On the possible existence of a S = - 3, I = 1 pentaquark

Isaac Vidaña, INFN Catania

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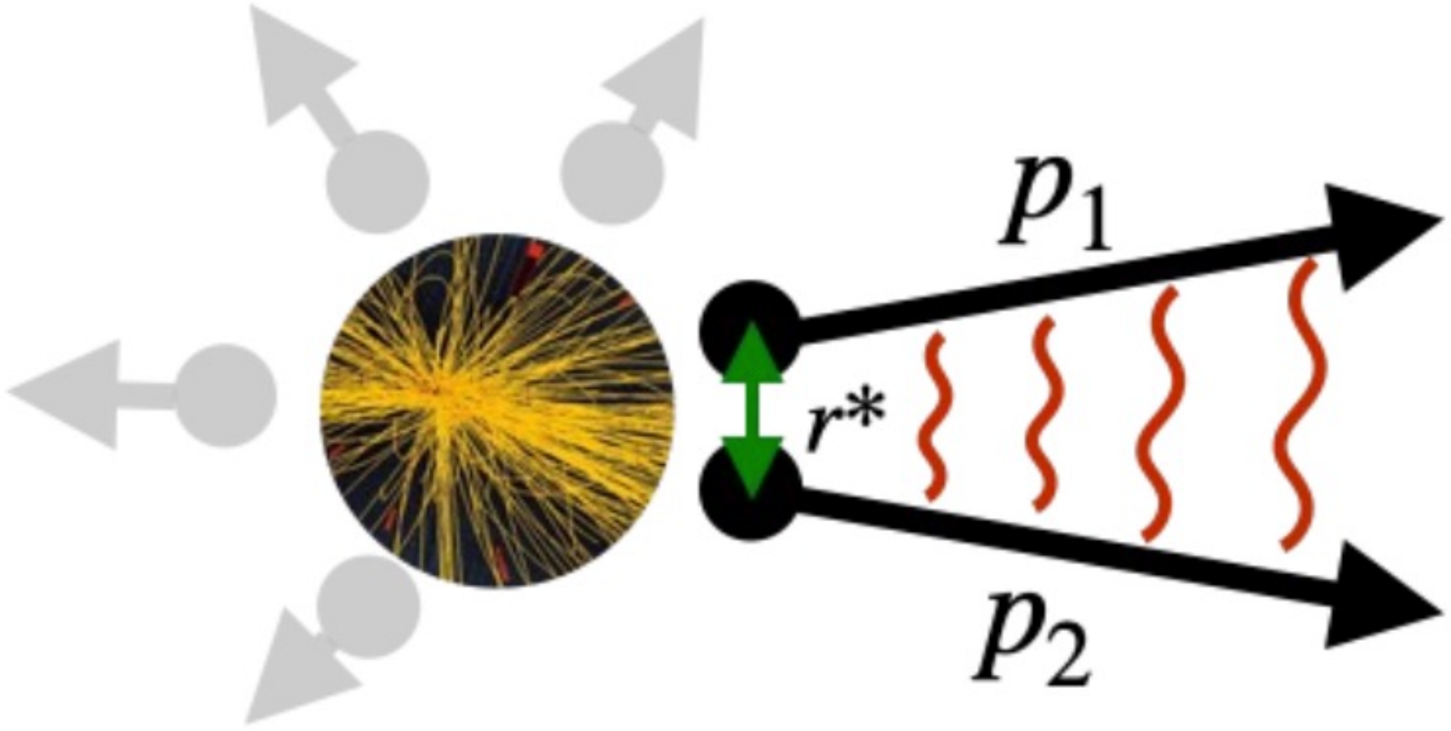


In collaboration with Albert Feijoo, IFIC Valencia

This talk in few words

In this work:

- We analyze the possible existence of a strangeness S = -3, isospin I = 1 pentaquark state P_{sss} generate dynamically from the $\bar{K}\Xi$ interaction

- We employ a unitarized scheme in coupled channels based on the chiral Lagrangian expanded up to NLO and show that the inclusion of the NLO terms is crucial to provide the necessary attraction that favours the existence of such pentaquark state

- The $\bar{K}\Xi$ femtoscopic correlation function is calculated as example of a possible experimental measurement in which a direct signal of the P_{sss} state could be observed (if it really exists, of course)

Details can be found in A. Feijoo & I. V. EPJA 61, 196 (2025)

Hidden-Charm Pentaquarks: From Discovery to Systematics

- Breakthrough (2015, LHCb)

  ✓ First observation of hidden-charm pentaquark in $\Lambda_b \longrightarrow J/\psi K^- p$

  $\Longrightarrow$ two $J/\psi p$ resonant structures: $P_\psi^N(4380), P_\psi^N(4450)$

- New states from combined analysis of Run I & Run II

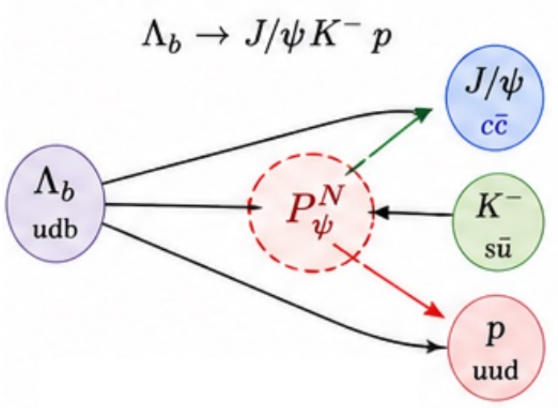
  ✓ New pentaquark $P_\psi^N(4310)$ & a double-peak structure resolved in the original $P_\psi^N(4450)$ signal thereby leaving four more accurate hidden charm pentaquarks: $P_\psi^N(4310), P_\psi^N(4380)$, $P_\psi^N(4440), P_\psi^N(4457)$

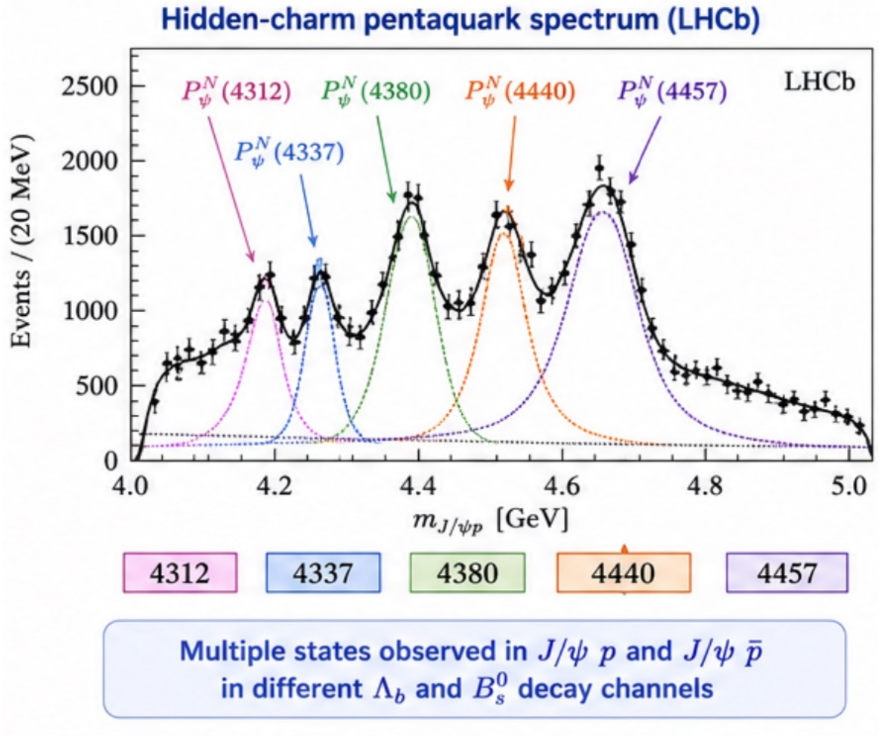
  ✓ Evidence for an additional $P_\psi^N(4337)$ structure in the $J/\psi p$ and $J/\psi \bar{p}$ invariant mass distribution of $B_s^0 \longrightarrow J/\psi p \bar{p}$ decay

- Strange S = -1 partners confirmed

  ✓ Observation of $P_{\psi s}^N(4338)$ and $P_{\psi s}^N(4459)$ in the $\Xi_b^- \longrightarrow J/\psi \Lambda K^-$ and $B^- \longrightarrow J/\psi \Lambda \bar{p}$ decays

- Hidden-charm strange S = -2 pentaquark (experimental evidence still pending)





Towards Triply-Strange Pentaquarks

- The $S = -3$ hadron spectroscopy remains **poorly explored experimentally**
  - ✓ Only **four Ω^* states** listed in PDG, all with low (2 – 3 star) status
  - ✓ No spin-partity J^P assignements established
- Theoretical progress has mostly relied on:
  - ✓ Coupled-channel (CC) unitary approaches with meson–baryon dynamics
  - ✓ Chiral and extended symmetry frameworks (e.g. SU(3), SU(6))
- Limitations of previous studies
  - ✓ Dominance of **leading order (LO) chiral interactions**
  - ✓ Limited treatment of **higher-order (NLO) effects**

Novelty of this work

- Main new ingredient

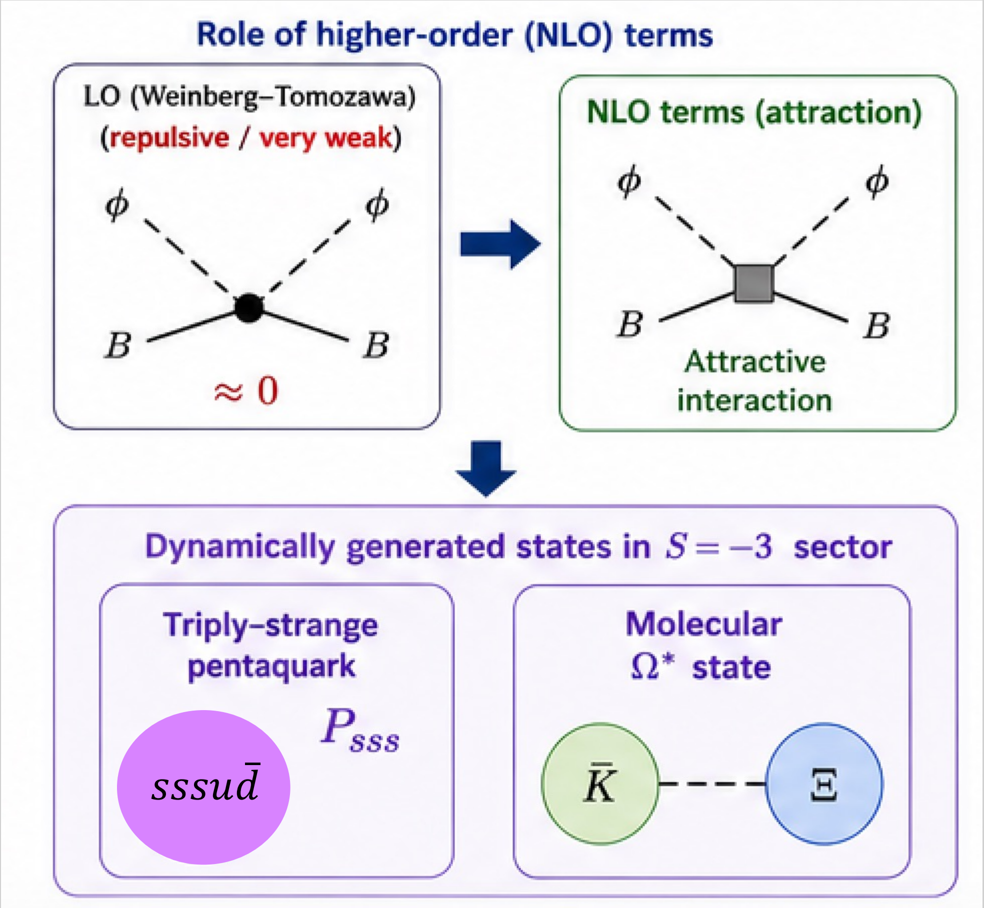
  Inclusion of **NLO corrections (LECs)**, not previously considered in the S = - 3 sector

- Main finding:

  ✓ LO interaction is **weakly repulsive**

  ✓ NLO terms can generate **sufficient attraction** enabling the dynamical generation of:

  - a **triply-strange pentaquark P_{sss}**
  - a **molecular Ω^* state**

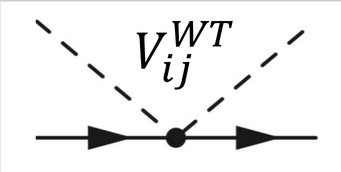


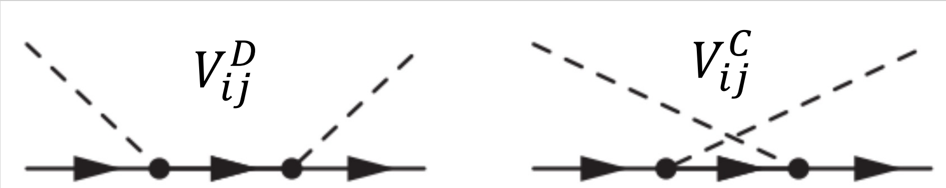
The S = - 3 Meson-Baryon Interaction Model

The S = - 3 meson-baryon is described by a chiral effective lagrangian $\mathcal{L}_{MB}^{eff} = \mathcal{L}_{MB}^{LO} + \mathcal{L}_{MB}^{NLO}$

- Leading order (LO)

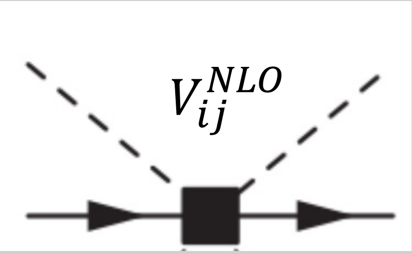
$$\mathcal{L}_{MB}^{LO} = \underbrace{i\langle \bar{B}\gamma_\mu [D^\mu, B]\rangle - M_0 \langle \bar{B}B\rangle}_{\text{Weinberg-Tomozawa term}} \underbrace{- \frac{1}{2} D \langle \bar{B}\gamma_\mu \gamma_5 \{u^\mu, B\}\rangle - \frac{1}{2} F \langle \bar{B}\gamma_\mu \gamma_5 [u^\mu, B]\rangle}_{\text{Direct (s-channel) \& Crossed (u-channel) Born terms}}$$





- Next to leading order (NLO) (novelty of this model, A. Feijoo et al., PLB 841, 137927 (2023))

$$\mathcal{L}_{MB}^{NLO} = b_D \langle \bar{B}\{\chi_+, B\}\rangle + b_F \langle \bar{B}[\chi_+, B]\rangle + b_0 \langle \bar{B}B\rangle\langle \chi_+ \chi\rangle$$
$$+ d_1 \langle \bar{B}\{u_\mu, [u^\mu, B]\}\rangle + d_2 \langle \bar{B}[u_\mu, [u^\mu, B]]\rangle$$
$$+ d_3 \langle \bar{B}u_\mu\rangle\langle u^\mu B\rangle + d_4 \langle \bar{B}B\rangle\langle u^\mu u_\mu\rangle$$



The S = - 3 Meson-Baryon Interaction Model

- Total interaction kernel: $V_{ij} = V_{ij}^{WT} + V_{ij}^{D} + V_{ij}^{C} + V_{ij}^{NLO}$

$$V_{ij}^{WT} = -\frac{C_{ij}^{WT}}{4f^2}\mathcal{N}_i\mathcal{N}_i\left(\sqrt{s} - M_i - M_j\right) \qquad V_{ij}^{D} = -\sum_{k=1}^{8}\frac{C_{ii,k}^{Born}C_{jj,k}^{Born}}{12f^2}\mathcal{N}_i\mathcal{N}_j\frac{(\sqrt{s}-M_i)(\sqrt{s}-M_k)(\sqrt{s}-M_j)}{s-M_k^2}$$

$$V_{ij}^{C} = \sum_{k=1}^{8}\frac{C_{ii,k}^{Born}C_{jj,k}^{Born}}{12f^2}\mathcal{N}_i\mathcal{N}_j\Big[\sqrt{s}+M_k - \frac{(M_i+M_k)(M_j+M_k)}{2(M_i+E_i)(M_j+E_j)}\left(\sqrt{s}-M_k+M_i+M_j\right) + \frac{(M_i+M_k)(M_j+M_k)}{4q_iq_j}$$
$$x\left[\left(\sqrt{s}+M_k-M_i-M_j\right) - \frac{s+M_k^2-m_i^2-m_j^2-2E_iE_j}{2(M_i+E_i)(M_j+E_j)}\left(\sqrt{s}-M_k+M_i+M_j\right)\right]\ln\frac{s+M_k^2-m_i^2-m_j^2-2E_iE_j-2q_iq_j}{s+M_k^2-m_i^2-m_j^2-2E_iE_j+2q_iq_j}\Big]$$

$$V_{ij}^{NLO} = \frac{1}{f^2}\mathcal{N}_i\mathcal{N}_i\left(D_{ij} - 2\left(\omega_i\omega_j + \frac{q_i^2q_j^2}{3(M_i+E_i)(M_j+E_j)}\right)L_{ij}\right)$$

Weinberg-Tomozawa coefficients C_{ij}^{WT} are determined by chiral SU(3) symmetry whereas Born & NLO ones $C_{ii,k}^{Born}, D_{ij}, L_{ij}$ are function of the Lagragian parameters

$D = 0.8, F =, 0.46$ (constrained by the value of the axial coupling $g_A = D + F = 1.26$)

$f, b_0, b_D, b_F, d_1, d_2, d_3, d_4$: to be determined by fitting experimental data

The S = - 3 Meson-Baryon Interaction Model

We consider two models that differ in the choice of the NLO coefficients to have a larger causity

- Barcelona (BCN) model

  Obtained fitting the model to a large set of low-energy $K^{-}p$ scattering data, as well as, the $\bar{K}N$ threshold observables typically employed in these studies (branching ratios and the scattering length extracted from the very precise SIDDHARTA measurements)

- Valencia-Barcelona-Catania (BCN) model

  Extracted from the high-precision $K^{-}\Lambda$ femtoscopic data

In summary, since both models were fitted to different observables in different sectors and that none of them necessarily describe the S = - 3 meson-baryon interaction properly, we would like to stress that there is no prevalence of one model over the other in the present study

Unitarized Scattering Amplitudes

- Coupled-channel Bethe-Salpeter equation

$$T_{ij} = V_{ij} + V_{il} G_l T_{lj} \xrightarrow[\text{system of algebraic equations}]{\text{on-shell factorization approach}} T_{ij} = (1 - V_{il} G_l)^{-1} V_{lj}$$

✓ meson-baryon propagator

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

$a_l(\mu)$ = - 2 : substraction constants (SCs) replace the logarithmic divergency of the propagator for the given dimensional regularization scale μ taken to be 630 MeV in this work.

Pole Content of the Scattering Amplitudes

A dynamically generated state appears as a pole of the scattering amplitude at complex energy $z_p = M_R - i\Gamma_R/2$ where the real and imaginary parts give its mass and width. Near the pole, the amplitude follows a Breit-Wigner form, $T_{ij} \sim g_i g_j / \left(\sqrt{s} - z_p\right)$, allowing extraction of the channel couplings g_i, g_j

- Both models generate a $J^P = 1/2^-$ Ω^* (I=0) state
  - ✓ BCN: Ω^* does not match $\Omega(2012)$ due to the large width
  - ✓ VBC: Ω^* appears as a bound state at ~ 100 MeV below the $\bar{K}\Xi$ threshold ($\Omega^* \longrightarrow \gamma\Omega$)
- Both models generate a exotic $J^P = 1/2^-$ P_{sss} (I=1) pentaquark state
  - ✓ BCN predicts a 2152 MeV pentaquark with a large width (Γ= 399 MeV), making detection difficult
  - ✓ The VBC model predicts a pentaquark about 10 MeV below the $\bar{K}\Xi$ threshold, supporting a more plausible molecular interpretation of its nature

(S = - 3, Q = -1)

BCN Model	Ω^*		P_{sss}	
M [MeV]	2014.06		2151.61	
Γ [MeV]	296.10		399.18	
	g_i	$\lvert g_i \rvert$	g_i	$\lvert g_i \rvert$
$\bar{K}\Xi(I=0)$	$1.15 + 1.78\,i$	2.12	$0.00 + 0.01\,i$	0.01
$\bar{K}\Xi(I=1)$	$-0.00 - 0.01\,i$	0.01	$1.05 + 1.95\,i$	2.21
VBC Model	Ω^*		P_{sss}	
M [MeV]	1707.24		1800.79	
Γ [MeV]	0.00		0.00	
	g_i	$\lvert g_i \rvert$	g_i	$\lvert g_i \rvert$
$\bar{K}\Xi(I=0)$	$4.27 + 0.00\,i$	4.27	$-0.00 + 0.00\,i$	0.00
$\bar{K}\Xi(I=1)$	$0.01 + 0.00\,i$	0.01	$2.52 - 0.00\,i$	2.52

Pole Content of the Scattering Amplitudes

- These outputs are also reflected in the other single channels with charge Q = -2 and Q = 0, since they are purely I=1

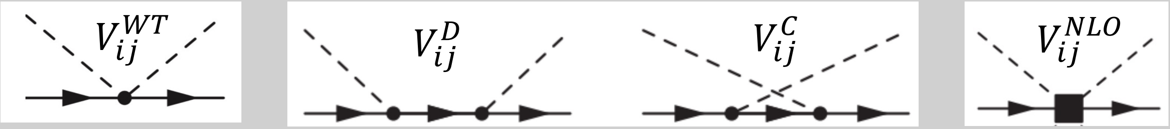
- The tiny differences observed in the pole location arise from isospin breaking due to the use in this case of physical meson and baryon masses. When equal masses are used, the states become degenerate as expected, confirming their **isospin-triplet nature** of the P_{sss} pentaquark state

(S = - 3, Q = -2) & (S = -3, Q = 0)

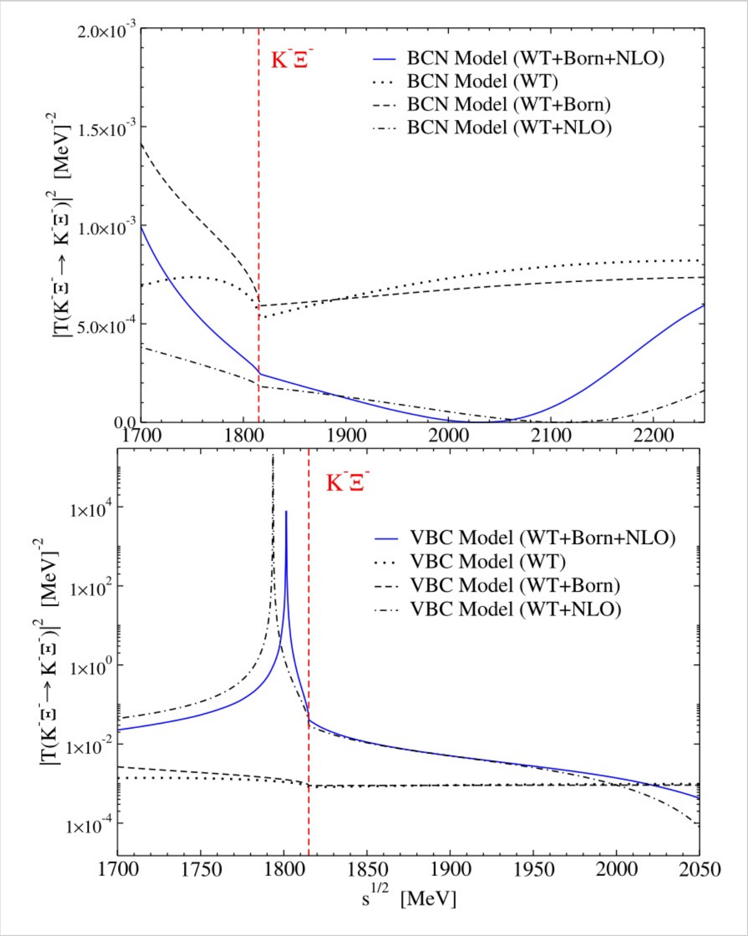
P_{sss}	BCN Model		VBC Model	
M [MeV]	2152.49		1801.47	
Γ [MeV]	399.19		0.00	
	g_i	$\lvert g_i \rvert$	g_i	$\lvert g_i \rvert$
$K^- \Xi^-$	$1.05 + 1.95\,i$	2.21	$2.54 - 0.00\,i$	2.54

P_{sss}	BCN Model		VBC Model	
M [MeV]	2147.79		1800.27	
Γ [MeV]	398.76		0.00	
	g_i	$\lvert g_i \rvert$	g_i	$\lvert g_i \rvert$
$\bar{K}^0 \Xi^0$	$1.05 + 1.95\,i$	2.22	$2.48 - 0.00\,i$	2.48

Role of the different interaction kernel terms



- VBC model
  - ✓ Signal of the P_{sss} state clearly seen peaking at ~ 1800 MeV
  - ✓ WT: shallow effect, repulsive contribution
  - ✓ Born: extra repulsion
  - ✓ NLO: provide the needed attraction to bind the meson-baryon molecule. Particularly, attraction comes from the chiral symmetry breaking terms: $b_D\langle\bar{B}\{\chi_+, B\}\rangle + b_F\langle\bar{B}[\chi_+, B]\rangle + b_0\langle\bar{B}B\rangle\langle\chi_+\chi\rangle$
- BCN model
  - ✓ No signal of P_{sss} due to its large width
  - ✓ WT & Born: similar role as in VBC given the values of couplings & LECs
  - ✓ NLO: provide attraction to bind the meson-baryon molecule but much less strength.

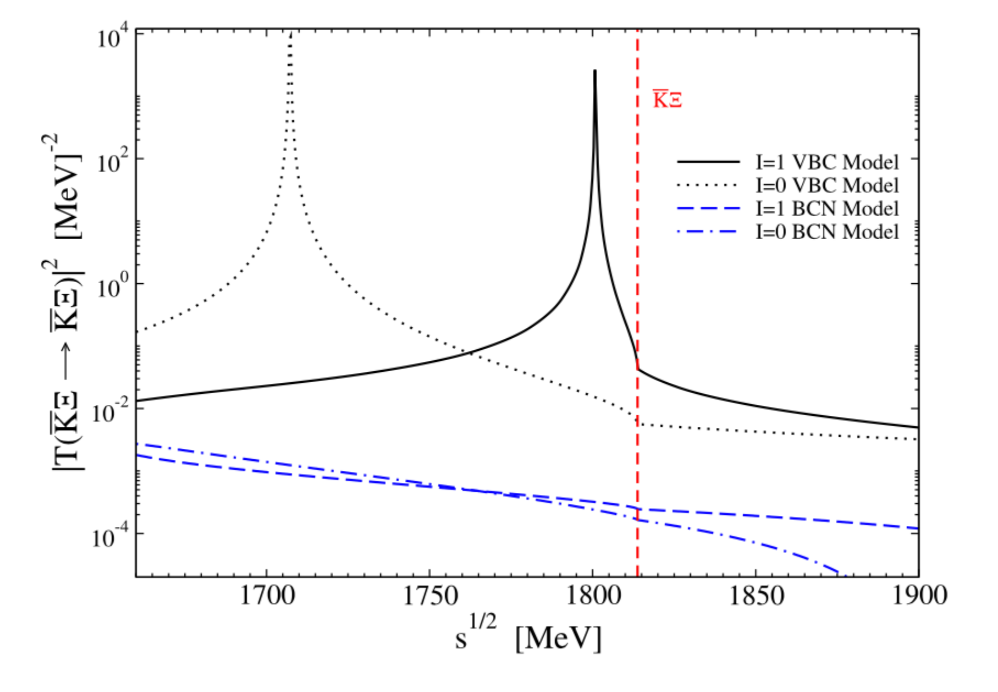


Role of the different interaction kernel terms

This analysis can be easily generalized for the other two charge sectors

- ✓ The modulus square of the elastic amplitude for the Q = 0 case, is very similar to that of Q = -2 by isospin symmetry

- ✓ The Q = -1 charge sector has an additional contribution coming from the I=0 component, where the interplay among terms entering into the interaction kernel develop a stronger attraction that makes the Ω^* state arise at ~ 100 MeV below the $\bar{K}\Xi$ threshold

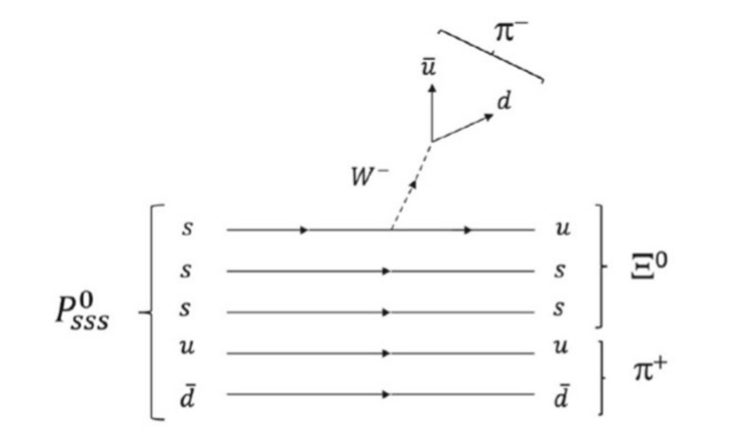


Possible experimental signals of the P_{sss} state

- P_{sss} 3-body decay

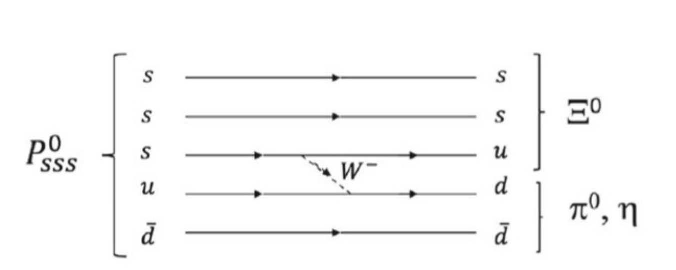
  ✓ Dominant decay mecanism: external emision $P_{sss} \longrightarrow \Xi\pi\pi$

  ✓ Traces of P_{sss} would come from correlations among the two π & the Ξ reflected in the invariant mass



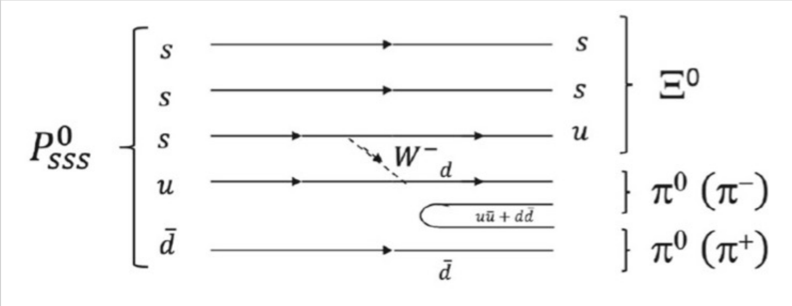
- P_{sss} traces in $\bar{K}\Lambda$ correlation function

We propose three additional decay modes, where the $\bar{K}\Lambda$ product pairs might leave some signal in the corresponding CF



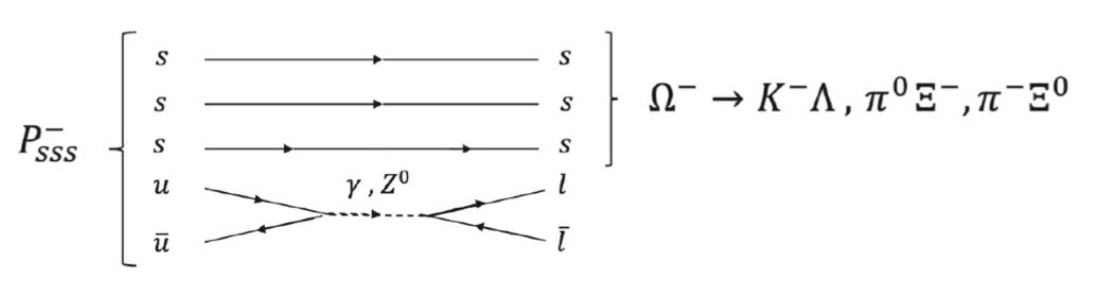
- Weak absorption decay process of P^0_{sss} resulting $\Xi^0\pi^0$ or $\Xi^0\eta$ pairs that via final state interaction (FSI) can end up in any pseudoscalar-baryon (S = -2, Q = 0) state and eventually in a $\bar{K}^0\Lambda$ pair

Possible experimental signals of the P_{sss} state



- Same absortion proccess with hadronization that gives rise to $\Xi^0\pi^0\pi^0$ or $\Xi^0\pi^+\pi^-$ triads. FSI between the Ξ^0 and the π^-can give a $K^-\Lambda$ pair afterwards

- Anihilation of the u and $\bar{u}$ quarks in the P_{sss} pentaquark via leptonic electroweak decay with mediating γ or Z^0 virtual boson which gives a lepton-antilepton pair jointly with a Ω^-



However …

- The observation of the P_{sss} state through any of these mechanisms is experimentally challenging because the pentaquark signal is weak and could be easily diluted or masked by backgrounds and known resonances

- For this reason, we suggest the study of the $\bar{K}\Xi$ femtoscopic correlation function as better and feasible option to observe a potential trace (or lack thereof) of the P_{sss} state that may clarify its existence

Correlation Function of a Multi-Channel System

In the case of a multi-channel system the correlation function of a given observed channel i is given by the generalization of the Koonin-Pratt formula

$$C_i(k^*) = \sum_j \omega_j^{prod} \int d^3r^* \, S_j(r^*) \left| \Psi_{ji}(k^*, r^*) \right|^2$$

- ω_j^{prod}: production weights take into account how many j pairs, produced as initial state, can convert to the measured i final state
  - ✓ Depend on yields & kinematics: $\omega_j^{prod} = \dfrac{N_j^{prim}}{N_i^{prim}} = \dfrac{N_{j_A}^{prim} N_{j_B}^{prim}}{N_{i_A}^{prim} N_{i_B}^{prim}}$
  - ✓ Particle abundances estimated from Thermal[1] & Transport[2] moldels

[1] V. Vovchenko & H. Stoecker, Comp. Phys. Commun. 244, 295 (2019)
[2] S. Portebouf et al., arXiv:1006.2987

In the present work we assume $\omega_j^{prod} = 1$

Correlation Function of a Multi-Channel System

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- $S_j(r^*)$: emitting source describes the probability of emitting the particle pair j at a relative distance r^*. It may be different for different channels. In this work, is taken for all the channels as a spherically symmetric Gaussian distribution normalized to unity with a radius R=1.1 fm.

$$S_j(r^*) = \frac{1}{\left(\sqrt{4\pi}R\right)^3} exp\left(-\frac{{r^*}^2}{4R^2}\right)$$

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- $\Psi_{ji}(k^*, r^*)$: relative wave function describes the scattering from any inital channel j to the final observed channel i & it can be obtained from the scattering amplitude T_{ji} as

$$\Psi_{ji}(k^*, r^*) = \delta_{ji} j_0\,(k^* r^*) + \int d^3q \, \frac{j_0\,(q r^*) T_{ji}(E, k^*, q)}{E - E_1^{(j)}(q) - E_2^{(j)}(q) + i\eta}$$

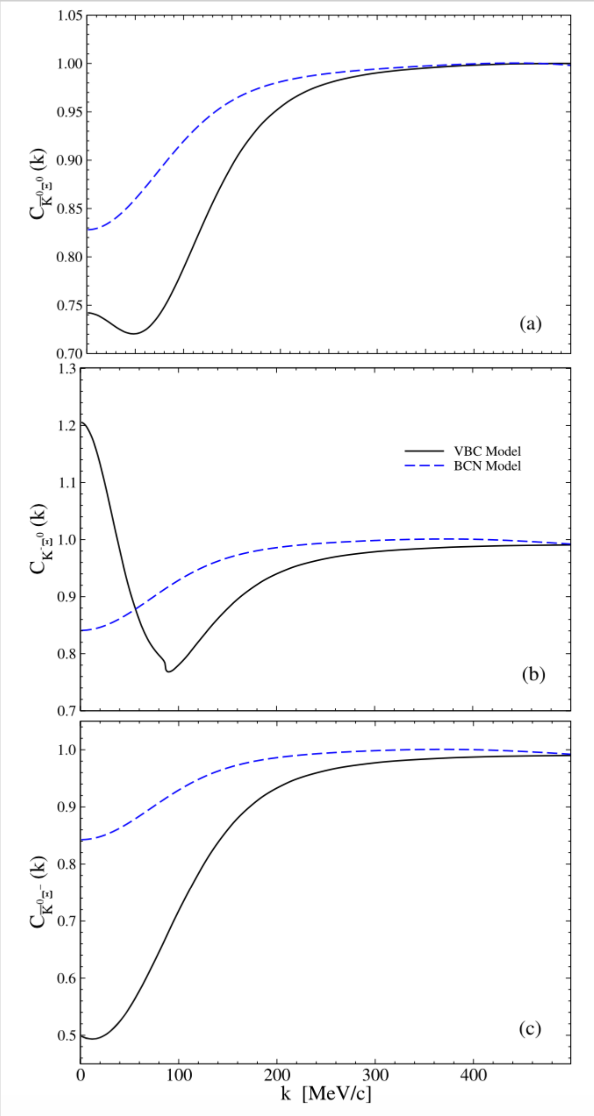
$\bar{K}\Xi$ Correlation Function

- BCN model (repulsive-like CFs)

All three CFs lie below 1 and increase monotonically towards unity, indicating an effective repulsion at low relative momenta. The attraction needed to generate the pentaquark arises from momentum-dependent NLO terms, which are not reflected in the CFs because they are insensitive to the higher-momentum region where this attractive contribution dominates

- VBC model (attractive + near-threshold state)

Predicts attraction and a near-threshold P_{sss} state, which manifests in the CFs as either enhancement above 1 (attractive channel) or suppression below 1 due to a nearby bound state



The final message of this talk

- We have investigated the possible existence of a **triply strange pentaquark $\mathbf{P_{sss}}$**, dynamically generated from the interaction of pseudoscalar mesons with ground-state baryons in the **strangeness S = −3, isospin I = 1** sector
- As as by-product, a **molecular $\boldsymbol{\Omega^*}$** state is also predicted
- For the first time in this sector, we employed a **unitarized coupled-channel approach** based on the **chiral Lagrangian up to next-to-leading order**
- The inclusion of **NLO terms** is crucial, providing the necessary **attractive interaction** to support the formation of the **$\mathbf{P_{sss}}$ state**
- We computed **femtoscopic correlation functions** for $\bar{K}^0\Xi^0, K^-\Xi^0, \bar{K}^0\Xi^-$ as representative observables where experimental signatures of P_{sss} could emerge
- This exploratory study aims to **motivate future experimental analyses** capable of confirming or ruling out the existence of this pentaquark
- Such measurements would provide **new insights into the poorly explored S = −3 sector**


MERCI!
THANK YOU!
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