Polarization Observables T and F in Single π^0 and η-Photoproduction off Quasi-Free Nucleons

Thomas Strub, A2 Collaboration

University of Basel

28th August 2014, PANIC 2014

FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

Outline

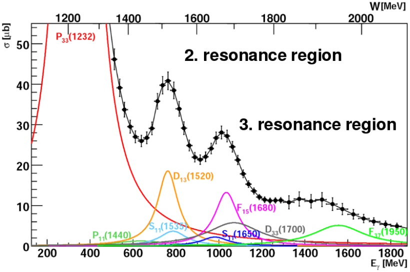
Motivation

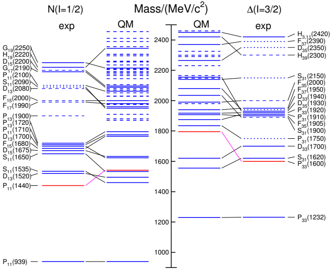
Problems on experimental side

- Nucleons' excitation spectrum is a complicated overlap of many short lived, broad resonances
- Cannot be understood from differential cross sections alone

Problems on theory side

- QM predicts more states than observed (missing resonances)
- Perturbative QCD cannot be applied in this energy region
- Lattice gauge QCD cannot (yet) reproduce all desired properties





Motivation

Solution

- Effective quark models
- Experiment delivers observables to fix the models parameters via PWA

Polarization observables from meson photoproduction

- Probing spin degrees of freedom
- Unique PWA solution
  $\Longrightarrow$ Need 8 (of 16) carefully chosen observables for complete experiment
- Include angular momentum $L \leq 3$, i.e., S, P, D, F-wave
  $\Longrightarrow$ Need full angular coverage, high precision measurements

Proton and neutron channel

- Probe isospin degree of freedom
- Isospin decomposition into A^{V3}, A^{IV}, A^{IS} for π photoproduction

$$A(\gamma p \to \pi^+ n) = -\sqrt{\frac{1}{3}}A^{V3} + \sqrt{\frac{2}{3}}\left(A^{IV} - A^{IS}\right) \quad A(\gamma p \to \pi^0 p) = +\sqrt{\frac{2}{3}}A^{V3} + \sqrt{\frac{1}{3}}\left(A^{IV} - A^{IS}\right)$$

$$A(\gamma n \to \pi^0 n) = +\sqrt{\frac{1}{3}}A^{V3} - \sqrt{\frac{2}{3}}\left(A^{IV} + A^{IS}\right) \quad A(\gamma n \to \pi^- p) = +\sqrt{\frac{2}{3}}A^{V3} + \sqrt{\frac{1}{3}}\left(A^{IV} + A^{IS}\right)$$

$\Longrightarrow$ At least one measurement off the *neutron* needed.

Motivation

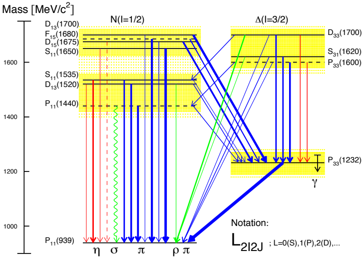
Special case η photoproduction

- Isospin $I = I_z = 0$.
- No isospin changing current ($A^{V3} = 0$)

$$A(\gamma p \to \eta p) = A^{IS} + A^{IV}$$
$$A(\gamma n \to \eta n) = A^{IS} - A^{IV}$$

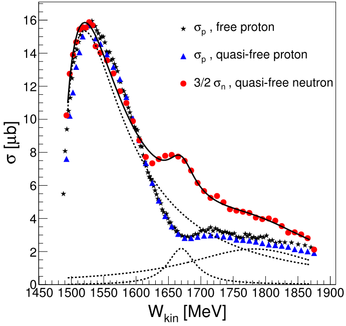
$\Longrightarrow$ only $N^*(I = \frac{1}{2})$ resonances contribute

- Recent results show a narrow structure around 1670 MeV



Photoproduction off the *neutron*

- Neutron bound in nucleus $\Longrightarrow$ quasi free neutron
- Correct treatment of Fermi motion
- Comparison of free and quasi free proton data (can differ due to FSI)



Experimental Setup

Experimental Setup

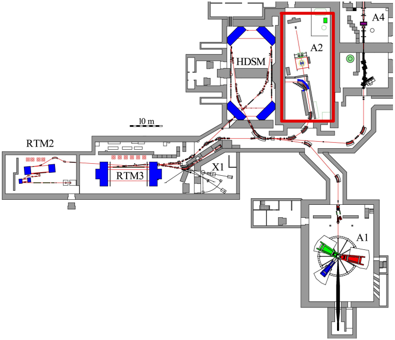
MAinzer MIcrotron

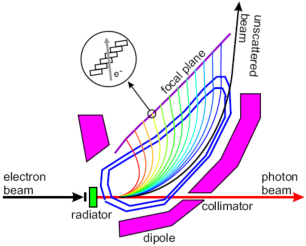
High quality electron beam

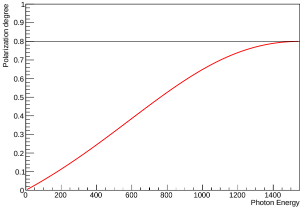
- Energy up to 1.5 GeV
- Intensity up to 100 μA
- Polarization $\approx$ 80%

Bremsstrahlung photons

- $1/E_\gamma$ distribution
- Photon polarization: Olsen maximum function





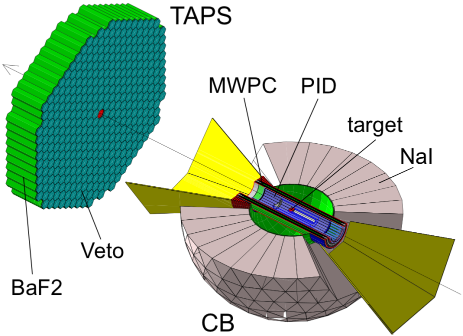


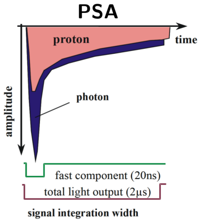
Crystal Ball/TAPS @ MAMI

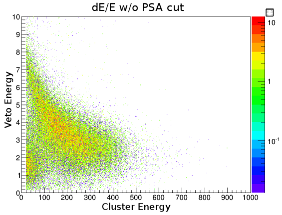
CB
- PID
- MPWC
- NaI crystals

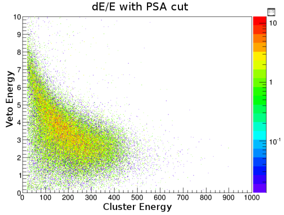
TAPS
- BaF2/PWO crystals
- Veto wall

$\Longrightarrow$ Almost 4π acceptance









Polarization Observables

Polarization Observables

General Formula

General decomposition of $d\sigma$ into 16 polarization observables reads

$$
\begin{aligned}
d\sigma^{\mathrm{B,T,R}}(\vec{P}^{\gamma},\vec{P}^{T},\vec{P}^{R}) = \frac{1}{2}\Big\{ & d\sigma_0 \left[1 - P_L^{\gamma} P_y^{T} P_{y'}^{R} \cos(2\phi_\gamma)\right] \\
& + \hat{\Sigma}\left[-P_L^{\gamma}\cos(2\phi_\gamma) + P_y^{T} P_{y'}^{R}\right] \\
& + \hat{T}\left[P_y^{T} - P_L^{\gamma} P_{y'}^{R}\cos(2\phi_\gamma)\right] \\
& + \hat{P}\left[P_{y'}^{R} - P_L^{\gamma} P_y^{T}\cos(2\phi_\gamma)\right] \\
& + \hat{E}\left[-P_c^{\gamma} P_z^{T} + P_L^{\gamma} P_x^{T} P_{y'}^{R}\sin(2\phi_\gamma)\right] \\
& + \hat{G}\left[P_L^{\gamma} P_z^{T}\sin(2\phi_\gamma) + P_c^{\gamma} P_x^{T} P_{y'}^{R}\right] \\
& + \hat{F}\left[P_c^{\gamma} P_x^{T} + P_L^{\gamma} P_z^{T} P_{y'}^{R}\sin(2\phi_\gamma)\right] \\
& + \hat{H}\left[P_L^{\gamma} P_x^{T}\sin(2\phi_\gamma) - P_c^{\gamma} P_z^{T} P_{y'}^{R}\right] \\
& + \hat{C}_{x'}\left[P_c^{\gamma} P_{x'}^{R} - P_L^{\gamma} P_y^{T} P_{z'}^{R}\sin(2\phi_\gamma)\right] \\
& + \hat{C}_{z'}\left[P_c^{\gamma} P_{z'}^{R} + P_L^{\gamma} P_y^{T} P_{x'}^{R}\sin(2\phi_\gamma)\right] \\
& + \hat{O}_{x'}\left[P_L^{\gamma} P_{x'}^{R}\sin(2\phi_\gamma) + P_c^{\gamma} P_y^{T} P_{z'}^{R}\right] \\
& + \hat{O}_{z'}\left[P_L^{\gamma} P_{z'}^{R}\sin(2\phi_\gamma) - P_c^{\gamma} P_y^{T} P_{x'}^{R}\right] \\
& + \hat{L}_{x'}\left[P_z^{T} P_{x'}^{R} + P_L^{\gamma} P_x^{T} P_{z'}^{R}\cos(2\phi_\gamma)\right] \\
& + \hat{L}_{z'}\left[P_z^{T} P_{z'}^{R} - P_L^{\gamma} P_x^{T} P_{x'}^{R}\cos(2\phi_\gamma)\right] \\
& + \hat{T}_{x'}\left[P_x^{T} P_{x'}^{R} - P_L^{\gamma} P_z^{T} P_{z'}^{R}\cos(2\phi_\gamma)\right] \\
& + \hat{T}_{z'}\left[P_x^{T} P_{z'}^{R} + P_L^{\gamma} P_z^{T} P_{x'}^{R}\cos(2\phi_\gamma)\right]\Big\}
\end{aligned}
$$

Definition of T and F

- Target asymmetry T
  $\Longrightarrow$ Transversally polarized target $\vec{P}^T = P_x^T \neq 0$

- Double polarization observable F
  $\Longrightarrow$ Transversally polarized target $\vec{P}^T = P_x^T \neq 0$
  Circularly polarized photon beam $\vec{P}^\gamma = P_c^\gamma \neq 0$

- For $\vec{P}^R = 0$ (unpolarized recoil), $\vec{P}^\gamma = P_c^\gamma$ (circular photon polarization) and $\vec{P}^T = P_x^T$ (transverse target polarization) the general decomposition reduces to

$$
\begin{aligned}
d\sigma(\vec{P}^\gamma, \vec{P}^T, 0) &= \frac{1}{2} d\sigma_0 \left\{ 1 + T P_y^T + F P_c^\gamma P_x^T \right\} \\
&= \frac{1}{2} d\sigma_0 \left\{ 1 + T |P^T| \cos(\phi') + F |P^\gamma| |P^T| \cos(\phi) \right\} .
\end{aligned}
$$

- Observables T and F manifest themselves by a cosine-$\phi^{(\prime)}$-modulated unpolarized cross-section

Definition of T and F (experimental approach)

T and F can be rewritten as

$$T\cos(\phi') = \frac{1}{P^T P^\gamma}\frac{d\sigma^\uparrow(\phi') - d\sigma^\downarrow(\phi')}{d\sigma^\uparrow(\phi') + d\sigma^\downarrow(\phi')},$$

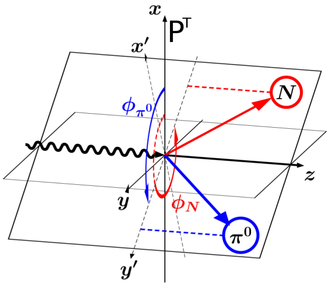
where $(\uparrow, \downarrow)$ denotes the target polarization state,

$$F\cos(\phi) = \frac{1}{P^T P^\gamma}\frac{d\sigma^-(\phi) - d\sigma^+(\phi)}{d\sigma^-(\phi) + d\sigma^+(\phi)},$$

where $(+, -)$ denotes the photon helicity state.

Here, $F = F(E,\theta)$, $T = T(E,\theta)$, $P^T = P^T(t)$ and $P^\gamma = P^\gamma(E^\gamma, P_B(t))$

- Symmetric contributions cancel in the numerator
- Denominator equals unpolarized $d\sigma$



- $\phi =$ Angle between target polarization vector and production plane
- $\phi' =$ Angle between target polarization vector and normal to production plane

Methods to extract T and F

Polarized target: D-butanol (C_4D_9OD)

- Only deuterons are polarized
- Carbon/oxygen contribution vanish in numerator

Two methods can be used:

- 1. Normalize with deuterium target

$$A\cos(\phi) = \frac{1}{P_T P_\gamma} \frac{d\sigma^-_{DB}(\phi) - d\sigma^+_{DB}(\phi)}{d\sigma^-_{D}(\phi) + d\sigma^+_{D}(\phi)}$$

$\Longrightarrow$ Needs flux and efficiency correction of count rates.

- 2. Normalize with D-butanol target

$$A\cos(\phi) = \frac{1}{P_T P_\gamma} \frac{dN^-_{DB}(\phi) - dN^+_{DB}(\phi)}{dN^-_{DB}(\phi) + dN^+_{DB}(\phi)} \cdot d$$

$\Longrightarrow$ No need for flux and efficiency correction, but dilution factor d, i.e.,

$$d = 1 + \frac{d\sigma^0_C}{d\sigma^0_{DB}}$$

Analysis Methods

Analysis Methods

Event selection

- Event selection
  - Full exclusive on proton (neutron as spectator)

$\gamma + d \longrightarrow \pi^0 + p(n)$	$\longrightarrow 2\gamma + p(n)$	2 neutral, 1 charged
$\gamma + d \longrightarrow \eta + p(n)$	$\longrightarrow 2\gamma + p(n)$	2 neutral, 1 charged
$\gamma + d \longrightarrow \eta + p(n) \longrightarrow 3\pi^0 + p(n)$	$\longrightarrow 6\gamma + p(n)$	6 neutral, 1 charged

  - Full exclusive on neutron (proton as spectator)

$\gamma + d \longrightarrow \pi^0 + n(p)$	$\longrightarrow 2\gamma + n(p)$	3 neutral, 0 charged
$\gamma + d \longrightarrow \eta + n(p)$	$\longrightarrow 2\gamma + n(p)$	3 neutral, 0 charged
$\gamma + d \longrightarrow \eta + n(p) \longrightarrow 3\pi^0 + p(n)$	$\longrightarrow 6\gamma + n(p)$	7 neutral, 0 charged

- Determination of the neutron candidate by χ^2-test.
- Invariant mass cut on all 3 π^0 from $\eta \rightarrow 6\gamma$ decay.

Applied Cuts

All cuts are determined from LD_2 target for all θ and energy bins.

- Coplanarity cut

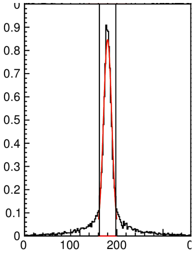
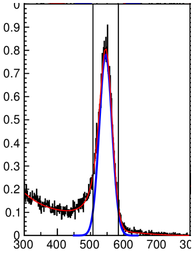
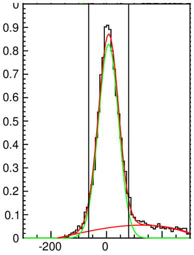
$$\Delta\phi = 180^\circ - |\phi_{\text{meson}} - \phi_{\text{recoil}}|$$

- Invariant mass cut

$$\Delta m_{\text{meson}} = |P^\mu_{\text{meson}}| - m^{\text{theo.}}_{\text{meson}}$$

- Missing mass cut

$$\Delta MM = |P^\mu_\gamma + P^\mu_{\text{nucleon}} - P^\mu_{\text{meson}}| - m^{\text{theo}}_{\text{nucleon}}$$

Reconstruction of Kinematics

Transfer kinematics into CM frame

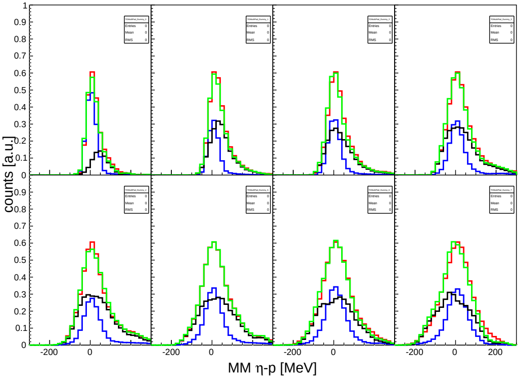
- Fermi momentum from deuterium (carbon/oxygen) target
  $\Longrightarrow$ Initial state not determined
- Reconstruction of nucleons Fermi momentum from final state, i.e., solve

$$P_{\gamma}^{\mu} + P_{\text{nucleon}}^{\mu} = P_{\text{meson}}^{\mu} + P_{\text{recoil}}^{\mu}$$

  for P_{nucleon}^{μ}.
- Have enough information to reconstruct Fermi momentum of nucleon.

Determination of Dilution Factor

- Determination of the dilution factor from missing mass spectra
- Carbon + x Deuterium = Sum ≈ D-butanol

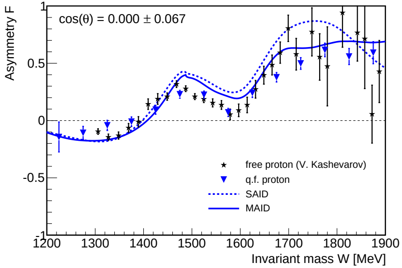


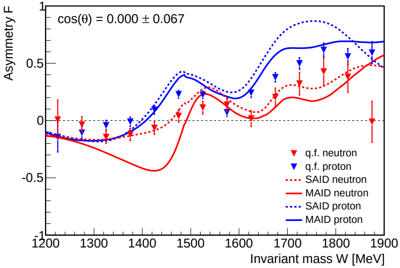
- Dilution factor $d = 1 + \int_{MMcut} \Delta MM_{\text{carbon}} \;/\; \int_{MMcut} \Delta MM_{\text{deuterium}}$

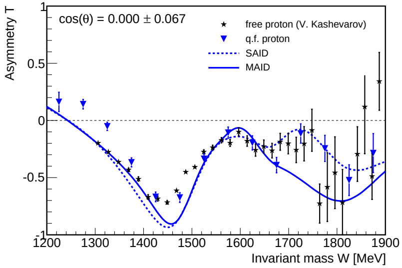
Selected Results

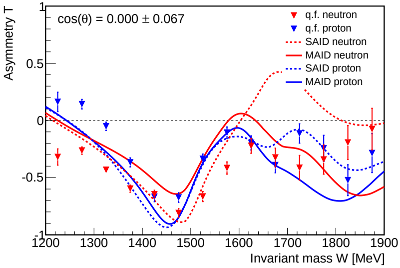
Selected Results (preliminary)

T and F for Single π^0 Photoproduction (preliminary)

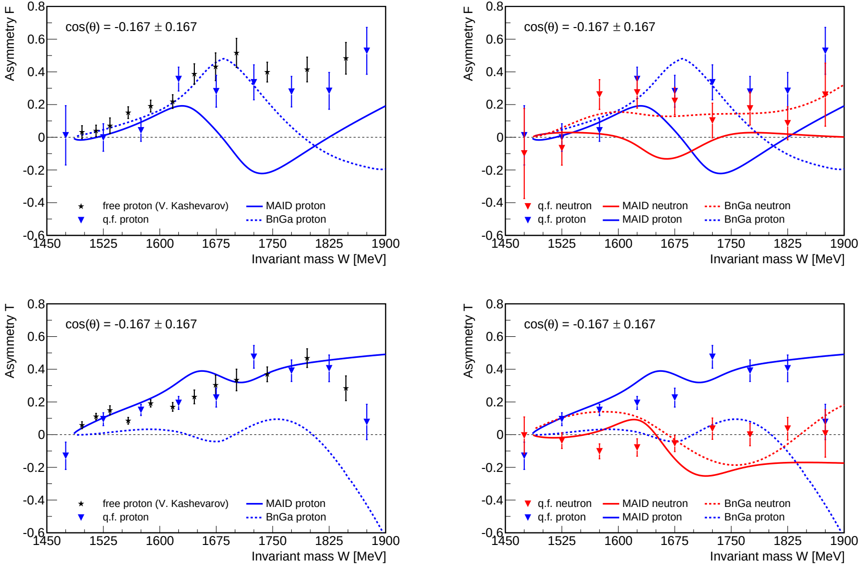








T and F for η Photoproduction (preliminary)



Conclusion

Conclusion

- Preliminary results for T and F for single π^0- and η photoproduction off quasi free nucleons
- Very good agreement with free proton data
- Models fail for ...
  ... higher energies
  ... the neutron channel
  ... the η channel

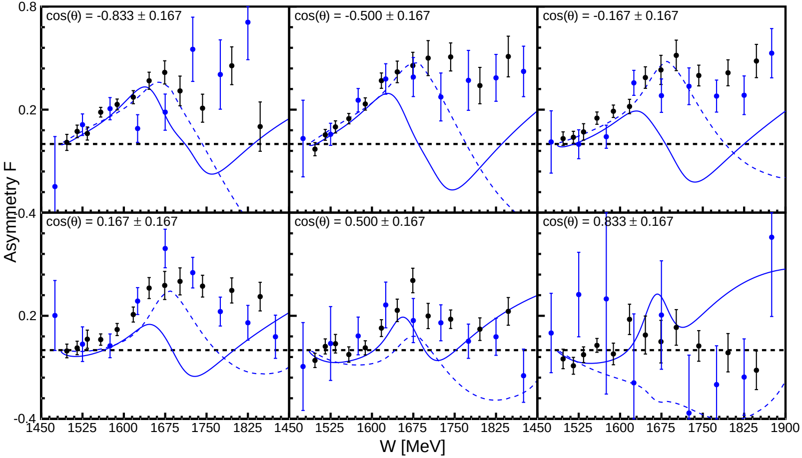
Outlook

- Use full statistic (here: $\pi^0 \approx 70\%$, $\eta \approx 50\%$)
- Observables for double meson photoproduction
- Final results will contribute to the 'complete experiment'
  $\Longrightarrow$ Possible impact on models

Thanks

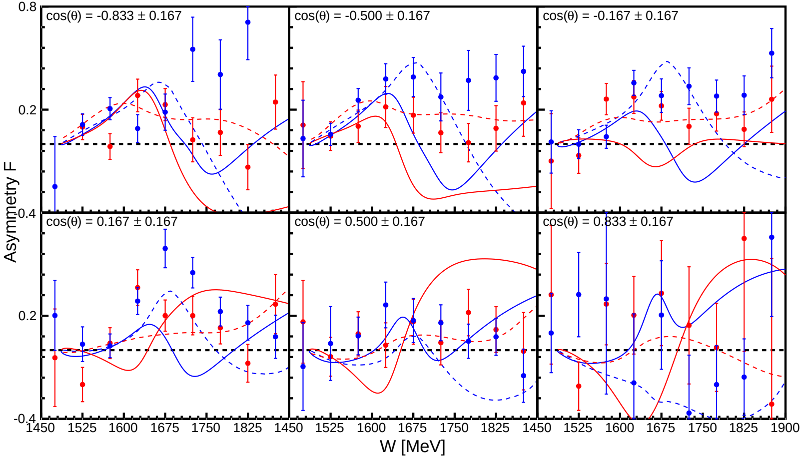
Thank you for your attention.

F: ηp

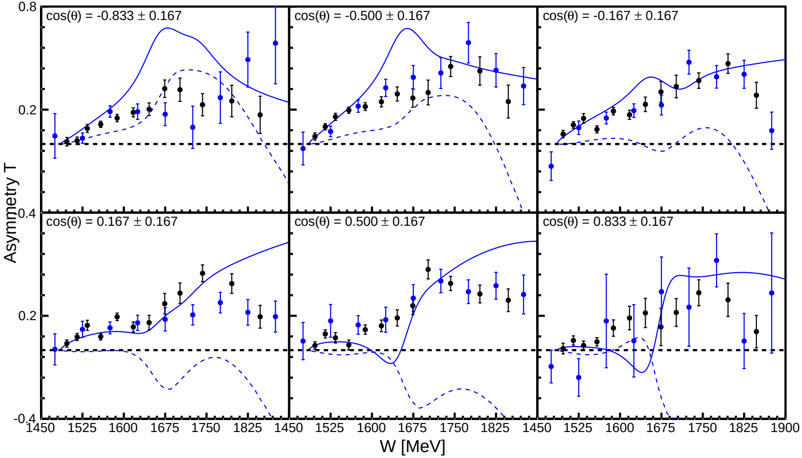


cos(θ) = -0.833 ± 0.167
cos(θ) = -0.500 ± 0.167
cos(θ) = -0.167 ± 0.167
cos(θ) = 0.167 ± 0.167
cos(θ) = 0.500 ± 0.167
cos(θ) = 0.833 ± 0.167
0.8
0.2
-0.4
Asymmetry F
1450
1525
1600
1675
1750
1825
1900
W [MeV]

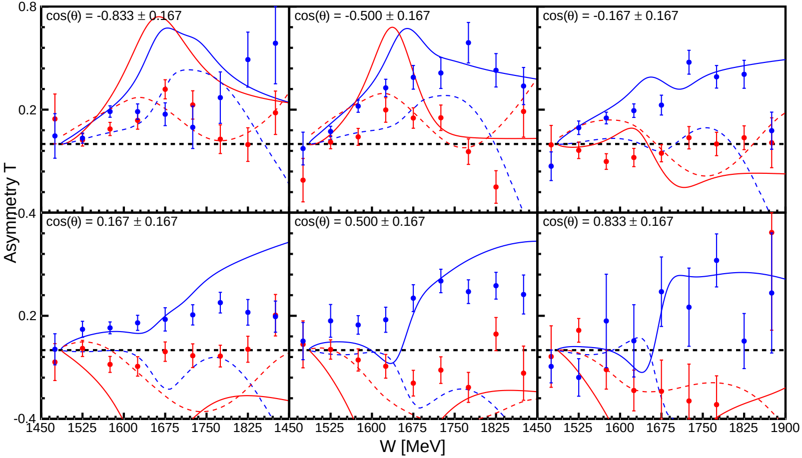
F: ηn


cos(θ) = -0.833 ± 0.167
cos(θ) = -0.500 ± 0.167
cos(θ) = -0.167 ± 0.167
cos(θ) = 0.167 ± 0.167
cos(θ) = 0.500 ± 0.167
cos(θ) = 0.833 ± 0.167
Asymmetry F
W [MeV]
0.8
0.2
-0.4
1450
1525
1600
1675
1750
1825
1900

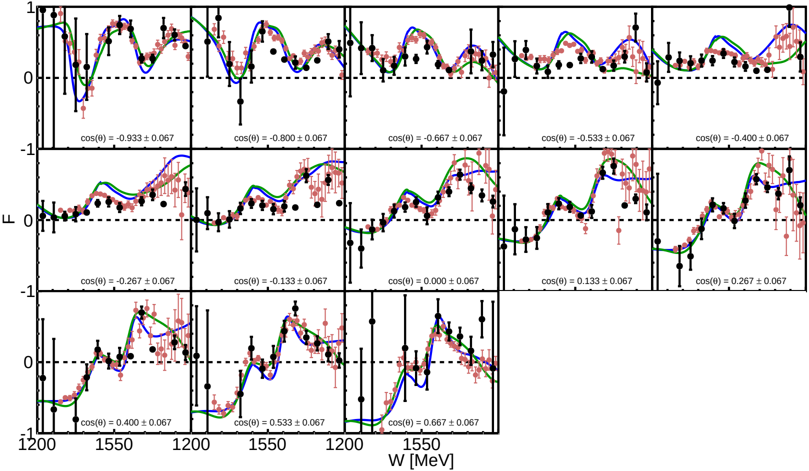
T: ηp


cos(θ) = -0.833 ± 0.167
cos(θ) = -0.500 ± 0.167
cos(θ) = -0.167 ± 0.167
cos(θ) = 0.167 ± 0.167
cos(θ) = 0.500 ± 0.167
cos(θ) = 0.833 ± 0.167
0.8
0.2
-0.4
Asymmetry T
1450 1525 1600 1675 1750 1825 1900
W [MeV]

T: ηn

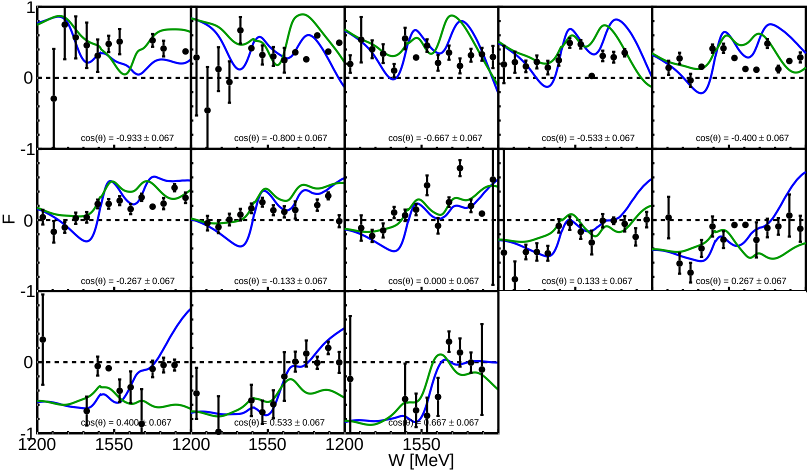

cos(θ) = -0.833 ± 0.167
cos(θ) = -0.500 ± 0.167
cos(θ) = -0.167 ± 0.167
cos(θ) = 0.167 ± 0.167
cos(θ) = 0.500 ± 0.167
cos(θ) = 0.833 ± 0.167
Asymmetry T
W [MeV]
0.8
0.2
-0.4
1450
1525
1600
1675
1750
1825
1900

F: $\pi^0 p$



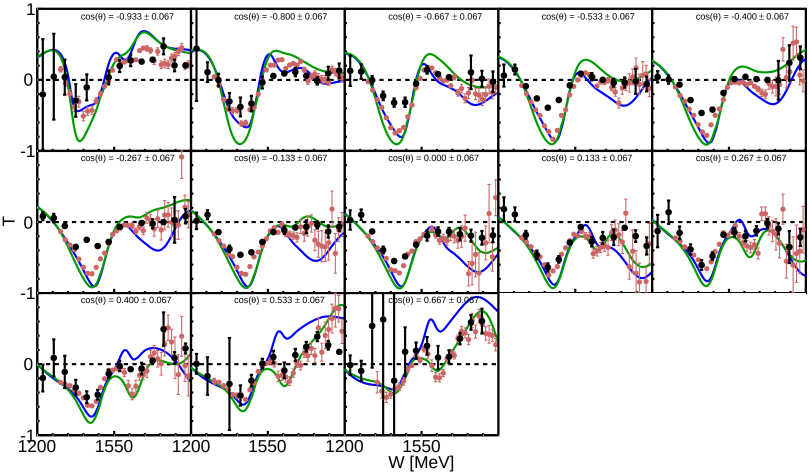
1
0
-1
F
cos(θ) = -0.933 ± 0.067
cos(θ) = -0.800 ± 0.067
cos(θ) = -0.667 ± 0.067
cos(θ) = -0.533 ± 0.067
cos(θ) = -0.400 ± 0.067
cos(θ) = -0.267 ± 0.067
cos(θ) = -0.133 ± 0.067
cos(θ) = 0.000 ± 0.067
cos(θ) = 0.133 ± 0.067
cos(θ) = 0.267 ± 0.067
cos(θ) = 0.400 ± 0.067
cos(θ) = 0.533 ± 0.067
cos(θ) = 0.667 ± 0.067
1200
1550
W [MeV]

F: $\pi^0 n$

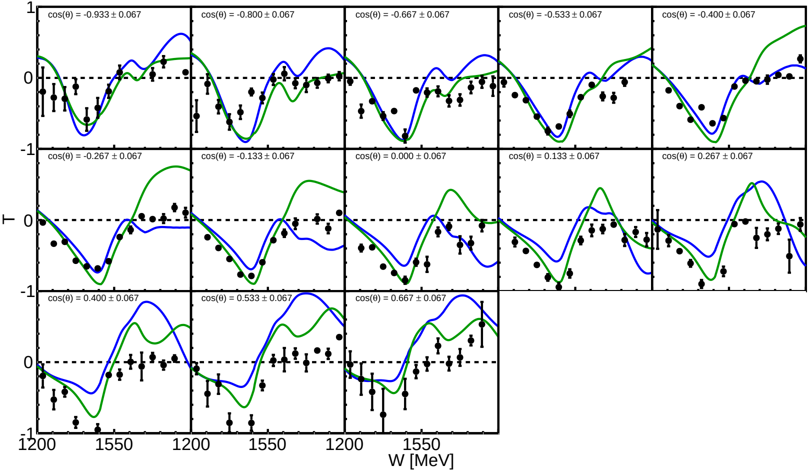


F
W [MeV]
1
0
-1
1200
1550
cos(θ) = -0.933 ± 0.067
cos(θ) = -0.800 ± 0.067
cos(θ) = -0.667 ± 0.067
cos(θ) = -0.533 ± 0.067
cos(θ) = -0.400 ± 0.067
cos(θ) = -0.267 ± 0.067
cos(θ) = -0.133 ± 0.067
cos(θ) = 0.000 ± 0.067
cos(θ) = 0.133 ± 0.067
cos(θ) = 0.267 ± 0.067
cos(θ) = 0.400 ± 0.067
cos(θ) = 0.533 ± 0.067
cos(θ) = 0.667 ± 0.067

T: $\pi^0 p$


cos(θ) = -0.933 ± 0.067
cos(θ) = -0.800 ± 0.067
cos(θ) = -0.667 ± 0.067
cos(θ) = -0.533 ± 0.067
cos(θ) = -0.400 ± 0.067
cos(θ) = -0.267 ± 0.067
cos(θ) = -0.133 ± 0.067
cos(θ) = 0.000 ± 0.067
cos(θ) = 0.133 ± 0.067
cos(θ) = 0.267 ± 0.067
cos(θ) = 0.400 ± 0.067
cos(θ) = 0.533 ± 0.067
cos(θ) = 0.667 ± 0.067
T
1
0
-1
1200
1550
W [MeV]

T: $\pi^0 n$


cos(θ) = -0.933 ± 0.067
cos(θ) = -0.800 ± 0.067
cos(θ) = -0.667 ± 0.067
cos(θ) = -0.533 ± 0.067
cos(θ) = -0.400 ± 0.067
cos(θ) = -0.267 ± 0.067
cos(θ) = -0.133 ± 0.067
cos(θ) = 0.000 ± 0.067
cos(θ) = 0.133 ± 0.067
cos(θ) = 0.267 ± 0.067
cos(θ) = 0.400 ± 0.067
cos(θ) = 0.533 ± 0.067
cos(θ) = 0.667 ± 0.067
T
1
0
-1
1200
1550
W [MeV]