New insights on Ω_c and Ω_b excited states from molecular picture.

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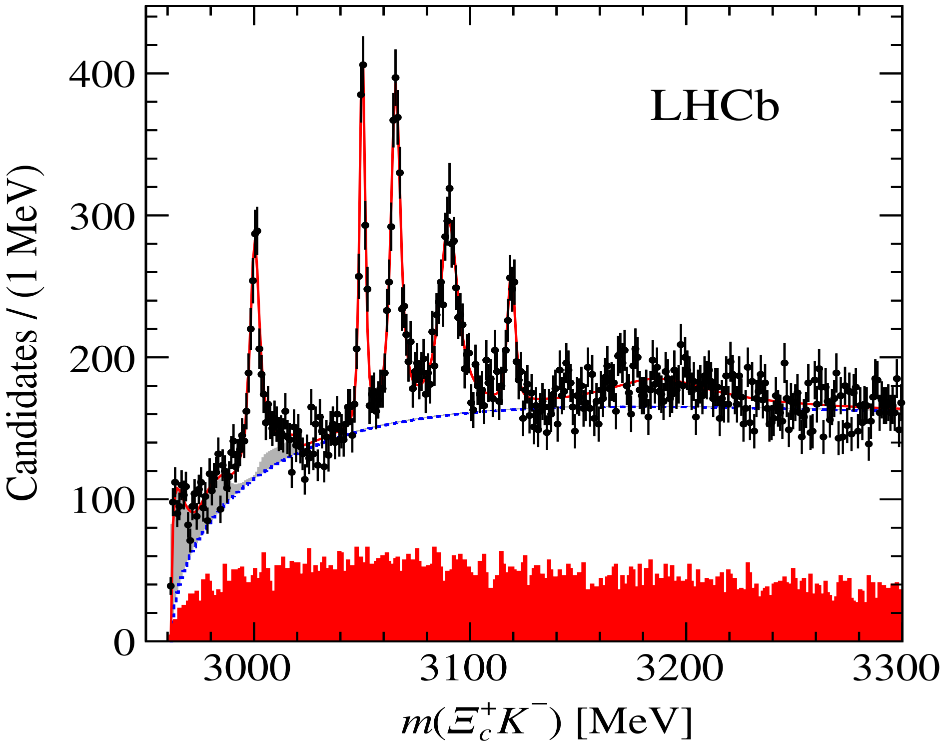
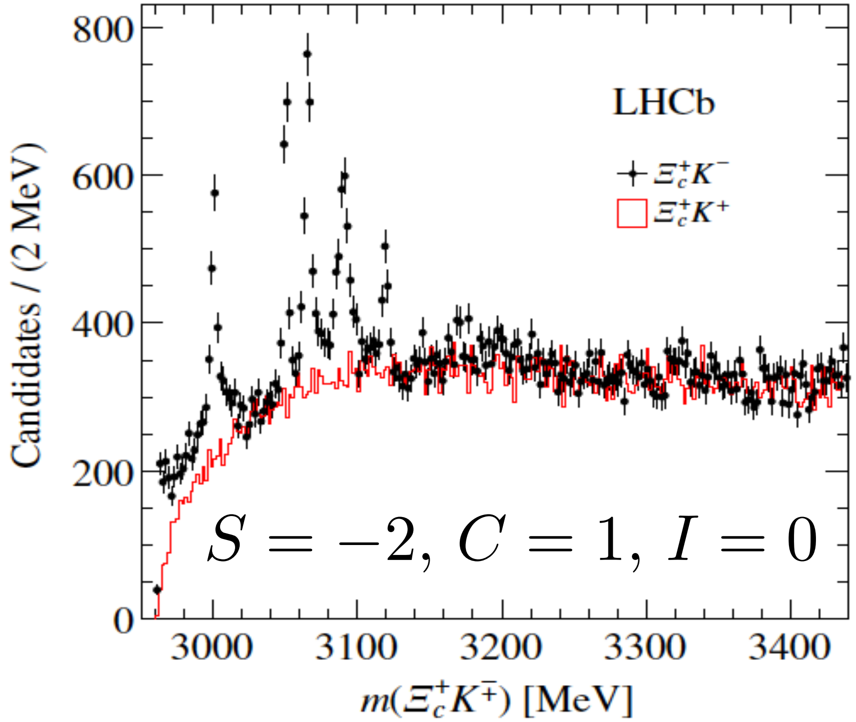
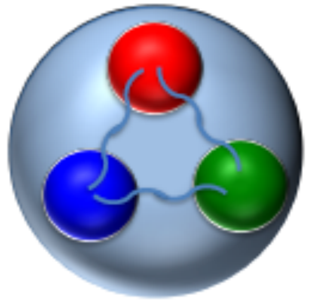
The new $\Omega_c' s$ observed at LHCb:

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





Constituent Quark Models (CQMs) interpretation:



- Bound states consisting of 1 heavy quark (c) and a P-wave (ss) diquark. (System that gives 5 possible combinations)

$$S_c = \frac{1}{2}, S_{ss} = 1 + L_{ss} = 1 \rightarrow J^P = \frac{1}{2}^-, \frac{3}{2}^-, \frac{5}{2}^-$$

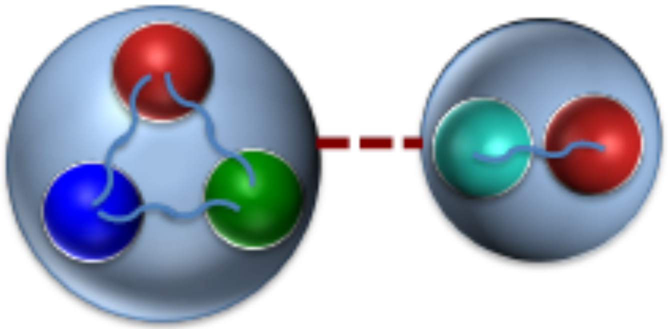
M. Karliner and J. L. Rosner, Phys. Rev. D 95, no.11, 114012 (2017).
W. Wang and R. L. Zhu, Phys. Rev. D 96, no.1, 014024 (2017).
Z.~G.~Wang, Eur. Phys. J. C 77, no.5, 325 (2017).
B.~Chen and X.~Liu, Phys. Rev. D 96, no.9, 094015 (2017).

- Alternative interpretation: some states (the 3 lightest ones) remain with (ss) diquark with 1P orbital excitation and the others with 2S radial excitations.

$$J^P = \frac{3}{2}^-, \frac{5}{2}^-, \frac{1}{2}^+, \frac{3}{2}^+$$

S. S. Agaev, K. Azizi and H. Sundu, EPL 118, no.6, 61001 (2017).
S. S. Agaev, K. Azizi and H. Sundu, Eur. Phys. J. C 77, no.6, 395 (2017).
H. Y. Cheng and C. W. Chiang, Phys. Rev. D 95, no.9, 094018 (2017).
K. L. Wang, L. Y. Xiao, X. H. Zhong and Q. Zhao, Phys. Rev. D 95, no.11, 116010 (2017).

What about a molecular interpretation of these states?



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

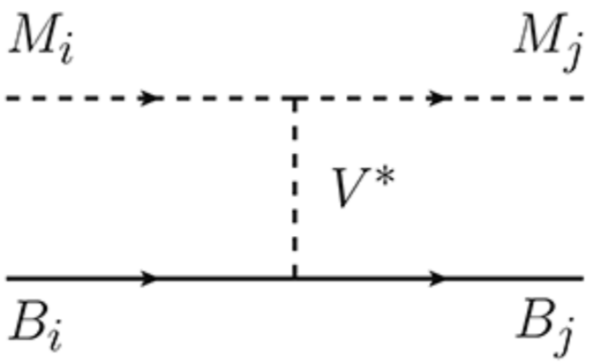
Resonance	Mass (MeV)	Γ (MeV)
$\Omega_c(3000)^0$	$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$	$4.5 \pm 0.6 \pm 0.3$
$\Omega_c(3050)^0$	$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$	$0.8 \pm 0.2 \pm 0.1$
		<1.2 MeV, 95% C.L.
$\Omega_c(3066)^0$	$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$	$3.5 \pm 0.4 \pm 0.2$
$\Omega_c(3090)^0$	$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$	$8.7 \pm 1.0 \pm 0.8$
$\Omega_c(3119)^0$	$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$	$1.1 \pm 0.8 \pm 0.4$
		<2.6 MeV, 95% C.L.

- The $\bar{K}\Xi_c$ (2964 MeV) and $\bar{K}\Xi_c'$ (3070 MeV) thresholds are very close or within the energy range where the physical Ω_c states pop up!!!
- Prior to the experimental measurement, some theoretical works predicted some states in this sector :

1. SU(8) spin-flavor sym. Model → 5 states much more bound than the LHCb ones. O. Romanets et al., Physical. Rev. D85,114032 (2012)
2. SU(4) finite range Model → 3 states below 2953 MeV. J. Hofmann and M.F.M. Lutz, Nucl. Phys. A 763, 90-139 (2005)
3. SU(4) finite range Model→ 3 Ω_c states, one of them at 3117 MeV ($\Gamma = 16$ MeV)!!! C. E. Jimenez-Tejero, A. Ramos and I. Vidaña, Phys. Rev. C 80, 055206 (2009)

Molecular-Picture Models revisited

G. Montaña, A. Feijoo and A. Ramos, Eur. Phys. J. A 54, no.4, 64 (2018)



$$\mathcal{L}_{VPP} = ig\langle[\partial_\mu\phi, \phi]\, V^\mu\rangle$$

$$\mathcal{L}_{VBB} = \frac{g}{2}\sum_{i,j,k,l=1}^{4} \bar{B}_{ijk}\gamma^\mu \left(V^k_{\mu,l}B^{ijl} + 2V^j_{\mu,l}B^{ilk}\right)$$

- When $t \ll m_V^2$ and projecting onto S-wave:

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

Molecular-Picture Models revisited

G. Montaña, A. Feijoo and A. Ramos, Eur. Phys. J. A 54, no.4, 64 (2018)

The basis considered in this sector consist of the following pseudoscalar-baryon channels:

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

C_{ij}	$\bar{K}\Xi_c$	$\bar{K}\Xi_c'$	$D\Xi$	$\eta\Omega_c^0$	$\eta'\Omega_c^0$
$\bar{K}\Xi_c$	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

Strong attraction in the $D\Xi$ channel

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

Molecular-Picture Models revisited

G. Montaña, A. Feijoo and A. Ramos, Eur. Phys. J. A 54, no.4, 64 (2018)

Unitarized T-matrix from coupled-channel Bethe-Salpeter equation solved through On-shell factorization and regularized by means of Dim. Reg.:

$$T = (1 - VG)^{-1}V,\; G(a_l(\mu))$$

Subtraction constants present in the loops are set to coincide with cut-off loop ($\Lambda = 800$ MeV)

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

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

Table 1: Values of the subtraction constants at a regularization scale $\mu = 1$ GeV and the equivalent cut-off Λ for Model 1.

Molecular-Picture Models revisited

G. Montaña, A. Feijoo and A. Ramos, Eur. Phys. J. A 54, no.4, 64 (2018)

Ω_c states dynamically generated by the interaction between a pseudoscalar meson and a ground state baryon:

$0^- \oplus \frac{1}{2}^+$ interaction in the $(I,S,C)=(0,-2,1)$ 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	$0.00+i\,0.00$

The state at 3051 MeV mainly composed by $K\Xi'_c$ and $\eta\Omega_c$

The state at 3103 MeV is basically a $D\Xi$ bound state

➔10 MeV too heavy and too wide…

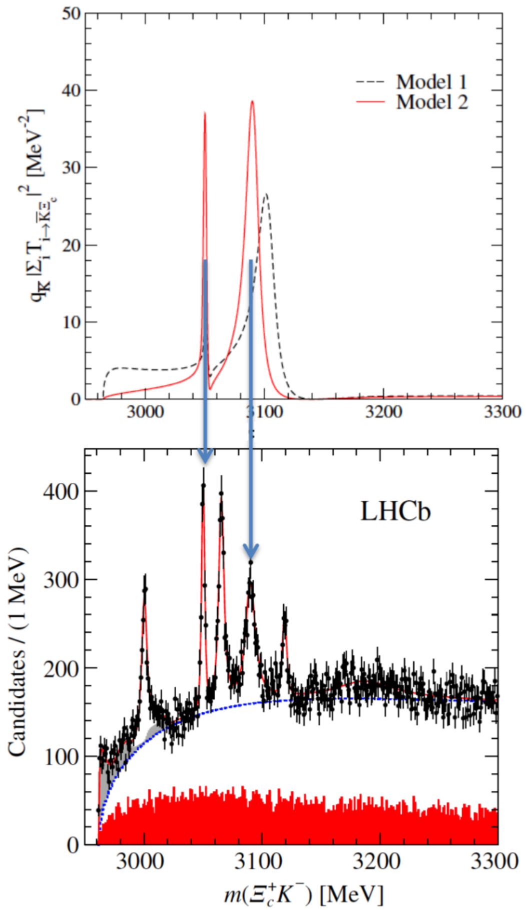
Experimental states

$$\Omega_c(3050)^0: \quad M = 3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}\ \text{MeV}, \quad \Gamma = 0.8 \pm 0.2 \pm 0.1\ \text{MeV},$$

$$\Omega_c(3090)^0: \quad M = 3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}\ \text{MeV}, \quad \Gamma = 8.7 \pm 1.0 \pm 0.8\ \text{MeV}$$

Molecular-Picture Models revisited

G. Montaña, A. Feijoo and A. Ramos, Eur. Phys. J. A 54, no.4, 64 (2018)



Quantity constructed to simulate the experimental spectrum:

$$q_{K^-} \,|\sum_i T_{i\to\bar{K}\Xi_c}\,|^2$$

- The states at 3050 MeV and 3090 MeV (from Model 2) are in very good agreement with experiment.
- If the molecular nature of these states is assumed, their spin-parity can be predicted to be 1/2-.

Molecular-Picture Models revisited

V. R. Debastiani, J. M. Dias, W. H. Liang and E. Oset, Phys. Rev. D 97, no.9, 094035 (2018)

- Extension of the local hidden gauge approach with heavy-baryon states as a spectator c quark + sym. wave funtions of the remaining light quarks
- Inclusion of pseudoscalar-decuplet baryon channels

➔ Same 2 states with $J^P = \frac{1}{2}^-$ and a new $J^P = \frac{3}{2}^-$ Ω_c resonance which could be identified with the LHCb $\Omega_c(3119)$

J. Nieves, R. Pavao and L. Tolos, Eur. Phys. J. C 78, no.2, 114 (2018)

- $SU(6)_{lsf}$ xHQSS-extended WT meson-baryon interaction
- The symmetries automatically account for the additional presence of additional vector mesons and $3/2^+$ baryons

➔ 2 states with $J^P = \frac{1}{2}^-$ and 1 $J^P = \frac{3}{2}^-$ state consistent with the experimental $\Omega_c(3000)$, $\Omega_c(3050)$ and $\Omega_c(3119)$

Born terms: Motivation

In heavy sectors, Born terms have been systematically ignored , assumed to play a very moderate role…
How solid this assumption is?

- Evidences of their non-negligible function in $\bar{K}N$ interaction:

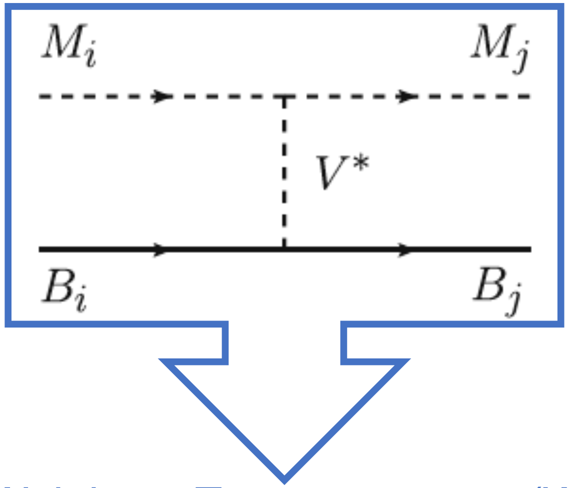
J. A. Oller and U.-G. Meissner, Phys. Lett. B 500, 263 (2001)
Born contributions reach $\sim$20% of the dominant WT contribution just 65 MeV above $\bar{K}N$ threshold (S-wave)
➔ Just the energy range where the LHCb Ω_c states are located is 120 MeV wide

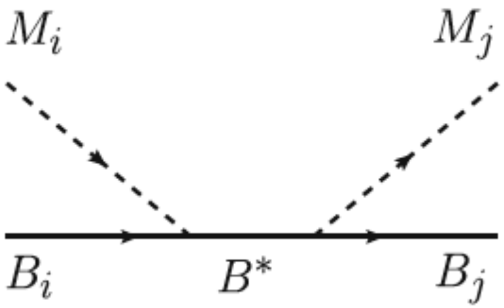
A. Feijoo, V. Magas and A. Ramos, Phys. Rev. C 99, no.3, 035211 (2019), Nucl. Phys. A 954, 58 (2016)
At slightly higher energies, the Born terms are essential to reproduce the experimental total cross section from $\bar{K}N \to \eta\Lambda, \eta\Sigma, K\Xi$ processes (η channel thresholds are around 200 MeV above $\bar{K}N$ threshold)

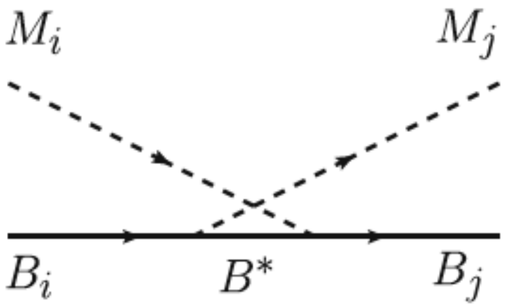
The incorporation of the s- and u-channel diagrams may have additional implications…

- Born terms contribute mainly to P-wave, one can consider the possibility of obtaining 1/2+ and 3/2+.states.
- the inclusión of new pieces in the interaction kernel can affects the interplay among the channels of the basis

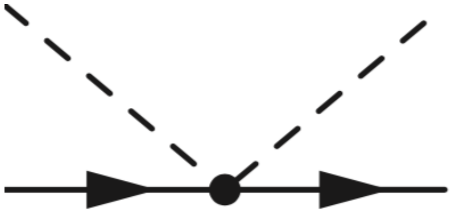
Born terms: Formalism







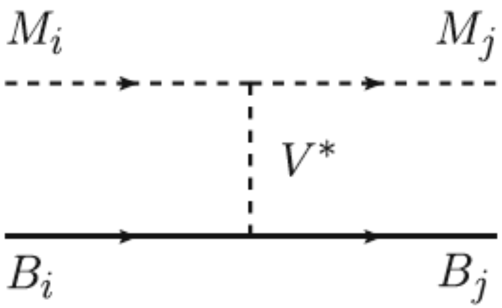
Weinberg-Tomozawa term (WT)



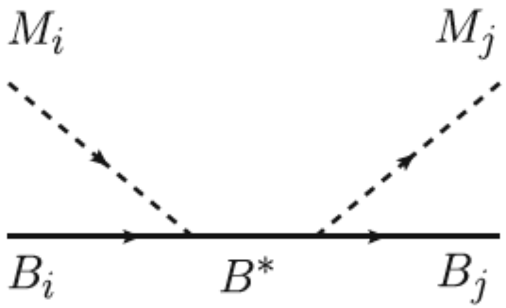
- Dominant contribution
- Interaction mediated, basically, by the constant ***f*** of the leptonic decay of the pseudoscalar meson

$$V_{ij}^{WT} = -\frac{N_i N_j}{4f^2} C_{ij} \left\{ (2\sqrt{s} - M_i - M_j) \chi_f^{\dagger s'} \chi_0^s + \frac{2\sqrt{s}+M_i+M_j}{(E_i+M_i)(E_j+M_j)} \chi_f^{\dagger s'} \left[\vec{q}_j \cdot \vec{q}_i + i(\vec{q}_j \times \vec{q}_i) \cdot \vec{\sigma} \right] \chi_0^s \right\}$$

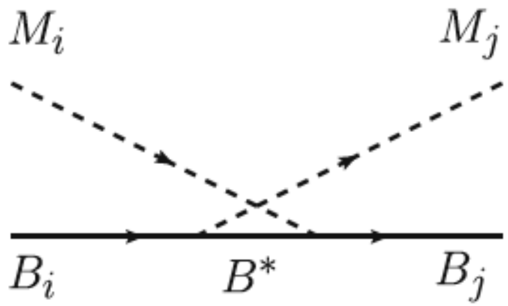
Born terms: Formalism



Direct Born term (s-channel)



Cross Born term (u-channel)



$$\begin{aligned} g_A &= D + F = 1.26 \\ D &= 0.8 \\ F &= 0.46 \end{aligned}$$

$$\mathcal{L}_{BBM} = \frac{\sqrt{2}}{4f} \sum_{i,j,k,l=1}^{4} \bar{B}_{ijk} \gamma^5 \gamma^\mu \left[(D+F) \partial_\mu \Phi_{kl} B_{ijl} - 2(D-F) \partial_\mu \Phi_{jl} B_{ilk} \right]$$

Born terms: Formalism

1. Direct diagram (s-channel Born term)

$$V_{ij}^{D} = \frac{N_i N_j}{12 f^2} \sum_k \frac{C_{\bar{i}i,k}^{(\mathrm{Born})} C_{\bar{j}j,k}^{(\mathrm{Born})}}{s - M_k^2} \Big\{ (\sqrt{s} - M_k)(s + M_i M_j - \sqrt{s}(M_i + M_j)) \chi_j^{\dagger s'} \chi_i^{s}$$
$$+ \frac{(s + \sqrt{s}(M_i + M_j) + M_i M_j)(\sqrt{s} + M_k)}{(E_i + M_i)(E_j + M_j)} \chi_j^{\dagger s'} \left[\vec{q}_j \cdot \vec{q}_i + i(\vec{q}_j \times \vec{q}_i) \cdot \vec{\sigma} \right] \chi_i^{s} \Big\}$$

2. Cross diagram (u-channel Born term)

$$V_{ij}^{C} = -\frac{N_i N_j}{12 f^2} \sum_k \frac{C_{\bar{j}k,i}^{(\mathrm{Born})} C_{\bar{i}k,j}^{(\mathrm{Born})}}{u - M_k^2} \Big\{ \big[u(\sqrt{s} + M_k) + \sqrt{s}(M_j(M_i + M_k) + M_i M_k)$$
$$- M_j (M_i + M_k)(M_i + M_j) - M_i^2 M_k \big] \chi_j^{\dagger s'} \chi_i^{s} + \big[u(\sqrt{s} - M_k) + \sqrt{s}(M_j(M_i + M_k) + M_i M_k)$$
$$+ M_j (M_i + M_k)(M_i + M_j) + M_i^2 M_k \big] \chi_j^{\dagger s'} \frac{\vec{q}_j \cdot \vec{q}_i + i(\vec{q}_j \times \vec{q}_i) \cdot \vec{\sigma}}{(E_i + M_i)(E_j + M_j)} \chi_i^{s} \Big\}$$

Born terms: Formalism

- **The T-matrix in the CM system can be split into spin-nonflip and spin-flip parts:**

$$T_{ij} = \chi_j^{\dagger s'} [f(\sqrt{s},\theta) - i(\vec{\sigma}\cdot\hat{n}) g(\sqrt{s},\theta)] \chi_i^s$$

Where:

$$\left.\begin{aligned} f(\sqrt{s},\theta) &= \sum_{l=0}^{\infty} f_l(\sqrt{s})\, P_l(cos\theta) \\ g(\sqrt{s},\theta) &= \sum_{l=1}^{\infty} g_l(\sqrt{s})\, sin\theta\, \frac{dP_l(cos\theta)}{d(cos\theta)} \end{aligned}\right\} \text{Expansion in } \textbf{Legendre} \text{ polynomials}$$

$$\hat{n} = \frac{\vec{q}_j \times \vec{q}_i}{|\vec{q}_j \times \vec{q}_i|}$$

Born terms: Formalism

Unitarization: e.g. via the Bethe-Salpeter equation with on-shell amplitudes

- Amplitudes with well definite total angular momentum exhibit independent unitary conditions

→ **They should be separated in the Bethe-Salpeter equation** and need to be redefined with a definite total angular momentum:

$$f^{tree}_{l+}(\sqrt{s}) = \frac{1}{2l+1}\left(f_l(\sqrt{s}) + l\, g_l(\sqrt{s})\right), \quad j = l + \tfrac{1}{2}$$

$$f^{tree}_{l-}(\sqrt{s}) = \frac{1}{2l+1}\left(f_l(\sqrt{s}) - (l+1)\, g_l(\sqrt{s})\right), \quad j = l - \tfrac{1}{2}$$

Finally, **unitarized amplitudes** …

$$f_{l\pm} = \left[1 - f^{tree}_{l\pm} G\right]^{-1} f^{tree}_{l\pm}$$

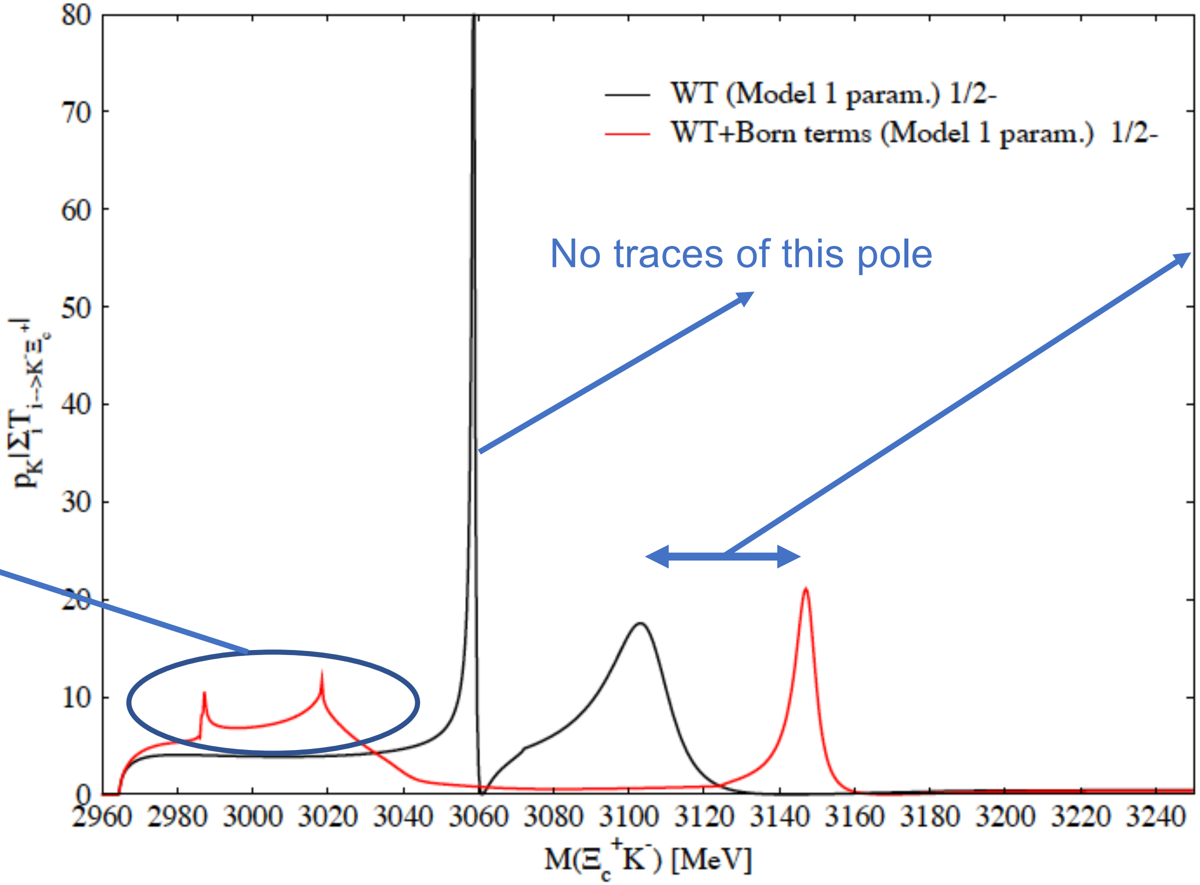
- meson-baryon loop function (dimensional regularitzation)

$$G_l = \frac{2M_l}{(4\pi)^2}\left\{ a_l(\mu) + \ln\frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s}\ln\frac{m_l^2}{M_l^2} + \frac{q_{\rm cm}}{\sqrt{s}}\ln\left[\frac{(s+2\sqrt{s}q_{\rm cm})^2 - (M_l^2 - m_l^2)^2}{(s-2\sqrt{s}q_{\rm cm})^2 - (M_l^2 - m_l^2)^2}\right]\right\}$$

subtraction constants for the dimensional regularization scale $\mu = 1GeV$ in all the k channels.

Born terms: checking their effects on the spectrum

WT spectrum vs. WT+Born terms spectrum keeping the old Model 1 parametrization (s-wave):



2 new structures pop up

The second pole has been shifted almost 50 MeV

Clear evidence of the non-negligible role of the s- and u-channels

Fitting parameters:

- Decay constant ***f***

Partially constrained: $f_\pi^{exp}(= 92.4 MeV) \leqslant f \leqslant 1.23 f_\pi^{exp}$

- 5 subtracting constants (isospín symmetry):

$$\left.\begin{array}{c} a_{\bar{K}\Xi_c} \\ a_{\bar{K}\Xi'_c} \\ a_{D\Xi} \\ a_{\eta\Omega_c} \\ a_{\eta'\Omega_c} \end{array}\right\} \sim -2.3, (\mu = 1000 MeV) \longrightarrow [-1, -4]$$

(natural size)

they are allowed to vary within the range:

Born terms: Fitting procedure

- Generation of pseudo-random points in the parameter space by means of Latin hypercube (LH) space filling
  LH guarantees homogeneity of the points through the whole parameter volume
  10^7 samples are generated
- An assumption should be made: How many and which states have molecular nature
- For each param. x (meson decay const, sub. const), we evaluate the generalized spectrum $f_i(x)$ defined as:

$$q_{K^-}\left(\left|\sum_i T^{\frac{1}{2}^-}_{i\to\bar{K}\Xi_c}\right|^2+2\left|\sum_i T^{\frac{1}{2}^+}_{i\to\bar{K}\Xi_c}\right|^2+\left|\sum_i T^{\frac{3}{2}^+}_{i\to\bar{K}\Xi_c}\right|^2\right)$$

- The algorithm looks for structures in the complex energy plane, once found it assigns $E(f_i(x))$ (mass and width)
- The implausibility measure discriminates param. for a chosen experimental peak and a given s (number of accepted σ)

$$I_M^2(x)=\max_{i\in Z} I_i^2(x)\equiv\max_{i\in Z}\frac{|\mathbb{E}(f_i(x))-z_i|^2}{\mathrm{Var}_i(x)},\ I_M^2(x)\leqslant s^2$$

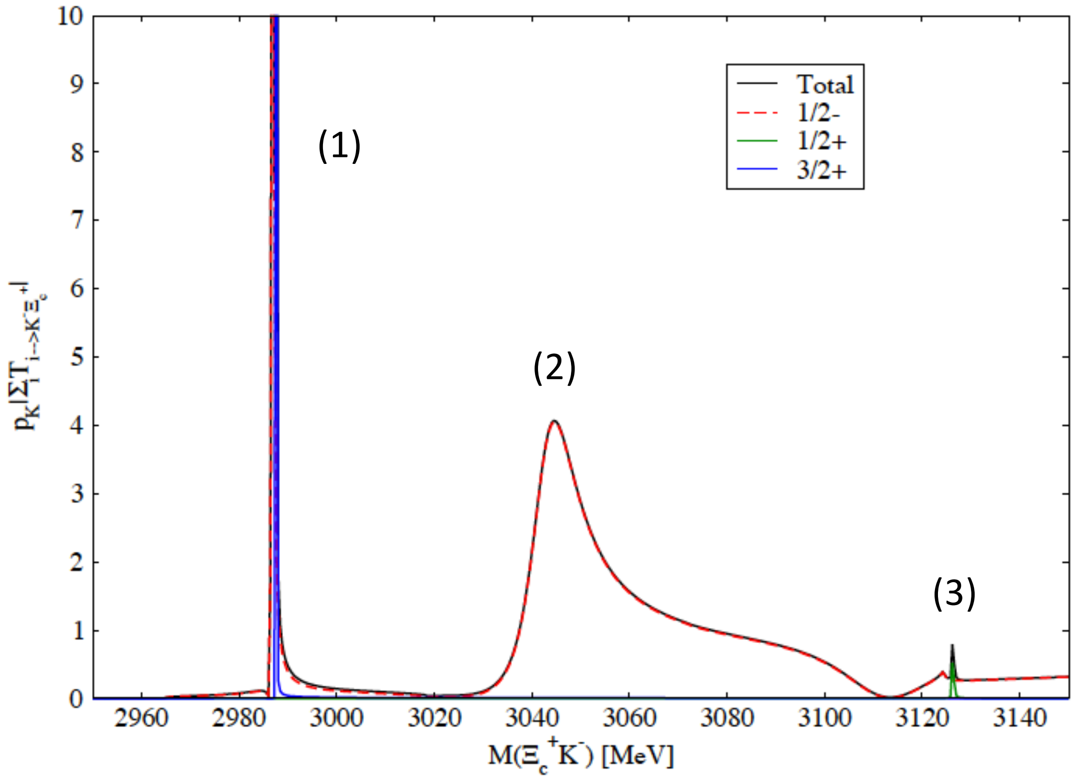
- Process iterated as many times as peaks assumed as molecular states we have
- The surviving parametrizations are reanalyzed to study the nature of their structures (ongoing work)

Born terms: preliminary results

	$a_{\bar{K}\Xi_c}$	$a_{\bar{K}\Xi'_c}$	$a_{D\Xi}$	$a_{\eta\Omega_c}$	$a_{\eta'\Omega_c}$
Daniel 5	-2.13	-3.59	-3.20	-2.07	-2.70
Λ (MeV)	710	2570	2200	540	1290

- Assumption:
  The LHCb measured states $\Omega_c(3000)$, $\Omega_c(3050)$ and $\Omega_c(3119)$ have molecular nature and they can be reproduced within 5 σ error.

- (1) Double pole structure: one at (M=2986.82, Γ=0.68) MeV with spin-parity 1/2- and the other at (M=2987.64, Γ=0.08) with 3/2+
- (2) Pole at (M=3042.01, Γ=0.86) MeV with spin-parity 1/2-
- (3) Pole at (M=3126.32, Γ=0.10) MeV with spin-parity 1/2+



Born terms: Ω_b states

R. Aaij et al. [LHCb], Phys. Rev. Lett. 124, no.8, 082002 (2020)

	δM_{peak} [MeV]	Mass [MeV]	Width [MeV]
$\Omega_b(6316)^-$	$523.74 \pm 0.31 \pm 0.07$	$6315.64 \pm 0.31 \pm 0.07 \pm 0.50$	< 2.8 (4.2)
$\Omega_b(6330)^-$	$538.40 \pm 0.28 \pm 0.07$	$6330.30 \pm 0.28 \pm 0.07 \pm 0.50$	< 3.1 (4.7)
$\Omega_b(6340)^-$	$547.81 \pm 0.26 \pm 0.05$	$6339.71 \pm 0.26 \pm 0.05 \pm 0.50$	< 1.5 (1.8)
$\Omega_b(6350)^-$	$557.98 \pm 0.35 \pm 0.05$	$6349.88 \pm 0.35 \pm 0.05 \pm 0.50$	< 2.8 (3.2) $1.4^{+1.0}_{-0.8} \pm 0.1$

Predictions by Molecular-Picture Models:

- W. H. Liang, J. M. Dias, V. R. Debastiani and E. Oset, Nucl. Phys. B 930, 524 (2018)

7 Ω_b^- states were generated dinamically with 1/2- and 3/2- (lowest mass 50MeV above $\Omega_b^-(6350)$)

- W. H. Liang and E. Oset, Phys. Rev. D 101, no.5, 054033 (2020)

Arguments against the molecular nature of these states, instead structures at higher energies should be analysed

- J. Nieves, R. Pavao and L. Tolos, Eur. Phys. J. C 80, 22 (2020)

Prediction of a 1/2- state $\Omega_b^-(6360)$ as member of a sextet jointly with $\Xi_b(6227)$ and $\Sigma_b(6227)$

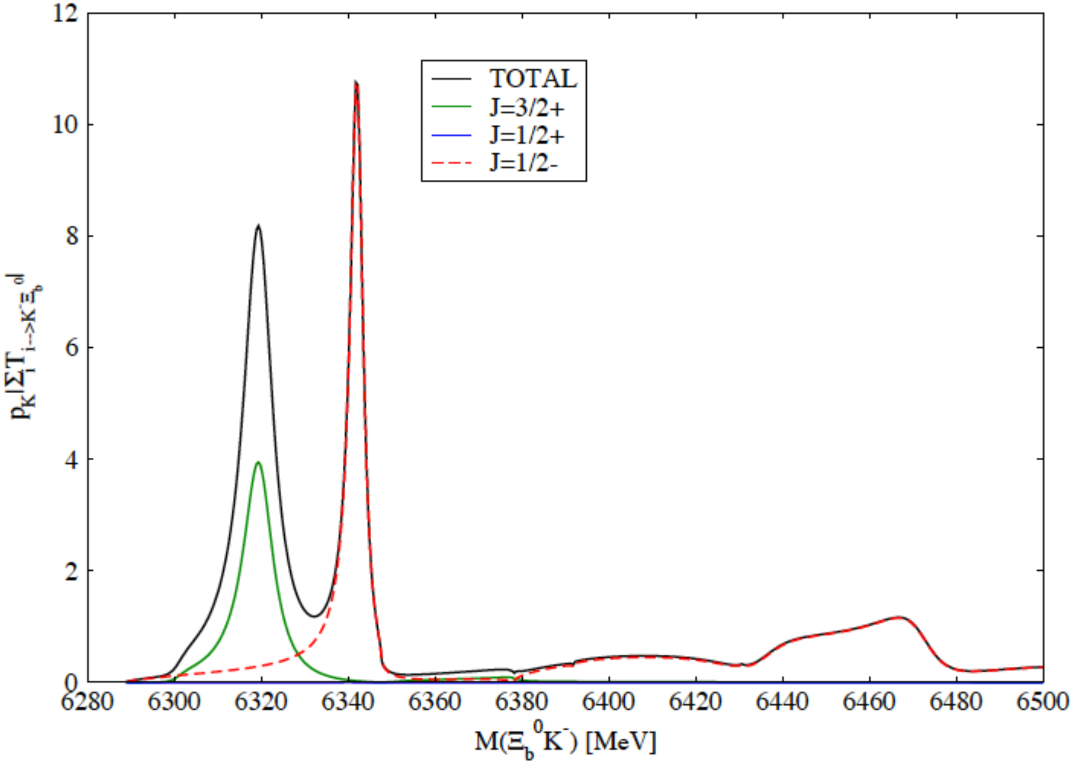
- G. Montaña, A. Feijoo and A. Ramos, Eur. Phys. J. A 54, no.4, 64 (2018)

2 Ω_b^- states were generated dinamically with 1/2- (lowest mass 70MeV above $\Omega_b^-(6350)$)

Born terms: illustrative output for Ω_b states

G. Montaña, A. Feijoo and A. Ramos, Eur. Phys. J. A 54, no.4, 64 (2018)

$a_{\bar{K}\Xi_b}$	$a_{\bar{K}\Xi'_b}$	$a_{\eta\Omega_b}$	$a_{\bar{B}\Xi}$	$a_{\eta'\Omega_b}$
-3.57	-3.62	-3.63	-3.24	-3.53



Far from being conclusive, these results demonstrate the need for a thorough investigation of all posible non-negligible terms of the meson-baryon interaction that may influence the generation of dynamical poles, paying a special attention to the dependence of the results on the assumed symmetries and on the free parameters of the theory.

A. Ramos, A. Feijoo, Q. Llorens and G. Montaña, Few Body Syst. 61, no.4, 34 (2020)

Thank you for your attention!