HADRON 2023

Volodymyr Magas

The Ξ(1620) and Ξ(1690) molecular states from meson-baryon interaction up to next-to-leading order

Collaborators: ***Albert Feijoo*** (IFIC, Valencia), ***Victoria Valcarce*** *(Barcelona)*

Universitat de Barcelona

ICCUB

Perturbative QCD, with ***quark*** and ***gluon*** d.o.f.,
works well at **high energies** and high momentum transfers,
but **fails** to describe **dynamics of hadrons** at **low energies**

→ **Chiral Perturbation Theory:** (χPT)
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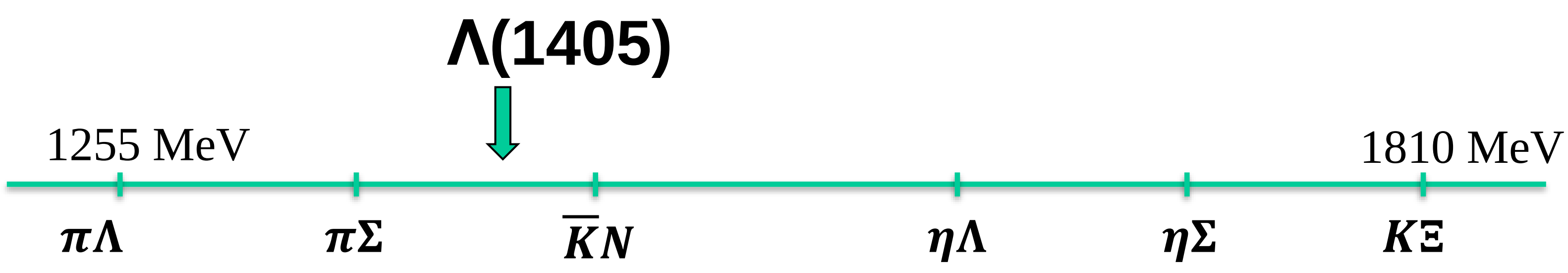
However $_{\chi}PT$ fails in the vicinity of resonances

For example, **S=-1 Q=0** sector



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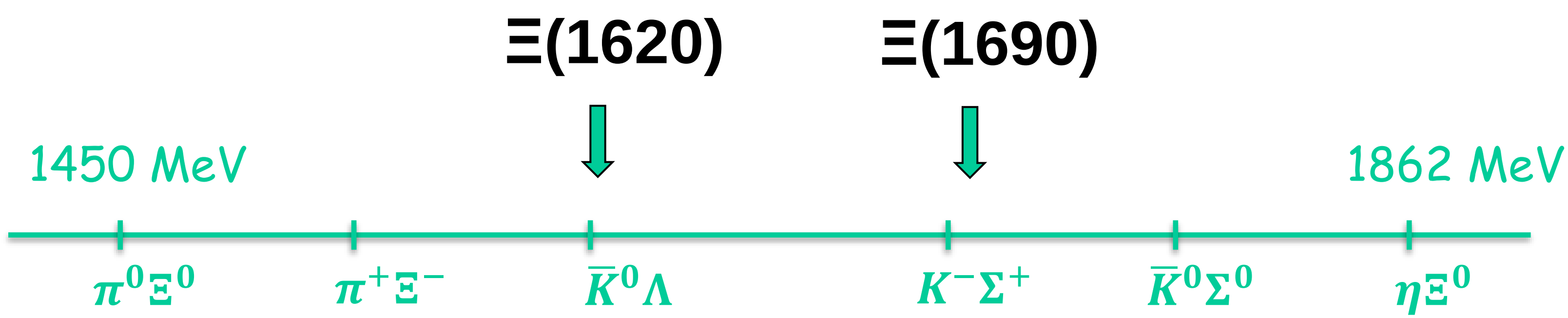
"New" sector **S=-2 Q=0**



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However χ***PT*** fails in the vicinity of resonances

Non-perturbative techniques implementing **unitarization in coupled channels** are needed

Unitary extension of Chiral Perturbation Theory $(U\chi PT)$

The pioneering work -- ***Kaiser, Siegel, Weise*** **, NP A594 (1995) 325**

Experimental status

Ξ(1620)*

$(\mathrm{assumed})\ J^P = 1/2^-$

$$M = 1610.4 \pm 6.0^{+6.1}_{-4.2}\ \mathrm{MeV},\ \Gamma = 59.9 \pm 4.8^{+2.8}_{-7.1}\ \mathrm{MeV}$$

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

Ξ(1690)***

$J^P = 1/2^-$

$$M = 1692.0 \pm 1.3^{+1.2}_{-0.4}\ \mathrm{MeV},\ \Gamma = 25.9 \pm 9.5^{+14.0}_{-13.5}\ \mathrm{MeV}$$

M. Sumihama, et al., PRL122 (7) (2019) 072501

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Are Ξ(1620) and Ξ(1690) molecular states?

Ξ(1620) is an “analogy” of **Λ(1405)** state in S=-1 (Q=0) sector

Well known for its molecular stucture

Ξ(1690) - experimental puzzle $\Gamma_{\pi\Xi}/\Gamma_{\bar{K}\Sigma} < 0.09$

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T. Sekihara, PTEP 2015 (9) (2015) 091

Can be understood if **Ξ(1690)** is a $\bar{K}\Sigma$ quasibound state with small coupling to $\pi\Xi$

FORMALISM

Effective Chiral Lagrangian up to **NLO**

$$\mathcal{L}^{eff}(B,U) = \mathcal{L}^{(1)}_{MB}(B,U) + \mathcal{L}^{(2)}_{MB}(B,U)$$

interaction kernel $\mathbf{V}_{ij}$

FORMALISM

Lippmann-Schwinger equation

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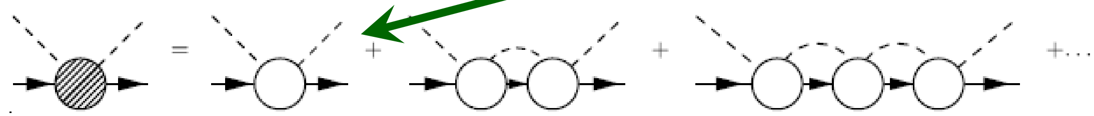

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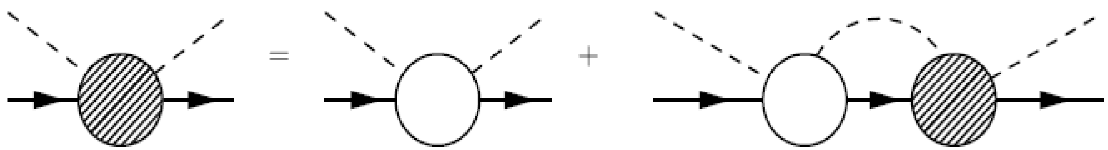

On shell factorization

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

$$\boxed{\boldsymbol{T = (1 - VG)^{-1} V}}$$

System of the algebraic equations

FORMALISM

Effective Chiral Lagrangian up to **NLO**

$$\mathcal{L}^{eff}(B,U) = \mathcal{L}^{(1)}_{MB}(B,U) + \mathcal{L}^{(2)}_{MB}(B,U)$$

- LEADING ORDER

$$\mathcal{L}^{(1)}_{MB} = \langle \bar{B}(i\gamma_\mu D^\mu - M_0)B\rangle + \frac{1}{2}D\langle \bar{B}\gamma_\mu\gamma_5\{u^\mu, B\}\rangle + \frac{1}{2}F\langle \bar{B}\gamma_\mu\gamma_5[u^\mu, B]\rangle$$

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

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

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

$$u_\mu = iu^\dagger\partial_\mu U u^\dagger$$

$$\Phi = \begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta & K^0 \\ K^- & \bar{K}^0 & -\frac{2}{\sqrt{6}}\eta \end{pmatrix} \quad \mathrm{B} = \begin{pmatrix} \frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & \Sigma^+ & p \\ \Sigma^- & -\frac{1}{\sqrt{2}}\Sigma^0 + \frac{1}{\sqrt{6}}\Lambda & n \\ \Xi^- & \Xi^0 & -\frac{2}{\sqrt{6}}\Lambda \end{pmatrix}$$

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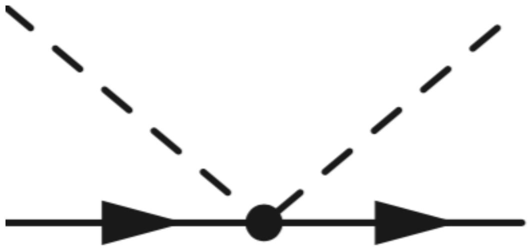
Weinberg-Tomozawa term (WT)



Dominant contribution

$$V_{ij}^{WT} = -C_{ij}\frac{1}{4f^2}\left(k^0 + k'^0\right)$$

The only model parameter is **pion decay constant**, $f = af_\pi$

FORMALISM
Effective Chiral Lagrangian up to **NLO**

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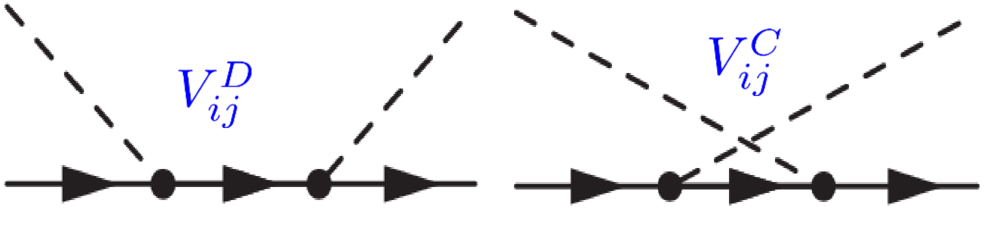
- LEADING ORDER

$$\mathcal{L}^{(1)}_{MB} = \langle \bar{B}(i\gamma_\mu D^\mu - M_0)B\rangle + \boxed{\frac{1}{2}D\langle \bar{B}\gamma_\mu\gamma_5\{u^\mu, B\}\rangle + \frac{1}{2}F\langle \bar{B}\gamma_\mu\gamma_5[u^\mu, B]\rangle}$$

Born terms



Direct diagram (s-channel Born term**)**

Cross diagram (u-channel Born term**)**

These depend on the axial vector couplings **D** and **F**

$$g_A = D + F = 1.26$$

FORMALISM

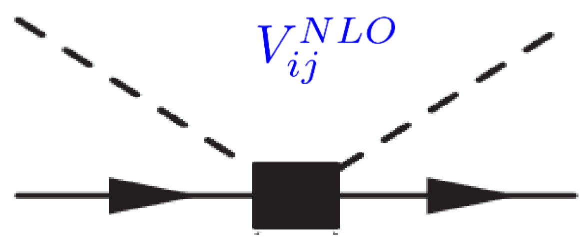
Effective Chiral Lagrangian up to **NLO**

$$\mathcal{L}^{eff}(B,U) = \mathcal{L}^{(1)}_{MB}(B,U) + \mathcal{L}^{(2)}_{MB}(B,U)$$

- NEXT-TO-LEADING ORDER

$$\begin{aligned}\mathcal{L}^{(2)}_{\phi B} \quad = \quad & b_D\langle \bar{B}\{\chi_+, B\}\rangle + b_F\langle \bar{B}[\chi_+, B]\rangle + b_0\langle \bar{B}B\rangle\langle\chi_+\rangle + \\ & +d_1\langle \bar{B}\{u_\mu, [u^\mu, B]\}\rangle + d_2\langle \bar{B}[u_\mu, [u^\mu, B]]\rangle \\ & +d_3\langle \bar{B}u_\mu\rangle\langle u^\mu B\rangle + d_4\langle \bar{B}B\rangle\langle u^\mu u_\mu\rangle\end{aligned}$$

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



7 new parameters: $\mathbf{b_0}, \mathbf{b_D}, \mathbf{b_F}, \mathbf{d_1}, \mathbf{d_2}, \mathbf{d_3}, \mathbf{d_4}$

BCN chiral model at NLO

Feijoo, Magas, Ramos

S=-1, Q=0 sector

- Determinar NLO parameters paying attention to the reactions particularly sensitive to the NLO (for example $\bar{K}N \rightarrow K\Xi$)

  PR C92 *(2015) 015206*

- Born and NLO terms in the Lagrangian appear to play a similar role for the reactions like $\bar{K}N \rightarrow K\Xi$

  NP A954 *(2016) 58*

- Studying the constraining effect of isospin filtering reactions especially sensitive to NLO

  PR C99 *(2019) 035211*

- Studying the S+P wave meson-baryon interaction

  F., Gazda, M., R., Symmetry **13** (2021) 8, 1434

BCN chiral model at NLO

Feijoo, Magas,
Valcarce Cadenas

Moving to **S=-2, Q=0** sector

“The **Ξ(1620)** and **Ξ(1690)** molecular states from S = −2 meson-baryon interaction up to next-to-leading order”

Phys. Lett. **B841** (2023) 137927

BCN chiral model at NLO

S=-2, Q=0 sector

Ξ(1620) and Ξ(1690) as dynamically generated resonances

The pioneering work -- Ramos, Oset, Bennhold, PRL 89 (2002) 252001

- Garcia-Recio, Lutz, Nieves, Phys. Lett. B 582 (2004) 49
- Gamermann, Garcia-Recio, Nieves, Salcedo, PR D84 (2011) 056017
- T. Sekihara, PTEP 2015 (9) (2015) 091.
- Nishibuchi, Hyodo, EPJ Web Conf. 271 (2022) 10002; arXiv:2305.10753 [hep-ph]

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Ξ(1620) and Ξ(1690) as dynamically generated resonances

- Even if **two resonances** are dynamically generated there exists a mutual incompatibility in pinning down **both masses simultaneously**

- $\boldsymbol{\Gamma_{\Xi(1690)} \approx 1\ \mathrm{MeV}}$

- **Ξ(1620)** can be reproduced very well [Nishibuchi, Hyodo], but only allowing some parameters to take unnatural-size values

BCN chiral model at NLO
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In all those works only a WT contact term was employed

What if we will add also Born and NLO terms?

$$V_{ij} = V_{ij}^{WT} + V_{ij}^{direct} + V_{ij}^{crossed} + V_{ij}^{NLO}$$

Role of Born and NLO terms

S=-1, Q=0 sector

J. A. Oller and U.-G. Meissner, Phys. Lett. B 500, 263 (2001)

Born contributions reach **~20%** of the dominant WT contribution just **65 MeV** above $\bar{K}N$ threshold (S-wave)

➔ The energy range between the lowest and the highest threshold in **S=-2** sector is about **410 MeV**

Feijoo, Magas, Ramos, PR. C 99, no.3, 035211 (2019), Nucl. Phys. A 954, 58 (2016)

At slightly higher energies, the NLO and the Born terms are essential to reproduce the experimental total cross section from $\bar{K}N \rightarrow \eta\Lambda, \eta\Sigma, K\Xi$ processes (η channel thresholds are around 200 MeV above $\bar{K}N$ threshold)

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(η channel thresholds are around 200 MeV above $\bar{K}N$ threshold)

New pieces in the interaction kernel will enable new processes
(not connected with the WT term) and, thus,
we can expect the increase of the Ξ(1690) width

$$V_{ij} = V_{ij}^{WT} + V_{ij}^{direct} + V_{ij}^{crossed} + V_{ij}^{NLO}$$

FORMALISM

Unitarized scattering amplitude

$$V_{ij} = V_{ij}^{WT} + V_{ij}^{D} + V_{ij}^{C} + V_{ij}^{NLO} \Longrightarrow T = (1 - VG)^{-1} V \Longrightarrow T_{ij}$$

Loop function

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

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Dimensional regularization :

$$\begin{aligned} G_l \;=\; & \frac{2M_l}{16\pi^2} \left\{ a_l(\mu) + \ln\frac{M_l^2}{\mu^2} + \frac{m_l^2 - M_l^2 + s}{2s} \ln\frac{m_l^2}{M_l^2} + \right. \\ & + \frac{\bar{q}_l}{\sqrt{s}} \left[\ln(s - (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) + \ln(s + (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) \right. \\ & \left.\left. - \ln(-s + (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) - \ln(-s - (M_l^2 - m_l^2) + 2\bar{q}_l\sqrt{s}) \right] \right\} \end{aligned}$$

subtraction constants (to be fitted): a_l

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subtraction constants (to be fitted): a_l

$a_l(\mu) \simeq -2$ → "natural size" (μ=630 MeV) **[Oller and Meissner, PL B500 (2001) 263]**

In our study we will allow ***a***'s to vary within [-3.5,-1]

FORMALISM

Unitarized scattering amplitude

$$V_{ij} = V_{ij}^{WT} + V_{ij}^{D} + V_{ij}^{C} + V_{ij}^{NLO} \Longrightarrow T = (1 - VG)^{-1} V \Longrightarrow T_{ij}$$

Model parameters for **S=-2, Q=0** sector

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Model parameters for **S=-2, Q=0** sector

Chiral Lagrangian is SU(3) symmetric $\Rightarrow$ Model parameters fitted in **S=-1** sector can be used

- Axial vector couplings: **D, F**
- 7 coefficients of the NLO lagrangian terms: $\mathbf{b_0, b_D, b_F, d_1, d_2, d_3, d_4}$

Fixed by BCN model

- Pion decay constant $f = af_\pi$
  - Model 1: a = 1.197 *(fixed by BCN model)*
  - Model 2: a ϵ [1.19, 2.1] *(constrained by the error band of **BCN model**)*
- 4 subtracting constants (isospín symmetry): $a_{\pi\Xi}$, $a_{\bar{K}\Lambda}$, $a_{\bar{K}\Sigma}$, $a_{\eta\Xi}$

constrained within [-3.5,-1]

Fitting model parameters

- Axial vector couplings: **D, F**
- 7 coefficients of the NLO lagrangian terms: $\mathbf{b_0, b_D, b_F, d_1, d_2, d_3, d_4}$

Fixed by BCN model

Table 2: Values of the parameters for the different models described in the text. The subtraction constants are taken at a regularization scale $\mu = 630$ MeV.

	Model I	**Model II**
$a_{\pi\Xi}$	-2.7981	-2.7228
$a_{\bar{K}\Lambda}$	-1.0071	-1.0000
$a_{\bar{K}\Sigma}$	-3.0938	-2.9381
$a_{\eta\Xi}$	-3.2665	-3.3984
f/f_π	1.197 (fixed [1])	1.204

Phys. Lett. **B841** (2023) 137927

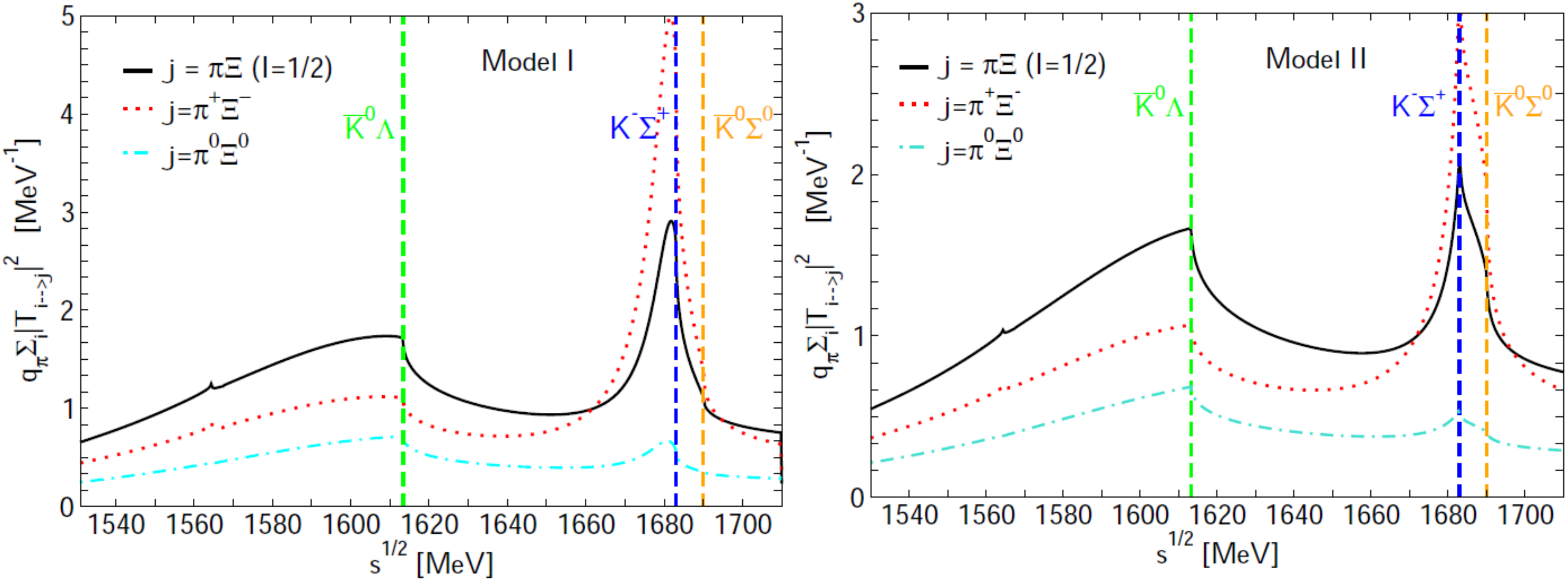
Results

2 dynamical generated resonances !

Model I	$\Xi(1620)$		$\Xi(1690)$	
M [MeV]	1599.95		1683.04	
Γ [MeV]	158.88		11.51	
	g_i	$\lvert g_i \rvert$	g_i	$\lvert g_i \rvert$
$\pi^+\Xi^-$	$1.70 + i0.78$	1.87	$0.44 + i0.07$	0.45
$\pi^0\Xi^0$	$-1.22 - i0.62$	1.37	$0.08 - i0.10$	0.13
$\bar{K}^0\Lambda$	$-2.11 - i0.08$	2.11	$0.50 - i0.06$	0.51
$K^-\Sigma^+$	$0.81 - i0.22$	0.84	$1.0 - i0.16$	1.01
$\bar{K}^0\Sigma^0$	$-0.41 + i0.28$	0.50	$-1.34 + i0.26$	1.37
$\eta\Xi^0$	$-0.23 + i0.13$	0.26	$-0.74 + i0.13$	0.76

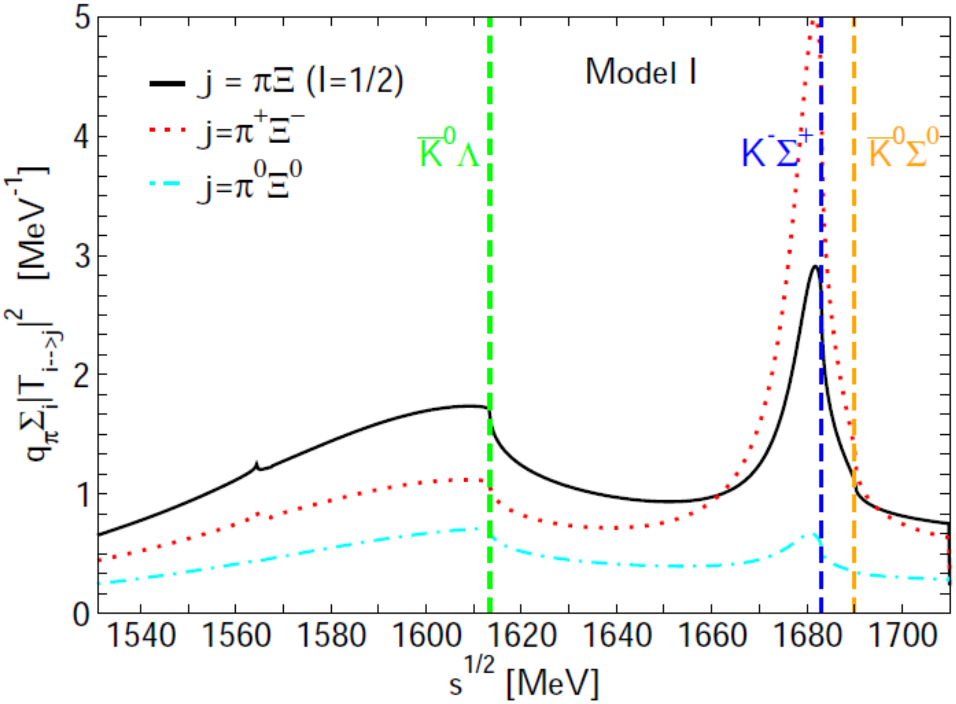
Model II	$\Xi(1620)$		$\Xi(1690)$	
M [MeV]	1608.51		1686.17	
Γ [MeV]	170.00		29.72	
	g_i	$\lvert g_i \rvert$	g_i	$\lvert g_i \rvert$
$\pi^+\Xi^-$	$1.73 + i0.85$	1.93	$0.51 + i0.25$	0.57
$\pi^0\Xi^0$	$-1.24 - i0.67$	1.41	$0.09 - i0.06$	0.11
$\bar{K}^0\Lambda$	$-2.12 - i0.09$	2.12	$0.81 - i0.02$	0.81
$K^-\Sigma^+$	$0.8 - i0.25$	0.84	$1.36 + i0.10$	1.36
$\bar{K}^0\Sigma^0$	$-0.36 + i0.31$	0.48	$-1.99 + i0.08$	1.99
$\eta\Xi^0$	$-0.20 + i0.12$	0.24	$-1.04 + i0.06$	1.04

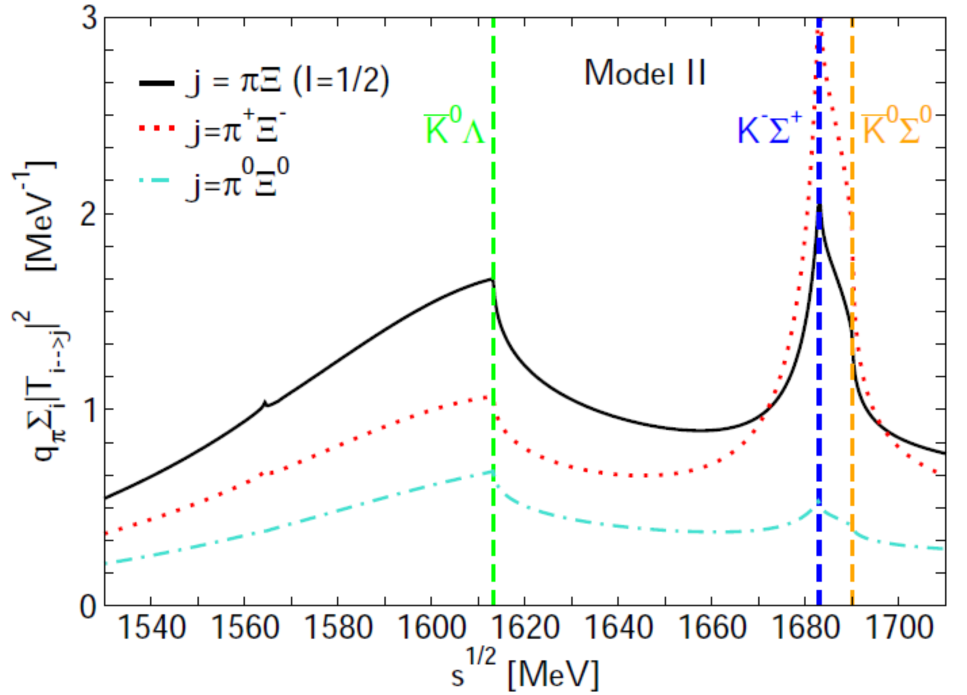
Results



$$\pi\Xi \text{ spectrum: } q_\pi \mid \sum_i T_{i\to\pi\Xi} \mid^2$$

Results





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

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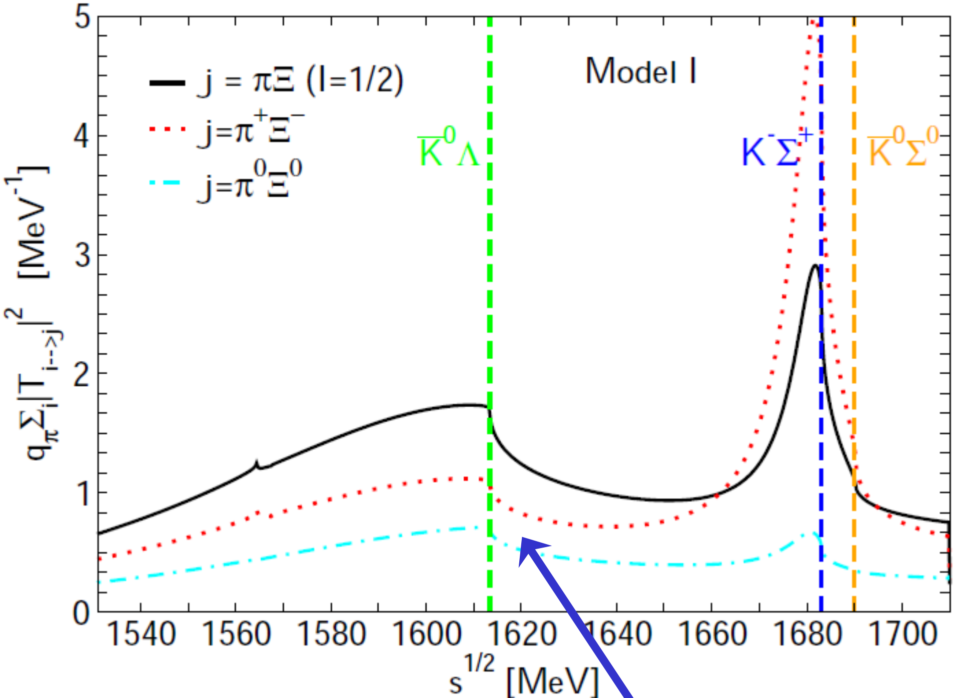

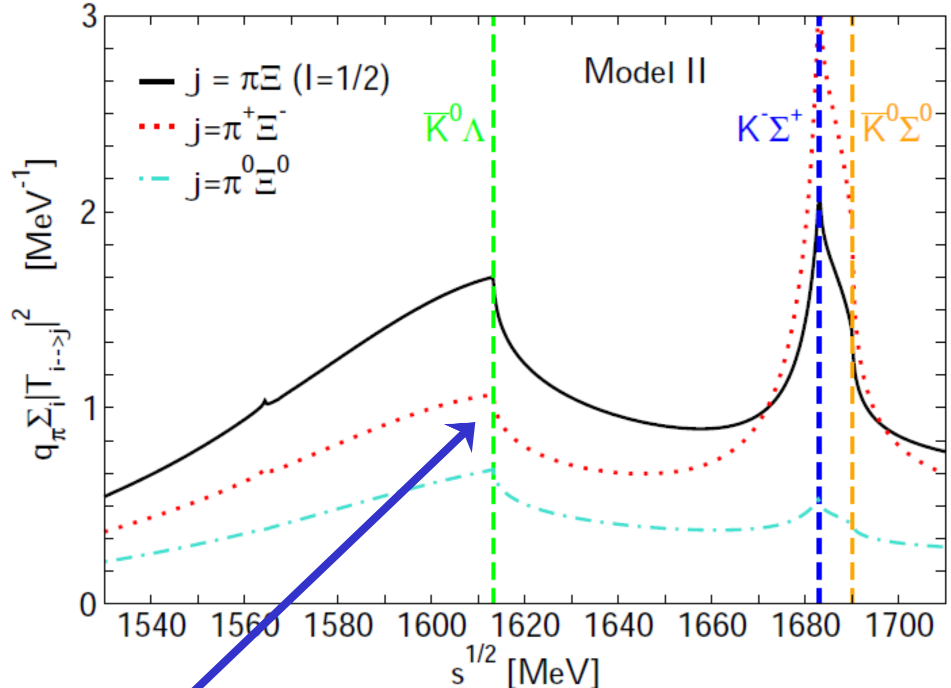

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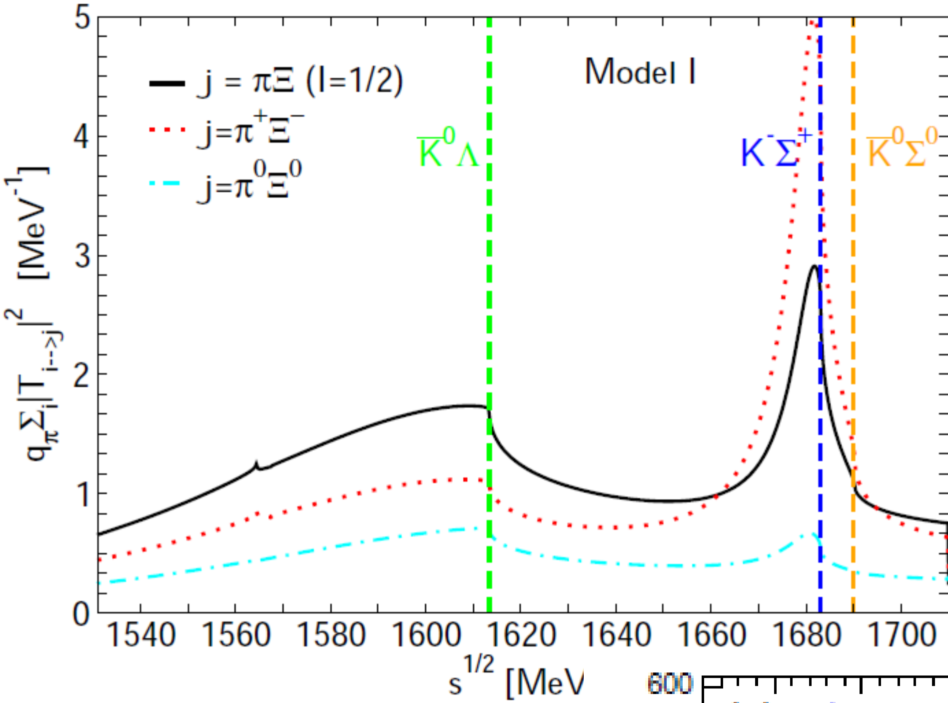
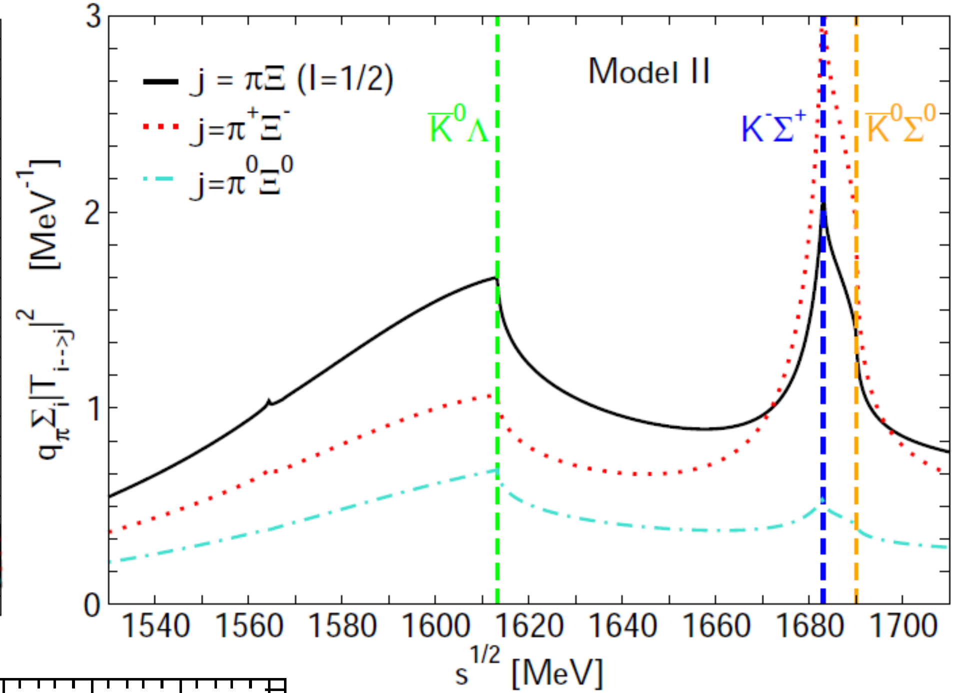
Flatte effect

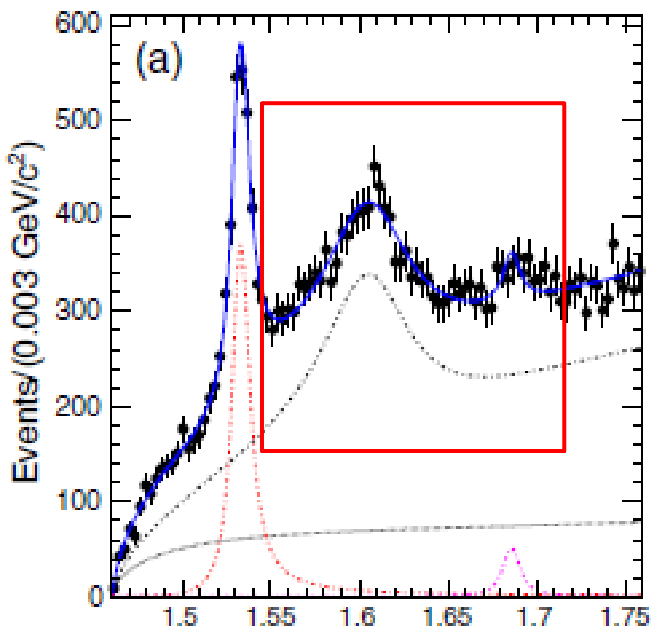
An effective reduction of the width compared to Γ_{th}

Flatte, PL **B63** (1976) 224

Results







$\pi\Xi$ spectrum:

$\Xi_c^+ \Rightarrow \Xi^-\pi^+\pi^+$

Sumihama, et al.,
PRL122 (7) (2019) 072501

Results
$\Xi(1690)$ branching ratios

Workman, et al.,
Review of Particle Physics,
PTEP 2022 (2022) 083C01

$\Xi(1690)$ BRANCHING RATIOS

$\Gamma(\Lambda\overline{K})/\Gamma_{total}$ Γ_1/Γ

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
seen	104	BIAGI	87	SPEC	$-$	Ξ^- Be 116 GeV

$\Gamma(\Sigma\overline{K})/\Gamma(\Lambda\overline{K})$ Γ_2/Γ_1

VALUE	EVTS	DOCUMENT ID		TECN	CHG	COMMENT
0.75 ± 0.39	75	ABE	02C	BELL		$e^+e^- \approx \Upsilon(4S)$
$2.7\ \pm0.9$		DIONISI	78	HBC	0	K^-p 4.2 GeV/c
$3.1\ \pm1.4$		DIONISI	78	HBC	$-$	K^-p 4.2 GeV/c

$\Gamma(\Xi\pi)/\Gamma(\Sigma\overline{K})$ Γ_3/Γ_2

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.09	DIONISI	78	HBC	0	K^-p 4.2 GeV/c

Results

$\Xi(1690)$ branching ratios

Workman, et al.,
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$\Xi(1690)$ BRANCHING RATIOS

$\Gamma(\Lambda\overline{K})/\Gamma_{total}$ — **Γ_1/Γ**

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$\Gamma(\Sigma\overline{K})/\Gamma(\Lambda\overline{K})$ — **Γ_2/Γ_1**

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0.75 ± 0.39	75	ABE	02C	BELL		$e^+ e^- \approx \Upsilon(4S)$
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3.1 ± 1.4		DIONISI	78	HBC	−	$K^- p$ 4.2 GeV/c

$\Gamma(\Xi\pi)/\Gamma(\Sigma\overline{K})$ — **Γ_3/Γ_2**

VALUE	DOCUMENT ID		TECN	CHG	COMMENT
<0.09	DIONISI	78	HBC	0	$K^- p$ 4.2 GeV/c

$$\frac{\Gamma^{\pi\Xi}_{\Xi(1690)}}{\Gamma^{\bar{K}\Sigma}_{\Xi(1690)}} = 0.25$$

Model II

$$\frac{\Gamma^{\bar{K}\Sigma}_{\Xi(1690)}}{\Gamma^{\bar{K}\Lambda}_{\Xi(1690)}} = 3.22\,!$$

Conclusions

- We have studied
  meson-baryon interaction in the ***S*=−2 (Q=0) sector**
  within an **extended** UChPT scheme **for the first time**

$$V_{ij} = V_{ij}^{WT} + V_{ij}^{direct} + V_{ij}^{crossed} + V_{ij}^{NLO}$$

- Our model is able to generate dynamically
  both **Ξ(1620)** and **Ξ(1690)** states **at the same time**
  in a **very reasonable agreement** with exp. data

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⇒ **Reliability of the chiral models with unitarization in coupled channels**

⇒ **Importance of considering Born and NLO contributions for precise calculations**

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⟹ Most of the model parameters have been assumed to be **SU(3)** symmetric and were taken from the BCN model fit in **S=-1** sector

⟹ Ref. [PR **C99** (2019) 035211] gives a **trustable set** of **NLO parameters**

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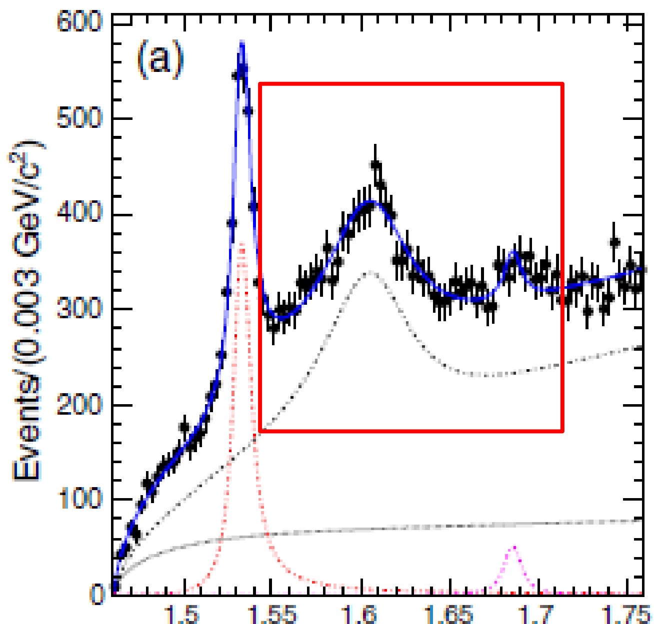
- Work in progress

$\pi\Xi$ spectrum for
$\Xi_c^+ \Rightarrow \Xi^- \pi^+ \pi^+$

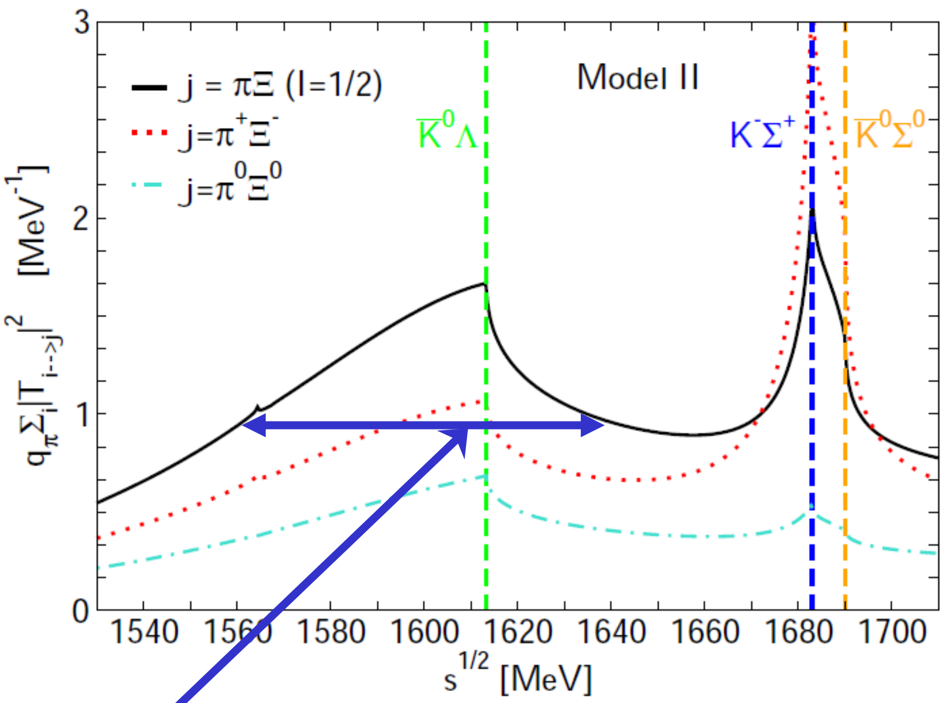
Sumihama, et al.,
PRL122 (7) (2019) 072501



Back up

Results

$\Gamma_{eff} \approx 90\ MeV$



Model II	$\Xi(1620)$
M [MeV]	1608.51
Γ [MeV]	170.00

Flatte effect

An effective reduction of the width compared to Γ_{th}

Flatte, PL **B63** (1976) 224

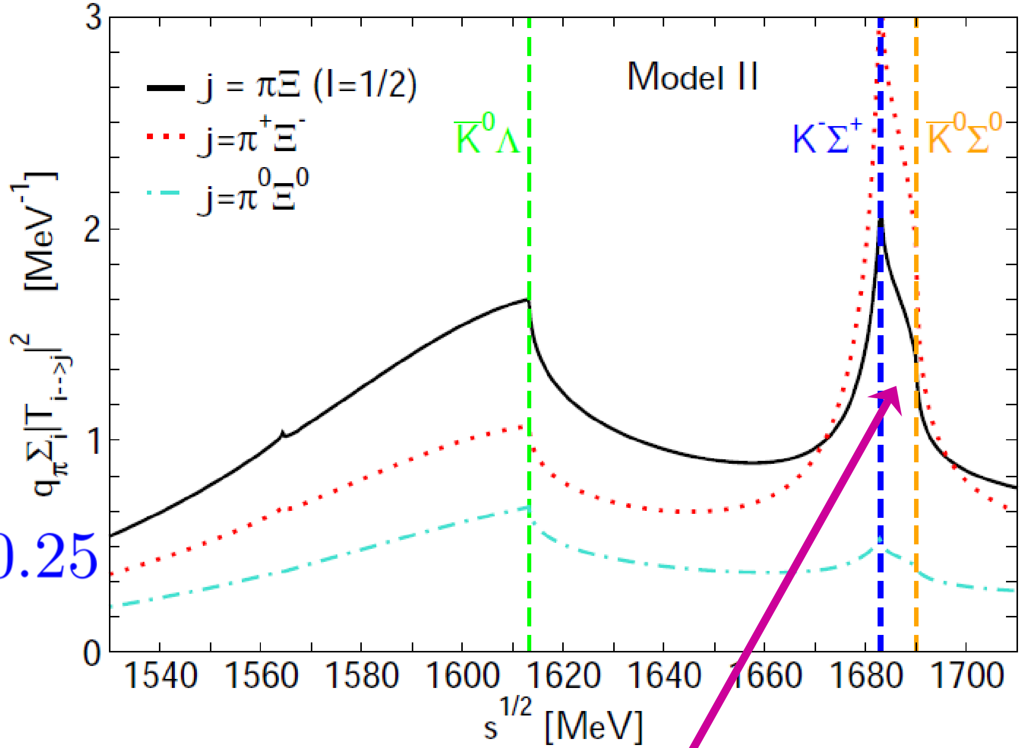
Results

Model II

$$\Gamma_R^i \sim p_i \, |g_{R,i}|^2 \, M_i/M_R$$

$$\frac{\Gamma^{\pi\Xi}_{\Xi(1690)}}{\Gamma^{\bar{K}\Sigma}_{\Xi(1690)}} = \frac{\Gamma^{\pi^+\Xi^-}_{\Xi(1690)} + \Gamma^{\pi^0\Xi^0}_{\Xi(1690)}}{\Gamma^{K^-\Sigma^+}_{\Xi(1690)} + \Gamma^{\bar{K}^0\Sigma^0}_{\Xi(1690)}} = 0.25$$

$$\frac{\Gamma^{\bar{K}\Sigma}_{\Xi(1690)}}{\Gamma^{\bar{K}\Lambda}_{\Xi(1690)}} = \frac{\Gamma^{K^-\Sigma^+}_{\Xi(1690)} + \Gamma^{\bar{K}^0\Sigma^0}_{\Xi(1690)}}{\Gamma^{\bar{K}\Lambda}_{\Xi(1690)}} = 3.22$$



$$\Gamma_{\mathrm{ave.}} = \frac{-\frac{1}{\pi}\int\limits_{M-\Gamma}^{M+\Gamma} \mathrm{d}\sqrt{s}\,\Gamma_{\gamma Y}\left(\sqrt{s}\right)\,\mathrm{Im}\,\frac{1}{\sqrt{s}-M+i\frac{\Gamma}{2}}\,\Theta\left(\sqrt{s}-\sqrt{s_{\mathrm{th}}}\right)}{-\frac{1}{\pi}\int\limits_{M-\Gamma}^{M+\Gamma} \mathrm{d}\sqrt{s}\,\mathrm{Im}\,\frac{1}{\sqrt{s}-M+i\frac{\Gamma}{2}}\,\Theta\left(\sqrt{s}-\sqrt{s_{\mathrm{th}}}\right)}$$

Eq. (17) [Geng, Oset, Doring, Eur. Phys. J. A 32 (2007) 201]

Results

Table 4
Effective range, r_{eff}, and scattering length, a_0, for $\bar{K}^0\Lambda$ threshold.

	Model I	Model II
$a_0^{\bar{K}^0\Lambda}$	$-0.155 + i0.501$	$-0.115 + i0.495$
$r_{eff}^{\bar{K}^0\Lambda}$	$-0.408 - i0.413$	$-0.507 - i0.205$

Phys. Lett. **B841** (2023) 137927