Ongoing Hadron Spectroscopy with CLAS(6) and CLAS12

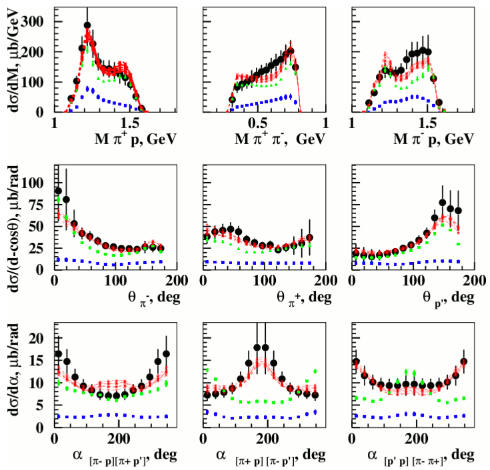
Derek Glazer
On behalf of the CLAS Hadron Spectroscopy Working Group

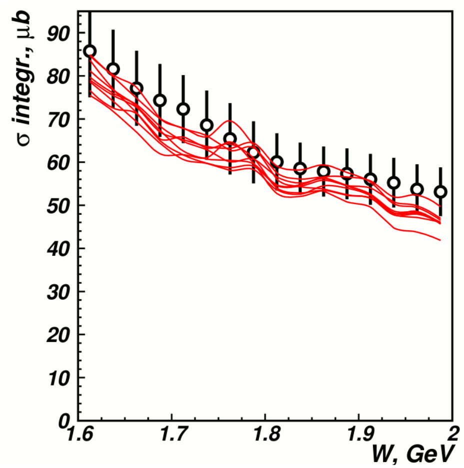
Overview

- CLAS experiment provided many high quality publications on spectroscopy
- Data with real photon and electron beams
- Many analysis still ongoing
- Wide variety of physics topics covered
- First run period for CLAS12 on hydrogen target completed
- Data reconstruction progressing, approaching physics level data quality

Baryon Spectroscopy with CLAS6

First results on N* photocouplings from π+π-p





E.N. Golovatch et al, CLAS Collaboration, Phys. Lett. B788, 371 (2019).

1.15 χ^2/d.p.<1.30

JM18 reaction model fit:

- **Full**
- **Resonant contributions**
- **Non-resonant contributions**

Resonances	$A_{1/2} \times 10^3$ from $\pi^+\pi^-p$ GeV$^{-1/2}$	$A_{1/2} \times 10^3$ PDG ranges GeV$^{-1/2}$	$A_{1/2} \times 10^3$ multichannel analysis [7] GeV$^{-1/2}$	$A_{3/2} \times 10^3$ from $\pi^+\pi^-p$ GeV$^{-1/2}$	$A_{3/2} \times 10^3$ PDG ranges GeV$^{-1/2}$	$A_{3/2} \times 10^3$ multichannel analysis [7] GeV$^{-1/2}$
$\Delta(1620)1/2^-$	29.0±6.2	30 – 60	55±7			
$N(1650)1/2^-$	60.5±7.7	35 – 55	32±6			
$N(1680)5/2^+$	−27.8±3.6	−18 – −5	−15±2	128±11	130 – 140	136±5
$N(1720)3/2^+$	80.9±11.5	80 – 120	115±45	−34.0±7.6	−48 – 135	135±40
$\Delta(1700)3/2^-$	87.2±18.9	100 – 160	165±20	87.2±16.4	90 – 170	170±25
$\Delta(1905)5/2^+$	19.0±7.6	17 – 27	25±5	−43.2±17.3	−55 – −35	−50±5
$\Delta(1950)7/2^+$	−69.8±14.1	−75 – −65	−67±5	−118.1±19.3	−100 – −80	−94±4

- **In 2019 partial update of the Review of Particle Physics the entries on photocouplings, πΔ and ρp decay widths for many resonances with masses >1.6 GeV were revised based on the studies of $\pi^+\pi^-$p photoproduction with CLAS**

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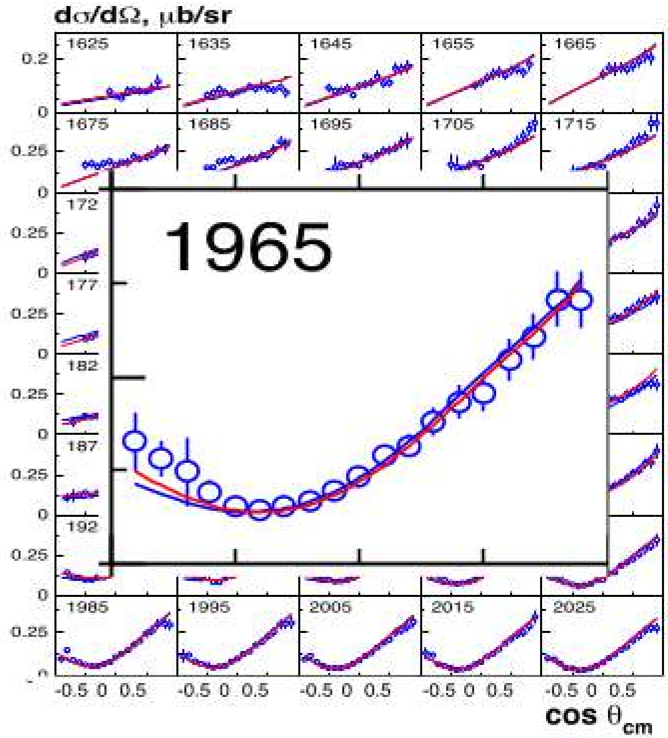
- **The global multi-channel analyses of exclusive meson photoproduction which employ the amplitudes from the independent studies of the Nπ, Nη, ππN, ωp, and KY channels will gain insight to the N* spectrum, in particular, in establishing the new state of baryon matter.**

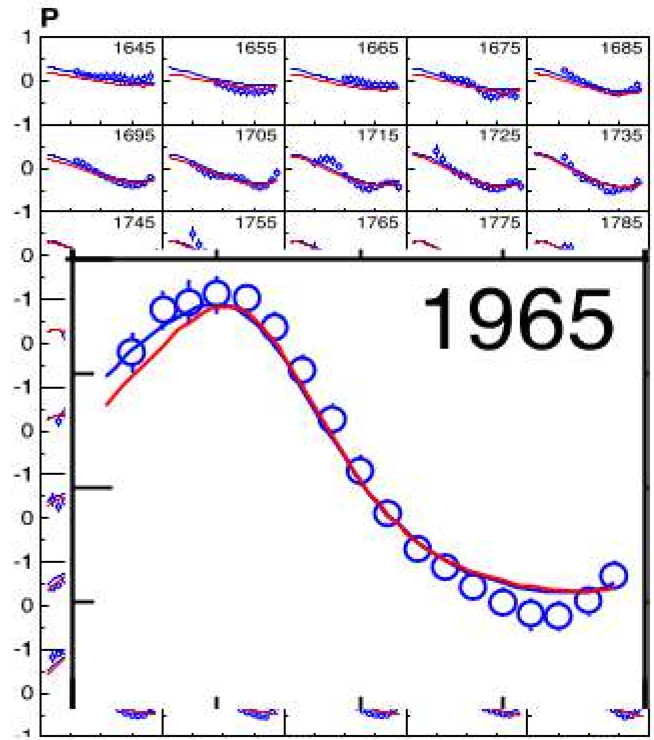
Establishing the N* Spectrum from CLAS KY data

Hyperon photoproduction **$\gamma p \rightarrow K^+\Lambda \rightarrow K^+ p\pi^-$** from CLAS

Bonn-Gatchina multichannel analysis:
9 new resonances were included

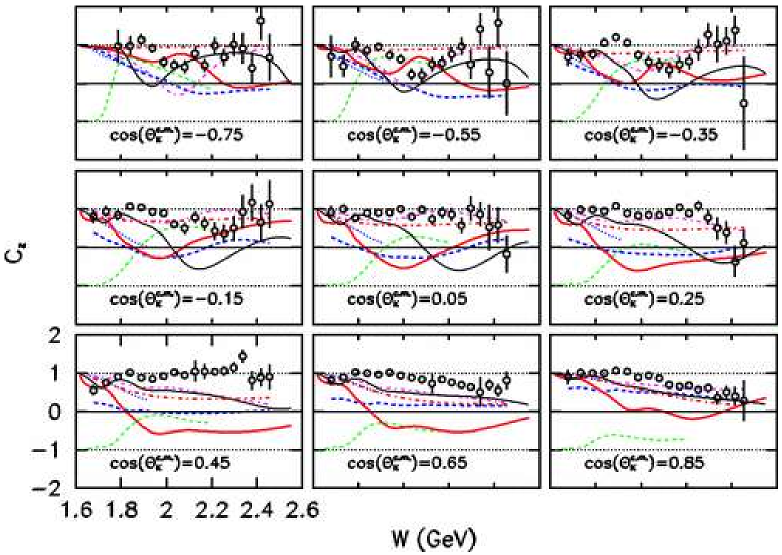


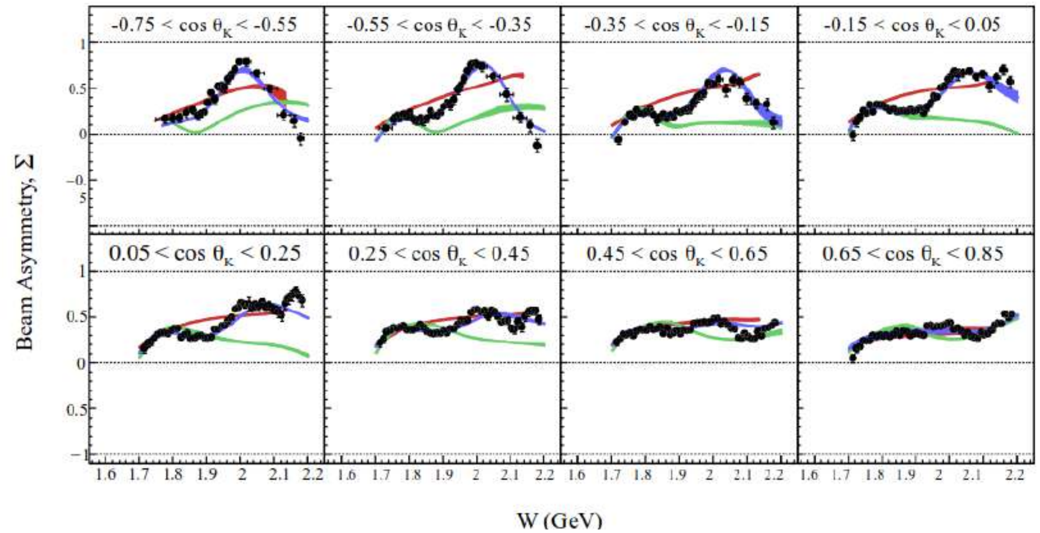
M. McCracken et al. (CLAS), Phys. Rev C 81, 025201 (2010)

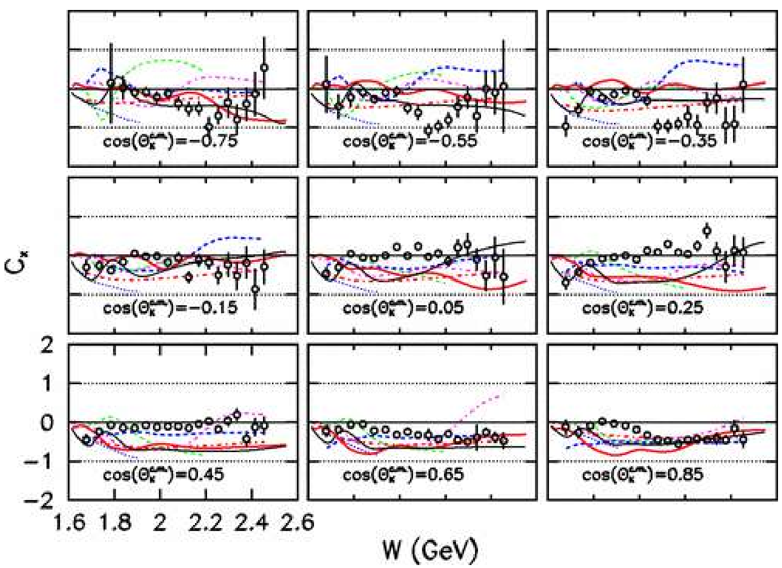


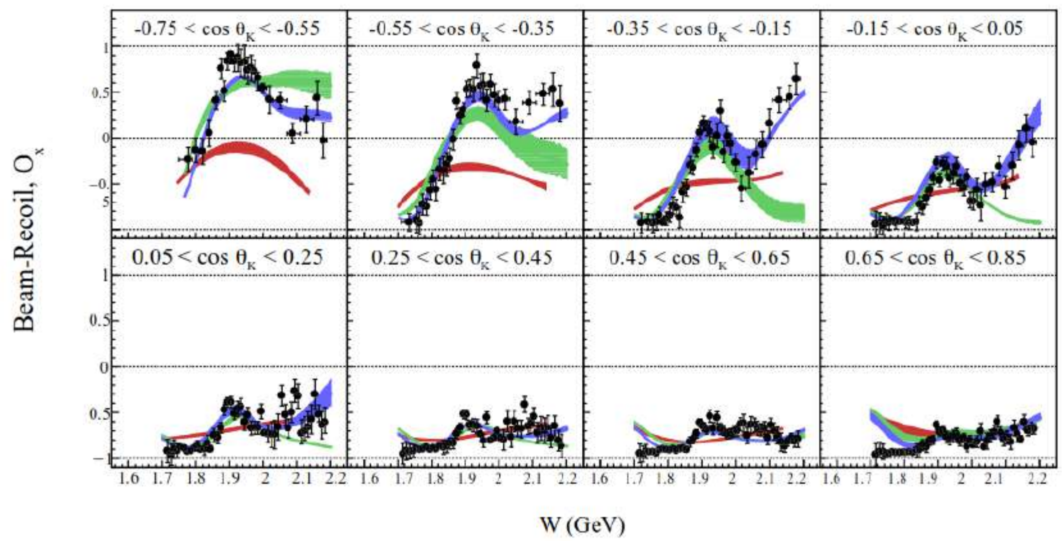
A.V. Anisovich et al, EPJ A48, 15 (2012)

Establishing the N* Spectrun from CLAS KY data



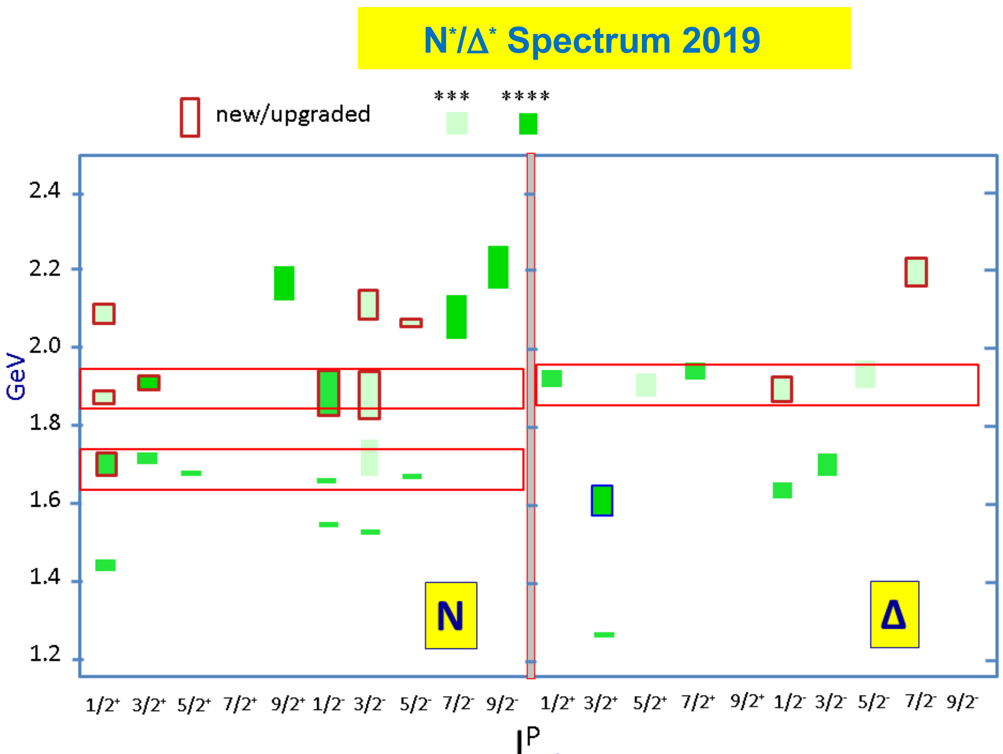






Advances in the exploration of the N* Spectrum

Several new nucleon resonances (``missing" states) have been discovered with the decisive impact of the CLAS open strangeness photoproduction data. A.V. Anisovich et al., Phys. Lett. B782, 662(2018), V.D. Burkert, Few Body Syst. 59, 57 (2018).



Nucleon resonances listed in Particle Data Group (PDG) tables

State N(mass)J^P	PDG pre 2016	PDG 2018*
$N(1710)1/2^+$	***	****
$N(1880)1/2^+$		***
$N(1895)1/2^-$		****
$N(1900)3/2^+$	**	****
$N(1875)3/2^-$		***
$N(2100)1/2^+$	*	***
$N(2120)3/2^-$		***
$N(2000)5/2^+$	*	**
$N(2060)5/2^-$		***
$\Delta(1600)3/2^+$	***	****
$\Delta(1900)1/2^-$	**	***
$\Delta(2200)7/2^-$	*	***

The next step: A description of the exclusive electroproduction data off the proton with the same masses and hadronic decay widths as in photoproduction will support the existence of new baryon states.

The request for theory support: Extension of the amplitude analysis approaches, which was successfully employed for the extraction of the N* photocouplings, towards the photon virtualities $Q^2>0$. for the extraction of the N* electrocouplings from exclusive meson electroproduction data represents the most important avenue for the theory support of the N* spectrum/structure studies with the CLAS and CLAS12.

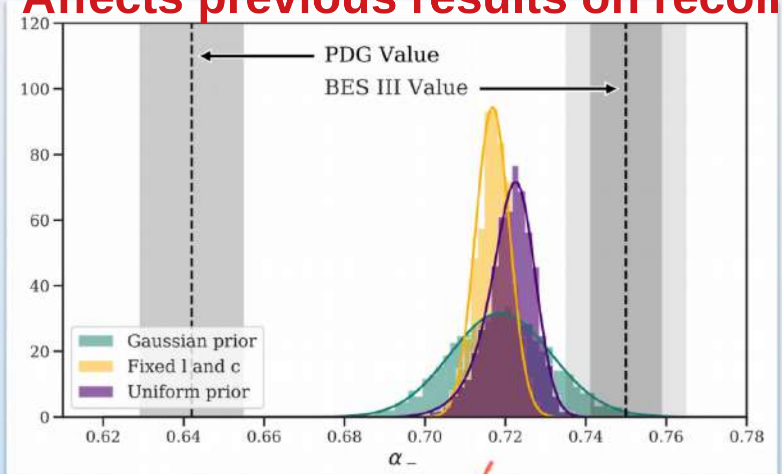
Kaon photoproduction and Fierz indentities

- **Helicity space maps on Clifford algebra ➤ Fierz identities:** Chiang, Tabakin (1997

$$\Sigma P - C_x O_z + C_z O_x - T = 0 \quad \& \quad O_x^{\,2} + O_z^{\,2} + C_x^{\,2} + C_z^{\,2} + \Sigma^2 - T^2 + P^2 = 1$$

- **A-priori:**
  - ⇒ *Observables are not independent*
  - ⇒ *determine* α_- *such that FI are fulfilled*
  - ⇒ *statistically non-trivial question*

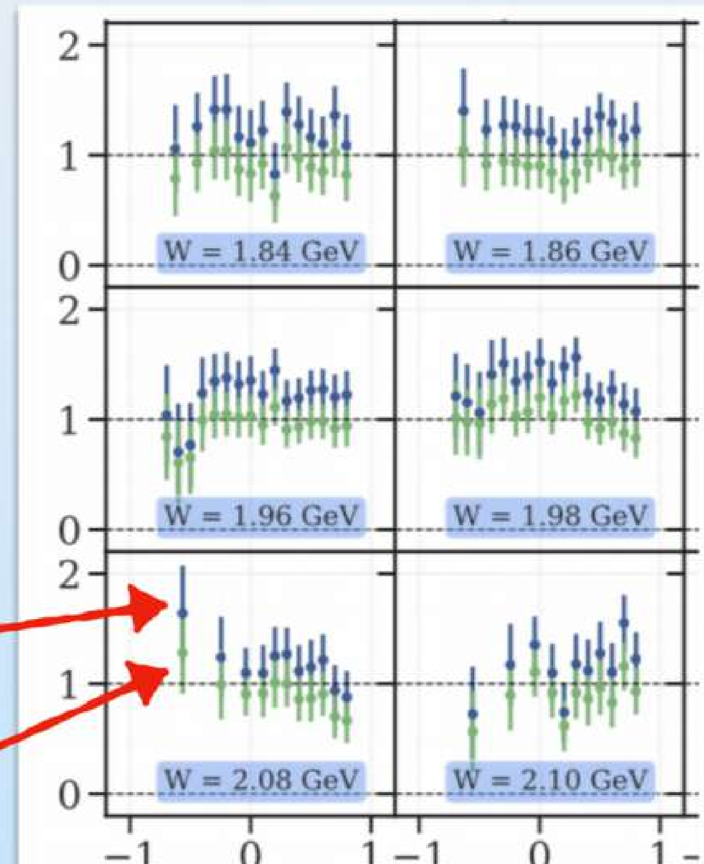
New value for Λ weak decay parameter
Affects previous results on recoil observables



$\alpha_- = 0.721 \pm 0.006 \pm 0.005$

α_[PDG]

α_[PDG] / a



arXiv.org > nucl-ex > arXiv:1904.07616

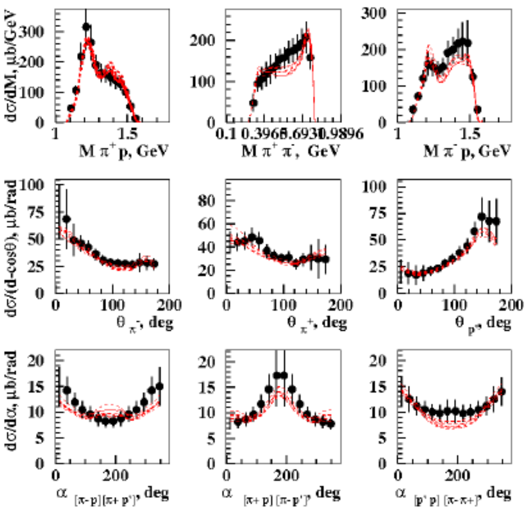
Nuclear Experiment

Kaon Photoproduction and the Λ Decay Parameter α_-

D. G. Ireland, M. Döring, D. I. Glazier, J. Haidenbauer, M. Mai, R. Murray-Smith, D. Rönchen

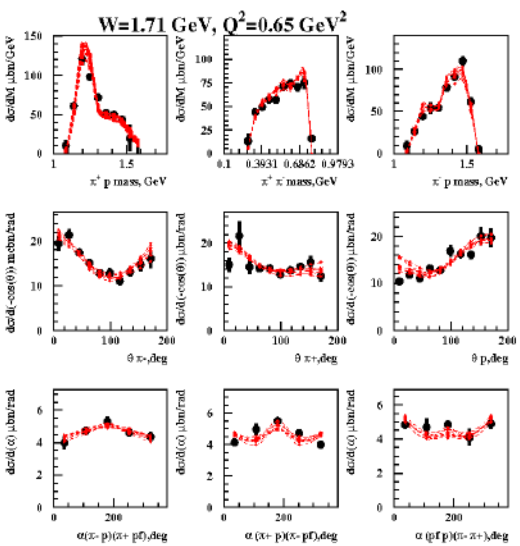
Evidence for the Existence of the New State N'(1720)3/2$^+$ from Combined $\pi^+\pi^-p$ Analyses in both Photo- and Electroproduction

W=1.71 GeV , Q^2=0. GeV^2



Photoproduction:
1.66 GeV<W<1.76 GeV
1.19 < χ^2/d.p. < 1.28

E.N. Golovatch et al,
CLAS Collaboration,
Phys. Lett.B788, 371 (2019).



Electroproduction:
1.66 GeV<W<1.76 GeV
0.5 GeV^2<Q^2<1.5 GeV^2
2.56 < χ^2/d.p. < 2.80
(stat. uncertainties only)

M. Ripani et al.,
CLAS Collaboration
Phys. Rev. Lett. 91, 022002 (2003).

N(1720)3/2$^+$ hadronic decays from the CLAS data fit with conventional resonances only

	BF($\pi\Delta$), %	BF(ρp), %
electroproduction	64-100	<5
photoproduction	14-60	19-69

The contradictory BF values for N(1720)3/2$^+$ decays to the $\pi\Delta$ and ρp final states deduced from photo- and electroproduction data make it impossible to describe the data with conventional states only.

Resonance	BF($\pi\Delta$), %	BF(ρp), %
N'(1720)3/2$^+$ electroproduction photoproduction	 47-64 46-62	 3-10 4-13
N(1720)3/2$^+$ electroproduction photoproduction	 39-55 38-53	 23-49 31-46

The successful description of the $\pi^+\pi^-p$ photo- and electroproduction data achieved by implementing new N'(1720)3/2$^+$ state with Q^2-independent hadronic decay widths of all resonances contributing at W~1.7 GeV <u>provides strong evidence for the existence of the new N'(1720)3/2$^+$ state.</u>

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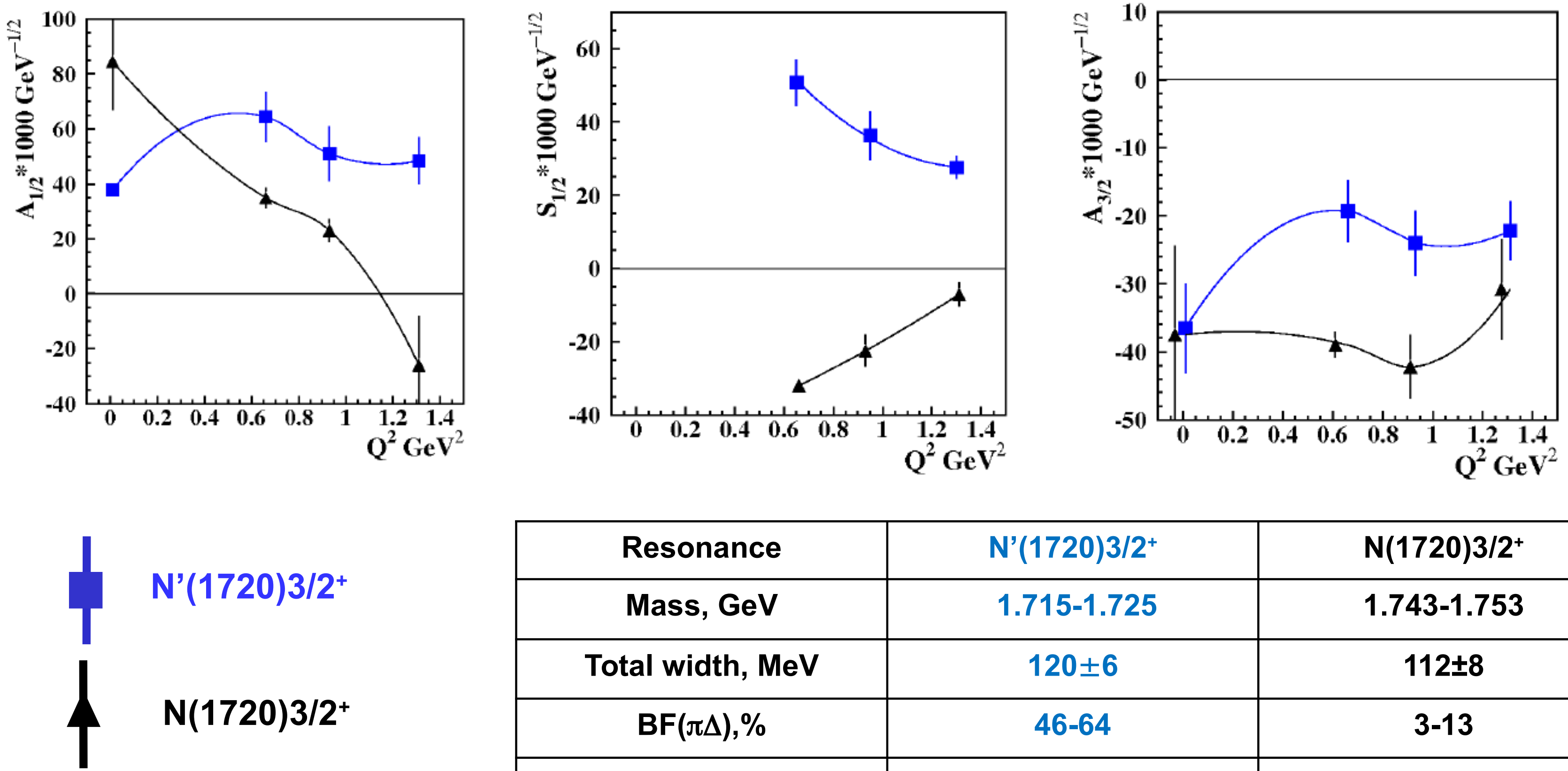
The Parameters of the N’(1720)3/2⁺ /N(1720)3/2⁺ States from the CLAS Data Fit



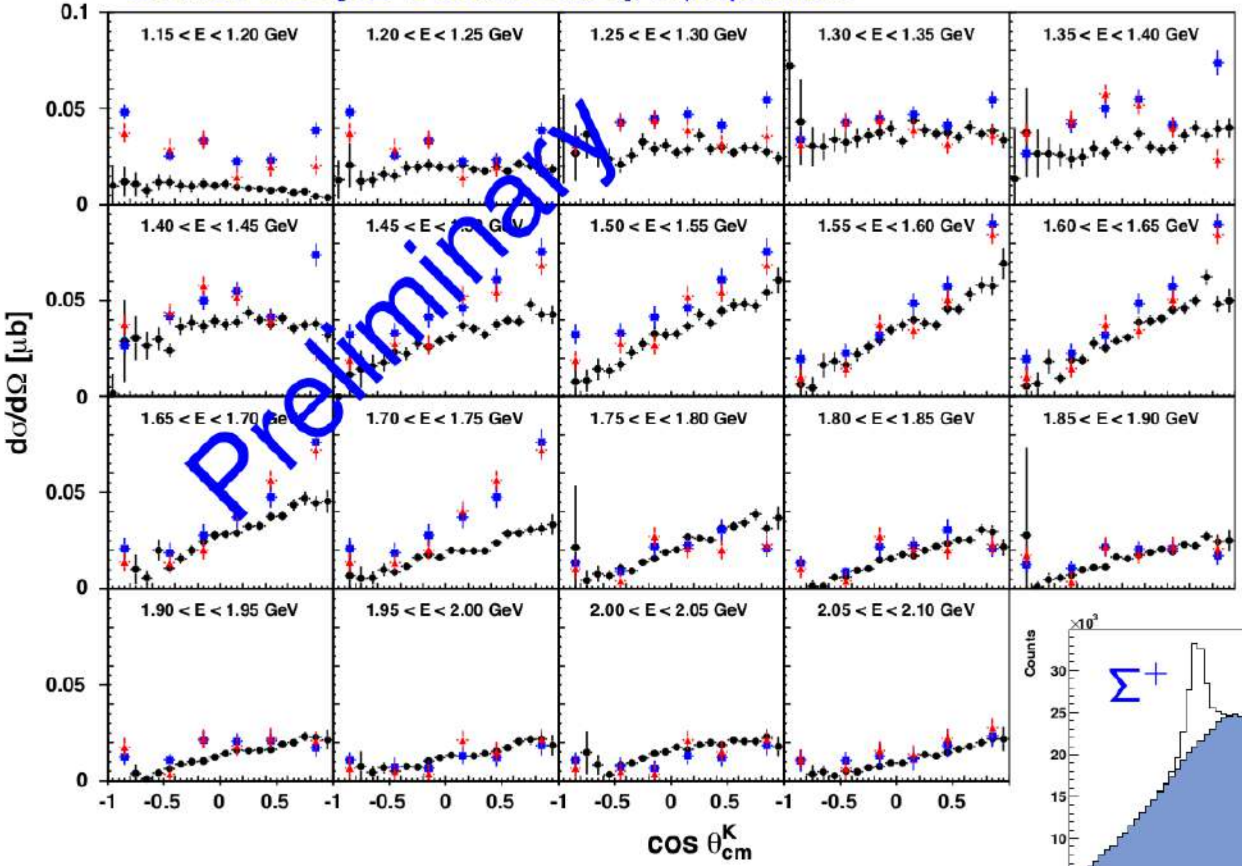
Resonance	N’(1720)3/2⁺	N(1720)3/2⁺
Mass, GeV	1.715-1.725	1.743-1.753
Total width, MeV	120±6	112±8
BF(πΔ),%	46-64	3-13
BF(ρp),%	38-55	23-49

- **N’(1720)3/2⁺ is the only new resonance for which data on electroexcitation amplitudes have become available.**
- **Gaining insight into the ``missing” resonance structure will shed light on their peculiar structural features that have made them so elusive, as well as on the emergence of new resonances from QCD.**

Meson Production with CLAS6

Cross Sections for $K^0\Sigma^+ \rightarrow p\pi^+\pi^-\pi^0$

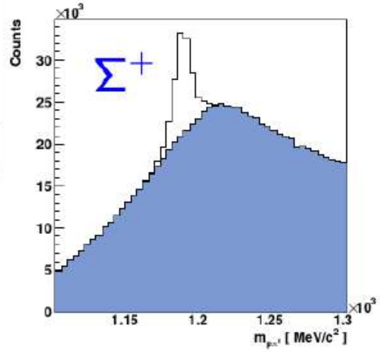
Z. Akbar *et al.* [CLAS Collaboration], in preparation.

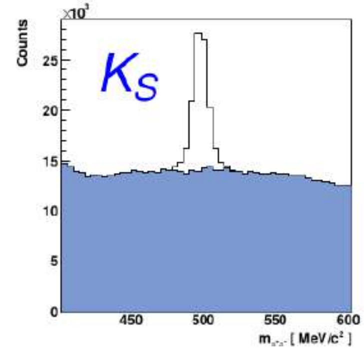


New cross section results in 50-MeV-wide E_γ bins for

$$1.15 < E_\gamma < 3.0 \text{ GeV}$$

➜ Need theory support to understand physics!!



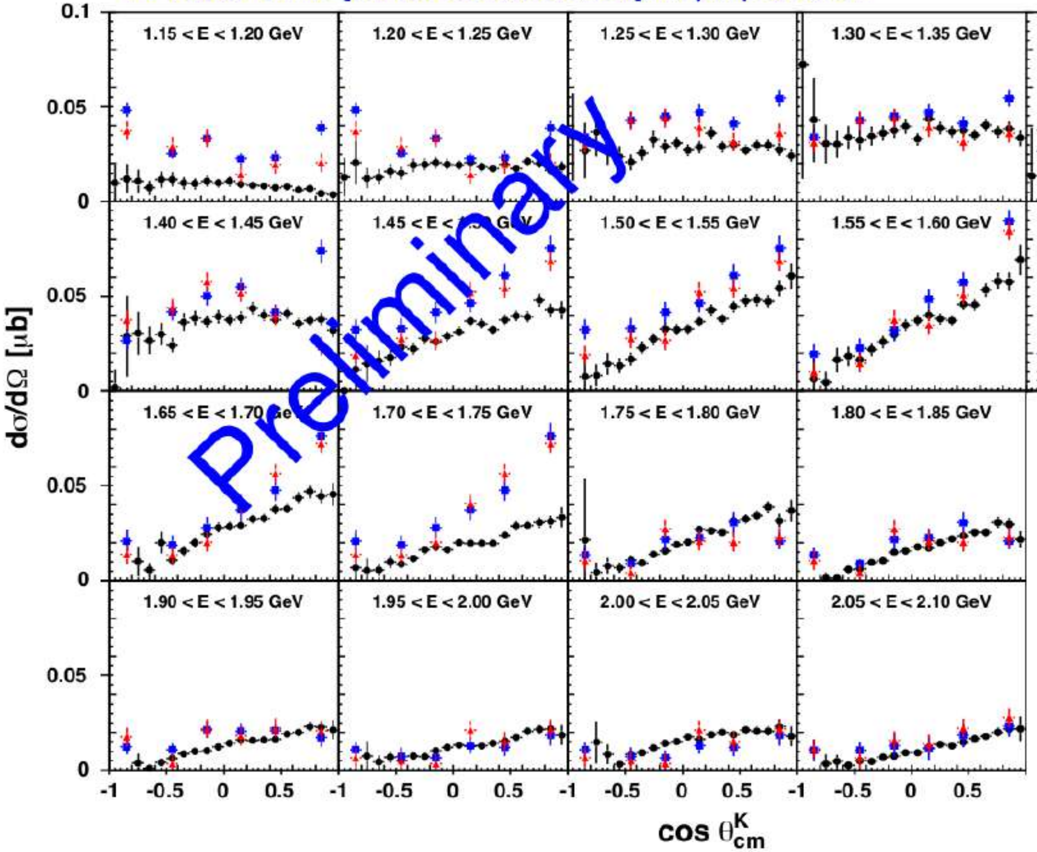


CLAS-g12 • CB-ELSA • CBELSA/TAPS •

Phys. Lett. B **713**, 180 (2012)

Cross Sections for $K^0\Sigma^+ \rightarrow p\pi^+\pi^-\pi^0$

Z. Akbar *et al.* [CLAS Collaboration], in preparation.



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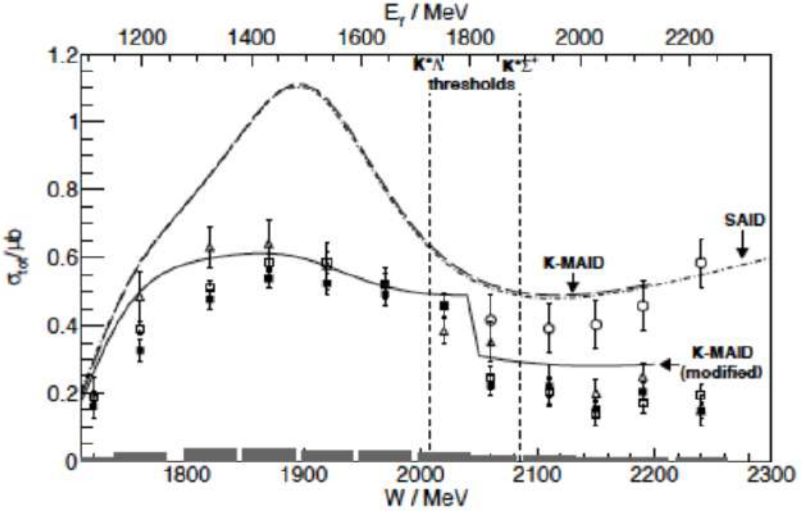
Phys. Lett. B **713**, 180 (2012)



CLAS-g12 • CB-ELSA • CBELSA/TAPS •

➜ Currently being analyzed for $K^0\,\Sigma^+$: E, P, C_x, C_z & Σ, O_x, O_z

(Complete measurements) in ω photoproduction

- Event-based background subtraction (event-based dilution factors)

  ➜ $\gamma p \to p\pi^+\pi^-$ ✓ $\gamma p \to p\pi^+\pi^-(\pi^0)$ ✓
- In analogy to pseudoscalar mesons:

$$\frac{d\sigma}{d\Omega} = \sigma_0\{1 - \delta_l \Sigma \cos 2\phi$$

$$+ \Lambda_x(-\delta_l H \sin 2\phi + \delta_\odot F)$$

published (+ SDME's) $$- \Lambda_y(-T + \delta_l P \cos 2\phi)$$

in progress $$- \Lambda_z(-\delta_l G \sin 2\phi + \delta_\odot E)\}$$

$\phi = \Psi \equiv$ Angle between $p\omega$ production plane and the photon polarization plane in the overall CM frame.

$\Phi \equiv$ Azimuthal angle of normal to the ω decay plane in helicity frame - quantization axis in the direction opposite the recoiling proton in the ω rest frame.

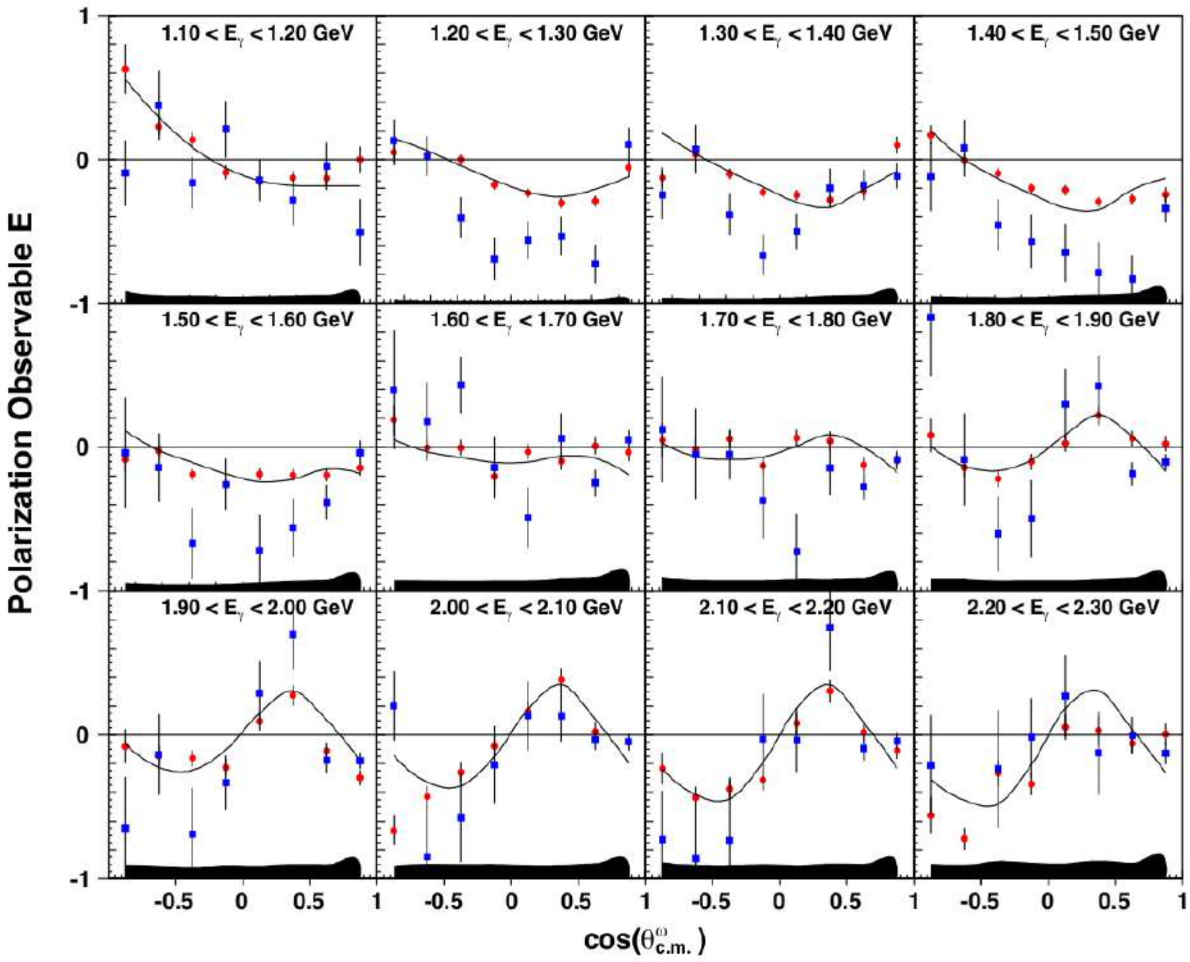
The ω is a vector meson (A. I. Titov and B. Kampfer, Phys. Rev. C 78, 038201 (2008))

$$2\pi W^f(\Phi,\Psi) = 1 - \Sigma^f_\Phi \cos 2\Phi - P_\gamma \Sigma^f_b \cos 2\Psi + P_\gamma \Sigma^f_d \cos 2(\Phi - \Psi)$$

$$\boxed{\Sigma^h_b = \Sigma^r_b = 2\rho^1_{11} + \rho^1_{00}} \qquad -\tfrac{1}{2}\Sigma^h_d = \Sigma^r_d = \rho^1_{1\,-1} \qquad -\tfrac{1}{2}\Sigma^h_\Phi = \Sigma^r_\Phi = -\rho^0_{1\,-1}$$

Pol. SDMEs: B. Vernarsky (CMU), PhD dissertation

Helicity Asymmetry in $\vec{\gamma}\,\vec{p} \rightarrow p\,\omega$



BnGa (coupled-channels) PWA

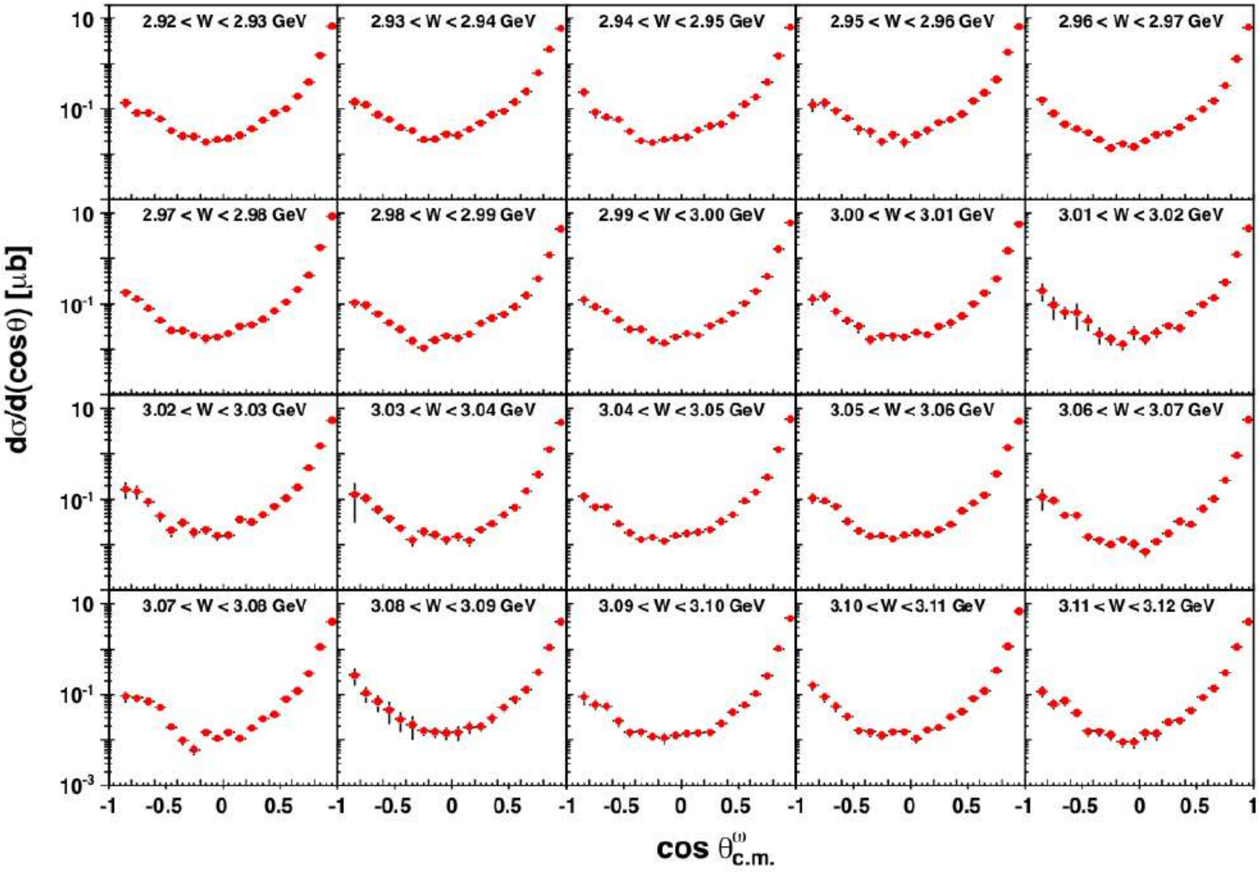
- Dominant $\mathbb{P}$ exchange
- Complex $3/2^+$ wave
  1. $N(1720)$
  2. $W \approx 1.9$ GeV
- $N(1895)\,1/2^-$ (new state)
- $N(1680), N(2000)\,5/2^+$
- 7/2 wave > 2.1 GeV

● CLAS-g9a

■ CBELSA/TAPS
Phys. Lett. B **750**, 453 (2015)

Z. Akbar *et al.* [CLAS Collaboration], PR C **96**, 065209 (2017)

Cross Sections for γ p → p ω



New cross section results in 10-MeV-wide *W* bins for

$1.15 < E_\gamma < 5.40$ GeV, or

$1.75 < W < 3.32$ GeV

➜ Need theory support to understand physics at these high energies!!

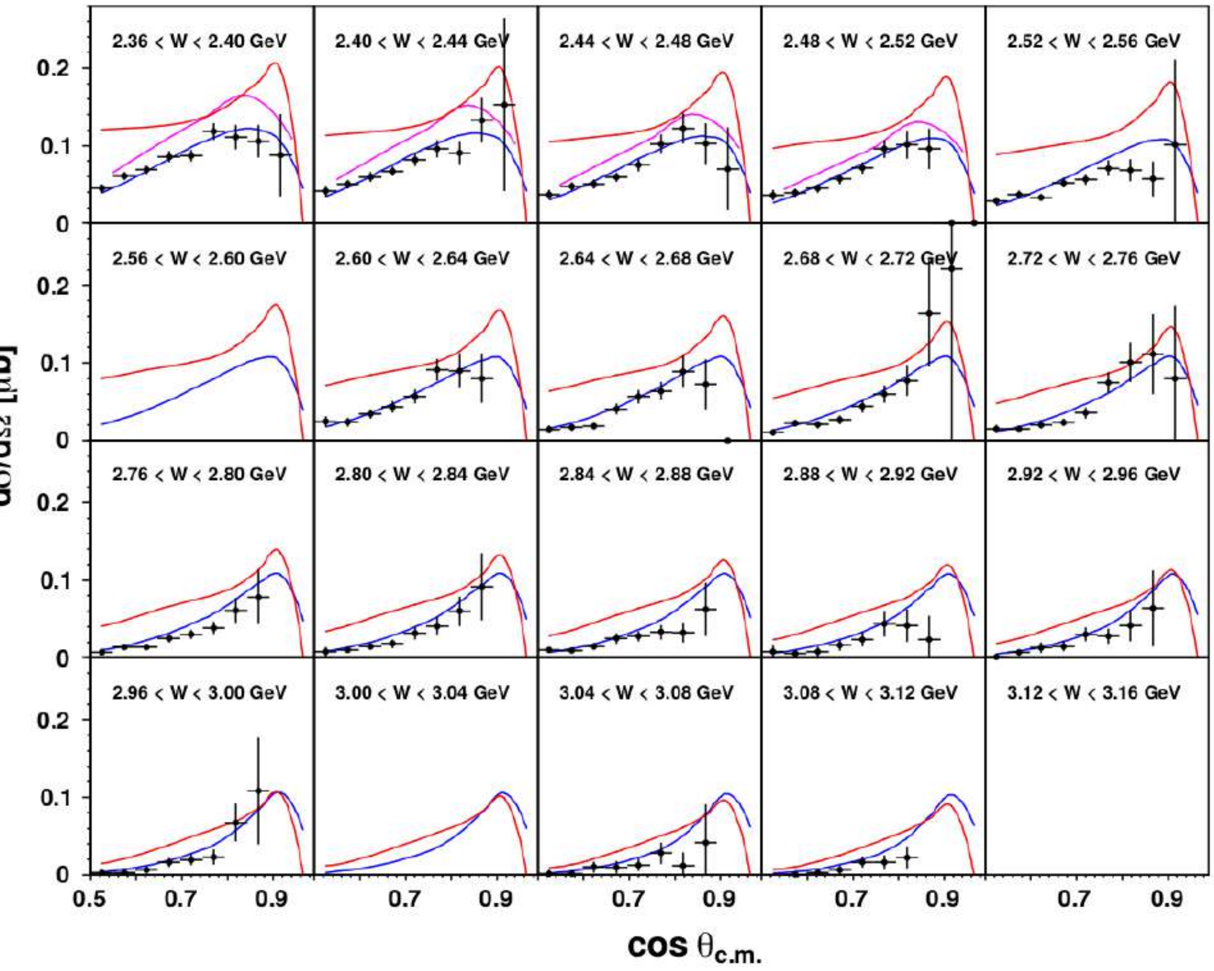
Working with JPAC.

(V. Mathieu *et al.*)

➜ Data of unprecedented quality

Z. Akbar *et al.* [CLAS Collaboration], in preparation + SDMEs

Cross Sections for $\gamma\, p \rightarrow p\, \eta$



New cross section results in 40-MeV-wide *W* bins for

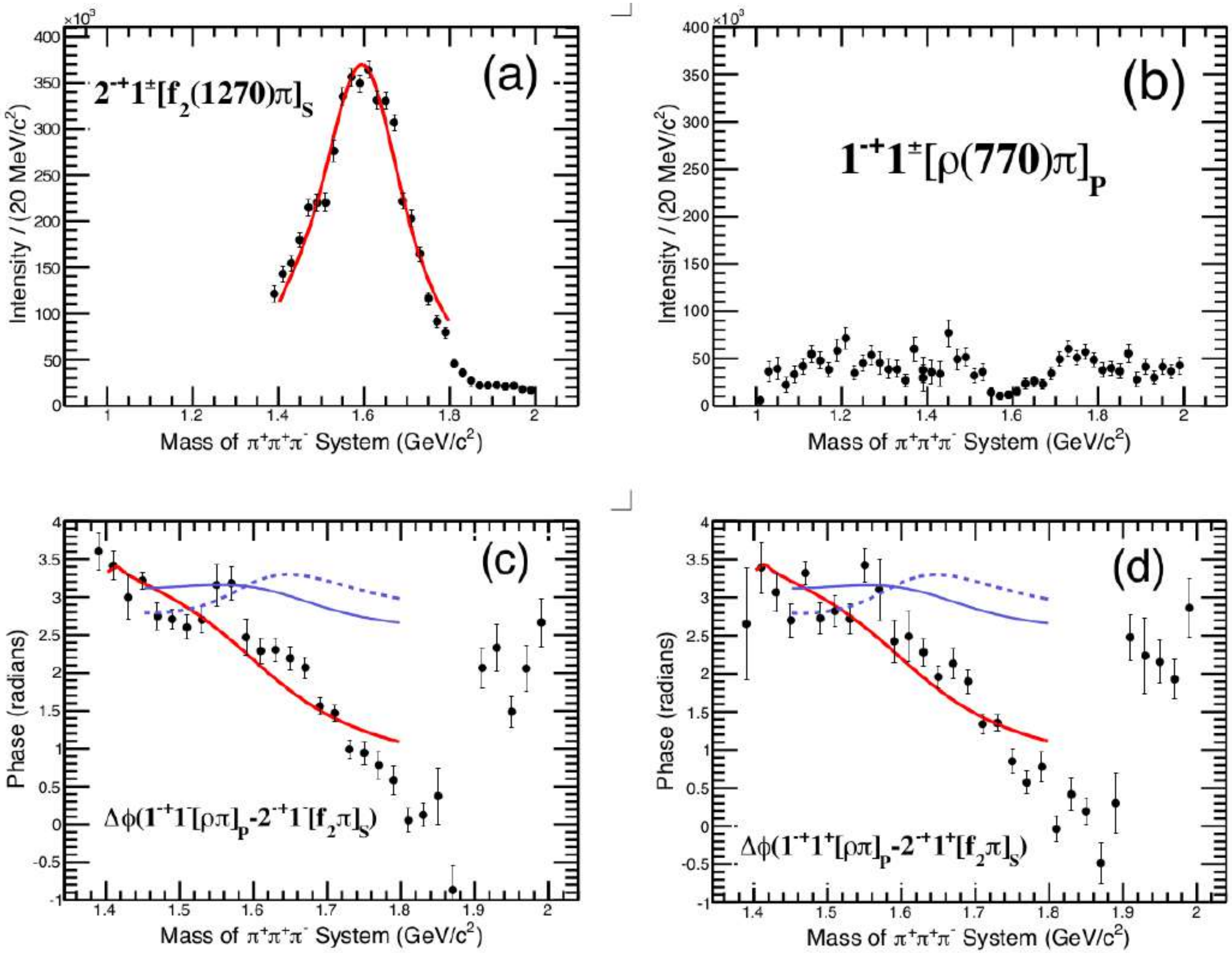
$$2.50 < E_\gamma < 4.72 \text{ GeV, or}$$

$$2.36 < W < 3.12 \text{ GeV}$$

- JPAC, J. Nys *et al.*
- ηMAID 2018
- BnGa 2014-02

T. Hu *et al.* [CLAS Collaboration], manuscript prepared for PRC, under review.

Search for Hybrid Mesons $\gamma p \to n\, \pi^+\pi^+\pi^-$



600k $\pi^+\pi^+\pi^-$ events

$a_2(1320)$ and $\pi_2(1670)$ [(a)]

First observation in γp: $a_1(1260)$

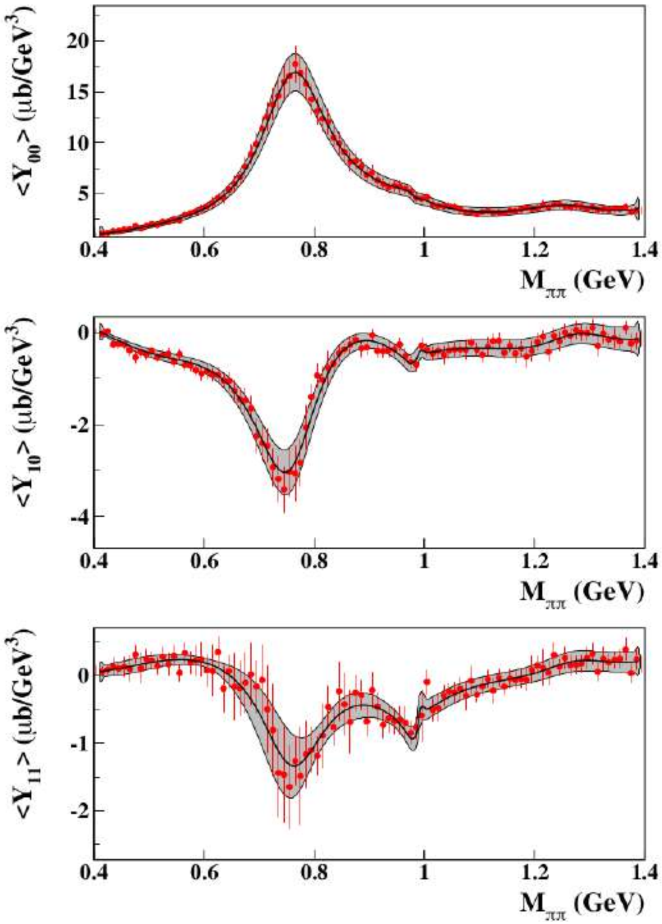
No evidence for exotic $J^{PC} = 1^{-+}$ meson in the $\rho\pi$ decay mode [(b)]

Phase motion shows non-resonant behavior [(c),(d)]

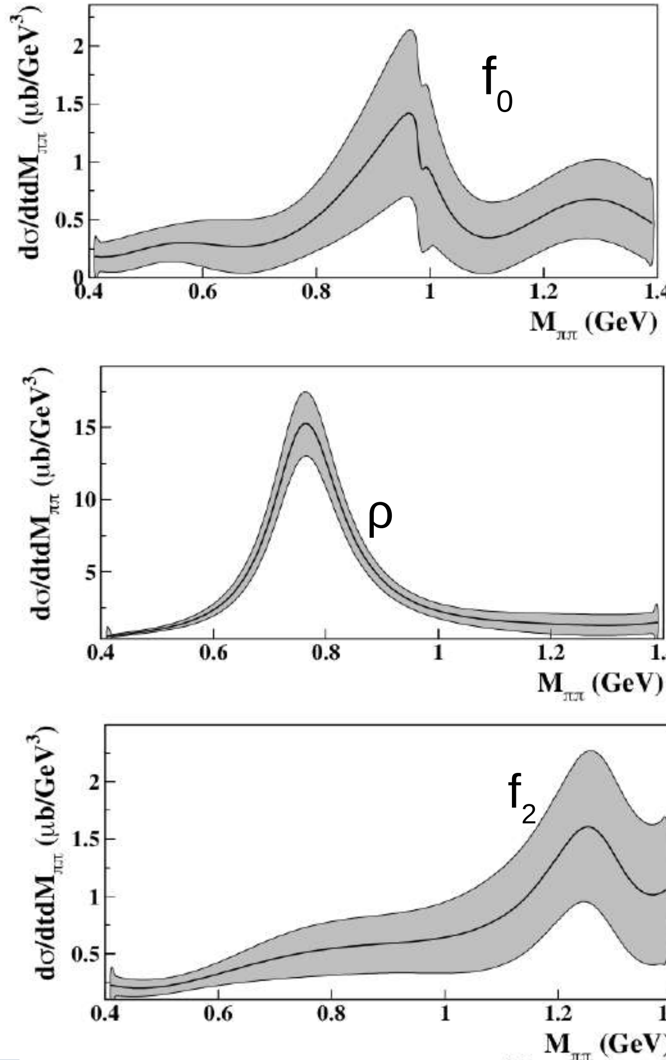
A. Tsaris *et al.* [CLAS Collaboration], manuscript prepared for PRL, under review.

Two Pion production and the $f_0(980)$

Extract moments of spherical harmonics
From 2π decay angular distributions
In bins of 2π mass



Fit moments with mass dependent
partial wave amplitudes



Avoids
ambiguities
in PWAs

"Model
independent"
Parameterisation
of data

Measurement of Direct $f_0(980)$ Photoproduction on the Proton

M. Battaglieri *et al.* (CLAS Collaboration)
Phys. Rev. Lett. **102**, 102001 – Published 11 March 2009

Two Pion production and the $f_0(980)$

Extract moments of spherical harmonics
From 2π decay angular distributions
In bins of 2

Fit moments with mass dependent partial wave amplitudes

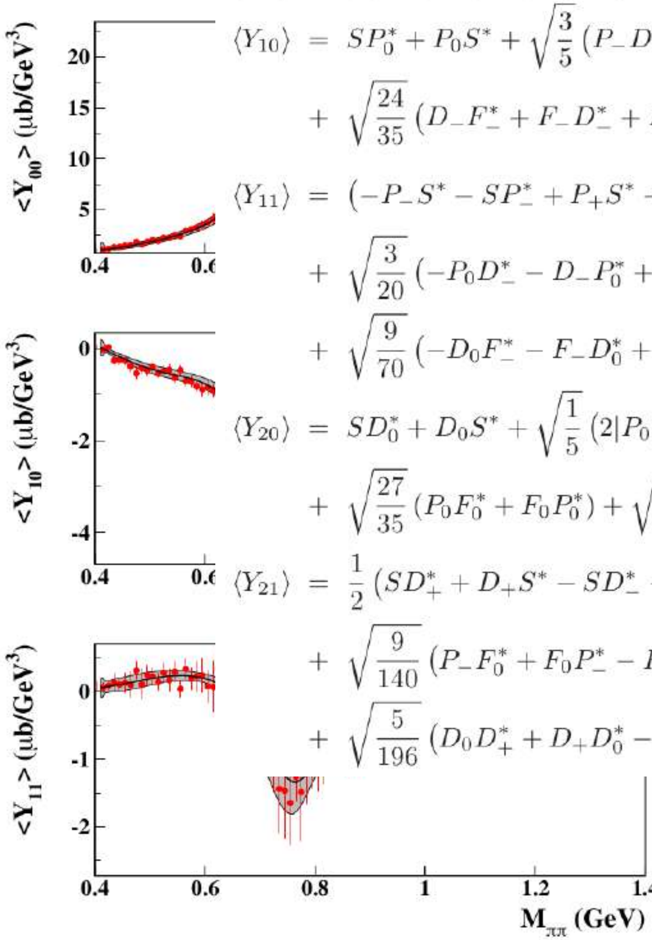
$$\langle Y_{00}\rangle = |S|^2 + |P_-|^2 + |P_0|^2 + |P_+|^2 + |D_-|^2 + |D_0|^2 + |D_+|^2 + |F_-|^2 + |F_0|^2 + |F_+|^2$$

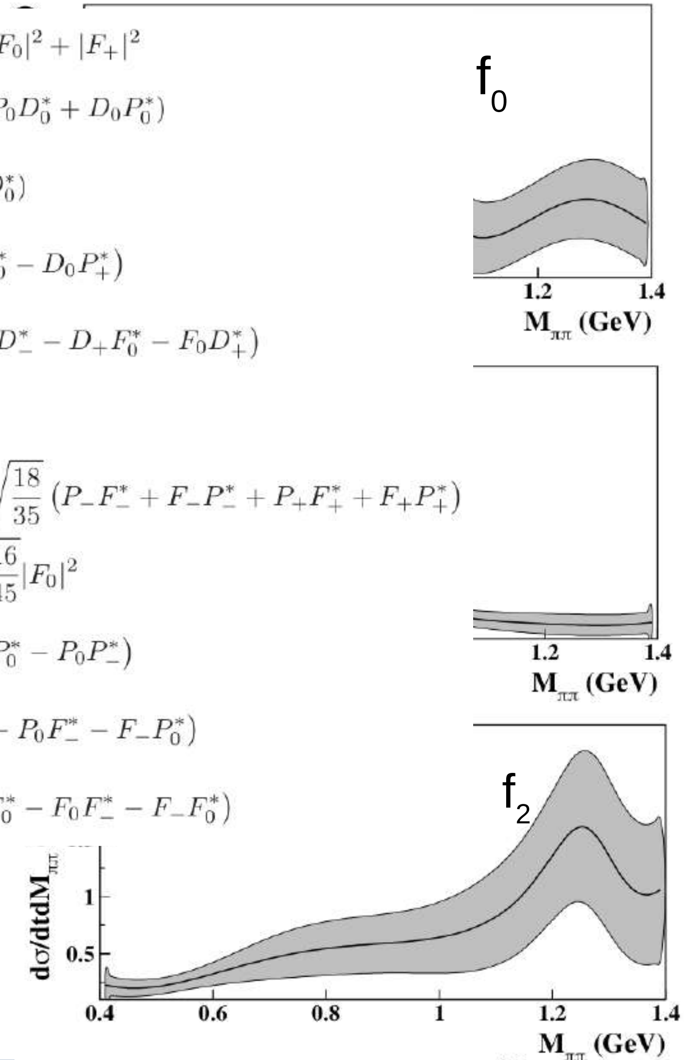
$$\langle Y_{10}\rangle = SP_0^* + P_0S^* + \sqrt{\frac{3}{5}}\left(P_-D_-^* + P_-^*D_- + P_+D_+^* + D_+P_+^*\right) + \sqrt{\frac{4}{5}}\left(P_0D_0^* + D_0P_0^*\right) + \sqrt{\frac{24}{35}}\left(D_-F_-^* + F_-D_-^* + D_+F_+^* + F_+D_+^*\right) + \sqrt{\frac{216}{280}}\left(D_0F_0^* + F_0D_0^*\right)$$

$$\langle Y_{11}\rangle = \left(-P_-S^* - SP_-^* + P_+S^* + SP_+^*\right) + \sqrt{\frac{1}{20}}\left(P_-D_0^* + D_0P_-^* - P_+D_0^* - D_0P_+^*\right) + \sqrt{\frac{3}{20}}\left(-P_0D_-^* - D_-P_0^* + P_0D_+^* + D_+P_0^*\right) + \sqrt{\frac{9}{140}}\left(D_-F_0^* + F_0D_-^* - D_+F_0^* - F_0D_+^*\right) + \sqrt{\frac{9}{70}}\left(-D_0F_-^* - F_-D_0^* + D_0F_+^* + F_+D_0^*\right)$$

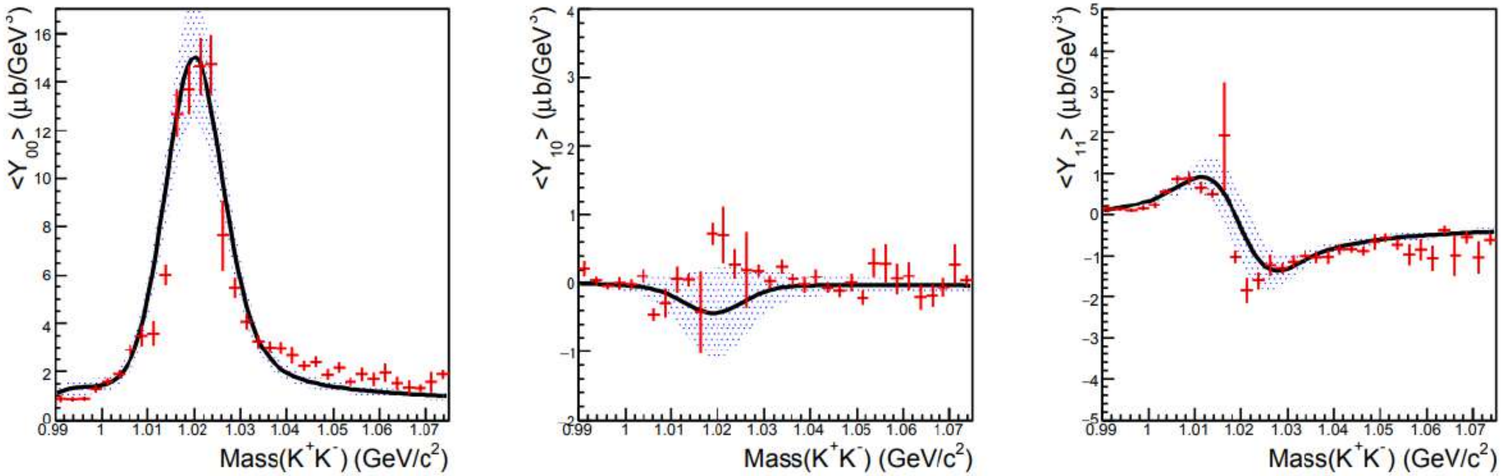
$$\langle Y_{20}\rangle = SD_0^* + D_0S^* + \sqrt{\frac{1}{5}}\left(2|P_0|^2 - |P_-|^2 - |P_+|^2 + |F_-|^2 + |F_+|^2\right) + \sqrt{\frac{18}{35}}\left(P_-F_-^* + F_-P_-^* + P_+F_+^* + F_+P_+^*\right) + \sqrt{\frac{27}{35}}\left(P_0F_0^* + F_0P_0^*\right) + \sqrt{\frac{5}{49}}\left(|D_-|^2 + |D_+|^2\right) + \sqrt{\frac{20}{49}}|D_0|^2 + \sqrt{\frac{16}{45}}|F_0|^2$$

$$\langle Y_{21}\rangle = \frac{1}{2}\left(SD_+^* + D_+S^* - SD_-^* - D_-S^*\right) + \sqrt{\frac{3}{20}}\left(P_0P_+^* + P_+P_0^* - P_-P_0^* - P_0P_-^*\right) + \sqrt{\frac{9}{140}}\left(P_-F_0^* + F_0P_-^* - P_+F_0^* - F_0P_+^*\right) + \sqrt{\frac{6}{35}}\left(P_0F_+^* + F_+P_0^* - P_0F_-^* - F_-P_0^*\right) + \sqrt{\frac{5}{196}}\left(D_0D_+^* + D_+D_0^* - D_0D_-^* - D_-D_0^*\right) + \sqrt{\frac{1}{90}}\left(F_0F_+^* + F_+F_0^* - F_0F_-^* - F_-F_0^*\right)$$





Two Kaon production and the $f_0(980)$

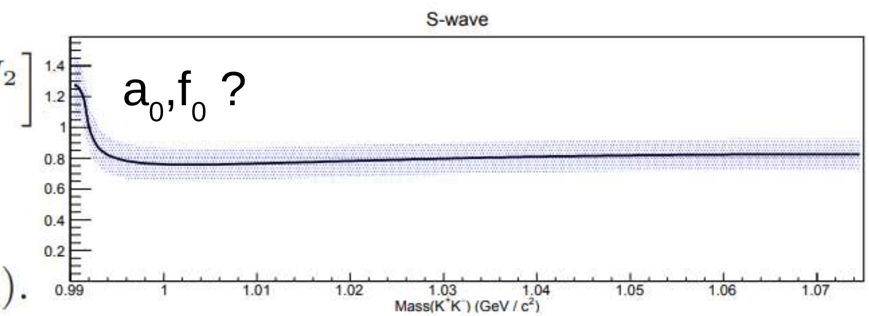


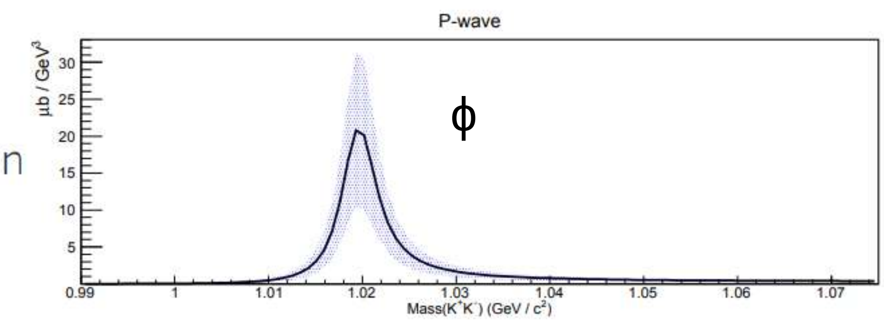
Extract moments

Fit for PWAs

$$\frac{\langle Y_{LM}\rangle}{\Phi} = \sum_{L_1,M_1,L_2,M_2;\{\lambda\}} c_{L_1,M_1,L_2,M_2;LM}\left[f^{L_1M_1*}_{\{\lambda\}} f^{L_2M_2}_{\{\lambda\}}\right]$$

$$f_{\{\lambda\}}(s,t,M_{K+K-},\Omega) = \sum_{LM} f^{LM}_{\{\lambda\}}(s,t,M_{K+K-})Y_{LM}(\Omega).$$





Photoproduction of K^+K^- meson pairs on the proton

S. Lombardo *et al.* (The CLAS Collaboration)

Phys. Rev. D **98**, 052009 – Published 27 September 2018

clas

CLAS g12 : Dalitz Plot Analysis for Light Mesons

example: $\eta \rightarrow \pi^+\pi^-\pi^0$

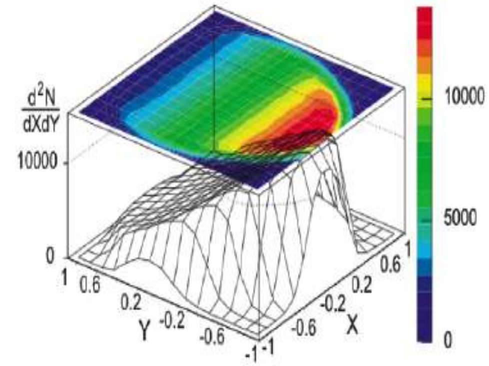
decay width gives access to quark mass ratio;
study via BR or Dalitz plot analysis

parametrization of decay width:

Dimensionless Dalitz Plot Variables:

$$X = \sqrt{3}\frac{T_{\pi^+} - T_{\pi^-}}{T_{\pi^+} + T_{\pi^-} + T_{\pi^0}}$$

$$Y = 3\frac{T_{\pi^0}}{T_{\pi^+} + T_{\pi^-} + T_{\pi^0}} - 1$$



(a) KLOE coll., *JHEP*, 05, (2008)

$$\frac{d^2\Gamma}{dXdY} \propto (1 + aY + bY^2 + cX + dX^2 + eXY + fY^3 + gX^2Y + ...)$$

	Parameter:	$-$ a	b	d	f
Exp.	KLOE (08)[(a)]	$1.090(5)(^{+8}_{-19})$	0.124(6)(10)	$0.057(6)(^{+7}_{-16})$	0.14(1)(2)
	WASA[(d)]	1.144(18)	0.219(19)(47)	0.086(18)(15)	0.115(37)
	KLOE (16)[(f)]	1.104(3)(2)	$0.142(3)(^{5}_{-4})$	$0.073(3)(^{+4}_{-3})$	$0.154(6)(^{+4}_{-5})$
Theor.	ChPT (NNLO)[(b)]	1.271(75)	0.394(102)	0.055(57)	0.025(160)
	NREFT[(c)]	1.213(14)	0.308(23)	0.050(3)	0.083(19)
	PWA[(e)]	1.116(32)	0.188(12)	0.063(4)	0.091(3)
	PWA[(g)]	1.077(29)	0.170(8)	0.060(2)	0.091(3)

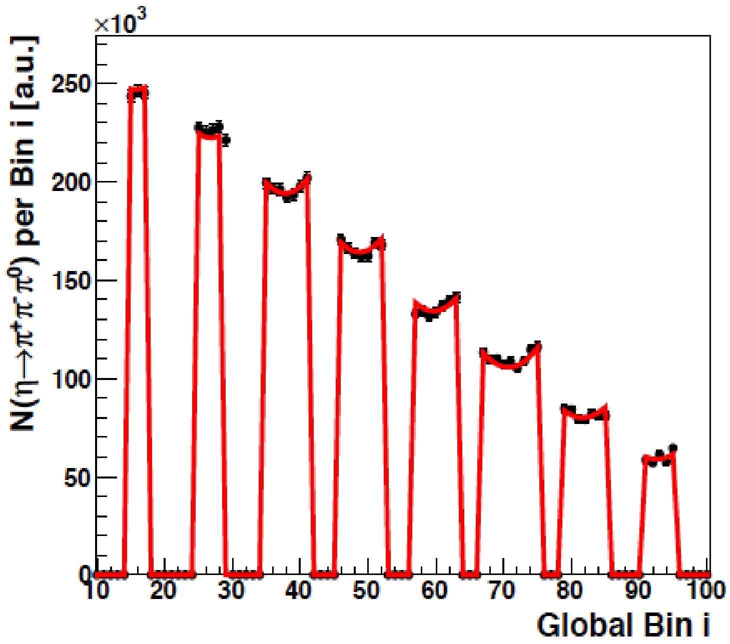
(a) KLOE coll., *JHEP*, 05, (2008)
(b) J. Bijnens and K. Ghorbani., *JHEP*, 11, (2007)
(c) S- P. Schneider et al., *JHEP*, 028, (2011)
(d) WASA-at-COSY coll., *Phys. Rev.*, C90(045207), 2014
(e) Peng Guo et al., *Phys. Rev.*, D92(05016), (2015)
(f) KLOE coll., *JHEP*, 019, (2016)
(g) Peng Guo et al., arXiv: 1608.01447v3, (2017)

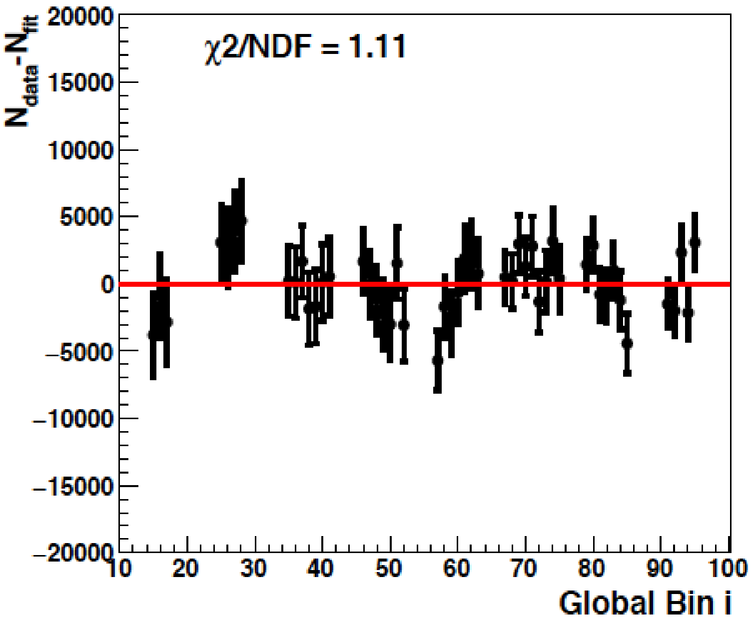
c ≠ 0 and e ≠ 0:
i) imply C-violation
ii) cause asymmetries within the Dalitz Plot

WASA-at-COSY: Q = 21.4 ± 1.1(e)
KLOE: Q = 21.7 ± 1.1(g)

Dalitz Plot Analysis for $\eta \rightarrow \pi^+\pi^-\pi^0$ with the CLAS G12 data set

CLAS g12 : Preliminary Analysis of $\eta \rightarrow \pi^+\pi^-\pi^0$





Parameter	-a	b	c	d	f
KLOE(08)	$1.090(5)(^{+8}_{-19})$	0.124(6)(10)	0.0	$0.057(6)(^{+7}_{-16})$	0.14(1)(2)
WASA	1.144(18)	0.219(19)(47)	0.0	0.086(18)(15)	0.115(37)
KLOE(16)	1.104(5)(2)	$0.142(3)(^{+5}_{-4})$	0.0	$0.073(3)(^{+4}_{-3})$	$0.154(6)(^{+4}_{-5})$
G12	1.102(20)(13)	0.127(18)(5)	0.011(7)(7)	0.106(19)(5)	0.248(45)(10)

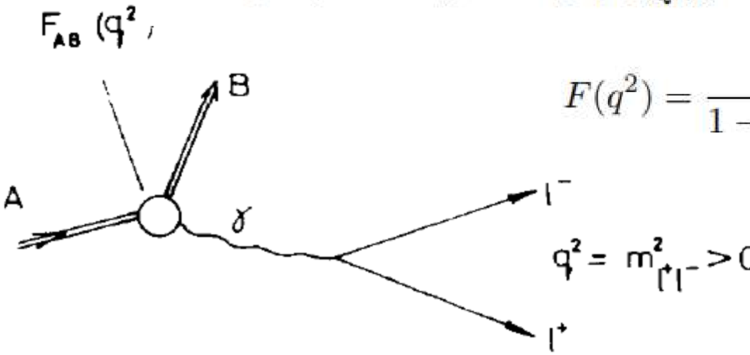
- Parameter e is 0
- Dalitz Plot Asymmetry $A = \frac{N^+ - N^-}{N^+ + N^-} = (0.9 \pm 2.9) \cdot 10^{-3}$
- Systematic uncertainties determined via random walk analysis

Reactions of Hadrons with Virtual Photons

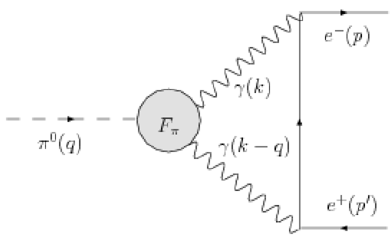
$$\frac{d\Gamma(A \to B + l^+ l^-)}{dq^2 \Gamma(A \to B\gamma)} = \left[\frac{d\Gamma}{dq^2}\right]_{\rm QED} \cdot \left|F(q^2)\right|^2$$

$$F(q^2) = \frac{1}{1 - q^2/\Lambda^2}$$

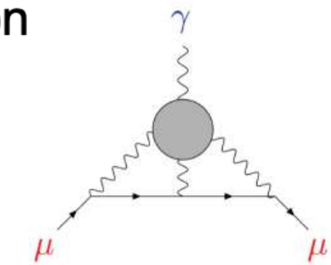
- **intrinsic structure of hadrons**
  - transition form factors
  - validity of vector meson dominance

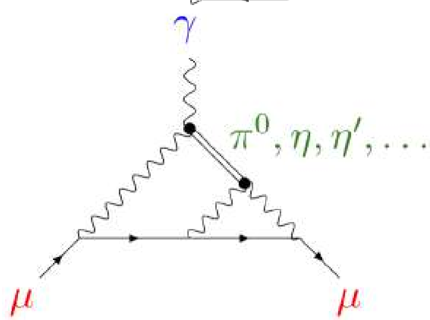


- **background for physics beyond the standard model**
  - rare decays
    - eg $\pi \to ee$
  - g-2 anomalous magnetic moment of the muon
    - light-by-light scattering

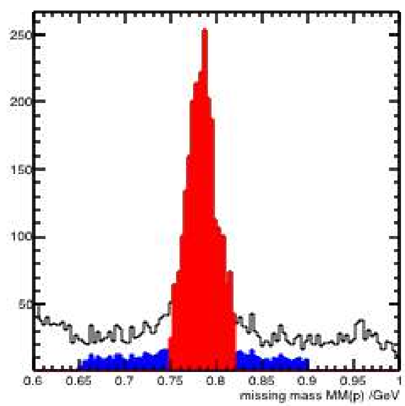


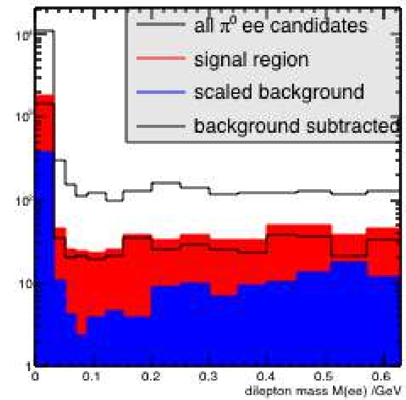
g-2 measurements: Fermilab and J-PARC

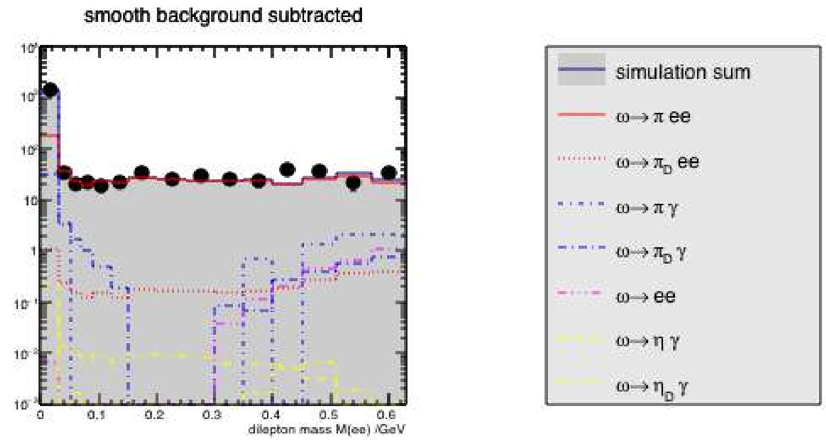




CLAS g12 : Preliminary ω-π^0 transition form factor

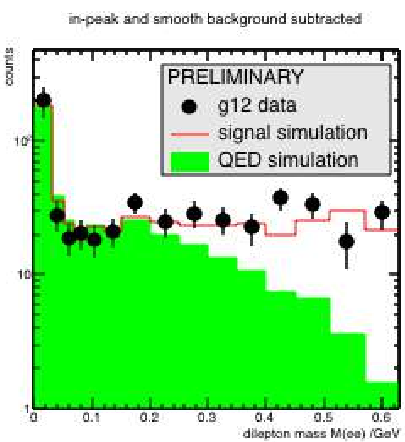


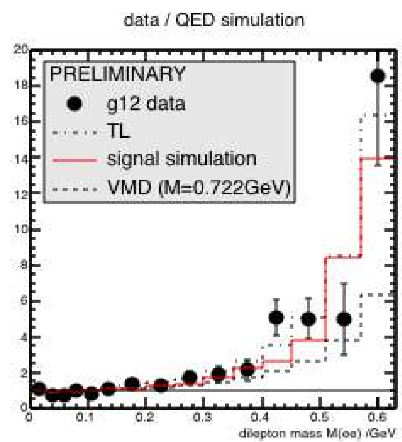




simulations for in-peak background reveal:

- **external conversion** at small masses
- **combinatorics** at large masses
- influence of rho/omega dilepton decay





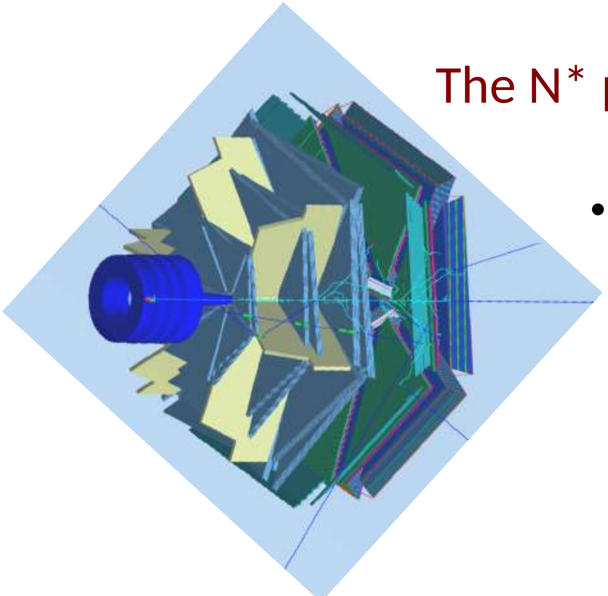
preliminary analysis: consistent with A2 result (and 'extended' VMD)?

C. Terschlüsen and S. Leupold, Phys. Lett. B 691, 191 (2010) VMD+contact term

CLAS12 will extend to η‘ transistion form factors

N* Spectroscopy with CLAS12
Hybrid Baryons

CLAS12 N* program – Meson Electroproduction



The N* program is one of the key physics foundations of Hall B

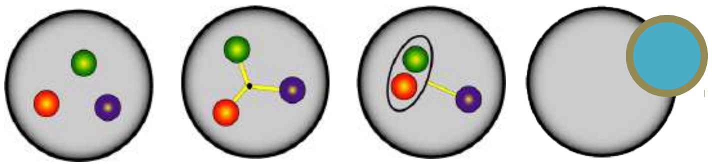
- CLAS12 was designed to measure cross sections and spin observables over a broad kinematic range for exclusive reaction channels:

  πN, ωN, ϕN, ηN, $\eta' N$, $\pi\pi N$, KY, K*Y, KY*

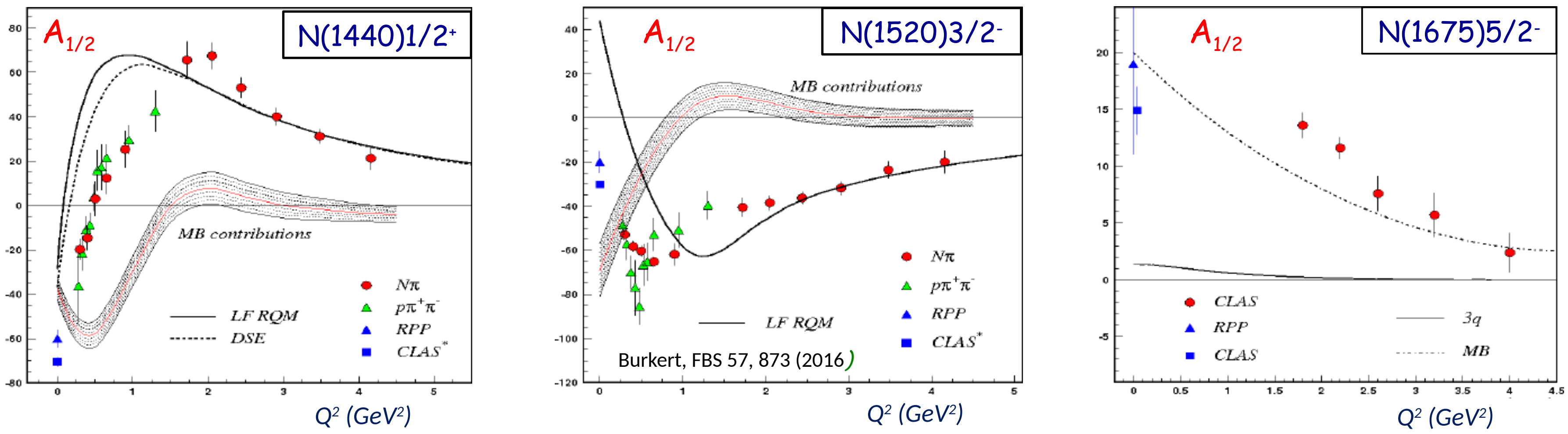
  - N* parameters do not depend on how they decay
  - Different final states have different hadronic decay parameters and different backgrounds
  - Agreement offers model-independent support for findings

- The program goal is to probe the *spectrum* of N* states and their *structure*
  - Probe the underlying degrees of freedom of the nucleon through studies of the Q^2 evolution of the production amplitudes

N* degrees of freedom??



CLAS N* - Structure Studies



- Electrocouplings reveal different interplay between quark core and meson cloud
  - *Important to study different N* states vs. distance scale*
- Good agreement of the extracted N* electrocouplings from Nπ and Nππ
  - *Compelling evidence for the reliability of the results*
  - *Channels have very different mechanisms for the non-resonant background*

Precision studies of N* structure are a key part of the CLAS12 experimental program

Hybrid Baryons : Baryons with gluonic degrees of freedom

Hybrid hadrons with dominant gluonic contributions are predicted to exist by QCD.

Experimentally:

- **Hybrid mesons** |qqg> states may have exotic quantum numbers J^{PC} not available to pure |qq> states → 0^{--}, 1^{-+}, 1^{--}, ...GlueX, MesonEx, COMPASS, PANDA ....

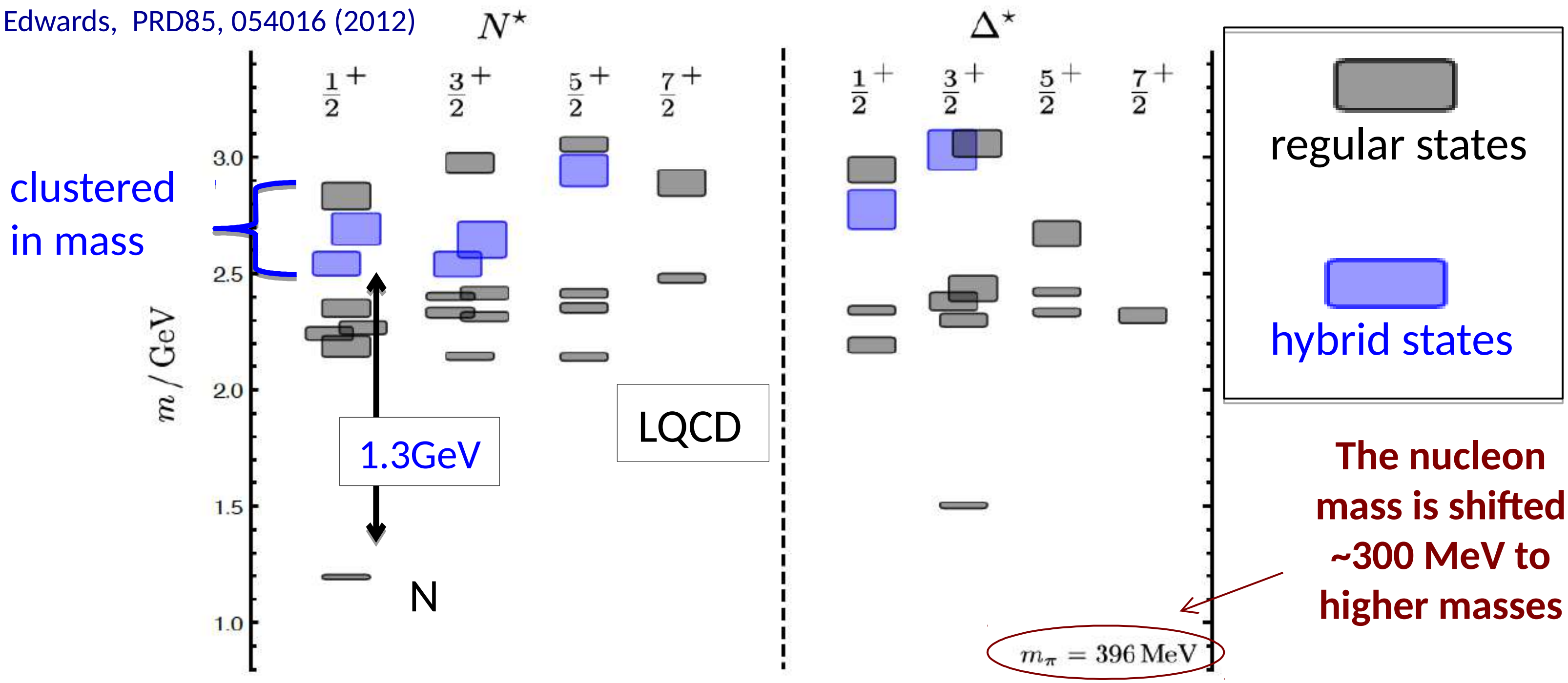
- **Hybrid baryons** |qqqg> have the same quantum numbers J^{P} as |qqq> → electroproduction with CLAS12 (Hall B).

Theoretical predictions:

- ◇ MIT bag model - T. Barnes and F. Close, Phys. Lett. 123B, 89 (1983).
- ◇ QCD Sum Rule - L. Kisslinger and Z. Li, Phys. Rev. D 51, R5986 (1995).
- ◇ Flux Tube model - S. Capstick and P. R. Page, Phys. Rev. C 66, 065204 (2002).
- ◇ LQCD - J.J. Dudek and R.G. Edwards, PRD85, 054016 (2012).

Hybrid Baryons in LQCD

J.J. Dudek and R.G. Edwards, PRD85, 054016 (2012)

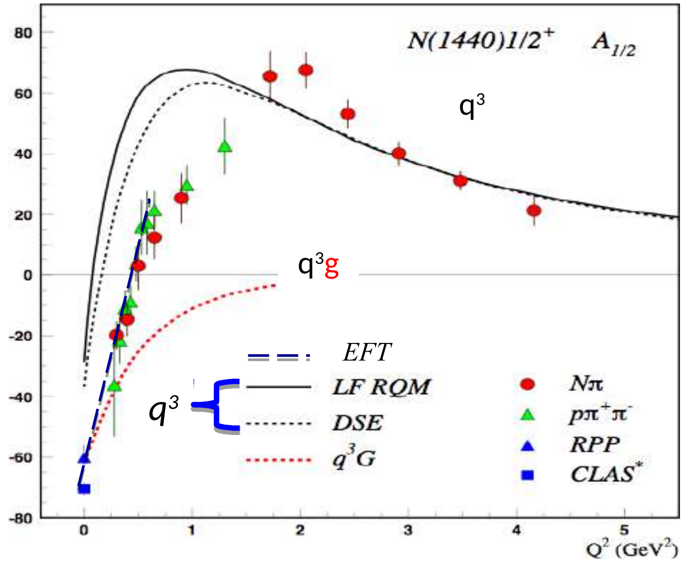


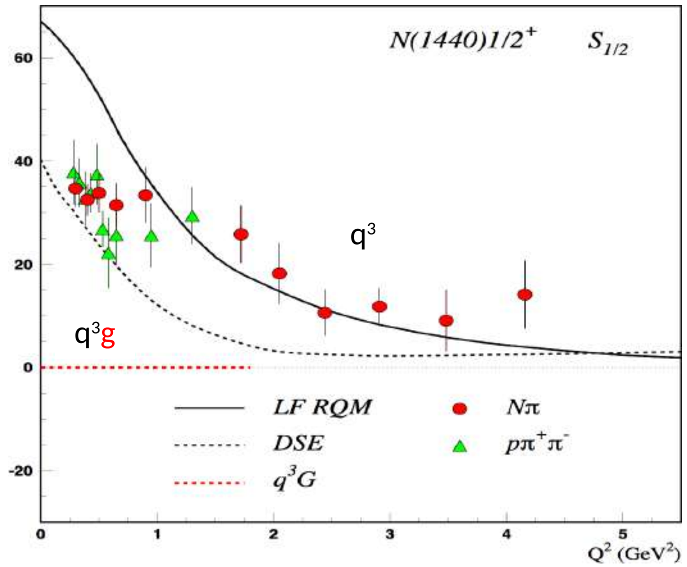
Hybrid states have same J^P values as qqq baryons. How to identify them?

- Overpopulation of N $1/2^+$ and N $3/2^+$ states compared to QM projections.
- **$A_{1/2}$ ($A_{3/2}$) and $S_{1/2}$ show different Q^2 evolution. Can we do it?**

Separating q^3g from q^3 States?

Precise CLAS results on electrocouplings clarified nature of the Roper





- $A_{1/2}$ and $S_{1/2}$ amplitudes at high Q^2 >2 GeV^2 indicate 1st radial q^3 excitation
- Significant meson-baryon coupling at small Q^2

For hybrid "Roper", $A_{1/2}(Q^2)$ drops off faster with Q^2 and $S_{1/2}(Q^2)$ ~ 0.

Hybrid Baryon Signatures

Based on available knowledge, the ***signatures*** for hybrid baryons consist of:

- **Extra resonances** with $J^p=1/2^+$ and $J^p=3/2^+$, with masses > 1.8 GeV and decays into $N\pi\pi$ or KY final states.
- A **drop** of the transverse helicity amplitudes $A_{1/2}(Q^2)$ and $A_{3/2}(Q^2)$ faster than for ordinary three quark states, because of extra glue-component in valence structure.
- A **suppressed** longitudinal amplitude $S_{1/2}(Q^2)$ in comparison with transverse electro-excitation amplitude ($J^P=1/2^+$).

Focusing on:

$$e\,p \longrightarrow e\,p\,\pi^+\pi^-$$

$$e\,p \longrightarrow e\,K^+\Lambda,\ e\,K^+\Sigma^0$$

The study will include other single meson channels.

Map out large range of W (up to 4 GeV) and Q^2

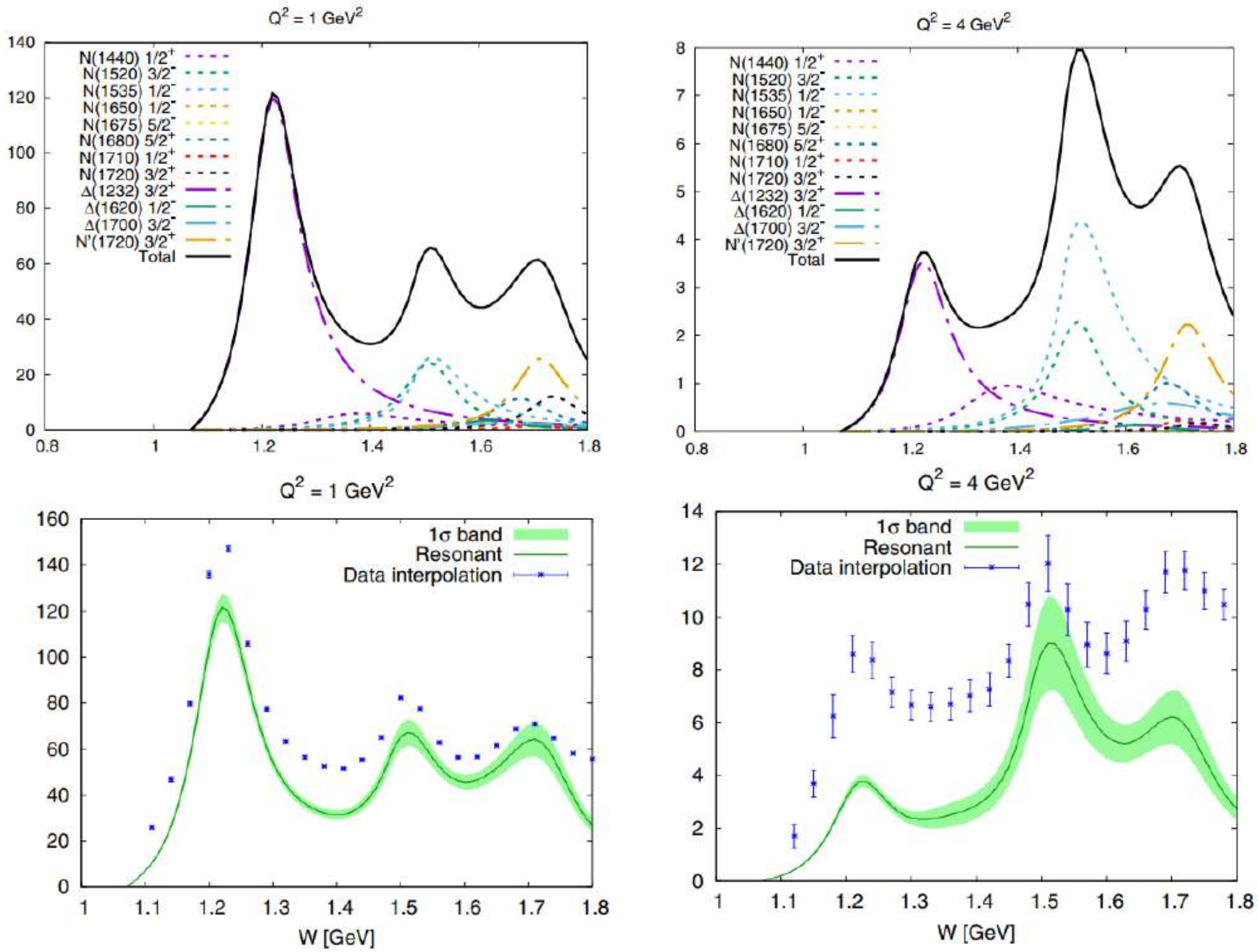
Dedicated beam times with E_e = 6.6, 8.8 GeV

Low Q2 quasi-real photoproduction with Forward Tagger

N* Contributions to electron scattering with CLAS12

Nucleon resonance contributions to unpolarized inclusive electron scattering

A. N. Hiller Blin, V. Mokeev, M. Albaladejo, C. Fernández-Ramírez, V. Mathieu, A. Pilloni, A. Szczepaniak, V. D. Burkert, V. V. Chesnokov, A. A. Golubenko, and M. Vanderhaeghen
Phys. Rev. C **100**, 035201 – Published 3 September 2019



Start from CLAS electrocouplings

Contributions of N* to inclusive e- scattering

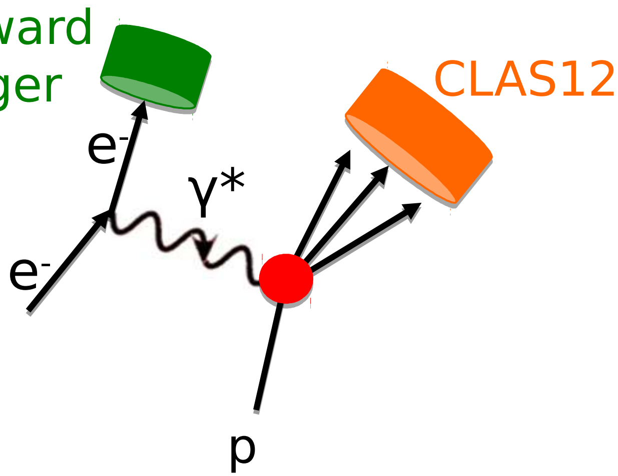
Different behaviours as function of Q^2 in the resonance regions

Sensitive to structure and nature of N*s

Blue = projected CLAS12 data

Meson Spectroscopy with CLAS12
MesonEx

Quasi-real photoproduction with CLAS12

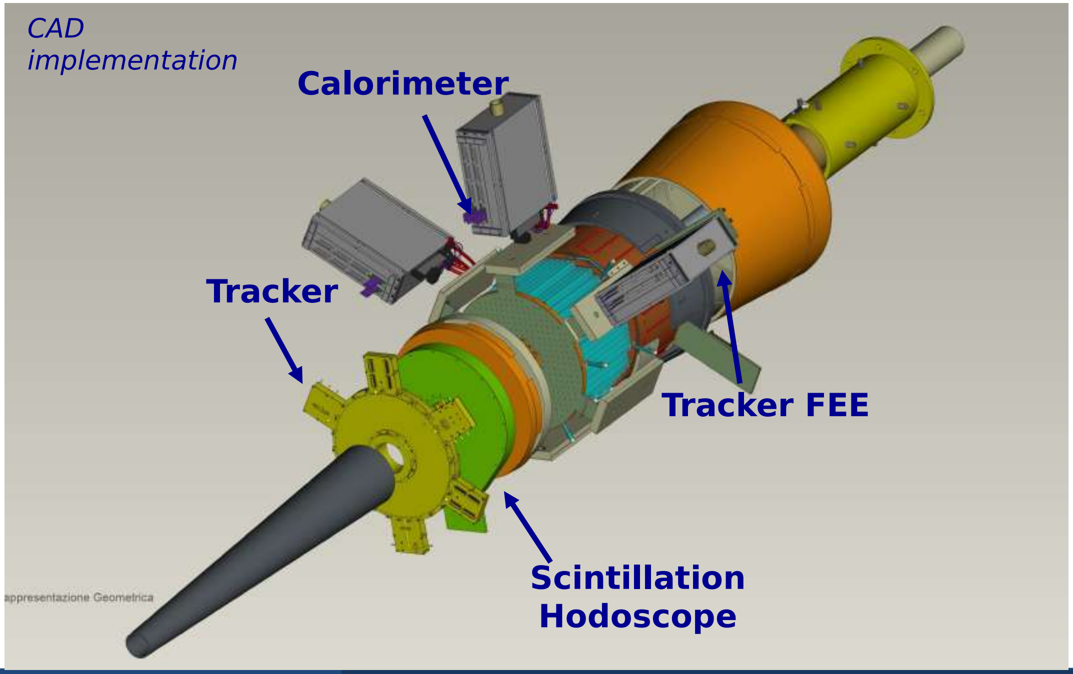


Trigger → FT e- + 2 charged CLAS12

Forward Tagger	
E’	0.5-4.5 GeV
ν	6-10 GeV
θ	2.5-4.5 deg
Q^2	0.007 – 0.3 GeV^2
W	3.6-4.5 GeV
Photon Flux	5 x 10^7 γ/s @ $L_e=10^{35}$

Quasi-real photoproduction:

- Detection of multiparticle final state from meson decay in the large acceptance spectrometer CLAS
- Detection of the scattered electron for the tagging of the quasi-real photon in the CLAS12 FT
- High-intensity and high-polarization tagged “photon” beam; degree of polarization determined event-by-event from the electron kinematics

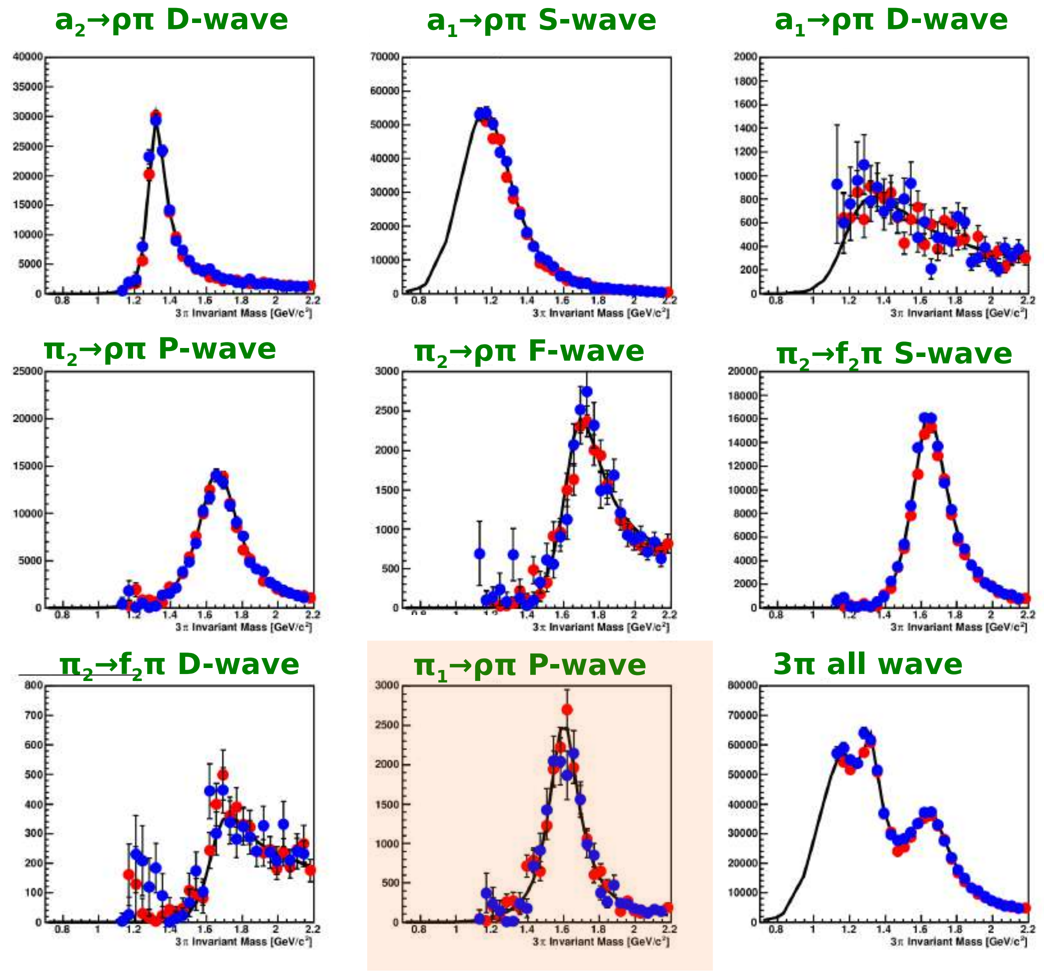


MesonEx program

Meson spectroscopy in the light-quark sector:

- Detailed mapping of the meson spectrum up to masses of 2.5 GeV
- Search for rare or poorly known states (strangeness-rich, scalars, …)
- Search states with unconventional quark-gluon configurations

Benchmark 3π Simulations



Note poor acceptance below 1.2GeV (half field)

MesonEx : Polarised Two meson production

arXiv.org > hep-ph > arXiv:1906.04841

Search...

Help | Advanc

High Energy Physics - Phenomenology

Moments of angular distribution and beam asymmetries in $\eta\pi^0$ photoproduction at GlueX

V. Mathieu, M. Albaladejo, C. Fernández-Ramírez, A. W. Jackura, M. Mikhasenko, A. Pilloni, A. P. Szczepaniak (JPAC collaboration)

(Submitted on 11 Jun 2019)

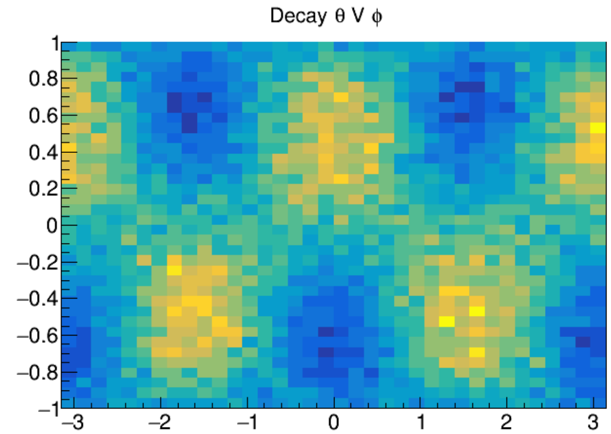
Intensity based on Real Photon Density matrix

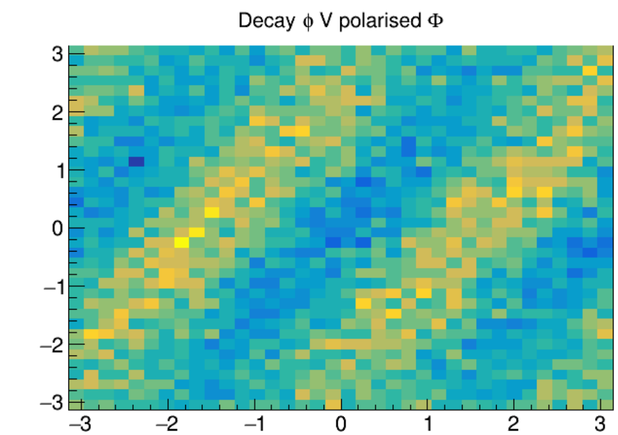
$$I(\Omega,\Phi)=I^0(\Omega)-P_\gamma I^1(\Omega)\cos(2\Phi)-P_\gamma I^2(\Omega)\sin(2\Phi)$$

$$I^0(\Omega)=\sum_L\sum_{M=0}^{M\le L}\sqrt{\left(\frac{2L+1}{4\pi}\right)}(2-\delta_{M,0})H^0(L,M)\Re\left[Y_L^M(\Omega)\right]$$

$$I^1(\Omega)=-\sum_L\sum_{M=0}^{M\le L}\sqrt{\left(\frac{2L+1}{4\pi}\right)}(2-\delta_{M,0})H^1(L,M)\Re\left[Y_L^M(\Omega)\right]$$

$$I^2(\Omega)=2\sum_L\sum_{M=0}^{M\le L}\sqrt{\left(\frac{2L+1}{4\pi}\right)}\Im\left[H^2(L,M)\right]\Im\left[Y_L^M(\Omega)\right]$$





Optimised Moments fitter ready for data!

Do we need anything different for quasi real ?
i.e. intensity with virtual photon density matrix
Should also have good data for high Q^2 2π

*Watch out for √(2L+1) factors !

MesonEx : Helicity Polarised Two Meson Production

$$I(\Omega,\Phi) = I^0(\Omega) + \boldsymbol{I}(\Omega)\cdot\boldsymbol{P}_\gamma(\Phi),$$

$$I^{0,1}(\Omega) = \pm\sum_{L,M\geqslant 0}\left(\frac{2L+1}{4\pi}\right)\tau(M)H^{0,1}(LM)d^L_{M0}(\theta)\cos M\phi,$$

$$I^{2,3}(\Omega) = \sum_{L,M>0}\left(\frac{2L+1}{4\pi}\right)\tau(M)\,\mathrm{Im}\,H^{2,3}(LM)d^L_{M0}(\theta)\sin M\phi,$$

Measure I^is via moments of spherical harmonics

We can also measure I^3
Is it useful?

$$U_k^{(\epsilon)}(\Omega) = \sum_{\ell,m}[\ell]^{(\epsilon)}_{m;k}Y_\ell^m(\Omega)\ ,$$

$$\widetilde{U}_k^{(\epsilon)}(\Omega) = \sum_{\ell,m}[\ell]^{(\epsilon)}_{m;k}\left[Y_\ell^m(\Omega)\right]^*$$

$$I^0(\Omega) = \kappa\sum_{\epsilon,k}|U_k^{(\epsilon)}(\Omega)|^2 + |\widetilde{U}_k^{(\epsilon)}(\Omega)|^2\ ,$$

$$I^1(\Omega) = -\kappa\sum_{\epsilon,k}2\epsilon\,\mathrm{Re}\left(U_k^{(\epsilon)}(\Omega)\left[\widetilde{U}_k^{(\epsilon)}(\Omega)\right]^*\right)\ ,$$

$$I^2(\Omega) = -\kappa\sum_{\epsilon,k}2\epsilon\,\mathrm{Im}\left(U_k^{(\epsilon)}(\Omega)\left[\widetilde{U}_k^{(\epsilon)}(\Omega)\right]^*\right)\ ,$$

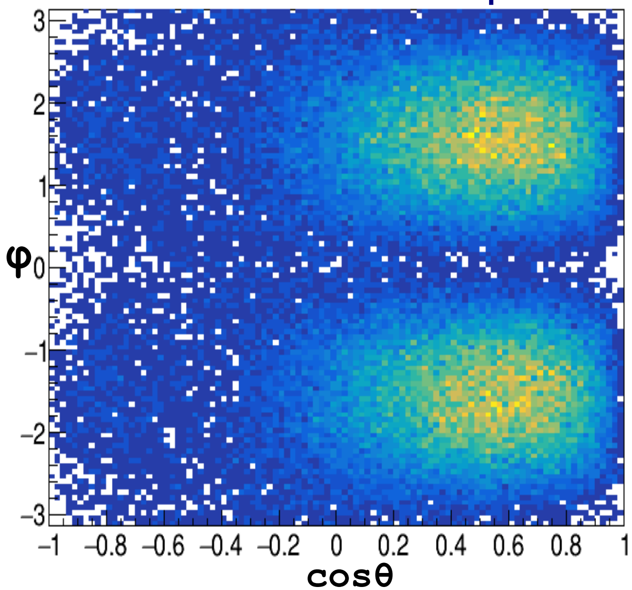
Linear polarisation allows to disentangle reflectivity ε=±1 amplitudes

$$I^3(\Omega) = \kappa\sum_{\epsilon,k}|U_k^{(\epsilon)}(\Omega)|^2 - |\widetilde{U}_k^{(\epsilon)}(\Omega)|^2\ .$$

Additional constraint ?
Can it help with phases , ambiguities?

MesonEx : Fit amplitudes with moments

Pseudo Data from Amplitudes



$$H^0(11) = H^1(11) + 2\sqrt{\frac{2}{5}}\,\mathrm{Re}(P_1^{(+)} D_2^{(+)*}) \ ,$$

$$H^1(11) = \frac{2}{15}\left[3\sqrt{5}\,\mathrm{Re}(P_0^{(+)} D_1^{(+)*}) - \sqrt{15}\,\mathrm{Re}(P_1^{(+)} D_0^{(+)*}) + 5\sqrt{3}\,\mathrm{Re}(S_0^{(+)} P_1^{(+)*})\right] \ ,$$

$$H^0(20) = H^1(20) - \frac{2}{35}\left[7|P_1^{(+)}|^2 - 5|D_1^{(+)}|^2 + 10|D_2^{(+)}|^2\right] \ ,$$

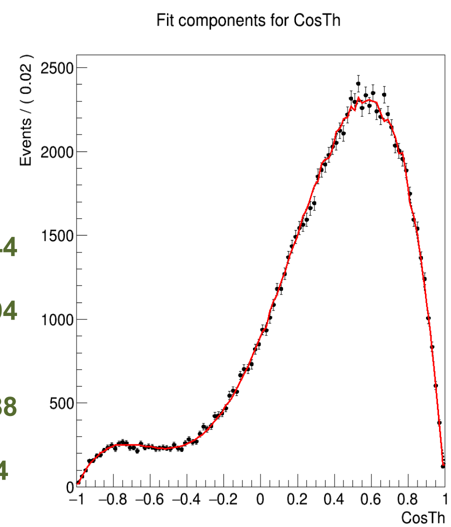
$$H^1(20) = \frac{4}{35}\left[7|P_0^{(+)}|^2 + 5|D_0^{(+)}|^2 + 7\sqrt{5}\,\mathrm{Re}(S_0^{(+)} D_0^{(+)*})\right] \ ,$$

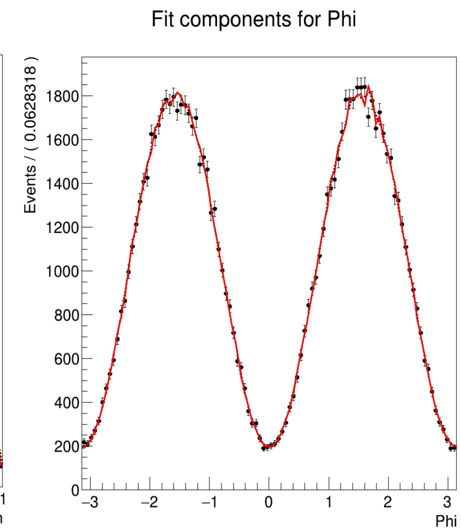
$$H^0(21) = H^1(21) + \frac{2}{7}\sqrt{6}\,\mathrm{Re}(D_1^{(+)} D_2^{(+)*}) \ ,$$

$$H^1(21) = \frac{2}{35}\left[7\sqrt{5}\,\mathrm{Re}(S_0^{(+)} D_1^{(+)*}) + 7\sqrt{3}\,\mathrm{Re}(P_0^{(+)} P_1^{(+)*}) + 5\,\mathrm{Re}(D_0^{(+)} D_1^{(+)*})\right] \ ,$$

Analytical Moments from Amplitudes | Fit Results

Analytical Moments from Amplitudes	Fit Results	
(L,M) = (1,0): H0 = 0.3578 ;	H_0_1_0	= 0.358112 +/- 0.00797507
(L,M) = (1,1): H0 = 0.0000 ;	H_0_1_1	= -0.000740184 +/- 0.000722244
(L,M) = (2,0): H0 = -0.0629 ;	H_0_2_0	= -0.0623866 +/- 0.000474004
(L,M) = (2,1): H0 = 0.0000 ;	H_0_2_1	= -0.000551358 +/- 0.000478794
(L,M) = (2,2): H0 = -0.1680 ;	H_0_2_2	= -0.169541 +/- 0.000885905
(L,M) = (3,0): H0 = -0.1533 ;	H_0_3_0	= -0.153232 +/- 0.00448687
(L,M) = (3,1): H0 = 0.0000	H_0_3_1	= -0.000258408 +/- 0.000334288
(L,M) = (3,2): H0 = -0.1400 ;	H_0_3_2	= -0.140019 +/- 0.00137683
(L,M) = (3,3): H0 = 0.0000 ;	H_0_3_3	= 0.000338522 +/- 0.000556094
(L,M) = (4,0): H0 = -0.0762 ;	H_0_4_0	= -0.0765479 +/- 0.000712912
(L,M) = (4,1): H0 = 0.0000 ;	H_0_4_1	= 0.00024877 +/- 0.00030687
(L,M) = (4,2): H0 = -0.0602 ;	H_0_4_2	= -0.0605708 +/- 0.000410417
(L,M) = (4,3): H0 = 0.0000 ;	H_0_4_3	= -0.000109336 +/- 0.000434857
(L,M) = (4,4): H0 = 0.0000 ;	H_0_4_4	= 0.000138865 +/- 0.000480976





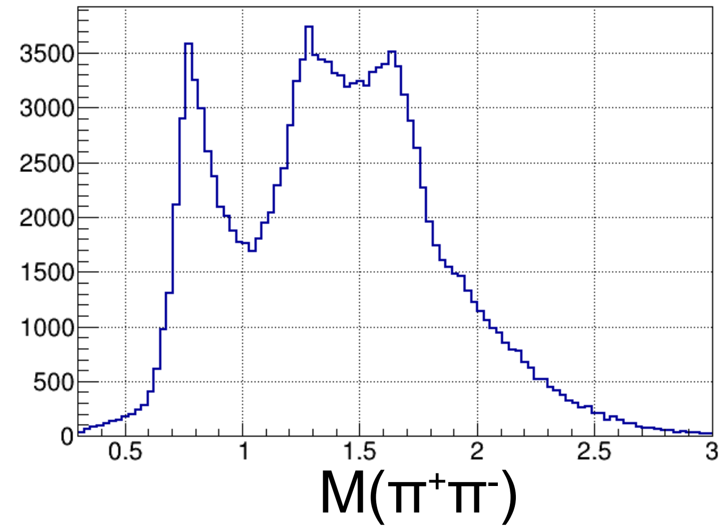
MesonEx : $\pi^+\pi^-$ p Preliminary Data

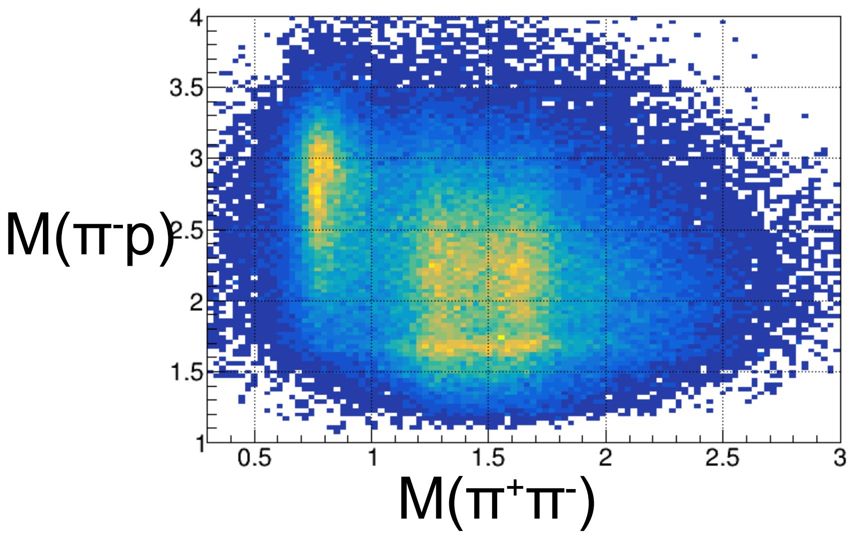
Exclusive final state

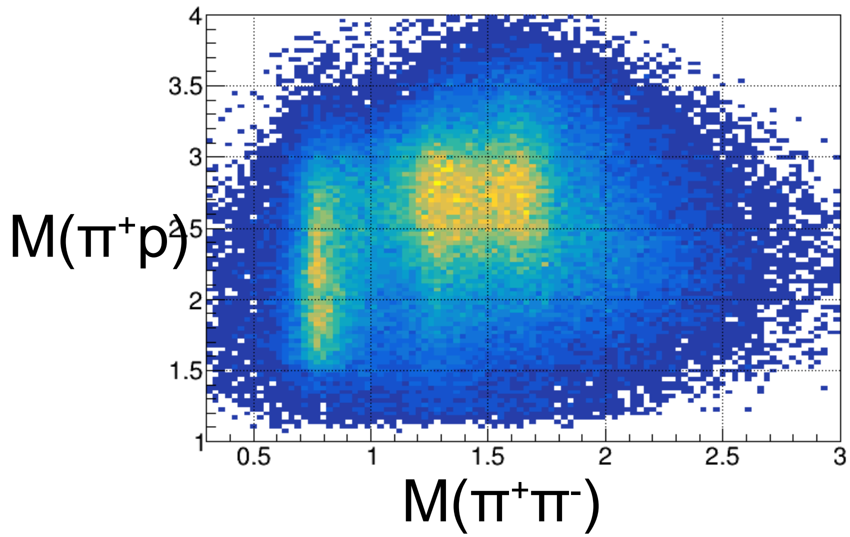
For ~10% (5%) of collected(expected) data

All t and 6<Eg<10 Gev

Trigger/Torus Field /Detector
=> Low acceptance below 1.1 GeV







Need to account for N*/Δ in Moments Fits, but contributions do not look too strong

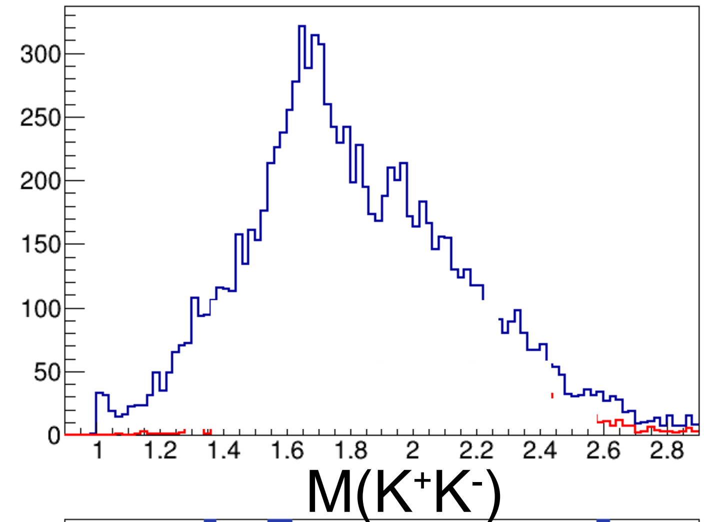
MesonEx : K^+K^- p Preliminary Data

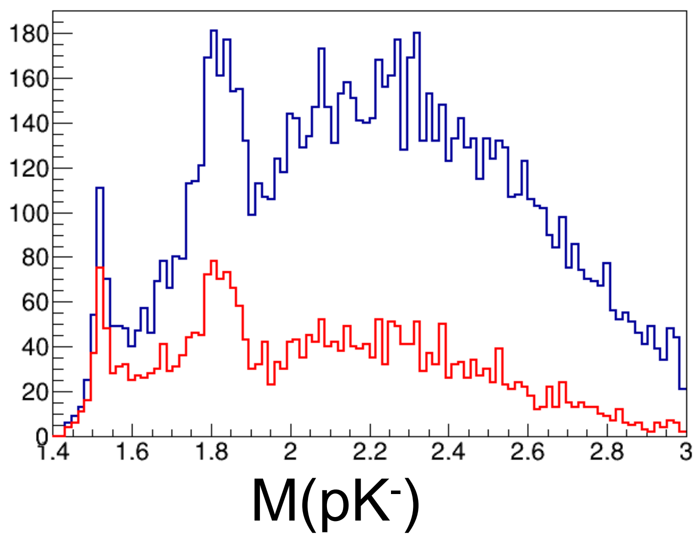
Exclusive final state

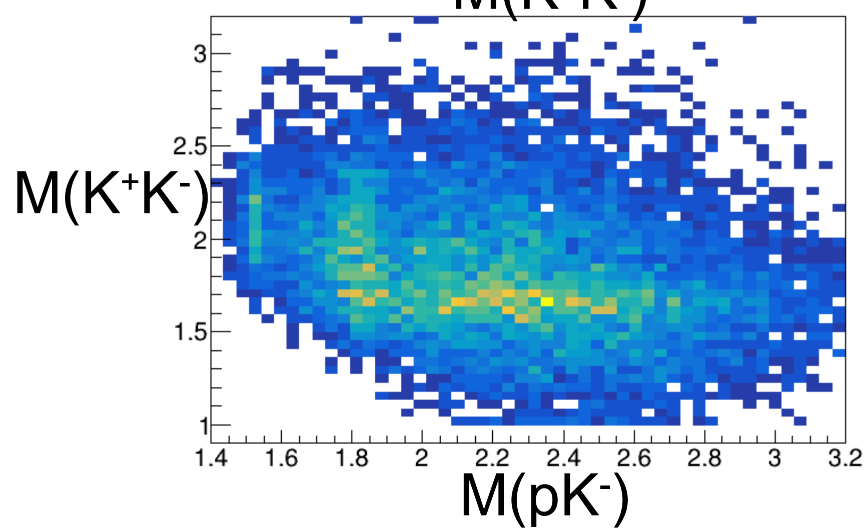
For ~10% (5%) of collected(expected) data

All t and 6<Eg<10 Gev

Trigger/Torus Field /Detector
=> Low acceptance below 1.1 GeV







Need to account for hyperons in Moments Fits

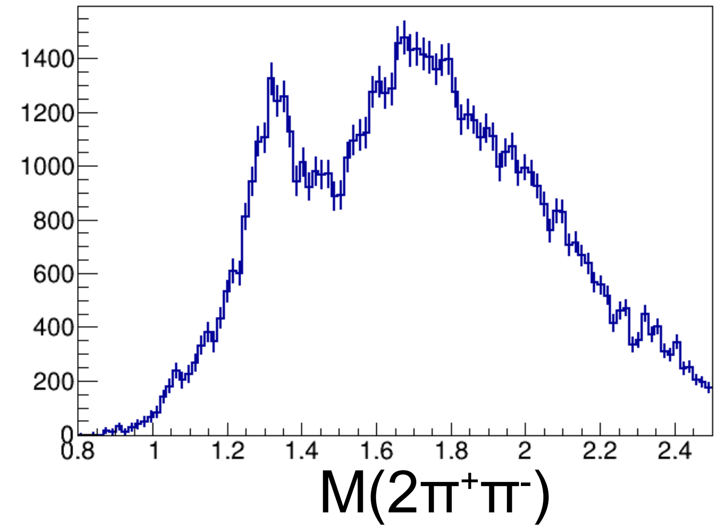
MesonEx : $\pi^+\pi^+\pi^-$ n Preliminary Data

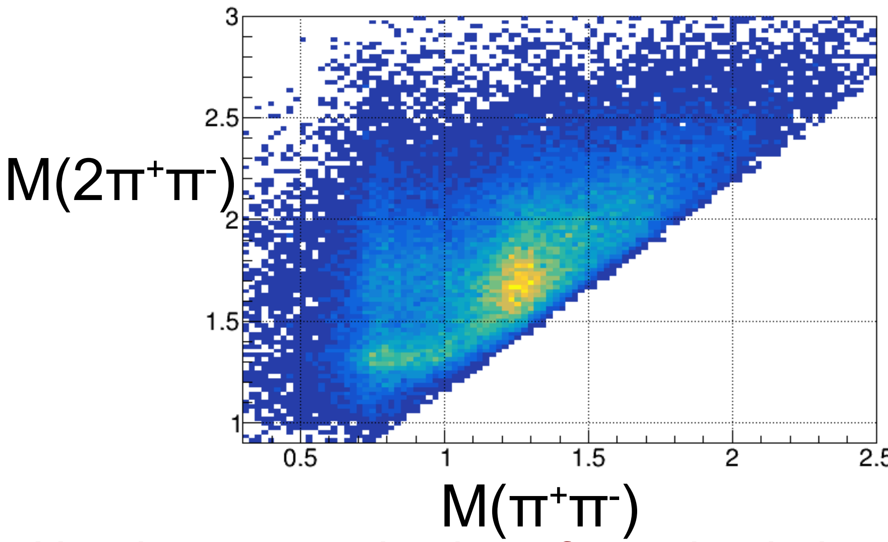
Missing neutron final state

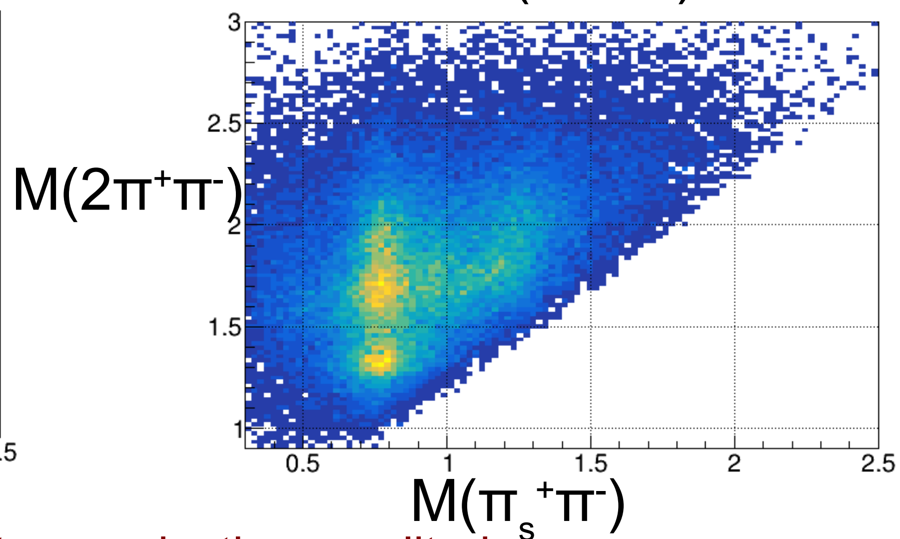
For ~10% (5%) of collected(expected) data

|t|>2 and 6<Eg<10 Gev

Trigger/Torus Field /Detector
=> Low acceptance below 1.3 GeV

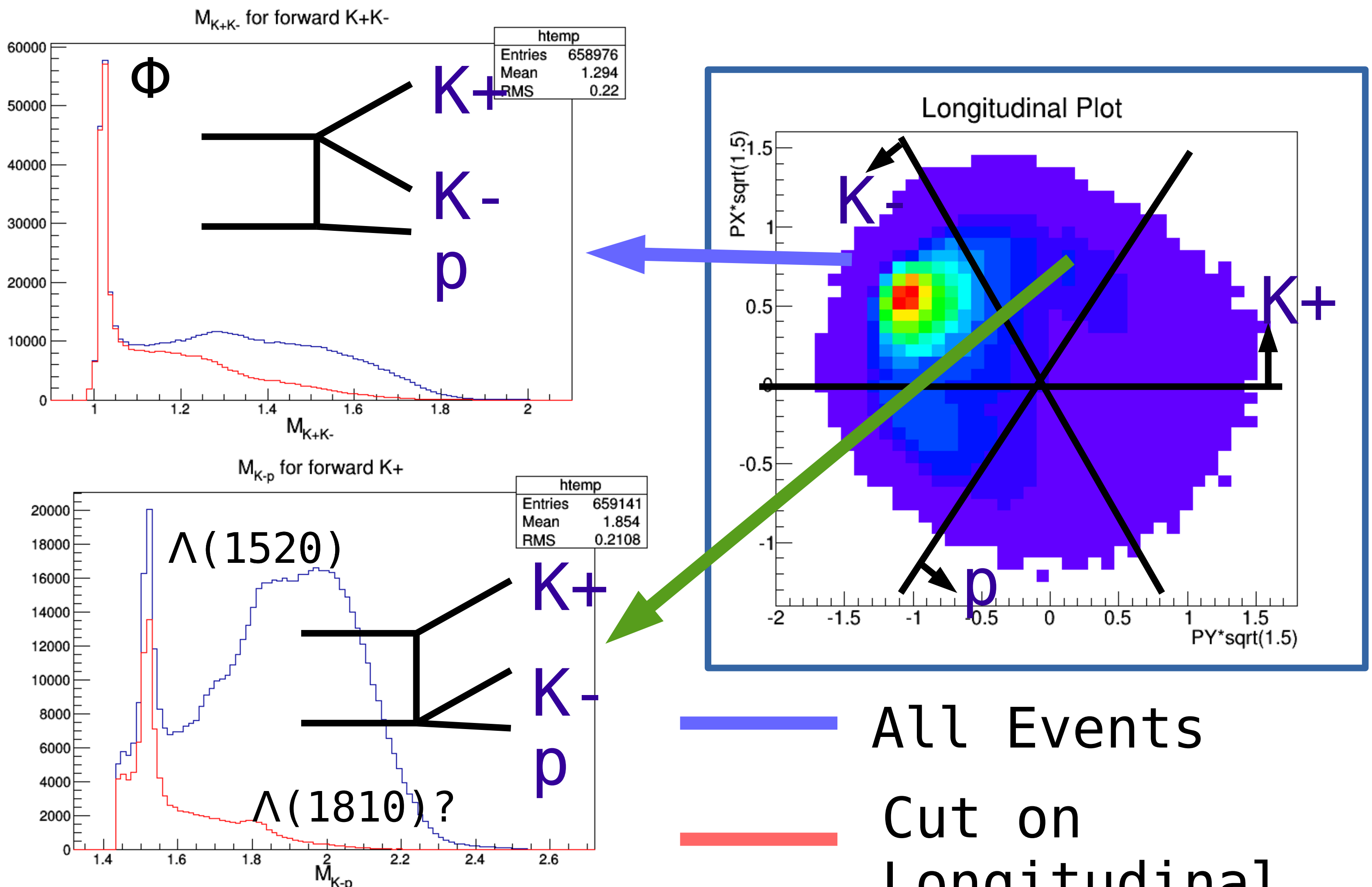






Need parameterisation of polarised photon production amplitudes
Need to include 2π + N* contributions (not shown)

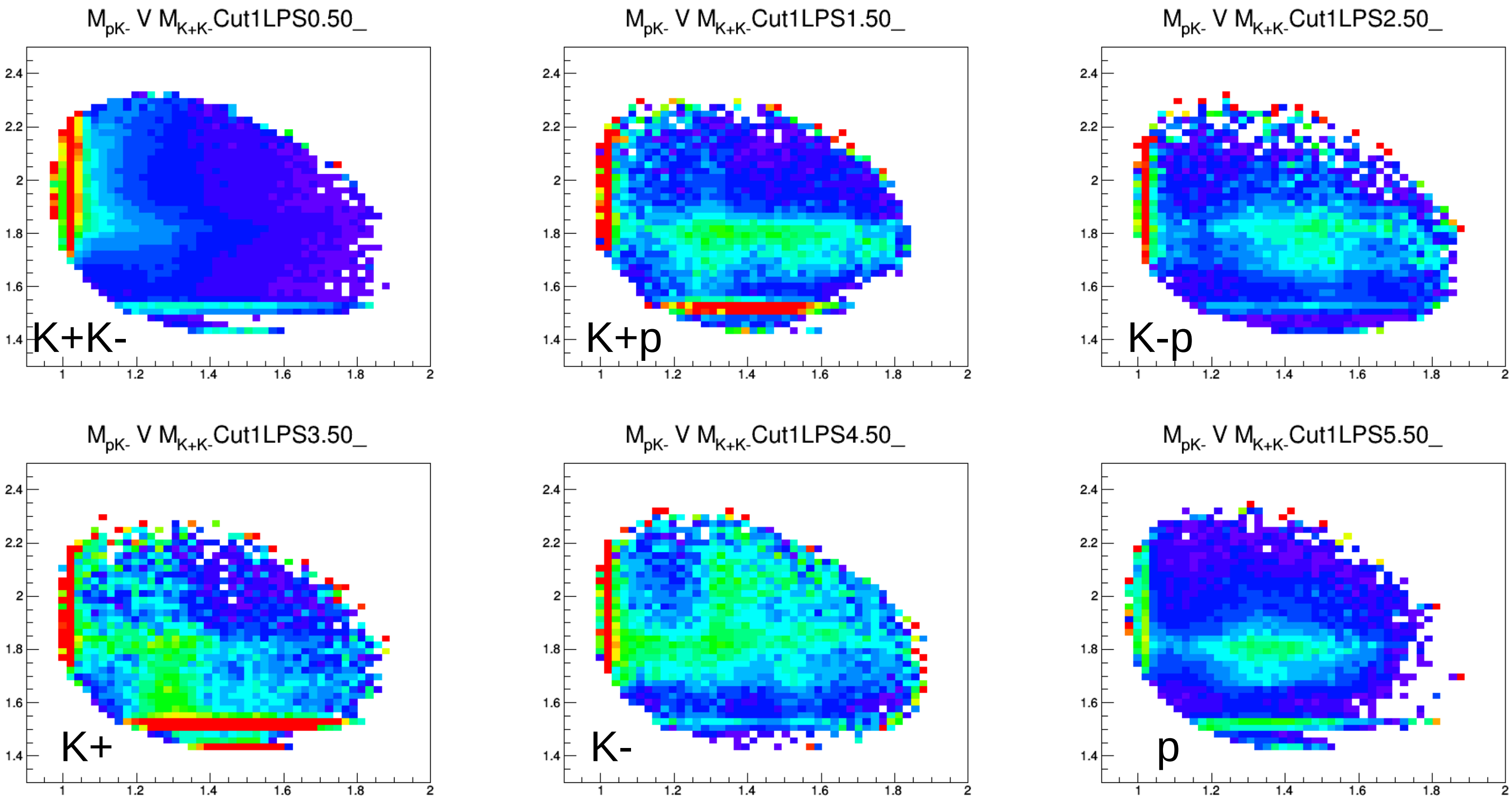
Longitudinal plot from CLAS photoproduction @3.5GeV



All Events

Cut on Longitudinal Plot sector

Longitudinal plot from CLAS photoproduction @3.5GeV



As resonance masses increase they leak into the wrong sector

Define Mass dependent cuts based on Meson or Baryon

Mass-dependent cuts in longitudinal phase space

P. Pauli, D. I. Glazier, M. Battaglieri, A. Celentano, R. De Vita, S. Diehl, A. Filippi, J. T. Londergan, V. Mathieu, and A. P. Szczepaniak
Phys. Rev. C **98**, 065201 – Published 26 December 2018

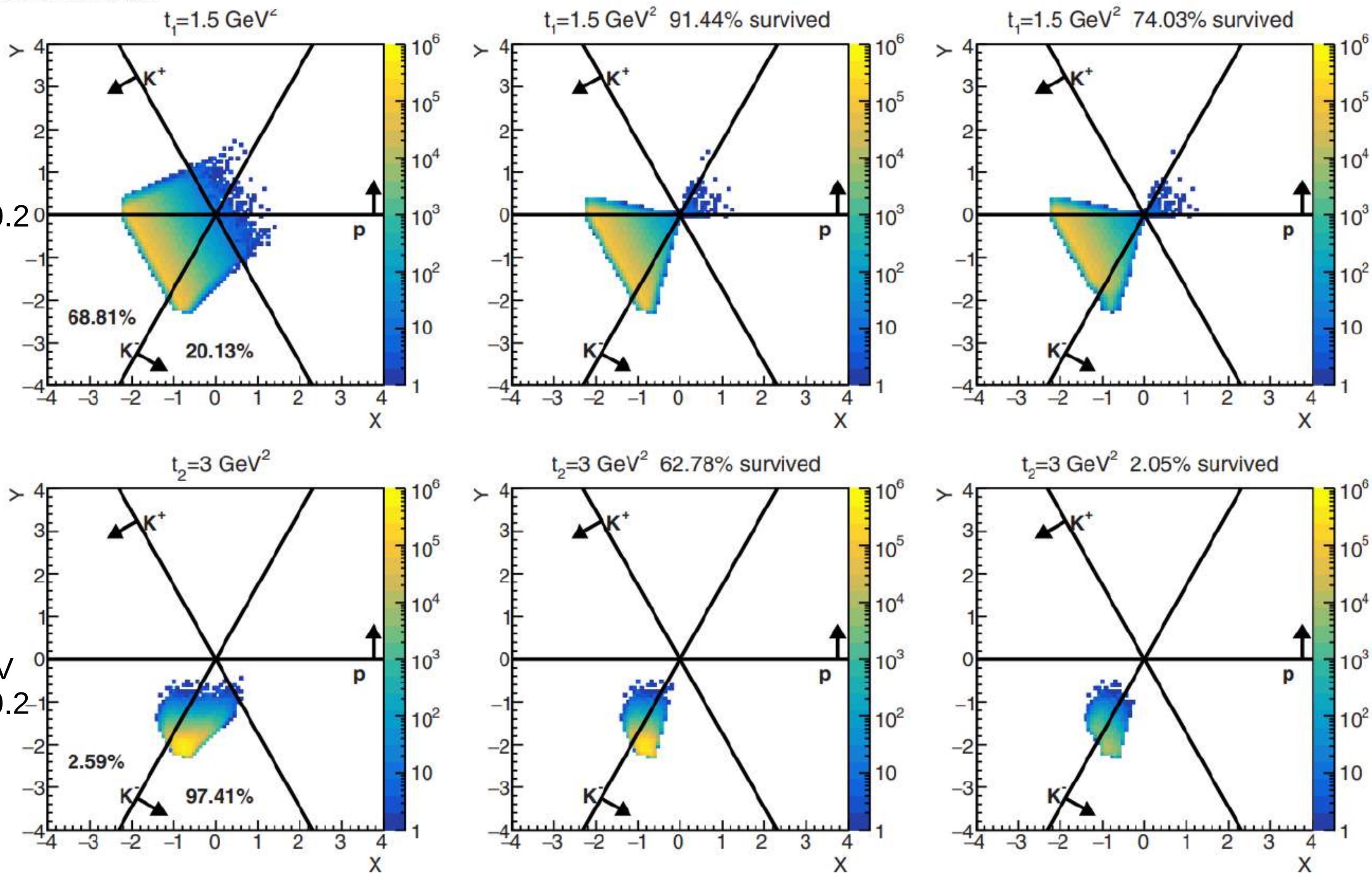
Cut IS BARYON

Cut IS BARYON
NOT MESON

Eγ=9 GeV

Hyperon
M=2.2 GeV
Cut |M(Y)|<0.2

Mesons
M=1-1.8 GeV
Cut |M(Y)|<0.2



Summary

- CLAS provides data on many different channels with both electron and photon beams
- Benefit from greater understanding of electron scattering as a tool for hadron spectroscopy and structure studies
- Seperation of t -channel meson and baryon resonance production
  - Through cuts or through amplitudes
- Can we perform spectroscopy on the baryons?
- General parameterisations of 3-body final states
  - Freed isobars?...

Backups