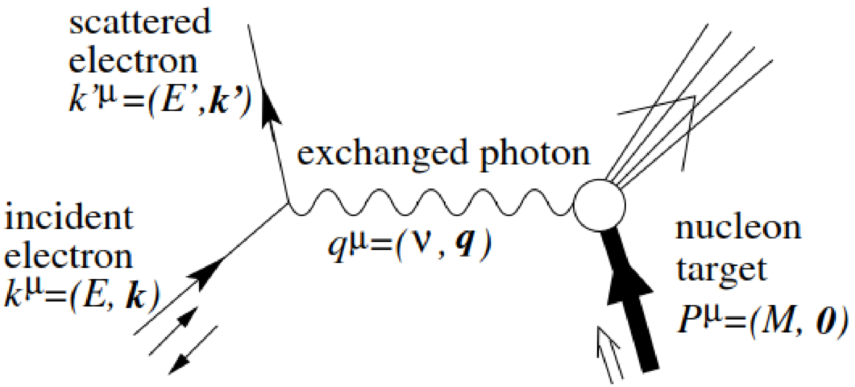
Experimental developments from JLab

Mark K Jones, Jefferson Lab

May 12 2023

Nucleon spin structure at low Q^2

Inclusive polarized electron scattering on longitudinally and perpendicularly polarized targets.



At low Q^2, the exchanged photon is a long range probe of nucleon.
Need non-perturbative QCD such as

- Lattice gauge theory
- Effective field theory

Spin observables on both proton and neutron provide stringent test of theory

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Spin Structure Functions and Sum rules

- With the helicity dependent cross sections, experiments can extract the g_1 and g_2 spin structure functions for protons and neutrons.

$$g_1 = \frac{MQ^2\nu}{4\alpha^2}\frac{E}{E'}\frac{1}{E+E'}\left[\Delta\sigma_{\parallel} + \tan\left(\frac{\theta}{2}\right)\Delta\sigma_{\perp}\right]$$

$$g_2 = \frac{MQ^2\nu}{8\alpha^2 E'(E+E')}\left[-\Delta\sigma_{\parallel} + \frac{E+E'\cos\ \theta}{E'\sin\ \theta}\Delta\sigma_{\perp}\right]$$

$$\Delta\sigma_{\parallel,\perp} = 2\sigma_0 A_{\parallel,\perp}$$

- Sum rules and moments of g_1 and g_2 can be a rigorous test of theories and relate the SSF to static properties of the nucleon.
- At low Q^2, sum rules are calculable in effective field theories of QCD.
- At infinite Q^2 , the Bjorken sum rule

$$\overline{\Gamma}_1^{p-n} \equiv \overline{\Gamma}_1^{p} - \overline{\Gamma}_1^{n} \equiv \int_0^{1^-}\left[g_1^p(x) - g_1^n(x)\right]dx = \frac{g_A}{6}$$

- Generalized GDH sum rule

$$\overline{\Gamma}_1^{p-n}(Q^2)\big|_{Q^2\to 0} = \frac{Q^2}{8}\left(\frac{\kappa_n^2}{M_n^2} - \frac{\kappa_p^2}{M_p^2}\right)$$

See talk by J.P. Chen

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Sum rules involving g_2

At high Q^2, d_2 is twist-3 matrix element which is related to quark-gluon-quark correlations

$$\overline{d_2}(Q^2) = \int_0^{x_0} x^2 \Big(2g_1(x,Q^2) + 3g_2(x,Q^2) \Big) dx$$

In general, d_2 has a twist-2 and twist-3 part, so need to measure of range of Q^2.

Another sum rule that is an important test of effective field theory calculations at low

$$\delta_{LT}(Q^2) = \frac{16\alpha M^2}{Q^6} \int_0^{x_0} x^2 \Big(g_1(x,Q^2) + g_2(x,Q^2) \Big) dx$$

See talks by D. Ruth and K. Slifer

Cohesive program in Hall A and B

- Experimental programs focused on going to as low Q^2 as possible with high precision to test effective field theories.

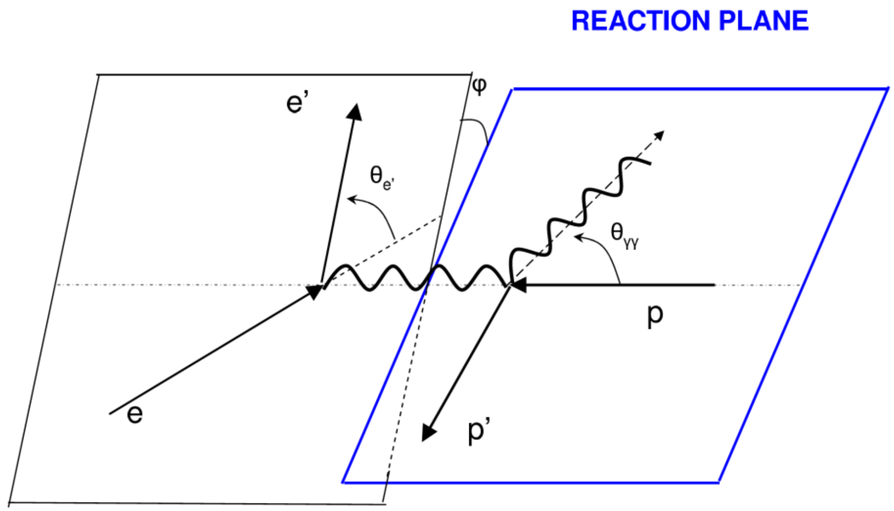
- Hall B has made measurements of inclusive polarized cross sections on longitudinally polarized protons and deuterons.

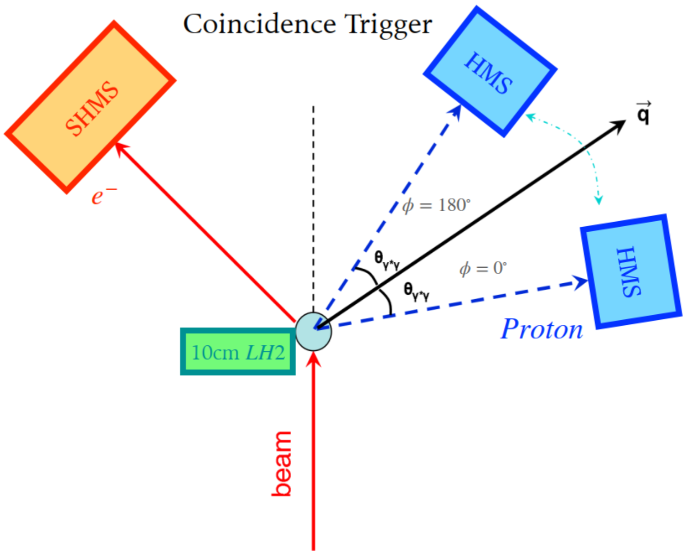
- Hall A focused on measurement of inclusive polarized cross sections on longitudinally and perpendicularly polarized protons and 3He.

- Determine the neutron SSF from deuteron or 3He have different systematics and is a necessary experimental test.

See talks by M. Ripani, C. Peng and A. Duer

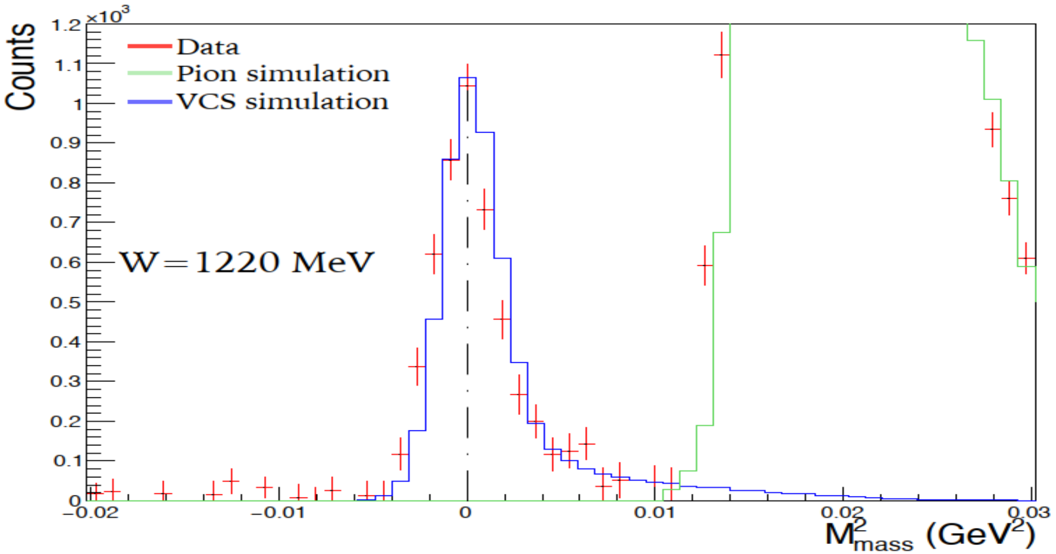
Virtual Compton Scattering in Hall C





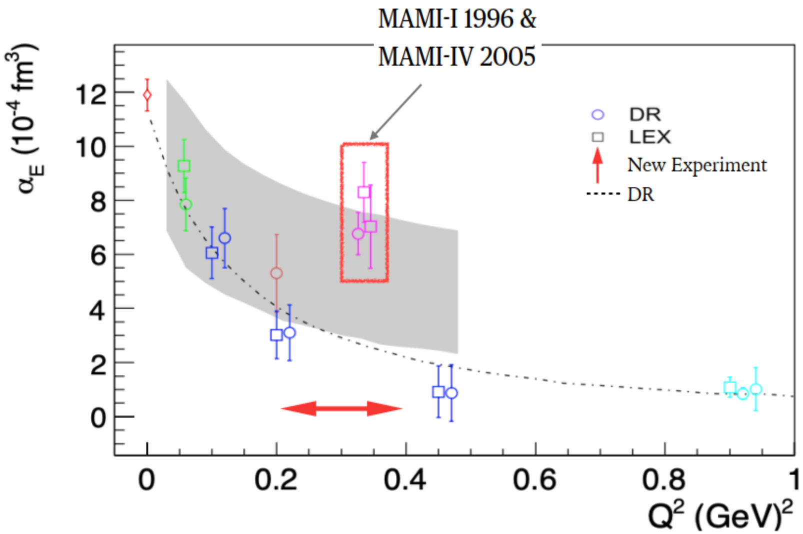
Calculate the missing mass to isolate the exclusive reaction

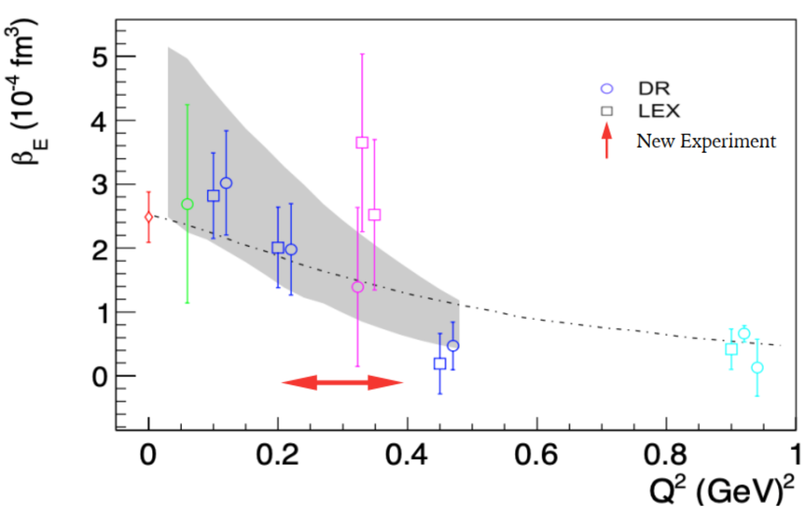
Determine cross sections for a range of Q^2, W, $\Theta_{\gamma\gamma}$ and ϕ bins



Virtual Compton Scattering in Hall C

- From fits to cross section data within the Dispersion Relation model
  Extract the generalized scalar electric α_E and magnetic β_M polarizabilities
- Measurements done at Q2 = 0.28, 0.33, 0.40 GeV^2
- See talk of N. Sparveris

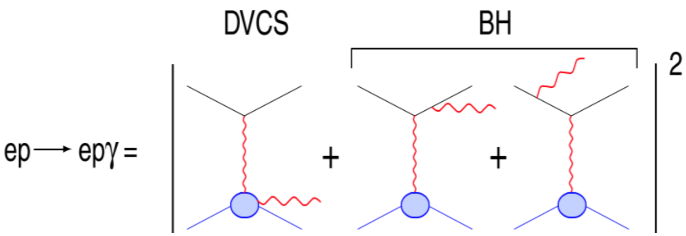




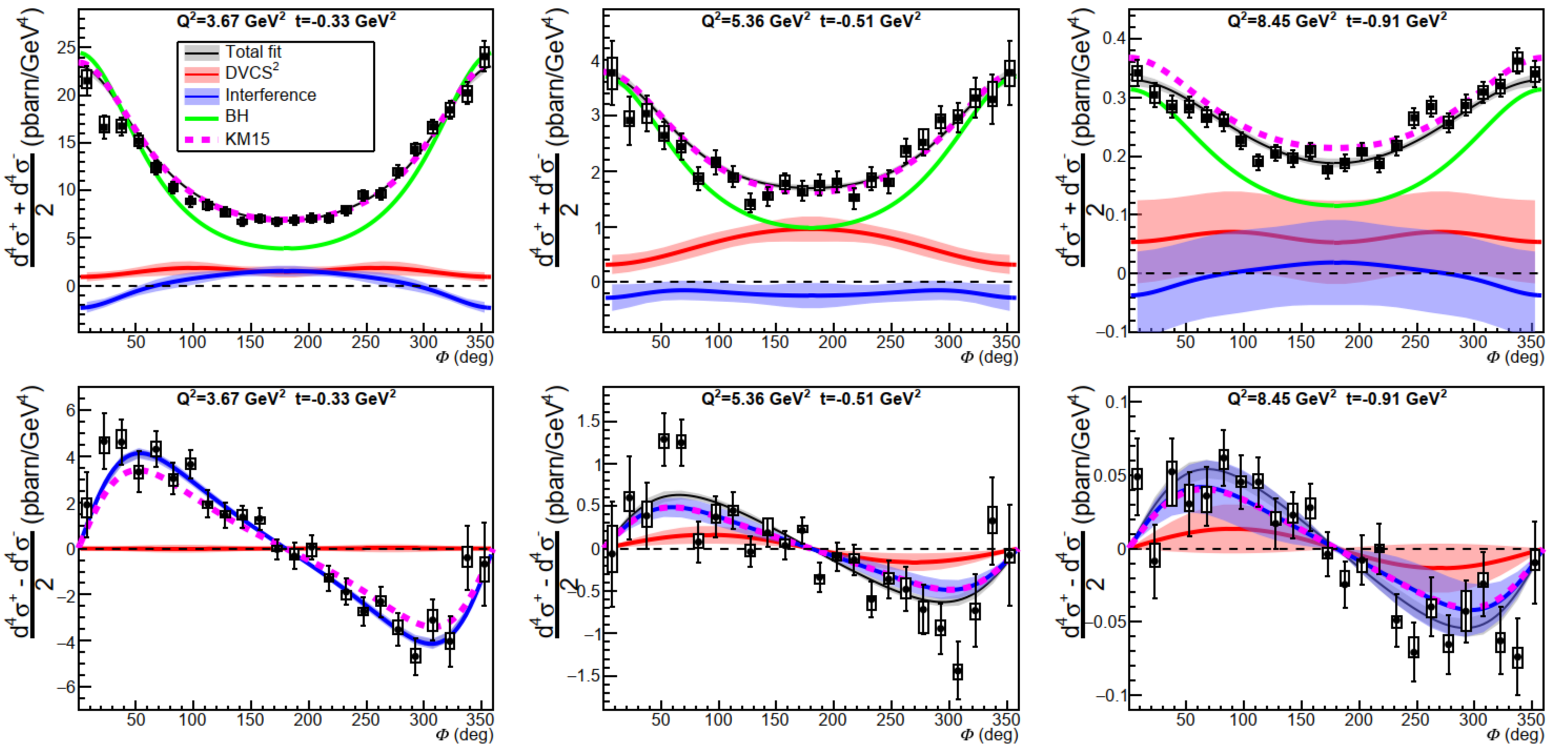
- Initial theoretical models predicted smooth fall off of α_E
  - data at $Q^2 = 0.33$ implies a non-trivial structure
- New experiment can:
  - Address puzzling α_E enhancement
  - Reduce error by 2

- Small values, 1/3 - 1/4 of α_E
- Large uncertainties
- New experiment can:
  - Improve precision
  - Explore para-& dia-magnetic mechanism inside nucleon

Deeply Virtual Compton Scattering in Hall A



GPDs enter the DVCS cross section through convolution integrals called Compton Form Factors (CFFs), whose real and imaginary parts can be separated using a polarized electron beam of varying energy and measuring both the helicity-dependent and the helicity-independent DVCS cross sections.



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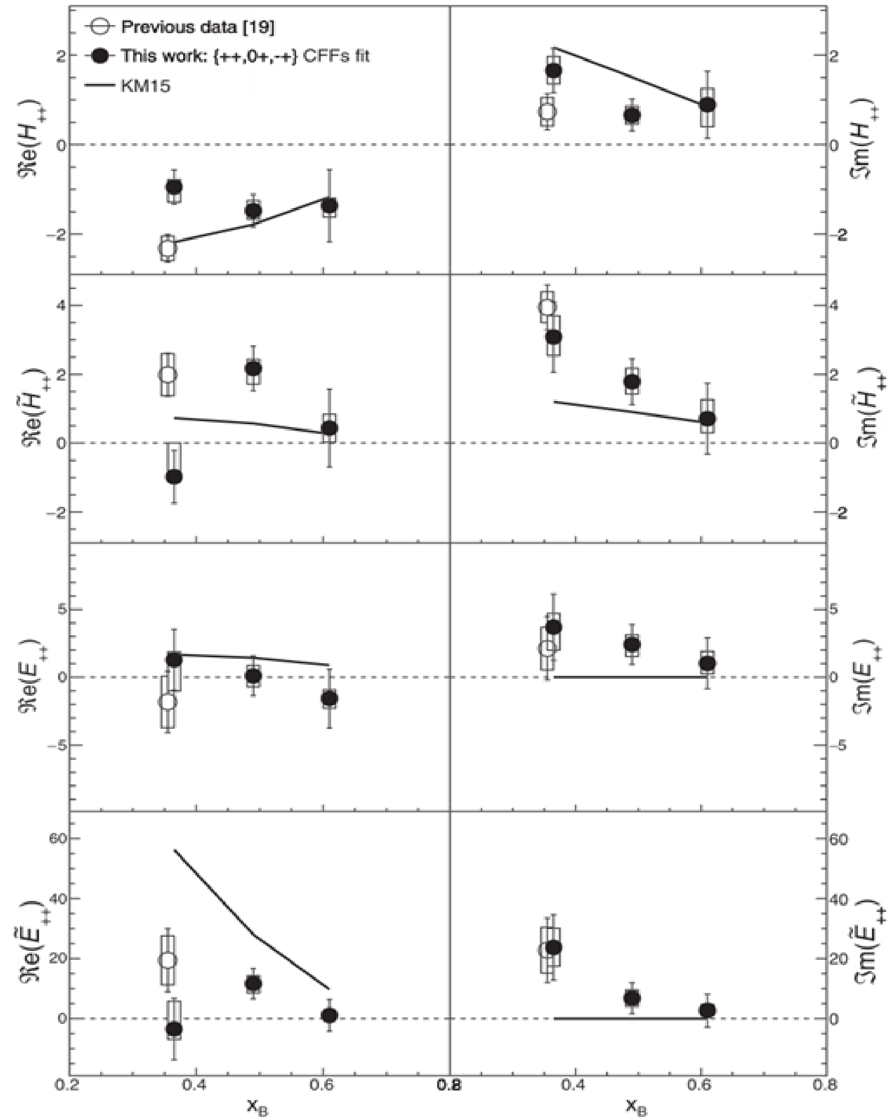
DVCS in Hall A

- Values of the helicity-conserving CFFs, averaged over t, as a function of X_B.
- Bars around the points indicate statistical uncertainty and boxes show the total systematic uncertainty.
- The fit results of previous data at X_B = 0.36 are displayed with the open markers.
- The solid lines show the KM15 GPD model. K. Kumericki and D. Muller, EPJ Web Conf. 112, 01012 (2016).
- Data published in Phys. Rev. Lett. **128**, 252002 (2022)



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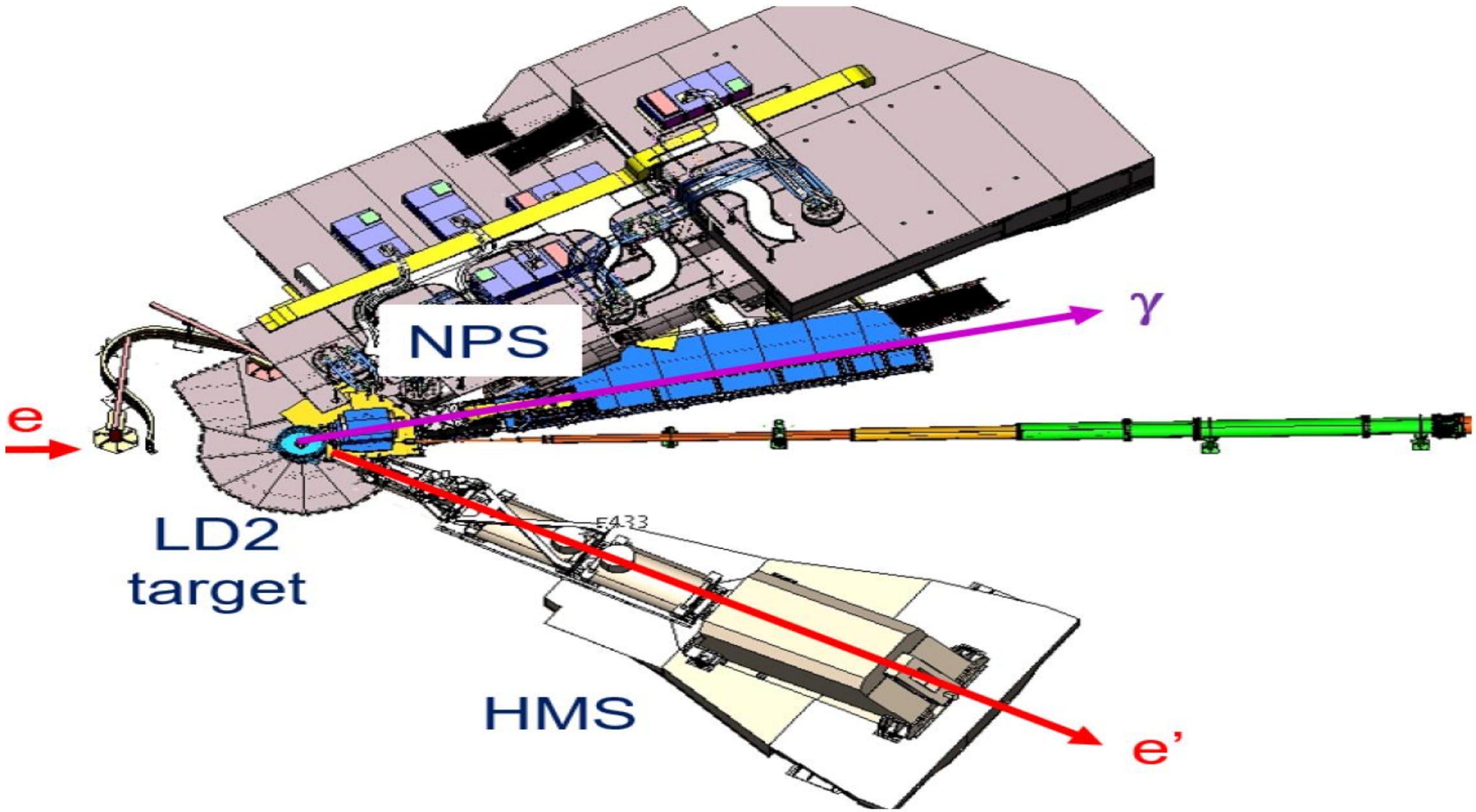
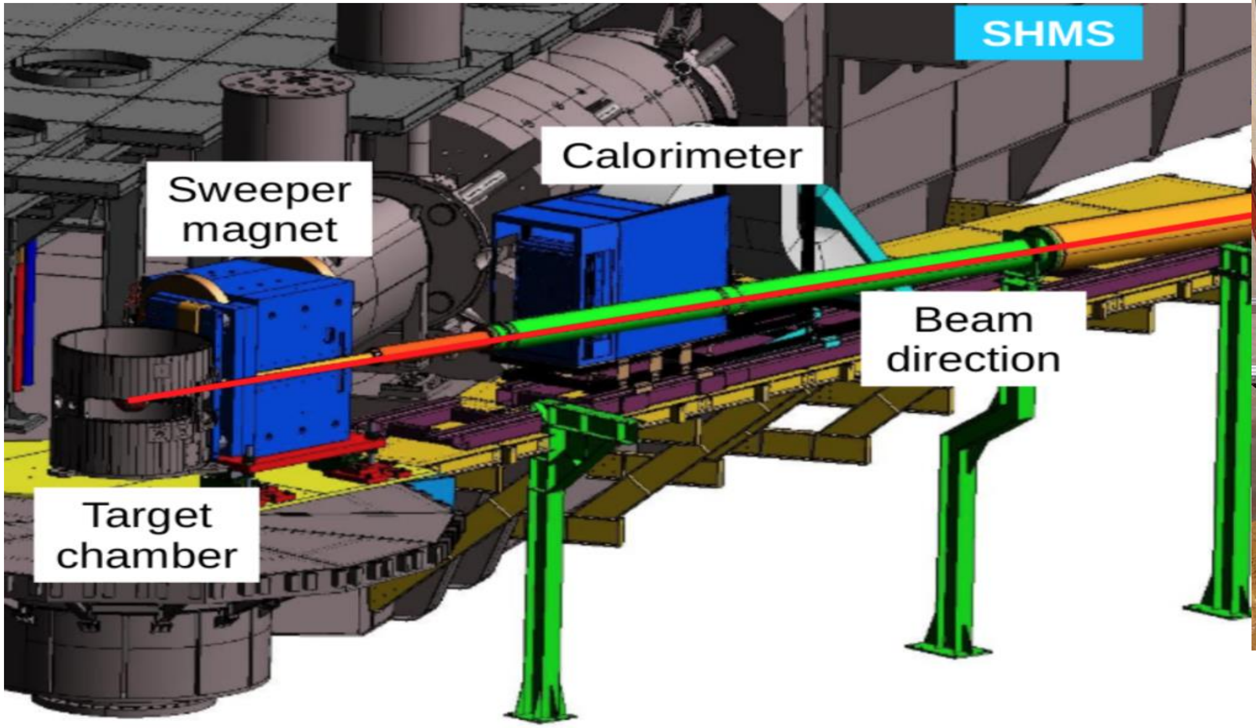
DVCS experiment in Hall C

- Experiments E12-13-010 and E12-22-006
  - Exclusive Deeply Virtual Compton on proton and deuteron
  - Subtract the proton data from deuteron data to get neutron.
  - Use 1080 block lead tungstate calorimeter for photon detection
  - HMS used for electron detection



DVCS experiment in Hall C

- Experiments E12-13-010 and E12-22-006
    - Presently being installed in Hall C
    - Will run from July 2023 to March 2024
    - Measure helicity dependent DVCS cross sections for XB for 0.2 to 0.6 and Q2 = 2 to 6 GeV



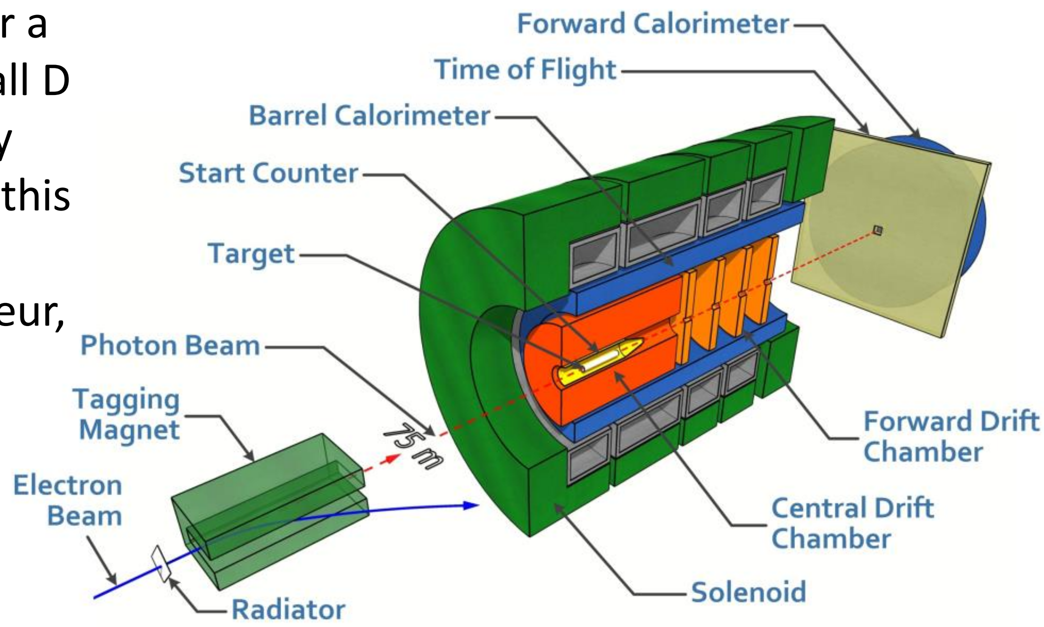
1080 Lead Tungstate calorimeter

High Energy contribution to the GDH sum rule

Proposed experiment in Hall D to measure the GDH sum rule on proton and neutron up to photon energy of 12 GeV

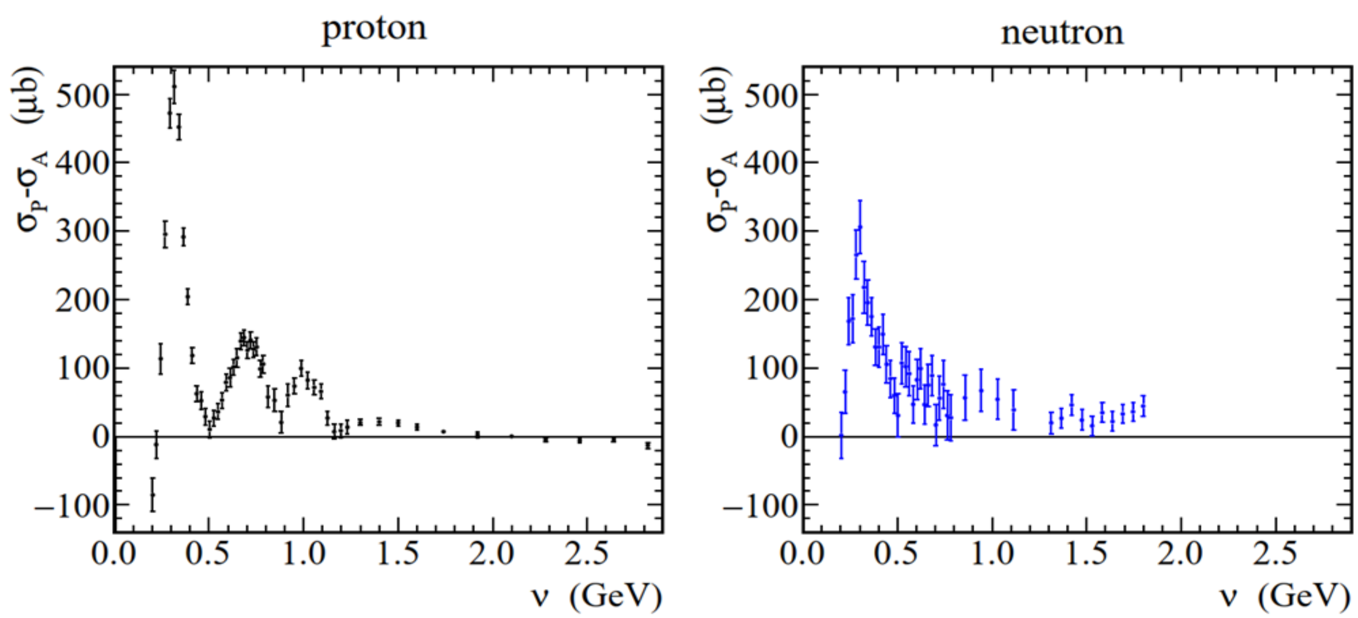
$$I \equiv \int_{\nu_0}^{\infty} \frac{\Delta\sigma(\nu)}{\nu}\, \mathrm{d}\nu = \frac{4\pi^2 S \alpha_{\mathrm{em}} \kappa^2}{M^2} \qquad \Delta\sigma \equiv \sigma_P - \sigma_A$$

- Construct a frozen-spin polarized target that can serve as the foundation for a new polarized target program in Hall D
- Above the resonance region usually Regge phenomenology is used but this has not been tested.
- Spokespersons: M. M. Dalton, A. Deur, C. D. Keith, S. Sirca and J. Stevens



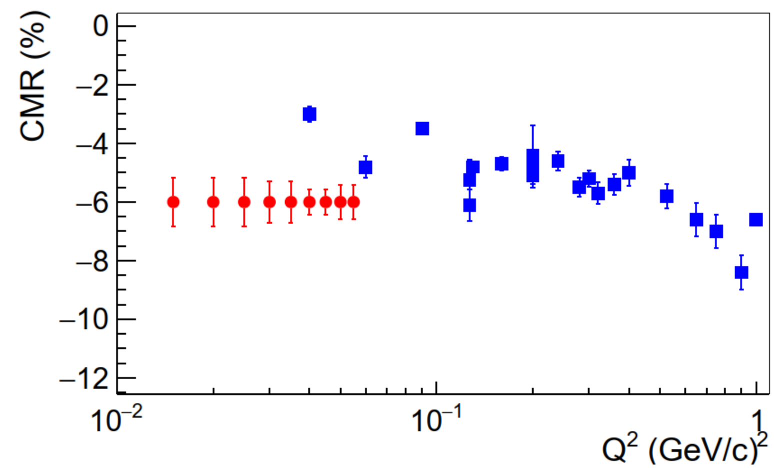
High Energy contribution to the GDH sum rule

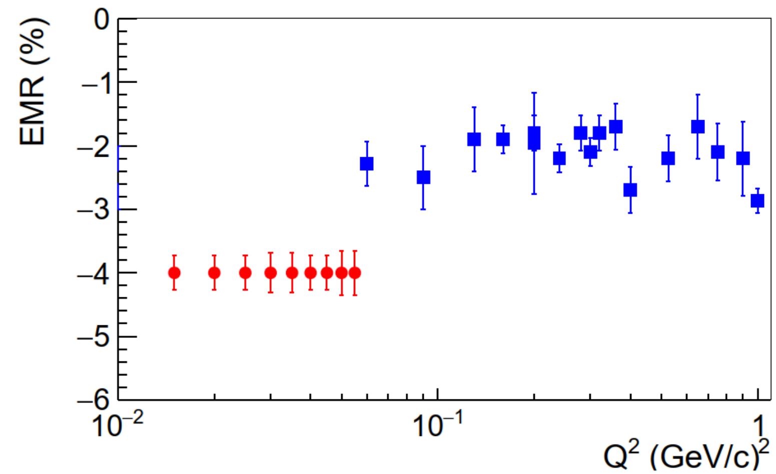
- The high-energy part is critical since it may reveal possible substructure or unknown structural processes
- The validity of the GDH sum rule on the neutron will be accurately tested for the first time, while for the proton the uncertainty will be improved by 25% relative.
- The first thrust is to verify that the GDH integral converges to a finite value.
- The data will allow precision testing of Regge phenomenology in the polarized domain.
- Chiral effective field theory will also be tested in a different regime than that covered by the low-Q^2 Jlab spin sum rule program.



N → Δ transition form factors at low Q^2

In Hall C, absolute cross sections and azimuthal asymmetry cross section measurements for the p(e,e′ p)π° reaction will be made at the Δ(1232) resonance region for Q^2 between 0.015 to 0.055 $(GeV/c)^2$.





N → Δ transition form factors the resonant quadrupole amplitudes $E^{3/2}_{1+}$ and $S^{3/2}_{1+}$ (or E2 and C2 photon absorption multipoles respectively) be extracted from fits to the cross section and the asymmetry measurements. Dominated by the M1 transition

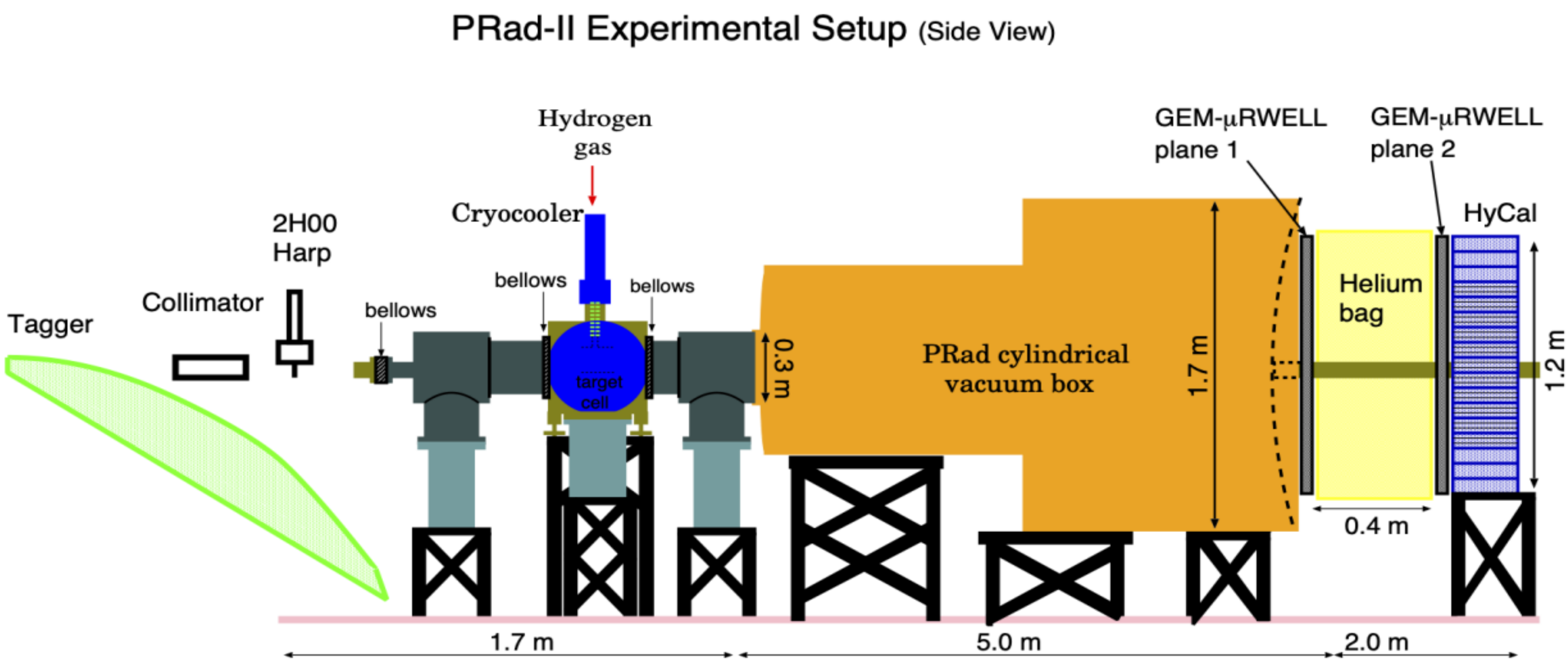
The proposed experiment will focus on a region where the mesonic cloud dynamics are dominant and rapidly changing

See talk of M. Paolone

Jefferson Lab

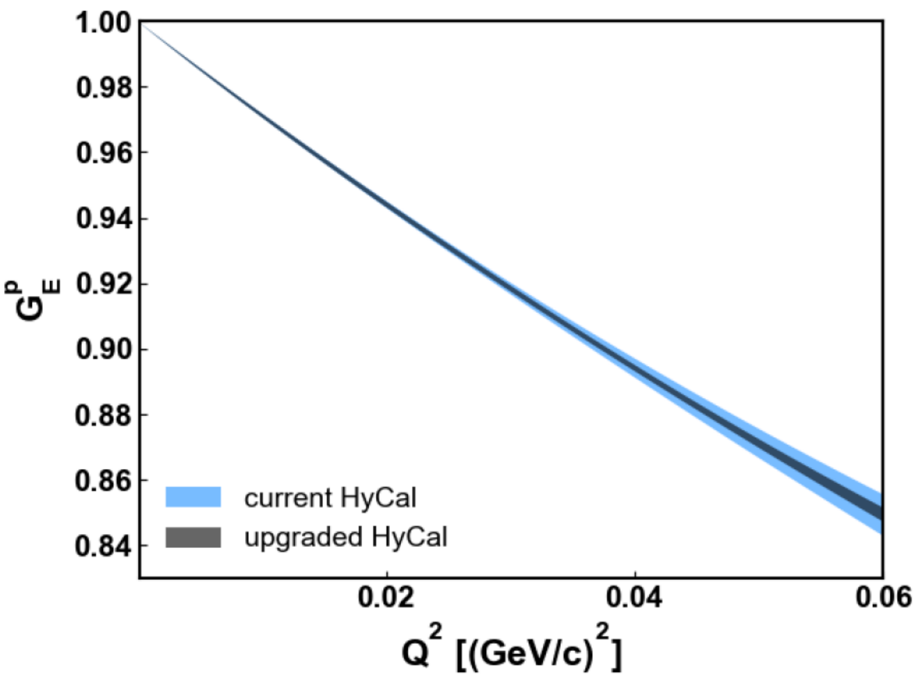
Proton radius with PRAD2 in Hall B

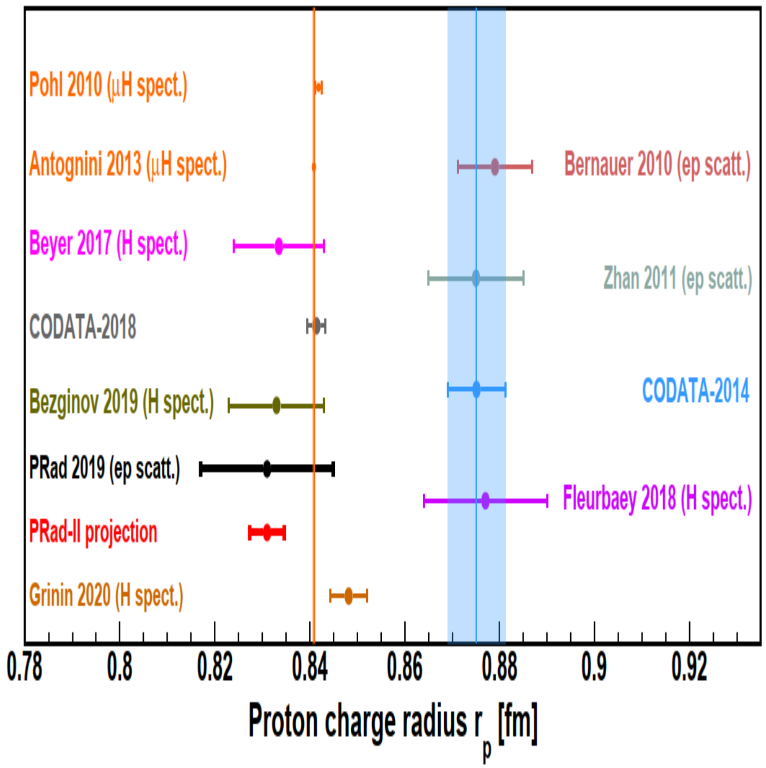
- Extend the low Q^2 reach to 10^{-5}
- Scintillator detector at 25cm
- 2^{nd} plane of tracking detectors
- All lead-tungstate calorimeter
- Upgrade front end electronics



Proton radius with PRAD2 in Hall B

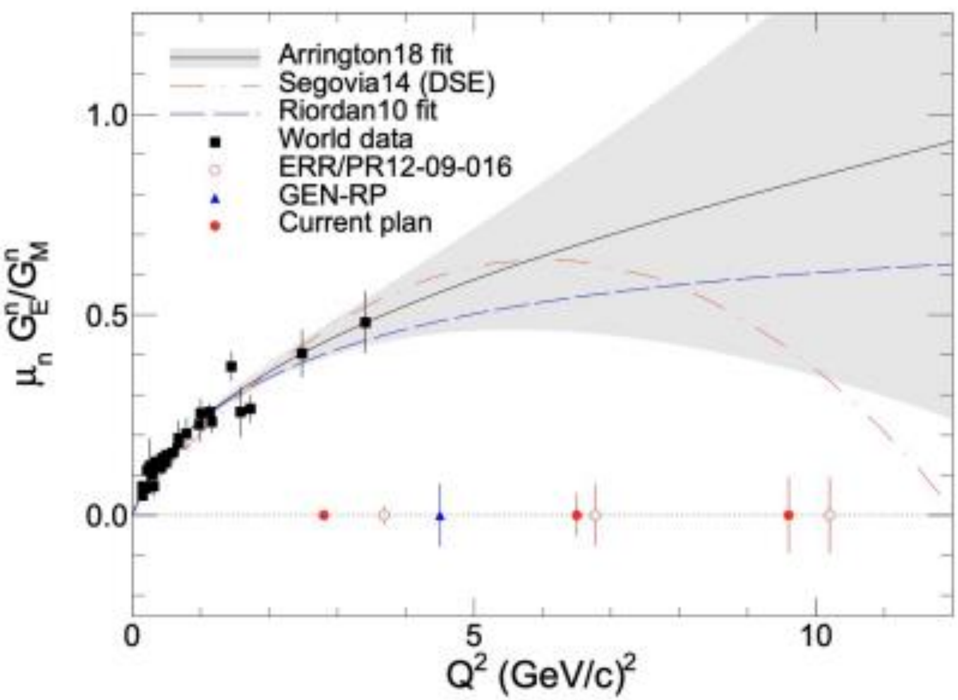
- Physics goals of precision proton radius measurements
  - Essential understanding how strong interactions work in the confinement region
  - Calculations of the energy levels and transition energies of the hydrogen atom
  - major impact determination of fundamental constants (i.e. Rydberg constant)
  - Motivate Lattice QCD predictions
  - New physics searches such as the violation of lepton universality
- See talks of J. Bernauer and D. Higinbotham

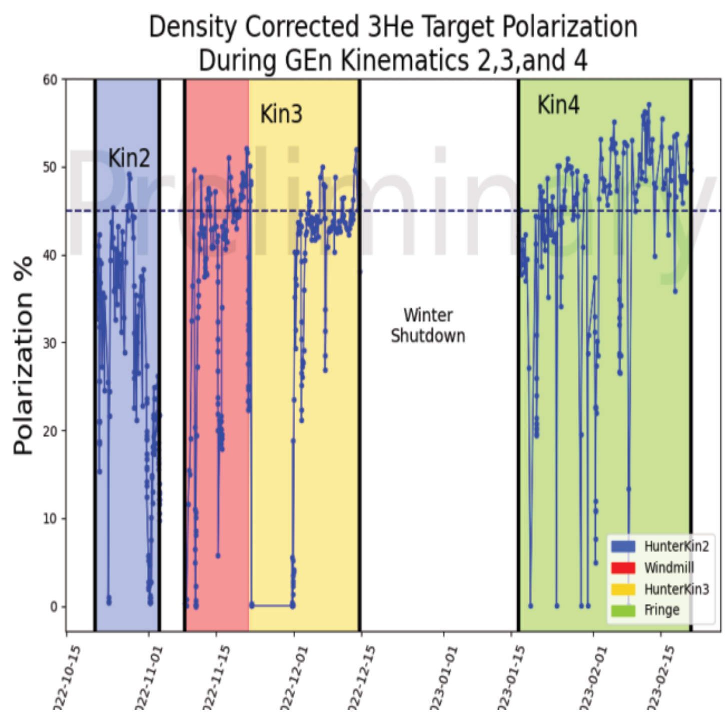




GEn using polarized helium target

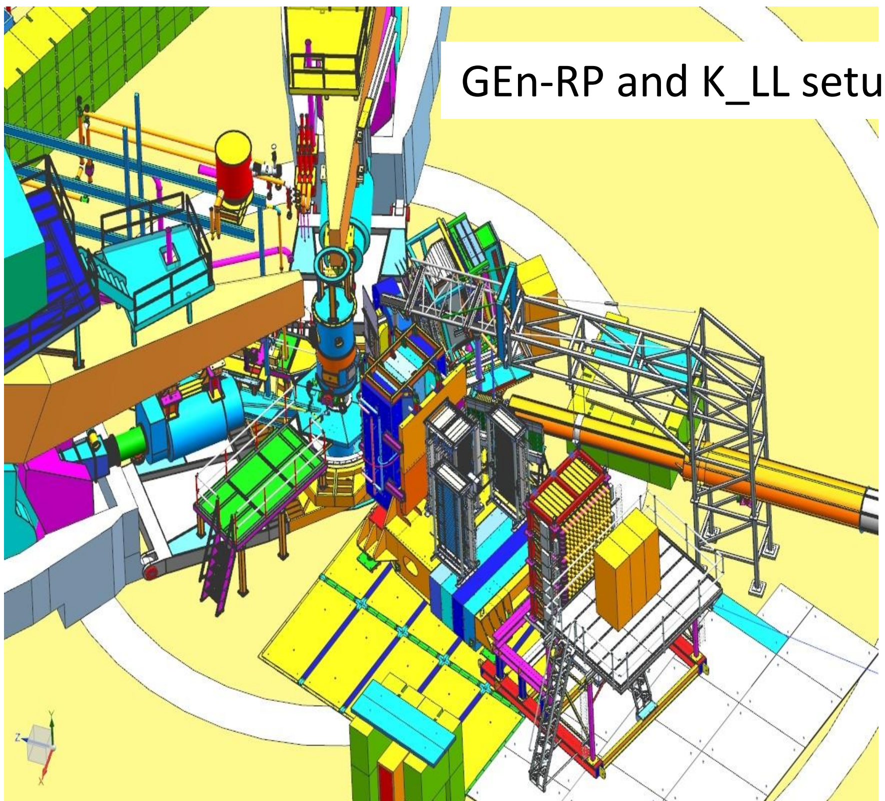
- Started running the experiment at beginning of Oct 2022
- First time running with 60cm long 3He cell
  - 45-50% polarization in beam!
- Completed the $Q^2 = 3.0$ and 6.8 kinematics by Dec 2022.
- Started the $Q^2 = 9.9$ kinematics in Jan to March 2023.
  - Only got 50C out of needed 157C.
  - Continue GEn experiment running in Aug-Sept 2023.





GEn and K_LL in Feb 2024

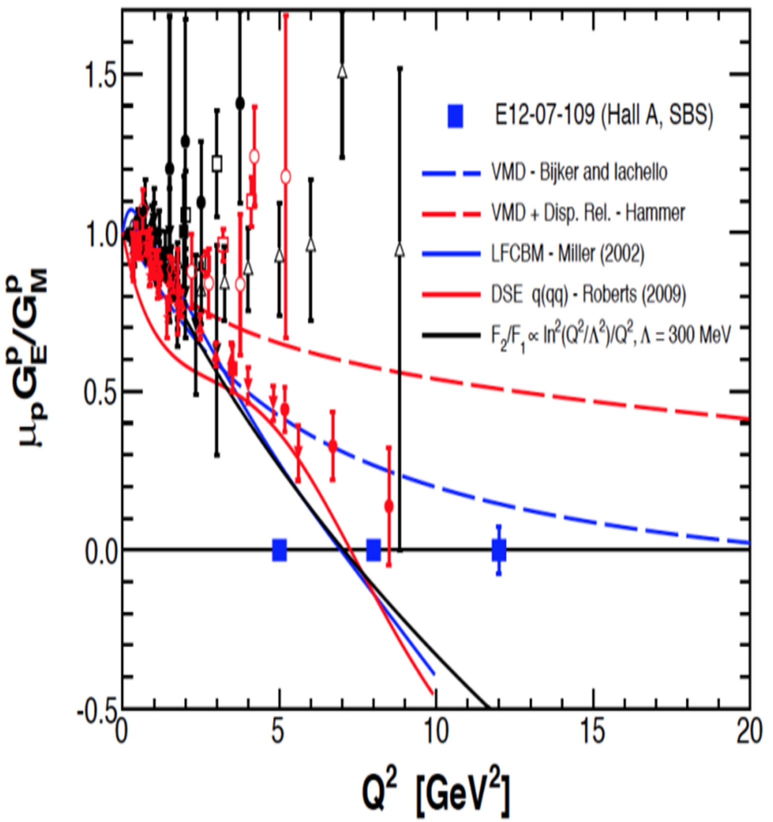
- Measurement of the Ratio GEn/GMn by the Double-polarized $^{2}\mathrm{H}(\vec{e},e'\vec{\pi})$ Reaction
  - Outgoing neutron polarization measured by charge exchange
  - Additional polarization measurement using the side detectors
- Polarization Transfer in Wide-Angle Charged Pion Photoproduction (K_LL)

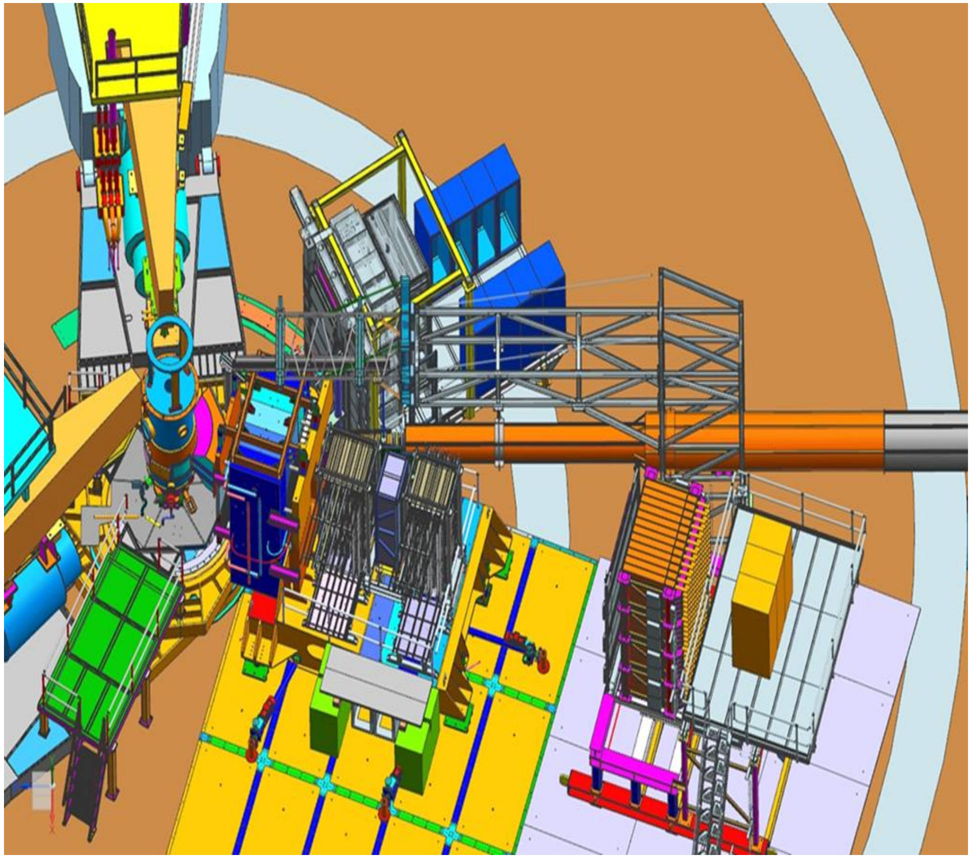

GEn-RP and K_LL setup

Inline SBS GEMs installed and used in GEn.

GEp experiment

- Measure the GEp/GMp ratio the recoil polarization observables P_T/P_L
- Installation begins in March 2024 and ends Aug 2024
- Experiment runs from Aug 2024 to Dec 2024
- Measure to Q^2 = 12





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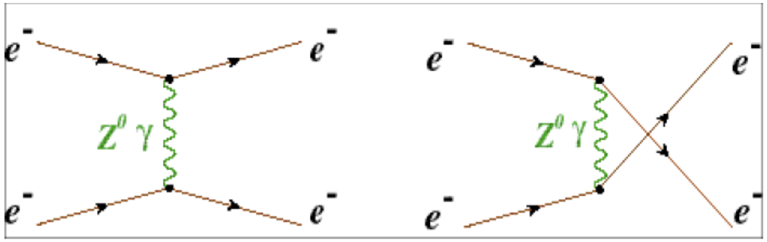
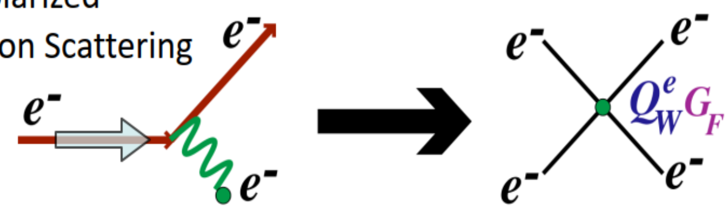
MOLLER Experiment in Hall A at Jefferson Lab

Measure parity violating asymmetry in Moller scattering at Q^2 of 0.0056 GeV^2



Fixed Target Polarized
Electron-Electron Scattering



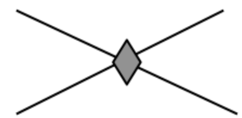
$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}Q^e_W$$

$$Q^e_W = 1 - 4\sin^2\theta_W \sim 0.075$$

11 GeV, 65 μA   90% beam polarization

A_{PV} ~ 32 ppb   δ(A_{PV}) ~ 0.8 ppb

$\delta(Q^e_W) = \pm 2.1$ % (stat.) ± 1.1 % (syst.)



$$+ \quad \frac{1}{\Lambda^2}\mathcal{L}_6$$

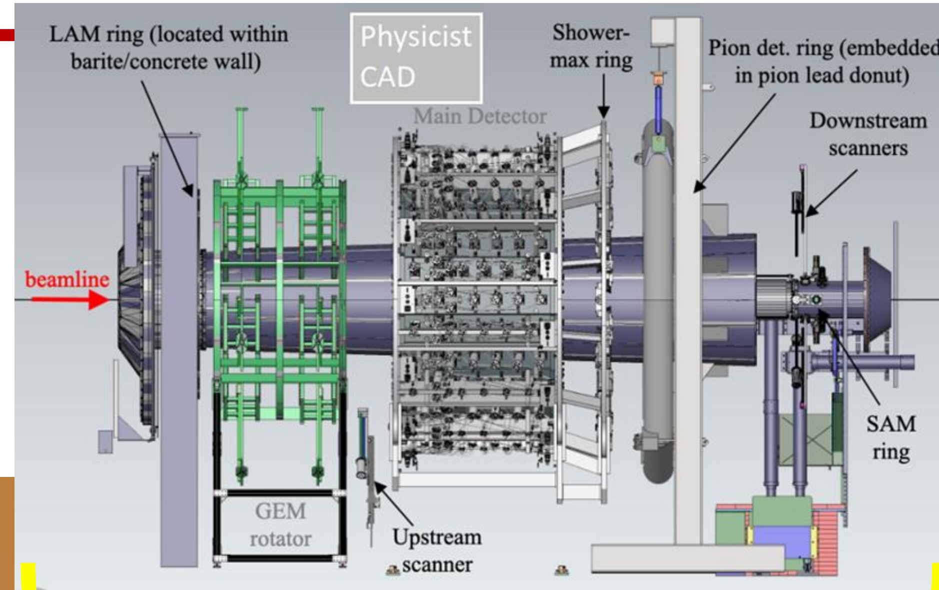
New Physics

$$\mathcal{L}_{e_1 e_2} = \sum_{i,j=L,R} \frac{g_{ij}^2}{2\Lambda^2}\bar{e}_i\gamma_\mu e_i \bar{e}_j\gamma^\mu e_j$$

$$\frac{\Lambda}{\sqrt{|g_{RR}^2 - g_{LL}^2|}} = 7.5 \text{ TeV}$$

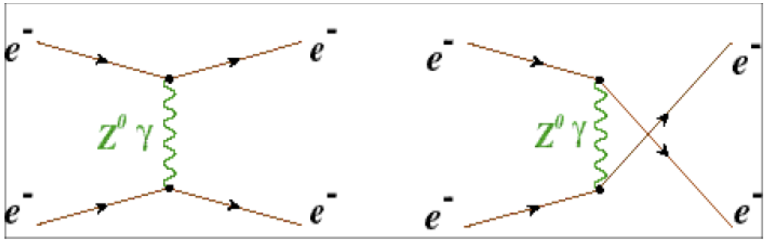
MOLLER Experiment Overview

- Full funding in Fall 2022.
- Passed Cd-3A review and spending CD-3A funds.
- CD2 /CD3 review in October.
- Aggressive installation schedule of 15 months after GEp run end in 2025
- 3 years of running from 2026-2029.



MOLLER Experiment

Measure parity violating asymmetry in Moller scattering at Q^2 of 0.0056 GeV^2



Fixed Targe
Electron-El

$$A_{PV} = \frac{\sigma_R - \sigma_L}{\sigma_R + \sigma_L} = -mE\frac{G_F}{\sqrt{2}\pi\alpha}\frac{16\sin^2\Theta}{(3+\cos^2\Theta)^2}Q_W^e$$

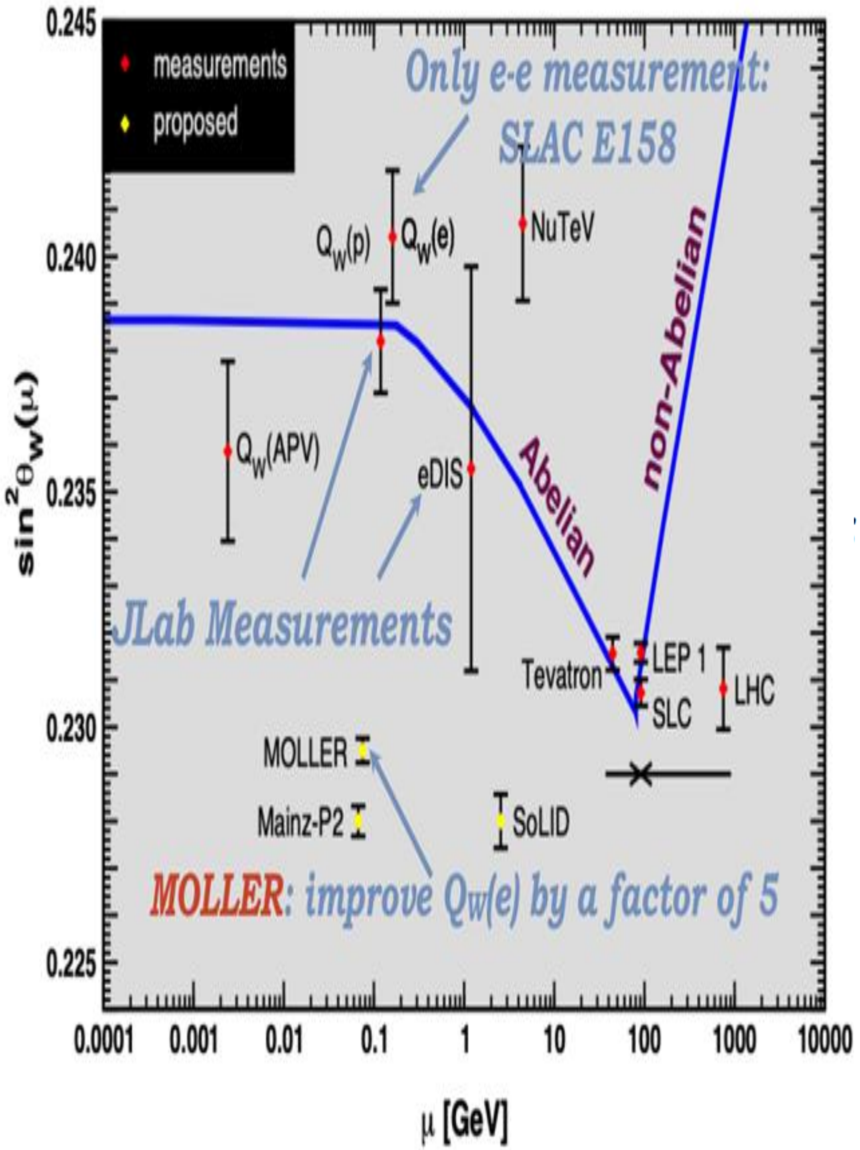
11 GeV, 65 μA 90% beam polarization

A_{PV} ~ 32 ppb $\delta(A_{PV})$ ~ 0.8 ppb

$\delta(Q^e_W) = \pm 2.1\ \%\ (stat.) \pm 1.1\ \%\ (syst.)$

$\delta(\sin^2\theta_W) = \pm 0.00023\ (stat.) \pm 0.00012\ (syst.)$

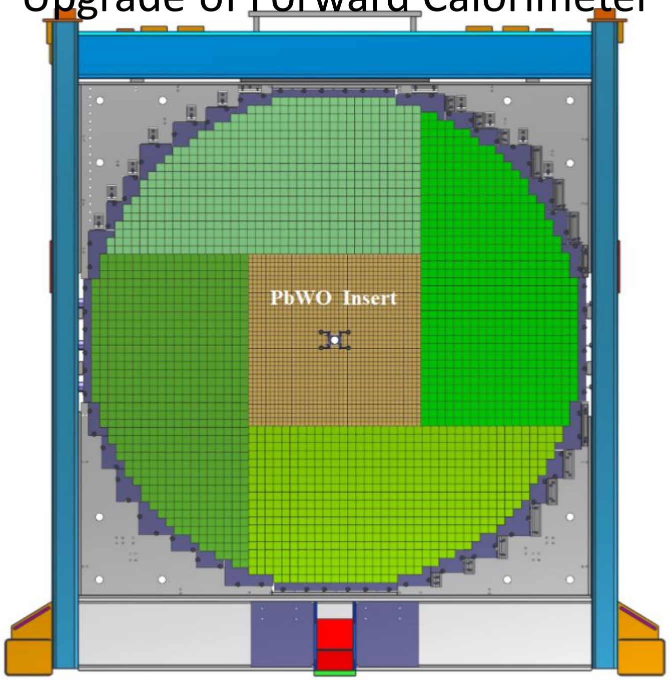
→ ~ 0.1%

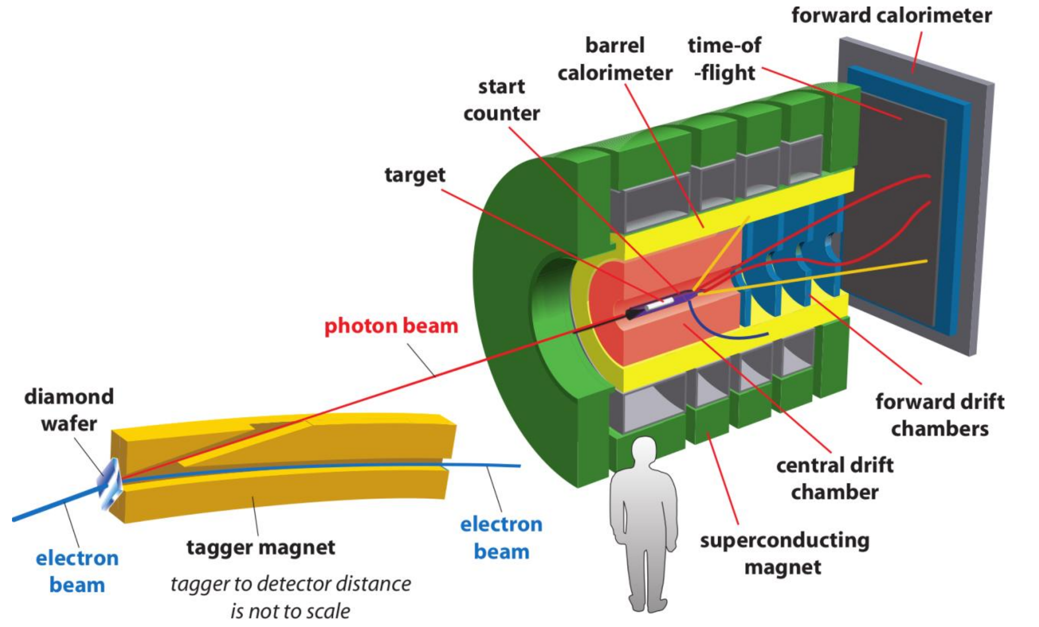


Jefferson Lab Eta Factory (JEF) in Hall D

- Eta and Eta' mesons will be produced in the reaction $\gamma + p \rightarrow eta(') + p$,
- Detection of photons and leptons originating from eta(') decays is performed by the forward and barrel calorimeters.
- Used for charged and neutral pion polarizability experiments (see talk of I. Larin)

Upgrade of Forward Calorimeter





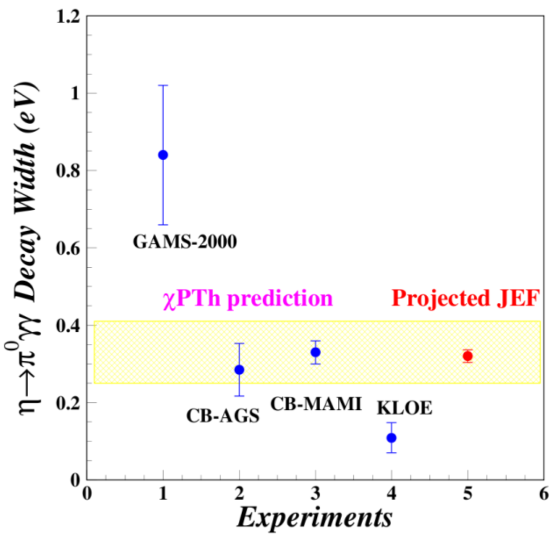
Figures from A. Somov in 10th Int. Workshop on Chiral Dynamics

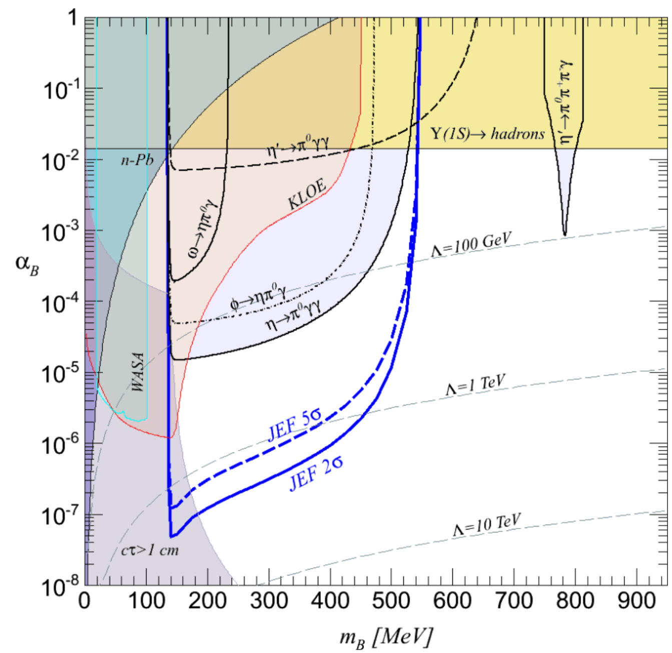
Jefferson Lab Eta Factory (JEF) in Hall D

Eta is one of the Goldstone bosons that arises from spontaneous symmetry breaking of QCD.

<u>Goals:</u>

- Constraining the light quark mass ratio.
- Directly constraining new C-violating/Parity-conserving physics.
- Probing the interplay of vector meson dominance and scalar resonances in Chiral Perturbation Theory at O(p6).
- Searching for a dark B−boson in the channel B → $\pi^0\gamma$.





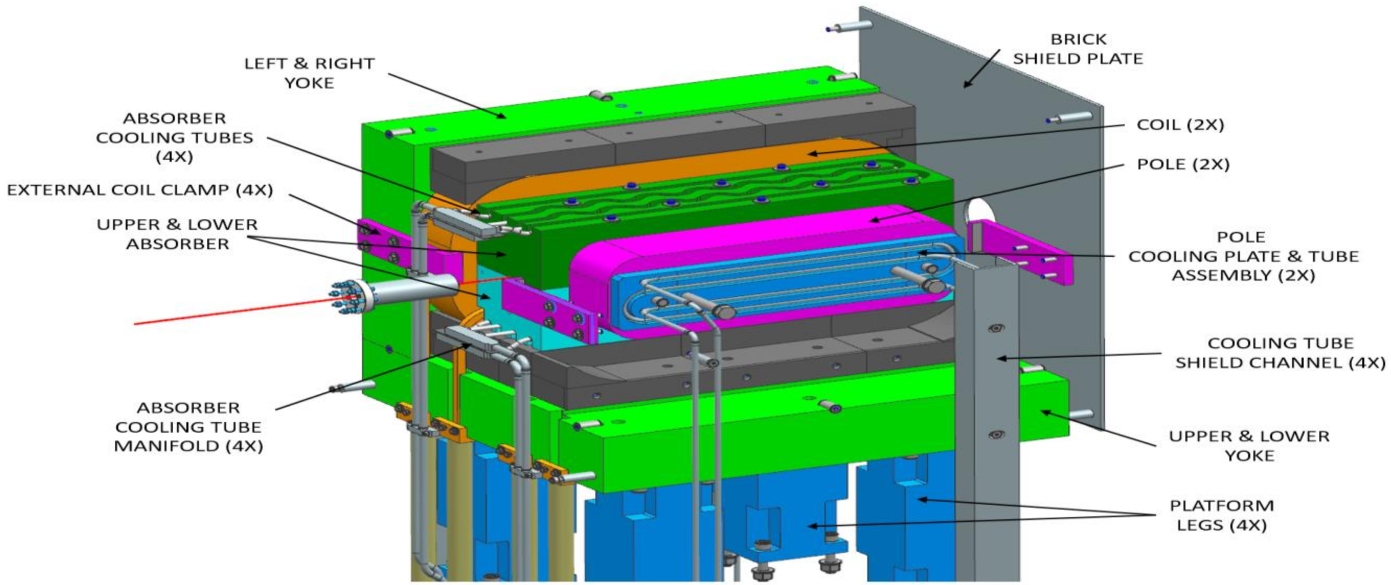
Plots from S. Taylor in 9th Int. Workshop on Chiral Dynamics

The Compact Photon Source in Hall C

An intense pure polarized photon beam will be produced from a 10% radiator at a distance of 2 m from the target and separated from the post radiator electron beam by employing a novel hermetic magnet-dump

The CPS provides a compact solution with a photon flux of 1.5×10^{12} equivalent photons/s.

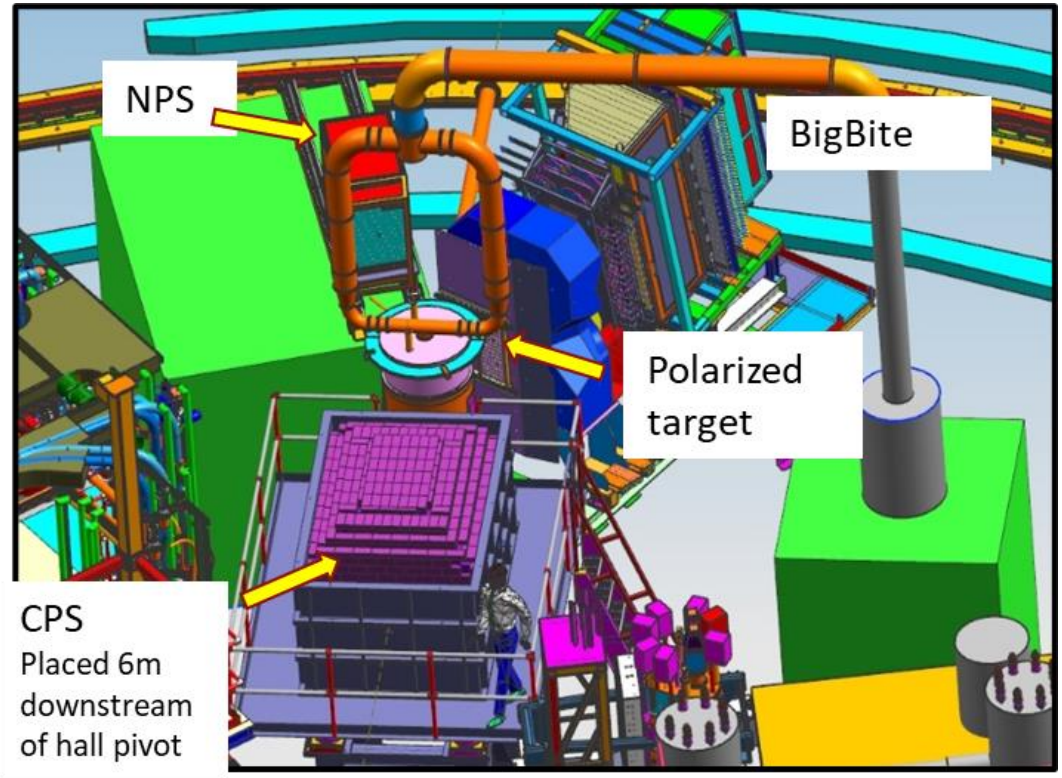
Details of CPS magnet



Nucl. Instrum. Meth. **A957**, 163429 (2020)

WACS using the CPS

- Measures the initial-state helicity correlation observables A_{LL} and A_{LS} in Wide-Angle Compton Scattering (WACS)
- A circularly polarized photon beam incident on a polarized proton target at invariant s in the range of 9 to 20 GeV^2 and scattering angles of $\theta_{cm}^{p} = 70^{\circ}$, 90° and 110°.



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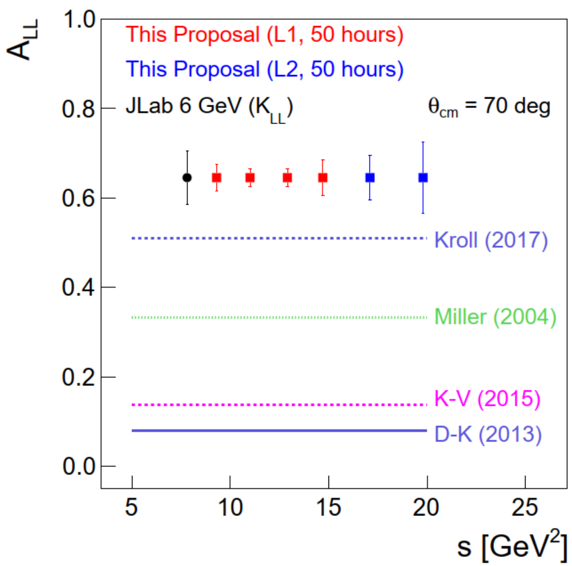
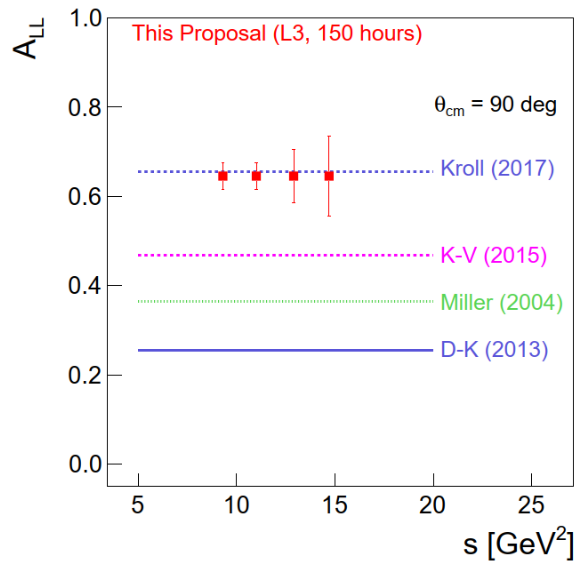
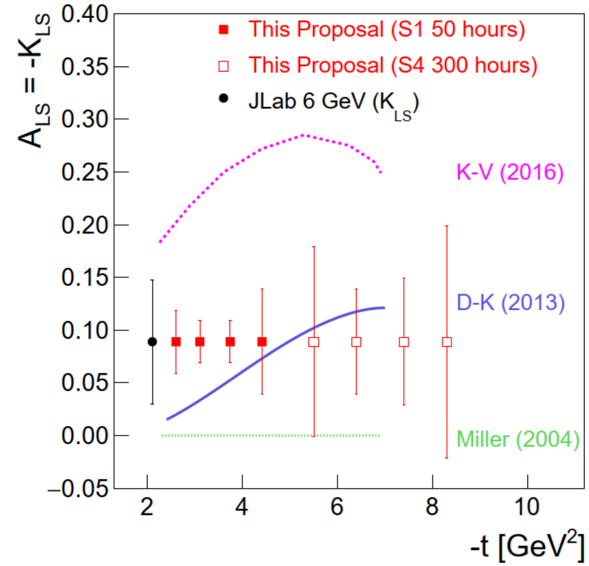
WACS proposed results

$$A_{LL}\frac{d\sigma}{dt} \equiv \frac{1}{2}\left[\frac{d\sigma(\uparrow\uparrow)}{dt} - \frac{d\sigma((\downarrow\uparrow)}{dt}\right] \qquad A_{LS}\frac{d\sigma}{dt} \equiv \frac{1}{2}\left[\frac{d\sigma(\uparrow\rightarrow)}{dt} - \frac{d\sigma(\downarrow\rightarrow)}{dt}\right]$$







Kivel-Vanderhaeghen is Soft Collinear Effective Theory
Diehl-Kroll is GPD approach
Miller is Relativistic Constituent Quark Model
Kroll (2017) is updated GPD

Summary

- Highlighted some of the upcoming talks and topics for workshop
- Look forward to lively discussions

- The strong program of experiments in Hall A and Hall B at Jefferson Lab to measure proton and neutron spin structure functions.
  - Test of effective field theory of QCD
- Excellent example of the interaction between theory and experiment.
- Upgraded facilities in Hall D
  - Improved barrel calorimeter
  - Planned use of polarized proton and deuteron target
- New equipment in Hall C
  - NPS and associated calorimeter
  - Compact Photon Source