Nucleon resonances in $\gamma p \rightarrow K^{*+}\Lambda$

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Outline

- Why $\gamma p \rightarrow K^{*+}\Lambda$?
- Current experimental & theoretical status
- Our approach
- Results & discussions
- Summary

Why $\gamma p \rightarrow K^{*+}\Lambda$?

- Extraction N^*'s from data & understanding their nature are essential to our understanding of NPQCD
- Our current knowledge of most of the N^*'s is coming from $\pi N \rightarrow \pi N$ & $\gamma N \rightarrow \pi N$

“missing N^*'s problem”

- Quark models predict more N^*'s than found
- N^*'s may couple weakly to πN but strongly to other channels
- $K^{*+}\Lambda$ threshold higher than that of πN: more suited to study N^*'s with higher masses
- $K^{*+}\Lambda$ has isospin 1/2: “isospin filter”

Experimental status

Available data for $\gamma p \rightarrow K^{*+}\Lambda$ all reported by CLAS@JLab:

① Preliminary σ from threshold up to 2.85 GeV:

L. Guo et al. [CLAS Collaboration], NSTAR 2005 proceedings

② Preliminary dσ/dΩ, W = 2.22 ~ 2.42 GeV:

K. Hicks et al. [CLAS Collaboration], MENU 2010 proceedings

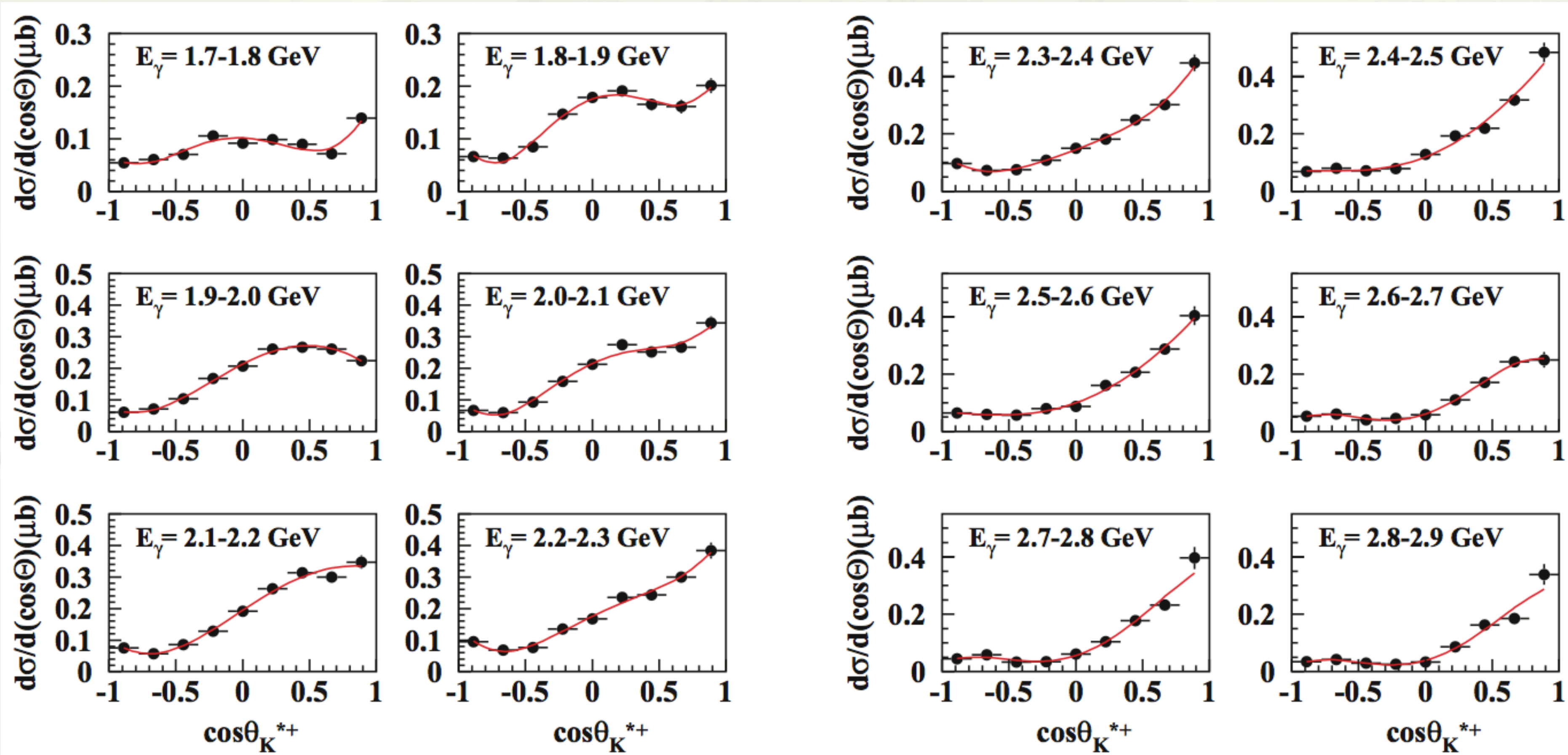
③ High statistics dσ/dΩ & σ, from threshold up to W ~ 2.85 GeV:

W. Tang et al. [CLAS Collaboration], PRC 87, 065204 (2013)

High statistics data from CLAS

W. Tang et al. [CLAS Collaboration], Phys. Rev. C 87 (2013) 065204.

W: 2.04~2.26 GeV **W: 2.30~2.50 GeV**



N*'s near $K^*\Lambda$ threshold

C. Patrignani et al. (Particle Data Group), Chin. Phys. C 40 (2016) 100001.

N^*	Status	Mass	Width
$N(2000)5/2^+$	**		
$N(2040)3/2^+$	*		
$N(2060)5/2^-$	**		
$N(2100)1/2^+$	*	~2100	
$N(2120)3/2^-$	**	~2120	
$N(2190)7/2^-$	****	2100~2200	300~700

Four-star N^* needs further investigation to improve the accuracy of its parameters;

One- or two-star N^*'s need more information to improve the evidences of their existences and to extract their parameters.

Theoretical status

Based on σ & dσ/dΩ reported at NSTAR 2005 & MENU 2010

① Y. Oh & H. Kim, PRC 73 (2006) 065202.

② Y. Oh & H. Kim, PRC 74 (2006) 015208.

③ S. Ozaki, H. Nagahiro, & A. Hosaka, PRC 81 (2010) 035206.

④ S. H. Kim, S. Nam, Y. Oh, & H. C. Kim, PRD 84 (2011) 114023.

Based on high statistics dσ/dΩ & σ from PRC 87 (2013) 065204

⑤ S. H. Kim, A. Hosaka, & H. C. Kim, PRD 90 (2014) 014021.
N(2000)$5/2^+$, N(2060)$5/2^-$, N(2120)$3/2^-$, N(2190)$7/2^-$

⑥ B.-G. Yu, Y. Oh, and K.-J. Kong, PRD 95 (2017) 074034.
Regge approach, no resonance, focus on t-channel K^*

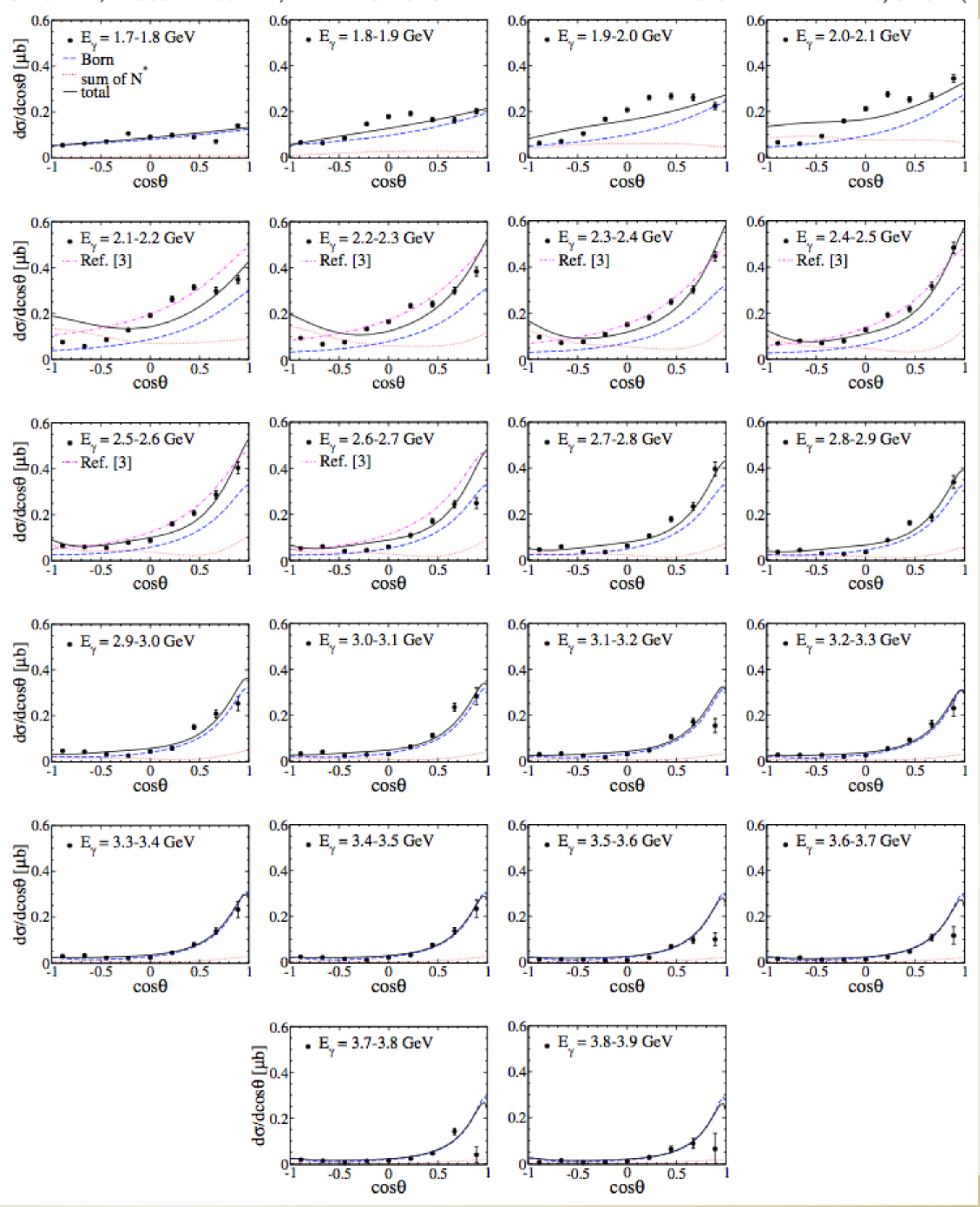
S. H. Kim et al., PRD90(2014)014021

N(2000)5/2$^+$

N(2060)5/2$^-$

N(2120)3/2$^-$

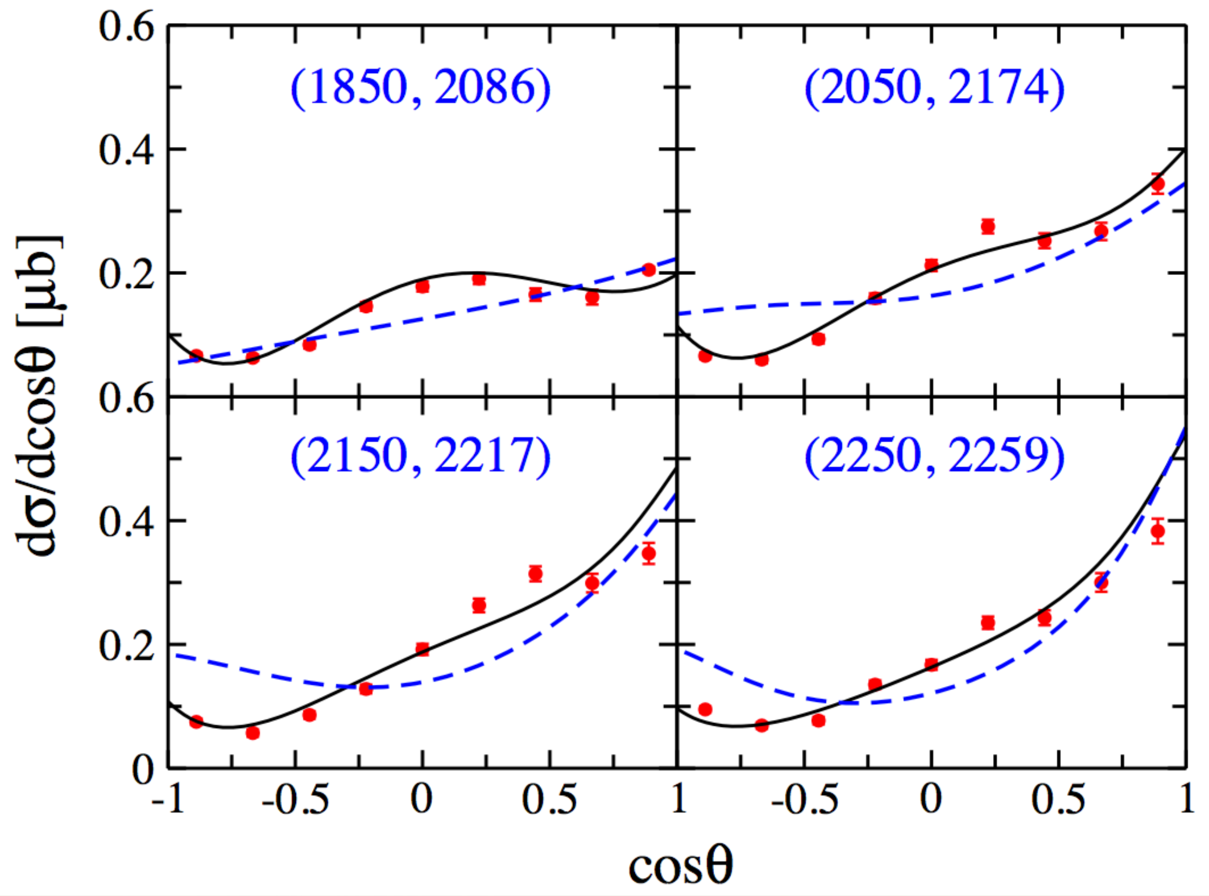
N(2190)7/2$^-$



Rooms to be improved

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

—— Our results (will be discussed later)



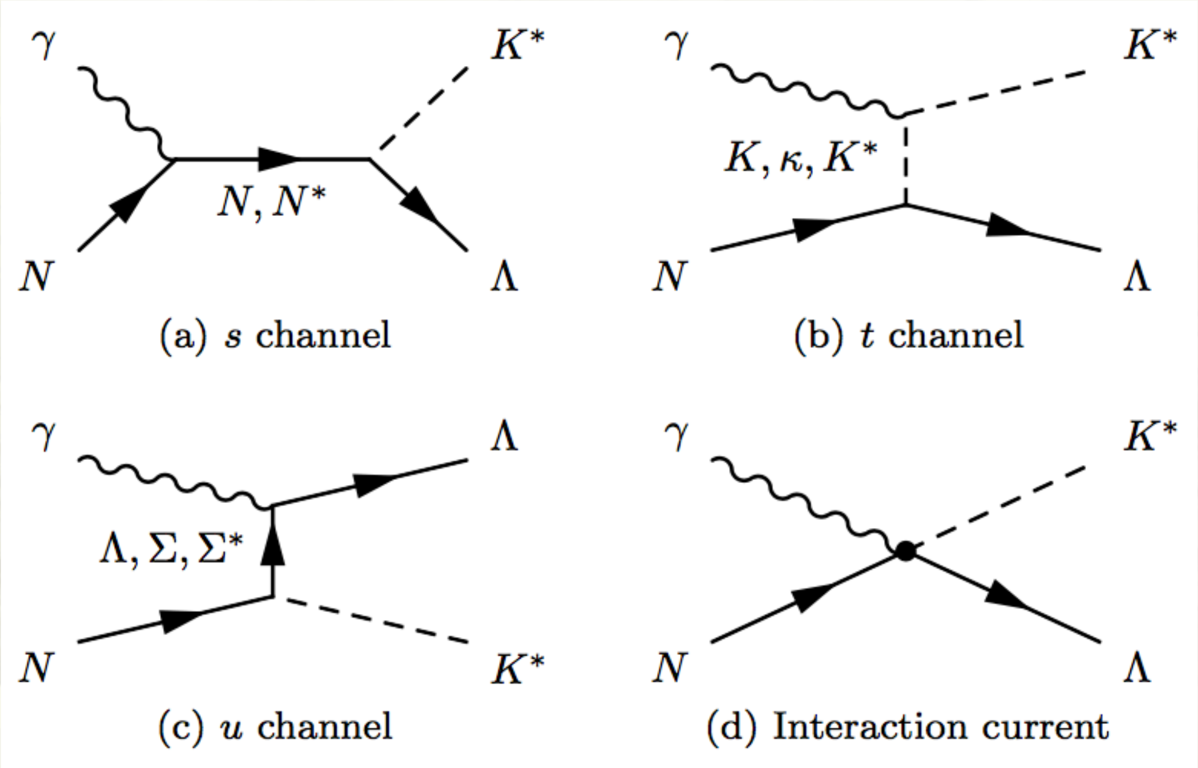
Aims of our work

Perform a better description of the data, and then answer the following questions:

- What's the reaction mechanism of $\gamma p \rightarrow K^{*+}\Lambda$?
- How many N^*'s are really needed to describe the data?
- What are the associated resonances parameters?

Our Model

A.C. Wang, W.L. Wang, F. Huang, H. Haberzettl, K. Nakayama, arXiv: 1704.04562



s-, t-, u-channel diagrams can be calculated straightforwardly;
The exact calculation of the interaction current is impractical

Prescription for gauge invariance

Full amplitude:

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

Interaction current:

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

Kroll-Ruderman term:

$$M_{\text{KR}}^{\nu\mu} = g_{\Lambda N K^*} \frac{\kappa_{\Lambda N K^*}}{2M_N} \sigma^{\nu\mu} Q_{K^*}$$

Auxiliary current:

$$C^{\mu} = -Q_{K^*} \frac{f_t - \hat{F}}{t - q^2} (2q - k)^{\mu} - Q_N \frac{f_s - \hat{F}}{s - p^2} (2p + k)^{\mu} ,$$

$$\hat{F} = 1 - \hat{h}\,(1 - f_s)\,(1 - f_t)$$

Strategy of choosing resonances

Strategy: Introduce N^*'s as few as possible to fit the data

N^*'s near $K^{*+}\Lambda$ threshold in PDG 2016:

N^*	Status	Mass	Width
$N(2000)5/2^+$	**		
$N(2040)3/2^+$	*		
$N(2060)5/2^-$	**		
$N(2100)1/2^+$	*	~2100	
$N(2120)3/2^-$	**	~2120	
$N(2190)7/2^-$	****	2100~2200	300~700

We allow all of them and perform numerous trials with different number of N^*'s and different combination of them.

How many N^{*}'s are really needed?

Strategy: Introduce N^{*}'s as few as possible

- 1 N^{*}: Data cannot be described. Particularly, the shape of angular distribution near threshold cannot be reproduced

- 2 N^{*}'s: 5 among 15 sets can well describe the data

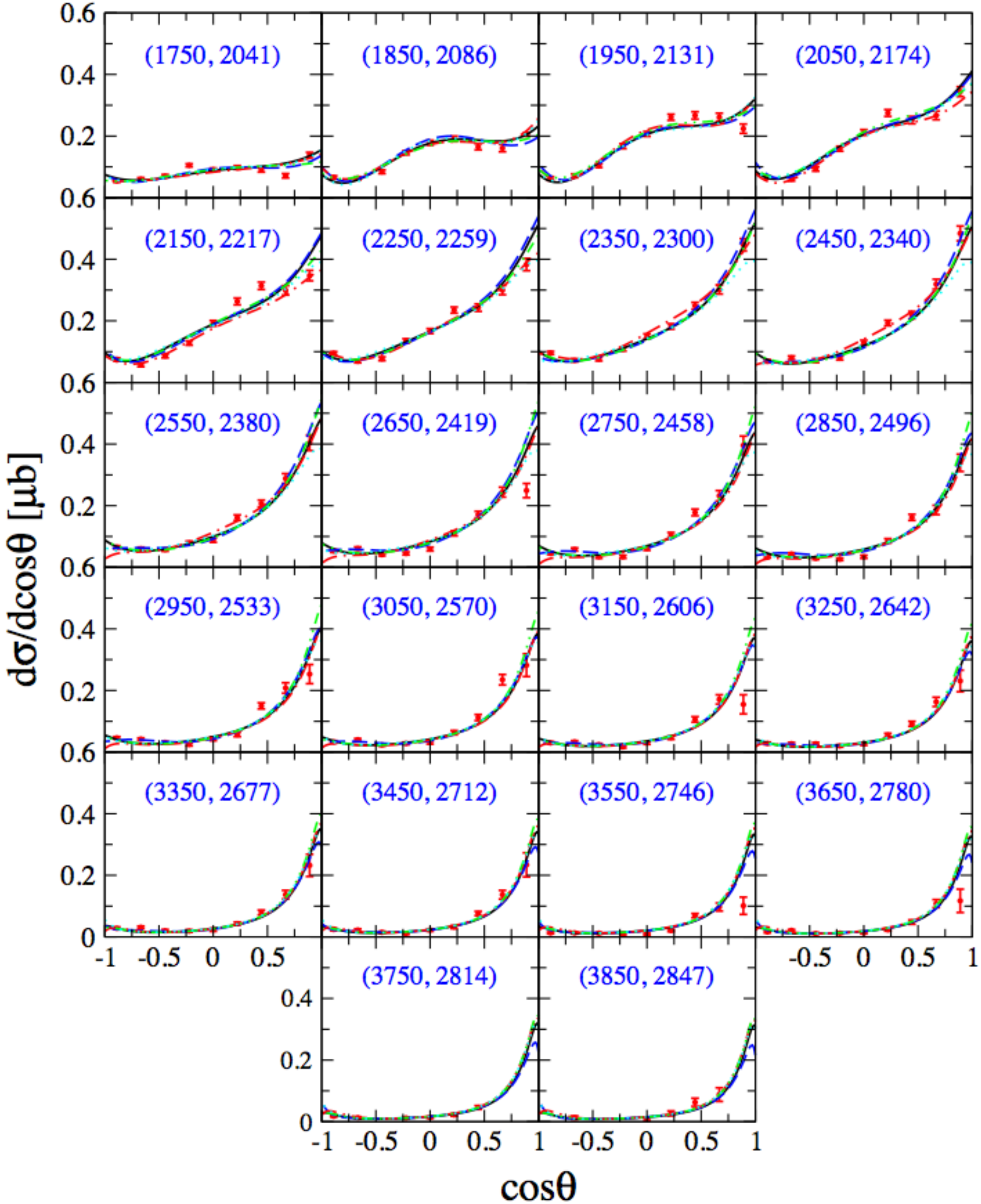
  $N(2060)5/2^{-}$ + one of

  $N(2000)5/2^{+}$, $N(2040)\ 3/2^{+}$, $N(2100)1/2^{+}$, $N(2120)3/2^{-}$, $N(2190)7/2^{-}$

- 3 N^{*}'s: χ^2 improves less than 12%

Analysis with 3 or more N*'s postponed until data for spin observables become available

Conclusion: One needs at least 2 N^{*}'s to describe the high statistics differential cross section data from CLAS

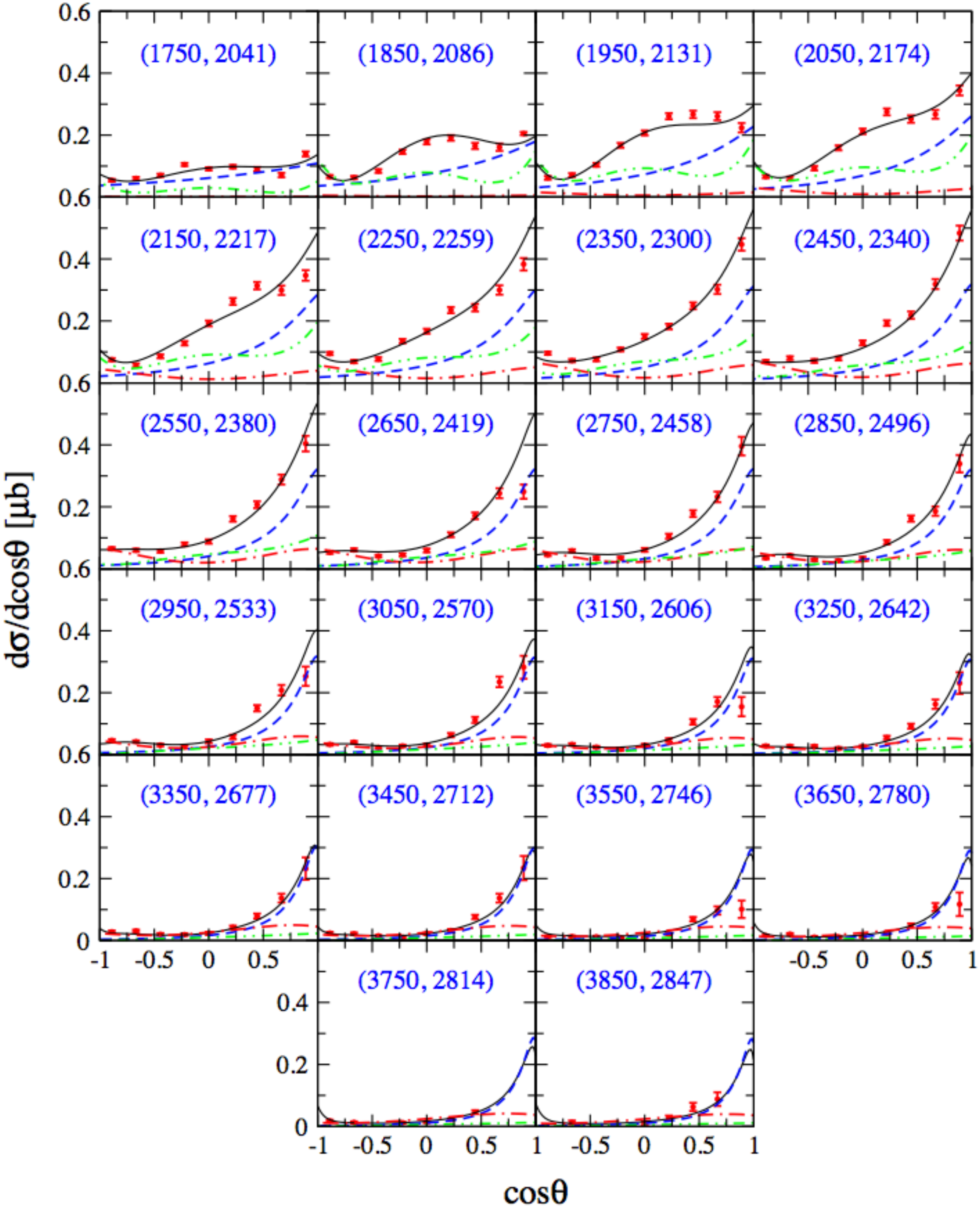


A.C. Wang, W.L. Wang, F. Huang, H. Haberzettl, K. Nakayama, arXiv: 1704.04562

- Data can be described by 2 N*'s
- 5 acceptable fits
- Differences are seen at forward & backward angles where data are sparse

Extracted N*'s parameters

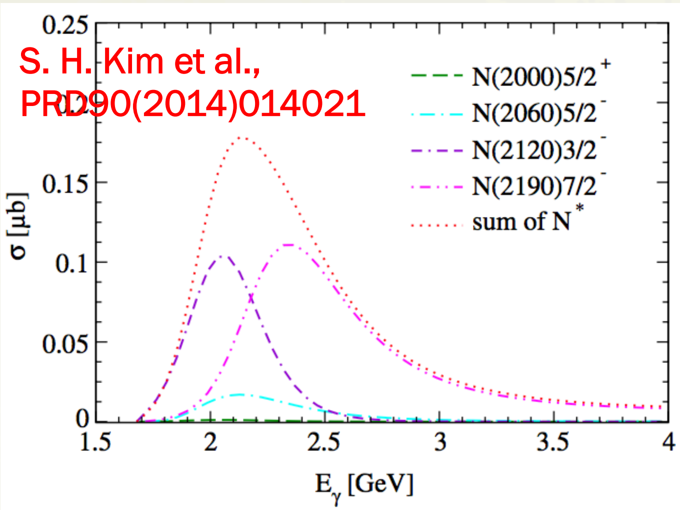
PDG	ratings	I	II	III	IV	V
$N(2060)5/2^-$	**	2033±2 65±4	2009±5 213±20	2032±3 81±8	2043±4 202±16	2038±3 77±8
$N(2000)5/2^+$	**	2115±22 450±10				
$N(2040)3/2^+$	*		2200±62 540±7			
$N(2120)3/2^-$ [~2120]	**			2203±9 433±33		
$N(2190)7/2^-$ [2100~2200] [300~700]	****				2243±6 450±33	
$N(2100)1/2^+$ [~2100]	*					2100±15 450±9

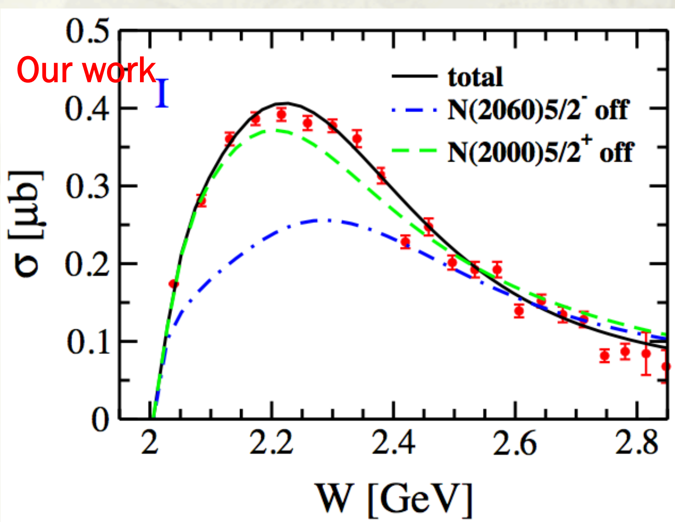


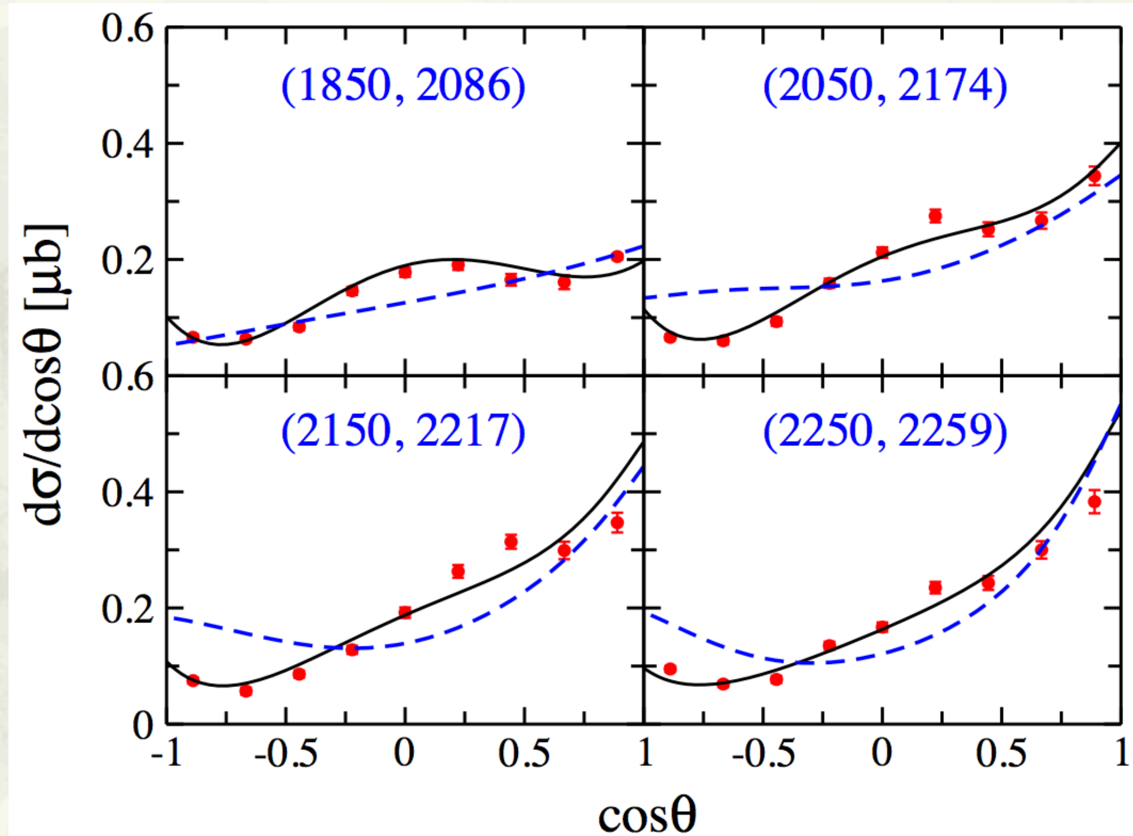
total
K
N(2060)5/2⁻

- **K dominates the cross sections at high energy**
- **N(2060)5/2⁻: significant contributions**
- **Near threshold shape: Interference of K & N(2060)5/2⁻**

Contribution of N(2060)$5/2^-$







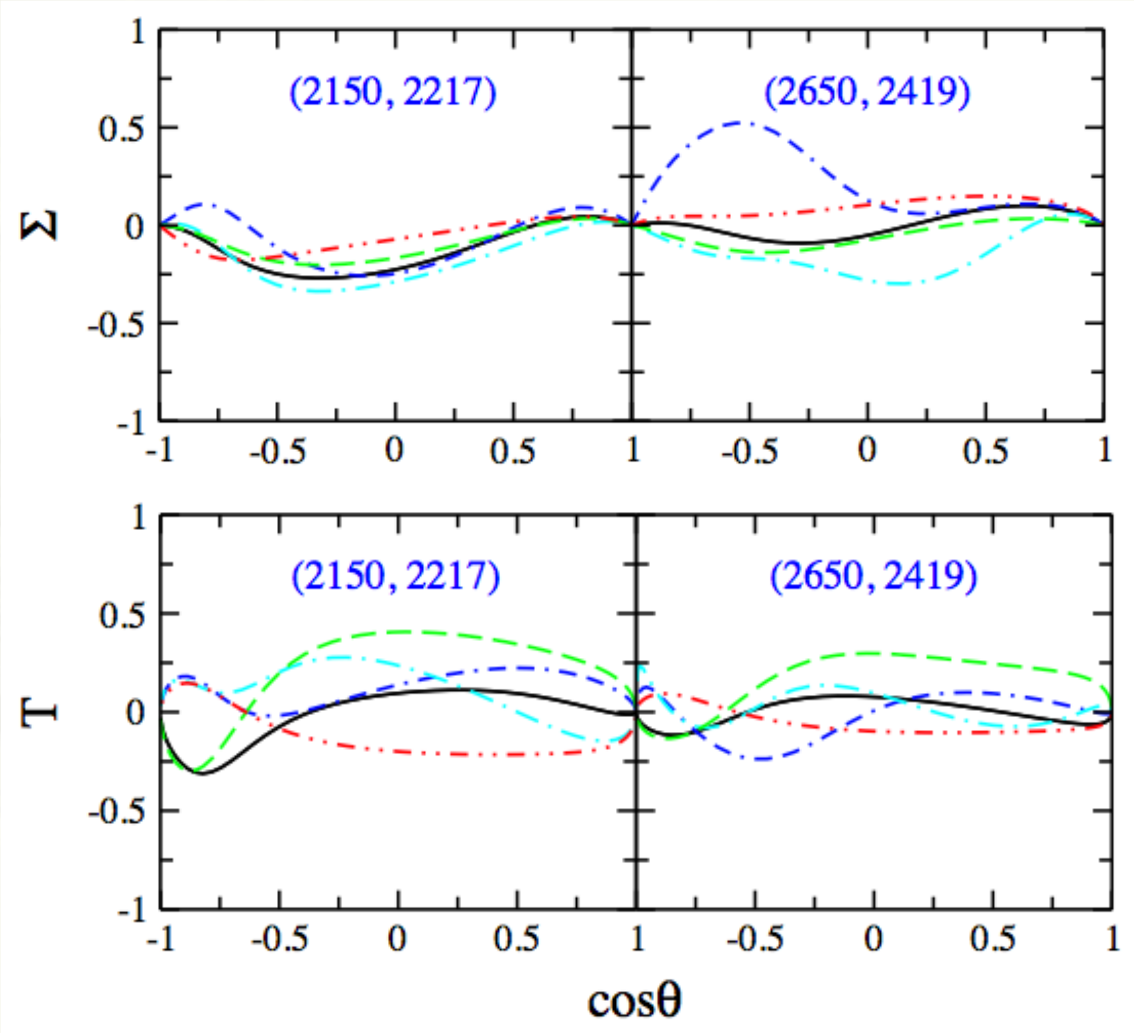
- - - S. H. Kim et al., PRD90(2014)014021, small N(2060)$5/2^-$

—— Our results with significant N(2060)$5/2^-$

Reaction mechanism of $\gamma p \to K^{*+}\Lambda$?

- K-exchange dominates the high energy cross sections
- 2 N^*'s are needed, one is $N(2060)5/2^-$, the other could be one of $N(2000)5/2^+$, $N(2040)\,3/2^+$, $N(2100)1/2^+$, $N(2120)3/2^-$, $N(2190)7/2^-$
- Interference of $N(2060)5/2^-$ & K is responsible for the near threshold shape of the cross sections

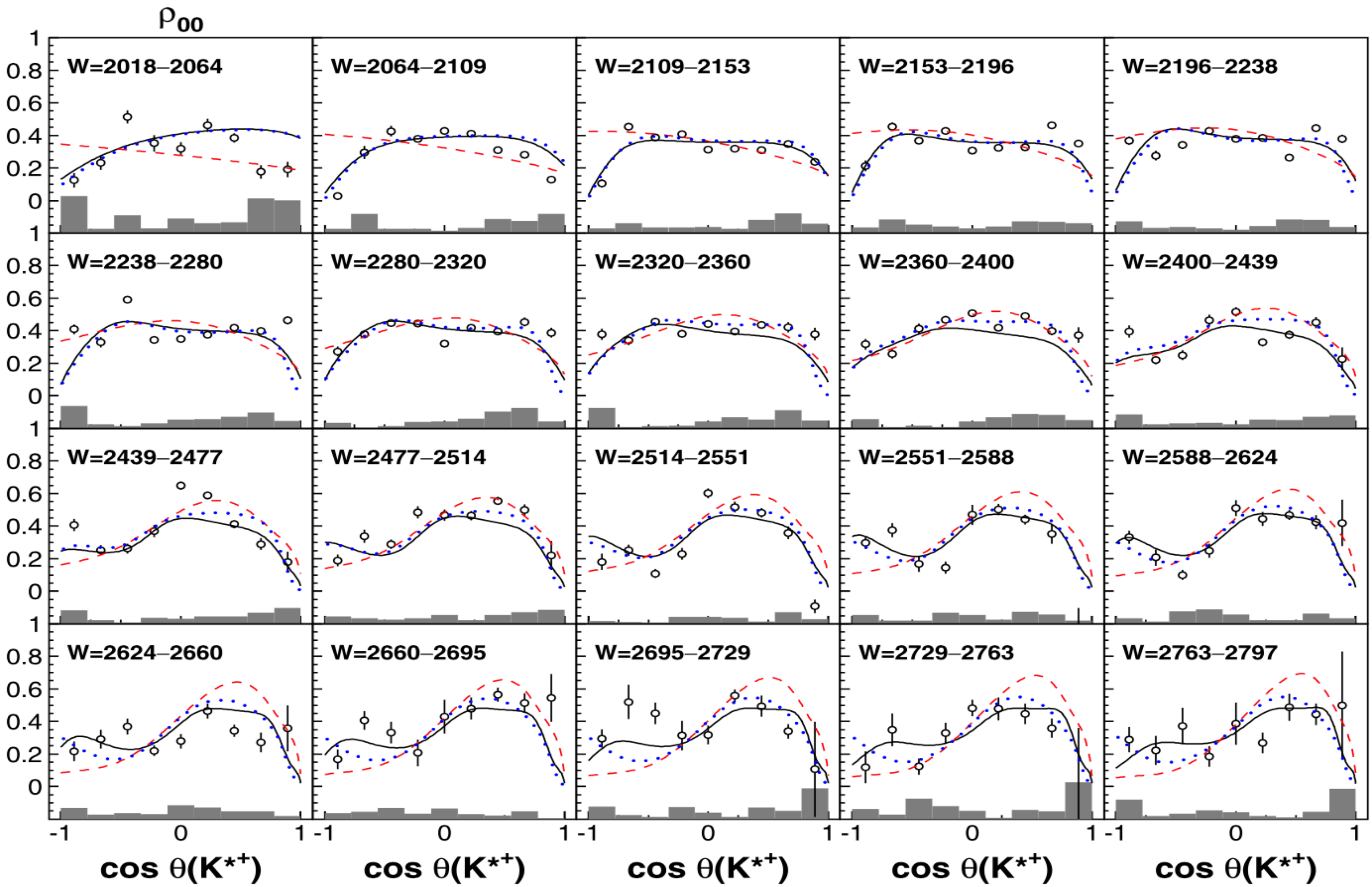
Predictions on spin observables



Summary

- Cross section data for $\gamma p \rightarrow K^{*+}\Lambda$ from CLAS have been well described in an effective Lagrangian approach
- K-exchange dominates the high energy behavior
- At least 2 N^*'s are needed, one is $N(2060)5/2^-$, the other could be one of $N(2000)5/2^+$, $N(2040)\ 3/2^+$, $N(2100)1/2^+$, $N(2120)3/2^-$, $N(2190)7/2^-$
- Interference of $N(2060)5/2^-$ & K is responsible for the near threshold shape of the cross sections
- Further data on spin observables are needed to further pin down the resonance contents & parameters

CLAS Collaboration, Phys. Lett. B 771 (2017) 142



Thank you for your patience!

Model Parameters

Model	I	II	III	IV	V
χ^2/N	1.35	1.79	1.85	2.09	2.18
$g^{(1)}_{\Sigma^*\Lambda\gamma}$	0.74 ± 0.16	-0.90 ± 0.17	-0.87 ± 0.14	-0.60 ± 0.18	-0.22 ± 0.16
Λ_K [MeV]	1000 ± 6	1019 ± 4	993 ± 7	1030 ± 3	1018 ± 4
N^* Name	$N(2060)5/2^-$	$N(2060)5/2^-$	$N(2060)5/2^-$	$N(2060)5/2^-$	$N(2060)5/2^-$
	**	**	**	**	**
M_R [MeV]	2033 ± 2	2009 ± 5	2032 ± 3	2043 ± 4	2038 ± 3
Γ_R [MeV]	65 ± 4	213 ± 20	81 ± 8	202 ± 16	77 ± 8
Λ_R [MeV]	1188 ± 20	965 ± 16	1126 ± 12	889 ± 13	981 ± 22
$\sqrt{\beta_{\Lambda K^*}} A_{1/2}$ [10^{-3} GeV$^{-1/2}$]	0.69 ± 0.06	0.03 ± 0.01	0.33 ± 0.03	0.60 ± 0.06	-0.21 ± 0.02
$\sqrt{\beta_{\Lambda K^*}} A_{3/2}$ [10^{-3} GeV$^{-1/2}$]	-1.39 ± 0.13	-0.10 ± 0.01	-1.10 ± 0.10	-1.94 ± 0.19	-1.56 ± 0.15
N^* Name	$N(2000)5/2^+$	$N(2040)3/2^+$	$N(2120)3/2^-$	$N(2190)7/2^-$	$N(2100)1/2^+$
	**	*	**	****	*
M_R [MeV]	2115 ± 22	2200 ± 62	2203 ± 9	2243 ± 6	2100 ± 15
			[≈ 2120]	[$2100 \sim 2200$]	[≈ 2100]
Γ_R [MeV]	450 ± 10	540 ± 7	433 ± 33	450 ± 33	450 ± 9
				[$300 \sim 700$]	
Λ_R [MeV]	1644 ± 21	1564 ± 36	1726 ± 58	936 ± 13	1431 ± 31
$\sqrt{\beta_{\Lambda K^*}} A_{1/2}$ [10^{-3} GeV$^{-1/2}$]	-2.87 ± 0.81	3.12 ± 0.85	4.53 ± 0.38	5.21 ± 0.33	-7.22 ± 1.40
$\sqrt{\beta_{\Lambda K^*}} A_{3/2}$ [10^{-3} GeV$^{-1/2}$]	-1.04 ± 0.29	7.87 ± 2.13	7.84 ± 0.65	3.71 ± 0.24	

A.C. Wang, W.L. Wang, F. Huang, H. Haberzettl, K. Nakayama, arXiv: 1704.04562

Effective Lagrangians

$$\mathcal{L}_{RN\gamma}^{1/2\pm} = e\frac{g_{RN\gamma}^{(1)}}{2M_N}\bar{R}\Gamma^{(\mp)}\sigma_{\mu\nu}\left(\partial^\nu A^\mu\right)N + \text{H.c.},$$

$$\mathcal{L}_{RN\gamma}^{3/2\pm} = -ie\frac{g_{RN\gamma}^{(1)}}{2M_N}\bar{R}_\mu\gamma_\nu\Gamma^{(\pm)}F^{\mu\nu}N + e\frac{g_{RN\gamma}^{(2)}}{(2M_N)^2}\bar{R}_\mu\Gamma^{(\pm)}F^{\mu\nu}\partial_\nu N + \text{H.c.},$$

$$\mathcal{L}_{RN\gamma}^{5/2\pm} = e\frac{g_{RN\gamma}^{(1)}}{(2M_N)^2}\bar{R}_{\mu\alpha}\gamma_\nu\Gamma^{(\mp)}\left(\partial^\alpha F^{\mu\nu}\right)N \pm ie\frac{g_{RN\gamma}^{(2)}}{(2M_N)^3}\bar{R}_{\mu\alpha}\Gamma^{(\mp)}\left(\partial^\alpha F^{\mu\nu}\right)\partial_\nu N + \text{H.c.},$$

$$\mathcal{L}_{RN\gamma}^{7/2\pm} = ie\frac{g_{RN\gamma}^{(1)}}{(2M_N)^3}\bar{R}_{\mu\alpha\beta}\gamma_\nu\Gamma^{(\pm)}\left(\partial^\alpha\partial^\beta F^{\mu\nu}\right)N - e\frac{g_{RN\gamma}^{(2)}}{(2M_N)^4}\bar{R}_{\mu\alpha\beta}\Gamma^{(\pm)}\left(\partial^\alpha\partial^\beta F^{\mu\nu}\right)\partial_\nu N + \text{H.c.},$$

$$\mathcal{L}_{R\Lambda K^*}^{1/2\pm} = -\frac{g_{R\Lambda K^*}}{2M_N}\bar{R}\Gamma^{(\mp)}\left\{\left[\left(\frac{\gamma_\mu\partial^2}{M_R \mp M_N} \pm i\partial_\mu\right) - \frac{f_{R\Lambda K^*}}{g_{R\Lambda K^*}}\sigma_{\mu\nu}\partial^\nu\right]K^{*\mu}\right\}\Lambda + \text{H.c.},$$

$$\mathcal{L}_{R\Lambda K^*}^{3/2\pm} = -i\frac{g_{R\Lambda K^*}^{(1)}}{2M_N}\bar{R}_\mu\gamma_\nu\Gamma^{(\pm)}K^{*\mu\nu}\Lambda + \frac{g_{R\Lambda K^*}^{(2)}}{(2M_N)^2}\bar{R}_\mu\Gamma^{(\pm)}K^{*\mu\nu}\partial_\nu\Lambda \mp \frac{g_{R\Lambda K^*}^{(3)}}{(2M_N)^2}\bar{R}_\mu\Gamma^{(\pm)}\left(\partial_\nu K^{*\mu\nu}\right)\Lambda + \text{H.c.},$$

$$\mathcal{L}_{R\Lambda K^*}^{5/2\pm} = \frac{g_{R\Lambda K^*}^{(1)}}{(2M_N)^2}\bar{R}_{\mu\alpha}\gamma_\nu\Gamma^{(\mp)}\left(\partial^\alpha K^{*\mu\nu}\right)\Lambda \pm i\frac{g_{R\Lambda K^*}^{(2)}}{(2M_N)^3}\bar{R}_{\mu\alpha}\Gamma^{(\mp)}\left(\partial^\alpha K^{*\mu\nu}\right)\partial_\nu\Lambda$$
$$\mp i\frac{g_{R\Lambda K^*}^{(3)}}{(2M_N)^3}\bar{R}_{\mu\alpha}\Gamma^{(\mp)}\left(\partial^\alpha\partial_\nu K^{*\mu\nu}\right)\Lambda + \text{H.c.},$$

$$\mathcal{L}_{R\Lambda K^*}^{7/2\pm} = i\frac{g_{R\Lambda K^*}^{(1)}}{(2M_N)^3}\bar{R}_{\mu\alpha\beta}\gamma_\nu\Gamma^{(\pm)}\left(\partial^\alpha\partial^\beta K^{*\mu\nu}\right)\Lambda - \frac{g_{R\Lambda K^*}^{(2)}}{(2M_N)^4}\bar{R}_{\mu\alpha\beta}\Gamma^{(\pm)}\left(\partial^\alpha\partial^\beta K^{*\mu\nu}\right)\partial_\nu\Lambda$$
$$\pm \frac{g_{R\Lambda K^*}^{(3)}}{(2M_N)^4}\bar{R}_{\mu\alpha\beta}\Gamma^{(\pm)}\left(\partial^\alpha\partial^\beta\partial_\nu K^{*\mu\nu}\right)\Lambda + \text{H.c.}.$$