N^* and Δ^* in K^*Y and KY^* ($Y = \Lambda, \Sigma$) production reactions

Fei Huang

University of Chinese Academy of Sciences, Beijing, China

Dec. 29, 2024, Lanzhou

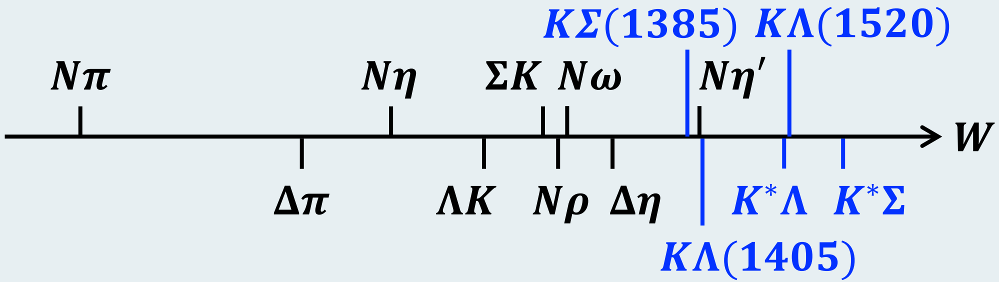
Outline

- Motivation
- Experimental & theoretical status, and our results for:
  - $\gamma p \to K^+\Sigma^0(1385), \gamma n \to K^+\Sigma^-(1385), \pi^+ p \to K^+\Sigma^+(1385)$
  - $\gamma p \to K^+\Lambda(1405)$
  - $\gamma p \to K^{*+}\Lambda, \gamma n \to K^{*0}\Lambda$
  - $\gamma p \to K^+\Lambda(1520)$
  - $\gamma p \to K^{*+}\Sigma^0, \gamma p \to K^{*0}\Sigma^+$
- Summary

Why K^*Y & KY^* production reactions?

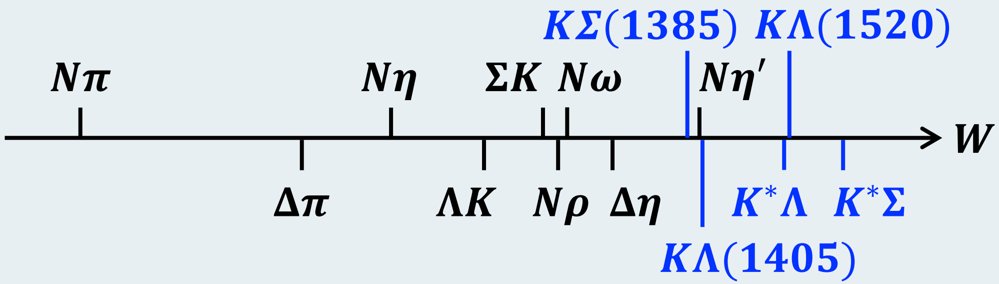
Particle	J^P	overall	Status as seen in $N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$
N	$1/2^+$	****										
$N(1440)$	$1/2^+$	****	****	****	****	***						
$N(1520)$	$3/2^-$	****	****	****	****	**	****					
$N(1535)$	$1/2^-$	****	****	****	***	*	****					
$N(1650)$	$1/2^-$	****	****	****	***	*	****	*				
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*			
$N(1680)$	$5/2^+$	****	****	****	****	***	*	*	*			
$N(1700)$	$3/2^-$	***	**	***	***	*	*			*		
$N(1710)$	$1/2^+$	****	****	****	*		***	**	*	*	*	
$N(1720)$	$3/2^+$	****	****	****	***	*	*	****	*	*	*	
$N(1860)$	$5/2^+$	**	*	**		*	*					
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**		*	**
$N(1990)$	$7/2^+$	**	**	**			*	*	*			
$N(2000)$	$5/2^+$	**	**	*	**	*	*				*	
$N(2040)$	$3/2^+$	*		*								
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*	
$N(2100)$	$1/2^+$	***	**	***	**	**	*	*		*	*	**
$N(2120)$	$3/2^-$	***	***	**	**	**		**	*		*	*
$N(2190)$	$7/2^-$	****	****	****	****	**	*	**	*	*	*	
$N(2220)$	$9/2^+$	****	**	****			*	*	*			
$N(2250)$	$9/2^-$	****	**	****			*	*	*			
$N(2300)$	$1/2^+$	**		**								
$N(2570)$	$5/2^-$	**		**								
$N(2600)$	$11/2^-$	***		***								
$N(2700)$	$13/2^+$	**		**								

PDG (2024)



- Most N^* & Δ^* come from $\gamma N, \pi N \to \pi N, \pi\Delta, N\eta, K\Lambda, K\Sigma$
- No N^* or Δ^* information on K^*Y & KY^*
- K^*Y & KY^* : suitable to study N^* & Δ^* with higher masses

How to study?



$$T_{fi} = V_{fi} + \sum \int V_{fm} G_m T_{mi}$$

Step 1: tree level $\quad T_{fi} = V_{fi} \quad$ done

Step 2: K^*Y & KY^* intermediate channels

$$T_{fi} = V_{fi} + \sum_{KY^*, K^*Y} \int V_{fm} G_m T_{mi}$$

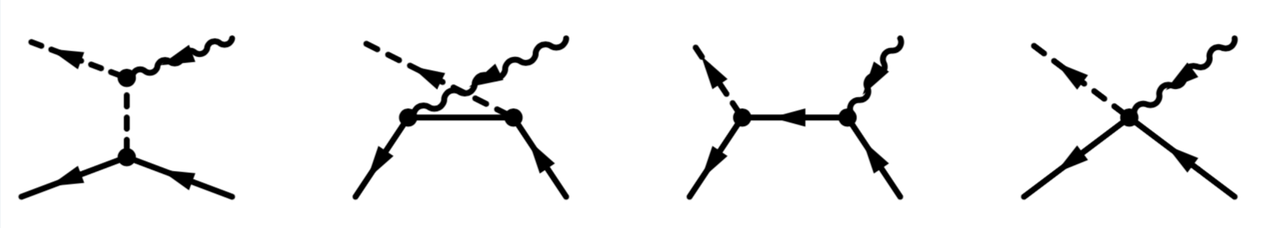
underway; meson-beam data needed

Step 3: all channels

$$T_{fi} = V_{fi} + \sum \int V_{fm} G_m T_{mi}$$

long future plan

Effective Lagrangian approach



$$M = M_t + M_u + M_s + M_{int}$$

- t channel: κ, K, K^*
- u channel: Λ, Σ, Λ^*, Σ^*
- s channel: N, Δ, N^*, Δ^*

SU(3) relations & known decay widths used to fix couplings

Others left as fit parameters

Cautions: resonance selection
gauge invariance

Strategy of choosing resonances

D.G. Ireland, E. Pasyuk and I. Strakovsky / Progress in Particle and Nuclear Physics 111 (2020) 103752

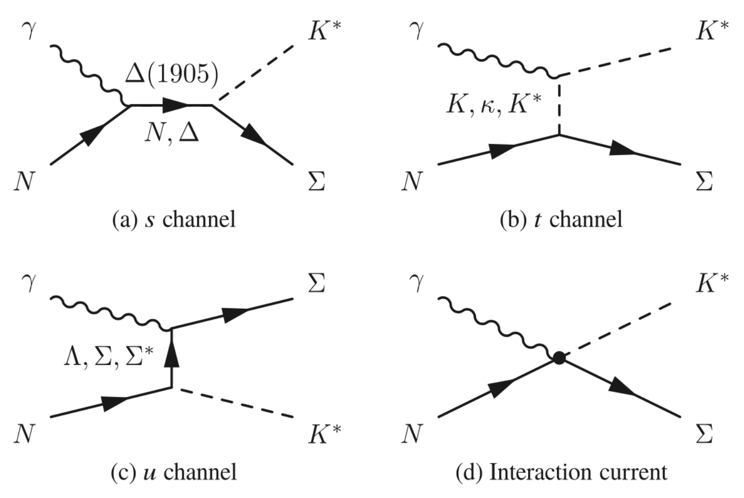
"… how does one choose which resonant states to include? This is a model comparison problem, since adding more resonances will mean the addition of more parameters, thereby making a fit to the data easier. On the other hand, an Occam's razor approach to keep the model as simple as possible should act to reduce the number of resonances that require to be invoked."

- **Introduce N^*'s & Δ^*'s as few as possible**
- **4-star or 3-star resonances: M_R, Γ_R, g_γ taken from PDG**
  Other resonances: fit parameters

Gauge invariance

H. Haberzettl, PRC 56 (1997) 2041

Take $\gamma p \to K^*\Sigma$ as an example:



$$M^{\nu\mu} = M_s^{\nu\mu} + M_t^{\nu\mu} + M_u^{\nu\mu} + M_{int}^{\nu\mu}$$

$$M_{int}^{\nu\mu} = \Gamma^{\nu}_{\Sigma N K^*}(q) C^{\mu} + M_{KR}^{\nu\mu} f_t$$

$$C^{\mu} = -Q_N \frac{f_s - \hat{F}}{s - p^2}(2p + k)^{\mu} - Q_{K^*} \frac{f_t - \hat{F}}{t - q^2}(2q - k)^{\mu} - Q_{\Sigma} \frac{f_u - \hat{F}}{u - p'^2}(2p' - k)^{\mu}$$

$$\hat{F} = 1 - \hat{h}(1 - \delta_s f_s)(1 - \delta_t f_t)(1 - \delta_u f_u)$$

$\hat{h}$: goes to unity in the high-energy limit; usually set to be 1 for simplicity.

f_t, f_s, f_u: form factors

$M^{\nu\mu}$: satisfies generalized WTI (fully gauge invariant)

$K\Sigma(1385)$ production reactions:

$$\gamma p \to K^+\Sigma^0(1385)$$

$$\gamma n \to K^+\Sigma^-(1385)$$

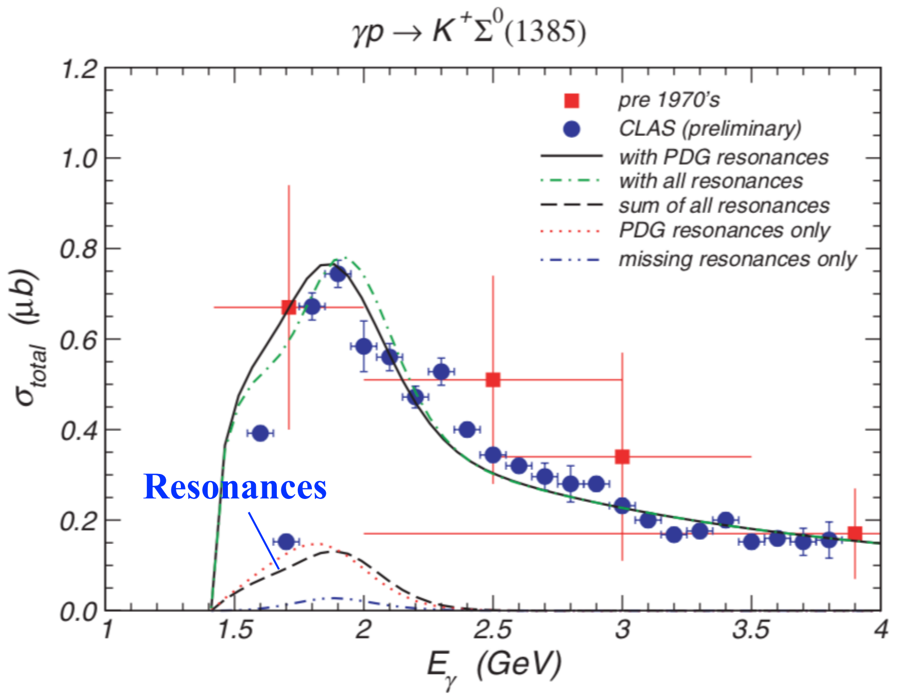
$$\pi^+ p \to K^+\Sigma^+(1385)$$

Experimental status

	Observable	Source	W (GeV)	ND	Reference
$\gamma p \to K^+\Sigma^0(1385)$	$d\sigma/d\Omega$	CLAS	2.0 ~ 2.8	144	PRC 88 (2013) 045201
	σ			9	
$\gamma n \to K^+\Sigma^-(1385)$	$d\sigma/d\Omega$	LEPS	1.92 ~ 2.32	36	PRL 102 (2009) 012501
	Σ			3	
	σ			9	
	$d\sigma/d\Omega$	CLAS	1.97 ~ 2.32	54	IJMPCS 26 (2014) 1460101
$\pi^+ p \to K^+\Sigma^+(1385)$	$d\sigma/d\Omega$	LBNL	1.89 ~ 2.09	60	PRD 4 (1971) 1296
	σ			7	

Work of Oh, Ko, and Nakayama

Y. Oh, C.M. Ko, and K. Nakayama, PRC 77 (2008) 045204



- **8 resonances considered**

  Masses & couplings taken from a quark model

  Widths set to be 300 MeV

- **Preliminary data on σ**

- **Main resonance contributions:**

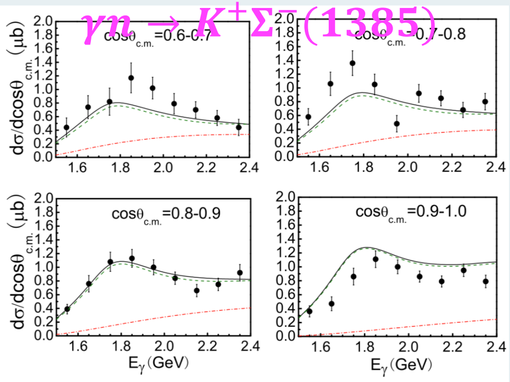
  $N(2080)3/2^-, N(2095)3/2^-,$

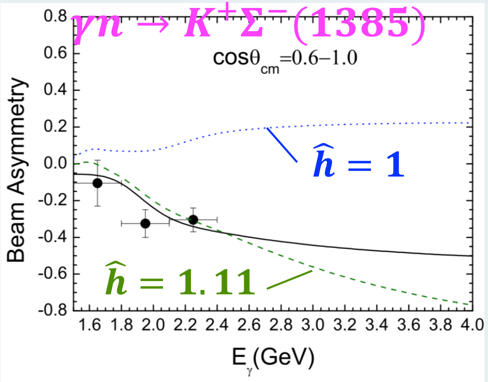
  $\Delta(1940)3/2^-, \Delta(2000)5/2^+$

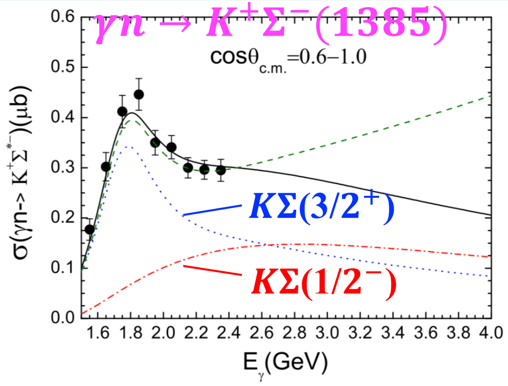
Work of Gao, Wu, and Zou

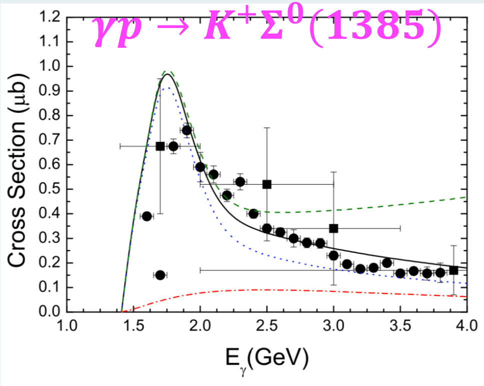
P. Gao, J.J. Wu, and B.S. Zou, PRC 81 (2010) 055203

- **Including $\gamma n \to K^+\Sigma^-(1380)$ helps to reproduce negative Σ**
- **$N(2080), \Delta(1940), \Delta(2000)$ are considered**
- **Σ data can also be described by adjust $\hat{h}$ parameter in contact current**





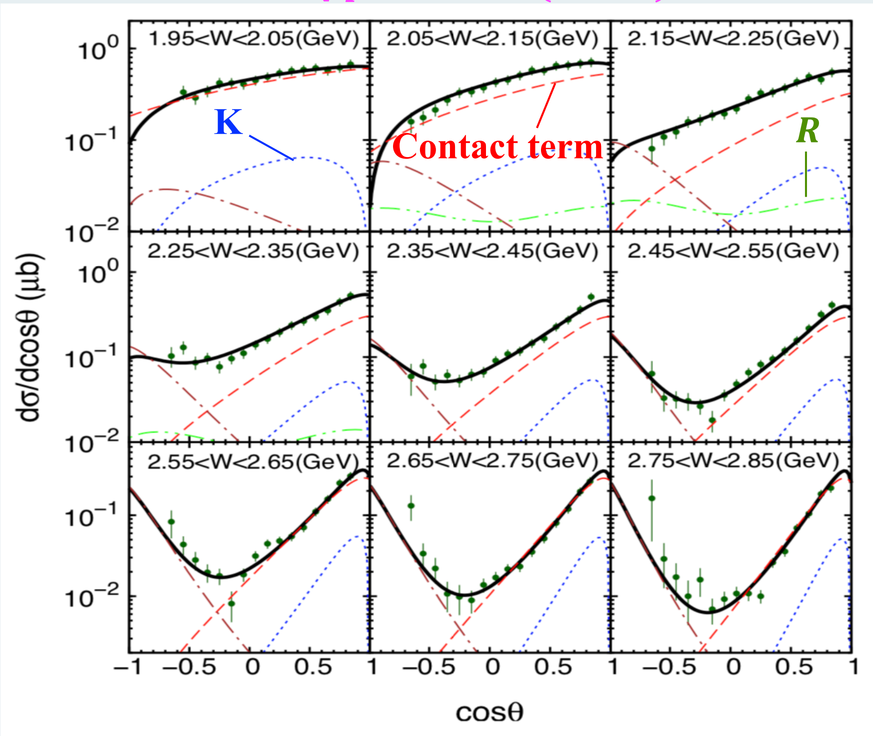




Work of He

J. He, PRC 89 (2014) 055204

$\gamma p \to K^+\Sigma^0(1385)$



- **9 resonances considered**

  Masses & couplings taken from a quark model

  Widths set to be 500 MeV

- **Fit data on $d\sigma/d\Omega$**
- **Main contributions from contact term**
- **Resonance contributions are small due to large widths**

Work of Xie, Wang, and Zou

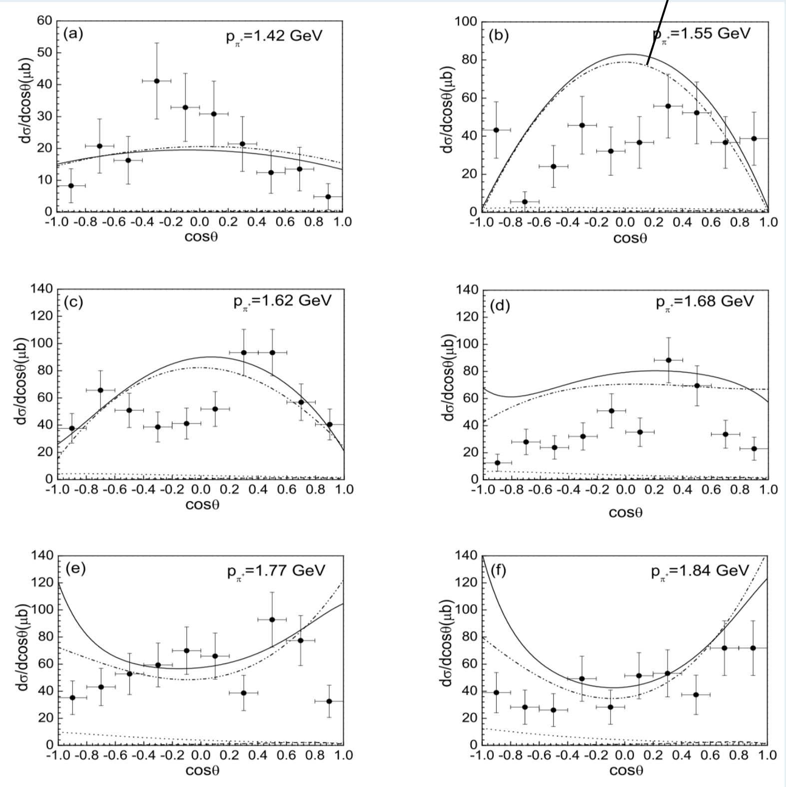
J.J. Xie, E. Wang, and B.S. Zou, PRC 90 (2014) 025207

- **Combined analysis of data on $\pi^+ p \to K^+\Sigma^+(1385)$ & $pp \to nK^+\Sigma^+(1385)$**

- **$\Delta(1940)3/2^-$ plays significant role on angular distributions for $\pi^+ p \to K^+\Sigma^+(1385)$**

$\pi^+ p \to K^+\Sigma^+(1385)$

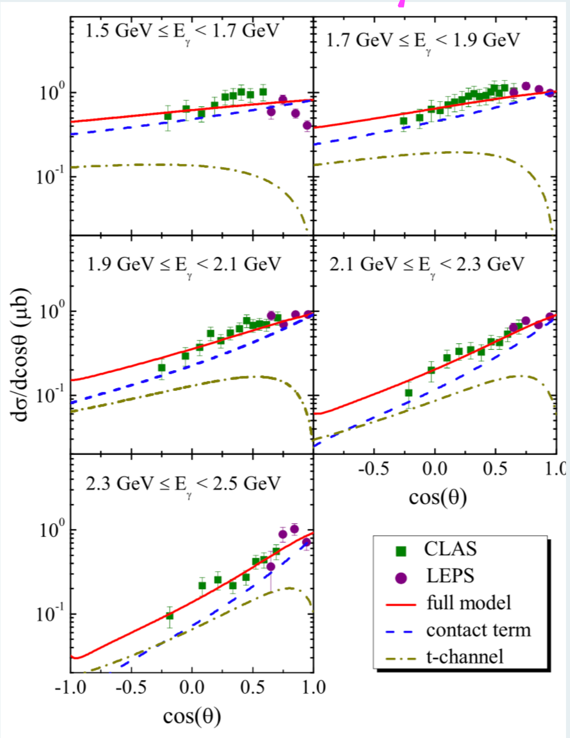
$\Delta(1940)\,3/2^-$

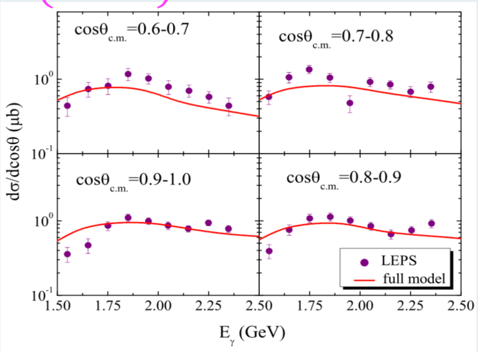


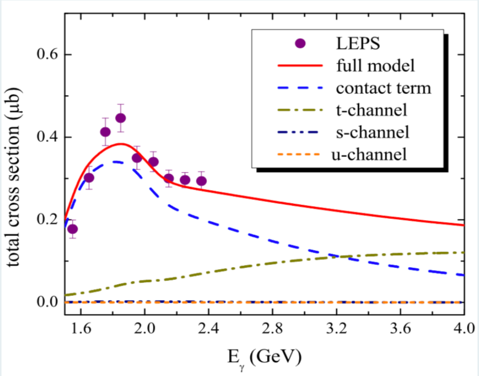
Work of Wang, He, and Haberzettl

X.Y. Wang, J. He, and H. Haberzettl, PRC 93 (2016) 045204

$\gamma n \to K^+\Sigma^-(1385)$





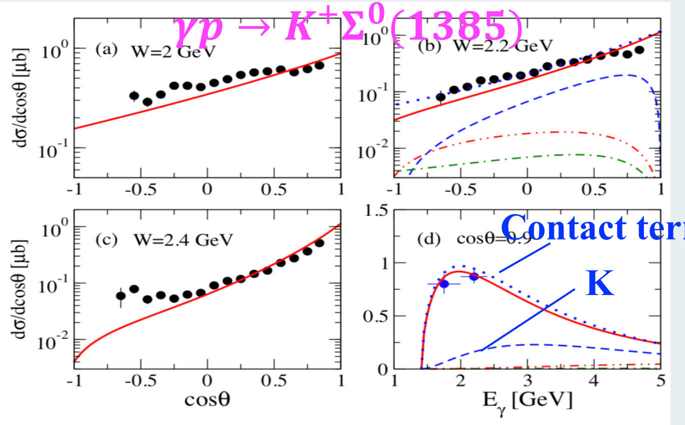


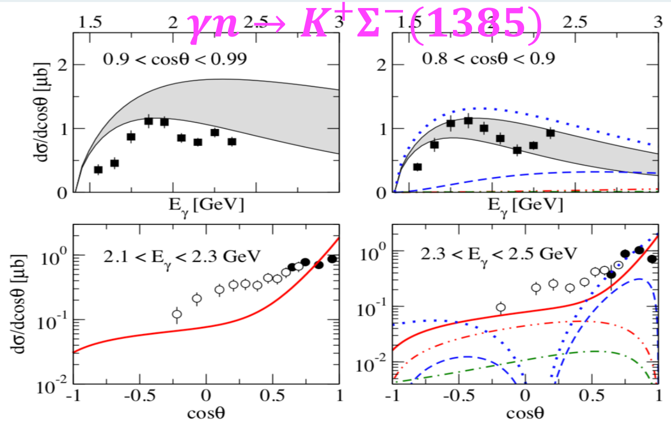
- **Interpolated Regge model for t-channel interaction**
- **Fit data on $d\sigma/d\Omega$**
- **Contact term dominates**
- **Resonances not needed**

Work of Yu and Kong

B.G. Yu and K.J. Kong, PRC 95 (2017) 065210

- Reggeized t-channel interaction
- No resonances considered
- Fit data on $d\sigma/d\Omega$ for $\gamma p \to K^+\Sigma^0(1385)$ and $\gamma n \to K^+\Sigma^-(1385)$
- Main contributions are from contact term and K exchange





Our model & results

A.C. Wang et al., PRD 101 (2020) 074025; 105 (2022) 034017

- Combined analysis of

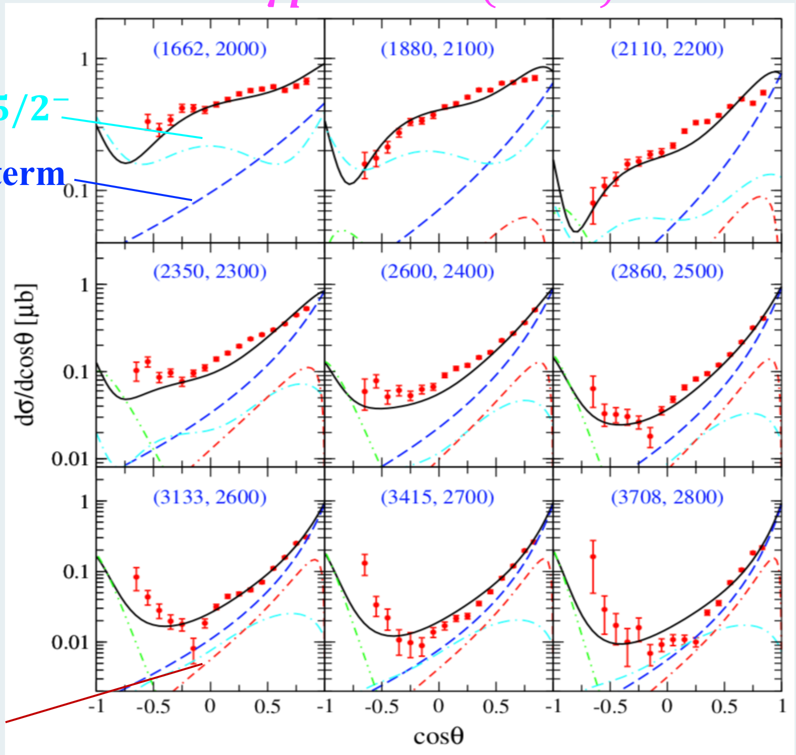
  $\gamma p \to K^+\Sigma^0(1385)$

  $\gamma n \to K^+\Sigma^-(1385)$

  $\pi^+ p \to K^+\Sigma^+(1385)$

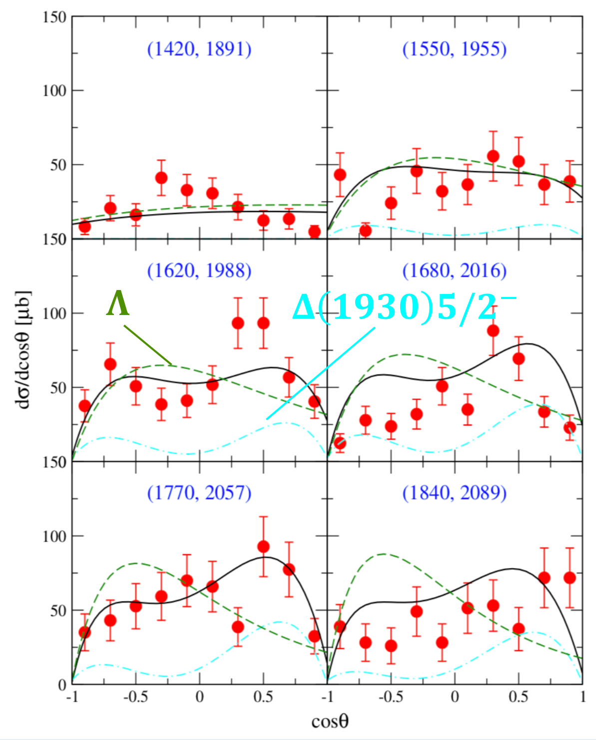
- All data are considered
- $\Delta(1930)5/2^-$ needed
- Photoproduction: $\Delta(1930)5/2^-$ (M & Γ from PDG), interaction current, and K dominate
- $\pi^+ p$ reaction: Λ dominates, $\Delta(1930)5/2^-$ considerable

$\gamma p \to K^+\Sigma^0(1385)$

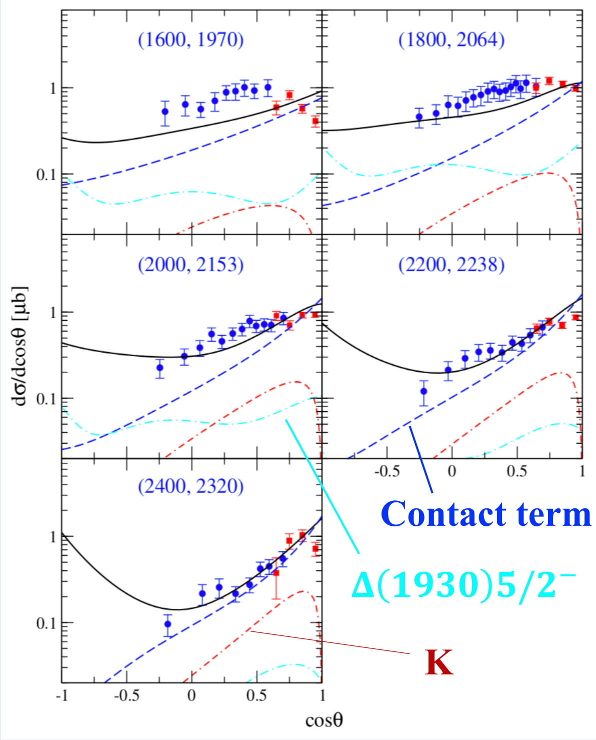


Our model & results

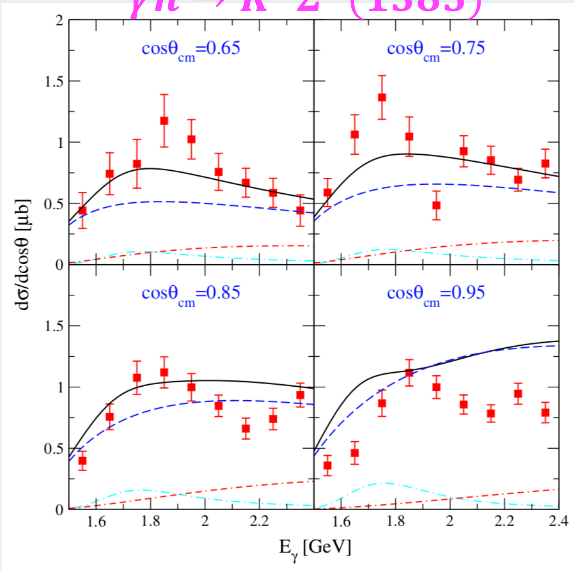
$\pi^+ p \rightarrow K^+ \Sigma^0(1385)$



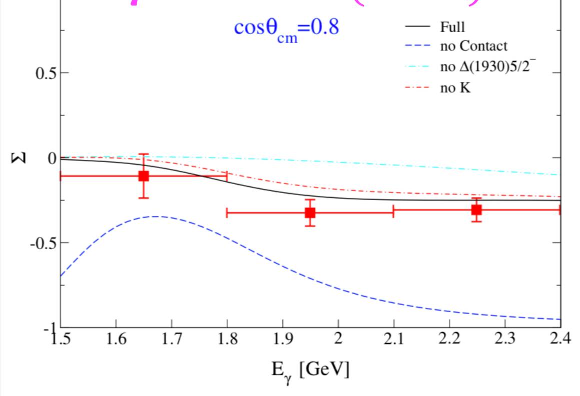
$\gamma n \rightarrow K^+ \Sigma^-(1385)$



$\gamma n \rightarrow K^+ \Sigma^-(1385)$



$\gamma n \rightarrow K^+ \Sigma^-(1385)$



$K\Lambda(1405)$ production reaction:

$$\gamma p \rightarrow K^{+}\Lambda(1405)$$

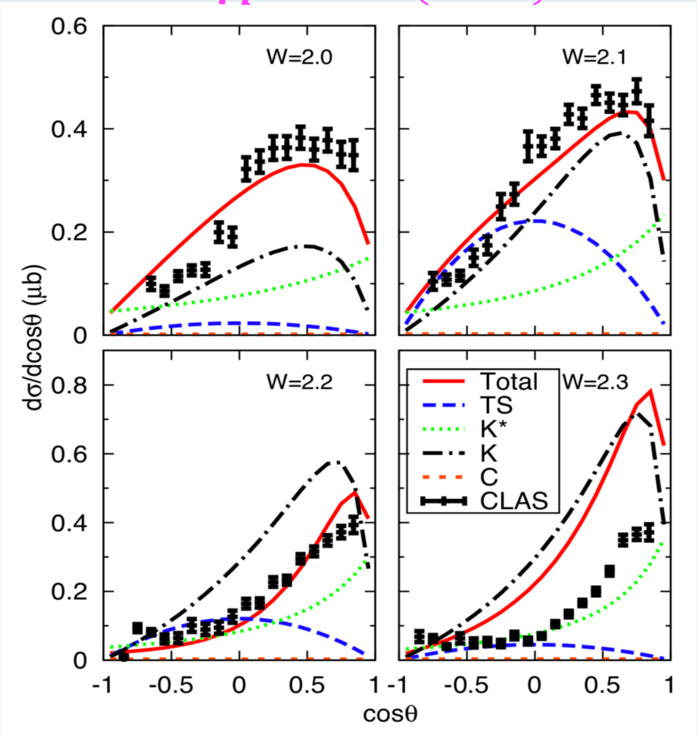
Experimental status

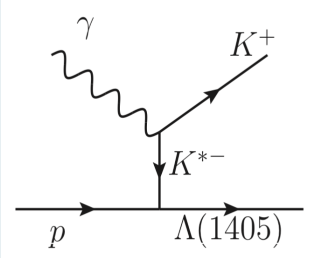
	Observable	Source	W (GeV)	ND	Reference
$\gamma p \rightarrow K^{+}\Lambda(1405)$	$d\sigma/d\Omega$	CLAS	$2.0 \sim 2.8$	162	PRC 88 (2013) 045201
	σ			9	

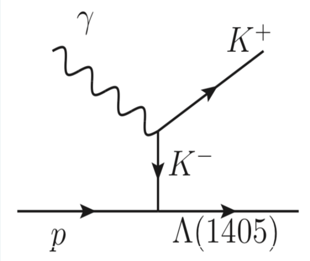
Work of Wang, Xie, and Liang et al.

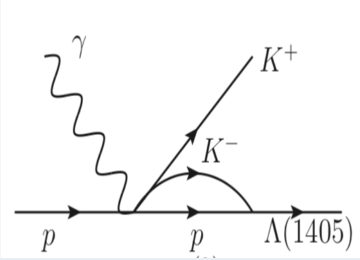
E. Wang, J.J. Xie, W.H. Liang, F.K. Guo, and E. Oset, PRC 95 (2017) 015205

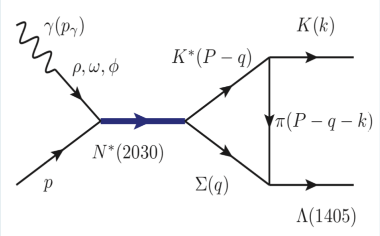
$\gamma p \to K^+ \Lambda(1405)$









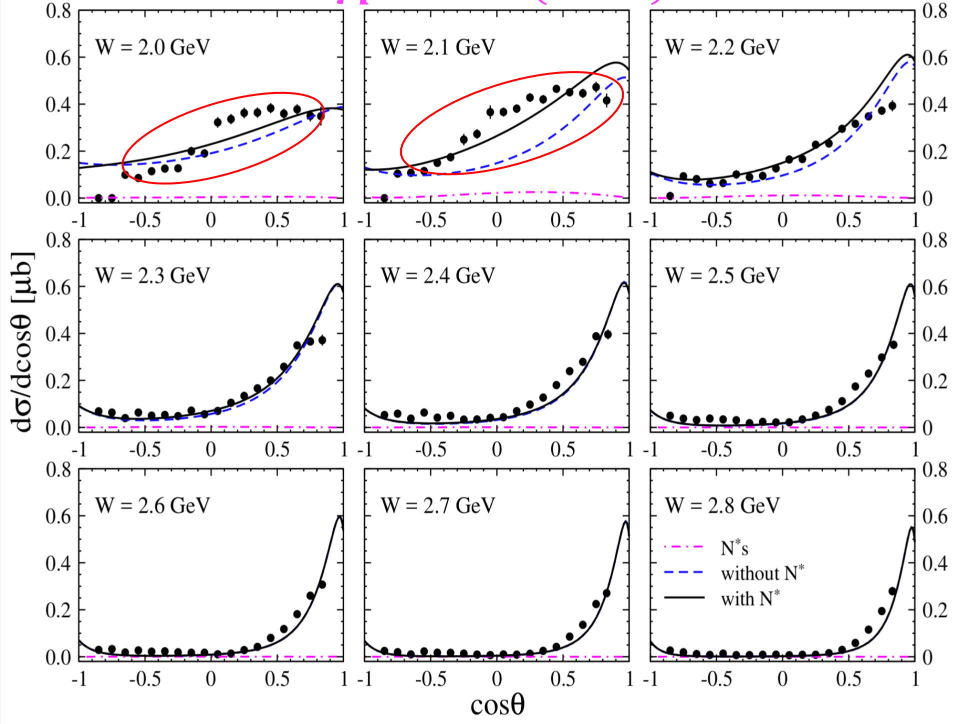


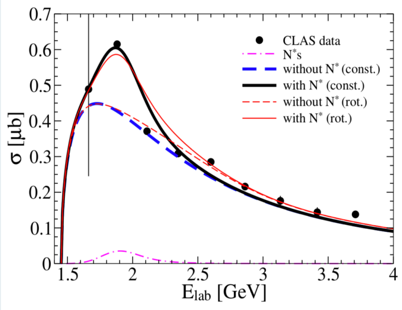
- **Triangle singularity produces a peak at 2.1 GeV**

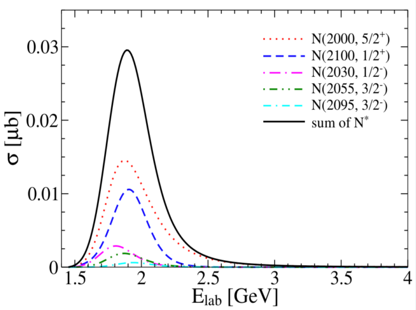
Work of Kim, Nam, Jido, and Kim

S.H. Kim, S-i. Nam, D. Jido, and H.C. Kim, PRD 96 (2017) 014003

$\gamma p \to K^+ \Lambda(1405)$







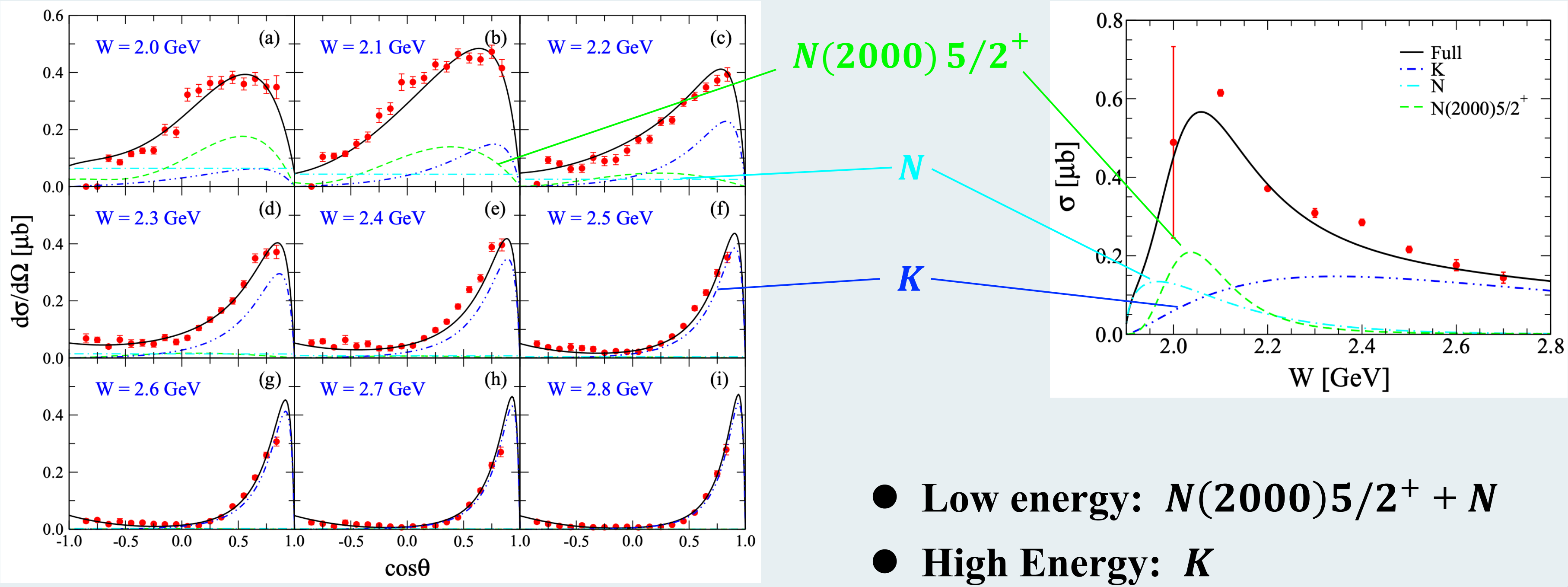
- **5 resonances included, 2 from PDG and 3 from quark model**

  Widths set to be 300 MeV
- $N(2000)5/2^+$, $N(2100)1/2^+$ **contributes considerably**

Our results

Y. Zhang and F. Huang, PRC 103 (2021) 025207

$\gamma p \to K^+ \Lambda(1405)$



- **Low energy:** $N(2000)5/2^+ + N$
- **High Energy:** K

$K^*\Lambda$ production reactions:

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

$$\gamma n \to K^{*0}\Lambda$$

Experimental status

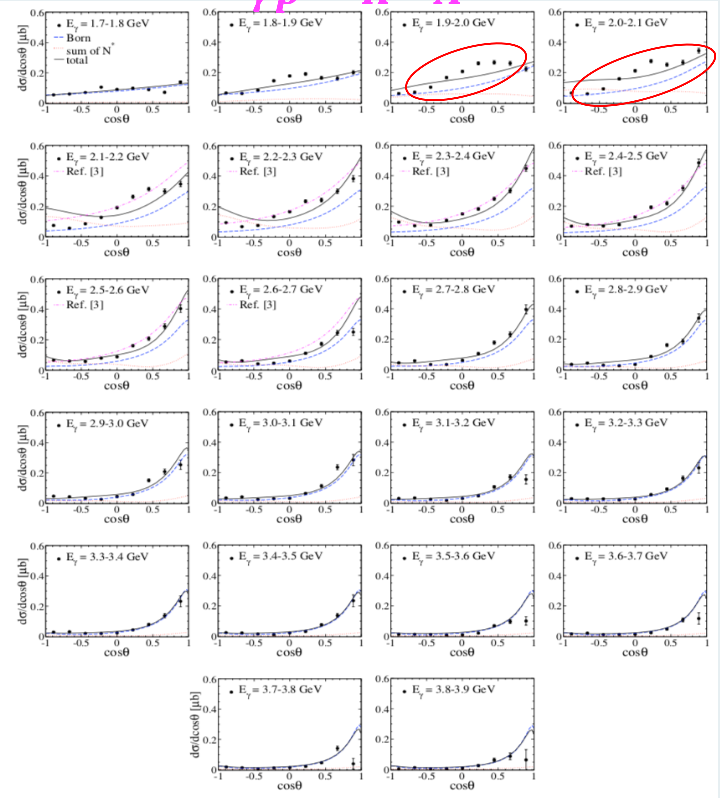
	Observable	Source	W (GeV)	ND	Reference
$\gamma p \to K^{*+}\Lambda$	$d\sigma/d\Omega$	CLAS	$2.04 \sim 2.85$	191	PRC 87 (2013) 065204
	σ			22	
	ρ_{00}, Re ρ_{10}, ρ_{1-1}		$2.04 \sim 2.78$	540	PLB 771 (2017) 142
$\gamma n \to K^{*0}\Lambda$	$d\sigma/d\Omega$		$2.13 \sim 2.34$	17	IJMPCS 26 (2014) 1460101

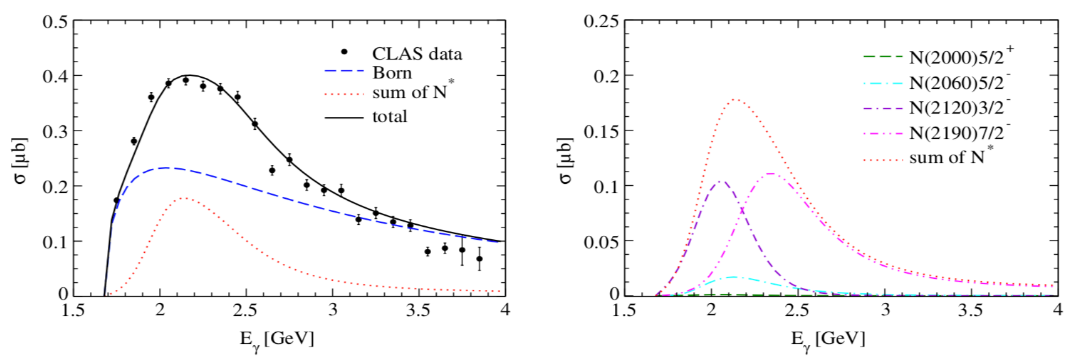
Preliminary data from CLAS for $\gamma p \to K^{*+}\Lambda$ published before 2013 are not listed in this table.

Work of Kim, Hosaka, and Kim

S.H. Kim, A. Hosaka, and H.C. Kim, PRD 90 (2014) 014021

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





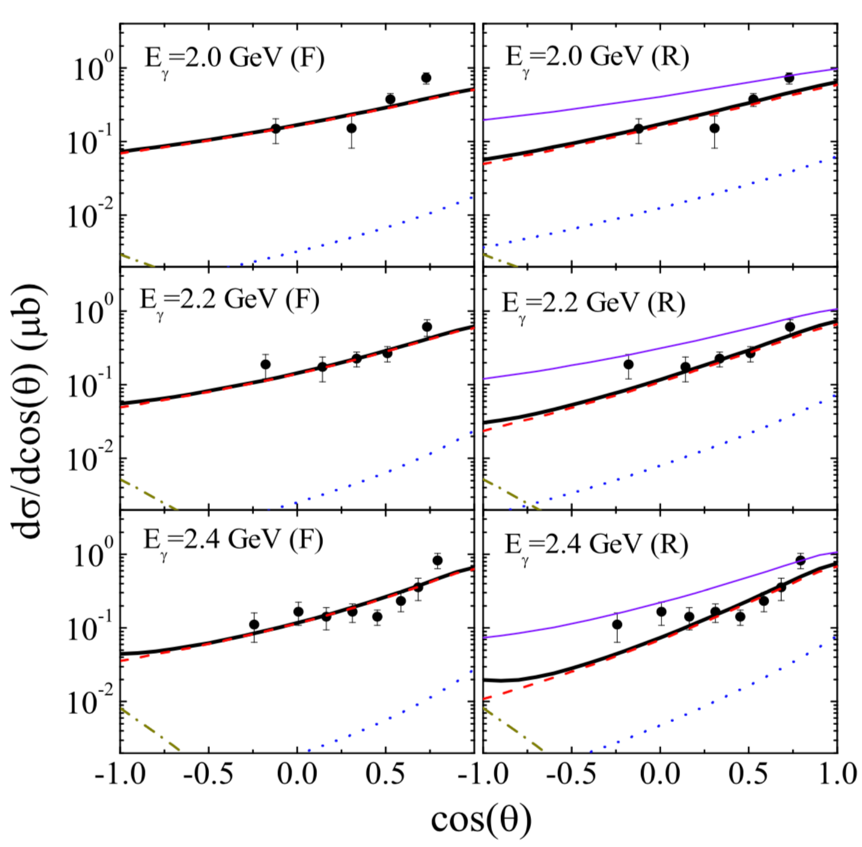
- **4 resonances included, 3 from PDG and 1 from quark model**
- **Fit data for $\gamma p \to K^{*+}\Lambda$**
- **$N(2120)3/2^-$ and $N(2190)7/2^-$ are important**

Work of Wang and He

X.Y. Wang and J. He, PRC 93 (2016) 035202

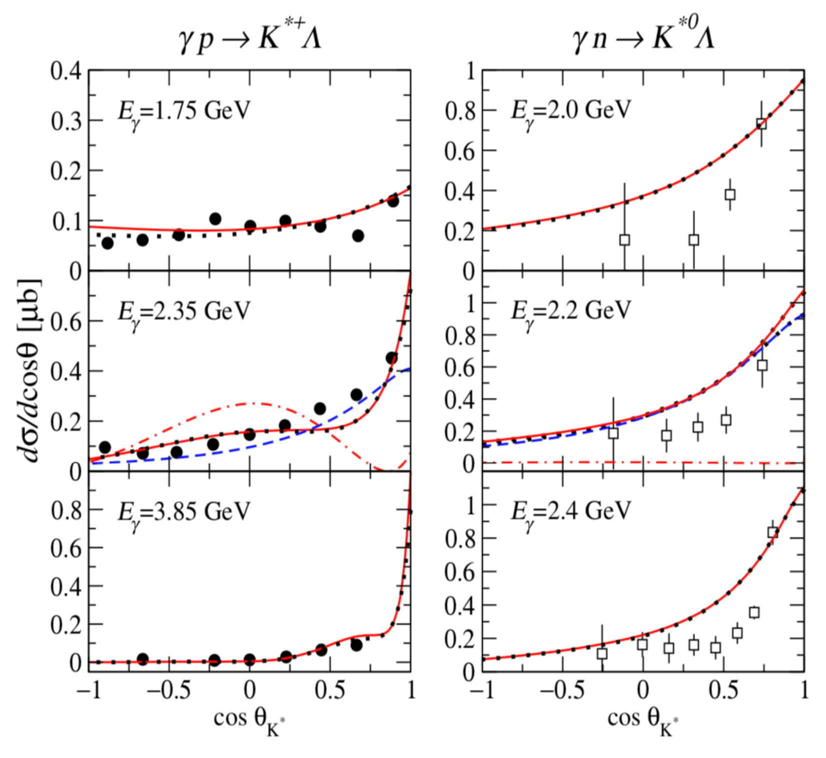
- **Feynman model (F) & Regge model (R) employed**
- **No resonances needed**
- ***K* exchange overwhelmingly dominates**

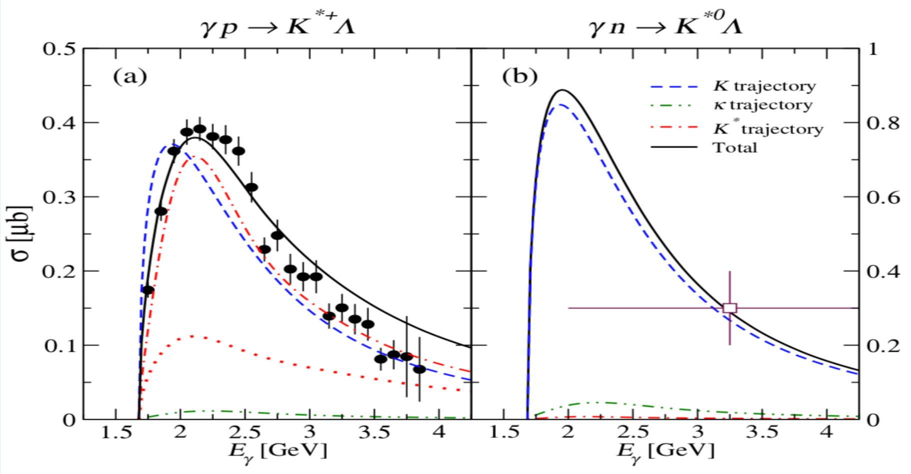
$\gamma n \to K^{*0}\Lambda$



Work of Yu, Oh, and Kong

B.G. Yu, Y. Oh, and K.J. Kong, PRD 95 (2017) 074034



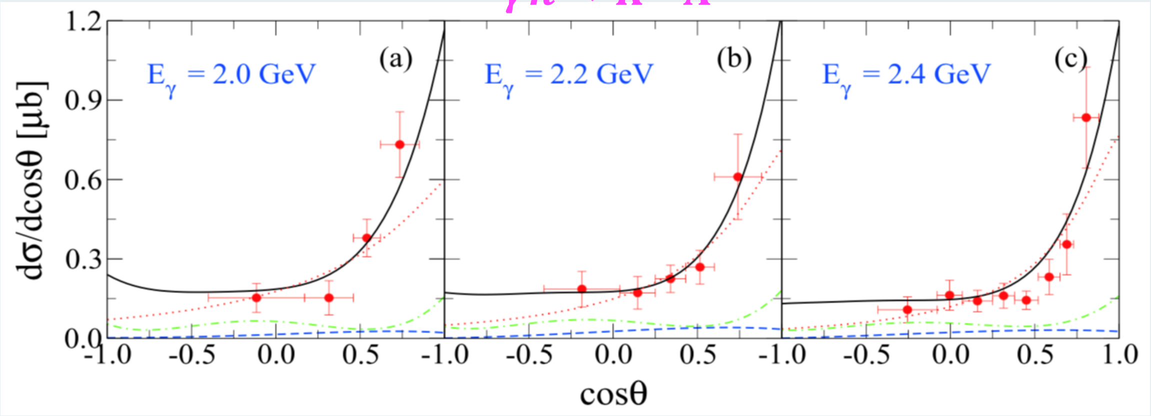


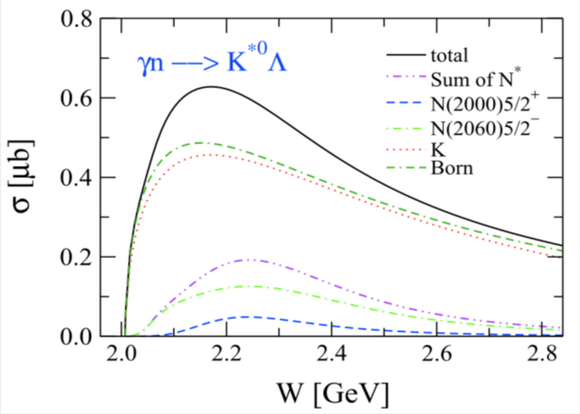
- **Reggeized t-channel interaction**
- **No resonances considered**
- **K & K* dominate**

Our model & results

A.C. Wang et al., PRC 96 (2017) 035206; N.C. Wei et al., PRC 101 (2020) 014003; N.C. Wei et al., CPC 46 (2022) 023106

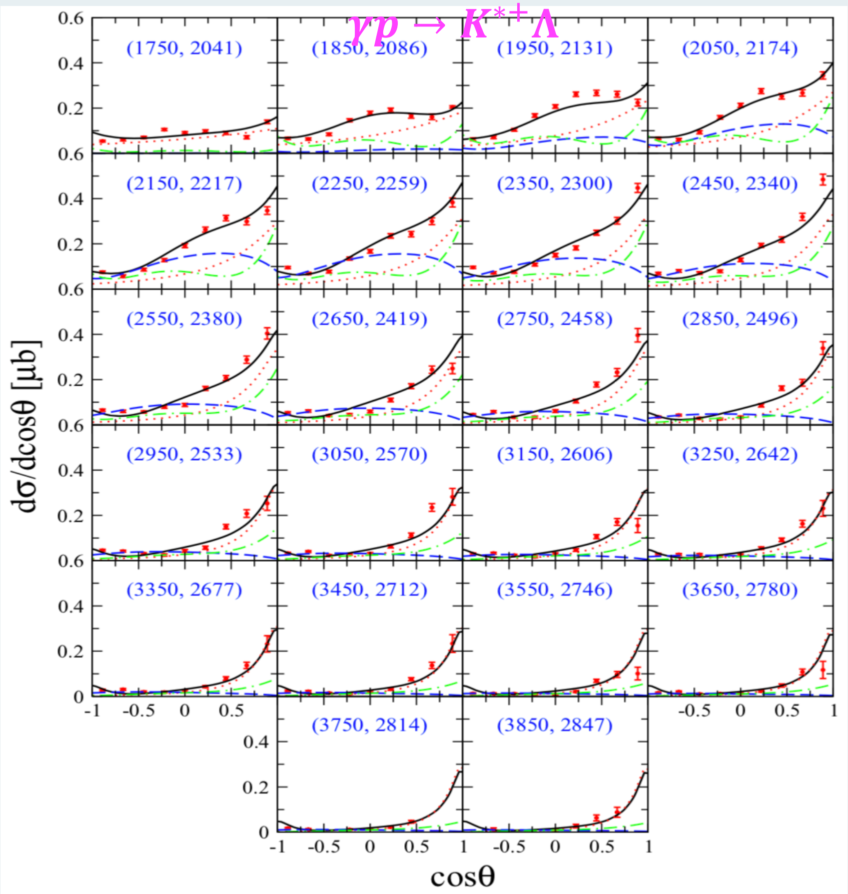
$\gamma n \to K^{*0}\Lambda$

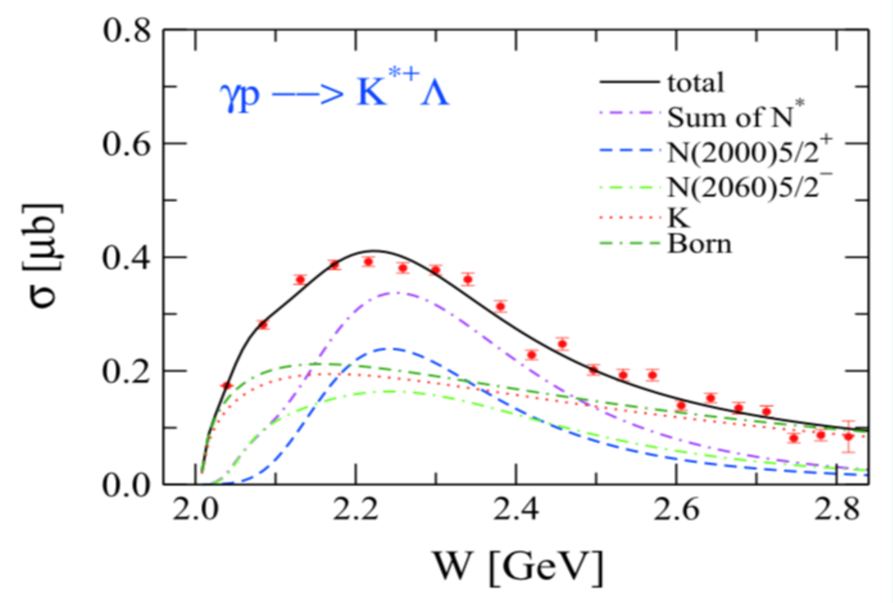




- Combined analysis of all data for both $\gamma p \to K^{*+}\Lambda$ & $\gamma n \to K^{*0}\Lambda$
- $N(2060)5/2^{-}$ & $N(2000)5/2^{+}$ needed
- γn reaction: K dominates, resonances significant

Our model & results



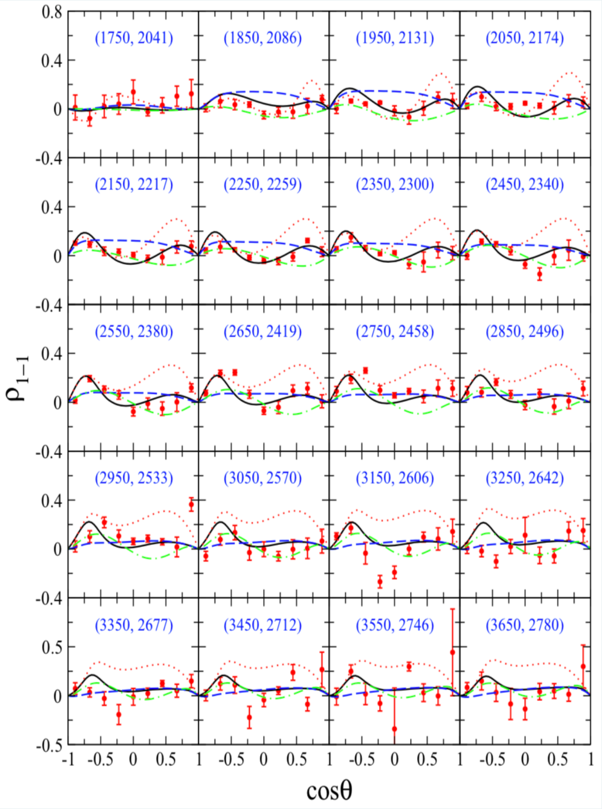


- γp reaction: K & resonances both are important

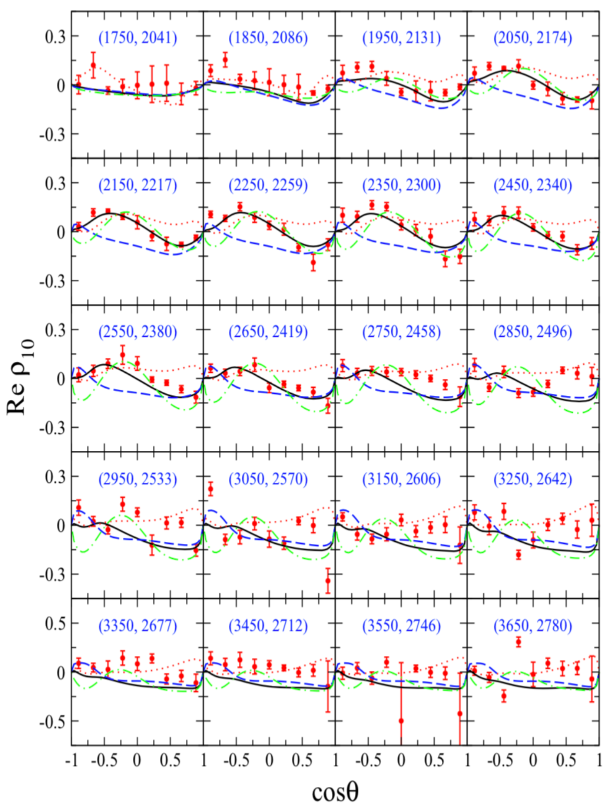
Our model & results

Problem solved by adding $N(2080)$

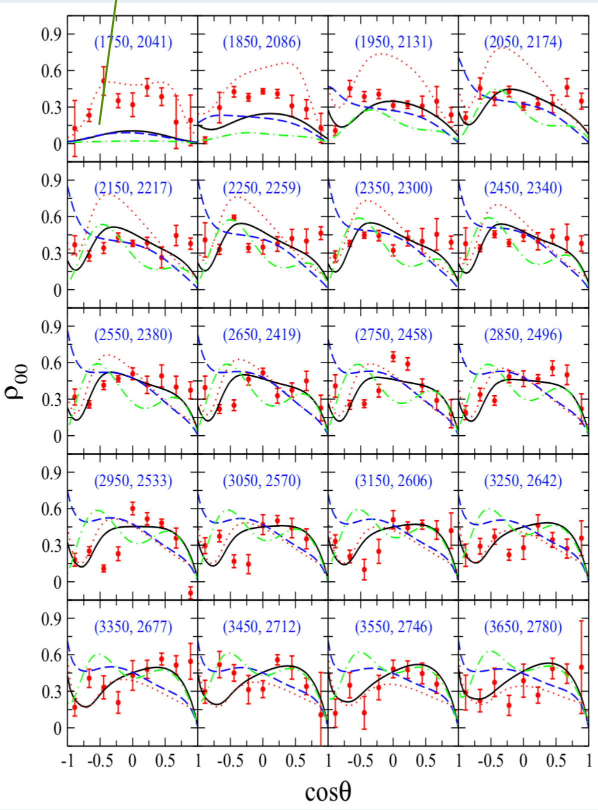
$\gamma p \to K^{*+}\Lambda$



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



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



$K\Lambda(1520)$ production reaction:

$$\gamma p \rightarrow K^{+}\Lambda(1520)$$

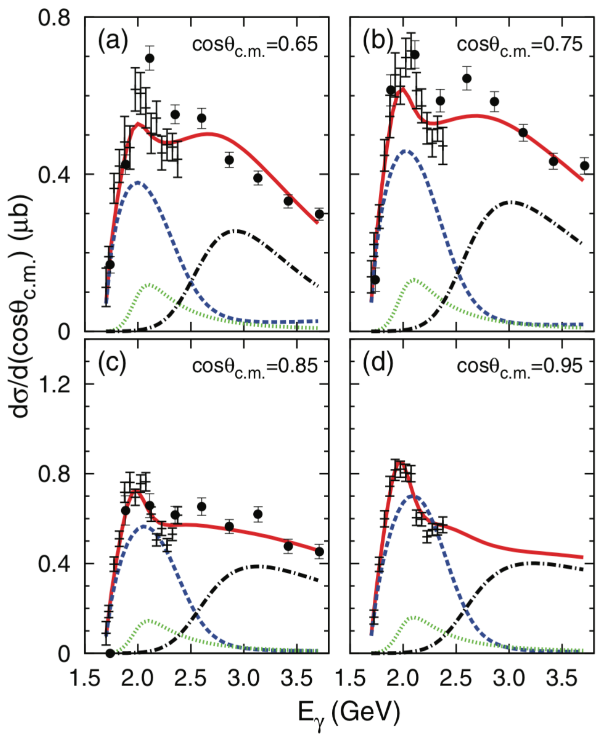
Experimental status

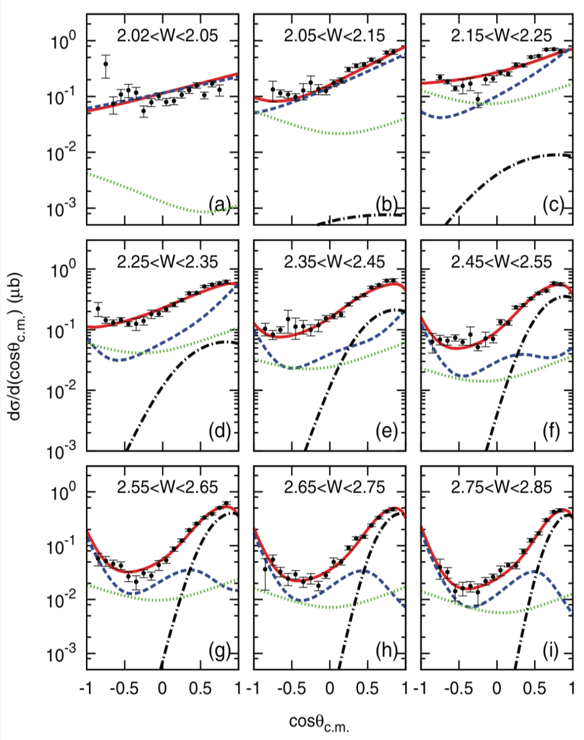
	Observable	Source	W (GeV)	ND	Reference
$\gamma p \to K^+\Lambda(1520)$	$d\sigma/d\Omega$	CLAS	2.04 ~ 2.80	144	PRC 88 (2007) 045201
	σ		2.1 ~ 2.8	8	
	$d\sigma/d\Omega$	LEPS	2.01 ~ 2.31	59	PRL 104 (2010) 172001
	Σ		2.04 ~ 2.30	7	

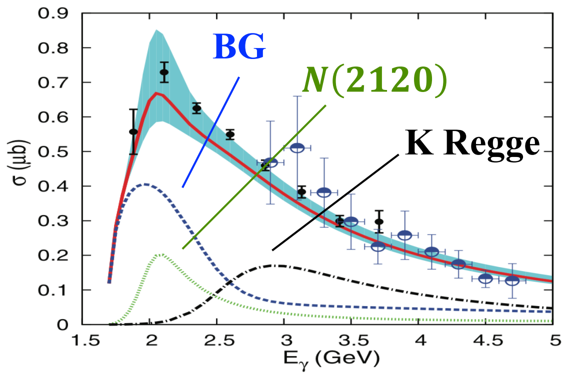
Work of Wang, Xie, and Nieves

E. Wang, J.J. Xie, and J. Nieves, PRC 90 (2014) 065203

$\gamma p \rightarrow K^+ \Lambda(1520)$





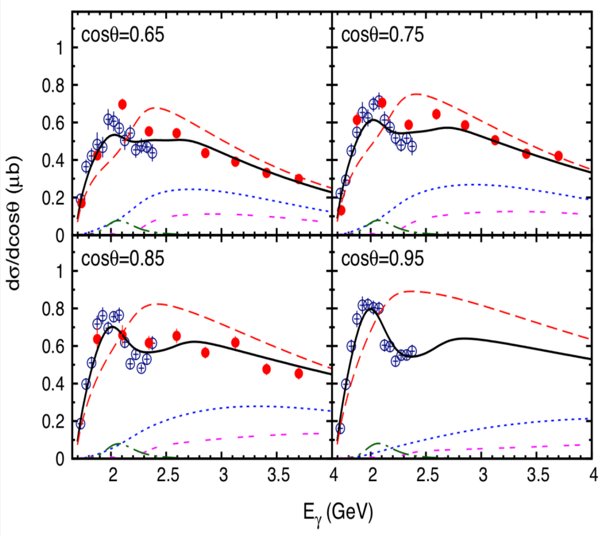


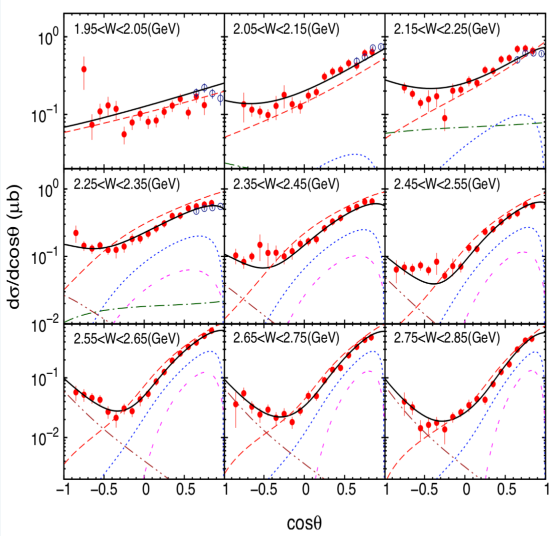
- $N(2120)3/2^-$ **needed**
- **Reggeized** K
- **Feynman background**

Work of He

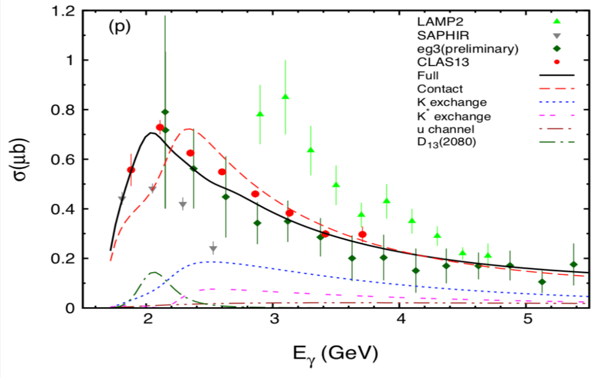
J. He, NPA 927 (2014) 24

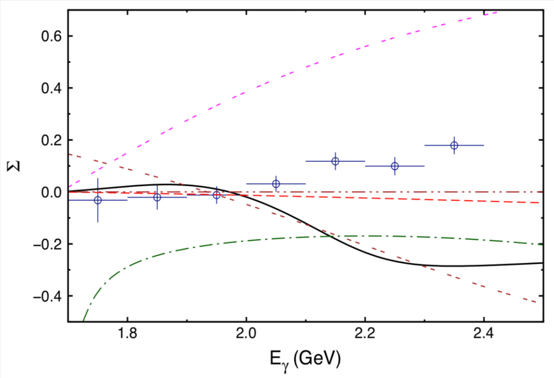
$\gamma p \rightarrow K^+\Lambda(1520)$





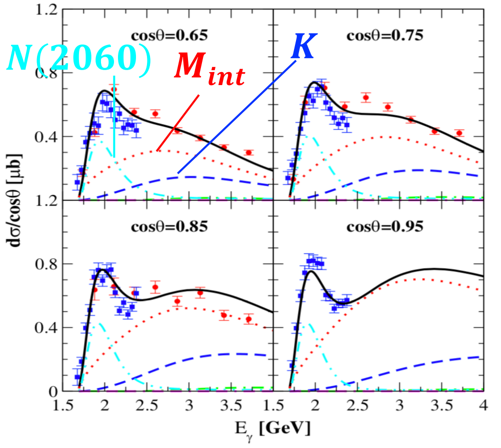
- **$N(2120)3/2^-$ needed**
- **Reggeized K, K^***
- **Contact term dominates**
- **Σ data not described**

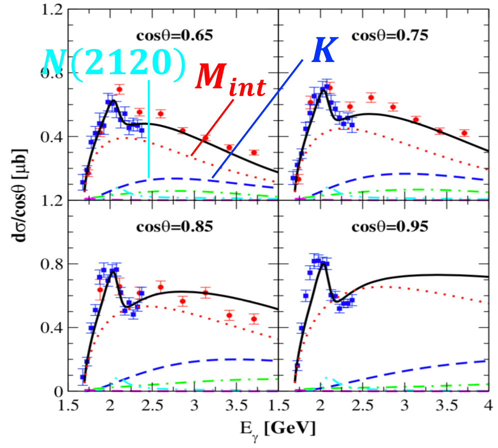


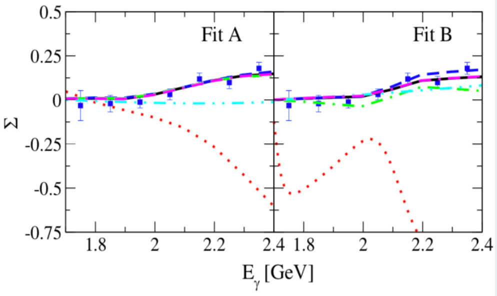


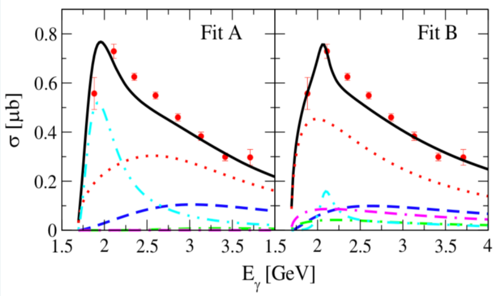
Our model & results

N.C. Wei, Y. Zhang, F. Huang, and D.M. Li, PRD 103 (2021) 034007





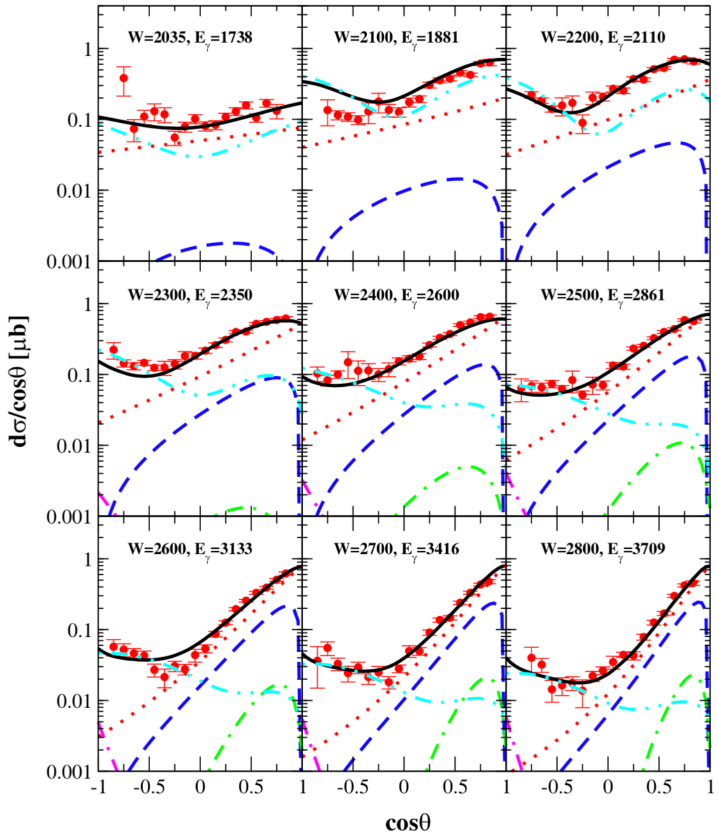




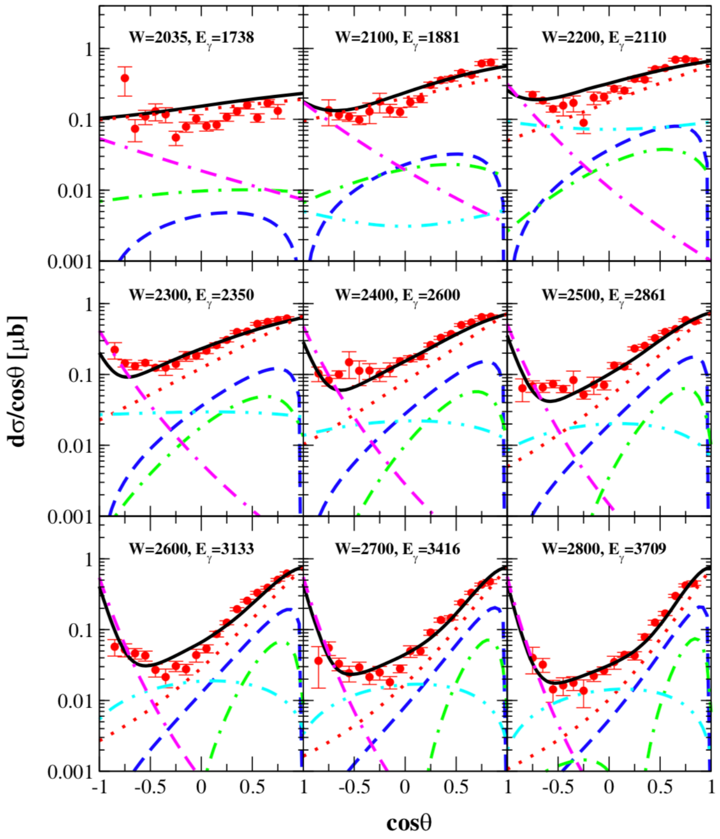
- **All data are well described**
- **One of the $N(2060)5/2^-$ and $N(2120)3/2^-$ is needed**
- **Background: M_{int} & K**
- **Fit A: $N(2060)5/2^-$ dominate**
  Fit B: $N(2120)3/2^-$ small

Our results

Fit A



Fit B



$K^*\Sigma$ production reactions:

$$\gamma p \to K^{*+}\Sigma^0$$

$$\gamma p \to K^{*0}\Sigma^+$$

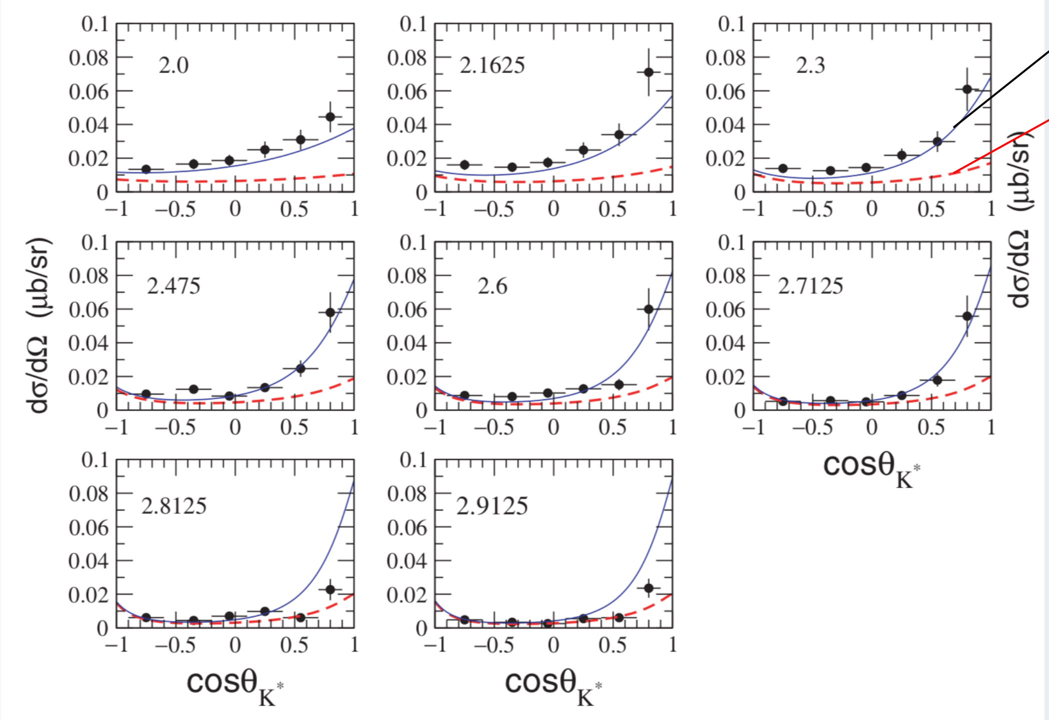
Experimental status

	Observable	Source	W (GeV)	ND	Reference
$\gamma p \to K^{*+}\Sigma^0$	$d\sigma/d\Omega$	CLAS	2.09 ~ 2.81	176	PRC 87 (2013) 065204
	σ		2.09 ~ 2.78	19	
$\gamma p \to K^{*0}\Sigma^+$	$d\sigma/d\Omega$	CLAS	2.15 ~ 2.52	48	PRC 75 (2007) 042201
		CBELSA/TAPS	2.45 ~ 2.68	24	EPJA 35 (2008) 333
	ρ^0, ρ^1, ρ^2	LEPS	2.42 ~ 2.91	9	PRL 108 (2012) 092001

Work of Oh and Kim

Y. Oh and H. Kim, PRC 74 (2006) 015208

$\gamma p \to K^{*0}\Sigma^+$



big κ contribution

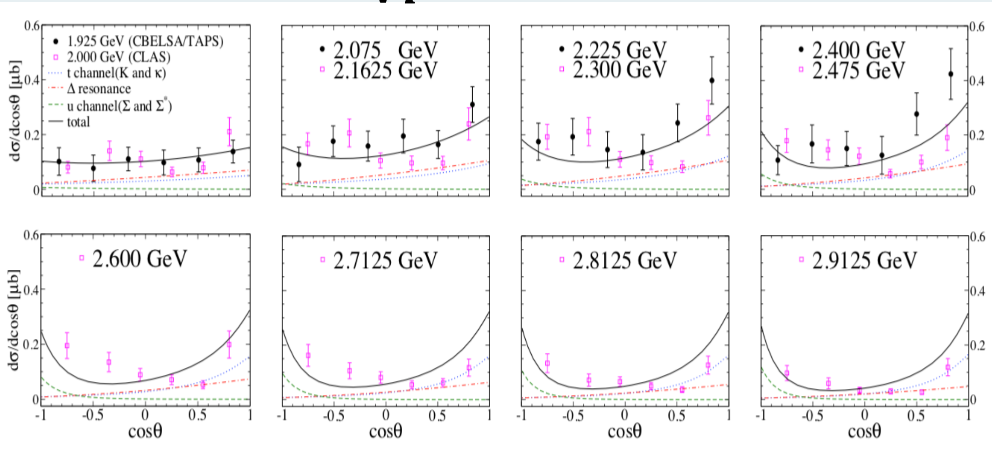
small κ contribution

- κ is very important

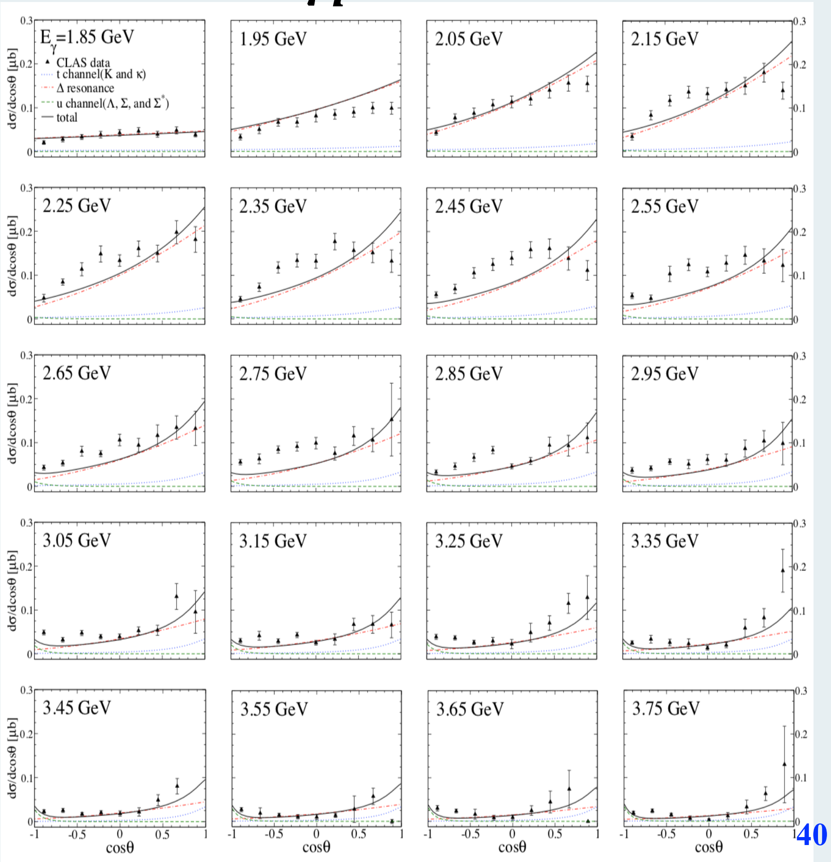
Work of Kim, Nam, Hosaka, and Kim

S.H. Kim, S. Nam, A. Hosaka, and H.C. Kim, PRD 88 (2013) 054012

$\gamma p \rightarrow K^{*0}\Sigma^{+}$



$\gamma p \rightarrow K^{*+}\Sigma^{0}$

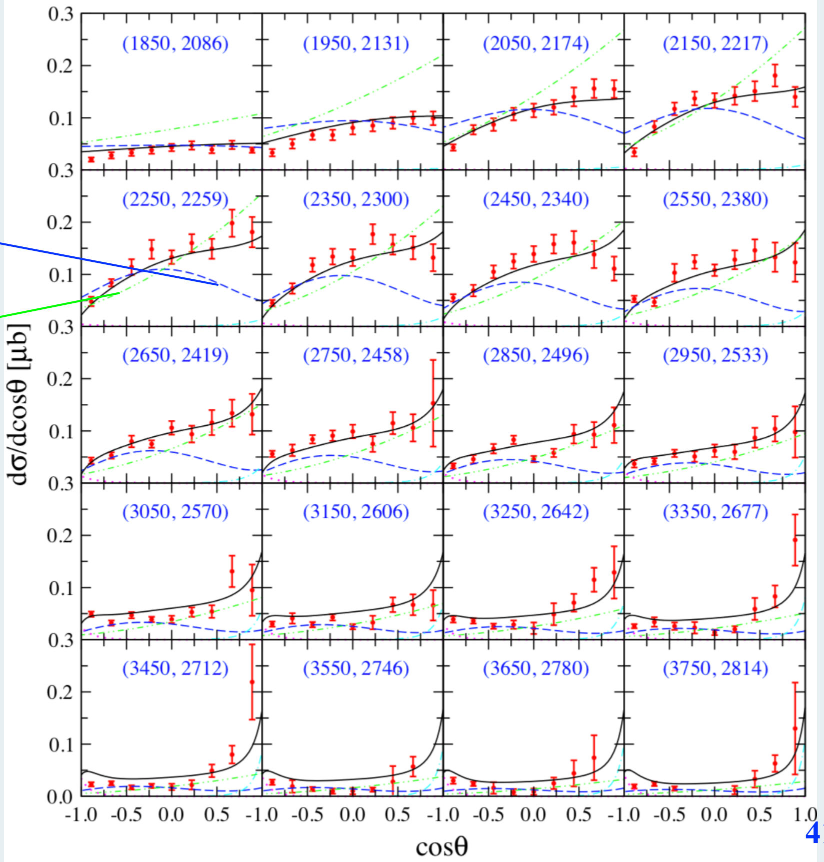


- **7 resonances considered**
- **Δ & *K* dominate; resonances negligible**

Our results

A.C. Wang, W.L. Wang, and F. Huang, PRC 98 (2018) 045209; A.C. Wang et al., in preparation

$\gamma p \rightarrow K^{*+}\Sigma^{0}$

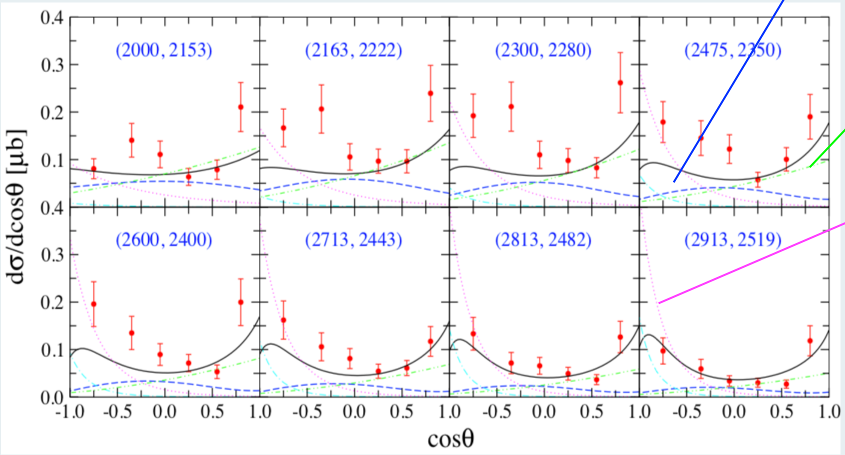


$\Delta(1905)\,5/2^{+}$

Δ

Σ

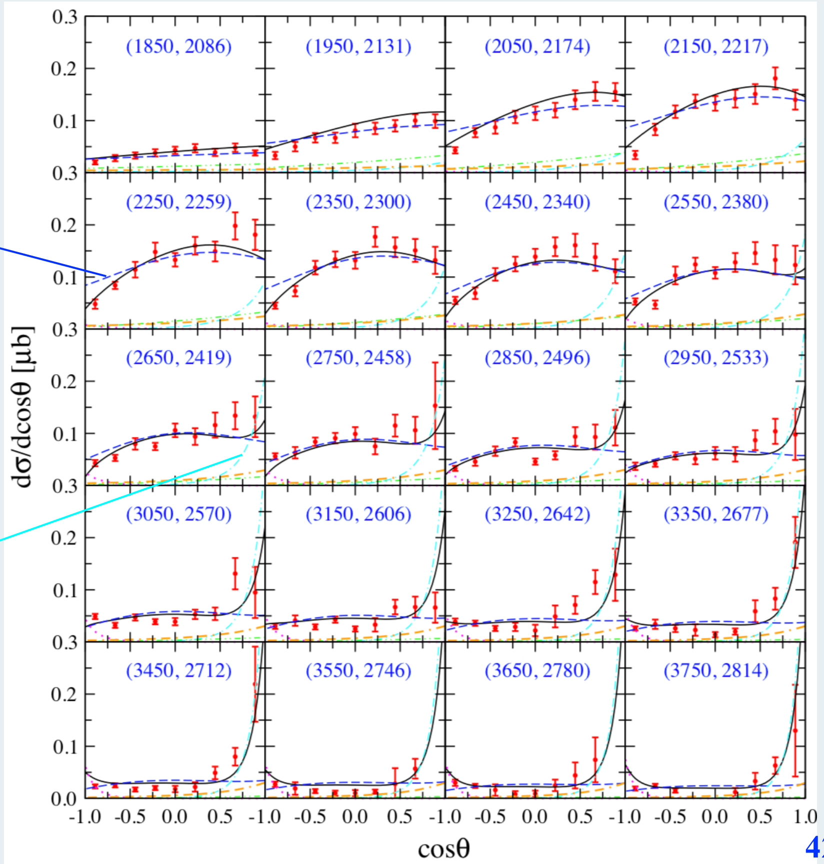
$\gamma p \rightarrow K^{*0}\Sigma^{+}$



Model I: $\Delta(1905)\,5/2^{+}$, Δ, Σ **dominate**

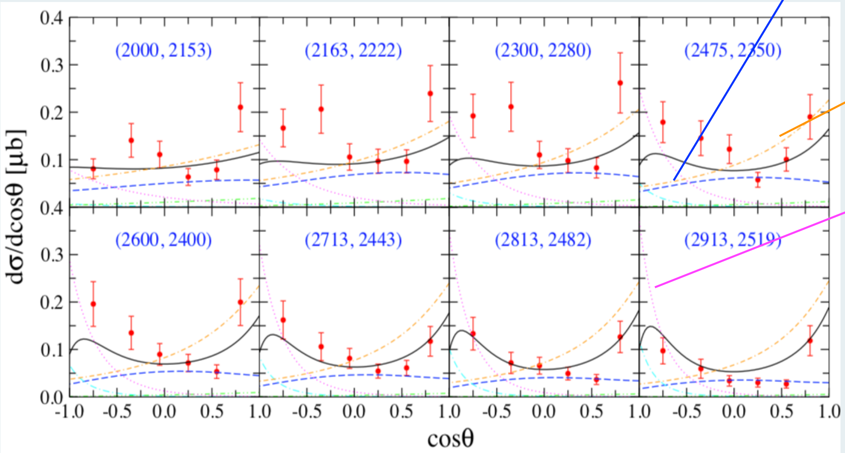
Our results

$\gamma p \to K^{*+}\Sigma^0$



$\Delta(1905)\,5/2^+$

$\gamma p \to K^{*0}\Sigma^+$



κ

Σ

K^*

Model II: $\Delta(1905)\,5/2^+$, κ, Σ, K^* **dominate**

κ exchange in $\gamma p \to K^{*0}\Sigma^{+}$

For t-channel meson exchanges,

T^N: natural parity $P = (-1)^J$

T^U: unnatural parity $P = (-1)^{J+1}$

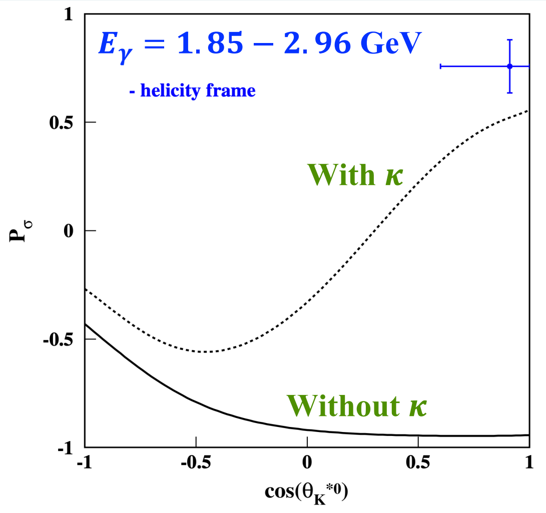
Spin-parity asymmetry:

$$P_\sigma = 2\rho^1_{1-1} - \rho^1_{00} = \frac{\sigma^N - \sigma^U}{\sigma^N + \sigma^U}$$

In the high energy limit at forward angles:

$$P_\sigma \to \begin{cases} -1: & K \text{ exchange} \\ 1: & \kappa \text{ exchange} \end{cases}$$

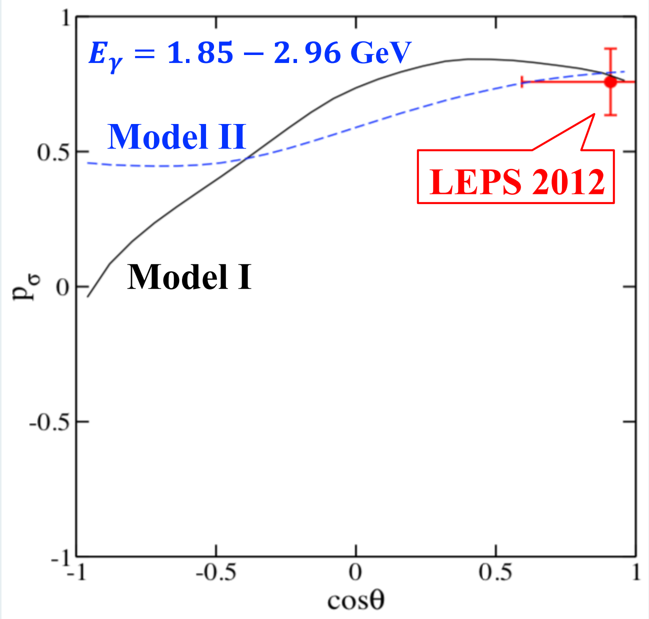
LEPS, PRL 108 (2012) 092001



"The measured parity spin asymmetry shows that natural-parity exchange is dominant. This result clearly indicates the need for t-channel exchange of the $\chi(800)$ scalar meson"

κ exchange in $\gamma p \to K^{*0}\Sigma^{+}$

A.C. Wang et al., in preparation

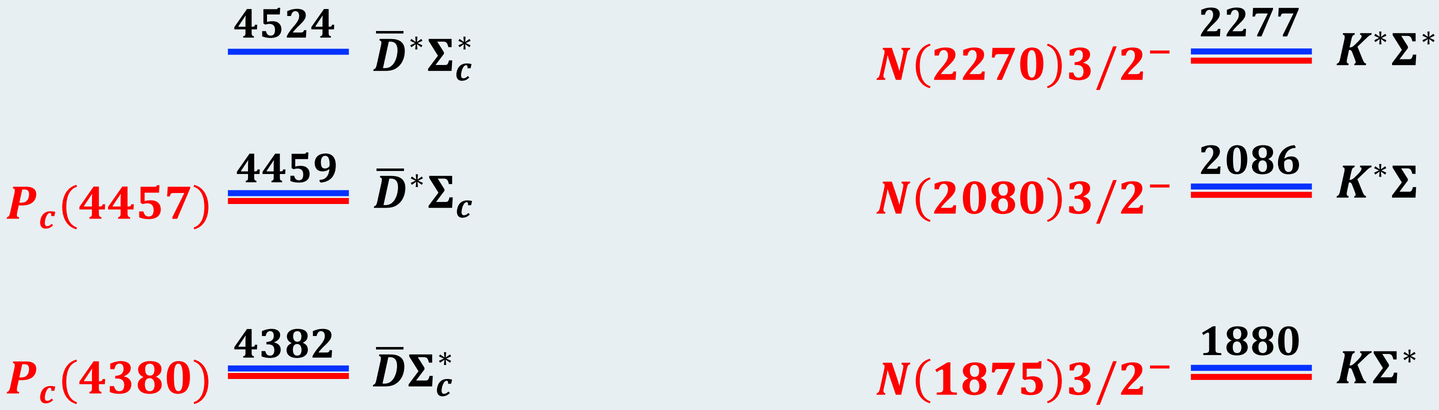


Model I: no κ
Model II: significant κ

- Either with or without dominant χ, LEPS P_σ data can be well reproduced
- $W \sim 2 - 2.5$ GeV: *s*-channel exchanges also contribute

  $P_\sigma \sim 1$: not necessarily caused by χ
- At $E_\gamma \approx 8.5$ GeV, $W \sim 4$ GeV:
  model with dominant κ: $P_\sigma \sim 1$
  model without dominant κ: small P_σ
- Data on P_σ at high energies are needed to confirm the role of χ exchange

Analogues of P_c states

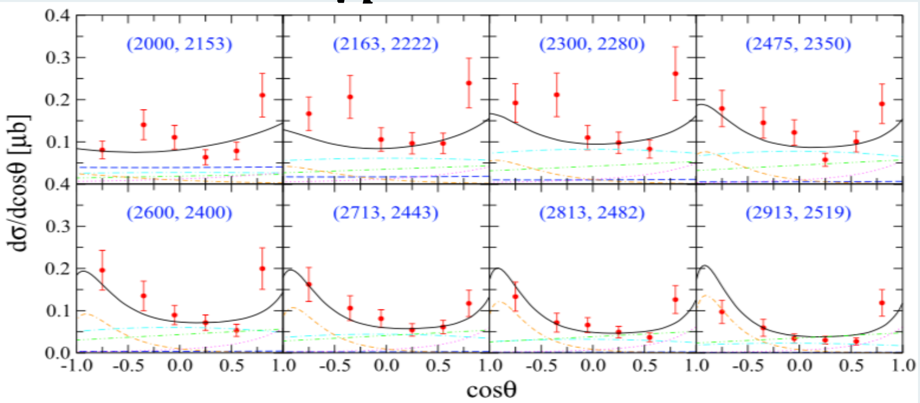


- P_c states reported by LHCb in $\Lambda_b^0 \to J/\psi\, p\, K^-$ [PRL 122 (2019) 222001]
- One popular interpretation: hadronic molecules
- Analogues in light quark sector: $N(1875)$, $N(2080)$, $N(2270)$
- Much more data for $K\Sigma^*$, $K^*\Sigma$ $\Rightarrow$ test molecular structures of $N(1875)$, $N(2080)$, $N(2270)$

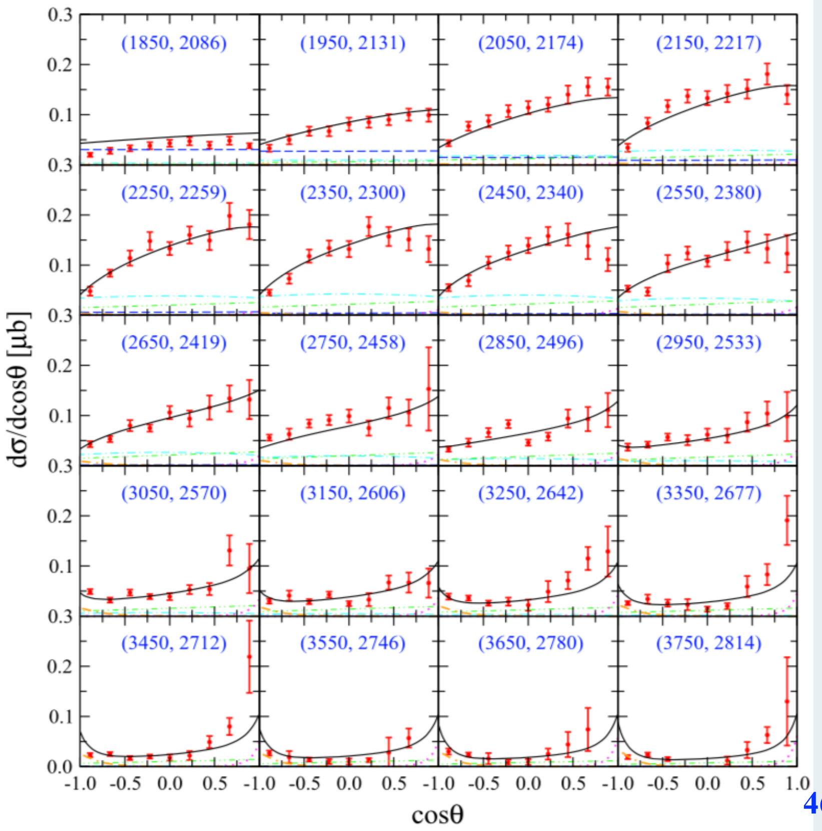
Test molecular N^*'s in $\gamma p \to K^*\Sigma$

D. Ben, A.C. Wang, F. Huang, and B.S. Zou,
PRC 108 (2023) 065201

$\gamma p \to K^{*0}\Sigma^+$



$\gamma p \to K^{*+}\Sigma^0$



- **Consider $N(2080)$ & $N(2270)$**
- **Data well reproduced ⇒ molecular picture compatible with data**

Summary

- K^*Y, KY^* production reactions systematically investigated
- Resonance information obtained:

	PDG	$K\Sigma(1385)$	$K\Lambda(1405)$	$K^*\Lambda$	$K\Lambda(1520)$	$K^*\Sigma$
$N(1895)1/2^-$	****	√				
$\Delta(1900)1/2^-$	***	√				
$\Delta(1905)\,5/2^+$	****					√
$\Delta(1930)5/2^-$	***	√				
$N(2000)5/2^+$	**		√	√		
$N(2060)5/2^-$	***			√	√	
$N(2120)3/2^-$	***				√	

Summary

- $\gamma p \to K^*\Sigma$: molecular picture of $N(2080)$ & $N(2270)$ compatible with data

  $\Delta(1905)\,5/2^+$; LEPS P_σ data not sufficient to claim dominant κ exchange
- $\gamma p \to K^*\Lambda$: molecular picture of $N(2080)$ helps to describe data
- More data are needed to get more reliable results

THANK YOU FOR YOUR ATTENTION

中国科学院大学
University of Chinese Academy of Sciences