Recent Results from CLAS

K. Hicks (Ohio U.)

Sept. 26, 2017

Hadron 2017 International Conf.

Outline

- Goals of the CLAS Baryon Spectroscopy group
- Linear Polarization data: new N*'s?
- Reactions on the neutron: new $K^0\Lambda$ data
- Meson electroproduction: N* structure
- Photoproduction of K_sK_s: scalar mesons

Goals of CLAS Spectroscopy

- Search for “missing” resonances:
  - More N* resonances predicted than observed.
  - Some resonances may couple weakly to πN.
  - Multi-prong approach: analyze many final states.
- Search for “exotic” hadrons:
  - Ongoing program (not presented in this talk)
  - Scalar mesons: new data from K_sK_s final state
- Many new results!! (I can show only a few)

Polarization Observables

$$
\begin{aligned}
\sigma_{\mathrm{total}} = \sigma_{\mathrm{unpol.}}[1 - \delta_l\,\mathbf{\Sigma}\cos(2\phi) \\
+\Lambda_x\,(-\delta_l\,\mathbf{H}\sin(2\phi) + \delta_\odot\,\mathbf{F}) \\
-\Lambda_y\,(-\mathbf{T} + \delta_l\,\mathbf{P}\cos 2\phi) \\
-\Lambda_z\,(-\delta_l\,\mathbf{G}\sin(2\phi) + \delta_\odot\,\mathbf{E}\,) + \ldots]
\end{aligned}
$$

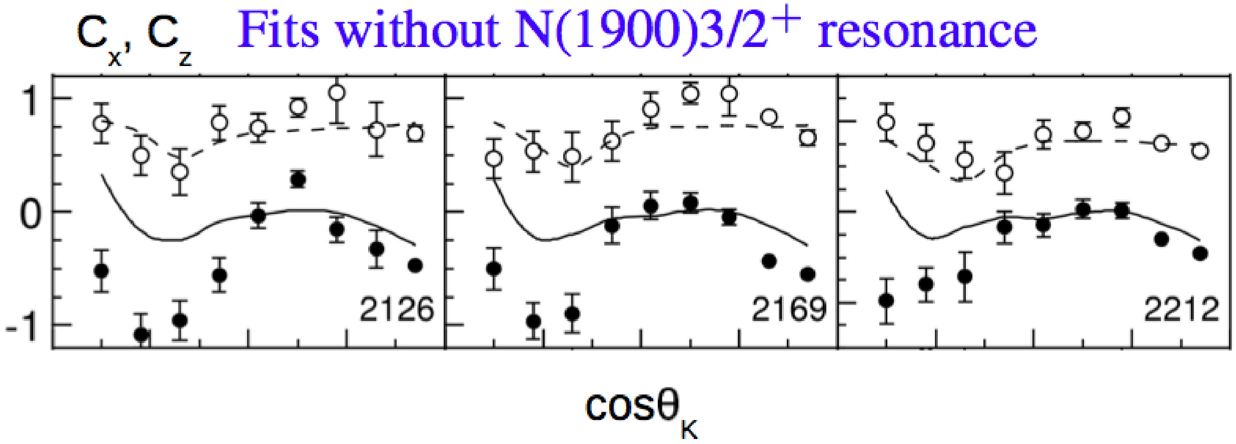
$\delta_\odot(\delta_l)$: degree of beam pol.

Λ : degree of target pol.

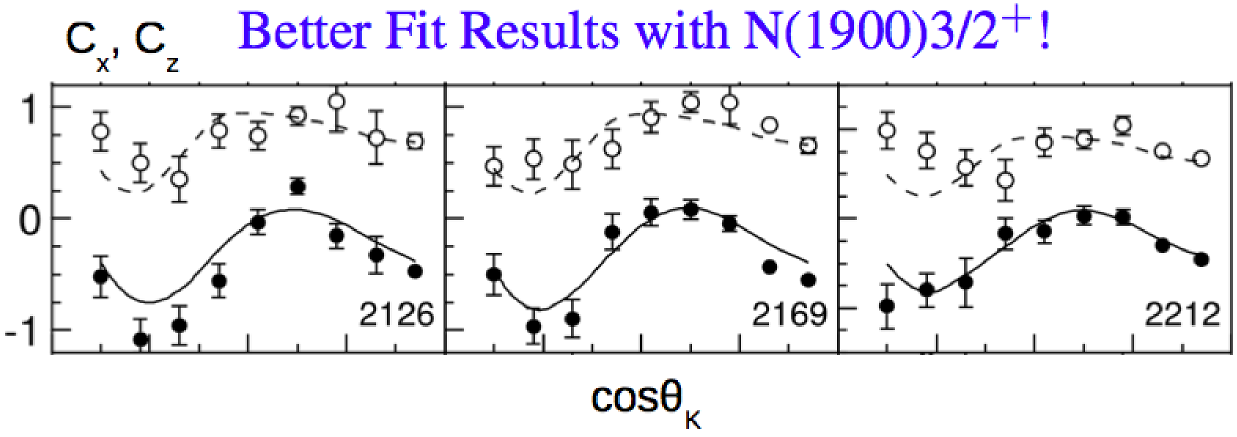
Talks by: Natalie Walford (Thursday, Sept. 28, 09:15)
Tsuneo Kageya (Tuesday, Sept. 26, 12:10)

Polarization Transfer: $\gamma p \rightarrow K^+\Lambda$

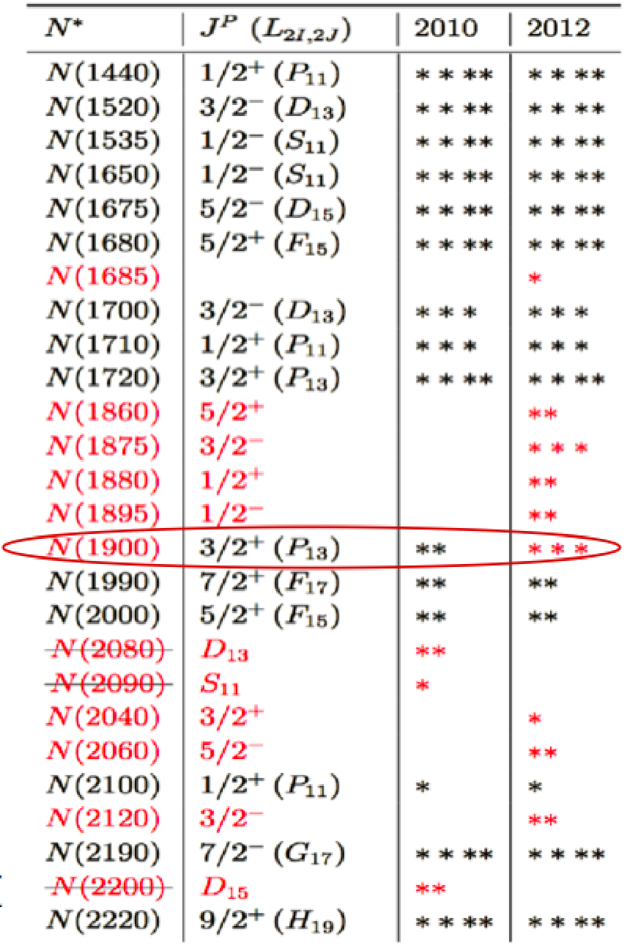
Fits without N(1900)3/2$^+$ resonance



Better Fit Results with N(1900)3/2$^+$!



[1] R. Bradford *et al.* (CLAS), PRC **75**, 035205 (2007), Observables C_x, C_z from $\vec{\gamma} p \rightarrow K^+ \vec{\Lambda}$
[2] Fits: BnGa Model, V.A. Nikonov *et al.*, Phy. Lett. B **662**, 245 (2008)



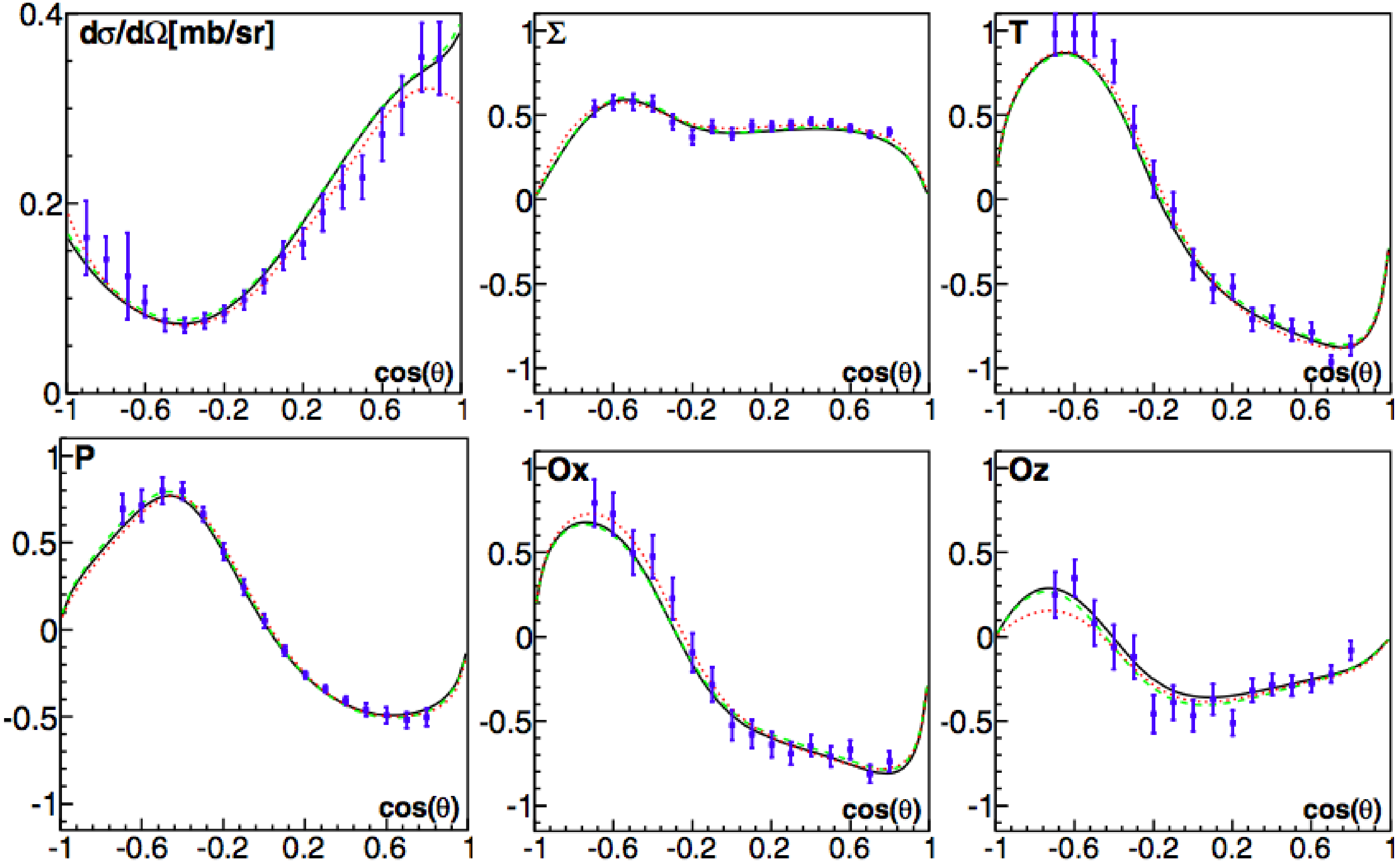
N^*	J^P $(L_{2I,2J})$	2010	2012
$N(1440)$	$1/2^+$ (P_{11})	****	****
$N(1520)$	$3/2^-$ (D_{13})	****	****
$N(1535)$	$1/2^-$ (S_{11})	****	****
$N(1650)$	$1/2^-$ (S_{11})	****	****
$N(1675)$	$5/2^-$ (D_{15})	****	****
$N(1680)$	$5/2^+$ (F_{15})	****	****
$N(1685)$			*
$N(1700)$	$3/2^-$ (D_{13})	***	***
$N(1710)$	$1/2^+$ (P_{11})	***	***
$N(1720)$	$3/2^+$ (P_{13})	****	****
$N(1860)$	$5/2^+$		**
$N(1875)$	$3/2^-$		***
$N(1880)$	$1/2^+$		**
$N(1895)$	$1/2^-$		**
$N(1900)$	$3/2^+$ (P_{13})	**	***
$N(1990)$	$7/2^+$ (F_{17})	**	**
$N(2000)$	$5/2^+$ (F_{15})	**	**
~~$N(2080)$~~	D_{13}	**	
~~$N(2090)$~~	S_{11}	*	
$N(2040)$	$3/2^+$		*
$N(2060)$	$5/2^-$		**
$N(2100)$	$1/2^+$ (P_{11})	*	*
$N(2120)$	$3/2^-$		**
$N(2190)$	$7/2^-$ (G_{17})	****	****
~~$N(2200)$~~	D_{15}	**	
$N(2220)$	$9/2^+$ (H_{19})	****	****

One example of a "missing" resonance now found!

PRL 119, 062004 (2017) PHYSICAL REVIEW LETTERS week ending 11 AUGUST 2017

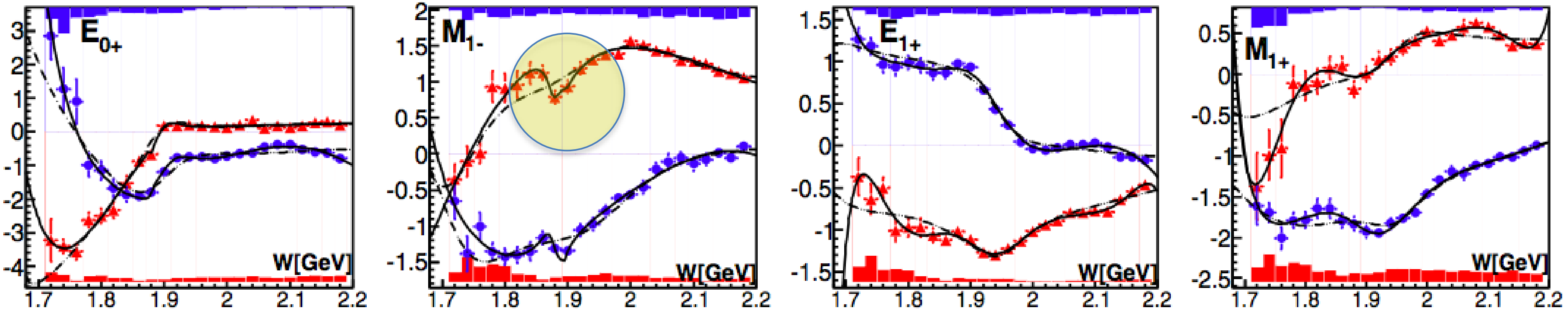
Strong Evidence for Nucleon Resonances near 1900 MeV

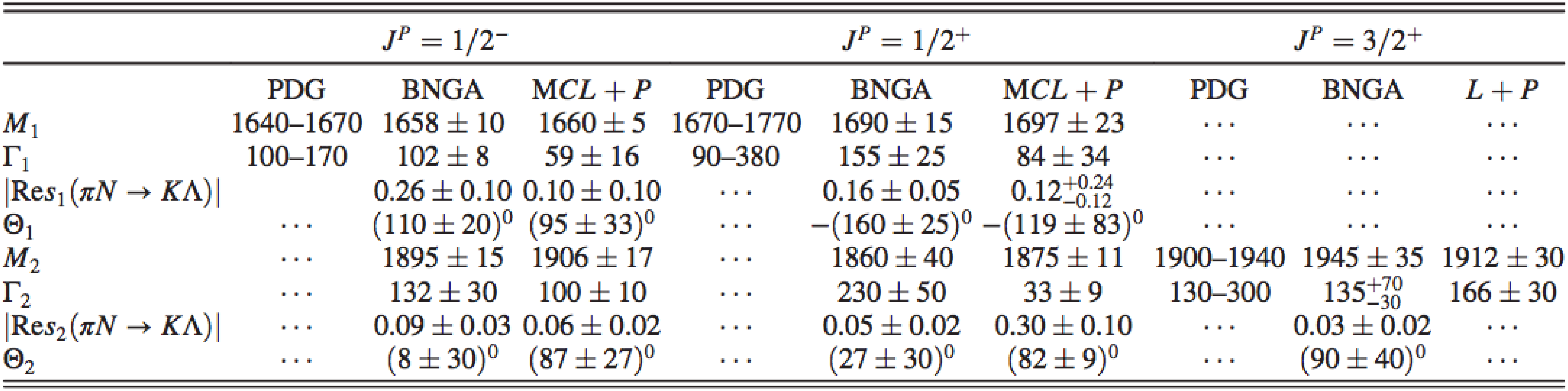
A. V. Anisovich,[1,2] V. Burkert,[3] M. Hadžimehmedović,[4] D. G. Ireland,[5] E. Klempt,[1,3] V. A. Nikonov,[1,2] R. Omerović,[4]
H. Osmanović,[4] A. V. Sarantsev,[1,2] J. Stahov,[4] A. Švarc,[6] and U. Thoma[1]



γp → $K^+\Lambda$ at W=1.95-1.97 GeV, fits using the Bonn-Gatchina model

$\gamma p \rightarrow K^+\Lambda$: Fits to the EM multipoles

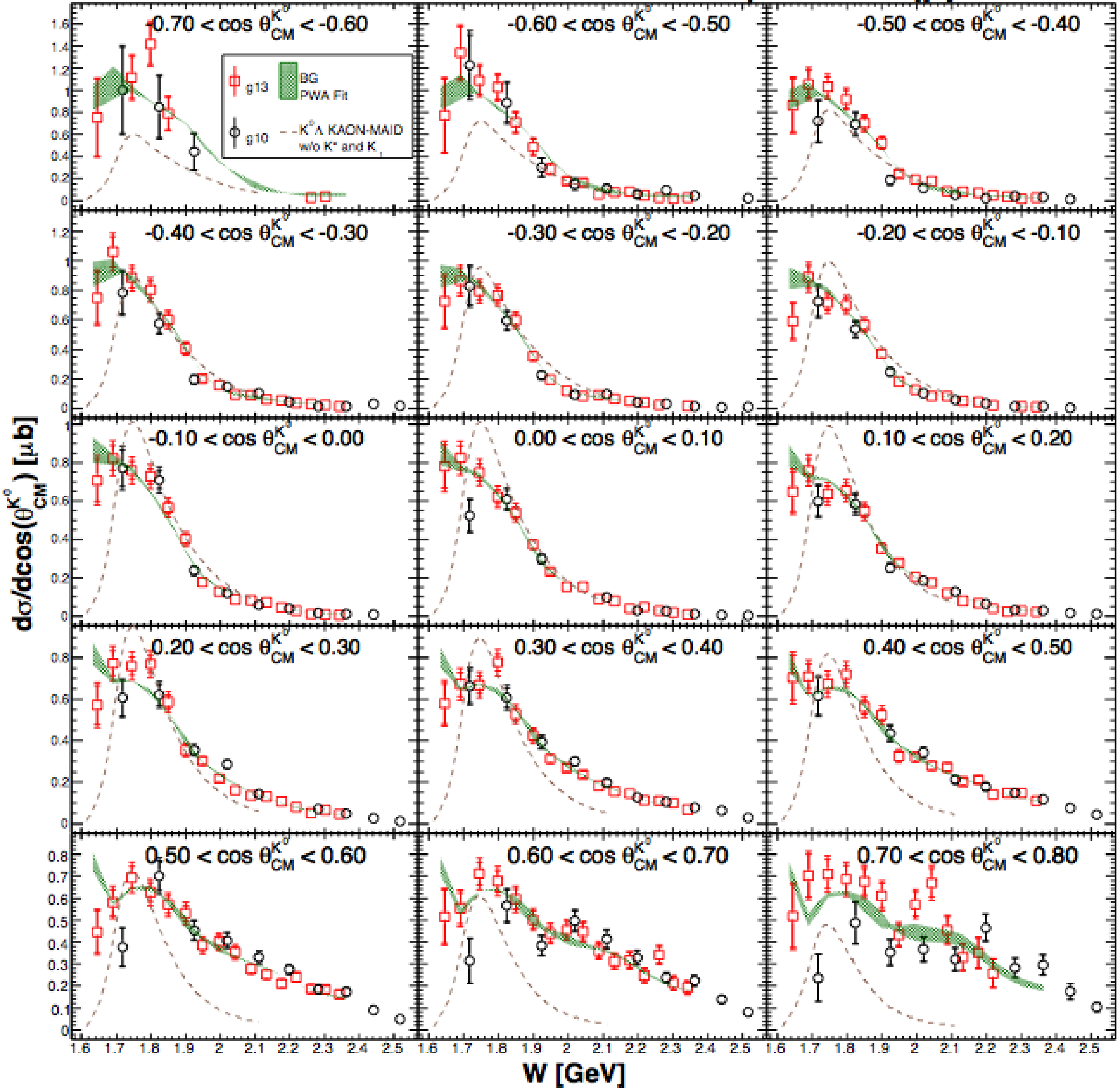




	$J^P = 1/2^-$			$J^P = 1/2^+$			$J^P = 3/2^+$		
	PDG	BNGA	$MCL + P$	PDG	BNGA	$MCL + P$	PDG	BNGA	$L + P$
M_1	1640–1670	1658 ± 10	1660 ± 5	1670–1770	1690 ± 15	1697 ± 23	⋯	⋯	⋯
Γ_1	100–170	102 ± 8	59 ± 16	90–380	155 ± 25	84 ± 34	⋯	⋯	⋯
$\lvert Res_1(\pi N \rightarrow K\Lambda)\rvert$		0.26 ± 0.10	0.10 ± 0.10	⋯	0.16 ± 0.05	$0.12^{+0.24}_{-0.12}$	⋯	⋯	⋯
Θ_1	⋯	$(110 \pm 20)^0$	$(95 \pm 33)^0$	⋯	$-(160 \pm 25)^0$	$-(119 \pm 83)^0$	⋯	⋯	⋯
M_2	⋯	1895 ± 15	1906 ± 17	⋯	1860 ± 40	1875 ± 11	1900–1940	1945 ± 35	1912 ± 30
Γ_2	⋯	132 ± 30	100 ± 10	⋯	230 ± 50	33 ± 9	130–300	135^{+70}_{-30}	166 ± 30
$\lvert Res_2(\pi N \rightarrow K\Lambda)\rvert$	⋯	0.09 ± 0.03	0.06 ± 0.02	⋯	0.05 ± 0.02	0.30 ± 0.10	⋯	0.03 ± 0.02	⋯
Θ_2	⋯	$(8 \pm 30)^0$	$(87 \pm 27)^0$	⋯	$(27 \pm 30)^0$	$(82 \pm 9)^0$	⋯	$(90 \pm 40)^0$	⋯

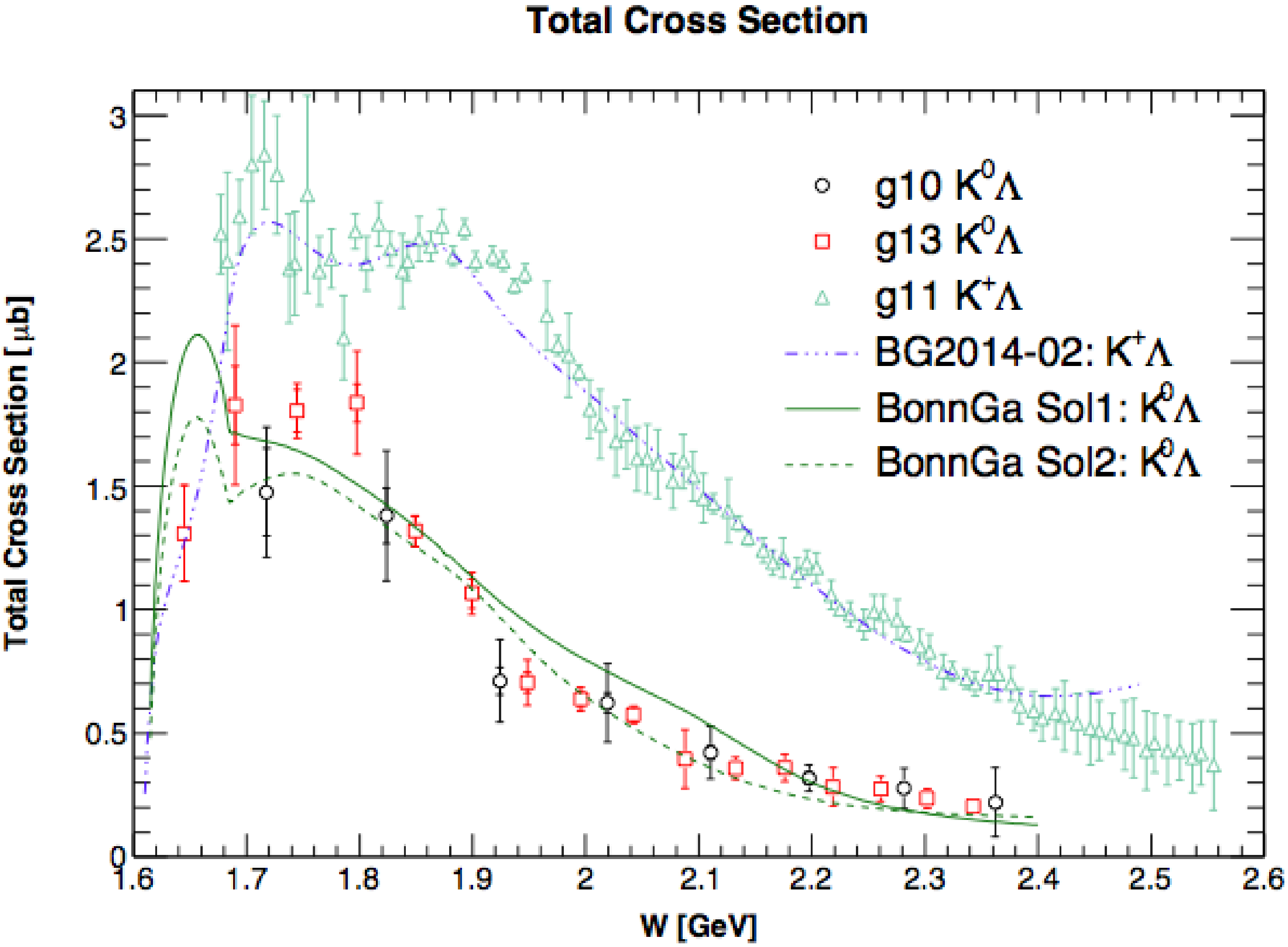
Evidence for 2 new “missing” resonances & 3 with more precision.
Made possible by precision data from CLAS.

N. Compton, PhD (Ohio U, 2017), submitted to PRC (arXiv:1706.04748).



Differential Cross Section of $\gamma d \to K^0 \Lambda (p)$

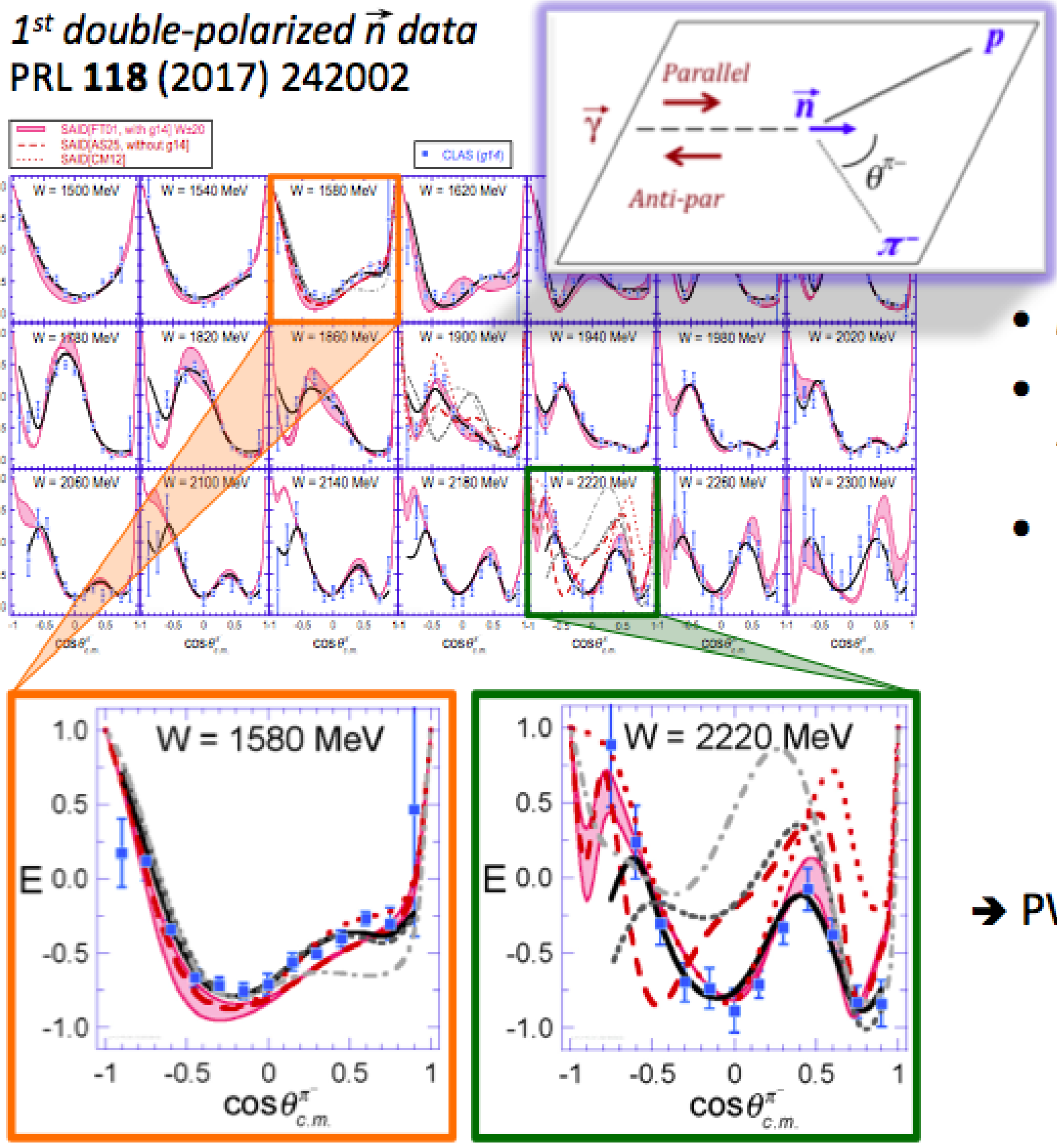
Cont'd: comparison with $K^+\Lambda$

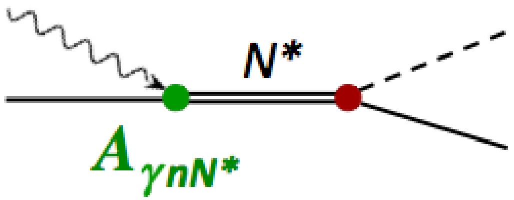


No "peak" near 1900 MeV for $K^0\Lambda$: photocouplings γnN* and γpN* are different.

g14 beam-target helicity asymmetries for $\gamma n \rightarrow \pi^- p$ and N states excited from the neutron*

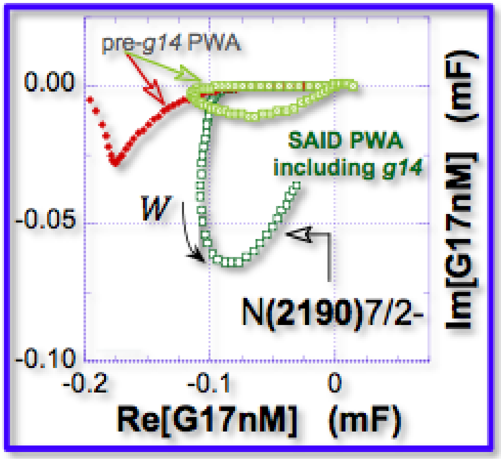
- *1^{st} double-polarized $\vec{n}$ data*
  PRL **118** (2017) 242002





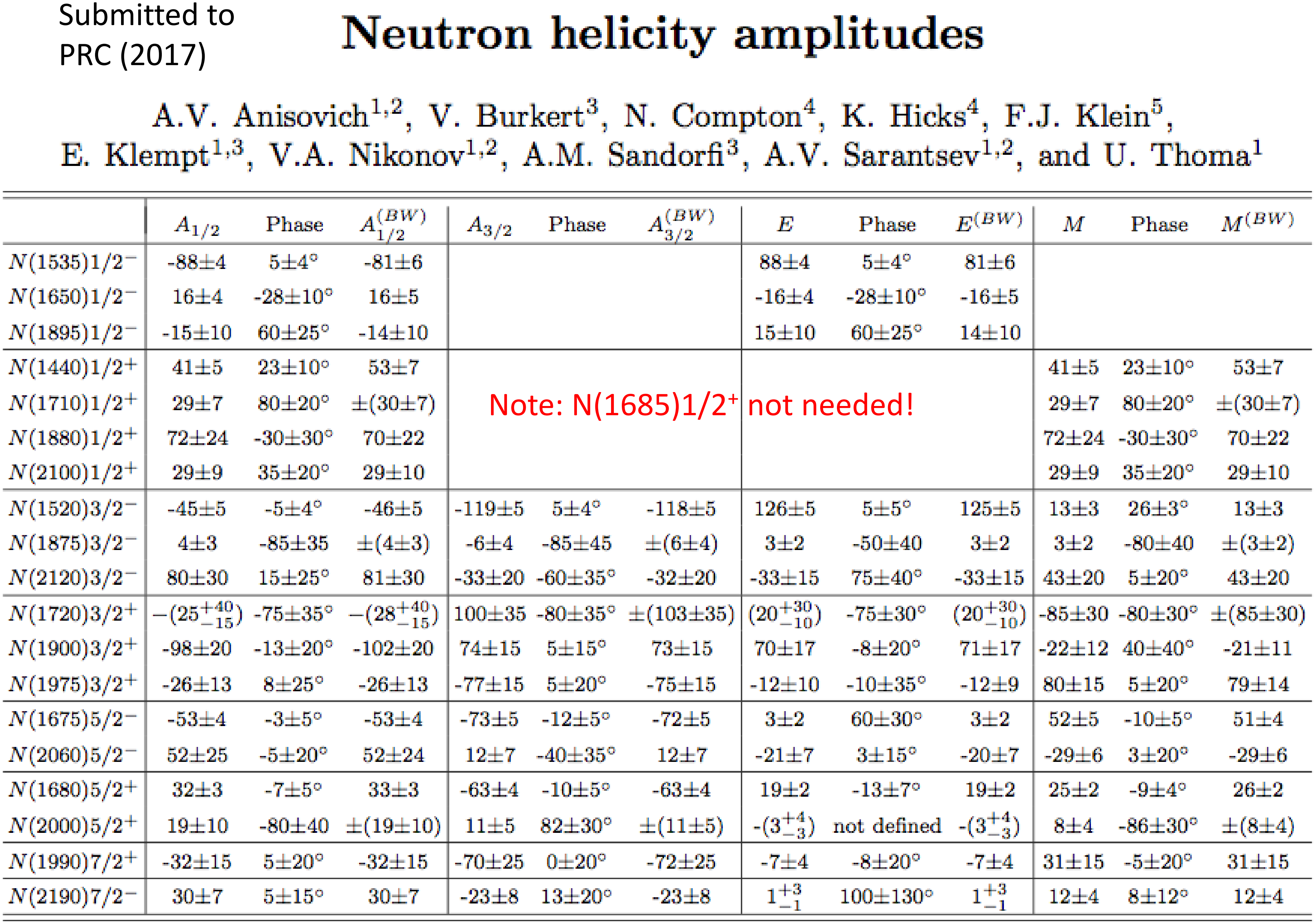
- *E&M* interaction is not isospin symmetric
- $\gamma n N^*$ and $\gamma p N^*$ couplings are different
  ⇔ probes of dynamics in N* excitation
- *eg. SAID Partial Wave Analysis (PWA)*:
  $A_{\gamma n}^{1/2}$ [N(2190)7/2-] → **-16 ±5** (10^{-3} GeV$^{-1/2}$)
  $A_{\gamma n}^{3/2}$ [N(2190)7/2-] → **-35 ±5** (10^{-3} GeV$^{-1/2}$)

→ PWA →



Talk by Tsuneo Kageya on Tuesday

Submitted to PRC (2017)



Neutron helicity amplitudes

A.V. Anisovich[1,2], V. Burkert[3], N. Compton[4], K. Hicks[4], F.J. Klein[5], E. Klempt[1,3], V.A. Nikonov[1,2], A.M. Sandorfi[3], A.V. Sarantsev[1,2], and U. Thoma[1]

	$A_{1/2}$	Phase	$A^{(BW)}_{1/2}$	$A_{3/2}$	Phase	$A^{(BW)}_{3/2}$	E	Phase	$E^{(BW)}$	M	Phase	$M^{(BW)}$
$N(1535)1/2^-$	-88±4	5±4°	-81±6				88±4	5±4°	81±6			
$N(1650)1/2^-$	16±4	-28±10°	16±5				-16±4	-28±10°	-16±5			
$N(1895)1/2^-$	-15±10	60±25°	-14±10				15±10	60±25°	14±10			
$N(1440)1/2^+$	41±5	23±10°	53±7							41±5	23±10°	53±7
$N(1710)1/2^+$	29±7	80±20°	±(30±7)							29±7	80±20°	±(30±7)
$N(1880)1/2^+$	72±24	-30±30°	70±22							72±24	-30±30°	70±22
$N(2100)1/2^+$	29±9	35±20°	29±10							29±9	35±20°	29±10
$N(1520)3/2^-$	-45±5	-5±4°	-46±5	-119±5	5±4°	-118±5	126±5	5±5°	125±5	13±3	26±3°	13±3
$N(1875)3/2^-$	4±3	-85±35	±(4±3)	-6±4	-85±45	±(6±4)	3±2	-50±40	3±2	3±2	-80±40	±(3±2)
$N(2120)3/2^-$	80±30	15±25°	81±30	-33±20	-60±35°	-32±20	-33±15	75±40°	-33±15	43±20	5±20°	43±20
$N(1720)3/2^+$	$-(25^{+40}_{-15})$	-75±35°	$-(28^{+40}_{-15})$	100±35	-80±35°	±(103±35)	(20^{+30}_{-10})	-75±30°	(20^{+30}_{-10})	-85±30	-80±30°	±(85±30)
$N(1900)3/2^+$	-98±20	-13±20°	-102±20	74±15	5±15°	73±15	70±17	-8±20°	71±17	-22±12	40±40°	-21±11
$N(1975)3/2^+$	-26±13	8±25°	-26±13	-77±15	5±20°	-75±15	-12±10	-10±35°	-12±9	80±15	5±20°	79±14
$N(1675)5/2^-$	-53±4	-3±5°	-53±4	-73±5	-12±5°	-72±5	3±2	60±30°	3±2	52±5	-10±5°	51±4
$N(2060)5/2^-$	52±25	-5±20°	52±24	12±7	-40±35°	12±7	-21±7	3±15°	-20±7	-29±6	3±20°	-29±6
$N(1680)5/2^+$	32±3	-7±5°	33±3	-63±4	-10±5°	-63±4	19±2	-13±7°	19±2	25±2	-9±4°	26±2
$N(2000)5/2^+$	19±10	-80±40	±(19±10)	11±5	82±30°	±(11±5)	$-(3^{+4}_{-3})$	not defined	$-(3^{+4}_{-3})$	8±4	-86±30°	±(8±4)
$N(1990)7/2^+$	-32±15	5±20°	-32±15	-70±25	0±20°	-72±25	-7±4	-8±20°	-7±4	31±15	-5±20°	31±15
$N(2190)7/2^-$	30±7	5±15°	30±7	-23±8	13±20°	-23±8	1^{+3}_{-1}	100±130°	1^{+3}_{-1}	12±4	8±12°	12±4

Note: $N(1685)1/2^+$ not needed!

γnN^* vs γpN^* couplings

(10^{-3} GeV$^{-1/2}$)	$A_n^{1/2}$	$A_p^{1/2}$	$A_n^{3/2}$	$A_p^{3/2}$
SAID				
$N(1720)3/2^+$	-15 ±5 [4]	95 ±2 [6]	13 ± 4 [4]	-48 ±2 [6]
$N(1895)1/2^-$	----	----		
$N(1975)3/2^+$	----	----	----	----
$N(2190)7/2^-$	-16 ±5 [4]	- -	-35 ±5 [4]	- -
BnGa				
$N(1720)3/2^+$	-(28 +40/-15) [3]	110 ±45 [5]	±(103 ±35) [3]	150 ±30 [5]
$N(1895)1/2^-$	-15 ±10 [3]	-11 ±6 [5]		
$N(1975)3/2^+$	-26 ±13 [3]		-77 ±15 [3]	
$N(2190)7/2^-$	+30 ±7 [1]	-65 ±8 [5]	-23 ± 8 [1]	+35 ±17 [5]

[1] CLAS/g14: *Phys. Rev. Lett.* ***118*** *(2017)*

[2] *SAID: Phys. Rev. C**85** (2012) 025201*

[3] *BnGa: Phys. Rev. C (submitted)*

[4] R.L. Workman and A. Švarc (*priv. comm.)*

[6] *SAID: Phys. Rev. C**86** (2012) 015202*

[5] *BnGa: Eur. Phys. J. A**48** (2012) 15*

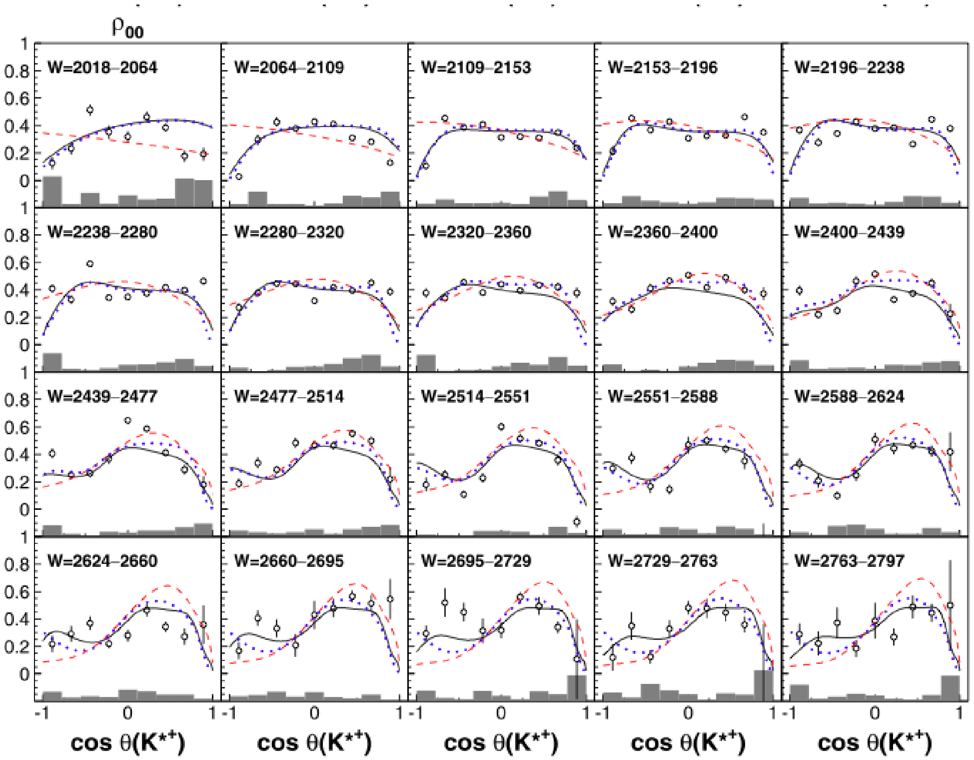
Slide borrowed from A. Sandorfi

Differential cross sections and polarization observables from CLAS K^* photoproduction and the search for new N^* states

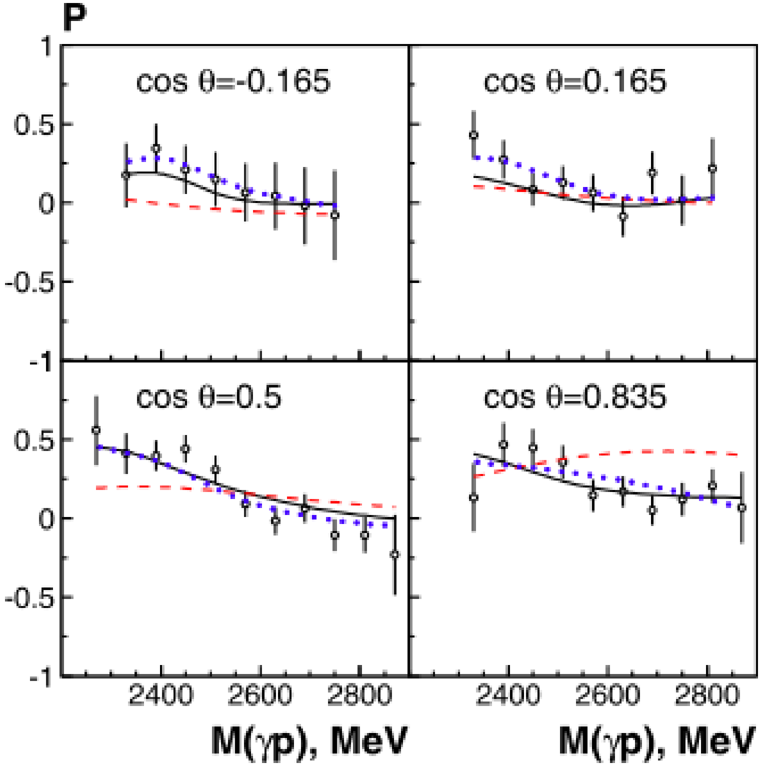
The CLAS Collaboration

A.V. Anisovich, KH, et al. PLB, 771, 142-150 (2017)
Based on analysis of W. Tang (PhD, Ohio U, 2012)

Extracted spin-density matrix elements:

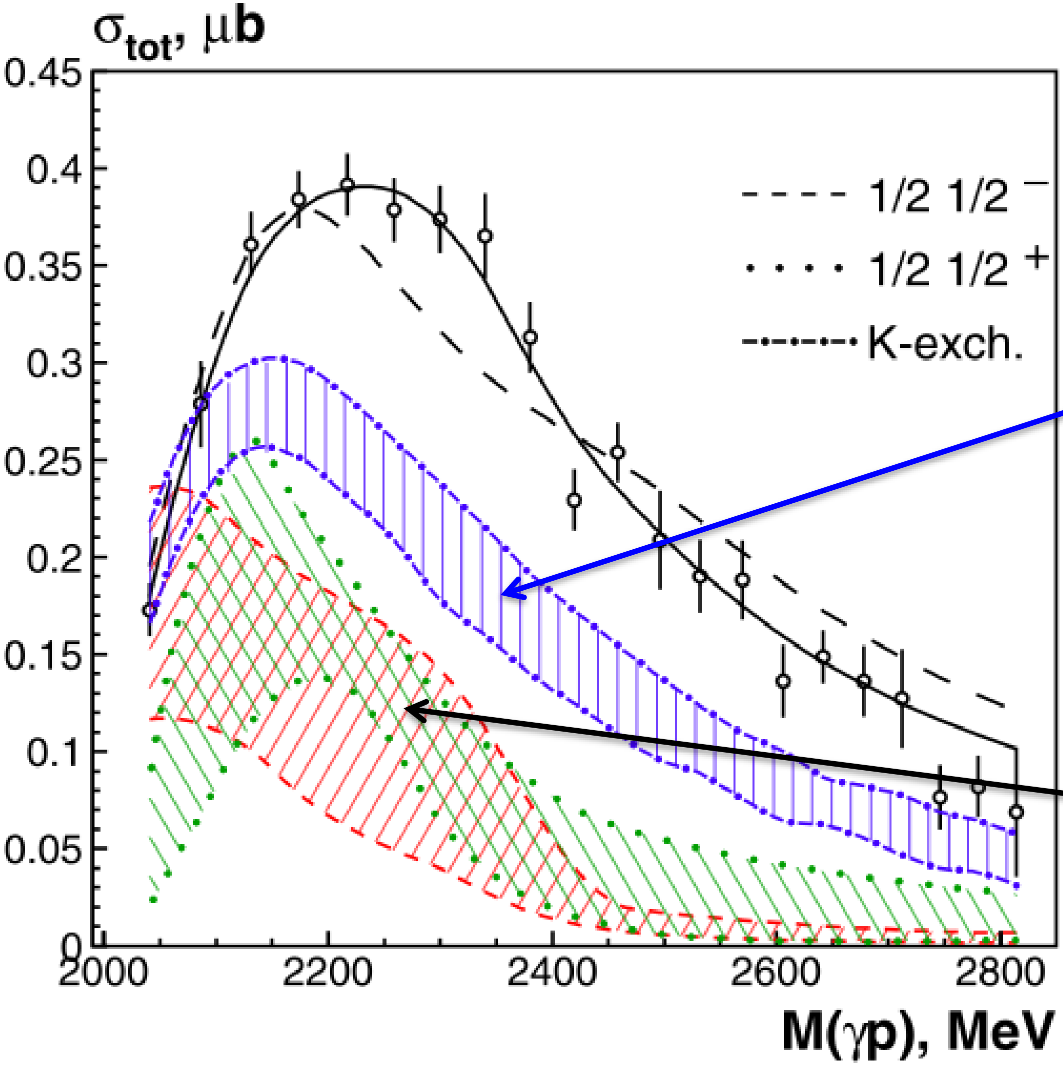


and Λ recoil polarization:



Additional fits to differential cross sections and other spin-density (ρ_{10}, ρ_{11}) done.

CLAS $\gamma p \rightarrow K^{*0}\Lambda$ Total Cross Section



Bonn-Gatchina model fit has two possible solutions (bounded hatched regions)

t-channel only

Considerable s-channel strength is needed

CLAS $\gamma p \rightarrow K^{*0}\Lambda$ BoGa fit results:

B.R. to $K^*\Lambda$

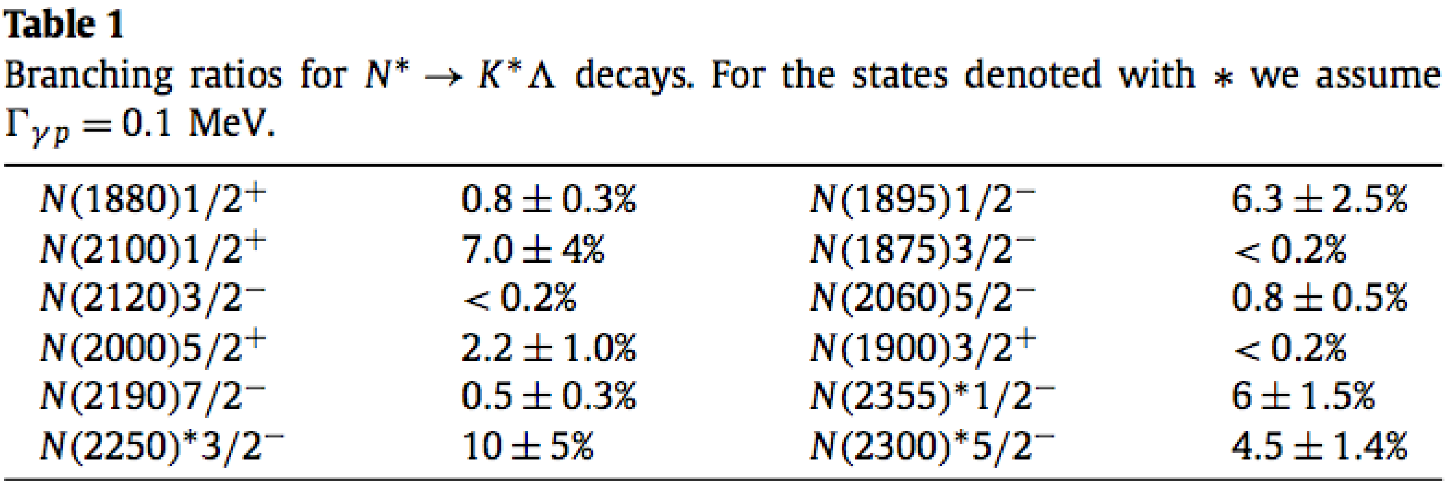


Table 1

Branching ratios for $N^* \to K^*\Lambda$ decays. For the states denoted with $*$ we assume $\Gamma_{\gamma p} = 0.1$ MeV.

$N(1880)1/2^+$	$0.8 \pm 0.3\%$	$N(1895)1/2^-$	$6.3 \pm 2.5\%$
$N(2100)1/2^+$	$7.0 \pm 4\%$	$N(1875)3/2^-$	$< 0.2\%$
$N(2120)3/2^-$	$< 0.2\%$	$N(2060)5/2^-$	$0.8 \pm 0.5\%$
$N(2000)5/2^+$	$2.2 \pm 1.0\%$	$N(1900)3/2^+$	$< 0.2\%$
$N(2190)7/2^-$	$0.5 \pm 0.3\%$	$N(2355)^*1/2^-$	$6 \pm 1.5\%$
$N(2250)^*3/2^-$	$10 \pm 5\%$	$N(2300)^*5/2^-$	$4.5 \pm 1.4\%$

Possible new high-mass N*'s

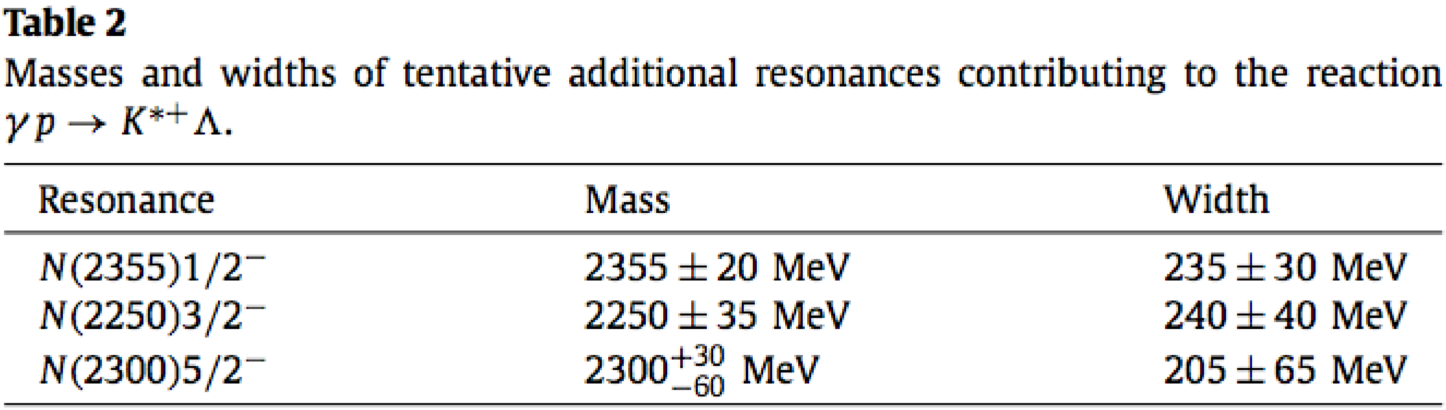


Table 2

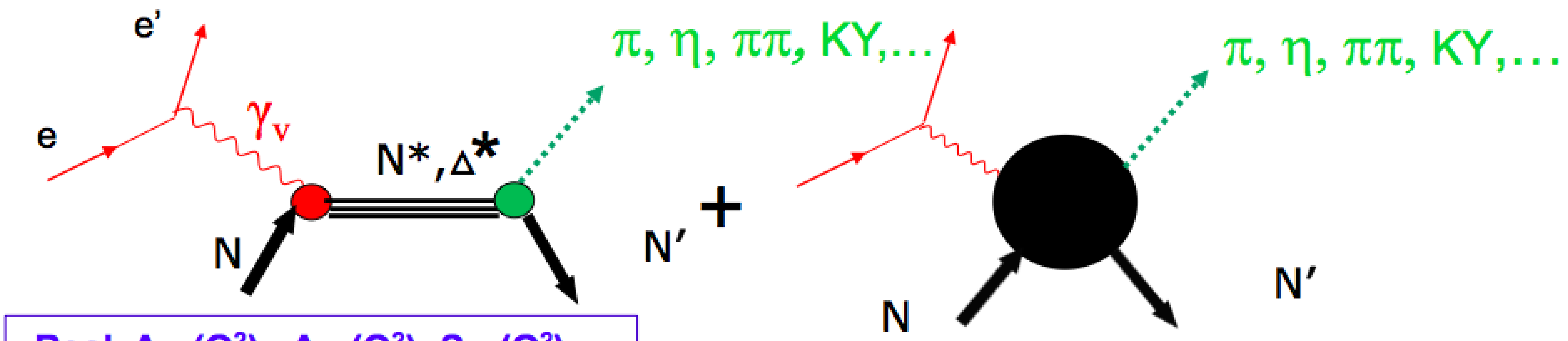
Masses and widths of tentative additional resonances contributing to the reaction $\gamma p \to K^{*+}\Lambda$.

Resonance	Mass	Width
$N(2355)1/2^-$	2355 ± 20 MeV	235 ± 30 MeV
$N(2250)3/2^-$	2250 ± 35 MeV	240 ± 40 MeV
$N(2300)5/2^-$	2300^{+30}_{-60} MeV	205 ± 65 MeV

Often we see N* resonances near the threshold of higher-mass meson production.

Extraction of $\gamma_v NN^*$ Electrocouplings from Exclusive Meson Electroproduction off Nucleons

Resonant amplitudes **Non-resonant amplitudes**



- **Real $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$**

  or
- **$G_1(Q^2)$, $G_2(Q^2)$, $G_3(Q^2)$**

  or
- **$G_M(Q^2)$, $G_E(Q^2)$, $G_C(Q^2)$**

I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012).

Definition of N* photo-/electrocouplings employed in the CLAS data analyses:

$$\Gamma_\gamma = \frac{k_{\gamma_{N^*}}^2}{\pi} \frac{2M_N}{(2J_r+1)M_{N^*}} \left[|A_{1/2}|^2 + |A_{3/2}|^2 \right]$$

Γ_γ: N* electromagnetic decay widths;
$W=M_{N^*}$ on the real energy axis.

- **Consistent results on $\gamma_v NN^*$ electrocouplings from different meson electroproduction channels and different analysis approaches demonstrate reliable extraction of these quantities.**

Slides borrowed from V. Mokeev

Summary of Published CLAS Data on Exclusive Meson Electroproduction off Protons in N* Excitation Region

Hadronic final state	Covered W-range, GeV	Covered Q^2-range, GeV^2	Measured observables
π^+n	**1.1-1.38** **1.1-1.55** **1.1-1.7** **1.6-2.0**	**0.16-0.36** **0.3-0.6** **1.7-4.5** **1.8-4.5**	$d\sigma/d\Omega$ $d\sigma/d\Omega$ $d\sigma/d\Omega$, A_b $d\sigma/d\Omega$
π^0p	**1.1-1.38** **1.1-1.68** **1.1-1.39**	**0.16-0.36** **0.4-1.8** **3.0-6.0**	$d\sigma/d\Omega$ $d\sigma/d\Omega$, A_b,A_t,A_{bt} $d\sigma/d\Omega$
ηp	**1.5-2.3**	**0.2-3.1**	$d\sigma/d\Omega$
$K^+\Lambda$	**thresh-2.6**	**1.40-3.90** **0.70-5.40**	$d\sigma/d\Omega$ P^0, P'
$K^+\Sigma^0$	**thresh-2.6**	**1.40-3.90** **0.70-5.40**	$d\sigma/d\Omega$ P'
$\pi^+\pi^-p$	**1.3-1.6** **1.4-2.1** **1.4-2.0**	**0.2-0.6** **0.5-1.5** **2.0-5.0**	**Nine 1-fold differential cross sections**

- $d\sigma/d\Omega$–CM angular distributions
- A_b,A_t,A_{bt}-longitudinal beam, target, and beam-target asymmetries
- P^0, P' –recoil and transferred polarization of strange baryon

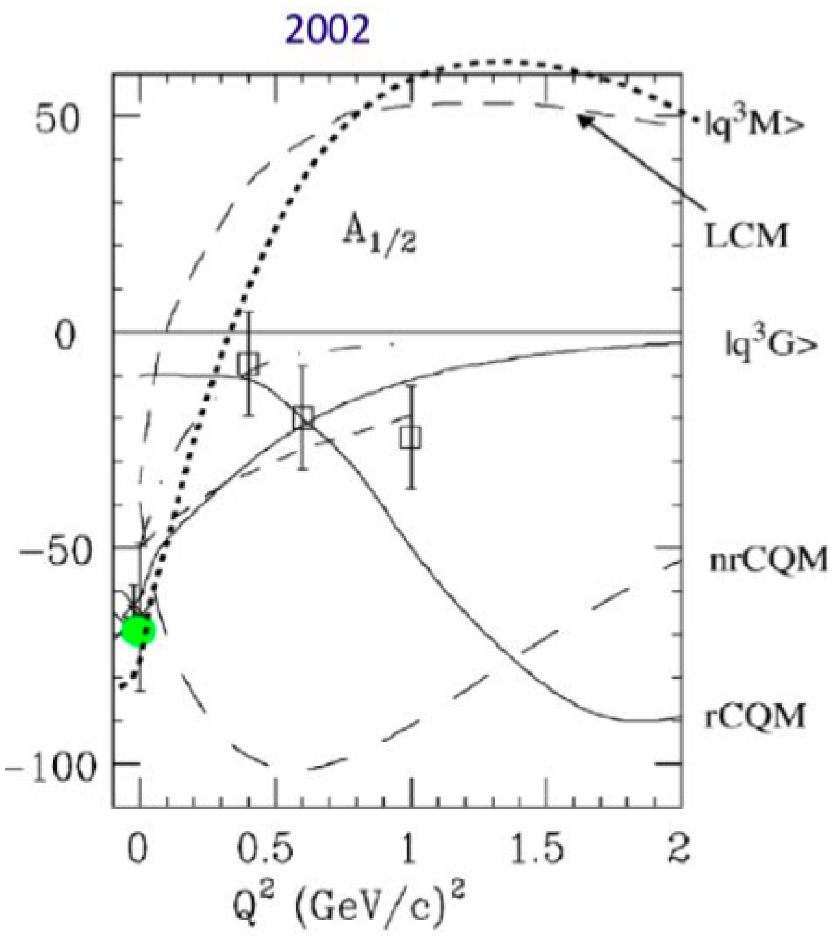
🟦 Recent extensions

Almost full coverage of the final hadron phase space in πN, $\pi^+\pi^-p$, ηp, KY electroproduction

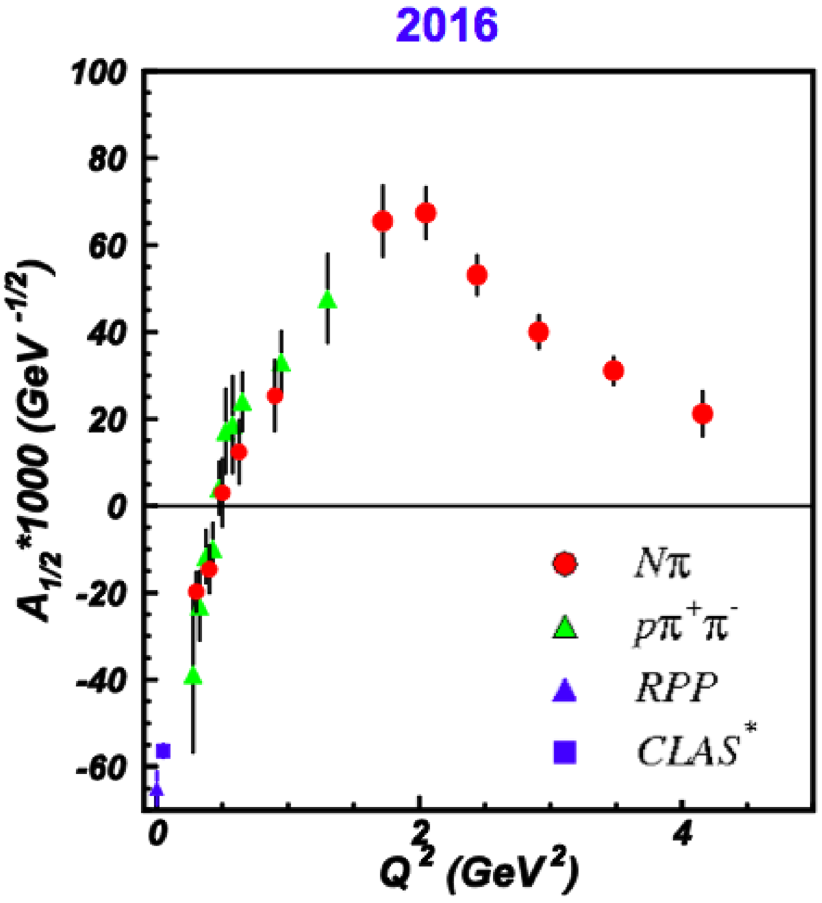
The measured observables from CLAS for the exclusive electroproduction of all listed final states are stored in the CLAS Physics Data Base http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi.

Slides borrowed from V. Mokeev

N(1440)1/2⁺ electrocoupling



V. Burkert, Baryons 2002



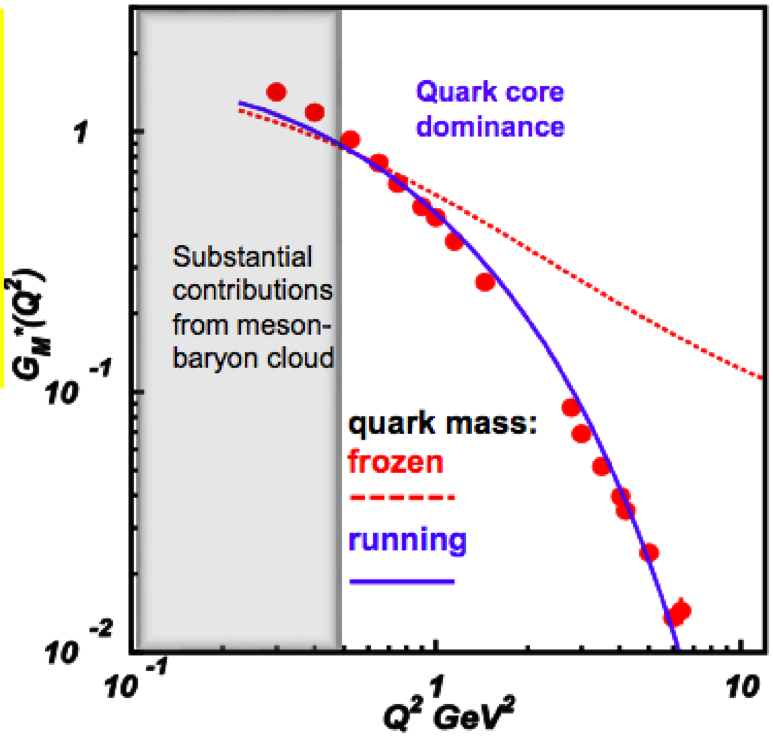
V. D. Burkert, Baryons 2016

Slides borrowed from V. Mokeev

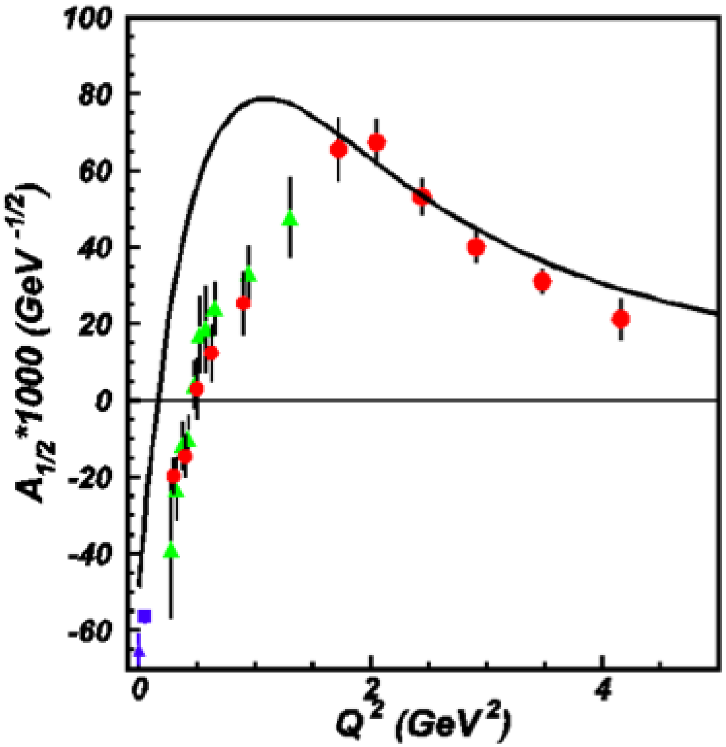
Access to the Dressed Quark Mass Function

Dyson-Schwinger Equations (DSE):

- J. Segovia et al., Phys .Rev. Lett. 115, 171801 (2015).
- J. Segovia et al., Few Body Syst. 55, 1185 (2014).



N→Δ(1232)3/2⁺ magnetic from factor
Jones-Scadron convention



N(1440)1/2⁺

DSE analyses of the CLAS data on Δ(1232)3/2⁺ electroexcitation for the first time demonstrated that dressed quark mass is running with momentum.

Good data description at Q^2>2.0 GeV^2 achieved with the same dressed quark mass function for the ground and excited nucleon states of distinctively different structure provides strong evidence for:

- the relevance of dressed quarks with dynamically generated mass and structure;
- access to quark mass function from the data on elastic and N→N* transition form factors.

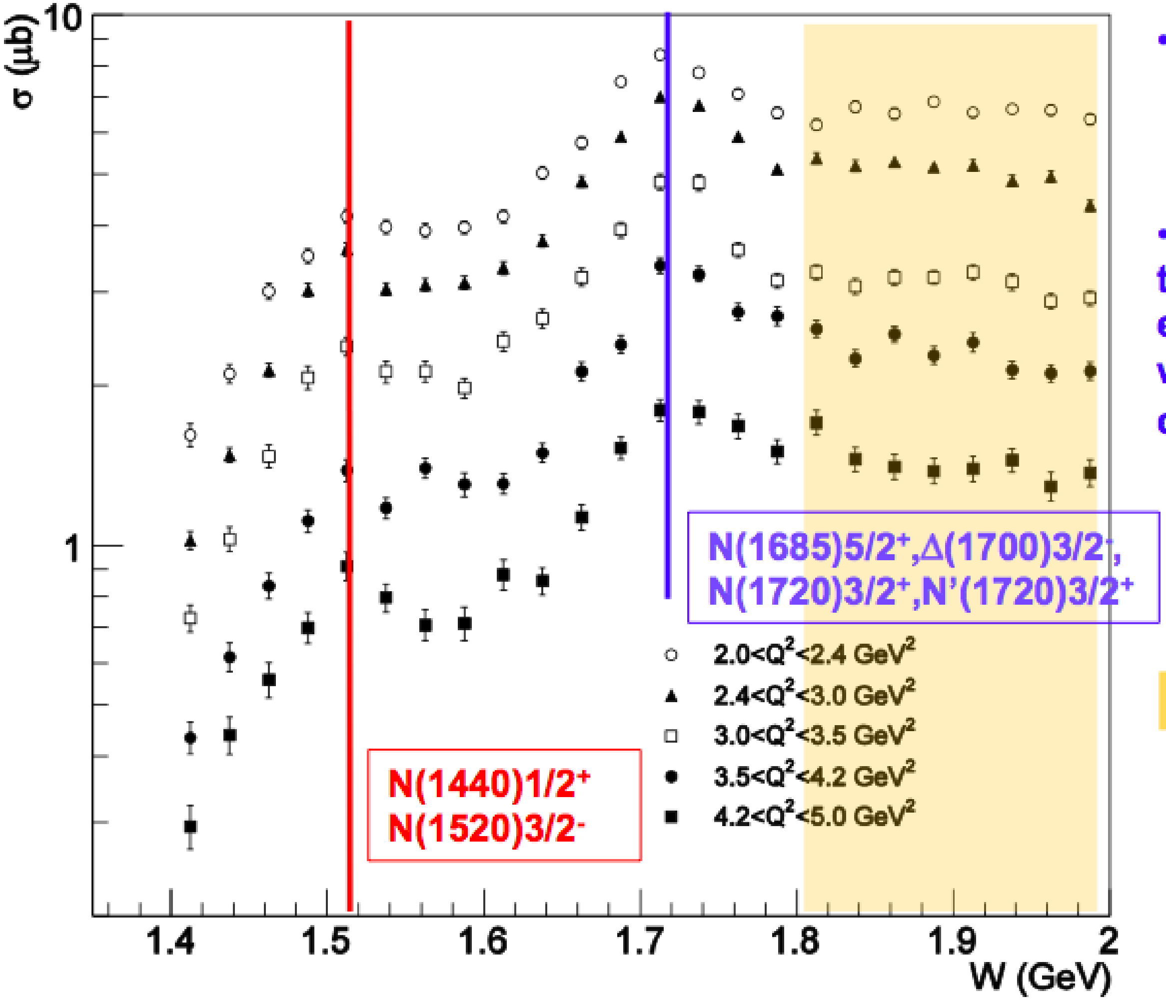
One of the most important achievements in hadron physics of the last decade obtained in synergistic efforts between experimentalists and theorists.

Slides borrowed from V. Mokeev

New CLAS $\pi^+\pi^-p$ Electroproduction Data at High Photon Virtualities

Fully integrated $\pi^+\pi^-p$ electroproduction cross sections off protons

1.40 GeV<W<2.00 GeV, 2.0 GeV^2<Q^2<5.0 GeV^2



E.L. Isupov et al. (CLAS), arXiv:1705.01901, in press by Phys. Rev. C

Analysis objectives:

- **Extraction of $\gamma_v pN^*$ electrocouplings for most N*s in mass range up to W=2.0 GeV and 2.0< Q^2< 5.0 GeV^2.**
- **Search for new baryon states through their manifestations in exclusive $\pi^+\pi^-p$ electroproduction with Q^2-independent masses and decay widths.**

🟨 **Mass range where the signals from new baryon states were reported, A.V. Anisovich et al., Eur. Phys. J. A48, 15 (2012).**

Slides borrowed from V. Mokeev

CLAS12 N* Program at High Q^2

E12-09-003

Nucleon Resonance Studies with CLAS12

Gothe, Mokeev, Burkert, Cole, Joo, Stoler

E12-06-108A

KY Electroproduction with CLAS12

Carman, Gothe, Mokeev

- Measure exclusive electroproduction cross sections from an unpolarized proton target with polarized electron beam for $N\pi$, $N\eta$, $N\pi\pi$, KY:

  E_b = 11 GeV, $Q^2 = 3 \rightarrow 12$ GeV^2, $W \rightarrow 3.0$ GeV with the almost complete coverage of the final state phase space

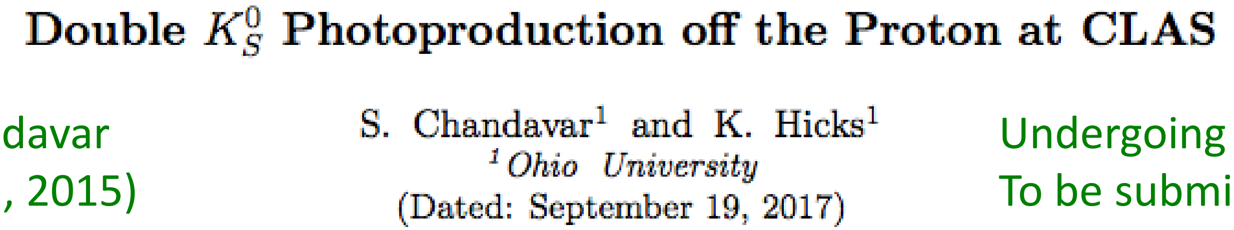
- Key Motivation

  Study the structure of all prominent N states in the mass range up to 2.0 GeV vs. Q^2 up to 12 GeV^2.*

  CLAS12 is the only facility foreseen in the world capable to map-out N quark core under almost negligible contributions from meson-baryon cloud*

The experiments will start at the end of 2017!

Slides borrowed from V. Mokeev

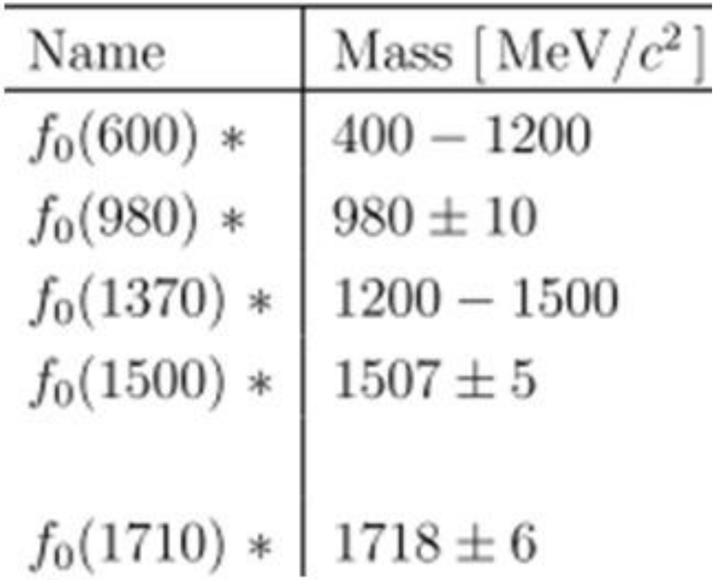


Double K_S^0 Photoproduction off the Proton at CLAS

S. Chandavar[1] and K. Hicks[1]
[1] *Ohio University*
(Dated: September 19, 2017)

Shloka Chandavar
(PhD, OhioU, 2015)

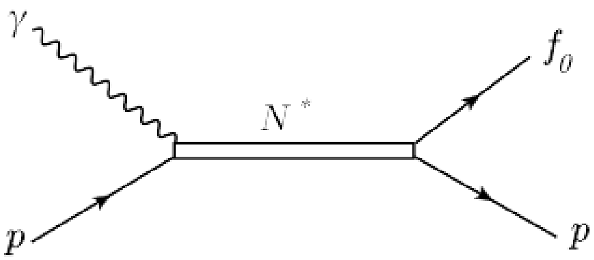
Undergoing CLAS review
To be submitted to PRC

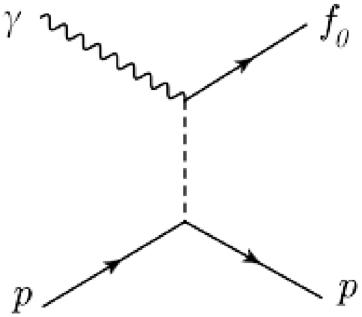


Name	Mass [MeV/c^2]
$f_0(600)$ *	400 – 1200
$f_0(980)$ *	980 ± 10
$f_0(1370)$ *	1200 – 1500
$f_0(1500)$ *	1507 ± 5
$f_0(1710)$ *	1718 ± 6

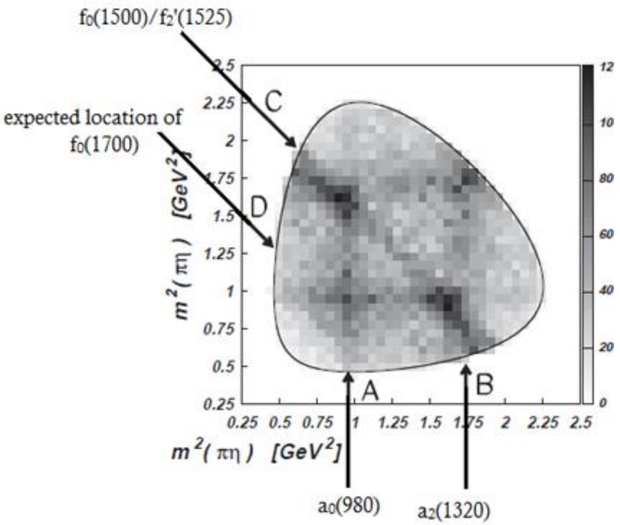
- There are 5 **isoscalar** states identified by experiment: f0(600),$f_0(980)$, $f_0(1370)$, $f_0(1500)$ and $f_0(1710)$
- There are only 2 slots for the f_0 states in the quark model

Photoproduction can give info on the coupling of the f_0 meson to the photon.





What previous experiments observed

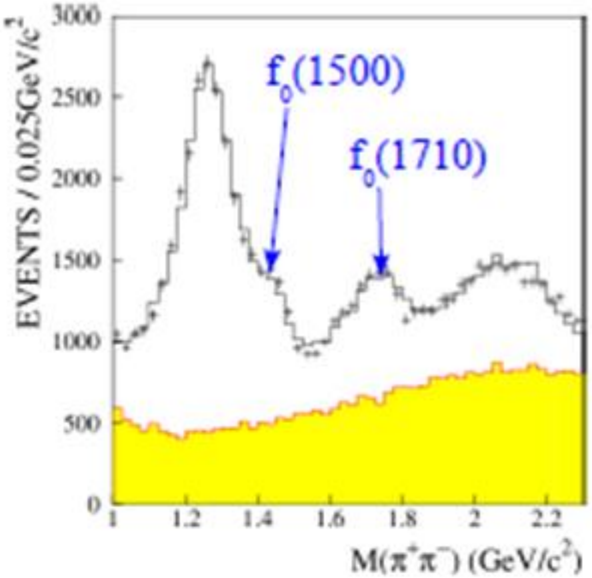


$p\bar{p} \to \pi^0\eta\eta$

$p\bar{p}$ annihilation :
Crystal Barrel

f$_0$(1500) is seen in the ηη mass projection

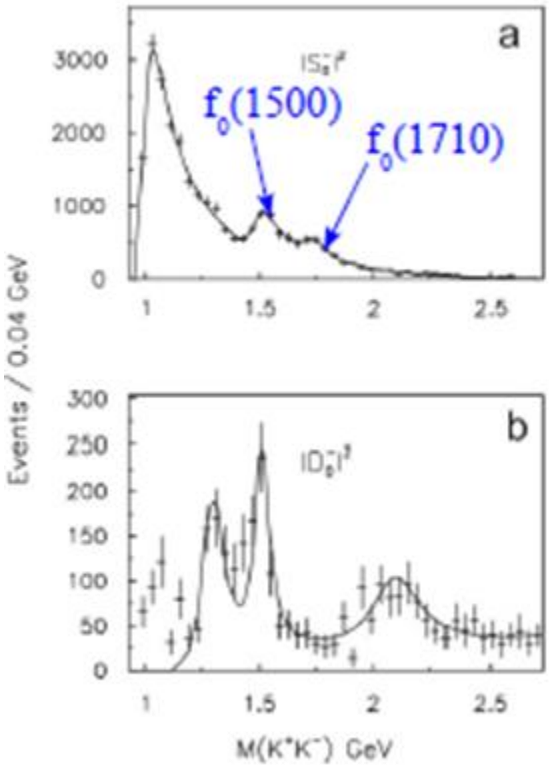
C. Amsler and N.A. Tornqvist, Phys. Rept. 389 (2004) 61.



BES II

J/Ψ –> γππ
PWA: J=0 -> f$_0$(1500)
Shaded region = J/Ψ –> $\pi^+\pi^-\pi^0$

D. Barberis et al., [WA102 Collaboration], Phys. Lett. B462 (1999) 462, hep-ex/9907055

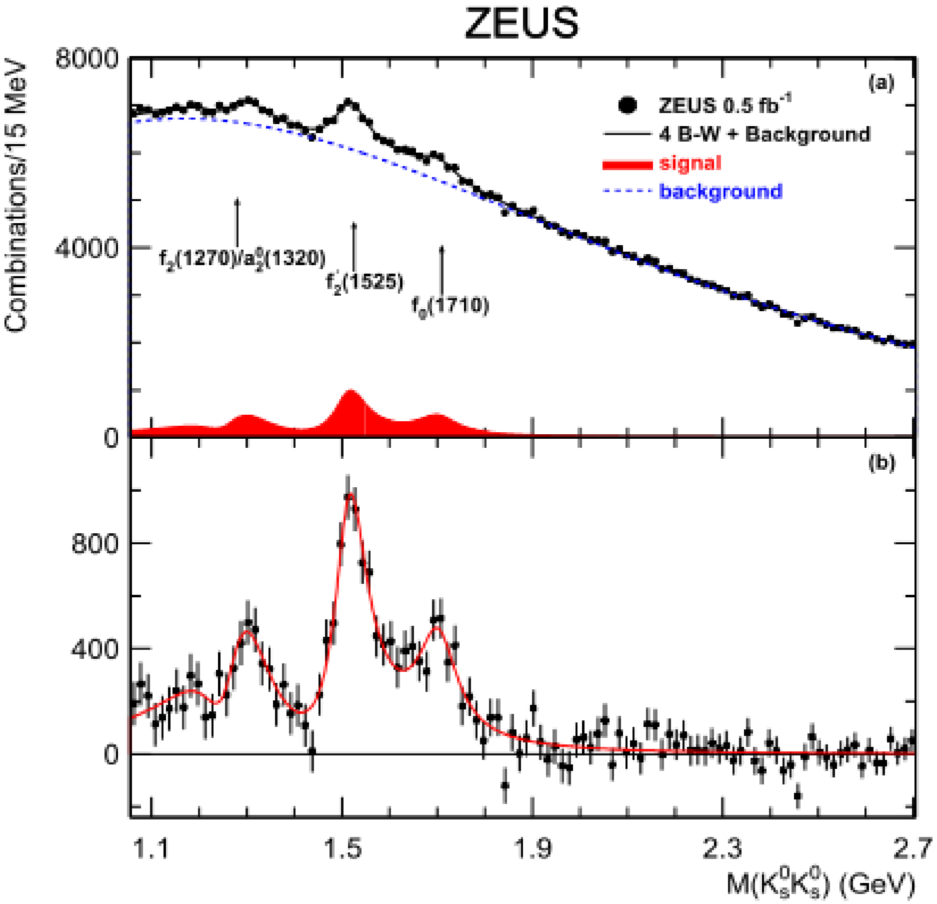


WA102 Central production

The f$_0$(1500) is clearly seen

M. Ablikim et al., [BES Collaboration] Phys. Lett. B 642 (2006) 441

ZEUS Experiment: detected $K_s^0K_s^0$



ZEUS Collaboration: S. Chekanov, et al, *Inclusive $K^0_sK^0_s$ resonance production in ep collisions at HERA, Phys.Rev.Lett.101:112003,2008, arXiv:0806.0807v2*

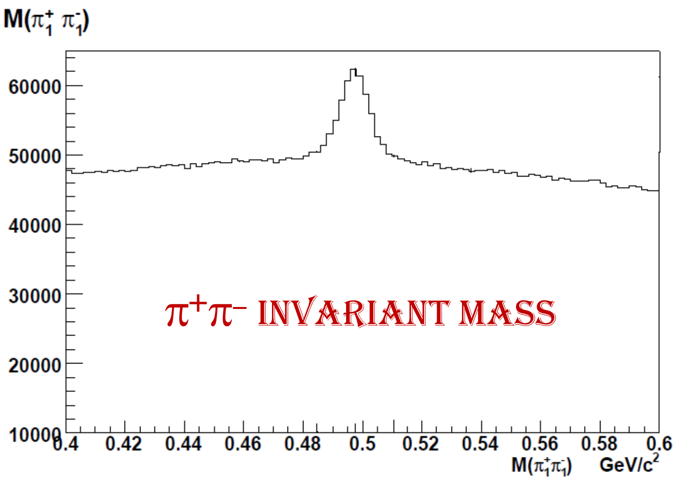
Why choose strange decay?

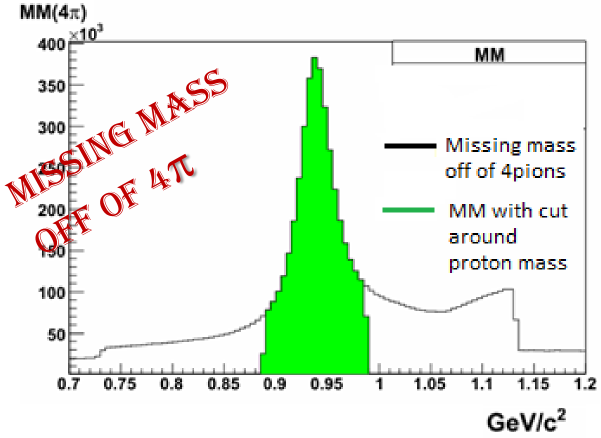
M.Chanowitz suggests in PRL 95, 172001 (2005) that glueballs are more likely to decay to strange channels

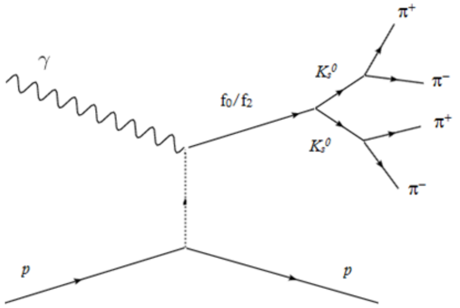
Why choose $K_s^0K_s^0$?

Ensure that the final state has the same PC =++ as the lightest glueball

CLAS: $\gamma p \rightarrow K_s^0 K_s^0 p$ (g12 run)





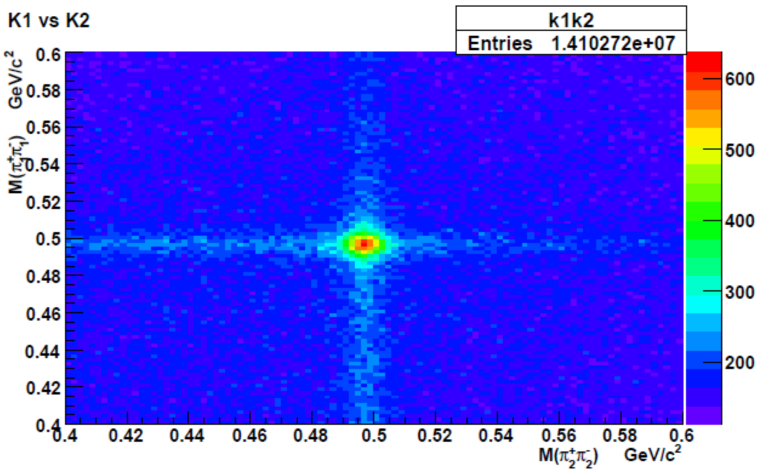


There is a clear kaon peak above the combinatorial background

Only those events are selected which have a missing mass of the proton

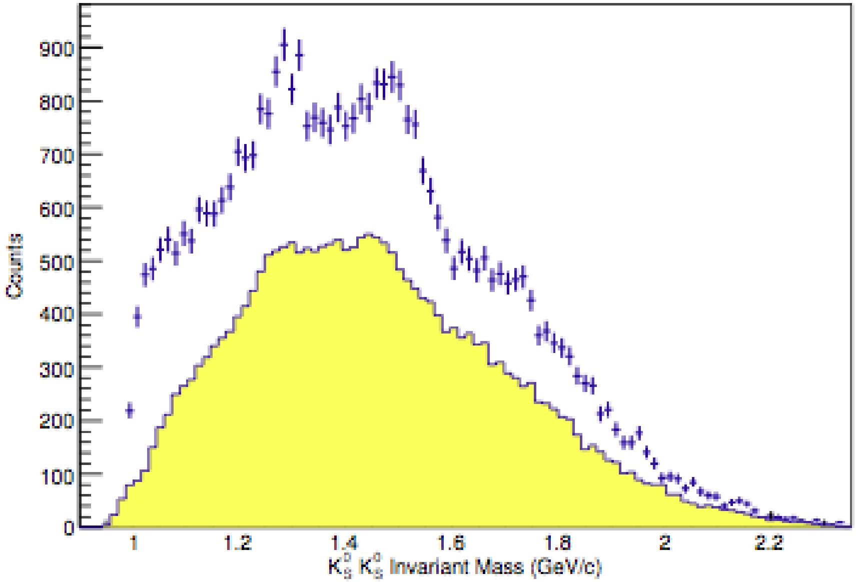
The plot of the two K_s^0 plotted against each other shows the high correlation between them.

4 combinations of $\pi^+\pi^-$ are possible. We select the 2 combinations that most closely match the value of the Ks mass.

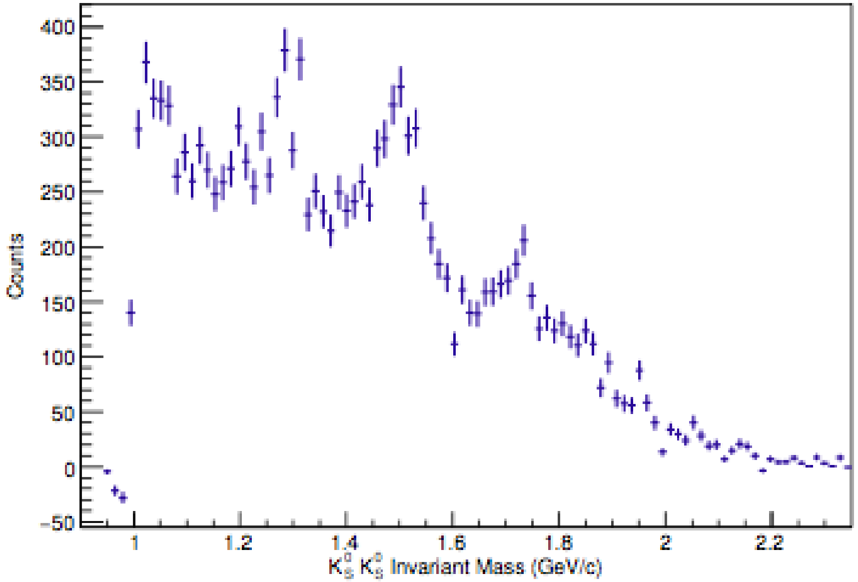


Invariant mass: $f_0 \rightarrow K_s^0 K_s^0$

All events: M(4π): M($K_s K_s$) + sidebands



Sideband-subtracted events



Cut Level	Type of Cut	Size of Cut
1	Timing Cut for identification of pions	±1 ns
2	Fiducial Cut	Fit to CLAS acceptance
3	Missing mass (proton)	±0.0497 GeV (3σ)
4	Photon beam energy	2.7-3.0 and 3.1-5.1 GeV
5	K_S^0 peak and sideband subtraction	0.01614 GeV (3σ)

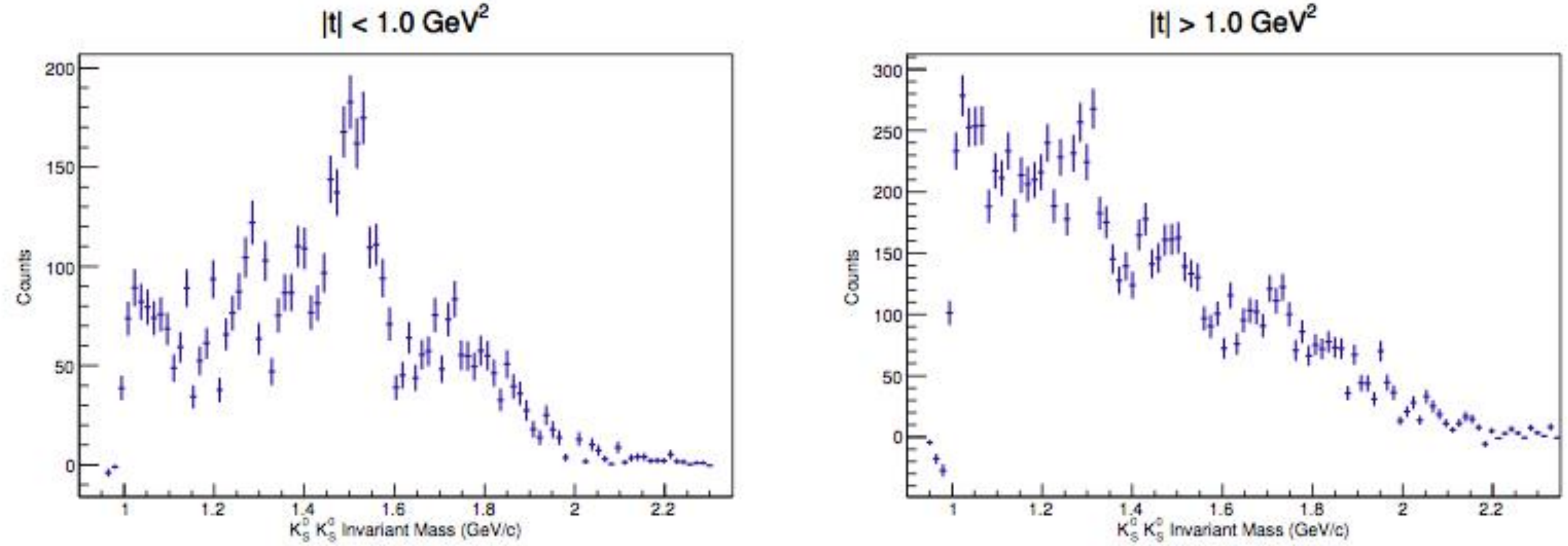
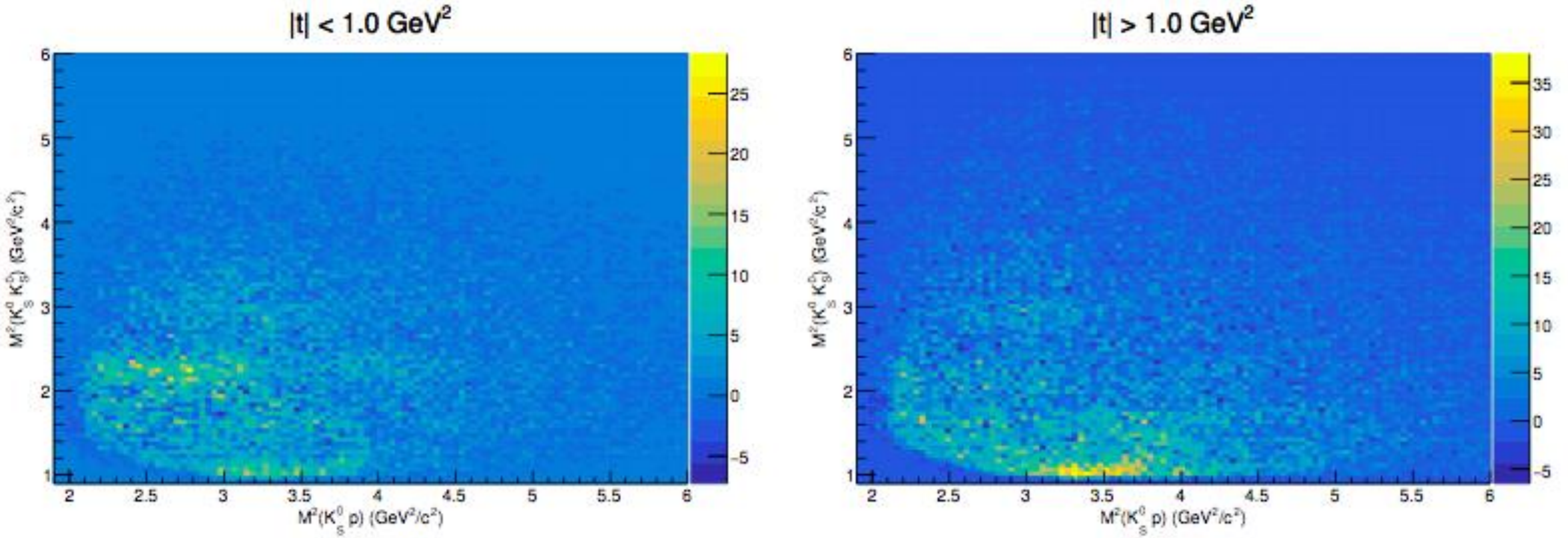
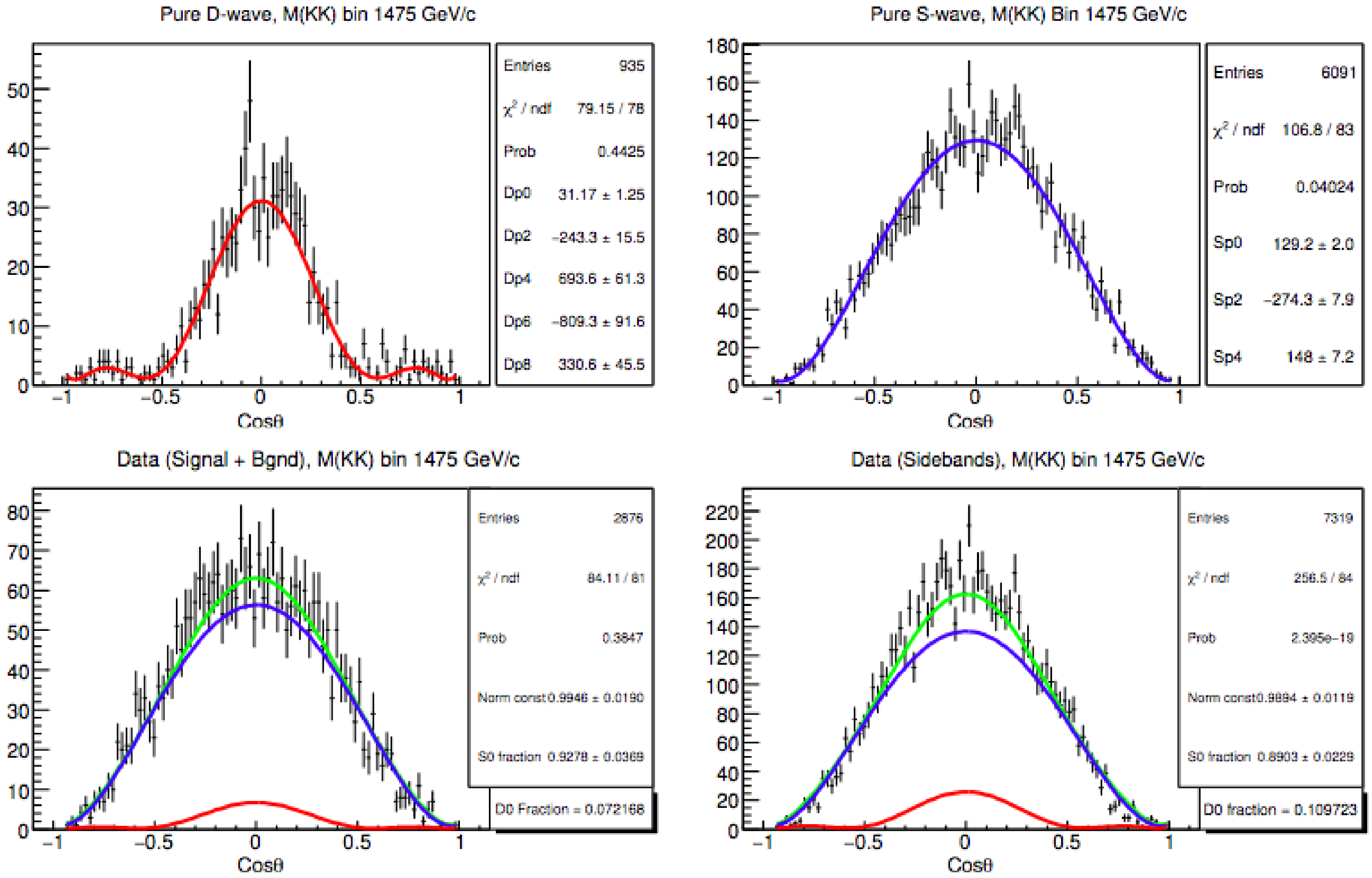


Figure 6. Background subtracted plots for the 4π invariant mass for $|t| < 1$ GeV^2 (left) and $|t| > 1$ GeV^2 (right).



Angular distributions (G.J.-frame)



Summary

- CLAS data, including polarization observables, are being used to identify “missing” N*’s.
  - KY data has been especially fruitful here.
- Electroproduction data used to extract the N* electrocouplings to give info on N* structure.
  - Meson-baryon terms contribute significantly:
    - Complex interplay of 3-quark core and meson-baryon cloud
- Preliminary results indicate $f_0(1500)$ produced via t-channel photoproduction.
  - Contrary to expectation of a “pure” glueball.