The molecular nature of some exotic hadrons

Àngels Ramos
(and G. Montaña, A. Feijoo, Q. Llorens)

University of Barcelona and ICCUB

UNIVERSITAT DE BARCELONA

24th European Conference on Few-Body Problems in Physics
September 2-6, 2019, University of Surrey

ICCUB

Outline

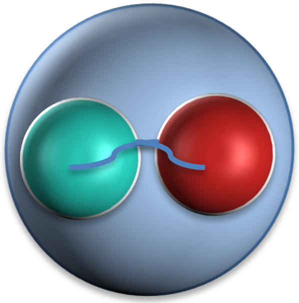
- Quark model hadrons vs. exotic hadrons
- Baryons interpreted as meson-baryon ``molecules'' in SU(3).
  (the Λ(1405), some N*'s)
- Extension to SU(4)
  (the new Ω_c states seen recently at LHCb, prediction of Ξ_{cc}'s)
- Conclusions

Conventional (quark model) hadrons

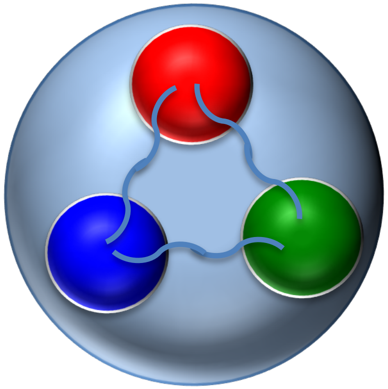
Although the basic constituents in QCD are quarks and gluons (permitting very complicated structures for mesons and baryons), the **conventional quark model** (Gell-Mann, 1964; Zweig, 1964) is probably one of the most successful approaches to hadron structure.

"50 Years of Quarks," edited by H. Fritzsch and M. Gell-Mann (World Scientific, 2015)

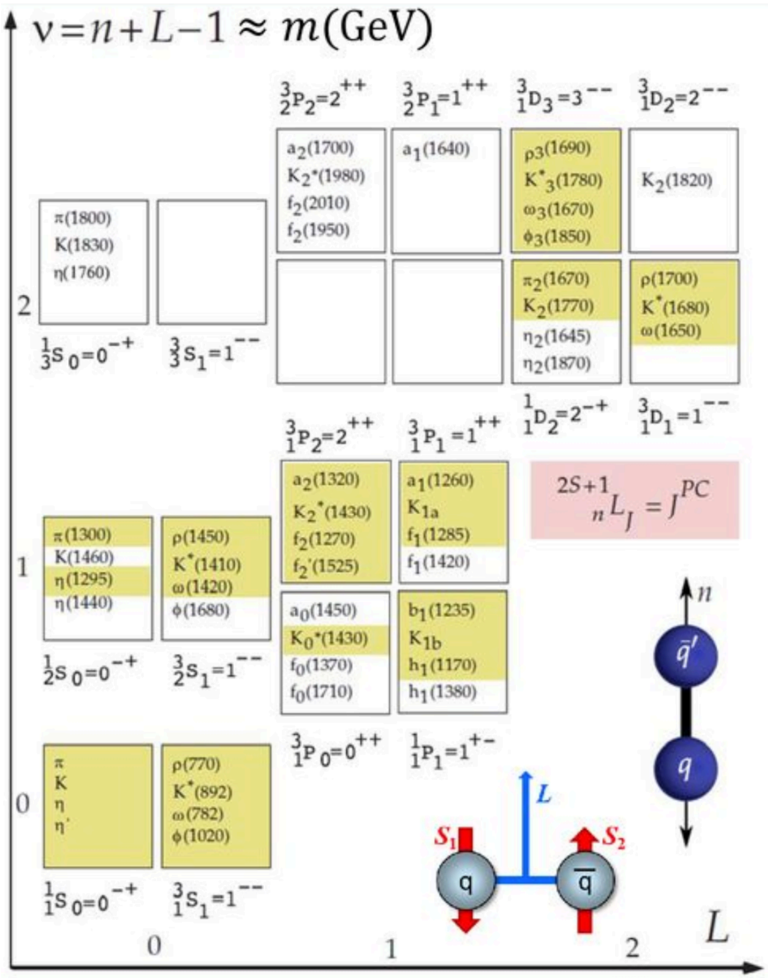
Mesons: $q\bar{q}$ states



Baryons: qqq states

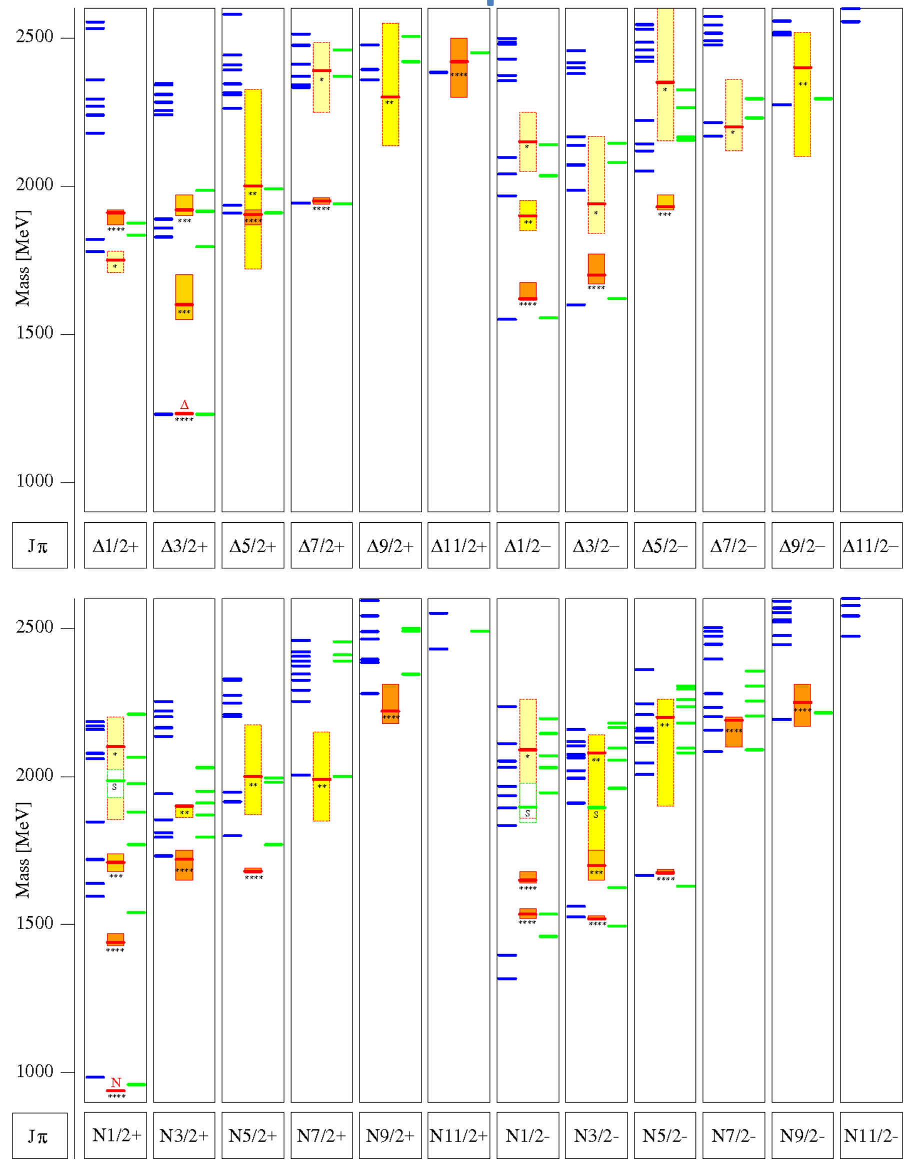


Light meson spectrum



C. Amsler, N.A. Tornqvist, Phys. Rep. 389 (2004) 61

N and Δ spectra



U. Löring, B. Metsch, H. Petry, Eur Phys J A 10 (2001) 395

In spite of the success of the conventional quark model, there are many (excited) hadrons that do not accommodate to the $q\bar{q}$ or qqq description:

Mesons	$I^G(J^{PC})$	
$f_0(500)$	$0^+(0^{++})$	→ the same orbital excitation
$a_0(980)$	$1^-(0^{++})$	(only different isospin): $(u\bar{u} \pm d\bar{d})/\sqrt{2}$
$f_0(980)$	$0^+(0^{++})$	→ $s\bar{s}$
$f_1(1420)$	$0^+(1^{++})$	

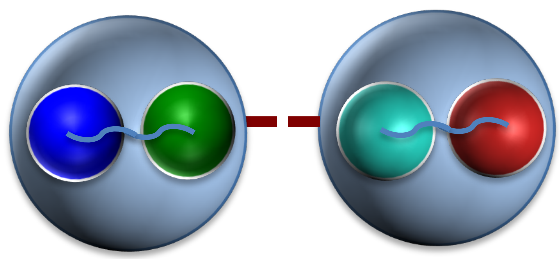
Baryons	$I^G(J^P)$	
$N(1440)$	$1/2^+$	→ radial excitation (too low mass)
$N(1535)$	$1/2^-$	→ orbital excitation (too high mass)
$\Lambda(1405)$	$1/2^-$	→ orbital excitation (too low mass)
$\Lambda(1670)$	$1/2^-$	

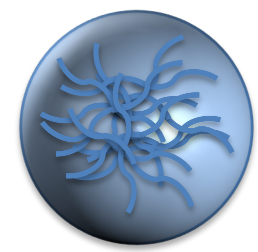
Exotic hadrons
(anything that goes beyond $q\bar{q}$ and qqq)

Mesons

Tetraquarks
($q\bar{q}q\bar{q}$)

Glueballs





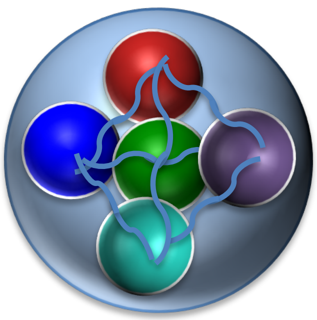
compact 4q system

meson-meson bound state
(or *molecule*)

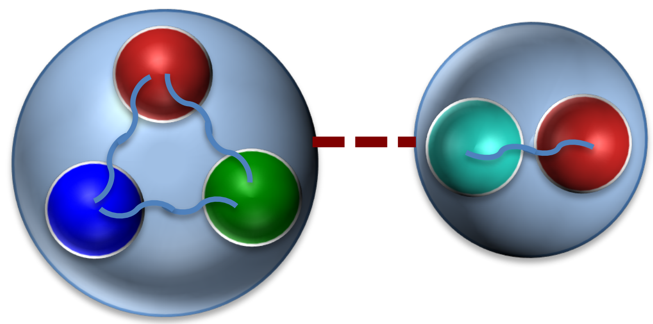
Exotic hadrons
(anything that goes beyond $q\bar{q}$ and qqq)

Baryons

Pentaquarks
(qqqqq)



compact 5q system



baryon-meson bound state
(or *molecule*)

- Nature gives clues to whether a particular hadron may have an exotic multiquark configuration structure

$f_0(500)$ ➔ from analyses of $\pi\pi$ scattering data

$\left.\begin{array}{l} a_0(980) \\ f_0(980) \end{array}\right\}$ ➔ couple strongly to $K\bar{K}$

$\Lambda(1405)$ ➔ very close to the $\bar{K}N$ threshold

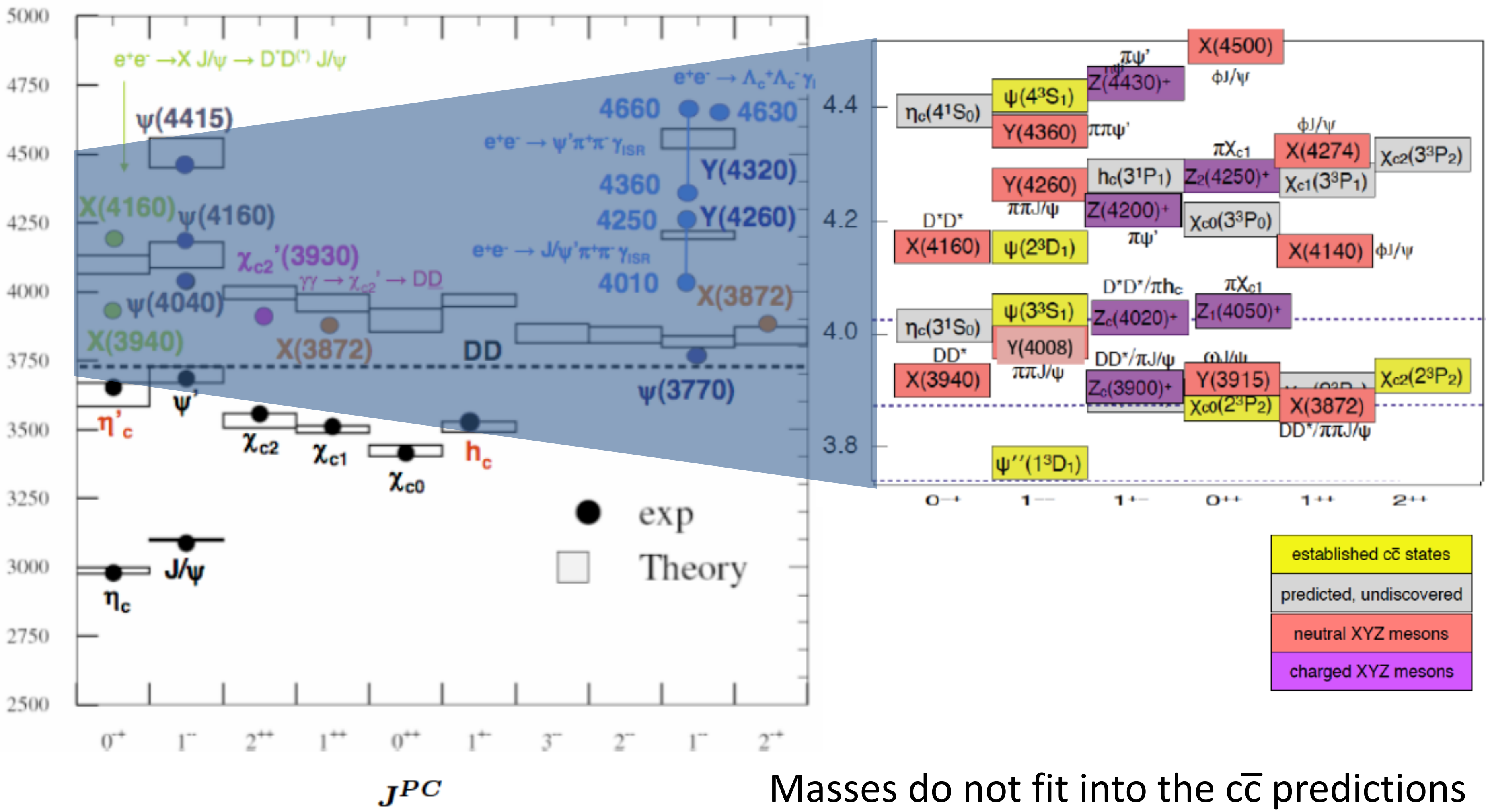
- A lot of activity for more than 20 years! …
…but disentangling the true nature of a particular hadron is not easy due to the mixing of *conventional* and *exotic* components.

Since the beginning of the millenium, an increasing amount of data covering the charm sector (collected at Belle, BaBar, LHCb and BESIII…), has provided clear evidence for many new **exotic** states which appear to be inconsistent with the predictions of the conventional quark model.

Charmonium spectrum

(M. Nielsen, Charm 2010)

(S. Olsen, Charm 2018)



Masses do not fit into the $c\bar{c}$ predictions

Charged Z_c states ➔ clearly not $c\bar{c}$!

X(3872)

Discovered at Belle in 2003

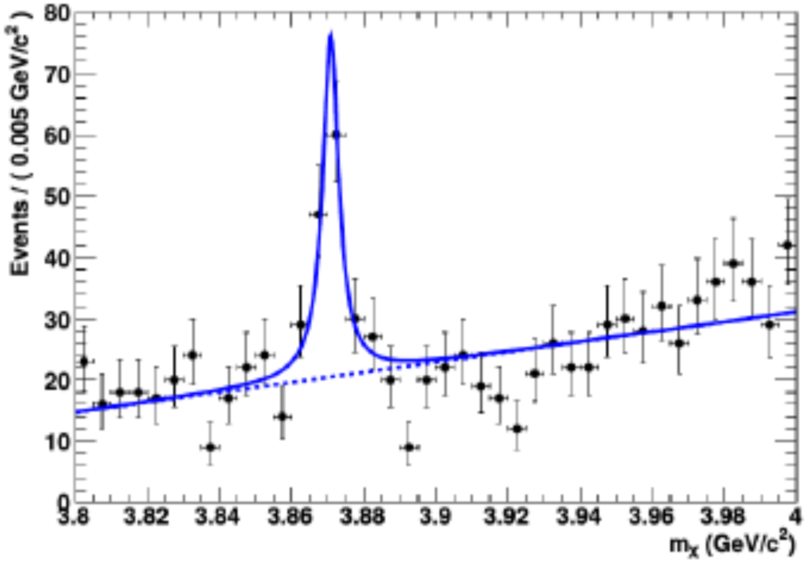
Phys. Rev. Lett. 91 (2003) 262001

Confirmed by BABAR

B. Aubert et al (BARBAR), Phys. Rev.D77 (2008) 1111

and by LHCb,
which settled quantum numbers $J^{PC}=1^{++}$

R. Aaij et al. (LHCb), PRL 110, 222001 (2013)



Mass very closes to $D^0\bar{D}^{*0}$ threshold, which was an indication of its possible *molecular* origin N.A. Törnqvist, Phys. Lett. B590 (2004) 209

- An impressive amount of experimental and theoretical work has been dedicated to understand the nature of the XYZ states discovered in the last decade.

  ➔ (recent) reviews:

  E. Eichten et al., Rev. Mod. Phys. 80 (2008) 1161
  N. Brambilla et al., Eur. Phys. J. C74 (2014) 2981
  H.X. Chen et al., Phys. Rep. 639 (2016) 1
  J.M. Richard, Few-Body Syst. 57 (2016) 1185
  A. Esposito et al., Phys. Rep. 668 (2017) 1
  R.F. Lebed et al., Prog. Part. Nucl. Phys. 93 (2017) 143
  S.L. Olsen et al., Rev. Mod. Phys. 90 (2018) 015003
  F.K. Guo et al., Rev. Mod. Phys. 90 (2018) 015004

- It is a hot topic! Also in this conference ("Hadrons and particles")

Monday afternoon: **Stadler**
García-Ortega
Takeuchi

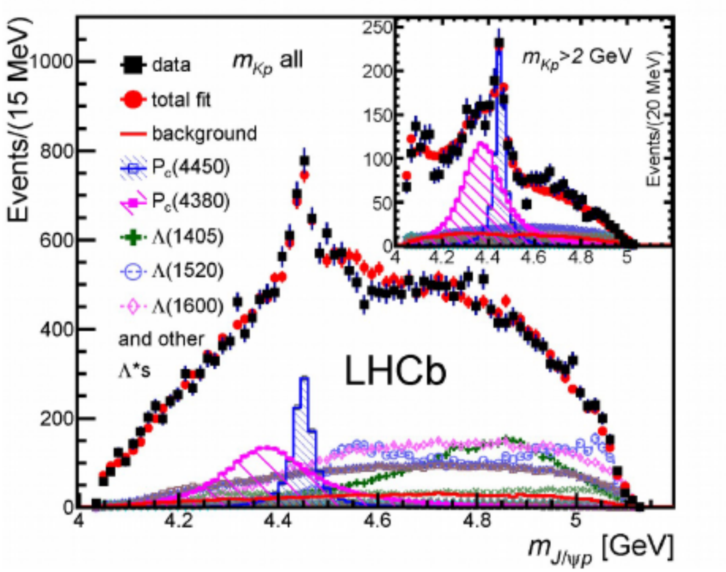
Thursday afternoon: **Yamaguchi**
Montaña

BARYONS

The LHCb pentaquarks

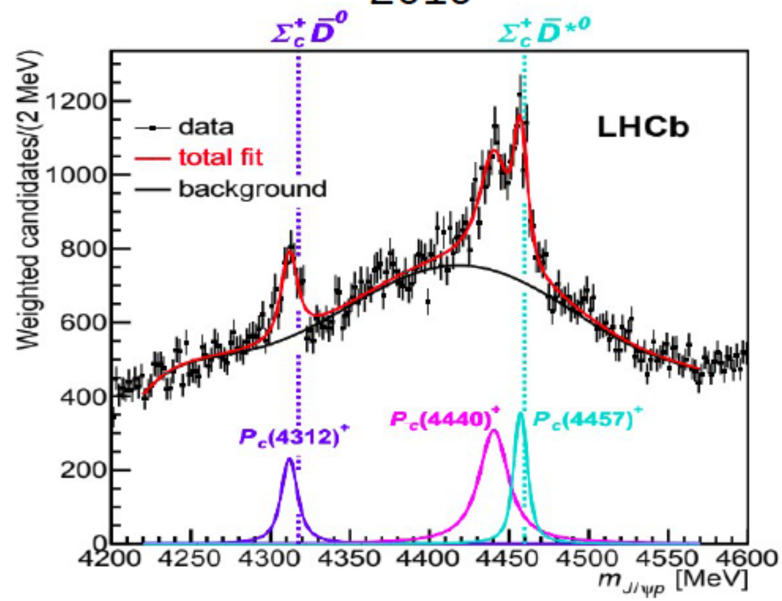
The interpretation of some baryons as being systems of 5 quarks has been revived by the observation of very "highly excited" N* in the reaction $\Lambda_b \to J/\psi\ p\ K^-$

2015



R. Aaij et al. LHCb coll. PRL 115, 072001 (2015)

2019



R. Aaij et al. LHCb coll. PRL 122, 222001 (2019)

Identified states:

$P_c(4450) \longrightarrow P_c(4440),\ P_c(4457)$

$P_c(4380) \longrightarrow P_c(4310)$

- The flavor content of the $P_c(4310)$, $P_c(4440)$, $P_c(4457)$ states is not exotic (uud) but the high mass and the observation from J/ψ p pairs makes them to be unambiguous pentaquark candidates ($c\bar{c}uud$).

These states find a natural explanation as baryon-meson molecules!

Threshold $\Sigma_c^+\bar{D}^0$: 4318 MeV → $P_c(4310)$

Threshold $\Sigma_c^+\bar{D}^{*0}$: 4460 MeV (J=1/2,3/2) → $P_c(4440)$, $P_c(4457)$

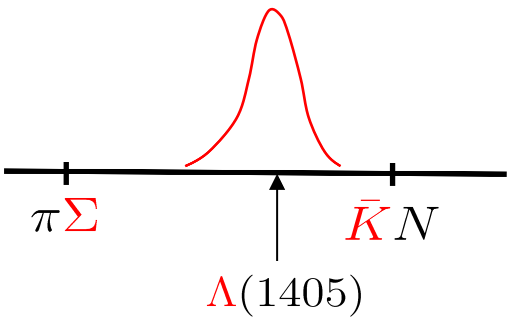
already predicted in: **J.J.Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. Lett. 105, 232001 (2010); Phys. Rev. C 84, 015202 (2011).**

- More on heavy **baryon** spectroscopy in this conference:
  Session "Hadrons and particles" Thursday afternoon: ➔ **Plessas**
  Yamaguchi

Some examples in SU(3)

The $\Lambda(1405)$

- The $\bar{K}N$ interaction in the isospin I=0 channel is able develop a **quasi-bound state**, the $\Lambda(1405)$, located only 27 MeV below the $\bar{K}N$ threshold



- Idea originally proposed by Dalitz and Tuan in the late 1950's
  R. H. Dalitz and S. F. Tuan, Annals of Phys. 10 (1960) 307

- Reformulated in terms of an effective chiral unitary theory in coupled channels by Kaiser, Siegel and Weise in 1995
  N. Kaiser, P. B. Siegel, and W. Weise, Nucl. Phys. A594 (1995) 325

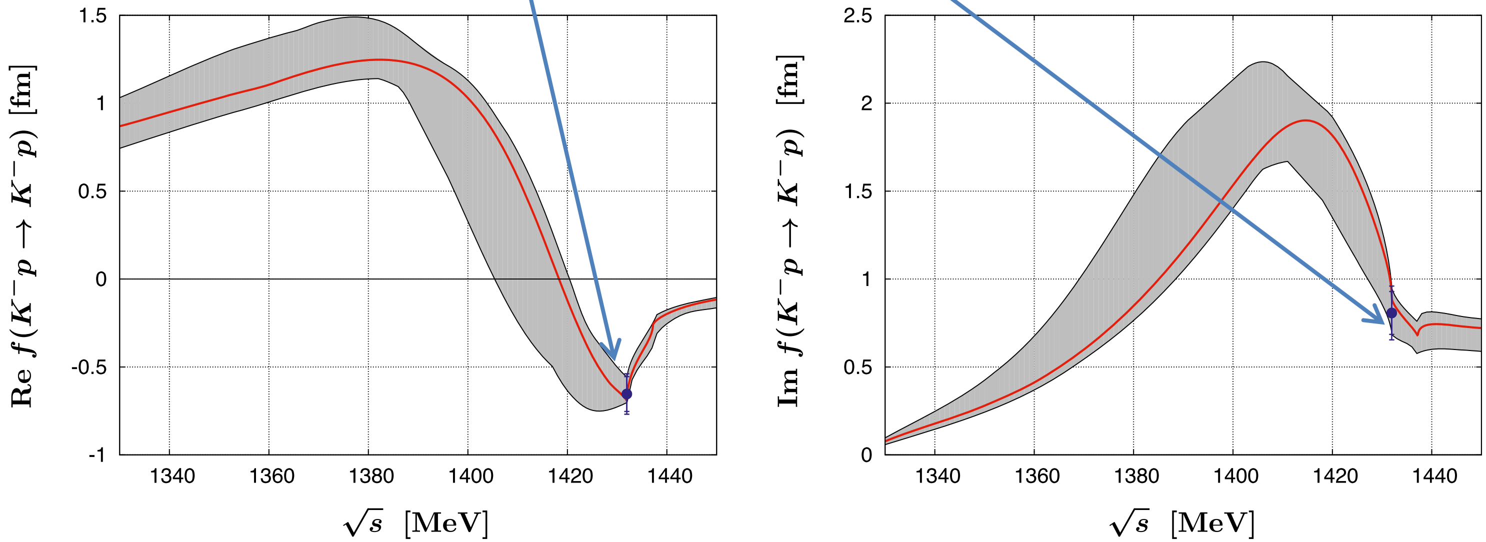
- Extended to the full coupled-basis by Oset and Ramos in 1998.
  E. Oset and A. Ramos, Nucl. Phys. A635 (1998) 99

- For ten more years (up to ~2006), plenty of theoretical work (NLO Lagrangian, s-channel and u-channel Born terms…,) finding similar features.
  Oller, Meissner, Lutz, Garcia-Recio, Borasoy, Jido, …

- Recently, the more precise SIDDHARTA measurement of the energy shift ΔE and width Γ of the 1s state in kaonic hydrogen, clarifying the inconsistency between earlier KEK and DEAR experiments, has injected a renovated interest in the field

M. Bazzi et al. Phys. Lett. B704 (2011) 113

ΔE [eV]	Γ [eV]
$283 \pm 36 \pm 6$	$541 \pm 89 \pm 22$



➔ the parameters of the NLO meson-baryon Lagrangian can be better constrained

➔ better knowledge of the KbarN interaction

Y. Ikeda, T. Hyodo, W. Weise, Nucl.Phys. A881 (2012) 98

Z-H. Guo , J.A. Oller, Phys.Rev. C87 (2013) 3, 035202

M. Mai, U-G. Meissner, Nucl.Phys. A900 (2013) 51; Eur. Phys. J. A51 (2015) 3, 30

V.K. Magas, A. Feijoo, A. Ramos, Phys. Rev. C92 (2015) 015206; Phys. Rev. C99 (2019) 035211

Essence of the non-perturbative chiral approach

1. Meson-baryon effective chiral Lagrangian:

Lowest order (LO), O(q)

$$\mathcal{L}_{MB}^{(1)}(B,U) = \langle \bar{B} i\gamma^{\mu}\nabla_{\mu} B\rangle - M_B\langle \bar{B}B\rangle + \frac{1}{2}D\langle \bar{B}\gamma^{\mu}\gamma_5\{u_{\mu},B\}\rangle + \frac{1}{2}F\langle \bar{B}\gamma^{\mu}\gamma_5[u_{\mu},B]\rangle$$

$$\nabla_{\mu}B = \partial_{\mu}B + [\Gamma_{\mu},B]$$

$$\Gamma_{\mu} = \frac{1}{2}(u^{\dagger}\partial_{\mu}u + u\partial_{\mu}u^{\dagger})$$

$$U = u^2 = exp\left(\frac{i\sqrt{2}\Phi}{f}\right)$$

$$u_{\mu} = iu^{\dagger}\partial_{\mu}Uu^{\dagger}$$

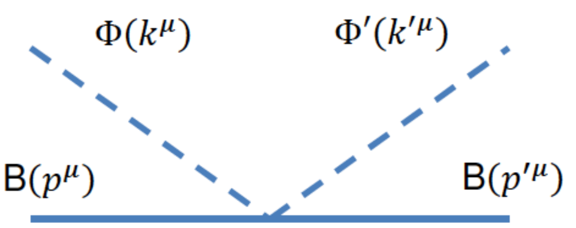
$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 \end{pmatrix}$$

$$B = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda^0 & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda^0 & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda^0 \end{pmatrix}$$

→ LO meson-baryon potential in s-wave (contact term):

$$V_{ij} = -C_{ij}\frac{1}{4f^2}\bar{u}(p)\gamma^{\mu}u(p)(k_{\mu} + k'_{\mu})$$

One parameter: f



Next to leading order (NLO), $O(q^2)$

$$\mathcal{L}_{MB}^{(2)}(B,U) = b_D\langle \bar{B}\{\chi_+, B\}\rangle + b_F\langle \bar{B}[\chi_+, B]\rangle + b_0\langle \bar{B}B\rangle\langle\chi_+\rangle + d_1\langle \bar{B}\{u_\mu,[u^\mu,B]\}\rangle + d_2\langle \bar{B}\left[u_\mu,[u^\mu,B]\right]\rangle + d_3\langle \bar{B}u_\mu\rangle\langle u^\mu B\rangle + d_4\langle \bar{B}B\rangle\langle u^\mu u_\mu\rangle$$

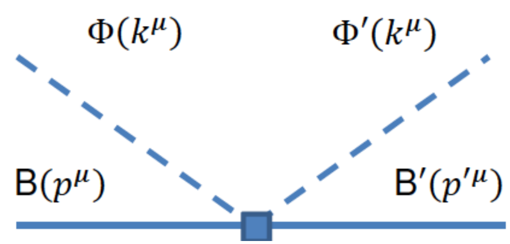
derivative terms: d_1, d_2, d_3, d_4

$$\chi_+ = -\frac{1}{4f^2}\{\Phi,\{\Phi,\chi\}\}$$

explicit chiral symmetry breaking terms: b_D, b_F, b_0

$$\chi = \begin{pmatrix} m_\pi^2 & 0 & 0 \\ 0 & m_\pi^2 & 0 \\ 0 & 0 & 2m_K^2 - m_\pi^2 \end{pmatrix}$$

➔ NLO contribution to the meson-baryon potential:

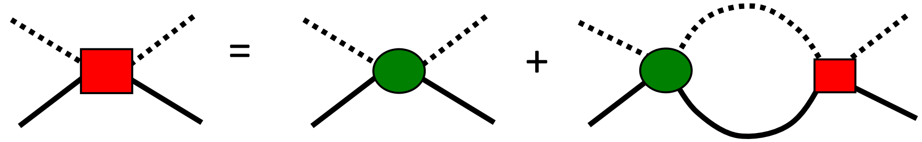


$$\tilde{V}_{ij} = \frac{1}{f^2}\left(D_{ij} - 2(k_\mu k'^\mu)L_{ij}\right)\sqrt{\frac{M_i+E_i}{2M_i}}\sqrt{\frac{M_j+E_j}{2M_j}}$$

D_{ij}, L_{ij}: matrices which depend on the 7 NLO parameters: b_D, b_F, b_0, d_1, d_2, d_3, d_4

2. Unitarization:

N/D, Bethe-Salpeter…



$$T_{ij} = V_{ij} + V_{il}\, G_l\, T_{lj}$$

Coupled channels in S=-1 meson-baryon sector:

$$K^-p, \bar{K}^0 n, \pi^0\Lambda, \pi^0\Sigma^0, \pi^+\Sigma^-, \pi^-\Sigma^+, \eta\Lambda,\ \eta\Sigma^0, K^+\Xi^-, K^0\Xi^0$$

3. Regularization of loop function:

$$G_l = i2M_l \int \frac{d^4q}{(2\pi)^4} \frac{1}{(P-q)^2 - M_l^2 + i\epsilon} \frac{1}{q^2 - m_l^2 + i\epsilon}$$

Dimensional regularization :

$$G_l = \frac{2M_l}{16\pi^2}\Big\{a_l(\mu) + \ln\frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s}\ln\frac{m_l^2}{M_l^2} +$$

$$+ \frac{\bar{q}_l}{\sqrt{s}}\Big[\ln(s - (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) + \ln(s + (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s})$$

$$- \ln(-s + (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) - \ln(-s - (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s})\Big]\Big\}$$

subtraction constants (to be fitted): a_l

$a_l(\mu) \simeq -2$ “natural size (μ~700 MeV)

J.A. Oller and U.G. Meissner, Phys. Lett. B500 (2001) 263

Threshold observables

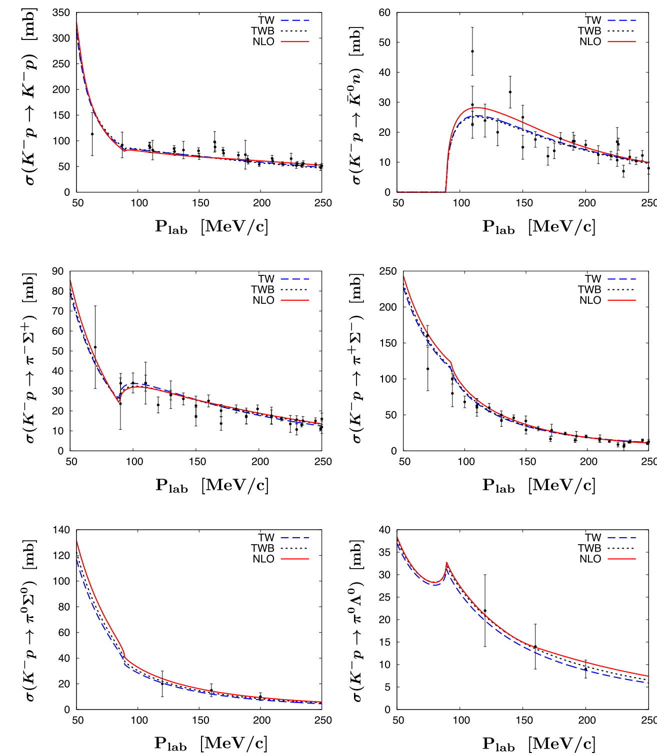
γ	R_n	R_c
2.36 ± 0.04	0.189 ± 0.015	0.664 ± 0.011

$$\gamma = \frac{\Gamma(K^- p \to \pi^+ \Sigma^-)}{\Gamma(K^- p \to \pi^- \Sigma^+)}$$

$$R_n = \frac{\Gamma(K^- p \to \pi^0 \Lambda)}{\Gamma(K^- p \to \text{neutral states})}$$

$$R_c = \frac{\Gamma(K^- p \to \pi^+ \Sigma^-, \pi^- \Sigma^+)}{\Gamma(K^- p \to \text{all inelastic channels})}$$

Cross sections



Photoproduction data

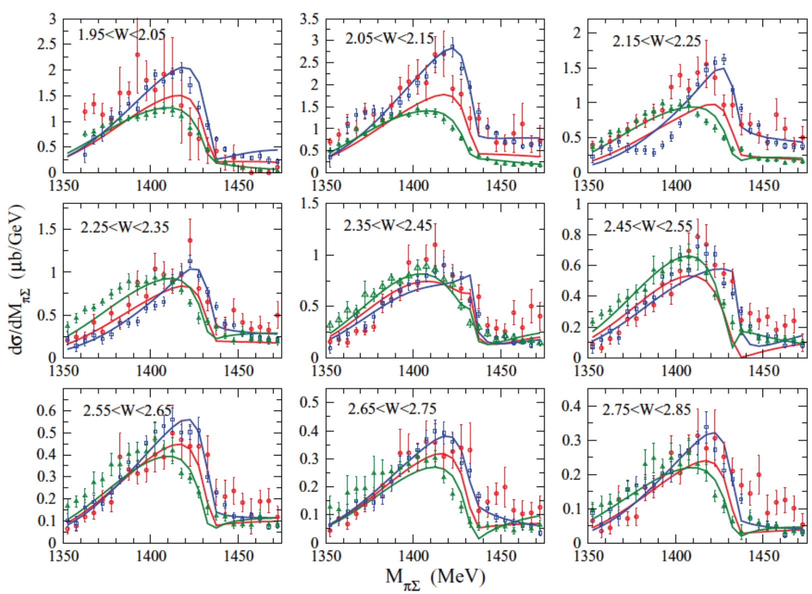


FIG. 2. (Color online) Fit to photoproduction data with fixed unitary amplitudes of $\alpha_i = 1$ and $\beta_i = 1$. Red: $\pi^0\Sigma^0$; blue: $\pi^-\Sigma^+$, green: $\pi^+\Sigma^-$. Experimental data are from Ref. [2].

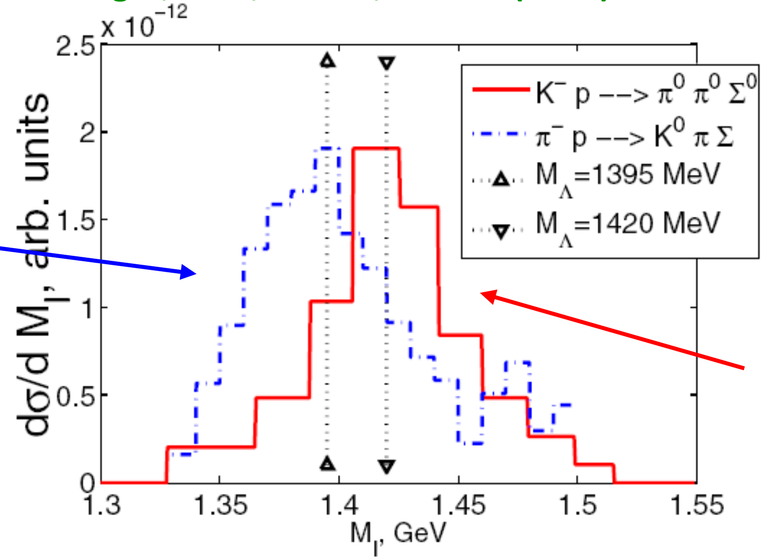
The two-pole structure of the $\Lambda(1405)$

T-matrix poles and couplings to physical states with I=0

$$T_{ij} = \frac{g_i g_j}{\sqrt{s} - M_R + i\Gamma/2},$$

z_R (I=0)	1390 - 66i $\lvert g_i \rvert$	1426 - 16i $\lvert g_i \rvert$
$\pi\Sigma$	2.9	1.5
$\bar{K}N$	2.1	2.7
$\eta\Lambda$	0.77	1.4
$K\Xi$	0.61	0.35

Magas, Oset, Ramos, PRL 95 (2005) 052301



$\pi^- p \rightarrow K^0 \pi\Sigma$

D.W.Thomas et al.
Nucl. Phys. B56, 15 (1973)

$M \sim 1385$ MeV
$\Gamma \sim 50$ MeV

$K^- p \rightarrow \pi^0\pi^0\Sigma^0$

S. Prakhov et al.,
Phys.Rev. C70,034605 (2004)

$M \sim 1420$ MeV
$\Gamma \sim 38$ MeV

→ The $\Lambda(1405)$ resonance shows different properties (position, width) in different reactions
→ Success of meson-baryon coupled-channel models!

UNIVERSITAT DE BARCELONA

ICCUB

C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).

POLE STRUCTURE OF THE $\Lambda(1405)$ REGION

Written November 2015 by Ulf-G. Meißner (Bonn Univ. / FZ Jülich) and Tetsuo Hyodo (YITP, Kyoto Univ.).

The $\Lambda(1405)$ resonance emerges in the meson-baryon scattering amplitude with the strangeness $S = -1$ and isospin $I = 0$. It is the archetype of what is called a dynamically generated resonance, as pioneered by Dalitz and Tuan [1]. The most powerful and systematic approach for the low-energy regime of the strong interactions is chiral perturbation theory (ChPT), see e.g. Ref. 2. A perturbative calculation is, however, not applicable to this sector because of the existence of the $\Lambda(1405)$ just below the $\bar{K}N$ threshold. In this case, ChPT has to be combined with a non-perturbative resummation technique, just as in the case of the nuclear forces. By solving the Lippmann-Schwinger equation with the interaction kernel determined by ChPT and using a particular regularization, in Ref. 3 a successful description of the low-energy K^-p scattering data as well as the mass distribution of the $\Lambda(1405)$ was achieved (for further developments, see Ref. 4 and references therein).

The study of the pole structure was initiated by Ref. 5, which finds two poles of the scattering amplitude in the complex energy plane between the $\bar{K}N$ and $\pi\Sigma$ thresholds. The spectrum in experiments exhibits one effective resonance shape, while the existence of two poles results in the reaction-dependent lineshape [6]. The origin of this two-pole structure is attributed

The acceptance of the $\Lambda(1405)$ as a meson-baryon quasibound state is a real success of the chiral unitary models in coupled channels!

Other sectors…

$J^P=1/2^-$

S=0 → N*(1535)

N. Kaiser, P.B. Siegel, W. Weise, Phys. Lett. B362 (1995) 23
J.C. Nacher et al., Nucl. Phys. A678 (2000) 187
T. Inoue, E. Oset, M.J. Vicente-Vacas, Phys. Rev. C65 (2002) 035204
J. Nieves and E. Ruiz Arriola, Phys. Rev. D64 (2001) 116008
M.F.M. Lutz, E.E. Kolomeitsev, Nucl. Phys. A730 (2004) 110 …

S=-2 → $\Xi(1620)$, $\Xi(1690)$

A. Ramos, E. Oset, C. Bennhold, Phys. Rev. Lett. 89 (2002) 252001
C. Garcia-Recio, J.Nieves, M.Lutz, Phys. Lett. B582 (2004) 49

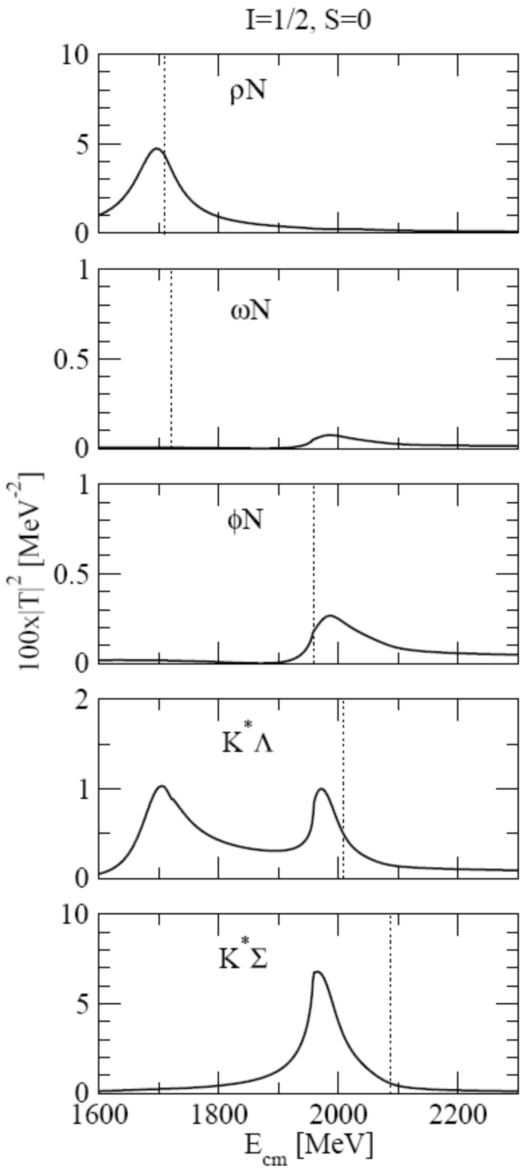
$J^P=3/2^-$ → $\Delta(1700)$,$\Lambda(1520)$,$\Sigma(1670)$,$\Xi(1820)$

(Interaction of the 0^- pseudoscalar meson octet with the $3/2^+$ baryon decuplet)

E.E. Kolomeitsev, M.F.M. Lutz, Phys. Lett. B585 (2004) 243
S. Sarkar, E. Oset, M.J. Vicente-Vacas, Phys. Rev. C72 (2005) 015206
L. Roca, S. Sarkar, V.K. Magas and E. Oset, Phys. Rev. C73 (2006) 045208
M. Döring, E. Oset, D. Strottman, Phys. Rev. C73 (2006) 045209
M. Döring, E. Oset, D. Strottman, Phys. Lett. B639 (2006) 59

for W < 2 GeV

Vector-Baryon scattering in coupled channels



N^* $J^P = 1/2^-, 3/2^-$

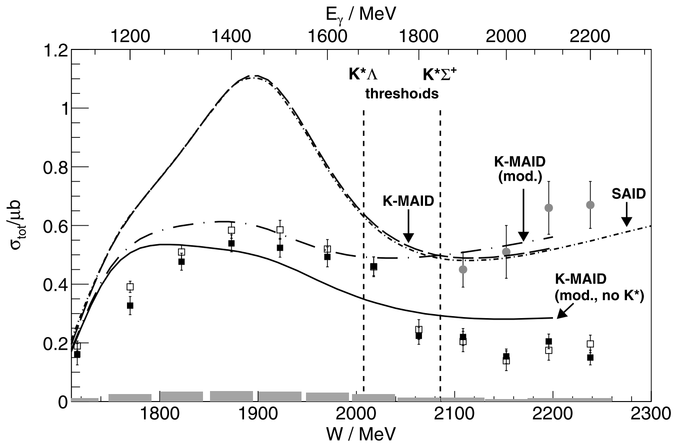
z_R	$1696^{(*)}$		$1977 + i53$	
	g_i	$\mid g_i \mid$	g_i	$\mid g_i \mid$
$\rho N(1710)$	$3.2 + i0$	3.2	$-0.3 - i0.5$	0.6
$\omega N(1721)$	$0.1 + i0$	0.1	$-1.1 - i0.4$	1.2
$\phi N(1958)$	$-0.2 + i0$	0.2	$1.5 + i0.6$	1.7
$K^*\Lambda(2010)$	$2.3 + i0$	2.3	$2.2 - i0.9$	2.3
$K^*\Sigma(2087)$	$-0.6 + i0$	0.6	$3.9 + i0.2$	3.9

We obtain two resonances, generated from the interaction of baryons with vector mesons.

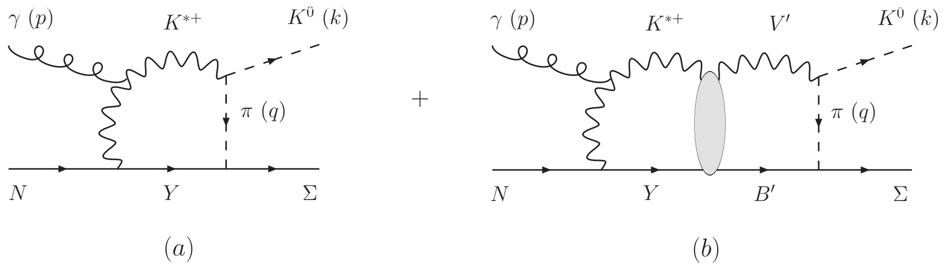
The state at 1977 MeV couples mostly to $K^*\Lambda$ and $K^*\Sigma$

E. Oset, A. Ramos, Eur.Phys.J. A44 (2010) 445-454.

Anomaly in the $K^0_S\,\Sigma^+$ photoproduction cross section in $\gamma p \rightarrow K^0\,\Sigma^+$



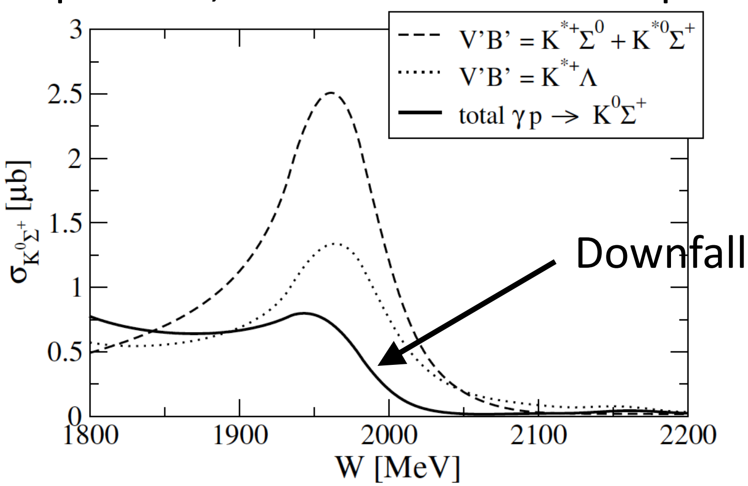
R. Ewald et al. (CBELSA/TAPS), Phys. Lett. B713 (2012) 180-185



A. Ramos and E. Oset, Phys. Lett. B 727, (2013) 287

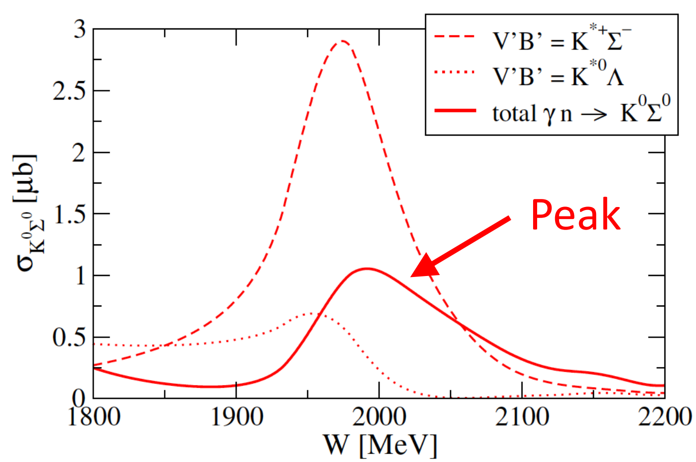
$\gamma\, p \rightarrow K^0\,\Sigma^+$

Destructive interference between $K^*\Sigma$ and $K^*\Lambda$ amplitudes, of similar size and shape.

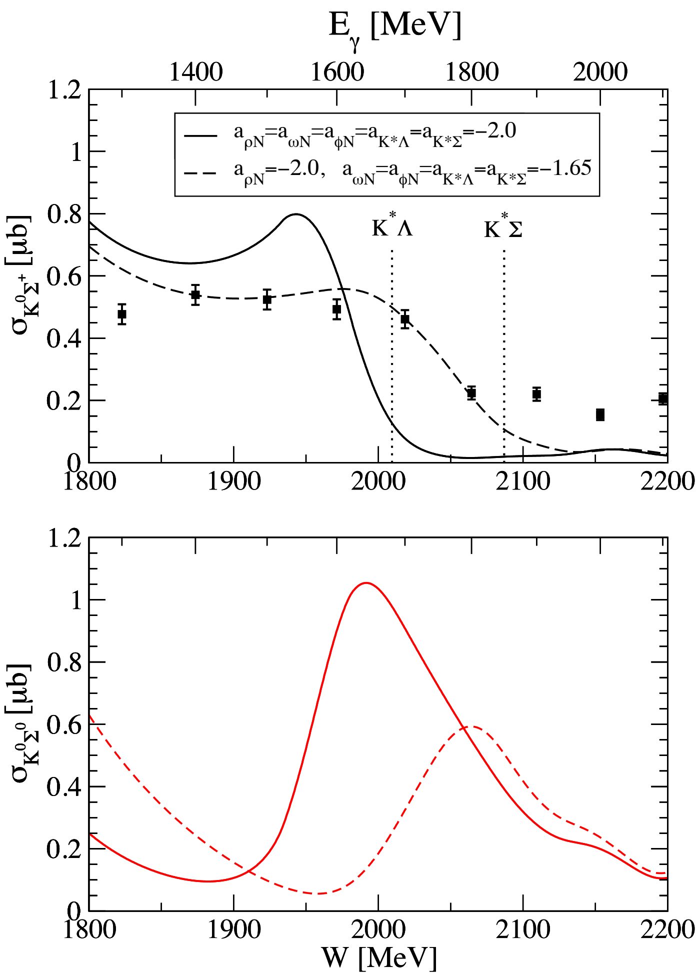


$\gamma\, n \rightarrow K^0\,\Sigma^0$ (PREDICTION)

$K^*\Sigma$ and $K^*\Lambda$ amplitudes of different size



Fine tuning to data



$J^P = 1/2^-, 3/2^-$

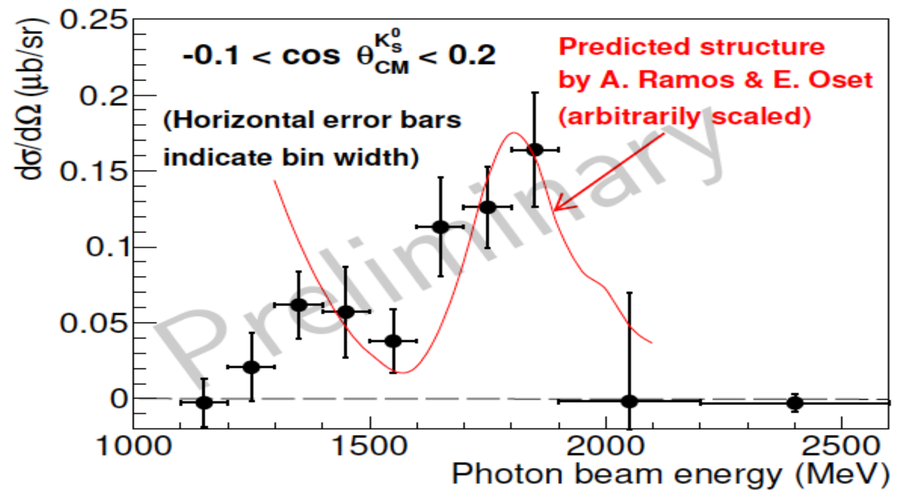
M_R = 1972 MeV Γ_R = 64 MeV

VB model adjusted to reproduce downfall:

M_R = 2035 MeV Γ_R = 125 MeV

NEW! γ n → $K^0 \Sigma^0$ measured by **BGO-OD@ELSA**

Tom Jude, NSTAR2019 (K. Kohl, PhD thesis)

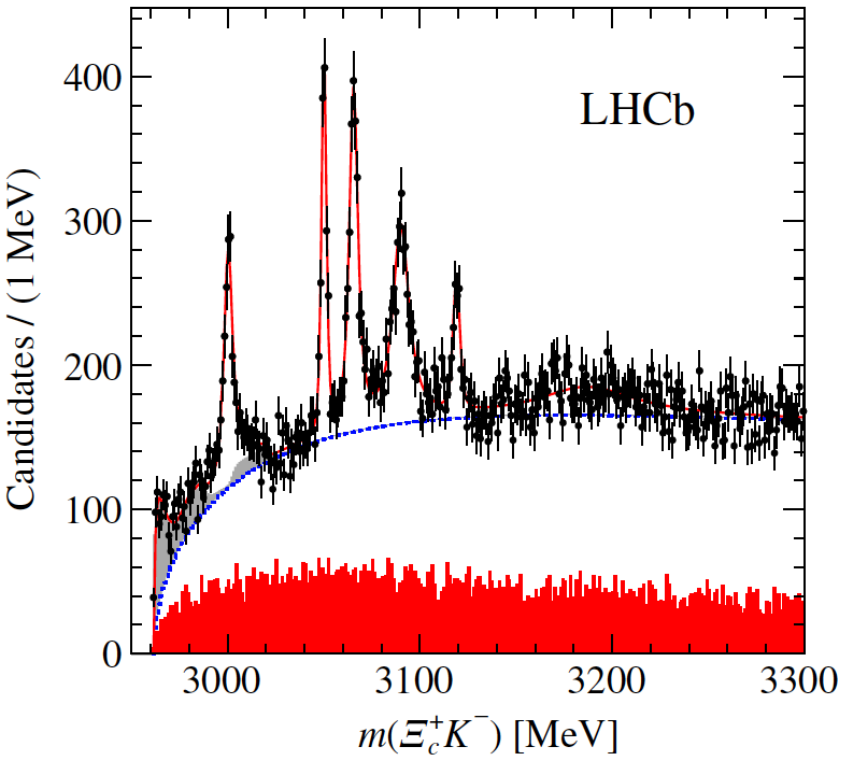


- N*(2080) (3/2-) and N*(2090) (1/2-) were in earlier PDG versions.
- We find them generated from the coupled channel Vector-Baryon dynamics !

Charm sector

The new Ω_c's seen at LHCb

R. Aaij et al. (LHCb Collaboration), Phys. Rev. Lett. 118, 182001 (2017).



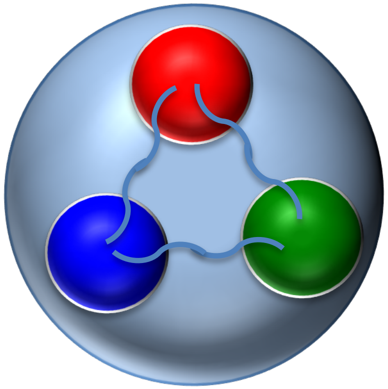
C=1, S=-2

state	mass	width
$\Omega_c(3000)$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c^0(3050)$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
$\Omega_c^0(3066)$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c^0(3090)$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c^0(3119)$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$

Similarly as the P_c pentaquarks, it is plausible that some Ω_c's can be obtained by adding a $u\bar{u}$ pair to the natural ssc content
➔ the hadronization of the 5q system could lead to *meson-baryon bound states*.

➔ Moreover, the $\bar{K}\Xi_c$ and $\bar{K}\Xi_c'$ thresholds, 2964 Mev and 3070 MeV, are in the energy range of interest.

Possible interpretation: css states



Quark models have been revisited after the LHCb discovery of the 5 Ω_c states decaying into $K^- \Xi_c^+$ pairs.

1 heavy quark (*c*) and 2 light quarks (*ss*):

→ 1P-wave orbital excitations of the *ss* pair w.r.t. the *c* quark

M.Karliner and J.L.Rosner, PRD95, 114012 (2017)[arXiv:1703.07774 [hep-ph]]
W.Wang and R.L.Zhu, PRD96, 014024 (2017) [arXiv:1704.00179 [hep-ph]]
Z.G.Wang, EPJC 77, 325 (2017 [arXiv:1704.01854 [hep-ph]]
B.Chen and X.Liu [arXiv:1704.02583 [hep-ph]]

$S_{ss} = 1$, $S_c = 1/2$ and P-wave excitation ➔ $J^P = 1/2^-$ (2), $3/2^-$ (2), $5/2^-$ (1)

→ Somes states 1P-wave orbital excitations and some others 2S radial excitations

H.X.Chen, Q.Mao, W.Chen, A.Hosaka, X.Liu and S.L.Zhu, PRD95, 094008 (2017) [arXiv:1703.07703 [hep-ph]]
S.S.Agaev, K.Azizi and H.Sundu, EPL 118, 61001 (2017 [arXiv:1703.07091 [hep-ph]]
S.S.Agaev, K.Azizi and H.Sundu, EPJC77,395 (2017) [arXiv:1704.04928 [hep-ph]]
H.Y.Cheng and C.W~Chiang, PRD95, 094018 (2017) [arXiv:1704.00396 [hep-ph]]
K.L.Wang, L.Y.Xiao, X.H.Zhong and Q.Zhao, PRD95, 116010 (2017 [arXiv:1703.09130 [hep-ph]]

➔ additional J^P possibilities: $1/2^+$, $3/2^+$

Could some of these states be "molecular?

Some earlier theoretical works already gave predictions for Ω_c resonances being meson-baryon molecules:

SU(8) model: O. Romanets et al., Phys. Rev. D85 (2012) 114032

TABLE VI. Ω_c and Ω_c^* resonances.

M_R	Γ_R	Couplings to main channels	J
2810.9	0.0	$g_{\Xi D} = 3.3$, $g_{\Xi D^*} = 1.7$, $g_{\Xi_c \bar{K}^*} = 0.9$, $g_{\Xi^* D^*} = 4.8$, $g_{\Omega_c \eta'} = 0.9$, $g_{\Omega D_s^*} = 4.2$	1/2
2814.3	0.0	$g_{\Xi D^*} = 3.7$, $g_{\Xi^* D} = 3.1$, $g_{\Xi^* D^*} = 3.8$, $g_{\Omega D_s} = 2.7$, $g_{\Omega_c^* \eta'} = 0.9$, $g_{\Omega D_s^*} = 3.4$	3/2
2884.5	0.0	$g_{\Xi_c \bar{K}} = 2.1$, $g_{\Xi D^*} = 1.7$, $g_{\Xi_c' \bar{K}^*} = 1.5$, $g_{\Xi_c^* \bar{K}^*} = 1.8$, $g_{\Omega_c \phi} = 0.9$, $g_{\Omega_c^* \phi} = 1.1$	1/2
2941.6	0.0	$g_{\Xi_c' \bar{K}} = 1.9$, $g_{\Xi D} = 1.5$, $g_{\Omega_c \eta} = 1.7$, $g_{\Xi_c \bar{K}^*} = 1.4$, $g_{\Xi_c' \bar{K}^*} = 1.1$, $g_{\Omega_c \phi} = 1.0$, $g_{\Omega D_s^*} = 0.9$	1/2
2980.0	0.0	$g_{\Xi_c^* \bar{K}} = 1.9$, $g_{\Omega_c^* \eta} = 1.6$, $g_{\Xi D^*} = 1.4$, $g_{\Xi_c \bar{K}^*} = 1.6$, $g_{\Xi_c^* \bar{K}^*} = 1.3$, $g_{\Omega_c^* \phi} = 1.2$	3/2

But these Ω_c states are much more bound than the LHCb ones

SU(4) finite range model: J. Hofmann, M.F.M. Lutz, Nucl. Phys. A 763 (2005) 90

➔ 3 Ω_c states (below 2953 MeV)

C. E. Jiménez-Tejero, A. Ramos, and I. Vidaña, Phys. Rev. C 80, 055206 (2009)

TABLE VI. Masses, widths, and couplings of the resonances in the $(I, S, C) = (0, -2, 1)$ sector.

M [MeV]	2959	2966	3117
Γ [MeV]	0.	1.1	16
	$\lvert g_i \rvert$	$\lvert g_i \rvert$	$\lvert g_i \rvert$
$\bar{K}\,\Xi_c(2964)$	1.36	0.43	0.51
$\bar{K}\,\Xi_c'(3070)$	2.04	4.49	0.27
$D\,\Xi(3189)$	2.03	1.68	5.34
$\eta\Omega_c(3246)$	1.67	3.69	0.24
$\eta'\Omega_c(3656)$	0.10	0.07	0.35
$D_s\Omega_{cc}(5528)$	0.17	1.17	0.19
$\eta_c\Omega_c(5678)$	0.28	0.21	1.03

←The only model that gives a prediction above 3 GeV !

We have revisited this model to the light of the new states observed in the C=1, S=-2 sector.

G. Montaña, A. Feijoo, A. Ramos, Eur.Phys.J. A54 (2018) 64

We consider the following pseudoscalar-baryon coupled channels:

$$\bar{K}\Xi_c(2964),\ \bar{K}\Xi_c'(3070),\ D\Xi(3189),\ \eta\Omega_c(3246),\ \eta'\Omega_c(3656),\ \underbrace{\cancel{\bar{D}_s\Omega_{cc}(5528),\ \eta_c\Omega_c(5678)}}_{\text{double charm (neglected)}}$$

	$\bar{K}\Xi_c$	$\bar{K}\Xi_c'$	$D\Xi$	$\eta\Omega_c^0$	$\eta'\Omega_c^0$
$\bar{K}\Xi_c$	1	0	$\sqrt{\frac{3}{2}}\kappa_c$	0	0
$\bar{K}\Xi_c'$		1	$\frac{1}{\sqrt{2}}\kappa_c$	$-\sqrt{6}$	0
$D\Xi$			2	$-\frac{1}{\sqrt{3}}\kappa_c$	$-\sqrt{\frac{2}{3}}\kappa_c$
$\eta\Omega_c^0$				0	0
$\eta'\Omega_c^0$					0

TABLE I: The C_{ij} coefficients for the $I = 0$, $C = 1$, $S = -2$ sector of the PB interaction.

κ_c is a reduction factor accounting for the larger mass in heavy vector meson exchange

strong attraction in the DΞ channel

$$V_{ij}(\sqrt{s}) = -C_{ij}\frac{1}{4f^2}(2\sqrt{s} - M_i - M_j)\sqrt{\frac{E_i + M_i}{2M_i}}\sqrt{\frac{E_j + M_j}{2M_j}}$$

Model 1: Subtraction constants in the dimensional regularization loops chosen so as to make it coincide with cut-off loop (Λ=800 MeV)

	$a_{\bar K\Xi_c}$	$a_{\bar K\Xi'_c}$	$a_{D\Xi}$	$a_{\eta\Omega_c}$	$a_{\eta'\Omega_c}$
Model 1	−2.19	−2.26	−1.90	−2.31	−2.26
Λ (MeV)	800	800	800	800	800

$$a_l(\mu) = \frac{16\pi^2}{2M_l}\left(G_l^{\rm cut}(\Lambda) - G_l(\mu, a_l = 0)\right)$$

The state at 3051 MeV mainly composed by $\bar K\Xi_c'$ and $\eta\Omega_c$

The state at 3103 MeV clearly qualifies as a $D\Xi$ bound state

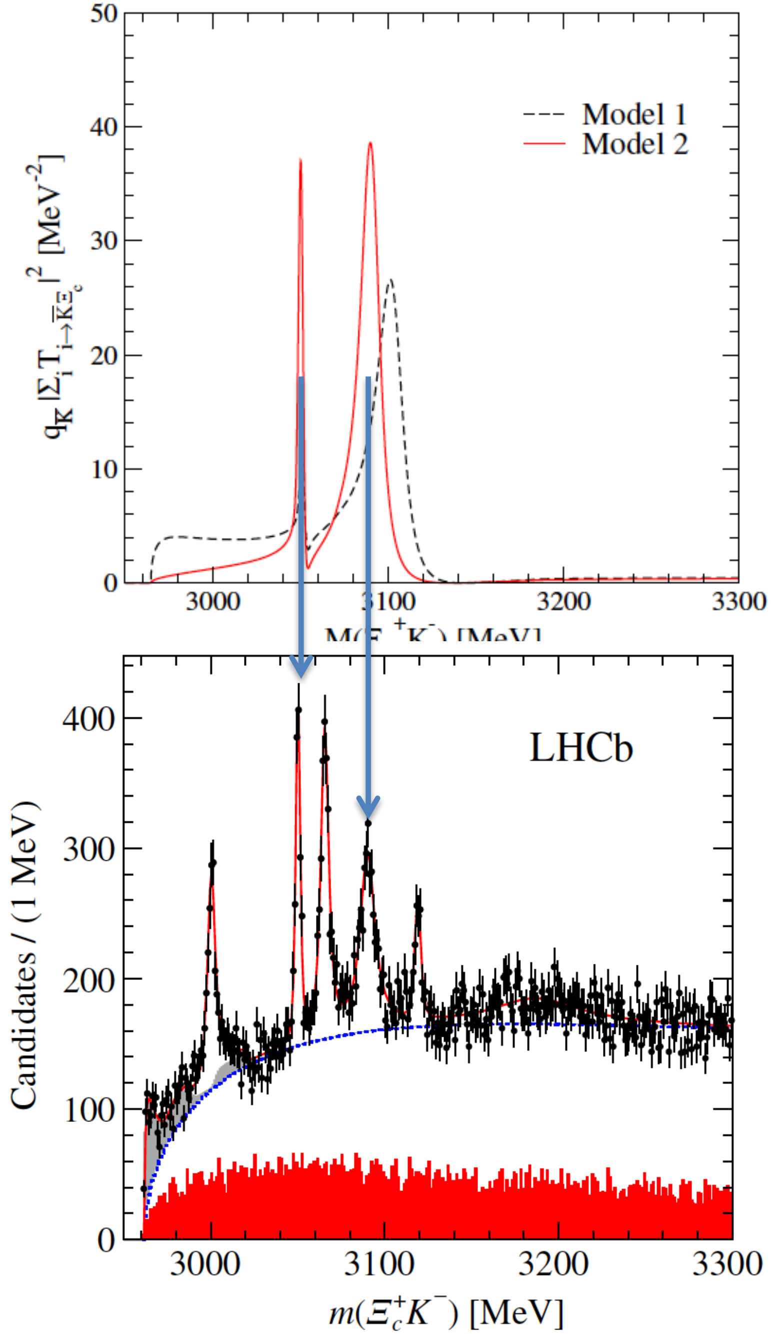
➔ 10 MeV too heavy and too wide…

Exp: $M = 3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$ MeV

$\Gamma = 8.7 \pm 1.0 \pm 0.8$ MeV.

$0^- \oplus \frac{1}{2}^+$ interaction in $(I,S,C) = (0,-2,1)$ sector

	Model 1			
M [MeV]	3051.6		3103.3	
Γ [MeV]	0.45		17	
	$\lvert g_i\rvert$	$-g_i^2 dG/dE$	$\lvert g_i\rvert$	$-g_i^2 dG/dE$
$\bar K\Xi_c(2964)$	0.11	$0.00 + i\,0.00$	0.58	$0.01 + i\,0.03$
$\bar K\Xi'_c(3070)$	1.67	$0.54 + i\,0.01$	0.30	$0.01 - i\,0.01$
$D\Xi(3189)$	1.10	$0.05 - i\,0.01$	4.08	$0.90 - i\,0.05$
$\eta\Omega_c(3246)$	2.08	$0.23 + i\,0.00$	0.44	$0.01 + i\,0.01$
$\eta'\Omega_c(3656)$	0.04	$0.00 + i\,0.00$	0.28	$0.00 + i\,0.00$



Preliminary comparison using:

$$q_{\bar{K}} \left|\Sigma_i T_{i\to\bar{K}\Xi_c}\right|^2 \ [\mathrm{MeV}^{-2}]$$

- The states at 3050 MeV and 3090 MeV are in very good agreement with experiment.
- If these states are interpreted as pseudoscalar meson-baryon molecules, their spin-parity can be predicted to be $1/2^-$.

- These results are corroborated by the recent work: (with identical diagonal amplitudes)

V.R. Debastiani, J.M. Dias, W.H. Liang and E. Oset, Phys.Rev. D97 (2018) 094035

but additional decuplet-pseudoscalar channels included!

➔ a $J^P=3/2^-$ Ω_c resonance is obtained, which could be identified with the $\Omega_c(3119)$

- Similarly, the SU(8) model was revisited recently, employing "cut-off oriented" regularization

J. Nieves, R. Pavao and L. Tolos, Eur.Phys.J. C78 (2018) 114

This model treats simultaneously: Pseudoscalar and vector mesons
$1/2^+$ and $3/2^+$ baryons

➔ results are qualitatively similar to the previous works

The double charm Ξ_{cc} sector

ucc
dcc

C=2, S=0

The doubly charmed (ground state) baryon Ξ_{cc}^{++} has been recently observed by LHCb

R. Aaij et al. (LHCb), Phys. Rev. Lett. 118, 182001 (2017)

$M(\Xi_{cc}^{++})$= 3621.2±0.7 MeV

- Are there Ξ_{cc} resonances with these quantum numbers?
- Could they have a dynamical origin (generated from the interaction of mesons with baryons)? **Q. Llorens, A. Ramos (in preparation)**

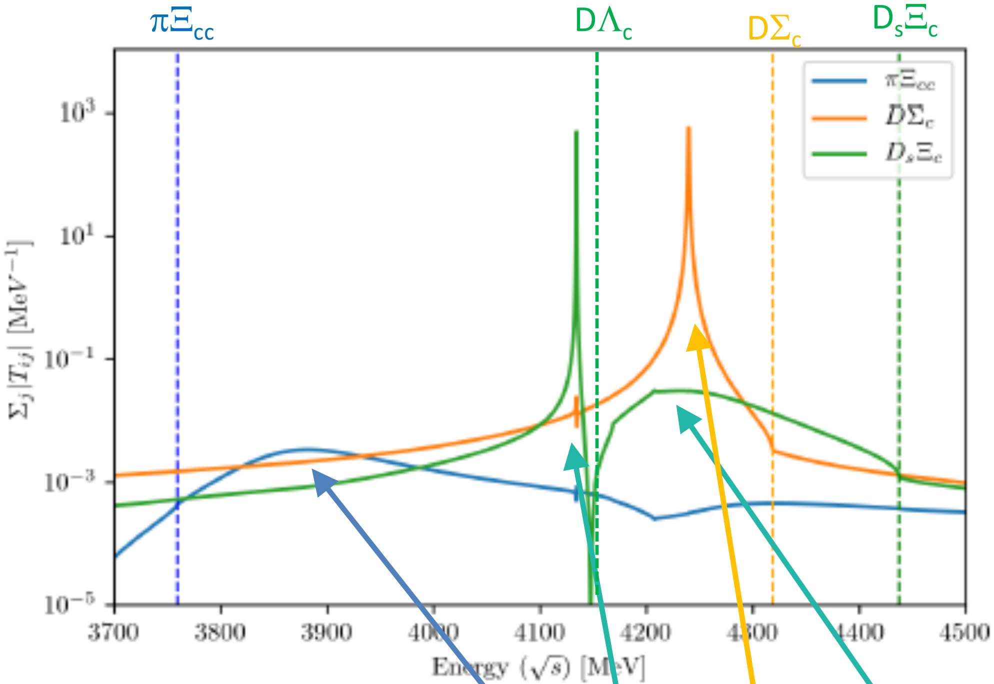
Pseudoscalar-Baryon channels with C=2, S=0 and JP=1/2$^-$

Channel	$\pi\Xi_{cc}$	$D\Lambda_c$	$\eta\Xi_{cc}$	$K\Omega_{cc}$	$D\Sigma_c$	$D_s\Xi_c$	$D_s\Xi'_c$	$\eta'\Xi_{cc}$
Threshold	3759	4152	4169	4208	4319	4438	4545	4579

C_{ij} coefficients for PB scattering

	$\pi\Xi_{cc}$	$D\Lambda_c$	$\eta\Xi_{cc}$	$K\Omega_{cc}$	$D\Sigma_c$	$D_s\Xi_c$	$D_s\Xi'_c$	$\eta'\Xi_{cc}$
$\pi\Xi_{cc}$	2	$\frac{3}{2}\kappa_c$	0	$\sqrt{\frac{3}{2}}$	$\frac{-1}{2}\kappa_c$	0	0	0
$D\Lambda_c$		$1-\xi_{cc}$	$\frac{-1}{2}\kappa_c$	0	0	1	0	$\frac{-1}{\sqrt{2}}\kappa_c$
$\eta\Xi_{cc}$			0	$\sqrt{\frac{3}{2}}$	$\frac{-1}{2}\kappa_c$	κ_c	$\frac{1}{\sqrt{3}}\kappa_c$	0
$K\Omega_{cc}$				1	0	$\sqrt{\frac{3}{2}}\kappa_c$	$\frac{-1}{\sqrt{2}}\kappa_c$	0
$D\Sigma_c$					$3-\xi_{cc}$	0	$\sqrt{3}$	$\frac{-1}{\sqrt{2}}\kappa_c$
$D_s\Xi_c$						$1-\xi_{cc}$	0	$\frac{-1}{\sqrt{2}}\kappa_c$
$D_s\Xi'_c$							$1-\xi_{cc}$	$\frac{-1}{\sqrt{6}}\kappa_c$
$\eta'\Xi_{cc}$								0

Amplitude to different final states:



Poles:

$\mathrm{Re}(z) = M_r$ [MeV]	$\boxed{3861.9}$	$\boxed{4134.5}$	$\boxed{4239.4}$	$\boxed{4240.4}$
$\mathrm{Im}(z) = \Gamma_r/2$ [MeV]	**79**	**0**	**0.38**	**83**
$\lvert g_{\pi\Xi_{cc}}\rvert$ (3759)	**2.10**	0.03	0.01	0.83
$\lvert g_{D\Lambda_c}\rvert$ (4152)	**1.29**	**1.73**	0.01	**1.13**
$\lvert g_{\eta\Xi_{cc}}\rvert$ (4169)	0.02	0.83	0.09	0.92
$\lvert g_{K\Omega_{cc}}\rvert$ (4208)	**1.22**	**1.10**	0.12	0.78
$\lvert g_{D\Sigma_c}\rvert$ (4319)	0.23	0.08	**2.88**	0.01
$\lvert g_{D_s\Xi_c}\rvert$ (4438)	0.36	**1.09**	0.02	**4.07**
$\lvert g_{D_s\Xi'_c}\rvert$ (4545)	0.18	0.01	**1.55**	0.01
$\lvert g_{\eta'\Xi_{cc}}\rvert$ (4579)	0.03	0.20	0.11	0.33

Two-narrow resonances are predicted:

$\Xi_{cc}(4134) \rightarrow D\Lambda_c$ molecule

$\Xi_{cc}(4239) \rightarrow D\Sigma_c$ molecule

Conclusions

- There are quite a few baryons than can be naturally described as meson-baryon molecules, generated by the interaction of their hadronic constituents (just as the Deuteron is a bound state of two nucleons)
  ➔ The $\Lambda(1405)$ is a well tested nice example!

- Disentangling their nature can be a difficult task!
  ➔ decay modes provide valuable information
  ➔ but also coupled channel dynamics (naturally associated to molecules) can manifest in some production reactions, as e.g. the $N^*(20XX)$

- The charm sector is offering a plethora of possibly composite states (pentaquarks P_c, charmonia XYZ, …)
  ➔ In the Ω_c (C=1, S=-2) sector we can identify two states having a pseudoscalar-baryon molecular nature, hence possibly having $J^P=1/2^-$
  ➔ We also predict molecular states in the doubly-charmed baryon spectrum

A combined theoretical effort (Quark model/Effective theories/Lattice QCD) is necessary to interpret the new data that is becoming available from various B-factories and LHCb (especially in the prolific charm sector).

Thank you for your attention