NRQCD and Quarkonia

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Quarkonium Working Group

In the last years Heavy Quarkonium Physics is passing throught a new revolution due to:

- Many new data coming from several experiments (with huge luminosities):
  Belle, BaBar, CLEO-III, CLEO-c, BES, Fermilab (E835, D0, CDF), Hera, RHIC (Star, Phenix), CERN (NA60), ...
  that have led to discovery of new states, new production mechanisms, new decays, precisions and high statistics data.

  More are expected in the future:
  BES-III, LHC, PANDA,
  and from possible future tau-charm factories, Super B factories, ILC, ...

- New theoretical tools:
  Effective Field Theories (EFTs) of QCD,
  progress in Lattice Gauge Theories.

Outline

- Motivations: scales and EFTs

Selected example applications to:

- Spectra
- Standard model parameters extraction
- New states
- Production
- Decays and Transitions
- Threshold $t\bar{t}$ cross section
- Gluelumps and hybrids

For many more applications and updates:

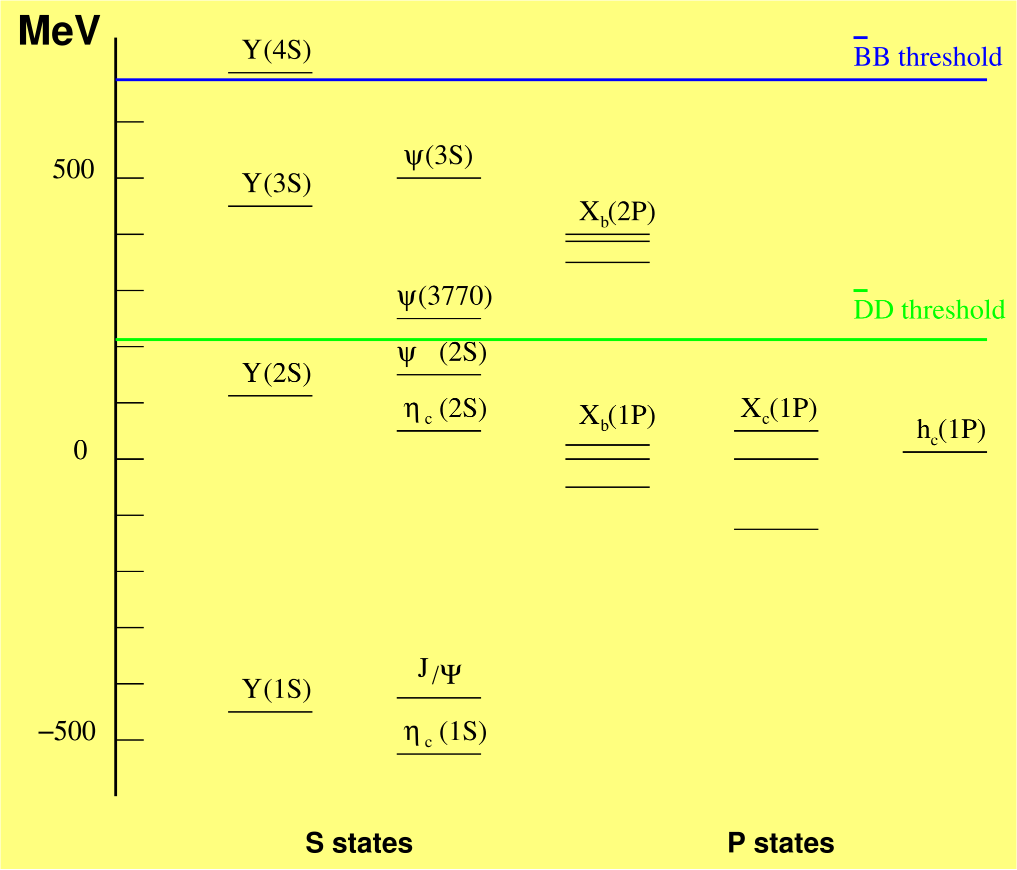
(1) Quarkonium Working Group http://www.qwg.to.infn.it
and slides of the QWG meeting @ BNL, June 2006

(2) N. Brambilla, M. Krämer, R. Mussa, A. Vairo *et al.*
Heavy Quarkonium Physics
CERN Yellow Report, CERN-2005-005, Geneva: CERN, 2005.- 487 p.
arXiv:hep-ph/0412158.

(3) N. Brambilla, A. Pineda, J. Soto and A. Vairo
Effective field theories for heavy quarkonium
Reviews of Modern Physics 77 n.4 (2005) - 161 p.
arXiv:hep-ph/0410047.

Scales and EFTs

$Q\bar{Q}$ scales



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

The mass scale is perturbative:

$m_b \simeq 5$ *GeV*, $m_c \simeq 1.5$ *GeV*

The system is non-relativistic:

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

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

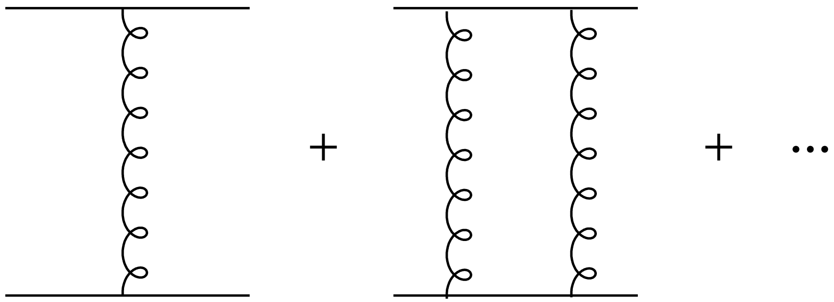
Non-relativistic bound states are characterized

by at least three energy scales

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

$Q\bar{Q}$ scales

- Even if $\alpha_s \ll 1$
  on bound state the perturbative expansion breaks down when $\alpha_s \sim v$:



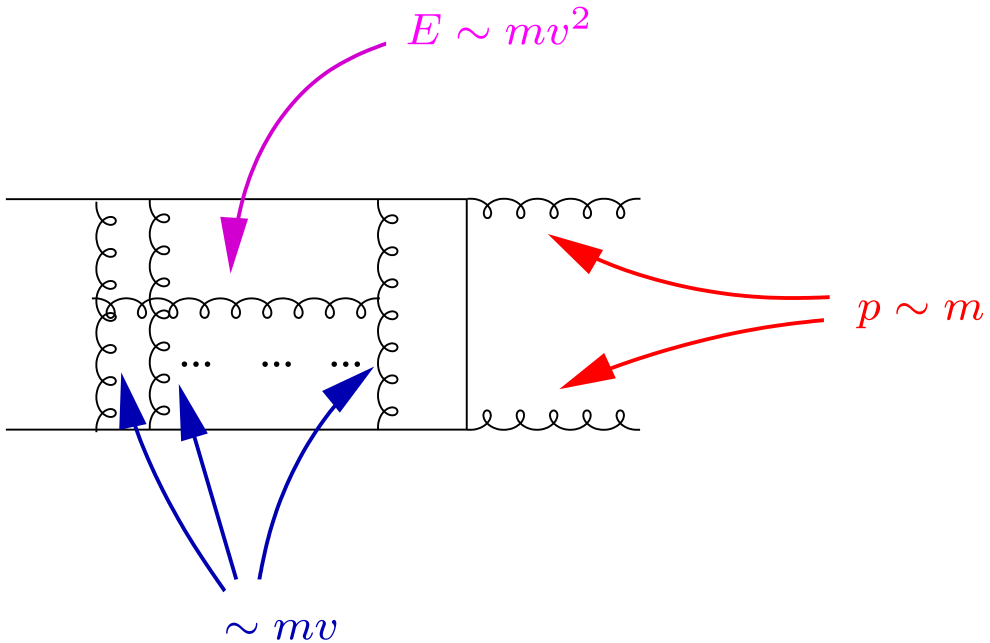
$$\approx \frac{1}{E - \left(\frac{p^2}{m} + V\right)}$$

$$\alpha_s \left(1 + \frac{\alpha_s}{v} + \dots\right)$$

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

$Q\bar{Q}$ scales

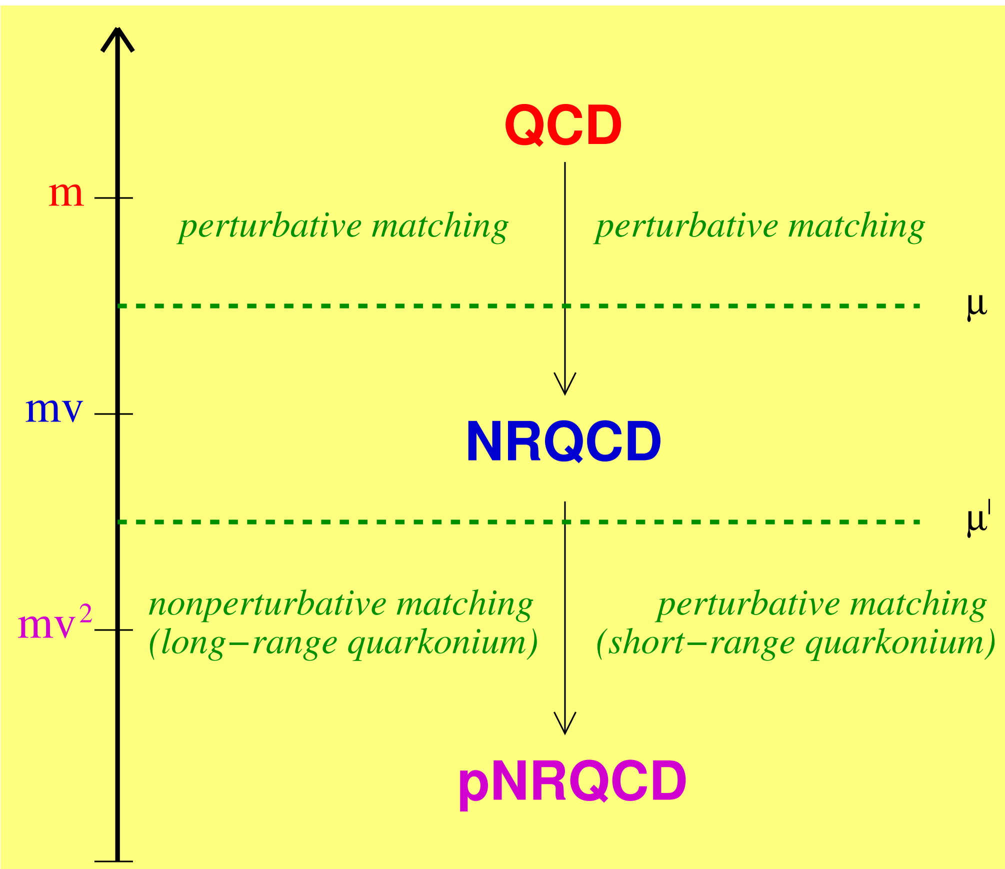
Scales get entangled.

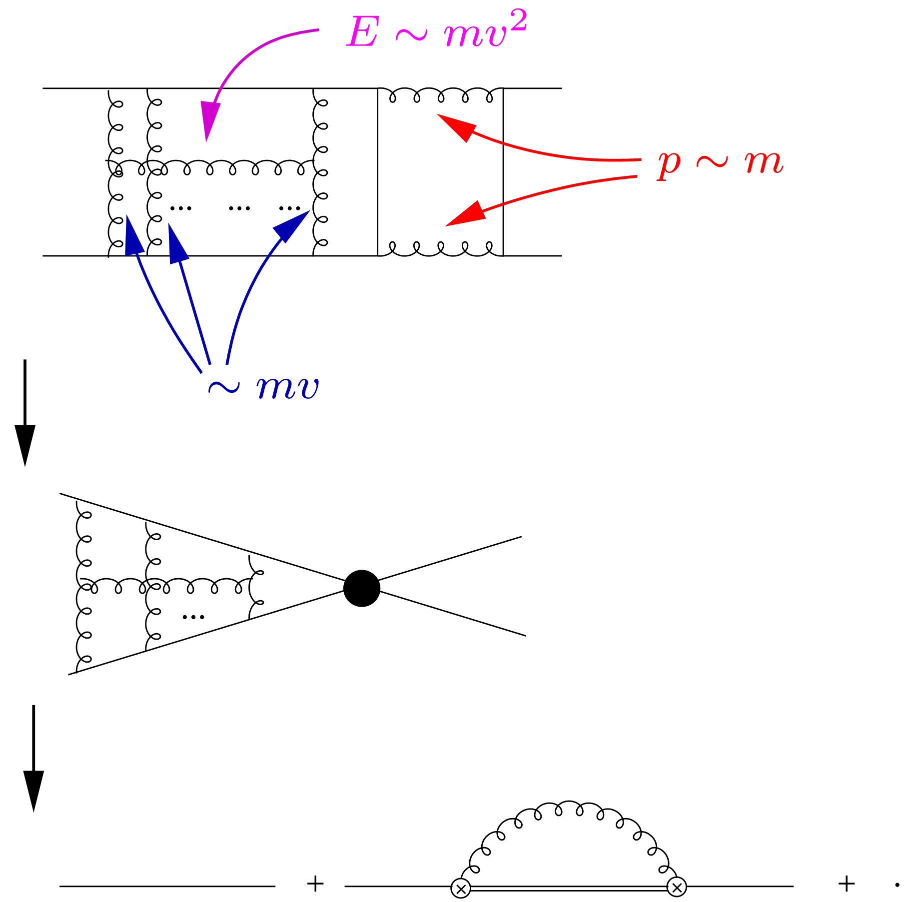


a way to disentangle them is by substituting QCD with equivalent but simpler EFTs.

Note: the low-energy scales will be sensitive to $\Lambda_{\rm QCD}$. A full perturbative treatment is not possible. Regardless of this the non-relativistic hierarchy $m \gg mv \gg mv^2$ will persist also below the $\Lambda_{\rm QCD}$ threshold.

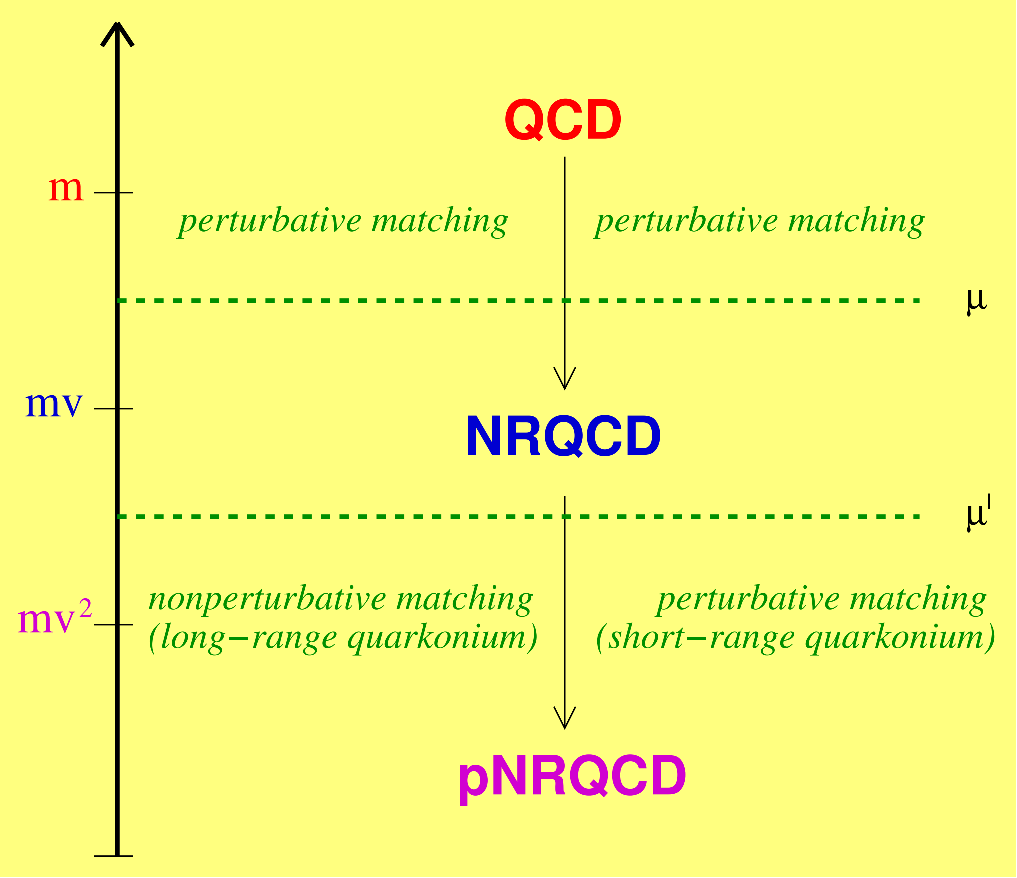
EFTs for systems made of two heavy quarks





- They exploit the expansion in v/ factorization of low and high energy contributions.
- They are renormalizable order by order in v.
- In perturbation theory (PT), RG techniques provide resummation of large logs.

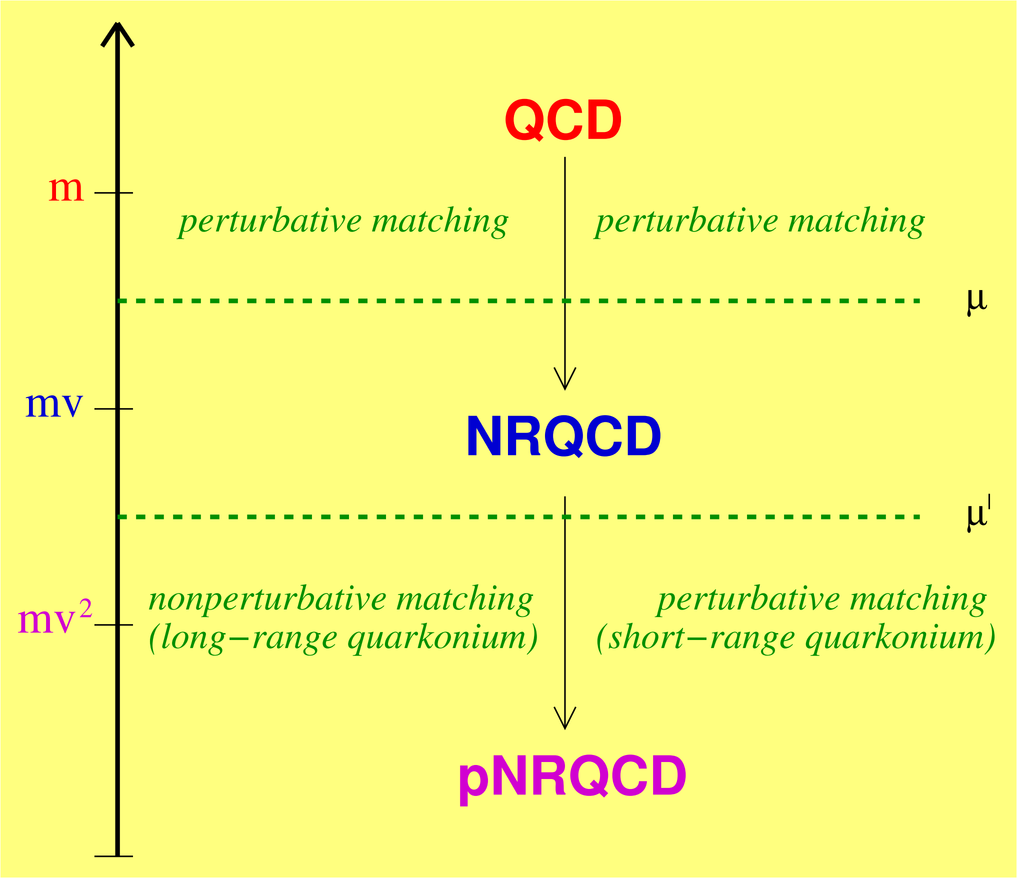
EFTs for systems made of two heavy quarks

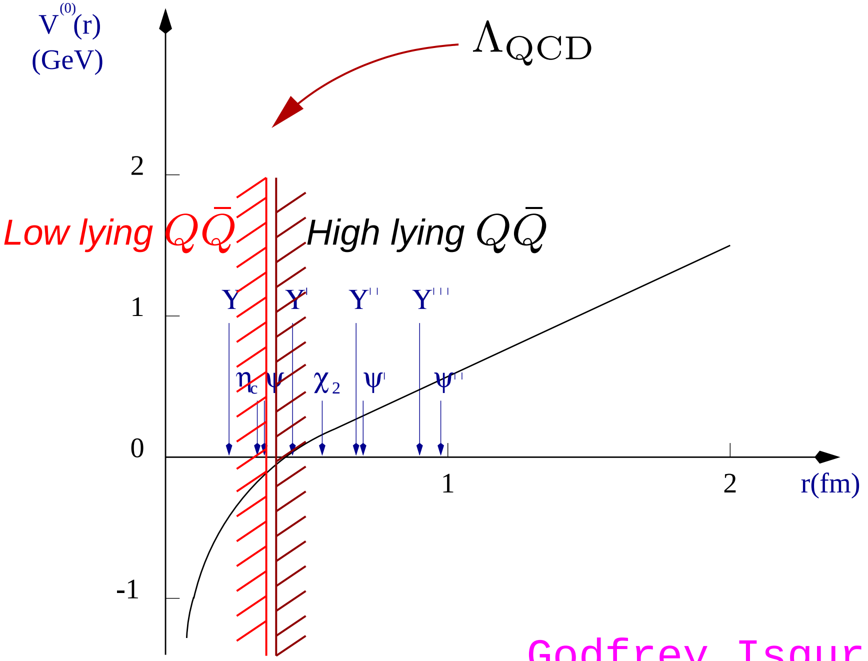


Caswell Lepage 86, Lepage Thacker 88
Bodwin Braaten Lepage 95, ...

Pineda Soto 97
Brambilla et al 99-06 $\longrightarrow$ pNRQCD
Kniehl, Penin et al, 99 ...
Luke Manohar 97, Luke Savage 98
Beneke and Smirnov 98
Labelle 98, Grinstein Rothstein 98
Griesshammer 98, Luke et al 00
Manohar and Stewart 00...
Hoang et al, 01 ... $\longrightarrow$ vNRQCD

EFTs for systems made of two heavy quarks





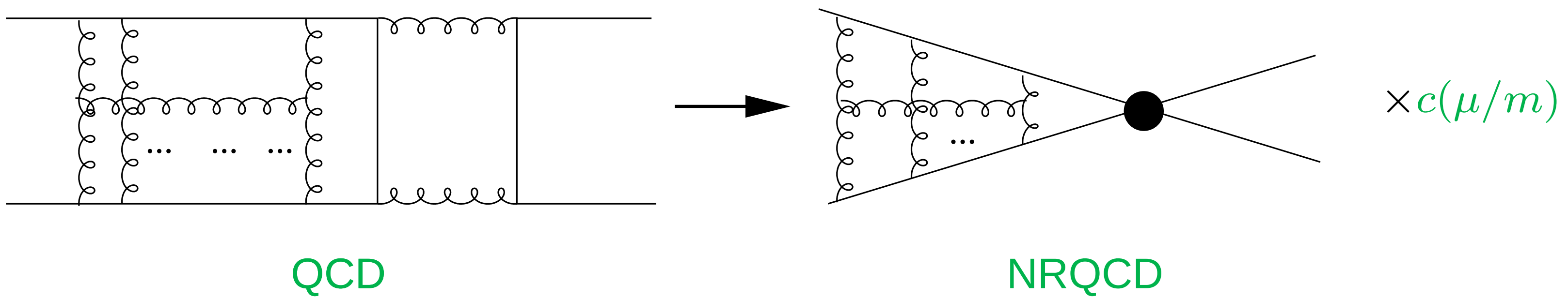
Godfrey Isgur 85

A potential picture arises at the level of pNRQCD:

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

NRQCD

NRQCD is the EFT that follows from QCD when $\Lambda = m$



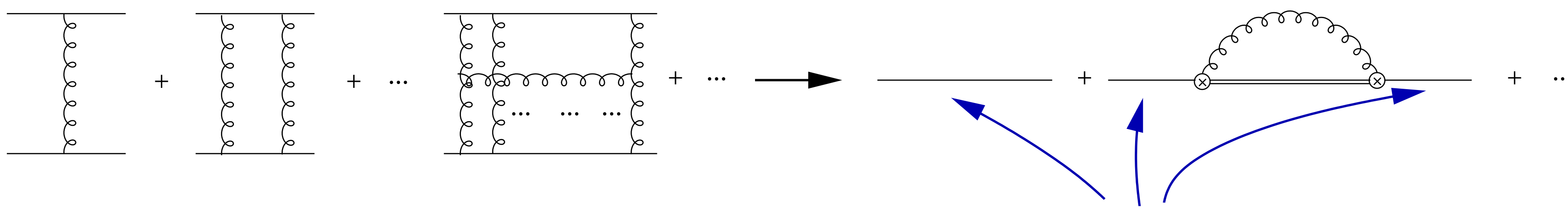
- The matching is perturbative.
- The Lagrangian is organized as an expansion in $1/m$ and $\alpha_s(m)$:

$$\mathcal{L}_{\rm NRQCD} = \sum_n c(\alpha_s(m/\mu)) \times O_n(\mu,\lambda)/m^n$$

Suitable to describe annihilation and production of quarkonium.

pNRQCD

pNRQCD is the EFT for heavy quarkonium that follows from NRQCD when $\Lambda = \frac{1}{r} \sim mv$



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

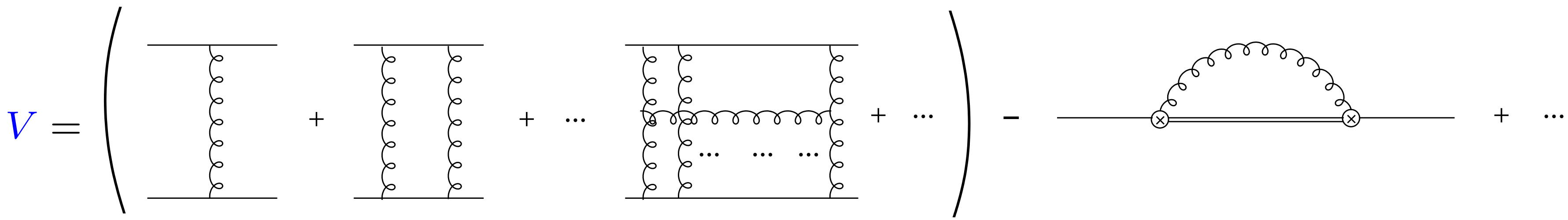
NRQCD pNRQCD

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

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

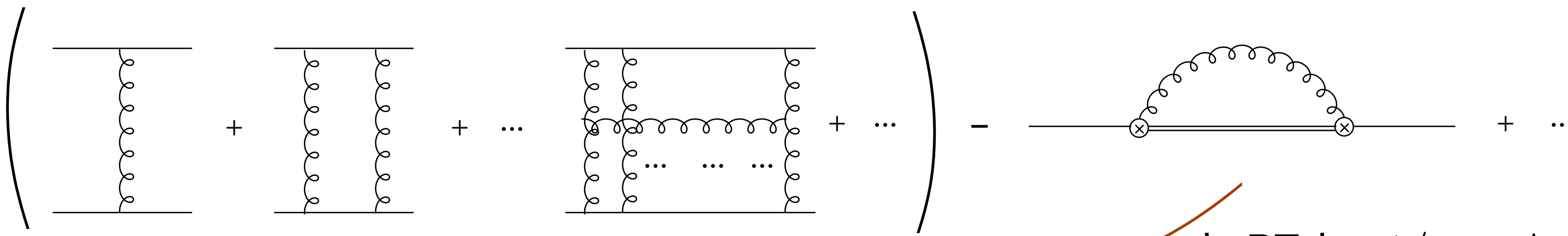
Potential and spectra

Potential



The potential is a Wilson coefficient of an EFT. In general, it undergoes renormalization, develops scale dependence and satisfies renormalization group equations, which allow to resum large logarithms.

Potential

$V =$ 

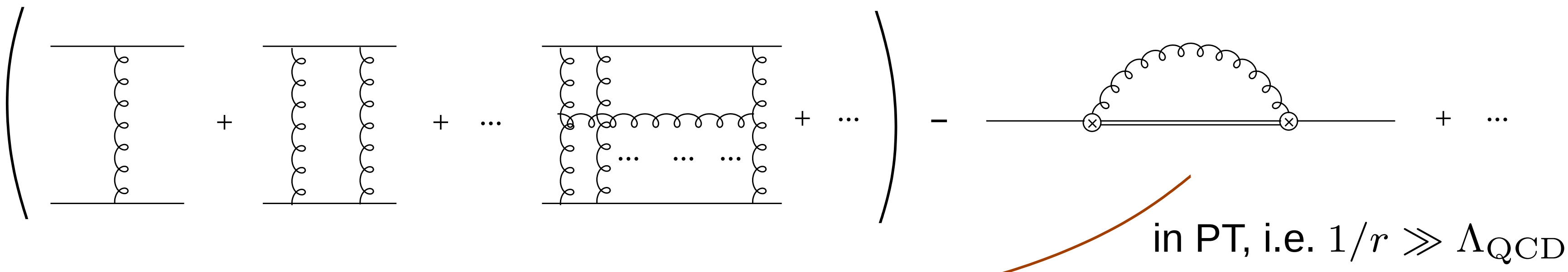
in PT, i.e. $1/r \gg \Lambda_{\rm QCD}$

$$= -\frac{4}{3}\frac{\alpha_{\rm s}}{r}\left[1 + a_1\alpha_{\rm s}(r) + a_2(\alpha_{\rm s}(r))^2 + \frac{9}{4}\frac{\alpha_{\rm s}^3}{\pi}\ln\mu r + \ldots\right]$$

Brambilla et al 99

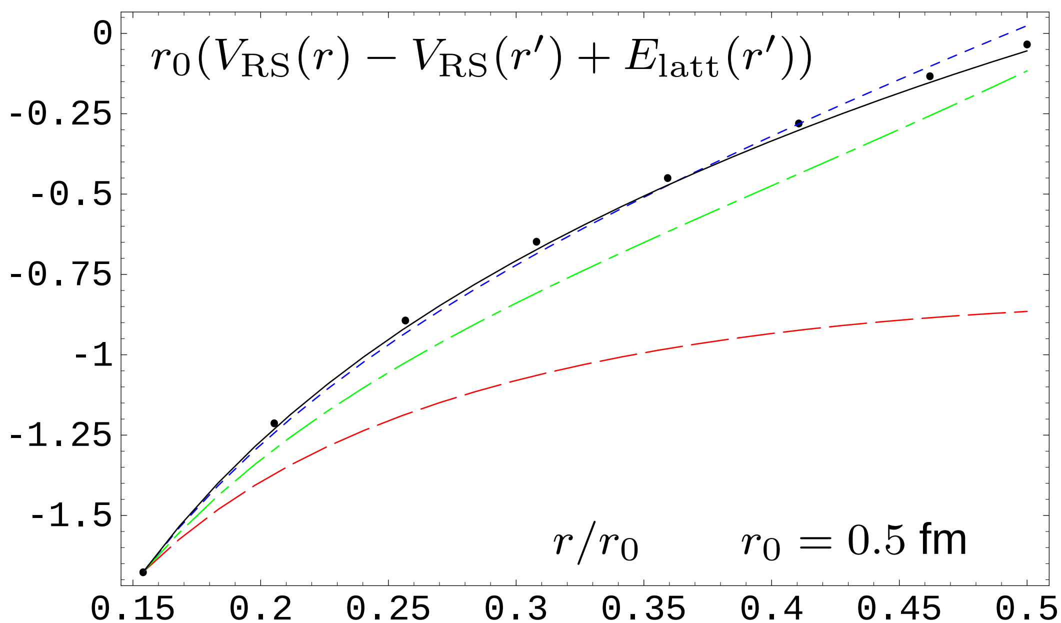
Potential

$V =$



$$= -\frac{4}{3}\frac{\alpha_s}{r}\left[1 + a_1\alpha_s(r) + a_2(\alpha_s(r))^2 + \frac{9}{4}\frac{\alpha_s^3}{\pi}\ln\mu r + \ldots\right]$$

Brambilla et al 99



NNLL + 3 loop est.

NNLO

NLO

LO

$\alpha_s = \alpha_s(1/r)$

$\nu_f = \nu_{us} = 2.5\, r_0^{-1}$

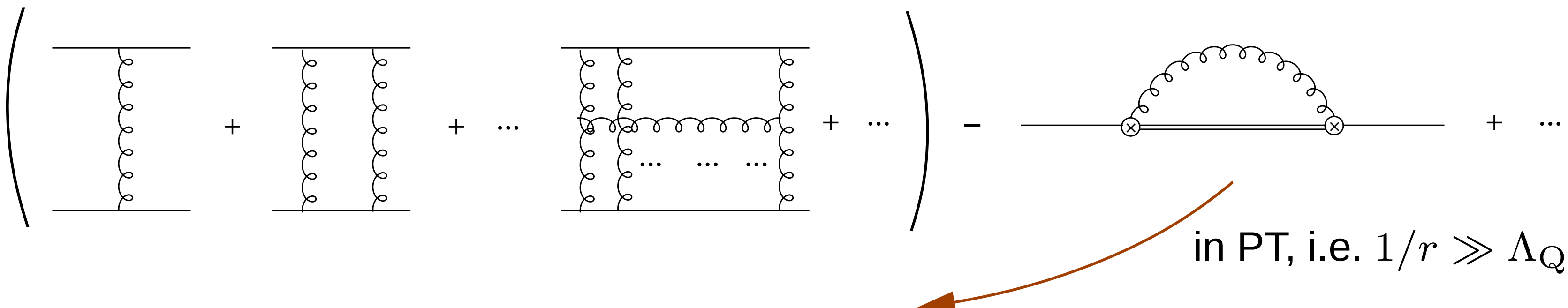
$r' = 0.15399\, r_0$

Necco Sommer 01, Pineda 02

Sumino 02, Lee 02 03

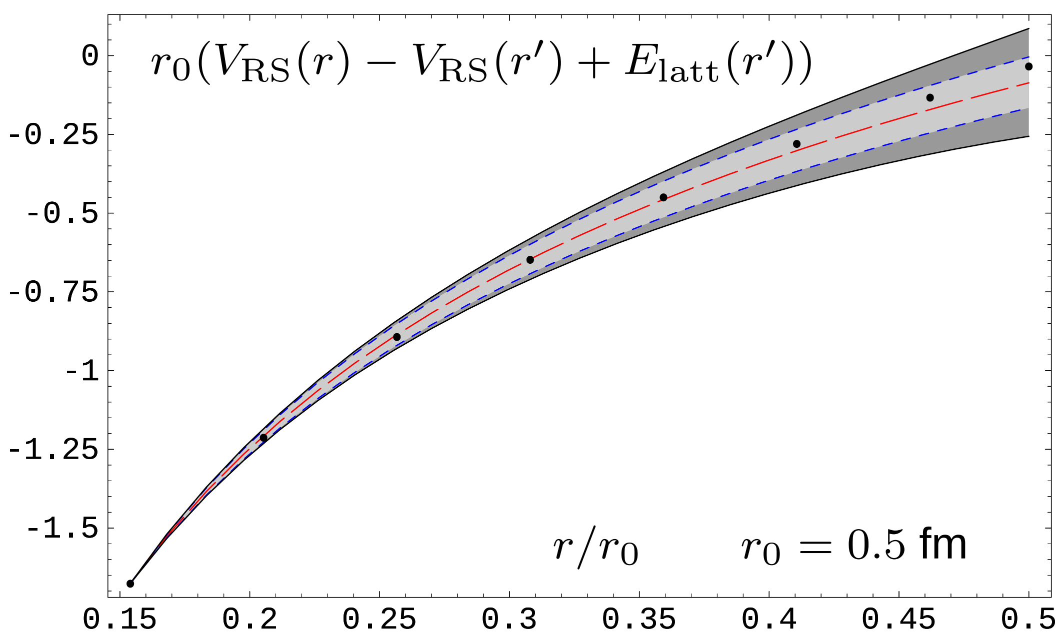
Potential

$V =$



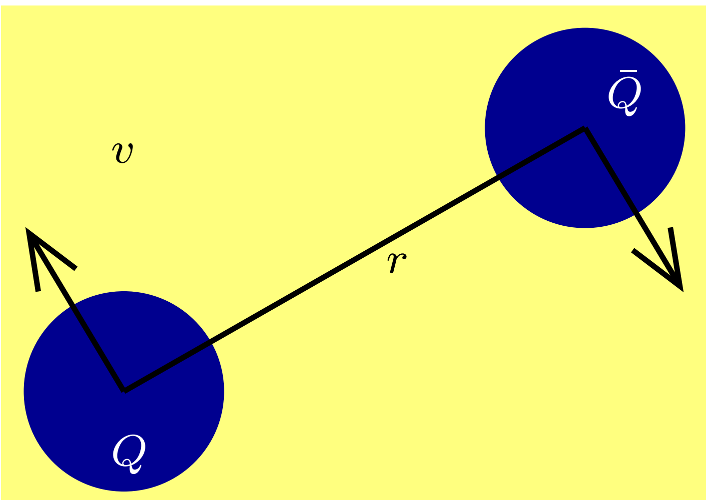
$$= -\frac{4}{3}\frac{\alpha_s}{r}\left[1 + a_1\alpha_s(r) + a_2(\alpha_s(r))^2 + \frac{9}{4}\frac{\alpha_s^3}{\pi}\ln\mu r + \ldots\right]$$

Brambilla et al 99



Necco Sommer 01, Pineda 02
Sumino 02, Lee 02 03

Low lying $Q\bar{Q}$



Low lying $Q\bar{Q}$ states are assumed to realize the hierarchy:

$m \gg 1/r \sim mv \gg \Lambda_{\mathrm{QCD}}$

At $mv \gg \mu \gg mv^2$ the degrees of freedom of pNRQCD are

- Q-$\bar{Q}$ (singlet and octet): $E \sim \Lambda_{\mathrm{QCD}}, mv^2$; $p \lesssim mv$
- Gluons: $E \sim p \sim \Lambda_{\mathrm{QCD}}, mv^2$

The quarkonium spectrum at $\mathcal{O}(m\alpha_{\mathrm{s}}^5)$ is

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

The bottleneck here are the nonperturbative effects (no control on them). But they are suppressed: precision calculations are possible

c and b masses

reference	order	$\overline{m}_b(\overline{m}_b)$ (GeV)
Beneke Signer 99	NNLO**	4.24 ± 0.09
Hoang 99	NNLO	4.21 ± 0.09
Pineda 01	NNNLO*	$4.210 \pm 0.090 \pm 0.025$
Brambilla et al 01	NNLO +charm	$4.190 \pm 0.020 \pm 0.025$
Eidemüller 02	NNLO	4.24 ± 0.10
Penin Steinhauser 02	NNNLO*	4.346 ± 0.070
Lee 03	NNNLO*	4.20 ± 0.04
Contreras et al 03	NNNLO*	4.241 ± 0.070
Pineda Signer 06	NNLL*	4.19 ± 0.06

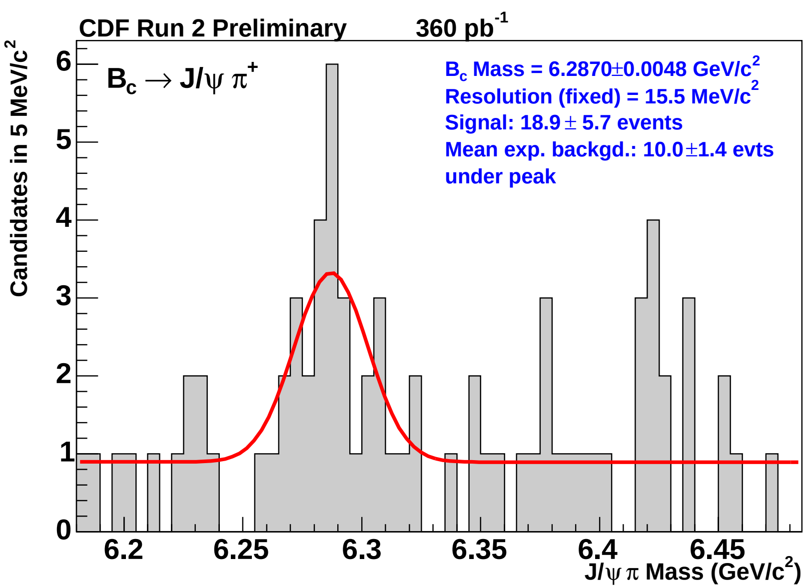
reference	order	$\overline{m}_c(\overline{m}_c)$ (GeV)
Brambilla et al 01	NNLO	1.24 ± 0.020
Eidemüller 02	NNLO	1.19 ± 0.11

B_c mass

State	expt	lattice04	BV00	BSV01	BSV02
		B_c mass (MeV)			
1^1S_0	$6400(400)$	6304(16)	6326(29)	6324(22)	6307(17)

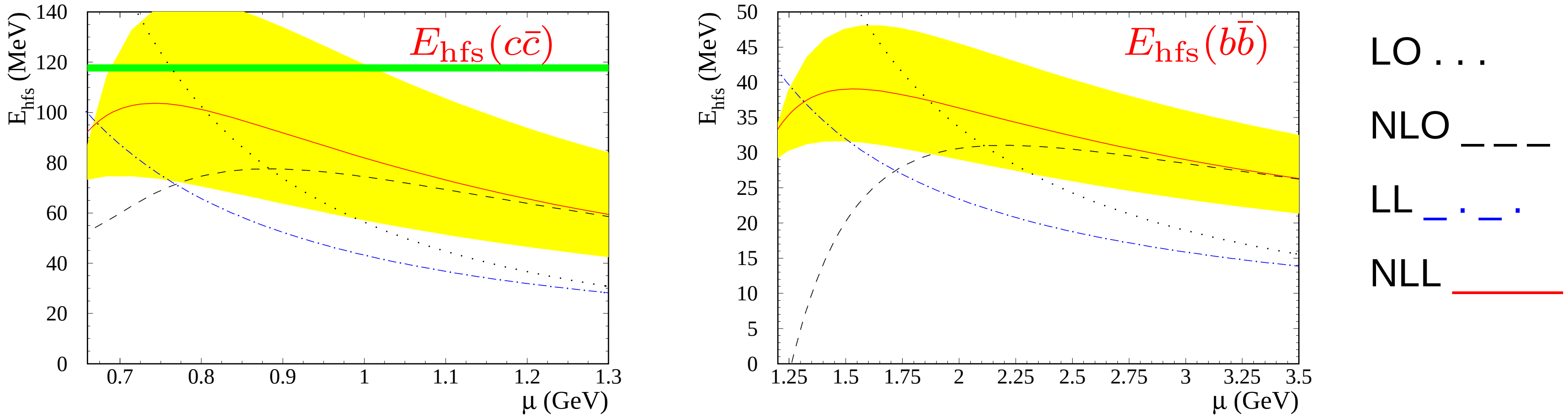
Brambilla et al 01 02, Brambilla Vairo 00, HPQCD-FNAL-UKQCD 04

In CDF 05 B_c is found in $B_c \to J/\psi\ \pi$.



$$M_{B_c} = 6287 \pm 4.8 \pm 1.1 \text{ MeV}$$

Hfs and the η_b mass



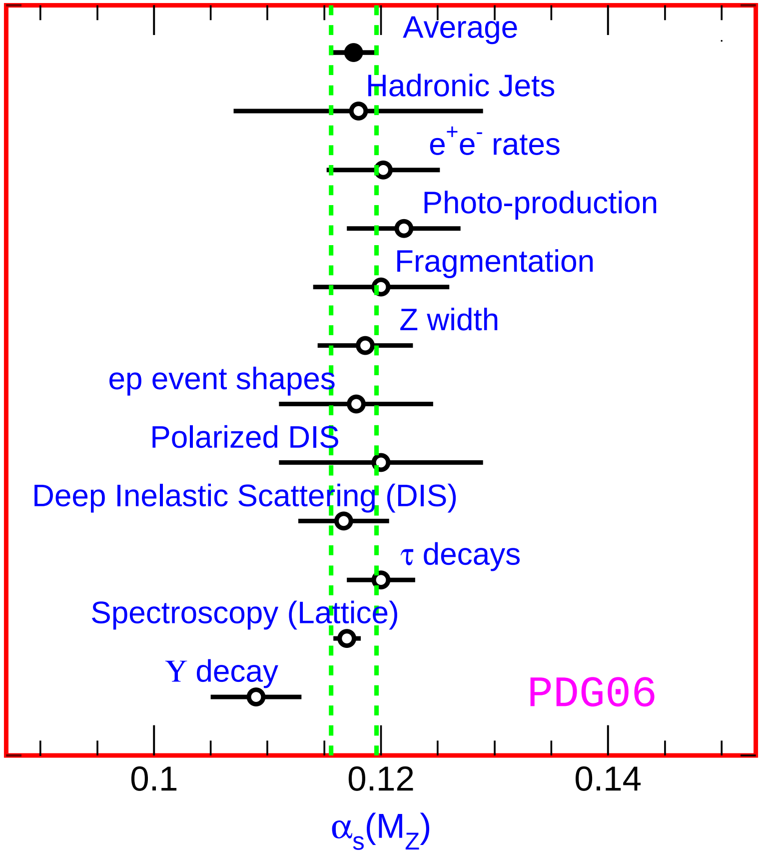
$M(\eta_b) = 9421 \pm 10\,(\text{th})\,^{+9}_{-8}\,(\delta\alpha_s)$ MeV Kniehl et al 03

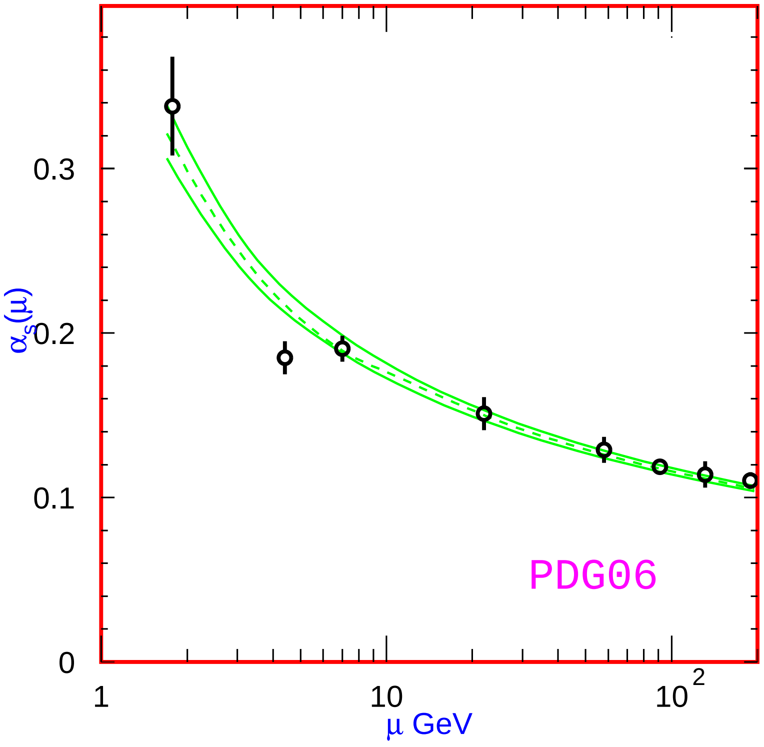
- A similar analysis in the B_c case gives:

$M(B_c^*) - M(B_c) = 65 \pm 24\,(\text{th})\,^{+19}_{-16}\,(\delta\alpha_s)$ MeV Penin et al 04

α_s from the Υ system

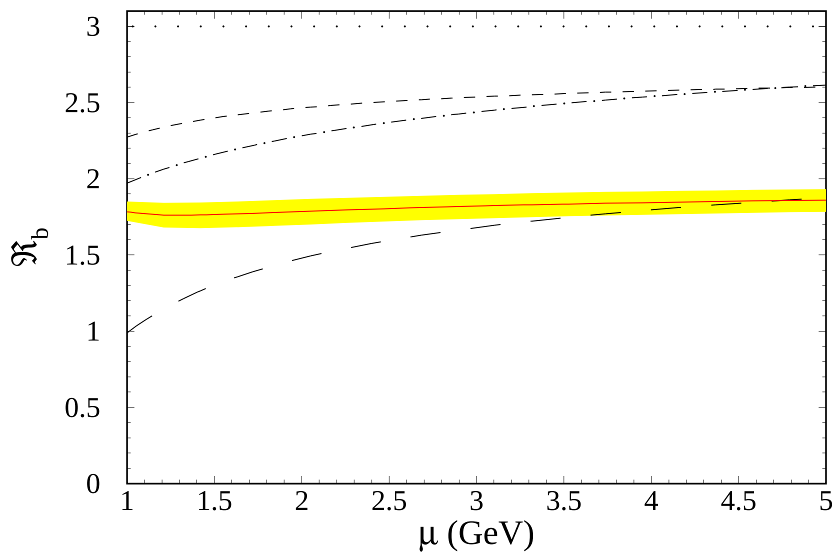
The discovery of the η_b *may provide new observables from which to extract* α_s *with an expected error* $\delta\alpha_s(M_Z) = \pm 0.003$*.*





Em decays of $\Upsilon(1S)$ and η_b

$$\mathcal{R}_b = \frac{\Gamma(\Upsilon(1S)\to e^+e^-)}{\Gamma(\eta_b\to\gamma\gamma)}$$



LO . . .

NLO _ _ _

NNLO __ __ __

NLL _ . _ .

NNLL ____

$$\Gamma(\eta_b(1S) \to \gamma\gamma) = 0.659 \pm 0.089(\text{th.})^{+0.019}_{-0.018}(\delta\alpha_s) \pm 0.015(\text{exp.})\ \text{keV}$$

Penin Pineda Smirnov Steinhauser 04

Pineda Signer 06

M1 Transitions

$\Gamma(J/\psi \to \eta_c \gamma) = (1.18 \pm 0.36)$ keV PDG 06

In potential models at leading order $\Gamma(J/\psi \to \eta_c \gamma) \sim 2.83\,\mathrm{KeV}$ this implies:

- large value of the charm mass
- large anomalous magnetic moment of the quark
- large relativistic corrections to the S-state wave functions

Eichten/QWG 02

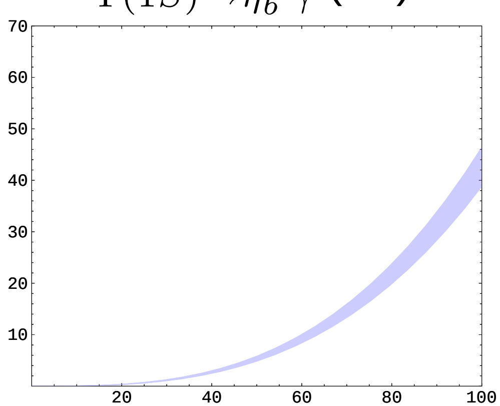
M1 Transitions: pNRQCD +US photons

- no nonperturbative effects at order v^2
- no large quarkonium anomalous magnetic moment
- exact relations at all order in α_s

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

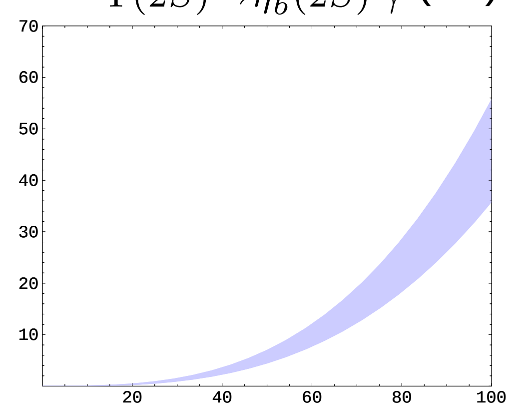
$\Gamma(J/\psi \to \eta_c\gamma) = (1.5 \pm 1.0)$ keV. Brambilla, Jia, Vairo05

$\Gamma_{\Upsilon(1S)\to\eta_b\,\gamma}$ (eV)



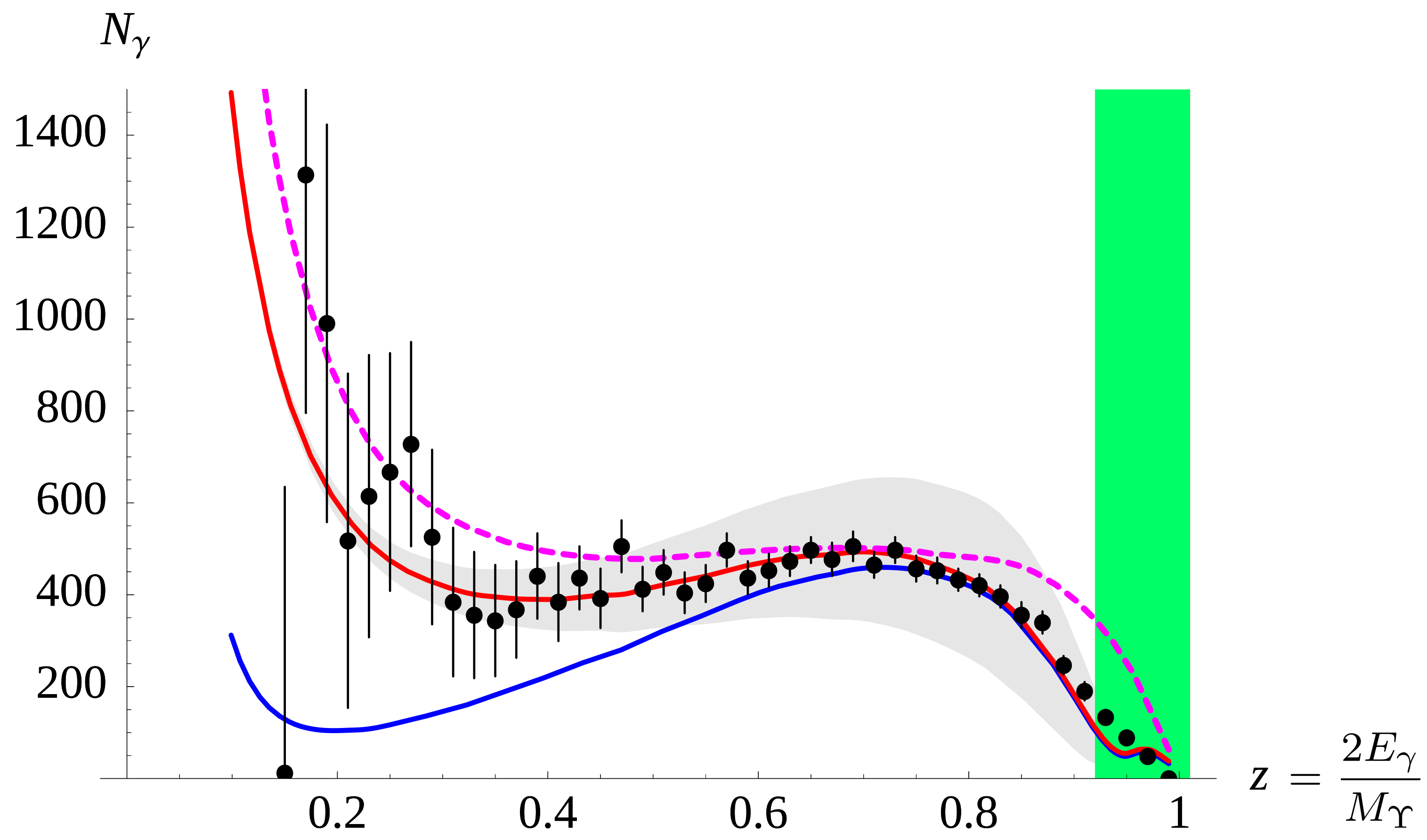
k_γ (MeV)

$\Gamma_{\Upsilon(2S)\to\eta_b(2S)\,\gamma}$ (eV)



k_γ (MeV)

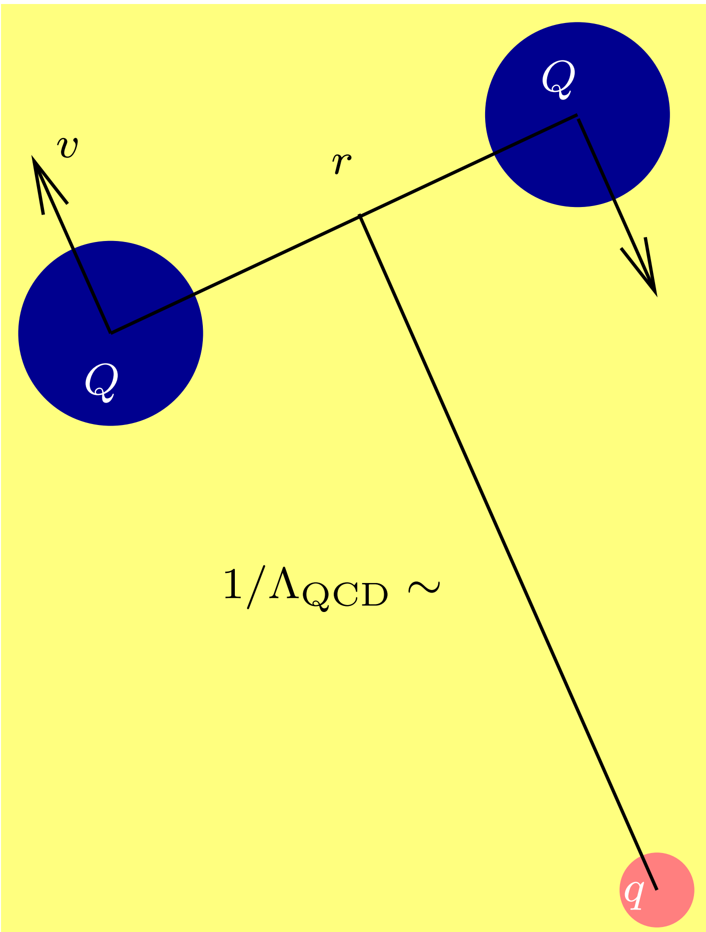
$$\Upsilon(1S) \to \gamma\, X$$



Photon spectrum at NLO (continuous lines, pNRQCD + SCET) vs CLEO data

Garcia Soto 04 05, Fleming Leibovich 03

Low lying QQq



Evidences of ccq states have been reported by SELEX 02 04 but not confirmed by FOCUS and BABAR (Kim @ ICHEP 06)

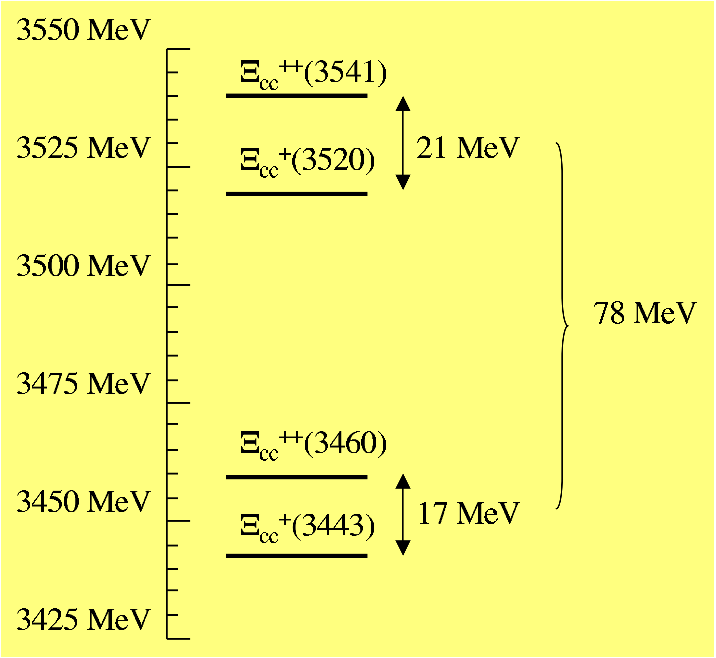
Low lying QQq states are assumed to realize the hierarchy:

$m \gg 1/r \sim mv \gg \Lambda_{\rm QCD}$

At $mv \gg \mu \gg mv^2$ the degrees of freedom of pNRQCD are:

- Q-Q (antitriplet and sextet): $E \sim \Lambda_{\rm QCD}, mv^2$; $p \lesssim mv$
- Gluons and light quarks: $E \sim p \sim \Lambda_{\rm QCD}, mv^2$

Low lying QQq



$$M_{\Xi^*_{cc}} - M_{\Xi_{cc}} = 120 \pm 40 \ \ \text{MeV}$$

$$M_{\Xi^*_{bb}} - M_{\Xi_{bb}} = 34 \pm 4 \ \ \text{MeV}$$

Savage Wise 90
Brambilla Rösch Vairo 05
Fleming Mehen 05

$$M_{\Xi^*_{cc}} - M_{\Xi_{cc}} = 89 \pm 15 \ \ \text{MeV}$$

Flynn Mescia Tariq 03 - quenched QCD

$$M_{\Xi^*_{cc}} - M_{\Xi_{cc}} = 80 \pm 10^{+3}_{-7} \ \ \text{MeV}$$

Lewis Mathur Woloshyn 01 - quenched QCD

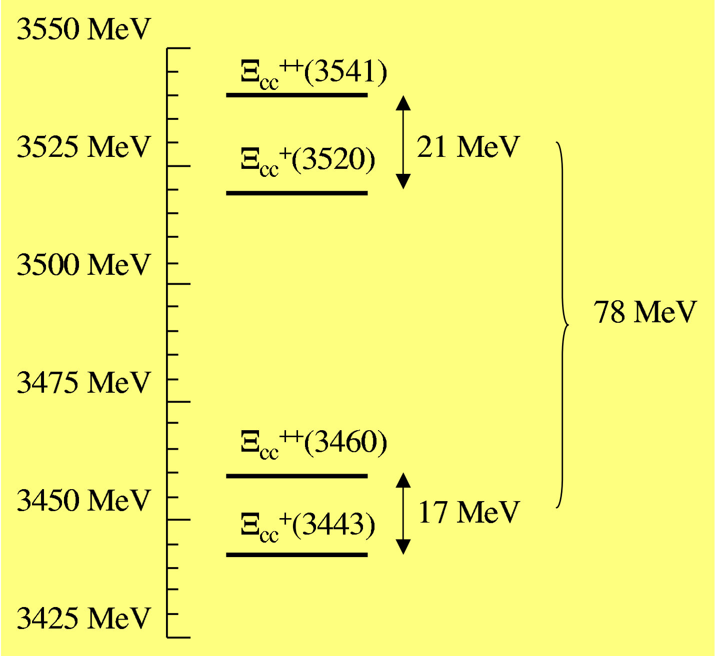
$$M_{\Xi^*_{bb}} - M_{\Xi_{bb}} = 20 \pm 6^{+2}_{-3} \ \ \text{MeV}$$

Ali Khan et al. 99 - quenched NRQCD

$$M_{\Xi^*_{bb}} - M_{\Xi_{bb}} = 20 \pm 6^{+3}_{-4} \ \ \text{MeV}$$

Mathur Lewis Woloshyn 02 - quenched NRQCD

Low lying QQq



Fit	β^{-1}(MeV)	m_c(MeV)	$\Gamma[\Xi_{cc}^{*++}]$ (keV)	$\Gamma[\Xi_{cc}^{*+}]$ (keV)
QM 1	379	1863	$3.3\left(\frac{E_\gamma}{80\,\mathrm{MeV}}\right)^3$	$2.6\left(\frac{E_\gamma}{80\,\mathrm{MeV}}\right)^3$
QM 2	356	1500	$3.4\left(\frac{E_\gamma}{80\,\mathrm{MeV}}\right)^3$	$3.2\left(\frac{E_\gamma}{80\,\mathrm{MeV}}\right)^3$
χPT 1	272	1432	$2.3\left(\frac{E_\gamma}{80\,\mathrm{MeV}}\right)^3$	$3.5\left(\frac{E_\gamma}{80\,\mathrm{MeV}}\right)^3$
χPT 2	276	1500	$2.3\left(\frac{E_\gamma}{80\,\mathrm{MeV}}\right)^3$	$3.3\left(\frac{E_\gamma}{80\,\mathrm{MeV}}\right)^3$

$\Gamma_{\Xi^*} \approx 3$ keV

- it is problematic for the interpretation of some of the resonances as higher states that no em decays are seen.

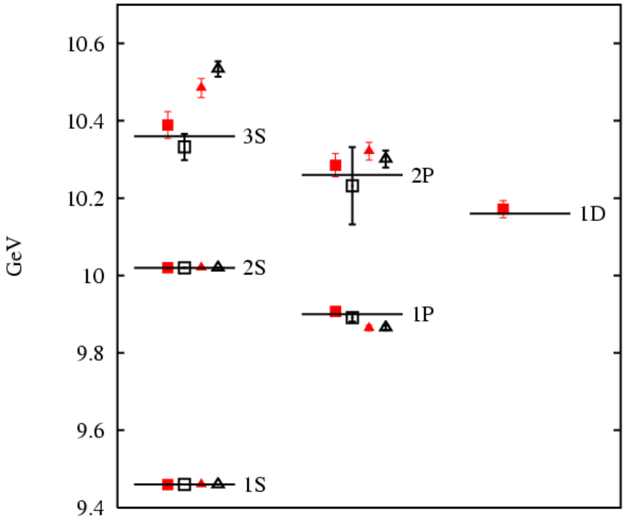
Hu Mehen 05

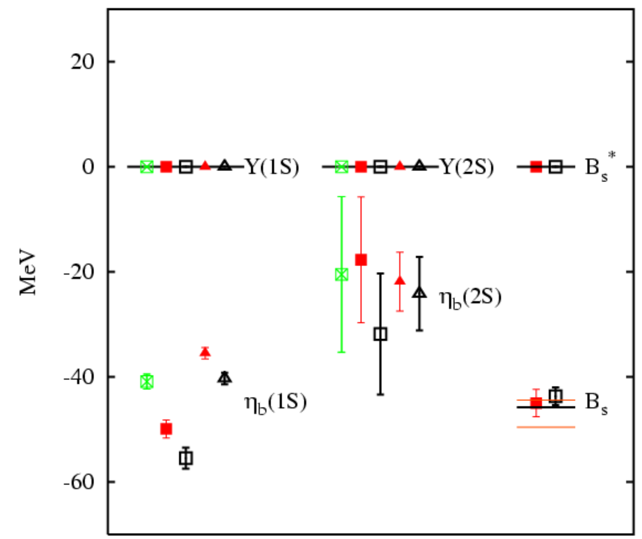
Higher resonances

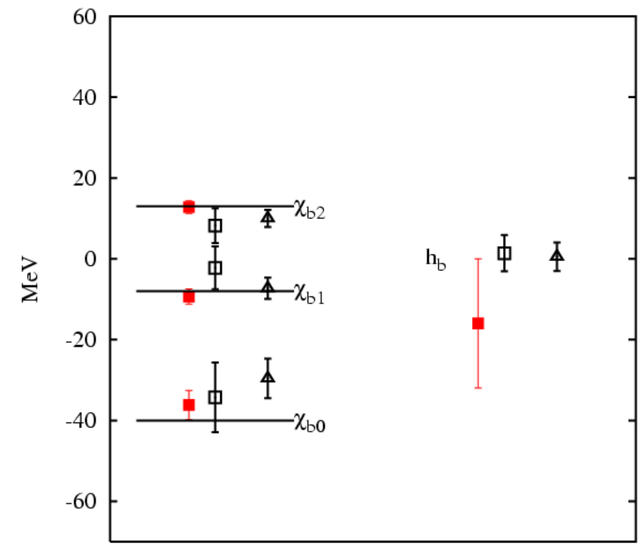
Higher $c\bar{c}$ resonances are better studied on the lattice.

- QCD ($ma \ll 1$)
- NRQCD (coarse lattices, $ma \gg 1$, no $a \longrightarrow 0$)
- pNRQCD (coarse lattices, no $a \longrightarrow 0$)

Bottomonium spectrum from lattice NRQCD







* Radial splittings up to

$\mathcal{O}(\alpha_s v^2) \simeq 0.2 \times 0.1 \simeq 2\%$

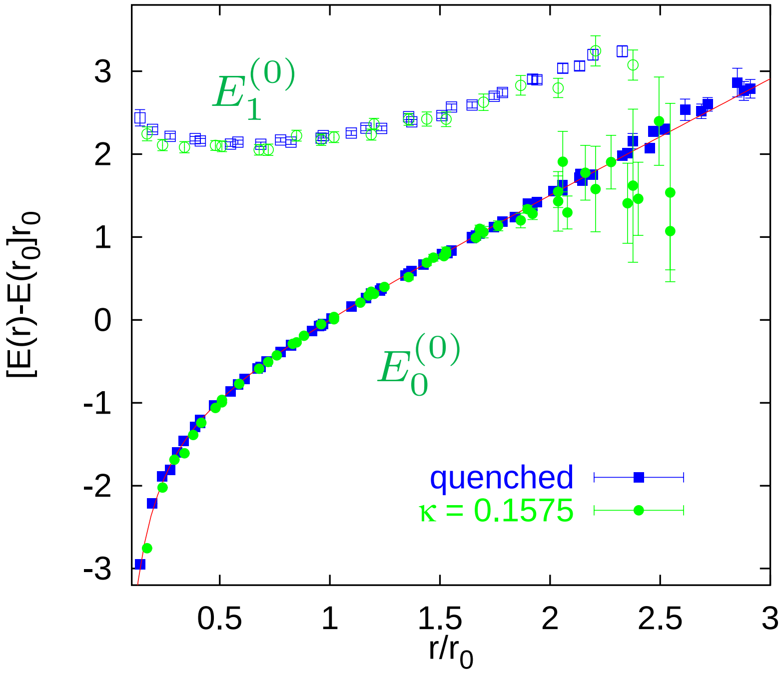
* Fine and hf splittings up to

$\mathcal{O}(\alpha_s) \simeq 0.2 \simeq 20\%$

HPQCD and UKQCD coll, Gray et al 05

pNRQCD for higher resonances

- All quarks with energy $\gg mv^2$ and momentum $\gg mv$ are integrated out.
- All gluonic excitations between heavy quarks are integrated out since they develop a gap of order $\Lambda_{\rm QCD}$ with the static $Q\bar{Q}$ energy.



Bali et al. 98

($r_0 \simeq 0.5$ fm)

$\Rightarrow$ The singlet quarkonium field S of energy mv^2 and momentum mv is the only the degree of freedom of pNRQCD (up to ultrasoft light quarks, e.g. pions).

pNRQCD for higher resonances

- All quarks with energy $\gg mv^2$ and momentum $\gg mv$ are integrated out.
- All gluonic excitations between heavy quarks are integrated out since they develop a gap of order $\Lambda_{\rm QCD}$ with the static $Q\bar{Q}$ energy.

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

pNRQCD for higher resonances

- All quarks with energy $\gg mv^2$ and momentum $\gg mv$ are integrated out.
- All gluonic excitations between heavy quarks are integrated out since they develop a gap of order Λ_{QCD} with the static $Q\bar{Q}$ energy.

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

- a “Potential model description” emerge from the EFT.

pNRQCD for higher resonances

- All quarks with energy $\gg mv^2$ and momentum $\gg mv$ are integrated out.
- All gluonic excitations between heavy quarks are integrated out since they develop a gap of order $\Lambda_{\rm QCD}$ with the static $Q\bar{Q}$ energy.

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

- a “Potential model description” emerge from the EFT.
- The potential $V = \mathrm{Re}\, V + i\, \mathrm{Im}\, V$ is a mixture of perturbative and non-perturbative contributions to be determined by the matching. It encodes all the information from $Q\bar{q}$-$\bar{Q}q$ pairs that develop a mass gap of order $\Lambda_{\rm QCD}$, non-Goldstone-like mesons, gluonic excitations between heavy quarks. $\mathrm{Im}\, V$ encodes the Q-$\bar{Q}$ annihilation.

pNRQCD for higher resonances

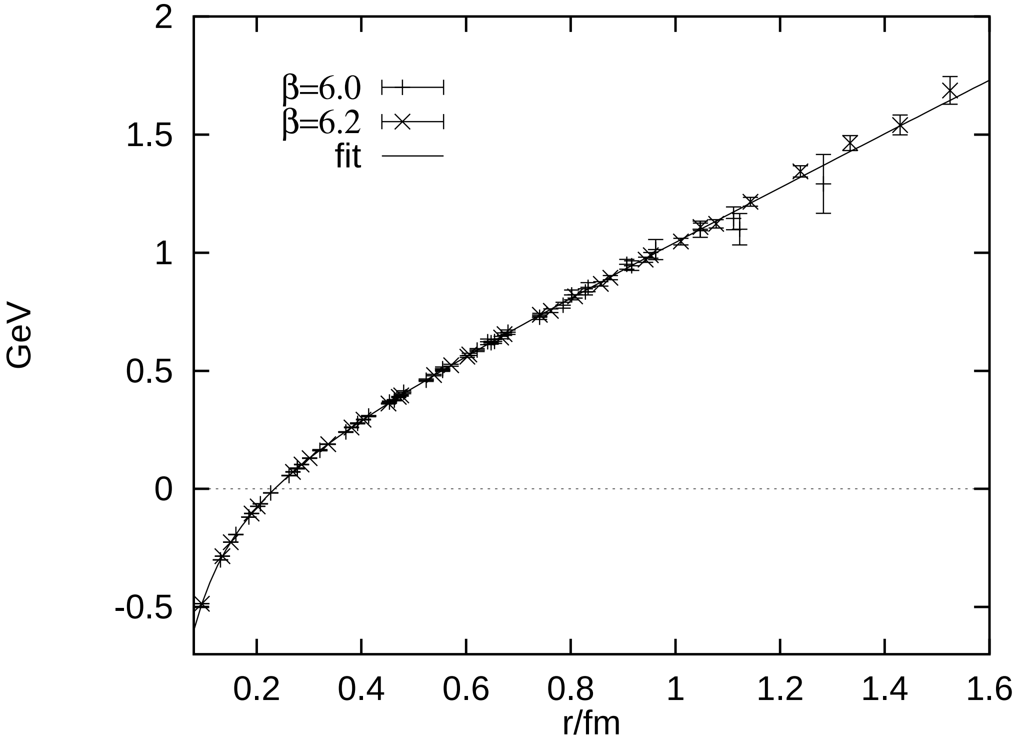
- All quarks with energy $\gg mv^2$ and momentum $\gg mv$ are integrated out.
- All gluonic excitations between heavy quarks are integrated out since they develop a gap of order $\Lambda_{\rm QCD}$ with the static $Q\bar{Q}$ energy.

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

- a "Potential model description" emerge from the EFT.
- The potential $V = \mathrm{Re}\, V + i\, \mathrm{Im}\, V$ is a mixture of perturbative and non-perturbative contributions to be determined by the matching. It encodes all the information from $Q\bar{q}$-$\bar{Q}q$ pairs that develop a mass gap of order $\Lambda_{\rm QCD}$, non-Goldstone-like mesons, gluonic excitations between heavy quarks. $\mathrm{Im}\, V$ encodes the Q-$\bar{Q}$ annihilation.
- The idea is to calculate once for ever the potentials on the lattice and determine the spectrum by solving the Schrödinger equation.

Static potential

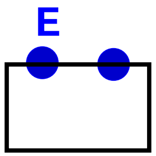
$$V_s^{(0)} = \lim_{T\to\infty} \frac{i}{T} \ln\langle W(r\times T)\rangle = \lim_{T\to\infty} \frac{i}{T} \ln \langle \square \rangle$$



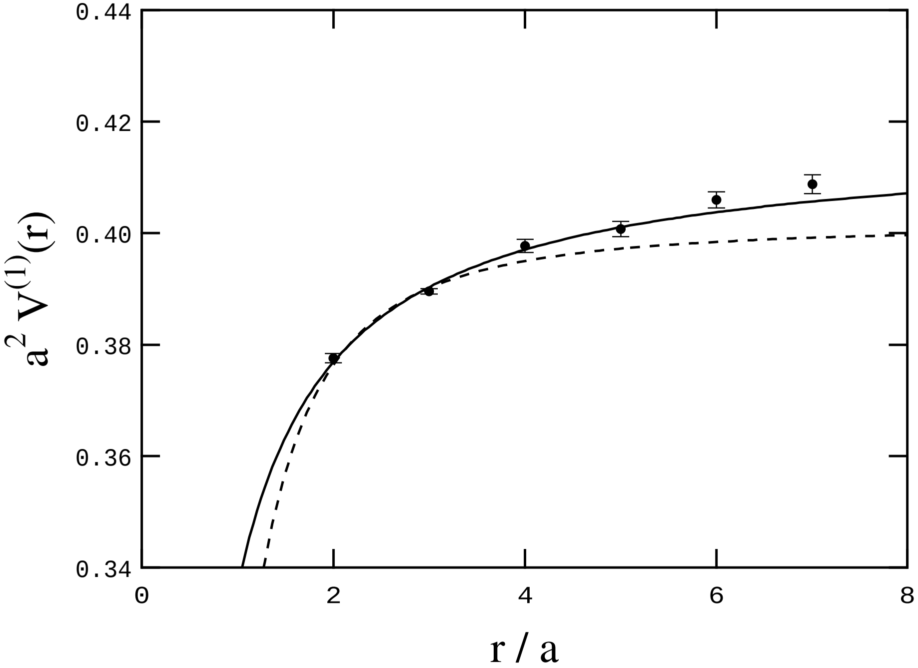
Bali Schilling Wachter 97

$1/m$ potential

$$V_s^{(1)} = -\frac{1}{2}\int_0^\infty dt\, t \left\langle \quad \right\rangle$$



Brambilla Pineda Soto Vairo 00



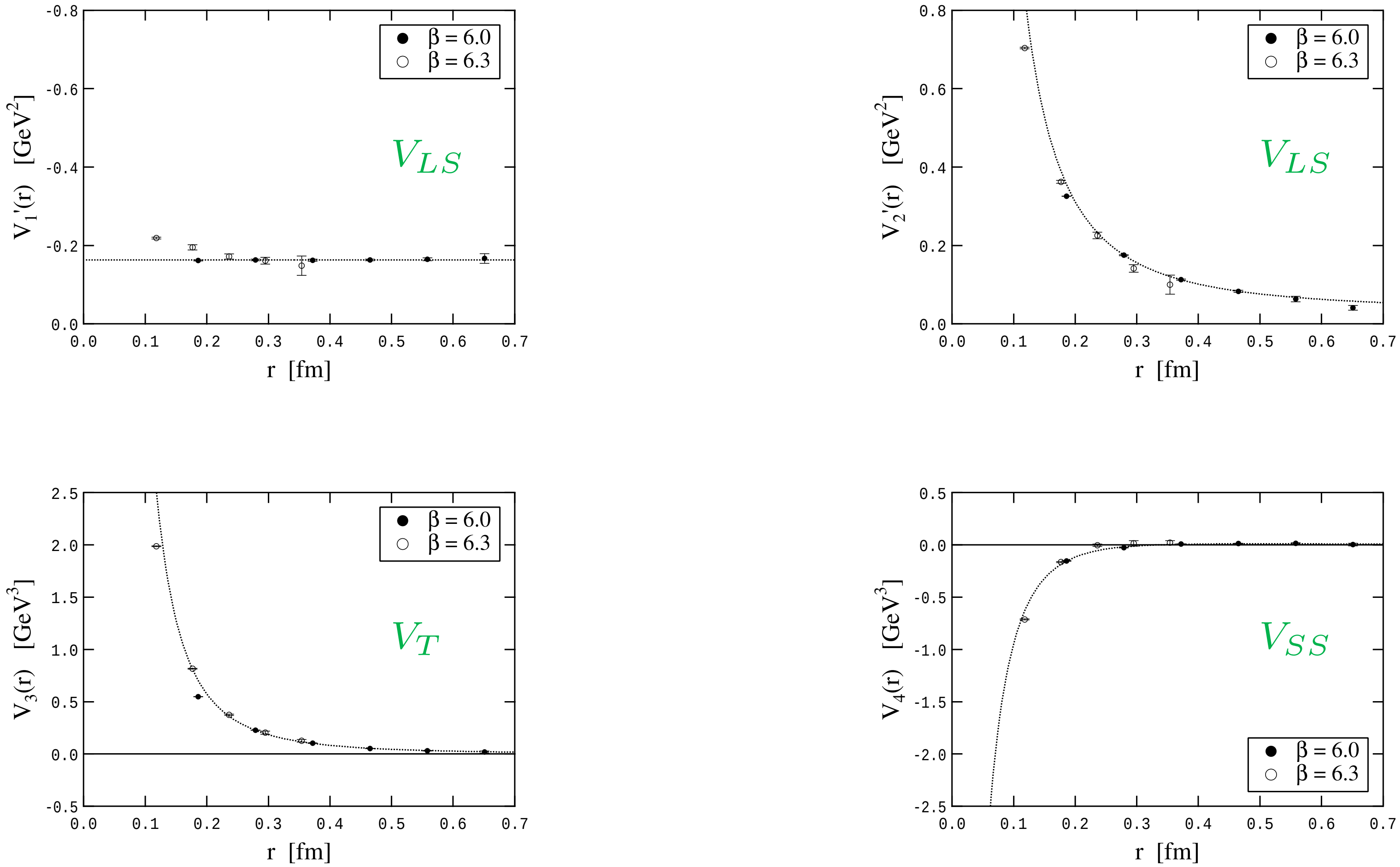
$$V^{(1)} = -\frac{c}{r} + d$$

$\frac{2c}{m_c}\frac{1}{r} \approx \frac{1}{r}$ part of the static potential

$\frac{2c}{m_b}\frac{1}{r} \approx$ 26% of the $\frac{1}{r}$ part of the static potential

Koma Koma Wittig 06

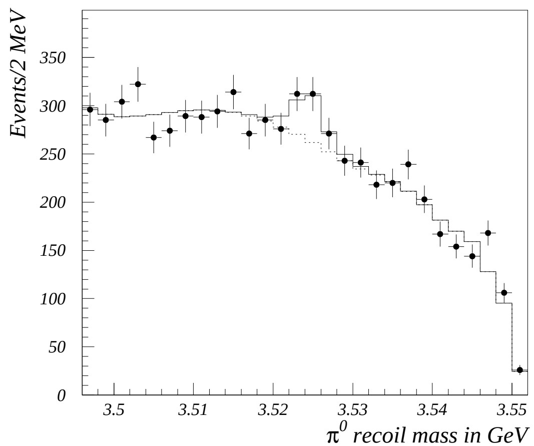
Spin-dependent potentials



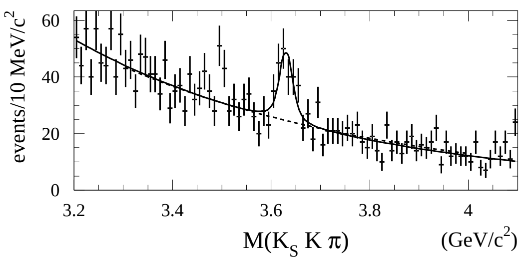
Koma Koma Wittig 05, Koma Koma 06

Terrific advance in the data precision with Lüscher multivel algorithm!

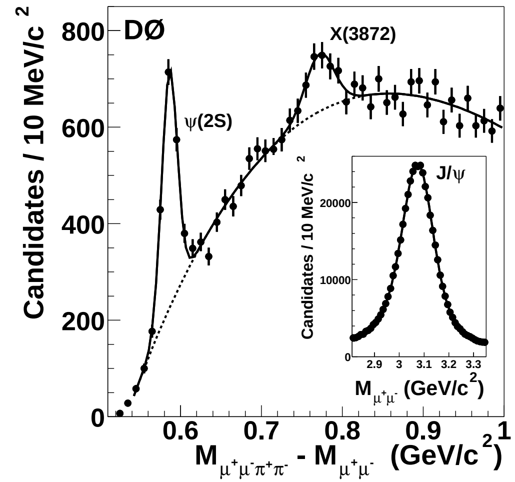
The emergence of a potential picture for $Q\bar{Q}$ bound states in the non-perturbative regime ($mv \sim \Lambda_{\rm QCD}$) guides the identification of several of the recently detected quarkonium resonances.



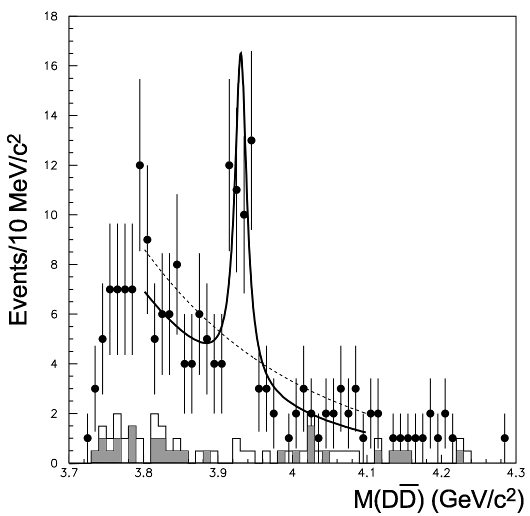
$h_c(3523)$ CLEO 05
E835 05



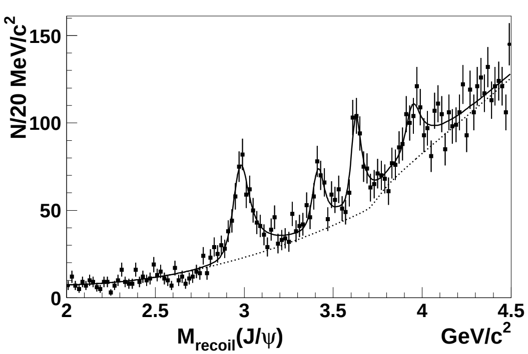
$\eta_c(2S)(3630)$ BaBar 04
CLEO 04
Belle 02



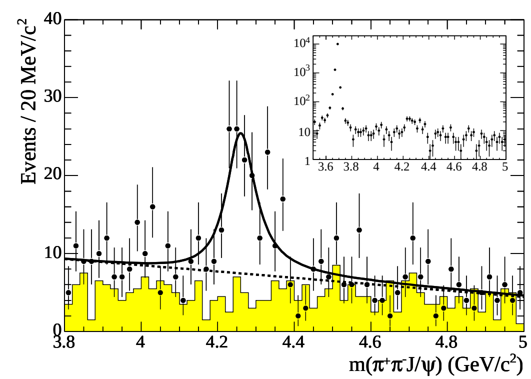
X(3872) CDF D0/QWG 04
Belle 02
BaBar 05



Z(3930) Belle 05



X(3940) Belle 05



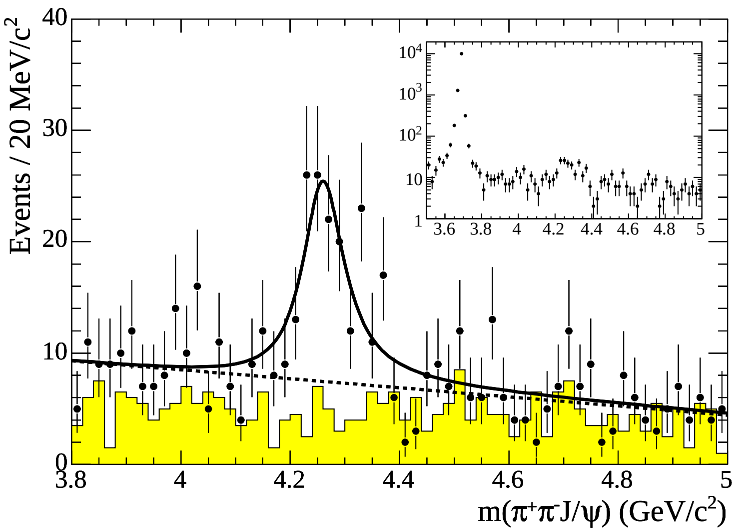
Y(4260) BaBar 05

Exotic states

Near or above the open flavour threshold exotic states are expected to appear in the spectrum: hybrids, molecular states, tetraquarks, ...

- In general, for states near or above threshold a systematic treatment does not exist so far. Also lattice calculations are inadequate. Most of the existing analyses rely on models (e.g. the Cornell coupled channel model).
- even for hybrids due to the large mass of the quarks, factorization and analytic approaches may be useful
- In some cases one may develop an EFT owing to special dynamical conditions.
  - An example is the $X(3872)$ intepreted as a $D^0\,\bar{D}^{*\,0}$ or $\bar{D}^0\,D^{*\,0}$ molecule. In this case, one may take advantage of the unnaturally (and accidentally) large $D^0\,\bar{D}^{*\,0}$ scattering length. Braaten Kusunoki 03

$Y(4260)$



in $e^+e^- \to \gamma\pi^+\pi^- J/\psi$

$M = 4259 \pm 8^{+2}_{-6}$ MeV

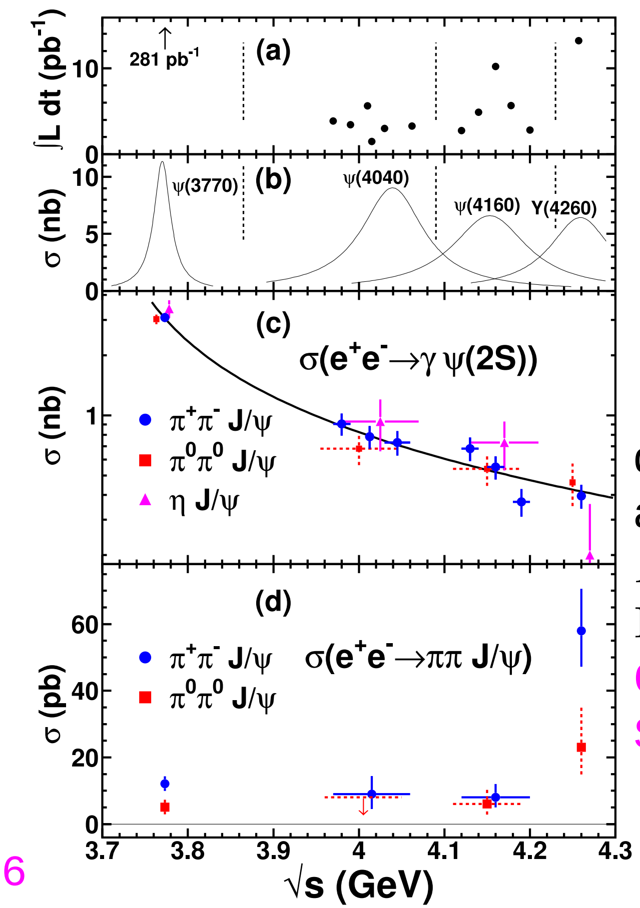
$\Gamma = 88 \pm 23^{+6}_{-4}$ MeV

BABAR 05, Lou @ ICHEP 06

Also in BELLE 06, Majumder @ ICHEP 06

$M = 4295 \pm 10^{+11}_{-5}$ MeV

$\Gamma = 133 \pm 26^{+13}_{-6}$ MeV



direct $e^+e^- \to Y$

at $\sqrt{s} = 4260$ MeV

$M = 4283^{+17}_{-16} \pm 4$ MeV

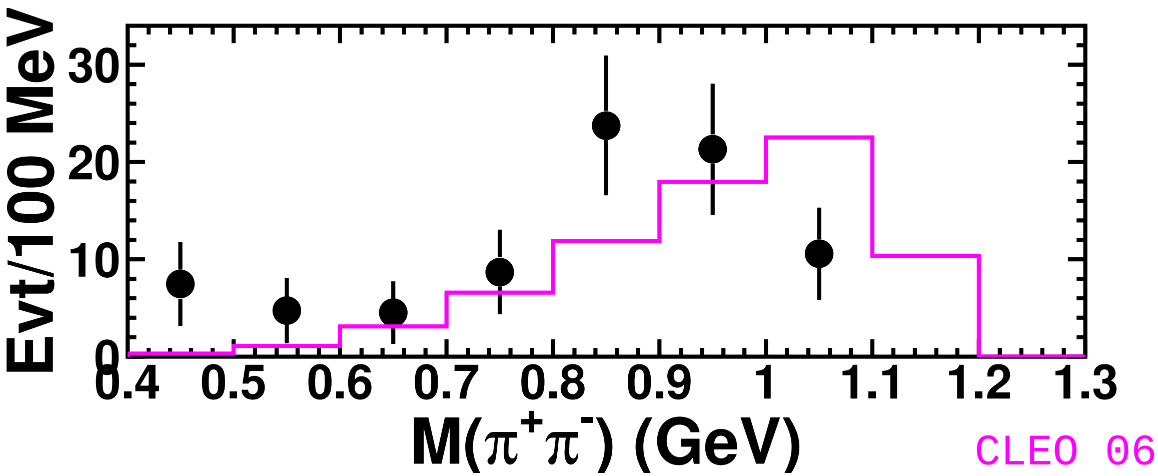
$\Gamma = 70^{+40}_{-25} \pm 5$ MeV

CLEO 06

Shipsey @ ICHEP 06

$Y(4260)$: summary of properties

- $J^{PC} = 1^{--}$
- No suggestion of $f_0(980)$ and $f_0(600)$ in the $\pi^+\pi^-$ spectrum:



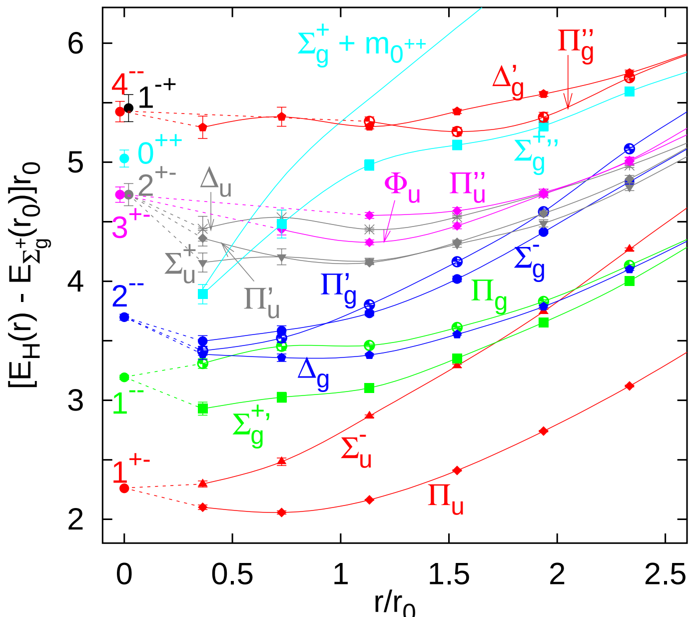
- $\frac{\mathcal{B}(Y \to D\bar{D})}{\mathcal{B}(Y \to J/\psi\pi^+\pi^-)} < 7.6$ (∼ 500 for $\psi(3770)$) BABAR 06

  while BELLE sees a strong drop and local minimum of the $D^{+\,*}D^{-\,(*)}$ invariant mass at 4260 MeV in $e^+e^- \to \gamma D^{+\,*}D^{-\,(*)}$ Majumder @ ICHEP 06.

$Y(4260)$: interpretations

- $Y \sim \psi(4S)$ Llanes-Estrada 05;
- $Y \sim \Lambda_c \bar{\Lambda}_c$ baryonium Qiao 05;
- $Y \sim [(cs)^{\bar{3}}_{S=0} \otimes (\bar{c}\bar{s})^{3}_{S=0}]_{\mathrm{P-wave}}$ with predominant decay into $D_s \bar{D}_s$ Maiani et al 05; a $[(cq)^{\bar{3}}_{S=0} \otimes (\bar{c}\bar{q})^{3}_{S=0}]_{\mathrm{P-wave}}$ based tetraquark interpretation has been proposed by Zhu 05, Ebert et al 06;
- $Y \sim \chi_{c1}\rho$ molecular state Liu et al 05;
- $Y \sim c\bar{c}$ hybrid Zhu 05, Kou Pene 05, Close Page 05.

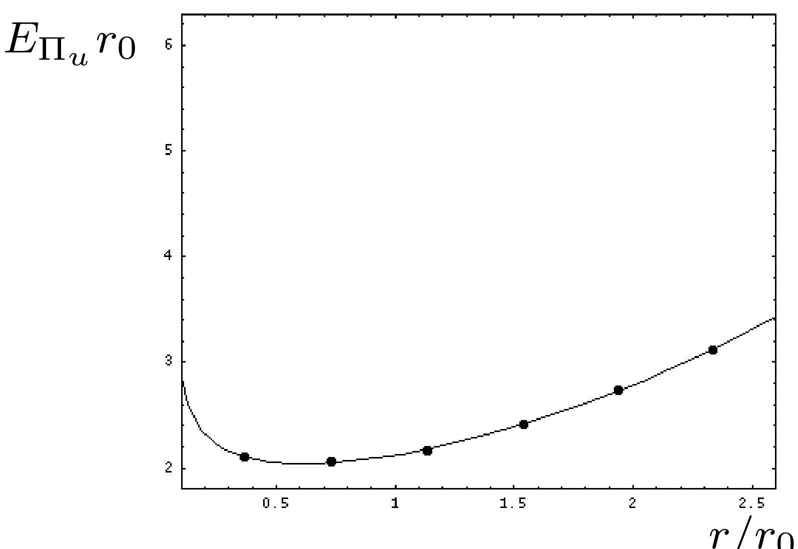
$Y(4260)$ as a $c\bar{c}$ hybrid



Juge Kuti Morningstar 00, 03

J^{PC}	H	$\Lambda_H^{RS} r_0$	Λ_H^{RS}/GeV
1^{+-}	B_i	2.25(39)	0.87(15)
1^{--}	E_i	3.18(41)	1.25(16)
2^{--}	$D_{\{i}B_{j\}}$	3.69(42)	1.45(17)
2^{+-}	$D_{\{i}E_{j\}}$	4.72(48)	1.86(19)
3^{+-}	$D_{\{i}D_jB_{k\}}$	4.72(45)	1.86(18)
0^{++}	$\mathbf{B}^2$	5.02(46)	1.98(18)
4^{--}	$D_{\{i}D_jD_kB_{l\}}$	5.41(46)	2.13(18)
1^{-+}	$(\mathbf{B} \wedge \mathbf{E})_i$	5.45(51)	2.15(20)

Foster Michael 99, Bali Pineda 03



Fitting the Π_u curve, $E_{\Pi_u} = (0.87 + 0.11/r + 0.24\, r^2)$ GeV and solving the Schrödinger equation, one gets

$$M(Y) = 2 \times 1.48 + 0.87 + 0.53 = 4.36 \quad \text{GeV}$$

For most of the new states we need:

- more data to confirm the signal, to establish the quantum numbers, to find the most relevant decay channels, ...;
- to develop and EFT for states close to the open flavour threshold.

Inclusive decays

NRQCD factorization

$$\Gamma(H \to l.h.) = \sum_n \frac{2\,\mathrm{Im}\, f^{(n)}}{m^{d_n-4}} \langle H | O_{4-\mathrm{fermion}} | H \rangle$$ Bodwin et al 95

Ratio	QWG 05	PDG 00	LO	NLO
$\frac{\Gamma(\chi_{c0} \to \gamma\gamma)}{\Gamma(\chi_{c2} \to \gamma\gamma)}$	5.1±1.1	13±10	3.75	$\approx$ 5.43
$\frac{\Gamma(\chi_{c2} \to l.h.) - \Gamma(\chi_{c1} \to l.h.)}{\Gamma(\chi_{c0} \to \gamma\gamma)}$	410±100	270±200	$\approx$ 347	$\approx$ 383
$\frac{\Gamma(\chi_{c0} \to l.h.) - \Gamma(\chi_{c1} \to l.h.)}{\Gamma(\chi_{c0} \to \gamma\gamma)}$	3600±700	3500±2500	$\approx$ 1300	$\approx$ 2781
$\frac{\Gamma(\chi_{c0} \to l.h.) - \Gamma(\chi_{c2} \to l.h.)}{\Gamma(\chi_{c2} \to l.h.) - \Gamma(\chi_{c1} \to l.h.)}$	7.9±1.5	12.1±3.2	2.75	$\approx$ 6.63
$\frac{\Gamma(\chi_{c0} \to l.h.) - \Gamma(\chi_{c1} \to l.h.)}{\Gamma(\chi_{c2} \to l.h.) - \Gamma(\chi_{c1} \to l.h.)}$	8.9±1.1	13.1±3.3	3.75	$\approx$ 7.63

$m_c = 1.5$ GeV $\quad \alpha_s(2m_c) = 0.245$

mainly from E835 (χ_{c0}, total width and $\gamma\gamma$)

also from BELLE ($\chi_{c0} \to \gamma\gamma$) and CLEO, BES

QWG report CERN-2005-005

NRQCD matrix elements

- By fitting charmonium P-wave decay data

$\langle O_1(^1P_1)\rangle_{h_c(1P)} \approx 8.1 \times 10^{-2}$ GeV^5 and $\langle O_8(^1S_0)\rangle_{h_c(1P)} \approx 5.3 \times 10^{-3}$ GeV^3
in $\overline{\rm MS}$ and at the factorization scale of 1.5 GeV.

Maltoni 00

- In quenched lattice simulations

$\langle O_1(^1P_1)\rangle_{h_c(1P)} \approx 8.0 \times 10^{-2}$ GeV^5 , $\langle O_8(^1S_0)\rangle_{h_c(1P)} \approx 4.7 \times 10^{-3}$ GeV^3 and
$\langle O_1(^1S_0)\rangle_{\eta_c(1S)} \approx 0.33$ GeV^3
in $\overline{\rm MS}$ and at the factorization scale of 1.3 GeV.

Bodwin Sinclair Kim 96

- In lattice simulations with three light-quark flavors (extrapolation)

$\langle O_1(^1S_0)\rangle_{\eta_b(1S)} \approx 4.1$ GeV^3, $\langle O_1(^1P_1)\rangle_{h_b(1P)} \approx 3.3$ GeV^5 and
$\langle O_8(^1S_0)\rangle_{h_b(1P)} \approx 5.9 \times 10^{-3}$ GeV^3
in $\overline{\rm MS}$ and at the factorization scale of 4.3 GeV.

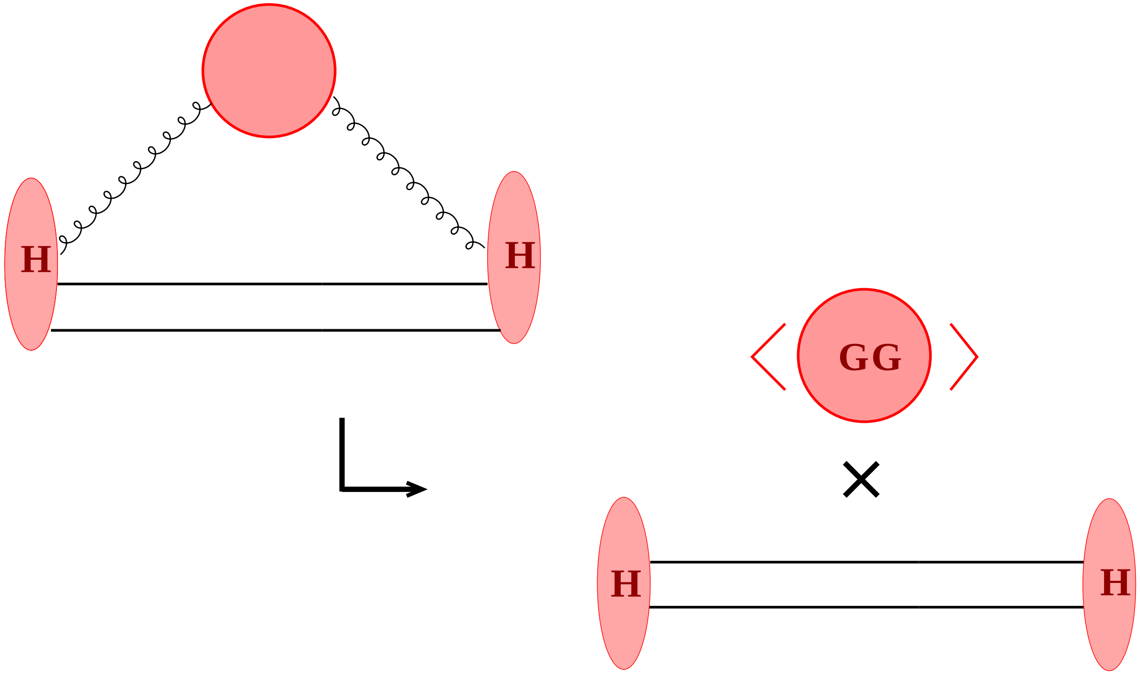
Bodwin Sinclair Kim 01

Some further recent (quenched) determinations are in Bodwin Lee Sinclair 05

pNRQCD factorization

A way to reduce the number of nonperturbative parameters is provided by pNRQCD:

$$\langle H|\psi^\dagger K^{(n)}\chi\chi^\dagger K'^{(n)}\psi|H\rangle = |R(0)|^2 \times \int dt\, t^n \,\langle G(t)G(0)\rangle$$



Brambilla Eiras Pineda Soto Vairo 02 03

P-wave decays at $\mathcal{O}(mv^5)$

- NRQCD

$$\Gamma(\chi_J \to \mathrm{LH}) = 9\,\mathrm{Im}\,f_1\,\frac{\left|R'(0)\right|^2}{\pi m^4} + \frac{2\,\mathrm{Im}\,f_8}{m^2}\,\langle\chi|O_8(^1S_0)|\chi\rangle$$

$$\Gamma(\chi_J \to \gamma\gamma) = 9\,\mathrm{Im}\,f_{\gamma\gamma}\,\frac{\left|R'(0)\right|^2}{\pi m^4} \qquad J = 0, 2$$

* *Bottomonium and charmonium P-wave decays depend on 6 non-perturbative parameters.*

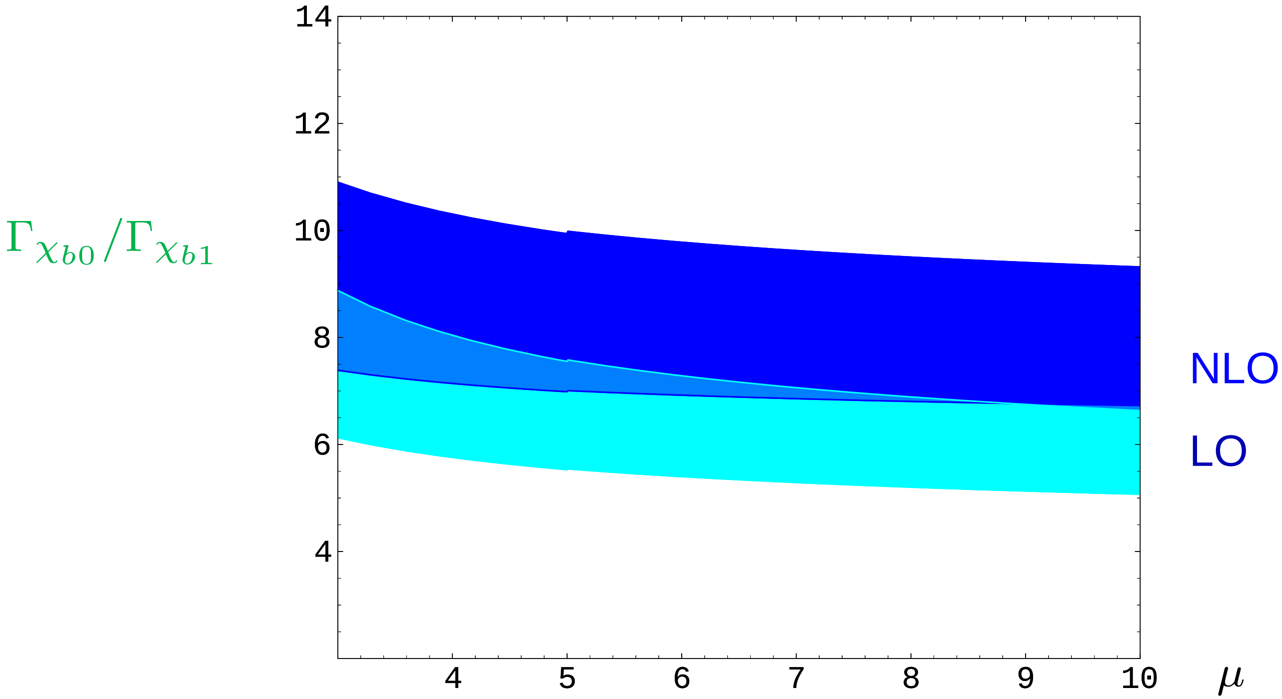
- pNRQCD

$$\langle\chi|O_8(^1S_0)|\chi\rangle = \frac{\left|R'(0)\right|^2}{18\pi m^2}\,\mathcal{E}; \quad \mathcal{E} \equiv \int_0^\infty dt\, t^3\, \langle \mathrm{Tr}(g\mathbf{E}(t)\, g\mathbf{E}(0))\rangle$$

* *The quarkonium state dependence factorizes.*

* *Bottomonium and charmonium P-wave decays depend on 4 non-perturbative parameters.*

Bottomonium P-wave decays



$$\frac{\Gamma(\chi_{b0}(1P) \to \mathrm{LH})}{\Gamma(\chi_{b1}(1P) \to \mathrm{LH})} = \frac{\Gamma(\chi_{b0}(2P) \to \mathrm{LH})}{\Gamma(\chi_{b1}(2P) \to \mathrm{LH})} = 8.0 \pm 1.3$$

(CleoIII 02) $= 19.3 \pm 9.8$

Brambilla Eiras Pineda Soto Vairo 01, Vairo 02, CLEO/QWG 04

$\Gamma(\eta_c \to LH)/\Gamma(\eta_c \to \gamma\,\gamma)$

- Large $\beta_0 \alpha_{\rm s}$ contributions.

$$\frac{\Gamma(\eta_c \to LH)}{\Gamma(\eta_c \to \gamma\,\gamma)} \approx (1.1 \text{ (LO)} + 1.0 \text{ (NLO)}) \times 10^3 = 2.1 \times 10^3$$

$$\frac{\Gamma(\eta_c \to LH)}{\Gamma(\eta_c \to \gamma\,\gamma)} = (3.3 \pm 1.3) \times 10^3 \text{ (EXP)}$$

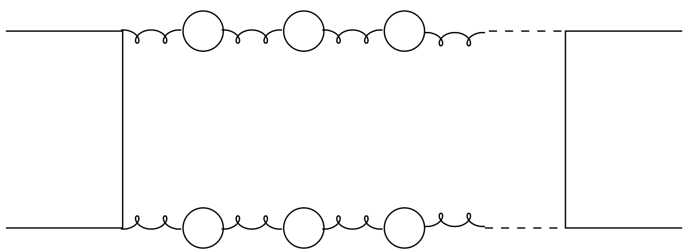
$\Gamma(\eta_c \to LH)/\Gamma(\eta_c \to \gamma\,\gamma)$

- Large $\beta_0 \alpha_{\rm s}$ contributions.

$$\frac{\Gamma(\eta_c \to LH)}{\Gamma(\eta_c \to \gamma\,\gamma)} \approx (1.1\ \text{(LO)} + 1.0\ \text{(NLO)}) \times 10^3 = 2.1 \times 10^3$$

$$\frac{\Gamma(\eta_c \to LH)}{\Gamma(\eta_c \to \gamma\,\gamma)} = (3.3 \pm 1.3) \times 10^3\ \text{(EXP)}$$

- scheme dependence
- renormalons



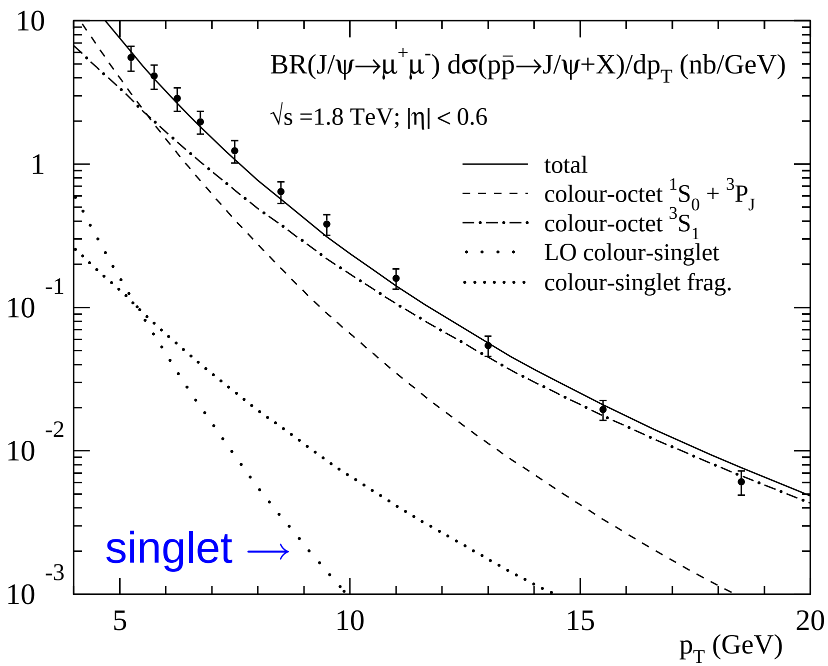
$$\frac{\Gamma(\eta_c \to LH)}{\Gamma(\eta_c \to \gamma\,\gamma)} = (3.01 \pm 0.30 \pm 0.34) \times 10^3$$

Bodwin Chen 01

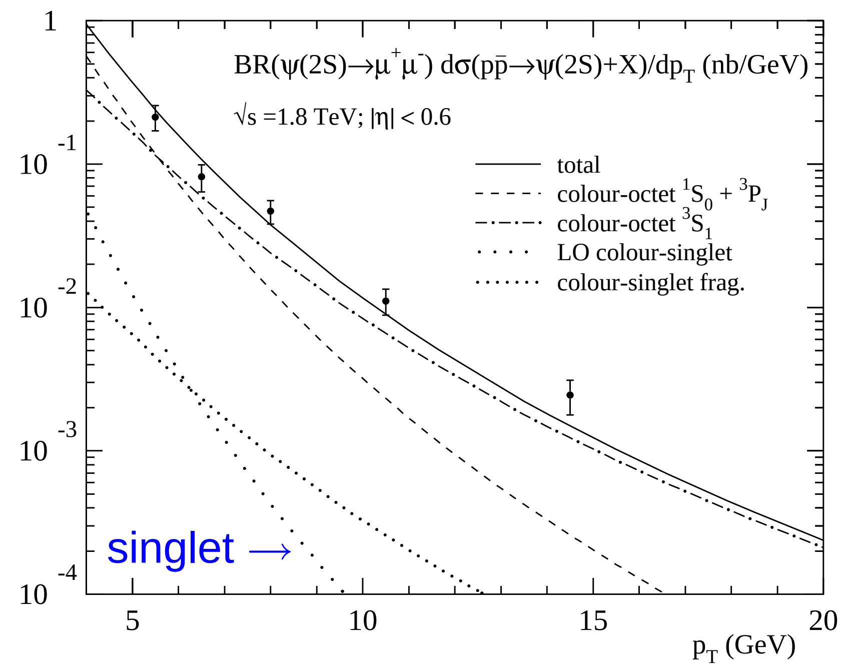
Production

Charmonium Production at the Tevatron

Octet contributions dominate in production at high p_T.
A great success of NRQCD (with respect to the color singlet model)



$p\bar{p} \longrightarrow J/\psi + X$



$p\bar{p} \longrightarrow \psi(2S) + X$

Krämer 01, CDF 97

Two open problems in Charmonium Production:

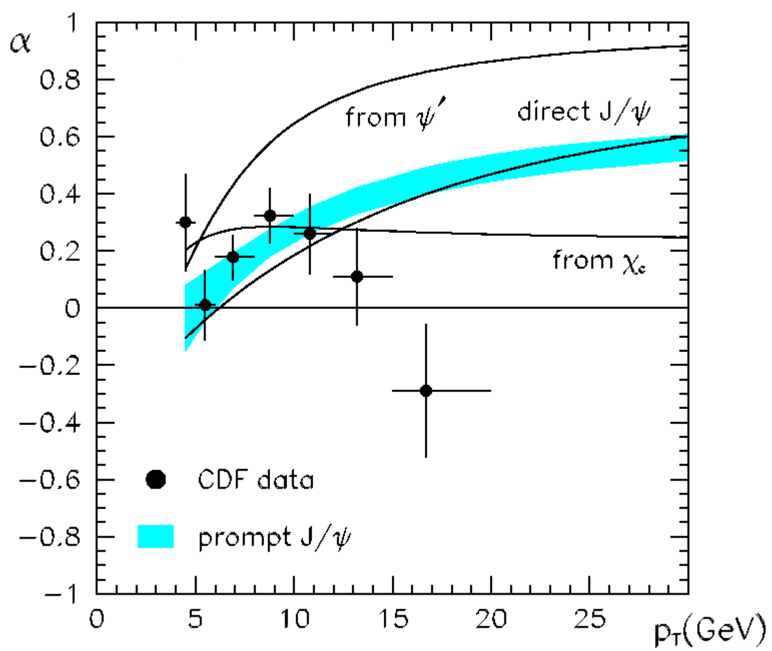
- Charmonium polarization at the tevatron
- Double charmonium production in e^+e^-

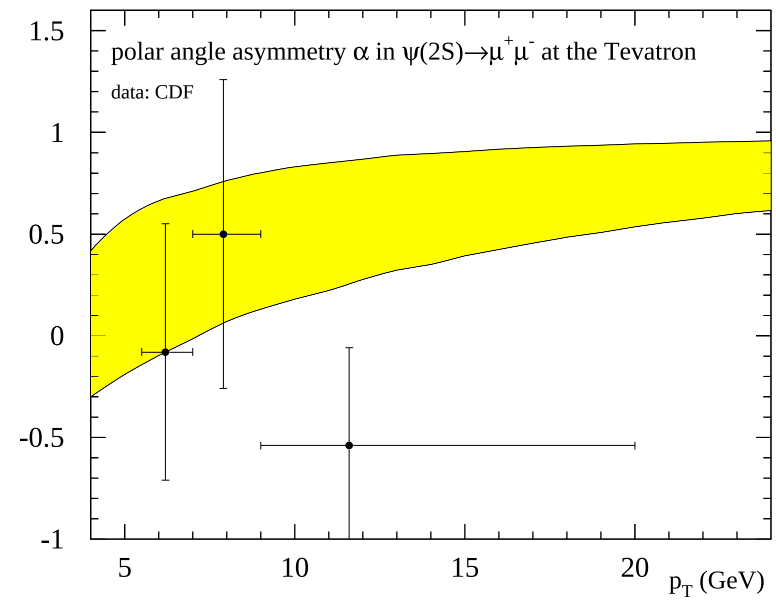
Charmonium Polarization at the Tevatron

- For large p_T quarkonium production, gluon fragmentation via the color-octet mechanism dominates: $\langle O_8^{J/\psi}({}^3S_1)\rangle$.
- At large p_T the gluon is nearly on mass shell and so is transversely polarized.
- In color octet gluon fragmentation, most of the gluon's polarization is transferred to the J/ψ.
- Radiative corretions, color singlet production dilute this.
- In the case of the J/ψ feeddown is important:
  feeddown from χ_c states is about 30% of the J/ψ sample and dilutes the polarization.
- feeddown from $\psi(2S)$ is about 10% of the J/ψ sample and is largely transversely polarized.

- *Spin-flippling terms are assumed suppressed. But This stricly depends on the power counting.*
  If they are not, polarization may dilute at high p_T.

Charmonium Polarization at the Tevatron



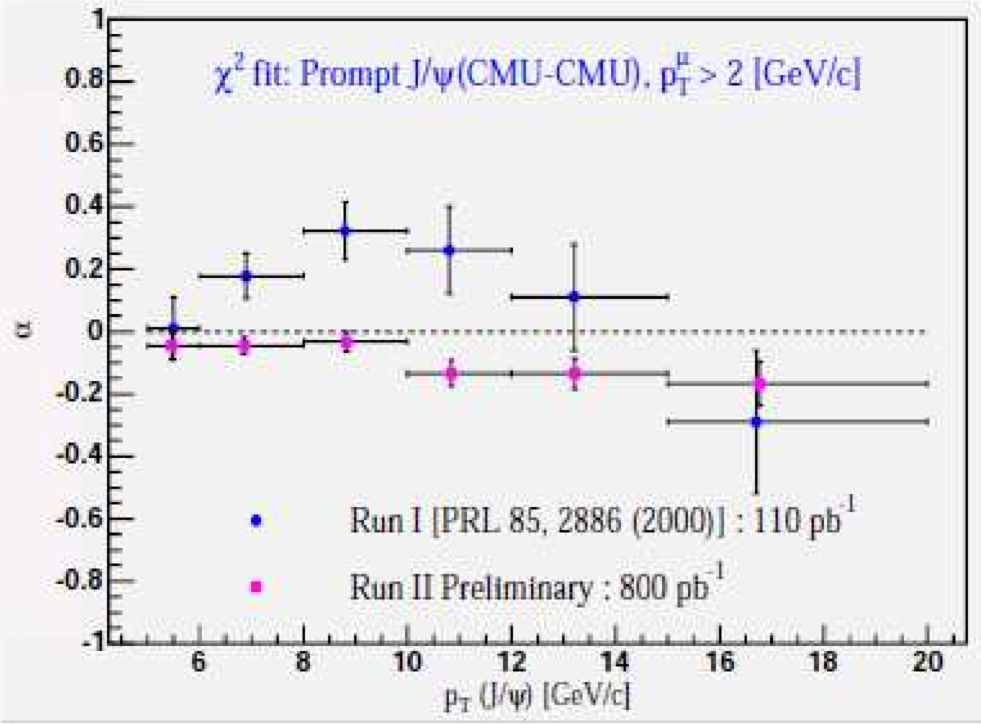


$$\frac{d\sigma}{d\cos\theta} \propto 1 + \alpha \cos^2\theta$$

$\alpha = 1$ is completely transverse $\alpha = -1$ is completely longitudinal.

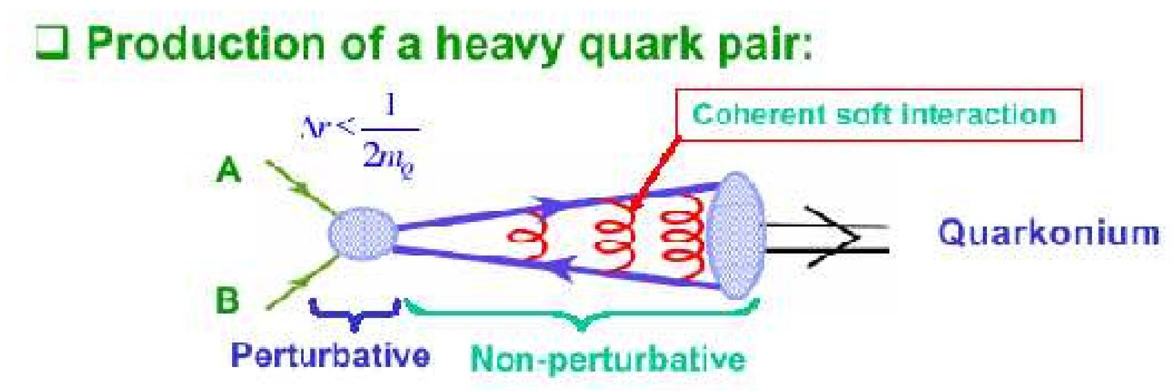
Krämer 01, Braaten et al 01, CDF 97

Charmonium Polarization at the Tevatron



CDF/QWG 06

- There is no formal proof of the NRQCD factorization yet.



Qiu 06

- The relevant 4-fermion operators are

$$\psi^\dagger K^{(n)} \chi \, a_H^\dagger a_H \, \chi^\dagger K'^{(n)} \psi$$

Recently it has been proved that the cancellation of the IR divergences at NNLO requires the modification of the 4 fermion operators into

$$\psi^\dagger K^{(n)} \chi \, \phi_l^\dagger(0,\infty) \, a_H^\dagger a_H \, \phi_l(0,\infty) \, \chi^\dagger K'^{(n)} \psi$$

$$\phi_l(0,\infty) = \mathrm{P} \, \exp\left(-ig \int_0^\infty d\lambda \, l \cdot A(\lambda \, l)\right), \qquad l^2 = 1$$

Nayak Qiu Sterman 05, Nayak/QWG 06

Still no solution for the polarization data even is NRQCD factorization is valid → open problem

Double Charmonium Production

$$\sigma(e^+e^- \to J/\psi + \eta_c) \gtrsim 25.6 \pm 2.8 \pm 3.4 \text{ fb}$$ Belle 04

$$\sigma(e^+e^- \to J/\psi + \eta_c) \gtrsim 17.6 \pm 2.8^{+1.5}_{-2.1} \text{ fb}$$ BaBar 05

$$\sigma(e^+e^- \to J/\psi + \eta_c) = 3.78 \pm 1.26 \text{ fb}$$ Braaten Lee 05

$$\sigma(e^+e^- \to J/\psi + \eta_c) = 5.5 \text{ fb}$$ Liu, He, Chao 02

NRQCD at LO in α_s and v (different choices of m_c, α_s and NRQCD matrix els. QED effects included in Braaten Lee 05).

Double Charmonium Production

Recently

- NLO corrections in α_s by Chao et al. 05
- and NLO correction in v have been calculated:

$$\sigma(e^+e^- \to J/\psi + \eta_c) = 16.2 \pm 5.7 \text{ fb}$$

Bodwin et al 06, QWG2006

Uncertainties from higher order in α_s, scale dependence, order $\alpha_s v^2$, power corrections have not yet been taken into account.

Is this the resolution of the puzzle? Big uncertainties in the higher order corrections.

Conclusions

- Many new data on heavy quark bound states are provided in these years by the B-factories, CLEO, BES and the Tevatron experiments. Many more will come from the still running facilities and in the future from the BES upgrade, LHC, GSI ...
- They will show new (exotic?) states, new production and decay mechanisms. Plenty of investigation opportunities will be given to experimentalists and theorists. Due to the several scales involved in these systems, systematic investigation in the realm of QCD are possible.
- Still challenging is the construction of a systematic approach to describe near or above threshold states and at finite T or in media.
- Heavy quark bound states are therefore a rather unique laboratory for the study of the strong interaction from the high energy scales where asymptotic freedom holds and where precision studies may be done, to the low energy ones dominated by confinement and the many manifestations of the non-perturbative dynamics.

Backup Slides

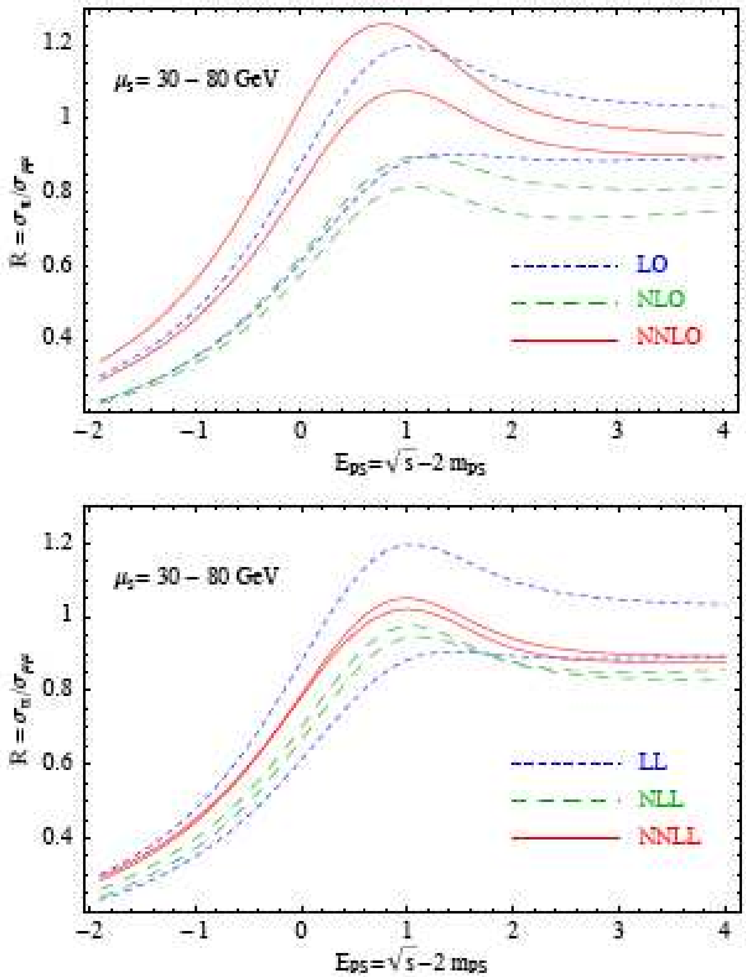
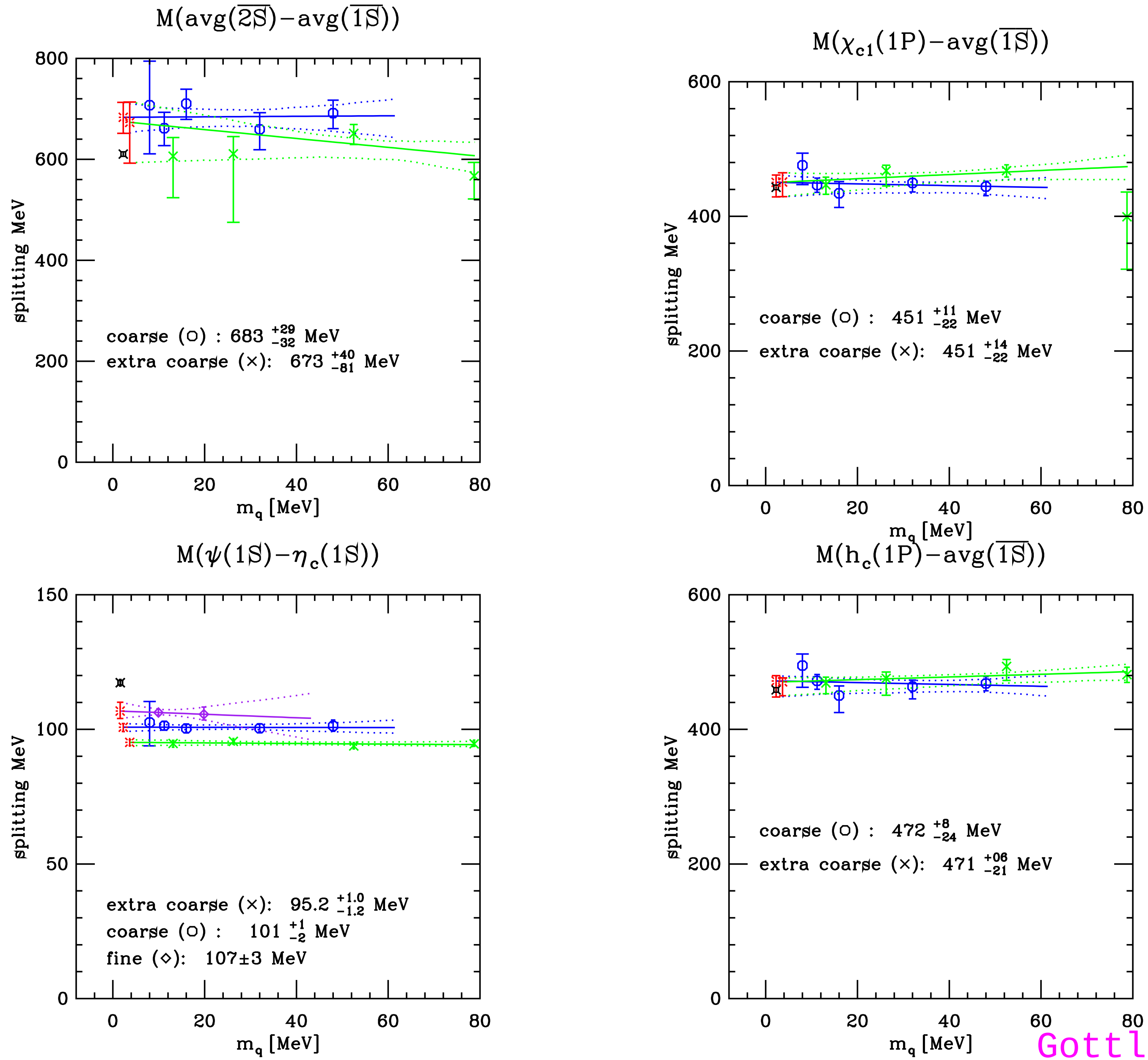


Figure 1: Threshold scan for $t\bar{t}$ using the PS mass, $m_{\rm PS}(20\,{\rm GeV}) = 175$ GeV. The upper panel shows the fixed order results, LO, NLO and NNLO, whereas in the lower panel the RGI results LL, NLL and NNLL are displayed. The soft scale is varied from μ_s=30 GeV to μ_s=80 GeV.

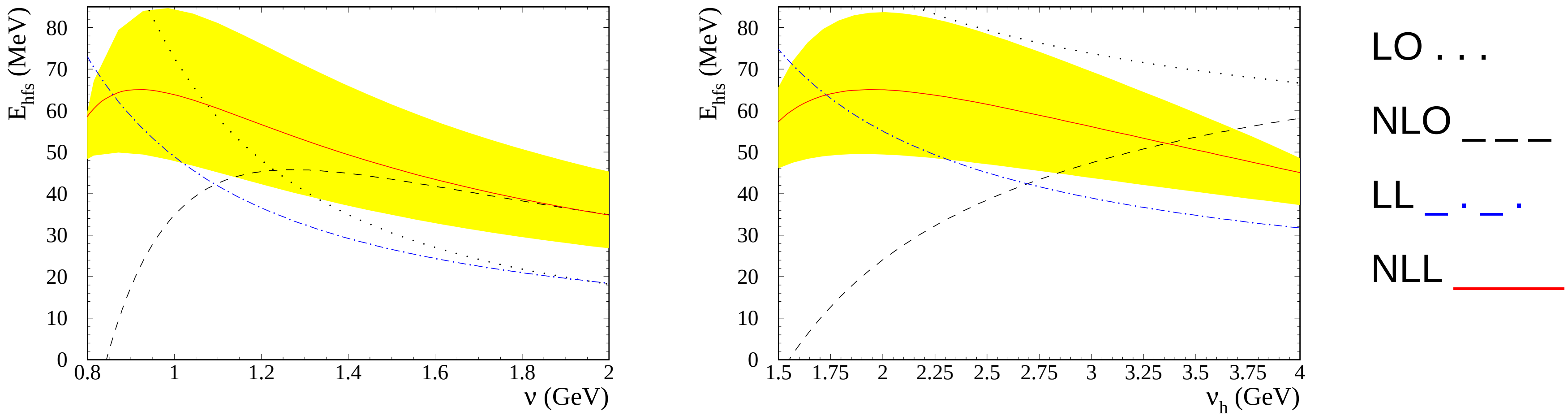
Threshold $t\bar{t}$ cross section Pineda Signer 2006

Charmonium spectrum in the Fermilab formulation



Gottlieb et al. 05

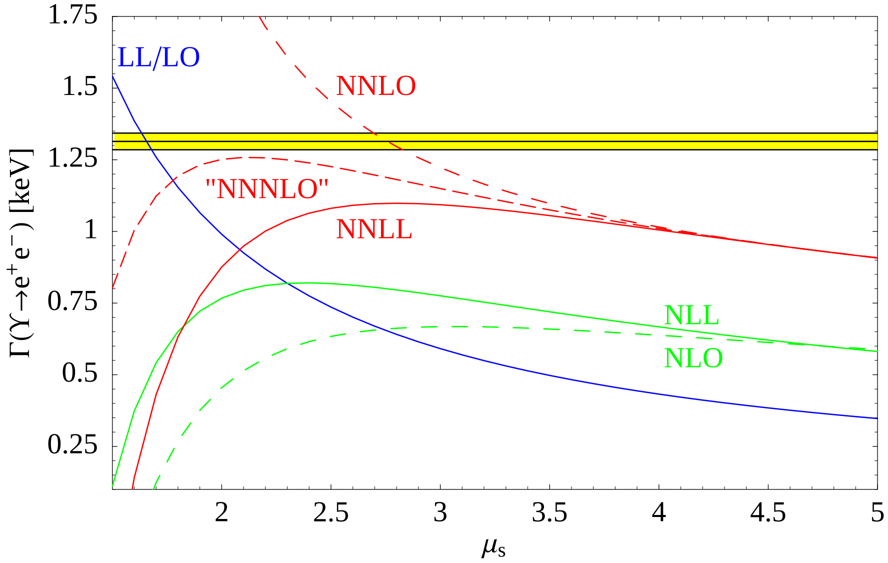
Hfs of the B_c ground state

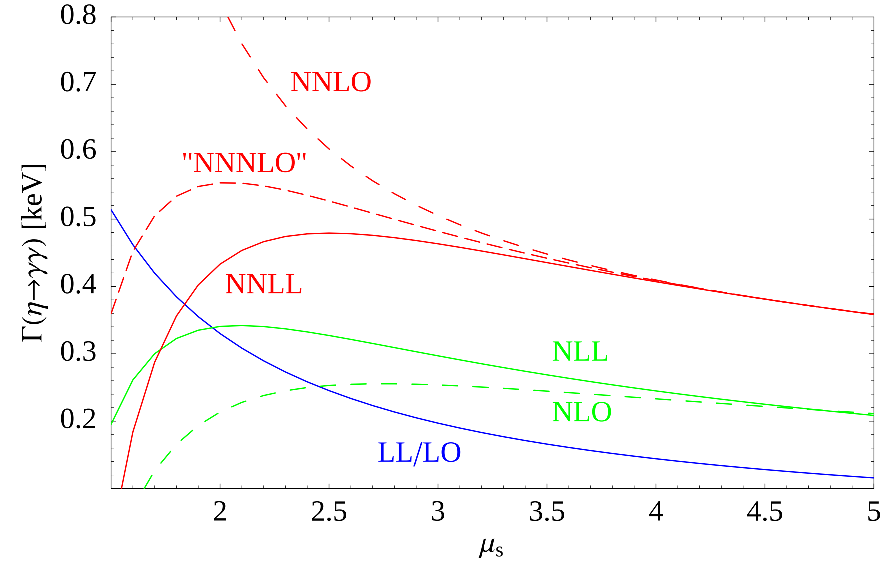


$$M(B_c^*) - M(B_c) = 65 \pm 24\,(\mathrm{th})\,{}^{+19}_{-16}\,(\delta\alpha_\mathrm{s})\ \mathrm{MeV}$$

Penin Pineda Smirnov Steinhauser 04

Em decays of $\Upsilon(1S)$ and η_b





Pineda Signer 06

$$\Gamma(\eta_b(1S) \to \gamma\gamma) = 0.659 \pm 0.089(\text{th.})^{+0.019}_{-0.018}(\delta\alpha_s) \pm 0.015(\text{exp.})\ \text{keV}$$

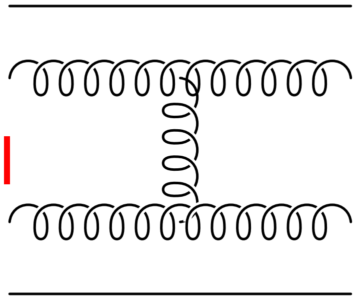
Penin Pineda Smirnov Steinhauser 04
Penin @ ICHEP 06

The Static Spectrum

Gluonic excitations between static quarks are of 3 types:

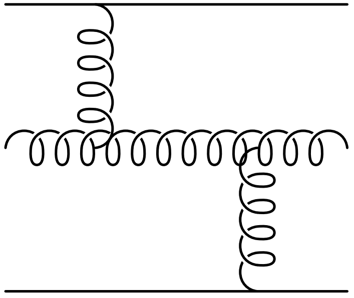
$(Q\bar{Q})_1$

$(Q\bar{Q})_1 +$ Glueball

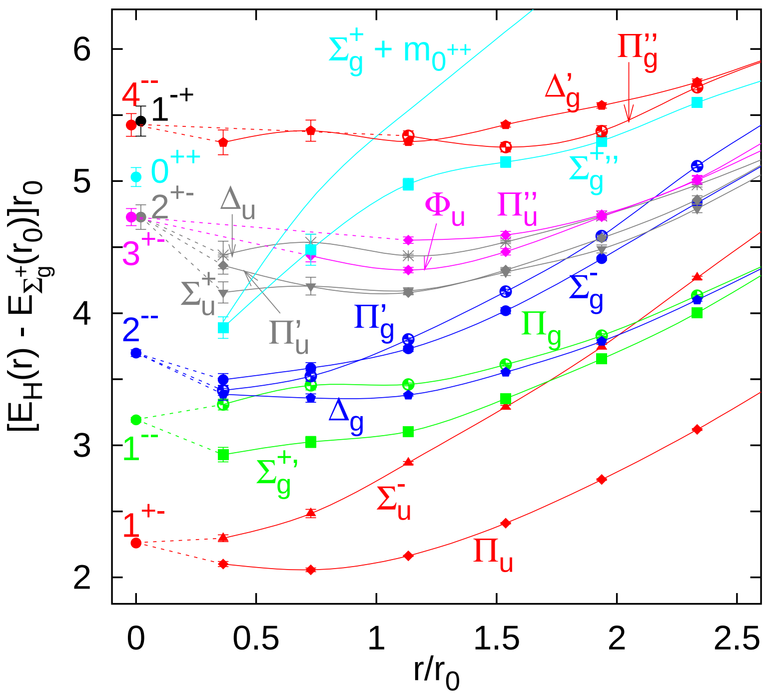


Hybrid

$(Q\bar{Q})_8 G$



Hybrids



Juge Kuti Morningstar 00, 03

At LO in the multipole expansion

$$= e^{-iTE_H}$$

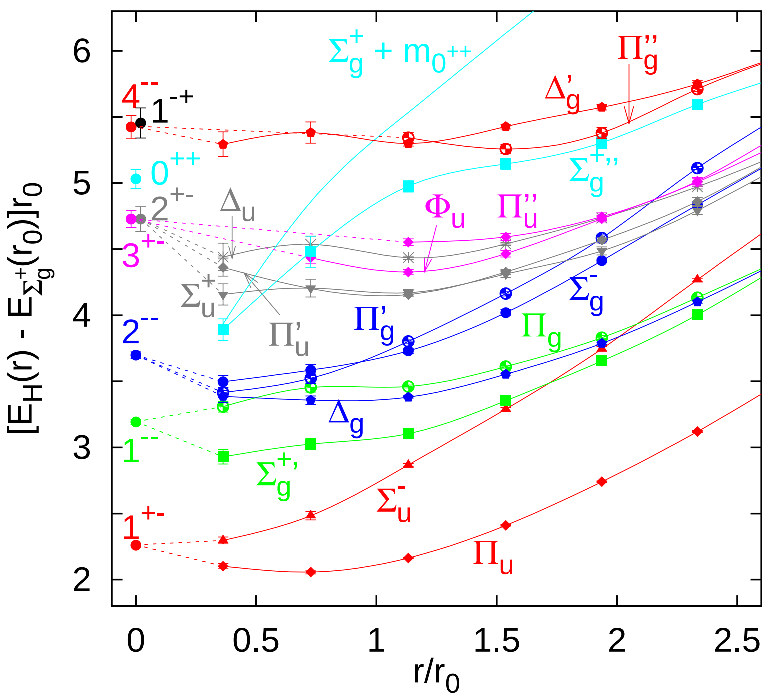
$$E_H = V_o + \frac{i}{T}\ln\langle H^a(\frac{T}{2})\phi^{\rm adj}_{ab}H^b(-\frac{T}{2})\rangle$$

From

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

$$E_H(r) = V_o(r) + \Lambda_H$$

Hybrids



Juge Kuti Morningstar 00, 03

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

Brambilla Pineda Soto Vairo

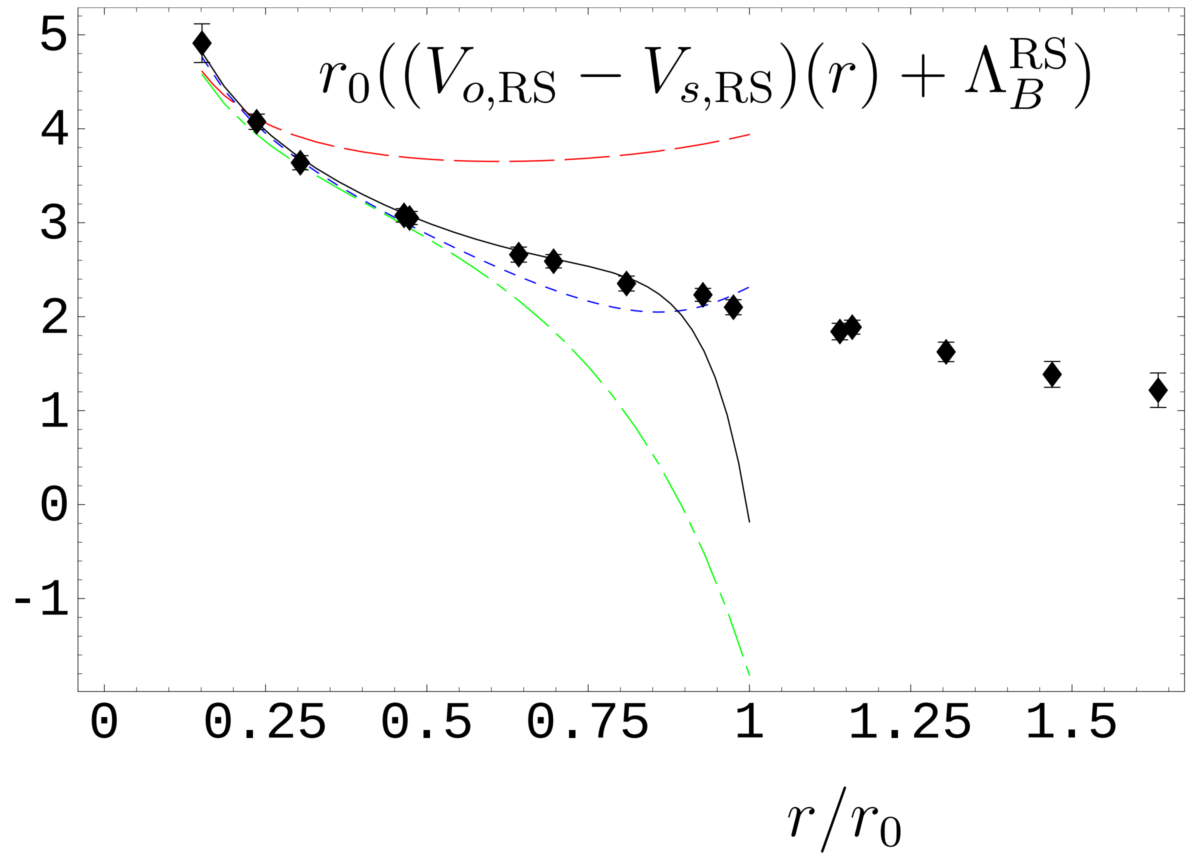
Hybrids

J^{PC}	H	$\Lambda_H^{\mathrm{RS}} r_0$	Λ_H^{RS}/GeV
1^{+-}	B_i	2.25(39)	0.87(15)
1^{--}	E_i	3.18(41)	1.25(16)
2^{--}	$D_{\{i}B_{j\}}$	3.69(42)	1.45(17)
2^{+-}	$D_{\{i}E_{j\}}$	4.72(48)	1.86(19)
3^{+-}	$D_{\{i}D_jB_{k\}}$	4.72(45)	1.86(18)
0^{++}	$\mathbf{B}^2$	5.02(46)	1.98(18)
4^{--}	$D_{\{i}D_jD_kB_{l\}}$	5.41(46)	2.13(18)
1^{-+}	$(\mathbf{B} \wedge \mathbf{E})_i$	5.45(51)	2.15(20)

Foster Michael, Brambilla Pineda Soto Vairo, Bali Pineda

Hybrids

Renormalon subtraction (RS) is crucial in comparing the perturbative static octet potential with lattice data.



NNLL + 3 loop est.

NNLO

NLO

LO

$\alpha_{\mathrm{s}} = \alpha_{\mathrm{s}}(1/r)$

$\nu_f = \nu_{us} = 2.5\, r_0^{-1}$

Lattice data of $E_{\Pi_u} - E_{\Sigma_g^+}$

Bali Pineda 03