Probing Chiral Dynamics with photopion experiments near threshold

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HIγS PROGRAM

MENU 2010

HIγS

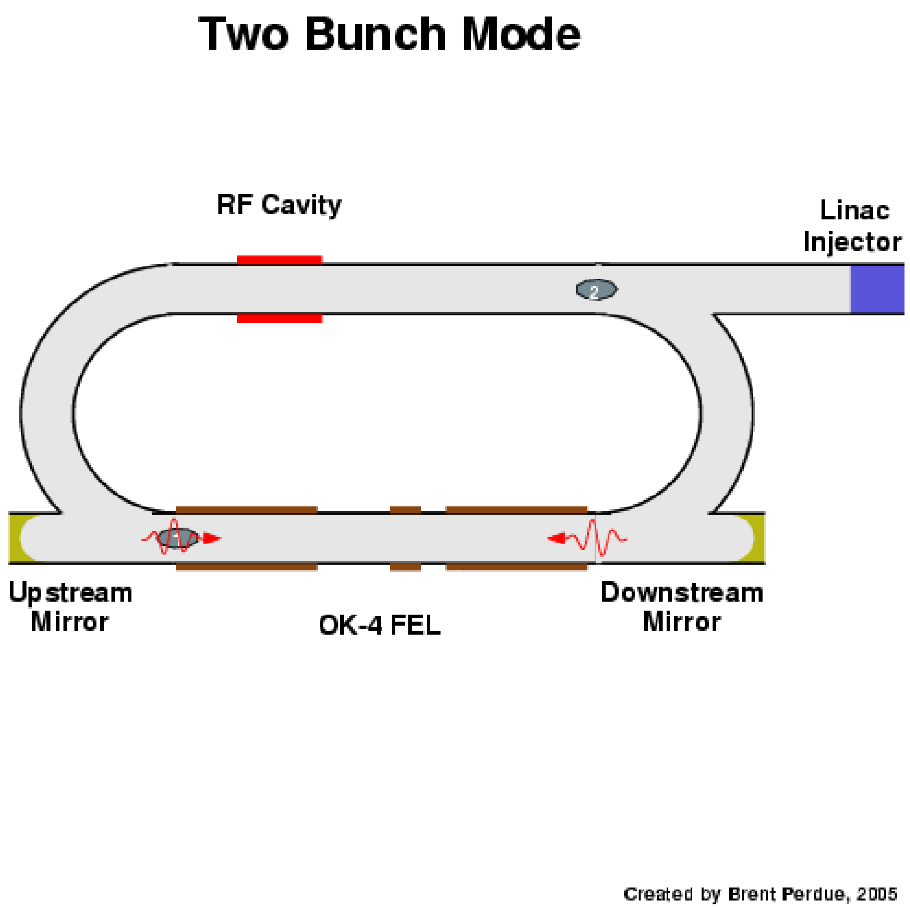
Nearly Mono-energetic γ-rays from 2 to 100 MeV
Up to 65 MeV now
Up to ~100 MeV in 2010
Up to ~160 MeV in 2011

~100% Linearly and Circularly Polarized γ-rays

High Beam Intensities

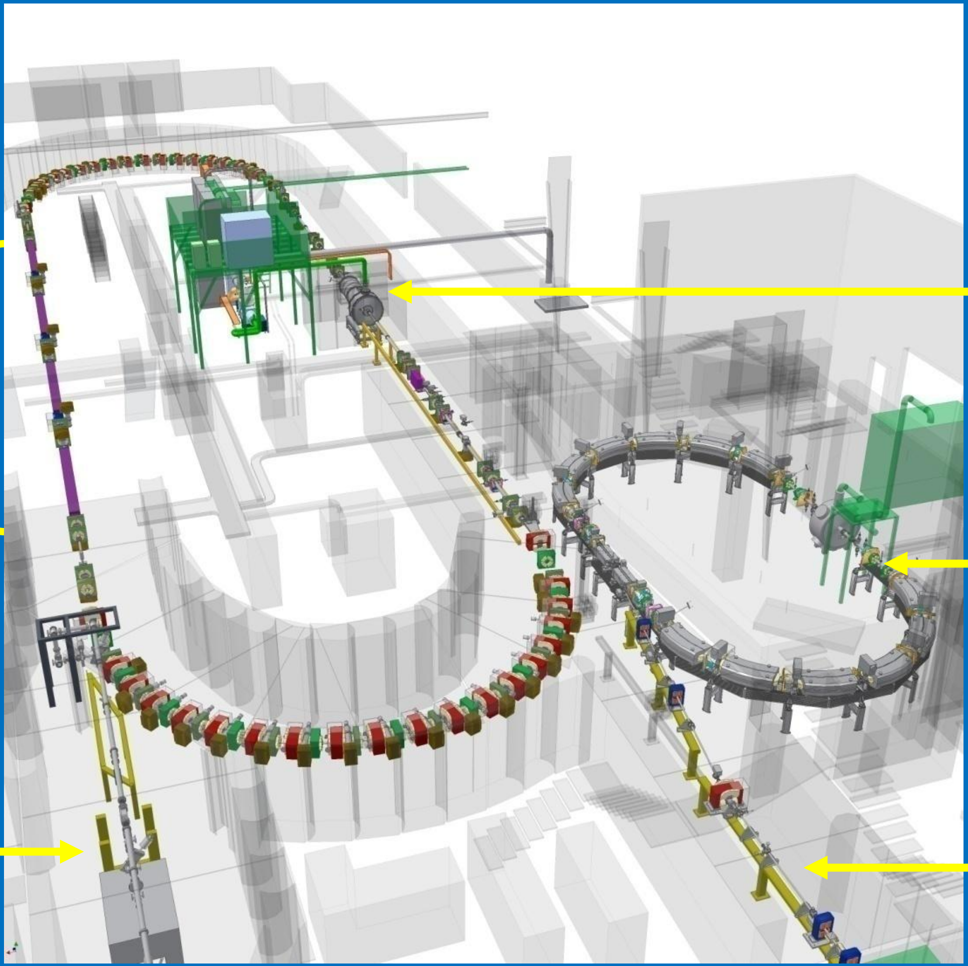
(Ran with $2x10^8$ on target at 15 MeV -June 2009)

HIγS –A free-electron laser generated γ-ray source



□HIγS γ-ray beam generation

- Provides circularly and linearly polarized, nearly monoenergetic γ–rays from 2 to 60 MeV
- Utilizes Compton backscattering to generate γ–rays



Some typical beam intensities

E_γ (MeV)	Total Intensity	
1 – 2	4×10^8 γ/s	
8 – 16	4×10^9	
20 – 45	2×10^8	
50 – 95	1×10^8	(by late 2010)*
95 – 160	$>10^7$	(by late 2011)

*The 193 nm mirrors needed for this are now in-house.

Mirror Development Project

The development of 150 nm mirrors required for producing γ-rays at ~160 MeV is underway.

We anticipate having acceptable mirrors by late 2011.

•***References:***

Research Opportunities at the Upgraded HIγS Facility
H.R. Weller et al.
Progress in Particle and Nuclear Physics 62 (2009) 257

and

Chiral Dynamics in Photopion Physics: Theory, Experiment and Future Studies at the HIγS Facility
Bernstein, Ahmed, Stave, Wu and Weller
Ann. Rev. Nucl. Part. Sci. Vol. 59 (2009) 115

Chiral Perturbation Theory

It is important to measure the near-threshold interactions because they are an explicit effect of chiral symmetry breaking, and have been evaluated in ChPT.

The s-wave amplitude in the **$\gamma p \rightarrow \pi^0 p$ reaction vanishes in the Chiral limit and is finite as a result of the small but finite quark masses.**

These experiments will provide stringent tests of

- The predictions of Chiral Perturbation Theory

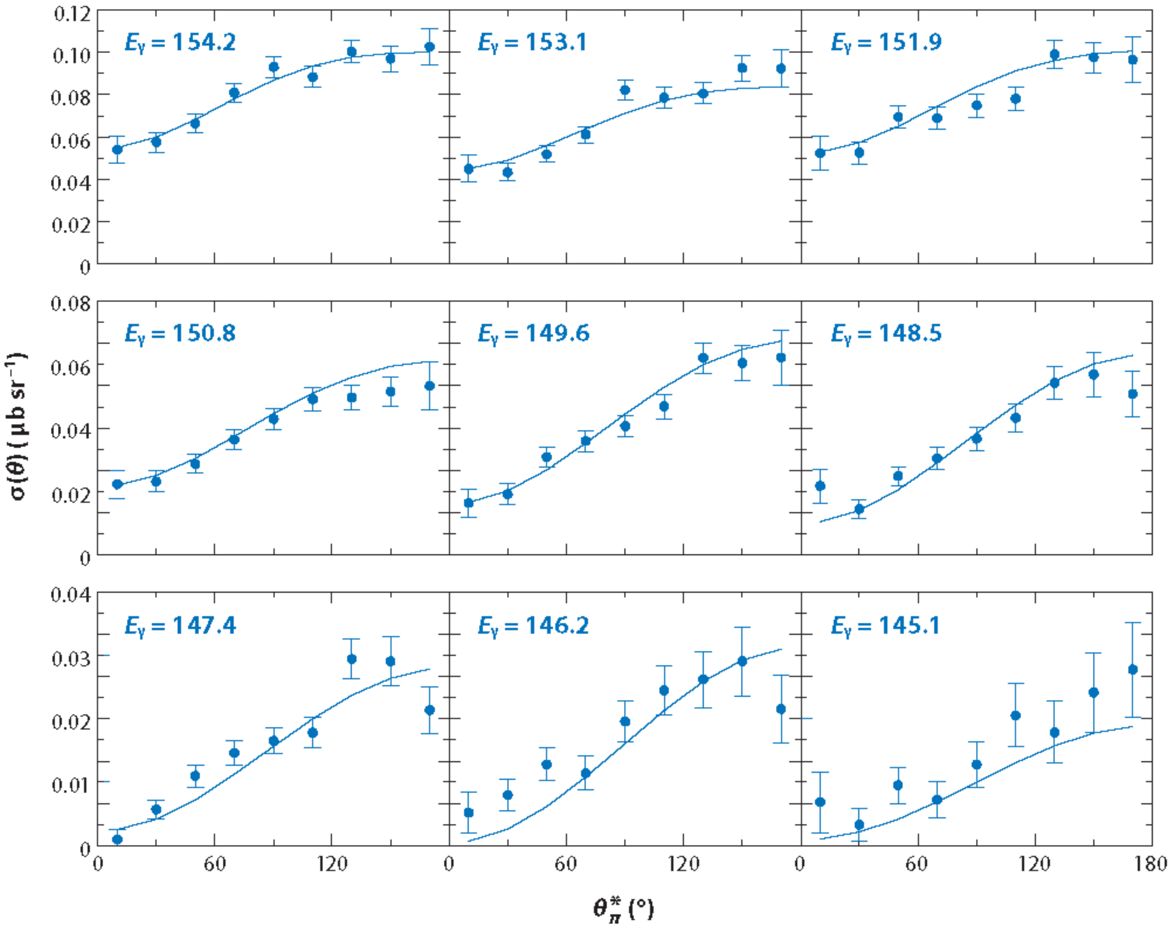
- Predictions of isospin breaking due to the mass differences of the up and down quarks.

$\gamma p \rightarrow \pi^0 p$

Total and differential cross sections have been measured at Mainz from threshold up to 168 MeV.

Ref. A. Schmidt et al. , Phys. Rev. Letts. 87, 232501 (2001)

The Mainz cross section data for the $\gamma p \rightarrow \pi^o p$ reaction at photon energies just above threshold, compared to $O(p^4)$ ChPT calculations of Bernard, Kaiser and Meissner.



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Extracting the s- and p-wave amplitudes

The cross section measurements provide three coefficients: $\sigma(\theta) = A + B \cos\theta + C \cos^2\theta$

A, B, and C can be written in terms of the four contributing amplitudes near threshold: E_{0+}, P_1, P_2, and P_3.

Where $P_1 = 3E_{1+} + M_{1+} - M_{1-}$,

$P_2 = 3E_{1+} - M_{1+} + M_{1-}$, and

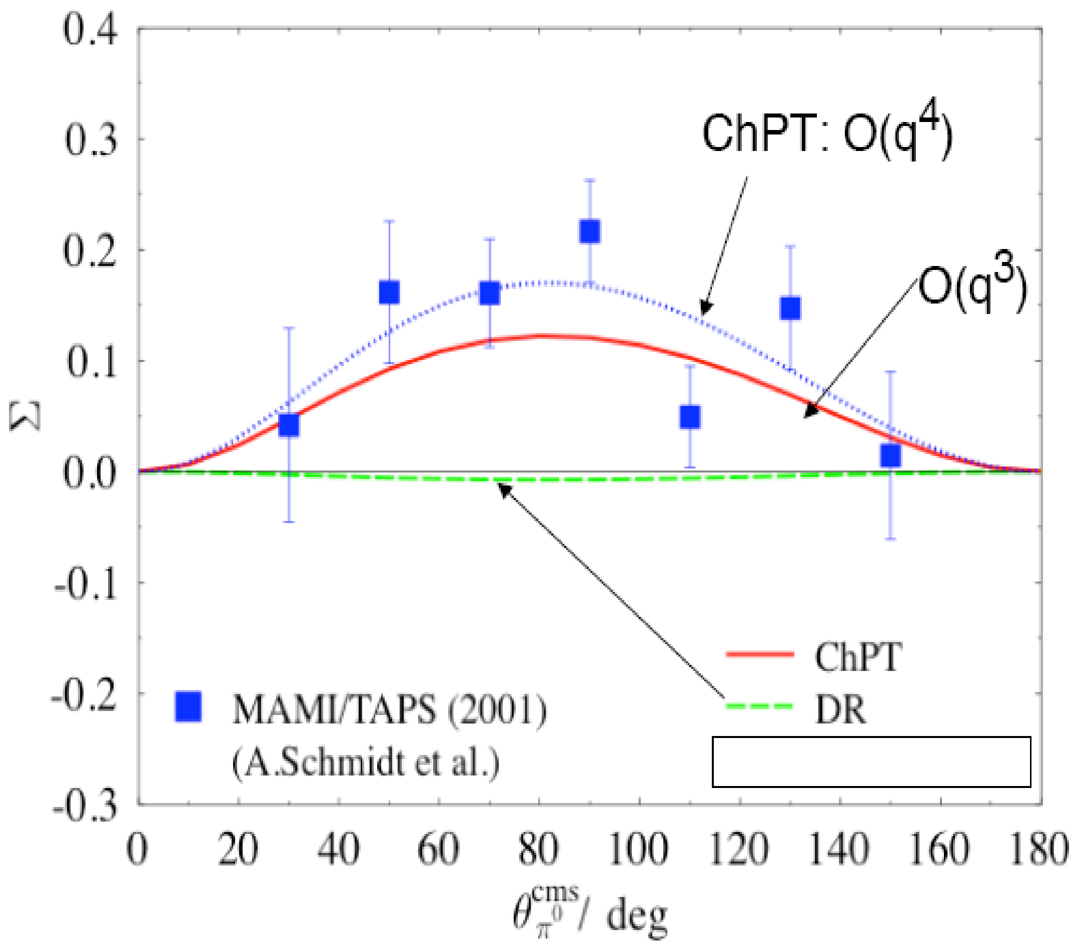
$P_3 = 2M_{1+} + M_{1-}$.

A fourth relationship is needed to solve these without invoking a model. Mainz has measured the photon asymmetry using a linearly polarized γ beam:

Success of ChPT at pion-threshold

Linearly Polarized Photon asymmetry for the $\gamma p \rightarrow \pi^0 p$ reaction at an average energy of 159.5 MeV

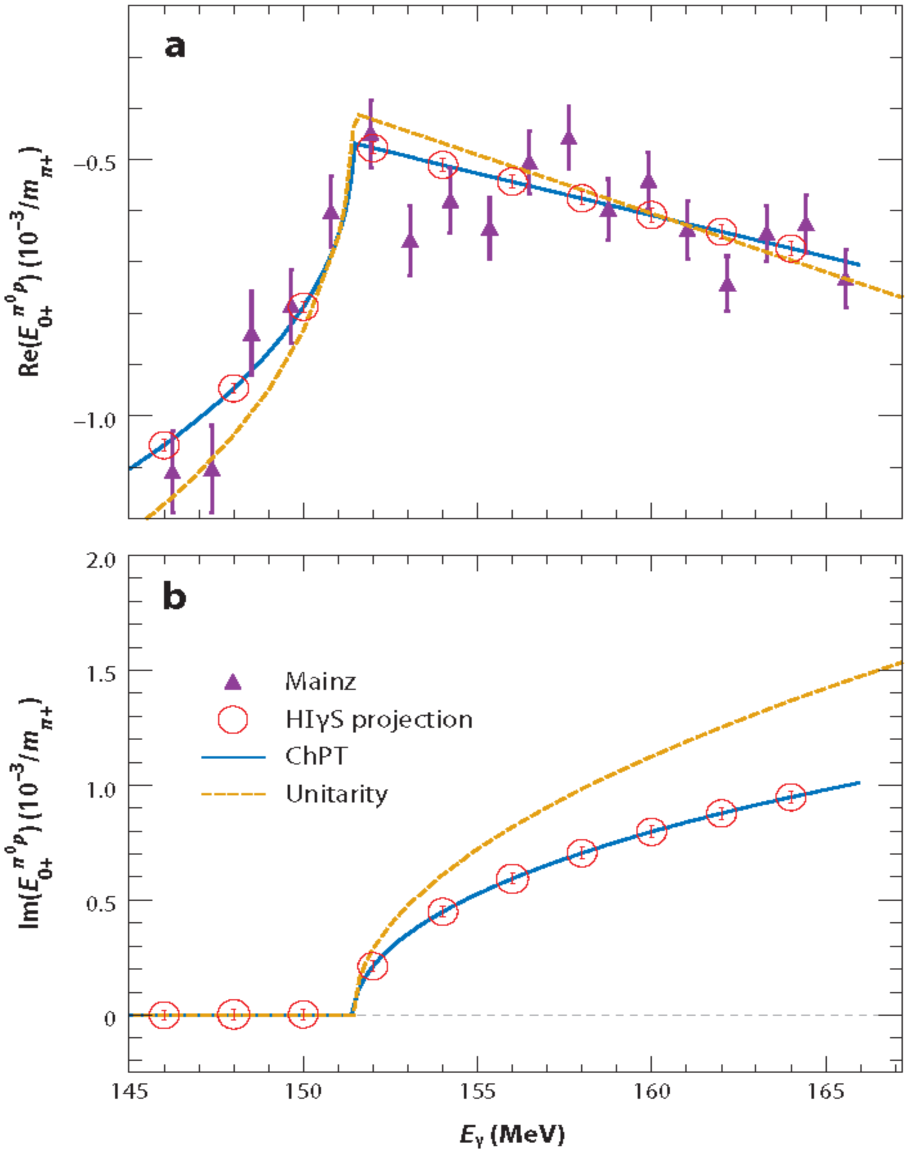
MAINZ 2001



$\gamma p \rightarrow \pi^0 p$

The real part of the s-wave electric dipole amplitude for the $\boldsymbol{\gamma p \rightarrow \pi^0 p}$ reaction has been determined from these data. The following figure shows their extracted results along with the predictions of ChPT and a fit based on Unitarity of the S-matrix.

Projected results for HIγS are also shown.


a
b
Mainz
HIγS projection
ChPT
Unitarity
$\mathrm{Re}(E_{0+}^{\pi^0 p})\ (10^{-3}/m_{\pi+})$
$\mathrm{Im}(E_{0+}^{\pi^0 p})\ (10^{-3}/m_{\pi+})$
E_γ (MeV)
−0.5
−1.0
2.0
1.5
1.0
0.5
0
145
150
155
160
165

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Recent results indicate that the inclusion of d-waves may be necessary to obtain reliable values of E_{0+}

REF: Fernandez-Ramirez, Bernstein, Donnelly arXiv:0902.3412v2 [nucl-th] 16 Jul 2009

They used the results of HBCHPT for the s- and p-waves, and included d-waves using the *customary* Born terms. A fit to all available data led to a significant change in the s-wave amplitude.

RED – SPD Model

BLUE – SP Model

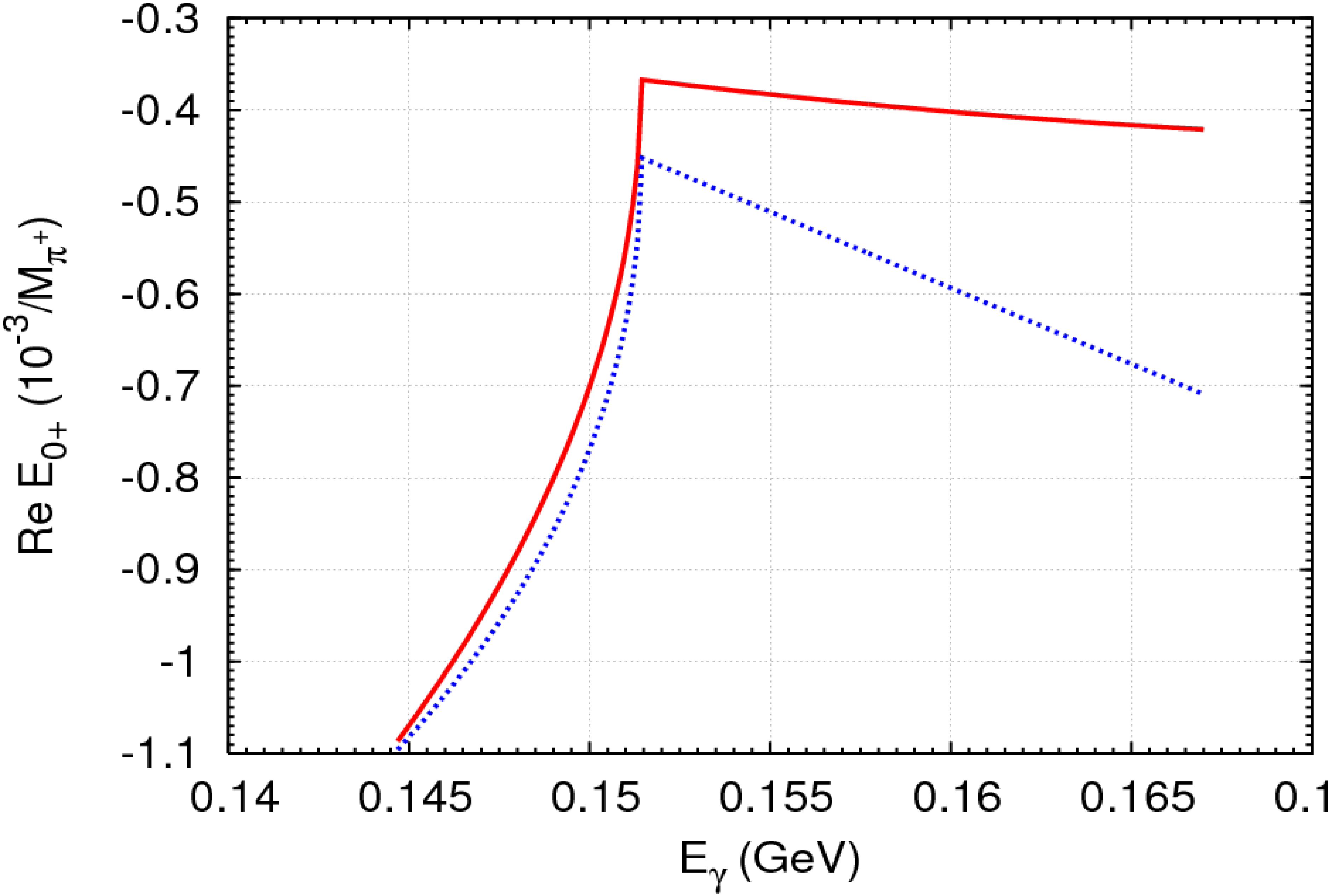


Fig. 3. (Color online) Extracted E_{0+} multipole

New Mainz Experiment, Dec. 2008:

Measurement of the Photon Asymmetry in Neutral Pion pnotoproduction from the Proton near Threshold

Spokesperson: David Hornidge – for the A2 Collaboration

Measured the linear analyzing powers for the $\gamma \mathbf{p} \rightarrow \pi^0 \mathbf{p}$ reaction at 5 energies: 147, 152, 157, 162, and 167 MeV

Used the Crystal Ball (672 NaI dets. Covering 93% of 4π) and the Two Armed Photon Spectrometer (TAPS).

Obtained a big improvement vs. previous data of Schmidt, with statistics at each energy better than previous energy averaged results.

Results will be presented by J. Arends on Friday morning.

Simulations

A full Monte Carlo simulation of the proposed experiments at HIγS was performed using *Geant4*, based on the predictions of ChPT.

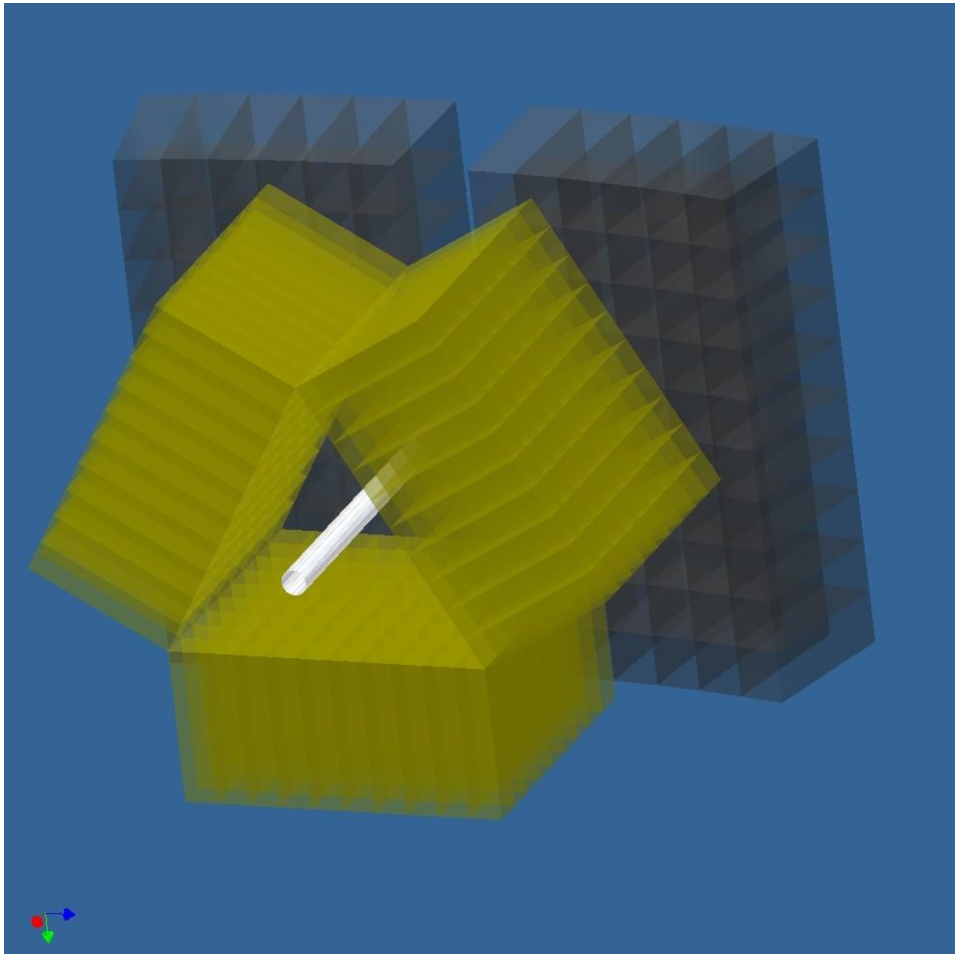
The π^0s were detected using the CBx assembly.

This consists of 270 NaI detectors arranged in 3 arrays of 9x10 crystals each. Each detector is 12 radiation lengths long. Each array gives an energy resolution of 1.3% @ 100 MeV photons.

The 3-arrays were placed in a triangular configuration with their long edges touching one-another, and parallel to the beam directon. The target is placed in the center of the triangle. This provides 3π coverage.

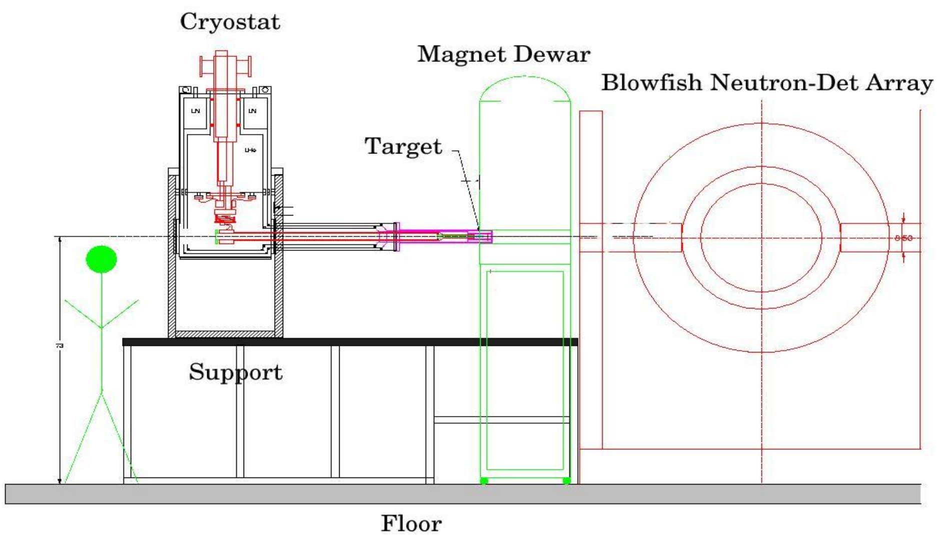
The proposed HIγS NMS

Consists of three refurbished (JLAB) arrays from the XTAL Box (LEGS) and two arrays from the LANL NMS.



Frozen Spin Polarized Target is presently being installed under the direction of Don Crabb (UVa)

- **Butanol**
- **Polarization ~ 80 %**
- **Polarizing Field ~ 2.5 T**
- **Holding Field ~ 0.6 T—both transverse and longitudinal**
- **~4 x 10^{23} d/cm^{2}**



Simulations

Beam on target was assumed to be 10^7 γ/s, and the polarized target thickness was 3.5 x 10^{23} p/cm^2.

All observables were measured at all CM angles.

Observables considered were σ, Σ, T, E, and F.

σ ---total and differential cross sections

Σ ---Linearly polarized photon asymmetries

T ---Target analyzing power

E ---Circ. photons, longitudinal target asymmetries

F ---Circ. photons, transverse target asymmetries

Each was run for 100 hours at each energy (with σ constructed from the polarized data).

Unitary cusp

The ratio of the electric dipole amps for neutral and charged pion channels is ~ -20 (Kroll-Ruderman LET plus Mainz data).

$$\frac{E_{0+}(\gamma p \rightarrow \pi^+ n)}{E_{0+}(\gamma p \rightarrow \pi^0 p)} \sim -20$$

So the two-step reaction $\gamma p \rightarrow \pi^+ n \rightarrow \pi^0 p$ is as strong as the direct path. Gives rise to a significant unitary cusp.

The 3-channel S-matrix (γp, $\pi^0 p$, $\pi^+ n$) + Unitarity leads to a coupled channel result for the $E_{0+}(\gamma p \rightarrow \pi^0 p)$ amplitude expressed in terms of the "cusp parameter" β:

$$\boldsymbol{\beta = \mathrm{Re}[E_{0+}(\gamma p \to \pi^+ n)]\, a_{cex}(\pi^+ n \to \pi^0 p)}$$

Calculation of β from Unitarity

If we ***assume*** that isospin is conserved so that

$$a(\pi^+ n \rightarrow \pi^0 p) = -a(\pi^- p \rightarrow \pi^0 n)$$

The observed width of the 1s state in pionic hydrogen (PSI) gives:

$a(\pi^- p \rightarrow \pi^0 n) = -(0.122 \pm 0.002)/m_\pi$

Previous measurement of $E_{0+}(\gamma p \rightarrow \pi^+ n)$ => 28.06 +/- 0.27 +/- 0.45 (Korkmaz et al., Phys. Rev. Lett. 83, 3609 (1999).

<u>This gives β = 3.43 +/- 0.08 (Unitarity)</u>
ChPT (at one loop $O(q^4)$ level gives β = 2.78.
Discrepancy attributed to truncation.

A direct measurement of β is needed.

Isospin Symmetry Breaking

A measurement of the imaginary part of the s-wave production amplitude (E_0^+) provides a determination of the cusp-parameter β which leads to a value of the charge exchange scattering length $a_{cex}(\pi^+ n \rightarrow \pi^0 p)$.

Requires measurement of the polarized target analyzing power T(θ).

$$T(\theta)/\sigma(\theta) = \mathrm{Im}[E_{0+}(P_3 - P_2)\sin(\theta)^2 \rightarrow \mathrm{Im}(E_{0+})$$

Our measurements will determine β to +/- 0.035 (~1%), where

$$\boldsymbol{Im}[E_{0+}(\gamma p \to \pi^0 p)] = \beta\, p_{\pi+}/m_\pi$$

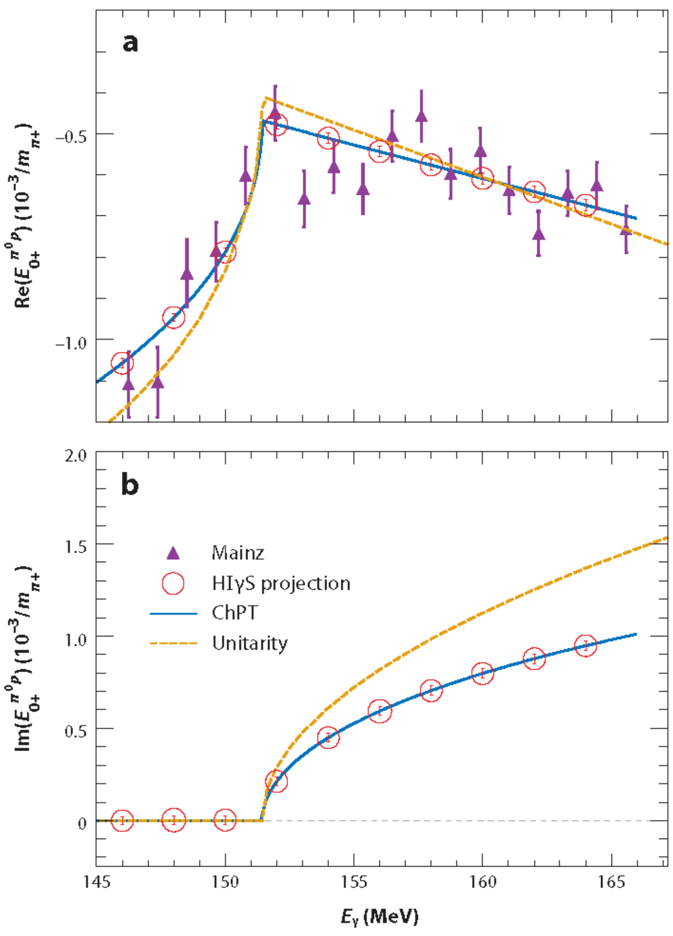
and where $\beta = \mathrm{Re}[E_{0+}(\gamma p \to \pi^+ n)]\, a_{cex}(\pi^+ n \to \pi^0 p)$

$\mathrm{Re}[E_{0+}(\gamma p \to \pi^+ n)]$ has been measured (=28.06 +/- 0.27 +/- 0.45), giving us $a_{cex}(\pi^+ n \to \pi^0 p)$.

Isospin conservation implies $a_{cex}(\pi^+ n \to \pi^0 p) = -a_{cex}(\pi^- p \to \pi^0 n)$.

The latter is well known from the width of pionic hydrogen (-0.1301 +/- 0.0059) after a decade of work. Our measurement of β will give a comparable accuracy for $a_{cex}(\pi^+ n \to \pi^0 p)$…~4-5%.

Mainz results for Re(E_0^+) and projected HIγS results for Re and Im parts. The results of ChPT and a fit based on unitarity are also shown.



The Full HIγS Experiment

Four polarization asymmetries will be measured at HIγS.

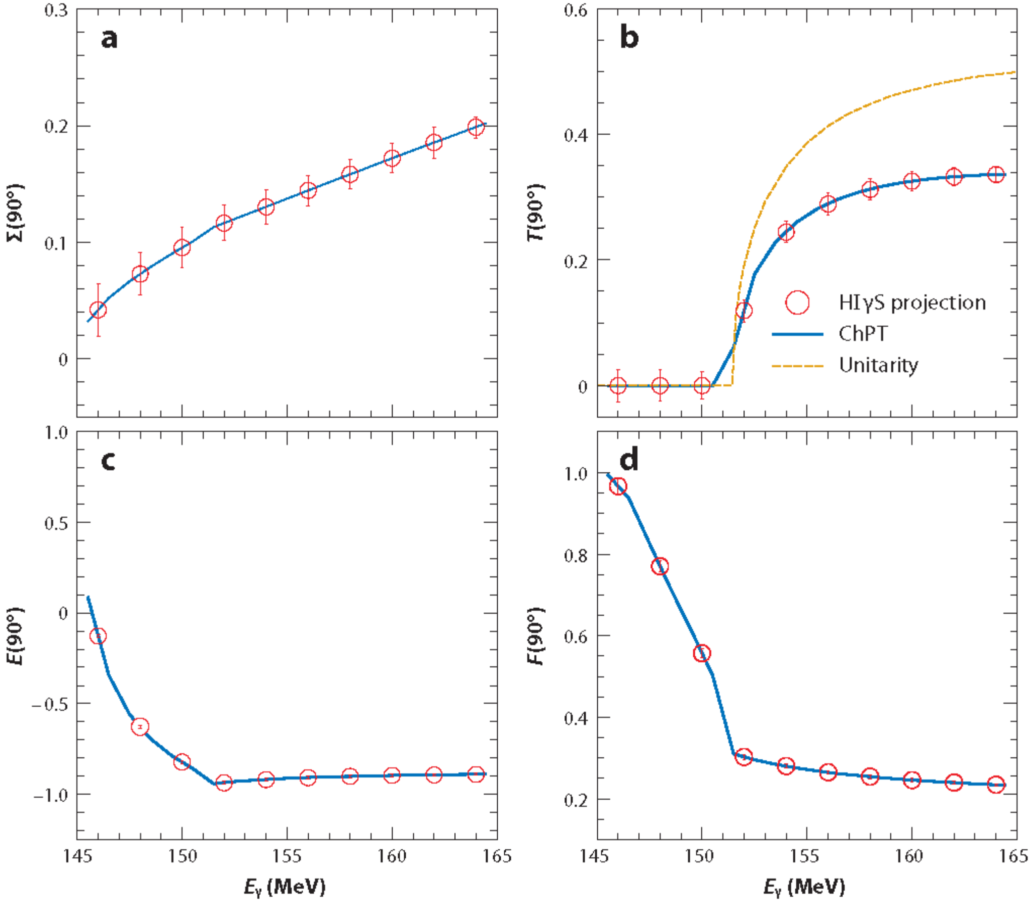
$\Sigma(\theta)$ Linearly polarized beam on unpolarized target

$T(\theta)$ Unpolarized beam on transversely polarized target

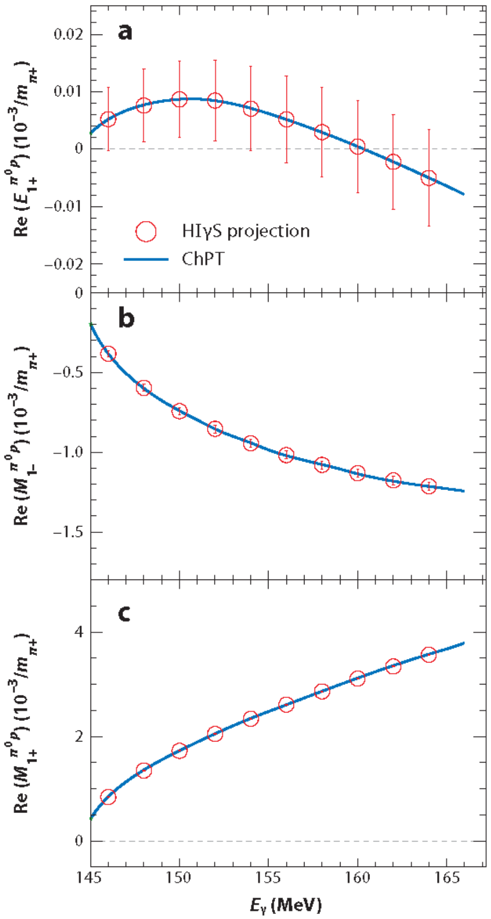
$E(\theta)$ Circularly polarized beam on Longitudinally polarized target

$F(\theta)$ Circularly polarized beam on transversely polarized target

a. $\Sigma(90)$ Linearly polarized beam on unpolarized target
b. T(90) Unpolarized beam on transversely polarized target
c. E(90) Circularly polarized beam on Longitudinally polarized target
d. F(90) Circularly polarized beam on transversely polarized target
Note the sensitivity of T(90) to β ($\beta = 3.43$ unitary vs 2.78 ChPT)→1% result



P-wave amplitudes predicted for the HIγS experiment where 100 hrs of beam time is used at each energy in four different beam-target polarization configurations. Theory is ChPT of Bernard, Kaiser and Meissner.



Isospin mixing due to u-d quark mass difference

The Holy Grail of Photopion-threshold physics

Weinberg predicted a sizeable (~20%) effect of u-d quark mass difference on the value of the s-wave π^0p scattering length.

A measurement of the Analyzing Power in the $\gamma p \rightarrow \pi^0 p$ reaction using **transversely polarized protons** between π^0 threshold (144.7 MeV) and π^+ threshold (151.4 MeV) will give the imaginary part of the E_{0+} amplitude, which, when combined with the real part, gives the phase and therefore the phase shift which **leads to the scattering length a(π^0p).**

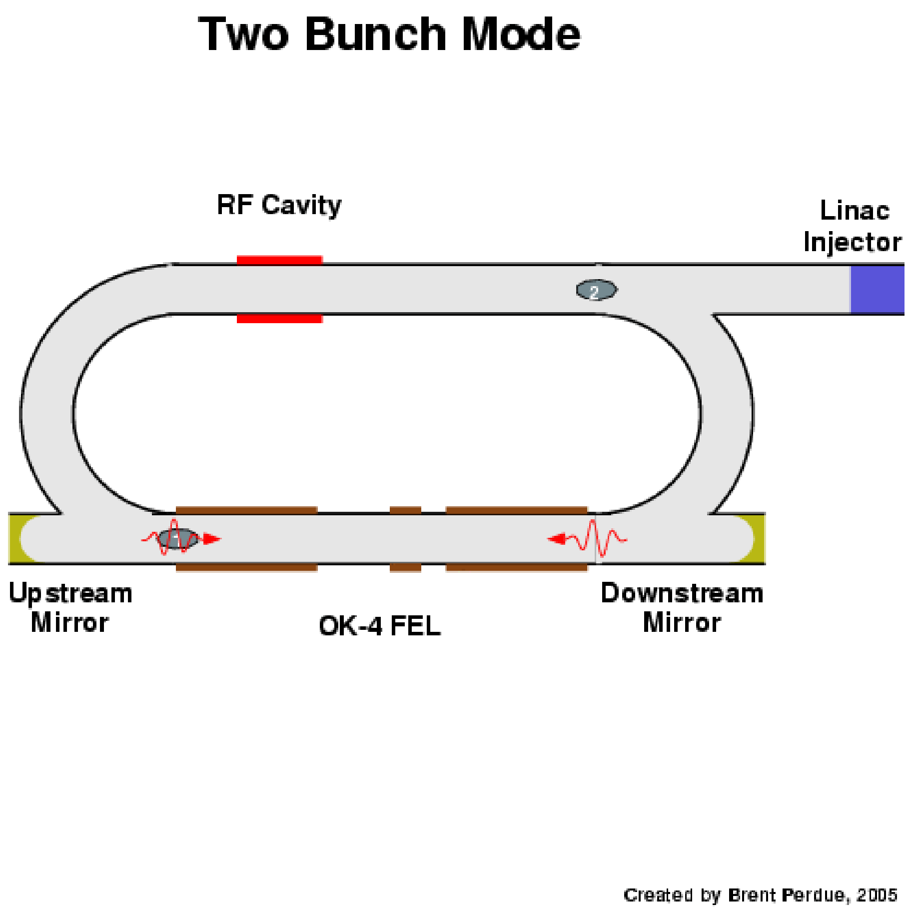
Isospin mixing due to u-d quark mass difference

The Holy Grail of Photopion-threshold physics

This requires a beam of 10^9 γ/s. When available, a 1000 hr. experiment should determine $a(\pi^0 p)$ with a statistical accuracy of $\sim 10^{-3}/m_{\pi}$.

This result will test the 20% violation of isospin symmetry.

•HIγS –A free-electron laser generated γ-ray source



End of Presentation

- Extra slides follow:

The $\gamma p \rightarrow \pi^+ n$ reaction

One modern experiment (SAL) gave:

$E_{0+}(\gamma p \rightarrow \pi^+ n)$ => (28.06 +/- 0.27 +/- 0.45) x $10^{-3}/m_\pi$

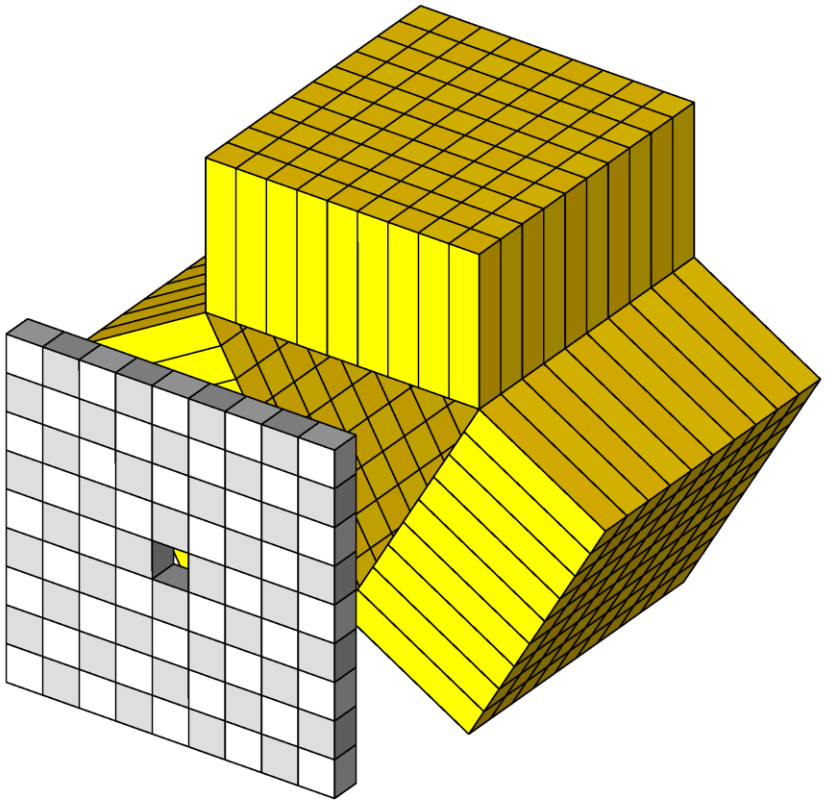
In good agreement with ChPT→ 28.2 +/- 0.6

Also leads to $f_{\pi N}^2$ = 0.078 +/- 0.004.

Better accuracy will give a more accurate determination of both quantities. Need ~1% accuracy in $E_{0+}(\gamma p \rightarrow \pi^+ n)$ to extract $\mathbf{a_{cex}\,(\pi^+ n \rightarrow \pi^0 p)}$ from the measured value of

$\boldsymbol{\beta} = \mathbf{Re[E_{0+}\,(\gamma p \rightarrow \pi^+ n)]\; a_{cex}\,(\pi^+ n \rightarrow \pi^0 p)}$, which we'll obtain from the $\gamma p \rightarrow \pi^0 p$ channel.

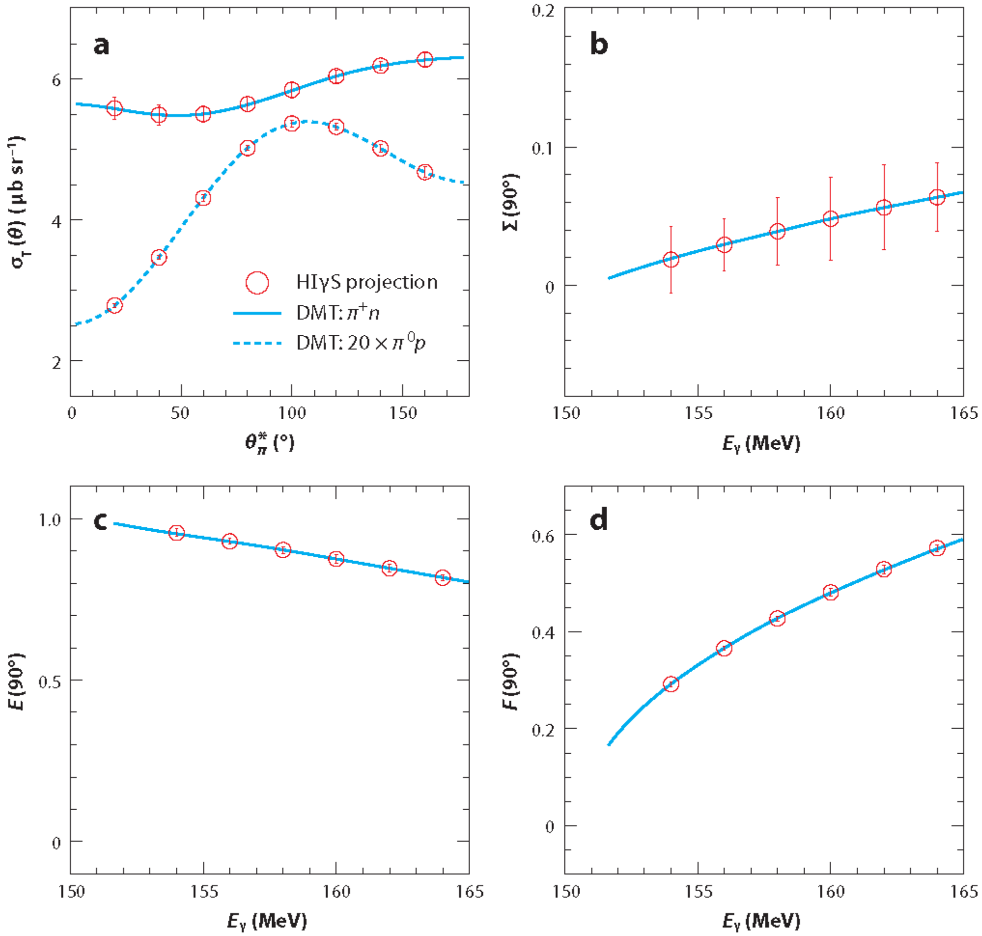
The 81 BC-505 neutron detectors (from *Blowfish*) arranged in the forward plane, giving full coverage of the corresponding pions. Each detector is 7.6 x 7.6 x 6.4 cm. The X-tal box detectors are also shown here. ***Projected HIγS data, based on the DMT model, are shown in the next figure.***



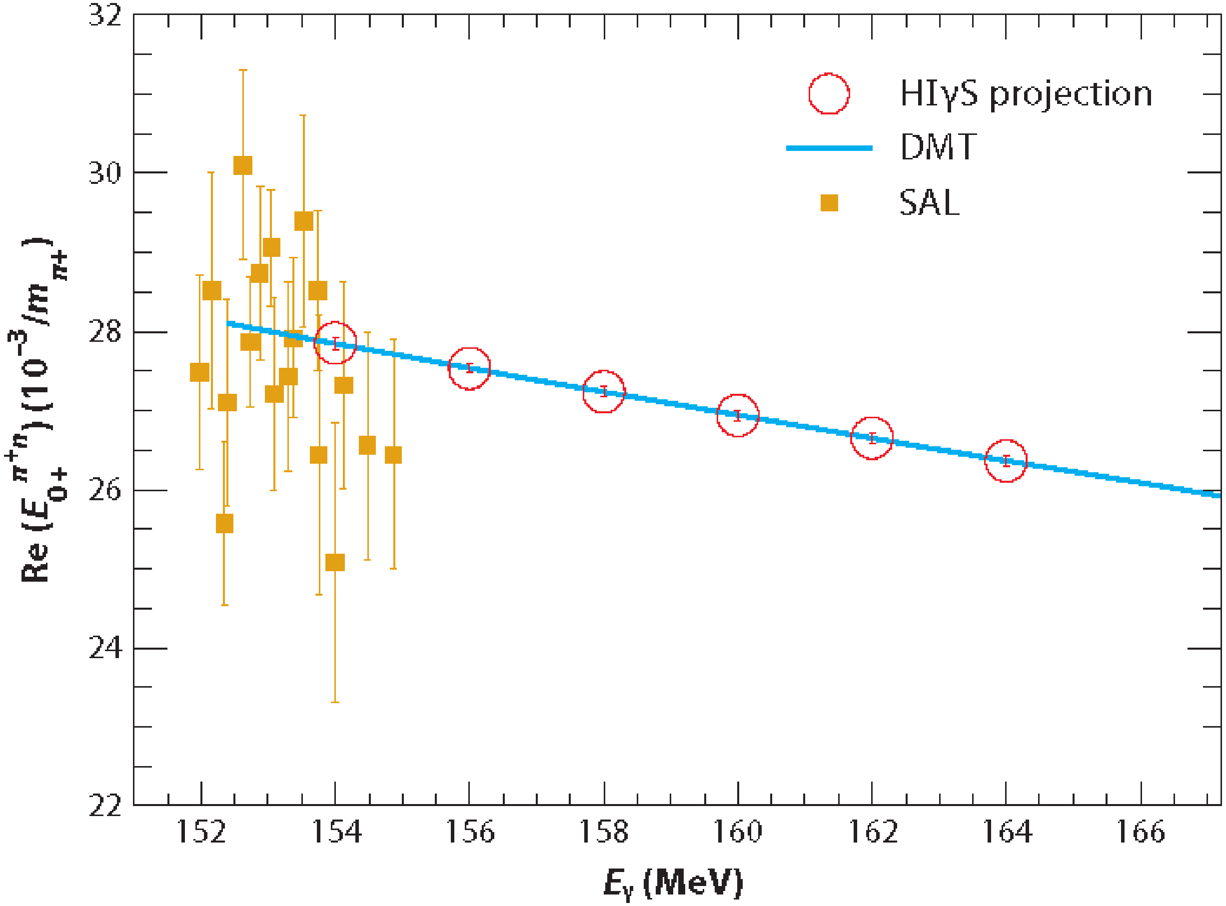
a. Predicted cross sections for $\pi^0 p$ and $\pi^+ n$ channels at E_γ= 164 MeV.

b. Polarization asymmetries for the $\gamma p \rightarrow \pi^+ n$ reaction at 90º based on the DMT model.

Each red data point represents 100 hours of running.



Resulting values and uncertainties for **Re[E_{0+} ($\gamma p \to \pi^+ n$)]** based on measurements of the 4-observables at all angles (there are slight losses at extreme angles).



RESULTS

The projected HIγS results will determine **Re[E_{0+} ($\gamma p \to \pi^+ n$)]** to better than 1-2%.

When combined with the precise measurement of β (~1%), the relationship $\boldsymbol{\beta} = $ **Re[E_{0+} ($\gamma p \to \pi^+ n$)] a_{cex} ($\pi^+ n \to \pi^0 p$)** will lead to a few percent determination of a_{cex} ($\pi^+ n \to \pi^0 p$), and therefore will provide a precision test of isospin violation.

•The Upgraded HIγS Facility