Neutral Pion Photoproduction in the Threshold Region

Testing Chiral Perturbation Theory

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Outline

1. Motivation
2. Single-Polarization Measurement: $\vec{\gamma} p \to \pi^0 p$
3. Double-Polarization Measurement: $\vec{\gamma} \vec{p} \to \pi^0 p$
4. Outlook

How do we test QCD in the non-perturbative regime?

High-precision measurements with polarization observables.

Near-Threshold π^0 Photoproduction

Can be used to test **Chiral Perturbation Theory (ChPT)**, an effective field-theory of the strong interaction based on the symmetries of QCD.

In its domain of validity, **ChPT** represents predictions of QCD *subject to the errors imposed by uncertainties in the LECs and by neglect of higher order terms.*

Any discrepancy which is significantly larger than the combined experimental and theoretical errors **MUST** be taken seriously!

Lattice QCD is another technique, and presently great strides are being made. . .

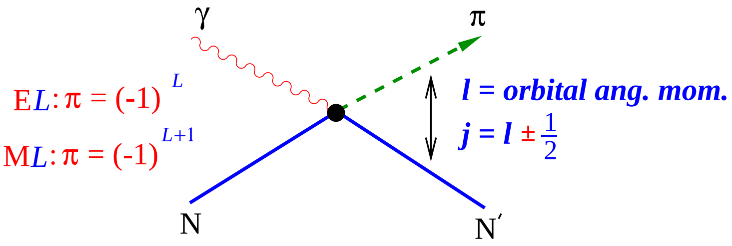
Partial-Wave Analysis and Multipoles

How can we compare experimental results to ChPT and other theoretical approaches?

Through partial-wave analysis by extracting multipoles.

- Multipoles are an instructive meeting ground between theory and experiment.
- A **Model-Independent Partial-Wave Analysis** can be used to obtain the multipoles from experiment.

Photoproduction Amplitudes



In the threshold region, S-, P- and even D-waves contribute:

$l = 0$	E_{0^+}	S-wave
$l = 1$	E_{1^+}, M_{1^+}, M_{1^-},	P-waves
$l = 2$	E_{2^+}, E_{2^-}, M_{2^+}, M_{2^-}	D-waves

Energy dependence of P-waves is not totally clear: $\sim q$, $\sim qk$ or something completely different?

The D-waves are small, but non-negligible.

Partial-Wave Analysis

A carefully chosen set of 8 independent observables is enough for a complete description of an experiment using photoproduction.

For a complete partial-wave analysis, one needs fewer observables, and with 4 one can obtain solutions with only discrete sign ambiguities.

Below the 2π threshold, we only need two observables and unitarity.

set	observables			
single	$\mathbf{d\sigma/d\Omega}$	$\mathbf{\Sigma}$	**T**	P
beam-target	G	H	E	**F**
beam-recoil	Ox'	Oz'	Cx'	Cz'
target-recoil	Tx'	Tz'	Lx'	Lz'

Model-Independent Partial-Wave Analysis

With help from

L. Tiator, M. Hilt, C. Fernández Ramírez, A.M. Bernstein

Complete PWA in π^0 photoproduction below 2π threshold.

Need only two observables, $d\sigma/d\Omega$, Σ, and unitarity.

How is it done?

- Use Empirical Single-Energy *and* Energy-Dependent Fits to $d\sigma/d\Omega$ and Σ.
- Extract coefficients and multipoles.
- Compare to ChPT and other theoretical approaches.

Empirical Single-Energy Fits to the Multipoles

S- and P-waves only

$$\frac{d\sigma}{d\Omega}(\theta) = \frac{q}{k}\left(a_0 + a_1 \cos\theta + a_2 \cos^2\theta\right)$$

$$\frac{d\sigma}{d\Omega}(\theta)\Sigma(\theta) = \frac{q}{k}\sin^2\theta\, b_0$$

Coefficients

$$a_0 = |E_{0+}|^2 + {P_{23}}^2 \qquad P_1 = 3E_{1+} + M_{1+} - M_{1-}$$

$$a_1 = 2\mathrm{Re}E_{0+}P_1 \qquad P_2 = 3E_{1+} - M_{1+} + M_{1-}$$

$$a_2 = {P_1}^2 - {P_{23}}^2 \qquad P_3 = 2M_{1+} + M_{1-}$$

$$b_0 = \frac{1}{2}\left({P_3}^2 - {P_2}^2\right) \qquad {P_{23}}^2 = \frac{1}{2}({P_2}^2 + {P_3}^2)$$

4 measured quantities, a_0, a_1, a_2, b_0, and 4 unknown real parameters, $\mathrm{Re}E_{0+}, P_1, P_2, P_3$.

Empirical Energy-Dependent Fits to the Multipoles

Multipoles are expanded as a function of W

Fit the coefficients using the following ansatz:

S-wave:

$$E_{0^+}(W) = E_{0^+}^{(0)} + E_{0^+}^{(1)} \left[\frac{k_\gamma^{\text{lab}}(W) - k_{\gamma,\text{thr}}^{\text{lab}}}{m_{\pi^+}} \right] + i\beta \frac{q_{\pi^+}(W)}{m_{\pi^+}}$$

P-wave:

$$P_i(W) = \frac{q_{\pi^0}(W)}{m_{\pi^+}} \left\{ P_i^{(0)} + P_i^{(1)} \left[\frac{k_\gamma^{\text{lab}}(W) - k_{\gamma,\text{thr}}^{\text{lab}}}{m_{\pi^+}} \right] \right\}$$

Superscripts (0),(1) denote intercept and slope, respectively.

Obtain smooth function of incident photon energy.

$\vec{\gamma}\mathbf{p} \to \pi^0\mathbf{p}$

Analysis done by S. Prakhov (UCLA) and DH. Paper in preparation.

Theory support from L. Tiator, M. Hilt, S. Scherer, C. Fernández Ramírez, and A.M. Bernstein. To be published very soon.

- Data taken in December 2008.
- CB-TAPS detector system.
- Big improvement over previous result (TAPS 2001, Schmidt et al.)

$\vec{\gamma}\mathbf{p} \to \pi^0\mathbf{p}$ – Experimental Details

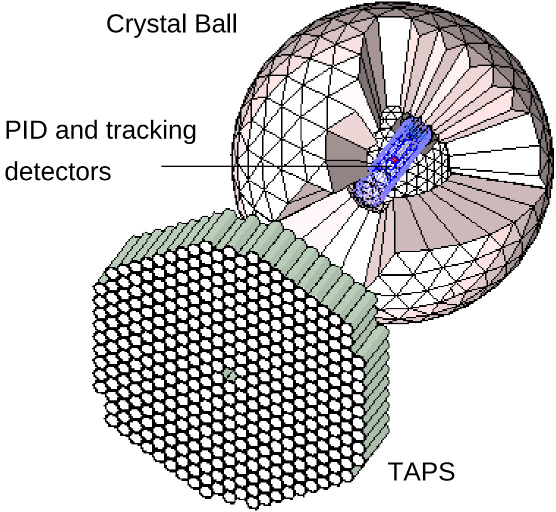
Equipment:

- A2 Hall.
- Glasgow-Mainz photon-tagging spectrometer.
- CB-TAPS.
- Cryogenic LH_2 "snout" target.

Run Parameters:

Electron Beam Energy	855 MeV
Target	10-cm LH_2
Radiator	100 μm Diamond
Tagged Energy Range	100 – 800 MeV
Channel Energy Resolution	2.4 MeV
Polarization Edge	$\sim$ 190 MeV
Degree of Polarization	40 – 70%
Beam on Target	90 h Full + 20 h Empty

Detector Set-Up



CB: 672 NaI detectors

PID: 24-scintillator veto barrel around target

TAPS: 384 BaF_2 detectors with individual vetoes

Covered $\approx$96% of 4π sr

Relatively complicated target set up due to "snout" configuration.

Comparison with TAPS 2001

Advantage CB-TAPS 2008

- Efficiency for π^0 detection: 90% vs. 10%.
- Target-empty data taken.
- Higher polarization.
- Smaller systematic errors.

Advantage TAPS 2001

- 40% less target-window material due to target and scattering-chamber design.
- Better incident photon energy resolution.

Disagreement for $\boldsymbol{\Sigma}$ with TAPS 2001

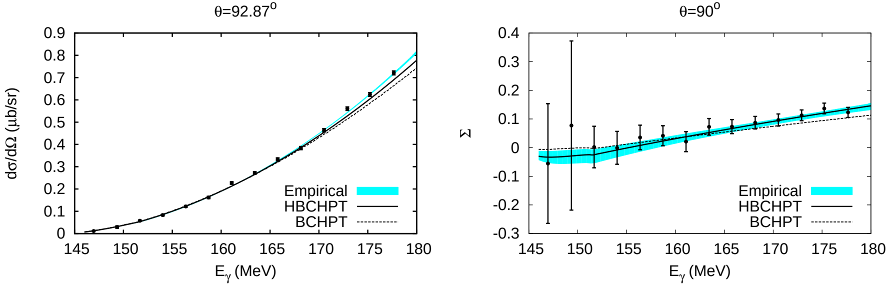
Serious disagreement between CB-TAPS 2008 and TAPS 2001 for Σ

Source? $\Rightarrow$ Target windows in TAPS 2001 measurement.

- 0^+ nuclei (C and O) have $\Sigma = 1$ and thus contribute *significantly* to the measured asymmetry.
- $d\sigma/d\Omega$ was corrected for target windows but Σ was NOT!

Erratum for TAPS 2001 has been submitted to PRL...

$d\sigma/d\Omega$ and Σ at 90°



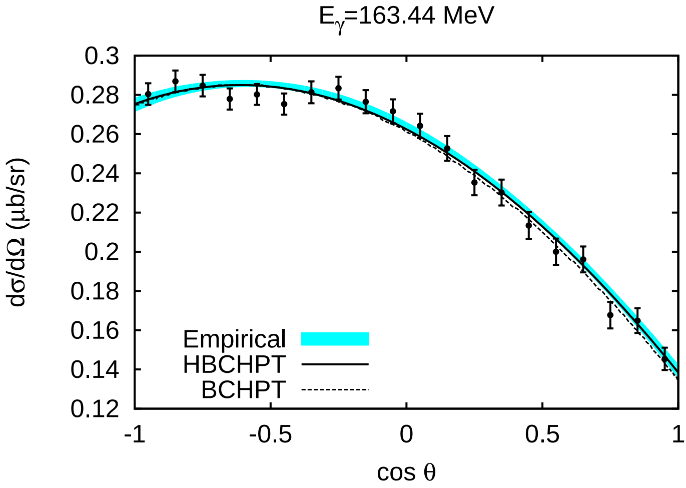
Plots courtesy of C. Fernández Ramírez

Excellent statistics in both $d\sigma/d\Omega$ and Σ

For the first time, energy dependence of Σ.

Good agreement with ChPT.

Sample Results



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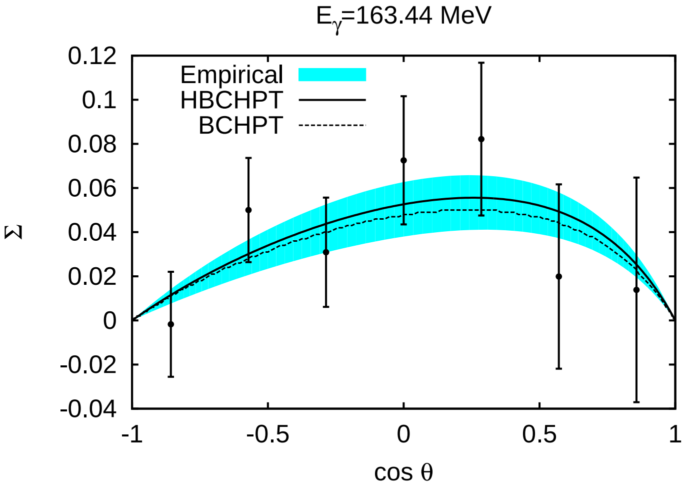
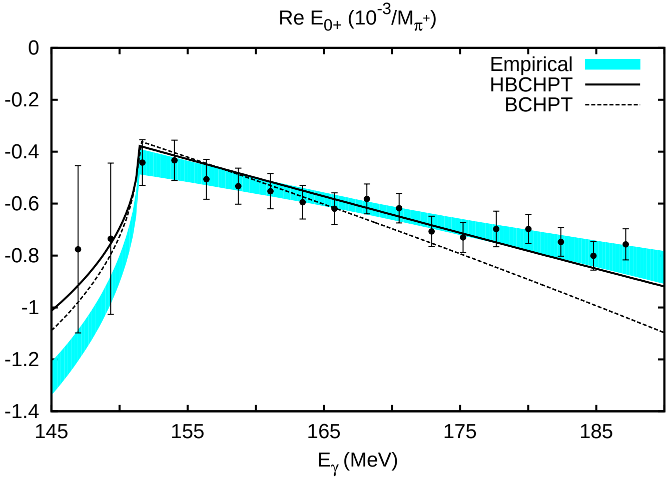
Sample Results



Plots courtesy of C. Fernández Ramírez

S-Wave Amplitude



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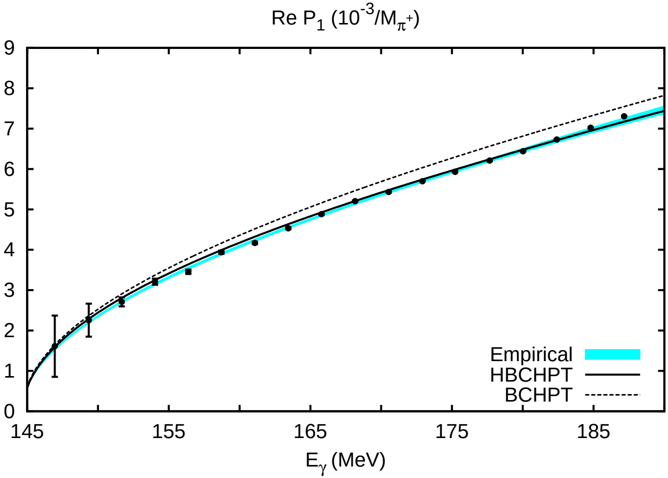
P-Wave Amplitudes



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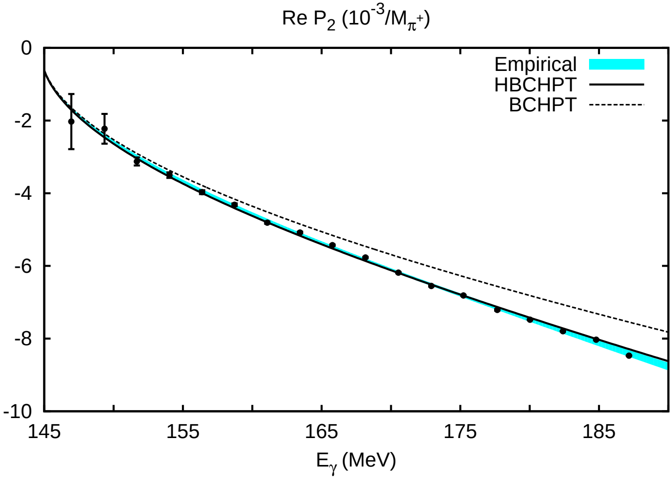

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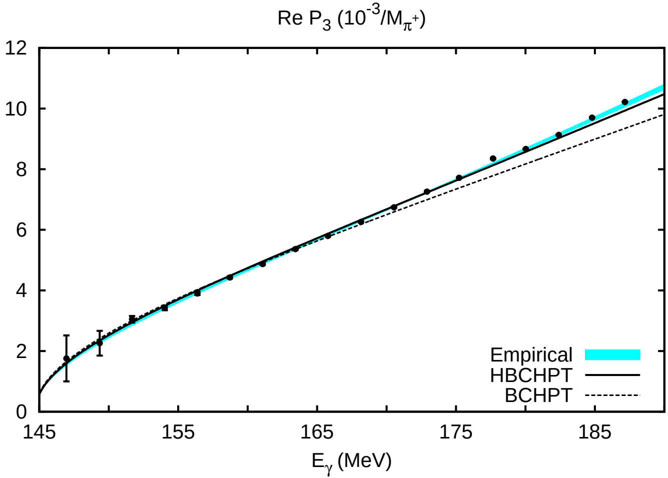


Plots courtesy of C. Fernández Ramírez

$\vec{\gamma}\mathbf{p} \to \pi^0\mathbf{p}$ — Conclusions

- Target-window contributions are very important near threshold, *even for the asymmetry*.
- HBChPT and Relativistic ChPT are in agreement, with good χ^2_{red} values up to around 168 MeV.
- Reasonable agreement with DMT2001 and Lutz-Gasparyan predictions.
- Energy dependence is obviously a big improvement.
- First draft of paper is currently in the works. . .

$\vec{\gamma}\vec{\mathbf{p}} \to \pi^0\mathbf{p}$

Proposal A2-10/09

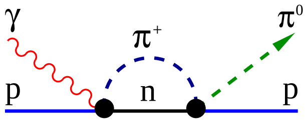
We measure two polarization observables simultaneously:

- **Transverse target asymmetry** T: sensitive to the πN phase shifts, and provides information for neutral charge states $(\pi^0 p, \pi^+ n)$ in a region of energies that are not accessible to conventional πN scattering experiments.

  With this we hope to test strong isospin breaking due to $m_d - m_u$.
- **Beam-target asymmetry** F: sensitive to D-wave multipoles, which have recently been shown to be important in the near-threshold region.

Complex Nature of Multipoles

Due to rescattering



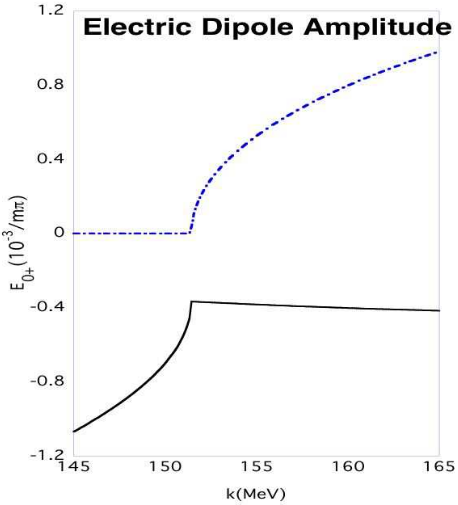
there exists a **Unitarity Cusp**

in the $E_{0+}^{\pi^0 p}$ amplitude:

$$E_{0+}^{\pi^0 p} = ReE_{0+}^{\pi^0 p} + i\beta q_{\pi^+}$$

where β is the *cusp function*:

$$\beta = E_{0+}^{\pi^+ n} a_{ex}(\pi^+ n \to \pi^0 p)$$



Imaginary Part of $E_{0+}^{\pi^0 p}$

Target Asymmetry, T

- Use $T = ImE_{0+}^{\pi^0 p}(P_3 - P_2)\sin\theta$ to make a direct determination of $ImE_{0+}^{\pi^0 p}$ above the $\pi^+ n$ threshold.
- Extract β.
- Use the known value of $E_{0+}^{\pi^+ n}$ to find $a_{ex}(\pi^+ n \to \pi^0 p)$
- Test **strong isospin breaking** since

$$a_{ex}(\pi^+ n \to \pi^0 p) = a_{ex}(\pi^- p \to \pi^0 n)$$

- 2% effect, so precise data with low systematic errors are necessary.

$\vec{\gamma}\vec{p} \to \pi^0 p$ – Experimental Details

Analysis done by S. Schumann (Mainz-MIT), P. Hall Barrientos (Edinburgh), and P. Otte (Mainz). Work in progress.

Polarized beam *and* target.

- Data taken in September 2010 and February 2011.
- CB-TAPS detector.
- Butanol Frozen-Spin Target.
- Circularly polarized photon beam.
- Measured target asymmetry, T, and beam-target asymmetry, F.

$\vec{\gamma}\vec{p} \to \pi^0 p$ – Experimental Details

Equipment:

- A2 Hall.
- Glasgow-Mainz photon-tagging spectrometer.
- CB-TAPS with MWPC and Čerenkov detector.
- Circularly polarized photons.
- Butanol frozen-spin target with transverse coil.

Run Parameters:

Electron Beam Energy	450 MeV
Target	Butanol
Radiator	Møller Foil
Tagged Energy Range	100 – 400 MeV
Channel Energy Resolution	1.2 MeV
Target Polarization	≈80%
Beam on Target	700 h $C_4H_{10}O$ and 100 h C

Experimental Challenges

- Butanol target is made up of $C_4H_{10}O$, and so there are lots of backgrounds. Essentially one heavy nucleus for every 2 protons.
- Swamped with π^0s from C and O, both coherent and incoherent.
- C and O nuclei are not polarized, but they dilute the asymmetries.

$$A = \frac{\sigma^+ - \sigma^-}{\sigma^+ + \sigma^-}$$
$$= \frac{(\sigma_p^+ + \cancel{\sigma_C}) - (\sigma_p^- - \cancel{\sigma_C})}{(\sigma_p^+ + \sigma_C) + (\sigma_p^- + \sigma_C)}$$
$$= \frac{\sigma_p^+ - \sigma_p^-}{\sigma_p^+ + \sigma_p^- + 2\sigma_C}$$

- Need to know the lineshapes very well, and we must be able to eliminate effect of unpolarized, heavy nuclei.

Heavy-Nucleus Backgrounds

Two main techniques for eliminating backgrounds:

1. Background subtraction:
   - Measure heavy-nucleus lineshape with C target
   - Normalize and subtract contributions
   - Technique used by Ph.D. students P. Hall Barrientos (Edinburgh) and P. Otte (Mainz)
   - Very tricky in the threshold region due to huge coherent C cross section.
2. Calculate Polarized Cross Sections
   - Doesn't use C data
   - Technique pioneered by S. Schumann (Mainz-MIT)

Polarized Cross Section Technique

Sven Schumann

Product of unpolarized cross section and asymmetries:

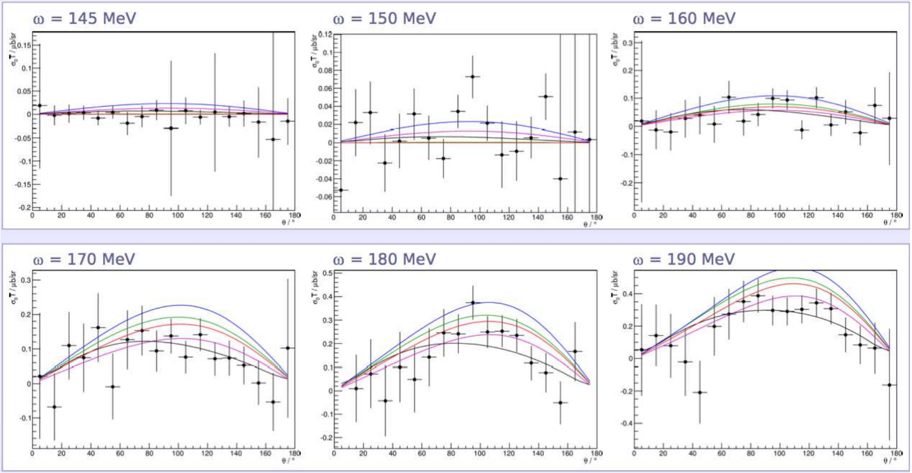
$$\sigma_0 T = \frac{1}{P^y_{\text{eff}}} \frac{N_p^+ - N_p^-}{\epsilon\, \Phi_\gamma\, \rho_p}$$

No unpolarized contributions in the difference of N^+ and N^- count rates:

$$N^+_{\text{but}} - N^-_{\text{but}} = N_p^+ + \cancel{N_C} - N_p^- - \cancel{N_C} = N_p^+ - N_p^-$$

$\Rightarrow$ Can obtain polarized cross sections directly from butanol data, meaning no explicit background subtraction from carbon measurement.

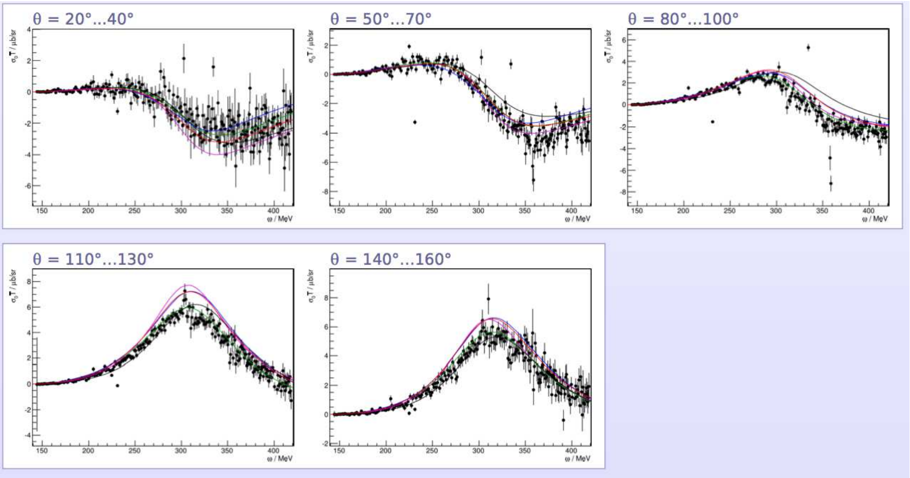
Preliminary Angular Distributions for $\sigma_0 T$



Plots courtesy of S. Schumann

Model predictions for: MAID, SAID, DMT, BnGa, Giessen

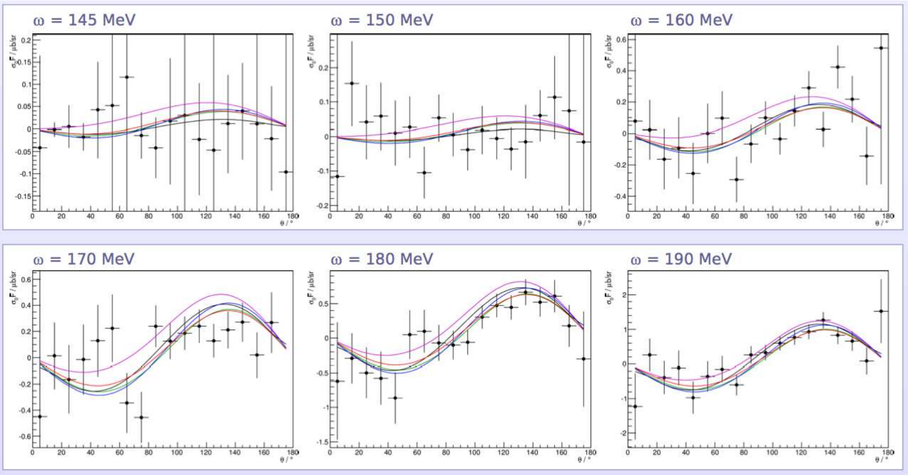
Preliminary Energy Dependence of $\sigma_0 T$



Plots courtesy of S. Schumann

Model predictions for: MAID, SAID, DMT, BnGa, Giessen

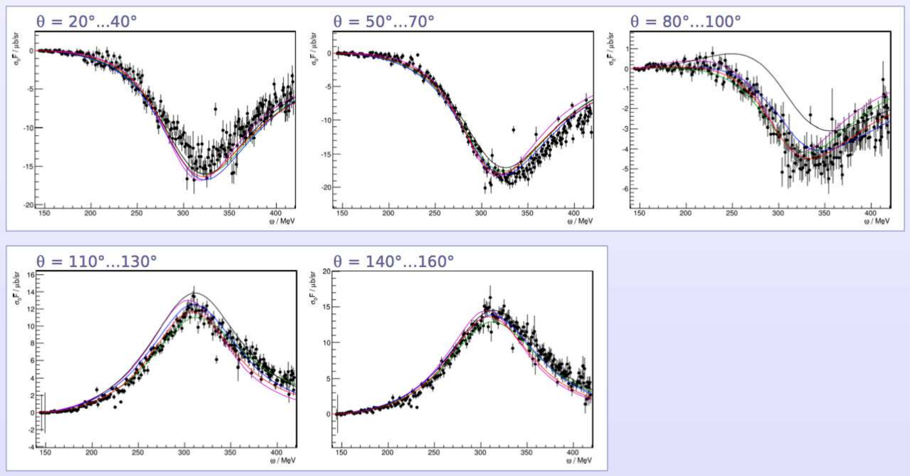
Preliminary Angular Distributions for $\sigma_0 F$



Plots courtesy of S. Schumann

Model predictions for: MAID, SAID, DMT, BnGa, Giessen

Preliminary Energy Dependence of $\sigma_0 F$



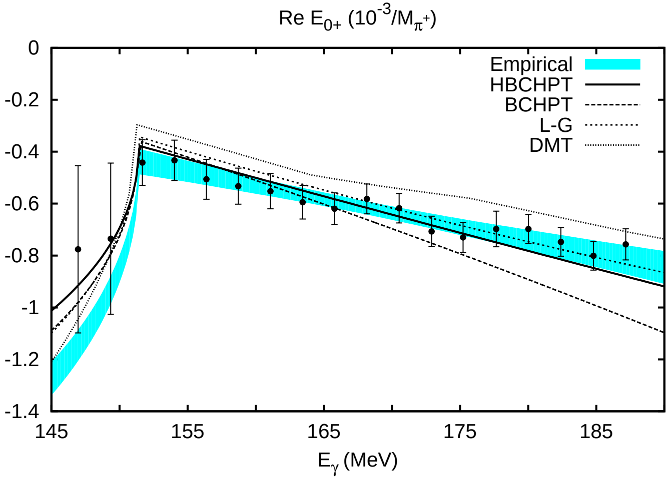
Plots courtesy of S. Schumann

Model predictions for: MAID, SAID, DMT, BnGa, Giessen

Conclusions/Outlook

- First measurements of T and F in neutral pion photoproduction in the threshold region.
- Still a work in progress.
- More running with transverse coil to improve statistics and therefore even smaller uncertainty in T.
- Build an active, polarized target eliminate heavy-nucleus backgrounds altogether, improving measurement of T.
- Test strong isospin breaking. . .

S-Wave Amplitude



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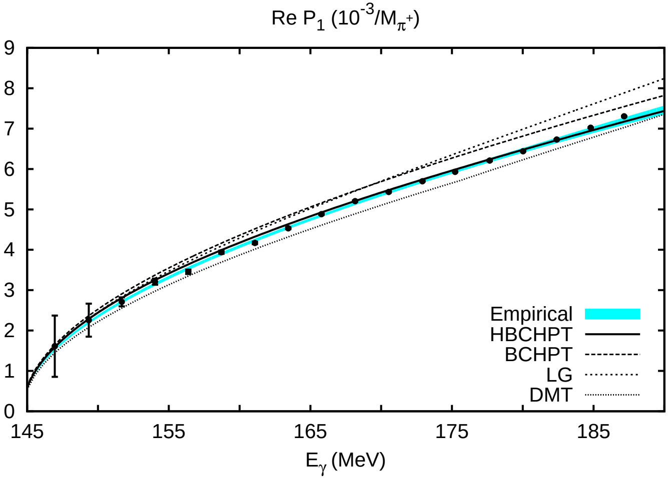

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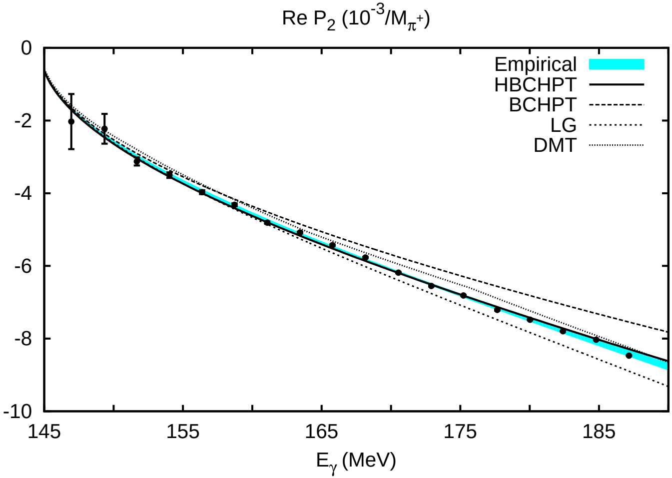

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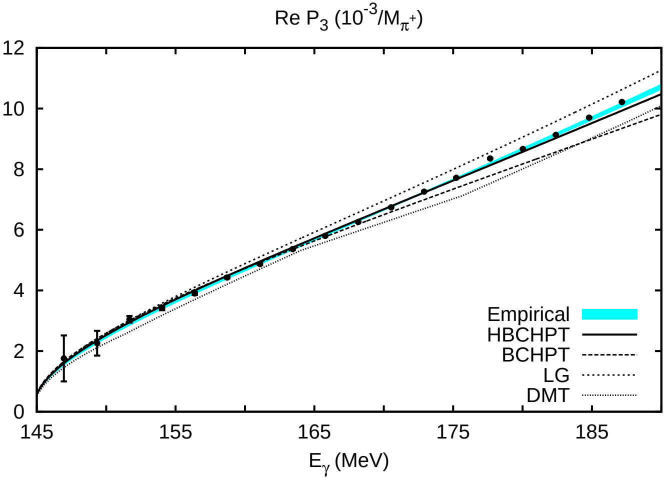

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