QCD spectroscopy

problems and new challenges

Pietro Colangelo
INFN – Bari

Cortona, 20 April 2015

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problems and new challenges

WHY STUDYING
QCD SPECTROSCOPY
IN THE LHC ERA?

overview and answers

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$$L_{QCD} = \bar{q}\left(i\gamma^{\mu}D_{\mu} - M\right)q - \frac{1}{4}G^{a,\mu\nu}G^{a}_{\mu\nu}$$

$SU(3)_c$

$D_\mu = \partial_\mu - i\, g_s T^a A^a{}_\mu$

$G^a{}_{\mu\nu} = \partial_\mu A^a{}_\nu - \partial_\nu A^a{}_\mu + g_s f^{abc} A^b{}_\mu A^c{}_\nu$

formidable phenomenological complexity

a completed/finished story?

$$\mathrm{L}_{\mathrm{QCD}} = \overline{\mathrm{q}}\left(i\gamma^{\mu}\mathrm{D}_{\mu} - \mathrm{M}\right)\mathrm{q} - \frac{1}{4}\,\mathrm{G}^{a,\mu\nu}\mathrm{G}^{a}_{\mu\nu}$$

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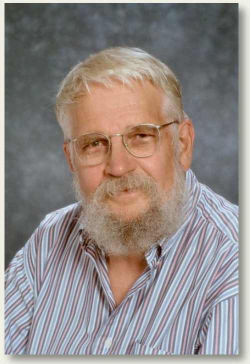
formidable phenomenological complexity

Not a finished story!



Not a finished story

θ term

$$L_{QCD} = \bar{q}\left(i\gamma^{\mu}D_{\mu} - M\right) q - \frac{1}{4} G^{a,\mu\nu} G^{a}_{\mu\nu} - \frac{\theta}{32\,\pi^{2}} \tilde{G}^{a,\mu\nu}\, G^{a}_{\mu\nu}$$

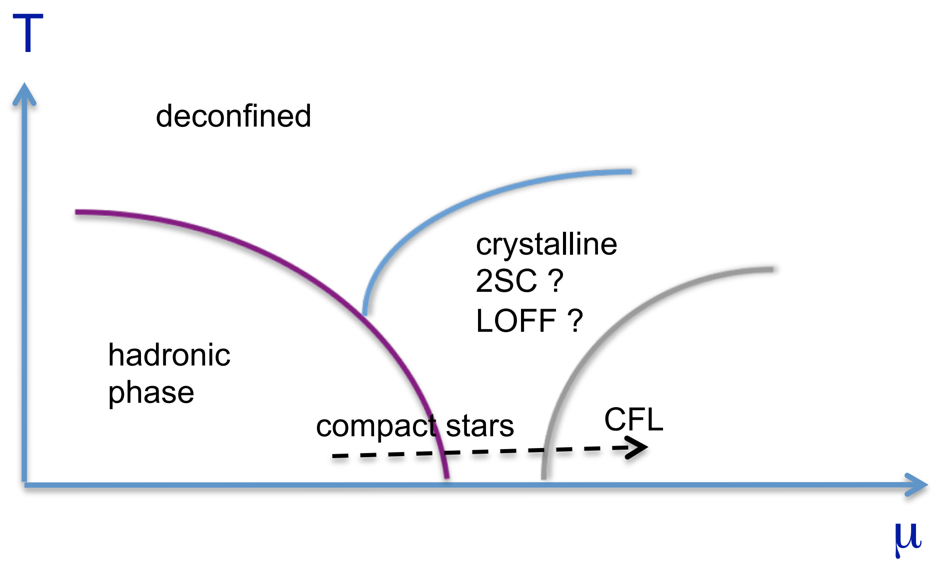
$$\theta = \theta_0 - Arg\,(\det\ M)$$

$$\theta\big|_{\exp} < 10^{-10}$$

answer probably beyond QCD, but of relevance for a complete understanding of the strong interaction phenomenology

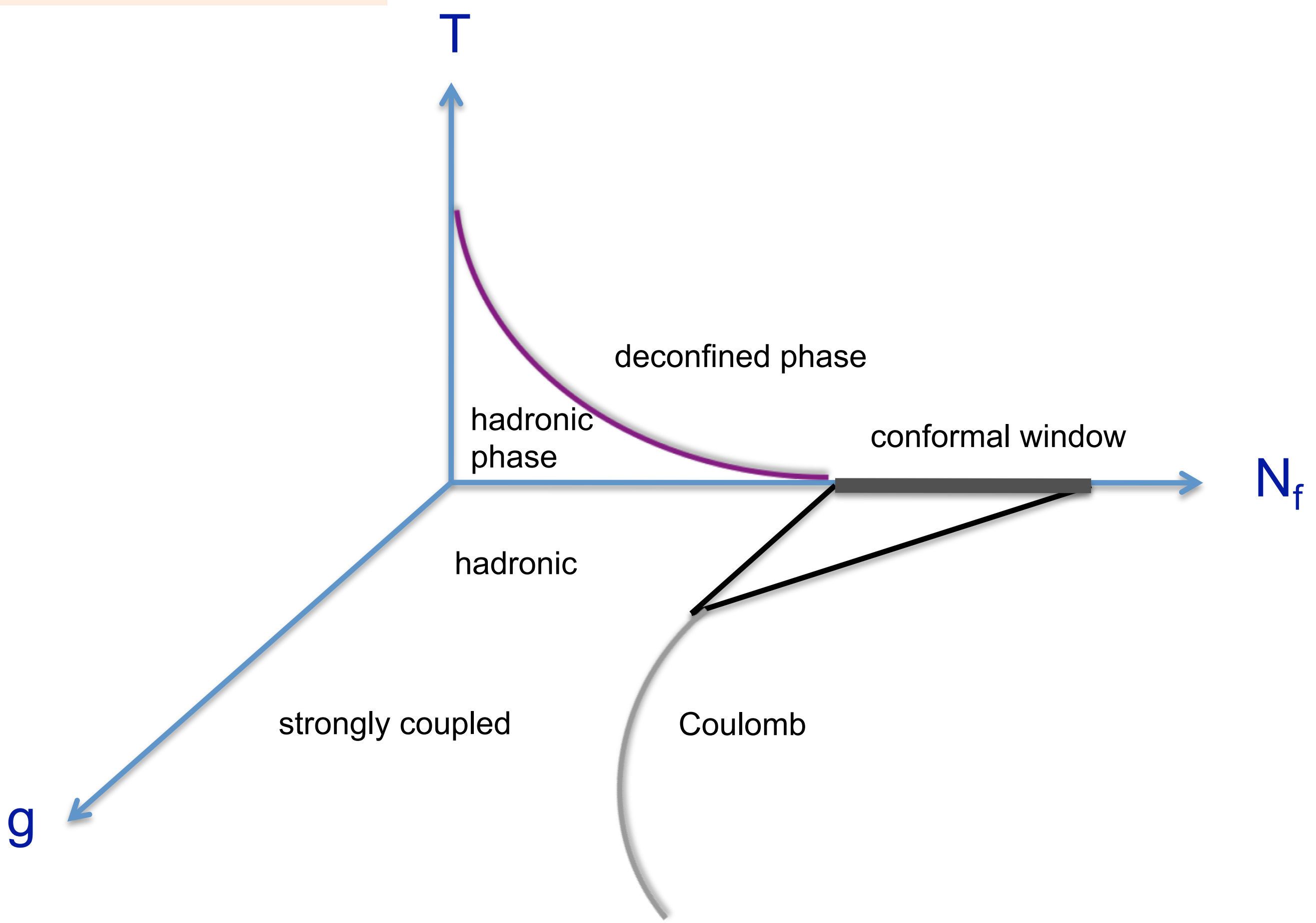
Not a finished story

phase diagram
hadronic vs deconfined phase
superconductive phases



Not a finished story

conformal window



QCD a template for SM extensions (compositeness)

full solution not known

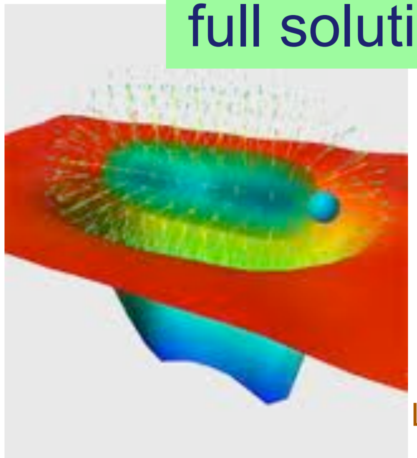
confined phase:
formidable phenomenological complexity

- light and heavy quarkonia, baryons
- exotics, glueballs
- chiral phenomenology
- Regge phenomenology (Pomeron, Odderon,…)
- exclusive processes, inclusive modes
- interplay between perturbative and nonperturbative processes
- interplay between strong and weak interaction phenomena
- nuclear physics

full solution not known

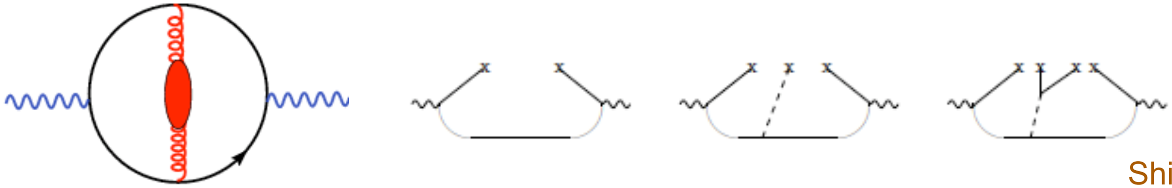
hadronic phase

confinement simulated



Leinweber

parameterized



Shifman Vainshtein Zakarov

measured

$$\frac{n_q}{n_P} \leq 10^{-27}$$ vs $$\frac{n_q}{n_P} \leq 10^{-12}$$ in the standard cosmological model

CERN SPS $$\sigma_q \equiv \sigma\left(p + p \to q[\bar{q}] + X\right) \leq 10^{-40} cm^2$$ vs 10^{-25} cm^2 for free quarks

Perl Lee Loomba

the visible (baryonic) matter of universe is connected to the QCD mass generation mechanism -> confinement full solution not known

WHAT IS CONFINEMENT IN THE HADRONIC PHASE

WHY THERE IS CONFINEMENT

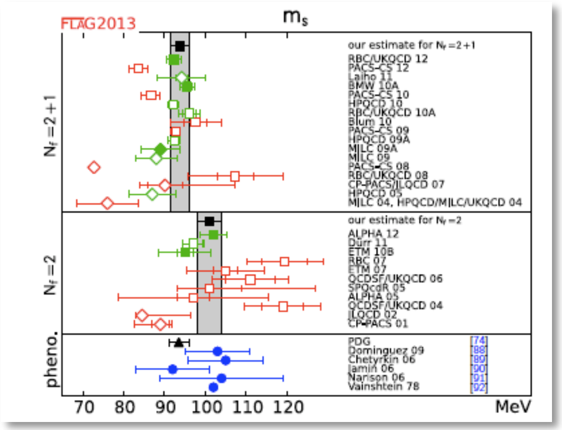
HOW IT IS RELATED TO CHIRAL SYMMETRY BREAKING

hadron spectrum emerges from the full strongly coupled QCD dynamics

investigate spectroscopy to understand the confining chirally-non invariant QCD dynamics

full solution not known

Lattice QCD: defines nonperturbatively the quantum theory
results of unprecedented and increasing accuracy



however: Euclidean (Maiani-Testa no go theorem -> finite volume needed)
several difficulties:

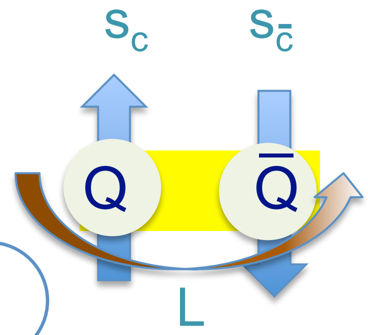
spectroscopy
- high mass resonances (excitations) difficult to compute
- many hadronic observables to evaluate
- little (or null) information on couplings and widths
- difficulties with the Minkowskian dynamics (interplay with thresholds, mixings, amplitudes and phases)

First-principle based methods:
Analyticity/Unitarity, Quark-Hadron duality, QCD Effective Theories

quark model color singlets (-> from atomic physics)

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

baryons $q \otimes q \otimes q = 3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$



$P=(-1)^{L+1}$
$C=(-1)^{L+S}$
$S=S_c+S_{\bar{c}}$
$J=L+S$

$n^{2S+1}L_J$

non quark model color singlets

hybrids $q \otimes \bar{q} \otimes G = 3 \otimes \bar{3} \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 8 \oplus 1$

glueballs $G \otimes G = 8 \otimes 8 = 27 \oplus 10 \oplus \overline{10} \oplus 8 \oplus 8 \oplus 1$

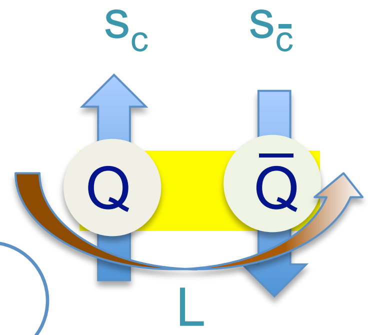
multi quarks, multi gluons, multi quark-gluons …

……….

WARNING!

$$\frac{n_q}{n_P} \leq 10^{-27}$$

quark model color singlets (-> from atomic physics)



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multi quarks, multi gluons, multi quark-gluons …

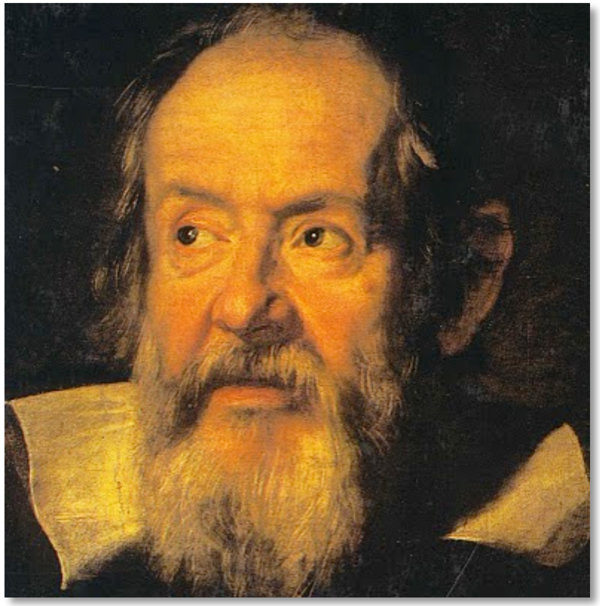
……….

distinction between "CONVENTIONAL" and "EXOTIC" spectrum arbitrary and misleading

hadrons emerge from the full QCD dynamics

states in the hadronic spectrum are poles of the S-matrix
with definite quantum numbers
and universal (process-independent) properties

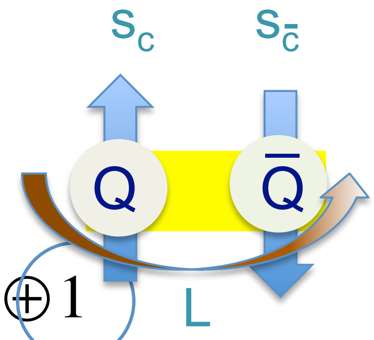
same physics in “conventional” and “exotic” states



Io stimo più il trovare un vero,
benchè di cosa leggiera,
che ‘l disputar lungamente
delle massime questioni
senza conseguir verità nissuna

G. Galilei, Scritti letterari

quark model color singlets (-> from atomic physics)



$P=(-1)^{L+1}$

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$S=S_c+S_{\bar{c}}$

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$n^{2S+1}L_J$

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

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non quark model color singlets

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multi quarks, multi gluons, multi quark-gluons …

……….

distinction between “CONVENTIONAL” and “EXOTIC” spectrum arbitrary and misleading

hadrons emerge from the full QCD dynamics

$1/N_c$ sensible expansion

unprecedented experimental situation

low/high energy

low/high intensity

leptonic/hadronic

different production processes

many decay modes

new facilities

Short discussion on few topics in hadron spectroscopy:

WHAT MUST BE FOUND
or recognized

gluonic resonances:
- scalar
- tensor
- odd-balls

gluon-enriched resonances: light hybrids

WHAT HAS BEEN FOUND
possible precision tests

WHAT HAS BEEN FOUND
and needs to be better understood

also discussed by
Fulvio Piccinini
Alexis Pompili
Marco Pappagallo

elusive glueball

reviews in Crede Meyer
Klempt Zaitsev
Ochs

helicity of each gluon $|\lambda = \pm 1\rangle$

2 gluons $\begin{cases} J_{tot} \neq 1 \\ C \ \ + \end{cases}$

$$(|11\rangle + |-1-1\rangle); \quad |1-1\rangle \,;\, |-11\rangle; \quad (|11\rangle - |-1-1\rangle)$$

$$\leftarrow\rightarrow + \rightarrow\leftarrow \qquad \rightarrow\rightarrow \quad \leftarrow\leftarrow \qquad \leftarrow\rightarrow - \rightarrow\leftarrow$$

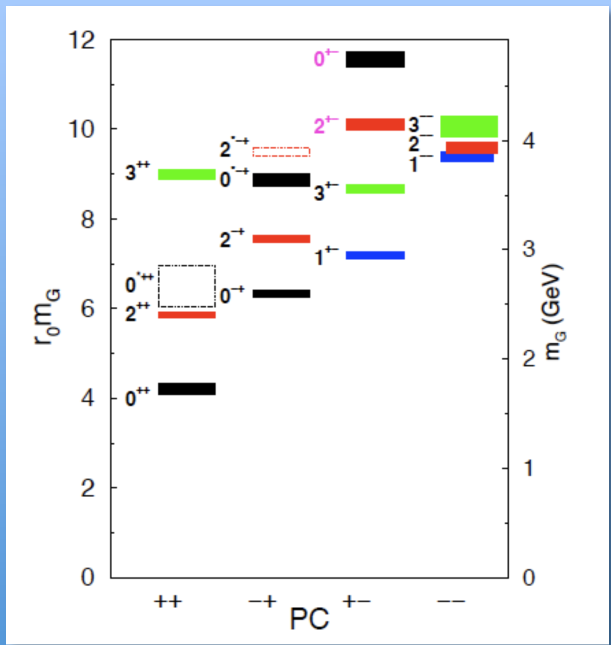
P + P + P -

$$0^{++} \qquad 2^{++} \quad \ldots \qquad 0^{-+} \qquad 2^{-+} \quad 4^{-+}\ldots$$

other quantum numbers for 3, …gluons

LQCD

Peardon
Morningstar



QCDSR

$J^{PC} = 0^{++}$	mass (GeV)	$\Gamma(G \to \pi\pi)$(GeV)
G_1	$0.9-1.1$	0.7
G_2	$1.5-1.6$	

Veneziano
Narison

	mass (GeV)
$G_1(J^{PC} = 0^{++})$	$1.23-1.27$
$G_1(J^{PC} = 0^{-+})$	$2.1-2.4$

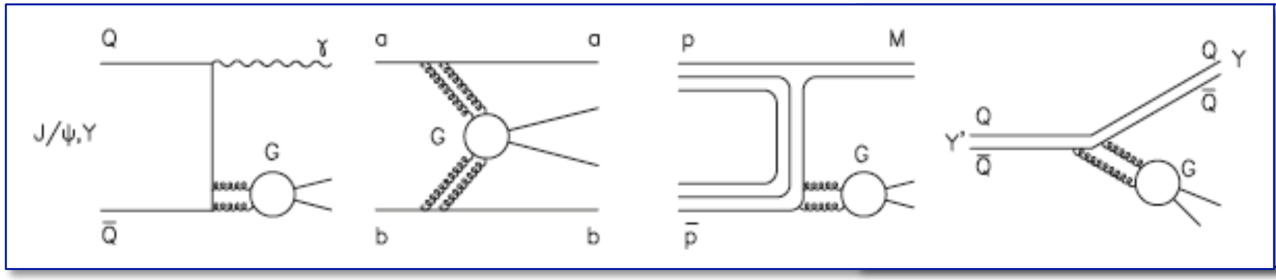
QCDSR+ Instantons
Forkel

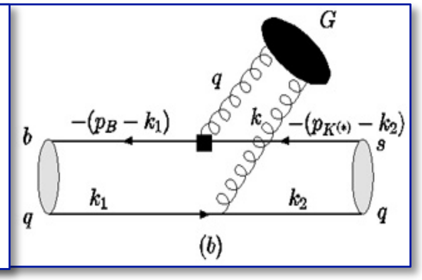
identification difficult due to the mixing with qq states with the same quantum numbers
uncertain predictions of couplings and widths

elusive glueball

production processes and decay modes important for the identification

production





radiative quarkonium decays | central production | p anti-p | quarkonium decays | b->sg

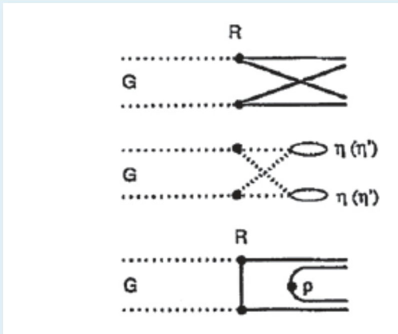
suppression in $\gamma\gamma$

decays
Amsler Close

$$G \rightarrow gg \rightarrow q\bar{q}q'\bar{q}'$$

$$G \rightarrow gg \rightarrow gggg \rightarrow \eta\eta,\ \eta'\eta'$$

$$G \rightarrow gg \rightarrow q\bar{q} \rightarrow q\bar{q}q'\bar{q}'$$



flavour blind couplings

$$G \rightarrow \pi\pi : K\bar{K} : \eta\eta : \eta'\eta' = 3:4:1:1$$

(observed in $\chi_{c0,2}$ decays)

extra states in hadronic multiplets

elusive scalar glueball: $J^{PC}=0^{++}$

PDG 2014: $I^G=0^+$ $J^{PC}=0^{++}$

possible qq quantum numbers: n^1P_0

	mass (MeV)	width (MeV)	decay modes
$f_0(500)$	$(400-550)-i(200-350)$		$\pi\pi, \gamma\gamma$
$f_0(980)$	990 ± 20	$40-100$	$\pi\pi, K\bar{K}, \gamma\gamma$
$f_0(1370)$	$(1200-1500)-i(150-250)$		$\pi\pi, 4\pi, \pi(1300)\pi, a_1\pi, K\bar{K}$
$f_0(1500)$	1505 ± 6	109 ± 7	$\pi\pi, 4\pi, \eta\eta, \eta\eta', K\bar{K}, \gamma\gamma$
$f_0(1710)$	1722^{+6}_{-5}	135 ± 7	$K\bar{K}, \eta\eta, \pi\pi, \omega\omega$
$f_0(2020)$ (?)	1992 ± 16	442 ± 60	$\rho\pi\pi, \pi\pi, \rho\rho, \omega\omega, \eta\eta$
$f_0(2100)$ (?)	2103 ± 8	209 ± 19	
$f_0(2200)$ (?)	2189 ± 13	238 ± 50	
$f_0(2330)$ (?)	2314 ± 25	144 ± 20	

ex: possible classification schemes

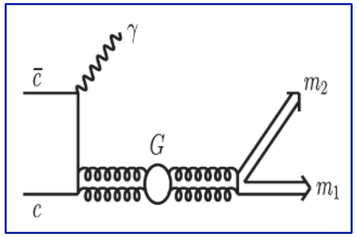
	$I=0$	$I=\frac{1}{2}$	$I=1$
		$K^*(1950)$	
10	$f_0(1710)$ $f_0(1500)$ $f_0(1370)$?	$K^*(1430)$	$a_0(1450)$
9	$f_0(980)$ $f_0(500)/\sigma$	$K^*(900)/\kappa$?	$a_0(980)$

$$\begin{array}{l} |f_0(1370)\rangle \\ |f_0(1500)\rangle \\ |f_0(1710)\rangle \end{array} = \begin{pmatrix} c_{11} & c_{12} & c_{13} \\ c_{21} & c_{22} & c_{13} \\ c_{31} & c_{32} & c_{33} \end{pmatrix} \begin{array}{l} |n\bar{n}\rangle \\ |s\bar{s}\rangle \\ |gg\rangle \end{array}$$

$I=0$	$I=\frac{1}{2}$	$I=1$	
	$K^*(1950)$		
$f_0(1710)$ $f_0(1500)$ $(f_0(1370)?)$ $f_0(980)$	$K^*(1430)$	$a_0(980)$	10
$f_0(500)/\sigma$	$(K^*(900)/\kappa?)$		

elusive scalar glueball: $J^{PC}=0^{++}$

radiative J/ψ decays



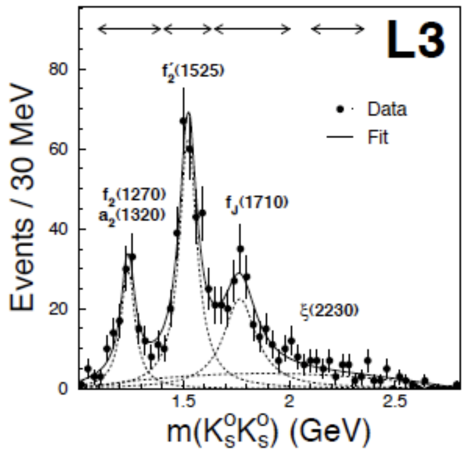
Decay Mode	BES	Br (10^{-4}) CLEO [3]
$J/\psi \to \gamma f_0(1500) \to \gamma\pi\pi$	1.01 ± 0.32 [4]	$1.21 \pm 0.29 \pm 0.24$
$J/\psi \to \gamma f_0(1500) \to \gamma\eta\eta$	$0.165^{+0.026+0.051}_{-0.031-0.140}$ [26]	
$J/\psi \to \gamma f_0(1710) \to \gamma\pi\pi$	4.0 ± 1.0 [4]	$3.71 \pm 0.30 \pm 0.43$
$J/\psi \to \gamma f_0(1710) \to \gamma K\overline{K}$	$8.5^{+1.2}_{-0.9}$ [4]	$11.76 \pm 0.54 \pm 0.94$
$J/\psi \to \gamma f_0(1710) \to \gamma\omega\omega$	$0.31 \pm 0.06 \pm 0.08$ [27]	
$J/\psi \to \gamma f_0(1710) \to \gamma\eta\eta$	$2.35^{+0.13+1.24}_{-0.11-0.74}$ [26]	

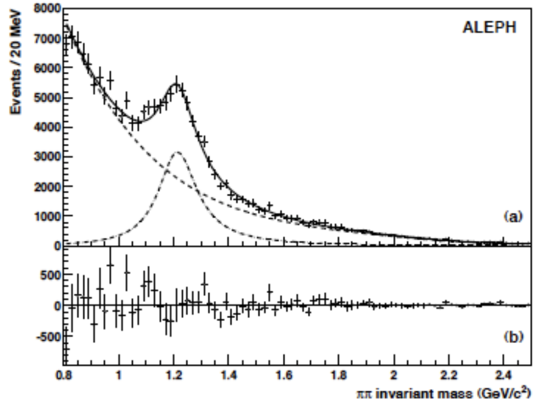
$$G \to \pi\pi : K\overline{K} : \eta\eta : \eta'\eta' = 3:4:1:1$$

$f_0(1500)$ or $f_0(1710)$ the scalar glueball?

elusive scalar glueball: $J^{PC}=0^{++}$

$\gamma\gamma$





LEP
only tensors

Belle

$\gamma\gamma \rightarrow \pi^0\pi^0$

dominated by $f_2(1270)$

S-wave: $f_0(980)$

f_0 $M = 1470^{+6+72}_{-7-255}\ MeV \quad \Gamma = 90^{+2+50}_{-1-22}\ MeV$

$f_0(1500)$ quark component

elusive scalar glueball: $J^{PC}=0^{++}$

central production (Crystal Barrel)

decays

Ratio	$f_0(1370)$	$f_0(1500)$
$\mathcal{B}(K\bar{K})\,/\,\mathcal{B}(\pi\pi)$	(0.37 ± 0.16) to (0.98 ± 0.42) [77]	$^a\,0.186 \pm 0.066$ [67, 70]
		$^b\,0.119 \pm 0.032$ [65]
$\mathcal{B}(\eta\eta)\,/\,\mathcal{B}(\pi\pi)$	0.020 ± 0.010 [77]	$^a\,0.226 \pm 0.095$ [66, 67]
		$^b\,0.157 \pm 0.062$ [65]
$\mathcal{B}(\eta\eta')\,/\,\mathcal{B}(\pi\pi)$		$^a\,0.066 \pm 0.028$ [63, 67]
		$^b\,0.042 \pm 0.015$ [65]
$\mathcal{B}(\rho\rho)\,/\,\mathcal{B}(4\pi)$	0.260 ± 0.070 [76]	0.130 ± 0.080 [76, 77]
$\mathcal{B}(\sigma\sigma)\,/\,\mathcal{B}(4\pi)$	0.510 ± 0.090 [76]	0.260 ± 0.070 [76]
$\mathcal{B}(\rho\rho)\,/\,\mathcal{B}(2[\pi\pi]_S)$		0.500 ± 0.340 [76]
$\mathcal{B}(4\pi)\,/\,\mathcal{B}_{\text{tot}}$	0.800 ± 0.050 [166]	0.760 ± 0.080 [76]

$3\pi^0 \quad 2\pi^0 \quad \eta\pi^0 \quad \eta\eta$

4π from $\bar{p}n$

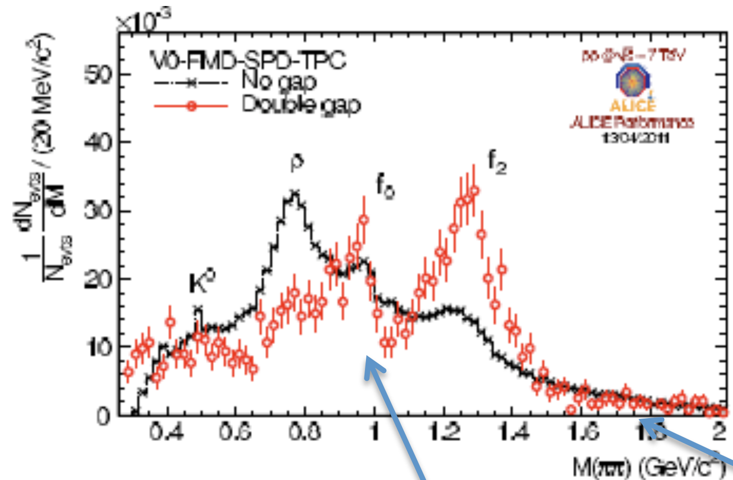
Scalar	$\pi\pi/K\bar{K}$
$f_0(1370)$	2.17 ± 0.90
$f_0(1500)$	3.13 ± 0.68
$f_0(1710)$	0.20 ± 0.03

ππ

KK

central production

Alice



$f_0(980)$

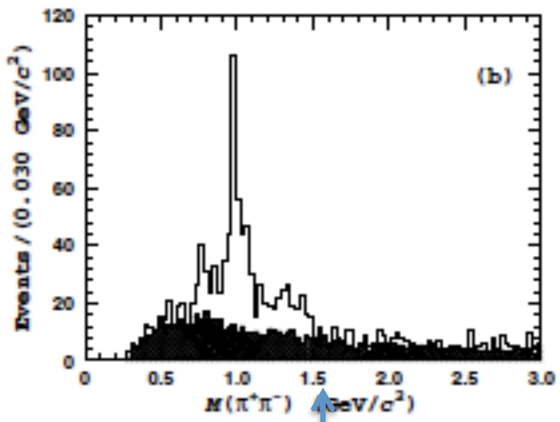
$f_0(1500)$ or $f_0(1710)$?

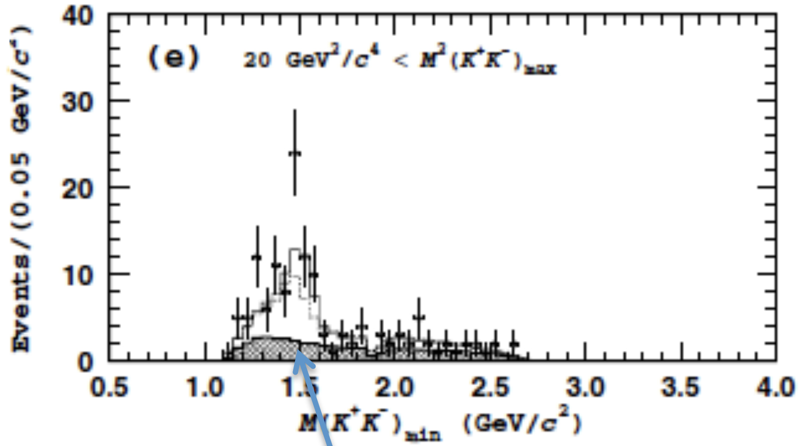
elusive scalar glueball: $J^{PC}=0^{++}$

light scalars in B decays

Belle

$B^+ \to K^+\pi^+\pi$





$B^+ \to K^+K^+K^-$

no $f_0(1500)$

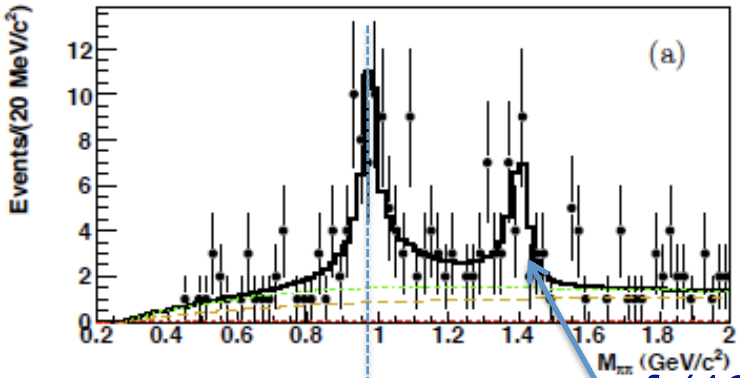
sizable contribution of $f_0(1500)$

strangeness component in $f_0(1500)$

elusive scalar glueball: $J^{PC}=0^{++}$

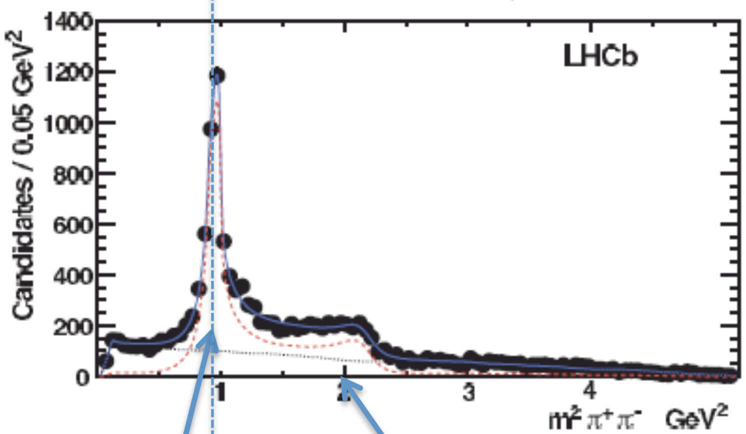
scalar in B_s decays

Belle 2012



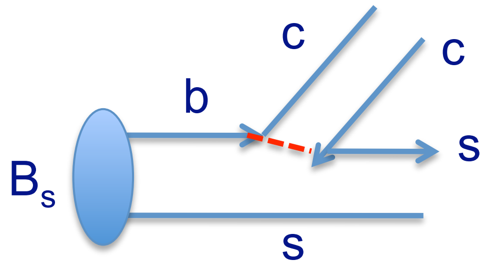
$f_0(1370)$

LHCb 2012



$f_0(980)$ f_0

large strangeness component in $f_0(980)$



$B_s \to J/\psi \pi^+ \pi^-$

De Fazio Wang PC

$$M = 1475.1 \pm 6.3\ MeV \quad \Gamma = 113 \pm 11\ MeV$$

elusive scalar glueball: $J^{PC}=0^{++}$

Is $f_0(1710)$ the lightest scalar glueballs?

issues

- nature of $f_0(980)$ (light scalar multiplet)
- $f_0(1370)$ genuine resonance / dynamically produced
- $f_0(1500)$ more qq than glueball
- $f_0(1710)$ scalar glueball vs qq
- classification of the higher states
- heavy unflavoured scalars

elusive tensor glueball: $J^{PC}=2^{++}$

observed $I^G=0^+$ $J^{PC}=2^{++}$

possible qq quantum numbers: n^3P_2 n^3F_2

	mass (MeV)	width (MeV)	decay modes
$f_2(1270)$	1275.1 ± 1.2	$185.1^{+2.9}_{-2.4}$	$\pi\pi, 4\pi, KK, \eta\eta, \gamma\gamma$
$f_2(1430)$ (?)	1430	$13 - 150$	$\pi\pi, , K\bar{K}$
$f_2'(1525)$	1525 ± 5	75^{+6}_{-5}	$K\bar{K}, \eta\eta, \pi\pi, \gamma\gamma$
$f_2(1565)$ (?)	1562 ± 13	134 ± 8	$\pi\pi, \rho\rho, 4\pi, \eta\eta, \pi\pi, \omega\omega$
$f_2(1640)$ (?)	1639 ± 6	99^{+60}_{-40}	$\omega\omega, 4\pi, K\bar{K}$
$f_2(1810)$ (?)	1815 ± 12	197 ± 22	$4\pi, \gamma\gamma$
$f_2(1910)$ (?)	1903 ± 9		$K^+K^-, \eta\eta, \omega\omega, \eta\eta', a_2(1320)\pi, f_2(1270)\eta$
$f_2(1950)$	1944 ± 12	472 ± 18	$K^*K^*, \pi\pi, 4\pi, \eta\eta, K\bar{K}, \gamma\gamma$
$f_2(2010)$	2011^{+62}_{-76}	202^{+67}_{-62}	$\phi\phi, K\bar{K}$
$f_2(2150)$ (?)	2157 ± 12	152 ± 30	$\eta\eta, K\bar{K}, a_2(1320)\pi, f_2(1270)\eta, p\bar{p}$
$f_2(2300)$	2297 ± 28	149 ± 41	$\phi\phi, K\bar{K}, \gamma\gamma$
$f_2(2340)$	2339 ± 55	319^{+81}_{-69}	$\phi\phi, \eta\eta$
$f_J(2220)$ (?)	2231.1 ± 3.5	23^{+8}_{-7}	$\pi\pi, , K\bar{K}, \eta\eta'$ (BES)

difficult assignment to the various multiplets

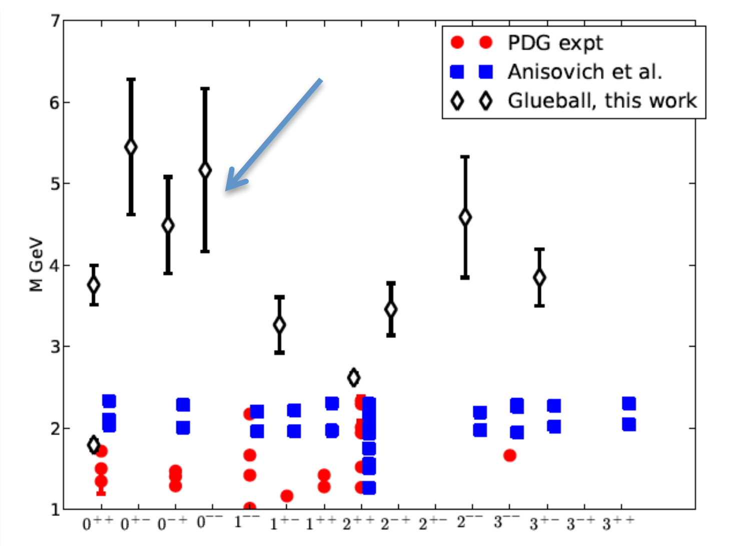
spin of the BES state $f_J(2220)$ (observed in $e^+e^- \to \gamma\pi\pi$) : 2 or 4

Regge trajectories of glueballs and mesons should have different slopes (useful for identification)

elusive glueball: $J^{PC}=0^{--}$

glueball states with exotic J^{PC}
C=-1-> odd number of constituent gluons: odd-balls

heavier than 0^{++} 2^{++}



LQCD

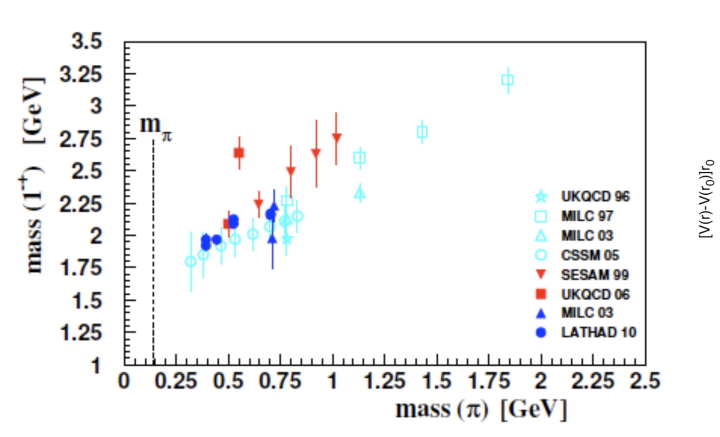
	mass (GeV)
$G_0(J^{PC}=0^{--})$	3.81 ± 0.12
$G_1(J^{PC}=0^{--})$	4.33 ± 0.13

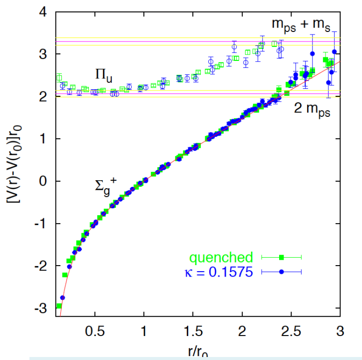
QCDSr

production	decays
$X(3872) \to G_0\, \gamma$	$G_0 \to \gamma f_1(1285)$
$Y(1S) \to f_1(1250)\, G_0$, $\chi_{c1} G_0$	$G_0 \to \gamma\, \chi_{c1}$
$\chi_{b1} \to J/\psi\, G_0$, $\omega\, G_0$	$G_0 \to \omega f_1(1285)$

“Exotics” $J^{PC} = 0^{+-} \quad 0^{--} \quad 1^{-+} \quad 2^{+-} \quad 3^{-+} \quad 4^{+-} \ldots$

LQCD





mode	Γ_{PSS} (MeV)	Γ_{IKP} (MeV)	$\Gamma_{lattice}$ (MeV)
$\pi_1 \to f_1\pi$	10-18	14	25
$\pi_1 \to b_1\pi$	40-78	51	80

QCDSR

1^{-+} mass (GeV)	Ref
1.3	[92]
~ 1	[93]
1.7(1)	[94]
1.65(5)	[95]
1.81(6)	[96]

mass

$G_1(J^{PC} = 1^{-+}) \quad 1.1 - 1.34\ GeV$

AdS/QCD
Bellantuono Giannuzzi PC

candidates

	mass (MeV)	width (MeV)	decay modes
$\pi_1(1400)$	1354 ± 25	330 ± 35	$\eta\pi^0, \eta'\pi$
$\pi_1(1600)$	1662 ± 8	241 ± 40	$b_1(1235)\pi, \eta'\pi, f_1(1285)\pi$
$\pi_1(2015)$	$2014 \pm 20 \pm 16$	$230 \pm 32 \pm 73$	$\omega 2\pi, \eta' 3\pi$

widths do not fit
LQCD results

new analyses important (Jlab, CERN)

elusive heavy glueballs and hybrids

issues

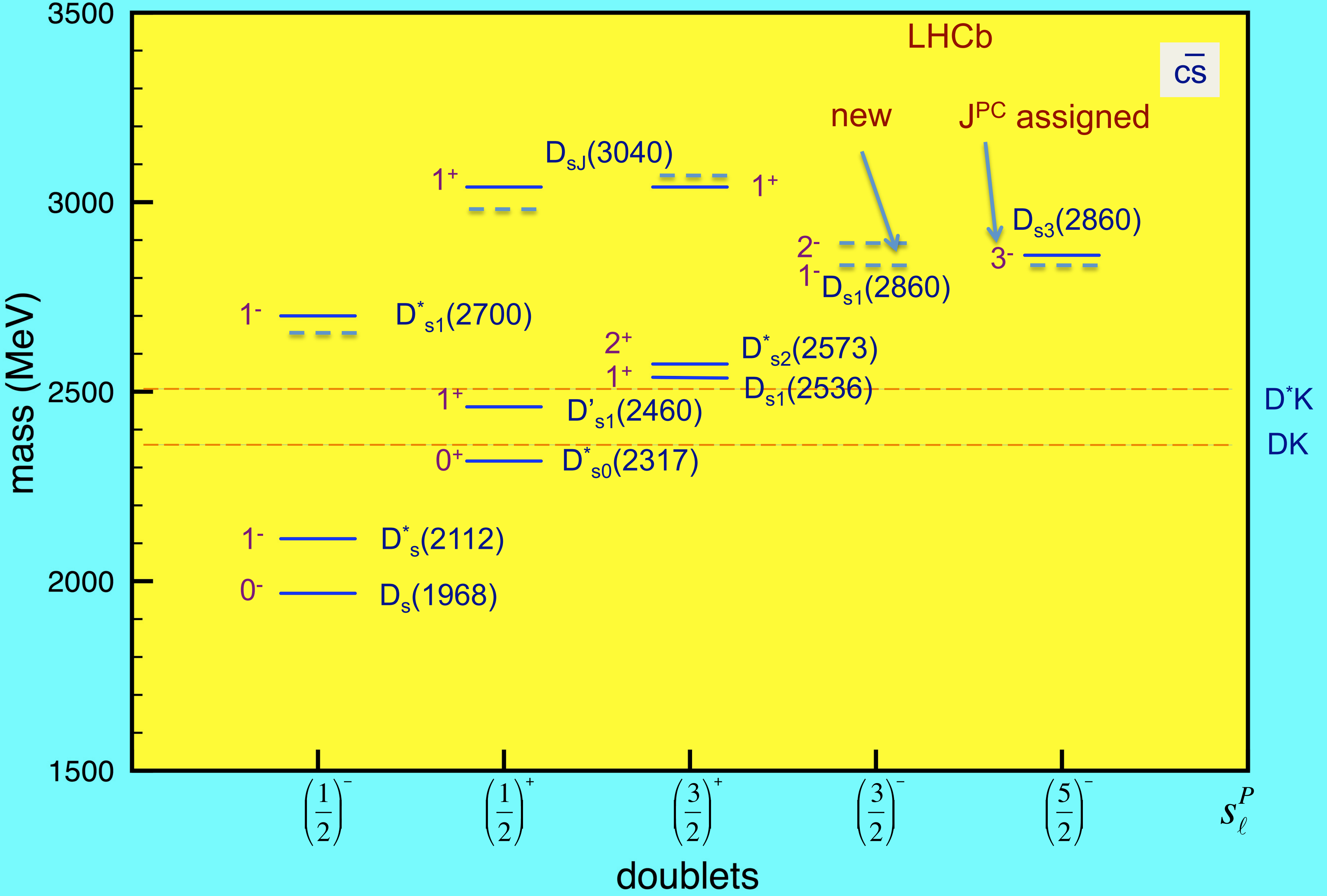
- classification of light tensors - qq vs glueballs

- heavy f_2 states

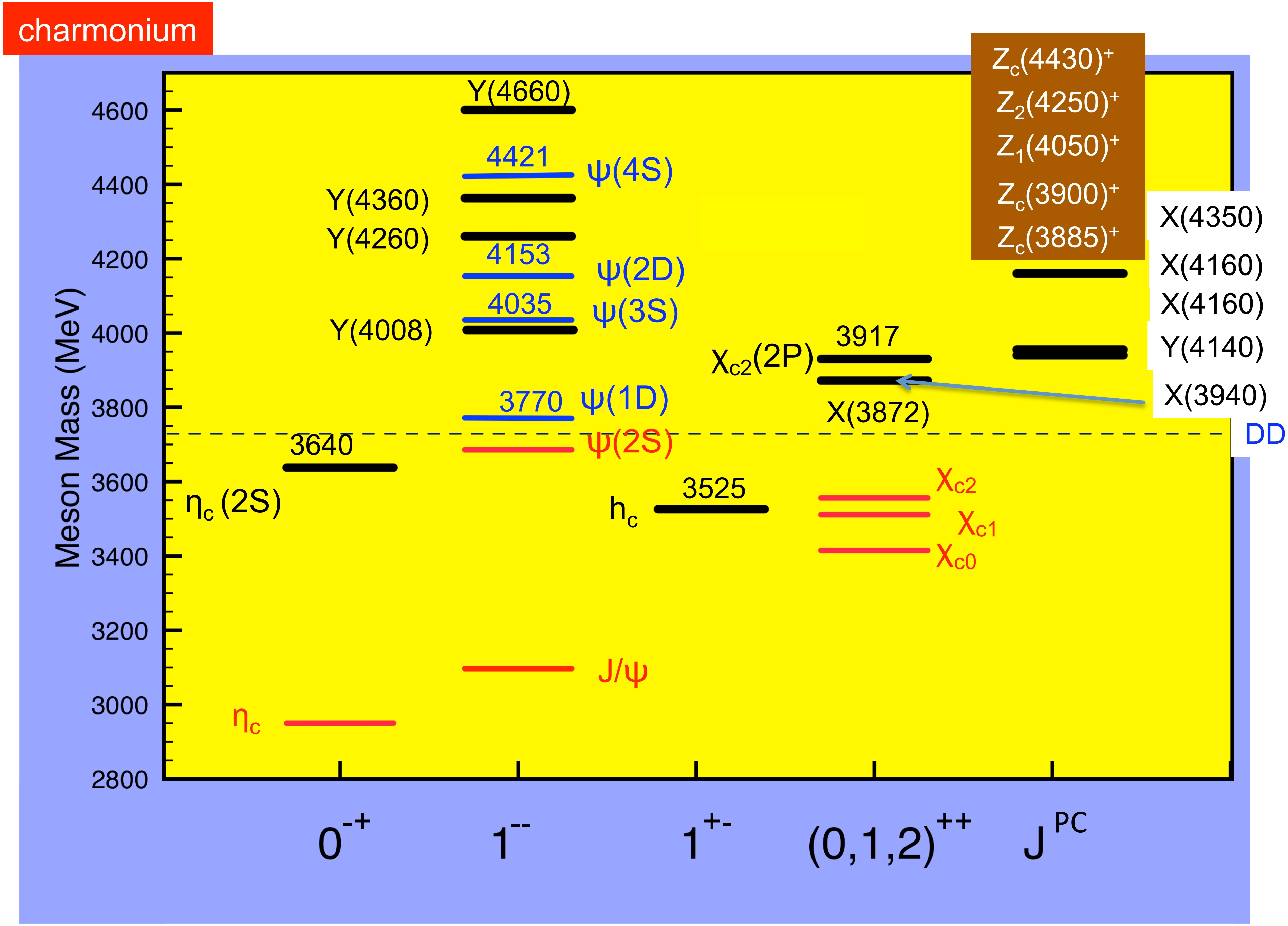
- exotic glueballs
  where to look for them?

- hybrid multiplets
  any connection with cc [Y(4260) 1^{--}] and bb candidates?

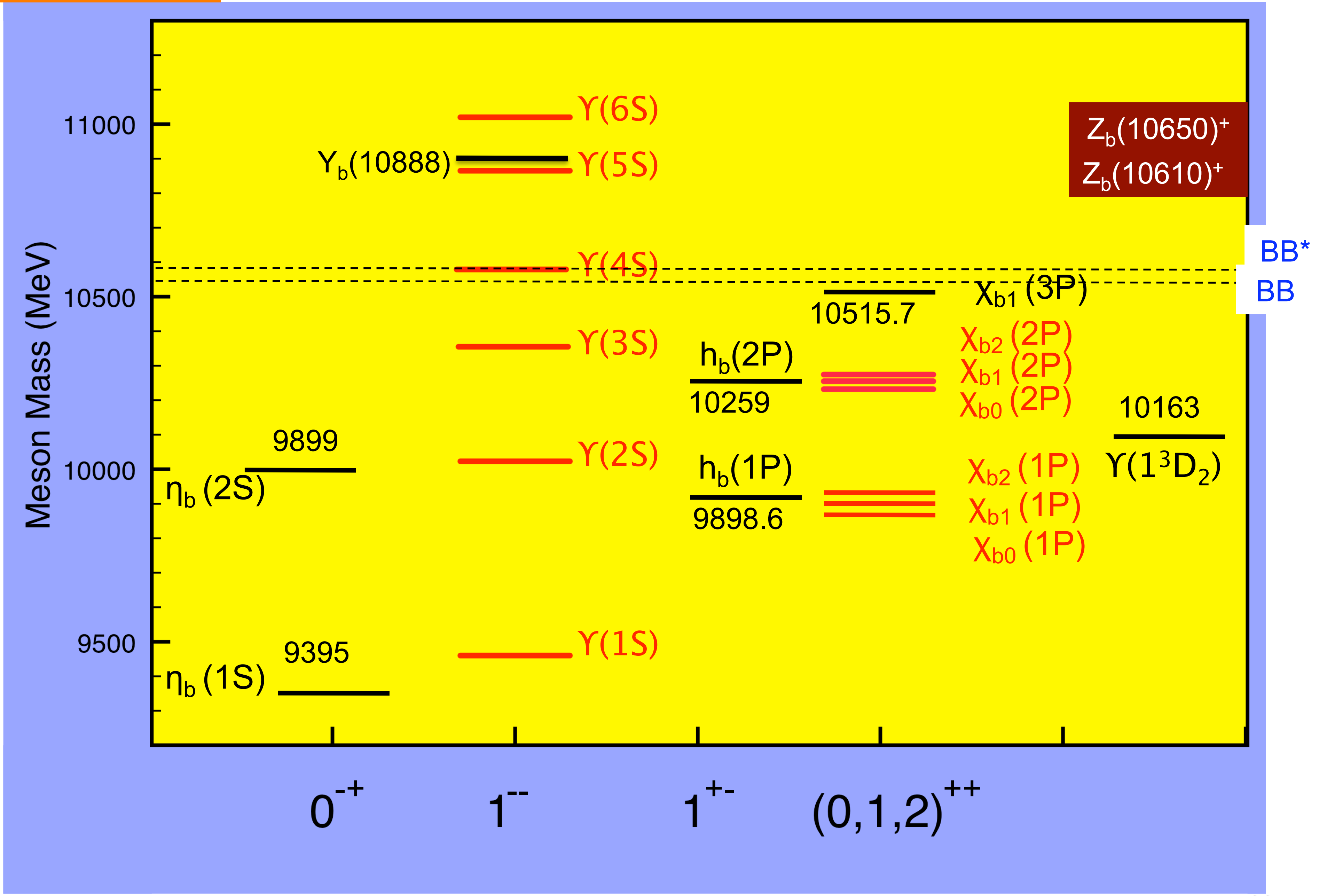
HEAVY MESONS



LHCb
cs̄
new
J^PC assigned
3500
3000
2500
2000
1500
mass (MeV)
1+
DsJ(3040)
1+
2-
1-
Ds1(2860)
Ds3(2860)
3-
1-
D*s1(2700)
2+
D*s2(2573)
1+
Ds1(2536)
1+
D's1(2460)
0+
D*s0(2317)
D*K
DK
1-
D*s(2112)
0-
Ds(1968)
(1/2)-
(1/2)+
(3/2)+
(3/2)-
(5/2)-
doublets


charmonium
Meson Mass (MeV)
4600
4400
4200
4000
3800
3600
3400
3200
3000
2800
Y(4660)
4421
ψ(4S)
Y(4360)
Y(4260)
4153
ψ(2D)
4035
ψ(3S)
Y(4008)
3917
Xc2(2P)
3770
ψ(1D)
X(3872)
3640
ψ(2S)
DD
ηc (2S)
3525
hc
Xc2
Xc1
Xc0
J/ψ
ηc
Zc(4430)+
Z2(4250)+
Z1(4050)+
Zc(3900)+
Zc(3885)+
X(4350)
X(4160)
X(4160)
Y(4140)
X(3940)
0-+
1--
1+-
(0,1,2)++
J PC

bottomonium



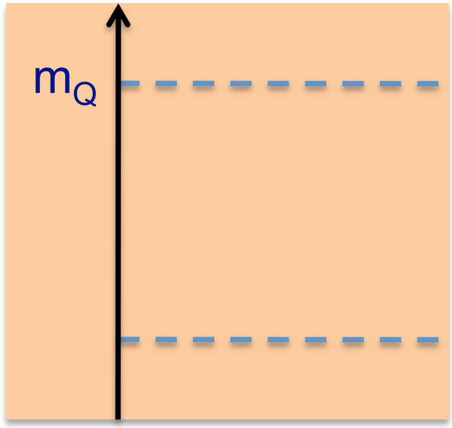
QCD Effective Theories

Qq: energy scales

$$p_H^\mu = m_H v$$

$$p_Q^\mu = m_Q v_Q = m_Q v + k \quad \Rightarrow \quad v_Q = v + \frac{k}{m_Q} \xrightarrow[m_Q \to \infty]{} v_Q = v$$

k: O(Λ_{QCD})



separation of scales -> effective theory

Effective Field Theory for qQ

$$\mathrm{L}_{\mathrm{eff},\,1/\mathrm{m}} = \bar{h}_v \, iv \cdot D \, h_v + \frac{1}{2m_Q} \bar{h}_v \, (i \not{D}_\perp)^2 h_v + \frac{g_s}{4m_Q} \bar{h}_v \, \sigma_{\alpha\beta} \mathrm{G}^{\alpha\beta} h_v + O\left(\frac{1}{m_Q^2}\right)$$

powerful symmetry
degenerate spin multiplets

$$h_v(x) = e^{im_Q v \cdot x} \frac{1+\not{v}}{2} Q(x)$$

$$D_\perp^\mu = D^\mu - (v \cdot D) v^\mu$$

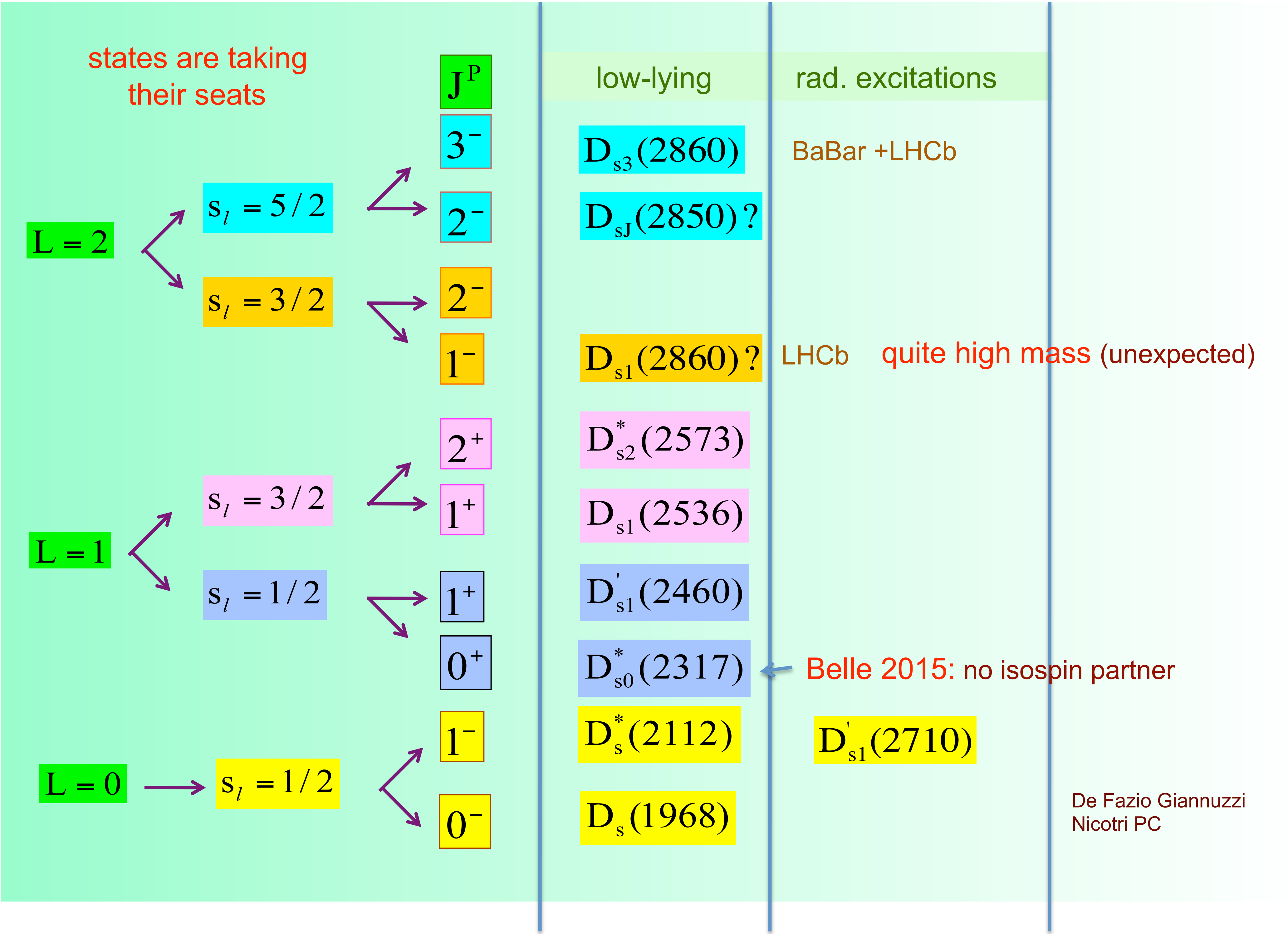
doublets $J = s_\ell \pm \frac{1}{2}$

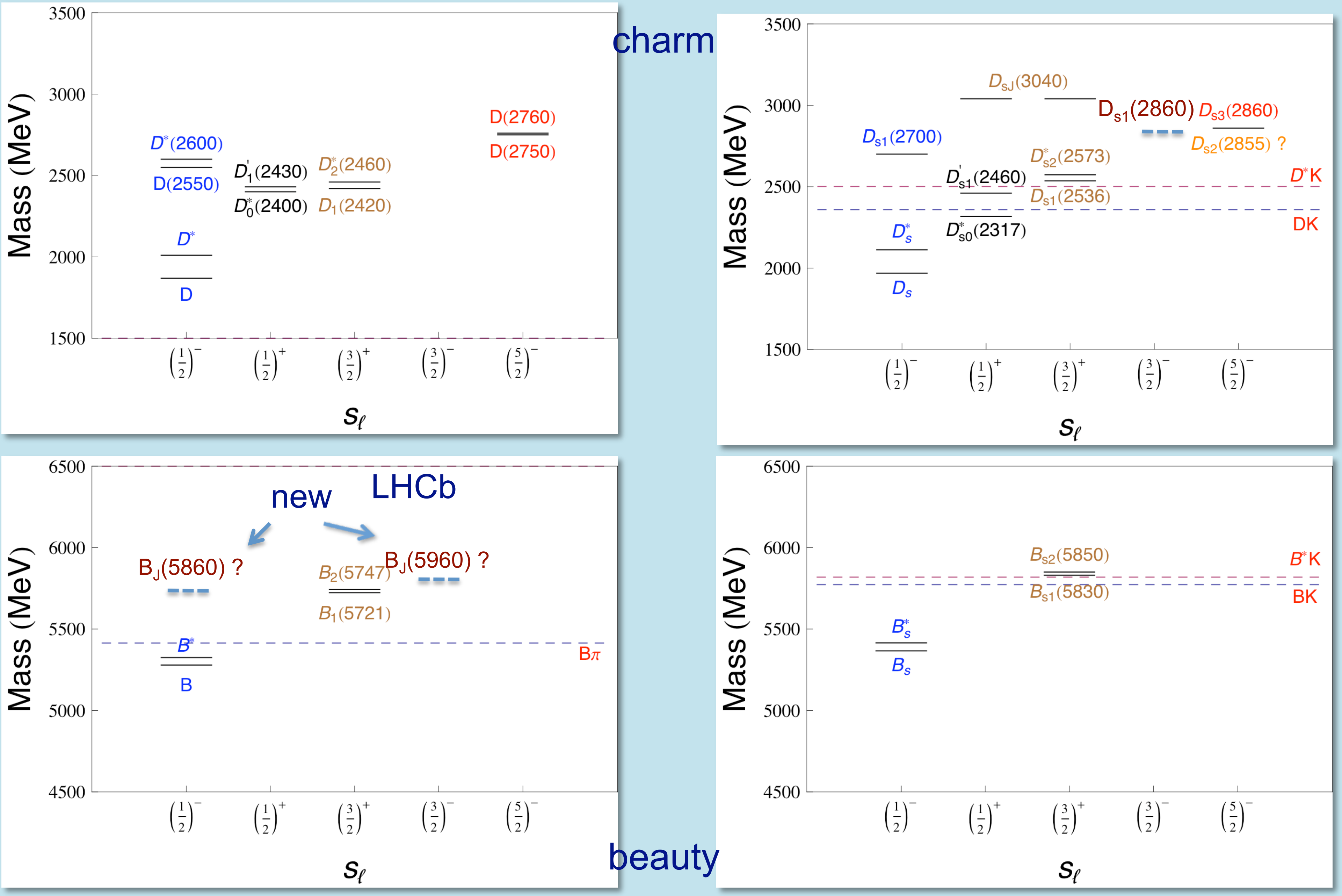
$$M_{H_Q} = m_Q + \bar{\Lambda} + \frac{\mu_\pi^2 - \mu_G^2}{2m_Q} + \mathcal{O}\left(\frac{1}{m_Q^2}\right)$$

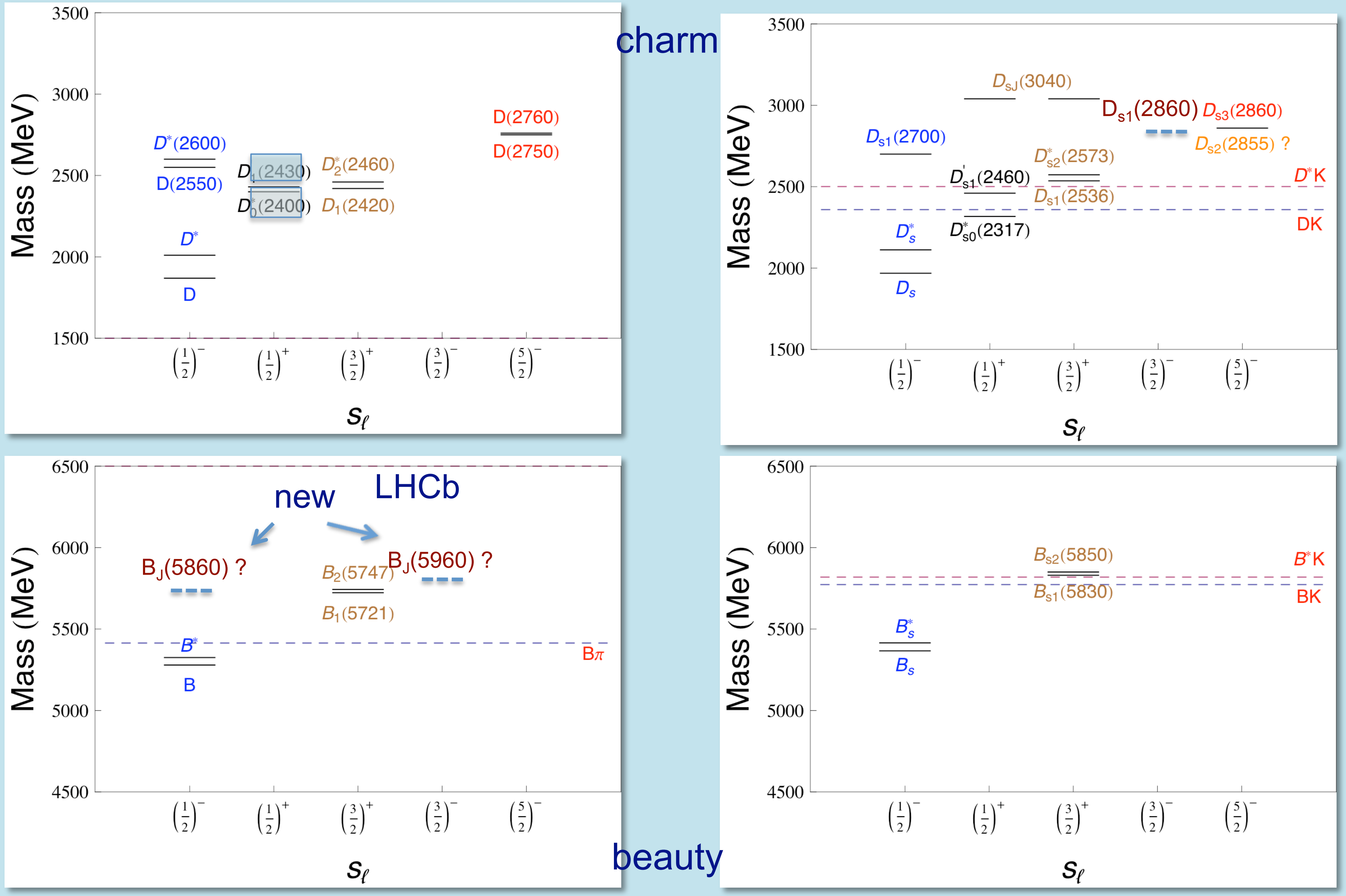
spin/flavour symmetry broken at $O(1/m_Q)$

$$\mu_\pi^2 = \frac{1}{2m_Q} \langle H_Q|\bar{h}_v(i \not{D}_\perp)^2 h_v|H_Q\rangle ,$$

$$\mu_G^2 = \frac{1}{2m_Q} \langle H_Q|\bar{h}_v \frac{g_s \sigma_{\alpha\beta} G^{\alpha\beta}}{2} h_v|H_Q\rangle$$


states are taking their seats
J^P
low-lying
rad. excitations
$L = 2$
$s_l = 5/2$
$s_l = 3/2$
3^-
2^-
2^-
1^-
$D_{s3}(2860)$
BaBar +LHCb
$D_{sJ}(2850)$?
$D_{s1}(2860)$?
LHCb
quite high mass (unexpected)
$L = 1$
$s_l = 3/2$
$s_l = 1/2$
2^+
1^+
1^+
0^+
$D^*_{s2}(2573)$
$D_{s1}(2536)$
$D'_{s1}(2460)$
$D^*_{s0}(2317)$
Belle 2015: no isospin partner
$L = 0$
$s_l = 1/2$
1^-
0^-
$D^*_s(2112)$
$D_s(1968)$
$D'_{s1}(2710)$
De Fazio Giannuzzi
Nicotri PC


charm
beauty
Mass (MeV)
s_ℓ
3500
3000
2500
2000
1500
$D^*(2600)$
D(2550)
D^*
D
$D_1'(2430)$
$D_0^*(2400)$
$D_2^*(2460)$
$D_1(2420)$
D(2760)
D(2750)
$D_{sJ}(3040)$
$D_{s1}(2860)$
$D_{s3}(2860)$
$D_{s2}(2855)$?
$D_{s1}(2700)$
$D_{s1}'(2460)$
$D_{s2}^*(2573)$
$D_{s1}(2536)$
$D_{s0}^*(2317)$
D_s^*
D_s
D^*K
DK
6500
6000
5500
5000
4500
new
LHCb
$B_J(5860)$?
$B_2(5747)$
$B_J(5960)$?
$B_1(5721)$
B^*
B
$B\pi$
$B_{s2}(5850)$
$B_{s1}(5830)$
B^*K
BK
B_s^*
B_s
$\left(\frac{1}{2}\right)^-$
$\left(\frac{1}{2}\right)^+$
$\left(\frac{3}{2}\right)^+$
$\left(\frac{3}{2}\right)^-$
$\left(\frac{5}{2}\right)^-$


charm
beauty
Mass (MeV)
s_ℓ
$D^*(2600)$
D(2550)
D^*
D
$D_1(2430)$
$D_0^*(2400)$
$D_2^*(2460)$
$D_1(2420)$
D(2760)
D(2750)
$D_{s1}(2700)$
$D_{sJ}(3040)$
$D_{s1}(2860)$
$D_{s3}(2860)$
$D_{s2}(2855)$?
$D_{s2}^*(2573)$
$D_{s1}'(2460)$
$D_{s1}(2536)$
$D_{s0}^*(2317)$
D_s^*
D_s
D^*K
DK
new
LHCb
$B_J(5860)$?
$B_J(5960)$?
$B_2(5747)$
$B_1(5721)$
B^*
B
$B\pi$
$B_{s2}(5850)$
$B_{s1}(5830)$
B_s^*
B_s
B^*K
BK

How does chiral symmetry/breaking work in heavy-light mesons?

Bardeen Eichten Hill

precision tests

couplings of chiral doublets

$s_\ell^P = \frac{1}{2}^-$ vs $s_\ell^P = \frac{1}{2}^+$

$\left(0^-, 1^-\right)$ vs $\left(0^+, 1^+\right)$

heavier doublets

$s_\ell^P = \frac{3}{2}^-$ vs $s_\ell^P = \frac{3}{2}^+$

couplings to light mesons

flavour independence

charm vs beauty

spin and flavour symmetries for Qqq baryons

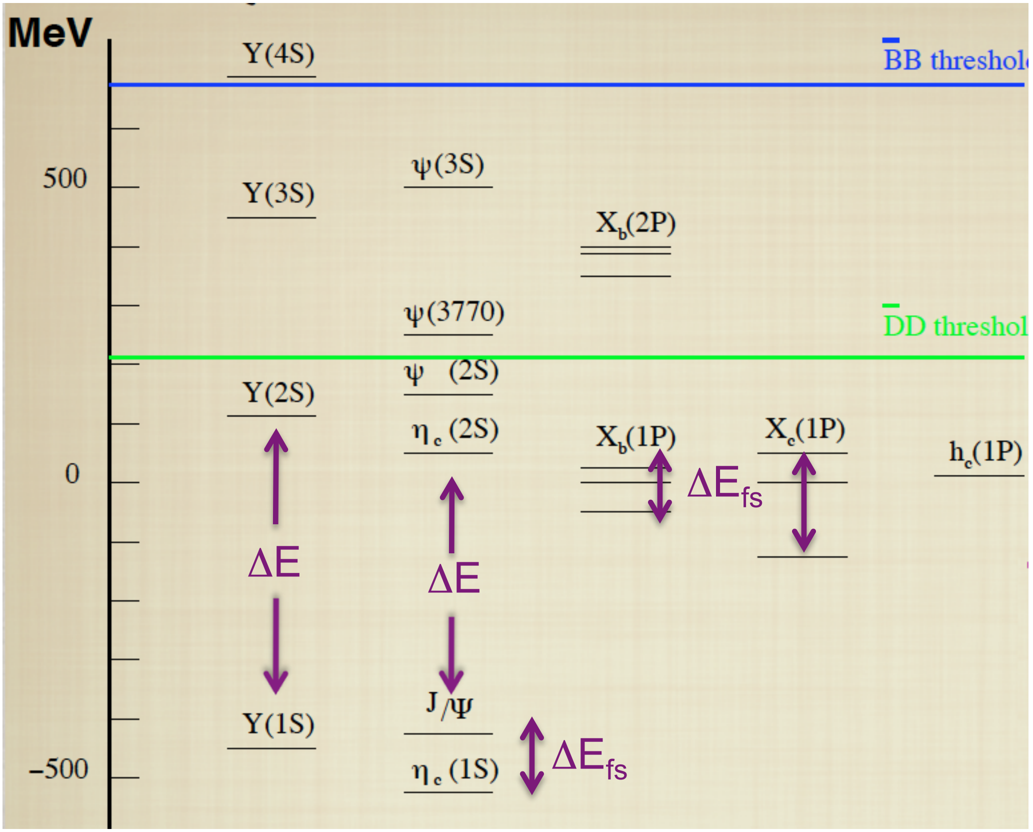
	mass (MeV)
Λ_b	5619.5 ± 0.4
$\Lambda_b(5912)$	$5912.1 \pm 0.1 \pm 0.4$
$\Lambda_b(5920)$	5919.73 ± 0.32
Σ_b	$5811^{+0.9}_{-0.8} \pm 0.17$
Σ_b^*	$5832 \pm 0.7^{+1.7}_{-1.8}$
Ξ_b	5794 ± 0.9
$\Xi_b(5945)$	$5949.3 \pm 0.8 \pm 0.9$
Ω_b	6048.8 ± 3.2

new observations/measurements

systematic study required

EFT for QQq baryons

$Q\bar{Q}$



$m_b >> \Lambda_{QCD}$ $\alpha_s(m_b) << 1$

$m_c > \Lambda_{QCD}$ $\alpha_s(m_c) < 1$

$m_Q \, v \approx r^{-1}$

$\Delta E \approx m_Q v^2$ $\Delta E_{fs} \approx m_Q v^4$

$v_b^2 \approx 0.1$ $v_c^2 \approx 0.3$

zero at the mass of $\chi_b(1P)$, $\chi_c(1P)$

hierarchy of scales

$m_Q >> m_Q v >> m_Q v^2$

separation of scales -> effective theory

Effective Field Theories for quarkonium

singlet and octet color dof

m_Q — QCD — hard momenta

μ $\quad \frac{E_\lambda}{E_\Lambda} = \frac{m_Q v}{m_Q}$

$m_Q v$ — NRQCD — soft momenta

μ' $\quad \frac{E_\lambda}{E_\Lambda} = \frac{m_Q v^2}{m_Q v}$

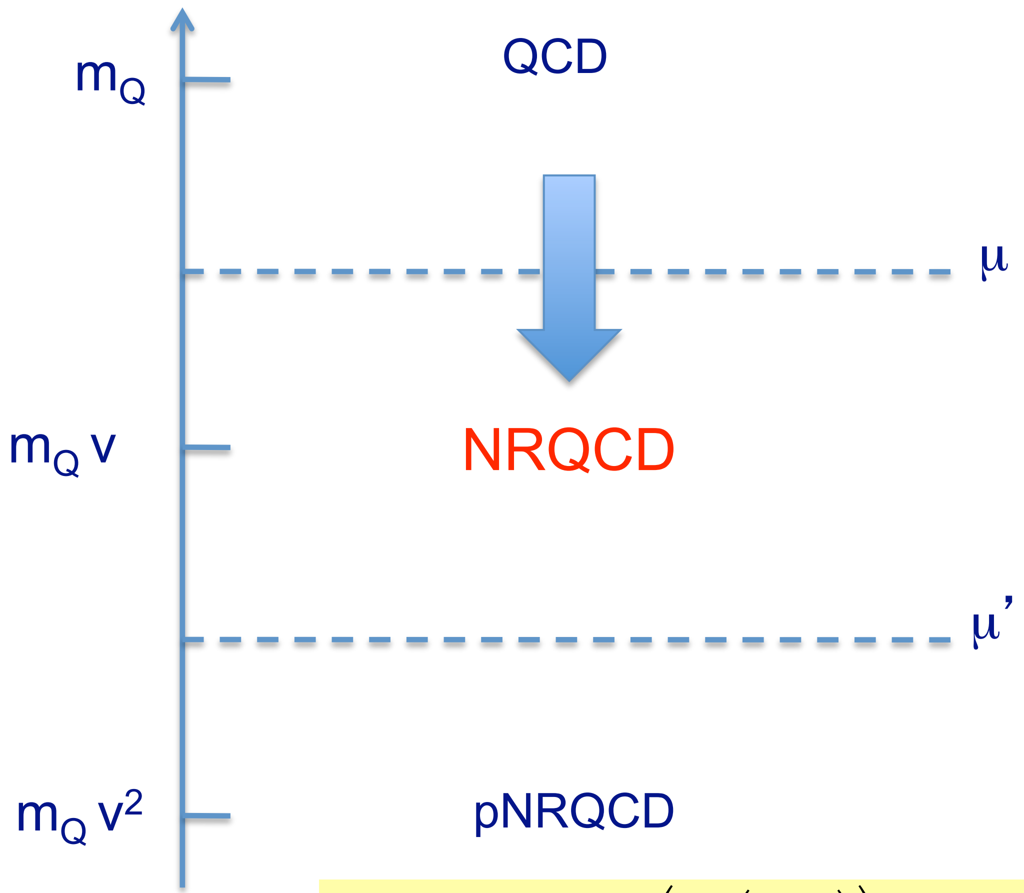
$m_Q v^2$ — pNRQCD — ultra-soft momenta

$$L_{EFT} = \sum_k c_k\left(\frac{E_\Lambda}{\mu}\right)\frac{O_k(\mu,\lambda)}{E_\Lambda^k}$$

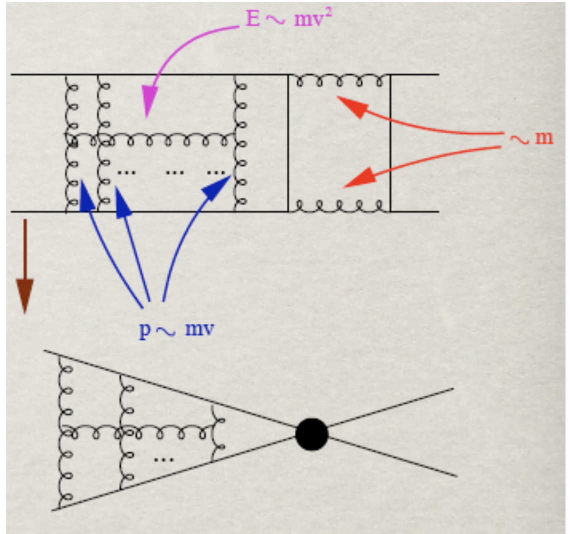
Wilson coefficients

operators

Effective Field Theories for quarkonium



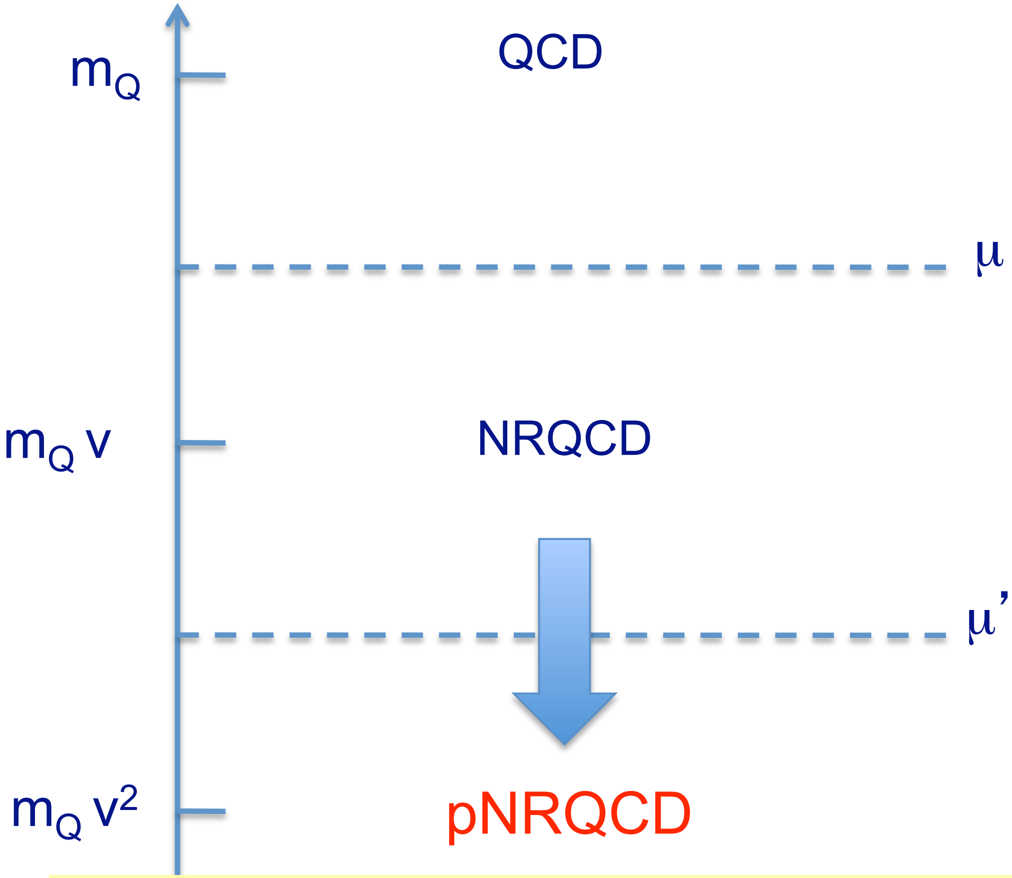
$$L_{NRQCD} = \sum_k c_k\left(\alpha_s\left(\frac{m_Q}{\mu}\right)\right)\frac{O_k(\mu,\lambda)}{m_Q^k}$$



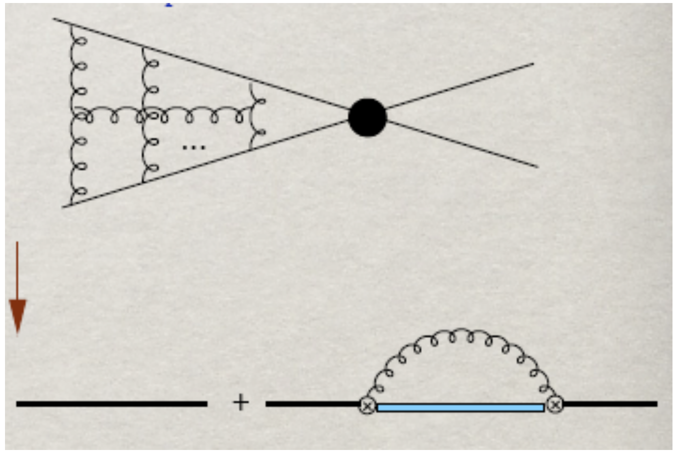
quarkonium production and decays

Caswell Lepage
Thacker
Bodwin Braaten
………

Effective Field Theories for quarkonium



bound state properties

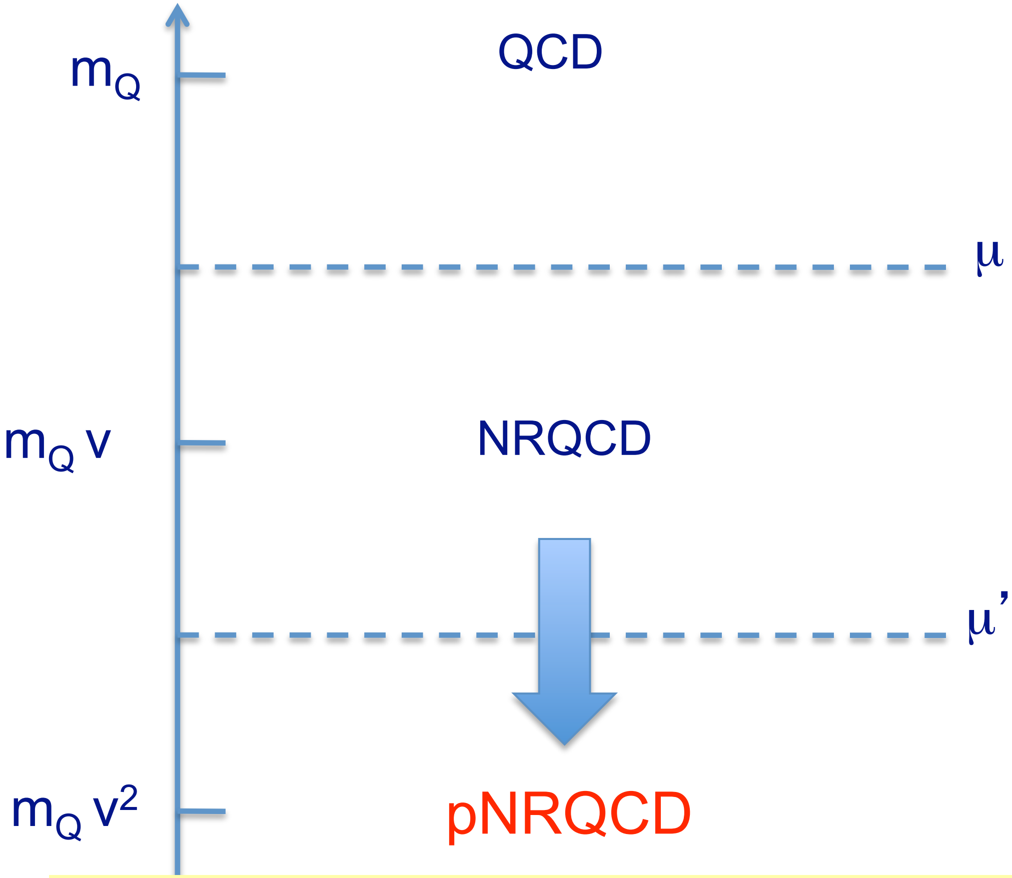


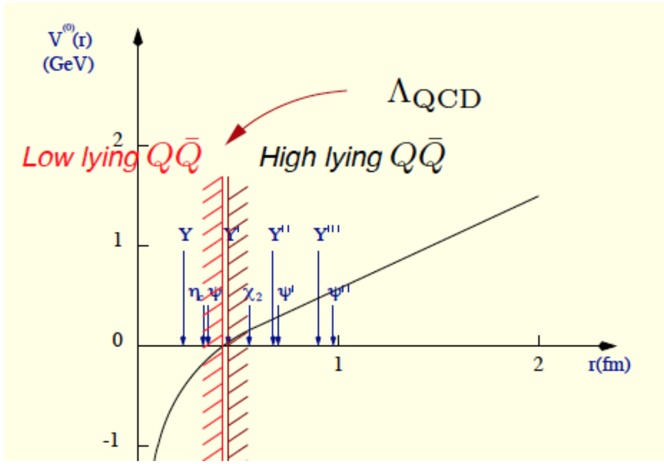
$$L_{pNRQCD} = \sum_k \frac{1}{m_Q^k} c_k\left(\alpha_s\left(\frac{m_Q}{\mu}\right)\right) \sum_n V(r\mu, r\mu')\; O_n(\mu',\lambda) r^n$$

Wilson coefficient

Luke Manohar Savage
Brambilla Pineda Soto Vairo
Beneke Smirnov
Labelle Grinstein Rothstein
Hoang Kniehl Penin
Stewart ....

Effective Field Theories for quarkonium





role of the QCD scale Λ_{QCD}:
potential perturbative if $m_Q v >> \Lambda_{QCD}$
nonperturbative if $m_Q v \ll \Lambda_{QCD}$

Brambilla, Pineda, Soto, Vairo,…

$$L_{pNRQCD} = \sum_k \frac{1}{m_Q^k} c_k\left(\alpha_s\left(\frac{m_Q}{\mu}\right)\right) \sum_n V(r\mu, r\mu') \, O_n(\mu',\lambda) r^n$$

Wilson coefficient

Effective Field Theories for quarkonium

$$\mathcal{L} = -\frac{1}{4}F^a_{\mu\nu}F^{\mu\nu\,a} + \mathrm{Tr}\left\{\mathrm{S}^\dagger\left(i\partial_0 - \frac{\mathbf{p}^2}{m} - V_s\right)\mathrm{S} + \mathrm{O}^\dagger\left(iD_0 - \frac{\mathbf{p}^2}{m} - V_o\right)\mathrm{O}\right\}$$

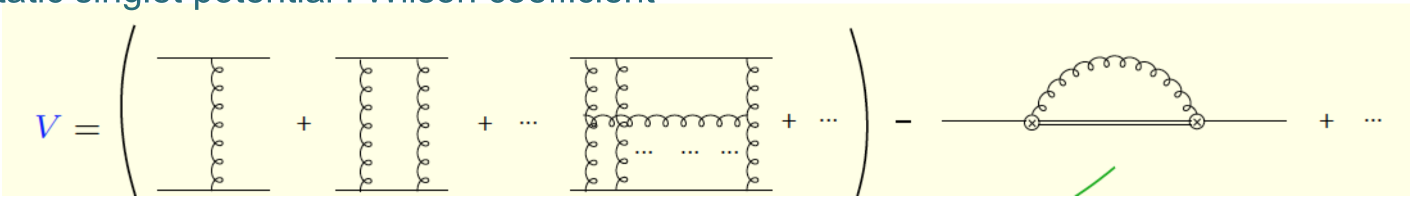
$$+V_A\,\mathrm{Tr}\left\{\mathrm{O}^\dagger\mathbf{r}\cdot g\mathbf{E}\,\mathrm{S} + \mathrm{S}^\dagger\mathbf{r}\cdot g\mathbf{E}\,\mathrm{O}\right\} + \frac{V_B}{2}\mathrm{Tr}\left\{\mathrm{O}^\dagger\mathbf{r}\cdot g\mathbf{E}\,\mathrm{O} + \mathrm{O}^\dagger\mathrm{O}\mathbf{r}\cdot g\mathbf{E}\right\} + \cdots$$

S, O singlet and octet field

V_S, V_O static singlet and octet potential

NLO terms ~ r

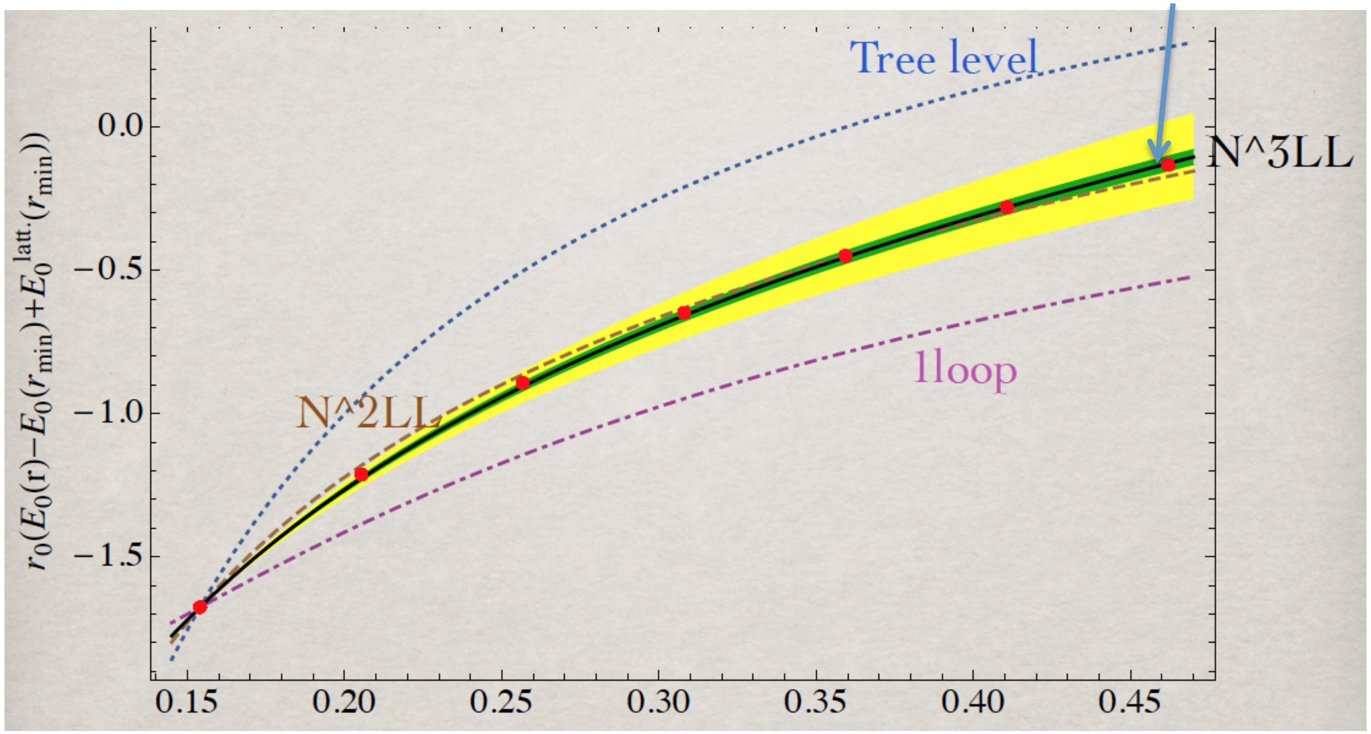
V_S static singlet potential : Wilson coefficient



$$V_s(r,\mu) = -C_F\frac{\alpha_s(1/r)}{r}\left[1 + a_1\frac{\alpha_s(1/r)}{4\pi} + a_2\left(\frac{\alpha_s(1/r)}{4\pi}\right)^2 + \left(\frac{16\,\pi^2}{3}C_A^3\,\ln r\mu + a_3\right)\left(\frac{\alpha_s(1/r)}{4\pi}\right)^3 + \left(a_4^{L2}\ln^2 r\mu + \left(a_4^L + \frac{16}{9}\pi^2\,C_A^3\beta_0(-5+6\ln 2)\right)\ln r\mu + a_4\right)\left(\frac{\alpha_s(1/r)}{4\pi}\right)^4\right]$$

V_S static singlet potential

lattice QCD: Necco Sommer 2009



r/r_0

Brambilla Garcia Soto Vairo 2010

Results in heavy quark spectroscopy

- B_c mass at NNLO
- B^*_c , $\eta_{c,b}$ mass at NLL
- QQ 1P fine splittings at NLO
- Υ(1S) -> $\eta_b \gamma$, J/ψ-> $\eta_c \gamma$
- σ_{tt} at NNLL

$$\Gamma(J/\psi \to \gamma\eta_c) = 2.12(40) KeV$$

$$\Gamma(\Upsilon(1S \to \gamma\eta_b) = 15.18(51) eV$$

$$\Gamma(\eta_b(1S) \to \gamma\gamma) = 0.54 \pm 0.15 \text{ keV} .$$

$$\Gamma(\eta_b(1S) \to \text{ LH}) = \text{7-16 MeV}$$

QWG

$Q\bar{Q}$ - spin symmetry in the heavy quark limit

Spin multiplets

L=0

$$J=\frac{1+\not v}{2}\left[H_1^{\mu}\gamma_{\mu}-H_0\gamma_5\right]\frac{1-\not v}{2}$$

J=1 J=0

$J/\psi \quad \eta_c$

L=1

$$J^{\mu}=\frac{1+\not v}{2}\left[H_1^{\mu\alpha}\gamma_{\alpha}+\frac{1}{\sqrt{2}}\varepsilon^{\mu\alpha\beta\gamma}v_{\alpha}\gamma_{\beta}H_{1\gamma}+\frac{1}{\sqrt{3}}\left(\gamma^{\mu}-v^{\mu}\right)H_0+K_{\mu}^{1}\gamma_5\right]\frac{1-\not v}{2}$$

J=2 J=1 J=0 J=1

$\chi_{c\,2,1,0} \quad h_c$

L=2

$$J^{\mu\nu}=\frac{1+\not v}{2}\left[H_3^{\mu\nu\alpha}\gamma_{\alpha}+\frac{1}{\sqrt{6}}(\ldots)H_{2\gamma}^{\mu}+(\ldots)H_1^{\mu}+K_2^{\mu\nu}\gamma_5\right]\frac{1-\not v}{2}$$

J=3 J=2 J=1 J=2

${}^3D_{3,2,1} \quad {}^1D_2$

Effective Lagrangian for radiative transitions

De Fazio

P<->S

$$L_{nP\leftrightarrow mS}=\delta_Q^{nPmS}Tr\left[\bar{J}(mS)J_{\mu}(nP)\right]v_{\nu}F^{\mu\nu}+hc$$

D<->P

$$L_{nD\leftrightarrow mP}=\delta_Q^{nDmP}Tr\left[\bar{J}_{\alpha}(mP)J_{\mu}^{\alpha}(nD)\right]v_{\nu}F^{\mu\nu}+hc$$

$$\mathcal{B}(\chi_{c0}(1P) \to J/\psi\,\gamma) = (1.28 \pm 0.11) \times 10^{-2}$$
$$\mathcal{B}(\chi_{c1}(1P) \to J/\psi\,\gamma) = (36.0 \pm 1.9) \times 10^{-2}$$
$$\mathcal{B}(\chi_{c2}(1P) \to J/\psi\,\gamma) = (20.0 \pm 1.0) \times 10^{-2}$$

→

$$\Gamma\big(h_c(1P) \to \eta_c(1P)\gamma\big) = 634 \pm 32\ keV$$

$$\mathcal{B}(\chi_{b0}(2P) \to \Upsilon(1S)\,\gamma) = (9 \pm 6) \times 10^{-3}$$
$$\mathcal{B}(\chi_{b0}(2P) \to \Upsilon(2S)\,\gamma) = (4.6 \pm 2.1) \times 10^{-2}$$
$$\mathcal{B}(\chi_{b1}(2P) \to \Upsilon(1S)\,\gamma) = (8.5 \pm 1.3) \times 10^{-2}$$
$$\mathcal{B}(\chi_{b1}(2P) \to \Upsilon(2S)\,\gamma) = (21 \pm 4) \times 10^{-2}$$
$$\mathcal{B}(\chi_{b2}(2P) \to \Upsilon(1S)\,\gamma) = (7.1 \pm 1.0) \times 10^{-2}$$
$$\mathcal{B}(\chi_{b2}(2P) \to \Upsilon(2S)\,\gamma) = (16.2 \pm 2.4) \times 10^{-2}$$

→

$$R_J^{(b)} = \frac{\Gamma\big(\chi_{bJ}(2P) \to Y(2S)\ \gamma\big)}{\Gamma\big(\chi_{bJ}(2P) \to Y(1S)\ \gamma\big)}$$

$$R_\delta^{(b)} = \frac{\delta_b^{2P1S}}{\delta_b^{2P2S}} = 8.8 \pm 0.7$$

charm

$$R_1^{(c)} = \frac{\Gamma\big(\chi_{c1}(2P) \to \psi(2S)\ \gamma\big)}{\Gamma\big(\chi_{c1}(2P) \to \psi(1S)\ \gamma\big)} = 1.64 \pm 0.25$$

$$R_X = \left.\frac{\Gamma\big(X(3872) \to \psi(2S)\ \gamma\big)}{\Gamma\big(X(3872) \to \psi(1S)\ \gamma\big)}\right|_{\exp} = 3.5 \pm 1.4$$

EFT for near threshold states

X(3872): if $D^0\ D^{*0}$ bound state
scale hierarchy

$$\Lambda_{QCD} >> m_\pi >> \frac{m_\pi^2}{M_{D^0}} >> E_{binding} \cong 0.1\ MeV$$

1^{--} above threshold states (Y(4260)) strongly coupled to
$J/\psi\ \pi\ \pi$, $\psi'\ \pi\ \pi$, $J/\psi\ \omega$, $J/\psi\ \eta$

what about conventional charmonium/bottomonium?
what about near threshold bottomonium?

EFT for other quark configurations (hadro-charmonium) ?

WHY STUDYING QCD SPECTROSCOPY IN THE LHC ERA?

our knowledge of fundamental interactions
is not complete

confinement and chiral symmetry breaking characterize strong interactions

spectroscopy is a tool to learn about confinement/χsB

ab initio: LQCD, QCDSr
scale hierarchies identified -> effective theories (pert. th. + external input)

long list of poorly (or not) understood issues

vast investigation programme
results envisaged for curious open-minded researchers