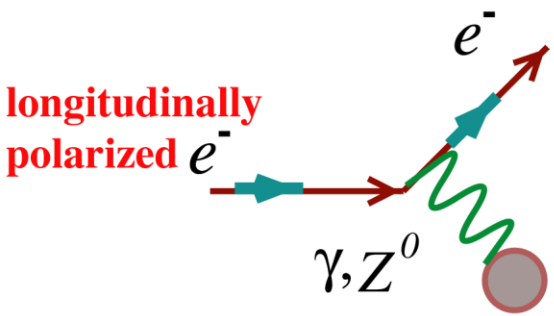
Precision Measurement of Parity-violation in Deep Inelastic Scattering Over a Broad Kinematic Range

P. A. Souder

Outline

- Physics potential
  - Standard Model Test
  - Charge Symmetry Violation (CSV)
  - Higher Twist
  - d/u for the Proton
- New Solenoidal Spectrometer (SoLID)
- Polarimetry

PV Asymmetries: Any Target and Any Scattering Angle



Forward — Backward

$$-A_{LR} = A_{PV} = \frac{\sigma_\uparrow - \sigma_\downarrow}{\sigma_\uparrow + \sigma_\downarrow} \sim \frac{A_{weak}}{A_\gamma} \sim \frac{G_F Q^2}{4\pi\alpha} \left(g_A^e g_V^T + \beta g_V^e g_A^T\right)$$

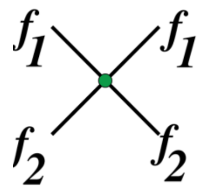
- *The couplings g^T depend on electroweak physics as well as on the weak vector and axial-vector hadronic current*
- *For PVDIS, both new physics at high energy scales as well as interesting features of hadronic structure come into play*
- *A program with a broad kinematic range can untangle the physics*

PVDIS: Electron-Quark Scattering

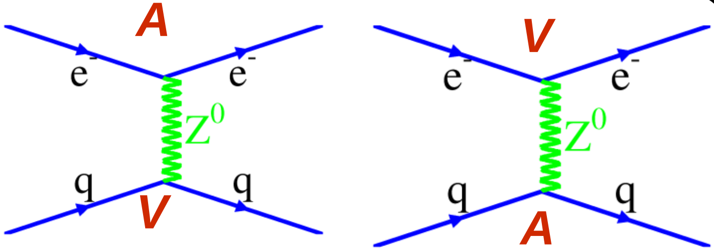
Many new physics models give rise to neutral 'contact' (4-Fermi) interactions: Heavy Z's, compositeness, extra dimensions…

Consider $f_1\bar{f}_1 \rightarrow f_2\bar{f}_2$ or $f_1 f_2 \rightarrow f_1 f_2$

$$\mathcal{L}_{f_1 f_2} = \sum_{i,j=L,R} \frac{g_{ij}}{\Lambda} \bar{f}_{1i}\gamma_\mu f_{1i} \bar{f}_{2j}\gamma^\mu f_{2j}$$



g_{ij}'s for all $f_1 f_2$ combinations and L,R combinations



$C_{1i} \equiv 2 g_A^e g_V^i$ $\quad$ $C_{2i} \equiv 2 g_V^e g_A^i$

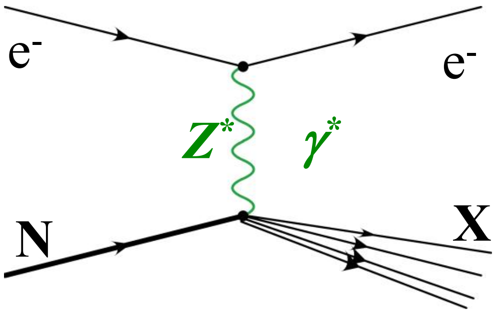
$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2(\theta_W) + \delta C_{1u} \approx -0.19$$
$$C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2(\theta_W) + \delta C_{1d} \approx 0.35$$
$$C_{2u} = -\frac{1}{2} + 2\sin^2(\theta_W) + \delta C_{2u} \approx -0.030$$
$$C_{2d} = \frac{1}{2} - 2\sin^2(\theta_W) + \delta C_{2d} \approx 0.025$$

Moller PV is insensitive to the C_{ij}

C_{2u} and C_{2d} are small and poorly known: one combination can be accessed in PV DIS

C_{1u} and C_{1d} will be determined to high precision by Q_{weak}, APV Cs

Deep Inelastic Scattering



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

a(x) and **b**(x) contain quark distribution functions $f_i(x)$

$$x \equiv x_{Bjorken}$$

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

$$f_i^{\pm} \equiv f_i \pm \overline{f}_i$$

$$\boldsymbol{a}(x) = \frac{\sum_i C_{1i} Q_i f_i^{+}(x)}{\sum_i Q_i^2 f_i^{+}(x)} \qquad \boldsymbol{b}(x) = \frac{\sum_i C_{2i} Q_i f_i^{-}(x)}{\sum_i Q_i^2 f_i^{+}(x)}$$

For an isoscalar target like ^{2}H, structure functions largely cancel in the ratio at high x

at high x

$$\boldsymbol{a}(x) = \frac{3}{10}(2C_{1u} - C_{1d})\left(1 + \frac{0.6\, s^{+}}{u^{+} + d^{+}}\right) \rightarrow 0$$

$$\boldsymbol{b}(x) = \frac{3}{10}(2C_{2u} - C_{2d})\left(\frac{u_v + d_v}{u^{+} + d^{+}}\right) + \cdots \rightarrow 1$$

At high x, A_{PV} becomes independent of x, W, with well-defined SM prediction for Q^2 and y

New combination of:
Vector quark couplings C_{1q}
Also axial quark couplings C_{2q}

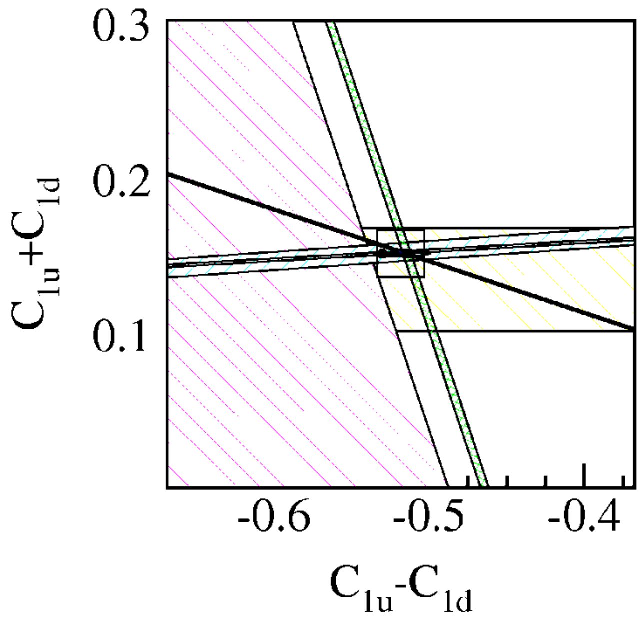
Sensitive to new physics at the TeV scale

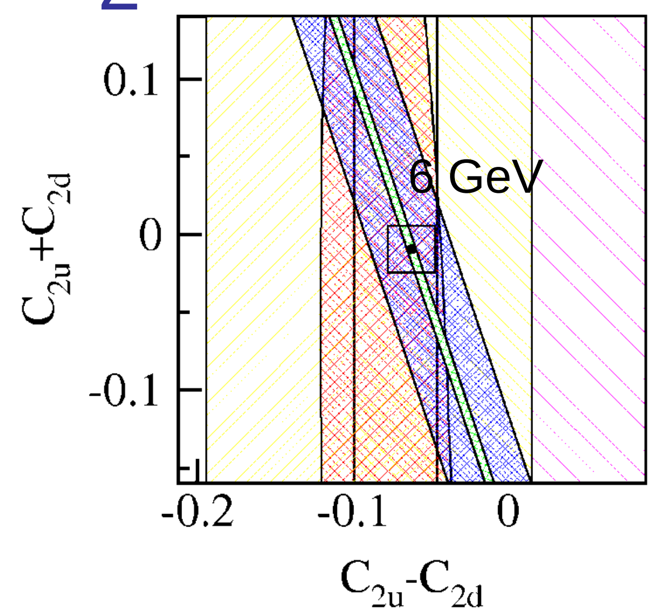
PVDIS: Only way to measure C_{2q}

Unknown radiative corrections for coherent processes

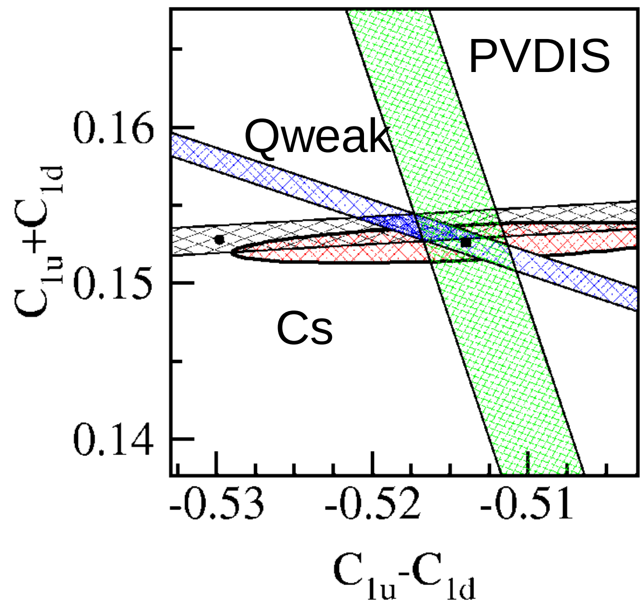
Sensitivity: C_1 and C_2 Plots

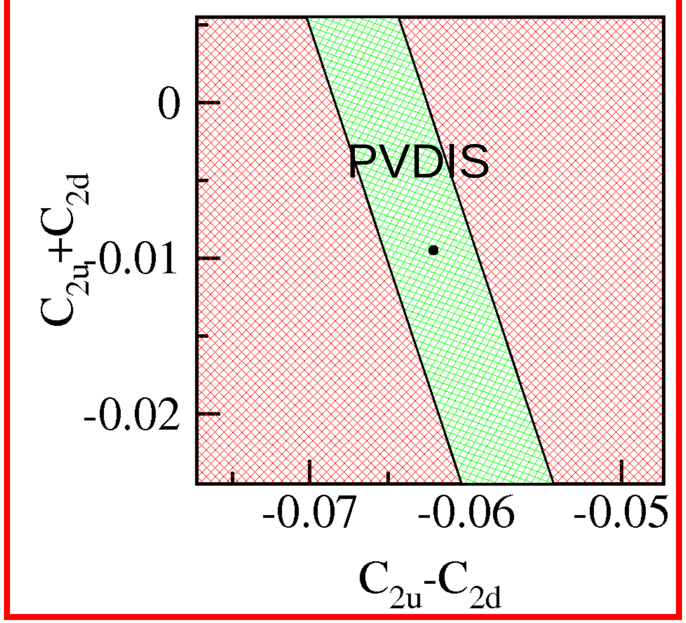
World's data





Precision Data





Search for CSV in PV DIS

$u^p(x) = d^n(x)?$

$d^p(x) = u^n(x)?$

- u-d mass difference
- electromagnetic effects

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

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

- ***Direct observation of parton-level CSV would be very exciting!***
- ***Important implications for high energy collider pdfs***
- ***Could explain significant portion of the NuTeV anomaly***

For A_{PV} in electron-^{2}H DIS:

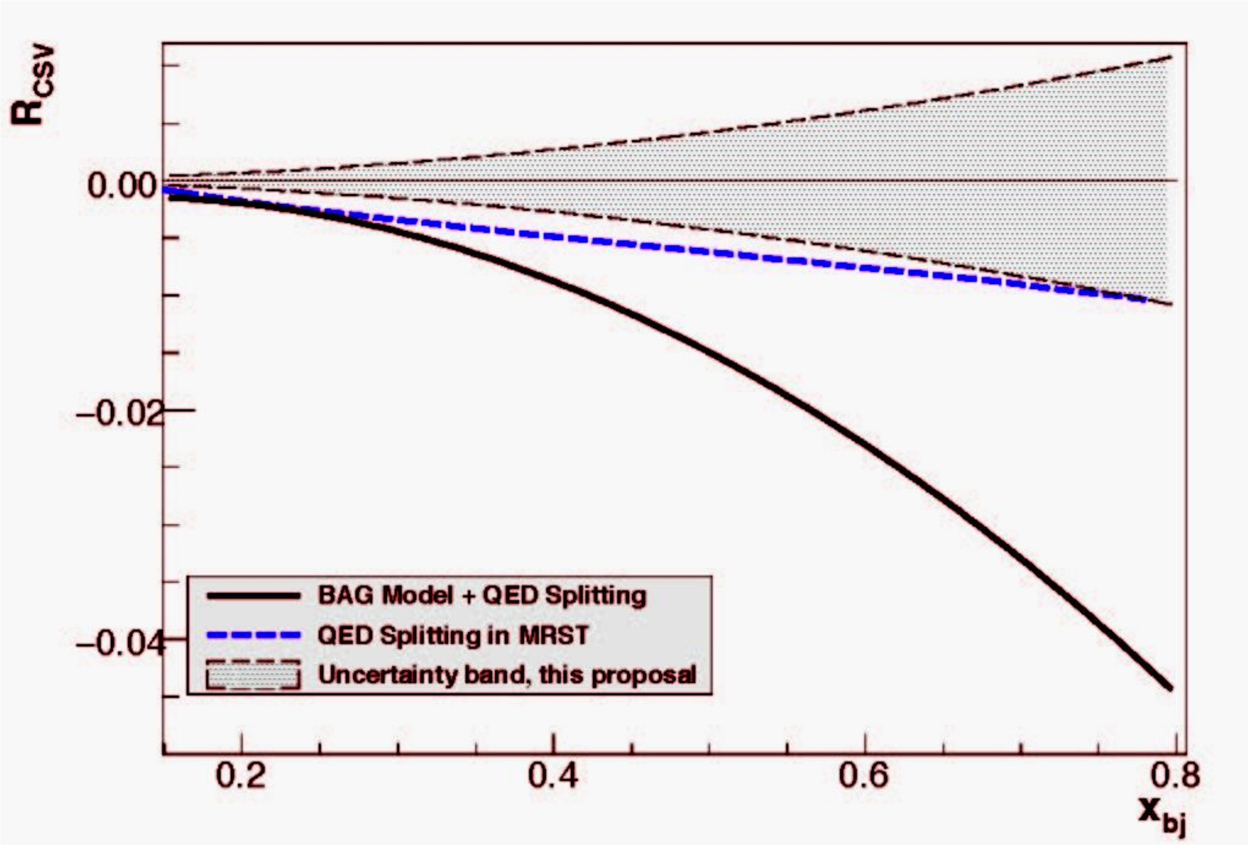
$$\frac{\delta A_{PV}}{A_{PV}} = 0.28 \frac{\delta u - \delta d}{u + d}$$

Sensitivity will be further enhanced if u+d falls off more rapidly than δu-δd as $x \to 1$

Strategy:

- ***measure or constrain higher twist effects at x ~ 0.5-0.6***
- ***precision measurement of A_{PV} at $x \to 0.8$ to search for CSV***

Sensitivity with PVDIS



$$R_{CSV} = \frac{\delta A_{PV}(x)}{A_{PV}(x)} = 0.28\,\frac{\delta u(x) - \delta d(x)}{u(x) + d(x)}$$

Need Full Phenomenology

$$\left[\frac{d^2\sigma}{dxdy}\right]_{EM} \propto 2xyF_1^{\gamma} + \frac{2}{y}(1-y-\frac{xyM}{2E})F_2^{\gamma}$$

$$F_1^{\gamma} = F_2^{\gamma}(1+R) \rightarrow R = \frac{\sigma_L}{\sigma_T}$$

$$\left[\frac{d^2\sigma}{dxdy}\right]_{\gamma Z}^{V} \propto \frac{G}{2\sqrt{2\pi\alpha}}[-g_A\{2xyF_1^{\gamma Z} + \frac{2}{y}(1-y-\frac{xyM}{2E})F_2^{\gamma Z}\}]$$

$$\left[\frac{d^2\sigma}{dxdy}\right]_{\gamma Z}^{A} \propto \frac{G}{2\sqrt{2\pi\alpha}}[-g_V x(2-y)F_3^{\gamma Z}]$$

There are 5 relevant structure functions

$$A_B^{PV} = \frac{\sigma_{\gamma Z}^{V} + \sigma_{\gamma Z}^{A}}{\sigma_{EM}}$$

$$a(x) = \frac{\sigma_{\gamma Z}^{V}}{\sigma_{EM}}$$

BIG

$$f(y)b(x) = \frac{\sigma_{\gamma Z}^{A}}{\sigma_{EM}}$$

Small; use ν data (Higher twist workshop at Madison, Wisconsin)

Why HT in PVDIS is Special

Bjorken,
PRD 18, 3239 (78)

Wolfenstein,
NPB146, 477 (78)

Start with Lorentz Invariance

$$A \propto \frac{l_{\mu\nu}\int \langle D|\, j^{\mu}(x)J^{\nu}(0) + J^{\mu}(x)j^{\nu}(0)\,|D\rangle e^{iq\cdot x} d^4x}{l_{\mu\nu}\int \langle D|\, j^{\mu}(x)j^{\nu}(0)\,|D\rangle e^{iq\cdot x} d^4}$$

$$V_{\mu} = \left(\bar{u}\gamma_{\mu}u - \bar{d}\gamma_{\mu}d\right) \Leftrightarrow S_{\mu} = \left(\bar{u}\gamma_{\mu}u + \bar{d}\gamma_{\mu}d\right)$$

$$\langle VV\rangle = l_{\mu\nu}\int \langle D|V^{\mu}(x)V^{\nu}(0)|D\rangle e^{iq\cdot x} d^4x$$

Next use CVC
(deuteron only)

$$A = \frac{(C_{1u} - C_{1d})\langle VV\rangle + \frac{1}{3}(C_{1u} + C_{1d})\langle SS\rangle}{\langle VV\rangle + \frac{1}{3}\langle SS\rangle}$$

Zero in QPM

$$\langle VV\rangle - \langle SS\rangle = \langle (V-S)(V+S)\rangle \propto l_{\mu\nu}\int \langle D|\bar{u}(x)\gamma^{\mu}u(x)\bar{d}(0)\gamma^{\nu}d(0)\rangle e^{iq\cdot x} d^4x$$

HT in F_2 is dominated
by quark-gluon correlations

Vector-hadronic piece only

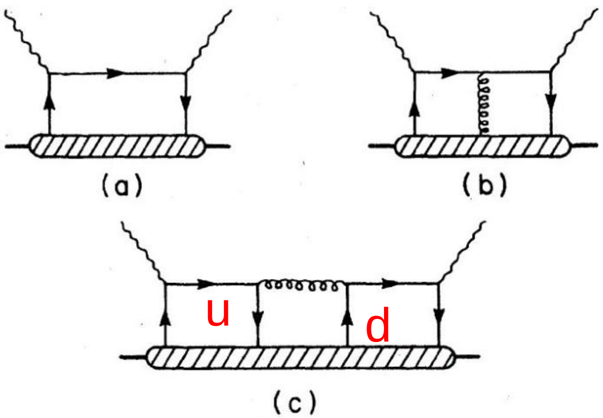
Higher-Twist valance
quark-quark correlations

Quark-Quark vs Quark-Gluon

PVDIS is the only known way to isolate quark-quark correlations

Parton Model
or
leading twist

Quark-gluon diagram



Di-quarks

Might be computed on the lattice

What is a true quark-gluon operator?

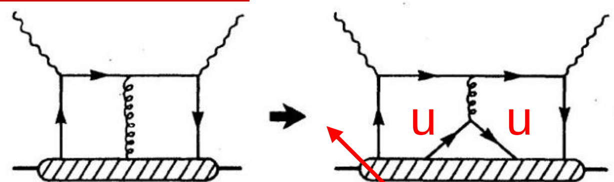


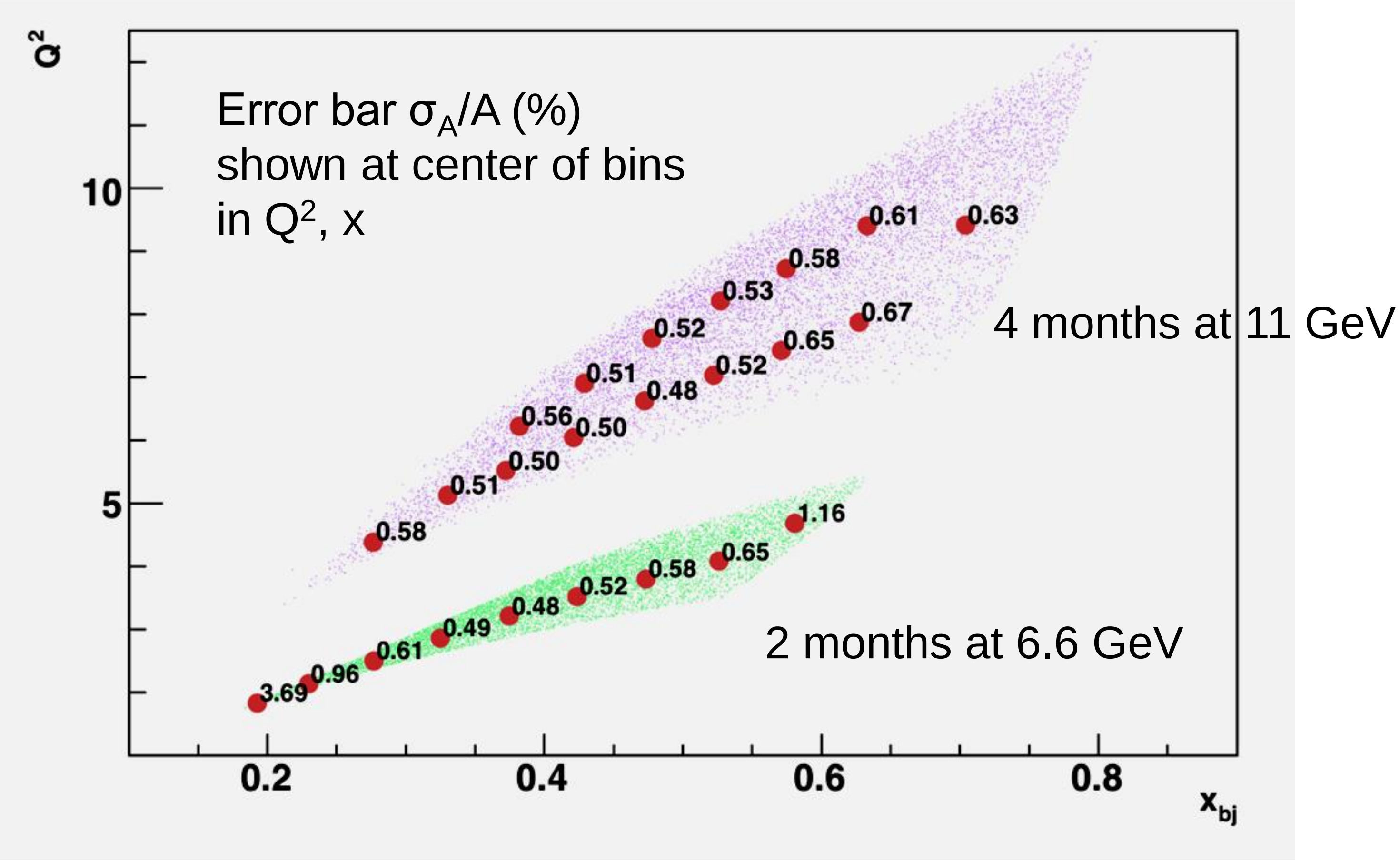
FIG. 3. The only gluon operator that we keep is the operator O^9, which can be expressed as a four-quark operator using the equations of motion.

Quark-gluon operators correspond to transverse momentum

QCD equations of motion

Statistical Errors (%) vs Kinematics

<u>Strategy:</u> sub-1% precision over broad kinematic range for **sensitive Standard Model test** *and* **detailed study of hadronic structure contributions**



Coherent Program of PVDIS Study

Strategy: requires precise kinematics and broad range

Fit data to:

$$A = A\left[1 + \beta_{HT}\frac{1}{(1-x)^3 Q^2} + \beta_{CSV}x^2\right]$$

$C(x)=\beta_{HT}/(1-x)^3$

- **Measure A_D in NARROW bins of x, Q^2 with 0.5% precision**
- **Cover broad Q^2 range for x in [0.3,0.6] to constrain HT**
- **Search for CSV with x dependence of A_D at high x**
- **Use x>0.4, high Q^2, and to measure a combination of the C_{iq}'s**

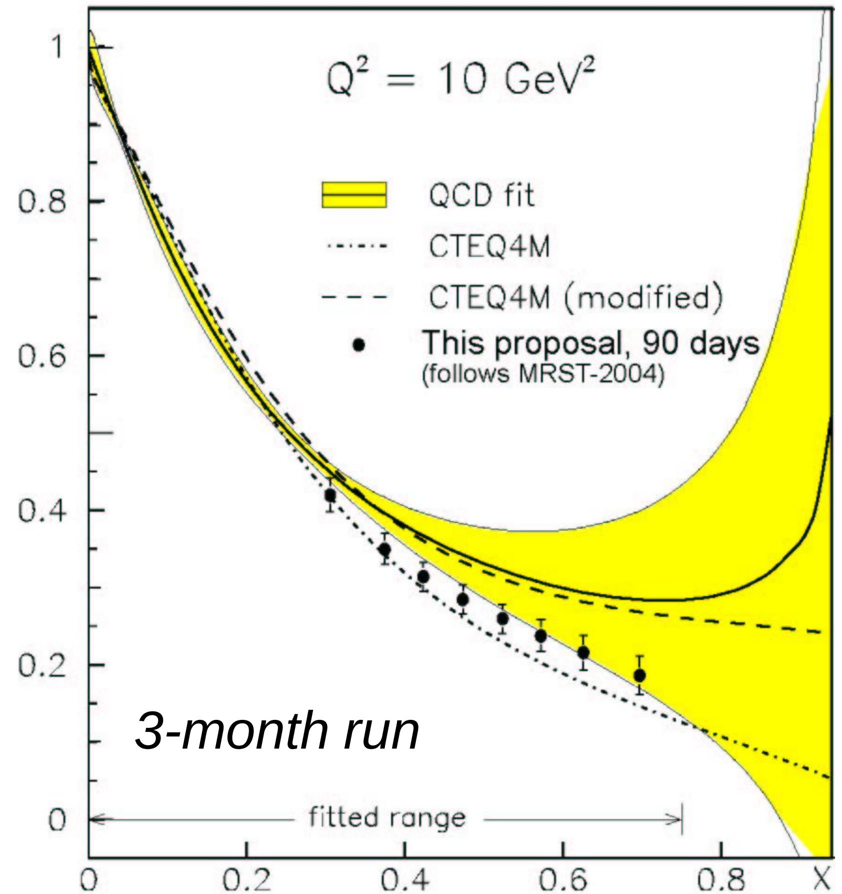
	x	y	Q^2
New Physics	no	yes	no
CSV	yes	no	no
Higher Twist	yes	no	yes

PVDIS on the Proton: d/u at High x

$$a^P(x) \approx \frac{u(x) + 0.91d(x)}{u(x) + 0.25d(x)}$$

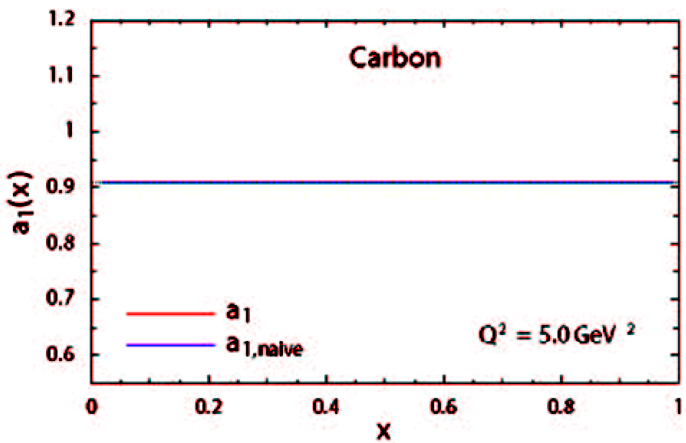
Deuteron analysis has large nuclear corrections (Yellow)

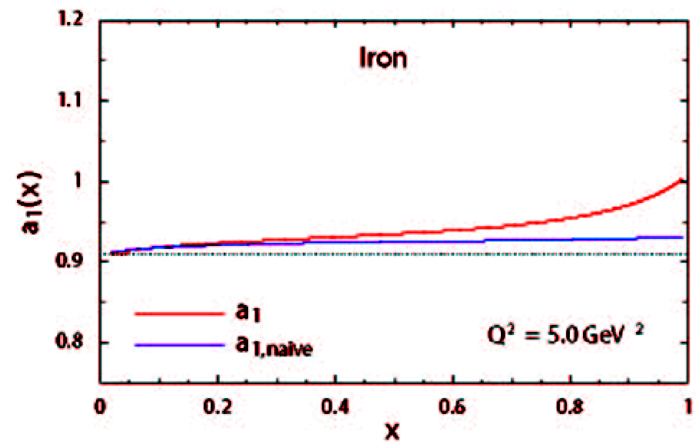
A_{PV} for the proton has no such corrections (complementary to BONUS)



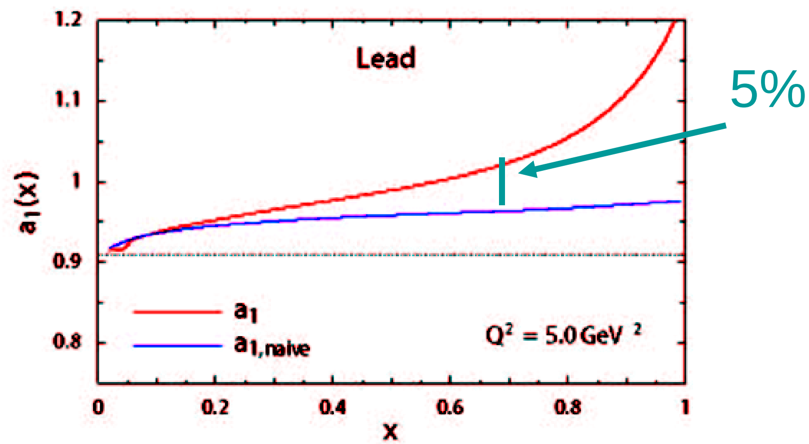
The challenge is to get statistical and systematic errors ~ 2%

CSV in Heavy Nuclei: EMC Effect



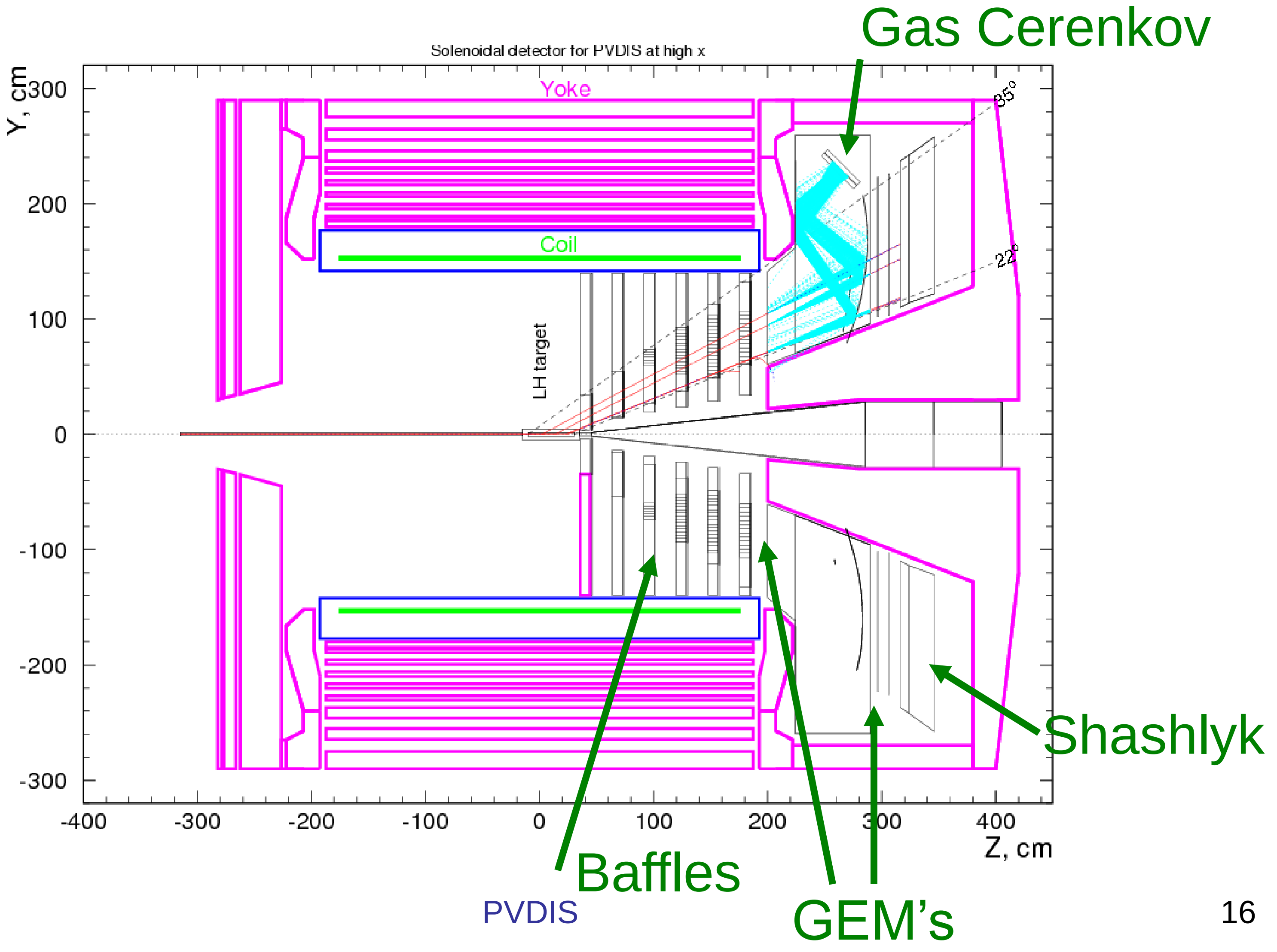


Additional possible application of SoLID

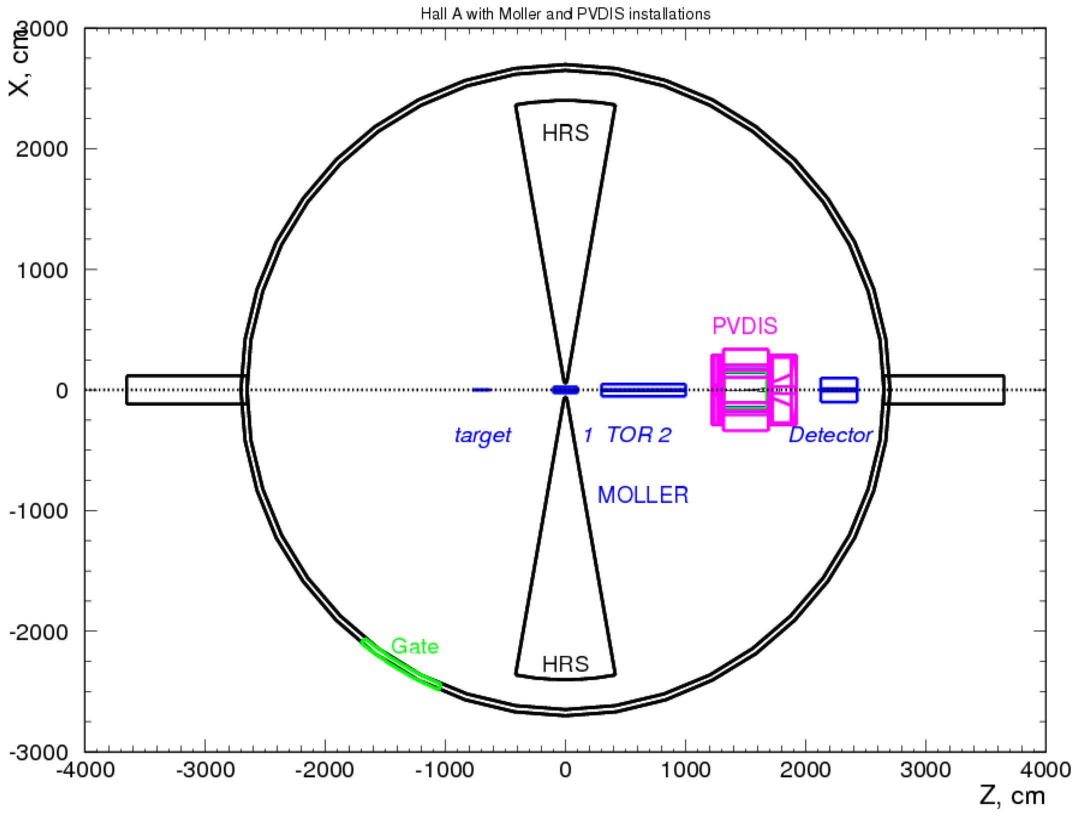


Isovector-vector mean field. (Cloet, Bentz, and Thomas)

SoLID Spectrometer

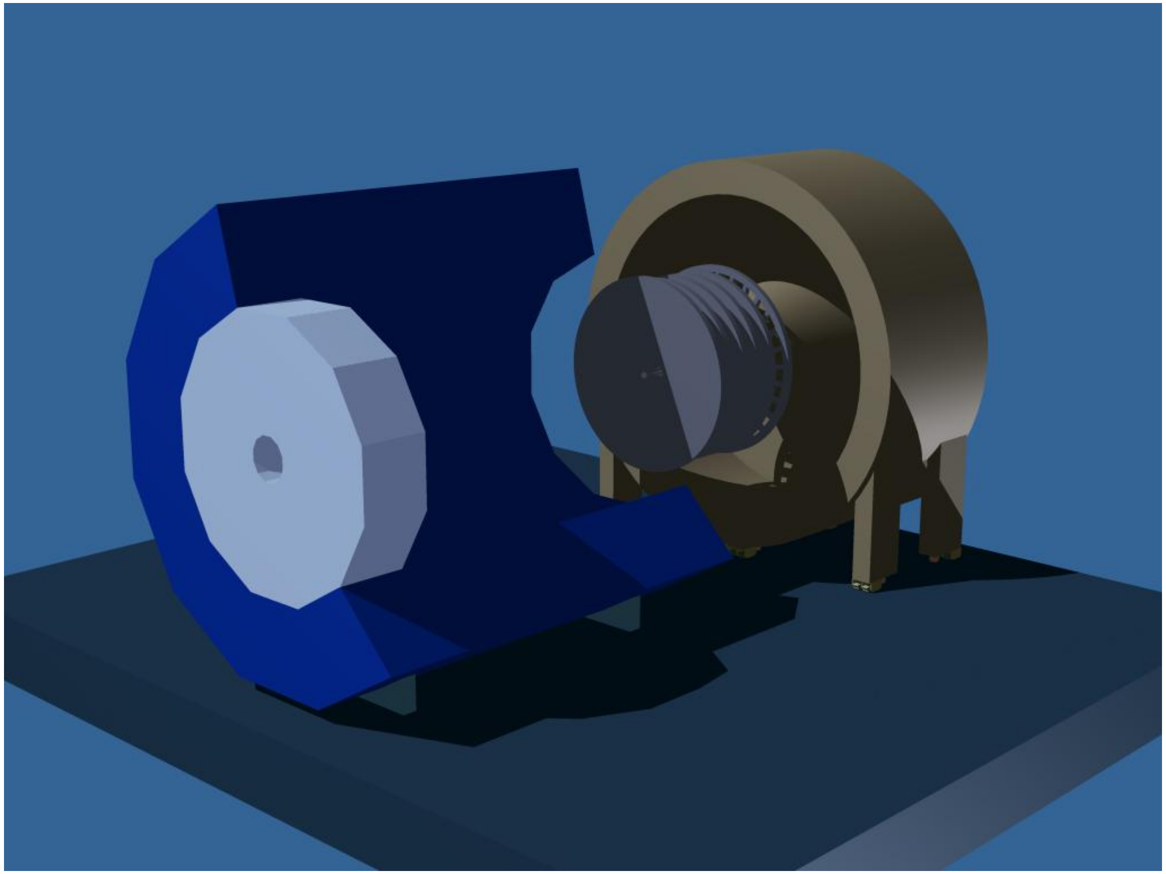


Layout of Moller and PVDIS

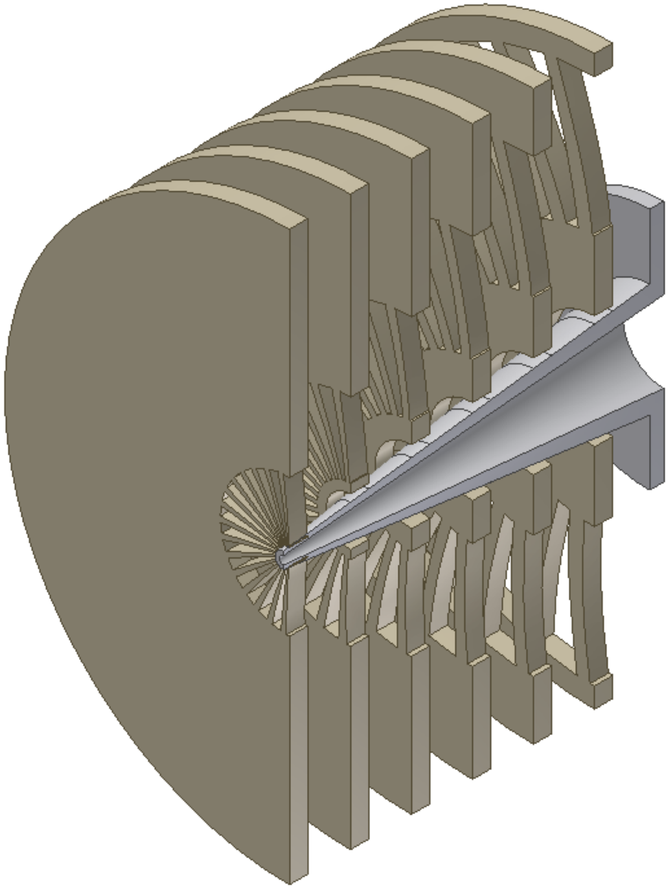


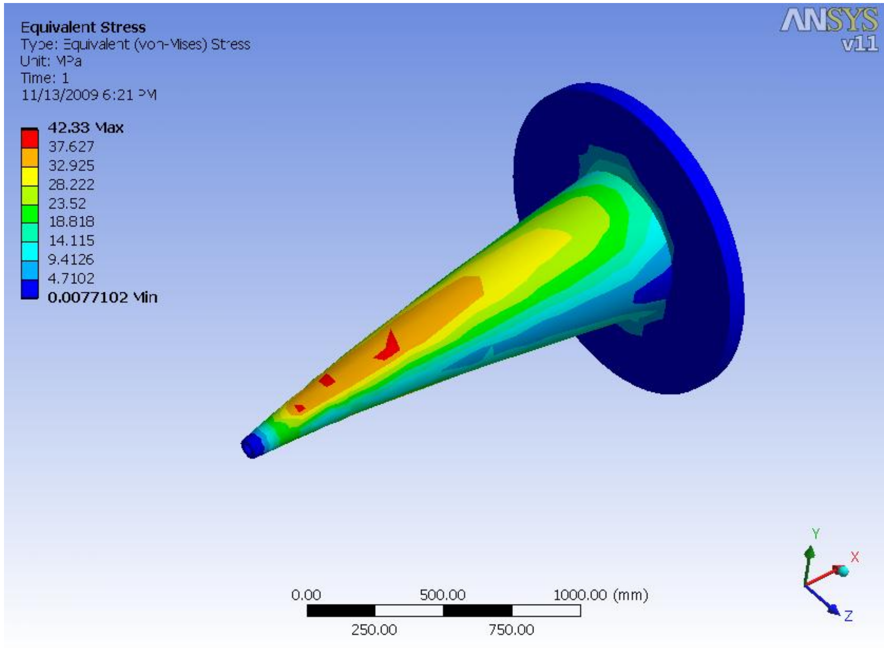
Access to the Detectors

- End Cap rolls backward along the beam line on Hilman Rollers
- 342 metric tons for both end caps with baffles installed
- Must allow for 5% rolling resistance



Baffle geometry and support





Error Projections for Moller Polarimetry

Variable	Hall C	Hall A		
		Fe at 3T		H_1 gas
Target polarization	0.25%	0.50%	0.25%	0.01%
Target angle	0.00%	0.00%	0.00%	0.00%
Analyzing power	0.24%	0.30%	0.20%	0.15%
Levchuk effect	0.30%	0.20%	0.20%	0.00%
Target temperature	0.05%	0.02%	0.02%	0.00%
Dead time	-	0.30%	0.15%	0.10%
Background	-	0.30%	0.15%	0.10%
Others	0.10%	0.30%	0.15%	0.15%
Beam extapolation	?	0.15%	0.15%	0.00%
Total	0.47%	0.82%	0.48%	0.25%

Table from MOLLER director's review by E. Chudakov

Summary of Compton Uncertainties

Relative Error (%)	electron	photon
E_{beam}	0.03	0.03
Laser Polarization	0.20	0.20
Radiative Corrections	0.1	0.1
False Asymmetries	0.01	0.01
Background	0.05	0.05
Deadtime / Pileup	0.2	0.1
Analyzing power	0.15	0.40
Total	0.34	0.47

correlated

uncorrelated

Independent detection of photons and electrons provides **two (nearly) independent polarization measurements**; **each should be better than 0.5%**

This would represent a significant step beyond what has been done at JLab before, but there is no fundamental reason why it should not be achievable.

Participants from UVa, Syracuse, JLab, CMU, ANL, Miss. St.

Error Budget in %

Statistics	0.3
Polarimetry	0.4
Q2	0.2
Radiative Corrections	0.3
Total	0.6

PVDIS Collaboration

P. Bosted, J. P. Chen,
E. Chudakov, A. Deur,
O. Hansen, C. W. de Jager,
D. Gaskell, J. Gomez,
D. Higinbotham, J. LeRose,
R. Michaels, S. Nanda,
A. Saha, V. Sulkosky,
B. Wojtsekhowski

Jefferson Lab

P. A. Souder, R. Holmes

Syracuse University

K. Kumar, D. McNulty,
L. Mercado, R. Miskimen

U. Massachusetts

H. Baghdasaryan, G. D. Cates,
D. Crabb, M. Dalton, D. Day,
N. Kalantarians, N. Liyanage,
V. V. Nelyubin, B. Norum,
K. Paschke, S. Riordan,
O. A. Rondon, M. Shabestari,
J. Singh, A. Tobias, K. Wang,
X. Zheng

University of Virginia

J. Arrington, K. Hafidi,
P. E. Reimer, P. Solvignon

Argonne

D. Armstrong, T. Averett,
J. M. Finn

William and Mary

P. Decowski

Smith College

L. El Fassi, R. Gilman,
R. Ransome, E. Schulte

Rutgers

W. Chen, H. Gao, X. Qian,
Y. Qiang, Q. Ye

Duke University

K. A. Aniol

California State

G. M. Urciuoli

INFN, Sezione di Roma

A. Lukhanin, Z. E. Meziani,
B. Sawatzky

Temple University

P. M. King, J. Roche

Ohio University

E. Beise

University of Maryland

W. Bertozzi, S. Gilad,
W. Deconinck, S. Kowalski,
B. Moffit

MIT

Benmokhtar, G. Franklin,
B. Quinn

Carnegie Mellon

G. Ron

Tel Aviv University

T. Holmstrom

Longwood University

P. Markowitz

Florida International

X. Jiang

Los Alamos

W. Korsch

University of Kentucky

J. Erler

Universidad Autonoma de Mexico

M. J. Ramsey-Musolf

University of Wisconsin

C. Keppel

Hampton University

H. Lu, X. Yan, Y. Ye, P. Zhu

University of Science and Technology of China

N. Morgan, M. Pitt

Virginia Tech

J.-C. Peng

University of Illinois

H. P. Cheng, R. C. Liu,
H. J. Lu, Y. Shi

Huangshan University

S. Choi, Ho. Kang, Hy. Kang B. Lee, Y. Oh

Seoul National University

J. Dunne, D. Dutta

Mississippi State

K. Grimm, K. Johnston,
N. Simicevic, S. Wells

Louisiana Tech

O. Glamazdin, R. Pomatsalyuk

NSC Kharkov Institute for Physics and Technology

Z. G. Xiao

Tsinghua University

B.-Q. Ma, Y. J. Mao

Beijing University

X. M. Li, J. Luan, S. Zhou

China Institute of Atomic Energy

B. T. Hu, Y. W. Zhang,
Y. Zhang

Lanzhou University

C. M. Camacho, E. Fuchey,
C. Hyde, F. Itard

LPC Clermont, Université Blaise Pascal

A. Deshpande

SUNY Stony Brook

A. T. Katramatou,
G. G. Petratos

Kent State University

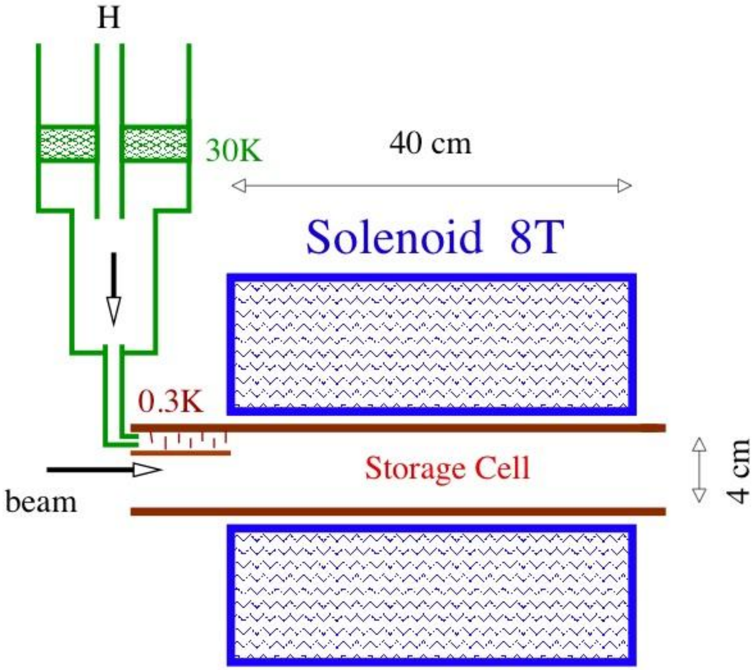
J. W. Martin

University of Winnipeg

Summary

- The physics is varied and exciting.
  - Excellent sensitivity to C_{2u} and C_{2d}.
  - Test CSV at quark level.
  - Unique window on higher twists.
- We will build a novel apparatus (with many other possible applications, eg. SIDIS)

Atomic Hydrogen For Moller Target



10 cm, $\rho = 3\times10^{15}/\text{cm}^3$
in B = 7 T at T=300 mK

$$\frac{n_+}{n_-} = e^{-2\mu B/kT} \approx 10^{-14}$$

Brute force polarization

Moller polarimetry from polarized atomic hydrogen gas, stored in an ultra-cold magnetic trap

- Tiny error on polarization
- Thin target (sufficient rates but no dead time)
- 100% electron polarization
- Non-invasive
- High beam currents allowed
- No Levchuk effect

E. Chudakov and V. Luppov, IEEE Transactions on Nuclear Science, v 51, n 4, Aug. 2004, 1533-40

High Precision Compton

At high energies, SLD achieved 0.5%.

Why do we think we can do better?

- SLD polarimeter near interaction region - background heavy
- No photon calorimeter for production

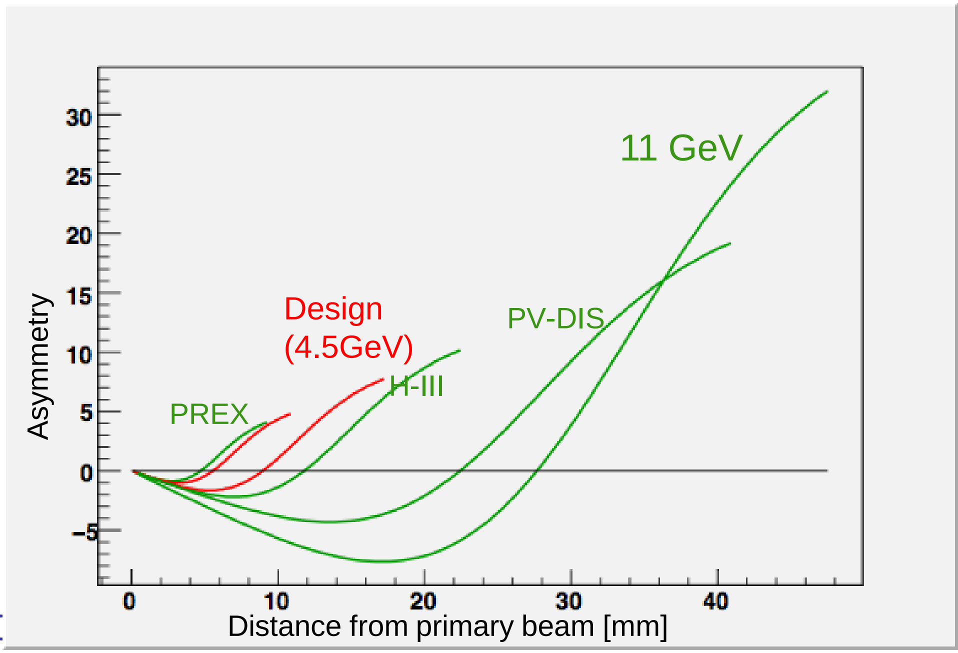
- Hall A has “counting” mode (CW)
- Efficiency studies
- Tagged photon beam

- Greater electron detector resolution

Its a major effort, but there is no obvious *fundamental* show-stopper

So why haven’t we done better before?

- Small asymmetries
  = long time to precision
  = cross-checks are difficult
- Zero-crossing technique is new. (zero crossing gets hard near the beam)
- Photon calorimetry is harder at small E_γ



Layout ofSpectrometer using CDF coil

- Coil mounting is well understood from CDF
  - Designed to be supported by end
  - Supports allow radial movement in both ends for thermal
  - One end fixed axially
- Will need to check for decentering forces due to field asymmetry (Lorentz forces)