Polarization Observables *T* and *F* in the $\gamma p \rightarrow \pi^0 p$ Reaction

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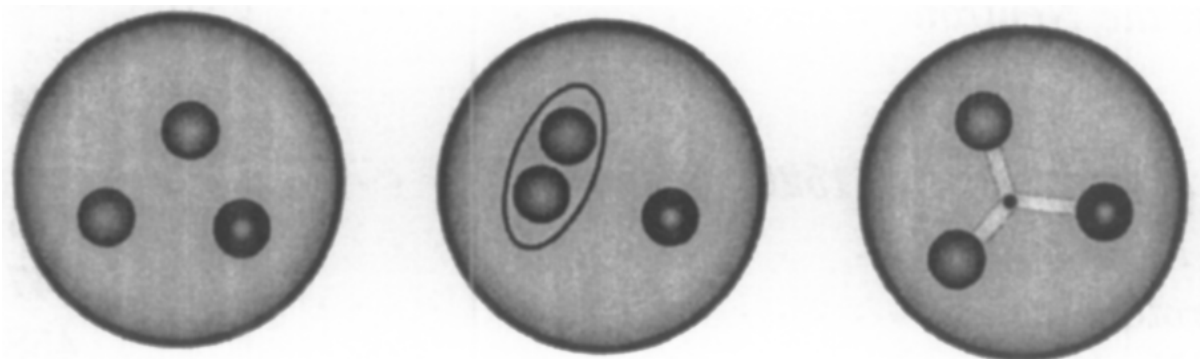
Baryon Spectroscopy

Baryon spectroscopy is a useful tool in the study of QCD as resonances reflect the dynamics and relevant degrees-of-freedom within hadrons. Different quark models may have different degrees-of-freedom.



There are still many resonances missing from quark model predictions, especially in the mass range higher than 1.7 GeV.

Figure Ref. : B. Krusche, S. Schadmand / Prog. Part. Nucl. Phys. 51 399-485 (2003)

Experimental Availability

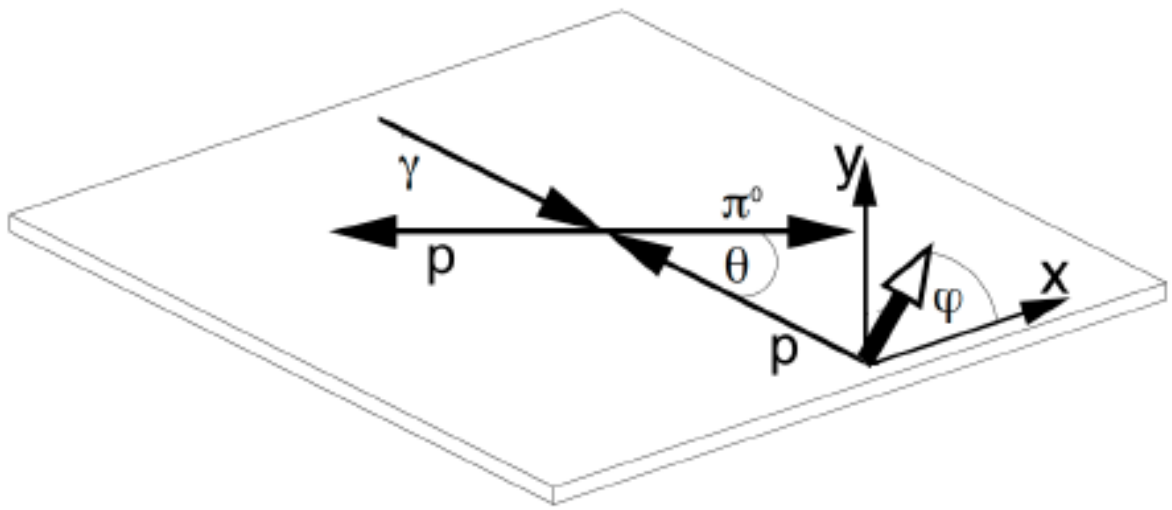
For the single-pion photoproduction reaction, with a polarized photon beam and a polarized target, the available observables are listed.

	Photon beam		
	unpolarized	circularly polarized	linearly polarized
Target			
unpolarized	$d\sigma/d\Omega$	—	Σ
longitudinally	—	E	G
transversely	$\boxed{T}$	$\boxed{F}$	H, P

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

Formalism

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

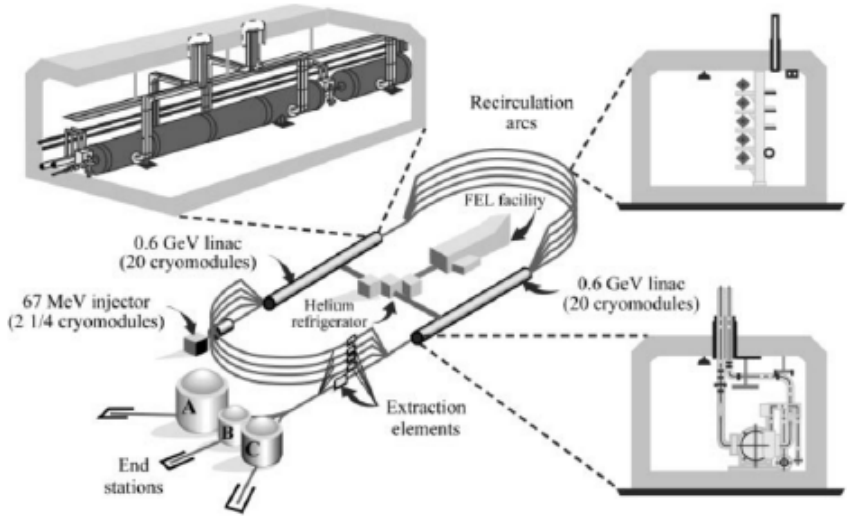


$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}(1 + P_t P_\gamma F \cos\varphi + P_t T \sin\varphi)$$

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

The Experiment at JLab

Jefferson Lab

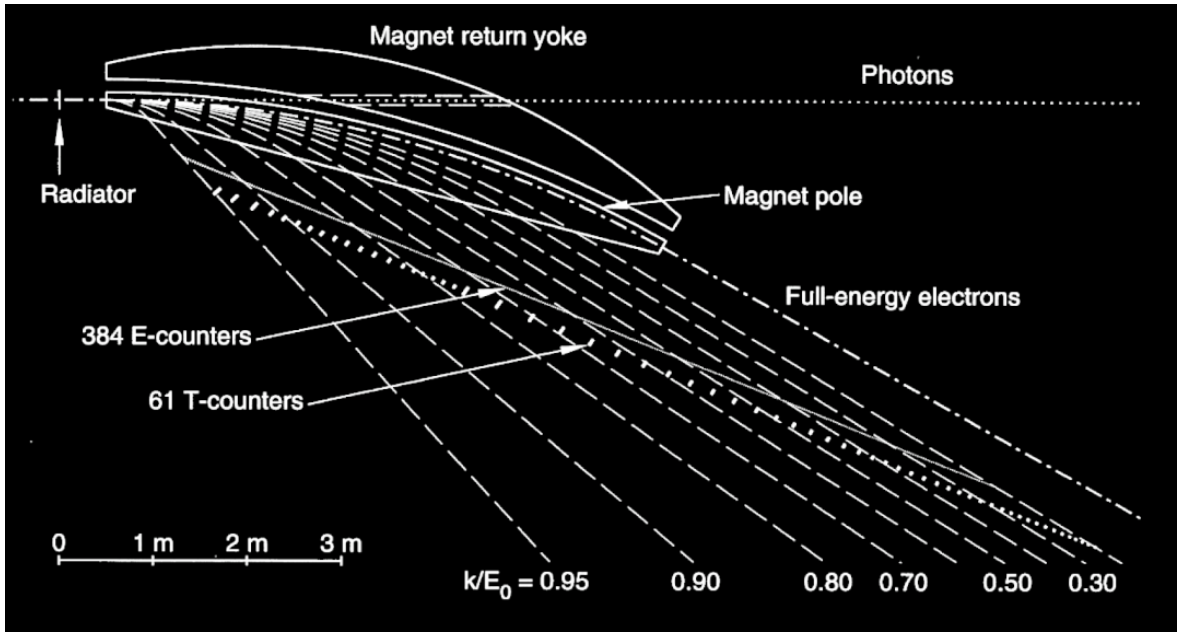


CEBAF accelerator

This experiment was conducted at Thomas Jefferson National Accelerator Facility (Jefferson Lab). The Continuous Electron Beam Accelerator Facility (CEBAF) was able to accelerate electrons up to 6 GeV (now 12 GeV).

Figures Ref.: C. W. Leemann, D. R. Douglas, and G. A. Krafft, "The Continuous Electron Beam Accelerator Facility: CEBAF at the Jefferson Laboratory," *Annual Review of Nuclear and Particle Science, vol. 51, p. 413, 2001.*

Circularly Polarized Tagged Photon Beam



Longitudinally polarized electrons, $P_e \approx 87\%$, with an energy of 3.082 GeV and 2.266 GeV were incident on the radiator and produced circularly tagged photons between 0.64 GeV and 2.96 GeV. The electron-beam helicity was pseudo-randomly flipped between +1 and −1 with a 240 Hz rate.

Figure Ref.: D. Sober *et al., "The bremsstrahlung tagged photon beam in Hall B at JLab," Nucl. Instrum. Meth. A, vol. 440, pp. 263–284, 2000.*

FROST Target

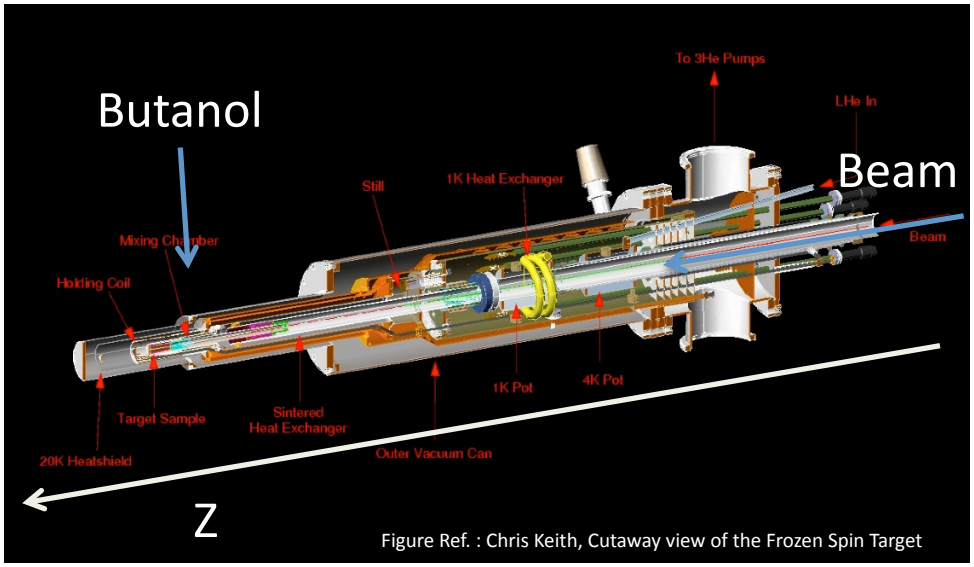
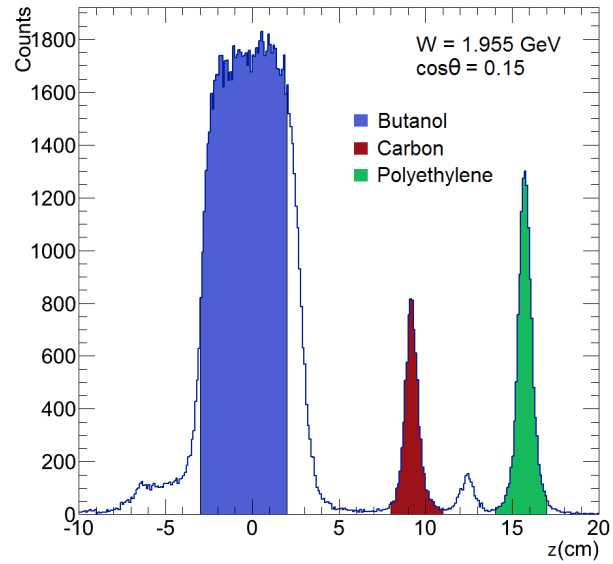


Figure Ref. : Chris Keith, Cutaway view of the Frozen Spin Target

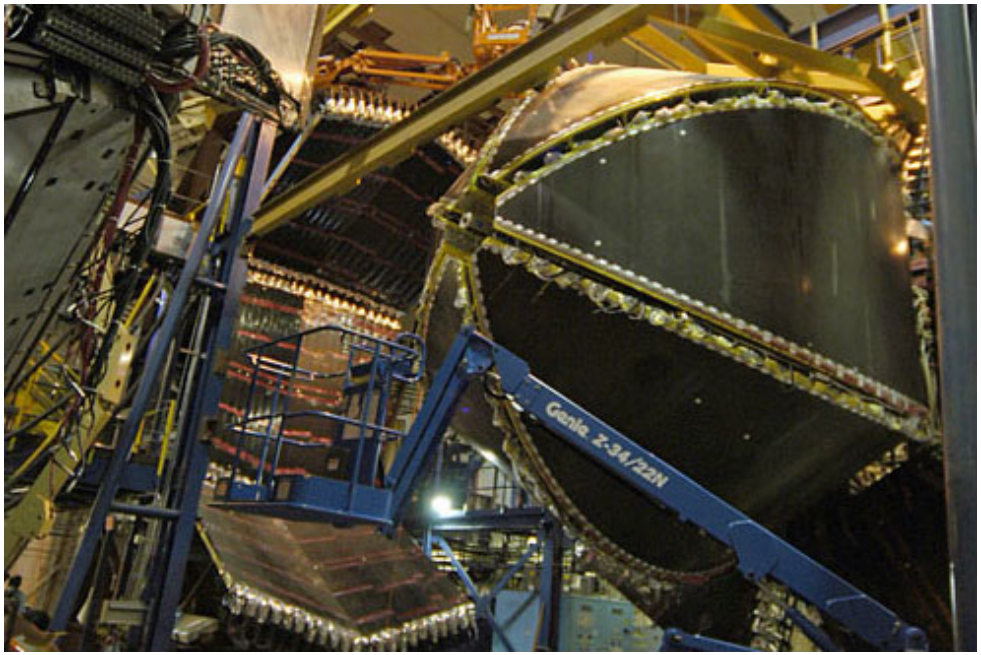
Reconstructed Reaction Vertex

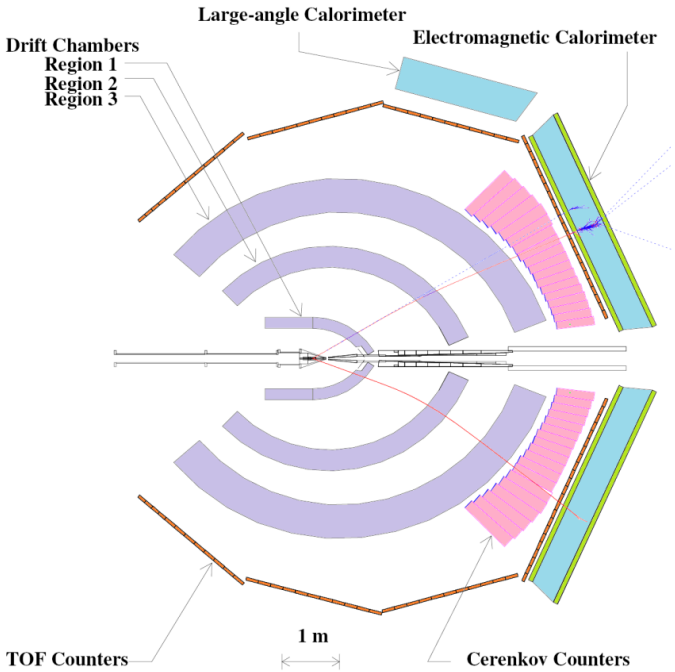


The FROzen Spin Target (FROST) is a polarized target. The free protons from hydrogen atoms in the butanol (C_4H_9OH) target were polarized, $P_t \approx 80\%$. The target-polarization orientations were also flipped regularly.

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

CEBAF Large Acceptance Spectrometer





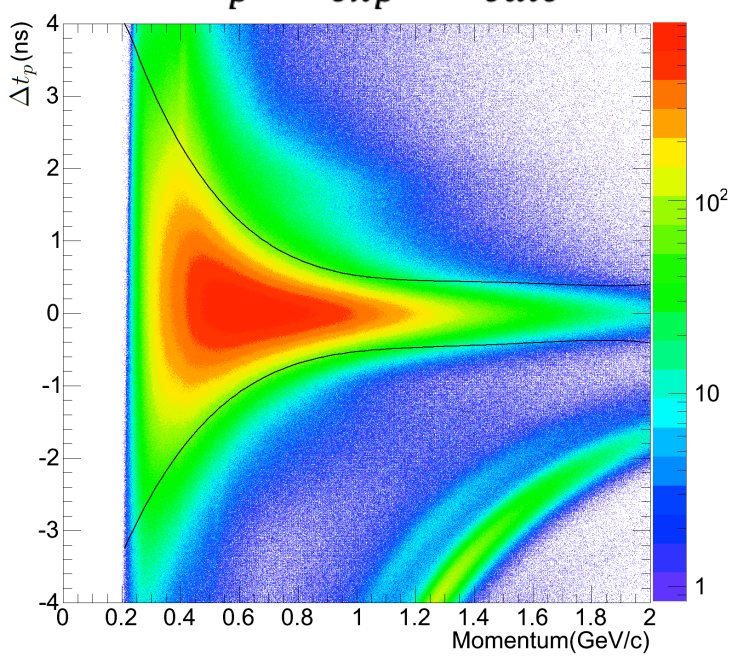
The momentum and velocity of final−state particles were measured by the drift chambers and the TOF counters respectively. Events with 1 positively charged particle and 0 negatively charged particles were filtered for the $\pi^0 p$ final state.

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

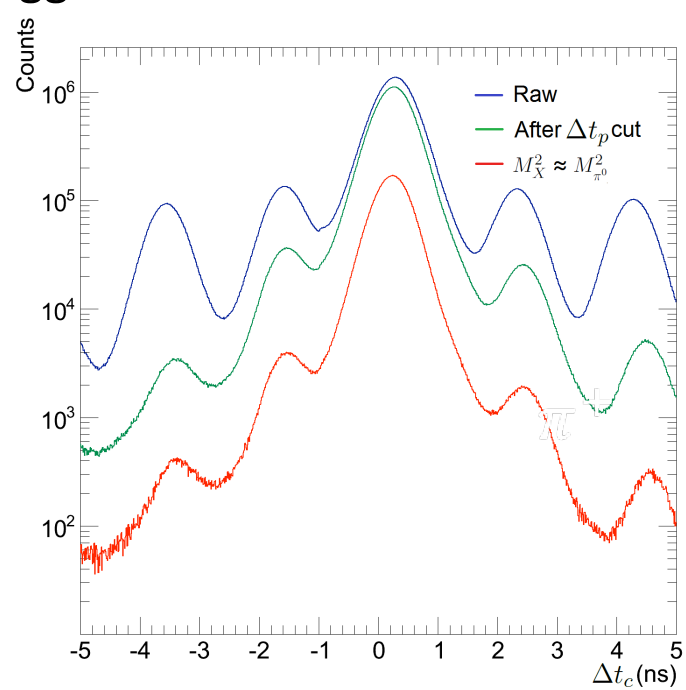
Proton Identification and Photon Selection

The identification of the final-state proton was done by using the time-of-fight difference.

$$\Delta t_p = t_{exp} - t_{calc}$$



The photon that initiated the reaction and was coincident with the detected proton was selected by using the CLAS-tagger coincidence time.

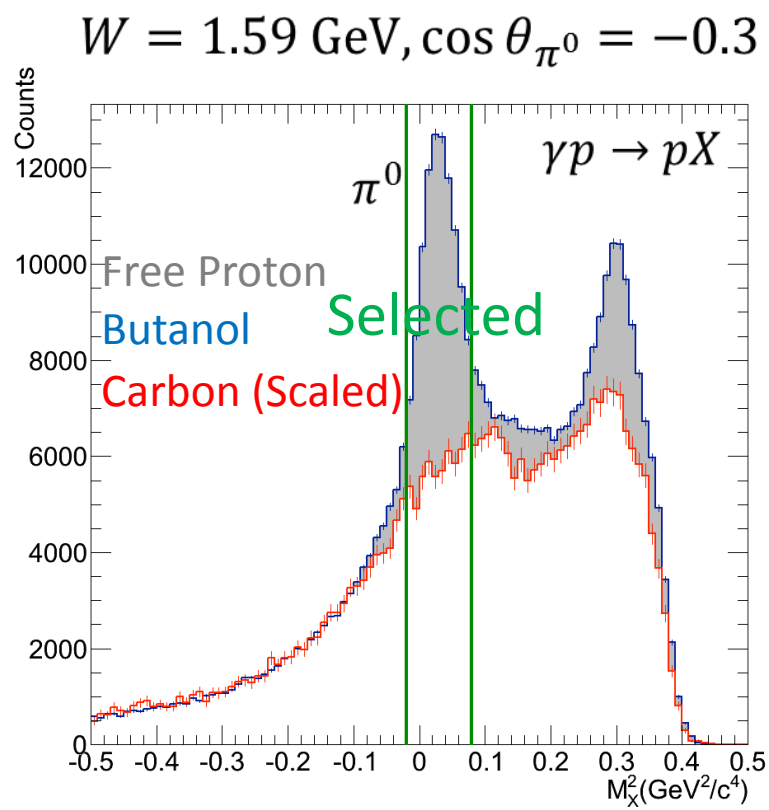


Reaction Channel and Extraction of Yields

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 $\gamma p \to pX$.

$$Y_{\sin^n \varphi} = \frac{\sum_i (\sin^n \varphi_i)}{N_c} \qquad Y_{\cos^n \varphi} = \frac{\sum_i (\cos^n \varphi_i)}{N_c}$$

The dilution factor is calculated from the butanol and carbon yields, $h = \frac{N_P}{N_B}$, and accounts for the bound-nucleon background.



Determination of Observables T and F

$$\frac{d\sigma}{d\Omega} = \frac{d\sigma_0}{d\Omega}(1 + P_t P_\gamma F \cos\varphi + P_t T \sin\varphi)$$

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

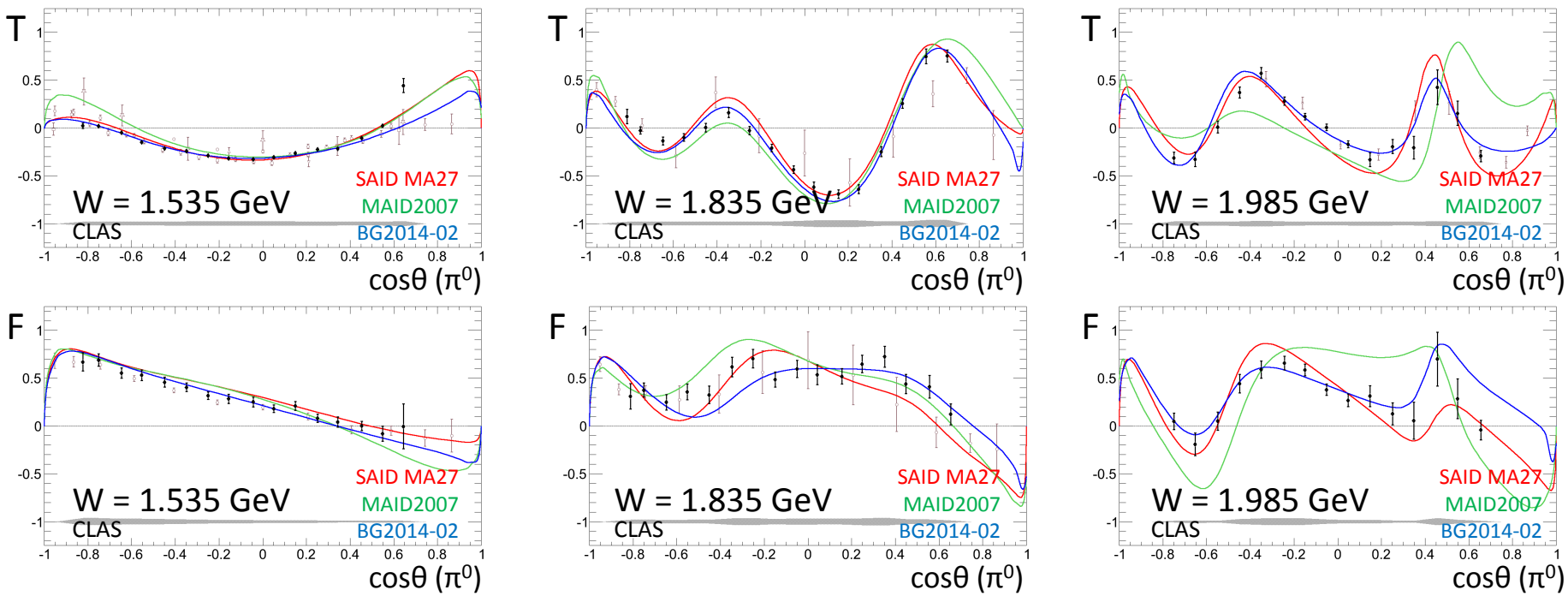
$$T = \frac{1}{h}\frac{Y_{\sin\varphi}{}^{\nearrow} - Y_{\sin\varphi}{}^{\swarrow}}{P_{t\swarrow} Y_{\sin^2\varphi}{}^{\nearrow} + P_{t\nearrow} Y_{\sin^2\varphi}{}^{\swarrow}}$$

$$F = \frac{1}{h}\frac{Y_{\cos\varphi}{}^{+\nearrow} - Y_{\cos\varphi}{}^{-\nearrow} + Y_{\cos\varphi}{}^{-\swarrow} - Y_{\cos\varphi}{}^{+\swarrow}}{P_\gamma P_{t\swarrow}(Y_{\cos^2\varphi}{}^{+\nearrow} + Y_{\cos^2\varphi}{}^{-\nearrow}) + P_\gamma P_{t\nearrow}(Y_{\cos^2\varphi}{}^{+\swarrow} + Y_{\cos^2\varphi}{}^{-\swarrow})}$$

$\nearrow/\swarrow$ indicates the direction of target polarization.
$+/-$ indicates the helicity of photon beam.
$Y_{\sin\varphi}$, $Y_{\cos\varphi}$, $Y_{\sin^2\varphi}$ and $Y_{\cos^2\varphi}$ are the normalized moments.
h is the dilution factor.

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

Observables were extracted for 34 bins in W from 1.49 GeV to 2.51 GeV.



Preliminary

BS(79) DNPL BUSSEY, NPB154, 492(79)
FK(78) TOKY FUKUSHIMA, NPB136, 189(78)
BH(77) DNPL BOOTH, NPB121, 45(77)
FE(76) TOKY FELLER, NPB110, 397(76)
HA(14) BONN HARTMANN, PRL113, 062001(2014)

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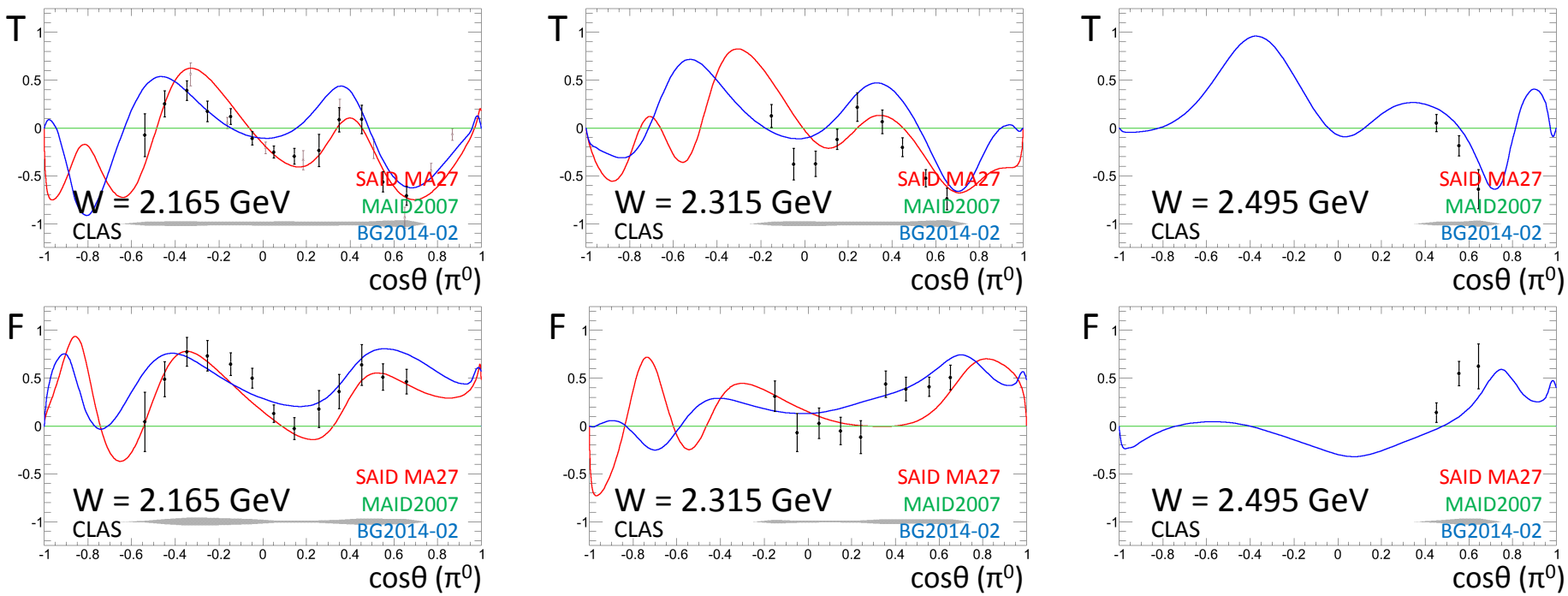

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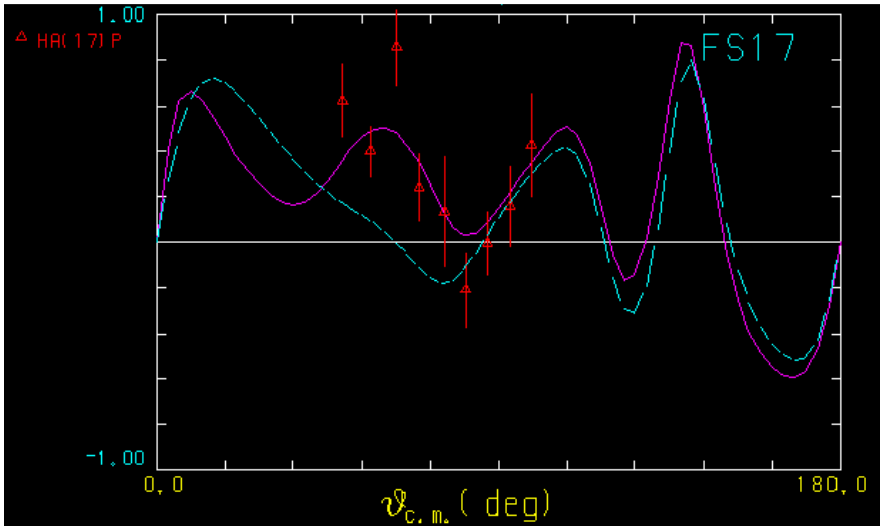
Interpretation of Results (SAID)

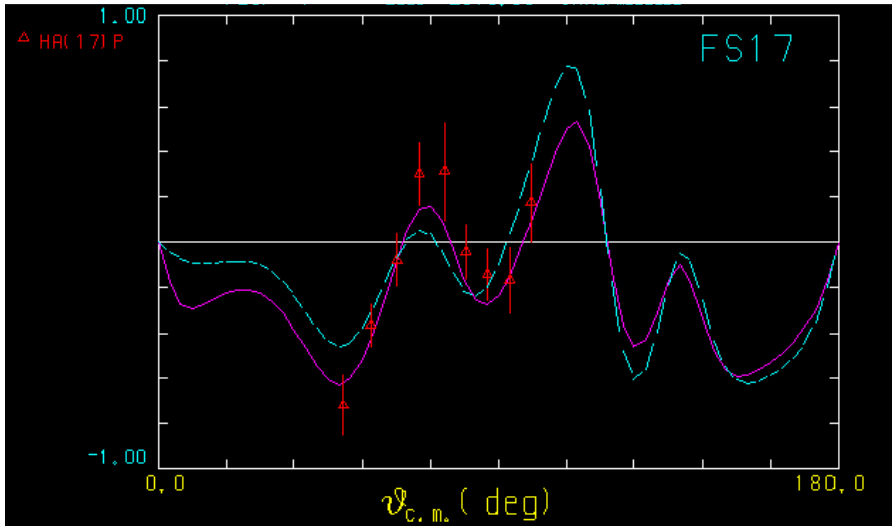
The fit by SAID is likely a fine-tuning of the existing waves.

W = 2.315 GeV

F



T



R. Workman (SAID), private communication (2017)

Fit of Results (JuBo)

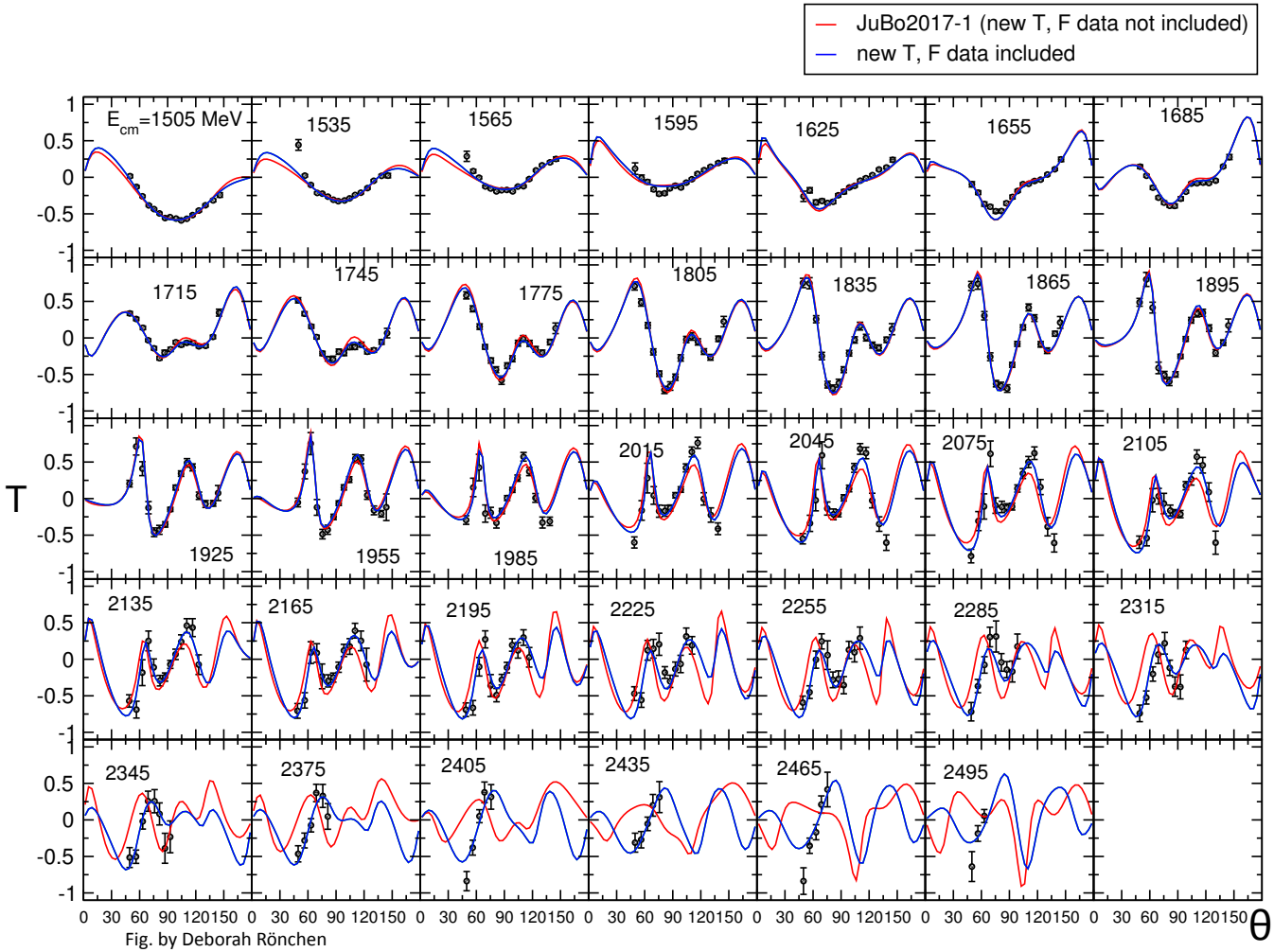


Fig. by Deborah Rönchen

Fit of Results (JuBo)

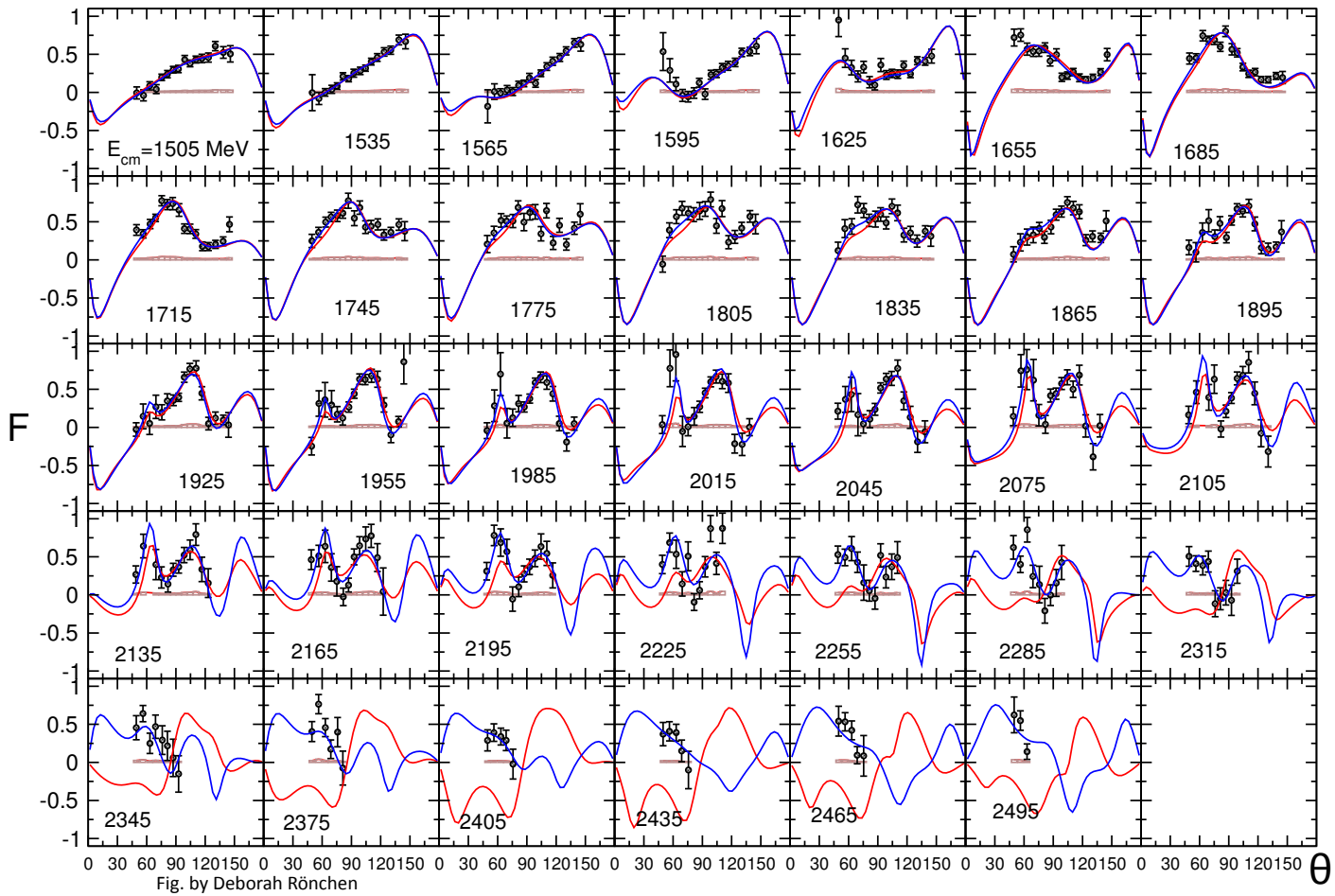


Fig. by Deborah Rönchen

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.

Preliminary 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 1.49 GeV to 2.51 GeV in the FROST experiment at JLab.

The present SAID, BnGa, and MAID model predictions generally agree with the data, but also show marked differences. The data constrain further partial-wave analyses and will improve the extraction of proton-resonance properties. The SAID and JuBo groups have made preliminary fits to the data and a more detailed analysis is ongoing.