New Measurements of Parity Violation in Deep Inelastic Electron Scattering

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Outline

- Electroweak Physics, Low Q^2 and JLab
- E08-010, 6 GeV PVDIS
- SoLID - 12 GeV proposed measurements

Collaboration

The Jefferson Lab PVDIS Collaboration

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- Kai Pan, MIT
- Diancheng Wang, UVa
- Ramesh Subedi, UVa

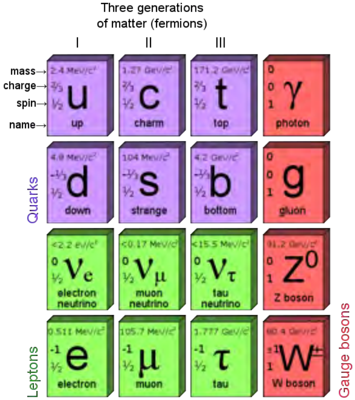
- Four vector bosons $(W^{\pm,0}, B)$ from $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
- "weak SU(2)" left-handed doublets:

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}, \begin{pmatrix} u \\ d \end{pmatrix}, \ldots$$

with EM charge

$$Q = T^3 + \frac{Y}{2}$$

$T = 1/2$ for left-handed, $T = 0$ for right-handed



$$\begin{aligned} A_\mu &= B_\mu \cos\theta_W + W^0_\mu \sin\theta_W \\ Z_\mu &= W^0_\mu \cos\theta_W - B_\mu \sin\theta_W \\ \sin^2\theta_W &\approx 0.2311 \end{aligned}$$

Electroweak Relations

- $W^{\pm,0}$ sees charge g, related to effective contact interaction:

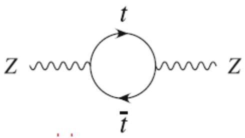
$$\frac{G_F}{\sqrt{2}} = \frac{g^2}{8M_W^2}$$

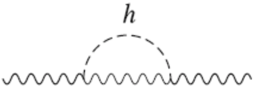
- B^0 sees charge g', must recover EM relation:

$$e = g\sin\theta_W = g'\cos\theta_W$$

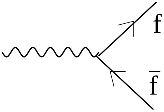
- Include Higgs mechanism for EW symmetry breaking to give $M_{Z,W} > 0$

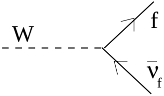
$$M_W = M_Z\cos\theta_W$$

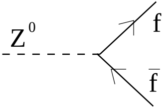




Boson	Vertex
γ	$-iQ\gamma^{\mu}$
$W^{\pm}$	$-i\frac{g}{\sqrt{2}}\gamma^{\mu}\frac{1}{2}\left(1-\gamma^{5}\right)$
Z^{0}	$-i\frac{g}{\cos\theta_W}\gamma^{\mu}\frac{1}{2}\left(c_V - c_A\gamma^{5}\right)$





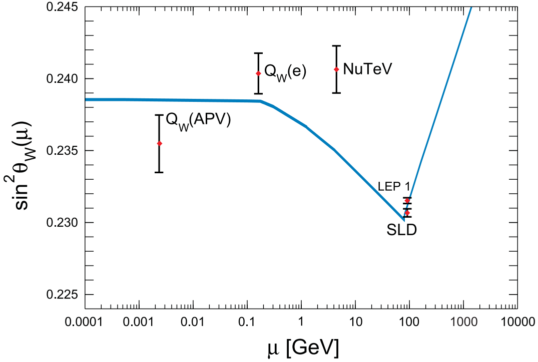


For neutral currents with electrons:

$$c_A^e = -\frac{1}{2}, \quad c_V^e = -\frac{1}{2} + 2\sin^2\theta_W = -0.03$$

Radiative Corrections and Running

- Value of $\sin^2 \theta_W$ runs with energy scale

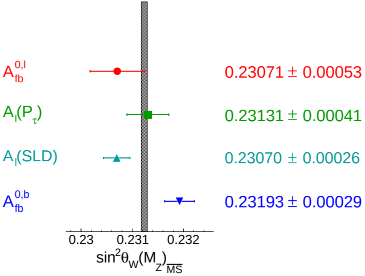


- Mapped out by APV, Moller scattering, e^+/e^- collisions, νN interactions
- Data has inconsistancies!
  - LEP and SLAC disagree by $\sim 3\sigma$, results typically averaged
  - NuTeV off by $> 2.5\sigma$, needs nuclear modification effects?

Higgs Constraints

Now that Higgs is found, $\sin^2\theta_W$ is predicted independently!

- With m_t, M_H, G_F, M_Z, α, one gets high precision predictions for M_W and $\sin^2\theta_W$ in
- With $M_H = 126$ GeV:

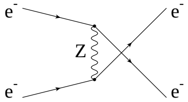


- Average of $\sin^2\theta_W$ measurements gives "right" answer

Some low Q^2 $\sin^2\theta_W$ Options

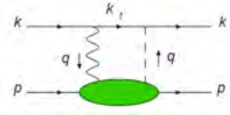
Moller (ee): E158, 12 GeV JLab Moller

- $Q_W^e = 1 - 4\sin^2\theta_W$ reduced by 40% by running



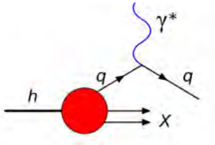
Elastic proton ($ep \to ep$): HAPPEX, Q_{weak}, Mainz P2

- Uncertainties in corrections from $\gamma - Z$ box



Deep inelastic e ($eN \to e'X$): SLAC Prescott, JLab 6 GeV PVDIS, SoLID

- Typically more backgrounds, complicated by hadron structure

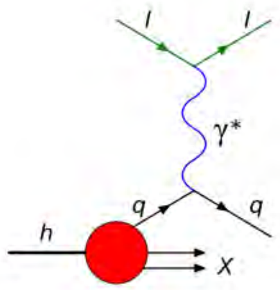


Inelastic scattering is rich information source

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\mathrm{d}E'} = \frac{\alpha^2}{4E^2\sin^4\frac{\theta}{2}}\left(W_2(E-E',Q^2)\cos^2\frac{\theta}{2} + 2W_1(E-E',Q^2)\sin^2\frac{\theta}{2}\right)$$

$$\approx \left.\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right|_{p=xP}^{\mathrm{point},S=1/2} F_2(x) \sim \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\sum_q e_q^2(q(x)+\bar{q}(x)), \quad x = \frac{Q^2}{2M(E-E')}$$

- Cross sections suggest behaving almost like point-like particles!
- x has interpretation of momentum fraction carried by quark in infinite- momentum frame



Inelastic scattering is rich information source

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\Omega\,\mathrm{d}E'} \approx \left.\frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\right|^{\mathrm{point},S=1/2}_{p=xP} F_2(x)$$

$$\sim \frac{\mathrm{d}\sigma}{\mathrm{d}\Omega}\sum_q e_q^2\left(q(x)+\bar{q}(x)\right)$$

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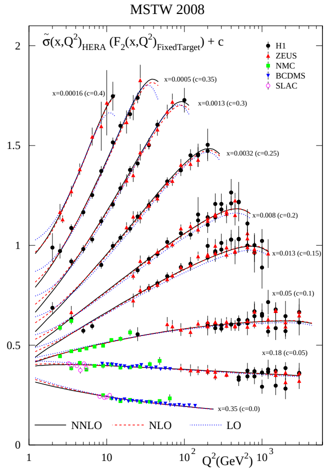


Nucleons Made of Partons

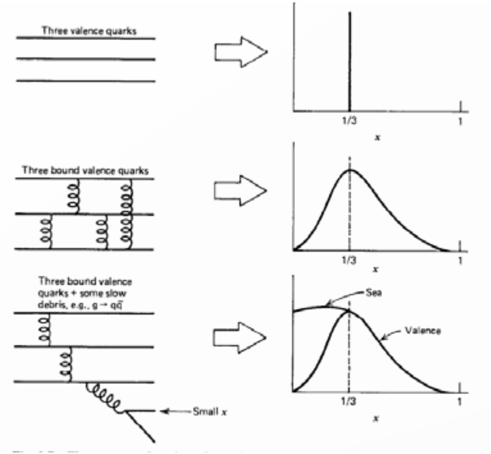
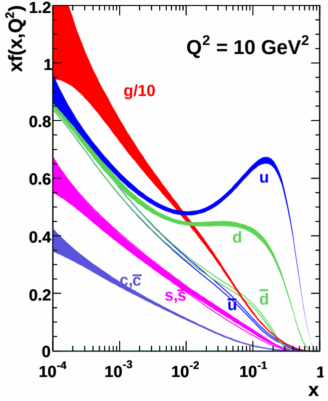


Figure from Halzen and Martin

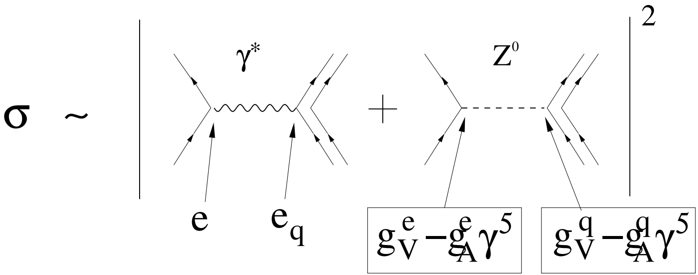


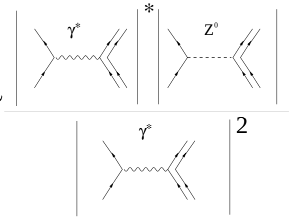
DIS parton distribution functions have been well measured

Parity Violation

Z^0 interacts similarly to γ but:

- Couples to weak charges
- Is $\sim 10^{-4}$ times weaker
- Has a parity-violating component!



$A_{PV} \sim$ 

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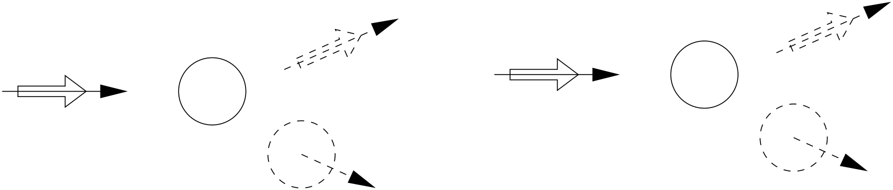
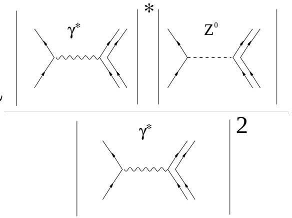


$A_{PV} \sim$ 

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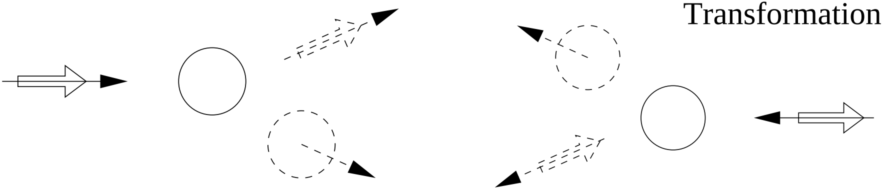
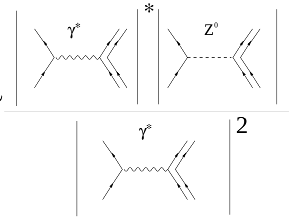


Parity Transformation

Parity Violation

$A_{PV} \sim$



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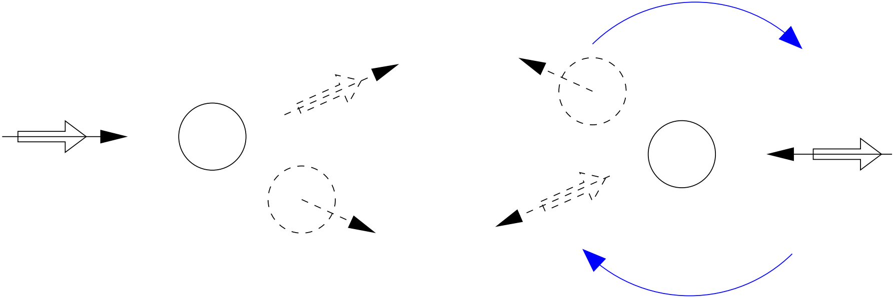
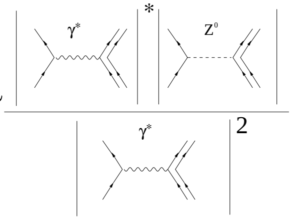


Parity Violation

$A_{PV} \sim$ 

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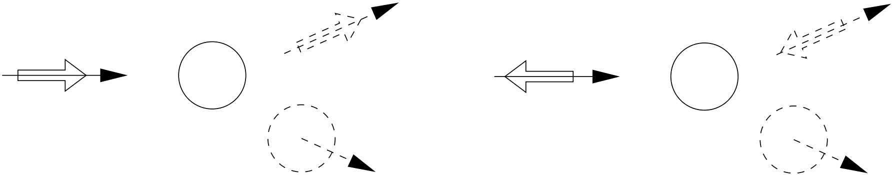
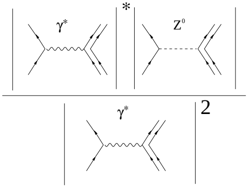


Parity Violating DIS

Sensitive to different effective charge couplings in PDFs...

$$A_{\mathrm{PV}} \sim$$



$$\sim 100 - 1000 \text{ ppm}$$

$$\approx -\frac{G_F Q^2}{4\sqrt{2}\pi\alpha}\left[a_1(x) + \frac{1-(1-y)^2}{1+(1-y)^2} a_3(x)\right], y = 1 - \frac{E'}{E}$$

$$a_1(x) = 2\frac{\sum C_{1q} e_q (q+\bar{q})}{\sum e_q^2 (q+\bar{q})}, a_3(x) = 2\frac{\sum C_{2q} e_q (q-\bar{q})}{\sum e_q^2 (q+\bar{q})}$$

New Effective Weak Couplings

$$C_{1u} = -\frac{1}{2} + \frac{4}{3}\sin^2\theta_W = -0.19 \qquad C_{2u} = -\frac{1}{2} + 2\sin^2\theta_W = -0.03$$

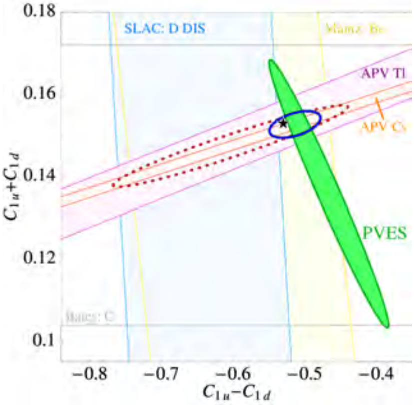
$$C_{1d} = \frac{1}{2} - \frac{2}{3}\sin^2\theta_W = 0.34 \qquad C_{2d} = \frac{1}{2} + 2\sin^2\theta_W = 0.03$$

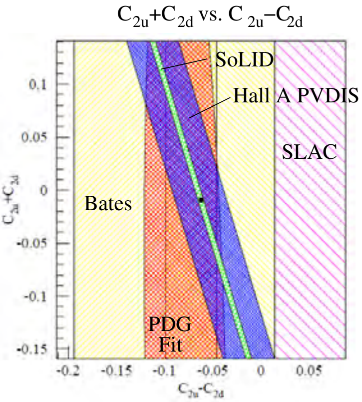
PVDIS Physics - Precision

- Deuterium powerful, since $q(x)$ cancel for large x

$$a_1^D(x) \approx 2\frac{C_{1u}e_u[u(x)+d(x)] + C_{1d}e_d[u(x)+d(x)]}{e_u^2[u(x)+d(x)] + e_d^2[u(x)+d(x)]}$$

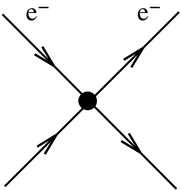
C_{2q} not as well constrained





New Contact Interactions at low Q^2

- Shifts in measured $\sin^2\theta_W$ can appear from new physics
  - New Z-like heavy bosons in contact interactions
  - Light “dark” Z showing up at low Q^2
  - Supersymmetry influencing radiative loops
- Sensitive to different channels - useful to look at on different targets



$$L \sim \sum_{i,j=L,R} \pm \frac{g_{ij}^2}{\Lambda_\pm^2} \bar{e}_i \gamma_\mu e_i \bar{f}_j \gamma^\mu f_j$$

- Reach of $\Lambda \sim$ few-several TeV possible experiments $\sim \mathrm{GeV}^2$ scale
- Competitive with direct production searches at colliders!

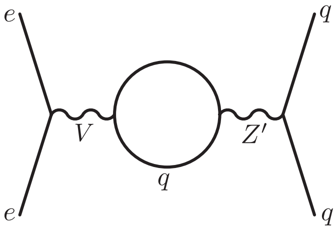
Review: K.S. Kumar *et al.*, arXiv:1302.6263

Leptophobic Z'

- New physics could be hiding in C_{2q} and not C_{1q}
- Leptophobic Z' could mix with photon through $q\bar{q}$ loops, requires vector coupling with $ee'\gamma$
- This type of interaction pops up in a variety of SM extensions

M.R. Buckley *et al.*, Phys Lett B 712, 261 (2012)

$$C_{1q} = 2g_A^e g_V^q$$
$$C_{2q} = 2g_V^e g_A^q$$

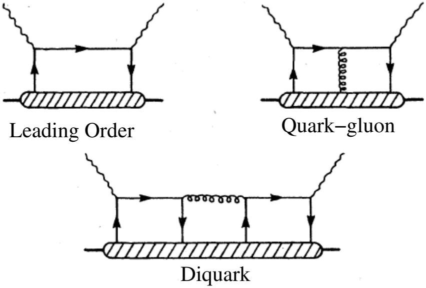


Higher Twist

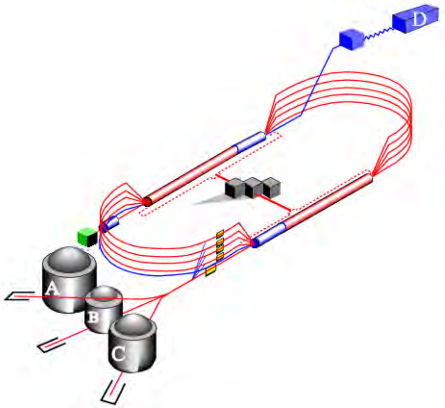
Large kinematic reach allows for evaluation of higher twist

$$a_1^D(x) \approx 2\frac{C_{1u}e_u[u(x)+d(x)] + C_{1d}e_d[u(x)+d(x)]}{e_u^2[u(x)+d(x)] + e_d^2[u(x)+d(x)]}$$

- In asymmetry measurement, Q^2 dependence from HT in qq correlations can show up while effects such as DGLAP cancel and $q(x)$ cancel for isoscalar targets



Continuous **E**lectron **B**eam **A**ccelerator **F**acility
at Jefferson Lab, Newport News, VA
"World's most powerful microscope"



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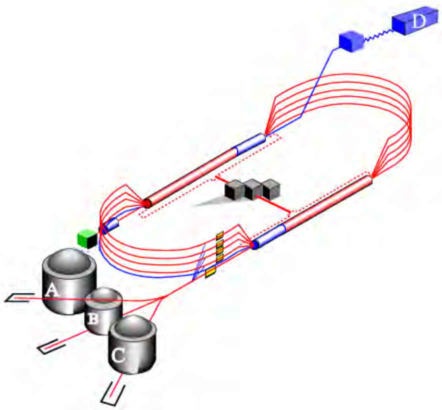
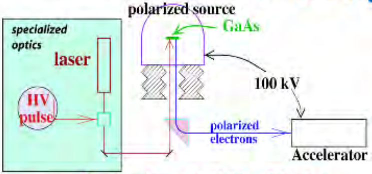


Features

- Electron accelerator by superconducting RF cavities
- 4 experimental halls
- $E = 2.2 - 11$ GeV
- $I_{\max} = 200\ \mu$A
- High $P_e \sim 85\%$

Excellent for studying low Q^2 EW physics

How to do a Parity Experiment (integrating method)



rapid, random, helicity flipping

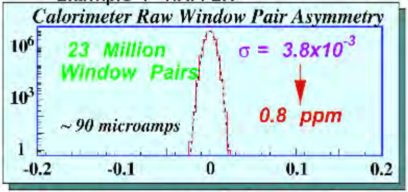
Rapid, Random Helicity Flips

Measure flux F for each window

$$A_{\text{window pair}} = \frac{F_R - F_L}{F_R + F_L}$$

Signal Average N Windows Pairs: $A \pm \frac{\sigma(A)}{\sqrt{N_{\text{windows}}}}$

Example : HAPPEX

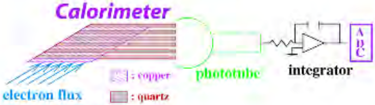


No non-gaussian tails to +/- 5σ

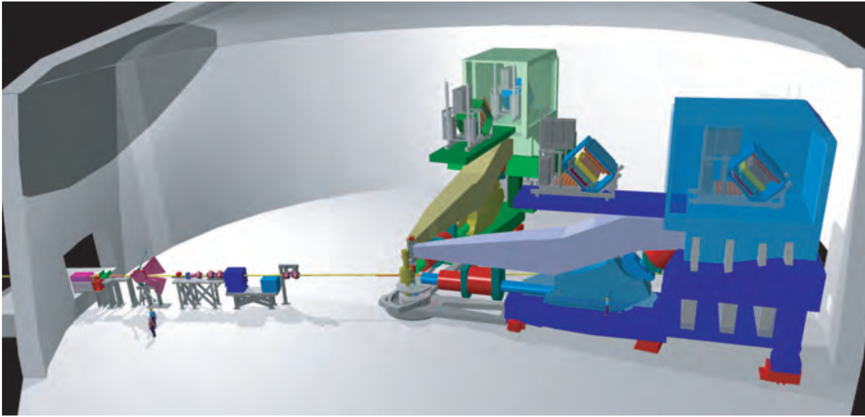
Flux Integration Technique:

HAPPEX: 2 MHz

PREX: 500 MHz



Experimental Configuration

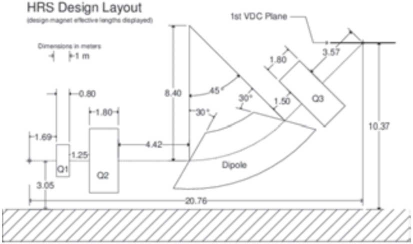


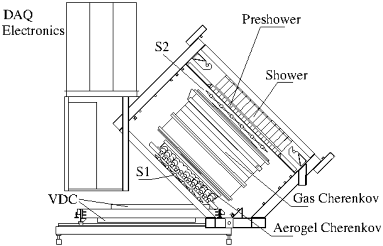
- Run both spectrometers independently
- Need online rejection for π^- background

HRS Design

Mangetic Chain

- $\sim 6\ \mathrm{msr}$ acceptance
- $-4.5 < \delta p/p < 4.5\%$ momentum acceptance





Detectors

- Trigger on shower+preshower
- Shower/preshower + gas cernekov provides pion rejection

PVDIS at 6 GeV (JLab E08-011)

- Ran in Oct-Dec 2009, 100uA, 90% pol beam, 20-cm LD2 target
- Q^2=1.1 and 1.9 GeV^2.
- Scaler-based fast counting DAQ ($100k) specifically built to accommodate the 500kHz DIS rate with 10^4 pion rejection

- Postdoc: Ramesh Subedi
- Graduate Students: Xiaoyan Deng (UVa), Huaibo Ding (China), Kai Pan (MIT), Diancheng Wang (UVa),

X. Zheng, July 2012

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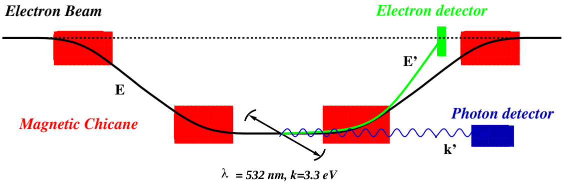
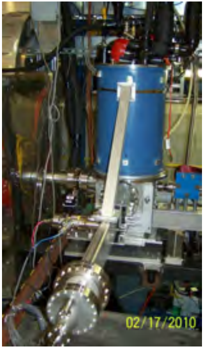
Polarimetry



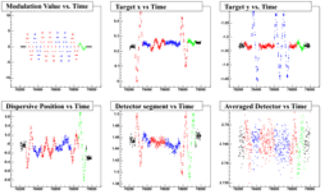


- Compton polarimetry offers non-invasive $\vec{P}$ measurement
- Moller with high field polarized iron foil - ee' scattering asymmetries
- Systematic uncertainty about 1.5% from each

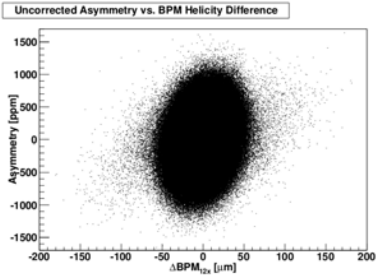
Modulation Correction

Modulation corrections provide narrower asymmetry widths

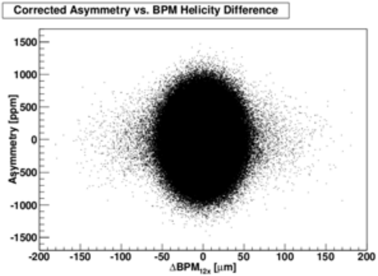
corrects for false asymmetries



$$A = A_0 + \Sigma \frac{dA}{dX_i} \Delta X_i$$

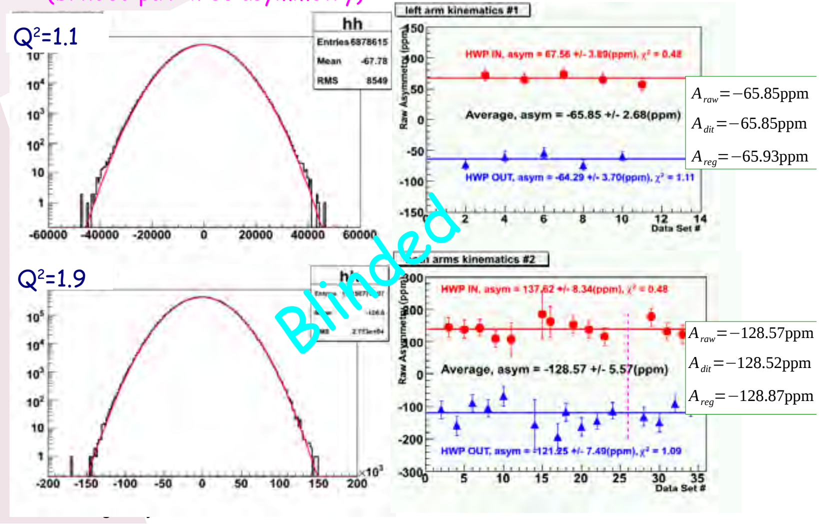


$\rightarrow$

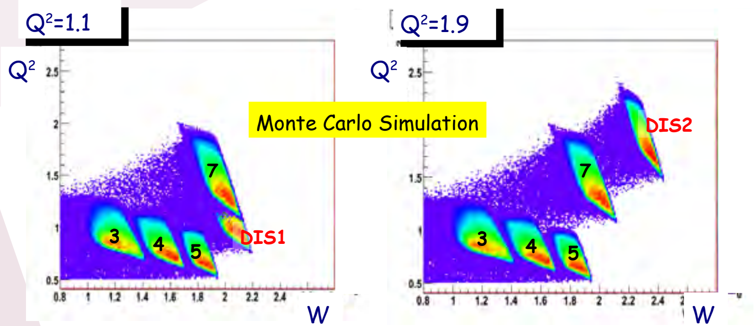


Quality of Asymmetry Measurement

(blinded pair-wise asymmetry):



Corrections for Resonance Background



- Implemented in MC: ionization loss, internal+ext. brem
- Measured resonance PV asymmetries (10-15% stat.) to constrain inputs of two resonance PV models: Delta agree at 2σ, 2nd and 3rd resonances agree within 1σ.
- Corrections to A DIS: ~(2±2)% (1.1 GeV^2); (2±0.4)% (1.9 GeV^2)

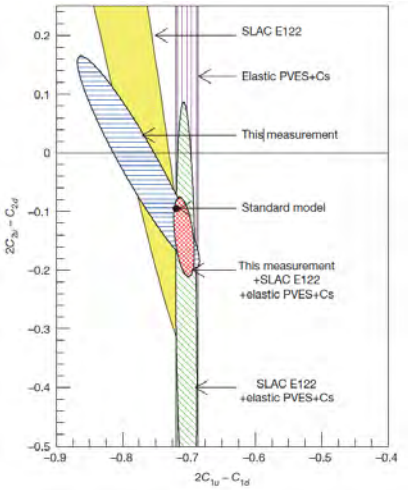
Results

$$A_{\rm exp} = -91.1 \pm 3.1({\rm stat}) \pm 3.0({\rm sys})\ \text{ppm}$$
$$A_{\rm exp} = -160.8 \pm 6.4({\rm stat}) \pm 3.1({\rm sys})\ \text{ppm}$$

- Dominiant systematic is polarimetery $\sim 1.2 - 1.8\%$

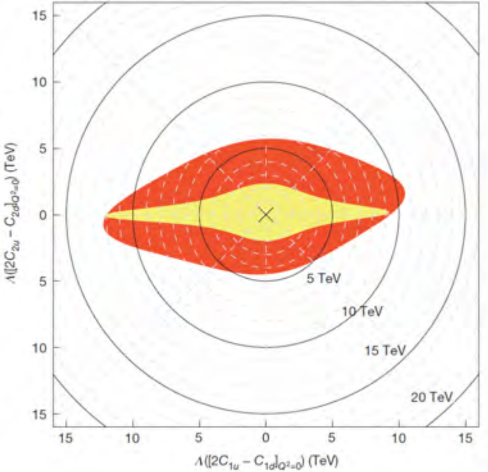
- Significant new constraints on C_2 couplings
- Result: $\sin^2\theta_W = 0.2299 \pm 0.0043$
- SM: $\sin^2\theta_W = 0.23126 \pm 0.00005$

$2C_{2u} - C_{2d}$ vs $2C_{1u} - C_{1d}$



Nature 506, 6770 (06 February 2014)

$2C_{2u} - C_{2d}$ vs $2C_{1u} - C_{1d}$



Nature 506, 6770 (06 February 2014)

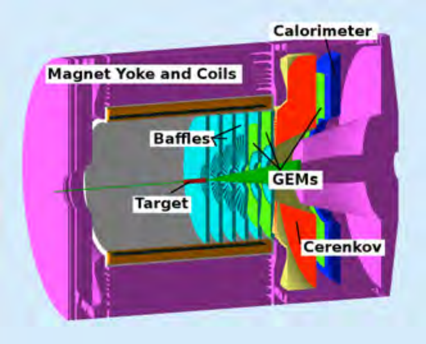
$$L \sim \sum_{i,j=L,R} \pm \frac{g_{ij}^2}{\Lambda_\pm^2} \bar{e}_i \gamma_\mu e_i \bar{f}_j \gamma^\mu f_j$$

For $2C_{2u} - C_{2d}$ no new physics:

- Our Result
- SLAC E122
- At 95% CL
  - $\Lambda^+ = 5.8$ TeV
  - $\Lambda^- = 4.6$ TeV

PVDIS Measurements - SoLID Proposed Setup

Solenoidal **L**arge **I**ntensity **D**evice - 12 GeV Hall A at JLab
More than 200 collaborators at over 60 institutions



SoLID provides large acceptance

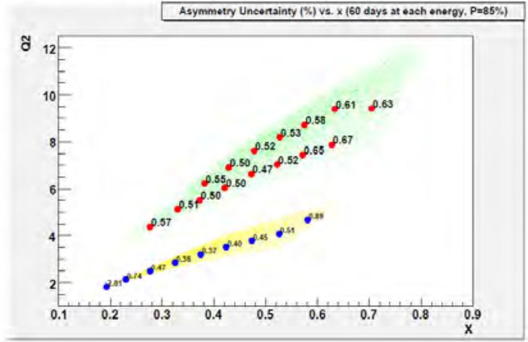
- $2 < p < 8$ GeV
- $2 < Q^2 < 10\ \mathrm{GeV}^2$
- $0.2 < x_{bj} < 1$
- Acceptance $\sim 40\%$
- Lumin $\sim 5 \times 10^{38}\ \mathrm{Hz/cm}^2$

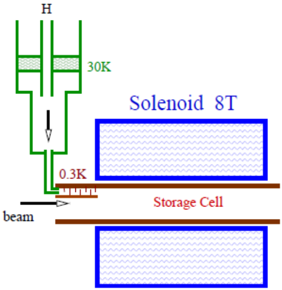
- Parity-violation requires lots of statistics - need high rate
- Want to cover broad kinematic range - need large acceptance
- High impact $40-50M project, 2020+ in the future
- Program also includes SIDIS, J/ψ at threshold, possible future w/ Pb PVDIS, DDVCS, PV polarized PDFs...

Approved Measurement

- Approved for 169 days (requested 338)

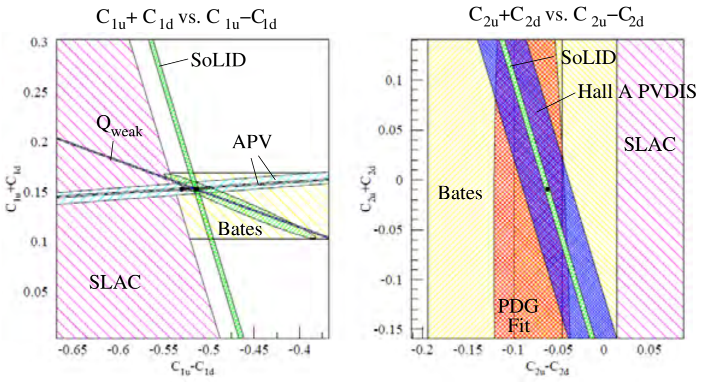
LD_2, 120 days:





- 120 days on LD_2 (60 at 11 GeV, 60 at 6.6 GeV)
- Sub-1% precision - need H-Moller polarimetry
- Also, 90 days on LH_2 11 GeV

Anticipated Results w/ World Data



- Can reach another order of magnitude in C_2

Anticipated Results w/ World Data

- Uncertainty of $\sim 0.1\%$ on $\sin^2\theta_W$ on par with best measurements

Summary

- By studying the unified electroweak processes, constraints on new physics can be placed, potential for discovery
- The recent PVDIS experiment puts new constraints on physics beyond the standard model as well as new data on hadronic physics
- Future PVDIS measurements with SoLID will provide larger coverage pushing these results to higher precision and testing for a superclass of physics

BACKUP

Correction Due to Pion Contamination

(work of K. Pan and D. Wang)

Pion asymmetry is observed to be non-zero:

	Left Kine#1	Left Kine#2	Right Kine#2
$A\pi$ narrow (ppm)	-48.01(7.54)	-14.00(14.89)	-9.51(4.22)
electron fraction	0.56 (0.16)	0.04(0.04)	0.011(0.001)
$A\pi$ corrected (ppm)	-30.85(12.84)	-8.91(16.31)	-8.04(4.27)

Pion correction uncertainty is the combination of:

$$\frac{\Delta A_e}{A_e} = \Delta f \oplus f \frac{\Delta A_\pi}{A_e}$$

	Kine#1	Kine#2
Correction to Ae	1.00019(0.00014)	1.00024(0.00003)

X. Zheng, July 2012

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Corrections and Uncertainties, Kine #1

blinding factor = -12.00665ppm

		Correction	Uncertainty
	Raw (Dithering) A_d (ppm)	-66.43	2.68
Run-by-Run	$\Delta P_b/P_b$	13.4%	2.0%
	Deadtime correction	1.49%	0.44%
	PID efficiency	0.048%	0.008%
Global	Radiative Correction	2.1%	2.0%
	Q^2	N/A	0.725%
	Transverse Asymmetry	N/A	0.55%
	Target Endcap	0.017%	0.003%
	False Asymmetry	N/A	0.16%
	Pair Production	0.025%	0.005%
	Pion Dilution	0.019%	0.014%
	Statistical (ppm)	3.15	
	Systematics	3.01%	

X. Zheng, July 2012

Corrections and Uncertainties, Left Kine #2

blinding factor = -12.00665ppm

		Correction	Uncertainty
	Raw (Dithering) A_d (ppm)	-128.48	10.43
Run-by-Run	$\Delta P_b/P_b$	12.0%	1.33%
	Deadtime correction	0.84%	0.25%
	PID efficiency	0.091%	0.013%
Global	Radiative Correction	1.9%	0.43%
	Q^2	N/A	0.575%
	Transverse Asymmetry	N/A	0.56%
	Target Endcap	0.023%	0.005%
	False Asymmetry	N/A	0.1%
	Pair Production	0.52%	0.052%
	Pion Dilution	0.025%	0.004%
	Statistical (ppm)	12.08	
	Systematics	1.64%	

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Corrections and Uncertainties, Right Kine #2

blinding factor = -12.00665ppm

		Correction	Uncertainty
	Raw (Dithering) A_d (ppm)	-128.56	6.58
Run-by-Run	$\Delta P_b/P_b$	12.7%	1.69%
	Deadtime correction	0.86%	0.25%
	PID efficiency	0.161%	0.018%
Global	Radiative Correction	1.9%	0.43%
	Q^2	N/A	0.640%
	Transverse Asymmetry	N/A	0.56%
	Target Endcap	0.023%	0.005%
	False Asymmetry	N/A	0.03%
	Pair Production	0.48%	0.048%
	Pion Dilution	0.024%	0.002%
	Statistical (ppm)	7.67	
	Systematics	1.96%	

X. Zheng, July 2012

Preliminary Asymmetries Compared with Calculation

x_{bj}=0.241, Q^2=1.085 GeV^2: Ad=-92.27 ±3.15 (stat.) ± 2.77 (syst) ppm
x_{bj}=0.295, Q^2=1.901 GeV^2: Ad=-163.60 ± 6.48 (stat.) ± 3.05 (syst) ppm

Still missing: γ-Z box corrections (1% for E158)

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

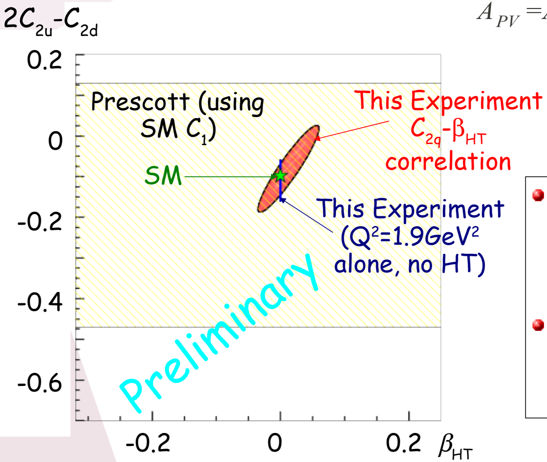
Q^2=1.085	x=0.241				
F_2^{γ}, $F_2^{\gamma Z}$, $F_3^{\gamma Z}$	"static (quark model) limit"	CTEQ/ JLab (NLO)	MSTW2008 LO+QPM	**MSTW2008 NLO+QPM**	MSTW2008 NNLO+QPM
A(C_1 term)	-83.15	NA	-83.69	**-84.32**	-84.35
A(C_2 term)	-5.58	NA	-4.60	**-4.74**	-4.78

Q^2=1.901	x=0.295				
F_2^{γ}, $F_2^{\gamma Z}$, $F_3^{\gamma Z}$	"static (quark model) limit"	CTEQ/ JLab (NLO)	MSTW2008 LO+QPM	**MSTW2008 NLO+QPM**	MSTW2008 NNLO+QPM
A(C_1 term)	-145.65	-147.74	-146.58	**-147.09**	-147.05
A(C_2 term)	-14.59	-13.62	-13.12	**-13.41**	-13.50

Results - Higher Twist

Preliminary C_{2q} - β_{HT} Correlation from Q^2=1.1 and 1.9 GeV^2 Combined

$$A_{PV} = A_{PV}^{EW}\left(1 + \frac{\beta_{HT}}{(1-x)^3 Q^2}\right)$$



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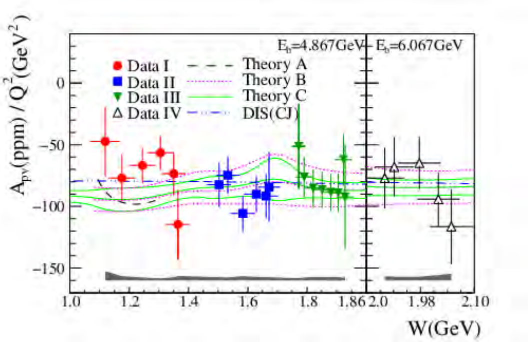
- No obvious Q^2 dependence (HT) at the 6 GeV precision.
- If using 1.1 GeV^2 point to extract C_2 → 10% better.

Results - Resonance

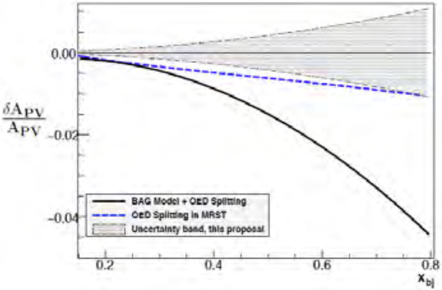


- Resonance data isn't just for systematics!
- Statistical uncertainties fairly large, but provide important constraints on theory

Results agree with quark-hadron duality
D. Wang et al., Phys. Rev. Lett. 111, 082501 (2013)

Charge Symmetry Violation - $u \leftrightarrow d$?

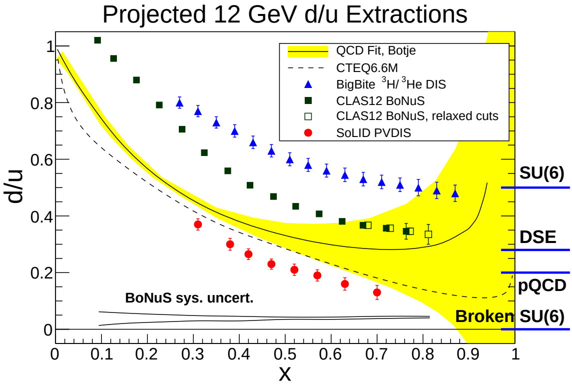
$$a_1^D(x) \approx 2\frac{C_{1u}e_u[u(x)+d(x)] + C_{1d}e_d[u(x)+d(x)]}{e_u^2[u(x)+d(x)] + e_d^2[u(x)+d(x)]}$$



- Uncertainties in MRST broad enough to fix or make NuTeV worse - constraint can be important!
- Differences in distributions would be present in deviation in x dependence from constant
- Important for other Z^0 experiments such as neutrino

Clean Measurement of d/u with PVDIS

- d/u as $x \to 1$ gives information on valence quark dynamics - models give varying predictions on behavior
- Flavor extraction difficult at high x because no free neutrons



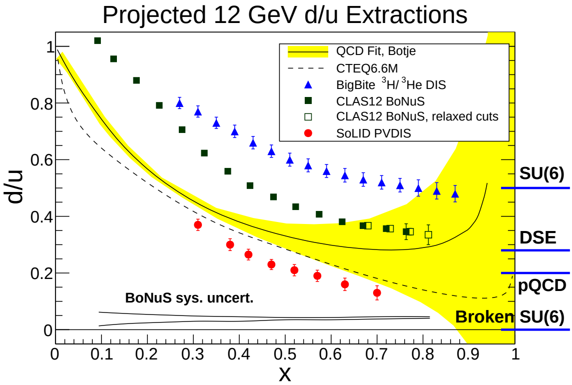
- Three JLab 12 GeV experiments:
  - CLAS12 BoNuS - spectator tagging
  - BigBite - DIS $^3\mathrm{H}/^3\mathrm{He}$ Ratio
  - SoLID - PVDIS *ep*
- The SoLID extraction of d/u is made directly from *ep* DIS: *no nuclear corrections*

DSE - Wilson *et al.*, Phys Rev C**89**, 025205 (2012)

Clean Measurement of d/u with PVDIS

For high x on proton target:

$$a_1^p(x) = \left[\frac{12C_{1u}u(x) - 6C_{1d}d(x)}{4u(x) + d(x)}\right] \approx \left[\frac{1 - 0.91d(x)/u(x)}{1 + 0.25d(x)/u(x)}\right]$$



- Three JLab 12 GeV experiments:
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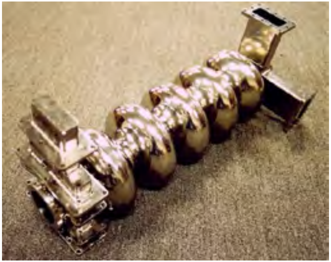
- The SoLID extraction of d/u is made directly from *ep* DIS: *no nuclear corrections*

DSE - Wilson *et al.*, Phys Rev C**89**, 025205 (2012)

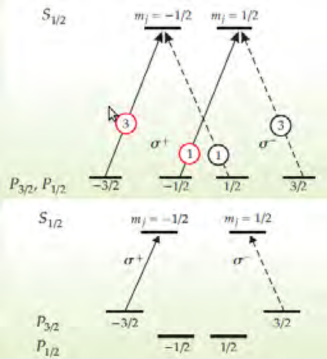
CEBAF Features



Properties

- Electron accelerator by superconducting RF cavities
- 4 experimental halls
- $E = 2.2 - 11\ \mathrm{GeV}$
- $I_{\max} = 200\ \mu\mathrm{A}$
- High $P_e \sim 85\%$

Polarized e^-, Strained GaAs



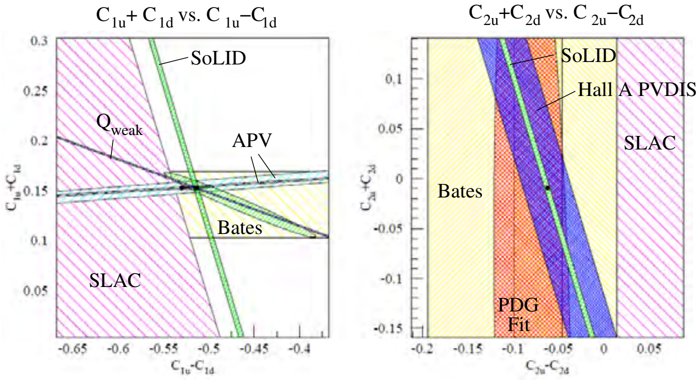
$\hbar c/m_p \sim 200\ \mathrm{MeV}$, ideal for studying inside of the nucleon

PVDIS Physics - Precision

- Deuterium powerful, since $q(x)$ cancel for large x

$$a_1^D(x) \approx 2\frac{C_{1u}e_u[u(x)+d(x)] + C_{1d}e_d[u(x)+d(x)]}{e_u^2[u(x)+d(x)] + e_d^2[u(x)+d(x)]}$$

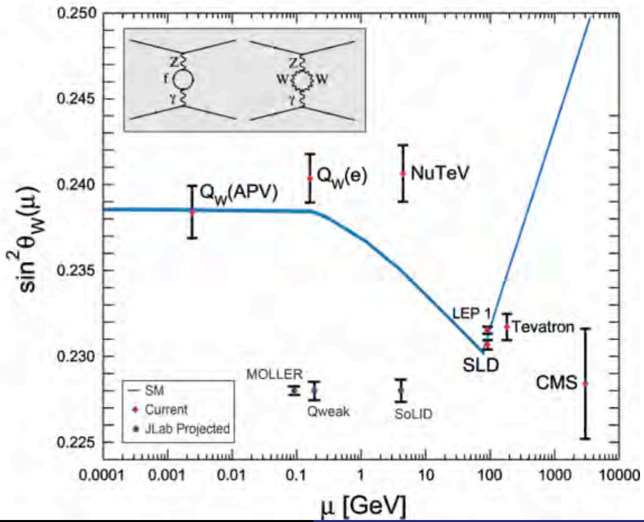
C_{2q} not as well constrained



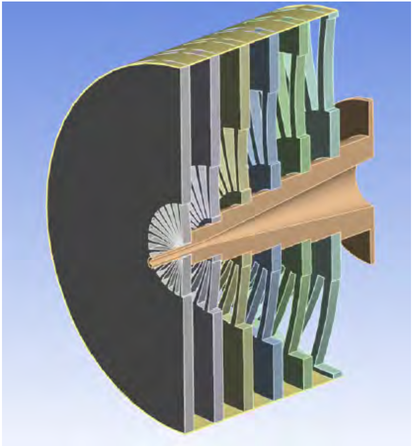
PVDIS Physics - Precision

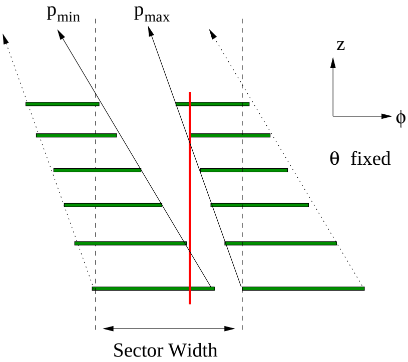
- Deuterium powerful, since $q(x)$ cancel for large x

Alternatively, gives us $\sin^2\theta_W$



Momentum Collimation





- Particles collimated by momentum through lead/tungsten "baffles"
- Line-of-sight photons must be blocked
- Reduces acceptance by $\sim$ 50%

Polarimetry

- Polarimetry required on the level of 0.4%
- Both Compton and Moller give 1% separately now
  - Run Compton electron and photon independently, must understand systematics - each $\sim 0.4\%$
  - Moller limited to about 0.8% systematics with brute force iron foils
- Atomic H_2 provides huge reduction in systematics
  - Use RF disassociation and trap in large $8\mathrm{T}$ solenoid
  - Could provide necessary 0.4% required
  - Enormous R&D effort required