Hadron Physics at the High Intensity γ-ray Source

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HIγS PROGRAM

HIγS

Nearly Mono-energetic γ-rays from 2 to 160 MeV

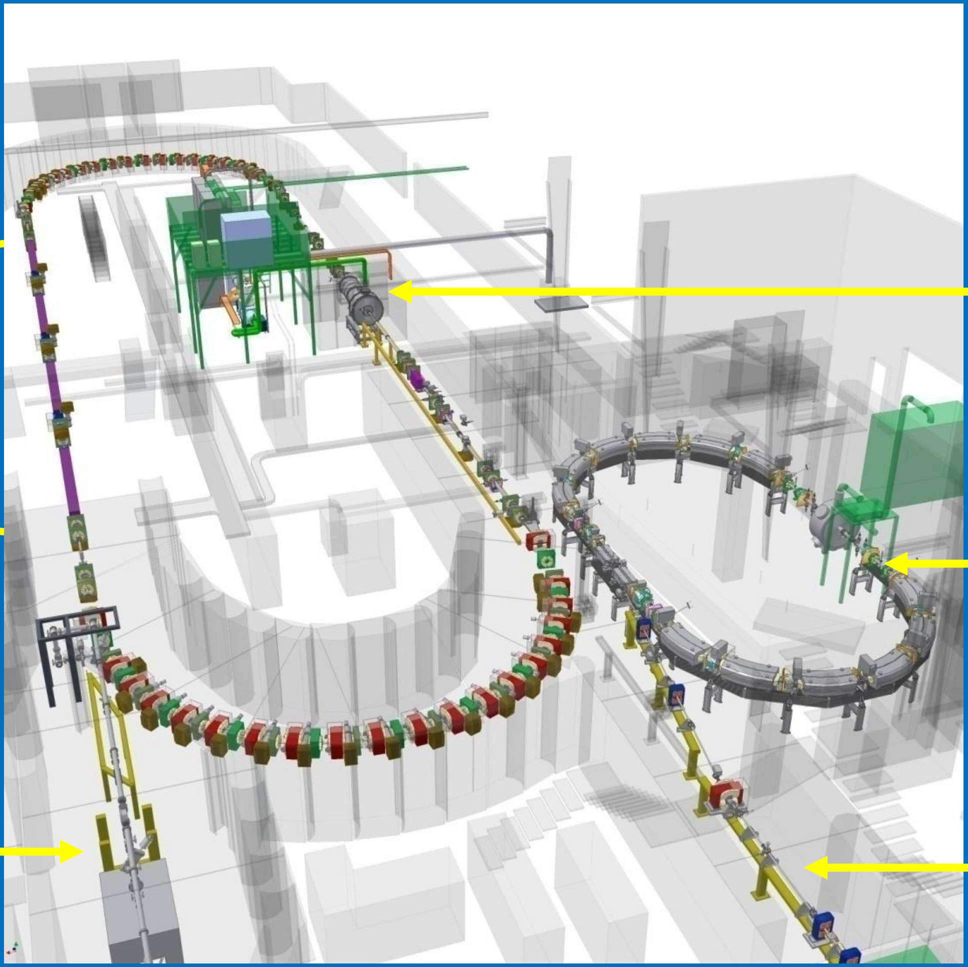
- ***Up to 100 MeV now***
- ***Up to ~160 MeV by 2017***

~100% Linearly and Circularly Polarized γ-rays

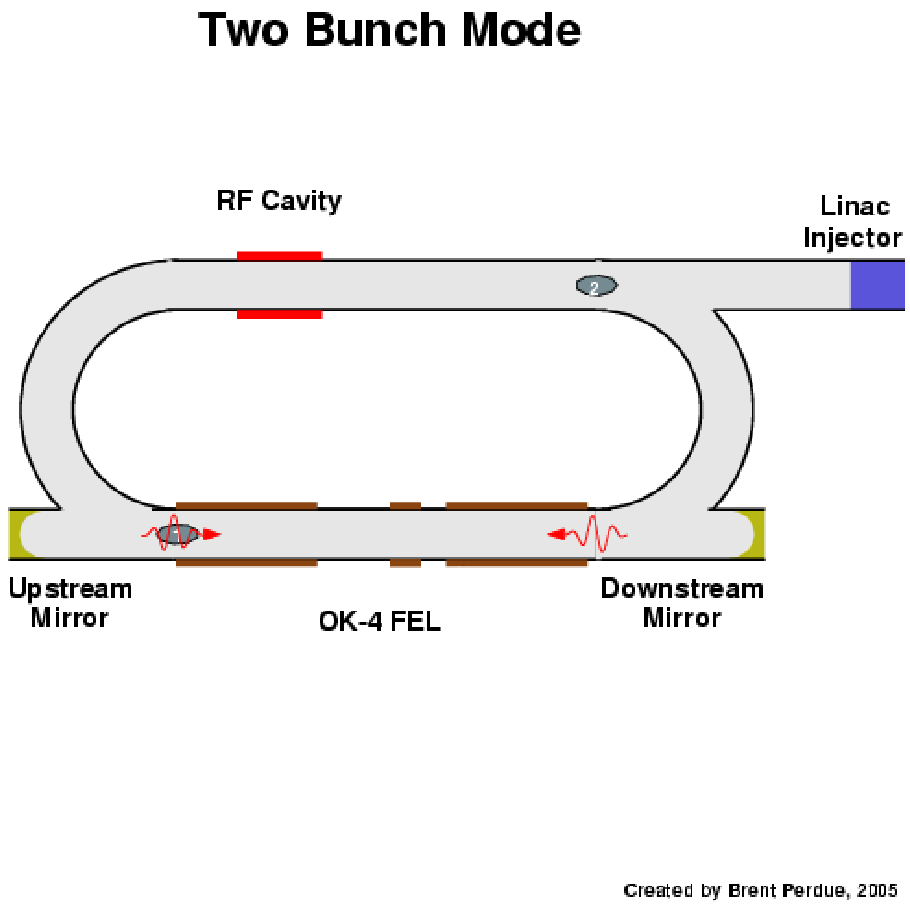
High Beam Intensities
(2x10^{8}/s on target at 15 MeV as of June 2009)

HIγS γ-ray beam generation

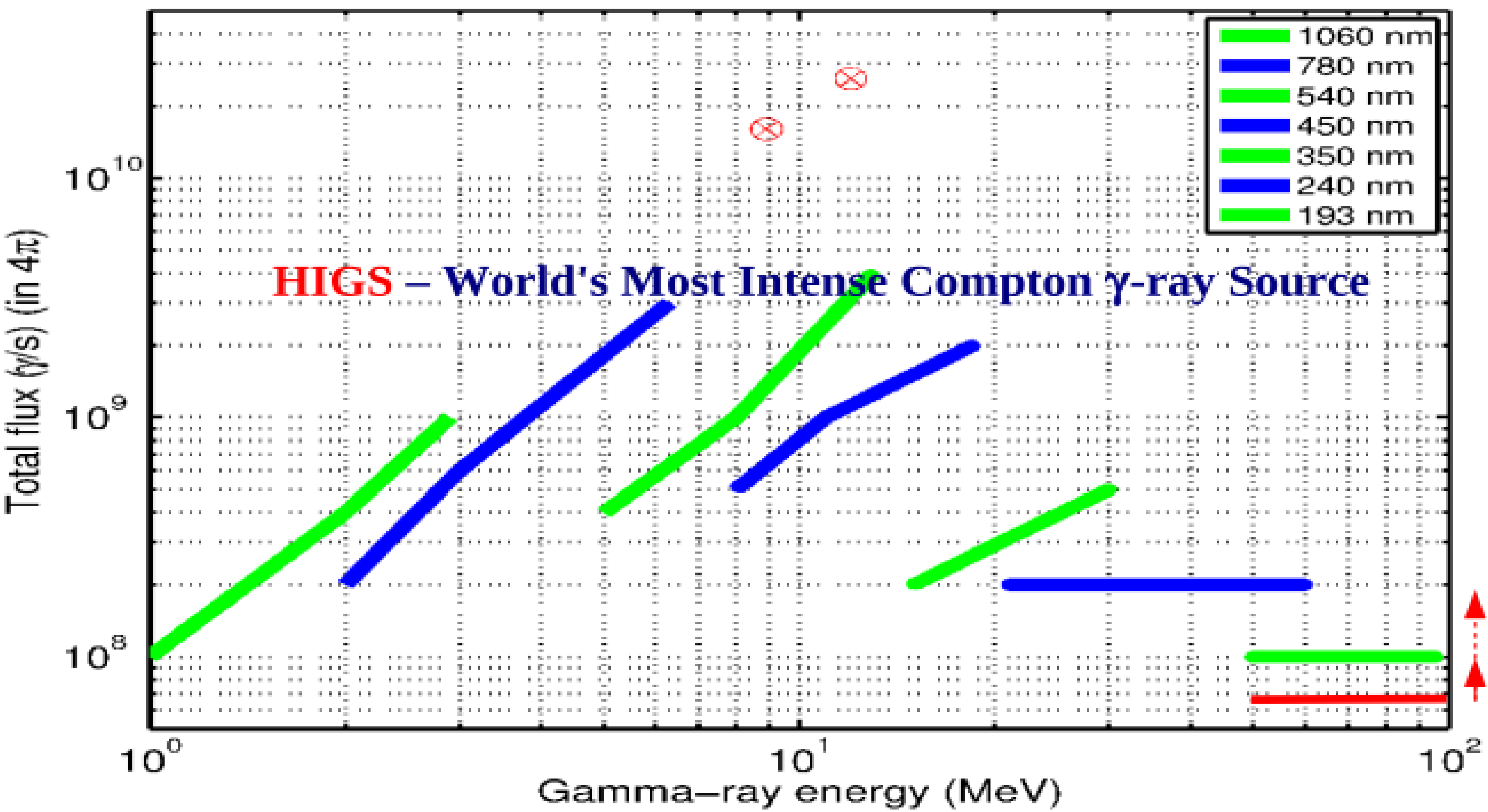
- Circularly and linearly polarized, nearly monoenergetic γ–rays from 2 to 100 MeV
- Utilizes Compton backscattering of FEL light to generate γ–rays



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



HIGS User Flux Capabilities with OK-5 FEL



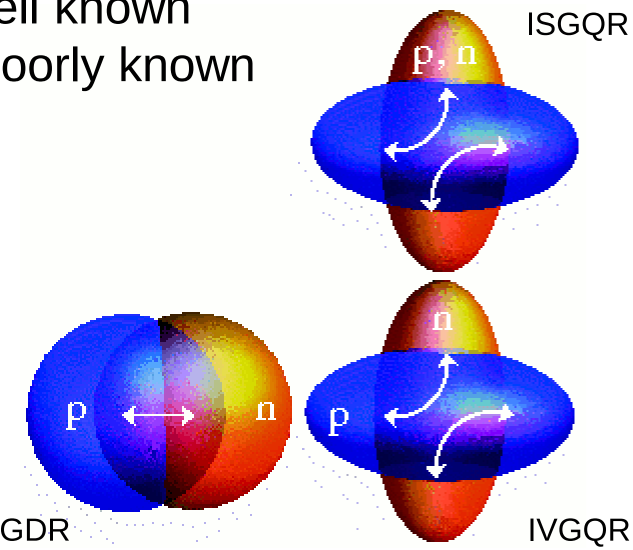
Peak Performance of HIGS

Total Flux: >2x 10^{10} γ/s, around 10 MeV

Compton scattering program began at low energies..used 15 – 35 MeV beams to study the IVGQR.

Giant resonances arise from the collective motion of the nucleons within the nucleus

- Isovector Giant Dipole (GDR) -- well known
- Isoscalar Giant Quadrupole (IVGQR) -- well known
- Isovector Giant Quadrupole (IVGQR) -- poorly known



Precision measurements of the IVGQR would be useful for:

- Establishing the A-dependence of the parameters of the IVGQR
- Determining the density dependence of the nuclear symmetry energy

  Needed to predict the behavior of matter under extreme conditions (e.g. within a neutron star)

Study of the Isovector Giant Quadrupole Resonance in Nuclei (Dissertation of Seth Henshaw, PhD, 2010) Phys. Rev. Lett. 107, 222501 (2011)

Linearly polarized Compton scattering

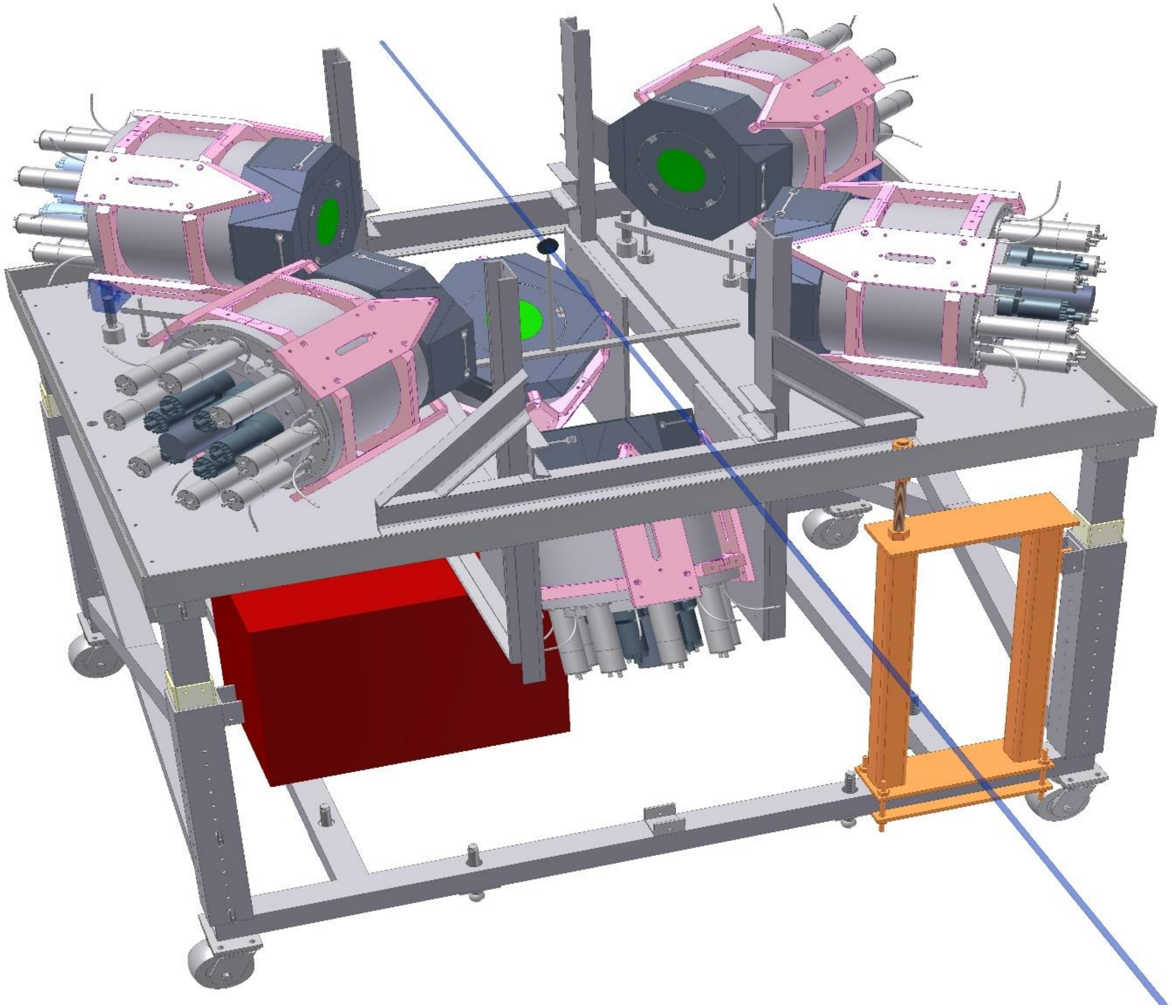
Exploits the 100% polarization of the HIγS beam along with the realization that the E1-E2 interference term flips sign when going from a forward to a backward angle.

HINDA Setup

^{209}Bi Scattering Target
- 2” Diameter x 1/8” thick
- $9*10^{21}$ nuclei/cm^2

6 Detectors
- 3 @ θ=60(55) (Left, Right,Down)
- 3@ θ=120(125) (Left, Right, Down)
- $\Delta\ \Omega$=55 msr

12mm collimated HIγS beam
- 3 x 10^7 γ’s/sec
- ΔE/E=2.5 %
- Eγ =15–26 MeV



Scattering Theory

Assumptions: (GDR Dominates)

Modified Thomson Amp included in C^{E1}

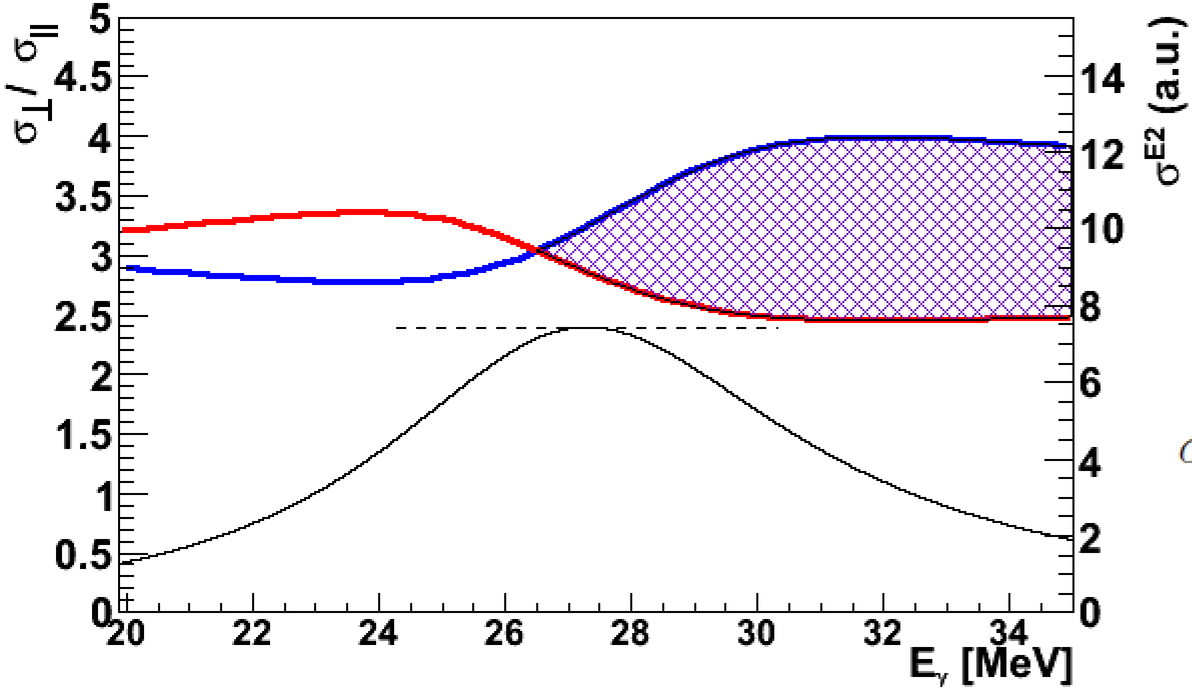
E2 strength due to IVGQR

$$\frac{\sigma_{\parallel}}{\sigma_{\perp}} = \cos^2\theta + \frac{2|C^{E2}|}{|C^{E1}|}\cos(\phi_{E2}-\phi_{E1})\left[\cos^3\theta - \cos\theta\right]$$

$$\cos(\phi_{E2}-\phi_{E1})\begin{cases} < 0,\ E < E_{res} \\ > 0,\ E > E_{res} \end{cases}$$

θ	$\cos^2\theta$	$\cos^3\theta - \cos\theta$
125°	0.33	0.38
55°	0.33	-0.38

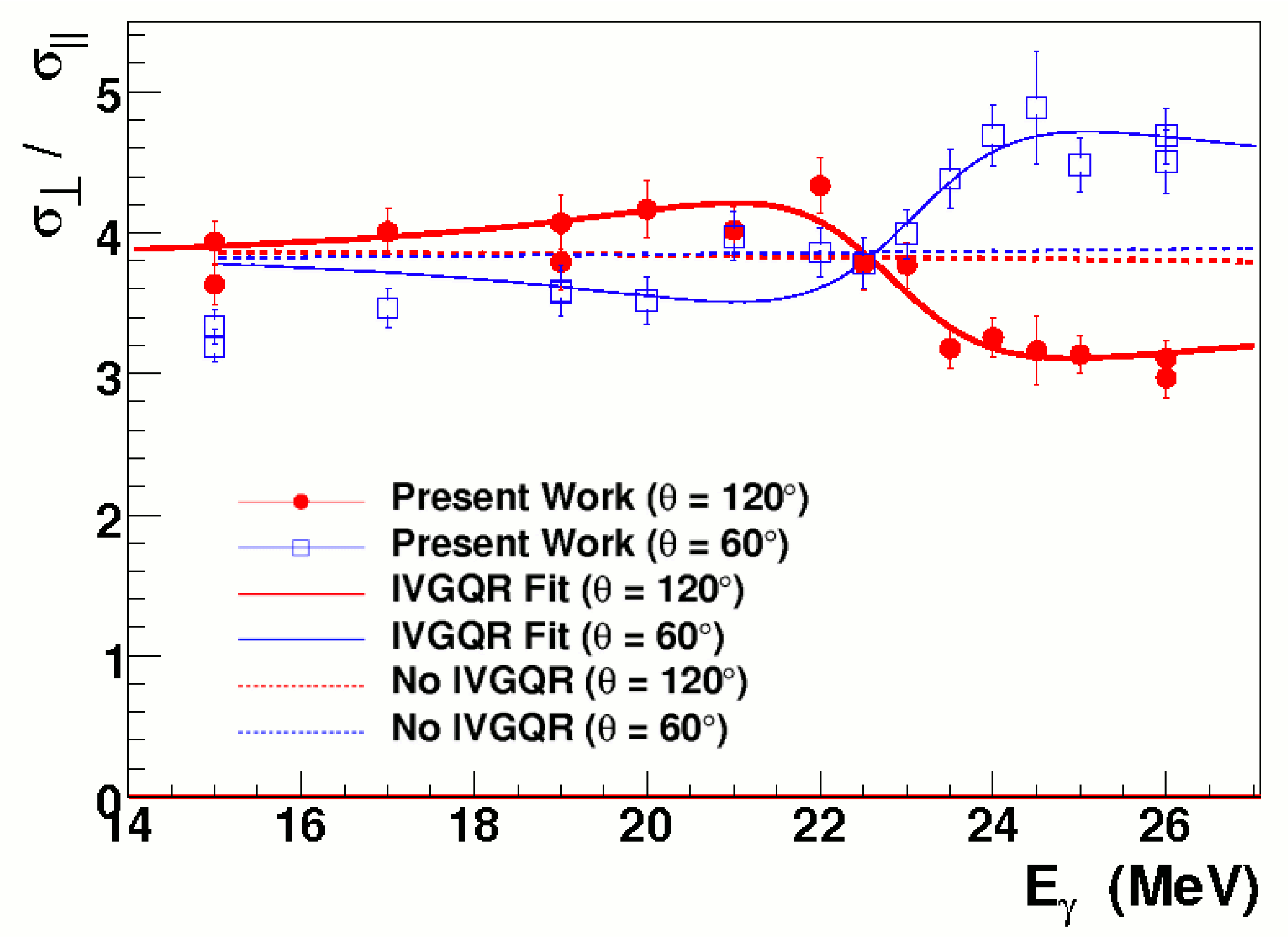
Fore/aft polarization ratios



$$\sigma_\gamma^\nu(E) = \frac{\sigma_0^\nu E^2 \Gamma_\nu^2}{(E^2 - E_\nu^2)^2 + E^2\Gamma_\nu^2}$$

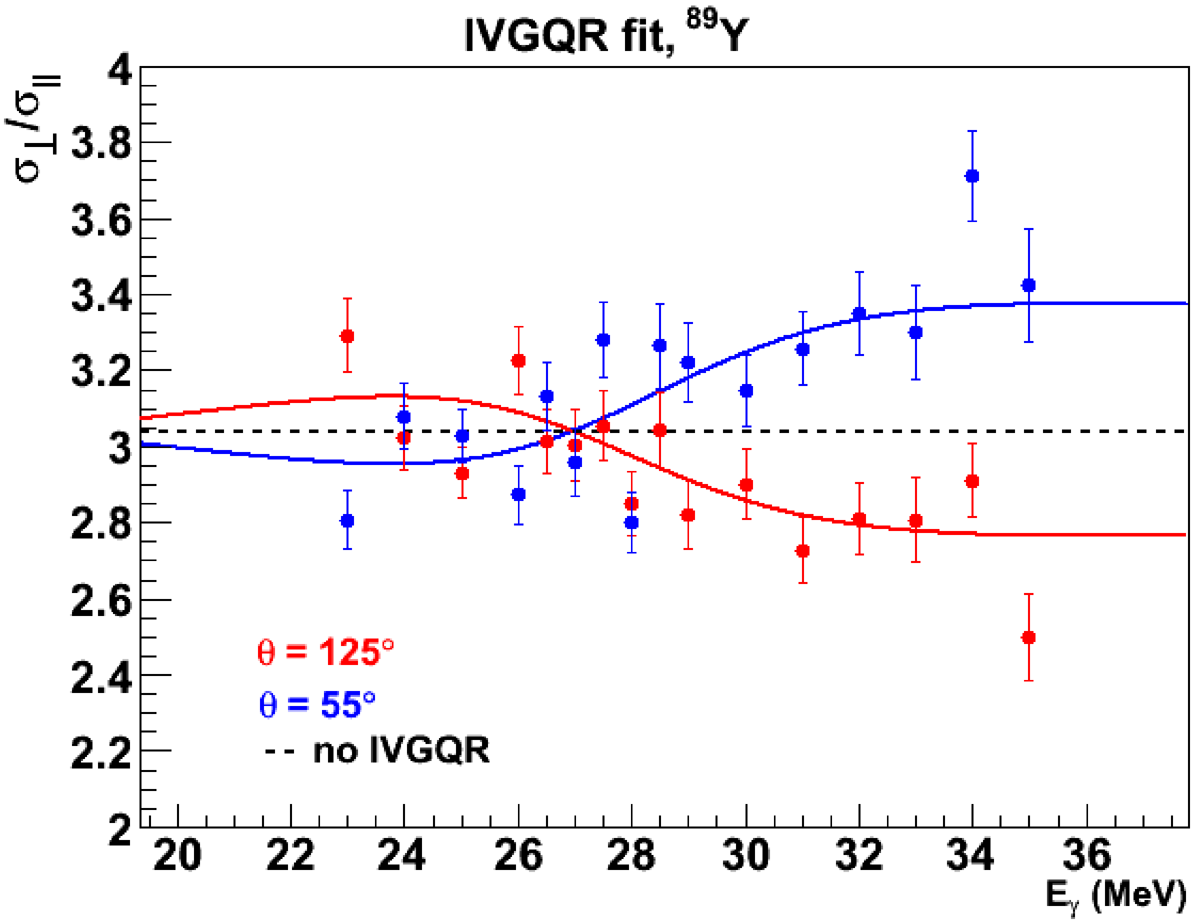
RESULTS FOR ^{209}Bi

E=23+/-0.13 MeV   Γ=3.9 +/- 0.7 MeV   SR=0.56 +/- 0.04 IVQ-EWSRs

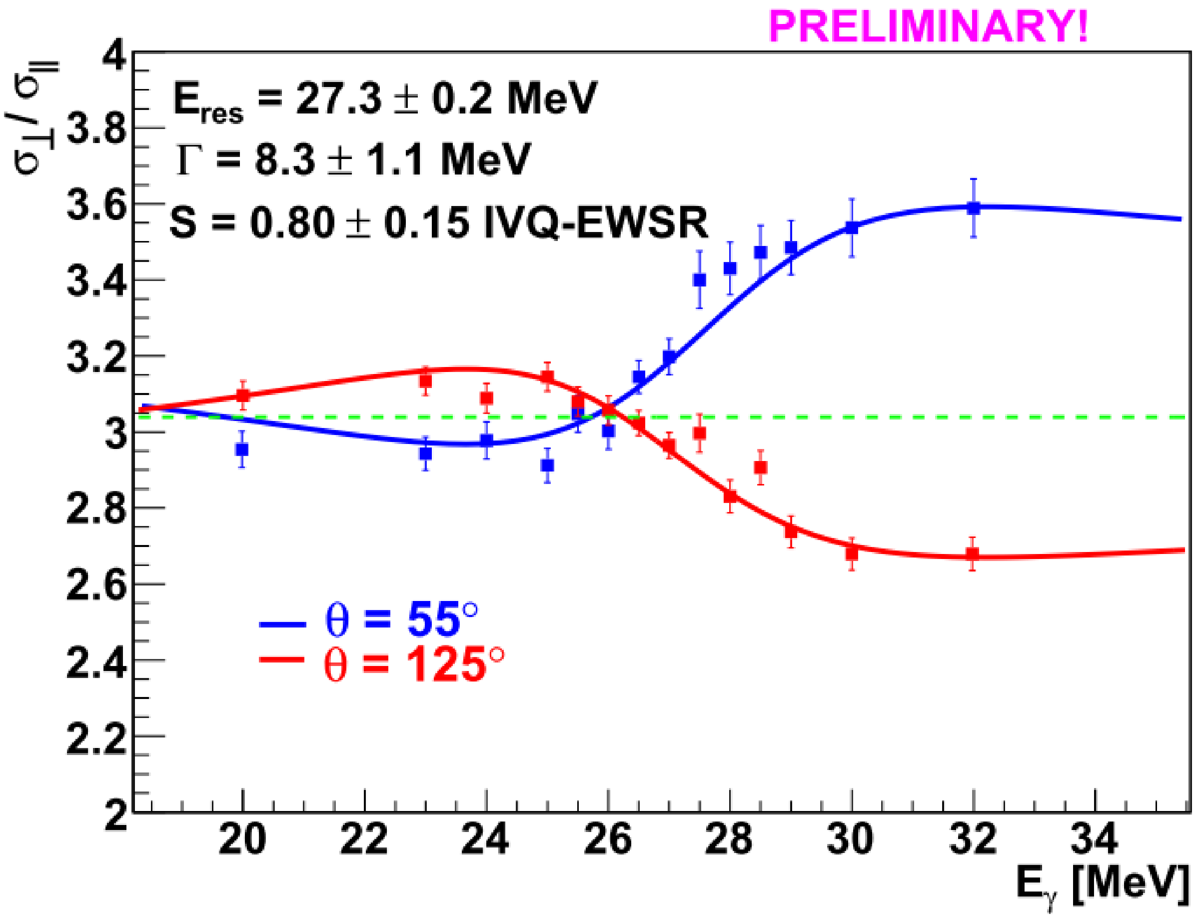


A second target—89Y—was studied in February, 2012.

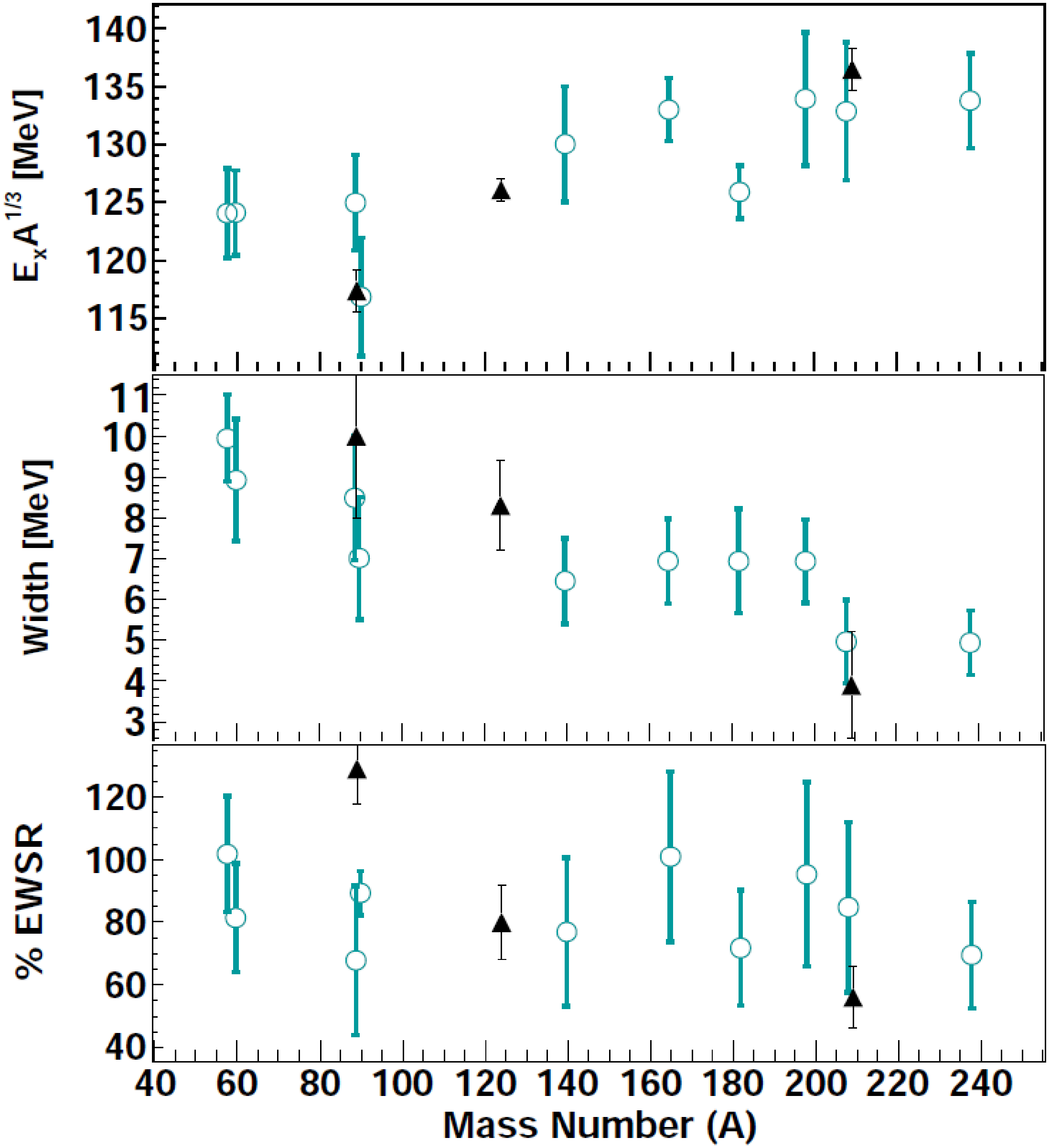
E_{res} = 28.0 +/- 0.4 MeV ; Γ=11 +/- 0.9 MeV; *IVQ-EWSR* = 0.93 +/- 0.11



RESULTS OBTAINED RECENTLY for 124Sn
(target courtesy of Heiko Scheit)



IVGQR Systematics



Note: displayed erroı are statistical only

R. Pitthan, *Giant Multipole Resonances; Proceedings of the Giant Multipole Resonance Topical Conference*, (Harwood Academic Publishers, Oak Ridge, TN, 1980) and references therein

Neutron star structure and collective excitations of finite nuclei

Nils Paar et al. using relativistic nuclear energy density functionals and quasi-particle RPA to determine the density dependence of the symmetry energy

arXiv:1403.7574v1 [nucl-th] 29 Mar 2014

J is the symmetry energy E_s at saturation density; L is the slope of E_s vs baryon density

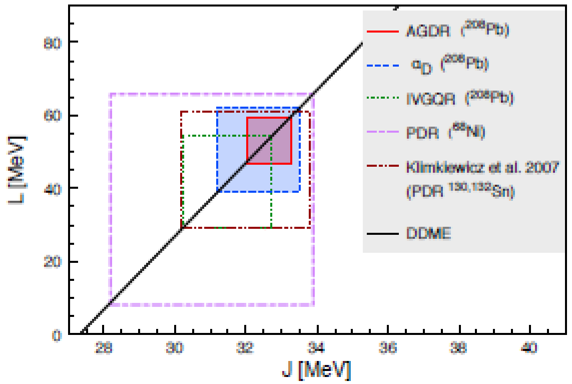


FIG. 2: (Color online). Constraints of the symmetry energy at saturation J and the slope parameter L, obtained from a comparison of RNEDF results and data on AGDR [35] and IVGQR [32] excitation energies (^{208}Pb), the dipole polarizability α_D of ^{208}Pb [33], and the PDR energy weighted strength (^{68}Ni [34], ^{130,132}Sn [30]).

Proposed Hadron Structure studies @ HIγS

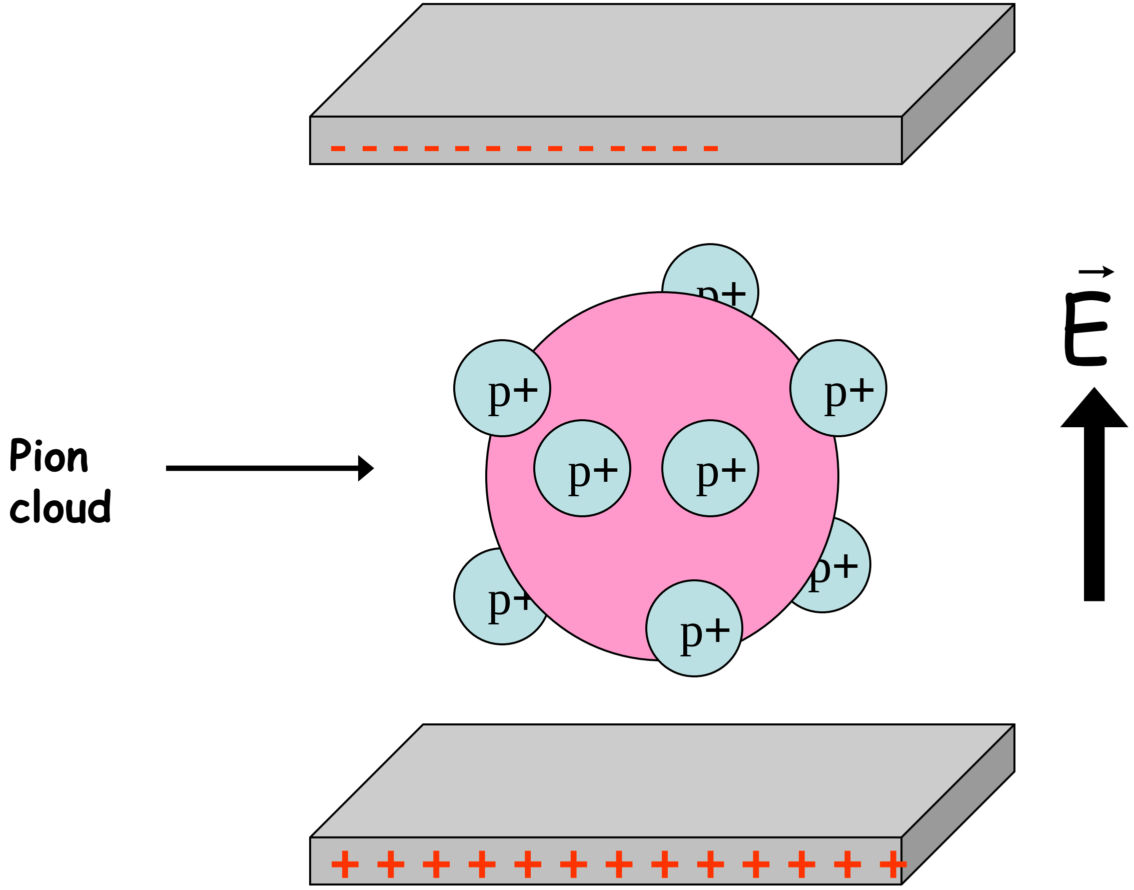
Deliverables and Completion dates:

- 2016: Reduce uncertainty in the static magnetic dipole polarizability of the neutron by a factor of two;
- 2017: Model-independent determination of proton's static electro-magnetic polarizabilities;
- 2018: Begin HPV experiment on the deuteron.
- 2019: First direct measurement of electric dipole spin polarizability of the proton below pion production threshold;
- 2020: Measurement of the π^0–p scattering length

Scientific Motivation

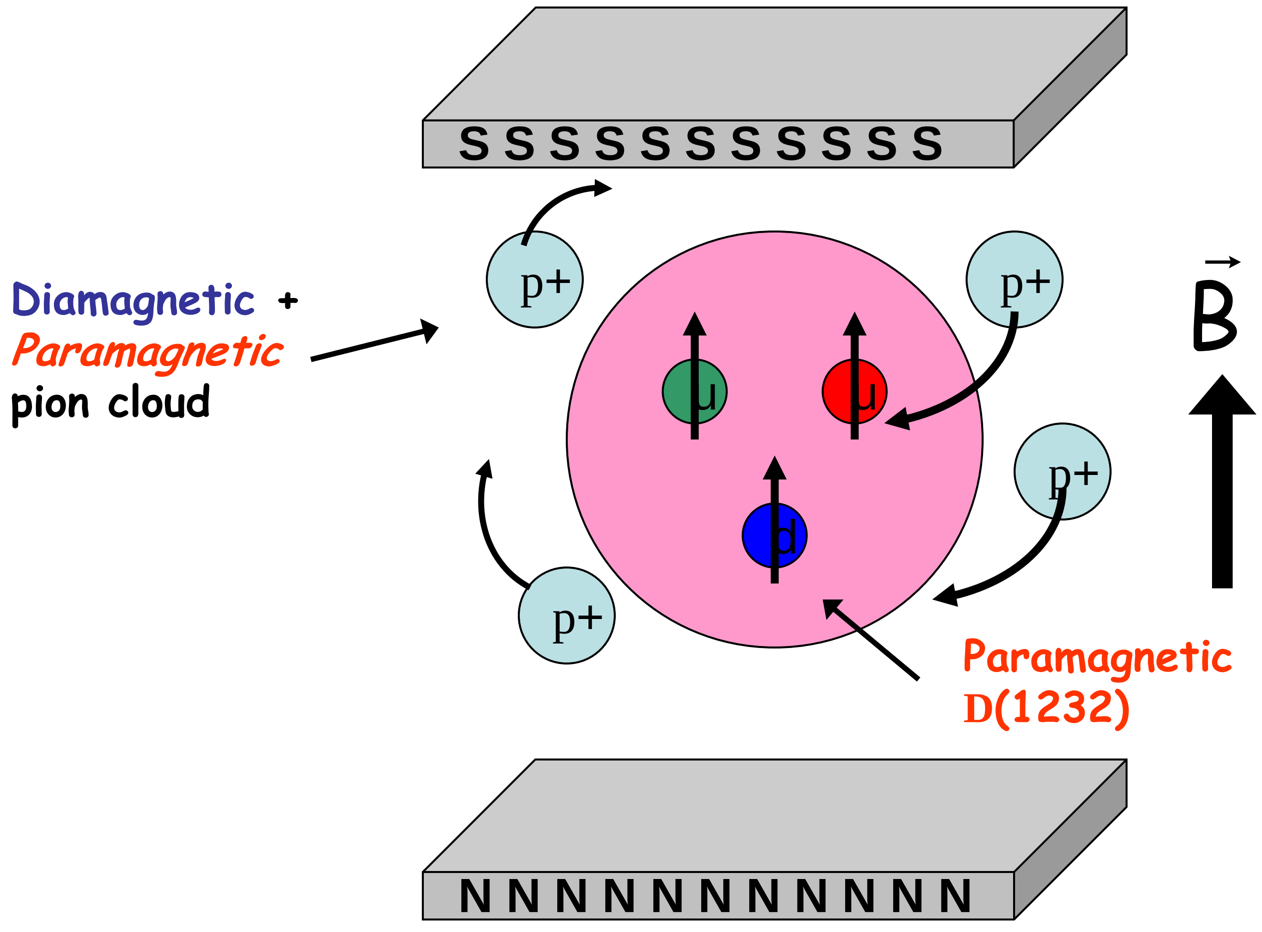
Measurement of the static and the spin polarizabilities of the nucleons via Compton Scattering *provide stringent tests of calculations that link the effective low-energy description of nucleons to QCD*; lattice calculations are imminent.

Proton electric polarizability



Electric polarizability: proton between charged parallel plates

Proton magnetic polarizability



Magnetic polarizability: proton between poles of a magnetic

The electric and magnetic polarizabilities of the proton

The values of the polarizabilities of the proton given by the recent PDG evaluation are:

$$\alpha_p = 11.2 \pm 0.4 \times 10^{-4}\ fm^3$$

$$\beta_p = 2.5 \pm 0.4 \times 10^{-4}\ fm^3$$

Lensky and Pascalutsa (BχPT) with pion, Dirac nucleons and Δ dof find (EPJ C65, 195 (2010)):

$$\alpha_p = 10.8 \pm 0.7 \times 10^{-4}\ fm^3$$

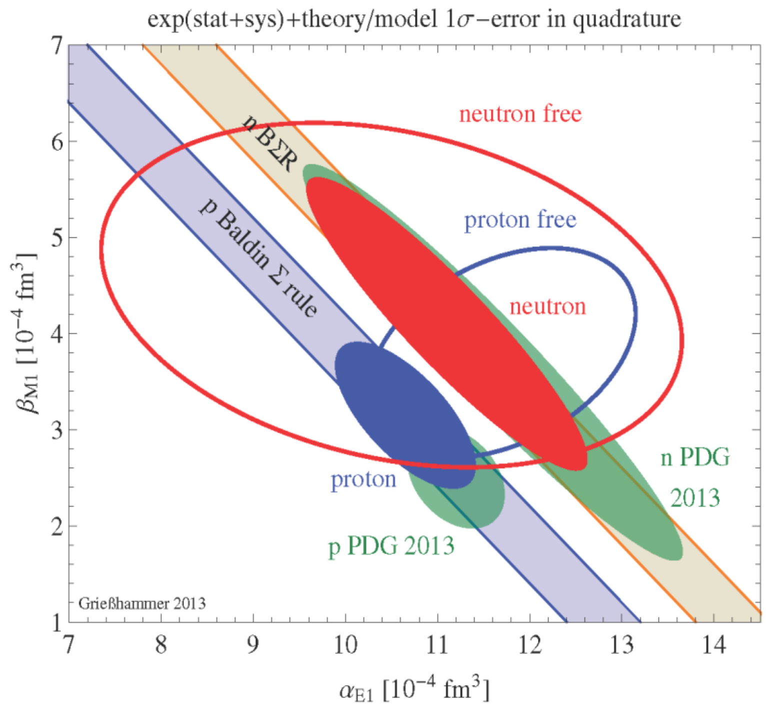
$$\beta_p = 4.0 \pm 0.7 \times 10^{-4}\ fm^3$$

Is the difference due to model dependence of previous determinations?

Impact of HIGS Measurements

I. The experiments at HIGS will make *model independent* measurements of the electromagnetic polarizabilities for the proton (bring the blue open circle to the same level of errors as the filled ellipse), and

II. reduce the error in the neutron magnetic polarizability (filled red ellipse) to one-half of its current value.



Comment

Measurements of Compton scattering from the proton using linearly polarized beams at 90^o with the detectors perpendicular to the plane of polarization of the beam will provide a direct determination of α, independent of β.

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

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

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

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

The HIγS Experiment

PAC approved

Will use **100% linearly polarized beam (2 x 10^7 γ/s) at 80 MeV**.

Recently constructed liquid hydrogen target: 10^{24} protons/cm^2.

Eight HINDA detectors at 90º (l,r,u,d), using two independent setups.

A **300 hour run** is expected to give A to 0.25%.

The electric polarizability will be determined to within 2.5% uncertainty

(eg 10.8 +/- 0.3 x 10^{-4} fm^3)

Nucleon Polarizabilities

Proton: First such measurement of alpha and beta separately

Quantity	Polarization	$E\gamma$	% Err
α_p	Linear	85 MeV	2.5 %
β_p	Linear	85 MeV	<10%

While the proton polarizabilities are "well-known", the neutron values come from Compton scattering from the deuteron which determines the average of the n and p polarizabiities. After almost 20 years of effort, the data are still in need of improvement.

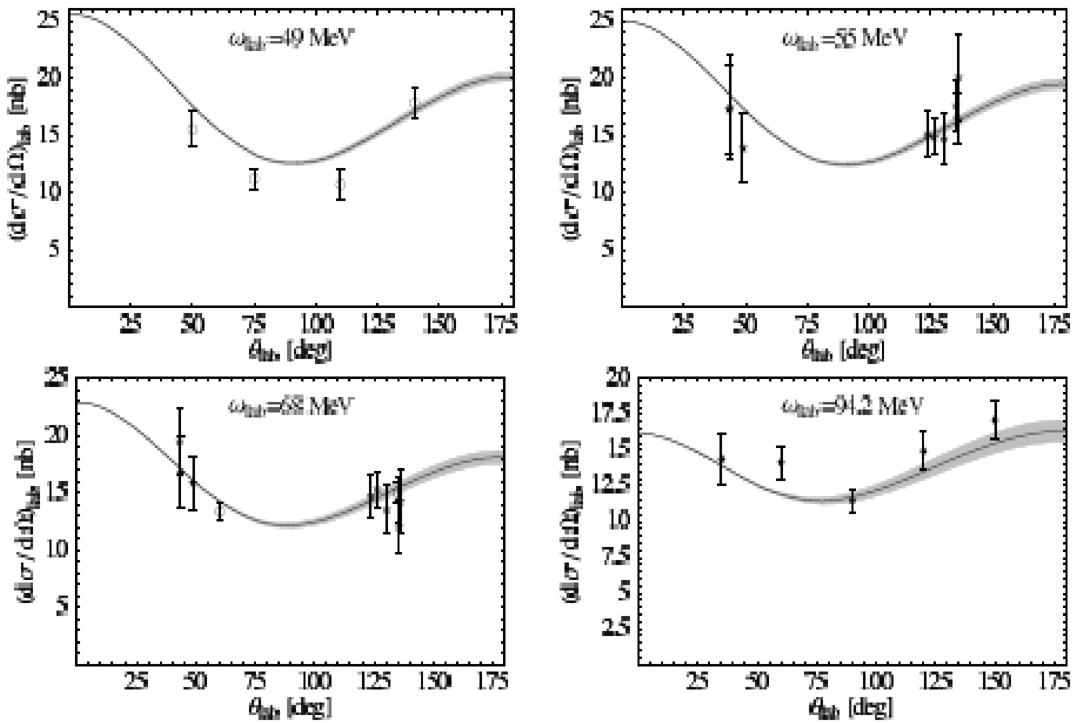
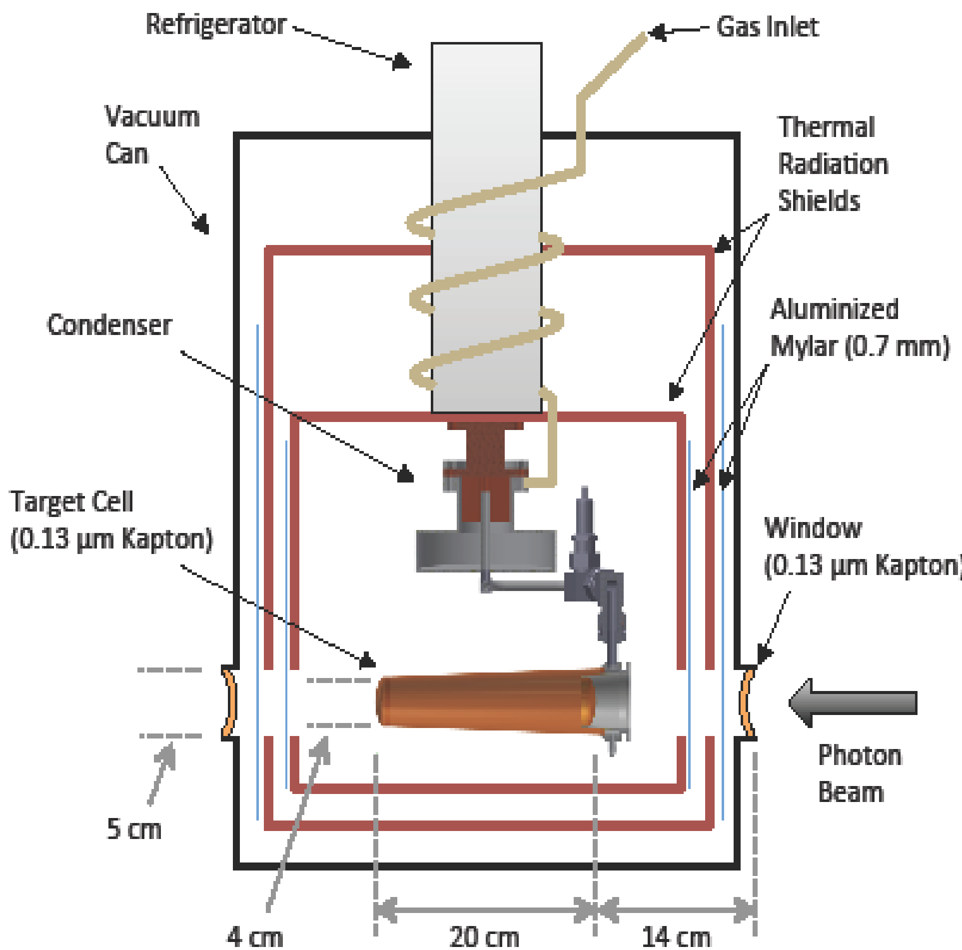


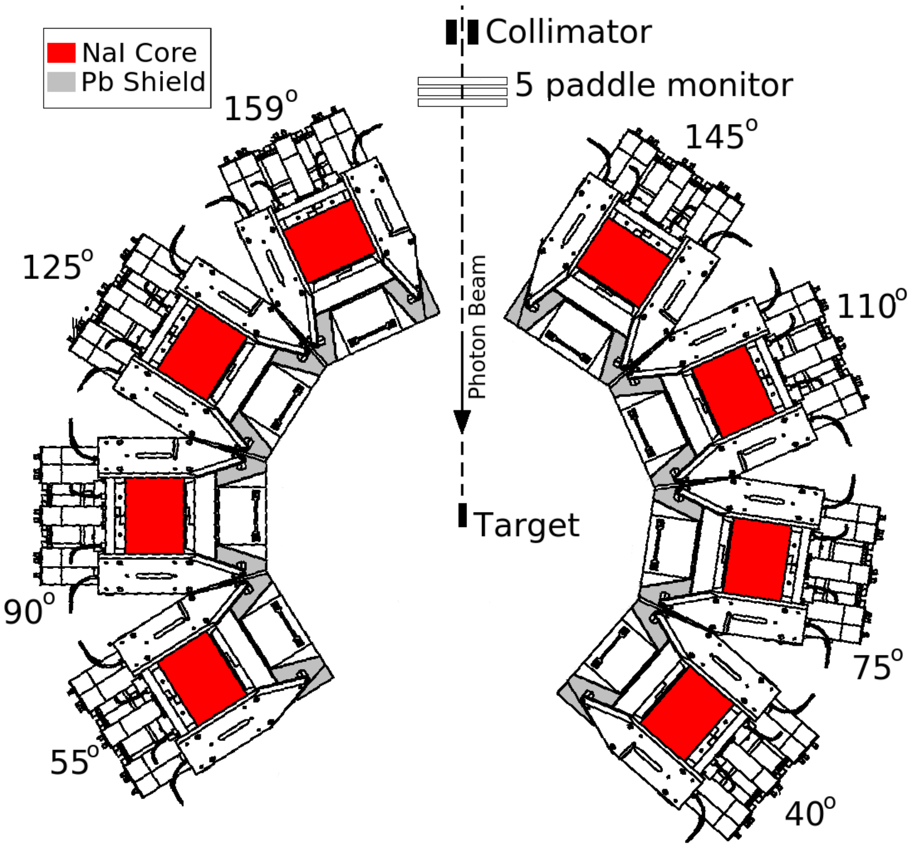
Figure 18: Results from a global fit of α_E^s to all existing elastic γd data, using the chiral wave function [36]. β_M^s is fixed via the Baldin sum rule, Eq. (4.3). The grey bands are derived from our statistical errors.

A New liquid He, hydrogen, deuterium target has been constructed.
Target thickness for $LD_2 = 9.8 \times 10^{23}$ D/cm^2
Total beam attenuation < 5%



HADRON 2014

The HINDA array setup for Compton scattering



Anticipated results for Compton scattering from the deuteron at 65 MeV –scheduled to run in the coming year.

Neutron: The 65 and 100 MeV measurements will reduce the error in βn from ~ 50% to ~20 %

Energy (MeV)	Angle	Cross Section (nb/sr)	Rate (counts/hour)	Time (hours)	%Err (stat)
65	45	16.5	47	300	0.84%
65	80	12.4	36	300	0.96%
65	115	13.7	40	300	0.91%
65	150	17.8	52	300	0.80%

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.

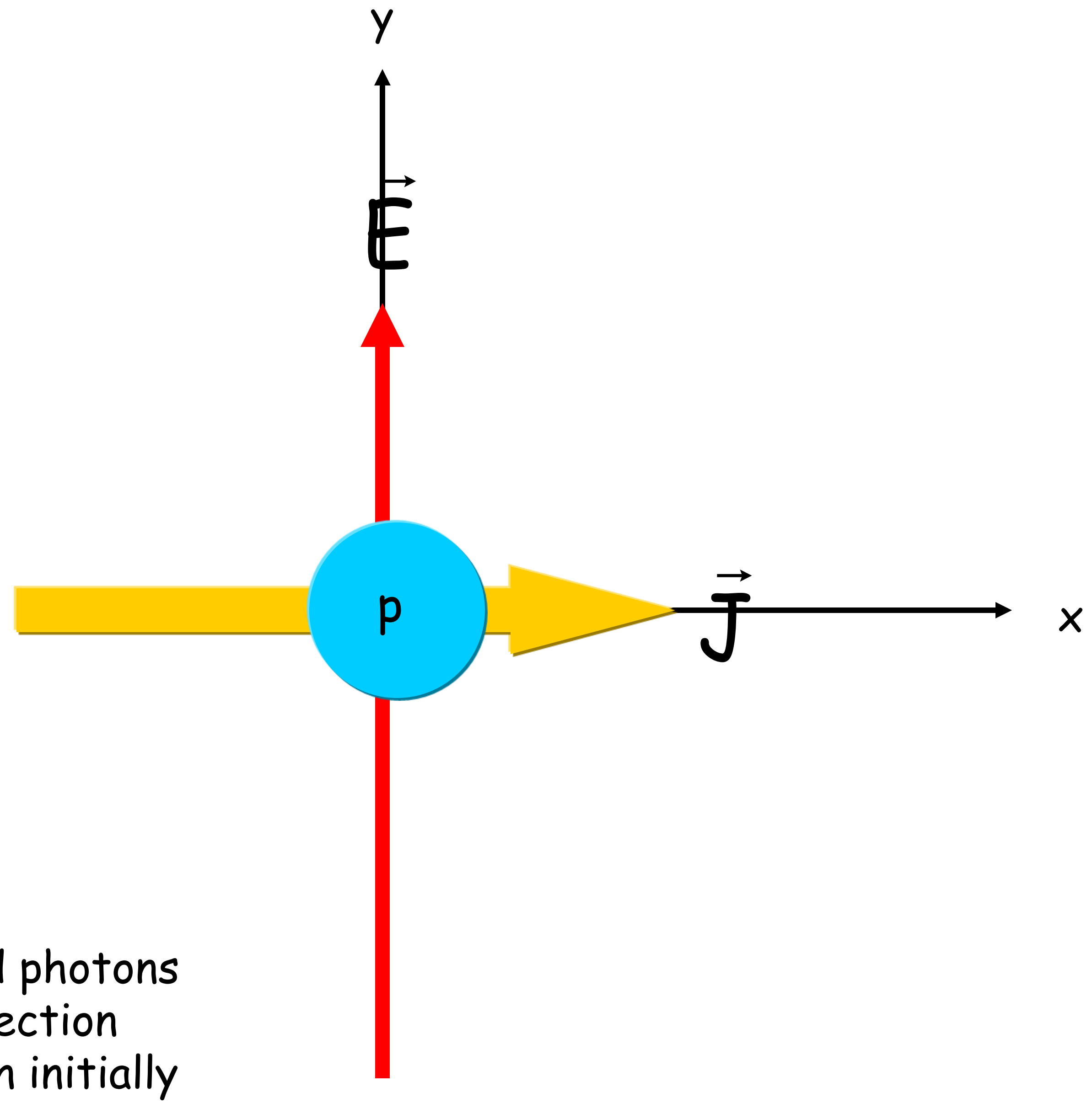
- Polarized protons will be provided by our frozen-spin target.

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.

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

• 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

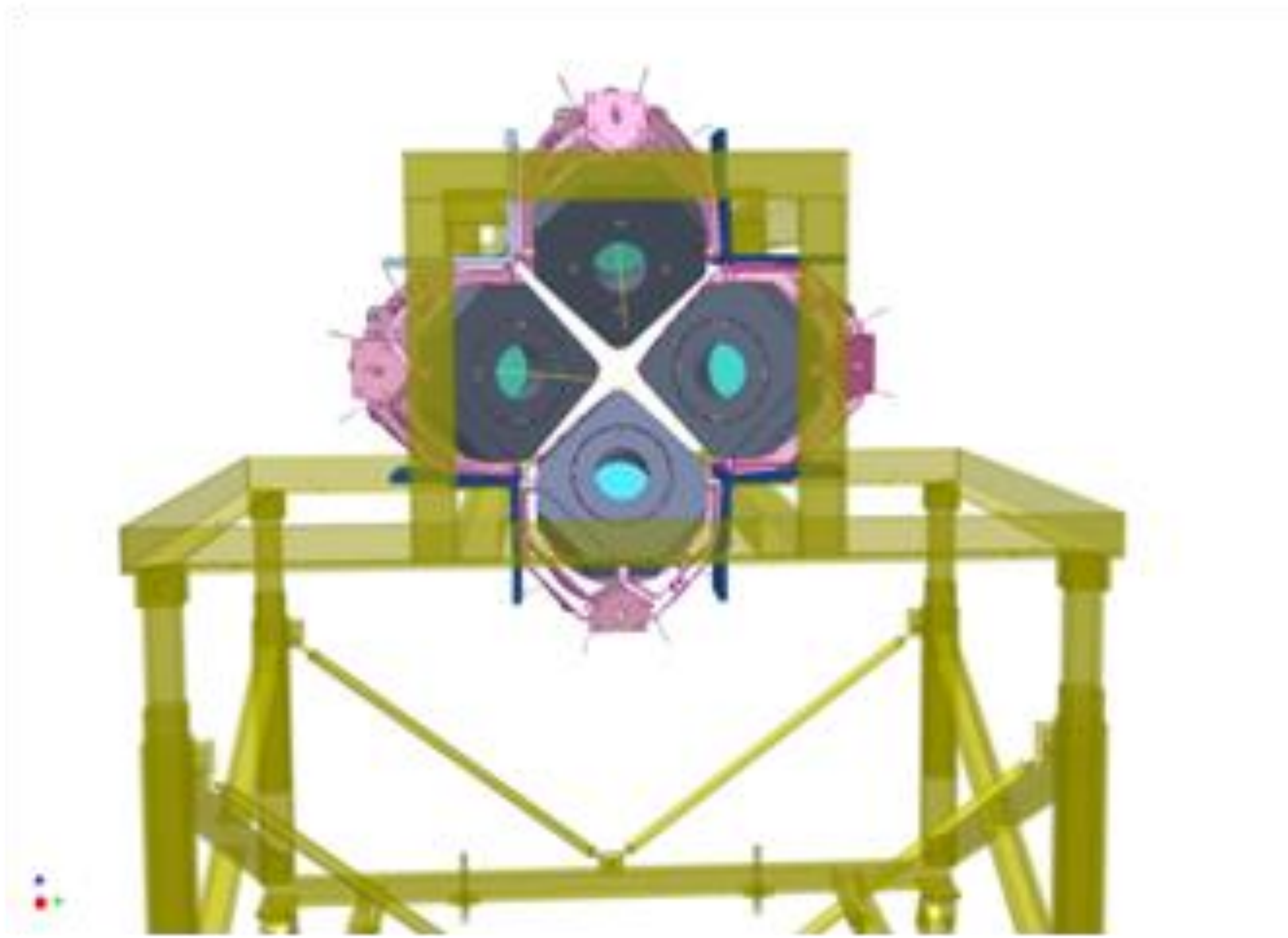
•***Proton spin-polarizabilities will be measured using a scintillating frozen-spin polarized target***

Rory Miskimen et al., U. Mass.

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

The initial experiment will run near 120 MeV.
The first experiment will determine γ_{E1E1} *by measuring* Σ_{2x} *using a transverse polarized target and 8 HINDA detectors near 90 degrees ---4 left and 4 right.*
Simulations indicate little sensitivity to γ_{M1M1}*, and we can use* γ_o *and* γ_π *to fix the other two.*

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

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

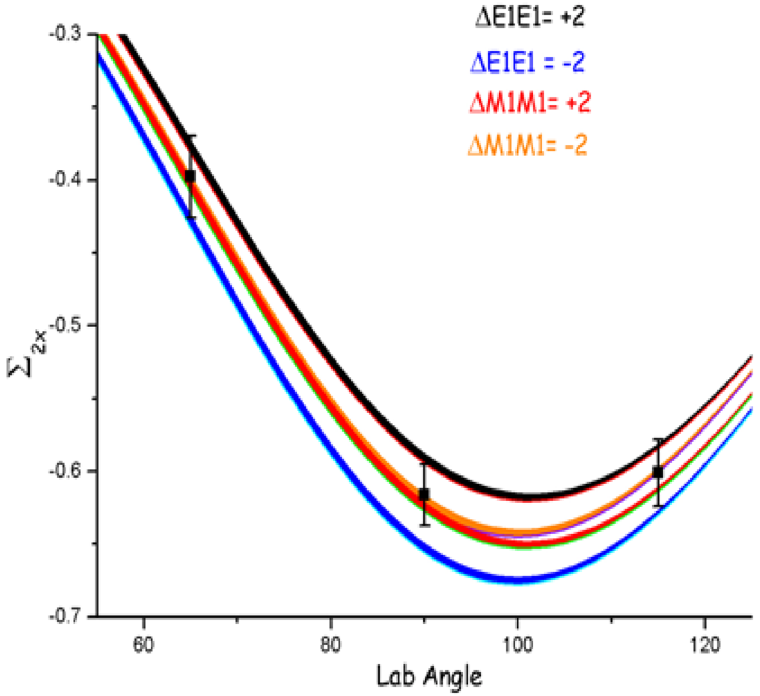
Beam intensity: 5 x 10^6 γ/s @ 100 MeV

The HINDA array with dets. 75 cm from the target

Running time: 800 hrs. transverse target polarization, 400 hrs. with +1 photon helicity, 400 hrs. with -1.

Can measure the polarizabilities at HIgS with a precision of ~ 0.4 x 10-4 fm4 , which is sufficient to test and differentiate between theoretical

models. Full Lattice QCD calculations are imminent.



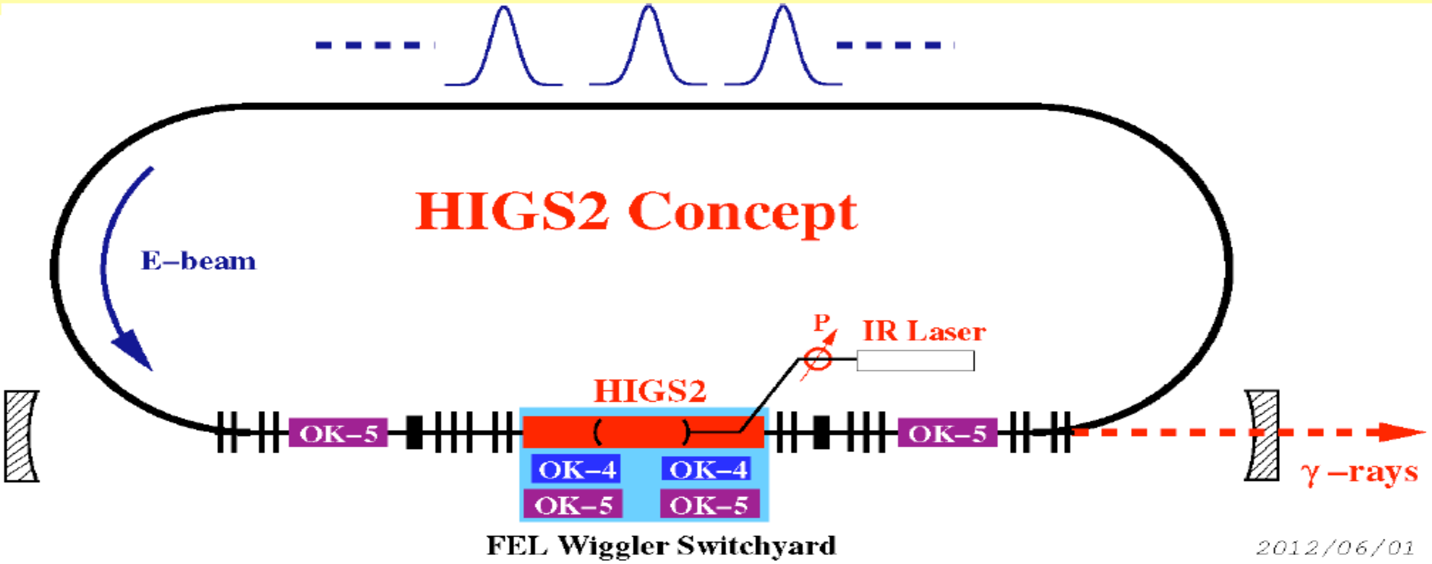
HADRONIC PARITY VIOLATION

May be the most profound opportunity for HIγS2.

Definitely IS the most challenging!

If funded today, first operation would be expected in 2018.

Parity Violation Experiments at HiGS2?



~10^{11} to 10^{12} polarized γ/sec (X100 increase in polarized gamma flux relative to HiGS1.)

Circularly polarized gammas (>~90%), fast (~100 Hz) gamma helicity reversal possible

Controlled beam phase space: ~1% energy resolution on gamma energy (2-12 MeV)

These are attractive features for parity violation experiments

Use parity violation to isolate the weak component of the N-N interacton.

The Parity Violating weak component of N-N interactions is the manifestation of weak quark-quark interactions on the hadronic level.

Since the strong interaction at low energy is largely controlled by QCD chiral symmetry, it can be parametrized by EFT methods.

Prefer a few-body system to minimize theoretical uncertainties, at the expense of a smaller signal.

Circularly polarized photodisintegration of unpolarized deuterium near threshold.

Measure the longitudinal asymmetry

$$A_L = \frac{\sigma+ - \sigma-}{\sigma+ + \sigma-}$$

for total break-up cross sections with photons of helicity + and -.

- Complements $n_{pol}\, p \rightarrow d\, \gamma$
- Sensitive to isoscalar and isotensor PV couplings
- Asym largest near threshold (~2.26 MeV) where s-waves dominate
- Expected size: ~ few x 10^{-8}

Previous attempt

Measurement of parity violation in photodisintegration of deuterium,

E.D. Earle, A.B. McDonald, S.H. Kidner, E.T.H. Clifford, J.J. Hill, G.H. Keech, T.E. Chupp, M.B. Schneider,

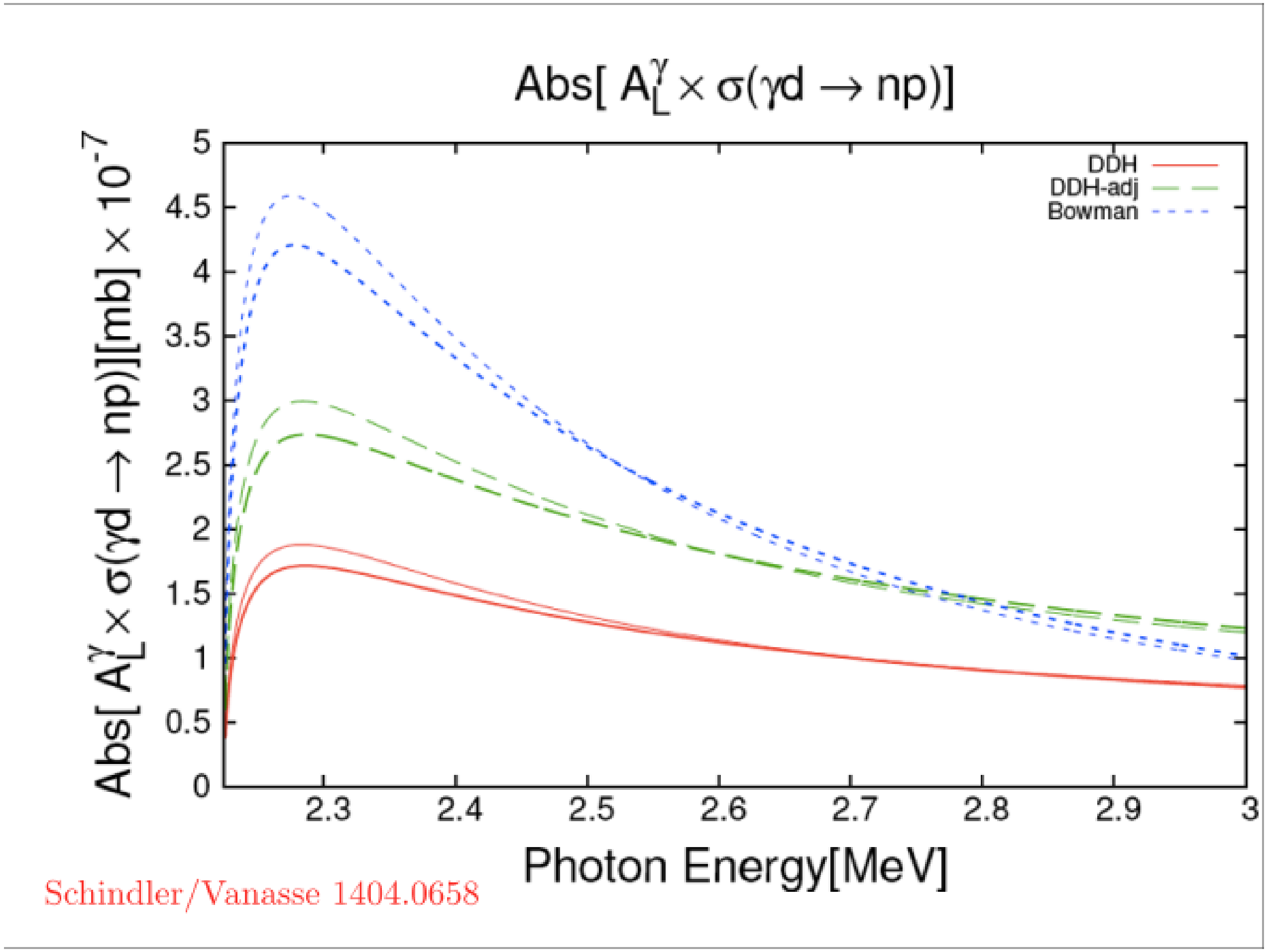
CJP 66(6), 534 (1988).

Used polarized brem with endpt. energy of 3.2 MeV.

Obtained $\boldsymbol{A_L = 7.7 \pm 5.3 \times 10^{-6}}$

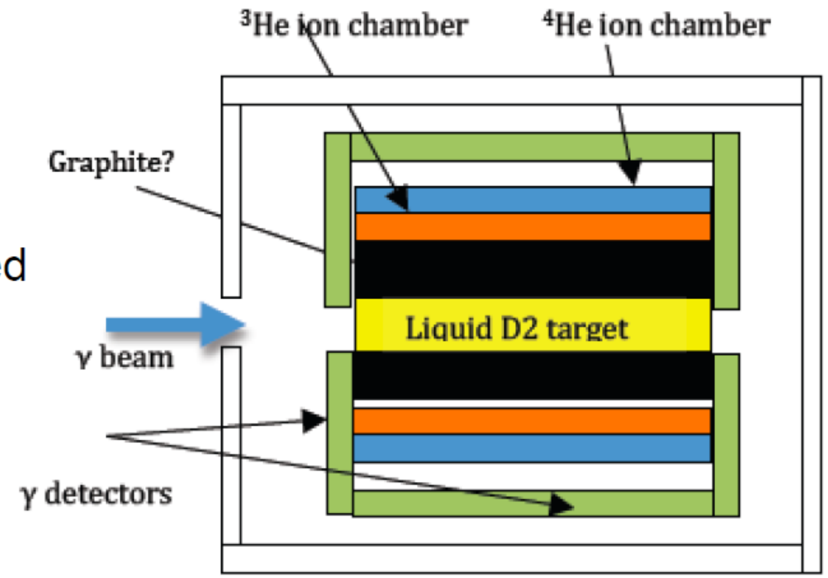
Need to improve this to an accuracy of 10^{-8}

Predicted asymmetry times cross section in pionless EFT for circ. pol. photons on deuterium using Desplanques, Donoghue, Holstein (DDH) model parameters. Best energy is ~ 2.26 MeV.



Concept of P-odd Deuteron Photodisintegration Expt.

Circularly-polarized
γ beam
from HiGS2

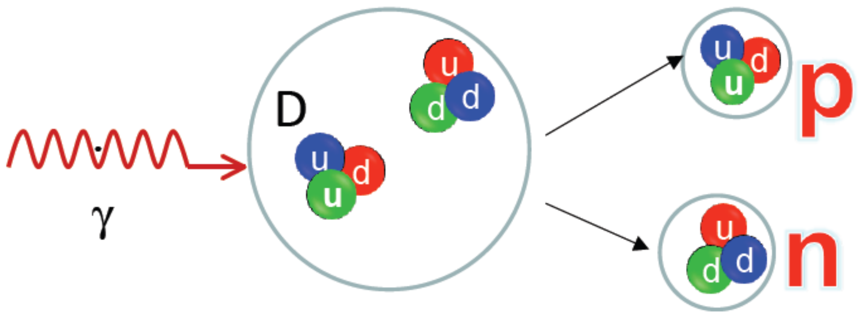


The neutron can be moderated in the liquid deuterium target, escape with low energy (~10 meV), and be detected efficiently in current mode in a 3He/4He ion chamber

The transmitted and scattered γs can be measured using current-mode γ detectors located behind the 3He/4He ion chamber

Cylindrical symmetry of detector array to help suppress possible systematic errors

Parity Violation in deuteron photodisintegration



Parity violation leads to helicity dependence of photodisintegration cross section

The neutron can escape the target and its intensity can be detected in current mode

Signal is helicity dependence of neutron current from target

Detect also scattered and transmitted gammas for normalization/systematics effect suppression

Need to observe >~10^{16} γs to be sensitive to a 1E-8 asymmetry. Not Impossible

Conclusions

Projected HIGS2 beam would deliver 10^{16} γs on target every 2 weeks

PV in deuteron photodisintegration: only known process with clean access to ΔI=2 piece of weak NN interaction

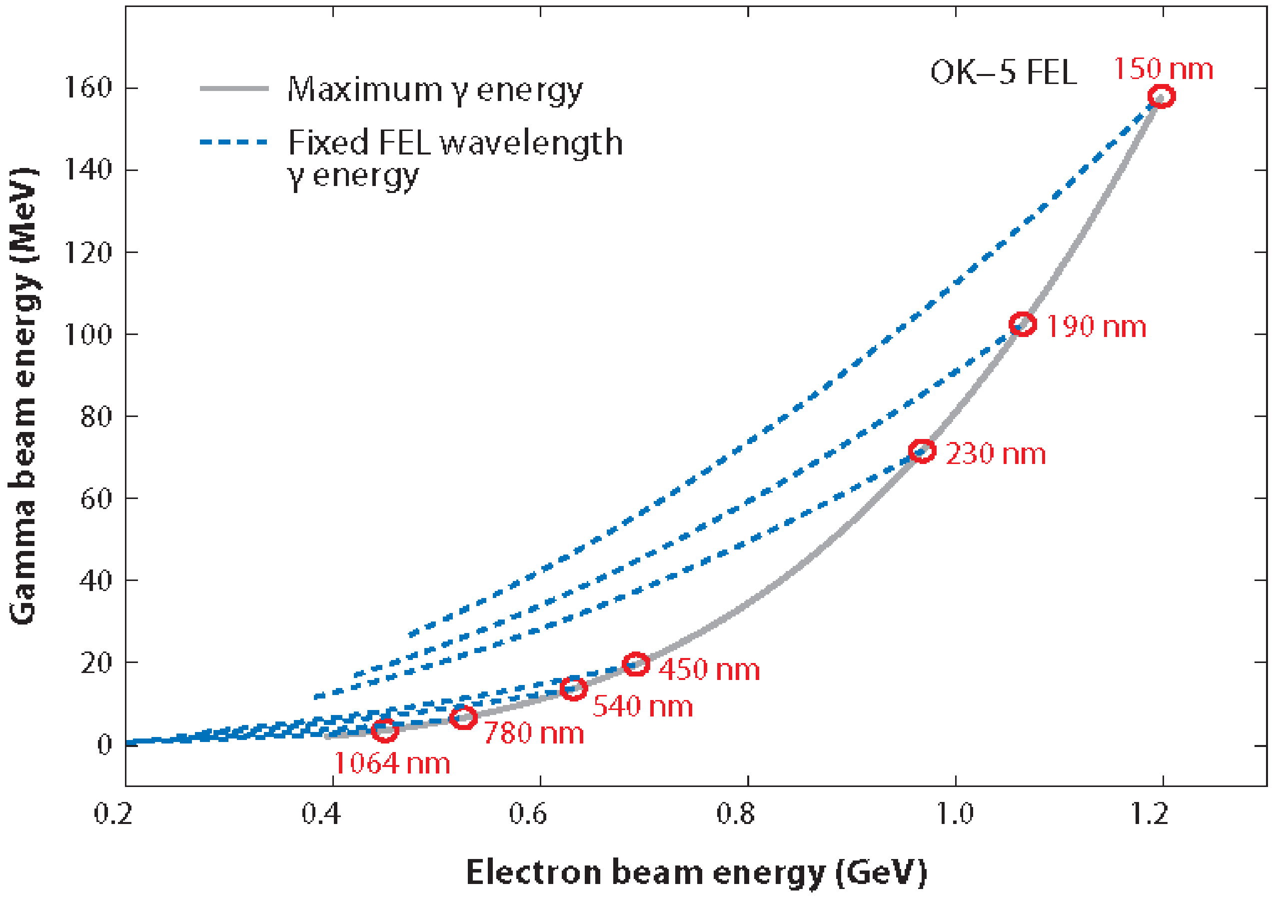
Experience with slow neutron and γ current mode detector technology exists

Outstanding questions:

What are the dominant systematic errors?

Young and young at heart volunteers are needed!

Upgrading HIγS to reach pion threshold energies



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 2017.

Measuring the s-wave π0 – proton scattering length @ HIγS using the $p(\gamma,\pi^0)p$ reaction

Run at an energy of 148 MeV with an energy spread of < 6 MeV.
This puts us in between the π^0 and the π^+ thresholds.
The experiment requires measuring the target analyzing power, T(θ), using a transverse polarized proton target (HIFROST).
Basically, T(θ) will give us the $Im(E_0+)$. Combining this with $Re(E_0+)$ gives the phase, which (Fermi-Watson; unitarity) is the phase shift.

$$\sigma = \frac{4\pi}{k^2} \sin^2 \delta = 4\pi\, a^2$$

which gives us the scattering length.

A 1000 hour run should determine the scattering length to ~ $10^{-3}/m_\pi$.
This is comparable to the accuracy of the isospin-even S-wave scattering length, a^+, obtained from pionic hydrogen and will test the predicted 25% violation of isospin symmetry.

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

Simulations

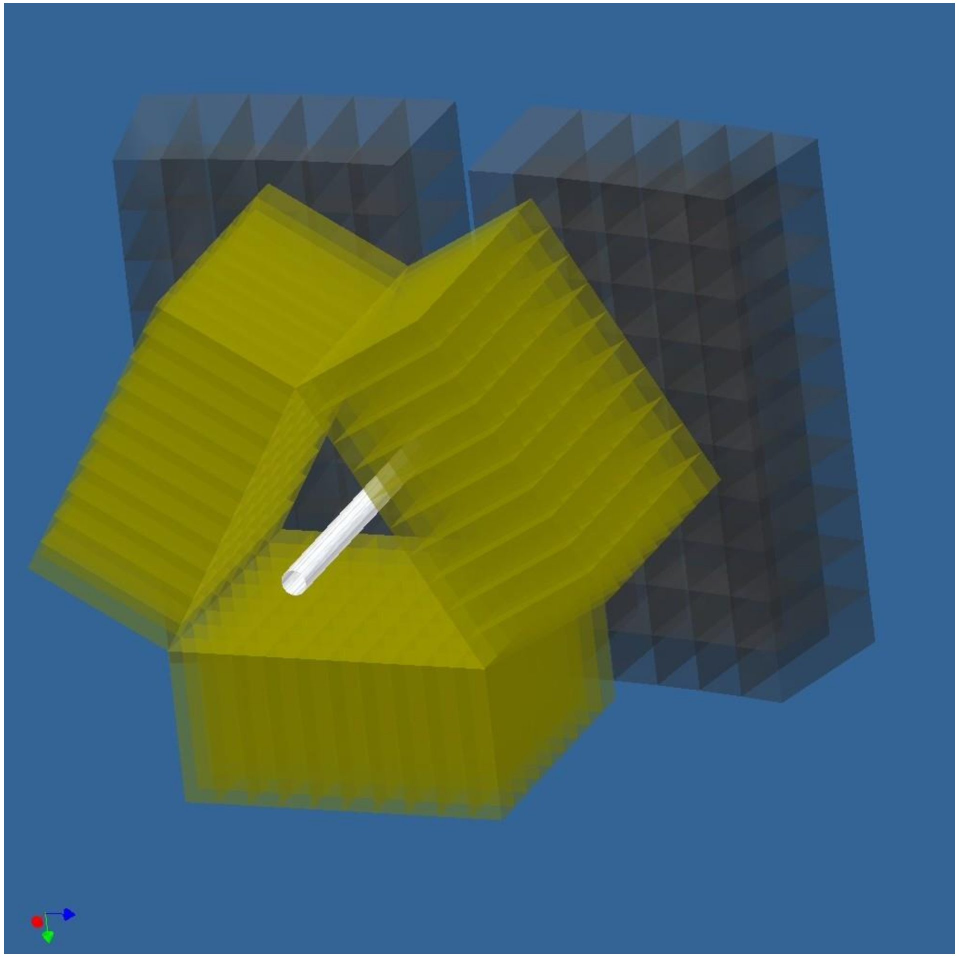
Beam on target was assumed to be 10^9 γ/s, and the polarized target thickness was 3.5×10^{23} p/cm^2.

The π^0 spectrometer is based on the crystal box and the NMS.

Results were published in Annual Reviews of Nuclear and Particle Science

The proposed HIγS NMS

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



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

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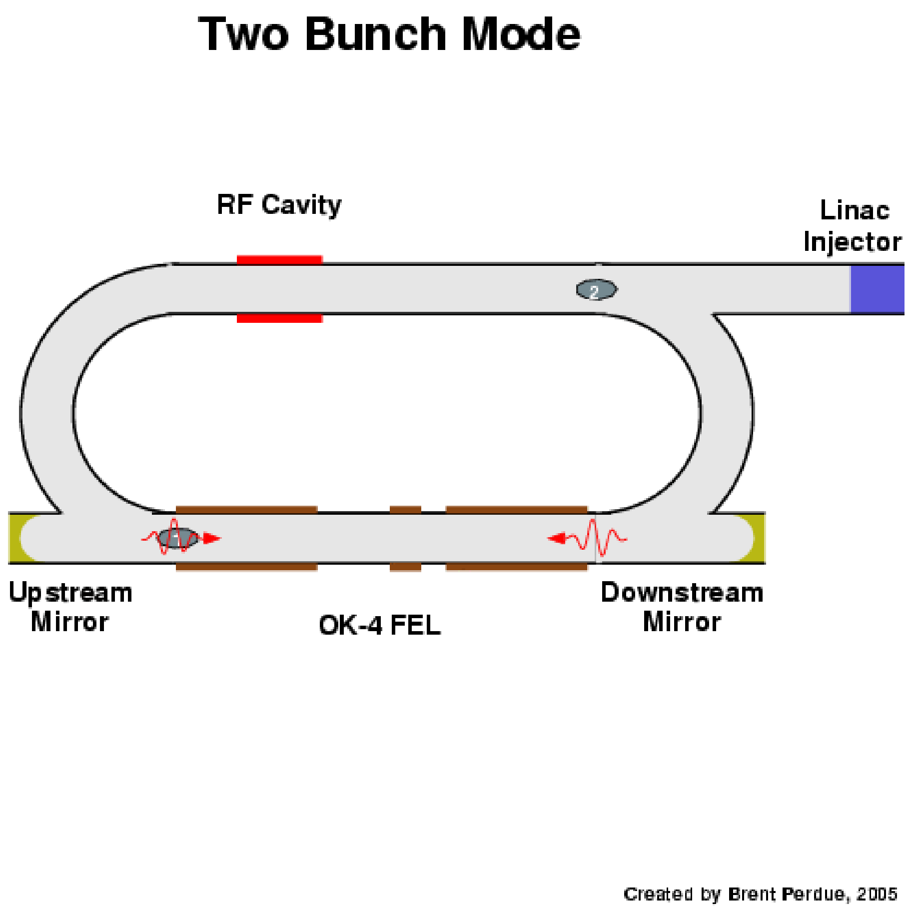
Mark Sikora (GWU)

Rory Miskimen (UMass)

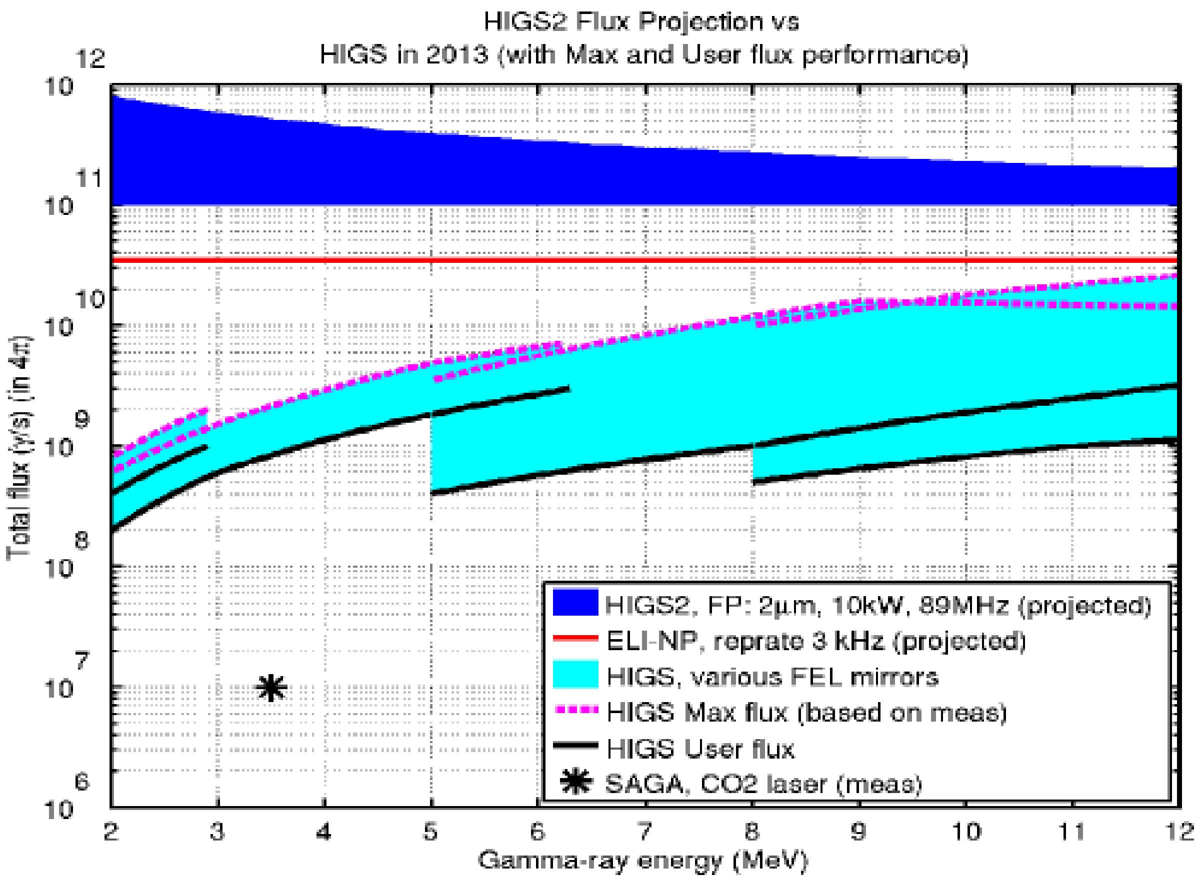
Don Crabb (UVa)

Aron Bernstein (MIT)

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



Projected HIGS2 Performance

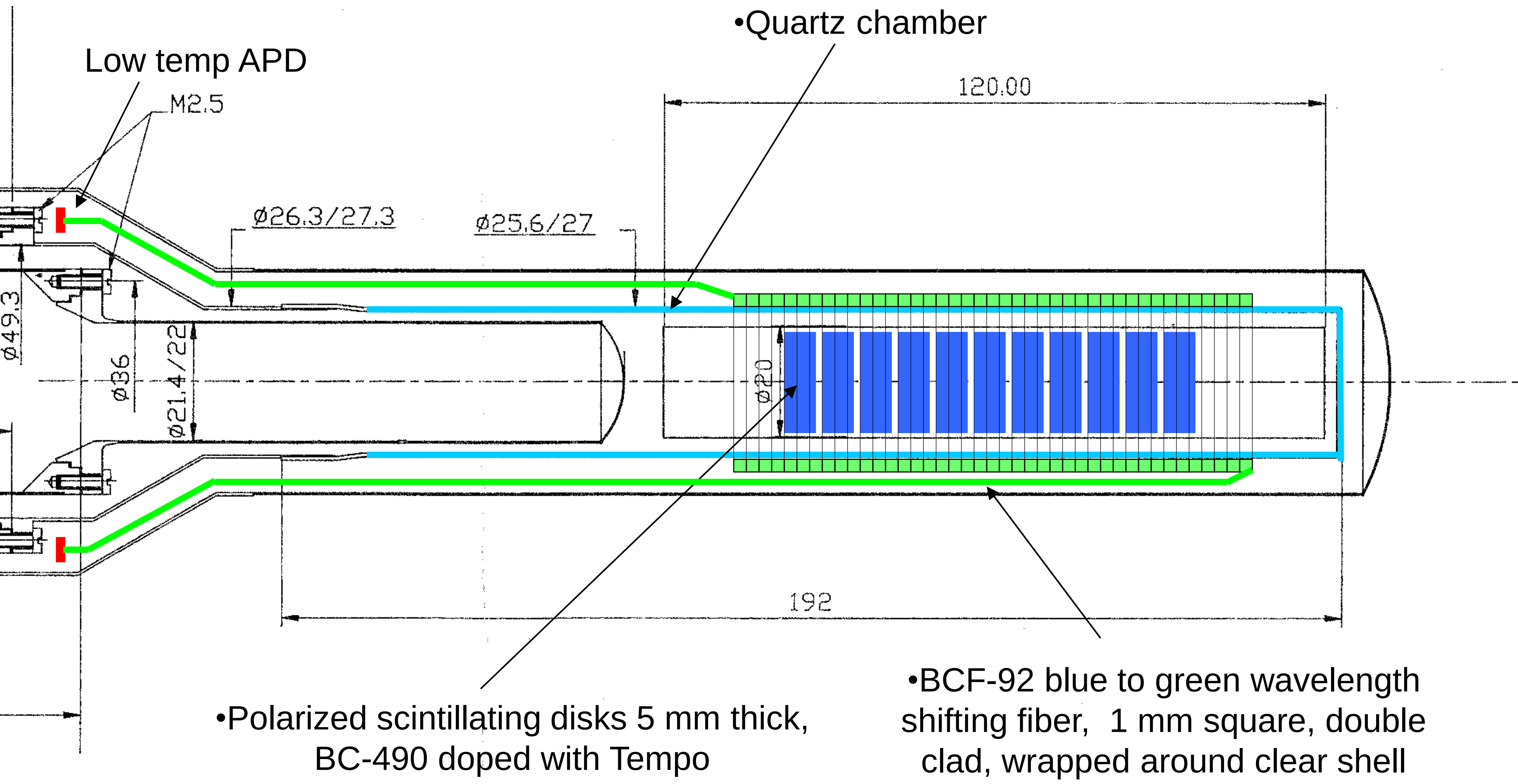


NN Weak Effective Field Theories

- Effective Field Theory approach: most general formulation for NN weak interaction consistent with QCD symmetries (Zhu et al 05)
- Can treat both strong and weak NN interaction consistently. "Pionless" (5 couplings) and "pionful" (6 couplings) versions available. Calculations in the NN system are in progress (Phillips, Schindler, Springer 09, Schindler, Springer arXiv:1305.4190)

Partial wave transition	I ⇔ I'	ΔI	n-n	n-p	p-p	Hybrid EFT coupling	Pionless EFT coupling
$^3S_1 \Leftrightarrow {}^3P_1$	0 ⇔ 1	1		✓		$m\rho_t$, C^π [$\sim f_\pi$]	$C\,(^3S_1 - {}^3P_1)$
$^3S_1 \Leftrightarrow {}^1P_1$	0 ⇔ 0	0		✓		$m\lambda_t$	$C(^3S_1 - {}^1P_1)$
$^1S_0 \Leftrightarrow {}^3P_0$	1 ⇔ 1	0	✓	✓	✓	$m\lambda_s^{nn}$	$C\,(^1S_0 - {}^3P_0, \Delta I=0)$
$^1S_0 \Leftrightarrow {}^3P_0$	1 ⇔ 1	1	✓		✓	$m\lambda_s^{np}$	$C\,(^1S_0 - {}^3P_0, \Delta I=1)$
$^1S_0 \Leftrightarrow {}^3P_0$	1 ⇔ 1	2	✓	✓	✓	$m\lambda_s^{pp}$	$C(^1S_0 - {}^3P_0, \Delta I=2)$

•Light capture with wavelength shifting fibers



•Overall light transport efficiency ≈ 2%