Correlation function constraints on meson-baryon interaction from UχPT in the *S* = - *2* sector

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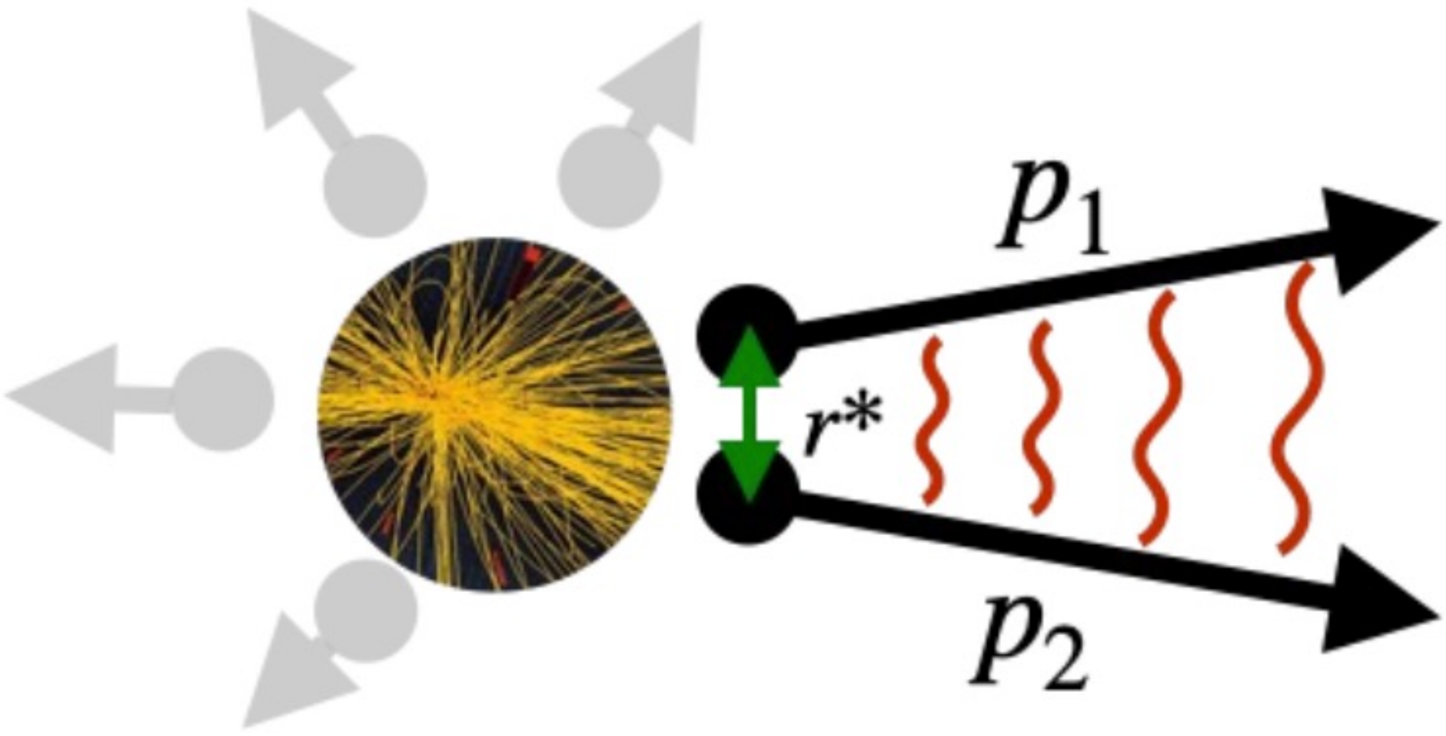

In collaboration with:

- Valentina Mantovani Sarti, TUM Munich (ALICE coll.)
- Albert Feijoo, IFIC Valencia
- Angels Ramos, UB Barcelona
- Francesco Giacosa, JKU Kielce
- Tetsuro Hyodo, TMU Tokyo
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This talk in few words

In this work:

- We use for the first time femtoscopic data to constrain the parameters of a low-energy chiral effective QCD Lagrangian
- Particularly, we focus on the strangeness $S = -2$ meson-baryon interaction sector probed via $K^{-}\Lambda$ correlations recently measured in *pp* collisions by the ALICE Collaboration
- We provide new insights on the molecular nature of the $\Xi(1620)$ state

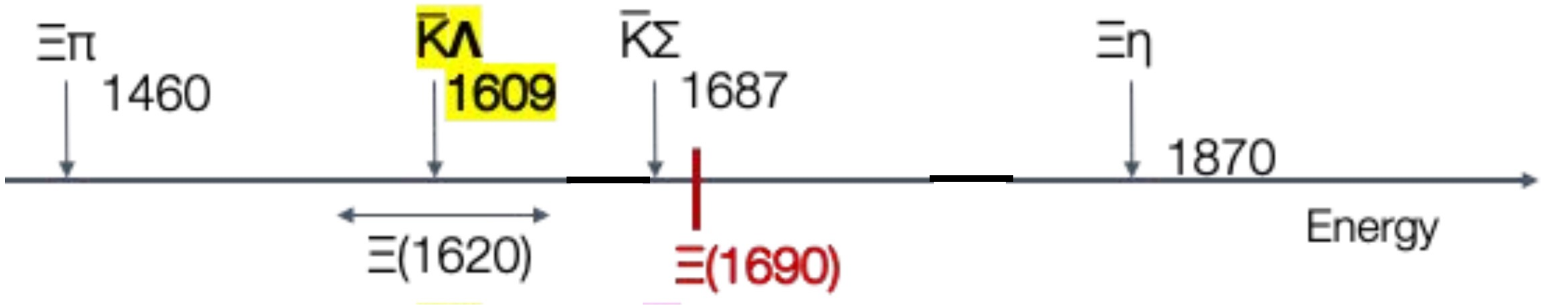
Details can be found in arXiv: 2309.08756

The S = - 2 Meson-Baryon Interaction

The lack of scattering data associated to technical experimental difficulties has not allowed to fix the meson-baryon interaction in the strangeness sector S = - 2 yet but the use of femtoscopic data offers an unprecedented opportunity to fix it

- This interaction is dominated by the presence of the Ξ(1620) & Ξ(1690) resonances whose nature and properties cannot be accommodated within the quark model picture, and are still subject to debate

- Similarly to the well known case of the Λ(1405), whose molecular state nature arises from the coupled dynamics of the πΣ & $\bar{K}$N channels, also the Ξ(1620) & Ξ(1690) resonances might be dynamically generated from the interplay of several channels, thereby acquiring a molecular nature



Observation of the Ξ(1620) & Ξ(1690) resonances

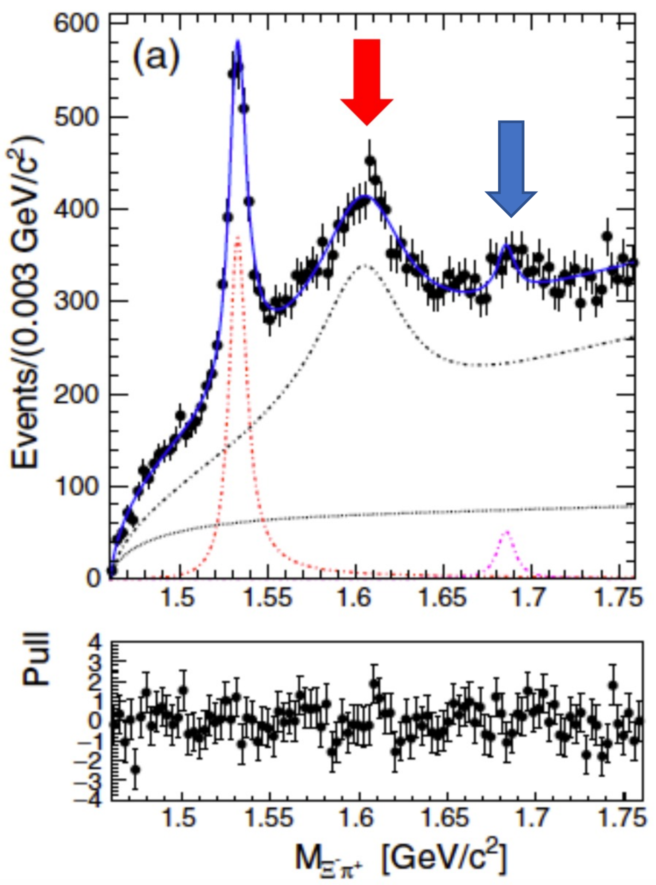
- The first observation of the neutral $\Xi^0(1620)$ decaying into $\Xi^-\pi^+$ via the $\Xi_c^+ \to \pi^+\pi^+\Xi^-$ process was reported in 2019 by the BELLE collaboration

$$M = 1610.4 \pm 6.0^{+6.1}_{-4.2}\ \text{MeV}$$

$$\Gamma = 59.9 \pm 4.8^{+2.8}_{-7.1}\ \text{MeV}$$

✓ PDG status: ∗

✓ $J^P = \frac{?}{?}^{?}$. Perhaps $J^P = \frac{1}{2}^-$ as the S = - 2 counterpart of Λ(1405)



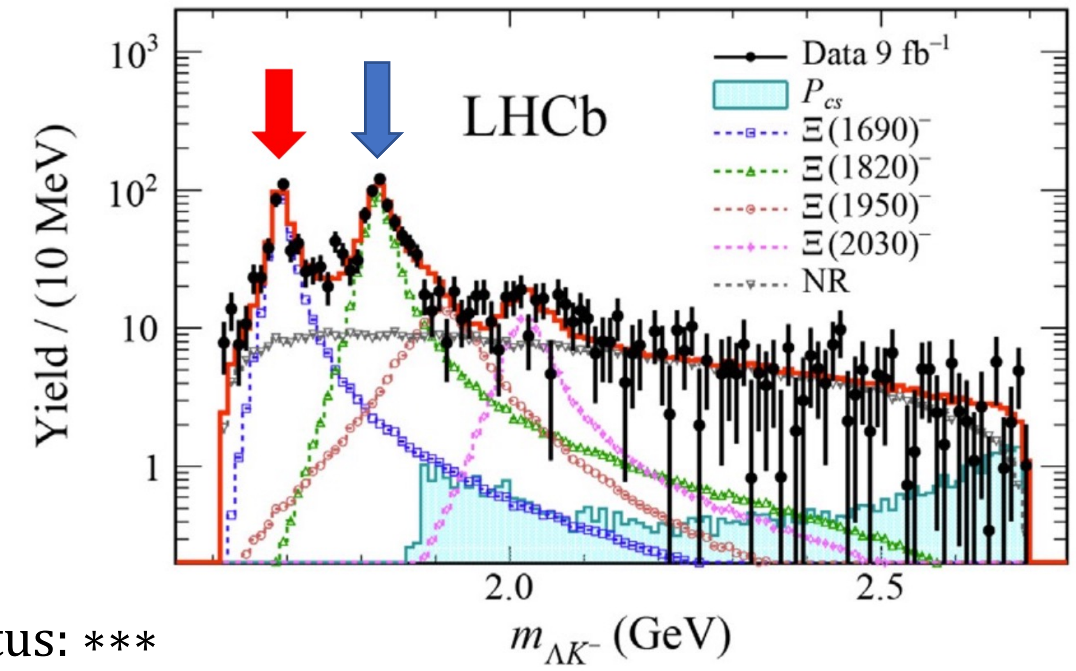
- A 4σ evidence of Ξ(1690) in the same data sample was also reported

M. Sumihama et al., PRL 122, 072501 (2019)

Observation of the Ξ(1690) & Ξ(1820) resonances

R. Aaij et al., Sci, Bull. 66, 1278 (2021)

- A couple of years later the LHCb collaboration reported the observation of two narrow excited Ξ^- states in the $K^-\Lambda$ invariant mass distribution obtined from the analysis of the $\Xi_b^- \to J/\Psi\Lambda K^-$ decay, identifiying the peak located at low energy with the $\Xi^-(1690)$ resonance



$$M = 1692.0 \pm 1.3^{+1.2}_{-0.4}\ \text{MeV}$$

$$\Gamma = 25.9 \pm 9.5^{+14.0}_{-13.5}\ \text{MeV}$$

- ✓ PDG status: ∗∗∗
- ✓ $J^P = \frac{1}{2}^+$ from $\Lambda_c^+ \to K^+\pi^+\Xi^-$ decay

B. Aubert et al., PRD 78, 034008 (2008)

- Second peak was identified with the $\Xi^-(1820)$ resonance

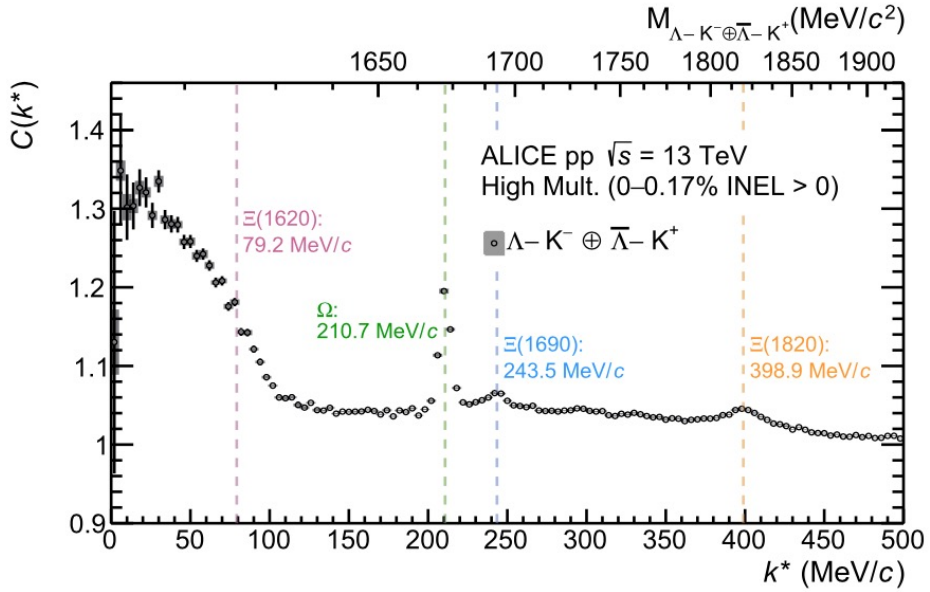
$$M = 1822.7 \pm 1.5^{+1.0}_{-0.6}\ \text{MeV} \qquad \Gamma = 36.0 \pm 4.4^{+7.8}_{-8.2}\ \text{MeV}$$

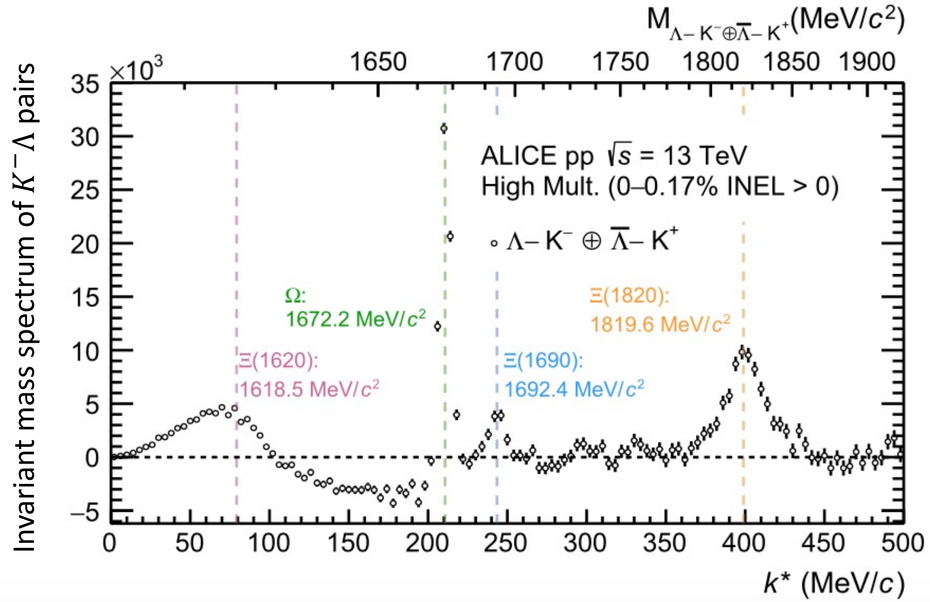
First experimental observation of the $\Xi(1620)$ decaying into $K^-\Lambda$ pairs

- Very recently the ALICE Collaboration measured the $K^-\Lambda$ correlation function in *pp* collisions at $\sqrt{s} = 13$ TeV

- This measurement represents nowadays the most precise data on the *S* = - *2* meson-baryon interaction and it has provided the first experimental observation of the $\Xi(1620)$ decaying into $K^-\Lambda$ pairs

- The measured correlation function presents also peak structures compatible with the Ω^-, and the strangeness *S*= - *2* states $\Xi(1690)$ & $\Xi(1820)$





<u>Unpredecented opportunity to fix the *S* = - *2* meson-baryon interaction</u>

ALICE Collaboration, PLB 845, 138145 (2023)

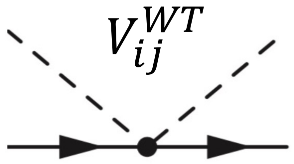
(see also Dimitar Mihaylov's talk on Monday)

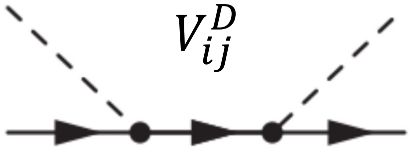
The S = - 2 Meson-Baryon Interaction Model

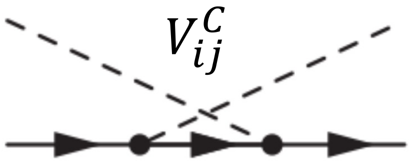
The S = - 2 meson-baryon is described by a chiral effective lagrangian $\mathcal{L}_{MB}^{eff} = \mathcal{L}_{MB}^{LO} + \mathcal{L}_{MB}^{NLO}$

- Leading order (LO)

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

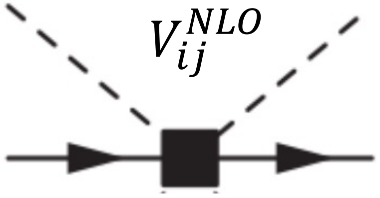






- Next to leading order (NLO) (novelty of this model, A. Feijoo et al., PLB 841, 137927 (2023))

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



The S = - 2 Meson-Baryon Interaction Model

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

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

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

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

✓ Weinberg-Tomozawa coefficients C_{ij}^{WT} are determined by chiral SU(3) symmetry

✓ Born coefficients $C_{ii,k}^{Born}$ are function of $D = 0.8, F = 0.46$ (constrained by $g_A = D + F = 1.26$)

✓ NLO coefficients D_{ij}, L_{ij} are function of the Lagragian parameters

$f, b_0, b_D, b_F, d_1, d_2, d_3, d_4$: **determined by fitting the $K^-\Lambda$ correlation function**

The S = - 2 Meson-Baryon Interaction Model

- 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

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

$a_l(\mu)$: substraction constants (SCs) replace the divergency for the given dimensional regularization scale μ taken to be 1 GeV.

Using isospin symmetry arguments the number of independent SC is 4 to be **determined aso in the fitting procedure of the $K^-\Lambda$ correlation function**

$$a_{\pi^-\Xi^0} = a_{\pi^0\Xi^-} \equiv a_{\pi\Xi}$$

$$a_{K^-\Lambda} \equiv a_{\bar{K}\Lambda}$$

$$a_{K^-\Sigma^0} = a_{\bar{K}^0\Sigma^-} \equiv a_{\bar{K}\Sigma}$$

$$a_{\eta\Xi^-} \equiv a_{\eta\Xi}$$

Correlation Function of a Multi-Channel System

In the case of a multi-channel system the correlation function of a given observed channel i (e.g., $K^-\Lambda$) reads

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

- 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: $\omega_j^{prod} = \frac{N_j^{prim}}{N_i^{prim}} = \frac{N_{j_A}^{prim} N_{j_B}^{prim}}{N_{i_A}^{prim} N_{i_B}^{prim}}$
  - ✓ Particle abundances estimated from Thermal[1] & Transport[2] moldels

Channel j	ω_j^{prod}
ΛK^-	1.000
$\pi^-\Xi^0$	$1.536^{+0.005}_{-0.012}$
$\pi^0\Xi^-$	$1.584^{+0.001}_{-0.006}$
$K^-\Sigma^0$	$0.682^{+0.001}_{-0.001}$
$\overline{K}^0\Sigma^-$	$0.630^{+0.001}_{-0.004}$
$\eta\Xi^-$	$0.178^{+0.023}_{-0.022}$

[1] V. Vovchenko & H. Stoecker, Comp. Phys. Commun. 244, 295 (2019)

[2] S. Portebouf et al., arXiv:1006.2987

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- $S_j(r^*)$: emitting source describes the probability of emitting the particle pair j at a relative distance r^*. In general it may be different for different channels

$$S_j(r^*) = \Lambda_s \left(\omega G_1^j(r^*) + (1-\omega) G_2^j(r^*)\right)$$

$$G_k^j(r^*) = \frac{1}{\sqrt{4\pi} R_k^{j\,3}} \exp\left(-\frac{r^{*2}}{4 R_k^{j\,2}}\right), \qquad (k = 1, 2)$$

Channels	R_1^j (fm)	R_2^j (fm)	ω	Λ_s
ΛK^-, $\Sigma\bar{K}$	$1.202^{+0.043}_{-0.042}$	$2.330^{+0.050}_{-0.045}$	$0.7993^{+0.0037}_{-0.0027}$	$0.9806^{+0.0006}_{-0.0008}$
$\pi\Xi$	$1.371^{+0.041}_{-0.040}$	$3.338^{+0.038}_{-0.035}$	$0.7415^{+0.0017}_{-0.0035}$	$0.9806^{+0.0019}_{-0.0013}$
$\eta\Xi^-$	$1.21^{+0.040}_{-0.040}$	$2.28^{+0.040}_{-0.040}$	0.86	$0.988^{+0.001}_{-0.001}$

ALICE Collaboration, PLB 845, 138145 (2023)

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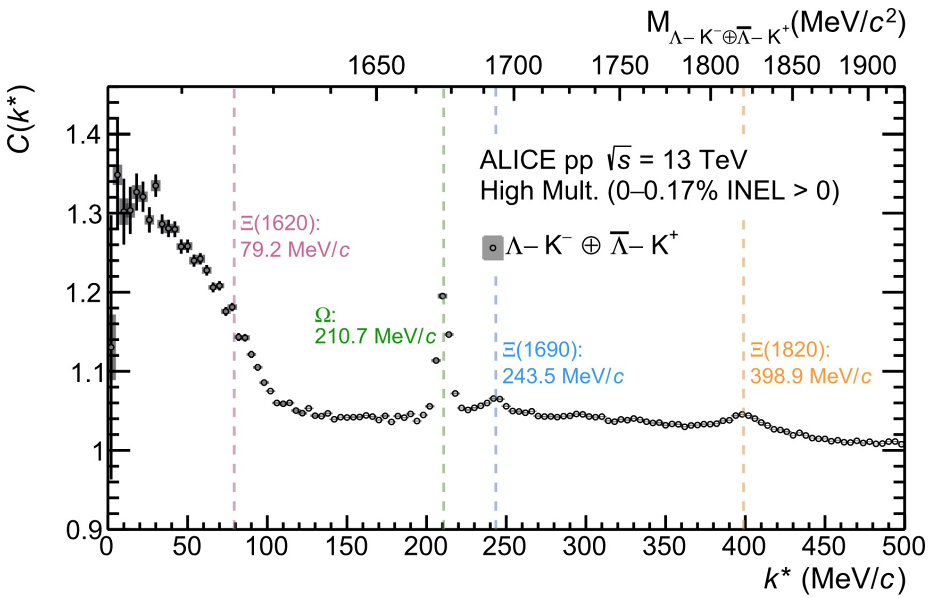
- $\Psi_{ji}(k^*, r^*)$: relative wave function describes the scattering from any inital channel j to the final observed channel i & it can be obtained from the scattering amplitude T_{ji} as

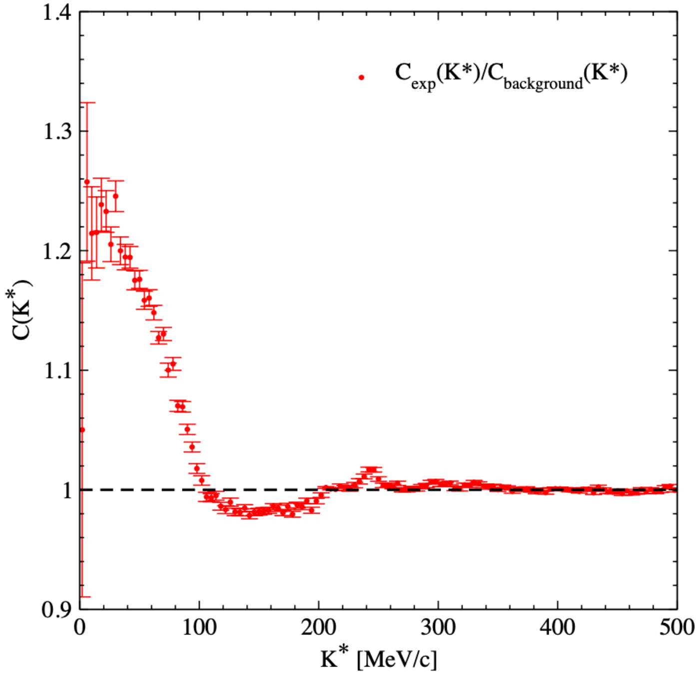
$$\Psi_{ji}(k^*, r^*) = \delta_{ji} j_0\,(k^* r^*) + \int d^3q \frac{j_0\,(q r^*) T_{ji}(E, k^*, q)}{E - E_1^{(j)}(q) - E_2^{(j)}(q) + i\eta}$$

Fitting the $K^{-}\Lambda$ Correlation Function

The first step of our fitting procedure is to remove the background in the experimental data



$$C^{exp}_{K^-\Lambda}(k^*) \rightarrow \frac{C^{exp}_{K^-\Lambda}(k^*)}{C^{background}_{K^-\Lambda}(k^*)}$$

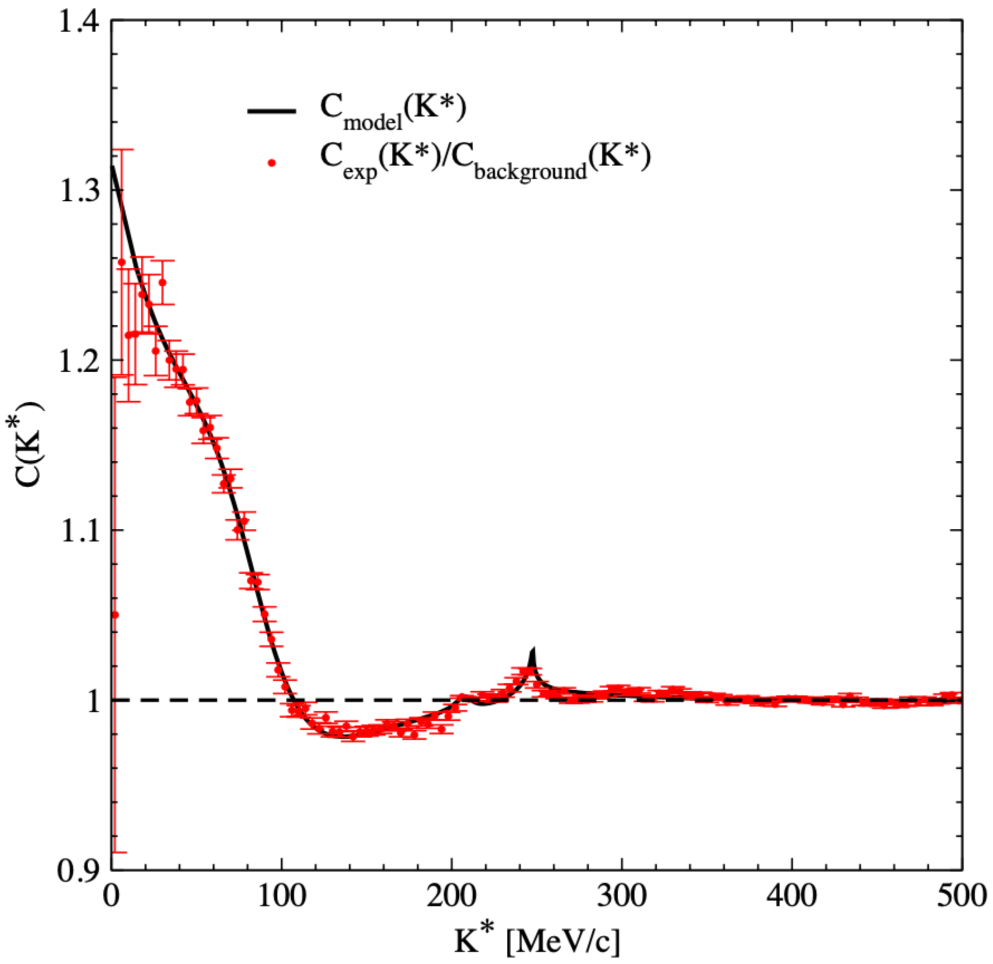


$C^{background}_{K^-\Lambda}(k^*)$ is taken from the experimental analysis performed by the ALICE collaboration

$$C^{background}_{K^-\Lambda}(k^*) = \alpha_{pol3}\left(1 + b{k^*}^2 + c{k^*}^3\right) + \alpha_{\Omega} f_G(M_{\Omega}, \sigma_{\Omega}) + \alpha_{\Xi(1820)}\, f_{BW}\left(M_{\Xi(1820)}, \Gamma_{\Xi(1820)}\right)$$

Fitting the $K^-\Lambda$ Correlation Function

$C_{K^-\Lambda}(k^*)$ is then fitted to the experimental data after removing the background contribution

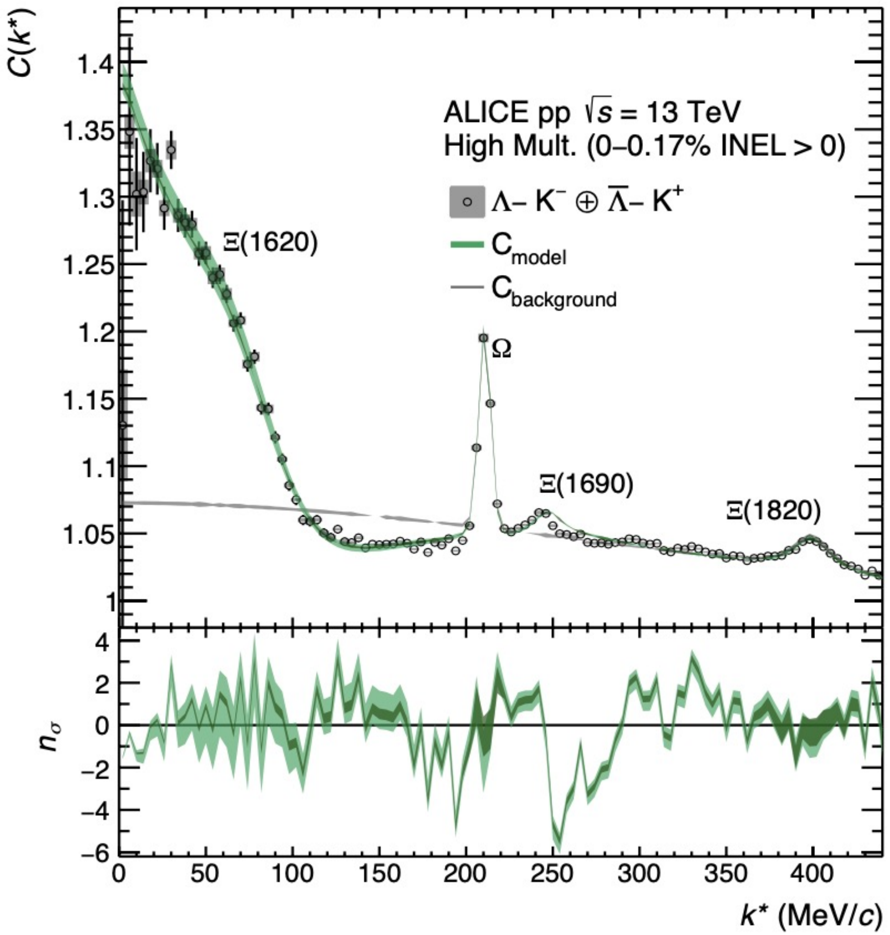


$a_{\Xi\pi}$	-3.71 ± 0.17
$a_{\Lambda\bar{K}}$	-2.02 ± 0.14
$a_{\Sigma\bar{K}}$	-1.69 ± 0.05
$a_{\Xi\eta}$	-3.93 ± 0.12
f/f_π	1.001 ± 0.006
b_0 [GeV^{-1}]	-1.13 ± 0.12
b_D [GeV^{-1}]	0.05 ± 0.13
b_F [GeV^{-1}]	0.30 ± 0.07
d_1 [GeV^{-1}]	-0.18 ± 0.03
d_2 [GeV^{-1}]	-0.26 ± 0.02
d_3 [GeV^{-1}]	-0.71 ± 0.09
d_4 [GeV^{-1}]	-0.44 ± 0.01
N_D	1.0024 ± 0.0005

Errors determined with the bootstrap method

Fitting the $K^{-}\Lambda$ Correlation Function

Restablishing the background contribution we can compare the fit with the total experimental $K^{-}\Lambda$ correlation function



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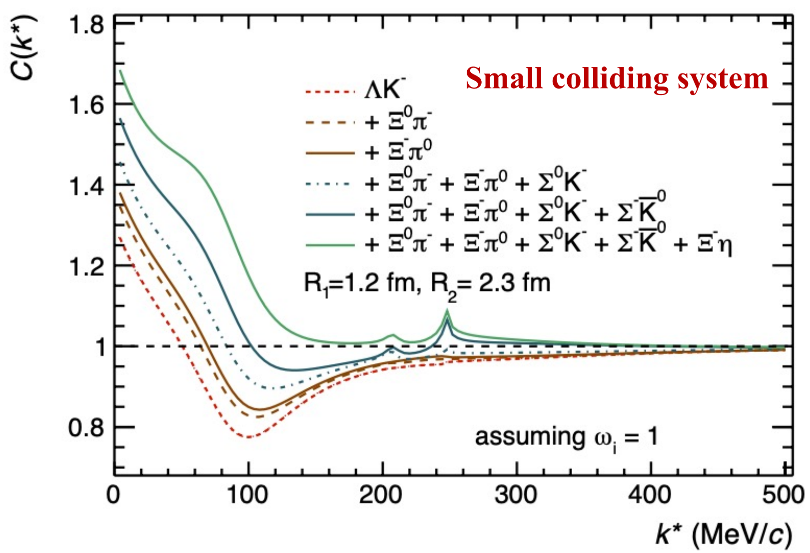
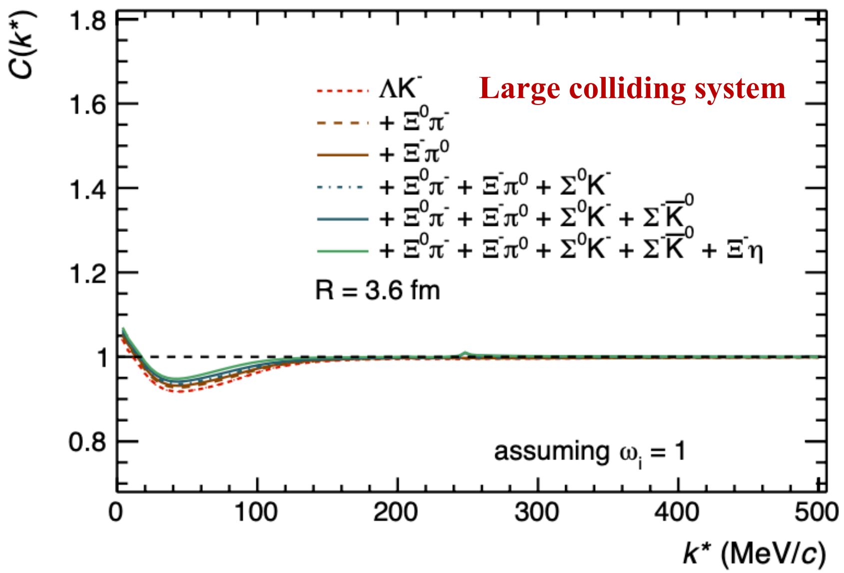
Errors determined with the bootstrap method

Effect of coupled channels in the $K^-\Lambda$ Correlation Function





All production weights are set equal to 1 to analyze the coupled channel dynamics stemming from the underlying strong interaction

We observe:

- Coupled-channel effects larger for small colliding systems where particle pairs are produced at 1 – 2 fm. As source size increase the $K^-\Lambda$ correlation function is dominated by the elastic contribution $K^-\Lambda \rightarrow K^-\Lambda$
- Increase of the $K^-\Lambda$ correlation function when including the contribution of the ineslastic channels
  - ✓ Inclusion of $\pi^-\Xi^0$ and $\pi^0\Xi^-$ shift upward it without modifying its momentum dependence
  - ✓ Inclusion of $K^-\Sigma^0$ and $\bar{K}^0\Sigma^-$ channels lead to a modification of the correlation function profile in the region where the $\Xi(1620)$ and the $\Xi(1690)$ are located
  - ✓ Inclusion of $\eta\Xi^-$ leads to an enhancement on these regions

$\Xi(1620)$ & $\Xi(1690)$ resonances

mass M:	1616.18 MeV		1670.43 MeV	
width Γ:	23.03 MeV		7.17 MeV	
Riemann sheet:	$(- - - + + +)$		$(- - - + + +)$	
	$\lvert g_i \rvert$	$\lvert g_i^2 dG/dE \rvert$	$\lvert g_i \rvert$	$\lvert g_i^2 dG/dE \rvert$
$\pi^-\Xi^0(1454)$	0.50	0.013	0.17	0.0014
$\pi^0\Xi^-(1456)$	0.33	0.006	0.41	0.0079
$K^-\Lambda(1609)$	0.92	0.155	0.06	0.0003
$K^-\Sigma^0(1686)$	1.24	0.099	2.30	0.836
$\bar{K}^0\Sigma^-(1695)$	1.51	0.135	1.32	0.215
$\eta\Xi^-(1868)$	2.97	0.243	0.16	0.0009
Experimental Ξ^*:	$\Xi(1620)$ [1]		$\Xi(1690)$ [2]	
mass M:	$1610.4 \pm 6.0^{+5.9}_{-3.5}$ MeV		1690 ± 10 MeV	
width Γ:	$59.9 \pm 4.8^{+2.8}_{-3.0}$ MeV		20 ± 15 MeV	

[1] M. Sumihama et al., PRL 122, 072501 (2019)

[2] R. L. Workman et al., PTEP 2022, 083C01 (2022)

- Both poles found in the physically relevant Riemann sheet

  Close to a pole $T_{ij} \sim \frac{g_i g_j}{\sqrt{s} - z_p}$, $M = \mathrm{Re}(z_p), \Gamma = -2\mathrm{Im}(z_p)$

- Masses & Widths compatible with experimental data (key role of Born & NLO terms)
- The strong coupling of $\Xi(1620)$ to $\bar{K}\Sigma$, & $\eta\Xi$ channels reveals a change of paradigm in the interpretation as a molecular state of this resonance
  - ✓ All former works: $\pi\Xi - \bar{K}\Lambda$ molecule with non-negligible coupling to the $\bar{K}\Sigma$ channel
  - ✓ This work: $\bar{K}\Sigma - \eta\Xi$ mixture
- $\Xi(1690)$ located ~ 20 MeV below the experimental value & ~ 16 MeV below the $K^-\Sigma^0$ thresold, reducing the possibility of decaying to it & leading to a reduction of its width w.r.t. that found in previous works

The final message of this talk

- We have used for the first time femtoscopic data to constraint the parameters of a low-energy chiral effective QCD Lagrangian
- Particularly, we have focused on the strangeness S = - *2* meson-baryon interaction sector using as experimental constraints the $K^{-}\Lambda$ correlation function recently measured in *pp* collisions by the ALICE Collaboration
- We have then used the interaction model to study the Ξ(1620) & Ξ(1690) states finding:
  - ✓ Masses & widths compatible experimental data
  - ✓ Change of paradigm in the molecular state interpretation of Ξ(1620) which would be a $\bar{K}\Sigma$ − ηΞ mixture rather than a $\pi\Xi$ − $\bar{K}\Lambda$ one predicted by previous works


MERCI! THANK YOU!
FRAPAR.