The decay of N*(1895) to light hyperon resonances

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N*(1895): some known facts

- $N^*(1895)$ is the highest mass nucleon known with $J^\pi = 1/2^-$. PDG lists all $1/2^-$ structures found above 1800 MeV together, under the label of $N^*(1895)$.

- $N^*(1895)$ cannot be described within the naïve quark model. The next S_{11} resonance after $N^*(1535)$ and $N^*(1650)$, within quark models based on the harmonic oscillator potential, is expected to appear with mass > 2100 MeV $\longrightarrow$ hadron interactions may play an important role in describing the properties of $N^*(1895)$.

- It lies in the scattering region of various meson baryon coupled channels.

- Indeed, in an earlier work , we studied coupled channel meson-baryon dynamics found found two poles, with overlapping width, in the $N^*(1895)$ mass region (more details in the next few slides).

- In some cases three-hadron dynamics is required to understand the properties of a state (See Talks by: Alberto Martinez Torres on Wednesday, parallel session *Analysis tools-4*, *10:05* conference time; Brenda B M on Thursday, parallel session, *Exotic hadrons and candidates-6 12:40h* conference time)

Motivation for further study of N*(1895)

- There is a clustering of nucleon resonances around 1890 MeV: besides, $N^*(1895)$ there exists $N^*(1900)\left[3/2^+\right]$ and $N^*(1890)\left[1/2^+\right]$.

- For example, $N^*(1895)$ used to be listed as $N^*(2090)\left[1/2^-\right]$ before 2012, by the PDG.

- Several different descriptions have been provided for a peak present around 1900 MeV in the $\gamma p \to K^+\Lambda$ total cross sections. *[PRC 61, 012201 (2000), PRD 49, 4570-4586 (1994), EPJA 48, 15 (2012), PRD 100, no. 5, 056008 (2019), PRC 86, 022201 (2012), EPJA 41, 361-368 (2009), Phys. Lett. B 771, 142-150 (2017)]*

- Decay properties of $N^*(1895)$ can be useful in distinguishing it from other N^*s present in the same energy region.

Motivation for further study of N*(1895)

- It lies close to the threshold of $K\Lambda(1405)$.
- The branching ratio for the decay $N^*(1895) \to K\Lambda(1405)$ can be significant.
- Such decay property can be important to study the photoproduction of $\Lambda(1405)$ or the process $\pi N \to K^*\pi\Sigma$, which is intended to be studied at J-PARC [H. Noumi, JPS Conf. Proc. 17, 111003 (2017)].
- $\Lambda(1405)$: although it has been within different models it is still not clear if it is associated to one or two poles in the complex plane.

Motivation for further study of N*(1895)

- Understanding the properties of hyperons is important due its implications, like, the existence of kaonic-nuclear bound states.

- There also exists a discussion on the existence of an isovector partner of $\Lambda(1405)$ [Oller, Meißner, PLB 500, 263 (2001),Guo, Oller, PRC87, 035202 (2013)Wu, Dulat, Zou, PRD 80, 017503 (2009), Wu, Dulat, Zou, PRC 81, 045210 (2010), Gao, Wu, Zou, PRC 81, 055203 (2010),Xie, Wu, Zou, PRC 90, 055204 (2014), Xie, Geng, PRD 95, 074024 (2017), Roca, Oset, Phys. Rev. C 88, 055206 (2013)]

- $N^*(1895)$ could decay to such a $\Sigma(1400)$ too, and can be a useful source of information on it.

Our model for studying meson-baryon interactions

- **Pseudoscalar-baryon interaction (standard, lowest order chiral Lagrangian):**

- $\mathscr{L}_{PB} = \langle \bar{B} i\gamma^\mu \partial_\mu B + \bar{B} i\gamma^\mu [\Gamma_\mu, B] \rangle - M_B \langle \bar{B} B \rangle + \frac{1}{2} D' \langle \bar{B} \gamma^\mu \gamma_5 \{u_\mu, B\} \rangle + \frac{1}{2} F' \langle \bar{B} \gamma^\mu \gamma_5 [u_\mu, B] \rangle$

- $u_\mu = i u^\dagger \partial_\mu U u^\dagger, \Gamma_\mu = \frac{1}{2}\left(u^\dagger \partial_\mu u + u \partial_\mu u^\dagger\right),\ U = u^2 = \mathbf{e}xp\left(i\frac{P}{f_P}\right)$

- $D' = 0.8,\ F' = 0.46$

$$P = \begin{pmatrix} \pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{1}{\sqrt{3}}\eta & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & \frac{-2}{\sqrt{3}}\eta \end{pmatrix}, \quad B = \begin{pmatrix} \frac{1}{\sqrt{6}}\Lambda + \frac{1}{\sqrt{2}}\Sigma^0 & \Sigma^+ & p \\ \Sigma^- & \frac{1}{\sqrt{6}}\Lambda - \frac{1}{\sqrt{2}}\Sigma^0 & n \\ \Xi^- & \Xi^0 & -\sqrt{\frac{2}{3}}\Lambda \end{pmatrix}$$

Our model for studying meson-baryon interactions

- Vector-baryon interactions (HLS):

- $$\mathscr{L}_{\mathbf{VB}} = -g\Bigg\{ \langle \bar{B}\gamma_\mu \left[V_8^\mu, B\right]\rangle + \langle \bar{B}\gamma_\mu B\rangle\langle V_8^\mu\rangle + \frac{1}{4M}\Big(F\langle \bar{B}\sigma_{\mu\nu}\left[V_8^{\mu\nu}, B\right]\rangle + D\langle \bar{B}\sigma_{\mu\nu}\left\{V_8^{\mu\nu}, B\right\}\rangle \Big) + \langle \bar{B}\gamma_\mu B\rangle\langle V_0^\mu\rangle + \frac{C_0}{4M}\langle \bar{B}\sigma_{\mu\nu}V_0^{\mu\nu}B\rangle \Bigg\}; \qquad g = \frac{m_v}{\sqrt{2}f_\pi}$$

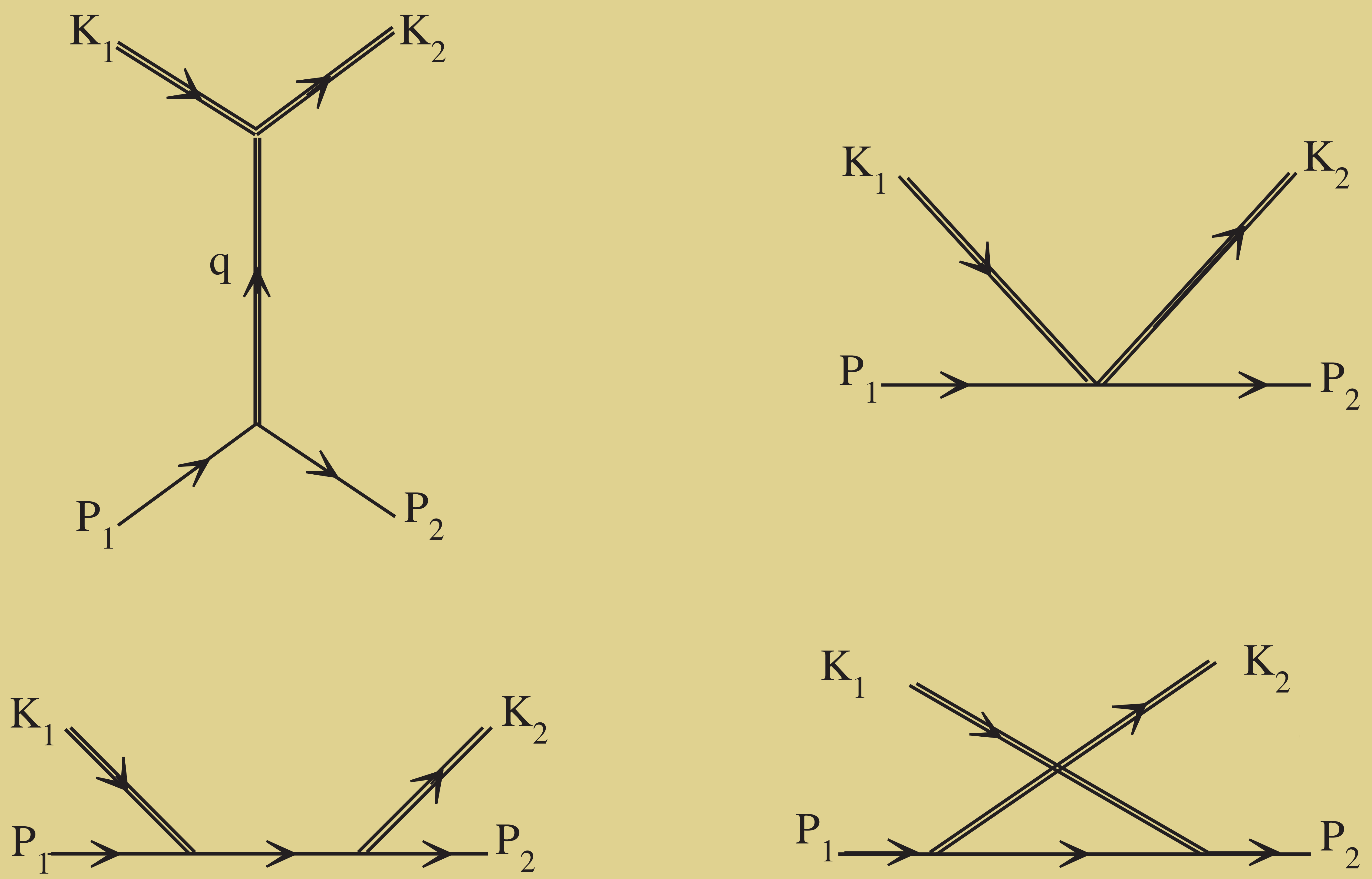
- $$\mathscr{L}_{V_0BB} = -g\left\{ \langle \bar{B}\gamma_\mu B\rangle\langle V_0^\mu\rangle + \frac{C_0}{4M}\langle \bar{B}\sigma_{\mu\nu}V_0^{\mu\nu}B\rangle \right\}, \; D = 2.4, \; F = 0.82, \; C_0 = 3F - D$$

- $$V^{\mu\nu} = \partial^\mu V^\nu - \partial^\nu V^\mu + ig\left[V^\mu, V^\nu\right]$$

$$V^\mu = \frac{1}{2}\begin{pmatrix} \rho^0+\omega & \sqrt{2}\rho^+ & \sqrt{2}K^{*^+} \\ \sqrt{2}\rho^- & -\rho^0+\omega & \sqrt{2}K^{*^0} \\ \sqrt{2}K^{*^-} & \sqrt{2}\bar{K}^{*^0} & \sqrt{2}\phi \end{pmatrix}^\mu$$

Our model for studying meson-baryon interactions

Lowest order amplitude is a sum of:



Our model for studying meson-baryon interactions

Transition between the two types of channels:

$$\mathscr{L}_{\mathrm{PBVB}} = \frac{-ig_{PBVB}}{2f_v}\left(F'\langle\bar{B}\gamma_\mu\gamma_5\left[\left[P,V^\mu\right],B\right]\rangle + D'\langle\bar{B}\gamma_\mu\gamma_5\left\{\left[P,V^\mu\right],B\right\}\rangle\right)$$

Extension of Kroll-Ruderman term $\gamma N \to \pi N$; replacing γ ⇨ V

Our model for studying meson-baryon interactions

- All amplitudes are projected on s-wave and used as an input in the equation T= V+VGT

- Nonstrange coupled channels $\pi N, \eta N, K\Lambda, K\Sigma, \rho N, \omega N, \phi N, K^*\Sigma$ and $K^*\Lambda$ [K. Khemchandani, A. Martínez Torres, H. Nagahiro and A. Hosaka, Phys. Rev. D 88, no.11, 114016 (2013)]

- χ^2-fit to reproduce, for example, the isospin 1/2 and 3/2 πN amplitudes extracted from partial wave analysis of the experimental data and the $\pi^- p \to \eta n$ and $\pi^- p \to K^0\Lambda$ cross sections up to a total energy of about 2 GeV.

- The study lead to the finding of poles associated with $N^*(1535)$, $N^*(1650)$, $N^*(1895)$ and $\Delta(1620)$.

- Poles associated to $N^*(1895)$: $1801 - i96$ MeV and $1912 - i54$ MeV.

Our model for studying meson-baryon interactions

- **Poles associated to** $N^*(1895)$**:** $1801 - i96$ **MeV and** $1912 - i54$ **MeV.**

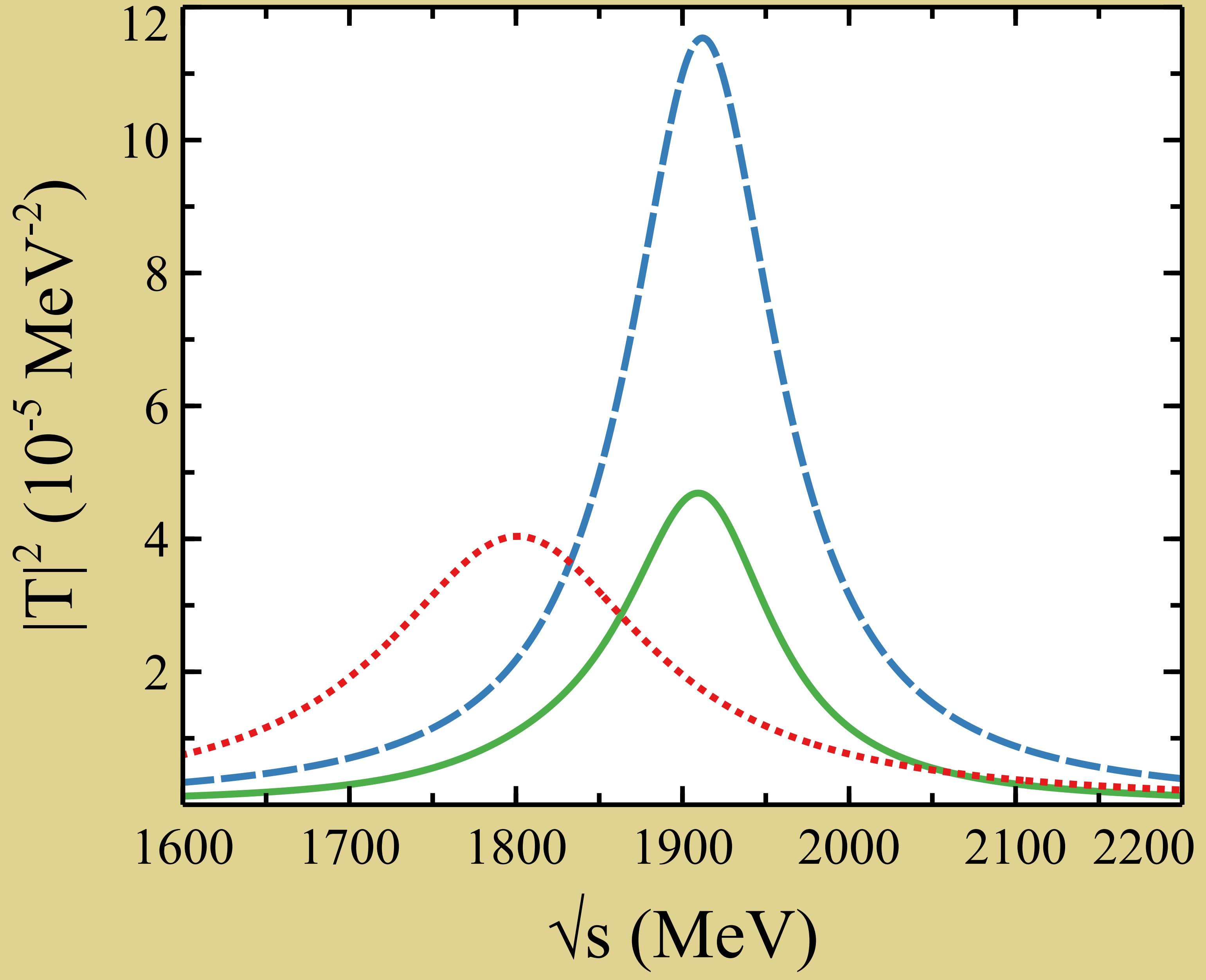
$$t_{K\Lambda} = \frac{g^2_{N_1^* K\Lambda}}{\sqrt{s} - M_{N_1^*} + i\Gamma_{N_1^*}/2} + \frac{g^2_{N_2^* K\Lambda}}{\sqrt{s} - M_{N_2^*} + i\Gamma_{N_2^*}/2}$$

***N*(1895)** $I(J^P) = 1/2(1/2^-)$

Before our 2012 *Review*, this state appeared in our Listings as the $N(2090)$. Any structure in the S_{11} *wave* above 1800 MeV is listed here. A few early results that are now obsolete have been omitted.

$N(1895)$ POLE POSITION

REAL PART	1890 to 1930 (≈ 1910) MeV
−2×IMAGINARY PART	80 to 140 (≈ 110) MeV



Light hyperons from our model:

- **Coupled channels:** $\bar{K}N,\ K\Xi,\ \pi\Sigma,\ \eta\Lambda,\ \pi\Lambda,\ \eta\Sigma, \bar{K}^*N,\ K^*\Xi, \rho\Sigma,\ \omega\Lambda,\ \phi\Lambda,\ \rho\Lambda,\ \omega\Sigma,\ \phi\Sigma$ [Phys. Rev. C 100, 015208 (2019)]

- **Following data were considered to constrain the parameters:**

- **Total cross sections on (175 data points)** $K^-p \to K^-p,\ \bar{K}^0n,\ \eta\Lambda,\ \pi^0\Lambda,\ \pi^0\Sigma^0,\ \pi^\pm\Sigma^\mp$ (Landolt and Börsntein, Numerical data and Functional Relationships in Science and Technology)

- **Kaonic hydrogen** (Siddharta collaboration) **ΔE = 283±36±6 eV and Γ = 549±89±22 eV** (M. Bazzi et al., PLB 704, 113 (2011))

- **Cross section ratios near threshold**

$$\gamma = \frac{\sigma\left(K^-p \to \pi^+\Sigma^-\right)}{\sigma\left(K^-p \to \pi^-\Sigma^+\right)} = 2.36 \pm 0.12,$$

$$R_c = \frac{\sigma\left(K^-p \to \text{charged particles}\right)}{\sigma\left(K^-p \to \text{all}\right)} = 0.664 \pm 0.033,$$

$$R_n = \frac{\sigma\left(K^-p \to \pi^0\Lambda\right)}{\sigma\left(K^-p \to \text{all neutral states}\right)} = 0.189 \pm 0.015,$$

Light hyperons from our model:

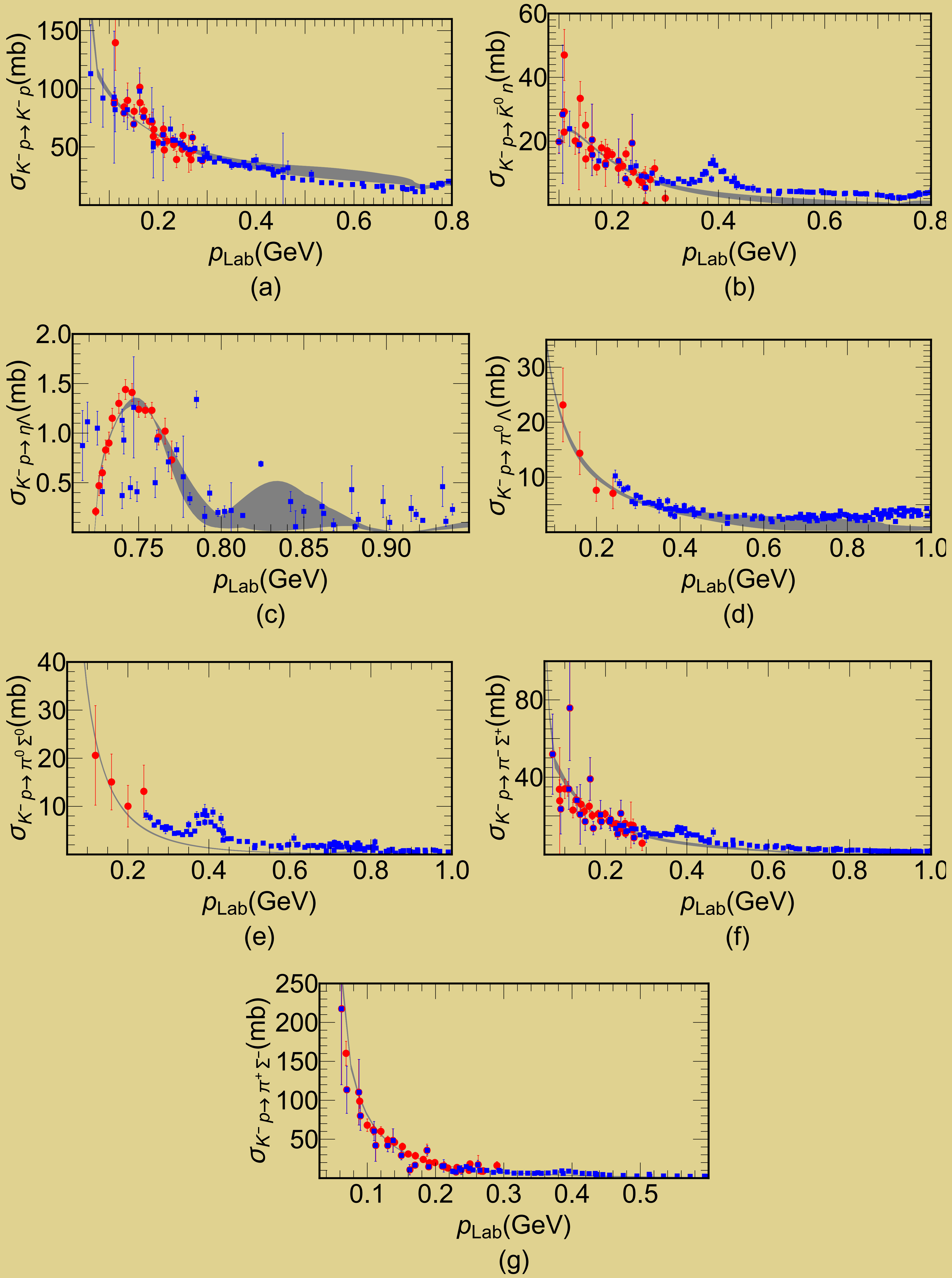
Scattering length from Siddharta data

$$a_{K^-p} = (-0.65 \pm 0.10) + i\,(0.81 \pm 0.15)\ \textbf{fm}$$

Model results:

	Fit I	Fit II
a_{K^-p}	$-0.74^{+0.01}_{-0.02} + i\,0.69^{+0.02}_{-0.01}$	$-0.74^{+0.07}_{-0.02} + i\,0.73^{+0.03}_{-0.08}$
$a^0_{\bar{K}N}$	$-1.58^{+0.03}_{-0.03} + i\,0.87^{+0.02}_{-0.03}$	$-1.60^{+0.03}_{-0.01} + i\,0.89^{+0.04}_{-0.13}$
$a^1_{\bar{K}N}$	$0.09^{+0.02}_{-0.02} + i\,0.50^{+0.04}_{-0.02}$	$0.12^{+0.10}_{-0.04} + i\,0.55^{+0.02}_{-0.04}$

- K. P. Khemchandani, A. Martínez Torres, and J. A. Oller *Phys. Rev. C 100, 015208 (2019)*



Types of fits obtained:

Light hyperons from our model:

- Two poles were obtained for $\Lambda(1405)$: $\left(1385 \pm 5 - i124 \pm 10\right)$ MeV and $\left(1426 \pm 1 - i15 \pm 2\right)$ MeV
- Comparison with other works:
- CLAS analysis of electroproduction data; poles ~1368 MeV, ~1423 MeV
- Mai, Meißner, EPJA51,30 (2015)
  $1325^{+15}_{-15} - i90^{+12}_{-18}$ MeV, and $1429^{+8}_{-7} - i12^{+2}_{-3}$ MeV
- Roca, Oset, PRC 88, 055206 (2013).
  $1352 - i48$ MeV, $1419 - i29$ MeV
- In addition to the pole, a state was also found in the isovector case at $\left(1399 \pm 35 - i36 \pm 9\right)$ MeV. We shall refer to this state as $\Sigma(1400)$.

Decay of N*(1895) to light hyperons

PHYSICAL REVIEW D **103**, 016015 (2021)

Decay properties of $N^*(1895)$

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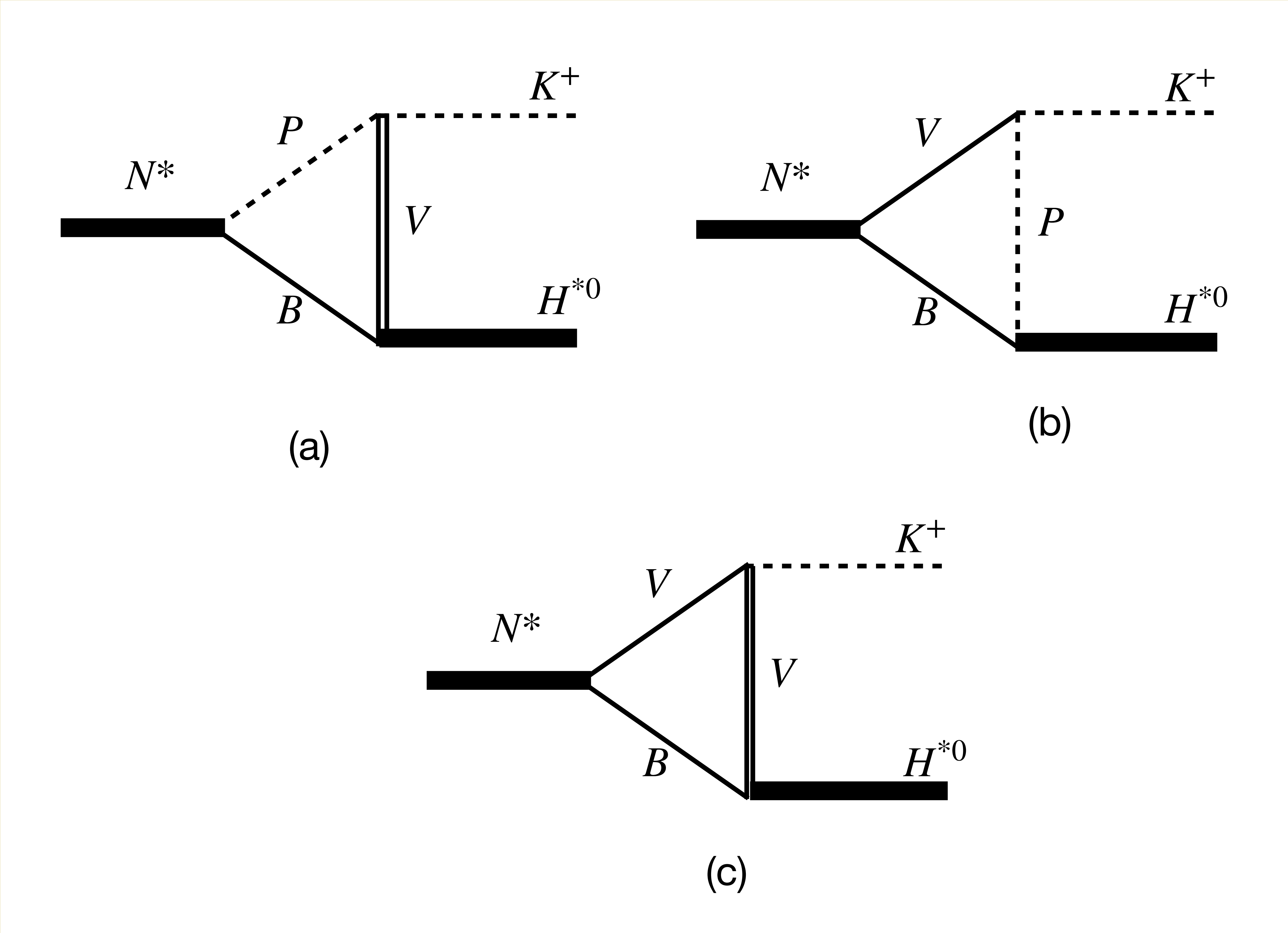
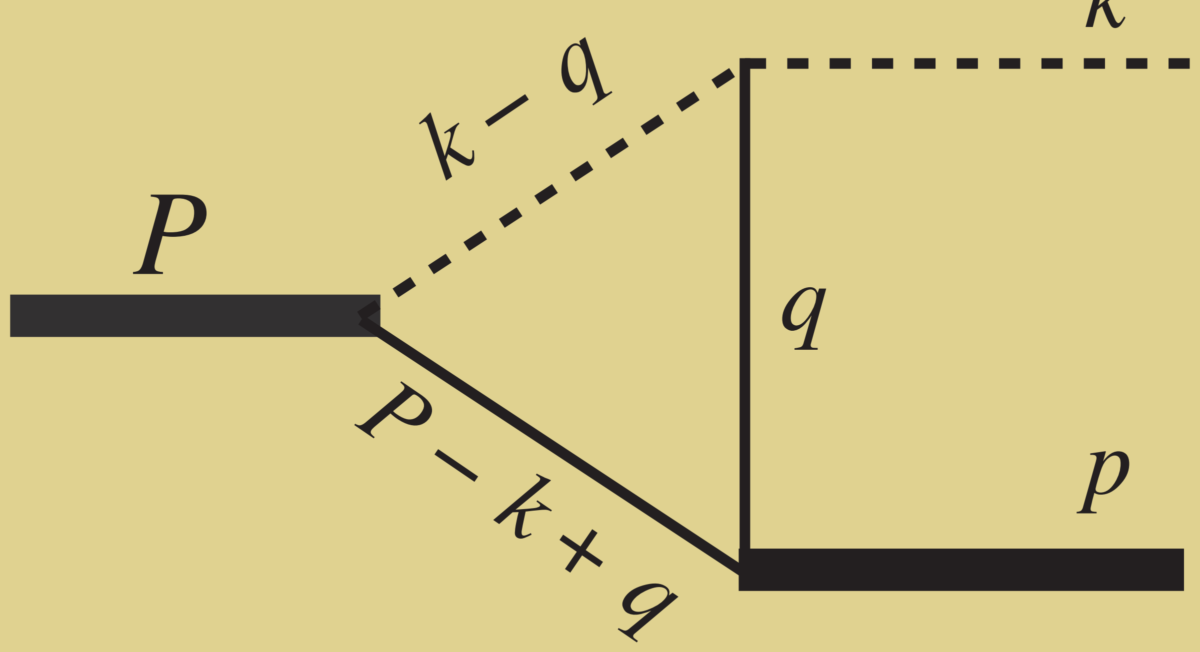


Decay of N*(1895) to light hyperons

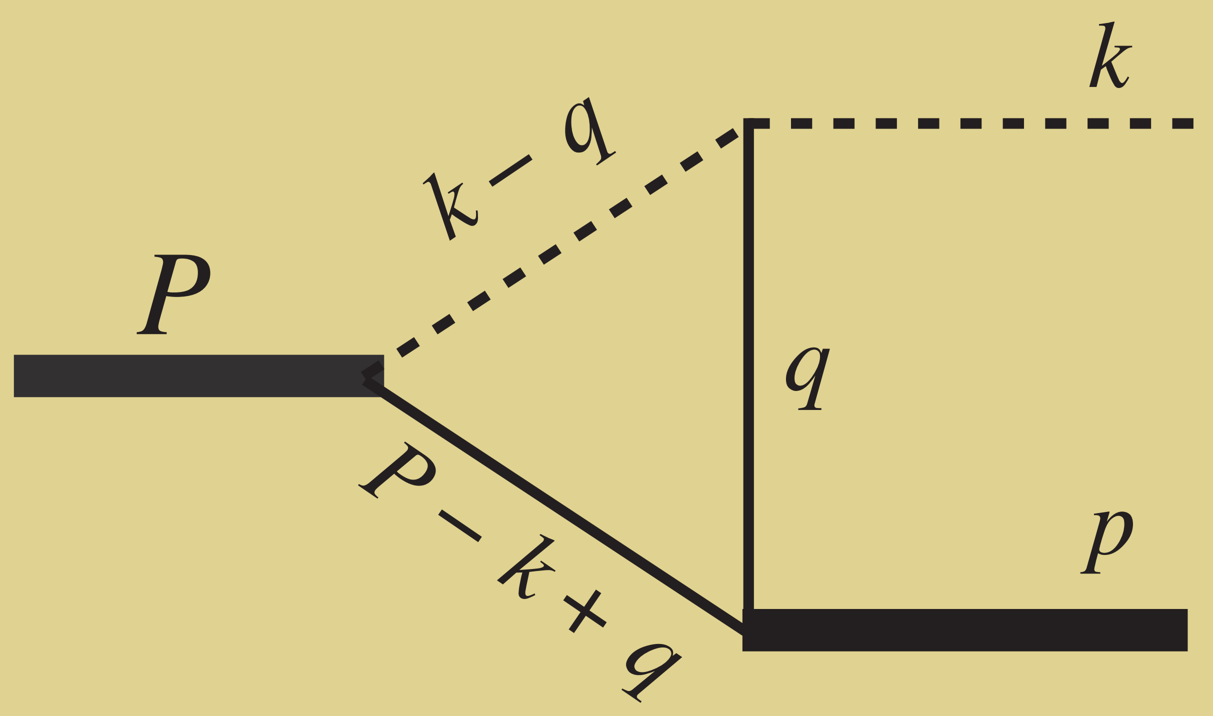


$$t_a = i\sum_j g_{VBH^*,j}\, g_{PBN^*,j}\, g_{PPV} C_j \bar{u}_{H^*}(p)\gamma_\nu\gamma_5$$
$$\times \int \frac{d^4q}{(2\pi)^4}\left\{\frac{(\not{P}-\not{k}+\not{q}+m_{Bj})}{(P-k+q)^2-m_{Bj}^2+i\epsilon}\right.$$
$$\left.\times \frac{(-g^{\nu\mu}+\frac{q^\nu q^\mu}{m_{Vj}^2})}{q^2-m_{Vj}^2+i\epsilon}\frac{(2k-q)_\mu}{(k-q)^2-m_{Pj}^2+i\epsilon}\right\} u_{N^*}(P)$$

Numerator:

$$N_a(q) = (4k\cdot p - 2p\cdot q - q^2)\bar{u}_{H^*}(p)\gamma_5 u_{N^*}(P) - 2(M_{H^*}+m_{Bj})\bar{u}_{H^*}(p)\not{k}\gamma_5 u_{N^*}(P)$$
$$\times (M_{H^*}+m_{Bj})\bar{u}_{H^*}(p)\not{q}\gamma_5 u_{N^*}(P) + 2\bar{u}_{H^*}(p)\not{k}\not{q}\gamma_5 u_{N^*}(P) + \left(\frac{2k\cdot q - q^2}{m_{vj}^2}\right)$$
$$\times [(M_{H^*}+m_{Bj})\bar{u}_{H^*}(p)\not{q}\gamma_5 u_{N^*}(P) - (2p\cdot q + q^2)\bar{u}_{H^*}(p)\gamma_5 u_{N^*}(P)],$$

Decay of N*(1895) to light hyperons



$$t_a = i\sum_j g_{VBH^*,j}\, g_{PBN^*,j}\, g_{PPV} \mathcal{N}_{H^*}\mathcal{N}_{N^*} C_j \int \frac{d^4q}{(2\pi)^4}\left\{\chi^\dagger\left(\sum_{i=0}^{4}\mathcal{A}_{i,j}[q^0]^i\right)\chi\right\}$$

$$\times \frac{1}{[(P-k+q)^2 - m_{Bj}^2 + i\epsilon][q^2 - m_{vj}^2 + i\epsilon][(k-q)^2 - m_{pj}^2 + i\epsilon]},$$

$$\mathcal{A}_{0,j} = \vec{\sigma}\cdot\vec{k}\left\{2\left(M_{H^*} + m_{Bj}\right) + \frac{1}{E_{H^*} + M_{H^*}}\left[2k^0\left(M_{H^*} + m_{Bj} + 2E_{H^*}\right) - 2\vec{k}\cdot\vec{q} + |\,\vec{q}\,|^2 + 4|\,\vec{k}\,|^2 \right.\right.$$

$$\left.\left. + \frac{|\vec{q}|^4 + 4\left(\vec{k}\cdot\vec{q}\right)^2 - 4\left(\vec{k}\cdot\vec{q}\right)|\vec{q}|^2}{m_{vj}^2}\right]\right\} - \vec{\sigma}\cdot\vec{q}\left\{\left(M_{H^*} + m_{Bj}\right)\left(1 - \frac{2\vec{k}\cdot\vec{q} - |\vec{q}|^2}{m_{vj}^2}\right)\right.$$

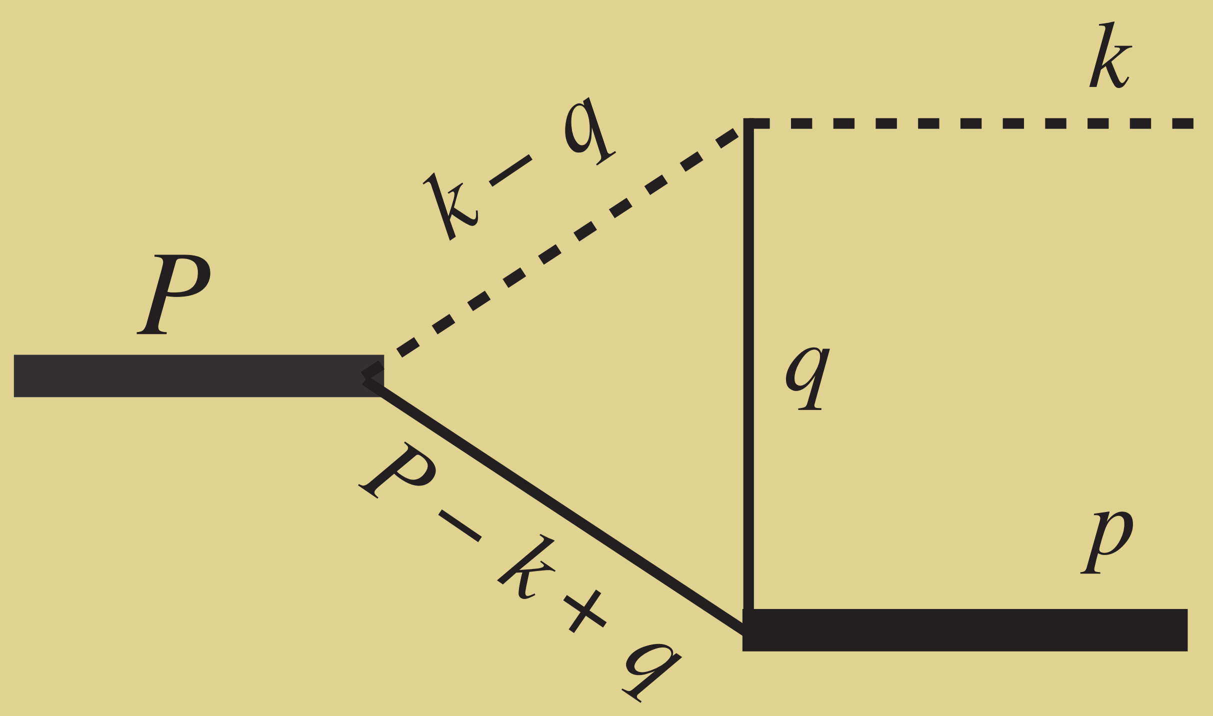
$$\left. + 2k^0 + 2\frac{|\,\vec{k}\,|^2}{E_{H^*} + M_{H^*}}\right\},$$

q^0 dependence:

Analytical integration

…etc., terms up to $\left[q^0\right]^4$

Decay of N*(1895) to light hyperons



$$t_a = i \sum_j g_{VBH^*,j}\, g_{PBN^*,j}\, g_{PPV}\, C_j \mathcal{N}_{H^*} \mathcal{N}_{N^*} \int d\Omega_q \int_0^\Lambda \frac{d|\vec{q}\,|}{(2\pi)^3} |\vec{q}\,|^2 \sum_{i=0}^{4} \chi^\dagger \left[\mathcal{A}_{i,j}(\vec{q}\,)\right] \chi \times \left(\frac{-iN_{i,j}(\vec{q}\,)}{\mathcal{D}_j(\vec{q}\,)} \right),$$

Numerical integration; Λ = 600-700 MeV

$$\frac{-iN_{i,j}(\vec{q}\,)}{\mathcal{D}_j(\vec{q}\,)} \equiv \int \frac{dq^0}{(2\pi)} \frac{(q^0)^i}{\left[(P-k+q)^2 - m_{Bj}^2 + i\epsilon\right]\left[q^2 - m_{vj}^2 + i\epsilon\right]\left[(k-q)^2 - m_{pj}^2 + i\epsilon\right]}$$

$$\Gamma_{N^* \to KH^*} = \frac{1}{32\pi^2} \frac{|\,\vec{p}\,|\,(4M_{H^*}M_{N^*})}{M_{N^*}^2} \frac{1}{2S_{N^*}+1} \int d\Omega \sum_{m_{N^*}, m_{H^*}} |t_{N^* \to KH^*}|^2$$

Decay of N*(1895) to light hyperons

Decay process	Partial width (MeV)
$N_1^{*+} \to K^+\Lambda_1^*$	10.4 ± 1.3
$N_1^{*+} \to K^+\Lambda_2^*$	6.4 ± 0.8
$N_1^{*+} \to K^+\Sigma^{*0}$	3.8 ± 0.5
$N_2^{*+} \to K^+\Lambda_1^*$	1.9 ± 0.1
$N_2^{*+} \to K^+\Lambda_2^*$	1.1 ± 0.2
$N_2^{*+} \to K^+\Sigma^{*0}$	4.1 ± 0.4

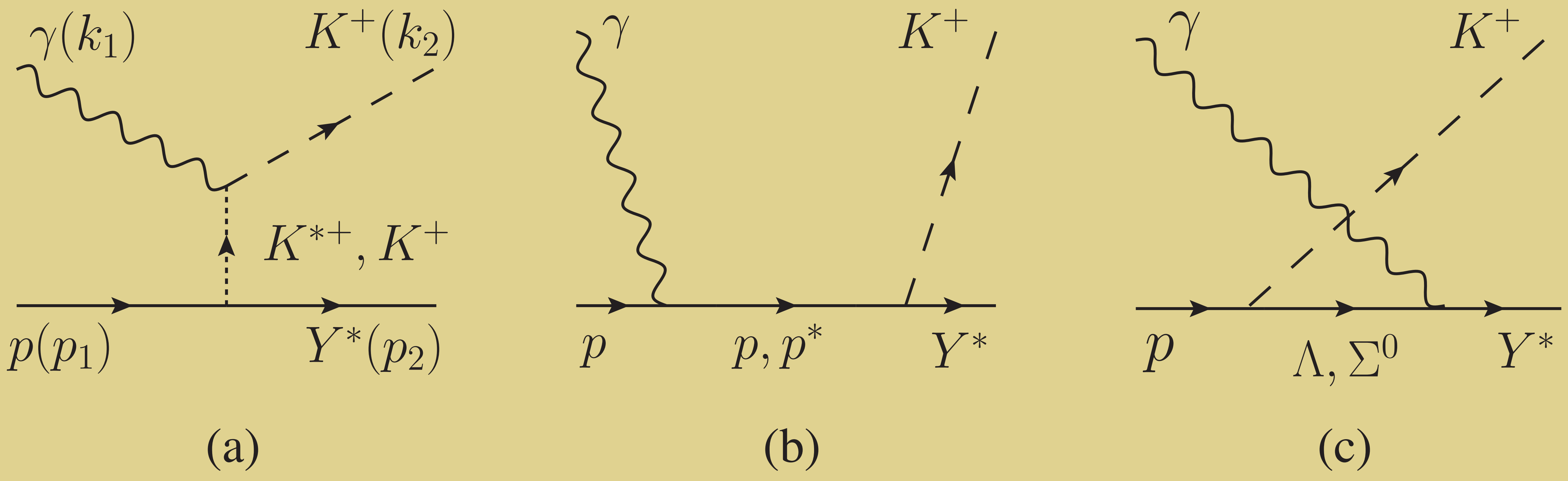
	Branching ratios (%)		Experimental
Decay channel	$N_1^*(1895)$	$N_2^*(1895)$	data [1]
πN	9.4	10.8	2–18
ηN	2.7	18.1	15–40
$K\Lambda$	10.9	19.4	13–23
$K\Sigma$	0.7	26.0	6–20
ρN	5.6	3.5	<18
ωN	25.7	6.2	16–40
ϕN	8.9	1.1	$\cdots$
$K^*\Lambda$	12.1	14.0	4–9
$K^*\Sigma$	6.1	0.3	$\cdots$

From Interference:

$$\Gamma_{N^{*+}(1895)\to K^+\Lambda(1405)} = 5.7 \pm 0.8\ \mathrm{MeV}$$

$$\Gamma_{N^{*+}(1895)\to K^+\Sigma^0(1400)} = 6.3 \pm 0.2\ \mathrm{MeV}$$

Impact on the cross sections of hyperon production



PHYSICAL REVIEW D **103,** 114017 (2021)

Photoproduction of Λ^* and Σ^* resonances with $J^P = 1/2^-$ off the proton

Sang-Ho Kim,[1,*] K. P. Khemchandani,[2,†] A. Martínez Torres,[3,‡] Seung-il Nam,[1,4,§] and Atsushi Hosaka[5,6,∥]

Impact on the cross sections of hyperon production

TABLE IV. Transition magnetic moments related to decays of $\Lambda(1405)$, $\Sigma(1400)$, and $N^*(1895)$. The underlined process means that a superposition of the two poles associated with the decaying hadron has been considered to obtain the decay width.

Decay process	Magnetic moment	Decay process	Magnetic moment
$\Lambda_1(1405) \to \Lambda\gamma$	0.28 ± 0.02	$N_1^*(1895) \to p\gamma$	0.56 ± 0.02
$\Lambda_2(1405) \to \Lambda\gamma$	0.26 ± 0.02	$N_2^*(1895) \to p\gamma$	0.20 ± 0.01
$\underline{\Lambda(1405) \to \Lambda\gamma}$	0.42 ± 0.03	$\underline{N^*(1895) \to p\gamma}$	0.45 ± 0.02
$\Lambda_1(1405) \to \Sigma\gamma$	0.33 ± 0.03	$\Sigma(1400) \to \Lambda\gamma$	0.60 ± 0.03
$\Lambda_2(1405) \to \Sigma\gamma$	0.15 ± 0.04	$\Sigma(1400) \to \Sigma\gamma$	1.28 ± 0.04
$\Lambda(1405) \to \Sigma\gamma$	0.20 ± 0.03		

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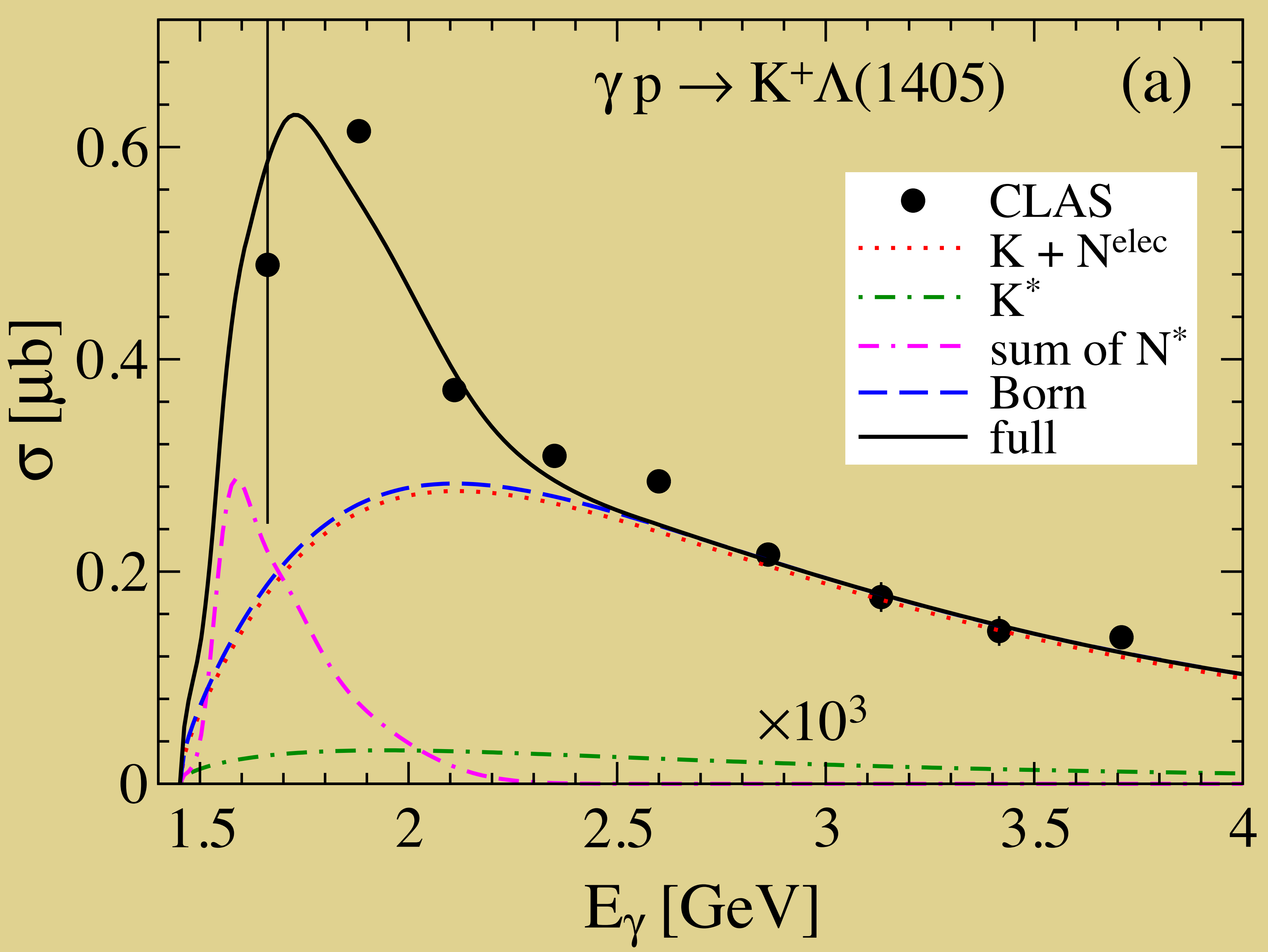

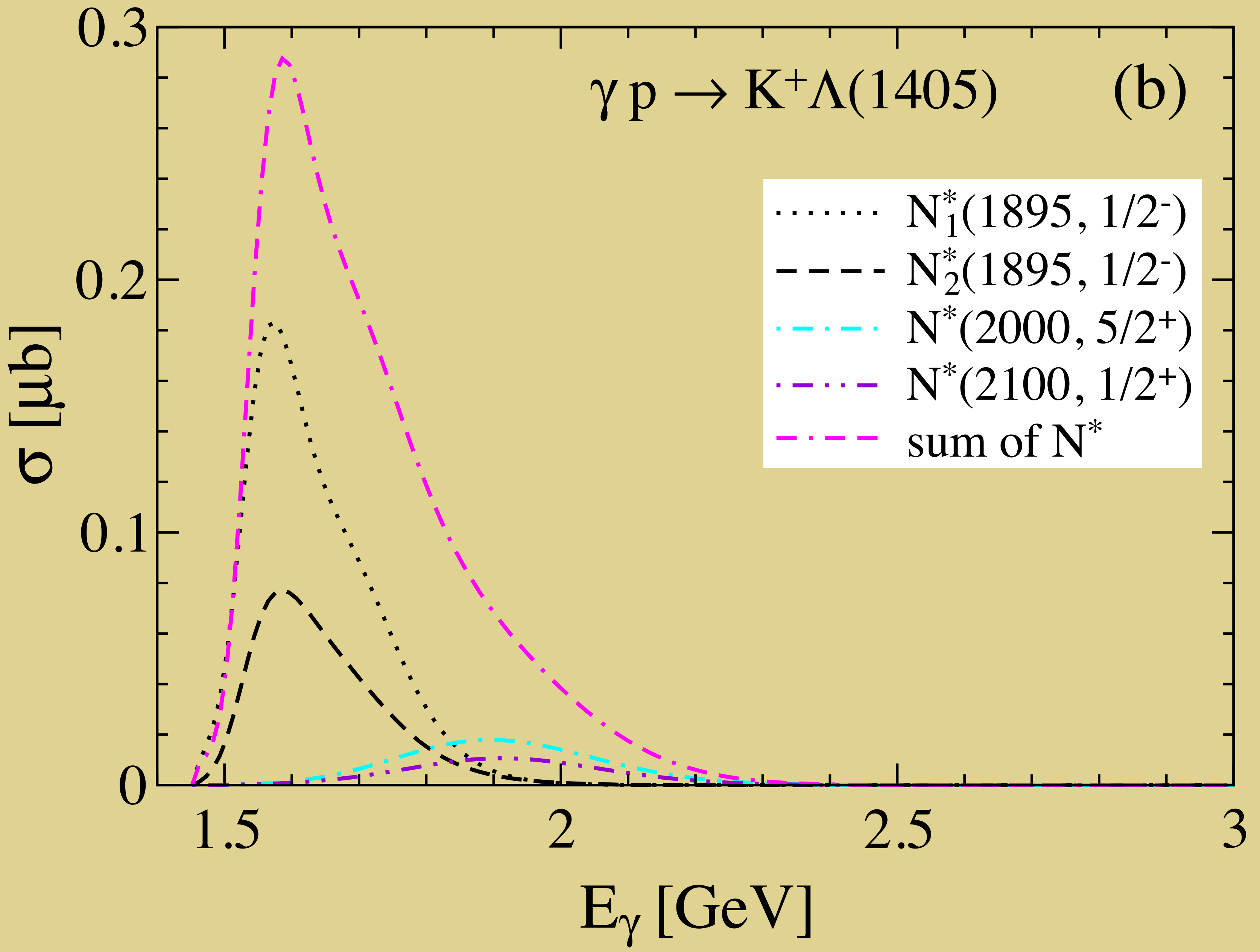

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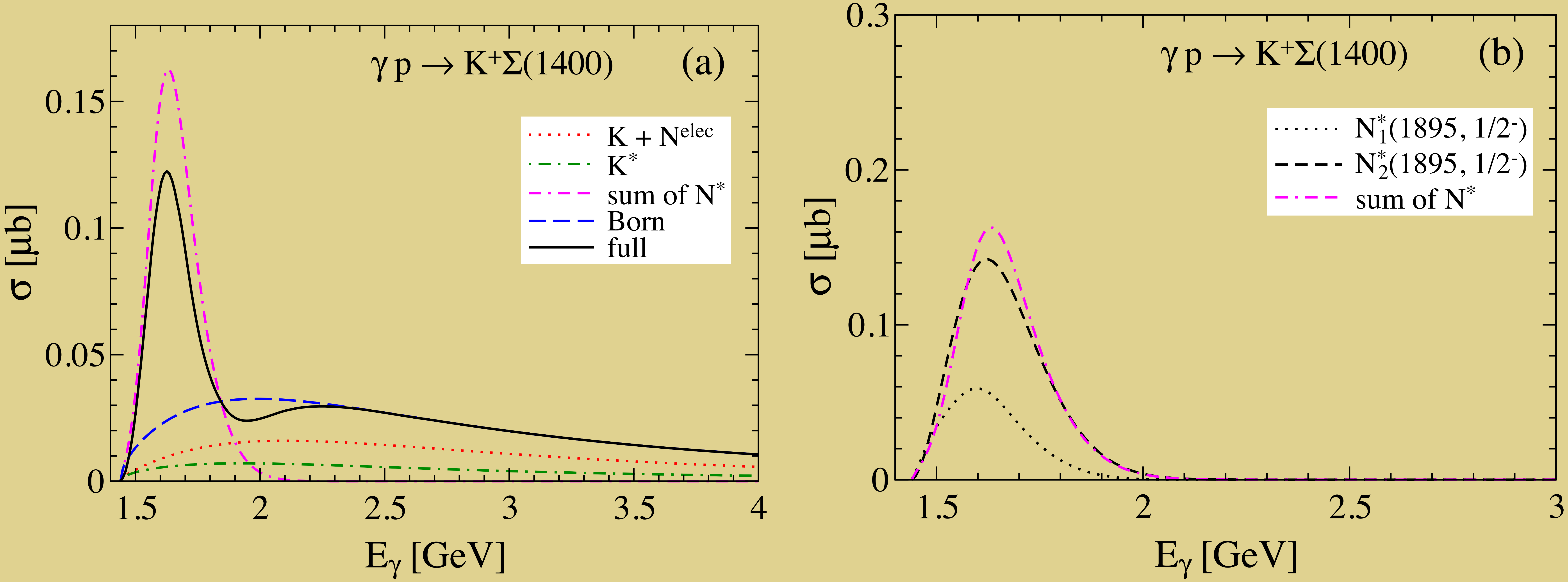

Results on polarization observables also available in our work.

Summary

- Coupled channel hadron dynamics plays an important role in understanding the properties of $N^*(1895)$.
- It's two pole nature describes well the width/branching ratios for the known decay processes.
- The decay width of $N^*(1895)$ to light hyperons is substancial, comparable to decay to πN.
- Such an information is useful in describing the cross sections of processes, like the photoproduction of light hyperons.
- Decay properties of $N^*(1895)$ can be useful in distinguishing it from other neighboring nucleons.

THANK YOU

Collaborators:

Alberto Martínez Torres

Sang-ho Kim

Seung-il Nam

Atsushi Hosaka

Hideko Nagahiro

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