Excited Nucleons and their Structure in Meson Production at CLAS

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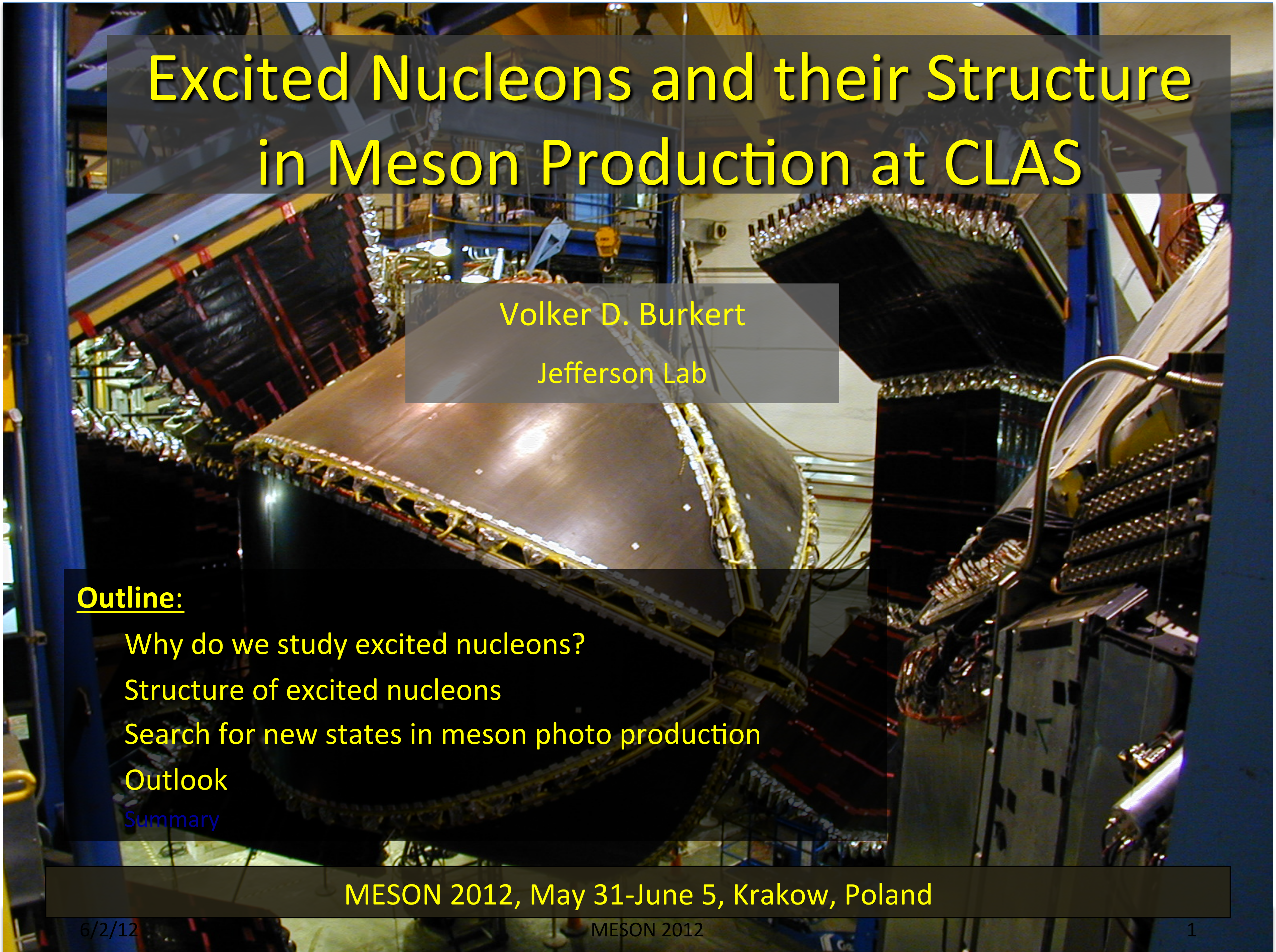
Jefferson Lab



Outline:

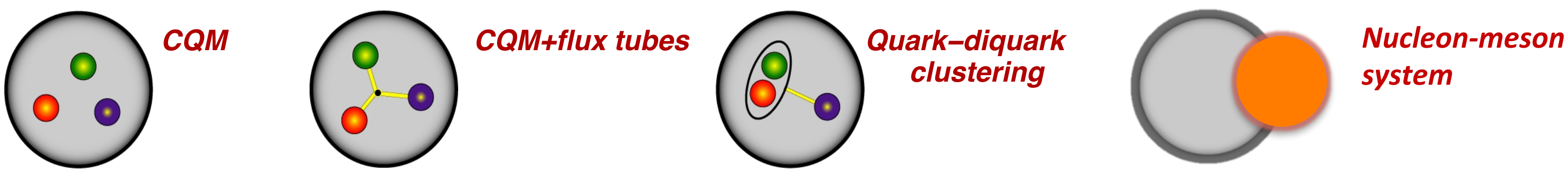
- Why do we study excited nucleons?
- Structure of excited nucleons
- Search for new states in meson photo production
- Outlook
- Summary

MESON 2012, May 31-June 5, Krakow, Poland

Why do we study excited nucleons?

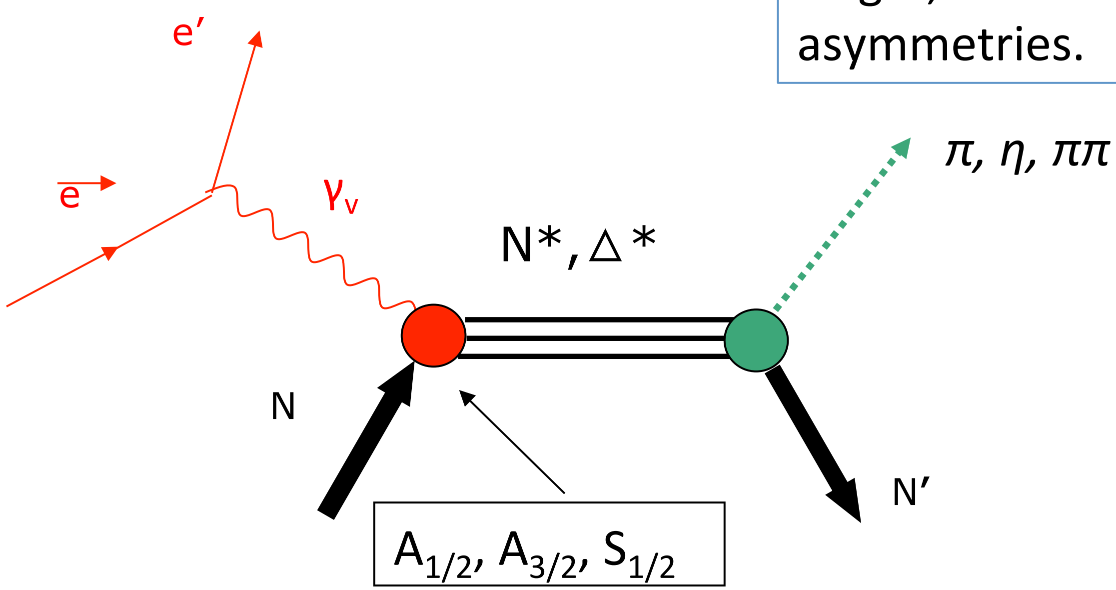
"Nucleons *are* the stuff of which our world is made. As such they must be at the center of any discussion of why the world we actually experience has the character it does" *Nathan Isgur, NStar2000*

- The N* spectrum reflects the underlying degrees of freedom of the nucleon where our knowledge is incomplete



- Two main components of the experimental N* program with CLAS
  - *Measure the excitation spectrum – search for "missing" excited states in meson photoproduction to understand underlying symmetries*
  - *Measure N* transition form factors in meson electroproduction and identify the relevant degrees-of-freedom vs distance scale, reveal the complex nature of states*

Electroexcitation of lowest S=0 baryon states



Analyses based on 120,000 cross sections, and beam, target, and double spin asymmetries.

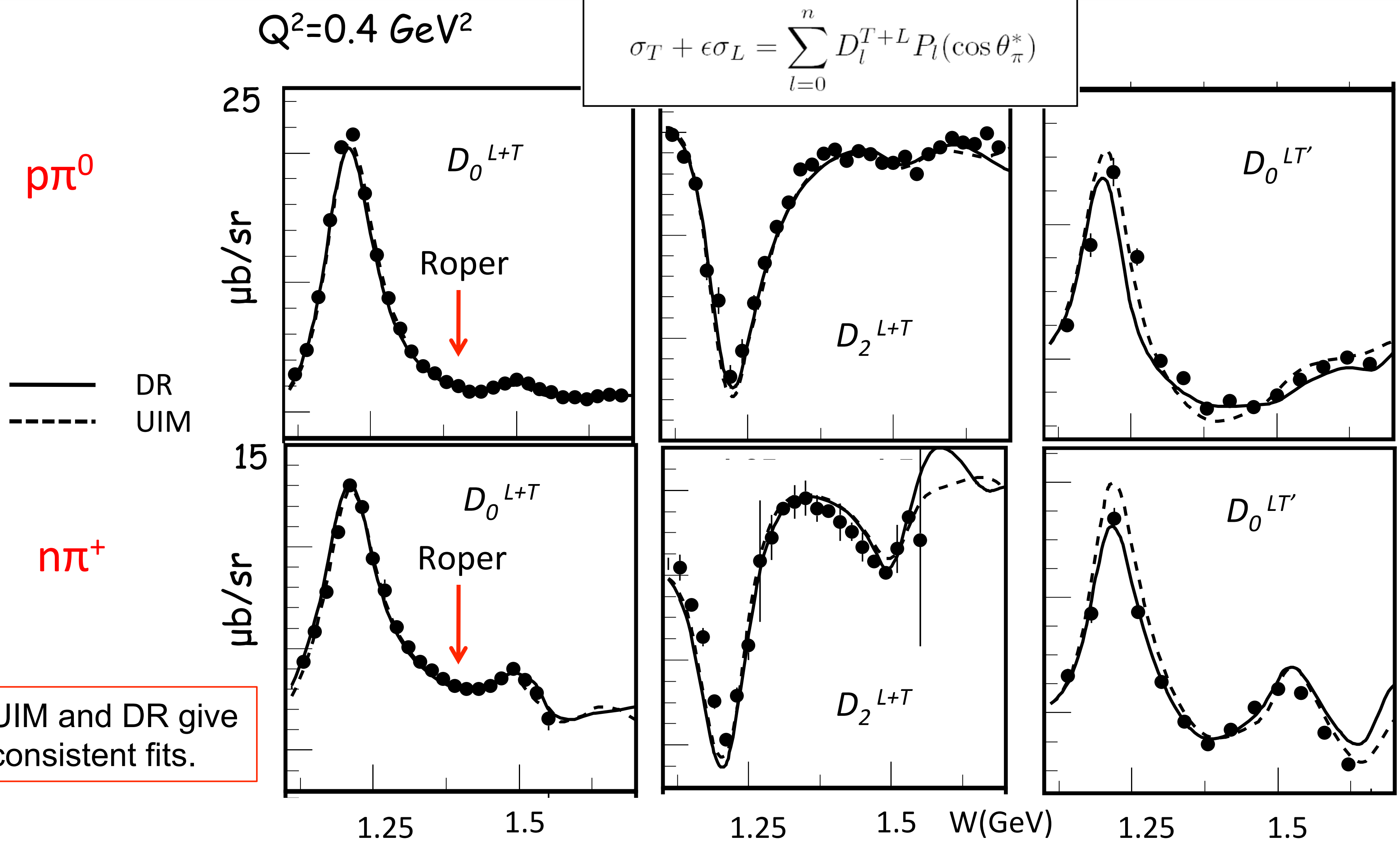
Analysis codes for single and double pseudo-scalar meson production:

- Unitary isobar model (UIM) for Nπ and Nη
- Fixed-t dispersion relations (DR) for Nπ and Nη
- Data driven reaction model for $p\pi^+\pi^-$ (JM09)

I. Aznauryan, V.B., Prog.Part.Nucl.Phys.67:1, 2012; I. Aznauryan et al. (CLAS), PRC80, 055203,2009

Legendre Moments for ep→eNπ

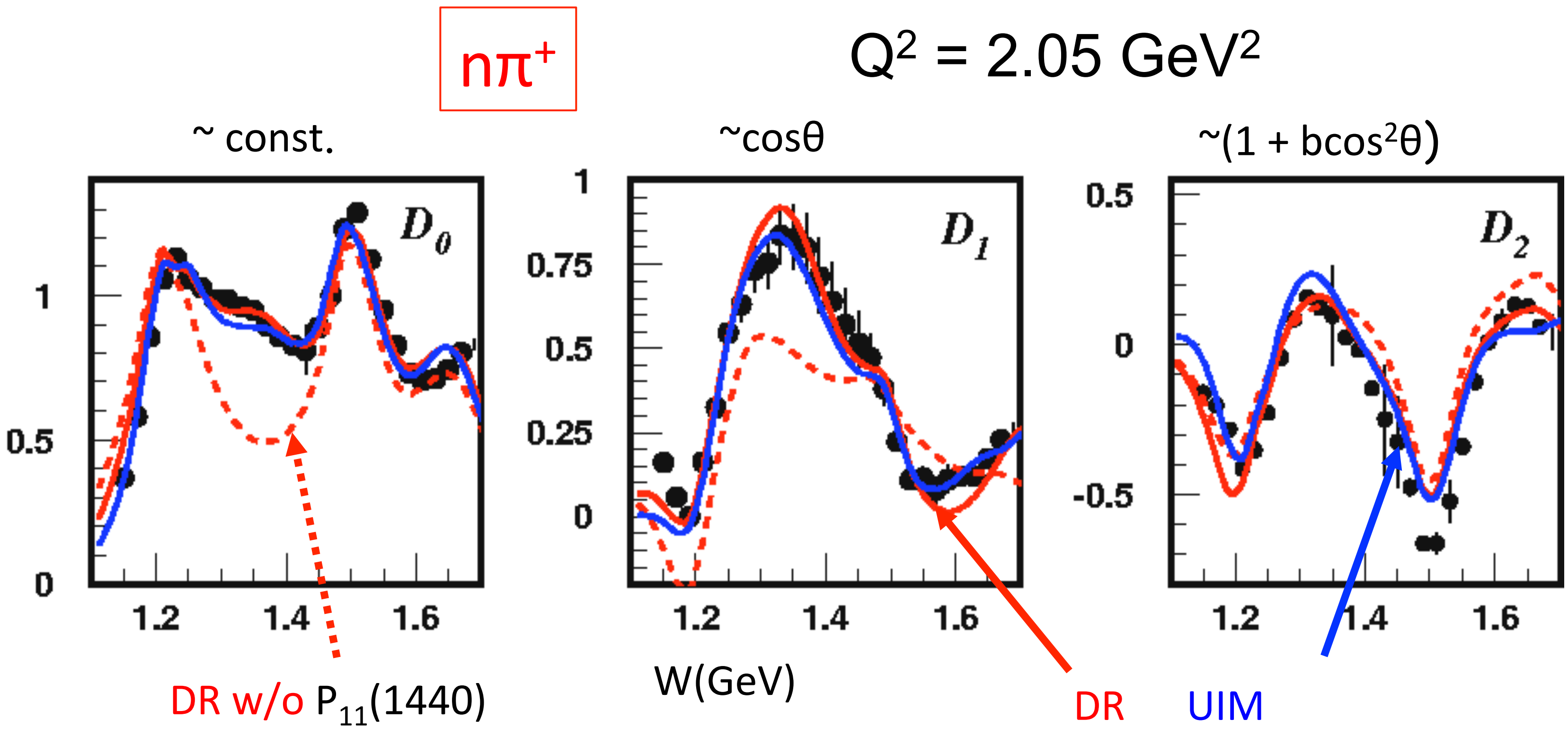
$$\sigma_T + \epsilon\sigma_L = \sum_{l=0}^{n} D_l^{T+L} P_l(\cos\theta_\pi^*)$$



UIM and DR give consistent fits.

Emergence of the “Roper” $P_{11}(1440)$

- At small Q^2, the Roper is sub leading resonance, it becomes a leading state at high Q^2.

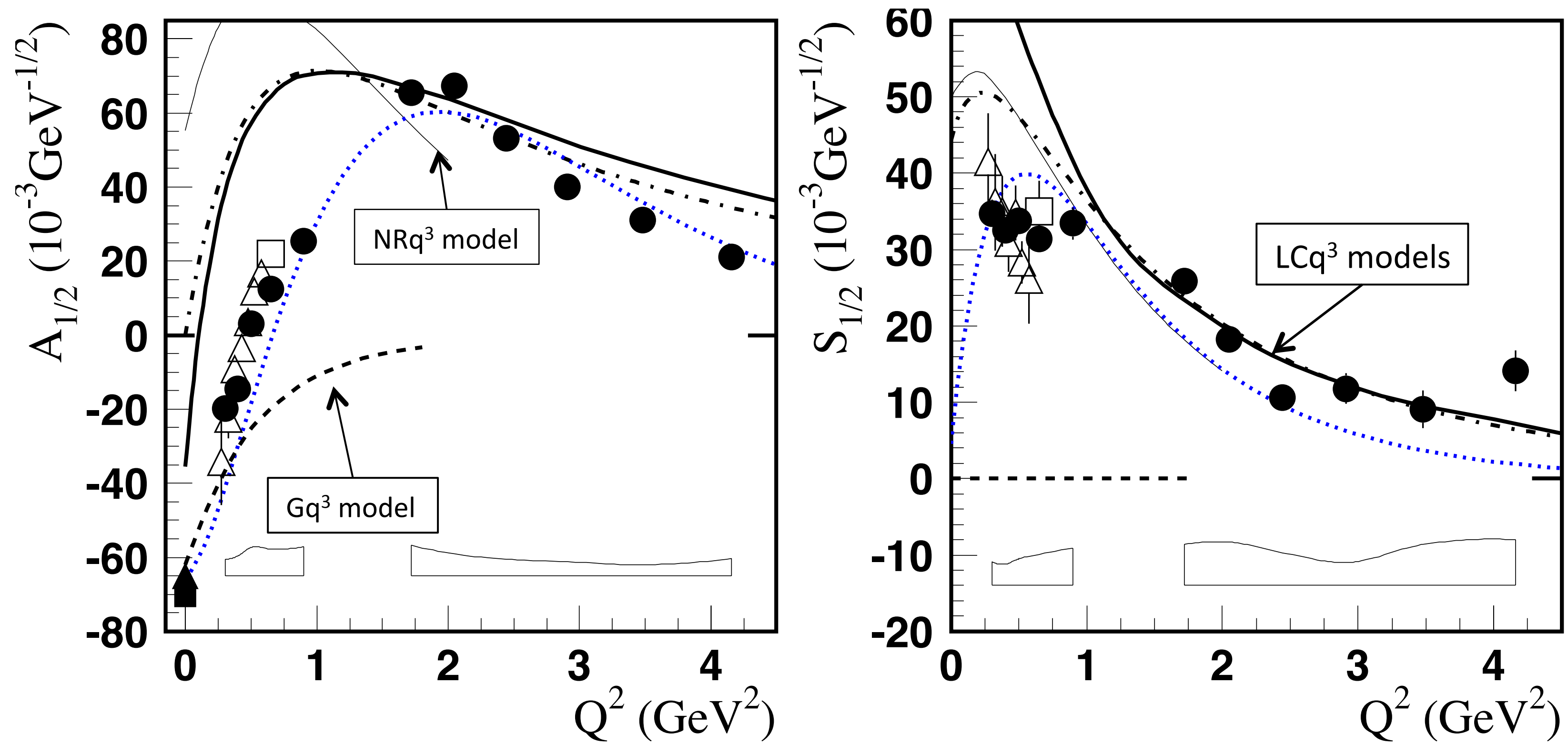


total cross section shows strong signal from Roper

sensitive to Roper resonance in s-p interference

little sensitivity to Roper resonance

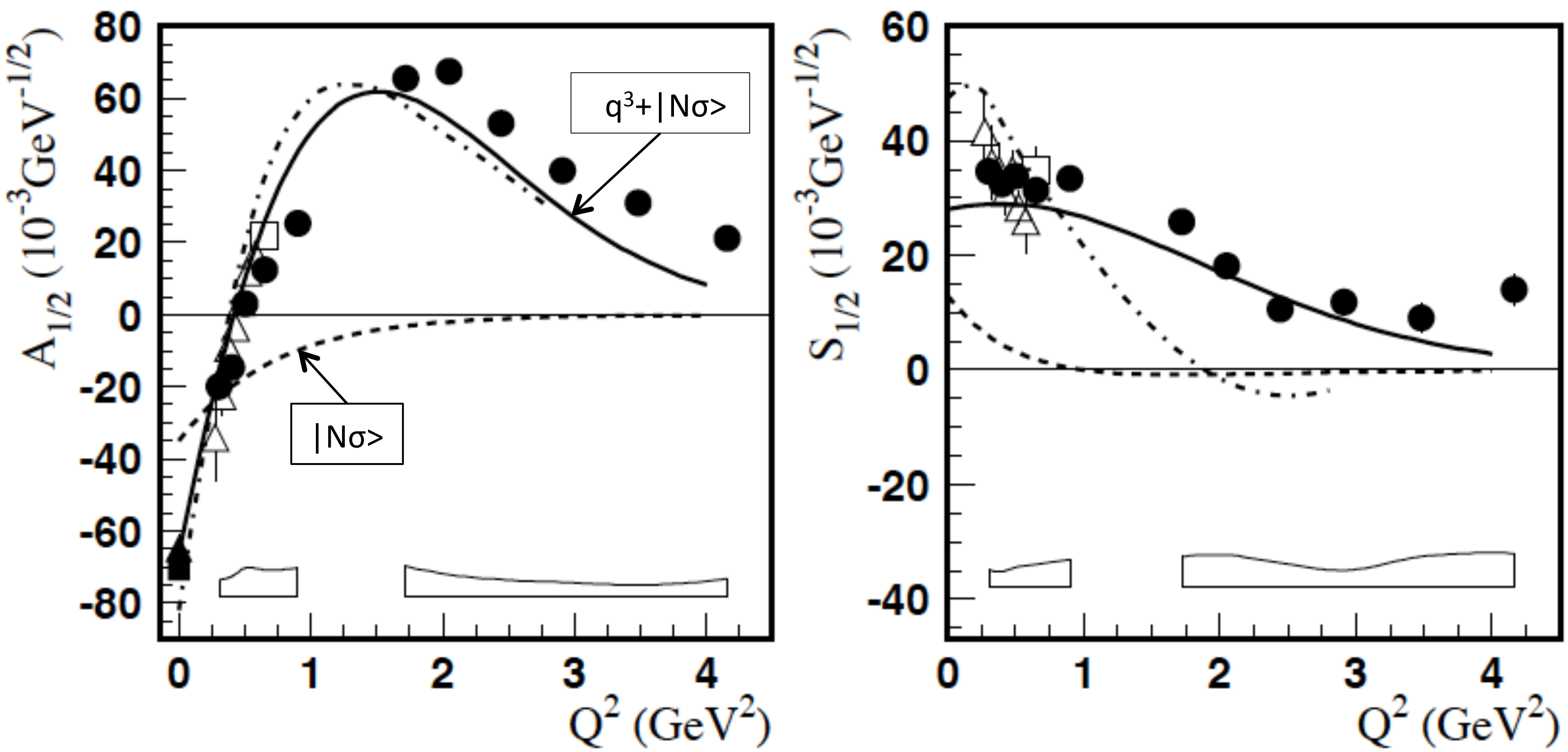
Electrocouplings of the Roper $P_{11}(1440)$



- $A_{1/2}$ has zero-crossing near Q^2=0.5, becomes dominant amplitude at high Q^2
- ep->eNπ (●) and ep->epπ$^+$π$^-$ (△) processes give consistent result
- Consistent with radial excitation of the nucleon at high Q^2
- The hybrid model (Gq^3) predicts a very different $A_{1/2}(Q^2)$ dependence, and $S_{1/2}(Q^2)$ = 0

I. Aznauryan, et al, PRC 80 (2009) 055203; V. Mokeev et al, arXiv:1205.3948 (subm. to PRC)

Electrocouplings of the Roper $P_{11}(1440)$



I. Aznauryan, et al, PRC 80 (2009) 055203;
V. Mokeev et al, arXiv:1205.3948 (subm. to PRC)

Quark model with Nσ contributions allows good description at low Q^2.

I.T. Obukhovsky et al, Phys.Rev. D84 (2011) 014004

LC Transition charge density $\gamma p \to P_{11}(1440)$

L. Tiator, M. Vanderhaeghen, PLB672, 344,2009

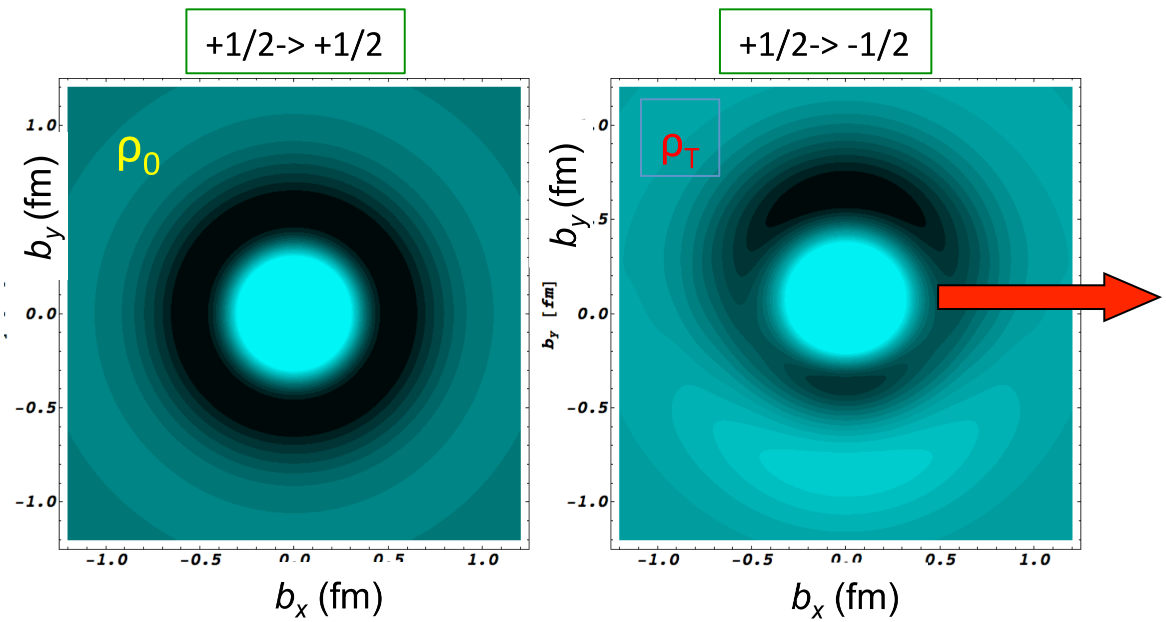
The helicity amplitudes give access to the transverse transition charge density in the LC frame.

$$A_{1/2} = e \frac{Q_-}{\sqrt{K}\,(4M_N M^*)^{1/2}} \left\{ F_1^{NN^*} + F_2^{NN^*} \right\},$$

$$S_{1/2} = e \frac{Q_-}{\sqrt{2K}\,(4M_N M^*)^{1/2}} \left(\frac{Q_+ Q_-}{2M^*}\right) \frac{(M^* + M_N)}{Q^2} \left\{ F_1^{NN^*} - \frac{Q^2}{(M^*+M_N)^2} F_2^{NN^*} \right\}$$

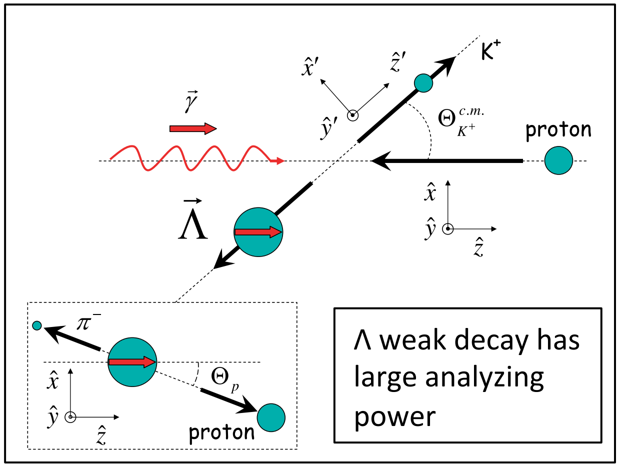
$$\rho_0^{NN^*}(\vec{b}) = \int_0^\infty \frac{dQ}{2\pi} Q\, J_0(b\,Q) F_1^{NN^*}(Q^2),$$

- The p → $P_{11}(1440)$ transition is dominated by *up* quarks in a central region of radius ~0.4 fm, and by *down* quarks in an outer band up to >1.0 fm.
- For a transversely polarized p→$P_{11}(1440)$ transition a partial separation of positive and negative charges occurs along b_y .



Similar analyses for $P_{33}(1232)$, $S_{11}(1535)$, $D_{13}(1520)$

Complete experiments in KΛ production



The holy grail of baryon resonance analysis

- Process described by 4 complex, parity conserving amplitudes
- 8 well-chosen measurements are needed to determine the amplitudes.
- Up to 16 observables are measured in CLAS ➠ allows many cross checks.

Photon		Target			Recoil			Target + Recoil			
	–	–	–	–	x'	y'	z'	x'	x'	z'	z'
	–	x	y	z	–	–	–	x	z	x	z
unpolarized	σ_0	0	T	0	0	P	0	$T_{x'}$	$-L_{x'}$	$T_{z'}$	$L_{z'}$
linear pol.	$-\Sigma$	H	(-P)	$-G$	$O_{x'}$	(-T)	$O_{z'}$	$(-L_{z'})$	$(T_{z'})$	$(-L_{x'})$	$(-T_{x'})$
circular pol.	0	F	0	$-E$	$-C_{x'}$	0	$-C_{z'}$	0	0	0	0

polarized photons on liq. H2 or D2

long. and transv. polar. target (together with polar. photons)

Search for S=0 states in single meson production on protons

✔ - published, ✔ - acquired

	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
$p\pi^0$	✔	✓	✓		✓	✓	✓	✓								
$n\pi^+$	✔	✓	✓		✓	✓	✓	✓								
$p\eta$	✔	✓	✓		✓	✓	✓	✓								
$p\eta'$	✔	✓	✓		✓	✓	✓	✓								
$p\omega/\phi$	✔	✓	✓		✓	✓	✓	✓								
$K^+\Lambda$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^+\Sigma^0$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^{0*}\Sigma^+$	✔	✓									✓	✓				

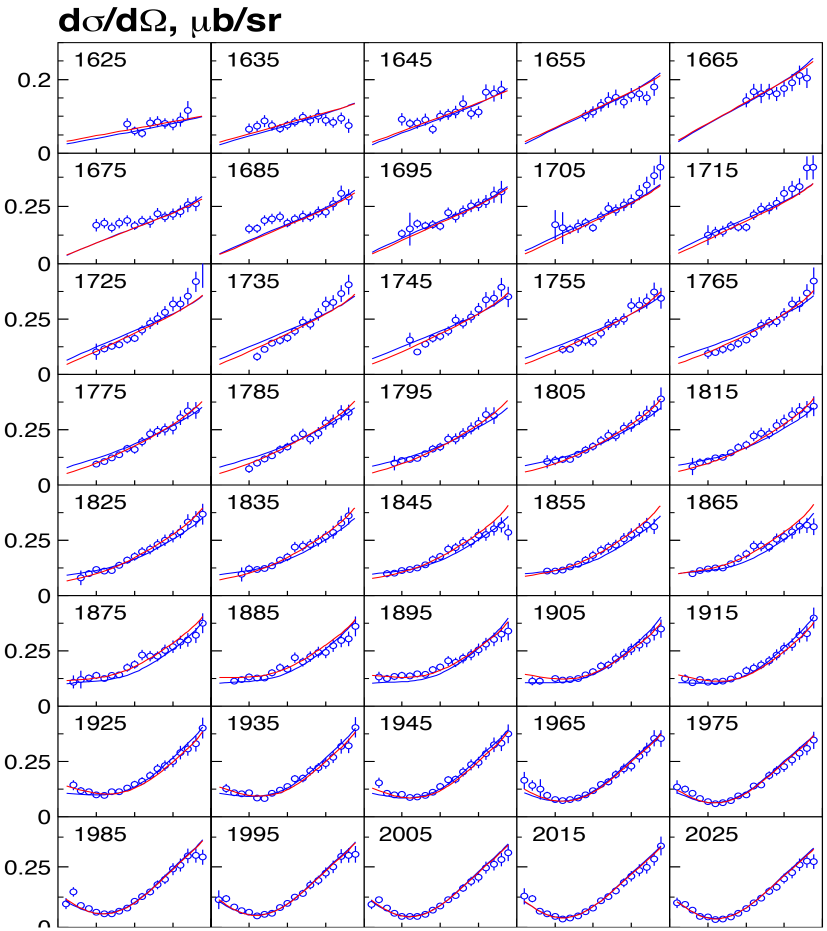
Proton targets

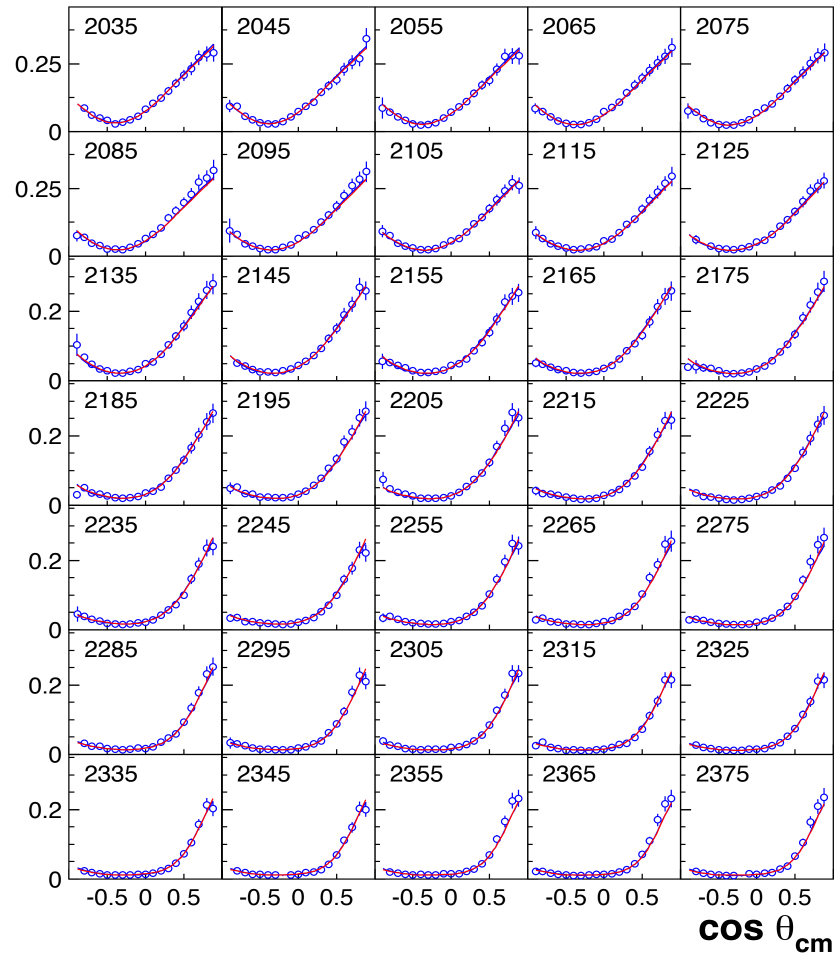
The impact of the hyperon data has been very significant in the search for new states

CLAS results $\vec{\gamma}\vec{p} \rightarrow K^+\vec{\Lambda} \rightarrow K^+p\pi^-$

Bonn-Gatchina Coupled Channel Analysis, A.V. Anisovich et al, EPJ A48, 15 (2012)

(Includes nearly all new photoproduction data)





M. Mc Cracken et al. (CLAS), Phys. Rev. C 81, 025201, 2010

CLAS results $\vec{\gamma}\vec{p} \rightarrow K^{+}\vec{\Lambda} \rightarrow K^{+}p\pi^{-}$

Bonn-Gatchina Coupled Channel Analysis, A.V. Anisovich et al, EPJ A48, 15 (2012)

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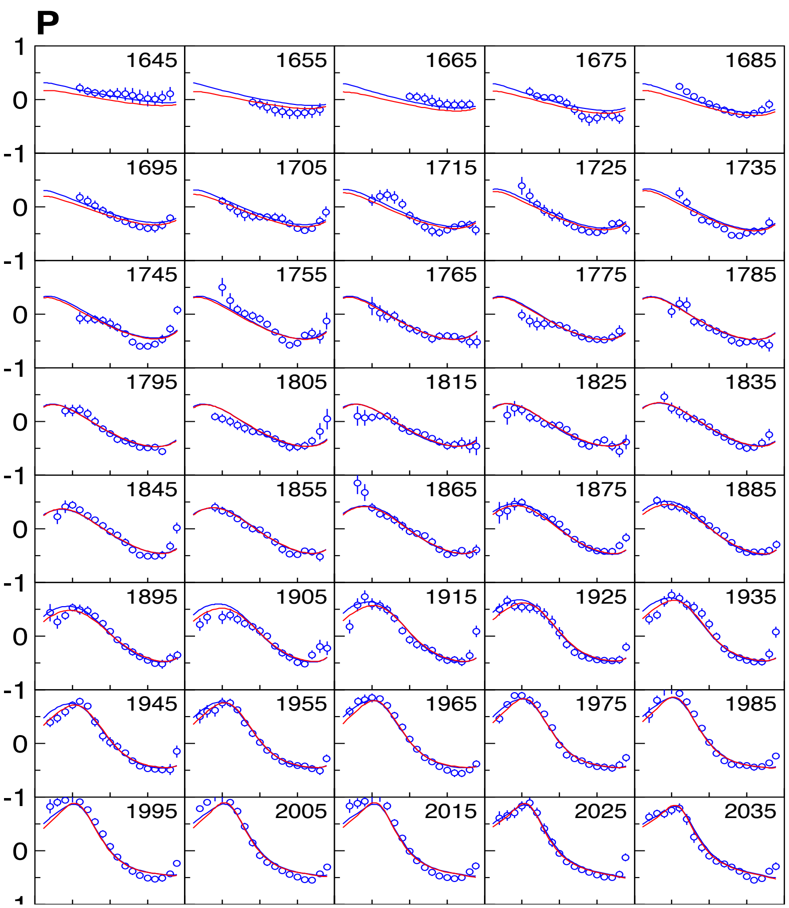
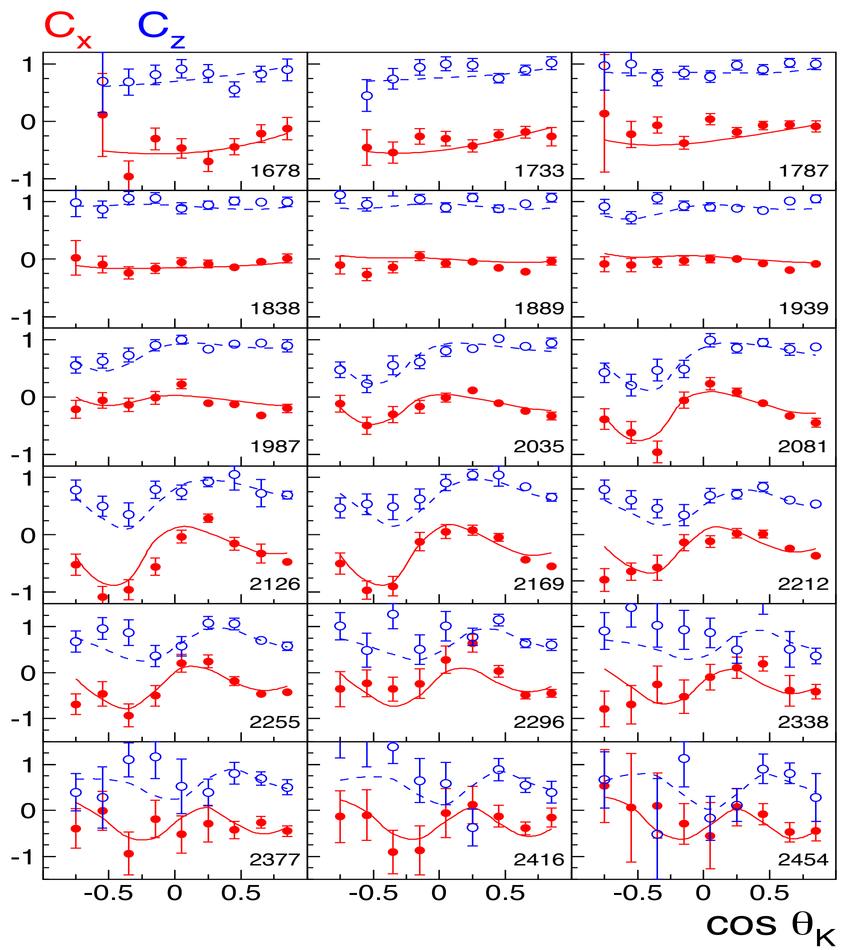


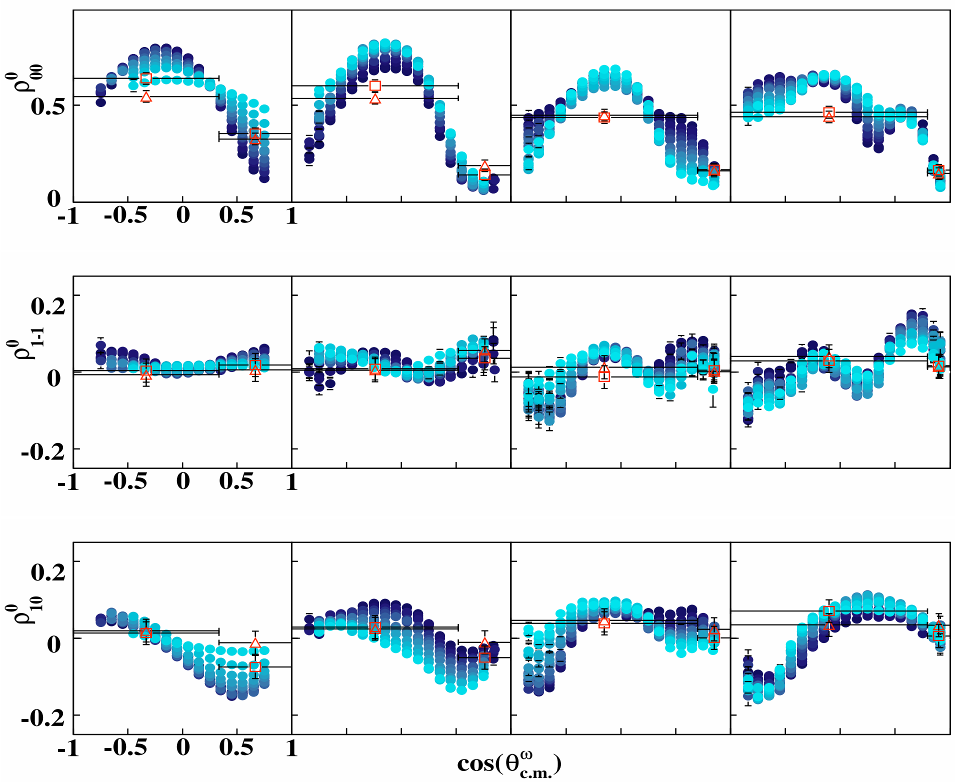
M. Mc Cracken et al. (CLAS), Phys. Rev. C 81, 025201, 2010



D. Bradford et al. (CLAS), Phys.Rev. C75, 035205, 2007

Search for N* states in $\gamma p \rightarrow p\omega \rightarrow p\pi^+\pi^-(\pi^0)$

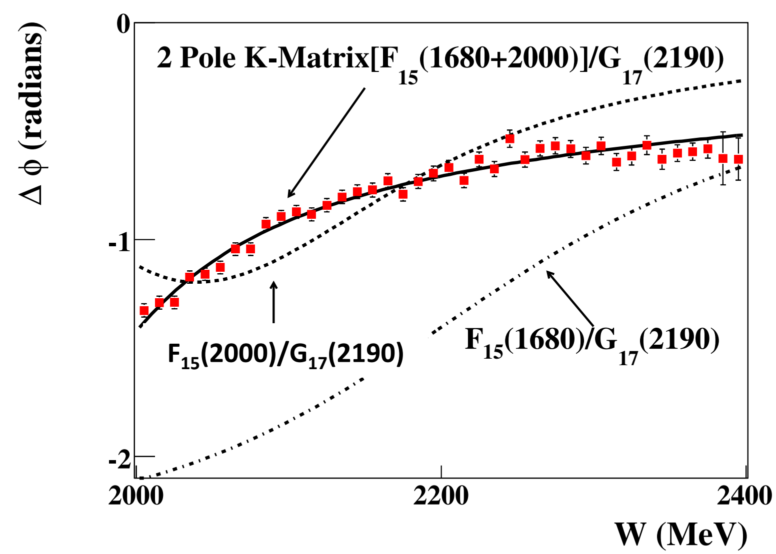
- Spin density matrix elements in bins ΔW = 10 MeV, for W = 1.7–2.4 GeV in blue - blue shades. Previous world data in red.



M. Williams, et al. (CLAS) , Phys.Rev.C80:065208,2009

- The CLAS data are used as input to a single channel event-based, energy independent partial wave analysis (the first ever for baryons).

- ω photoproduction is dominated by the well known $F_{15}(1680)$, $D_{13}(1700)$ and $G_{17}(2190)$, and a predicted "missing" **$F_{15}(2000)$**.



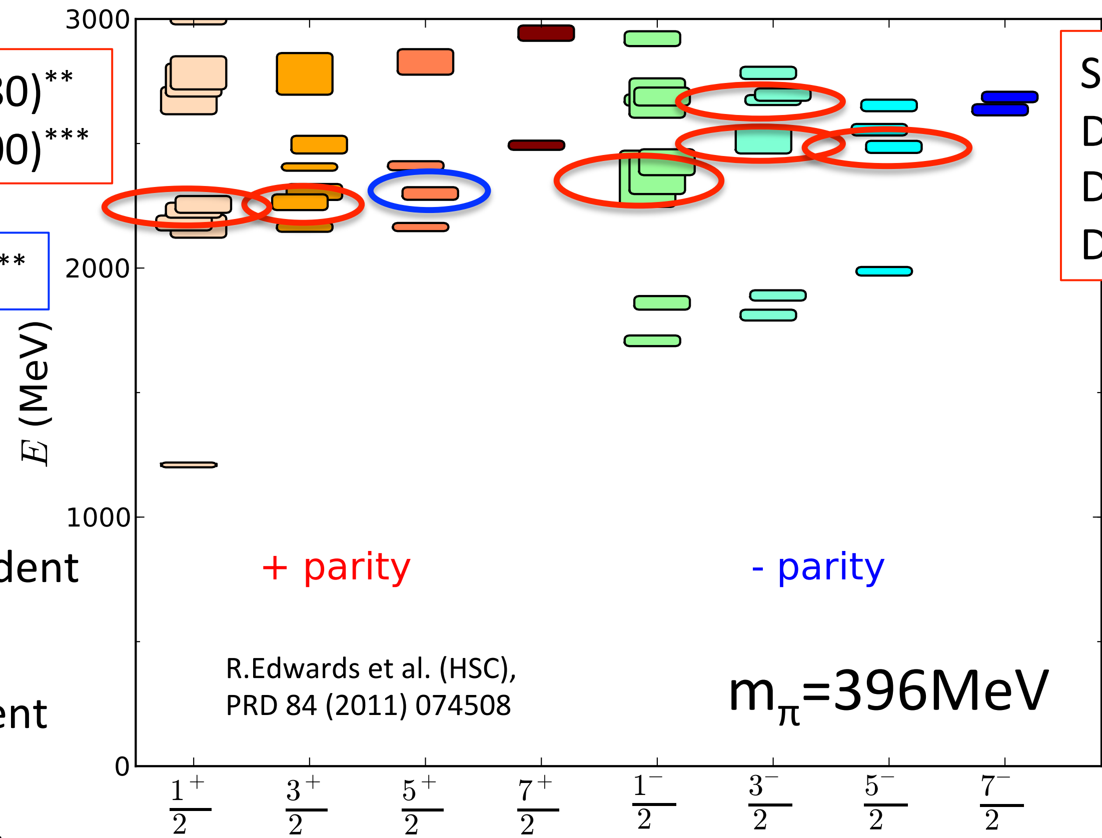
M. Williams, et al. (CLAS) , Phys.Rev.C80:065209,2009

N* spectrum in LQCD

New states as constrained mainly from $K^+\Lambda$, $K^+\Sigma^0$ and $p\omega$ data

$P_{11}(1880)^{**}$
$P_{13}(1900)^{***}$

$F_{15}(2000)^{***}$



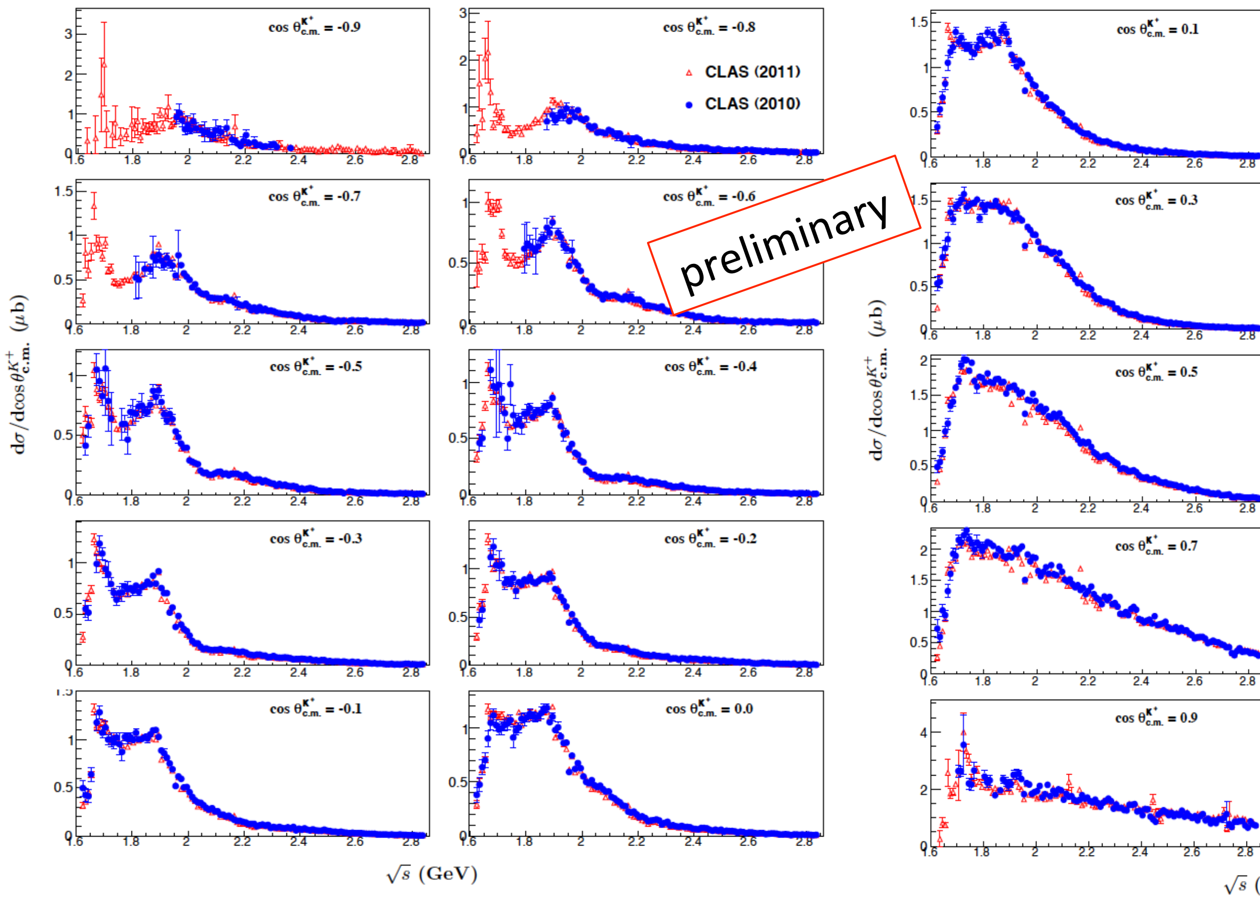
$S_{11}(1895)^{**}$
$D_{13}(1875)^{***}$
$D_{13}(2150)^{**}$
$D_{15}(2060)^{***}$

○ CMU energy-independent PWA of CLAS $p\omega$ data.

○ BnGa energy-dependent coupled-channel PWA of $K^+\Lambda$, $K^+\Sigma^0$ and world data.

Should be verified with increased data base and independent analyses.

Extension of $K^+\Lambda$ diff. cross section

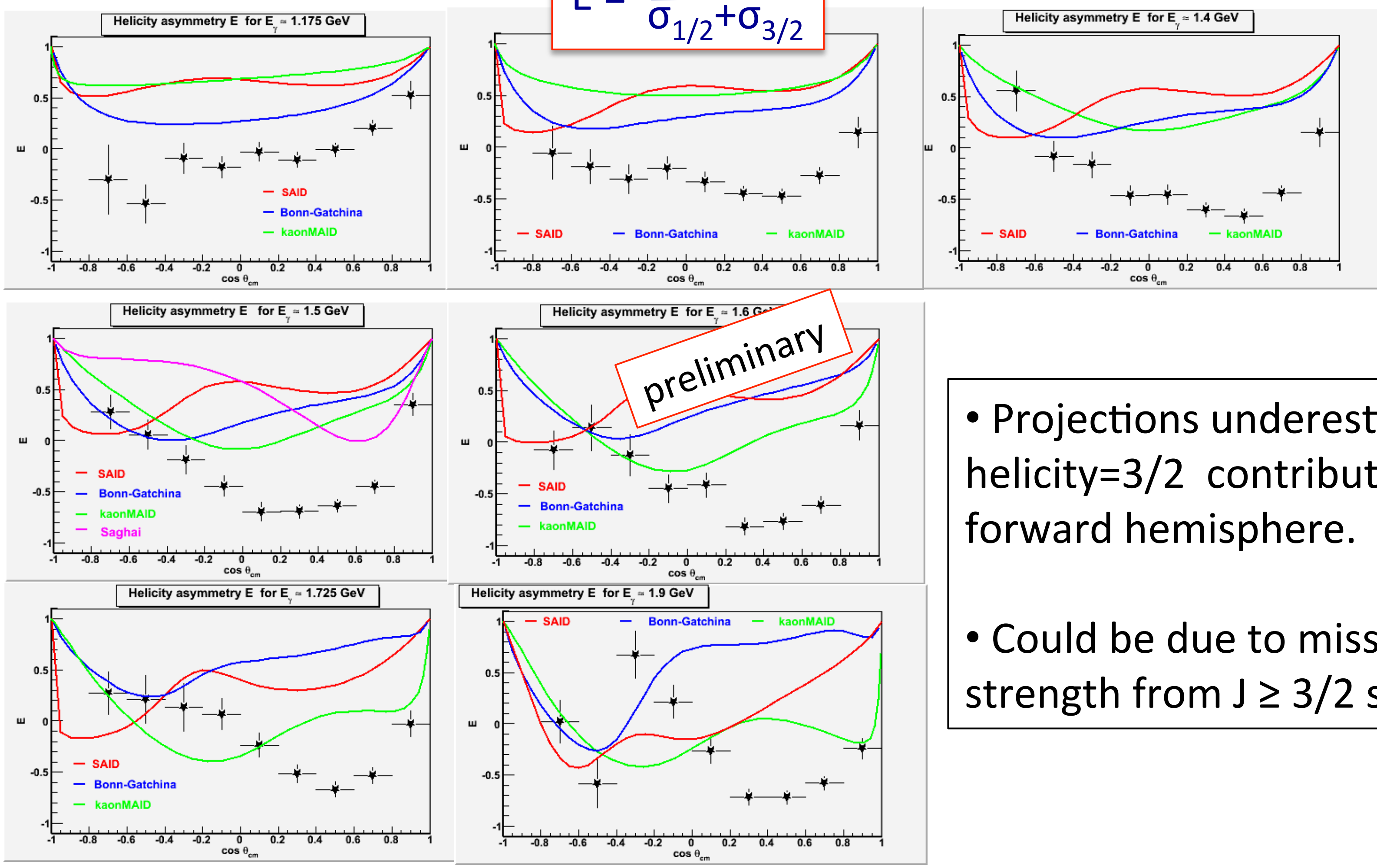


B. Dey (2011,PhD)

Increase of kinematic domain and statistics in 2-track analysis $K^+p(\pi^-)$ shows strong evidence for resonance-like structure at ~1.67GeV. The structure is present at all angles but dominated by background at more forward angles.

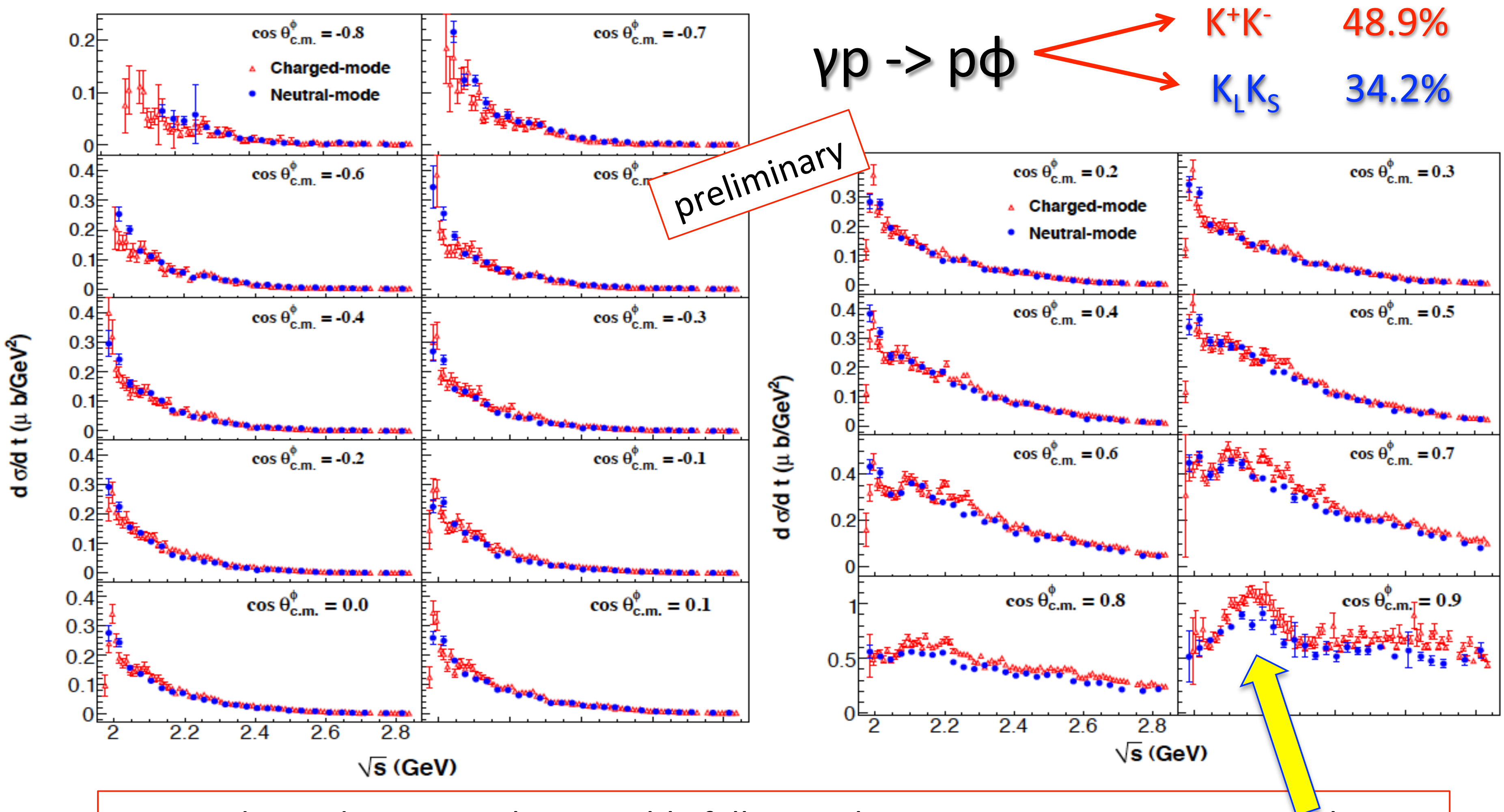
Helicity asymmetry E for $\vec{\gamma}\vec{p} \rightarrow K^+\Lambda$

$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$



- Projections underestimate helicity=3/2 contribution in forward hemisphere.
- Could be due to missing strength from J ≥ 3/2 states.

Unpolarized pφ cross sections

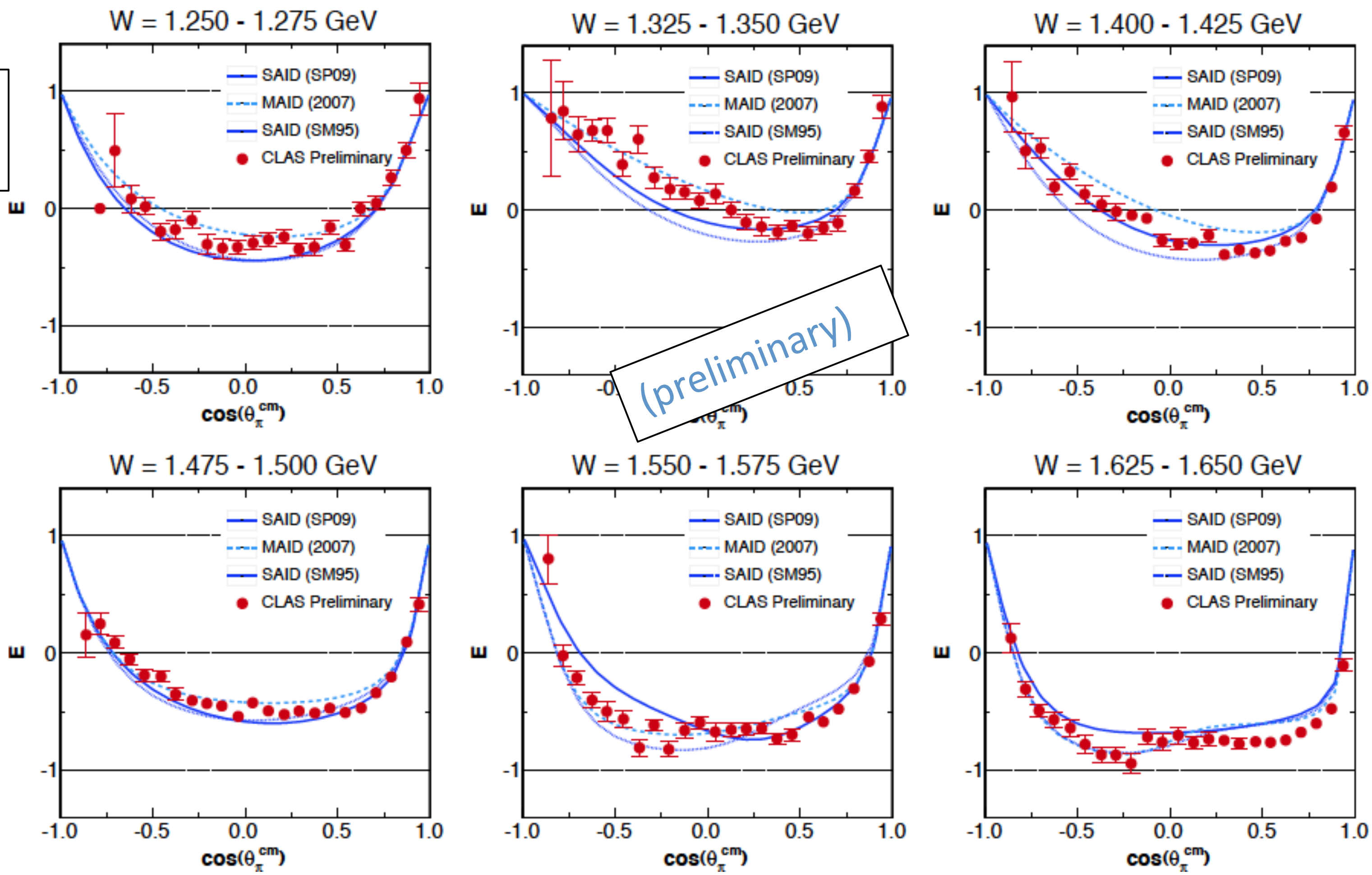


Energy dependence mostly smoothly falling with √s, except at $\cos\Theta_{cm} > 0.7$, where a structure near √s= 2.15 GeV emerges in both channels.

FROST g9- Double asymmetry E $\vec{\gamma}\vec{p} \to n\pi^+$

Selected results (preliminary)

$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$



All model parameterizations describe the low mass range but ……… .

FROST g9- Double asymmetry E $\vec{\gamma}\vec{p} \rightarrow n\pi^+$

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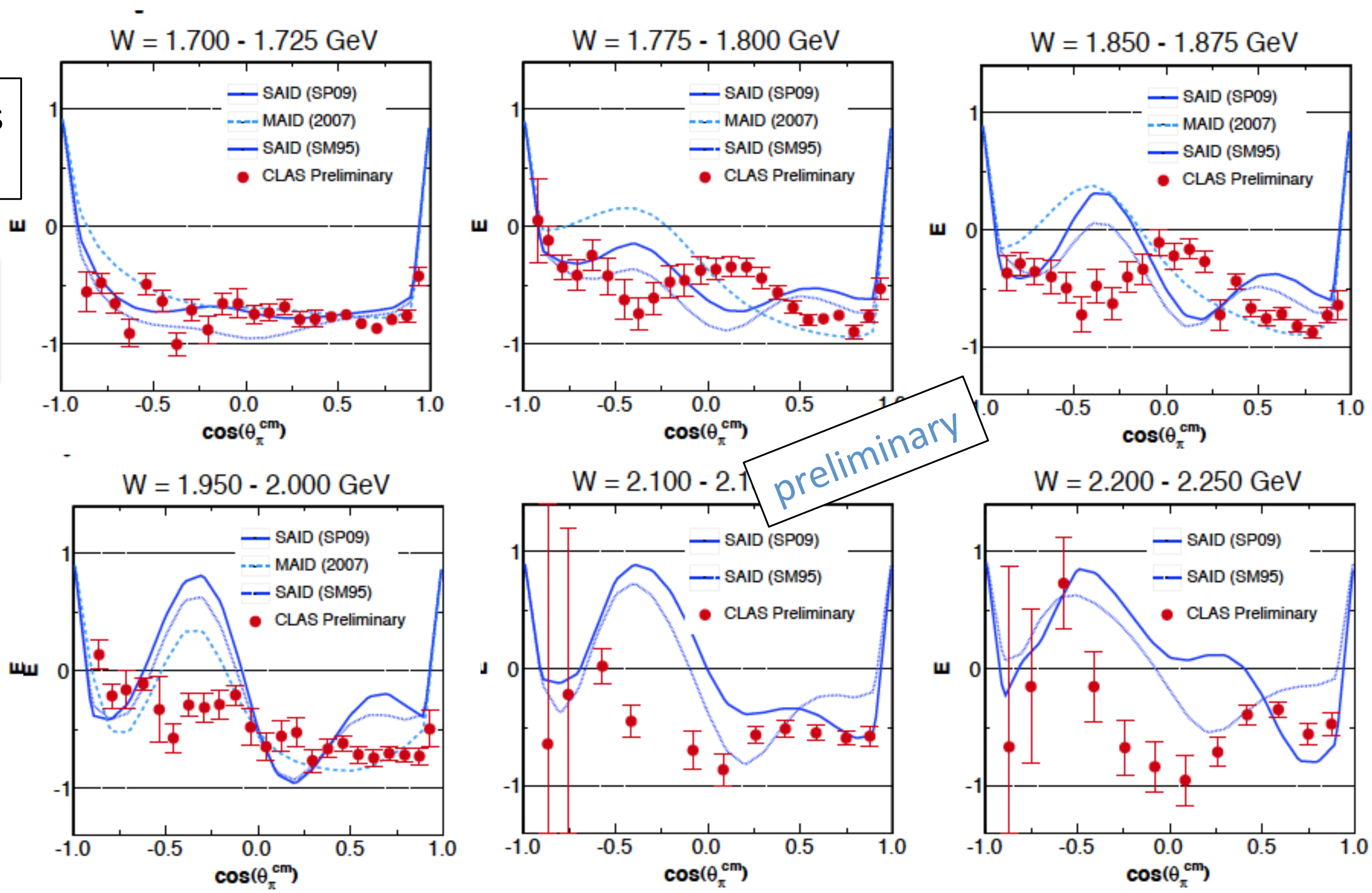
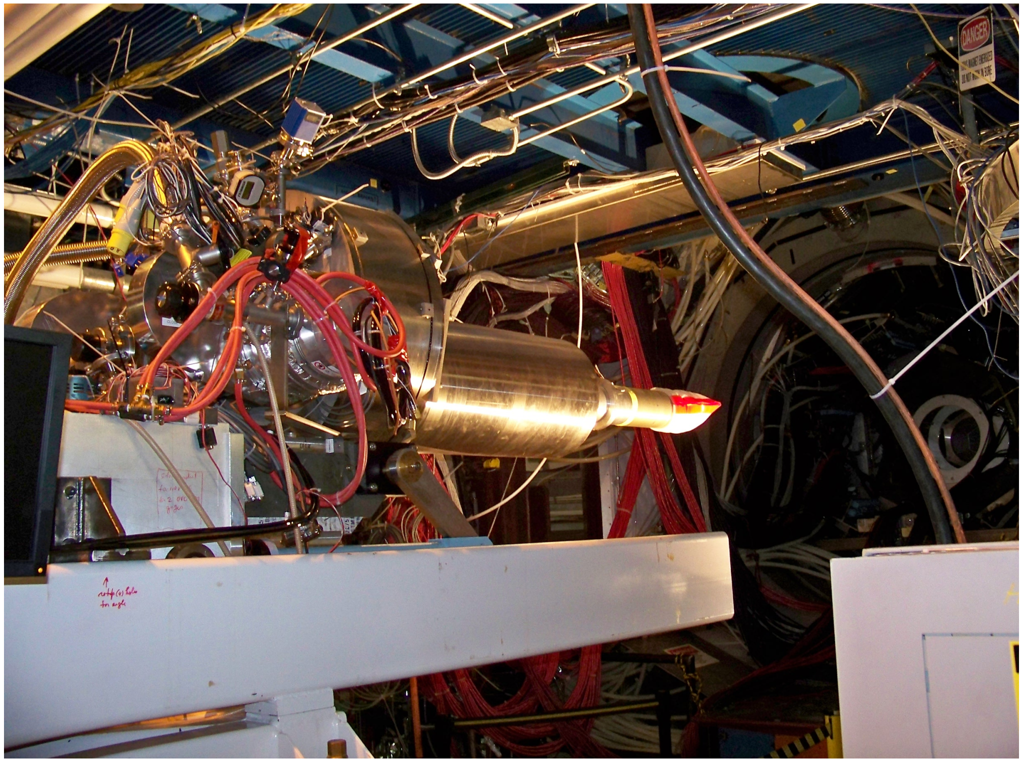


All model parameterizations describe the low mass range but fail in the high mass region.

HD-Ice target in G14 experiment

- HD targets condensed, polarized and aged to the Frozen-Spin state in HDice Lab at T=10mK and B=15T
- transferred as solid, polarized HD between cryostats; moved to Hall B
- In-Beam Cryostat (IBC) operates at 50mK, 0.9T
- G14 ran from Nov 2011 to May 2012 with 15mm Ø ×50mm long HD cells



Lifetimes of years with photon beams of ~10^8 γ/s

Search for S=0 states in single meson production on protons & neutrons

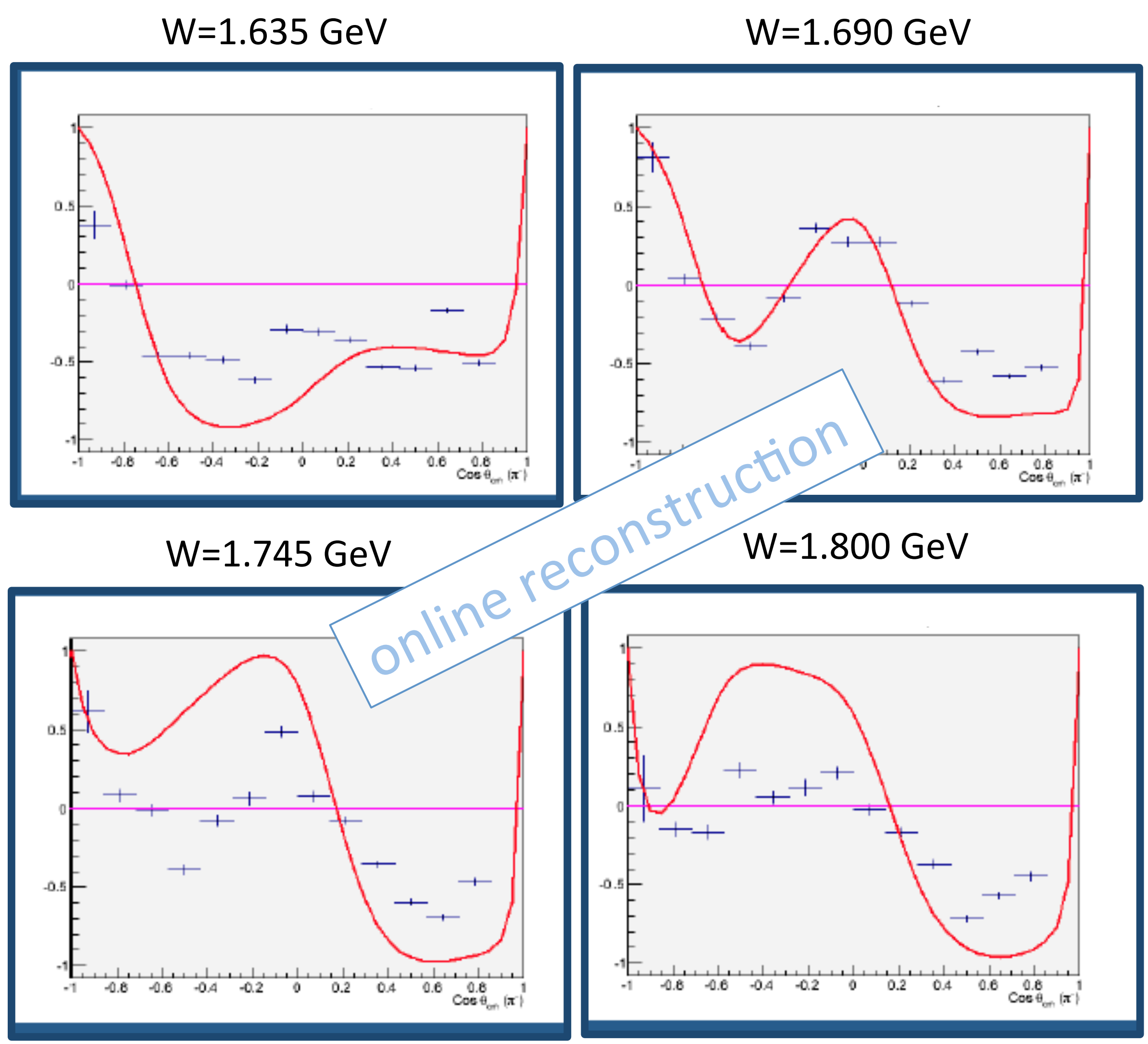
✔ - published, ✓ - acquired

	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
Proton targets																
$p\pi^0$	✔	✓	✓		✓	✓	✓	✓								
$n\pi^+$	✔	✓	✓		✓	✓	✓	✓								
$p\eta$	✔	✓	✓		✓	✓	✓	✓								
$p\eta'$	✔	✓	✓		✓	✓	✓	✓								
$p\omega/\phi$	✔	✓	✓		✓	✓	✓	✓								
$K^+\Lambda$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^+\Sigma^0$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^{0*}\Sigma^+$	✔	✓									✓	✓				
Neutron targets																
$p\pi^-$	✔	✓			✓		✓									
$p\rho^-$	✓	✓			✓		✓									
$K^-\Sigma^+$	✓	✓			✓		✓									
$K^0\Lambda$	✓	✓		✓	✓		✓				✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓		✓	✓		✓				✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓														

Double asymmetry E^n on neutron

$\vec{\gamma}\vec{n} \rightarrow \pi^- p$

—— projection from SAID



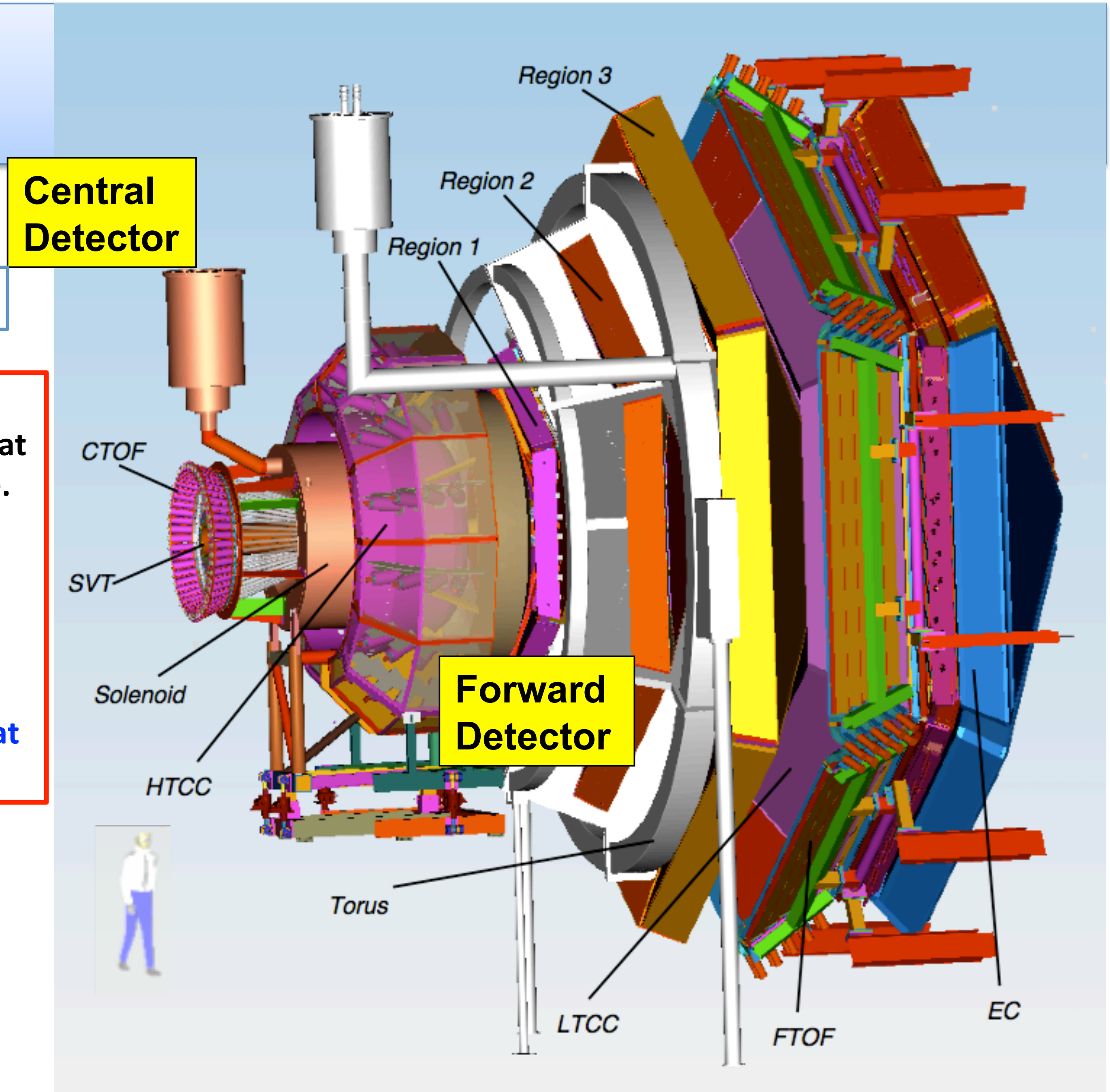
CLAS12

Luminosity = $10^{35}cm^{-2}s^{-1}$

CLAS12 **will support a broad program in hadronic physics at the 12 GeV electron machine.**

Proposals to study excited baryons and mesons:

- **Spectroscopy of Ξ^* , Ω^-**
- **Search for hybrid mesons**
- **N* Transition form factors at high Q^2.**



Summary

- **Precise meson photoproduction measurements are providing strong signals of new excited states of the nucleon.**
- **Much more data are in preparation, especially polarization observables involving polarized proton and neutron target and polarized photons.**
- **N* transition form factors have been measured for several well-known states. They reveal effective degrees of freedom and characterize the internal structure of excited states.**
- ***CLAS12* is under construction to support a broad program in hadron physics, including programs in meson and baryon spectroscopy, and the measurement of N* transition form factor at high Q^2.**

Additional slides

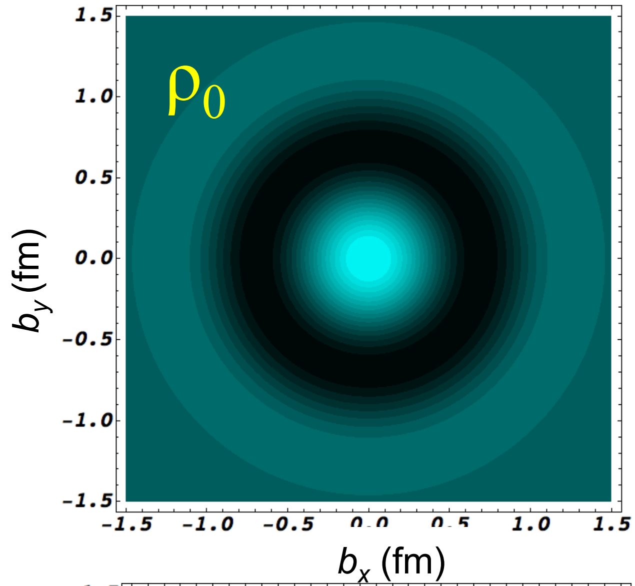
LC Transition charge density of p->D_{13}(1520)

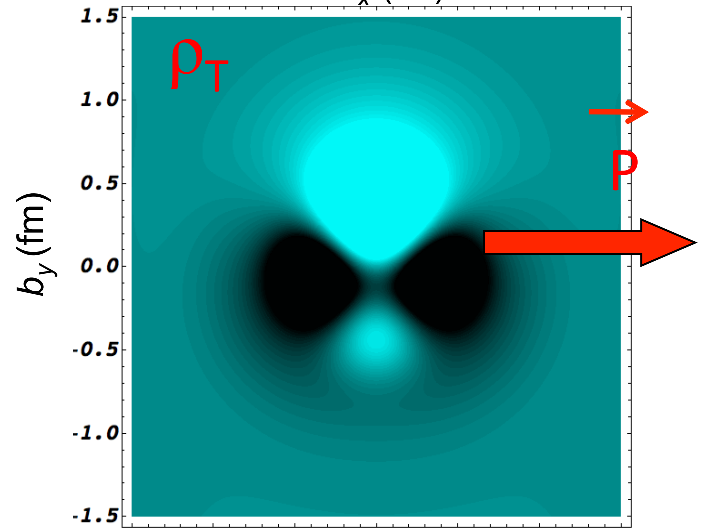
$\gamma p \rightarrow D_{13}$(1520) in LF helicity +1/2→ +1/2 transition

○ Transition induced by positive charge in the center and by negative charge in the outer region.

○ Quadrupole pattern extending to large radius.

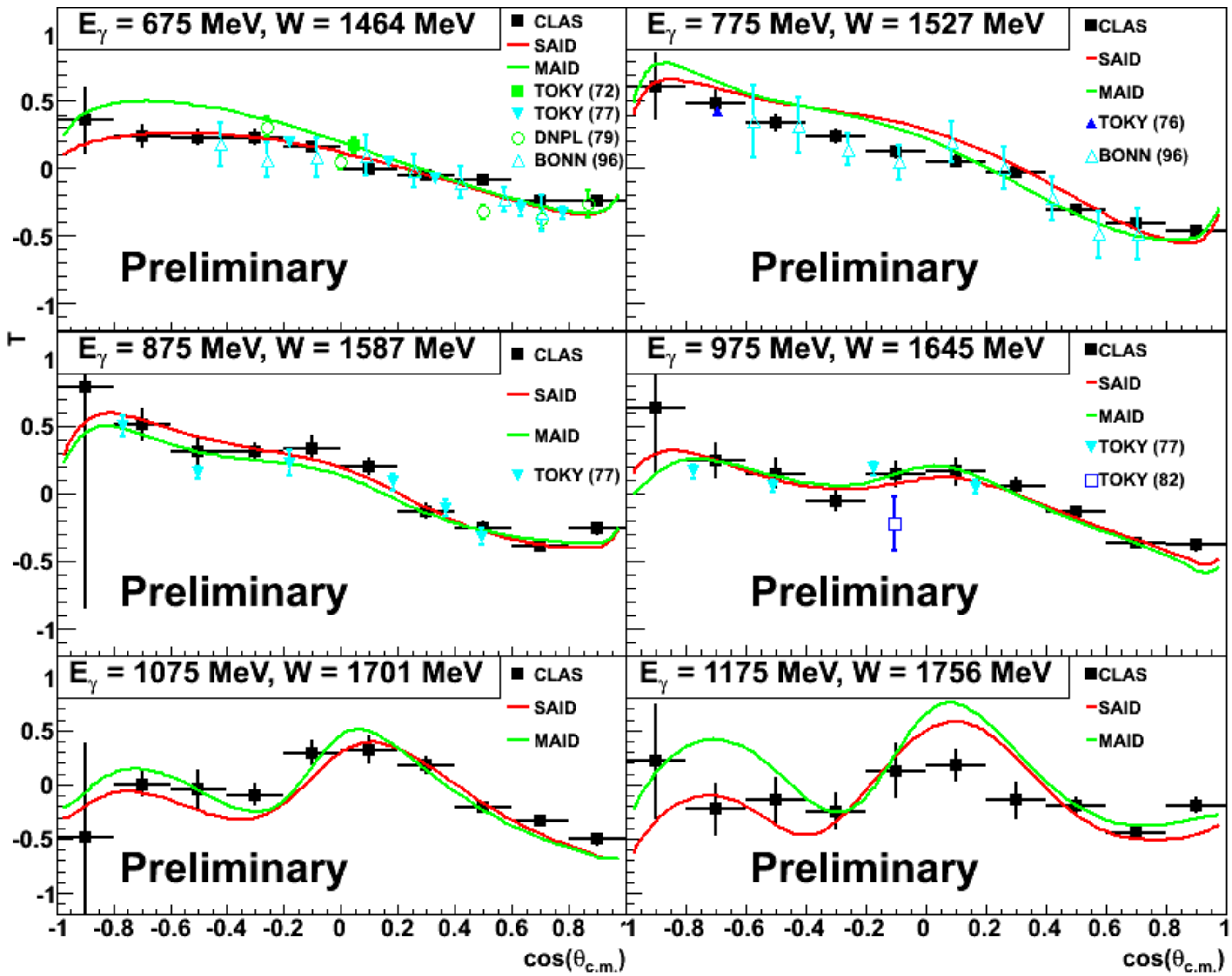
○ For polarized transitions with -1/2-> +1/2 spin projections one observes a distorted quadrupole pattern.



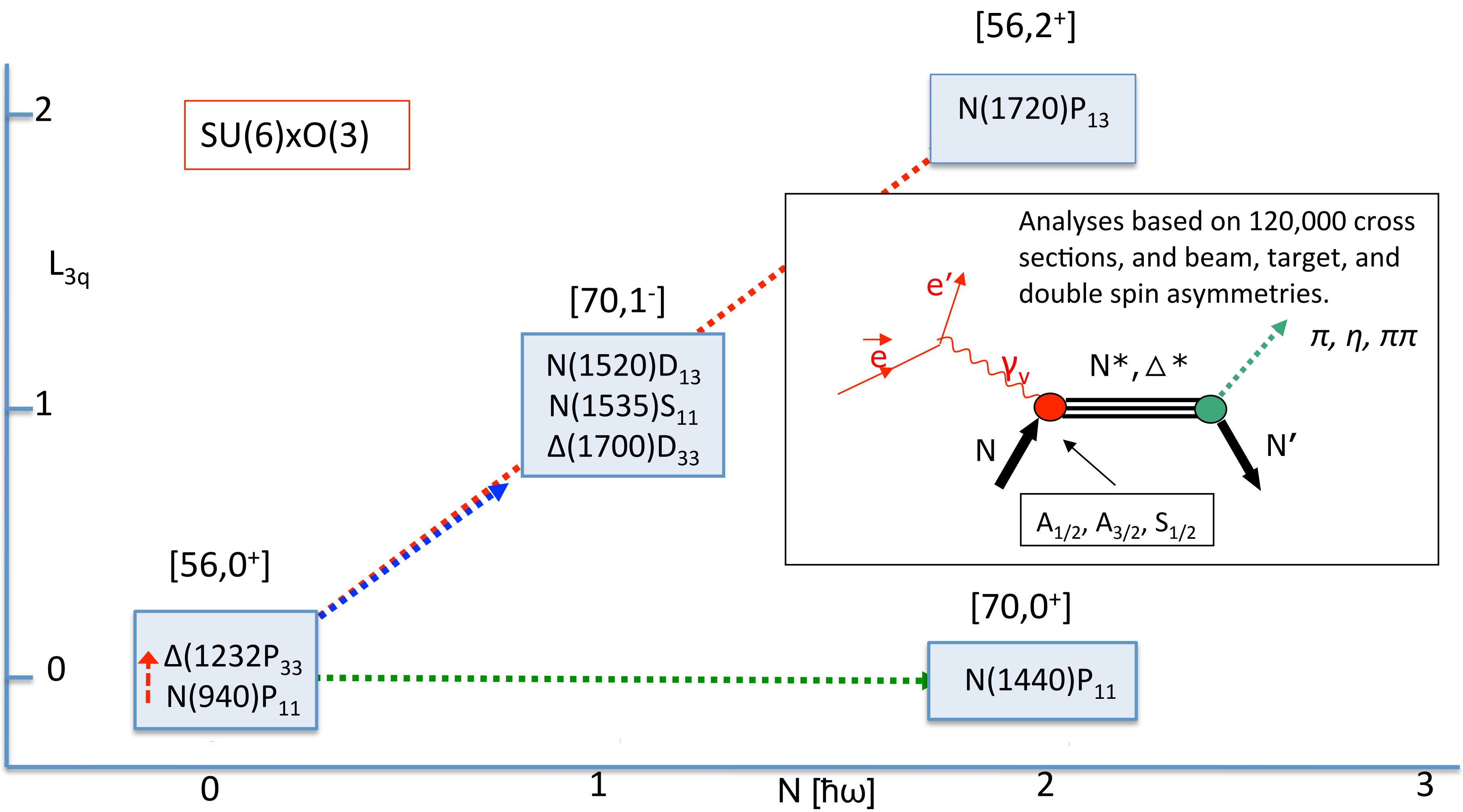


FROST g9 - Target asymmetry T in $\gamma\vec{p}\rightarrow n\pi^+$

< 2% of full statistics



Electroexcitation of lowest S=0 baryon states



1^{st} through 3^{rd} nucleon resonance regions

State	$\beta_{N\pi}$	$\beta_{N\eta}$	$\beta_{N\pi\pi}$
$\Delta(1232)P_{33}$	0.995		
$N(1440)P_{11}$	0.55-0.75		0.3-0.4
$N(1520)D_{13}$	0.55-0.65		0.4-0.5
$N(1535)S_{11}$	0.48±0.03	0.46±0.02	
$\Delta(1700)D_{33}$	0.1-0.2		0.8-0.9
$N(1720)P_{13}$	0.1-0.2		> 0.7

Analysis codes for single and double pseudo-scalar meson production:

- Unitary isobar model (UIM) for $N\pi$ and $N\eta$
- Fixed-t dispersion relations (DR) for $N\pi$ and $N\eta$
- Data driven reaction model for $p\pi^+\pi^-$ (JM09)

Status of single meson production on protons

✔ - completed, ✓ - data acquired

	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
$p\pi^0$	✔	✓	✓		✓	✓	✓	✓								
$n\pi^+$	✔	✓	✓		✓	✓	✓	✓								
$p\eta$	✔	✓	✓		✓	✓	✓	✓								
$p\eta'$	✔	✓	✓		✓	✓	✓	✓								
$p\omega, p\phi$	✔	✓	✓		✓	✓	✓	✓								
$K^+\Lambda$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^+\Sigma^0$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^{0*}\Sigma^+$	✔	✓									✓	✓				

Proton targets