Studies of Compton scattering and nucleon polarizabilities at the upgraded HIγS facility

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HIγS PROGRAM

HUGS_3, June 2009

HIγS

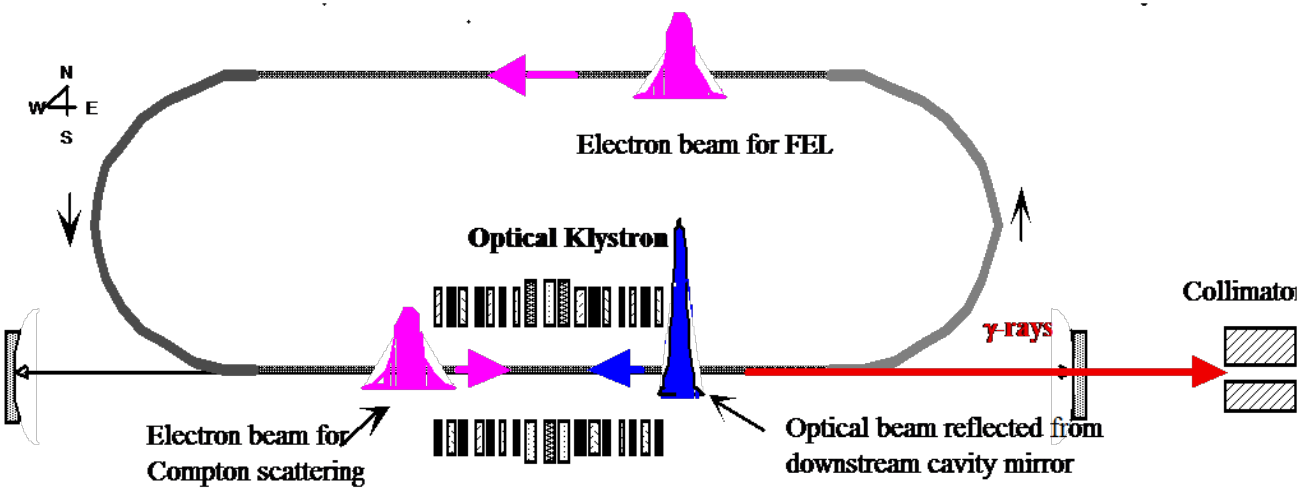
Nearly Mono-energetic γ-rays from 2 to 158 MeV

- ***Up to 65 MeV now***
- ***Up to ~100 MeV in 2010***
- ***Up to 158 MeV by 2012***

~100% Linearly and Circularly Polarized γ-rays

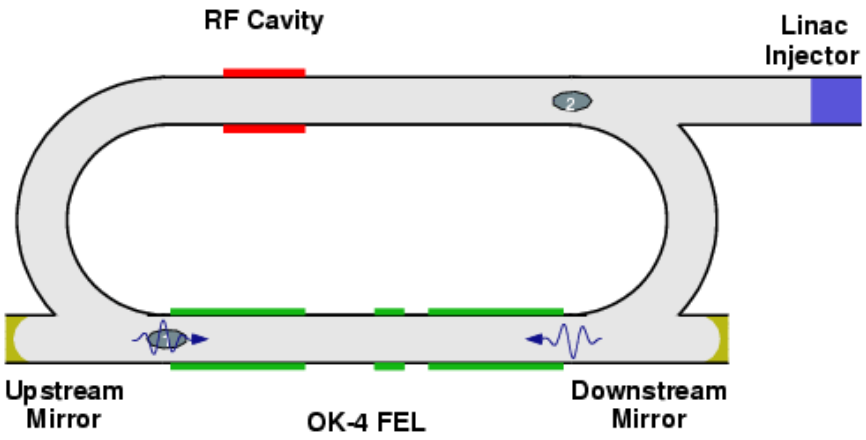
High Beam Intensities
(Ran with $2x10^7$ on target at 45 MeV (October, 2008))

γ-ray Production at HIγS



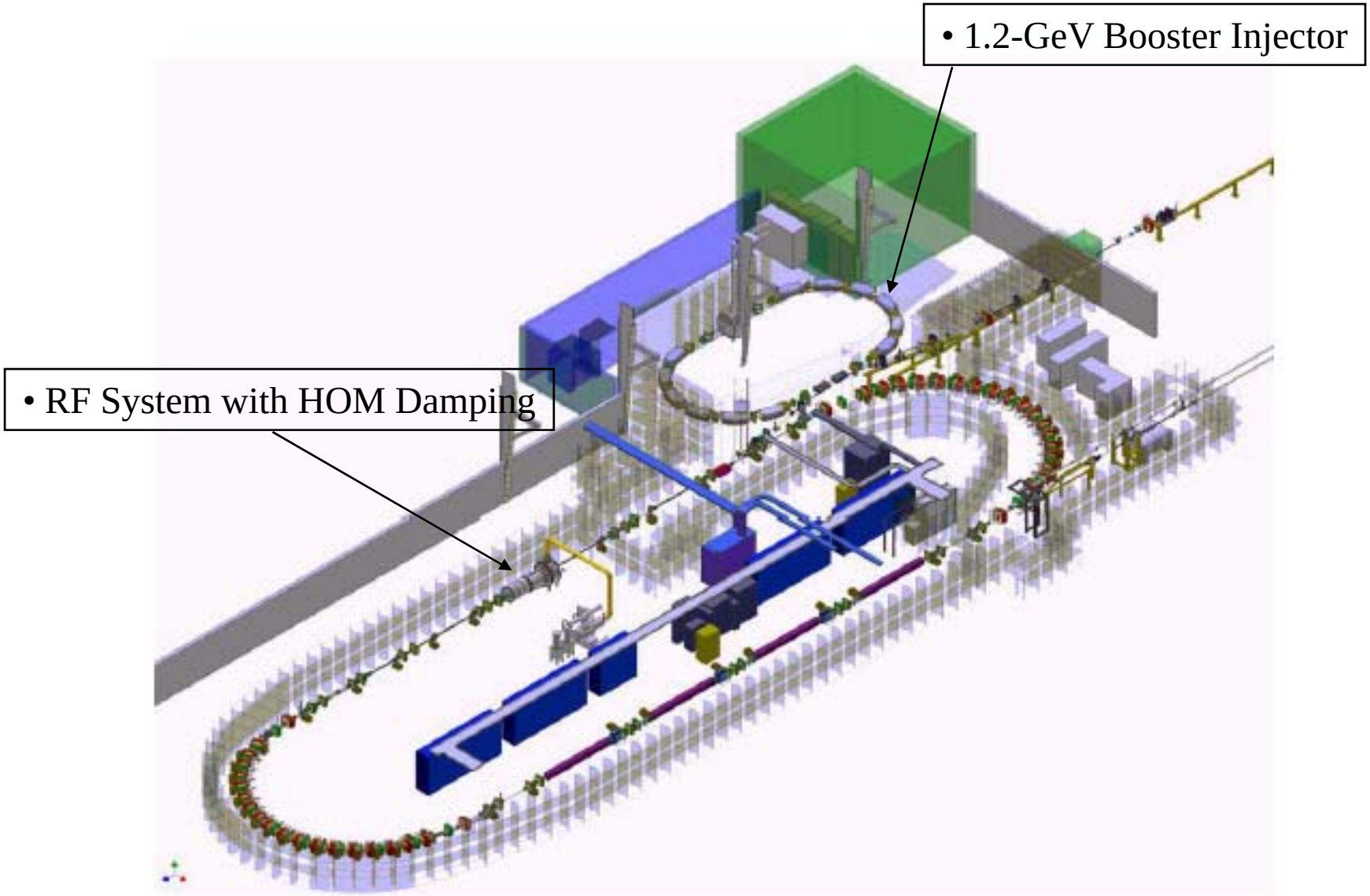
- **<u>Two modes of operation:</u>**
- No electron loss (E_γ < 20 MeV)
- Electron loss (E_γ > 20 MeV)

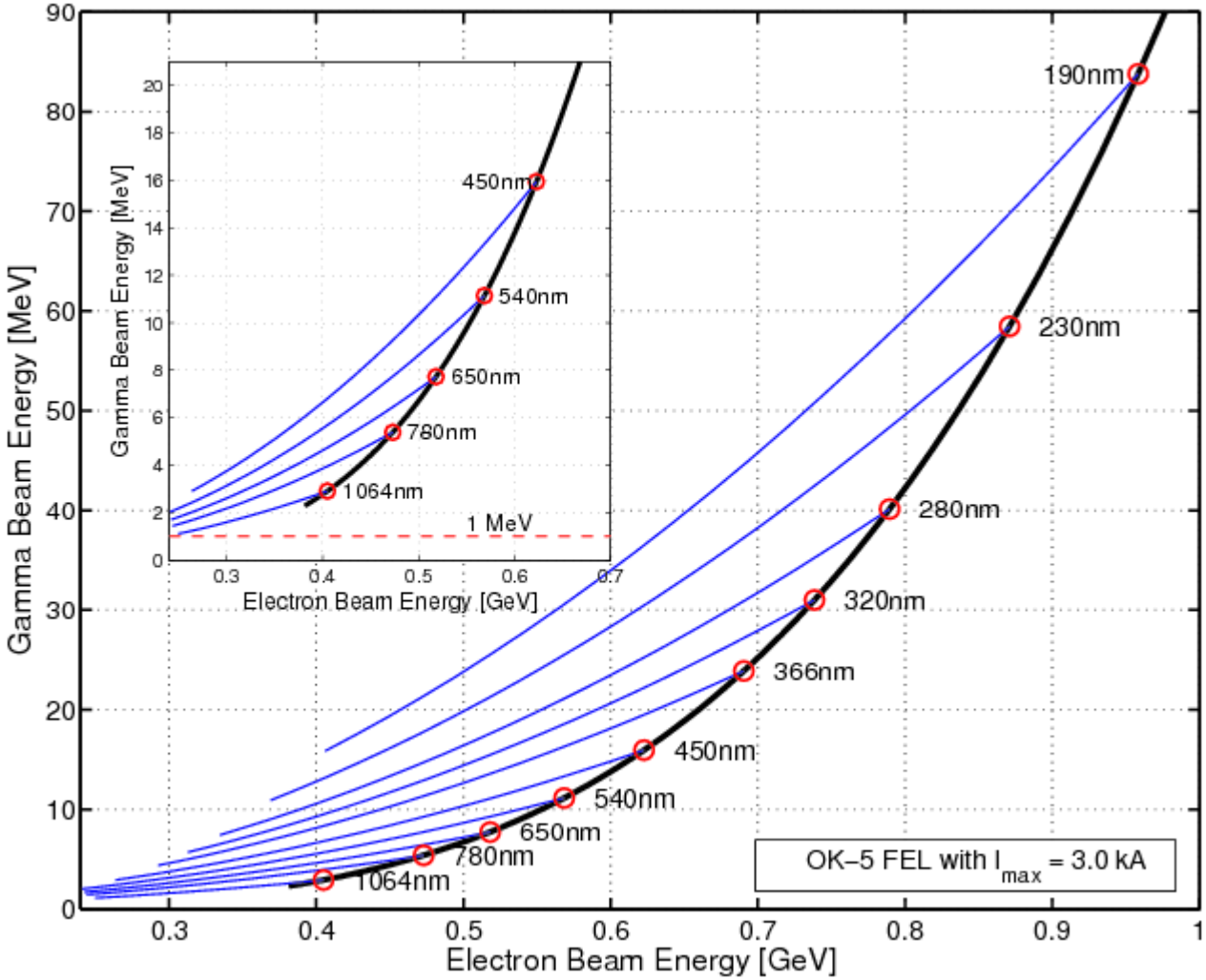
Two Bunch Mode



Created by Brent Perdue, 2005

The Upgraded HIγS Facility




Gamma Beam Energy [MeV]
Electron Beam Energy [GeV]
190nm
230nm
280nm
320nm
366nm
450nm
540nm
650nm
780nm
1064nm
OK–5 FEL with I max = 3.0 kA
Gamma Beam Energy [MeV]
Electron Beam Energy [GeV]
450nm
540nm
650nm
780nm
1064nm
1 MeV

Some typical beam intensities

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

•The research program at HIγS

•There is a very broad program of research underway at HIGS. This is expected to take over five years to execute, and will require over 2000 hrs. per year of beam time. The program includes:

•Nuclear Astrophysics
•Few Body Physics
•GDH Sum rule for deuterium and ^{3}He
•Nuclear Structure studies using NRF
•Compton scattering from nucleons and few body nuclei
•Pion Threshold studies

Compton@HIγS

Study of the fundamental structure of the nucleon:

GOALS:

Use the intense polarized beams at HIγS to obtain precise values of the electric and magnetic polarizabilities of the proton and the neutron.

Perform double polarization experiments to obtain precise values of the spin-polarizabilities of the proton and the neutron.

See: ***Research Opportunities at the upgraded HIGS Facility*, just published in *Progress in Particle and Nuclear Physics 62 (2009) 257-303.***

The Compton @HIγS Collaboration consists of 32 physicists from 14 Institutions and includes:

Averett, Calarco, Feldman, Gao, Kovash, Miskimen, Nathan, Norum, Weller, Whisnant, Wu

The Compton@HIγS Program

1. *Use linearly polarized γs at ~100 MeV to obtain accurate values for α and β of the proton.*

2. *Perform Compton scattering on the deuteron below 80 MeV to determine the neutron polarizabilities.*

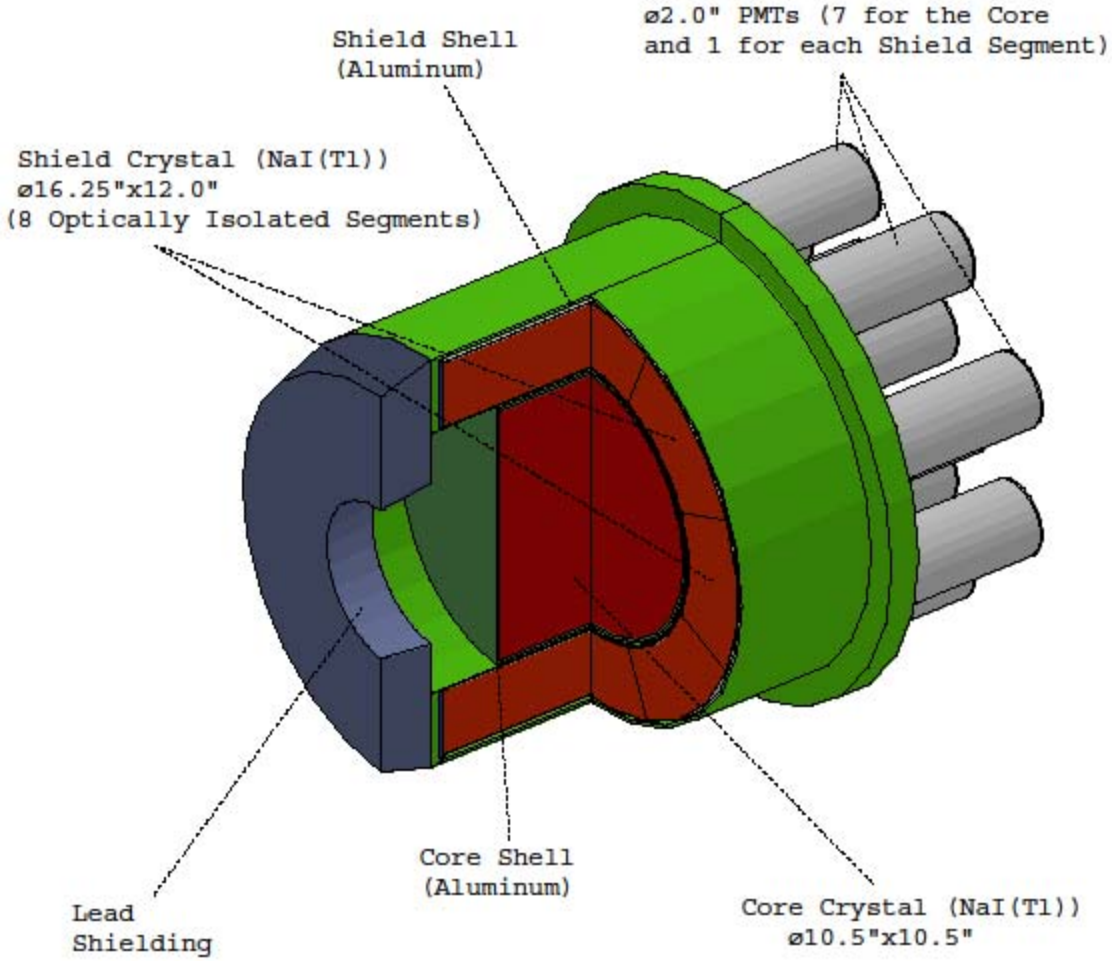
3. *Use a scintillating polarized proton target and determine the proton spin-polarizabilities with circularly polarized beam at 100 – 140 MeV.*

4. *Use a polarized ^{3}He target and measure elastic scattering to extract neutron spin-polarizabilities using circularly polarized beams.*

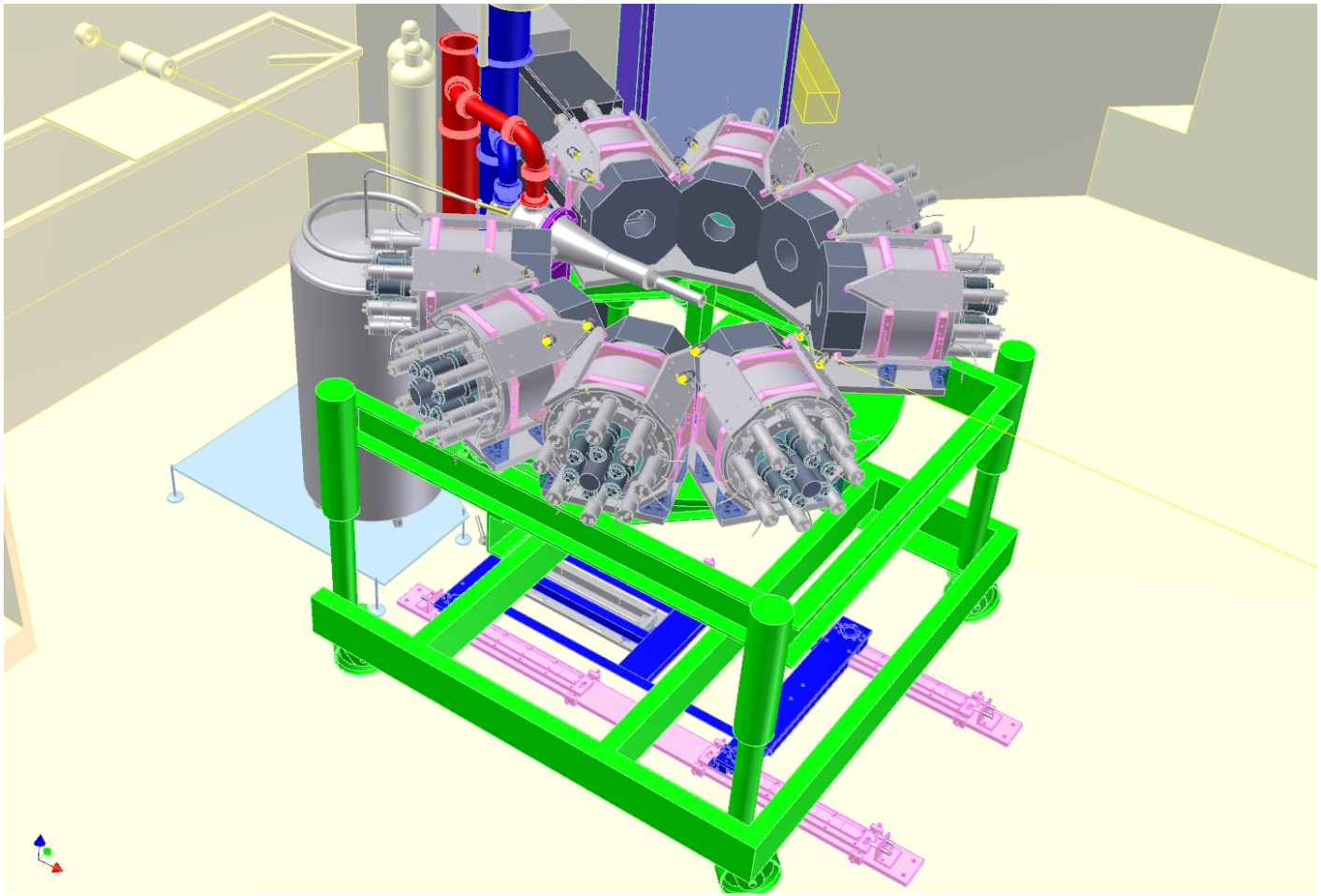
•The HINDA Array
(HIγS **N**aI **D**etector **A**rray)

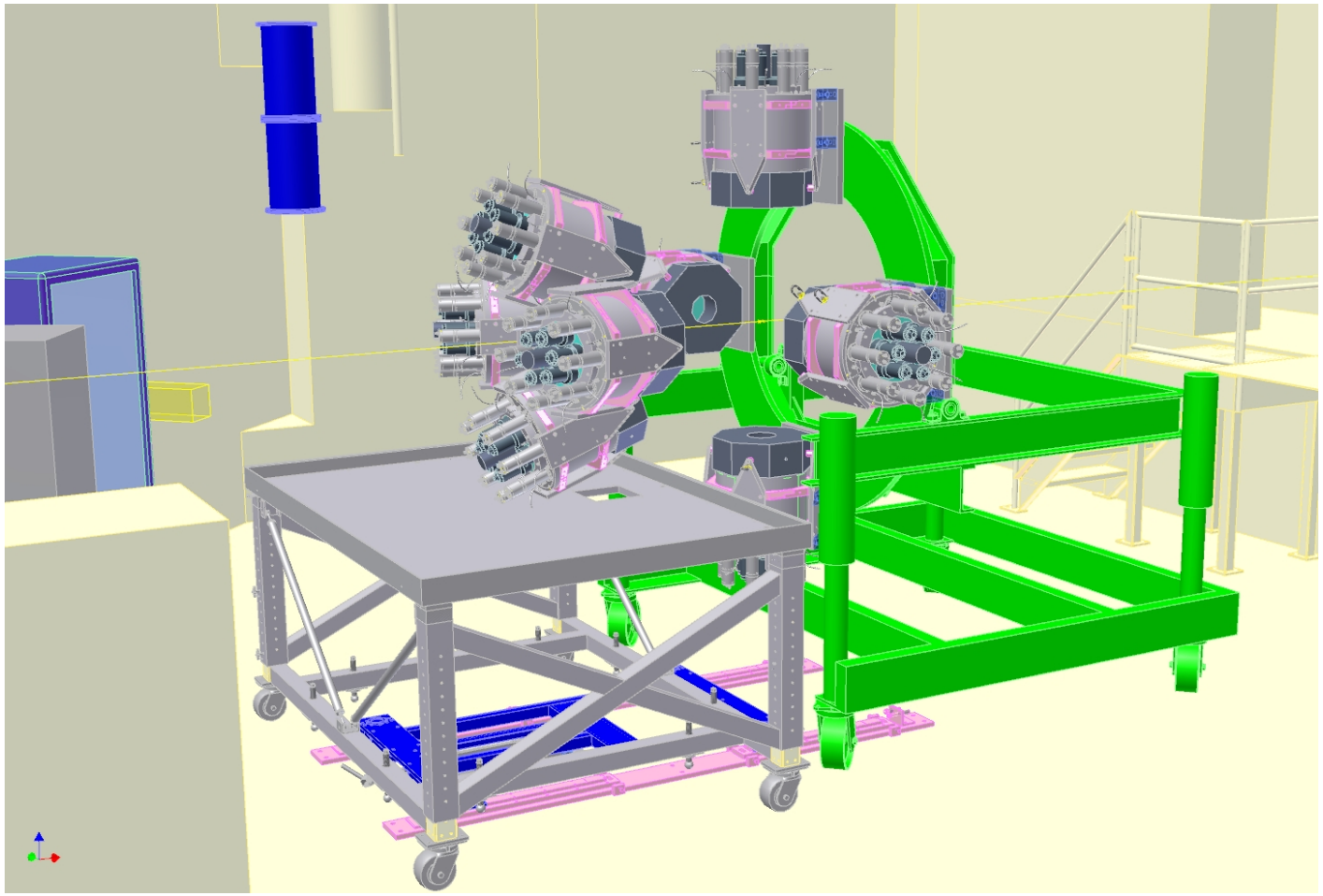
- NSF/MRI funded project—a high resolution-high acceptance gamma-ray spectrometer consisting of eight 10”x12” NaI detectors in 3” thick segmented NaI shields.

- The Compton@HIγS Collaboration


ø2.0" PMTs (7 for the Core
and 1 for each Shield Segment)
Shield Shell
(Aluminum)
Shield Crystal (NaI(Tl))
ø16.25"x12.0"
(8 Optically Isolated Segments)
Core Shell
(Aluminum)
Lead
Shielding
Core Crystal (NaI(Tl))
ø10.5"x10.5"

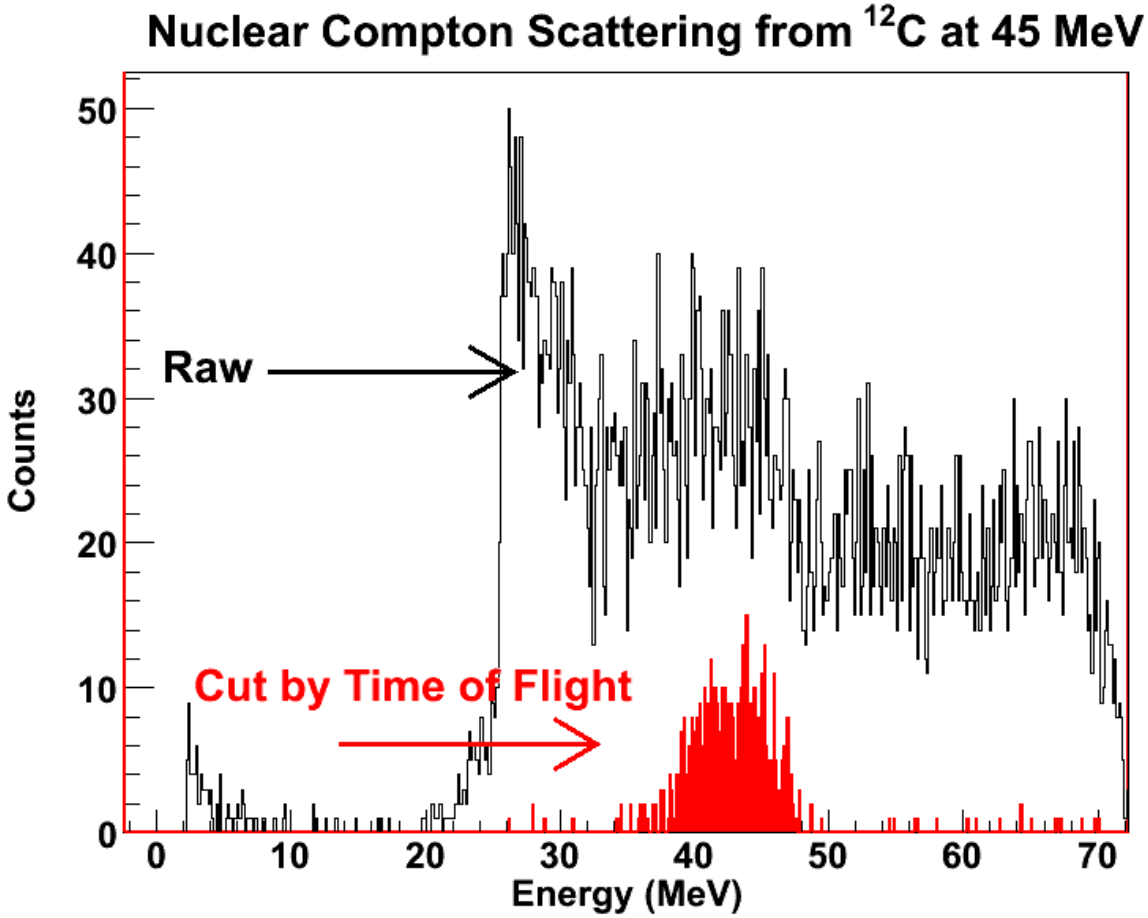
The HINDA Array @ HIγS



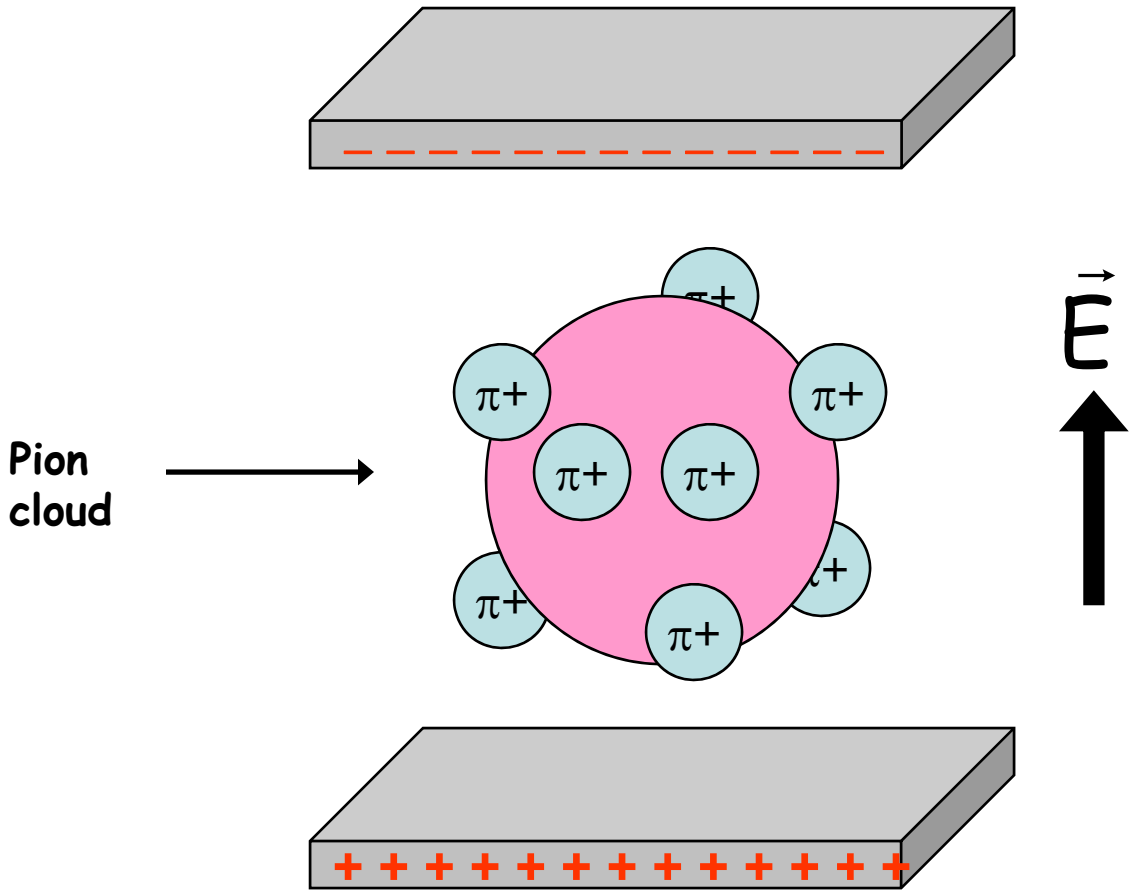


HUGS_3, June 2009

First test run using a HINDA detector. Spectrum obtained in 30 minutes (470 counts) with a 45 MeV beam (2 x 10^7 γ/s) on a 7.6 cm thick ^{12}C target.



Proton electric polarizability



Electric polarizability: proton between charged parallel plates

Proton electric and magnetic polarizabilities from real Compton scattering†

$$\alpha = (12.0 \pm 0.6)\text{x}10^{-4}\,\text{fm}^3$$

$$\beta = (1.9 \mp 0.6)\text{x}10^{-4}\,\text{fm}^3$$

Some observations…

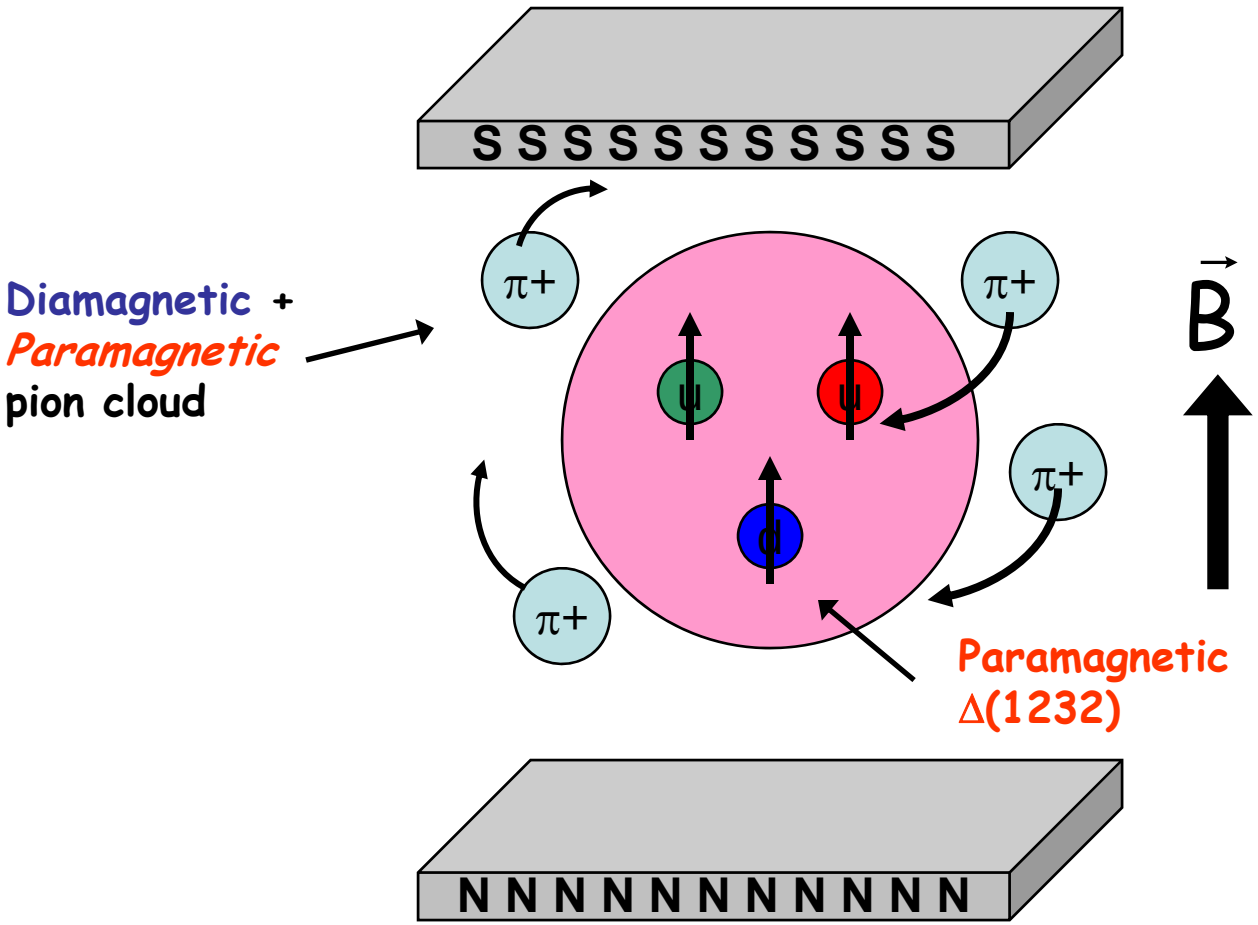
i. the numbers are small: the proton is very "stiff"

ii. the magnetic polarizability is around 20% of the electric polarizability

Cancellation of positive paramagnetism by negative diamagnetism

† M. Schumacher, Prog. Part. and Nucl. Phys. **55**, 567 (2005) and PDG.

Proton magnetic polarizability



Magnetic polarizability: proton between poles of a magnetic

Linearly polarized γs allow for independent measurements of the electric (α) and the magnetic (β) polarizabilities of the proton.

(Leonard Maximon, PRC39, 347 (1989))

Present values (x 10^{-4} fm^3)

$\alpha = 12.0 +/- 1.1$ (stat +sys) +/-0.5 (th); $\beta = 1.9 +/- 0.8$ (stat + sys) +/- 0.5 (th)

$$\frac{d\sigma_\perp}{d\Omega}\Big|_{\theta=90} - \frac{d\sigma_\perp^{pt}}{d\Omega}\Big|_{\theta=90} = -K\alpha$$

$$\cos^2\theta\left(\frac{d\sigma_\perp}{d\Omega} - \frac{d\sigma_\perp^{pt}}{d\Omega}\right) - \left(\frac{d\sigma_\parallel}{d\Omega} - \frac{d\sigma_\parallel^{pt}}{d\Omega}\right) = K\beta\cos\theta\sin^2\theta$$

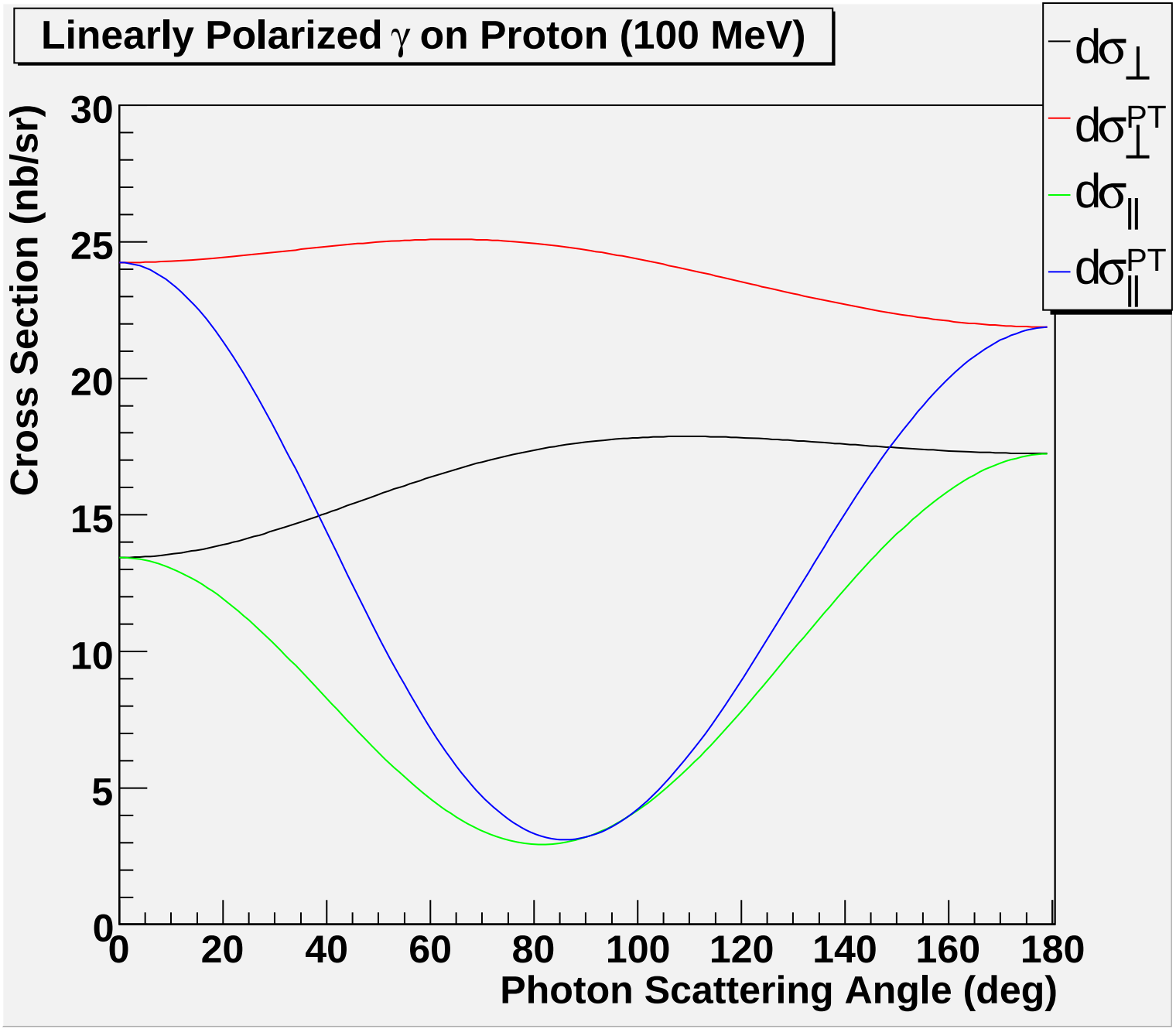
where $K = 2\left(\frac{e^2}{Mc^2}\right)\left(\frac{\omega'}{\omega}\right)^2\omega\omega'$

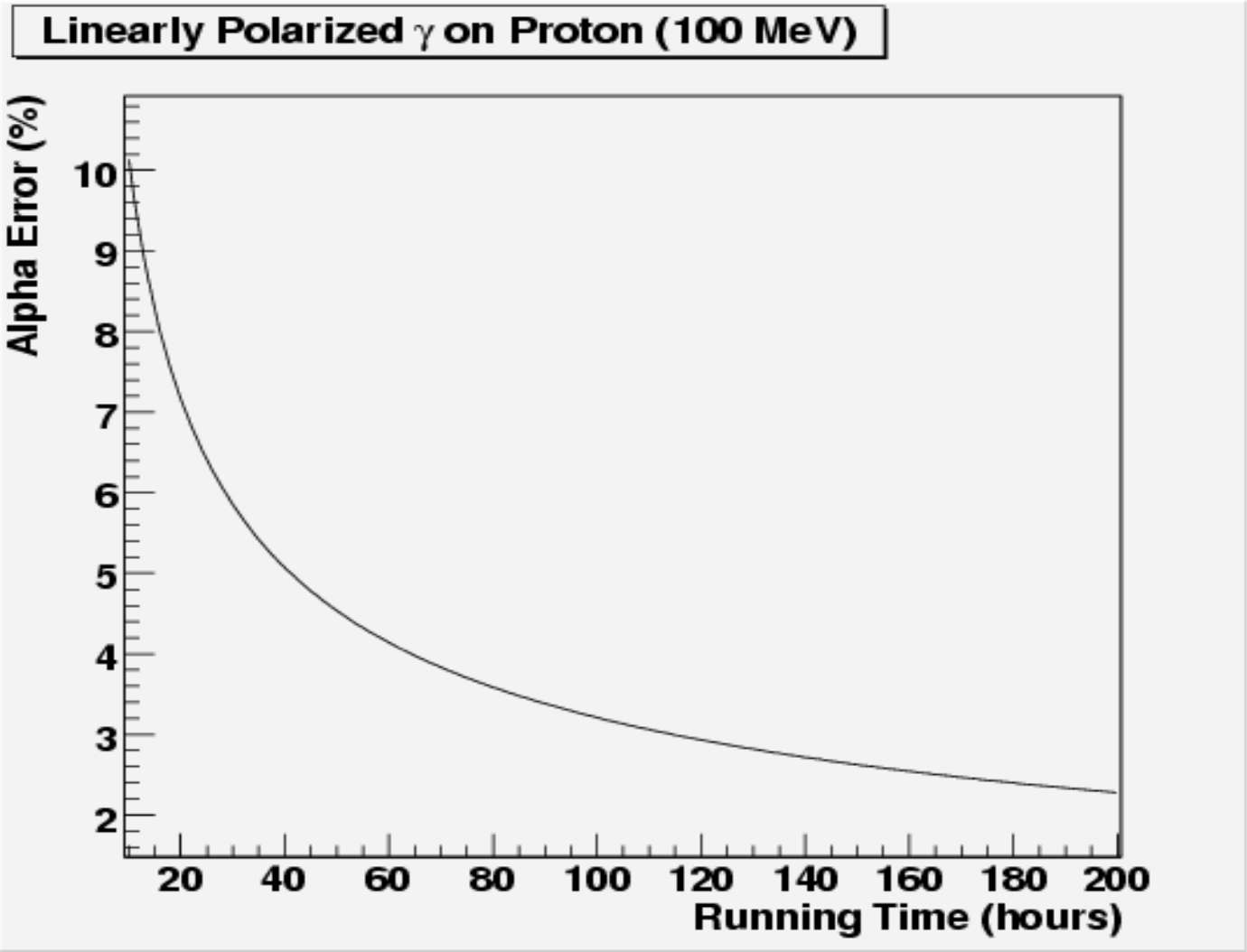
Comments

Explicit expressions for the *point values* of the cross section for polarizations perpendicular and parallel to the scattering plane are given by Maximon for a point proton with charge, spin and magnetic moment.

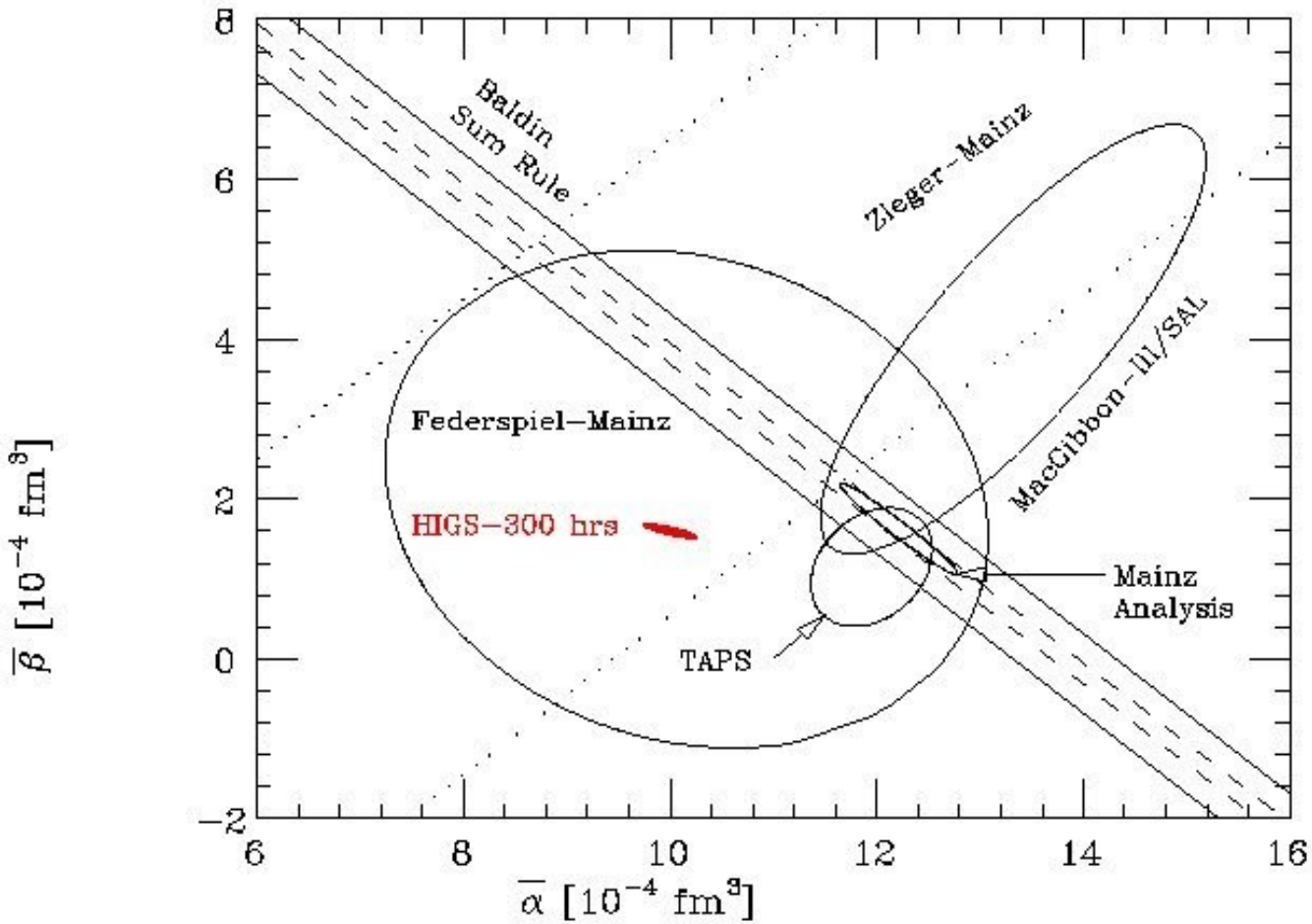
Measurements at 90° with the detectors perpendicular to the plane of polarization of the beam will provide a direct determination of α, independent of β.

The results of Maximon only include the polarizabilities at order $(\omega/M)^2$. If contributions of order $(\omega/M)^4$ are significant, they will show up as a deviation in the measured value of the cross section in a 90^0 detector parallel to the plane of polarization wrt. the point value.


Linearly Polarized γ on Proton (100 MeV)
Cross Section (nb/sr)
Photon Scattering Angle (deg)
0
5
10
15
20
25
30
0
20
40
60
80
100
120
140
160
180
dσ⊥
dσ⊥PT
dσ∥
dσ∥PT


Linearly Polarized γ on Proton (100 MeV)
Alpha Error (%)
10
9
8
7
6
5
4
3
2
20
40
60
80
100
120
140
160
180
200
Running Time (hours)

•Determination of the electric and magnetic polarizabilities of the proton using 100% linearly polarized gammas@HIγS –a ~300 hr experiment with a beam intensity of 5 x 10^7 γ/s ***will yield ~5% errors on α (now~15%) and β (now~40%).***



Compton scattering from the deuteron—determining the neutron polarizabilities

This determines the *isoscalar polarizabilites* α_N *and* β_N*, which lead to the neutron polarizabilities using the known values of the proton.*

Data to date:

Illinois, E_γ *= 49, 69 MeV* *M. Lucas, PhD thesis, 1994*

Saskatoon, E_γ *= 95 MeV* *D. L. Hornidge et al. PRL 84, 2334(2000)*

Lund, E_γ *= 60 MeV M. Lundinet et al, PRL 90 (2003) 192501*

Compton Scattering from the deuteron below 100 MeV

Measurements yield the isoscalar polarizabilities:

$\alpha_E^s = ½(\alpha_E^p + \alpha_E^n)$ and $\beta_M^s = ½(\beta_M^p + \beta_M^n)$

Hildebrandt, Griesshammer and Hemmert have used *Chiral Effective Field Theory with explict Δ(1232) degrees of freedom* within the Small Scale Expansion up to leading-one loop order and calculated this process up to 100 MeV.

(nucl-th/0512063)

Their results have resolved a "long standing" problem, obtaining consistent fits to the data, especially the 94.2 MeV data.

(Dissertation project of Seth Henshaw (Duke))

A global fit to all existing γd data using the Baldin sum rule. The results are

$$\alpha_E^s = (11.3 +/- 0.7 \text{ (stat)} +/- 0.6 \text{ (Baldin)}) \times 10^{-4} \text{ fm}^3$$

$$\beta_M^s = (3.2 -/+ 0.7 \text{ (stat)} +/- 0.6 \text{ (Baldin)}) \times 10^{-4} \text{ fm}^3$$

which indicates, by comparing to the proton values, that ***the n and p polarizabilities are essentially the same within experimental errors.***

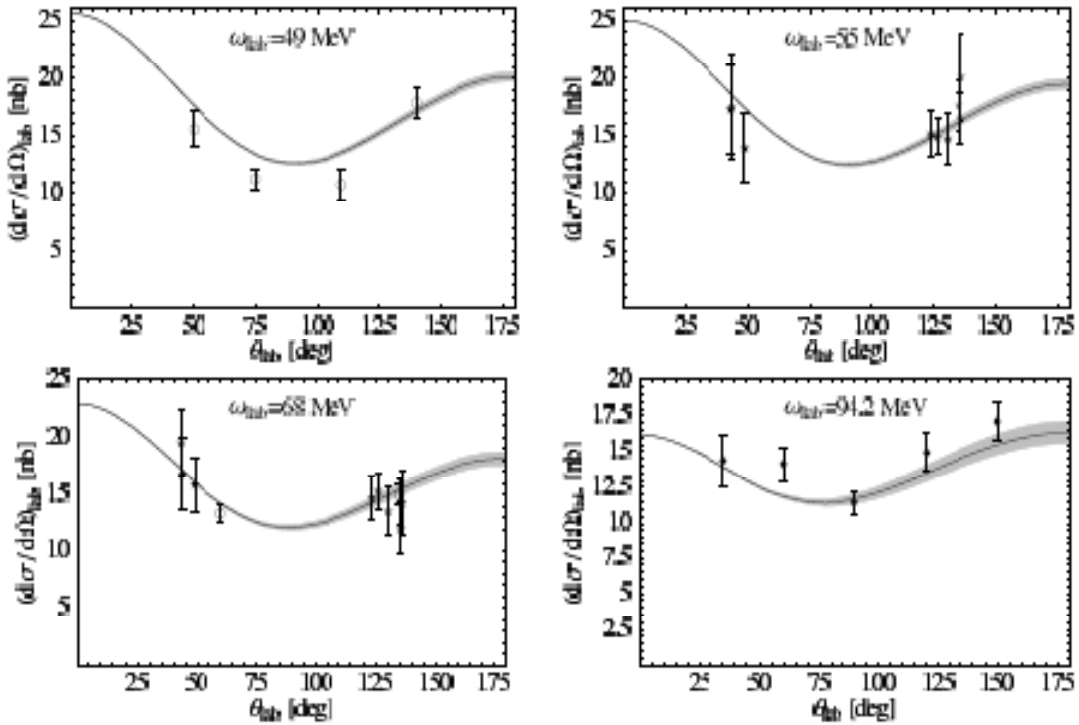
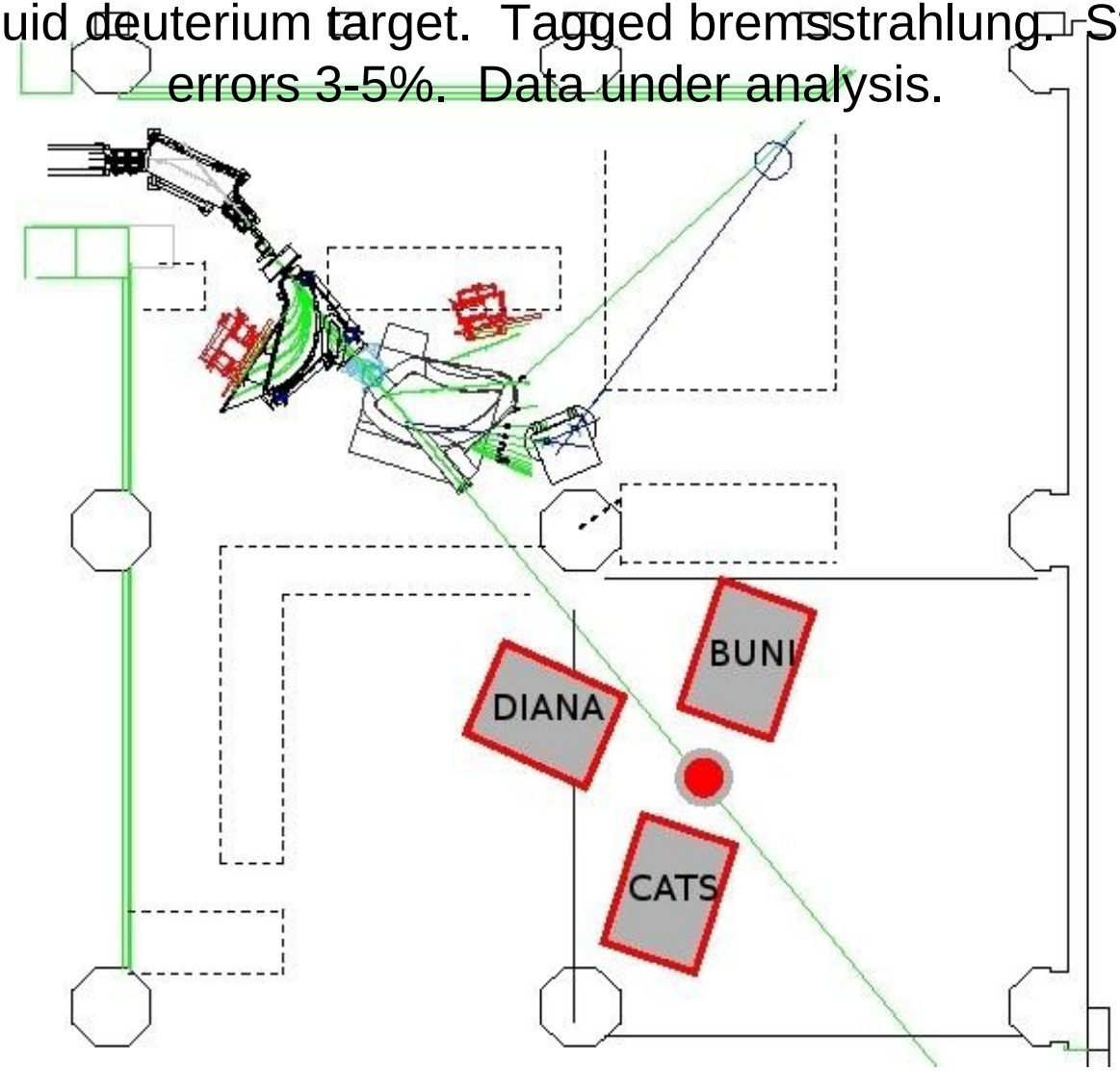


Figure 18: Results from a global fit of α_E^s to all existing elastic γd data, using the chiral wave function [36]. β_M^s is fixed via the Baldin sum rule, Eq. (4.3). The grey bands are derived from our statistical errors.

New LUND Experiment (Meyers, Nathan, Feldman, Kovash, Weller, et al.)–Took data from 66 to 116 MeV. Used three 20” NaI spectrometers and a liquid deuterium target. Tagged bremsstrahlung. Statistical errors 3-5%. Data under analysis.



Compton on the deuteron @ HIγS

The ***HINDA spectrometer*** and a liquid ***scintillating target*** will be used in these experiments.

Angular distributions will be measured in 10 MeV steps between 30 and 80 MeV. **We expect to obtain 1.5% statistics in each of 8 detectors at 6 energies in ~300 hours.** The absolute cross section will be determined to an accuracy of ~7%.

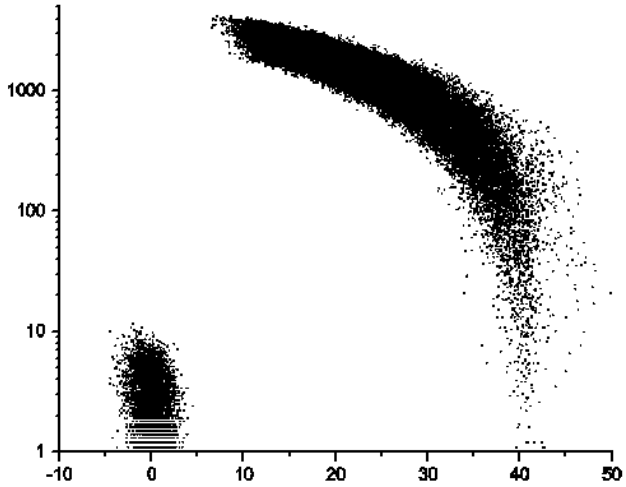
These measurments will ***determine the neutron polarizabilities to an accuracy of ~10%.***

COMPTON ON d WITH A SCINTILLATING TARGET

Vertical axis : number of photons detected

Horizontal axis: Missing energy (binding energy)

Courtesy of Rory Miskimen



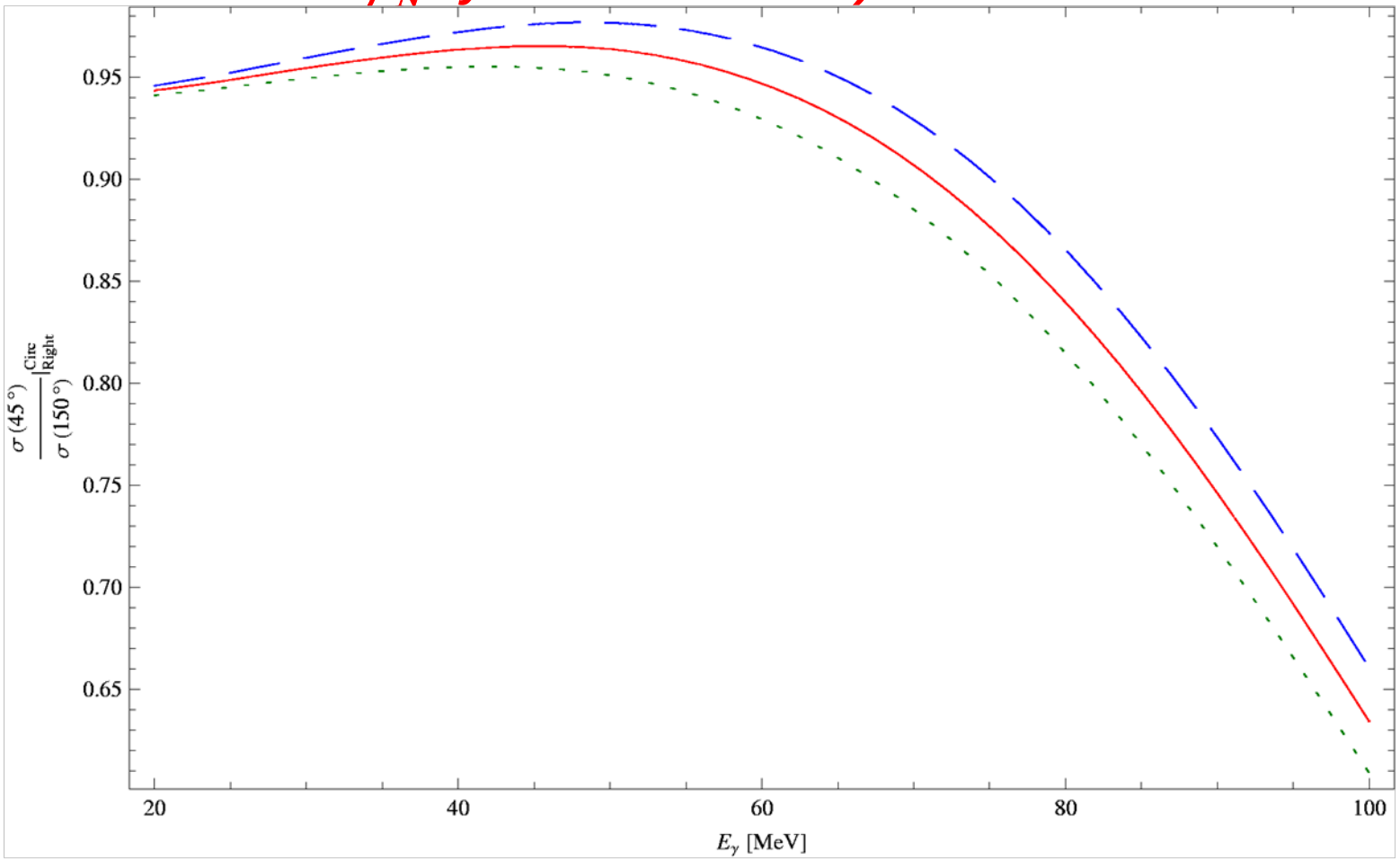
Compton on the deuteron @ HIγS

The ratio of $\sigma(45)$ to $\sigma(150)$, for example, is insensitive to the values of α_N, but varies with β_N.

Compton on the deuteron @ HIγS

This will determine β_n to better than +/- 1.0 x 10^{-4} fm^3 in just 100 hrs at 60 MeV.

(plot below varies β_N by +/- 1.0 x 10^{-4} fm^3) from "theoretical" value)



Spin polarizabilities.

- They tell us about the response of the spin of the nucleon to the polarization of the photons. The stiffness of the spin can be thought of as arising from the nucleon's spin interacting with the pion cloud.

- Measuring these requires circularly polarized beams and polarized targets – ideally suited to HIγS.

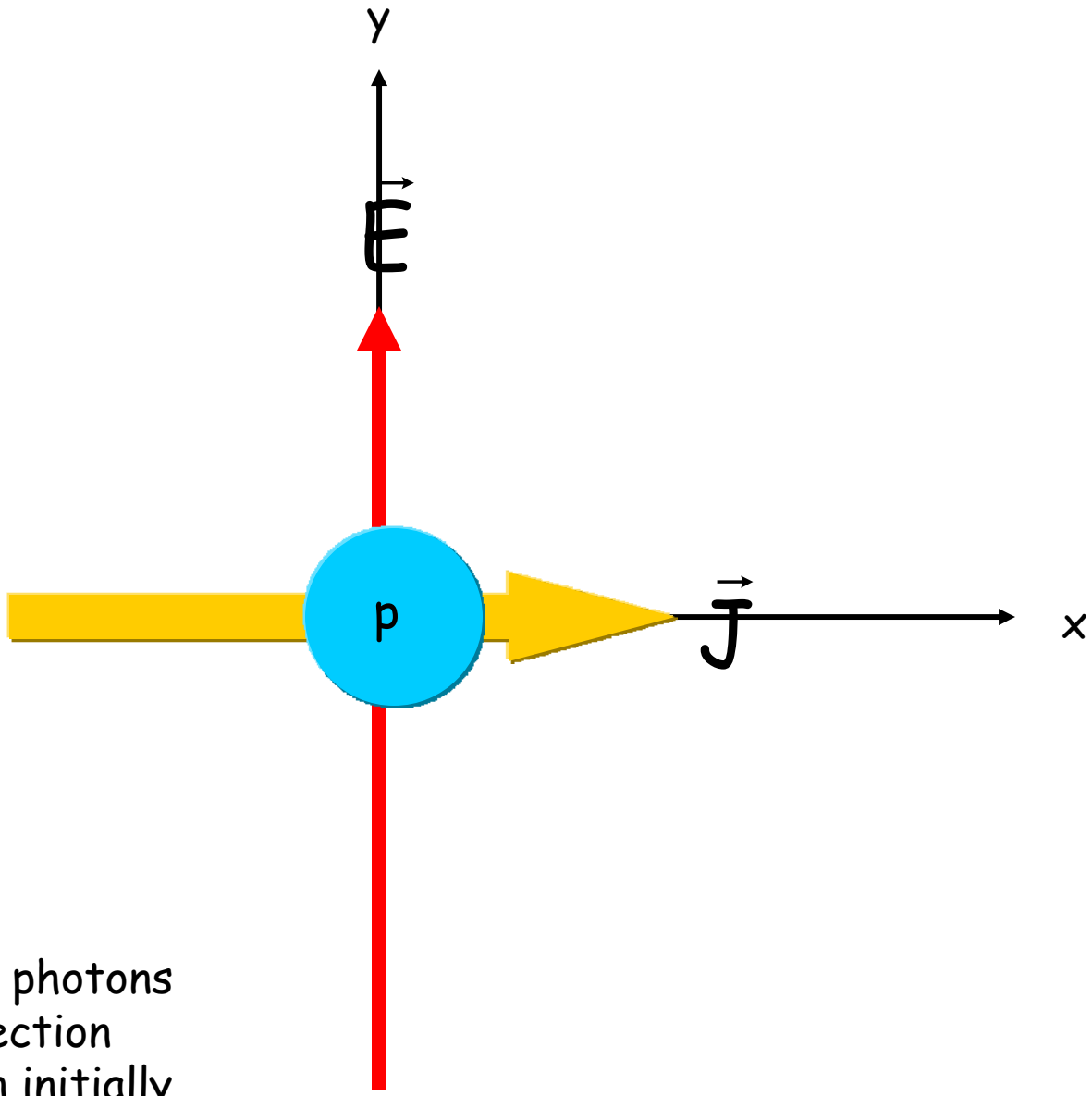
- Polarized protons will be provided by our frozen-spin target. A polarized ^{3}He target will be used to obtain the neutron spin-polarizabilities.

The spin-polarizabilities of the nucleon

- At $O(\omega^3)$ <u>four</u> new nucleon structure terms that involve nucleon spin-flip operators enter the RCS expansion.

$$H_{eff}^{(3),spin} = -\frac{1}{2} 4\pi \left(\gamma_{E1E1} \vec{\sigma} \cdot \vec{E} \times \dot{\vec{E}} + \gamma_{M1M1} \vec{\sigma} \cdot \vec{B} \times \dot{\vec{B}} - 2\gamma_{M1E2} E_{ij} \sigma_j H_j + 2\gamma_{E1M2} H_{ij} \sigma_j E_j \right)$$

- A rotating electric field will induce a precession of the proton spin around the direction of the polarized photon, with a rate proportional to the spin-polarizability.



Circularly polarized photons moving in the z-direction incident on a proton initially polarized in the x-direction

Experiments

The GDH experiments at Mainz and ELSA used the Gell-Mann, Goldberger, and Thirring sum rule to evaluate the forward S.-P. γ_0

$$\gamma_0 = -\gamma_{E1E1} - \gamma_{E1M2} - \gamma_{M1M1} - \gamma_{M1E2}$$

$$\gamma_0 = \frac{1}{4\pi^2} \int_{m_\pi}^{\infty} \frac{\sigma_{1/2} - \sigma_{3/2}}{\omega^3} d\omega$$

$$\gamma_0 = (-1.00 \pm 0.08 \pm 0.10) \times 10^{-4}\,\mathrm{fm}^4$$

Backward spin polarizability from dispersive analysis of backward angle Compton scattering

$$\gamma_\pi = -\gamma_{E1E1} - \gamma_{E1M2} + \gamma_{M1M1} + \gamma_{M1E2}$$

$$\gamma_\pi = (-38.7 \pm 1.8) \times 10^{-4}\,\mathrm{fm}^4$$

Alternative notation

Also denote the four spin polarizabilties as

$\gamma_1 \ \gamma_2 \ \gamma_3 \ \gamma_4$

$$\gamma_{E1E1} = -\gamma_1 - \gamma_3$$

$$\gamma_{M1M1} = \gamma_4$$

$$\gamma_{E1M2} = \gamma_3$$

$$\gamma_{M1E2} = \gamma_2 + \gamma_4$$

Proton spin-polarizabilities will be measured using a scintillating frozen-spin polarized target

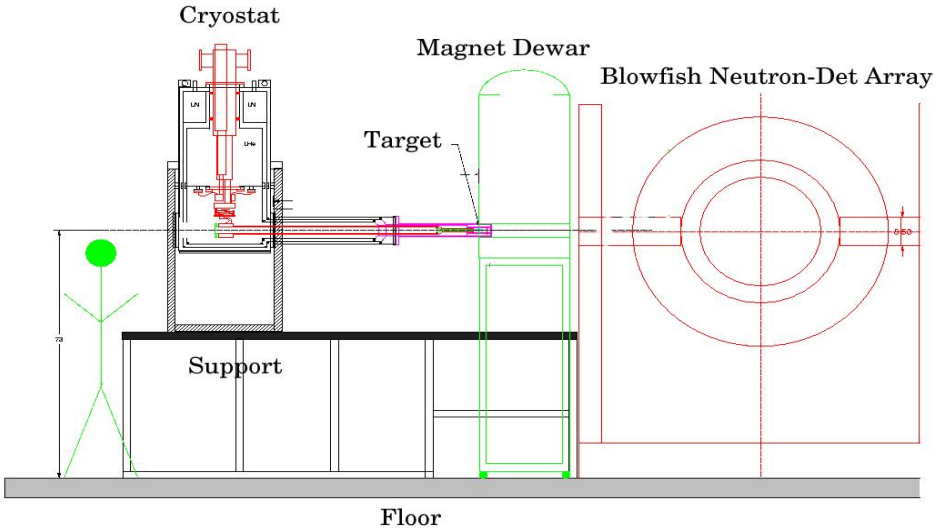
Rory Miskimen et al., U. Mass.

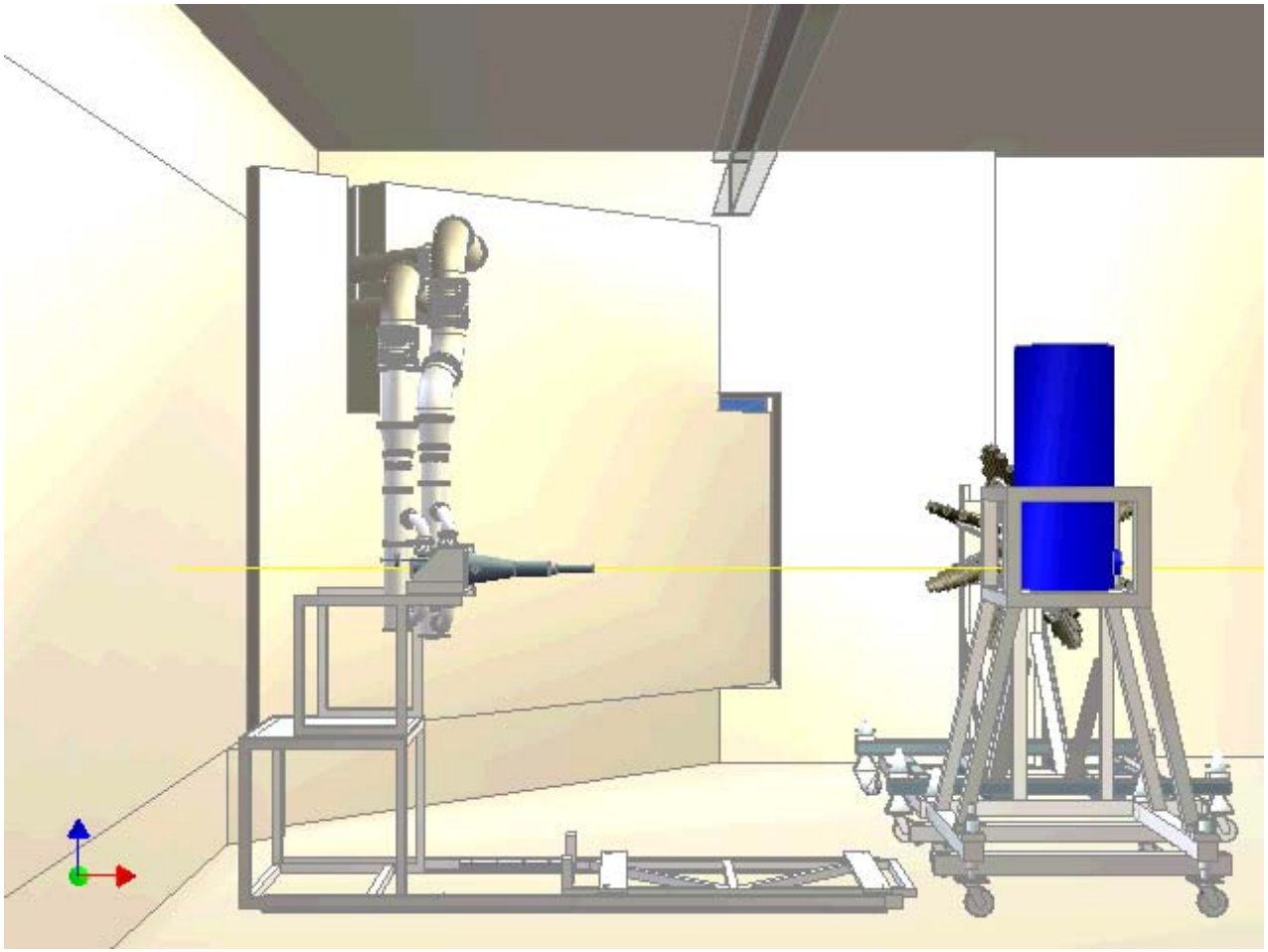
Simulations have been performed. A working prototype is under construction.

The initial experiment will run near 100 MeV.

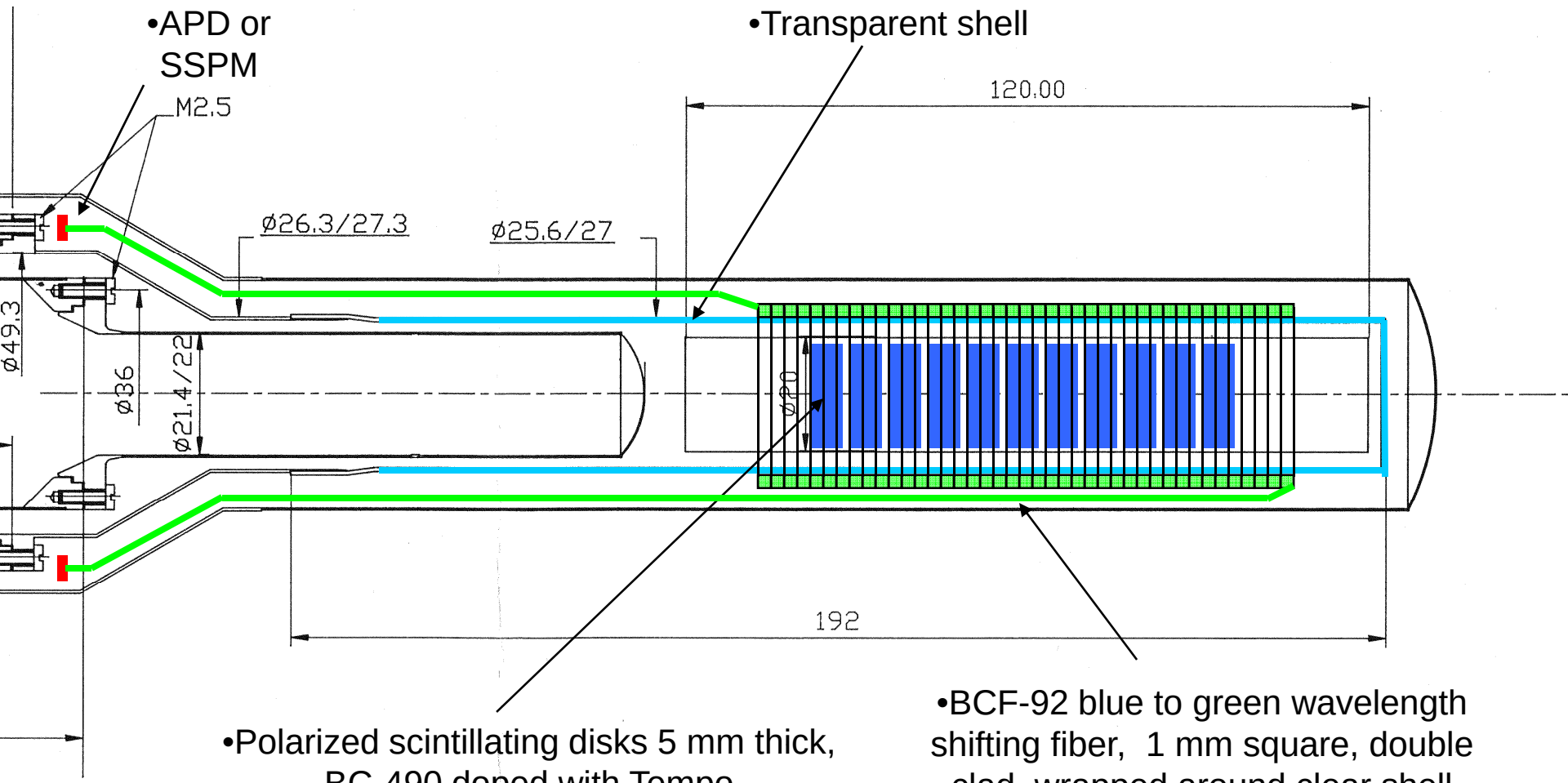
HIγS **Frozen** Spin Polarized Target (HIFROST)

- Butanol
- Polarization ~ 80 %
- Polarizing Field ~ 2.5 T
- Holding Field ~ 0.6 T





•Light capture with wavelength shifting fibers



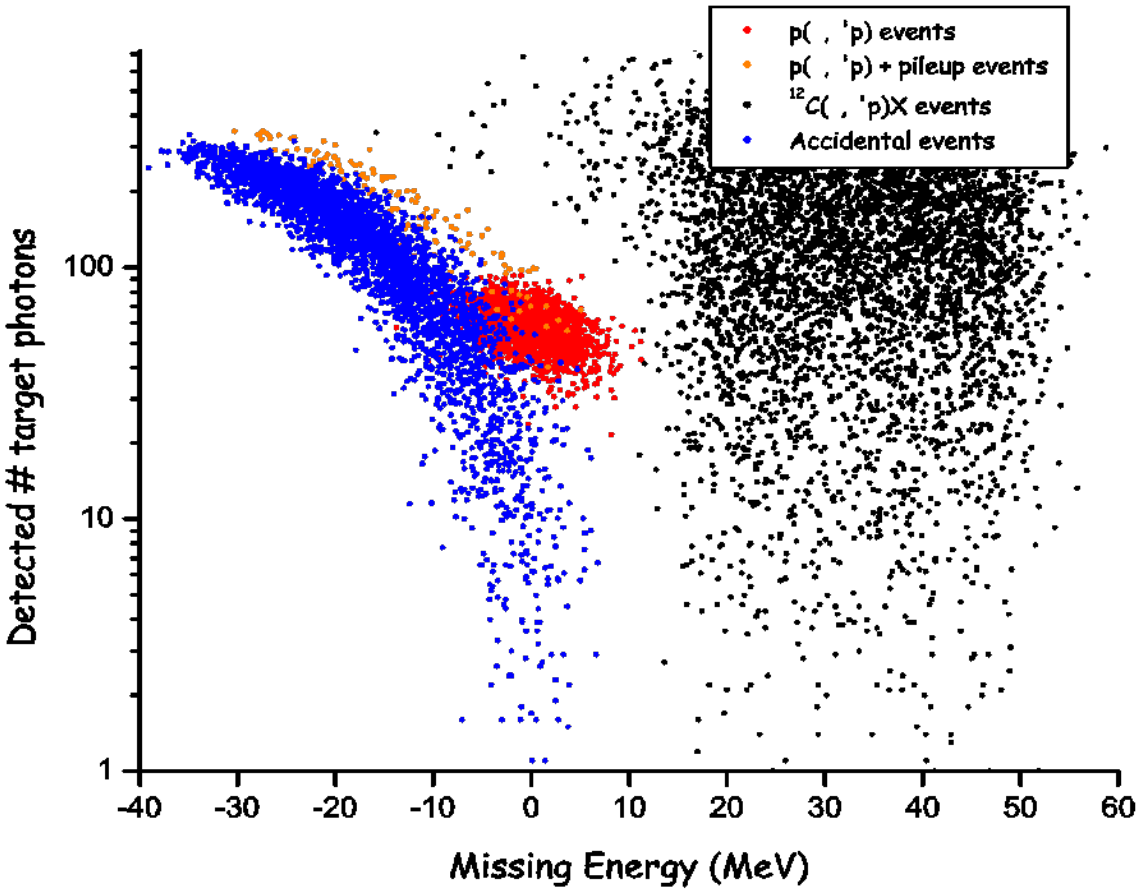
•Polarized scintillating disks 5 mm thick, BC-490 doped with Tempo

•BCF-92 blue to green wavelength shifting fiber, 1 mm square, double clad, wrapped around clear shell

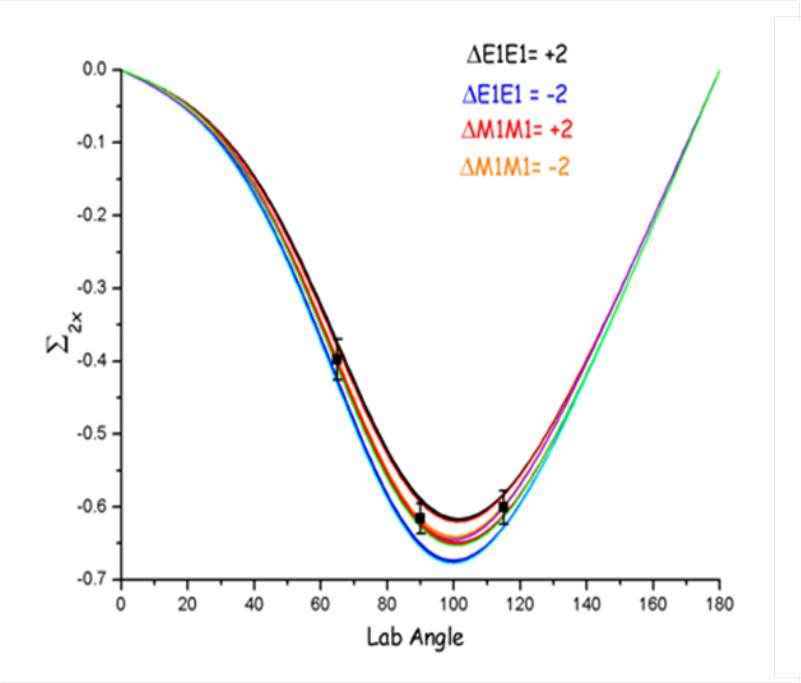
•Overall light transport efficiency ≈ 2%

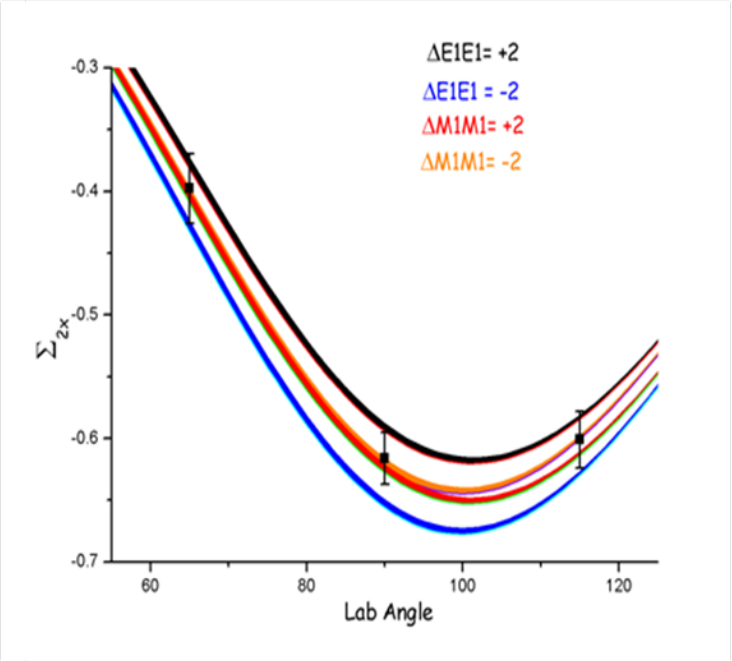
Results of a simulation using the scintillating Butanol target and a HINDA detector (performed by Rory Miskimen).

(Missing Energy = $E_{beam} - E_{NaI} - E_{target}$)

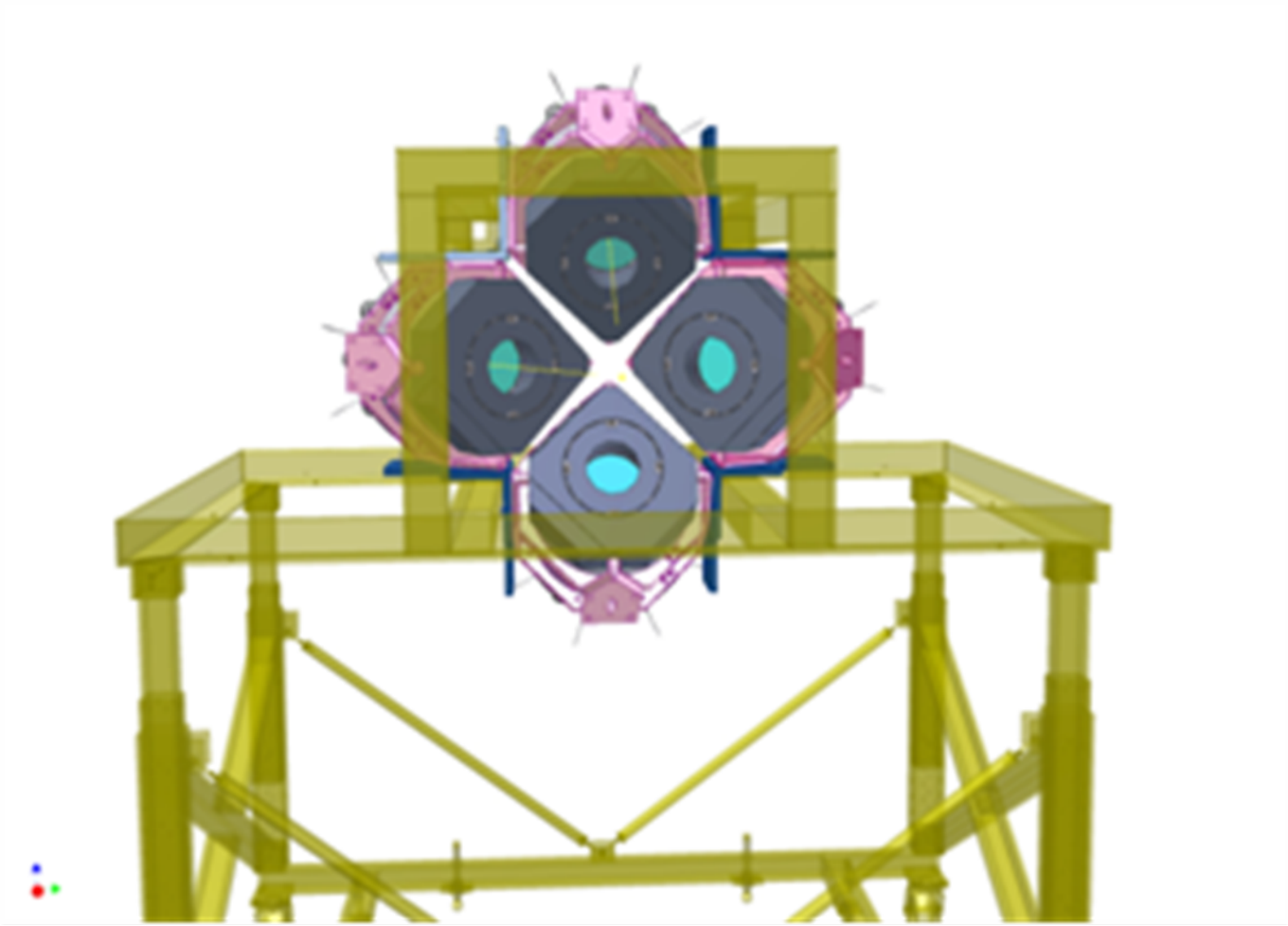


The first experiment will determine $\gamma_{E1\ E1}$ by measuring Σ_{2x} using a transverse polarized target and 8 HINDA detectors near 90° at 100 MeV. Find little sensitivity to $\gamma_{M1\ M1}$ and use γ_0 and γ_π to fix the other two. Anticipated uncertainty in γ_{E1E1} is ~1.0 x 10^{-4} fm^4.





Four HINDA detectors will be located clustered around 90° in the horizontal plane on both the right and left sides of the beam.



Count rate calculations and projections

Used the theoretical study of Hildebrandt et al. (Eur. Phys. J. A20 (2004) 329 which examined the sensitivity of Compton scattering to the spin-polarizabilities.

Target thickness: 2.6×10^{23} p/cm^2 ; 80% polarization

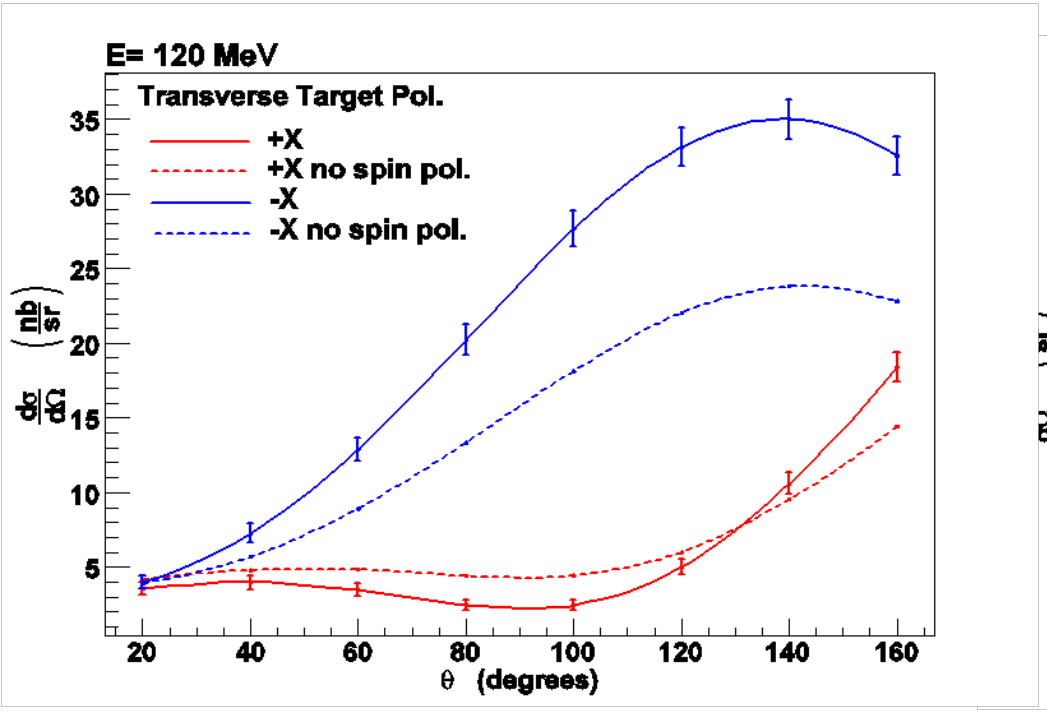
Beam intensity: 1×10^7 γ/s @ 120 MeV

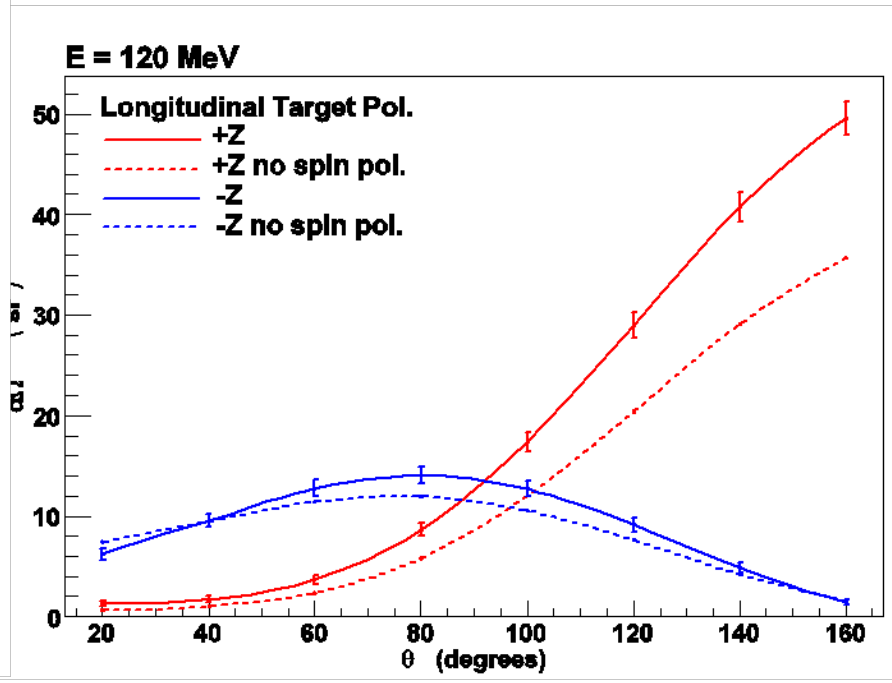
The HINDA array with dets. 75 cm from the target

Running time: 200 hrs. longitudinal, 200 hrs. transverse

Spin pols. were fit to *pseudo-data* using theoretical model of Hildebrandt to generate the uncertainties.

Running at 120 MeV with both transverse and longitudinal targets will produce ~5% results for the dipole spin polarizabilities in ~400 hours of beam time (200 hrs. transverse polarization and 200 hrs. longitudinal).





Total beam time for proton measurement: 400 hrs

100 hrs for each target spin orientation

Theory curves: Hildebrandt, Griesshammer, Hemmer
•Nucl-th/0308054

•*Experiments are being developed by Dr. Haiyan Gao at Duke/HIγS to measure the spin-polarizabilities of the neutron.*

Haiyan Gao has built a high pressure spin-polarized ^{3}He target. Target thickness is about 10^{22} atoms/cm^2 with a length of 40 cm. Polarizations of ~40% have been achieved.

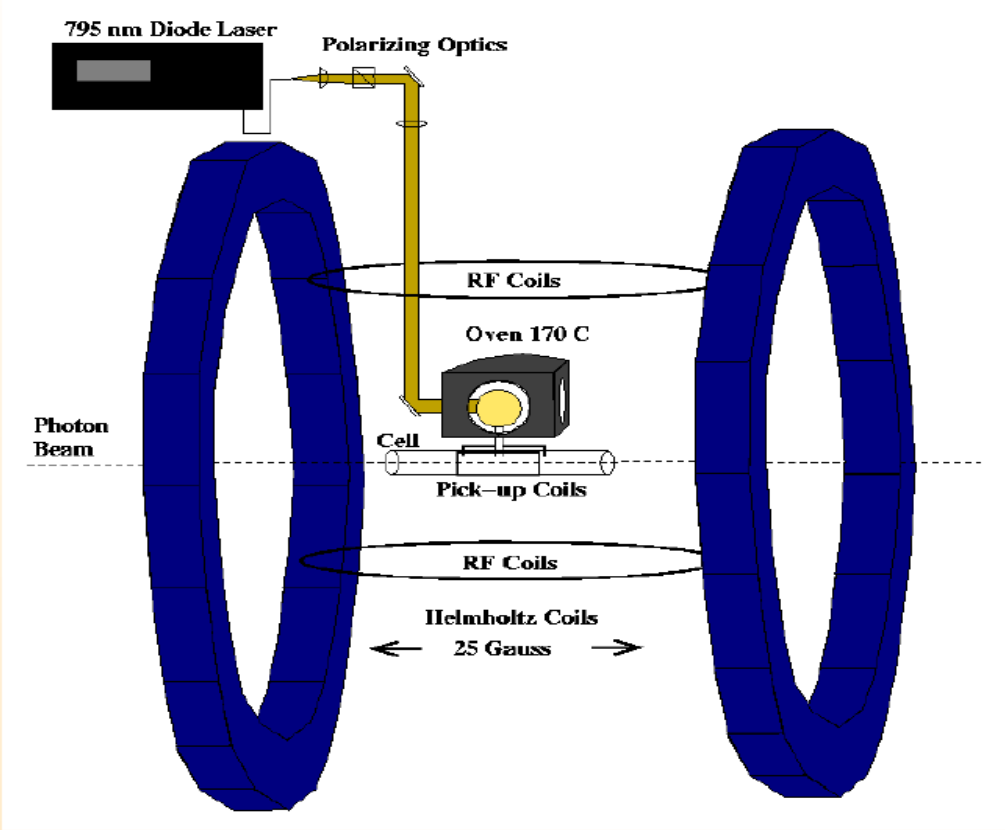
•

Effect of the reduced target thickness is offset by the increased sensitivity in the observables.

Polarized target reference:
K. Kramer et al., NIM A ***582, 318 (2007)***

Target polarization ~40%
Target thickness ~ 10^{22} nuclei/cm^2

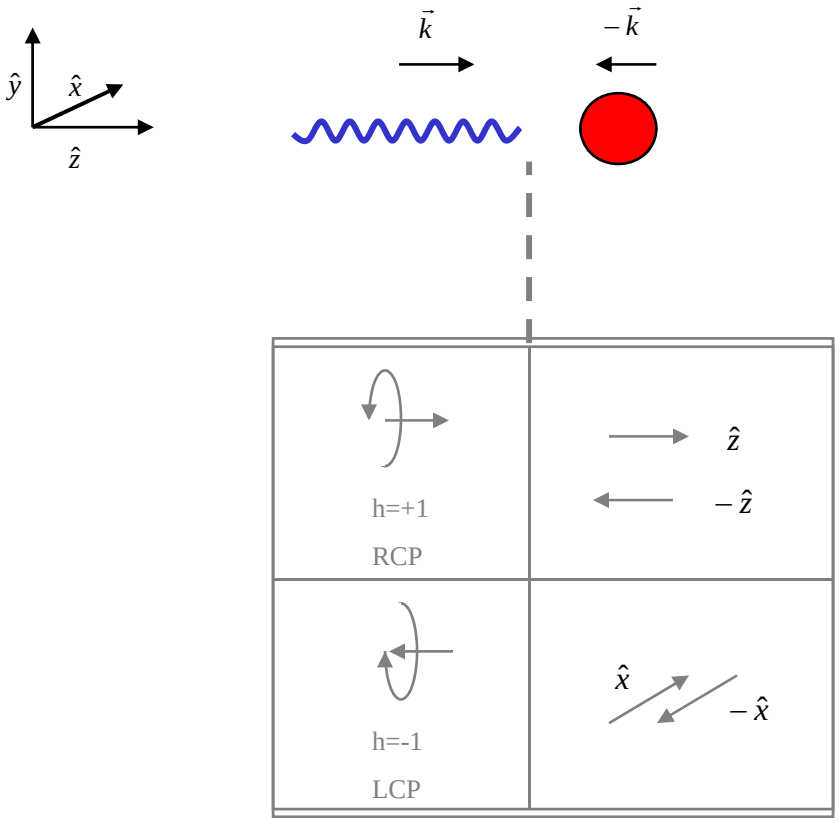
Polarized ^{3}He Target

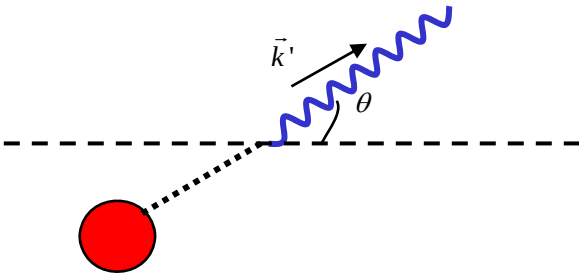


•Present proposed experiments

ChPT calculations by Choudury, Nogga and Phillips make extraction of spin-polarizabilities possible from elastic scattering data.

With a gamma intensity of 2×10^7/sec at 114 MeV and the target and detector system just described, a **2000 hour** experiment will give neutron spin polarizabilities with errors of about **+/- 0.5×10^{-4}** fm^4.

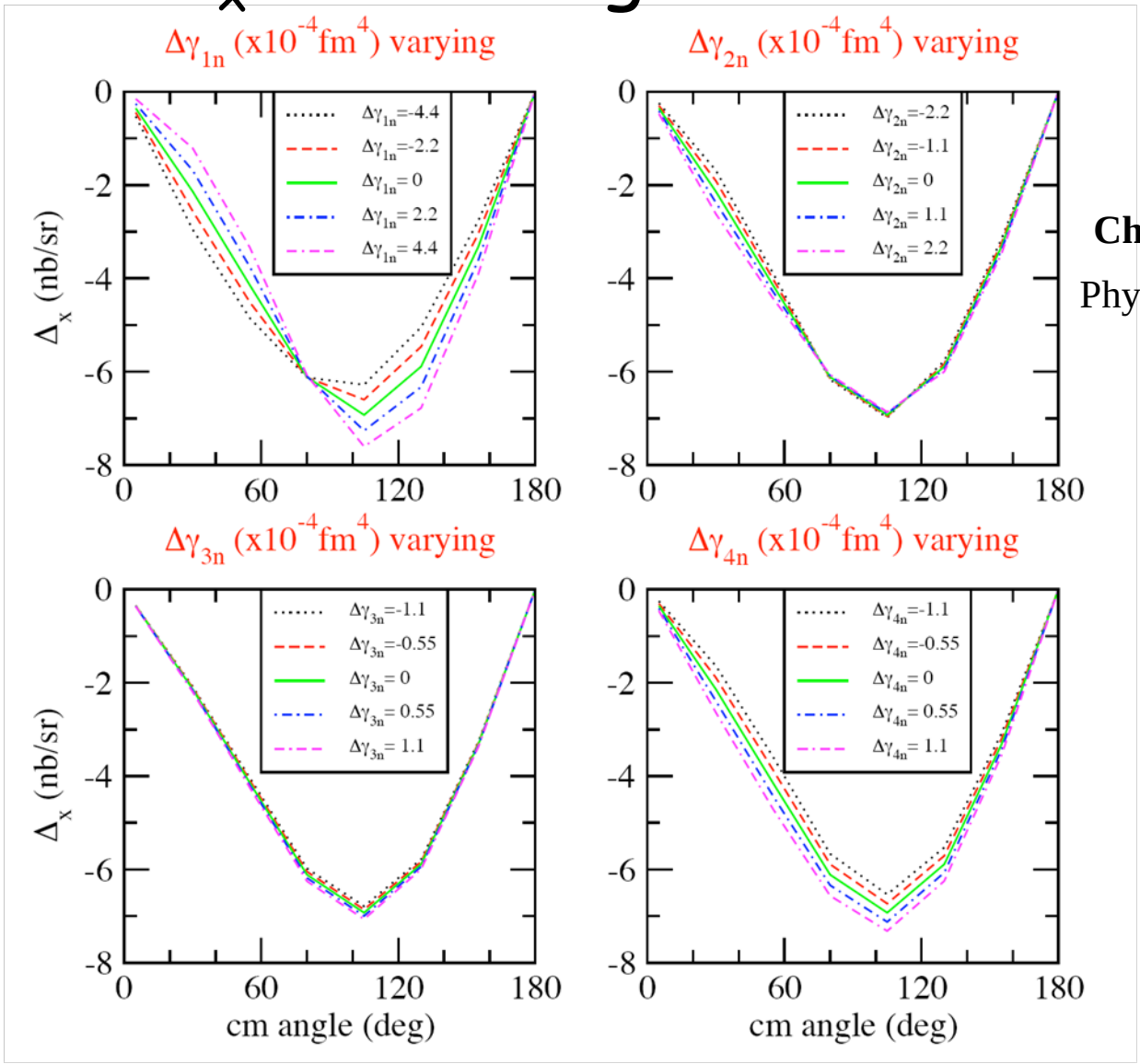




$$\left[\Delta_z = \left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\uparrow} - \left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\downarrow}\right]_{h=\pm 1}$$

$$\left[\Delta_x = \left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\rightarrow} - \left(\frac{d\sigma}{d\Omega}\right)_{\uparrow\leftarrow}\right]_{h=\pm 1}$$

Δ_x vs cm angle at 120 MeV



Choudury, Nogga and Phillips, Phys.Rev. Lett. 98, 232303 (2007

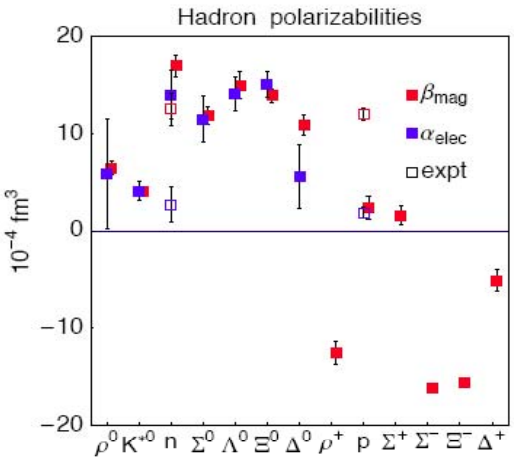
Projected HIγS measurements on Nucleon Spin Polarizabilities (all x 10^{-4} fm^4)—Theoretical values are from Gellas, Hemmert and Meissner PRL 85 (2

Proton HIγS projected uncertainties		Neutron HIγS projected uncertainties	
γ^p_1=1.1	±0.10	γ^n_1=3.7	±0.43
γ^p_2=-1.5	±0.36	γ^n_2=-0.1	±0.03
γ^p_3=0.2	±0.24	γ^n_3=0.4	
γ^p_4=3.3	±0.17	γ^n_4=2.3	±0.57

Summary:

- Measuring the spin-polarizabilities of the nucleon is an important next step. These are fundamental structure constants of the nucleons. The beam, targets, and detectors are now available for these experiments.
- Spin-polarizabilities represent the spin-response functions of the nucleon in a regime where pions and Δ's, not quarks and gluons, are the relevant degrees of freedom
- Can measure the polarizabilities at HIGS with a precision of from 0.2 to 0.4 x 10^{-4} fm^4 , which is sufficient to test and differentiate between theoretical models. Full Lattice QCD calculations are imminent.

Spin Polarizabilities from Lattice QCD



Quenched Lattice QCD results J.Christensen *et.al.*

$(m_\pi \simeq 500\,\mathrm{MeV})$ α_{elec} PRD73 (2006) 100 configurations

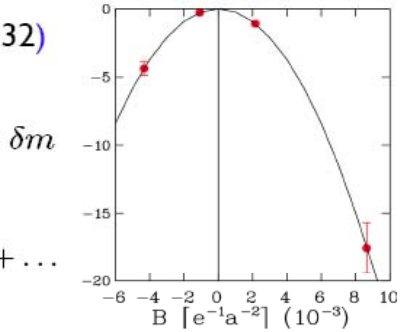
β_{mag} PRD72 (2005) 150 configurations

(see also E.Shintani *et.al.* hep-lat/0611032)

Measure mass shift in background field:

eg: magnetic polarizability

$$\delta m = m(B) - m(0) = -\vec{\mu}\cdot\vec{B} - \frac{1}{2}\beta_{mag}\vec{B}^2 + \ldots$$



Can also determine neutron (and proton) spin polarizabilites from lattice QCD with varying external field W.Detmold, B.C.Tiburzi, A.Walker-Loud PRD73 (2006)

- Exploratory, *quenched* calculation at $m_\pi \simeq 500\ \mathrm{MeV}$ possible today. Precision similar to that of electromagnetic polarizabilities, α_{elec} , β_{mag}
- First full QCD calculation of all isovector electromagnetic and spin polarizabilities possible with moderate computational resources: 1-2 year time frame.
- Complete calculation will require significant computational investment:
  - Need studies on multiple volumes and lattice spacings
  - For isoscalar polarizabilities, need new gauge configurations with EM fields (expensive but also useful for other EM lattice studies)

Spin-exchange optical pumping