Nucleon Structure Studies in Hall A

Neutron Charge Form Factor

Deeply Virtual Compton Scattering

Low-Energy Tests of the Standard Model

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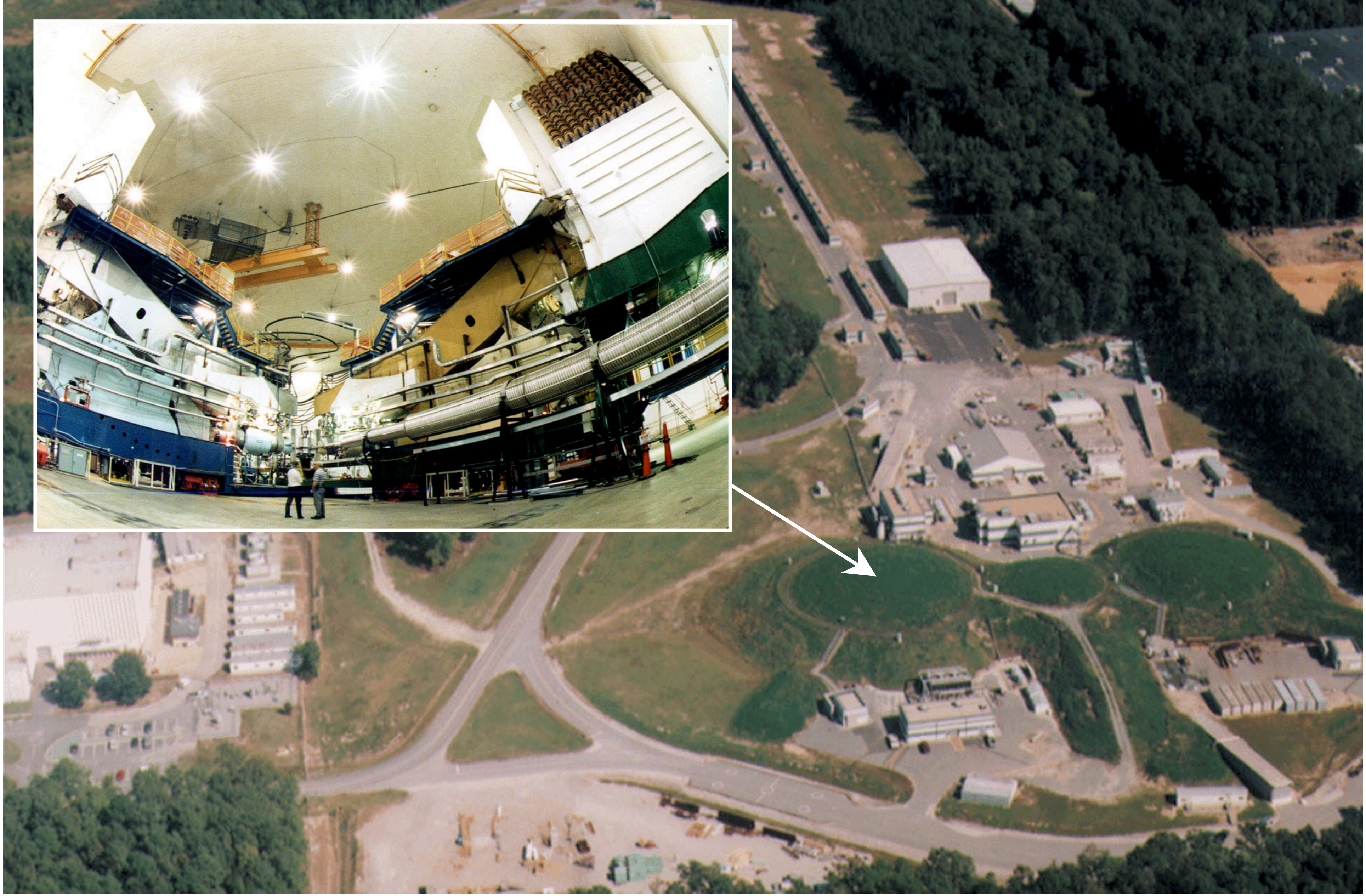
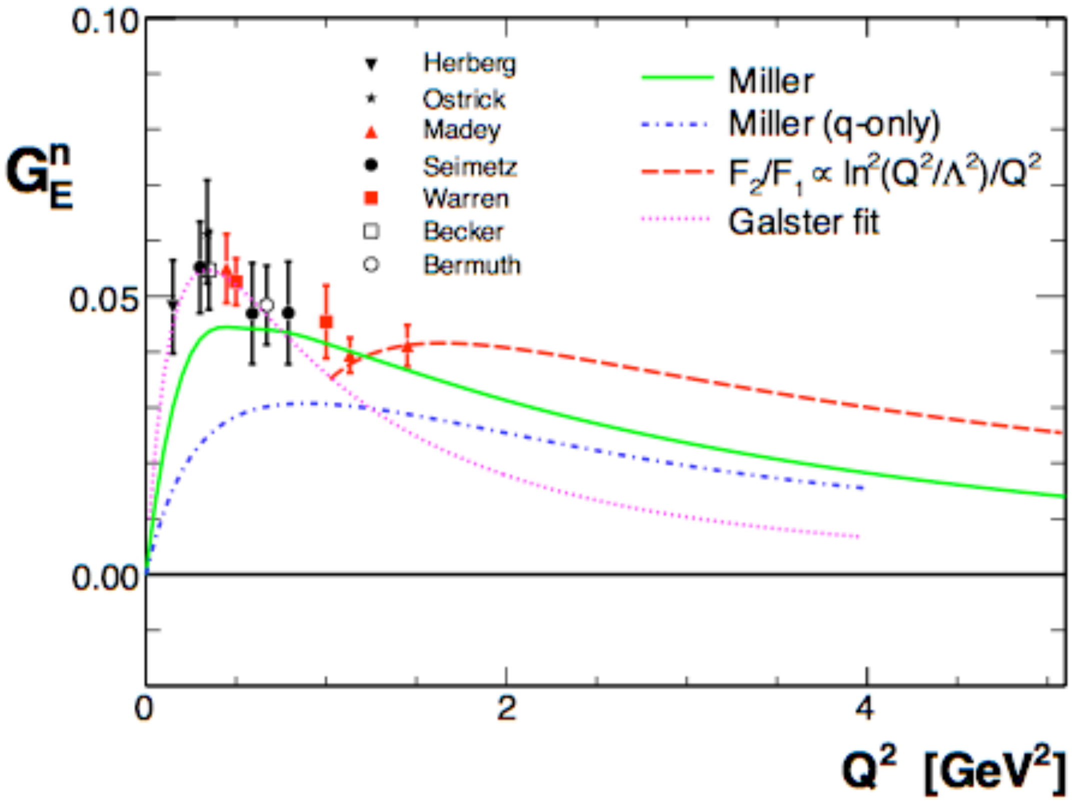
Hall A: Two High Resolution (10^{-4}) Spectrometers

Maximum luminosity 10^{38} $cm^{-2}s^{-1}$



Elastic EM Form Factors: the Neutron



- G_E^n more sensitive than other FF to details of the pion cloud at low Q^2
- G_E^n is not precisely measured above 1.5 GeV^2
- Permits disentanglement of F_2^n
- Provides access to Generalized Parton Distributions (GPDs)

$$F_1^n(t) = \frac{2}{3}F_1^u(t) - \frac{2}{3}F_1^d(t)$$

$$F_2^n(t) = \frac{2}{3}F_2^u(t) - \frac{2}{3}F_2^d(t)$$

$$F_1^q(t) = \int_{-1}^{+1} dx\ e_q H^q(x,\xi,t)$$

$$F_2^q(t) = \int_{-1}^{+1} dx\ e_q E^q(x,\xi,t)$$

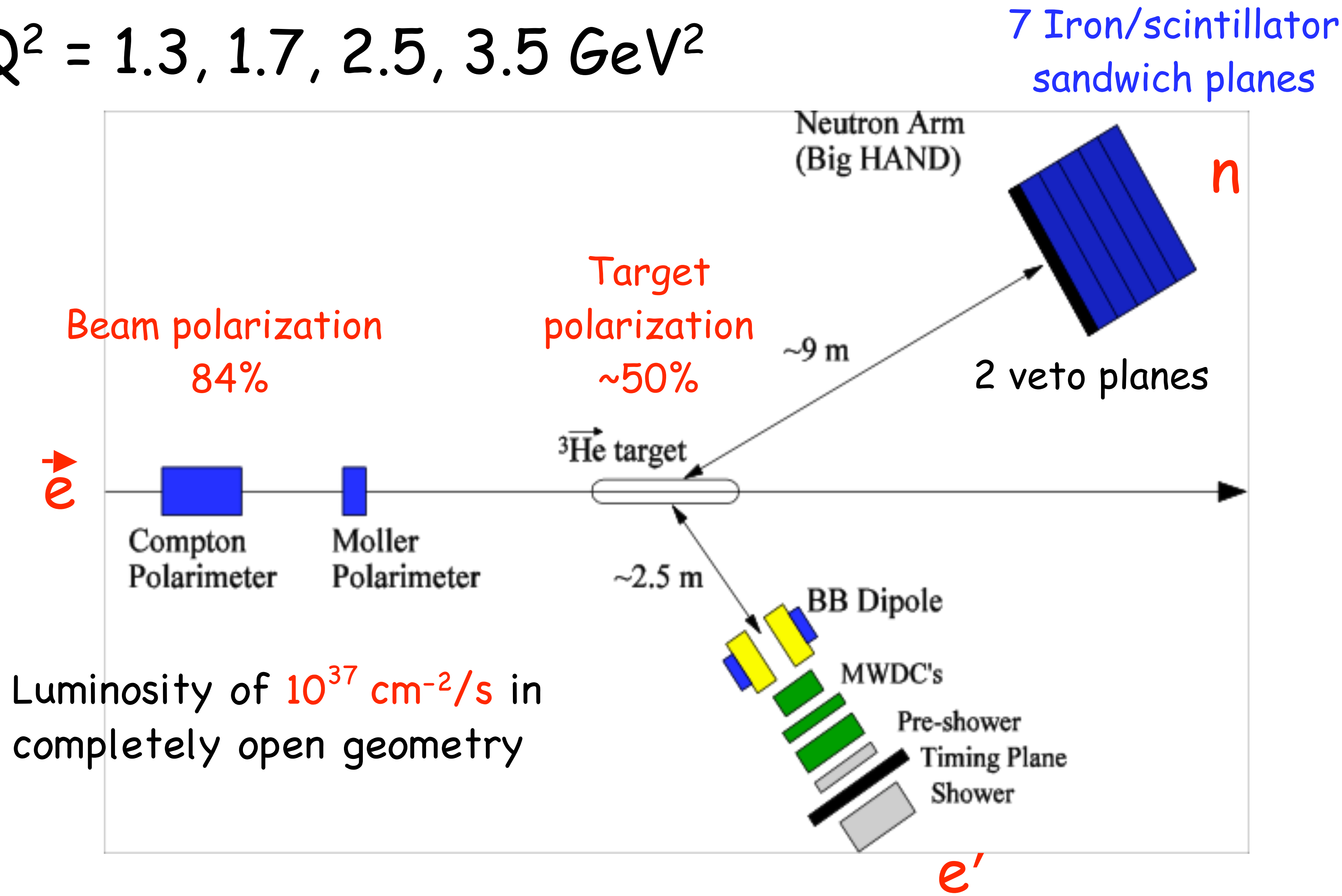
High Q^2 G_E^n

- ✓ Since 1984, when Blankleider & Woloshin first suggested $^3\vec{H}e(\vec{e},e'n)$, several experiments of this type have been performed at NIKHEF and Mainz for Q^2 up to 0.7 GeV^2, with large success in part due to new accurate 3-body calculations at low Q^2 (Gloeckle et al.)
- ✓ At Q^2 above 1-2 GeV^2 the Glauber method becomes sufficiently accurate (Sarksian)
- ✓ An electron-polarized neutron luminosity and the high polarization of the ^3He target made the measurement about 10 times more effective than with ND_3. In combination with a large acceptance electron spectrometer the total FOM enhancement is more than 100, which allows to reach a momentum transfer of 3.5 GeV^2

- Polarized target
- Electron spectrometer
- Neutron detector

Exclusive QE scattering: $^3\vec{He}(\vec{e},e'n)$

$Q^2 = 1.3, 1.7, 2.5, 3.5\ GeV^2$

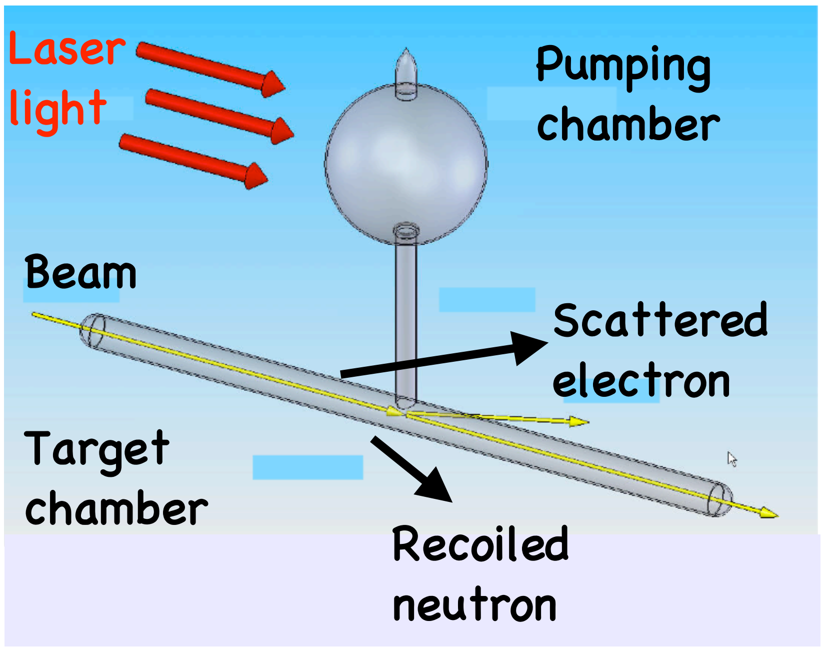


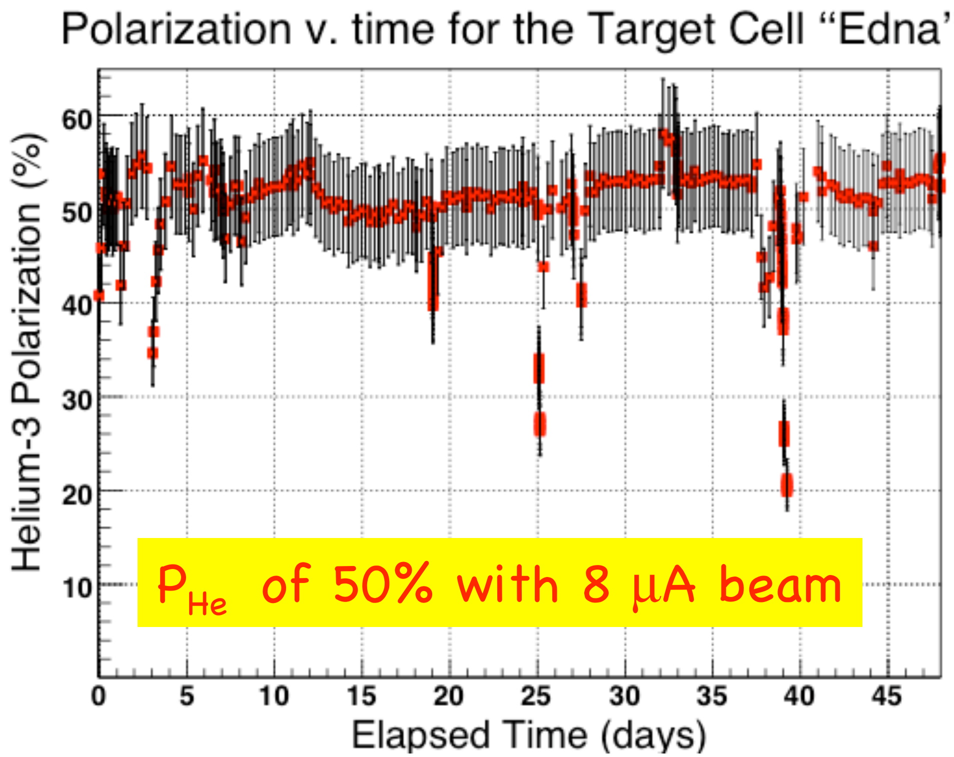
Polarized target

$^3He = p + p + n$

$S + S' + P$ waves

$P_n = 0.86\ P_{He}$





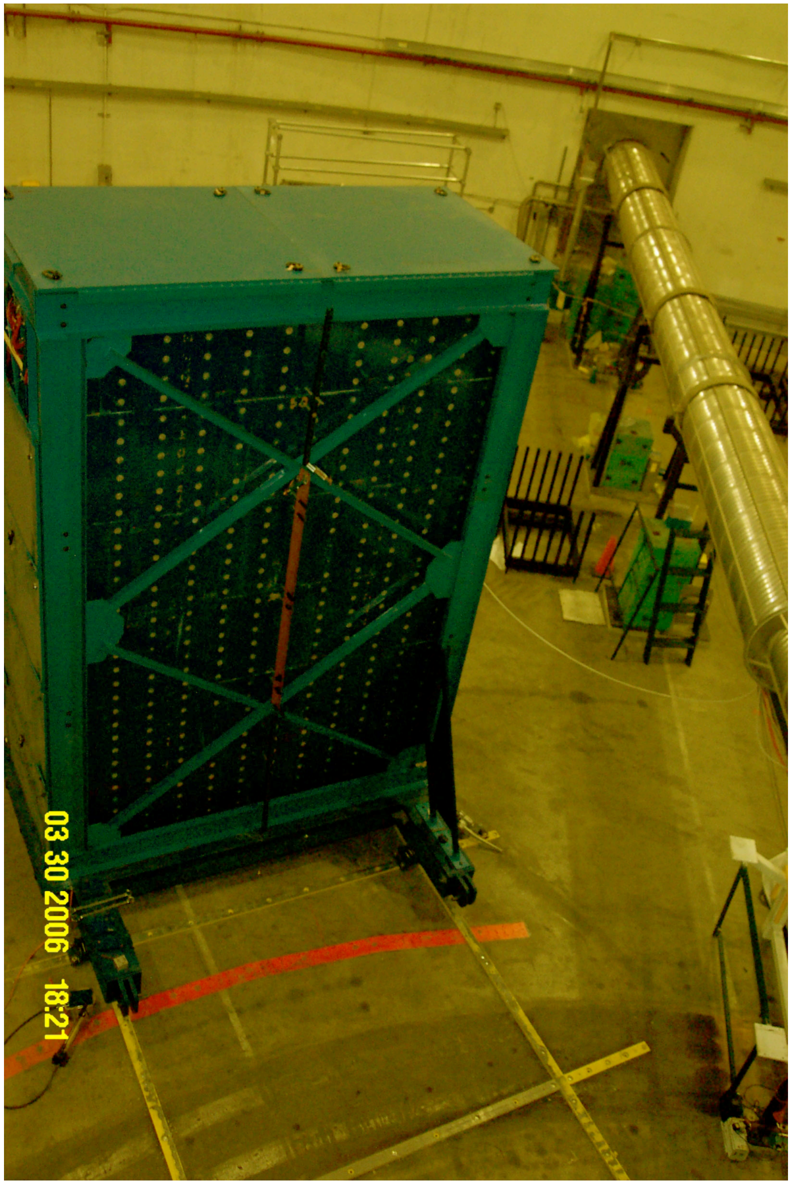
Rb + K mixture has shortened spin-up time to 5-8 hours. Hybrid method used for the first time in actual target.

Neutron Detector

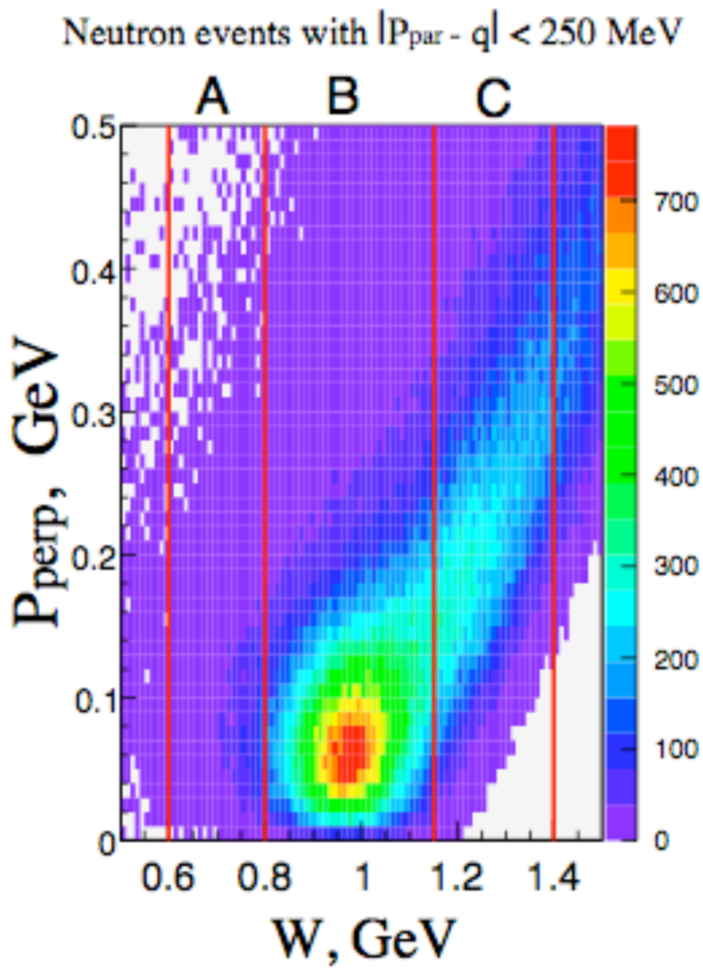
- Match BigBite 100 msr solid angle to QE kinematics
- Flight distance ~ 10 m
- Operation at $3 \cdot 10^{37}$ cm^2/s
- 1.6 x 5 m^2 active area
- 0.38 ns time resolution

- Active layers:
- 2 thin "veto" planes (200 bars)
- 7 planes of scintillator (~250 bars)
- Shielding/Conversion material:
- 2" Pb + 1" Fe before veto planes
- 1" before each detector plane

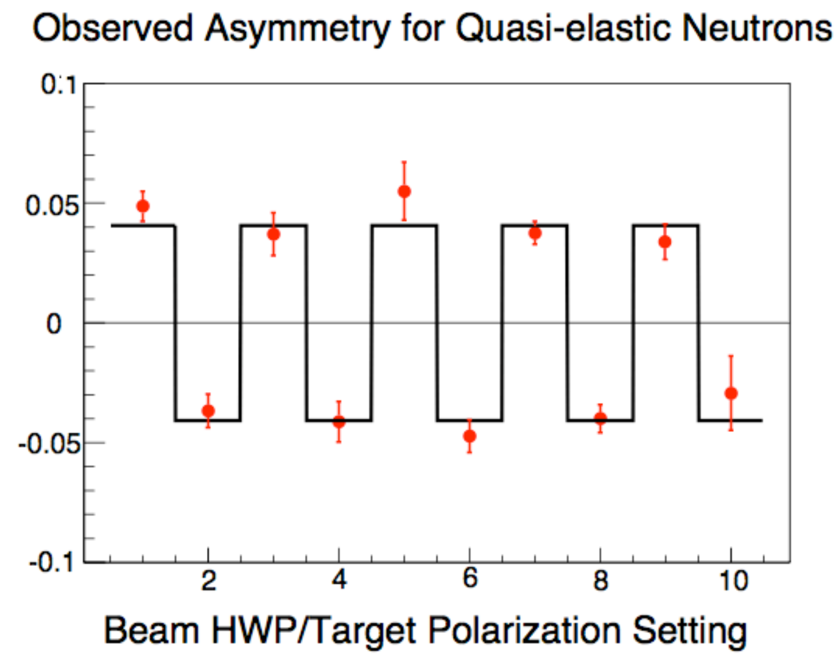
Shielding necessary to reduce background rate on the veto planes, but causes the complication of p↔n conversion....



Data analysis



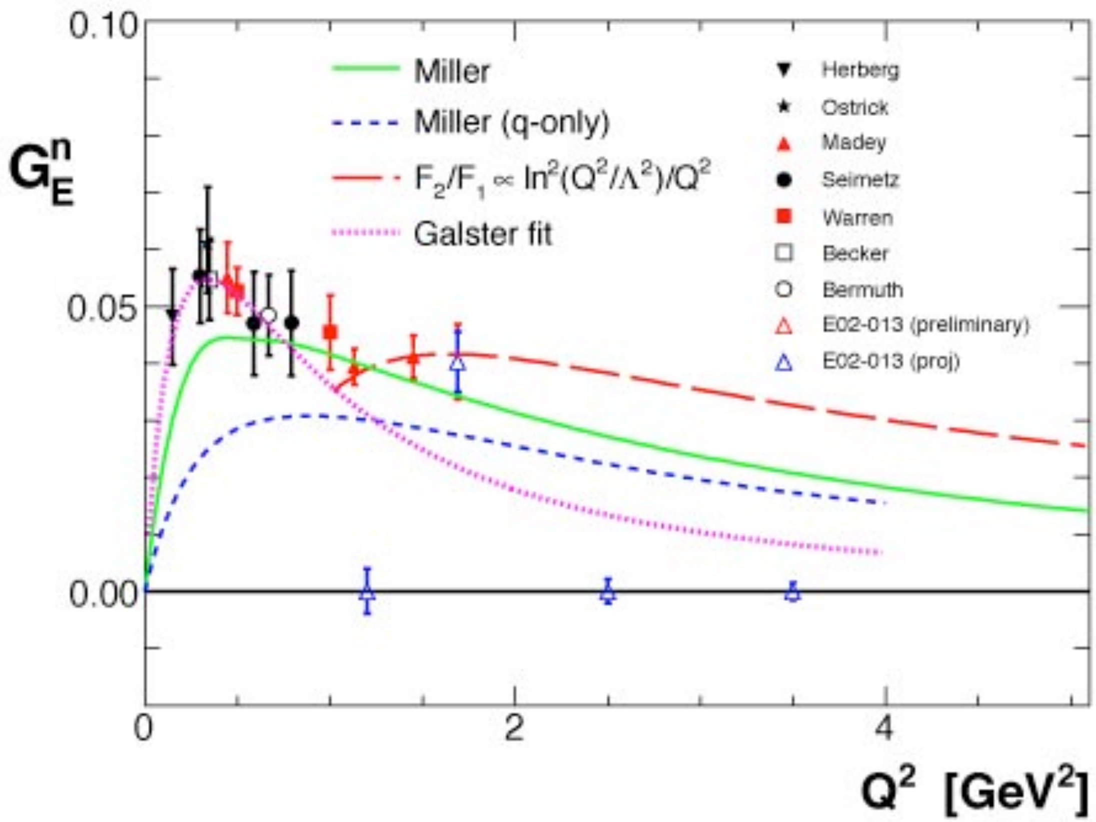
Selection of QE (e,e'n) events



Asymmetry then corrected for

1. p-n identification
2. $A_{||}$ contribution
3. FSI for e,e'n process
4. Target and beam polarizations

First physics result from Hall A G_E^n



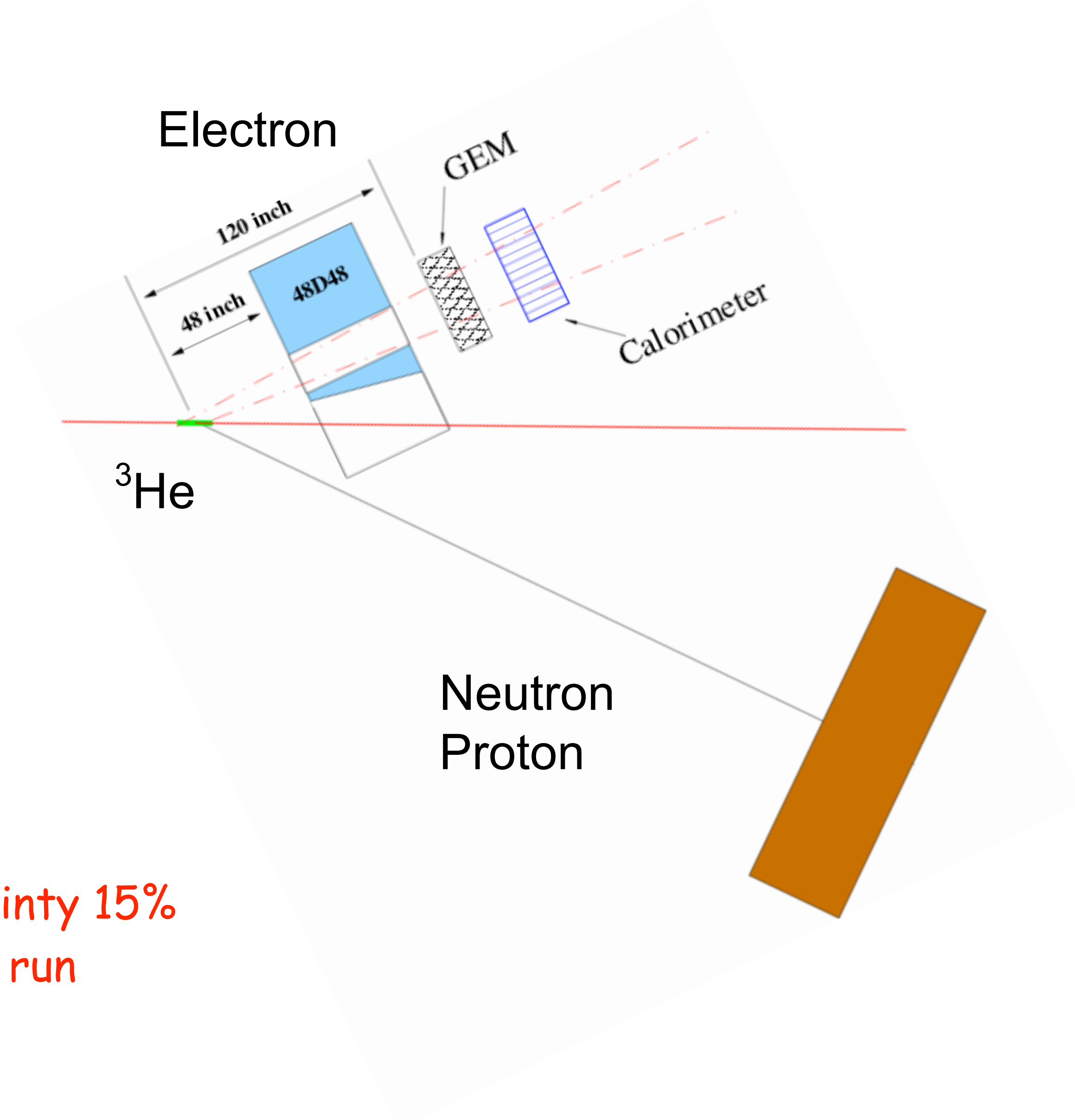
- Result is well above Galster
- Nuclear corrections include neutron polarization and estimate (5%) of Glauber correction
- 3.4 GeV^2 result to be released soon

Perspective: G_E^n up to 7 GeV^2

The plan for GEN-7 is:

$$^3\vec{H}e(\vec{e},e'n)$$

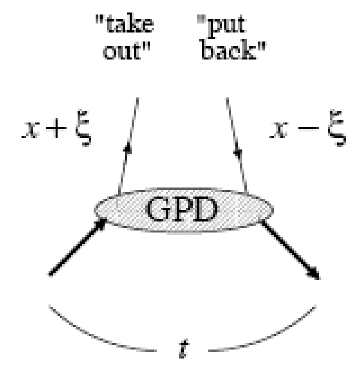
- Beam at 8.8 GeV
- Resolution σ_p/p for electron - BNL magnet, GEM
- He-3 cell in vacuum, lower background in neutron arm
- Hybrid He-3 cell with narrow pumping laser line



G_E^n at 7 GeV^2 with uncertainty 15% of Miller's value in 30-day run

Definition of Generalized Parton Distributions

The four Generalized Parton Distributions can be defined through a generalization of the so-called Wigner distributions:



$$F_{\gamma^+}(x,\xi,t) = \frac{1}{2p^+}\bar{U}(\vec{q}/2)\left[H(x,\xi,t)\gamma^+ + E(x,\xi,t)\frac{i\sigma^{+i}q_i}{2M}\right]U(-\vec{q}/2)$$

$$F_{\gamma^+\gamma_5}(x,\xi,t) = \frac{1}{2p^+}\bar{U}(\vec{q}/2)\left[\tilde{H}(x,\xi,t)\gamma^+ + \tilde{E}(x,\xi,t)\frac{i\sigma^{+i}q_i}{2M}\right]U(-\vec{q}/2)$$

helicity flip

separate GPDs for each quark flavor and for gluons

x - quark momentum fraction
2ξ - longitudinal momentum transfer
√-t - Fourier conjugate to transverse impact parameter

Integrals of GPDs give access to

- quark angular momenta (Ji's sum rule)
- mass distribution inside nucleon
- quark-quark forces

$$J^q = \frac{1}{2} - J^G = \frac{1}{2}\int_{-1}^{1} x dx\left[H^q(x,\xi,0) + E^q(x,\xi,0)\right]$$

Relating GPDs to nucleon FFs and PDFS

- forward limit : ordinary parton distributions

$$H^q(x, \xi = 0, t = 0) \quad = \quad q(x)$$ unpolarized quark distribution

$$\tilde{H}^q(x, \xi = 0, t = 0) \quad = \quad \Delta q(x)$$ polarized quark distribution

E^q , $\tilde{E}^q$: do NOT appear in DIS ➡ new information

- first moments : nucleon electroweak form factors

$$\int_{-1}^{1} dx H^q(x, \xi = 0, t) = F_1^q(t)$$ Dirac

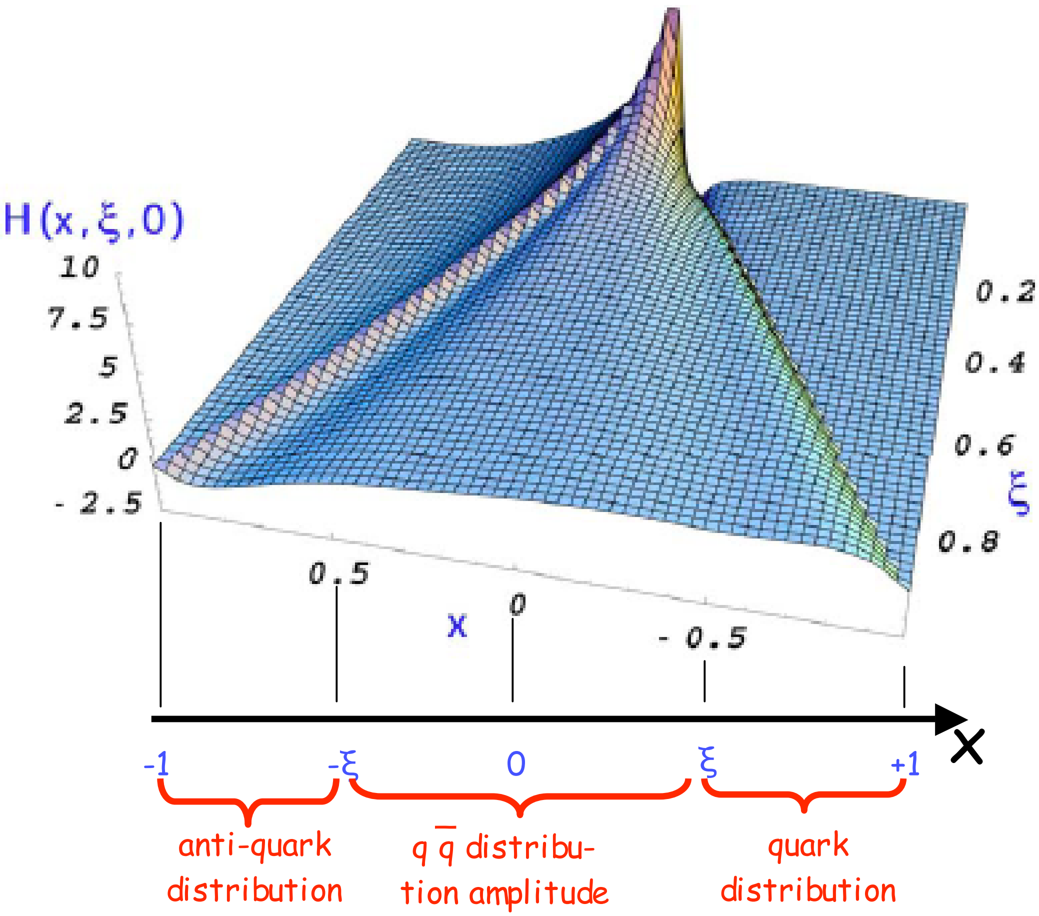
$$\int_{-1}^{1} dx E^q(x, \xi = 0, t) = F_2^q(t)$$ Pauli

$$\int_{-1}^{1} dx \tilde{H}^q(x, \xi = 0, t) = G_A^q(t)$$ axial

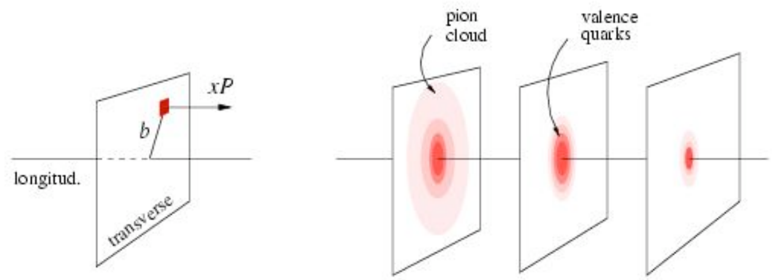
$$\int_{-1}^{1} dx \tilde{E}^q(x, \xi = 0, t) = G_P^q(t)$$ pseudo-scalar

Visualization of GPDS

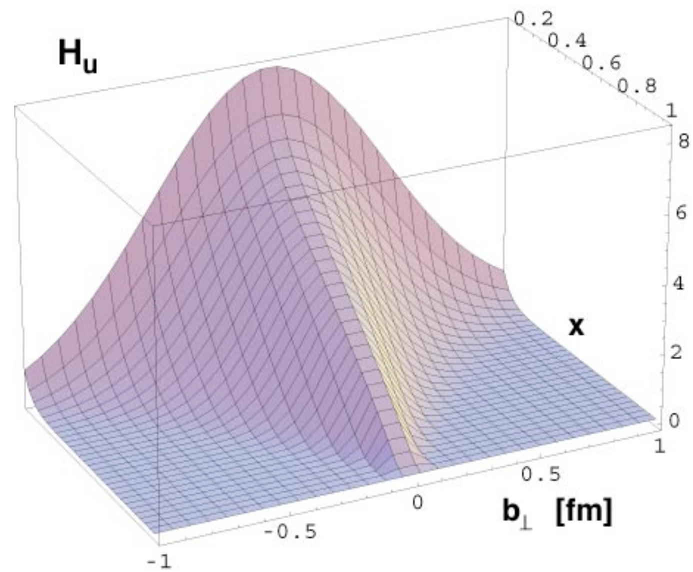
x - ξ correlations



Vanderhaeghen, Guidal, Guichon (VGG)



x - t correlations

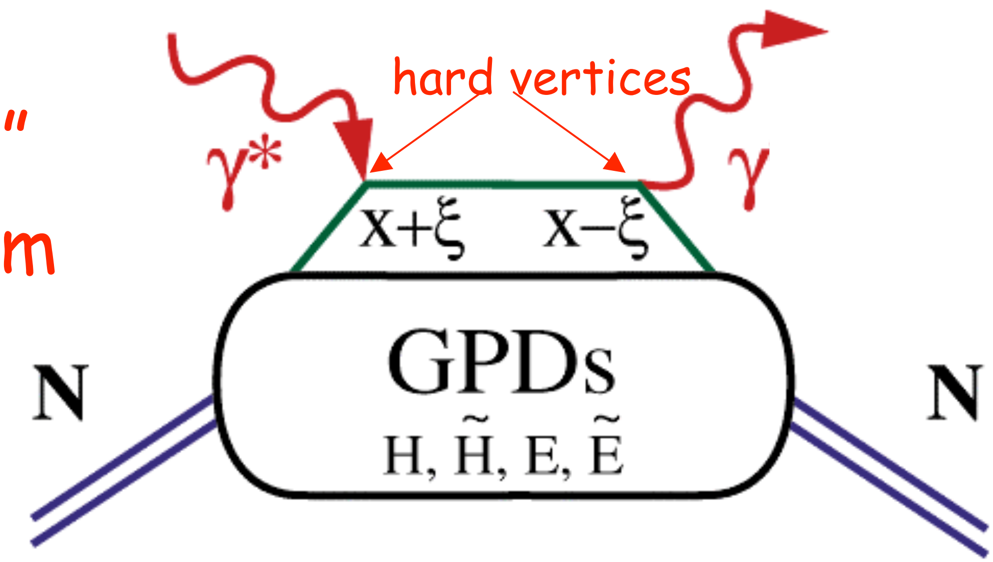


Burkardt

Deeply Virtual Compton Scattering (DVCS)

Simplest reaction to study GPDs

"handbag" mechanism

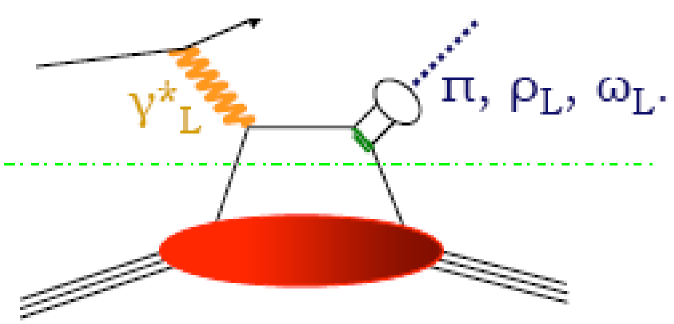


x – quark momentum fraction

2ξ – longitudinal momentum transfer

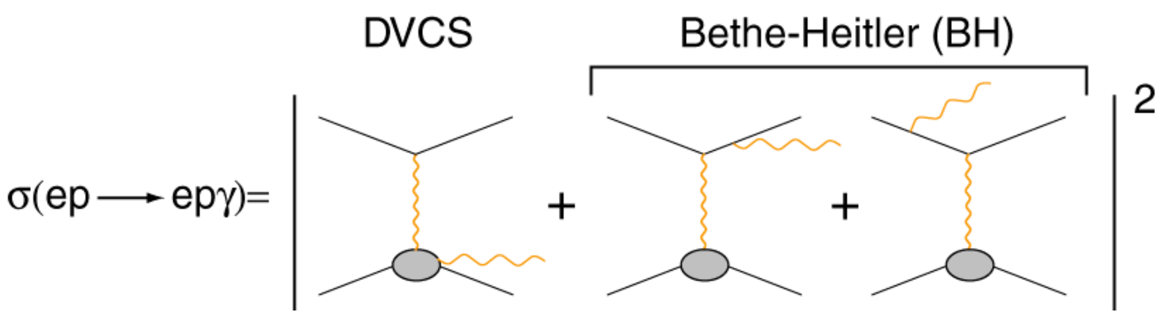
√-t – Fourier conjugate to transverse impact parameter

Flavor separation through Deeply Virtual Meson Production



Experimental observables linked to GPDs

Experimentally, DVCS is indistinguishable from Bethe-Heitler



However, since we know the EMFF at low t, the BH process is exactly calculable

Using a polarized beam on an unpolarized target, 2 observables can be measured:

$$\frac{d^4\sigma}{dx_B dQ^2 dt d\varphi} \approx \left|T^{BH}\right|^2 + 2T^{BH} \cdot \mathbf{Re}\left(T^{DVCS}\right) + \left|T^{DVCS}\right|^2$$

At JLab energies, $|T^{DVCS}|^2$ is supposed to be small, but….

$$\frac{d^4\overrightarrow{\sigma} - d^4\overleftarrow{\sigma}}{dx_B dQ^2 dt d\varphi} \approx 2T^{BH} \cdot \mathbf{Im}\left(T^{DVCS}\right) + \left[\left|\overrightarrow{T}^{DVCS}\right|^2 - \left|\overleftarrow{T}^{DVCS}\right|^2\right]$$

Kroll, Guichon, Diehl, Pire, …

The harmonic structure of DVCS

$$\frac{d^4\sigma}{dx_B dQ^2 dt d\varphi} = \frac{1}{P_1(\varphi)P_2(\varphi)}\Gamma_1(x_B,Q^2,t)\left\{c_0^{BH} + c_1^{BH}\cos\varphi + c_2^{BH}\cos 2\varphi\right\}$$

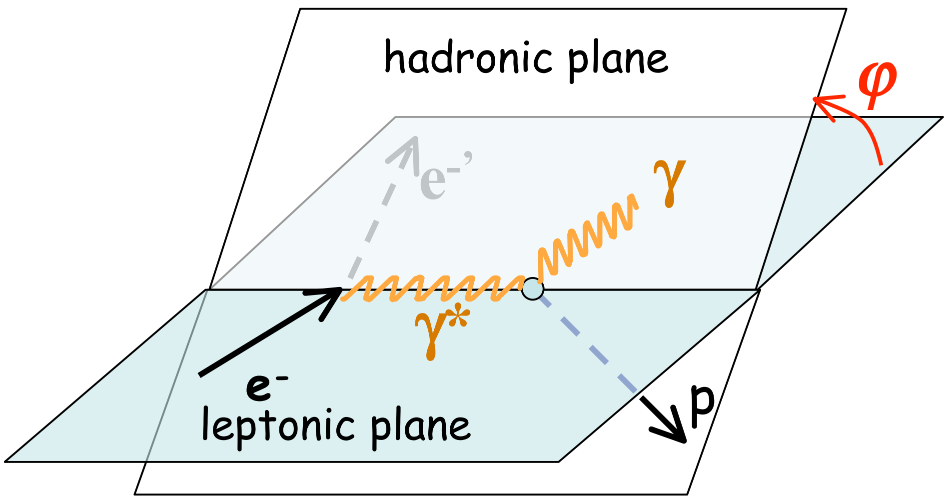
$|T^{BH}|^2$

$$\pm\frac{1}{P_1(\varphi)P_2(\varphi)}\Gamma_2(x_B,Q^2,t)\left\{c_0^I + c_1^I\cos\varphi + c_2^I\cos 2\varphi + c_3^I\cos 3\varphi\right\}$$

twist-2

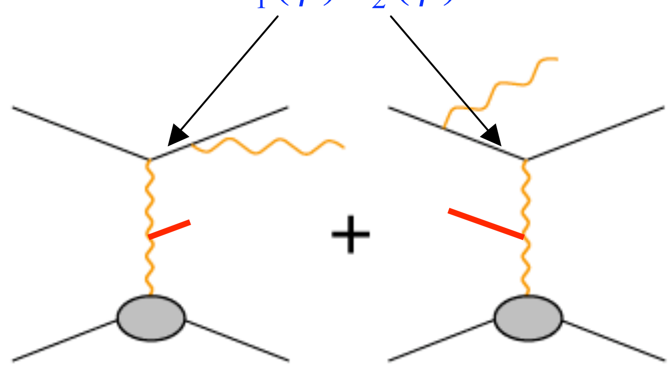
$$\frac{d^4\vec{\sigma} - d^4\overleftarrow{\sigma}}{dx_B dQ^2 dt d\varphi} = \frac{\Gamma(x_B,Q^2,t)}{P_1(\varphi)P_2(\varphi)}\left\{s_1^I\sin\varphi + s_2^I\sin 2\varphi\right\}$$

Interference term



Belitsky, Mueller, Kirchner

$$\frac{1}{P_1(\varphi)P_2(\varphi)}$$



BH propagators φ dependence

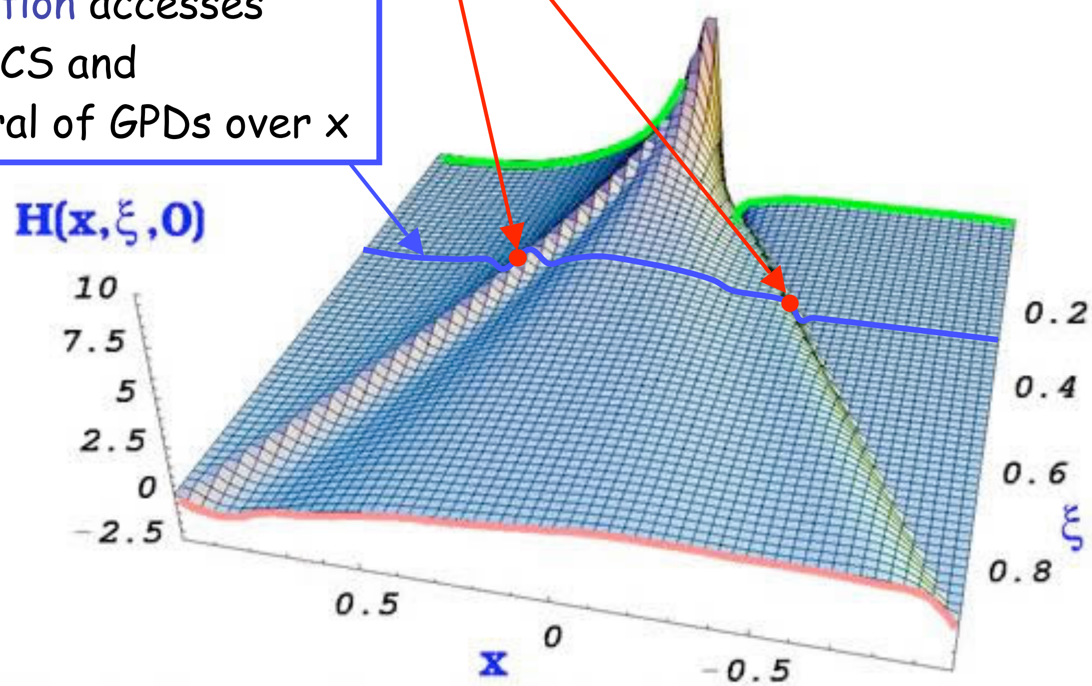
Observables and their relationship to GPDs

$$T^{DVCS} = \int_{-1}^{+1} \frac{GPD(x,\xi,t)}{x-\xi+i\varepsilon}dx \quad + \quad \cdots$$

The cross-section difference accesses the imaginary part of DVCS and therefore GPDs at $x = \pm\xi$

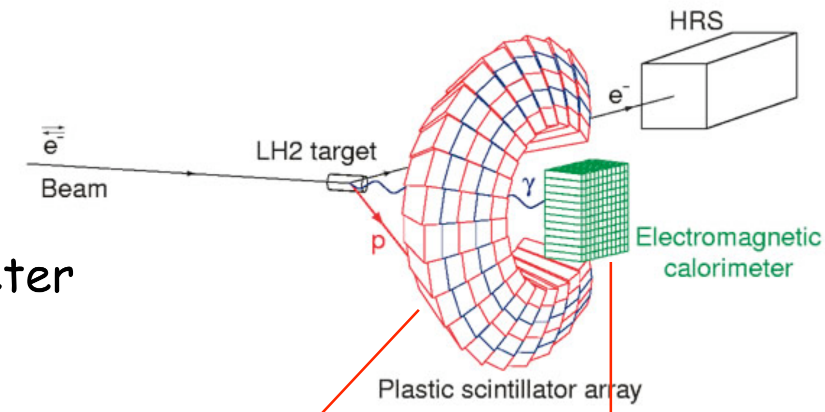
$$= P\int_{-1}^{+1} \frac{GPD(x,\xi,t)}{x-\xi}dx \quad - \quad i\pi GPD(x=\xi,\xi,t) \quad + \quad \cdots$$

The total cross section accesses the real part of DVCS and therefore an integral of GPDs over x

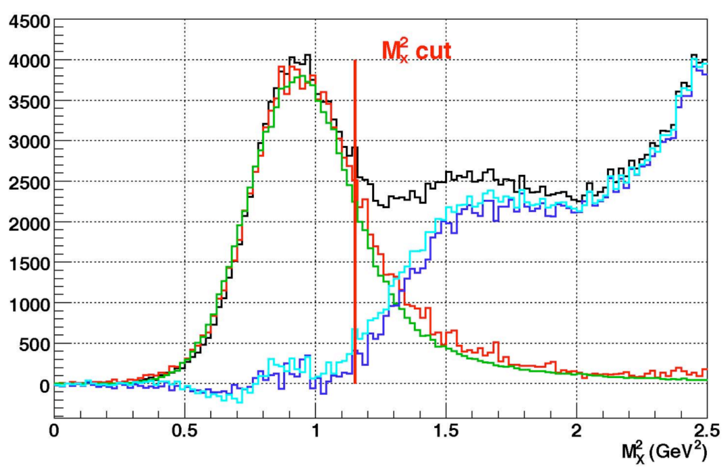


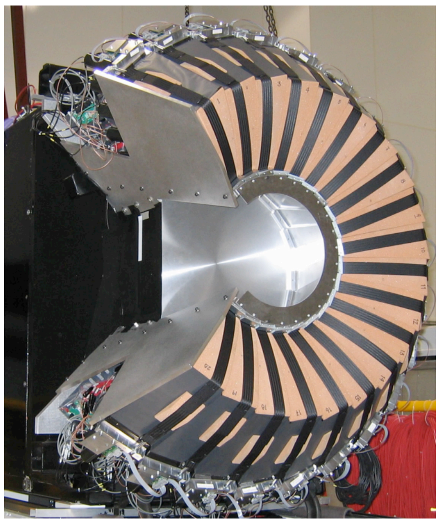
DVCS in Hall A (E00-110 and E03-106)

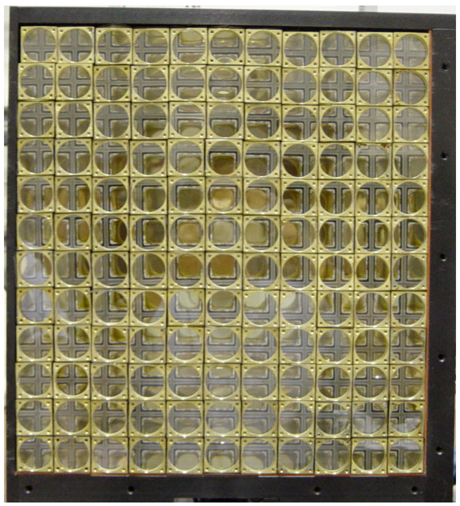
- 75% polarized 2.5 μA electron beam
- 15 cm LH2 target -> $L = 10^{37}\ cm^{-2}s^{-1}$
- Left Hall A HRS with electron package
- 11x12 blocks PbF_2 electromagnetic calorimeter
- 5x20 blocks plastic scintillator array
- Digital sampling of PMT signals at 1 GHz



- Clear DVCS identification from HRS+calo







Clermont-Ferrand, Saclay, Grenoble, ODU, Rutgers

Difference of cross sections

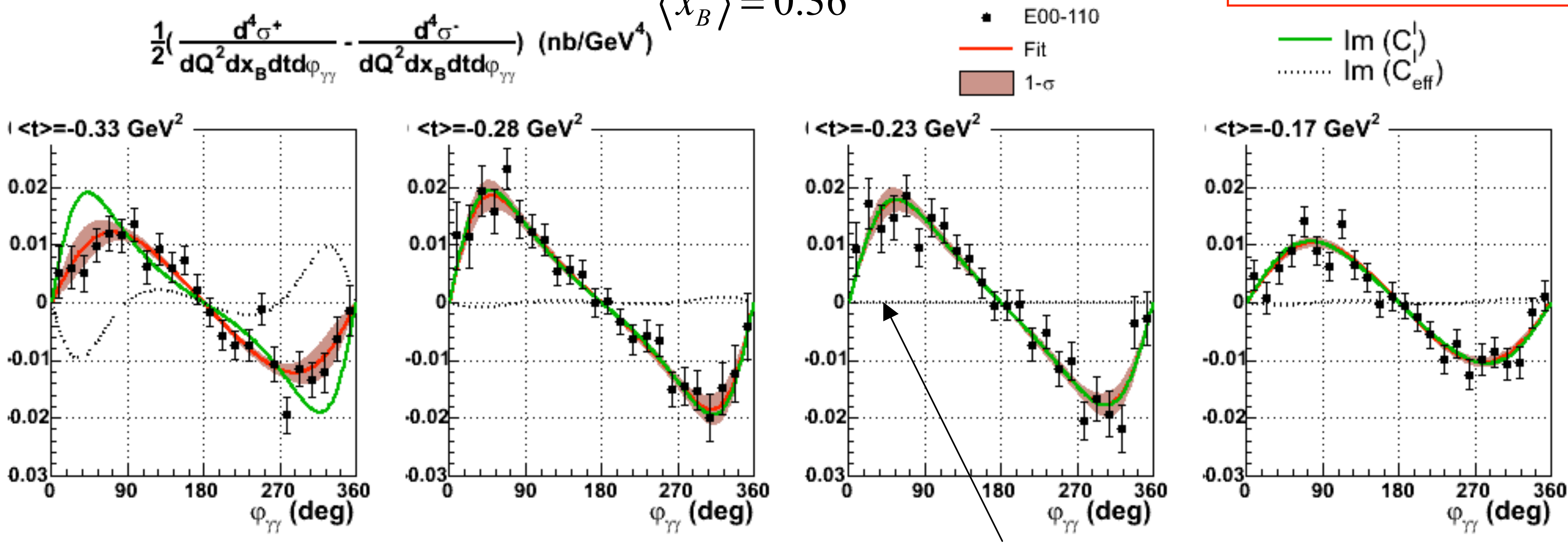
PRL97, 262002 (2006)

$$\langle Q^2 \rangle = 2.3 \text{ GeV}^2$$

$$\langle x_B \rangle = 0.36$$

$\text{Im}(C_I{}^I) \propto s_1{}^I$ Twist-2

$\text{Im}(C_{eff}) \propto s_2{}^I$ Twist-3



Extracted twist-3 contribution small !

- Corrected for real+virtual RadCor
- Corrected for efficiency
- Corrected for acceptance
- Corrected for resolution effects
- Checked elastic cross section @ ~1%

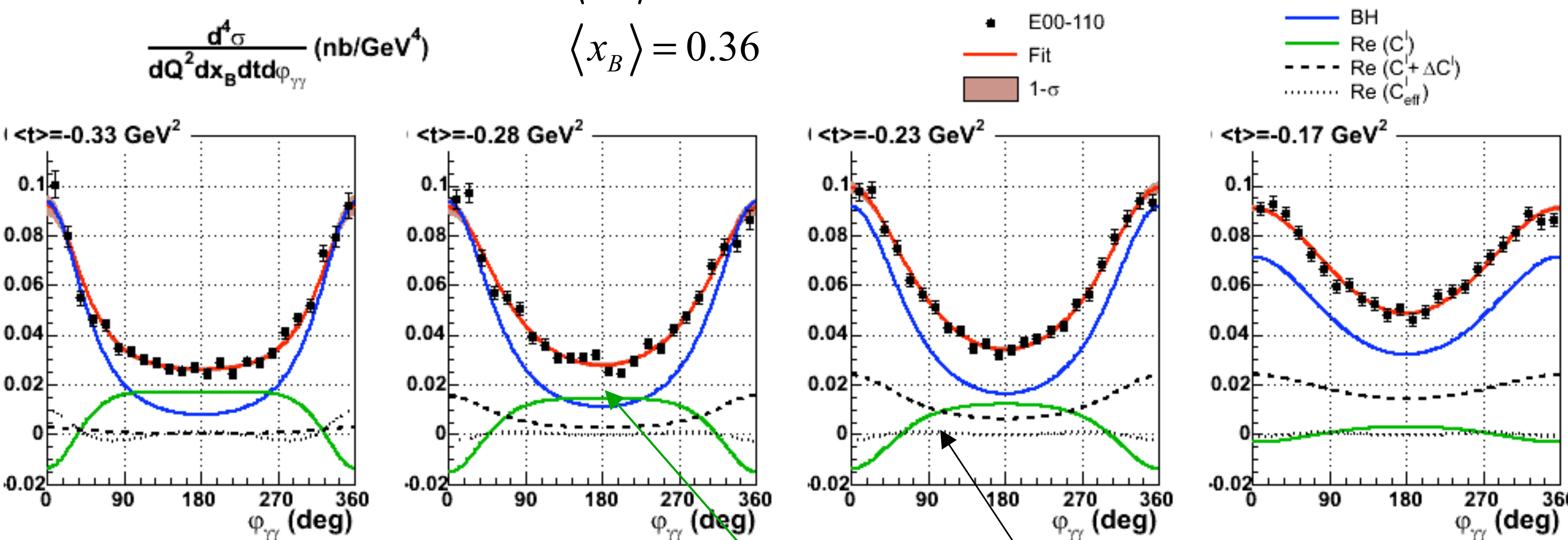
New work by P. Guichon

Total cross section

PRL97, 262002 (2006)

$$\langle Q^2 \rangle = 2.3\ \mathrm{GeV}^2$$

$$\langle x_B \rangle = 0.36$$



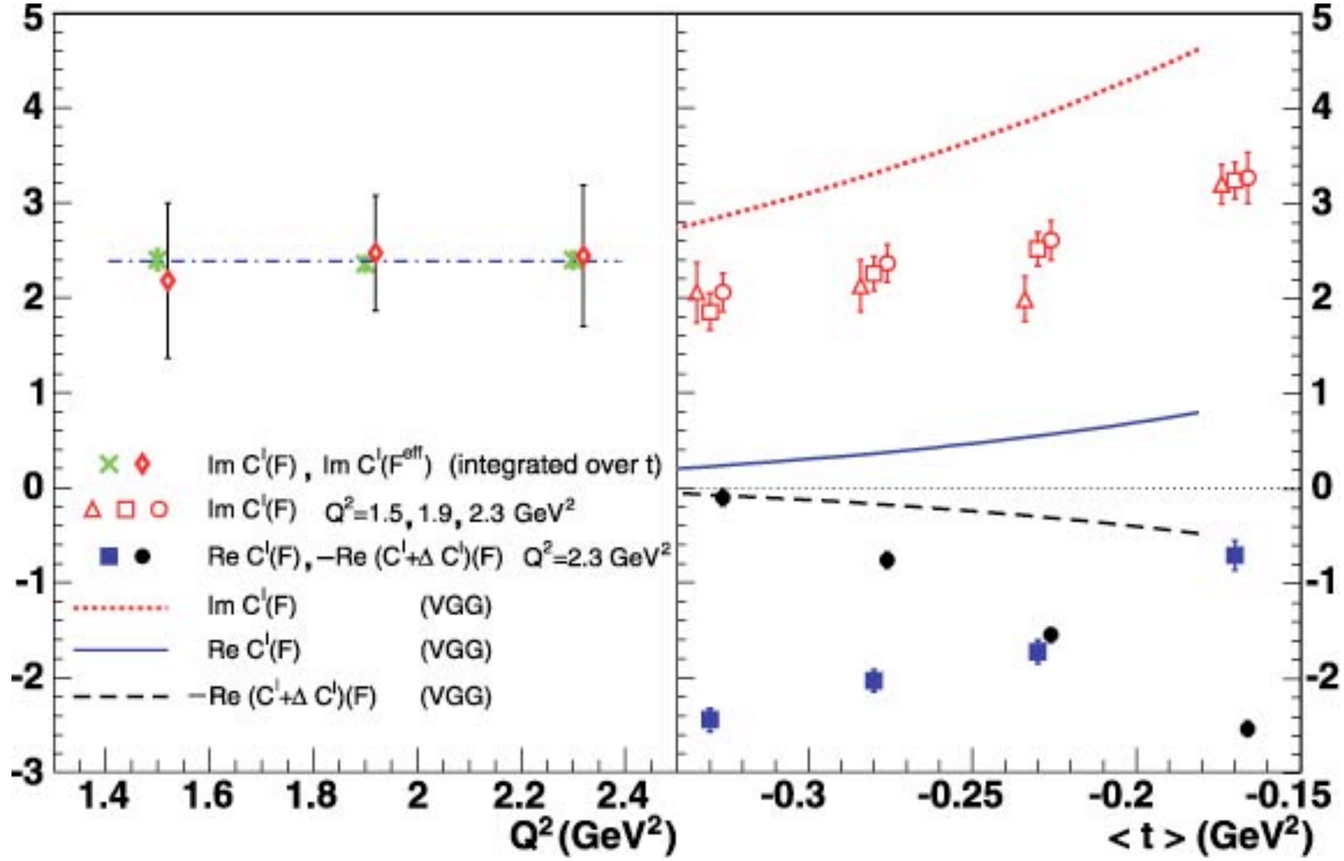
Corrected for real+virtual RC
Corrected for efficiency
Corrected for acceptance
Corrected for resolution effects

Again, extracted twist-3 contribution small !

BH*DVCS + DVCS² is large, comparable to BH²

Q^2 dependence and test of scaling

Twist-2
Twist-3

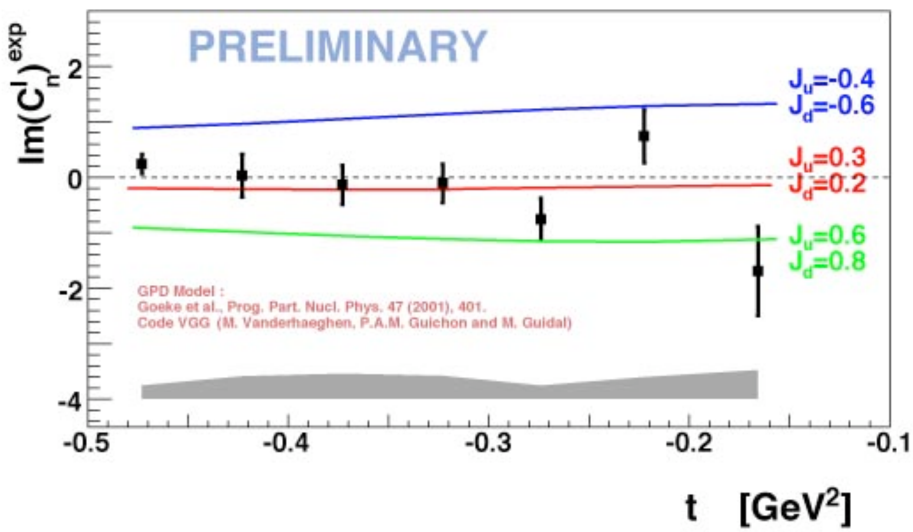


No Q^2 dependence: strong indication for scaling behavior and handbag dominance

Cross-section coefficients much larger than VGG

DVCS on the neutron in JLab/Hall A: E03-106

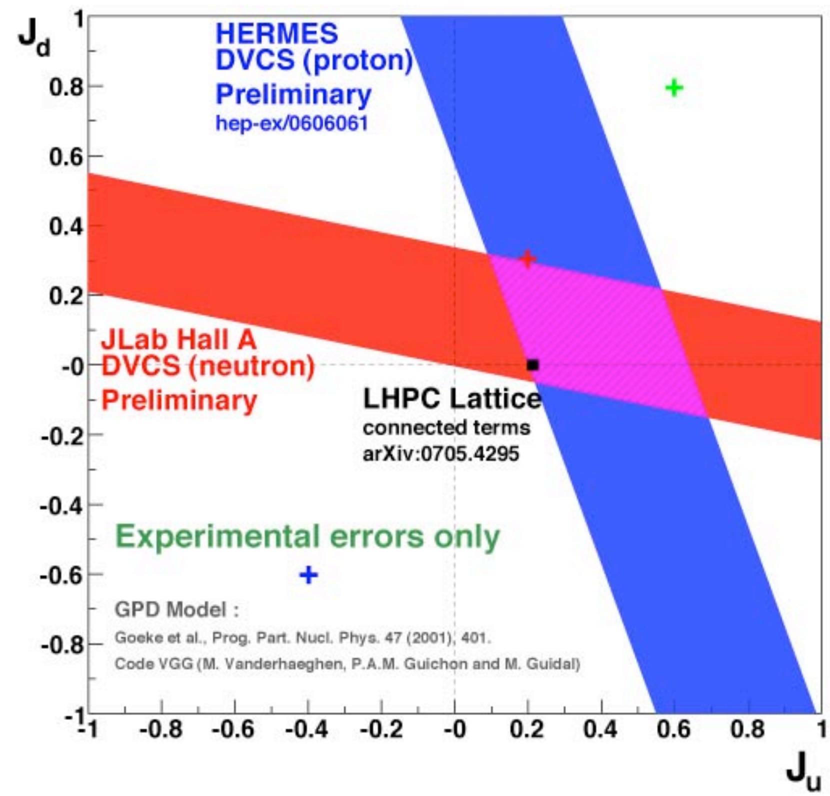
LD_2 target
24000 fb^{-1}
x_B=0.36, Q^2=1.9 GeV^2



Follow-up experiment in Hall A (to be proposed to PAC-33) will reduce experimental error significantly (larger x_B-range)

MODEL-DEPENDENT

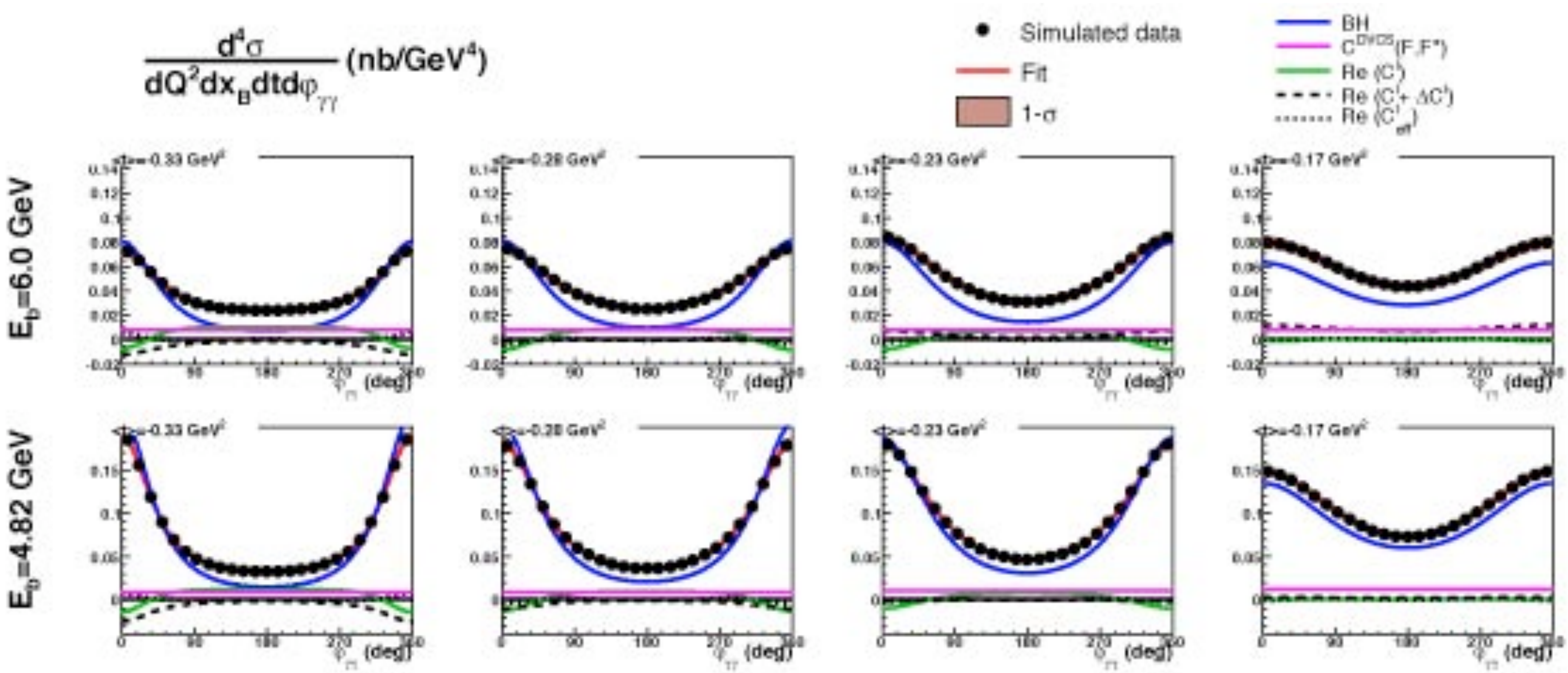
J_u-J_d extraction



VGG Code
GPD model : LO/Regge/D-term=0
Goeke et al., Prog. Part. Nucl. Phys 47 (2001), 401.

Next Hall A DVCS experiment : E07-007

- Measure the total DVCS cross section at fixed x_B = 0.36 for three Q^2-values - 2.3, 1.9 and 1.5 GeV^2- at two beam energies with improved π^o subtraction in order to
  - → separate the $DVCS^2$ term
  - → Provide further tests of scaling of the unpolarized cross section
  - → separate the five response functions of deep π^o production



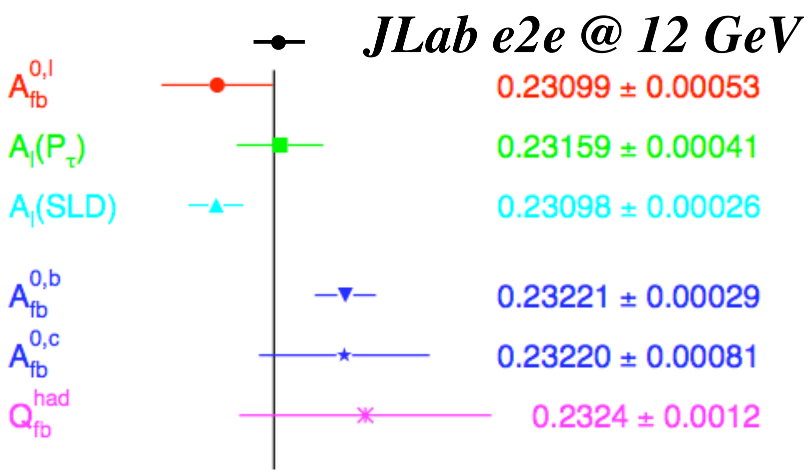
Future Possibilities (Purely Leptonic)

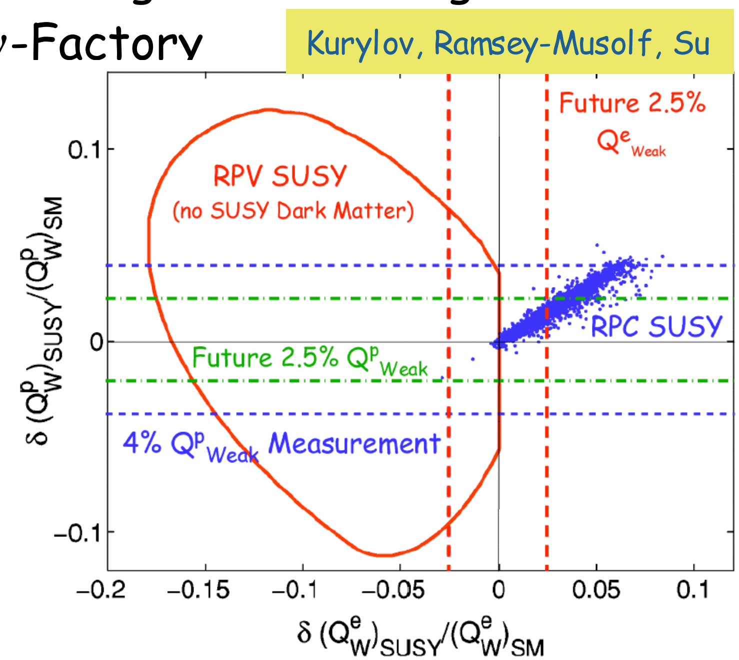
Møller at 11 GeV at JLab

Higher luminosity and acceptance ⇒ $\sin^2\theta_W$ to ± 0.00025; Λ_{ee} ~ 25 TeV reach

e.g. Z' reach ~ 2.5 TeV

- Comparable to single Z-pole measurement: shed light on 4σ disagreement
- Best low-energy measurement until ILC or ν-Factory
- Could be launched ~ 2015



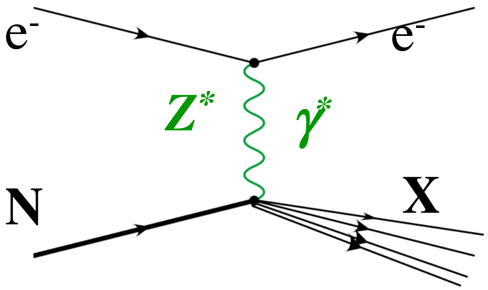


Does Supersymmetry (SUSY) provide a candidate for dark matter?

→ Neutralino is stable if baryon (B) and lepton (L) numbers are conserved

→ In RPV B and L need not be conserved: neutralino decay

PV DIS at 11 GeV with an LD_2 target



$$A_{PV} = \frac{G_F Q^2}{\sqrt{2}\pi\alpha}[a(x) + f(y)b(x)]$$

$$y \equiv 1 - E'/E$$

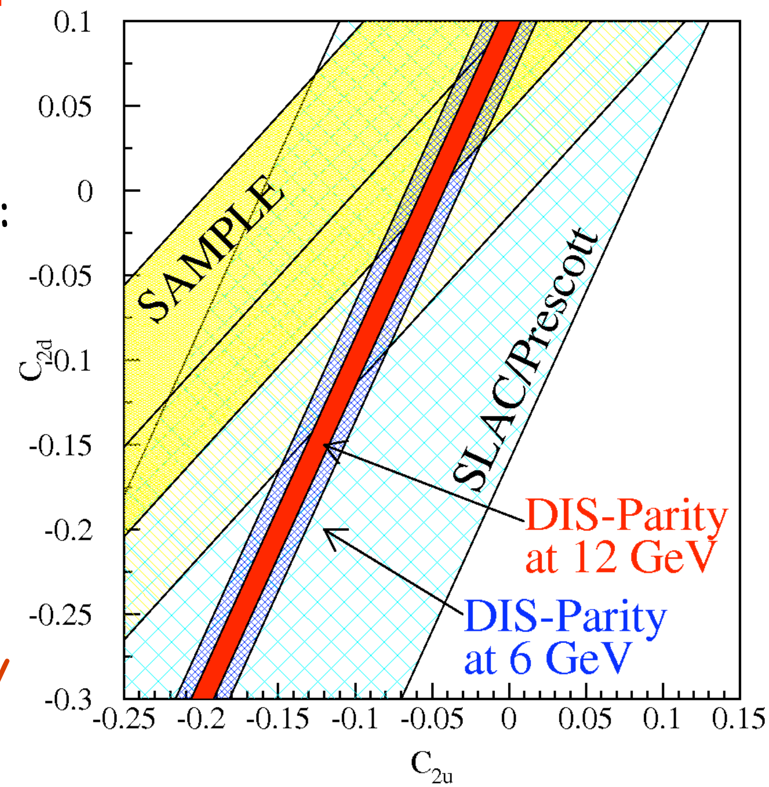
For an isoscalar target like ^2H,
the structure functions largely cancel in the ratio:

$$a(x) = \frac{3}{10}[(2C_{1u} - C_{1d})] + \cdots$$

$$b(x) = \frac{3}{10}\left[(2C_{2u} - C_{2d})\frac{u_v(x) + d_v(x)}{u(x) + d(x)}\right] + \cdots$$

($Q^2 >> 1$ GeV^2 , $W^2 >> 4$ GeV^2, $x \sim 0.3$-0.5)

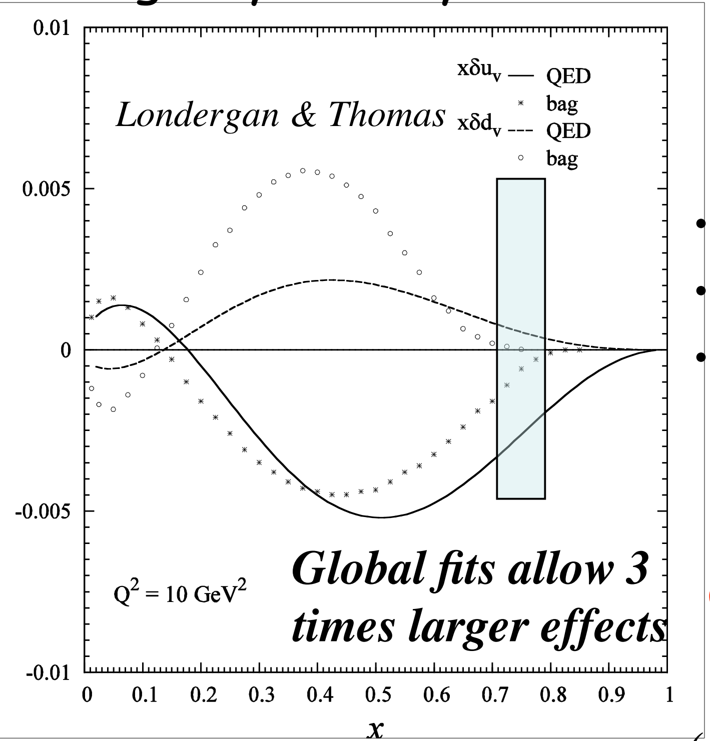
- Must measure A_{PV} to 0.5% fractional accuracy
- Luminosity and beam quality available at JLab



- 6 GeV experiment will launch PV DIS measurements at JLab (2009)
- Only 11 GeV experiment will allow tight control of systematic errors
- Important constraint should LHC observe an anomaly

Precision High-x Physics with PV DIS

Charge Symmetry Violation (CSV) at High x: clean observation possible



$$\delta u(x) = u^p(x) - d^n(x)$$
$$\delta d(x) = d^p(x) - u^n(x)$$

$$\frac{\delta A_{PV}(x)}{A_{PV}(x)} = 0.3\frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

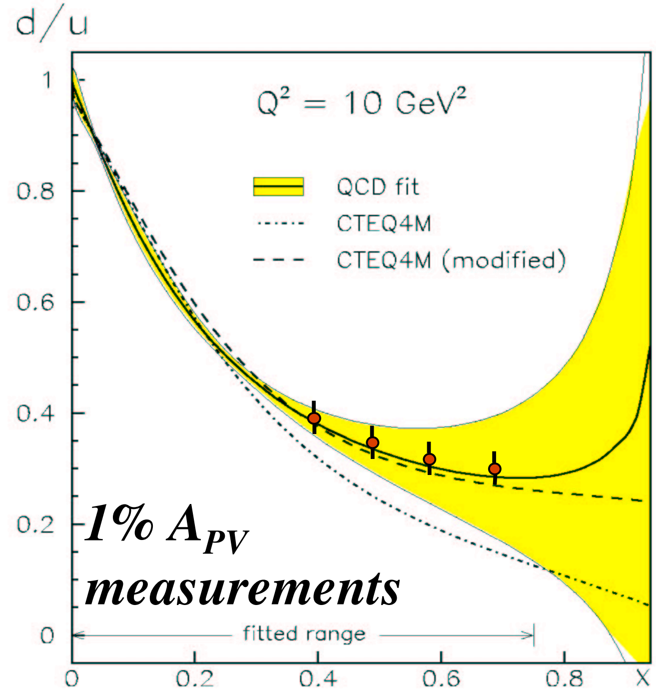
- Direct observation of CSV at parton level
- Implications for high-energy collider pdfs
- Could explain large portion of the NuTeV anomaly

Requires 1% measurement of A_{PV} at x ~ 0.75

For hydrogen [1]H: $$a(x) = \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$

Longstanding issue: d/u as x→1

- Allows d/u measurement on a single proton

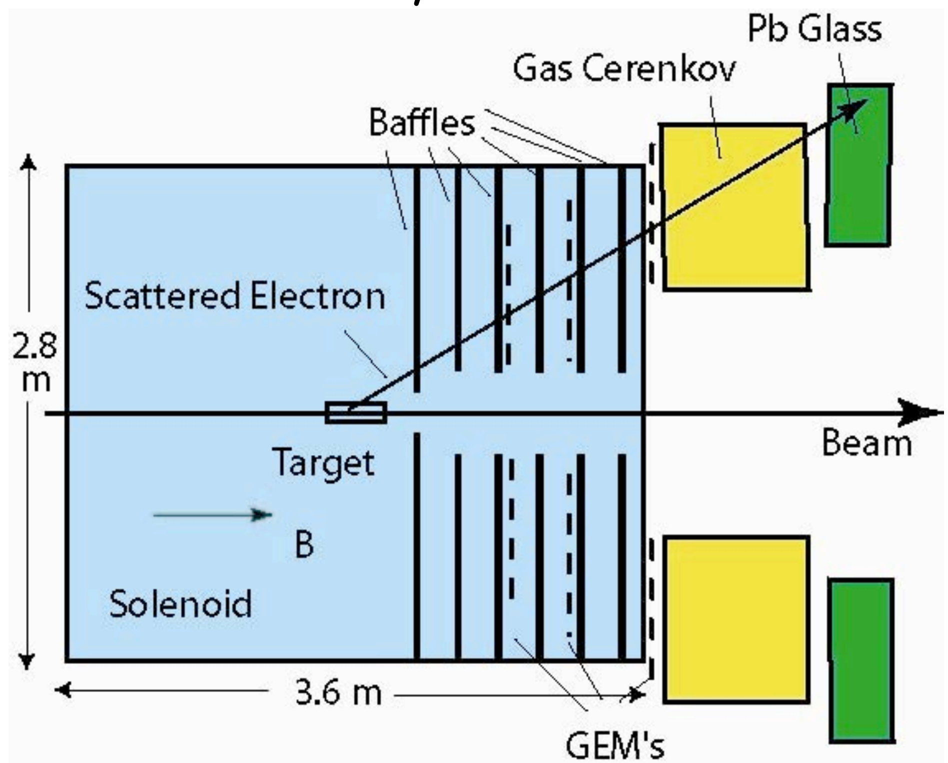


A Vision for Precision PV DIS Physics

- Hydrogen and Deuterium targets
- Better than 2% errors
  (unlikely that any effect is larger than 10%)
- x-range 0.25-0.75
- W^2 well over 4 GeV^2
- Q^2 range a factor of 2 for each x
  (except x~0.75)
- Moderate running times

- solid angle > 200 msr
- count at 100 kHz
- on-line pion rejection of 10^2 to 10^3

- CW 90 μA at 11 GeV
- 40 cm liquid H_2 and D_2 targets
- Luminosity > $10^{38}/cm^2/s$



Goal: Form a collaboration, start real design and simulations, after the successful pitch to US community at the 2007 Nuclear Physics Long Range Plan

Summary

- Presented results of two recent experiments from JLab Hall A
  - G_E^n to higher Q^2
  - DVCS at high luminosity
- First preliminary datum for G_E^n indicates that G_E^n indeed drops off slower than ancient Galster parametrization, possibly in agreement with similar scaling as G_E^p
- Results of the first dedicated DVCS experiment in Hall A have indicated that
  - → factorization (handbag dominance) is applicable at $Q^2 \approx 2$ GeV^2
  - → the DVCS^2 term is much larger than previously assumed
- and provided a model-dependent estimate of the quark angular momenta
- Initial studies have shown that the 12 GeV upgrade will allow highly sensitive tests of the Standard Model