Heavy Quark Spectroscopy

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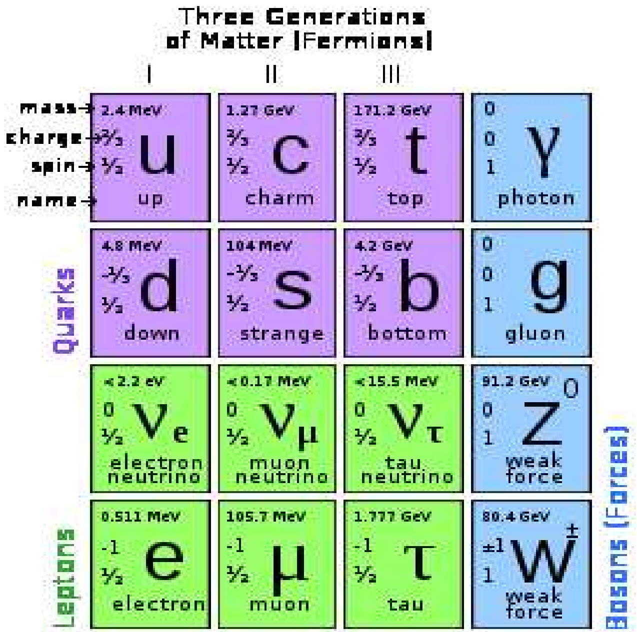
Elementary Particles in 2011



The SM at low energies

For $p \ll m_{W,Z}$ the Standard Model (SM) reduces to

$$\mathcal{L}_{QCD+QED} = -\frac{1}{2} tr\left(F_{\mu\nu}F^{\mu\nu}\right) - \frac{1}{4} F^{em}_{\mu\nu} F^{em\ \mu\nu} + \\ + \sum_{q=u,d,s} \bar{q}\left(i\not{D}^{q} - m_q\right) q + \sum_{Q=c,b} \bar{Q}\left(i\not{D}^{Q} - m_Q\right) Q + \\ + \sum_{l=e,\mu,\tau} \bar{l}\left(i\not{D}^{l} - m_l\right) l + \bar{\nu}_l i\not{\partial}\nu_l + \mathcal{O}(1/m_{W,Z})$$

- $-igF_{\mu\nu} - iee_q F^{em}_{\mu\nu} = [D^q_\mu, D^q_\nu]$, $D^{q,Q}_\mu = \partial_\mu - igA_\mu - iee_{q,Q}A^{em}_\mu$, $D^l_\mu = \partial_\mu - iee_l A^{em}_\mu$
- e, charge of the positron
- $e_{q,Q,l}$, the fraction of the charge of the electron that the corresponding particles have.

QCD

QCD (early 70's) is the current theory of the strong interactions.

$$\mathcal{L}_{QCD} = \mathcal{L}_g + \sum_{q=u,d,s} \mathcal{L}_q + \sum_{Q=c,b,t} \mathcal{L}_Q$$

$$\mathcal{L}_g = -\frac{1}{2} tr \left(F_{\mu\nu} F^{\mu\nu} \right)$$

$$\mathcal{L}_q = \bar{q} \left(i \not{D} - m_q \right) q \quad , \quad \mathcal{L}_Q = \bar{Q} \left(i \not{D} - m_Q \right) Q$$

- $-igF_{\mu\nu} = [D_\mu, D_\nu]$, $D_\mu = \partial_\mu - igA_\mu$, $A_\mu = T^a A^a_\mu$,
- $A^a_\mu \in 8$ of $SU(3)$, the gluon fields
- q and $Q \in 3$ of $SU(3)$, the light and heavy quark fields
- T^a are the generators of 3 of $SU(3)$
- g is the QCD coupling constant

QCD

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- There is also $\Lambda_{QCD} \sim 300 - 700 MeV$, dynamically generated scale. Heavy quarks have $m_Q \gg \Lambda_{QCD}$
- Asymptotic freedom (Gross, Wilczek; Politzer, 1971) implies $\alpha_s(m_Q) \ll 1$, $\alpha_s = g^2/4\pi$

QCD

The light quarks fulfil $m_q \ll \Lambda_{QCD} \longrightarrow$ there is an approximate $U(3) \times U(3)$ chiral symmetry,

- It is explicitely broken in the quantum theory down to $U(1) \times SU(3) \times SU(3)$
- And spontaneously broken down to flavor $SU(3)$ producing pseudo-Goldstone bosons, $G = \{\pi$s, Ks , $\eta\}$, $m_G \ll \Lambda_{QCD}$

Lattice QCD

Put (Euclidean) QCD on a lattice of N^4 points separated a distance a

- a is an UV regulator, hence $1/a \gg m_h$, m_h being the typical scale of the process we wish to study (e.g. a hadron mass).
- Na is an IR cut-off, hence $1/Na \ll m_G$ due to the existence of Goldstone bosons, otherwise $1/Na \ll \Lambda_{QCD}$ would be enough.

The second constrain holds for any system we wish to study. The first one changes depending on the system

Lattice QCD

- For hadrons involving light quarks only, we have $1/a \gg \Lambda_{QCD}$
- For hadrons involving heavy quarks, we have $1/a \gg m_Q$

QCD lattice calculations involving heavy quarks are very costly. A wise way to proceed is to calculate (factorize) the effects at the scale m_Q using perturbation theory, and leave for a less costly lattice calculation the effects at lower scales.

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  - Identify relevant degrees of freedom
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  - Exploit the hierarchy of energy scales
- The EFT gives equivalent physical results in the region where it holds
  - It may make apparent accidental symmetries in that region, which help constraining the physics.
  - Calculations are usually simpler.

Heavy-light systems

$Q\bar{q}$ bound state , $m_Q >> \Lambda_{QCD}$, $\alpha_s(m_Q) << 1$

- The heavy quark is essentially at rest in the rest frame of the heavy meson
- If the heavy meson moves with velocity v, $v^2 = 1$, the heavy quark will also move with velocity v up to fluctuations $\sim \Lambda_{QCD}$, namely its momentum can be written as $p = m_Q v + k$, $k \sim \Lambda_{QCD} \ll m_Q$
- Naïvely, we can write $Q(x) = e^{-im_Q vx} p_+ h_v^{(Q)}(x)$, $p_\pm = (1 \pm \not{v})/2$ projects onto the particle subspace, and $h_v^{(Q)}(x)$ contains the momentum fluctuations $k \sim \Lambda_{QCD}$

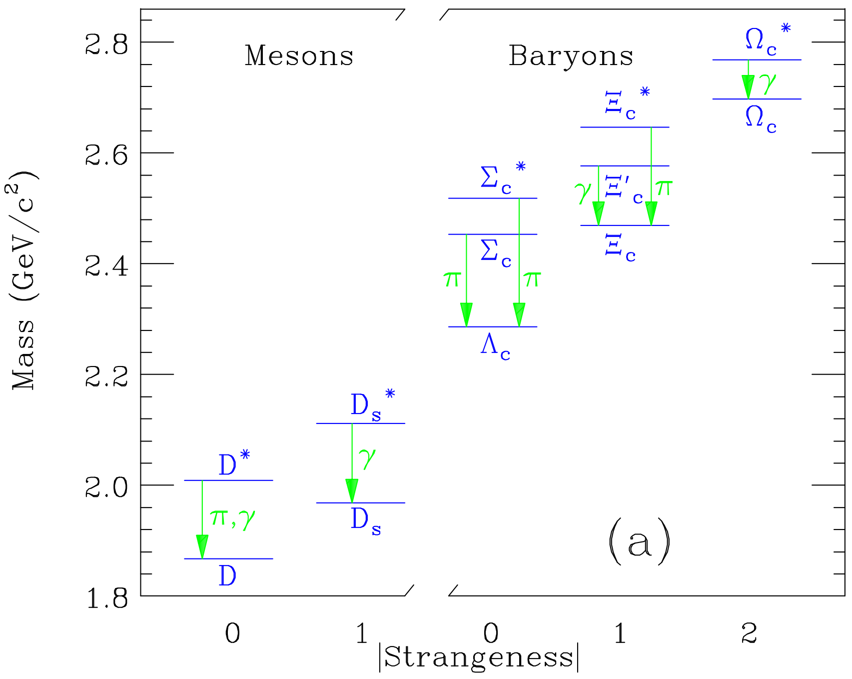
Heavy-light systems

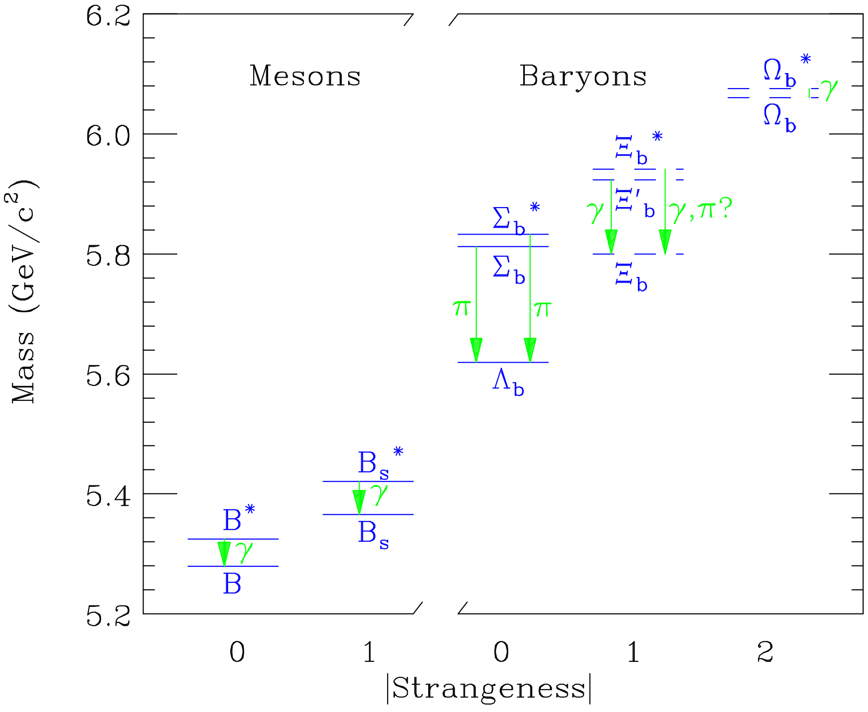
If this is done for all heavy quarks in the heavy quark part of the QCD lagrangian

$$\sum_{Q=c,b} \mathcal{L}_Q \longrightarrow \sum_{Q=c,b} \mathcal{L}_{HQET}^{(Q)} = \sum_{Q=c,b} \bar{h}_v^{(Q)} iv.Dh_v^{(Q)}$$

- It enjoys an accidental $SU(2N_Q)$ spin-flavor symmetry
  - $m_{b\bar{q}} - m_b \sim m_{c\bar{q}} - m_c$. E.g. $m_{D_1^0} - m_{D^0} \sim m_{B_1^0} - m_{B^0}$
  - For each Q, spin doublets $(S, S+1)$. E.g. $m_B \sim m_{B^*}$, $m_D \sim m_{D^*}$
- One expects the naïve picture to be modified by
  - Power corrections: $\sim 1/m_Q$ suppressed terms
  - Radiative corrections: $\sim \alpha_s(m_Q)$ suppressed terms

Heavy-light systems





Rosner, hep-ph/0612332

Power + Radiative Corrections

- For $v = (1, \mathbf{0})$, we have

$$\mathcal{L} = \bar{h}_v \left\{ iD^0 + c_2 \frac{\mathbf{D}^2}{2m} + c_4 \frac{\mathbf{D}^4}{8m^3} + c_F\, g \frac{\boldsymbol{\sigma} \cdot \mathbf{B}}{2m} + c_D\, g \frac{[\mathbf{D} \cdot \mathbf{E}]}{8m^2} \right.$$

$$\left. + ic_S\, g \frac{\boldsymbol{\sigma} \cdot (\mathbf{D} \times \mathbf{E} - \mathbf{E} \times \mathbf{D})}{8m^2} + \mathcal{O}(1/m^3) \right\} h_v,$$

- v arbitrary is recovered by $D^0 \to v.D$, $\mathbf{D} \to D^\mu - v^\mu v.D$ and $\boldsymbol{\sigma} \to i p_+ \gamma^\nu p_- \gamma^\rho p_+ \epsilon_{\mu\nu\rho\sigma} v^\sigma / 2$

Matching

$$
\begin{aligned}
c_2 &= c_4 = 1 \\
c_F &= 1 + \frac{\alpha}{\pi}\left[\frac{1}{2}C_f + \left(\frac{1}{2} - \frac{1}{2}\log\frac{m}{\mu}\right)C_A\right] \\
c_D &= 1 + \frac{\alpha}{\pi}\left[\left(\frac{8}{3}\log\frac{m}{\mu}\right)C_f + \left(\frac{1}{2} + \frac{2}{3}\log\frac{m}{\mu}\right)C_A\right] \\
c_S &= 1 + \frac{\alpha}{\pi}\left[C_f + \left(1 - \log\frac{m}{\mu}\right)C_A\right] \quad , \quad C_A = N_c
\end{aligned}
$$

$$
\Big[\quad \mathcal{L} = \bar{h}_v \Big\{ iD^0 + c_2\,\frac{\mathbf{D}^2}{2m} + c_4\,\frac{\mathbf{D}^4}{8m^3} + c_F\, g\,\frac{\boldsymbol{\sigma}\cdot\mathbf{B}}{2m} + c_D\, g\,\frac{[\mathbf{D}\cdot\mathbf{E}]}{8m^2}
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$$

Renormalization Group

The solution of the RG equations at one loop reads

$$c_F(\mu) = z^{-C_A}$$

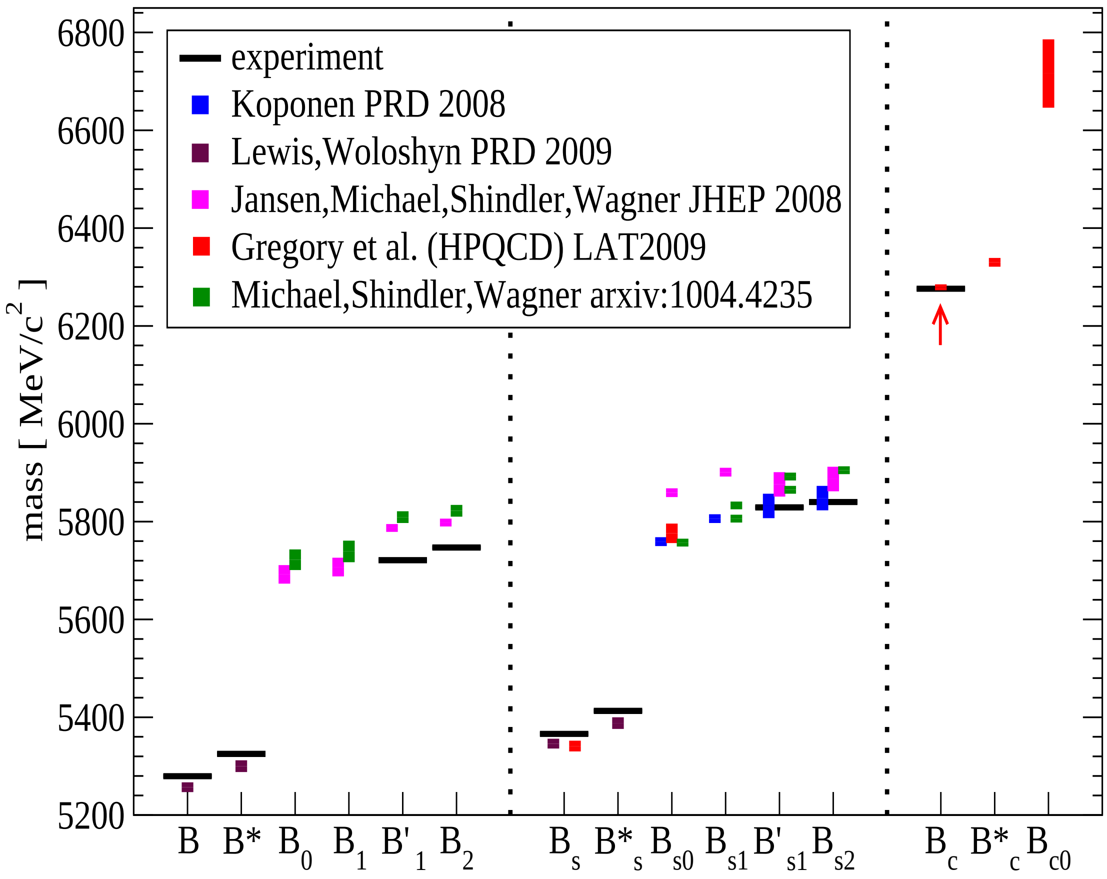
$$c_D(\mu) = z^{-2C_A} + \left(\frac{20}{13} + \frac{32}{13}\frac{C_F}{C_A}\right)\left[1 - z^{-13C_A/6}\right]$$

$$z = \left[\frac{\alpha_s(\mu)}{\alpha_s(m)}\right]^{1/b_0} \quad , \quad b_0 = 11C_A/3 - 4T_F n_f/3$$

- Application:

$$\frac{m_{B*}^2 - m_B^2}{m_{D*}^2 - m_D^2} = \left[\frac{\alpha_s(m_D)}{\alpha_s(m_B)}\right]^{-C_A/b_0} + \mathcal{O}\left(\frac{\Lambda_{QCD}}{m_c}, \frac{\Lambda_{QCD}}{m_b}, \alpha_s\right)$$

Heavy-light systems



Lewis, 1010.0889

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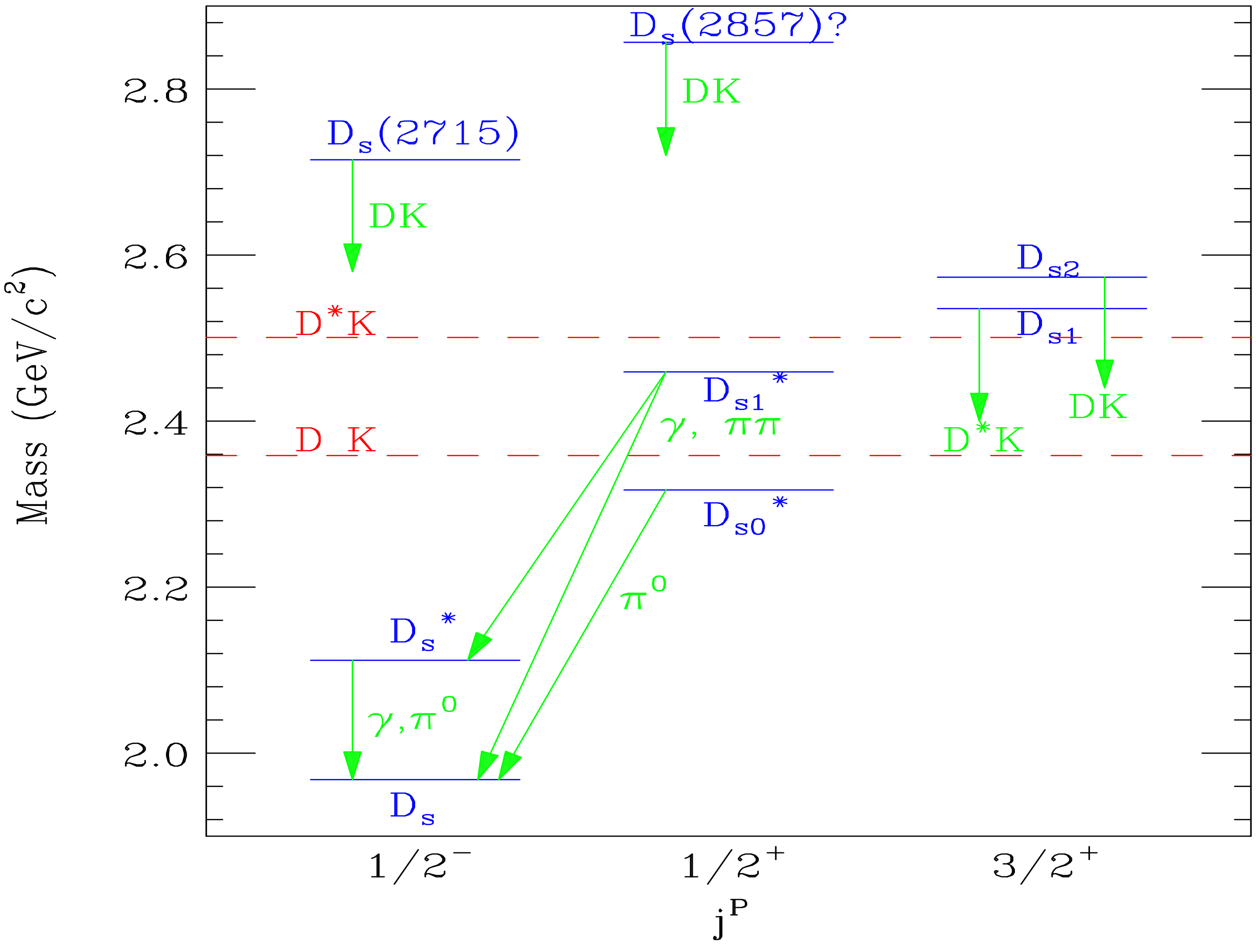

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- Also:
  - B_c ($b\bar{c}$)
  - t-$\bar{t}$
  - $\tilde{q}\bar{\tilde{q}}$, $\tilde{g}\bar{\tilde{g}}$, $\cdots$
  - Double-heavy baryons (ccq, $q = u, d, s$)

Early approaches

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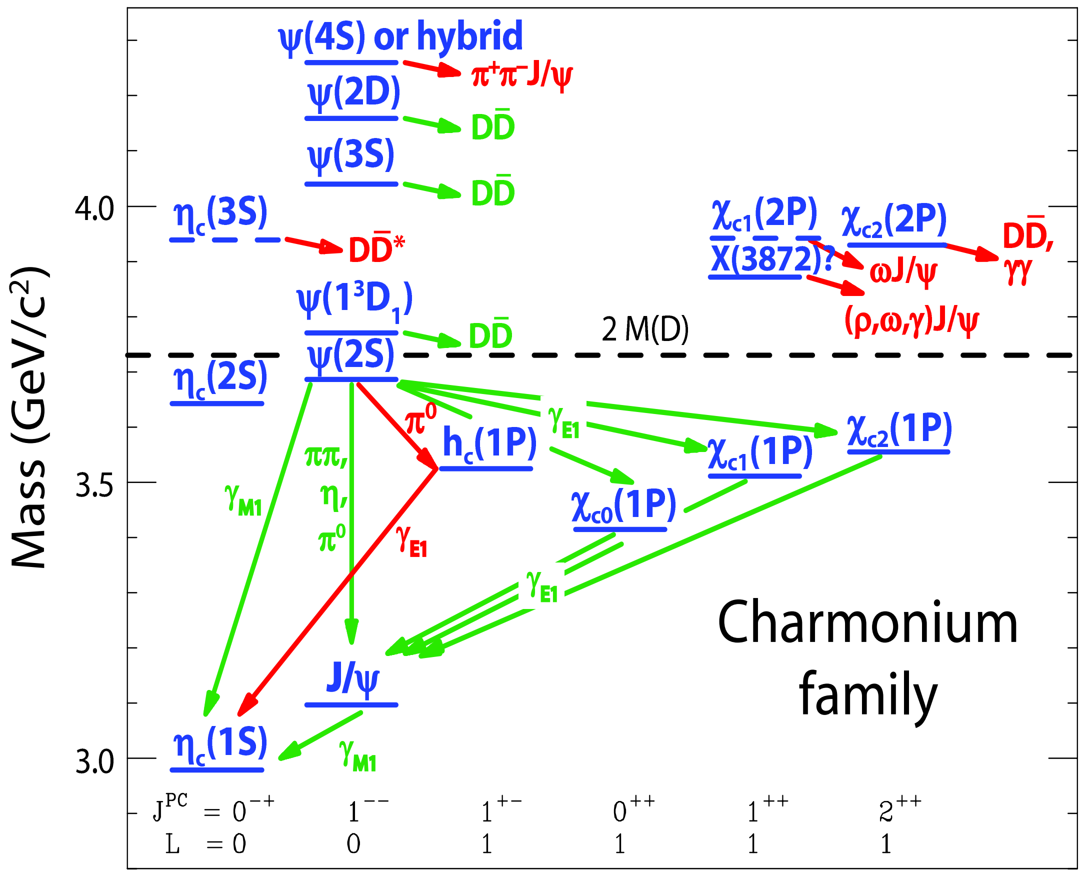
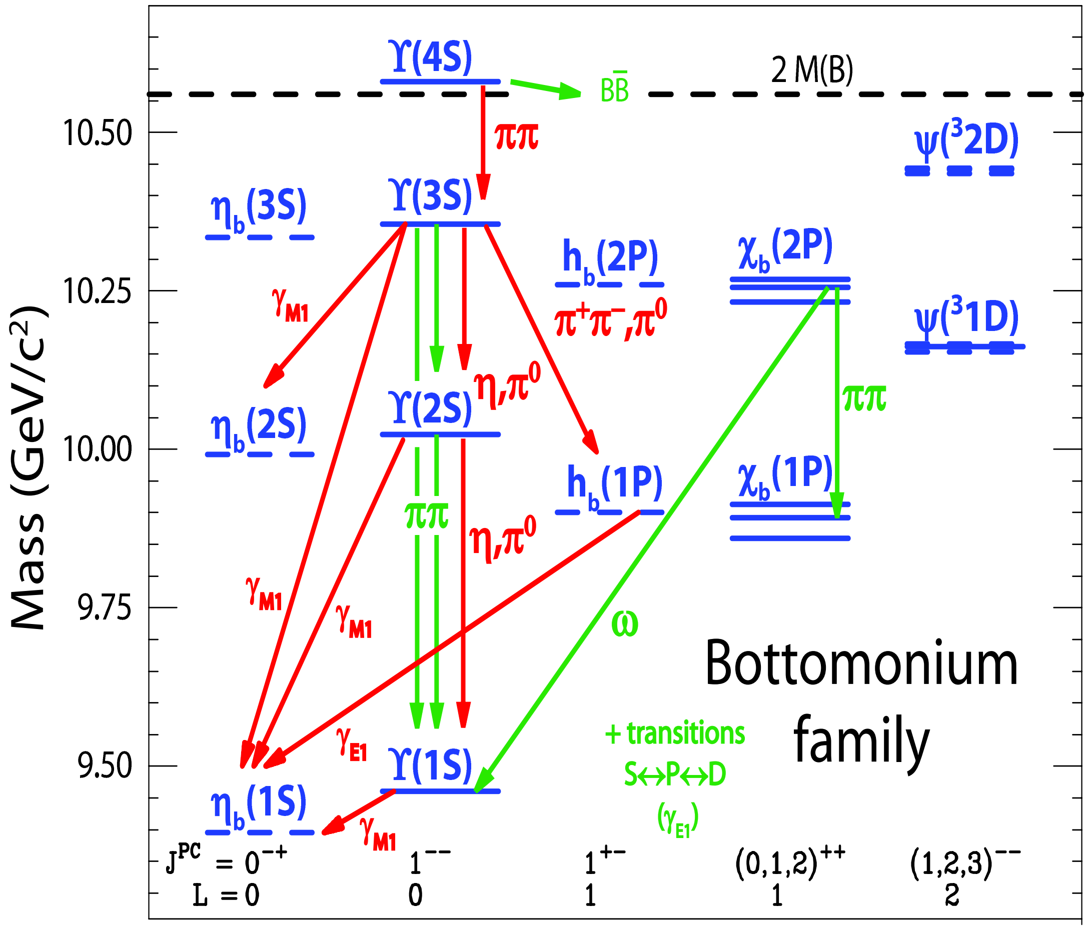
  - But did not quite follow the pattern of the positronium spectrum. They need not to if Λ_{QCD} is taken into account (Voloshin, 1979; Leutwyler, 1981)
- Potential models: modify the Coulomb-type potential, e.g. Cornell potential (1980): $V(r) = \sigma r - \frac{b}{r}$

Charmonium



Eichten, Godfrey, Mahlke, Rosner (2007)

Bottomonium



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  - $m_Q >> m_Q v >> m_Q v^2$
  - $m_Q >> \Lambda_{QCD}$
- EFTs are useful (N. Brambilla, A. Pineda, JS and A. Vairo, Rev. Mod. Phys. 77, 1423 (2005))

NRQCD

W.E. Caswell and G.P. Lepage, Phys. Lett. **167B**, 437 (1986)
G. T. Bodwin, E. Braaten and G. P. Lepage, Phys. Rev. D **51** (1995) 1125

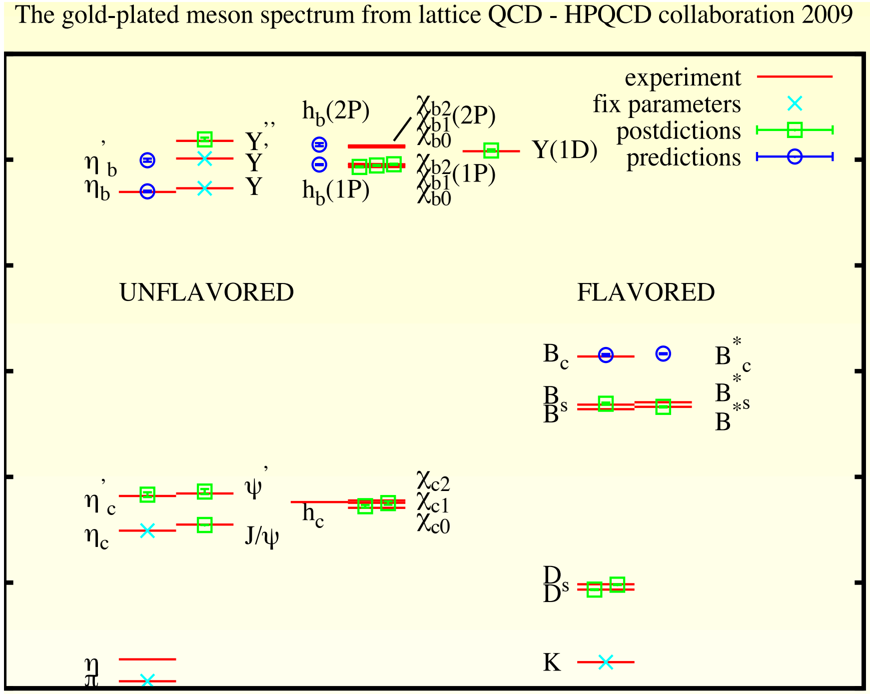
$$m_Q \quad >> \quad m_Q v \quad , \quad m_Q v^2 \quad , \quad \Lambda_{QCD}$$

$$\mathcal{L}_\psi = \psi^\dagger \left\{ iD_0 + \frac{1}{2m_Q}\mathbf{D}^2 + \frac{1}{8m_Q^3}\mathbf{D}^4 + \frac{c_F}{2m_Q}\boldsymbol{\sigma}.g\mathbf{B} + \right.$$
$$\left. + \frac{c_D}{8m_Q^2}\left(\mathbf{D}.g\mathbf{E} - g\mathbf{E}.\mathbf{D}\right) + i\,\frac{c_S}{8m_Q^2}\boldsymbol{\sigma}.\left(\mathbf{D}\times g\mathbf{E} - g\mathbf{E}\times\mathbf{D}\right) \right\}\psi$$

c_F, c_D and c_S are short distance matching coefficients which depend on m_Q and μ (factorization scale)

NRQCD(Cont.)

- Spectroscopy $\longrightarrow$ Lattice NRQCD



Gregory et al. [HPQCD] PRL.104:022001(2010)

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    - Mode decomposition

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pNRQCD

$\Lambda_{QCD} \lesssim m_Q v^2$: weak coupling regime

$$\mathcal{L}_{\rm pNRQCD} = \int d^3\mathbf{r}\ {\rm Tr}\left\{ {\rm S}^\dagger \left(i\partial_0 - h_s(\mathbf{r},\mathbf{p},\mathbf{P_R},\mathbf{S}_1,\mathbf{S}_2,\mu)\right) {\rm S} + \right.$$

$$\left. + {\rm O}^\dagger \left(iD_0 - h_o(\mathbf{r},\mathbf{p},\mathbf{P_R},\mathbf{S}_1,\mathbf{S}_2,\mu)\right) {\rm O} \right\}$$

$$+ V_A(r,\mu) {\rm Tr}\left\{ {\rm O}^\dagger \mathbf{r}\cdot g\mathbf{E}\,{\rm S} + {\rm S}^\dagger \mathbf{r}\cdot g\mathbf{E}\,{\rm O} \right\} +$$

$$+ \frac{V_B(r,\mu)}{2} {\rm Tr}\left\{ {\rm O}^\dagger \mathbf{r}\cdot g\mathbf{E}\,{\rm O} + {\rm O}^\dagger {\rm O}\mathbf{r}\cdot g\mathbf{E} \right\}$$

h_s, h_o = quantum mechanical Hamiltonians with scale dependent potentials calculable in perturbation theory in $\alpha_{\rm s}(m_Q v)$

pNRQCD (Cont.)

$\Lambda_{QCD} \lesssim mv$: strong coupling regime

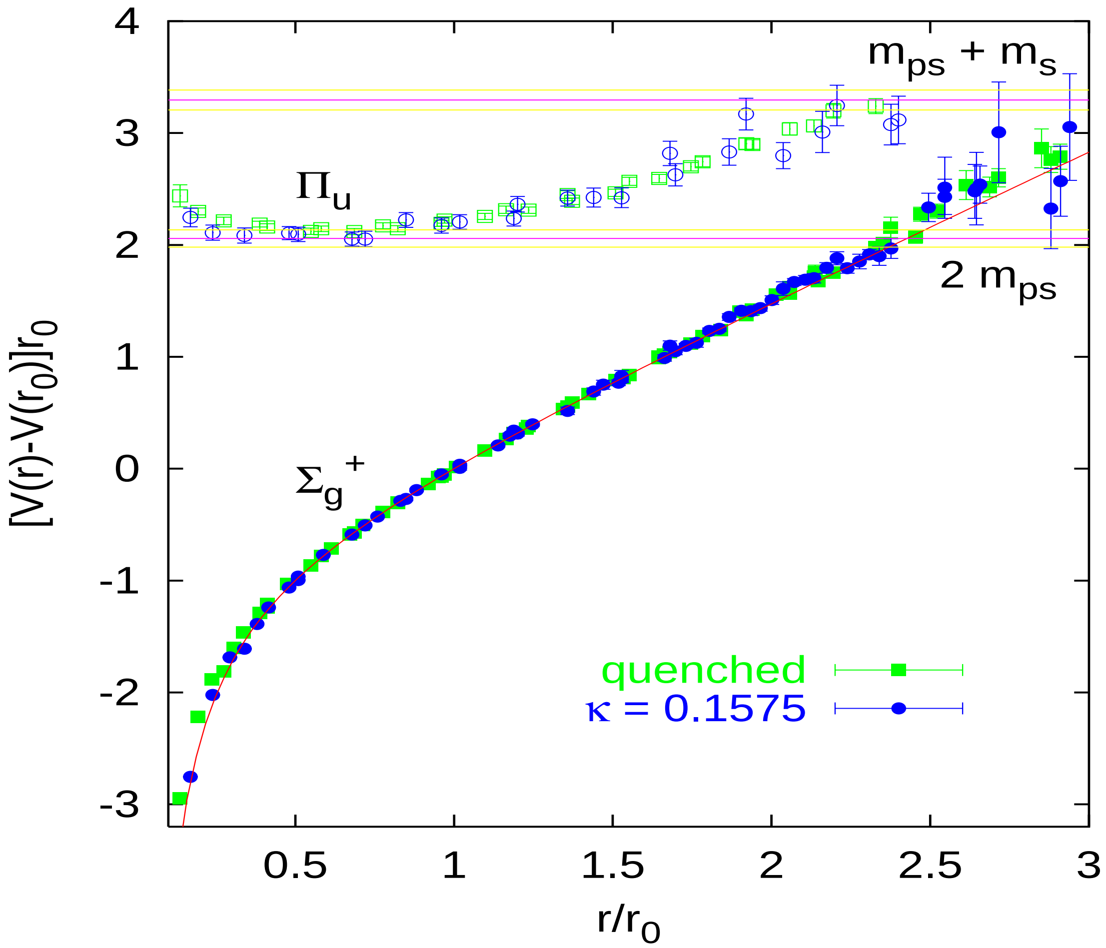
$$L_{\rm pNRQCD} = \int d^3\mathbf{x}_1 \int d^3\mathbf{x}_2 \, S^\dagger (i\partial_0 - h_s(\mathbf{x}_1, \mathbf{x}_2, \mathbf{p}_1, \mathbf{p}_2, \mathbf{S}_1, \mathbf{S}_2))S,$$

$$h_s(\mathbf{x}_1, \mathbf{x}_2, \mathbf{p}_1, \mathbf{p}_2, \mathbf{S}_1, \mathbf{S}_2) = \frac{\mathbf{p}_1^2}{2m_Q} + \frac{\mathbf{p}_2^2}{2m_Q} + V_s(\mathbf{x}_1, \mathbf{x}_2, \mathbf{p}_1, \mathbf{p}_2, \mathbf{S}_1, \mathbf{S}_2),$$

$$V_s = V_s^{(0)} + \frac{V_s^{(1)}}{m_Q} + \frac{V_s^{(2)}}{m_Q^2} + \cdots,$$

All V_ss can be, and most of them have been, calculated on the lattice

pNRQCD(Cont.)



G.S. Bali at al. (TXL Collaboration), Phys. Rev. **D62**,(2000):054503

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- Lattice NRQCD: $\frac{1}{a} \gg m_Q v \gg m_Q v^2 \gg \frac{1}{Na} \quad \longrightarrow \quad N \gg 1/v$

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- Lattice NRQCD: $\frac{1}{a} \gg m_Q v \gg m_Q v^2 \gg \frac{1}{Na} \quad \longrightarrow \quad N \gg 1/v$
- Lattice pNRQCD: $\frac{1}{a} \gg m_Q v^2 \gg \frac{1}{Na} \quad \longrightarrow \quad N \gg 1$

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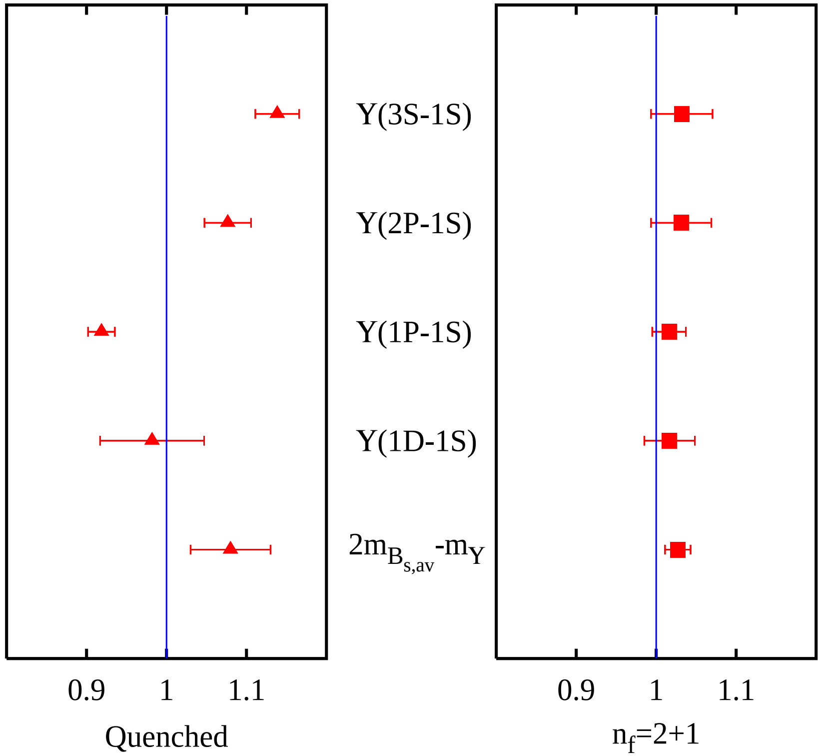
- Lattice NRQCD: $\frac{1}{a} \gg m_Q v \gg m_Q v^2 \gg \frac{1}{Na} \quad \longrightarrow \quad N \gg 1/v$
- Lattice pNRQCD: $\frac{1}{a} \gg m_Q v^2 \gg \frac{1}{Na} \quad \longrightarrow \quad N \gg 1$
- Charmonium: $v^2 \sim 0.3$

$$N^4_{QCD} \sim 10 N^4_{NRQCD} \sim 100 N^4_{pNRQCD}$$

- Bottomonium: $v^2 \sim 0.1$

$$N^4_{QCD} \sim 100 N^4_{NRQCD} \sim 10000 N^4_{pNRQCD}$$

Lattice NRQCD



A. Gray, I. Allison, C.T.H. Davies, Emel Dalgic, G.P. Lepage, J. Shigemitsu, M. Wingate, Phys.Rev.D72:094507,2005.

Spectrum at weak coupling

- LO: $m_Q\alpha_{\rm s}^2$, trivial
- NLO: $m_Q\alpha_{\rm s}^3$, (Billoire,1980)
- NNLO: $m_Q\alpha_{\rm s}^4$, (Pineda, Yndurain, 1997)
- NNNLO: $m_Q\alpha_{\rm s}^5 \ln\alpha_{\rm s}$ only, (Brambilla, Pineda, JS, Vairo, 1999)
- NNLL: $m_Q\alpha_{\rm s}^{4+n} \ln^n \alpha_{\rm s}$, (Pineda, 2001)
- NNNLO: $m_Q\alpha_{\rm s}^5$, almost complete, (Kniehl, Penin, Smirnov, Steinhauser, 2002; Beneke, Kiyo, Schuller, 2005)

The static potential

$$
\begin{aligned}
V_s(r,\mu) \;=\; & -\frac{C_F\alpha_s(1/r)}{r}\Bigg\{1+\frac{\alpha_s(1/r)}{4\pi}\,[\tilde{a}_1]+\left(\frac{\alpha_s(1/r)}{4\pi}\right)^2[\tilde{a}_2] \\
& +\left(\frac{\alpha_s(1/r)}{4\pi}\right)^3\left[a_3^L\log\mu r+\tilde{a}_3\right] \\
& +\left(\frac{\alpha_s(1/r)}{4\pi}\right)^4\left[a_4^{L2}\log^2\mu r+a_4^L\log\mu r+\tilde{a}_4\right]+\cdots\Bigg\},
\end{aligned}
$$

$\tilde{a}_1$, W. Fischler, Nucl. Phys. B **129** (1977) 157; A. Billoire, Phys. Lett. B **92** (1980) 343

$\tilde{a}_2$, M. Peter, Phys. Rev. Lett. **78** (1997) 602; Nucl. Phys. B **501** (1997) 471; Y. Schröder, Phys. Lett. B **447** (1999) 321

a_3^L, . Brambilla, A. Pineda, JS, A. Vairo, Phys. Rev. D60, 091502 (1999)

$\tilde{a}_3$, ???

a_4^{2L}, A. Pineda and JS, Phys. Lett. B **495** (2000) 323

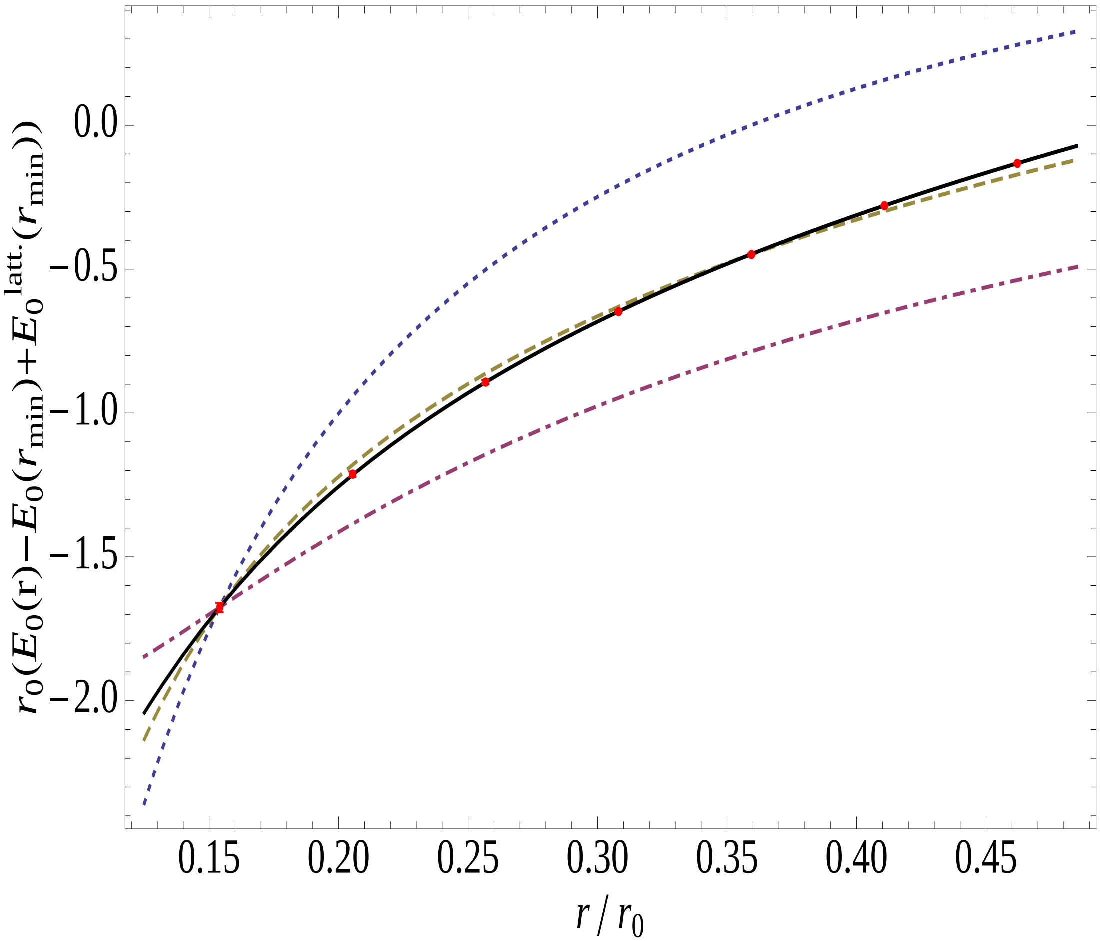
a_4^L, N. Brambilla, X. Garcia i Tormo, JS, A. Vairo, Phys. Lett. B647, 185 (2007)

The 3-loop potential

$$\tilde{a}_3 = \tilde{a}_3^{(0)} + \tilde{a}_3^{(1)} n_f + \tilde{a}_3^{(2)} n_f^2 + \tilde{a}_3^{(3)} n_f^3$$

- $\tilde{a}_3^{(i)}$, $i = 1, 2, 3$: Smirnov, Smirnov, Steinhauser, 2008
- $\tilde{a}_3^{(0)}$: Padé estimate $\sim 313 \times 4^3$, Chishtie, Elias, 2001
- $\tilde{a}_3^{(0)}$: Renormalon estimate $\sim 292 \times 4^3$, Pineda, 2001
- $\tilde{a}_3^{(0)}$: NNNLL calculation + lattice data $=$ $(202 - 337) \times 4^3$, Brambilla, Garcia i Tormo, JS, Vairo, 2009

The 3-loop potential



(Brambilla, Garcia i Tormo, JS, Vairo, 2009)

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- $\tilde{a}_3^{(0)}$: NNNLO $\sim 209.885(1) \times 4^3$, Anzai, Kiyo, Sumino, arXiv:0911.4335; Smirnov, Smirnov, Steinhauser, arXiv:0911.4742

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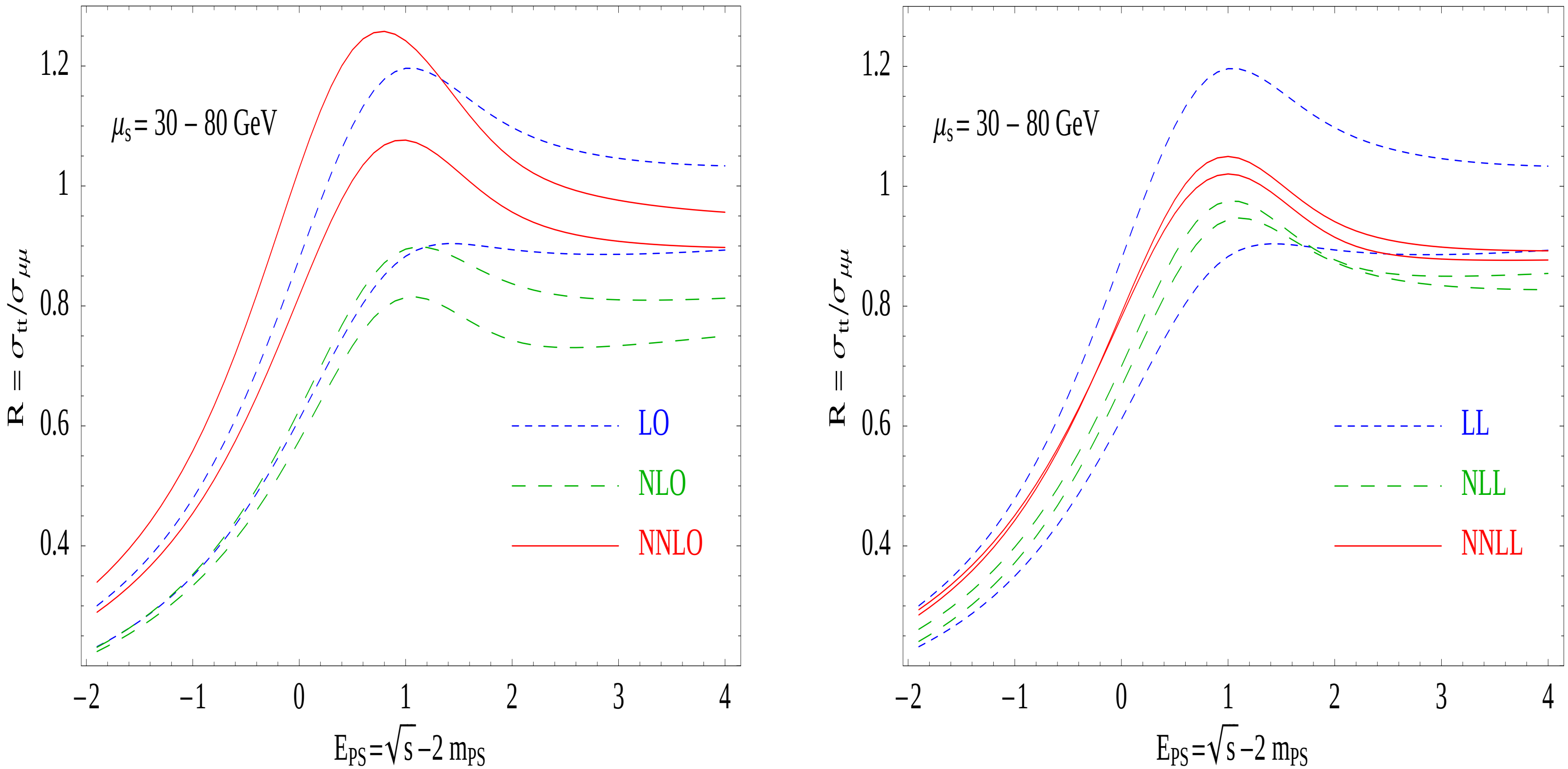
- NNNLO: $m_Q\alpha_{\rm s}^5$, complete, (Smirnov, Smirnov, Steinhauser, 2009)

pNRQCD: weak coupling regime (Cont.)

- Hyperfine splitting at NNLL accuracy (Kniehl, Penin, Pineda, Smirnov, and Steinhauser (03))
  - $m_{J/\psi} - m_{\eta_c(1S)} \sim 112 \pm 40\,(\delta\alpha_{\rm s})\,\mathrm{MeV}$
    [Exp: $116.6 \pm 1.0\,,\mathrm{MeV}$]
    [MILC/Fermilab: $116 \pm 7.4\,,\mathrm{MeV}$]
  - $m_{\Upsilon(1S)} - m_{\eta_b(1S)} = 39 \pm 11\,(\mathrm{th})\,{}^{+9}_{-8}\,(\delta\alpha_{\rm s})\,\mathrm{MeV}$
    [Exp: $69.6 \pm 2.9\,\mathrm{MeV}$]
    [HPQCD: $61 \pm 14\,,\mathrm{MeV}$]
    [MILC/Fermilab: $54 \pm 12.4\,,\mathrm{MeV}$]
    [RBC/UKQCD: $60.3 \pm 7.7\,,\mathrm{MeV}$]
  - $m_{B_c^*} - m_{B_c} \sim 40 \pm 17^{+15}_{-12}$
    [HPQCD: $53 \pm 7 \pm 2 \pm 6\,,\mathrm{MeV}$]

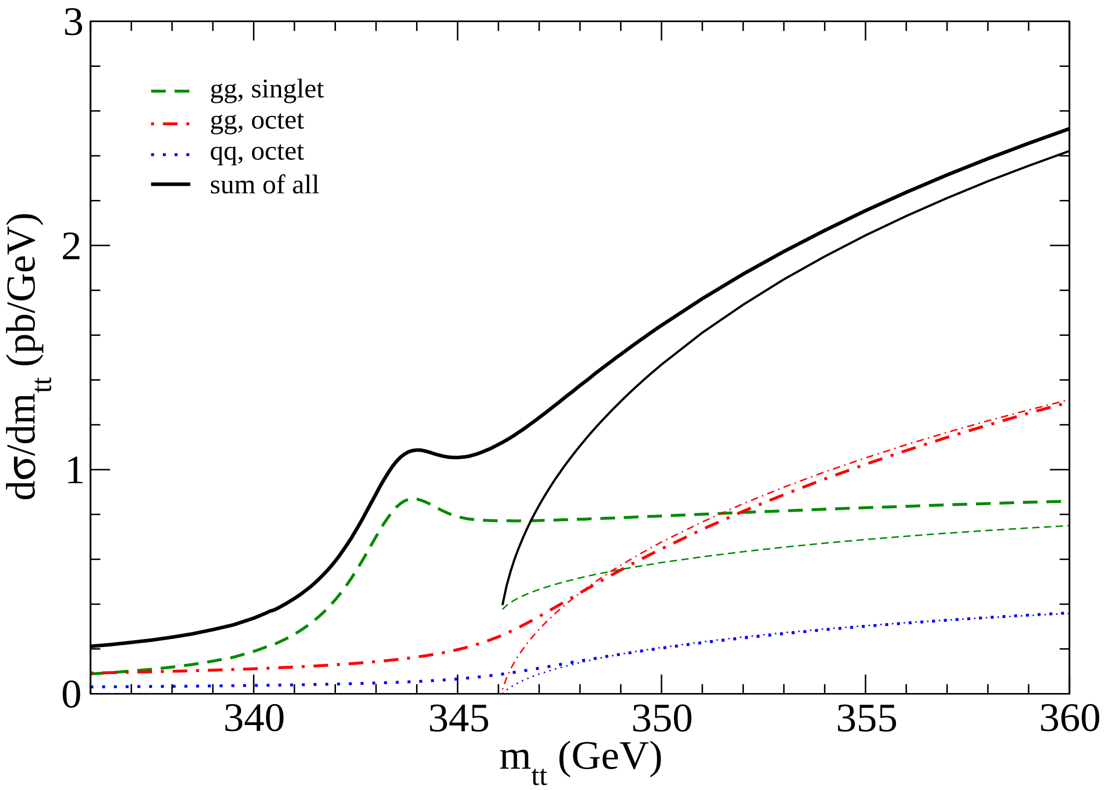
$t\bar{t}$ at ILC



(Pineda, Signer, 2006)

$t\bar{t}$ at LHC ?

$t\bar{t}$ at LHC ?



(Hagiwara, Sumino, Yokoya, 2008)

pNRQCD: strong coupling regime

$\Lambda_{QCD} \lesssim mv$: strong coupling regime

$$L_{\rm pNRQCD} = \int d^3\mathbf{x}_1 \int d^3\mathbf{x}_2 \; S^\dagger (i\partial_0 - h_s(\mathbf{x}_1, \mathbf{x}_2, \mathbf{p}_1, \mathbf{p}_2, \mathbf{S}_1, \mathbf{S}_2)) S,$$

$$h_s(\mathbf{x}_1, \mathbf{x}_2, \mathbf{p}_1, \mathbf{p}_2, \mathbf{S}_1, \mathbf{S}_2) = \frac{\mathbf{p}_1^2}{2m_Q} + \frac{\mathbf{p}_2^2}{2m_Q} + V_s(\mathbf{x}_1, \mathbf{x}_2, \mathbf{p}_1, \mathbf{p}_2, \mathbf{S}_1, \mathbf{S}_2),$$

$$V_s = V_s^{(0)} + \frac{V_s^{(1)}}{m_Q} + \frac{V_s^{(2)}}{m_Q^2} + \cdots,$$

All V_ss can be, and most of them have been, calculated on the lattice

Lattice pNRQCD

Lattice pNRQCD

Example: the $1/m_Q$ potential (N. Brambilla, A. Pineda, JS, A. Vairo, Phys. Rev. D63:014023,2001)

$$V^{(1)}(r) \;=\; -\frac{1}{2}\int_0^\infty dt\, t\, \langle\!\langle g\mathbf{E}_1(t)\cdot g\mathbf{E}_1(0)\rangle\!\rangle_c,$$

Lattice pNRQCD

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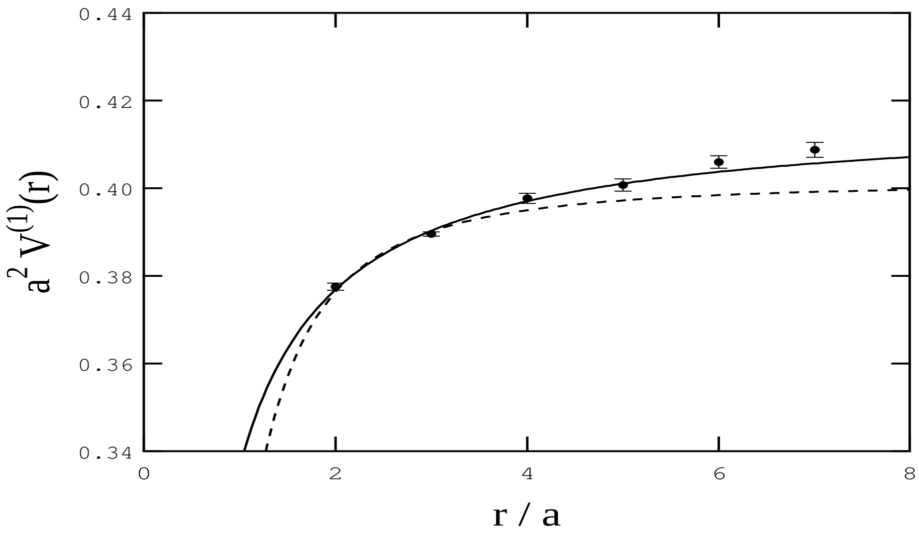

$$\text{Dashed}: \quad V^{(1)}(r) = \frac{a}{r^2} + c \quad , \qquad \text{Solid}: \quad V^{(1)}(r) = \frac{a}{r} + c$$

Y. Koma, M. Koma, H. Wittig, Phys. Rev. Lett. 97:122003,2006

Lattice pNRQCD

Constraints on $V^{(1)}(r)$:

Lattice pNRQCD

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- $r \ll 1/\Lambda_{QCD}$: $V^{(1)}(r) \sim \alpha_{\rm s}^2(1/r)/r^2$, from perturbation theory

Lattice pNRQCD

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- $r \gg 1/\Lambda_{QCD}$: $V^{(1)}(r) \sim a \ln r + c$, from the QCD effective string theory (Guillem Perez-Nadal, JS, Phys.Rev.D79:114002,2009)

Lattice pNRQCD

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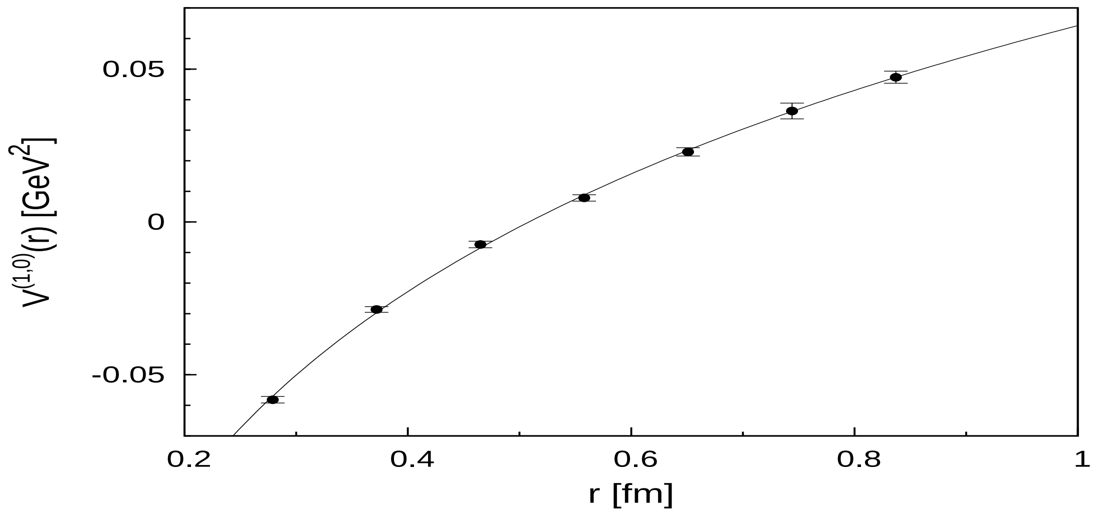
- $r \gg 1/\Lambda_{QCD}$: $V^{(1)}(r) \sim a \ln r + c$, from the QCD effective string theory (Guillem Perez-Nadal, JS, Phys.Rev.D79:114002,2009)



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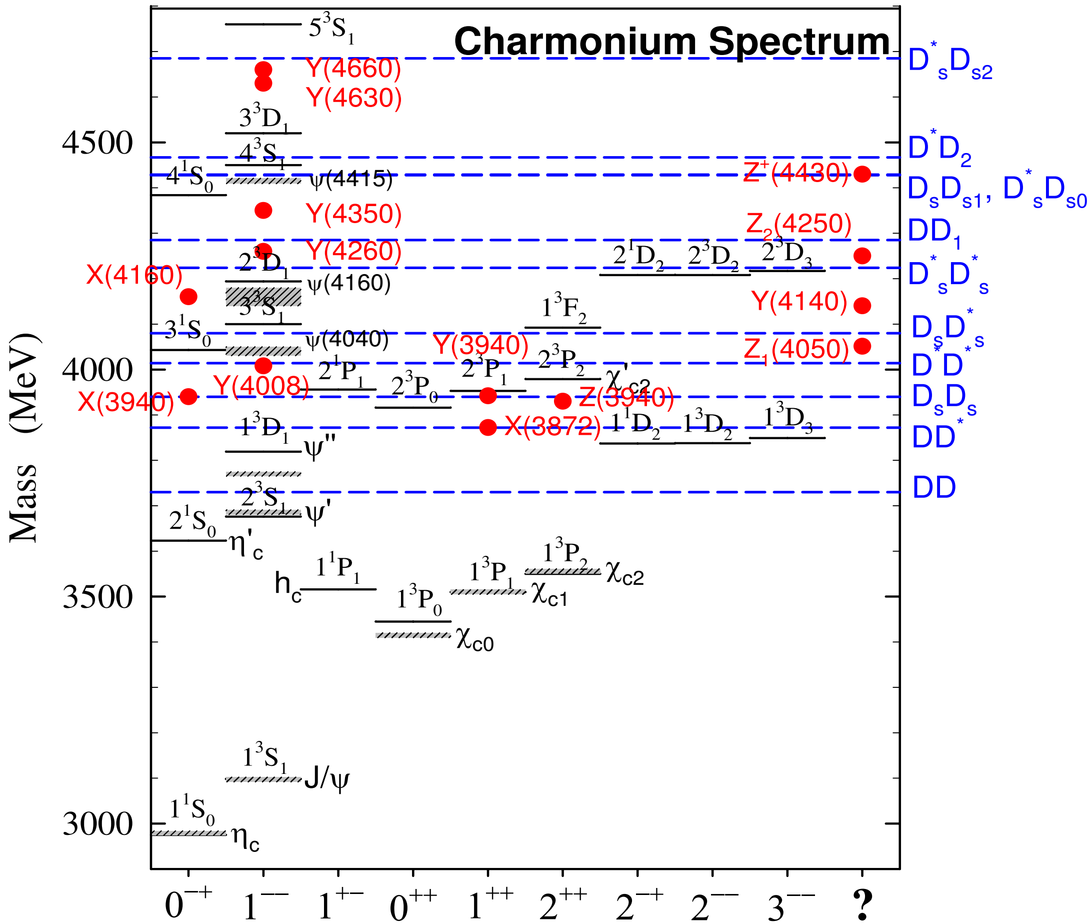
Current challenges

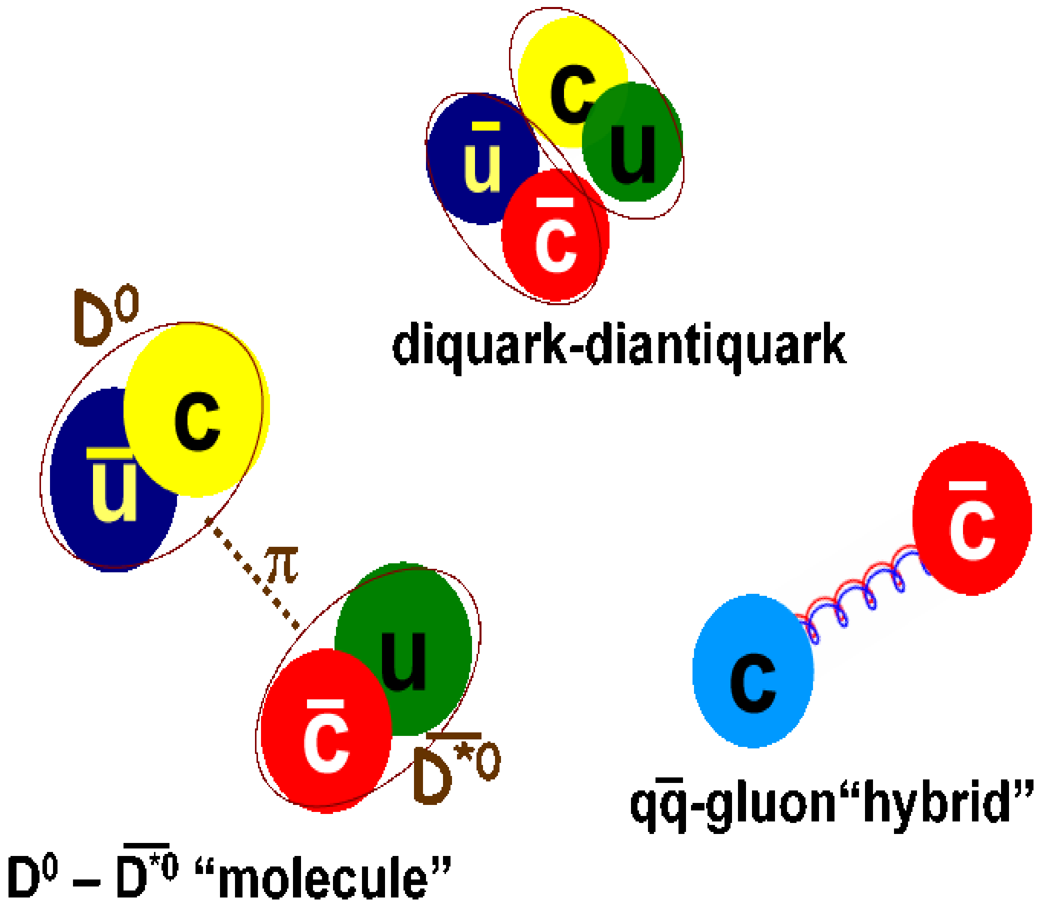
- States above open flavor threshold
  - In 2003 Belle reported the X(3872)
  - Since then quite a few new states have been reported: Z(3930), Y(3940), X(3940), X(4160), Y(4260), Y(4350), Y(4660)
  - Do not fit potential model expectations. Theoretical possibilities: molecules, tetraquarks, hybrids,...

"New" Charmonium Spectrum



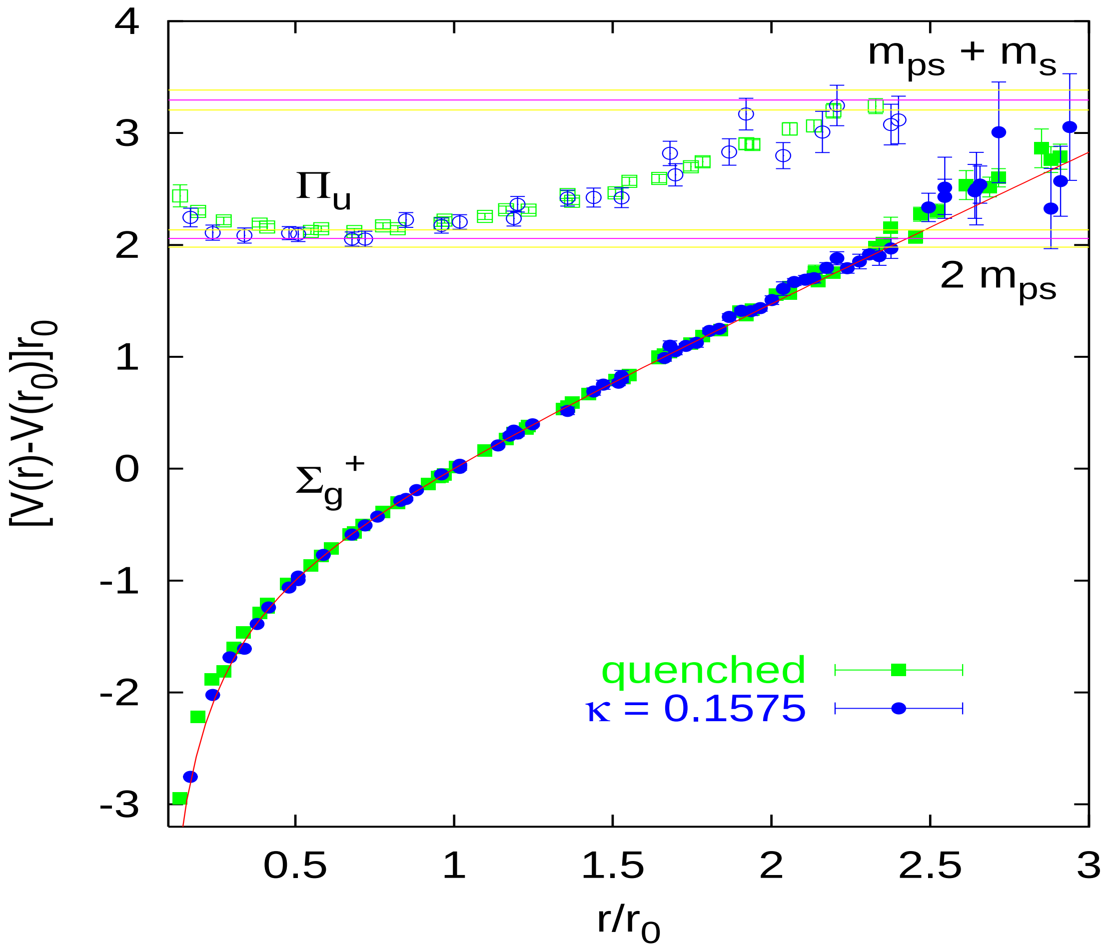
Godfrey, 2009

Exotics



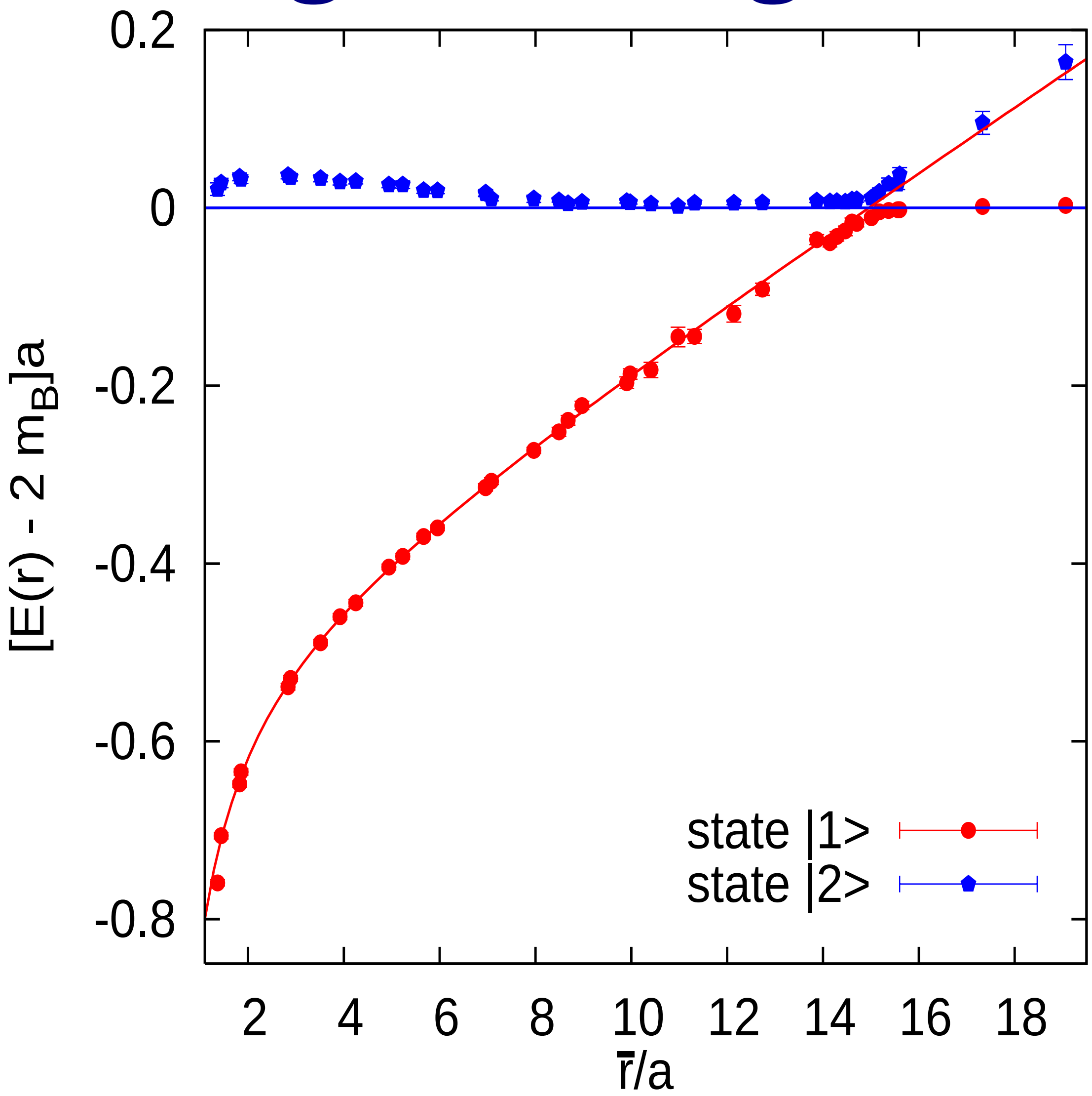
Godfrey, Olsen, 2008

pNRQCD(Cont.)



G.S. Bali at al. (TXL Collaboration), Phys. Rev. **D62**,(2000):054503

String breaking



Bali, Neff, Düssel, Lippert, Schilling (2005)

Unconventional charmonium states, (N. Brambilla et al., 1010.5827)

State	m (MeV)	Γ (MeV)	J^{PC}	Process (mode)	Experiment ($\#\sigma$)	Year	Status
$X(3872)$	3871.52±0.20	1.3±0.6	$1^{++}/2^{-+}$	$B \to K(\pi^+\pi^- J/\psi)$	Belle [85, 86] (12.8), *BABAR* [87] (8.6)	2003	OK
		(<2.2)		$p\bar{p} \to (\pi^+\pi^- J/\psi) + ...$	CDF [88–90] (np), DØ [91] (5.2)		
				$B \to K(\omega J/\psi)$	Belle [92] (4.3), *BABAR* [93] (4.0)		
				$B \to K(D^{*0}\bar{D}^0)$	Belle [94, 95] (6.4), *BABAR* [96] (4.9)		
				$B \to K(\gamma J/\psi)$	Belle [92] (4.0), *BABAR* [97, 98] (3.6)		
				$B \to K(\gamma\psi(2S))$	*BABAR* [98] (3.5), Belle [99] (0.4)		
$X(3915)$	3915.6 ± 3.1	28±10	$0/2^{?+}$	$B \to K(\omega J/\psi)$	Belle [100] (8.1), *BABAR* [101] (19)	2004	OK
				$e^+e^- \to e^+e^-(\omega J/\psi)$	Belle [102] (7.7)		
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (6.0)	2007	NC!
				$e^+e^- \to J/\psi\ (...)$	Belle [54] (5.0)		
$G(3900)$	3943 ± 21	52±11	1^{--}	$e^+e^- \to \gamma(D\bar{D})$	*BABAR* [27] (np), Belle [21] (np)	2007	OK
$Y(4008)$	$4008^{+121}_{-\ 49}$	226±97	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	Belle [104] (7.4)	2007	NC!
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4140)$	4143.4 ± 3.0	$15^{+11}_{-\ 7}$	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [106, 107] (5.0)	2009	NC!
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$e^+e^- \to J/\psi(D\bar{D}^*)$	Belle [103] (5.5)	2007	NC!
$Z_2(4250)^+$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$B \to K(\pi^+\chi_{c1}(1P))$	Belle [105] (5.0)	2008	NC!
$Y(4260)$	4263 ± 5	108±14	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^- J/\psi)$	*BABAR* [108, 109] (8.0)	2005	OK
					CLEO [110] (5.4)		
					Belle [104] (15)		
				$e^+e^- \to (\pi^+\pi^- J/\psi)$	CLEO [111] (11)		
				$e^+e^- \to (\pi^0\pi^0 J/\psi)$	CLEO [111] (5.1)		
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	CDF [107] (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 [112] (3.2)	2009	NC!
$Y(4360)$	4353 ± 11	96±42	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	*BABAR* [113] (np), Belle [114] (8.0)	2007	OK
$Z(4430)^+$	4443^{+24}_{-18}	$107^{+113}_{-\ 71}$	?	$B \to K(\pi^+\psi(2S))$	Belle [115, 116] (6.4)	2007	NC!
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$e^+e^- \to \gamma(\Lambda_c^+\Lambda_c^-)$	Belle [25] (8.2)	2007	NC!
$Y(4660)$	4664±12	48±15	1^{--}	$e^+e^- \to \gamma(\pi^+\pi^-\psi(2S))$	Belle [114] (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 [37, 117] (3.2)	2010	NC!

Unconventional charmonium states, (N. Brambilla et al., 1010.5827)

State	m (MeV)	Γ (MeV)	J^{PC}	Modes	Interpretation	Reference(s)
$X(3872)$	3871.52±0.20	1.3±0.6	$1^{++}/2^{-+}$	$\pi^+\pi^- J/\psi$	$D^{*0}\bar{D}^0$ molecule (bound)	[121, 122] [383–385]
				$D^{*0}\bar{D}^0$	$D^{*0}\bar{D}^0$ unbound	
				$\gamma J/\psi$, $\gamma\psi(2S)$	if 1^{++}, $\chi_{c2}(2P)$	[71]
				$\omega J/\psi$	if 2^{-+}, $\eta_{c2}(1D)$	[81, 93, 126]
					charmonium + mesonic-molecule mixture	[381]
					QCDSR: $[cq]_3\,[\bar{c}\bar{q}]_3$ (S+A)	[381]
					QCDSR: $[c\bar{q}]_1\,[\bar{c}q]_1$ (P+V)	[381]
					QCDSR: $[c\bar{c}]_1$(A) + $[c\bar{q}]_1\,[\bar{c}q]_1$ (P+V)	[381]
$X(3915)$	3915.6 ± 3.1	28±10	$0, 2^{?+}$	$\omega J/\psi$	$D^{*+}D^{*-} + D^{*0}\bar{D}^{*0}$	[386]
$Z(3930)$	3927.2 ± 2.6	24.1±6.1	2^{++}	$D\bar{D}$	$\chi_{c2}(2P)$ (*i.e.*, $2\,^3P_2$ $c\bar{c}$)	
					$1\,^3F_2$ $c\bar{c}$	[71]
$X(3940)$	3942^{+9}_{-8}	37^{+27}_{-17}	$?^{?+}$	$D\bar{D}^*$		
$G(3900)$	3943 ± 21	52±11	1^{--}	$D\bar{D}$	Coupled-channel effect	[34]
$Y(4008)$	$4008^{+121}_{-\ 49}$	226±97	1^{--}	$\pi^+\pi^- J/\psi$		
$Z_1(4050)^+$	4051^{+24}_{-43}	82^{+51}_{-55}	?	$\pi^+\chi_{c1}(1P)$	hadrocharmonium	[282, 355]
$Y(4140)$	4143.0 ± 3.1	$11.7^{+9.1}_{-6.2}$	$?^{?+}$	$\phi J/\psi$	QCDSR: $[c\bar{q}]_1\,[\bar{c}q]_1$ (V+V)	[381]
					QCDSR: $[c\bar{s}]_1\,[\bar{c}s]_1$ (V+V)	[381]
					$D_s^{*+}D_s^{*-}$	[386]
$X(4160)$	4156^{+29}_{-25}	139^{+113}_{-65}	$?^{?+}$	$D\bar{D}^*$		
$Z_2(4250)^+$	$4248^{+185}_{-\ 45}$	$177^{+321}_{-\ 72}$	?	$\pi^+\chi_{c1}(1P)$	hadrocharmonium	[282, 355]
$Y(4260)$	4263 ± 5	108±14	1^{--}	$\pi^+\pi^- J/\psi$	charmonium hybrid	[276–278]
				$\pi^0\pi^0 J/\psi$	$J/\psi f_0(980)$ bound state	[313]
					$D_0\bar{D}^*$ molecular state	[375]
					$[cs][\bar{c}\bar{s}]$ tetraquark state	[345, 381]
					hadrocharmonium	[282, 355]
					QCDSR: $[c\bar{q}]_1\,[\bar{c}q]_1$ (S+V)	[381]
					QCDSR: $[c\bar{q}]_1\,[\bar{c}q]_1$ (P+A)	[381]
$Y(4274)$	$4274.4^{+8.4}_{-6.7}$	32^{+22}_{-15}	$?^{?+}$	$B \to K(\phi J/\psi)$	(see $Y(4140)$)	
$X(4350)$	$4350.6^{+4.6}_{-5.1}$	$13.3^{+18.4}_{-10.0}$	$0{,}2^{++}$	$\phi J/\psi$		
$Y(4360)$	4353 ± 11	96±42	1^{--}	$\pi^+\pi^-\psi(2S)$	hadrocharmonium	[282, 355]
					crypto-exotic hybrid	[71]
					$Y_B(4360) = [cd][\bar{c}\bar{d}](1P)$, baryonium	[321]
					QCDSR: $[cq]_3\,[\bar{c}\bar{q}]_3$ (S+V)	[381]
					QCDSR: $[c\bar{s}]_1\,[\bar{c}s]_1$ (S+V)	[381]
$Z(4430)^+$	4443^{+24}_{-18}	$107^{+113}_{-\ 71}$	?	$\pi^+\psi(2S)$	$D^{*+}\bar{D}_1^0$ molecular state	[378, 387]
					$[cu][\bar{c}\bar{d}]$ tetraquark state	[379]
					hadrocharmonium	[282, 355]
					QCDSR: $[c\bar{d}]_1\,[\bar{c}u]_1$ (V+A)	[381]
					QCDSR: $[cu]_3\,[\bar{c}\bar{d}]_3$ (S+P)	[381]
$X(4630)$	$4634^{+\ 9}_{-11}$	92^{+41}_{-32}	1^{--}	$\Lambda_c^+\Lambda_c^-$	$Y_B(4660) = [cd][\bar{c}\bar{d}](2P)$, baryonium	[321]
					$\psi(2S)f_0(980)$ molecule	[324]
$Y(4660)$	4664±12	48±15	1^{--}	$\pi^+\pi^-\psi(2S)$	$\psi(2S)f_0(980)$ molecule	[306]
					$[cs][\bar{c}\bar{s}]$ tetraquark state	[375]
					hadrocharmonium	[282, 355]
					$Y_B(4660) = [cd][\bar{c}\bar{d}](2P)$, baryonium	[321]
					QCDSR: $[cs]_3\,[\bar{c}\bar{s}]_3$ (S+V)	[381]
$Y_b(10888)$	10888.4±3.0	$30.7^{+8.9}_{-7.7}$	1^{--}	$\pi^+\pi^-\Upsilon(nS)$	$\Upsilon(5S)$	[388]
					b-flavored $Y(4260)$	[37, 117]

Conclusions

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- Will super-B uncover more?