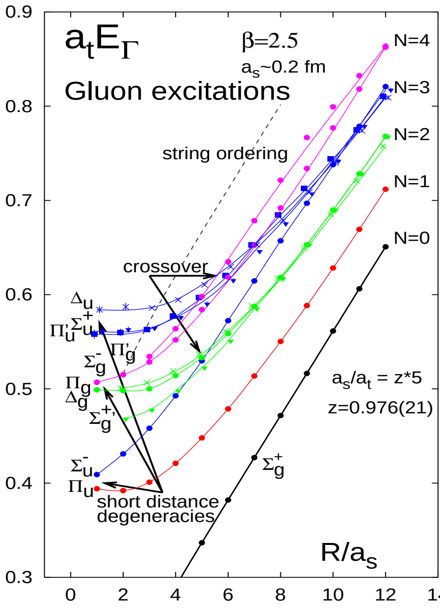


☞ *In the $r \to 0$ limit extra symmetries for the gluonic excitations between static quarks appear: $D_{\infty h} \to O(3) \times C$:*

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

They are Nonperturbative quantities!!

- $E^{(0)}_{\Sigma_g^+}(r)$ is the ground state potential that generates the standard Quarkonium states.
- The rest of the static energies correspond to gluonic excitations that generate hybrids.
- The two lowest hybrid static energies are $E^{(0)}_{\Pi_u}(r)$ and $E^{(0)}_{\Sigma_u^-}(r)$.
  $\to$ Nearly degenerate at short distances.
- Good agreement was found between quenched and unquenched computations.



Juge et al. PRL 90 (2003) 161601

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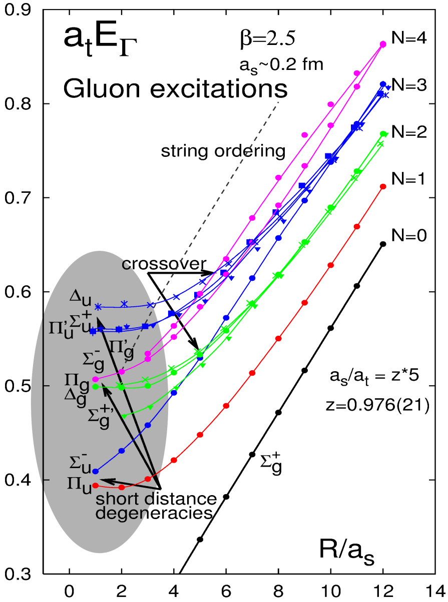


Juge et al. PRL 90 (2003) 161601

☞ The lowest static energies are given by:

$$\boxed{E_n^{(0)}(r) = \lim_{T\to\infty} \frac{i}{T} \log\langle X_n,\ T/2|X_n,\ -T/2\rangle}$$

☞ Any state $|X_n\rangle$ can be written as an expansion:

$$|X_n\rangle = c_n\ |\underline{n};\ \mathbf{x}_1,\ \mathbf{x}_2\rangle^{(0)} + c_{n'}\ |\underline{n}';\ \mathbf{x}_1,\ \mathbf{x}_2\rangle^{(0)} + \ldots$$

☞ The static states $|\underline{n};\ \mathbf{x}_1,\ \mathbf{x}_2\rangle^{(0)}$ form a complete basis and fulfill:

$$^{(0)}\langle \underline{n};\ \mathbf{x}_1,\ \mathbf{x}_2,\ T/2|\ \underline{n};\ \mathbf{x}_1,\ \mathbf{x}_2,\ -T/2\rangle^{(0)} = \mathcal{N}\ \exp\left[-iE_n^{(0)}(r)\ T\right]$$

$$\langle X_n,\ T/2|X_n,\ -T/2\rangle = \mathcal{N}|c_n|^2 \exp\left[-iE_n^{(0)}(r)\ T\right] + \mathcal{N}|c_{n'}|^2 \exp\left[-iE_{n'}^{(0)}(r)\ T\right] + \ldots$$

☞ The Hamiltonian of NRQCD up to $1/m_Q$ for the one-quark-one-antiquark sector:

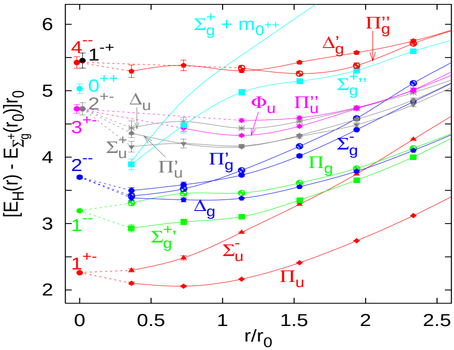
$$H_{\rm NRQCD} = H^{(0)} + \frac{1}{m_Q} H^{(1,0)} + \frac{1}{m_{\bar Q}} H^{(0,1)} + \ldots$$

$$H^{(0)} = \int d^3x\, \frac{1}{2}\left(\mathbf{E}^a\cdot\mathbf{E}^a + \mathbf{B}^a\cdot\mathbf{B}^a\right) - \sum_{j=1}^{n_f}\int d^3\mathbf{x}\, \bar q_j\, i\mathbf{D}\cdot\gamma\, q_j$$

$$H^{(1,0)} = -\frac{1}{2}\int d^3x\, \psi^\dagger \left(\mathbf{D}^2 + g\, c_F\, \boldsymbol{\sigma}\cdot\mathbf{B}\right)\psi$$

$$H^{(0,1)} = \frac{1}{2}\int d^3x\, \chi^\dagger \left(\mathbf{D}^2 + g\, c_F\, \boldsymbol{\sigma}\cdot\mathbf{B}\right)\chi$$

Bali et al. PRD 69 (2004) 094001



Λ_η^σ	J^{PC}	P_n^a
Σ_u^-	1^{+-}	$\hat{\mathbf{r}}\cdot\mathbf{B}$, $\hat{\mathbf{r}}\cdot(\mathbf{D}\times\mathbf{E})$
Π_u	1^{+-}	$\hat{\mathbf{r}}\times\mathbf{B}$, $\hat{\mathbf{r}}\times(\mathbf{D}\times\mathbf{E})$
$\Sigma_g^{+\,\prime}$	1^{--}	$\hat{\mathbf{r}}\cdot\mathbf{E}$, $\hat{\mathbf{r}}\cdot(\mathbf{D}\times\mathbf{B})$
Π_g	1^{--}	$\hat{\mathbf{r}}\times\mathbf{E}$, $\hat{\mathbf{r}}\times(\mathbf{D}\times\mathbf{B})$
Σ_g^-	2^{--}	$(\hat{\mathbf{r}}\cdot\mathbf{D})(\hat{\mathbf{r}}\cdot\mathbf{B})$
Π_g'	2^{--}	$\hat{\mathbf{r}}\times((\hat{\mathbf{r}}\cdot\mathbf{D})\mathbf{B}+\mathbf{D}(\hat{\mathbf{r}}\cdot\mathbf{B}))$
Δ_g	2^{--}	$(\hat{\mathbf{r}}\times\mathbf{D})^i(\hat{\mathbf{r}}\times\mathbf{B})^j+(\hat{\mathbf{r}}\times\mathbf{D})^j(\hat{\mathbf{r}}\times\mathbf{B})^i$
Σ_u^+	2^{+-}	$(\hat{\mathbf{r}}\cdot\mathbf{D})(\hat{\mathbf{r}}\cdot\mathbf{E})$
Π_u'	2^{+-}	$\hat{\mathbf{r}}\times((\hat{\mathbf{r}}\cdot\mathbf{D})\mathbf{E}+\mathbf{D}(\hat{\mathbf{r}}\cdot\mathbf{E}))$
Δ_u	2^{+-}	$(\hat{\mathbf{r}}\times\mathbf{D})^i(\hat{\mathbf{r}}\times\mathbf{E})^j+(\hat{\mathbf{r}}\times\mathbf{D})^j(\hat{\mathbf{r}}\times\mathbf{E})^i$

Brambilla et al. NPB 566 (2000) 275

- A convenient choice for the $|X_n\rangle$ states gives the static energies in terms of Wilson loops, so we define:

$$|X_n\rangle = \chi(\mathbf{x}_2)\,\phi(\mathbf{x}_2,\mathbf{R})\,T^a P_n^a(\mathbf{R})\phi(\mathbf{R},\mathbf{x}_1)\,\psi^\dagger(\mathbf{x}_1)|\mathrm{vac}\rangle$$

- The large time correlator of these states is given by a static Wilson loop with insertions of P_n^a in the strings at the center-of-mass.

- For $E^{(0)}_{\Sigma^+}(r)$: Insert a color-neutral gluonic operator with $J^{PC}=0^{++}$.

- Matching between NRQCD and pNRQCD for the static (gluelump) eigenstates:

$$|\underline{n}; \mathbf{x}_1, \mathbf{x}_2\rangle^{(0)} \stackrel{\sim}{=} \Big(O^{a\,\dagger}(\mathbf{r}, \mathbf{R})\, \hat{n}_i\; G^a_{n,\,i}(\mathbf{R}) + \mathcal{O}(r) \Big)\, |0\rangle$$

- Matching between NRQCD and pNRQCD for the $|X_n\rangle$ state:

$$|X_n\rangle \stackrel{\sim}{=} \Big(Z_n(r)\, O^{a\,\dagger}(\mathbf{r}, \mathbf{R}) P^a_n(\hat{\mathbf{r}}, \mathbf{R}) + \mathcal{O}(r) \Big)\, |0\rangle$$

- The large time correlators are then given by

$$\langle X_n, T/2 | X_n, -T/2 \rangle = \mathcal{N} e^{-iV_o(r)T} \langle 0 | P^a_n(T/2) \phi^{ab}_{\rm adj}(T/2, -T/2) P^b_n(-T/2) | 0 \rangle + \mathcal{O}\left(r^2\right)$$

- The gluonic correlator can only be evaluated nonperturbatively. We can argue that

$$\langle 0 | P^a_n(T/2) \phi(T/2, -T/2)^{\rm adj}_{ab} P^b_n(-T/2) | 0 \rangle = |c_n|^2 e^{-i\Lambda_H T} + |c_{n'}|^2 e^{-i\Lambda_{H'} T} + \dots$$

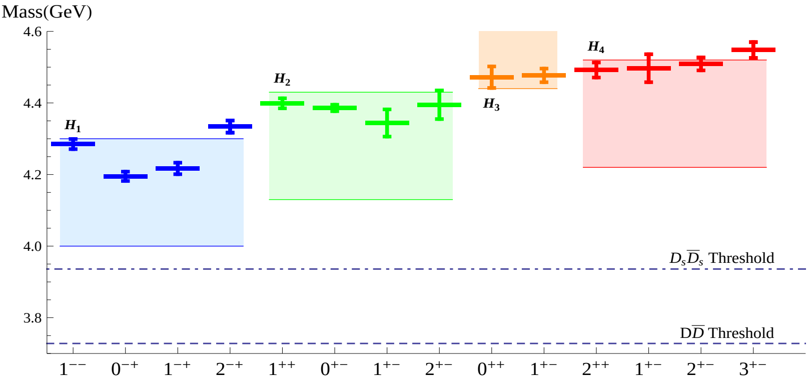
- Matching between NRQCD and pNRQCD for the static energy:

$$\boxed{E^{(0)}_n(r) = \lim_{T\to\infty} \frac{i}{T} \log \langle X_n, T/2 | X_n, -T/2 \rangle = V_o(r) + \Lambda_H + \mathcal{O}\left(r^2\right)}$$

See Berwein's talk on Wed. 5.55pm for details

Berwein, Brambilla, Tarrus-Castella and Vairo, PRD 92 (2015) 114019

- Masses computed by the Hadron Spectrum Collaboration using unquenched lattice QCD with a pion mass of 400 MeV. *Liu et al. JHEP 07 (2012) 126.*
- Their results are given with the η_c mass subtracted.



Overall agreement with the mass gaps between multiplets.

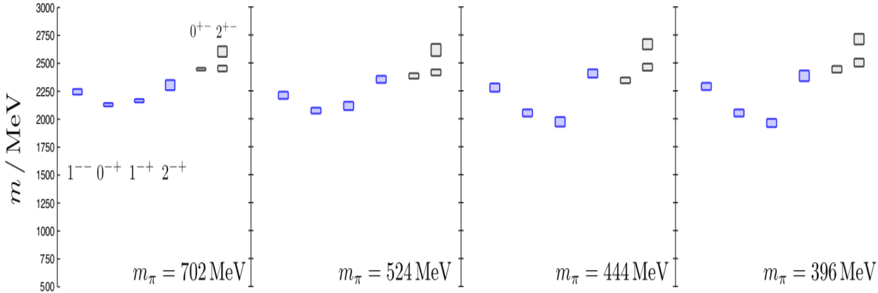
Error bands take into account the uncertainty on the gluelump mass: $0.87 \pm 0.15\,\mathrm{GeV}$

See Berwein's talk on Wed. 5.55pm for details

Berwein, Brambilla, Tarrus-Castella and Vairo, PRD 92 (2015) 114019

Some insight can be extracted from the quark mass-dependence of the lightest hybrid (light-quark) multiplet

Dudek PRD 84 (2011) 074023



- The P-wave 0^{+-} and 2^{+-} are approximately independent of quark mass.
  $\rightarrow$ **A short range potential dominates the hybrid spin-dependent potential.**
- The 1^{--} state is also largely spin-independent, which implies that quark spin-triplets are required in the spin-dependent potential.
- The spin-triplet J^{-+} multiplet slowly splits as the quark mass is reduced: $J = 0$ decreases slowly; $J = 1$ decreases more rapidly; and $J = 2$ increases slowly.

Mass splittings within the same spin-multiplet (II)

The **Flux-tube model** *predicts an opposite behaviour of the splittings*

- The idea was to map the operators of the leading spin-orbit term in the heavy quark expansion of QCD, $(g/2M)\,\boldsymbol{\sigma}\cdot\mathbf{B}$, onto phonon degrees of freedom.
- Spin-orbit splittings are small and the majority of the splittings arise from Thomas precession.
- This was modeled by including the effects of phonons on the quark coordinate.

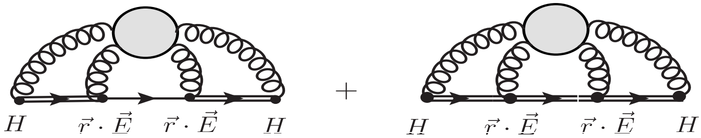
J^{PC}	1^{--}	0^{-+}	1^{-+}	2^{-+}	1^{++}	0^{+-}	1^{+-}	2^{+-}
δM (MeV)	0	$+40$	$+20$	-20	0	$+280$	$+140$	-140

Merlin and Paton PRD 35 (1987) 1668

No calculation of spin-splittings has been done in **constituent gluon models**

- Models of constituent gluons with $J^P = 1^-$ and in a relative S-wave with respect the $q\bar{q}$ systems fail to describe the observed lattice states.
- If the dynamics favours a P-wave coupling: the lowest hybrid multiplet can be explained if the $q\bar{q}$ is in an S-wave and the heavier if the $q\bar{q}$ is in a P-wave.

☞ Interaction with ultrasoft gluons:



- Proportional to r^2 due to rotational invariance and the multipole expansion.
- A nonperturbative quantity. Fitted to the lattice data on the static energies.
- Responsible for the attractive part of the hybrid potential.

☞ Spin-dependent contributions that will break the spin degeneracy and give a more detailed structure to the hybrid multiplets:

$$H_{\rm NRQCD} = H^{(0)} + \frac{1}{m_Q} H^{(1,0)} + \frac{1}{m_{\bar{Q}}} H^{(0,1)} + \dots$$

$$H^{(0)} = \int d^3x \, \frac{1}{2} \left(\mathbf{E}^a \cdot \mathbf{E}^a + \mathbf{B}^a \cdot \mathbf{B}^a \right) - \sum_{j=1}^{n_f} \int d^3\mathbf{x} \, \bar{q}_j \, i\mathbf{D} \cdot \gamma \, q_j$$

$$H^{(1,0)} = -\frac{1}{2} \int d^3x \, \psi^\dagger \left(\mathbf{D}^2 + g \, c_F \, \boldsymbol{\sigma} \cdot \mathbf{B} \right) \psi$$

$$H^{(0,1)} = \frac{1}{2} \int d^3x \, \chi^\dagger \left(\mathbf{D}^2 + g \, c_F \, \boldsymbol{\sigma} \cdot \mathbf{B} \right) \chi$$

Our long-range plan

Work out a systematic, model-independent and QCD-based description of hybrid states with the development of novel EFTs from the ones that we know at present.

☞ In order to do so, the following tangible objectives must be completed:

1.- Determination of the $1/m^0$, $1/m^1$ and $1/m^2$ hybrid potentials at short distances within the framework of pNRQCD at weak coupling.

2.- Determination of the $1/m^0$, $1/m^1$ and $1/m^2$ hybrid potentials at long distances within the framework of an Effective String Theory representation.

3.- Identify nonperturbative contributions and rewrite them in terms of Wilson loops in order to be calculated on the lattice.

4.- Complement the study of spectrum with the computation of decays and transitions.