# Observables *T* and *F* at CLAS and the Partial Wave Analysis

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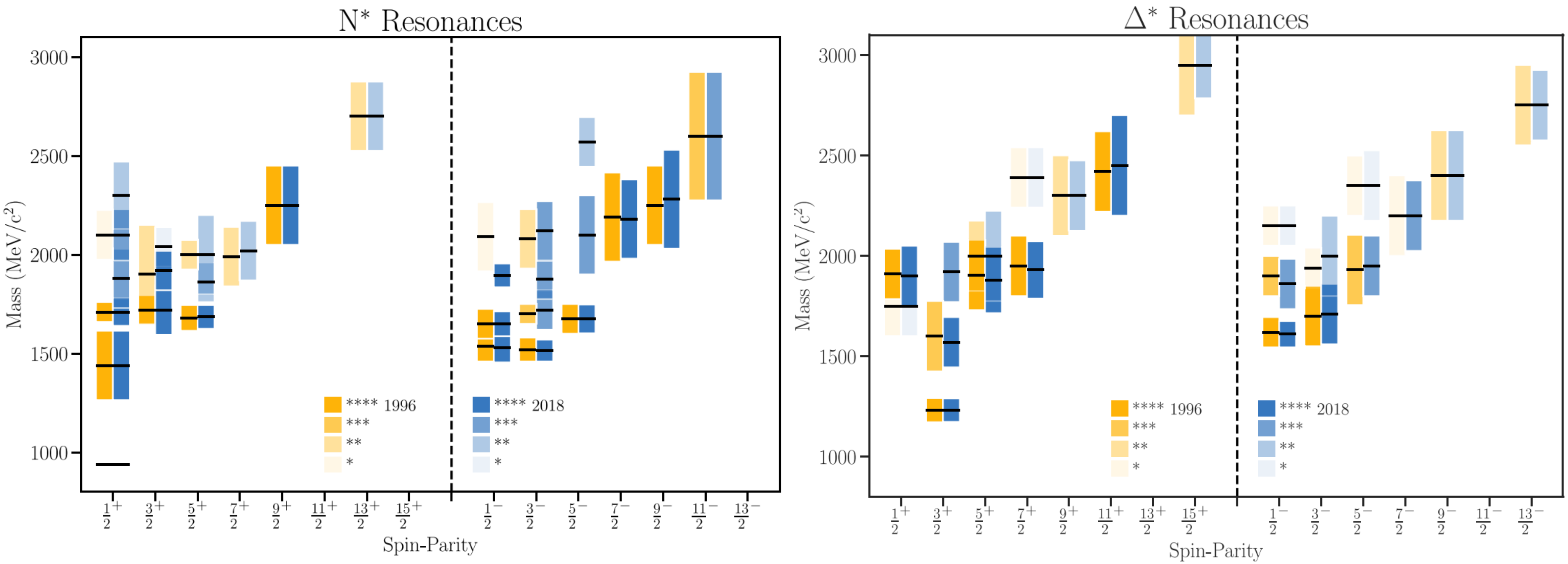
# “Missing” Resonances




The phenomenon observed states are less than the predictions of the quark model is known as the “missing” resonance problem.

*Figure Ref.: D. G. Ireland, E. Pasyuk, and I. Strakovsky, Photoproduction reactions and non-strange baryon spectroscopy, Progress in Particle and Nuclear Physics 111, 103752 (2020).*

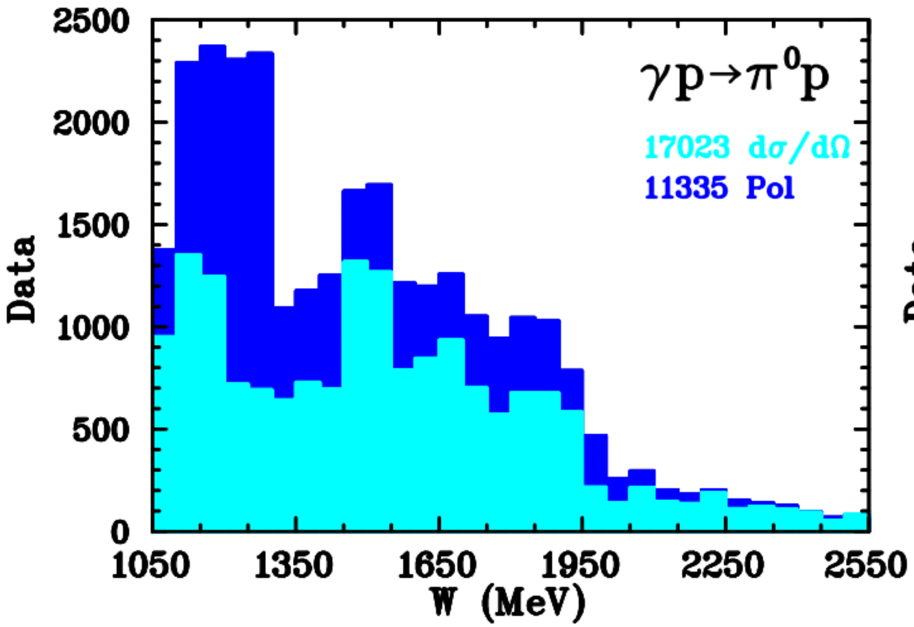
# Polarization Observables

The single-pion photoproduction process is one of the most important processes for the study of the baryon excited states. For the single-pion photoproduction reaction, with a polarized photon beam and a polarized target, the available observables are listed.

| | Photon beam | | |
|---|---|---|---|
| | unpolarized | circularly polarized | linearly polarized |
| Target | | | |
| unpolarized | $d\sigma/d\Omega$ | — | $\Sigma$ |
| longitudinally | — | $E$ | $G$ |
| transversely | $T$ | $F$ | $H$, $P$ |

# Data Availability

The number of data available in the SAID database from previous measurements. Although the polarization data increased after 2014, more data are still expected for W above 1950 MeV.



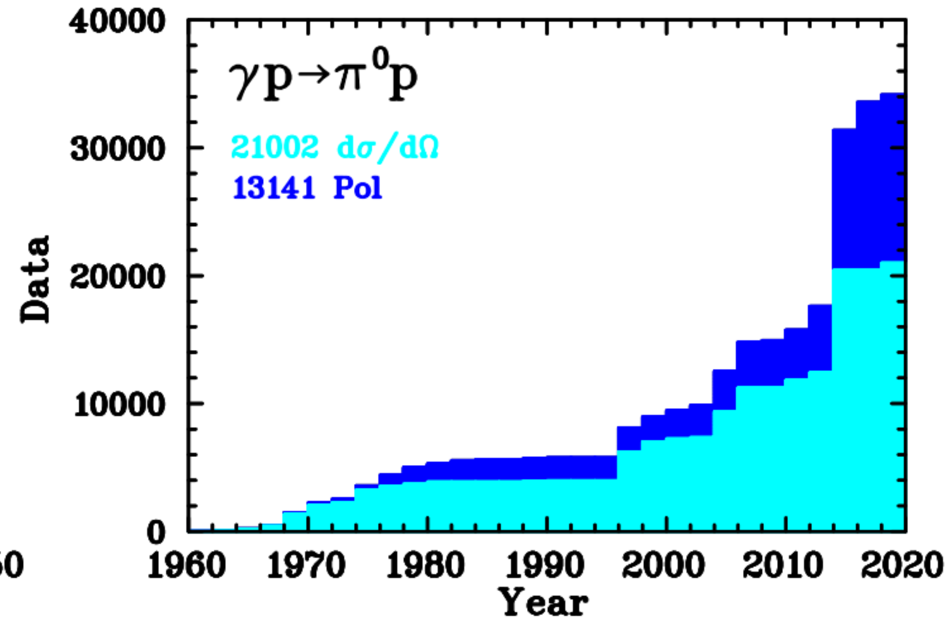
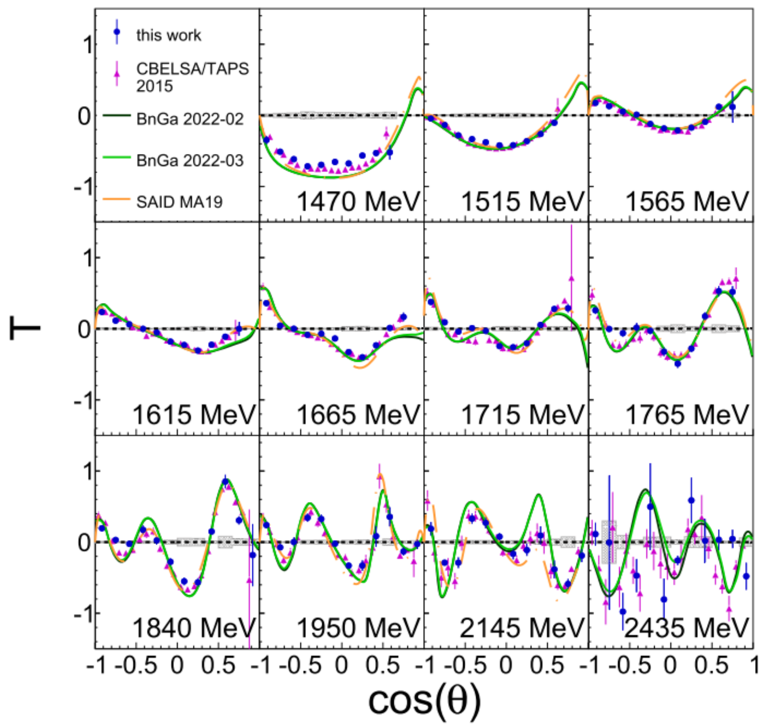
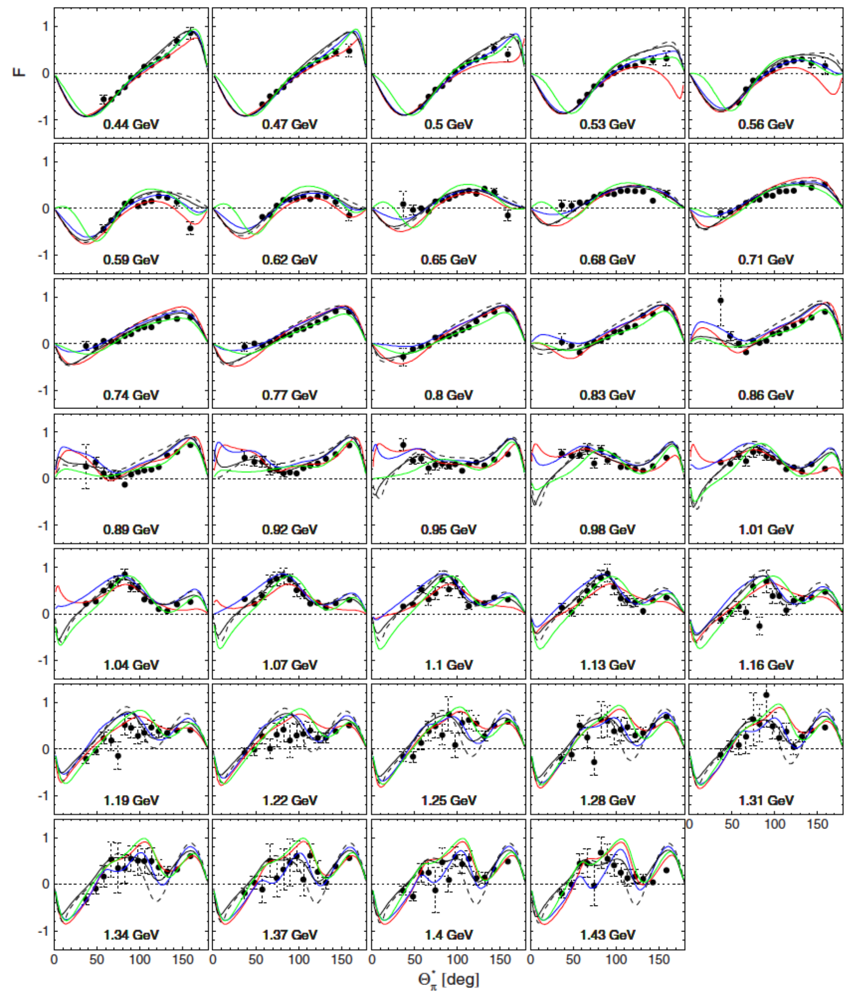




*Figure Ref.: D. G. Ireland, E. Pasyuk, and I. Strakovsky, Photoproduction reactions and non-strange baryon spectroscopy, Progress in Particle and Nuclear Physics 111, 103752 (2020).*

# Recent Experiments




CBELSA/TAPS (2023)

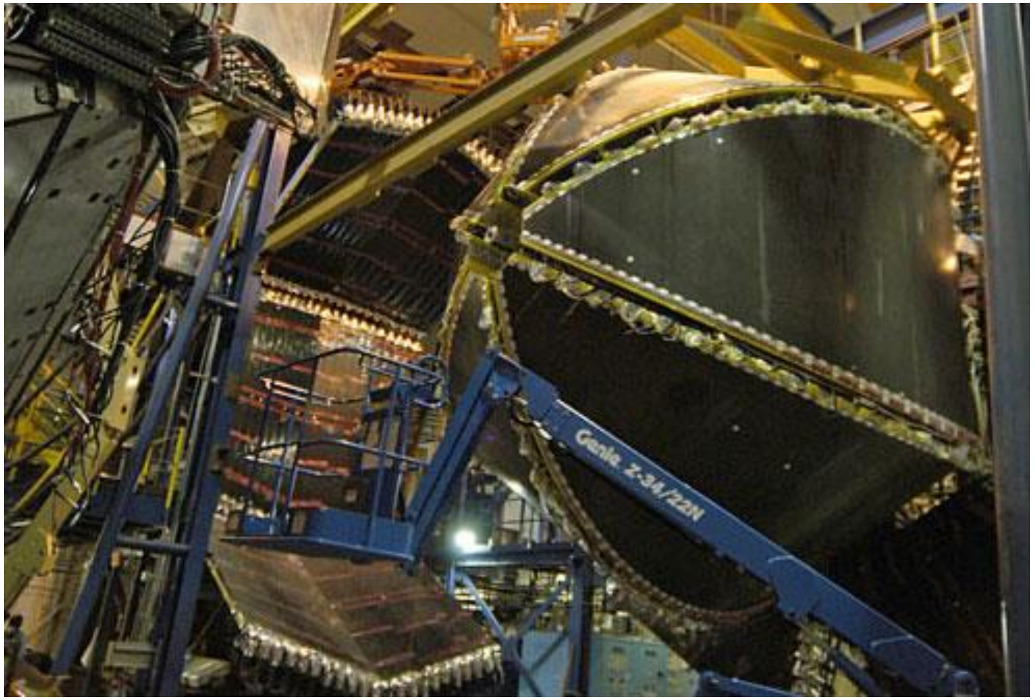



MAMI (2016)

CBELSA/TAPS (top) and MAMI (right) have published their results of T and F with W up to 2.4 GeV and 1.9 GeV.

# The Experiment at JLab

Jefferson Lab



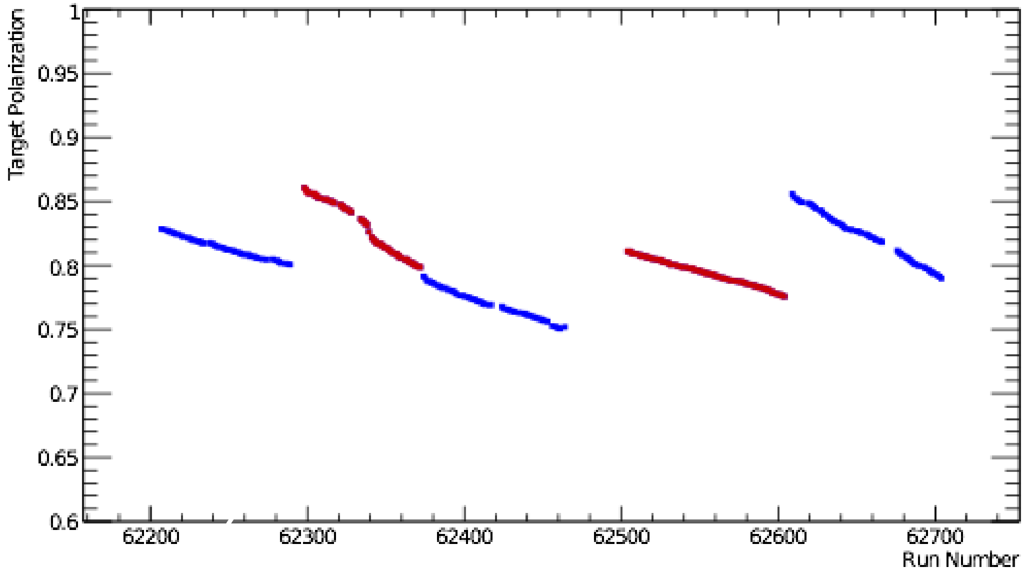

CLAS detector (6 GeV era)

This experiment was conducted at Thomas Jefferson National Accelerator Facility (Jefferson Lab). The g9b experimental data were taken between March 2010 and August 2010.

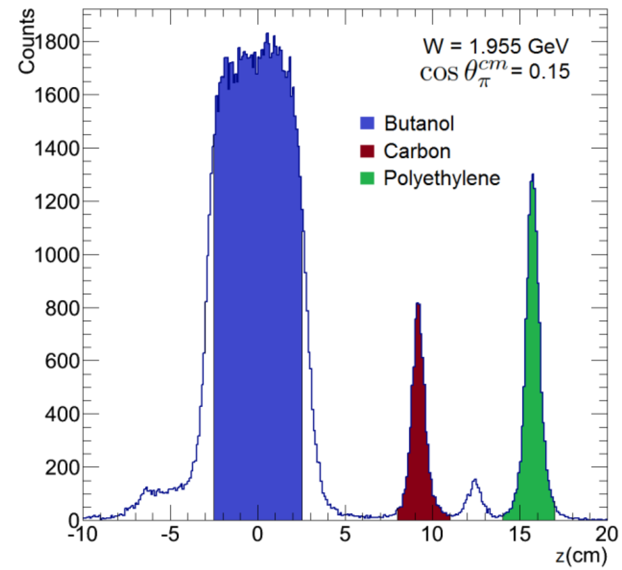


*Figure Ref.: B. A. Mecking et al., "The CEBAF Large Acceptance Spectrometer (CLAS)," Nucl. Instrum. Meth., vol. A503, pp. 513–553, 2003.*

# FROST Target




Reconstructed Reaction Vertex

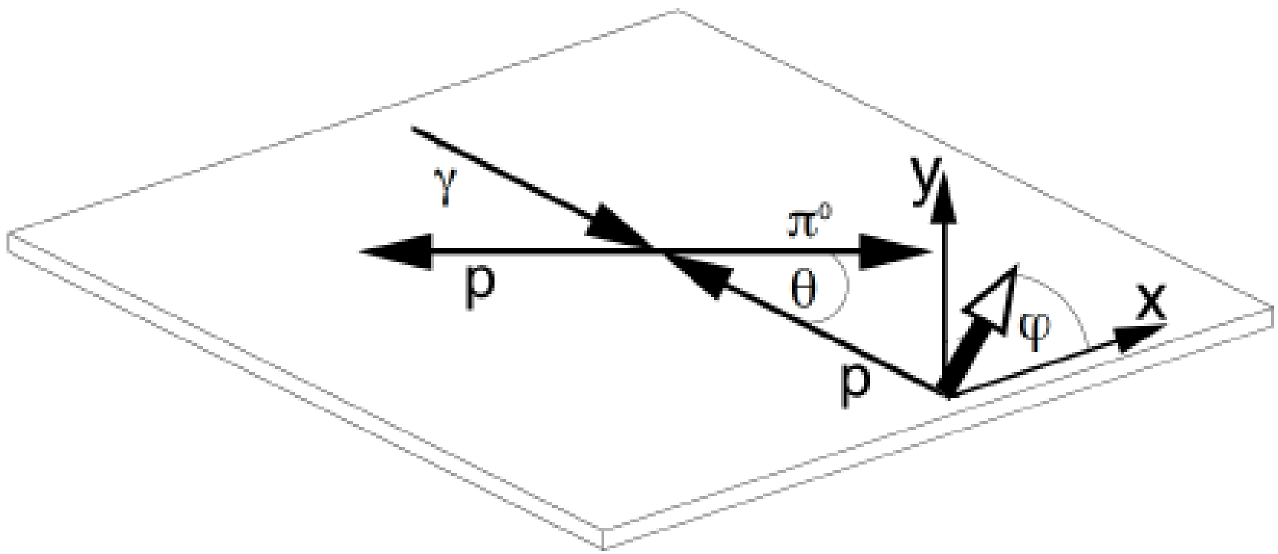



The FROzen Spin Target (FROST) is a polarized target. The free protons from hydrogen atoms in the butanol ($C_4H_9OH$) target were polarized, $P_t \approx 80\%$. The target-polarization orientations were also flipped regularly.

A Carbon target was placed downstream to provide bound protons to measure the bound-nucleon background of the butanol data.

# Formalism

The polarization observables T and F can be extracted from the angular and helicity dependence of the polarized cross section.




$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}\left(1 + P_T T \sin(\varphi) + P_T P_\odot F \cos(\varphi)\right)$$



*Eq. Ref. : I. S. Barker, A. Donnachie, and J. K. Storrow, Nucl. Phys. B75, 347 (1975).*

# Extraction of Yields

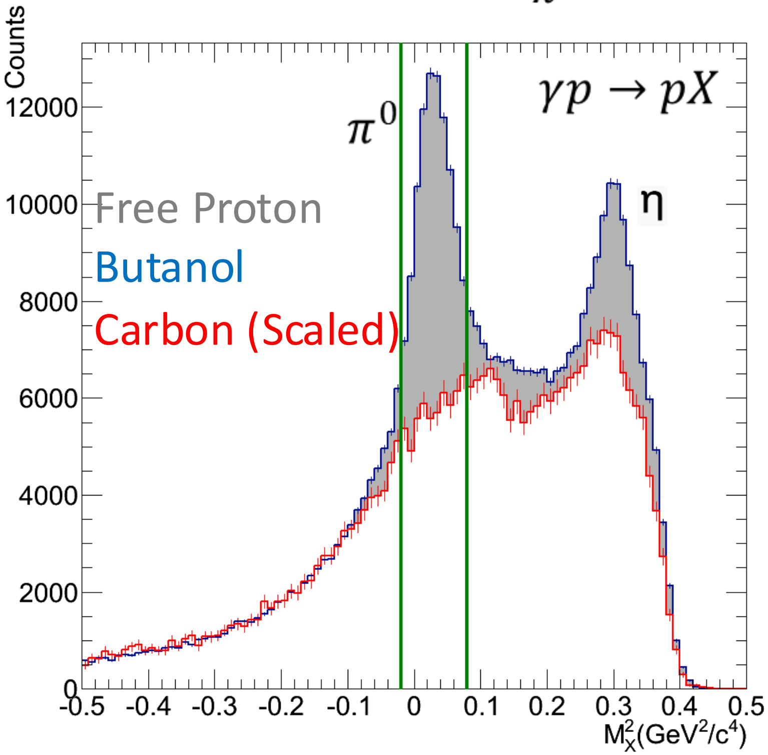
Experimentally, integrated polarized yields and moments were extracted for events of the $\pi^0 p$ final state ($M_X{}^2 \approx M_{\pi_0}{}^2$) from the reaction $\gamma p \rightarrow pX$.

$$Y = \frac{\sum_i (1)}{N},$$

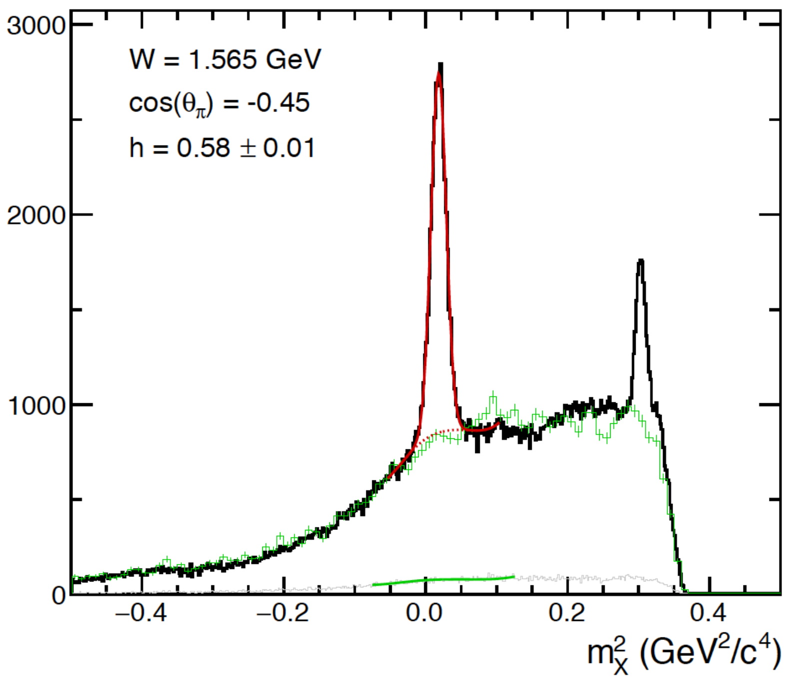
$$Y_{\sin m\varphi} = \frac{\sum_i (\sin m\varphi_i)}{N}$$

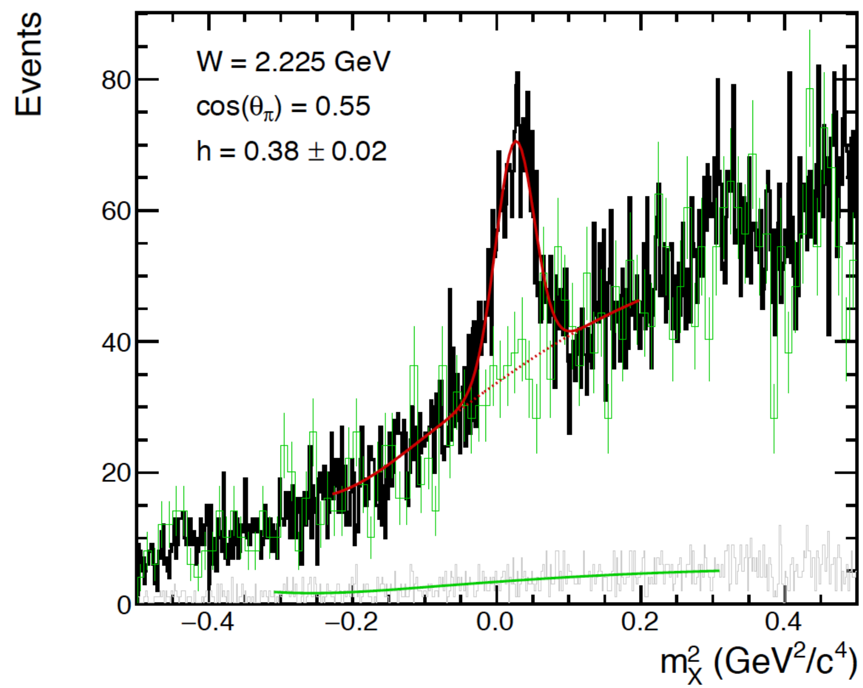
$$Y_{\cos m\varphi} = \frac{\sum_i (\cos m\varphi_i)}{N}$$

$W = 1.59$ GeV, $\cos\theta_{\pi^0} = -0.3$



# Determination of Dilution Factors




The dilution factors are determined as $h = \dfrac{N^B - \kappa \int C(m^2)dm^2}{N^B}$ .

*Figures with assistance from S. Strauch*

# Determination of Observables T and F

The polarized cross section

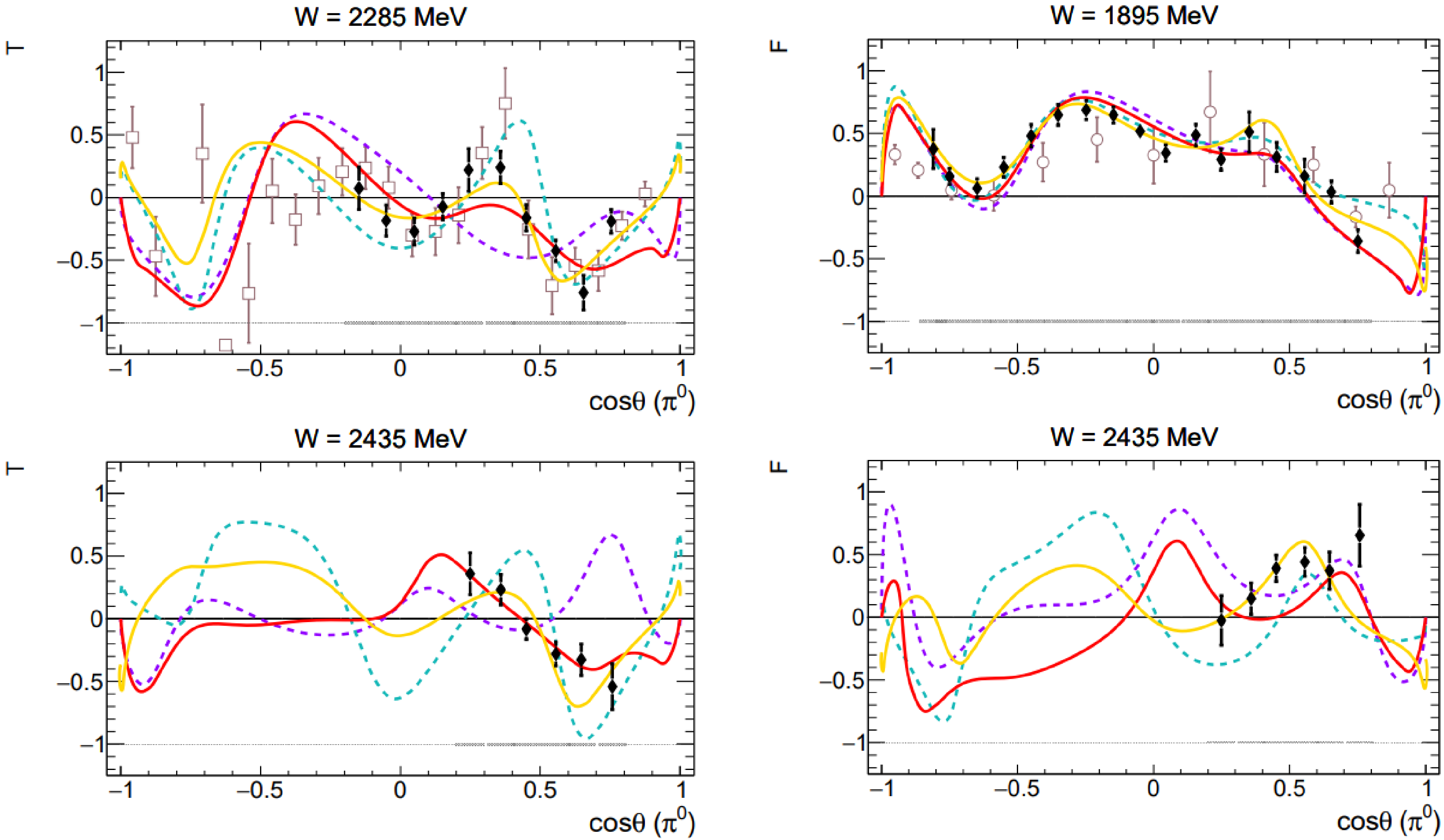
$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}\left(1 + P_T T \sin(\varphi) + P_T P_\odot F \cos(\varphi)\right)$$

By utilizing the moment method, the observables T and F are determined.

$$T = \frac{1}{h}\frac{2(Y^{\rightarrow}_{\sin\varphi} - Y^{\leftarrow}_{\sin\varphi})}{P_T^{\leftarrow}(Y^{\rightarrow} - Y^{\rightarrow}_{\cos 2\varphi}) + P_T^{\rightarrow}(Y^{\leftarrow} - Y^{\leftarrow}_{\cos 2\varphi})}$$

$$F = \frac{1}{h}\frac{2(Y^{\rightarrow +}_{\cos\varphi} - Y^{\rightarrow -}_{\cos\varphi} - Y^{\leftarrow +}_{\cos\varphi} + Y^{\leftarrow -}_{\cos\varphi})}{P_\odot P_T^{\leftarrow}(Y^{\rightarrow} + Y^{\rightarrow}_{\cos 2\varphi}) + P_\odot P_T^{\rightarrow}(Y^{\leftarrow} + Y^{\leftarrow}_{\cos 2\varphi})}$$

# Observables T and F in $\gamma p \rightarrow \pi^0 p$




SAID: -KX23 -SM22 JüBo: -2023 -2022 CLAS: ◆ MAMI: ○ CBELSA/TAPS: □

# Partial Wave Analysis - SAID

The SAID KX23 solution has the present results included. Compared with the previous SM22 solution, the KX23 solution agrees with the present data well in both lower and higher W ranges. Since they were data-driven, large $\chi^2$ would be possible.

| $W$ | Avg. $\chi^2$/data (SM22) | Avg. $\chi^2$/data (KX23) |
|---|---|---|
| $< 2.1$ GeV ($T$) | 3.94 | 3.25 |
| $> 2.1$ GeV ($T$) | 10.06 | 2.79 |
| $< 2.1$ GeV ($F$) | 1.97 | 1.48 |
| $> 2.1$ GeV ($F$) | 5.72 | 2.46 |

*Fits collaborated with I. Strakovsky, R. Workman, and SAID*

# Partial Wave Analysis - JüBo

## $\Delta(1910)1/2^+$

| **** | **JüBo (2023)** | **JüBo (2022)** | **PDG** |
|---|---|---|---|
| $Re\ W_0$ [MeV] | 1748 | 1802 | 1860 ± 30 |
| $-2Im\ W_0$ [MeV] | 353 | 550 | 300 ± 100 |

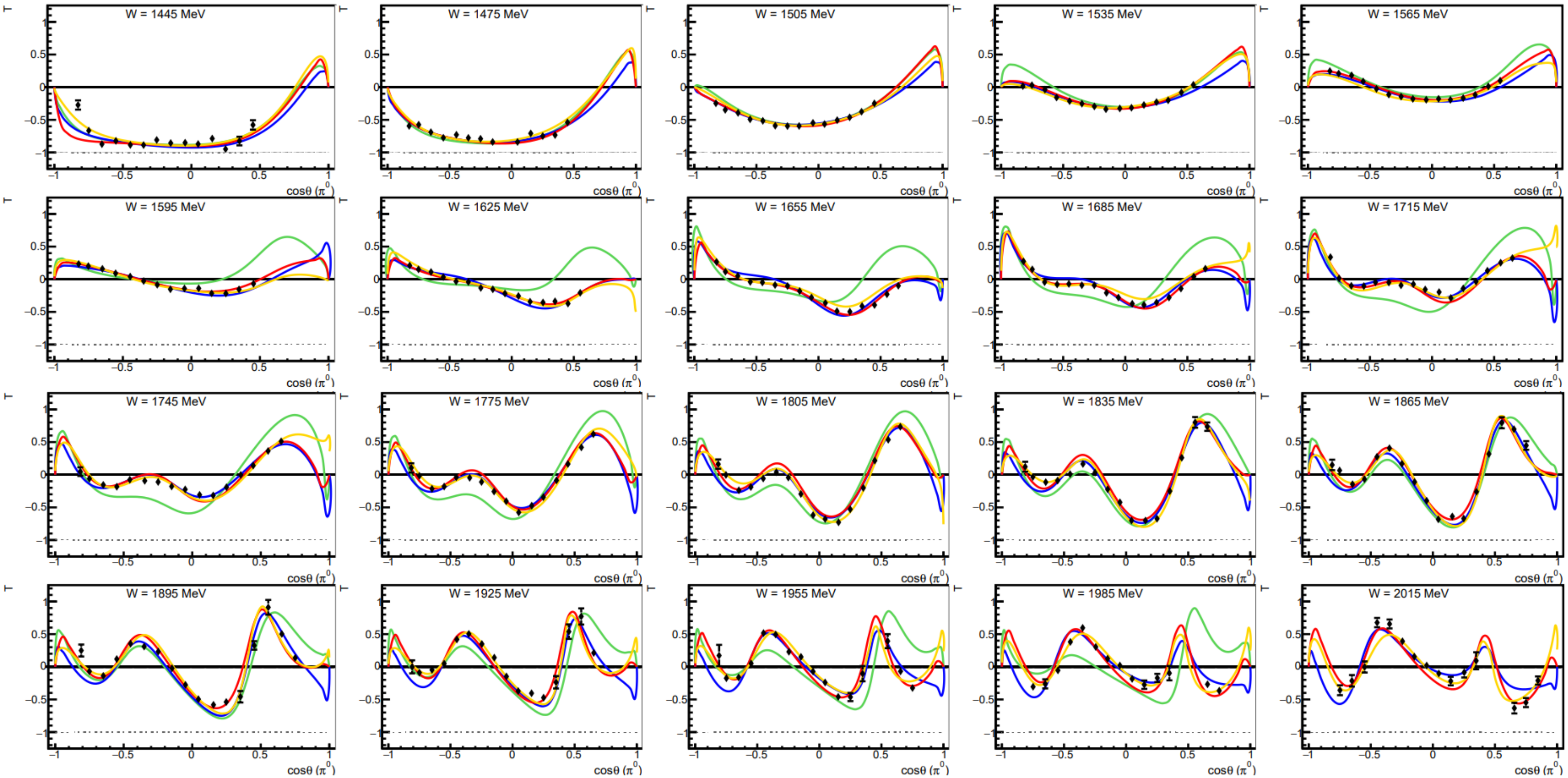
## $N(2190)7/2^-$

| **** | **JüBo (2023)** | **JüBo (2022)** | **PDG** |
|---|---|---|---|
| $Re\ W_0$ [MeV] | 1950 | 1965 | 2100 ± 50 |
| $-2Im\ W_0$ [MeV] | 156 | 287 | 400 ± 100 |

Photo couplings changes with $N(2220)9/2^+$ $\Delta(1930)5/2^-$ $\Delta(2200)7/2^-$

*Fits collaborated with D. Rönchen and Jülich-Bonn*

# Observables T and F in $\gamma p \to \pi^0 p$




SAID: -KX23 JüBo: -2023 BnGa: -2019 MAID: -2007 CLAS:◆

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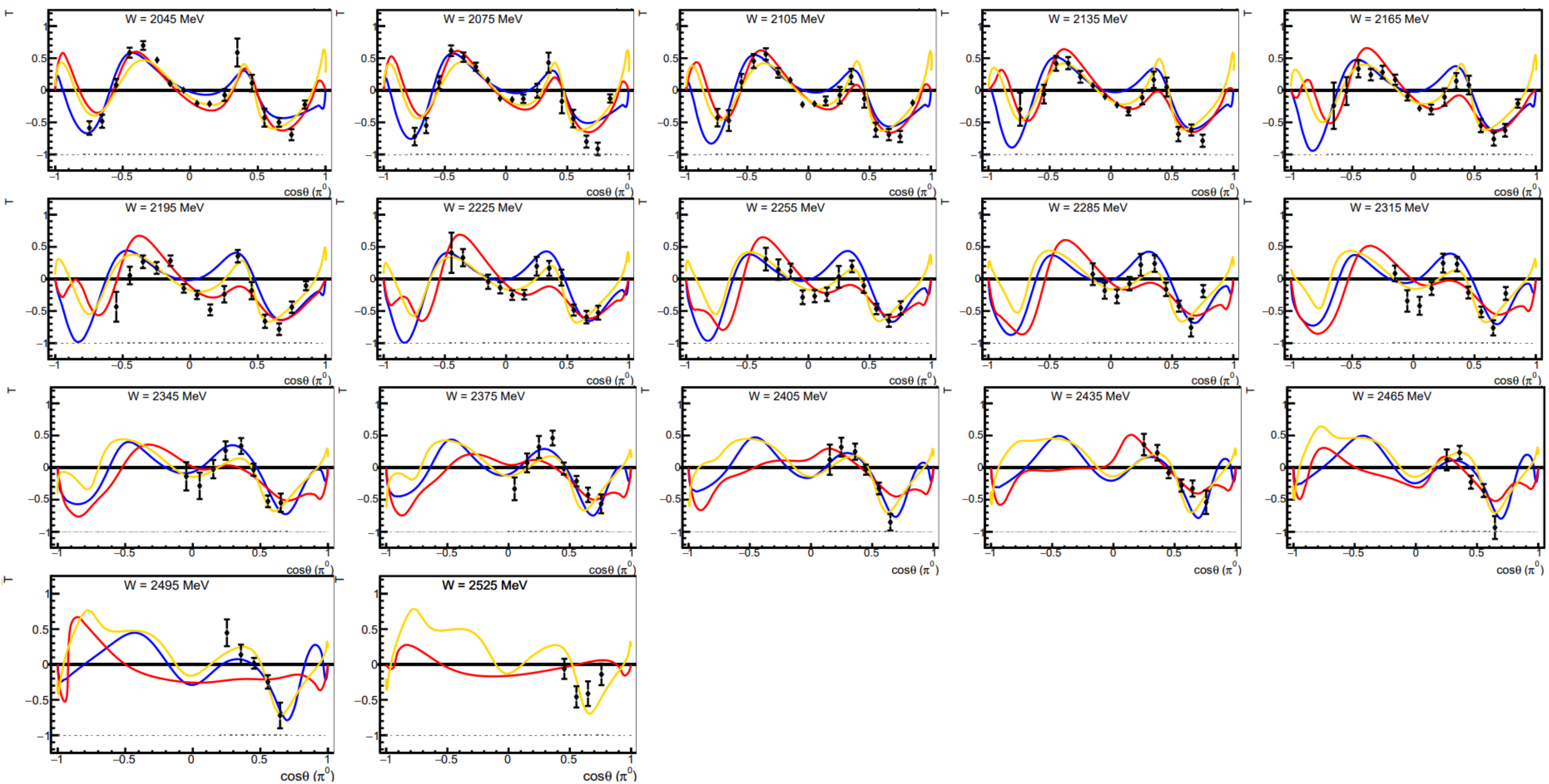


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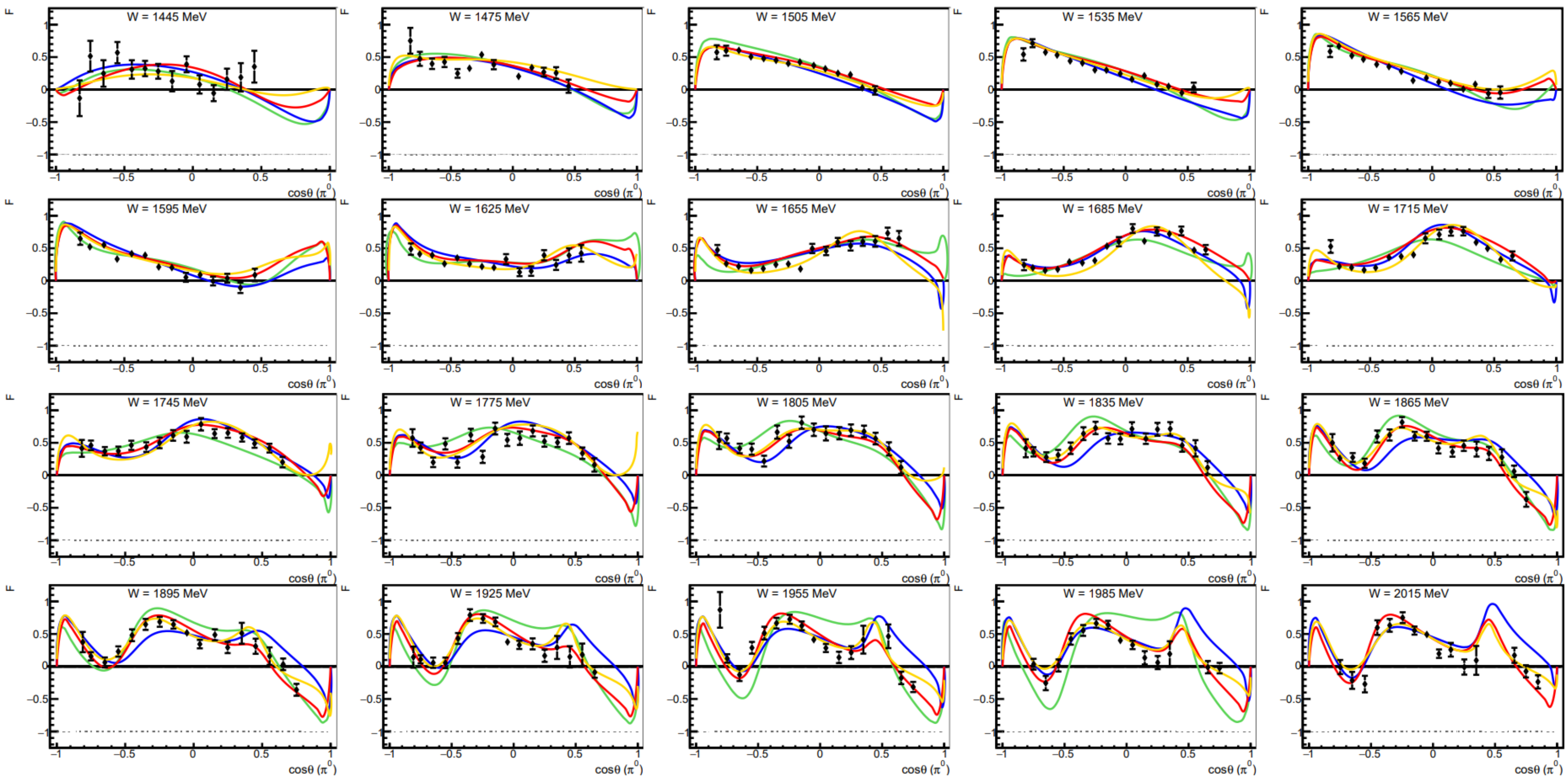


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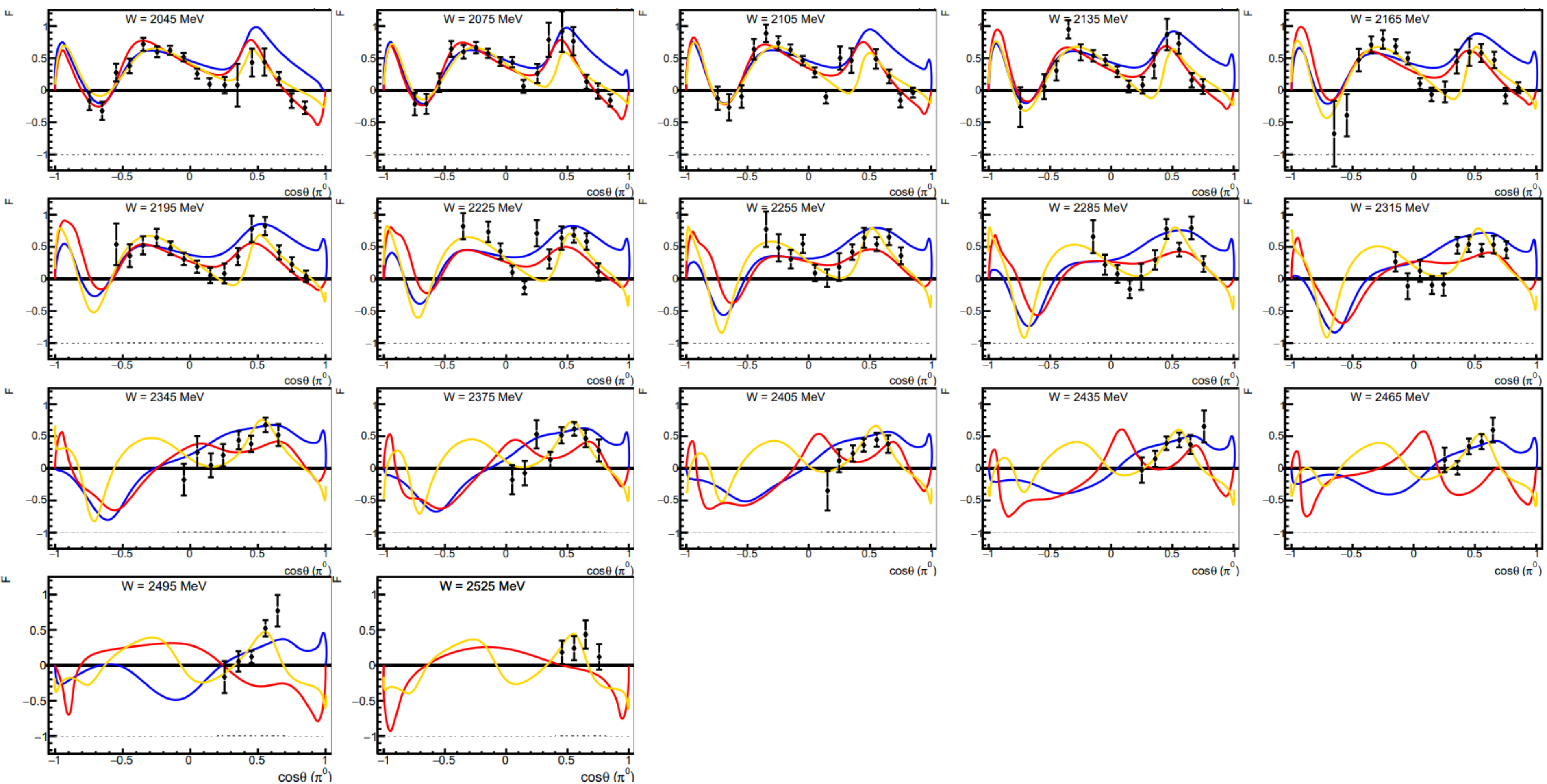


SAID: -KX23 JüBo: -2023 BnGa: -2019 MAID: -2007 CLAS: ◆

# Summary

Polarization observables are sensitive to small amplitudes and phase differences. They provide important constraints to reveal the dynamics and relevant degrees-of-freedom within hadrons.

Results of polarization observables T and F in the $\gamma p \rightarrow \pi^0 p$ reaction have been extracted for the center-of-mass energy from 1.43 GeV to 2.54 GeV in the FROST experiment at JLab.

The data generally agree with predictions of present partial-wave analyses, but also show marked differences. By incorporating the present data into the databases, the SAID fits have been improved with relatively small $\chi^2$ and significant changes in the parameters of the $\Delta(1910)1/2^+$ and $N(2190)7/2^-$ have been found with the JüBo model.