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Hadron Physics, a quark-model analysis.

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Sixth International Conference on PERSPECTIVES IN HADRONIC PHYSICS

Hadron structure: quark-model analysis

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Outline

- QCD: Hadron physics & constituent quark model
- Heavy hadrons
  - Heavy baryons: New bottom states, doubly heavy states.
  - Heavy mesons: New open-charm and hidden charm states.
- Light hadrons
  - Light mesons: Scalar mesons.
  - Light baryons: Improving its description.
- Multiquarks
  - Exotic states.

Non-exotic multiquark states

Advances (Exp.) $\Rightarrow$ Challenges (Theor.)

- Summary

QCD. Hadron physics & quark model

QCD is the correct theory of the strong interaction. It has been tested to very high accuracy in the perturbative regime. The low energy sector ("strong QCD"), i.e. hadron physics, remains challenging

I am convinced that the keys to a qualitative understanding of "strong QCD" [1] are the same as in most other areas of physics: identifying the appropriate degrees of freedom and the effective forces between them.

N. Isgur, Overview talk at N*2000, nucl-th/0007008

All roads lead to valence "constituent quarks" and effective forces inspired in the properties of QCD: asymptotic freedom, confinement and chiral symmetry $\Rightarrow$ Constituent quark models

Constituent quarks (appropriate degrees of freedom) behave in a remarkably simple fashion (CDF)

Effective forces: confining mechanism, a spin-spin force (ρ-π, Δ-N) and a long-range force

The limitations of the quark model are as obvious as its successes. Nevertheless almost all hadrons can be classified as relatively simple configurations of a few confined quarks.

Although quark models differ in their details, the qualitative aspects of their spectra are determined by features that they share in common, these ingredients can be used to project expectations for new sectors.

Almost all known hadrons can be described as bound states of qqq or $q\bar{q}$:

• QCD conserves the number of quarks of each flavor, hadrons can be labeled by their minimun, or VALENCE, quark content: BARYONS and MESONS. QCD can augment this with flavor neutral pairs

$$\Lambda \Rightarrow uds \ (+ \bar{u}u + s\bar{s} + ...)$$

• NON-EXOTIC MULTIQUARK states do not in general correspond to stable hadrons or even resonances. Most, perharps even all fall apart into valence mesons and baryons without leaving more than a ripple on the meson-meson or meson-baryon scattering amplitude. If the multiquark state is unsually light or sequestered from the scattering channel, it may be prominent. If not, it is just a silly way of enumerating the states of the continuum.

• Hadrons whose quantum numbers require a valence quark content beyond qqq or $q\bar{q}$ are termed EXOTICS (hybrids, $q\bar{q}g$) $\theta^+ \Rightarrow uudd\bar{s}$

Exotics are very rare in QCD, perhaps entirely absent. The existence of a handful of exotics has to be understood in a framework that also explains their overall rarity

We have the tools to deepen our understanding of "strong QCD"

- Powerful numerical techniques imported from few-body physics
  - Faddeev calculations in momentum space *[Rept. Prog. Phys. 68, 965(2005)]*
  - Hyperspherical harmonic expansions *[Phys. Rev. D 73 054004 (2006)]*
  - Stochastic variational methods *[Lect. Not. Phys. M 54, 1 (1998)]*
- Increasing number of experimental data

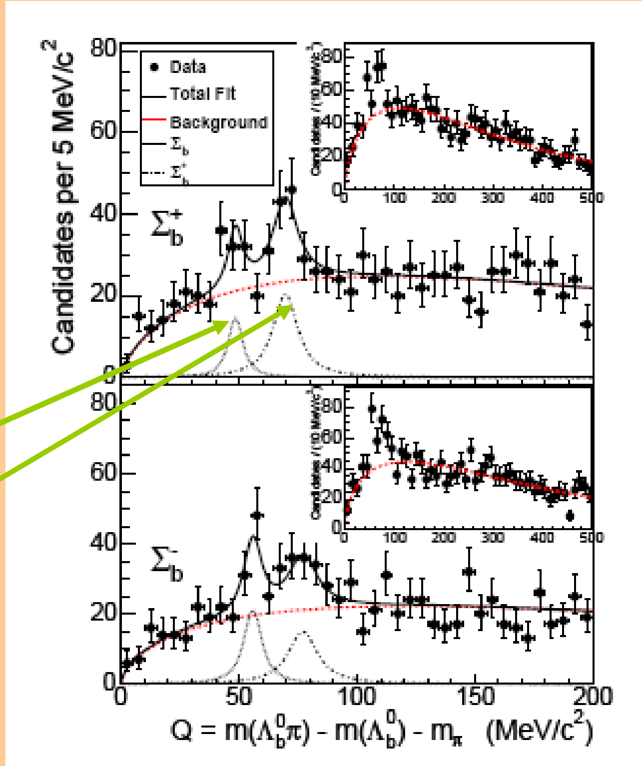
Heavy baryons

1985 Bjorken: " We should strive to study triply charmed baryons because their excitation spectrum should be close to the perturbative QCD regime. For their size scales the quark-gluon coupling constant is small and therefore the leading term in the perturbative expansion may be enough"

nnQ   nQQ   QQQ

- The larger the number of heavy quarks the simpler the system
- nQQ and QQQ $\Rightarrow$ one-gluon exchange and confinement
- nnQ $\Rightarrow$ there is still residual interaction between light quarks
- nnQ and nQQ $\Rightarrow$ the presence of light and heavy quarks may allow to learn about the dynamics of the light diquark subsystem
- Ideal systems to check the assumed flavor independence of confinement

State	J^P	Q=Strange	Q=Charm	Q=Bottom
Λ (udQ)	1/2+	1116, 1600	2286, 2765[1]	5625
	3/2+	1890	2940[3]	
	1/2−	1405, 1670	2595	
	3/2−	1520, 1690	2628, 2880[1]	
	5/2+	1820	2880[1]	
Σ (uuQ)	1/2+	1193, 1660	2454	5811[5]
	3/2+	1385, 1840	2518, 2940[3]	5833[5]
	1/2−	1480, 1620	2765[1]	
	3/2−	1560, 1670	2800[2]	
Ξ (usQ)	1/2+	1318	2471, 2578	5792[5]
	3/2+	1530	2646, 3076[2]	
	1/2−		2792, 2980[2]	
	3/2−	1820	2815	
	5/2+		3055[3], 3123[3]	
Ω (ssQ)	1/2+		2698	
	3/2+	1672	2768[3]	
Ξ (uQQ)	3/2−	--	3519[4]	

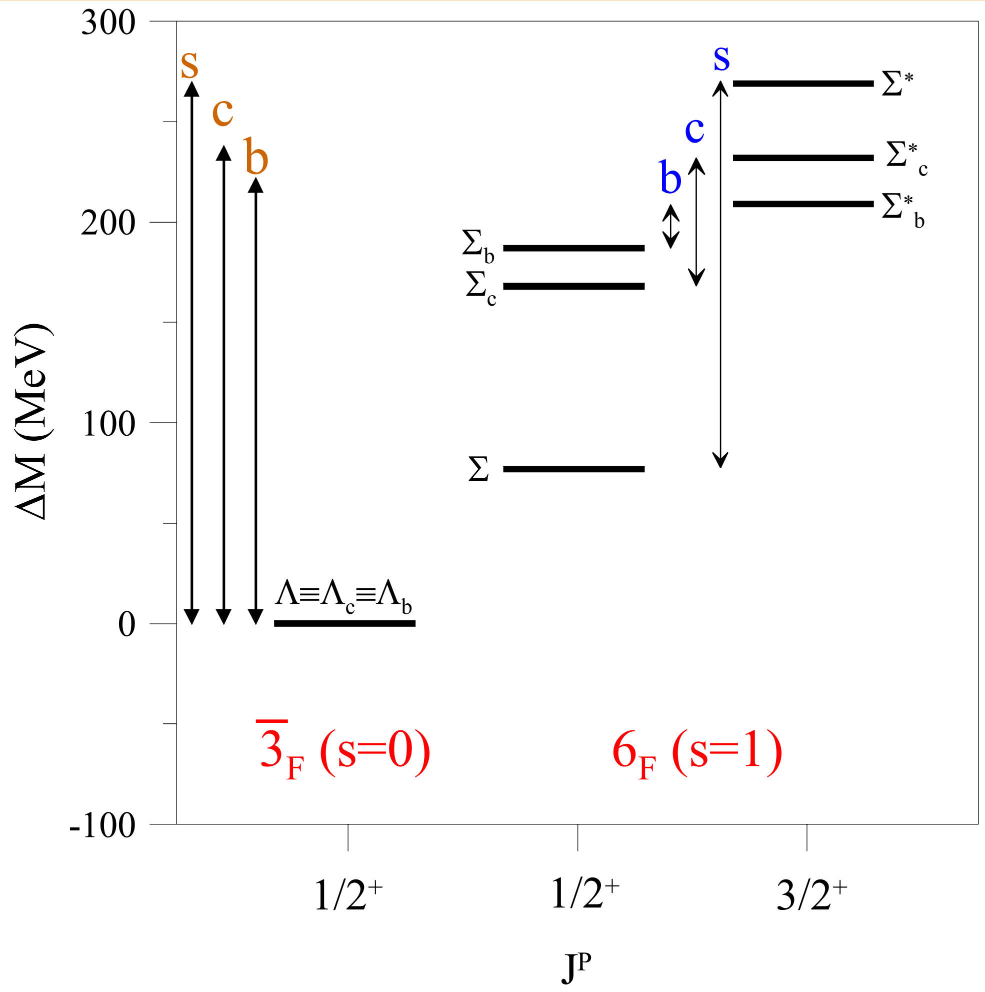


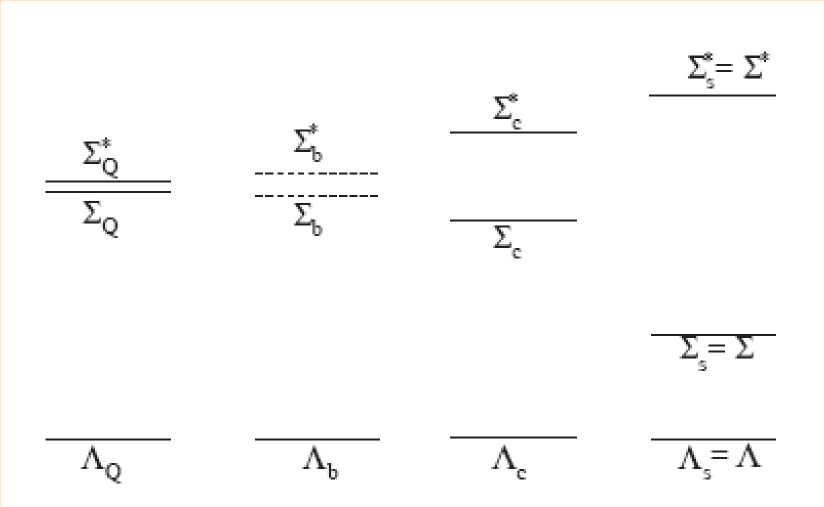
CDF, Phys.Rev.Lett.99, 202001 (2007)

1 ⇒ CLEO
2 ⇒ Belle
3 ⇒ BaBar
4 ⇒ SELEX
5 ⇒ CDF

Regularities ⇒ ΔL=1 300 MeV
Δn=1 500 MeV

Heavy baryons: I.a. Spin splitting





Heavy baryons: I.a. Spin splitting

Roberts et al., arXiV:0711.2492   Valcarce et al., submitted to PRD

ΔM (MeV)	Exp.	OGE(μ)	OGE +OPE
$\Sigma_c(3/2^+) - \Lambda_c(1/2^+)$	232	251	217
$\Sigma_c(3/2^+) - \Sigma_c(1/2^+)$	64	64	67
$\Sigma_b(3/2^+) - \Lambda_b(1/2^+)$	209	246	205
$\Sigma_b(3/2^+) - \Sigma_b(1/2^+)$	22	25	22

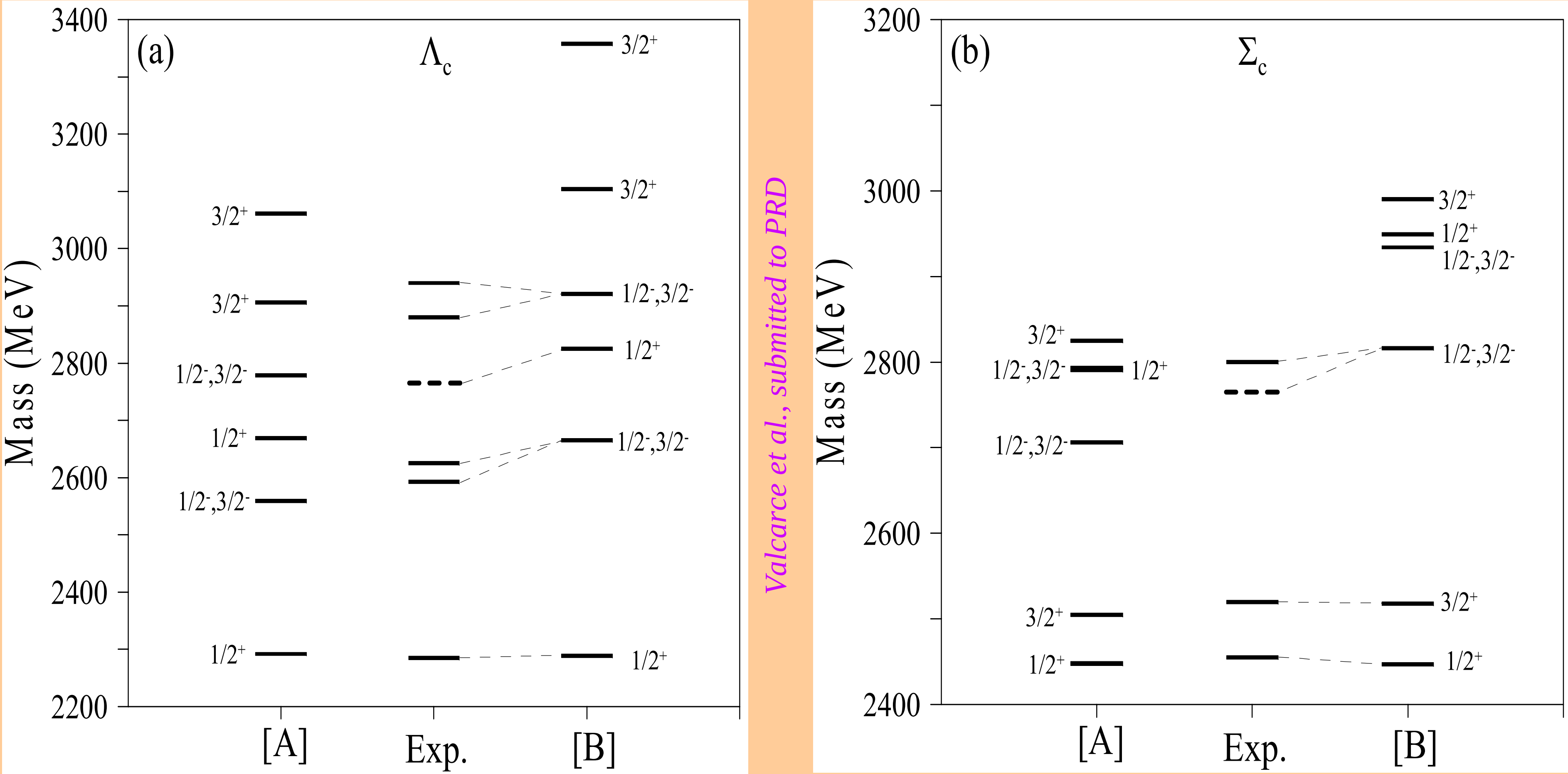
ΔM (MeV)	Latt.	OGE (+ OPE)
$\Xi_{cc}(3/2^+) - \Xi_{cc}(1/2^+)$	≅ 75	77 (77)
$\Omega_{cc}(3/2^+) - \Omega_{cc}(1/2^+)$	≅ 60	72 (61)

Double charm baryons ⇒ no OPE

M (MeV)	Full	OPE=0	ΔE
$\Sigma_b(1/2^+)$	5807	5822	– 15
$\Sigma_b(3/2^+)$	5829	5844	– 15
$\Lambda_b(1/2^+)$	5624	5819	– 195
$\Lambda_b(3/2^+)$	6388	6387	< 1
$\Sigma(1/2^+)$	1408	1417	– 9
$\Sigma(3/2^+)$	1454	1462	– 8
$\Lambda(1/2^+)$	1225	1405	– 180

	Ξ_{cc}	Ω_{cc}
OGE +OPE	3579	3697 (118)
OGE(μ)	3676	3815 (139)
Latt.	3588	3698 (110)

Heavy baryons: II. Confinement strength



Valcarce et al., submitted to PRD

[A] Fits the Roper in the light sector
[B] Fits the 1/2⁻ in the light sector

Flavor independence of confinement

State	J^P	CQC	Exp	[18]	[19]
Λ_b	$1/2^+$	5624	5624	5612	5622
	$1/2^+$	6106		6107	6086
	$1/2^-$	5947		5939	5930
	$1/2^-$	6245		6180	6328
	$3/2^+$	6388		6181	6189
	$3/2^+$	6637		6401	6540
Σ_b	$1/2^+$	5807	5808	5833	5805
	$1/2^+$	6247		6294	6202
	$1/2^-$	6103		6099	6108
	$1/2^-$	6241			6401
	$3/2^+$	5829	5829	5858	5834
	$3/2^+$	6260		6308	6222
Ξ_b	$1/2^+$	5801	5793	5844	5812
	$1/2^+$	6258			6264
	$1/2'^+$	5939		5958	5937
	$1/2'^+$	6360			6327
	$1/2^-$	6109		6108	6119
	$1/2^-$	6223		6192	6238
	$3/2^+$	5961		5982	5963
	$3/2^+$	6373		6294	6341
Ω_b	$1/2^+$	6056		6081	6065
	$1/2^+$	6479		6472	6440
	$1/2^-$	6340		6301	6352
	$1/2^-$	6458			6624
	$3/2^+$	6079		6102	6088
	$3/2^+$	6493		6478	6518

State	J^P	CQC	Exp.	[18]	[19]
Λ_c	$1/2^+$	2285	2286	2268	2297
	$1/2^+$	2785	2765	2791	2772
	$1/2^-$	2627	2595	2625	2598
	$1/2^-$	2880	2880	2816	3017
	$3/2^+$	3061		2887	2874
	$3/2^+$	3308		3073	3262
	$5/2^+$	2888	2880	2887	2883
Σ_c	$1/2^+$	2435	2454	2455	2439
	$1/2^+$	2904		2958	2864
	$1/2^-$	2772	2765	2748	2795
	$1/2^-$	2893			3176
	$3/2^+$	2502	2518	2519	2518
	$3/2^+$	2944	2940	2995	2912
	$3/2^-$	2772	2800	2763	2761
Ξ_c	$1/2^+$	2471	2471	2492	2481
	$1/2^+$	3137	3123		2923
	$1/2'^+$	2574	2578	2592	2578
	$1/2'^+$	3212			2984
	$1/2^-$	2799	2792	2763	2801
	$1/2^-$	2902		2859	2928
	$1/2^-$	3004	2980		3186
	$3/2^+$	2642	2646	2650	2654
	$3/2^+$	3071	3076	2984	3030
	$5/2^+$	3049	3055		3042
	$5/2'^+$	3132	3123		3123
Ω_c	$1/2^+$	2699	2698	2718	2698
	$1/2^+$	3159		3152	3065
	$1/2^-$	3035		2977	3020
	$1/2^-$	3125			3371
	$3/2^+$	2767	2768	2776	2768
	$3/2^+$	3202		3190	3119

CQC Valcarce et al., submitted to PRD
[18] Roberts et al. arXiV:0711.2492
[19] Ebert et al., Phys. Lett. B659, 618 (2008)

$\Lambda_Q(3/2^+)$

$\Sigma(3/2^+) - \Sigma(1/2^+) \Rightarrow 6_F - 6_F \equiv qQ$

$\Sigma(1/2^+) - \Lambda(1/2^+) \Rightarrow 6_F - 3_F \equiv qq$

	CQC	[18]	[19]
$\Lambda_c(3/2^+)$	3061	2887	287 4
$\Lambda_c(3/2^+)^*$	3308	3073	326 2
$\Lambda_b(3/2^+)$	6388	6181	618 9
$\Lambda_b(3/2^+)^*$	6637	6401	654 0

State	J^P	CQC	[18]
Ξ_{bb}	$3/2^+$	29	27
	$3/2^{+*}$	312	238
	$1/2^{+*}$	293	236
	$1/2^-$	217	153
	$1/2^{-*}$	423	370
Ω_{bb}	$3/2^+$	28	32
	$3/2^{+*}$	329	267
	$1/2^{+*}$	311	239
	$1/2^-$	226	162
	$1/2^{-*}$	390	309
Ξ_{cc}	$3/2^+$	77	77
	$3/2^{+*}$	446	366
	$1/2^{+*}$	397	353
	$1/2^-$	301	234
	$1/2^{-*}$	439	398
Ω_{cc}	$3/2^+$	72	61
	$3/2^{+*}$	463	373
	$1/2^{+*}$	415	365
	$1/2^-$	312	231
	$1/2^{-*}$	404	320

Heavy mesons

More than 30 years after the so-called *November revolution*, heavy meson spectrocospy is being again a challenge. The formerly comfortable world of heavy meson spectroscopy is being severely tested by new experiments

Heavy-light mesons (QCD hydrogren)

Open charm

$D_{sJ}^*(2317)$
- $J^P=0^+$
- P $c\bar{s} \sim 2.48$ GeV
- $\Gamma < 4.6$ MeV

$D_{sJ}(2460)$
- $J^P=1^+$
- P $c\bar{s} \sim 2.55$ GeV
- $\Gamma < 5.5$ MeV

$D_0^*(2308)$
- $J^P=0^+$
- P $c\bar{n} \simeq 2.46$ GeV
- $\Gamma \sim 276$ MeV

$D_{sJ}(2632)$ (Selex)
$D_{sJ}^*(2715)$ (Belle)
$D_{sJ}(2860)$ (Babar)
....

Heavy-heavy mesons

Charmonium

X (3872)
- $J^{PC}=1^{++}$ (2^{-+})
- P $c\bar{c} \sim 3.9$-4.0 GeV
- $\Gamma < 2.3$ MeV

Y(4260) : ??

Y(4385) : $4^3S_1, 3^3D_1$

X (3940)
Y (3940):$2^3P_{J=1,2,3}$
Z (3940)

Z(4433)
X(3876)
....

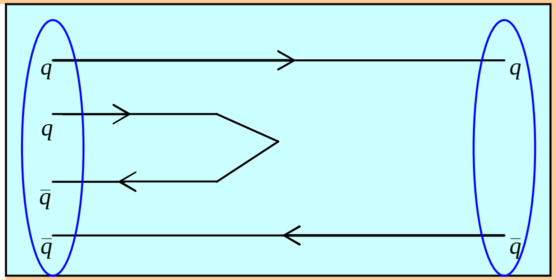
• The area that is phenomenologically understood extends to: Heavy-light mesons, states where the quark-antiquark pair is in relative S wave; Heavy-heavy mesons: states below the $D\bar{D}$ ($B\bar{B}$) threshold

• In the positive parity sector (P wave, L=1) a number of states have been discovered with masses and widths much different than expected from quark potential models.

2007 Close: "I have always felt that this is an example of where naive quarks models are too naive"

When a $q\bar{q}$ state occurs in L=1 but can couple to hadron pairs in S waves, the latter will distort the $q\bar{q}$ picture. The $\bar{c}\bar{s}$ states 0^+ and 1^+ predicted above the DK (D*K) thresholds couple to the continuum what mixes DK (D*K) components in the wave function

UNQUENCHING THE NAIVE QUARK MODEL



$$|B=0\rangle = \Omega_1 |q\bar{q}\rangle + \Omega_2 |q\bar{q}q\bar{q}\rangle + \ldots$$

$$q\bar{q}\left[J^{PC}=0^{++}\right] \Rightarrow \quad S=1=L$$

- S=0

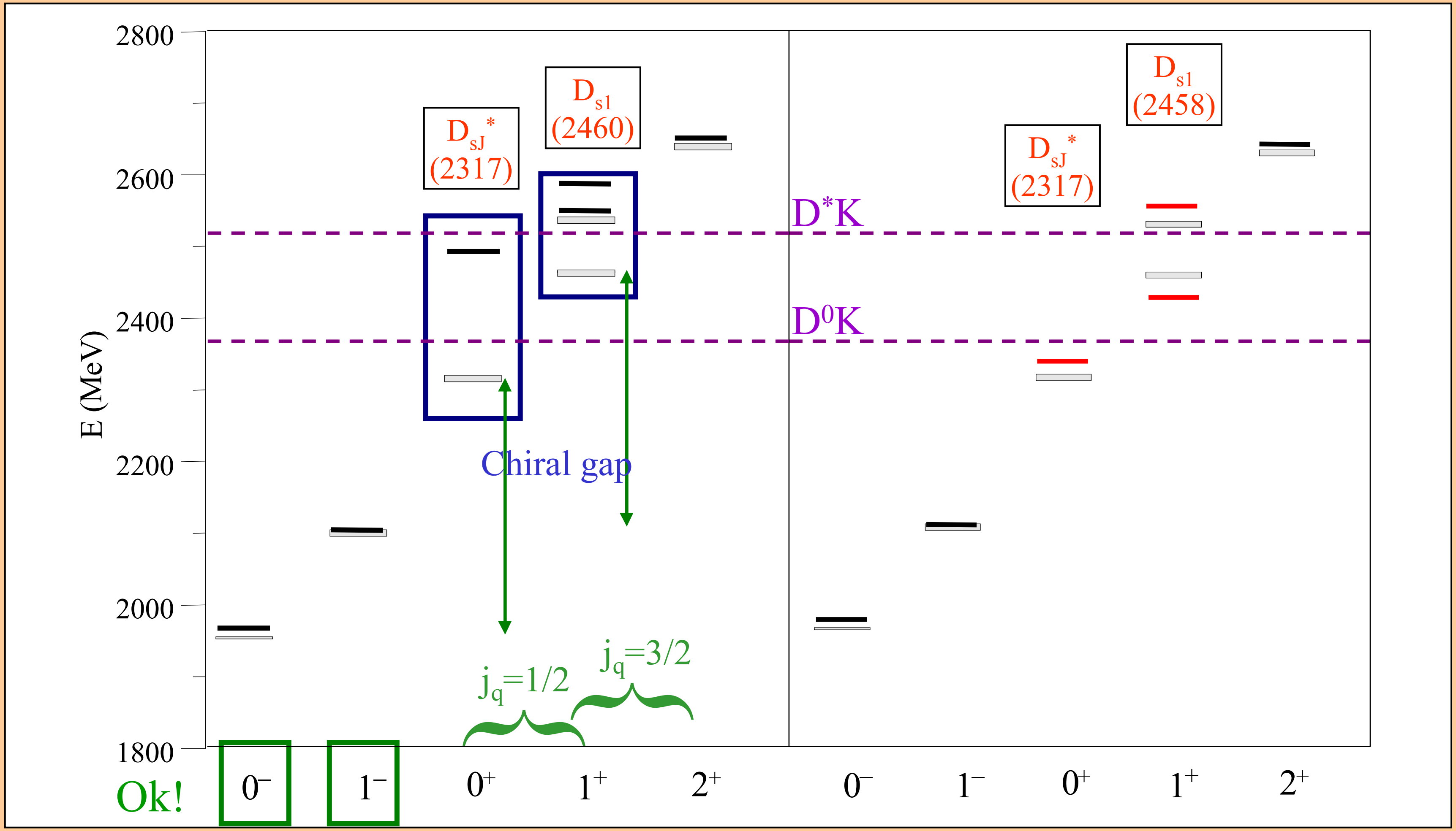
$$E(L=1)-E(L=0)=\begin{Bmatrix} h_1(1170)-\eta(550) \\ h_1(1595)-\eta'(958) \\ h_c(3526)-\eta_c(2980) \end{Bmatrix} \approx 0.5-0.6 \text{ GeV}$$

- S=1

$$[L=0]\begin{Bmatrix} \rho(770) \\ \omega(782) \end{Bmatrix} \Rightarrow [L=1] \quad X(J^{++}) \approx 1.3-1.4 \text{ GeV}$$

	$q\bar{q}$ (~ $2m_q$)	$q\bar{q}q\bar{q}$ (~ $4m_q$)
Negative parity	$0^-,1^-$ (L=0)	$0^-,1^-$ ($\ell_i \neq 0$)
Positive parity	$0^+,1^+,2^+$ (L=1)	$0^+,1^+,2^+$ ($\ell_i=0$)

D_{sJ} mesons: quark-antiquark pairs ?



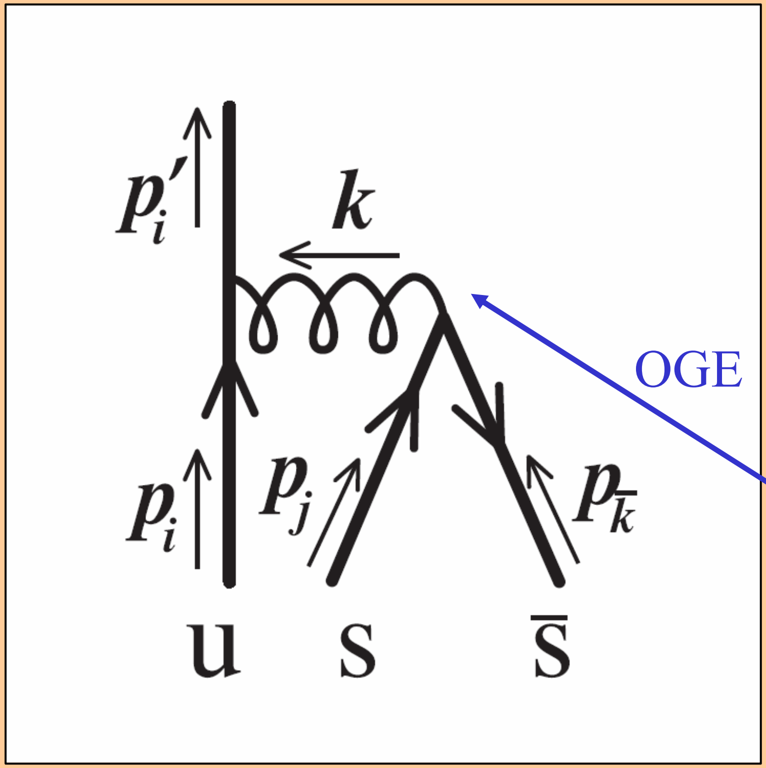
Bardeen et al.,Phys. Rev. D68, 054024 (2003)

Phys. Rev. D73, 034002 (2006)

Light baryons

The effect of the admixture of hidden flavor components in the baryon sector has also been studied. With a 30% of 5q components a larger decay width of the Roper resonance has been obtained. 10% of 5q components improves the agreement of the quark model predictions for the octet and decuplet baryon magnetic moments. The admixture is for positive parity states and it is postulated. *Riska et al. Nucl. Phys. A791, 406-421 (2007)*

From the spectroscopic point of view one would expect the effect of 5q components being much more important for low energy negative parity states (5q S wave)



Takeuchi et al., Phys. Rev. C76, 035204 (2007)

$\Lambda(1405)$ [1/2$^-$], QM 1500 MeV ($\Lambda(1520)$ [3/2$^-$])

$\Lambda = \alpha\,|3q\,[(0s)^2 0p]\rangle + \beta\,|5q[(0s)^5]\rangle$

$\alpha=0$; QCM $\Sigma\pi - N\bar{K} - \Lambda\eta_{ud} \Rightarrow$ No resonance found

$\alpha, \beta \neq 0 \Rightarrow$ A resonance is found

Dynamically generated resonances UχPT
Oset et al., Phys. Rev. Lett. 95, 052301(2005)

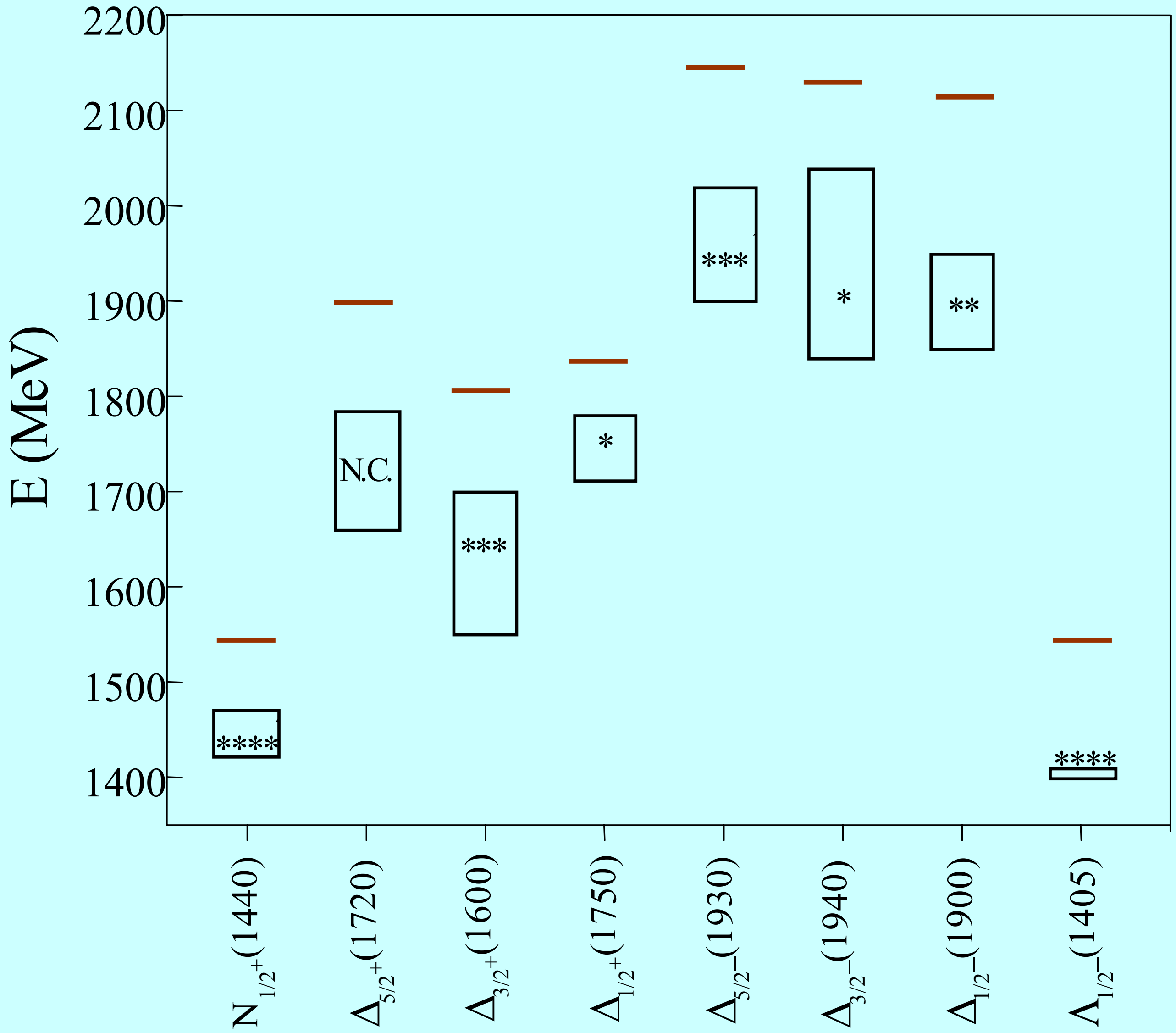
Meson-baryon threshold effects in the light-quark baryon spectrum

Abstract

We argue that selected S wave meson-baryon channels may play a key role to match poor baryon mass predictions from quark models with data. The identification of these channels with effective inelastic channels in data analysis allows to derive a prescription which could improve the extraction and identification of baryon resonances.

Meson-baryon threshold effects in the light-quark baryon spectrum

P. González et al., IFIC-USAL submitted to PRC



Capstick and Isgur, Phys. Rev. D34, 2809 (1986)

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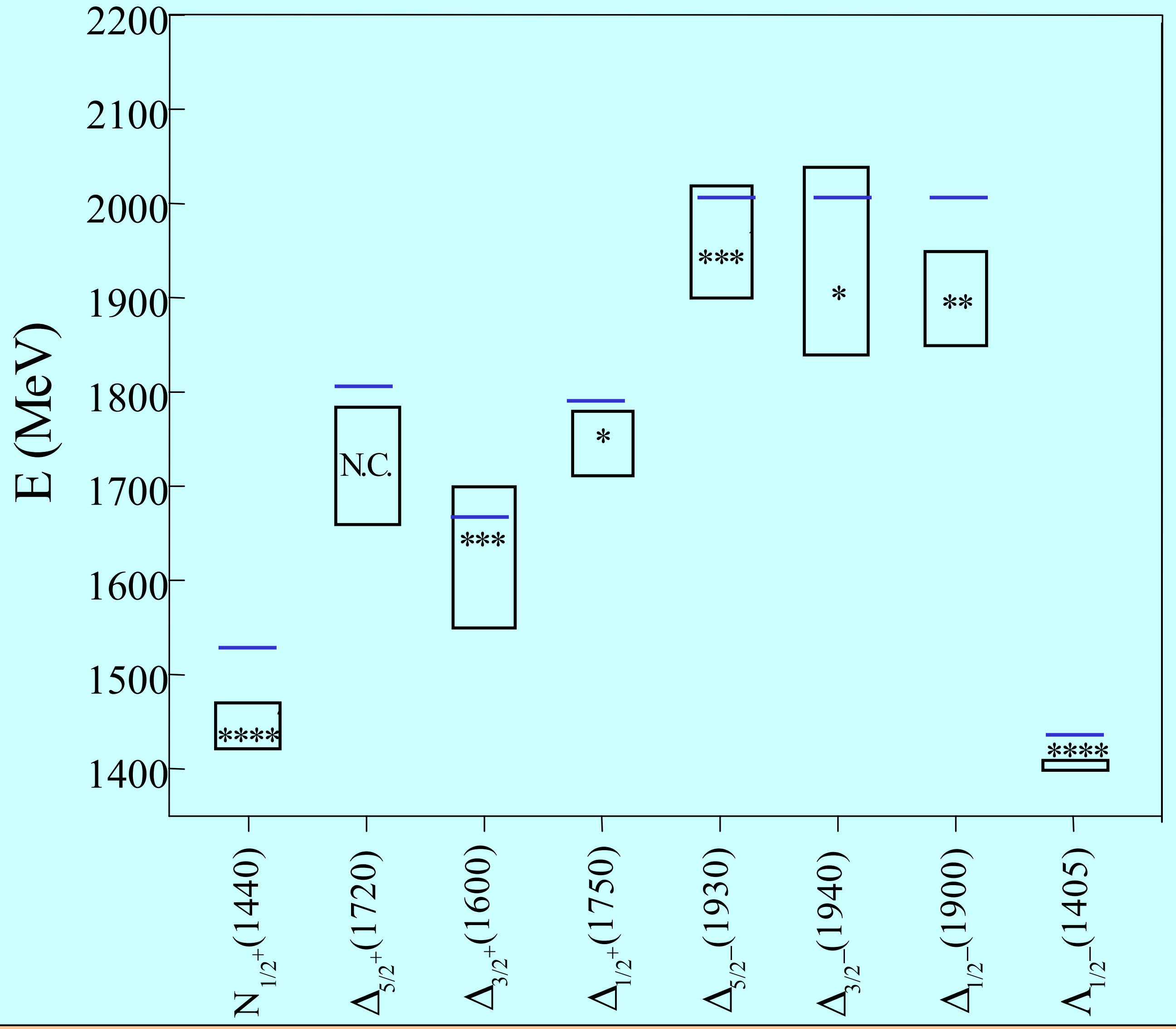
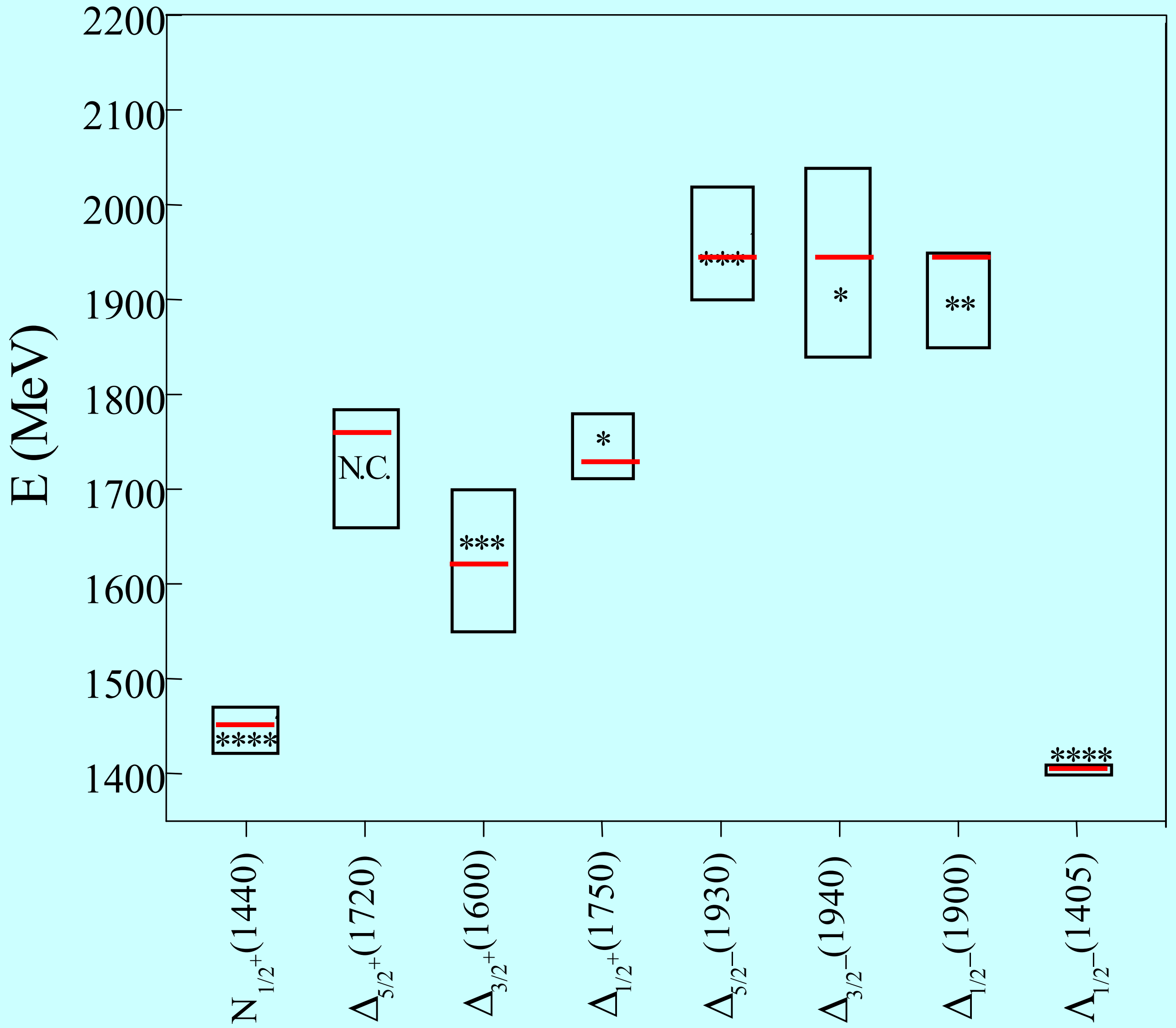


Meson-baryon S-wave thresholds

Meson-baryon threshold effects in the light-quark baryon spectrum



Mixing of 3q plus M-B (5q) a=85 MeV

P. González et al., IFIC-USAL submitted to PRC

Exotics

Solving the Schrödinger equation for $cc\bar{n}\bar{n}$: HH

$$|\Psi\rangle = |\text{Color}\rangle|\text{Isospin}\rangle\left[|\text{Spin}\rangle\otimes|R\rangle\right]^{JM}$$

$$|\text{Color}\rangle = \left\{|\bar{3}_{12}3_{34}\rangle, |6_{12}\bar{6}_{34}\rangle\right\}$$

$$|\text{Spin}\rangle = |((s_1,s_2)S_{12},(s_3,s_4)S_{34})S\rangle = |(S_{12},S_{34})S\rangle$$

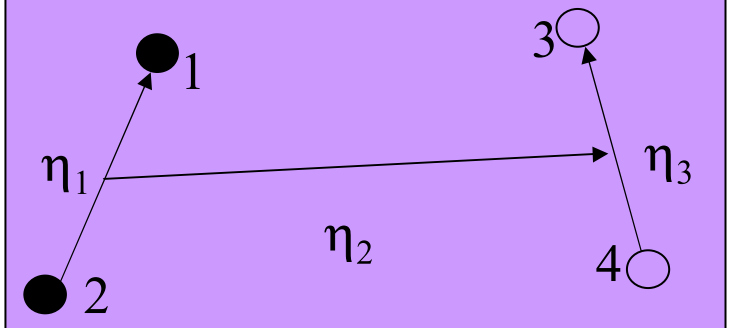
$$|\text{Isospin}\rangle = |(i_3,i_4)I_{34}\rangle$$

$$\langle\rho\Omega|R\rangle = U_n(\rho)\,\Omega Y_{[K]}(\Omega)$$

$$[K] \equiv KK_{12}LM_L L_{12}\ell_1\ell_2\ell_3$$

$Y_{[K]} \rightarrow$ HH functions

$U_n(\rho) \rightarrow$ Laguerre functions



$1,2 \rightarrow c \quad 3,4 \rightarrow n$

$$|\bar{3}_{12}3_{34}\rangle \rightarrow \begin{cases} (-1)^{S_{12}+\ell_1} = -1 \\ (-1)^{S_{34}+I+\ell_3} = +1 \end{cases}$$

$$|6_{12}\bar{6}_{34}\rangle \rightarrow \begin{cases} (-1)^{S_{12}+\ell_1} = +1 \\ (-1)^{S_{34}+I+\ell_3} = -1 \end{cases}$$

$cc\bar{n}\bar{n}$

		CQC (BCN)			
	J^P (K_{max})	E_{4q} (MeV)	Δ_E^{The}	R_{4q}	$R_{4q}/(r^1_{2q}+r^2_{2q})$
I=0	0^+ (28)	4441	+ 15	0.624	> 1
	1^+ (24)	3861	– 76	0.367	0.808
	2^+ (30)	4526	+ 27	0.987	> 1
	0^- (21)	3996	+ 59	0.739	> 1
	1^- (21)	3938	+ 66	0.726	> 1
	2^- (21)	4052	+ 50	0.817	> 1
I=1	0^+ (28)	3905	+ 33	0.752	> 1
	1^+ (24)	3972	+ 35	0.779	> 1
	2^+ (30)	4025	+ 22	0.879	> 1
	0^- (21)	4004	+ 67	0.814	> 1
	1^- (21)	4427	+ 1	0.516	0.876
	2^- (21)	4461	– 38	0.465	0.766

Vijande et al., in progress

Janc et al., Few Body Syst. 35, 175 (2004)

Solving the Schrödinger equation for $cn\bar{c}\bar{n}$: HH

$$|\Psi\rangle = |Color\rangle |Isospin\rangle \left[|Spin\rangle \otimes |R\rangle \right]^{JM}$$

$$|Color\rangle = \{ |1_{12} 1_{34}\rangle, |8_{12} 8_{34}\rangle \} \quad !$$

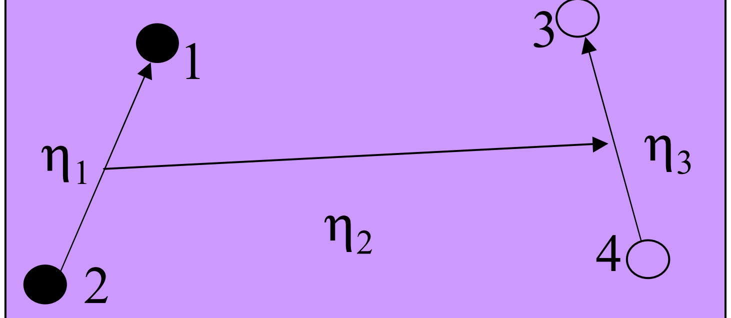
C-parity is a good symmetry of the system

$$|C_{12}{}^{\Gamma_{12}}\rangle = 1/\sqrt{2} \left(|C_{12}\rangle + \Gamma_{12} |C_{21}\rangle \right)$$

$|C_{12}\rangle = \{1_{12}, 8_{12}\}$ and Γ_{12}=+/- S/A

$$|(C_{34} I_{34})^{\Gamma 34}\rangle = 1/2 \left(|C_{34}\rangle \left(|u\bar{u}\rangle \pm |d\bar{d}\rangle \right) + \Gamma_{34} |C_{43}\rangle \left(|\bar{u}u\rangle \pm |\bar{d}d\rangle \right) \right)$$

$|C_{34}\rangle = \{1_{34}, 8_{34}\}$, Γ_{34}=+/- S/A , $|I_{34} = 1/0, I_{34}^z = 0\rangle$



$$|C_{12}{}^{\Gamma_{12}} (C_{34} I_{34})^{\Gamma_{34}}\rangle$$

Good symmetry states
C-parity=$\Gamma_{12}\Gamma_{34}$

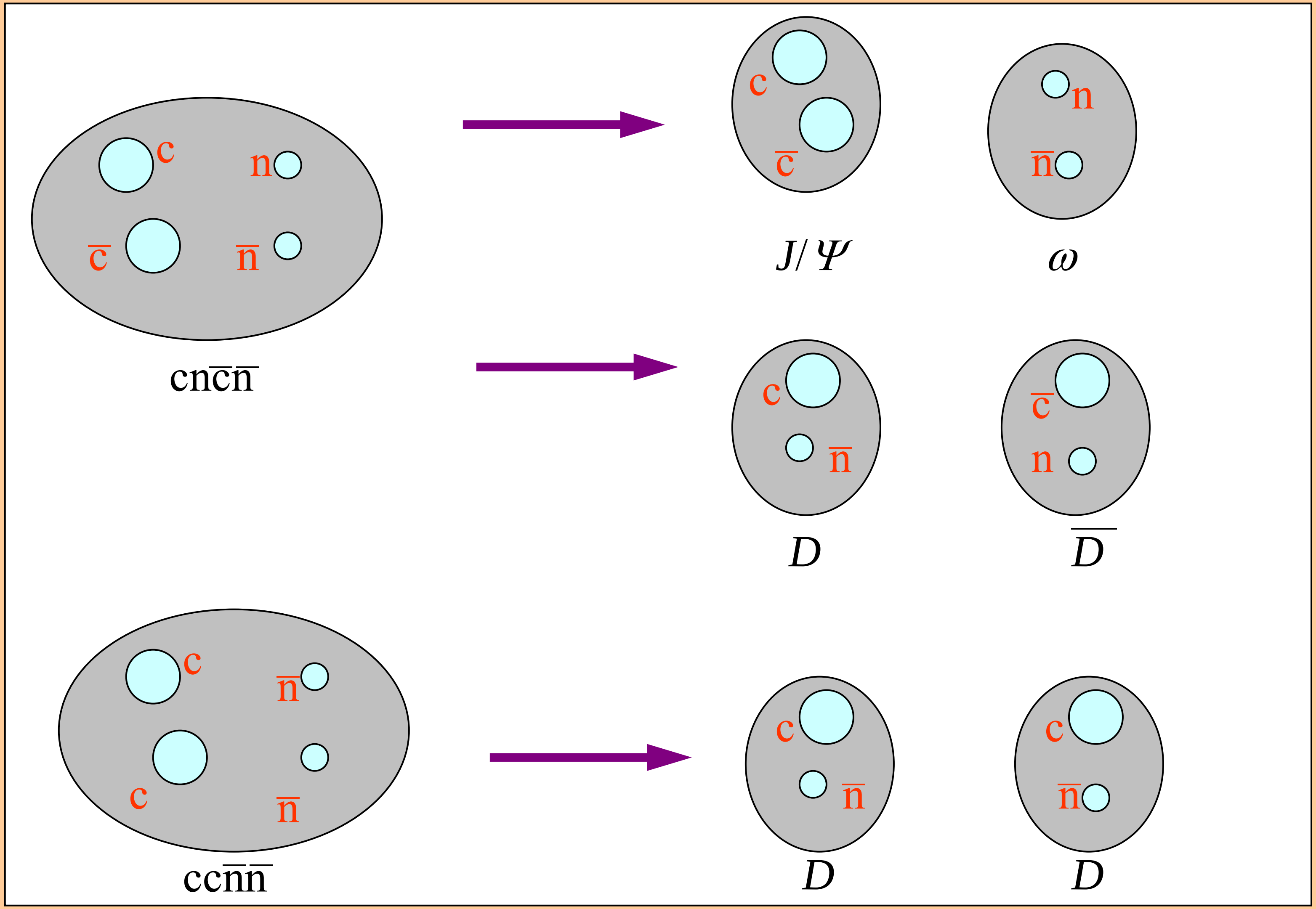
$$\rightarrow \begin{cases} \Gamma_{12}(-1)^{S_{12}+\ell_1} = +1 \\ \Gamma_{34}(-1)^{S_{34}+\ell_3} = +1 \end{cases}$$

Compact four-quark structure $cn\bar{c}\bar{n}$ (I=0)

Phys. Rev. D76, 094022 (2007)

	CQC			BCN		
J^{PC} (K_{max})	E_{4q} (MeV)	Δ_E^{The}	Δ_E^{Exp}	E_{4q} (MeV)	Δ_E^{The}	Δ_E^{Exp}
0^{++} (24)	3779	+ 34	+ 251	3249	+ 75	– 279
0^{+-} (22)	4224	+ 64	+ 438	3778	+ 140	+ 81
1^{++} (20)	3786	+ 41	+ 206	3808	+ 153	+ 228
1^{+-} (22)	3728	+ 45	+ 84	3319	+ 86	– 325
2^{++} (26)	3774	+ 29	– 106	3897	+ 23	+ 17
2^{+-} (28)	4214	+ 54	+ 517	4328	+ 32	+ 631
1^{-+} (19)	3829	+ 84	+ 301	3331	+ 157	– 197
1^{--} (19)	3969	+ 97	+ 272	3732	+ 94	+ 35
0^{-+} (17)	3839	+ 94	– 32	3760	+ 105	– 111
0^{--} (17)	3791	+ 108	+147	3405	+ 172	– 239
2^{-+} (21)	3820	+ 75	– 60	3929	+ 55	+ 49
2^{--} (21)	4054	+ 52	+ 357	4092	+ 52	+ 395
Total		0	3 !		0	5 !

Difference between the two physical systems



Many body forces do not give binding in this case

Phys. Rev. D76, 114013 (2007)

$$V_s = \min(V_f, V_b)\ .$$

V_f stands for the so-called “flip-flop” model

$$V_f = \lambda \min(r_{13} + r_{24}, r_{23} + r_{14})\ ,$$

V_b is the butterfly-like configuration,

$$V_b = \lambda \min_{k,\ell}(r_{1k} + r_{2k} + r_{k\ell} + r_{\ell 3} + r_{\ell 4})\ .$$

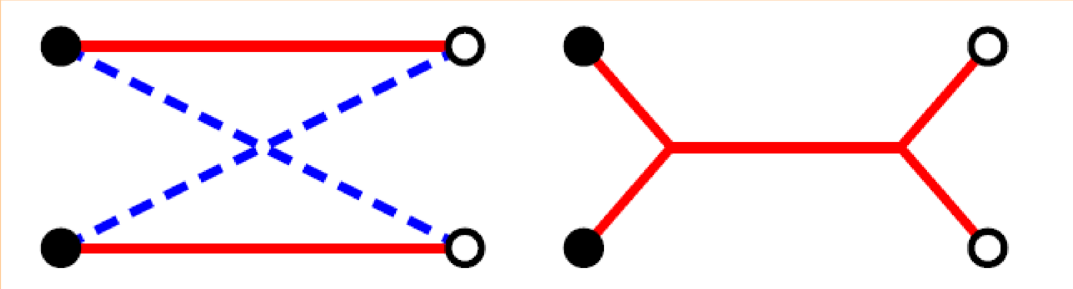
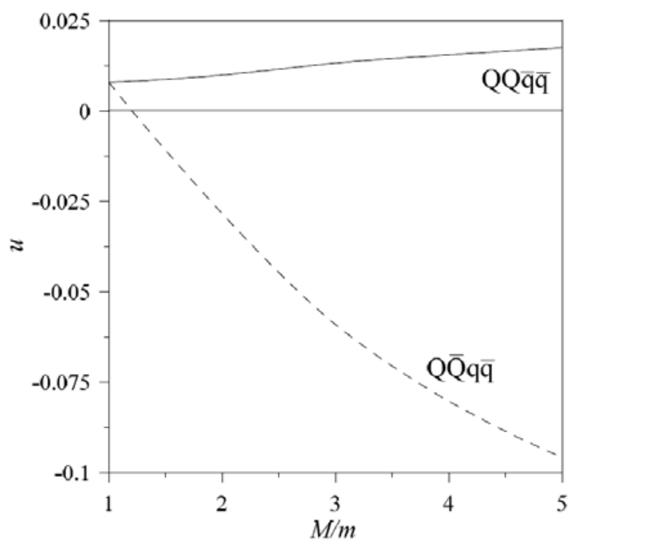


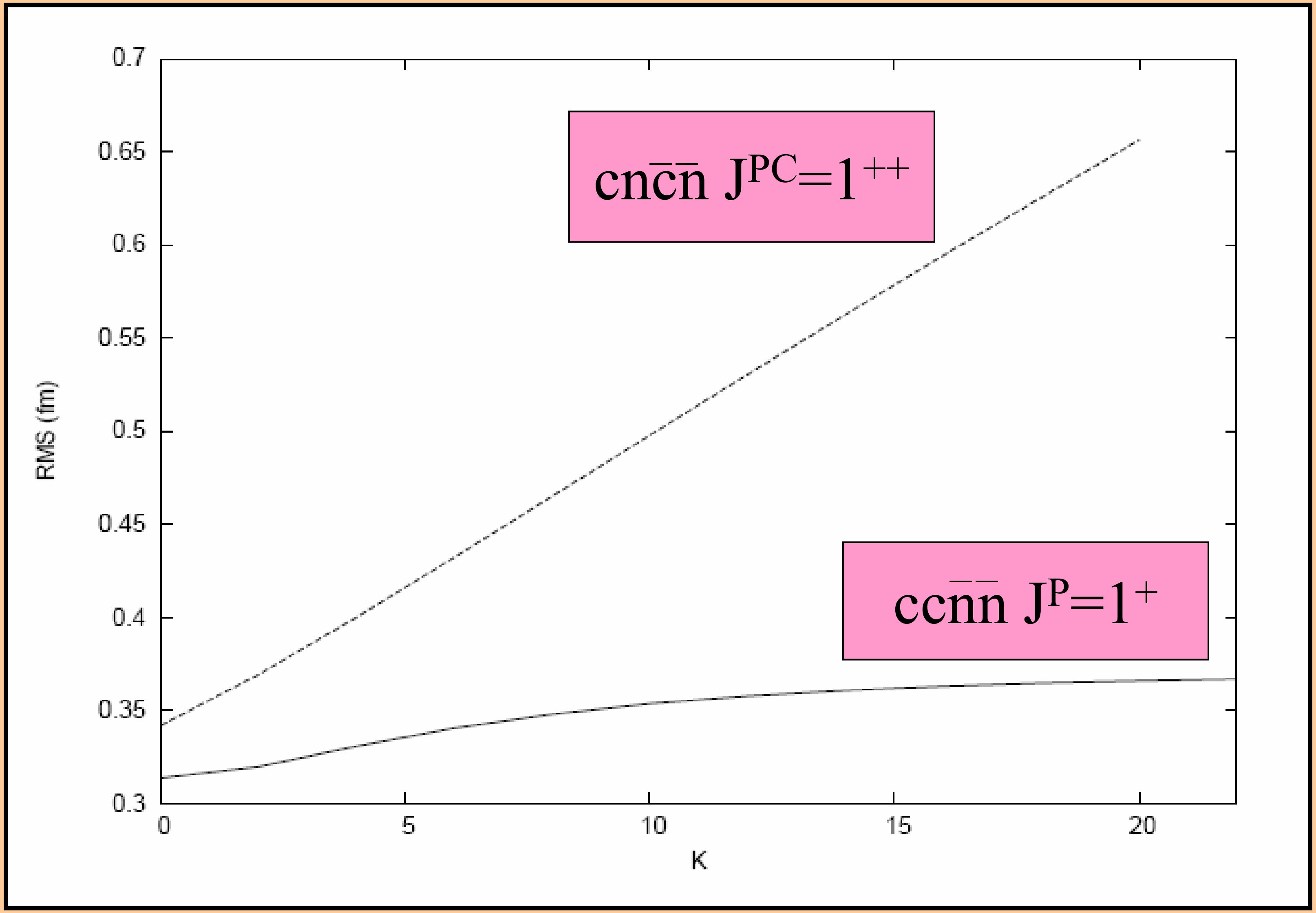
TABLE I: Four–quark variational energy E_4 of $(QQ\overline{qq})$ for the different confinement models described in Eq. (4), compared to its threshold, $T_4 = 2E_2(1,M)$, and variational energy E_4' of $(Q\overline{Q}q\overline{q})$ with the flip-flop model V_f, compared to its threshold $T_4' = E_2(M,M) + E_2(1,1)$, as a function of the mass ratio.

M/m	E_4			T_4	E_4'	T_4'
	V_f	V_b	V_s		V_f	
1	4.644	5.886	4.639	4.676	4.644	4.676
2	4.211	5.300	4.206	4.248	4.313	4.194
3	4.037	5.031	4.032	4.086	4.193	3.959
4	3.941	4.868	3.936	3.998	4.117	3.811
5	3.880	4.754	3.873	3.942	4.060	3.705

$$E_4 = (1-u)T_4\ ,$$



Behavior of the radius (CQC)



Summary

• There is an increasing interest in hadron spectroscopy due to the advent of a large number of experimental data in several cases of difficult explanation.

• These data provide with the best laboratory for studying the predictions of QCD in what has been called the strong limit. We have the methods, so we can learn about the dynamics. There are enough data to learn about the glue holding quarks together inside hadrons.

• Simultaneous study of nnQ and nQQ baryons is a priority to understand low-energy QCD. The discovery $\Lambda_Q(3/2^+)$ is a challenge.

• Hidden flavor components, unquenching the quark model, seem to be neccessary to tame the bewildering landscape of hadrons, but an amazing folklore is borning around.

• Compact four-quark bound states with non-exotic quantum numbers are hard to justify while “many-body (medium)” effects do not enter the game.

• Exotic many-quark systems should exist if our understanding of the dynamics does not hide some information. I hope experimentalists can answer this question to help in the advance of hadron spectroscopy.

Acknowledgements

Let me thank the people I collaborated with in the different subjects I covered in this talk

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P. González (Univ. Valencia, Spain)	E. Weissman (Hebrew Univ. Jerusalem, Israel)

Thanks!

See you in the 2010 European Few-Body Conference in Salamanca

Which is the nature of scalar mesons?

A Theory of Scalar Mesons

Phys. Lett. B, in press

G. 't Hooft[a], G. Isidori[b], L. Maiani[c,d], A.D. Polosa[d], V. Riquer[d],

from light scalar decays. A coherent picture of scalar mesons as a mixture of tetraquark states (dominating in the lightest mesons) and heavy $q\bar{q}$ states (dominating in the heavier mesons) emerges.

PHYSICAL REVIEW D **72**, 034025 (2005)

Nature of the light scalar mesons

J. Vijande,[1] A. Valcarce,[1] F. Fernández,[1] and B. Silvestre-Brac[2]

Despite the apparent simplicity of meson spectroscopy, light scalar mesons cannot be accommodated in the usual $q\bar{q}$ structure. We study the description of the scalar mesons below 2 GeV in terms of the mixing of a chiral nonet of tetraquarks with conventional $q\bar{q}$ states. A strong diquark-antidiquark component is

$$\Gamma_{\gamma\gamma}[a_0(980)] = 0.65 \pm 0.04 \text{ keV}; \quad \Gamma_{\gamma\gamma}[f_0(980)] = 0.23 \pm 0.02 \text{ keV} \tag{5}$$

that compares rather well with the experiment [2],

$$\Gamma^{\rm Exp}_{\gamma\gamma}[a_0(980)] = 0.3 \pm 0.1 \text{ keV}; \quad \Gamma^{\rm Exp}_{\gamma\gamma}[f_0(980)] = 0.39^{+0.10}_{-0.13} \text{ keV}. \tag{6}$$

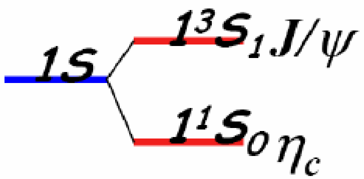
Charmonium: playground of new models

Central potential:

$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + br$$

Spin-spin interaction:

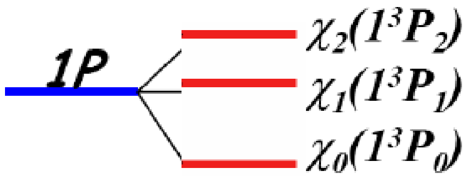
$$\frac{4\alpha_s(r)}{3m_im_j}\left\{\frac{8\pi}{3}\vec{S}_i\cdot\vec{S}_j\,\delta^3(\vec{r}_{ij}) + \frac{1}{r_{ij}^3}\left[\frac{3\vec{S}_i\cdot\vec{r}_{ij}\vec{S}_j\cdot\vec{r}_{ij}}{r_{ij}^2} - \vec{S}_i\cdot\vec{S}_j\right]\right\}$$



Spin-orbit interaction:

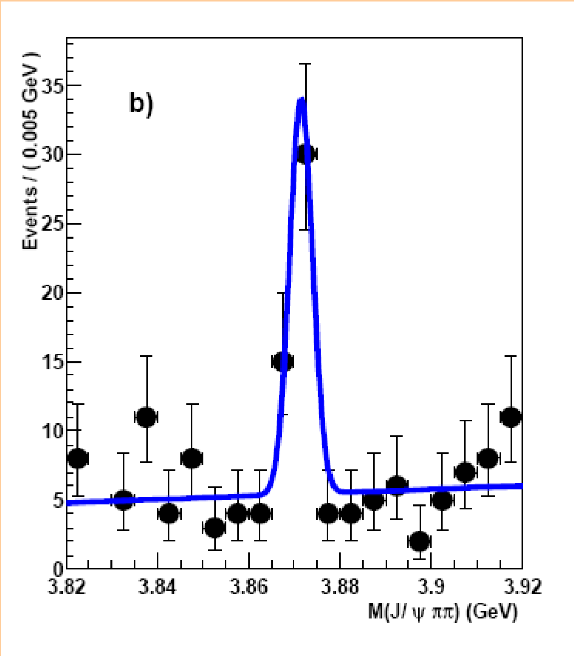
$$H_{ij}^{s.o.(cm)} = \frac{4\alpha_s(r)}{3r_{ij}^3}\left(\frac{1}{m_i}+\frac{1}{m_j}\right)\left(\frac{\vec{S}_i}{m_i}+\frac{\vec{S}_j}{m_j}\right)\cdot\vec{L}$$

$$H_{ij}^{s.o.(tp)} = \frac{-1}{2r_{ij}}\frac{\partial V(r)}{\partial r_{ij}}\left(\frac{\vec{S}_i}{m_i^2}+\frac{\vec{S}_j}{m_j^2}\right)\cdot\vec{L}$$



Barnes et al., Phys. Rev. D72, 054026 (2005)

Multiplet	State	Expt.	Input (NR)	Theor. NR	Theor. GI
1S	$J/\psi(1^3S_1)$	3096.87 ± 0.04	3097	3090	3098
	$\eta_c(1^1S_0)$	2979.2 ± 1.3	2979	2982	2975
2S	$\psi'(2^3S_1)$	3685.96 ± 0.09	3686	3672	3676
	$\eta_c'(2^1S_0)$	3637.7 ± 4.4	3638	3630	3623
3S	$\psi(3^3S_1)$	4040 ± 10	4040	4072	4100
	$\eta_c(3^1S_0)$			4043	4064
4S	$\psi(4^3S_1)$	4415 ± 6	4415	4406	4450
	$\eta_c(4^1S_0)$			4384	4425
1P	$\chi_2(1^3P_2)$	3556.18 ± 0.13	3556	3556	3550
	$\chi_1(1^3P_1)$	3510.51 ± 0.12	3511	3505	3510
	$\chi_0(1^3P_0)$	3415.3 ± 0.4	3415	3424	3445
	$h_c(1^1P_1)$	see text		3516	3517
2P	$\chi_2(2^3P_2)$			3972	3979
	$\chi_1(2^3P_1)$			3925	3953
	$\chi_0(2^3P_0)$			3852	3916
	$h_c(2^1P_1)$			3934	3956
3P	$\chi_2(3^3P_2)$			4317	4337
	$\chi_1(3^3P_1)$			4271	4317
	$\chi_0(3^3P_0)$			4202	4292
	$h_c(3^1P_1)$			4279	4318
1D	$\psi_3(1^3D_3)$			3806	3849
	$\psi_2(1^3D_2)$			3800	3838
	$\psi(1^3D_1)$	3769.9 ± 2.5	3770	3785	3819
	$\eta_{c2}(1^1D_2)$			3799	3837
2D	$\psi_3(2^3D_3)$			4167	4217
	$\psi_2(2^3D_2)$			4158	4208
	$\psi(2^3D_1)$	4159 ± 20	4159	4142	4194
	$\eta_{c2}(2^1D_2)$			4158	4208



Belle, Phys. Rev. Lett. 91, 262001 (2003)

$B^+ \to K^+ X(3872) \to K^+\pi^+\pi^- J/\Psi$

CDF, D0, .. $p\bar{p}$

PDG, M = 3871.2 ± 0.5 MeV; Γ < 2.3 MeV

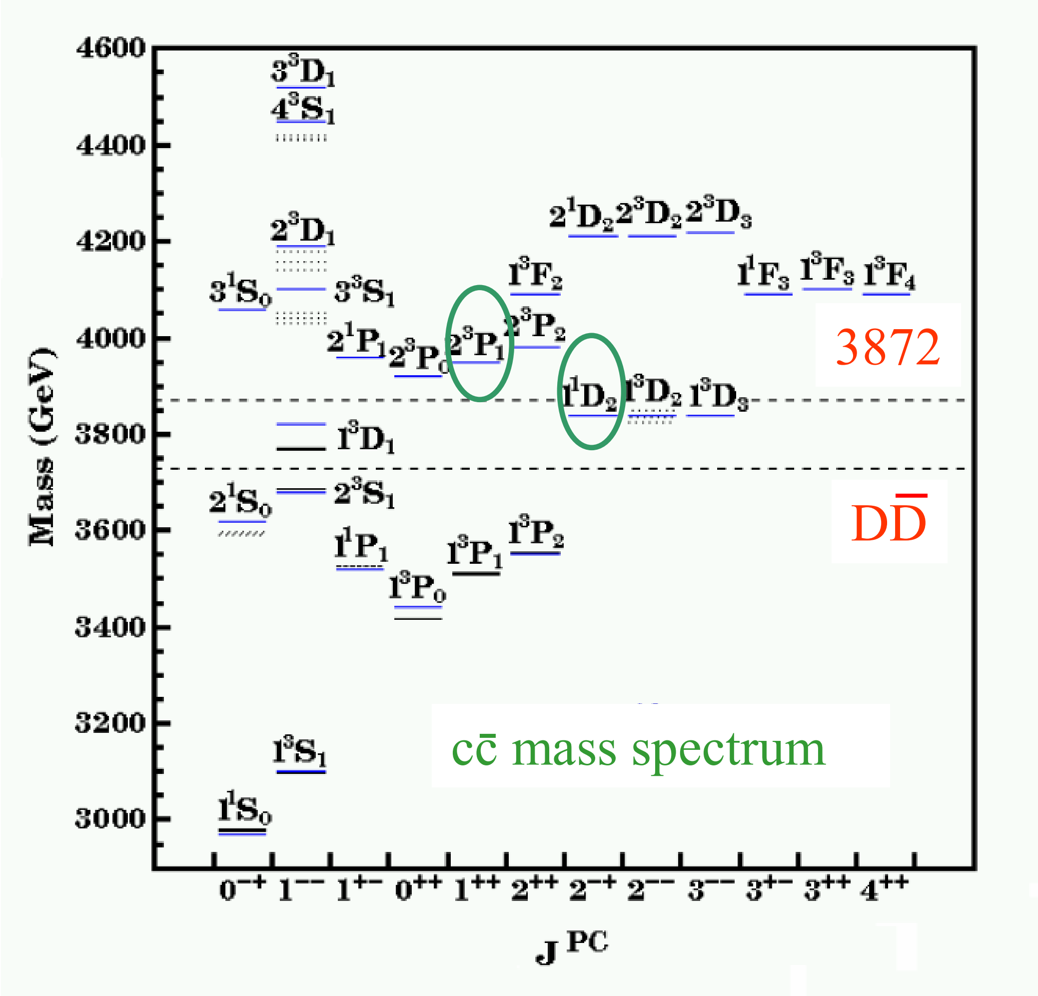
$m_D + m_{D^*} = (3870.3 \pm 2.0)$MeV $\Delta M = (+0.9 \pm 2.0)$MeV

Production properties very similar to $\Psi'(2^3S_1)$

Seen in $\to \gamma\, J/\Psi \Rightarrow C = +$

Belle rules out 0^{++} and 0^{-+}, favors 1^{++}

CDF only allows for 1^{++} or 2^{-+}



cc̄ state ?

2^{-+}: is a spin-singlet D wave while J/Ψ is a spin-triplet S wave, so in the NR limit the E1 transition $2^{-+} \rightarrow \gamma J/\Psi$ is forbidden. D and S radial wave functions are orthogonal what prohibits also M1

1^{++}: Expected larger mass and width ($\rightarrow \rho J/\Psi$ violates isospin).

Tetraquark ?

Wave function:

• Compact four-quark structure (diquark – antidiquark)

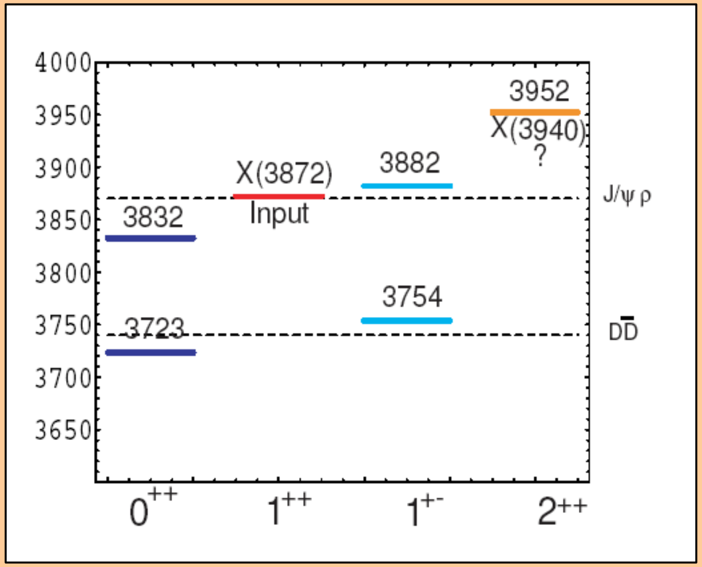
$[qq]$: color = $\bar{3}$, flavor= $\bar{3}$, spin = 0

Maiani et al., Phys. Rev. D71, 014028 (2005)

2 neutral states: $X_u=[cu][\bar{c}\bar{u}]$ $X_d=[cd][\bar{c}\bar{d}]$ $\Delta M=(7\pm 2)$ MeV

2 charged states: $X^+=[cu][\bar{c}\bar{d}]$ $X^-=[cd][\bar{c}\bar{u}]$

No evidence for charged states



Interaction:

• S wave $D^0 \bar{D}^{*0}$ molecule

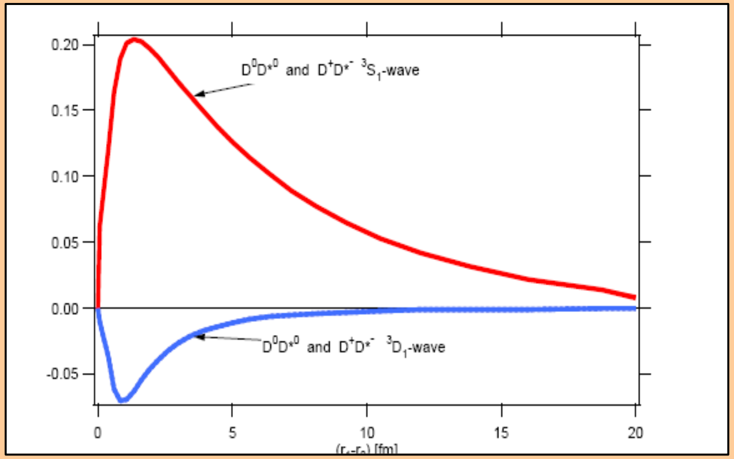
Tornqvist, Phys. Lett. B590, 209 (2004)

Long range one-pion exchange B=0.5 MeV⇒M ≈3870 MeV

Favors $J^{PC}=1^{++}$

$\Gamma(X\to\gamma J/\psi) < \Gamma(X\to\pi\pi J/\psi)$

Binding increases with the mass, 50 MeV for B mesons



• 1^{++} charmonium mixed with $(D\bar{D}^* + \bar{D}^*D)$

Suzuki, Phys. Rev.. D72, 114013 (2005)