PHOTO- AND ELECTROPRODUCTION OF HYPERON AND HYPERTRITON

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HYP 2015

Tohoku University, Japan, September 2015

Contents

- Motivation
- Progress in the elementary photo- and electroproduction of kaon
  - Old models
  - New models
- Hypertriton production
  - Previous calculation
  - Future calculation
- Conclusion

Motivation, Kaon-Maid is getting Old

K

MAID 2000

Institut für Kernphysik, Universität Mainz, Germany

An effective Lagrangian Model for Kaon Photo- and Electroproduction on the Nucleon

T. Mart (University of Indonesia), C. Bennhold and H. Haberzettl (George Washington University), and L. Tiator

References:

For kaon photoproduction:	F.X. Lee, T. Mart, C. Bennhold, H. Haberzettl, L.E. Wright, Nucl. Phys. A695 (2001) 237, or nucl-th/9907119
For the missing resonance $D_{13}(1900)$:	T. Mart, C. Bennhold, Phys. Rev. C61 (2000) 012201, or nucl-th/9906096 C. Bennhold *et al.*, nucl-th/0008024
For kaon electroproduction:	C. Bennhold, H. Haberzettl, T. Mart, nucl-th/9909022

- Electromagnetic Multipoles ($E_{l\pm}$, $M_{l\pm}$, $L_{l\pm}$, $S_{l\pm}$)
- CGLN and Helicity Amplitudes ($F_1,\ldots,F_6$, $H_1,\ldots,H_6$)
- Polarized Response Functions ($R_T, R_L, R_{LT}, R_{TT}, R_{LT'}, R_{TT'}$)
- Unpolarized 2-fold Diff. Cross Sections (L,T,L,T,TT,LT')
- 5-fold Diff. Cross Section
- Total Cross Sections (T,L,LT,LT',TT')
- Transverse Polarization Observables (ds/dW,T,S,P,E,F,...)
- Target Polarization (P_x, P_y, P_z)
- Recoil Polarization (P_x, P_y, P_z)

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Motivation, formulation is not clearly revealed

APPENDIX C

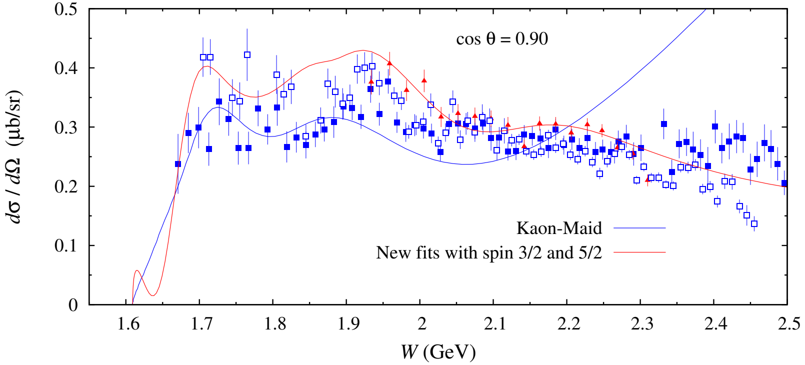
The contributions to the invariant amplitudes corresponding to the exchange of a $N^*(5/2^+)$ resonance have the same structure as in the spin-3/2 case. We give only the photoproduction amplitudes

$$\mathcal{A}_j = \frac{1}{10(s - M_{N*}^2 + iM_{N*}\Gamma_{N*})} \sum_{i=1}^{2} G_i P_{ij}, \quad j = 1, \ldots, 4.$$

Defining $w = \sqrt{s}$, the contributions coming from the G_1 coupling are

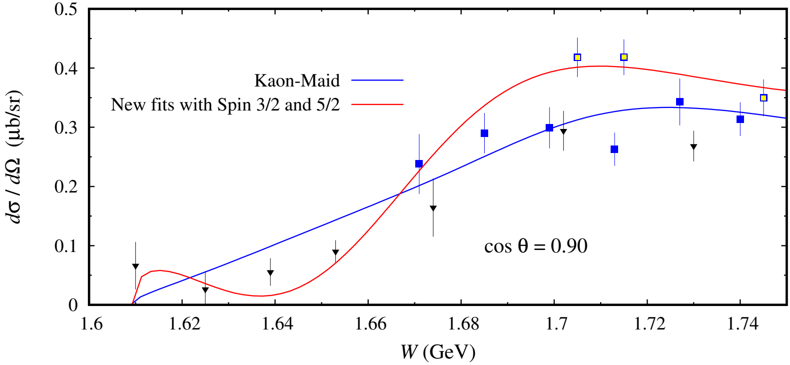
J.-C. David, *et al.*, Phys. Rev. C **53**, 2613 (1996).

Motivation, models do not work



- Problem of Data consistency at forward direction
- Even with spin 3/2 and 5/2 [David, *et al.*, PRC **53**, 2613 (1996)] the prediction is far from ideal

Motivation, models do not work

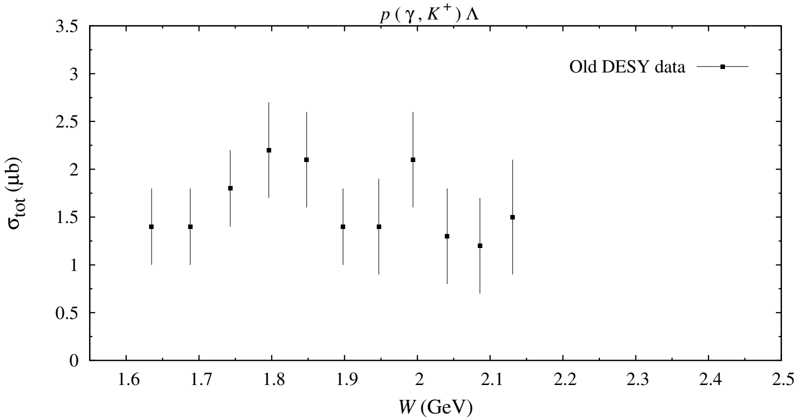


- ▼ SAPHIR data 1998, not included in the fit
- Data consistency?
- Even with spin 3/2 and 5/2 [David, *et al.*, PRC **53**, 2613 (1996)]

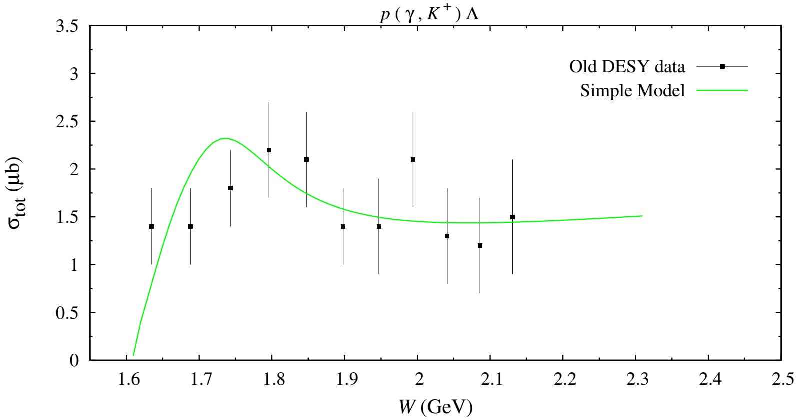
Conclusion:

"We have to search for other spin 3/2 and spin 5/2 formulations"

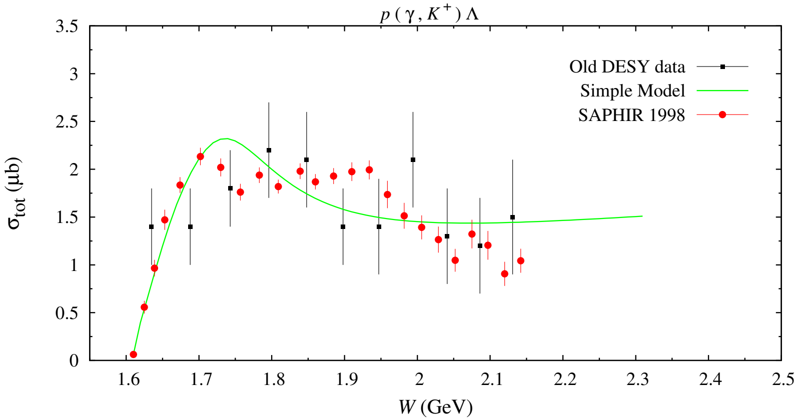
Progress in Isobar Model, before 1998



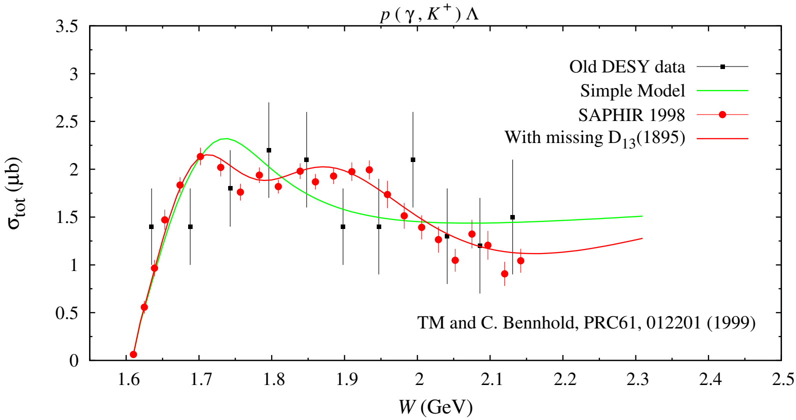
Progress in Isobar Model, before 1998



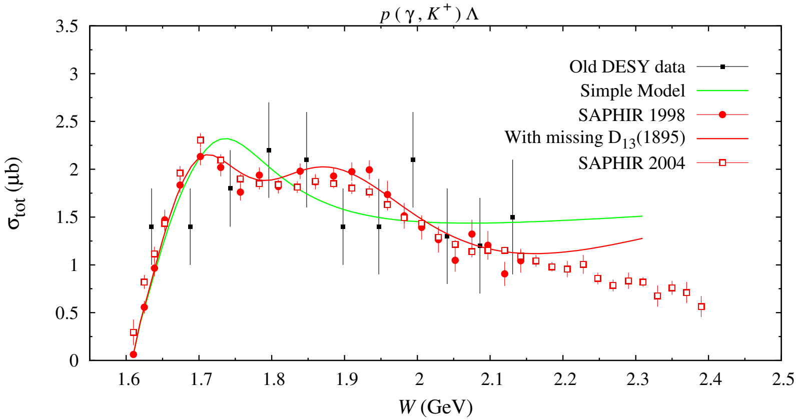
Progress in Isobar Model, 1998



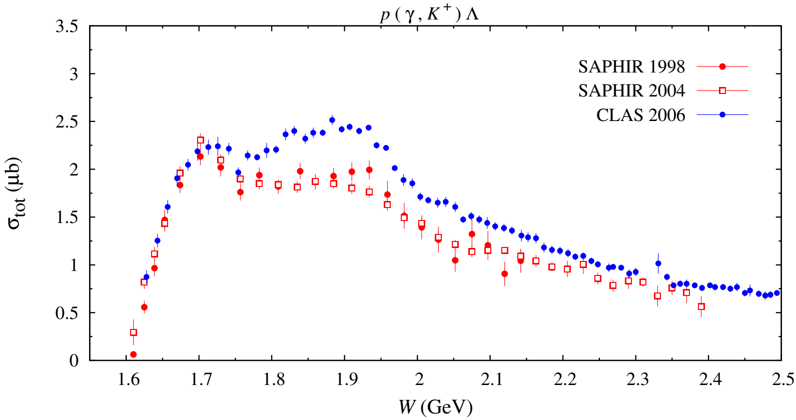
Progress in Isobar Model, 1998



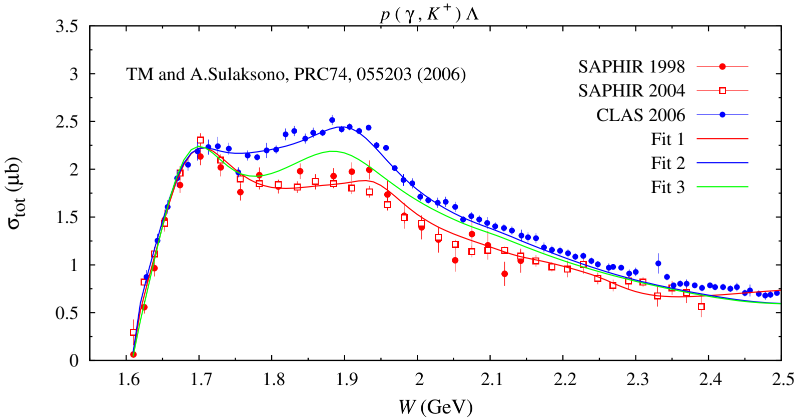
Progress in Isobar Model, 2006



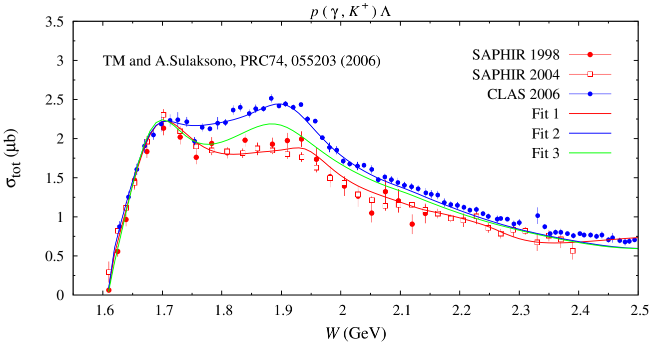
Progress in Isobar Model, 2006



Progress in Isobar Model, 2006



Problems



- Fitting all data simultaneously → democratic model which is not consistent with both data sets
- This problem is simply forgotten, but seems to appear mildly in the new Crystal Ball data
- Unsolved homework!

Problems with the spin 3/2 and 5/2 formalism

- W. Rarita and J. Schwinger, Phys. Rev. **60**, 61 (1941).
- P. A. Moldauer and K. M. Case, Phys. Rev. **102**, 279 (1956).
- L. M. Nath, B. Etemadi and J. D. Kimel, Phys. Rev. D **3**, 2153 (1971).
- H. T. Williams, Phys. Rev. C **31**, 2297 (1985).
- M. Benmerrouche, R.M. Davidson and N.C. Mukhopadhyay, Phys. Rev. C **39**, 2339 (1989).
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- V. Pascalutsa, Phys. Rev. D **58**, 096002 (1998).
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- V. Pascalutsa and R. Timmermans, Phys. Rev. C **60**, 042201 (1999).
- V. Pascalutsa, Phys. Lett. B **503**, 85 (2001).
- O. V. Maxwell, Phys. Rev. C **70**, 044612 (2004)
- V. Shklyar, H. Lenske and U. Mosel, Phys. Rev. C **82**, 015203 (2010).
- T. Vrancx, L. De Cruz, J. Ryckebusch, P. Vancraeyveld, Phys. Rev. C **84**, 045201 (2011).
- ...
- ...

Problems with the spin 3/2 and 5/2 formalism

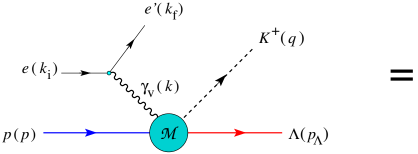
Finding a consistent propagator without background coming from the lower spin components.

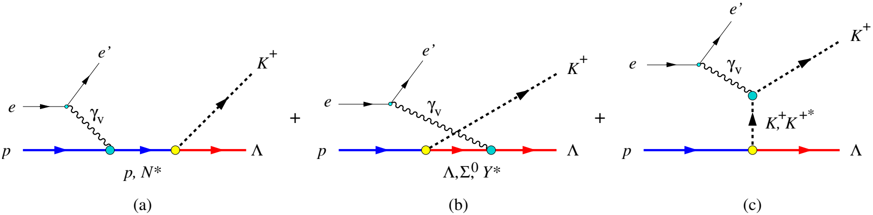
Our solution relies on

Pascalutsca & Timmermans, PRC60, 042201 (1999):

> *"Our basic premise is that a consistent interaction should not activate the spurious DOF, and therefore the full interacting theory must obey similar symmetry requirements as the corresponding free theory"*

Isobar Model





Isobar Model

From the feynman diagrams we calculate $\mathscr{M}$ and decompose it to the six gauge- and Lorentz-invariant M_i matrices

$$
\begin{aligned}
\mathscr{M} &= \mathscr{M}_p + \mathscr{M}_\Lambda + \mathscr{M}_{\Sigma^0} + \mathscr{M}_{K^*} + \mathscr{M}_{N^*} + \cdots \\
&= \bar{u}_\Lambda \sum_{i=1}^{6} A_i M_i u_p \ ,
\end{aligned}
$$

where

$$
\begin{aligned}
M_1 &= \tfrac{1}{2}\gamma_5 \left(\not{\epsilon}\not{k} - \not{k}\not{\epsilon}\right) \ , \\
M_2 &= \gamma_5 \left[(2q-k)\cdot\epsilon P\cdot k - (2q-k)\cdot k P\cdot\epsilon\right] \ , \\
M_3 &= \gamma_5 \left(q_K\cdot k\not{\epsilon} - q\cdot\epsilon\not{k}\right) \ , \\
M_4 &= i\epsilon_{\mu\nu\rho\sigma}\gamma^\mu q^\nu \epsilon^\rho k^\sigma \ , \\
M_5 &= \gamma_5 \left(q\cdot\epsilon k^2 - q\cdot k k\cdot\epsilon\right) \ , \\
M_6 &= \gamma_5 \left(k\cdot\epsilon\not{k} - k^2\not{\epsilon}\right) \ ,
\end{aligned}
$$

we obtain the amplitudes $A_1, \ldots, A_6$ and calculate the observables.

Model 1, Propagator

Spin 3/2 resonance[1]

$$P^{3/2}_{\mu\nu} = \frac{\not p + \not k + \sqrt{s}}{3(s - m^2_{N^*} + i m_{N^*}\Gamma_{N^*})}\left[g_{\mu\nu} + \gamma_\nu\gamma_\mu - \frac{2}{s}(p+k)_\mu\,(p+k)_\nu - \frac{1}{\sqrt{s}}\left\{\gamma_\mu(p+k)_\nu - \gamma_\nu(p+k)_\nu\right\}\right]$$

Spin 5/2 resonance[1,2]

$$\begin{aligned} P^{5/2}_{\mu\nu\alpha\beta} \quad = \quad & \frac{\not p + \not k + \sqrt{s}}{10(s - m^2_{N^*} + i m_{N^*}\Gamma_{N^*})}\Big[5P_{\mu\alpha}P_{\nu\beta} - 2P_{\mu\nu}P_{\alpha\beta} + 5P_{\mu\beta}P_{\nu\alpha} + P_{\mu\rho}\gamma^\rho\gamma^\sigma P_{\sigma\alpha}P_{\nu\beta} \\ & + P_{\nu\rho}\gamma^\rho\gamma^\sigma P_{\sigma\beta}P_{\mu\alpha} + P_{\mu\rho}\gamma^\rho\gamma^\sigma P_{\sigma\beta}P_{\nu\alpha} + P_{\nu\rho}\gamma^\rho\gamma^\sigma P_{\sigma\alpha}P_{\mu\beta}\Big], \end{aligned}$$

with

$$P_{\mu\nu} = -g_{\mu\nu} + \frac{1}{s}(p+k)_\mu(p+k)_\nu\ .$$

1. J.-C. David, *et al.*, Phys. Rev. C **53**, 2613 (1996).
2. V. Shklyar, H. Lenske and U. Mosel, Phys. Rev. C **82**, 015203 (2010).

Model 1, vertex factors

For spin 3/2 resonances the electromagnetic vertex is[†]

$$\Gamma^{\nu(\pm)}_{N^* p\gamma} = \left\{ g^a_{N^* p\gamma}\left(\epsilon^\nu - \frac{\not\epsilon\, k^\nu}{\sqrt{s}\pm m_p}\right) + g^b_{N^* p\gamma}\frac{p\cdot\epsilon\, k^\nu - p\cdot k\epsilon^\nu}{(\sqrt{s}\pm m_p)^2} + g^c_{N^* p\gamma}\frac{k\cdot\epsilon\, k^\nu - k^2\epsilon^\nu}{(\sqrt{s}\pm m_p)^2}\right\}\Gamma_\pm \, ,$$

where $\Gamma_+ = i\gamma_5$ and $\Gamma_- = 1$.
and the hadronic vertex reads

$$\Gamma^{\mu(\pm)}_{K\Lambda N^*} = \frac{g_{K\Lambda N^*}}{m_{N^*}}\, p^\mu_\Lambda\, \Gamma_\mp \, .$$

The vertex factors for spin 5/2 resonances are analogous.

[†] J.-C. David, *et al.*, Phys. Rev. C **53**, 2613 (1996).

Model 2, Propagator

Spin 3/2 resonance[1]

$$P_{\mu\nu}^{3/2} = \frac{\not{p}+\not{k}+m_{N^*}}{3(s-m_{N^*}^2+im_{N^*}\Gamma_{N^*})}\left[-3g_{\mu\nu}+\gamma_\mu\gamma_\nu+\frac{1}{s}\left\{(\not{p}+\not{k})\gamma_\mu(p+k)_\nu+(p+k)_\mu\gamma_\nu(\not{p}+\not{k})\right\}\right]$$

Spin 5/2 resonance[2]

$$\begin{aligned} P_{\mu\nu\alpha\beta}^{5/2} \quad = \quad & \frac{\not{p}+\not{k}+\sqrt{s}}{10(s-m_{N^*}^2+im_{N^*}\Gamma_{N^*})}\Big[5P_{\mu\alpha}P_{\nu\beta}-2P_{\mu\nu}P_{\alpha\beta}+5P_{\mu\beta}P_{\nu\alpha}+P_{\mu\rho}\gamma^\rho\gamma^\sigma P_{\sigma\alpha}P_{\nu\beta} \\ & +P_{\nu\rho}\gamma^\rho\gamma^\sigma P_{\sigma\beta}P_{\mu\alpha}+P_{\mu\rho}\gamma^\rho\gamma^\sigma P_{\sigma\beta}P_{\nu\alpha}+P_{\nu\rho}\gamma^\rho\gamma^\sigma P_{\sigma\alpha}P_{\mu\beta}\Big], \end{aligned}$$

with

$$P_{\mu\nu} = -g_{\mu\nu}+\frac{1}{s}(p+k)_\mu(p+k)_\nu \; .$$

1. V. Pascalutsa, Phys. Lett. B **503**, 85 (2001).
2. J.-C. David, *et al.*, PRC **53**, 2613 (1996), V. Shklyar, *et al.*, PRC **82**, 015203 (2010), T. Vrancx, *et al.*, PRC **84**, 045201 (2011).

For spin 3/2 resonances the electromagnetic vertex is[†]

$$\Gamma^{\nu(\pm)}_{N^* p\gamma} = -\frac{i}{m_{N^*}^2}\Big[g^{(1)}(\varepsilon^\nu \not{k} - k^\nu \not{\varepsilon})\not{p} + g^{(2)}(k^\nu p\cdot\varepsilon - \varepsilon^\nu p\cdot k) + g^{(3)} p^\nu (\not{\varepsilon}\not{k} - \not{k}\not{\varepsilon}) + g^{(4)}\gamma^\nu(\not{k}\not{\varepsilon} - \not{\varepsilon}\not{k})\not{p} + g^{(5)}\gamma^\nu(p\cdot k\not{\varepsilon} - p\cdot\varepsilon\not{k})\Big]\Gamma_\pm \ ,$$

where $\Gamma_+ = i\gamma_5$ and $\Gamma_- = 1$.
and the hadronic vertex reads

$$\Gamma^{\mu(\pm)}_{K\Lambda N^*} = \frac{g_{K\Lambda N^*}}{m_{N^*}^2}\Gamma_\mp\, i\varepsilon^{\mu\nu\rho\sigma} p_{\Lambda\nu}\gamma_5\gamma_\rho q_\sigma \ .$$

The vertex factors for spin 5/2 resonances are analogous.

[†] V. Pascalutsa and R. Timmermans, Phys. Rev. C **60**, 042201 (1999).

Spin 3/2 Model 1

e.g. $A_1, \cdots, A_4$ for Spin 3/2

$$
\begin{aligned}
A_1 &= \pm\Big[(m_p+m_\Lambda)\big(\tfrac{3}{2}-\tfrac{1}{s}c_\Lambda \pm \tfrac{1}{2\sqrt{s}}m_\Lambda\big) \mp c_\pm\{s-m_K^2-3b_\Lambda+m_\Lambda(\pm 2\sqrt{s}+m_p)\} \mp \tfrac{2}{s}c_\Lambda c_\pm c_k \pm \tfrac{1}{\sqrt{s}}c_\pm \\
&\quad \times(m_\Lambda c_k + m_\Lambda c_\Lambda - m_p c_\Lambda)\Big]\, G_1 \mp \Big[\tfrac{1}{2}(m_p+m_\Lambda)\Big\{b_p-3b_\Lambda+2c_\Lambda+m_\Lambda(\pm\sqrt{s}-m_p)+\tfrac{2}{s}k^2 c_\Lambda \\
&\quad \mp \tfrac{1}{\sqrt{s}}[k^2 m_\Lambda \pm c_\Lambda(\sqrt{s}\pm m_p)]\Big\} + b_p(m_p \mp \tfrac{1}{\sqrt{s}}c_\Lambda)\Big]\, G_2 \pm k^2\Big[\tfrac{1}{2s}(m_p+m_\Lambda)(2c_\Lambda - s \mp m_\Lambda\sqrt{s}) - m_p \pm \tfrac{1}{\sqrt{s}}c_\Lambda\Big]\, G_3 \,, \\
A_2 &= \frac{1}{t-m_K^2}\Big[\Big\{3c_\pm(c_4-2b_\Lambda)\pm 2m_\Lambda + \tfrac{2}{s}c_\pm c_\Lambda(2c_k - s + m_p^2) \mp \tfrac{1}{\sqrt{s}}m_\Lambda c_\pm[(\sqrt{s}\pm m_p)^2+2c_k]\Big\}\, G_1 \\
&\quad + \Big\{3(b_\Lambda - b_p)(\sqrt{s}\mp m_p) + k^2[\pm m_\Lambda - \tfrac{2}{s}c_\Lambda c_\pm(s-m_p^2) - \tfrac{1}{\sqrt{s}}c_\Lambda \mp \tfrac{1}{\sqrt{s}}m_\Lambda(\sqrt{s}\pm m_p)]\Big\}\, G_2 \\
&\quad + k^2\Big\{-3(\sqrt{s}\mp m_p)\mp 2m_\Lambda + \tfrac{2}{s}c_\pm c_\Lambda(s-m_p^2) \pm \tfrac{1}{\sqrt{s}}m_\Lambda(\sqrt{s}\pm m_p)\Big\}\, G_3\Big] \,, \\
A_3 &= \mp\tfrac{1}{2}\Big\{3\mp 2c_\pm m_\Lambda + \tfrac{2}{s}c_\Lambda \mp \tfrac{1}{\sqrt{s}}(m_\Lambda \pm 2c_\pm c_\Lambda)\Big\}\, G_1 \pm \tfrac{1}{2}\Big[3(b_p+b_\Lambda) - 2c_\Lambda \mp c_\pm m_\Lambda(s-m_p^2) - \tfrac{2}{s}k^2 c_\Lambda \\
&\quad \pm \tfrac{1}{\sqrt{s}}\Big\{k^2 m_\Lambda \pm c_\Lambda(\sqrt{s}\pm m_p)\Big\}\Big]\, G_2 \pm \tfrac{1}{2}k^2(3+\tfrac{2}{s}c_\Lambda \mp \tfrac{1}{\sqrt{s}}m_\Lambda)\, G_3 \,, \\
A_4 &= \pm\tfrac{1}{2}\Big\{3\pm 2c_\pm m_\Lambda - \tfrac{2}{s}c_\Lambda \pm \tfrac{1}{\sqrt{s}}(m_\Lambda \pm 2c_\pm c_\Lambda)\Big\}\, G_1 \mp \tfrac{1}{2}\Big[3(b_p-b_\Lambda) + 2c_\Lambda \pm c_\pm m_\Lambda(s-m_p^2) + \tfrac{2}{s}k^2 c_\Lambda \\
&\quad \mp \tfrac{1}{\sqrt{s}}\Big\{k^2 m_\Lambda \pm c_\Lambda(\sqrt{s}\pm m_p)\Big\}\Big]\, G_2 \mp \tfrac{1}{2}k^2(3-\tfrac{2}{s}c_\Lambda \pm \tfrac{1}{\sqrt{s}}m_\Lambda)\, G_3 \,,
\end{aligned}
$$

Note: A_5 and A_6 have been also calculated $\rightarrow$ only for electroproduction

Spin 5/2 Model 1

e.g. $A_1, \cdots, A_3$ for Spin 5/2

$$
\begin{aligned}
A_1 \quad = \quad & \mp\Big[5c_1\{(m_p+m_\Lambda)c_s \mp 2c_\mp c_1\} \mp 2c_2\{c_\mp c_3 \mp \tfrac{1}{2s}(m_p+m_\Lambda)c_k\} - d_\mp\Big\{2c_1\sqrt{s}[1+2c_\mp(\sqrt{s} \\
& \pm m_\Lambda)] - 4c_1 c_\mp c_k \pm (m_p+m_\Lambda)[c_1 - c_s\sqrt{s}(\sqrt{s}\pm m_p) + c_s c_k]\Big\}\Big]\, G_1 \pm \Big[(m_p+m_\Lambda)\Big\{5c_1 \\
& \times(\tfrac{1}{s}k^2 c_\Lambda + b_p - b_\Lambda) - k^2 c_2(\tfrac{1}{s}c_k - 1)\Big\} + d_\mp\Big\{-c_1(2b_p\sqrt{s} + (m_p+m_\Lambda)[\sqrt{s}(m_p\pm\sqrt{s}) \\
& \mp k^2]) \mp (m_p+m_\Lambda)(k^2 c_s - b_q)[\sqrt{s}(\sqrt{s}\pm m_p) - c_k]\Big\}\Big]\, G_2 \pm k^2\Big[(m_p+m_\Lambda)(5c_1 c_s + \tfrac{1}{s}c_k c_2) \\
& + d_\mp\Big\{-2c_1\sqrt{s} \mp c_1(m_p+m_\Lambda) \pm c_s(m_p+m_\Lambda)[\sqrt{s}(\sqrt{s}\pm m_p) - c_k]\Big\}\Big]\, G_3\ , \\
A_2 \quad = \quad & \frac{2}{t-m_K^2}\Big(\Big[5c_1\,\{(\sqrt{s}\pm m_p)c_s - 2c_\mp c_1\} + k^2 c_\mp c_2(2-\tfrac{1}{s}c_k) \pm d_\mp\,\Big\{c_1 c_\mp(k^2+2c_k) \\
& -c_s(b_p\sqrt{s}\pm m_p c_k)\Big\}\Big]\, G_1 + \Big[(\sqrt{s}\pm m_p)\times\Big\{5c_1(k^2 c_s - b_q) + k^2 c_2(\tfrac{1}{s}c_k - 1)\Big\} - d_\mp \\
& \times\Big\{c_1 k^2 m_p \pm (k^2 c_s - b_q)[b_p\sqrt{s}\pm c_k m_p]\Big\}\Big]\, G_2 - k^2\Big[(\sqrt{s}\pm m_p)(5c_1 c_s + \tfrac{1}{s}c_2 c_k) \mp d_\mp\{c_1 \\
& \times\ (\sqrt{s}\pm m_p) + c_s(b_p\sqrt{s}\pm c_k m_p)\}\Big]\, G_3\Big), \\
A_3 \quad = \quad & \pm\Big[5c_1(1+\tfrac{1}{s}c_\Lambda) - \tfrac{1}{s}c_k c_2 \pm d_\mp\Big\{c_1(1+4c_\mp\sqrt{s}) + (1+\tfrac{1}{s}c_\Lambda)[b_p \pm m_p(\sqrt{s}\pm m_p)]\Big\}\Big]\, G_1 \mp \Big[5c_1(2b_p \\
& -b_q + k^2 c_s) + k^2 c_2(\tfrac{1}{s}c_k - 1) \mp d_\mp\Big\{c_1[k^2 - \sqrt{s}(\sqrt{s}\pm m_p)] + (2b_p - b_q + k^2 c_s)[c_k - \sqrt{s} \\
& \times(\sqrt{s}\pm m_p)]\Big\}\Big]\, G_2 \mp k^2\Big[5c_1(1+\tfrac{1}{s}c_\Lambda) - \tfrac{1}{s}c_k c_2 \pm d_\mp\Big\{c_1 + (1+\tfrac{1}{s}c_\Lambda)[\sqrt{s}(\sqrt{s}\pm m_p) - c_k]\Big\}\Big]\, G_3\ ,
\end{aligned}
$$

Note: $A_4, \cdots, A_6$ have been also calculated.

Spin 3/2 Model 2

e.g. $A_1, \cdots, A_4$ for Spin 3/2

$$
\begin{aligned}
A_1 &= \pm m_p\sqrt{s}\Big[d_\pm\{-2\sqrt{s}(m_\Lambda \mp \sqrt{s}) \mp (c_k + \tfrac{1}{2}(m_p+m_\Lambda)(m_p \mp \sqrt{s}))\} - 3\{c_1 + \tfrac{1}{2}c_s(m_p+m_\Lambda) \\
&\quad \times(m_p \pm \sqrt{s})\}\Big]\, G_1 \pm \tfrac{1}{2}\sqrt{s}\Big[d_\pm\{2b_p\sqrt{s} + (m_p+m_\Lambda)(m_p \mp \sqrt{s})\sqrt{s} \pm k^2(m_p+m_\Lambda)\} + 3(m_p+m_\Lambda)(c_1 - b_p c_s)\Big]\, G_2 \\
&\quad \pm 2\sqrt{s}\Big[d_\pm\{2b_p\sqrt{s} + (m_p+m_\Lambda)(m_p \mp \sqrt{s})\sqrt{s} - (m_p\sqrt{s} \mp c_p)(m_\Lambda \mp \sqrt{s})\} - 3c_1(m_\Lambda \pm \sqrt{s})\Big]\, G_3\,, \\
A_2 &= \pm\frac{1}{t-m_k^2}\Big[m_p\sqrt{s}\Big\{\pm k^2 d_\pm + 3(k^2 c_s - 2b_q)\Big\}\, G_1 + \sqrt{s}\Big\{\mp d_\pm m_p k^2 - 3(m_p \mp \sqrt{s})(c_1 - b_p c_s)\Big\}\, G_2 + 4sk^2 d_\pm\, G_3\Big]\,, \\
A_3 &= \pm m_p\sqrt{s}\Big[d_\pm\{-2\sqrt{s} \mp \tfrac{1}{2}(m_p \mp \sqrt{s})\} + \tfrac{3}{2}(m_p \pm \sqrt{s})(1 + \tfrac{1}{s}c_\Lambda)\Big]\, G_1 \pm \tfrac{1}{2}\sqrt{s}\Big[d_\pm\{(m_p \mp \sqrt{s})\sqrt{s} \pm k^2\} \\
&\quad + 3\{c_1 + b_p(1 + \tfrac{1}{s}c_\Lambda)\}\Big]\, G_2 \mp 2\sqrt{s}(\pm c_k d_\pm + 3c_1)\, G_3 \\
A_4 &= \pm m_p\sqrt{s}\Big[d_\pm\{-2\sqrt{s} \mp \tfrac{1}{2}(m_p \mp \sqrt{s})\} - \tfrac{3}{2}(m_p \pm \sqrt{s})c_s\Big]\, G_1 \pm \tfrac{1}{2}\sqrt{s}\Big[d_\pm\{(m_p \mp \sqrt{s})\sqrt{s} \pm k^2\} \\
&\quad + 3\{c_1 - b_p c_s\}\Big]\, G_2 \mp 2\sqrt{s}(\pm c_k d_\pm + 3c_1)\, G_3
\end{aligned}
$$

Spin 5/2 Model 2

e.g. $A_1, \cdots, A_4$ for Spin 5/2

$$
\begin{aligned}
A_1 \quad = \quad & \pm 2m_p\sqrt{s}\Big[d_\mp\{-3c_1\sqrt{s}(m_\Lambda \pm \sqrt{s}) - \tfrac{1}{2}c_s k^2(m_p+m_\Lambda)\sqrt{s} \pm [2c_1 c_k + \tfrac{1}{2}(m_p+m_\Lambda)(m_p \pm \sqrt{s})(c_1 + c_k c_s)]\} \\
& +\{-(5c_1^2 + c_2 c_3) - \tfrac{1}{2}(m_p+m_\Lambda)(m_p \mp \sqrt{s})(5c_1 c_s + \tfrac{1}{s}c_2 c_k\}\Big]\, G_1 \pm \sqrt{s}\Big[d_\mp\{2b_p c_1\sqrt{s} + (m_p+m_\Lambda)(m_p \pm \sqrt{s}) \\
& \times\sqrt{s}(2c_1 - b_p c_s) \pm (m_p+m_\Lambda)(b_p b_q - 2c_1 k^2)\} + (m_p+m_\Lambda)\{5c_1(c_1 - b_p c_s) - \tfrac{1}{s}c_2 c_p k^2\}\Big]\, G_2 \\
& \pm 2\sqrt{s}\Big[4\sqrt{s}c_1 d_\mp(b_p \pm \frac{1}{\sqrt{s}}c_k m_\Lambda) - (m_\Lambda \mp \sqrt{s}) \times (10c_1^2 + 2c_2 c_3)\Big]\, G_3 \,, \\
A_2 \quad = \quad & \pm\frac{1}{t - m_k^2}\Big(2m_p\sqrt{s}\Big[d_\mp\{c_s k^2\sqrt{s}(m_p \mp \sqrt{s}) \mp [(c_1 + c_k c_s)k^2 - 2b_q c_k]\} + \{5c_1(k^2 c_s - 2b_q) - c_2 k^2(2 - \tfrac{1}{s}c_k)\}\Big]\, G_1 \\
& +2\sqrt{s}\Big[d_\mp\{(2c_1 k^2 + b_p c_s k^2 - 2b_p b_q)\sqrt{s} \pm (m_p \mp \sqrt{s})(2c_1 k^2 - b_p b_q)\} + (m_p \pm \sqrt{s})\{5c_1(b_p c_s - c_1) + \tfrac{1}{s}c_p c_2 k^2\}\Big] \\
& \times G_2 + 16 s k^2 c_1 d_\mp G_3\Big) \,, \\
A_3 \quad = \quad & \pm\sqrt{s}\Big(2m_p\Big[d_\mp\sqrt{s}\{-3c_1 + \tfrac{1}{2}k^2(1 + \tfrac{1}{s}c_\Lambda) \pm \tfrac{1}{2\sqrt{s}}(m_p \pm \sqrt{s})[c_1 - (1 + \tfrac{1}{s}c_\Lambda)c_k]\} + \tfrac{1}{2}(m_p \mp \sqrt{s})\{5c_1(1 + \tfrac{1}{s}c_\Lambda) \\
& - \tfrac{1}{s}c_2 c_k\}\Big]\, G_1 + \Big[d_\mp\{(m_p \pm \sqrt{s})\sqrt{s}[2c_1 + b_p(1 + \tfrac{1}{s}c_\Lambda)] \pm (b_p b_q - 2c_1 k^2 - 2b_p c_k)\} \\
& + \{5c_1[c_1 + b_p(1 + \tfrac{1}{s}c_\Lambda)] - \tfrac{1}{s}c_2 c_p k^2\}\Big]\, G_2 + 2\Big[\pm 4c_1 c_k d_\mp - (10c_1^2 + 2c_2 c_3)\Big]\, G_3 \,, \\
A_4 \quad = \quad & \pm\sqrt{s}\Big(2m_p\Big[d_\mp\sqrt{s}\{-(3c_1 + \tfrac{1}{2}c_s k^2) \pm \tfrac{1}{2\sqrt{s}}(m_p \pm \sqrt{s})(c_1 + c_k c_s)\} - \tfrac{1}{2}(m_p \mp \sqrt{s})\{5c_1 c_s \\
& + \tfrac{1}{s}c_2 c_k\}\Big]\, G_1 + \Big[d_\mp\{(m_p \pm \sqrt{s})\sqrt{s}[2c_1 - b_p c_s] \pm (b_p b_q - 2c_1 k^2)\} + \{5c_1[c_1 - b_p c_s] \\
& - \tfrac{1}{s}c_2 c_p k^2\}\Big]\, G_2 + 4\{\pm 2c_1 c_k d_\mp - (5c_1^2 + c_2 c_3)\} \times G_3\Big) \,,
\end{aligned}
$$

Four Models Analyzed

From the two formulations of spin 3/2 and 5/2 resonances used in the present analysis we obtain four combinations (models)

Model	Spin 3/2	Spin 5/2
Model A	Model 1	Model 1
Model B	Model 2	Model 1
Model C	Model 1	Model 2
Model D	Model 2	Model 2

Database

Observables	N_{data}
$d\sigma/d\Omega$	4745
P_Λ	2006
Σ	100
T	66
C_x	159
C_z	160
O_x	66
O_z	66
Total	7433

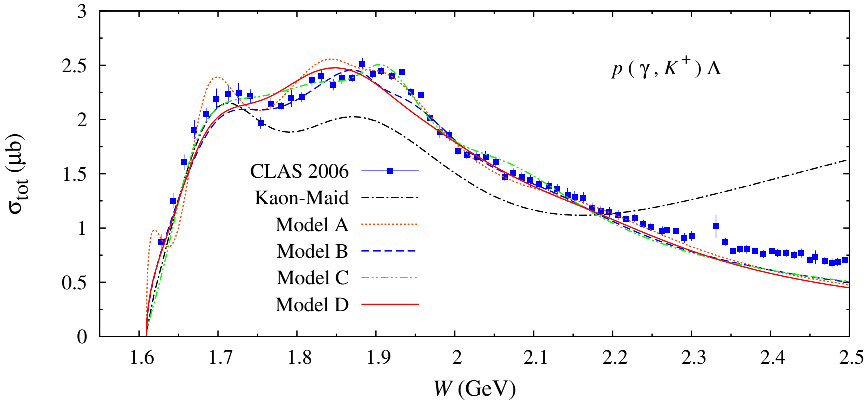
Nucleon resonances used in our calculation (PDG2014)

Resonance	Status	Mass (MeV)	Width (MeV)
$N(1440)P_{11}$	****	1430 ± 20	350 ± 100
$N(1520)D_{13}$	****	1515 ± 5	115^{10}_{-15}
$N(1535)S_{11}$	****	1535^{+20}_{-10}	150 ± 25
$N(1650)S_{11}$	****	1655^{+15}_{-10}	140 ± 30
$N(1675)D_{15}$	****	1675 ± 5	150^{+15}_{-20}
$N(1680)F_{15}$	****	1685 ± 5	130 ± 10
$N(1700)D_{13}$	***	1700 ± 50	150^{+100}_{-50}
$N(1710)P_{11}$	***	1710 ± 30	100^{+150}_{-50}
$N(1720)P_{13}$	****	1720^{+30}_{-20}	250^{+150}_{-100}
$N(1860)F_{15}$	**	1860^{+100}_{-40}	270^{+140}_{-50}
$N(1875)D_{13}$	***	1875^{+45}_{-55}	200 ± 25
$N(1880)P_{11}$	**	1870 ± 35	235 ± 65
$N(1895)S_{11}$	**	1895 ± 15	90^{+30}_{-15}
$N(1900)P_{13}$	***	1900	250
$N(2000)F_{15}$	**	2050 ± 100	198 ± 2
$N(2060)D_{15}$	**	2060	375 ± 25
$N(2120)D_{13}$	**	2120	330 ± 45

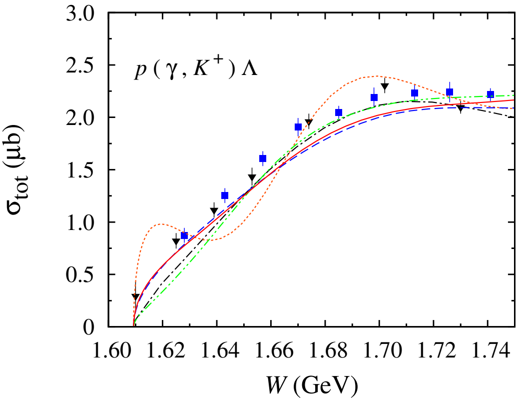
Extracted background parameters and the resonance hadronic cutoff Λ_R

Parameters	A	B	C	D
$g_{K\Lambda N}/\sqrt{4\pi}$	-3.37	-3.00	-3.00	-3.00
$g_{K\Sigma N}/\sqrt{4\pi}$	0.90	0.90	1.30	1.27
$G^V_{K^*}/4\pi$	-0.25	0.12	-0.37	0.15
$G^T_{K^*}/4\pi$	0.17	-0.08	0.72	0.26
$G^V_{K_1}/4\pi$	0.42	0.43	0.23	1.46
$G^T_{K_1}/4\pi$	-0.72	-0.08	-0.91	0.07
$G_{\Lambda(1600)}/4\pi$	-6.30	-9.00	5.12	8.41
$G_{\Lambda(1810)}/4\pi$	10.00	10.00	-4.48	-9.61
Λ_B (GeV)	0.72	0.89	0.70	0.70
Λ_R (GeV)	2.00	2.0	2.00	1.31
$\theta_\mathrm{had.}$ (deg)	180	122	56	130
$\phi_\mathrm{had.}$ (deg)	72	180	180	177
χ^2	15736	13192	14679	11724
N_data	7433	7433	7433	7433
$N_\mathrm{par.}$	74	86	84	96
$\chi^2/N_\mathrm{d.o.f}$	2.14	1.77	1.97	1.58

Comparison with experimental data, total cross section

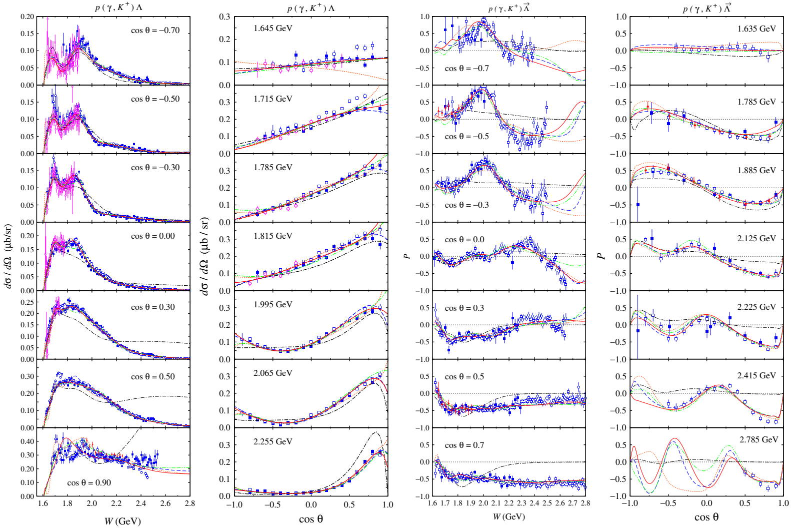


Total CS data are not used in the fit database

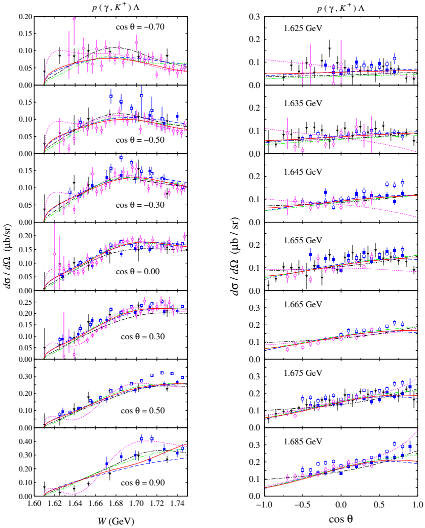


Oscillation in Model A originates from diff. CS

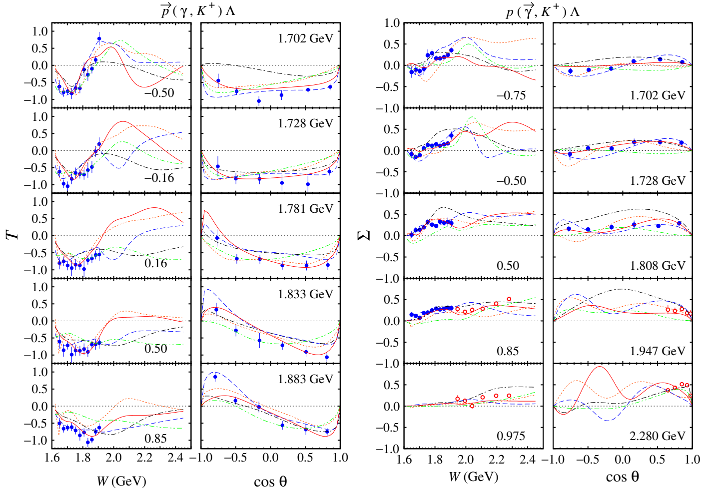
Comparison with experimental data, diff. cross section & recoil pol.



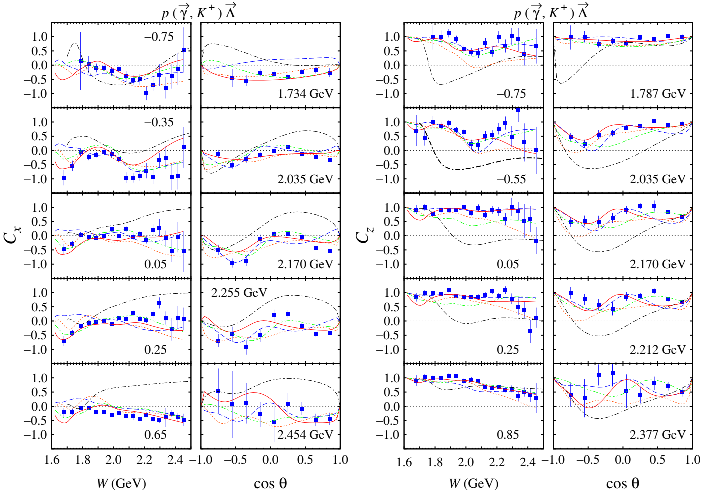
Comparison with experimental data, diff. cross section & recoil pol.



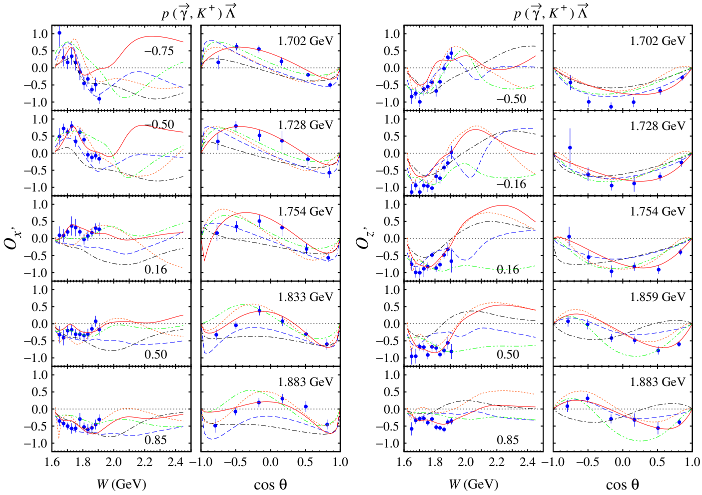
Comparison with experimental data, target & photon polarization



Comparison with experimental data, photon-recoil double polarization

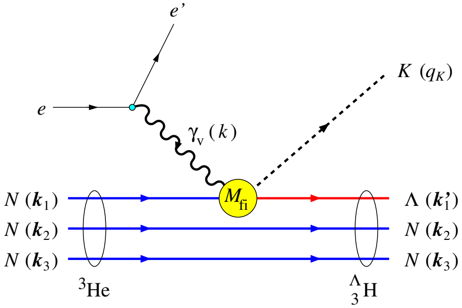


Comparison with experimental data, photon-recoil double polarization



To calculate the cross section we need the transition current

$$\langle \mathrm{f}|J^\mu|\mathrm{i}\rangle \quad = \quad \sqrt{3}\int d^3p\, d^3q\, \Psi_\mathrm{f}^*(p,q')\, J^\mu\,(k^0,k,k_1^0,k_1,k_1'^0,k_1',q_K^0,q_K)\Psi_\mathrm{i}(p,q)\ ,$$



where the three-body momentum coordinates

$$p \;=\; \frac{1}{2}(k_2-k_3)\ \ ,\ \ q \;=\; k_1\ ,$$

and the hyperon momentum in the hypertriton

$$q' \quad \equiv \quad k_1' \;=\; k_1+\frac{m_2+m_3}{m_1+m_2+m_3}\,Q,$$

with $Q = k - q_K$.

The transition amplitude $M_{\rm fi}$ is obtained from the isobar model.

Three-body wave functions

The initial wave function $\Psi_{\rm i}$ (Similar for the final $\Psi_{\rm f}$)

$$\begin{aligned}
\Psi_{\rm i}(p,q) &= \sum_{\alpha=(LSJljT)} \phi_\alpha(p,q) \left| \{(LS)J,(l\tfrac{1}{2})j\}\tfrac{1}{2}M_{\rm i} \right\rangle \left| (T\tfrac{1}{2})\tfrac{1}{2}M_t \right\rangle \\
&= \sum_{\alpha=(LSJljT)} \sum_{m_L m_S m_l m_s m_J m_j} \phi_\alpha(p,q)\,(Lm_L Sm_S|Jm_J) \\
&\quad (lm_l \tfrac{1}{2} m_s|jm_j)(Jm_J jm_j|\tfrac{1}{2}M_{\rm i})\, Y^L_{m_L}(\hat{p})\, Y^l_{m_l}(\hat{q}) \chi^S_{m_S} \chi^{\frac{1}{2}}_{m_s} \left| (T\tfrac{1}{2})\tfrac{1}{2}M_t \right\rangle ,
\end{aligned}$$

The transition current

$$\begin{aligned}
\langle {\rm f}|J^\mu|{\rm i}\rangle &= \sqrt{6} \sum_{\alpha,\alpha'} \sum_{\rm m,m'} \sum_{n,m_n} (Lm_L Sm_S|Jm_J)\,(Lm_L Sm_S|J'm_{J'})\,\left(lm_l\tfrac{1}{2}m_s|jm_j\right) \\
&\times \left(l'm_{l'}\tfrac{1}{2}m_{s'}|j'm_{j'}\right)\left(Jm_J jm_j|\tfrac{1}{2}M_{\rm i}\right)\left(J'm_{J'}j'm_{j'}|\tfrac{1}{2}M_{\rm f}\right)\left(\tfrac{1}{2}-m_{s'}\tfrac{1}{2}m_s|nm_n\right) \\
&\times (-1)^{n-\frac{1}{2}-m_{s'}}\,\delta_{LL'}\,\delta_{m_L m_{L'}}\,\delta_{SS'}\,\delta_{m_S m_{S'}}\,\delta_{T0} \\
&\times \int p^2 dp\, d^3q\, \phi_{\alpha'}(p,q')\,\phi_\alpha(p,q)\,Y^{l'}_{m_{l'}}(\hat{q}')\,Y^l_{m_l}(\hat{q})\,[j^\mu]^{(n)}_{m_n} .
\end{aligned}$$

The $[j^\mu]^{(n)}_{m_n} \to$ elementary operator $\propto \varepsilon_\mu j^\mu$.

Three-body wave functions

α	L	S	J	l	$2j$	$2T$	$P(^3\mathrm{He})$	$P(^3_\Lambda\mathrm{H})$
1	0	0	0	0	1	1	44.580	-
2	0	1	1	0	1	0	44.899	93.491
3	2	1	1	0	1	0	2.848	5.794
4	0	1	1	2	3	0	0.960	0.034
5	2	1	1	2	3	0	0.189	0.027
6	1	0	1	1	1	0	0.089	0.004
7	1	0	1	1	3	0	0.198	0.008
8	1	1	0	1	1	1	1.107	-
9	1	1	1	1	1	1	1.113	-
10	1	1	1	1	3	1	0.439	-
11	1	1	2	1	3	1	0.064	-
12	3	1	2	1	3	1	0.306	-
13	1	1	2	3	5	1	1.018	-
14	3	1	2	3	5	1	0.024	-
15	2	0	2	2	3	1	0.274	-
16	2	0	2	2	5	1	0.425	-
17	2	1	2	2	3	0	0.122	0.024
18	2	1	2	2	5	0	0.095	0.018
19	2	1	3	2	5	0	0.205	0.053
20	4	1	3	2	5	0	0.053	0.006
...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...
33	4	1	4	4	7	0	0.011	0.004
34	4	1	4	4	9	0	0.009	0.003

Nuclear cross section

Calculate

$$W^{\mu\nu} = \frac{1}{2}\sum_{M_{\rm i} M_{\rm f}} \langle \mathrm{f} | J^{\mu} | \mathrm{i} \rangle \langle \mathrm{f} | J^{\nu} | \mathrm{i} \rangle^* ,$$

related to the nuclear structure functions by

$$\begin{aligned}
W_{\rm T} &= \frac{1}{4\pi}\,(W_{xx} + W_{yy}) ,\\
W_{\rm L} &= \frac{1}{4\pi}\,W_{00} ,\\
W_{\rm TT} &= \frac{1}{4\pi}\,(W_{xx} - W_{yy}) ,\\
W_{\rm LT} &= \frac{1}{4\pi}\,(W_{0x} + W_{x0}) .
\end{aligned}$$

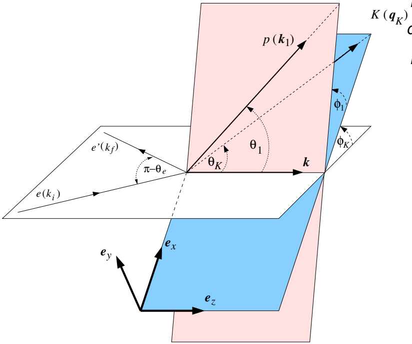
and obtain the cross sections

$$\begin{aligned}
\frac{d\sigma_{\rm T}}{d\Omega_K^{\rm c.m.}} &= \alpha_e\,\frac{q_K^{\rm c.m.}}{K_L}\,\frac{M_{^3_\Lambda{\rm H}}}{2W}\,W_{\rm T}^{\rm c.m.} ,\\
\frac{d\sigma_{\rm L}}{d\Omega_K^{\rm c.m.}} &= \alpha_e\,\frac{q_K^{\rm c.m.}}{K_L}\,\frac{M_{^3_\Lambda{\rm H}}}{W}\,W_{\rm L}^{\rm c.m.} ,\\
\frac{d\sigma_{\rm TT}}{d\Omega_K^{\rm c.m.}} &= \alpha_e\,\frac{q_K^{\rm c.m.}}{K_L}\,\frac{M_{^3_\Lambda{\rm H}}}{2W}\,W_{\rm TT}^{\rm c.m.} ,\\
\frac{d\sigma_{\rm LT}}{d\Omega_K^{\rm c.m.}} &= -\alpha_e\,\frac{q_K^{\rm c.m.}}{K_L}\,\frac{M_{^3_\Lambda{\rm H}}}{2W}\,W_{\rm LT}^{\rm c.m.} ,
\end{aligned}$$

where

$$\frac{d\sigma_v}{d\Omega_K} = \frac{d\sigma_{\rm T}}{d\Omega_K} + \varepsilon_{\rm L}\,\frac{d\sigma_{\rm L}}{d\Omega_K} + \varepsilon\,\frac{d\sigma_{\rm TT}}{d\Omega_K}\,\cos 2\phi_K + \sqrt{2\varepsilon_{\rm L}(1+\varepsilon)}\,\frac{d\sigma_{\rm LT}}{d\Omega_K}\,\cos\phi_K ,$$

Kinematics



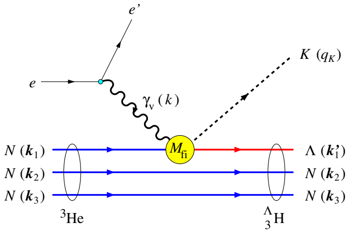
Required for technical calculation, e.g.,

$$
\begin{aligned}
\mathbf{k}_1 &= k_1\,(\sin\theta_1\cos\phi_1\,\mathbf{e}_x + \sin\theta_1\sin\phi_1\,\mathbf{e}_y + \cos\theta_1\,\mathbf{e}_z)\,,\\
\mathbf{q}_K &= q_K\,(\sin\theta_K\,\mathbf{e}_x + \cos\theta_K\,\mathbf{e}_z)\,,\\
\mathbf{k}_1' &= \mathbf{k}_1 + \tfrac{2}{3}\,(\mathbf{k} - \mathbf{q}_K)\\
&= (k_1\sin\theta_1\cos\phi_1 - \tfrac{2}{3}q_K\sin\theta_K)\,\mathbf{e}_x + (k_1\sin\theta_1\sin\phi_1)\,\mathbf{e}_y\\
&\quad +(k_1\cos\theta_1 + \tfrac{2}{3}k - \tfrac{2}{3}q_K\cos\theta_K)\,\mathbf{e}_z\\
&\equiv k_1'\,(\sin\theta_1'\cos\phi_1'\,\mathbf{e}_x + \sin\theta_1'\sin\phi_1'\,\mathbf{e}_y + \cos\theta_1'\,\mathbf{e}_z)
\end{aligned}
$$

$$
\begin{aligned}
\mathbf{q}_K\cdot\mathbf{k} &= q_K k\,\cos\theta_K\,,\\
\mathbf{k}_1\cdot\mathbf{k} &= k_1 k\,\cos\theta_1\,,\\
\mathbf{q}_K\cdot\mathbf{k}_1 &= q_K k_1\,(\sin\theta_K\,\sin\theta_1\,\cos\phi_1 + \cos\theta_K\,\cos\theta_1)\,,\\
\mathbf{k}\times\mathbf{q}_K &= k q_K\,\sin\theta_K\,\mathbf{e}_y\,,\\
\mathbf{k}_1\times\mathbf{k} &= k_1 k\,\sin\theta_1\,(\sin\phi_1\,\mathbf{e}_x - \cos\phi_1\,\mathbf{e}_y)\,,\\
\mathbf{k}_1'\times\mathbf{k}_1 &= \tfrac{2}{3}\,(\mathbf{k}\times\mathbf{k}_1 - \mathbf{q}_K\times\mathbf{k}_1)\,,
\end{aligned}
$$

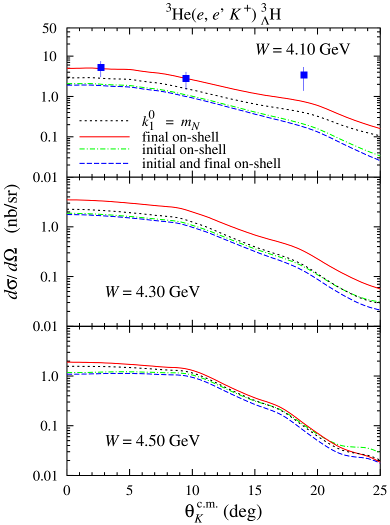
Investigate the Off-Shell Assumptions

- both initial and final baryons are on-shell $[k_1^0 = (m_N^2 + k_1^2)^{1/2}$, $k_1'^0 = (m_Y^2 + k_1'^2)^{1/2}]$,
- the initial nucleon is on-shell and the final hyperon is off-shell $[k_1^0 = (m_N^2 + k_1^2)^{1/2}$, $k_1'^0 = k_1^0 + k_0 - E_K]$,



- the initial nucleon is off-shell and the final hyperon is on-shell, $[k_1^0 = k_1'^0 + E_K - k_0,\ k_1'^0 = (m_Y^2 + k_1'^2)^{1/2}]$,
- both initial and final baryons are off-shell. In this case the static approximation $k_1^0 = m_N$ is used for the initial nucleon, while $k_1'^0 = k_1^0 + k_0 - E_K$.

Result

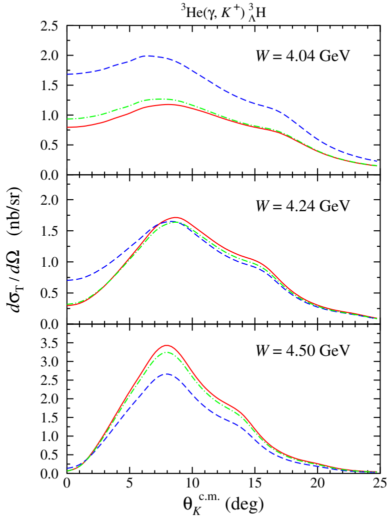


"final on-shell" is closer to exp. data
$\rightarrow$ Hyperon in the final state is weakly bound
$\rightarrow$ 130 keV

Data from: F. Dohrmann *et al.*, Phys. Rev. Lett. **93**, 242501 (2004)

T.M. and B. Van Der Ventel, Phys. Rev. C **78**, 014004 (2008)

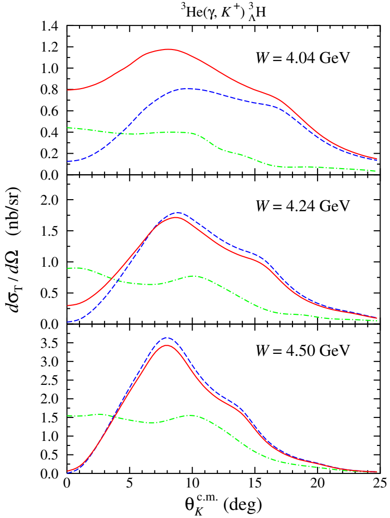
Effects of Fermi motion



- dashed curve → "frozen nucleon" approximation $\langle k_1 \rangle = 0$
- dash-dotted curve → average momentum approximation $\langle k_1 \rangle = -\frac{1}{3} Q$
- solid curve → exact treatment of Fermi motion

T.M. and B. Van Der Ventel, Phys. Rev. C **78**, 014004 (2008)

Different elementary models



- dashed curve → Kaon-Maid without missing resonance
- dash-dotted curve → Very simple model
- solid curve → Kaon-Maid with missing resonance

T.M. and B. Van Der Ventel, Phys. Rev. C **78**, 014004 (2008)

Limiting the number of partial waves

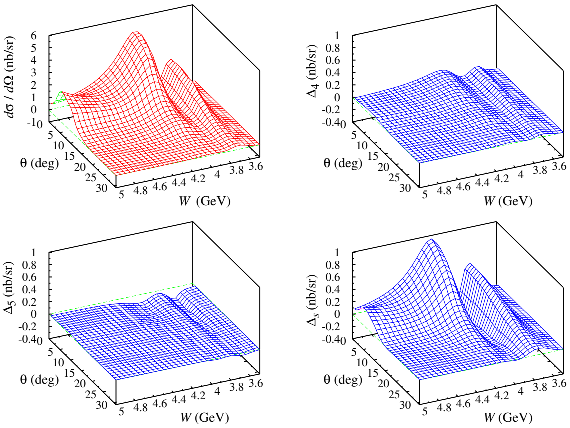
The integrations requires heavy numerical calculation. To obtain one point in the plot of observables integrations using $34 \times 16 \times 34 \times 20 \times 30 \times 10 = 110{,}976{,}000$ grid points is necessary

$\rightarrow$ limit the number of partial waves

α	L	S	J	l	$2j$	$2T$	$P(^3\mathrm{He})$	$P(^3_\Lambda\mathrm{H})$
1	0	0	0	0	1	1	44.580	-
2	0	1	1	0	1	0	44.899	93.491
3	2	1	1	0	1	0	2.848	5.794
4	0	1	1	2	3	0	0.960	0.034
5	2	1	1	2	3	0	0.189	0.027
6	1	0	1	1	1	0	0.089	0.004
7	1	0	1	1	3	0	0.198	0.008
8	1	1	0	1	1	1	1.107	-
9	1	1	1	1	1	1	1.113	-
...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...
...	...	...	...	...	...	...	...	...
33	4	1	4	4	7	0	0.011	0.004
34	4	1	4	4	9	0	0.009	0.003

Limiting the number of partial waves

full calculation | full $-\alpha \leq 5$



full $-\alpha \leq 4$ | full $-s$ wave only

T.M. Nucl. Phys. A **815**, 18 (2009)

New calculation

In this approach the ^{3}He wave functions reads

$$\Psi_{J_bM_b}(\mathbf{r}_b,\mathbf{R}_b) = \sum_{b=1}^{3}\sum_{t_a,s_b,\Sigma_b}\sum_{\ell_b,L_b,I_b}\left[\left[\eta_{1/2}(N_i)\,\eta_{1/2}(N_j)\right]_{t_a}\eta_{1/2}(N_k)\right]_{T,T_z}$$
$$\times\left[\left[\left[\chi_{1/2}(N_i)\,\chi_{1/2}(N_j)\right]_{s_b}\chi_{1/2}(N_k)\right]_{\Sigma_b}\left[\phi_{\ell_b}(\mathbf{r}_b)\,\varphi_{L_b}(\mathbf{R}_b)\right]_{I_b}\right]_{J_bM_b},$$

whereas the hypertriton wave function can be written as

$$\Psi_{J_aM_a}(\mathbf{r}_a,\mathbf{R}_a) = \sum_{a=1}^{3}\sum_{s_a,\Sigma_a}\sum_{\ell_a,L_a,I_a}\left[\eta_{1/2}(N_1)\,\eta_{1/2}(N_2)\right]_{t=0,t_z=0}$$
$$\times\left[\left[\left[\chi_{1/2}(N_1)\,\chi_{1/2}(N_2)\right]_{s_a}\chi_{1/2}(\Lambda)\right]_{\Sigma_a}\left[\phi_{\ell_a}(\mathbf{r}_a)\,\varphi_{L_a}(\mathbf{R}_a)\right]_{I_a}\right]_{J_aM_a}.$$

Jacoby coordinate system for three-body states

The relation between the possible configurations is expressed by

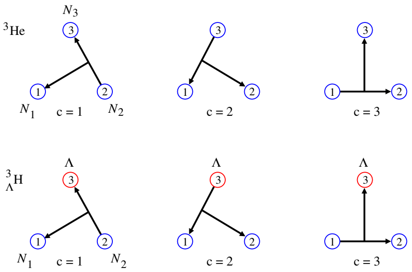
$$\chi^{(b)}_{1/2}(s_b, 1/2) \quad = \quad \sum_s U^{(\pm,0)}_{1/2}(s_b, s)\, \chi^{(3)}_{1/2}(s, 1/2),$$

with the "transportation" coefficients

$$U^{(+)}_{1/2} \quad = \quad \begin{pmatrix} -1/2 & -\sqrt{3}/2 \\ \sqrt{3}/2 & -1/2 \end{pmatrix},$$

$$U^{(-)}_{1/2} \quad = \quad \begin{pmatrix} -1/2 & \sqrt{3}/2 \\ -\sqrt{3}/2 & -1/2 \end{pmatrix},$$

$$U^{(0)}_{1/2} \quad = \quad \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}.$$



Jacobi coordinates for the possible ^{3}He and $^3_\Lambda$H configurations

The transition matrix

By writing the elementary operator as

$$\mathscr{O} \;=\; \mathscr{O}_I\,(L + i\sigma\cdot\mathbf{K})\, e^{i\mathbf{t}\cdot\mathbf{r}_p},$$

where L and $\mathbf{K}$ are obtained from the isobar model, the nuclear transition matrix element in the laboratory frame can be written as

$$\begin{aligned}
&\left\langle \Psi_{J_aM_a}({}^3_\Lambda\mathrm{H})\,|\mathscr{O}|\,\Psi_{J_bM_b}({}^3\mathrm{He})\right\rangle \;=\; \sum_{a,b}\sum_{t} U_T^{b\to 3}(t_b,t) \\
&\times\left\langle \left[\left[\eta_{1/2}(N_1)\,\eta_{1/2}(N_2)\right]_t\,\eta_0(\Lambda)\right]_{T=0}\,|\mathscr{O}_I|\left[\left[\eta_{1/2}(N_i)\,\eta_{1/2}(N_j)\right]_{t_a}\eta_{1/2}(N_k)\right]_{T=1/2}\right\rangle \\
&\times\sum_{\Sigma_a\Sigma_b}\sum_{s_as_b}\sum_{l_al_b}\sum_{s} U_{\Sigma_b}^{b\to 3}(s_b,s)\left\langle\left[\left[\chi_{1/2}(N_1)\chi_{1/2}(N_2)\right]_{s_a}\chi_{1/2}(N_3)\right]_{\Sigma_a m_{\Sigma_a}}\,|L+i\sigma\cdot\mathbf{K}| \right. \\
&\times\left.\left[\left[\chi_{1/2}(N_1)\,\chi_{1/2}(N_2)\right]_{s_b}\,\chi_{1/2}(N_3)\right]_{\Sigma_b m_{\Sigma_b}}\right\rangle \\
&\times\left\langle\left[\phi_{\ell_a}(\mathbf{r}_a)\,\varphi_{L_a}(\mathbf{R}_a)\right]_{l_aM_a}|e^{i\mathbf{t}\cdot\mathbf{r}_p}|\left[\phi_{\ell_b}(\mathbf{r}_b)\,\varphi_{L_b}(\mathbf{R}_b)\right]_{l_bM_b}\right\rangle,
\end{aligned}$$

The transition matrix

The last bracket can be written as

$$\begin{aligned} F_{\alpha\beta}(\mathbf{t}) &= \left\langle \left[\phi_{\ell_a}(\mathbf{r}_a)\,\varphi_{L_a}(\mathbf{R}_a)\right]_{I_a M_a} \middle| e^{i\mathbf{t}\cdot\mathbf{r}_p} \middle| \left[\phi_{\ell_b}(\mathbf{r}_b)\,\varphi_{L_b}(\mathbf{R}_b)\right]_{I_b M_b} \right\rangle \\ &= \sum_{\lambda,\mu} i^{\lambda}\, f^{(\lambda)}_{I_a I_b}(t)\, Y_{\lambda\mu}(\hat{\mathbf{x}})\,(I_b M_b \lambda\mu | I_a M_a) \ , \end{aligned}$$

with

$$f^{(\lambda)}_{I_a I_b}(t) = \sum_n A_n(\lambda, I_a, I_b)\left(\frac{\pi}{u_n}\right)^{\frac{3}{2}}\left(\frac{t}{2u_n}\right)^{\lambda} e^{-t^2/4u_n} \ ,$$

where $A_n(\lambda, I_a, I_b)$ is obtained from the Gaussian expansion method:
E. Hiyama, Y. Kino and M. Kamimura, Prog. Part. Nucl. Phys. **51**, 223 (2003)

$$\frac{d\sigma}{d\Omega} \quad \propto \quad \left|\left\langle \Psi_{J_a M_a}({}^3_\Lambda\mathrm{H})\,|\mathscr{O}|\,\Psi_{J_b M_b}({}^3\mathrm{He})\right\rangle\right|^2$$

Conclusion

- New model for kaon photoproduction which includes spin 3/2 and 5/2 nucleon resonances has been proposed
- The consistent gauge-invariant formulation of the spin 3/2 and 5/2 interactions leads to a better agreement with experimental data
- A reliable elementary model is required for accurate prediction of the hypernuclear photo- and electroproduction
- A new framework has been established to calculate the hypernuclear photo- and electroproduction

THANK YOU FOR YOUR PATIENCE