ηn & $K^0\Lambda$ photoproduction off the neutron with nucleon resonances

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Contents based on
- PLB. 786. 756 (2018)
- arXiv: 1810.05056 [hep-ph]

with
- Hyun-Chul Kim (Inha Univ.)
- Jung-Min Suh (Inha Univ.)

Contents

$\gamma n \rightarrow \eta n$

$\gamma n \rightarrow K^0 \Lambda$

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  helicity-dependent cross sections ($\sigma_{3/2}$, $\sigma_{1/2}$)
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Introduction

Nucleon resonances in Particle Data Group (PDG 2018)

❑ A total of 27 N* are listed in PDG 2018.

N(1440)	$1/2^+$	****
N(1520)	$3/2^-$	****
N(1535)	$1/2^-$	****
N(1650)	$1/2^-$	****
N(1675)	$5/2^-$	****
N(1680)	$5/2^+$	****
N(1700)	$3/2^-$	***
N(1710)	$1/2^+$	****
N(1720)	$3/2^+$	****
N(1860)	$5/2^+$	**
N(1875)	$3/2^-$	***
N(1880)	$1/2^+$	***
N(1895)	$1/2^-$	****
N(1900)	$3/2^+$	****
N(1990)	$7/2^+$	**
N(2000)	$5/2^+$	**
N(2040)	$3/2^+$	*
N(2060)	$5/2^-$	***
N(2100)	$1/2^+$	***
N(2120)	$3/2^-$	***
N(2190)	$7/2^-$	****
N(2220)	$9/2^+$	****
N(2250)	$9/2^-$	****
N(2300)	$1/2^+$	**
N(2570)	$5/2^-$	**
N(2600)	$11/2^-$	***
N(2700)	$13/2^+$	**

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- N(1685,1/2$^+$)
  - is firstly predicted by the chiral-quark soliton model in 1997 and listed in PDG.
  - has a narrow width ($\Gamma \simeq 30$MeV) and contains a hidden strangeness.
  - is excluded several years ago since the evidence of its existence is likely to be poor.

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  - is excluded several years ago since the evidence of its existence is likely to be poor.

- However, theoretical interpretations on its existence are still not in consensus.

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❑ Pseudoscalar-Meson photoproduction

- provides useful information for identifying $N(1685, 1/2^+)$, especially ηN & $K\Lambda$ phtoproduction, since their thresholds are below 1685 MeV.

  (ηN_{th} = 1490, $K\Lambda_{th}$ = 1610, [MeV])

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Introduction

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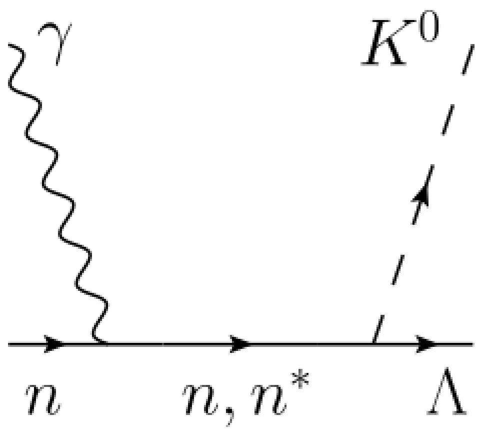
❑ We can include a number of N* in the s-channel diagram.



ηN (threshold from N(1520) downward) | KΛ (threshold from N(1650) downward)

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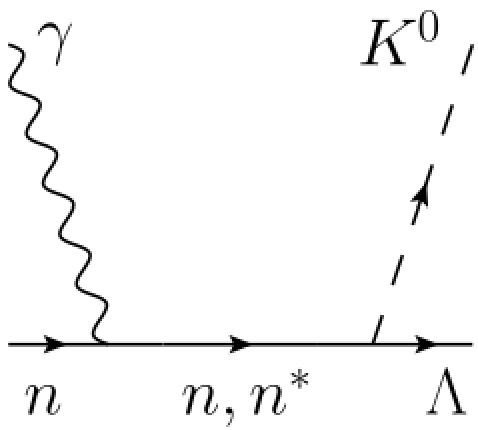

❑ Other possibility for investigating N(1685,1/2⁺) would be πN and πΔ channels.

❑ KΣ channel is not useful since its W_{th} is almost 1685 MeV.

ηN (from N(1520) downward) KΛ (from N(1650) downward)

N(1440)	1/2⁺	****
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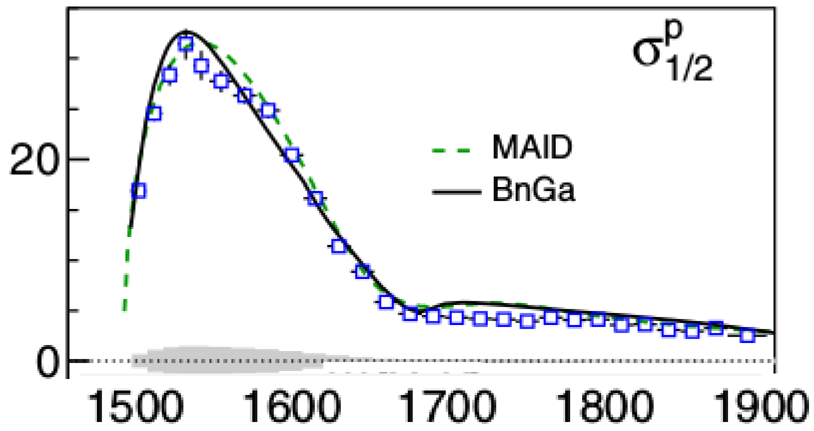
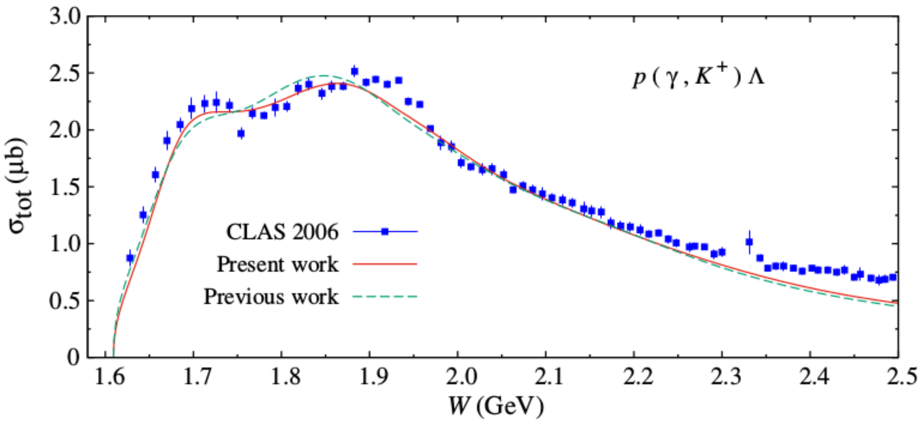
Total cross section

$\gamma\, p \to \eta\, p$



$\gamma\, p \to K^{+}\, \Lambda$



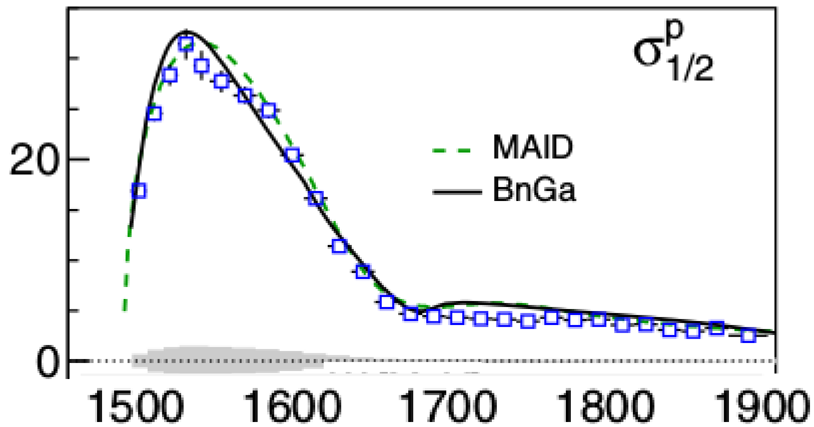
❑ No peak (or structure) near W=1685 MeV for reactions off the proton.

$\gamma\, n \to \eta\, n$

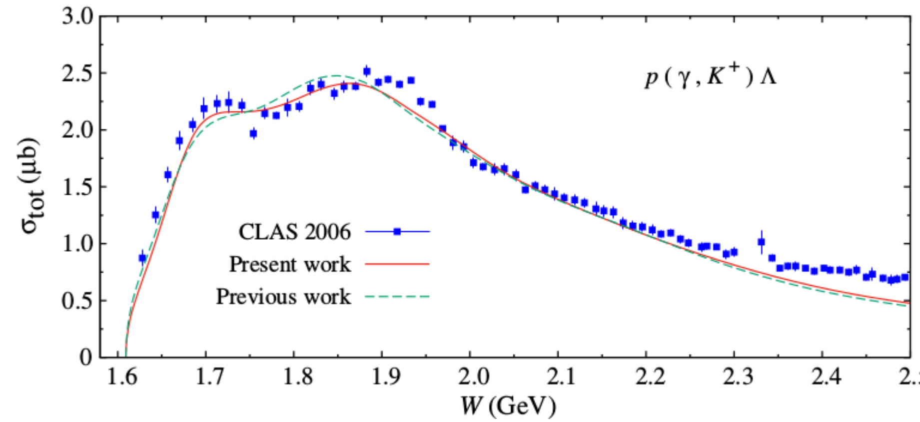
$\gamma\, n \to K^{0}\, \Lambda$ [$\gamma\, d \to K^{0}\, \Lambda$ (p)]

Total cross section

$\gamma\, p \rightarrow \eta\, p$



$\gamma\, p \rightarrow K^{+}\,\Lambda$



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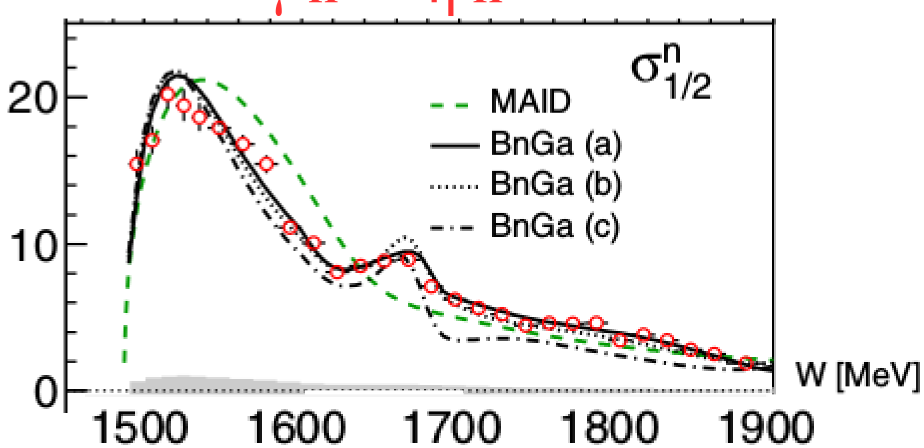
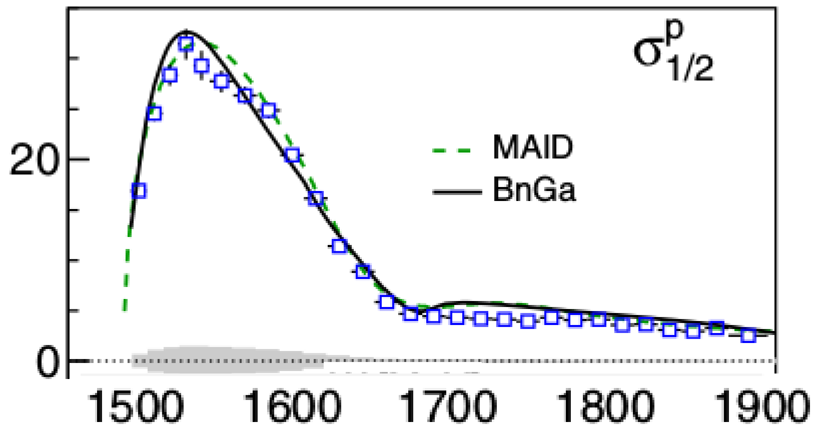


$\gamma\, n \rightarrow K^{0}\,\Lambda$ $[\gamma\, d \rightarrow K^{0}\,\Lambda\,(p)]$

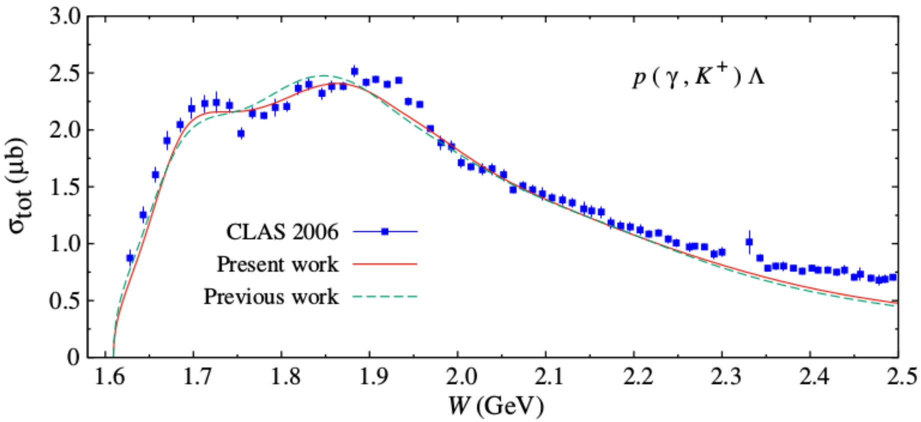
❑ The finding that the narrow bump-like structure is only clearly seen in η photoproduction off the neutron is coined neutron anomaly.

Total cross section

γ p → η p

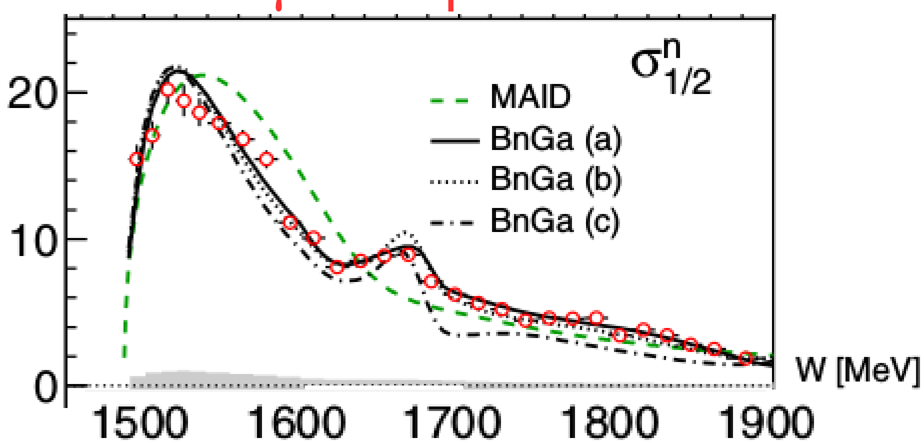


γ p → K⁺ Λ



❑ No peak (or structure) near W=1685 MeV for reactions off the proton.

γ n → η n



γ n → K⁰ Λ [γ d → K⁰ Λ (p)]

first exp.al (CLAS [PRC.96.065201(2017)]) & theoretical studies last year including ours [PLB.786.156(2018)]

❑ The finding that the narrow bump-like structure is only clearly seen in η photoproduction off the neutron is coined neutron anomaly.

Theoretical Framework

- Multi-channel framework (rescattering effect)
  - ▻ ANL-Osaka, Bonn-Gatchina, Giessen, Juelich, Shyam & Scholten & Usov

- Single-channel framework
  - Isobar model (effective hadronic Lagrangians)
    - ▻ Williams-Cotanch-Ji, Mart, Kaon-MAID, Skoupil-Bydzovsky

  - Regge-plus-Resonance model
    - ▻ Ghent group: RPR-2007, RPR-2011

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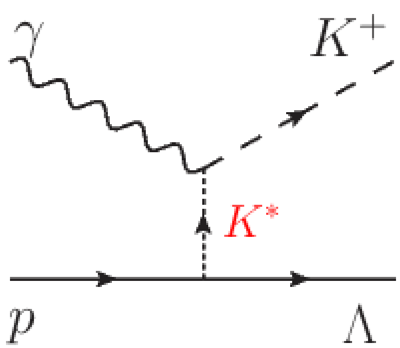
❑ Our approach is similar to the RPR model but avoids a complex fitting procedure. We construct the relation between "the coupling constants" of effective Lagrangians and "the partial decay widths" that can be obtained by PDG or hadron models. Thus model parameters are much reduced.

Regge-plus-Resonance model

❑ preserves unitarity.

Single particle exchange in the t-channel of spin J

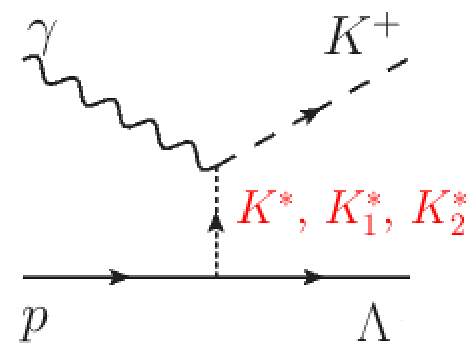


$$\sigma \sim s^{J-1}$$

Froissart bound :

$$\sigma^{\text{Tot}}(s) \leq \text{constant} \times \log^2(s/s_0)$$

Sum up all meson exchanges of various J



$$\sigma \sim s^{\alpha(0)-1}$$

K and K* trajectories are degenerated :

$$\alpha_K = \alpha_K(t) = \frac{0.7}{\text{GeV}^2}(t - M_K^2)$$

$$\alpha_{K^*} = \alpha_{K^*}(t) = \frac{0.83}{\text{GeV}^2} t + 0.25.$$

Regge-plus-Resonance model

Invariant amplitude: M^{Regge} (background) + $M^{\text{Resonance}}$

- ❑ interpolates between the low and high momentum transfer regions.
- ❑ Regge propagators (P^{Regge}) in a gauge invariant manner

$$\mathcal{M}_{t,s}^{\text{Regge}} = [(\mathcal{M}_K + \mathcal{M}_N)(t - M_K^2)P_K^{\text{Regge}} + \mathcal{M}_{K^*}(t - M_{K^*}^2)P_{K^*}^{\text{Regge}}]$$

$$\frac{1}{t-M_K^2} \to P_K^{\text{Regge}} = \left(\frac{s}{s_0}\right)^{\alpha_K} \frac{\pi\alpha_K'}{\sin(\pi\alpha_K)} \left\{ \begin{array}{c} 1 \\ e^{-i\pi\alpha_K} \end{array} \right\} \frac{1}{\Gamma(1+\alpha_K)},$$

$$\frac{1}{t-M_{K^*}^2} \to P_{K^*}^{\text{Regge}} = \left(\frac{s}{s_0}\right)^{\alpha_{K^*}-1} \frac{\pi\alpha_{K^*}'}{\sin(\pi\alpha_{K^*})} \left\{ \begin{array}{c} 1 \\ e^{-i\pi\alpha_{K^*}} \end{array} \right\} \frac{1}{\Gamma(\alpha_{K^*})}$$

Guidal, NPA.627.645(1997)

- ❑ Strong coupling constants
  - ▻ $SU(3)_f$ symmetry : $-4.4 \le g_{K N\Lambda}/4\sqrt{\pi} \le -3.0$
  - ▻ Nijmegen potentials : $-4.9 \le g_{K N\Lambda}/4\sqrt{\pi} \le -3.8$

  are constrained by the high energy region.

Regge-plus-Resonance model

Invariant amplitude: M^{Regge} (background) + $M^{\text{Resonance}}$

- PDG & missing resonances
- Hadronic form factors: monopole, dipole, Gaussian
- Rarita-Schwinger propagators ($S(p)$) for spin-3/2, -5/2, -7/2 N*'s

[PRD.60.61(1941), Behrends,PR.106.345(1957), Rushbrooke,PR.143.1345(1966), Chang,PR.161.1308(1967)]

$$(i\partial\!\!\!/ - M)R_{\alpha_1\alpha_2\ldots\alpha_{n-1}} = 0 \qquad \gamma^{\alpha_1}R_{\alpha_1\alpha_2\ldots\alpha_s} = 0, \qquad \partial^{\alpha_1}R_{\alpha_1\alpha_2\ldots\alpha_s} = 0,$$
$$g^{\alpha_1\alpha_2}R_{\alpha_1\alpha_2\ldots\alpha_s} = 0.$$

$$S(p) = \frac{i}{p\!\!\!/ - M}\Delta(J) \qquad \sum_{\text{spins}} R_{\alpha_1\ldots}\bar{R}^{\beta_1\cdots} = \Lambda_\pm \Delta^{\beta_1\cdots}_{\alpha_1\cdots}$$

($\Delta_\alpha{}^\beta$: spin projection operator)

$$\Delta^\beta_\alpha(\tfrac{3}{2}) = -g^\beta_\alpha + \frac{1}{3}\gamma_\alpha\gamma^\beta + \frac{1}{3M}\left(\gamma_\alpha p^\beta - p_\alpha\gamma^\beta\right) + \frac{2}{3M^2}p_\alpha p^\beta$$

$$\Delta^{\beta_1\beta_2}_{\alpha_1\alpha_2}(\tfrac{5}{2}) = \frac{1}{2}\left(\theta^{\beta_1}_{\alpha_1}\theta^{\beta_2}_{\alpha_2} + \theta^{\beta_2}_{\alpha_1}\theta^{\beta_1}_{\alpha_2}\right) - \frac{1}{5}\theta_{\alpha_1\alpha_2}\theta^{\beta_1\beta_2} - \frac{1}{10}\left(\Gamma_{\alpha_1}\Gamma^{\beta_1}\theta^{\beta_2}_{\alpha_2} + \Gamma_{\alpha_1}\Gamma^{\beta_2}\theta^{\beta_1}_{\alpha_2} + \Gamma_{\alpha_2}\Gamma^{\beta_1}\theta^{\beta_2}_{\alpha_1} + \Gamma_{\alpha_2}\Gamma^{\beta_2}\theta^{\beta_1}_{\alpha_1}\right)$$

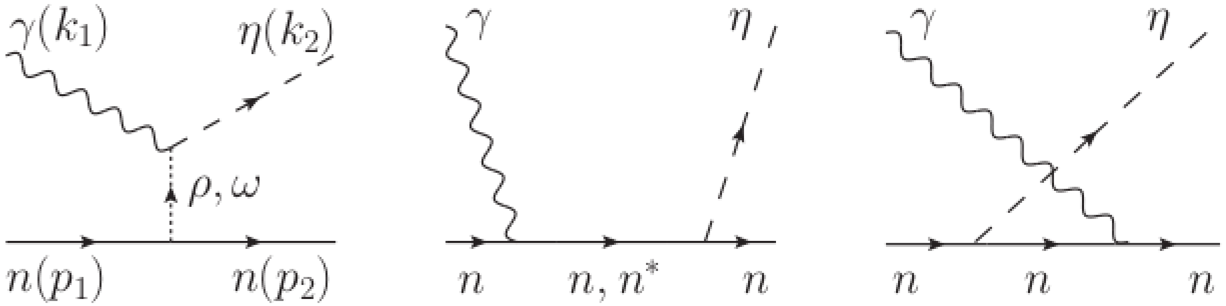
$$\Delta^{\beta_1\beta_2\beta_3}_{\alpha_1\alpha_2\alpha_3}(\tfrac{7}{2}) =$$

Oh,JKPS.59.3344(2011)

$$\theta_{\alpha\beta} = -\left(g_{\alpha\beta} - \frac{1}{M^2}p_\alpha p_\beta\right) \qquad \Gamma^\alpha = i\left(\gamma^\alpha - \frac{1}{M^2}p\!\!\!/ p^\alpha\right)$$

Tree-diagrams

$\gamma\, n \rightarrow \eta\, n$



t channel s channel u channel

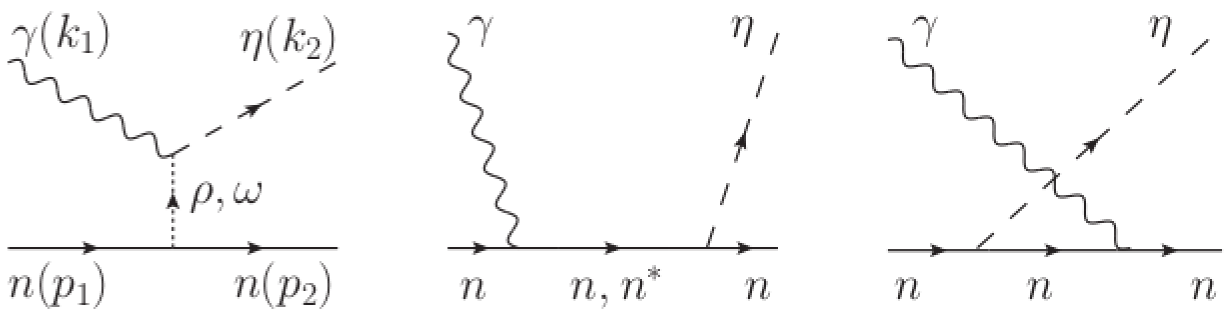
$\gamma\, n \rightarrow K^0 \Lambda$

Theoretical Framework

Tree-diagrams

The structures of interaction Lagrangians are the same.

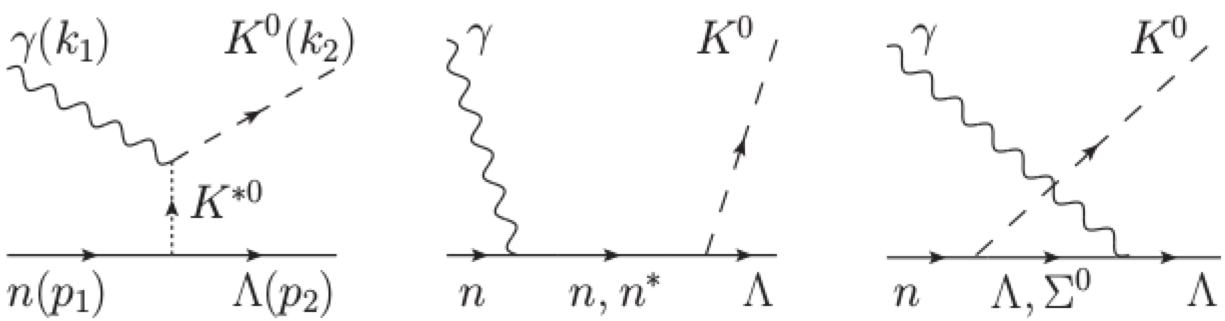
$\gamma\, n \rightarrow \eta\, n$



t channel   s channel   u channel

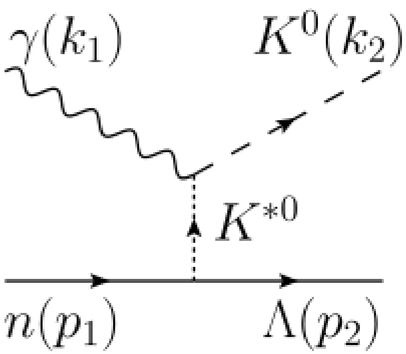
Change particles & couplings.

$\gamma\, n \rightarrow K^0 \Lambda$

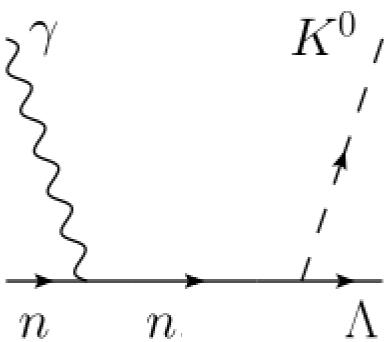


- ❑ K exchange is excluded because of charge.
- ❑ Other higher strange mesons are excluded because of their small photocouplings, e.g., $Br(K^*(1410) \rightarrow K_0\gamma) < 2.2 \times 10^{-4}$.

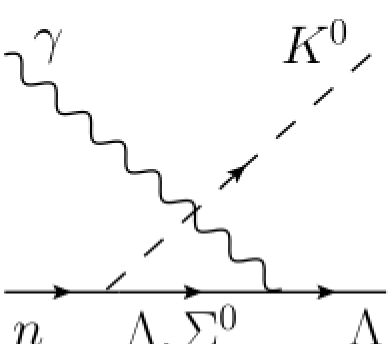
1. Background contributions



t channel



s channel



u channel

Effective hadronic Lagrangians

Electromagnetic interactions

$$\mathcal{L}_{\gamma KK^*} = g^0_{\gamma KK^*}\epsilon^{\mu\nu\alpha\beta}\partial_\mu A_\nu(\partial_\alpha \bar{K}^{*0}_\beta K^0 + \bar{K}^0\partial_\alpha K^{*0}_\beta),$$

$$\mathcal{L}_{\gamma NN} = -\bar{N}\left[e_N\gamma_\mu - \frac{e\kappa_N}{2M_N}\sigma_{\mu\nu}\partial^\nu\right]A^\mu N,$$

$$\mathcal{L}_{\gamma\Lambda\Lambda} = \frac{e\kappa_\Lambda}{2M_N}\bar{\Lambda}\sigma_{\mu\nu}\partial^\nu A^\mu\Lambda,$$

$$\mathcal{L}_{\gamma\Sigma\Lambda} = \frac{e\mu_{\Sigma\Lambda}}{2M_N}\bar{\Sigma}^0\sigma_{\mu\nu}\partial^\nu A^\mu\Lambda + \text{H.c.},$$

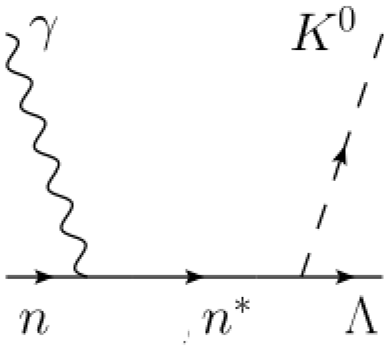
Strong interactions

$$\mathcal{L}_{K^*N\Lambda} = -g_{K^*N\Lambda}\bar{N}\left[\gamma_\mu\Lambda - \frac{\kappa_{K^*N\Lambda}}{M_N+M_\Lambda}\sigma_{\mu\nu}\Lambda\partial^\nu\right]K^{*\mu} + \text{H.c.},$$

$$\mathcal{L}_{KNY} = \frac{g_{KNY}}{M_N+M_Y}\bar{N}\gamma_\mu\gamma_5 Y\partial^\mu K + \text{H.c.},$$

form factor: $F_B(q^2) = \left[\frac{\Lambda_B^4}{\Lambda_B^4 + (q^2 - M_B^2)^2}\right]^2$

2. Resonance contributions



$$\Gamma^{\pm} = \begin{pmatrix} \gamma_5 \\ I_{4\times4} \end{pmatrix}, \quad \Gamma^{\pm}_{\nu} = \begin{pmatrix} \gamma_\nu \gamma_5 \\ \gamma_\nu \end{pmatrix}$$

Gaussian form factor:

$$F_{N^*}(q_s^2) = \exp\left\{ -\frac{(q_s^2 - M_{N^*}^2)^2}{\Lambda_{N^*}^4} \right\}$$

$\Lambda_B = \Lambda_{N^*} = 0.9$ GeV

Effective hadronic Lagrangians

Electromagnetic interactions

$$\mathcal{L}^{1/2^\pm}_{\gamma N N^*} = \frac{e h_1}{2M_N} \bar{N} \Gamma^{\mp} \sigma_{\mu\nu} \partial^\nu A^\mu N^* + \text{H.c.},$$

$$\mathcal{L}^{3/2^\pm}_{\gamma N N^*} = -ie \left[\frac{h_1}{2M_N} \bar{N} \Gamma^{\pm}_{\nu} - \frac{i h_2}{(2M_N)^2} \partial_\nu \bar{N} \Gamma^{\pm} \right] F^{\mu\nu} N^*_\mu + \text{H.c.},$$

$$\mathcal{L}^{5/2^\pm}_{\gamma N N^*} = e \left[\frac{h_1}{(2M_N)^2} \bar{N} \Gamma^{\mp}_{\nu} - \frac{i h_2}{(2M_N)^3} \partial_\nu \bar{N} \Gamma^{\mp} \right] \partial^\alpha F^{\mu\nu} N^*_{\mu\alpha} + \text{H.c.},$$

$$\mathcal{L}^{7/2^\pm}_{\gamma N N^*} = ie \left[\frac{h_1}{(2M_N)^3} \bar{N} \Gamma^{\pm}_{\nu} - \frac{i h_2}{(2M_N)^4} \partial_\nu \bar{N} \Gamma^{\pm} \right] \partial^\alpha \partial^\beta F^{\mu\nu} N^*_{\mu\alpha\beta} + \text{H.c.}$$

Strong interactions

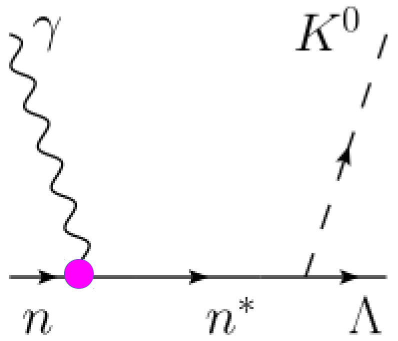
$$\mathcal{L}^{1/2^\pm}_{K\Lambda N^*} = -i g_{K\Lambda N^*} \bar{K} \bar{\Lambda} \Gamma^{\pm} N^* + \text{H.c.},$$

$$\mathcal{L}^{3/2^\pm}_{K\Lambda N^*} = \frac{g_{K\Lambda N^*}}{M_K} \partial^\mu \bar{K} \bar{\Lambda} \Gamma^{\mp} N^*_\mu + \text{H.c.},$$

$$\mathcal{L}^{5/2^\pm}_{K\Lambda N^*} = \frac{i g_{K\Lambda N^*}}{M_K^2} \partial^\mu \partial^\nu \bar{K} \bar{\Lambda} \Gamma^{\pm} N^*_{\mu\nu} + \text{H.c.},$$

$$\mathcal{L}^{7/2^\pm}_{K\Lambda N^*} = -\frac{g_{K\Lambda N^*}}{M_K^3} \partial^\mu \partial^\nu \partial^\alpha \bar{K} \bar{\Lambda} \Gamma^{\mp} N^*_{\mu\nu\alpha} + \text{H.c.}.$$

2. Resonance contributions



Oh,Ko,Nakayama, PRC.77.045204(2008)

"Transition magnetic moments" h_1, h_2 &
"Helicity amplitudes" A_λ

$$A_\lambda(j) = \frac{1}{\sqrt{8M_N M_R k_\gamma}} \frac{2j+1}{4\pi} \times \int d\cos\theta d\phi e^{-i(m-\lambda)\phi} d^j_{\lambda m}(\theta) \langle \mathbf{k}_\gamma, \lambda_\gamma, \lambda_N \mid -i\mathcal{M} \mid jm \rangle$$

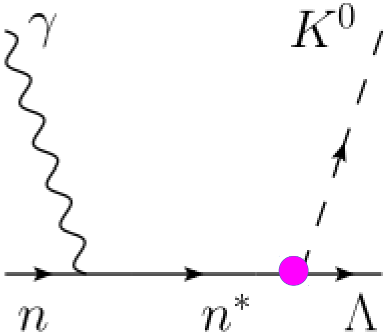
$$A_{1/2}(\tfrac{1}{2}^\pm) = \mp \frac{ef_1}{2M_N}\sqrt{\frac{k_\gamma M_R}{M_N}}$$

$$\begin{cases} A_{1/2}(\tfrac{3}{2}^\pm) = \mp \frac{e\sqrt{6}}{12}\sqrt{\frac{k_\gamma}{M_N M_R}}\left[f_1 + \frac{f_2}{4M_N^2}M_R(M_R \mp M_N)\right] \\ A_{3/2}(\tfrac{3}{2}^\pm) = \mp \frac{e\sqrt{2}}{4M_N}\sqrt{\frac{k_\gamma M_R}{M_N}}\left[f_1 \mp \frac{f_2}{4M_N}(M_R \mp M_N)\right] \end{cases}$$

$$\begin{cases} A_{1/2}(\tfrac{5}{2}^\pm) = \pm \frac{e}{4\sqrt{10}}\frac{k_\gamma}{M_N}\sqrt{\frac{k_\gamma}{M_N M_R}}\left[f_1 + \frac{f_2}{4M_N^2}M_R(M_R \pm M_N)\right] \\ A_{3/2}(\tfrac{5}{2}^\pm) = \pm \frac{e}{4\sqrt{5}}\frac{k_\gamma}{M_N^2}\sqrt{\frac{k_\gamma M_R}{M_N}}\left[f_1 \pm \frac{f_2}{4M_N}(M_R \pm M_N)\right] \end{cases}$$

A_λ can be taken from PDG.

2. Resonance contributions



$$m_l + m_f = m_j$$

S.H.Kim, Oh, in preparation

$$\Gamma(N^* \to K\Lambda) = \sum_{\ell} |G(\ell)|^2$$

$$\Gamma(\tfrac{1}{2}^{\pm} \to K\Lambda^*) = \frac{1}{4\pi}\frac{q}{M_{N^*}} g^2_{K\Lambda^* N^*}(E_{\Lambda^*} \pm M_{\Lambda^*}),$$

$$\Gamma(\tfrac{3}{2}^{\pm} \to K\Lambda^*) = \frac{1}{12\pi}\frac{q^3}{M_{N^*}}\frac{g^2_{K\Lambda^* N^*}}{M_K^2}(E_{\Lambda^*} \mp M_{\Lambda^*}),$$

$$\Gamma(\tfrac{5}{2}^{\pm} \to K\Lambda^*) = \frac{1}{30\pi}\frac{q^5}{M_{N^*}}\frac{g^2_{K\Lambda^* N^*}}{M_K^4}(E_{\Lambda^*} \pm M_{\Lambda^*}),$$

"Strong coupling constants" $g_{K\Lambda N^*}$ &
"Decay amplitudes" $G(\ell)$

$$\langle K(\vec{q})\,\Lambda(-\vec{q}, m_f)| - i\mathcal{H}_{\rm int}|N^*(\mathbf{0}, m_j)\rangle$$
$$= 4\pi M_{N^*}\sqrt{\frac{2}{|\vec{q}|}}\sum_{\ell, m_\ell}\langle \ell\, m_\ell\, \tfrac{1}{2}\, m_f | j\, m_j\rangle Y_{\ell, m_\ell}(\hat{q}) G(\ell)$$

$$G\left(\frac{1+P}{2}\right) = \mp\sqrt{\frac{|\vec{q}|(E_\Lambda \mp M_\Lambda)}{4\pi M_{N^*}}}\, g_{K\Lambda N^*} \quad \text{for} \quad N^*(1/2^P),$$

$$G\left(\frac{3-P}{2}\right) = \pm\sqrt{\frac{|\vec{q}|^3(E_\Lambda \pm M_\Lambda)}{12\pi M_{N^*}}}\, \frac{g_{K\Lambda N^*}}{M_K} \quad \text{for} \quad N^*(3/2^P),$$

$$G\left(\frac{5+P}{2}\right) = \mp\sqrt{\frac{|\vec{q}|^5(E_\Lambda \mp M_\Lambda)}{30\pi M_{N^*}}}\, \frac{g_{K\Lambda N^*}}{M_K^2} \quad \text{for} \quad N^*(5/2^P),$$

$$G\left(\frac{7-P}{2}\right) = \pm\sqrt{\frac{|\vec{q}|^7(E_\Lambda \pm M_\Lambda)}{70\pi M_{N^*}}}\, \frac{g_{K\Lambda N^*}}{M_K^3} \quad \text{for} \quad N^*(7/2^P),$$

$G(\ell)$ can be taken from quark model predictions.

constituent quark model
Capstick,PRD.58.074011(1998)

EM ($\gamma n n^*$) interactions

"Transition magnetic moments" h_1, h_2 &
"Helicity amplitudes" A_λ

$\gamma\, n \rightarrow \eta n$

$\gamma\, n \rightarrow K^0 \Lambda$

State	Rating	Width [MeV]	$A_{1/2}$	$A_{3/2}$	h_1	h_2
$N(1520, 3/2^-)$	****	100-120 (110)	≈ -50	≈ -115	-0.77	-0.62
$N(1535, 1/2^-)$	****	125-175 (140)	≈ -75	$\cdots$	-0.53	$\cdots$
$N(1650, 1/2^-)$	****	100-150 (125)	≈ -10	$\cdots$	0.063	$\cdots$
$N(1675, 5/2^-)$	****	130-160 (145)	-60 ± 5	-85 ± 10	4.88	5.45
$N(1680, 5/2^+)$	****	100-135 (120)	≈ 30	≈ -35	$\cdots$	$\cdots$
$N(1700, 3/2^-)$	***	100-300 (200)	25 ± 10	-32 ± 18	-1.43	1.64
$N(1710, 1/2^+)$	****	80-200 (140)	-40 ± 20	$\cdots$	0.24	$\cdots$
$N(1720, 3/2^+)$	****	150-400 (250)	-80 ± 50	-140 ± 65	1.50	1.61
$N(1860, 5/2^+)$	**	300	21 ± 13	34 ± 17	0.28	1.09
$N(1875, 3/2^-)$	***	120-250 (200)	10 ± 6	-20 ± 15	-0.55	0.54
$N(1880, 1/2^+)$	***	200-400 (300)	-60 ± 50	$\cdots$	0.30	$\cdots$
$N(1895, 1/2^-)$	****	80-200 (120)	13 ± 6	$\cdots$	0.067	$\cdots$
$N(1900, 3/2^+)$	****	100-320 (200)	0 ± 30	-60 ± 45	0.29	-0.56
$N(2000, 5/2^+)$	**	300	-18 ± 12	-35 ± 20	-0.47	-0.56
$N(2120, 3/2^-)$	***	260-360 (300)	110 ± 45	40 ± 30	-1.71	2.41
$N(1685, 1/2^+)$		30			-0.315 [41]	

△ 2018 edition of PDG

❑ A_λ is taken from PDG.

Strong interactions

"Strong coupling constants" $g_{K\Lambda N^*}$ &
"Decay amplitudes" $G(\ell)$

$\gamma\, n \to \eta n$

State	$G(\ell)$	$g_{\eta N N^*}$	$\Gamma_{N^* \to \eta N}/\Gamma_{N^*}[\%]$	$\lvert g_{\eta N N^*}\rvert$	$g_{\eta N N^*}$(final)
$N(1520, 3/2^-)$	$0.4^{+2.9}_{-0.4}$	-8.30	$0.07 - 0.09$	$5.23 - 6.49$	-5.23
$N(1535, 1/2^-)$	8.1 ± 0.8	2.05	$30 - 55$	$1.58 - 2.14$	2.10
$N(1650, 1/2^-)$	-2.4 ± 1.6	-0.43	$15 - 35$	$0.76 - 1.16$	-0.80
$N(1675, 5/2^-)$	-2.5 ± 0.2	-2.50	< 1	< 0.90	-0.90
$N(1680, 5/2^+)$	0.6 ± 0.1	-2.98	< 1	< 4.07	-2.47
$N(1700, 3/2^-)$	-0.2 ± 0.1	0.38	seen		0.38
$N(1710, 1/2^+)$	5.7 ± 0.3	-4.23	$10 - 50$	$2.93 - 6.55$	-4.00
$N(1720, 3/2^+)$	5.7 ± 0.3	2.08	$1 - 5$	$0.43 - 4.50$	1.00
$N(1860, 5/2^+)$	1.9 ± 0.8	-2.84	$2 - 6$	$2.47 - 4.27$	-2.47
$N(1875, 3/2^-)$	4.0 ± 0.2	-3.58	< 1	< 0.89	-0.80
$N(1880, 1/2^+)$			$5 - 55$	$2.02 - 6.69$	2.00
$N(1895, 1/2^-)$			$15 - 40$	$0.60 - 0.99$	0.60
$N(1900, 3/2^+)$			$2 - 14$	$0.33 - 0.87$	0.33
$N(2000, 5/2^+)$	1.9 ± 0.8	-1.57	< 4	< 0.90	-0.50
$N(2120, 3/2^-)$	4.0 ± 0.2	-1.91			-1.91
$N(1685, 1/2^+)$					1.4

- ❑ $G(\ell)$ is taken from quark model predictions [Capstick,PRD.58.074011(1998)].
- ❑ $Br(N^* \to \eta n)$ is taken from PDG.

Strong interactions

"Strong coupling constants" $g_{K\Lambda N^*}$ &
"Decay amplitudes" $G(\ell)$

$\gamma\, n \rightarrow K^0 \Lambda$

State	$G(\ell)$	$g_{K\Lambda N^*}$	$\Gamma_{N^*\to K\Lambda}/\Gamma_{N^*}$ [%]	$\lvert g_{K\Lambda N^*}\rvert$	$g_{K\Lambda N^*}$ (final)
$N(1650, 1/2^-)$	-3.3 ± 1.0	-0.78	$5-15$	$0.59-1.02$	-0.78
$N(1675, 5/2^-)$	0.4 ± 0.3	1.23			1.23
$N(1680, 5/2^+)$	$\simeq 0.1 \pm 0.1$	-2.84			-2.84
$N(1700, 3/2^-)$	-0.4 ± 0.3	2.34			2.34
$N(1710, 1/2^+)$	4.7 ± 3.7	-7.49	$5-25$	$4.2-9.4$	-4.2
$N(1720, 3/2^+)$	-3.2 ± 1.8	-1.80	$4-5$	$1.8-2.0$	-1.1
$N(1860, 5/2^+)$	-0.5 ± 0.3	1.40	seen		1.40
$N(1875, 3/2^-)$	$\simeq 1.7 \pm 1.0$	-2.47	seen		-2.47
$N(1880, 1/2^+)$			$12-28$	$4.5-6.4$	3.0
$N(1895, 1/2^-)$	2.3 ± 2.7	0.34	$13-23$	$0.58-0.77$	0.34
$N(1900, 3/2^+)$			$2-20$	$0.53-1.7$	0.6
$N(1990, 7/2^+)$	$\simeq 1.5 \pm 2.4$	0.61			0.61
$N(2000, 5/2^+)$	-0.5 ± 0.3	0.61			0.61
$N(2060, 5/2^-)$	$\simeq -2.2 \pm 1.0$	-0.52	seen		-0.52
$N(2120, 3/2^-)$	$\simeq 1.7 \pm 1.0$	-1.05			-1.05
$N(2190, 7/2^-)$	$\simeq -1.1$	0.67			0.67
$N(1685, 1/2^+)$					-0.9

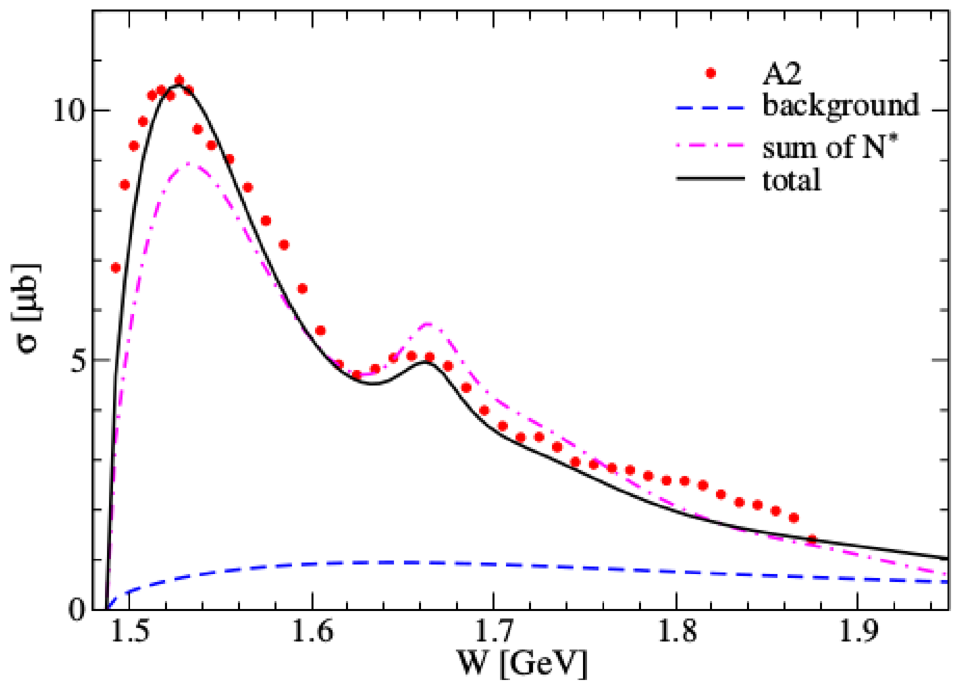
- ❑ $G(\ell)$ is taken from quark model predictions [Capstick,PRD.58.074011(1998)].
- ❑ $Br(N^* \rightarrow K\Lambda)$ is taken from PDG.

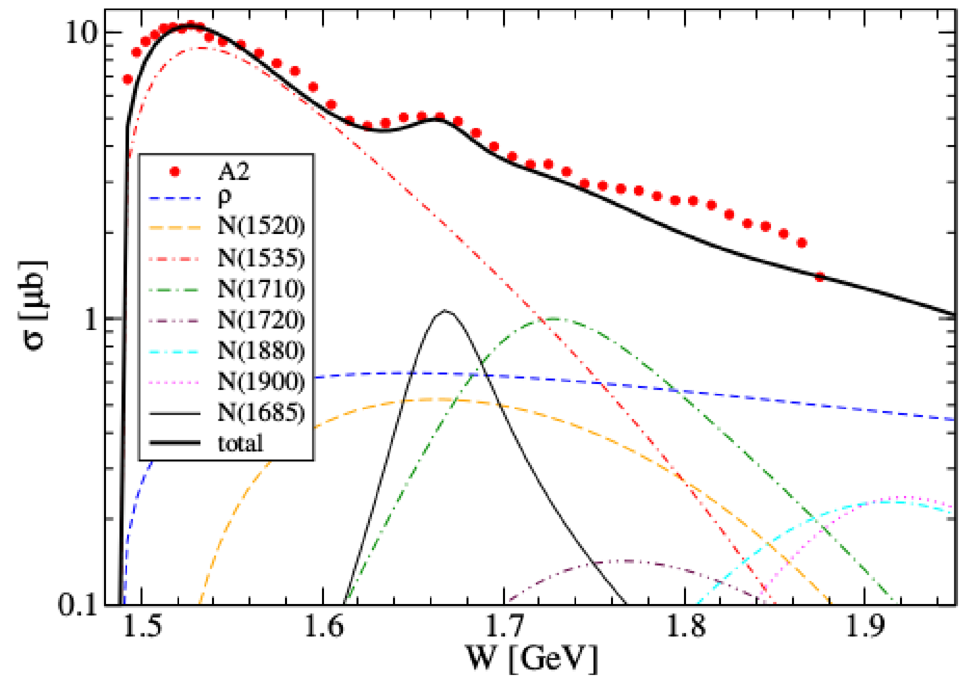
Results

$\gamma\, n \to \eta n$

Total Cross Section

A2 [PRC.90.015205(2014)]

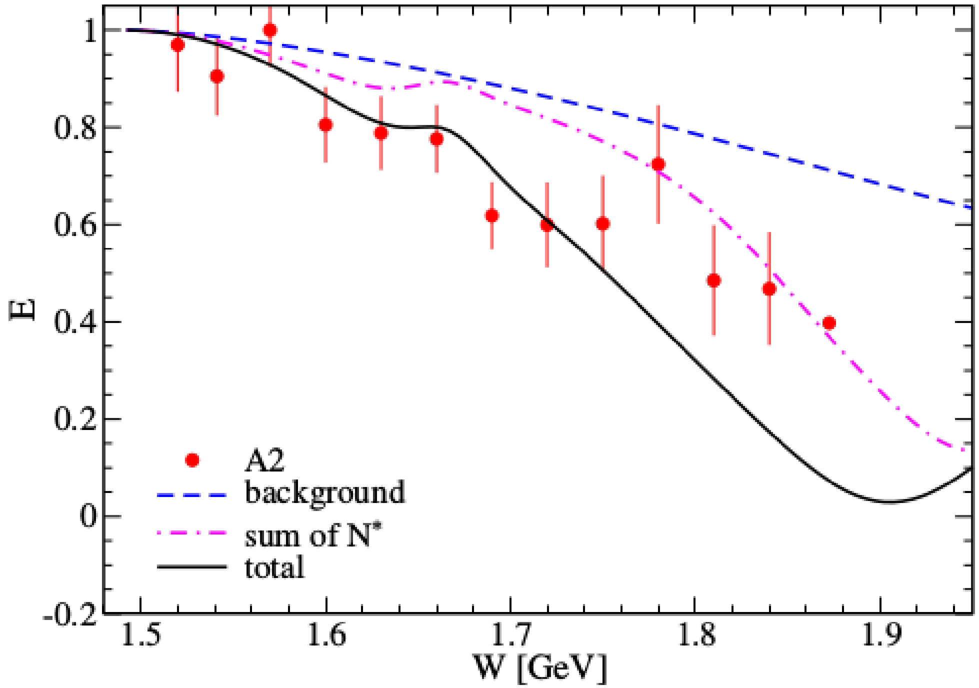




- Background contributions reach only the level of 30% compared to the total result at high energies.
- Among a total of 16 N*s, the A2 data is reproduced mainly by the predominant N(1535,1/2⁻), and N(1685,1/2⁺) and N(1710,1/2⁺).

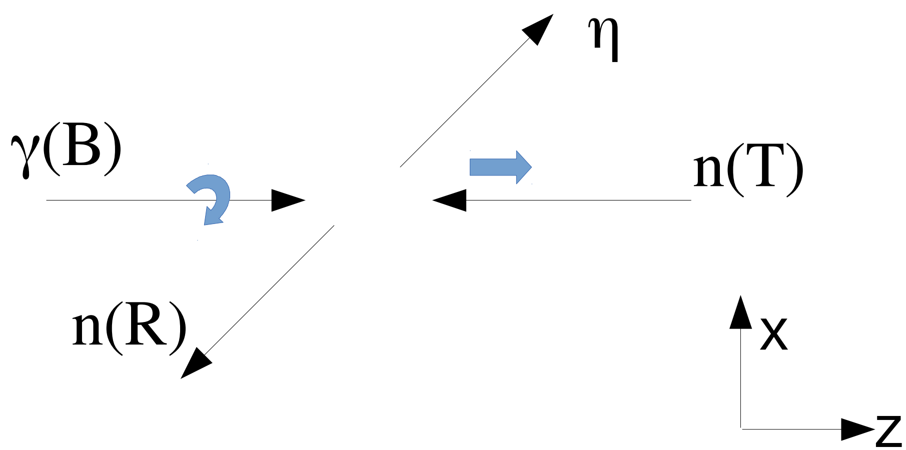
$\gamma\, n \rightarrow \eta n$ Beam-Target Asymmetry

A2
[PRL.117.132502(2016)]



(Beam, Target, Recoil)

$$E = \frac{\sigma^{(r,+z,0)} - \sigma^{(r,-z,0)}}{\sigma^{(r,+z,0)} + \sigma^{(r,-z,0)}} = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$



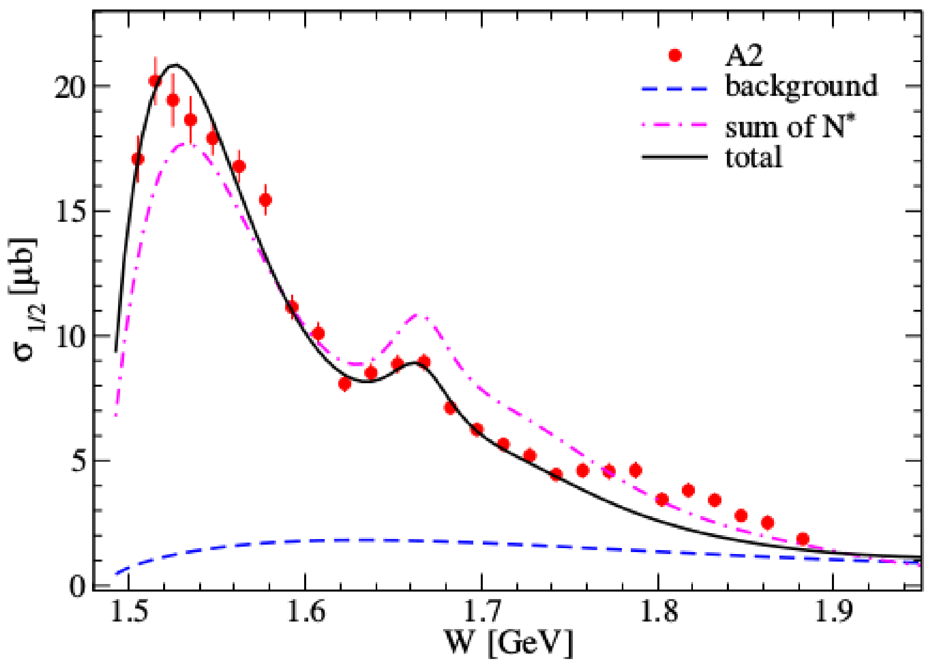
- ❑ Background contribution is not sufficient to describe the A2 data.
- ❑ The inclusion of N^*s pulls down E and it finally reaches zero at W = 1.9 GeV revealing some bump structure near W = 1.68 GeV.

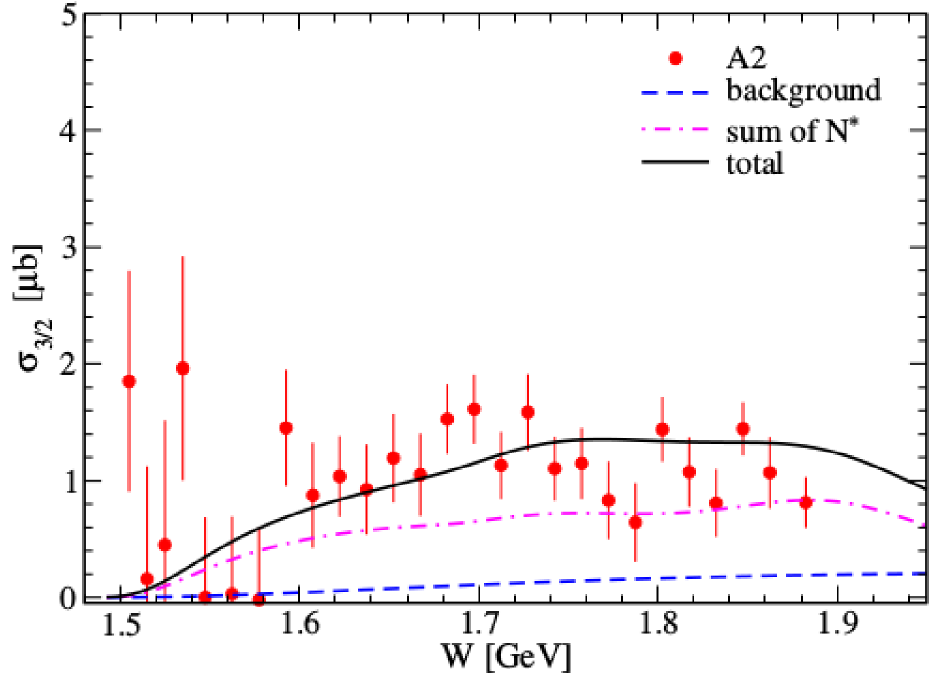
$\gamma\, n \rightarrow \eta n$

Helicity-Dependent Cross Sections

$$\sigma_{1/2} = \sigma_0(1+E), \quad \sigma_{3/2} = \sigma_0(1-E)$$

A2
[PRL.117.132502(2016)]





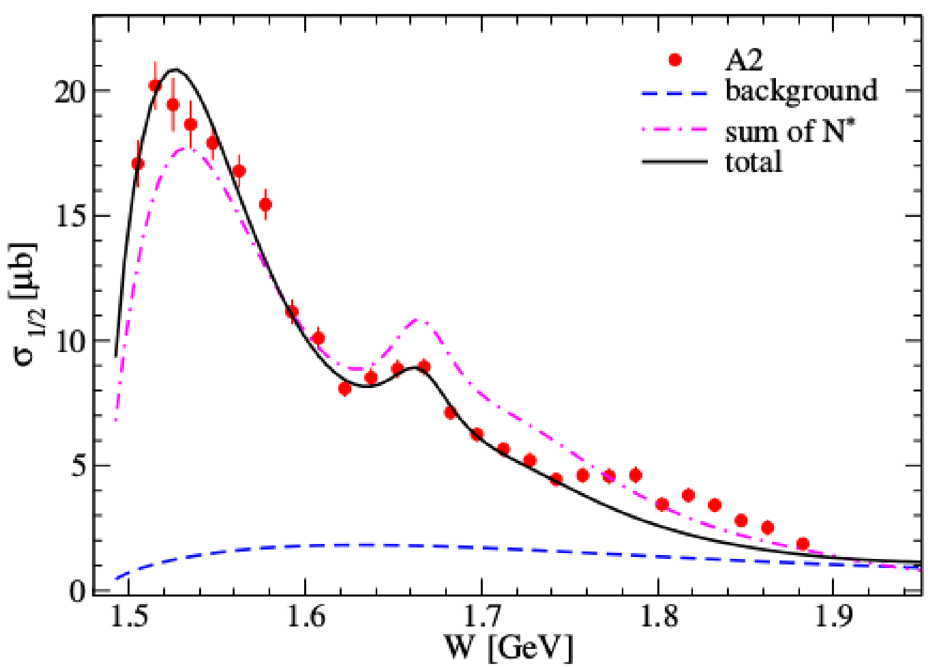
- N*s with spin J = 1/2 (J ≥ 3/2) contribute to $\sigma_{1/2}$ ($\sigma_{3/2}$).
  N*s with spin "J = 1/2" & "J ≥ 3/2" are all separately well described.

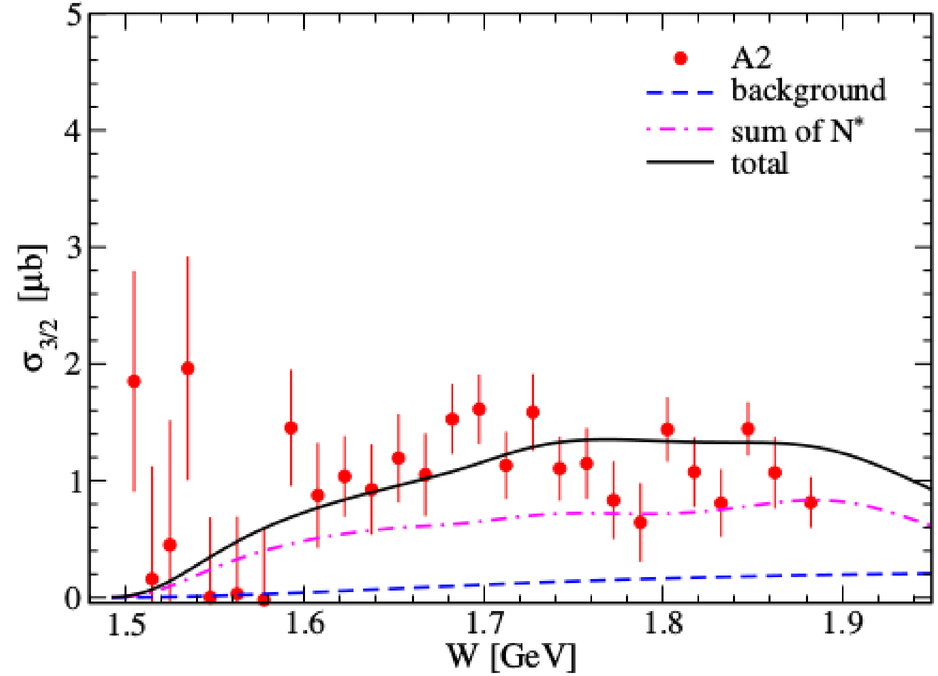
$\gamma\, n \to \eta n$

Helicity-Dependent Cross Sections

$$\sigma_{1/2} = \sigma_0(1+E), \quad \sigma_{3/2} = \sigma_0(1-E)$$

A2
[PRL.117.132502(2016)]





- ❑ N*s with spin J = 1/2 (J ≥ 3/2) contribute to $\sigma_{1/2}$ ($\sigma_{3/2}$).
  N*s with spin "J = 1/2" & "J ≥ 3/2" are all separately well described.

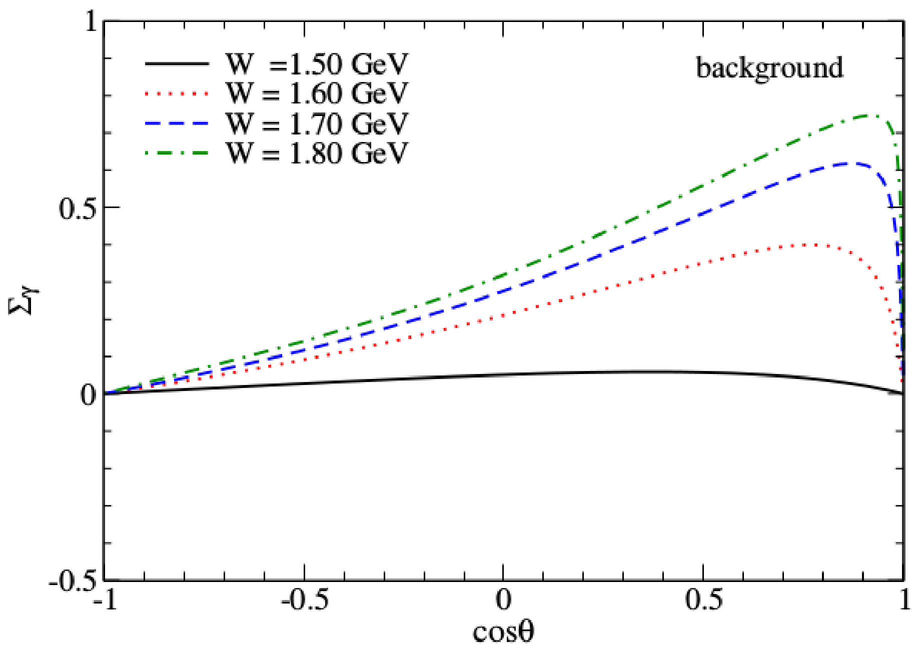
- ❑ Background term interferes constructively [destructively] with $N(1535,1/2^-)$ [$N(1685,1/2^+)$ & $N(1710,1/2^+)$].

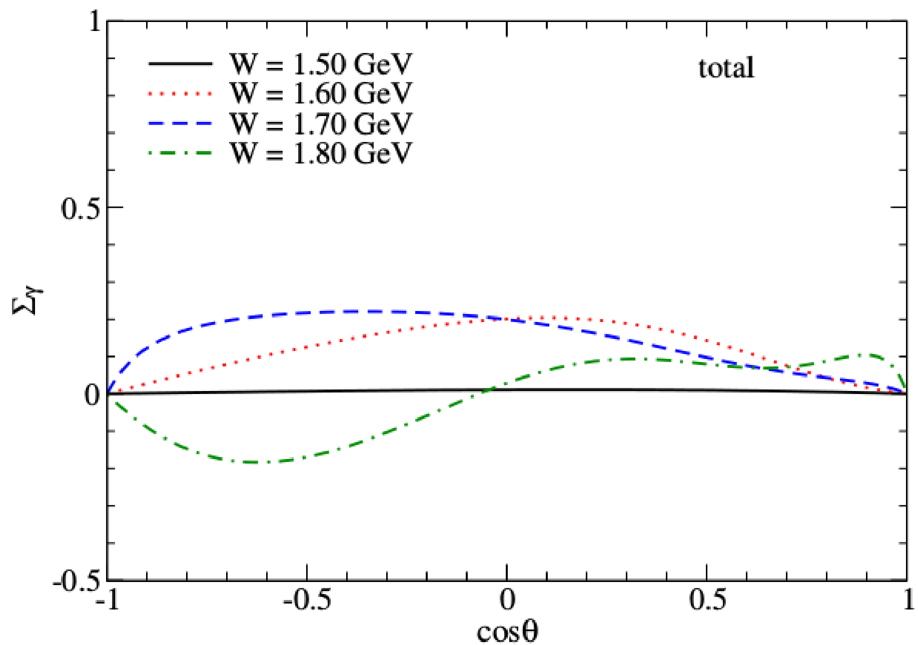
- ❑ $N(1520,3/2^-)$, $N(1720,3/2^+)$, and $N(1900,3/2^+)$ are also necessary although their contributions are small.

$\gamma\, n \rightarrow \eta n$

Beam Asymmetry

$$\Sigma = \frac{\frac{d\sigma}{d\Omega}_{\perp} - \frac{d\sigma}{d\Omega}_{\parallel}}{\frac{d\sigma}{d\Omega}_{\perp} + \frac{d\sigma}{d\Omega}_{\parallel}}$$





- When N^* are included, the changes are dramatic.
- Σ_γ gets diminished and the magnitudes of Σ_γ becomes overall equal or less than 0.2.

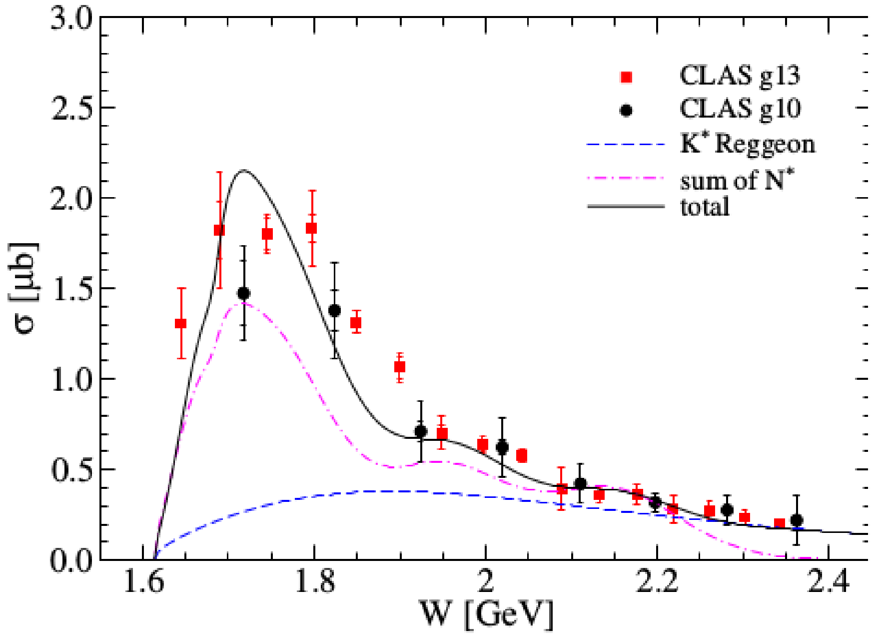
- Future exp.al measurements (Σ_γ & other polarization observables) will become a touchstone to judge which interpretation will turn out right.

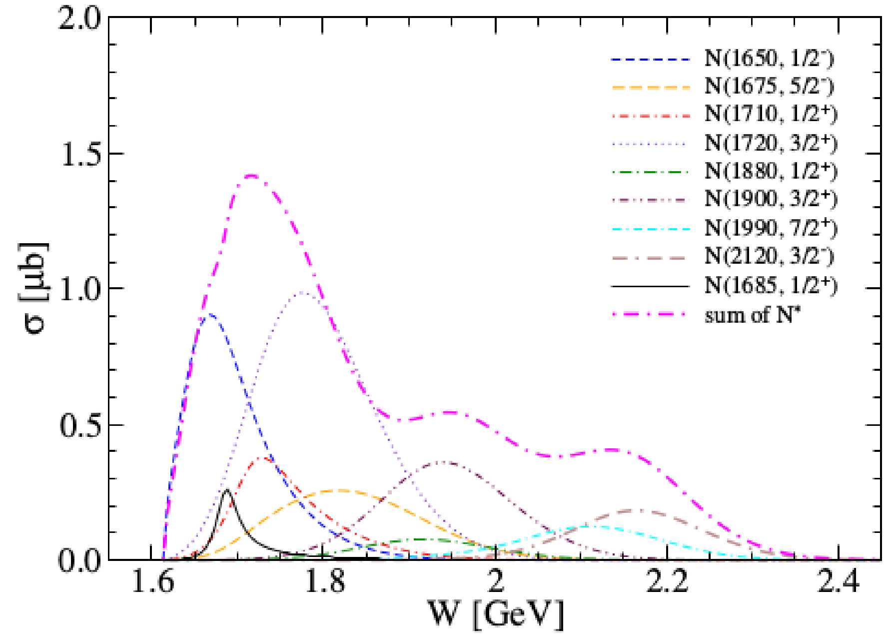
$\gamma\, n \rightarrow K^0 \Lambda$

Total Cross Section

CLAS

[PRC.96.065201(2017)]



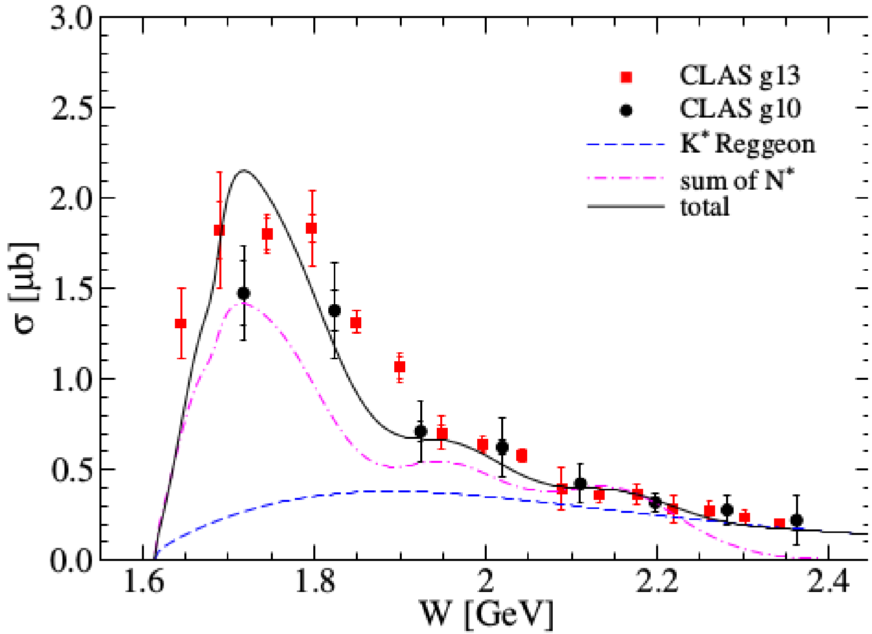


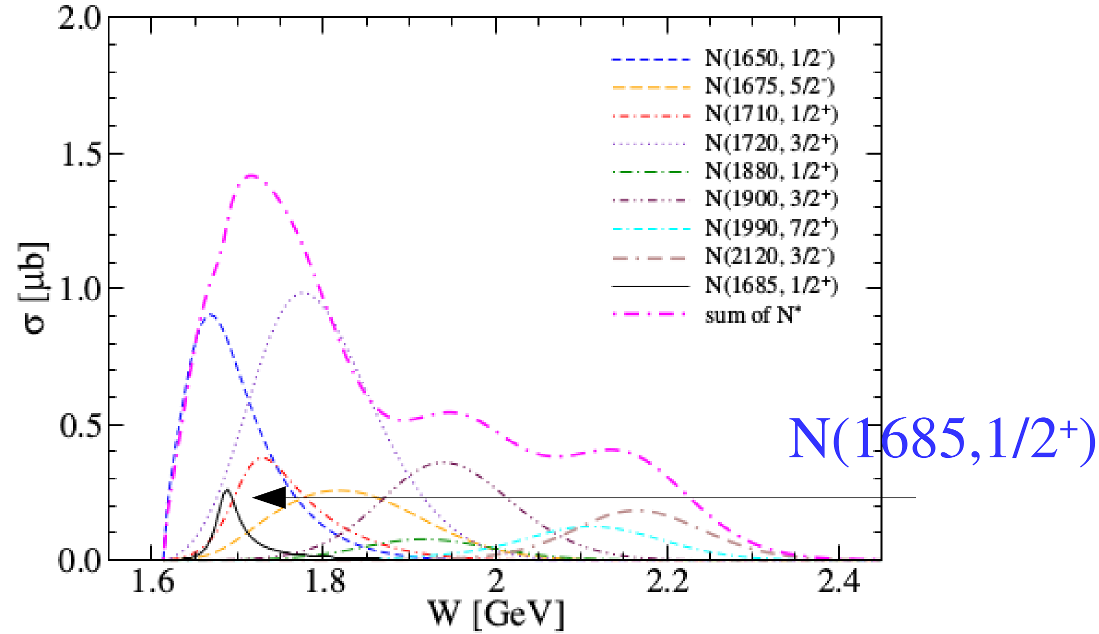
- ❑ Only rotating phase is acceptable.
- ❑ Main contribution comes from $1/2^+$, $1/2^-$, $3/2^+$ N^* resonances.

Results-2

$\gamma\, n \rightarrow K^0 \Lambda$ Total Cross Section

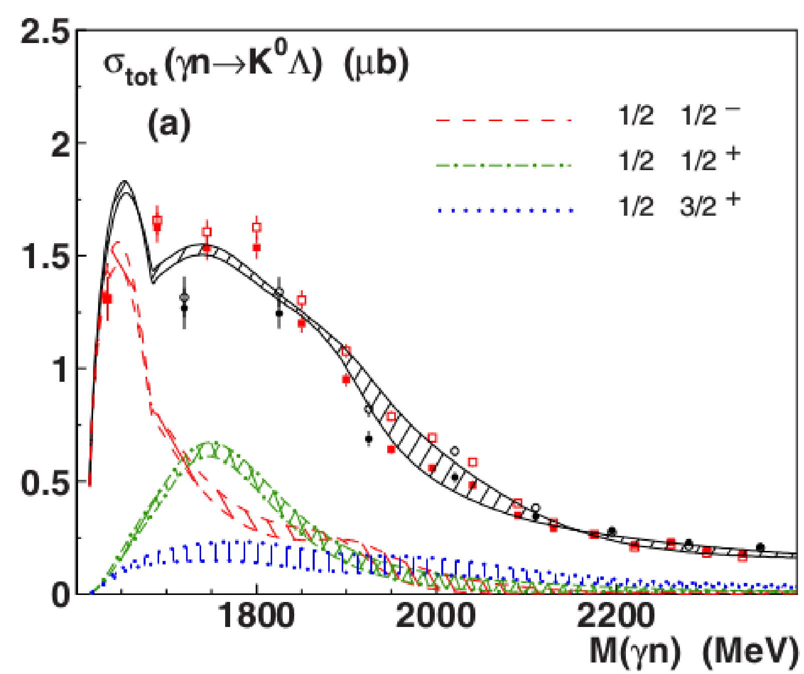
CLAS
[PRC.96.065201(2017)]





- ❑ Only rotating phase is acceptable.
- ❑ Main contribution comes from $1/2^+$, $1/2^-$, $3/2^+$ N^* resonances.

Bonn-Gachina, PRC.96.055202 (2017)



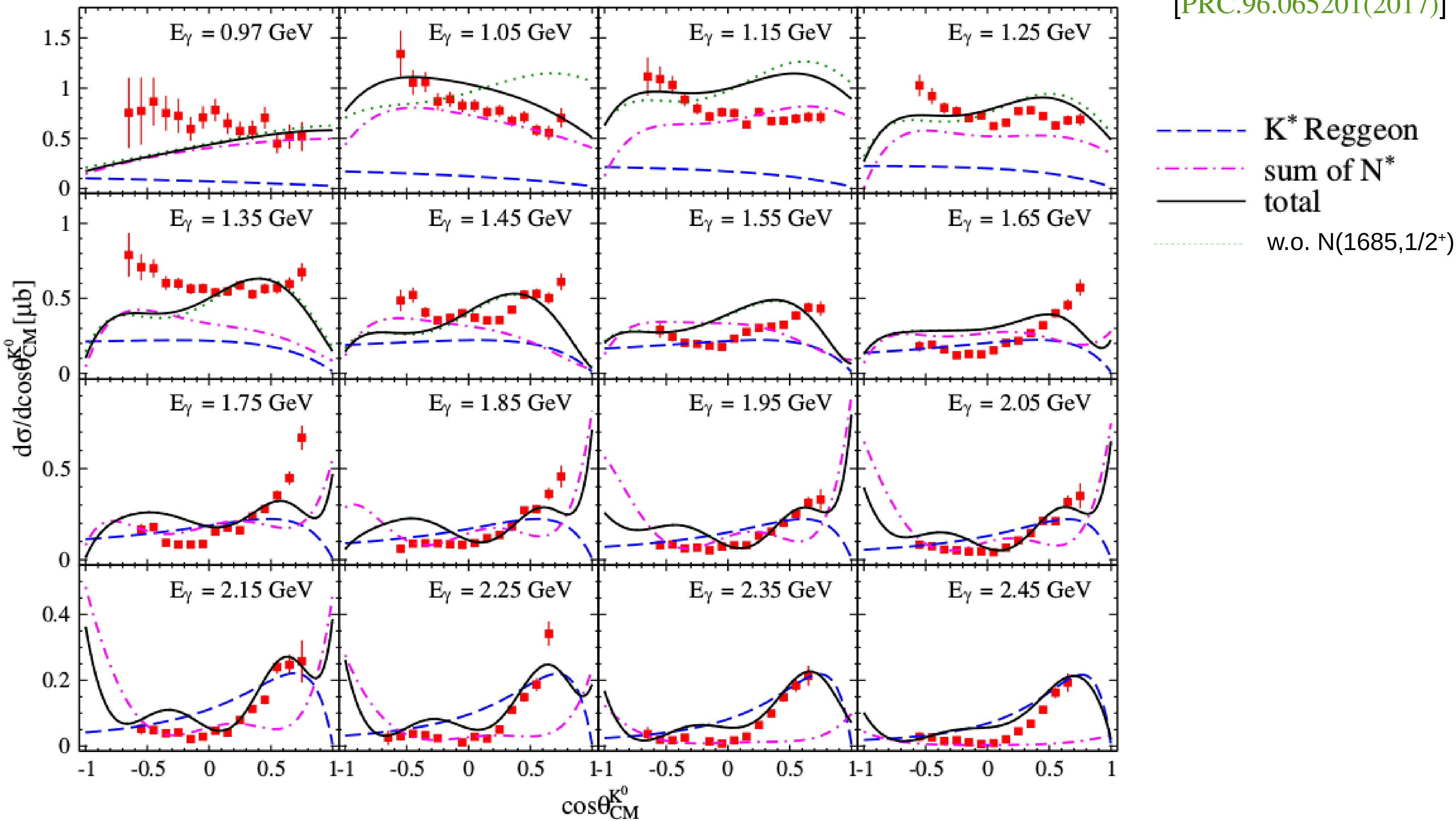
no evidence of N(1685,$1/2^+$)

$\gamma\, n \rightarrow K^0 \Lambda$

Differential Cross Sections (vs cosθ)

CLAS

[PRC.96.065201(2017)]



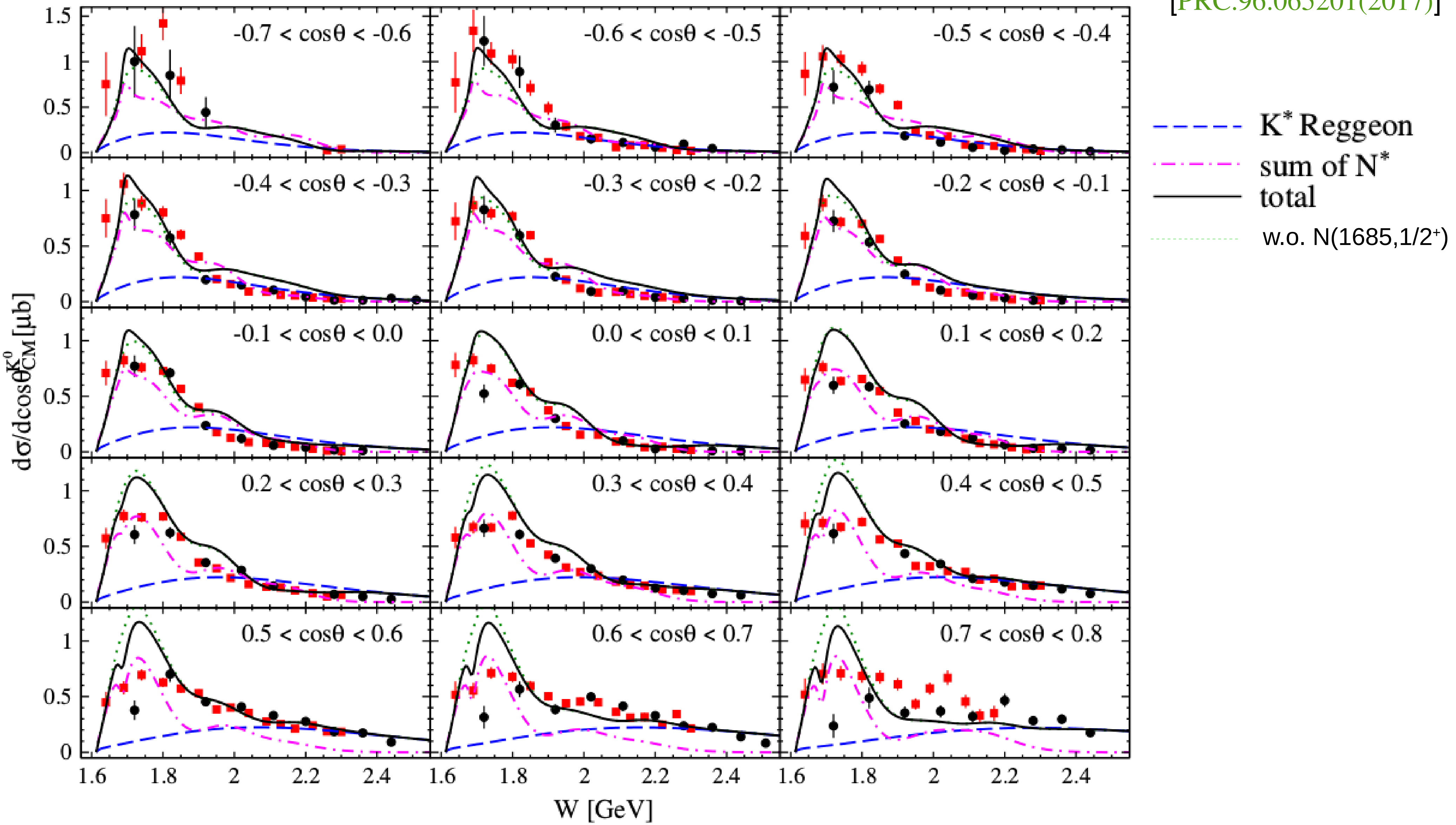
❑ The inclusion of N(1685,1/2⁺) helps to improve the results near threshold.

$\gamma\, n \rightarrow K^0 \Lambda$

Differential Cross Sections (vs W)

CLAS

[PRC.96.065201(2017)]

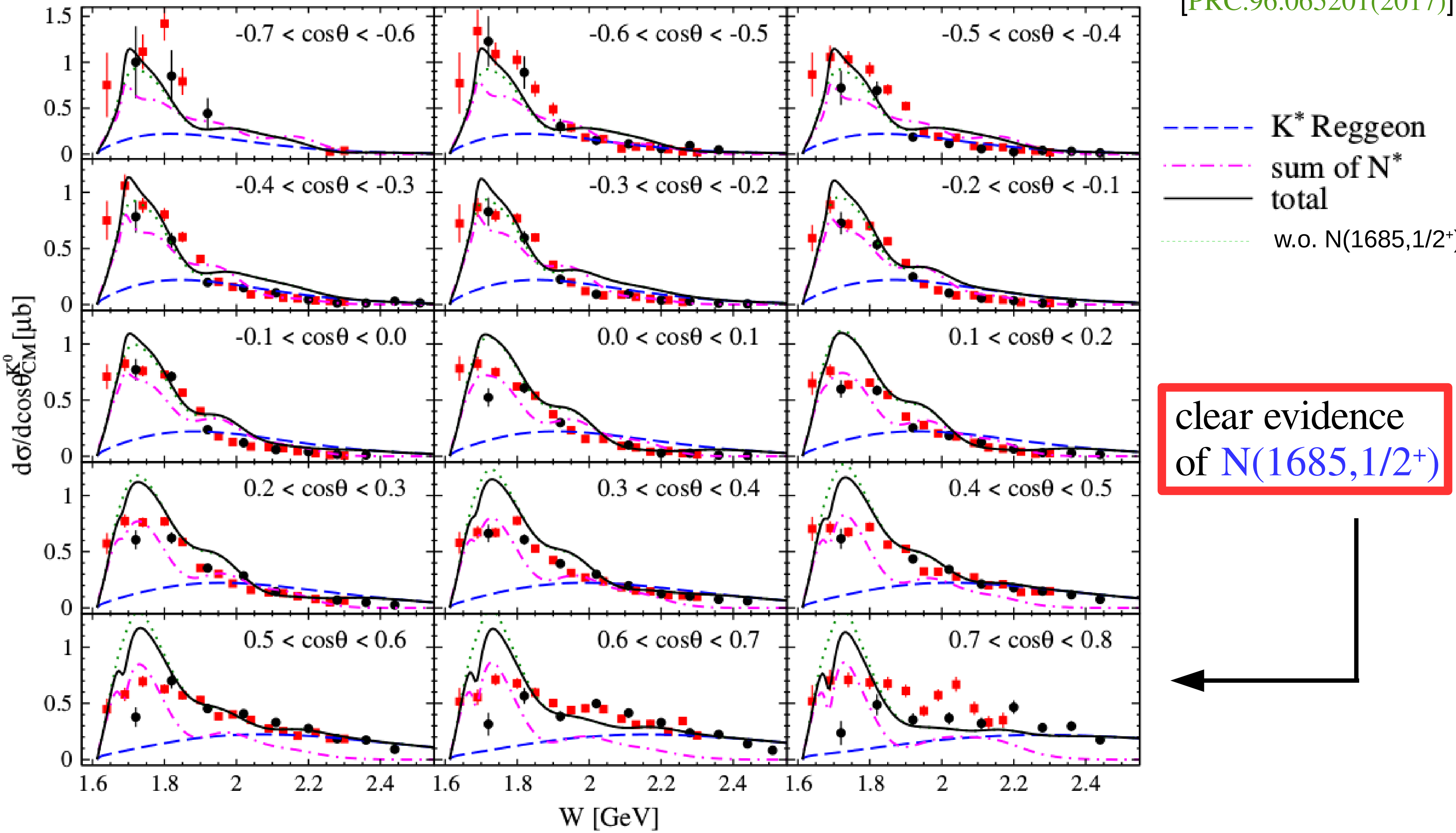


❑ Destructive effects (Dip structures) between N(1685,1/2$^+$) & other N*s begin to appear at the corresponding pole position as cosθ increases.

$\gamma\, n \rightarrow K^0 \Lambda$

Differential Cross Sections (vs W)

CLAS
[PRC.96.065201(2017)]



clear evidence of N(1685,1/2$^+$)

- Destructive effects (Dip structures) between N(1685,1/2$^+$) & other N*s begin to appear at the corresponding pole position as cosθ increases.

Summary

◇ $\gamma n \to \eta n$ & $\gamma n \to K^0\Lambda$ are studied using an effective Lagrangian approach combining with a Regge model.

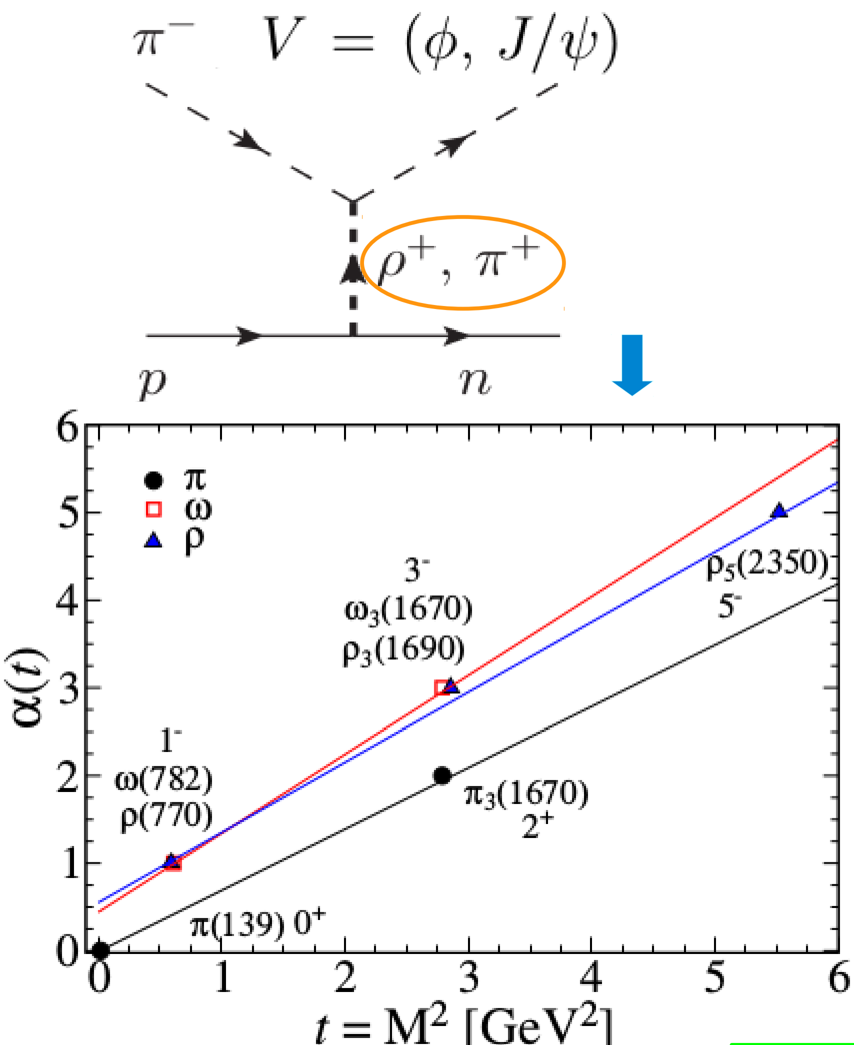
◇ ρ- & K^*-Reggeon trajectories are dominant background contributions, respectively.

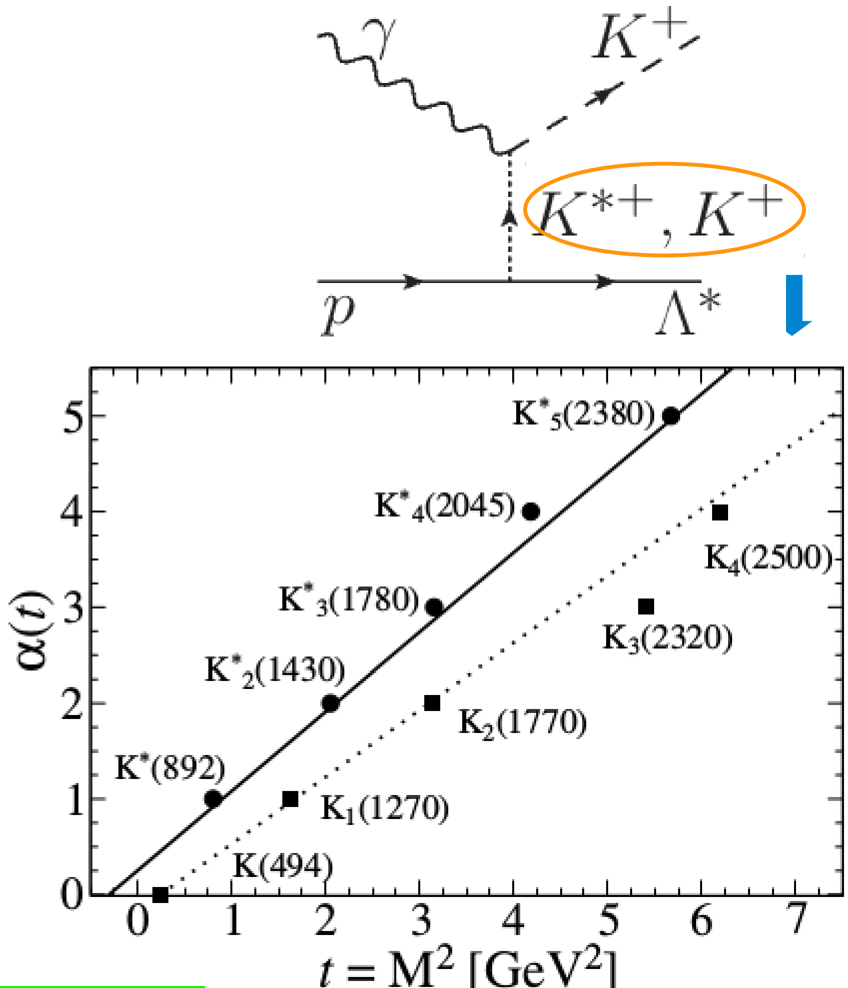
◇ $N(1685,1/2^+)$ is crucial to reproduce the FOREST & CLAS data, respectively, near threshold.

Future work:

◇ Improve our results by χ^2 fittings (MINUIT) with CLAS collaboration.
◇ Polarization observables will be also calculated.
◇ Vector meson (ρ,ω,φ) photo- & electro-production off the nucleon and nuclei(^{4}He,…)

Back Up





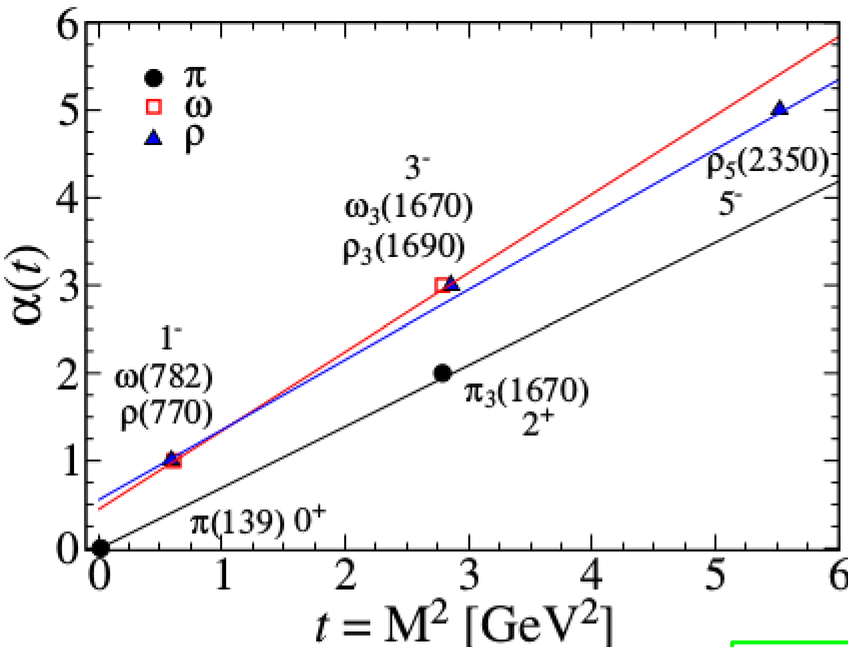
$$\alpha(M^2) = J$$

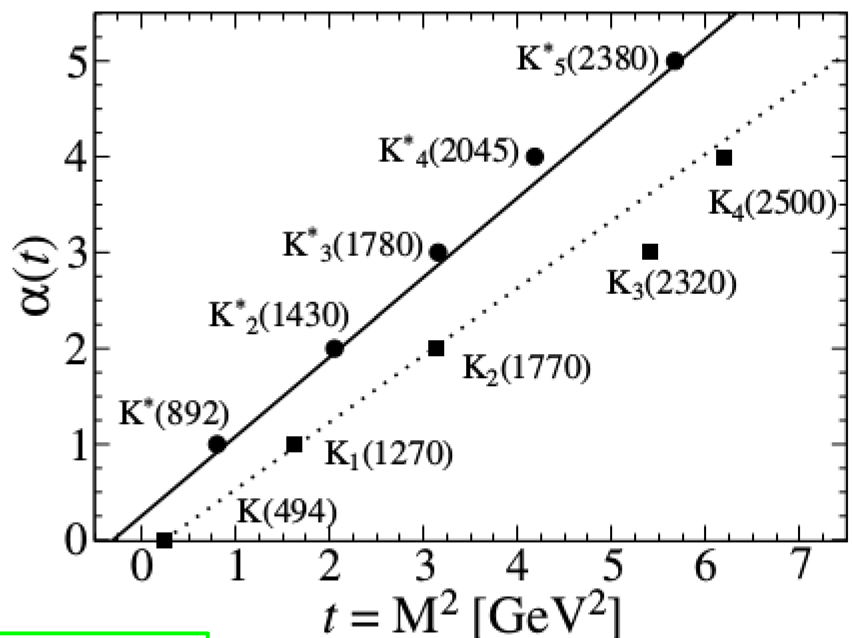
Chew–Frautschi plots

$$\begin{aligned}
\alpha_\pi(t) &= 0.7(t - M_\pi^2), \\
\alpha_\rho(t) &= 0.55 + 0.8t, \\
\alpha_\omega(t) &= 0.44 + 0.9t.
\end{aligned}$$

$$\begin{aligned}
\alpha_K(t) &= 0.7(t - M_K^2) \\
\alpha_{K^*}(t) &= 0.25 + 0.83t.
\end{aligned}$$

α(t) categorizes hadrons with the same internal quantum numbers,
M and J are the mass and the spin of related hadrons.





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