Probing Chiral Dynamics with photopion experiments near threshold

Henry R. Weller

Duke University and Triangle Universities Nuclear Laboratory

HIγS PROGRAM

EINN 09--October 2009

HIγS

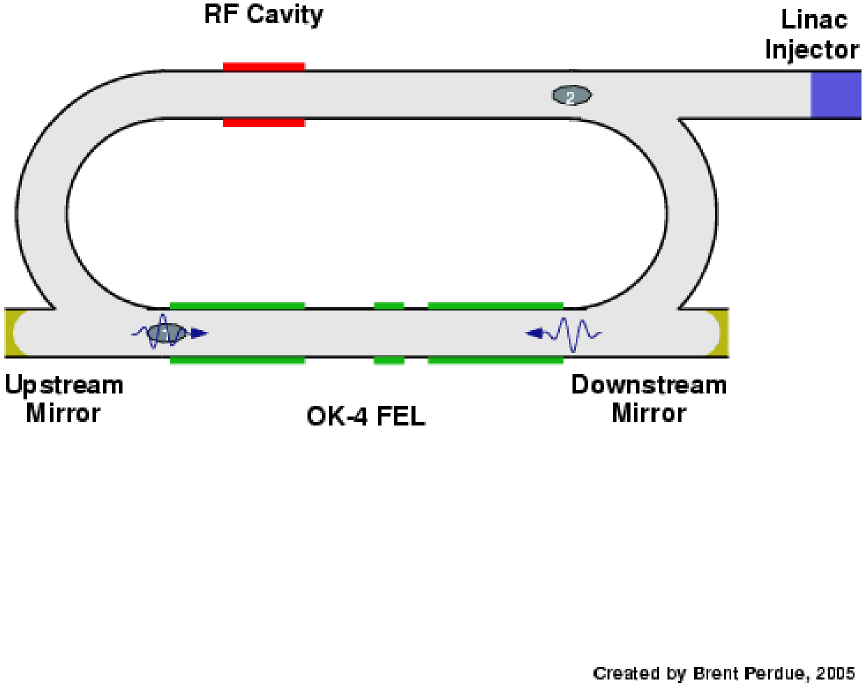
Nearly Mono-energetic γ-rays from 2 to 100 MeV
Up to 65 MeV now
Up to ~100 MeV in 2010
Up to ~160 MeV in 2011

~100% Linearly and Circularly Polarized γ-rays

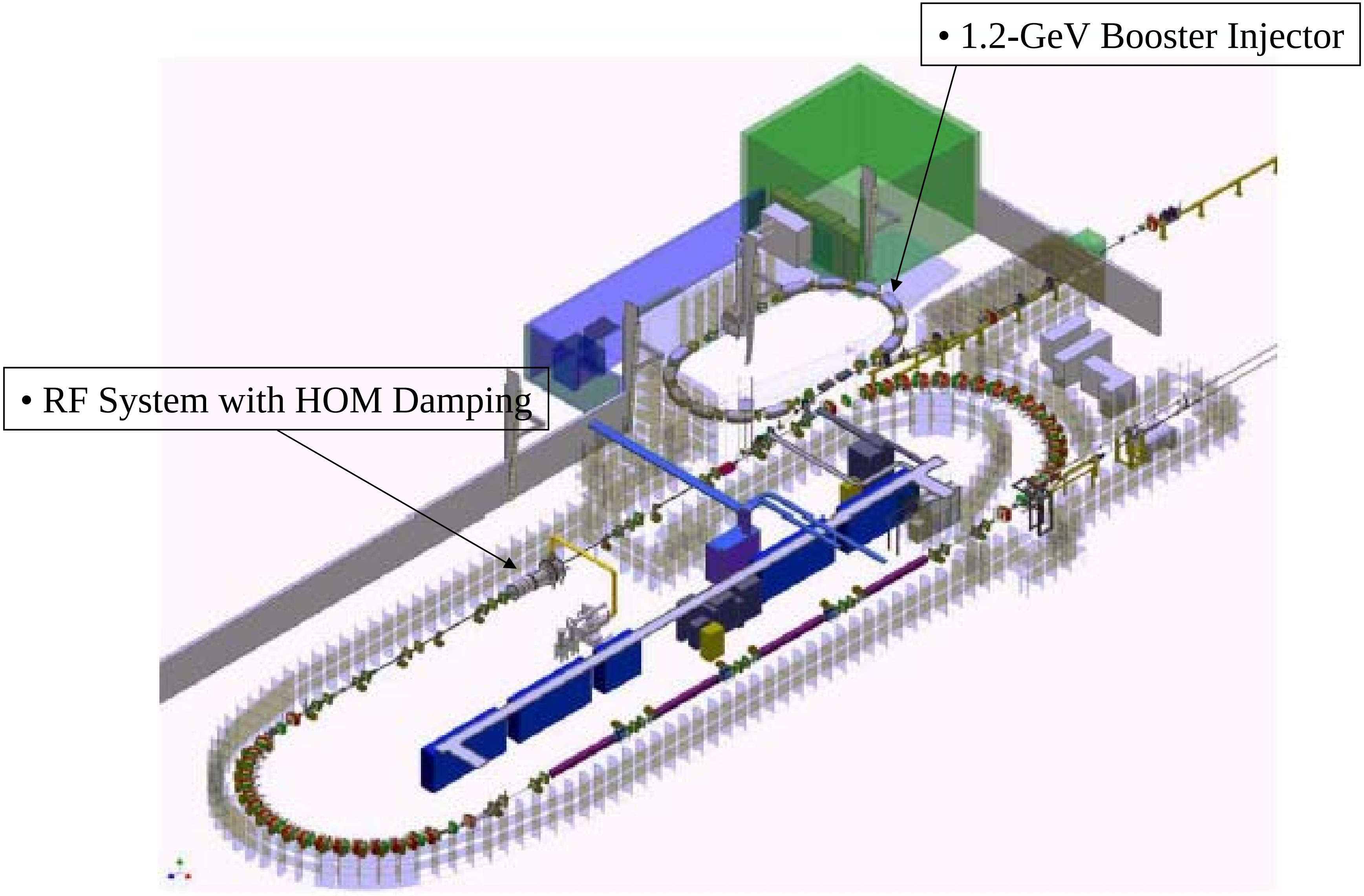
High Beam Intensities

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

Two Bunch Mode



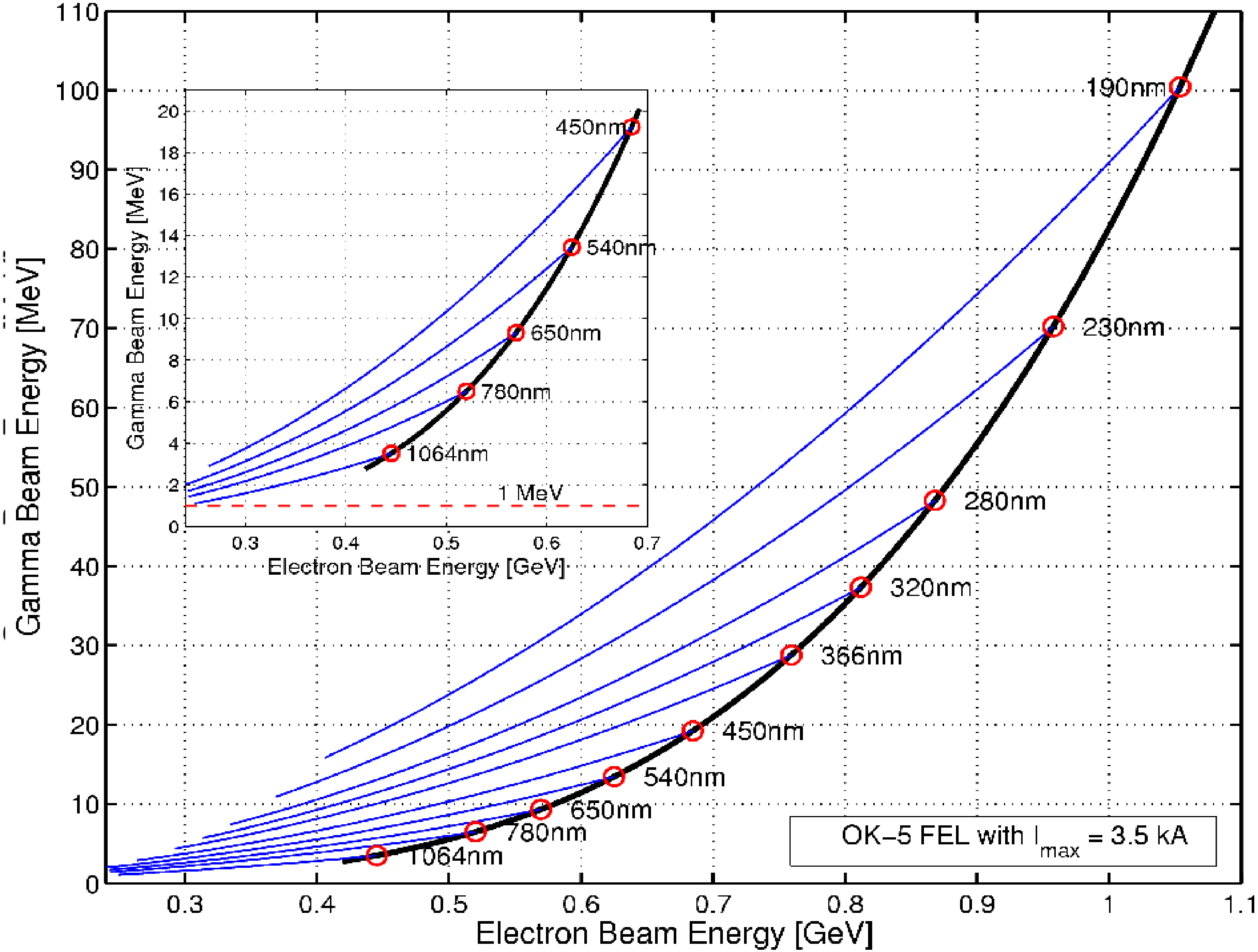
•The Upgraded HIγS Facility

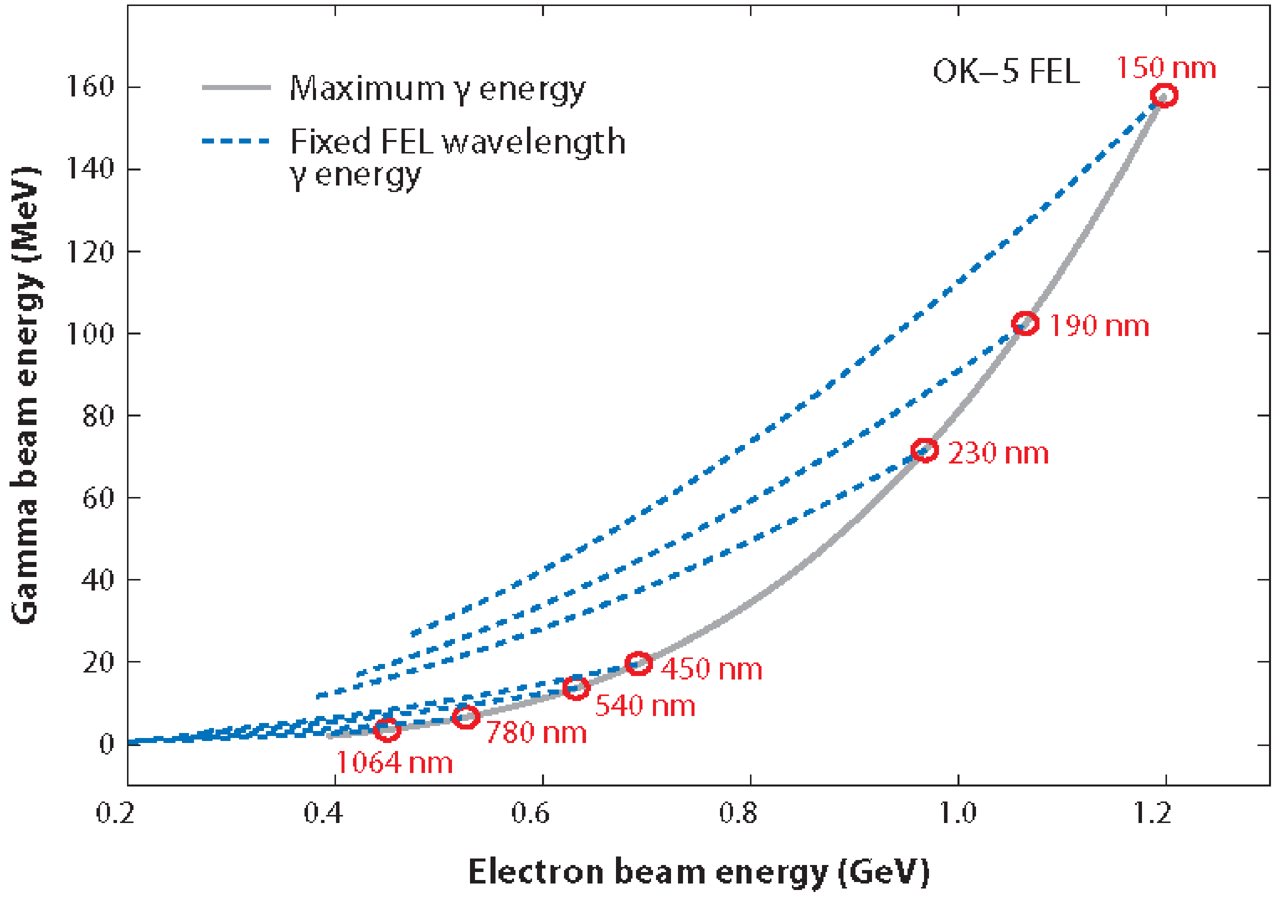


Some typical beam intensities

E_γ (MeV)	Beam on target ($\Delta E/E$ = 3%)
1 – 2	2 x 10^7 γ/s
8 – 16	8 x 10^7 (total flux of 2 x 10^9)
20 – 45	8 x 10^6
50 – 95	4 x 10^6 (by late 2010)
95 – 160	>10^6 (by late 2011)

Gamma-ray Tuning Range with OK-5 FEL (3.5 kA)





Maximum γ energy
Fixed FEL wavelength
γ energy
OK–5 FEL
150 nm
190 nm
230 nm
450 nm
540 nm
780 nm
1064 nm
Gamma beam energy (MeV)
Electron beam energy (GeV)
0
20
40
60
80
100
120
140
160
0.2
0.4
0.6
0.8
1.0
1.2

Mirror Development Project

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

CaF_2 substrates will be produced by Layertec Optical Coatings (Millingen, Germany).

Coatings will be done by Laser Zentrum Hannover (LZH).

Iterations will be required to produce mirrors having acceptable lifetimes and reflectivities. 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. 2009
(to be published October 2009)

Chiral Perturbation Theory

ChPT is a simultaneous expansion of the effective Lagrangian in powers of (external) momenta and explicit chiral symmetry breaking terms (light quark masses) where successive terms in the chiral expansion are suppressed by the inverse powers of the chiral symmetry breaking scale Λ_x~1 GeV.

The small masses make the low-energy interaction weaker than a typical strong interaction, but not zero.

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.

These experiments will provide stringent tests of

- The predictions of Chiral Perturbation Theory

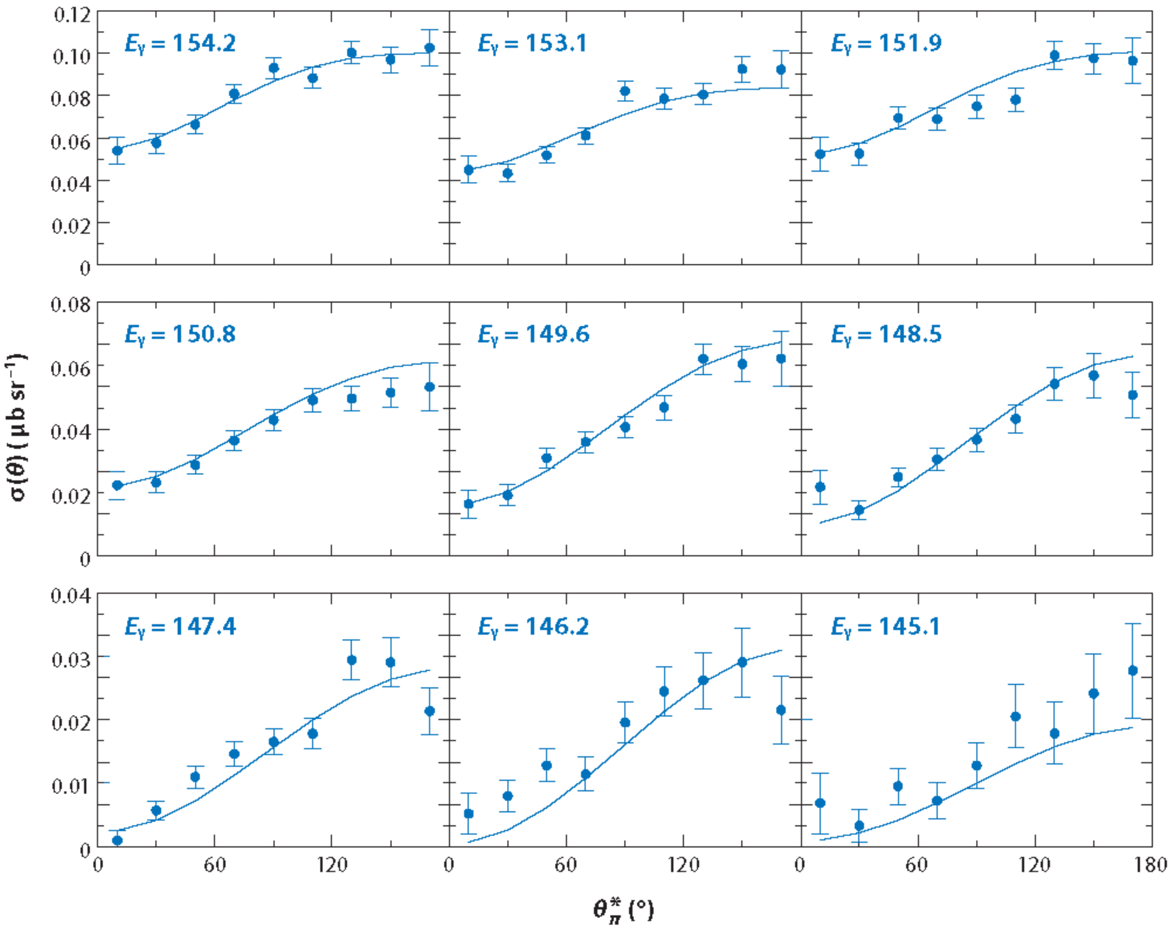
- Predictions of isospin breaking due to the mass differences of the up and down quarks.

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

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.



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

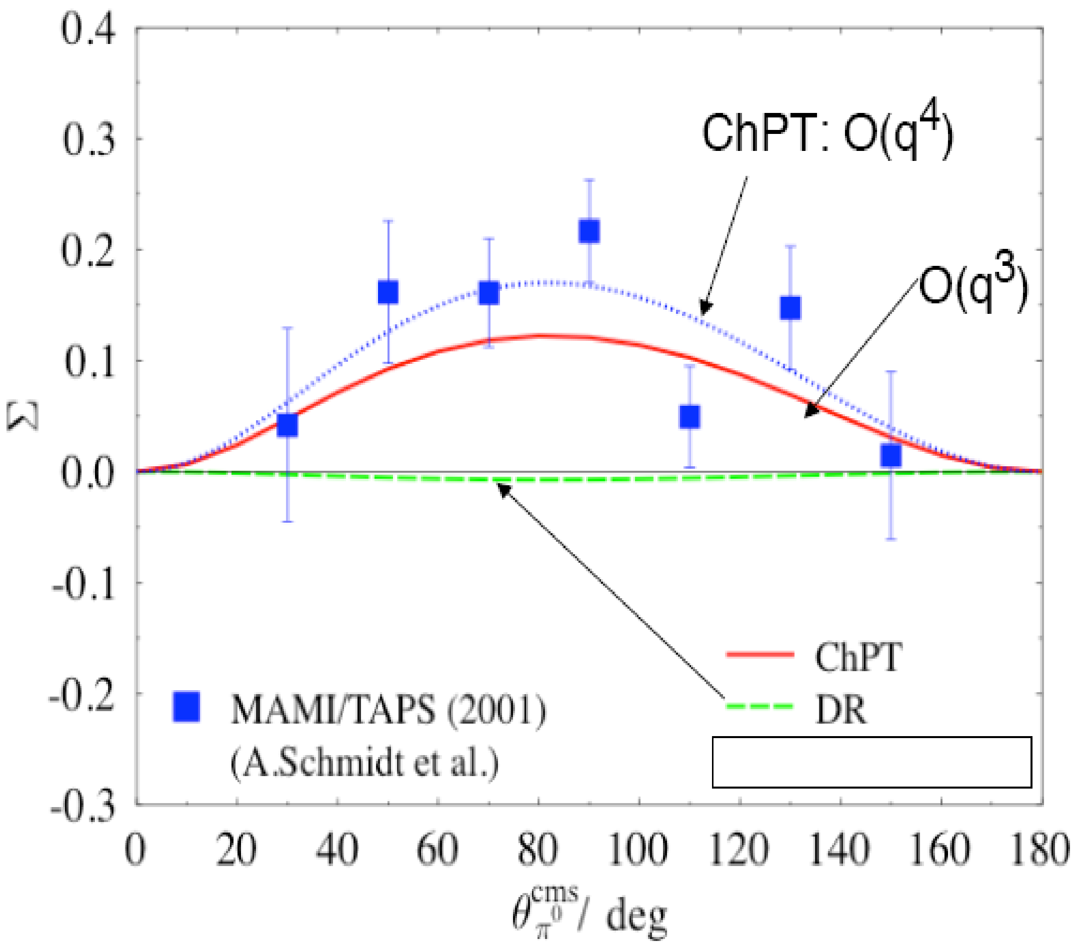
$P_3 = 2M_{1+} + M_{1-}$.

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

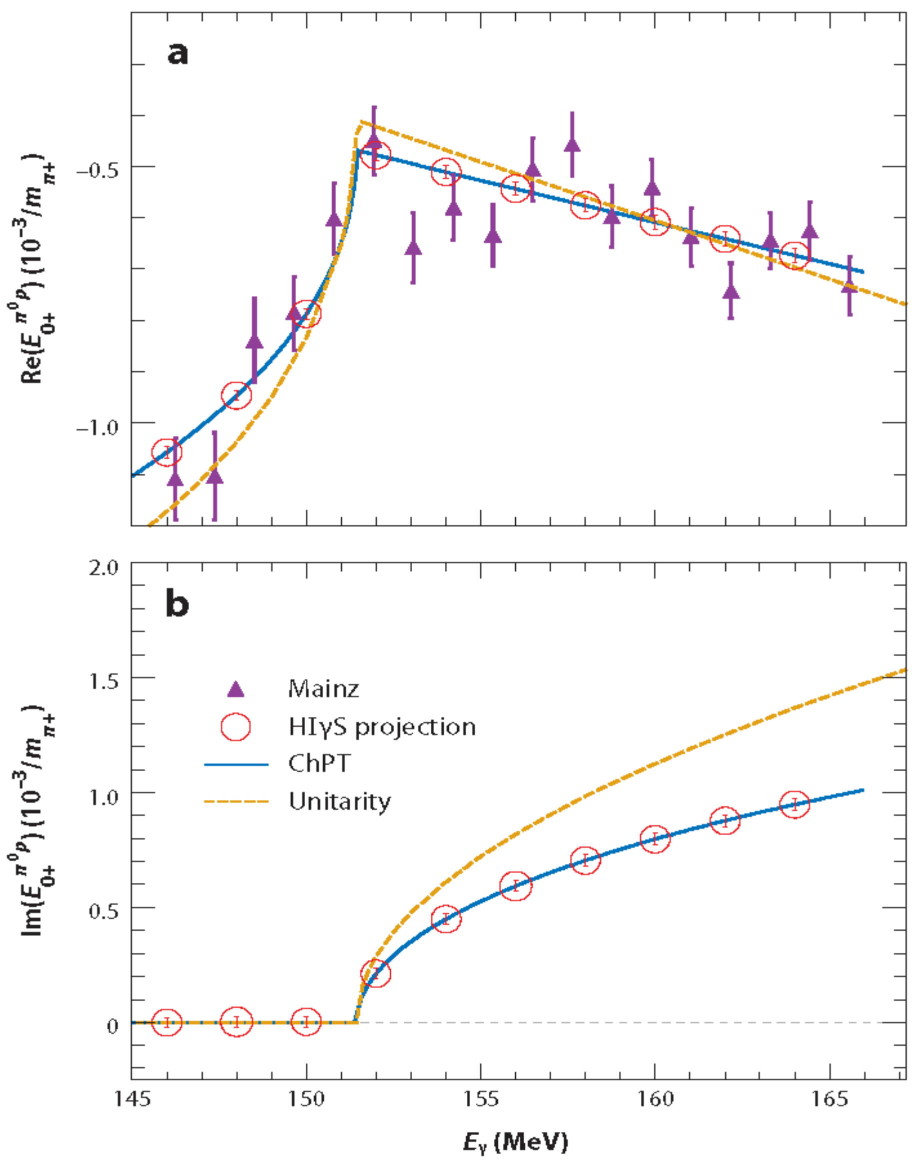


$\gamma p \rightarrow \pi^0 p$

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

The ChPT calculations include the p-waves to $O(p^4)$ consistent with older s-wave calculations. Two new p-wave low-energy parameters were determined by fitting the data.

Also see projected data points for a proposed experiment at HIγS, where each point is the result of running for 100 hours. More on this later.


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

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 performed two fits to the Mainz data, including the analyzing power data of Schmidt et al. They used the results of HBCHPT for the s- and p-waves, and included d-waves using the *customary* Born terms. Five LECs were adjusted to fit the data. Fits for both cases had the same χ^2. While the p-wave results were almost identical, the LECs of the E_{0+} counter-term differ, leading to a significant change in the value of E_{0+}. Clearly, more accurate data are needed to confirm this.

RED – SPD Model
BLUE – SP Model

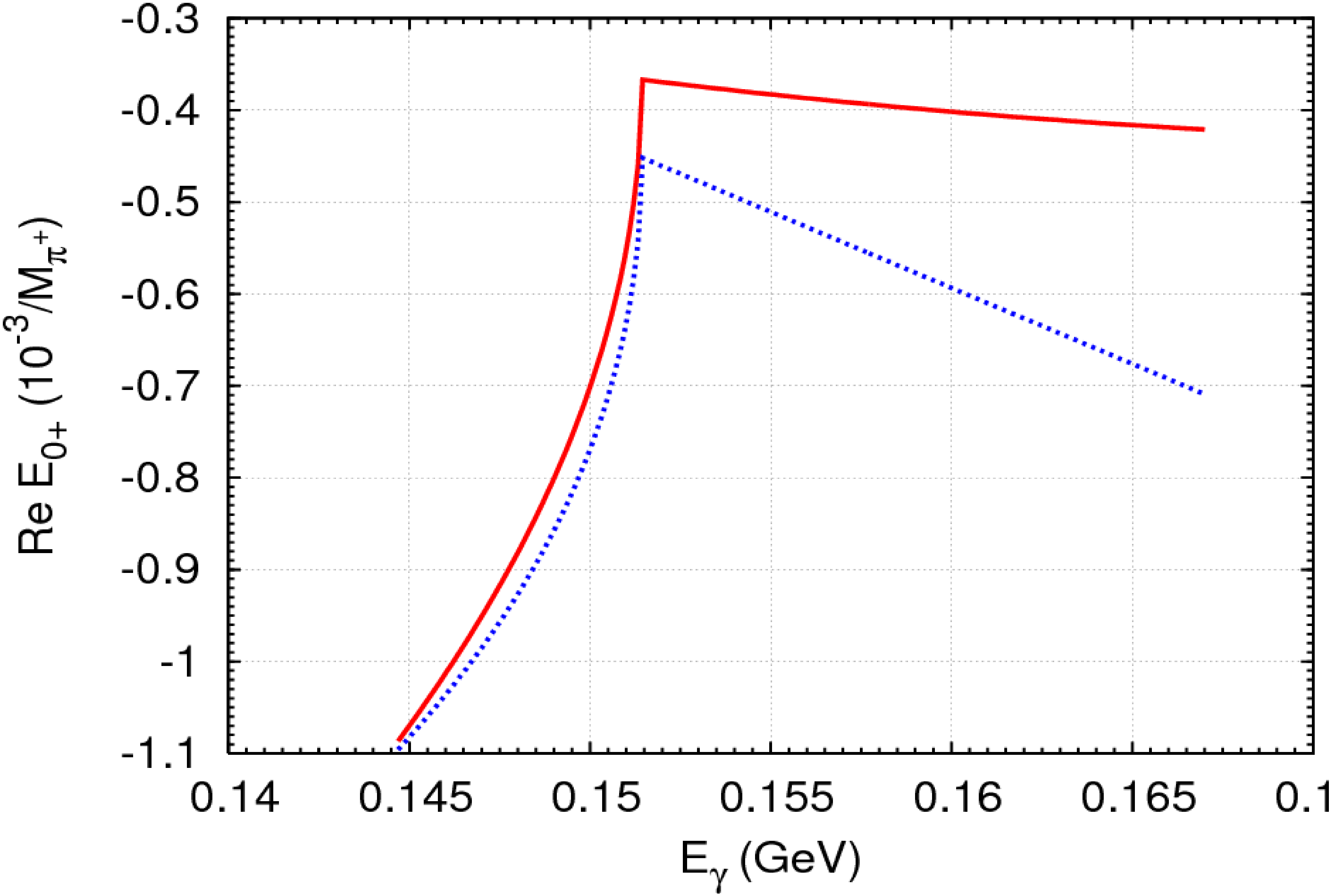


Fig. 3. (Color online) Extracted E_{0+} multipole

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).

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

Dave says asymmetries will be available *Very Soon*.

Simulations

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

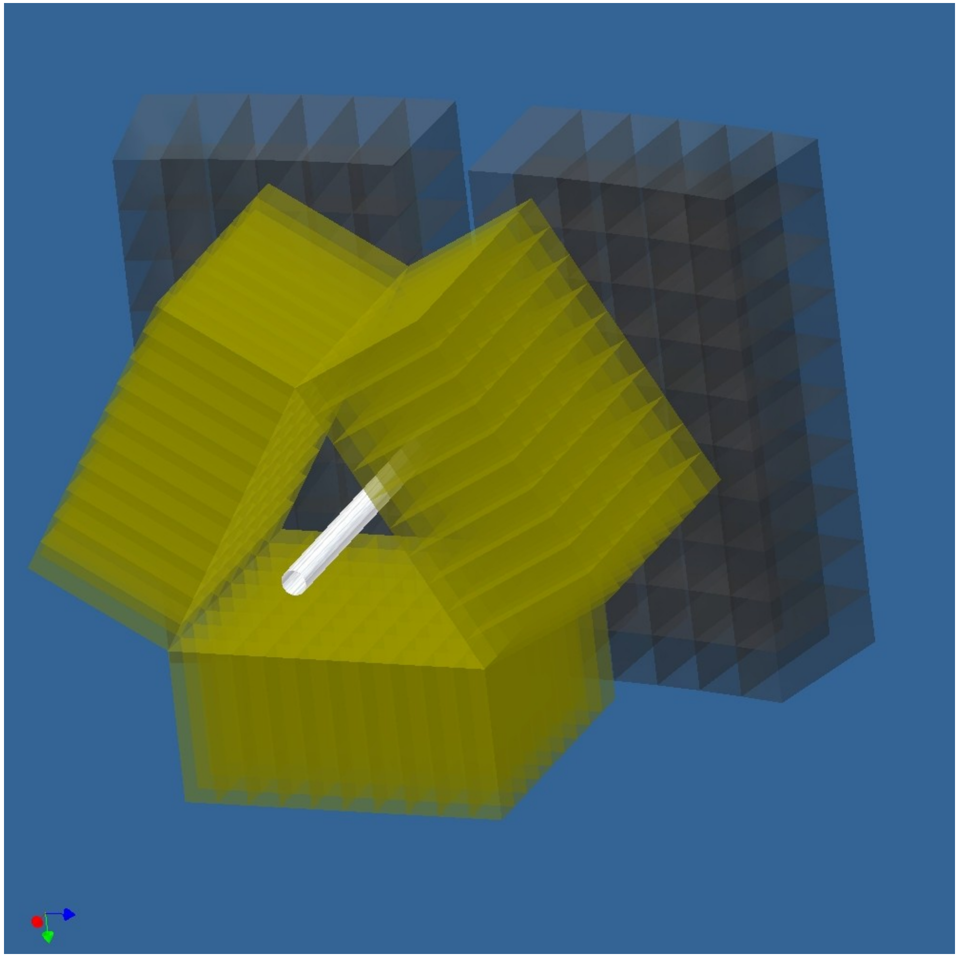
The π^0s were detected using the CBx assembly.

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.



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

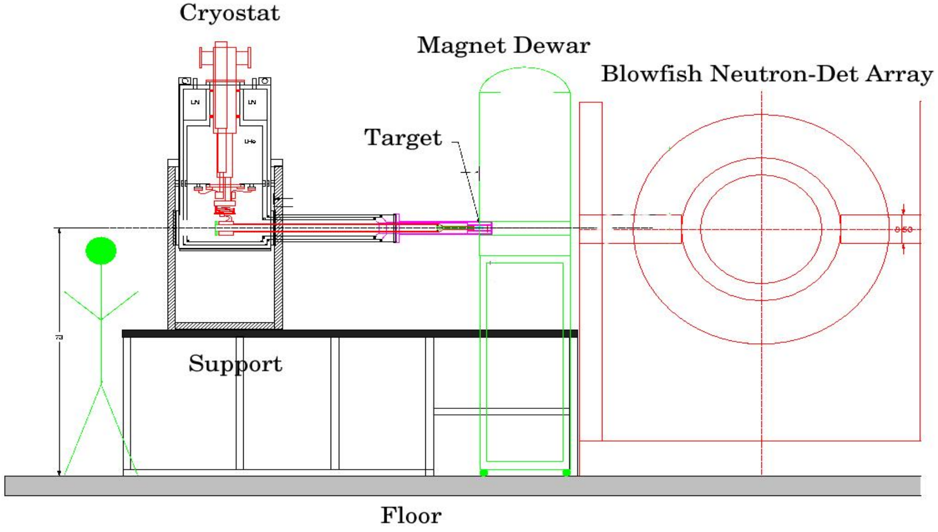
E ---Circ. photons, longitudinal target asymmetries

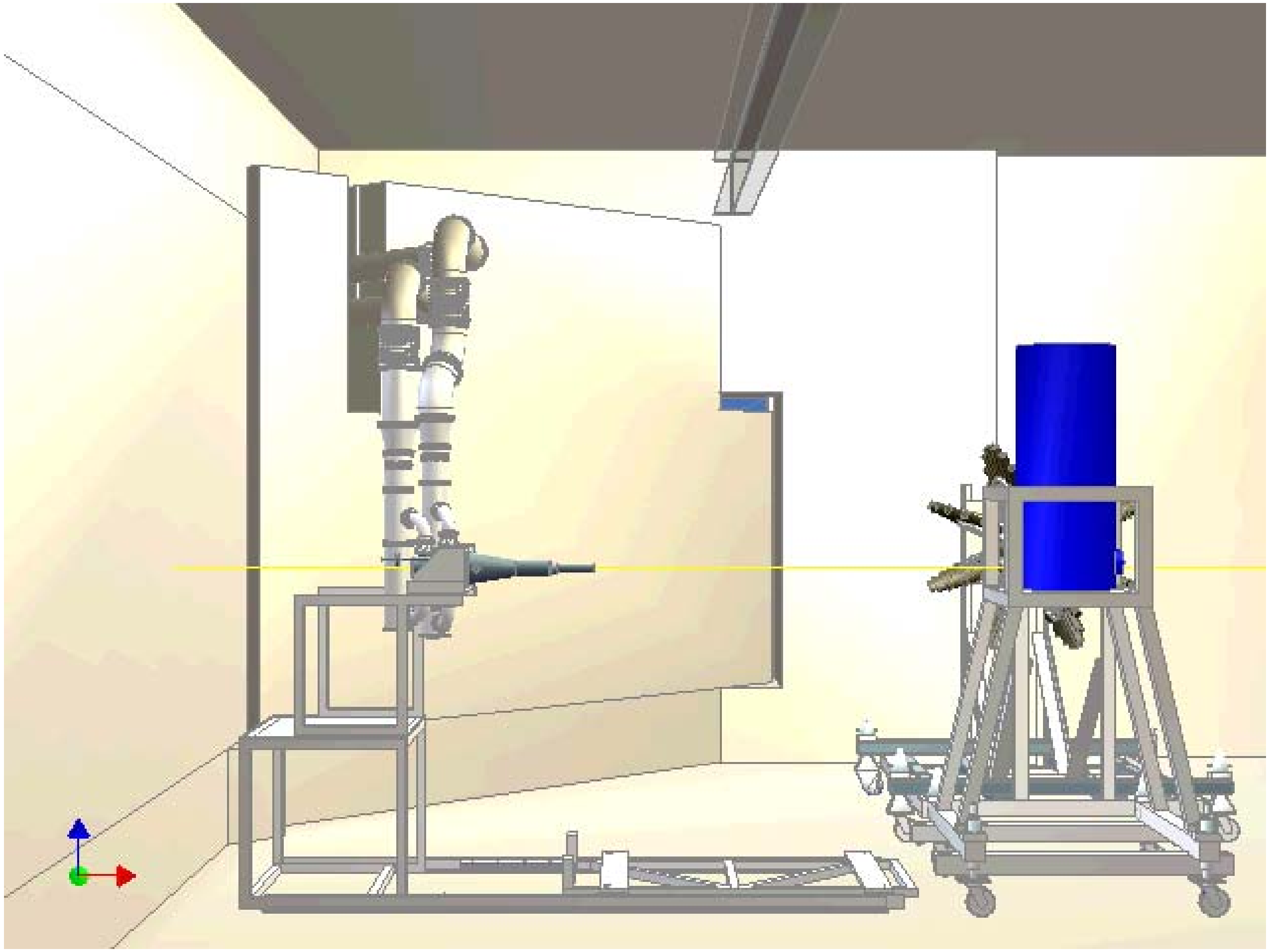
F ---Circ. photons, transverse target asymmetries

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

Frozen Spin Polarized Deuterium Target

- Butanol
- Polarization ~ 80 %
- Polarizing Field ~ 2.5 T
- Holding Field ~ 0.6 T
- ~4 x 10^{23} d/cm^2





Motivation

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

$$\mathbf{\mathit{Im}[E_{0+}(\gamma p \rightarrow \pi^0 p)] = \beta\ p_{\pi+}/m_\pi}$$

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

$Re[E_{0+}$ (γp -> π^+n)] has been measured (=28.06 +/- 0.27 +/- 0.45), giving us a_{cex} (π^+n -> π^0p).

Isospin conservation implies a_{cex} (π^+n -> π^0p) = -a_{cex} (π^-p -> π^0n).

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} (π^+n -> π^0p)…~4-5%.

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:

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

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:

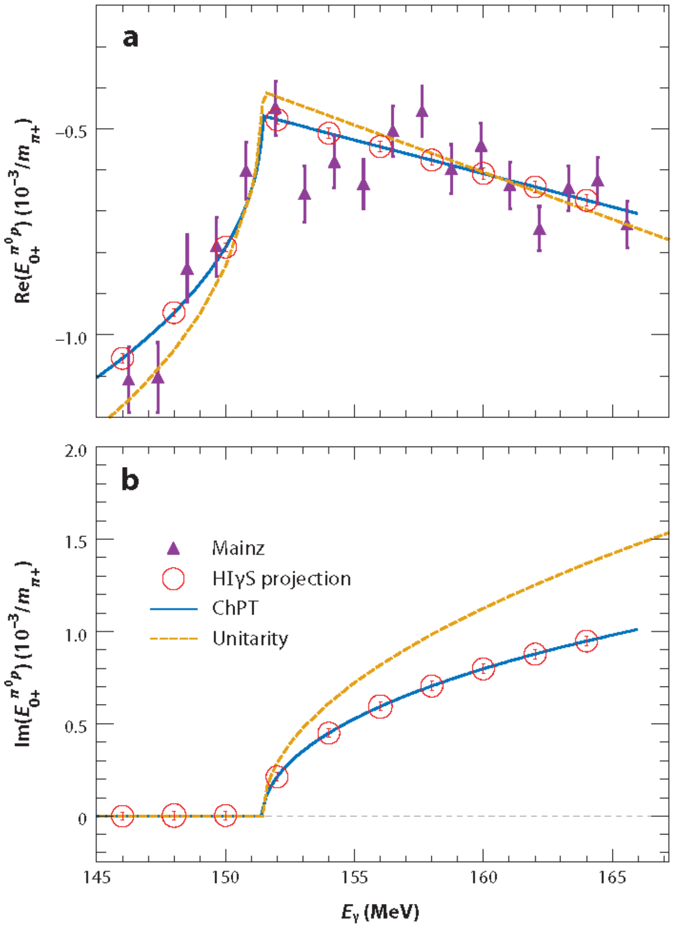
$a(\pi^- p \rightarrow \pi^0 n) = -(0.122 +/- 0.002)/m_\pi$

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).

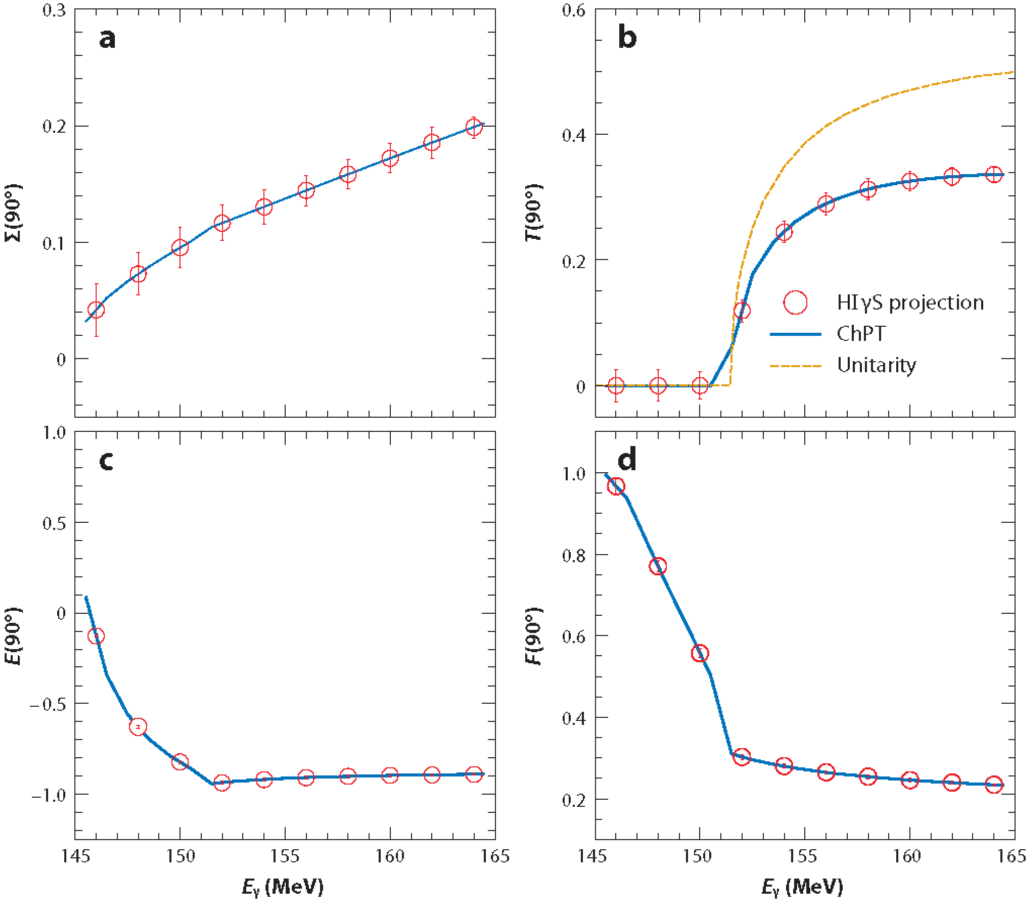
<u>This gives β = 3.43 +/- 0.08 (Unitarity)</u>
ChPT (at one loop $O(q^4)$ level gives β = 2.78.
Discrepancy attributed to truncation.

A direct measurement of β is needed.

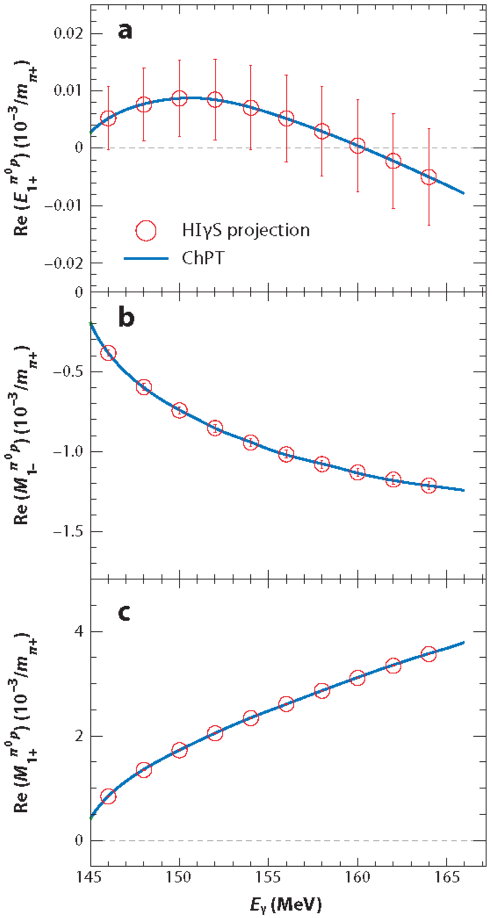
Mainz results for Re(E_{0}^{+}) and projected HIγS results for Re and Im parts. The results of ChPT and a fit based on unitarity are also shown.



a. Σ(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 (β = 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 configuration. Theory is ChPT of Bernard, Kaiser and Meissner.



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

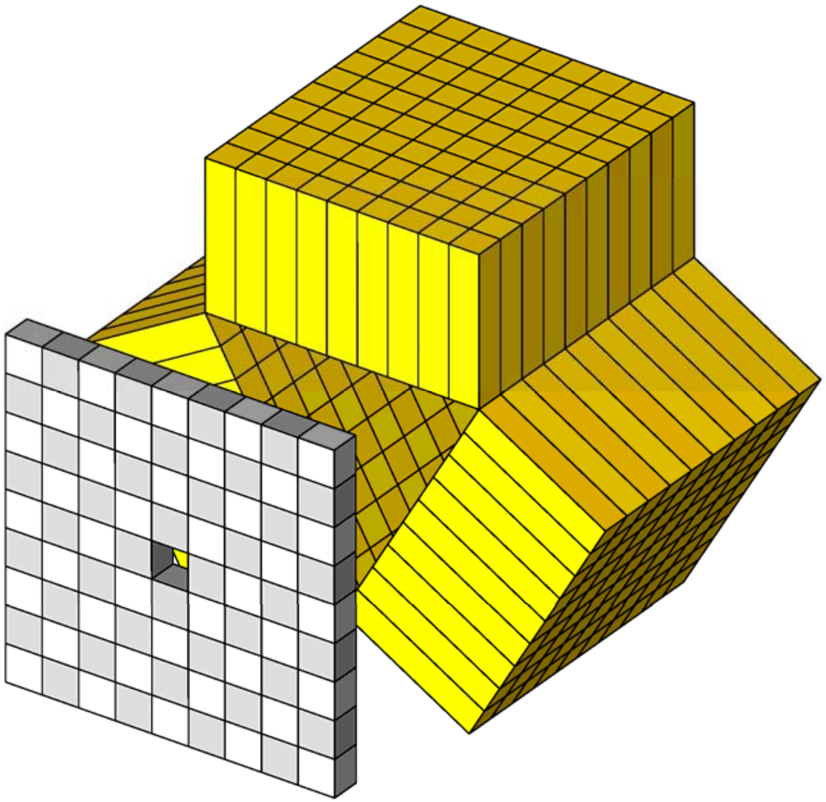
Also leads to $f_{\pi N}^2$ = 0.078 +/- 0.004.

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

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

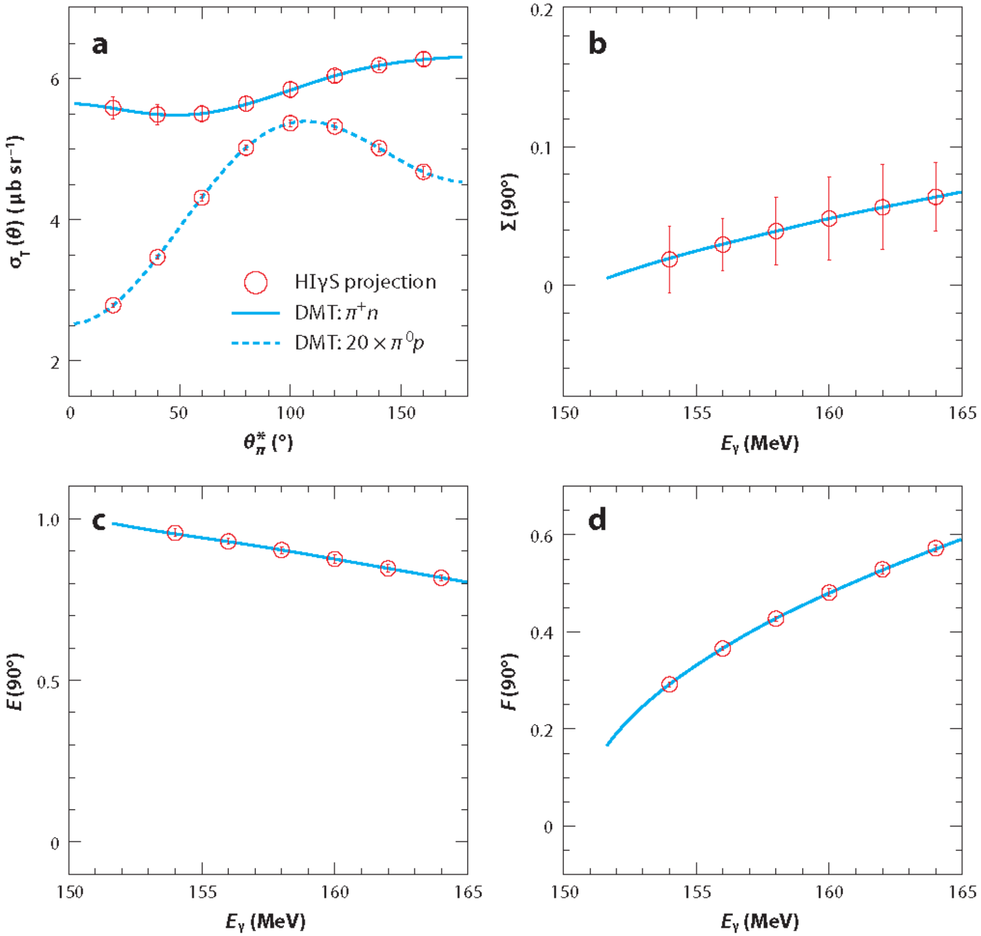
The 81 BC-505 neutron detectors (from *Blowfish*) arranged in the forward plane, giving full coverage of the corresponding pions. Each detector is 7.6 x 7.6 x 6.4 cm. The X-tal box detectors are also shown here. ***Projected HIγS data, based on the DMT model, are shown in the next figure.***



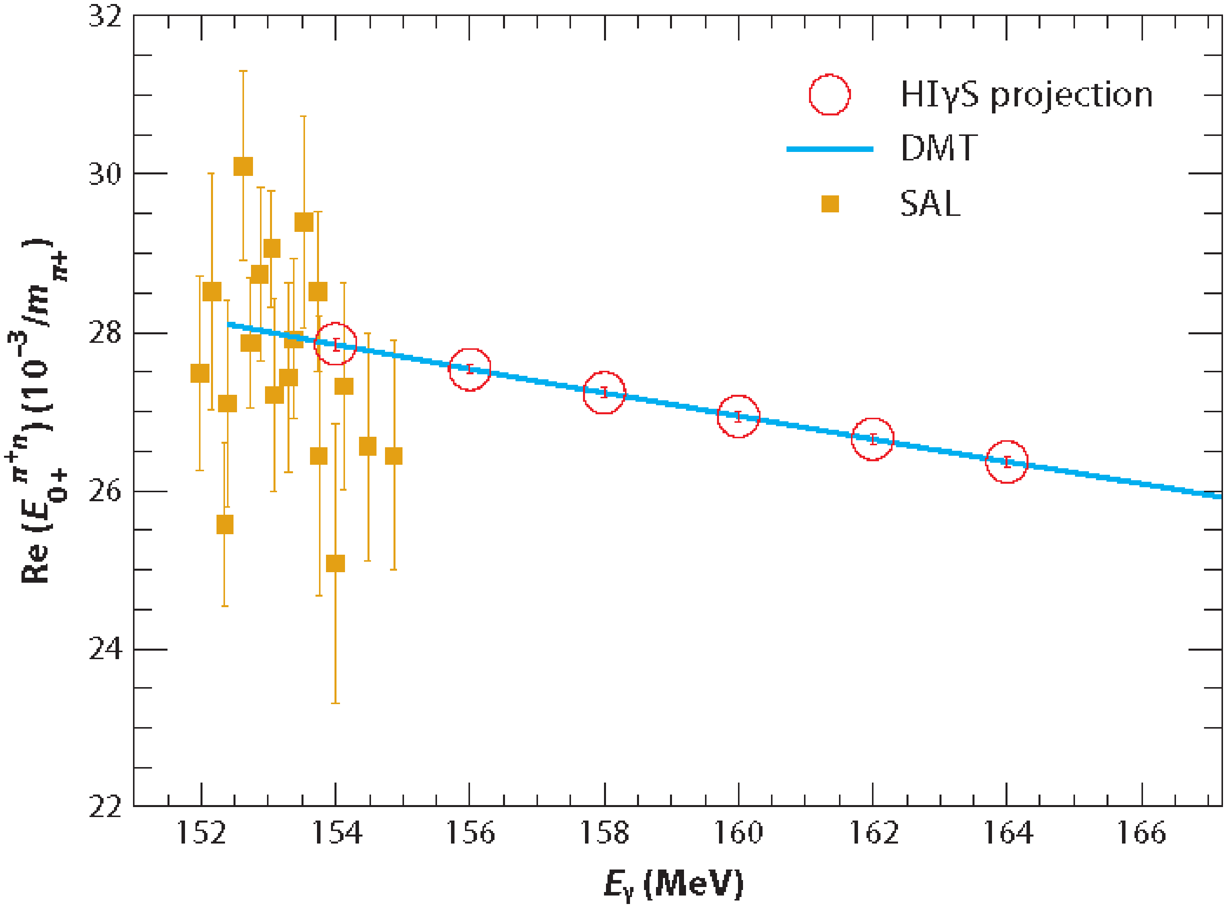
a. Predicted cross sections for $\pi^0 p$ and $\pi^+ n$ channels at E_γ= 164 MeV.

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

Each **red** **data point represents 100 hours of running.**



Resulting values and uncertainties for **Re[E_{0+} ($\gamma p \rightarrow \pi^+ n$)]** 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+} ($\gamma p \rightarrow \pi^+ n$)]** to better than 1-2%.

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

Isospin mixing due to u-d quark mass difference

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

This quantity cannot be directly measured since π^0 beams don't exist.

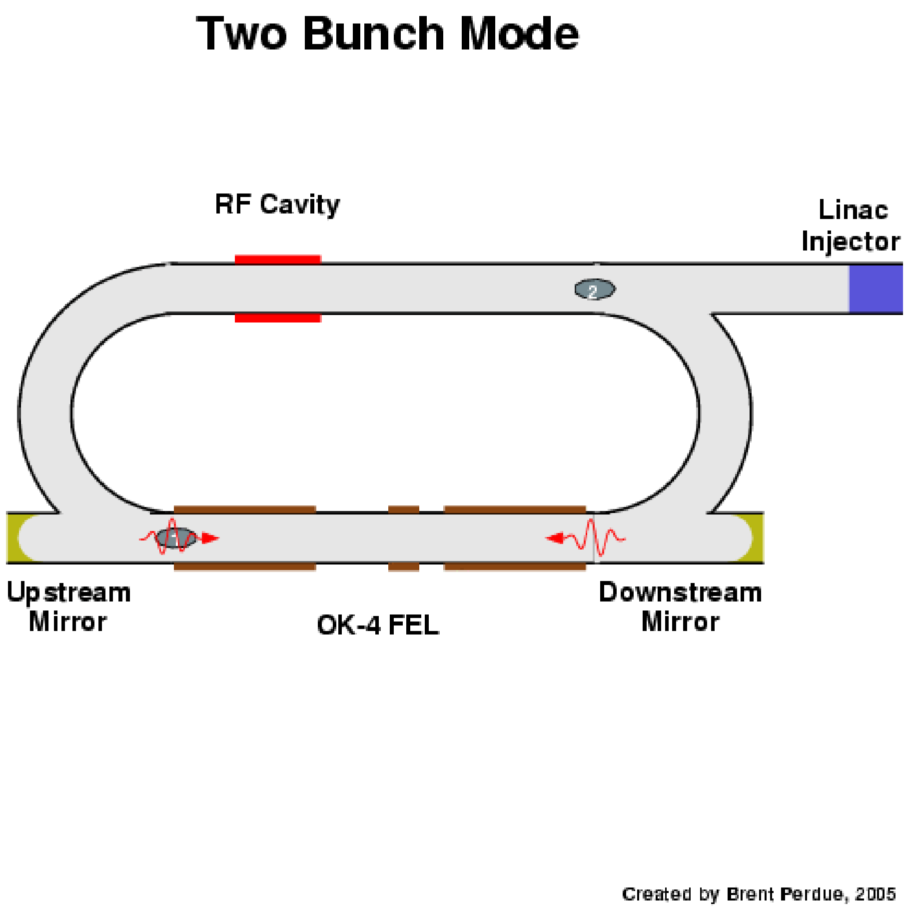
However, a measurement of the Analyzing power in the $\gamma p \rightarrow \pi^0 p$ reaction using transversely polarized protons between π^0 threshold (144.7 MeV) and π^+ threshold (151.4 MeV) will give the imaginary part of the E_{0+} amplitude, which, when combined with the real part, gives the phase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

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 $\sim 10^{-3}/m_\pi$ which is comparable to the uncertainty in the value of the isoscalar s-wave scattering length obained from pionic hydrogen and deuterium:

$$a^+ = [a(\pi^- p) + a(\pi^- n)]/2 = 0.0069 \pm 0.0034\ m_\pi^{-1}$$

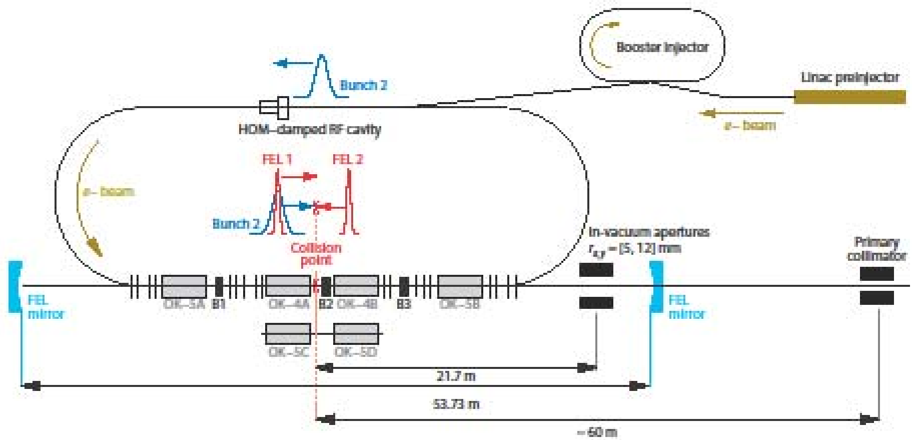
Since isospin symmetry implies $a^+ = a(\pi^0 p)$, this result should be adequate to test the 20% violation of isospin symmetry.

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



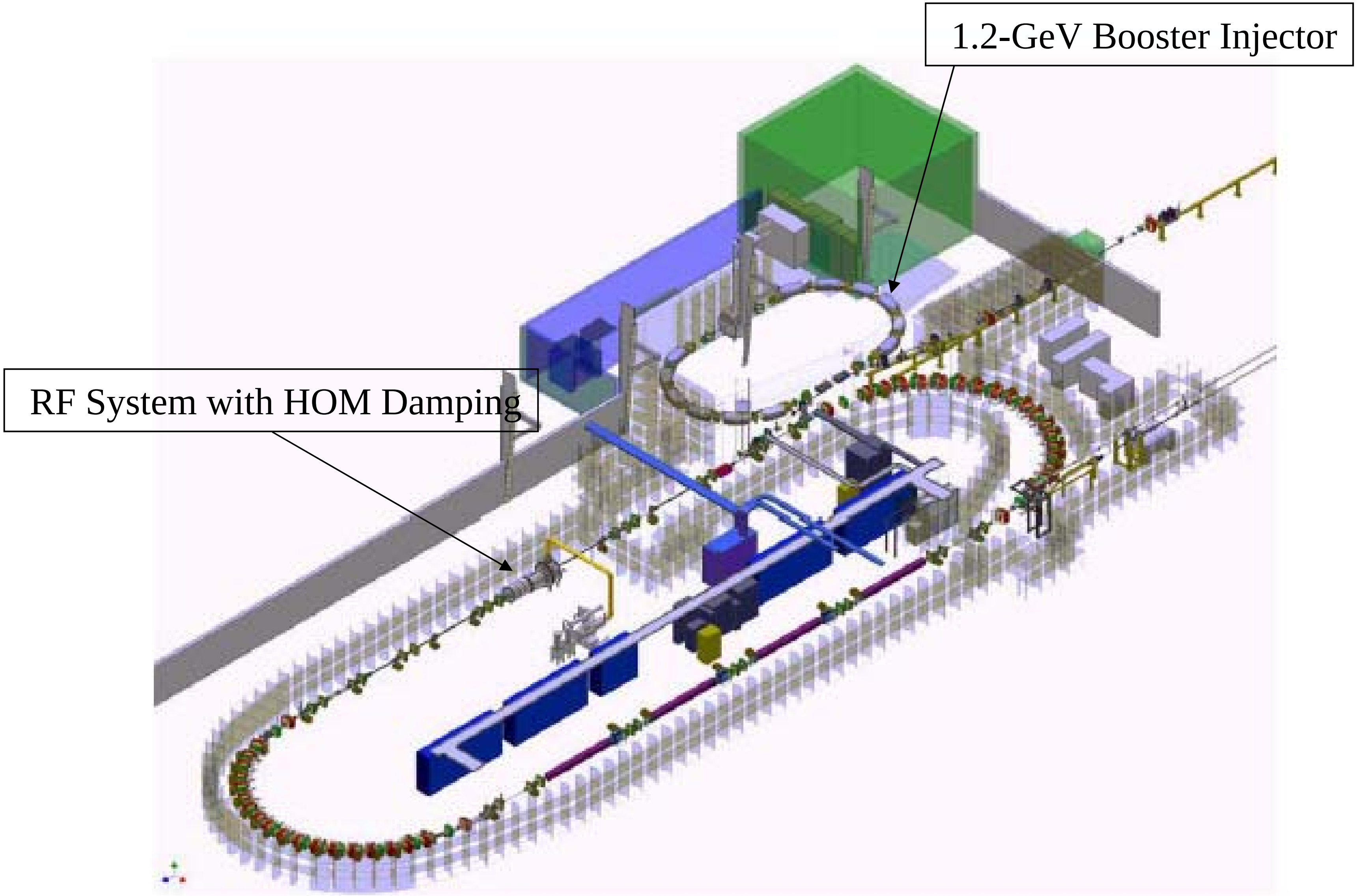
End of Presentation

- Extra slides follow:



Booster injector
Linac preinjector
Bunch 2
HOM–damped RF cavity
e– beam
FEL 1
FEL 2
e– beam
Bunch 2
Collision point
In-vacuum apertures
Primary collimator
FEL mirror
OK–5A
B1
OK–4A
B2
OK–4B
B3
OK–5B
FEL mirror
OK–5C
OK–5D
21.7 m
53.73 m
~60 m

Upgraded Facility



Threshold pion-photoproduction from the proton @ HIγS
p(γ,π^0)p

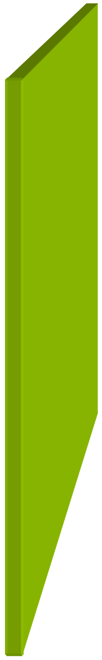
Co-spokesperson: Aron Bernstein

The first experiment:

A measurement of the Target analyzing power at $E_\gamma = 158$ MeV.

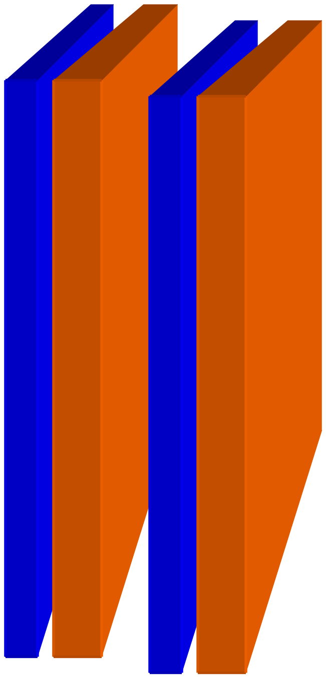
The Neutral Meson Spectrometer (NMS)

- **14 Plastic**
- **Scintillators**



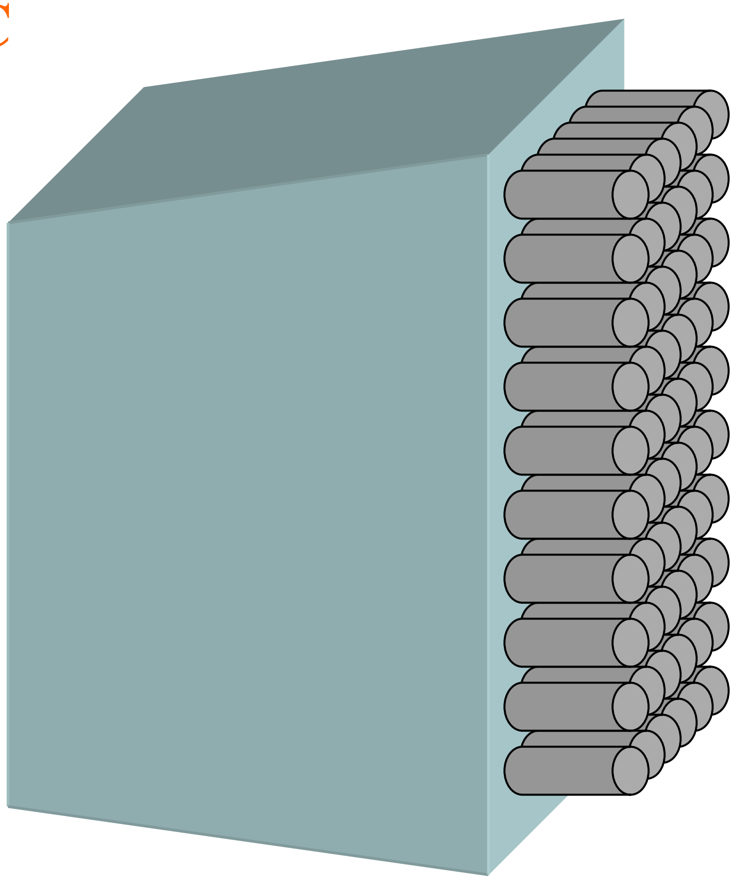
- **All Phases**
- **Veto Scint.**

- **2 BGO Layers +**
- **2 Sets of MWPC**

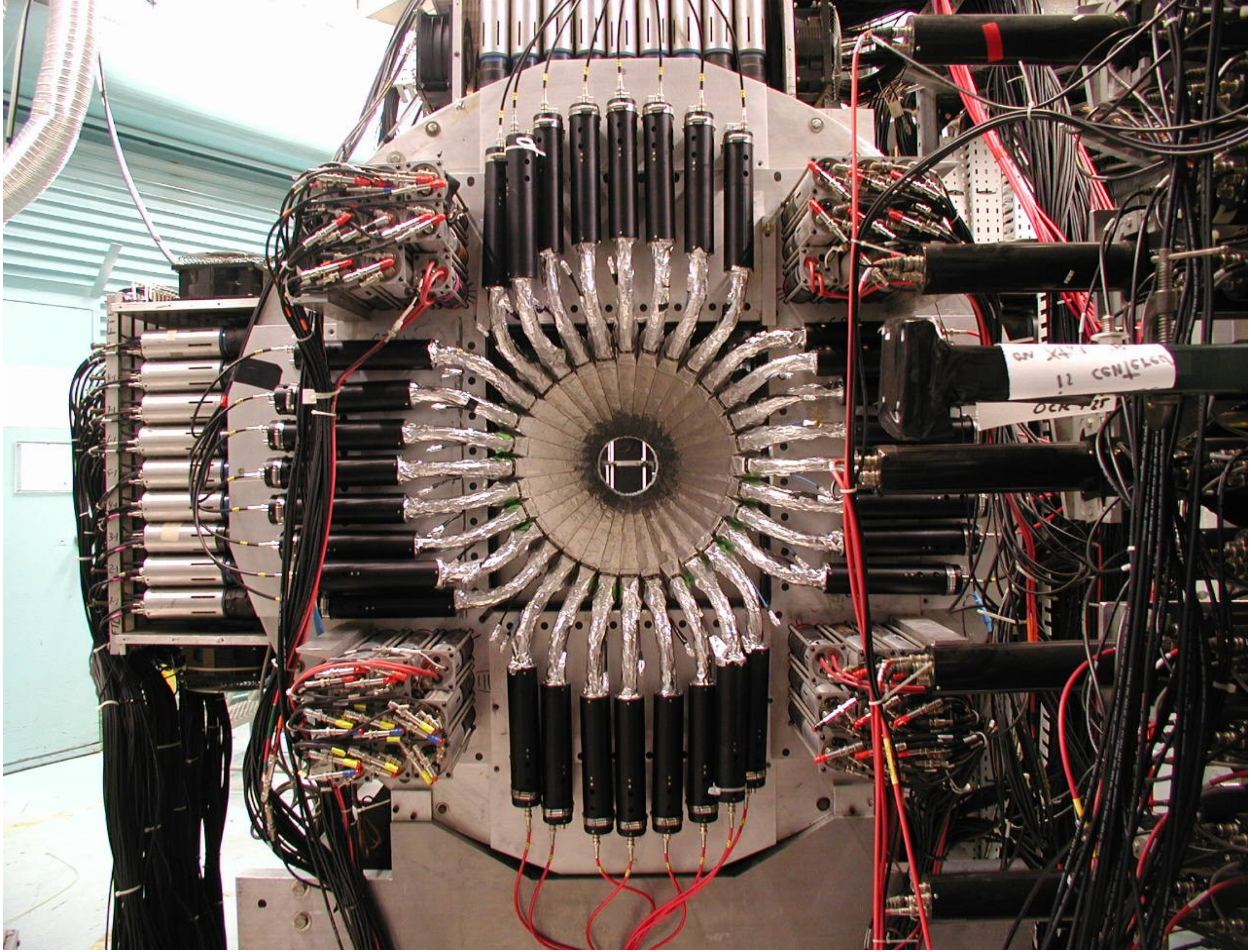


- **Phase II**
- **Tracking**

- **60 CsI Crystals**

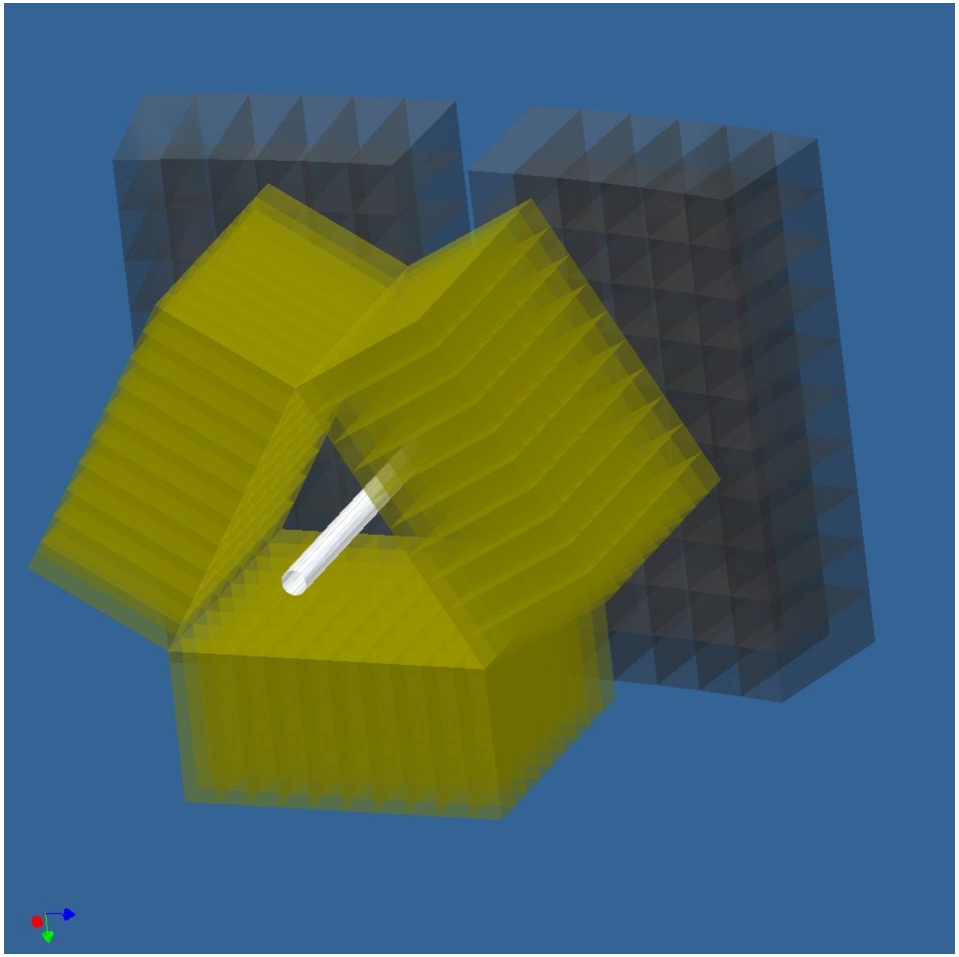


- **Phase I**
- **Calorimetry Only**



The proposed HIγS NMS

Consists of three refurbished (JLAB) arrays from the XTAL Box (LEGS) and two arrays from the LANL NMS. Mohammad will give details soon.



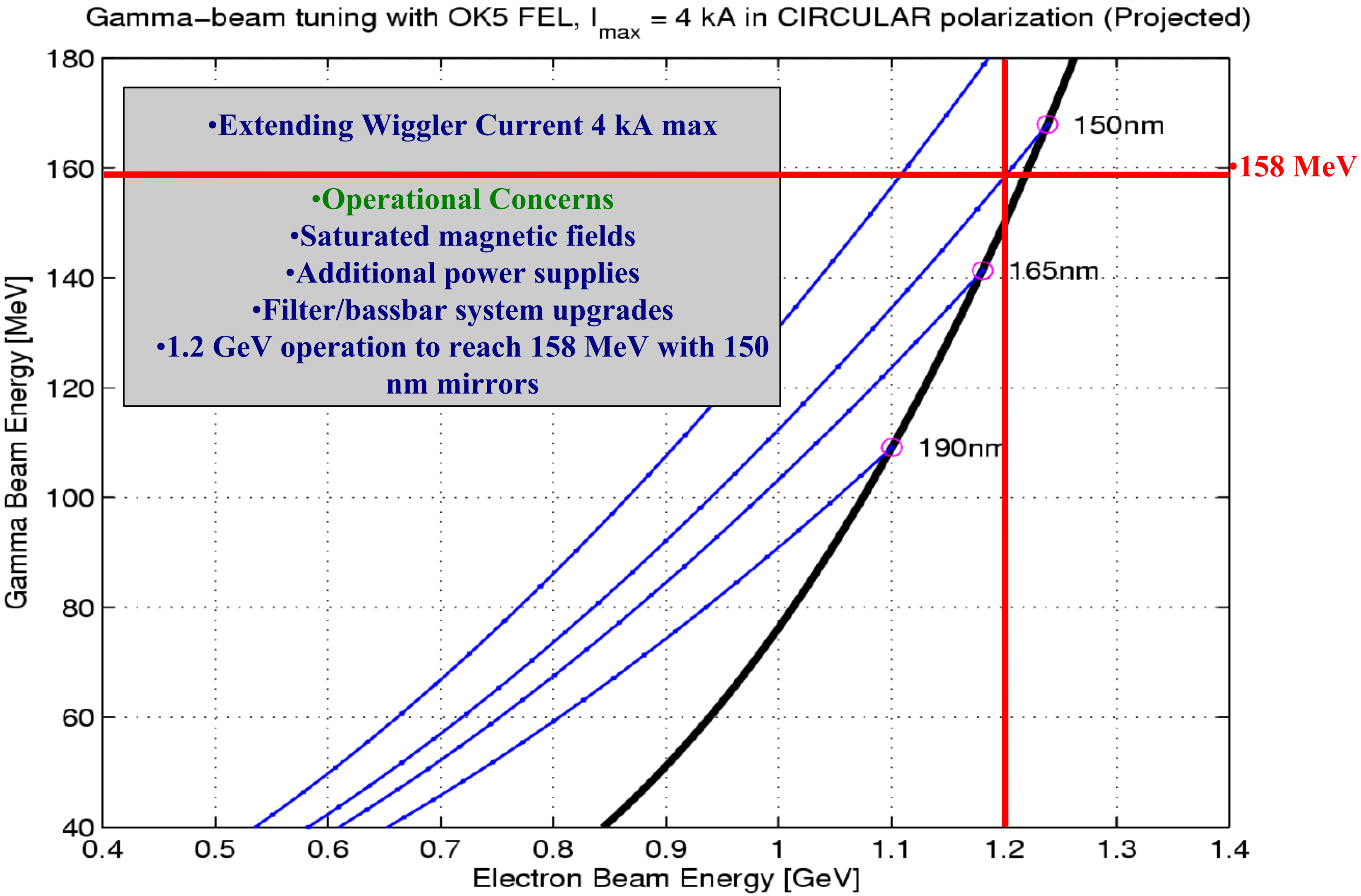
Resources at HIγS

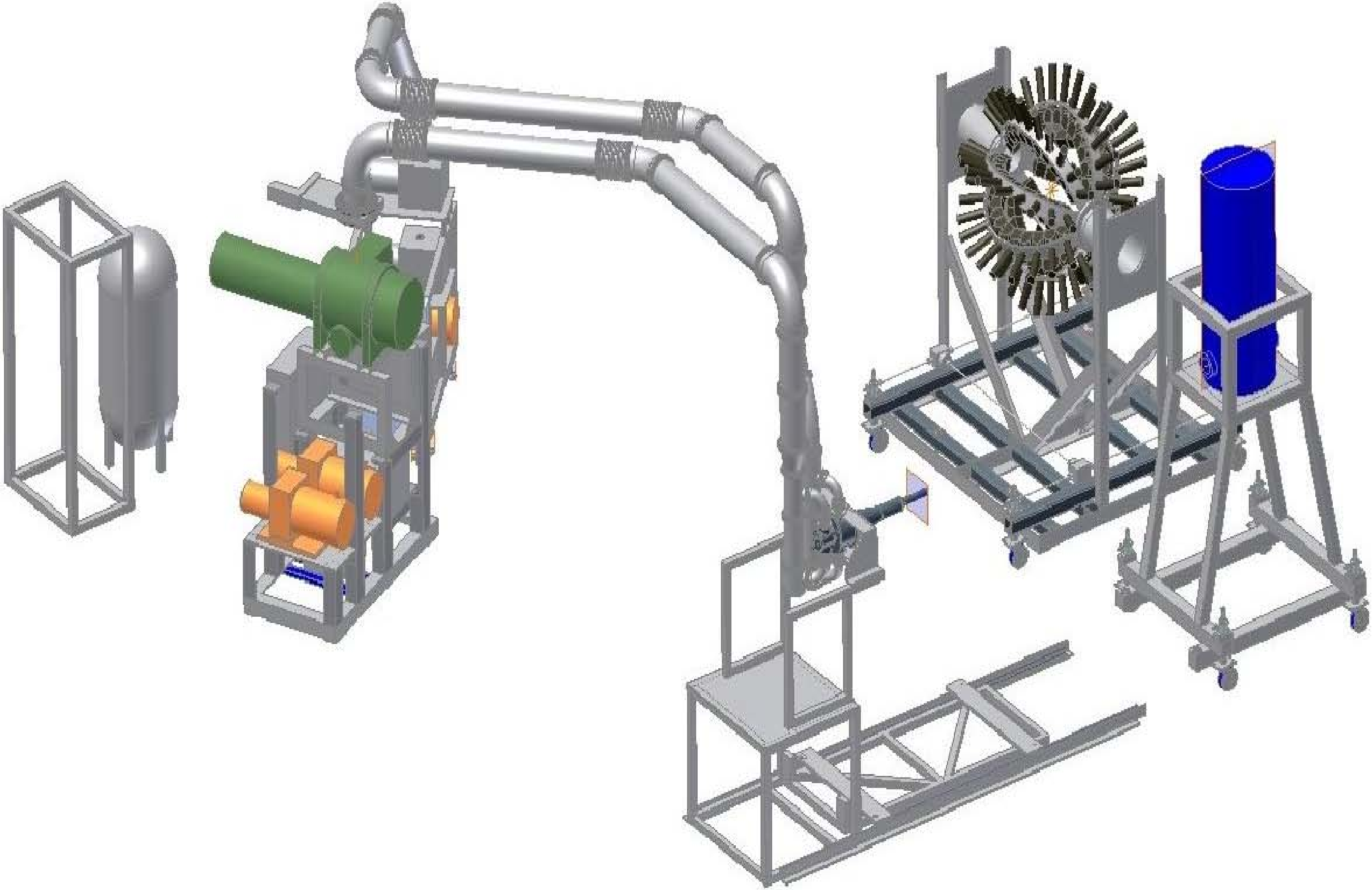
Mirror development is the key to pion threshold Physics at HIγS.

Present mirrrors can take us up to 110 MeV.

A development plan is in place for 150 nm mirrors which **are needed to reach 160 MeV.**

•Extending Gamma Energy Range (4 kA Wiggler Op)





Our measurement will determine β to +/- 0.10, where

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

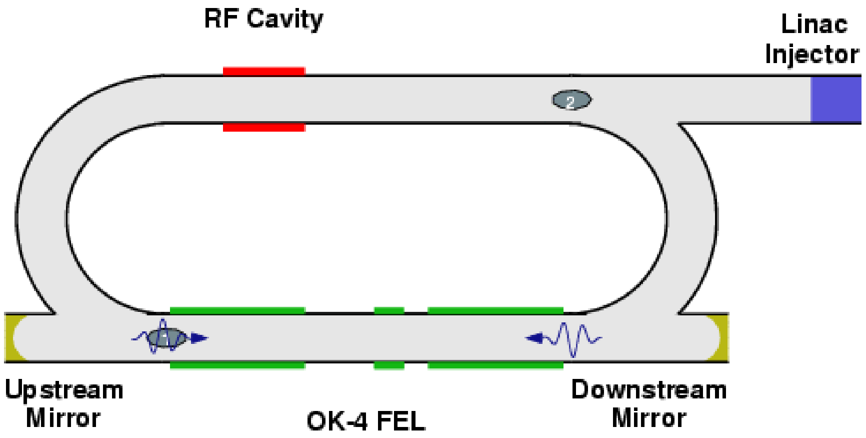
and $$\beta = Re[E_{0+}(\gamma p \to \pi^+ n)]\, a_{cex}(\pi^+ n \to \pi^0 p)$$

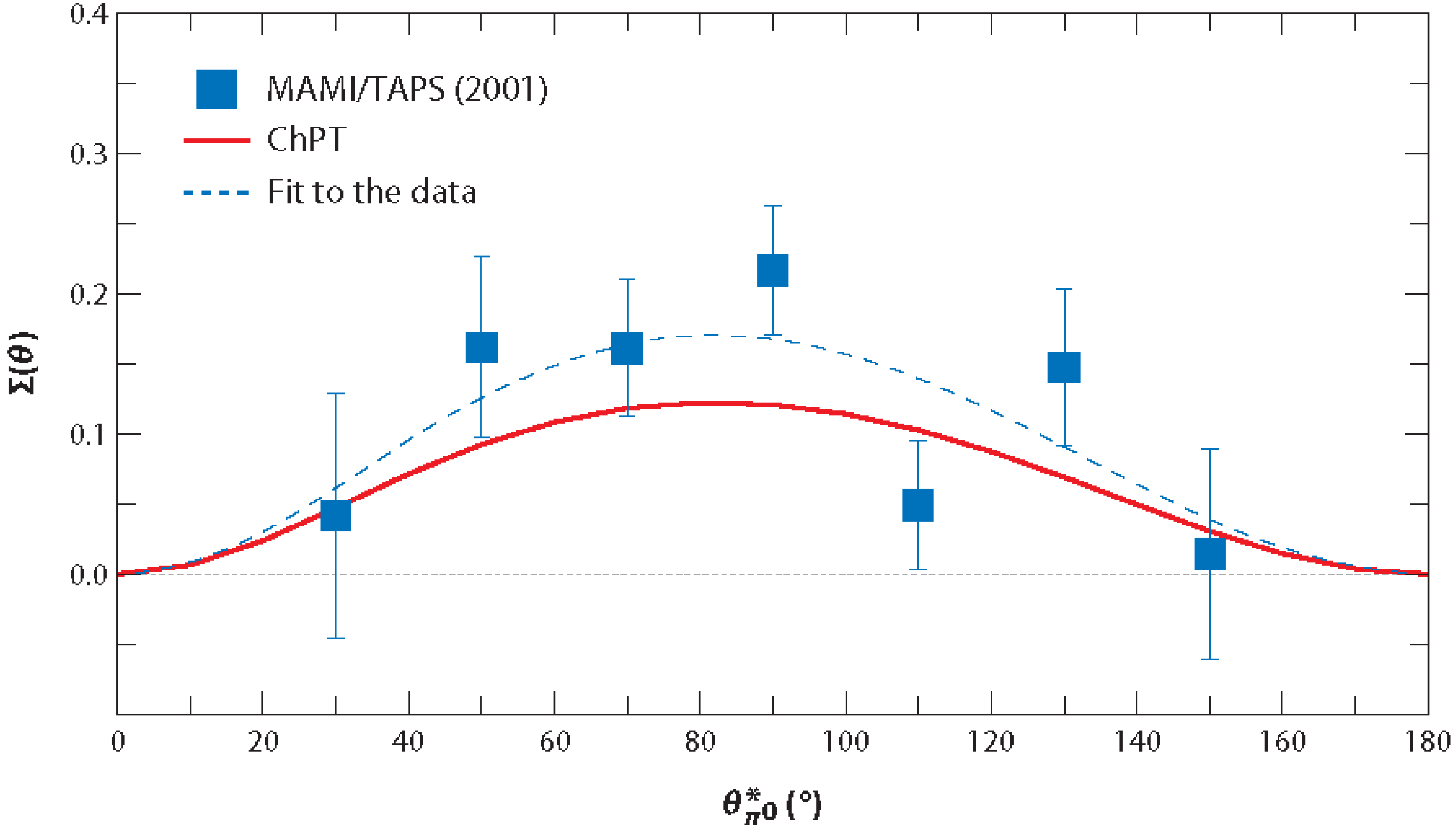
$Re[E_{0+}(\gamma p \to \pi^+ n)]$ is well measured (=28.06 +/- 0.27 +/- 0.45), giving us $a_{cex}(\pi^+ n \to \pi^0 p)$.

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 will give a comparable accuracy for $a_{cex}(\pi^+ n \to \pi^0 p)$.

Two Bunch Mode





MAMI/TAPS (2001)
ChPT
Fit to the data
Σ(θ)
0.4
0.3
0.2
0.1
0.0
0
20
40
60
80
100
120
140
160
180
$\theta^*_{\pi^0}$ (°)

A wide variety of process can be used to study Chiral Dynamics, guided mainly by the results of CHPT, an expansion of the Lagrangian for low energy QCD about the chiral limit, m_q=0.

EXAMPLES:

1. **PrimEx at JLAB—a precision measurement of the π^0 lifetime.**

2. **Pion-electroproduction from the proton near threshold at Mainz and JLAB**. *ChPT at finite Q^2.*

3. **N/Δ Physics at Mainz**: *the pion-cloud to quark-parton transition.*

4. ***Compton scattering from the deuteron at LUND—neutron polarizabilities.***

5. **Precision measurements of the polarizabilities of the proton at HIγS.**
   Obtain ~5% measurements of α_p and β_p.

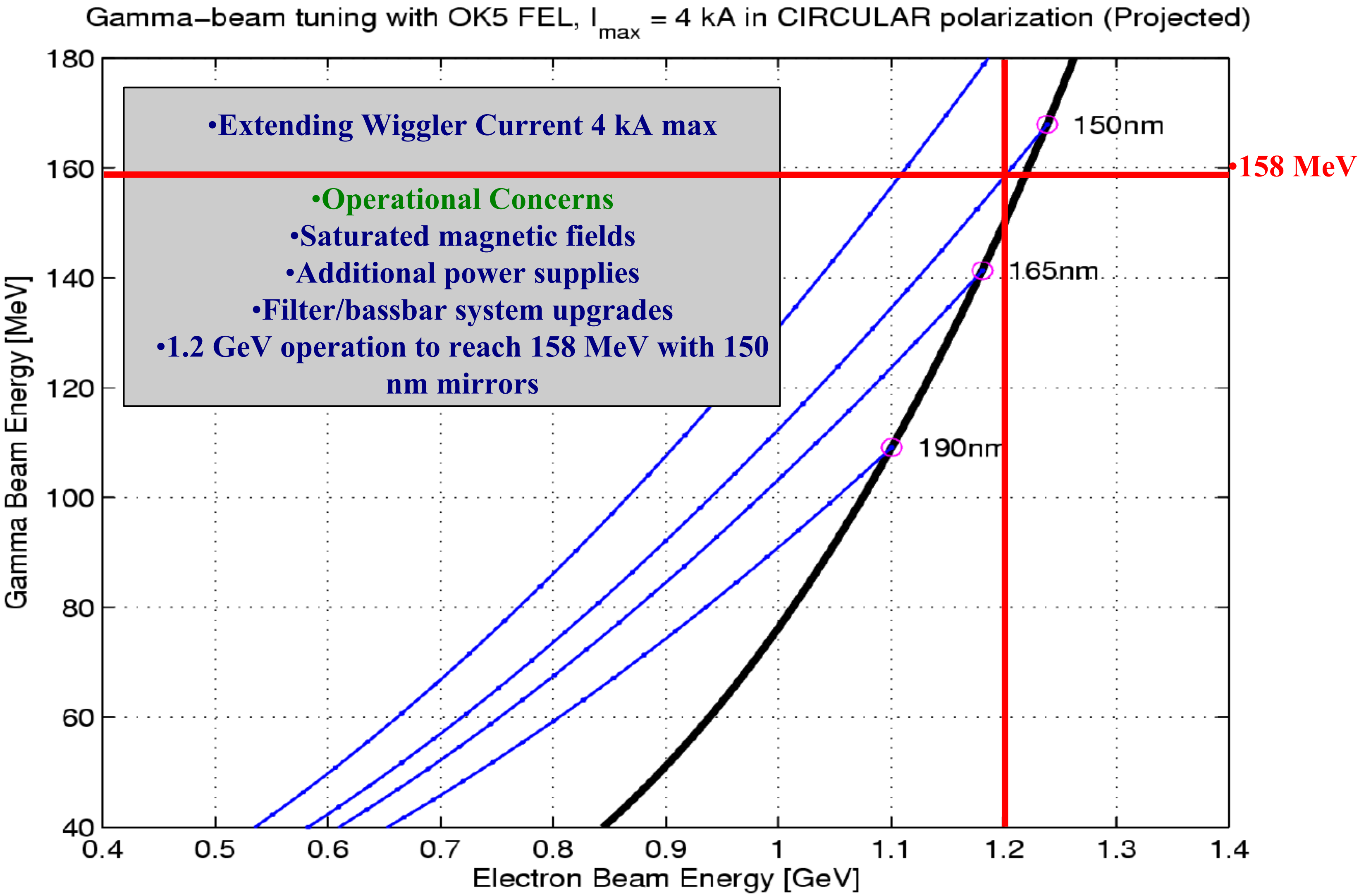
6. **Double-polarization measurements at LEGS using the HD target.**

7. **Spin-polarizability measurements for both p and n at HIγS using polarized p, d and ^{3}He targets.**
   Test ChPT and Lattice QCD results

.

8. **Pion-threshold measurements at HIγS using polarized beam and target.**

•Extending Gamma Energy Range (4 kA Wiggler Op)



Simulations

The results indicate that ***we can measure ImE$_{0+}$ with a statistical uncertainty of ~3% in 100 hours of actual data taking at 158 MeV.***

This gives us the value of **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 result will give a comparable accuracy for a_{cex} ($\pi^+ n \to \pi^0 p$).