Photoproduction of $\pi^+\pi^-\pi^0$ using CLAS at Jefferson Laboratory

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Outline

- Introduction and Motivation
- CLAS Detector at Jefferson Laboratory
- CLAS-g12 and CLAS-FROST Experiment
- Data Analysis
- Result and Discussion
- Summary & Outlook

Introduction & Motivation

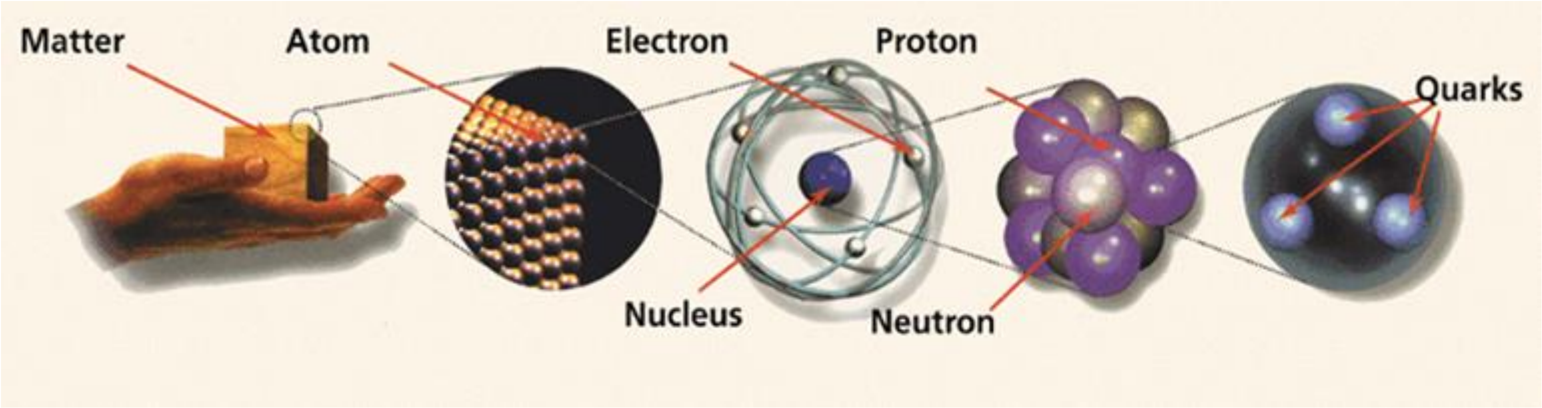
- The Principle Questions
- Nucleon Resonance Spectrum
- Photoproduction of $\pi^+\pi^-\pi^0$

The principle questions

- The families of the fundamental Particles : Quark, Lepton, Gauge Boson.
- QCD governs the **Strong** interaction among quarks.
- Quarks/Antiquarks always form composite object called **Hadrons**.

Principle questions :

- How does the behavior of quarks determine the properties of hadrons?
- How does the quark dynamics give rise to the spectrum of hadrons?
- What are the fundamental degrees of freedom inside hadrons?

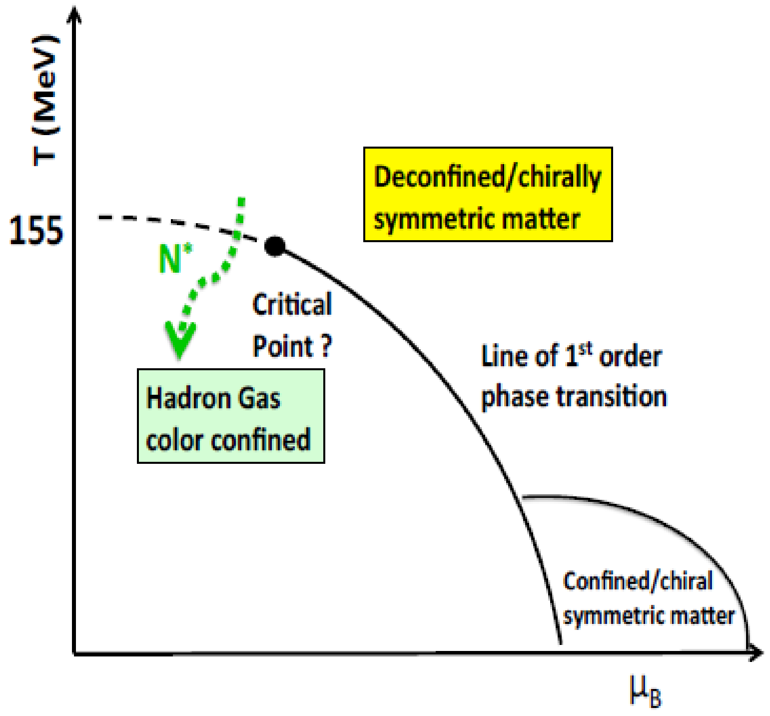


Nucleon Resonances Spectrum

- Missing nucleon resonances

- Mapping out the whole spectrum of resonances is very important to test the models :
  Constituent Quark Model (CQM)
  Lattice QCD
  Quark-Diquark clustering
  Hybrid Baryon
  Baryon-Meson cloud
  CQM + Flux tube

- In particular the N* resonances play significant role on the evolution of the universe



Courtesy of Volker D. Burkert

Status of N* in PDG 2016

Plenty of room to explore

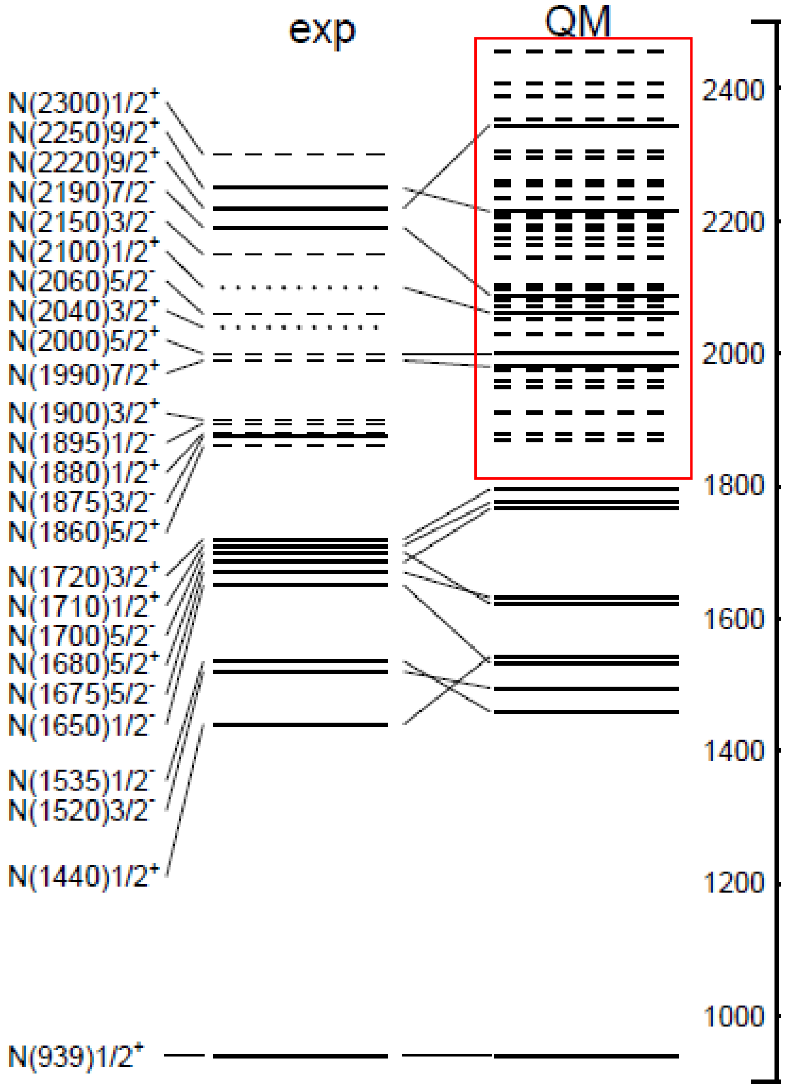
- *N*ω channel is under explored
- *KY* channel are promising (BnGa PWA group has claimed/improve evidence a set of 8 resonances from this channel)

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

****	Existence is certain, and properties are at least fairly well explored.
***	Existence is very likely but further confirmation of decay modes is required.
**	Evidence of existence is only fair.
*	Evidence of existence is poor.

The need of γp -> pω

- The *N** may couple strongly to photon.
- Vector meson and photon share the same quantum number ($J^{PC} = 1^{--}$).
- Vector meson production channel (pω, pρ, pφ) are underexplored.
- The ω is an isospin filter.
- The ω has a lot of statistics.
- The ω threshold lies at the higher lying third resonance region where a lot of resonances are notably missing.
- The relatively narrow width of the ω (8.5 MeV) enables a clean detection above background.



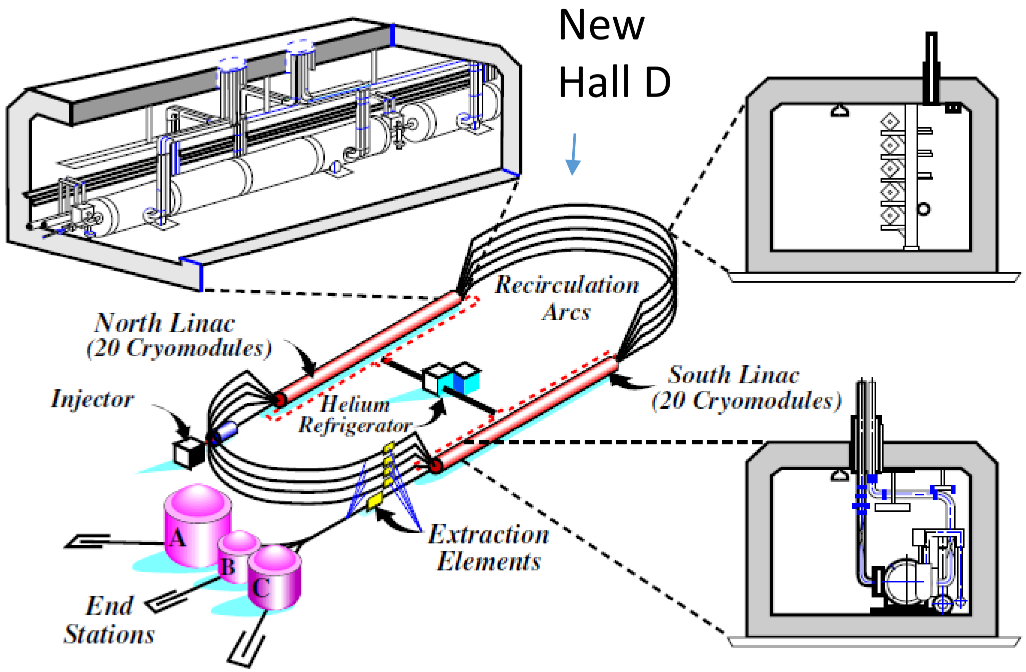
Dashed lines under QM : No observed resonance states which are predicted by Quark Model (PDG 2014)

Photoproduction of $\pi^+\pi^-\pi^0$

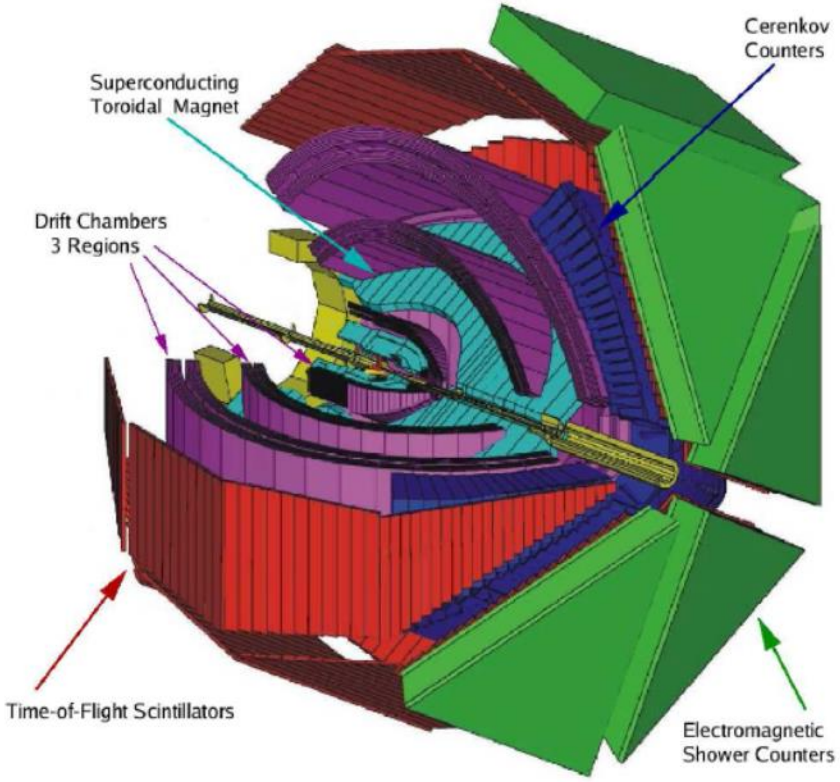
- The primary motivation of this talk is the Photoproduction of ω meson
- Fortunately, Photoproduction of ω, $K^0\Sigma^+$,and η share the same final states ($p\,\pi^+\pi^-\pi^0$)
- Therefore, three important reactions : $\gamma p \to p\omega/p\eta/K^0\Sigma^+ \to p\pi^+\pi^-\pi^0$ can be studied simultaneously as an effort to study the systematics
- The agreement for those three reactions with the previous measurement will establish a solid measurement result

In this talk, we will present the differential cross section of $\gamma p \to p\omega/p\eta/K^0\Sigma^+$ from the CLAS-g12 as well as the double polarization observables E of $\gamma p \to p\omega$ from CLAS-frost.

CLAS Detector at JLAB



Continuous Electron Beam Accelerator Facility (CEBAF)



CEBAF Large Acceptance Spectrometer (CLAS)

CLAS-g12 and CLAS-FROST (g9a) Experiment

FROST-g9a Experiment :

Electron Energy	Maximum at 2.4 GeV
Electron Degree of Polarization	Maximum 84.8 %
Tagged Photon Energy	Maximum 2.3 GeV
Target Material	Frozen Spin Butanol
Target Polarization	Longitudinal
Photon Polarization	Circular and Linear

g12 Experiment :

Electron Energy	5.7 GeV
Electron Degree of Polarization	67.2 %
Tagged Photon Energy	1.1 – 5.45 GeV
Target Material	Liquid Hydrogen
Target Polarization	Unpolarized
Photon Polarization	Circular

FROST experiment designed to do a "complete measurement". It consist of g9a experiment and also g9b experiment that used transverse polarized target and circular/linear polarized photon beam. We use g9a-circular beam (longitudinal polarized target) dataset to measure the polarization observable E of $\gamma p \rightarrow p\omega$ reaction. And we use g12 dataset to measure the cross section of $\gamma p \rightarrow p\omega / p\eta / K^0\Sigma^+$

Data Analysis

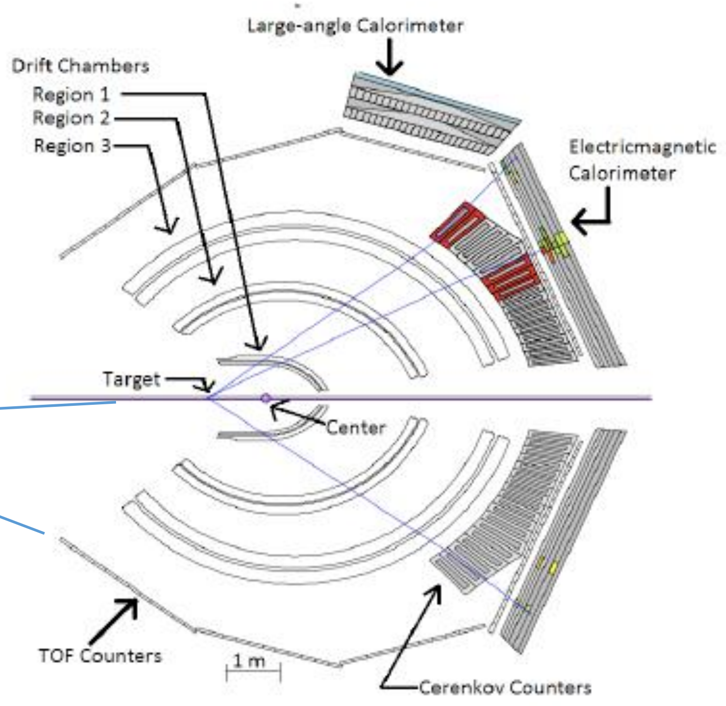
- PID
- Event Selection
- Background Substraction

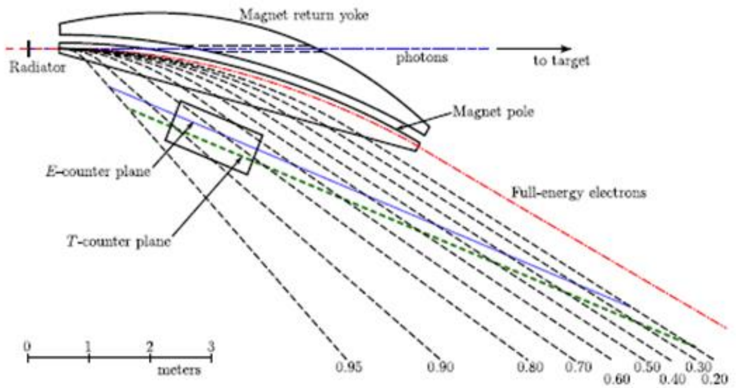
Data Analysis

1. Vertex Identification : ST & TOF provide the flight time of a particle. DC provide momentum and track. Hence particle speed, vertex time and position can be determined (propagated inward through ST).

$$\Delta t = |t_v - t_\gamma| < 1ns,$$

2. Photon identification : T-Scintillator on the tagger has photon time information. Then it is propagated to the vertex to get photon vertex time. We choose photon who has coincidence with particle's vertex time within 1 ns.





3. Proton and Pion Identification : we can measure the empirical mass of a particle : $m = \frac{p}{\gamma\beta_m},$

and assign the particle ID according to the table :

particle ID	mass
Pion (π)	$m < 0.3$ GeV
Kaon (K)	$0.35 < m < 0.65$ GeV
Proton (p)	$0.8 < m < 1.2$ GeV
Deuteron (d)	$1.75 < m < 2.2$ GeV

4. Delta Beta Cut : The calculated beta is

$$\beta_{calc} = \sqrt{\frac{p^2}{m_{PDG}^2 + p^2}}.$$

$$\Delta\beta = |\beta_{calc} - \beta_m| < 3\sigma.$$

In summary, the PID processes were done using the information from Start counter (ST), Time of flight (TOF), Drift Chamber (DC) and Tagger.

5. Kinematic Fitting :

- Event selections using the decay mode of $p\omega/p\eta/ K^0\Sigma^+ \rightarrow \pi^+\pi^-(\pi^0)$.
- We select all $\gamma p \rightarrow p\pi^+\pi^-(X)$ events, where X is missing.
- Selection of $\gamma p \rightarrow p\pi^+\pi^-(\pi^0)$ events ($X = \pi^0$) using kinematic fitting. The π^0 is reconstructed by imposing energy and momentum conservation.
- All $\gamma p \rightarrow p\pi^+\pi^-(\pi^0)$ events have CL > 0.01.

6. Signal-Background separation using Q-factor methods :

- Locating the peak
- Define kinematic distance to find the nearest neighbor
- Fit using signal and background pdf
- Determine the signal/background fraction and Q-value

Differential Cross Section & Polarization Observable E

The differential cross section

$$\frac{d\sigma}{dcos\theta^{\omega}_{CM}} = \left(\frac{A_{target}}{\rho_{target} . l_{target} . N_A . \text{Flux}}\right)\frac{\sum_i^n Q_i}{\Delta cos\theta^{\omega}_{CM} . \varepsilon_{MC} . BR}$$

- The number of events yields is the sum of Q-value.
- The detector acceptance is modelled using montecarlo simulation
- Photon flux normalization is required

The Polarization observable E

$$E = -\frac{1}{\Lambda_z \delta_o}\left(\frac{N_+ - N_-}{N_+ + N_-}\right)$$

- Polarization observable E is the asymmetry between the ω produced when the polarization of the beam and target are parallel and antiparallel).
- Measured asymmetry is normalized by the product of beam and target polarizations,

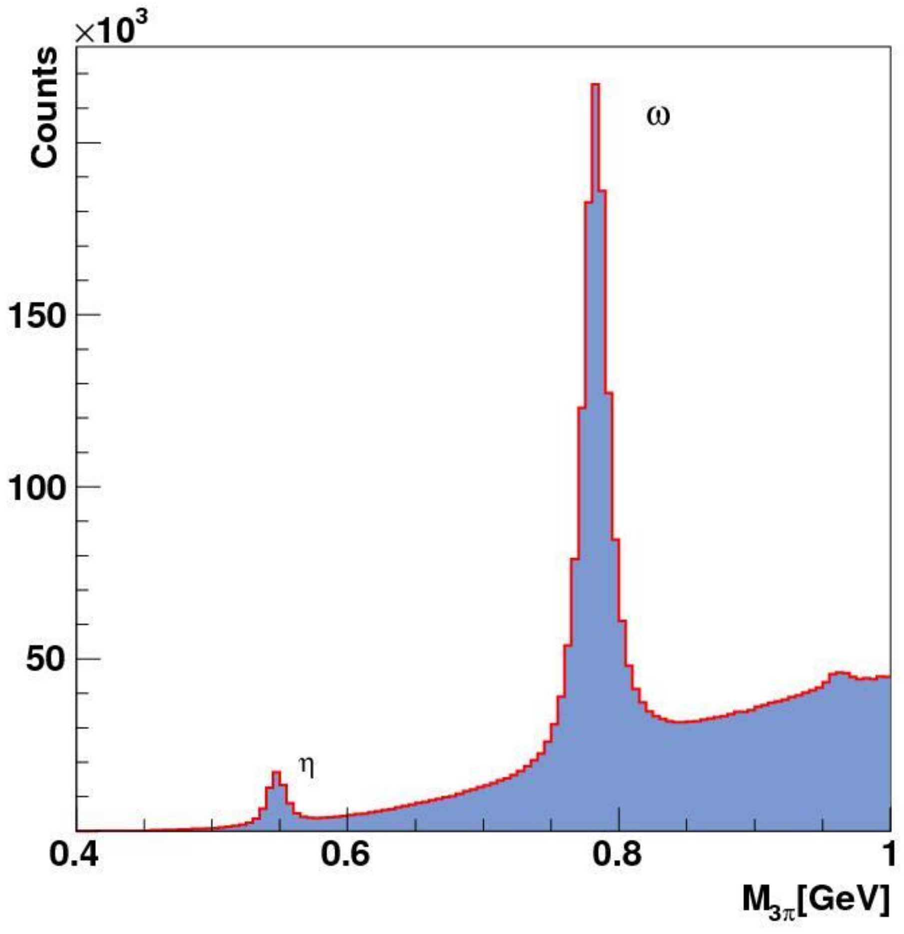
Locating the peak/coordinate reference

Since $\eta/\omega \rightarrow \pi^+\pi^-\pi^0$,we use the $M_{3\pi}$ as the coordinate reference for the $\gamma p \rightarrow p\eta/\omega$ channel.

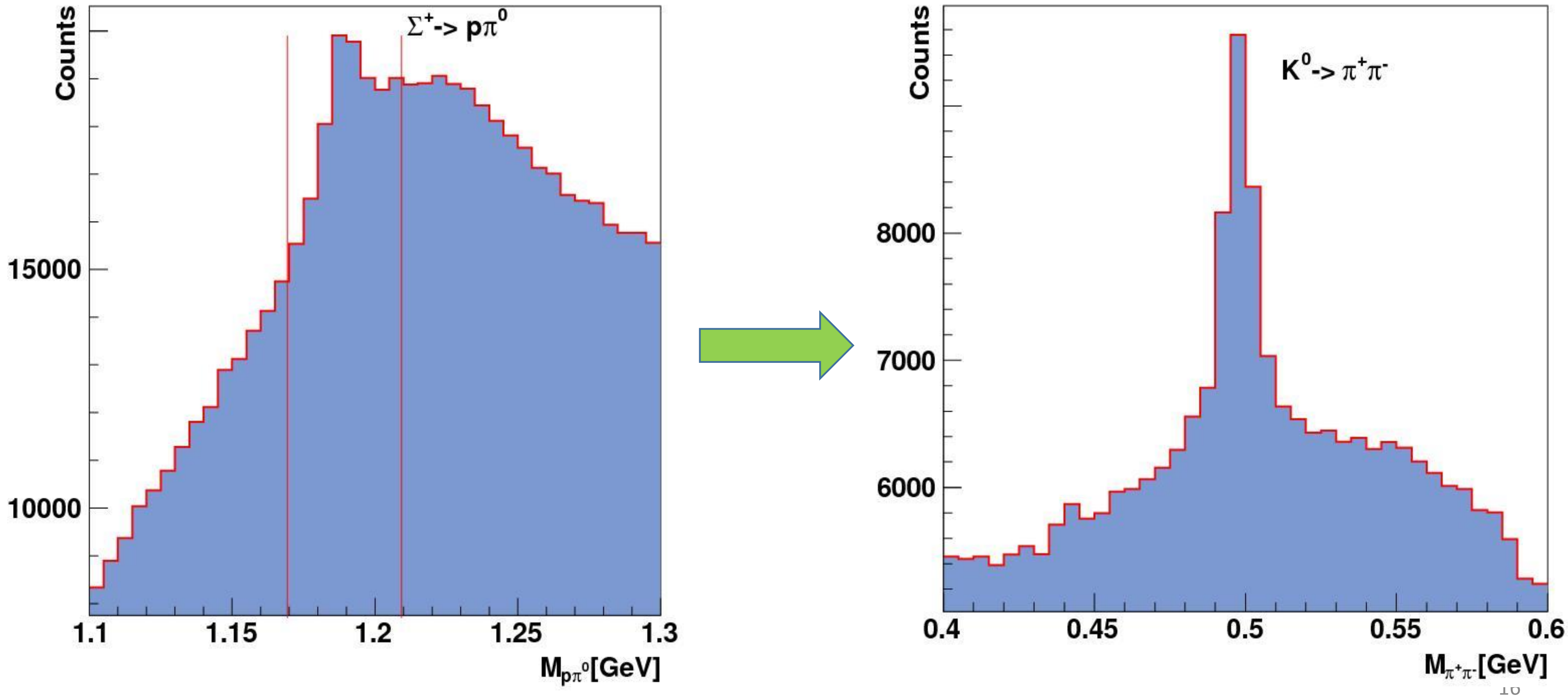
Since $\gamma p \rightarrow K^0\Sigma^+$ → $\Sigma^+ \rightarrow p\,\pi^0$

→ $K^0 \rightarrow \pi^+\pi^-$

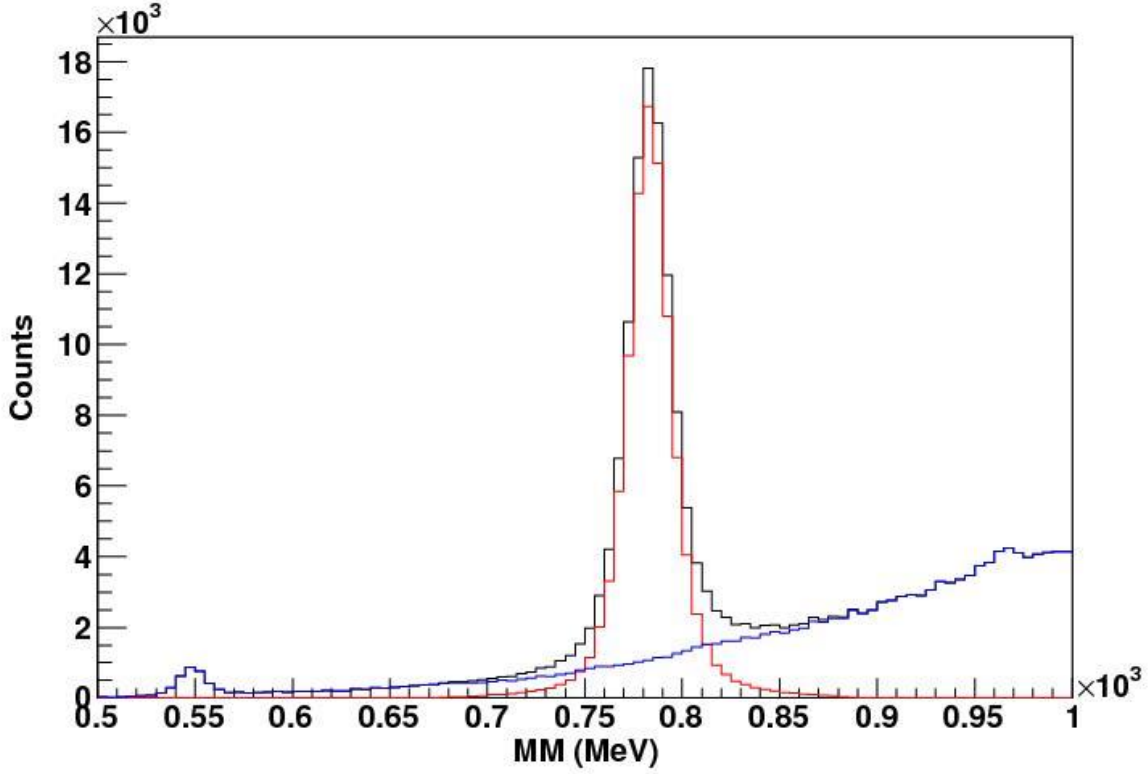
We use the $M_{\pi\pi}$ as the coordinate reference for the $\gamma p \rightarrow K^0\Sigma^+$ channel after applying a cut on sigma region.

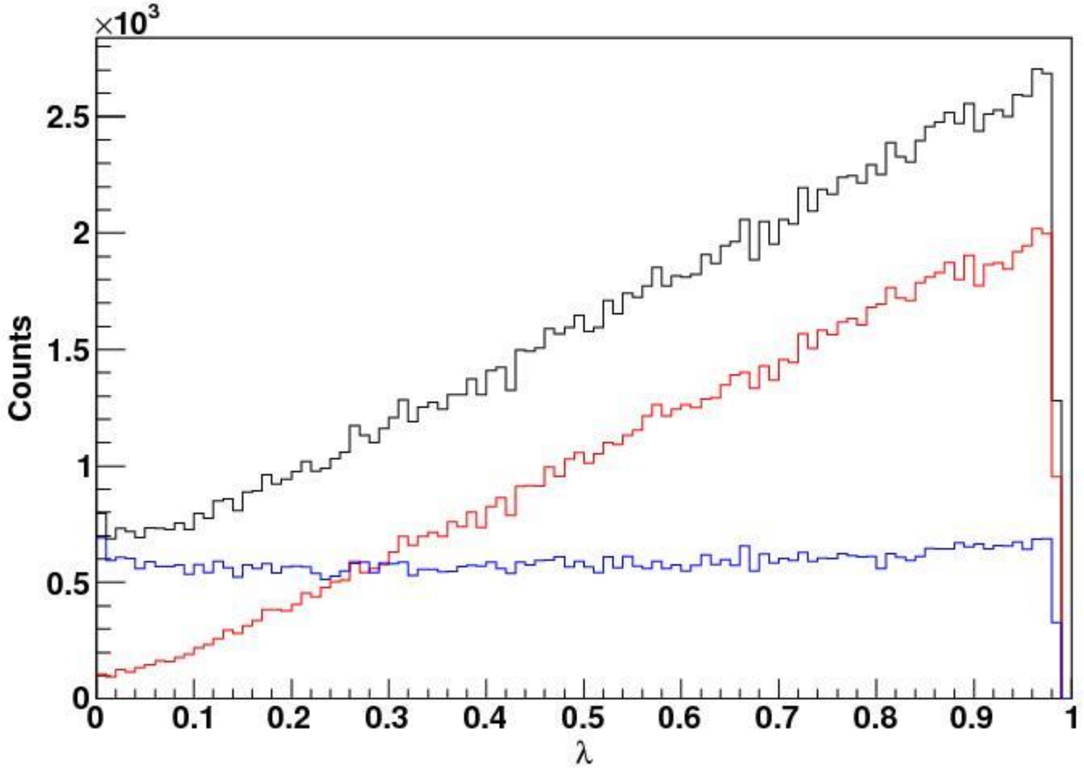


Locating the peak/coordinate reference

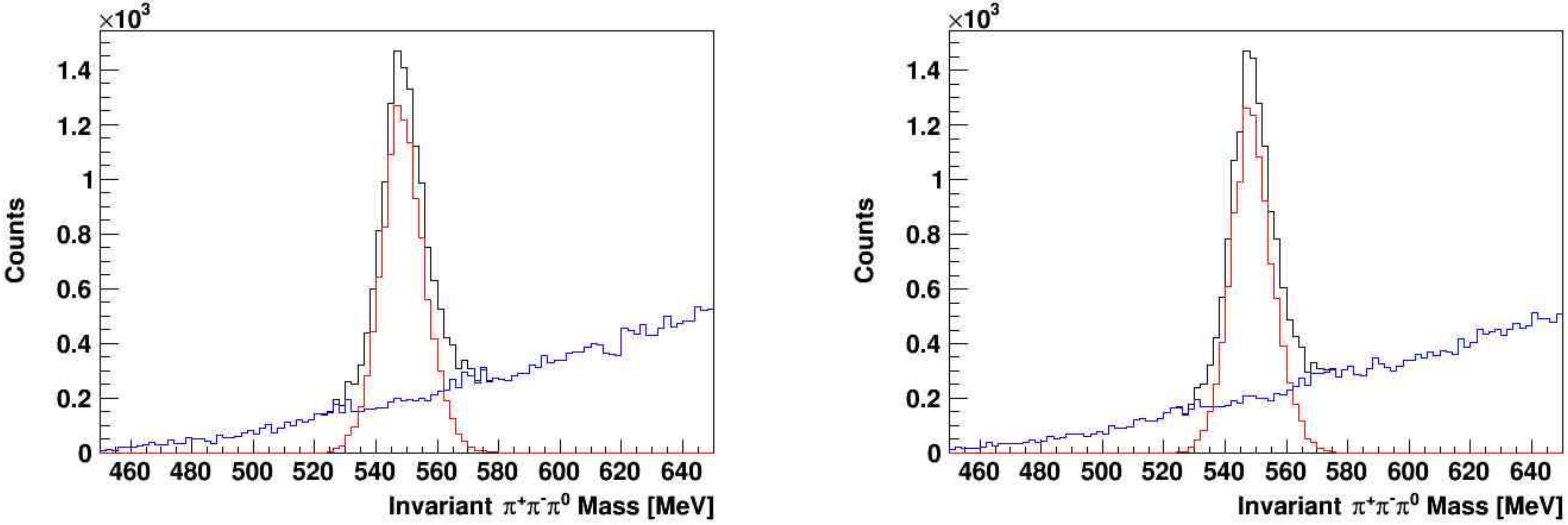


Q-factor methods : result for ω ($E_\gamma = 2.125\ GeV$)

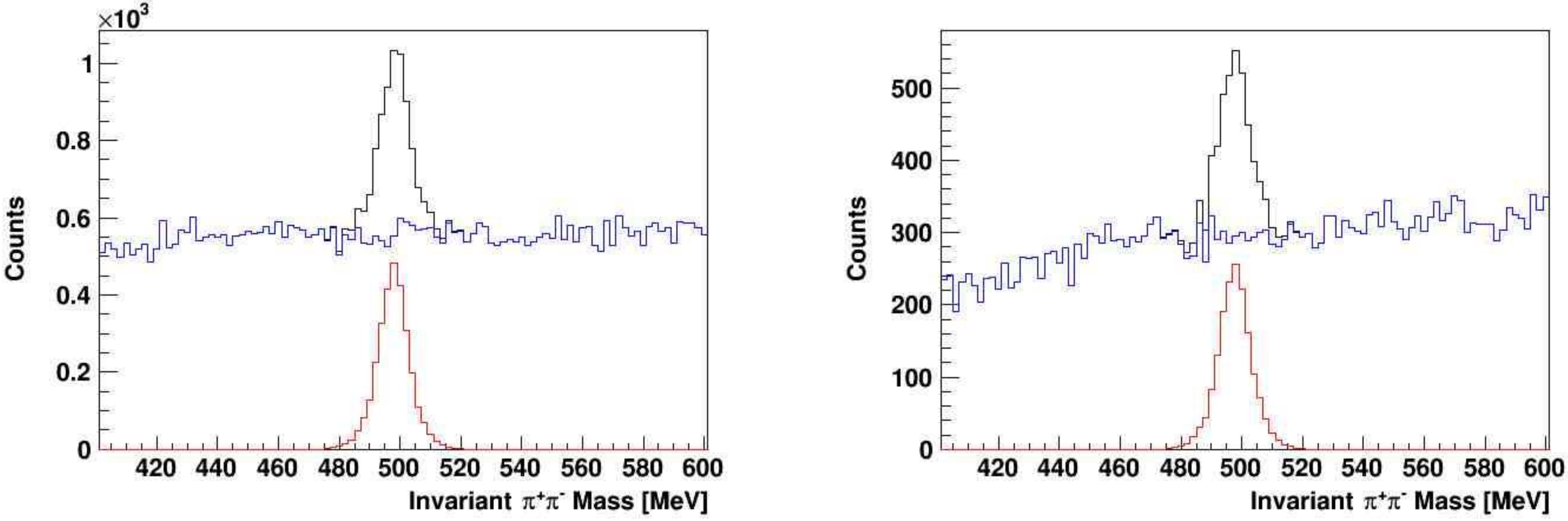




Q-factor result for η ($E_\gamma = 1.85\ GeV$ & $2.05\ GeV$)



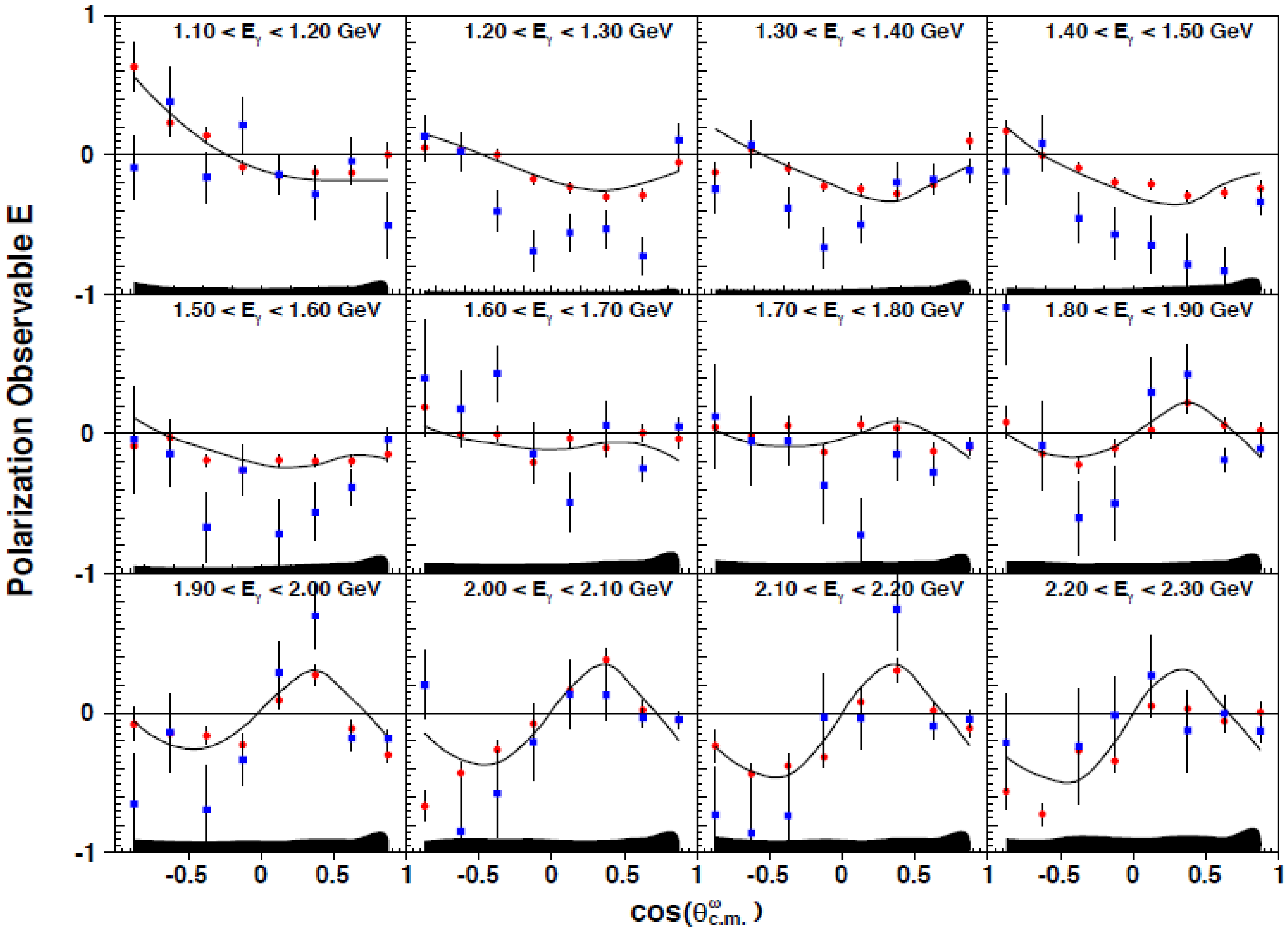
Data Analysis : Q-factor result for K^0 (E_γ =1.95 GeV & 2.35 GeV)



Result and Discussion

- The double polarization observable E of γp -> pω
- The differential cross section of γp -> p ω
- The differential cross section γp -> $K^0\Sigma^+$
- The differential cross section of γp -> pη

The double polarization observable E of γp -> pω along with the Bonn-Gatchina Partial Wave Analysis result



- The figure shows the polarization observable E from CLAS-FROST at 1.1 – 2.3 GeV (red point) along with the Bonn-Gatchina PWA fit result (**solid line**), in comparison with the previous measurement from CBELSA/TAPS (blue point)
- The dominant contribution from N(1720) $3/2^+$ is found.
- The background is dominated by the t-channel contributions (pomeron-exchange and a smaller π-exchange).
- The full description of the data also need the contribution from:
  N(1680) $5/2^+$
  N(2000) $5/2^+$
  N(1895) $1/2^-$
  N(2100) $3/2^-$

Submitted in PRC
arXiv : 1708.02606v1 [nucl-ex]]

Those *N resonances will fill in :**

			Status as seen in								
Particle	J^P	overall	$N\gamma$	$N\pi$	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
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$N(1650)$	$1/2^-$	****	****	****	***			***	**	**	***
$N(1675)$	$5/2^-$	****	****	****	*			*		*	***
$N(1680)$	$5/2^+$	****	****	****	*	**				***	***
$N(1700)$	$3/2^-$	***	**	***	*			*	*	*	***
$N(1710)$	$1/2^+$	****	****	****	***		**	****	**	*	**
$N(1720)$	$3/2^+$	****	****	****	***			**	**	**	*
$N(1860)$	$5/2^+$	**		**						*	*
$N(1875)$	$3/2^-$	***	***	*			**	***	**		***
$N(1880)$	$1/2^+$	**	*	*		**		*			
$N(1895)$	$1/2^-$	**	**	*	**			**	*		
$N(1900)$	$3/2^+$	***	***	**	**		**	***	**	*	**
$N(1990)$	$7/2^+$	**	**	**					*		
$N(2000)$	$5/2^+$	**	**	*	**			**	*	**	
$N(2040)$	$3/2^+$	*		*							
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$N(2120)$	$3/2^-$	**	**	**				*	*		
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**** Existence is certain, and properties are at least fairly well explored.
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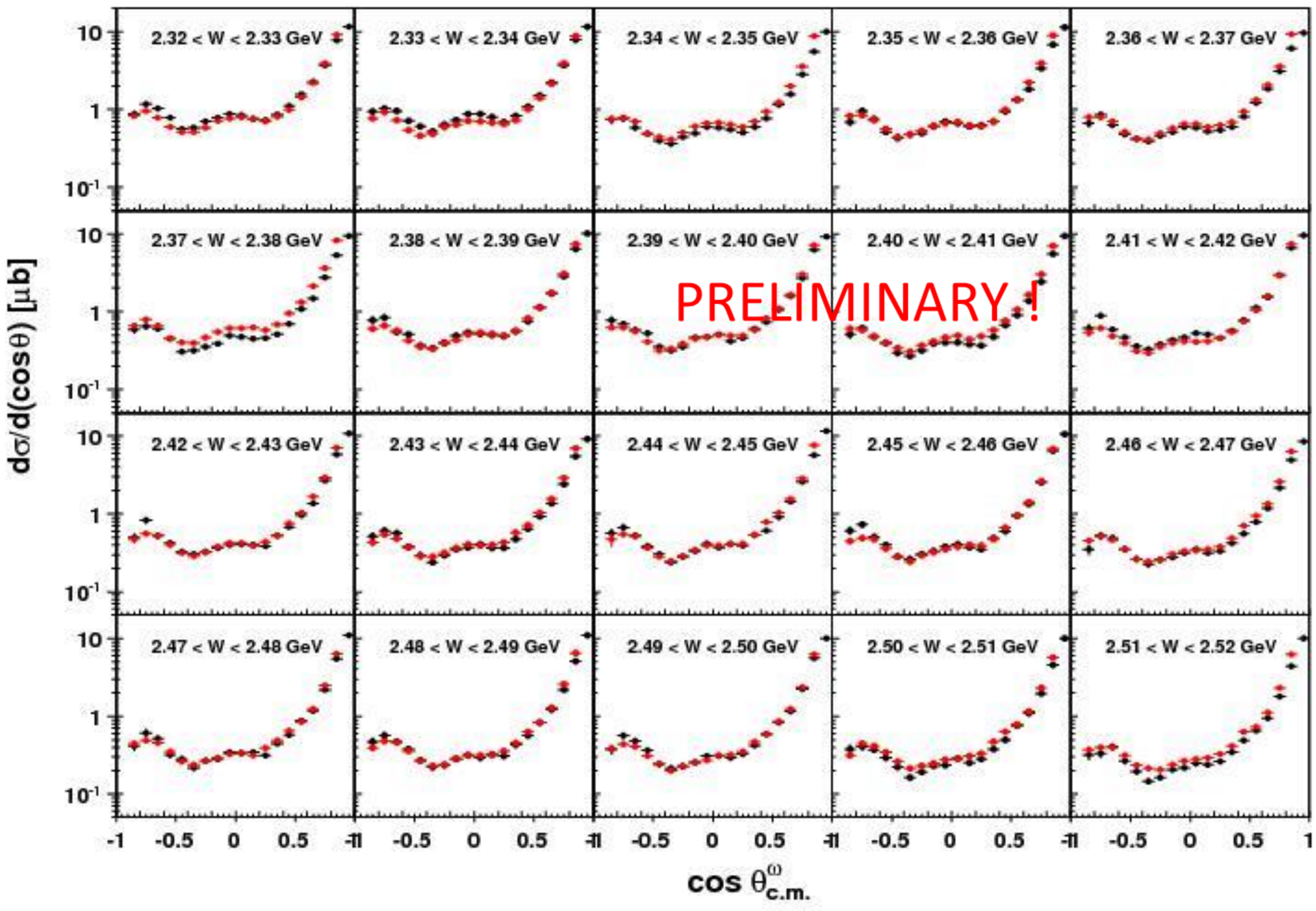
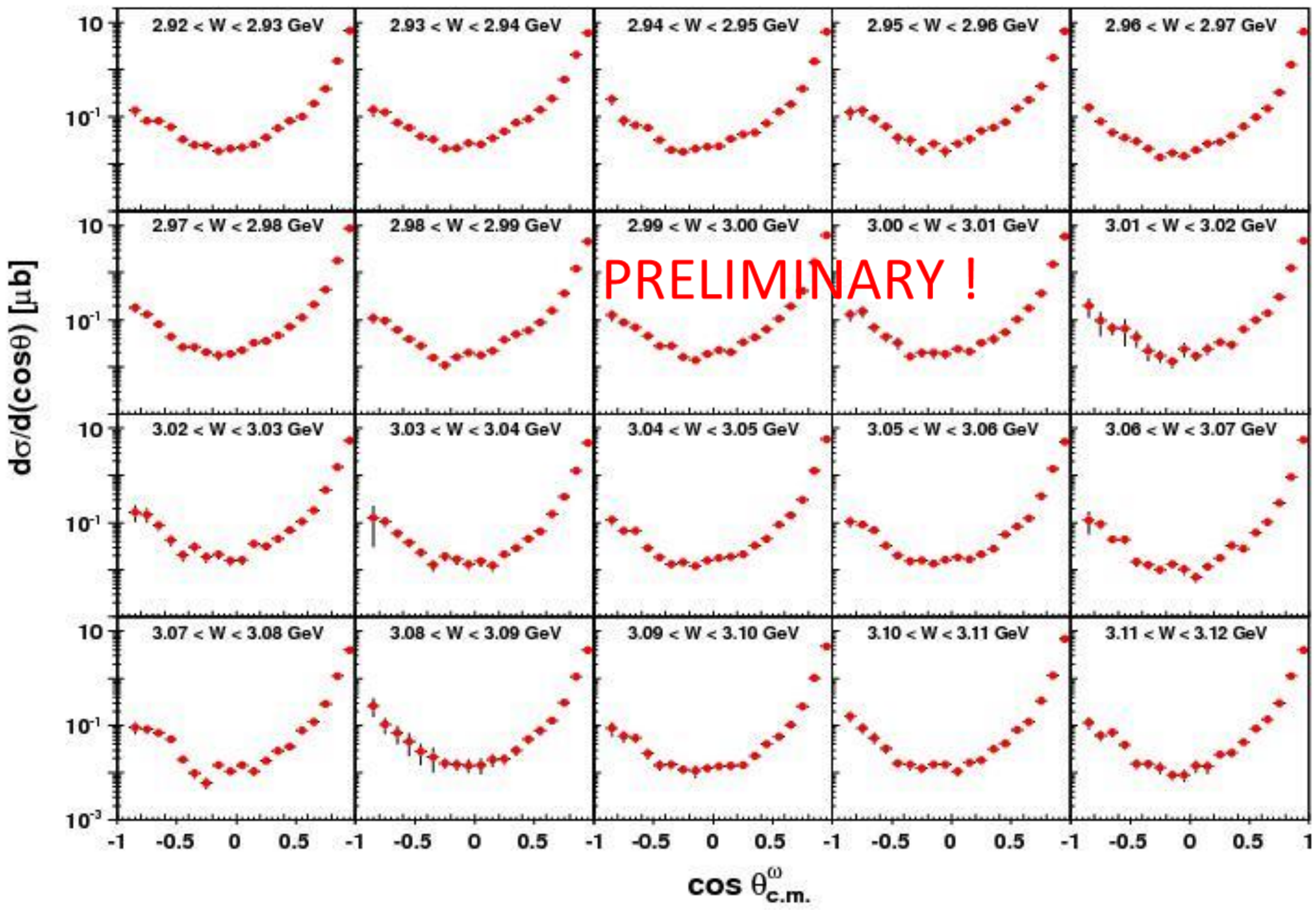
Differential cross section of γp ->pω



- We have obtained the Differential cross section of γp ->pω from CLAS-g12 with the energy range from threshold to 5.4 GeV

- The figure shows the Differential cross section of γp ->pω (**BLACK**) from CLAS-g12 in comparison with the previous measurement from CLAS-g11 (RED)



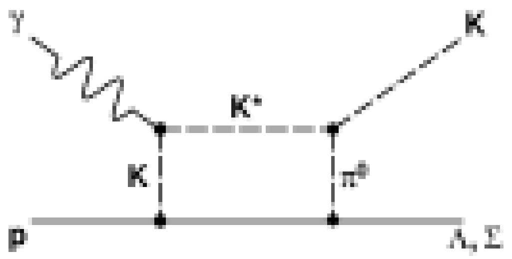
The figure shows the Differential cross section of γp ->pω (**BLACK**) from CLAS-g12 at higher energy.

The need of $\gamma p \rightarrow K^0\Sigma^+$

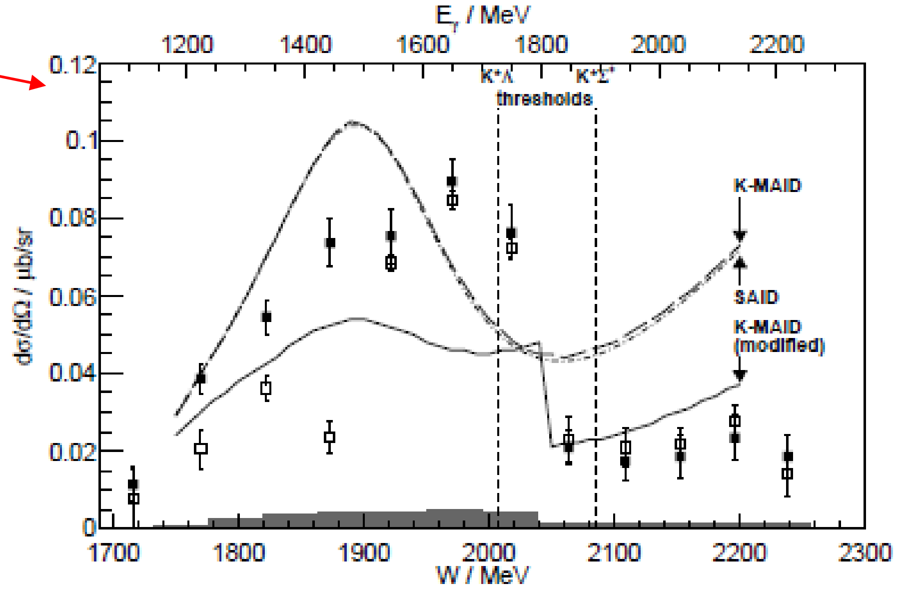
- Provide a cleaner probe to s-channel resonances
- Model parameter constraint through Isospin related channel.
- Lack of the charge hyperon (Σ^+) photoproduction data in comparison to the neutral hyperon.
- Uncertainty do to discrepancy on previous measurement.
- Certain model requires high energy data (Regge Plus Resonance model)
- Investigate the anomaly (dip structure) seen in previous measurement

Observable	N_{data}	χ^2	χ^2/N_{data}
$\sigma(\gamma p \rightarrow \Lambda K^+)$	720	804	1.12
$\sigma(\gamma p \rightarrow \Lambda K^+)$	770	1282	1.67
$P(\gamma p \rightarrow \Lambda K^+)$	202	374	1.85
$\Sigma(\gamma p \rightarrow \Lambda K^+)$	45	62	1.42
$\sigma(\gamma p \rightarrow \Sigma^0 K^+)$	660	834	1.27
$\sigma(\gamma p \rightarrow \Sigma^0 K^+)$	782	2446	3.13
$P(\gamma p \rightarrow \Sigma^0 K^+)$	95	166	1.76
$\Sigma(\gamma p \rightarrow \Sigma^0 K^+)$	45	20	0.46
$\sigma(\gamma p \rightarrow \Sigma^+ K^0)$	48	104	2.20
$\sigma(\gamma p \rightarrow \Sigma^+ K^0)$	120	109	0.91

The photoproduction of *KY* data used in BnGa PWA fit.

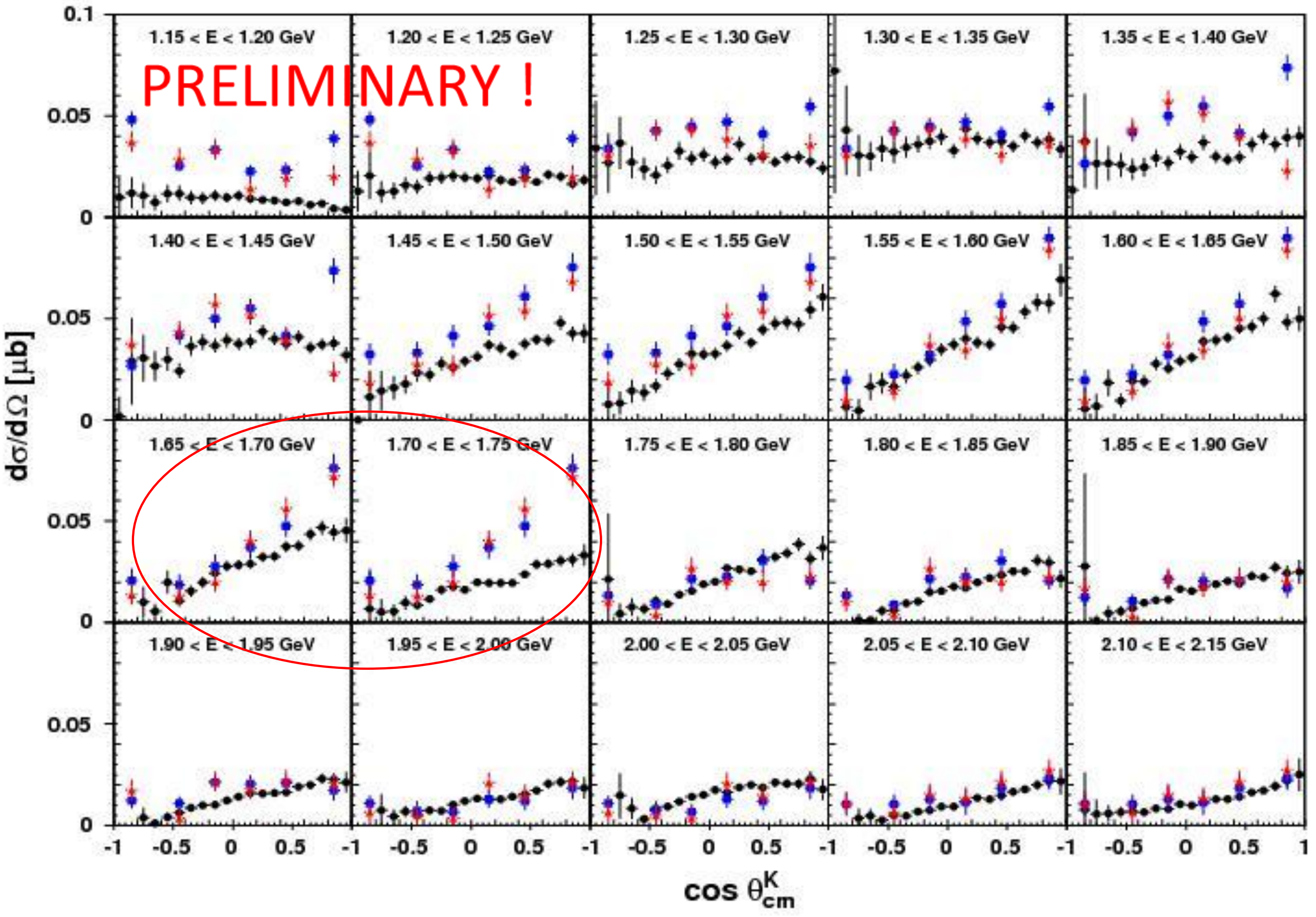


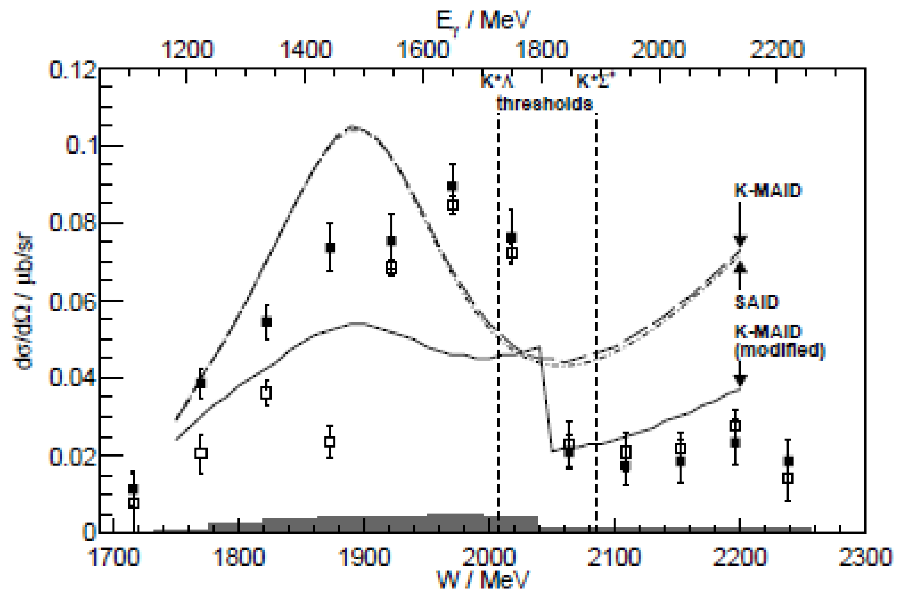
The diagram behind the anomaly



The anomaly seen in the total cross section of $\gamma p \rightarrow K^0\Sigma^+$ from CBELSA/TAPS

Differential cross section of $\gamma p \to K^0\Sigma^+$

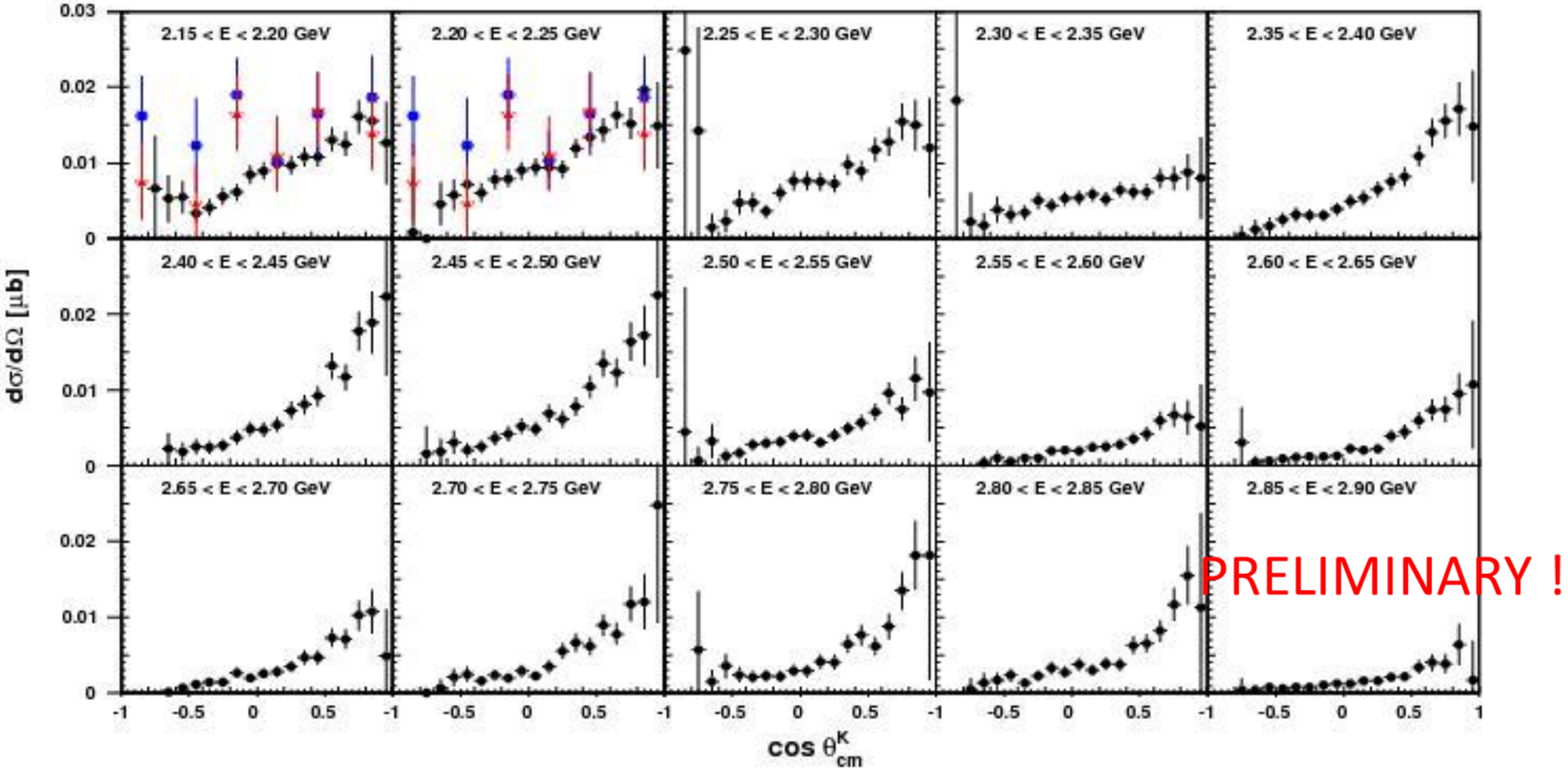




The CLAS-g12 data :

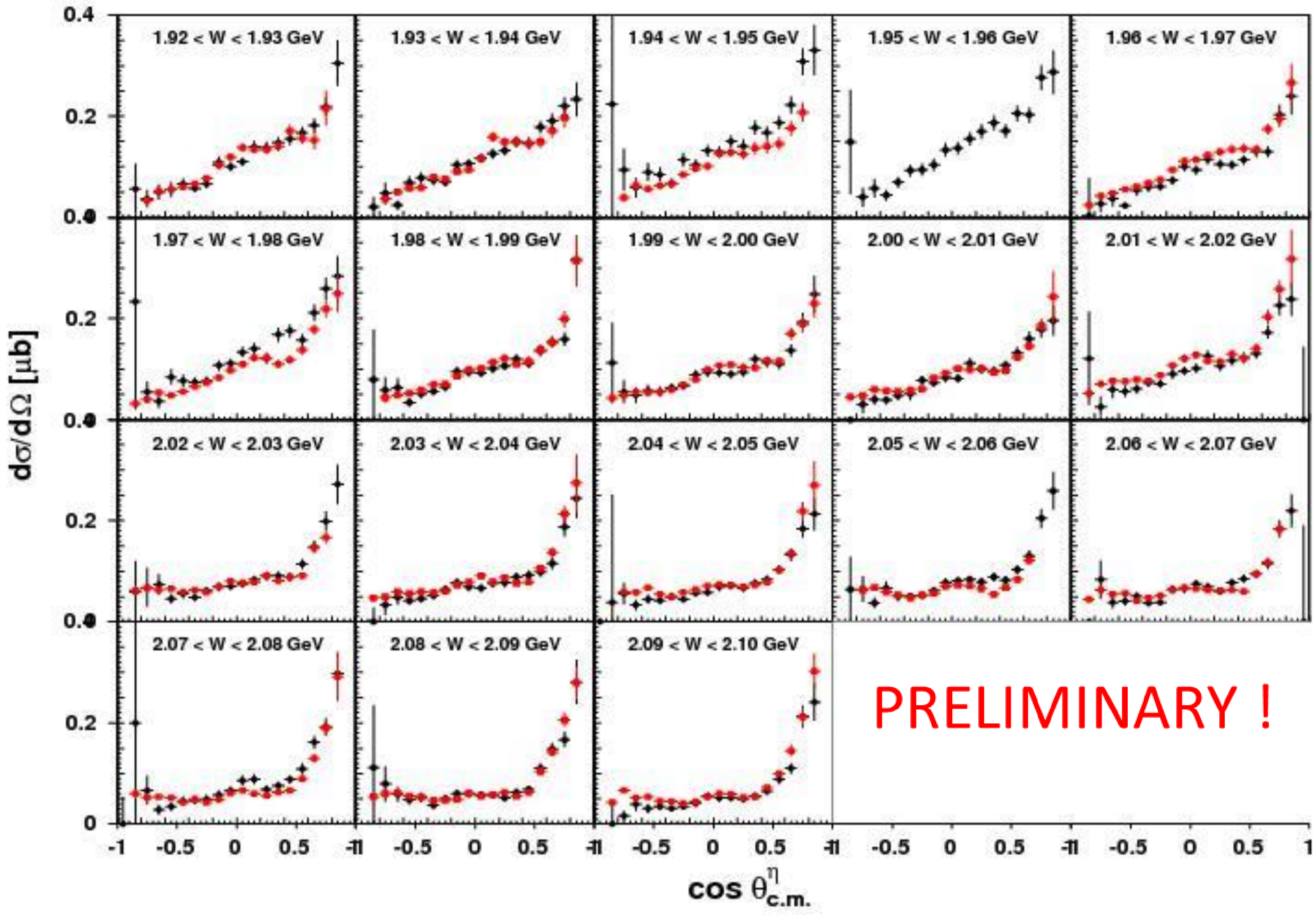
- Smooth transition between energy bin
- No indication of cusp-like structure (anomaly)

The figure shows the differential cross section of $\gamma p \to K^0\Sigma^+$ from CLAS-g12 (**BLACK**) in comparison with the previous measurement from CBELSA/TAPS (**BLUE**) and Cristal Barrel (**RED**)



The figure shows the differential cross section of γp -> $K^0\Sigma^+$ from CLAS-g12 (**BLACK**) at higher energy

Differential cross section of γp ->pη



- The figure shows the Differential cross section of γp ->pη (**BLACK**) from CLAS-g12 in comparison with the previous measurement from CLAS-g11 (RED)
- The availability of the data at higher energy will be used to test the model (See D2: 14.30) by JPAC.

Summary & Outlook

The double polarization observable E of γp ->pω establish some *N resonances that will fill in :**

A lot more high statistic data point on the differential cross section of γp -> $K^0\Sigma$

Observable	N_{data}	χ^2	χ^2/N_{data}
$\sigma(\gamma p \to \Lambda K^+)$	720	804	1.12
$\sigma(\gamma p \to \Lambda K^+)$	770	1282	1.67
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More than new 1000 data points

Particle J^P	overall	Status as seen in								
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$N(1680)$ $5/2^+$	****	****	****	*	**				***	***
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$N(2220)$ $9/2^+$	****		****							
$N(2250)$ $9/2^-$	****		****							
$N(2300)$ $1/2^+$	**		**							
$N(2570)$ $5/2^-$	**		**							
$N(2600)$ $11/2^-$	***		***							
$N(2700)$ $13/2^+$	**		**							

**** Existence is certain, and properties are at least fairly well explored.
*** Existence is very likely but further confirmation of decay modes is required.
** Evidence of existence is only fair.
* Evidence of existence is poor.

Summary & Outlook

The Differential cross section of γp ->pη/ω at higher will be used to test the model by JPAC based on finite energy sum rules

The ongoing research at FSU :

Channel	Observable
γp -> pω	Cross Section
	Spin Density Matrix
	E, T, F, Σ, …..
	Dalitz Analysis
γp -> $K^0\Sigma^+$	Cross section
	P, Cx, Cz
γp -> pη	Cross section
γp -> $p\pi^+\pi^-$	Cross section
	$I_{\odot}, P_z, P_z^{\odot}, I^s, P_{x,y}, \ldots$
γp -> pφ	Cross Section

Notes : High energy data are available !

THANK YOU